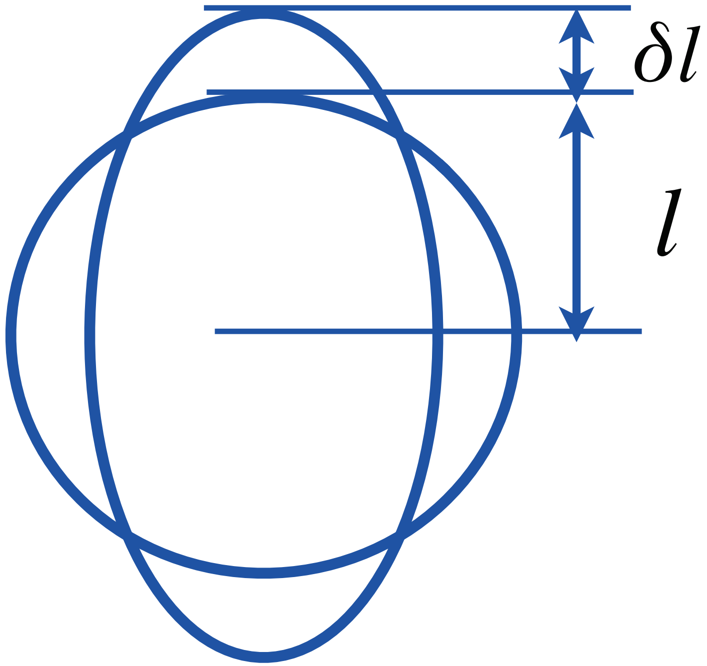
GW Searches: An Introduction

ISGWA-University of Delhi, December 2010

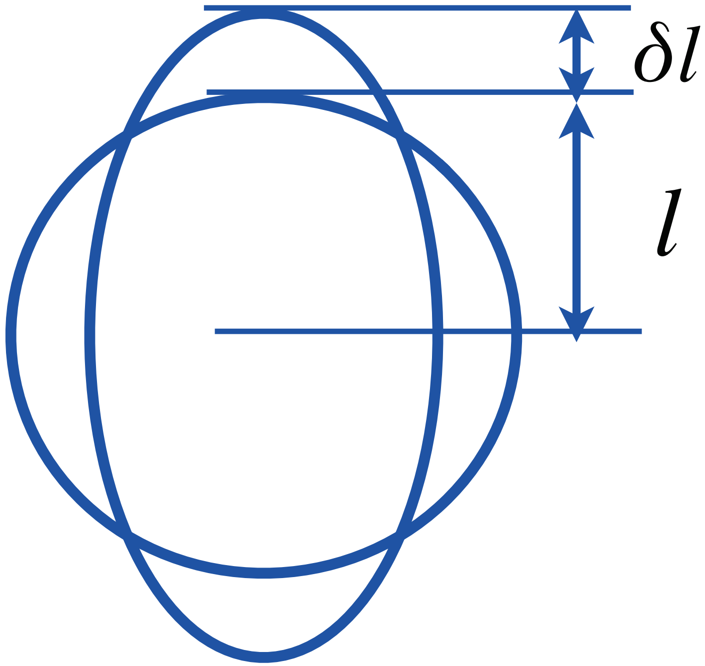
B.S. Sathyaprakash
Cardiff University

What do detectors measure?



$$\delta l = \frac{h}{2} l$$

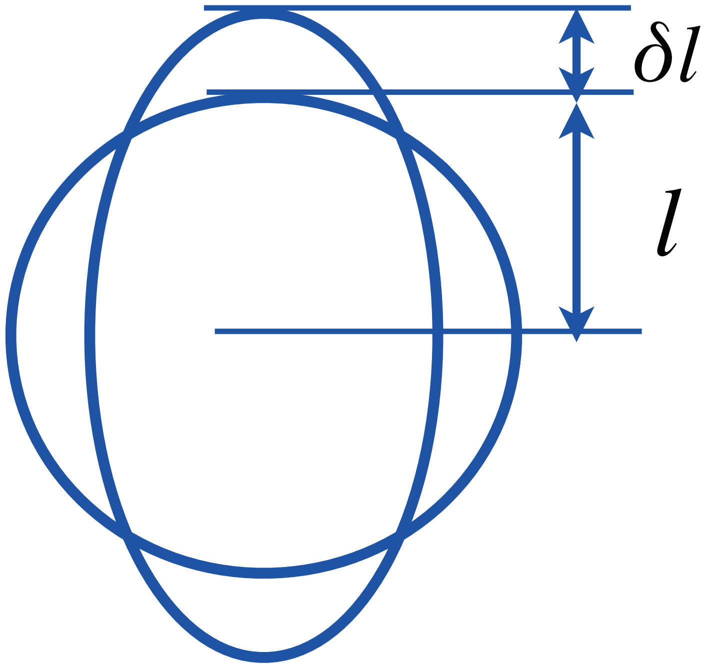
What do detectors measure?



$$\delta l = \frac{h}{2} l$$

- Gravitational waves cause a strain in space as they pass

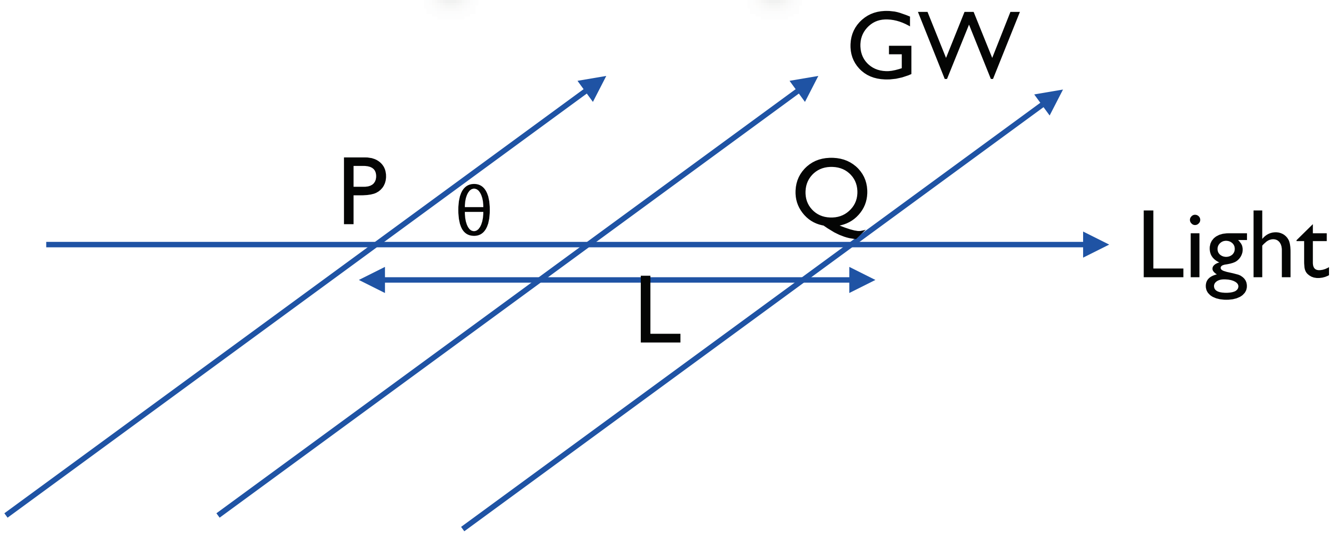
What do detectors measure?



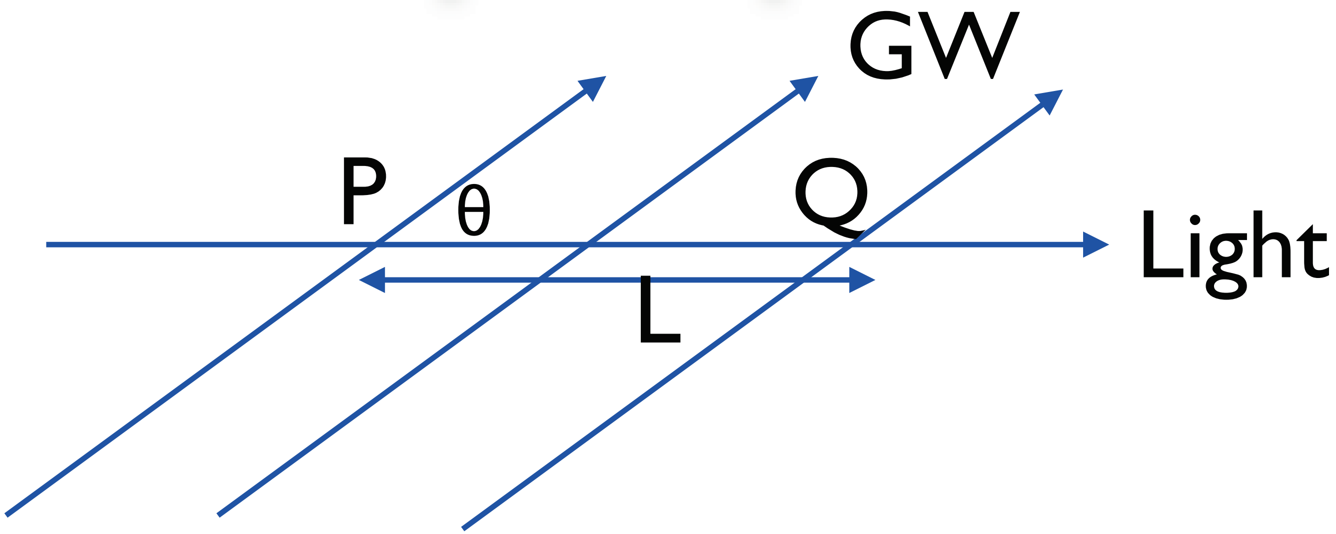
$$\delta l = \frac{h}{2} l$$

- Gravitational waves cause a strain in space as they pass
- Measurement of the strain gives the amplitude of gravitational waves but this is not the full metric perturbation h_{ij} that we are after

A Simple Experiment

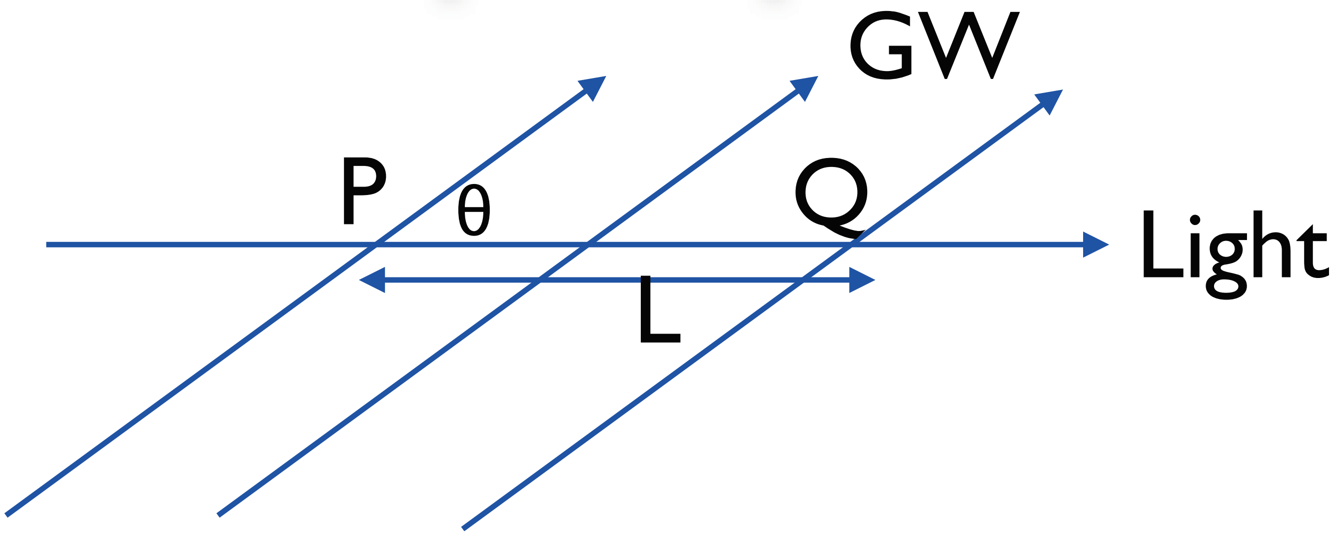


A Simple Experiment



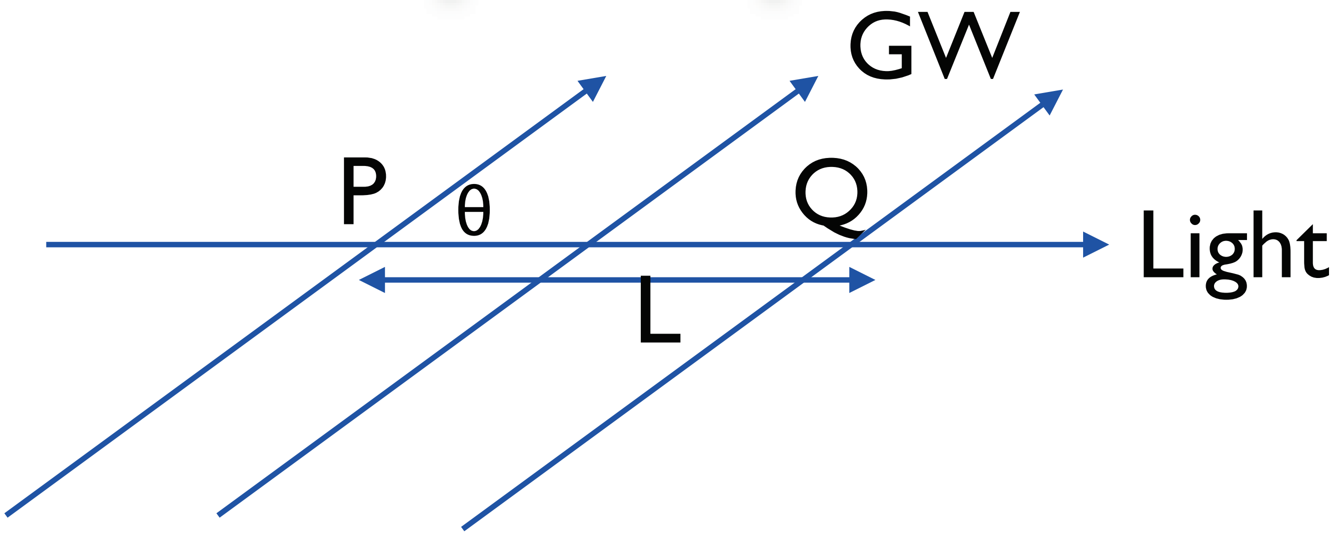
- A light beam starts at a point P and reaches a point Q a distance L away.

A Simple Experiment



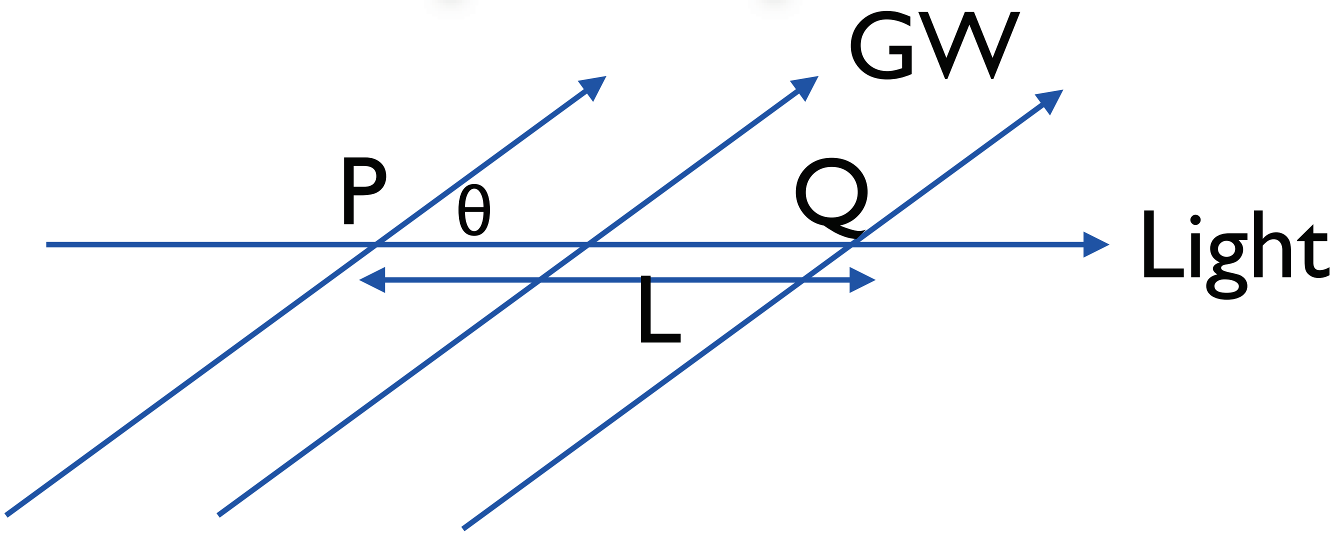
- A light beam starts at a point P and reaches a point Q a distance L away.
  - Clocks at P and Q have proper times t and t_f.

A Simple Experiment



- A light beam starts at a point P and reaches a point Q a distance L away.
  - Clocks at P and Q have proper times t and t_f.
- Gravitational wave h_+ is incident at an angle θ to the light beam

A Simple Experiment



- A light beam starts at a point P and reaches a point Q a distance L away.
  - Clocks at P and Q have proper times t and t_f.
- Gravitational wave h_+ is incident at an angle θ to the light beam

$$\frac{dt_f}{dt} = 1 + \frac{1}{2}(1 + \cos\theta)\left\{h_+[t + (1 - \cos\theta)L] - h_+(t)\right\}$$

Formula for return time

Formula for return time

- If we consider the round trip of a light beam from P to Q and back to Q then the time of return varies as

Formula for return time

- If we consider the round trip of a light beam from P to Q and back to Q then the time of return varies as

$$\begin{aligned}\frac{dt_{\mathrm{return}}}{dt} &= 1 + \frac{1}{2}\left\{(1-\cos\theta)\, h_+(t+2L) - (1+\cos\theta)\, h_+(t)\right. \\ &+ \left. 2\,\cos\theta\, h_+[t + L(1-\cos\theta)]\right\}.\end{aligned}$$

Formula for return time

- If we consider the round trip of a light beam from P to Q and back to Q then the time of return varies as

$$\begin{aligned}\frac{dt_{\rm return}}{dt} &= 1 + \frac{1}{2}\left\{(1-\cos\theta)\,h_+(t+2L) - (1+\cos\theta)\,h_+(t)\right.\\ &+ \left. 2\cos\theta\,h_+[t+L(1-\cos\theta)]\right\}.\end{aligned}$$

- In the long wavelength approximation this becomes

Formula for return time

- If we consider the round trip of a light beam from P to Q and back to Q then the time of return varies as

$$
\begin{aligned}
\frac{dt_{\mathrm{return}}}{dt} &= 1+\frac{1}{2}\left\{(1-\cos\theta)\,h_+(t+2L)-(1+\cos\theta)\,h_+(t)\right.\\
&+ \left. 2\,\cos\theta\,h_+[t+L(1-\cos\theta)]\right\}.
\end{aligned}
$$

- In the long wavelength approximation this becomes

$$\frac{dt_{\mathrm{return}}}{dt} = 1+\sin^2\theta L\dot{h}_+(t).$$

Timing formula for an interferometer

Timing formula for an interferometer

- In an interferometer we have two arms, say x-arm and y-arm.

Timing formula for an interferometer

- In an interferometer we have two arms, say x-arm and y-arm.
- What interferometers measure is the differential change in the return time

Timing formula for an interferometer

- In an interferometer we have two arms, say x-arm and y-arm.
- What interferometers measure is the differential change in the return time

$$\left(\frac{d\delta t_{\rm return}}{dt}\right) = \left(\frac{dt_{\rm return}}{dt}\right)_{\rm x-arm} - \left(\frac{dt_{\rm return}}{dt}\right)_{\rm y-arm}$$

Response of a detector to an incident wave

$$\mathbf{h}(t) = h_+(t)\mathbf{e}_+ + h_\times(t)\mathbf{e}_\times,$$

$$\mathbf{e}_+ = (\hat{e}_x^R \otimes \hat{e}_x^R - \hat{e}_y^R \otimes \hat{e}_y^R)$$

$$\mathbf{e}_\times = (\hat{e}_x^R \otimes \hat{e}_y^R + \hat{e}_y^R \otimes \hat{e}_x^R).$$

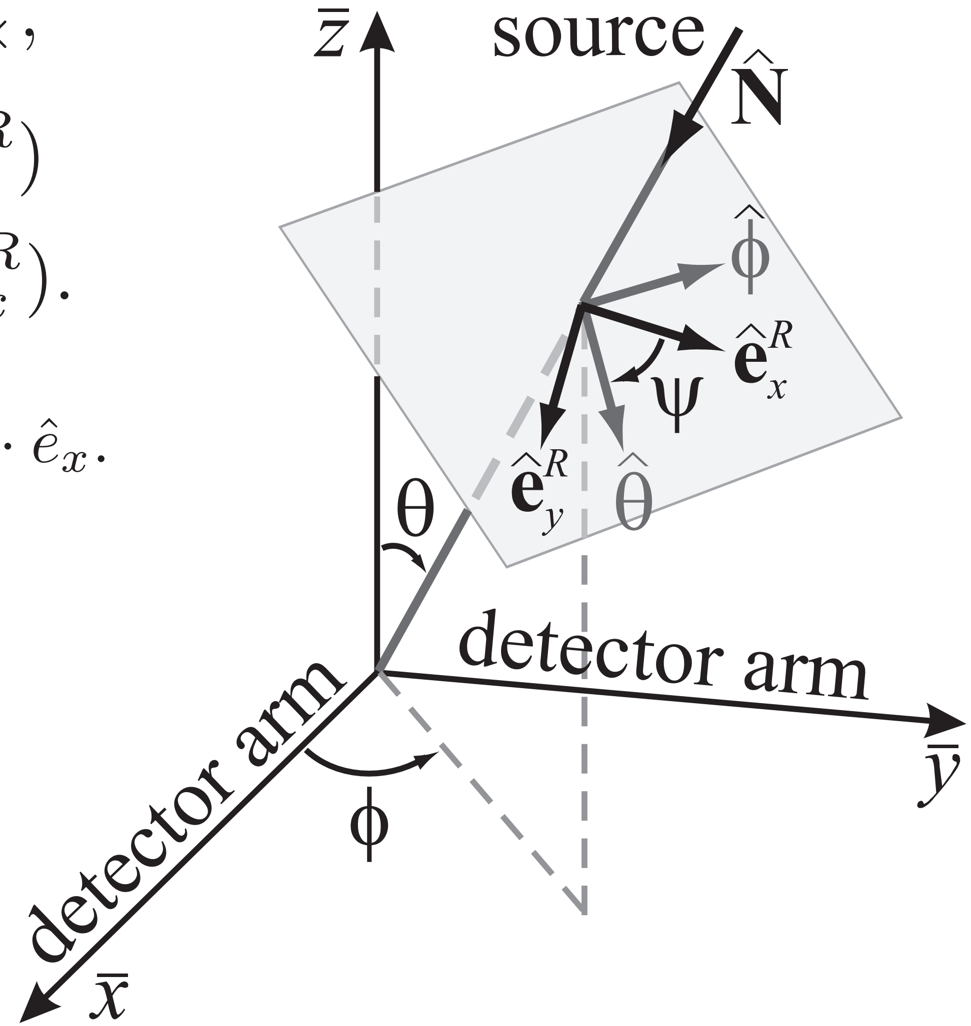
$$\left(\frac{dt_{\rm return}}{dt}\right)_{\rm x-arm} = 1 + L\hat{e}_x \cdot \dot{\mathbf{h}} \cdot \hat{e}_x.$$

$$\left(\frac{d\delta t_{\rm return}}{dt}\right) = \mathbf{d} : \dot{\mathbf{h}},$$

$$\delta t_{\rm return}(t) = \mathbf{d} : \mathbf{h}.$$

$$\mathbf{d} = L(\hat{e}_x \otimes \hat{e}_x - \hat{e}_y \otimes \hat{e}_y).$$

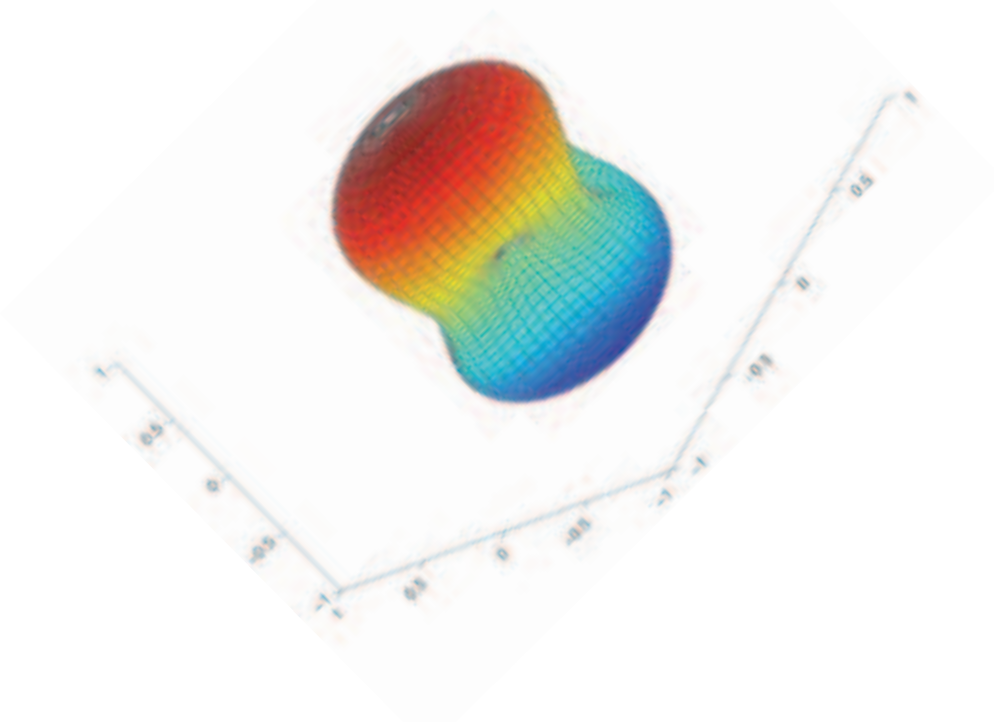
$$\delta L(t) = \frac{1}{2}\mathbf{d} : \mathbf{h}.$$

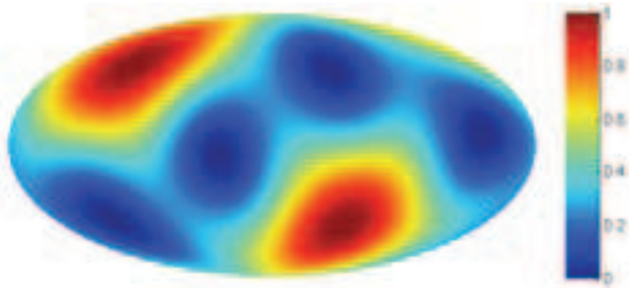


Antenna Pattern Functions

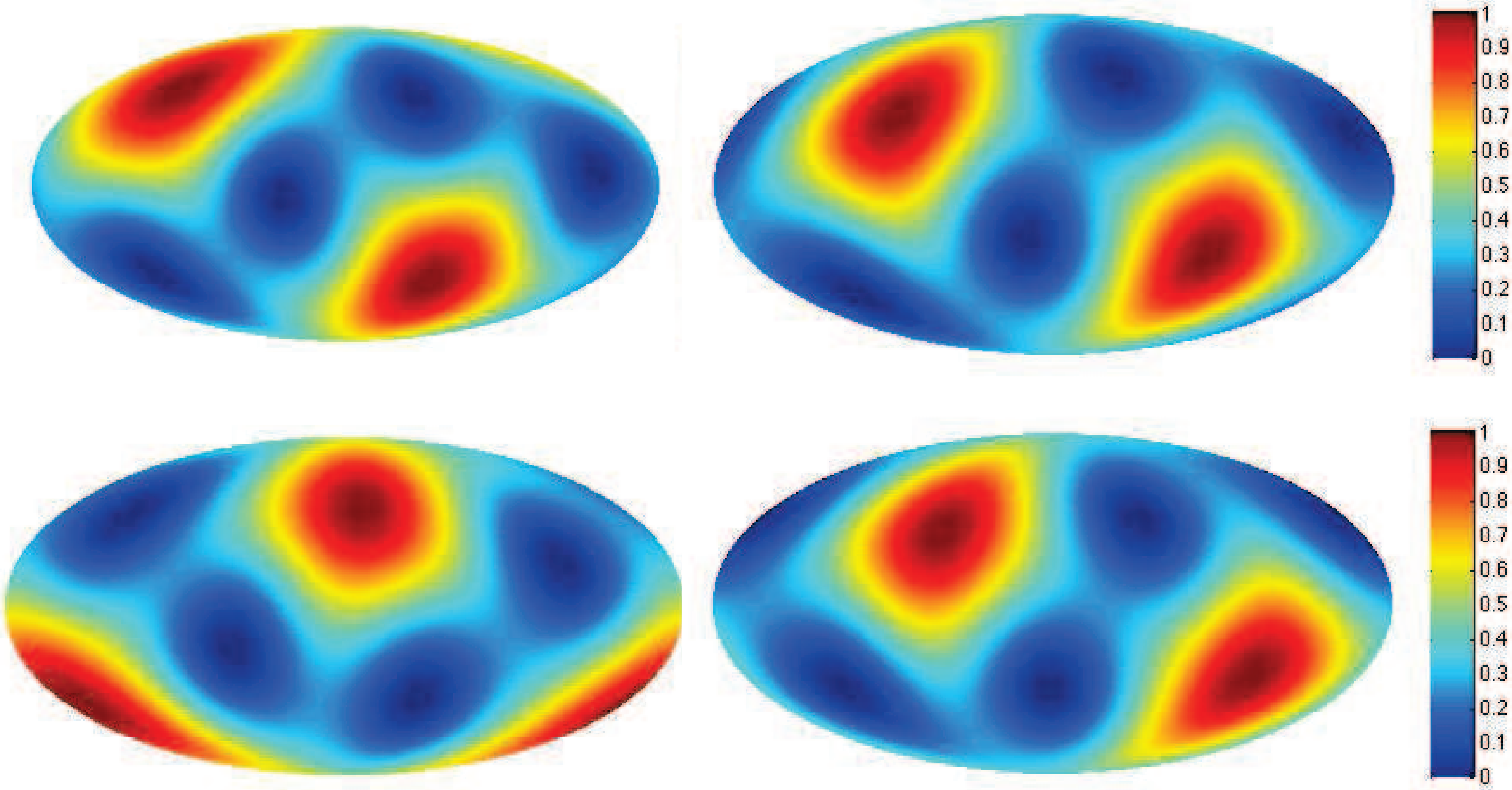
$$F_+ \equiv \mathbf{d} : \mathbf{e}_+, \quad F_\times \equiv \mathbf{d} : \mathbf{e}_\times .$$

$$\begin{aligned} F_+ &= \frac{1}{2}\left(1+\cos^2\theta\right)\cos 2\phi\cos 2\psi - \cos\theta\sin 2\phi\sin 2\psi, \\ F_\times &= \frac{1}{2}\left(1+\cos^2\theta\right)\cos 2\phi\sin 2\psi + \cos\theta\sin 2\phi\cos 2\psi. \end{aligned}$$





Antenna Patterns of Hanford, Livingston, Gingin and Virgo detectors



Why a global network

Why a global network

- Improved sky coverage

Why a global network

- Improved sky coverage
  - Non-overlapping antenna pattern => sky coverage

Why a global network

- Improved sky coverage
  - Non-overlapping antenna pattern => sky coverage
- Improved angular resolution/localization

Why a global network

- Improved sky coverage
  - Non-overlapping antenna pattern => sky coverage
- Improved angular resolution/localization
  - Longer baselines lead to greater time-delays and therefore improved angular resolution

Why a global network

- Improved sky coverage
  - Non-overlapping antenna pattern => sky coverage
- Improved angular resolution/localization
  - Longer baselines lead to greater time-delays and therefore improved angular resolution
- Improved distance reach

Why a global network

- Improved sky coverage
  - Non-overlapping antenna pattern => sky coverage
- Improved angular resolution/localization
  - Longer baselines lead to greater time-delays and therefore improved angular resolution
- Improved distance reach
  - For detectors in overlapping antenna patterns, great improvement in distance reach

Why a global network

- Improved sky coverage
  - Non-overlapping antenna pattern => sky coverage
- Improved angular resolution/localization
  - Longer baselines lead to greater time-delays and therefore improved angular resolution
- Improved distance reach
  - For detectors in overlapping antenna patterns, great improvement in distance reach
- Improved 3-way duty cycle

Why a global network

- Improved sky coverage
  - Non-overlapping antenna pattern => sky coverage
- Improved angular resolution/localization
  - Longer baselines lead to greater time-delays and therefore improved angular resolution
- Improved distance reach
  - For detectors in overlapping antenna patterns, great improvement in distance reach
- Improved 3-way duty cycle
  - If each detector has 80% duty cycle

Why a global network

- Improved sky coverage
  - Non-overlapping antenna pattern => sky coverage
- Improved angular resolution/localization
  - Longer baselines lead to greater time-delays and therefore improved angular resolution
- Improved distance reach
  - For detectors in overlapping antenna patterns, great improvement in distance reach
- Improved 3-way duty cycle
  - If each detector has 80% duty cycle
    - With three detectors, 3-way duty cycle is about 50%

Why a global network

- Improved sky coverage
  - Non-overlapping antenna pattern => sky coverage
- Improved angular resolution/localization
  - Longer baselines lead to greater time-delays and therefore improved angular resolution
- Improved distance reach
  - For detectors in overlapping antenna patterns, great improvement in distance reach
- Improved 3-way duty cycle
  - If each detector has 80% duty cycle
    - With three detectors, 3-way duty cycle is about 50%
    - With four detectors, >= 3-way duty cycle improves to 82%

Why a global network

- Improved sky coverage
  - Non-overlapping antenna pattern => sky coverage
- Improved angular resolution/localization
  - Longer baselines lead to greater time-delays and therefore improved angular resolution
- Improved distance reach
  - For detectors in overlapping antenna patterns, great improvement in distance reach
- Improved 3-way duty cycle
  - If each detector has 80% duty cycle
    - With three detectors, 3-way duty cycle is about 50%
    - With four detectors, >= 3-way duty cycle improves to 82%
    - With five detectors, >= 3-way duty cycle improves to 94%

Capabilities of Advanced GW Detector Networks

Schutz, 2010

Network	Maximum Range	Detection Volume	Capture Rate (at 80%)	Capture Rate (at 95%)	Sky Coverage	Network Accuracy
L	1.00	1.23	-	-	33.6%	-
HLV	1.43	5.76	2.95	4.94	71.8%	0.98
HHLV	1.74	8.98	4.86	7.81	47.3%	1.15
HLVA	1.69	8.93	6.06	8.28	53.5%	5.09
HHLVJ	1.82	12.1	8.37	11.25	73.5%	4.65
HHLVI	1.81	12.3	8.49	11.42	71.8%	3.93
HLVJA	1.76	12.1	8.71	11.25	85.0%	7.48
HHLVJI	1.85	15.8	11.43	14.72	91.4%	6.01
HLVJAI	1.85	15.8	11.50	14.69	94.5%	9.01

Source Localization

Source Localization

- A single detector cannot localize the source on the sky

Source Localization

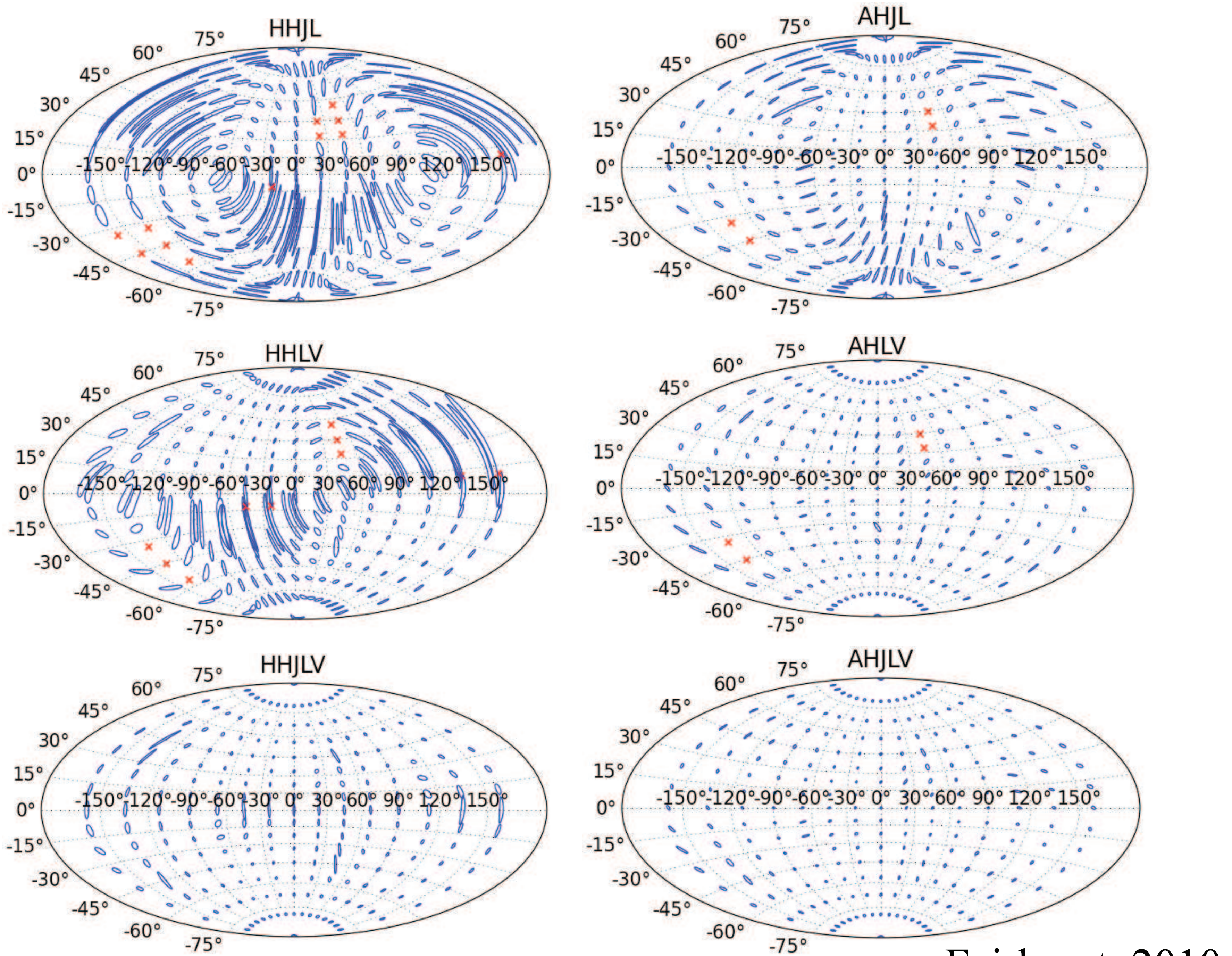
- A single detector cannot localize the source on the sky
  - The antenna pattern is too wide: good for sky coverage but bad for source localization

Source Localization

- A single detector cannot localize the source on the sky
  - The antenna pattern is too wide: good for sky coverage but bad for source localization
- A network of three or more detectors needed to reconstruct the source

Source Localization

- A single detector cannot localize the source on the sky
  - The antenna pattern is too wide: good for sky coverage but bad for source localization
- A network of three or more detectors needed to reconstruct the source
  - Alternatively, if the source lasts long enough, the detector motion can mimic multiple detectors and triangular a source



Fairhurst, 2010

Source Localization with Advanced Detector Network

Network	Detectable Sources	Sources Localized within			
		$1\,\mathrm{deg}^2$	$5\,\mathrm{deg}^2$	$10\,\mathrm{deg}^2$	$20\,\mathrm{deg}^2$
HHL	59	0	0	0	0
AHL	59	0.4	5	13	30
HHJL	85	0.2	2	5	14
AHJL	85	1	14	36	59
HHLV	83	0.4	5	13	35
AHLV	84	2	21	48	76
HHJLV	112	2	19	47	77
AHJLV	114	3	34	84	111

Fairhurst, 2010

Basic Problem: Measuring the Posterior Probability

Basic Problem: Measuring the Posterior Probability

- Let us imagine that it is required to determine if data *D* contains a Signal *S*

Basic Problem: Measuring the Posterior Probability

- Let us imagine that it is required to determine if data *D* contains a Signal *S*
- The problem can be cast in terms of Baye's theorem

Basic Problem: Measuring the Posterior Probability

- Let us imagine that it is required to determine if data D contains a Signal S
- The problem can be cast in terms of Baye's theorem

$$P(S|D)=P(D|S)\ P(S)/P(D)$$

Basic Problem: Measuring the Posterior Probability

- Let us imagine that it is required to determine if data D contains a Signal S
- The problem can be cast in terms of Baye's theorem

$$P(S|D)=P(D|S)\ P(S)/P(D)$$

- In words this states the following

$$\text{The posterior probability of finding signal } S \text{ in data } D = \frac{\text{Likelihood of getting data } D \text{ given that it contains signal } S \times \text{The prior probability of getting a signal } S}{\text{The probability getting in data } D}$$

An Illustrative Problem in Disease Diagnostics

An Illustrative Problem in Disease Diagnostics

- Brent's syndrome is a very rare disease occurring only in one in a million people

An Illustrative Problem in Disease Diagnostics

- Brent's syndrome is a very rare disease occurring only in one in a million people
- A test called Cytose-A is performed to see if John Smith has Brent's Syndrome

An Illustrative Problem in Disease Diagnostics

- Brent's syndrome is a very rare disease occurring only in one in a million people
- A test called Cytose-A is performed to see if John Smith has Brent's Syndrome
- The following statistics is known about Cytose-A

An Illustrative Problem in Disease Diagnostics

- Brent's syndrome is a very rare disease occurring only in one in a million people
- A test called Cytose-A is performed to see if John Smith has Brent's Syndrome
- The following statistics is known about Cytose-A
  - The test gives a true positive (true alarm probability) 99% of the time

An Illustrative Problem in Disease Diagnostics

- Brent's syndrome is a very rare disease occurring only in one in a million people
- A test called Cytose-A is performed to see if John Smith has Brent's Syndrome
- The following statistics is known about Cytose-A
  - The test gives a true positive (true alarm probability) 99% of the time
    - The test returns a positive result for every 99 out of 100 patients with Brent's Syndrome

An Illustrative Problem in Disease Diagnostics

- Brent's syndrome is a very rare disease occurring only in one in a million people
- A test called Cytose-A is performed to see if John Smith has Brent's Syndrome
- The following statistics is known about Cytose-A
  - The test gives a true positive (true alarm probability) 99% of the time
    - The test returns a positive result for every 99 out of 100 patients with Brent's Syndrome
  - The test gives a false positive (false alarm probability) 0.1% of the time

An Illustrative Problem in Disease Diagnostics

- Brent's syndrome is a very rare disease occurring only in one in a million people
- A test called Cytose-A is performed to see if John Smith has Brent's Syndrome
- The following statistics is known about Cytose-A
  - The test gives a true positive (true alarm probability) 99% of the time
    - The test returns a positive result for every 99 out of 100 patients with Brent's Syndrome
  - The test gives a false positive (false alarm probability) 0.1% of the time
    - The test returns a positive result one in 1000 cases when the subject has no disease

An Illustrative Problem in Disease Diagnostics

- Brent's syndrome is a very rare disease occurring only in one in a million people
- A test called Cytose-A is performed to see if John Smith has Brent's Syndrome
- The following statistics is known about Cytose-A
  - The test gives a true positive (true alarm probability) 99% of the time
    - The test returns a positive result for every 99 out of 100 patients with Brent's Syndrome
  - The test gives a false positive (false alarm probability) 0.1% of the time
    - The test returns a positive result one in 1000 cases when the subject has no disease
- The test on John Smith returns a positive result

An Illustrative Problem in Disease Diagnostics

- Brent’s syndrome is a very rare disease occurring only in one in a million people
- A test called Cytose-A is performed to see if John Smith has Brent’s Syndrome
- The following statistics is known about Cytose-A
  - The test gives a true positive (true alarm probability) 99% of the time
    - The test returns a positive result for every 99 out of 100 patients with Brent’s Syndrome
  - The test gives a false positive (false alarm probability) 0.1% of the time
    - The test returns a positive result one in 1000 cases when the subject has no disease
- The test on John Smith returns a positive result
  - How likely is it that John Smith has Brent’s Syndrome?

Generality of Baye’s Theorem

Generality of Baye's Theorem

- Baye's theorem is completely general; it can be used to ask very sophisticated questions

Generality of Baye’s Theorem

- Baye’s theorem is completely general; it can be used to ask very sophisticated questions
- Examples:

Generality of Baye's Theorem

- Baye's theorem is completely general; it can be used to ask very sophisticated questions
- Examples:
  - What is the posterior probability that the data contains inspiral of a neutron star binary composed of components of masses 1.483 and 1.926, located at the Virgo supercluster with the epoch of merger being 14 December 2010 at 5 past mid-night?

Generality of Baye's Theorem

- Baye's theorem is completely general; it can be used to ask very sophisticated questions
- Examples:
  - What is the posterior probability that the data contains inspiral of a neutron star binary composed of components of masses 1.483 and 1.926, located at the Virgo supercluster with the epoch of merger being 14 December 2010 at 5 past mid-night?
  - What is the probability that the data contains a glitch in the frequency band 200-450 Hz lasting for 20 ms at the same time as supernova 2010a?

The goal of any search

The goal of any search

- The goal of any search is to detect a signal and measure its parameters: Maximize the likelihood

The goal of any search

- The goal of any search is to detect a signal and measure its parameters: Maximize the likelihood
- The joint problem is generally very hard to solve and computationally formidable

The goal of any search

- The goal of any search is to detect a signal and measure its parameters: Maximize the likelihood
- The joint problem is generally very hard to solve and computationally formidable
  - For example, the best strategy to search for coalescences of black holes is to carry out a fully coherent search in a 16-dimensional parameter space using data from a network of detectors

The goal of any search

- The goal of any search is to detect a signal and measure its parameters: Maximize the likelihood
- The joint problem is generally very hard to solve and computationally formidable
  - For example, the best strategy to search for coalescences of black holes is to carry out a fully coherent search in a 16-dimensional parameter space using data from a network of detectors
  - But this is far too computationally expensive and algorithmically hard to implement

The goal of any search

- The goal of any search is to detect a signal and measure its parameters: Maximize the likelihood
- The joint problem is generally very hard to solve and computationally formidable
  - For example, the best strategy to search for coalescences of black holes is to carry out a fully coherent search in a 16-dimensional parameter space using data from a network of detectors
  - But this is far too computationally expensive and algorithmically hard to implement
- One has to resort to approximate techniques

The goal of any search

- The goal of any search is to detect a signal and measure its parameters: Maximize the likelihood
- The joint problem is generally very hard to solve and computationally formidable
  - For example, the best strategy to search for coalescences of black holes is to carry out a fully coherent search in a 16-dimensional parameter space using data from a network of detectors
  - But this is far too computationally expensive and algorithmically hard to implement
- One has to resort to approximate techniques
  - Treat the two problems separately

The goal of any search

- The goal of any search is to detect a signal and measure its parameters: Maximize the likelihood
- The joint problem is generally very hard to solve and computationally formidable
  - For example, the best strategy to search for coalescences of black holes is to carry out a fully coherent search in a 16-dimensional parameter space using data from a network of detectors
  - But this is far too computationally expensive and algorithmically hard to implement
- One has to resort to approximate techniques
  - Treat the two problems separately
  - Make simplifying assumptions about the signal: For example search carry out a coincidence search for non-spinning black hole binaries in a network of detectors

The goal of any search

- The goal of any search is to detect a signal and measure its parameters: Maximize the likelihood
- The joint problem is generally very hard to solve and computationally formidable
  - For example, the best strategy to search for coalescences of black holes is to carry out a fully coherent search in a 16-dimensional parameter space using data from a network of detectors
  - But this is far too computationally expensive and algorithmically hard to implement
- One has to resort to approximate techniques
  - Treat the two problems separately
  - Make simplifying assumptions about the signal: For example search carry out a coincidence search for non-spinning black hole binaries in a network of detectors
  - If interesting signals are found carry out a more exhaustive search

Matched Filtering

Matched Filtering

- From Baye's theorem it is clear that posterior probability will be maximized if the likelihood is maximized

Matched Filtering

- From Baye's theorem it is clear that posterior probability will be maximized if the likelihood is maximized
- The problem of searching for a signal of known shape buried in noise boils down to maximizing the likelihood

Matched Filtering

- From Baye's theorem it is clear that posterior probability will be maximized if the likelihood is maximized
- The problem of searching for a signal of known shape buried in noise boils down to maximizing the likelihood
- Assume that the detector noise obeys normal distribution with zero mean and width σ

Matched Filtering

- From Baye's theorem it is clear that posterior probability will be maximized if the likelihood is maximized
- The problem of searching for a signal of known shape buried in noise boils down to maximizing the likelihood
- Assume that the detector noise obeys normal distribution with zero mean and width σ

$$P(x)\ dx = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-x^2}{2\sigma^2}\right)\ dx$$

Matched Filtering

- From Baye's theorem it is clear that posterior probability will be maximized if the likelihood is maximized
- The problem of searching for a signal of known shape buried in noise boils down to maximizing the likelihood
- Assume that the detector noise obeys normal distribution with zero mean and width σ

$$P(x)\ dx = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-x^2}{2\sigma^2}\right)\ dx$$

- In the presence of a signal the detector output will again be normal but with the mean shifted to a non-zero value

Matched Filtering

- From Baye's theorem it is clear that posterior probability will be maximized if the likelihood is maximized
- The problem of searching for a signal of known shape buried in noise boils down to maximizing the likelihood
- Assume that the detector noise obeys normal distribution with zero mean and width σ

$$P(x)\ dx = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(\frac{-x^2}{2\sigma^2}\right)\ dx$$

- In the presence of a signal the detector output will again be normal but with the mean shifted to a non-zero value
- Instead of maximizing the likelihood one can, equivalently, maximize the Log(likelihood). This gives the matched filtering statistic.

Matched Filtering Statistic

Matched Filtering Statistic

- The matched filtering statistic is the cross-correlation between the detector output and a matched filter

Matched Filtering Statistic

- The matched filtering statistic is the cross-correlation between the detector output and a matched filter

$$c(\tau) \equiv \int_{-\infty}^{\infty} x(t) q(t+\tau)\, \mathrm{d}t. \qquad c(\tau) = \int_{-\infty}^{\infty} \tilde{x}(f) \tilde{q}^*(f) e^{-2\pi i f \tau}\, \mathrm{d}f$$

$$\tilde{q}(f) = \gamma \frac{\tilde{h}(f) e^{i2\pi f(\tau - t_a)}}{S_h(f)} \qquad \overline{\tilde{n}(f)\tilde{n}^*(f')} = \frac{1}{2} S_h(f) \delta(f - f')$$

Matched Filtering Statistic

- The matched filtering statistic is the cross-correlation between the detector output and a matched filter

$$c(\tau) \equiv \int_{-\infty}^{\infty} x(t)q(t+\tau)\ \mathrm{d}t. \qquad c(\tau) = \int_{-\infty}^{\infty} \tilde{x}(f)\tilde{q}^*(f)e^{-2\pi i f \tau}\ \mathrm{d}f$$

$$\tilde{q}(f) = \gamma \frac{\tilde{h}(f)e^{i2\pi f(\tau - t_a)}}{S_h(f)} \qquad \overline{\tilde{n}(f)\tilde{n}^*(f')} = \frac{1}{2}S_h(f)\delta(f-f')$$

- The optimal signal-to-noise ratio resulting from the matched filtering statistic is

Matched Filtering Statistic

- The matched filtering statistic is the cross-correlation between the detector output and a matched filter

$$c(\tau) \equiv \int_{-\infty}^{\infty} x(t)q(t+\tau)\ \mathrm{d}t. \qquad c(\tau) = \int_{-\infty}^{\infty} \tilde{x}(f)\tilde{q}^*(f)e^{-2\pi i f\tau}\,\mathrm{d}f$$

$$\tilde{q}(f) = \gamma\frac{\tilde{h}(f)e^{i2\pi f(\tau-t_a)}}{S_h(f)} \qquad \overline{\tilde{n}(f)\tilde{n}^*(f')} = \frac{1}{2}S_h(f)\delta(f-f')$$

- The optimal signal-to-noise ratio resulting from the matched filtering statistic is

$$\rho_{\mathrm{opt}} = \langle h, h\rangle^{1/2} = 2\left[\int_0^{\infty}\mathrm{d}f\,\frac{\left|\tilde{h}(f)\right|^2}{S_h(f)}\right]^{1/2}$$

Matched Filtering Statistic

- The matched filtering statistic is the cross-correlation between the detector output and a matched filter

$$c(\tau) \equiv \int_{-\infty}^{\infty} x(t)q(t+\tau)\ \mathrm{d}t. \qquad c(\tau) = \int_{-\infty}^{\infty} \tilde{x}(f)\tilde{q}^*(f)e^{-2\pi i f\tau}\,\mathrm{d}f$$

$$\tilde{q}(f) = \gamma \frac{\tilde{h}(f)e^{i2\pi f(\tau - t_a)}}{S_h(f)} \qquad \overline{\tilde{n}(f)\tilde{n}^*(f')} = \frac{1}{2}S_h(f)\delta(f-f')$$

- The optimal signal-to-noise ratio resulting from the matched filtering statistic is

$$\rho_{\mathrm{opt}} = \langle h, h\rangle^{1/2} = 2\left[\int_0^{\infty} \mathrm{d}f \frac{\left|\tilde{h}(f)\right|^2}{S_h(f)}\right]^{1/2}$$

$$\langle a, b\rangle \equiv 2\int_0^{\infty} \frac{\mathrm{d}f}{S_h(f)}\left[\tilde{a}(f)\tilde{b}^*(f) + \tilde{a}^*(f)\tilde{b}(f)\right]$$

Geometrical approach to signal analysis

Geometrical approach to signal analysis

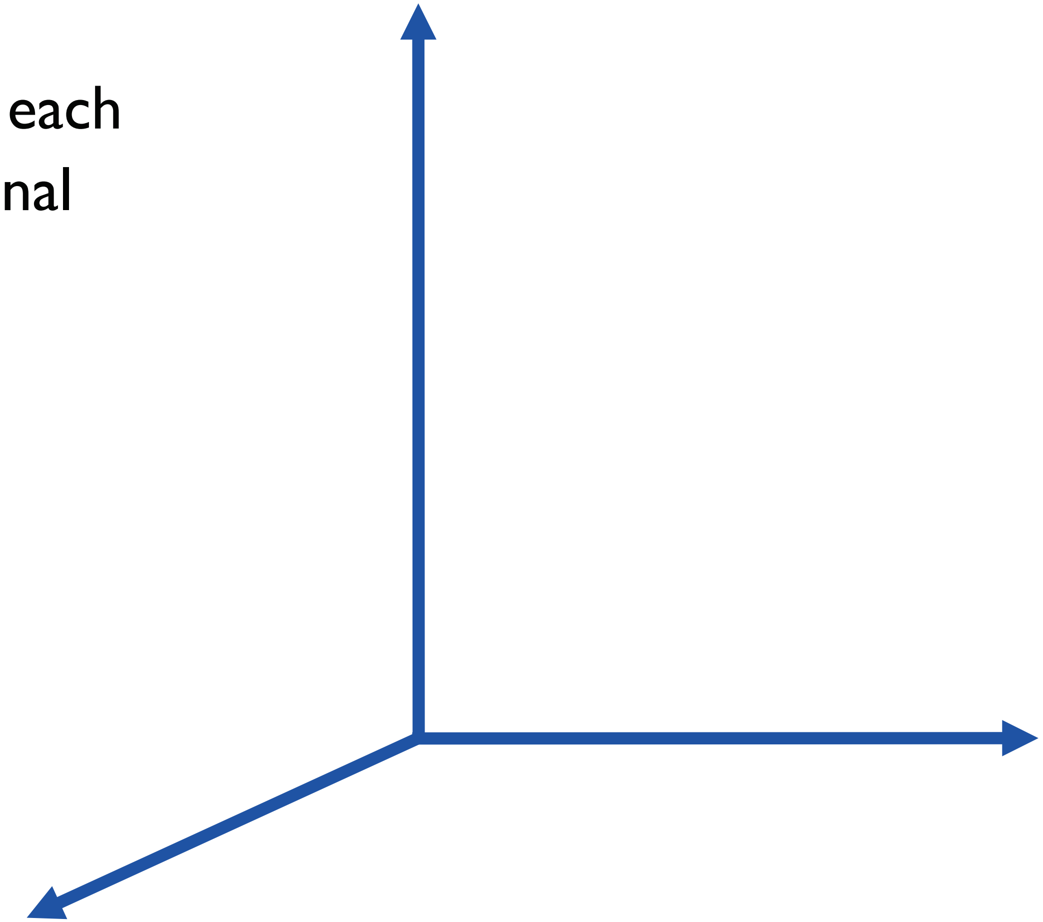
- An analysis begins with a chunk of data *N* samples long

Geometrical approach to signal analysis

- An analysis begins with a chunk of data N samples long
- The set of all data chunks $\{x_k\}$ each of size N form an N-dimensional vector space

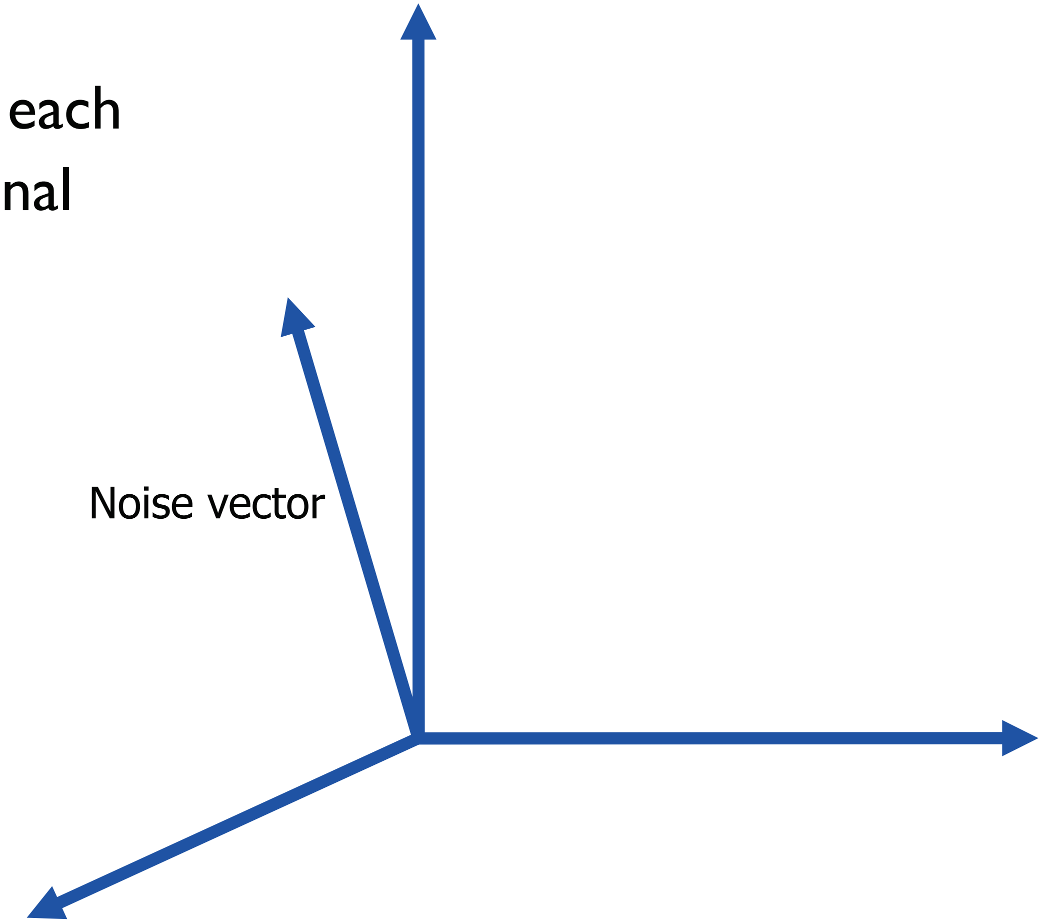
Geometrical approach to signal analysis

- An analysis begins with a chunk of data N samples long
- The set of all data chunks $\{x_k\}$ each of size N form an N-dimensional vector space



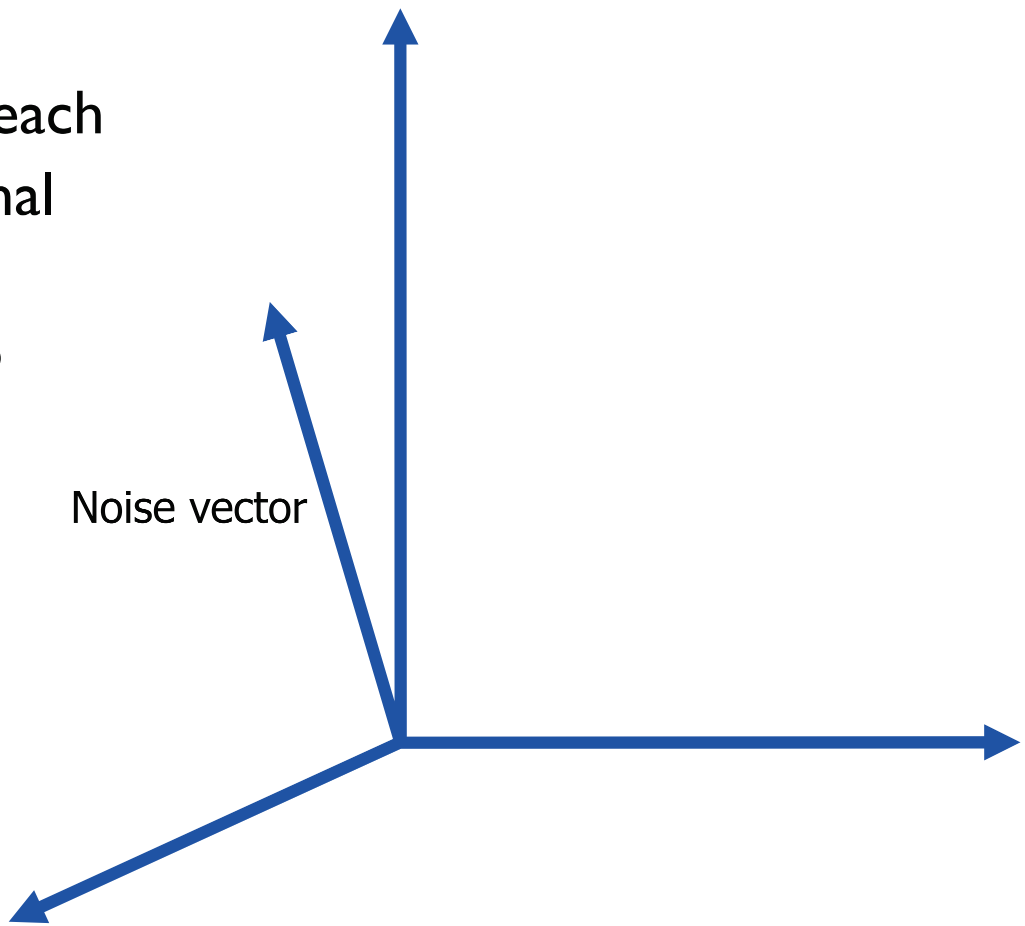
Geometrical approach to signal analysis

- An analysis begins with a chunk of data N samples long
- The set of all data chunks $\{x_k\}$ each of size N form an N-dimensional vector space



