Gravitational Astronomy

ISGWA-University of Delhi, December 2010

B.S. Sathyaprakash
Cardiff University

Resources for the Lecture

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- B.S. Sathyaprakash and Bernard F. Schutz, "Physics, Astrophysics and Cosmology with Gravitational Waves", *Living Rev. Relativity* **12**, (2009), 2.

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- S1, S2, S3, ... stand for the first, second, third, ..., science runs of the LSC and Virgo

Standard Sirens

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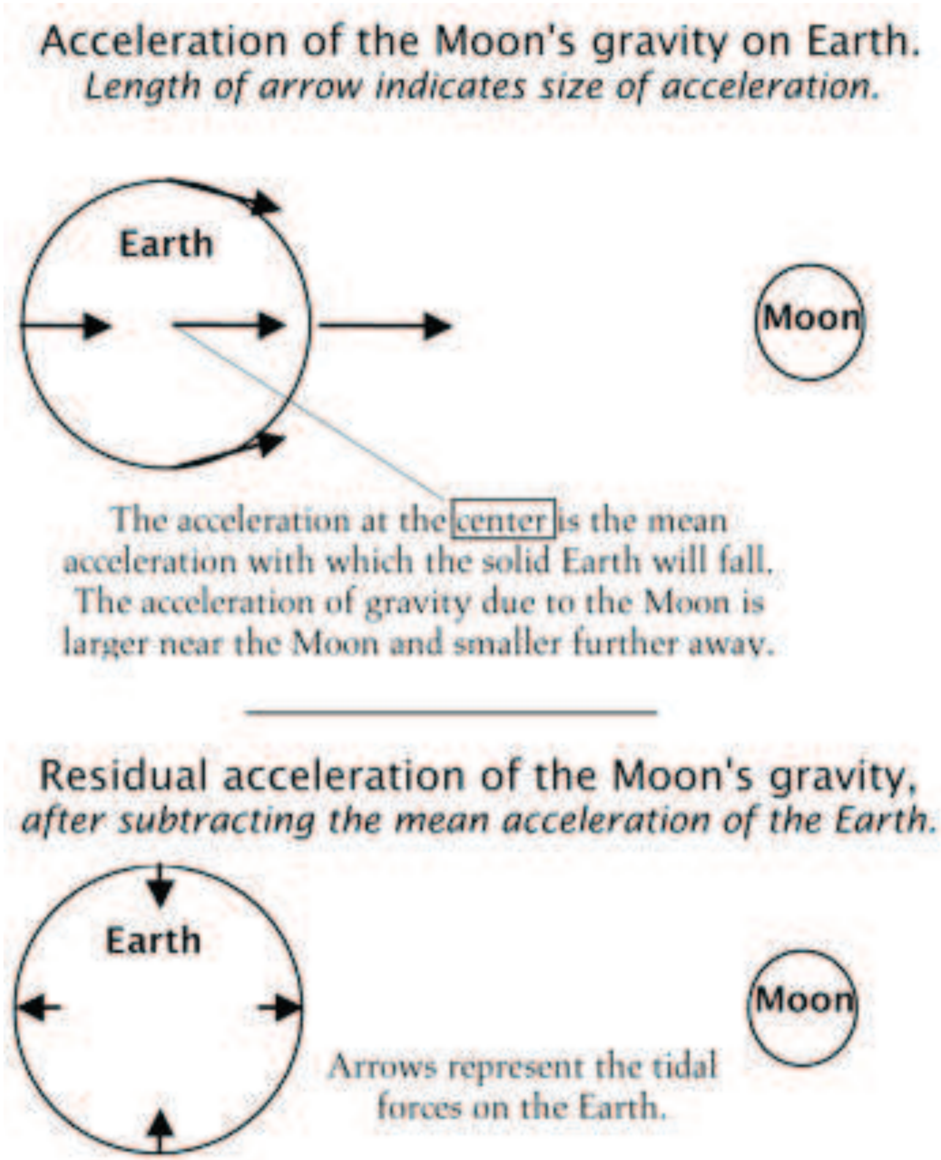
- Here $\bar{h}_{\alpha\beta} = h_{\alpha\beta} - \frac{1}{2}\eta_{\alpha\beta}\eta^{\mu\nu}h_{\mu\nu}$ is the trace-reverse tensor.

Tidal Gravitational Forces of GW



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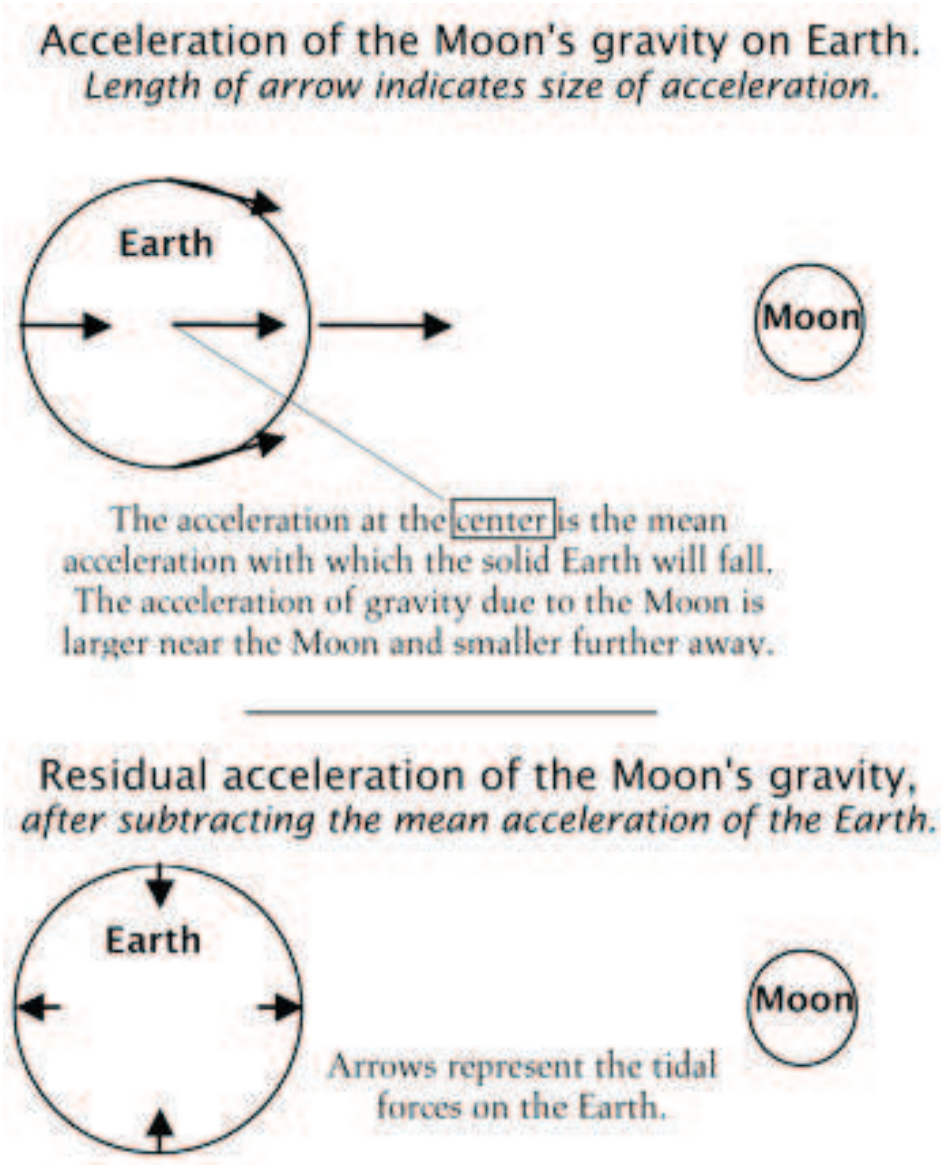

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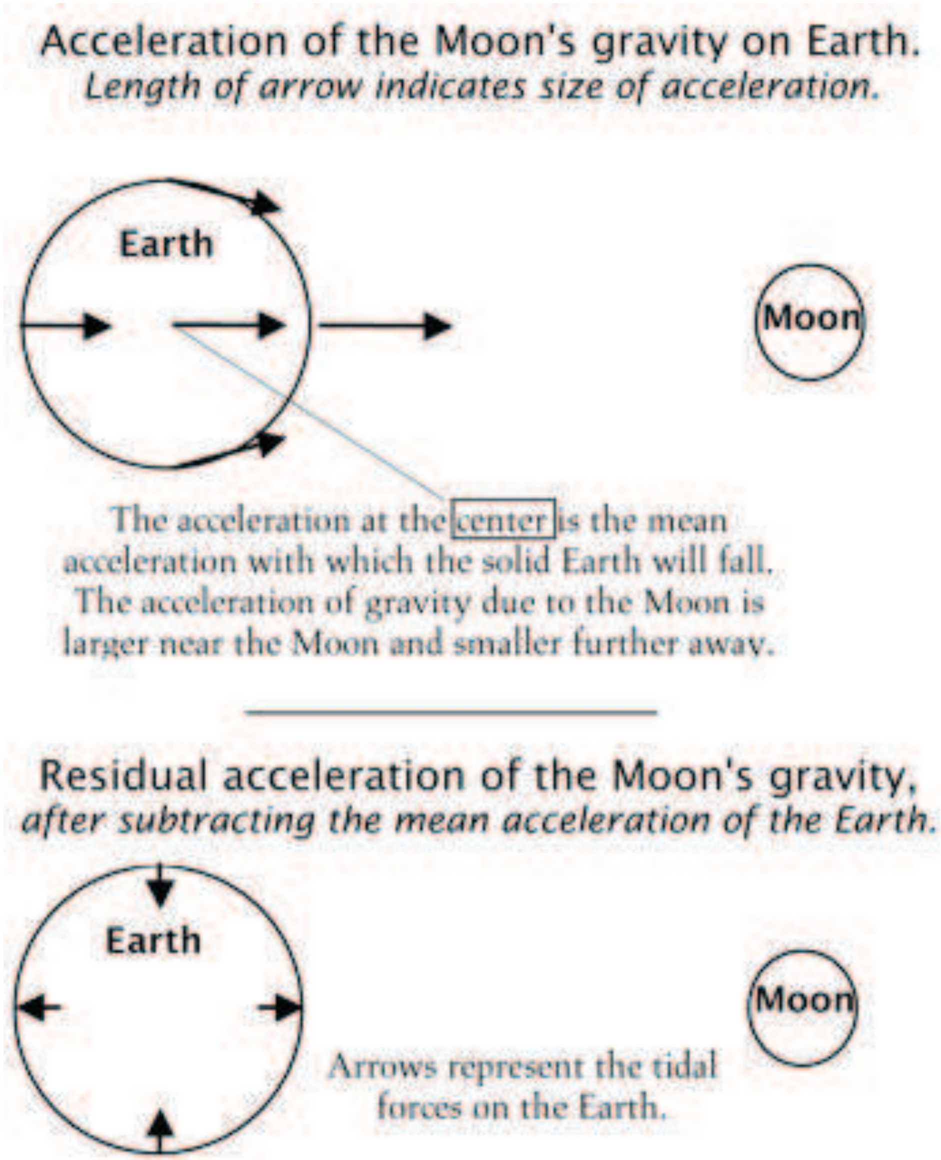

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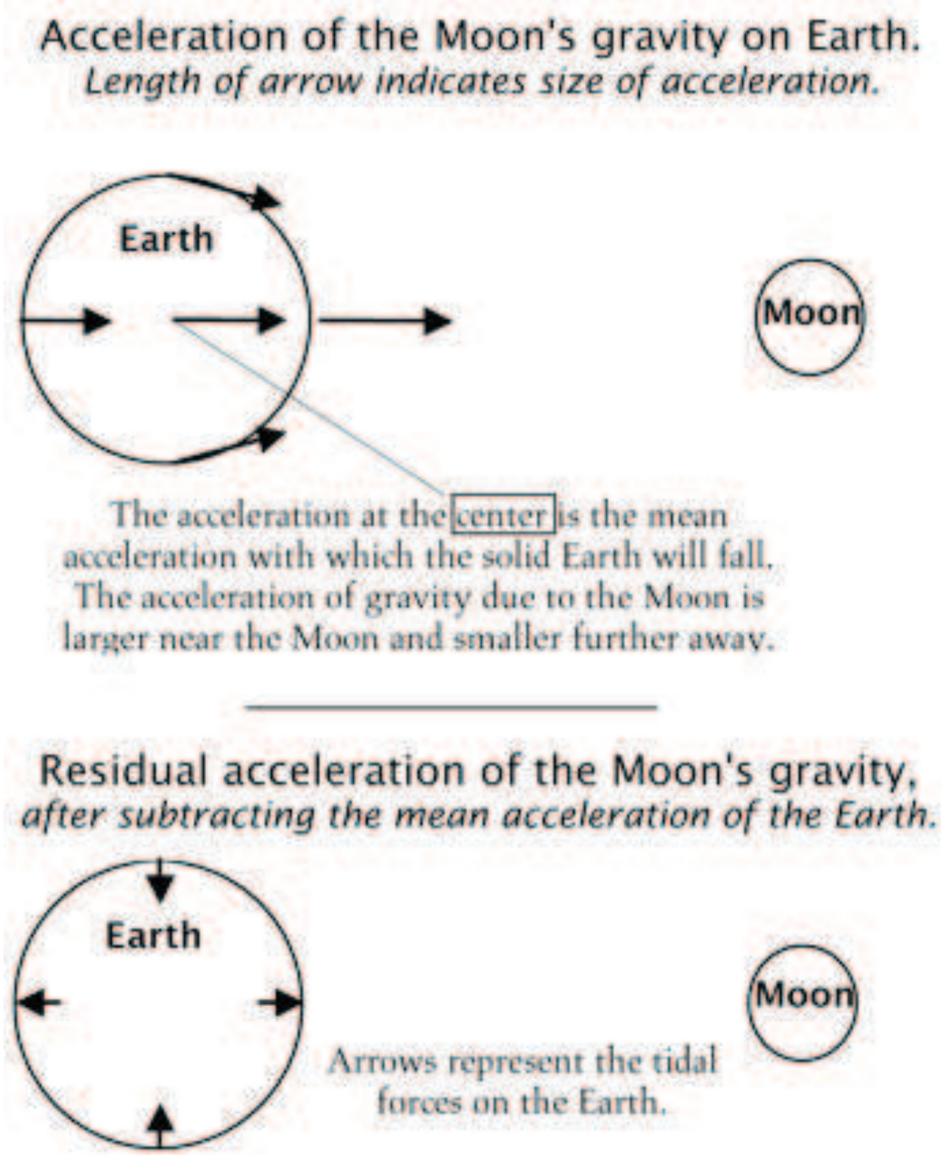

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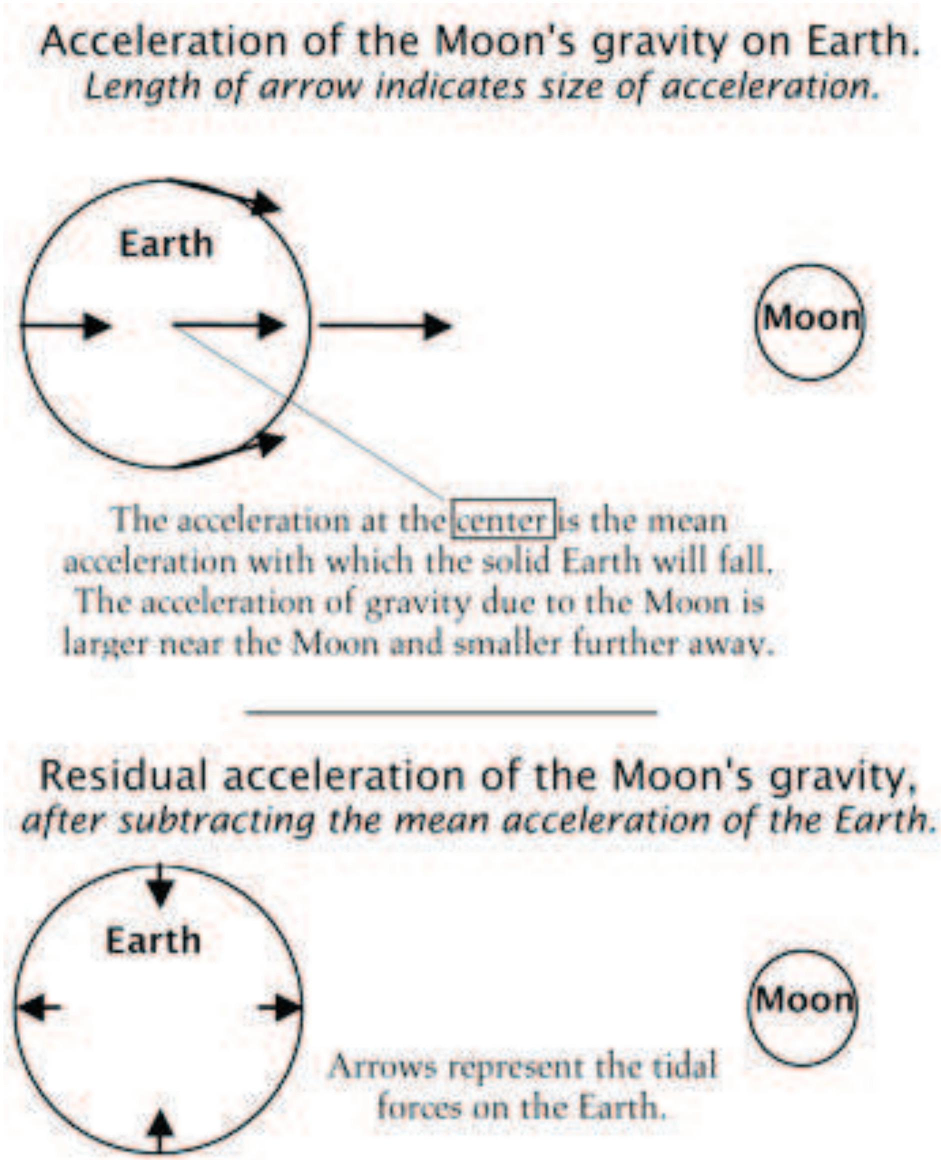

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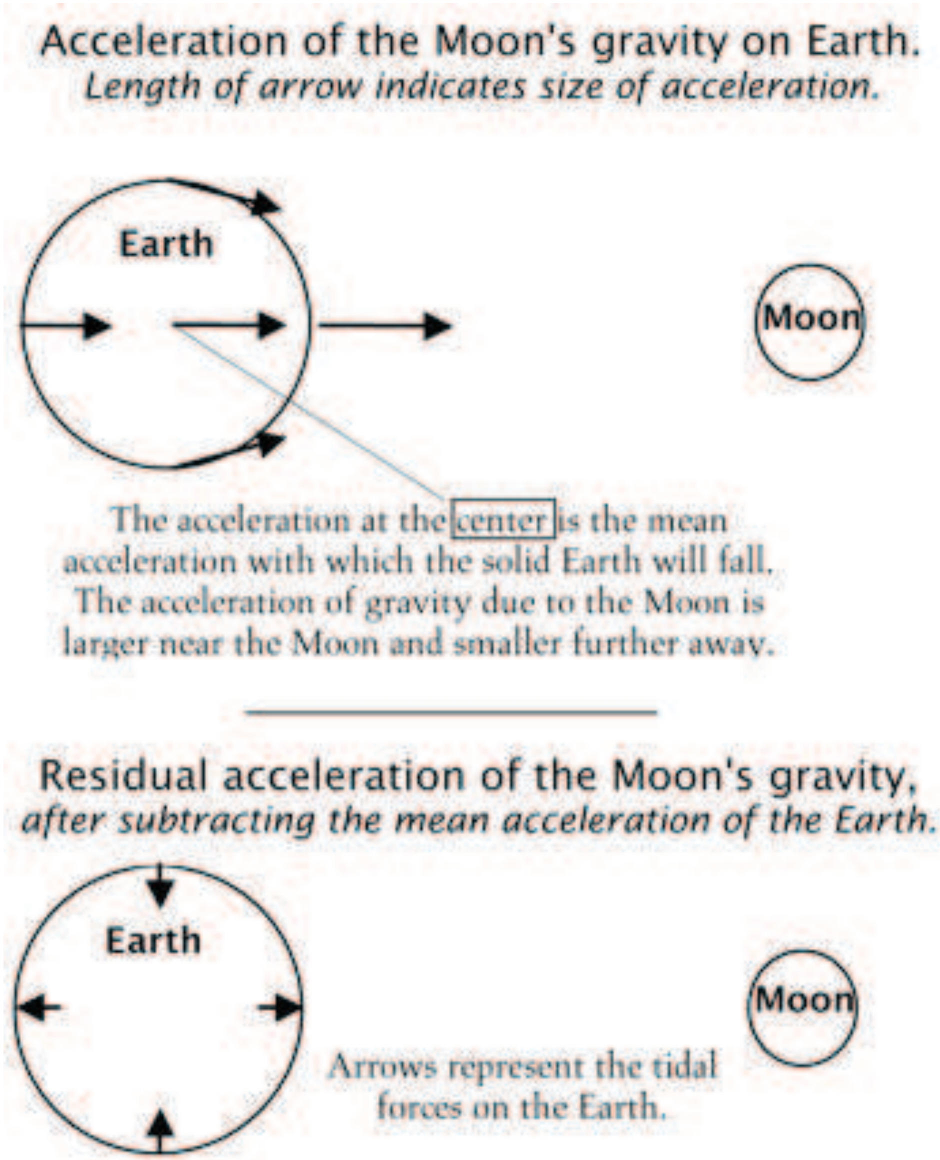
- Gravitational waves also cause a tidal effect the only difference is that the effect falls off as $1/r$



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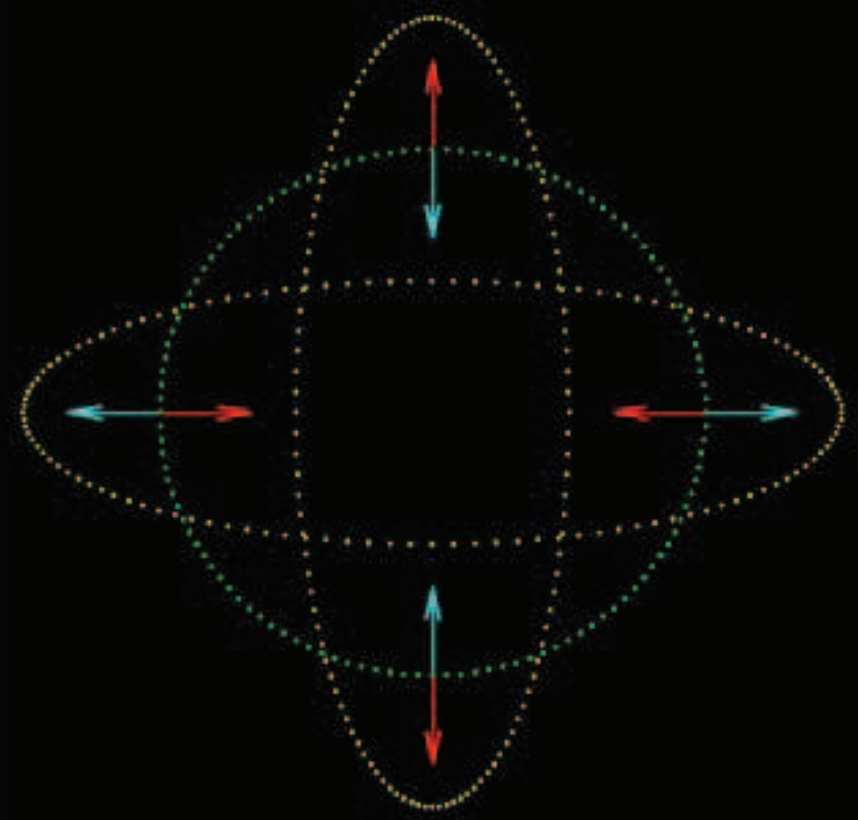
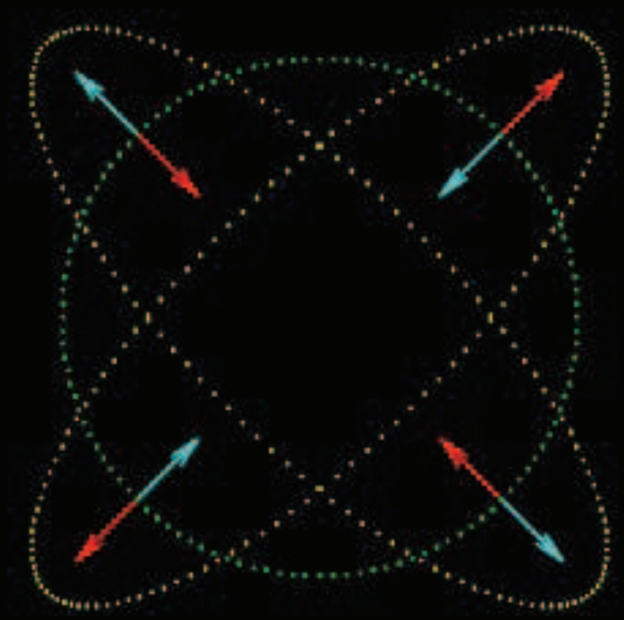


Plus polarization



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  - In Einstein's theory two polarizations - plus and cross

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- Sensitive to wide areas over the sky

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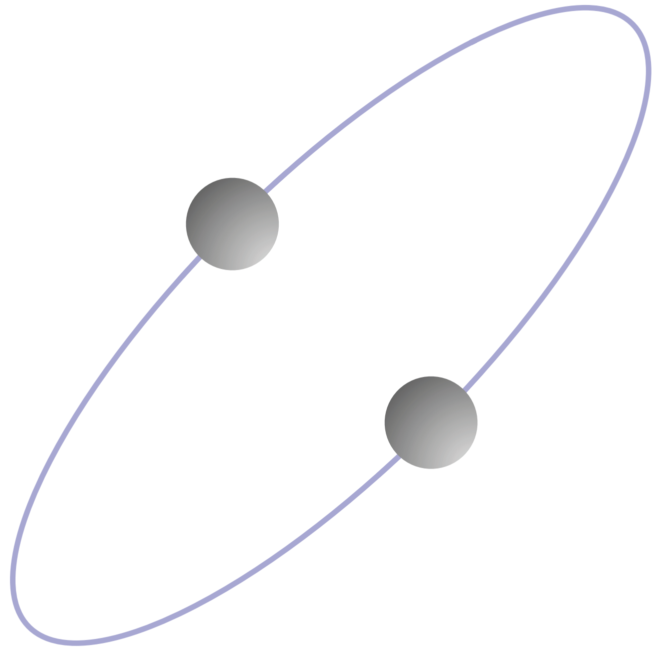
PSR 1913+16



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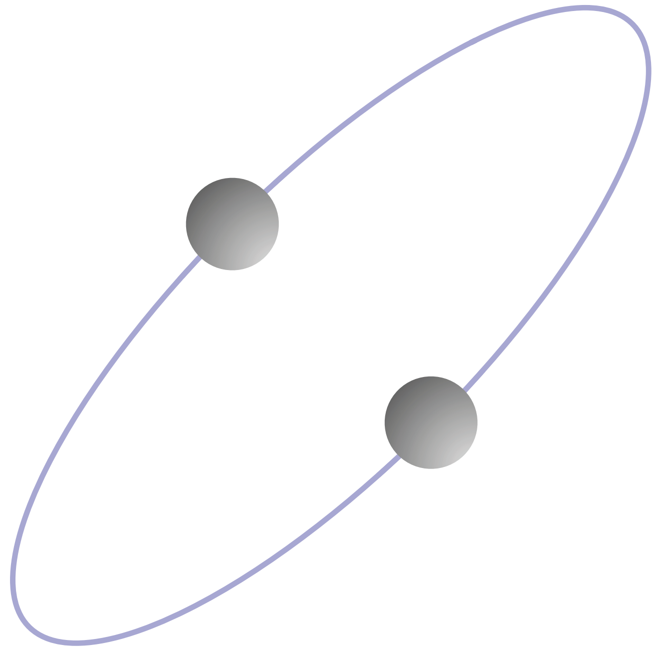

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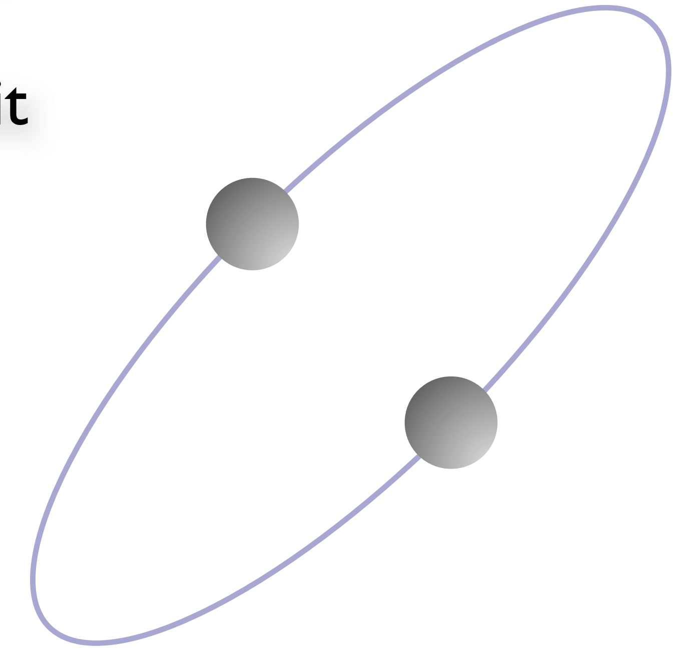

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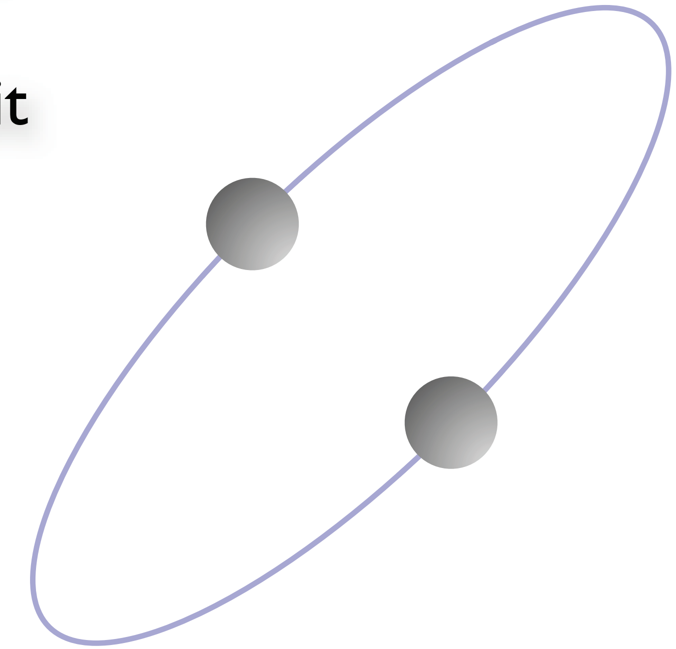

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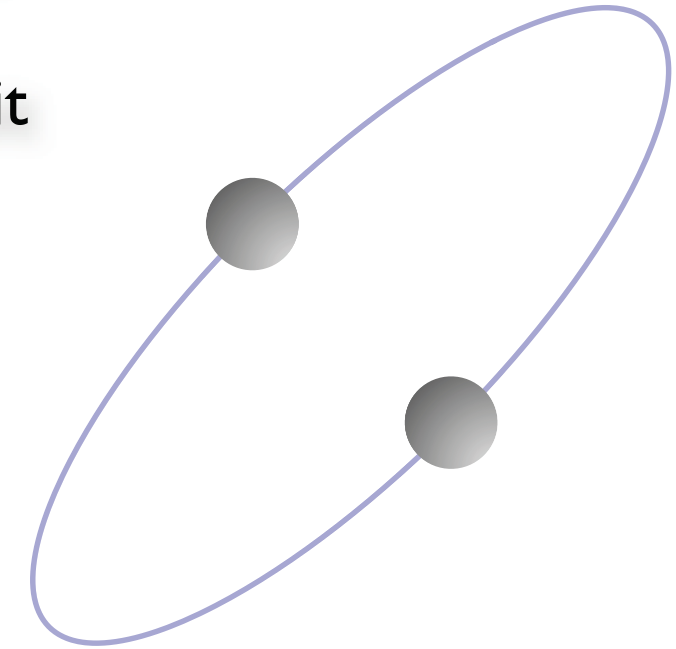

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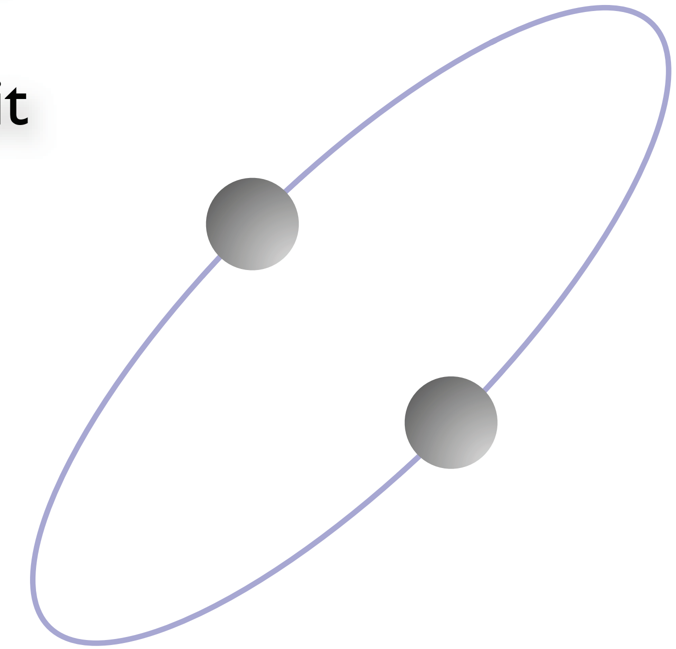

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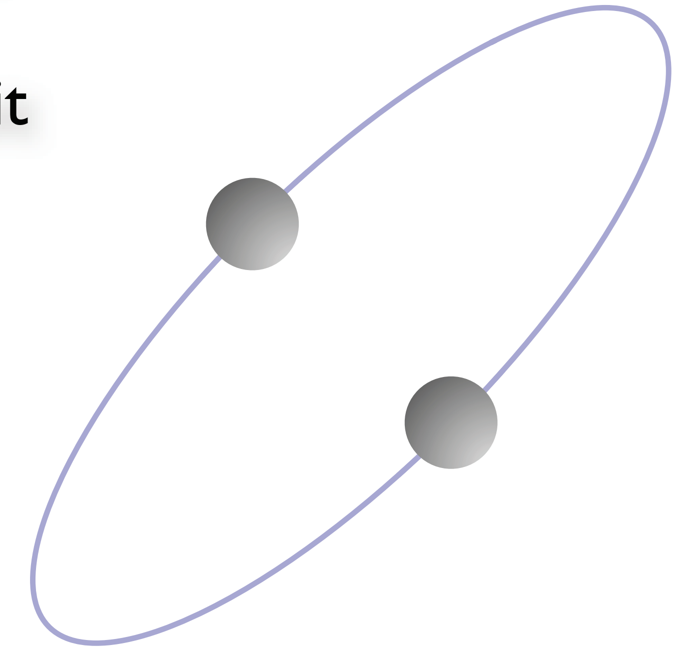

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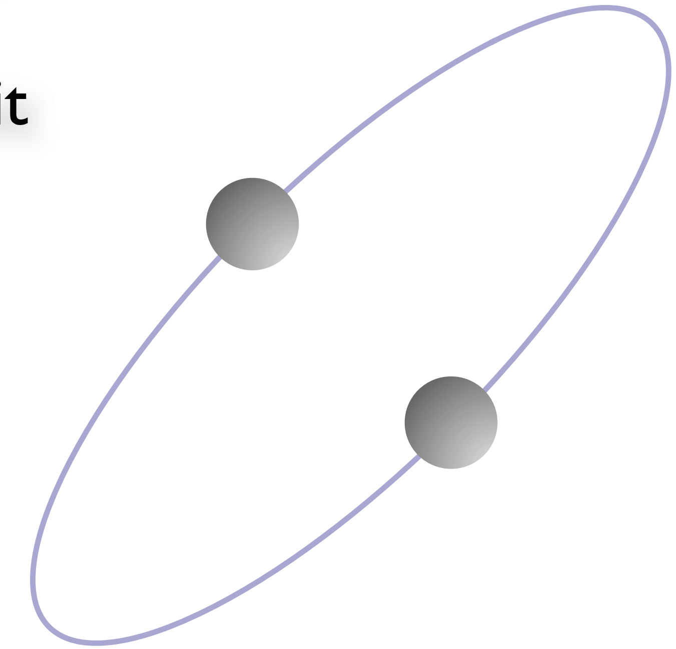

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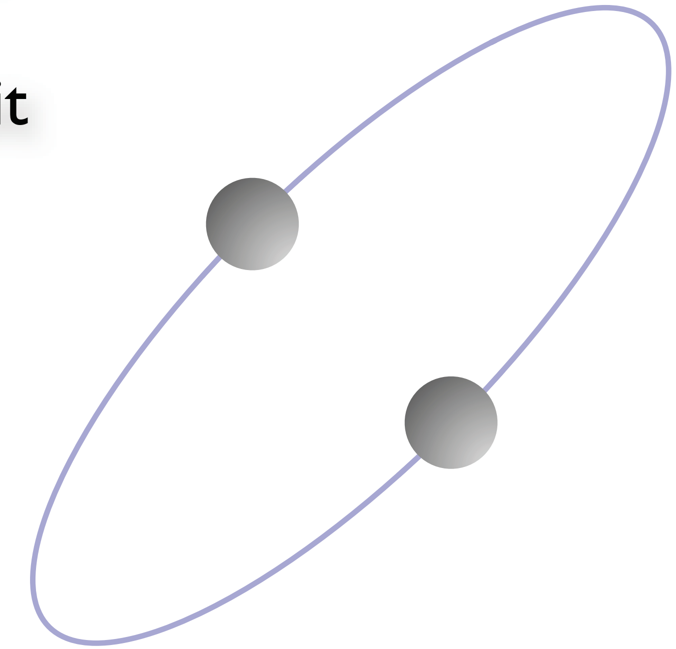
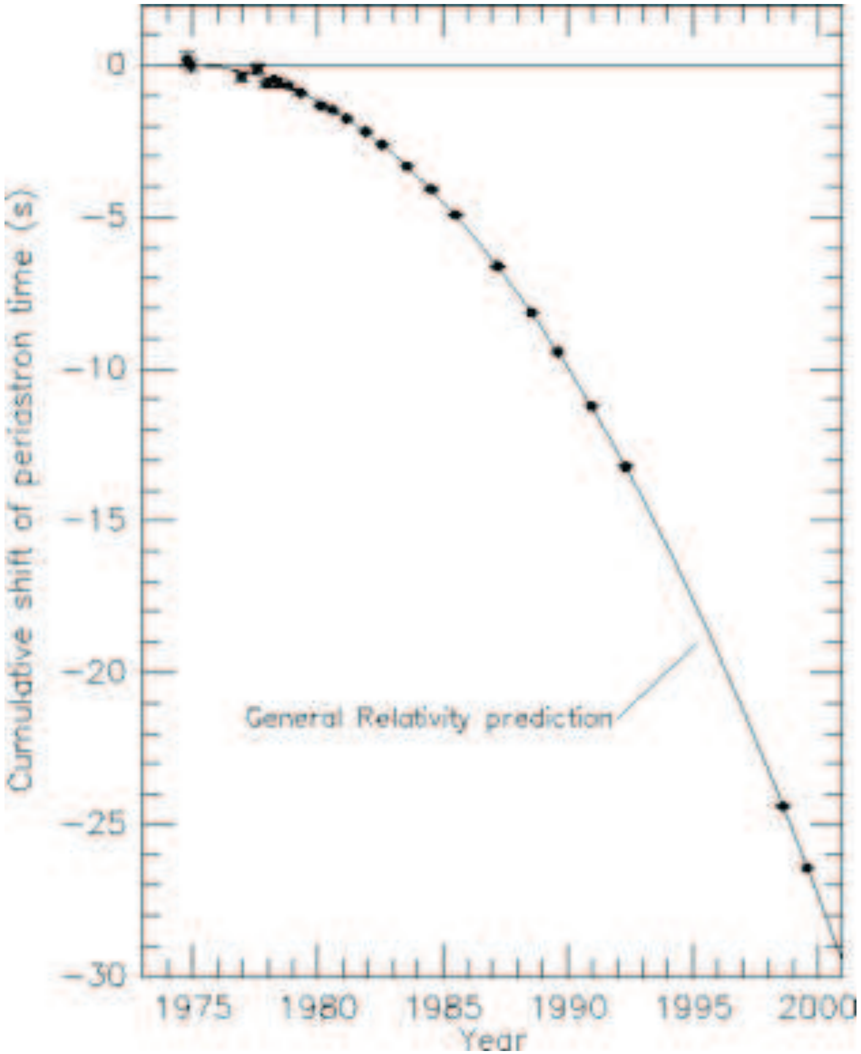
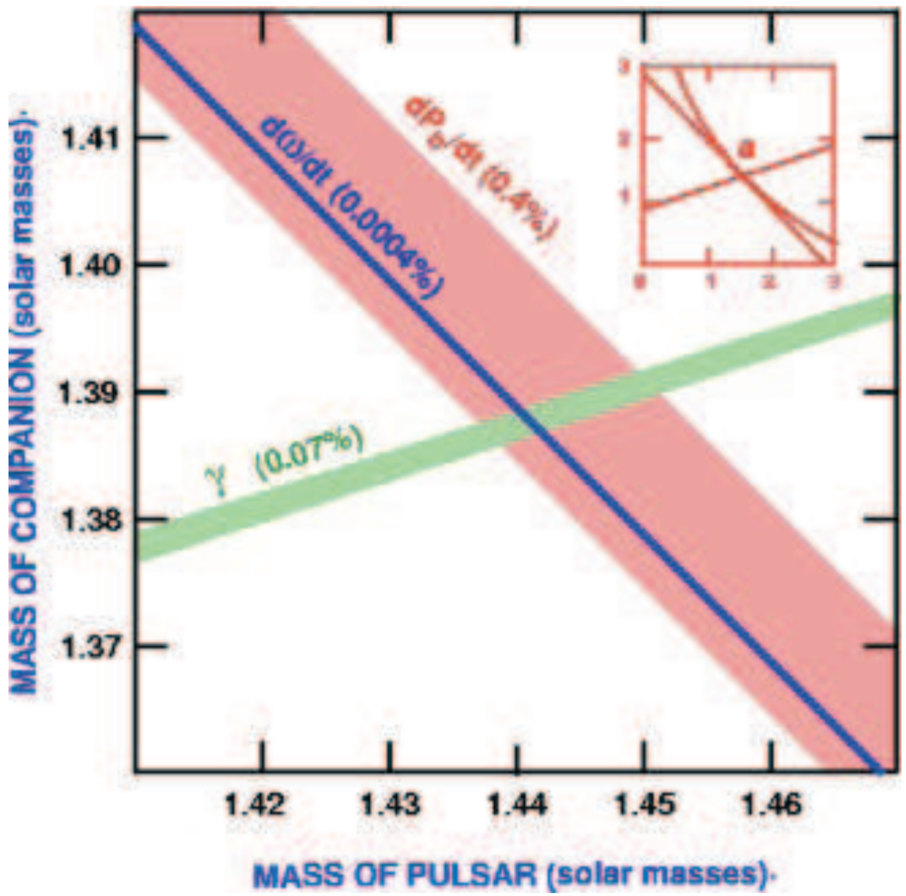
  - Observed decrease in period - about 10 micro seconds per year - is in agreement with Einstein's theory to fraction of a percent



Accumulated orbital phase shift in PSR 1913+16

Taylor and Weisberg, 2000, Will Living Review





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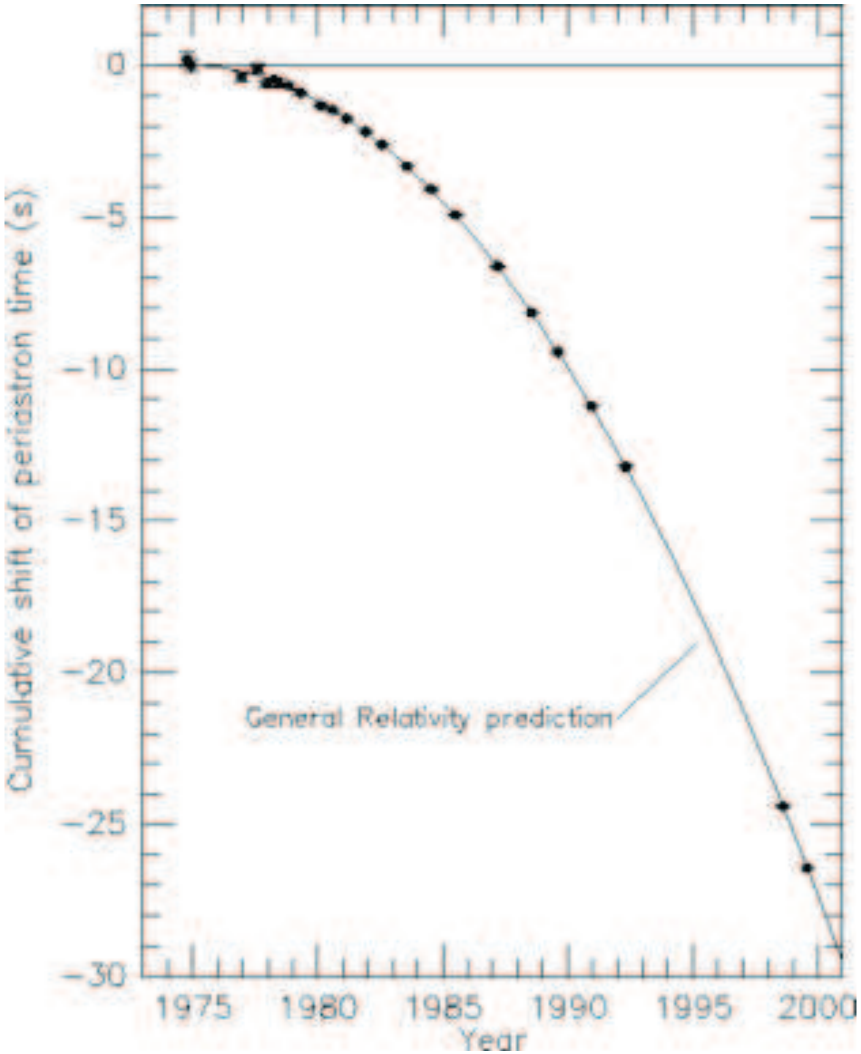
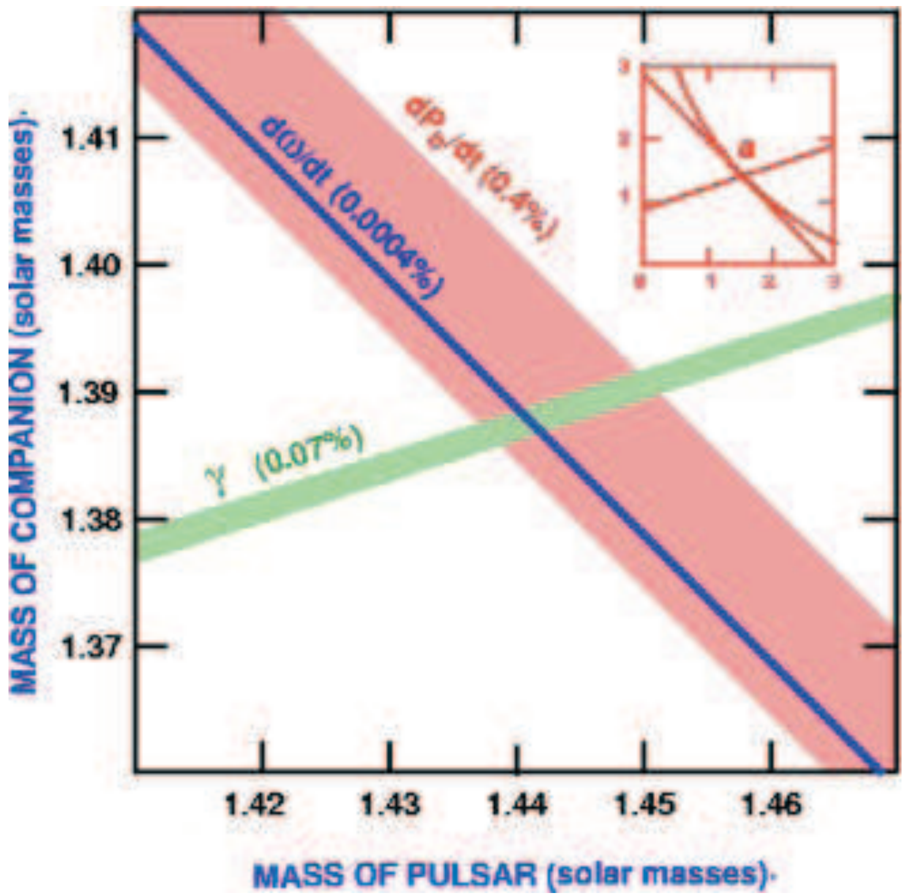
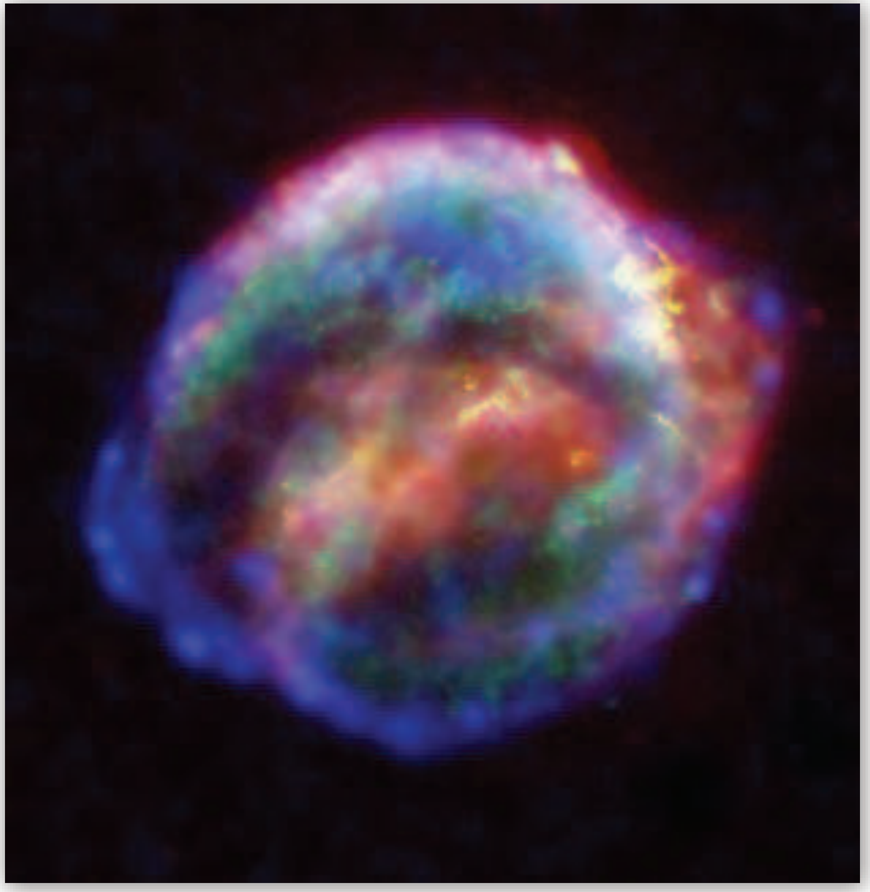




