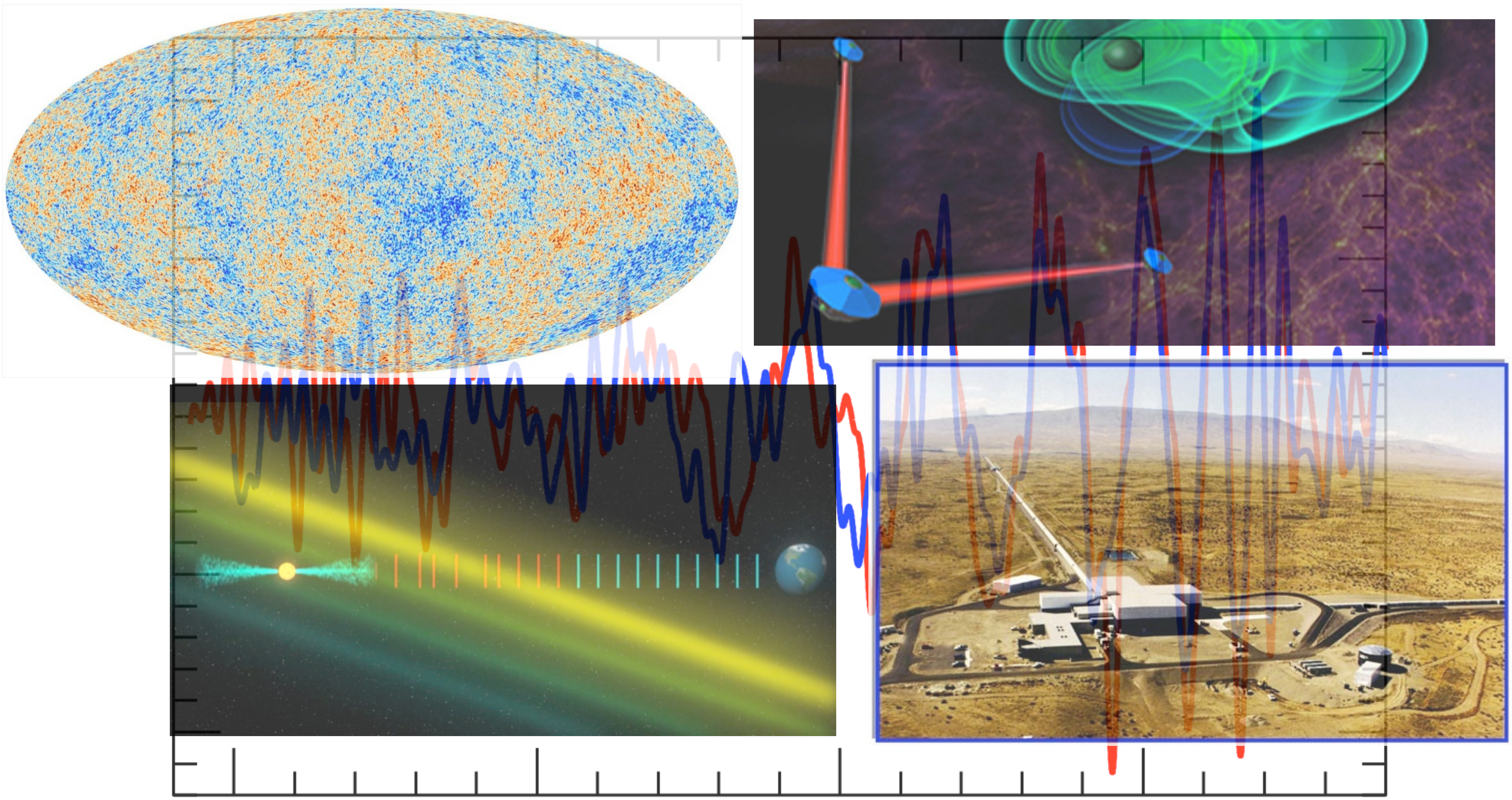
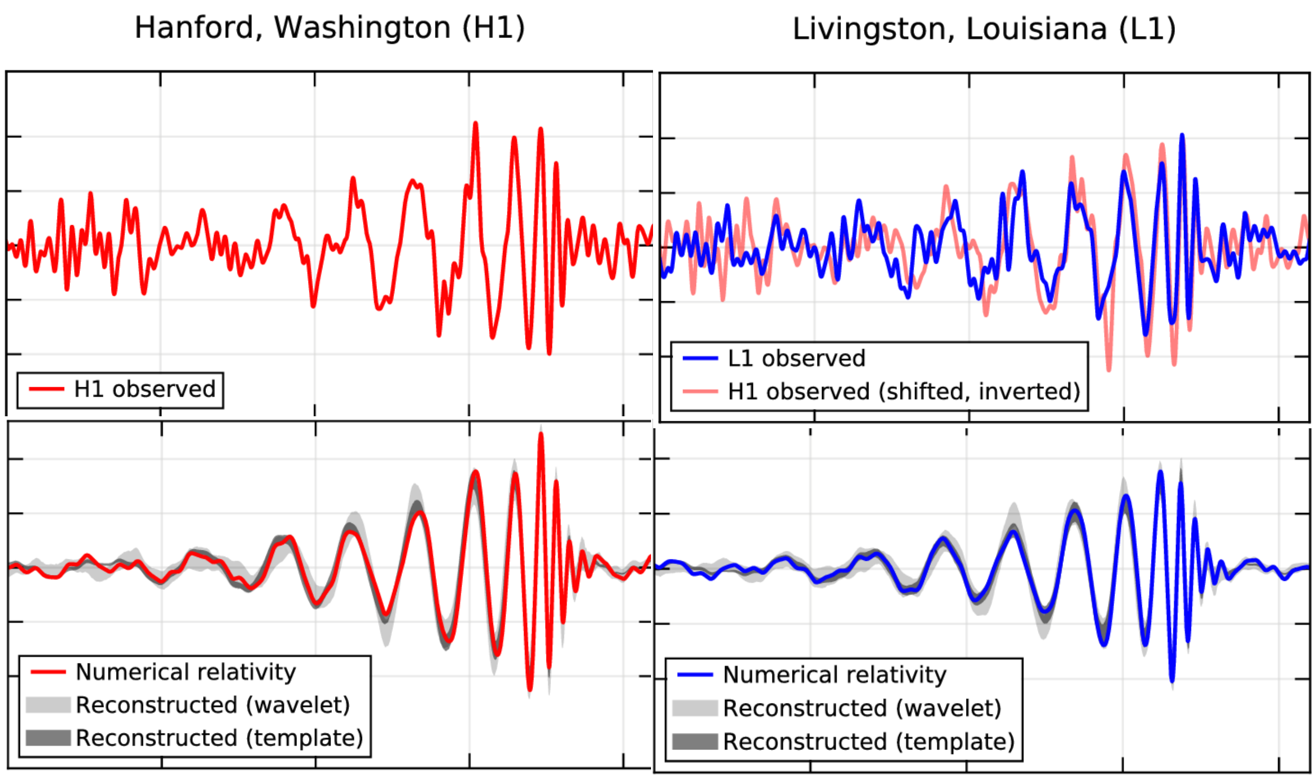
Gravitational wave astronomy



Where do we go from here?

Two black holes: Exemplifies the surprise of opening a new window



$$m_1 = (36 \pm 4)M_\odot$$

$$m_2 = (29 \pm 4)M_\odot$$

$$m_{\rm fin} = (62 \pm 4)M_\odot$$

$$\Delta m = (3 \pm 0.5)M_\odot$$

$$D = (410 \pm 170)\ \mathrm{Mpc}$$

Self aggrandizement

PHYSICAL REVIEW D VOLUME 57, NUMBER 8 15 APRIL 1998

Measuring gravitational waves from binary black hole coalescences. I. Signal to noise for inspiral, merger, and ringdown

Éanna É. Flanagan
Cornell University, Newman Laboratory, Ithaca, New York 14853-5001

Scott A. Hughes
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125
(Received 17 January 1997; published 2 April 1998)

We estimate the expected signal-to-noise ratios (SNRs) from the three phases (inspiral, merger, and ringdown) of coalescing binary black holes (BBHs) for initial and advanced ground-based interferometers (LIGO-VIRGO) and for the space-based interferometer LISA. Ground-based interferometers can do moderate SNR (a few tens), moderate accuracy studies of BBH coalescences in the mass range of a few to about 2000 solar masses; LISA can do high SNR (of order 10^4), high accuracy studies in the mass range of about $10^5 - 10^8$ solar masses. BBHs might well be the first sources detected by LIGO-VIRGO: they are visible to much larger distances—up to 500 Mpc by initial interferometers—than coalescing neutron star binaries (heretofore regarded as the ''bread and butter'' workhorse source for LIGO-VIRGO, visible to about 30 Mpc by initial interferometers). Low-mass BBHs (up to $50M_\odot$ for initial LIGO interferometers, $100M_\odot$ for advanced, $10^6 M_\odot$ for LISA) are best searched for via their well-understood inspiral waves; higher mass BBHs must be searched for via their poorly understood merger waves and/or their well-understood ringdown waves. A matched filtering search for massive BBHs based on ringdown waves should be capable of finding BBHs in the mass range of about $100M_\odot$–$700M_\odot$ out to $\sim$200 Mpc for initial LIGO interferometers, and in the mass range of $\sim 200M_\odot$ to $\sim 3000M_\odot$ out to about $z=1$ for advanced interferometers. The required number of templates is of the order of 6000 or less. Searches based on merger waves could increase the number of detected massive BBHs by a factor of the order of 10 over those found from inspiral and ringdown waves, without detailed knowledge of the waveform shapes, using a noise monitoring search algorithm which we describe. A full set of merger templates from numerical relativity simulations could further increase the number of detected BBHs by an additional factor of up to $\sim$4. [S0556-2821(98)06508-4]

PACS number(s): 04.80.Nn, 04.25.Dm, 04.30.Db, 95.55.Ym

Why such a weak "prediction"

3 Conclusion

"Theoretical" and "observational" merger rates of NS binaries produce similar results if the ejection of CE is highly efficient and nascent neutron stars receive, on average, velocity kicks of the order of $(200 \div 300)\,\mathrm{km\ s^{-1}}$.

The rate of NS mergers is $\sim 2\times10^{-5}\,\mathrm{yr}^{-1}$ for a galaxy with constant astration rate of 4 $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ (and $M_{min} = 0.1\,\mathrm{M}_\odot$ and 100% binarity). This rate is uncertain by a factor of a few mainly due to uncertainties in the kicks velocity distribution and the efficiency of energy deposition into the CE.

Merger rate is mainly determined by the current star formation rate and much less by the star formation history of the Galaxy. The time to coalesce two NS stars is typically a few times 10^8 years.

Extrapolating the Galactic merger rate of NS binaries, we arrive at a detection rate of once every $\sim 200\,\mathrm{yr}$ for the first generation GWR detectors (which are expected to be sensitive up to $\sim 25\,\mathrm{Mpc}$). BH+NS mergers may be registered at the rate comparable with binary NS mergers.

Mergers of BH+BH binaries are not to be expected because the severe mass loss in the stellar winds of their very massive progenitors results in too large for merger orbital separations.

L. Yungelson and S. F. Portegies-Zwart, From "Proceedings of the 2nd Workshop of Gravitational Wave Data Analysis"; astro-ph/9801127.