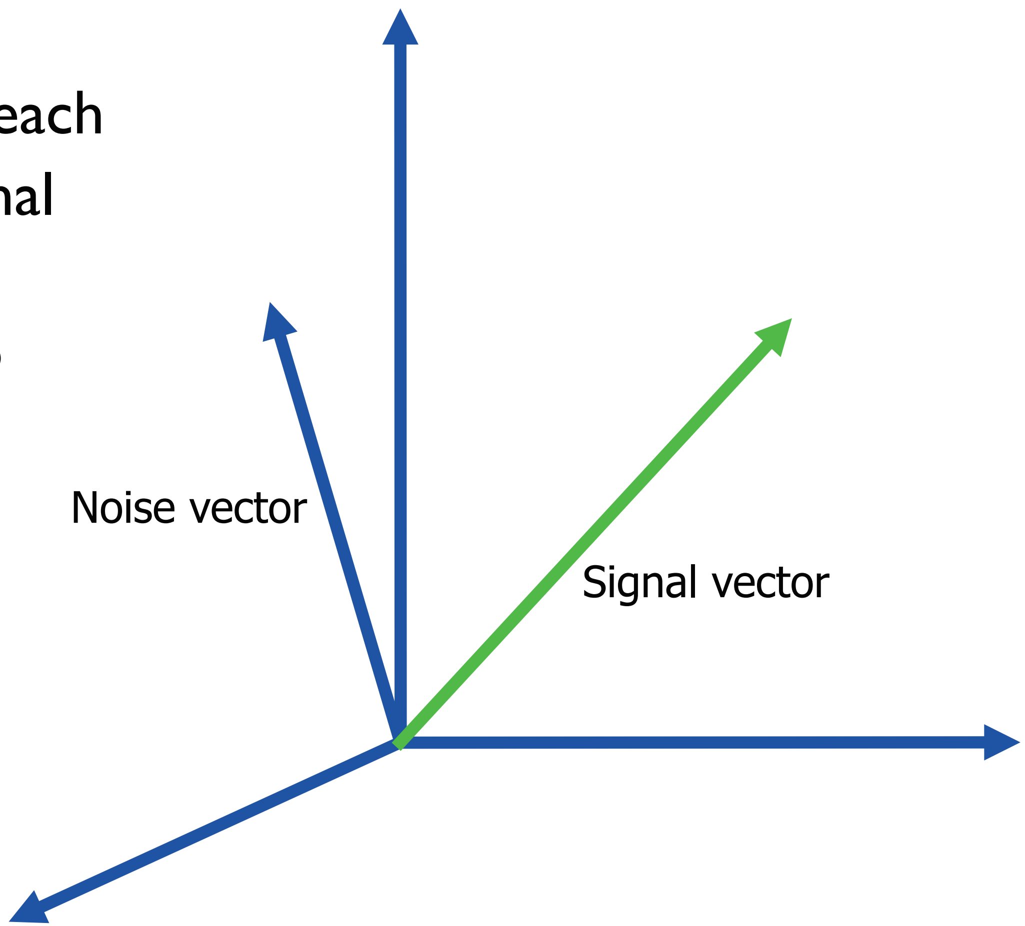
Geometrical approach to signal analysis

- An analysis begins with a chunk of data N samples long
- The set of all data chunks $\{x_k\}$ each of size N form an N-dimensional vector space
- Signals from a source are also vectors but they don't form a vector space



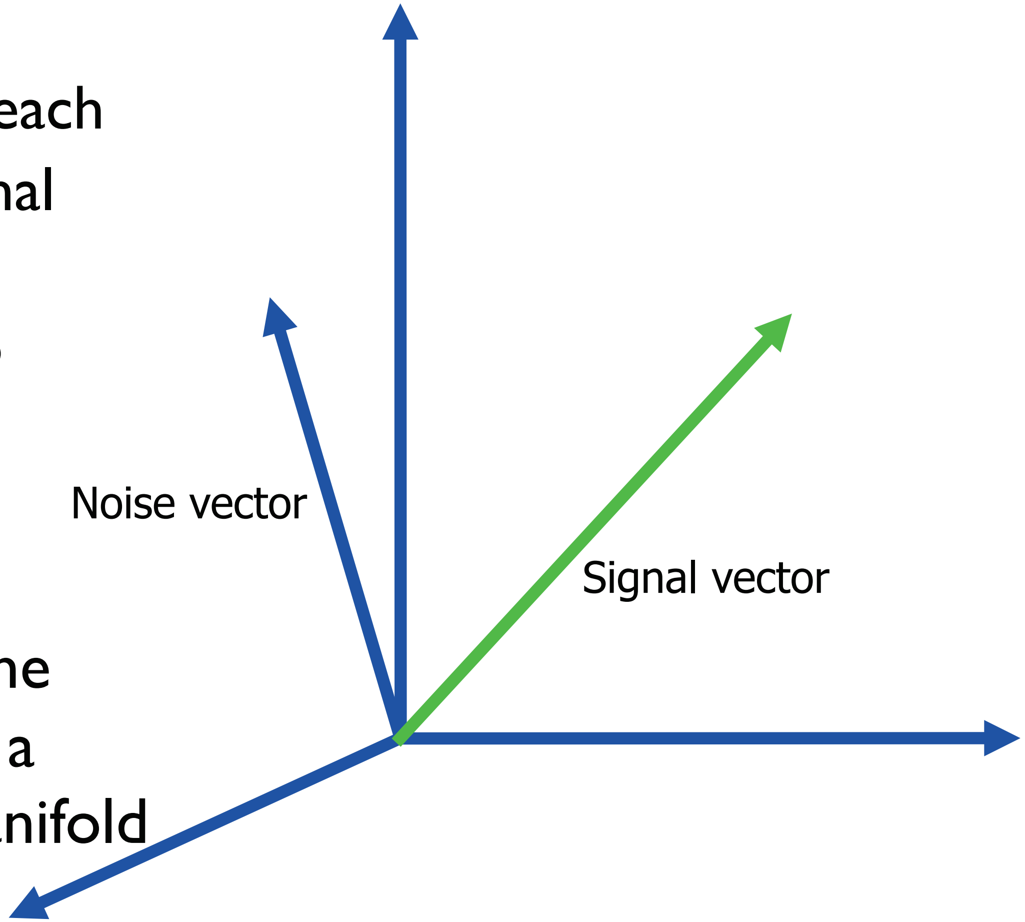
Geometrical approach to signal analysis

- An analysis begins with a chunk of data N samples long
- The set of all data chunks $\{x_k\}$ each of size N form an N-dimensional vector space
- Signals from a source are also vectors but they don't form a vector space



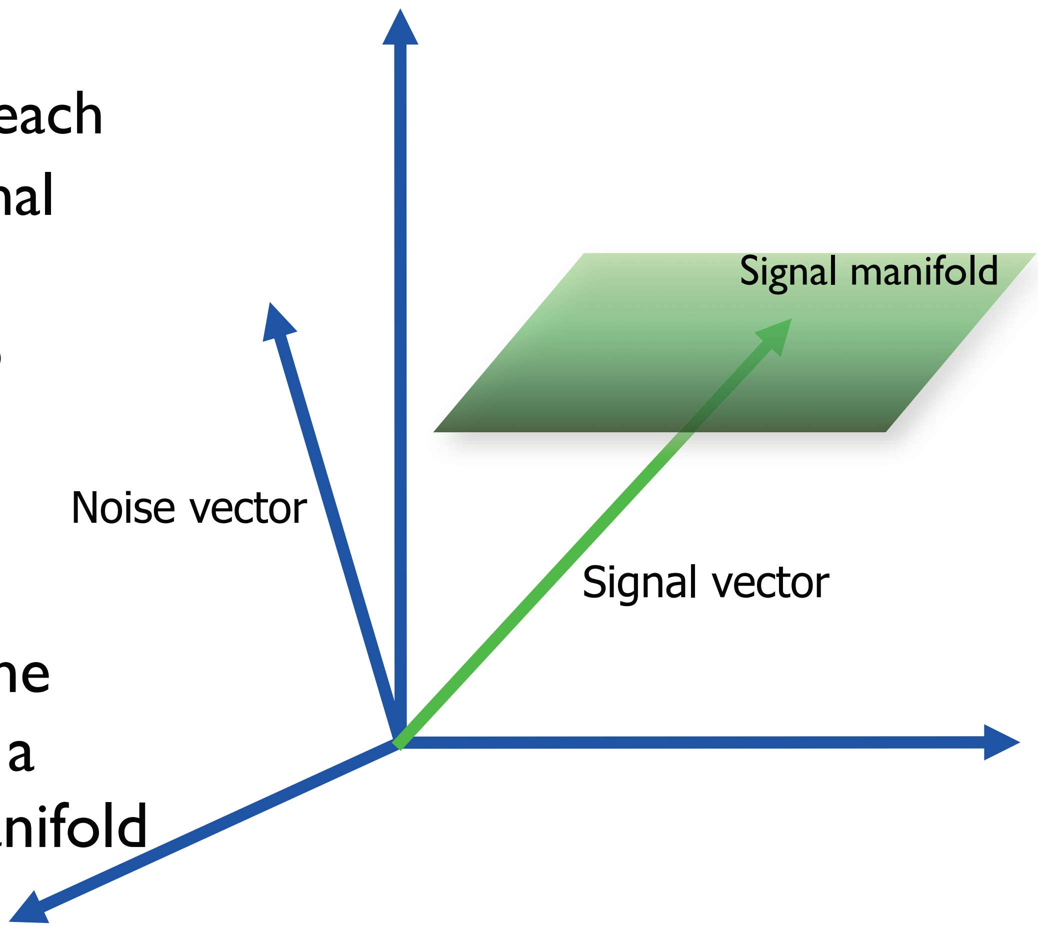
Geometrical approach to signal analysis

- An analysis begins with a chunk of data N samples long
- The set of all data chunks $\{x_k\}$ each of size N form an N-dimensional vector space
- Signals from a source are also vectors but they don't form a vector space
- However, the set of all signal vectors do form a manifold; the signal parameters λ^a serve as a coordinate system on this manifold



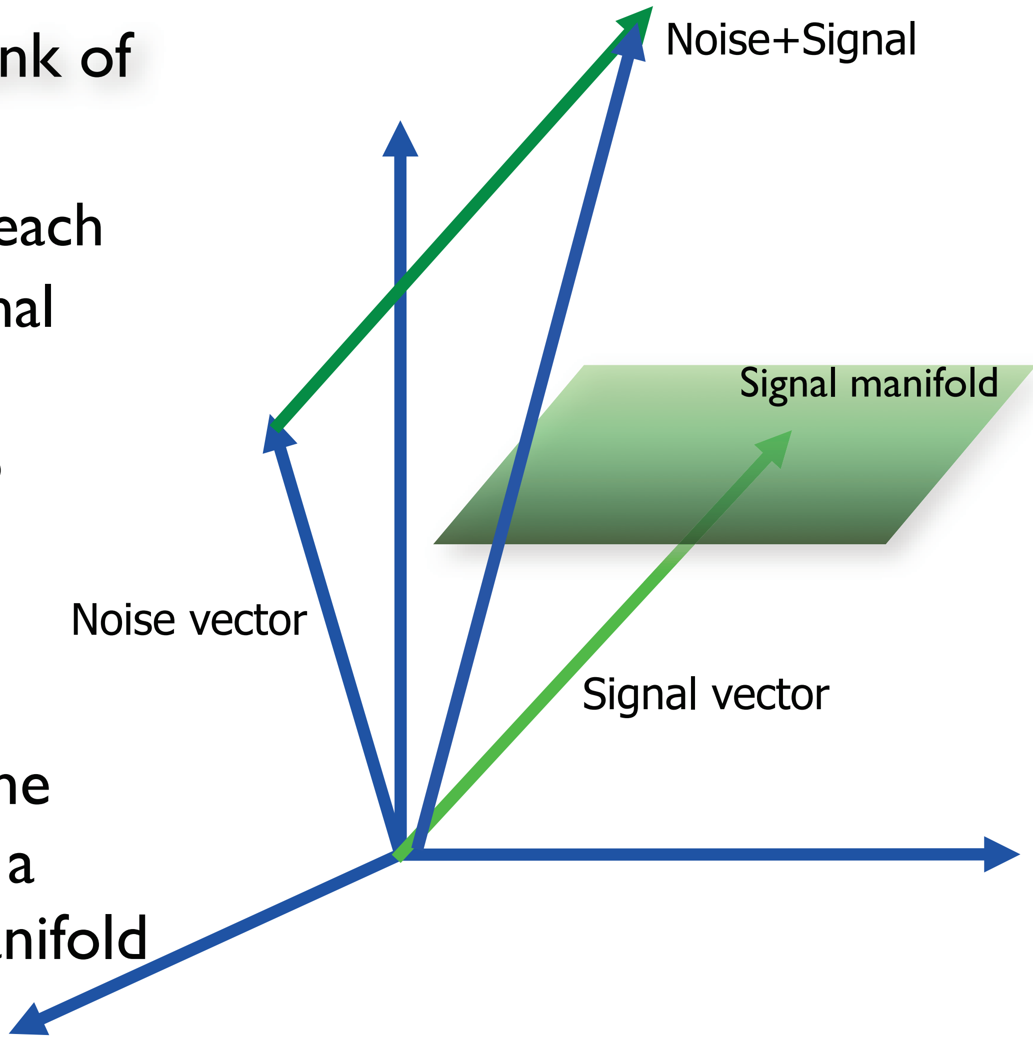
Geometrical approach to signal analysis

- An analysis begins with a chunk of data N samples long
- The set of all data chunks $\{x_k\}$ each of size N form an N-dimensional vector space
- Signals from a source are also vectors but they don't form a vector space
- However, the set of all signal vectors do form a manifold; the signal parameters λ^a serve as a coordinate system on this manifold



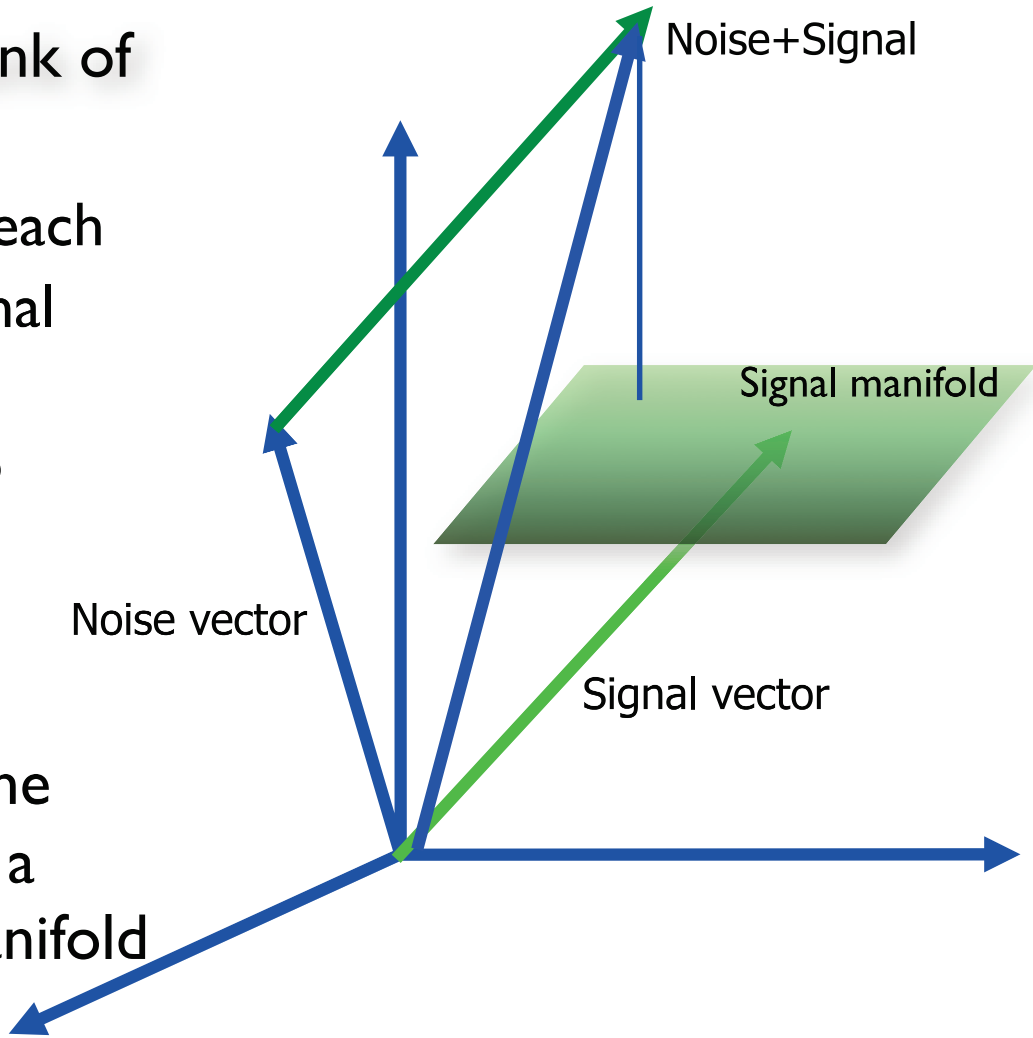
Geometrical approach to signal analysis

- An analysis begins with a chunk of data N samples long
- The set of all data chunks $\{x_k\}$ each of size N form an N-dimensional vector space
- Signals from a source are also vectors but they don't form a vector space
- However, the set of all signal vectors do form a manifold; the signal parameters λ^a serve as a coordinate system on this manifold



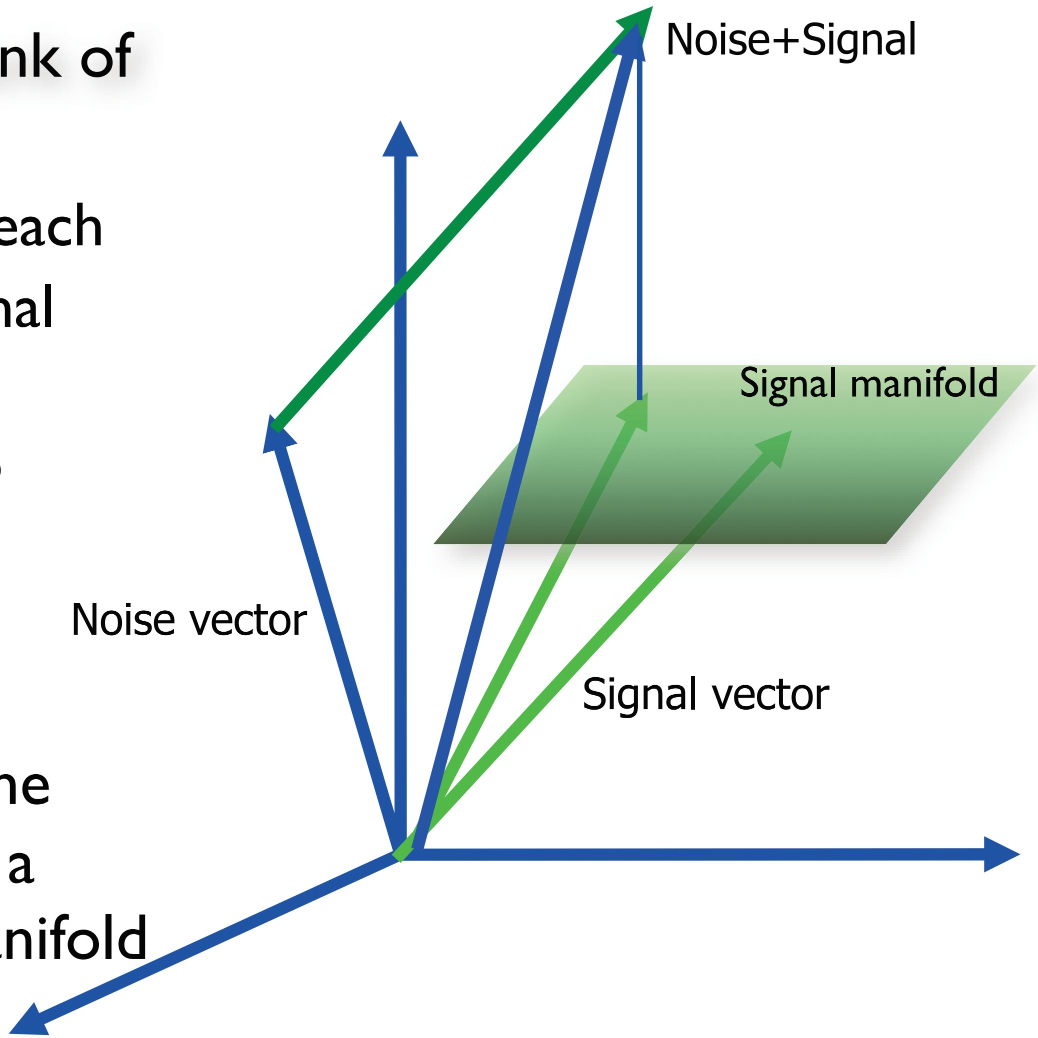
Geometrical approach to signal analysis

- An analysis begins with a chunk of data N samples long
- The set of all data chunks $\{x_k\}$ each of size N form an N-dimensional vector space
- Signals from a source are also vectors but they don't form a vector space
- However, the set of all signal vectors do form a manifold; the signal parameters λ^a serve as a coordinate system on this manifold



Geometrical approach to signal analysis

- An analysis begins with a chunk of data N samples long
- The set of all data chunks $\{x_k\}$ each of size N form an N-dimensional vector space
- Signals from a source are also vectors but they don't form a vector space
- However, the set of all signal vectors do form a manifold; the signal parameters λ^a serve as a coordinate system on this manifold



Scalar product and the metric

Scalar product and the metric

- The matched filtering statistic defines a natural scalar product between any two vectors

Scalar product and the metric

- The matched filtering statistic defines a natural scalar product between any two vectors
- The scalar product naturally defines a metric on the signal manifold:

Scalar product and the metric

- The matched filtering statistic defines a natural scalar product between any two vectors
- The scalar product naturally defines a metric on the signal manifold:

$$g_{\alpha\beta} \equiv \left\langle \partial_\alpha \hat{h}, \partial_\beta \hat{h} \right\rangle, \qquad \partial_\alpha \hat{h} \equiv \frac{\partial \hat{h}}{\partial p^\alpha}.$$

Scalar product and the metric

- The matched filtering statistic defines a natural scalar product between any two vectors
- The scalar product naturally defines a metric on the signal manifold:

$$g_{\alpha\beta} \equiv \left\langle \partial_\alpha \hat{h},\, \partial_\beta \hat{h} \right\rangle, \qquad \partial_\alpha \hat{h} \equiv \frac{\partial \hat{h}}{\partial p^\alpha}.$$

$$\langle a, b \rangle \equiv 2 \int_0^\infty \frac{\mathrm{d}f}{S_h(f)} \left[\tilde{a}(f) \tilde{b}^*(f) + \tilde{a}^*(f) \tilde{b}(f) \right]$$

Scalar product and the metric

- The matched filtering statistic defines a natural scalar product between any two vectors
- The scalar product naturally defines a metric on the signal manifold:

$$g_{\alpha\beta} \equiv \left\langle \partial_\alpha \hat{h},\, \partial_\beta \hat{h} \right\rangle, \qquad \partial_\alpha \hat{h} \equiv \frac{\partial \hat{h}}{\partial p^\alpha}.$$

$$\langle a, b \rangle \equiv 2 \int_0^\infty \frac{\mathrm{d}f}{S_h(f)} \left[\tilde{a}(f) \tilde{b}^*(f) + \tilde{a}^*(f) \tilde{b}(f) \right]$$

- Correlation between a signal and a nearby template can be expressed in terms of the metric

Scalar product and the metric

- The matched filtering statistic defines a natural scalar product between any two vectors
- The scalar product naturally defines a metric on the signal manifold:

$$g_{\alpha\beta} \equiv \left\langle \partial_\alpha \hat{h},\, \partial_\beta \hat{h} \right\rangle, \qquad \partial_\alpha \hat{h} \equiv \frac{\partial \hat{h}}{\partial p^\alpha}.$$

$$\langle a, b \rangle \equiv 2 \int_0^\infty \frac{\mathrm{d}f}{S_h(f)} \left[\tilde{a}(f) \tilde{b}^*(f) + \tilde{a}^*(f) \tilde{b}(f) \right]$$

- Correlation between a signal and a nearby template can be expressed in terms of the metric

$$C = 1 - g_{ab}\, d\lambda^a\, d\lambda^b + \ldots$$

Covariance Matrix

Covariance Matrix

- The posterior probability distribution of the measured parameters is given by

Covariance Matrix

- The posterior probability distribution of the measured parameters is given by

$$\mathcal{P}(\Delta p^\alpha)\,\mathrm{d}^n\Delta p = \frac{\mathrm{d}^n\Delta p}{(2\pi)^{n/2}\sqrt{C}}\exp\left[-\frac{1}{2}C^{-1}_{\alpha\beta}\,\Delta p^\alpha\Delta\, p^\beta\right]$$

Covariance Matrix

- The posterior probability distribution of the measured parameters is given by

$$\mathcal{P}(\Delta p^{\alpha})\,\mathrm{d}^n\Delta p = \frac{\mathrm{d}^n\Delta p}{(2\pi)^{n/2}\sqrt{C}}\exp\left[-\frac{1}{2}C^{-1}_{\alpha\beta}\,\Delta p^{\alpha}\Delta\, p^{\beta}\right]$$

- It can also be written as

Covariance Matrix

- The posterior probability distribution of the measured parameters is given by

$$\mathcal{P}(\Delta p^\alpha)\,\mathrm{d}^n\Delta p = \frac{\mathrm{d}^n\Delta p}{(2\pi)^{n/2}\sqrt{C}}\exp\left[-\frac{1}{2}C^{-1}_{\alpha\beta}\,\Delta p^\alpha\Delta\,p^\beta\right]$$

- It can also be written as

$$\mathcal{P}(\Delta p^\alpha)\,\mathrm{d}^n\Delta p = \frac{\rho^n\,\sqrt{g}\,\mathrm{d}^n\Delta p}{(2\pi)^{n/2}}\exp\left[-\frac{\rho^2}{2}\,g_{\alpha\beta}\,\Delta p^\alpha\Delta\,p^\beta\right]$$

Time-Frequency Analysis

$$H_{mn} = \sum X_k W_{k+m} \exp [2\pi i\ kn/N]$$

Time-Frequency Analysis

$$H_{mn} = \sum X_k W_{k+m} \exp\,[2\pi i\, kn/N]$$

- Construct spectrograms
  - Short-period Fourier transforms of data X using a window W
  - J. Sylvestre used spectrograms to study GW bursts - TF clusters

Time-Frequency Analysis

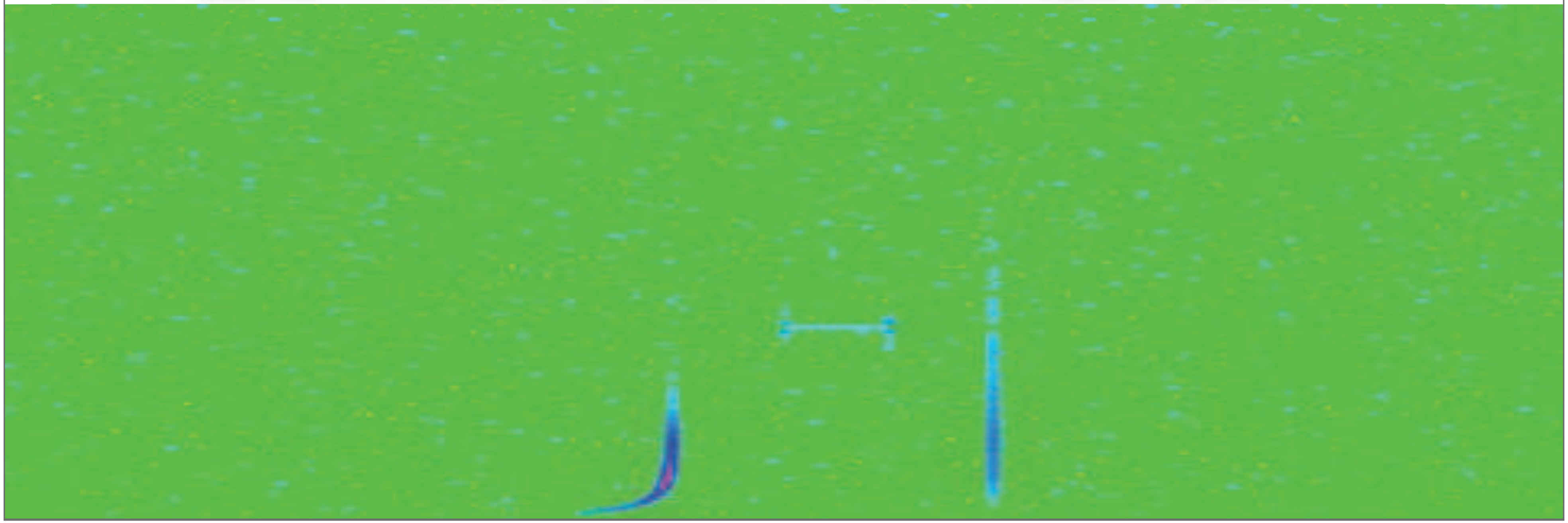
$$H_{mn} = \sum X_k W_{k+m} \exp [2\pi i\, kn/N]$$

- Construct spectrograms
  - Short-period Fourier transforms of data *X* using a window *W*
  - J. Sylvestre used spectrograms to study GW bursts - TF clusters
- Classify features in spectrogram
  - ***glitch*** - a broadband burst lasting for a short duration
  - ***line*** - a narrow band signal with a high-Q
  - ***blob*** - a homogeneous cluster in the time-frequency plane
  - ***curve*** - a filamentary feature in the time-frequency plane

Time-Frequency Analysis

$$H_{mn} = \sum X_k W_{k+m} \exp [2\pi i\, kn/N]$$

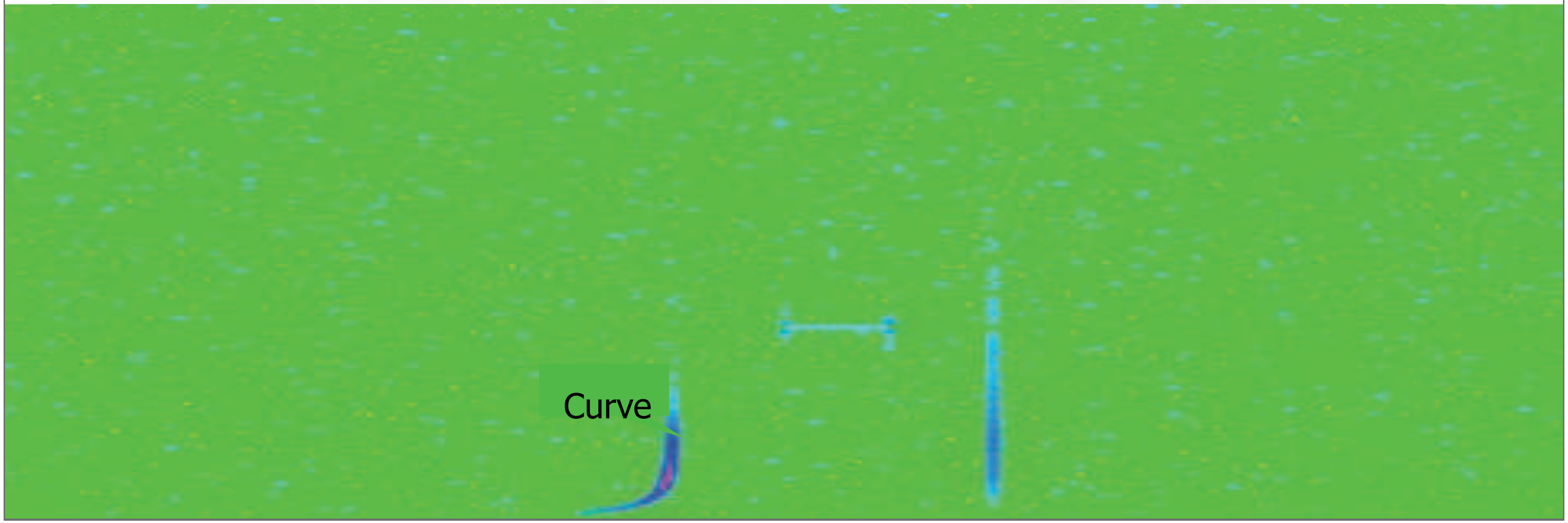
- Construct spectrograms
  - Short-period Fourier transforms of data *X* using a window *W*
  - J. Sylvestre used spectrograms to study GW bursts - TF clusters
- Classify features in spectrogram
  - ***glitch*** - a broadband burst lasting for a short duration
  - ***line*** - a narrow band signal with a high-Q
  - ***blob*** - a homogeneous cluster in the time-frequency plane
  - ***curve*** - a filamentary feature in the time-frequency plane



Time-Frequency Analysis

$$H_{mn} = \sum X_k W_{k+m} \exp [2\pi i\, kn/N]$$

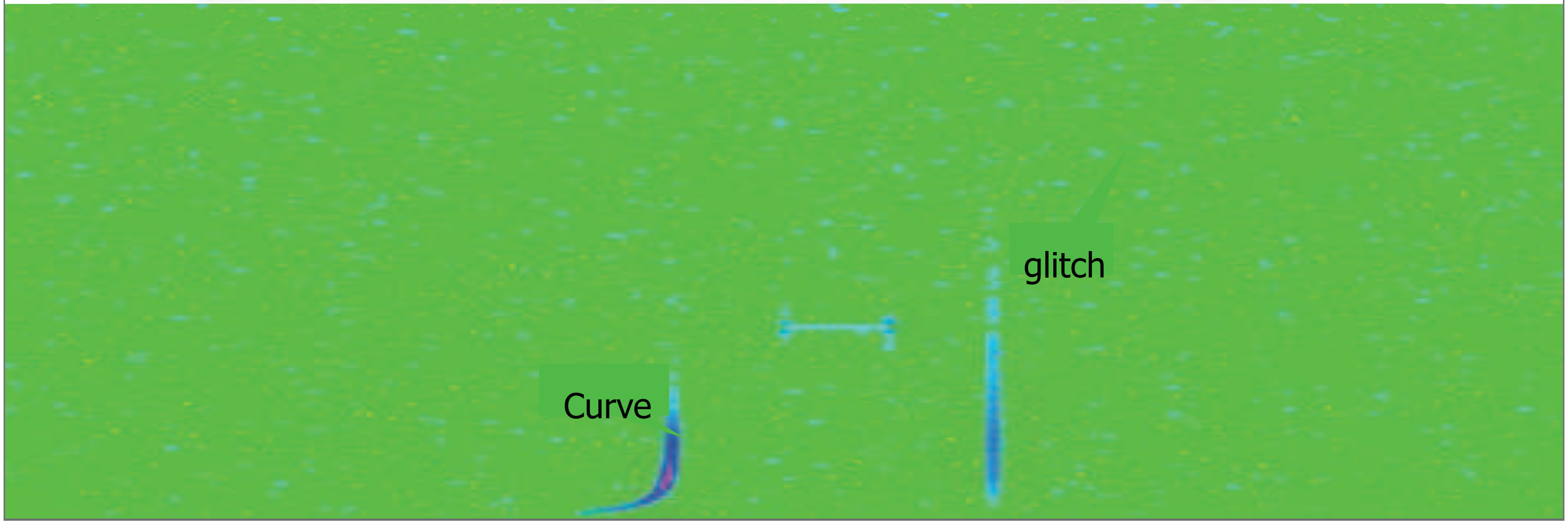
- Construct spectrograms
  - Short-period Fourier transforms of data X using a window W
  - J. Sylvestre used spectrograms to study GW bursts - TF clusters
- Classify features in spectrogram
  - ***glitch*** - a broadband burst lasting for a short duration
  - ***line*** - a narrow band signal with a high-Q
  - ***blob*** - a homogeneous cluster in the time-frequency plane
  - ***curve*** - a filamentary feature in the time-frequency plane



Time-Frequency Analysis

$$H_{mn} = \sum X_k W_{k+m} \exp [2\pi i\, kn/N]$$

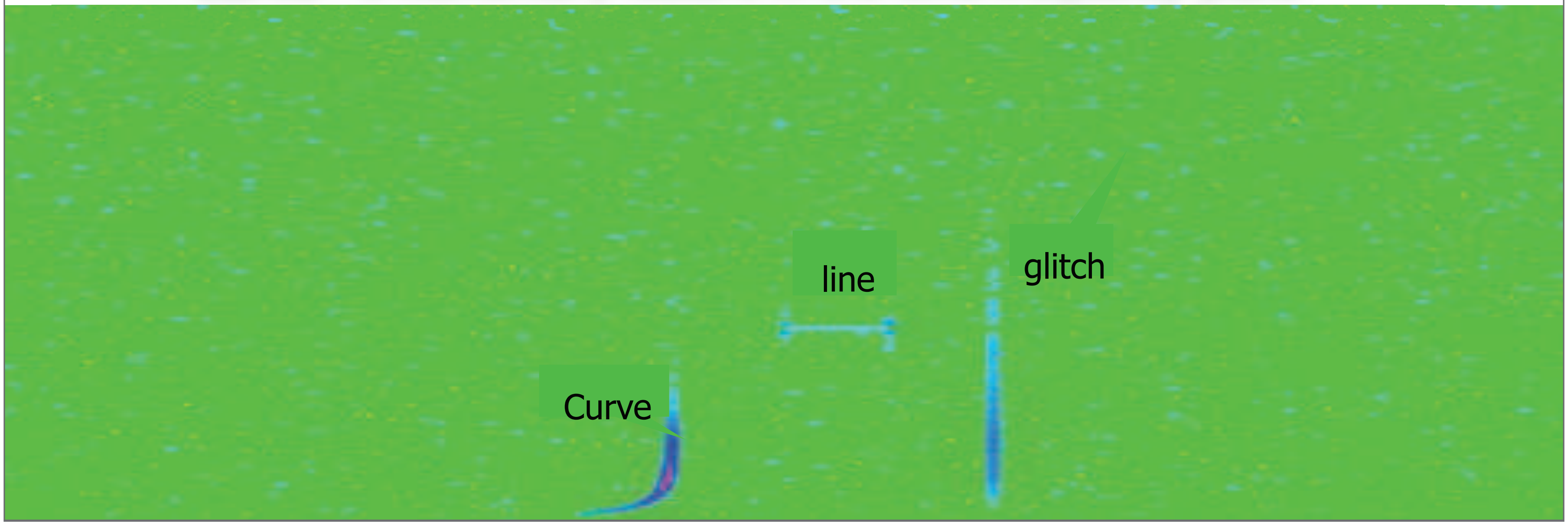
- Construct spectrograms
  - Short-period Fourier transforms of data X using a window W
  - J. Sylvestre used spectrograms to study GW bursts - TF clusters
- Classify features in spectrogram
  - ***glitch*** - a broadband burst lasting for a short duration
  - ***line*** - a narrow band signal with a high-Q
  - ***blob*** - a homogeneous cluster in the time-frequency plane
  - ***curve*** - a filamentary feature in the time-frequency plane



Time-Frequency Analysis

$$H_{mn} = \sum X_k W_{k+m} \, exp\,[2\pi i\, kn/N]$$

- Construct spectrograms
  - Short-period Fourier transforms of data X using a window W
  - J. Sylvestre used spectrograms to study GW bursts - TF clusters
- Classify features in spectrogram
  – ***glitch*** - a broadband burst lasting for a short duration
  – ***line*** - a narrow band signal with a high-Q
  – ***blob*** - a homogeneous cluster in the time-frequency plane
  – ***curve*** - a filamentary feature in the time-frequency plane



Detecting EMRIs with Time-Frequency Maps

Detecting EMRIs with Time-Frequency Maps

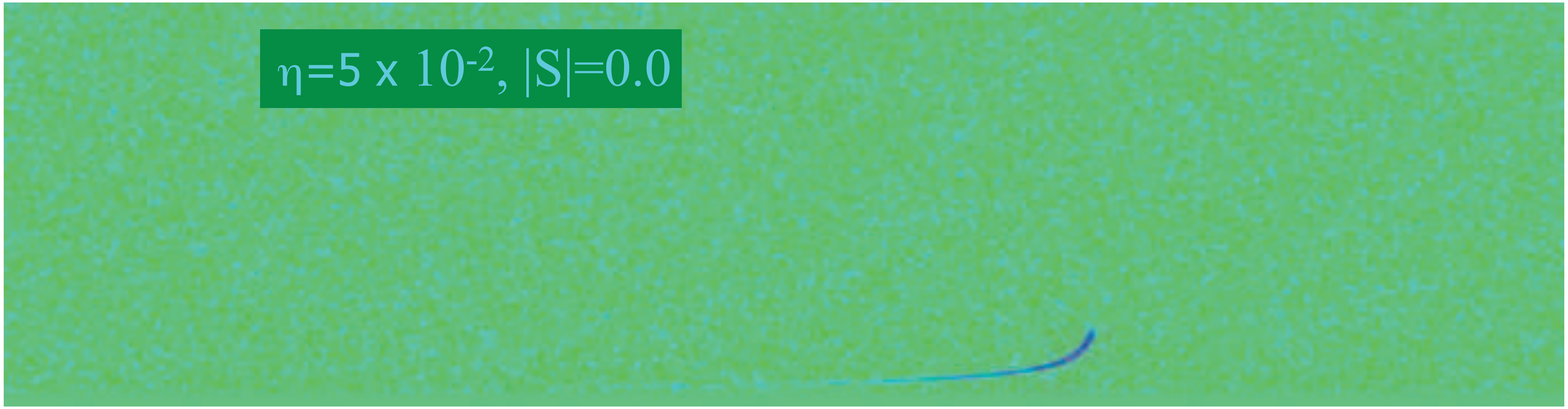
- Dynamics of Extreme Mass Ratio Inspirals or EMRIs, where in a small black hole falls into a supermassive black hole on an eccentric orbit can be very complicated involving precession of the periastron and of the orbital plane due to spin-orbit and spin-spin couplings.

Detecting EMRIs with Time-Frequency Maps

- Dynamics of Extreme Mass Ratio Inspirals or EMRIs, where in a small black hole falls into a supermassive black hole on an eccentric orbit can be very complicated involving precession of the periastron and of the orbital plane due to spin-orbit and spin-spin couplings.
- This leads to modulation in the signal as can be seen below

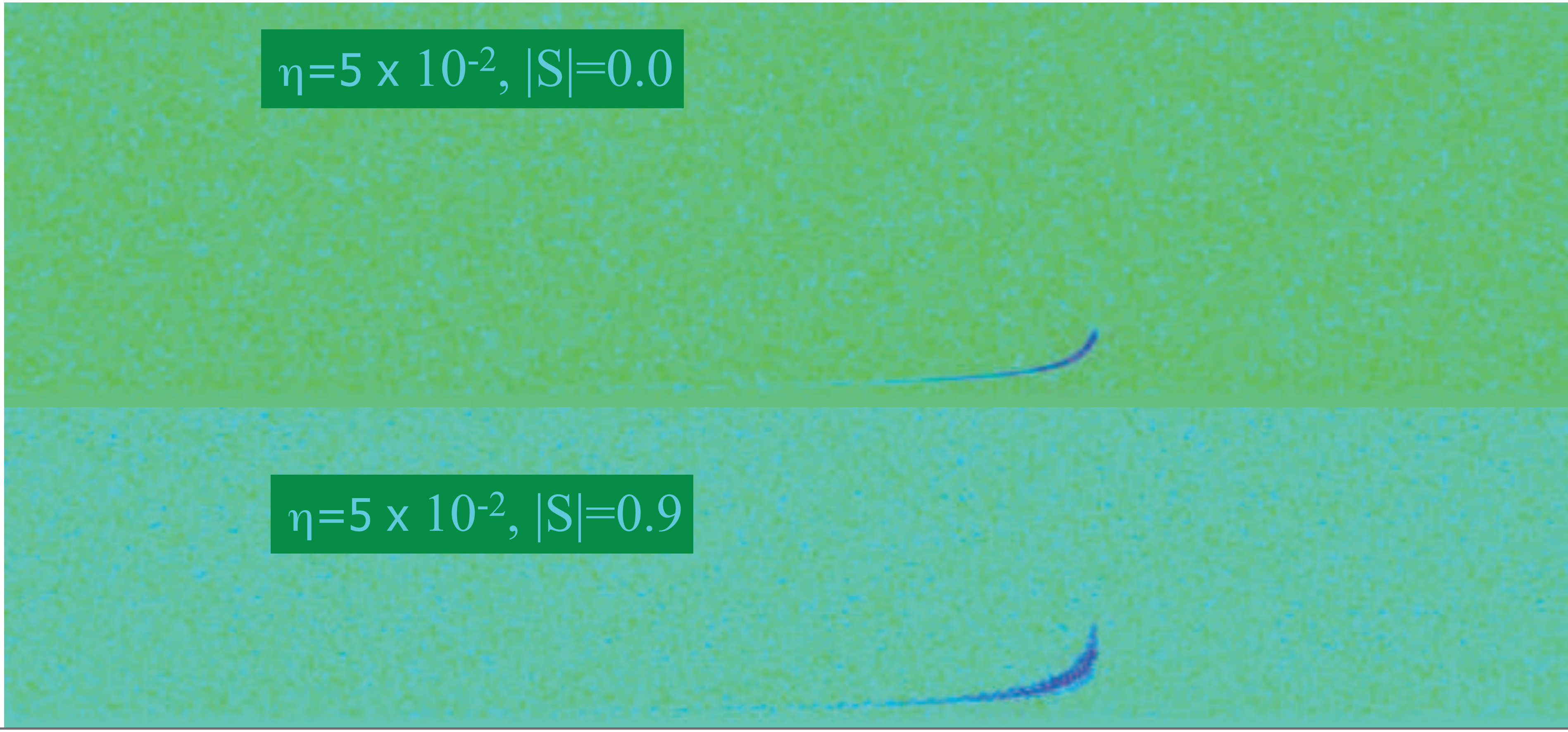
Detecting EMRIs with Time-Frequency Maps

- Dynamics of Extreme Mass Ratio Inspirals or EMRIs, where in a small black hole falls into a supermassive black hole on an eccentric orbit can be very complicated involving precession of the periastron and of the orbital plane due to spin-orbit and spin-spin couplings.
- This leads to modulation in the signal as can be seen below



Detecting EMRIs with Time-Frequency Maps

- Dynamics of Extreme Mass Ratio Inspirals or EMRIs, where in a small black hole falls into a supermassive black hole on an eccentric orbit can be very complicated involving precession of the periastron and of the orbital plane due to spin-orbit and spin-spin couplings.
- This leads to modulation in the signal as can be seen below



A method to Identify EMRIs

A method to Identify EMRIs

- Use a first upper threshold to identify peaks in the TF map

A method to Identify EMRIs

- Use a first upper threshold to identify peaks in the TF map
- Find pixels attached to the peaks by using a second lower threshold

A method to Identify EMRIs

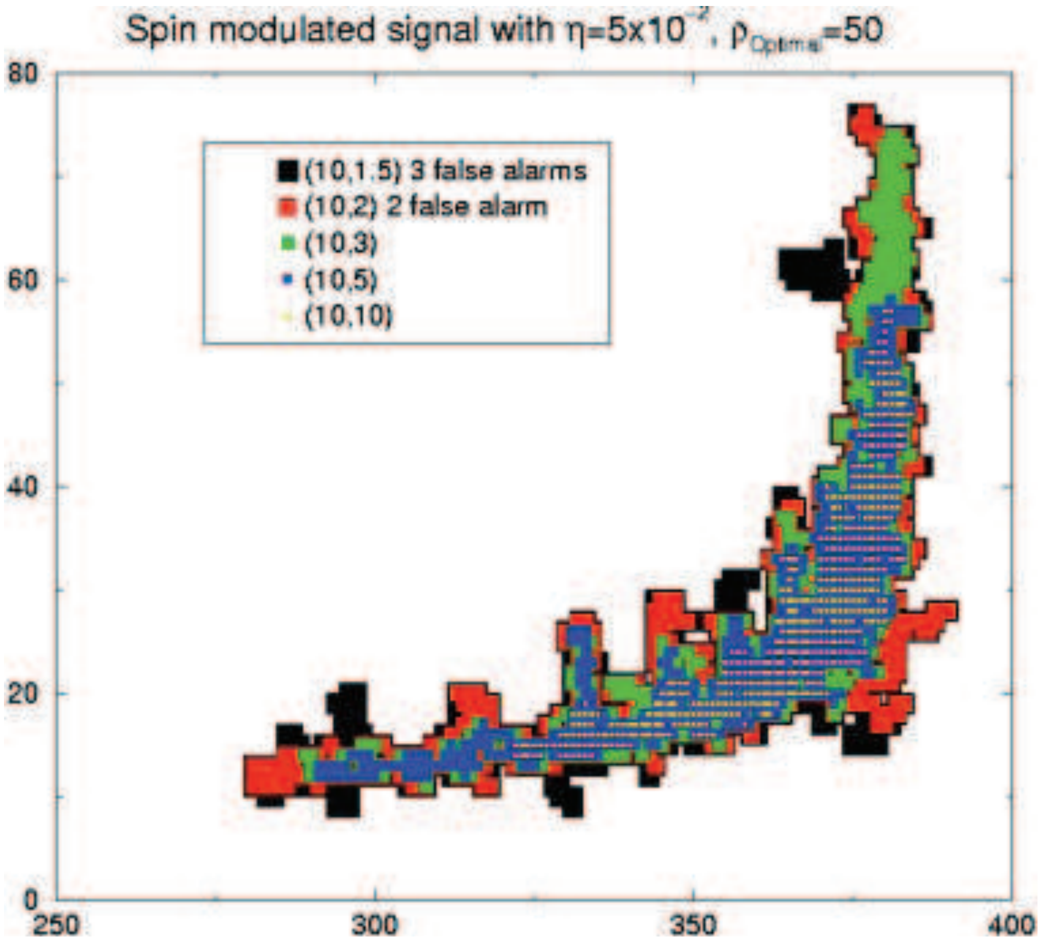
- Use a first upper threshold to identify peaks in the TF map
- Find pixels attached to the peaks by using a second lower threshold
- Define a threshold pair (u,l) and study TF maps

A method to Identify EMRIs

- Use a first upper threshold to identify peaks in the TF map
- Find pixels attached to the peaks by using a second lower threshold
- Define a threshold pair (u,l) and study TF maps
- This study selects curves that have a fixed number of pixels, but ...

A method to Identify EMRIs

- Use a first upper threshold to identify peaks in the TF map
- Find pixels attached to the peaks by using a second lower threshold
- Define a threshold pair (u,l) and study TF maps
- This study selects curves that have a fixed number of pixels, but ...



Tracking EMRIs*: HACR* Algorithm

Tracking EMRIs*: HACR* Algorithm

- We call this two-threshold method signal track search (Anderson and RB)

Tracking EMRIs: *HACR* Algorithm

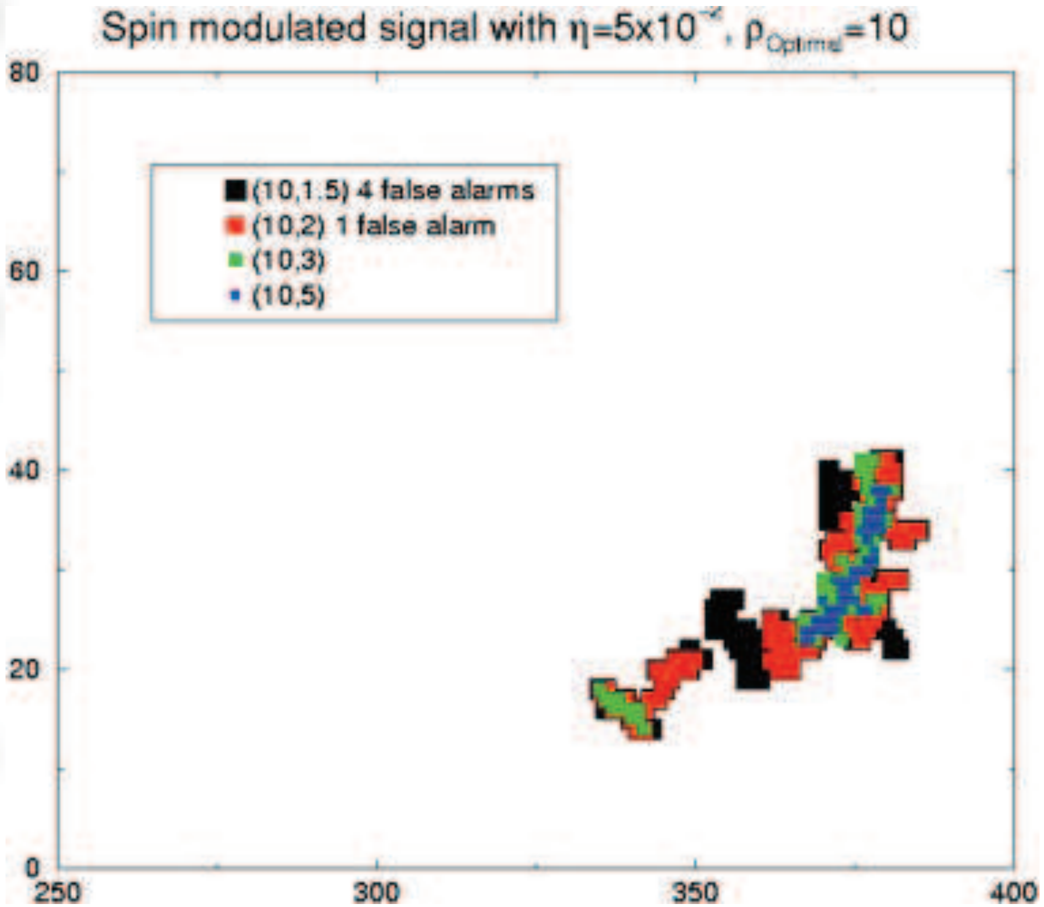
- We call this two-threshold method signal track search (Anderson and RB)
- At a fixed upper threshold a lower threshold of u/l ~ 3 maximizes the area keeping low false alarm rate

Tracking EMRIs: *HACR* Algorithm

- We call this two-threshold method signal track search (Anderson and RB)
- At a fixed upper threshold a lower threshold of u/l ~ 3 maximizes the area keeping low false alarm rate
- A single threshold would miss most of the signals as would large values of the ratio u/l

Tracking EMRIs: *HACR* Algorithm

- We call this two-threshold method signal track search (Anderson and RB)
- At a fixed upper threshold a lower threshold of u/l ~ 3 maximizes the area keeping low false alarm rate
- A single threshold would miss most of the signals as would large values of the ratio u/l



Demo of GW Search with Black Hole Hunter

Demo of GW Search with Black Hole Hunter

- An on-line game to demonstrate matched filtering

Demo of GW Search with Black Hole Hunter

- An on-line game to demonstrate matched filtering
  - www.blackholehunter.org

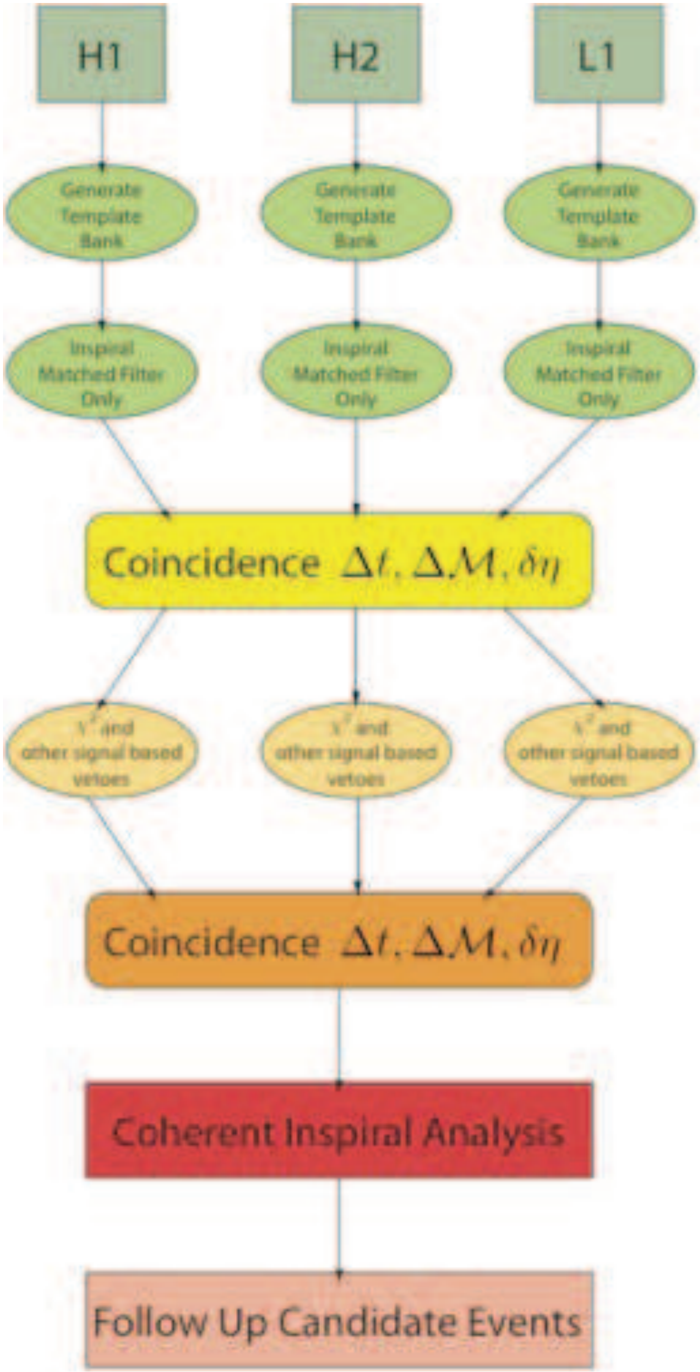
Demo of GW Search with Black Hole Hunter

- An on-line game to demonstrate matched filtering
  - www.blackholehunter.org
- Illustrates how a prior knowledge of what we are looking for helps in identifying the signal buried in very noisy data

Demo of GW Search with Black Hole Hunter

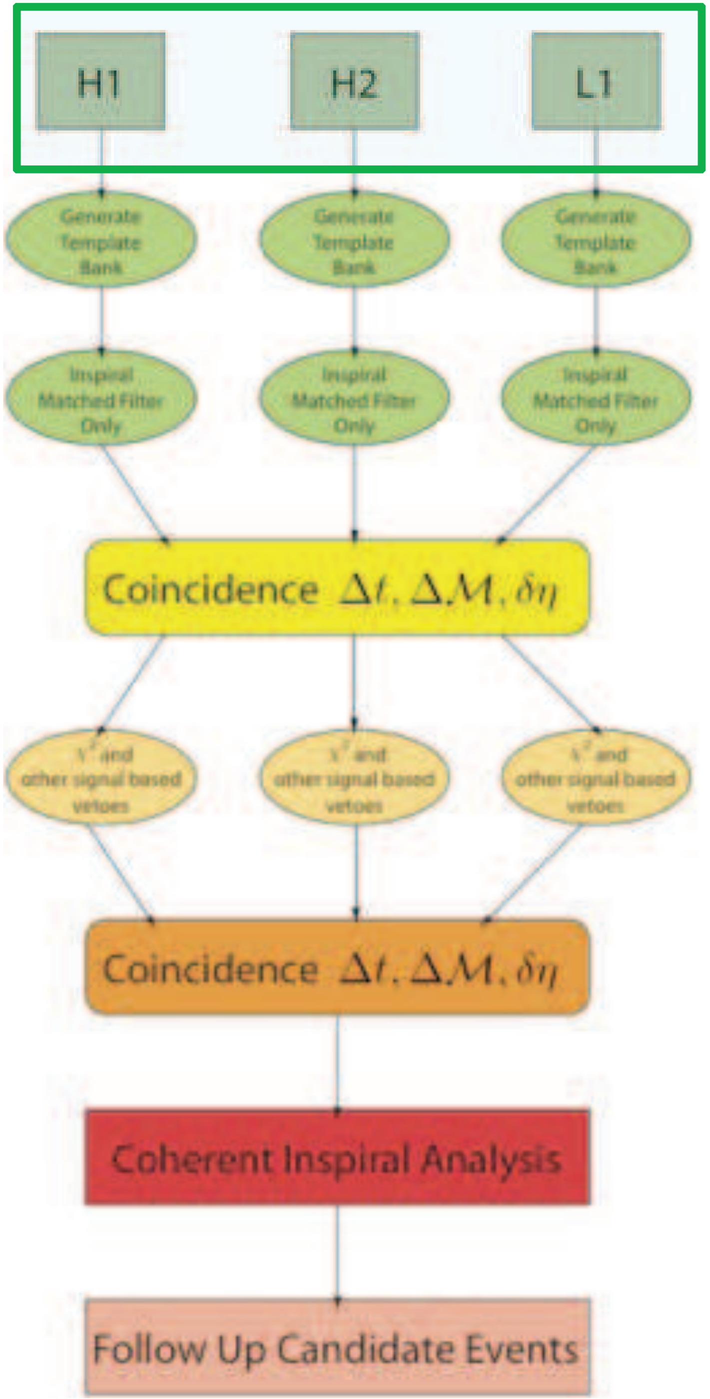
- An on-line game to demonstrate matched filtering
  - www.blackholehunter.org
- Illustrates how a prior knowledge of what we are looking for helps in identifying the signal buried in very noisy data
- Audio recognition continues to be a good method even when the signal amplitude is pretty small compared to noise RMS

LSC inspiral pipeline

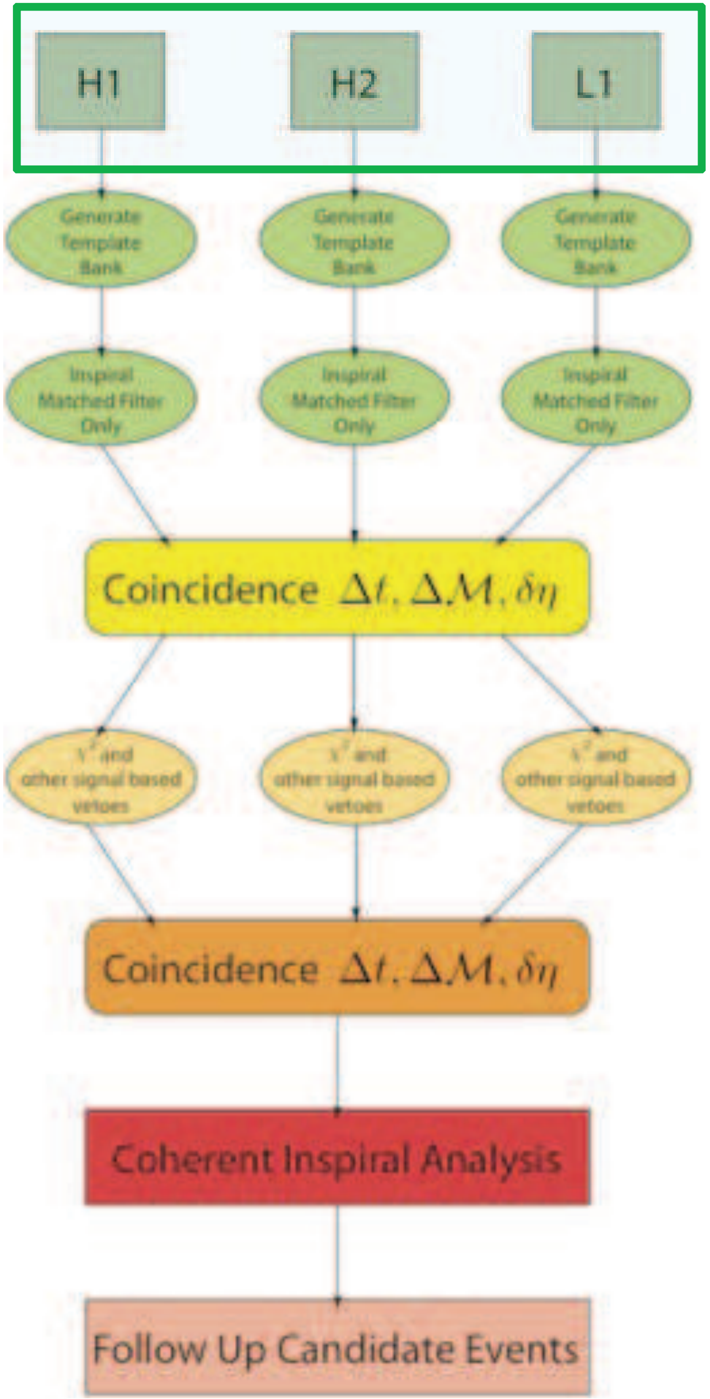


Slides by Dietz and Sengupta

LSCdataFind



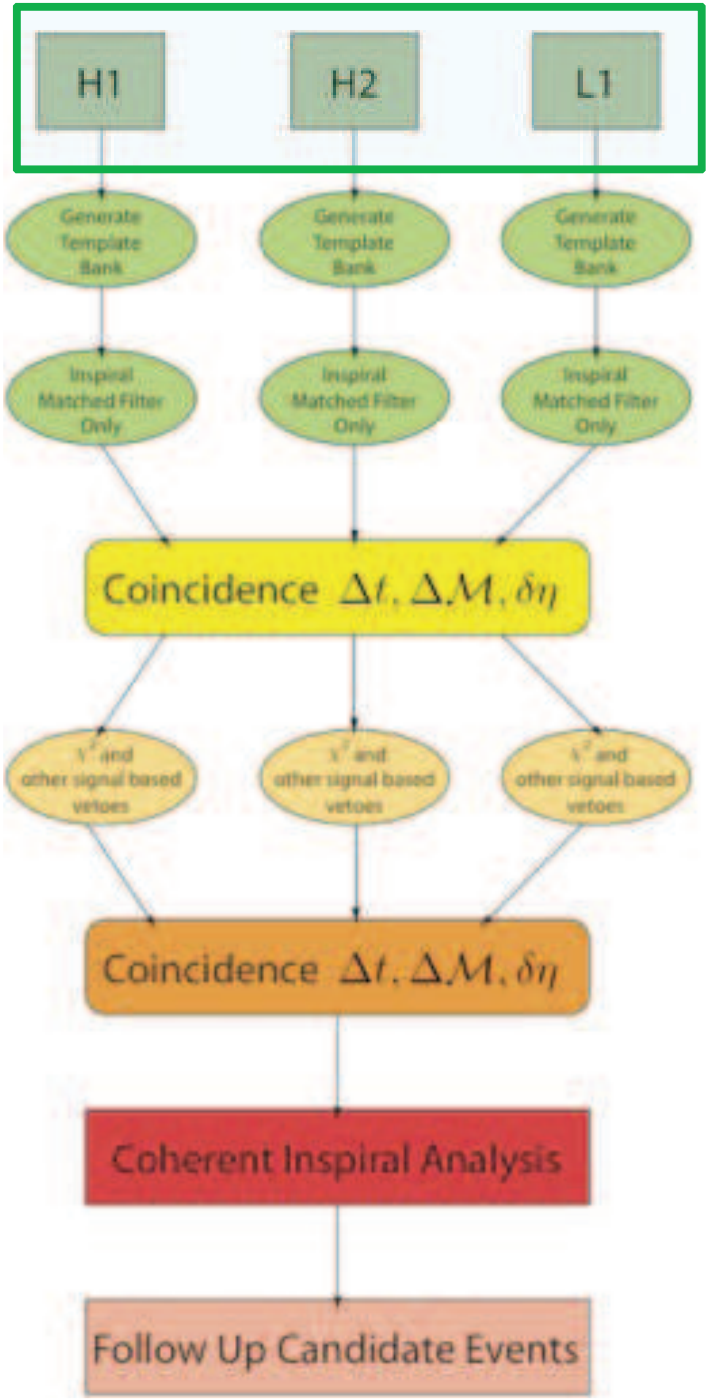
Slides by Dietz and Sengupta



LSCdataFind

- First step in the data analysis.