Eventually the two stars will coalesce, but that will take another 100 million years

Sources of Gravitational Waves

Burst Sources



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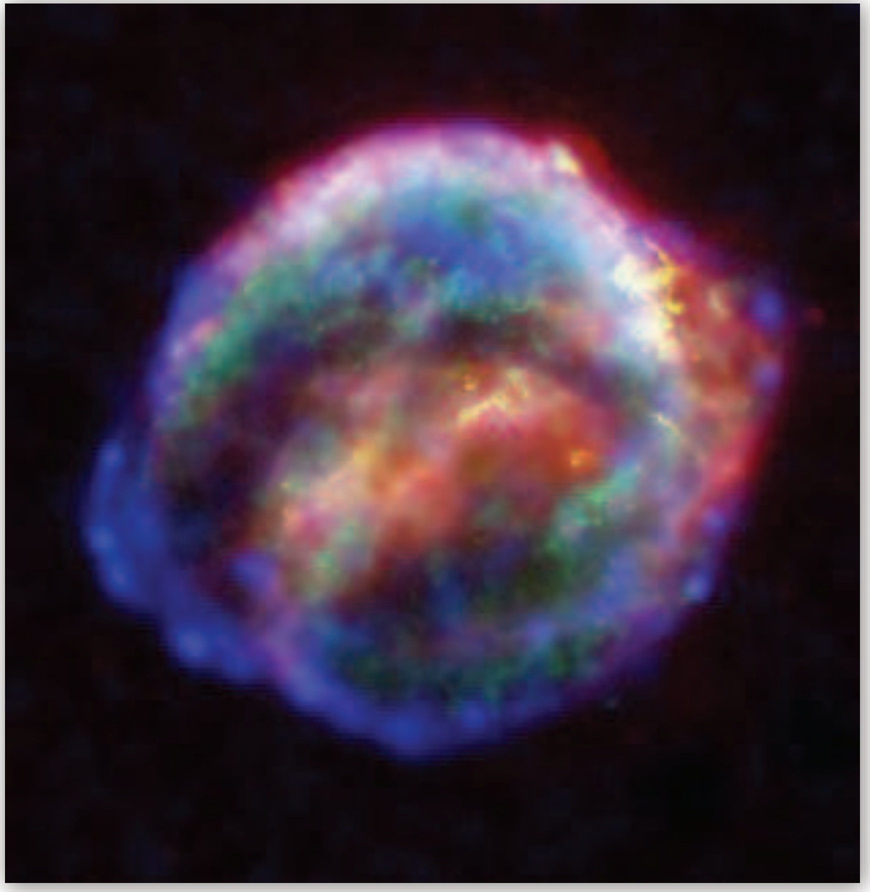

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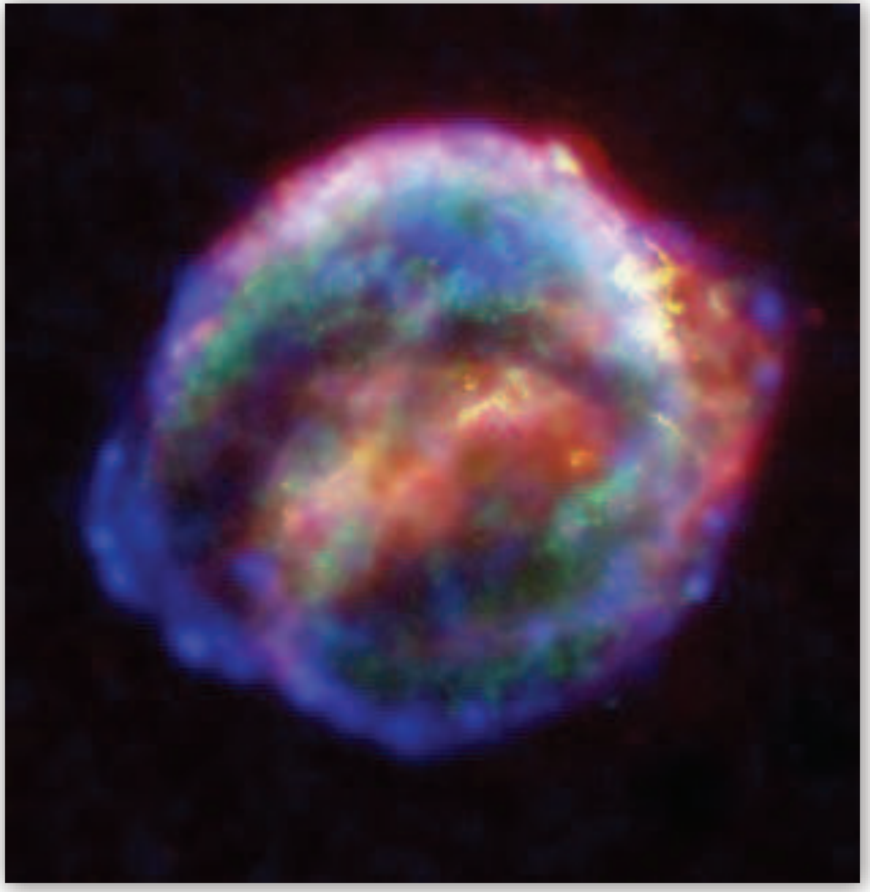

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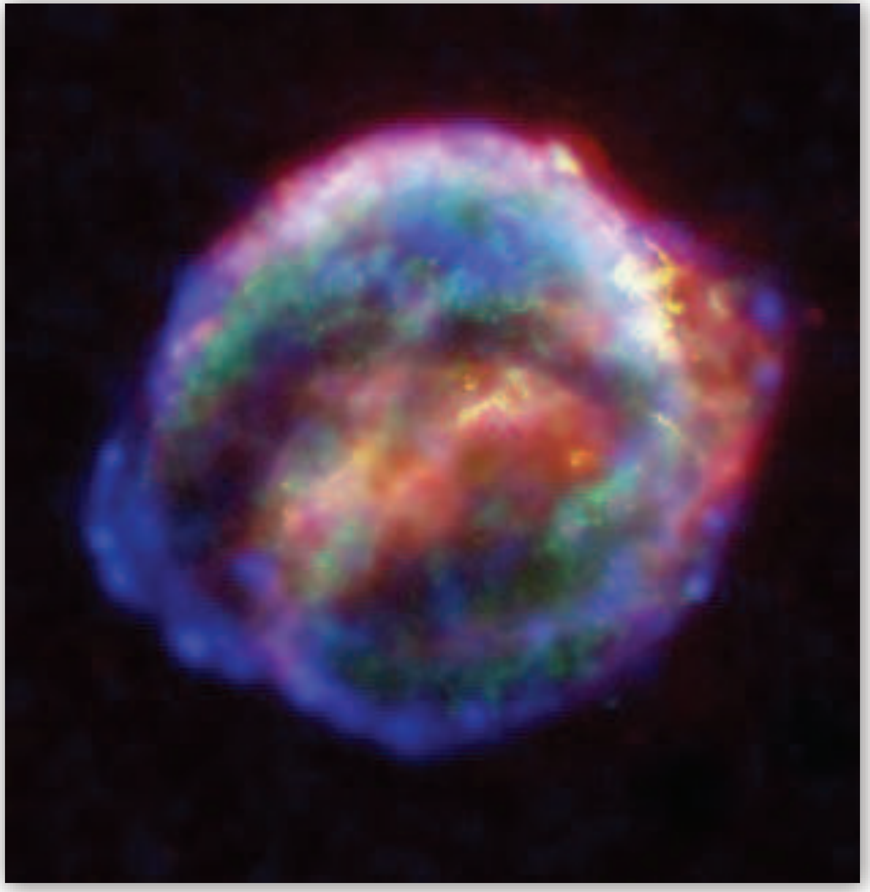

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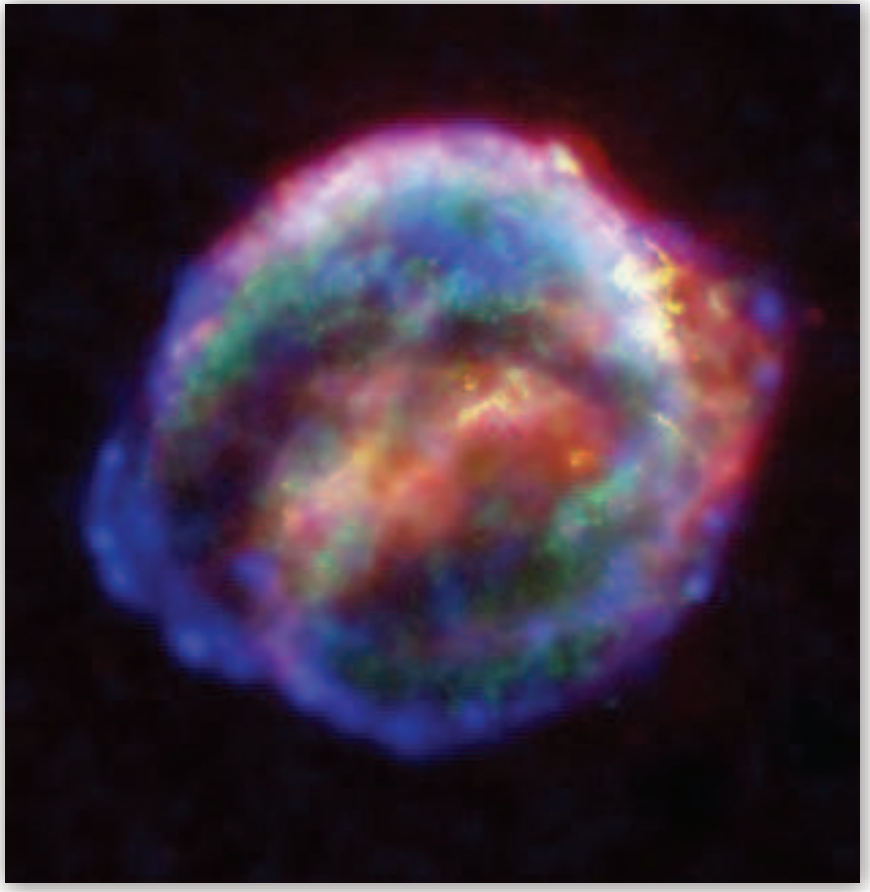

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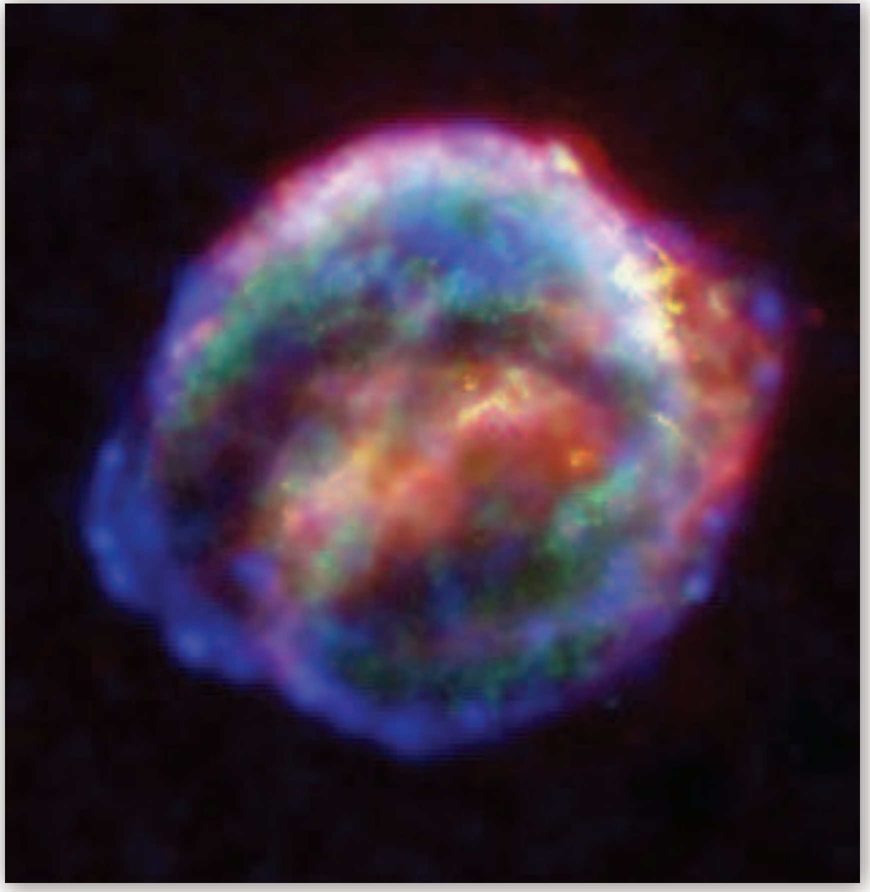

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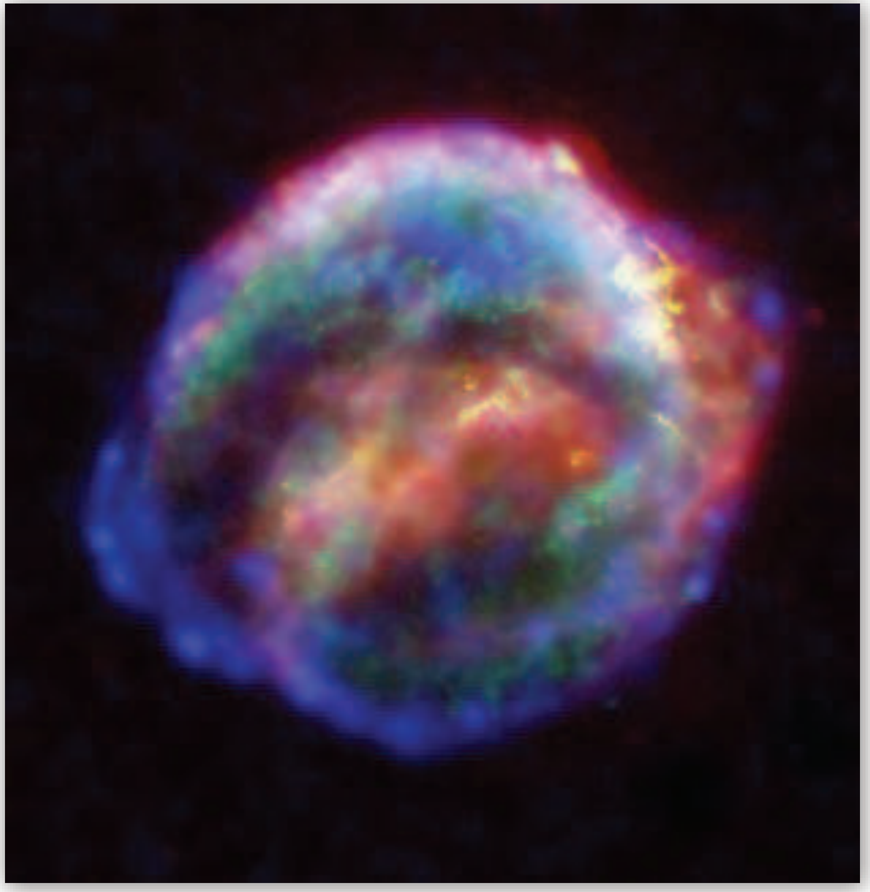

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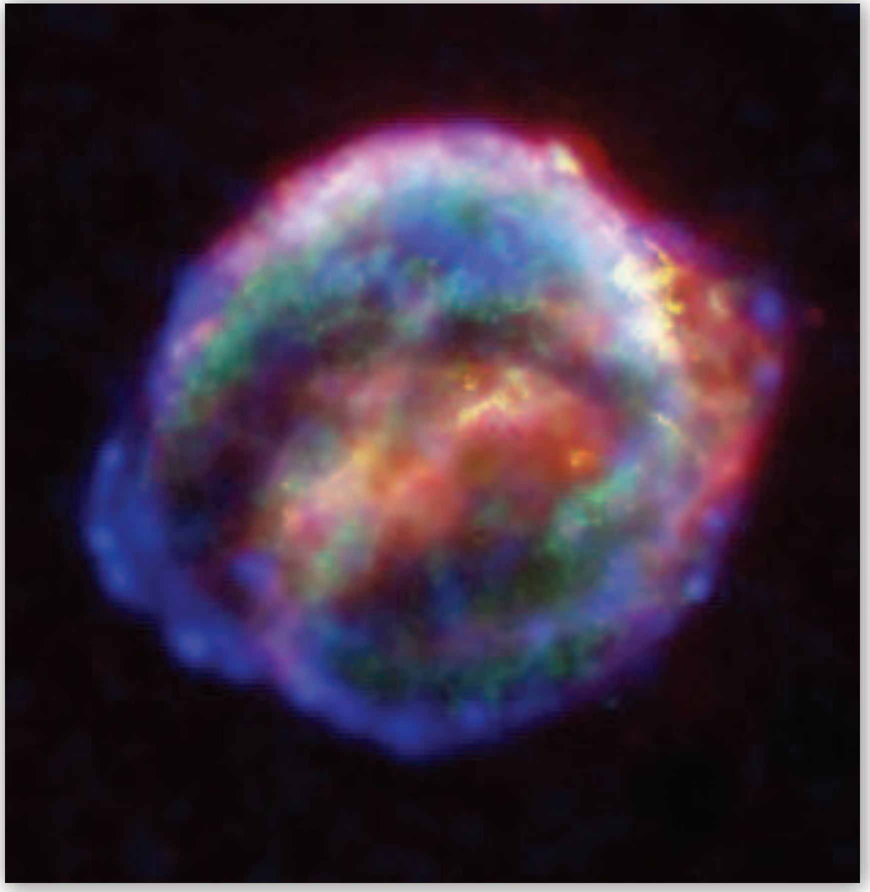
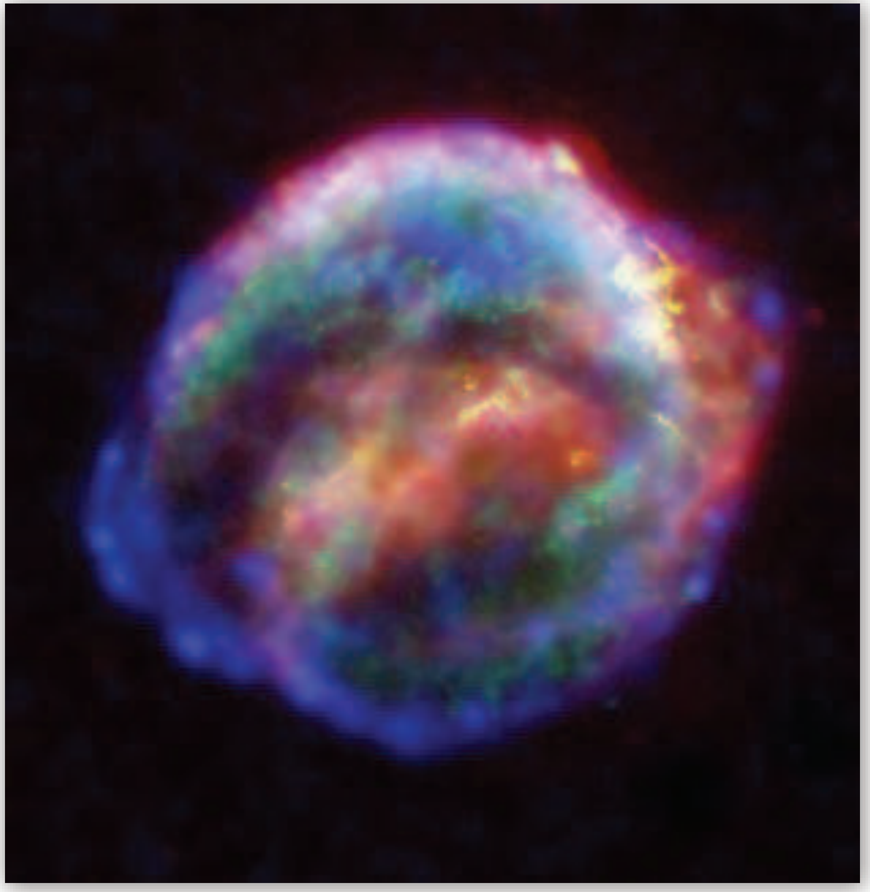
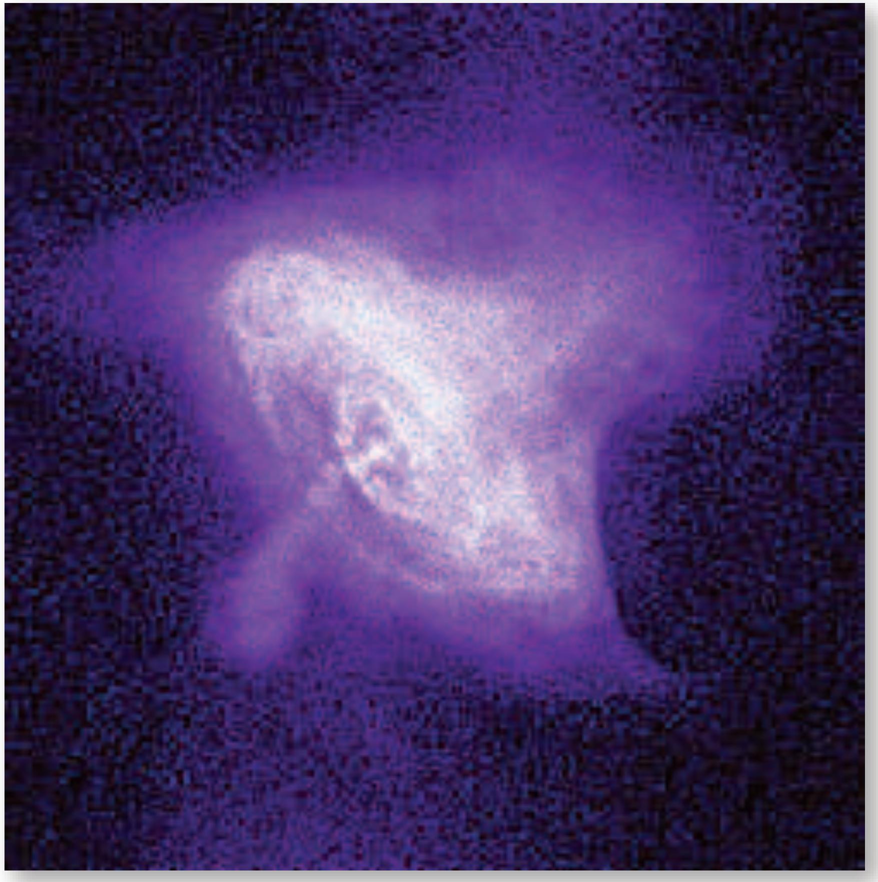


Burst Sources

- Gravitational wave bursts
  - Black hole collisions
  - Supernovae
  - gamma-ray bursts (GRBs)
- Short-hard GRBs
  - could be the result of merger of a neutron star with another NS or a BH
- Long-hard GRBs
  - could be triggered by supernovae



Continuous Wave Sources



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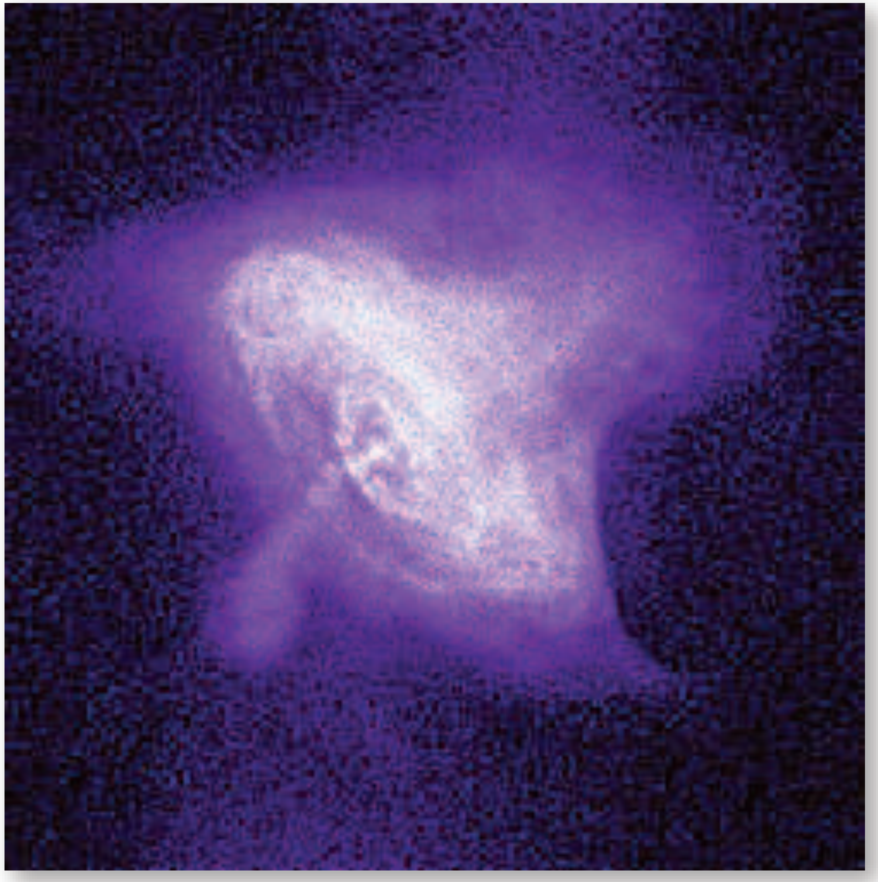

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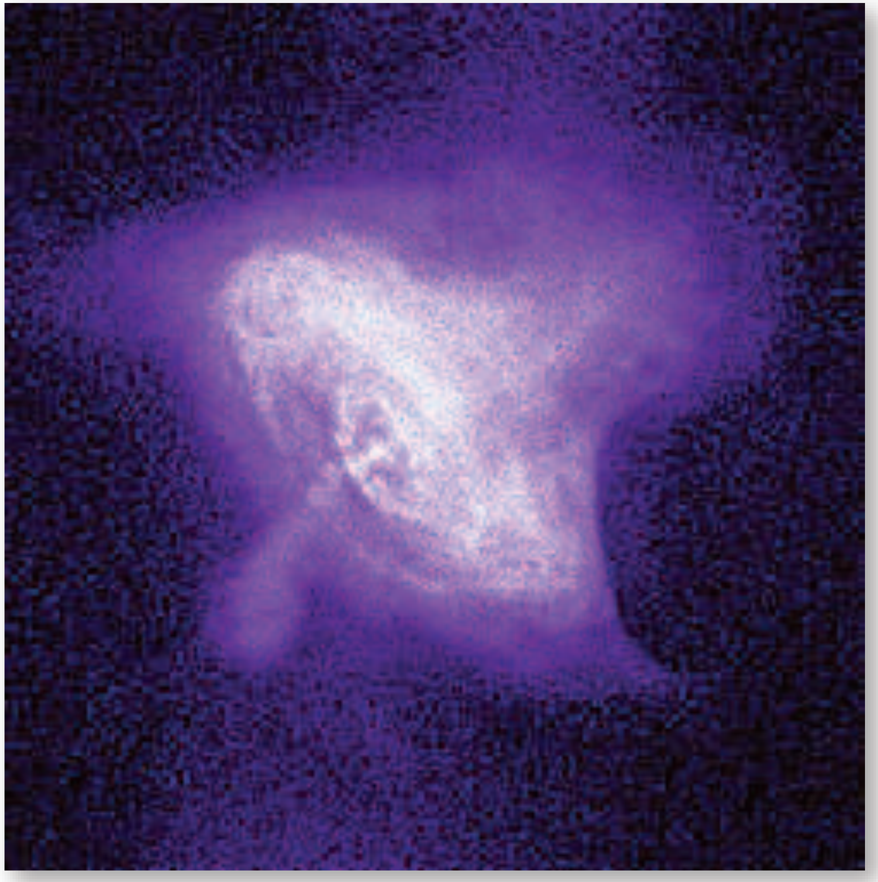

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- Rapidly spinning neutron stars or other objects
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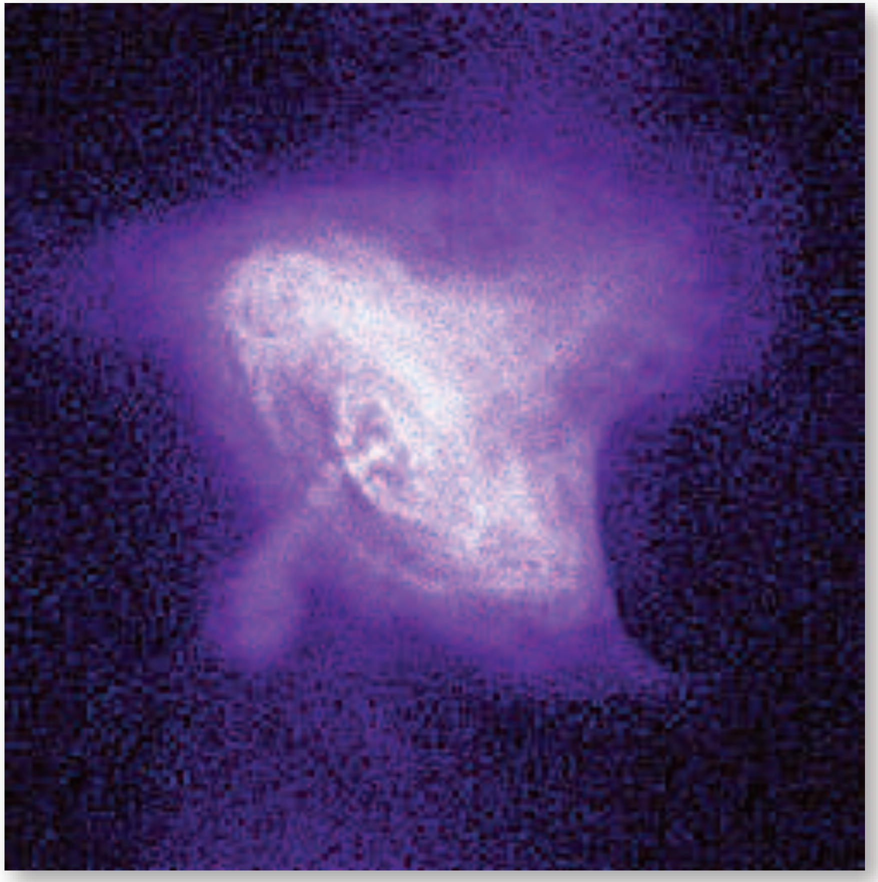
- Low mass X-ray binaries



Continuous Wave Sources

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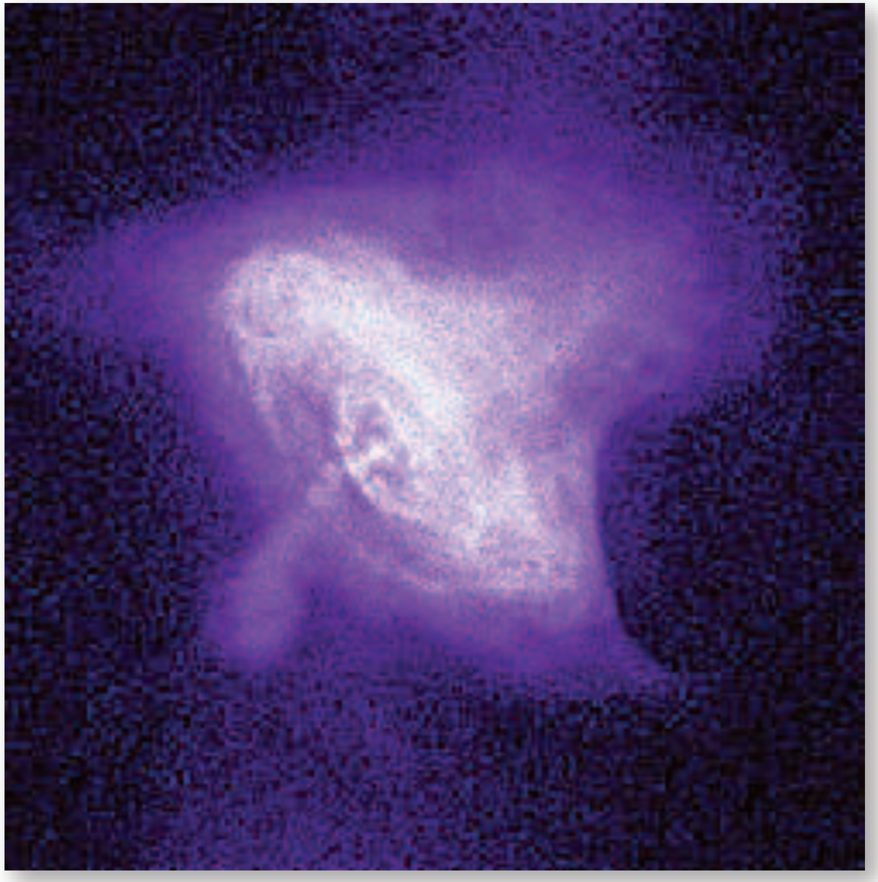

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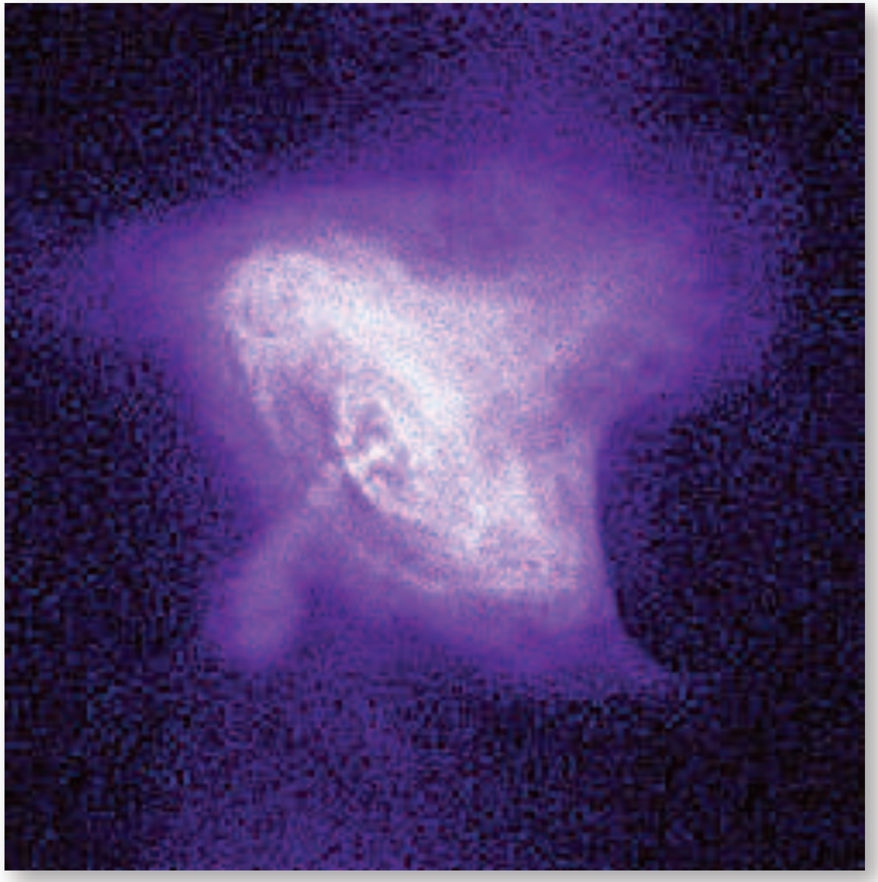

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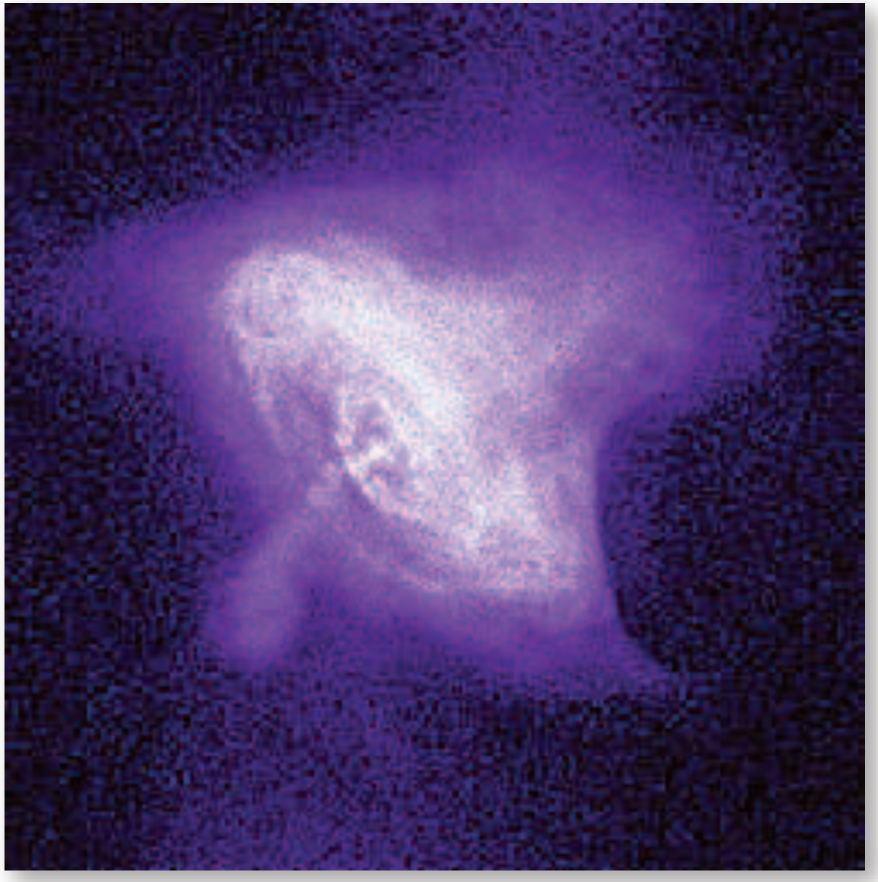

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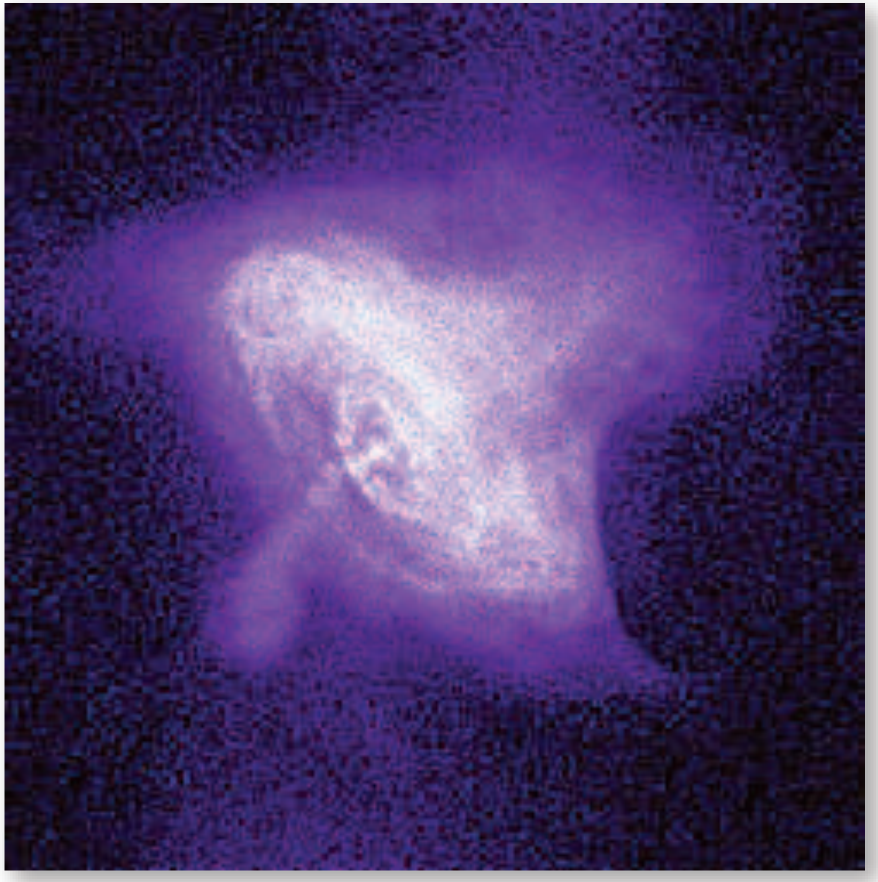

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- Magnetars and other compact objects
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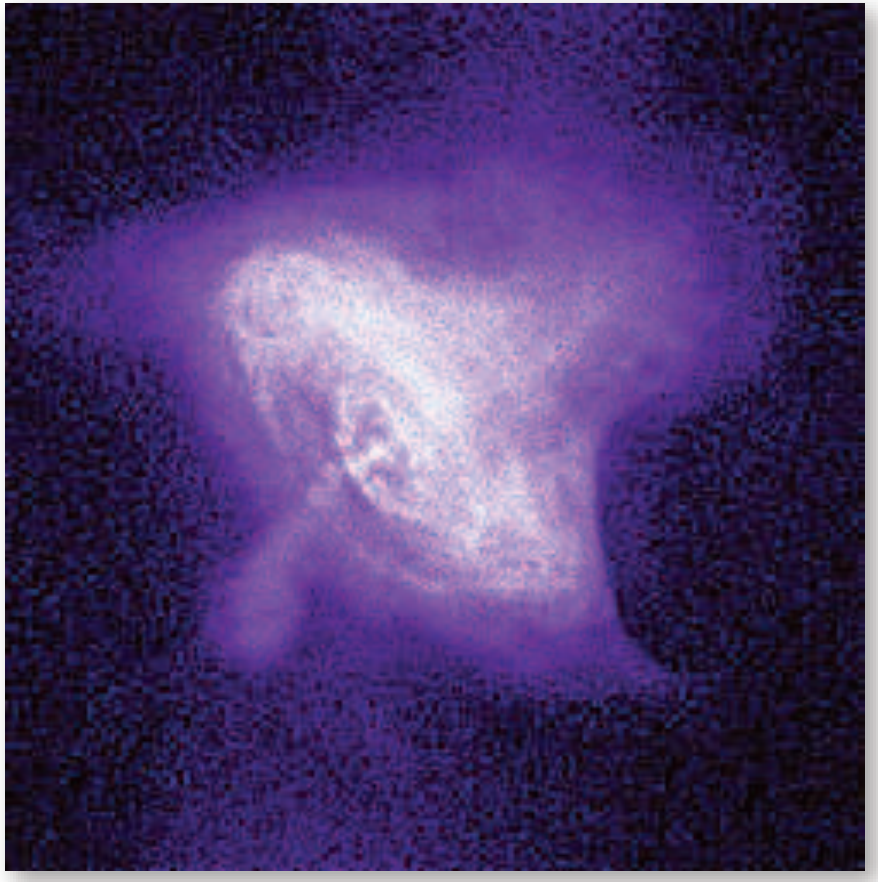
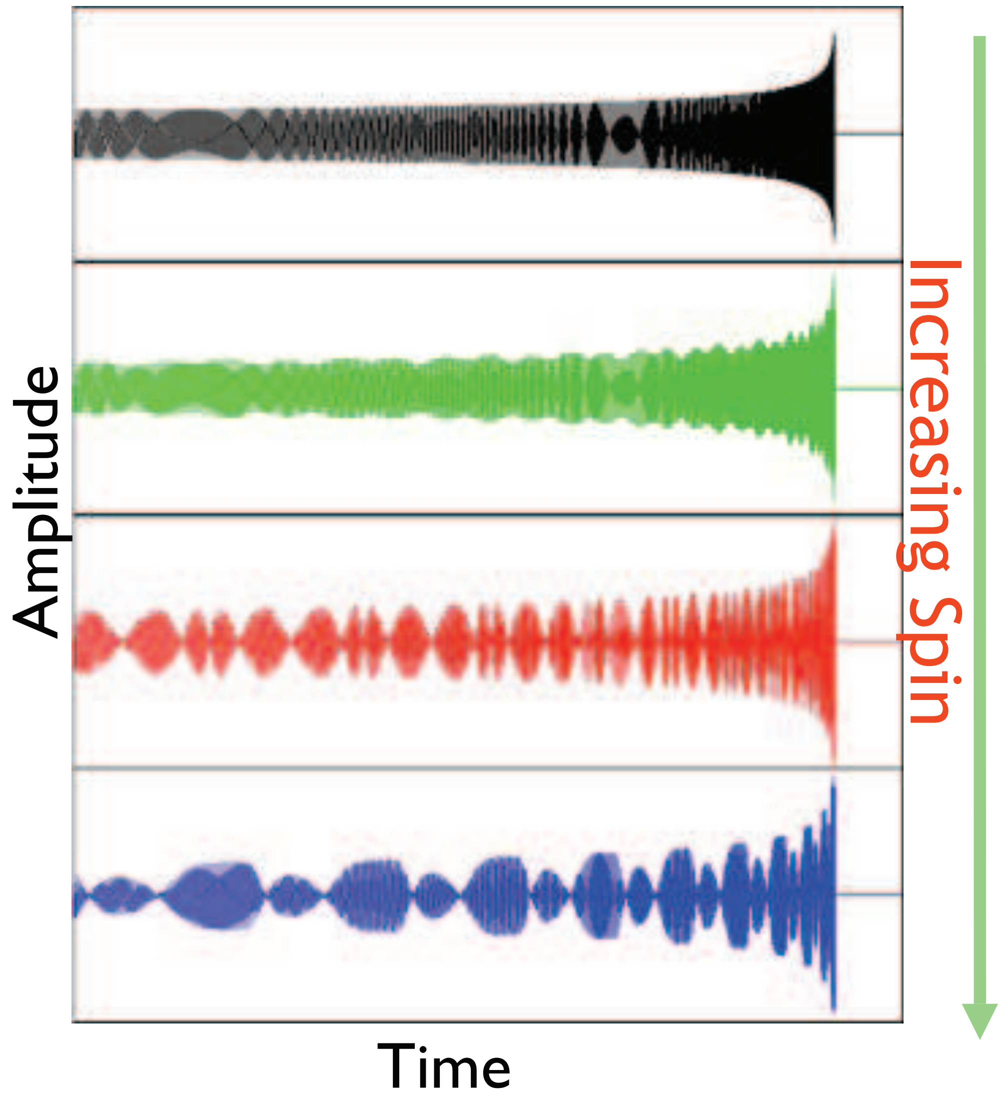
- Relativistic instabilities
  - r-modes, etc.



