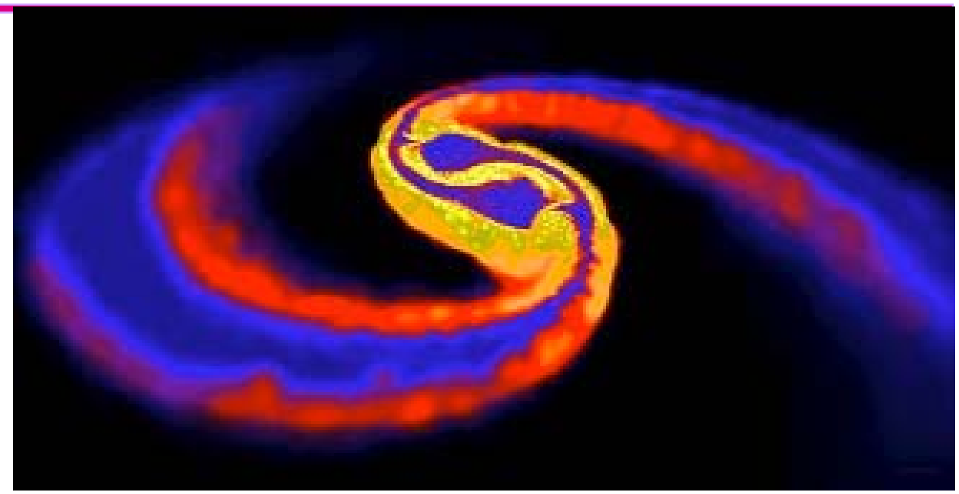
Status of the search for Gravitational Waves

- Gravitational waves
- Detection of GW's
- The LIGO project
  and its sister projects
- Astrophysical sources
- Recent results
- Conclusions



"Merging Neutron Stars" (Price & Rosswog)

**No discovery
to report here!**

Fig. 1.1 – LIGO detector with 4 km arms at Livingston, Louisiana

Fig. 1.2 – Virgo Detector, with 3 km arms, at Cascina, near Pisa

Alan Weinstein, Caltech

for the LIGO Scientific Collaboration

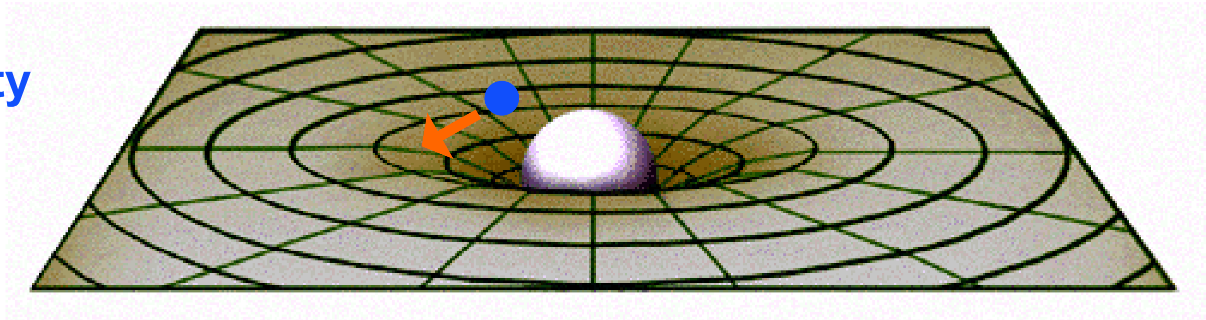
LIGO-G0900681

The **Study of gravitational waves** is at the *frontiers of science* in at least four different fields:

- General Relativity (GR) – physics at the extremes: strong (non-linear) gravity, relativistic velocities
- Astrophysics of compact sources – neutron stars, black holes, the big bang – the most energetic processes in the universe
- Interferometric gravitational wave detectors – the most precise measuring devices ever built
- GW data analysis – the *optimal* extraction of the weakest signals possible out of noisy data.

Gravitational Waves

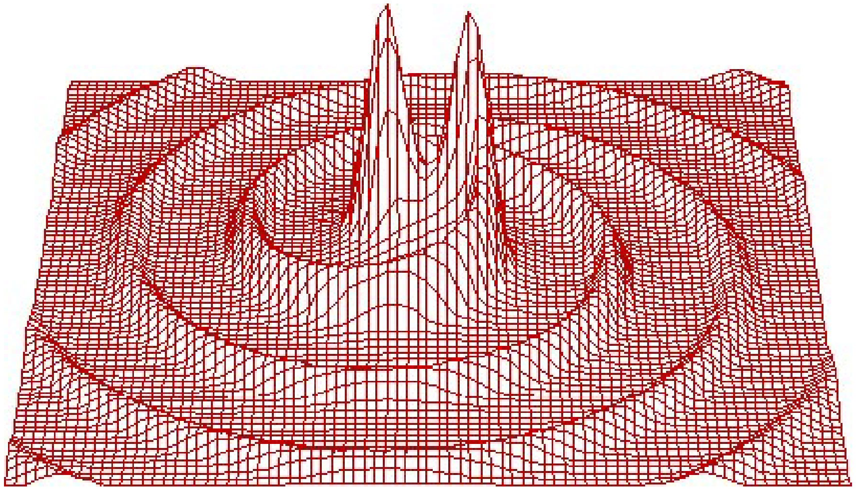
Static gravitational fields are described in General Relativity as a curvature or warpage of space-time, changing the distance between space-time events.



$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

Shortest straight-line path of a nearby test-mass is a ~Keplerian orbit.

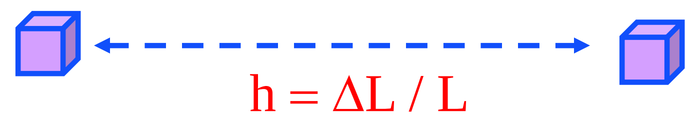
If the source is moving (at speeds close to c), ***eg,*** **because it's orbiting a companion, the "news" of the changing gravitational field propagates outward as gravitational radiation – a wave of spacetime curvature**

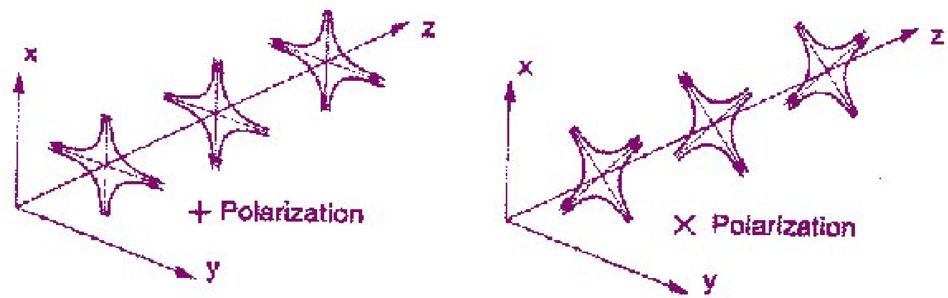


Nature of Gravitational Radiation

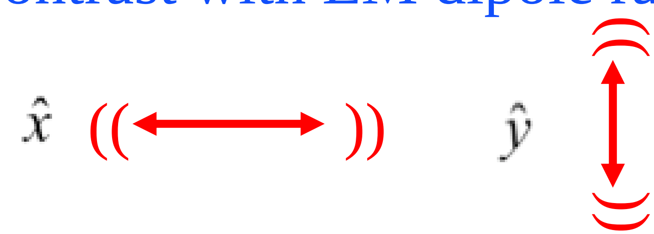
General Relativity predicts that rapidly changing gravitational fields produce ripples of curvature in fabric of spacetime

- Stretches and squeezes space between "test masses" – strain $h = \Delta L / L$
- propagating at speed of light
  - *mass of graviton = 0*
- space-time distortions are transverse to direction of propagation
- GW are tensor fields (EM: vector fields)
  two polarizations: plus (⊕) and cross (⊗)
  (EM: two polarizations, x and y)
  Spin of graviton = 2





Contrast with EM dipole radiation:



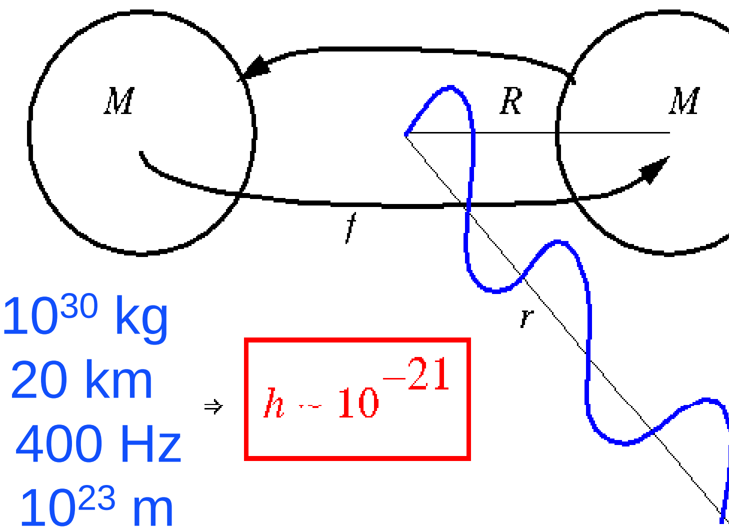
Sources of GWs

- Accelerating charge $\Rightarrow$ electromagnetic radiation (dipole)
- Accelerating mass $\Rightarrow$ gravitational radiation (quadrupole)
- Amplitude of the gravitational wave (dimensional analysis):

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \quad \Rightarrow \quad h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$

- $\ddot{I}_{\mu\nu}$ = second derivative of mass quadrupole moment (non-spherical part of kinetic energy – tumbling dumb-bell)
- *G* is a small number! (space-time is *stiff*).
- Waves can carry huge energy with minimal amplitude
- Need huge mass, relativistic velocities, nearby.
- For a binary neutron star pair, 10m light-years away, solar masses moving at 15% of speed of light:

Energy-momentum conservation:
energy cons $\Rightarrow$ no monopole radiation
momentum cons $\Rightarrow$ no dipole radiation
$\Rightarrow$ lowest multipole is quadrupole wave



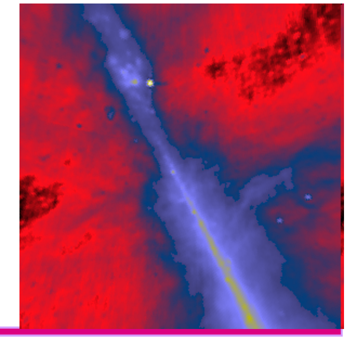
M ~ 10^{30} kg
R ~ 20 km
f ~ 400 Hz
r ~ 10^{23} m

$\Rightarrow$ $\boxed{h \sim 10^{-21}}$

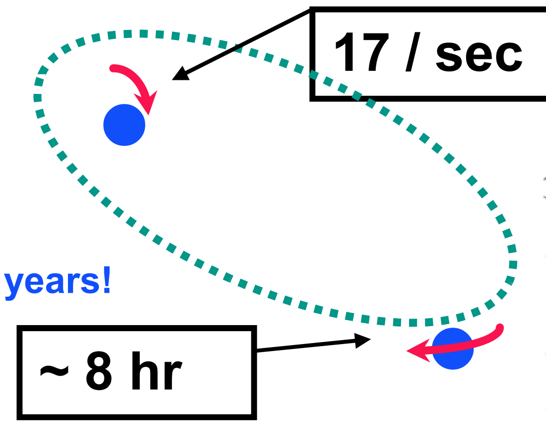
Terrestrial sources *TOO WEAK*!

LIGO

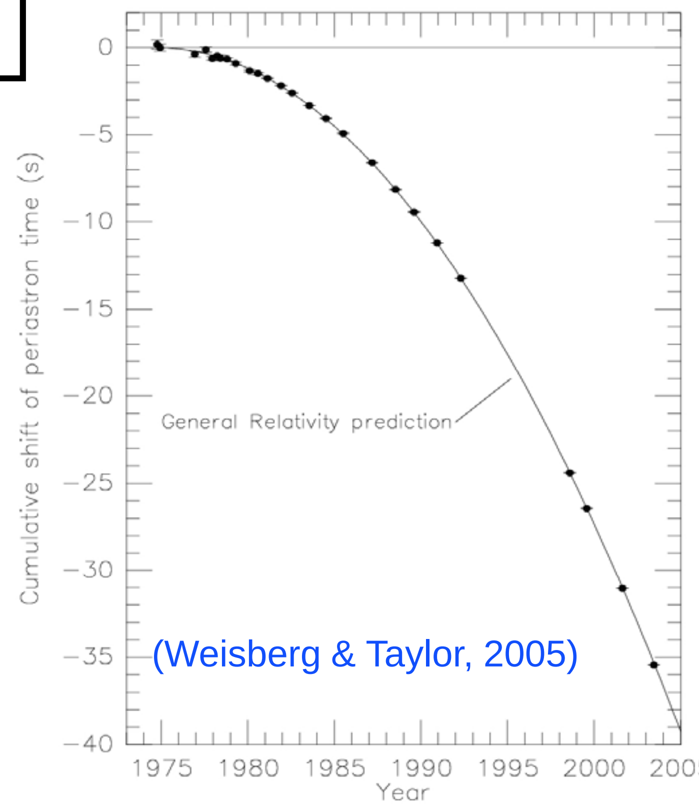
Indirect Evidence for GWs from Hulse-Taylor binary



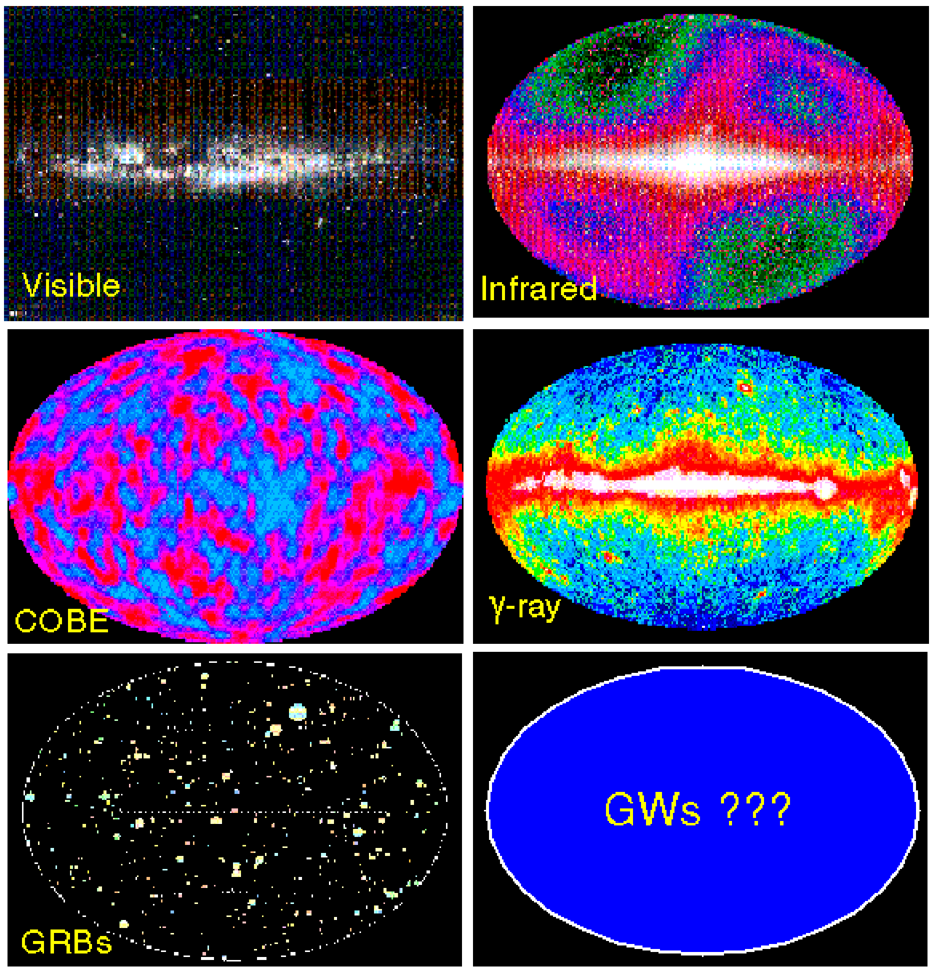
emission of gravitational waves by compact binary system



- Binary pulsar PSR 1913 + 16
- Discovered in 1974
- orbital parameters measured continuously measured over 30 years!
- Only 7 kpc away
- 8 hr period speeds up 35 sec from 1975-2005
- measured to ~50 msec accuracy
- deviation grows quadratically with time
- shortening of period ⇐ orbital energy loss
- Compact: negligible loss from friction, material flow
- beautiful agreement with GR prediction
- Apparently, loss is due to GWs!
- Nobel Prize, 1993
- Merger in about 300M years (<< age of universe!)
- GW emission will be strongest near the end – Coalescence of black holes!



A NEW WINDOW ON THE UNIVERSE



The history of Astronomy:
new bands of the EM spectrum opened → major discoveries!

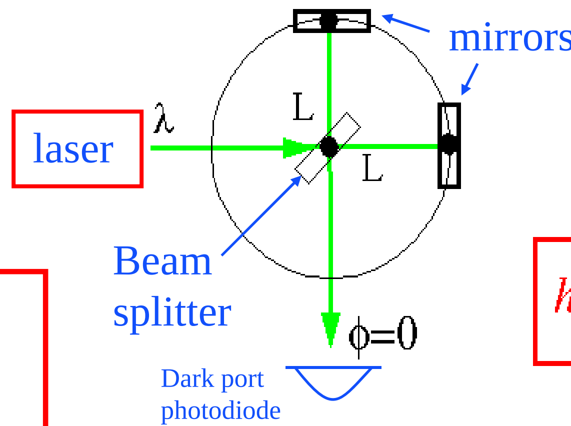
GWs aren't just a new band, they're a new spectrum, with very different and complementary properties to EM waves.

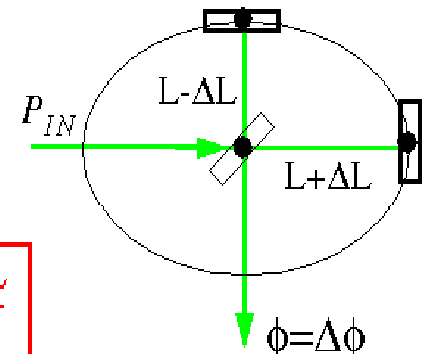
- Vibrations *of* space-time, not *in* space-time
- Emitted by coherent motion of huge masses moving at near light-speed; not vibrations of electrons in atoms
- Can't be absorbed, scattered, or shielded.

GW astronomy is a totally new, unique window on the universe

Interferometric detection of GWs

GW acts on freely falling masses:



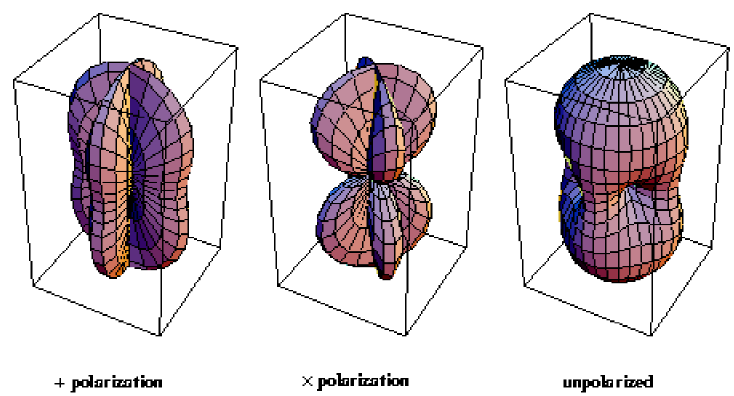


$$h = \frac{\Delta L}{L}$$

$$P_{out} = P_{in} \sin^2(2k\Delta L)$$

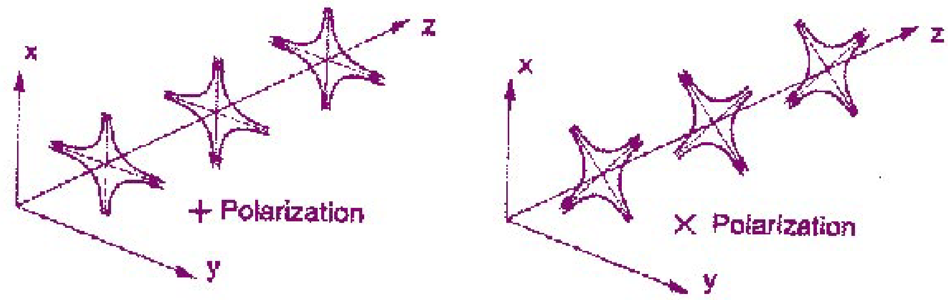
For fixed ability to measure ΔL, make L as big as possible!

Antenna pattern:
(not very directional!)