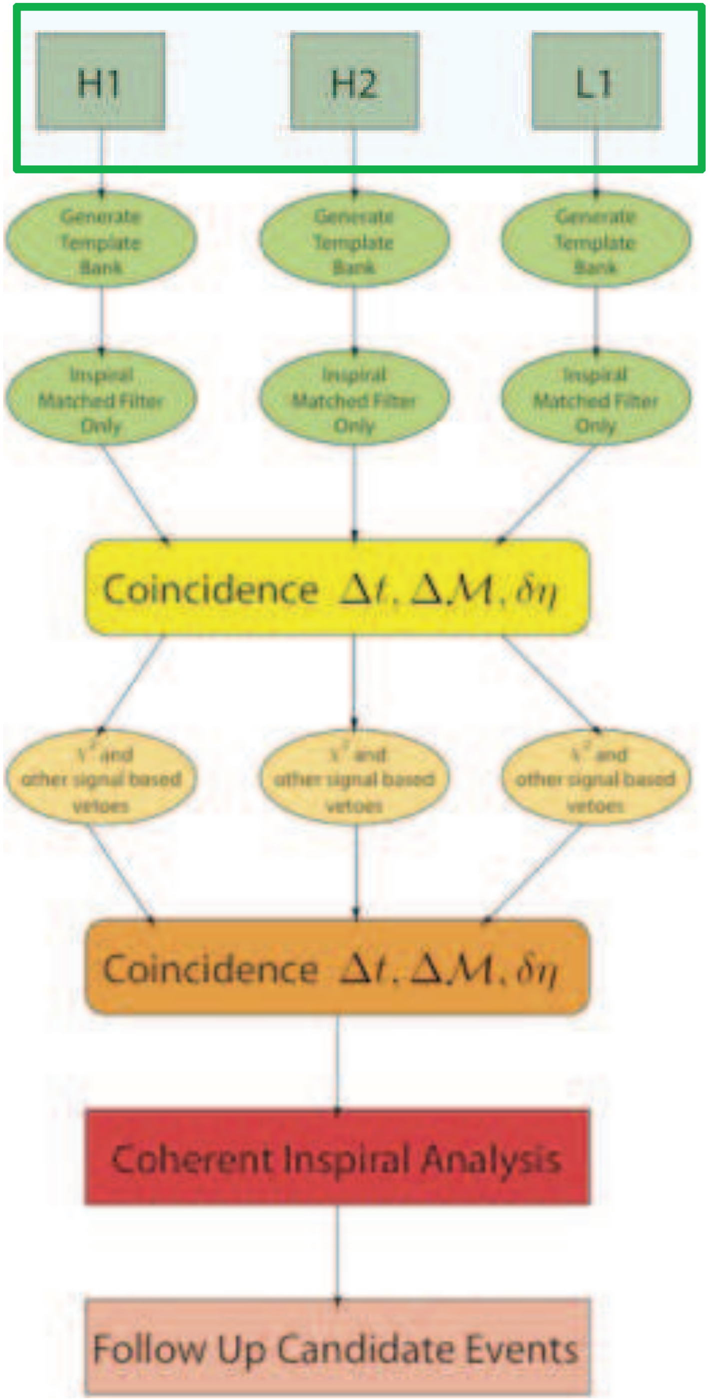
Slides by Dietz and Sengupta



LSCdataFind

- First step in the data analysis.
- Queries the dataFind server on

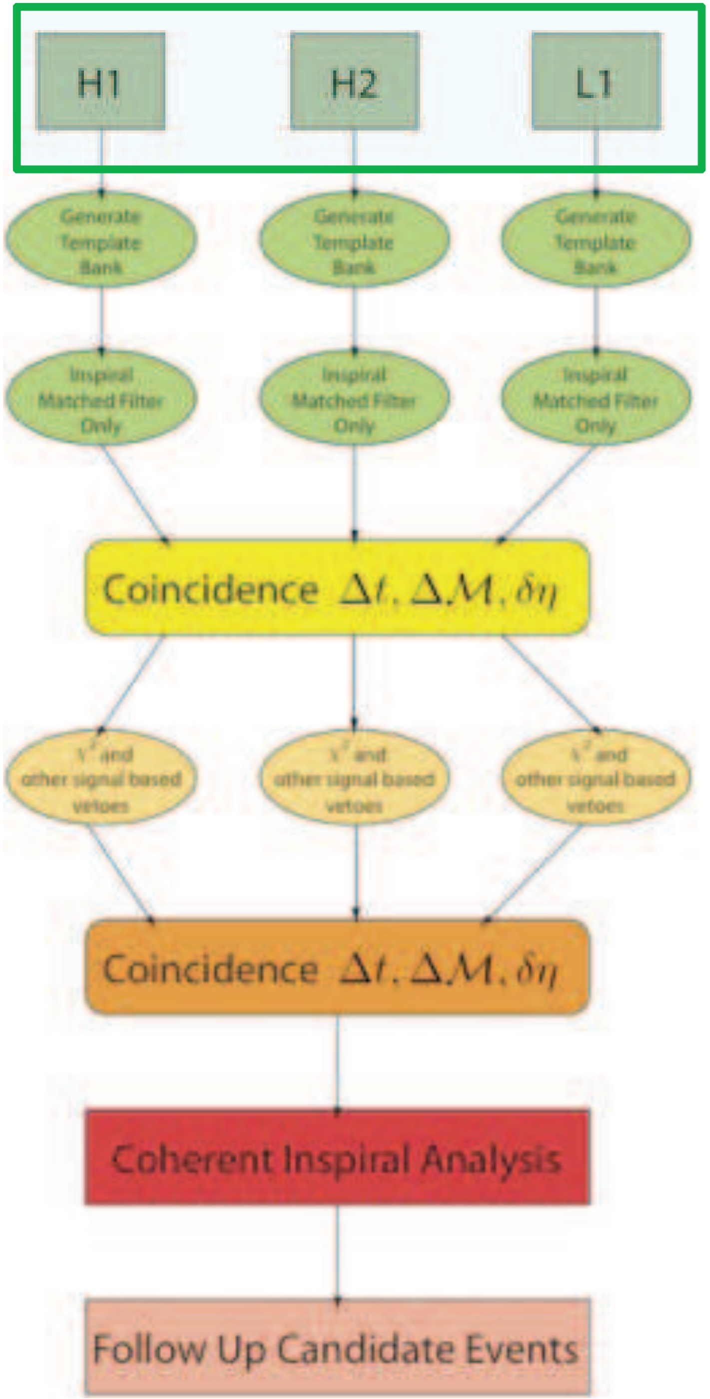
Slides by Dietz and Sengupta



LSCdataFind

- First step in the data analysis.
- Queries the dataFind server on
  - IFO name

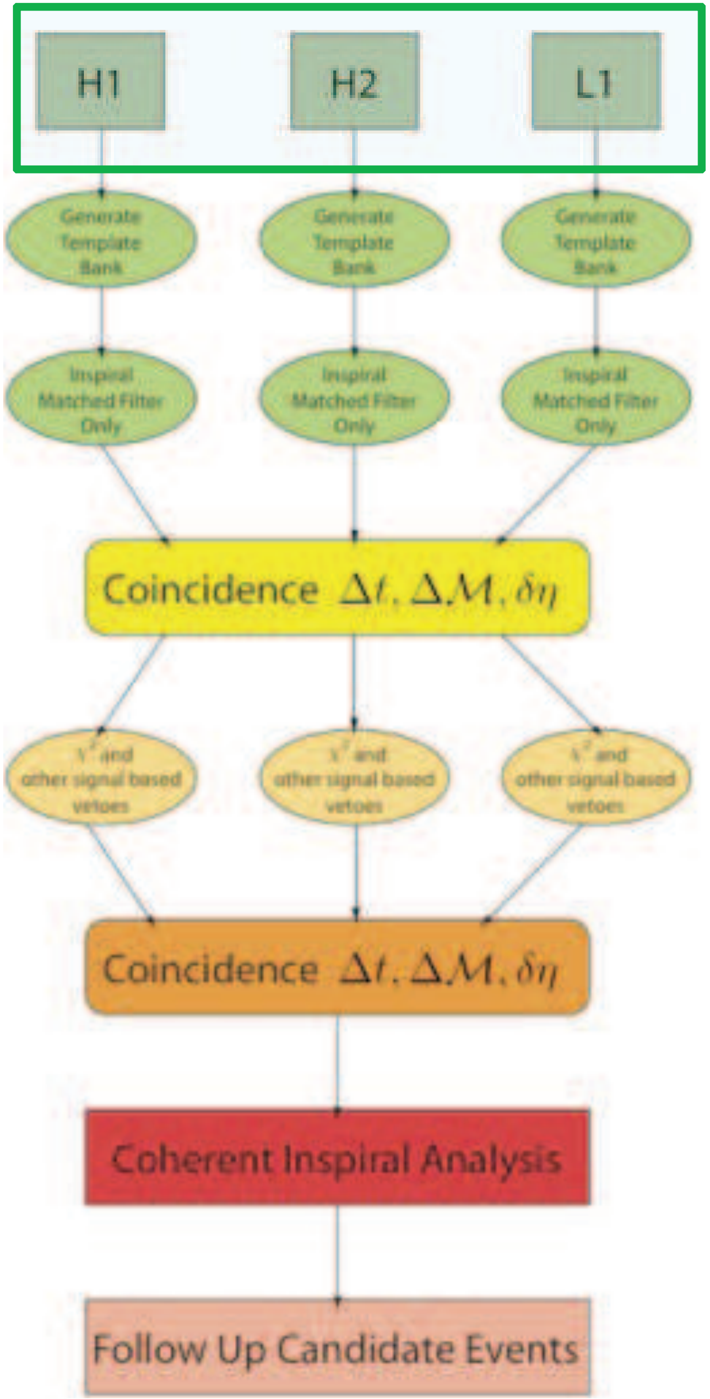
Slides by Dietz and Sengupta



LSCdataFind

- First step in the data analysis.
- Queries the dataFind server on
  - IFO name
  - **start** and **end** times of the analysis

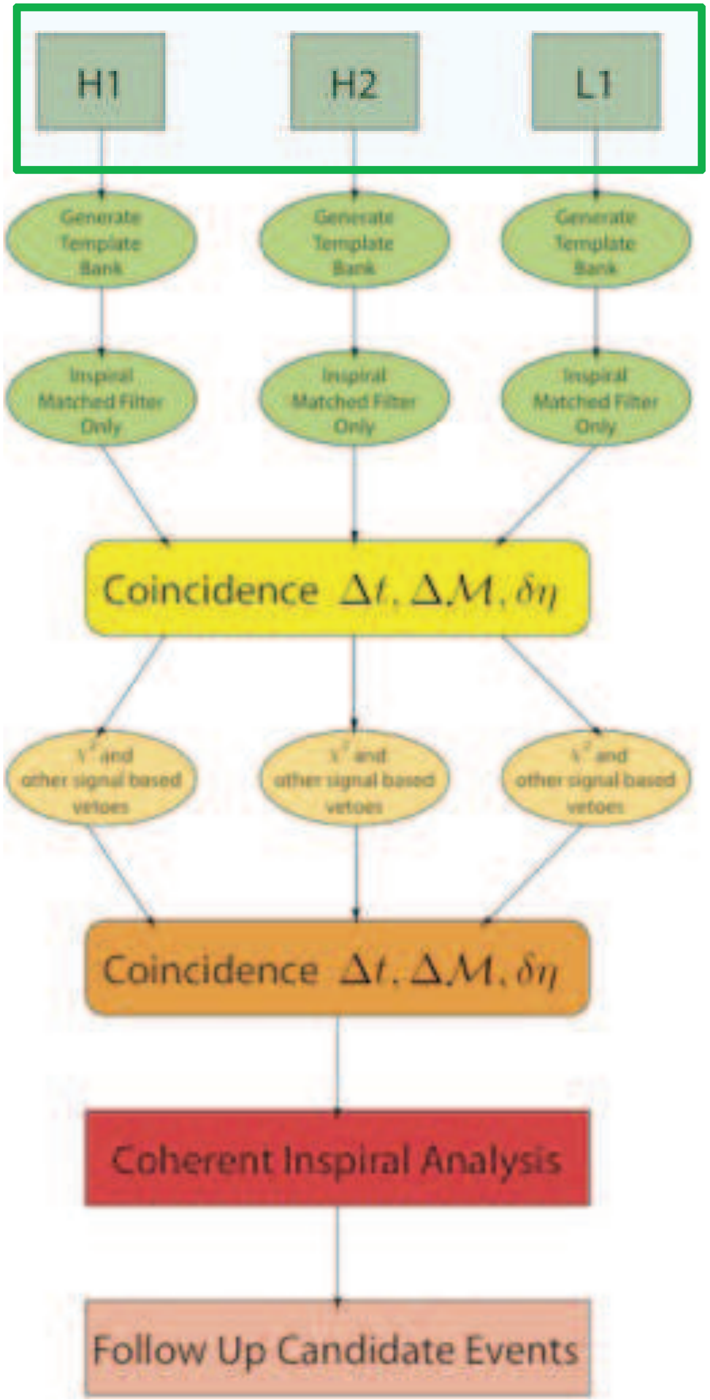
Slides by Dietz and Sengupta



LSCdataFind

- First step in the data analysis.
- Queries the dataFind server on
  - IFO name
  - **start** and **end** times of the analysis
- Cache file containing location of data files is generated.

Slides by Dietz and Sengupta

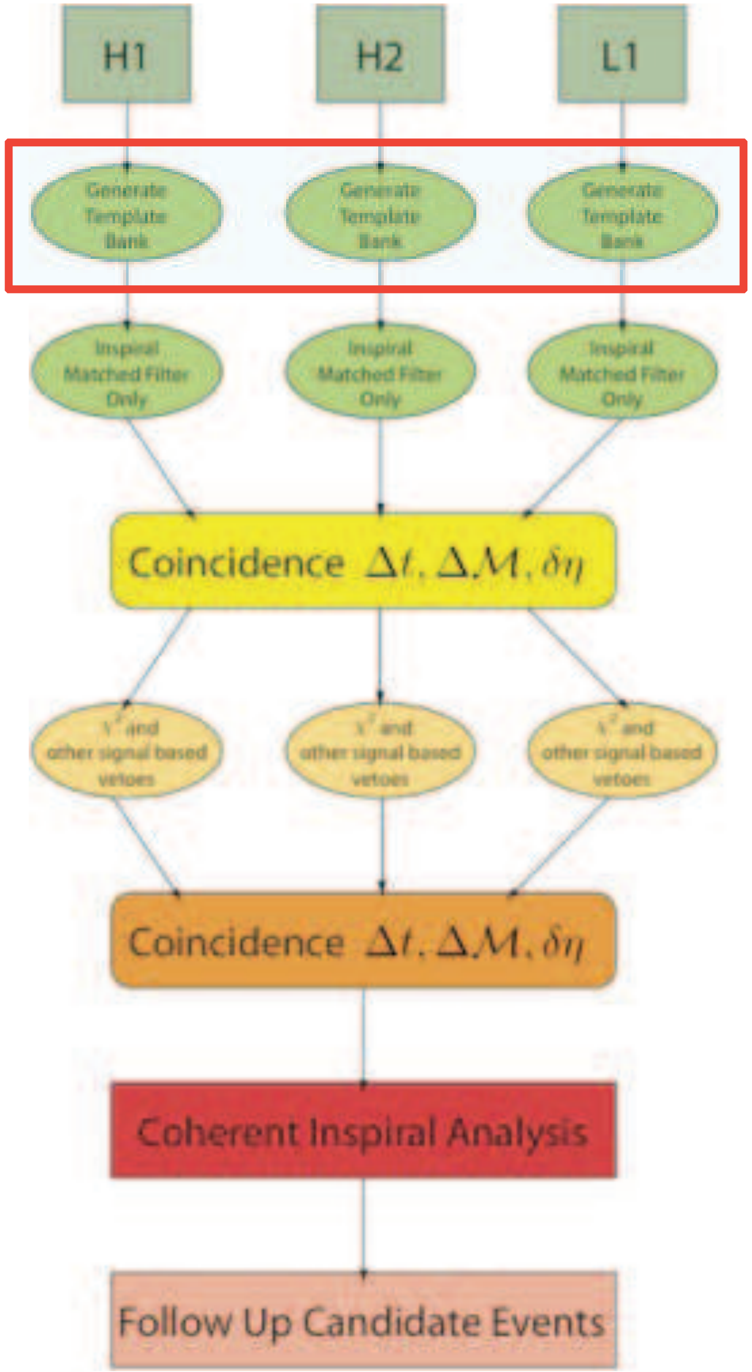


LSCdataFind

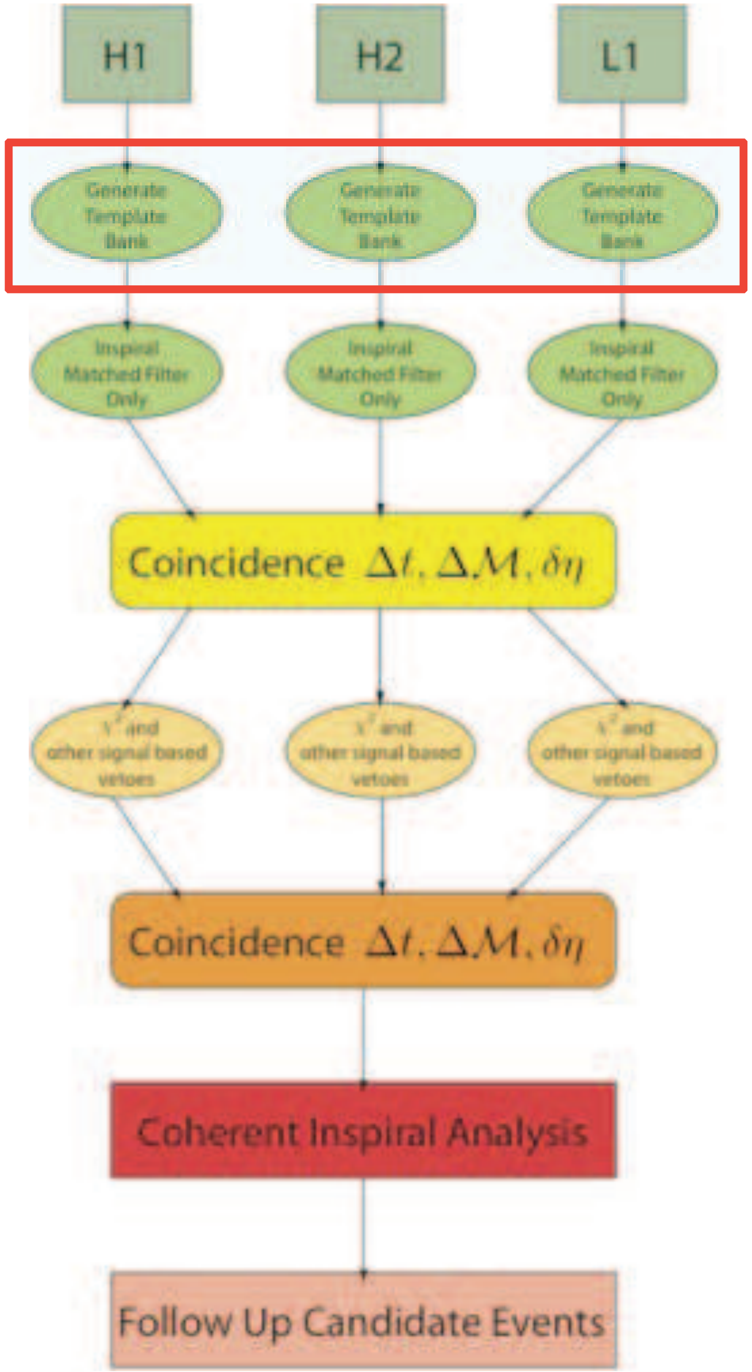
- First step in the data analysis.
- Queries the dataFind server on
  - IFO name
  - **start** and **end** times of the analysis
- Cache file containing location of data files is generated.
- Subsequent steps can use this cache file to read the data from disk.

Slides by Dietz and Sengupta

Template Bank



Slides by Dietz and Sengupta

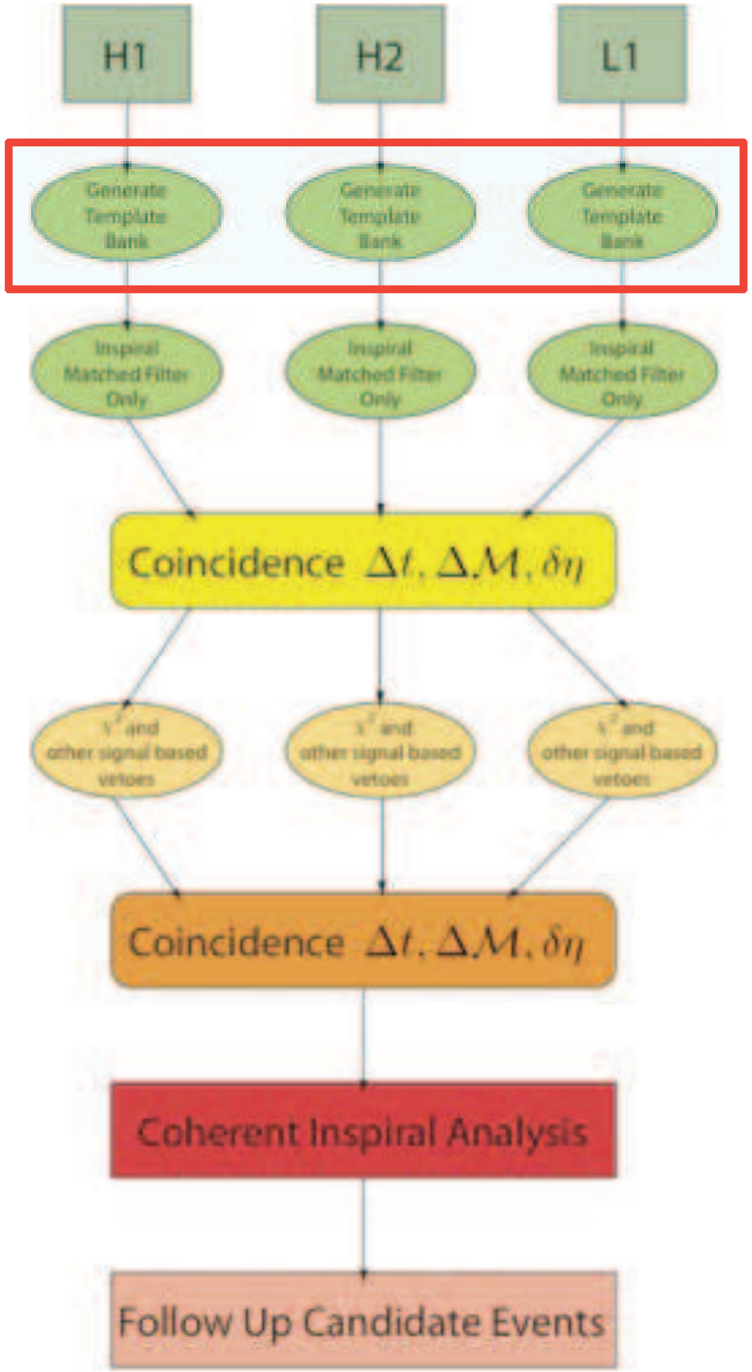


Template Bank

- Spans the search parameter space in discrete steps such that the correlation between the signal and template is at least a prescribed minimum.

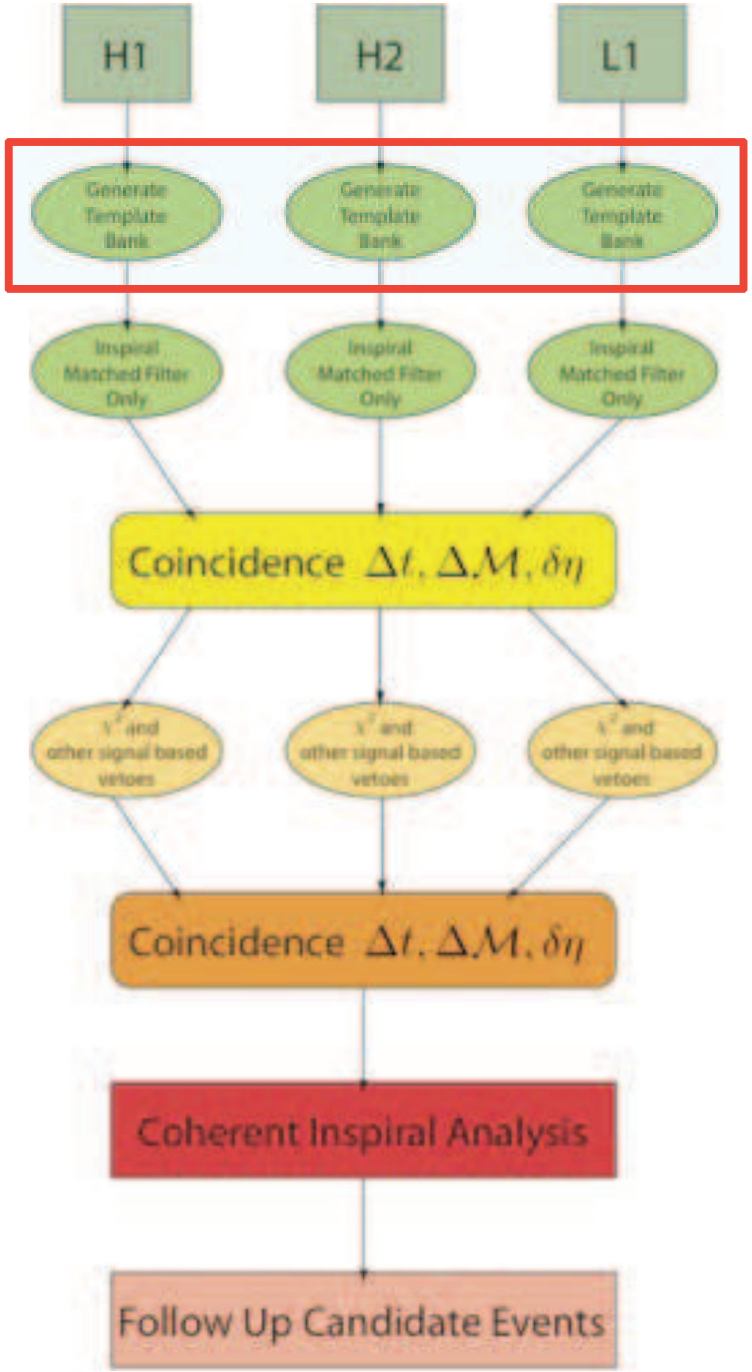
Slides by Dietz and Sengupta

Template Bank



- Spans the search parameter space in discrete steps such that the correlation between the signal and template is at least a prescribed minimum.
- A list of (m1,m2) ordered pairs

Slides by Dietz and Sengupta

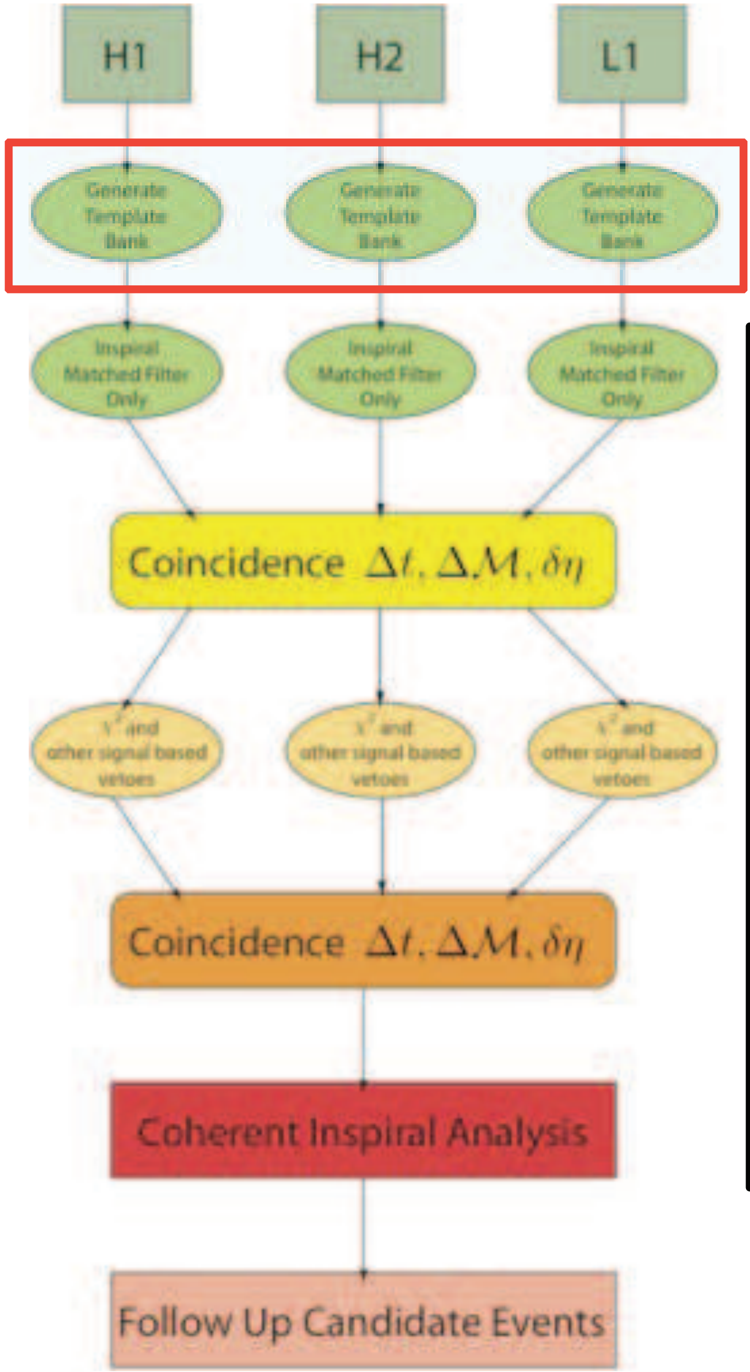


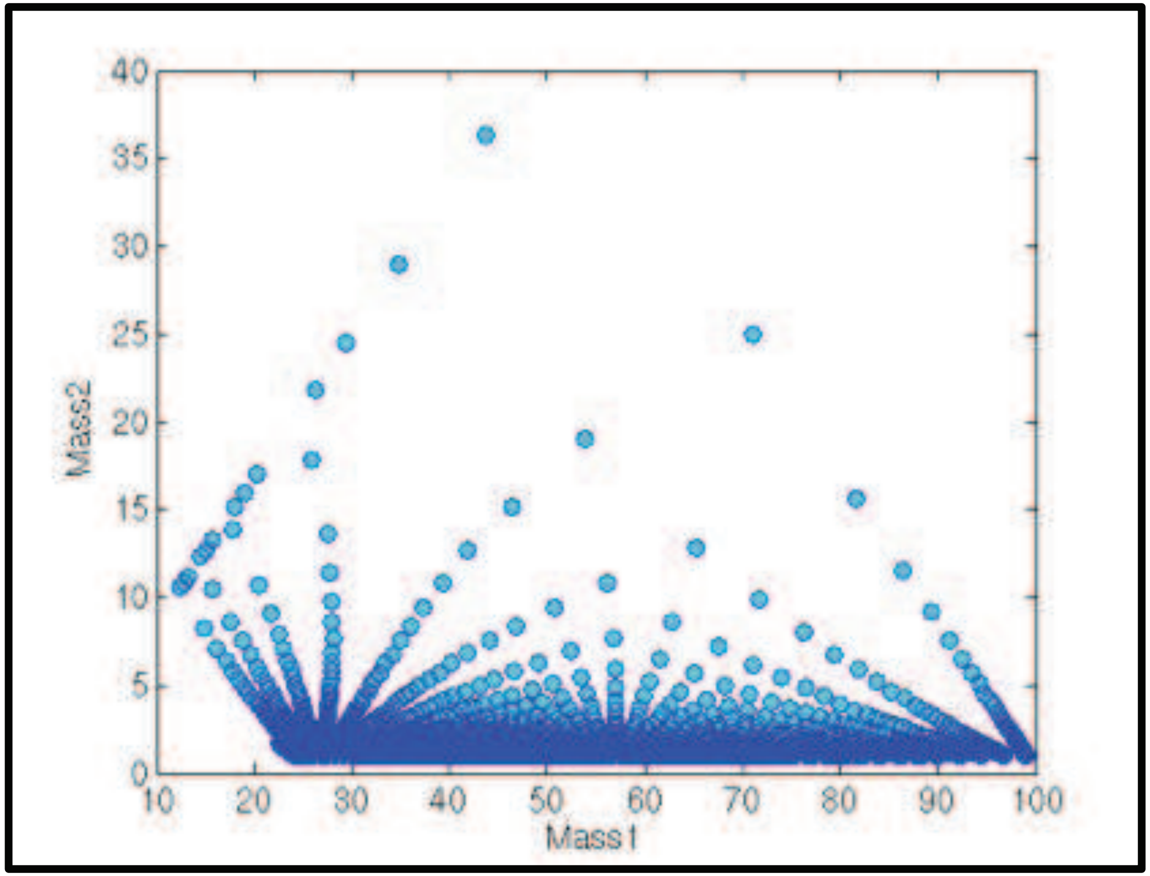
Template Bank

- Spans the search parameter space in discrete steps such that the correlation between the signal and template is at least a prescribed minimum.
- A list of (m1,m2) ordered pairs
- Used as a look-up table to generate template waveforms which will then filter the data.

Slides by Dietz and Sengupta

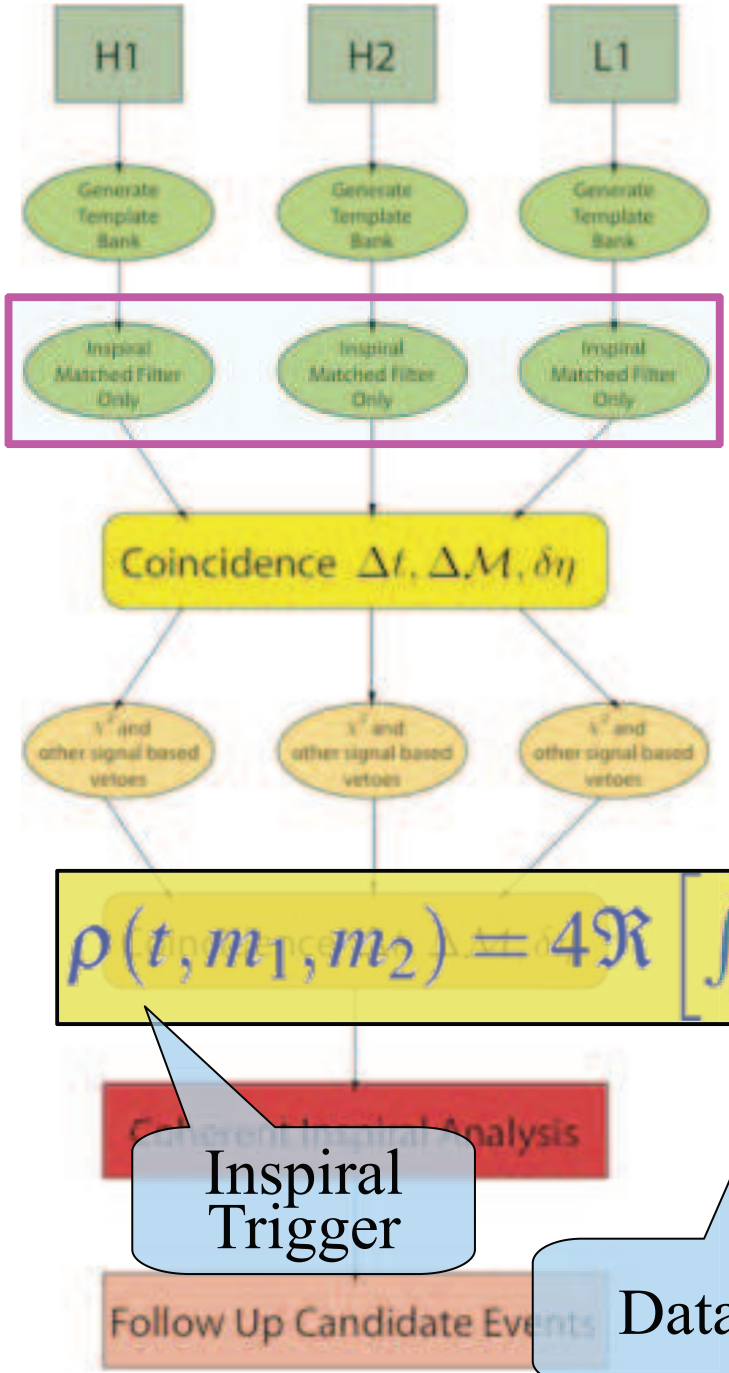
Template Bank





Slides by Dietz and Sengupta

Inspiral Stage
(Matched filter only)



$$\rho(t, m_1, m_2) = 4\Re\left[\int_0^\infty \tilde{x}(f)\, \frac{\tilde{T}^*(f; m_1, m_2)}{S_h(f)}\, \exp(2\pi i f t)\, df\right]$$

Template

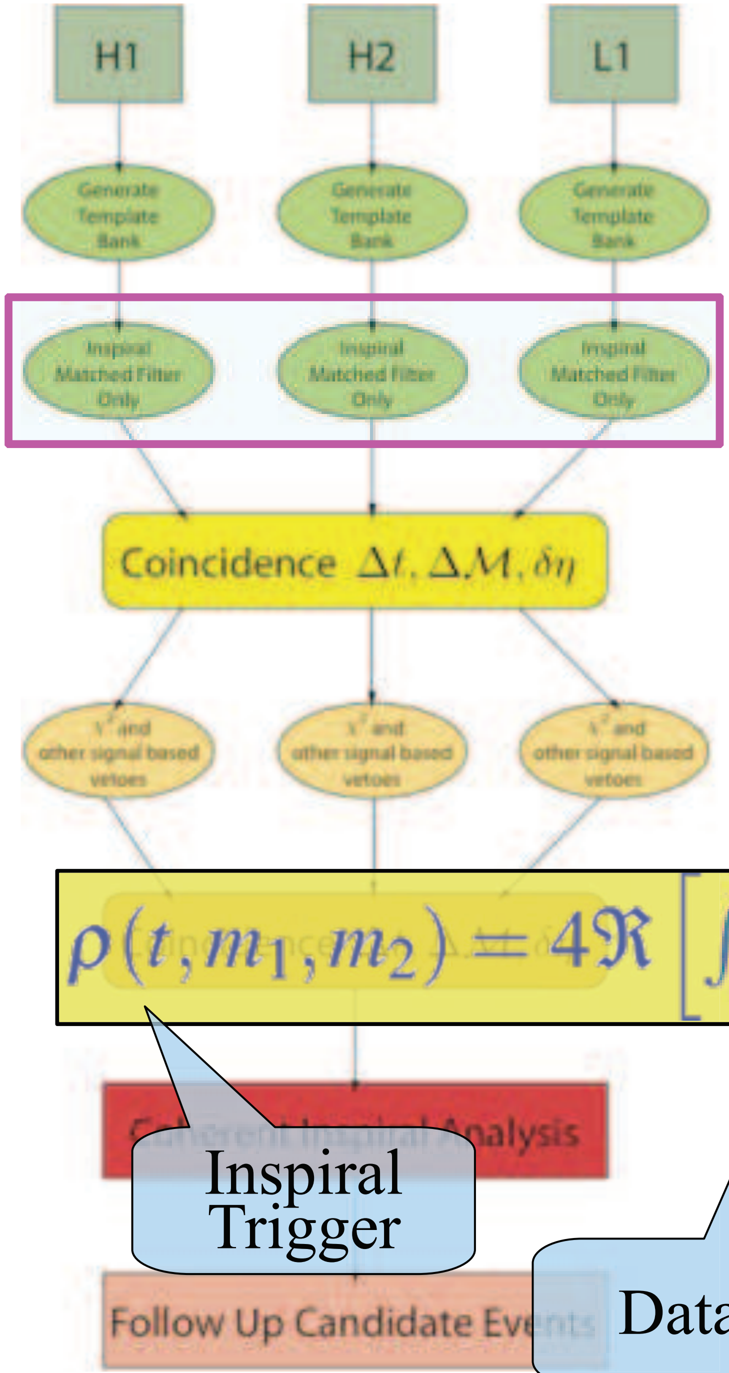
Inspiral Trigger

Data

Slides by Dietz and Sengupta

Inspiral Stage (Matched filter only)

- Filters the data and generates the detection statistic.



$$\rho(t, m_1, m_2) = 4\Re\left[\int_0^\infty \tilde{x}(f)\,\frac{\tilde{T}^*(f; m_1, m_2)}{S_h(f)}\,\exp(2\pi i f t)\,df\right]$$

Template

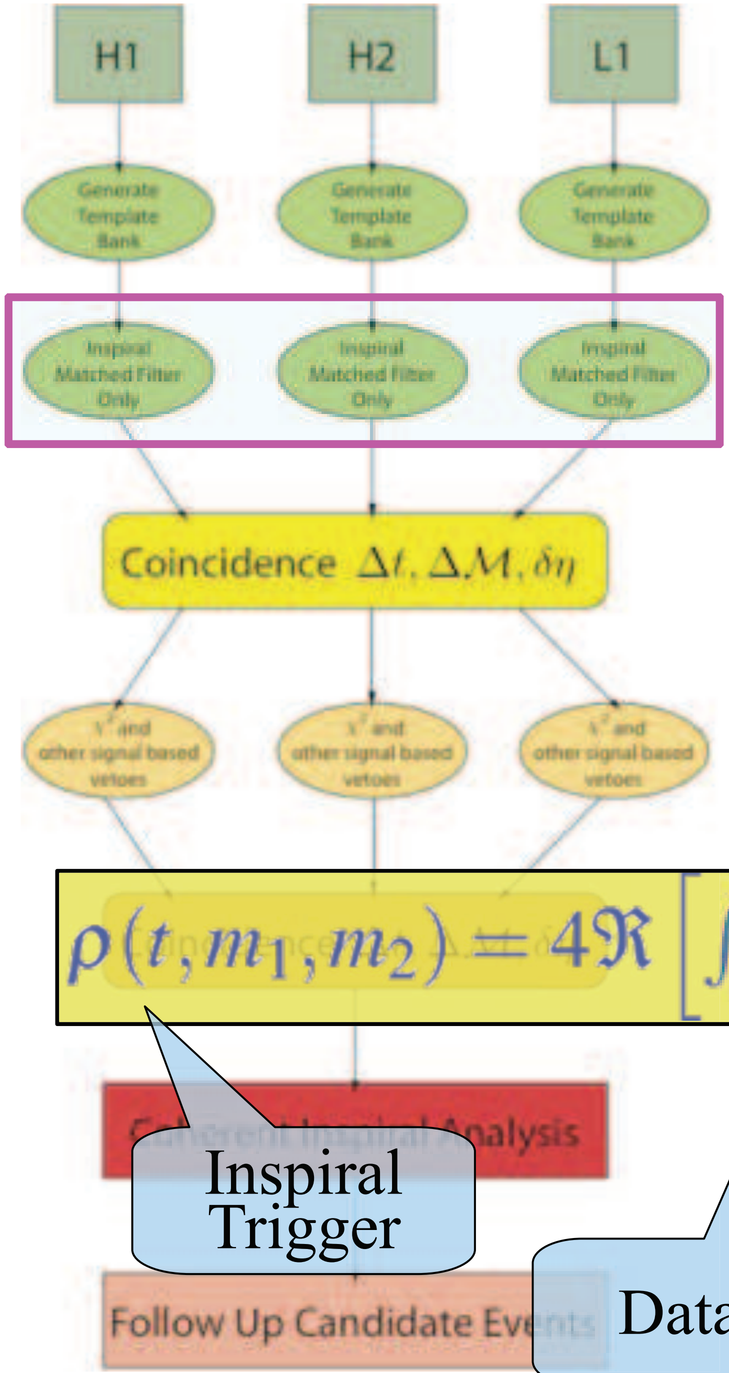
Inspiral Trigger

Data

Slides by Dietz and Sengupta

Inspiral Stage (Matched filter only)

- Filters the data and generates the detection statistic.
- All instances of the detection statistic that exceed a (pre-set) threshold are recorded for further analysis.



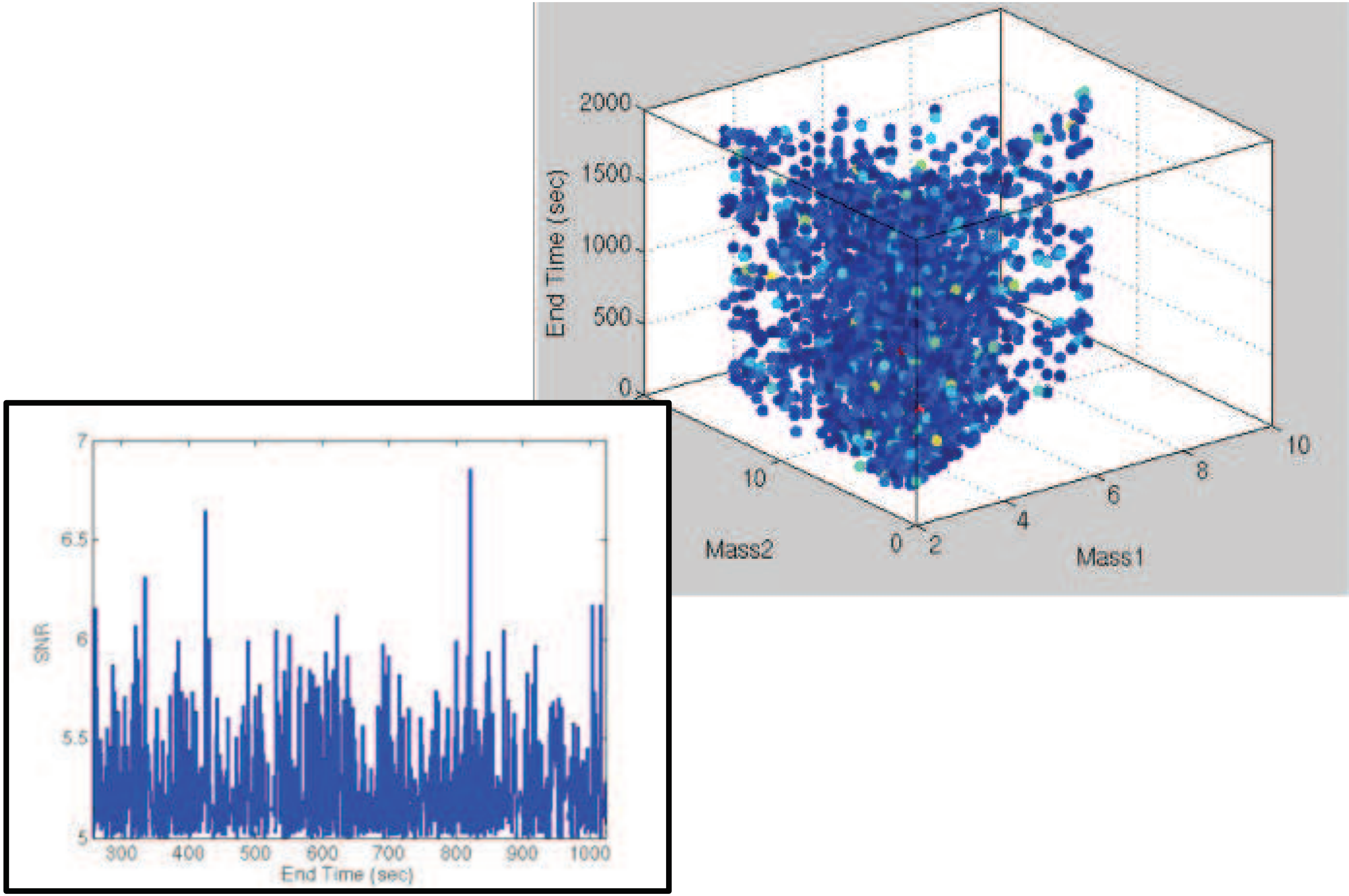
Template

$$\rho(t,m_1,m_2) = 4\Re\left[\int_0^\infty \tilde{x}(f)\,\frac{\tilde{T}^*(f;m_1,m_2)}{S_h(f)}\,\exp(2\pi i f t)\,df\right]$$

Inspiral Trigger

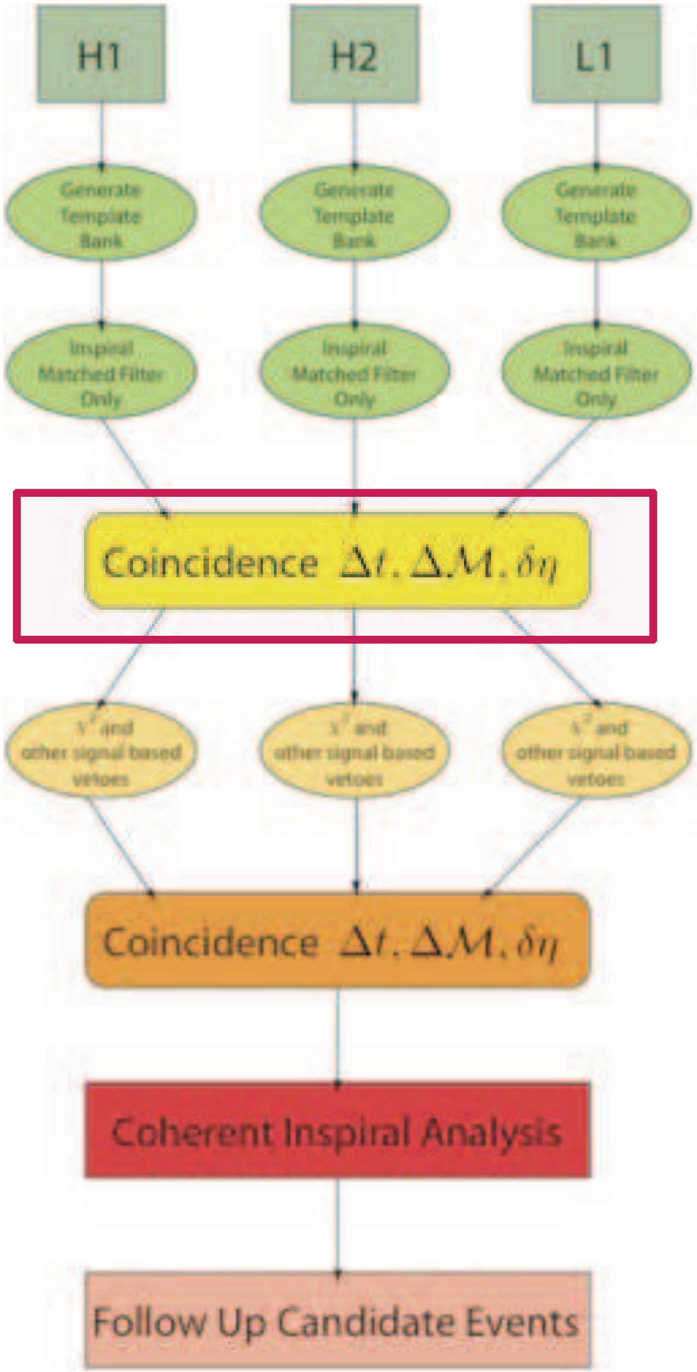
Data

Slides by Dietz and Sengupta

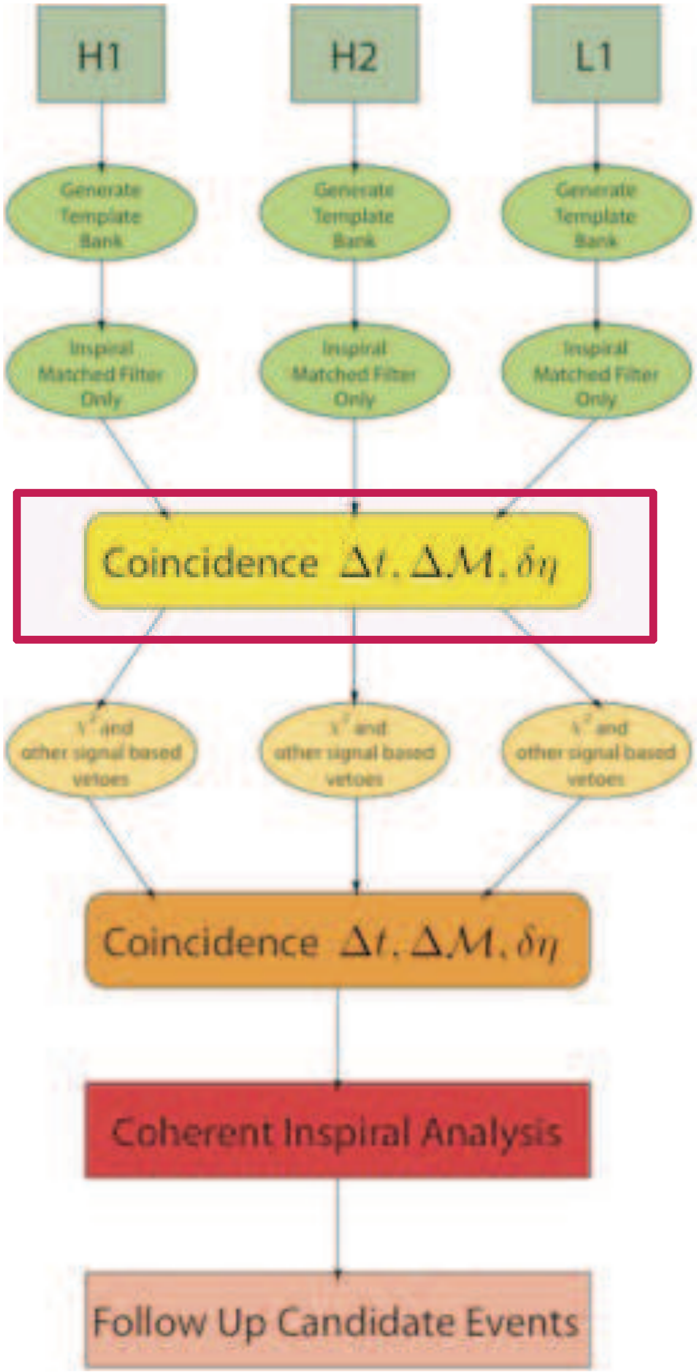


Slides by Dietz and Sengupta

Coincidence of triggers



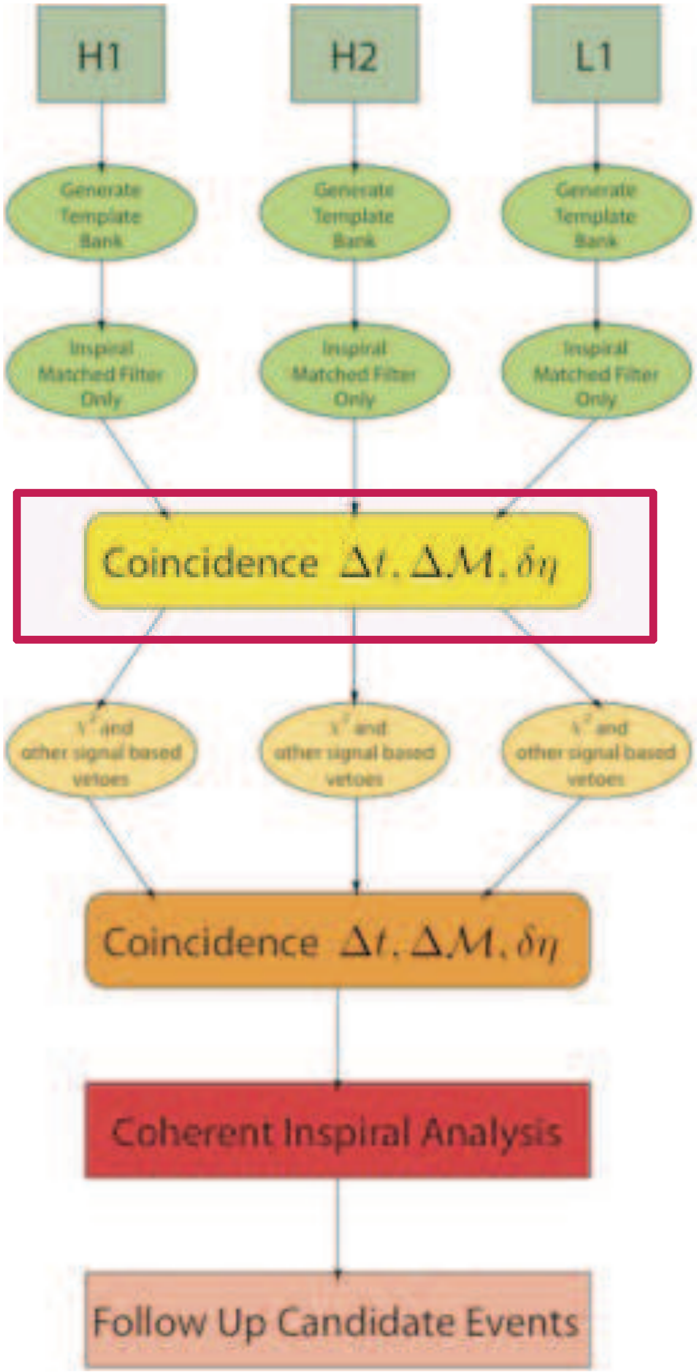
Slides by Dietz and Sengupta



Coincidence of triggers

- Check for consistency in parameters of triggers across interferometers.