Not everyone was so worried

PHYSICAL REVIEW D VOLUME 57, NUMBER 8 15 APRIL 1998

Measuring gravitational waves from binary black hole coalescences. I. Signal to noise for inspiral, merger, and ringdown

Éanna É. Flanagan
Cornell University, Newman Laboratory, Ithaca, New York 14853-5001

Scott A. Hughes
Theoretical Astrophysics, California Institute of Technology, Pasadena, California 91125

(Received 17 January 1997; published 2 April 1998)

We estimate the expected signal-to-noise ratios (SNRs) from the three phases (inspiral, merger, and ringdown) of coalescing binary black holes (BBHs) for initial and advanced ground-based interferometers (LIGO-VIRGO) and for the space-based interferometer LISA. Ground-based interferometers can do moderate SNR (a few tens), moderate accuracy studies of BBH coalescences in the mass range of a few to about 2000 solar masses; LISA can do high SNR (of order 10^4), high accuracy studies in the mass range of about 10^5-10^8 solar masses. BBHs might well be the first sources detected by LIGO-VIRGO: they are visible to much larger distances—up to 500 Mpc by initial interferometers—than coalescing neutron star binaries (heretofore regarded as the ''bread and butter'' workhorse source for LIGO-VIRGO, visible to about 30 Mpc by initial interferometers). Low-mass BBHs (up to $50M_\odot$ for initial LIGO interferometers, $100M_\odot$ for advanced, $10^6M_\odot$ for LISA) are best searched for via their well-understood inspiral waves; higher mass BBHs must be searched for via their poorly understood merger waves and/or their well-understood ringdown waves. A matched filtering search for massive BBHs based on ringdown waves should be capable of finding BBHs in the mass range of about $100M_\odot-700M_\odot$ out to $\sim$200 Mpc for initial LIGO interferometers, and in the mass range of $\sim 200M_\odot$ to $\sim 3000M_\odot$ out to about $z=1$ for advanced interferometers. The required number of templates is of the order of 6000 or less. Searches based on merger waves could increase the number of detected massive BBHs by a factor of the order of 10 over those found from inspiral and ringdown waves, without detailed knowledge of the waveform shapes, using a noise monitoring search algorithm which we describe. A full set of merger templates from numerical relativity simulations could further increase the number of detected BBHs by an additional factor of up to $\sim$4. [S0556-2821(98)06508-4]

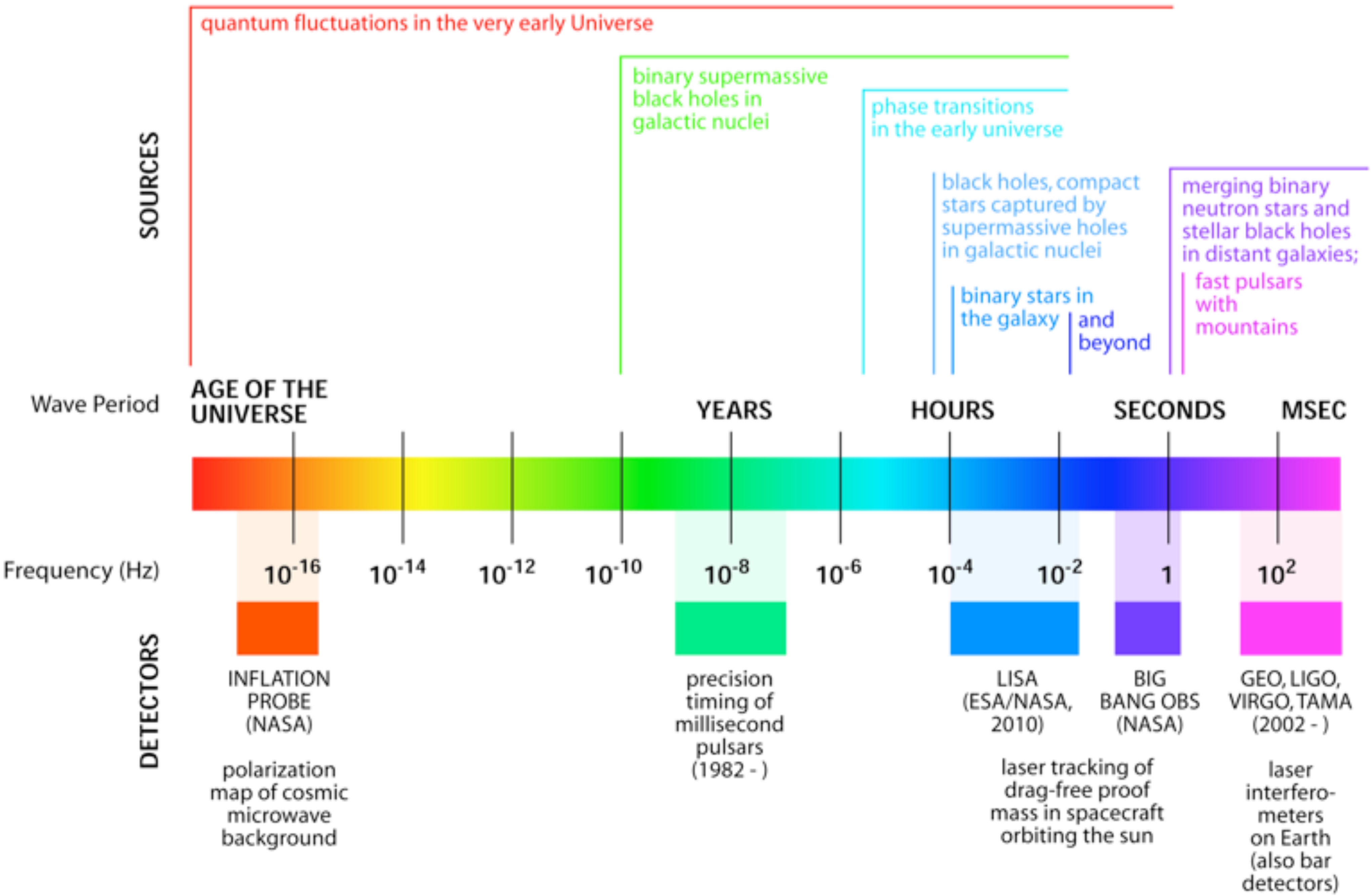
PACS number(s): 04.80.Nn, 04.25.Dm, 04.30.Db, 95.55.Ym

"Dear Scott and Eanna: I think you are going to regret not phrasing this prediction more strongly **when LIGO is regularly measuring merging black holes in about 5 years.**"

(Comment by Kip Thorne on our draft manuscript, sometime in late *1996*.)

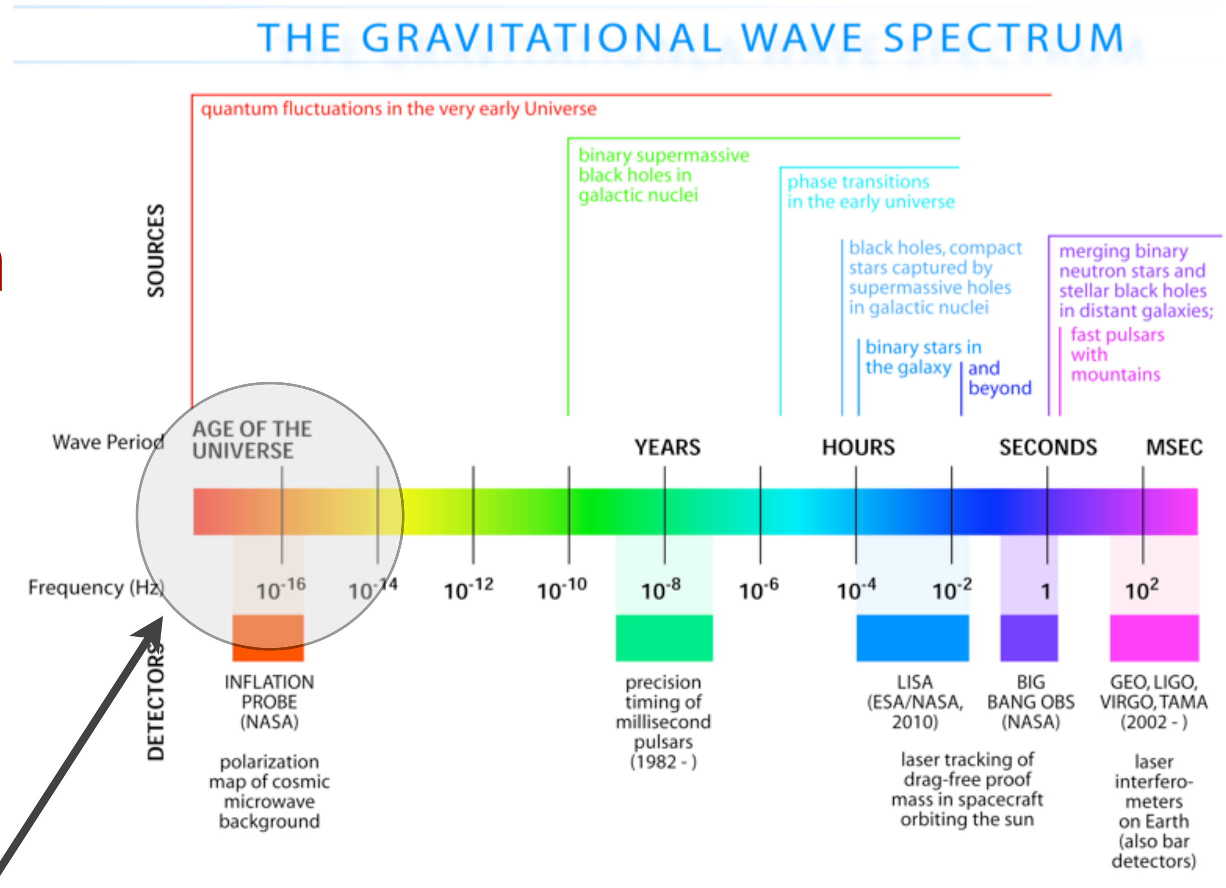
(See also papers by K. Belczynski: Considered binary black holes as early as 2004; predicted masses similar to GW150914 in 2010.)

THE GRAVITATIONAL WAVE SPECTRUM



Programs to measure GWs

How you measure waves depends on where in spectrum you are probing.



Lowest frequency (longest wavelength): Best detector is plasma at recombination epoch. GW's tidal pattern on plasma density leaves unique signature in polarization of photons that begin free-streaming at that time.

Hubble-scale GWs

More specifically: On longest scales, use fact that the polarization of the CMB can be decomposed by parity:

Image by Seljak and Zaldarriaga
http://wwwphy.princeton.edu/cosmology/capmap/polscience.html

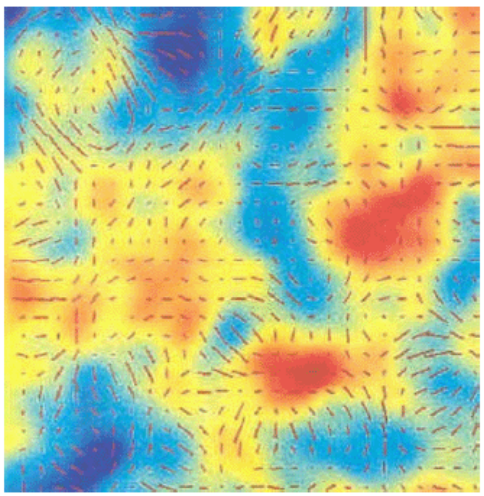
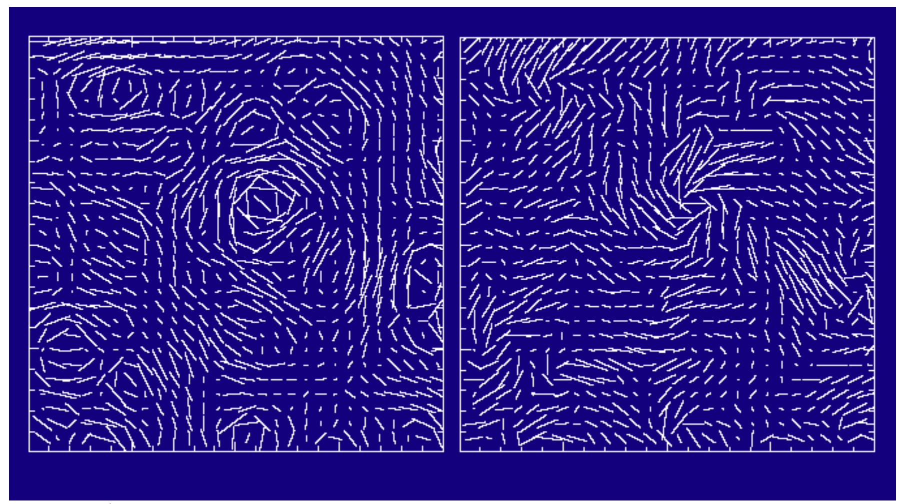


