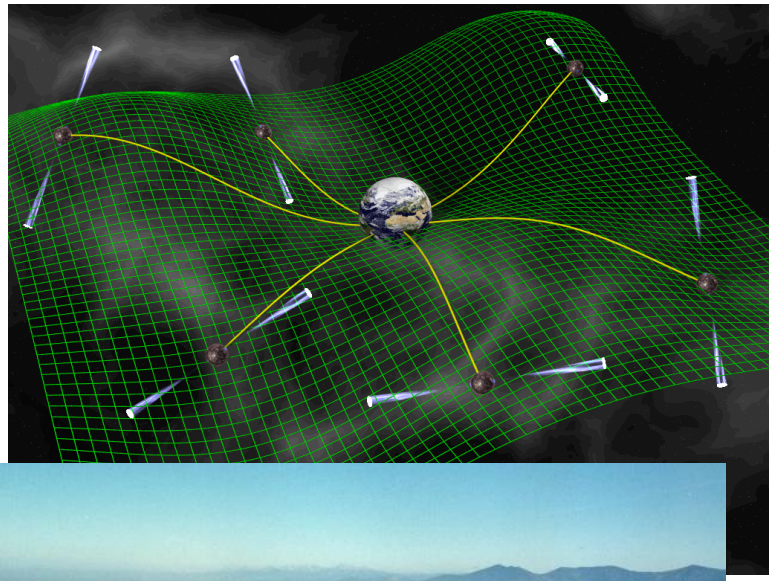
To Catch a Wave - Direct Searches for Gravitational Radiation



Keith Riles
University of Michigan

Shanghai Particle Physics and Cosmology Symposium

June 3-5, 2013.

LIGO-G1300024

What <u>are</u> Gravitational Waves?

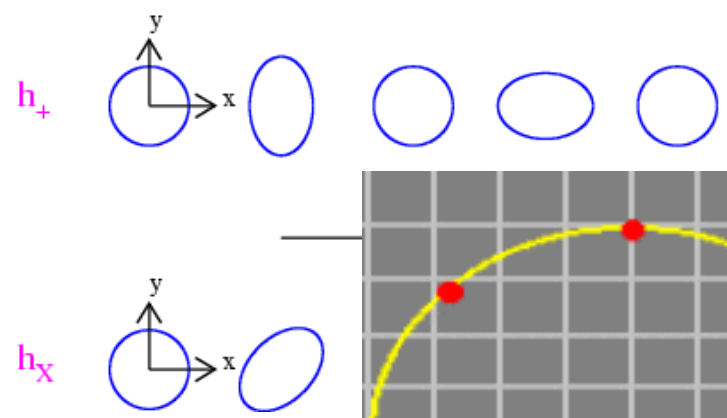
- **Gravitational Waves = "Ripples in space-time"**
- **Perturbation propagation similar to light (obeys same wave equation!)**
  - Propagation speed = c
  - Two transverse polarizations - <u>quadrupolar</u>: + and x

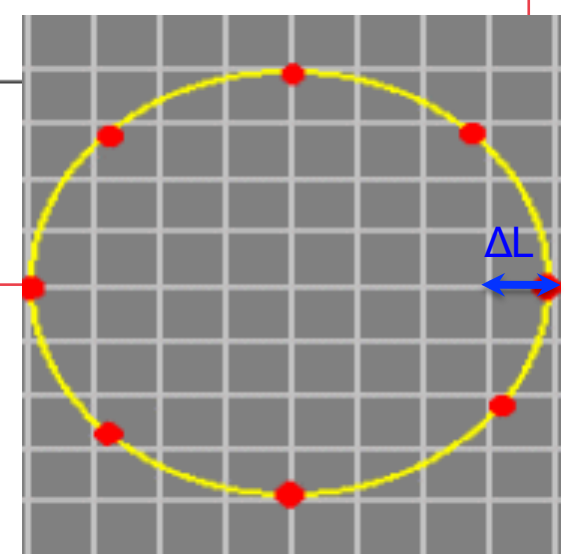
Example:

Ring of test masses

responding to wave

propagating along z





Amplitude parameterized by (tiny) dimensionless strain h: ΔL ~ h(t) x L

Why look for Gravitational Radiation?

- Because it's there! (presumably)

- Tests General Relativity:
  - Quadrupolar radiation? Travels at speed of light?
  - Unique probe of strong-field gravity

- Gain different view of Universe:
  - Sources cannot be obscured by dust / stellar envelopes
  - Detectable sources some of the most interesting, least understood in the Universe
  - Opens up entirely new non-electromagnetic spectrum

What makes Gravitational Waves?

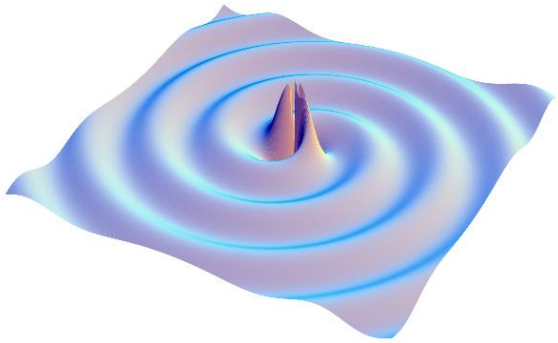
- Radiation generated by quadrupolar mass movements:

$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}(I_{\mu\nu})$$

(with I_{mn} = quadrupole tensor, r = source distance)

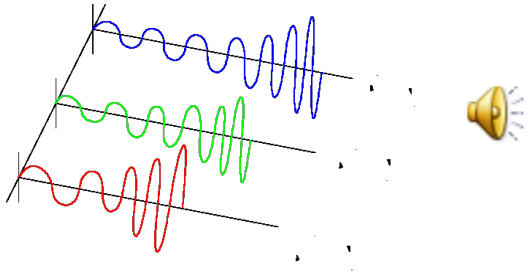
- Example: Pair of 1.4 M_{solar} neutron stars in circular orbit of radius 20 km (imminent coalescence) at orbital frequency 400 Hz gives 800 Hz radiation of amplitude:

$$h \approx \frac{10^{-21}}{(r/15\mathrm{Mpc})}$$

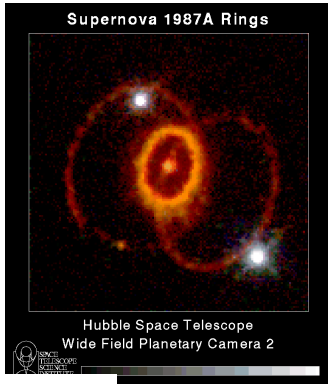


What makes Gravitational Waves?

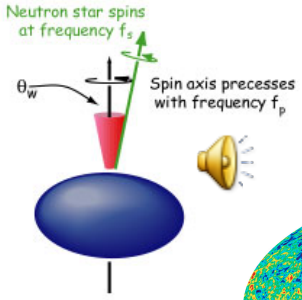
- Compact binary inspiral: *"chirps"*
  - NS-NS* waveforms are well described
  - BH-BH* need better waveforms



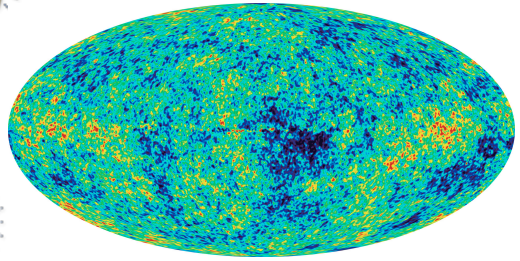
- Supernovae / GRBs: *"bursts"*
  - burst signals in coincidence with signals in electromagnetic radiation / neutrinos
  - all-sky untriggered searches too



- Spinning neutron stars in our galaxy: *"periodic"*
  - search for observed pulsars
  - all-sky search (computing challenge)



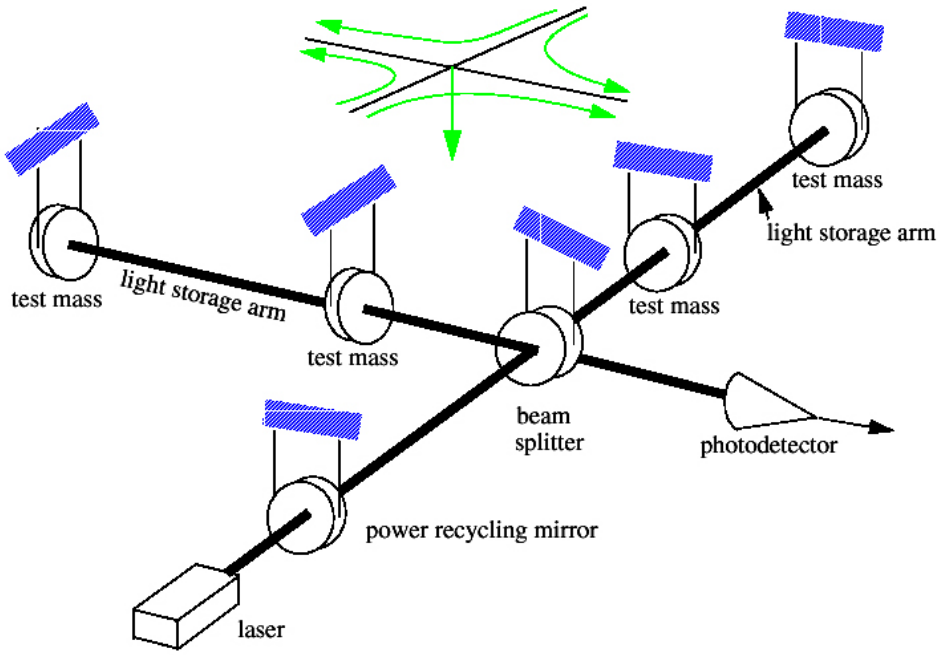
- Cosmological Signals *"stochastic background"*