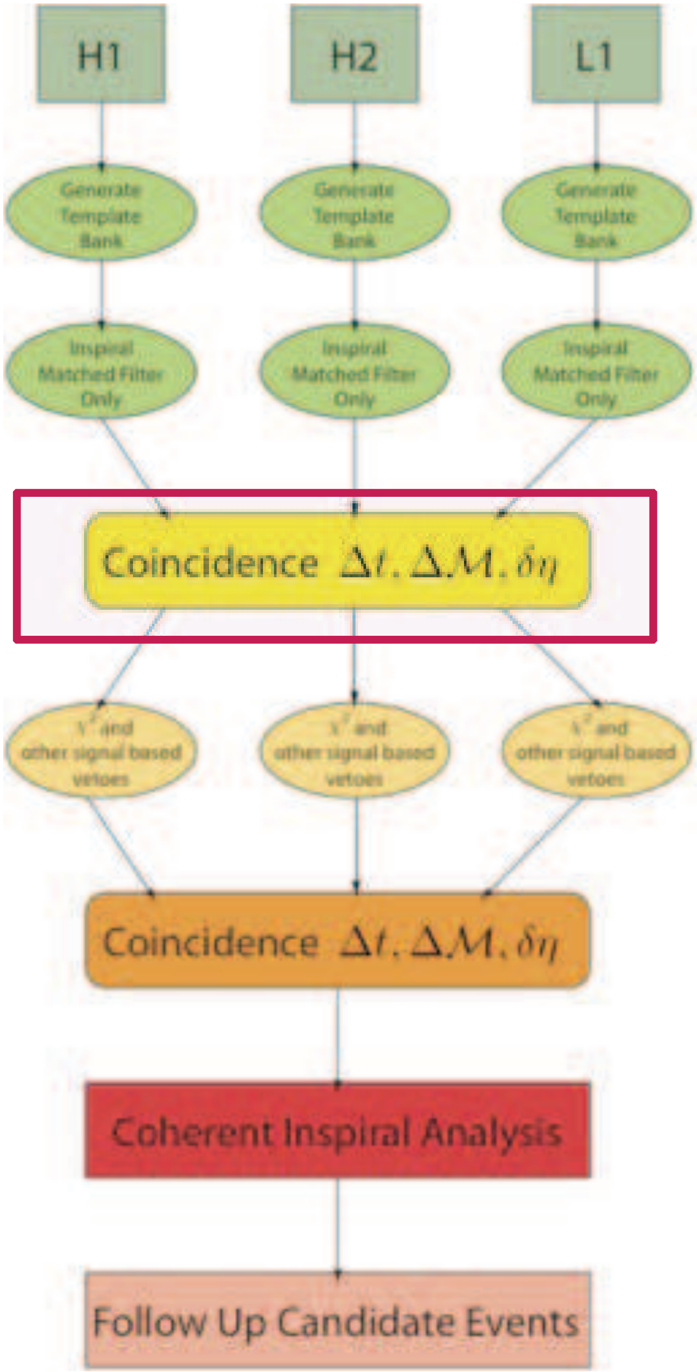
Slides by Dietz and Sengupta



Coincidence of triggers

- Check for consistency in parameters of triggers across interferometers.
- Can slide triggers from one IFO with respect to another – to estimate the chances of *accidental coincidences (background)*.

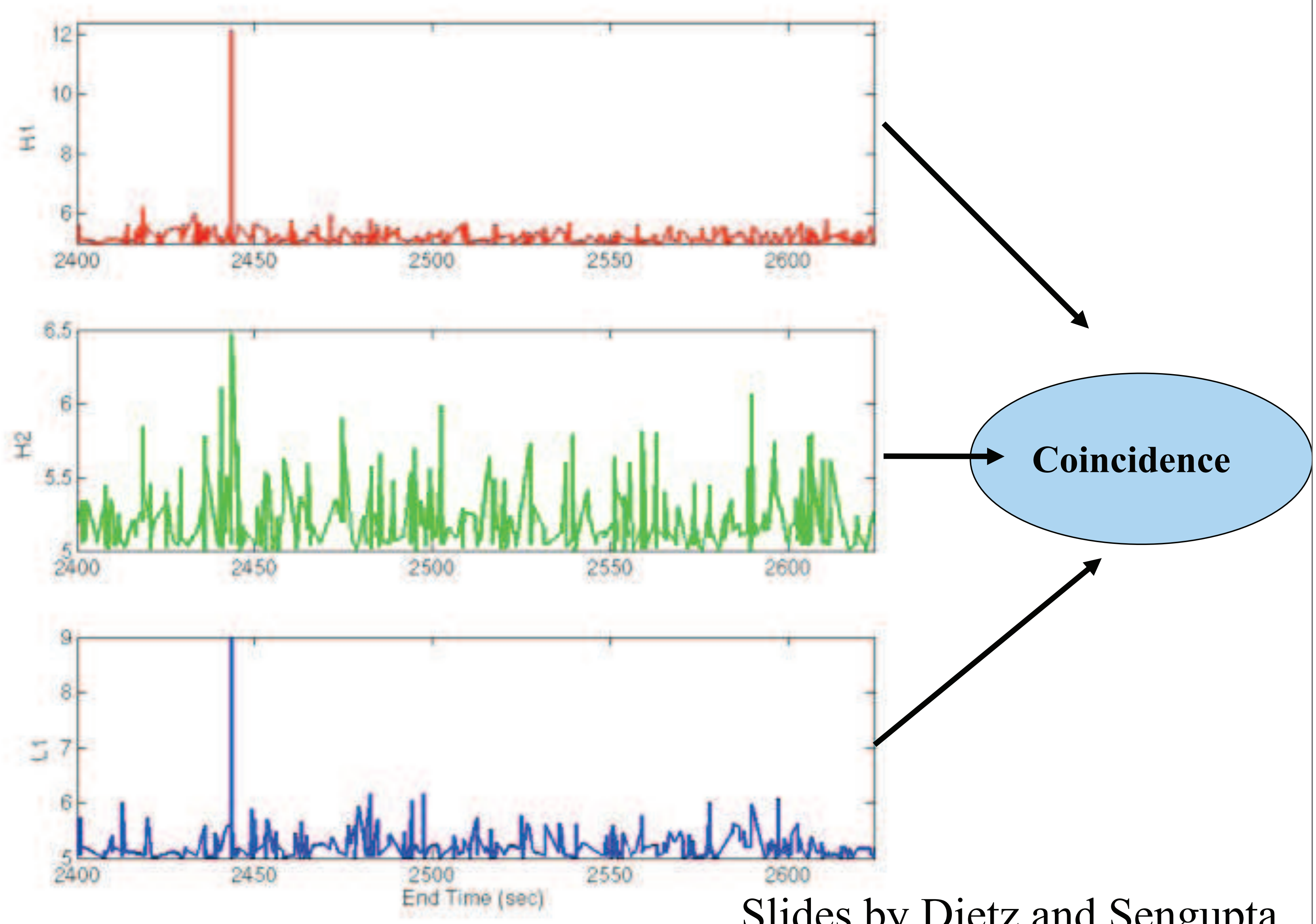
Slides by Dietz and Sengupta



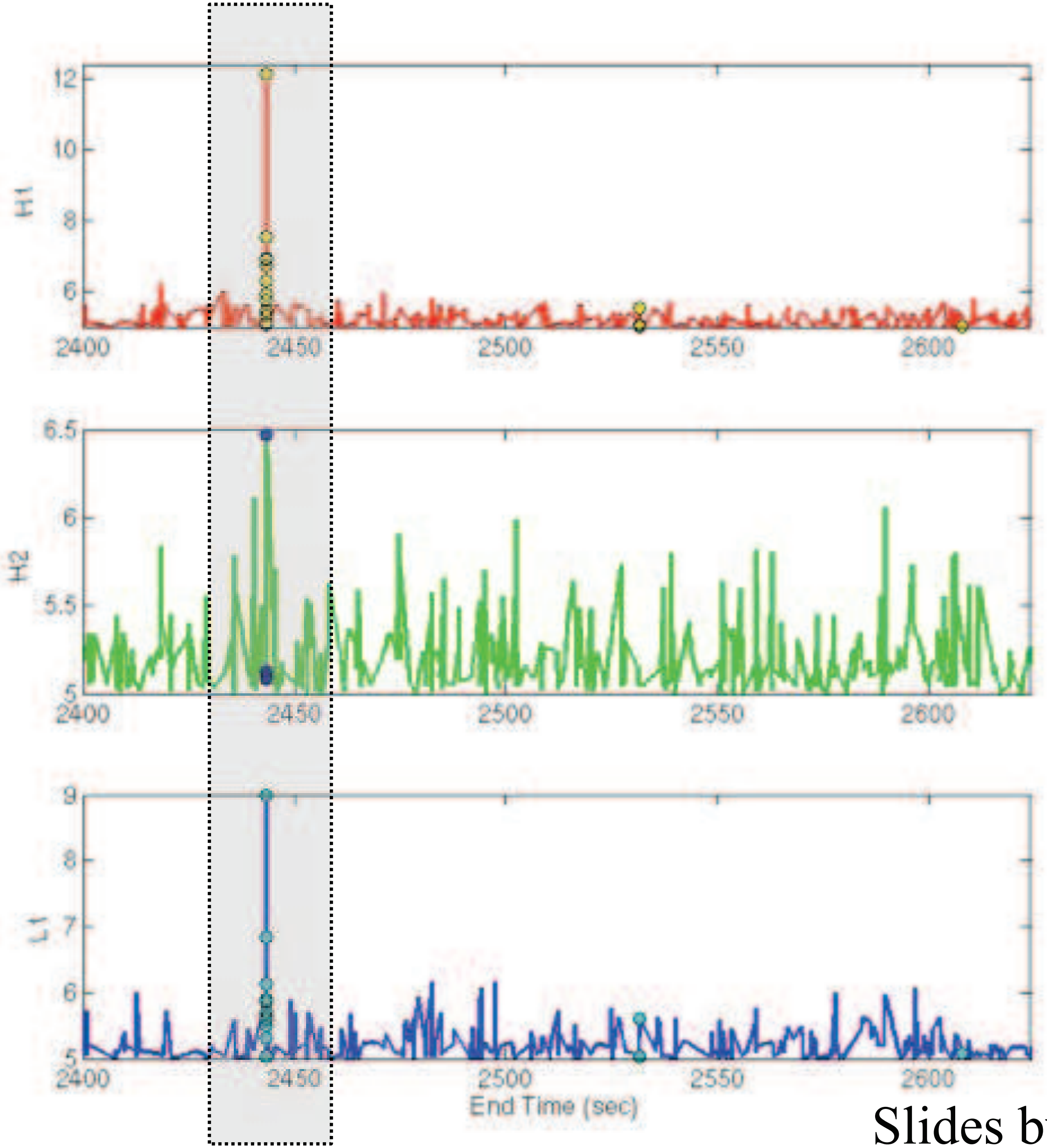
Coincidence of triggers

- Check for consistency in parameters of triggers across interferometers.
- Can slide triggers from one IFO with respect to another – to estimate the chances of *accidental coincidences (background)*.
- Real GW trigger identified if distinct or well-separated from background triggers.

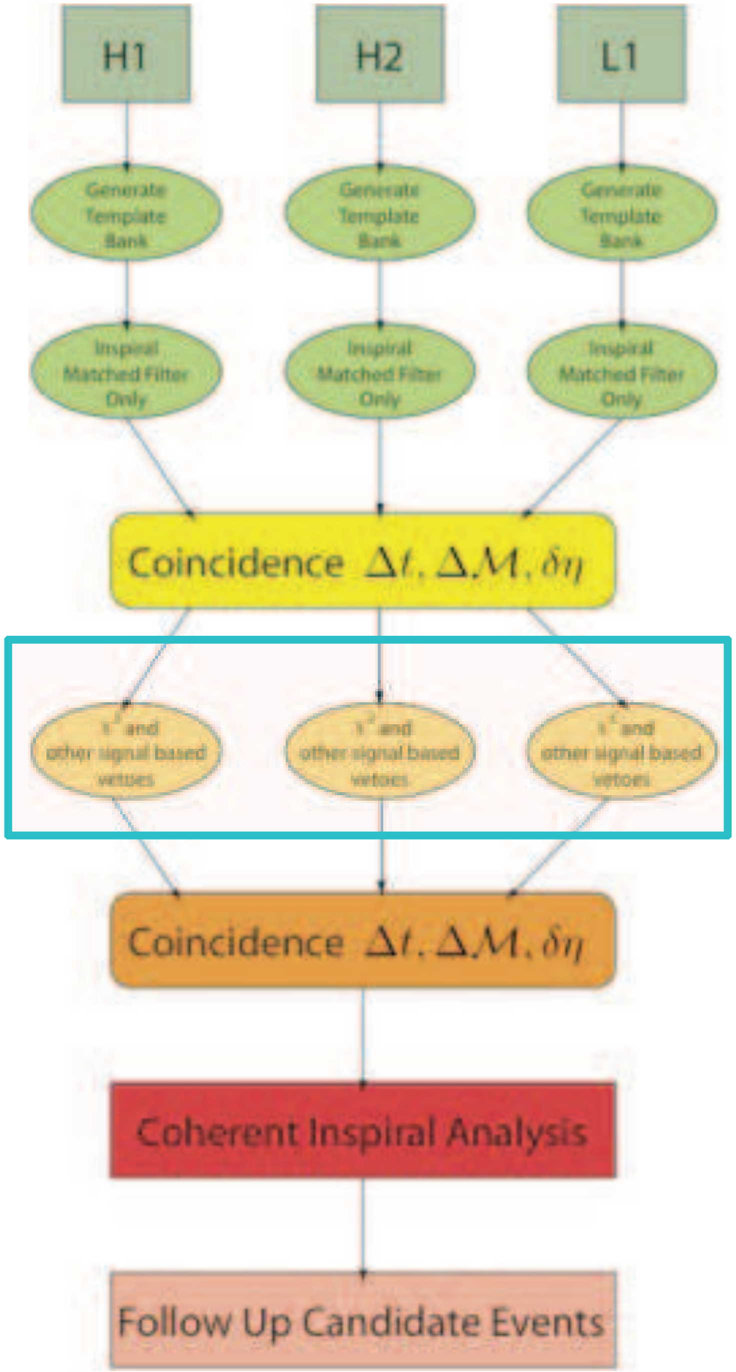
Slides by Dietz and Sengupta



Slides by Dietz and Sengupta

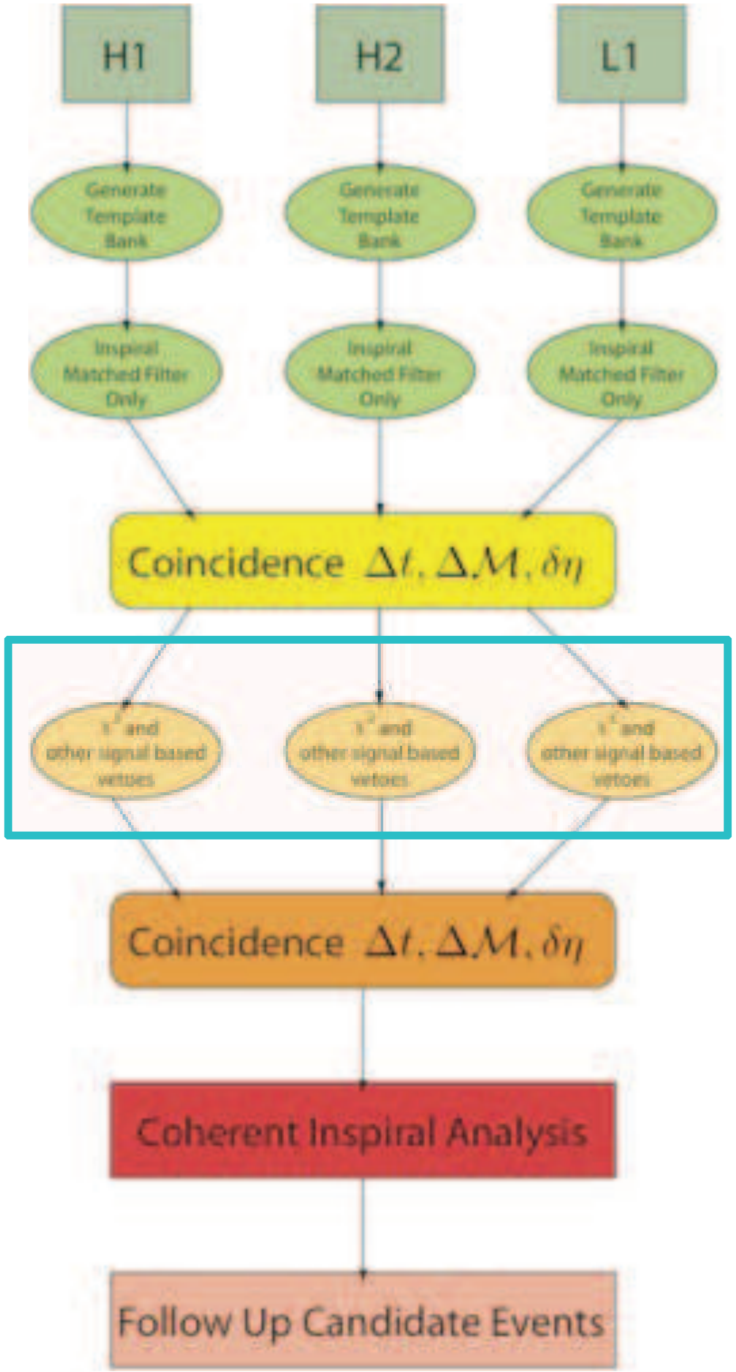


Slides by Dietz and Sengupta



Second stage

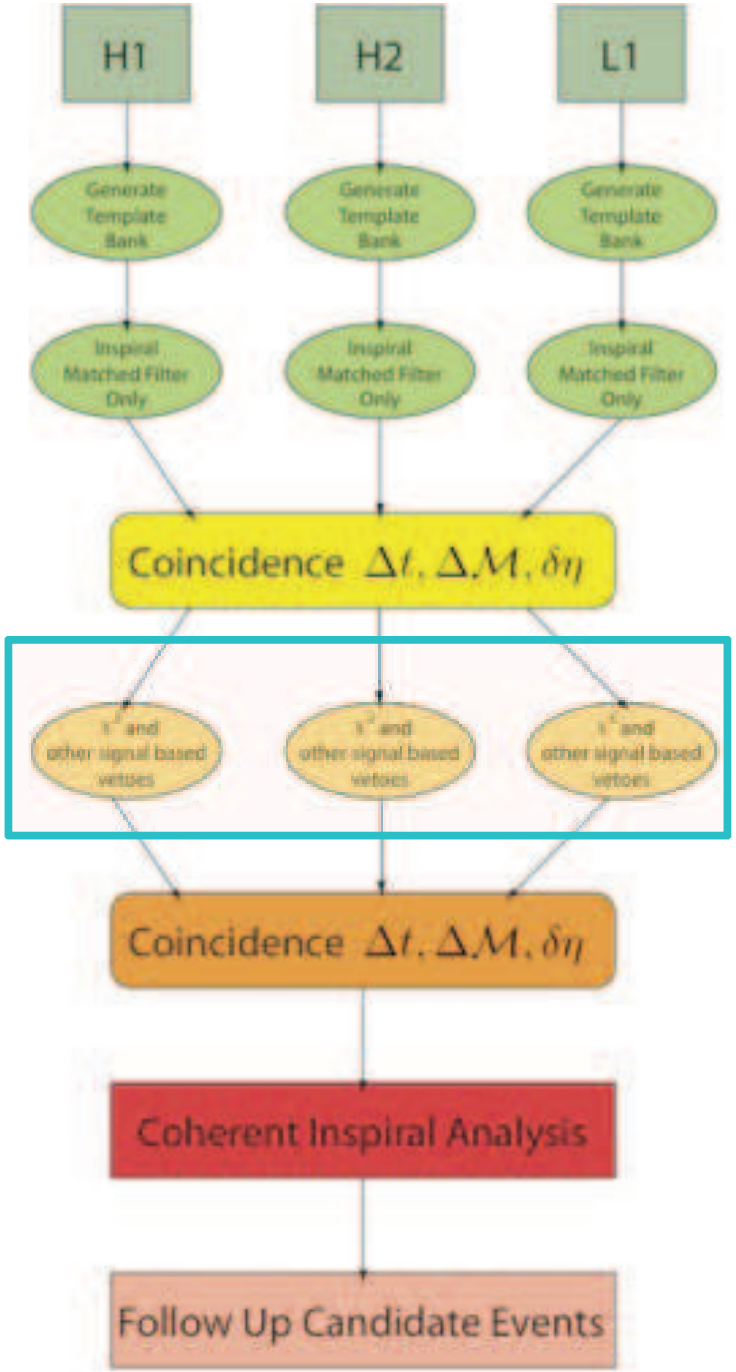
Slides by Dietz and Sengupta



Second stage

- Second stage template bank is a *triggered bank* using 1st coincidence triggers.

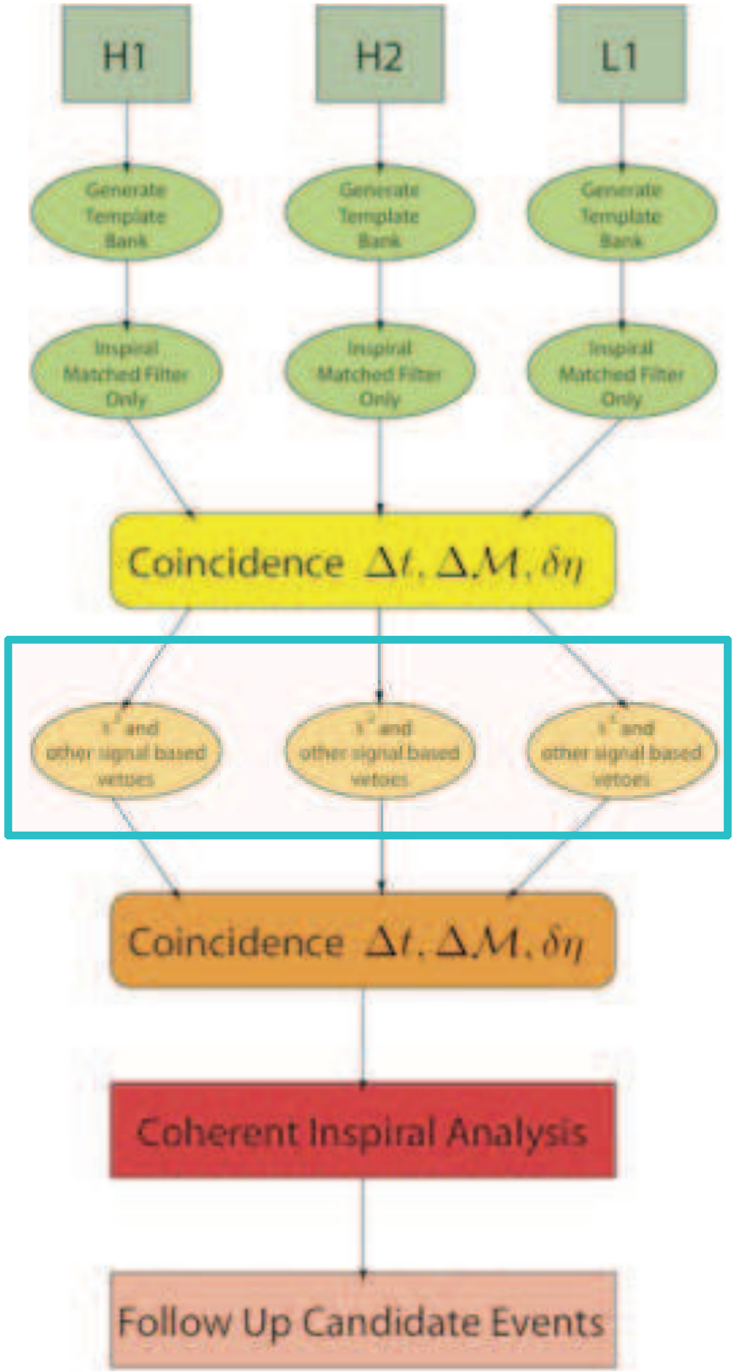
Slides by Dietz and Sengupta



Second stage

- Second stage template bank is a *triggered bank* using 1st coincidence triggers.
- Second (veto) inspiral stage performed using the above triggered bank.

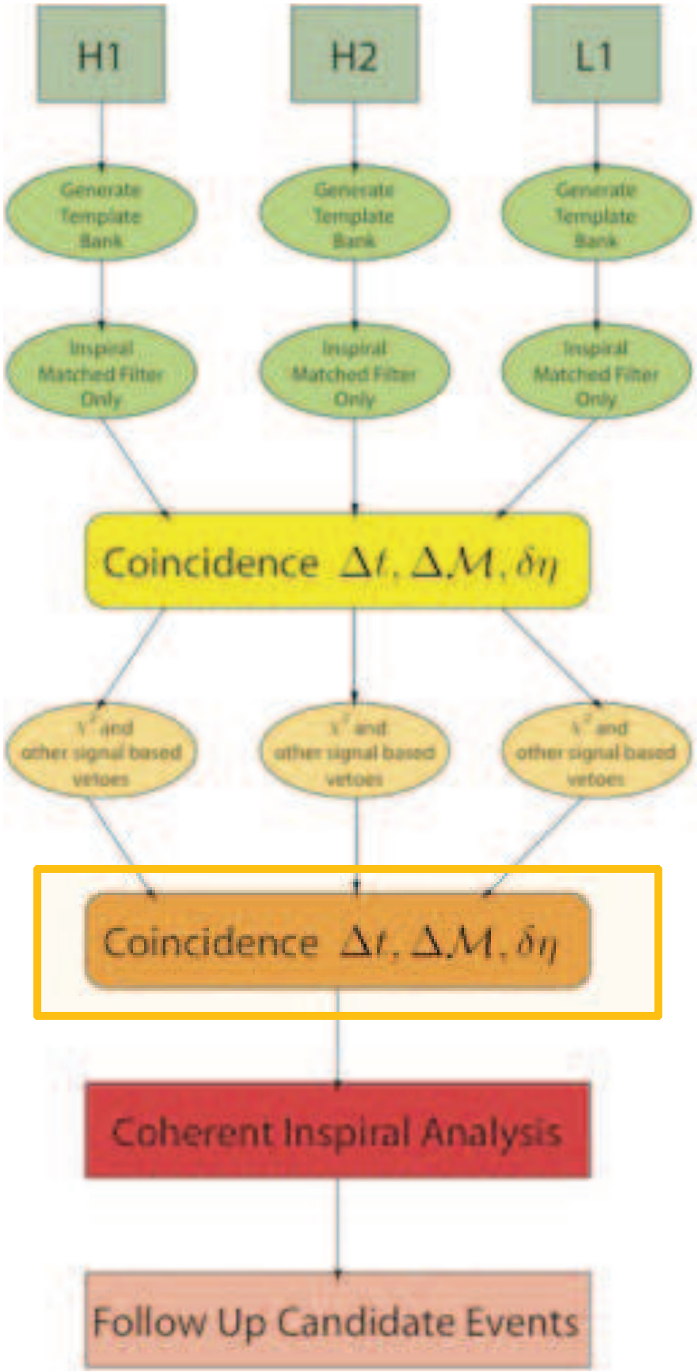
Slides by Dietz and Sengupta



Second stage

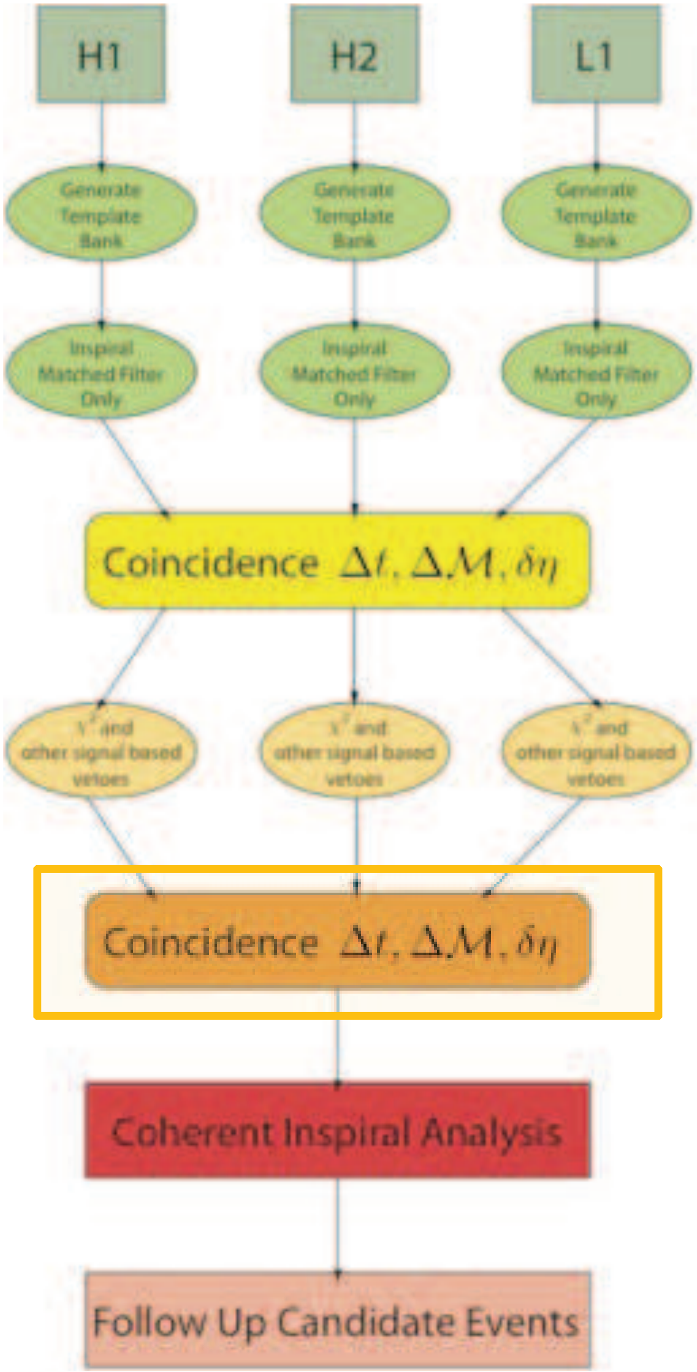
- Second stage template bank is a *triggered bank* using 1st coincidence triggers.
- Second (veto) inspiral stage performed using the above triggered bank.
- Hierarchical approach saves computational cycles.

Slides by Dietz and Sengupta



2nd Coincidence

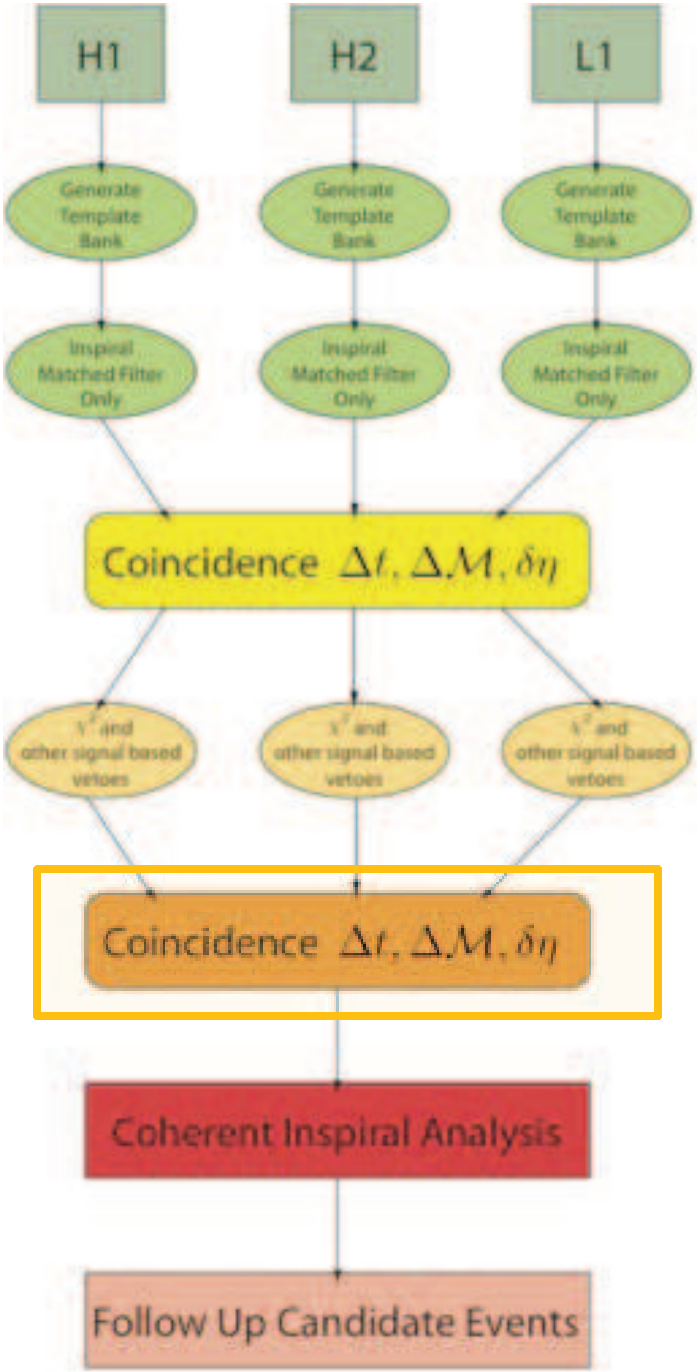
Slides by Dietz and Sengupta



2nd Coincidence

- Checks for consistency in parameters of triggers generated in the second inspiral

Slides by Dietz and Sengupta



2nd Coincidence

- Checks for consistency in parameters of triggers generated in the second inspiral
- "Interesting" zero lag coincidences can be followed up by a coherent search.

Slides by Dietz and Sengupta

Astrophysics

Astrophysics

Astrophysics

- Unveiling progenitors of short-hard GRBs

Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs believed to be merging NS-NS and NS-BH

Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs believed to be merging NS-NS and NS-BH
- Understanding Supernovae

Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs believed to be merging NS-NS and NS-BH
- Understanding Supernovae
  - Astrophysics of gravitational collapse and supernova?

Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs believed to be merging NS-NS and NS-BH
- Understanding Supernovae
  - Astrophysics of gravitational collapse and supernova?
- Evolutionary paths of compact binaries

Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs believed to be merging NS-NS and NS-BH
- Understanding Supernovae
  - Astrophysics of gravitational collapse and supernova?
- Evolutionary paths of compact binaries
- Finding why pulsars glitch and magnetars flare

Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs believed to be merging NS-NS and NS-BH
- Understanding Supernovae
  - Astrophysics of gravitational collapse and supernova?
- Evolutionary paths of compact binaries
- Finding why pulsars glitch and magnetars flare
  - What causes sudden excursions in pulsar spin frequencies

Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs believed to be merging NS-NS and NS-BH
- Understanding Supernovae
  - Astrophysics of gravitational collapse and supernova?
- Evolutionary paths of compact binaries
- Finding why pulsars glitch and magnetars flare
  - What causes sudden excursions in pulsar spin frequencies
  - What is behind ultra high-energy transients in magnetars

Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs believed to be merging NS-NS and NS-BH
- Understanding Supernovae
  - Astrophysics of gravitational collapse and supernova?
- Evolutionary paths of compact binaries
- Finding why pulsars glitch and magnetars flare
  - What causes sudden excursions in pulsar spin frequencies
  - What is behind ultra high-energy transients in magnetars
- Ellipticity of neutron stars

Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs believed to be merging NS-NS and NS-BH
- Understanding Supernovae
  - Astrophysics of gravitational collapse and supernova?
- Evolutionary paths of compact binaries
- Finding why pulsars glitch and magnetars flare
  - What causes sudden excursions in pulsar spin frequencies
  - What is behind ultra high-energy transients in magnetars
- Ellipticity of neutron stars
  - Mountains of what size can be supported on neutron stars?

Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs believed to be merging NS-NS and NS-BH
- Understanding Supernovae
  - Astrophysics of gravitational collapse and supernova?
- Evolutionary paths of compact binaries
- Finding why pulsars glitch and magnetars flare
  - What causes sudden excursions in pulsar spin frequencies
  - What is behind ultra high-energy transients in magnetars
- Ellipticity of neutron stars
  - Mountains of what size can be supported on neutron stars?
- NS spin frequencies in LMXBs

Astrophysics

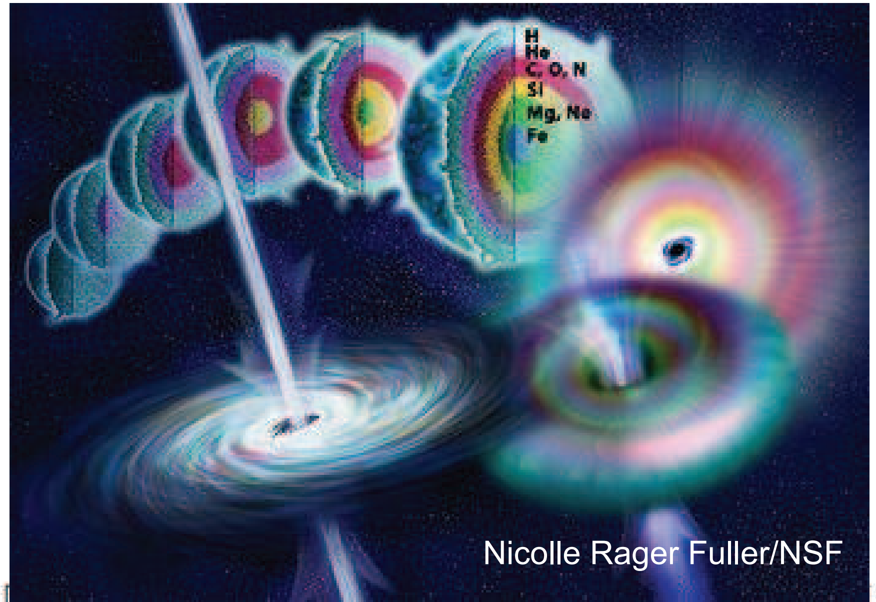
- Unveiling progenitors of short-hard GRBs
  - Short-hard GRBs believed to be merging NS-NS and NS-BH
- Understanding Supernovae
  - Astrophysics of gravitational collapse and supernova?
- Evolutionary paths of compact binaries
- Finding why pulsars glitch and magnetars flare
  - What causes sudden excursions in pulsar spin frequencies
  - What is behind ultra high-energy transients in magnetars
- Ellipticity of neutron stars
  - Mountains of what size can be supported on neutron stars?
- NS spin frequencies in LMXBs
  - Why are spin frequencies of neutron stars in low-mass X-ray binaries bounded, CFS instability and r-modes

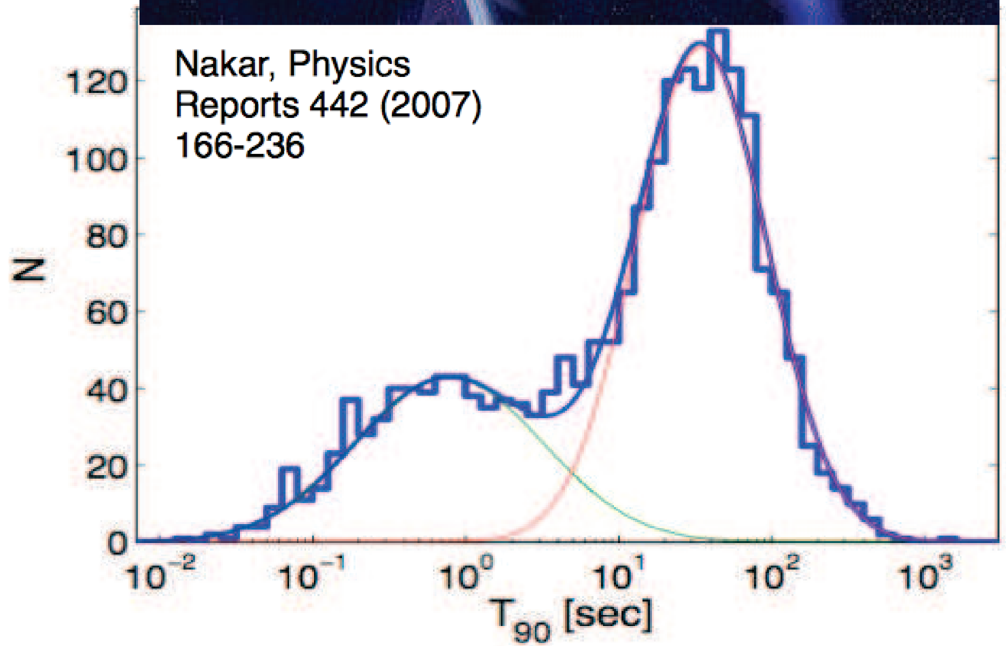
Expected Annual Coalescence Rates

- Rates are mean of the distribution; in a 95% confidence interval, rates uncertain by 3 orders of magnitude
- Rates are for Binary Neutron Stars (BNS) Binary Black Boles (BBH) and Neutron Star-Black Hole binaries (NS-BH)

	BNS	NS-BH	BBH
Initial LIGO (2002-06)	0.02	0.006	0.01
Adv. LIGO (2014+)	40	10	20
ET	Millions	100,000	Millions

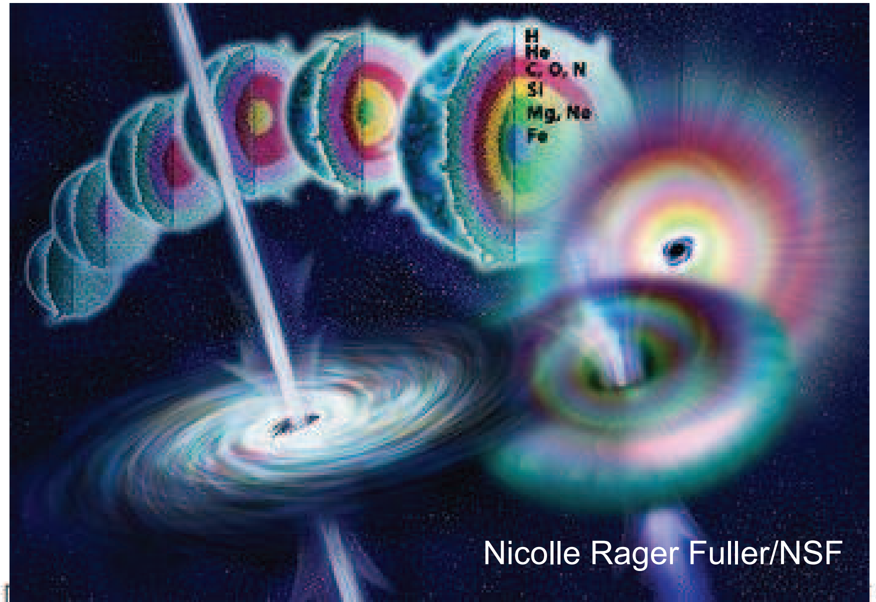
GRB Progenitors

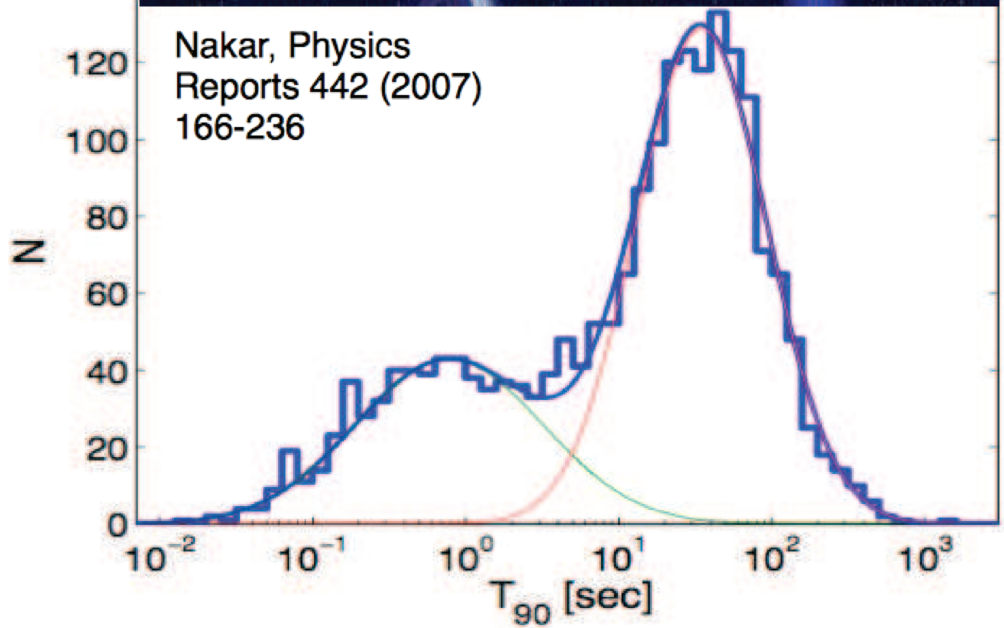




GRB Progenitors

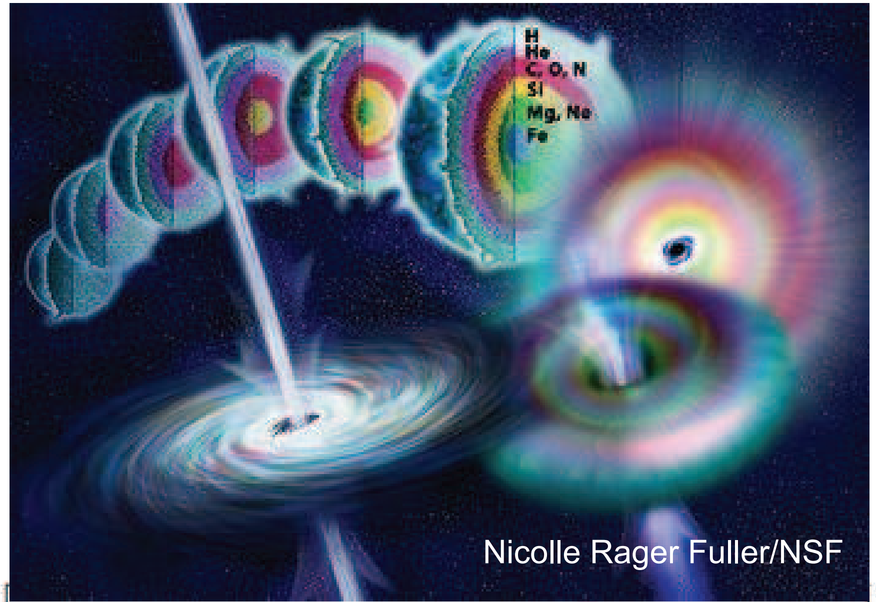
- Intense flashes of gamma-rays:

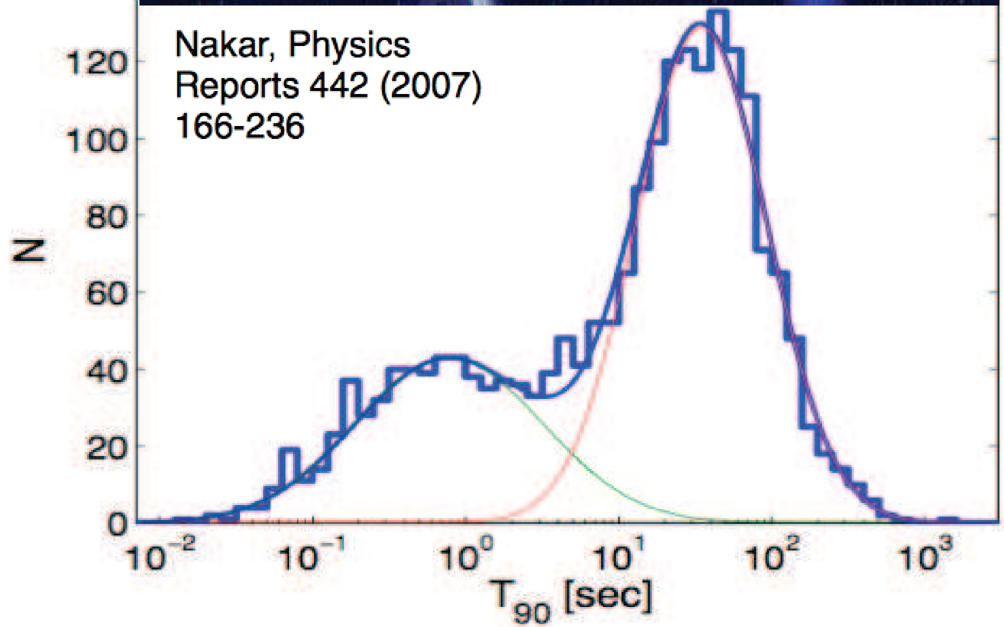




GRB Progenitors

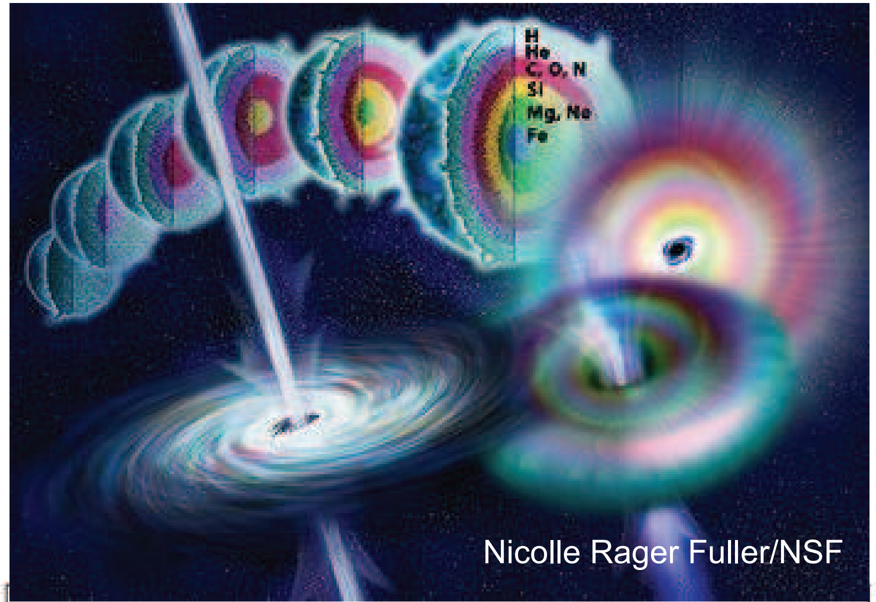
- Intense flashes of gamma-rays:
  - Most luminous EM source since the Big Bang

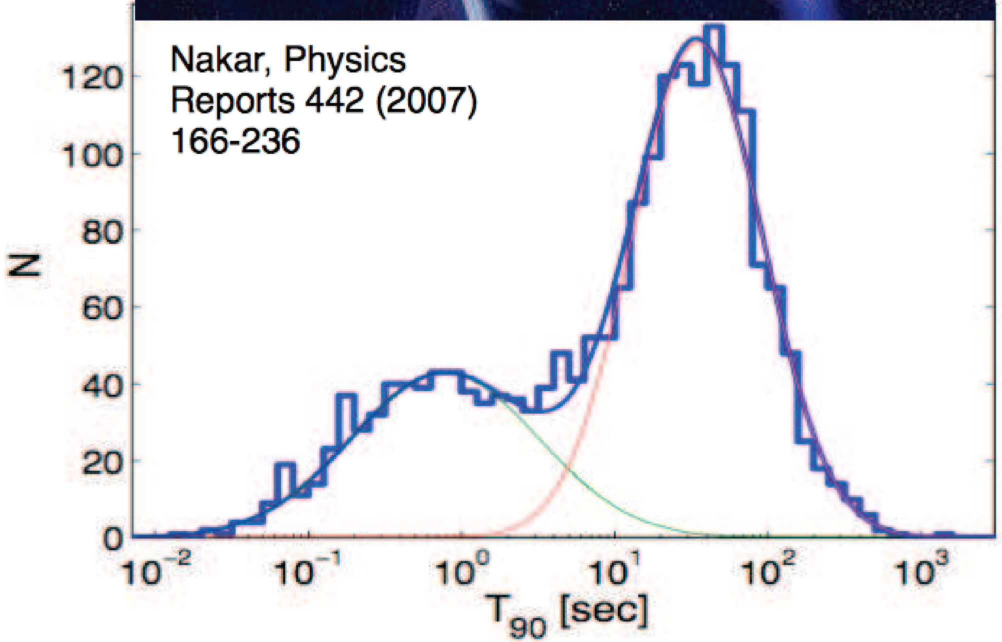




GRB Progenitors

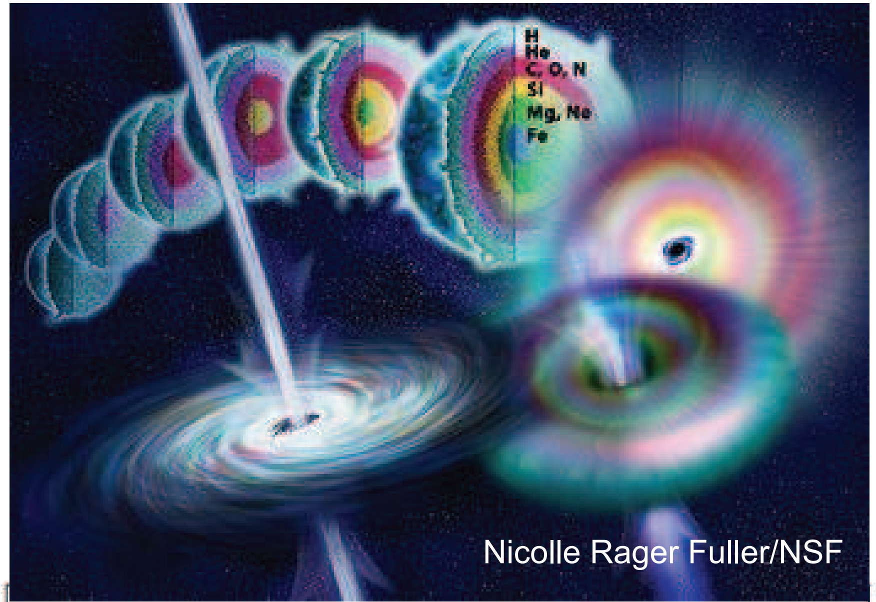
- Intense flashes of gamma-rays:
  - Most luminous EM source since the Big Bang
  - X-ray, UV and optical afterglows

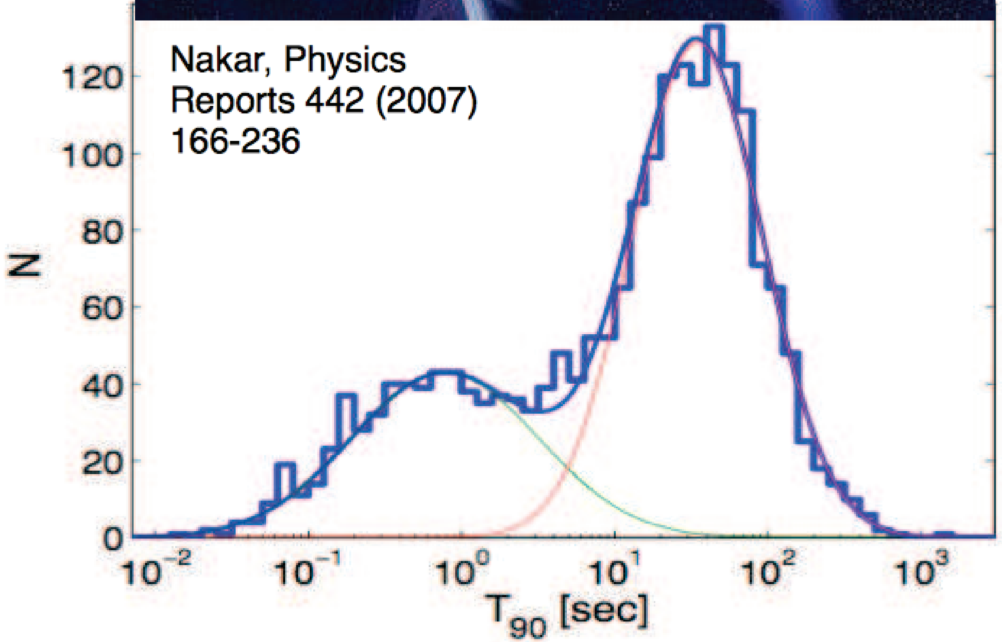




GRB Progenitors

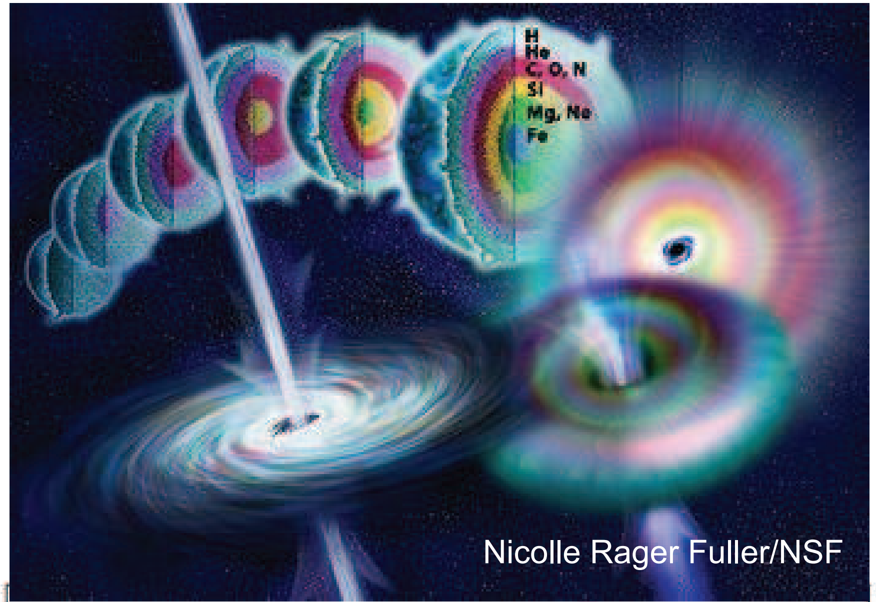
- Intense flashes of gamma-rays:
  - Most luminous EM source since the Big Bang
  - X-ray, UV and optical afterglows
- Bimodal distribution of durations

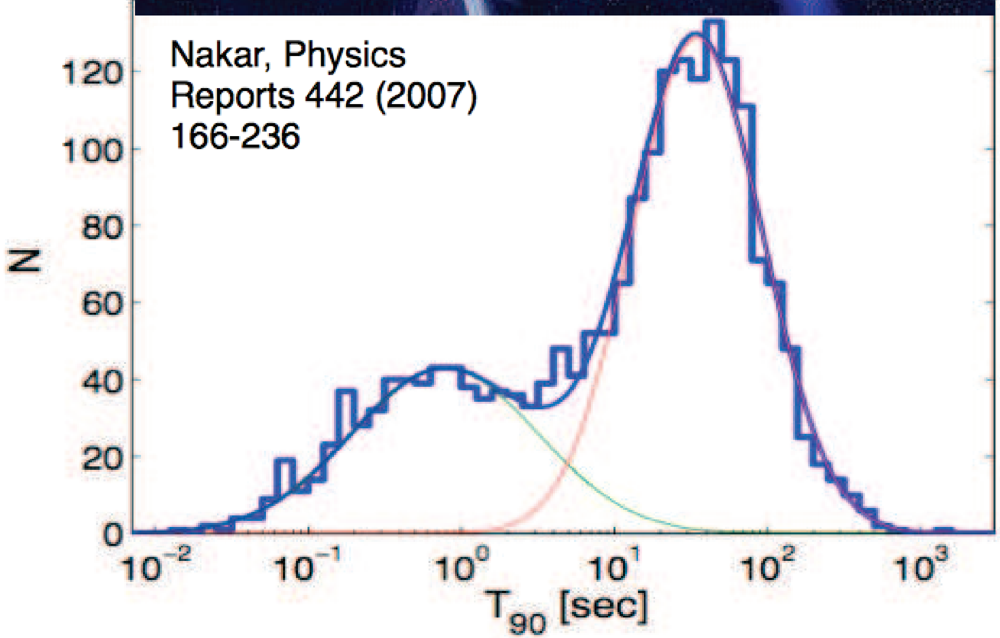




GRB Progenitors

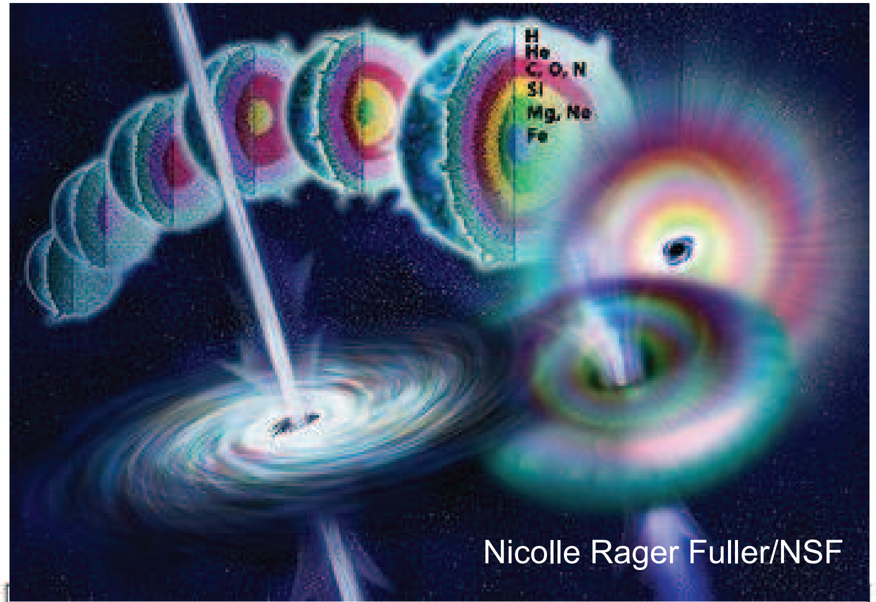
- Intense flashes of gamma-rays:
  - Most luminous EM source since the Big Bang
  - X-ray, UV and optical afterglows
- Bimodal distribution of durations
  - Short GRBs

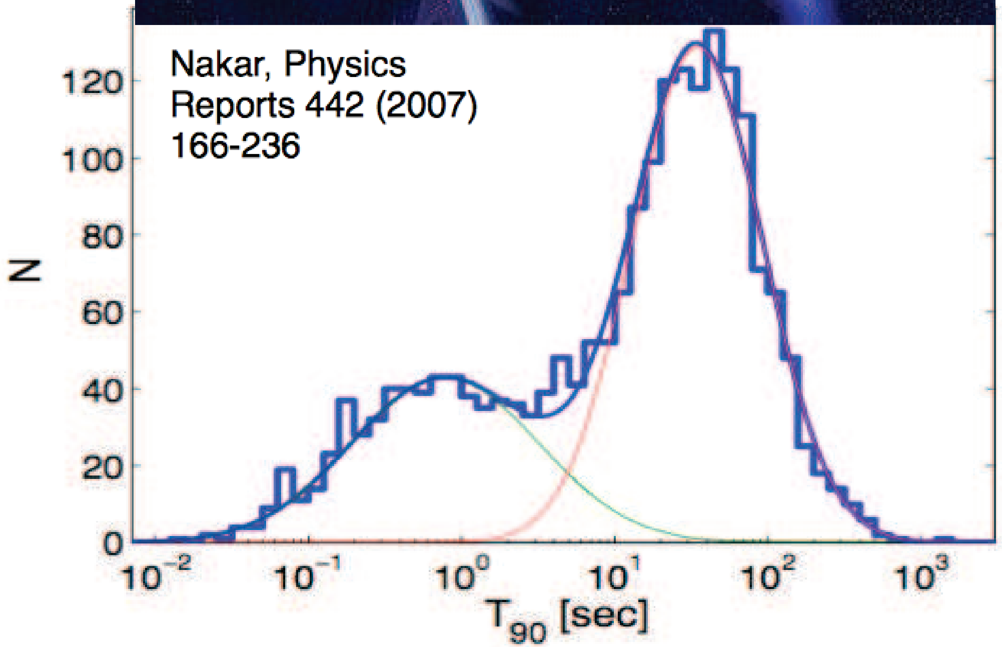




GRB Progenitors

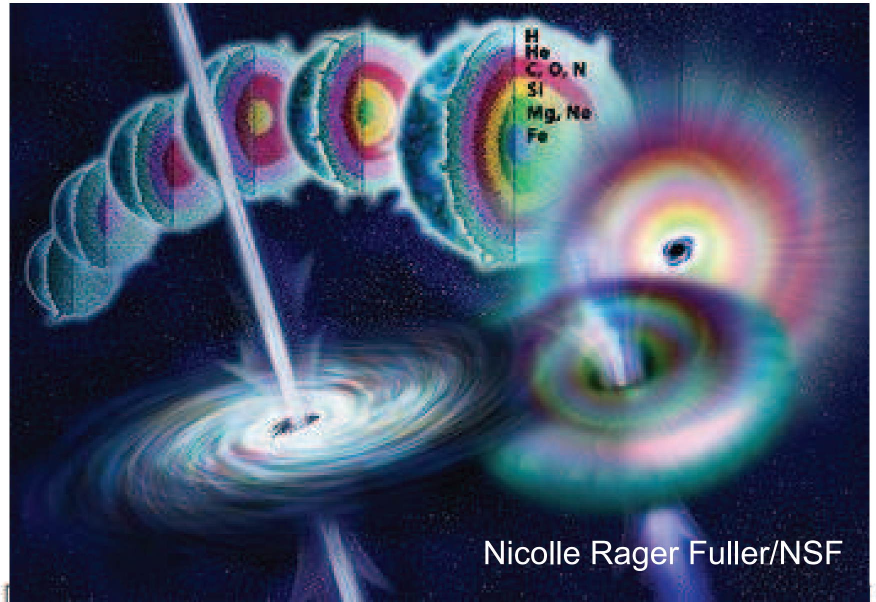
- Intense flashes of gamma-rays:
  - Most luminous EM source since the Big Bang
  - X-ray, UV and optical afterglows
- Bimodal distribution of durations
  - Short GRBs
    - Duration: $T_{90} < 2$ s