Image by Wayne Hu
http://background.uchicago.edu/~whu/intermediate/Polarization/polar5.html



Even parity polarization modes

Odd parity polarization modes

Hubble-scale GWs

More specifically: On longest scales, use fact that the polarization of the CMB can be decomposed by parity:

Image by Seljak and Zaldarriaga
http://wwwphy.princeton.edu/cosmology/capmap/polscience.html

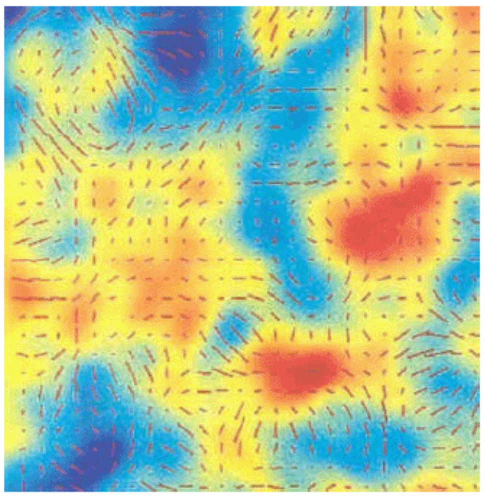
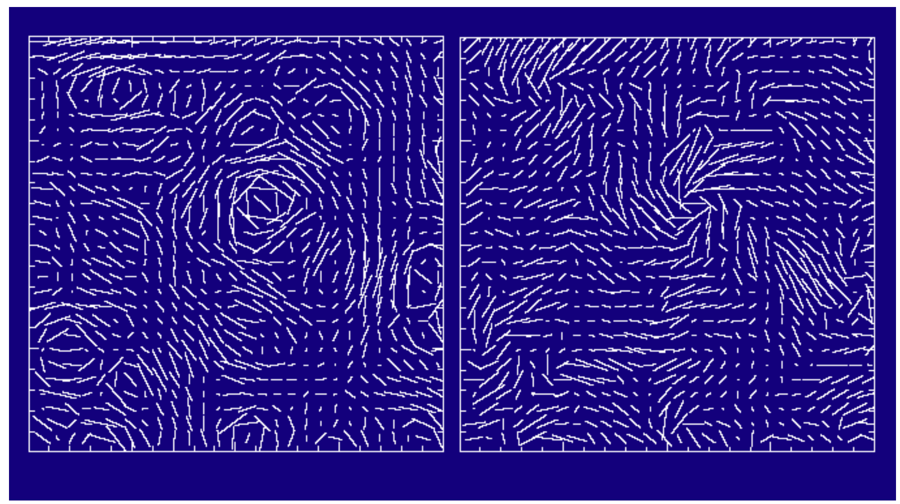


Image by Wayne Hu
http://background.uchicago.edu/~whu/intermediate/Polarization/polar5.html



Even parity (*E*-modes): Sourced by fluctuations in inflaton (with a subdominant contribution from spacetime fluctuations — ie, GWs).

Hubble-scale GWs

More specifically: On longest scales, use fact that the polarization of the CMB can be decomposed by parity:

Image by Seljak and Zaldarriaga
http://wwwphy.princeton.edu/cosmology/capmap/polscience.html

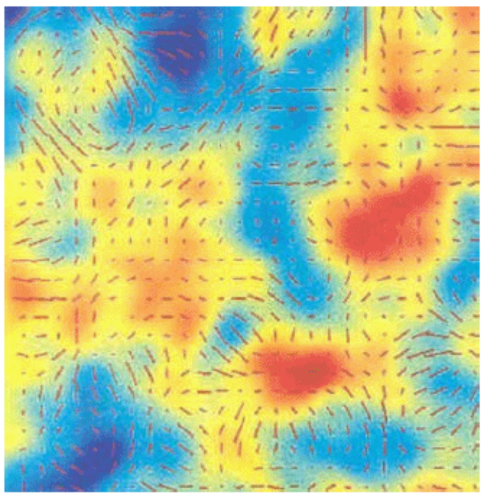
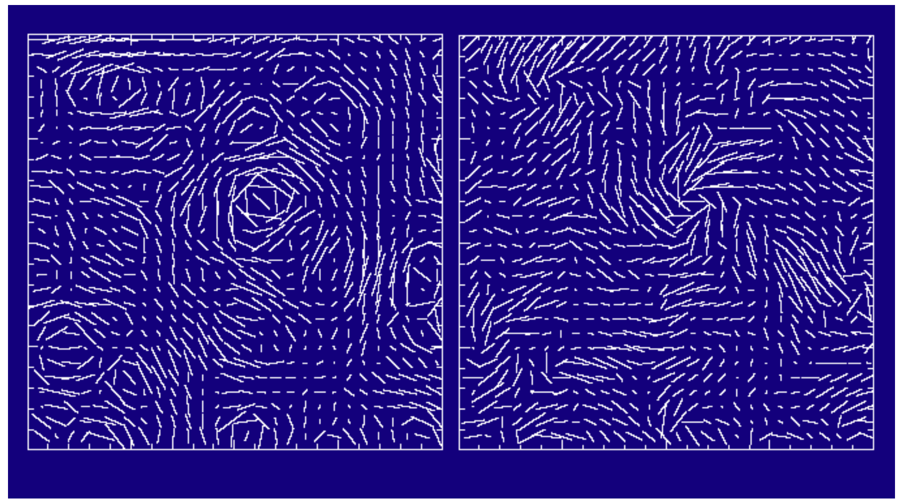


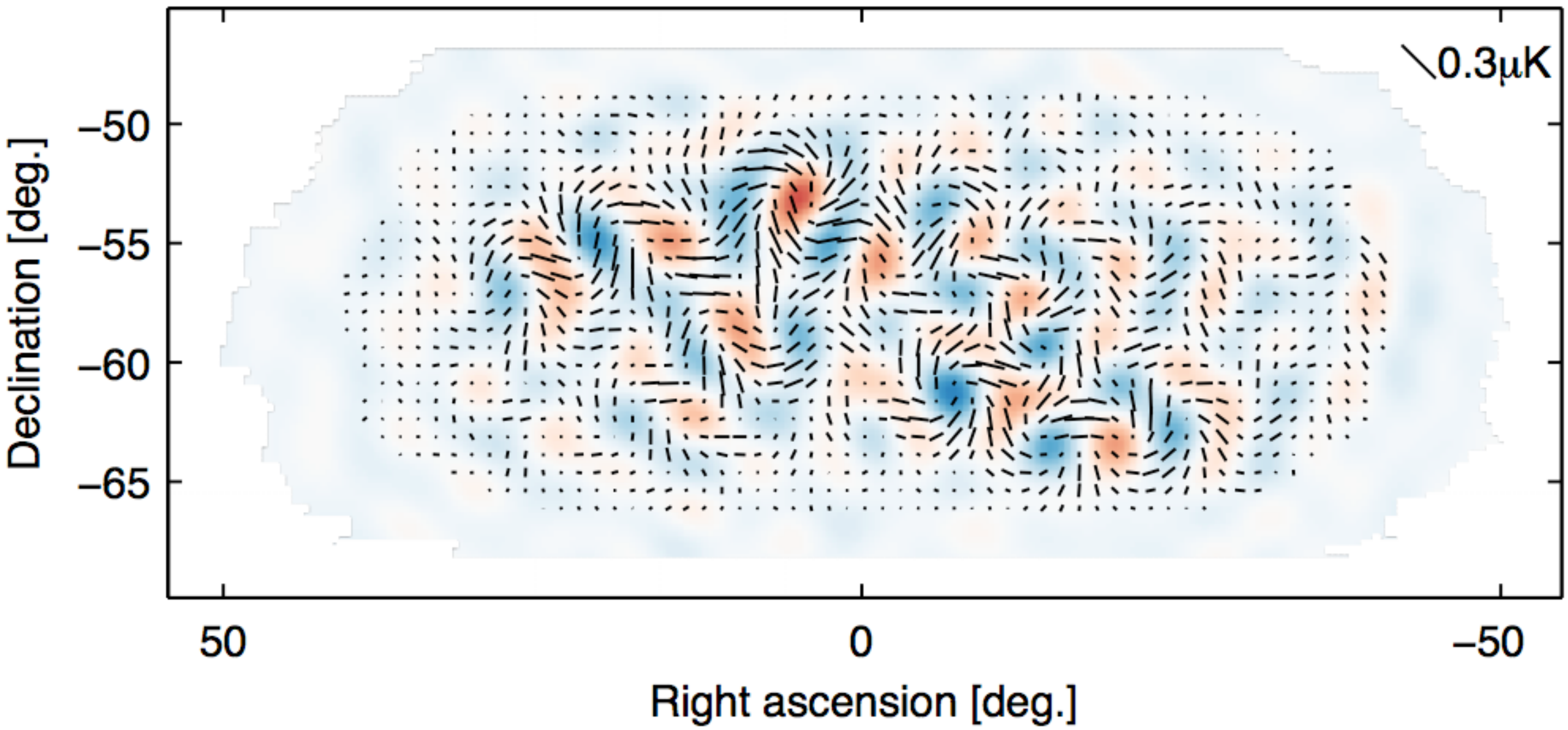
Image by Wayne Hu
http://background.uchicago.edu/~whu/intermediate/Polarization/polar5.html



Odd parity (*B*-modes): *Fundamentally* arise only from spacetime fluctuations — GWs.

(Plus foreground “noise” from gravitational lensing: Turns *E*-modes into *B*-modes. Signal describing mass distribution ... but noise for GWs.)

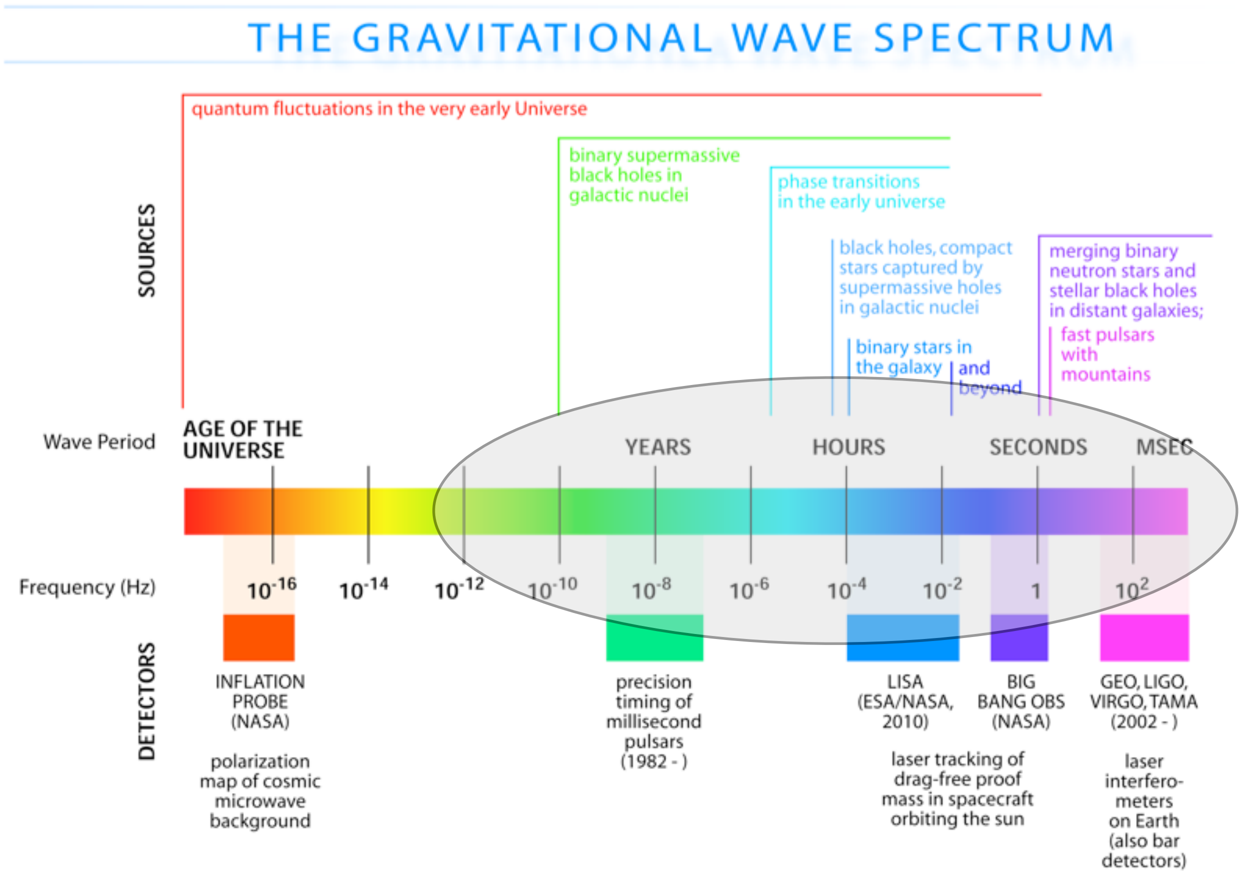
Premature announcement by BICEP II: Illustrates challenge



B-modes seen with significant excess vs lensing of E-modes … but did not properly account for systematic noise due to polarized dust emission.