* NS = Neutron Star, BH = Black Hole

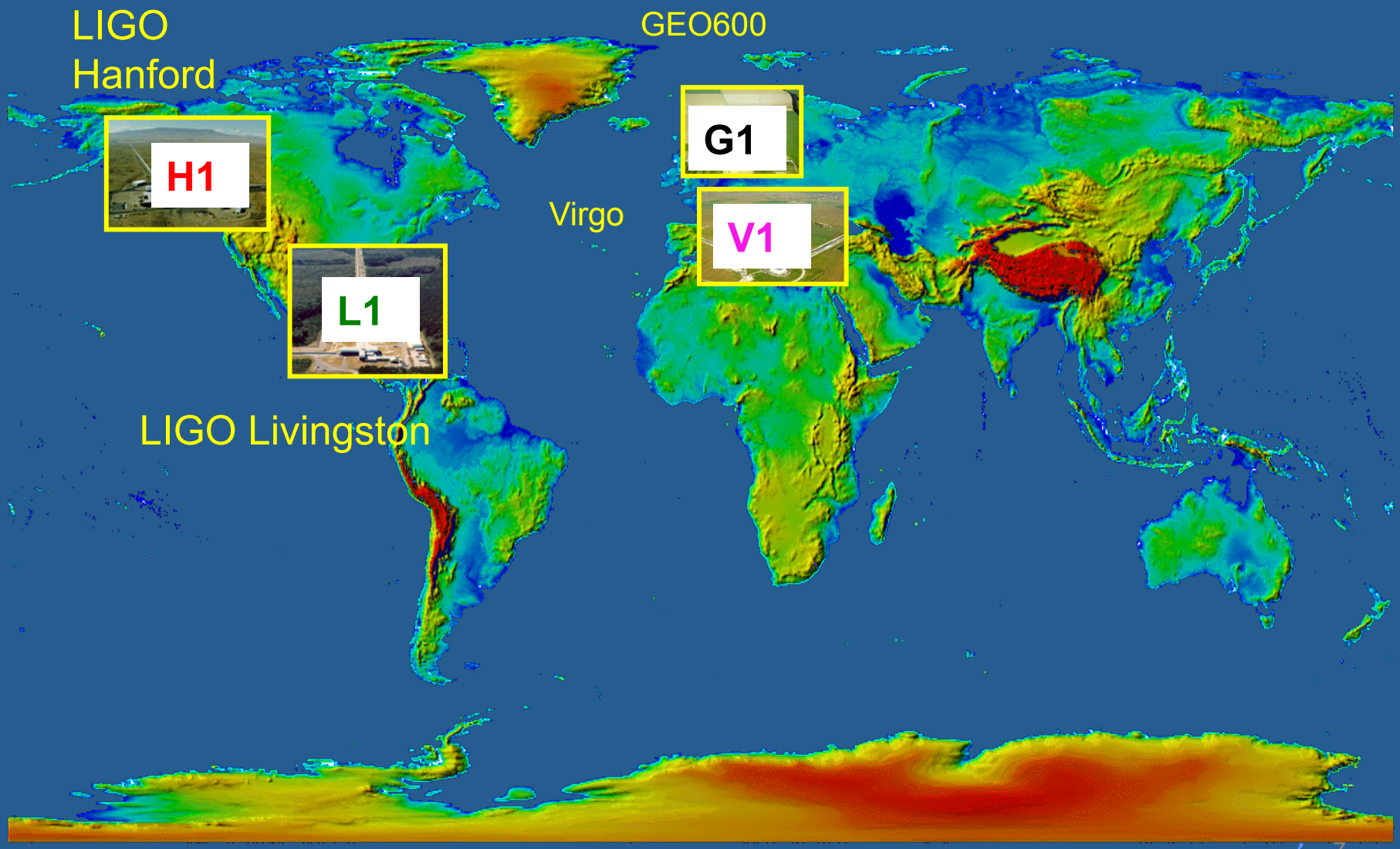
Gravitational Wave Detection

- Suspended Interferometers
  - Suspended mirrors in "free-fall"
  - Michelson IFO is "natural" GW detector
  - Broad-band response (~50 Hz to few kHz)
  - Waveform information (e.g., chirp reconstruction)

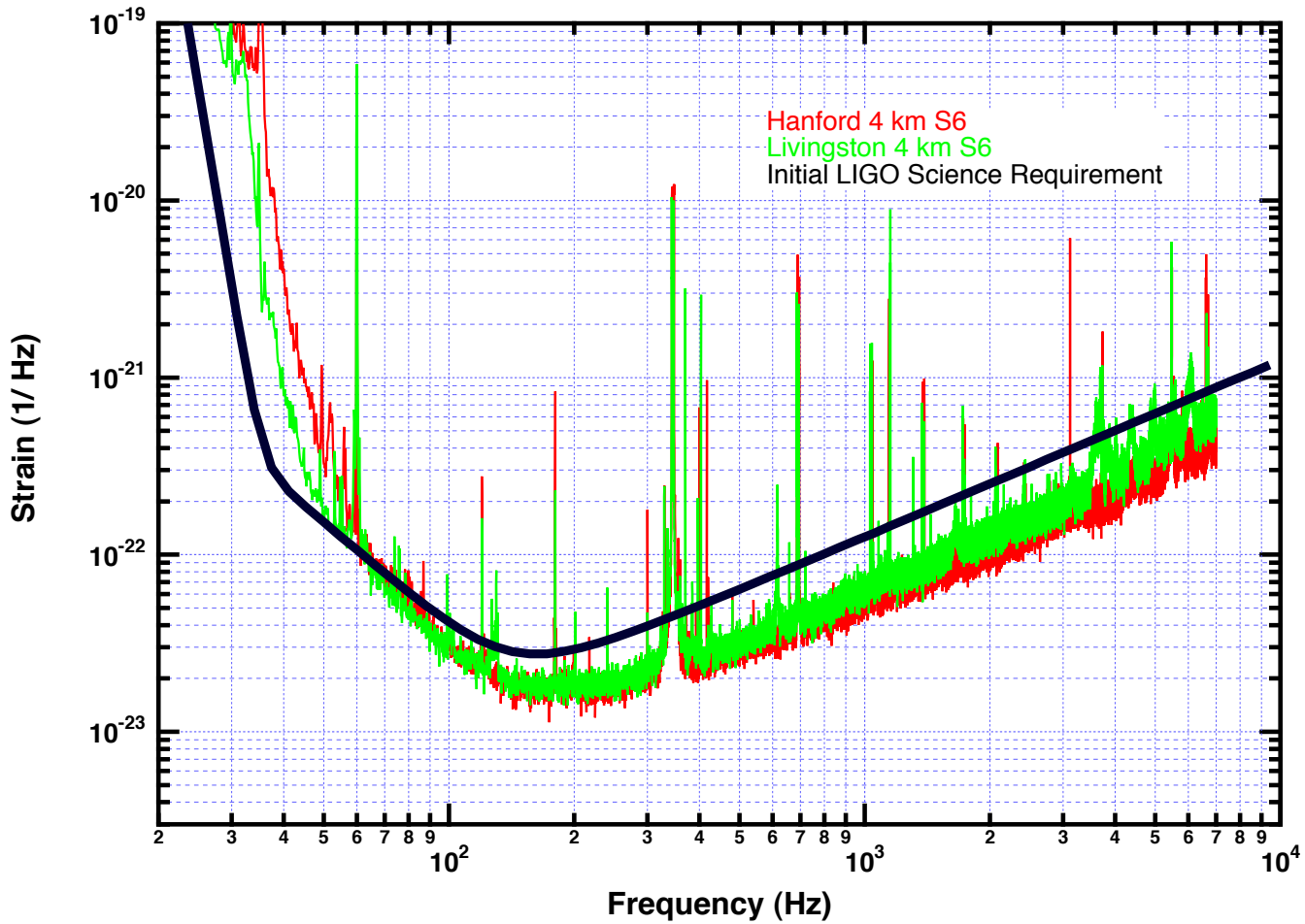


The GW Detector Network 2005-2010

Network increases detection confidence, allows source triangulation



LIGO strain spectral noise in 2009-2010 Science Run S6



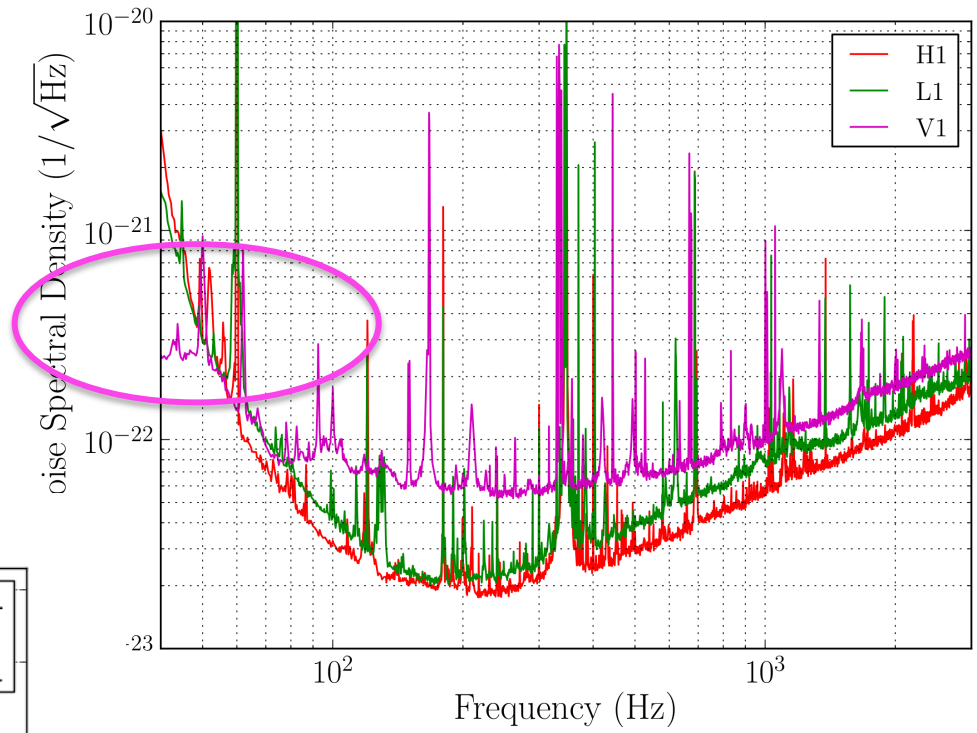
<u>Amplitude</u> sensitivity ≈ (statistical scale factor) x (strain noise) / sqrt(signal duration)

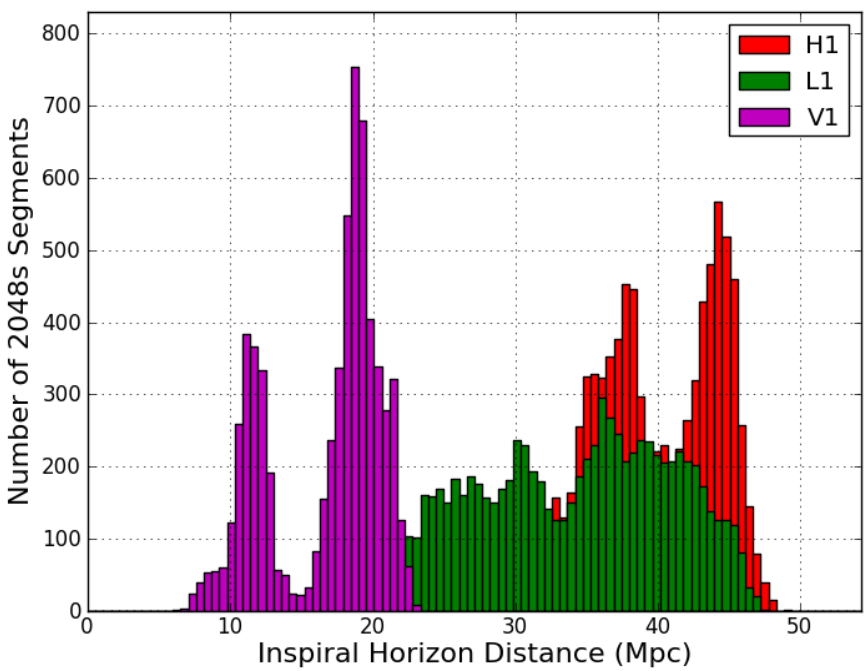
10-ms transient
$h_{sens} \approx 10^{-21}$