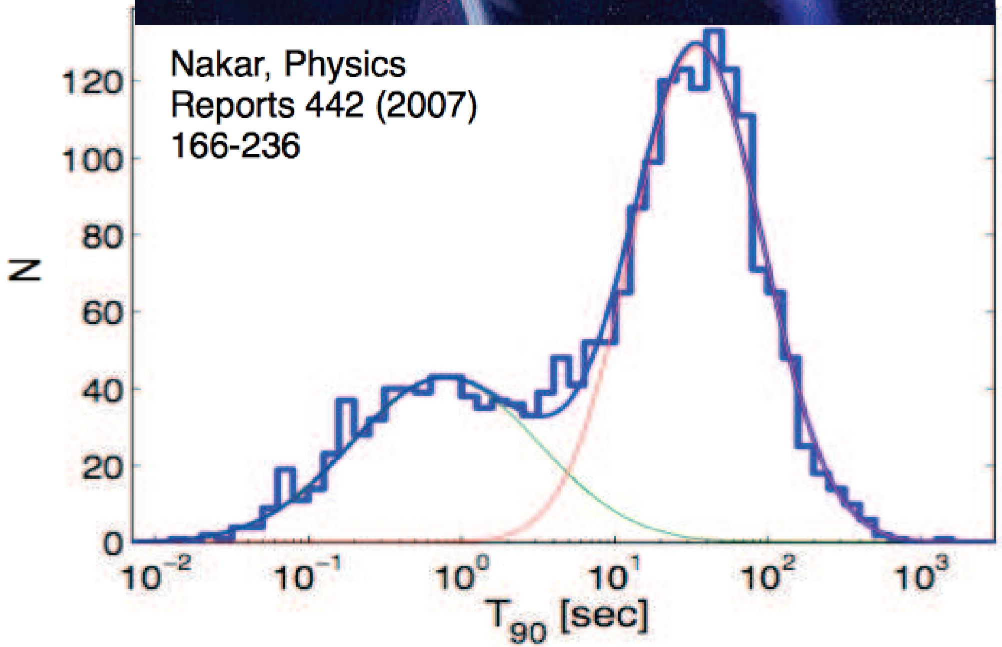




GRB Progenitors

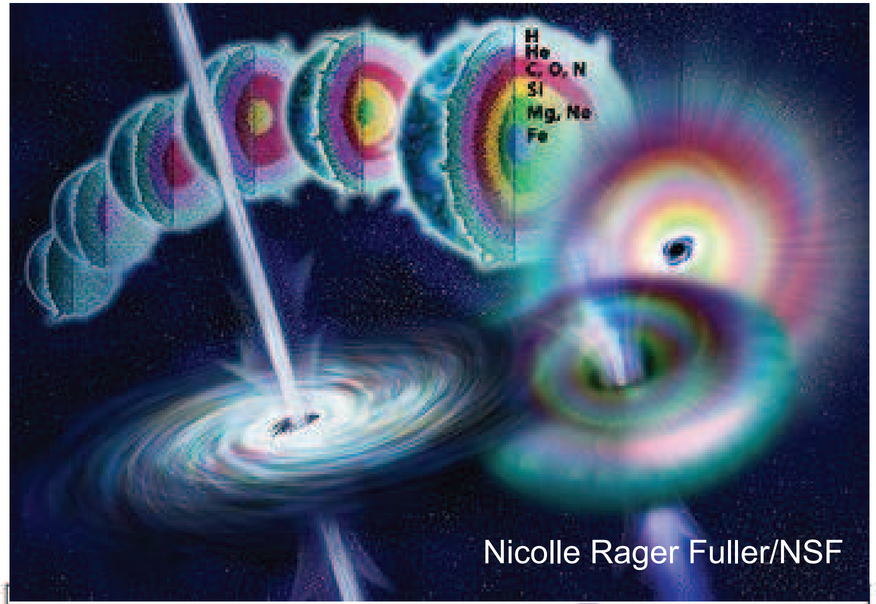
- Intense flashes of gamma-rays:
  - Most luminous EM source since the Big Bang
  - X-ray, UV and optical afterglows
- Bimodal distribution of durations
  - Short GRBs
    - Duration: $T_{90} < 2$ s
    - Mean redshift of 0.5

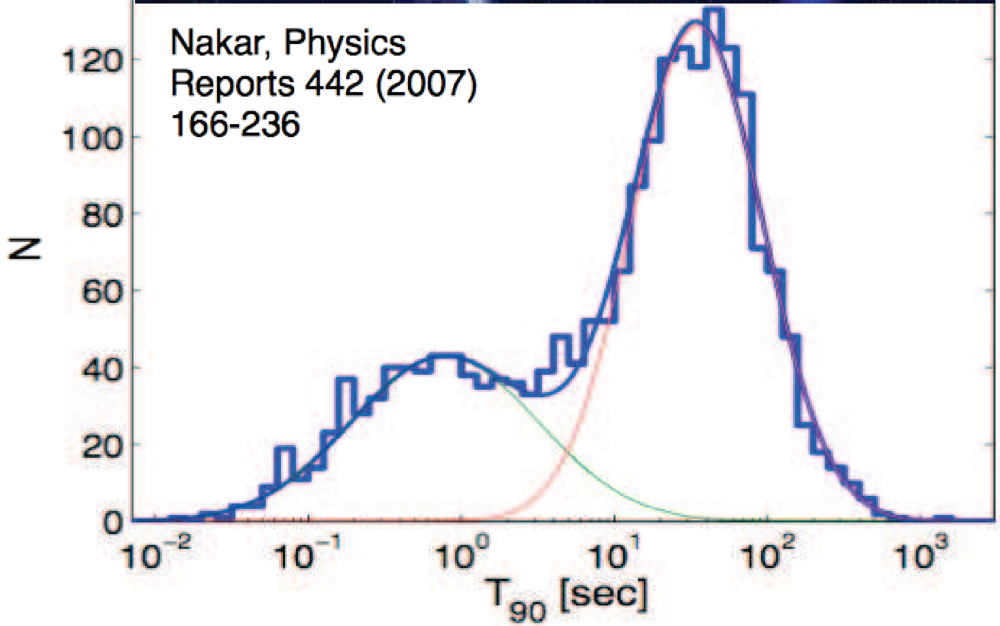




GRB Progenitors

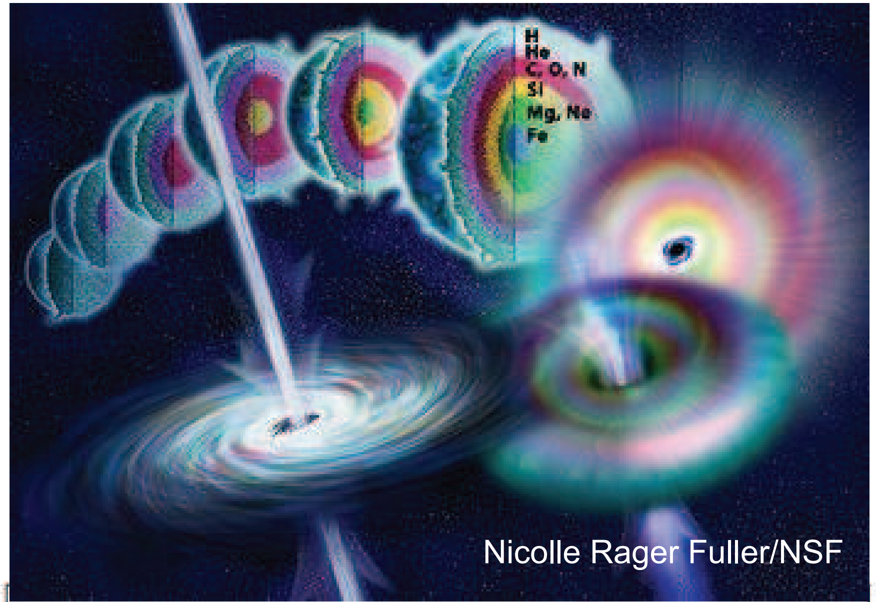
- Intense flashes of gamma-rays:
  - Most luminous EM source since the Big Bang
  - X-ray, UV and optical afterglows
- Bimodal distribution of durations
  - Short GRBs
    - Duration: $T_{90} < 2$ s
    - Mean redshift of 0.5
  - Long GRBs

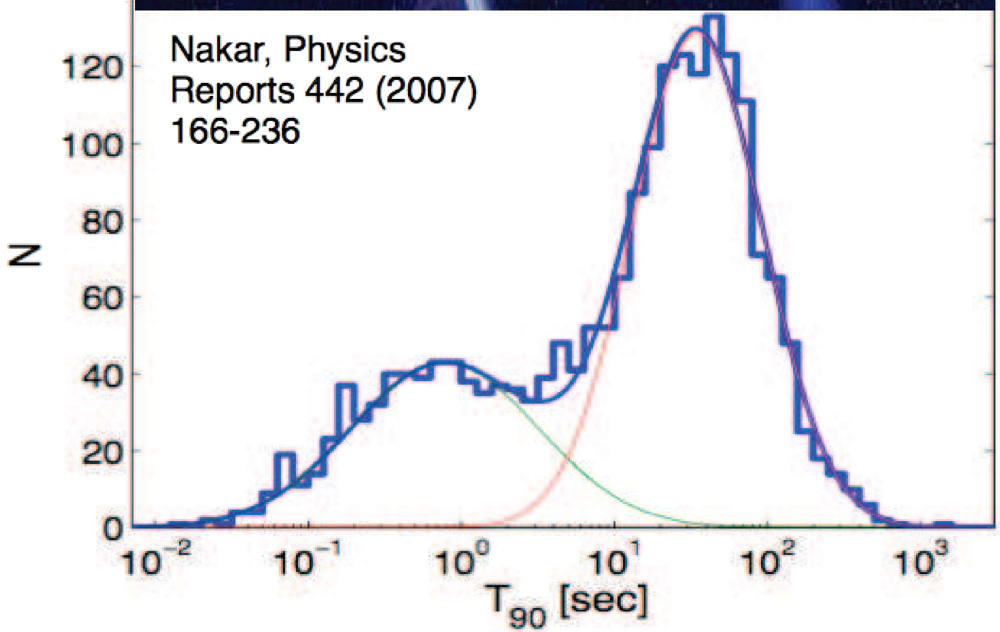




GRB Progenitors

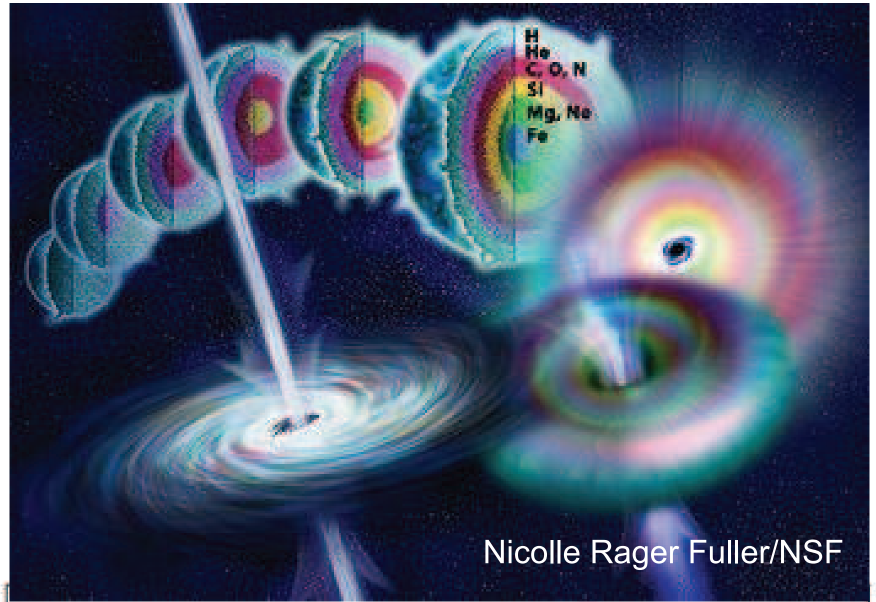
- Intense flashes of gamma-rays:
  - Most luminous EM source since the Big Bang
  - X-ray, UV and optical afterglows
- Bimodal distribution of durations
  - Short GRBs
    - Duration: $T_{90} < 2$ s
    - Mean redshift of 0.5
  - Long GRBs
    - Duration $T_{90} > 2$ s

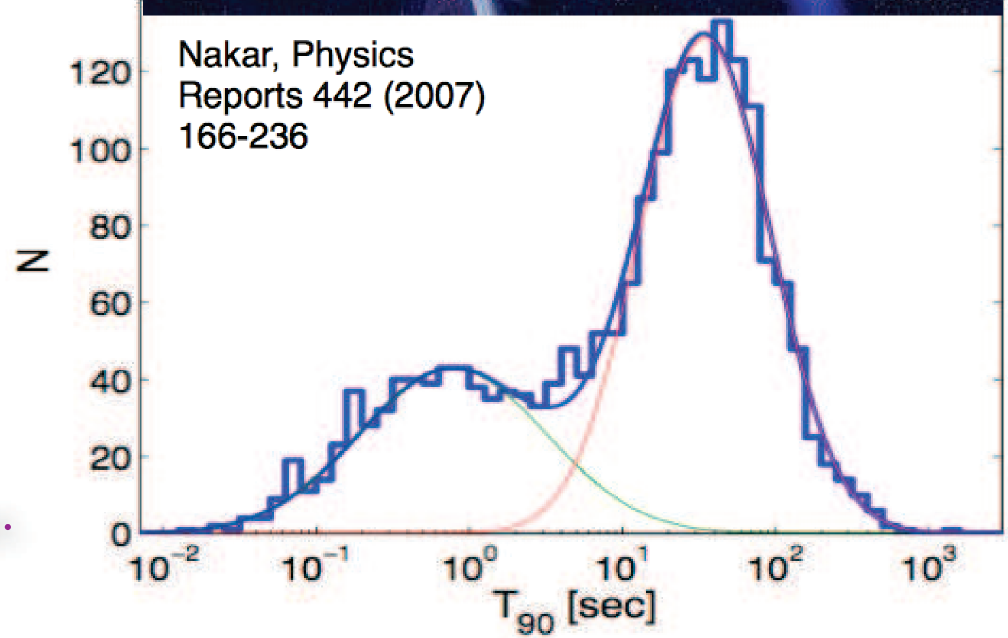




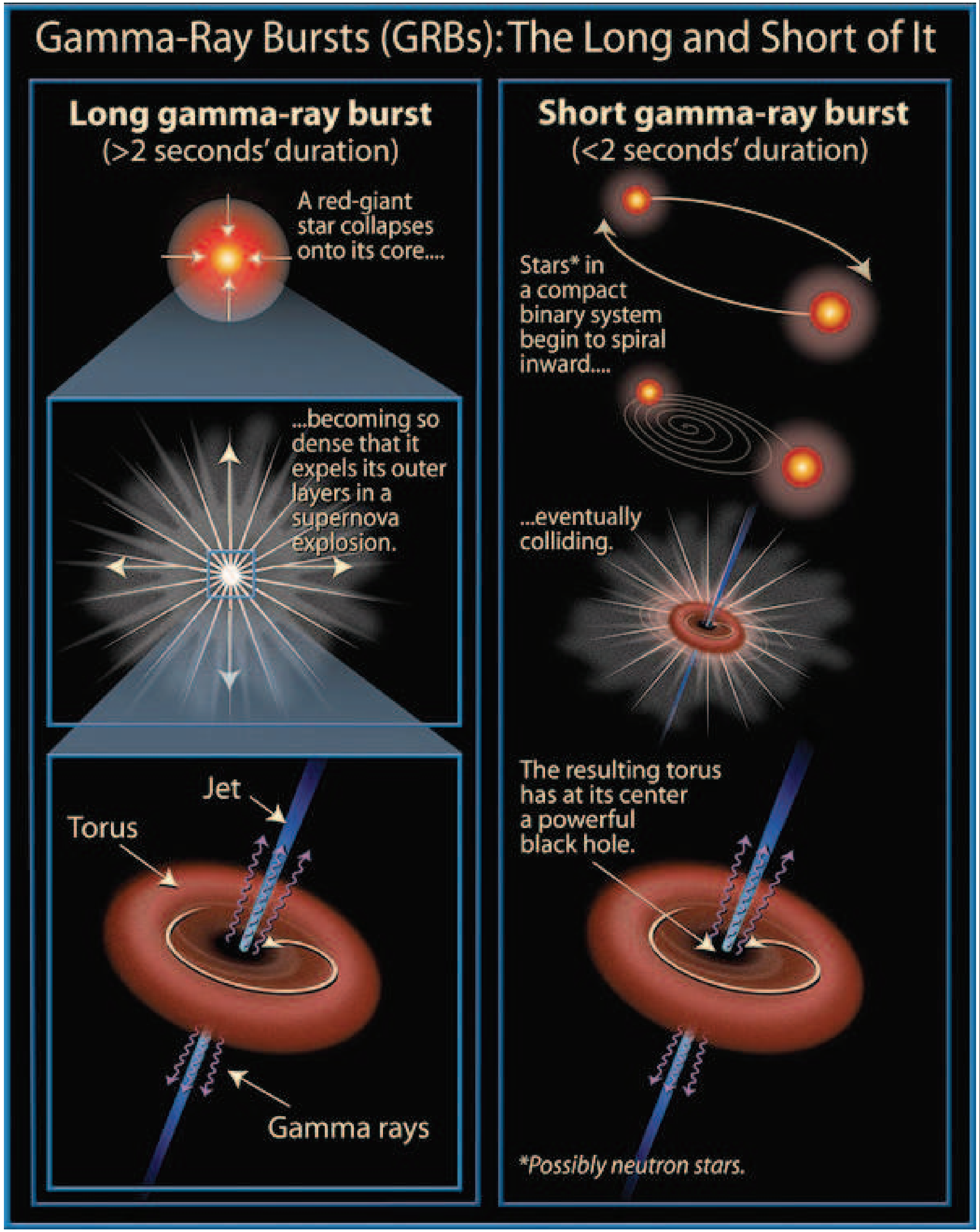
GRB Progenitors

- Intense flashes of gamma-rays:
  - Most luminous EM source since the Big Bang
  - X-ray, UV and optical afterglows
- Bimodal distribution of durations
  - Short GRBs
    - Duration: $T_{90} < 2$ s
    - Mean redshift of 0.5
  - Long GRBs
    - Duration $T_{90} > 2$ s
    - Higher z, track Star Form. Rate.



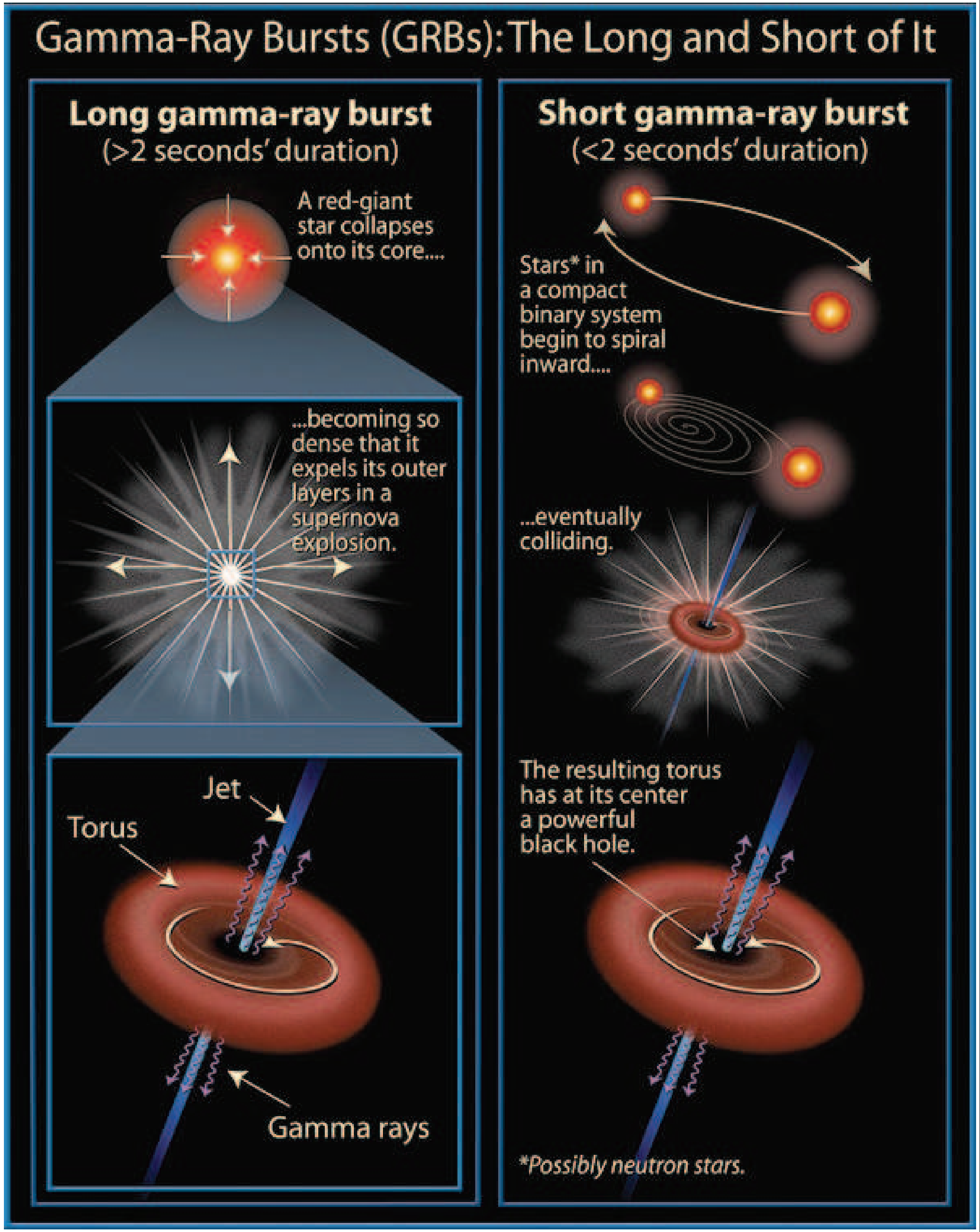


GRBs - The Long and Short of it



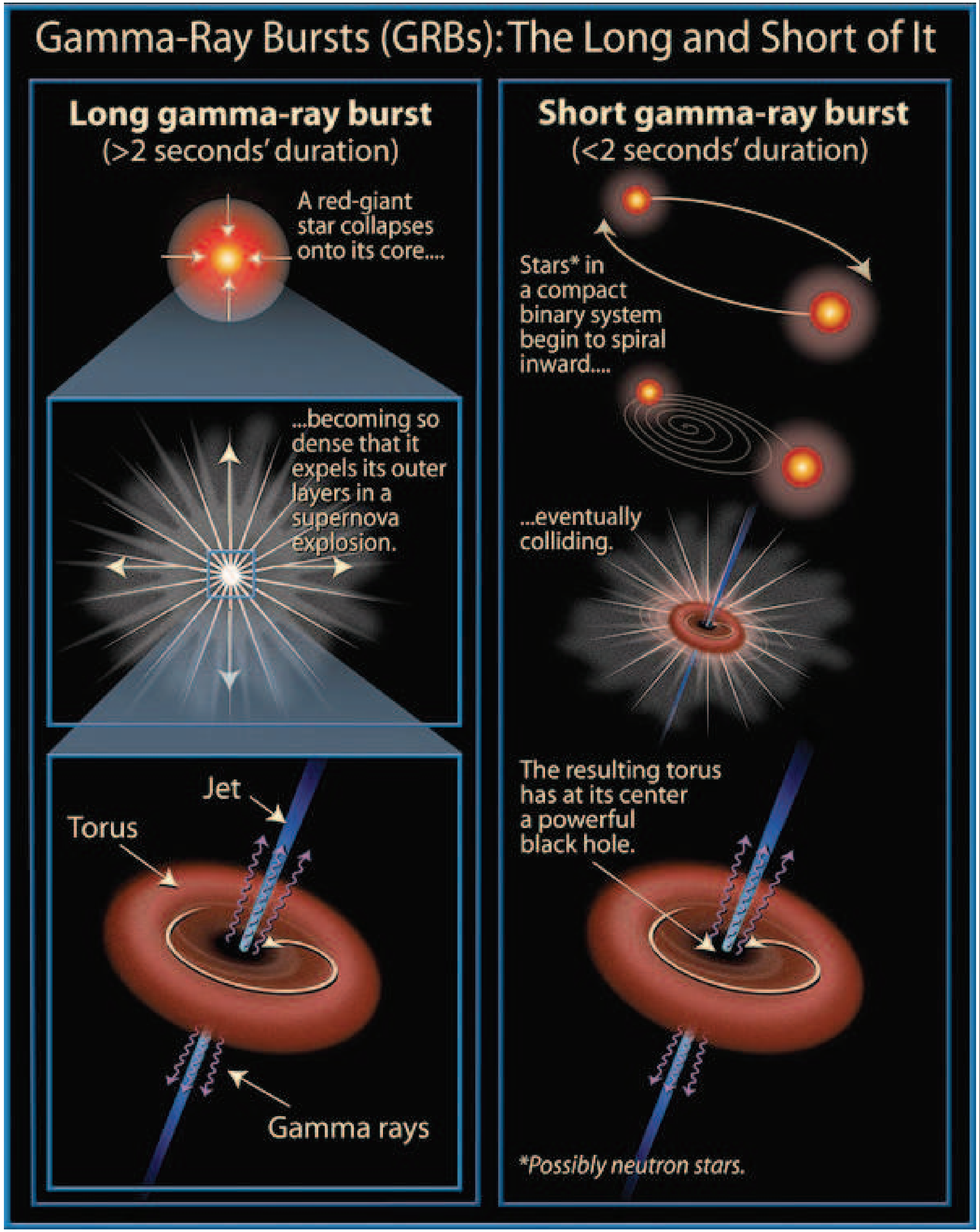
GRBs - The Long and Short of it

- Long GRBs



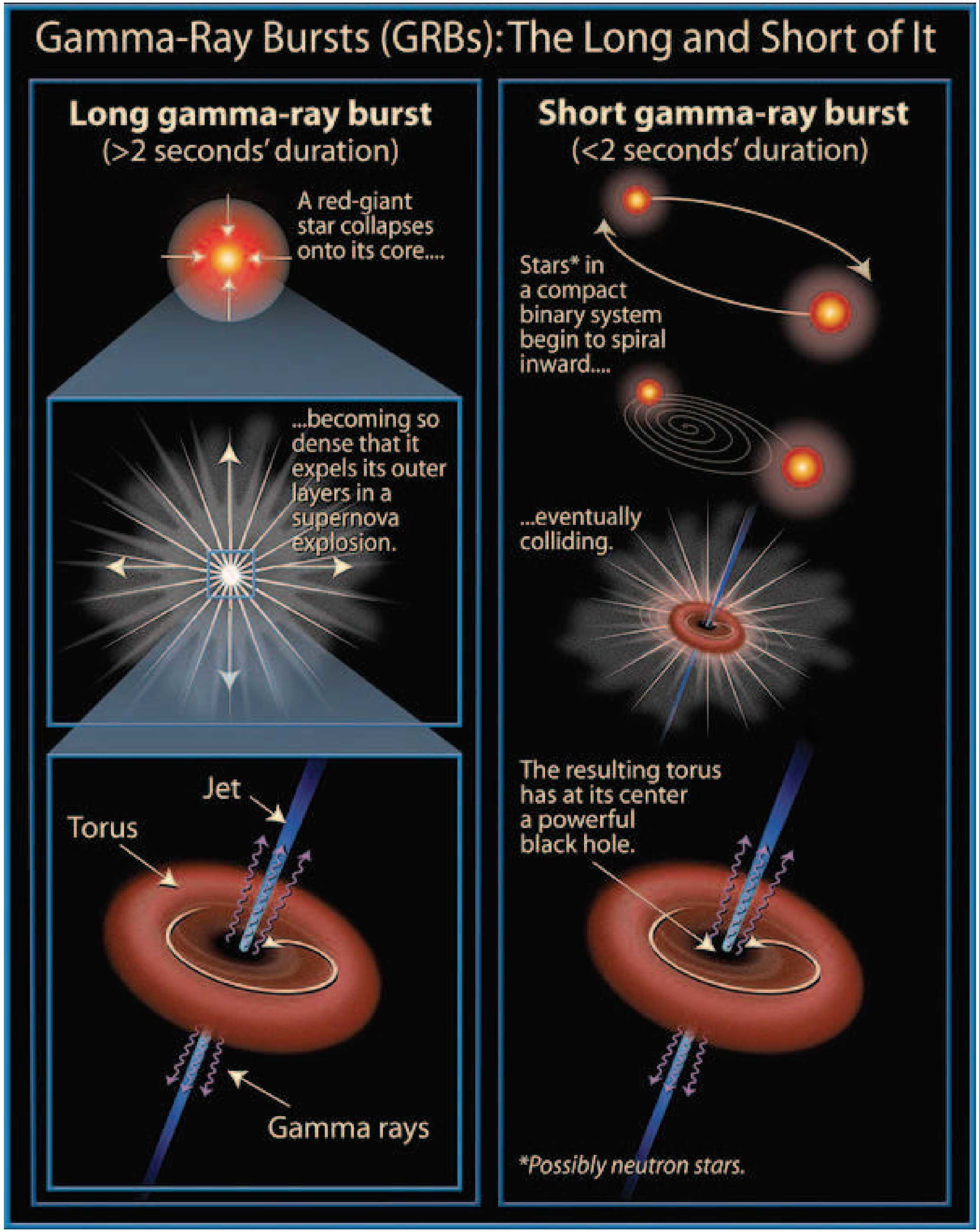
GRBs - The Long and Short of it

- Long GRBs
  - Core-collapse SNe, GW emission not well understood



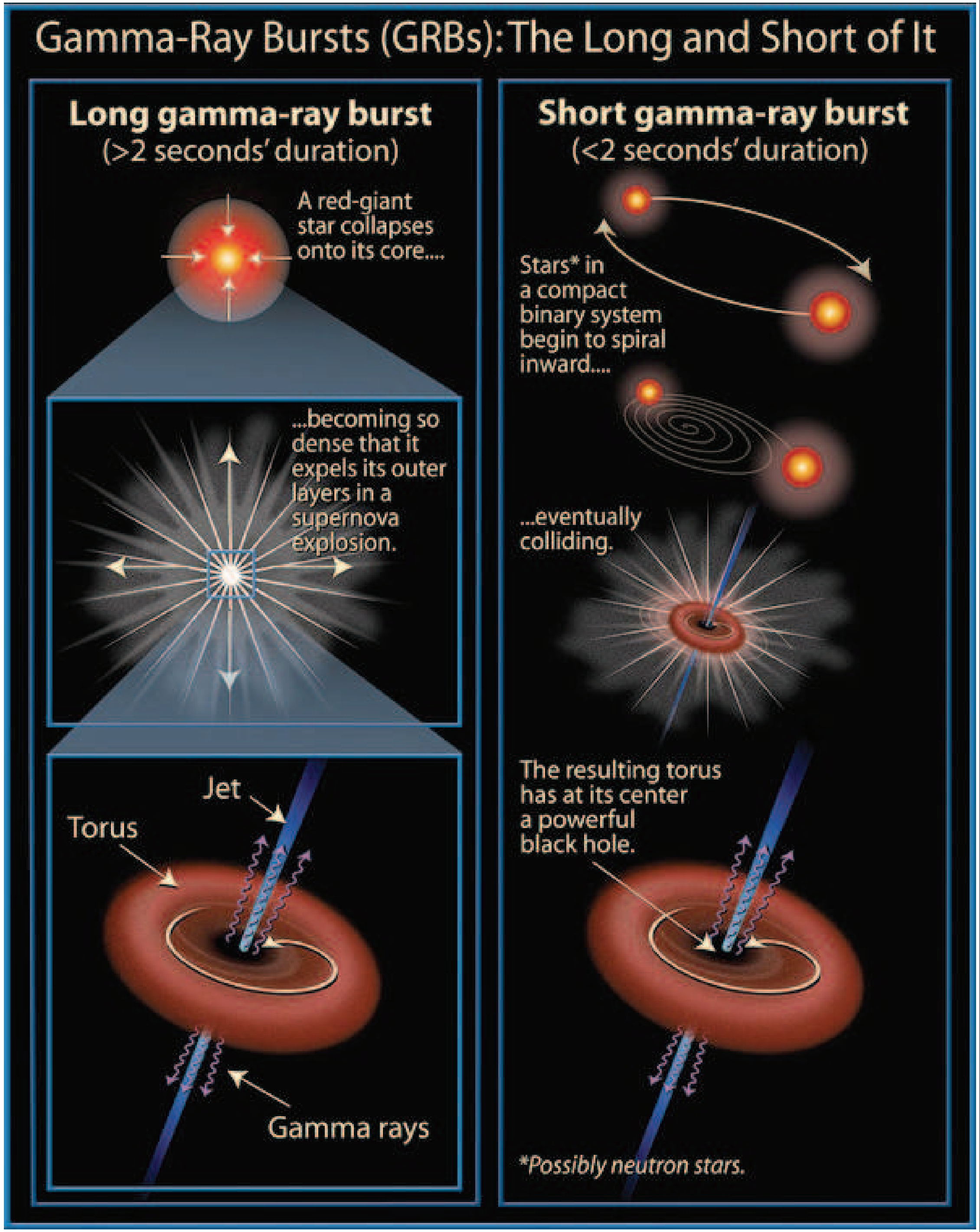
GRBs - The Long and Short of it

- Long GRBs
  - Core-collapse SNe, GW emission not well understood
    - Could emit burst of GW



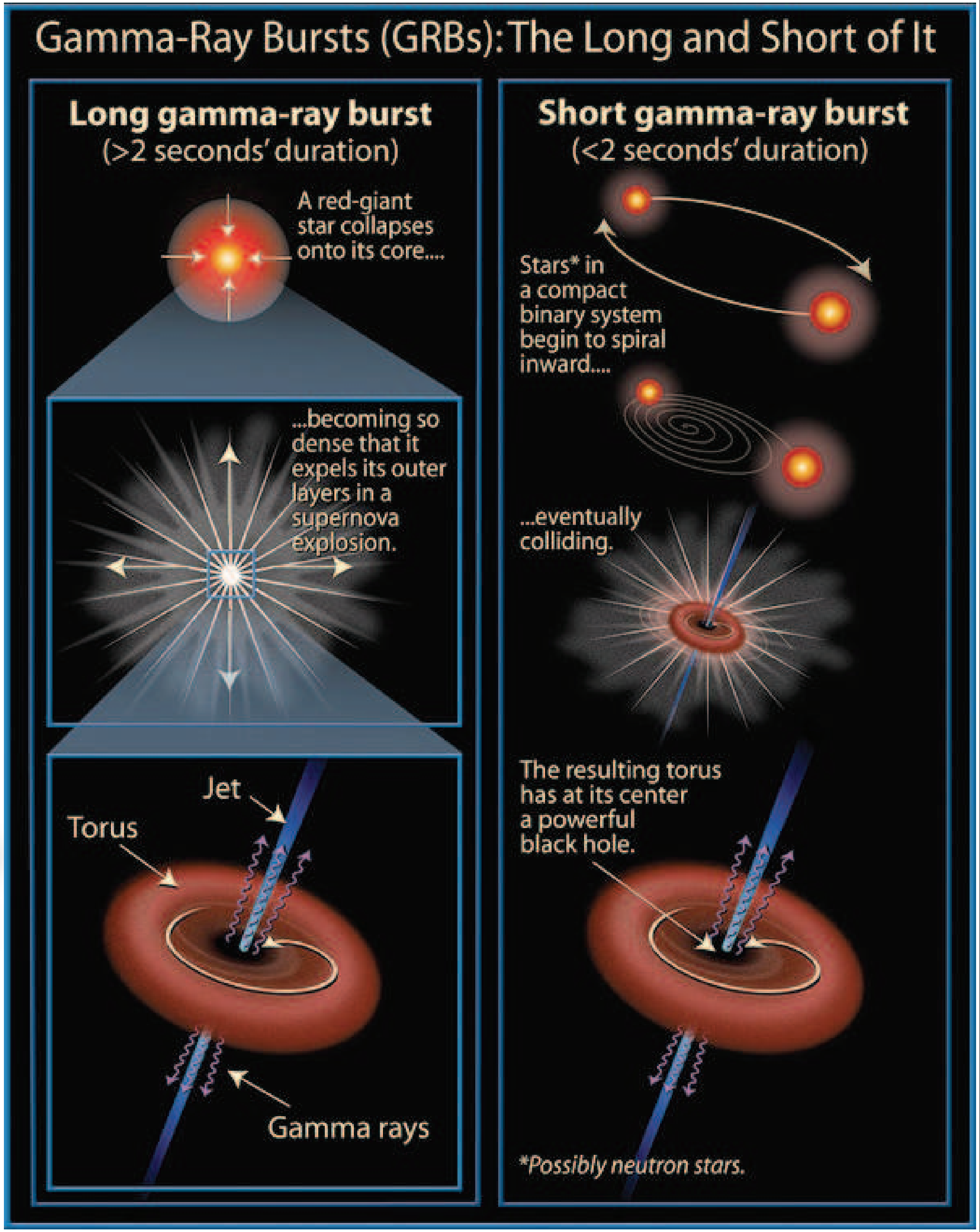
GRBs - The Long and Short of it

- Long GRBs
  - Core-collapse SNe, GW emission not well understood
    - Could emit burst of GW
- Short GRBs



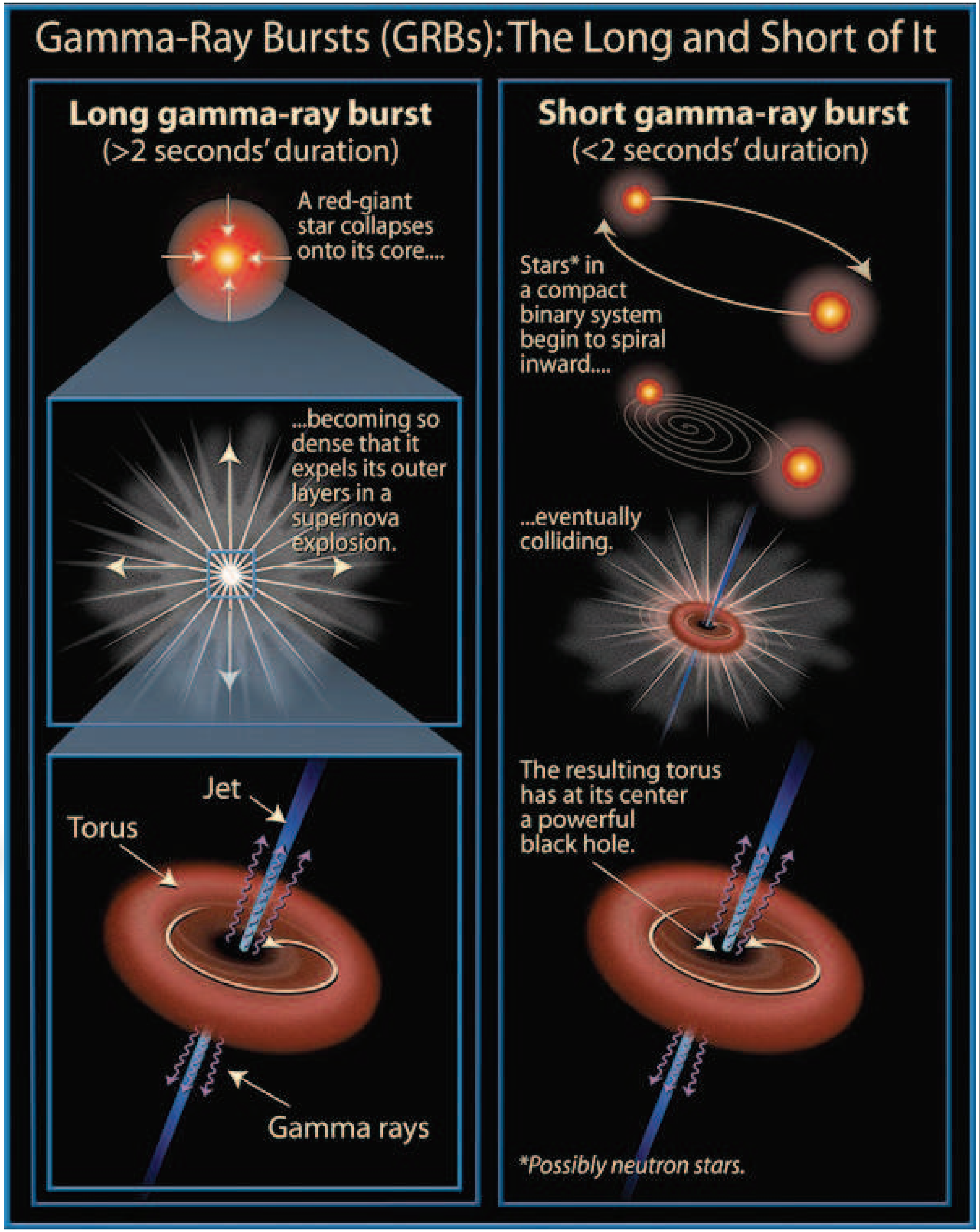
GRBs - The Long and Short of it

- Long GRBs
  - Core-collapse SNe, GW emission not well understood
    - Could emit burst of GW
- Short GRBs
  - Could be the end state of the evolution of compact binaries



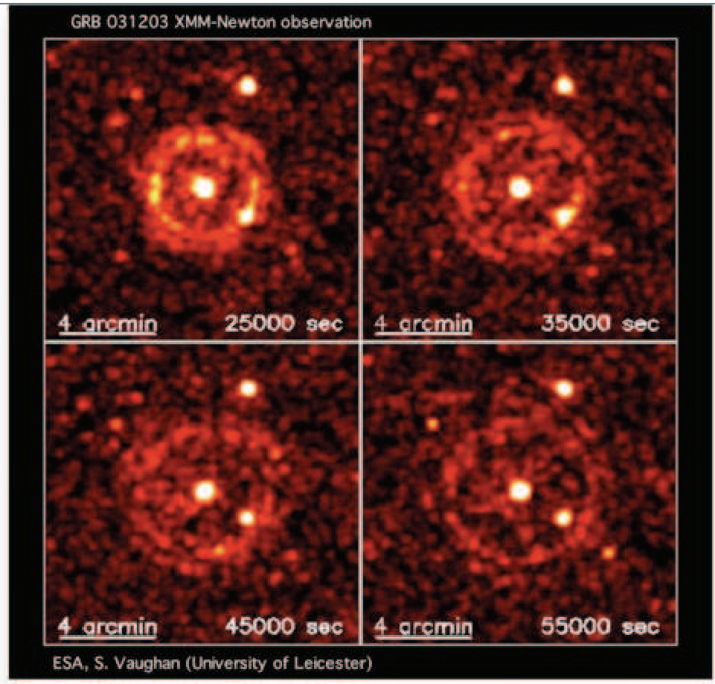
GRBs - The Long and Short of it

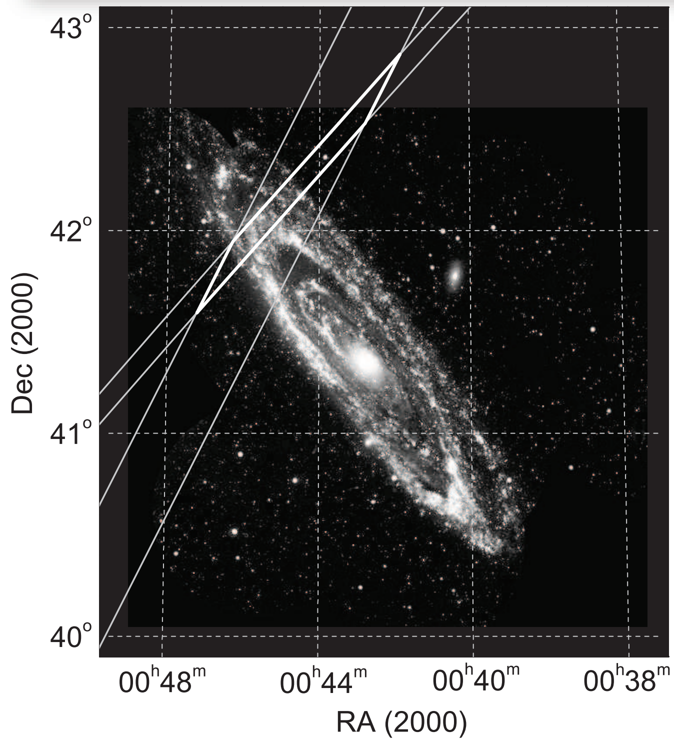
- Long GRBs
  - Core-collapse SNe, GW emission not well understood
    - Could emit burst of GW
- Short GRBs
  - Could be the end state of the evolution of compact binaries
    - BNS, NS-BH



Origin of GRB 070201 from LIGO Observations

LSC, Astrophys. J. **681,** (2008) 1419

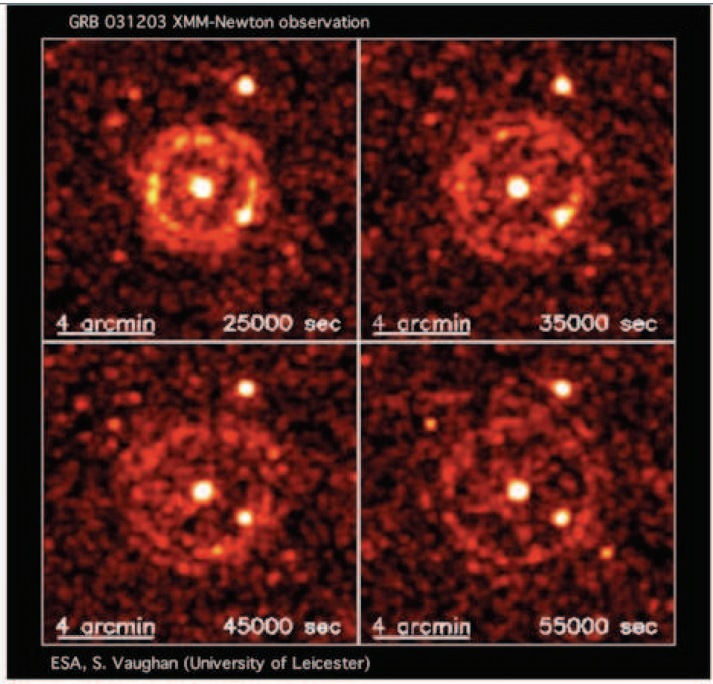


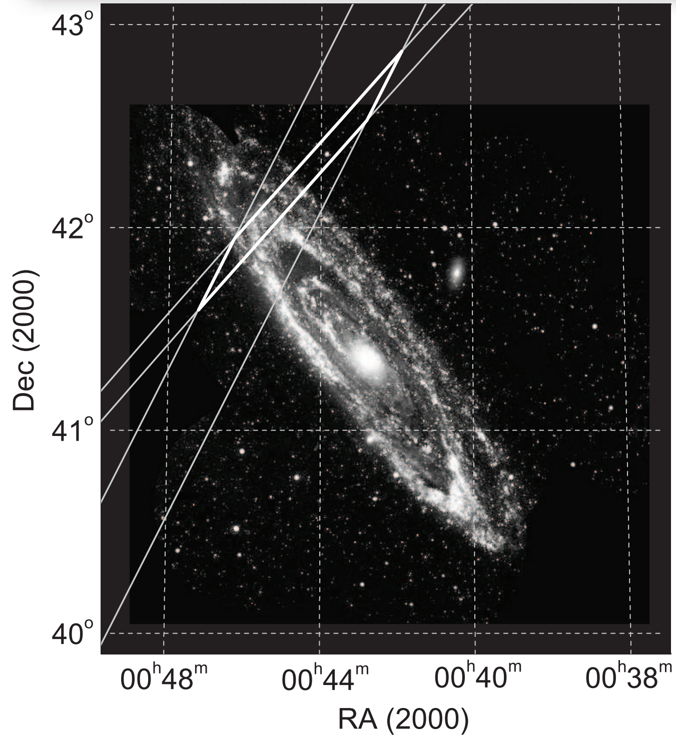


Origin of GRB 070201 from LIGO Observations

LSC, Astrophys. J. **681,** (2008) 1419

- LSC searched for binary inspirals and did not find any events: results in ApJ 681 1419 2008



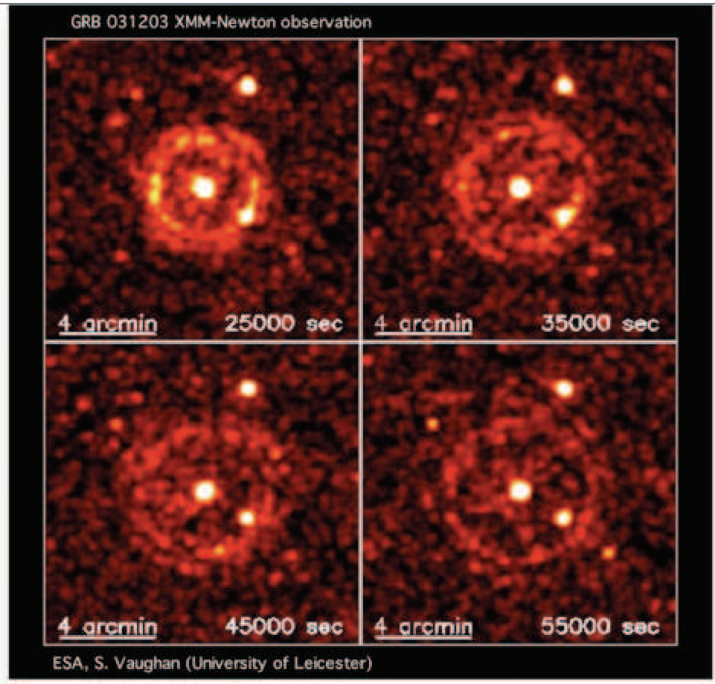


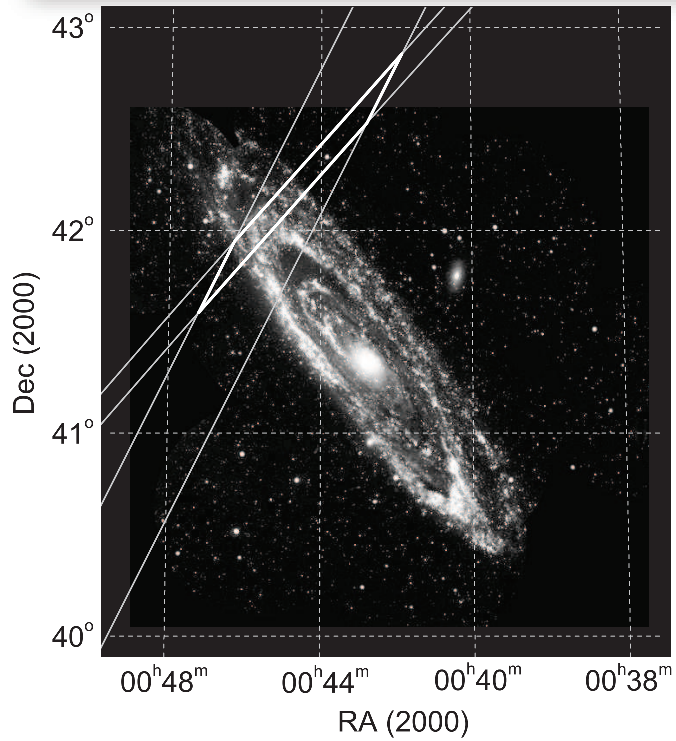
Tuesday, 14 December 2010

Origin of GRB 070201 from LIGO Observations

LSC, Astrophys. J. **681,** (2008) 1419

- LSC searched for binary inspirals and did not find any events: results in ApJ 681 1419 2008
- Null inspiral search result excludes binary progenitor in M31

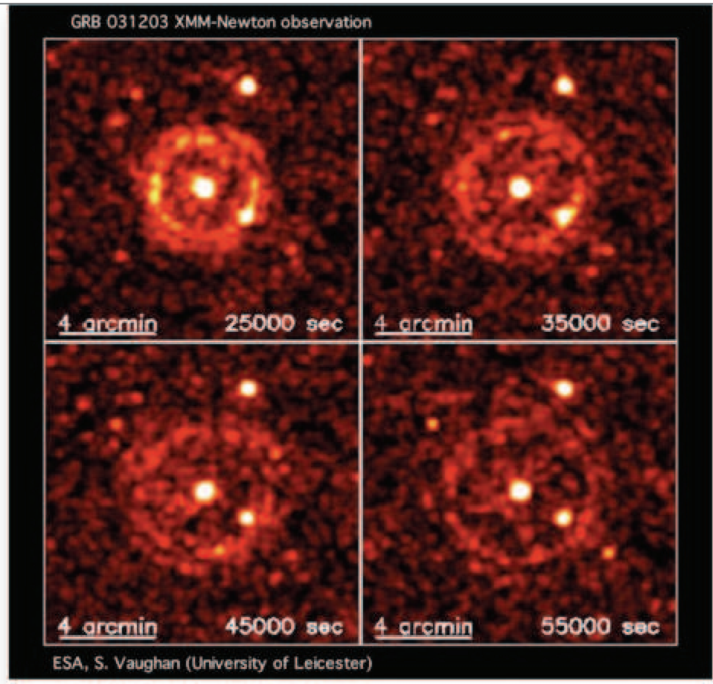


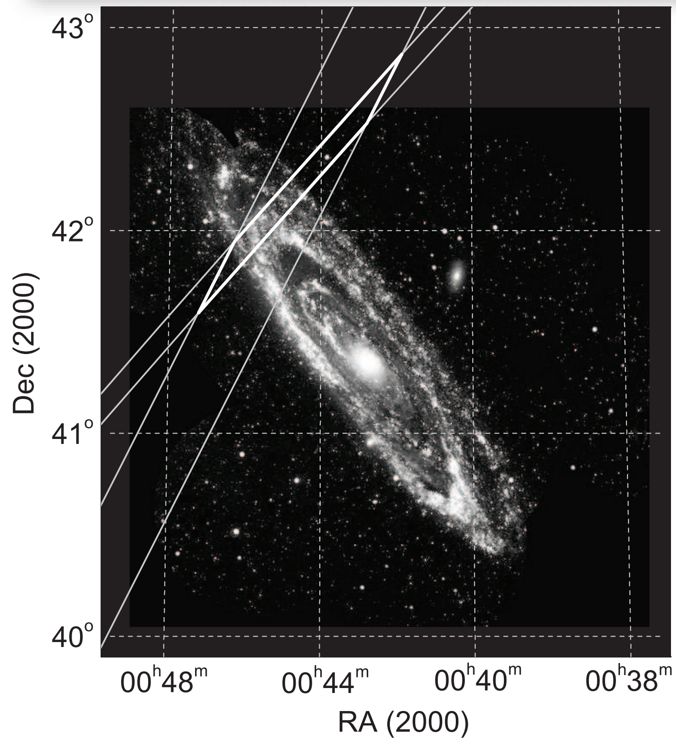


Origin of GRB 070201 from LIGO Observations

LSC, Astrophys. J. **681,** (2008) 1419

- LSC searched for binary inspirals and did not find any events: results in ApJ 681 1419 2008
- Null inspiral search result excludes binary progenitor in M31
- Soft Gamma-ray Repeater (SGR) models predict energy release <= 10^{46} ergs.