Programs to measure GWs

How you measure waves depends on where in spectrum you are probing.



All other bands: Goal is to look for minute effect of coherent space-time oscillations.

Nature of gravitational waves

The leading radiation must be *quadrupolar*:

$$h_{ij} = \frac{2}{D}\frac{G}{c^4}\left(\frac{d^2 I_{ij}}{dt^2}\right)^{\mathrm{TT}} \qquad I_{ij} = \int \rho(\mathbf{x}) x_i x_j \, d^3x'$$

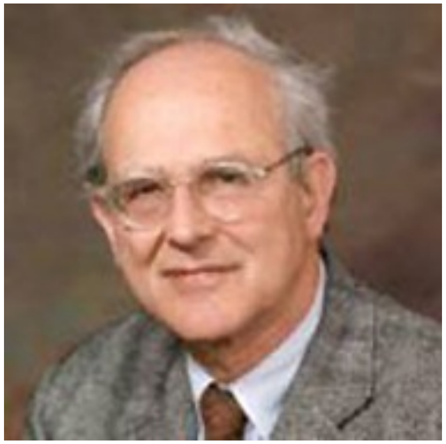
(Lower moments cannot radiate due to conservation laws.)

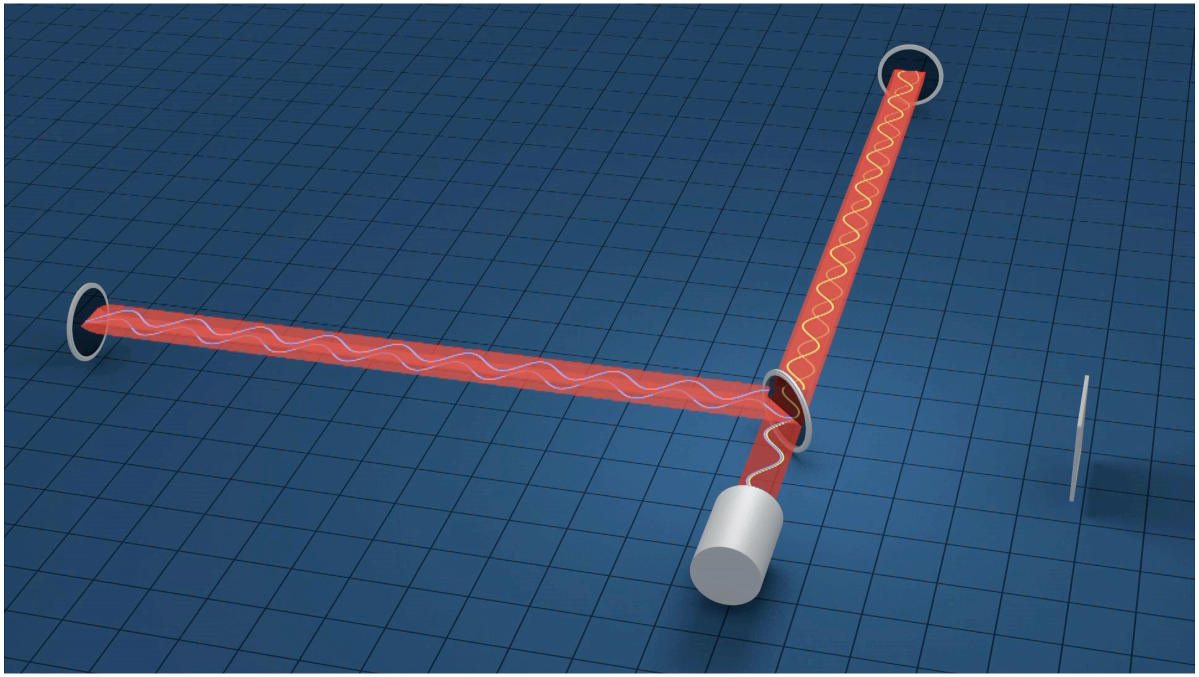
Size of typical component *h* related to source mass, distance, and speed of non-spherical dynamics:

$$h \sim \left(\frac{v_{\mathrm{NS}}}{c}\right)^2 \left(\frac{GM/c^2}{D}\right) \sim 10^{-15} - 10^{-23}$$

Measuring a 10^{-22} level effect

1972: Weiss showed that this can be done using ***laser interferometry***: resolve 10^{-12} of wavelength, pick up oscillations due to GW influence.





Phase shift due to GW:

$$\Delta\Phi_{\rm GW} \simeq 2\mathcal{F} \times (hL) \times \frac{2\pi}{\lambda_{\rm laser}}$$

Phase error due to noise:

$$\Delta\Phi_{\rm noise} \simeq \frac{1}{\sqrt{N_{\rm phot}}}$$

GW wins if $P_{\rm laser} \gtrsim 100$ Watts.

Scale of noise

Waves have a tidal action on distant masses. Can convert *strain* of GW to a tidal *force* ... gives a good sense of challenge for isolating measurement from impact of noise:

$$F \simeq mRL$$

Magnitude of tidal force

Mass of test masses

Riemann curvature of GW

Separation of test masses

Scale of noise

Waves have a tidal action on distant masses. Can convert *strain* of GW to a tidal *force* ... gives a good sense of challenge for isolating measurement from impact of noise:

$$F \simeq mRL$$

Plug in

$$R \simeq (2\pi f)^2 h$$

Scale of noise

Waves have a tidal action on distant masses. Can convert *strain* of GW to a tidal *force* ... gives a good sense of challenge for isolating measurement from impact of noise:

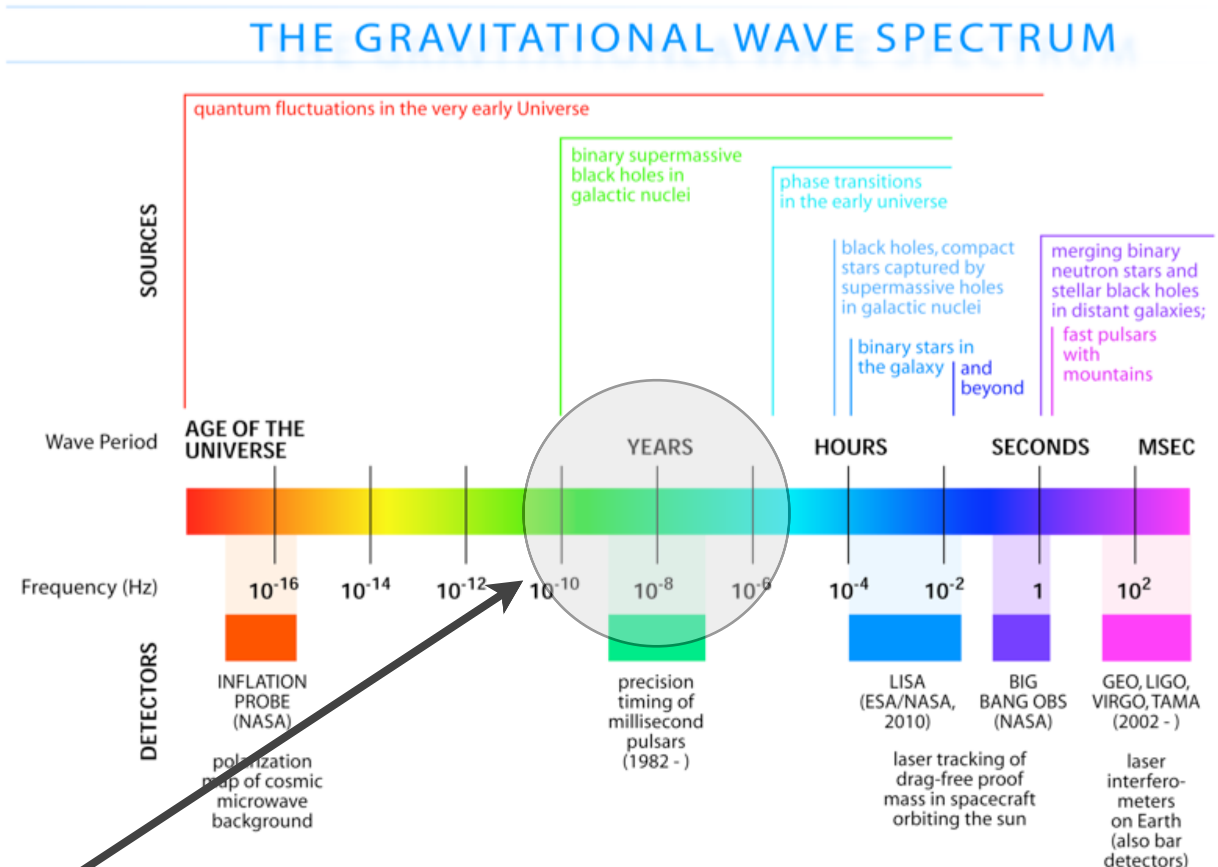
$$F \approx 5\,\mathrm{piconewton}\left(\frac{m}{40\,\mathrm{kg}}\right)\left(\frac{f}{100\,\mathrm{Hz}}\right)^2\left(\frac{4000\,\mathrm{m}}{L}\right)\left(\frac{h}{10^{-22}}\right)$$

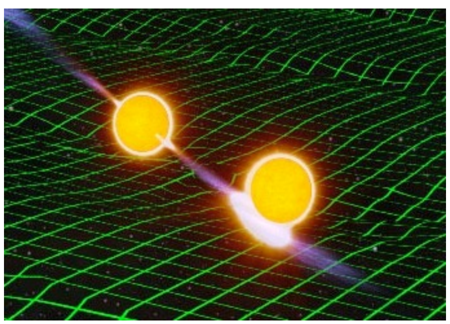
... small, but not ridiculous! Comparable to the weight of an animal cell.

Measuring GWs requires isolating from forces of this magnitude in chosen frequency band.

Programs to measure GWs

How you measure waves depends on where in spectrum you are probing.