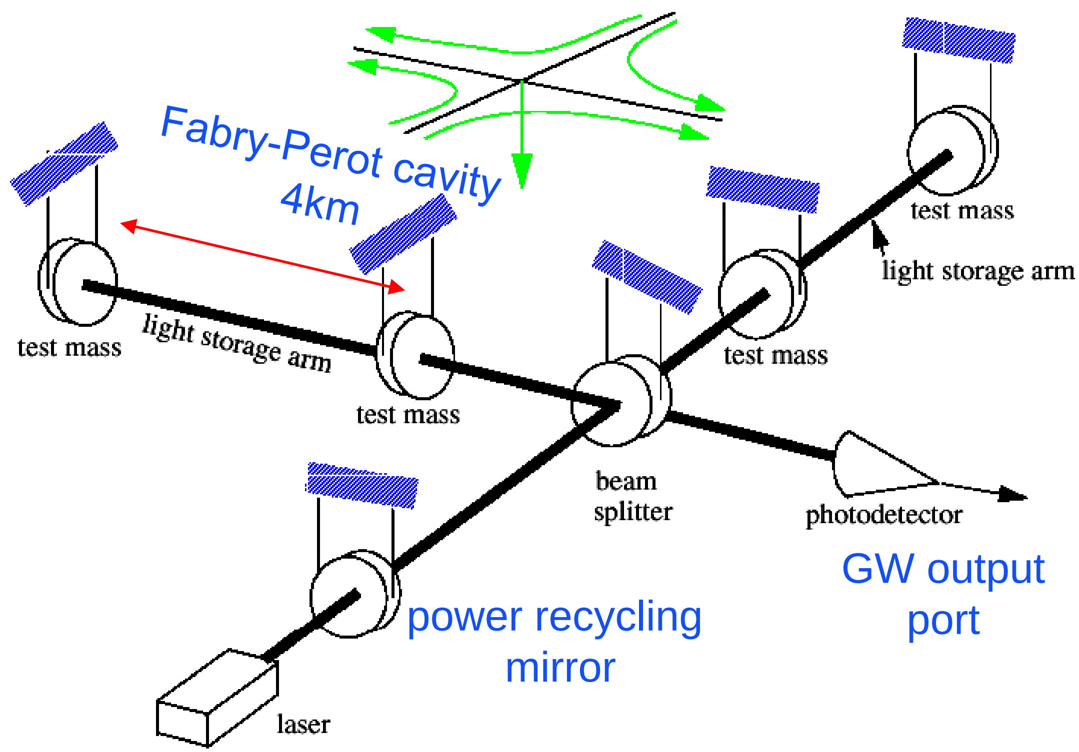


Interferometric GW detectors

- Quadrupolar radiation pattern

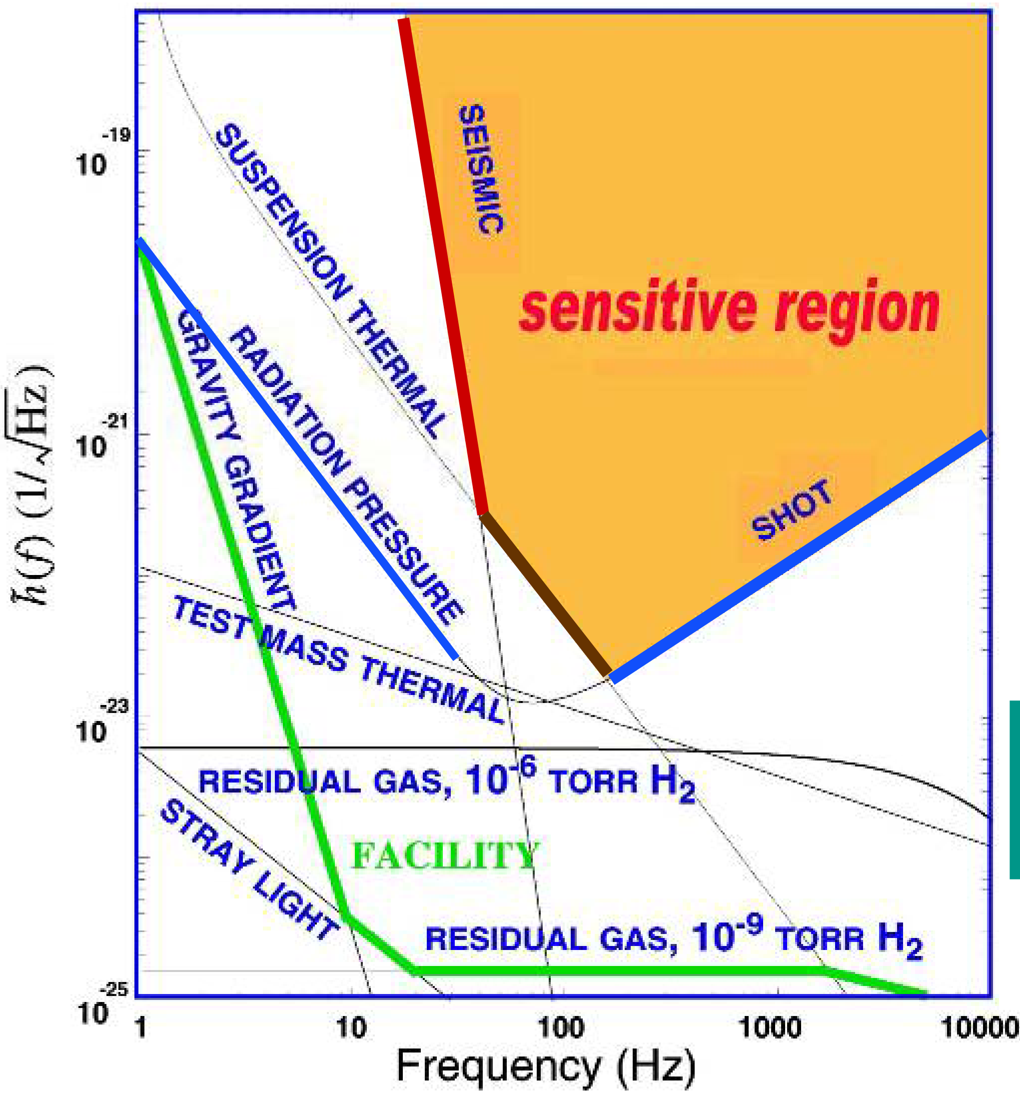


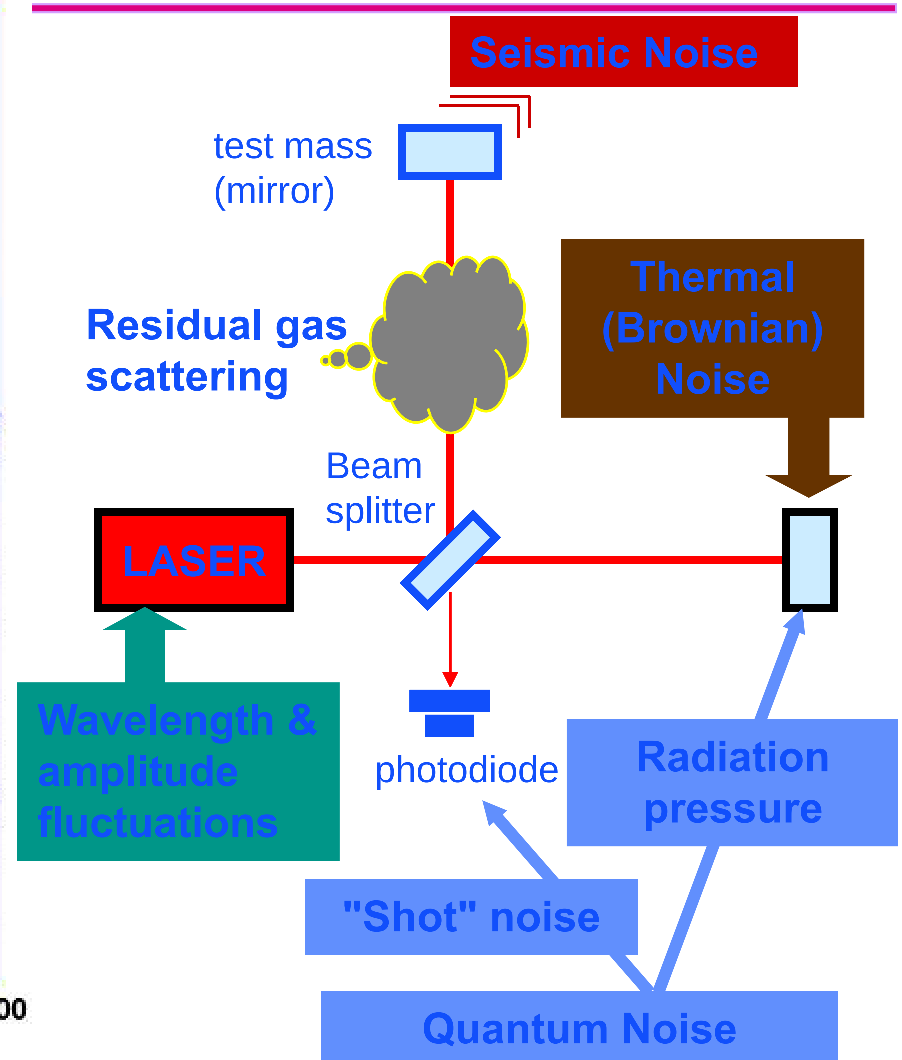
- Michelson interferometer
  "natural" GW detector
- Suspended mirrors
  in "free-fall"
- Broad-band response
  ~50 Hz to few kHz
- Waveform detector
  e.g., chirp reconstruction



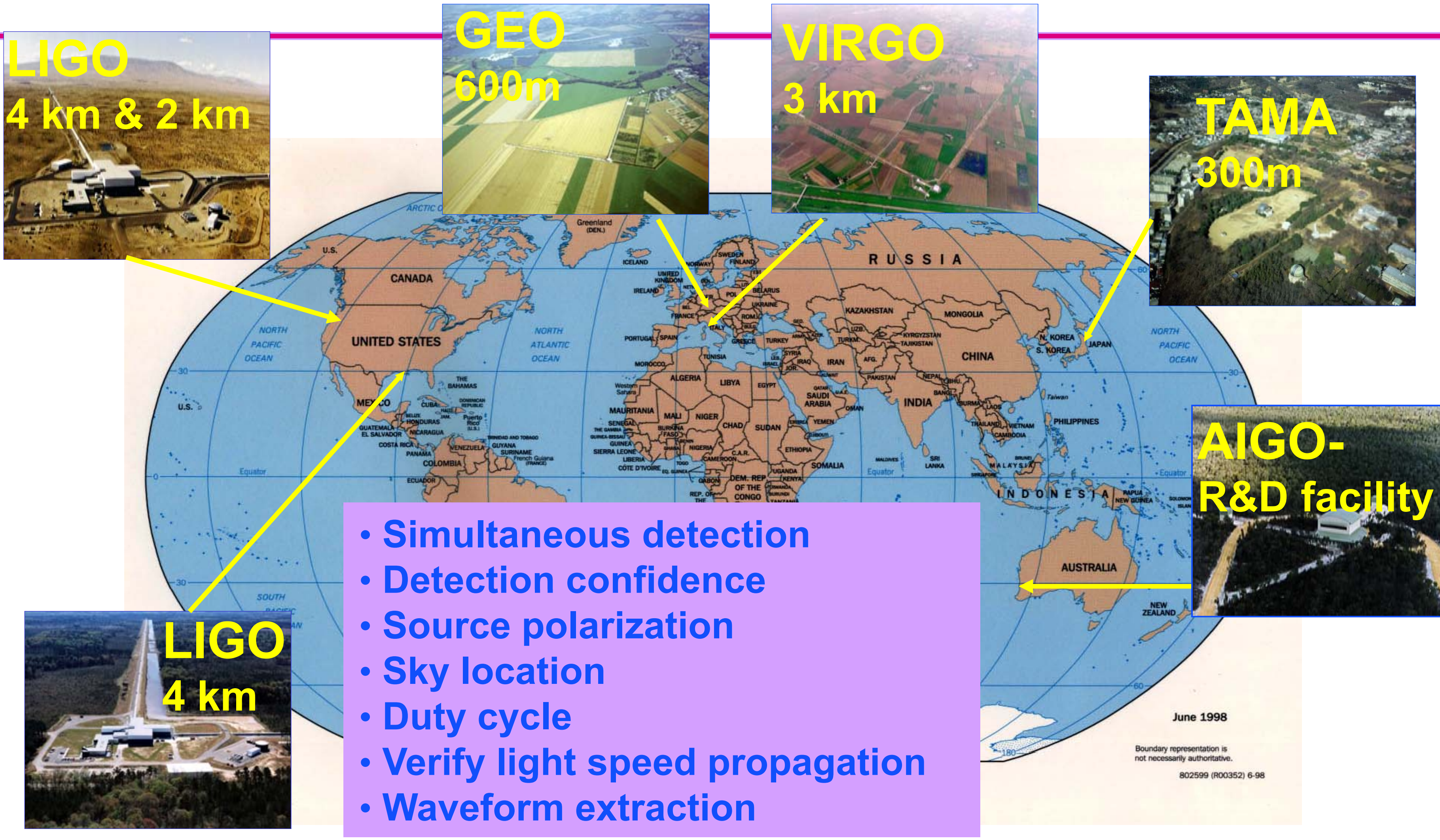
- ***h* = *ΔL* / *L***
  Goal: get $h \leq 10^{-22}$;
  can build L = 4 km;
  must measure
  $\Delta L = h\,L \leq 4 \times 10^{-19}$ m

Limits to Initial LIGO Sensitivity





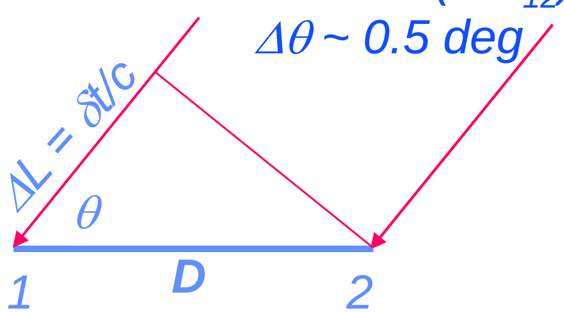
Global network of interferometers

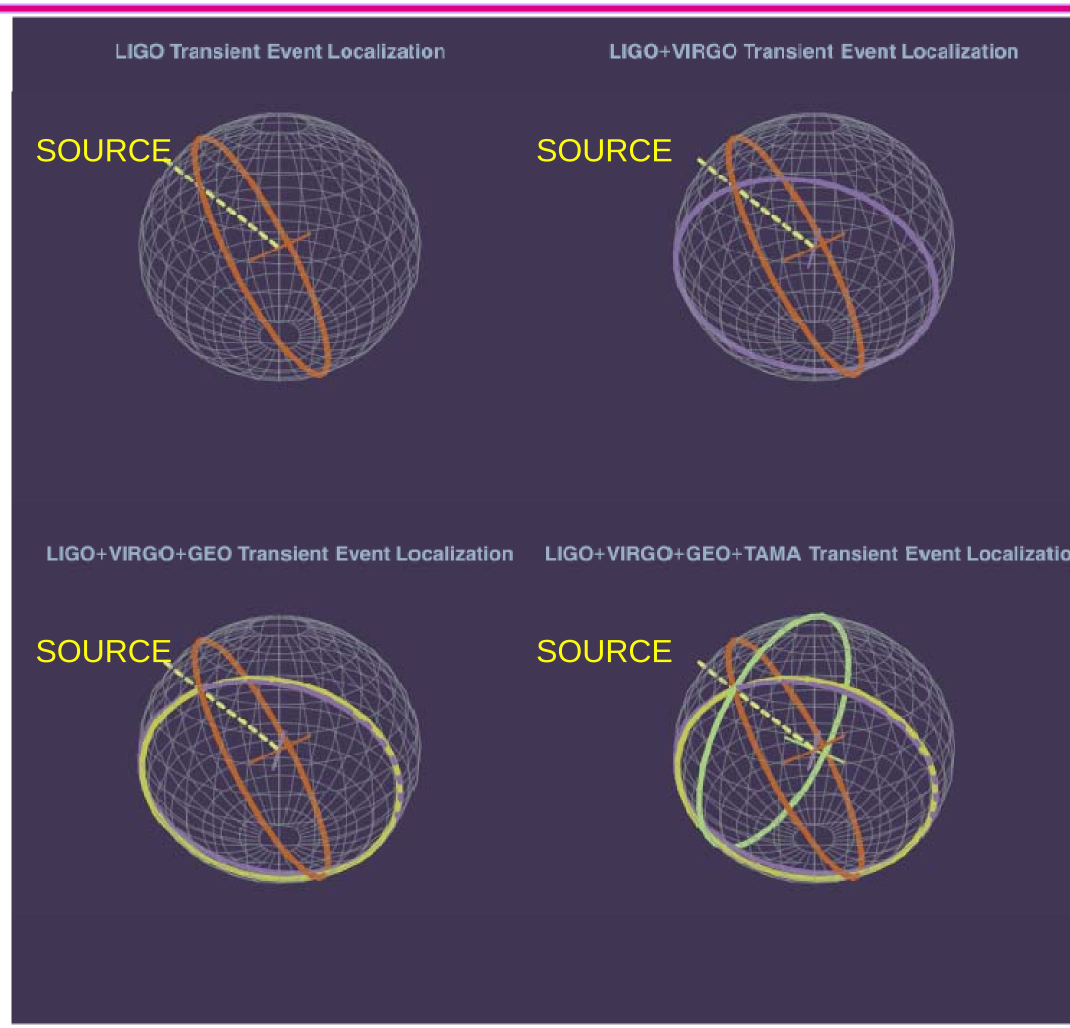


- Simultaneous detection
- Detection confidence
- Source polarization
- Sky location
- Duty cycle
- Verify light speed propagation
- Waveform extraction

Event Localization With An Array of GW Interferometers

$$\cos\theta = \delta t / (c\, D_{12})$$
$$\Delta\theta \sim 0.5 \text{ deg}$$





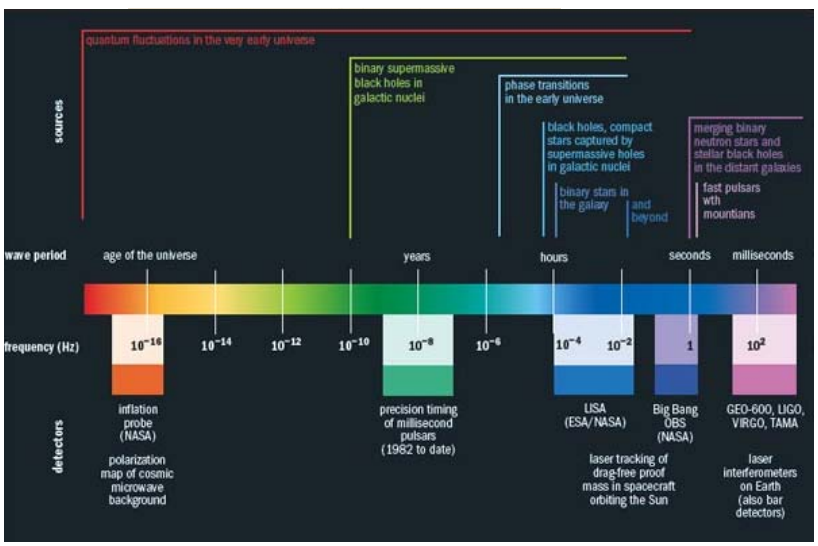
Frequency range of GW Astronomy

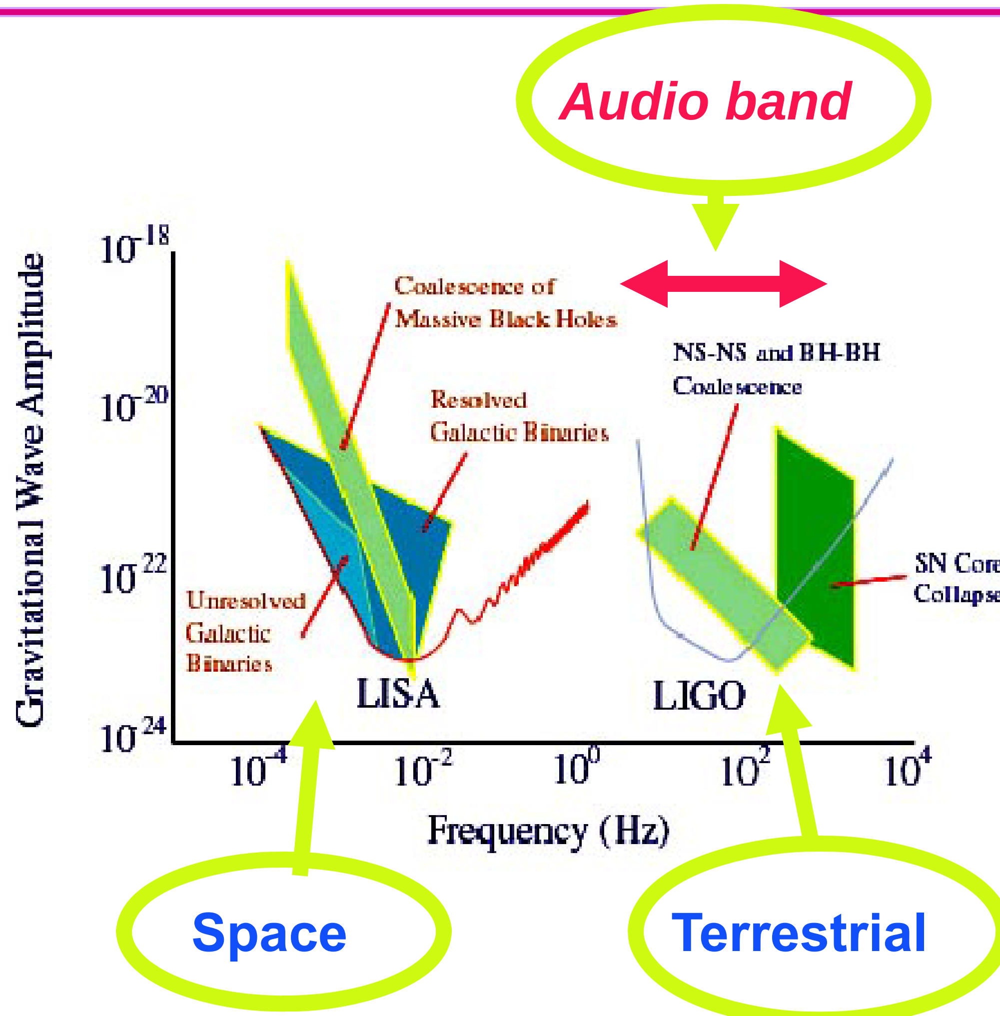
Electromagnetic waves

- over ~16 orders of magnitude
- Ultra Low Frequency radio waves to high energy gamma rays