1-year pulsar emission
$h_{sens} \approx$ few × 10^{-26}

LIGO and Virgo sensitivity comparison

Virgo's seismic isolation allowed probing lower frequencies than initial LIGO (low-freq pulsars, BH-BH binaries)





Histogram of maximum distances to which a NS-NS inspiral could have been seen in S6 and Virgo VSR2/3 data runs

Searching for Gravity Waves

Short-Lived ⟷ **Long-Lived**

Known waveform

↕

Unknown waveform

Binary Inspirals

(NS-NS)

Spinning BH-BH merger

Continuous waves

(Isolated spinning NS)

Accreting NS

Bursts

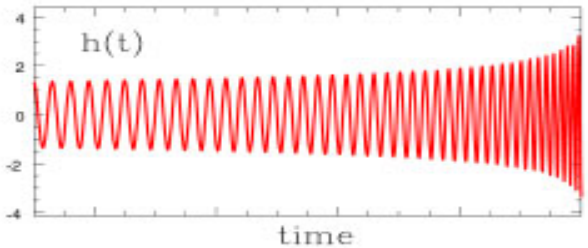
(Supernovae)

Stochastic background

(Cosmological, astrophysical)

Searching for binary systems

Fourier transform of data time series (noise n + signal h):



$$\tilde{x}(f) = \int_{-\infty}^{\infty} dt\ e^{-i2\pi ft}\ [x(t) = n(t) + h(t)]$$

Define signal strength vs time (optimal filter):

$$z(t) = 2\int_{-\infty}^{\infty} \frac{\tilde{h}(f)\tilde{x}^*(f)}{S_n(f)}\ e^{i2\pi ft}\ df$$

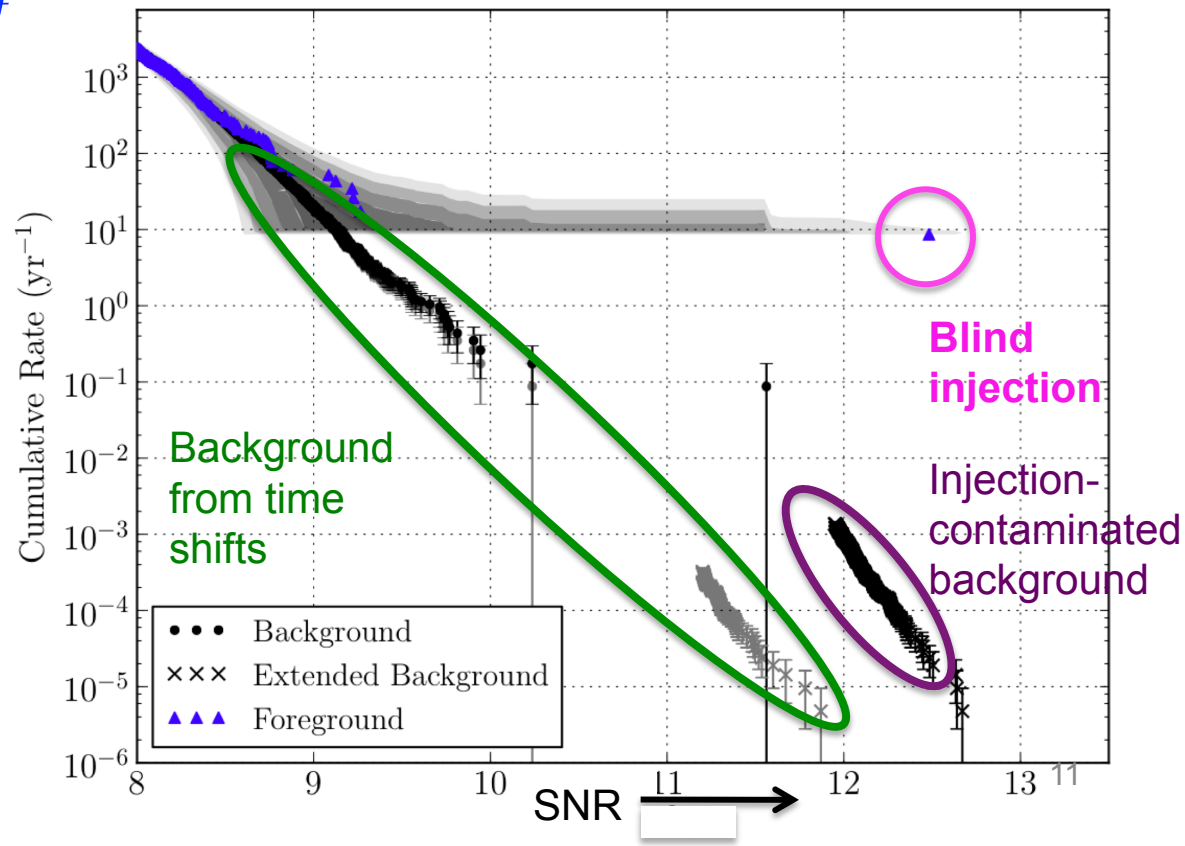
Signal-to-noise ratio:

$$\rho(t) = \frac{|z(t)|}{\sigma}$$

with

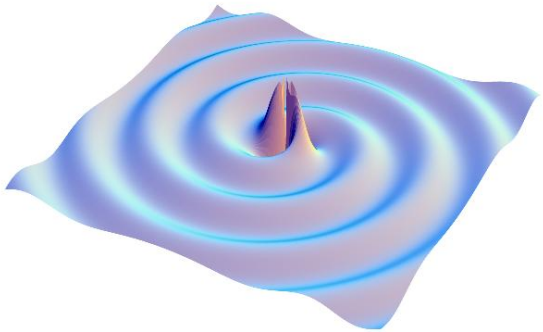
$$\sigma^2 = 2\int_{-\infty}^{\infty} \frac{|\tilde{h}(f)|^2}{S_n(f)}\ e^{i2\pi ft}\ df$$

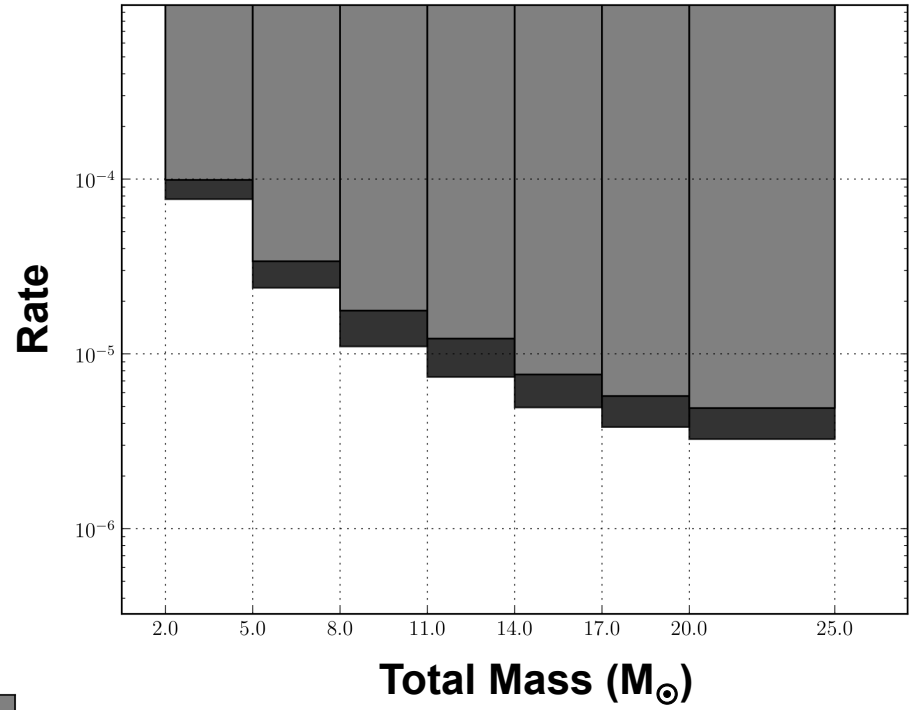
Cumulative events vs SNR (sample mass bin)



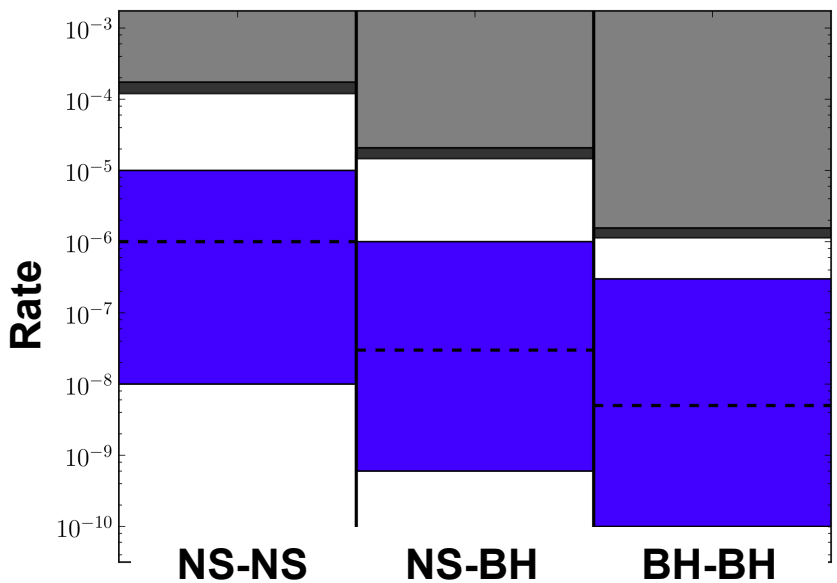
No evidence of (real) excess

→ Set upper limits on inspiral rate (# per Mpc^3 per year) vs stellar mass:





Now assume $M_{BH} \approx 10\ M_\odot$



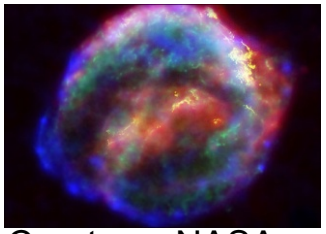
Excluded rate

Expected rate (95%)

(- - - = "Realistic")

Phys Rev. D85 (2012) 082002

Searching for generic bursts (untriggered)



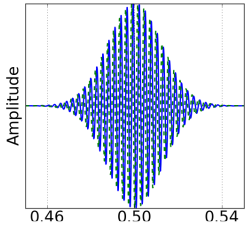
Courtesy: NASA

- Search for coincident triggers ("Coherent WaveBurst")
- Check waveform consistency among interferometers – apply vetoes
- Set a threshold for detection for low false alarm probability
- Evaluate efficiency for variety of simple generic waveforms