Waveforms from Inspiralling Binaries



Waveforms from Inspiralling Binaries

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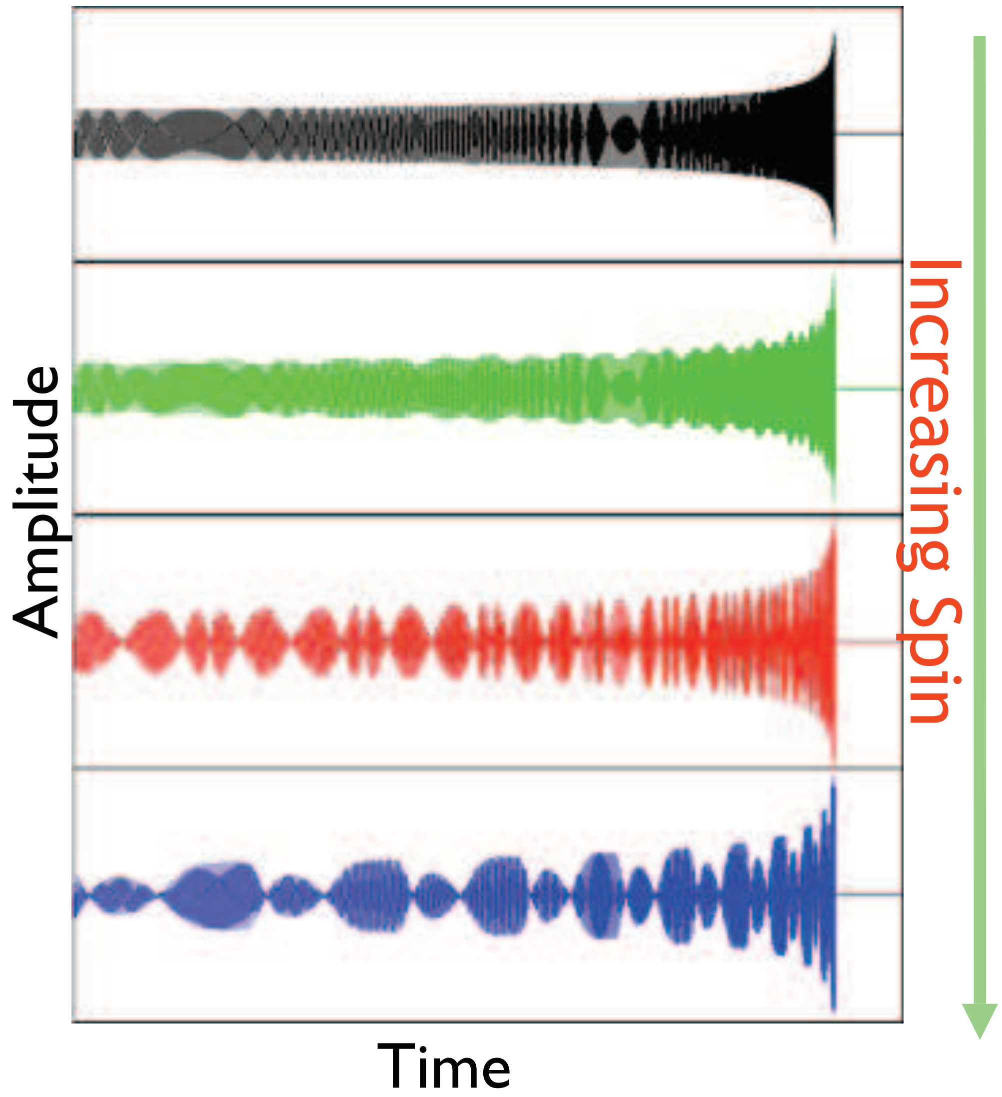

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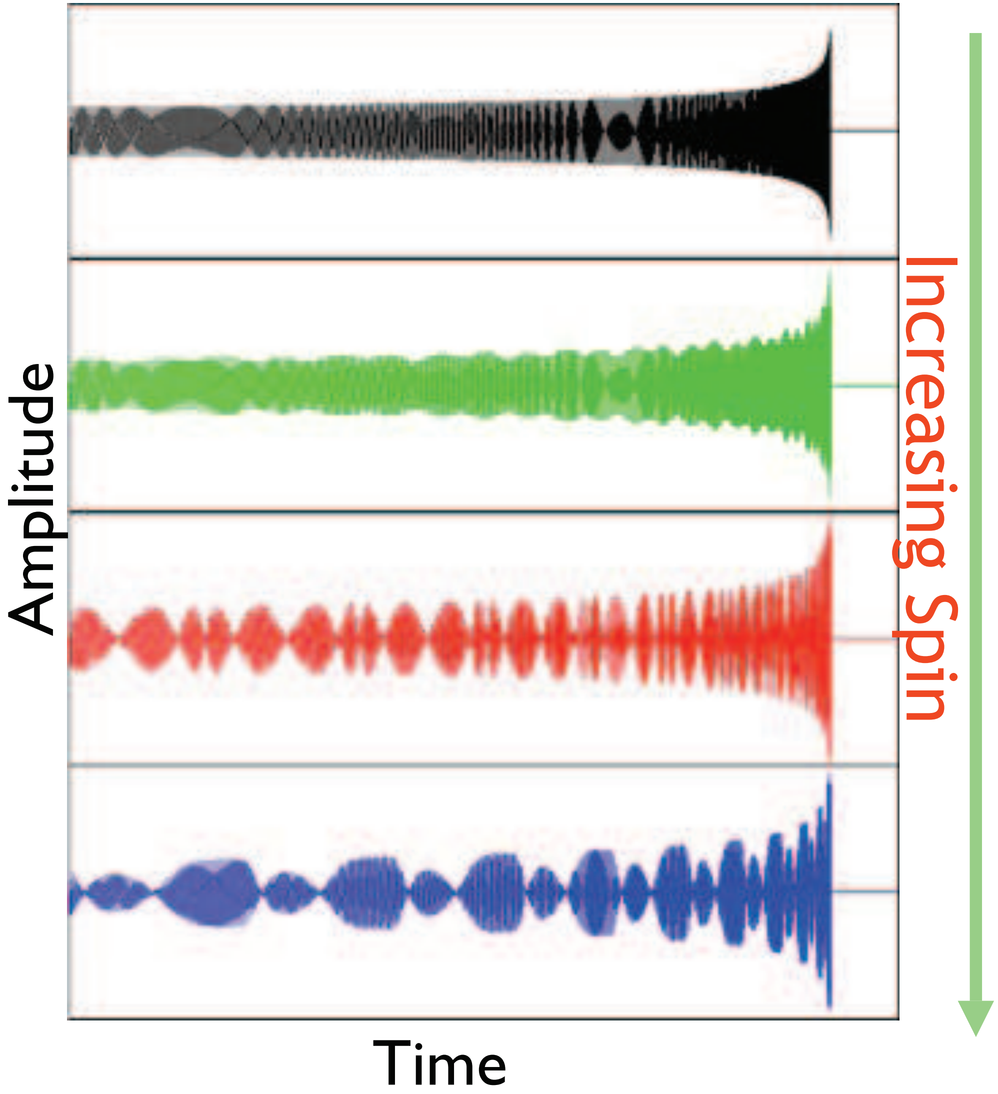

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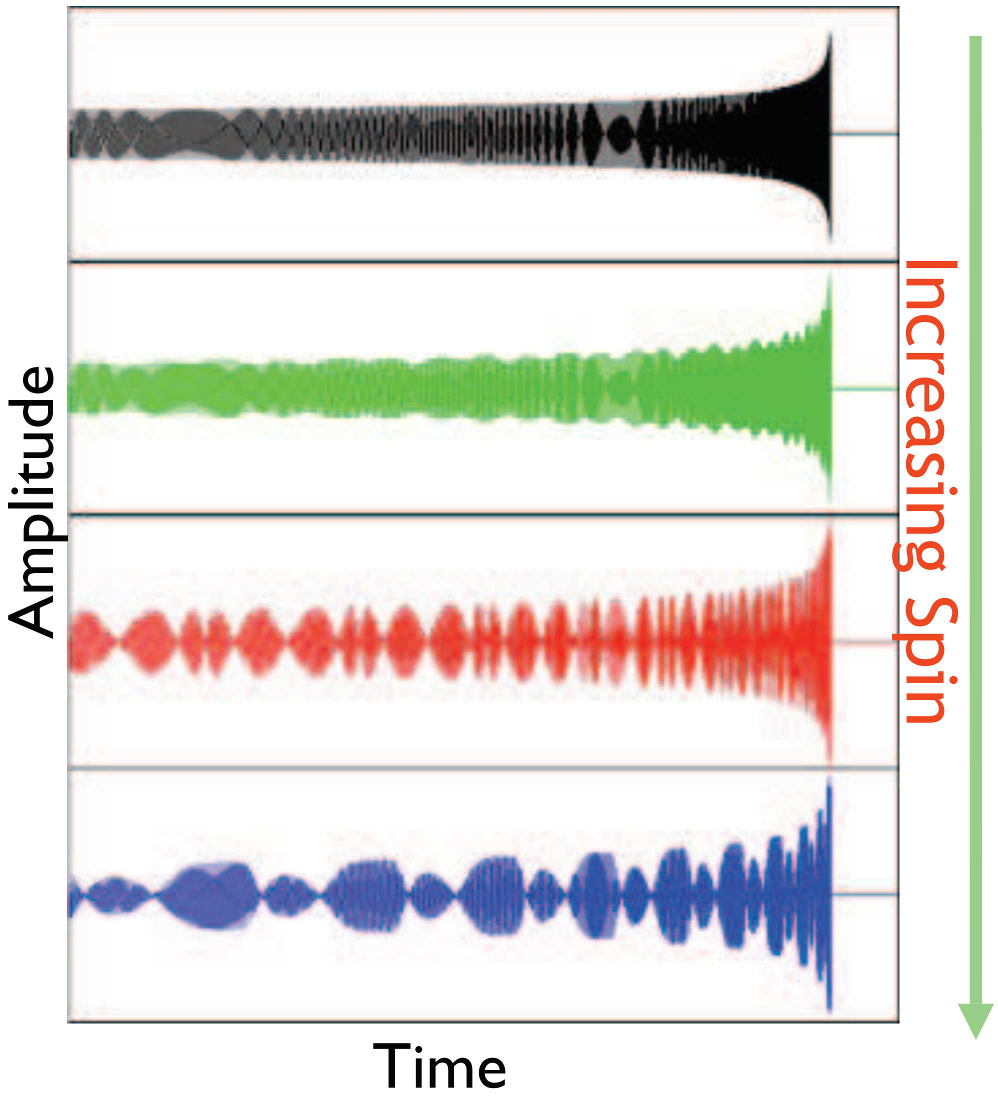

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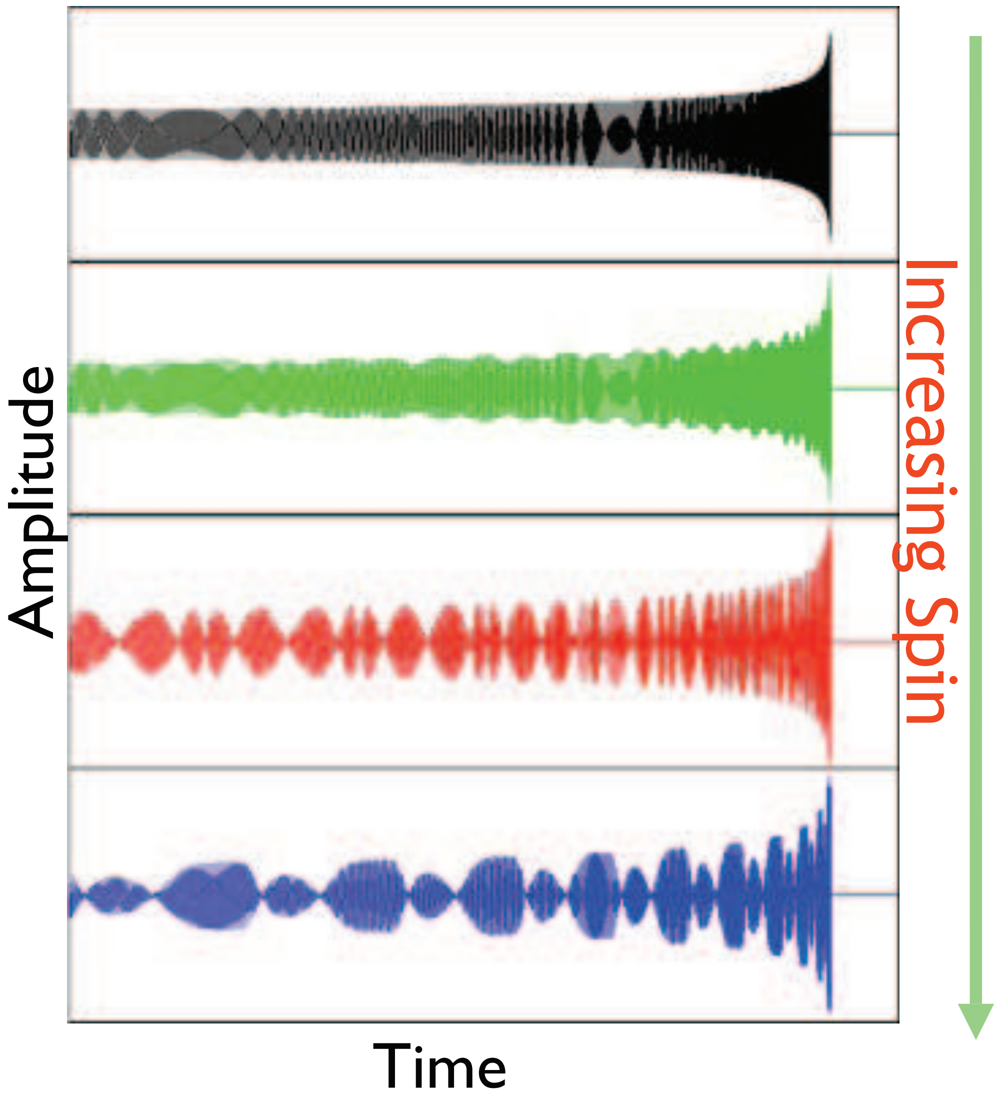
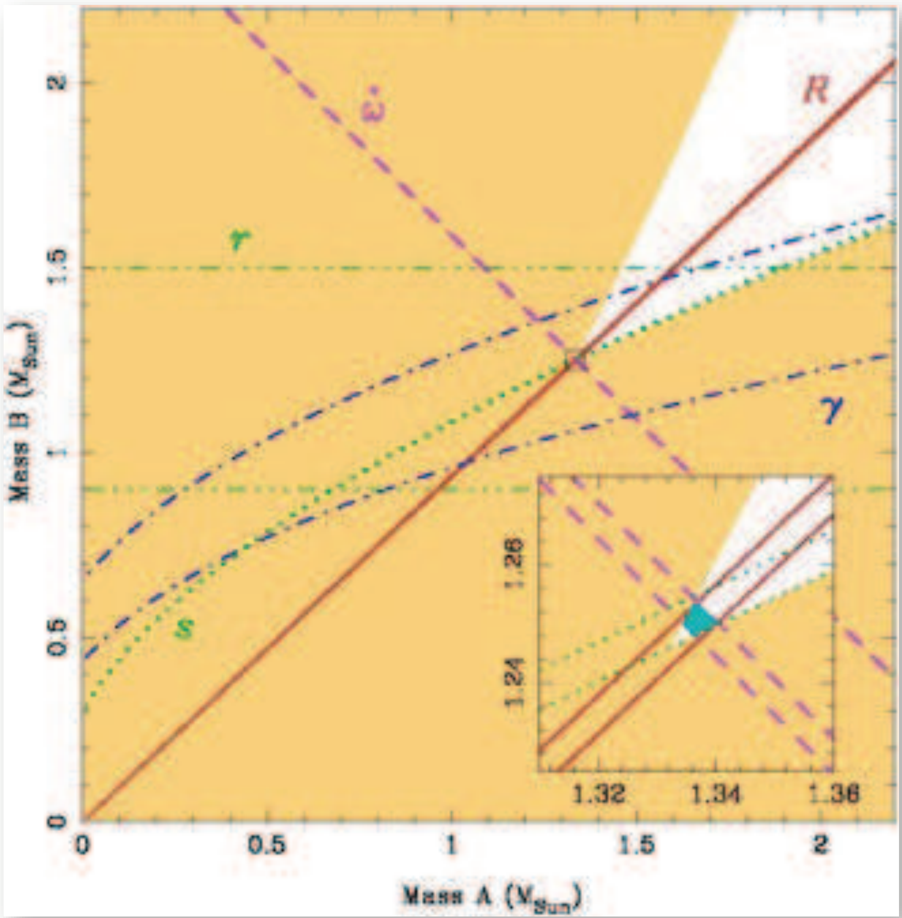
$$h(t) = 4\eta \frac{M}{D} \frac{M}{r(t)} \cos 2\varphi(t)$$



Examples of Merging Neutron Star Binaries

Burgay et al Nature 2003



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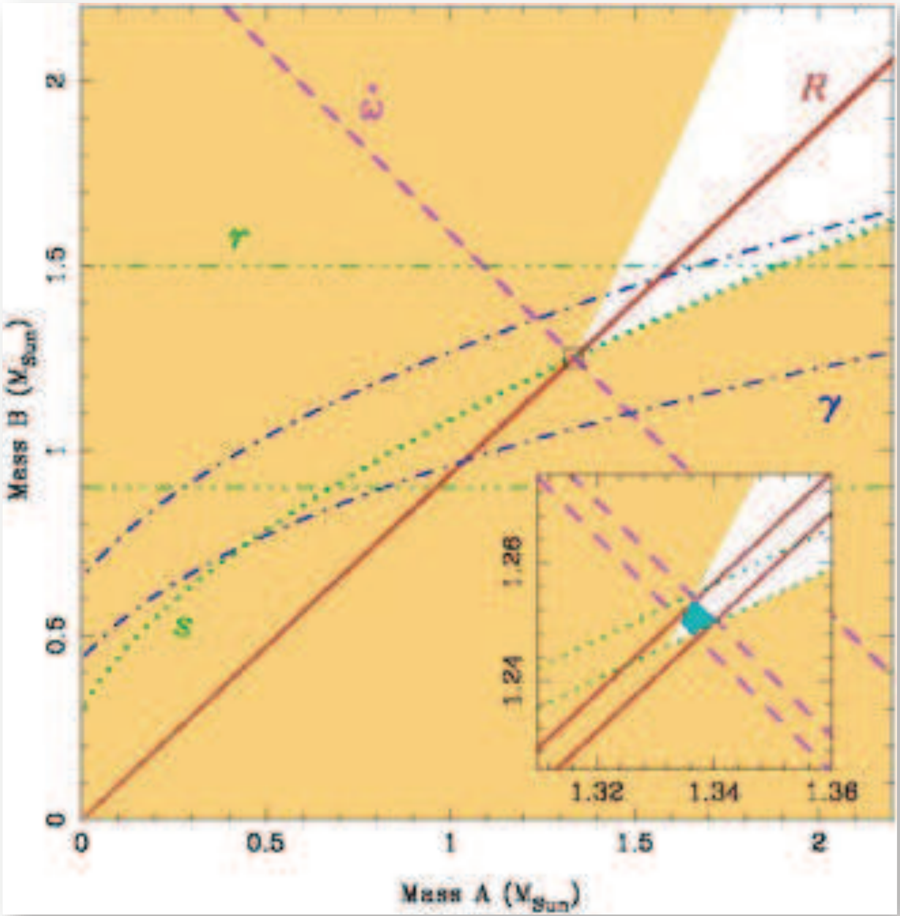

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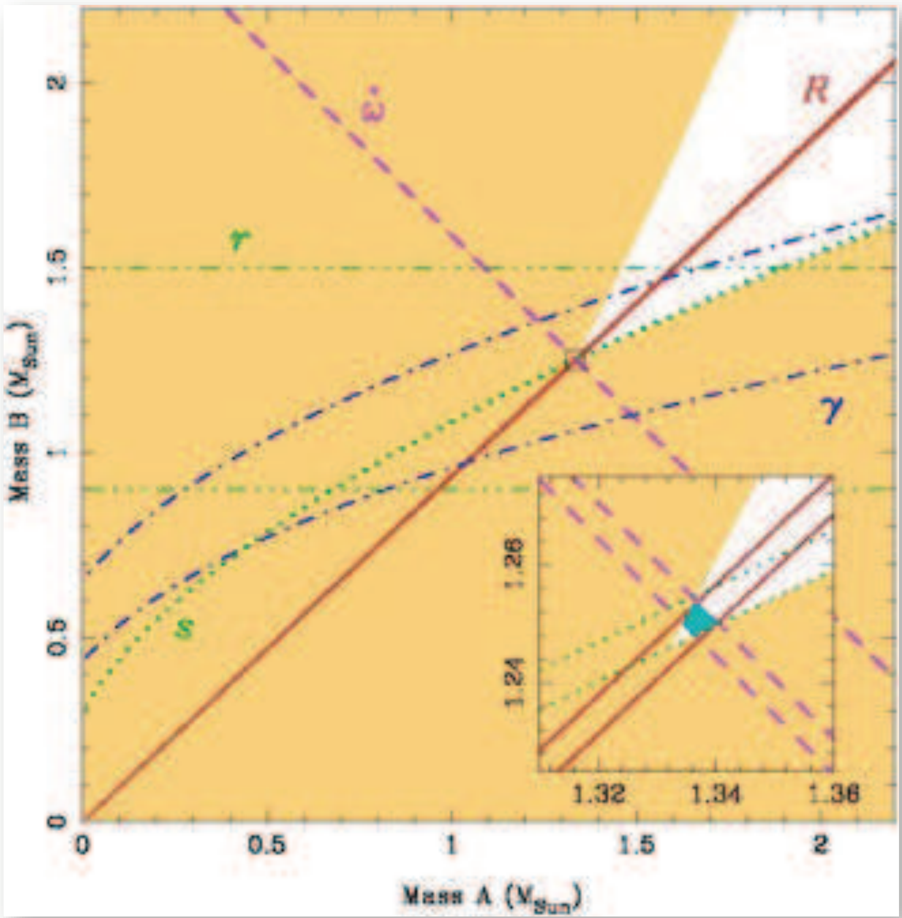

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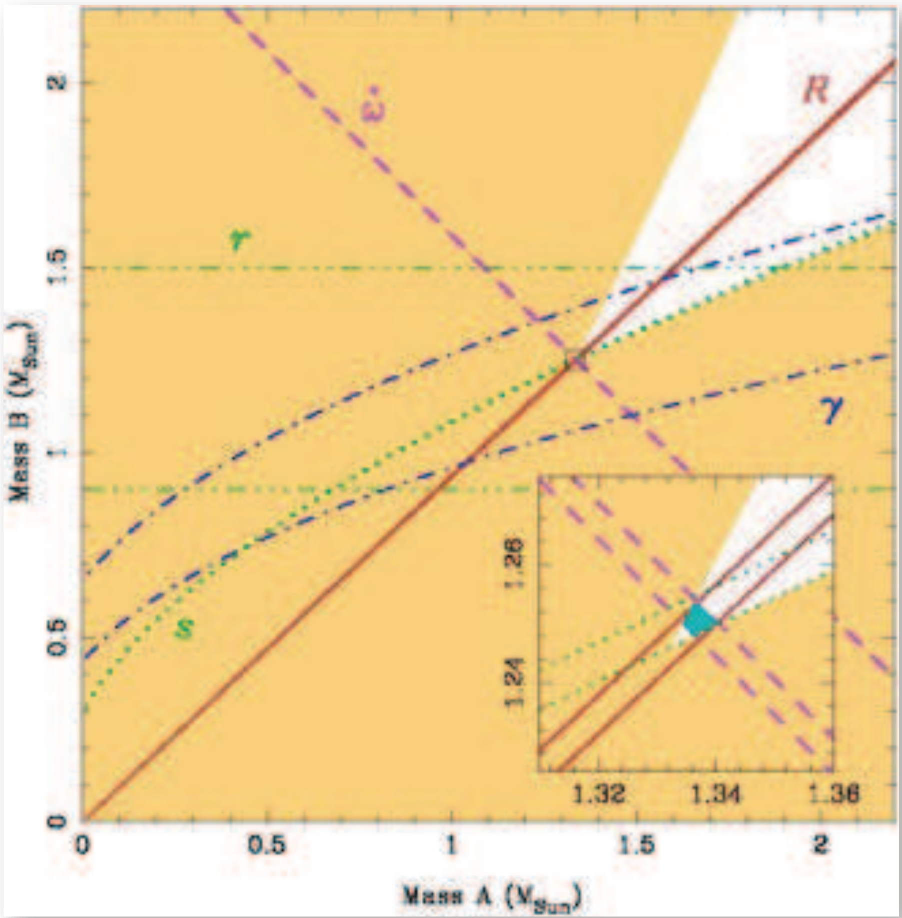

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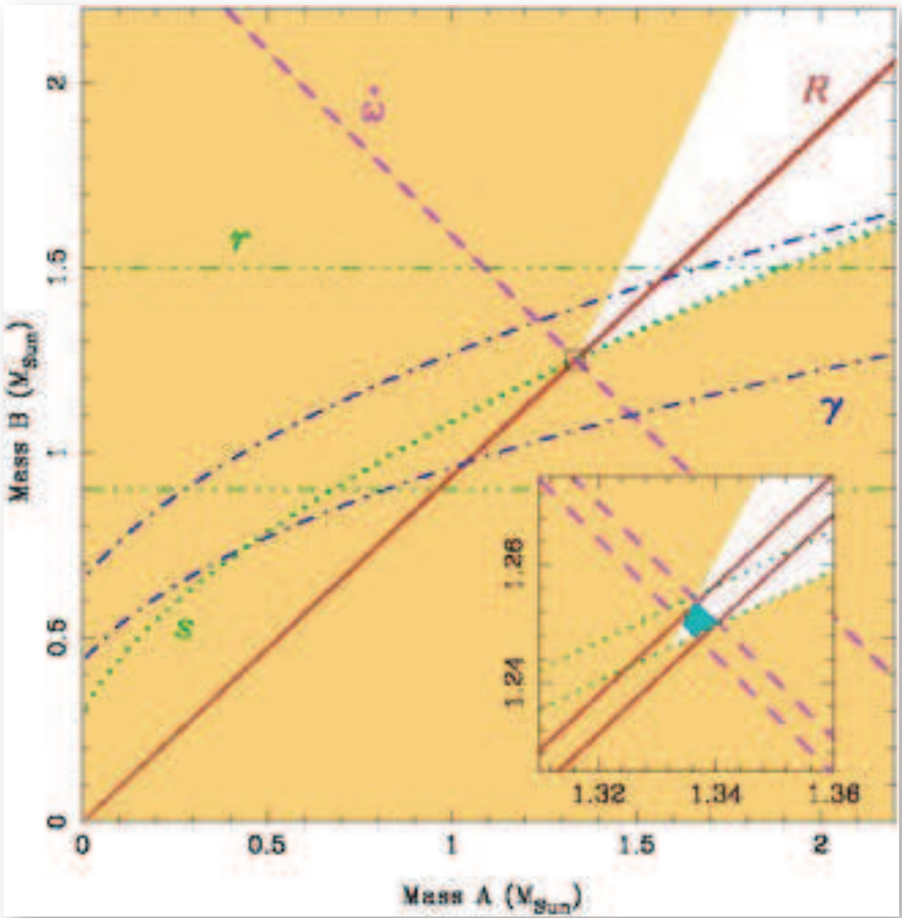

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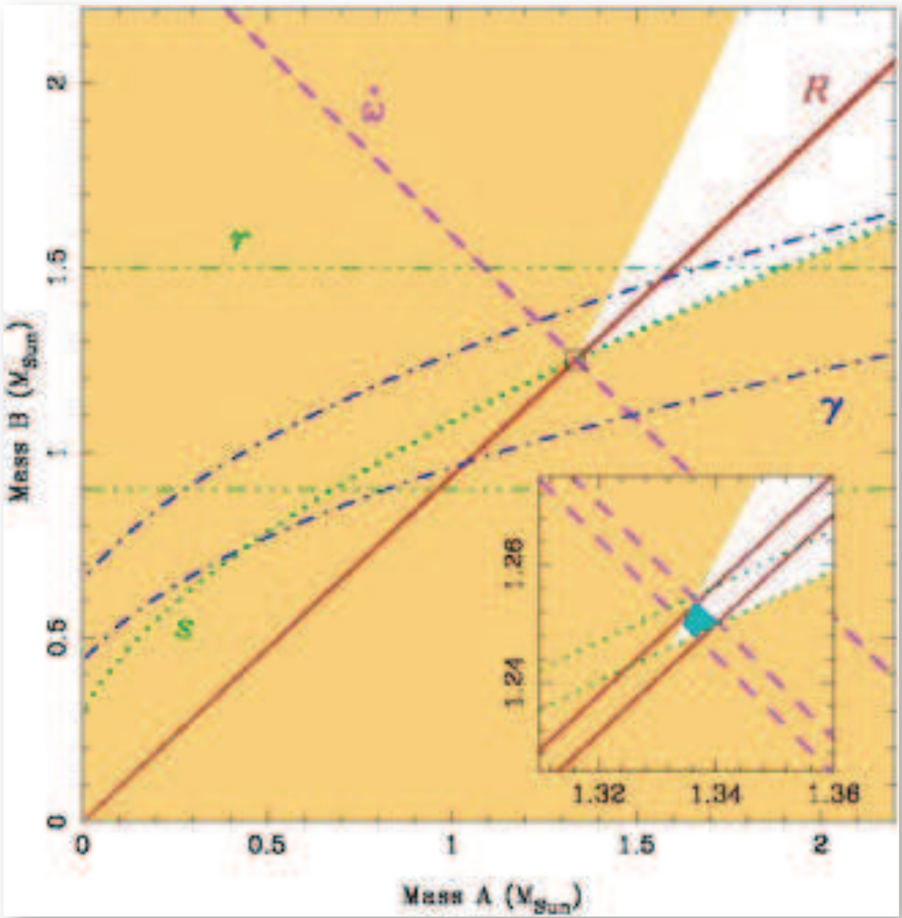

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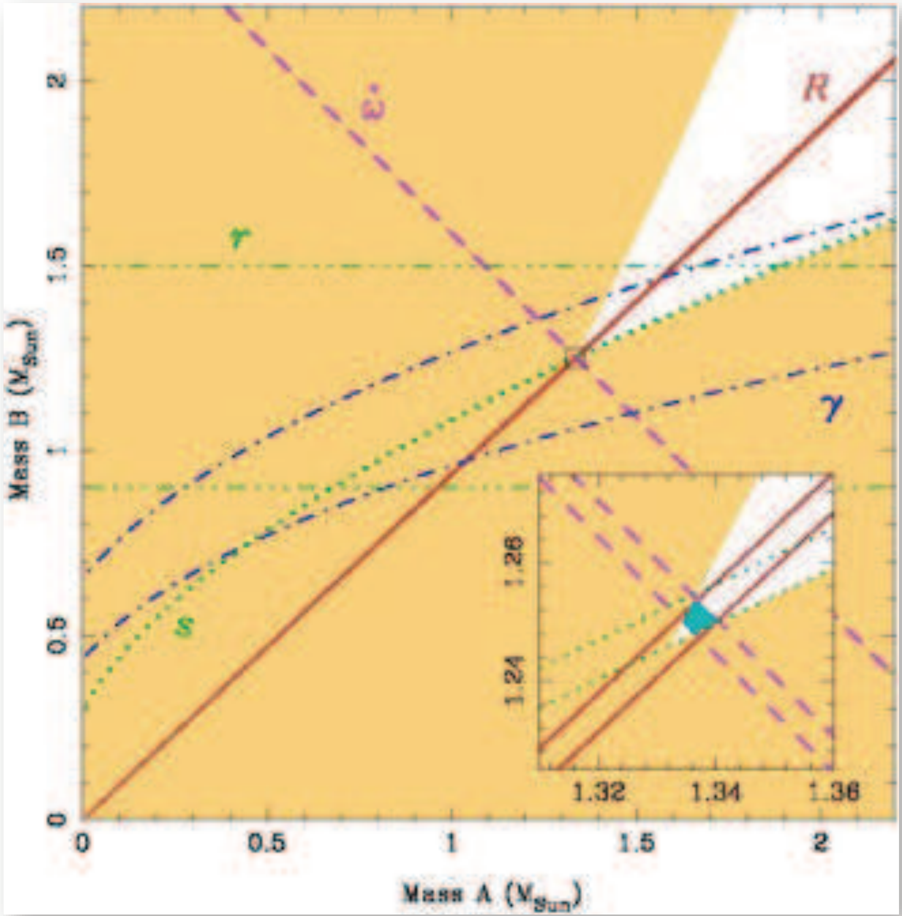

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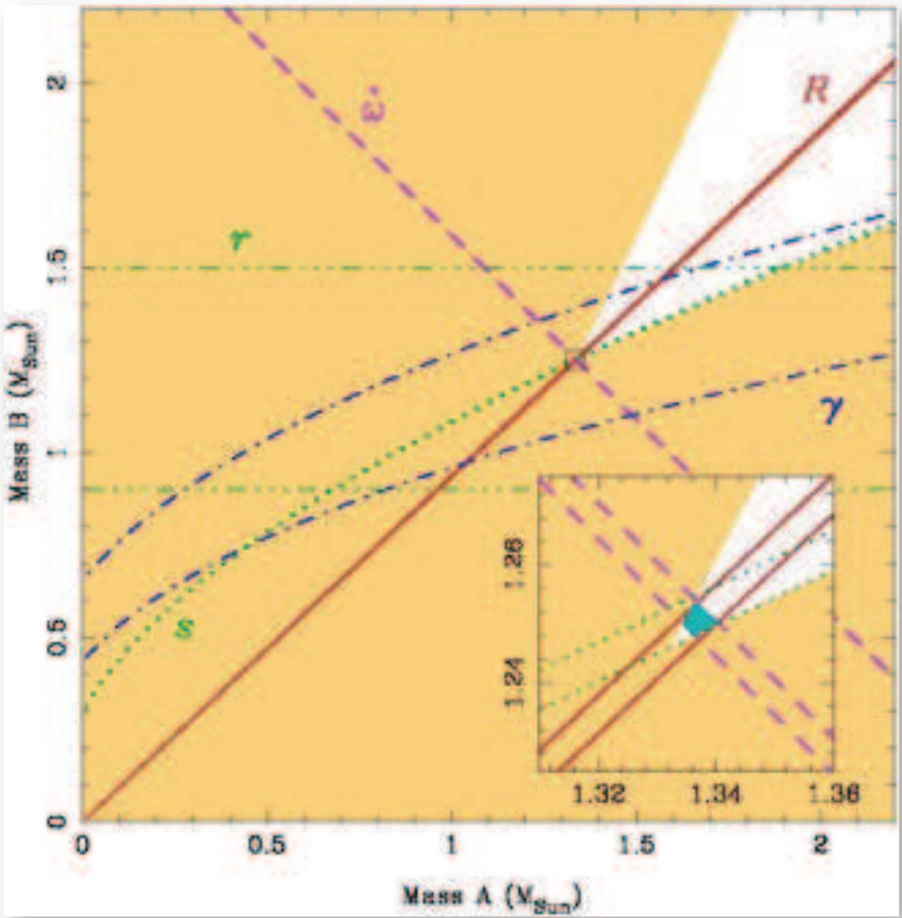

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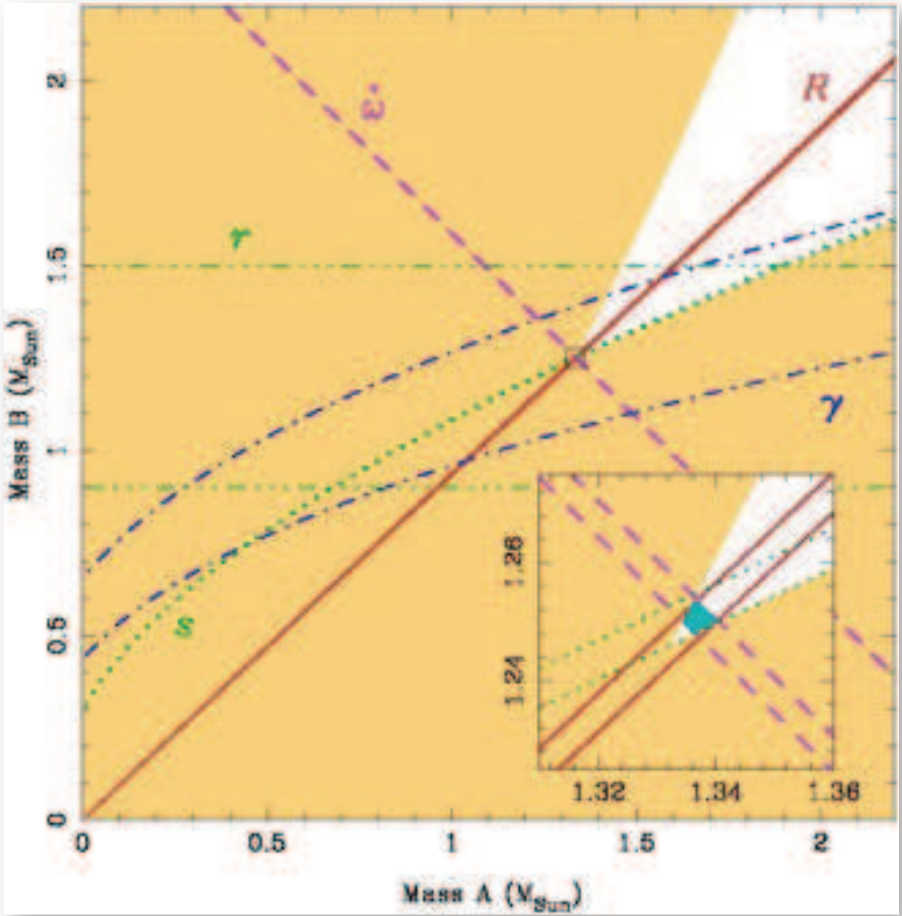
  - Orbit is shrinking by a few millimeters each year due to gravitational radiation reaction



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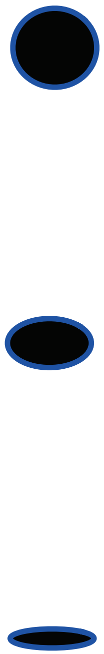
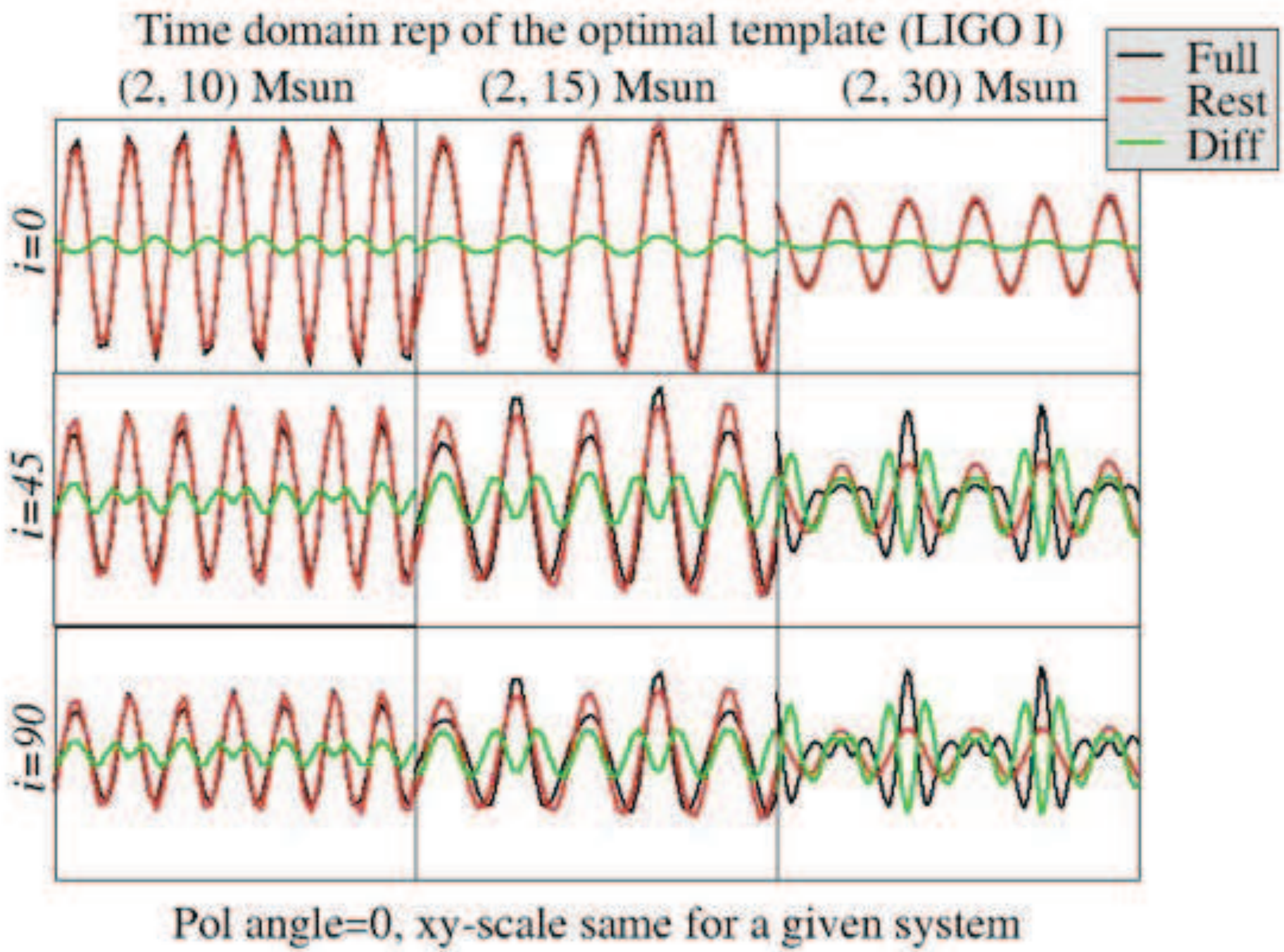
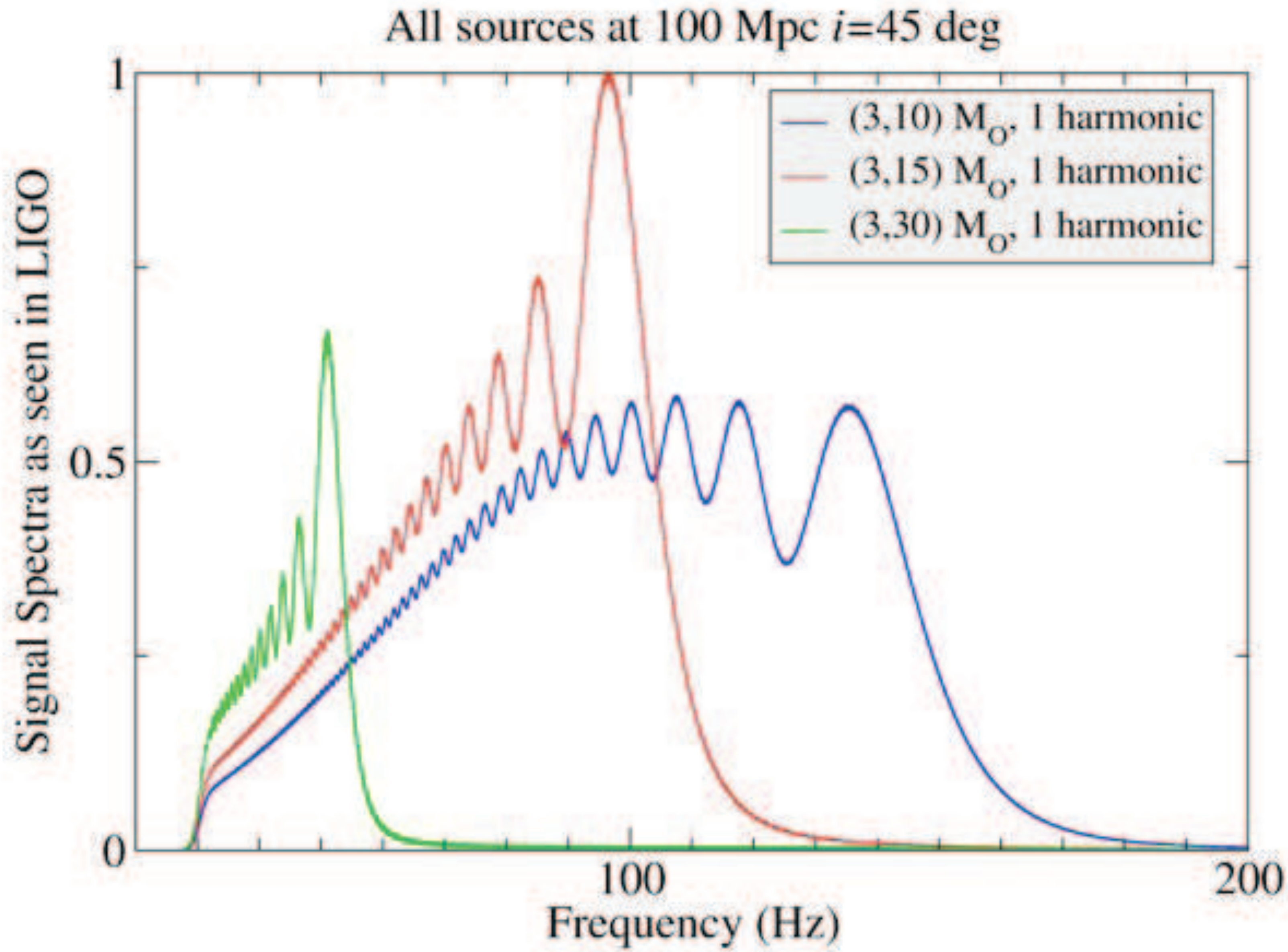
- Blanchet, Damour, Iyer, Jaranowski, Schaefer, Will, Wiseman
- Andrade, Arun, Buonanno, Gopakumar, Joguet, Esposito-Farase, Faye, Kidder, Nissanke, Ohashi, Owen, Ponsot, Qusaillah, Tagoshi …

Edge-on vs face-on binaries





McKechan et al (2009)



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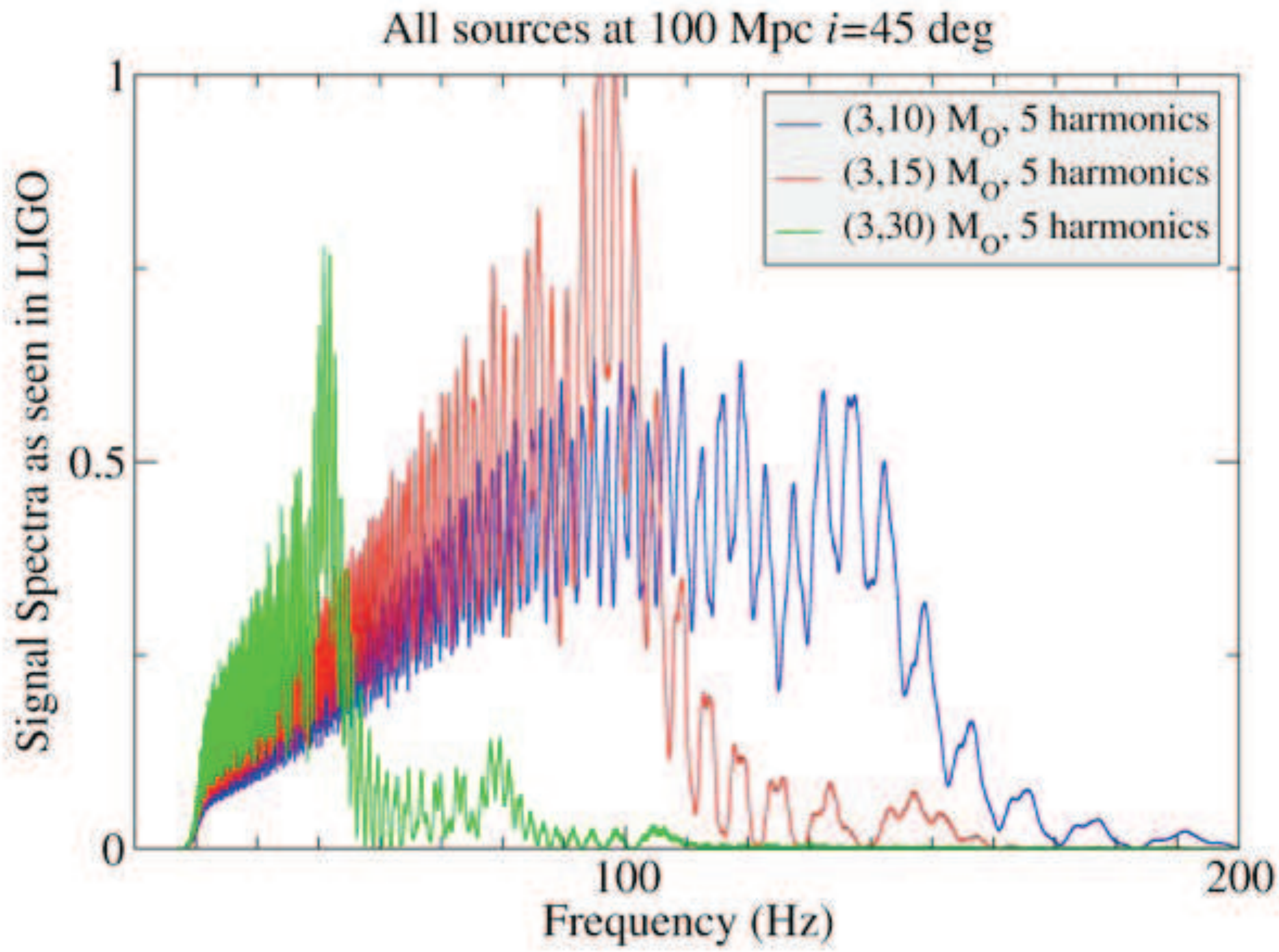

Black Hole Mergers from Numerical Relativity

A Big Industry: Golm, Jena (Germany), Maryland, Princeton, Rochester, Baton Rouge, Georgia Tech, Caltech, Cornell (USA), Canada, Mexico, Spain, Cardiff

Black Hole Mergers from Numerical Relativity

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Black Hole Mergers from Numerical Relativity

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  - New physics - e.g. super-kick velocities
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- We should be able to see further and more massive objects

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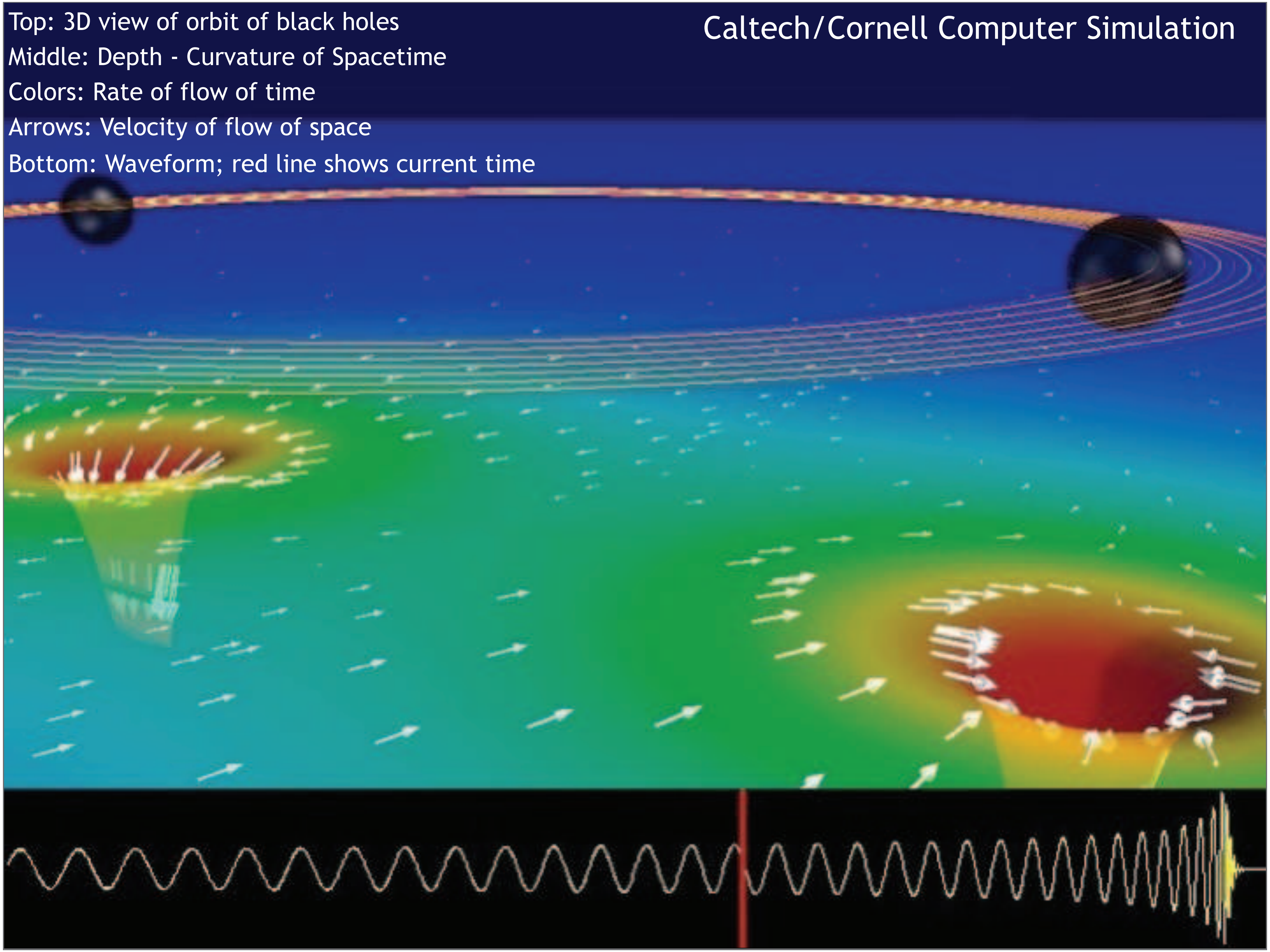
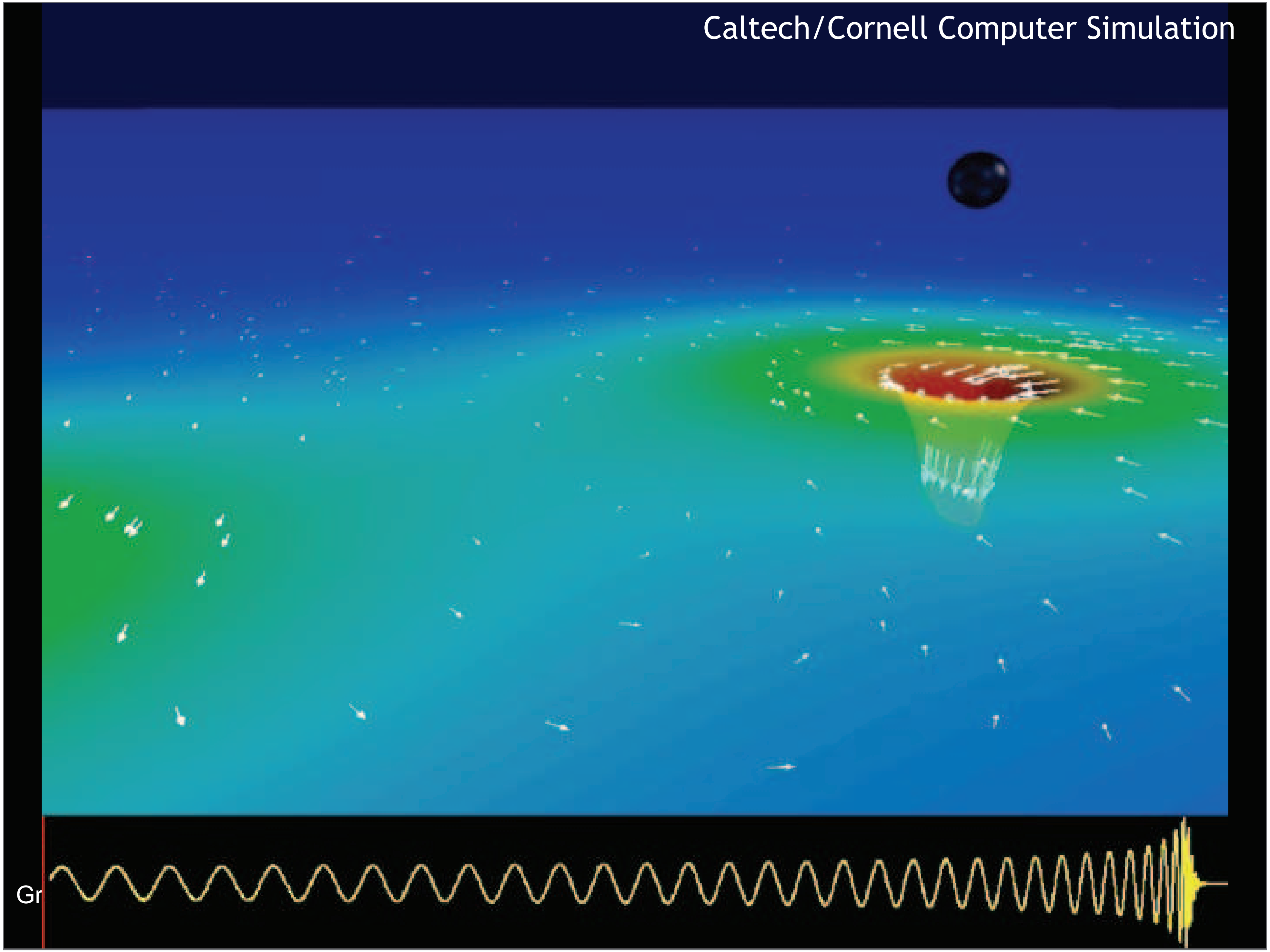