Gravitational waves

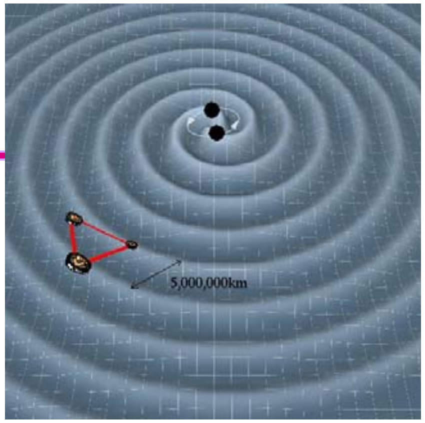
- over ~8 orders of magnitude
- Terrestrial + space detectors





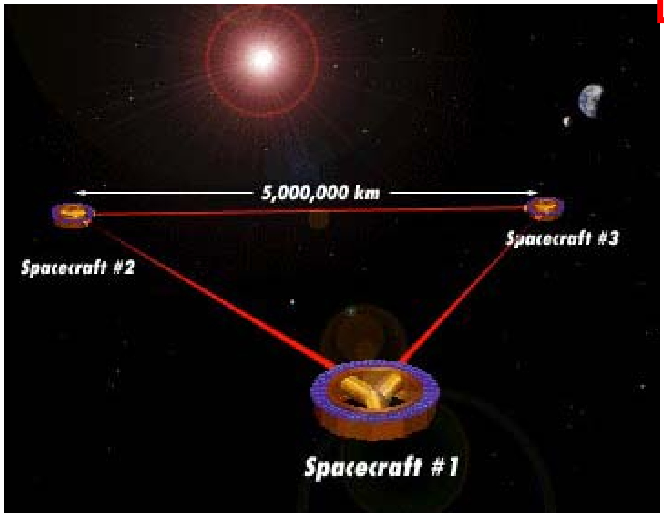
The Laser Interferometer Space Antenna

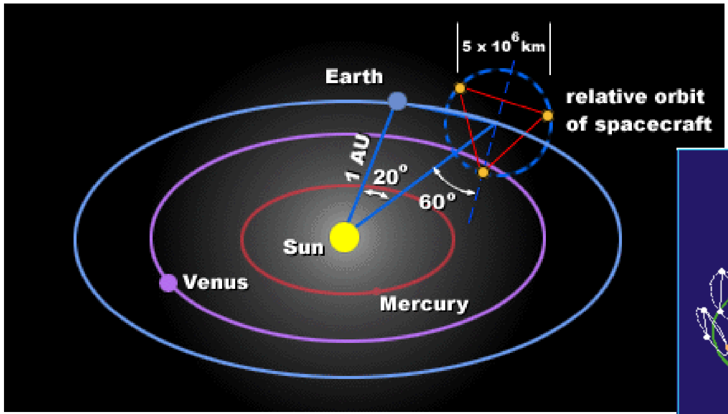
LISA

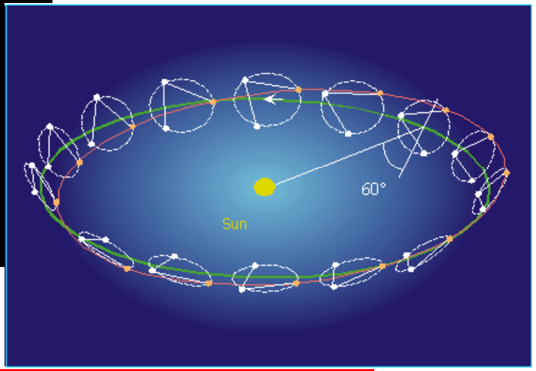


Three spacecraft in orbit about the sun,
with 5 million km baseline

The center of the triangle formation will be in the ecliptic plane
1 AU from the Sun and 20 degrees behind the Earth.



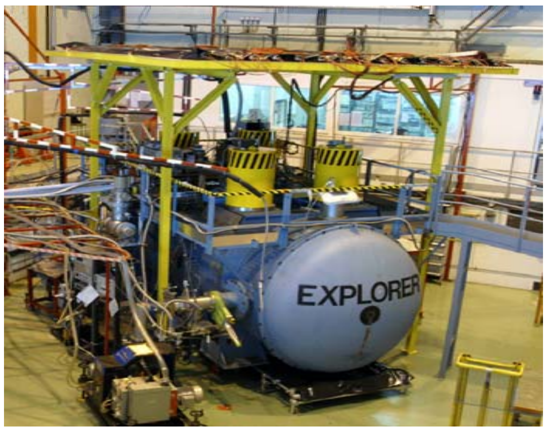




LISA (NASA/JPL, ESA) may fly in the next 10 years!

Cryogenic Resonant detectors

Explorer (at CERN)
Univ. of ROME ROG group



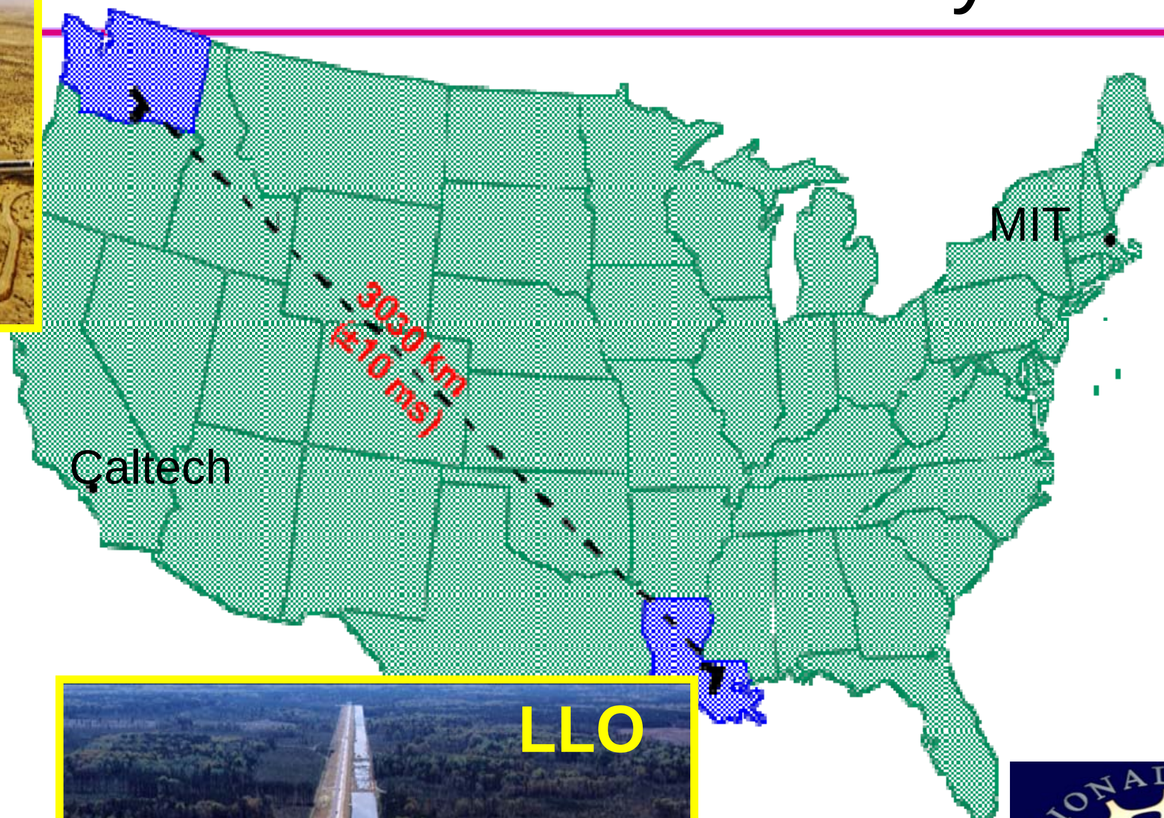
Nautilus (at Frascati)
Univ. of ROME ROG group

sensitivity:
$h_{rms} \sim 10^{-19}$;
excellent duty cycle

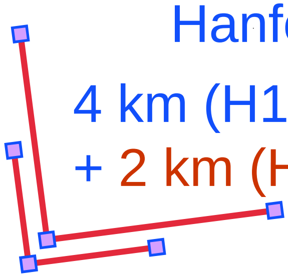
AURIGA, LNL (Padova)

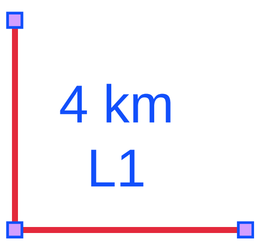
ALLEGRO, LSU (Baton Rouge)

LIGO: Laser Interferometer Gravitational-wave Observatory



Hanford, WA





Livingston, LA

LIGO Scientific Collaboration

LIGO

LSC

University of Maryland 1856

Michigan

University of Strathclyde

ACIGA

Leland Stanford Junior University 1891

Montana State University

Loyola University New Orleans

University of Washington

Syracuse University Founded AD 1870

University of Glasgow

Università degli Studi del Sannio

Trinity University

San José State University

University of Wisconsin UW Milwaukee

ANU The Australian National University

LSU

UTB TSC

The University of Western Australia

1754

NASA Goddard Space Flight Center

California Institute of Technology 1891

Northwestern University

Rochester Institute of Technology R·I·T 1829

Andrews University

Massachusetts Institute of Technology 1861

Southern Louisiana University

The University of Texas at Austin

Moscow State University

The University of Adelaide Australia

PAN

Embry-Riddle Aeronautical University

University of Massachusetts Amherst 1863

University of Southampton

PennState 1855

Carleton College Northfield, Minn. A.D. 1866

GEO 600

Cardiff University

Universitat de les Illes Balears

Washington State University

UF University of Florida

The University of Mississippi 1848

Charles Sturt University

University of Rochester

NAOJ

Southern University Agricultural & Mechanical College

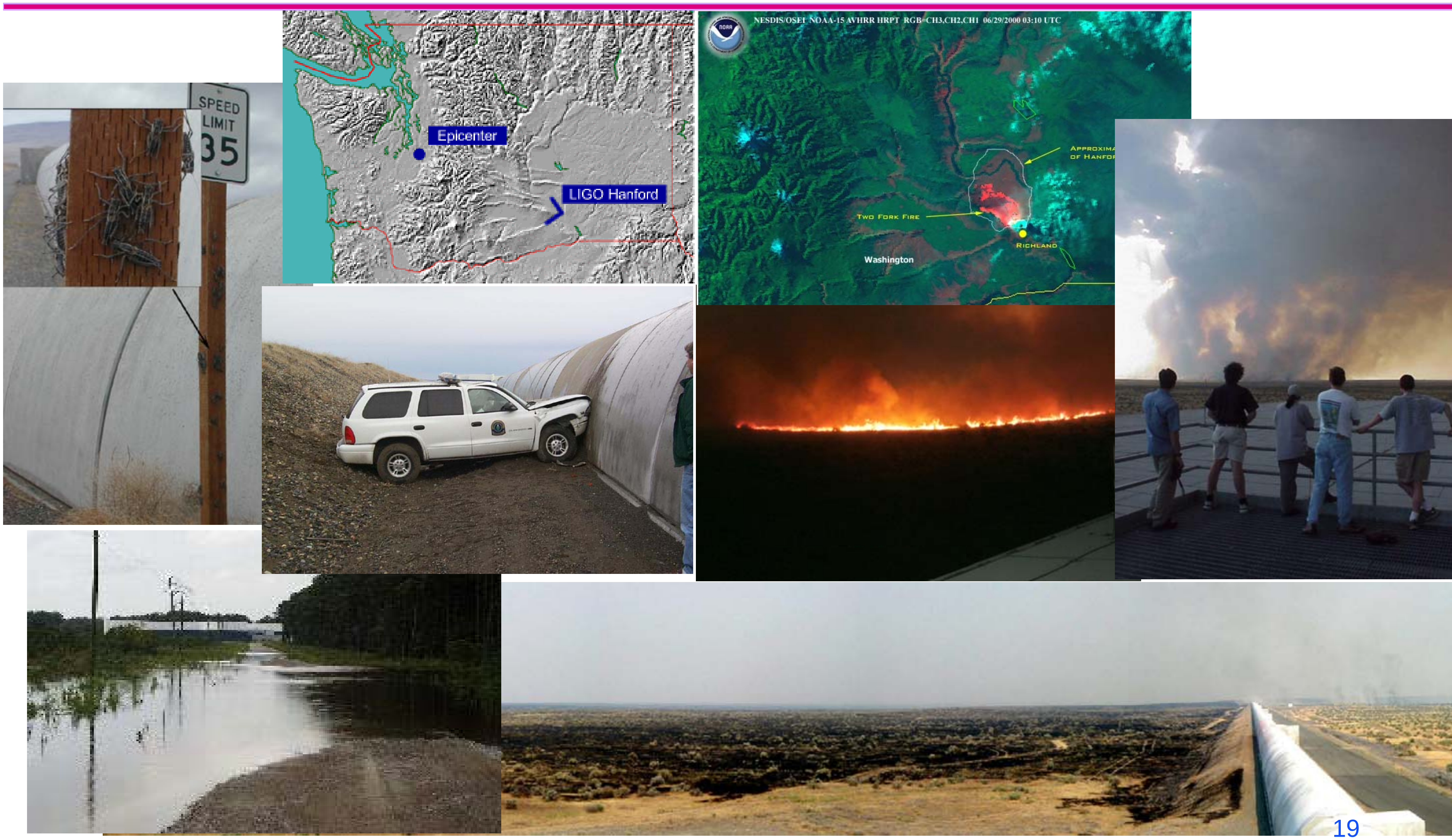
Hobart and William Smith Colleges

University of Minnesota

Universität Hannover

Science & Technology Facilities Council Rutherford Appleton Laboratory

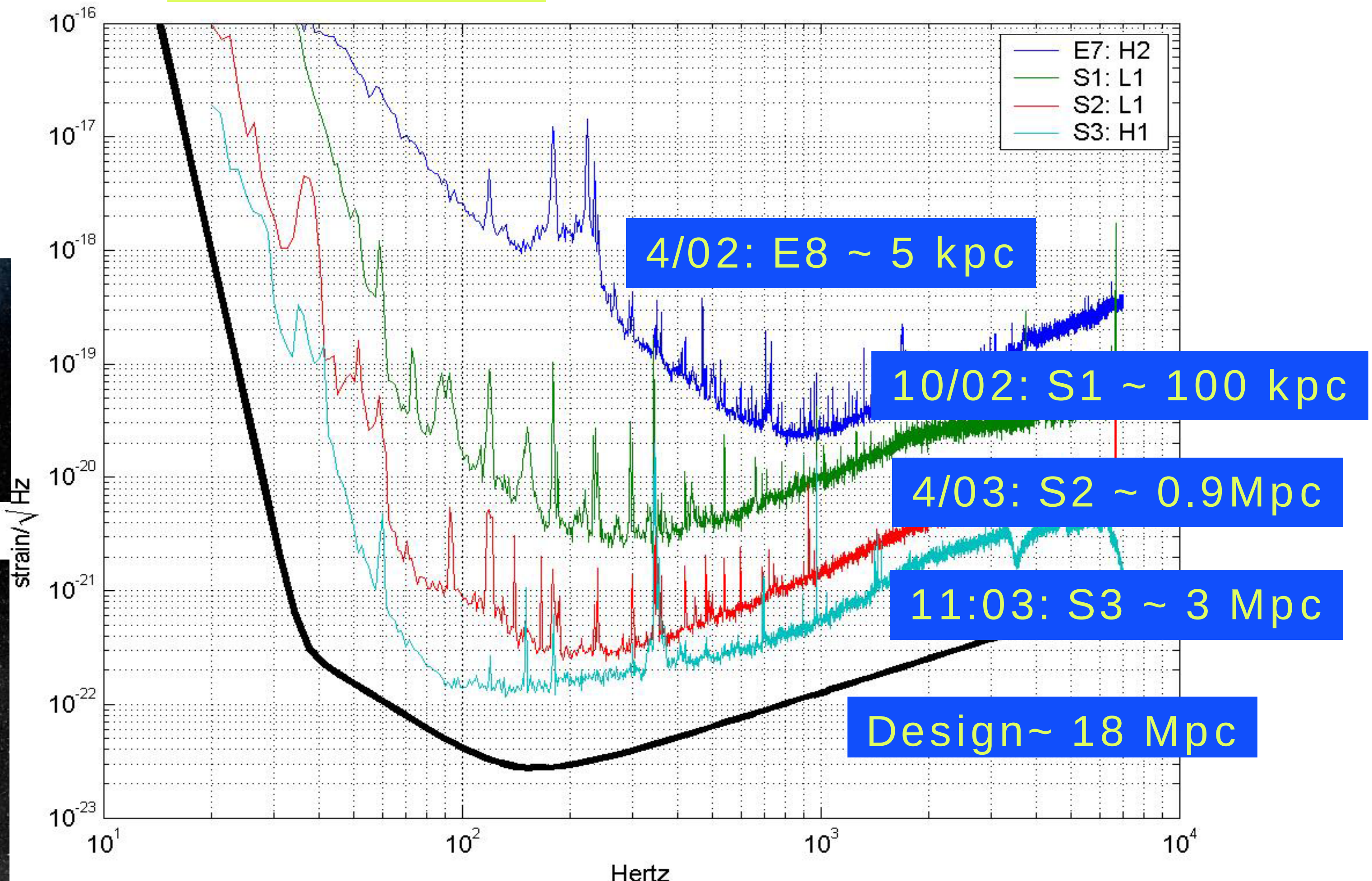
Despite a few difficulties, science runs started in 2002.



Science Runs

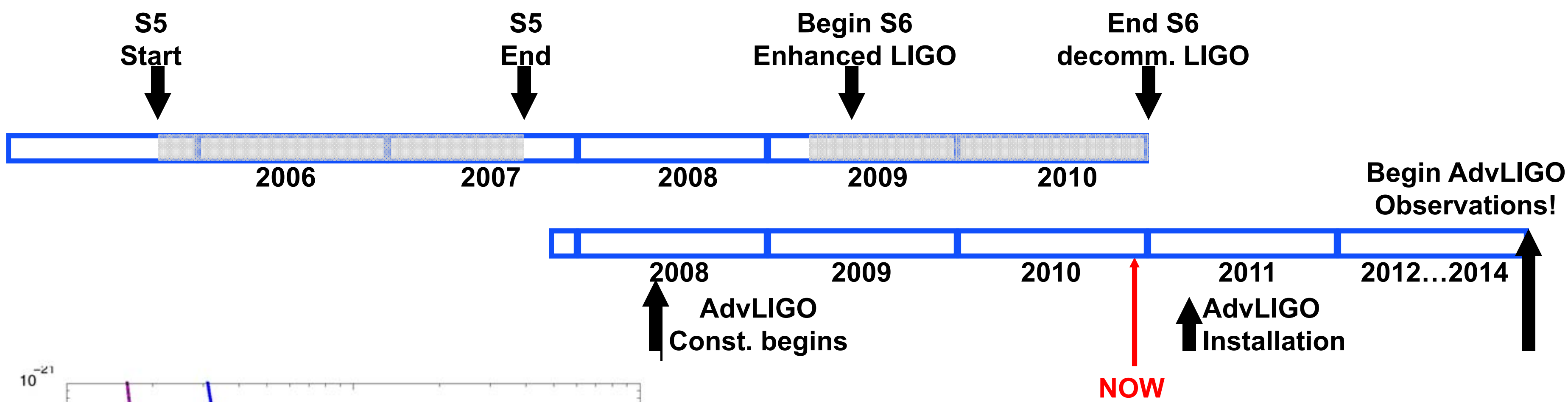
A Measure of Progress:

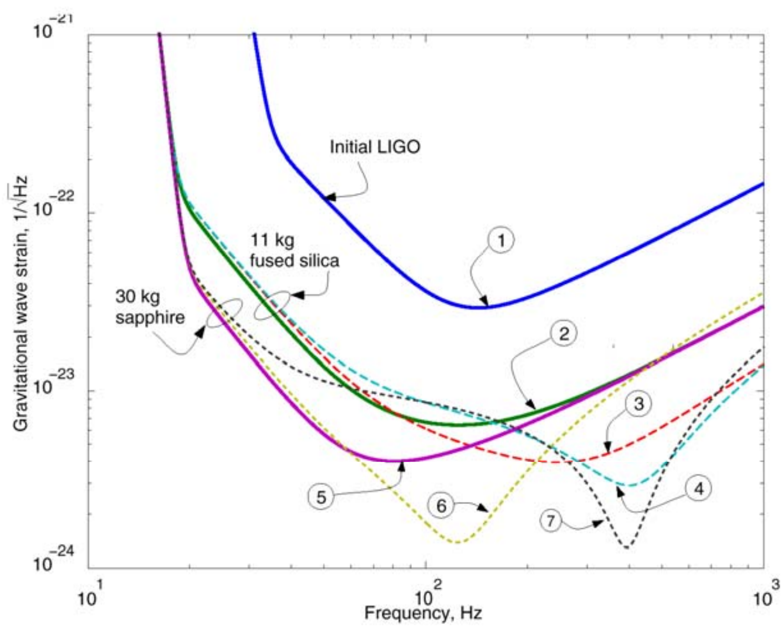
Binary neutron star Inspiral Range




Strain Sensitivity for the LIGO 4km Interferometers
h[f], 1/Sqrt[Hz]
1e-24
10
100
1000
10000
Frequency [Hz]
Frequency [Hz]
WE DiD iT!
13 5:31PM
1995
t

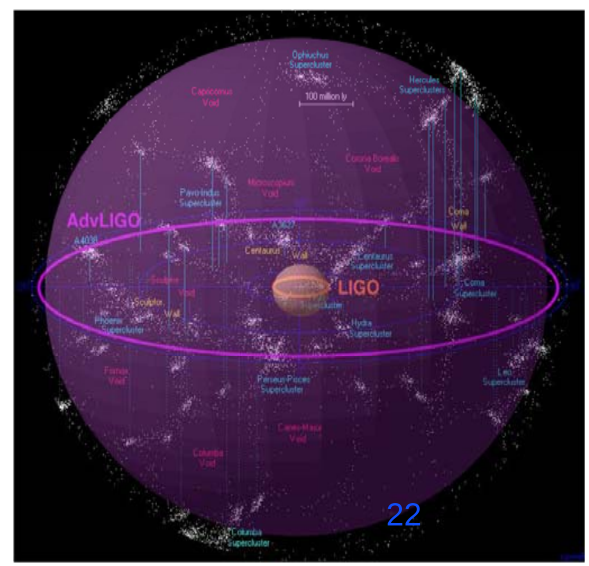
LIGO → eLIGO → AdvLIGO





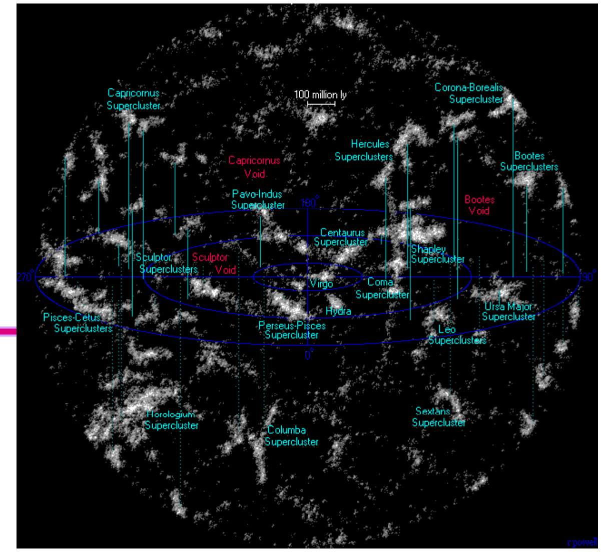
Improve amplitude sensitivity by a factor of 10x, and…

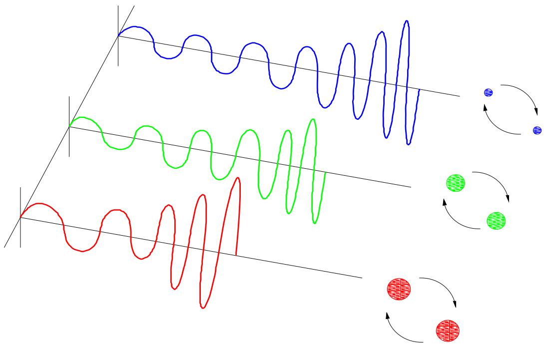
⇒ Number of sources goes up 1000x!