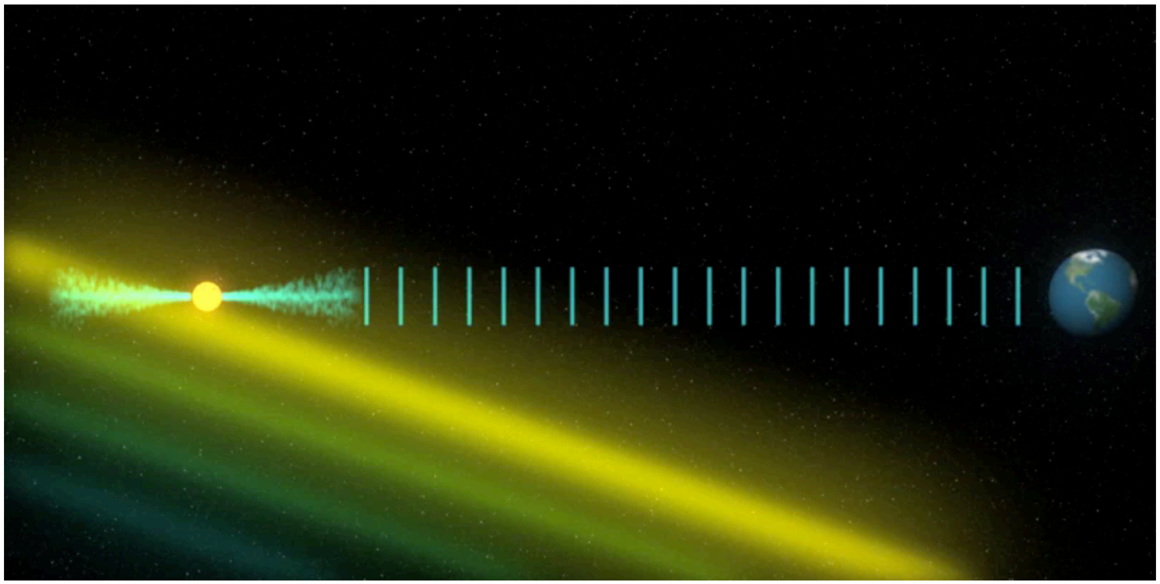




Year periods: Millisecond pulsars as light source, radio telescope as receiver. Enough pulsars & control of timing noise, can detect waves.

Pulsar Timing Arrays (PTAs)

Uses a network of pulsars with properties sufficiently well understood that they can be used as clocks to detect GWs with periods of months to years:



Movie courtesy Penn State Gravitational Wave Astronomy Group, http://gwastro.org

Presently monitoring 49 pulsars, have set upper limit on a "stochastic background" of waves in this frequency band.

Merging massive black holes

Prime source in this band: Binary black holes that form through the merger of their host galaxies.

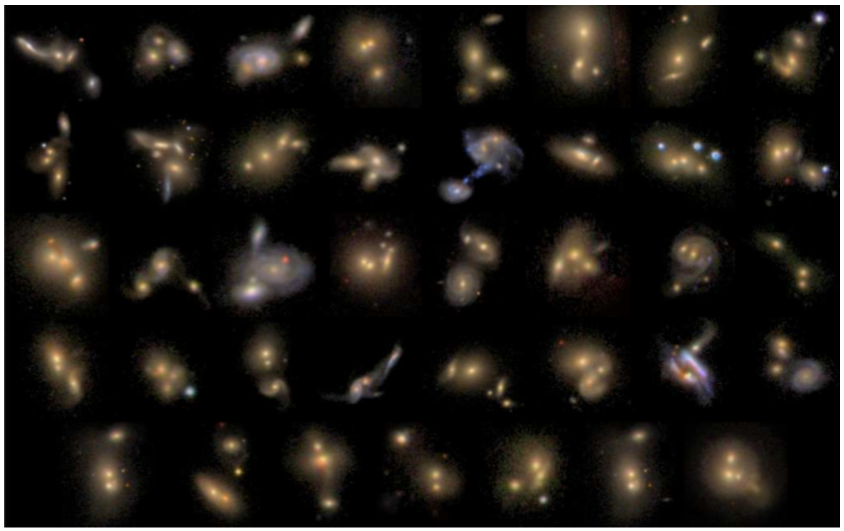
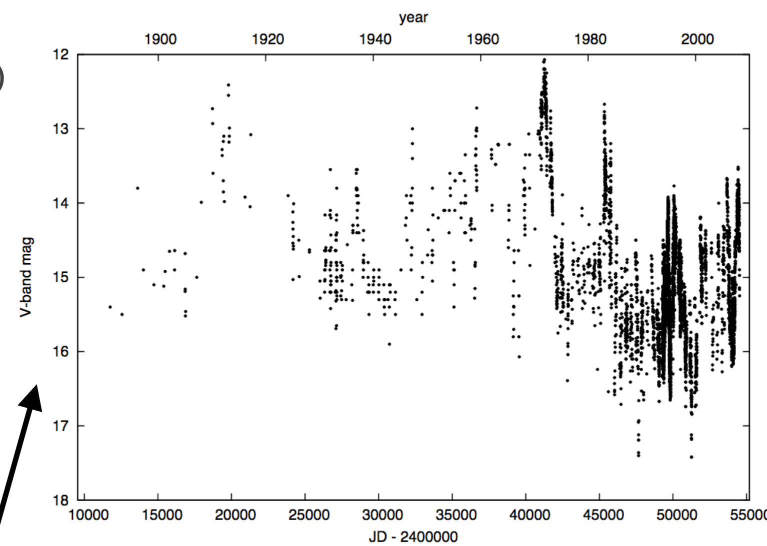


Image: blog.galaxyzoo.org

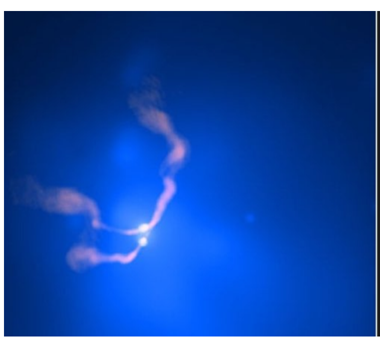
Merging galaxies are common; black holes in galaxy cores appear to be ubiquitous.

Periodic (~12 yr) outbursts from blazar OJ 287

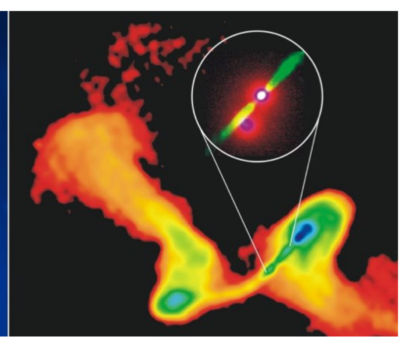
[Valtonen et al, *Nature* **452**, 851 (2008)]



Some double black holes tentatively identified



3C75 x-ray/radio composite



NGC326 radio image

Merging massive black holes

Prime source in this band: Binary black holes that form through the merger of their host galaxies.

$$h_c^2(f) = \int \frac{dN}{dz\, dM\, dq\, d(\ln f)} h_s^2\, dz\, dM\, dq$$

Measured wave strain at frequency *f*

Number of sources per unit redshift, mass, mass ratio, and frequency band.

Single source wave strain

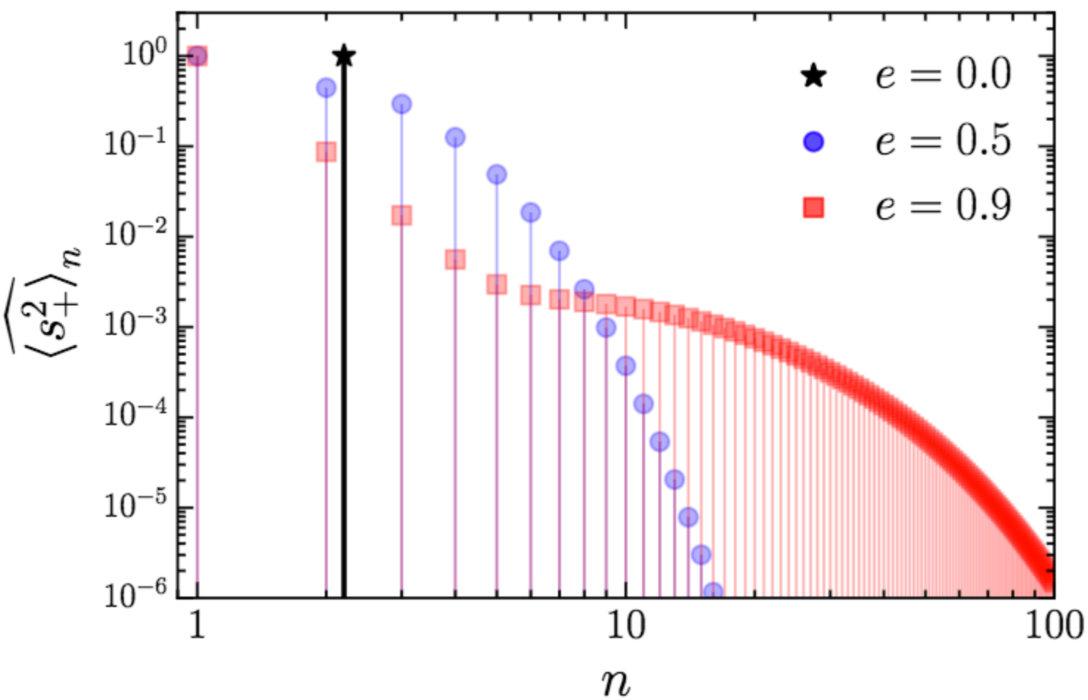
No detection so far … but measurements have ruled out the simplest possible models (isotropic & homogeneous population, circular orbits, purely GW-driven evolution during the late inspiral).

Merging massive black holes

Prime source in this band: Binary black holes that form through the merger of their host galaxies.

$$h_c^2(f) = \int \frac{dN}{dz\,dM\,dq\,d(\ln f)} h_s^2\,dz\,dM\,dq$$

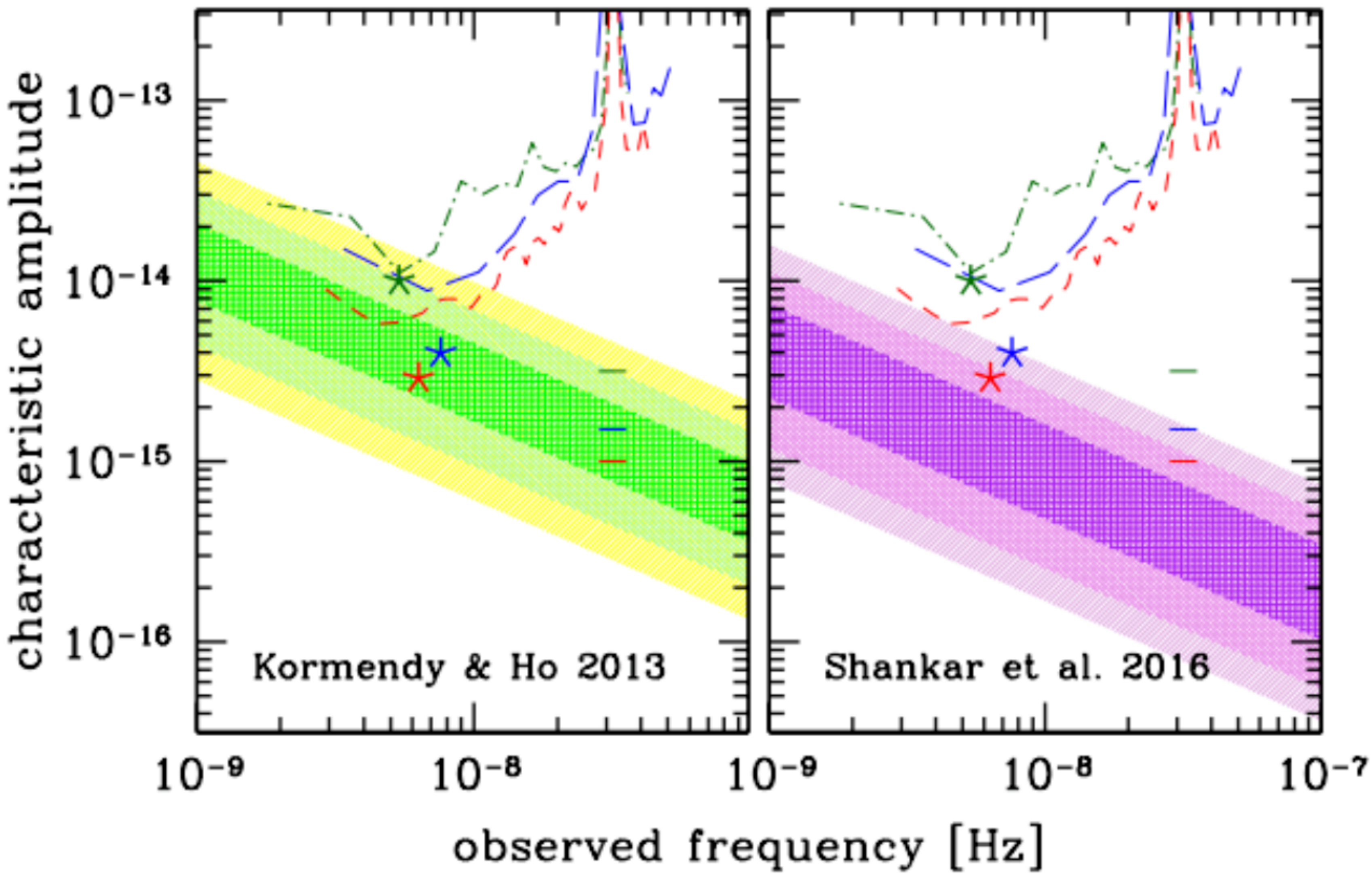
Taylor, Huerta, Gair, McWilliams, Astrophys. J. **817**, 1 (2016).