Top: 3D view of orbit of black holes
Middle: Depth - Curvature of Spacetime
Colors: Rate of flow of time
Arrows: Velocity of flow of space
Bottom: Waveform; red line shows current time
Caltech/Cornell Computer Simulation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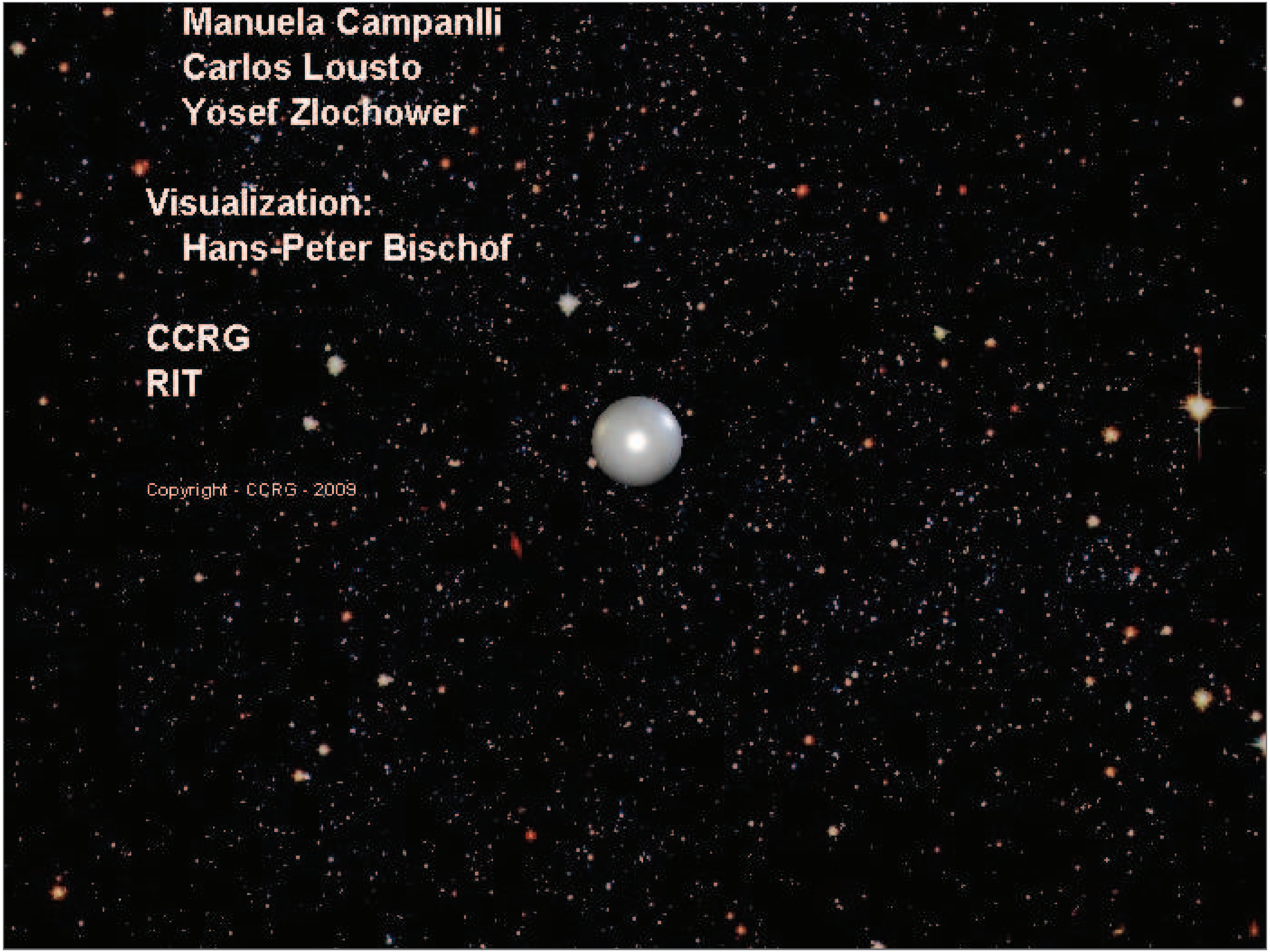
Gr


Manuela Campanlli
Carlos Lousto
Yosef Zlochower
Visualization:
Hans-Peter Bischof
CCRG
RIT
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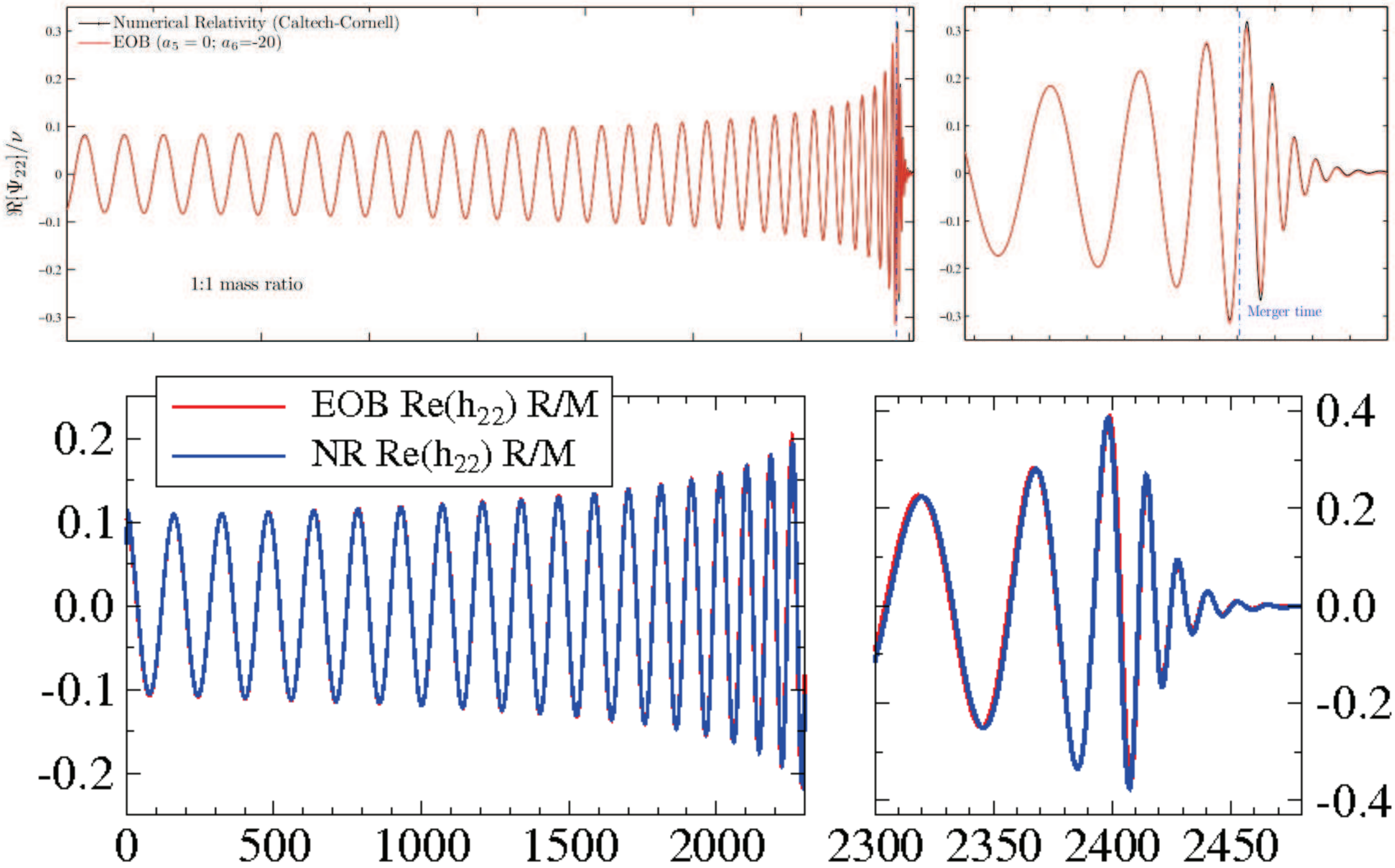
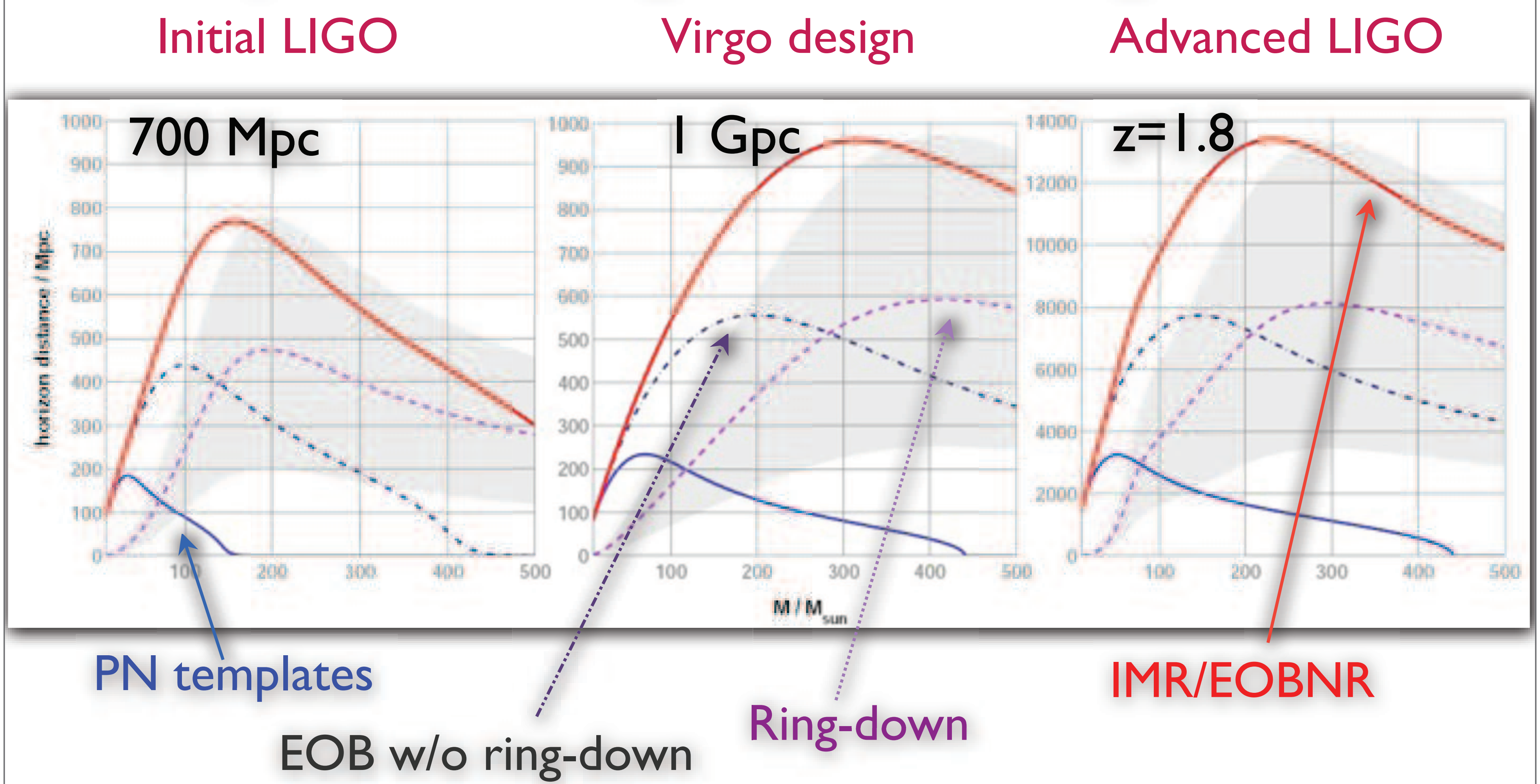
Effective-One-Body Formalism for Inspiral-Merger-Ringdown Dynamics

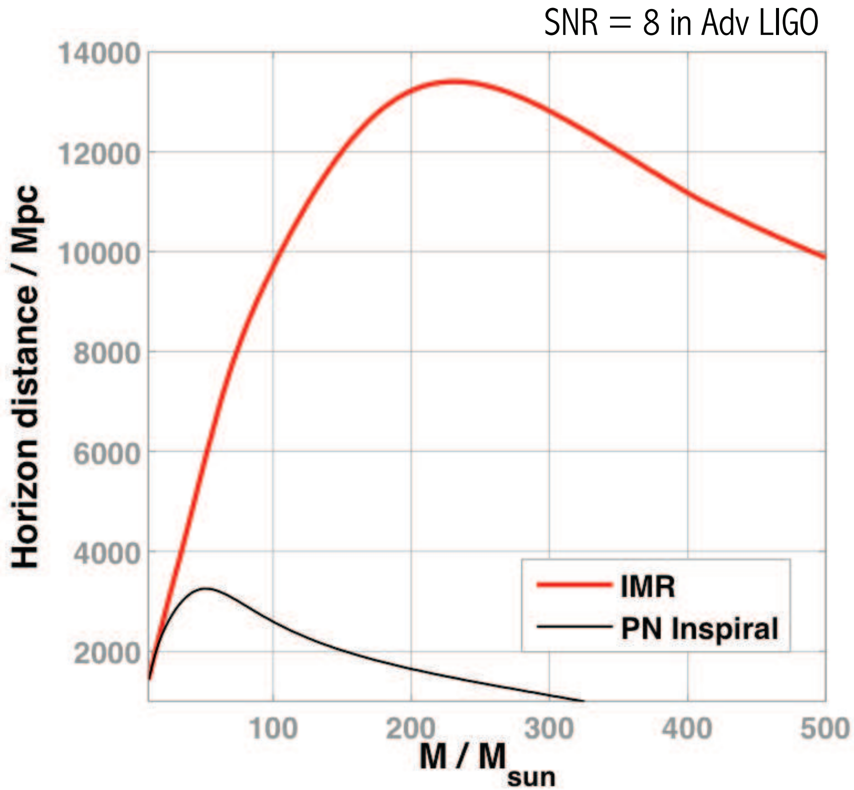


How further can we see with Inspiral, Merger and Ringdown?

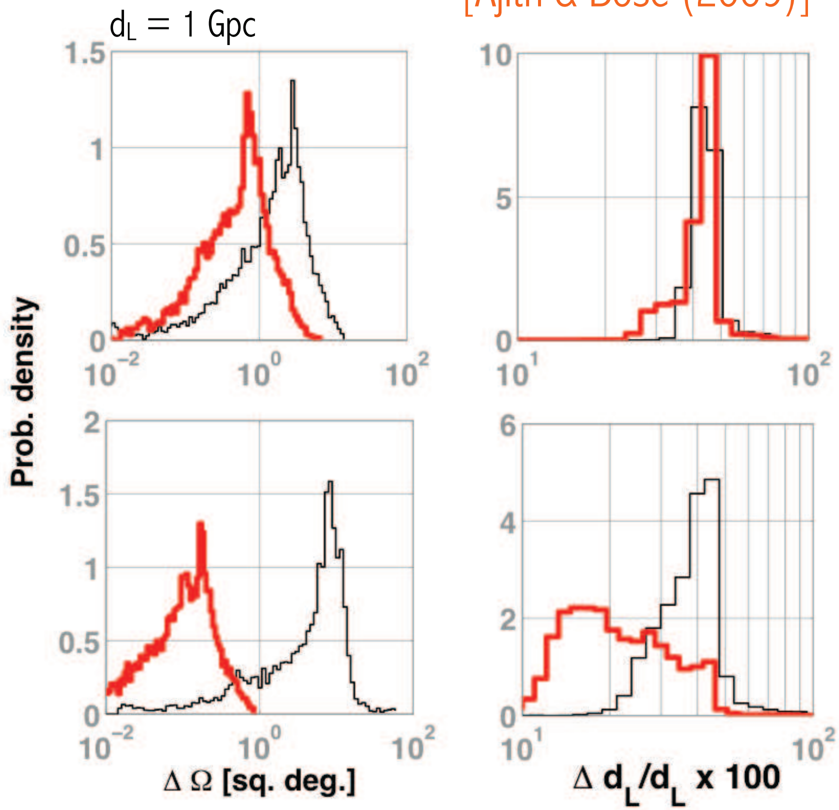


Ajith et al

Comparison of Inspiral and Inspiral-Merger-Ringdown waveforms: Distance Reach (left) Parameter Estimation (right)



[Ajith & Bose (2009)]



Astrophysics

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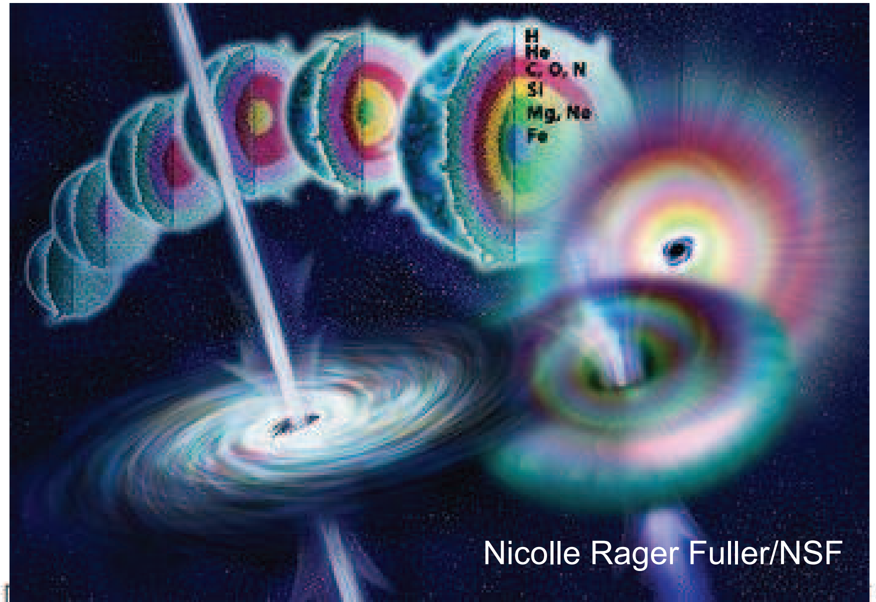
- NS spin frequencies in LMXBs
  - Why are spin frequencies of neutron stars in low-mass X-ray binaries bounded, CFS instability and r-modes

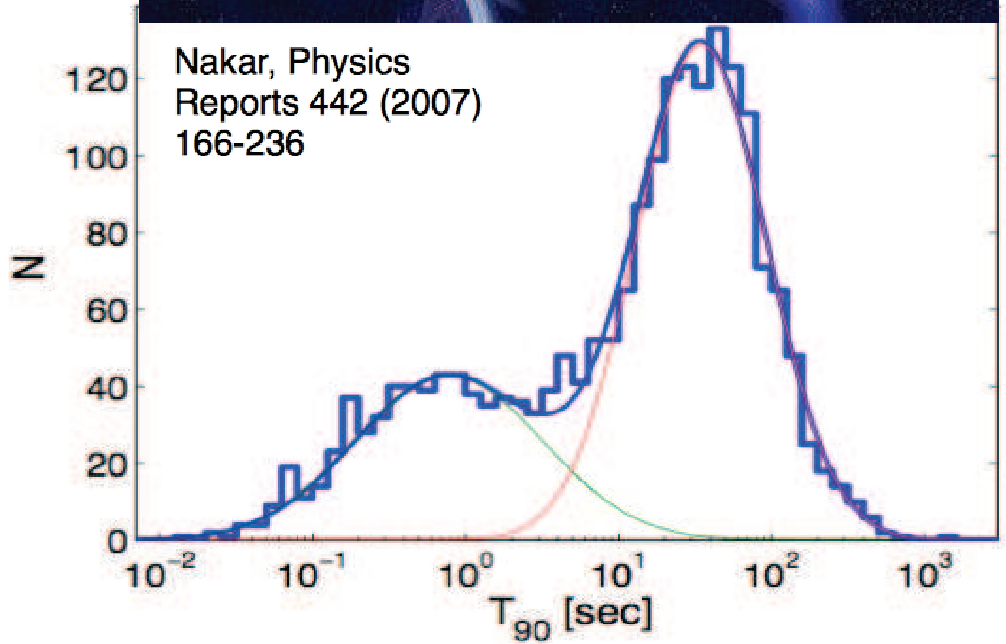
Expected Annual Coalescence Rates

- 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

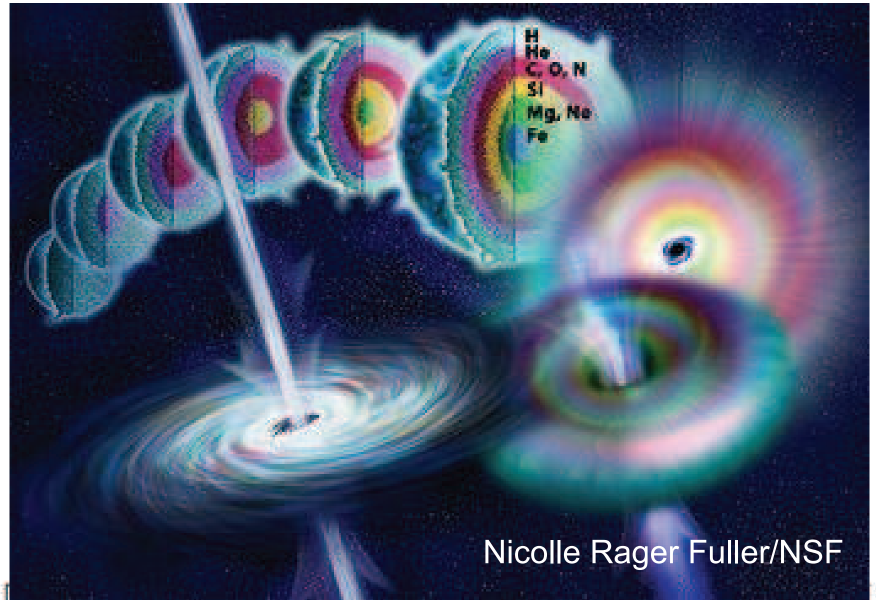
GRB Progenitors

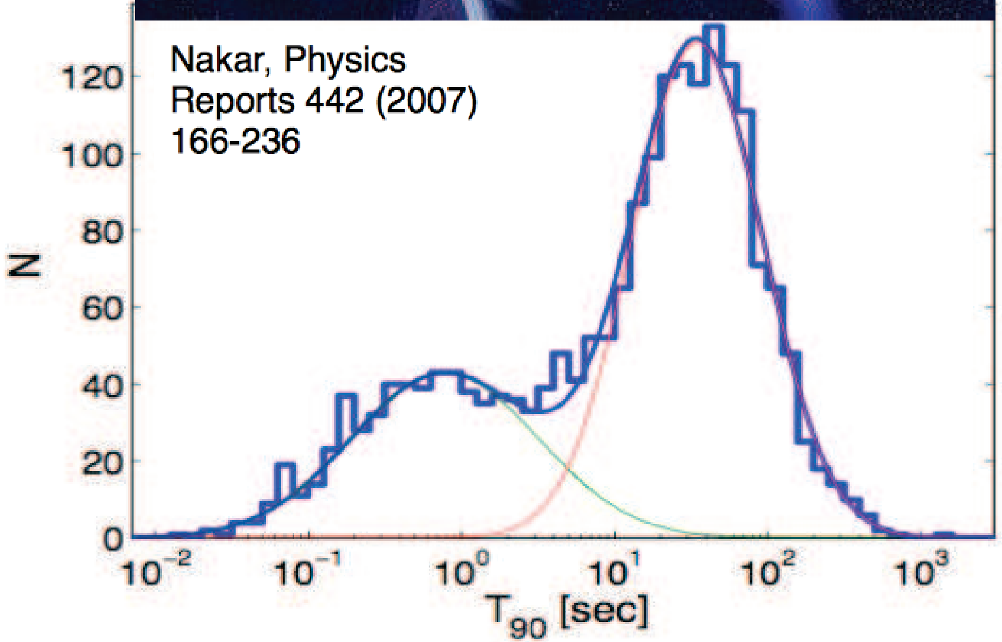




GRB Progenitors

- Intense flashes of gamma-rays:





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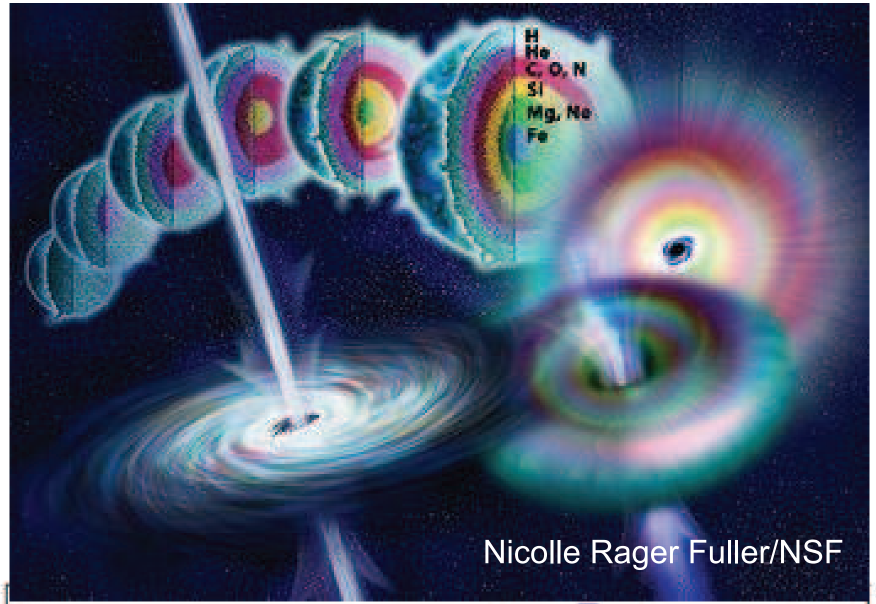

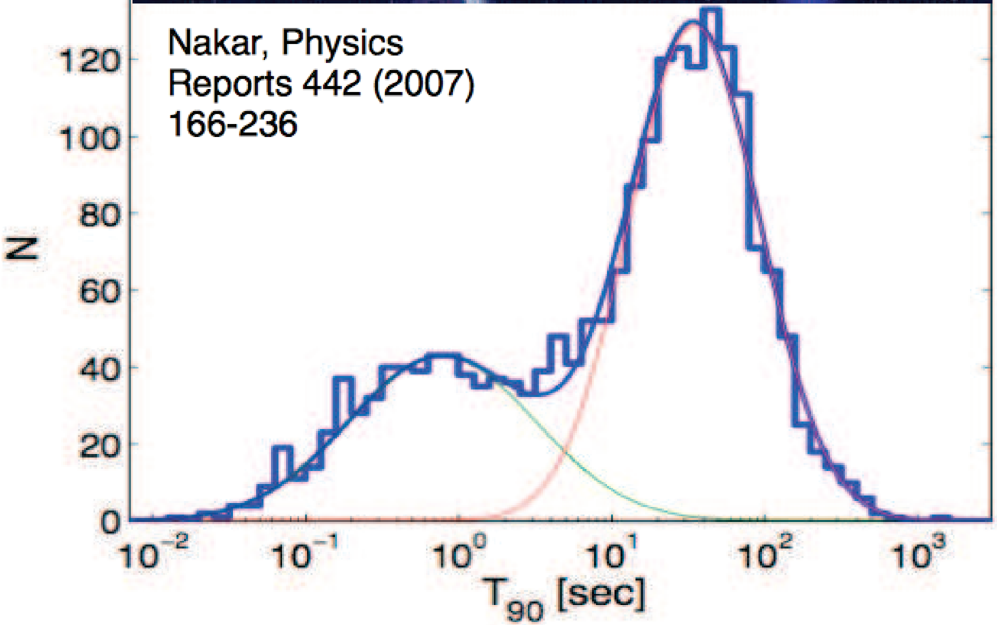

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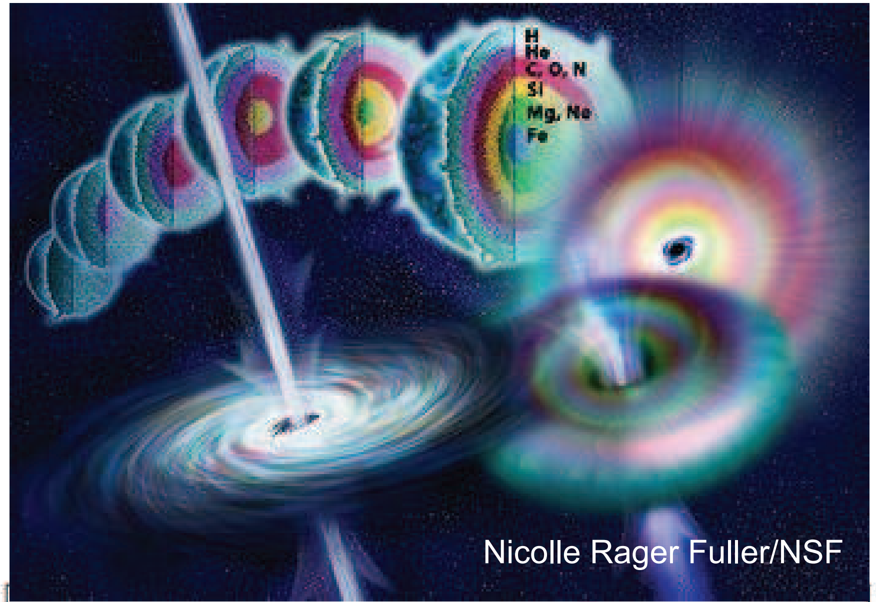

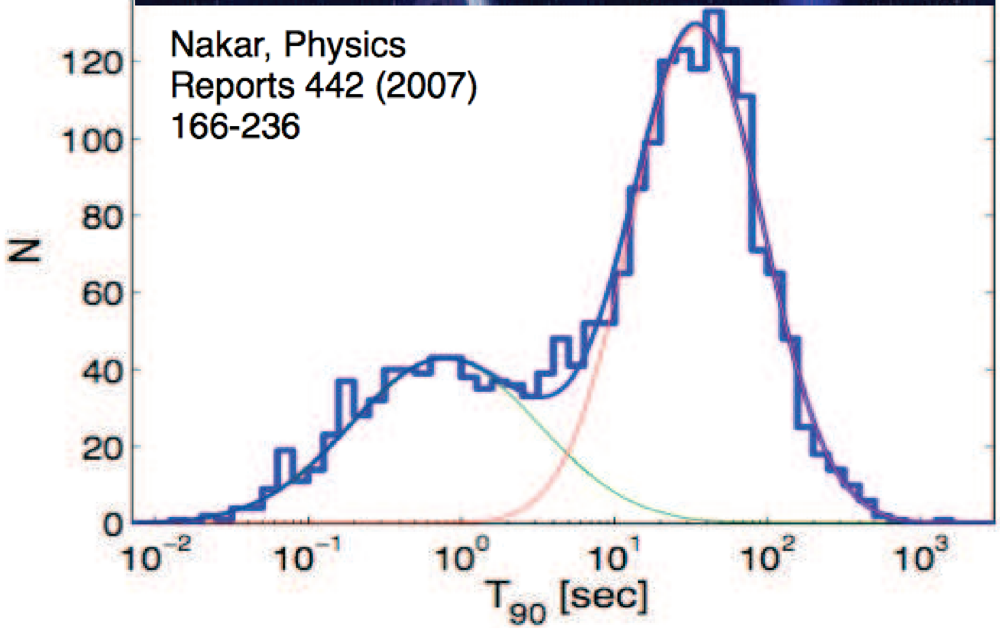

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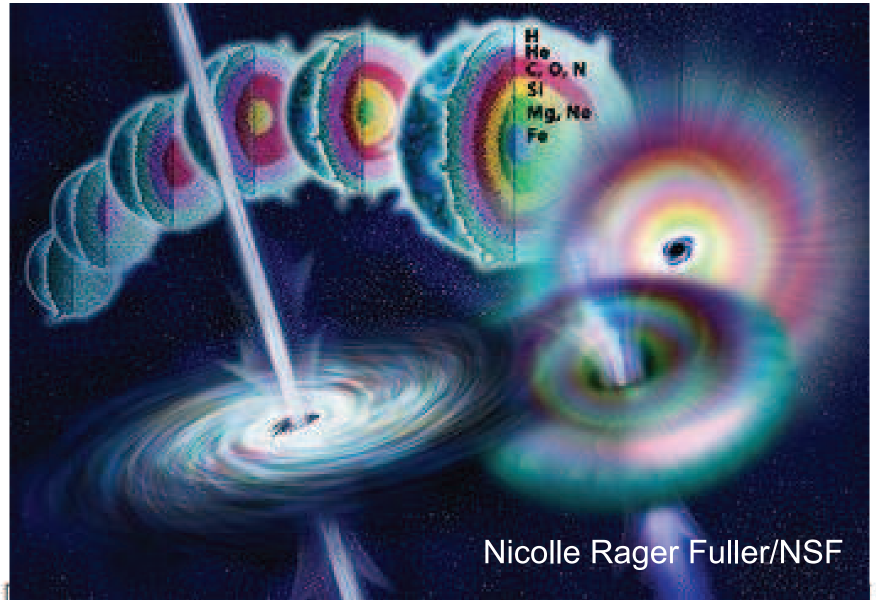

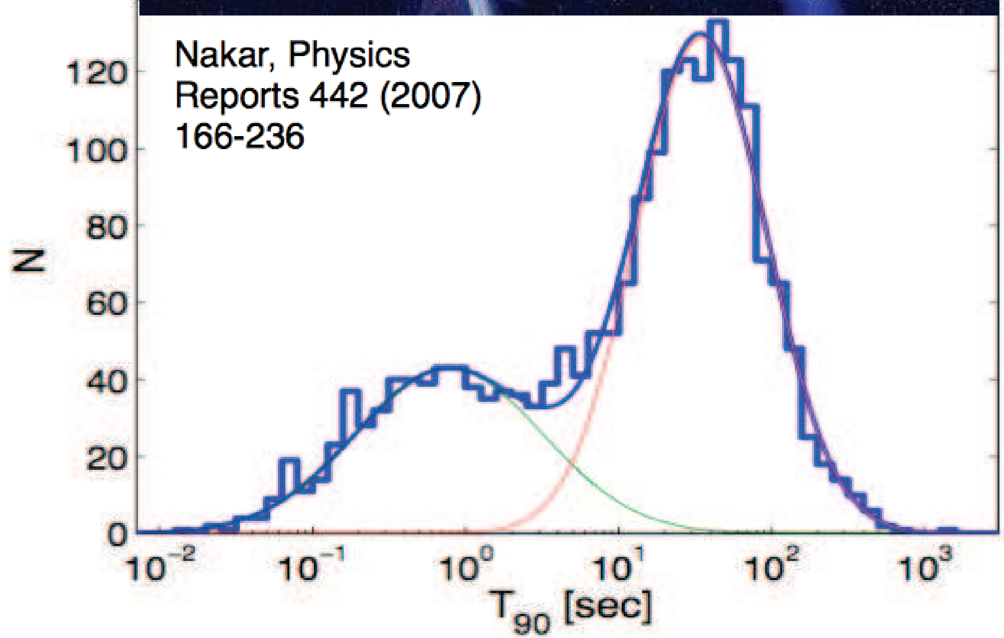

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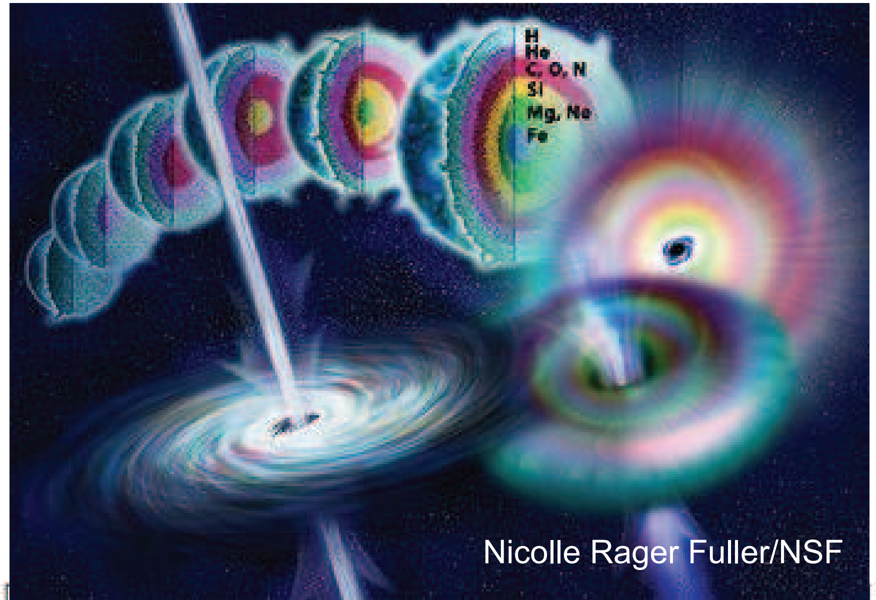

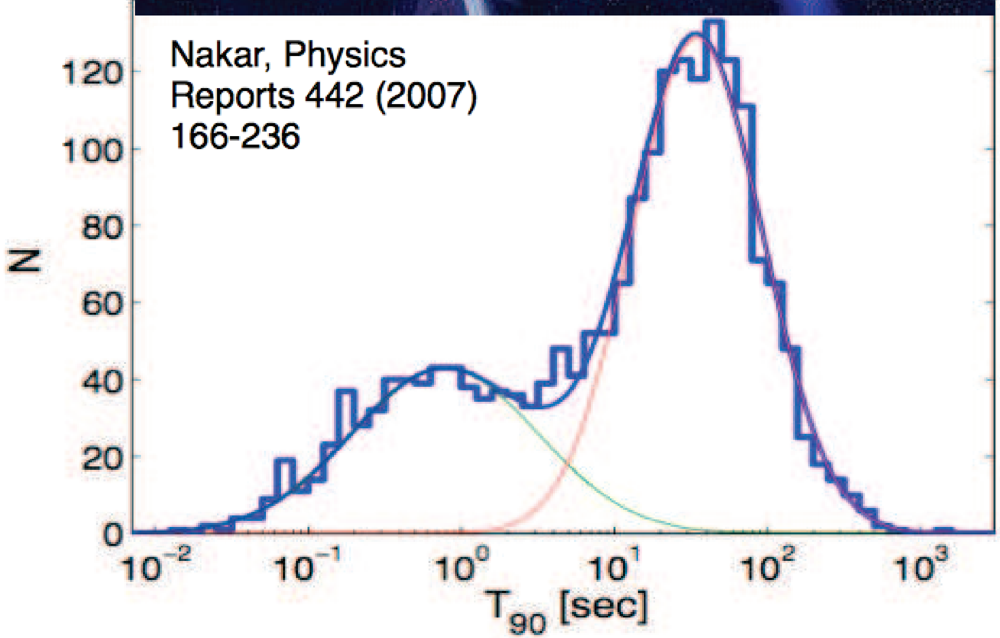

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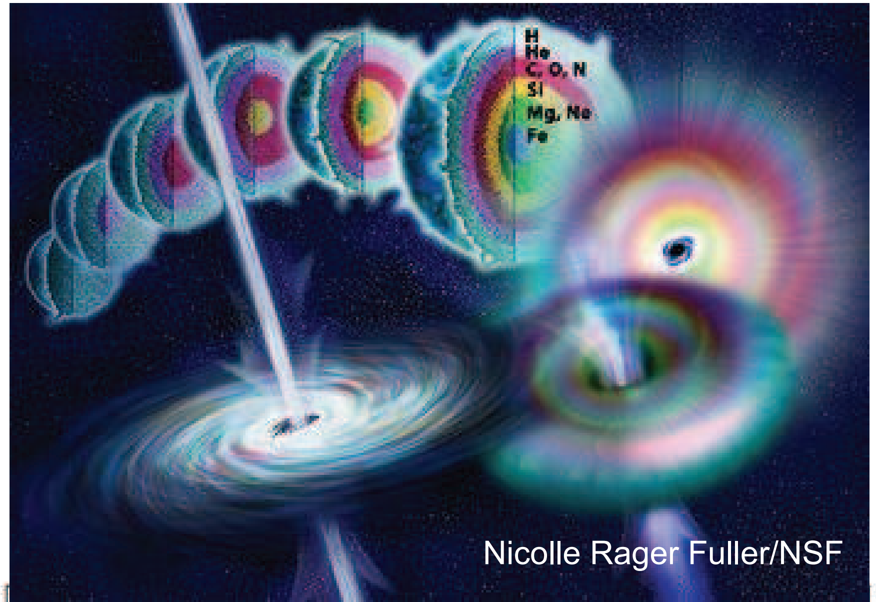

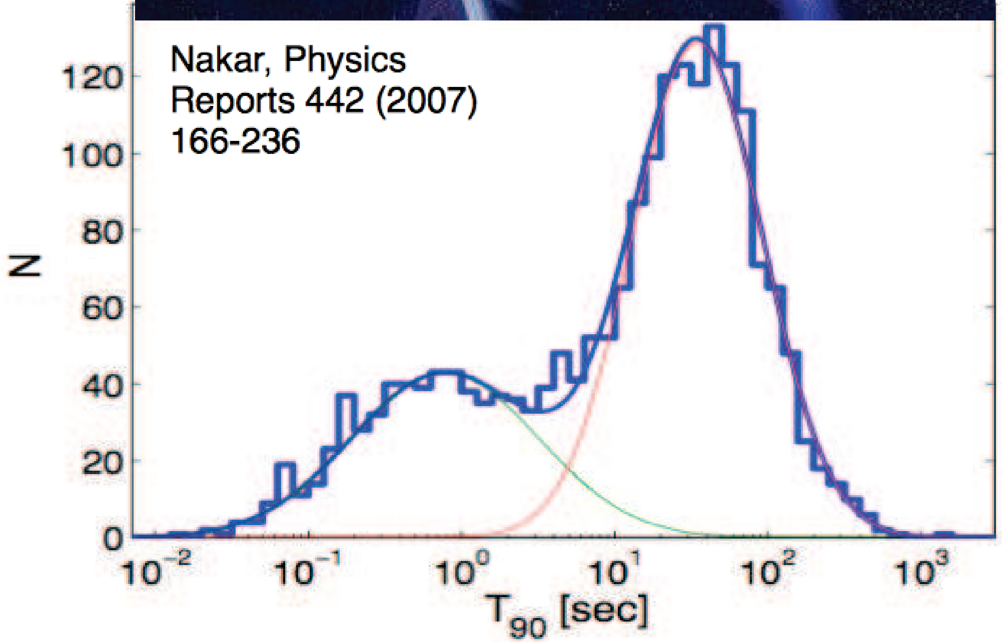

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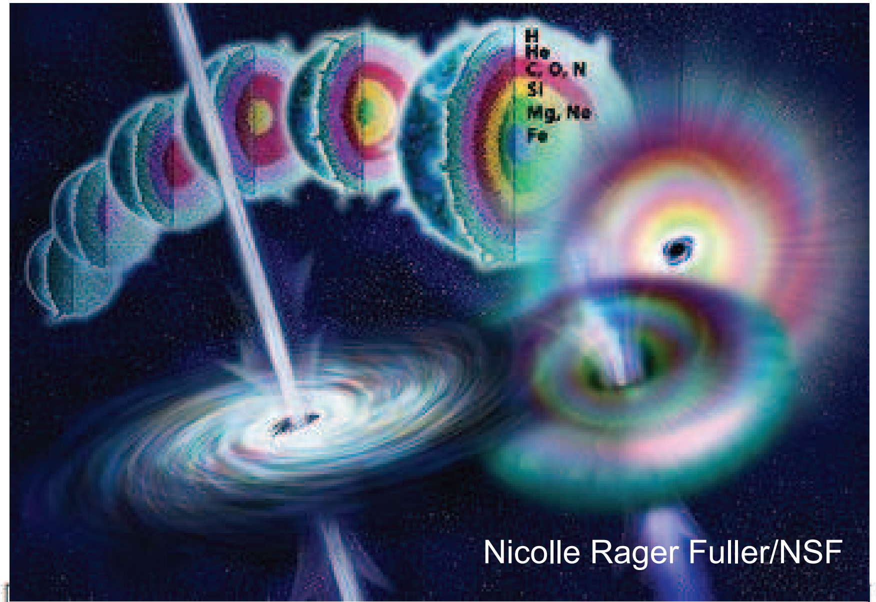

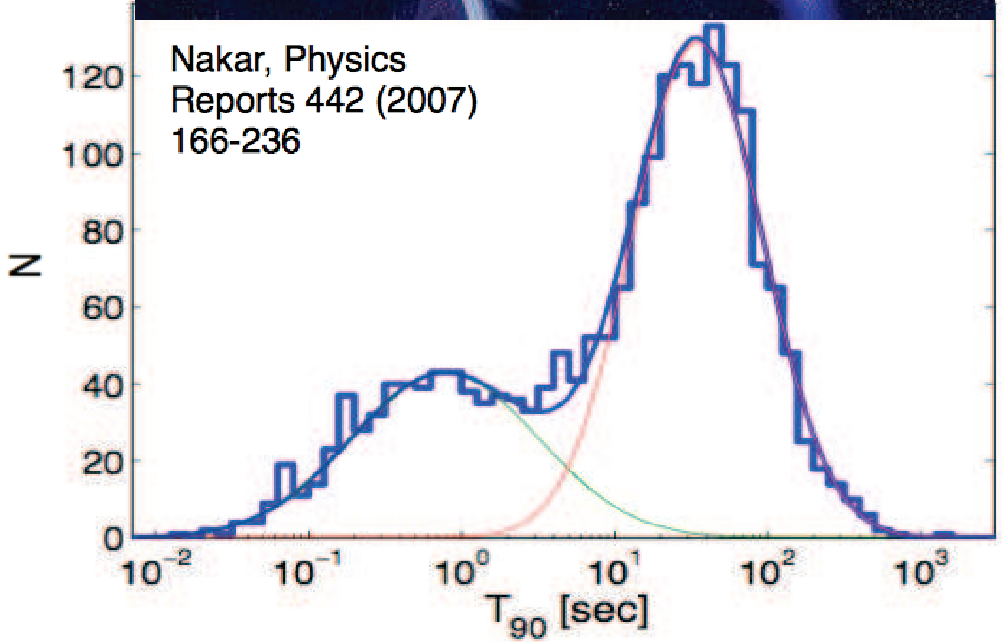

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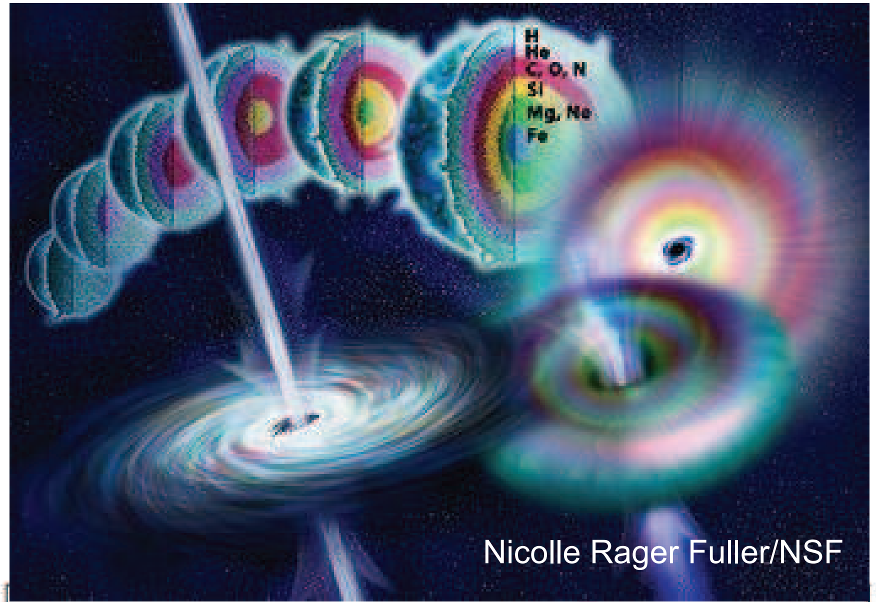

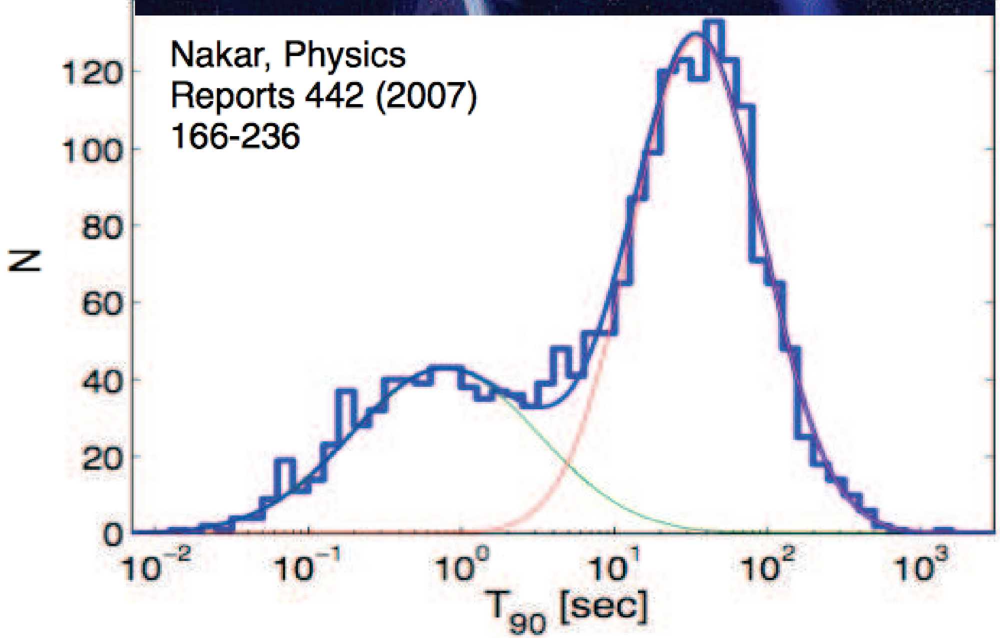

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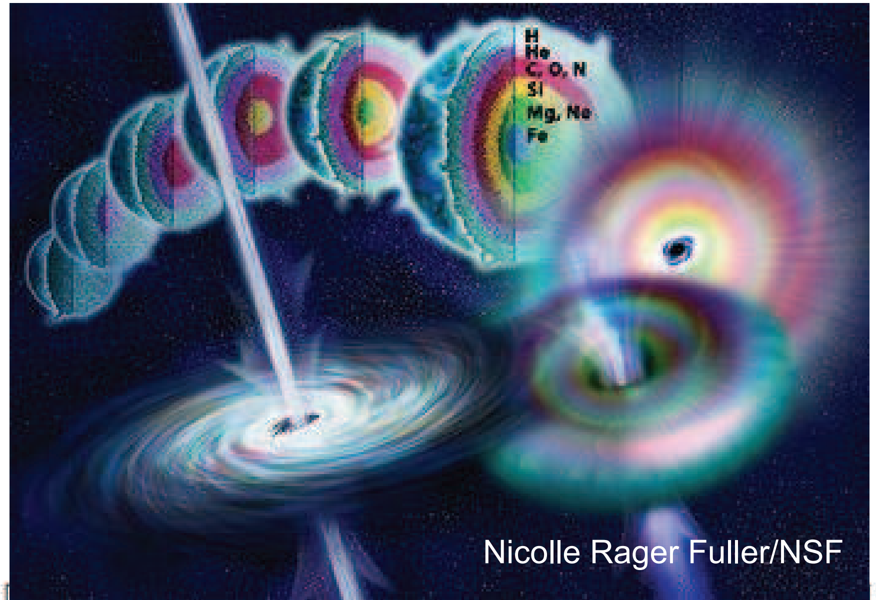