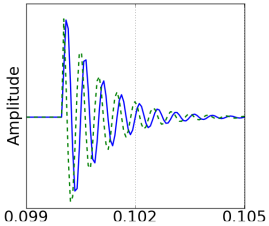
Parameterize strength in terms of "root sum square of h" : h_{RSS}

$$(h_{RSS})^2 = \int_{-\infty}^{+\infty} (|h_+(t)|^2 + |h_\times(t)|^2)dt$$

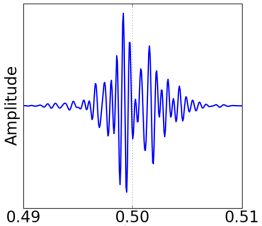
Sine-Gaussian

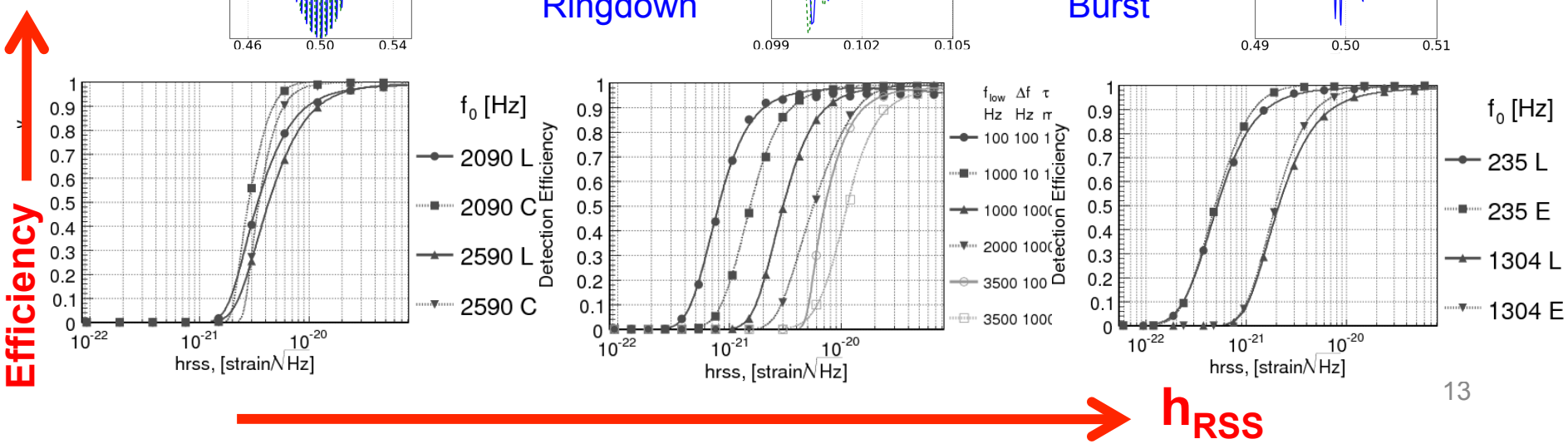


Black Hole Ringdown



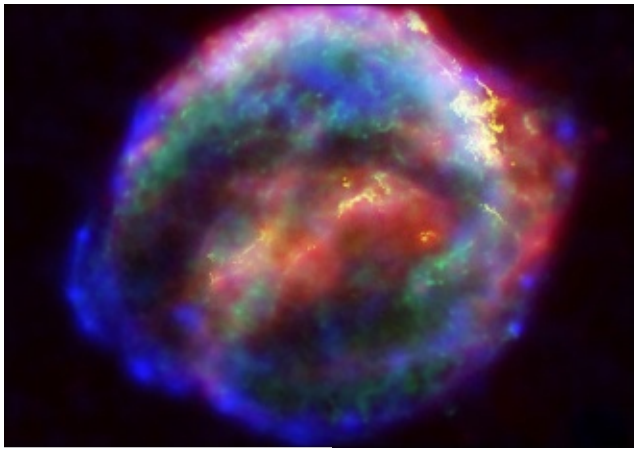
White Noise Burst



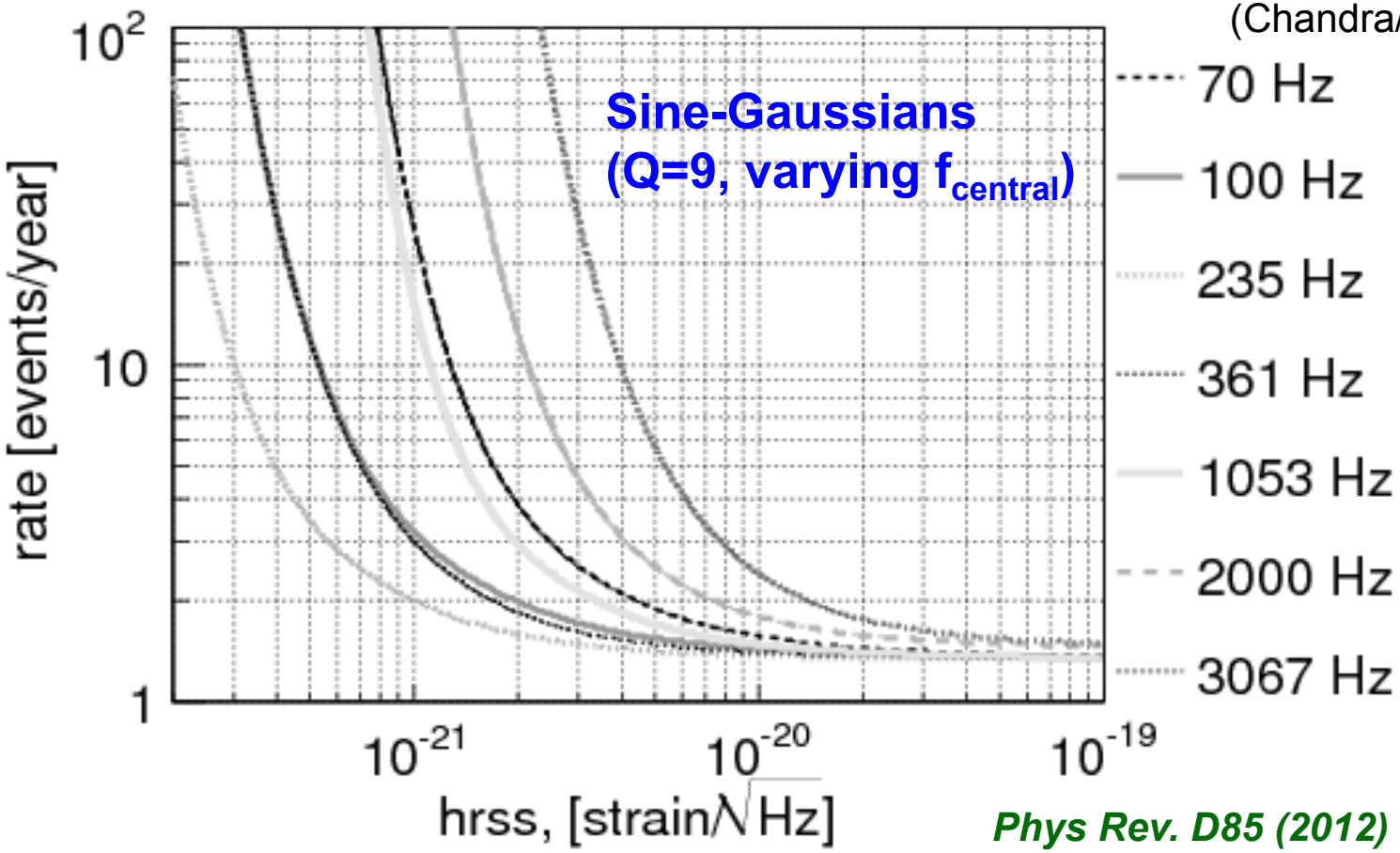


Searching for generic bursts

No candidates found above threshold
(false alarm rate = 1 / (8 yr)
→ Set upper limits on rate vs h_{RSS}



Kepler's Supernova remnant
(Chandra/Hubble/Spitzer)



Phys Rev. D85 (2012) 122007

Searching for continuous waves

Bayesian heterodyne algorithm applied to 116 <u>known</u> pulsars over 23 months of LIGO data (using radio / X-ray ephemerides)

Lowest upper limit on strain:

$$h_0 < 2.3 \times 10^{-26}$$

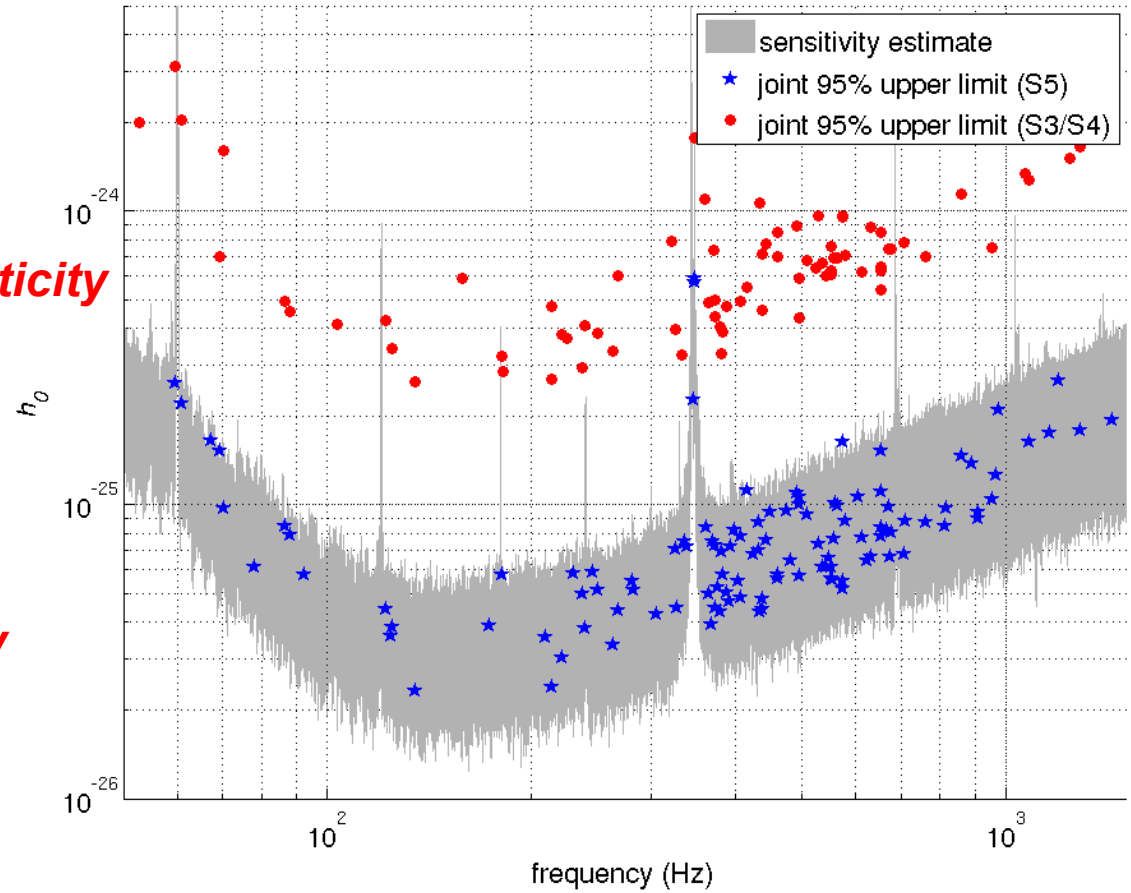
Lowest upper limit on ellipticity (non-axisymmetry):

$$\varepsilon < 7 \times 10^{-8}$$

Upper limit on Crab energy loss due to GW:

2%

Astroph. J. 713 (2010) 671

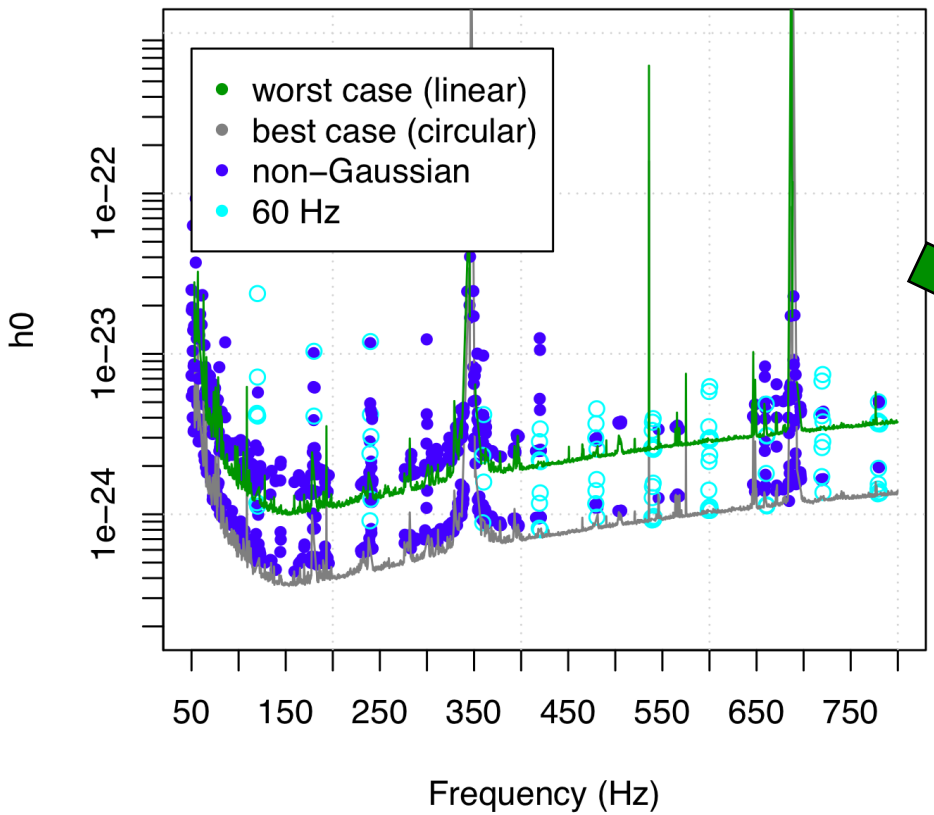


Searches for unknown pulsars over the entire sky computationally bound (Doppler effects due to Earth's motion)

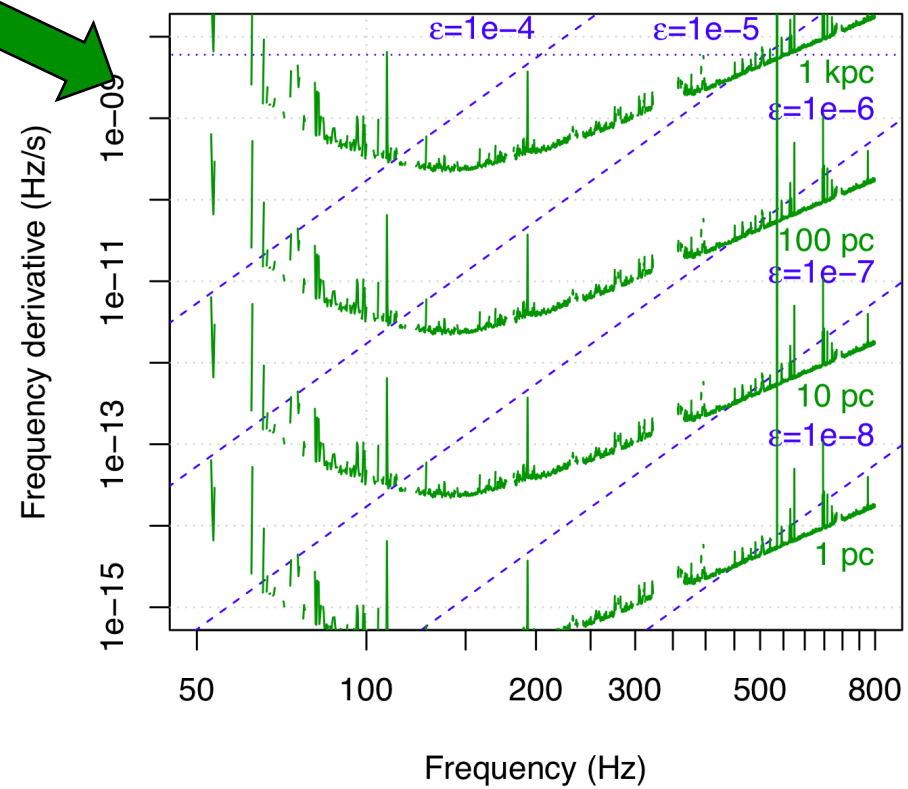
→ Must make tradeoffs in sensitivity vs parameter space coverage

"PowerFlux" approach:

Semi-coherent, stacks (~2 years) of 30-minute, demodulated power spectra



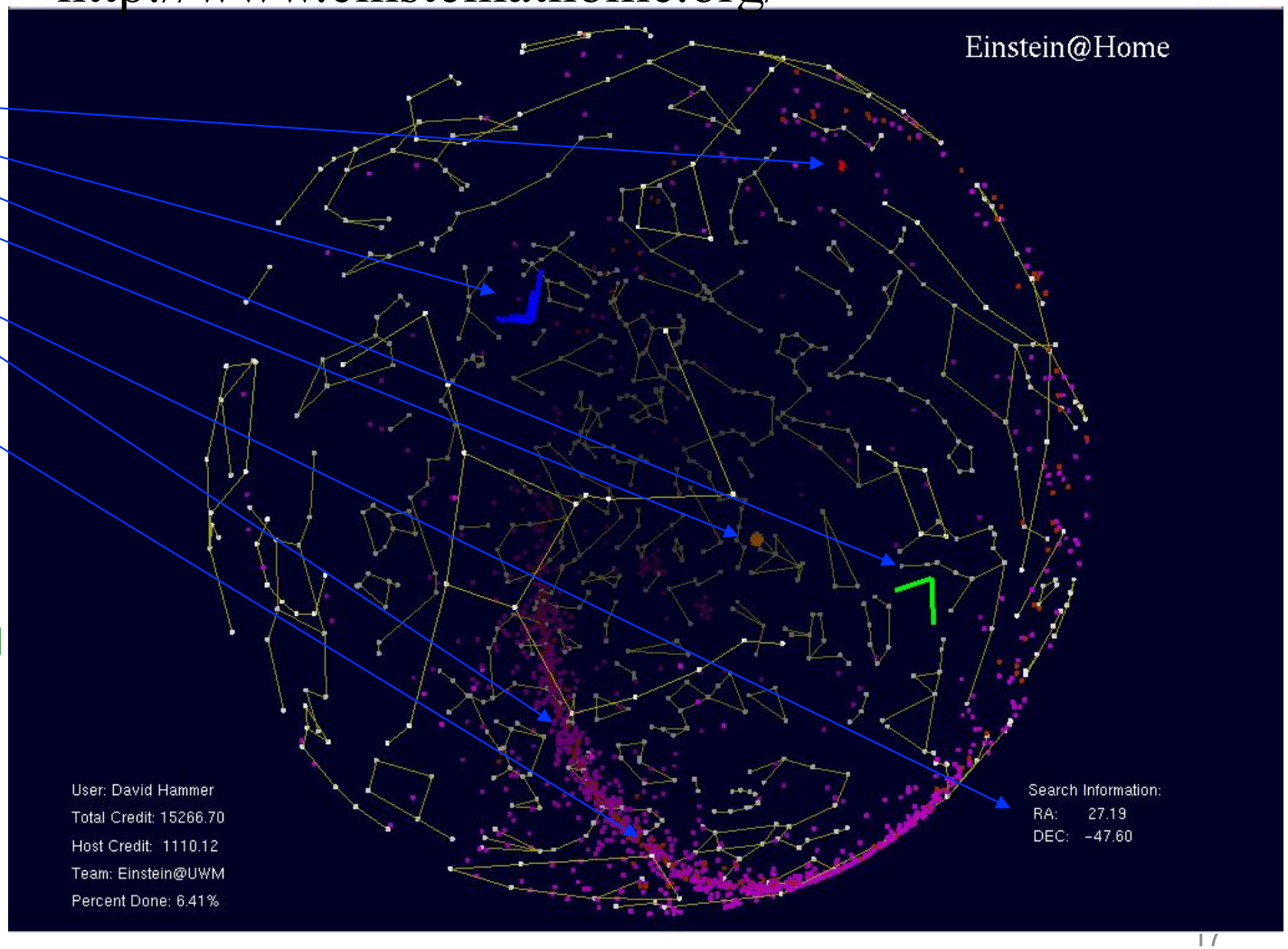
Astrophysical reach



Phys. Rev. D85 (2012) 022001

http://www.einsteinathome.org/

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

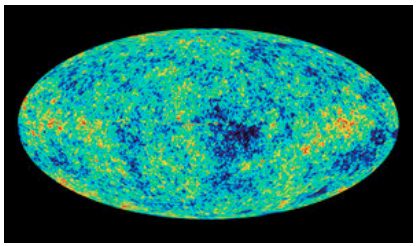


Comparable limits over larger band obtained recently with E@H

PRD87 (2013) 042001

Your computer can help too!