Example of how relaxing assumptions changes the model: Wave power redistributed by orbital harmonic going from circular to eccentric orbits.

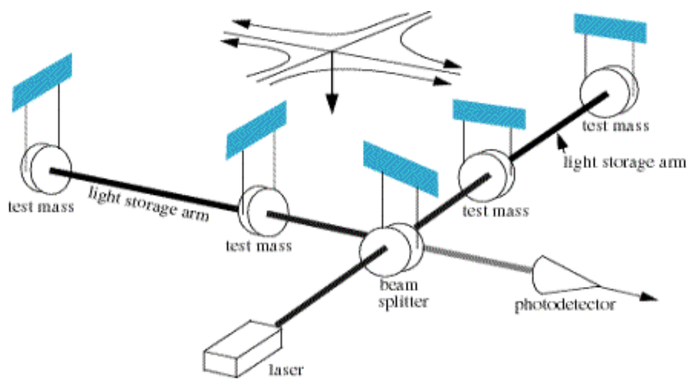
Merging massive black holes

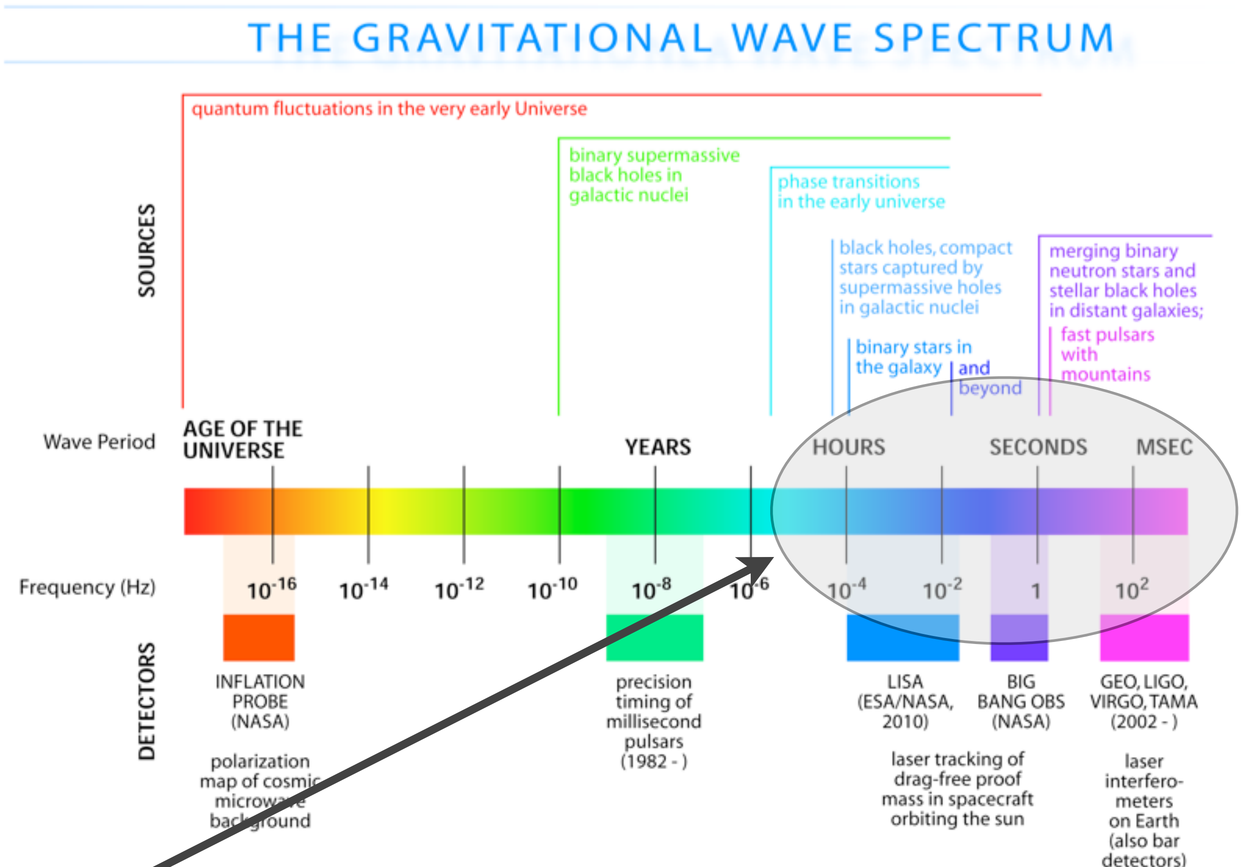
Prime source in this band: Binary black holes that form through the merger of their host galaxies.



Programs to measure GWs

How you measure waves depends on where in spectrum you are probing.





Hours to millisecond periods: Laser interferometry on freely falling or suspended test masses.

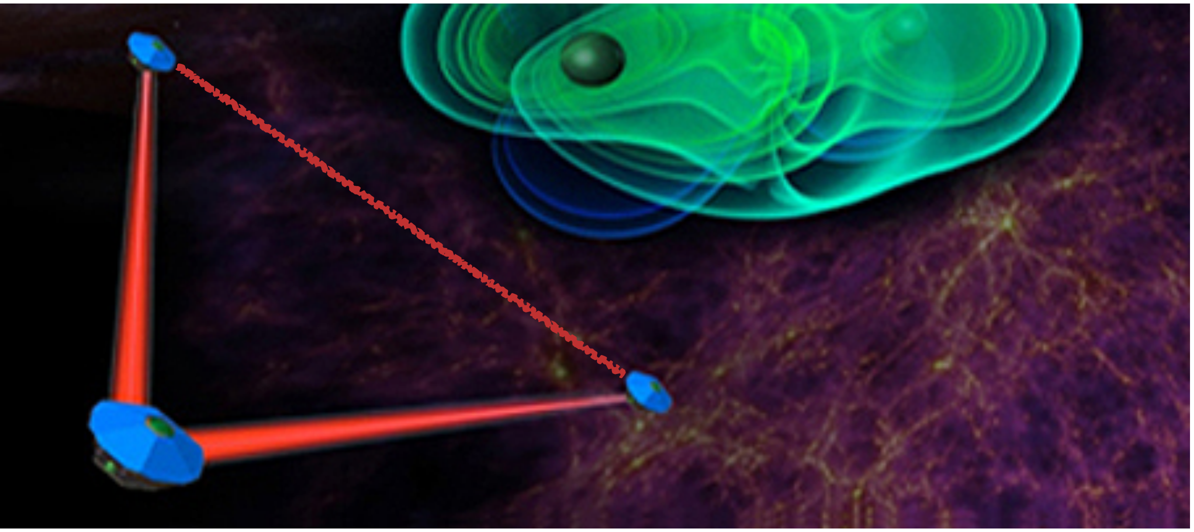
Ground-based detectors

Three large-scale facilities operating: Hanford, WA & Livingston, LA (LIGO); and Pisa, Italy (Virgo).

Arms of length 3 km (Virgo) or 4 km (LIGO). Sensitive in band ~10 Hz < f < (a few) kHz.

Talk by Bruce Allen

Space-based detectors: LISA



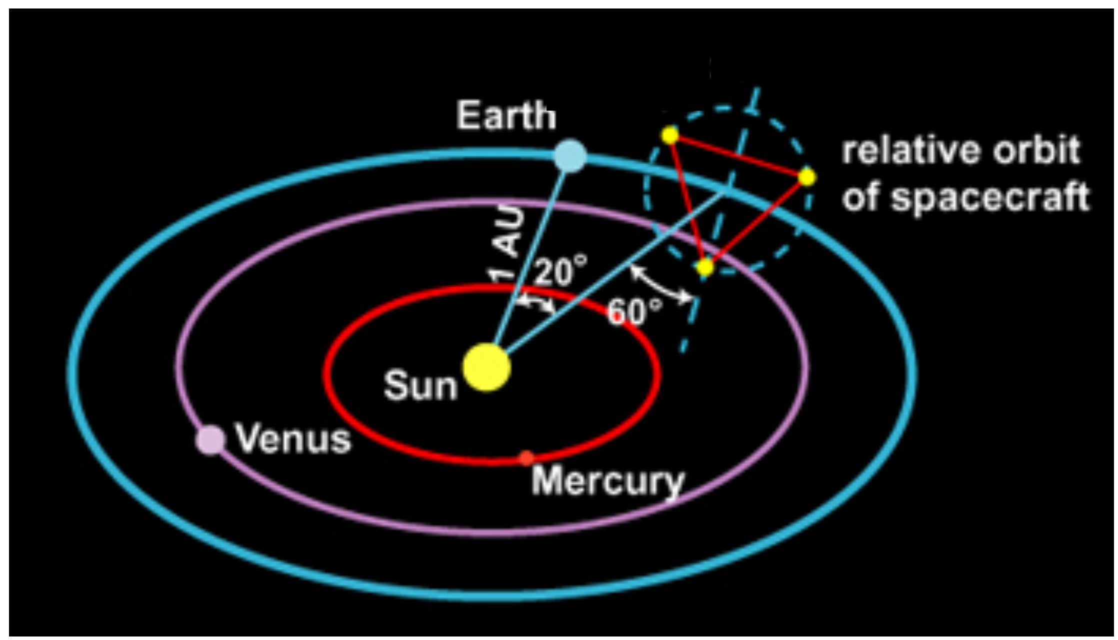
Several million km interferometer antenna in space.

ESA mission … details in flux. Working for NASA involvement.

Go to space to escape low-frequency noise: sensitive in band

$\sim 3\times10^{-5}$ Hz < f < 1 Hz

A **target-rich** frequency band.