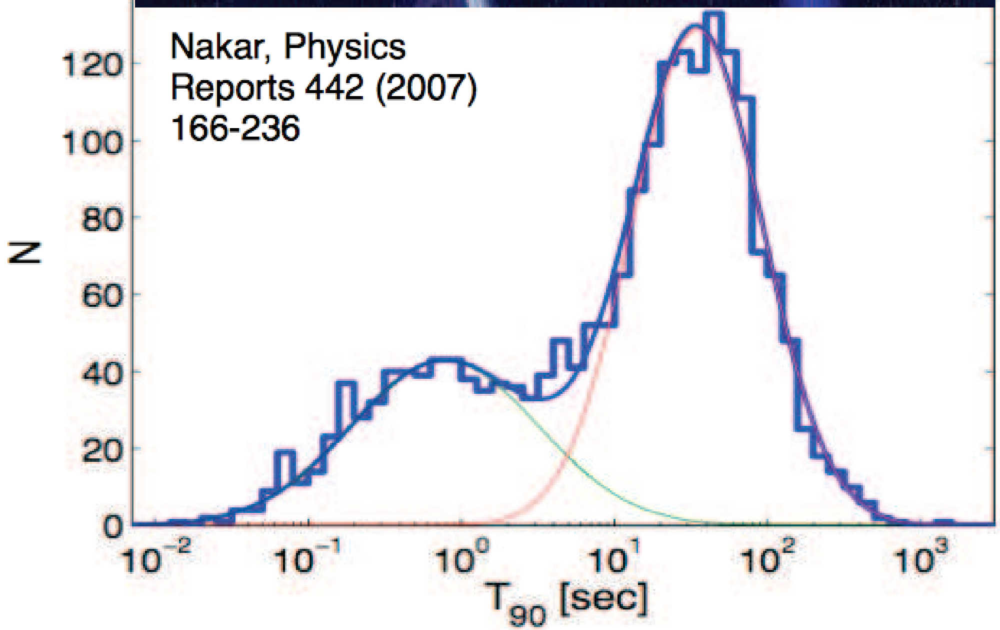

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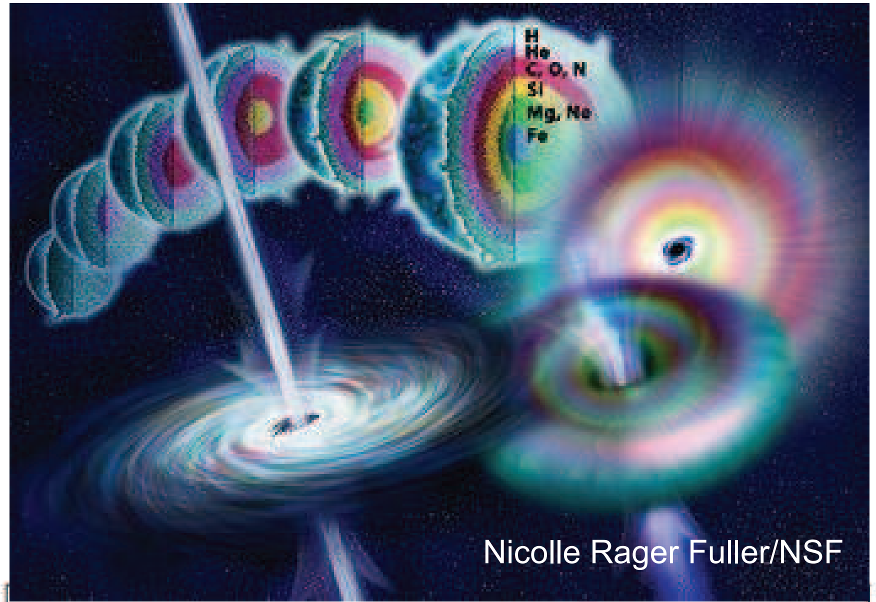
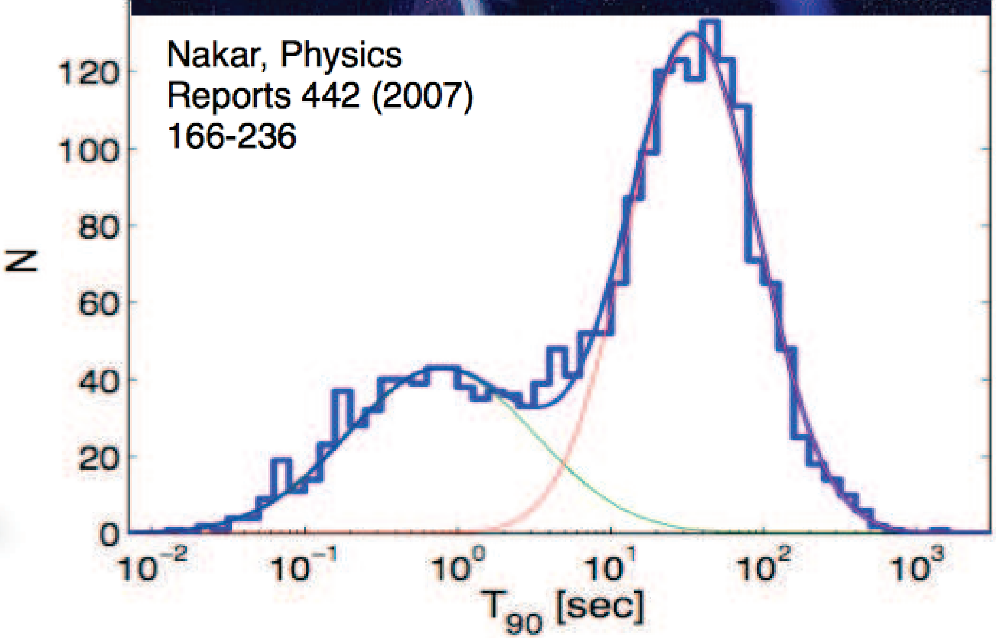
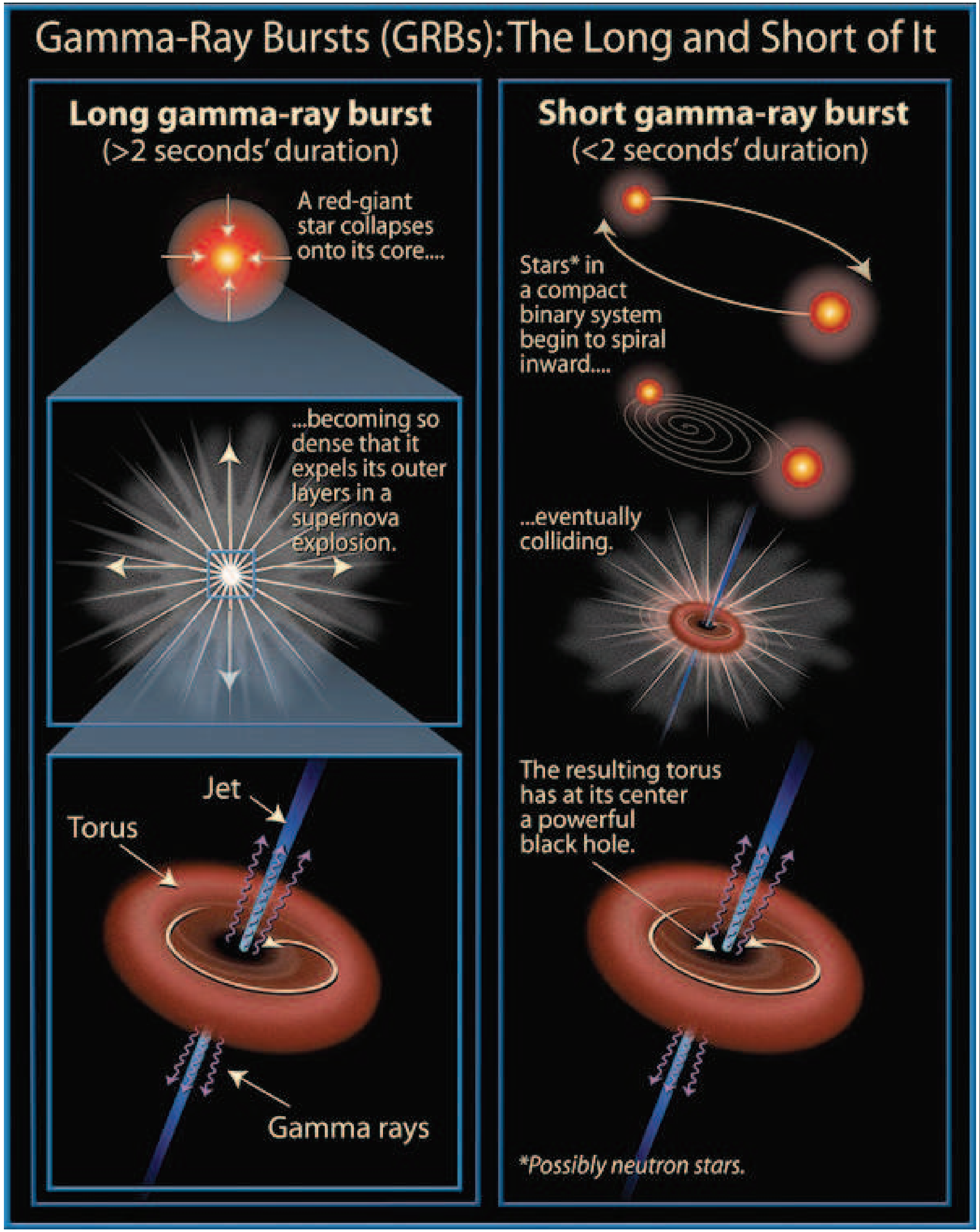




GRBs - The Long and Short of it



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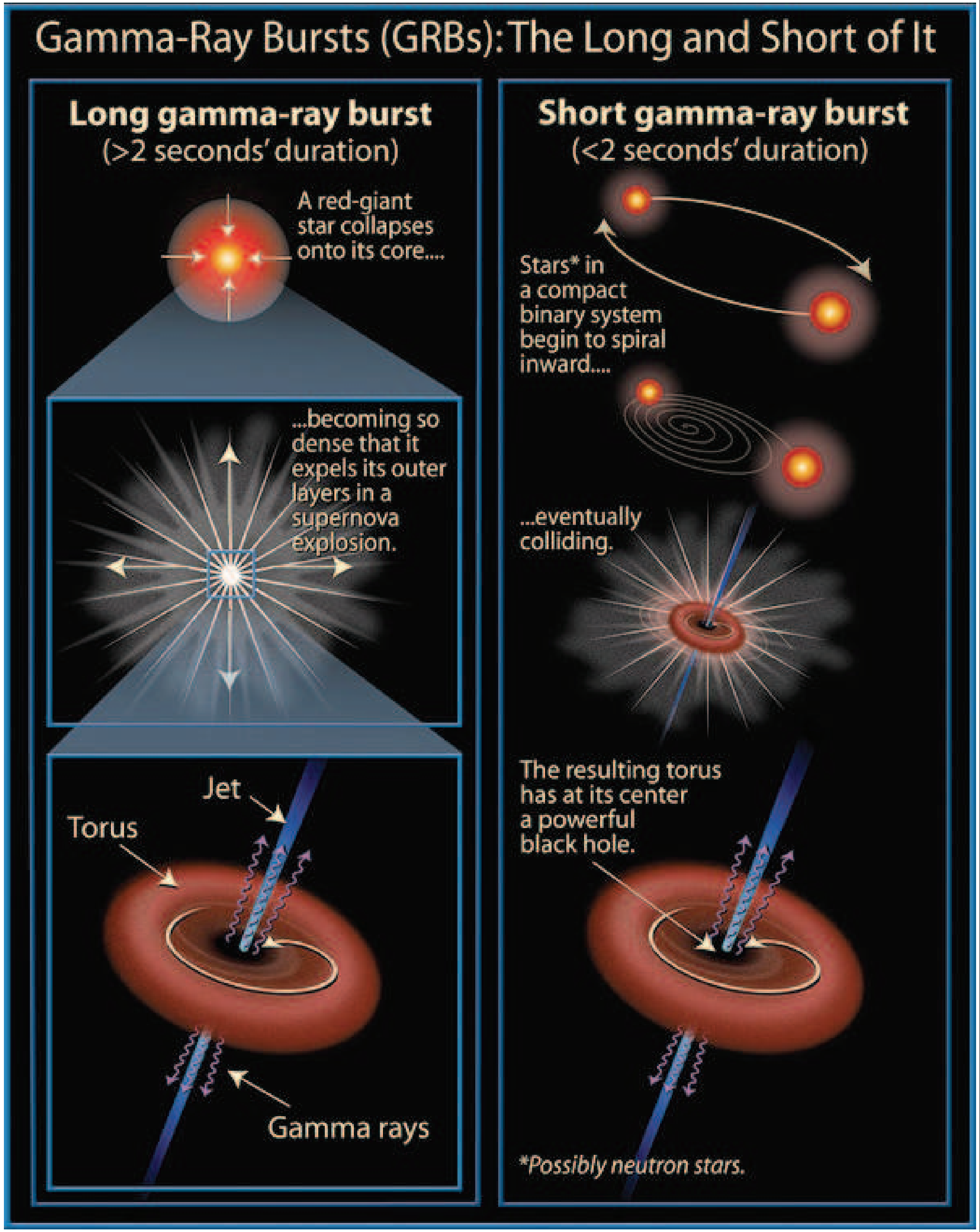

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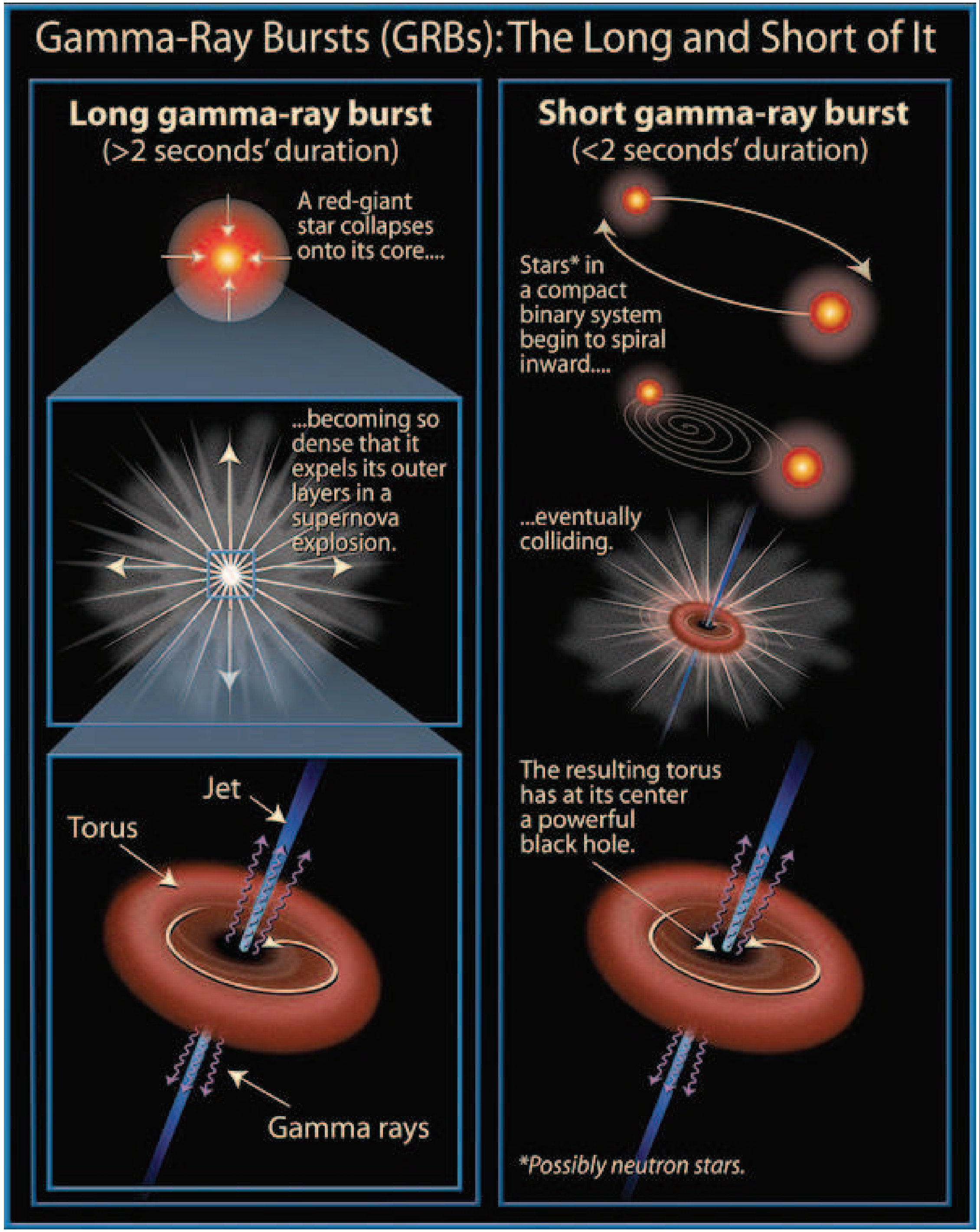

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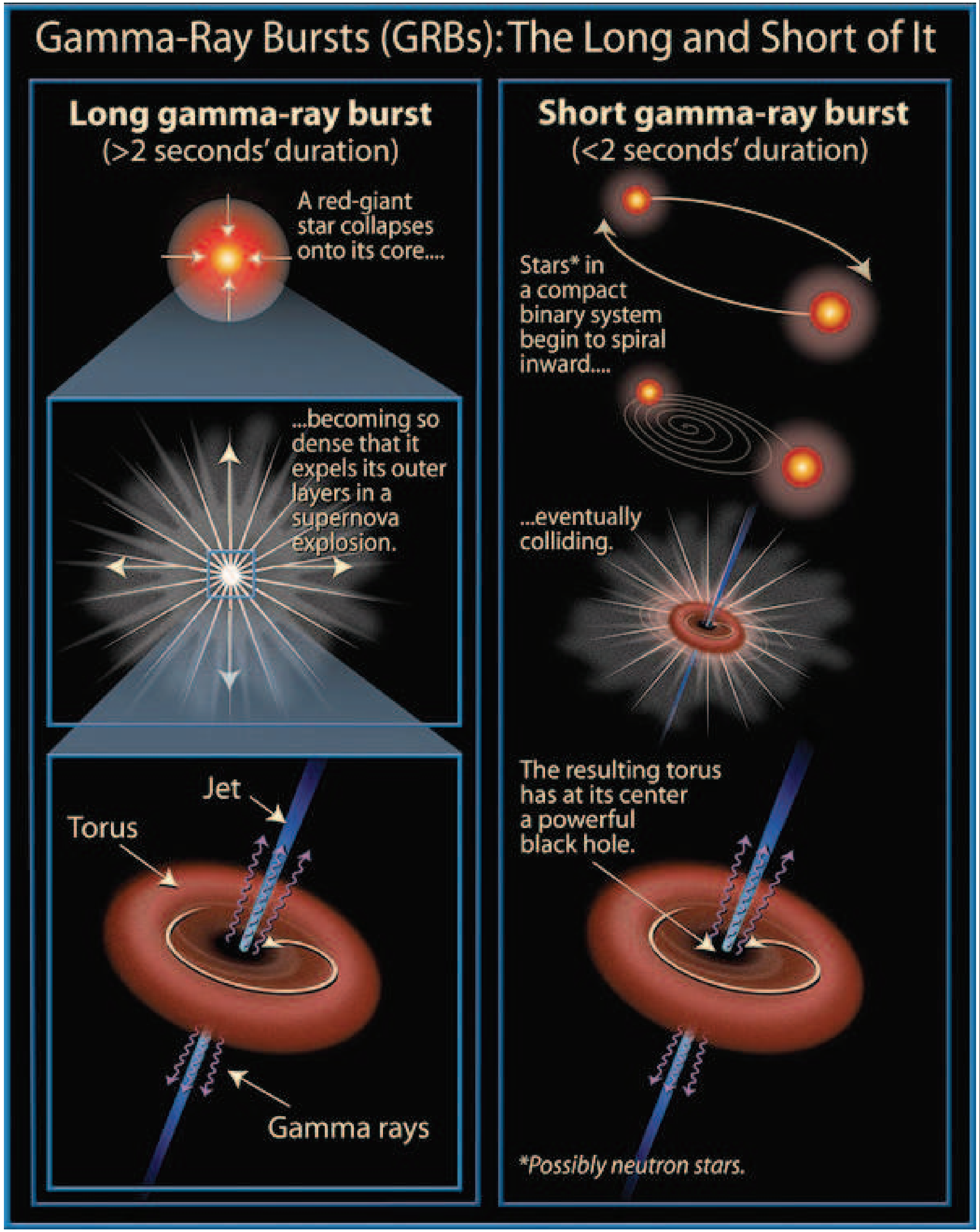

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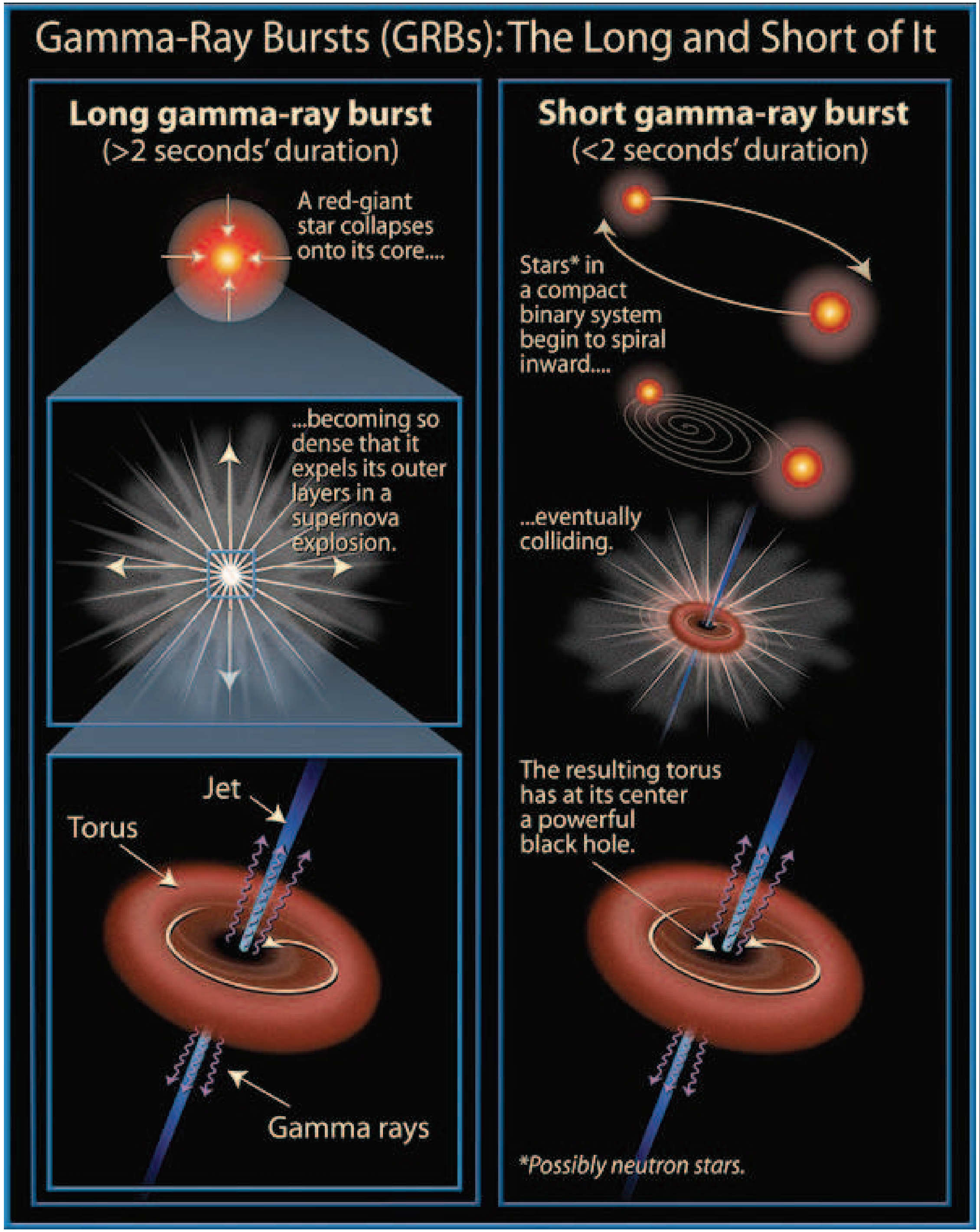

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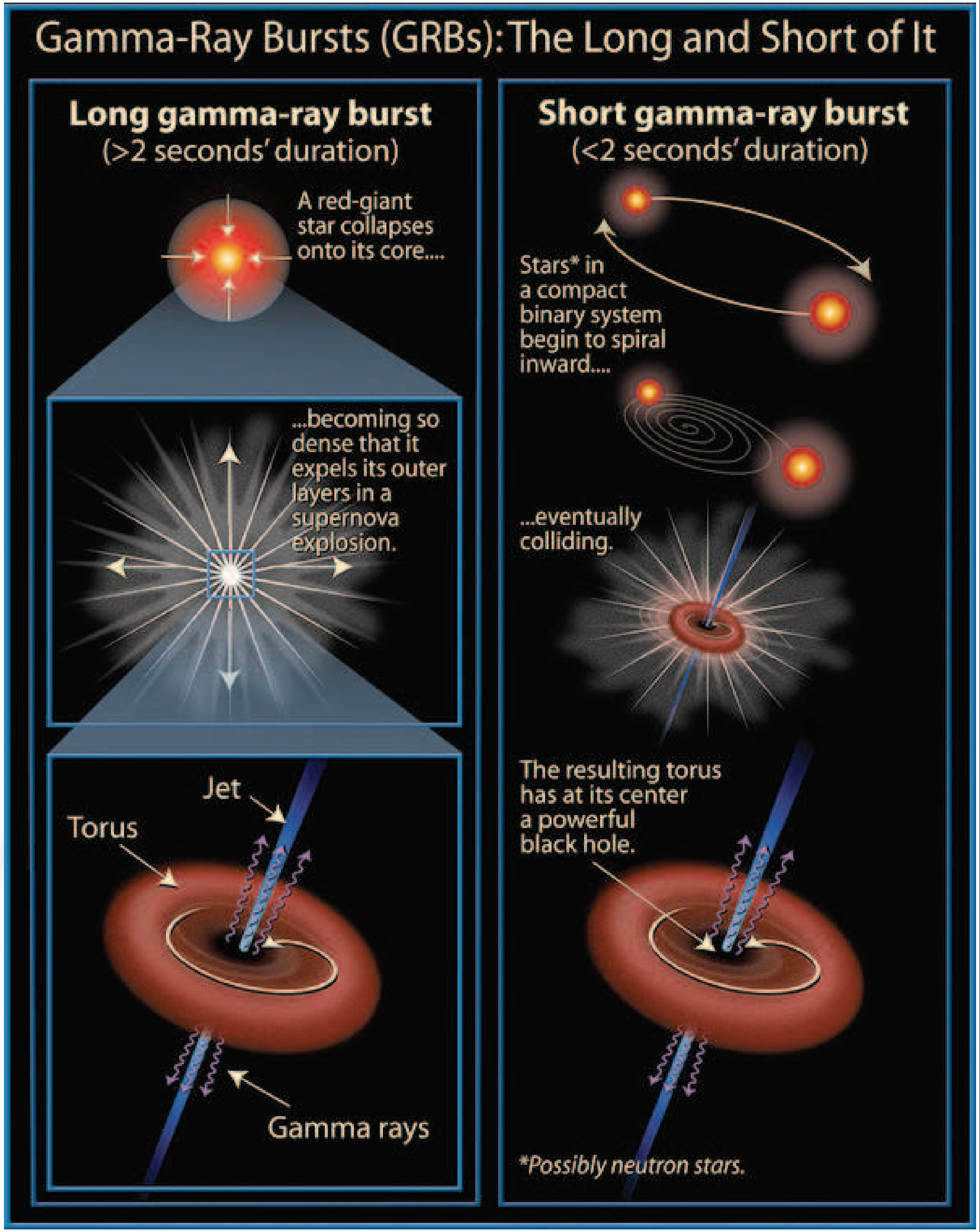

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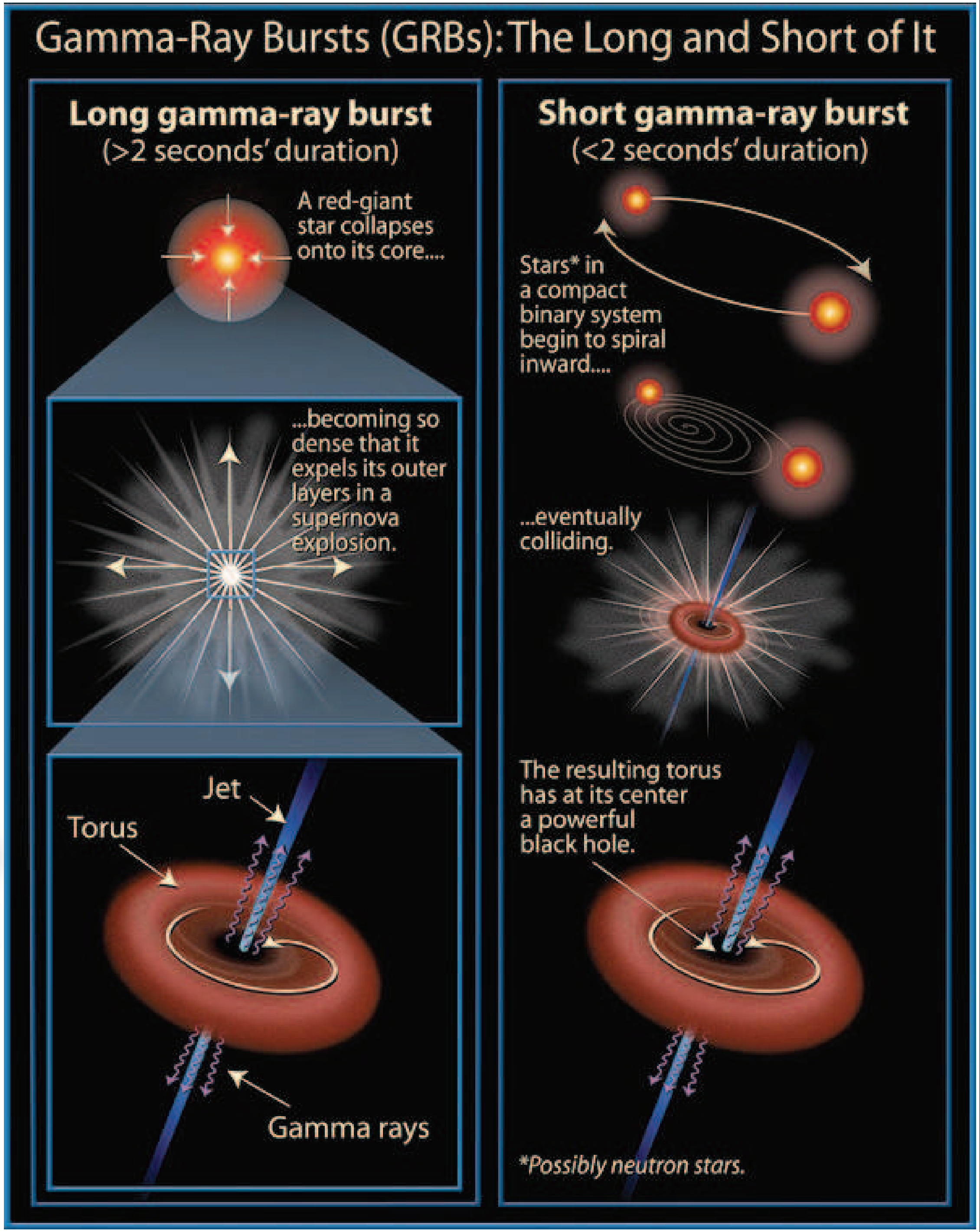
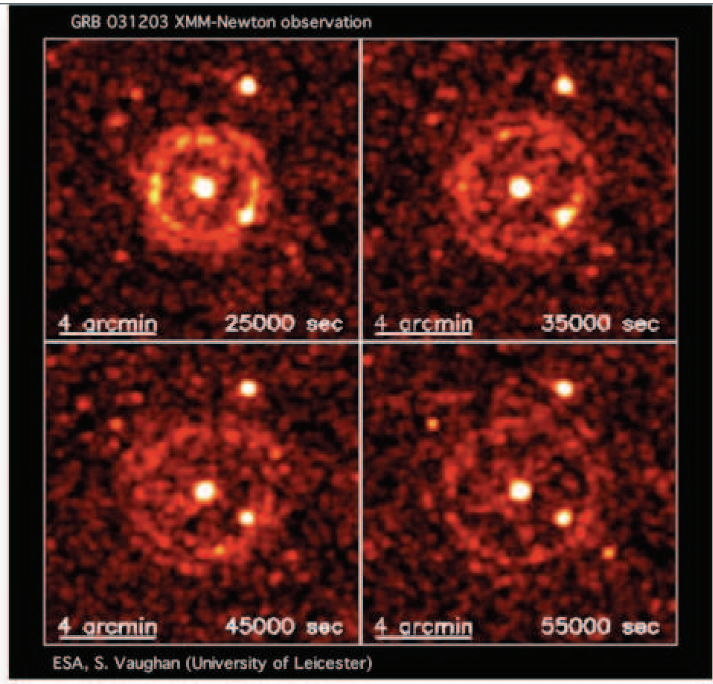
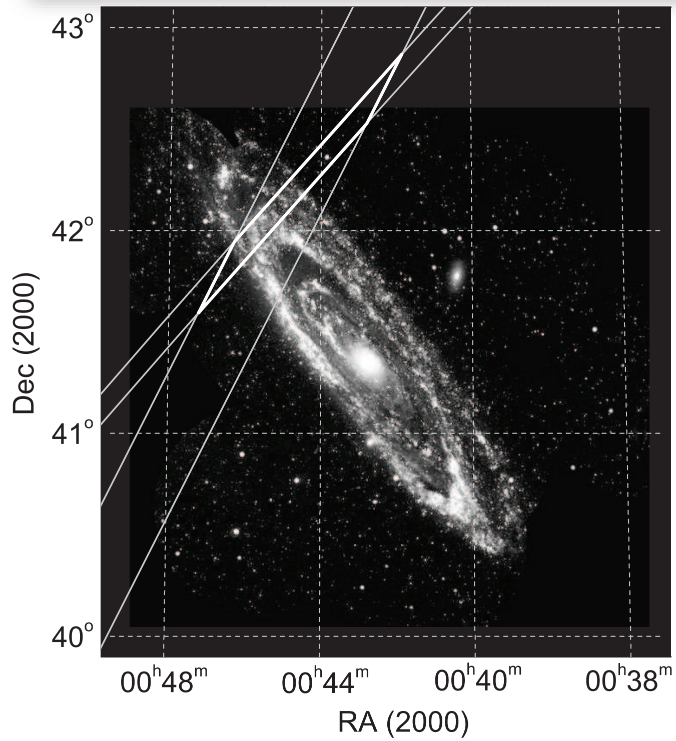


Origin of GRB 070201 from LIGO Observations

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





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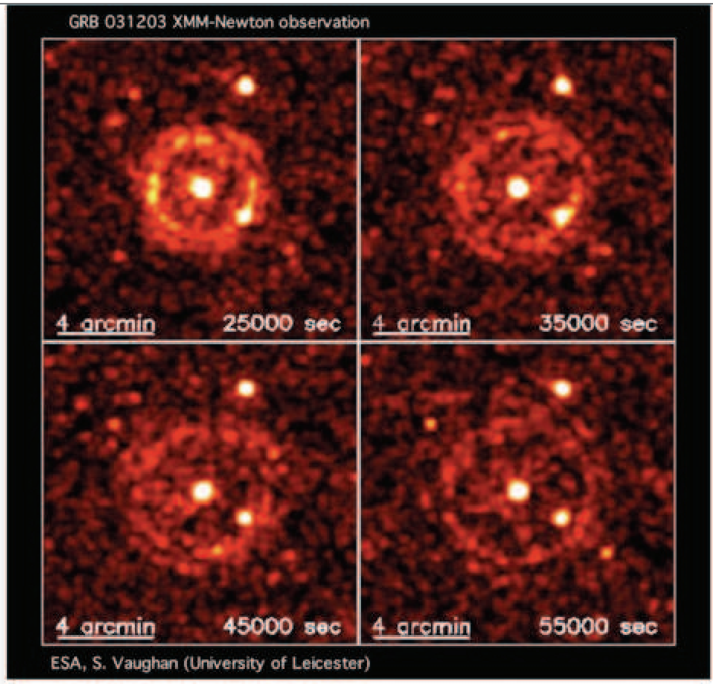

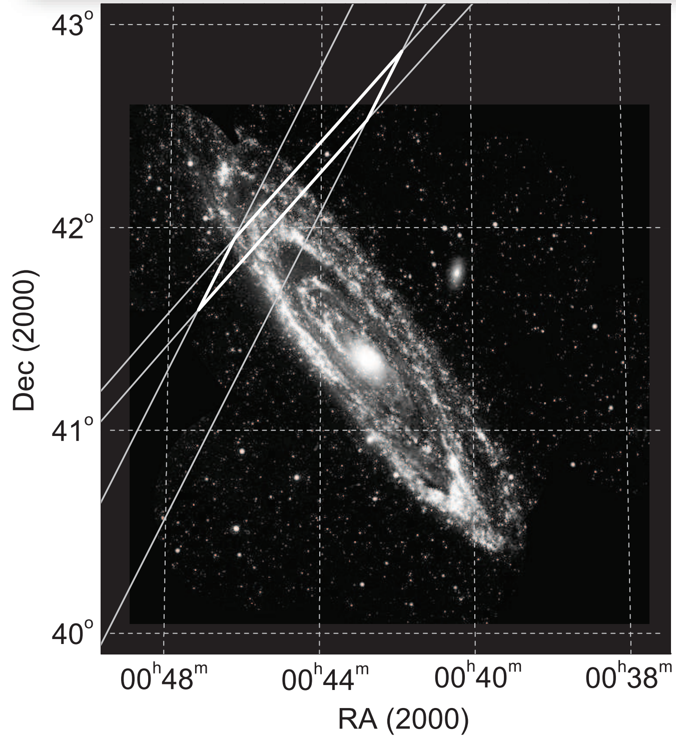

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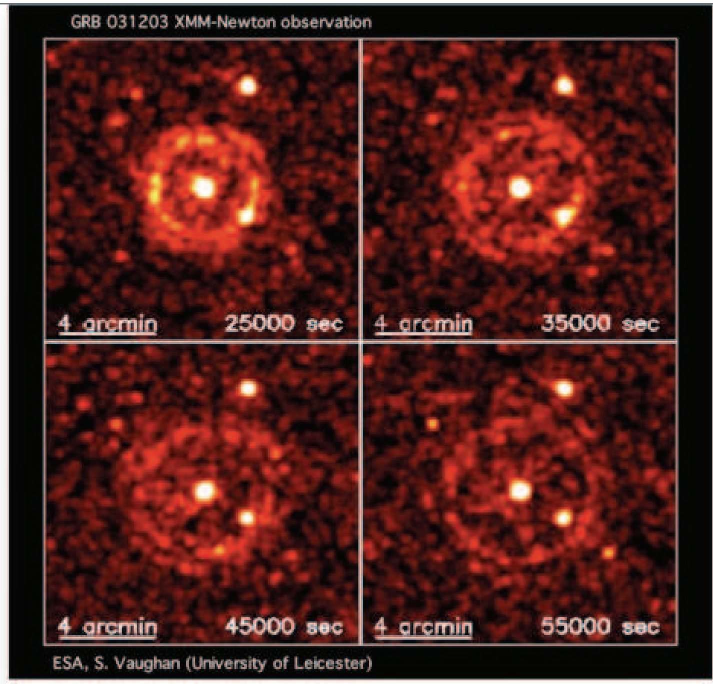

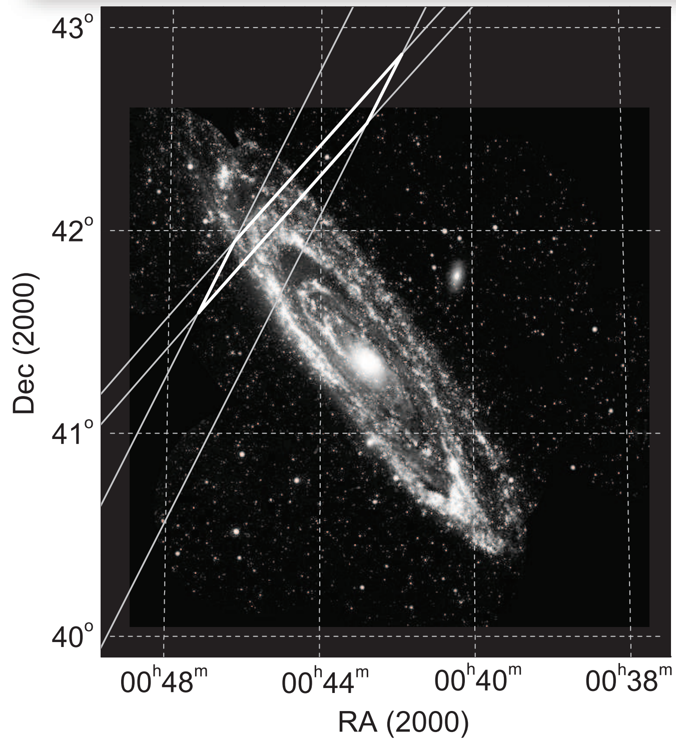

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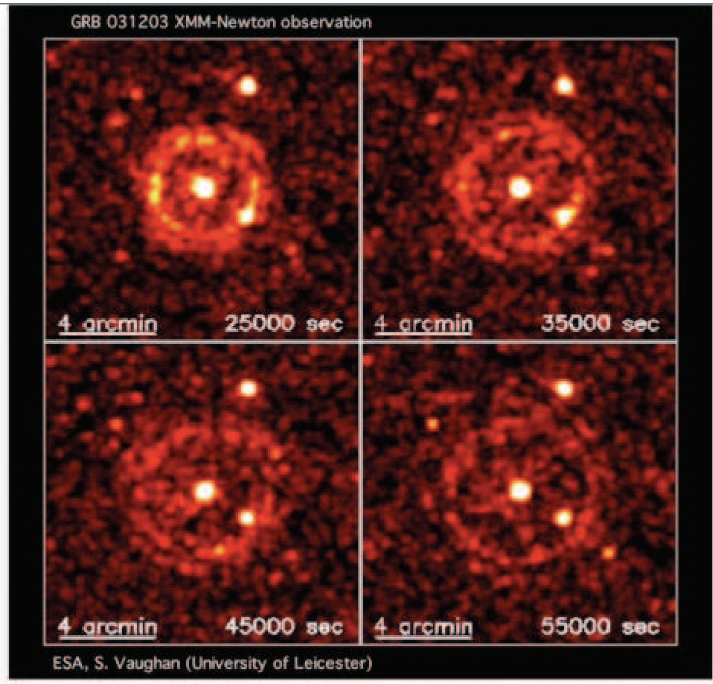

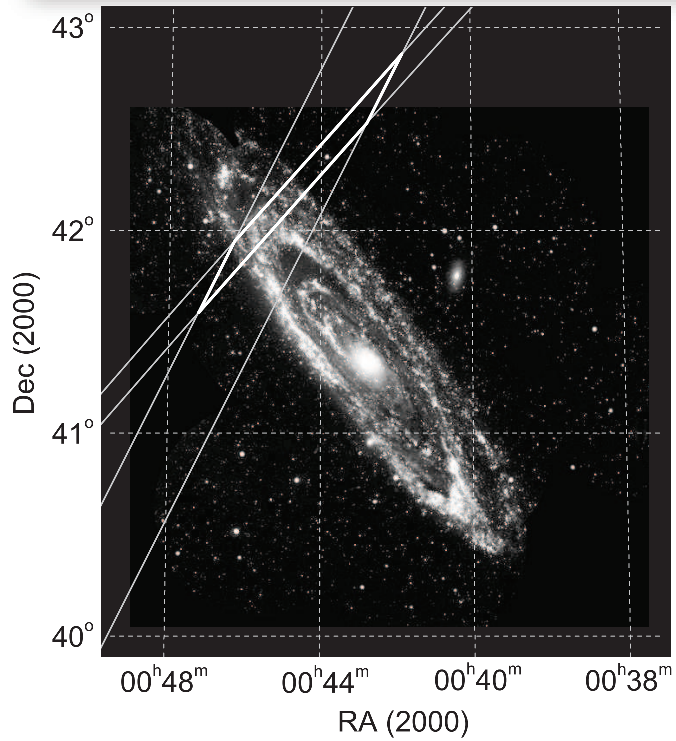

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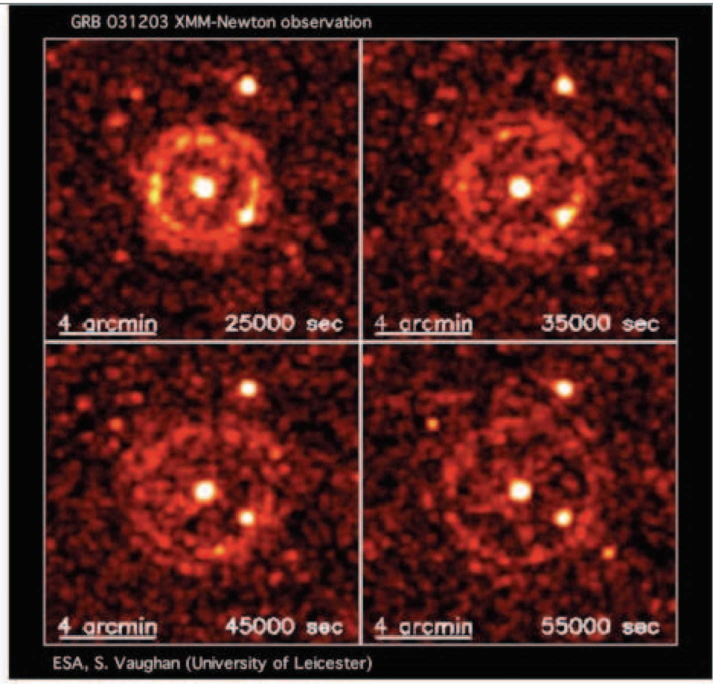
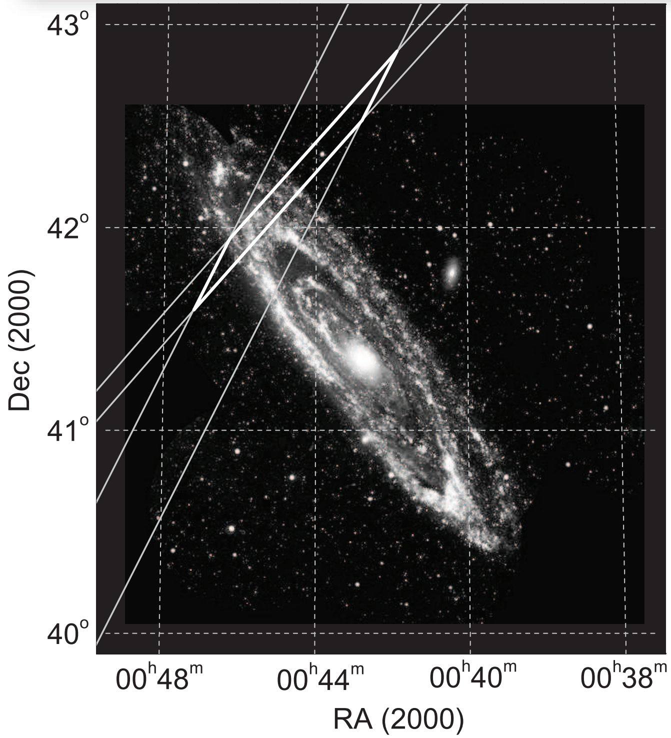
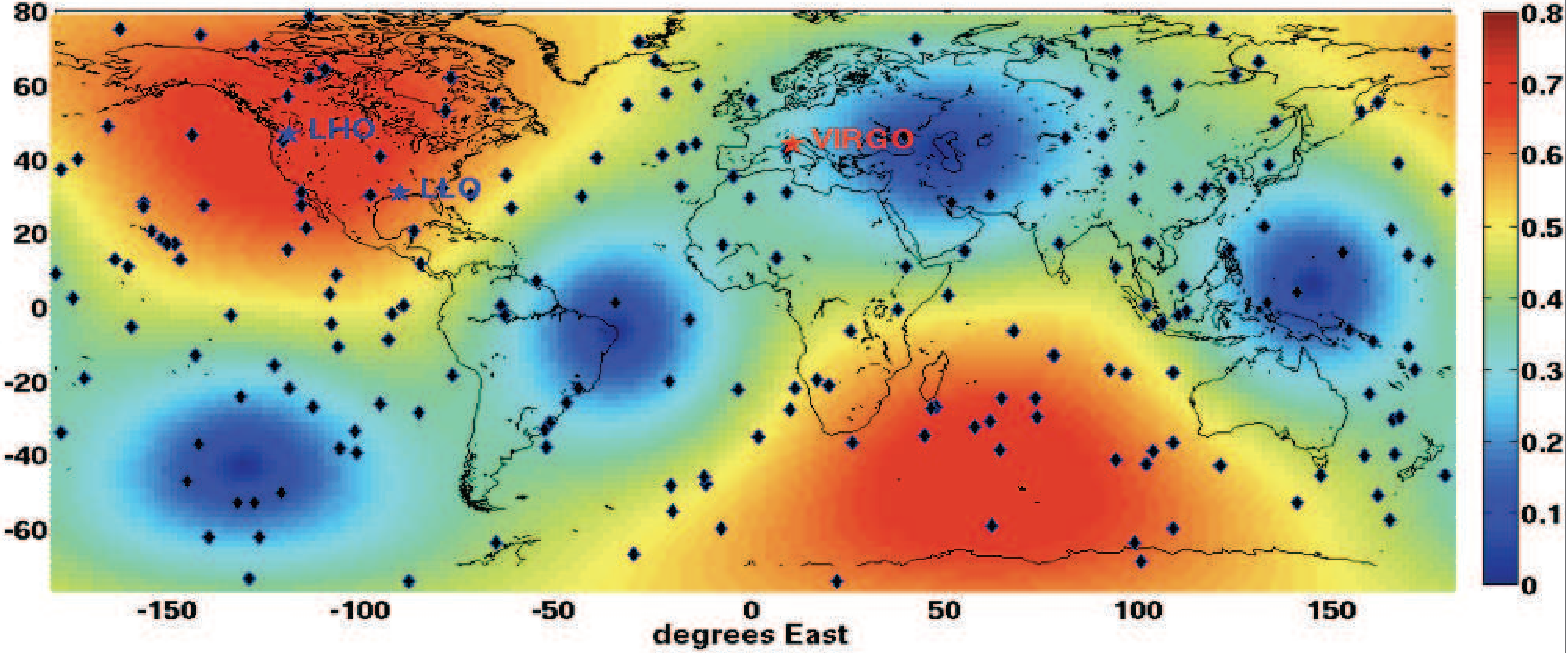