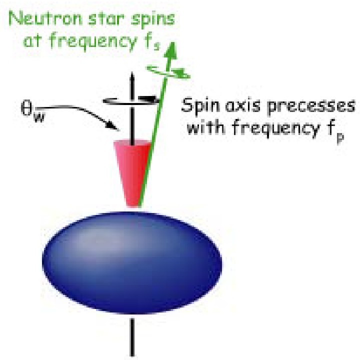


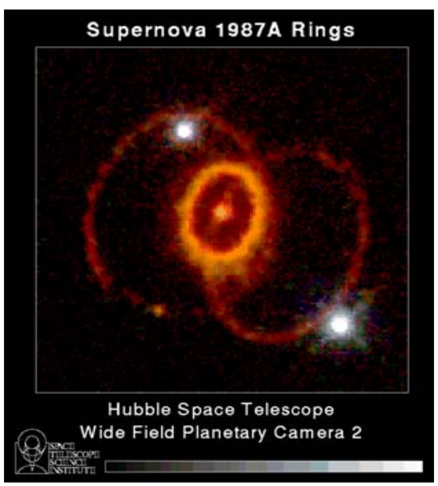
LIGO

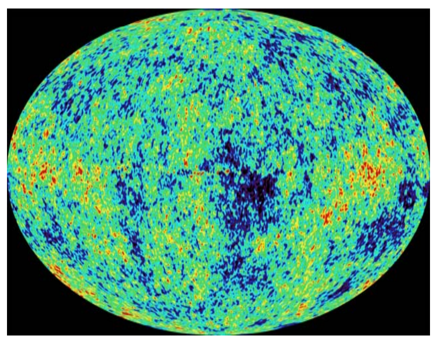
What will we see?









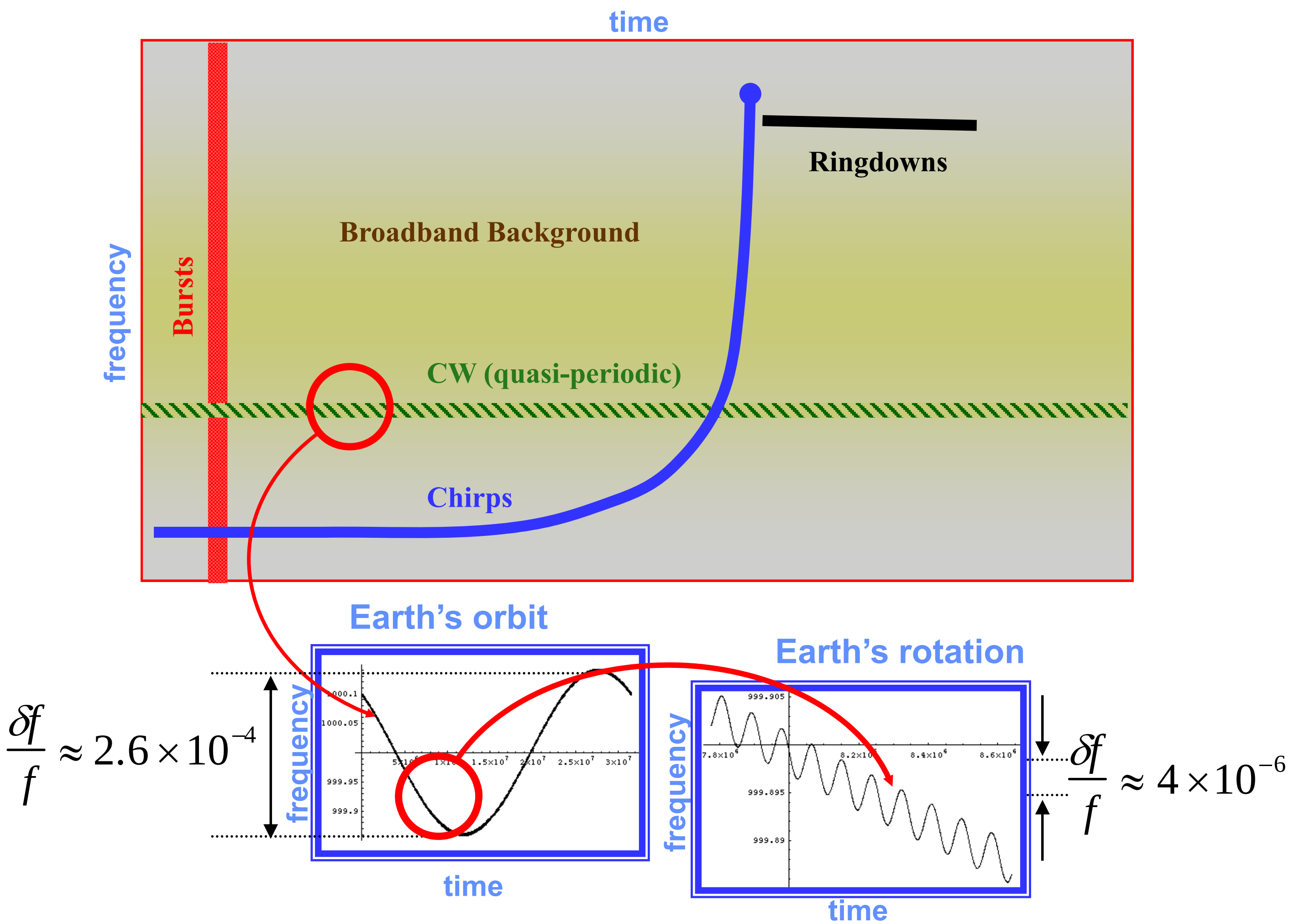


Analog from cosmic microwave background -- WMAP 2003

GWs from the most energetic processes in the universe!

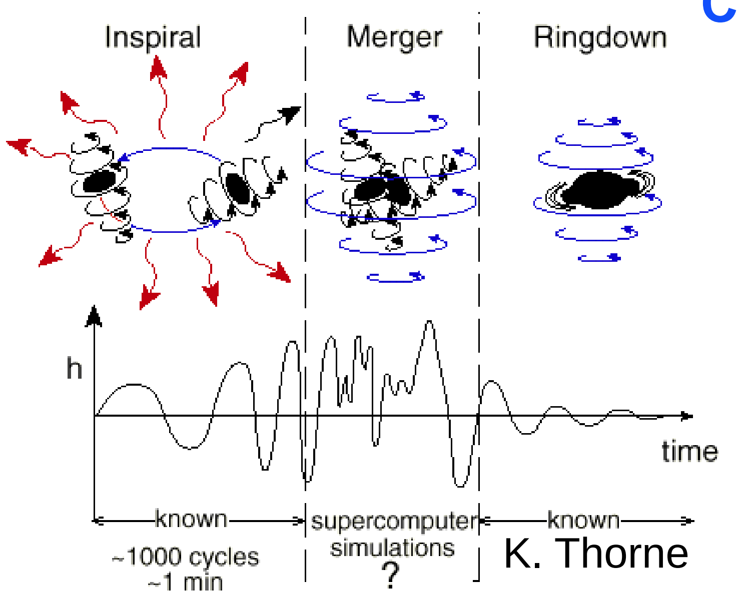
- Compact Binary Coalescences: black holes orbiting each other and then merging together
- GW bursts of unknown waveform: Supernovas, SGRs, GRB engines
- Continuous waves from pulsars, rapidly spinning neutron stars
- Stochastic GW background from vibrations from the Big Bang

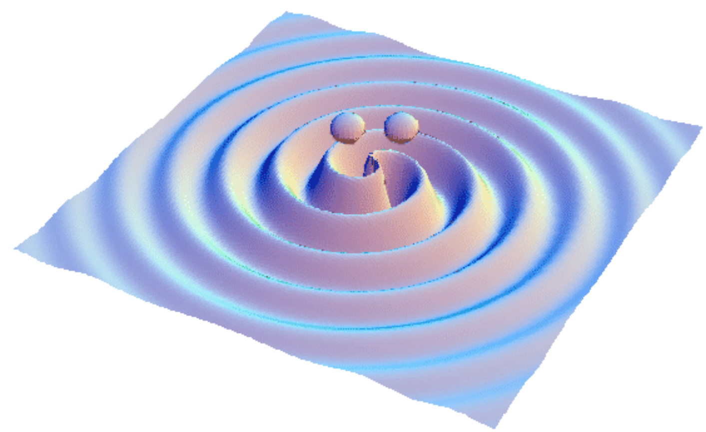
Frequency-Time Characteristics of GW Sources



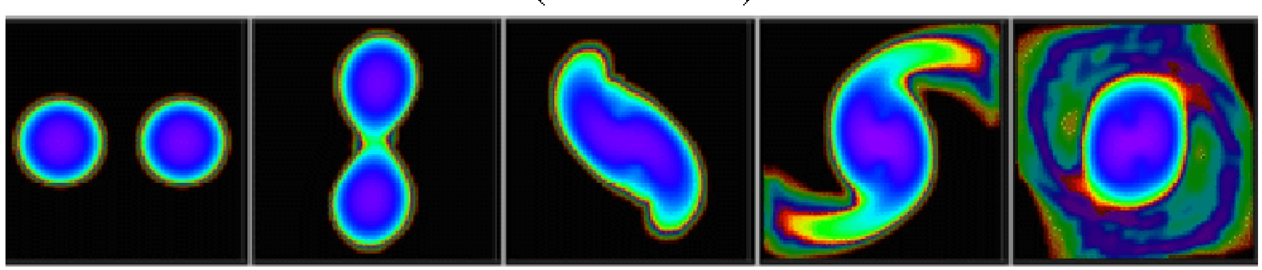
GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)

Compact binary mergers

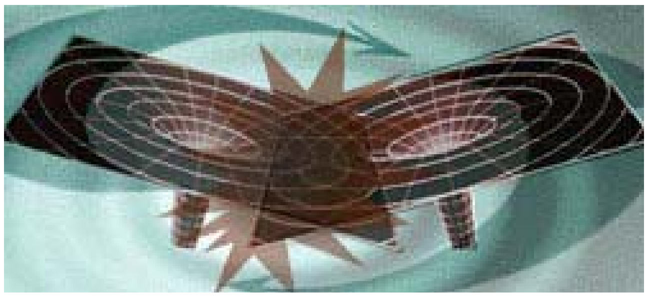


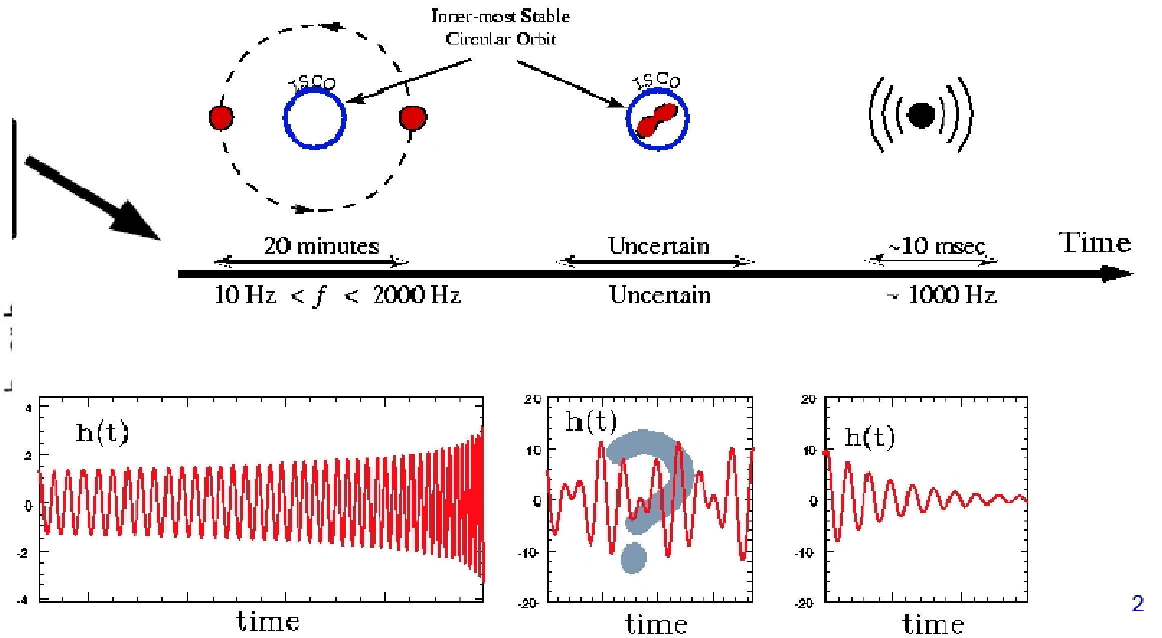


- Neutron star – neutron star (Centrella et al.)



Binary Inspiral Phases



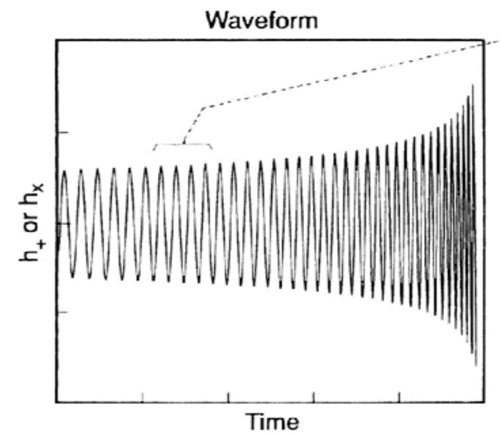


determine

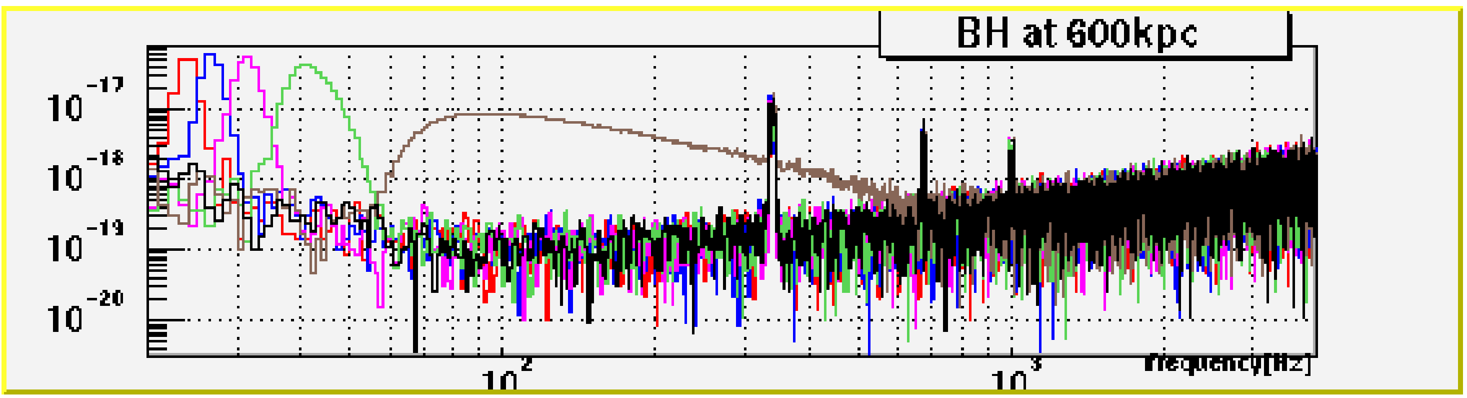
- distance from the earth r
- masses of the two bodies
- orbital eccentricity e and orbital inclination *I*
- *Over-constrained parameters: TEST GR*

The sound of a chirp

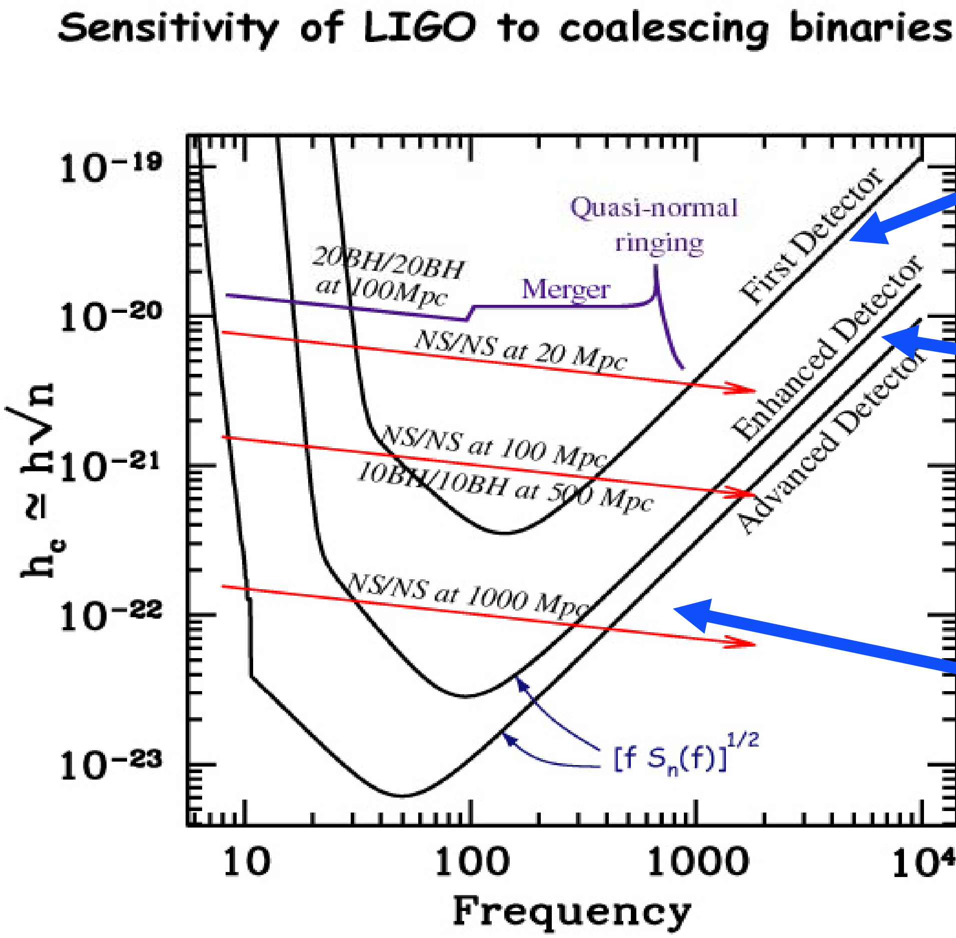
BH-BH collision, no noise



The sound of a BH-BH collision,
Fourier transformed over 5 one-second intervals
(red, blue, magenta, green, purple)
along with expected IFO noise (black)



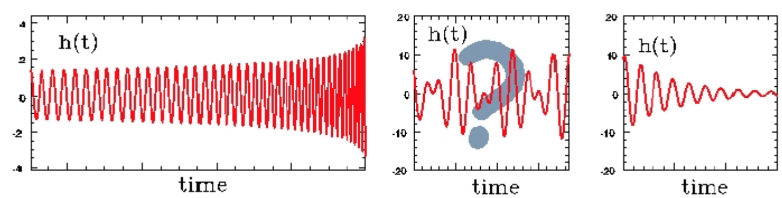
Astrophysical sources: Thorne diagrams



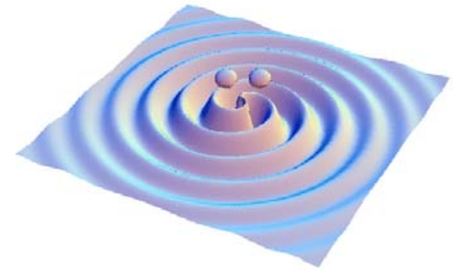
Initial LIGO (2002-2008)