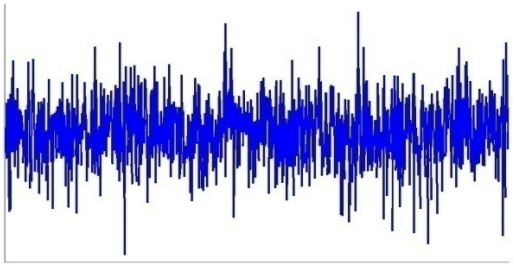
Searching for a stochastic background



NASA, WMAP

- **A primordial isotropic GW stochastic background is predicted by most cosmological theories.**
- **Given an energy density spectrum $W_{gw}(f)$, there is a strain power spectrum:**

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



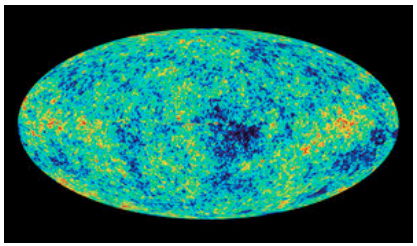
$$S_{\rm gw}(f) = \frac{3H_0^2}{10\pi^2} f^{-3}\Omega_{\rm gw}(f)$$

$$h(f) = S_{\rm gw}^{1/2}(f) = 5.6\times10^{-22}\, h_{100}\sqrt{\Omega_0}\left(\frac{100{\rm Hz}}{f}\right)^{3/2} {\rm Hz}^{1/2}$$

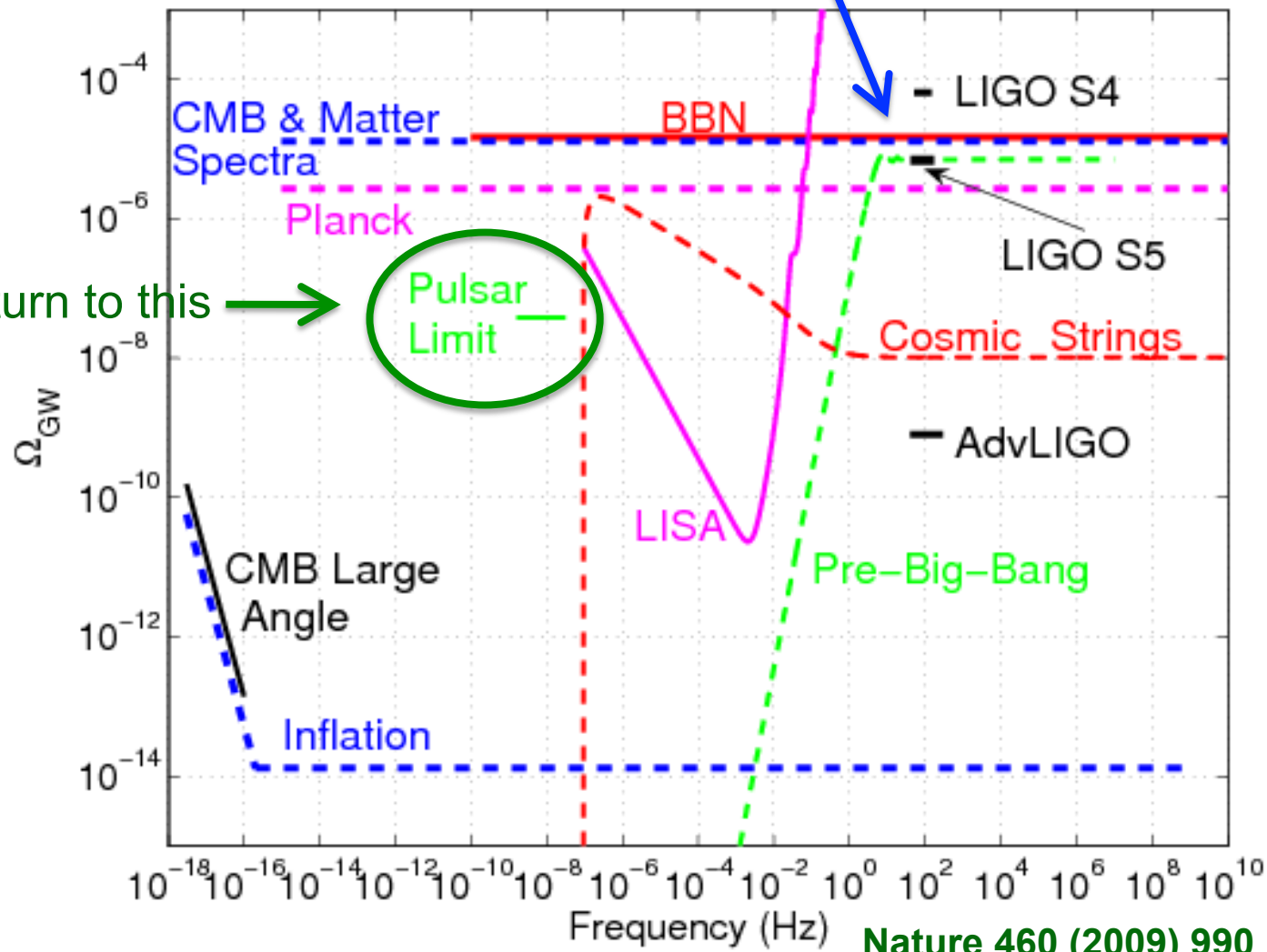
- **The signal can be searched from <u>cross-correla*tions*</u> *in different pairs of detectors, e.g., L1-H1***
- **The farther apart the detectors, the lower the frequencies that can be searched.**

Published H1-L1 Bayesian 90% UL:

$$\Omega_{90\%} = 6.9 \times 10^{-6} \text{ (40-170 Hz)}$$



Will return to this



Nature 460 (2009) 990

Other GW emission not (yet) seen by LIGO/Virgo

Binary coalescence:

- ***Low-mass inspirals (primordial black holes)***
- ***High-mass inspirals***
- ***Spinning black holes***
- ***Ringdown of final black hole (merger final state)***

Gravitational Wave transients coincident with

- ***Gamma Ray Bursts***
- ***Soft Gamma Repeaters***
- ***Magnetar flares***
- ***High Energy Neutrinos***

Continuous gravitational waves from

- ***Vela (low-frequency pulsar)***
- ***Cassiopea A (isolated neutron star)***
- ***Scorpius X-1 (low-mass X-ray binary)***

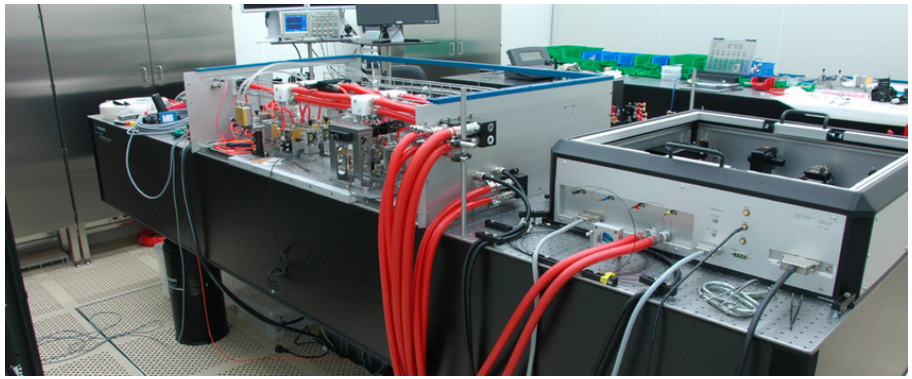
Anisotropic stochastic gravitational radiation
(including from galactic center, Sco X-1, Supernova 1987A)

Advanced LIGO

Increased laser power:

10 W → 200 W

Improved shot noise (high freq)



Higher-Q test mass:

Fused silica with better optical coatings

Lower internal thermal noise in band

Increased test mass:

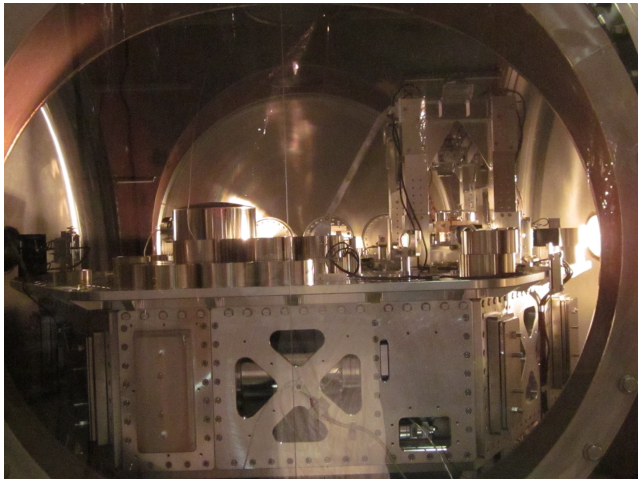
10 kg → 40 kg

Compensates increased radiation pressure noise

Advanced LIGO

New suspensions:

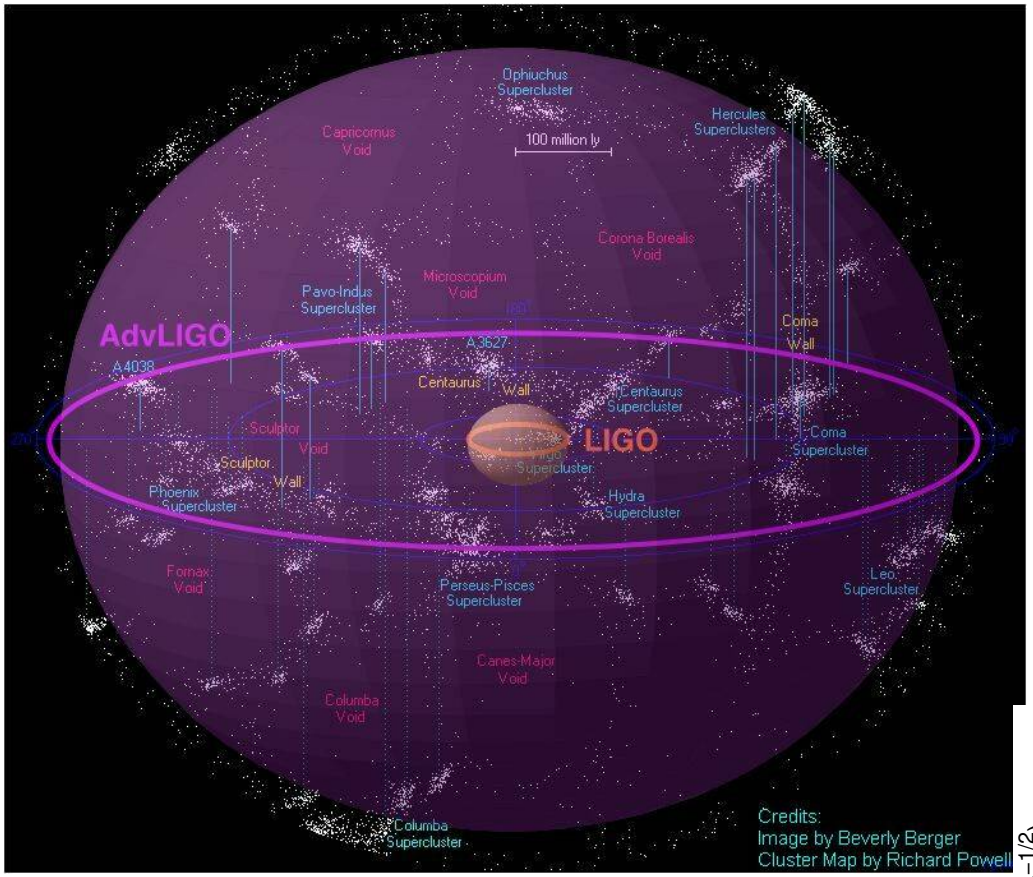
- **Single → Quadruple pendulum**
- **Lower suspensions thermal noise in bandwidth**