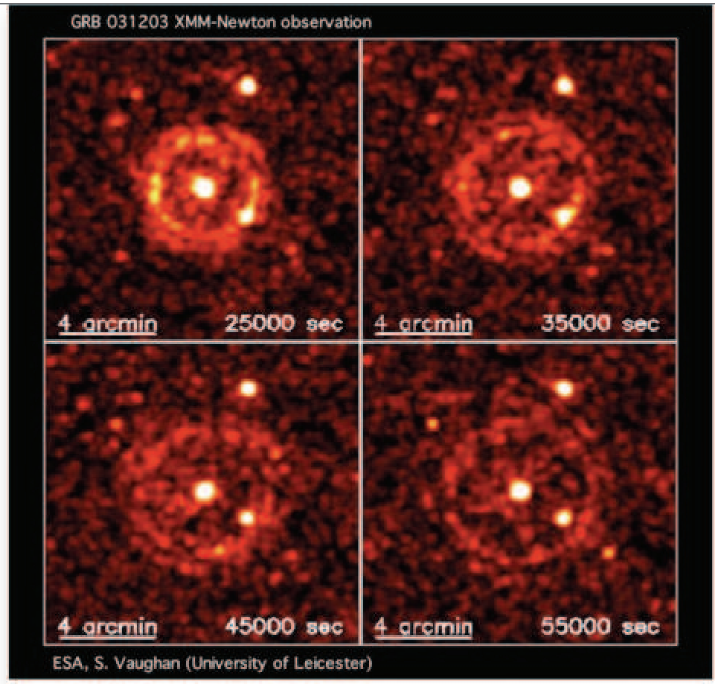


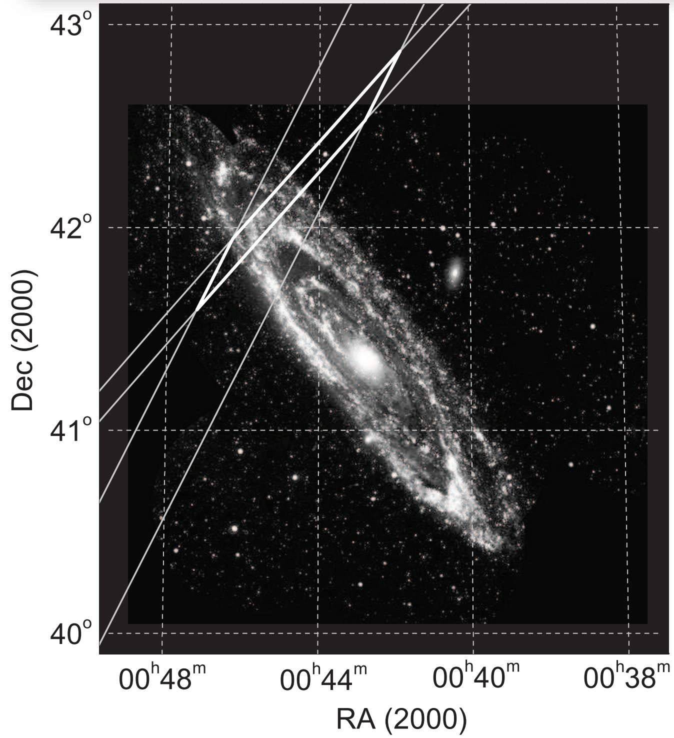
Tuesday, 14 December 2010

Origin of GRB 070201 from LIGO Observations

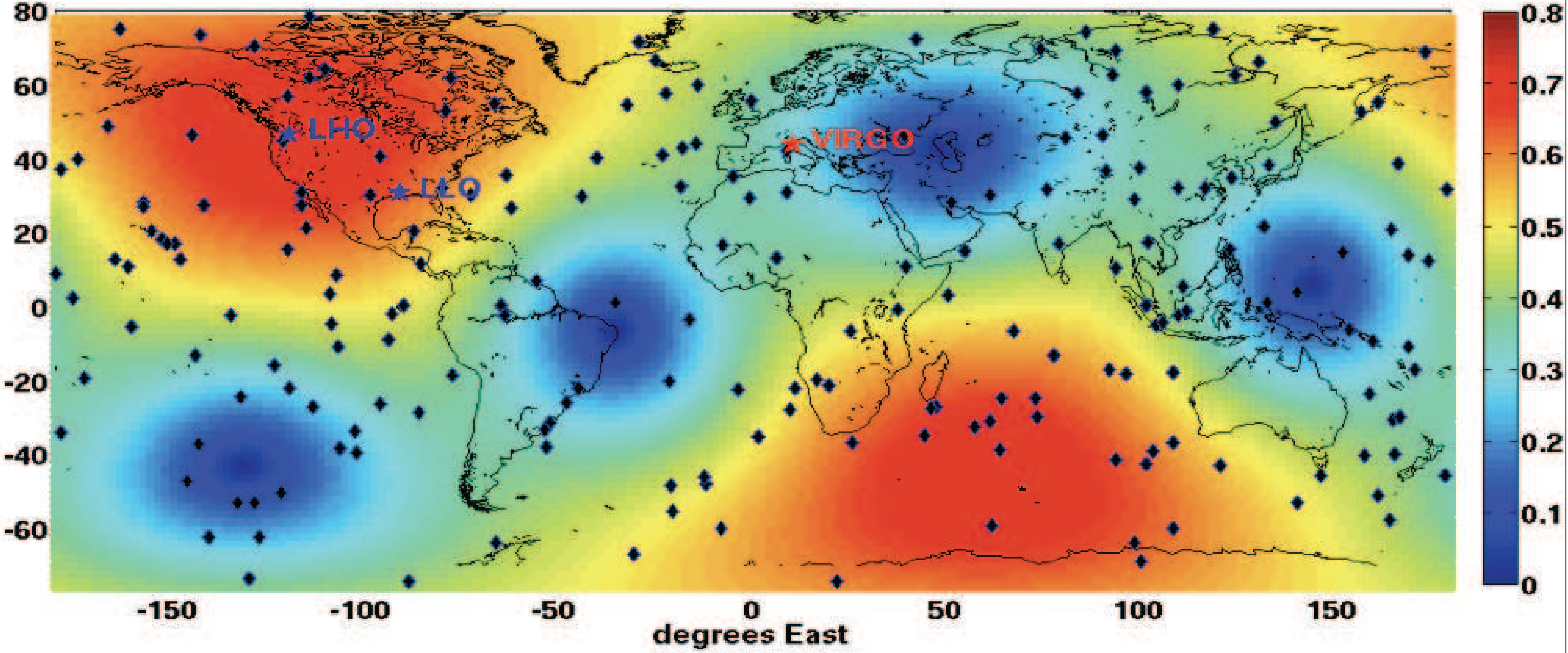
LSC, Astrophys. J. **681,** (2008) 1419

- LSC searched for binary inspirals and did not find any events: results in ApJ 681 1419 2008
- Null inspiral search result excludes binary progenitor in M31
- Soft Gamma-ray Repeater (SGR) models predict energy release <= 10^{46} ergs.
- LIGO has helped to confirm the first ever extragalactic SGR



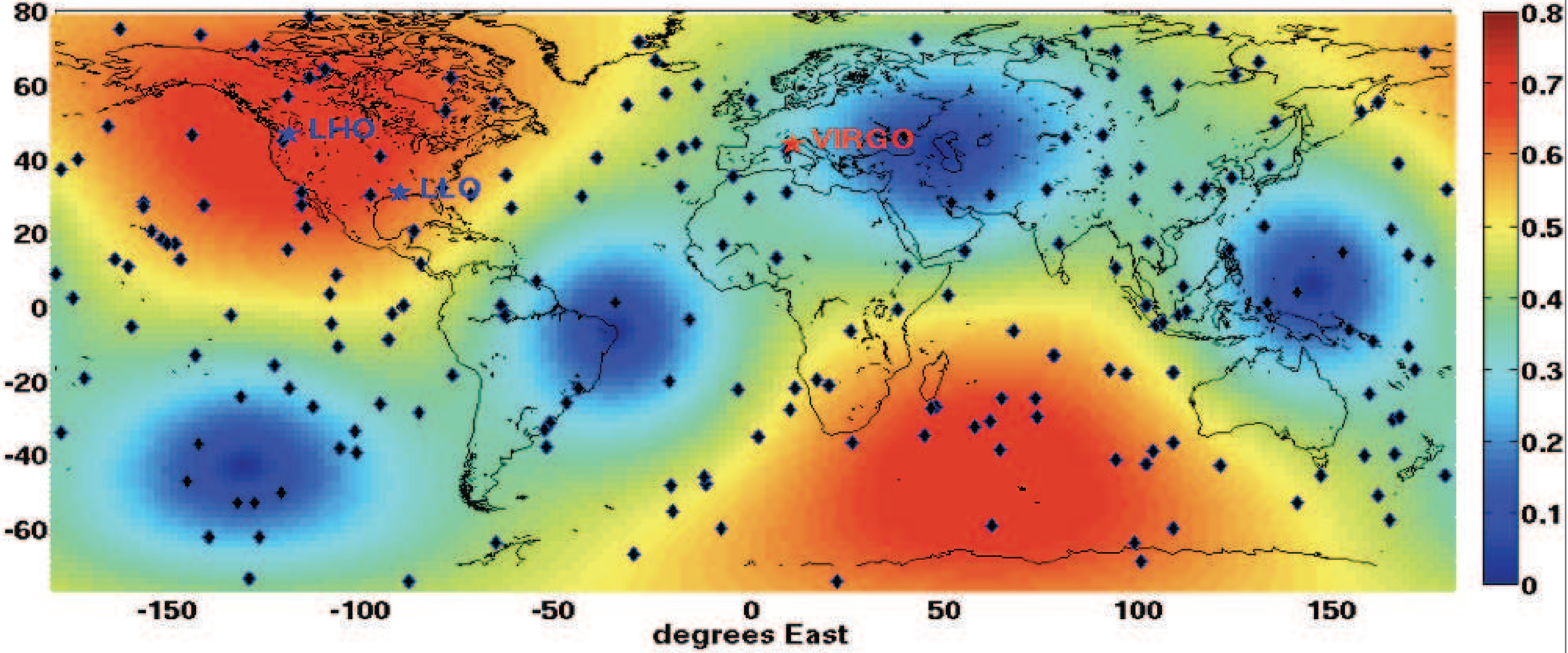


Search for GRBs during all of S5



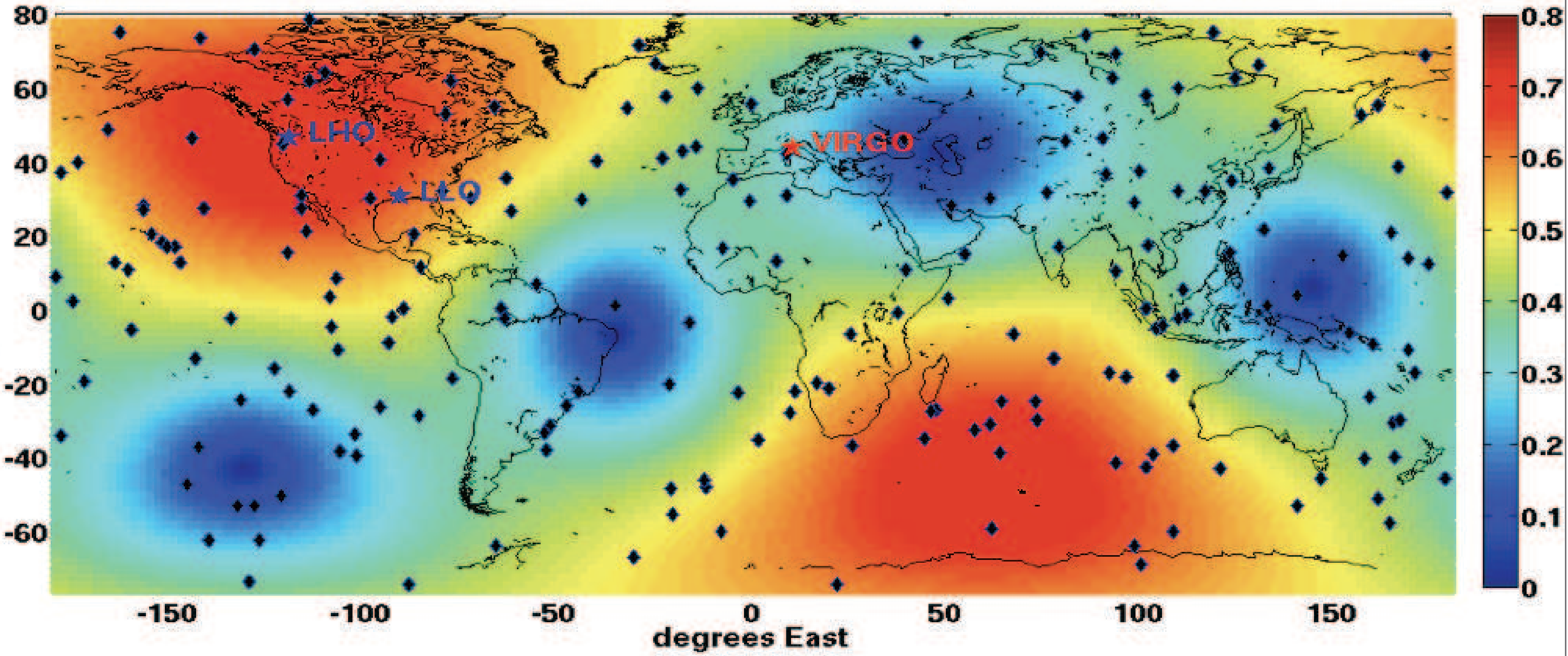
Search for GRBs during all of S5

- Nov 2005 - Oct 2007: 212 GRBs



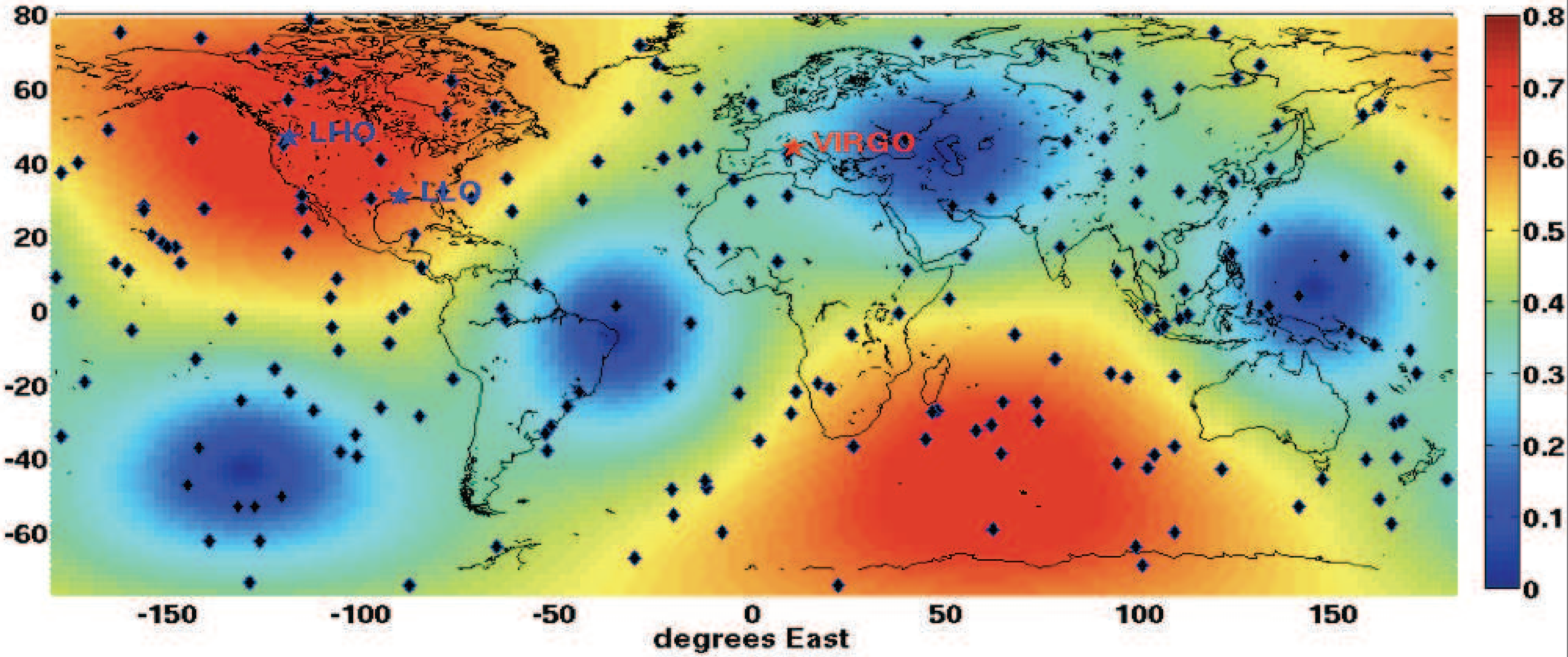
Search for GRBs during all of S5

- Nov 2005 - Oct 2007: 212 GRBs
- LSC-Virgo searched for 137 GRBs with 2 or more LIGO-Virgo detectors: ~25% with redshift, ~10% short duration: Null result



Search for GRBs during all of S5

- Nov 2005 - Oct 2007: 212 GRBs
- LSC-Virgo searched for 137 GRBs with 2 or more LIGO-Virgo detectors: ~25% with redshift, ~10% short duration: Null result
- Polarization-averaged antenna response of LIGO-Hanford, dots show location of GRBs during S5-VSR1



Spin-down limit on the Crab pulsar

LSC, ApJ Lett., **683,** (2008) 45

Spin-down limit on the Crab pulsar

LSC, ApJ Lett., **683,** (2008) 45

- 2 kpc away, formed in a spectacular supernova in 1054 AD

Spin-down limit on the Crab pulsar

LSC, ApJ Lett., **683,** (2008) 45

- 2 kpc away, formed in a spectacular supernova in 1054 AD
- Losing energy in the form of particles and radiation, leading to its spin-down

Spin-down limit on the Crab pulsar

LSC, ApJ Lett., **683,** (2008) 45

- 2 kpc away, formed in a spectacular supernova in 1054 AD
- Losing energy in the form of particles and radiation, leading to its spin-down

spin frequency of $\nu = 29.78\,\mathrm{Hz}$

Spin-down limit on the Crab pulsar

LSC, ApJ Lett., **683,** (2008) 45

- 2 kpc away, formed in a spectacular supernova in 1054 AD
- Losing energy in the form of particles and radiation, leading to its spin-down

spin frequency of $\nu = 29.78\,\mathrm{Hz}$

spin-down rate, $\dot{\nu} \approx -3.7{\times}10^{-10}\,\mathrm{Hz\,s^{-1}}$.

Spin-down limit on the Crab pulsar

LSC, ApJ Lett., **683,** (2008) 45

- 2 kpc away, formed in a spectacular supernova in 1054 AD
- Losing energy in the form of particles and radiation, leading to its spin-down

spin frequency of $\nu = 29.78\,\mathrm{Hz}$

spin-down rate, $\dot{\nu} \approx -3.7{\times}10^{-10}\,\mathrm{Hz\,s^{-1}}$

$$\dot{E} = 4\pi^2 I_{zz}\nu|\dot{\nu}| \approx 4.4{\times}10^{31}\,\mathrm{W}$$

Spin-down limit on the Crab pulsar

LSC, ApJ Lett., **683,** (2008) 45

- 2 kpc away, formed in a spectacular supernova in 1054 AD
- Losing energy in the form of particles and radiation, leading to its spin-down

spin frequency of $\nu = 29.78\,\mathrm{Hz}$

spin-down rate, $\dot{\nu} \approx -3.7\times 10^{-10}\,\mathrm{Hz\,s^{-1}}$

$$\dot{E} = 4\pi^2 I_{zz}\nu|\dot{\nu}| \approx 4.4\times 10^{31}\,\mathrm{W}$$

$$h_0^{\rm sd} = 8.06\times 10^{-19}\, I_{38} r_{\rm kpc}^{-1} (|\dot{\nu}|/\nu)^{1/2}$$

Spin-down limit on the Crab pulsar

LSC, ApJ Lett., **683,** (2008) 45

- 2 kpc away, formed in a spectacular supernova in 1054 AD
- Losing energy in the form of particles and radiation, leading to its spin-down

spin frequency of $\nu = 29.78\,\mathrm{Hz}$

spin-down rate, $\dot{\nu} \approx -3.7\times 10^{-10}\,\mathrm{Hz\,s^{-1}}$

$$\dot{E} = 4\pi^2 I_{zz}\nu|\dot{\nu}| \approx 4.4\times 10^{31}\,\mathrm{W}$$

$$h_0^{\mathrm{sd}} = 8.06\times 10^{-19}\, I_{38} r_{\mathrm{kpc}}^{-1} (|\dot{\nu}|/\nu)^{1/2}$$

- LSC have searched for gravitational waves in data from the fifth science run of LIGO detectors

Spin-down limit on the Crab pulsar

LSC, ApJ Lett., **683,** (2008) 45

- 2 kpc away, formed in a spectacular supernova in 1054 AD
- Losing energy in the form of particles and radiation, leading to its spin-down

$$\text{spin frequency of } \nu = 29.78\,\mathrm{Hz}$$
$$\text{spin-down rate, } \dot{\nu} \approx -3.7\times10^{-10}\,\mathrm{Hz\,s^{-1}}$$
$$\dot{E} = 4\pi^2 I_{zz}\nu|\dot{\nu}| \approx 4.4\times10^{31}\,\mathrm{W}$$
$$h_0^{\mathrm{sd}} = 8.06\times10^{-19}\, I_{38} r_{\mathrm{kpc}}^{-1}(|\dot{\nu}|/\nu)^{1/2}$$

- LSC have searched for gravitational waves in data from the fifth science run of LIGO detectors
- Lack of GW at S5 sensitivity means a limit on ellipticity a factor 4 better than spin-down upper limit - less than 4% of energy in GW

$$h_0^{95\%} = 3.4\times10^{-25}. \quad \varepsilon = 1.8\times10^{-4}$$

Spin-down limit on the Crab pulsar

LSC, ApJ Lett., **683**, (2008) 45

- 2 kpc away, formed in a spectacular supernova in 1054 AD
- Losing energy in the form of particles and radiation, leading to its spin-down

spin frequency of $\nu = 29.78\,\mathrm{Hz}$

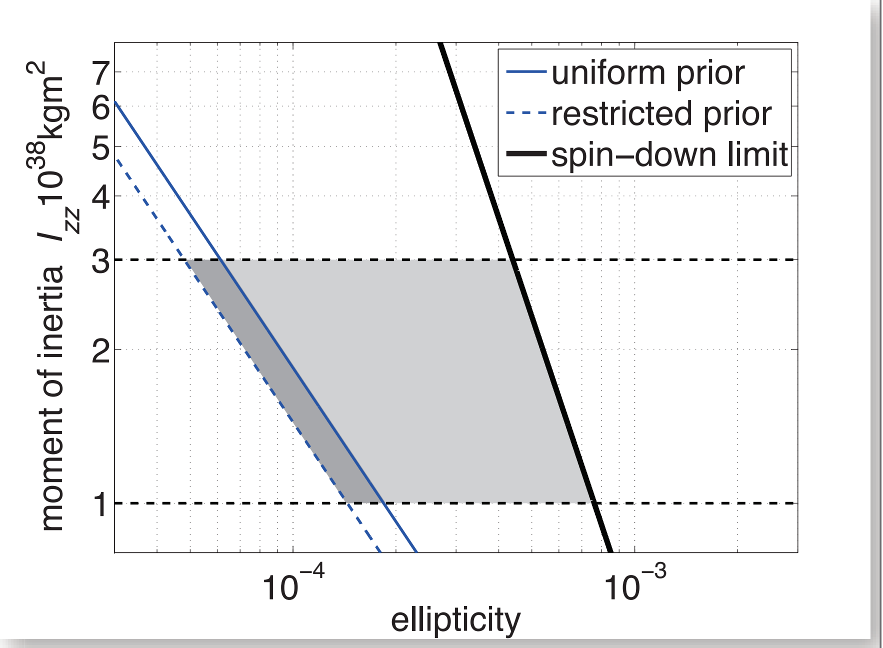
spin-down rate, $\dot{\nu} \approx -3.7\times 10^{-10}\,\mathrm{Hz\,s^{-1}}$

$$\dot{E} = 4\pi^2 I_{zz}\nu|\dot{\nu}| \approx 4.4\times 10^{31}\,\mathrm{W}$$

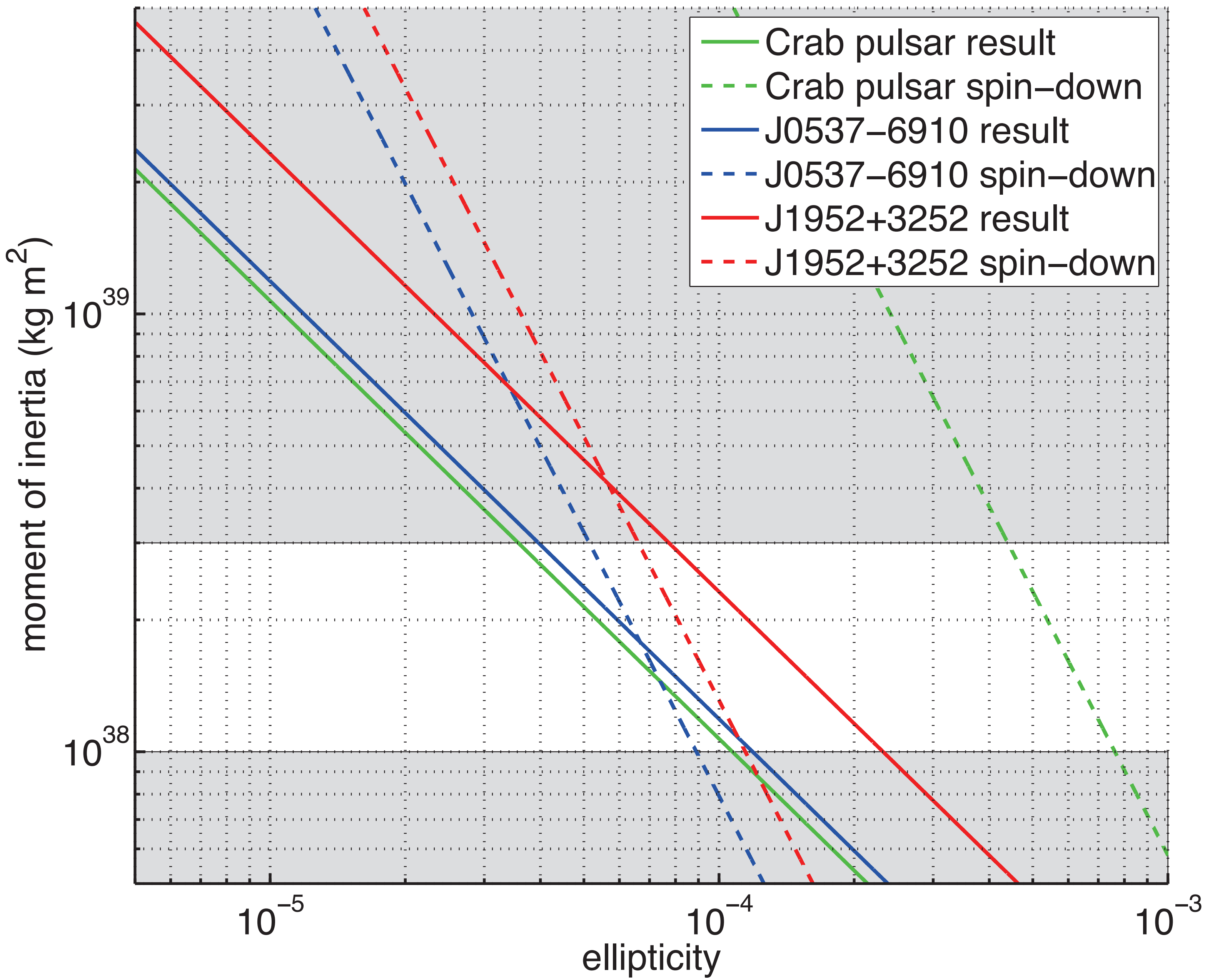
$$h_0^{\mathrm{sd}} = 8.06\times 10^{-19}\, I_{38} r_{\mathrm{kpc}}^{-1} (|\dot{\nu}|/\nu)^{1/2}$$

- LSC have searched for gravitational waves in data from the fifth science run of LIGO detectors
- Lack of GW at S5 sensitivity means a limit on ellipticity a factor 4 better than spin-down upper limit - less than 4% of energy in GW

$$h_0^{95\%} = 3.4\times 10^{-25}. \quad \varepsilon = 1.8\times 10^{-4}$$



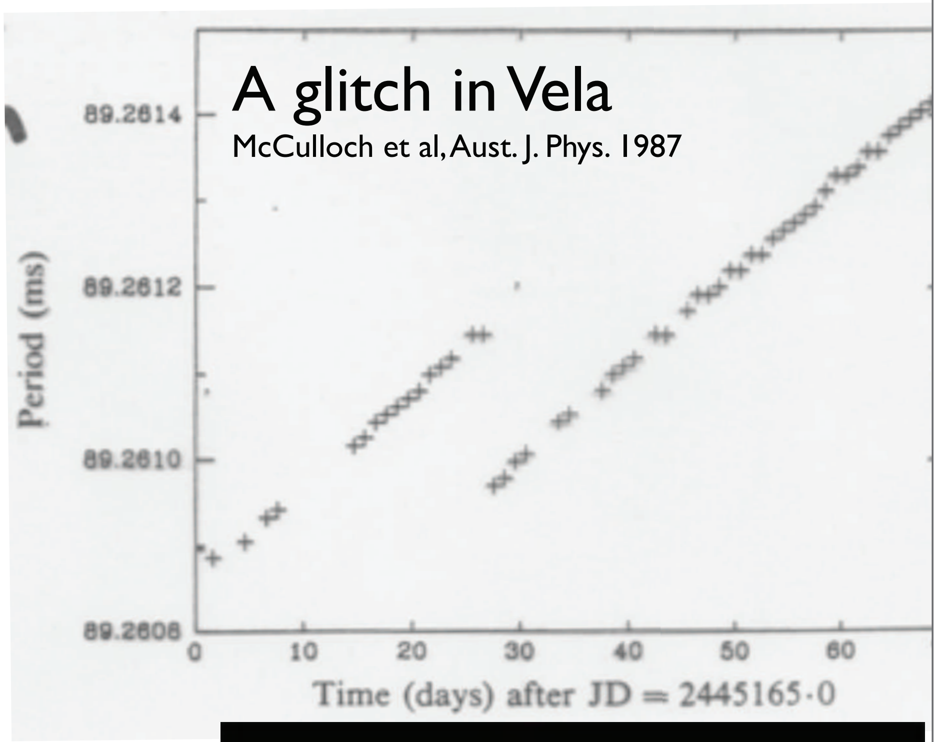
S5 Key Results



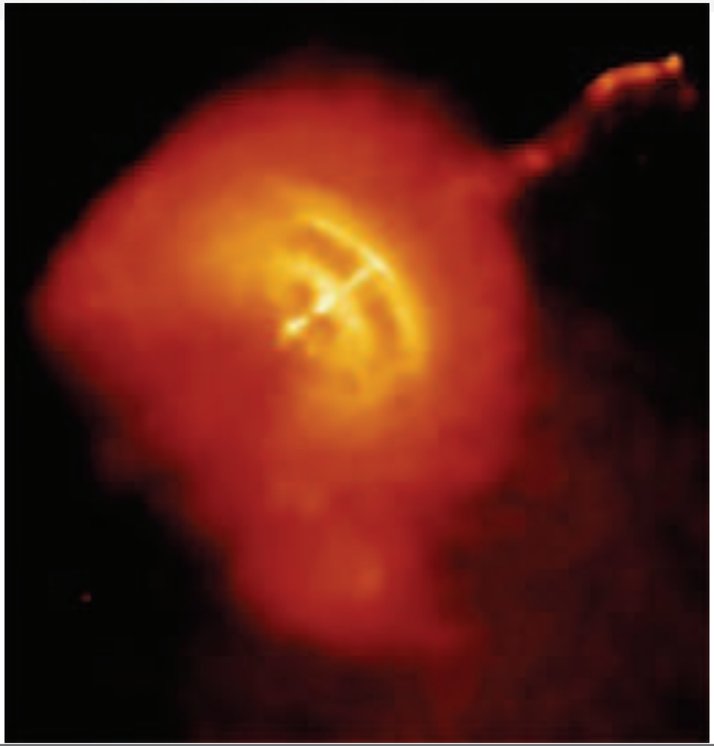
Some Interesting Upper Limits

JD)	ν (Hz)	$\dot{\nu}$ (Hz s^{-1})	distance (kpc)	spin-down limit	joint $h_0^{95\%}$	ellipticity	$h_0^{95\%}/h_0^{\rm sd}$
520	221.80	$-6.1 \times 10^{-16\dagger}$	1.3	1.04×10^{-27}	7.57×10^{-26}	4.65×10^{-7}	73
510	202.79	$-5.1 \times 10^{-16\dagger}$	0.2	5.13×10^{-27}	4.85×10^{-26}	6.96×10^{-8}	9.4
388	268.36	$-2.0 \times 10^{-15\dagger}$	2.5	8.71×10^{-28}	6.12×10^{-26}	5.13×10^{-7}	70

Pulsar Glitches

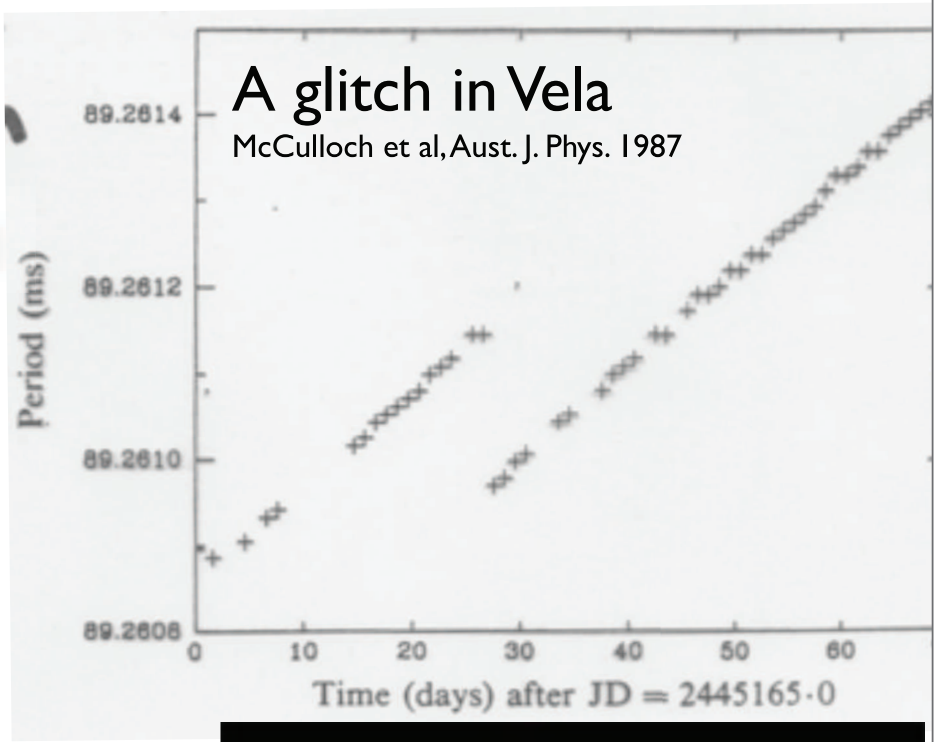


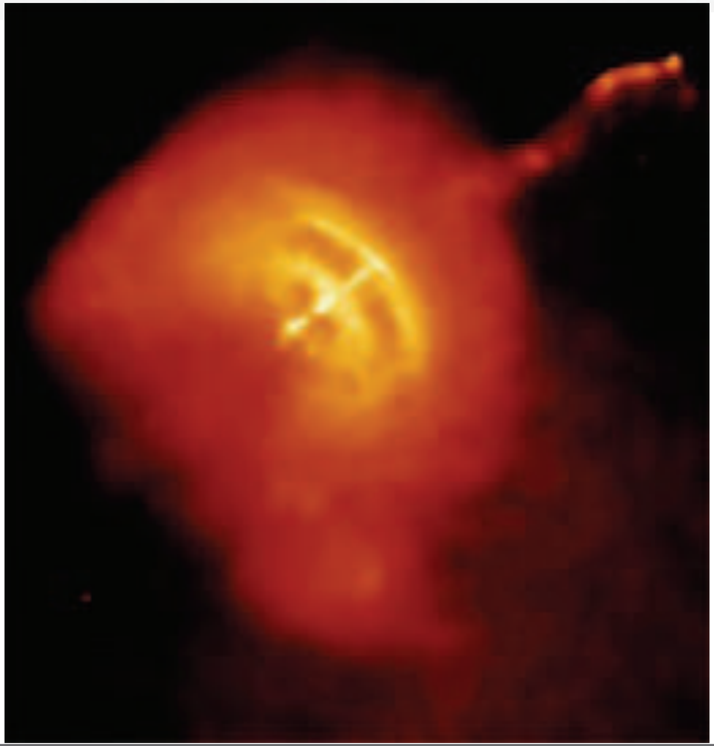
A composite Vela image



Pulsar Glitches

- Pulsars have stable rotation rates:

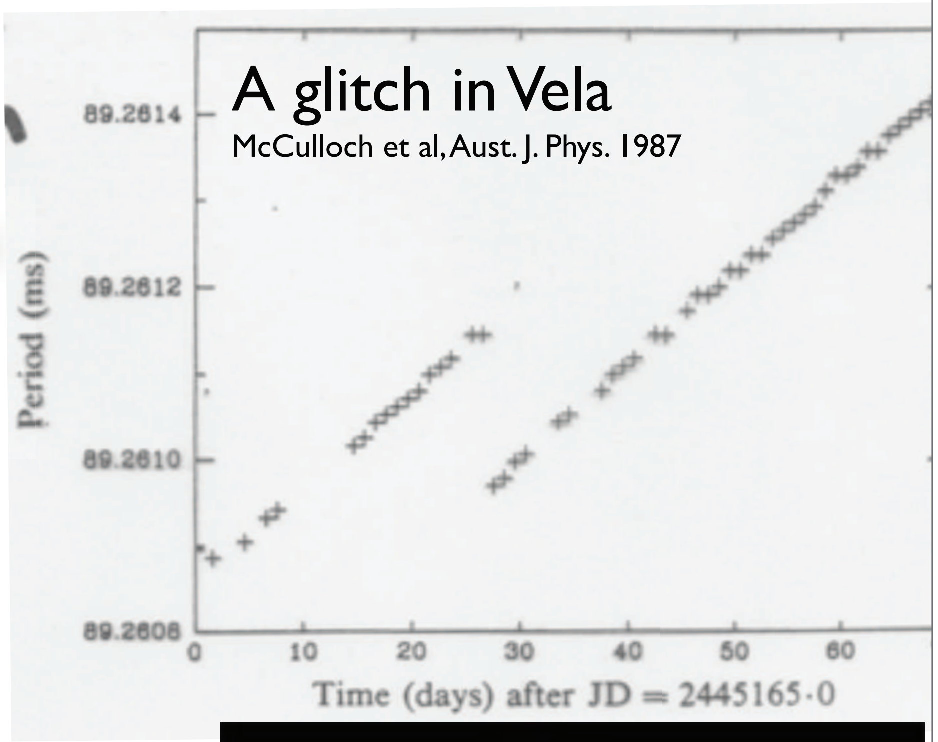


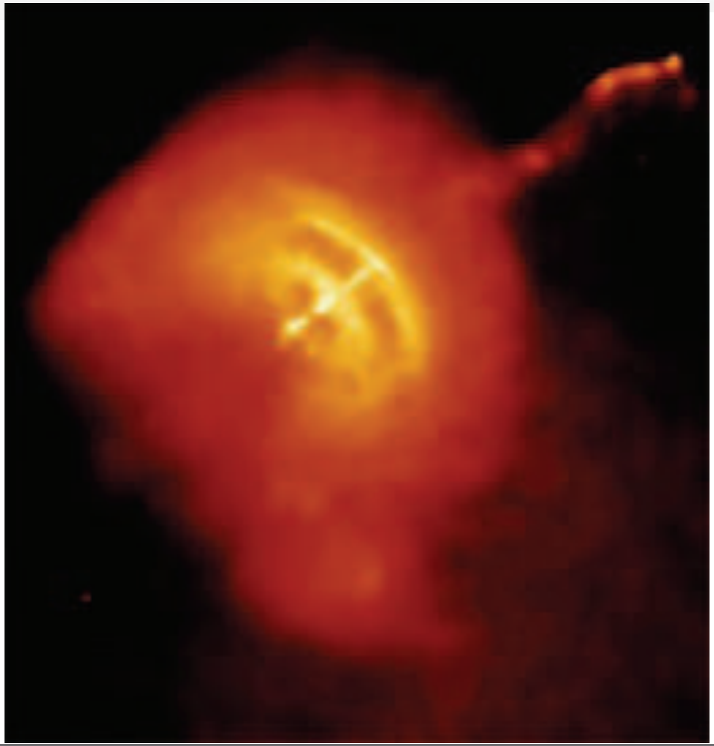


A composite Vela image

Pulsar Glitches

- Pulsars have stable rotation rates:
  - However, observe secular increase in pulse period

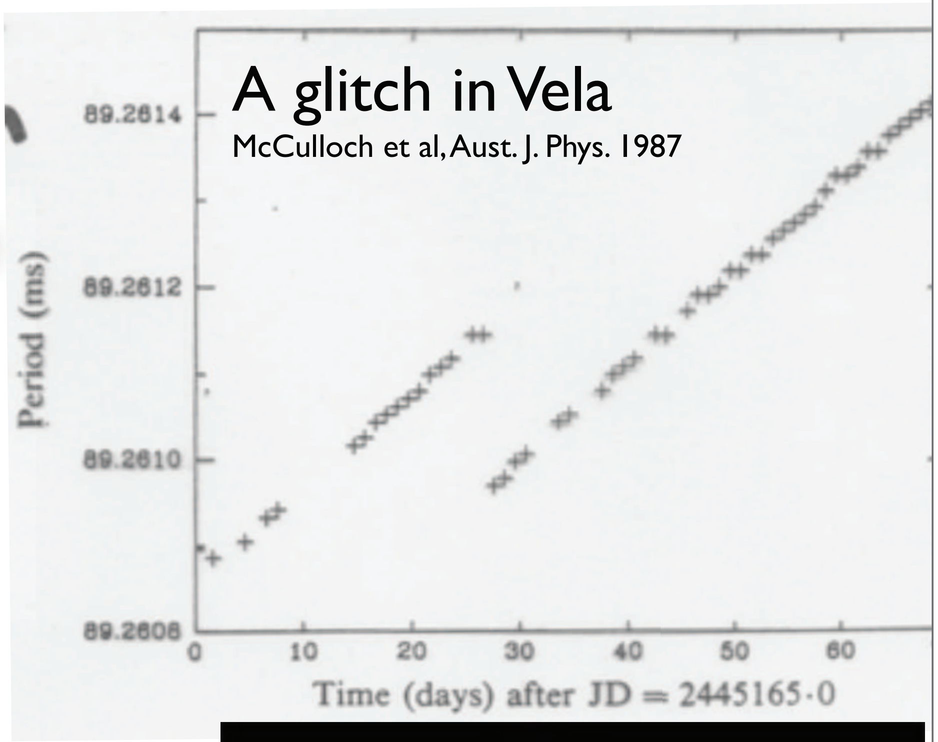


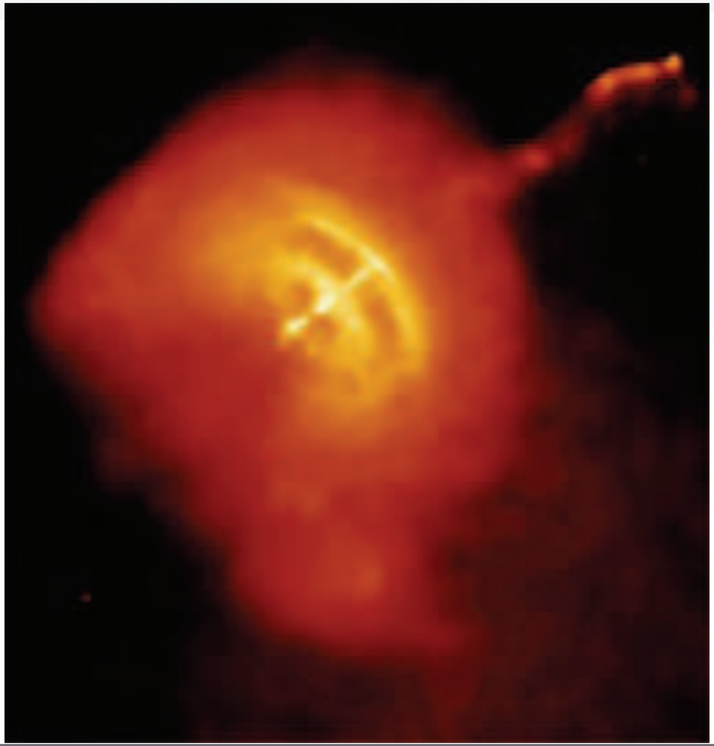


A composite Vela image

Pulsar Glitches

- Pulsars have stable rotation rates:
  - However, observe secular increase in pulse period
- Glitches are sudden dips in period

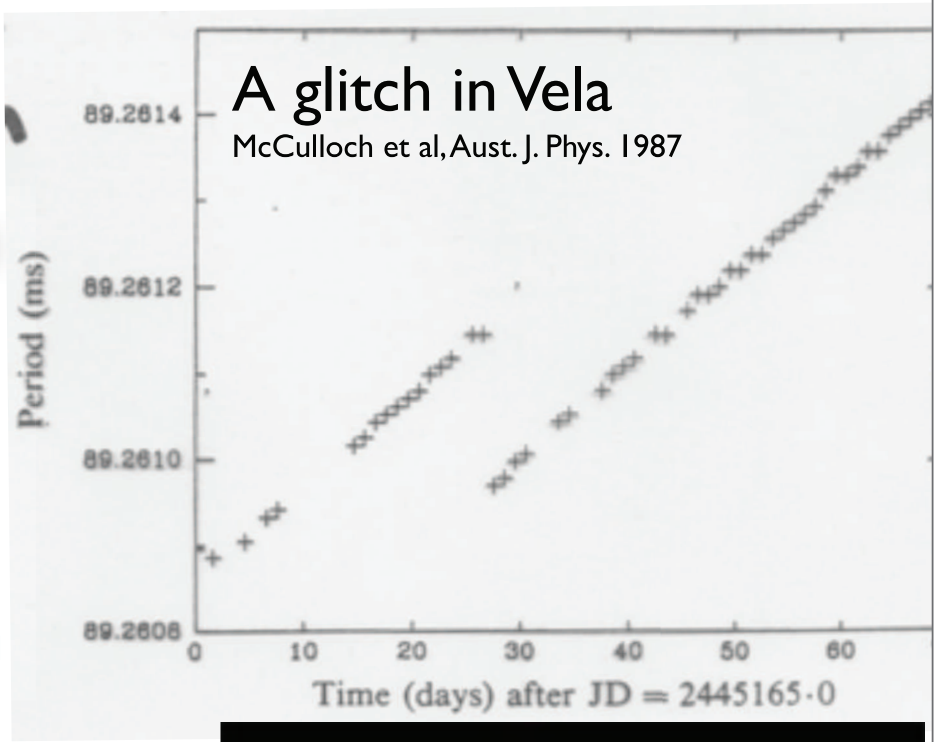




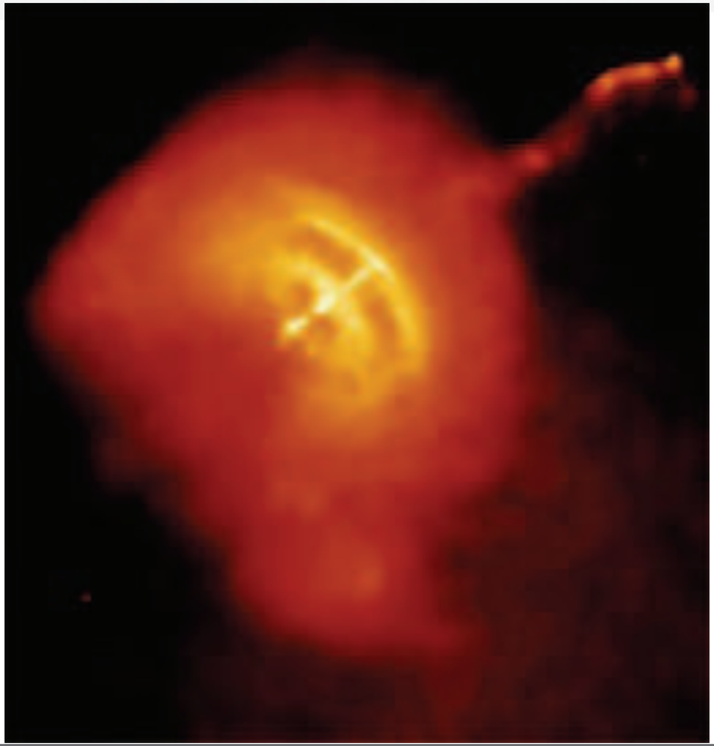
A composite Vela image

Pulsar Glitches

- Pulsars have stable rotation rates:
  - However, observe secular increase in pulse period
- Glitches are sudden dips in period
  - Vela glitches once every few yrs

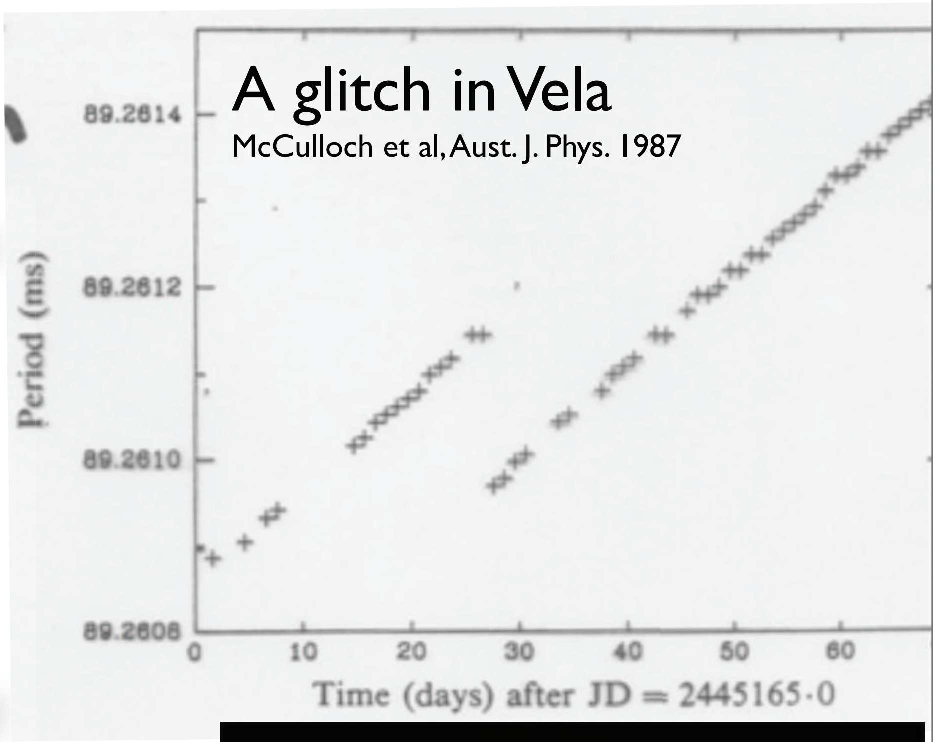


A composite Vela image

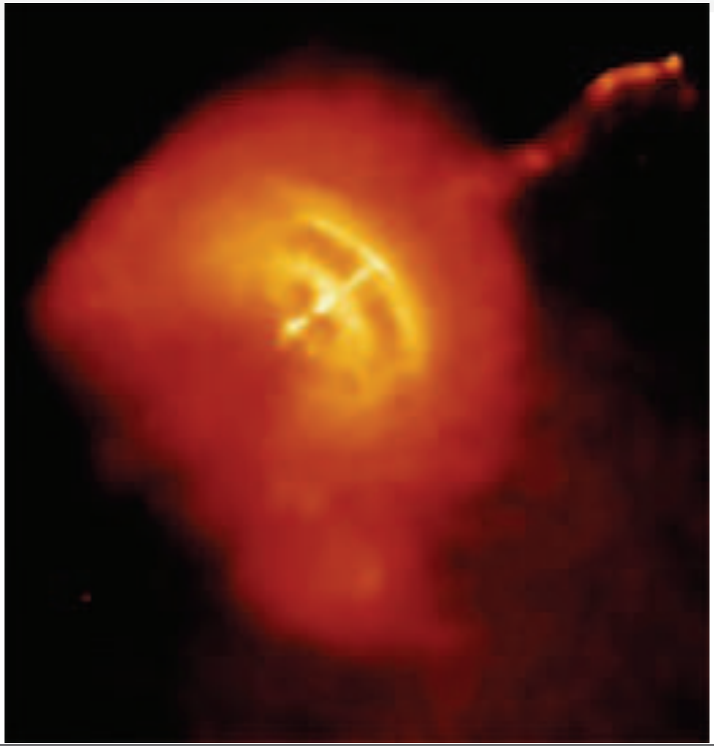


Pulsar Glitches

- Pulsars have stable rotation rates:
  - However, observe secular increase in pulse period
- Glitches are sudden dips in period
  - Vela glitches once every few yrs
- Could be the result of transfer of angular momentum from core to crust

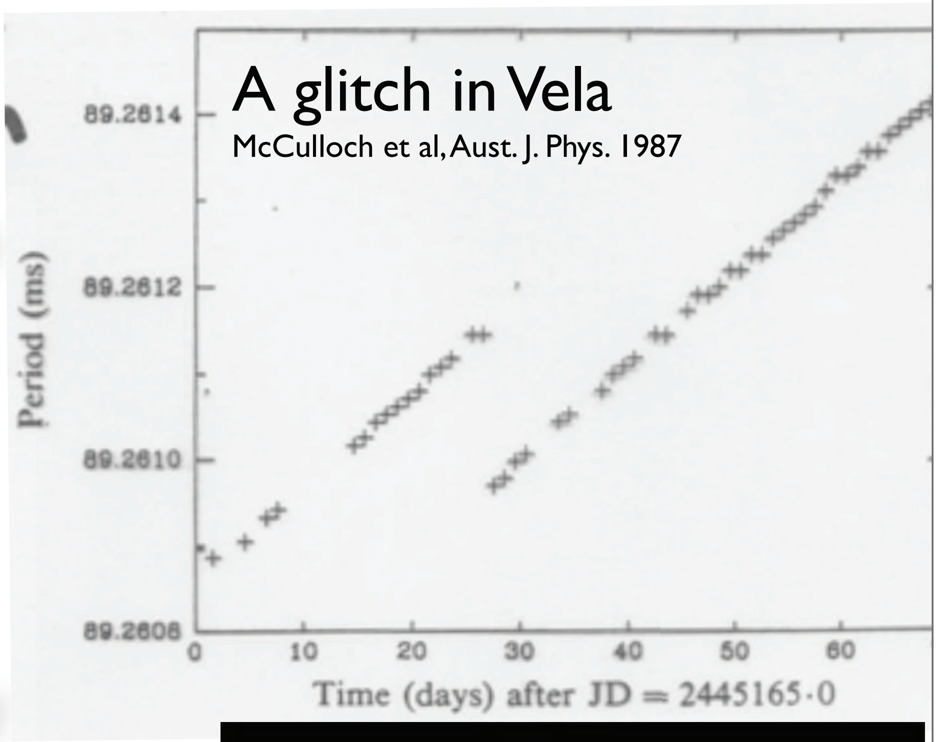


A composite Vela image

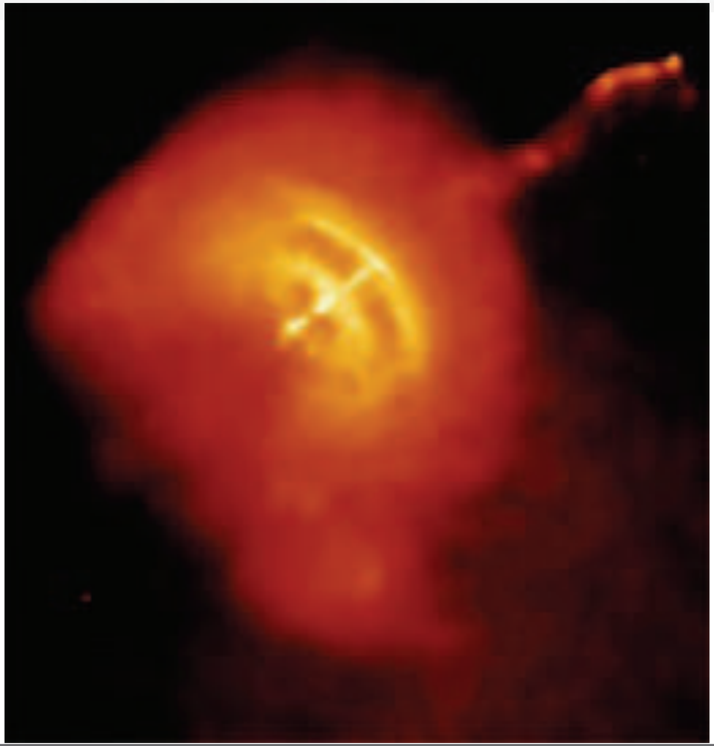


Pulsar Glitches

- Pulsars have stable rotation rates:
  - However, observe secular increase in pulse period
- Glitches are sudden dips in period
  - Vela glitches once every few yrs
- Could be the result of transfer of angular momentum from core to crust
  - At some critical lag rotation rate superfluid core couples to the curst imparting energy to the crust



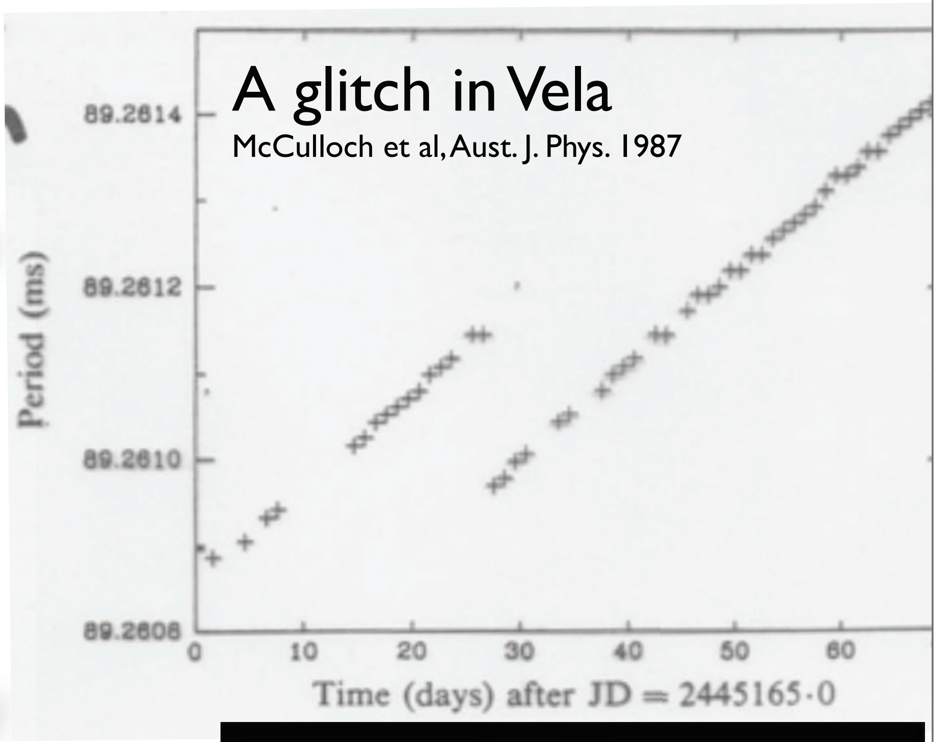
A composite Vela image



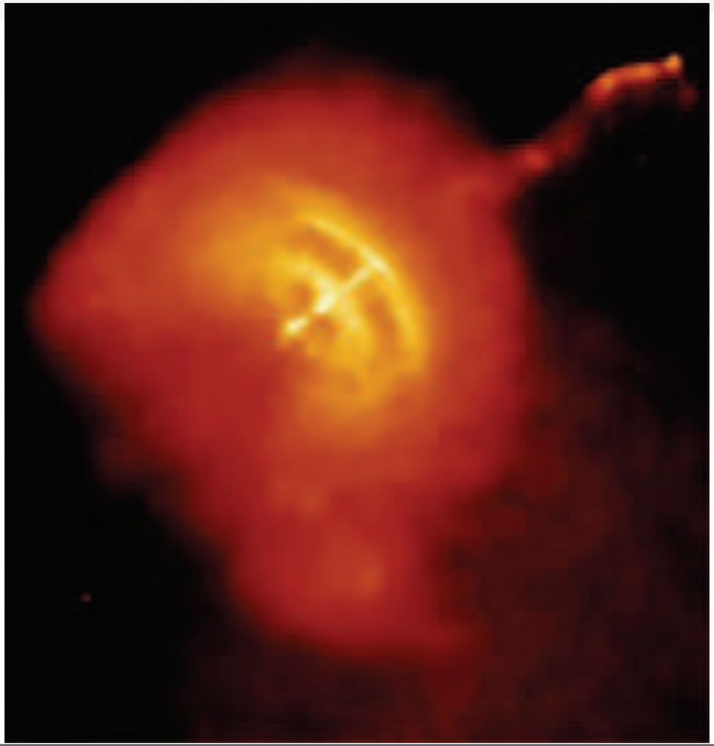
Pulsar Glitches

- Pulsars have stable rotation rates:
  - However, observe secular increase in pulse period
- Glitches are sudden dips in period
  - Vela glitches once every few yrs
- Could be the result of transfer of angular momentum from core to crust
  - At some critical lag rotation rate superfluid core couples to the curst imparting energy to the crust

$$\Delta J \sim I_* \Delta\Omega \qquad \Delta E = \Delta J \Omega_{\rm lag}$$



A composite Vela image

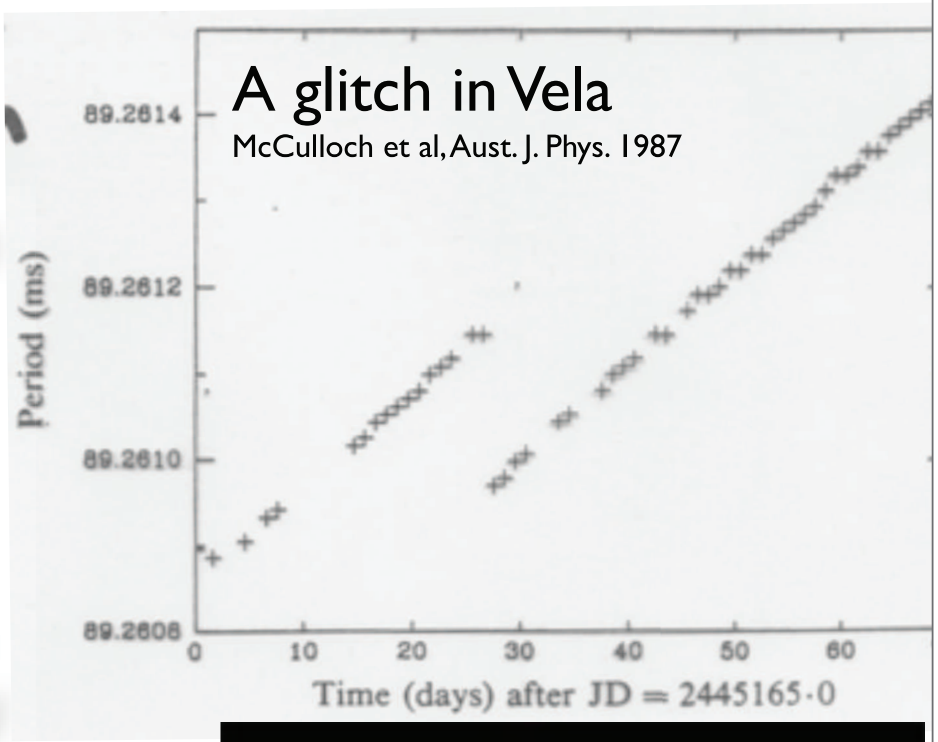


Pulsar Glitches

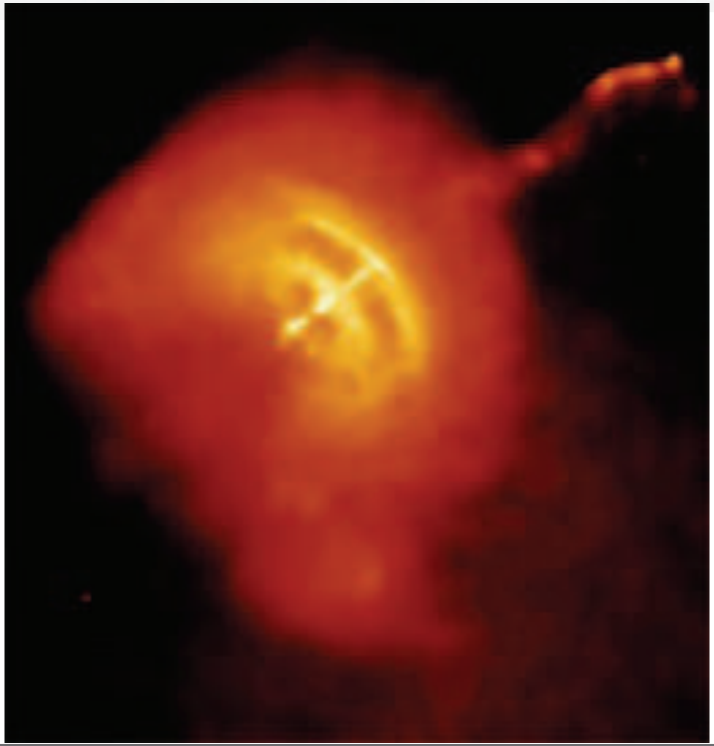
- Pulsars have stable rotation rates:
  - However, observe secular increase in pulse period
- Glitches are sudden dips in period
  - Vela glitches once every few yrs
- Could be the result of transfer of angular momentum from core to crust
  - At some critical lag rotation rate superfluid core couples to the curst imparting energy to the crust

$$\Delta J \sim I_* \Delta\Omega \qquad \Delta E = \Delta J \Omega_{\rm lag}$$

$$\Delta\Omega / \Omega \sim 10^{-6}$$



A composite Vela image



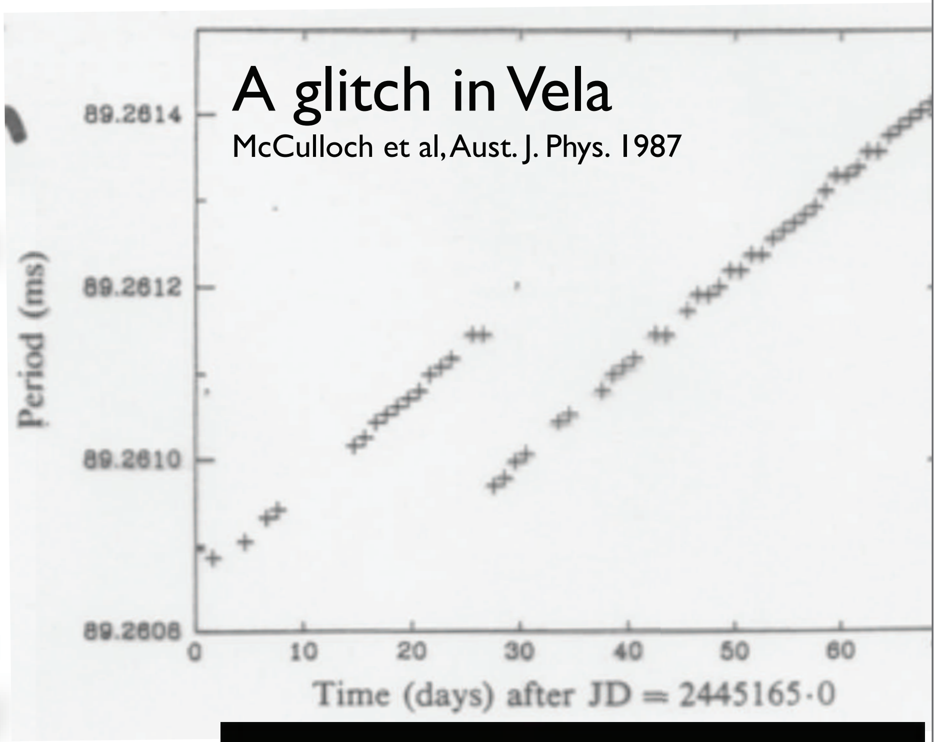
Pulsar Glitches

- Pulsars have stable rotation rates:
  - However, observe secular increase in pulse period
- Glitches are sudden dips in period
  - Vela glitches once every few yrs
- Could be the result of transfer of angular momentum from core to crust
  - At some critical lag rotation rate superfluid core couples to the curst imparting energy to the crust