Advanced LIGO (2012-)

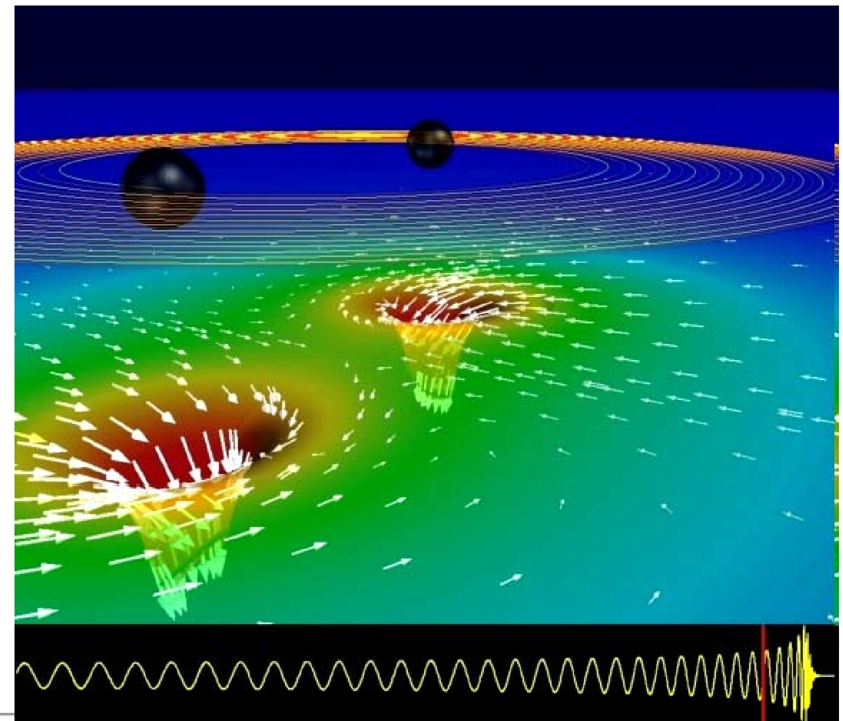
Beyond Advanced LIGO

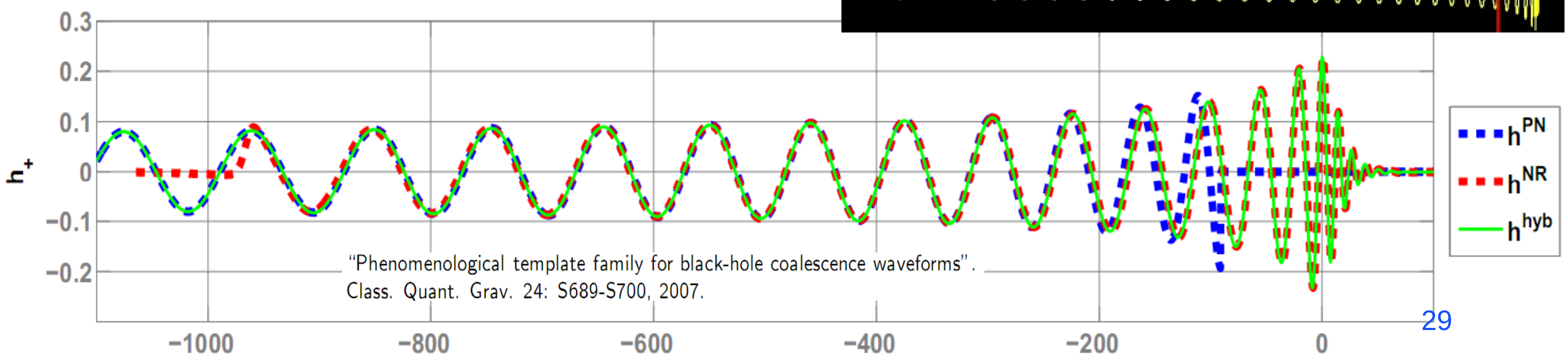


Understanding Inspiral-Merger-Ringdown



- **The key to optimal detection is a well-modeled waveform, especially the phase evolution**
- **Low-mass systems (BNS) merge above ~1500 Hz, where LIGO noise is high - we see the inspiral**
- **Higher-mass systems (BBH) merge or ring down in-band.**
- **These systems are unique: highly relativistic, dynamical, strong-field gravity – exactly where Einstein’s equations are most non-linear, intractable, interesting, and poorly-tested.**
- **Numerical relativity is devoted to deriving waveforms for such systems, to aid in detection and to test our understanding of strong-field gravity.**
- **HUGE progress in the last few years!**





“Phenomenological template family for black-hole coalescence waveforms”. Class. Quant. Grav. 24: S689-S700, 2007.

Mass space for template-based search

- The more massive the system, the lower the GW frequency
- Binary neutron star (BNS) waveforms are in LIGO band during inspiral.
- Higher-mass Binary black hole (BBH) waveforms merge in-band
- Above ~100 M_{sun}, all LIGO can see is the merger and ringdown

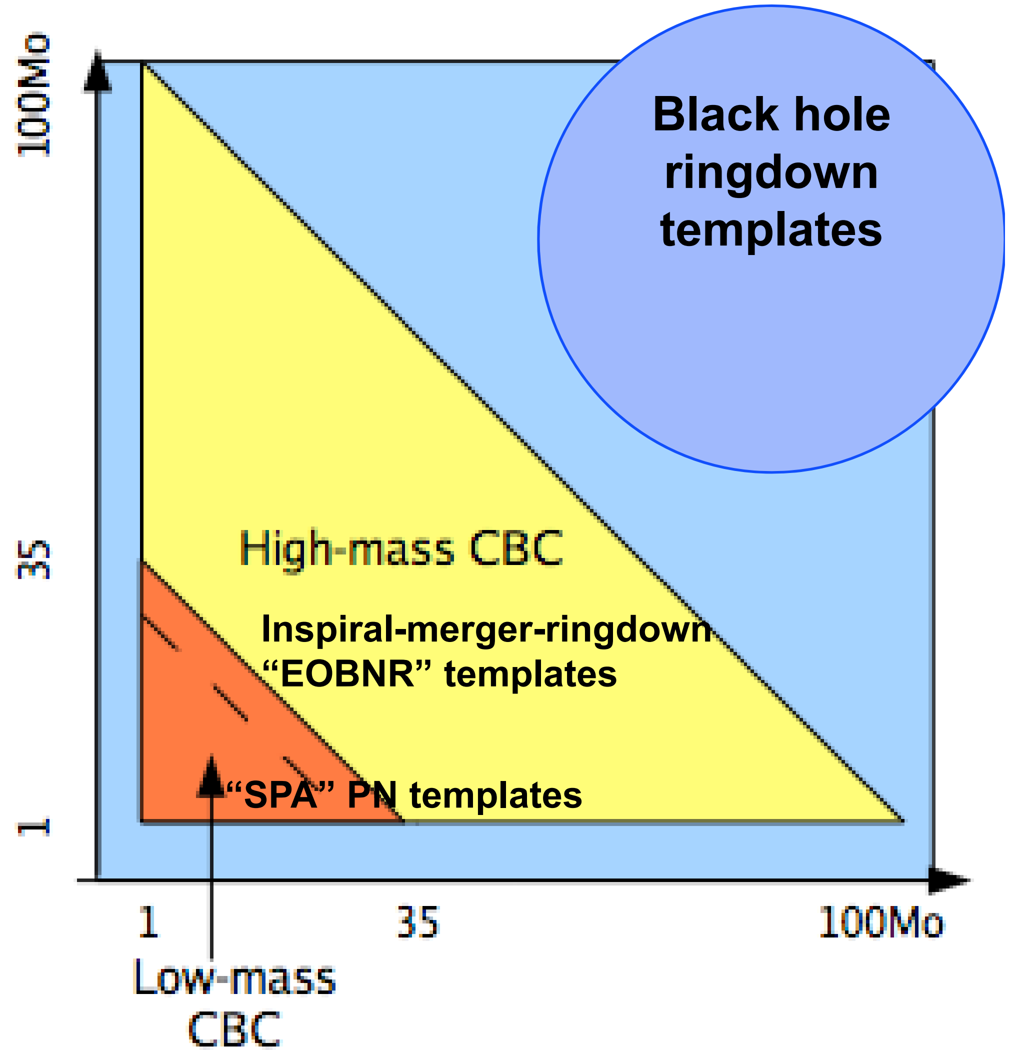
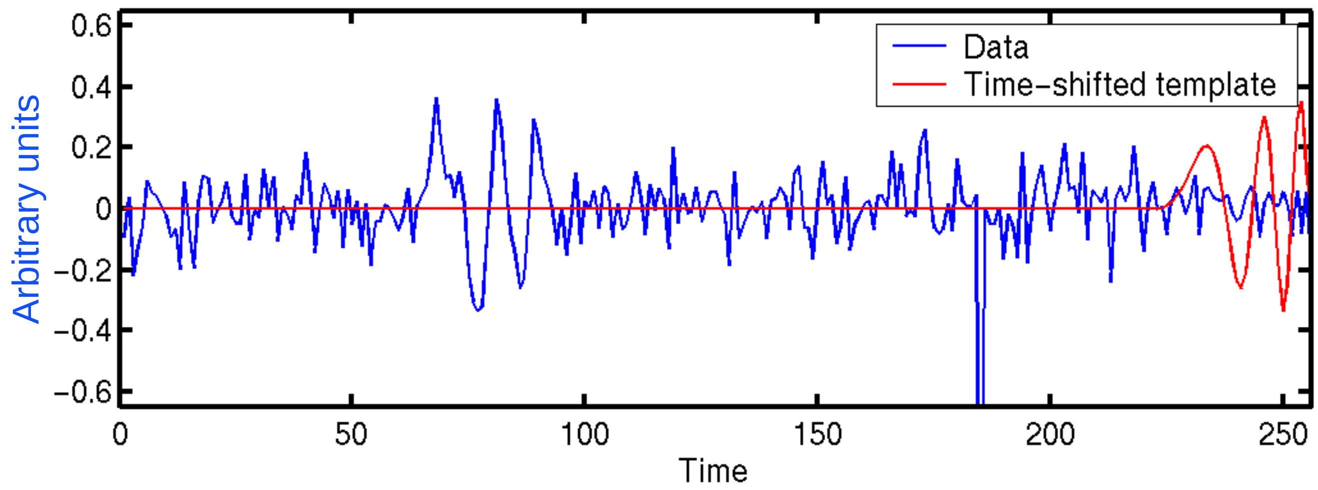
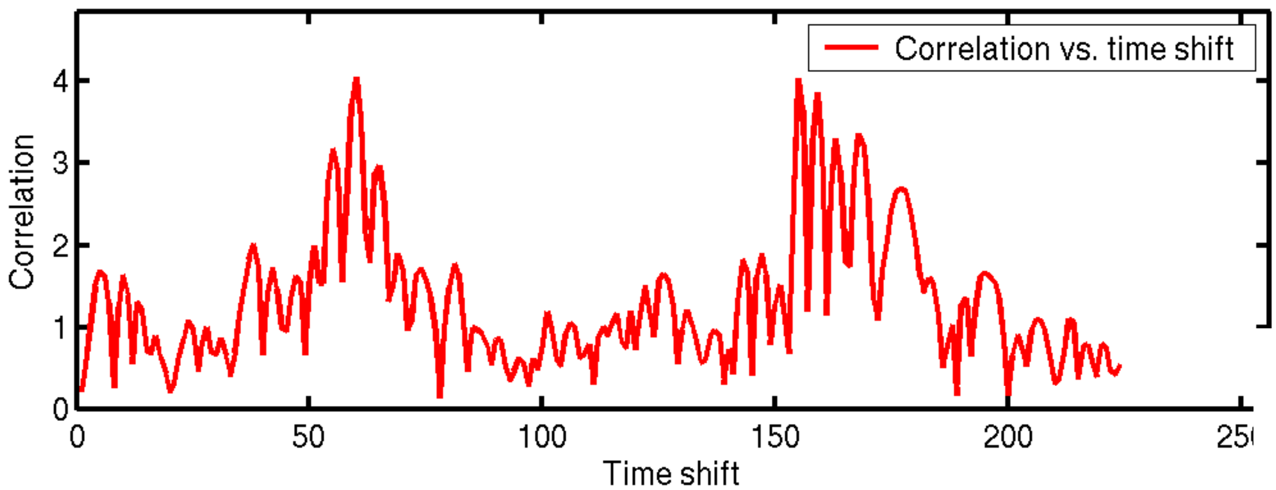
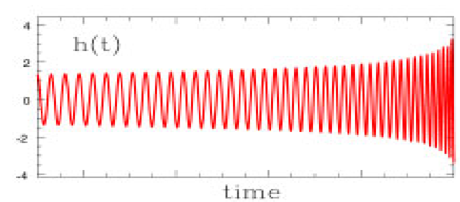


Illustration of Matched Filtering



- Bank of 2110 post[2] –Newtonian stationary-phase templates for $1 < m_1 \leq m_2 < 3\ M_\odot$ with 3% maximum mismatch

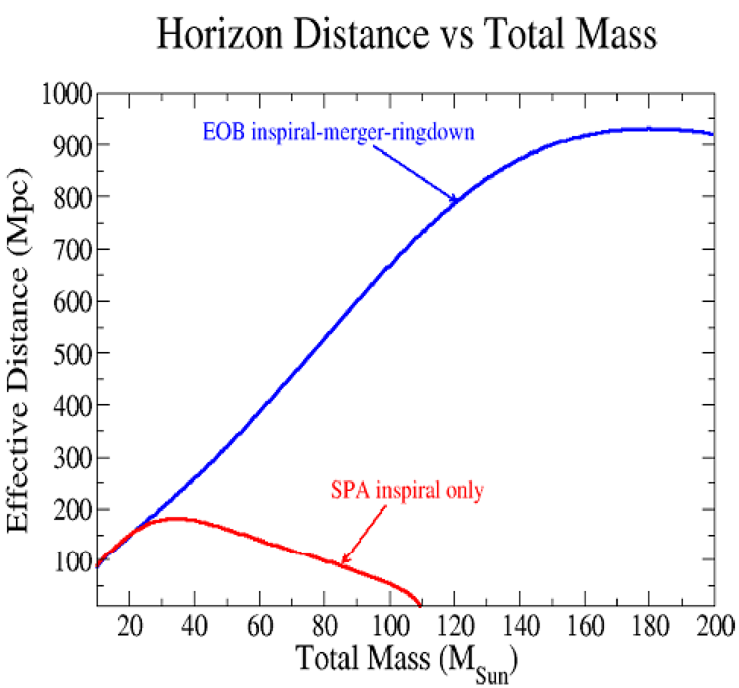




AJW, SURF 2008

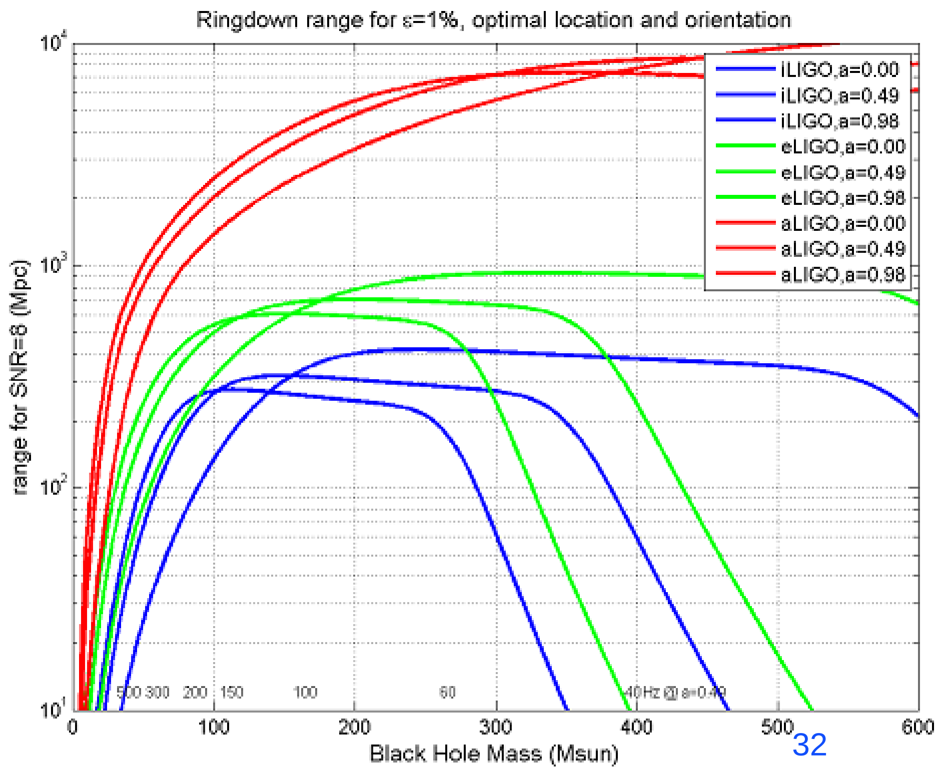
Horizon distance is a strong function of mass

Horizon distance (Mpc)
versus mass (M_{sun})
Inspiral-Merger-Ringdown
Initial LIGO



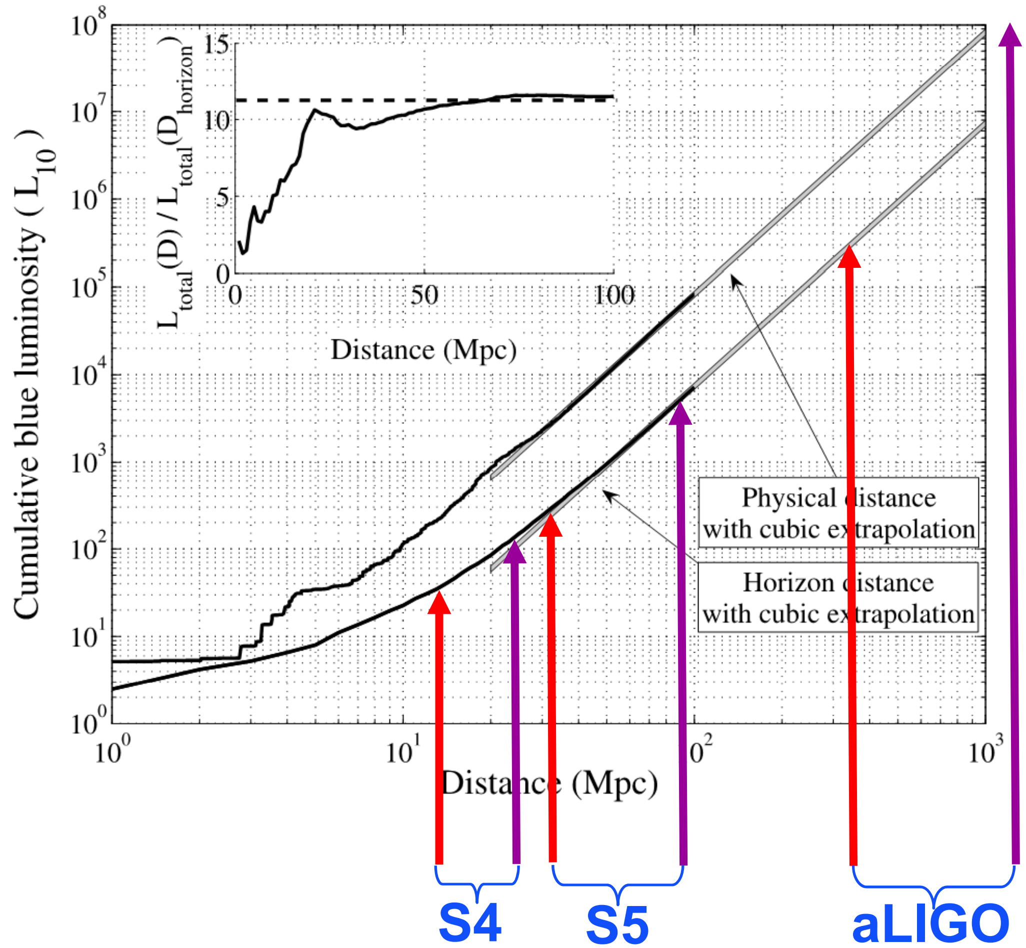
Calculated with analytic noise curve

Horizon distance (Mpc)
versus mass (M_{sun})
for ringdowns
iLIGO ⇒ eLIGO ⇒ aLIGO



Expected detection rate: How many sources can we see?

- CBC waveforms have known amplitude
  $h \sim (GM/c^2 r) \times F(\alpha, \delta, \iota)$
- Measured detector sensitivity defines a *horizon distance*
- This encloses a known number of sources:
  MWEG = 1.7×10^{10} L_s =1.7 L_{10}
- From galactic binary pulsars:
  R(BNSC) ~10-170 /Myr/L_{10}
- From population synthesis:
  R(BBHC) ~0.1 - 15 /Myr/L_{10}
- To see more than 10 events/yr, we need to be sensitive to
  10^5 - 10^7 galaxies!