Improved seismic isolation:

- **Passive → Active**
- **Lowers seismic "wall" to ~10 Hz**

Advanced LIGO



Neutron Star Binaries:

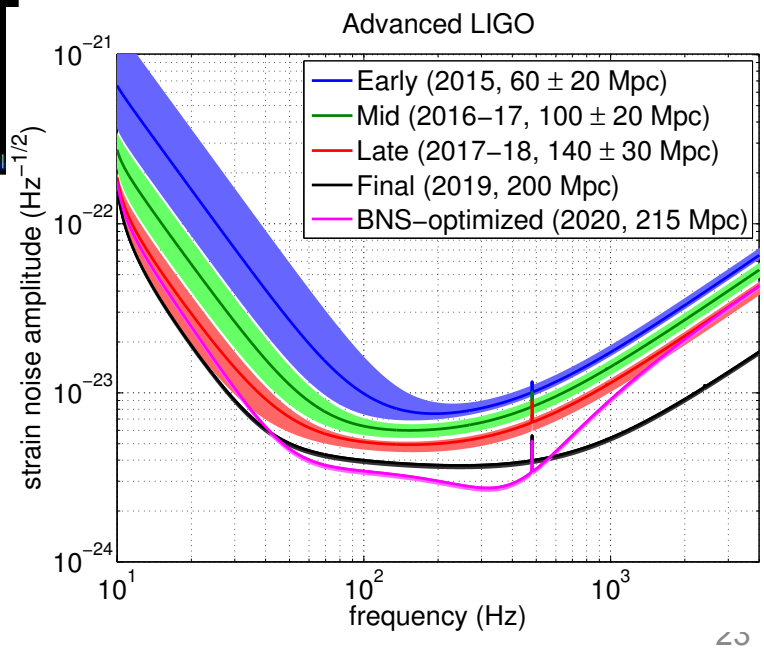
Average range ~ 200 Mpc

Most likely rate ~ 40/year

The science from the first 3 hours of Advanced LIGO should be comparable to 1 year of initial LIGO

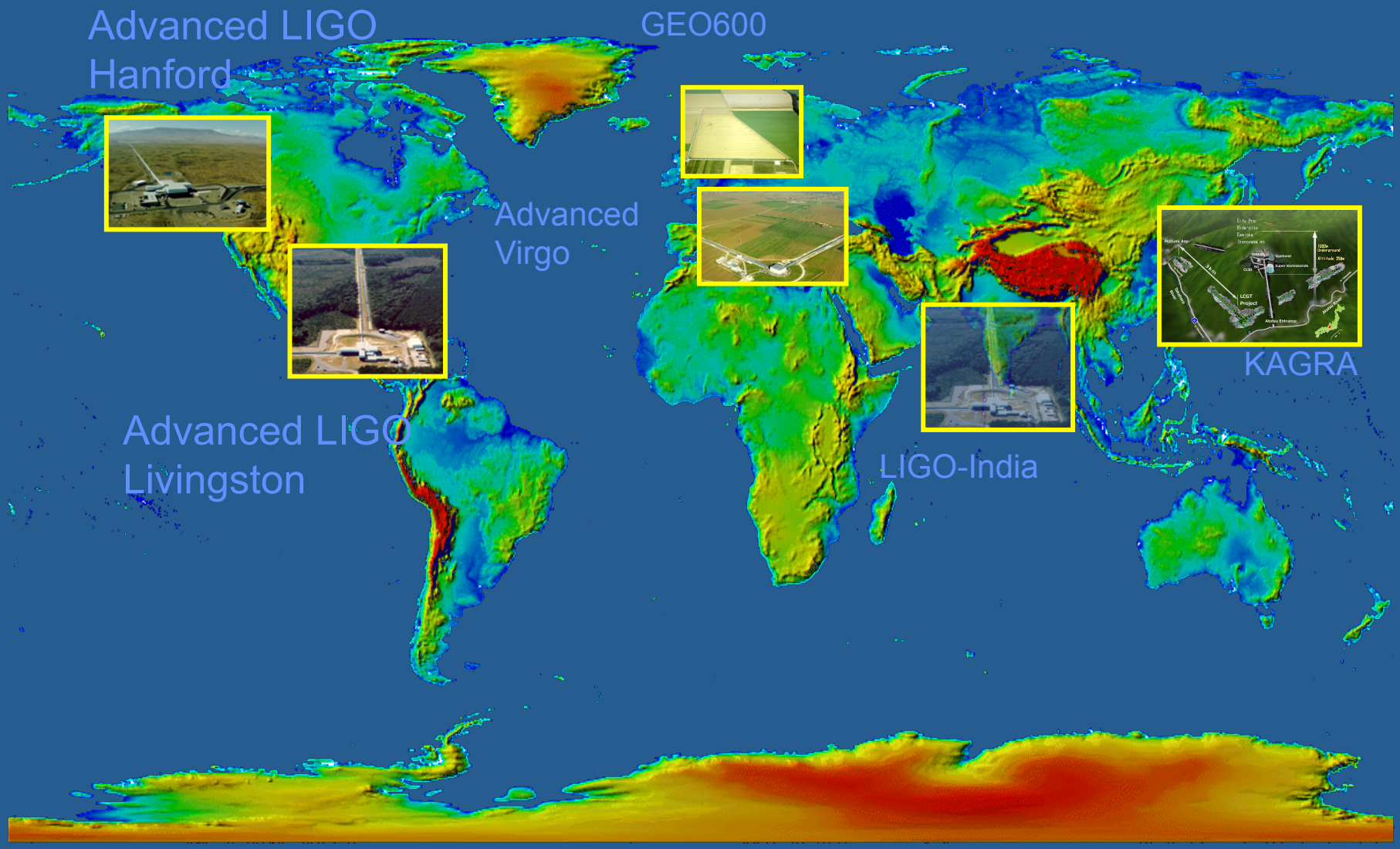
(Range x ~10 → Volume x ~1000)

But that sensitivity will not be achieved instantly…

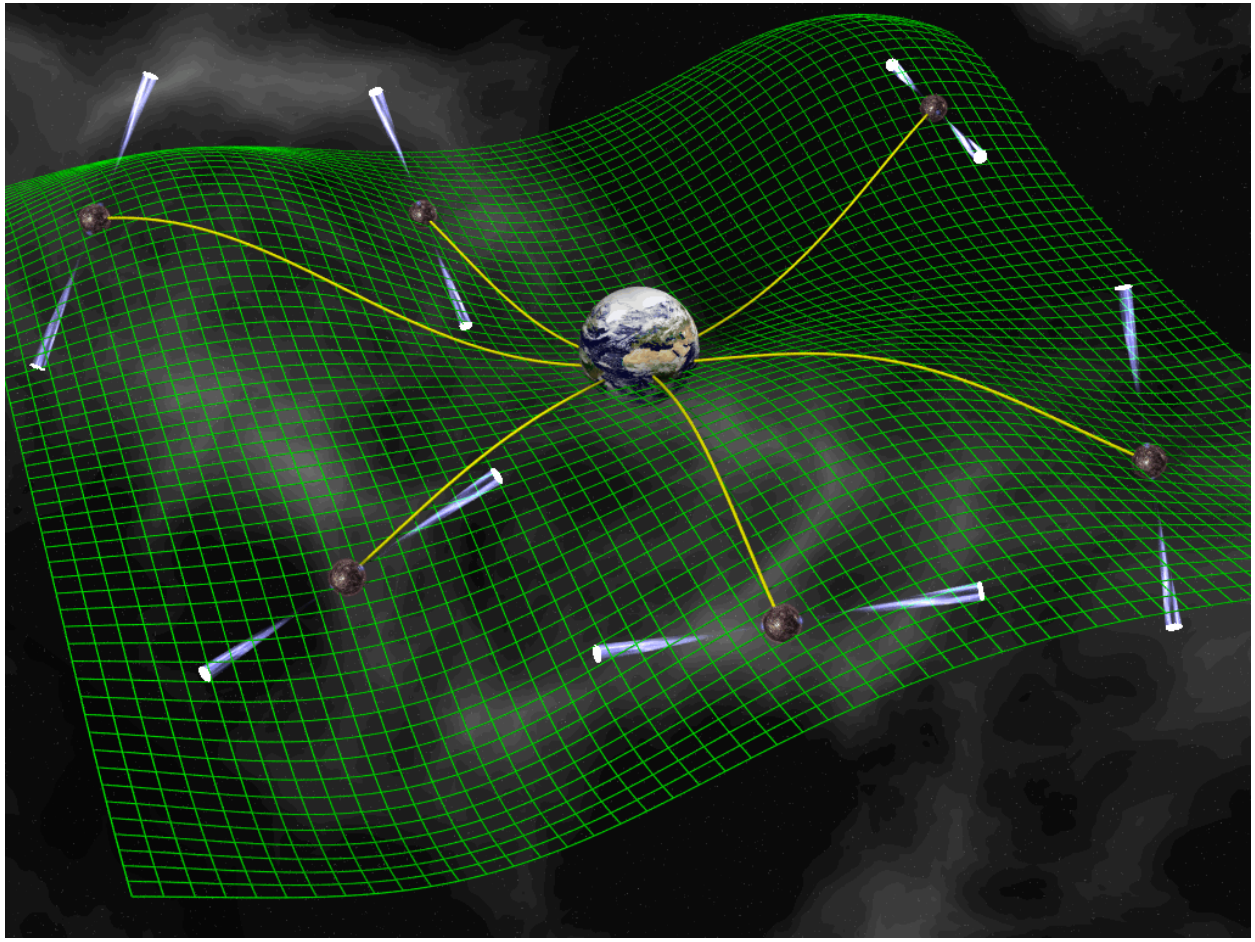


arXiv: 1304.0670

The GW Detector Network~2020



Alternate Path to Direct GW Detection
Pulsar Timing Arrays



Courtesy: NanoGrav

If our galactic neighborhood is bathed in very-long-wavelength GW radiation, the timing pulses received from distant pulsars may be distorted in a quadrupolar spatial pattern