Search for GRBs during all of S5



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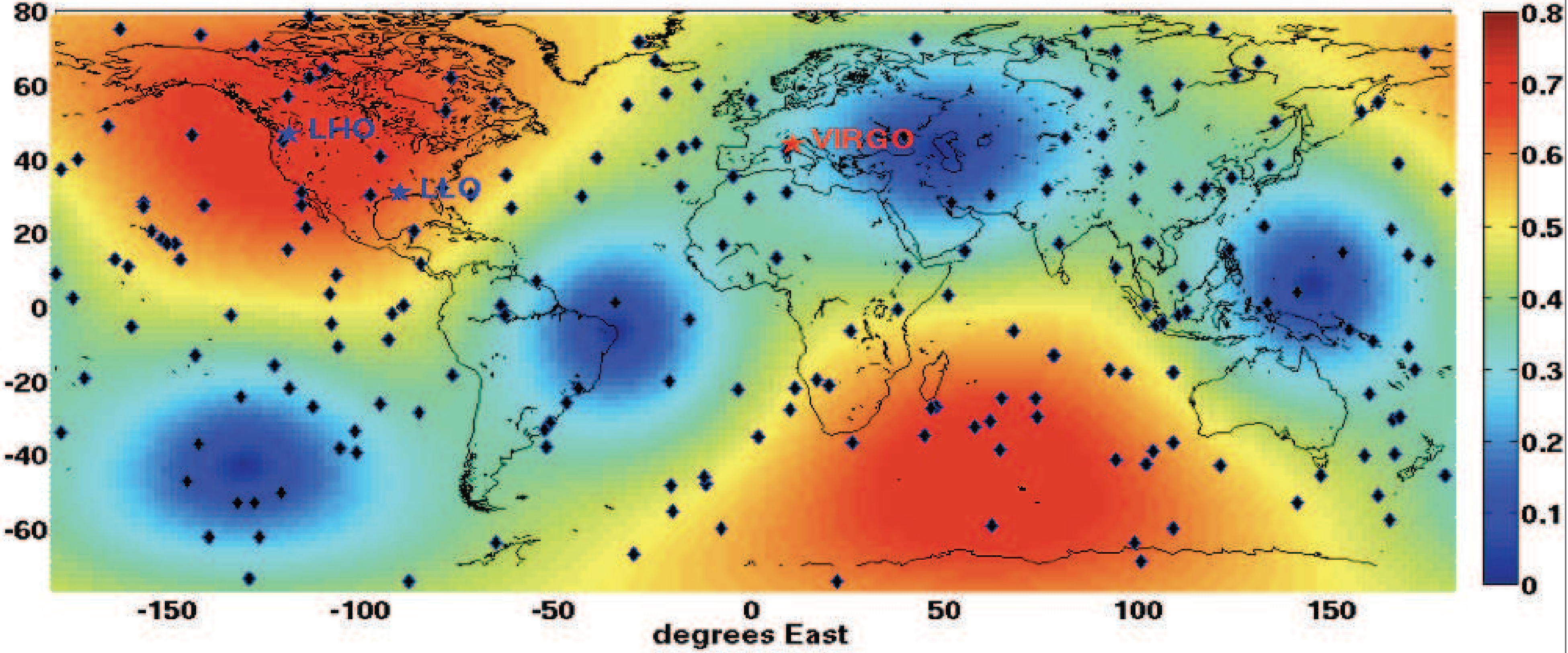

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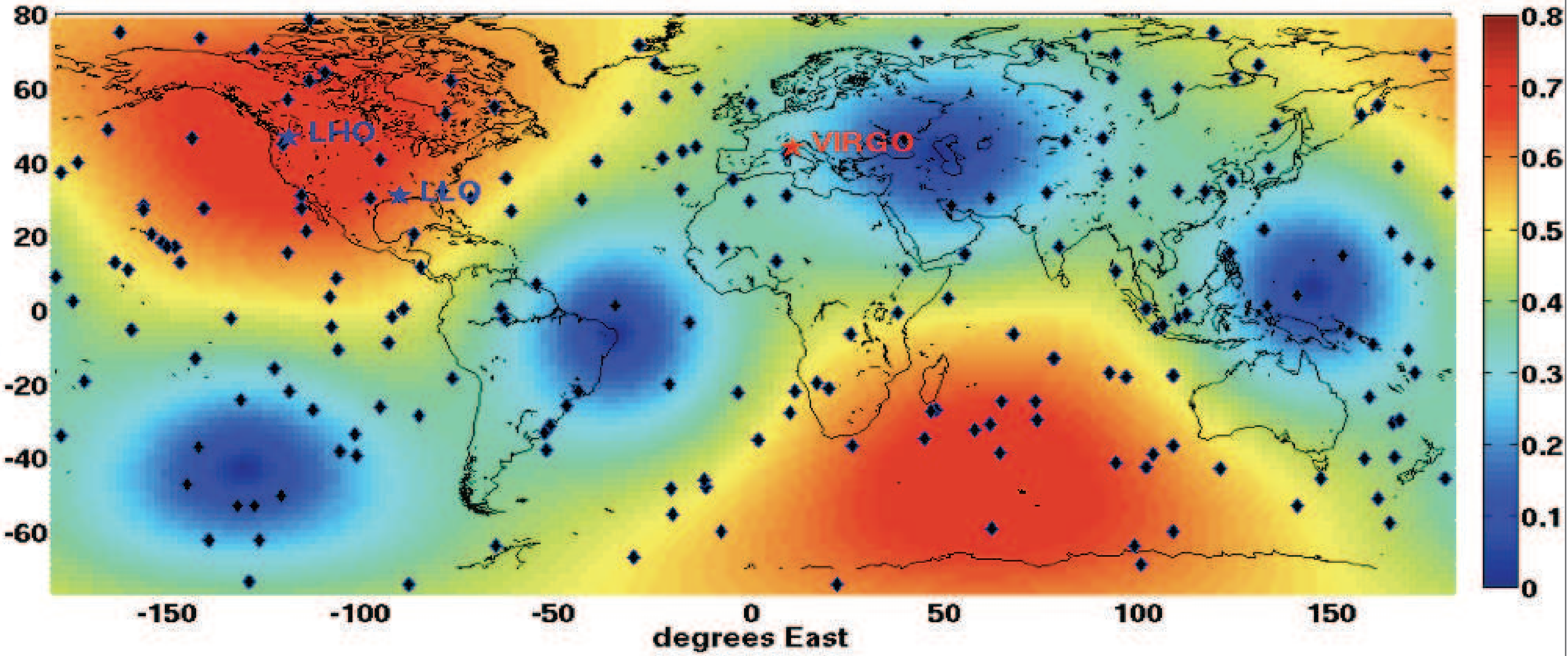

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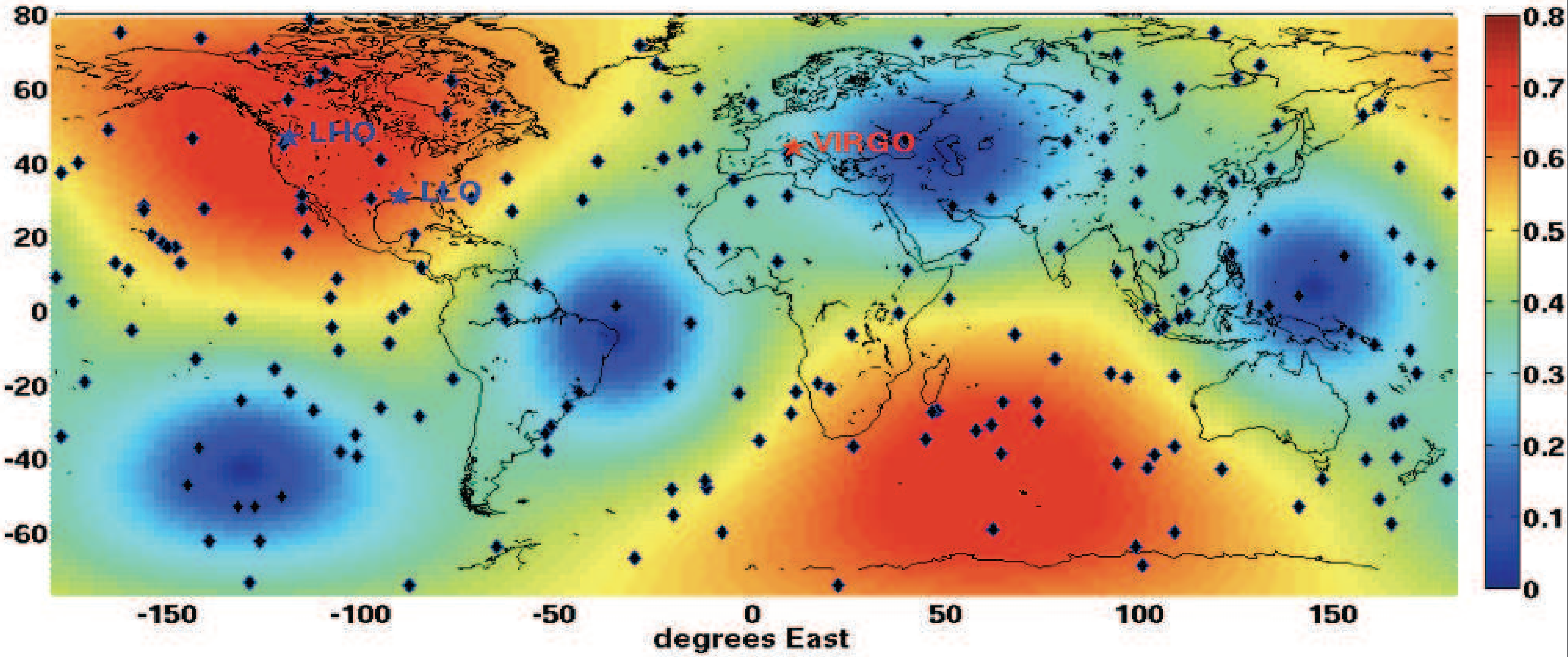

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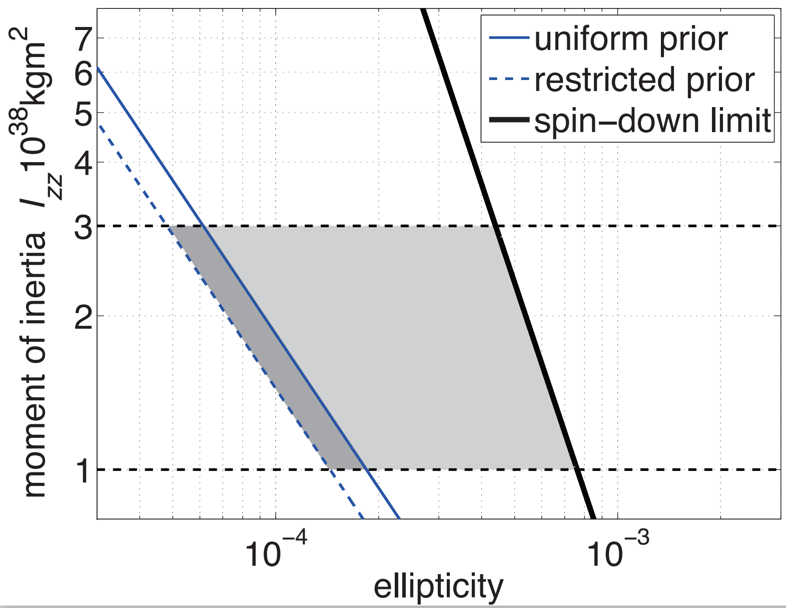
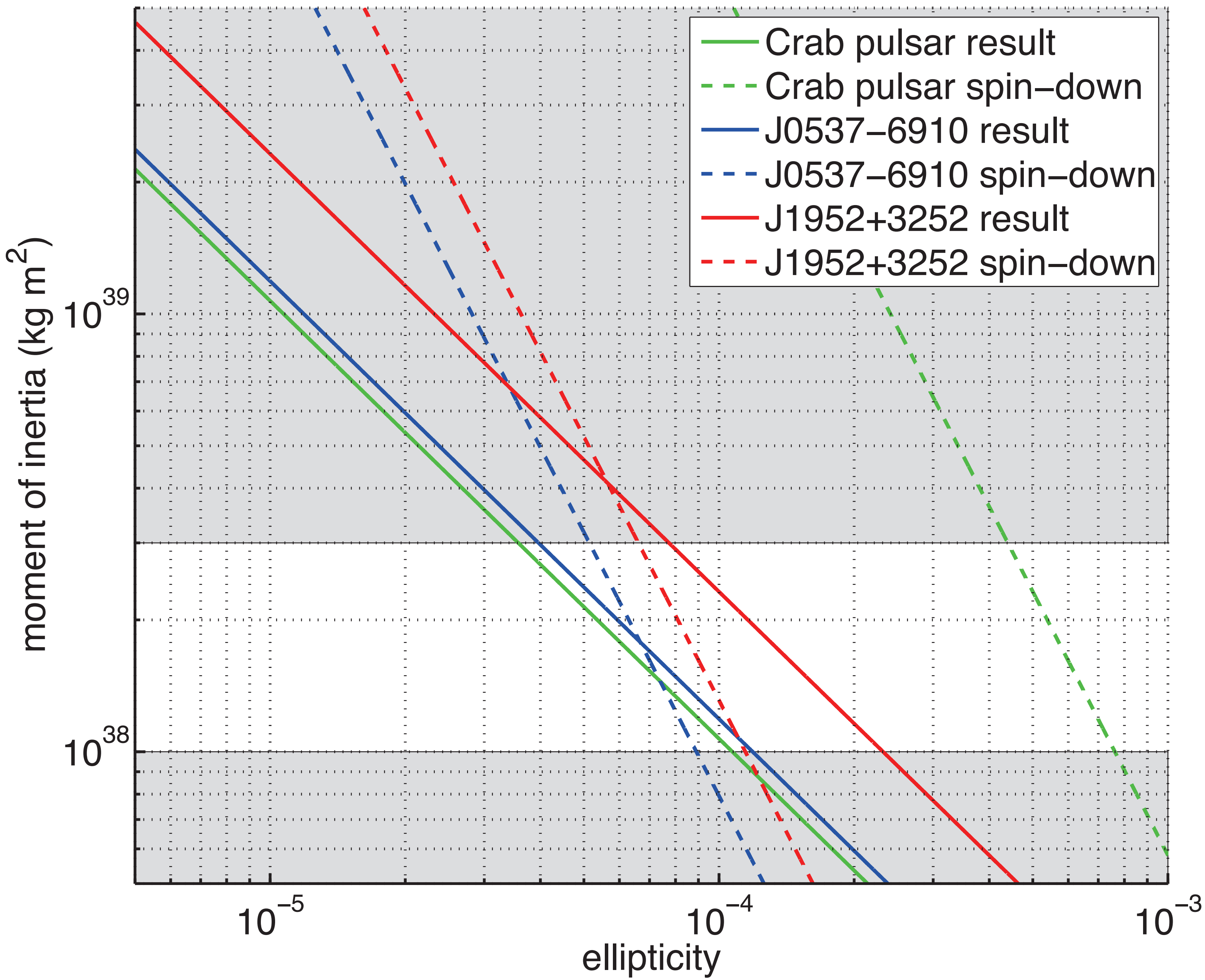


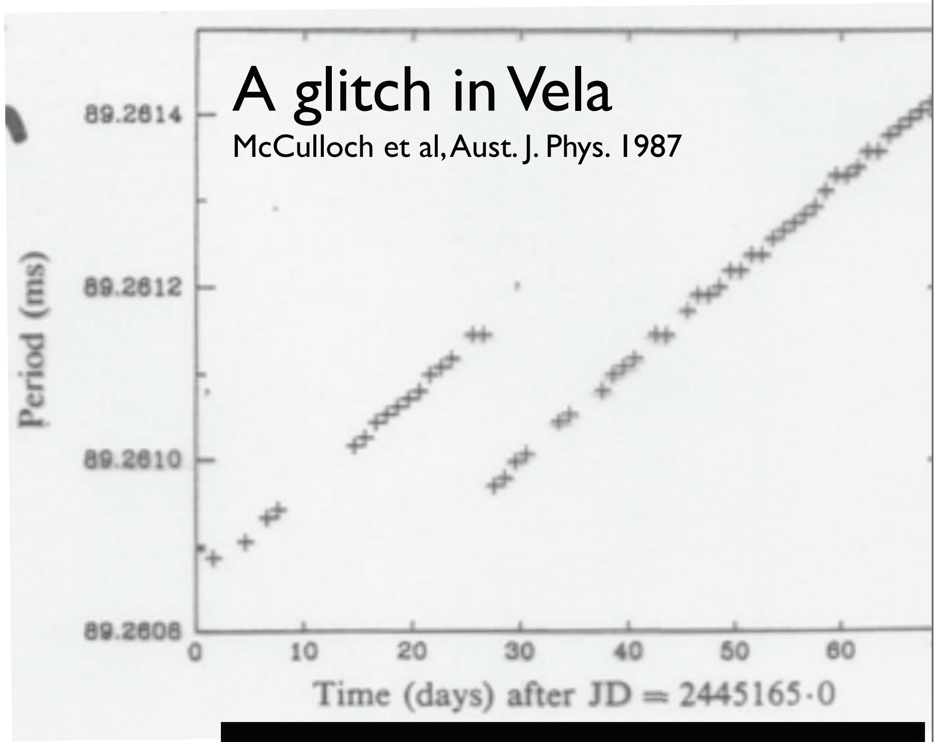
S5 Key Results



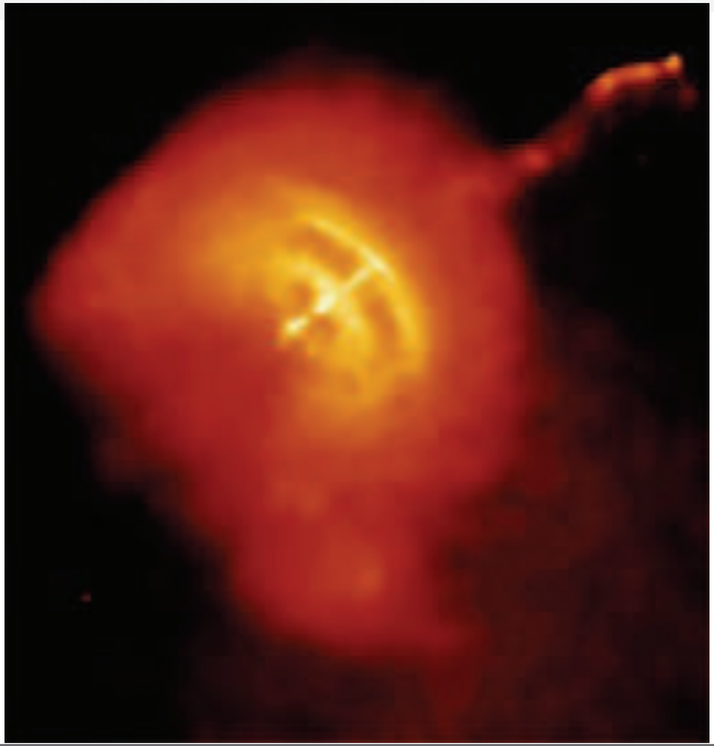
Some Interesting Upper Limits

(JD)	ν (Hz)	$\dot{\nu}$ (Hz s^{-1})	distance (kpc)	spin-down limit	joint $h_0^{95\%}$	ellipticity	$h_0^{95\%}/h_0^{sd}$
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



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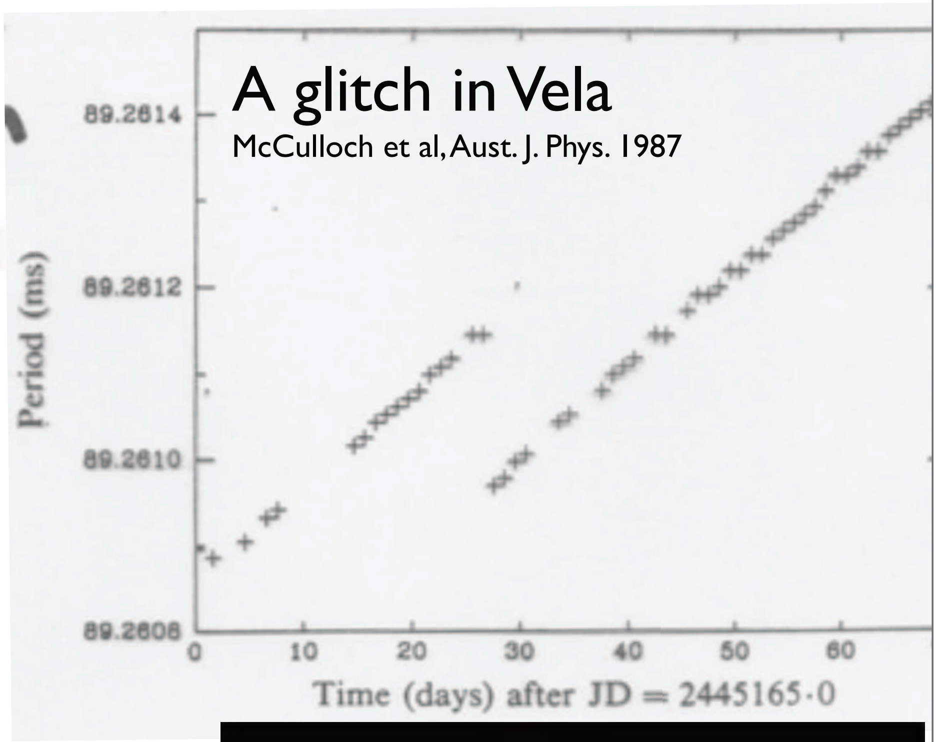
- Pulsars have stable rotation rates:



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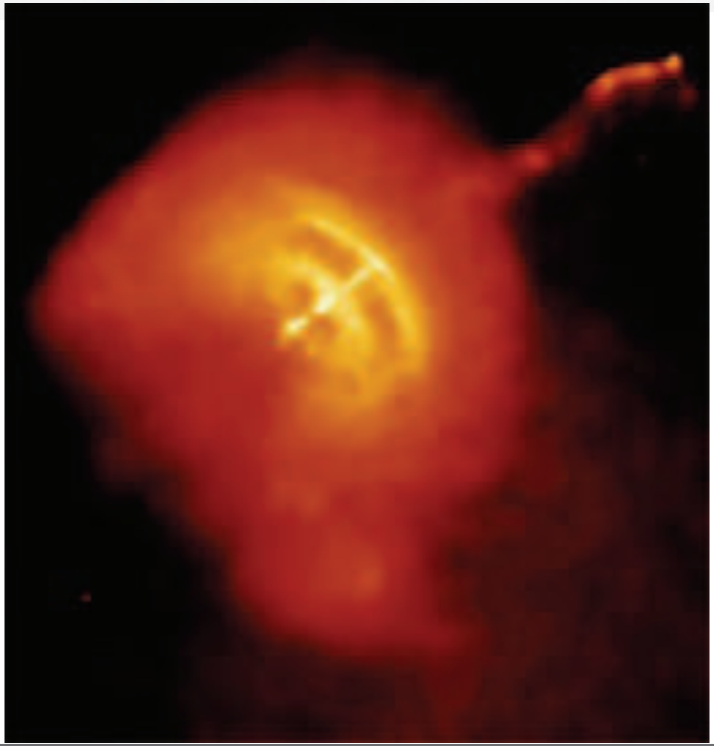

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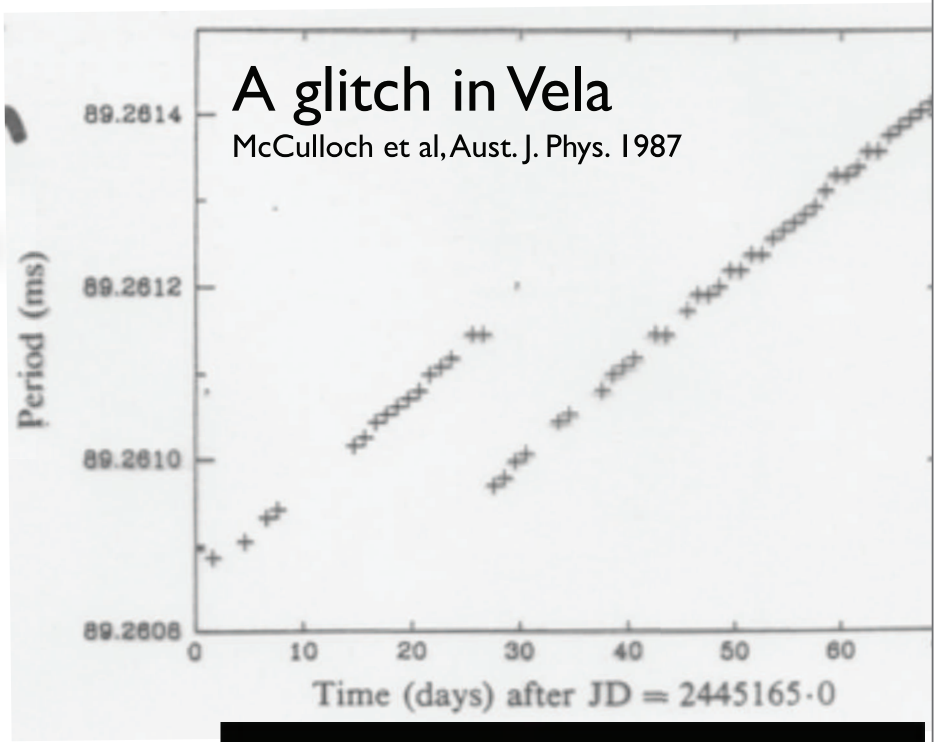

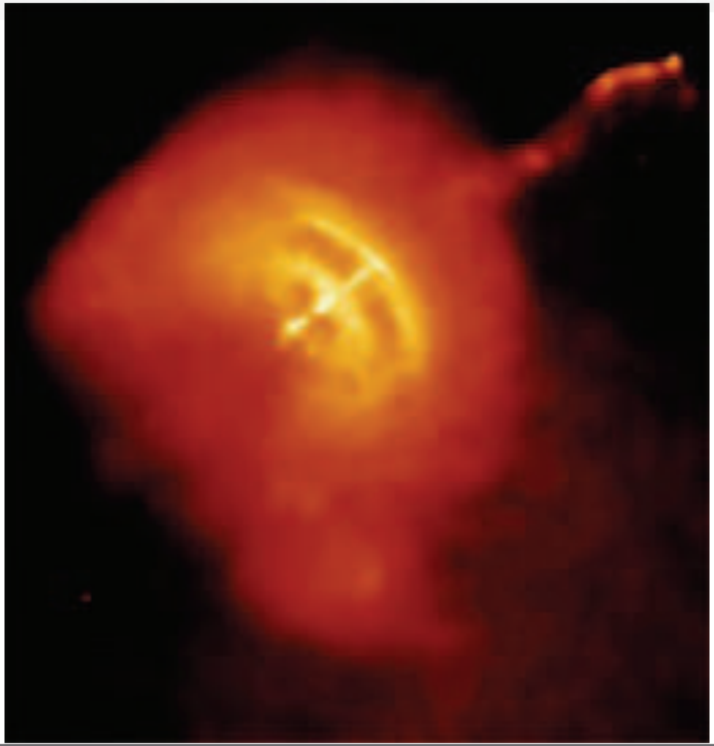

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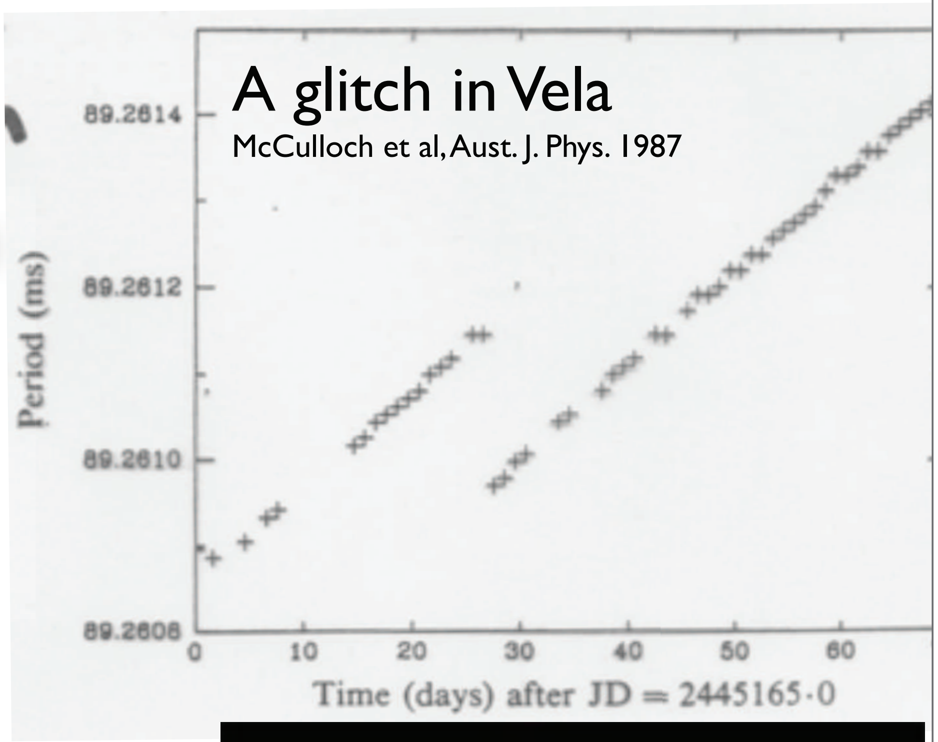

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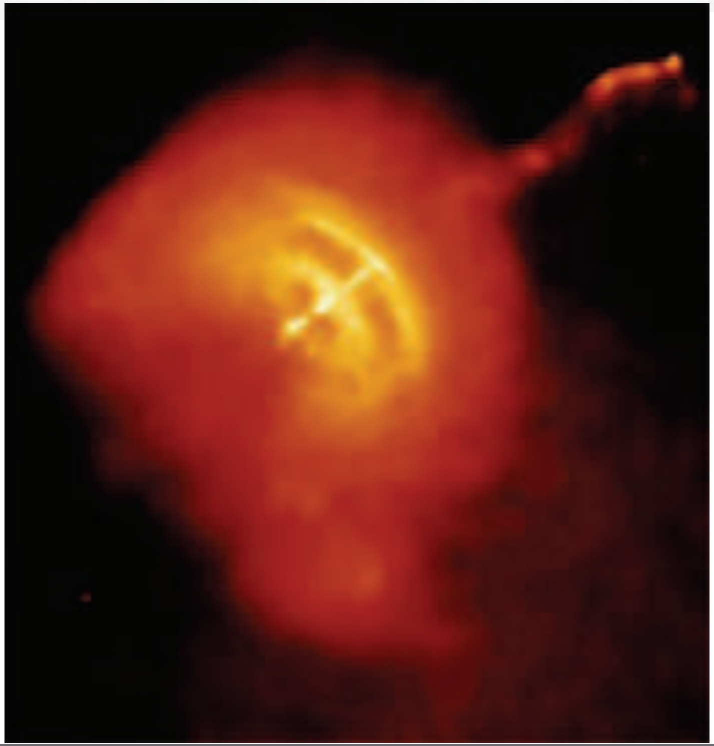

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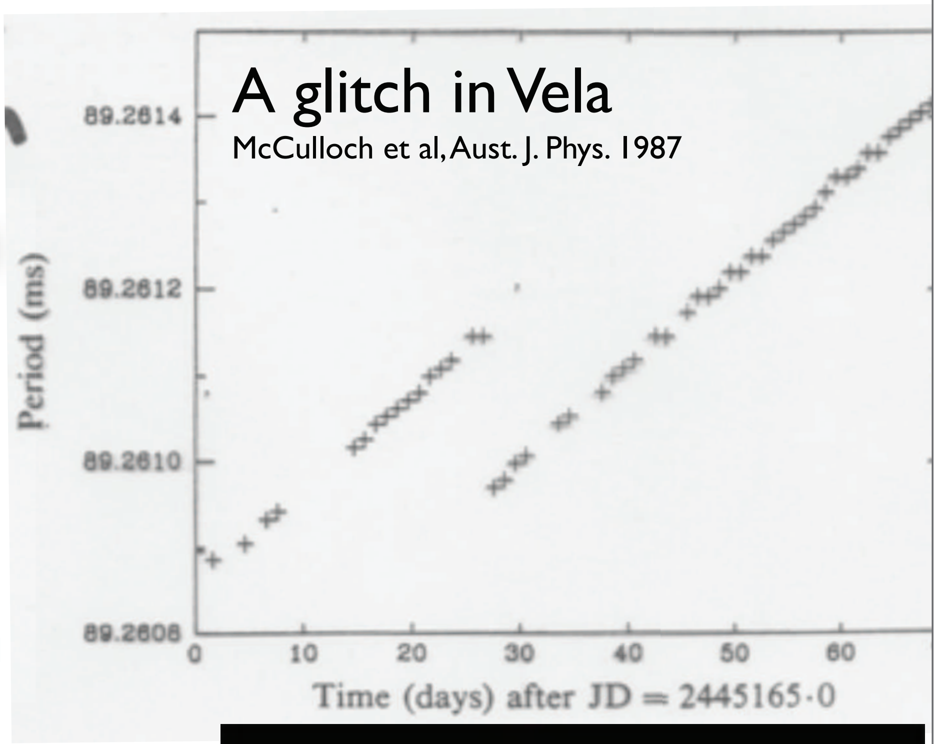

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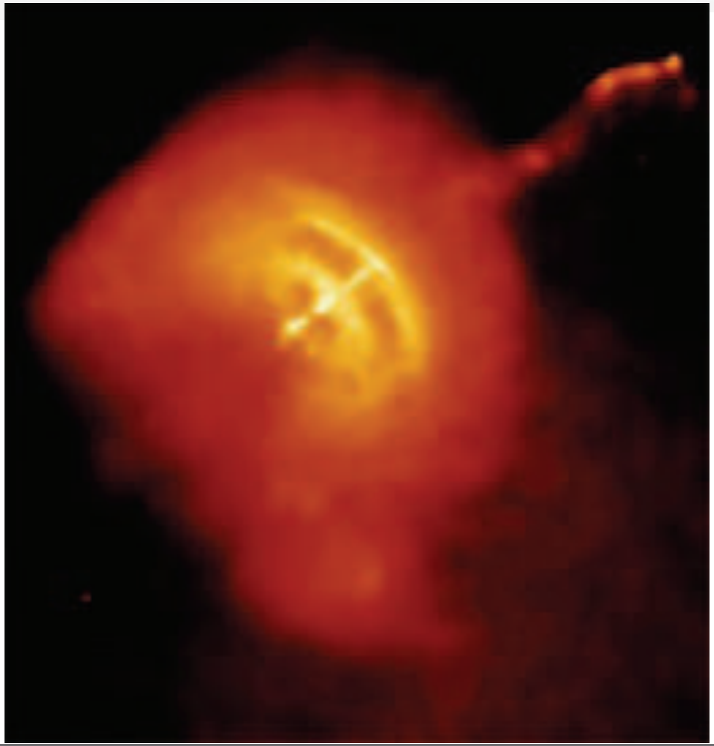

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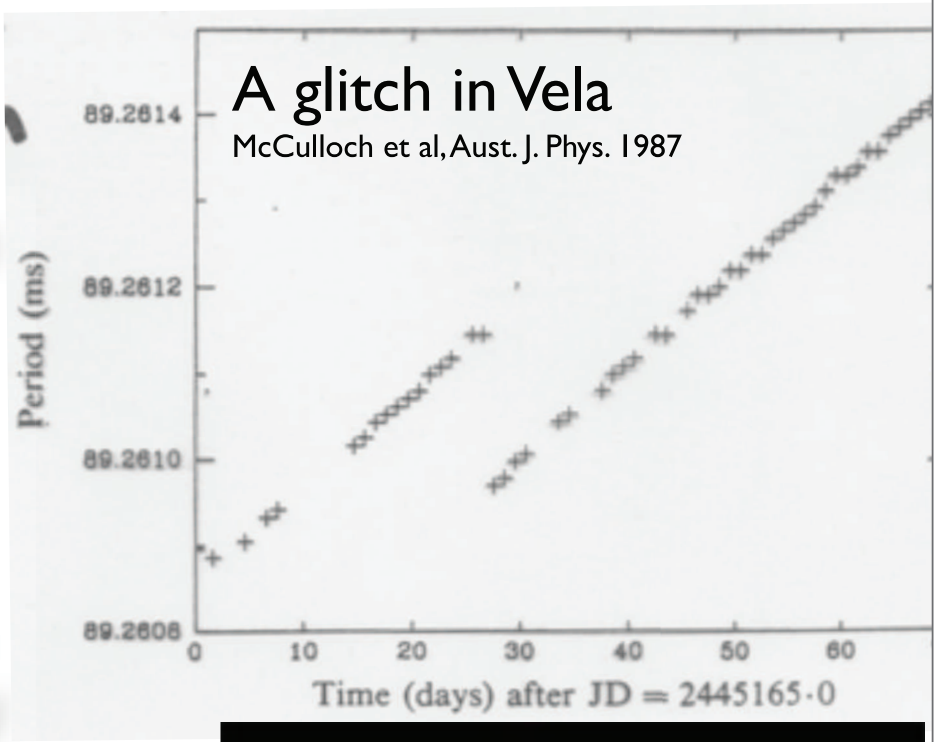

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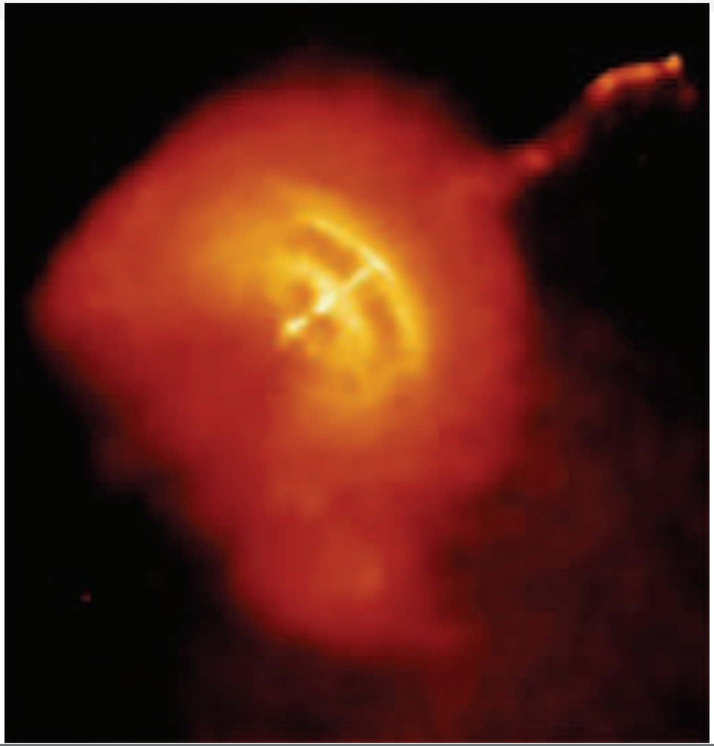

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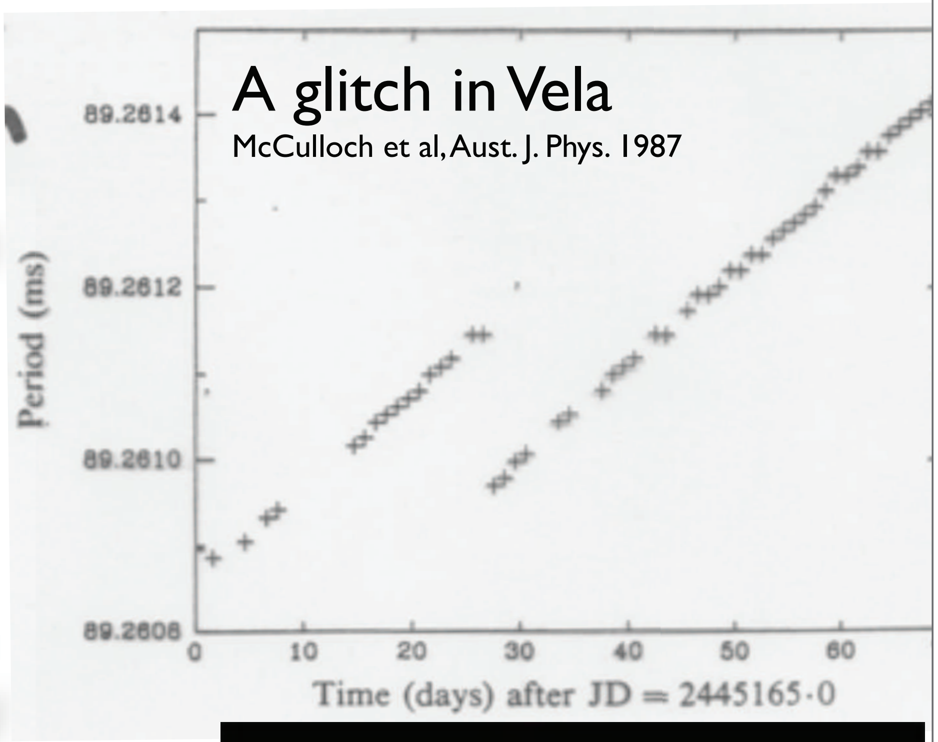

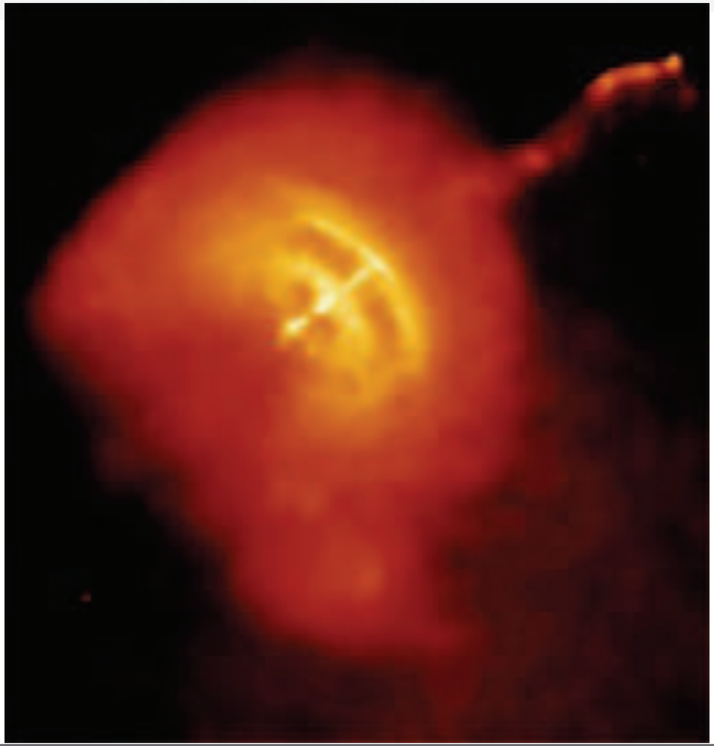
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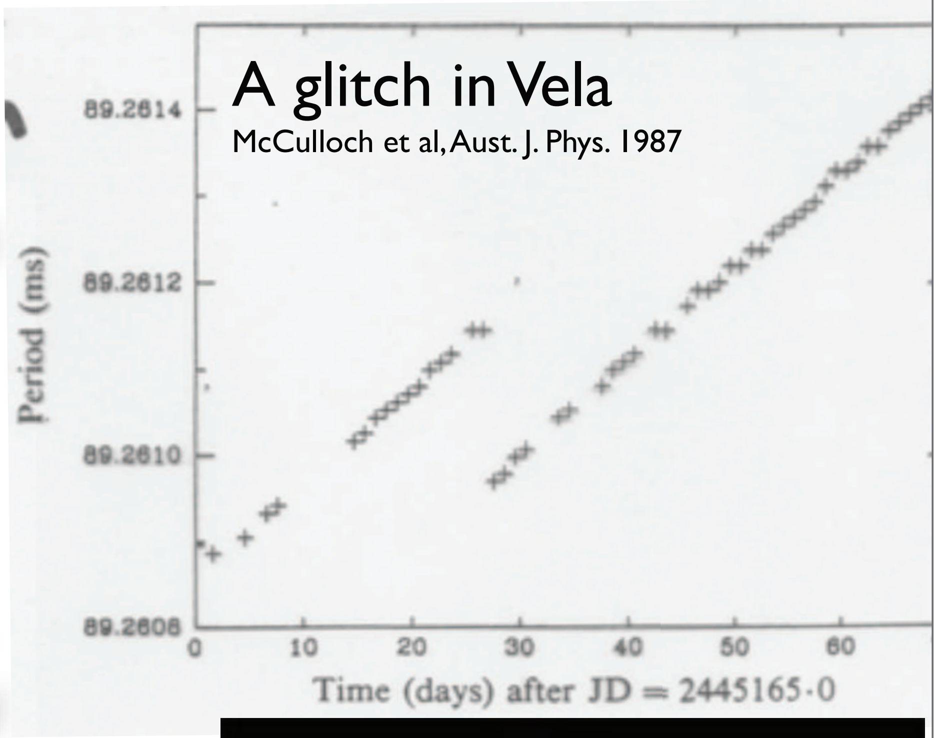

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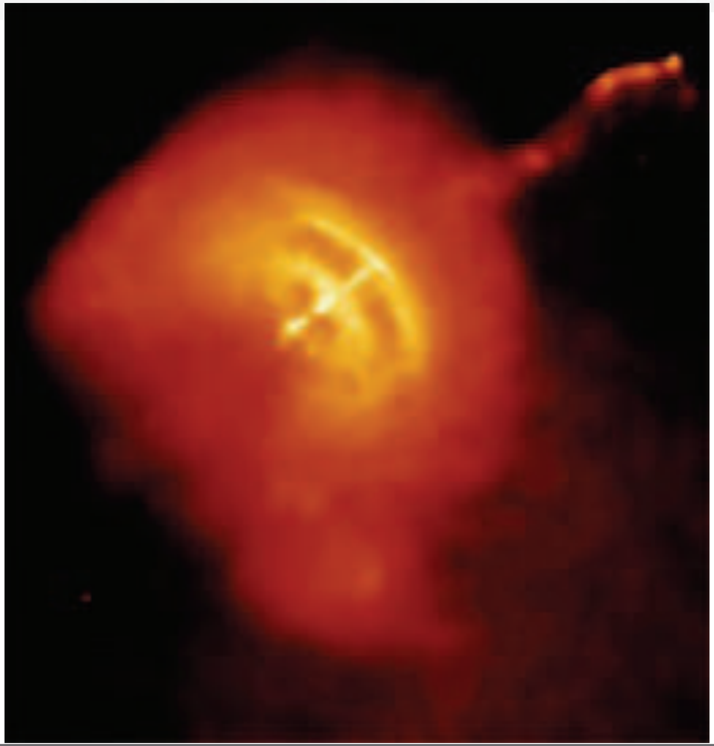

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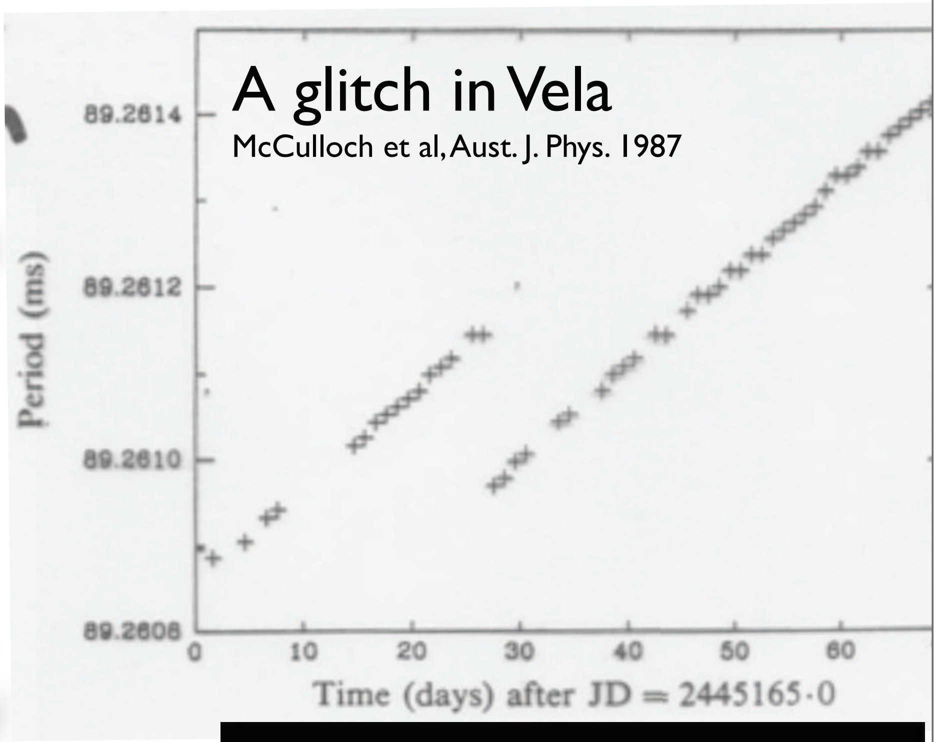

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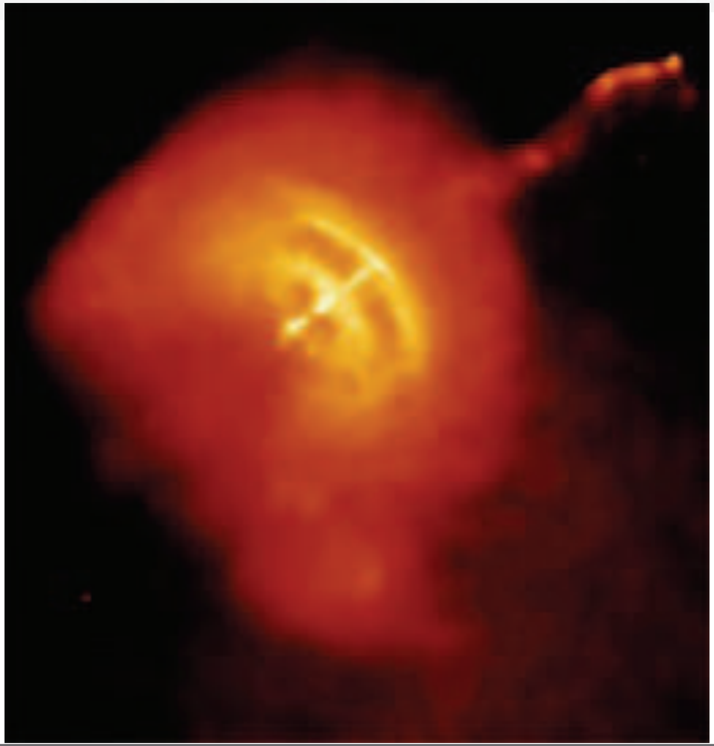