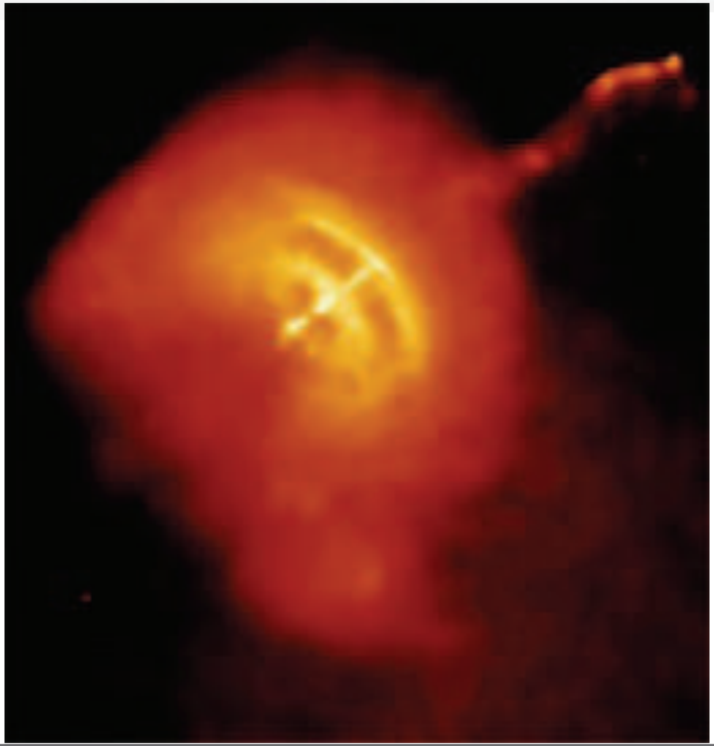
$$\Delta J \sim I_* \Delta\Omega \qquad \Delta E = \Delta J \Omega_{\rm lag}$$

$$\Delta\Omega / \Omega \sim 10^{-6}$$

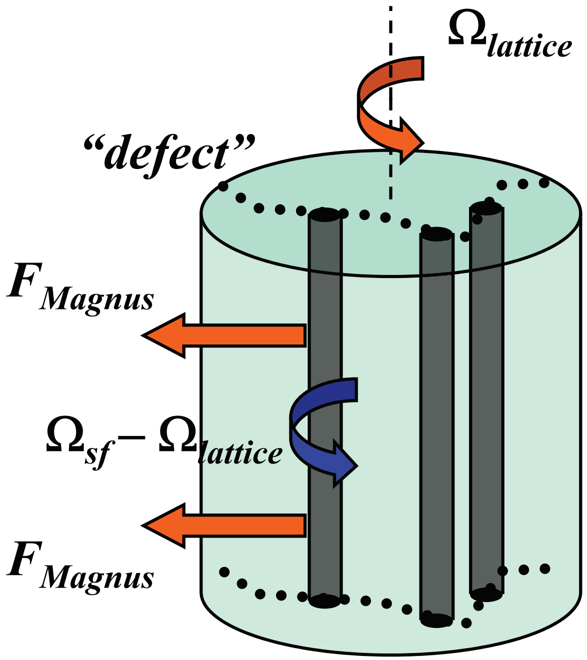
$$\Delta E \sim 10^{-13}\text{-}10^{-11} M_\odot c^2$$

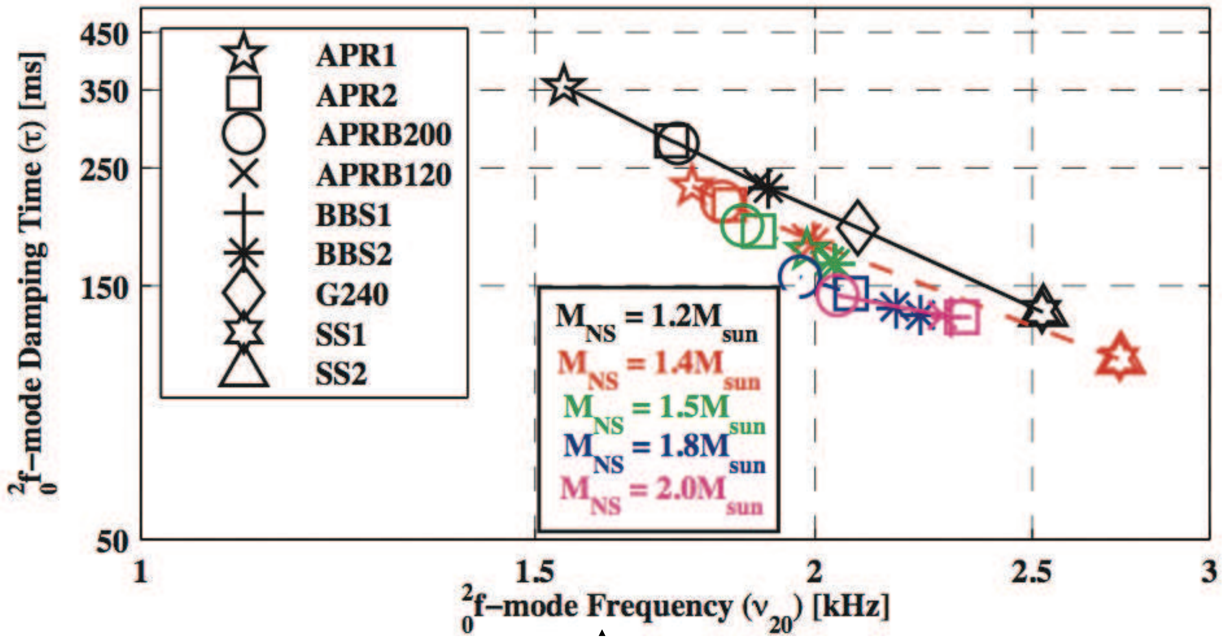


A composite Vela image



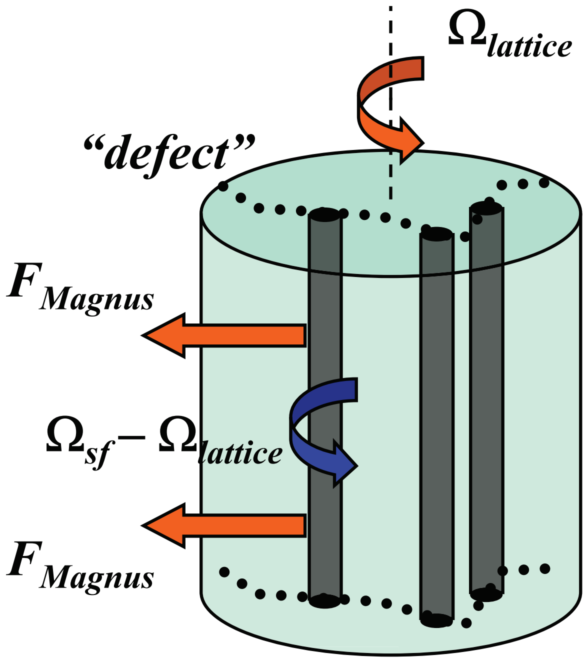
NS Normal Mode Oscillations

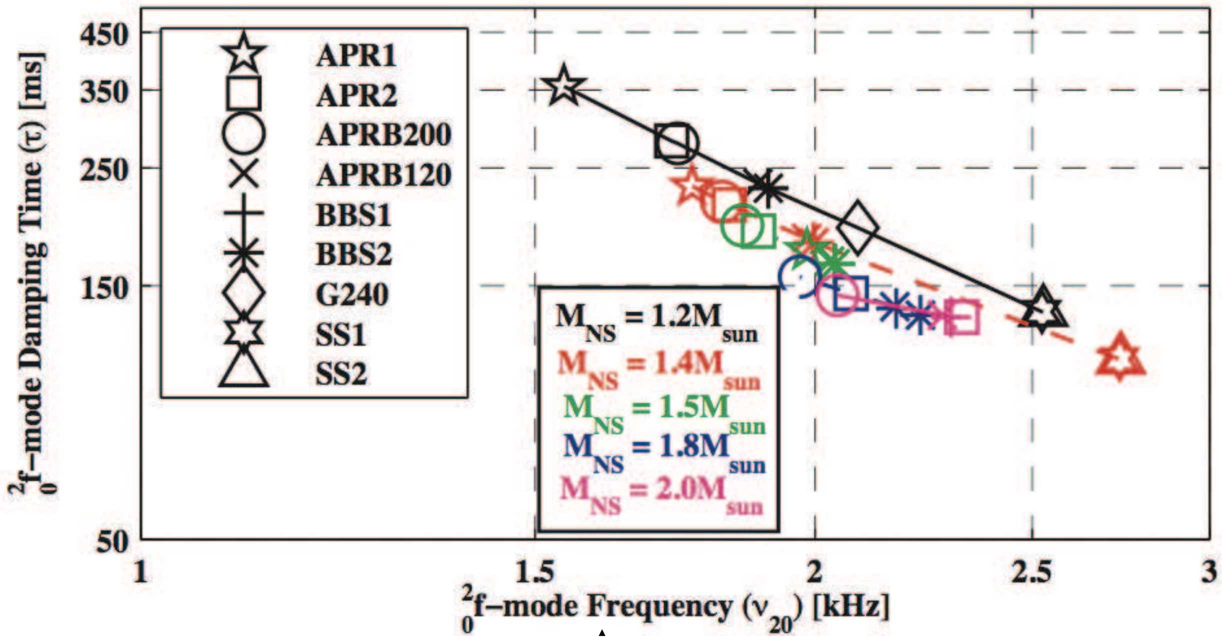




NS Normal Mode Oscillations

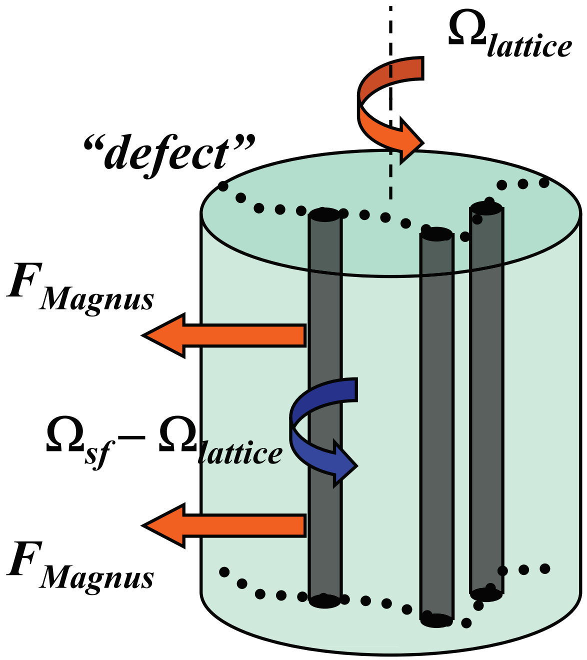
- Sudden jolt due to a glitch, and superfluid vortex unpinning, could cause oscillations of the core, emitting gravitational waves

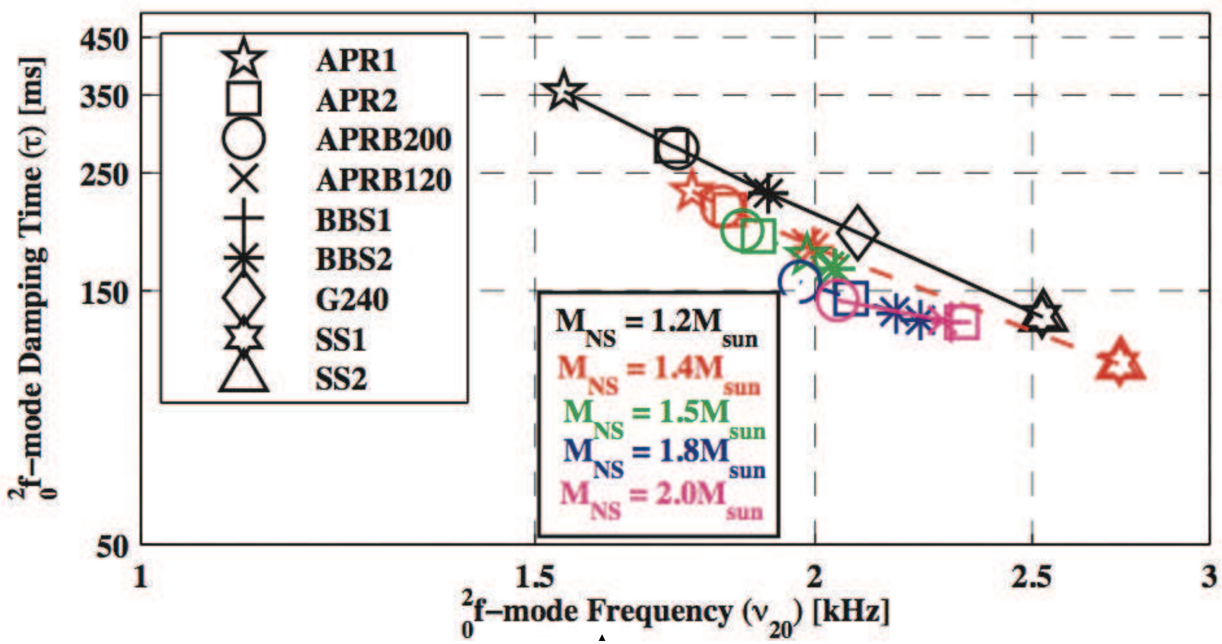




NS Normal Mode Oscillations

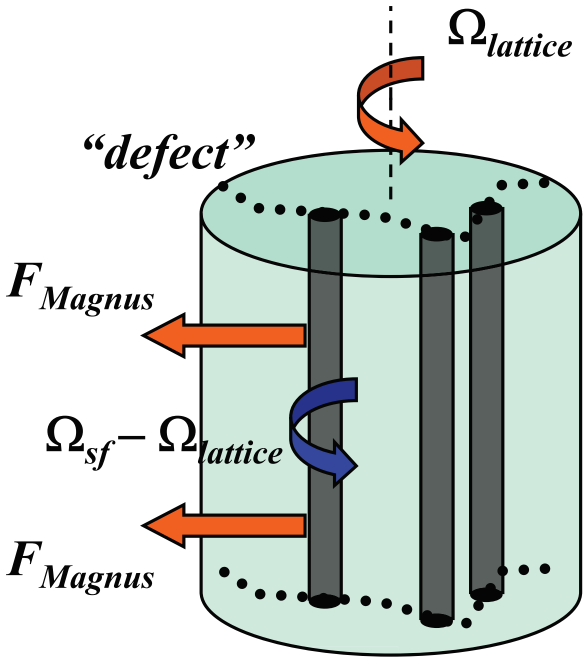
- Sudden jolt due to a glitch, and superfluid vortex unpinning, could cause oscillations of the core, emitting gravitational waves
  - These normal mode oscillations have characteristic frequencies and damping times that depend on the equation-of-state

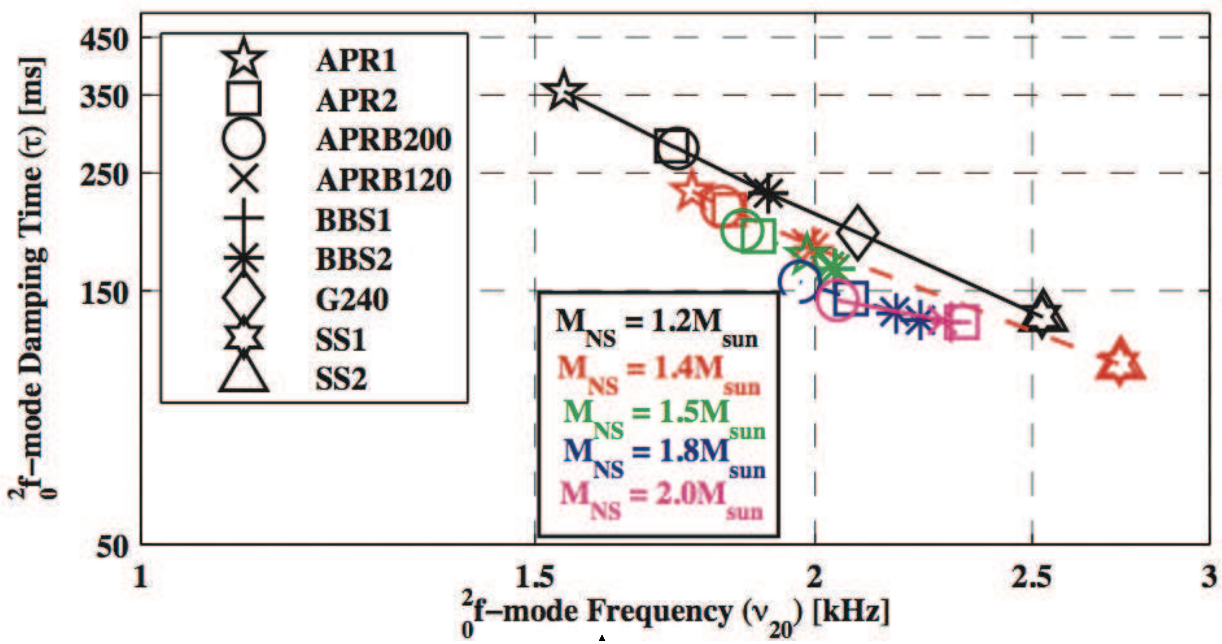




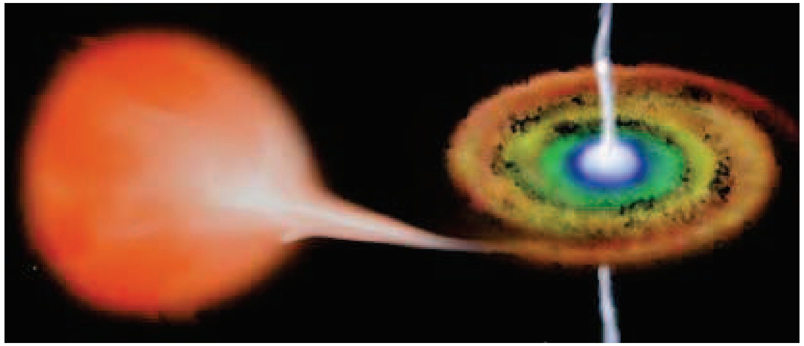
NS Normal Mode Oscillations

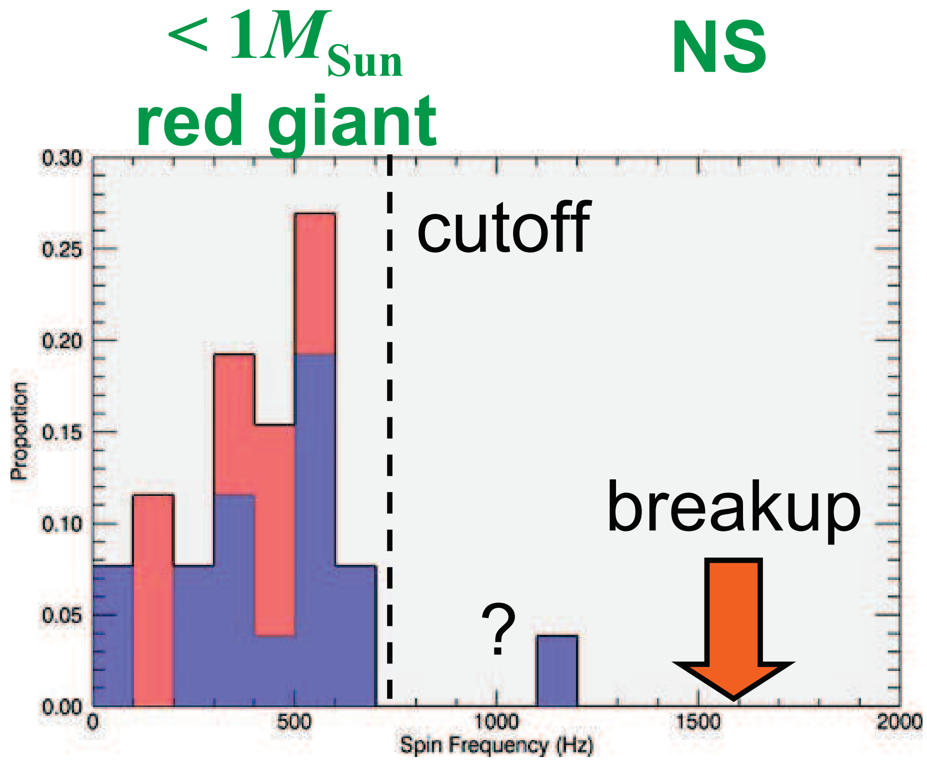
- Sudden jolt due to a glitch, and superfluid vortex unpinning, could cause oscillations of the core, emitting gravitational waves
  - These normal mode oscillations have characteristic frequencies and damping times that depend on the equation-of-state
- Detecting and measuring normal modes could reveal the equation-of-state of neutron stars and their internal structure





Accreting Neutron Stars

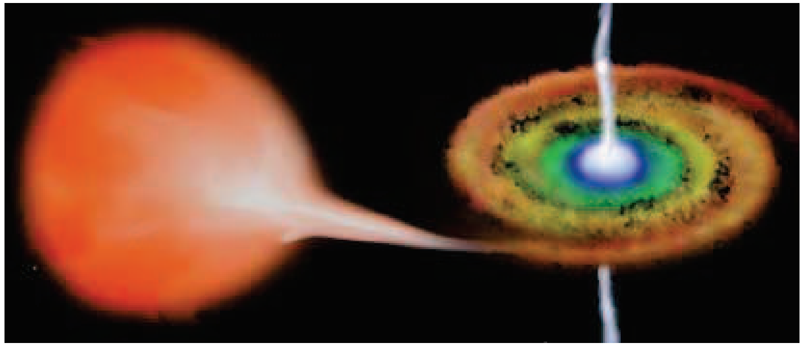


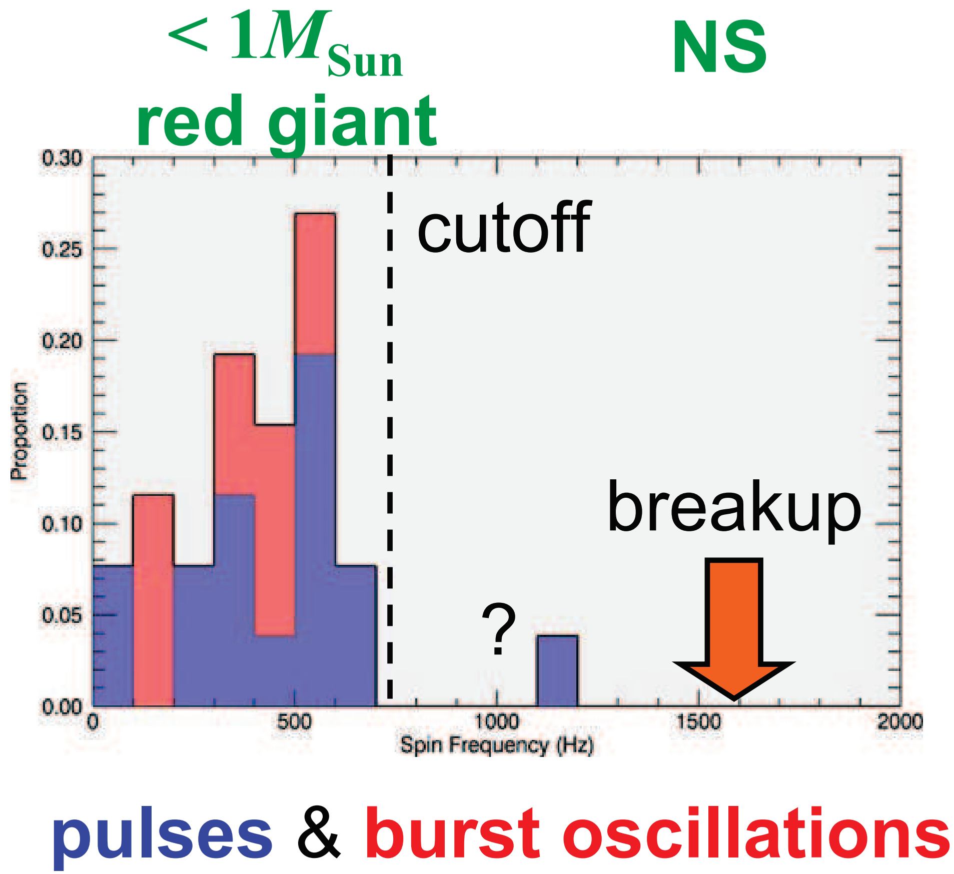


pulses & **burst oscillations**

Accreting Neutron Stars

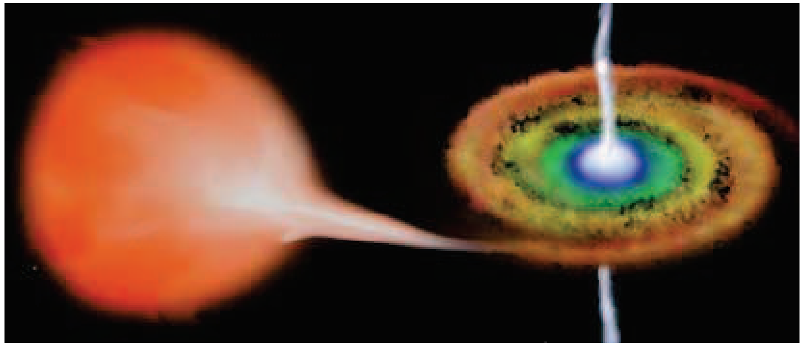
- Spin frequencies of accreting NS seems to be stalled below 700 Hz



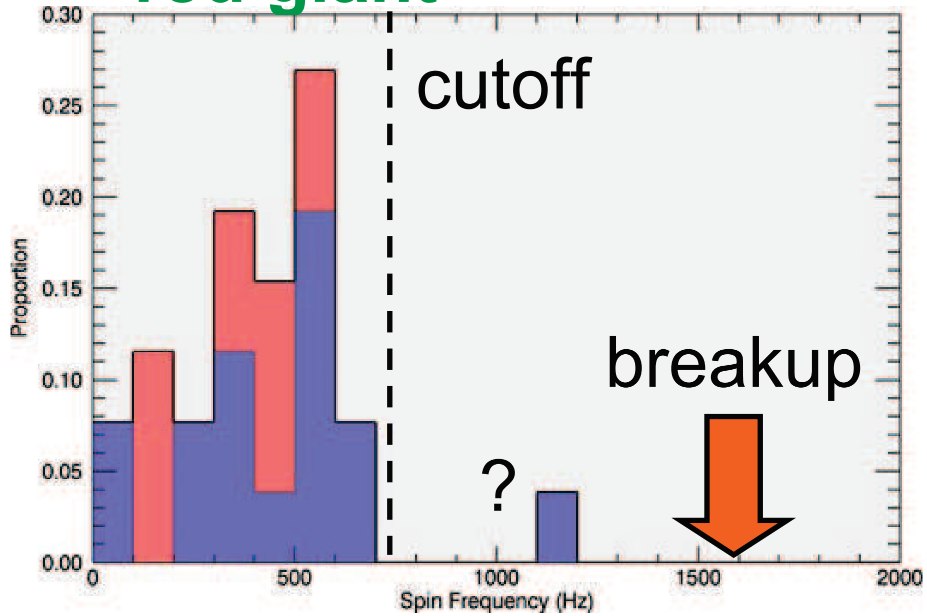


Accreting Neutron Stars

- Spin frequencies of accreting NS seems to be stalled below 700 Hz
  - Well below the break-up speed



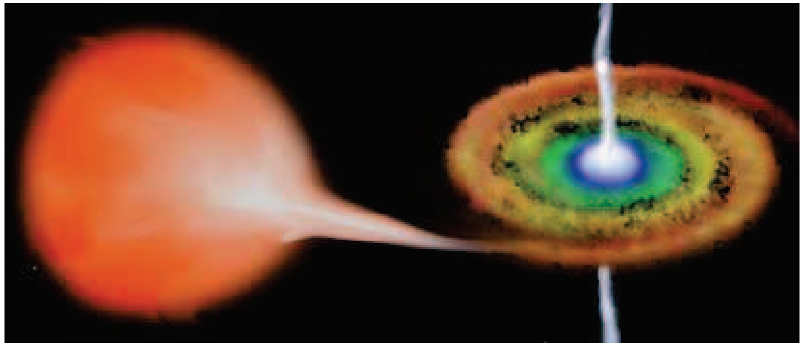
$< 1M_{\mathrm{Sun}}$ **red giant** **NS**

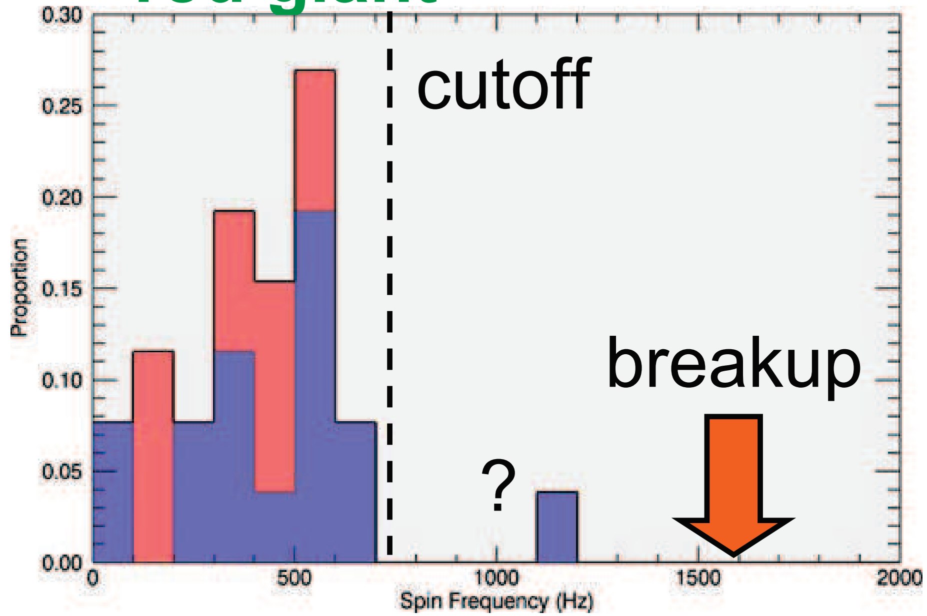


pulses & **burst oscillations**

Accreting Neutron Stars

- Spin frequencies of accreting NS seems to be stalled below 700 Hz
  - Well below the break-up speed
- What could be the reason for this stall?

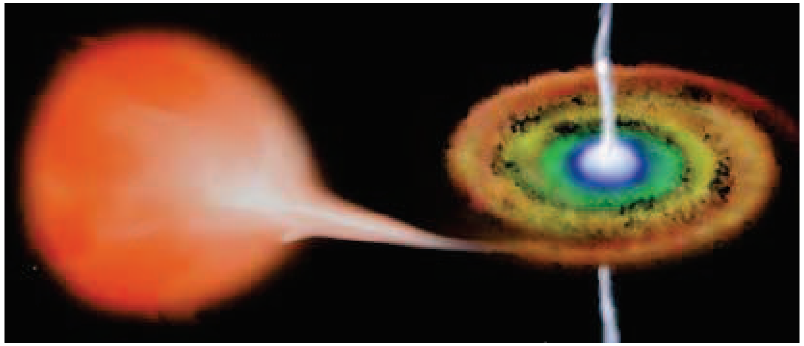




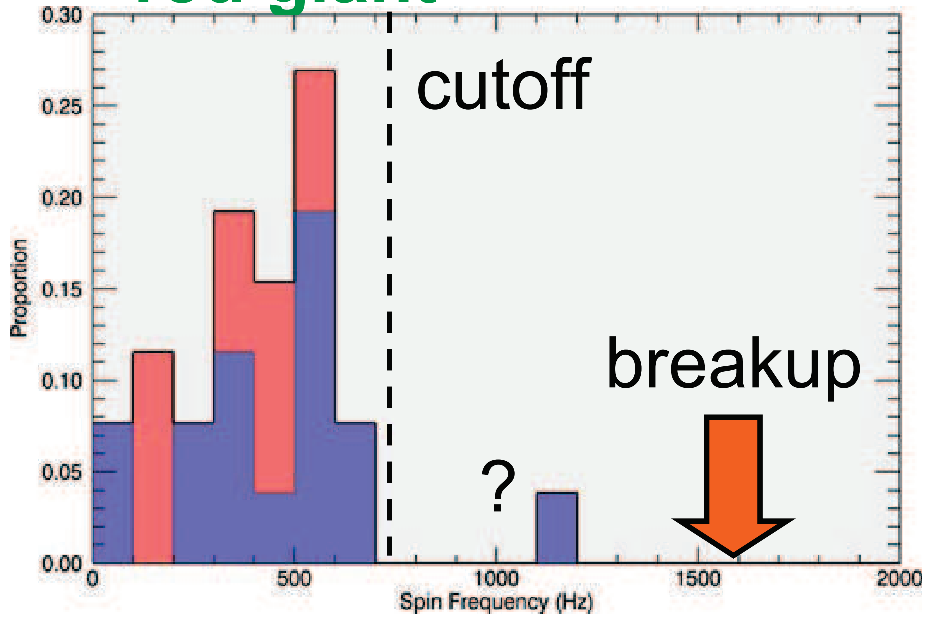
pulses & **burst oscillations**

Accreting Neutron Stars

- Spin frequencies of accreting NS seems to be stalled below 700 Hz
  - Well below the break-up speed
- What could be the reason for this stall?
  - Balance of accretion torque with GW back reaction torque



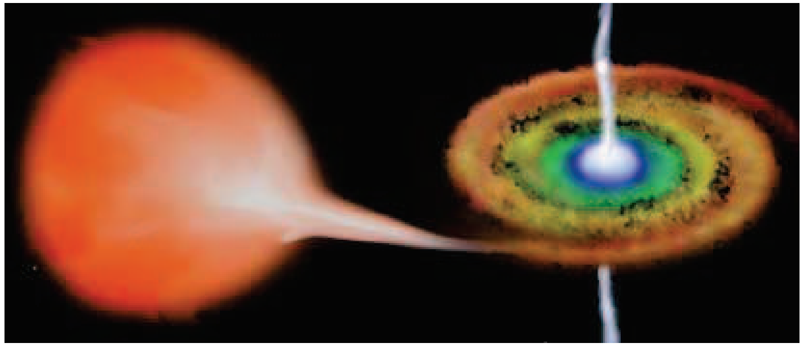
$< 1M_{Sun}$ **red giant** **NS**



pulses & **burst oscillations**

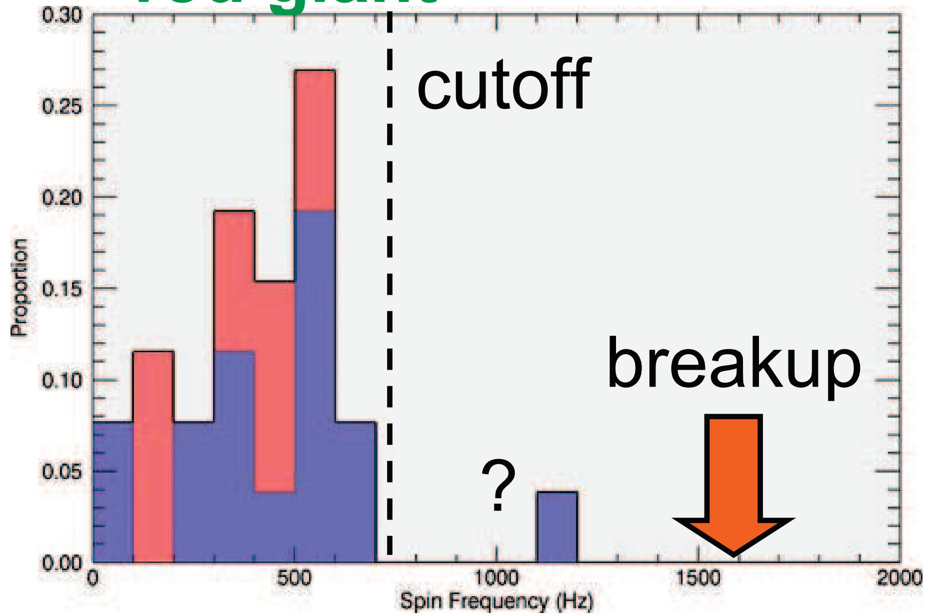
Accreting Neutron Stars

- Spin frequencies of accreting NS seems to be stalled below 700 Hz
  - Well below the break-up speed
- What could be the reason for this stall?
  - Balance of accretion torque with GW back reaction torque
- Could be explained if ellipticity is ~ 10^{-8}



$< 1M_{Sun}$ **red giant**

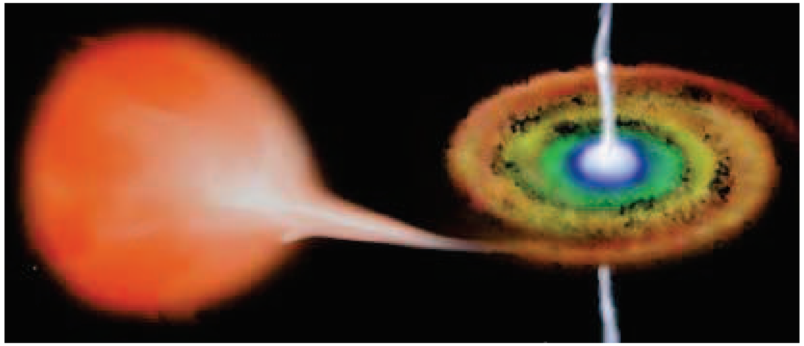
NS

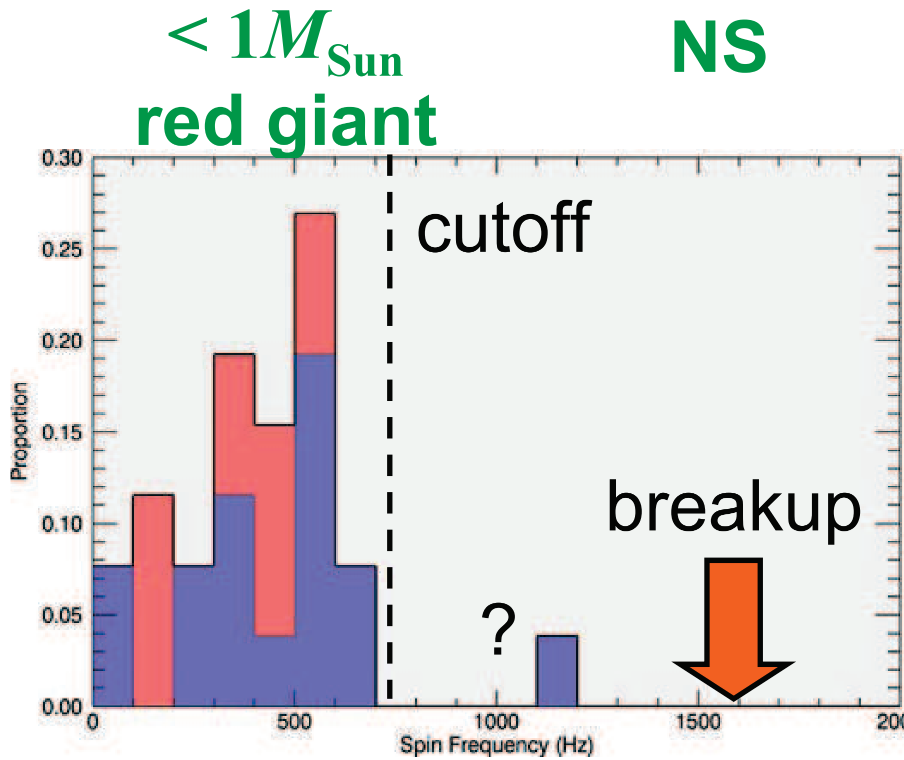


pulses & **burst oscillations**

Accreting Neutron Stars

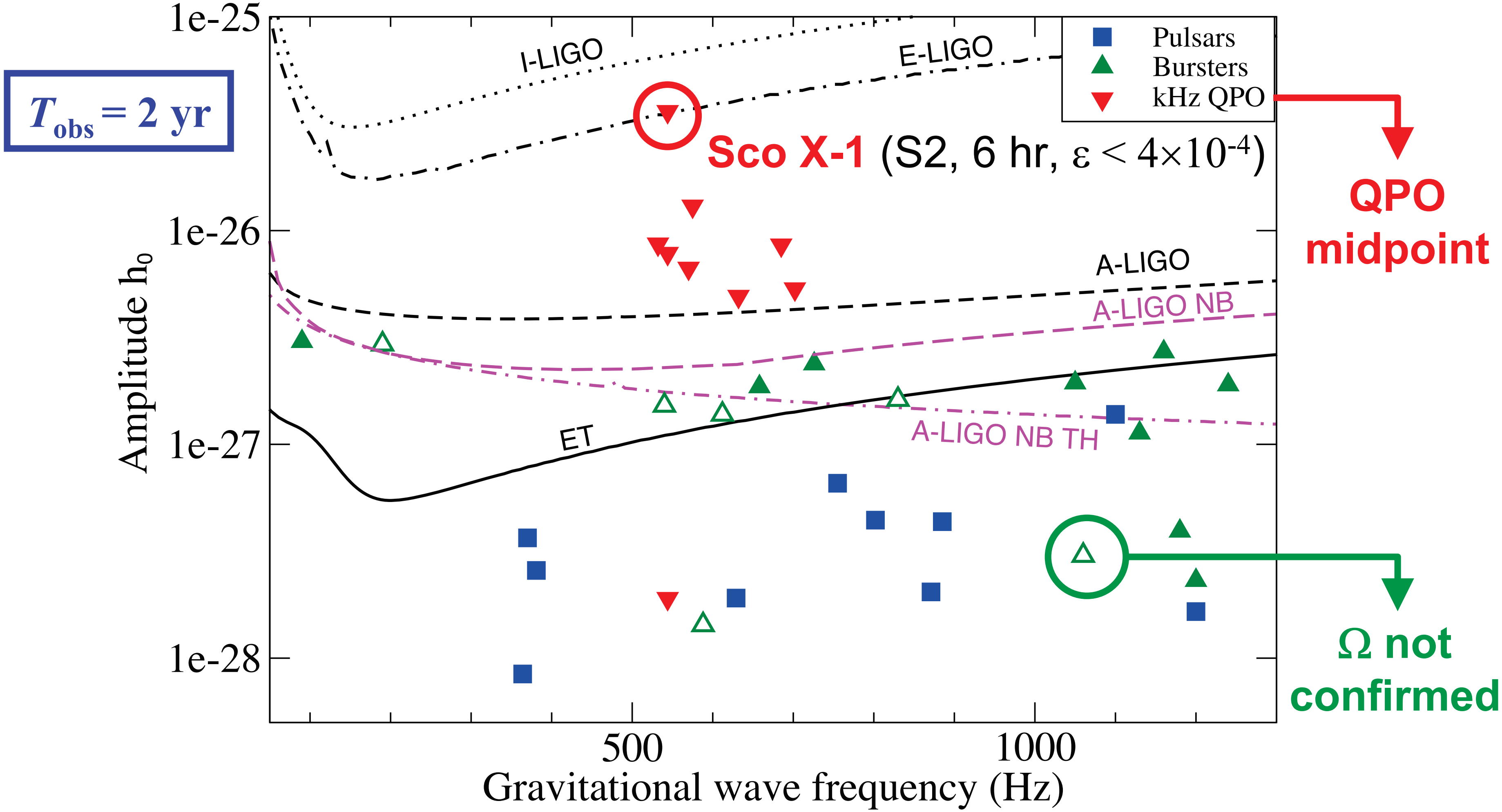
- Spin frequencies of accreting NS seems to be stalled below 700 Hz
  - Well below the break-up speed
- What could be the reason for this stall?
  - Balance of accretion torque with GW back reaction torque
- Could be explained if ellipticity is ~ 10^{-8}
  - Could be induced by mountains or relativistic instabilities, e.g. r-modes





pulses & **burst oscillations**

Sensitivity to Accreting NS



Cosmology

Cosmology

Cosmology

- Cosmography

Cosmology

- Cosmography
  - H_0, dark matter and dark energy densities, dark energy EoS w

Cosmology

- Cosmography
  - H_0, dark matter and dark energy densities, dark energy EoS w
- Black hole seeds

Cosmology

- Cosmography
  - H_0, dark matter and dark energy densities, dark energy EoS w
- Black hole seeds
  - Black hole seeds and their hierarchical growth

Cosmology

- Cosmography
  - H_0, dark matter and dark energy densities, dark energy EoS w
- Black hole seeds
  - Black hole seeds and their hierarchical growth
- Anisotropic cosmologies

Cosmology

- Cosmography
  - H_0, dark matter and dark energy densities, dark energy EoS w
- Black hole seeds
  - Black hole seeds and their hierarchical growth
- Anisotropic cosmologies
  - In an anisotropic Universe the distribution of H on the sky could show residual quadrupole and higher-order anisotropies

Cosmology

- Cosmography
  - H_0, dark matter and dark energy densities, dark energy EoS w
- Black hole seeds
  - Black hole seeds and their hierarchical growth
- Anisotropic cosmologies
  - In an anisotropic Universe the distribution of H on the sky could show residual quadrupole and higher-order anisotropies
- Primordial gravitational waves

Cosmology

- Cosmography
  - H_0, dark matter and dark energy densities, dark energy EoS w
- Black hole seeds
  - Black hole seeds and their hierarchical growth
- Anisotropic cosmologies
  - In an anisotropic Universe the distribution of H on the sky could show residual quadrupole and higher-order anisotropies
- Primordial gravitational waves
  - Quantum fluctuations in the early Universe, stochastic BG

Cosmology

- Cosmography
  - H_0, dark matter and dark energy densities, dark energy EoS w
- Black hole seeds
  - Black hole seeds and their hierarchical growth
- Anisotropic cosmologies
  - In an anisotropic Universe the distribution of H on the sky could show residual quadrupole and higher-order anisotropies
- Primordial gravitational waves
  - Quantum fluctuations in the early Universe, stochastic BG
- Production of GW during early Universe phase transitions

Cosmology

- Cosmography
  - H_0, dark matter and dark energy densities, dark energy EoS w
- Black hole seeds
  - Black hole seeds and their hierarchical growth
- Anisotropic cosmologies
  - In an anisotropic Universe the distribution of *H* on the sky could show residual quadrupole and higher-order anisotropies
- Primordial gravitational waves
  - Quantum fluctuations in the early Universe, stochastic BG
- Production of GW during early Universe phase transitions
  - Phase transitions, pre-heating, re-heating, etc.

Stochastic Backgrounds

Stochastic Backgrounds

- Primordial background

Stochastic Backgrounds

- Primordial background
  - Quantum fluctuations produce a background GW that is amplified by the background gravitational field

Stochastic Backgrounds

- Primordial background
  - Quantum fluctuations produce a background GW that is amplified by the background gravitational field
- Phase transitions in the Early Universe

Stochastic Backgrounds

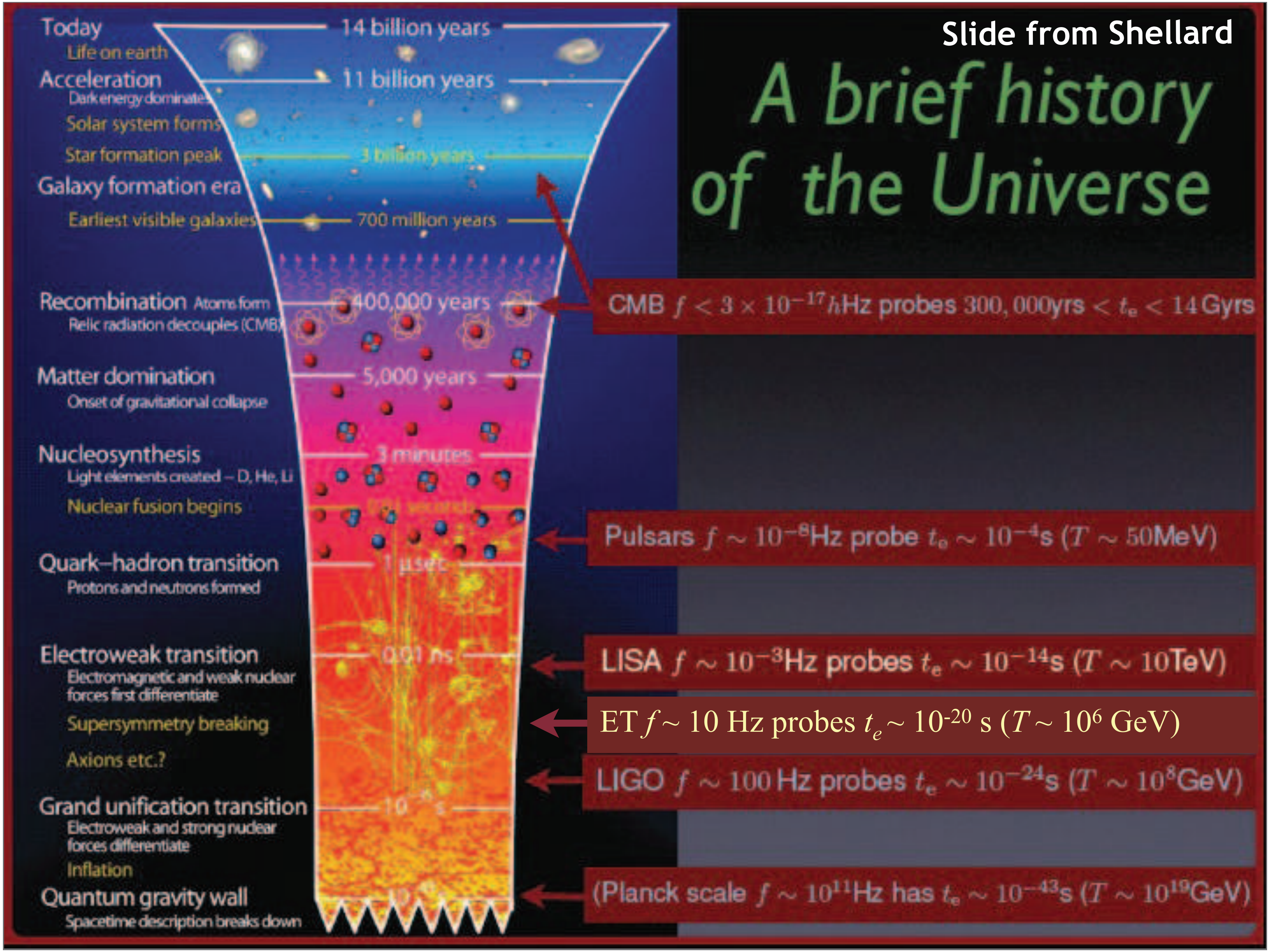
- Primordial background
  - Quantum fluctuations produce a background GW that is amplified by the background gravitational field
- Phase transitions in the Early Universe
  - Cosmic strings - kinks can form and "break" producing a burst of gravitational waves

Stochastic Backgrounds

- Primordial background
  - Quantum fluctuations produce a background GW that is amplified by the background gravitational field
- Phase transitions in the Early Universe
  - Cosmic strings - kinks can form and "break" producing a burst of gravitational waves
- Astrophysical background

Stochastic Backgrounds

- Primordial background
  - Quantum fluctuations produce a background GW that is amplified by the background gravitational field
- Phase transitions in the Early Universe
  - Cosmic strings - kinks can form and "break" producing a burst of gravitational waves
- Astrophysical background
  - A population of Galactic white-dwarf binaries produces a background above instrumental noise in LISA



Slide from Shellard
A brief history of the Universe
Today
Life on earth
Acceleration
Dark energy dominates
Solar system forms
Star formation peak
Galaxy formation era
Earliest visible galaxies
Recombination Atoms form
Relic radiation decouples (CMB)
Matter domination
Onset of gravitational collapse
Nucleosynthesis
Light elements created – D, He, Li
Nuclear fusion begins
Quark–hadron transition
Protons and neutrons formed
Electroweak transition
Electromagnetic and weak nuclear forces first differentiate
Supersymmetry breaking
Axions etc.?
Grand unification transition
Electroweak and strong nuclear forces differentiate
Inflation
Quantum gravity wall
Spacetime description breaks down
14 billion years
11 billion years
3 billion years
700 million years
400,000 years
5,000 years
3 minutes
1 μsec
CMB $f < 3 \times 10^{-17} h$Hz probes 300,000yrs $< t_e <$ 14 Gyrs
Pulsars $f \sim 10^{-8}$Hz probe $t_e \sim 10^{-4}$s ($T \sim$ 50MeV)
LISA $f \sim 10^{-3}$Hz probes $t_e \sim 10^{-14}$s ($T \sim$ 10TeV)
ET $f \sim$ 10 Hz probes $t_e \sim 10^{-20}$ s ($T \sim 10^6$ GeV)
LIGO $f \sim$ 100 Hz probes $t_e \sim 10^{-24}$s ($T \sim 10^8$GeV)
(Planck scale $f \sim 10^{11}$Hz has $t_e \sim 10^{-43}$s ($T \sim 10^{19}$GeV)

Stochastic Backgrounds in LIGO

Stochastic Backgrounds in LIGO

- Strength of stochastic background

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_{\rm crit}} \frac{d\rho_{\rm gw}}{d\ln f}$$

Stochastic Backgrounds in LIGO

- Strength of stochastic background
- Nucleosynthesis upper-limit

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_{\rm crit}} \frac{d\rho_{\rm gw}}{d\ln f}$$

$$\int \frac{df}{f} \Omega_{\rm gw}(f) \lesssim 1.5 \times 10^{-5}.$$

Stochastic Backgrounds in LIGO

- Strength of stochastic background

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_{\rm crit}} \frac{d\rho_{\rm gw}}{d\ln f}$$

- Nucleosynthesis upper-limit

$$\int \frac{df}{f} \Omega_{\rm gw}(f) \lesssim 1.5 \times 10^{-5}.$$

- Upper limit from LIGO data from the 4th Science run

$$\Omega_{\rm gw}(f) < 6.5 \times 10^{-5}$$

LSC, Astrophys. J. 659 (2007) 918

Stochastic Backgrounds in LIGO

- Strength of stochastic background

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_{\rm crit}} \frac{d\rho_{\rm gw}}{d\ln f}$$

- Nucleosynthesis upper-limit

$$\int \frac{df}{f}\Omega_{\rm gw}(f) \lesssim 1.5 \times 10^{-5}.$$

- Upper limit from LIGO data from the 4th Science run

$$\Omega_{\rm gw}(f) < 6.5 \times 10^{-5}$$

LSC, Astrophys. J. 659 (2007) 918

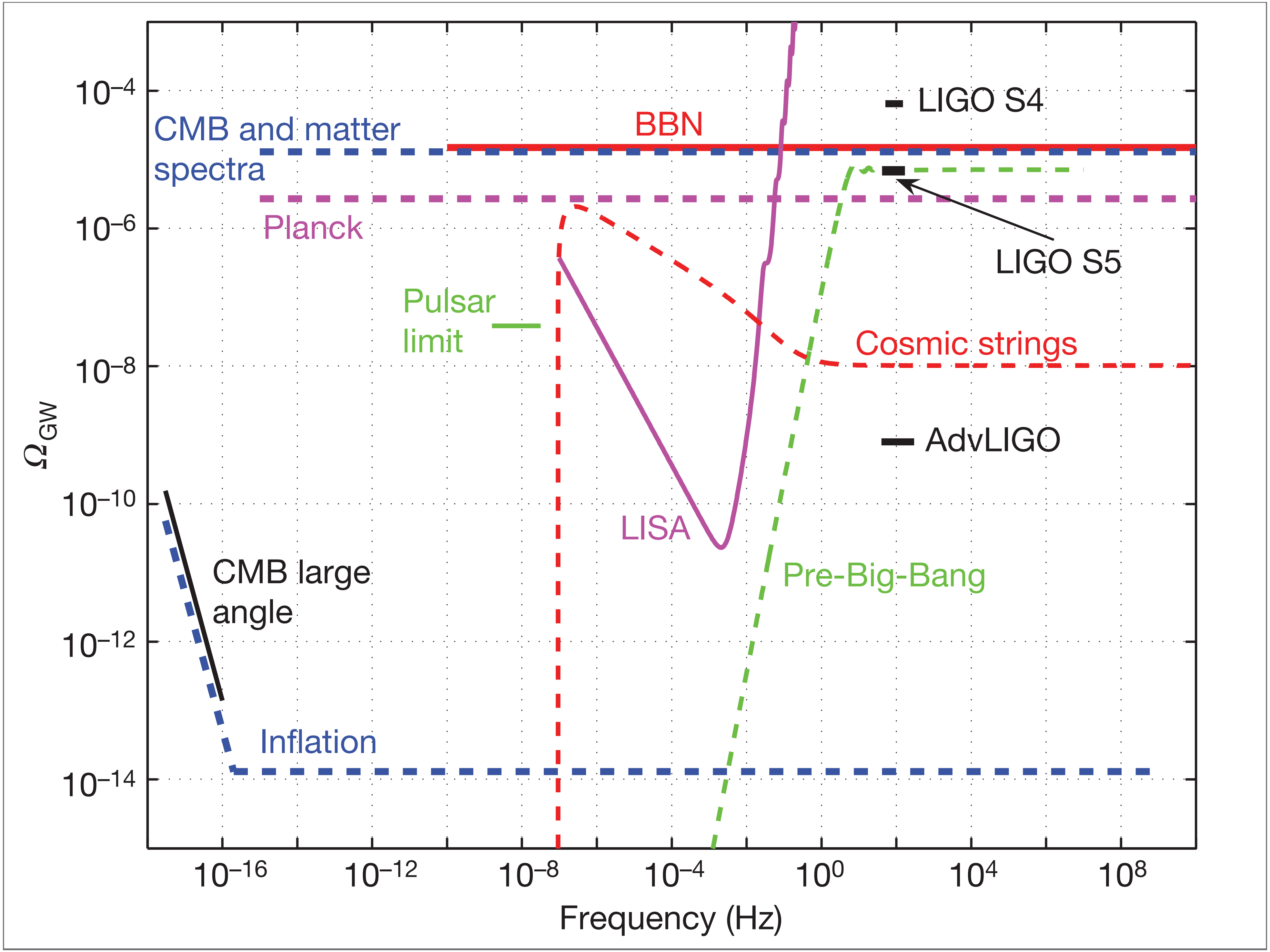
nature

Vol 460 | 20 August 2009 | **doi:10.1038/nature08278**

LETTERS

An upper limit on the stochastic gravitational-wave background of cosmological origin

The LIGO Scientific Collaboration* & The Virgo Collaboration*



Tuesday, 14 December 2010

Cosmological parameters

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}]^{1/2}}$$

Cosmological parameters

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}]^{1/2}}$$

- Luminosity distance Vs. red shift depends on a number of cosmological parameters H_0, Ω_M, Ω_b, Ω_Λ, w, etc.

Cosmological parameters

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{[\Omega_M (1+z)^3 + \Omega_\Lambda (1+z)^{3(1+w)}]^{1/2}}$$

- Luminosity distance Vs. red shift depends on a number of cosmological parameters H_0, Ω_M, Ω_b, Ω_Λ, w, etc.
- Einstein Telescope will detect 1000's of compact binary mergers for which the source can be identified (e.g. GRB) and red-shift measured.

Cosmological parameters

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}]^{1/2}}$$

- Luminosity distance Vs. red shift depends on a number of cosmological parameters H_0, Ω_M, Ω_b, Ω_Λ, w, etc.
- Einstein Telescope will detect 1000's of compact binary mergers for which the source can be identified (e.g. GRB) and red-shift measured.
- A fit to such observations can determine the cosmological parameters to better than a few percent.