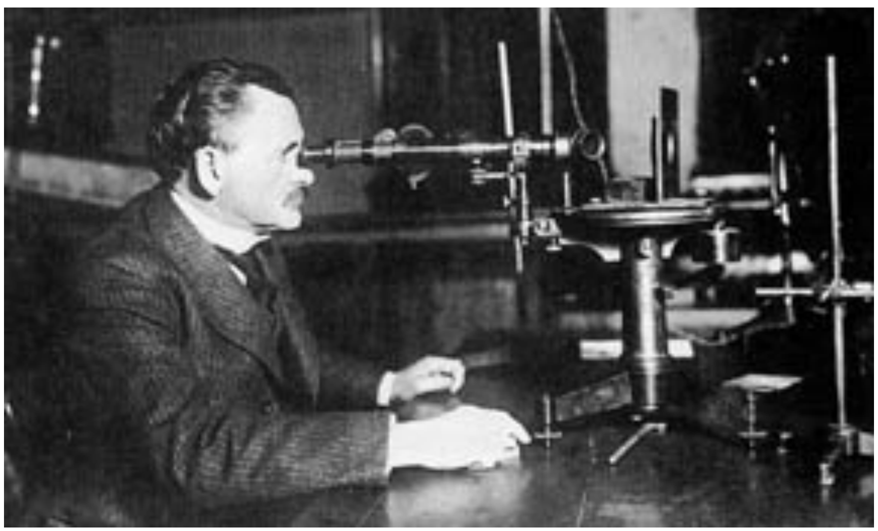
LISA metrology

Thanks to its much longer arms, effect of a GW is relatively large:

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

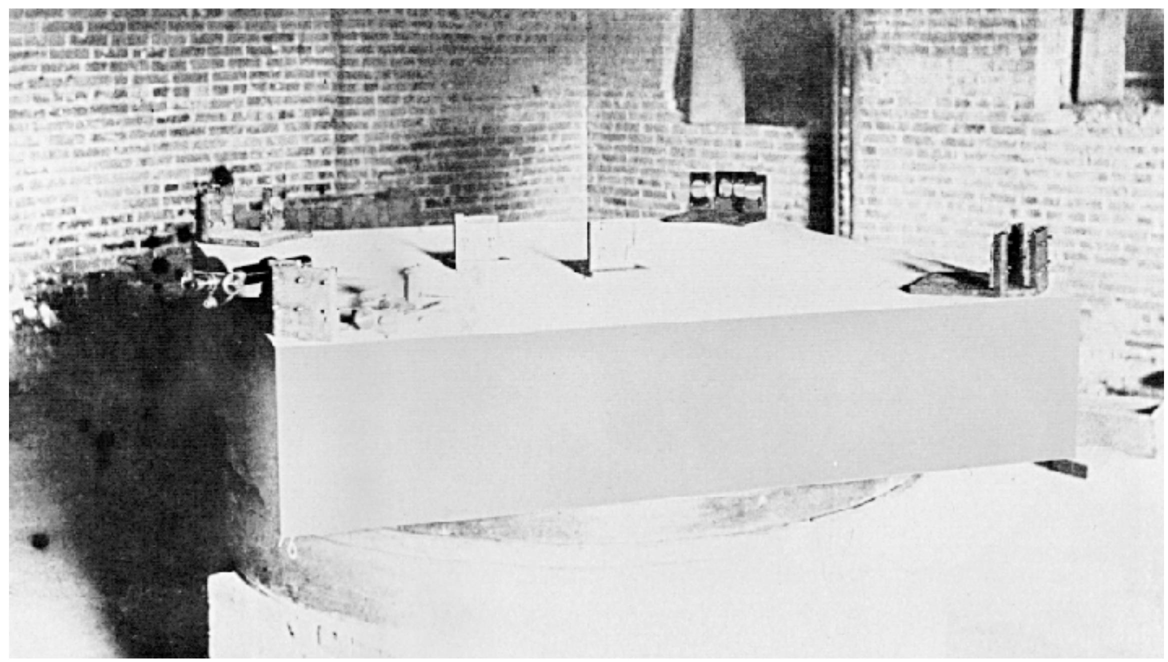
Ground: $h \lesssim 10^{-21}$, $L \sim$ kilometers: $\Delta L \lesssim 10^{-3}$ fm

Space: $h \lesssim 10^{-20}$, $L \sim 10^6$ kilometers: $\Delta L \lesssim 10$ pm



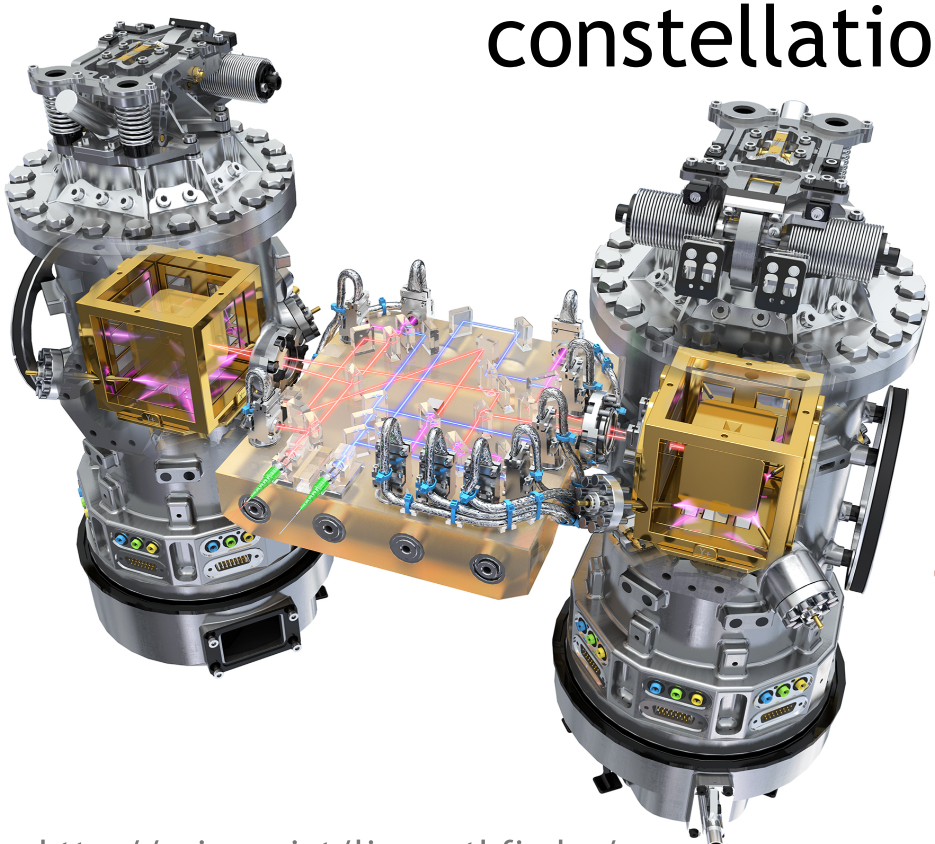
Measured at DC by eye.

About an order of magnitude from fringe shift of original Michelson interferometer.



LISA noise

Far more challenging: Ensuring the noise budget can be met for each element of a free-flying constellation of spacecraft.



http://sci.esa.int/lisa-pathfinder/

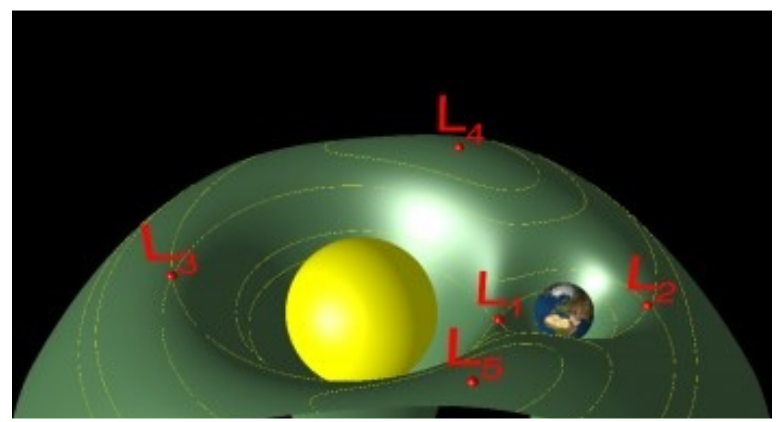
LISA Pathfinder: Testbed for technologies to demonstrate that free fall, control, and metrology can be done with the precision needed for LISA.

LISA noise

Far more challenging: Ensuring the noise budget can be met for each element of a free-flying constellation of spacecraft.

LISA Pathfinder**:** Testbed for technologies to demonstrate that free fall, control, and metrology can be done with the precision needed for LISA.

Launched: 3 Dec 2015
Arrived at L1: 22 Jan 2016
Began science operations: 8 Mar 2016



LISA noise

Far more challenging: Ensuring the noise budget can be met for each element of a free-flying constellation of spacecraft.