Detectable statistically from an ensemble of stable pulsars

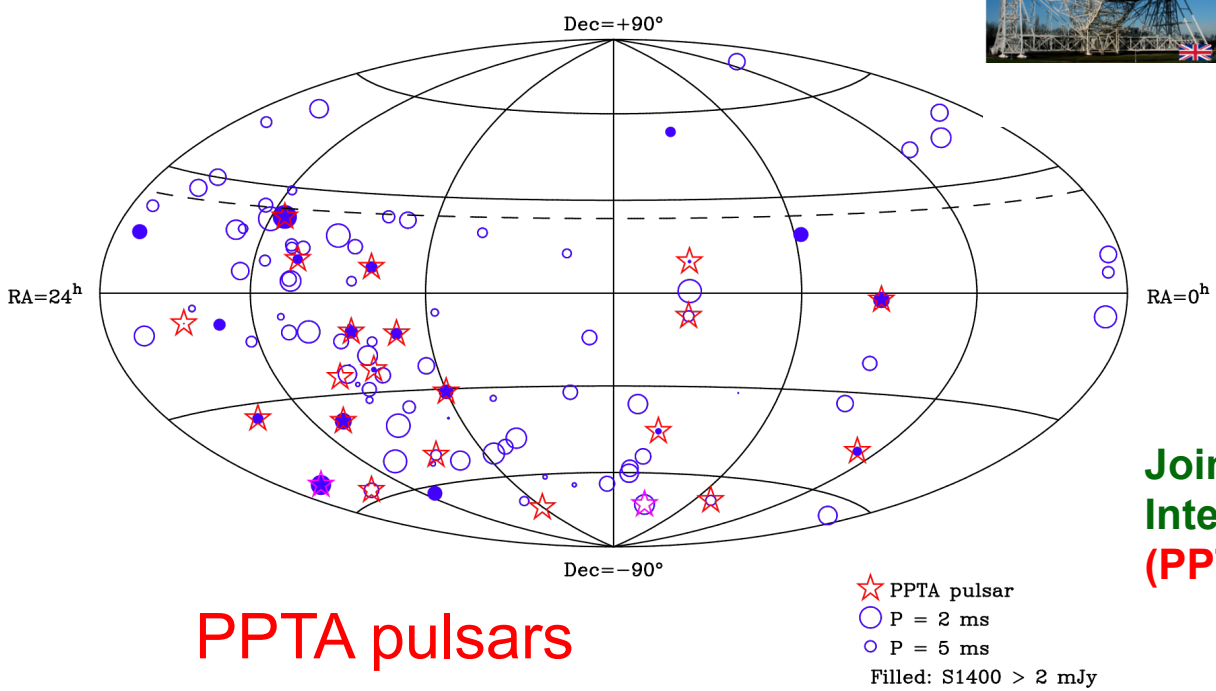
→ Look for correlations in timing residuals after fitting to pulse model

Pulsar Timing Arrays

Three radio astronomy consortia:

- Parkes PTA (Australia)
- European PTA
- NanoGrav (N. America)

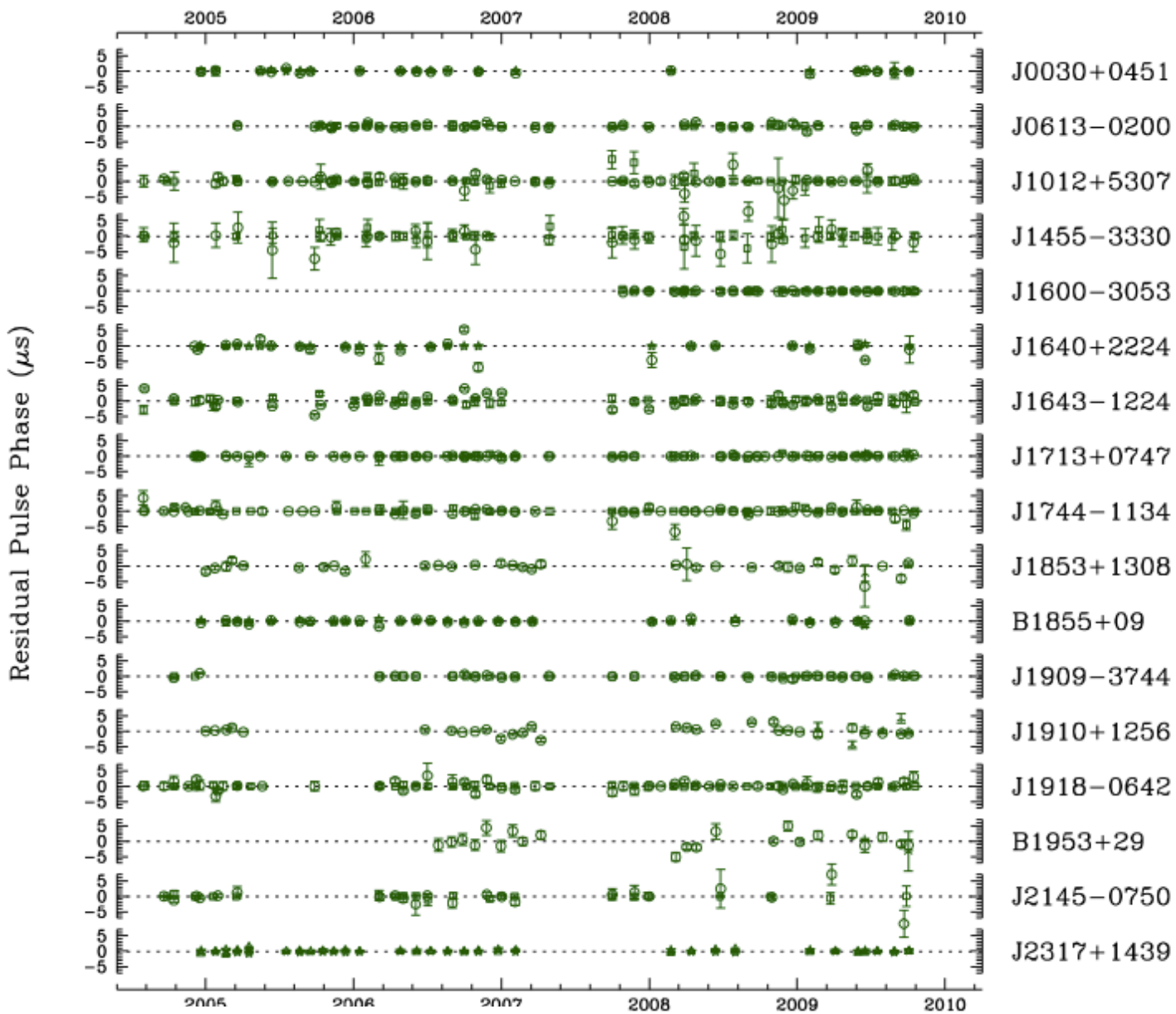
Courtesy: Andrea Lommen



PPTA pulsars

Joint analysis planned as part of International Pulsar Timing Array (PPTA+EPTA+NanoGrav = IPTA)

NanoGrav Pulsar Timing Residuals [μs]



41 ns

47 ns

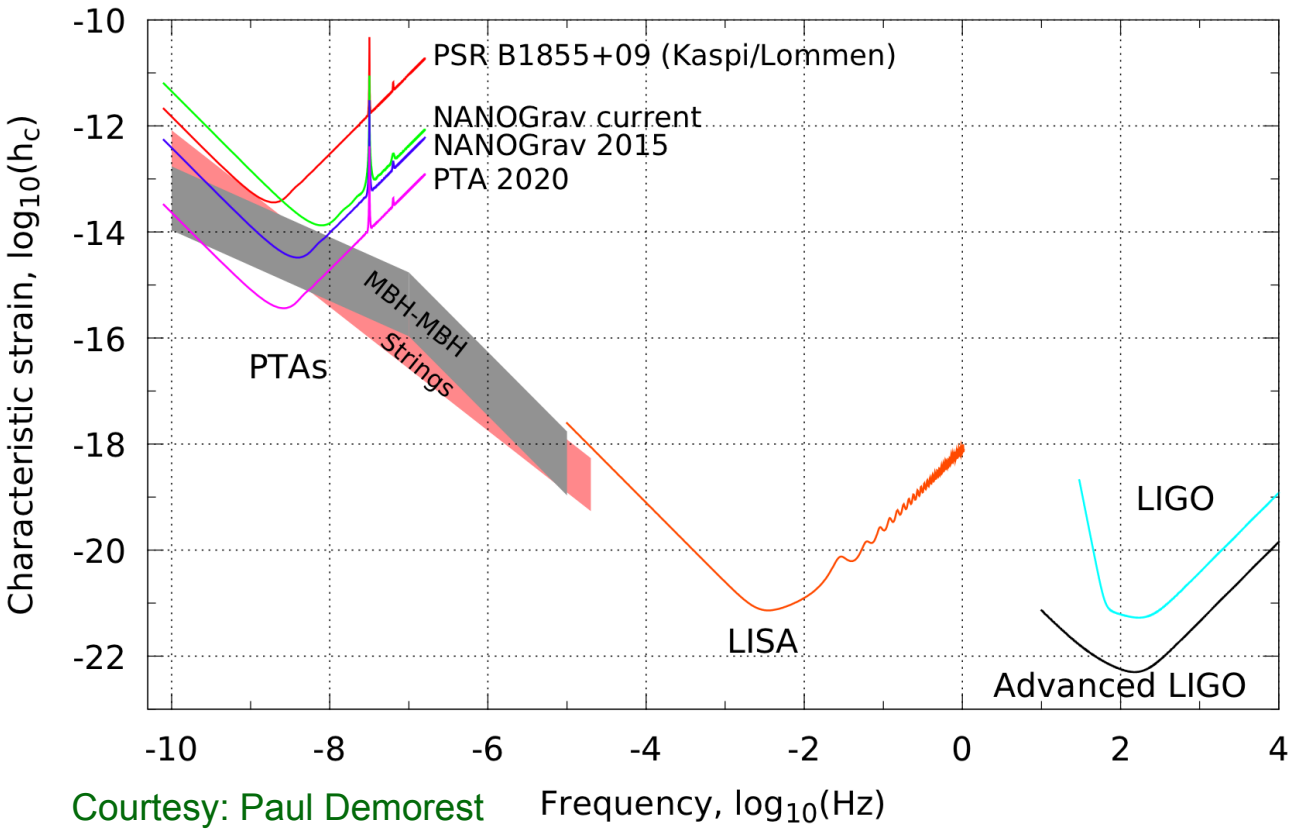
Courtesy: David Nice

Pulsar Timing Arrays

Sensitive to gravitational waves at extremely low frequencies (~10 nHz)

Most likely source – stochastic background from incoherent superposition of many distant supermassive black hole inspirals

But detecting a single "nearby" CW source is possible too



Courtesy: Paul Demorest

Challenge:

Separating stochastic GW background from experimental noise

Best solution:

Find more millisecond pulsars!

→ Intense hunt ongoing

Summary

Bottom line:

No GW signal detected yet ☹

But

- **Not all initial LIGO/Virgo searches completed**
- **Advanced LIGO / Virgo will bring major sensitivity improvements with orders of magnitude increase in expected event rates**

First LIGO/Virgo discovery likely in next 3-5 years

- **Depends on commissioning progress**
  – unexpected technical obstacles are the worry
- **Also depends on Nature's kindness**

Wild Card: PTAs may see first glimpse of ~nHz GWs on same time scale!

New field of astronomy will open soon – exciting era ahead!