Schutz 86

Compact Binaries are Standard Sirens

Schutz 86

Compact Binaries are Standard Sirens

- Amplitude of gravitational waves depends on $h \propto \frac{\mathcal{M}^{5/6}}{D_{\mathrm{L}}}$

Schutz 86

Compact Binaries are Standard Sirens

- Amplitude of gravitational waves depends on $h \propto \frac{\mathcal{M}^{5/6}}{D_{\mathrm{L}}}$
  - Chirp-mass=$\mu^{3/5}M^{2/5}$

Schutz 86

Compact Binaries are Standard Sirens

- Amplitude of gravitational waves depends on $h \propto \frac{\mathcal{M}^{5/6}}{D_\mathrm{L}}$
  - Chirp-mass=$\mu^{3/5} M^{2/5}$
- Gravitational wave observations can measure both

Schutz 86

Compact Binaries are Standard Sirens

- Amplitude of gravitational waves depends on $h \propto \frac{\mathcal{M}^{5/6}}{D_\mathrm{L}}$
  - Chirp-mass=$\mu^{3/5}M^{2/5}$
- Gravitational wave observations can measure both
  - Amplitude (this is the strain caused in our detector)

Schutz 86

Compact Binaries are Standard Sirens

- Amplitude of gravitational waves depends on $h \propto \frac{\mathcal{M}^{5/6}}{D_\mathrm{L}}$
  - Chirp-mass=$\mu^{3/5}M^{2/5}$
- Gravitational wave observations can measure both
  - Amplitude (this is the strain caused in our detector)
  - Chirp-mass (because the chirp rate depends on the chirp mass)

Schutz 86

Compact Binaries are Standard Sirens

- Amplitude of gravitational waves depends on $h \propto \frac{\mathcal{M}^{5/6}}{D_{\mathrm{L}}}$
  - Chirp-mass=$\mu^{3/5}M^{2/5}$
- Gravitational wave observations can measure both
  - Amplitude (this is the strain caused in our detector)
  - Chirp-mass (because the chirp rate depends on the chirp mass)
- Therefore, binary black hole inspirals are standard sirens

Schutz 86

Compact Binaries are Standard Sirens

- Amplitude of gravitational waves depends on $h \propto \frac{\mathcal{M}^{5/6}}{D_L}$
  - Chirp-mass=$\mu^{3/5}M^{2/5}$
- Gravitational wave observations can measure both
  - Amplitude (this is the strain caused in our detector)
  - Chirp-mass (because the chirp rate depends on the chirp mass)
- Therefore, binary black hole inspirals are standard sirens
  - From the apparent luminosity (the strain) we can conclude the luminosity distance

Schutz 86

Compact Binaries are Standard Sirens

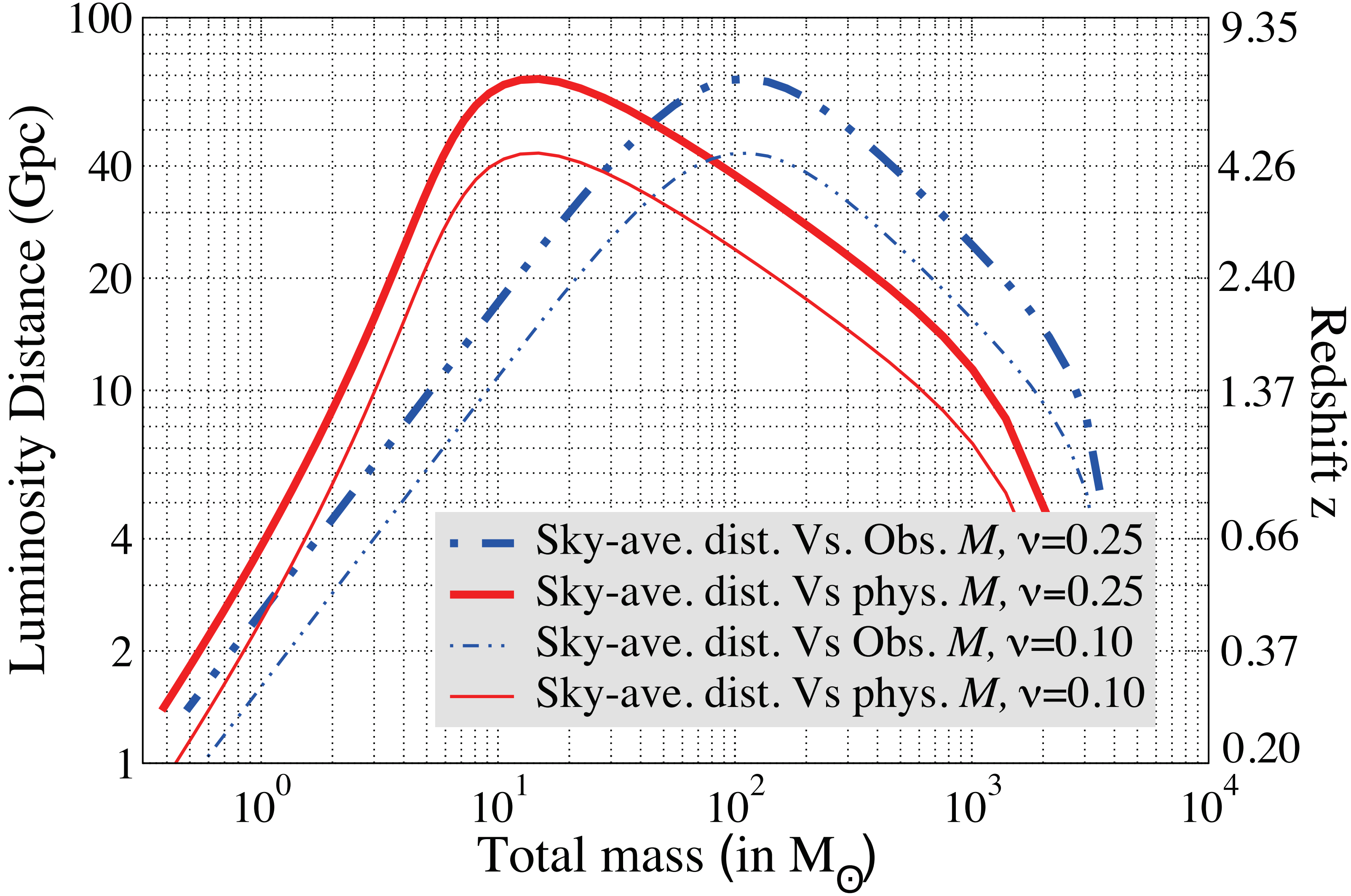
- Amplitude of gravitational waves depends on $h \propto \frac{\mathcal{M}^{5/6}}{D_L}$
  - Chirp-mass=$\mu^{3/5}M^{2/5}$
- Gravitational wave observations can measure both
  - Amplitude (this is the strain caused in our detector)
  - Chirp-mass (because the chirp rate depends on the chirp mass)
- Therefore, binary black hole inspirals are standard sirens
  - From the apparent luminosity (the strain) we can conclude the luminosity distance
- However, GW observations alone cannot determine the red-shift to a source

Schutz 86

Compact Binaries are Standard Sirens

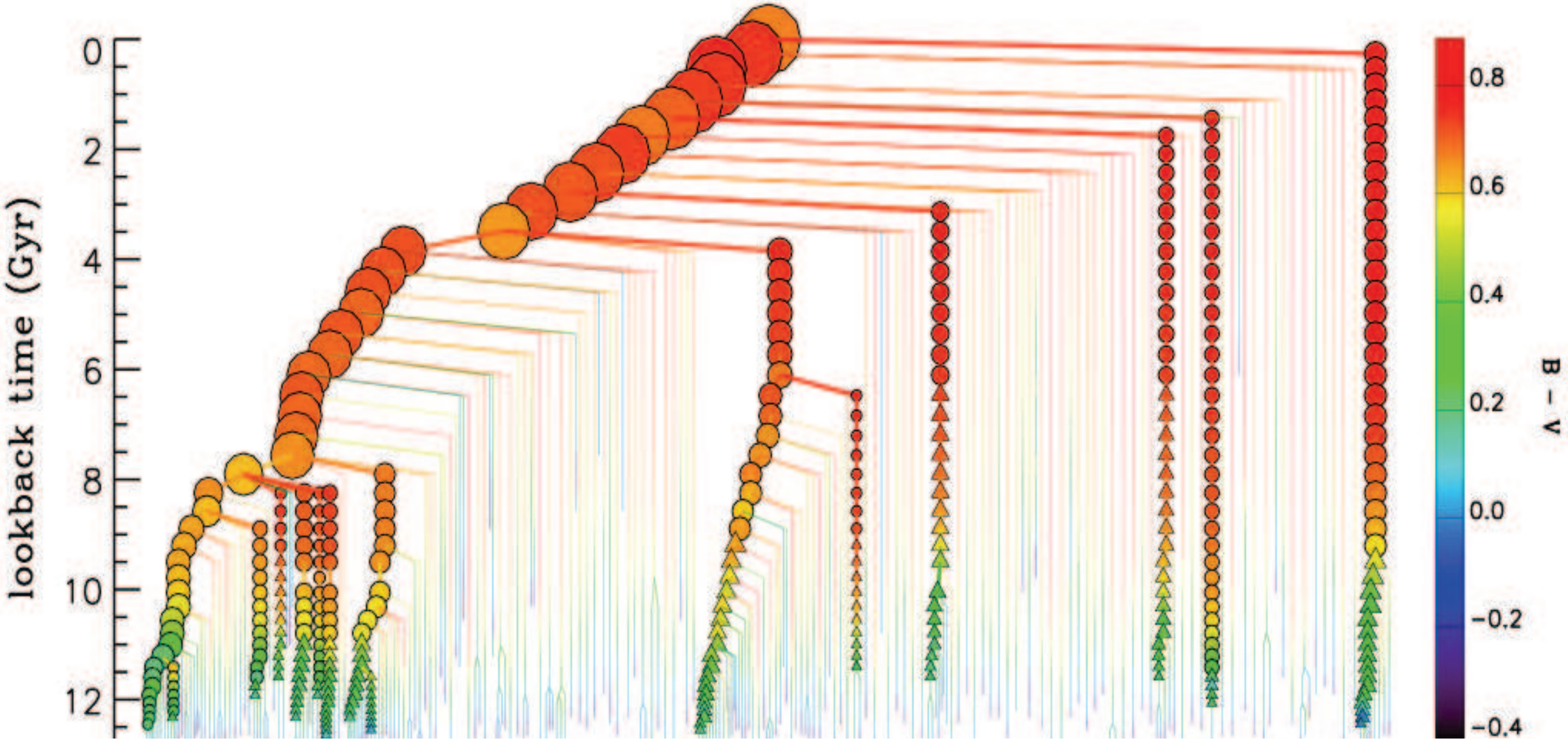
- Amplitude of gravitational waves depends on $h \propto \frac{\mathcal{M}^{5/6}}{D_\mathrm{L}}$
  - Chirp-mass=$\mu^{3/5}M^{2/5}$
- Gravitational wave observations can measure both
  - Amplitude (this is the strain caused in our detector)
  - Chirp-mass (because the chirp rate depends on the chirp mass)
- Therefore, binary black hole inspirals are standard sirens
  - From the apparent luminosity (the strain) we can conclude the luminosity distance
- However, GW observations alone cannot determine the red-shift to a source
- Joint gravitational-wave and optical observations can facilitate a new cosmological tool

Distance Reach of ET

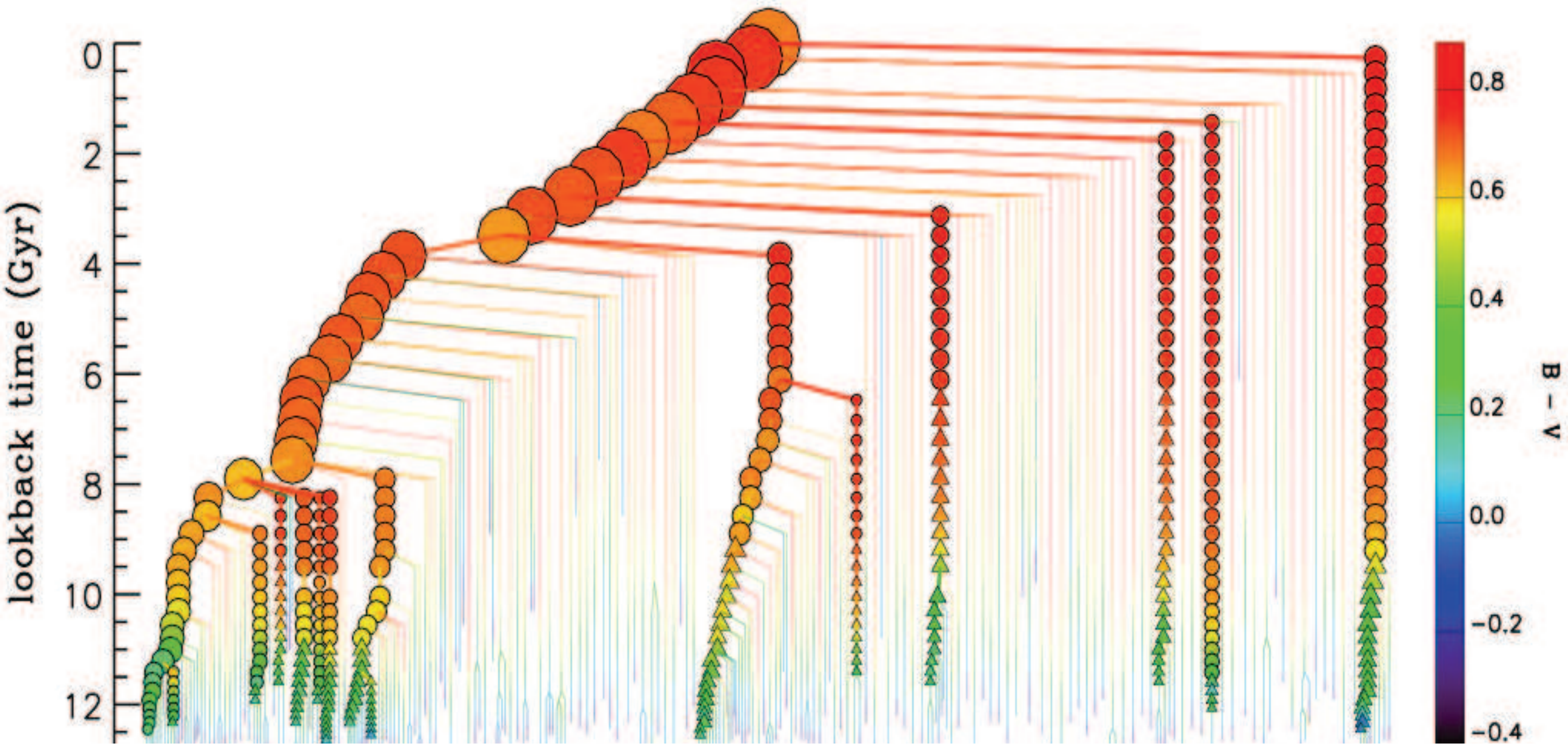


CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

Hierarchical Growth of Black Holes in Galactic Nuclei

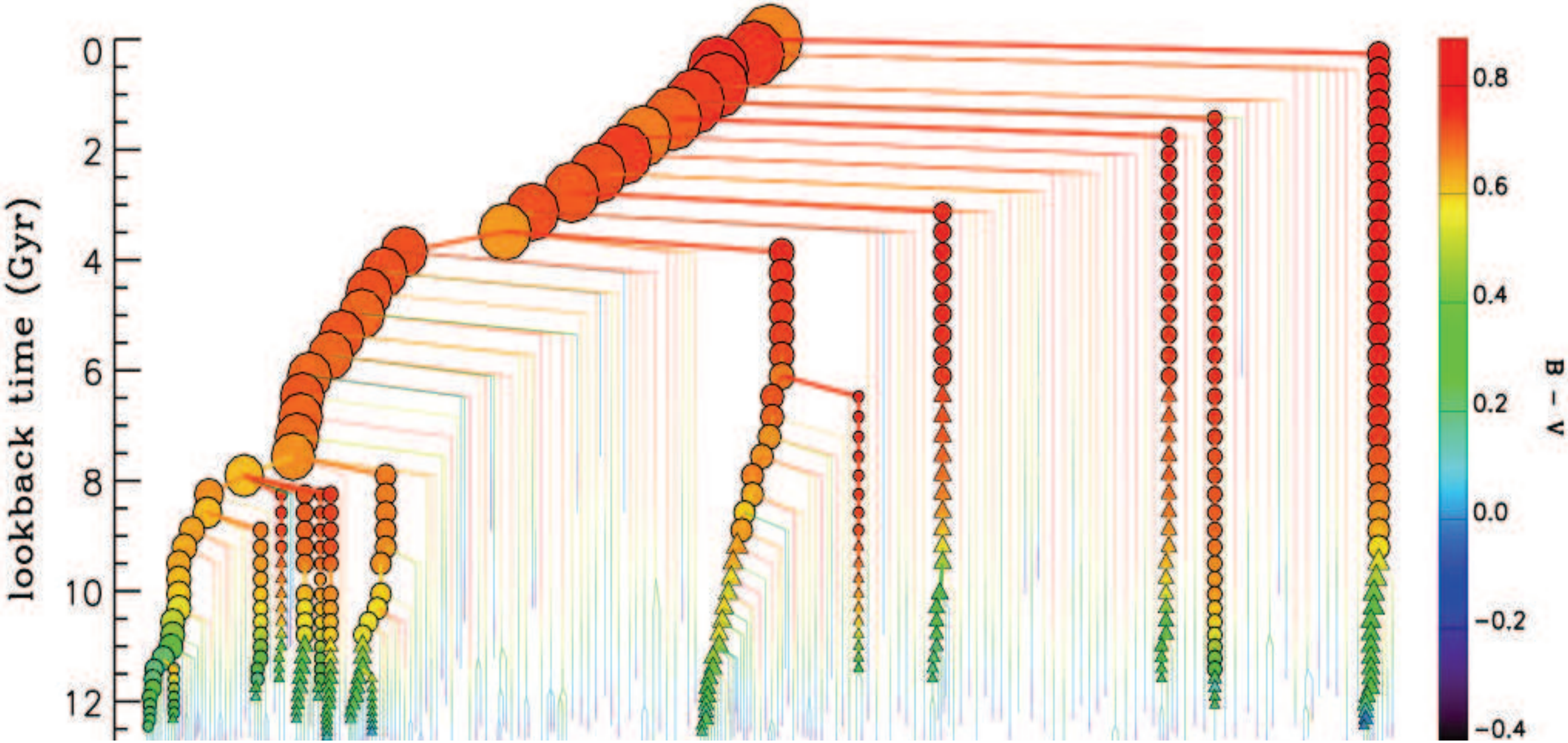


Hierarchical Growth of Black Holes in Galactic Nuclei



- Initially small black holes may grow by hierarchical merger

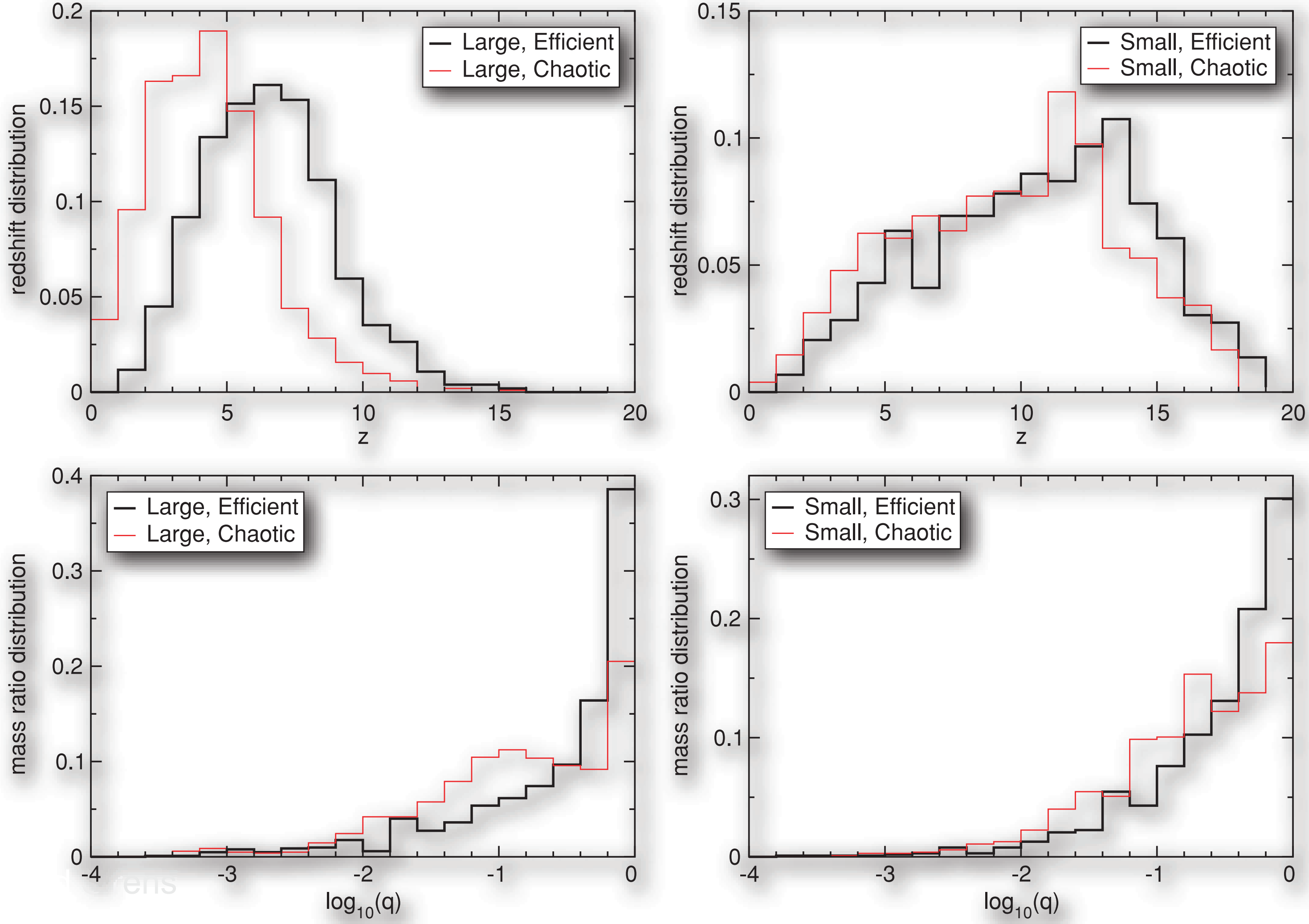
Hierarchical Growth of Black Holes in Galactic Nuclei



- Initially small black holes may grow by hierarchical merger
  - ET could observe seed black holes if they are of order 1000 solar mass

Models of Black Hole Seeds and Their Evolution

Class. Quantum Grav. **26** (2009) 094027 K G Arun *et al*



Fundamental Physics

Fundamental Physics

Fundamental Physics

- Properties of gravitational waves

Fundamental Physics

- Properties of gravitational waves
  - Test wave generation formula beyond quadrupole approx.

Fundamental Physics

- Properties of gravitational waves
  - Test wave generation formula beyond quadrupole approx.
  - Number of GW polarizations?

Fundamental Physics

- Properties of gravitational waves
  - Test wave generation formula beyond quadrupole approx.
  - Number of GW polarizations?
  - Do gravitational waves travel at the speed of light?

Fundamental Physics

- Properties of gravitational waves
  - Test wave generation formula beyond quadrupole approx.
  - Number of GW polarizations?
  - Do gravitational waves travel at the speed of light?
- Equation-of-State of dark energy

Fundamental Physics

- Properties of gravitational waves
  - Test wave generation formula beyond quadrupole approx.
  - Number of GW polarizations?
  - Do gravitational waves travel at the speed of light?
- Equation-of-State of dark energy
  - GW from inspiralling binaries are standard sirens

Fundamental Physics

- Properties of gravitational waves
  - Test wave generation formula beyond quadrupole approx.
  - Number of GW polarizations?
  - Do gravitational waves travel at the speed of light?
- Equation-of-State of dark energy
  - GW from inspiralling binaries are standard sirens
- Equation-of-State of supra-nuclear matter

Fundamental Physics

- Properties of gravitational waves
  - Test wave generation formula beyond quadrupole approx.
  - Number of GW polarizations?
  - Do gravitational waves travel at the speed of light?
- Equation-of-State of dark energy
  - GW from inspiralling binaries are standard sirens
- Equation-of-State of supra-nuclear matter
  - Signature NS of EoS in GW from binary neutron star mergers

Fundamental Physics

- Properties of gravitational waves
  - Test wave generation formula beyond quadrupole approx.
  - Number of GW polarizations?
  - Do gravitational waves travel at the speed of light?
- Equation-of-State of dark energy
  - GW from inspiralling binaries are standard sirens
- Equation-of-State of supra-nuclear matter
  - Signature NS of EoS in GW from binary neutron star mergers
- Black hole no-hair theorem and cosmic censorship

Fundamental Physics

- Properties of gravitational waves
  - Test wave generation formula beyond quadrupole approx.
  - Number of GW polarizations?
  - Do gravitational waves travel at the speed of light?
- Equation-of-State of dark energy
  - GW from inspiralling binaries are standard sirens
- Equation-of-State of supra-nuclear matter
  - Signature NS of EoS in GW from binary neutron star mergers
- Black hole no-hair theorem and cosmic censorship
  - Are black hole candidates black holes of general relativity?

Fundamental Physics

- Properties of gravitational waves
  - Test wave generation formula beyond quadrupole approx.
  - Number of GW polarizations?
  - Do gravitational waves travel at the speed of light?
- Equation-of-State of dark energy
  - GW from inspiralling binaries are standard sirens
- Equation-of-State of supra-nuclear matter
  - Signature NS of EoS in GW from binary neutron star mergers
- Black hole no-hair theorem and cosmic censorship
  - Are black hole candidates black holes of general relativity?
- Merger dynamics of spinning black hole binaries

Black hole quasi-normal modes

Black hole quasi-normal modes

- Damped sinusoids with characteristic frequencies and decay times

Black hole quasi-normal modes

- Damped sinusoids with characteristic frequencies and decay times
  - In general relativity frequencies f_{lmn} and decay times t_{lmn} all depend only on the mass M and spin q of the black hole

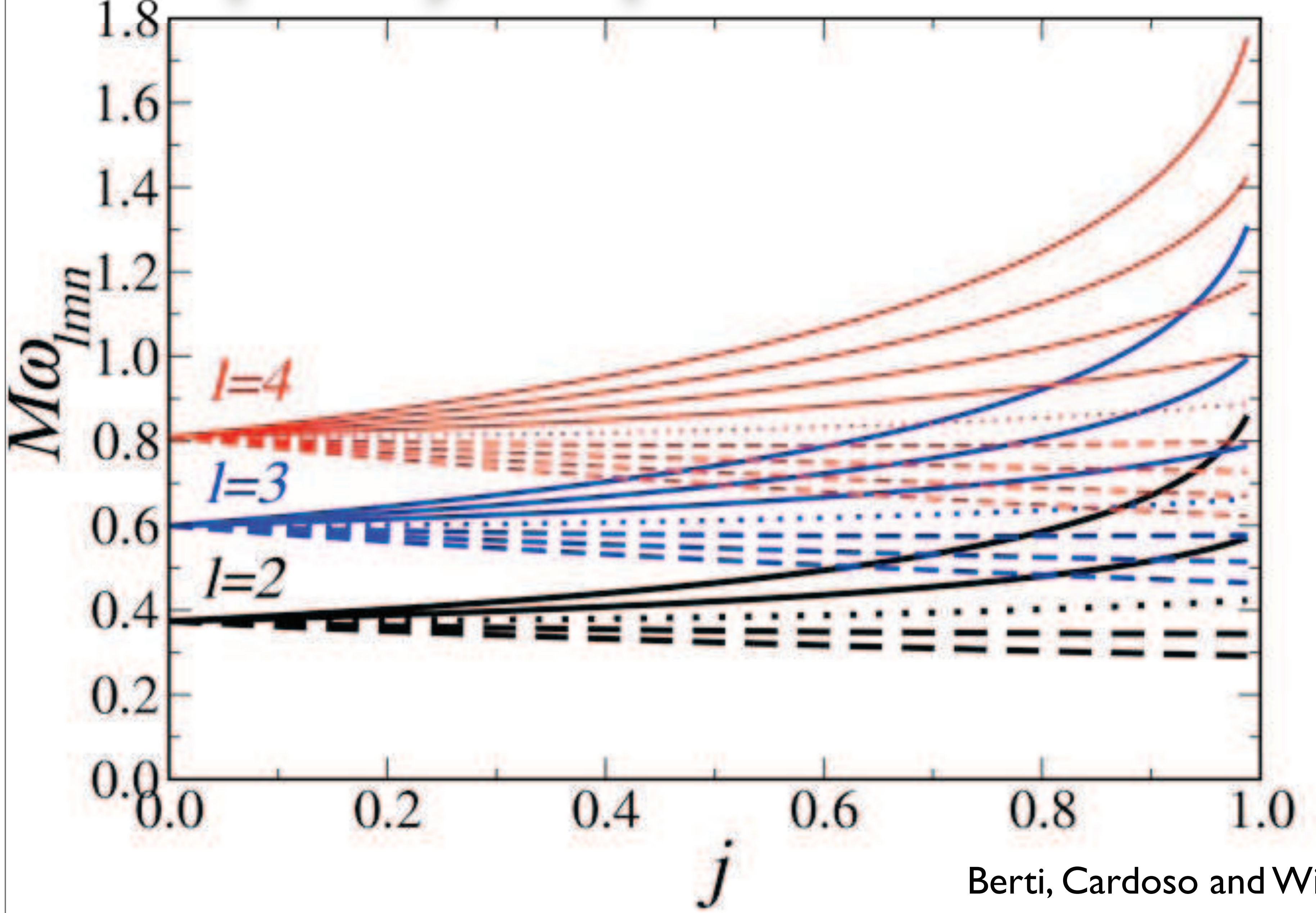
Black hole quasi-normal modes

- Damped sinusoids with characteristic frequencies and decay times
  - In general relativity frequencies f_{lmn} and decay times t_{lmn} all depend only on the mass M and spin q of the black hole
- Measuring two or modes unambiguously, would severely constrain general relativity

Black hole quasi-normal modes

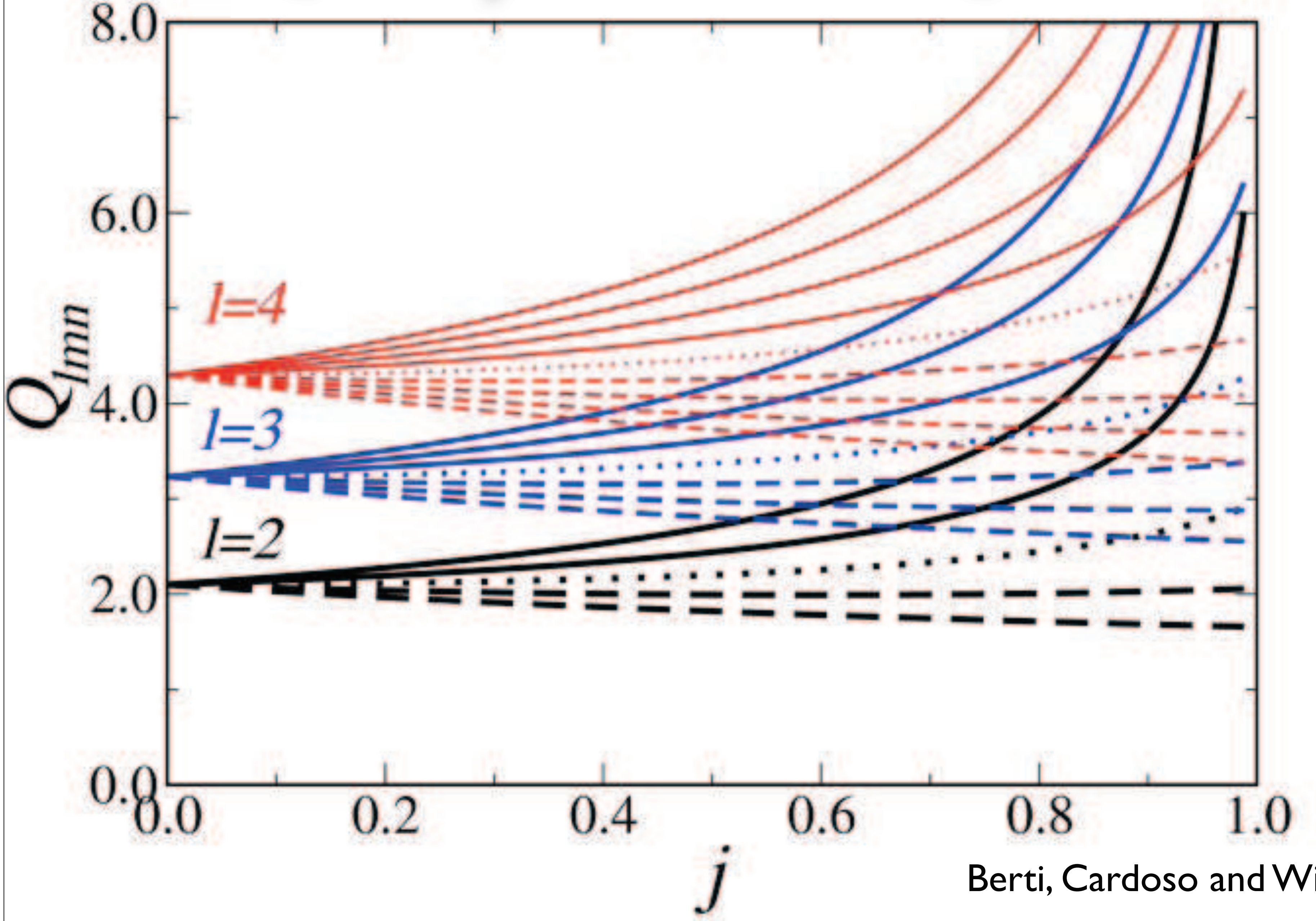
- Damped sinusoids with characteristic frequencies and decay times
  - In general relativity frequencies f_{lmn} and decay times t_{lmn} all depend only on the mass M and spin q of the black hole
- Measuring two or modes unambiguously, would severely constrain general relativity
  - If modes depend on other parameters (e.g., the structure of the central object), then test of the consistency between different mode frequencies and damping times would fail

Frequency of quasi normal modes



Berti, Cardoso and Will

Quality Factor of QNMs



Berti, Cardoso and Will

Tests with QNM

Kamaretsos, Hannam, Husa, Sathyaprakash, 2010

Tests with QNM

Kamaretsos, Hannam, Husa, Sathyaprakash, 2010

- Studying QNM from NR simulations at various mass ratios: 1:1, 1:2, 1:4, 1:8, final spins from -0.8 to +0.8

Tests with QNM

Kamaretsos, Hannam, Husa, Sathyaprakash, 2010

- Studying QNM from NR simulations at various mass ratios: 1:1, 1:2, 1:4, 1:8, final spins from -0.8 to +0.8
  - It is not too difficult to generate the QNM only part of the merger signal

Tests with QNM

Kamaretsos, Hannam, Husa, Sathyaprakash, 2010

- Studying QNM from NR simulations at various mass ratios: 1:1, 1:2, 1:4, 1:8, final spins from -0.8 to +0.8
  - It is not too difficult to generate the QNM only part of the merger signal
  - Can carry out a wide exploration of the parameter space

Tests with QNM

Kamaretsos, Hannam, Husa, Sathyaprakash, 2010

- Studying QNM from NR simulations at various mass ratios: 1:1, 1:2, 1:4, 1:8, final spins from -0.8 to +0.8
  - It is not too difficult to generate the QNM only part of the merger signal
  - Can carry out a wide exploration of the parameter space
- What is the relative energy in the various ringdown modes?

Tests with QNM

Kamaretsos, Hannam, Husa, Sathyaprakash, 2010

- Studying QNM from NR simulations at various mass ratios: 1:1, 1:2, 1:4, 1:8, final spins from -0.8 to +0.8
  - It is not too difficult to generate the QNM only part of the merger signal
  - Can carry out a wide exploration of the parameter space
- What is the relative energy in the various ringdown modes?
  - Are there at least two modes containing enough energy so that their damping times and frequencies can be measured with good (i.e. at least 10% accuracy)?

Tests with QNM

Kamaretsos, Hannam, Husa, Sathyaprakash, 2010

- Studying QNM from NR simulations at various mass ratios: 1:1, 1:2, 1:4, 1:8, final spins from -0.8 to +0.8
  - It is not too difficult to generate the QNM only part of the merger signal
  - Can carry out a wide exploration of the parameter space
- What is the relative energy in the various ringdown modes?
  - Are there at least two modes containing enough energy so that their damping times and frequencies can be measured with good (i.e. at least 10% accuracy)?
  - 33 seems to contain contain enough energy compared to 22 modes; should be possible to extract the total mass and spin magnitude

Tests with QNM

Kamaretsos, Hannam, Husa, Sathyaprakash, 2010

- Studying QNM from NR simulations at various mass ratios: 1:1, 1:2, 1:4, 1:8, final spins from -0.8 to +0.8
  - It is not too difficult to generate the QNM only part of the merger signal
  - Can carry out a wide exploration of the parameter space
- What is the relative energy in the various ringdown modes?
  - Are there at least two modes containing enough energy so that their damping times and frequencies can be measured with good (i.e. at least 10% accuracy)?
  - 33 seems to contain contain enough energy compared to 22 modes; should be possible to extract the total mass and spin magnitude
  - Measuring the relative amplitudes of the different modes can shed light on the binary progenitor, namely the total mass and its mass ratio

Tests with QNM

Kamaretsos, Hannam, Husa, Sathyaprakash, 2010

- Studying QNM from NR simulations at various mass ratios: 1:1, 1:2, 1:4, 1:8, final spins from -0.8 to +0.8
  - It is not too difficult to generate the QNM only part of the merger signal
  - Can carry out a wide exploration of the parameter space
- What is the relative energy in the various ringdown modes?
  - Are there at least two modes containing enough energy so that their damping times and frequencies can be measured with good (i.e. at least 10% accuracy)?
  - 33 seems to contain contain enough energy compared to 22 modes; should be possible to extract the total mass and spin magnitude
  - Measuring the relative amplitudes of the different modes can shed light on the binary progenitor, namely the total mass and its mass ratio
  - Polarization of ringdown modes can measure the spin axis of merged BH

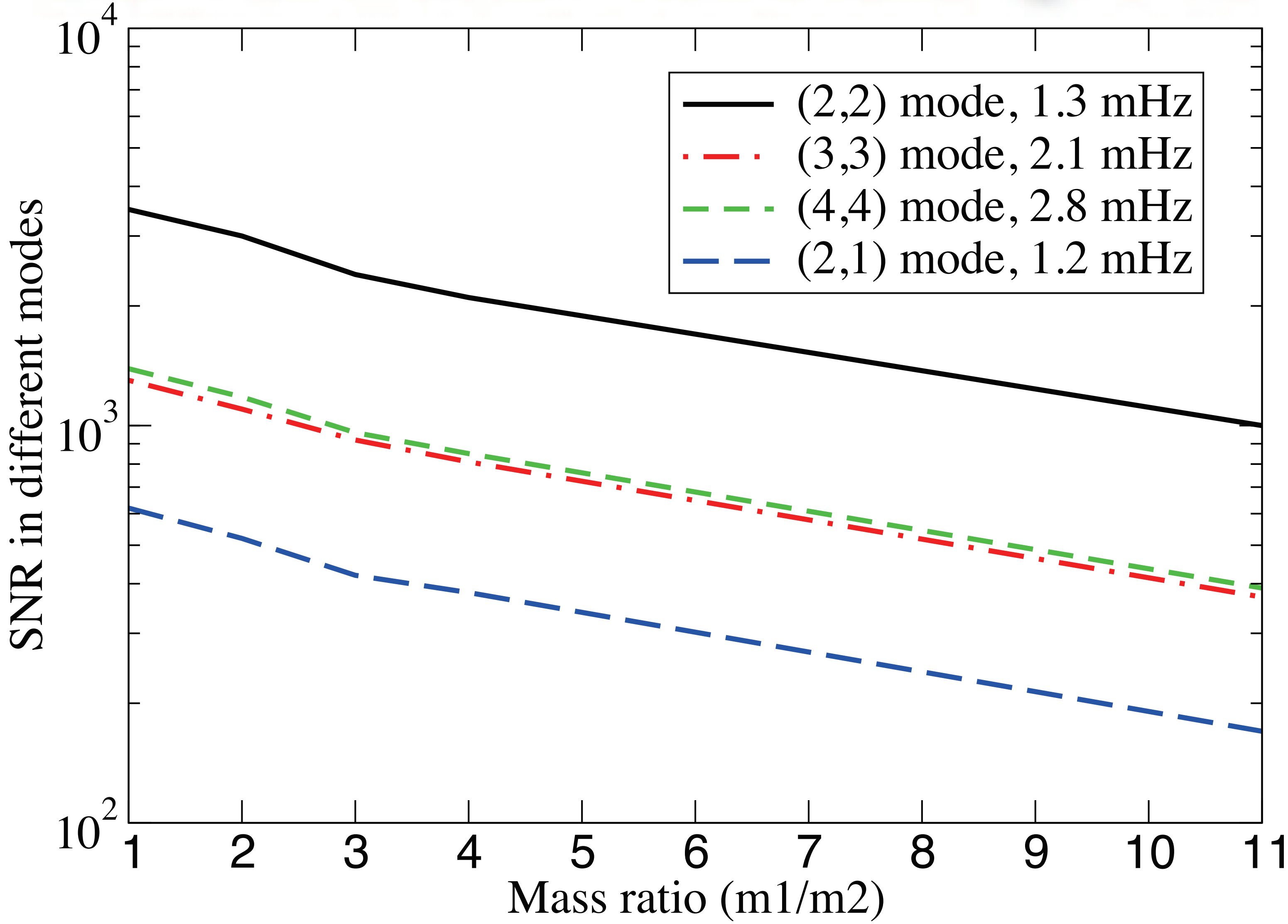
Emitted energy and relative amplitudes of different quasi-normal modes

Kamaretsos, Hannam, Husa, Sathyaprakash, 2010

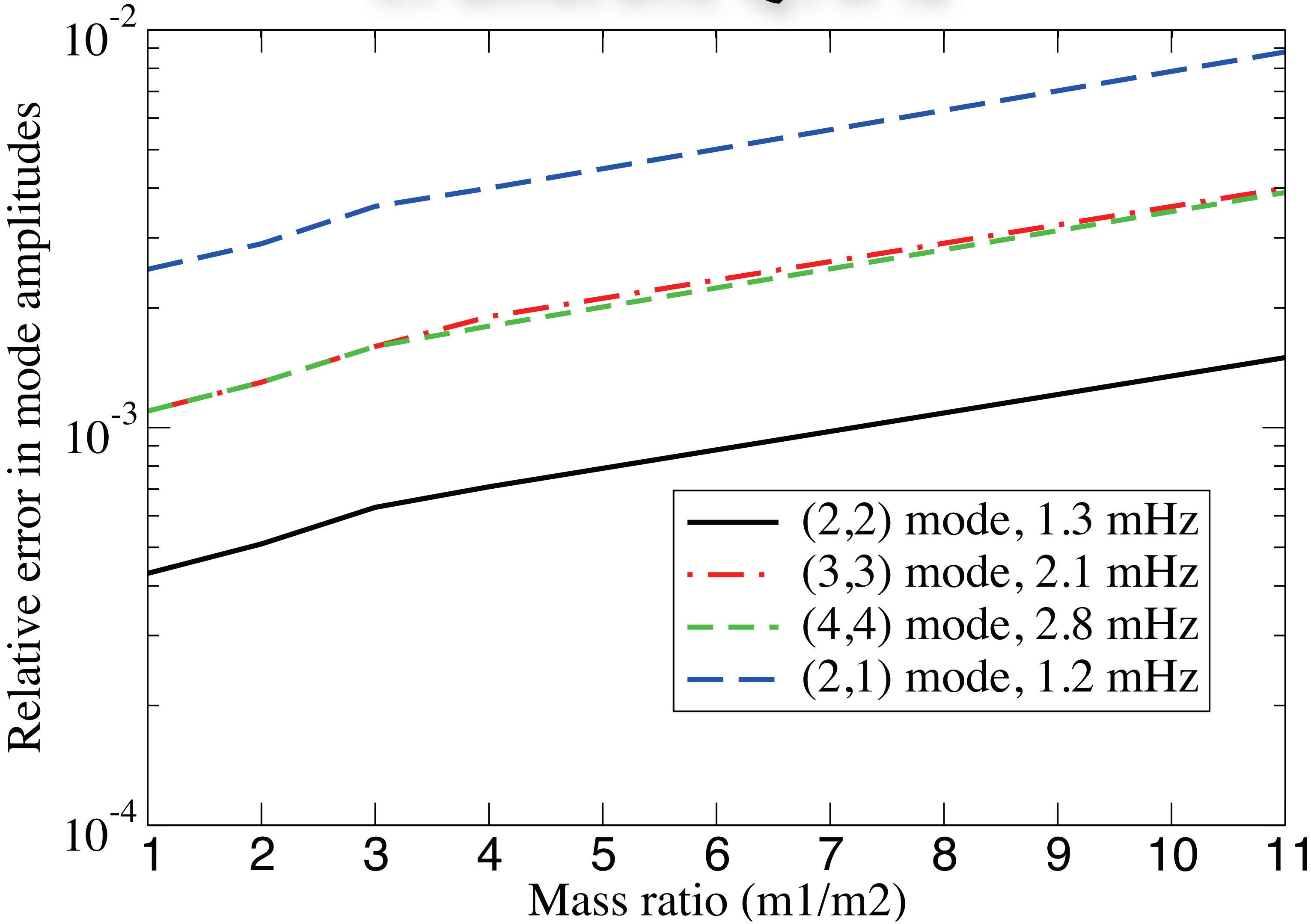
Table 1: For different mass ratios (q=1, 2, 3, 4, 11), we show the final spin of the black hole, percent of energy in the radiation, amplitude of (2,1), (3,3), (4,4) modes relative to (2,2) mode.

q	j	% total energy	A_{21}/A_{22}	A_{33}/A_{22}	A_{44}/A_{22}
1	0.69	4.9	0.04	0.00	0.05
2	0.62	3.8	0.05	0.13	0.06
3	0.54	2.8	0.07	0.21	0.08
4	0.47	2.2	0.08	0.25	0.09
11	0.25	0.7	0.14	0.31	0.14

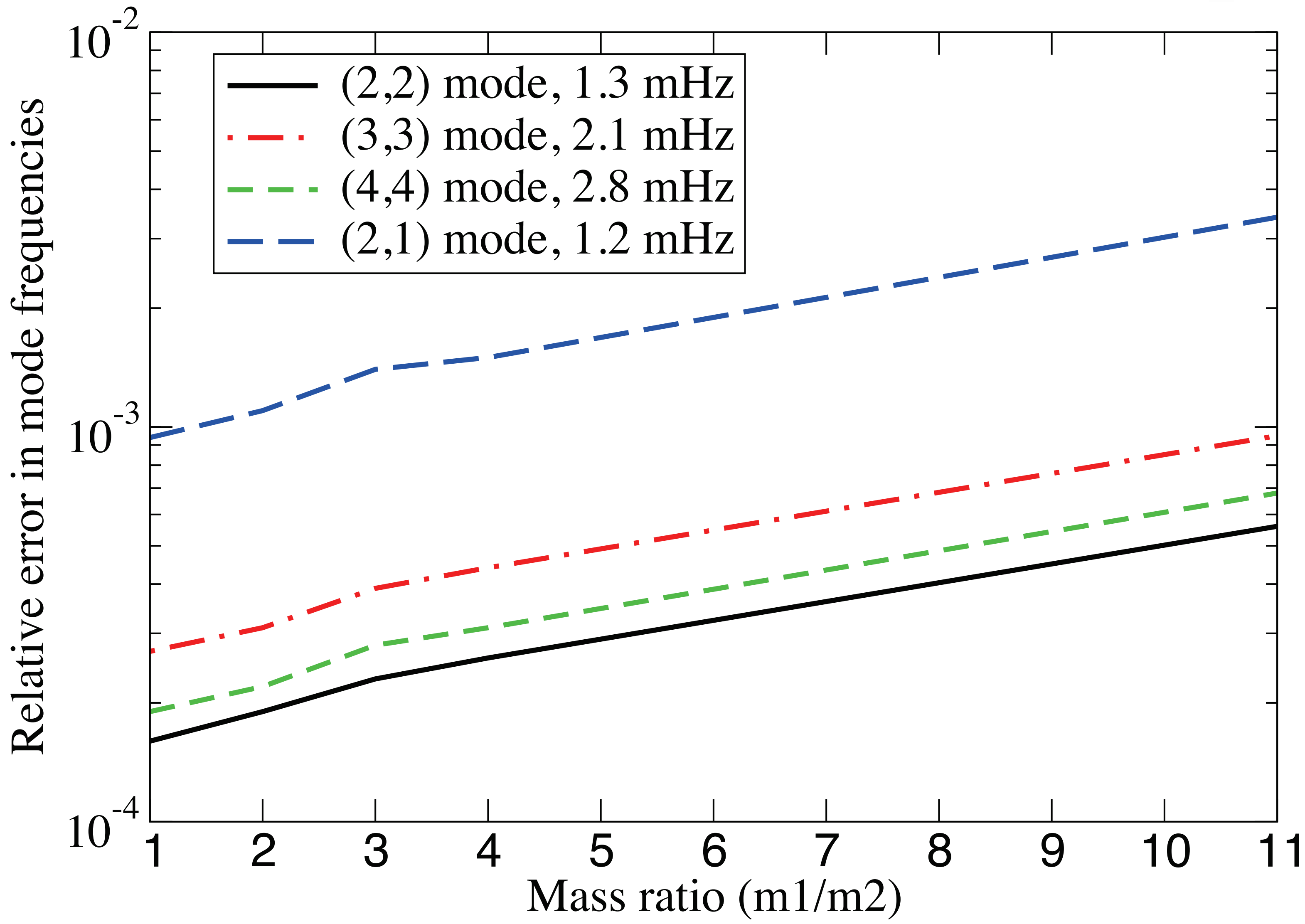
LISA SNRs for different QNMs



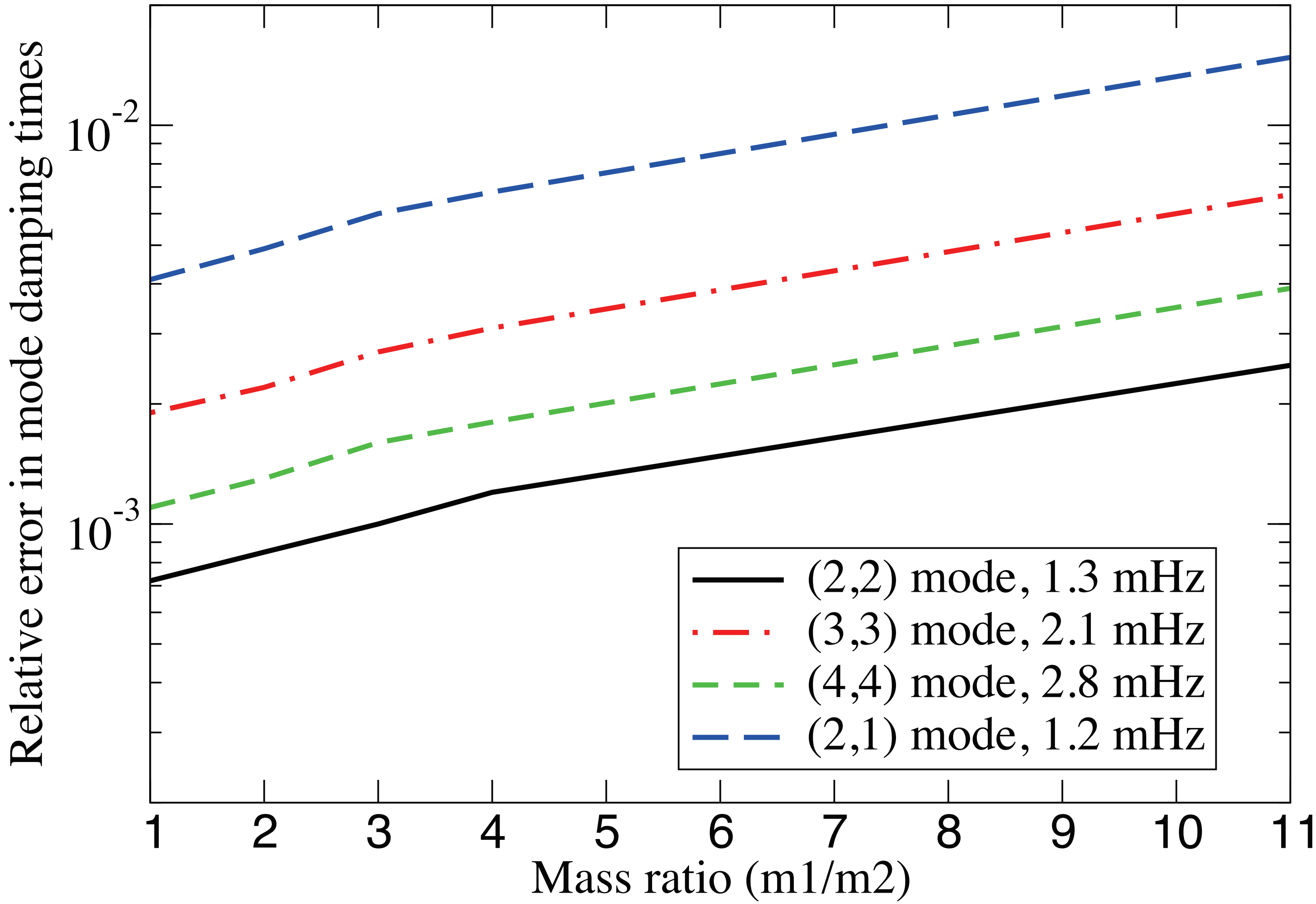
LISA measurement accuracies of amplitudes in different QNMs



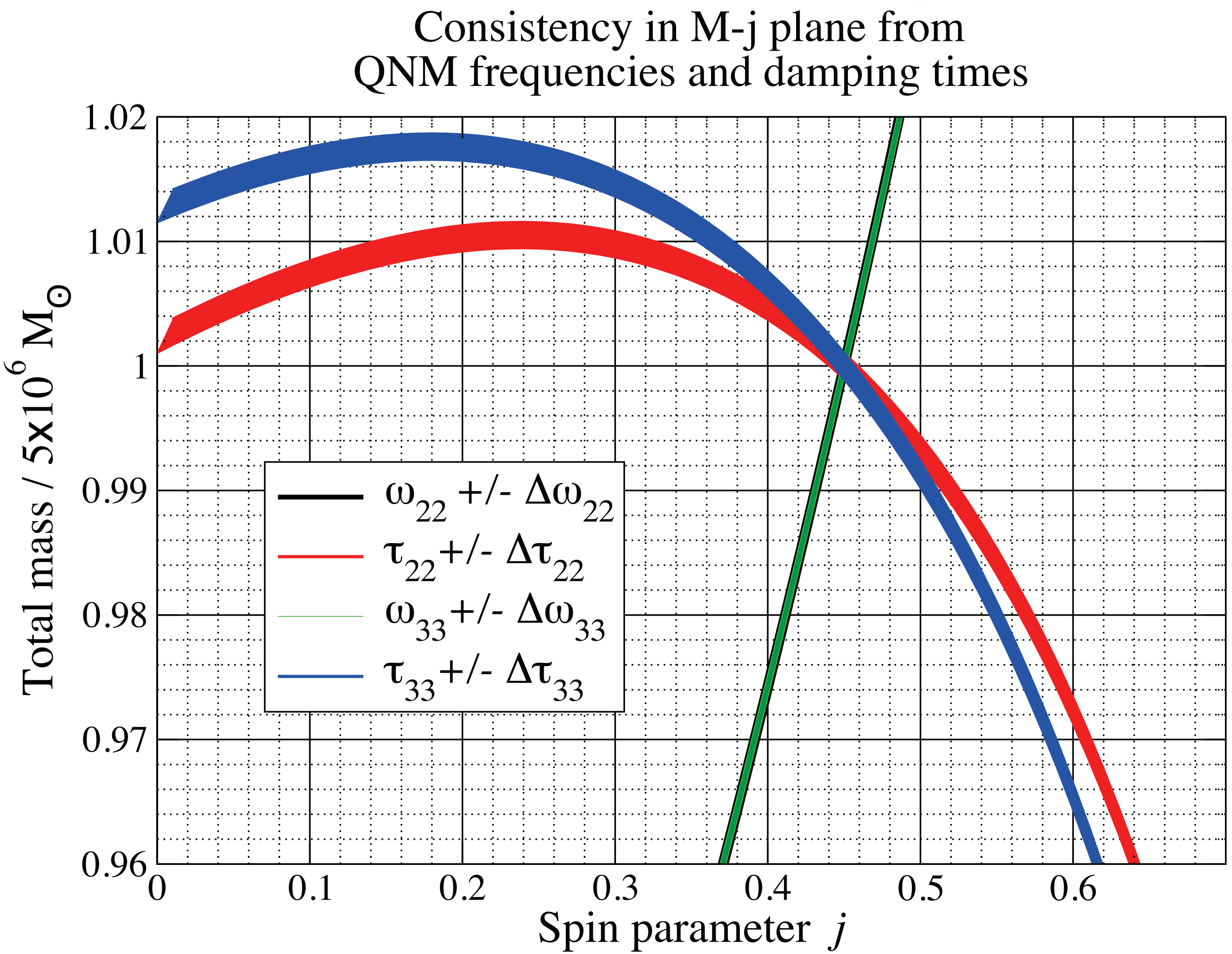
LISA measurement accuracies of mode frequencies



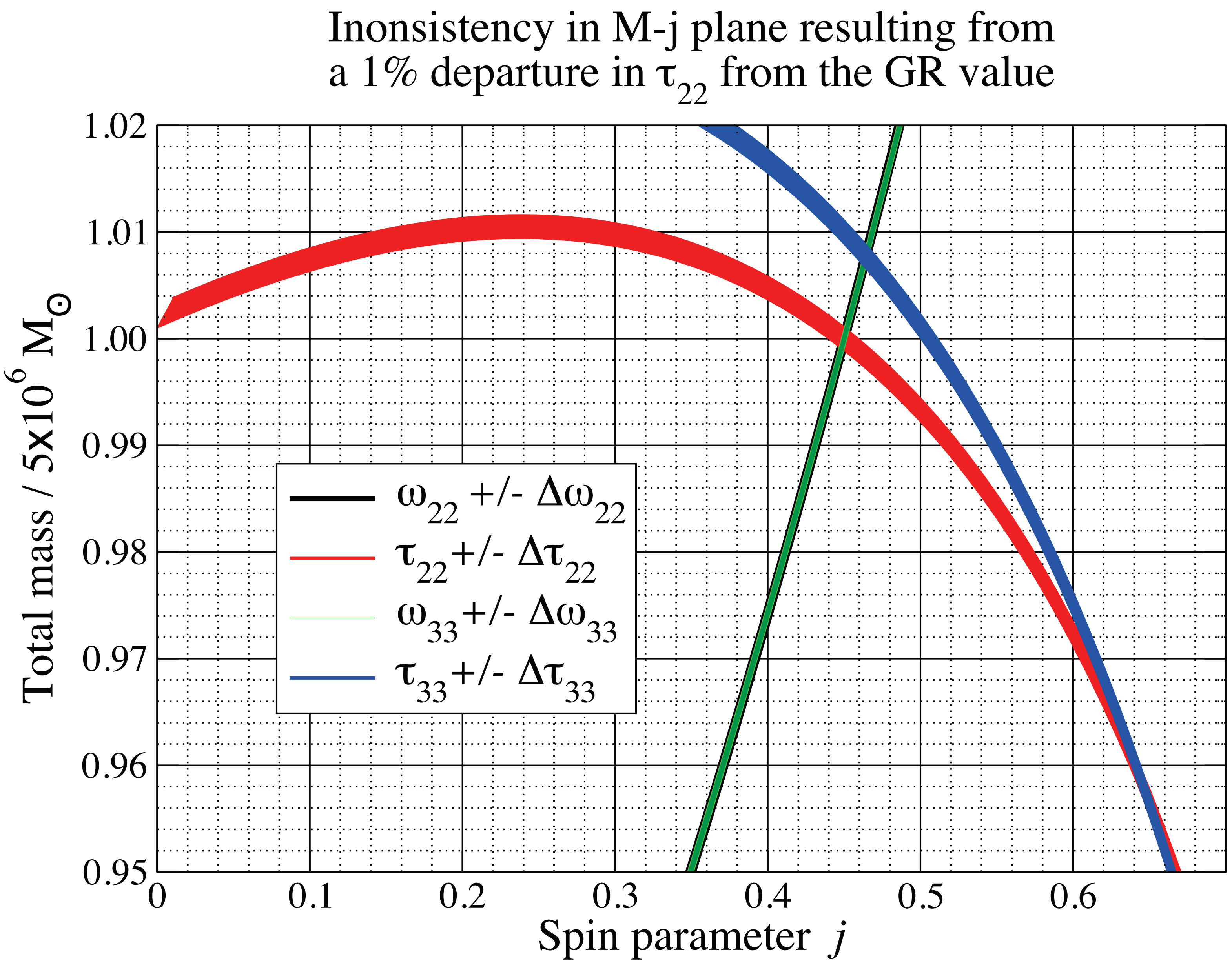
LISA measurement accuracies damping times



How can QNMs help test GR



How can QNMs help test GR



Black Holes Ain’t Got No Hair
But They Do *Grin*

Black Holes Ain't Got No Hair But They Do *Grin*

- Black hole no hair theorems don't apply to deformed black holes

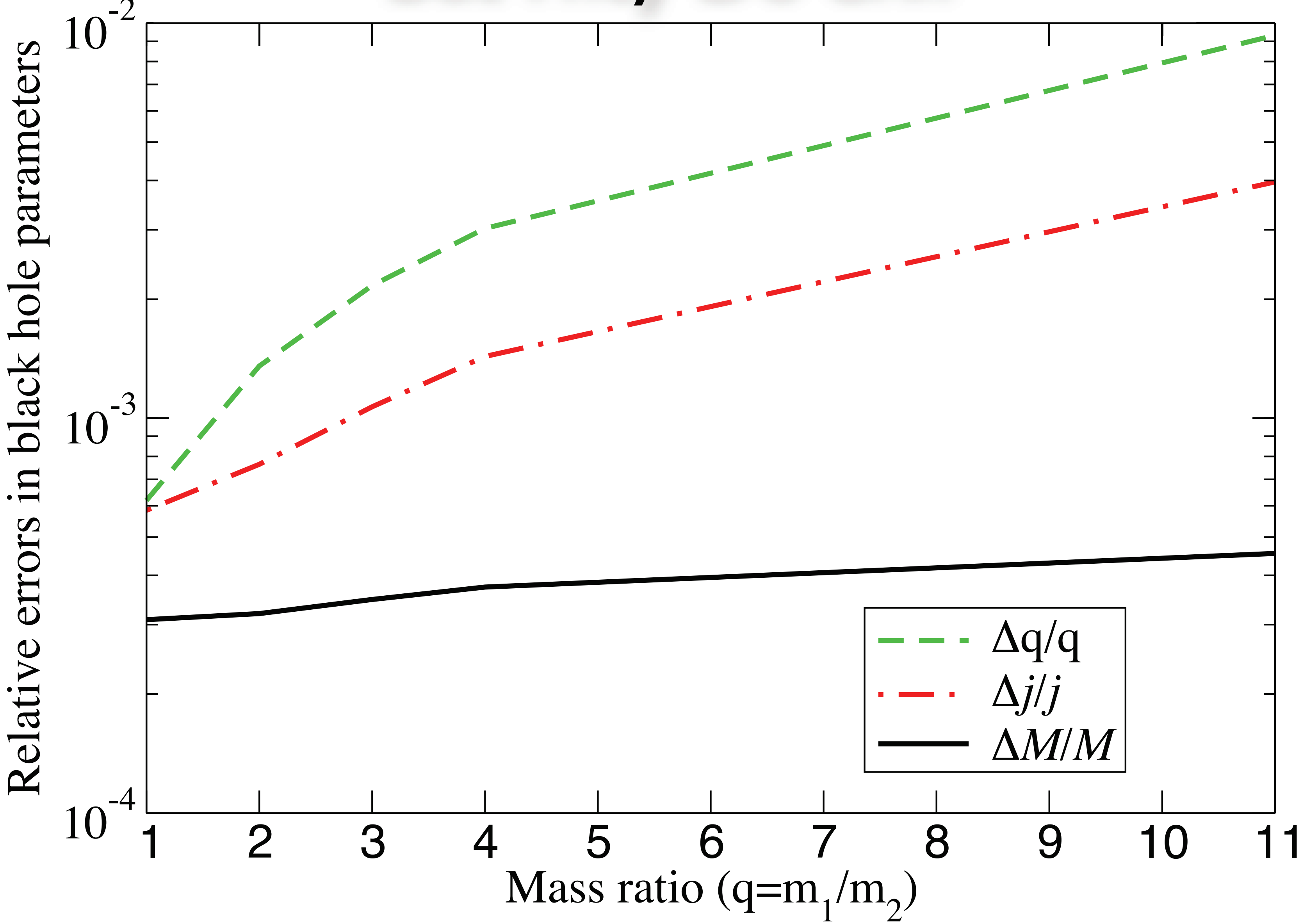
Black Holes Ain't Got No Hair But They Do *Grin*

- Black hole no hair theorems don't apply to deformed black holes
- From the ringdown signals it should in principle be possible to infer the nature of the perturber

Black Holes Ain't Got No Hair But They Do *Grin*

- Black hole no hair theorems don't apply to deformed black holes
- From the ringdown signals it should in principle be possible to infer the nature of the perturber
- In the case of binary mergers it should be possible to measure the masses and spins of the component stars that resulted in the final black hole

Black Holes Ain't Got No Hair But They Do *Grin*



Summary

Summary

- Was Einstein right?

Summary

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?

Summary

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes in nature black holes of GR?

Summary

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?

Summary

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?
- Unsolved problems in astrophysics

Summary

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?
- Unsolved problems in astrophysics
  - What is the origin of gamma ray bursts?

Summary

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?
- Unsolved problems in astrophysics
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?

Summary

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?
- Unsolved problems in astrophysics
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?
- Cosmology

Summary

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?
- Unsolved problems in astrophysics
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?
- Cosmology
  - Measurement of Hubble parameter, dark matter density, etc.

Summary

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?
- Unsolved problems in astrophysics
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?
- Cosmology
  - Measurement of Hubble parameter, dark matter density, etc.
  - Demography of massive black holes at galactic nuclei?

Summary

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?
- Unsolved problems in astrophysics
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?
- Cosmology
  - Measurement of Hubble parameter, dark matter density, etc.
  - Demography of massive black holes at galactic nuclei?
  - Phase transitions in the early Universe?

Summary

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?
- Unsolved problems in astrophysics
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?
- Cosmology
  - Measurement of Hubble parameter, dark matter density, etc.
  - Demography of massive black holes at galactic nuclei?
  - Phase transitions in the early Universe?
- Fundamental questions

Summary

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?
- Unsolved problems in astrophysics
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?
- Cosmology
  - Measurement of Hubble parameter, dark matter density, etc.
  - Demography of massive black holes at galactic nuclei?
  - Phase transitions in the early Universe?
- Fundamental questions
  - What were the physical conditions at the big bang?

Summary

- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?
- Unsolved problems in astrophysics
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?
- Cosmology
  - Measurement of Hubble parameter, dark matter density, etc.
  - Demography of massive black holes at galactic nuclei?
  - Phase transitions in the early Universe?
- Fundamental questions
  - What were the physical conditions at the big bang?
  - What is dark energy?