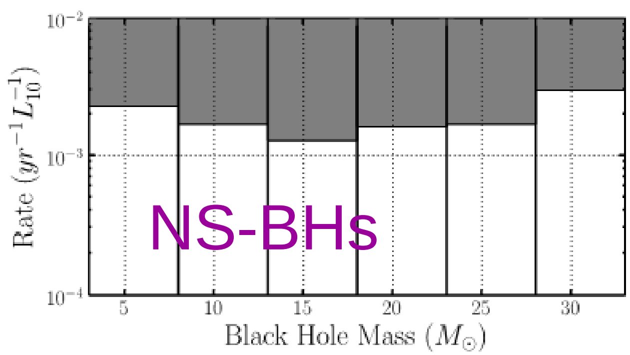


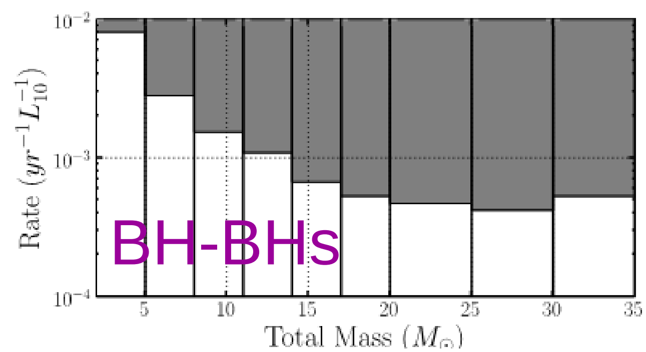
Kopparapu etal ApJ 675 (2008) 1459

S5 upper limits
compact binary coalescence

- Rate/year/L_{10} vs. binary total mass
  $L_{10} = 10^{10}\ L_{sun,B}$ (1 Milky Way = 1.7 L_{10})
- Dark region excluded at 90% confidence.

arXiv:0905.3710v1

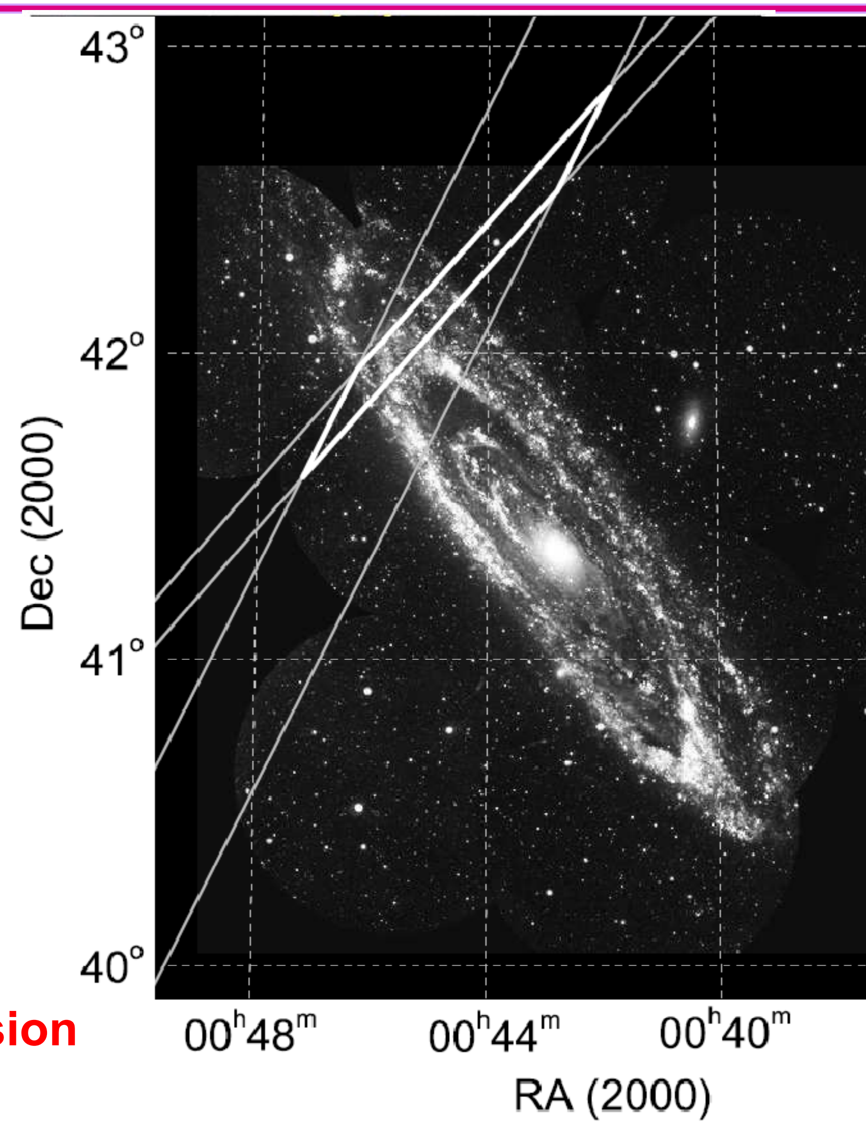




Binary type	Our upper limit, 90% confidence, L_{10}^{-1} yr $^{-1}$	Astrophysical Optimistic Rates, L_{10}^{-1} yr $^{-1}$	Astrophysical most likely Rates, L_{10}^{-1} yr $^{-1}$	Comparison
BNS	1.4 x 10^{-2}	5 x 10^{-4}	5 x 10^{-5}	~2-3 orders
NSBH	3.6 x 10^{-3}	6 x 10^{-5}	2 x 10^{-6}	~2-3 orders
BBH	7.3 x 10^{-4}	6 x 10^{-5}	4 x 10^{-7}	~1-3 orders

Triggered searches: GRB 070201

- Feb 1, 2007: short hard GRB (T_{90}=0.15 s)
- Observed by five spacecraft
- Location consistent with M31 (Andromeda) spiral arms (0.77 Mpc)
- At the time of the event, both Hanford instruments were recording data (H1, H2), while others were not (L1, V1, G1)
- Short GRB: could be inspiral of compact binary system (NS/BH), or perhaps soft gamma repeater



talk by Isabel Leonor in Multimessenger Astronomy parallel session

Inspiral search - GRB 070201

- Matched template analysis, $1M_\odot < m_1 < 3M_\odot$, $1M_\odot < m_2 < 40M_\odot$
- H1 ~ 7200 templates, H2 ~ 5400 templates, obtain filter SNR
- Require consistent timing and mass parameters between H1, H2
- Also searched for using burst (coherent excess power) methods

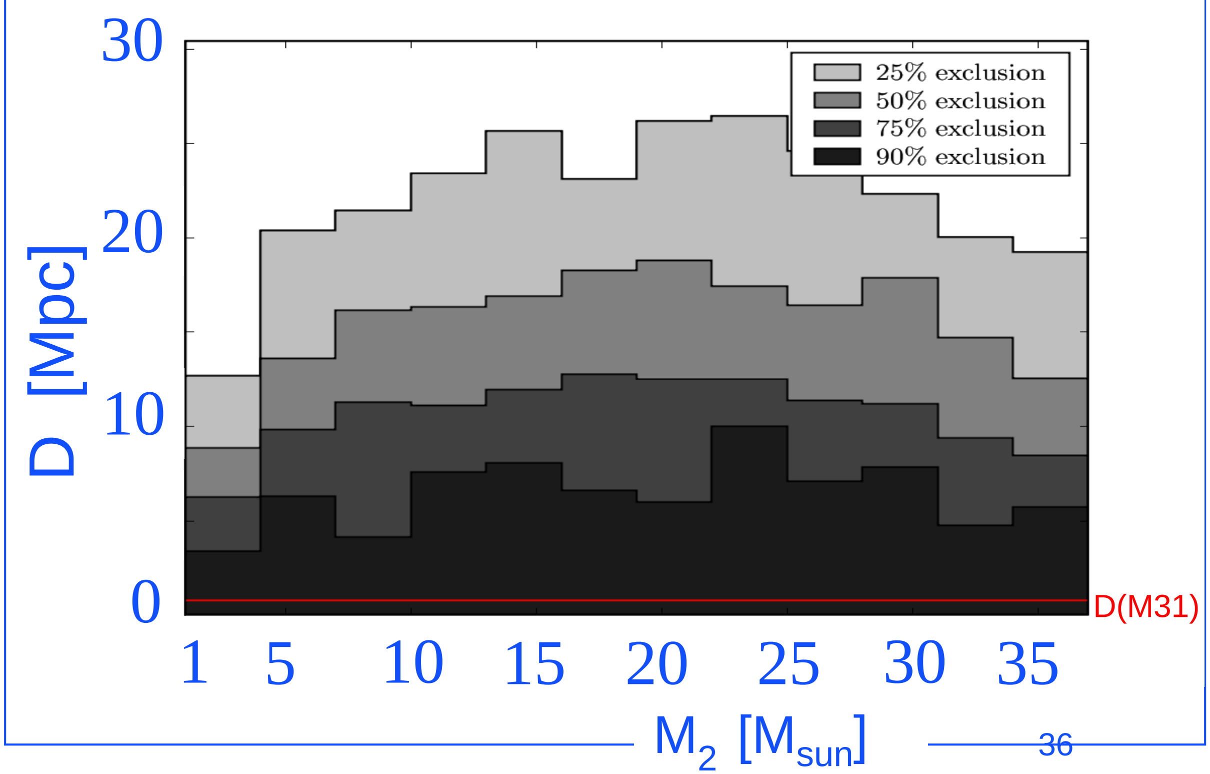
No plausible gravitational wave signal found

Compact binary in M31 with
$1M_\odot < m_1 < 3M_\odot$
$1M_\odot < m_2 < 40M_\odot$
excluded at 99% confidence

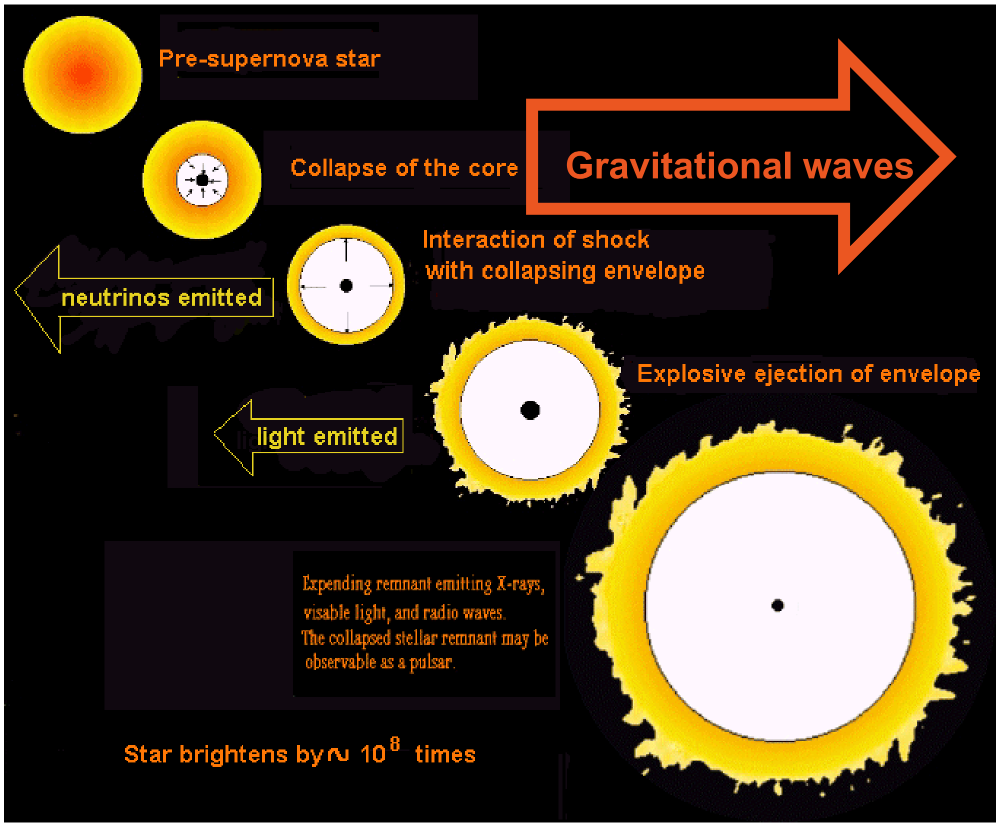
Conclusion: it was most likely an SGR giant flare in M31

- Mazets et al., ApJ 680, 545
- Ofek et al., ApJ 681, 1464

Astrophys.J 681, 1419 (2008)

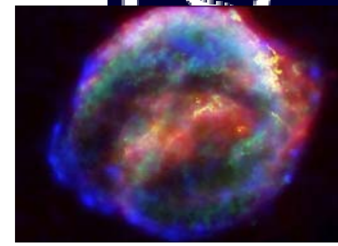


GW Bursts from core collapse supernova



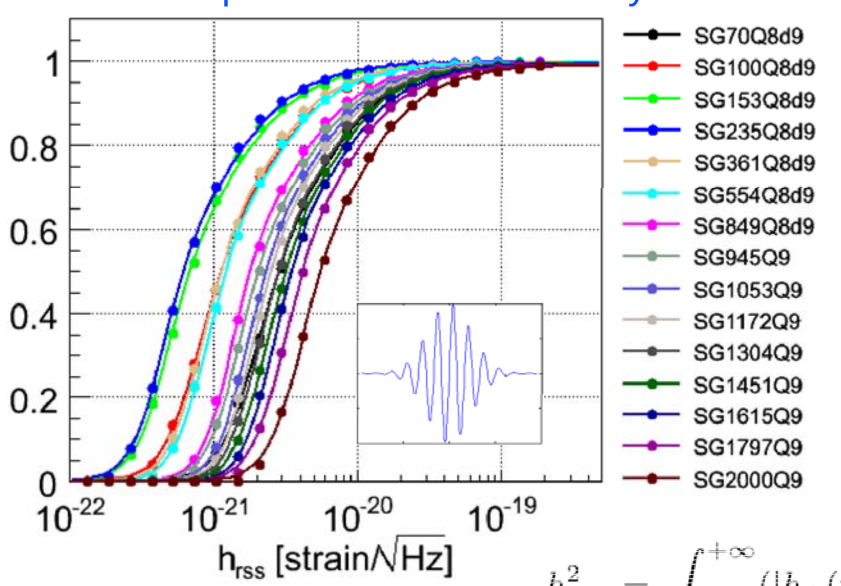
- Within about 0.1 second, the core collapses and gravitational waves are emitted.
- After about 0.5 second, the collapsing envelope interacts with the outward shock. Neutrinos are emitted.
- Within 2 hours, the envelope of the star is explosively ejected. When the photons reach the surface of the star, it brightens by a factor of 100 million.
- Over a period of months, the expanding remnant emits X-rays, visible light and radio waves in a decreasing fashion.

LIGO Untriggered GW burst search in S5 1st year data

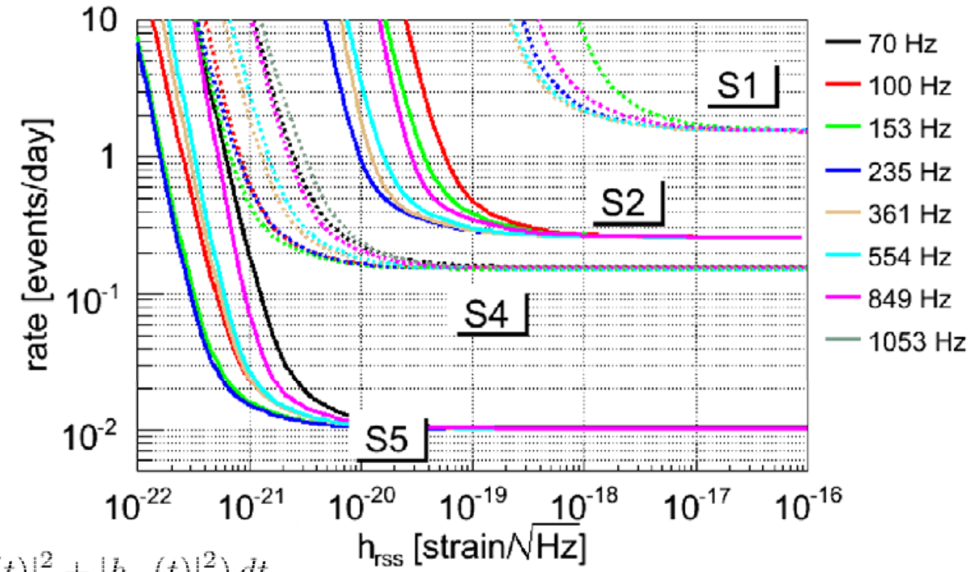


- Look for short, unmodeled GW signals in LIGO's frequency band
  - –From stellar core collapse, compact binary merger, etc. — or unexpected source
- Look for excess signal power and/or cross-correlation from different detectors
- No events observed above thresholds

Isotropic detection efficiency

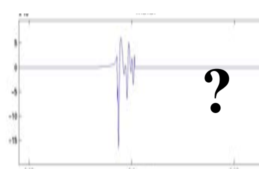


SG rate vs. strength exclusion curves



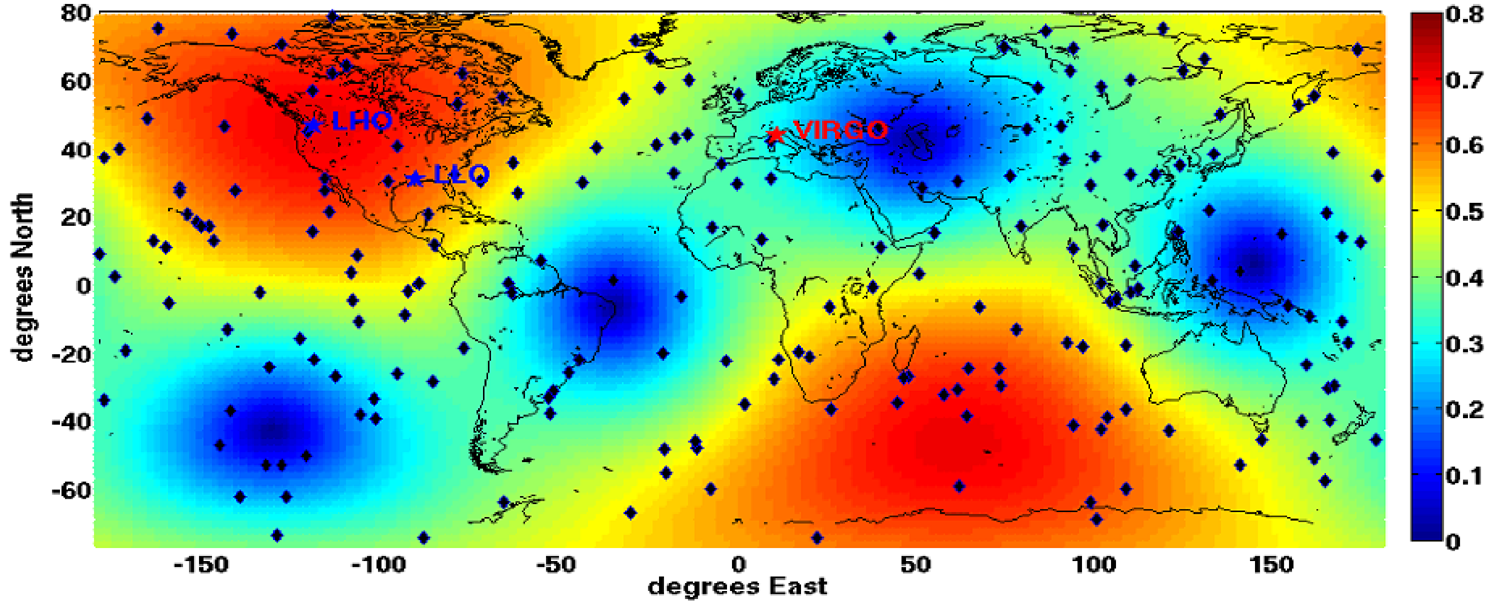
$$h_{\rm rss}^2 = \int_{-\infty}^{+\infty} \left(|h_+(t)|^2 + |h_\times(t)|^2\right) dt$$

- 0.044 solar masses radiated in SG153Q9 for 50% efficiency at Virgo cluster
- 100/100 solar mass BH/BH merger detectable out to 180 Mpc
- Core collapse supernova models detectable out to 0.6-24 kpc



GRB-triggered searches in LIGO S5 / Virgo VSR1 data

- Nov 2005 – Oct 2007: 212 GRBs
  - 137 with 2+ LIGO-Virgo detectors operating.
  - ~25% with redshift ~10% short duration
- Polarization-averaged antenna response of LIGO-Hanford
  - dots show location of GRBs during S5-VSR1



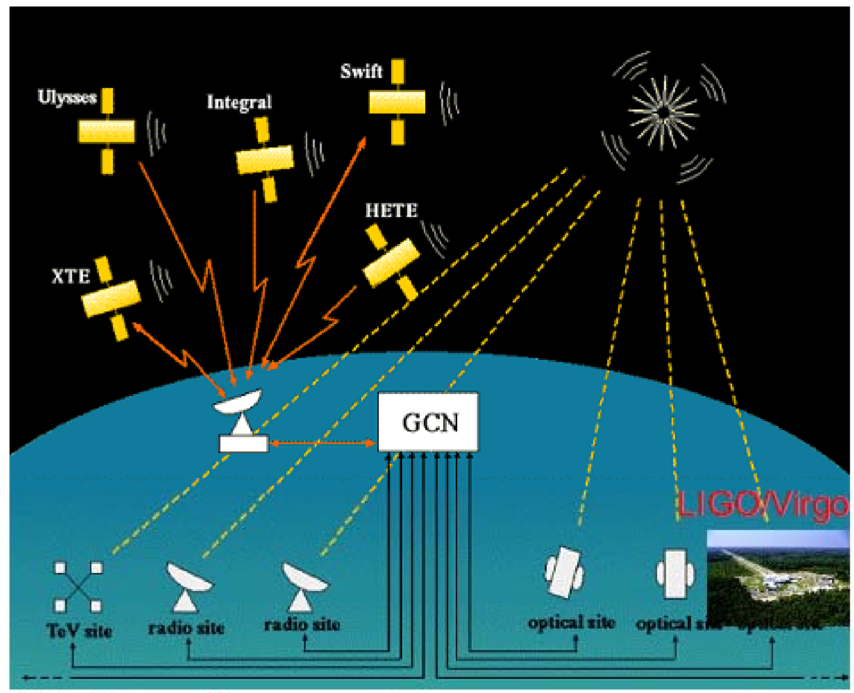
No significant GW signals found within ~180s of and GRB

talk by Isabel Leonor in Multimessenger Astronomy parallel session

Low-latency searches during S6/VSR2

- Enhanced LIGO S6 & Virgo VSR1 began July 6, 2009.
- A major goal is to identify GW inspiral or burst signals within minutes of detecting them.