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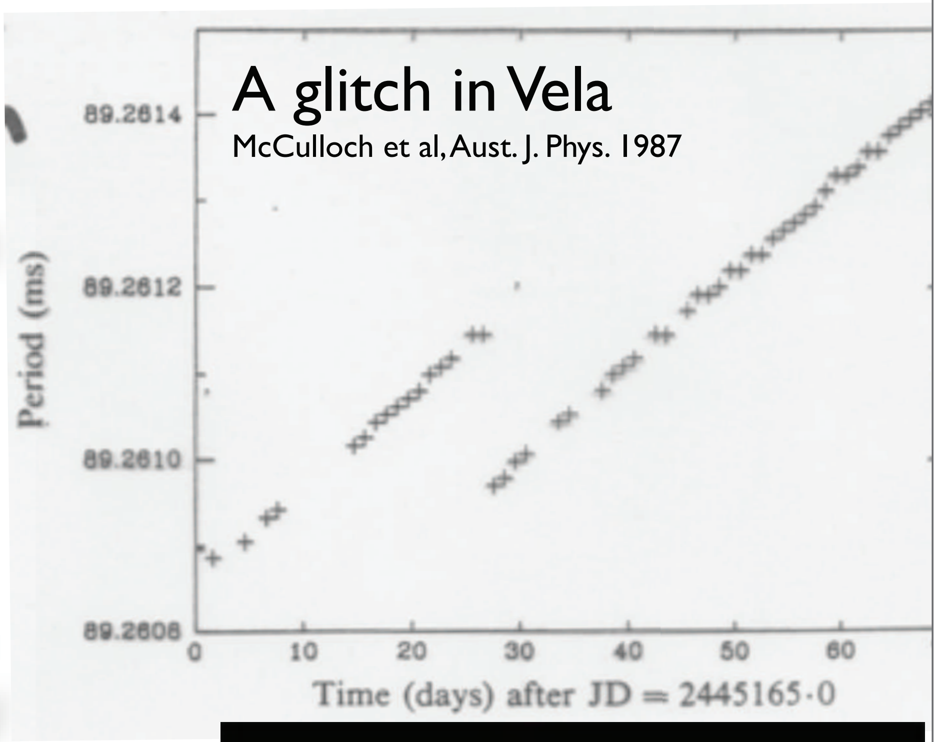

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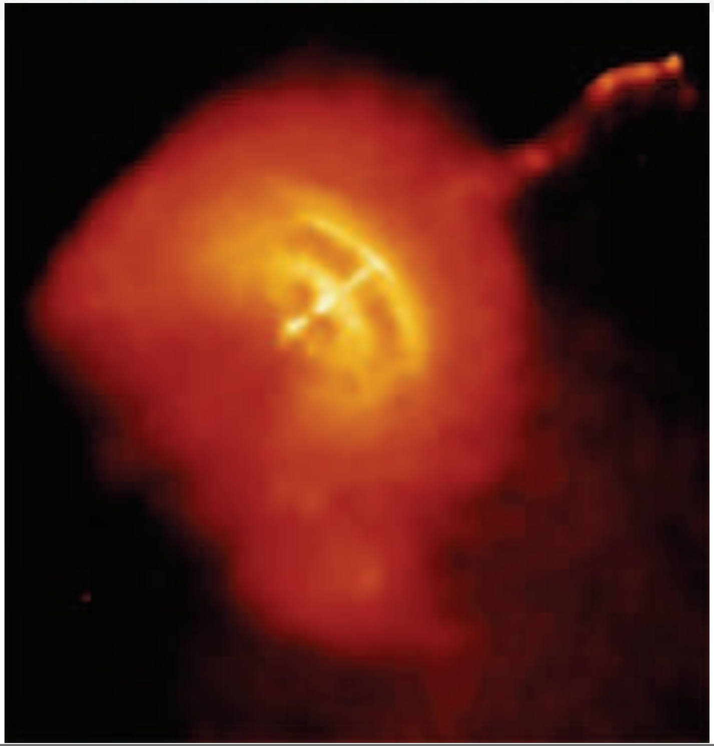
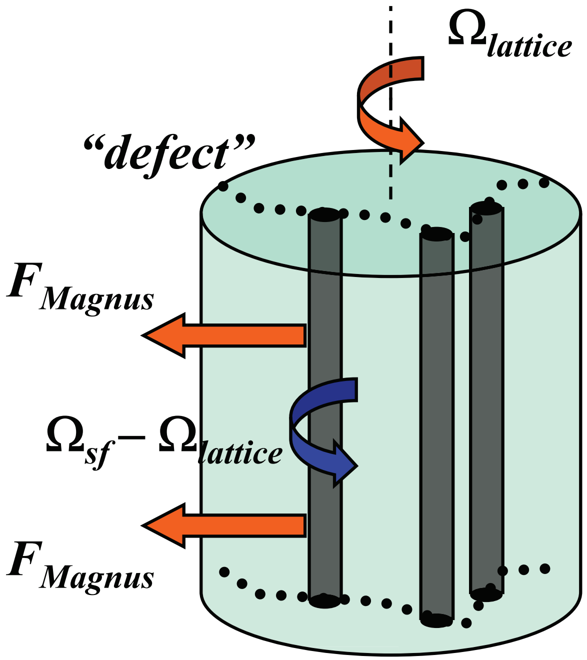
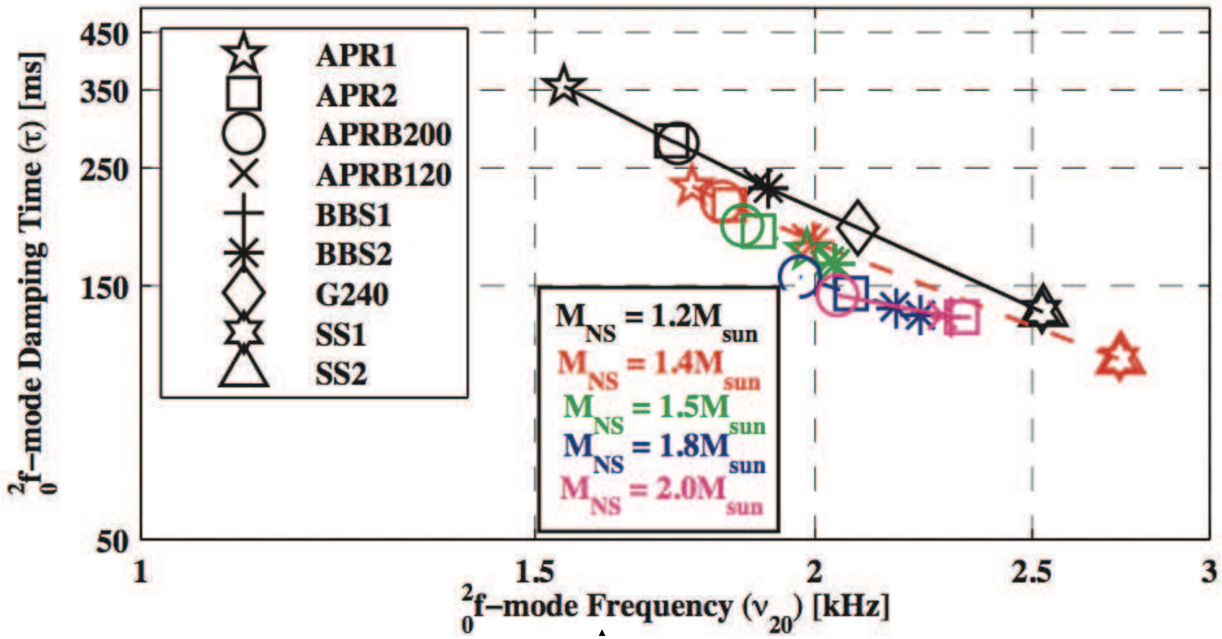


NS Normal Mode Oscillations





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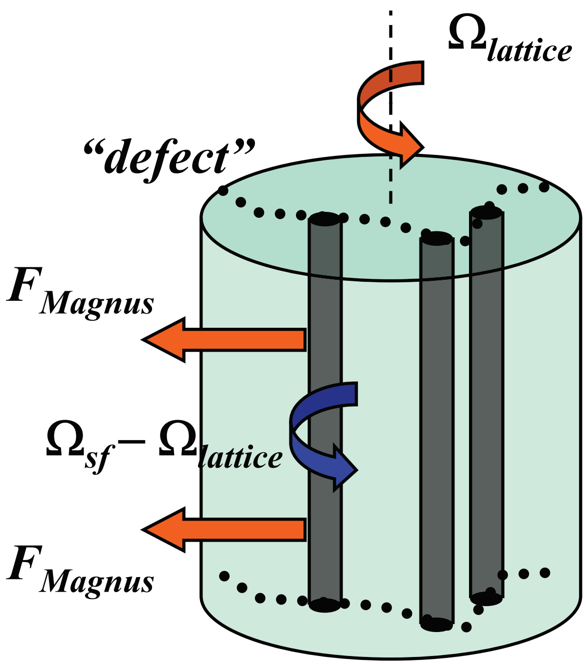

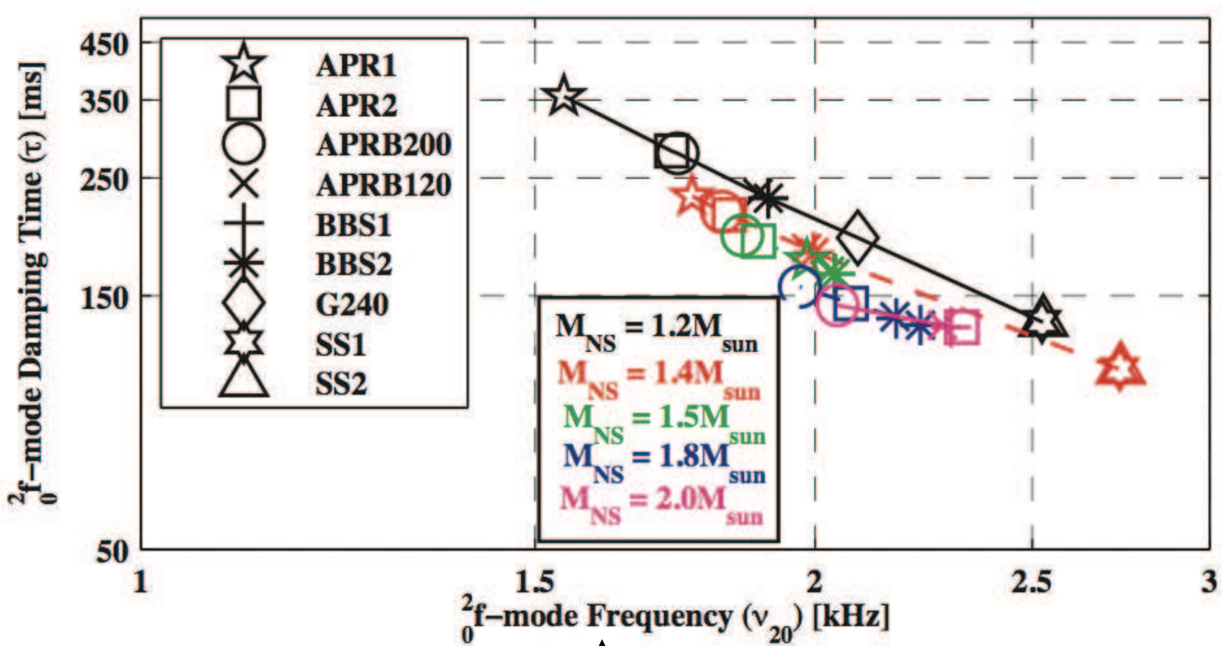

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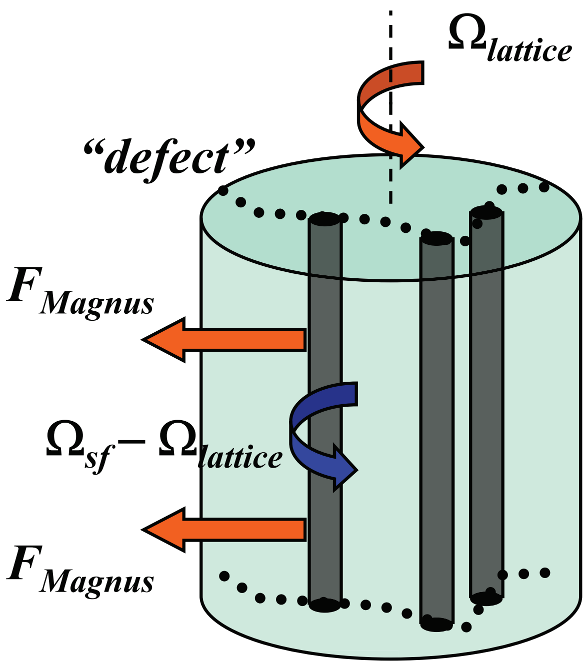

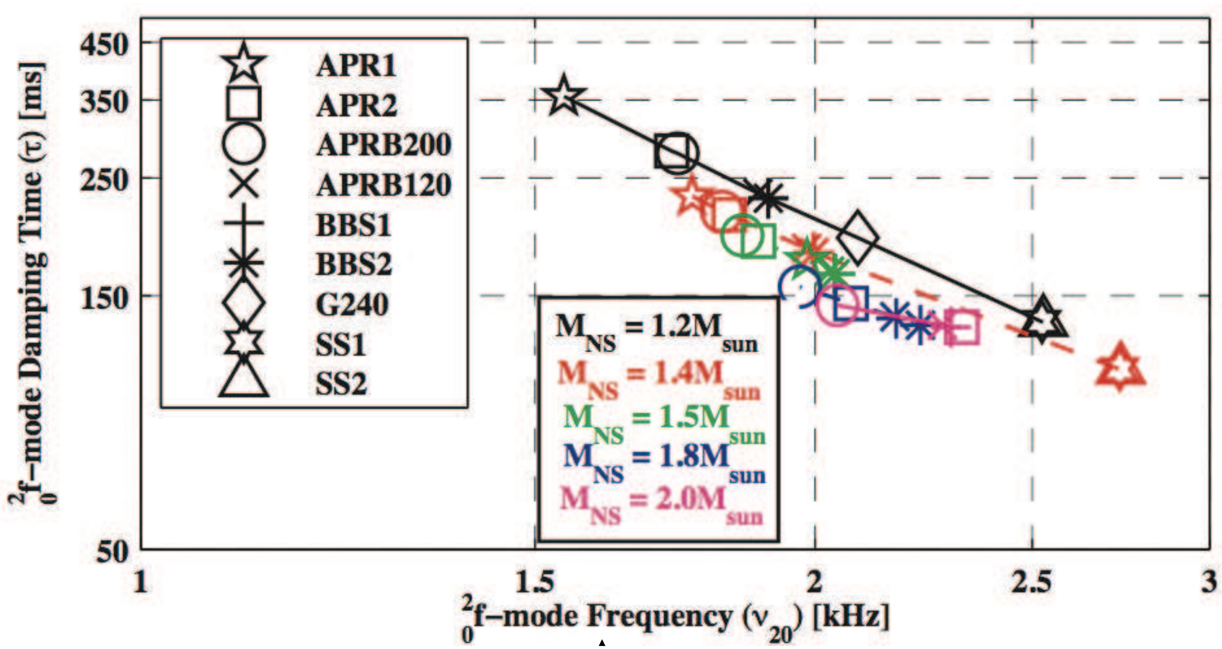

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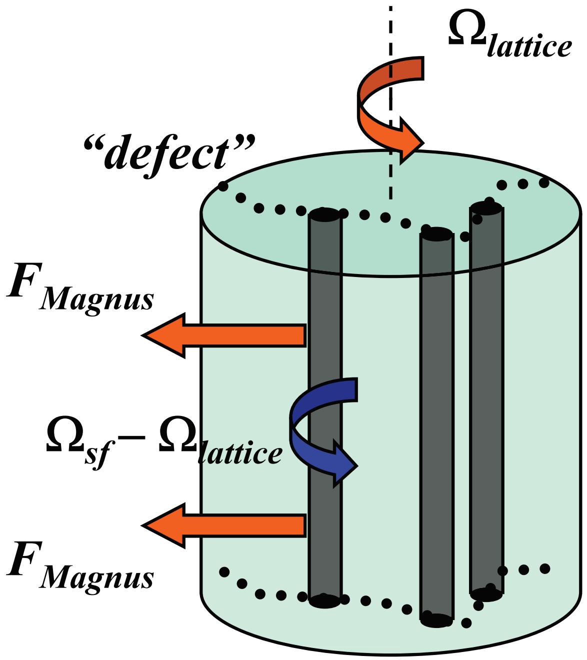
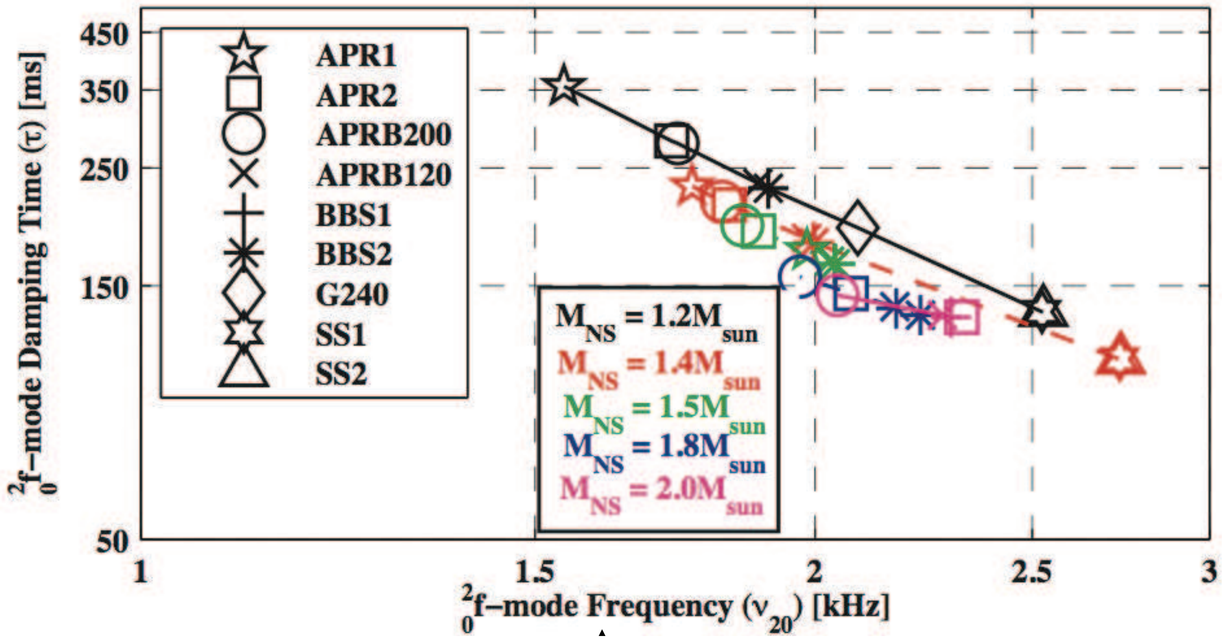
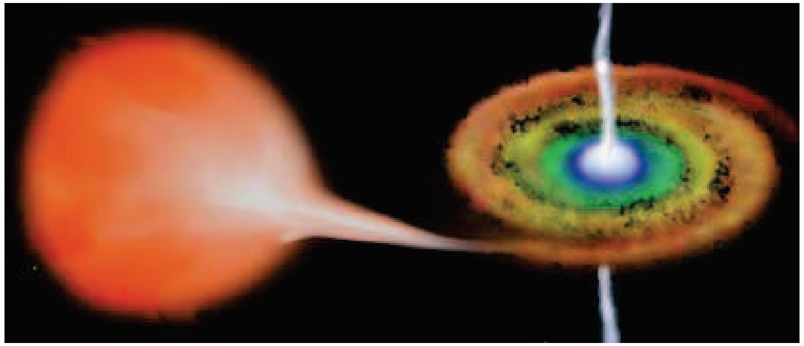
- Detecting and measuring normal modes could reveal the equation-of-state of neutron stars and their internal structure



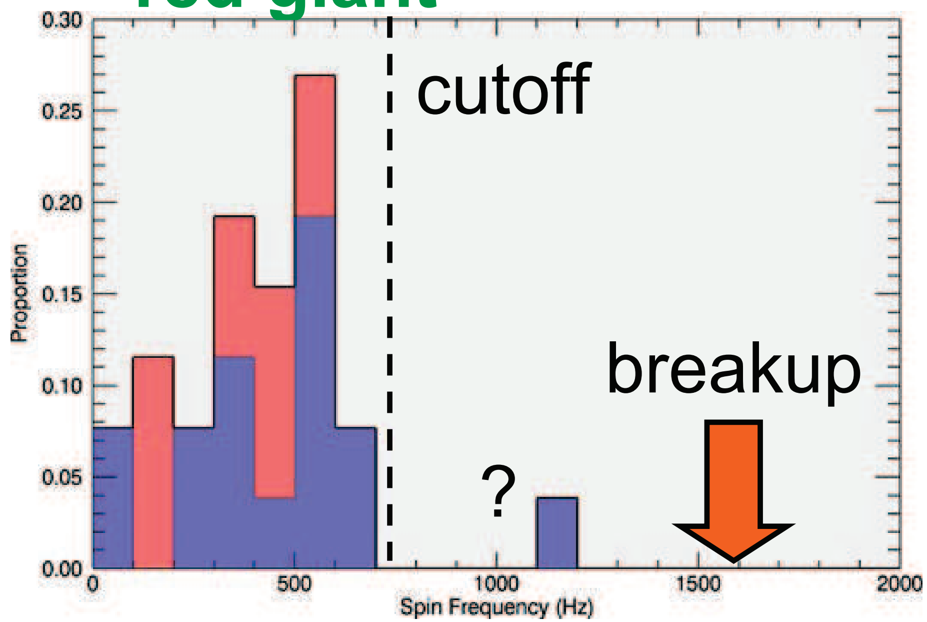


Accreting Neutron Stars



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

NS



pulses & **burst oscillations**

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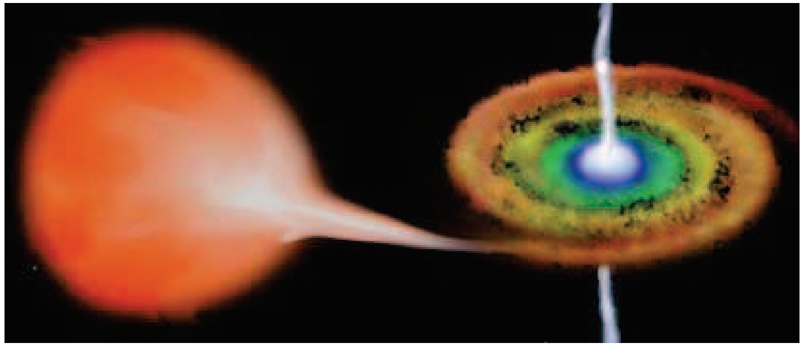

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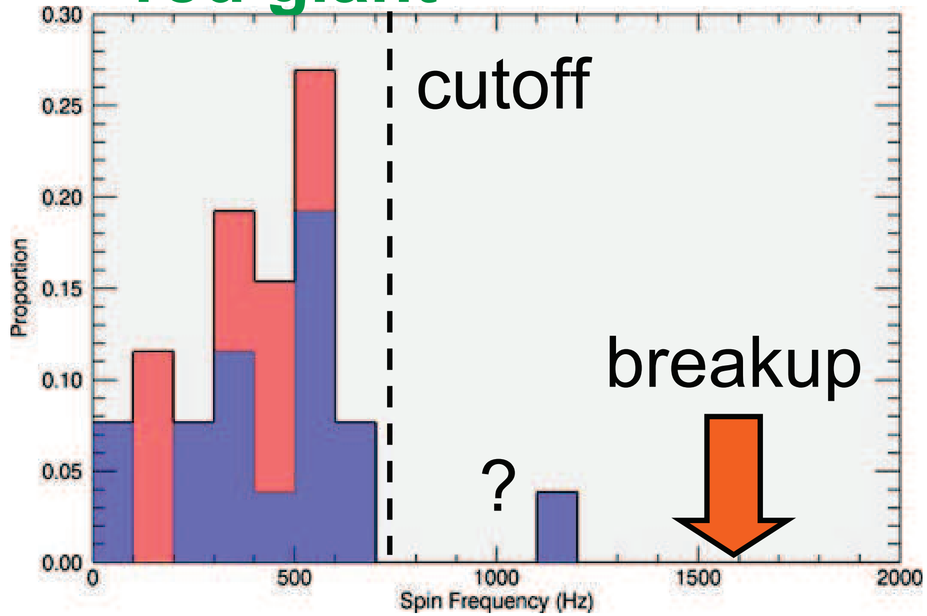

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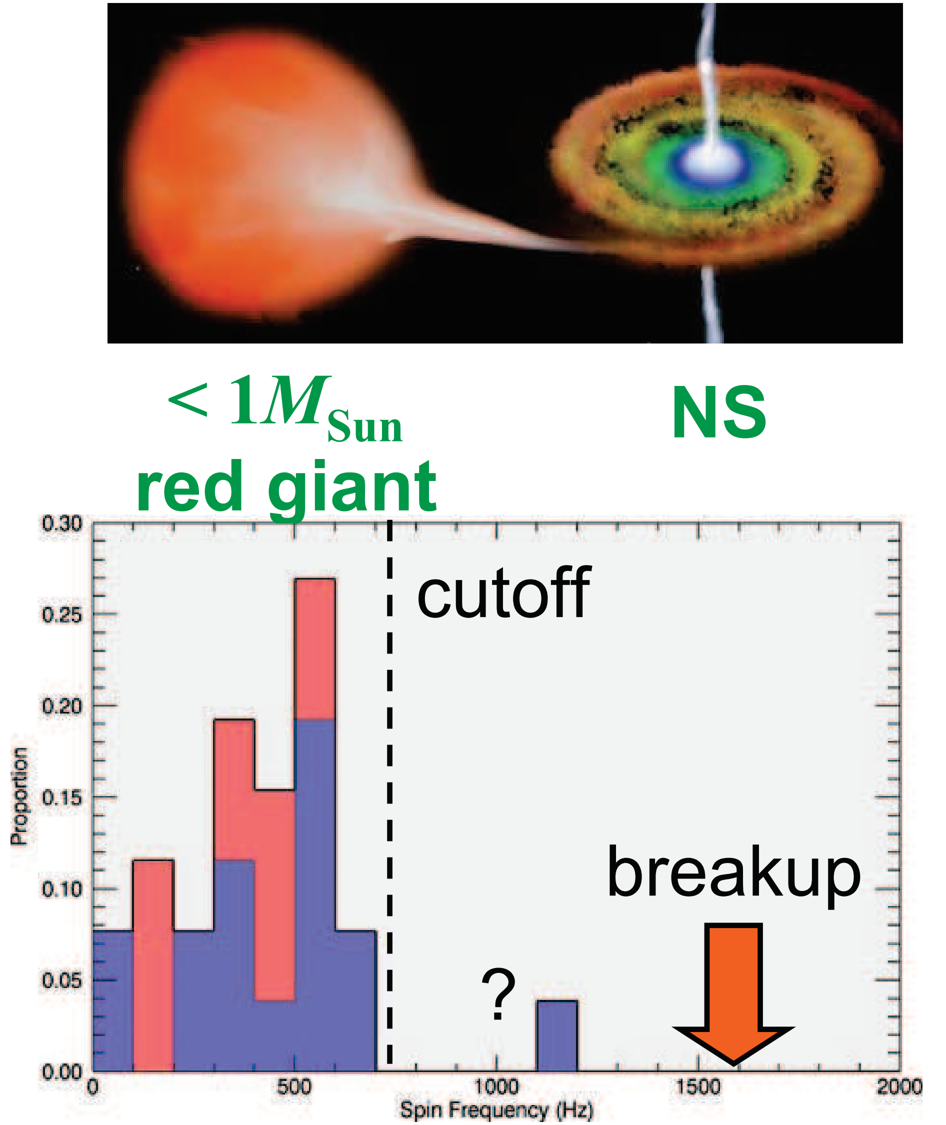

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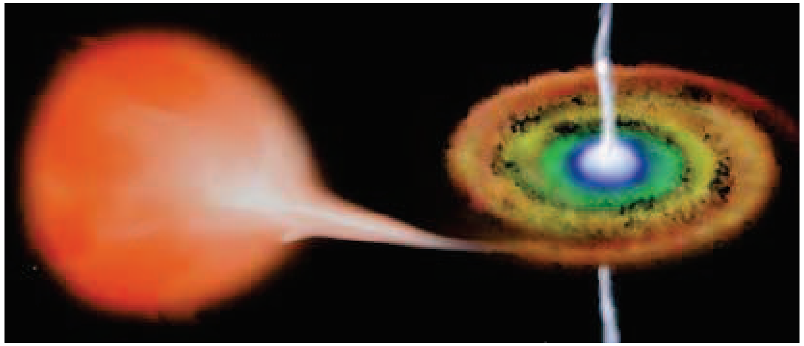

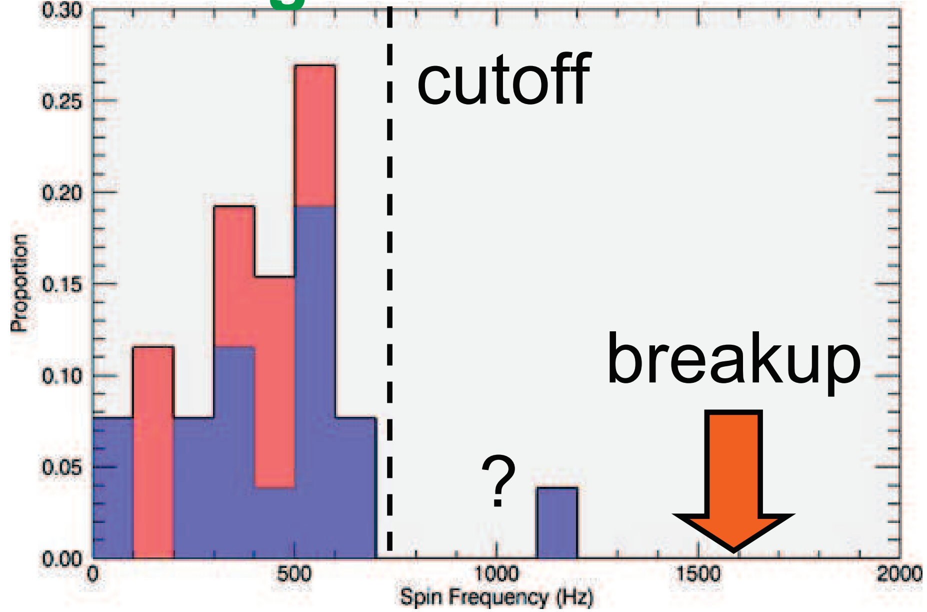

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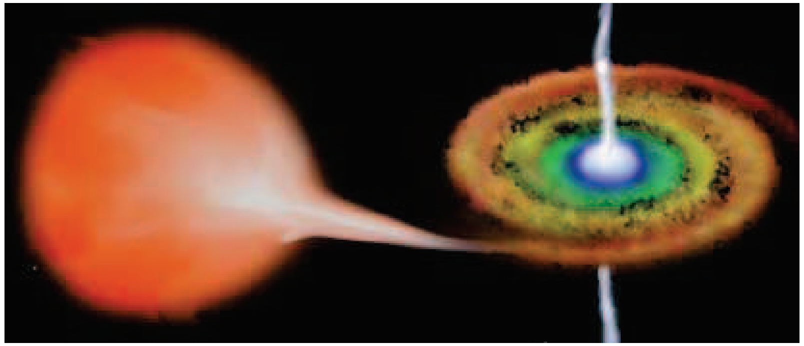

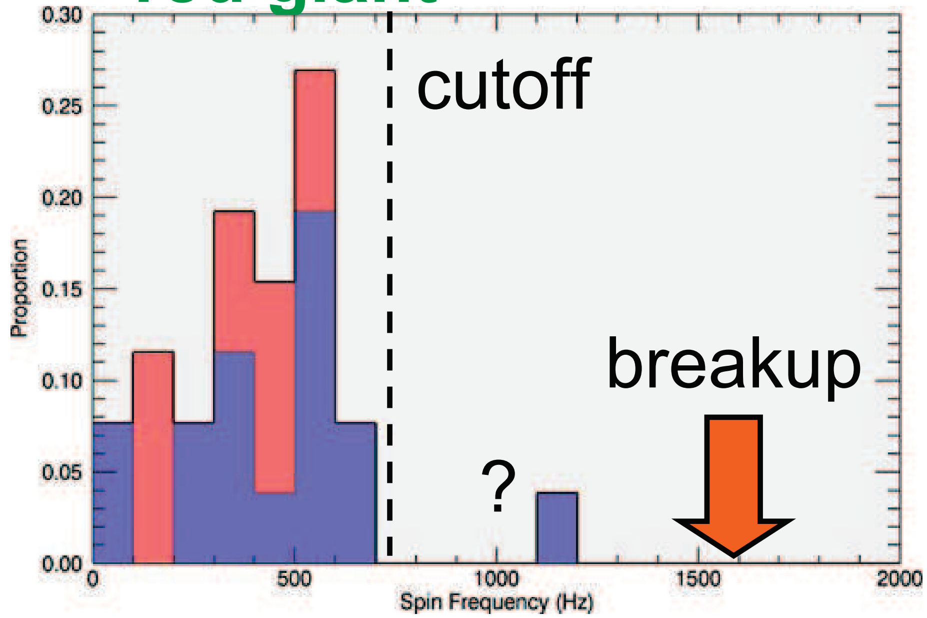

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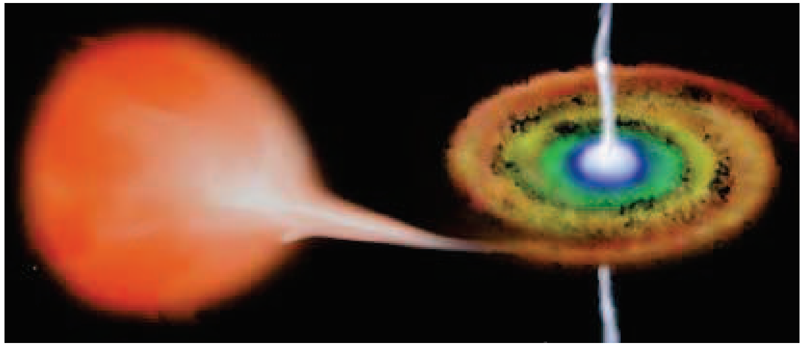

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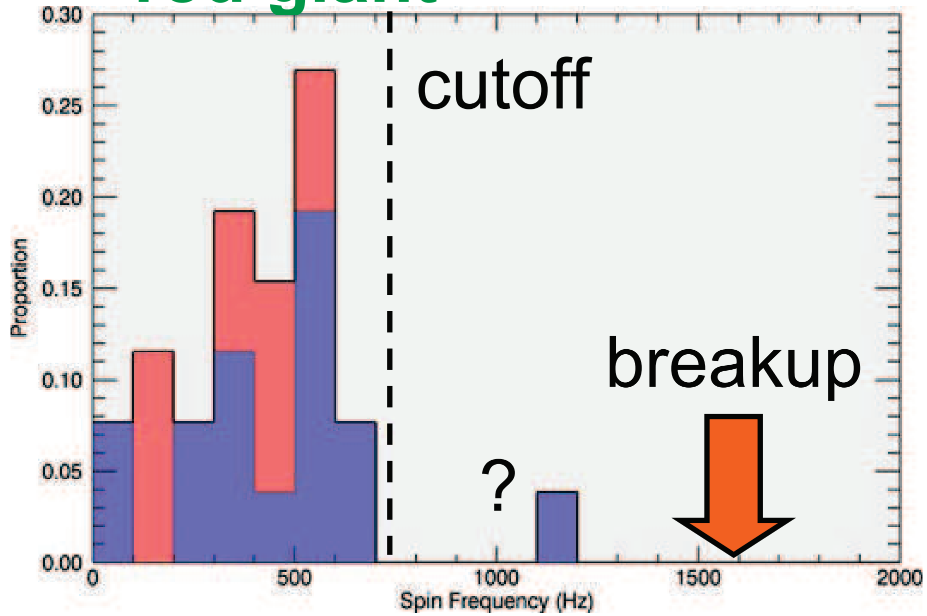

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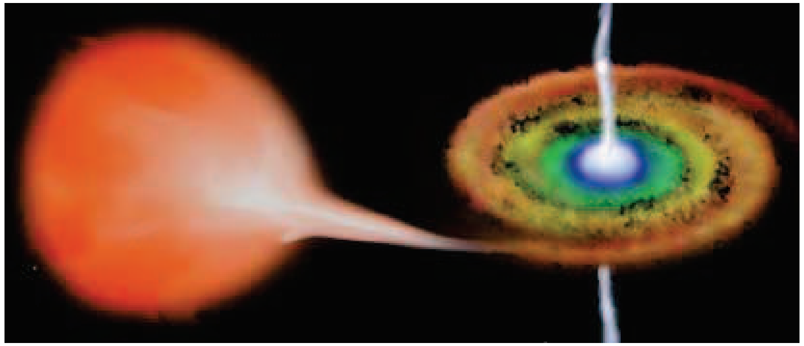

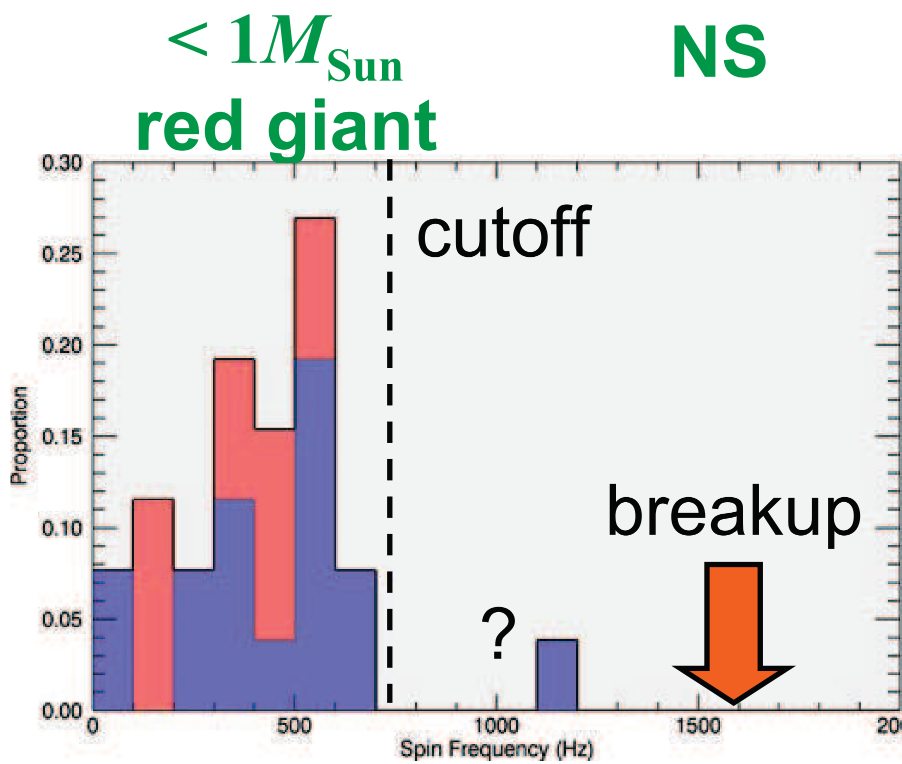

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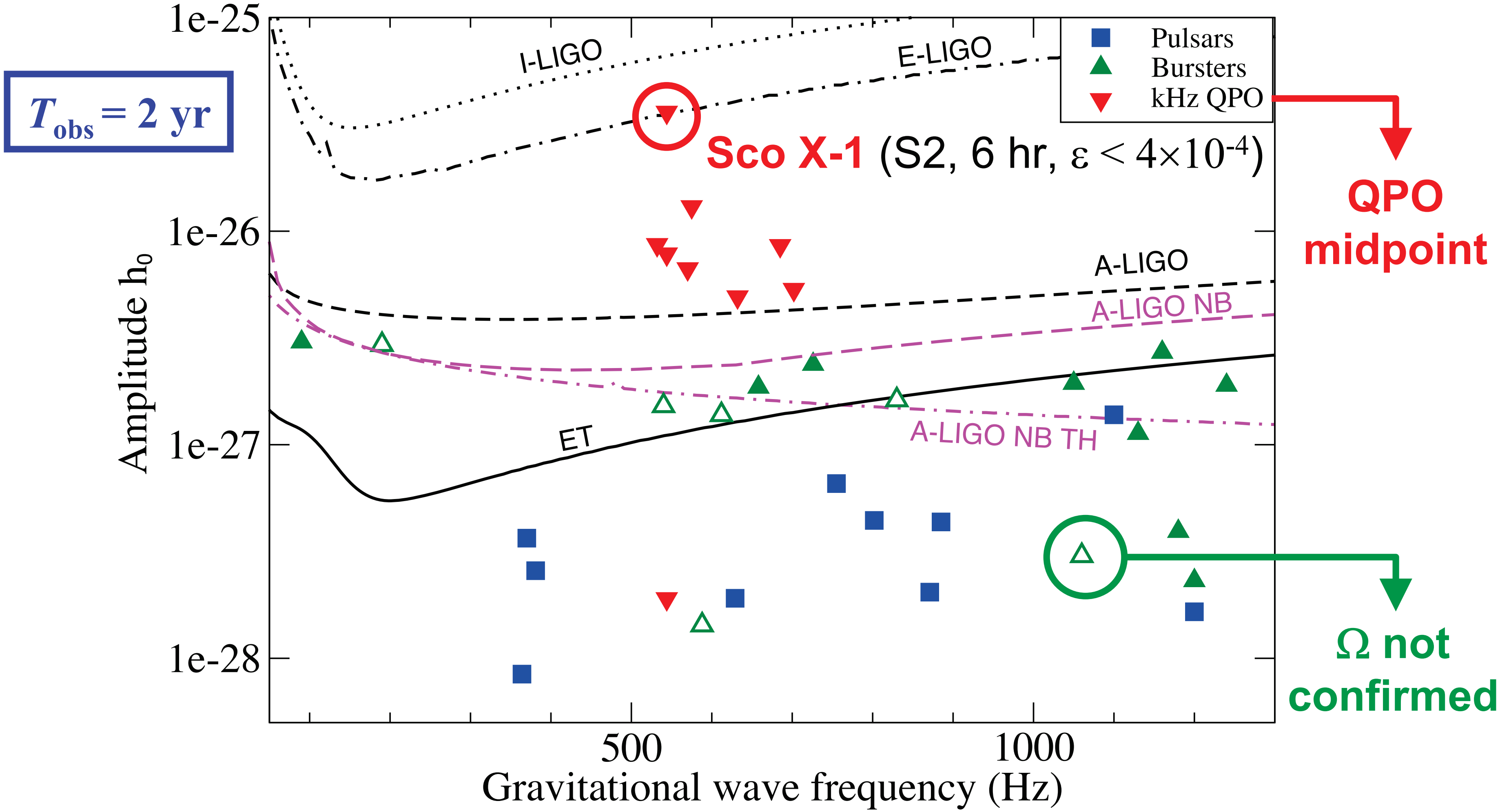
Sensitivity to Accreting NS



Cosmology

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- Cosmography

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  - Phase transitions, pre-heating, re-heating, etc.

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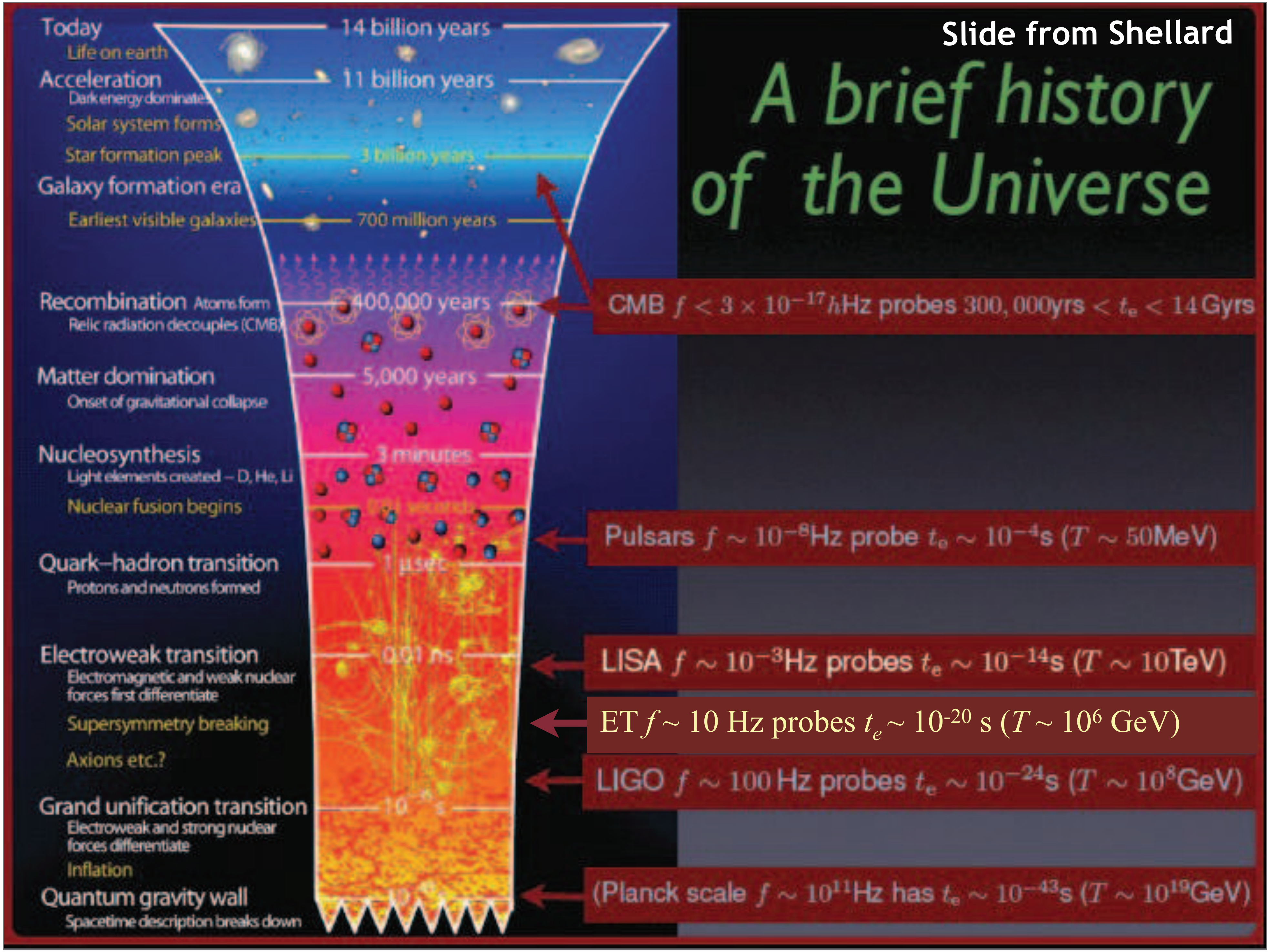

Slide from Shellard
A brief history of the Universe
Today
Life on earth
14 billion years
Acceleration
Dark energy dominates
11 billion years
Solar system forms
Star formation peak
3 billion years
Galaxy formation era
Earliest visible galaxies
700 million years
Recombination Atoms form
Relic radiation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

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- Strength of stochastic background

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LSC, Astrophys. J. 659 (2007) 918

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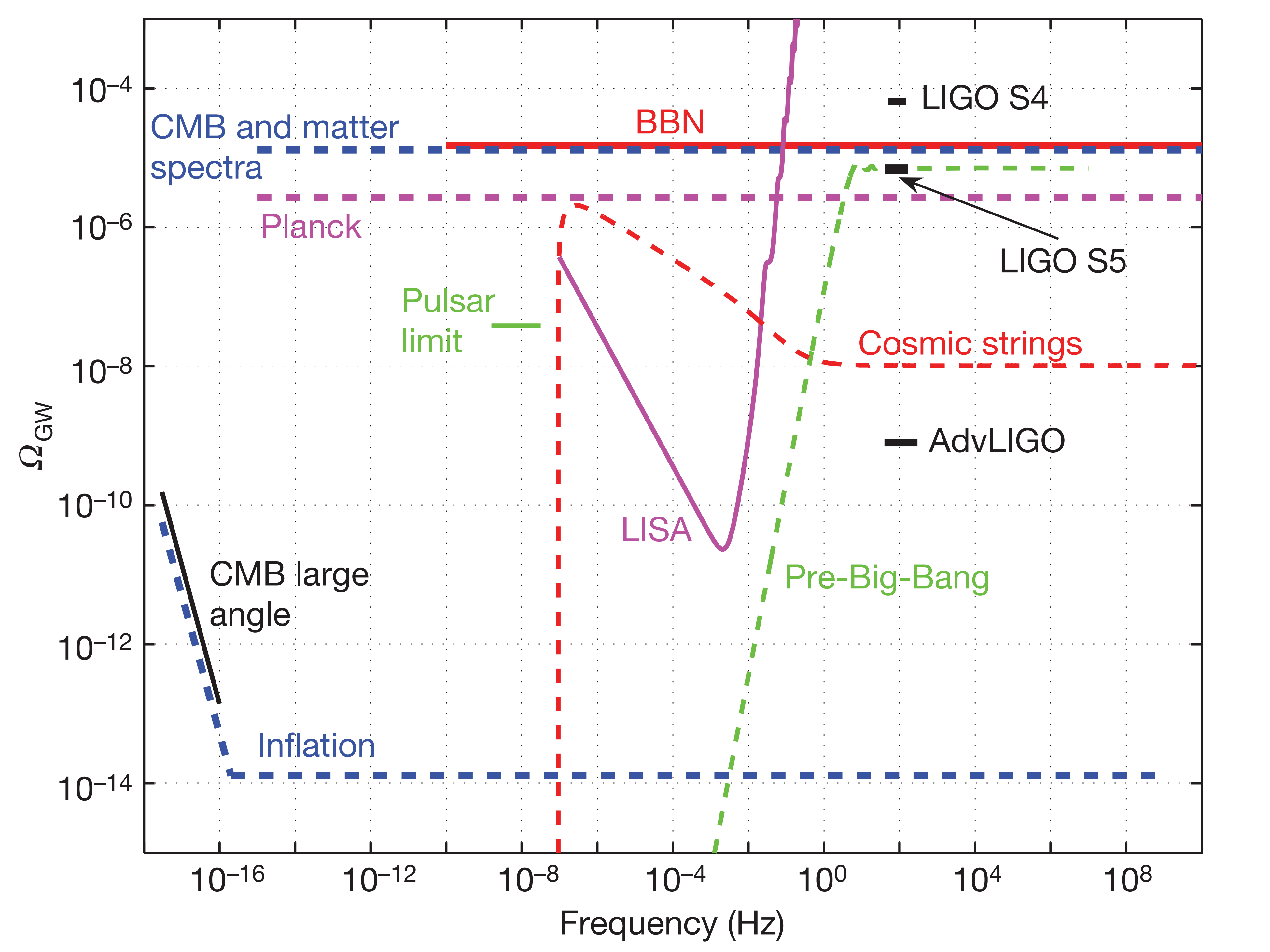
nature Vol 460 | 20 August 2009 | doi:10.1038/nature08278

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

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

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- 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