- With three detector sites, locate sources to ~ 10 sqdg.
- Alert ground- and spaced-based telescopes to point at presumed source location.
- Unlikely to actually detect a GW and associate it with EM counterpart … this is just practice, and maybe we'll get very lucky!
- Also receive alerts via SNEWS and SGR, GRB detectors
  - » Goal – Identification of GW signal within ~ 1 day of receipt of external trigger



http://gcn.gsfc.nasa.gov/

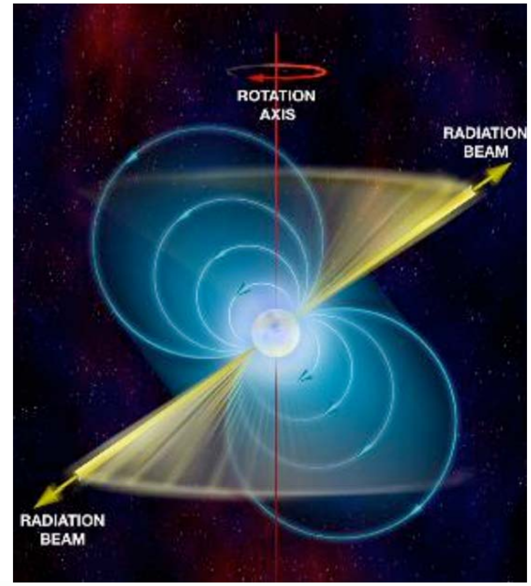
talk by Isabel Leonor in Multimessenger Astronomy parallel session

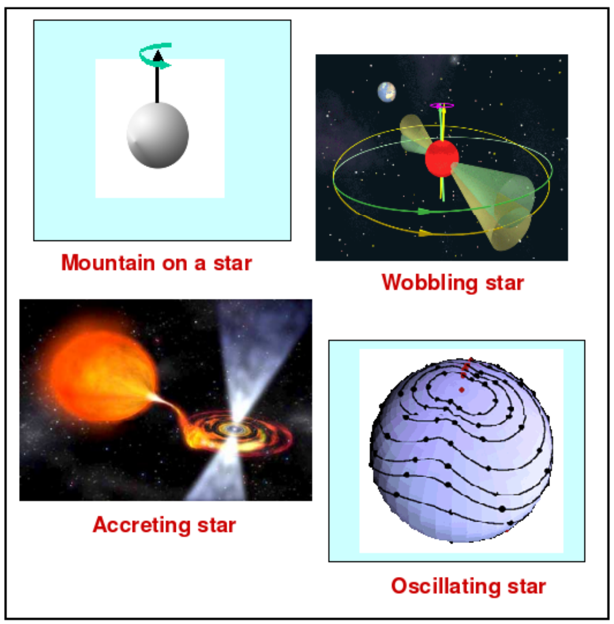
Pulsars and continuous wave sources

- **Pulsars in our galaxy**
  - » non axisymmetric: $10^{-4} < \varepsilon < 10^{-6}$
  - » science: EOS; precession; interiors
  - » "R-mode" instabilities
  - » narrow band searches best

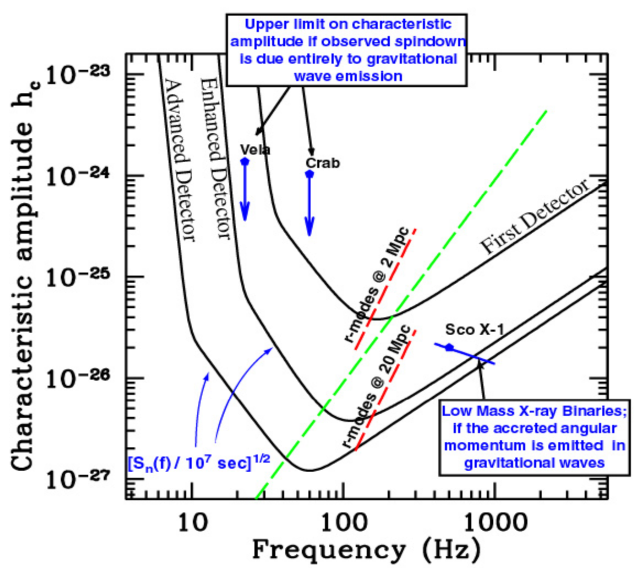
$$f_{GW} = 2 f_{ROT}$$

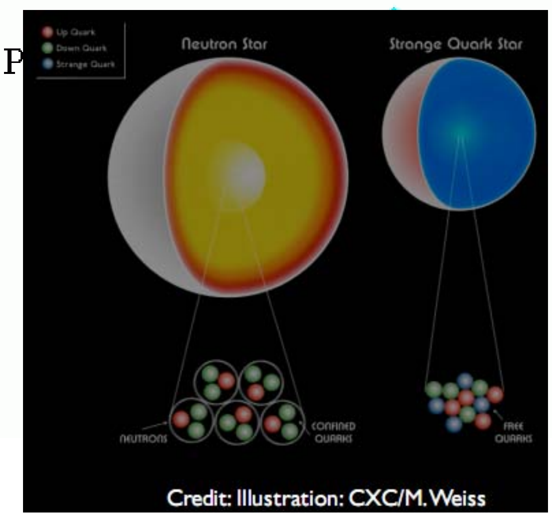
$$h = \frac{4\pi^2 G}{c^4} \frac{I_{zz} f_{GW}^2}{r} \varepsilon$$





Sensitivity of LIGO to continuous wave sources

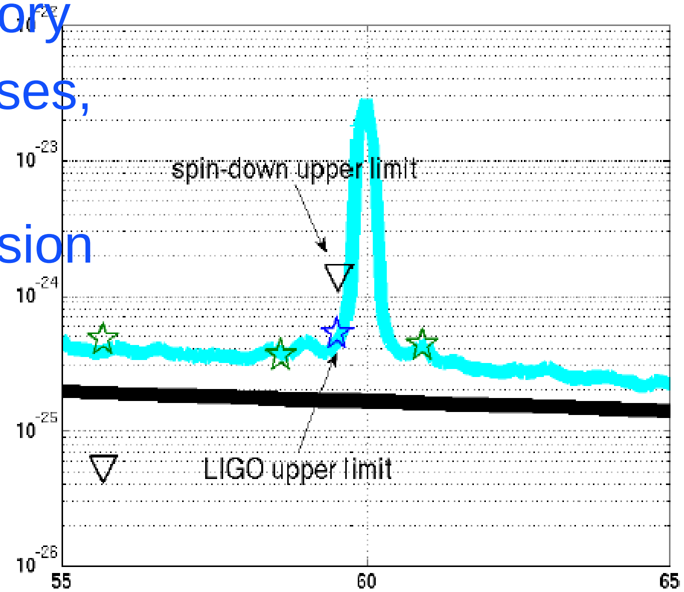




The Crab pulsar

- PSR B0531+21; SN 1054AD; ~2 kpc away ; spinning at 29.8 Hz.
- Spinning down rapidly; energy loss ~ 4×10^{31} W
    - A significant fraction of that could be going into GWs @ 59.6 Hz
    - Searched for signal in first 9 months of LIGO S5 data. using timing data from Jodrell Bank Observatory
    - Assuming that GW signal is locked to EM pulses, null search result implies that no more than **4–6%** of the spin-down energy is in GW emission
    - Crab pulsar is spherical; $\boldsymbol{\varepsilon < 1.4 \times 10^{-4}}$ (1/10 of Mt Everest)

Spin-down limit: $$h_{\rm sd} = \left(\frac{5}{2}\frac{G I_{zz}|\dot{\nu}|}{c^3 r^2 \nu}\right)^{1/2}$$

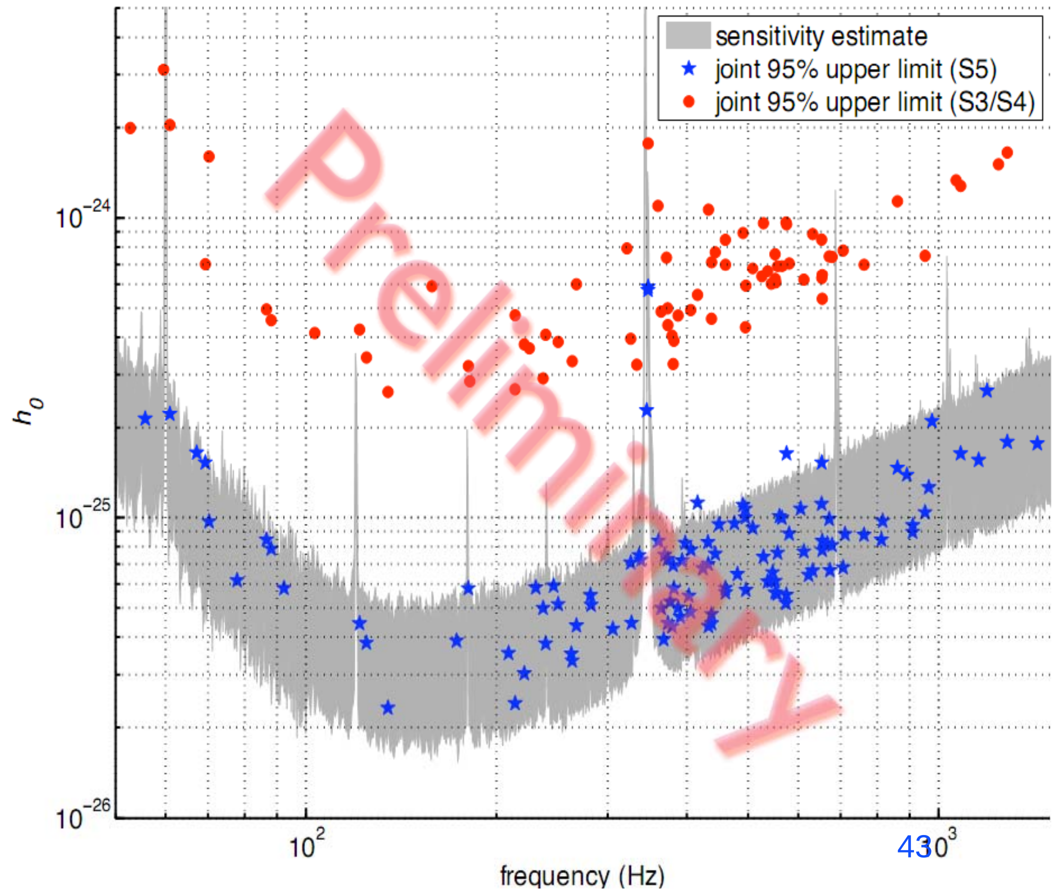


Abbott et al., ApJL 683, L45

Search for known pulsars- preliminary

Search for signals from 116 pulsars (including binaries) with f_{GW} > 40 Hz.
NO SIGNALS SEEN above Gaussian noise in 3 LIGO detectors.
Joint 95% upper limits using data from the LIGO S5 run:

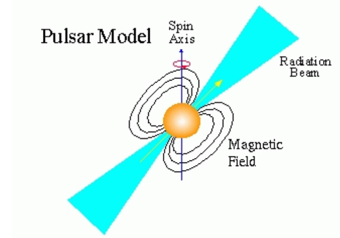
Pulsar timings provided by
Jodrell Bank, Green Bank, and
Parkes Telescopes



Lowest GW strain upper limit:
PSR J1603-7272
(f_{gw} = 135 Hz, r = 1.6 kpc)
$\mathbf{h_0 < 2.3 \times 10^{-26}}$

Lowest ellipticity upper limit:
PSR J2124-3358
(f_{gw} = 405.6 Hz, r = 0.25 kpc)
$\boldsymbol{\varepsilon < 7 \times 10^{-8}}$

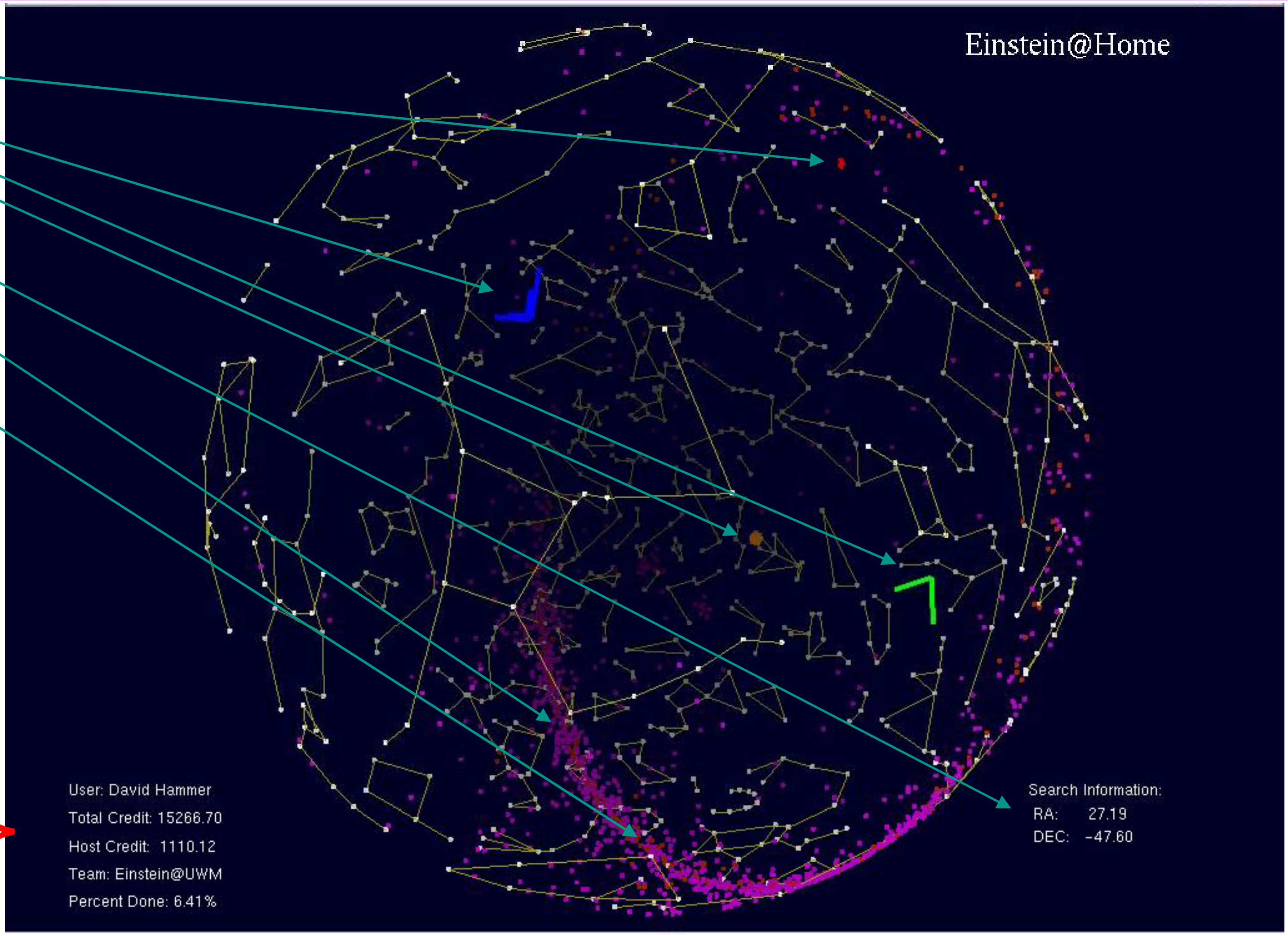
All sky searches



- Most spinning neutron stars are not observed pulsars; EM dim and hard to find.
- But they all emit GWs in all directions (at some level)
- Some might be very close and GW-loud!
- Must search over huge parameter space:
  - » sky position: 150,000 points @ 300 Hz, more at higher frequency or longer integration times
  - » frequency bins: 0.5 mHz over hundreds of Hertz band, more for longer integration times
  - » df/dt: tens(s) of bins
- Computationally limited! Full coherent approach requires ~100,000 computers (Einstein@Home)

Einstein@Home: the Screensaver

- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remnants



- User name
- User's total credits
- Machine's total credits
- Team name
- Current work % complete

The second-largest distributed computing project in the world!

Einstein@Home - Server Status

Einstein@Home server status as of 8:49 PM UTC on Tuesday, 7 October 2008 (updated every 20 minutes).
The Einstein@Home main server has been continuously up for 65 days 7 hours 33 minutes.

Server status

Program	Host	Status
Web server	einstein	Running
BOINC database feeder	einstein	Running
BOINC transitioner	einstein	Running
BOINC scheduler	einstein	Running
BOINC file uploads	einstein	Running
Einstein S5R2 validators	einstein	Running
Einstein S5R3 validators	einstein	Running
Einstein S5R4 validators	einstein	Running
Einstein S5R2 assimilator	einstein	Running
Einstein S5R3 assimilator	einstein	Running
Einstein S5R4 assimilator	einstein	Running
BOINC file deleter	einstein	Running
BOINC database	einstein	Running

Download mirror status

Site	Status	Last failure
Albert Einstein Institute	Running	153 h 43 m ago
University of Glasgow LSC group	Running	151 h 44 m ago
MIT LIGO Lab	Not running	1 h 19 m ago
Penn State LSC group	Running	15 h 19 m ago
Caltech LIGO Lab	Running	None

S5R4 search progress

Total needed	Already done	Work still remaining
12,104,080 units	1,753,310 units	10,350,770 units
100 %	14.485 %	85.515 %
442.1 days	64.0 days	378.1 days (estimated)

Users and Computers

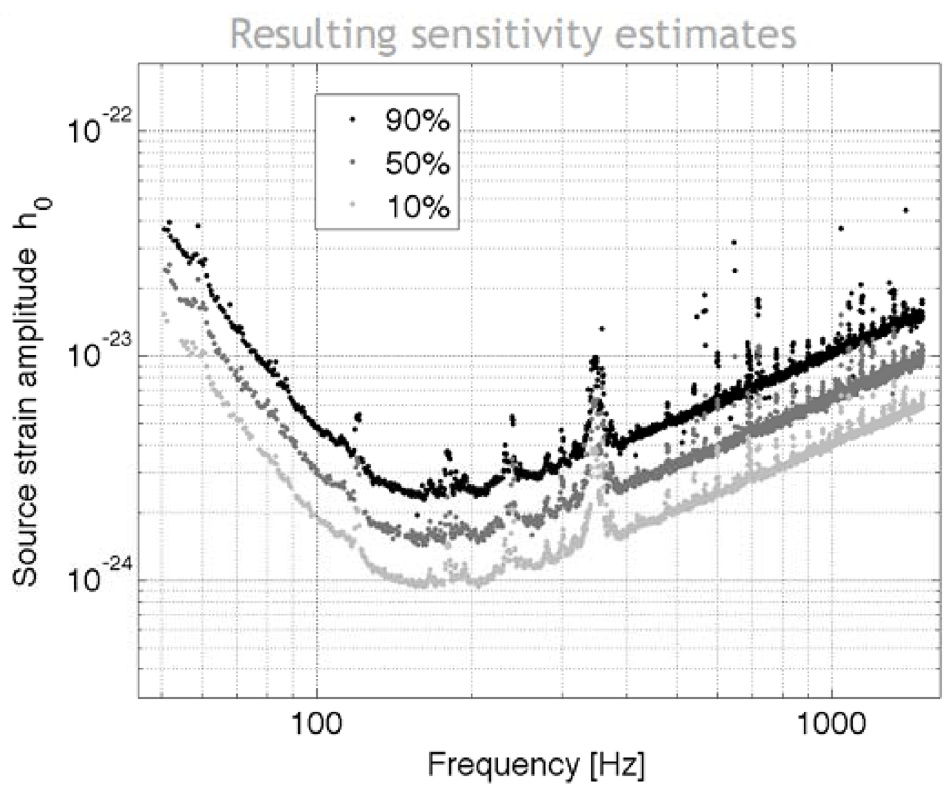
USERS	Approximate #
in database	348,417
with credit	210,758
registered in past 24 hours	219
HOST COMPUTERS	**Approximate #**
in database	1,373,249
registered in past 24 hours	1,044
with credit	694,247
active in past 7 days	65,436
floating point speed[1)]	107.5 TFLOPS

Work and Results

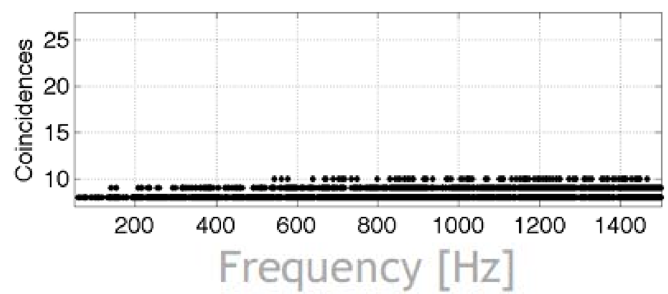
WORKUNITS	Approximate #
in database	402,319
with canonical result	169,610
no canonical result	232,709
RESULTS	**Approximate #**
in database	960,965
unsent	137,942
in progress	167,333
deleted	362,616
valid	340,158
valid last week	238,386
invalid	66
Oldest Unsent Result	11 d 10 h 51 m