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

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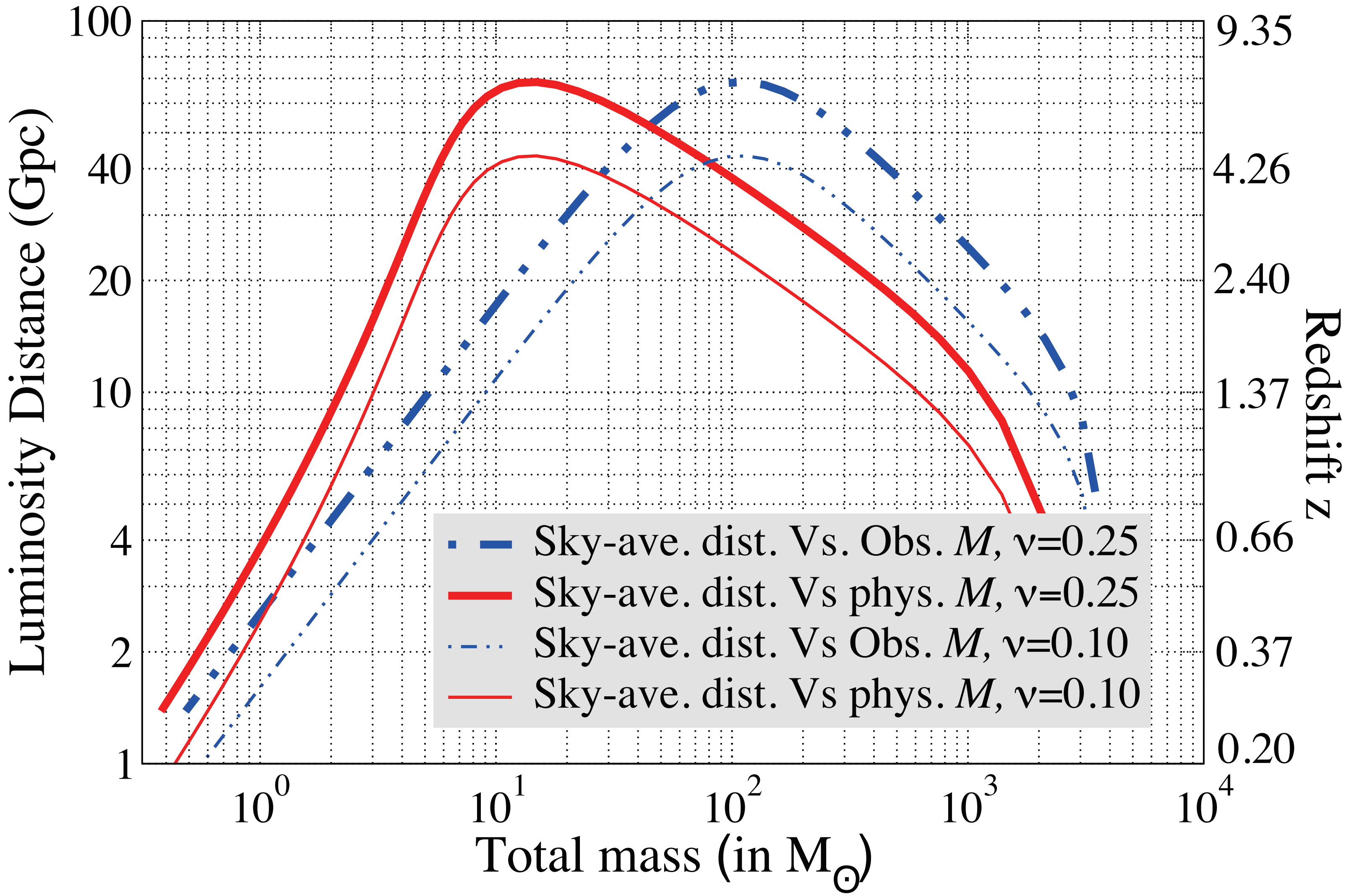
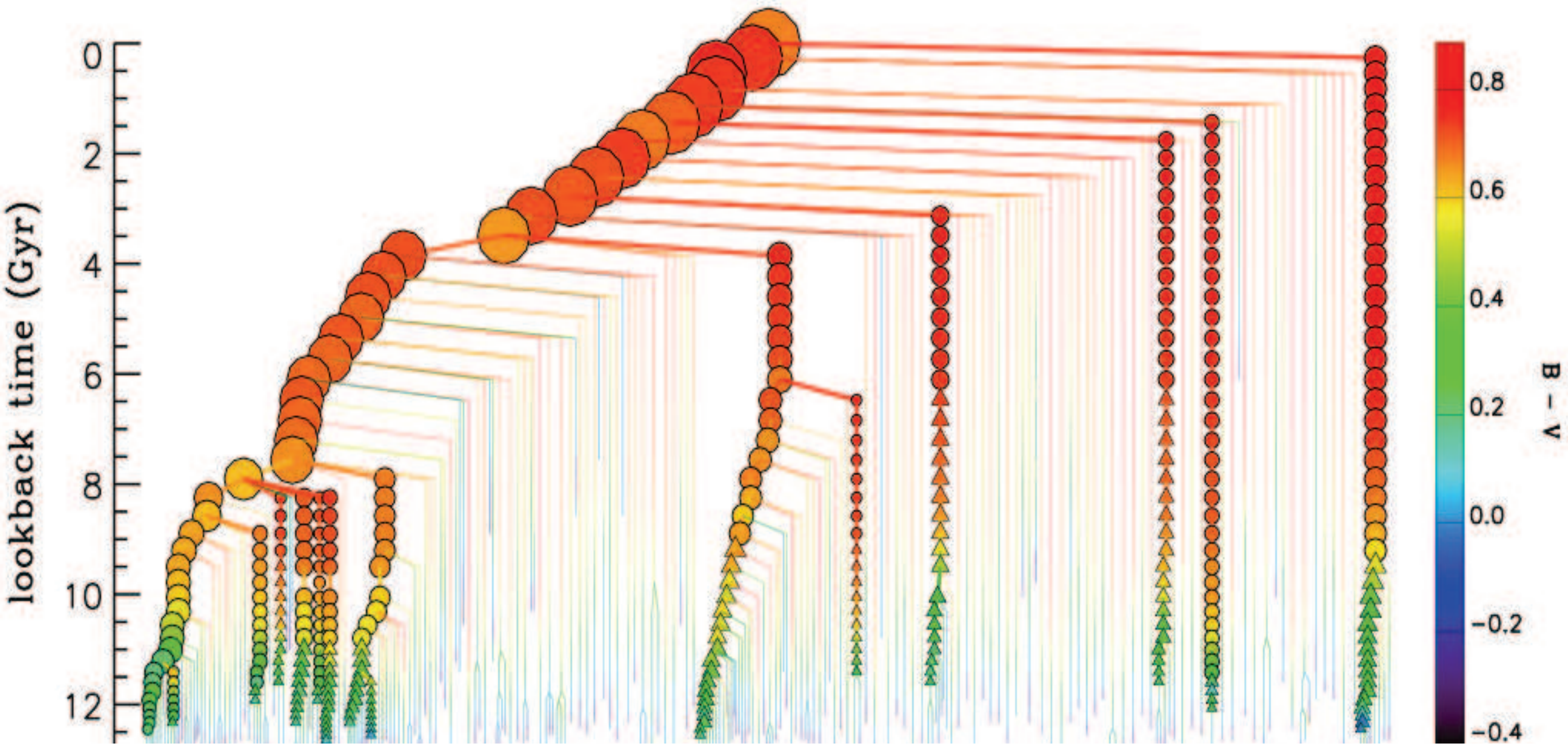
- Joint gravitational-wave and optical observations can facilitate a new cosmological tool

Distance Reach of ET



Hierarchical Growth of Black Holes in Galactic Nuclei



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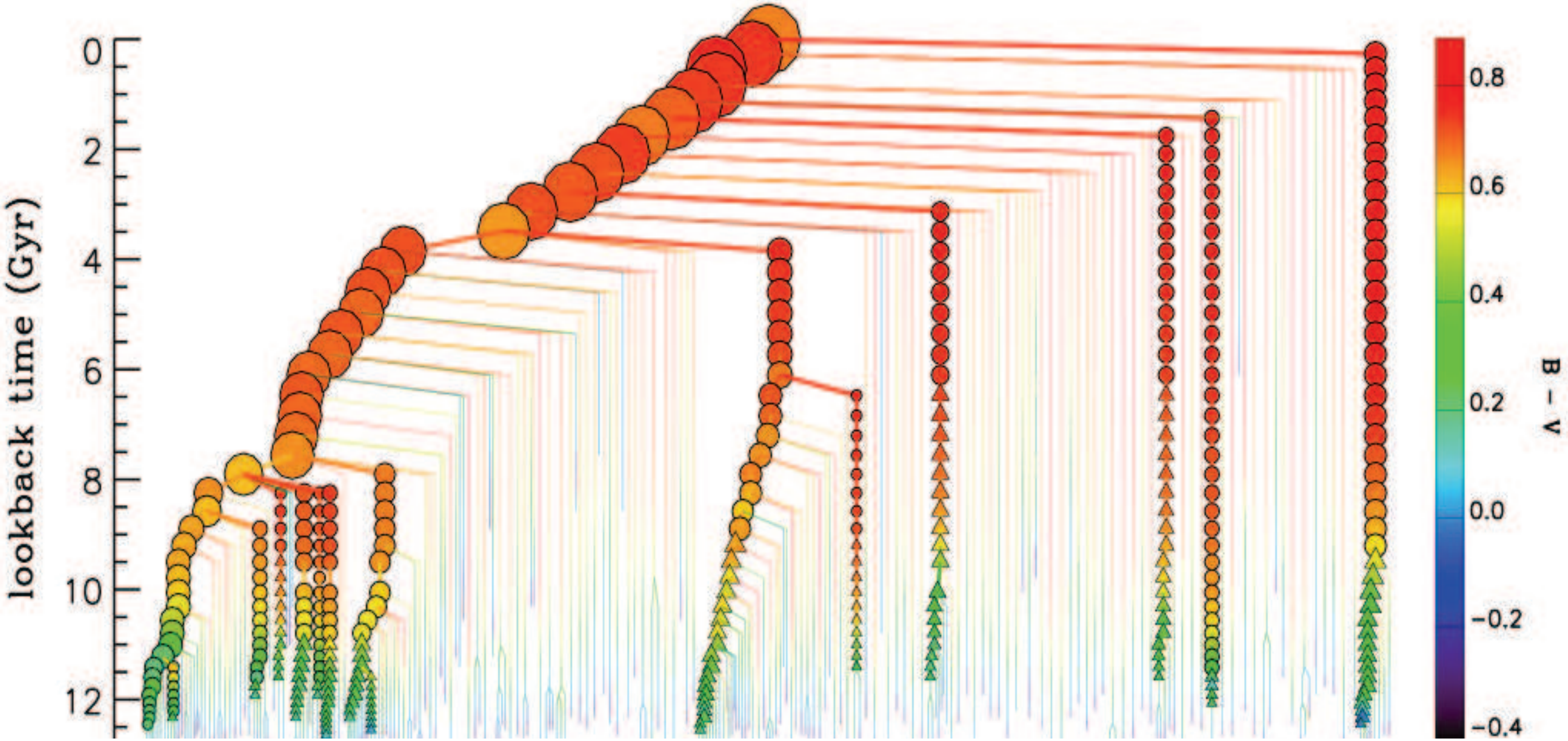

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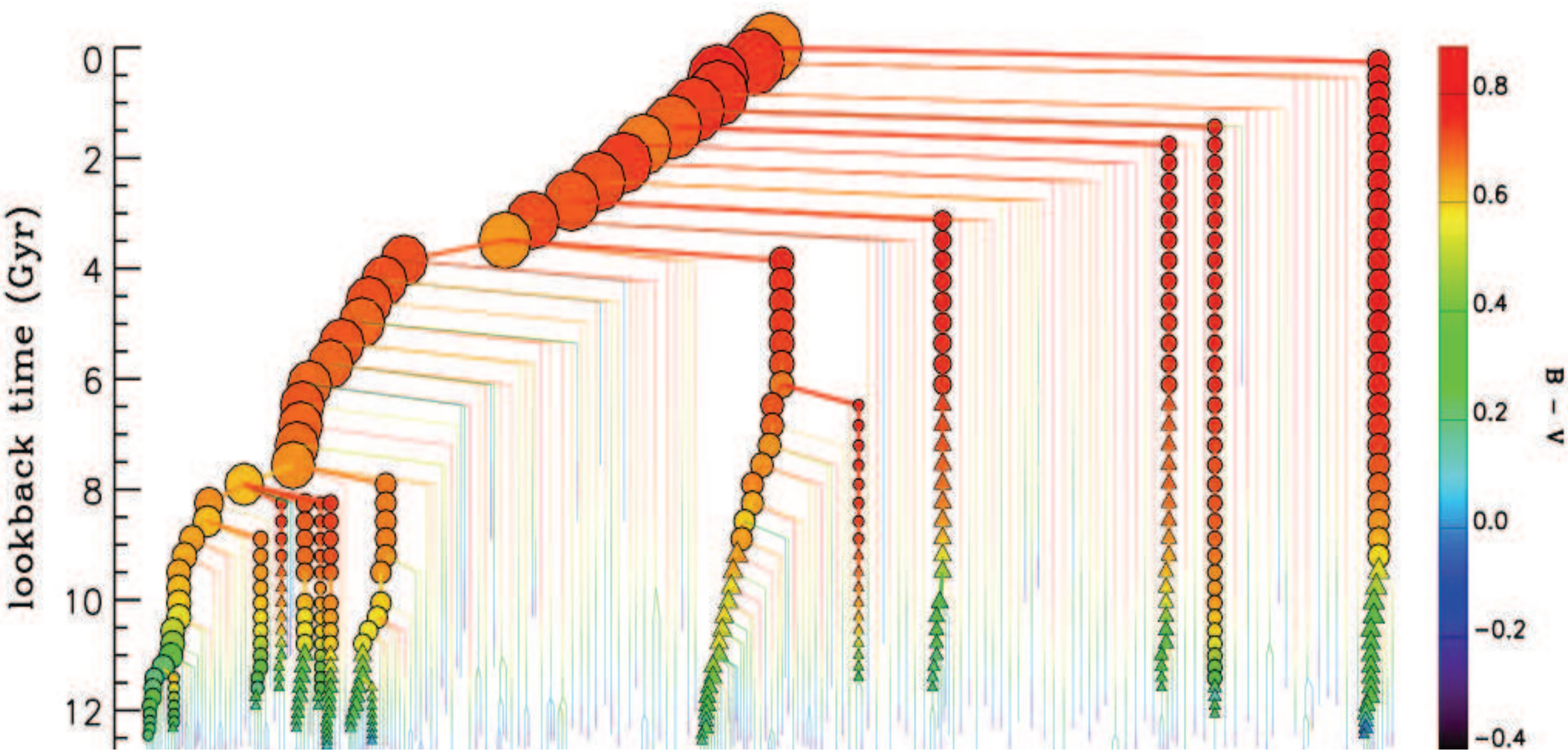

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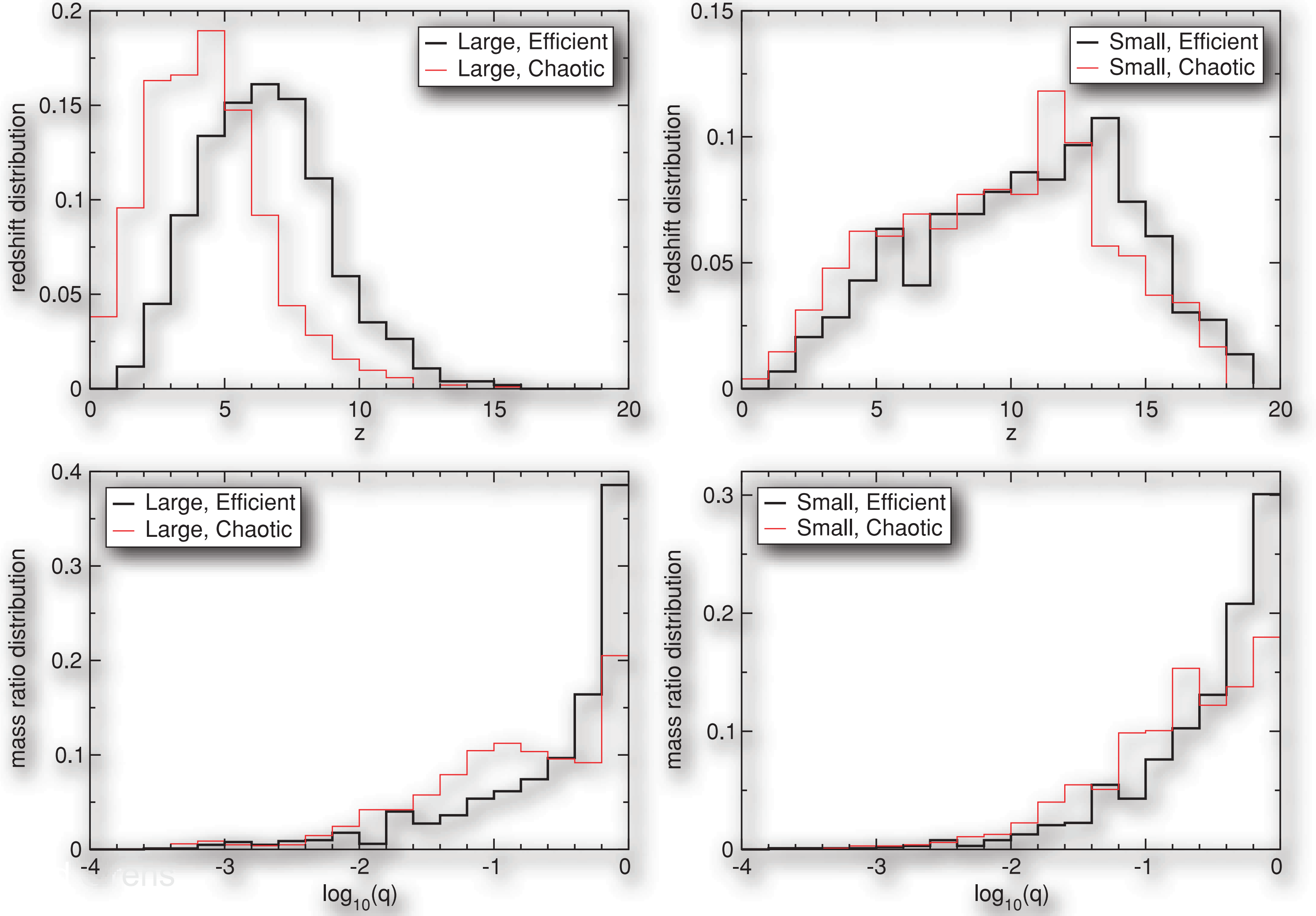
  - ET could observe seed black holes if they are of order 1000 solar mass

Models of Black Hole Seeds and Their Evolution

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



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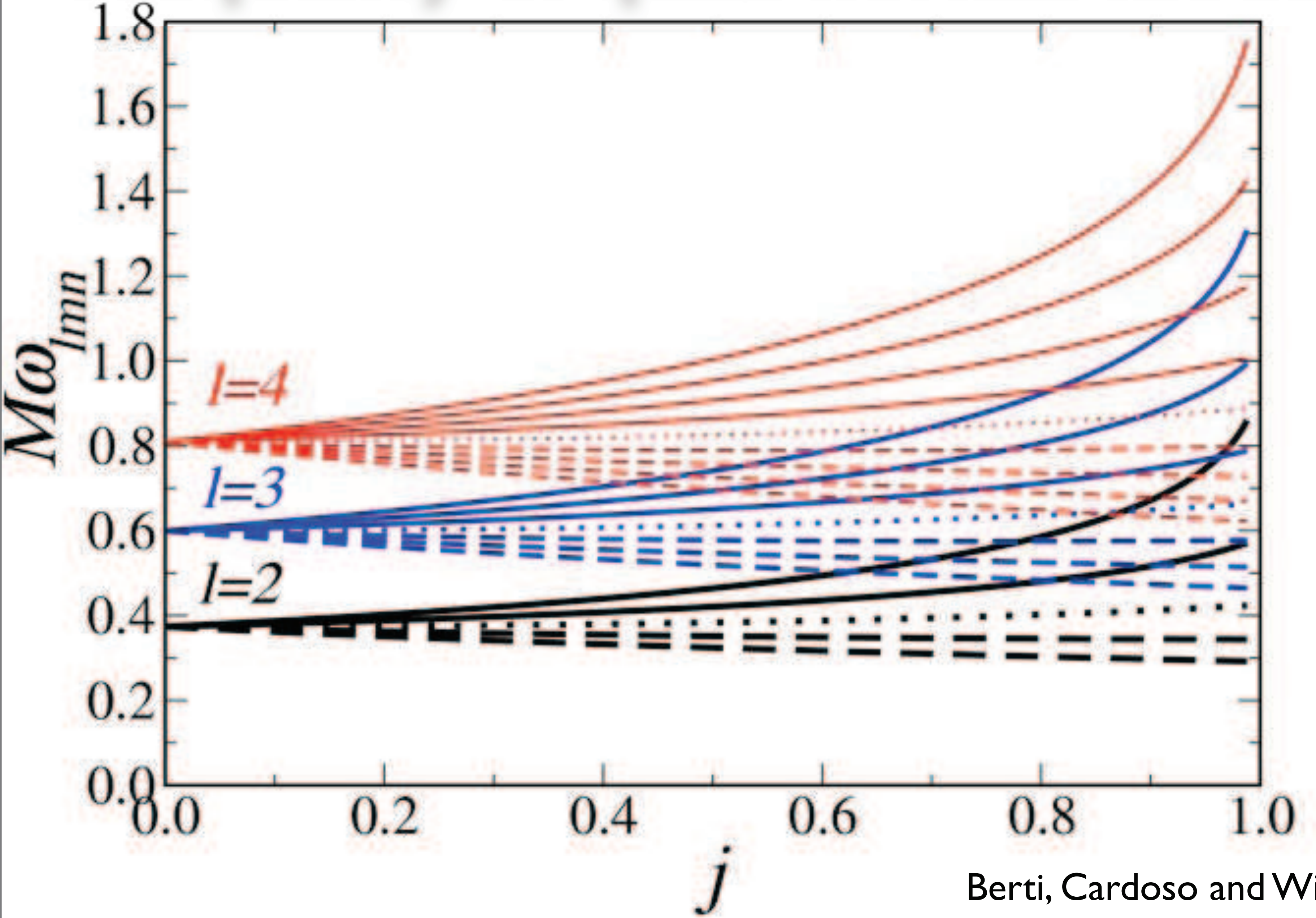
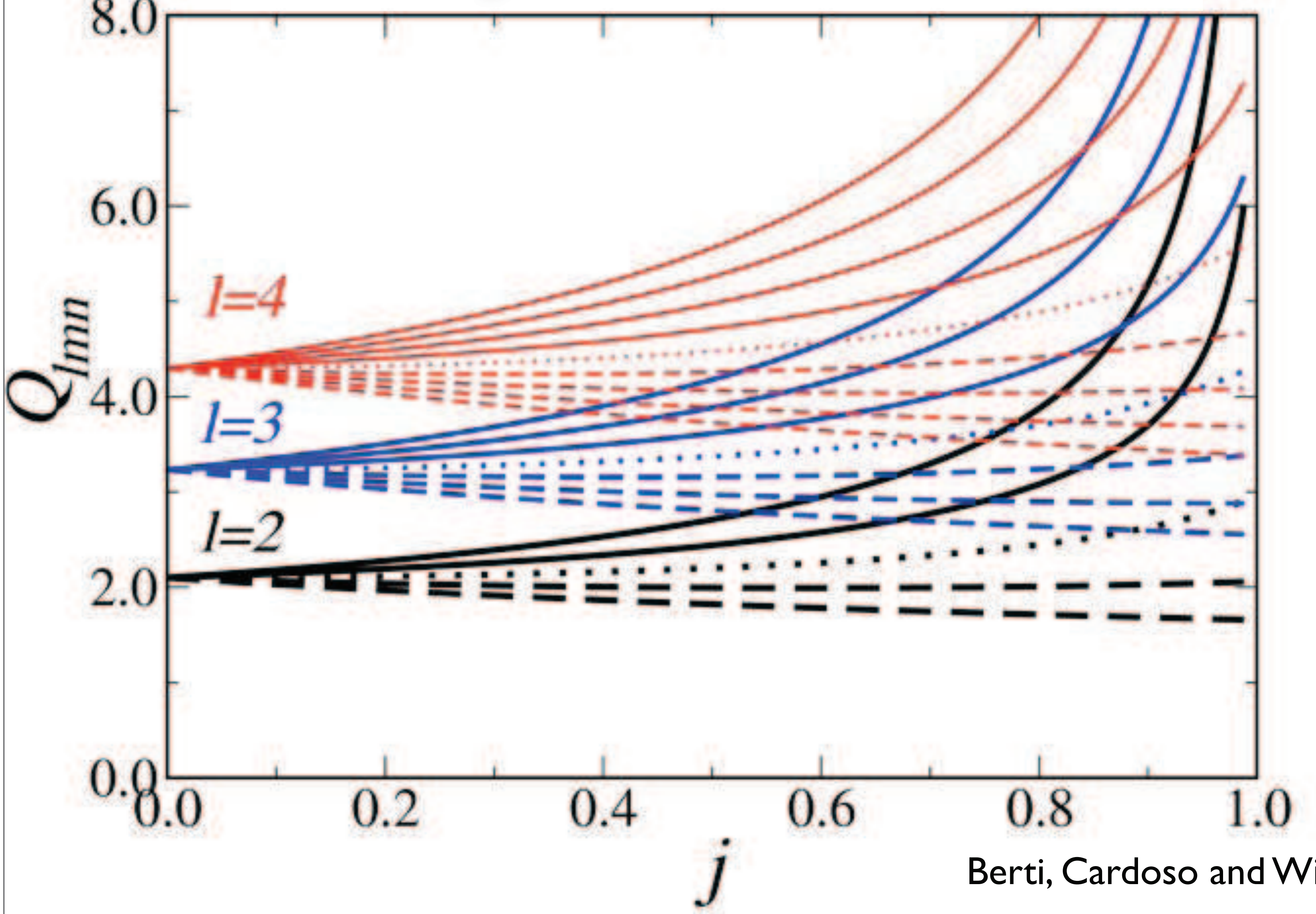
Frequency of quasi normal modes



Berti, Cardoso and Will

Quality Factor of QNMs



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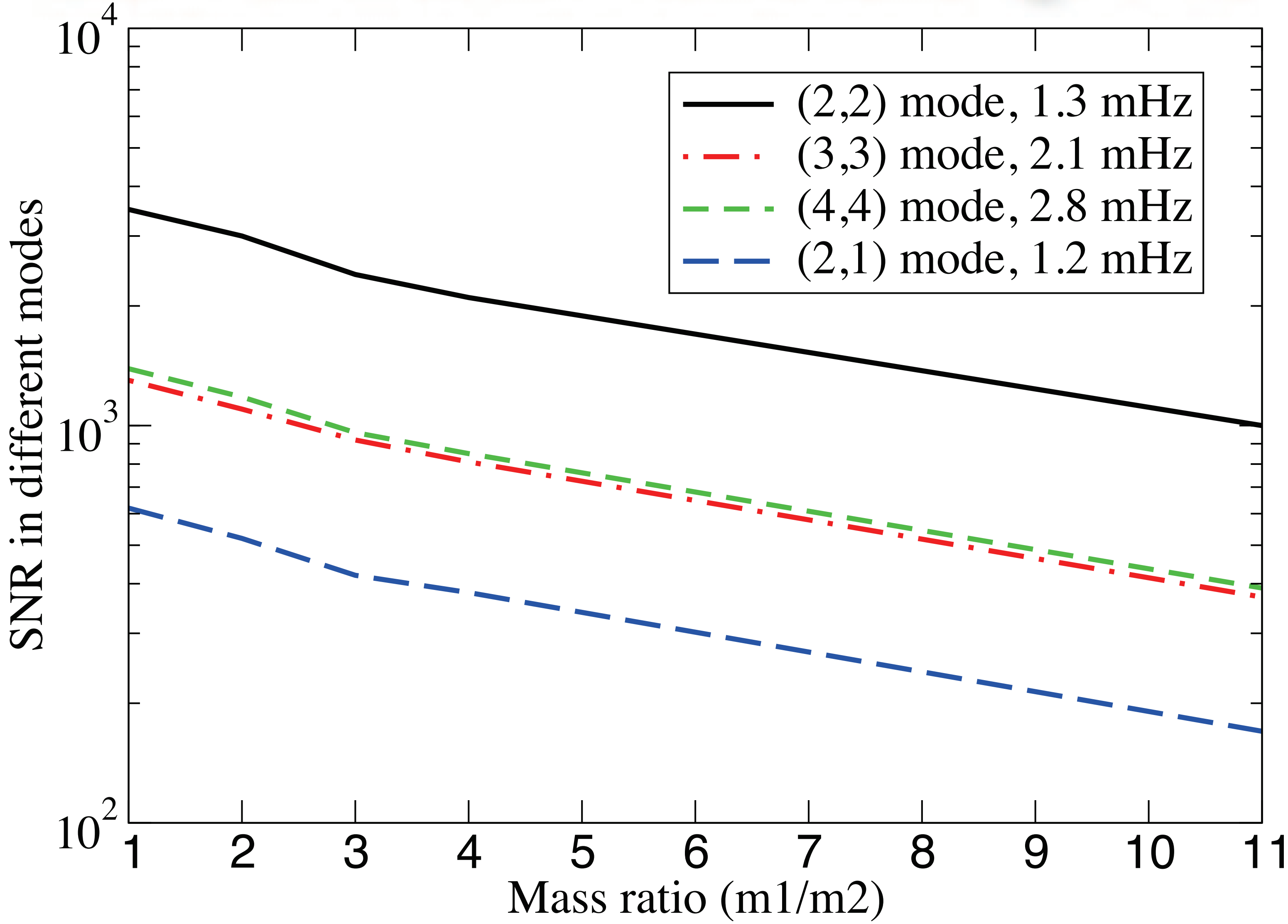
Emitted energy and relative amplitudes of different quasi-normal modes

Kamaretsos, Hannam, Husa, Sathyaprakash, 2010

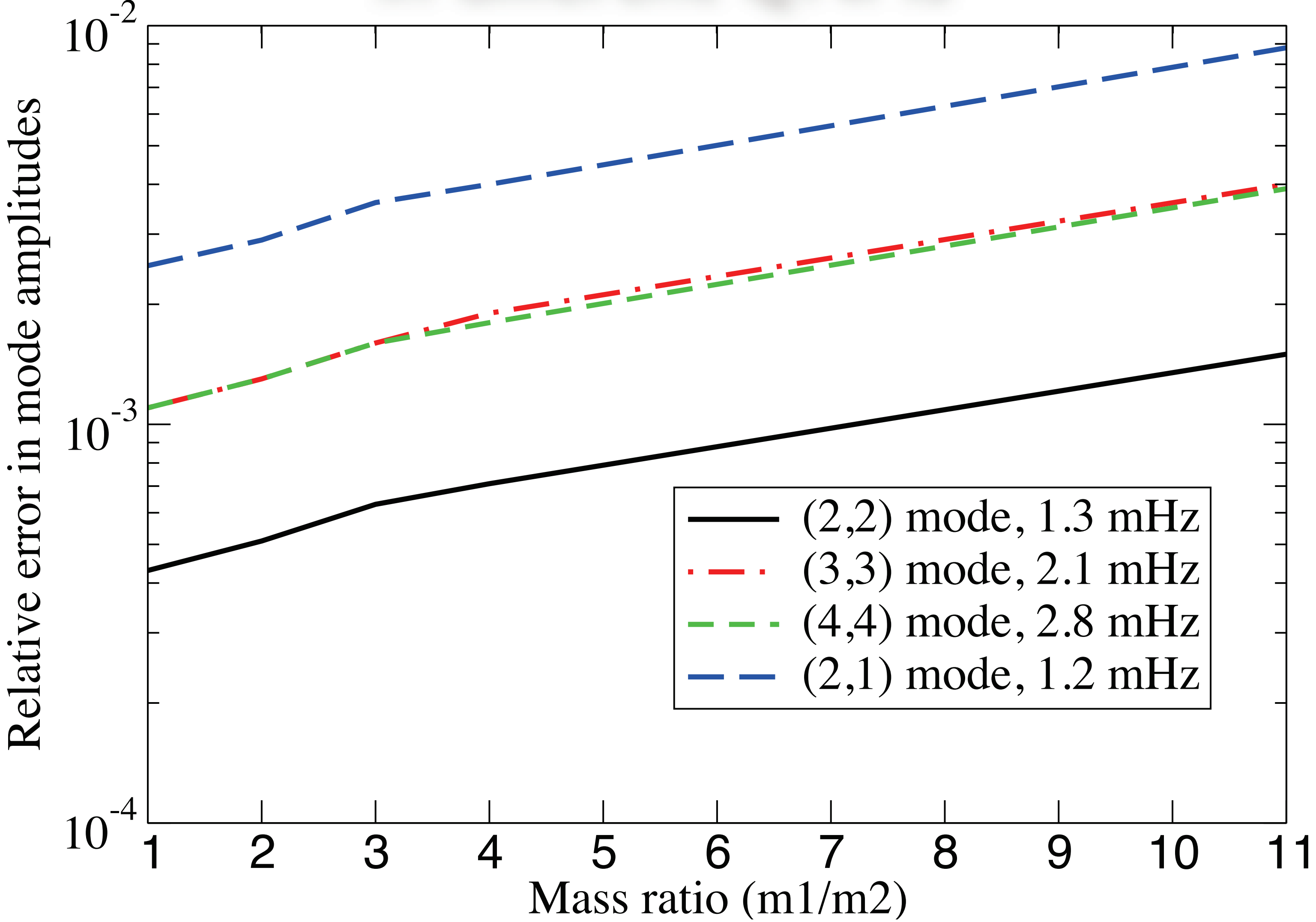
Table 1: For different mass ratios (q=1, 2, 3, 4, 11), we show the final spin of the black hole, percent of energy in the radiation, amplitude of (2,1), (3,3), (4,4) modes relative to (2,2) mode.

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

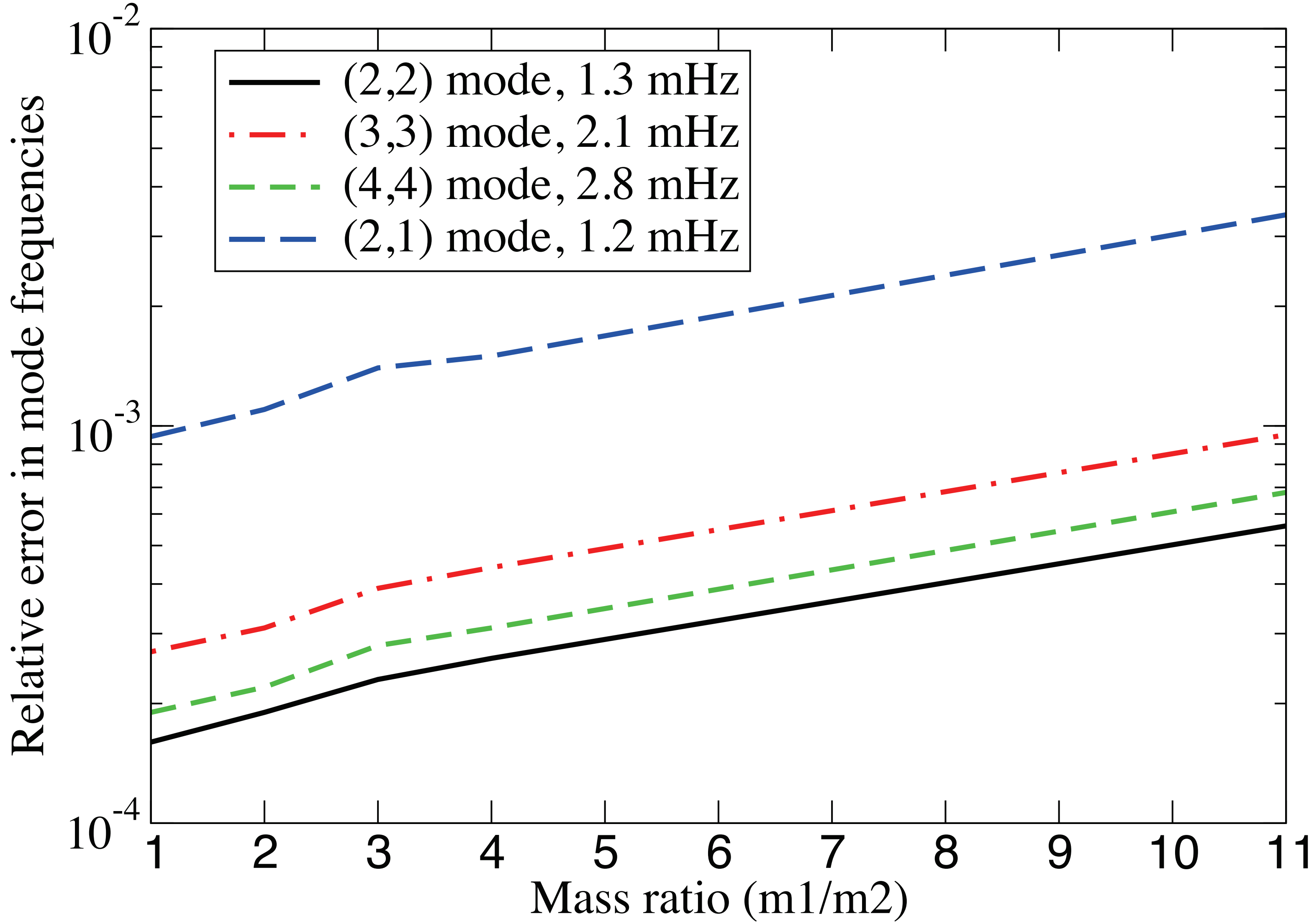
LISA SNRs for different QNMs



LISA measurement accuracies of amplitudes in different QNMs



LISA measurement accuracies of mode frequencies



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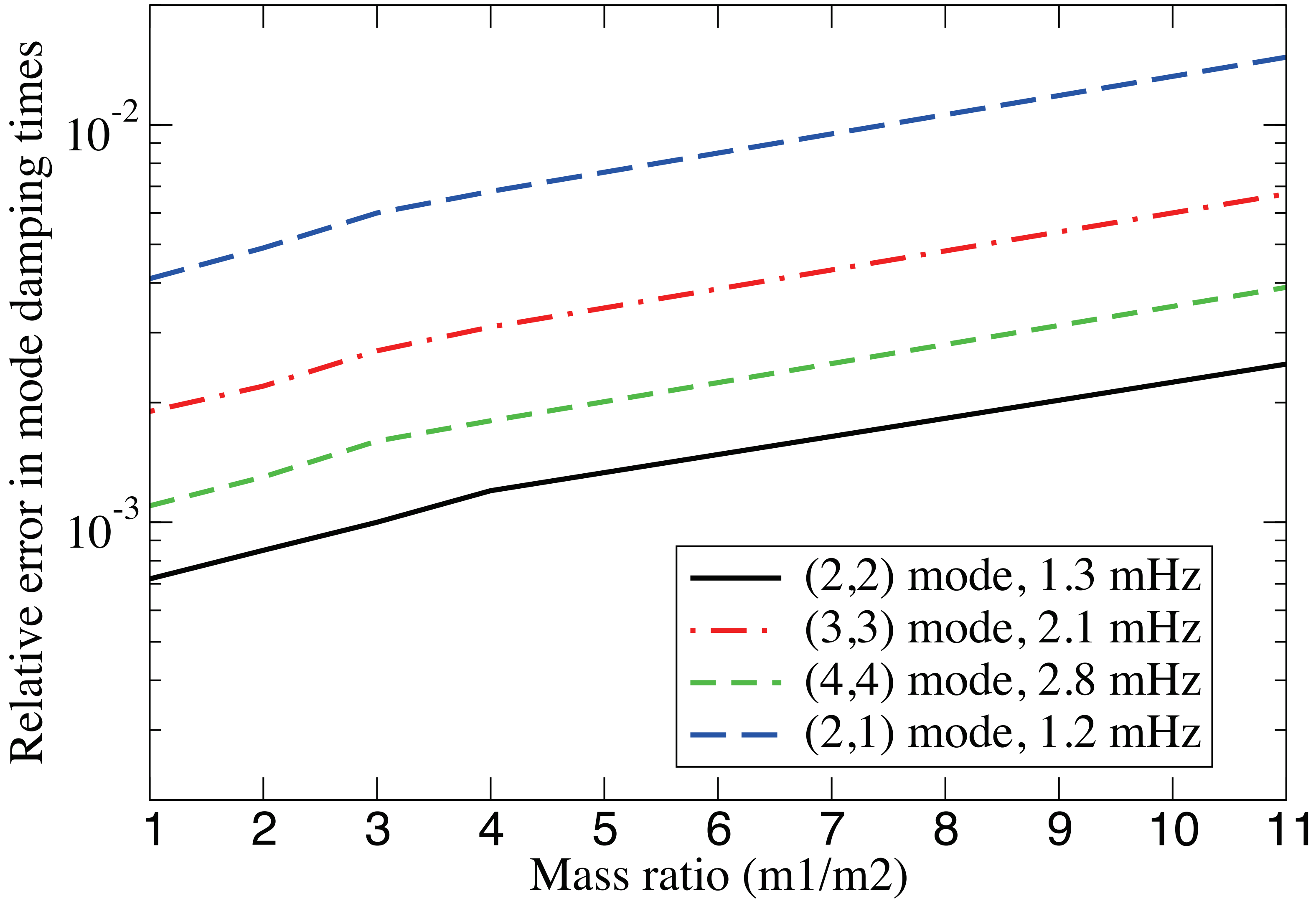
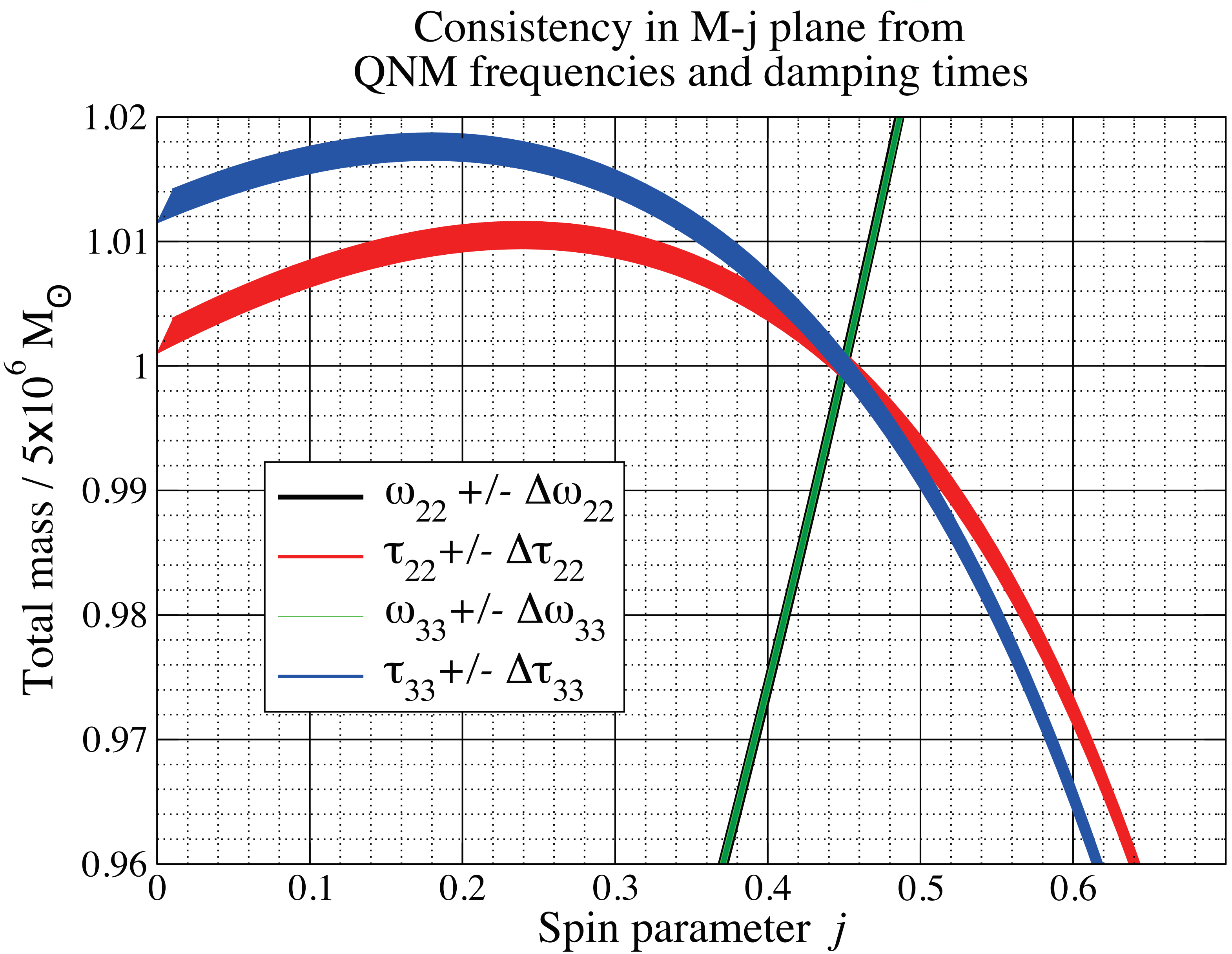


How can QNMs help test GR



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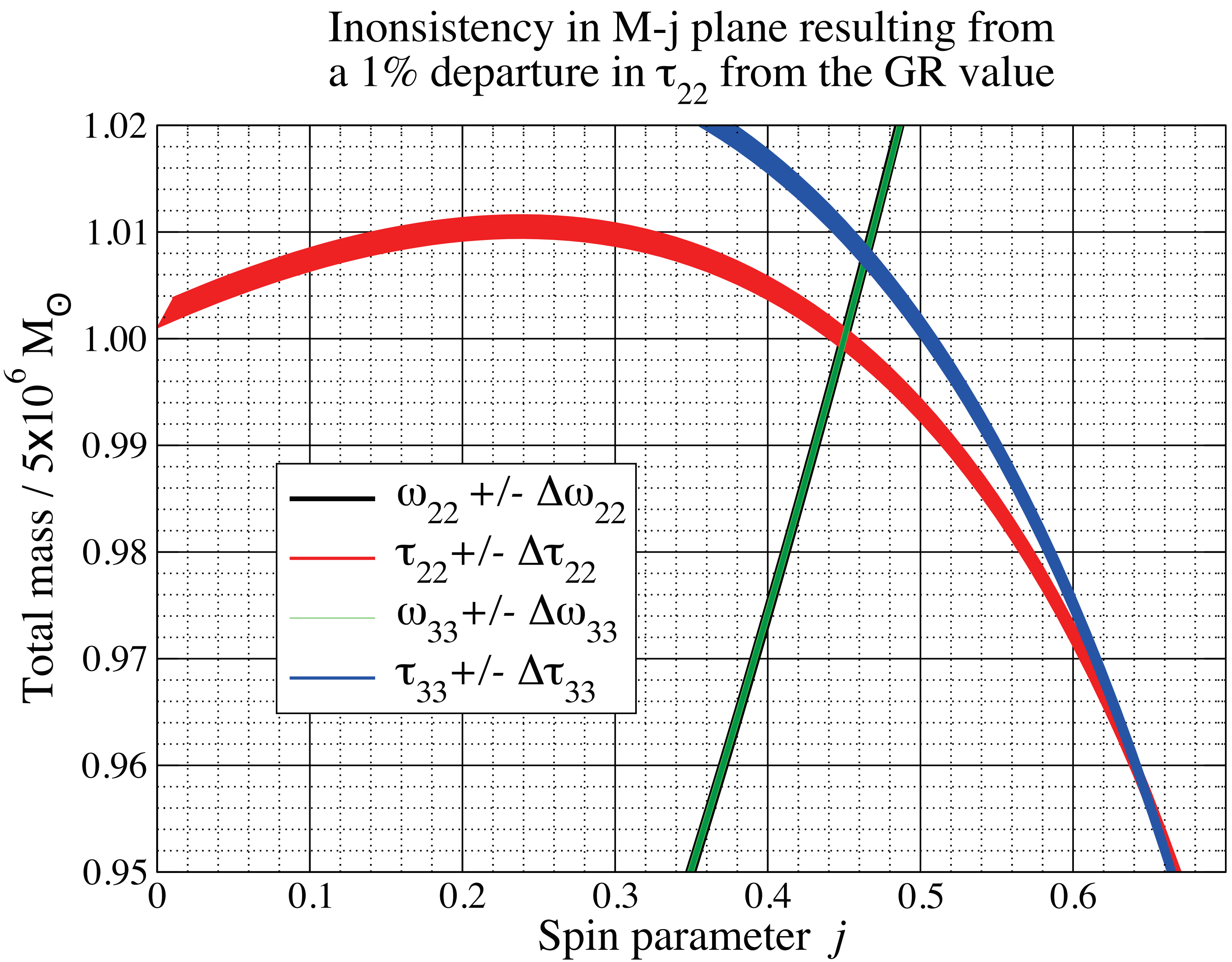

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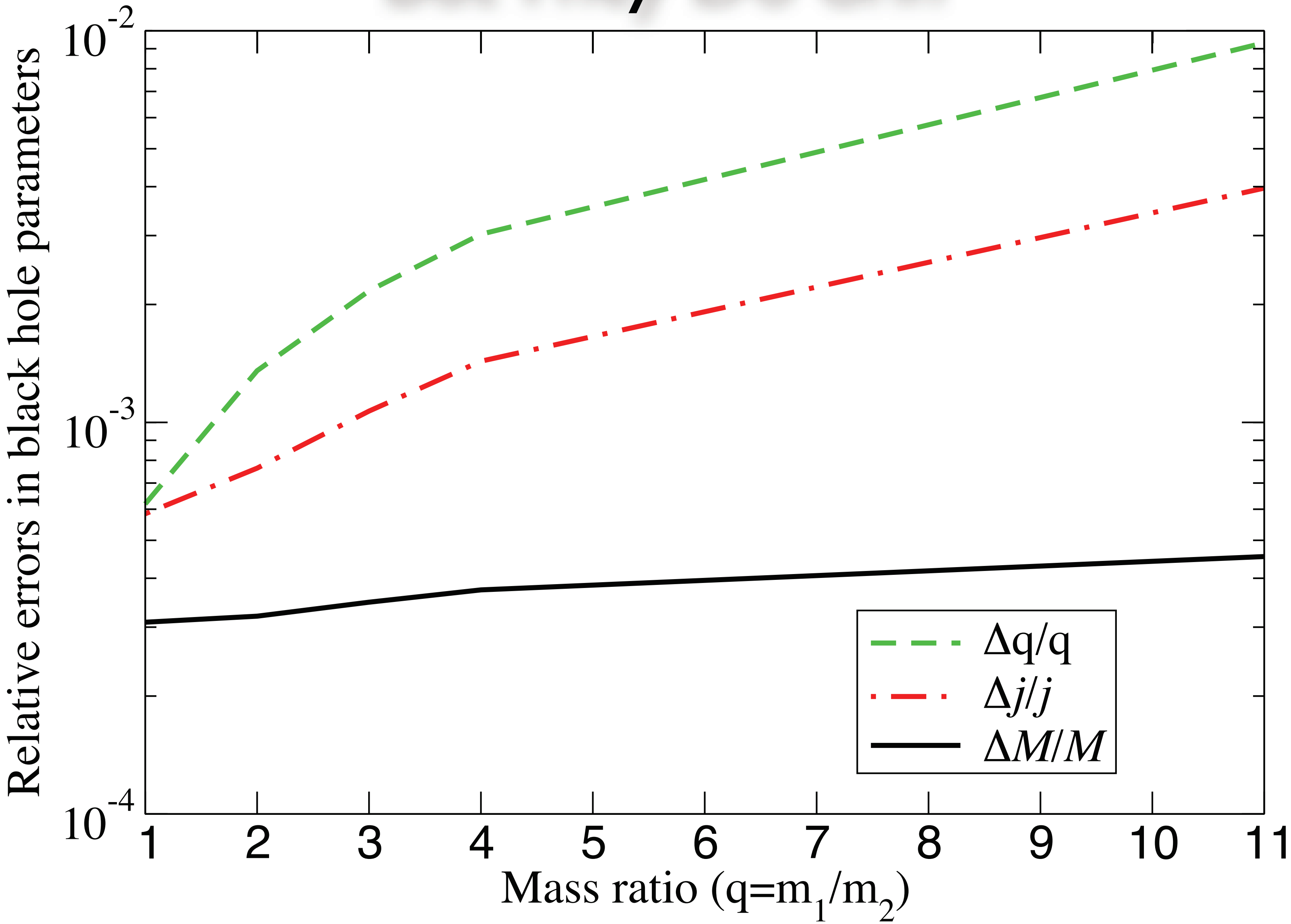

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