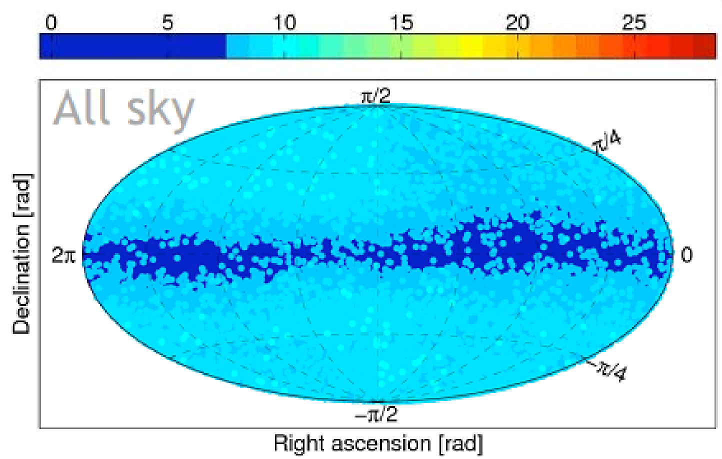
Einstein@Home results from early-S5 "all sky" search

Strain sensitivity of search



Results:
No significant signals in full frequency band and sky location

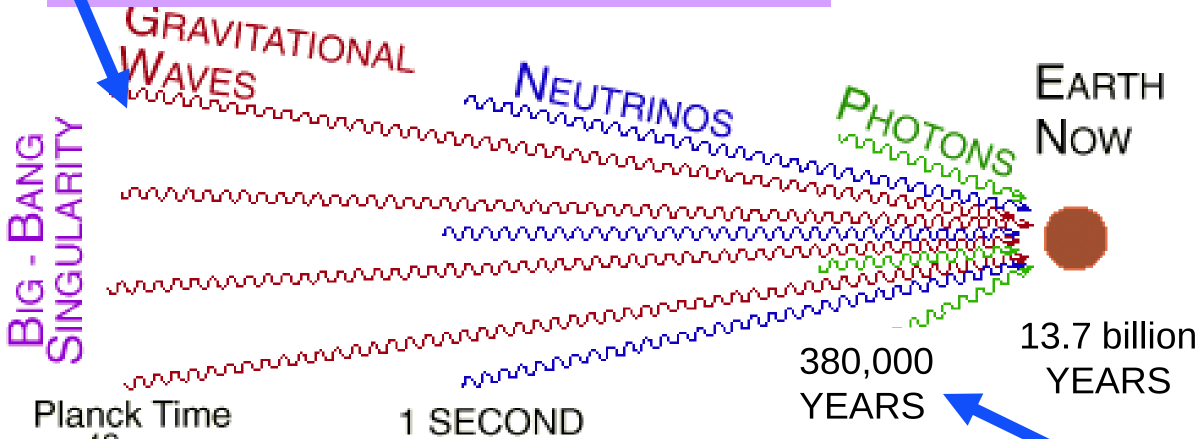




arXiv:0905.1705v1

Gravitational waves from Big Bang

Waves now in the LIGO band were produced 10^{-22} sec after the big bang

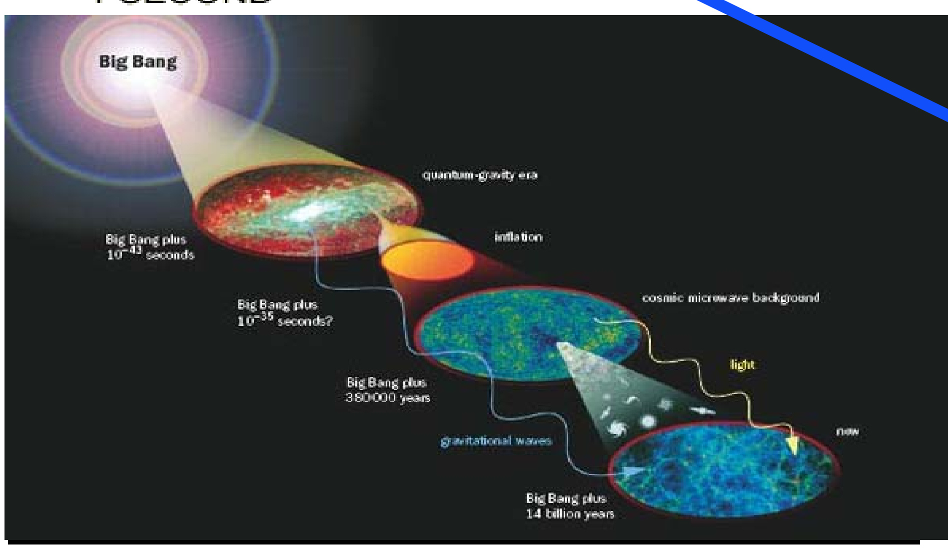


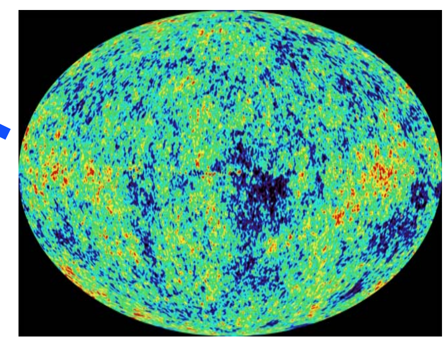
$$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d \ln f}$$

$$\rho_{GW} = \frac{c^2}{32\pi G} < \dot{h}_{ab} \, \dot{h}^{ab} >$$

$$h(f) = 6.3 \times 10^{-22} \sqrt{\Omega_{GW}(f)} \left(\frac{100 \text{ Hz}}{f}\right)^{3/2} \text{Hz}^{-1/2}$$

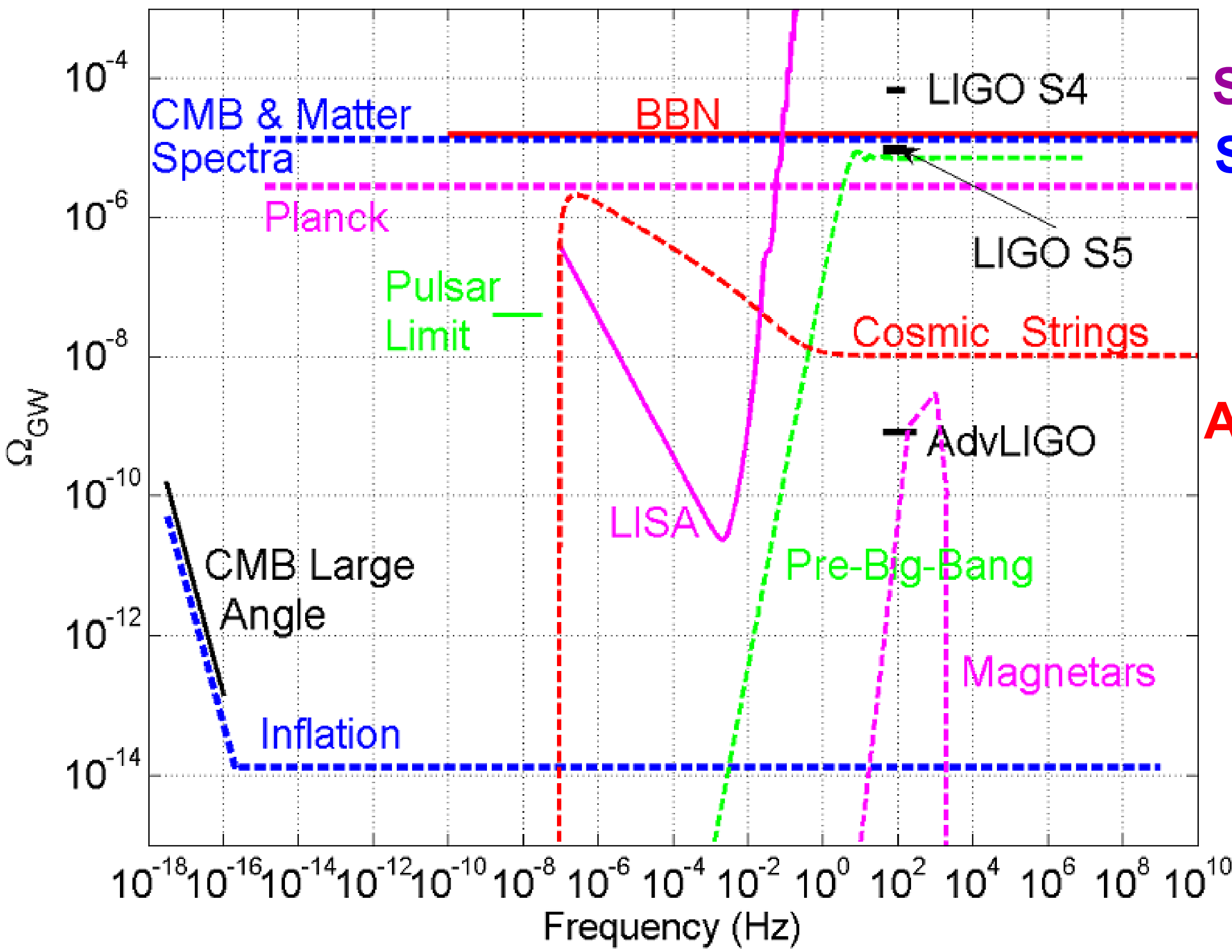
Planck Time
10^{-43} SECONDS
Singularity creates Space & Time of our universe





cosmic microwave background -- WMAP 2003

LIGO limits and expectations on Ω_{GW}



S4 result: $\Omega_{GW} < 6.5\times10^{-5}$

S5 *preliminary* result:

$\Omega_{GW} < 9 \times 10^{-6}$

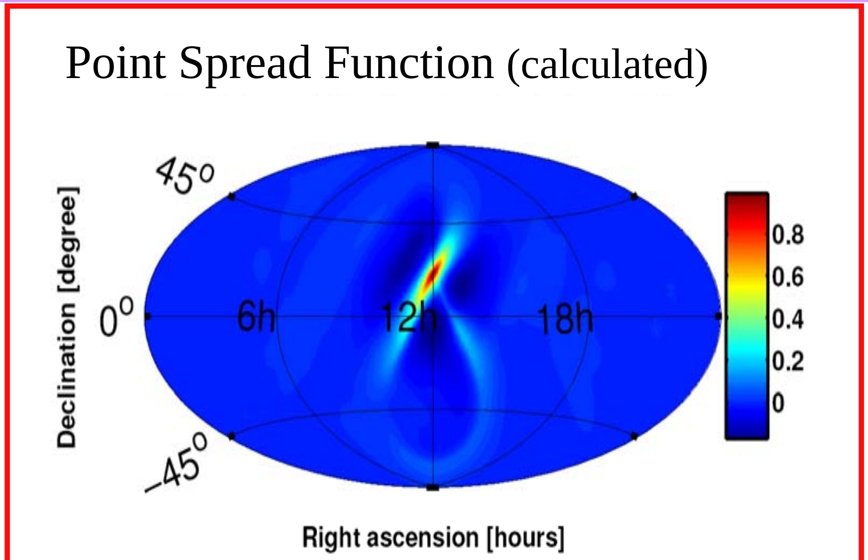
Advanced LIGO, 1 year:

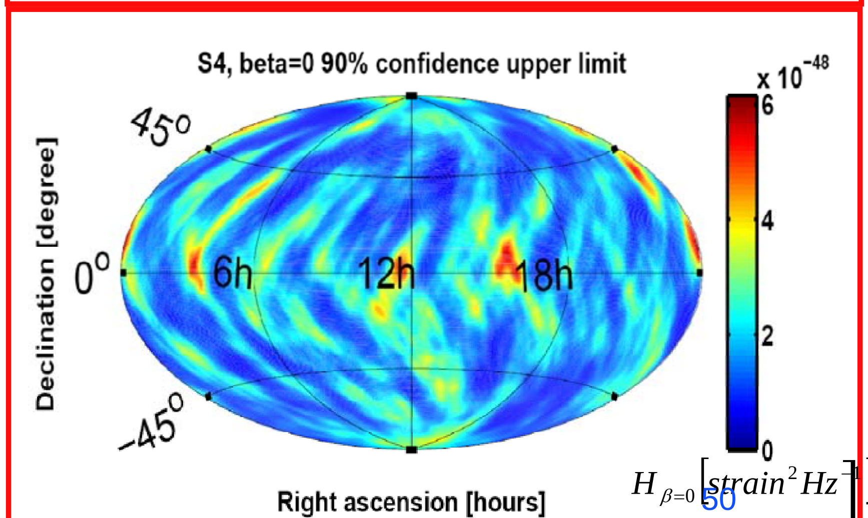
Ω_{GW} <~ 10^{-9}

Upper limit map of a stochastic GW background

- S4 data- 16 days of 2 site coincidence data
- Get positional information from sidereal modulation in antenna pattern and time shift between signals at 2 separated sites
- **No signal was seen**.
- Upper limits on broadband radiation source strain power originating from any direction.

  (0.85-6.1 x 10^{-48} (Hz^{-1}) for min-max on sky map; flat source power spectrum)

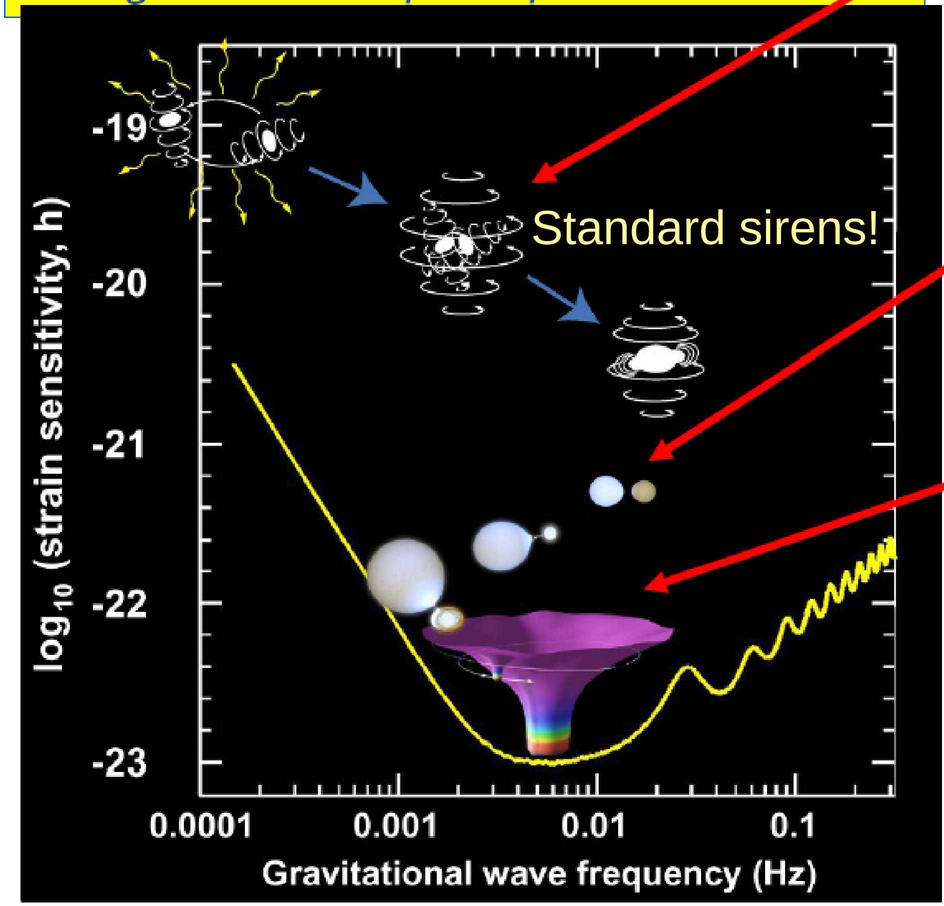




Phys.Rev.D76:082003,2007

LISA Sources

LISA will record a rich symphony of thousands of long-lived (>year) individually identifiable sources, plus backgrounds and perhaps bursts.



Massive Black Hole Binary (BHB) inspiral and merger
Sample: last 40 days of 10^6Msun at z=1, S/N=2500.

Ultra-compact Galactic binaries
Samples: 1kpc, S/N=6-210

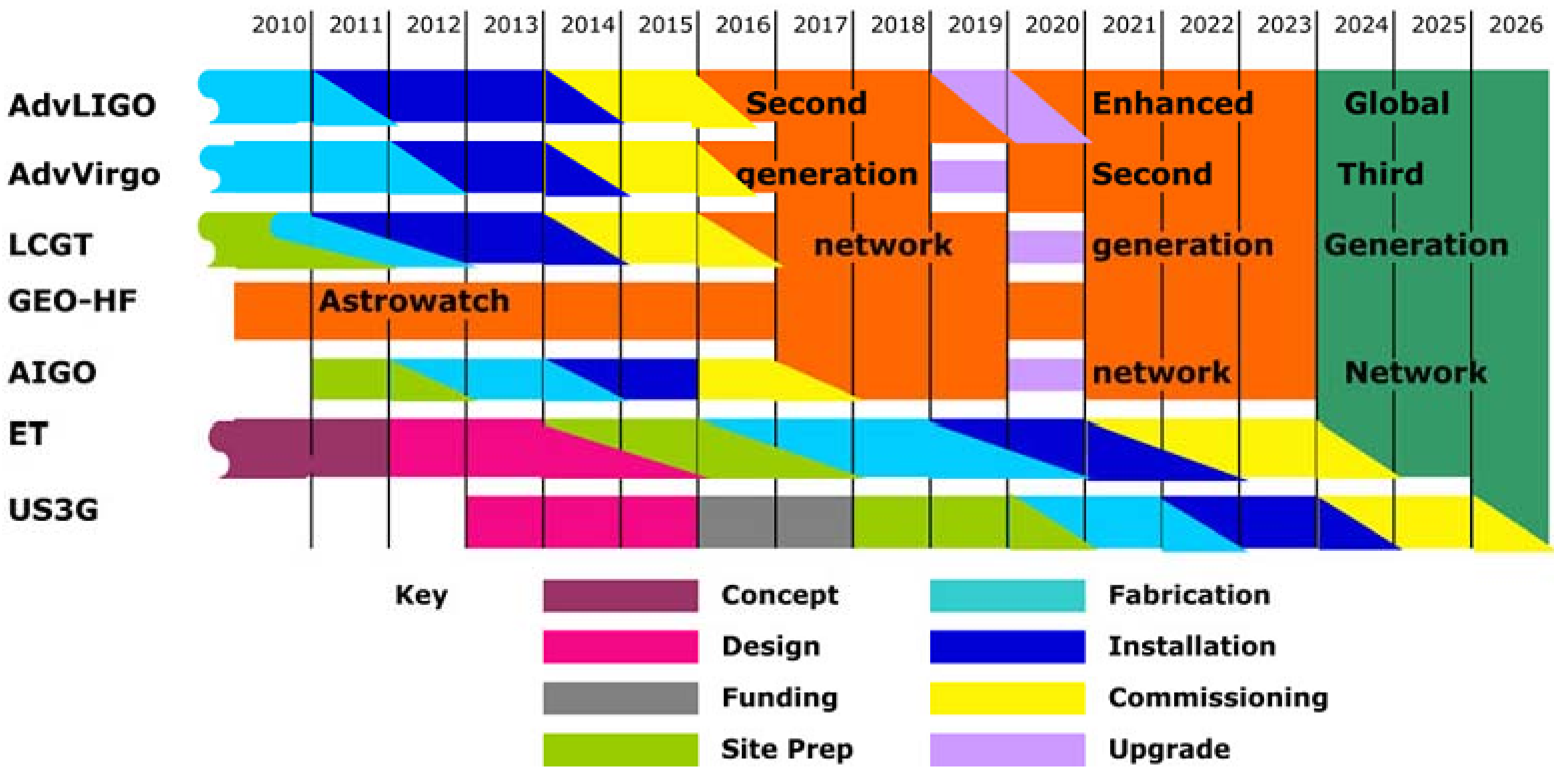
Extreme Mass Ratio Inspiral (EMRI):
Samples: last 5 years of 1Msun into 10^6Msun, z=0.2, S/N=30

Cosmological backgrounds, superstring bursts?

Ultimate Goals for the Observation of GWs

- **Tests of General Relativity – Gravity as space-time curvature**
  - **Wave propagation speed (delays in arrival time of bursts)**
  - **Spin character of the radiation field (polarization of radiation from sources)**
  - **Detailed tests of GR in P-P-N approximation (chirp waveforms)**
  - **Black holes & strong-field gravity (merger, ringdown of excited BH)**
- **Gravitational Wave Astronomy (observation, populations, properties of the most energetic processes in the universe):**
  - **Compact binary inspirals**
  - **Gamma ray burst engines**
  - **Black hole formation**
  - **Supernovae in our galaxy**
  - **Newly formed neutron stars - spin down in the first year**
  - **Pulsars, rapidly rotating neutron stars, LMXBs**
  - **Stochastic background**

Plans for the future: GWIC Roadmap



Summary

- An international network of ground-based GW detectors is taking shape.
- LIGO's first long science run (S5) at design sensitivity completed in 2007
  - No detections to report yet – but there may be some in the can!
  - LIGO searches producing some interesting upper limits
- VIRGO, GEO, TAMA and CLIO approaching design sensitivity
- Enhanced LIGO (S6) and Virgo (VSR2) science runs began July 7, 2009
- Advanced LIGO is funded and in construction, first observations in ~2014
  - Sensitivity/range will be increased by a factor of 10-15
  - We expect to found the field of GW astrophysics with advanced detectors
- LISA (ESA, NSF) recommended for Beyond Einstein flagship mission
  - LISA Pathfinder mission will launch in 2011
  - Japanese DECIGO Pathfinder mission aims for launch in 2013
- Detections, and the exploration of the universe with GWs, will begin over the next decade!

The Beginning of a New Astronomy…