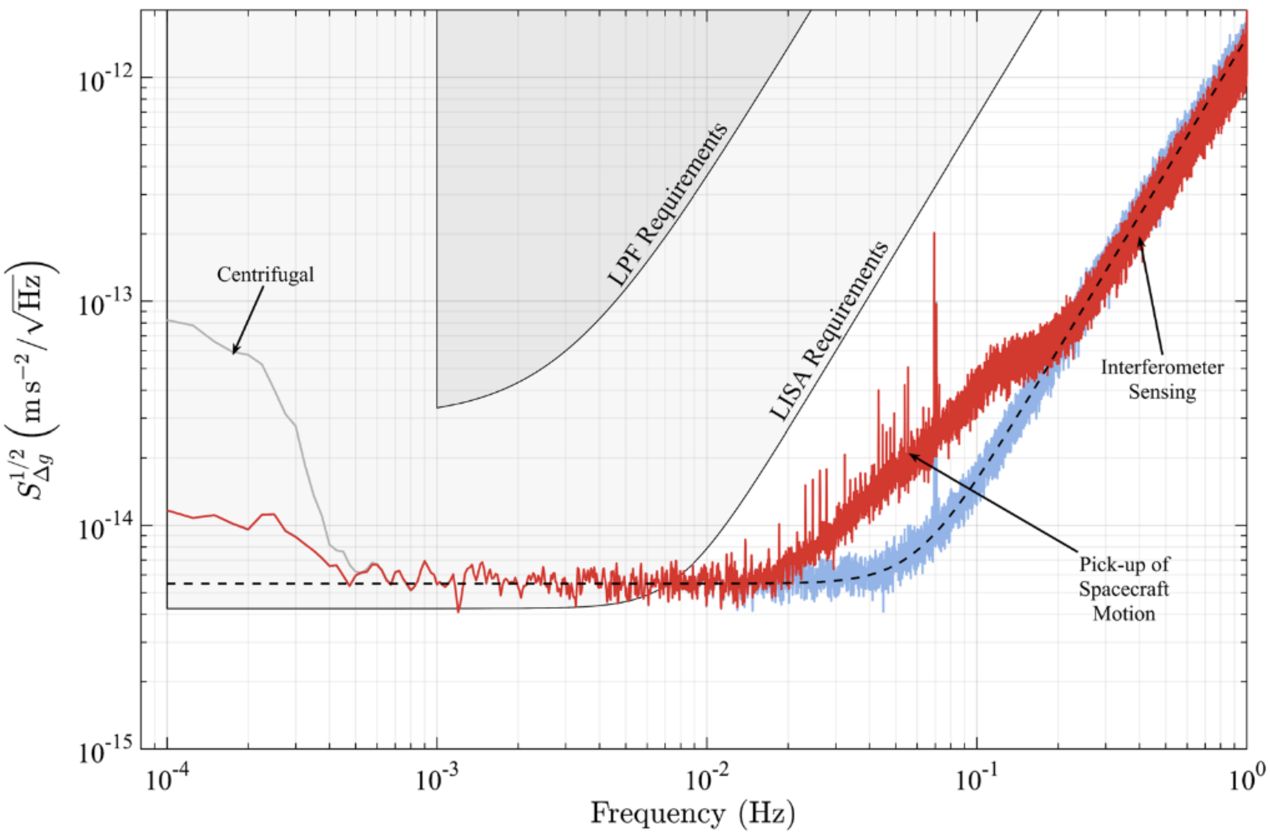


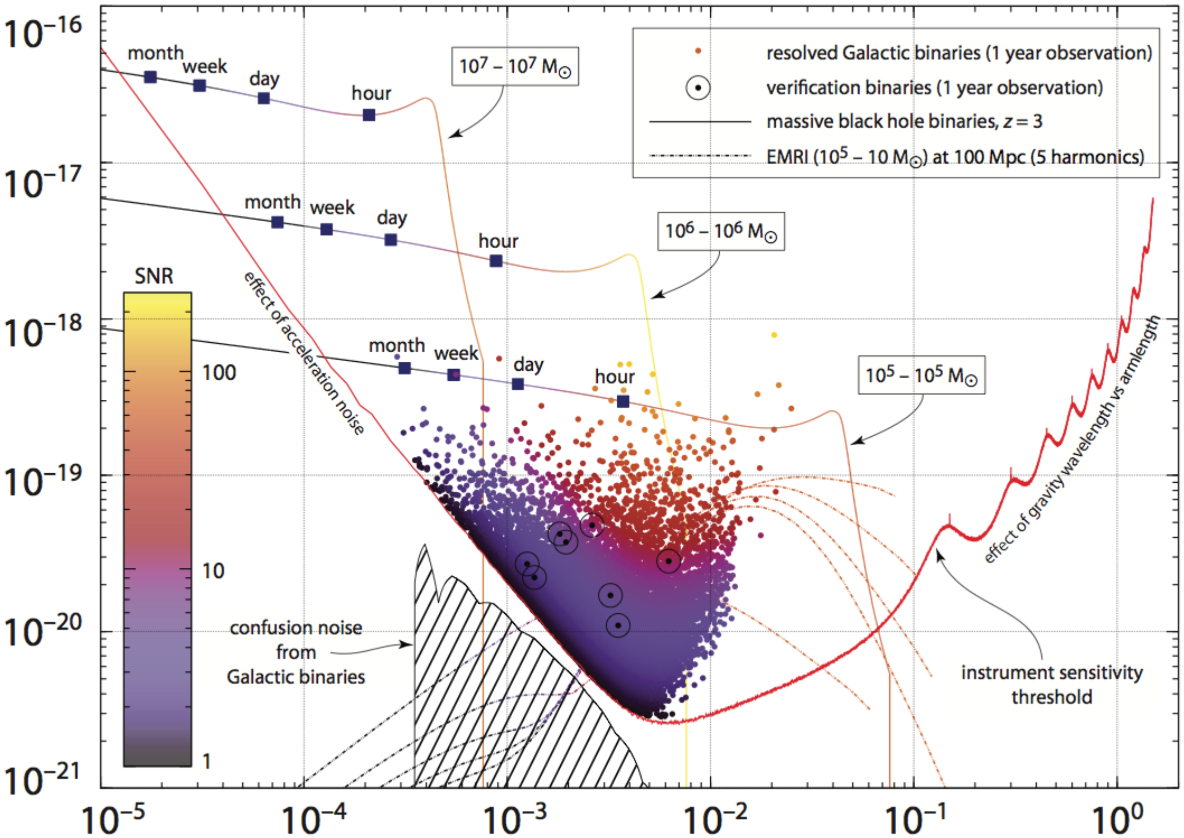
Figure 1 of Armano et al, Phys. Rev. Lett. **116**, 231101 (2016).

Results significantly exceeded mission specifications.

LISA is now within reach.

LISA sources and science

A wide range of sources generate gravitational waves with periods of minutes to hours.



Massive black hole binaries: Form as consequence of the hierarchical galaxy growth, in band for months to years.

Extreme mass ratio binaries: Capture of stellar-mass compact body by massive black hole; also in band for months to years.

Compact binaries: Stellar mass binaries in our galaxy (low masses) to z ~ 0.1 (high mass).

Processes in the early universe

Early universe

Early universe phase transitions produce GWs by a variety of mechanisms (e.g., domain wall collisions, sound waves, MHD turbulence) … wave frequency determined by energy scale of transition.

$$f_{\rm GW} \sim (1.5 - 3) \times 10^{-4}\,{\rm Hz} \times \left(\frac{T_*}{1\,{\rm TeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

Transition at ~TeV: waves right in LISA band!

Wave strength characterized by energy density in frequency band:

$$\Omega_{\rm GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{\rm GW}}{d\ln f} = \frac{2\pi^2}{3H_0^2} f^2 h_c^2(f)$$

Early universe

Early universe phase transitions produce GWs by a variety of mechanisms (e.g., domain wall collisions, sound waves, MHD turbulence) … wave frequency determined by energy scale of transition.

$$f_{\rm GW} \sim (1.5 - 3) \times 10^{-4}\,{\rm Hz} \times \left(\frac{T_*}{1\,{\rm TeV}}\right)\left(\frac{g_*}{100}\right)^{1/6}$$

Transition at ~TeV: waves right in LISA band!

Fold in LISA noise characteristics:

$$\Omega_{\rm GW}(f) \ge 10^{-12} - 10^{-13}$$

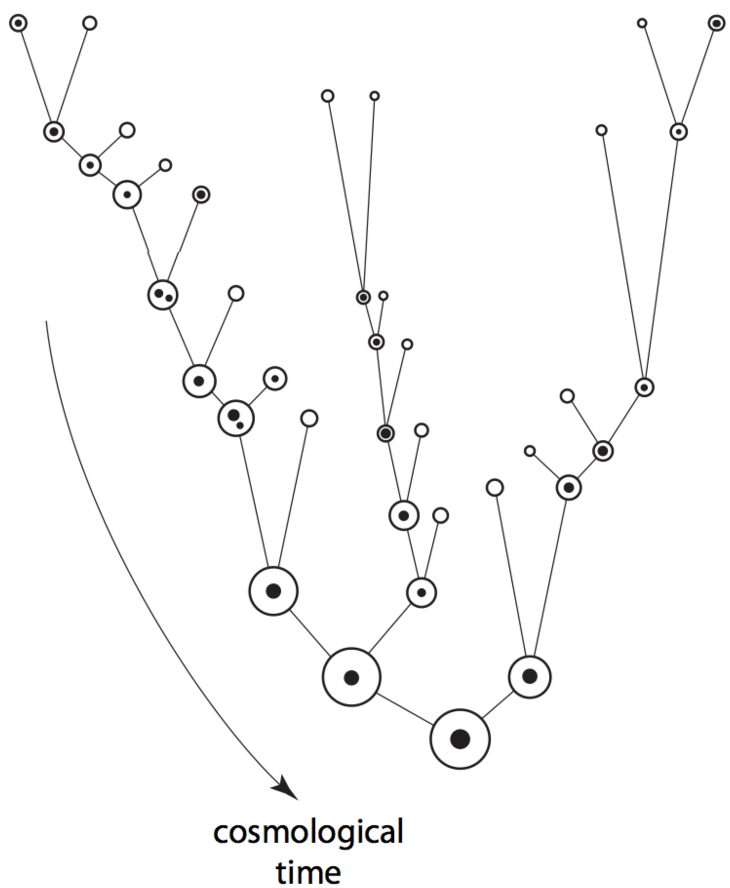
Sensitive enough to probe and set constraints on a wide range of BSM scenarios

[Caprini et al, JCAP **4**, 001 (2016)]

Massive black hole science

Galaxies were built hierarchically: Big galaxies assembled through repeated mergers of subunits.

Evidence from quasars tells us that black holes have existed since the earliest cosmic times.



Combining these facts indicates that massive black hole mergers should be common over the history of the universe. Events with masses

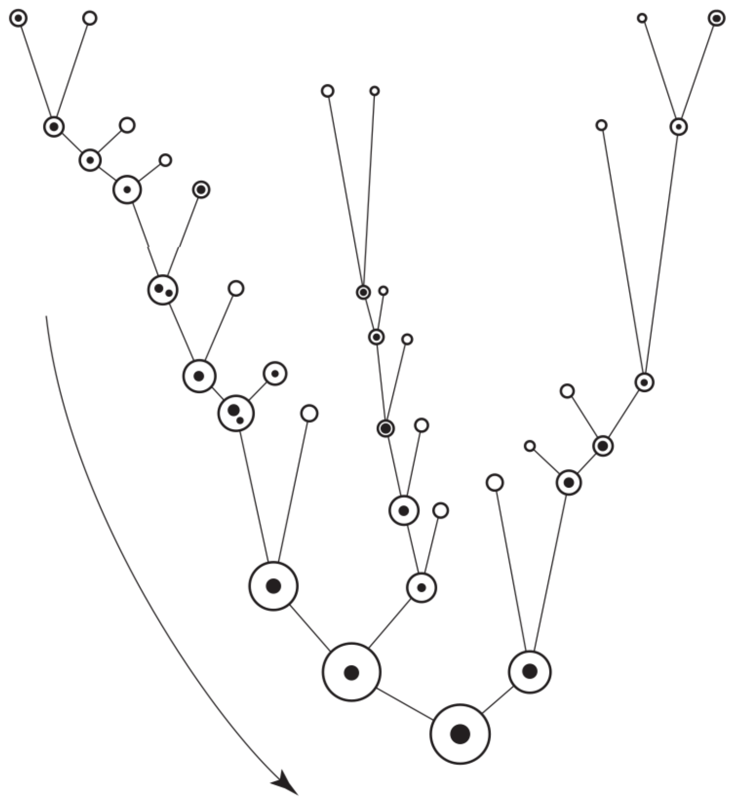
(a few) $10^4 \leq (1 + z)\ M/M_{sun} \leq$ (a few) 10^7

they will be in band of a space-based low-f detector, and detectable out to $z \sim 15$.

Massive black hole science

Galaxies were built hierarchically: Big galaxies assembled through repeated mergers of subunits.

Evidence from quasars tells us that black holes have existed since the earliest cosmic times.



Black holes quite different from pulsar timing array black holes!

PTA: $M_{\rm typical} \sim 10^8 - 10^9\ M_{\rm sun}$, $z \sim 0.1$—1

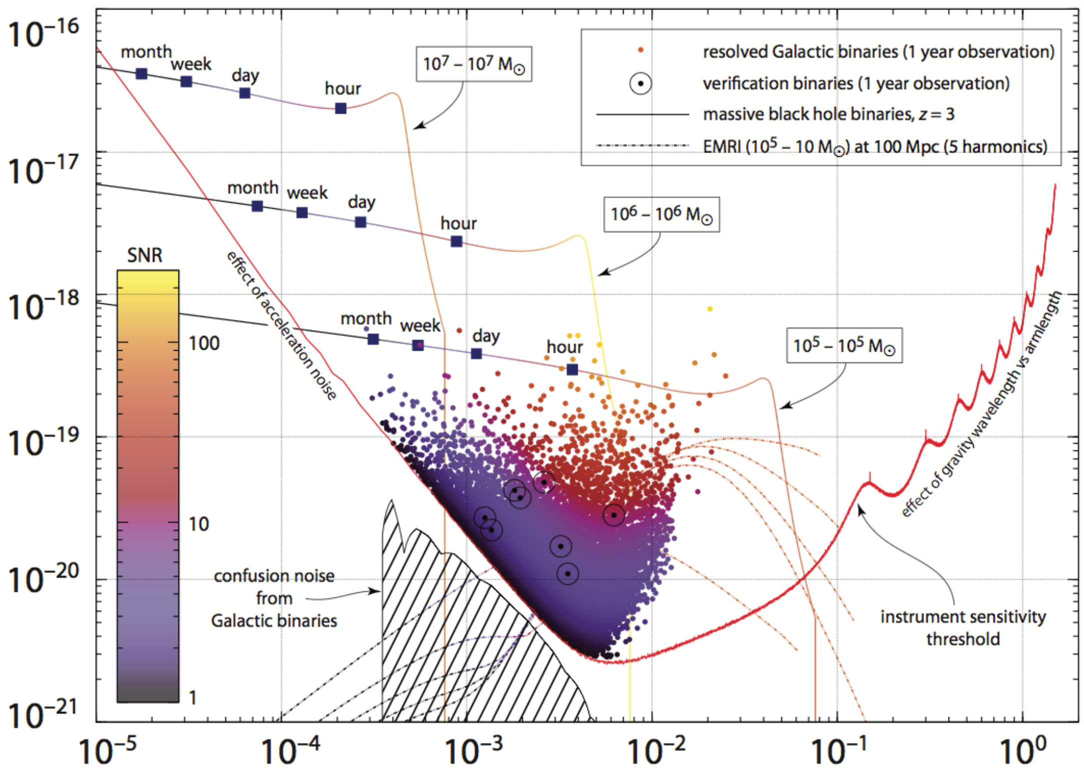
"Mature," nearby black holes in cores of late-type galaxies; fossils of quasars and AGN.

LISA: $M_{\rm typical} \sim 10^4 - 10^7\ M_{\rm sun}$, $z \sim 1$—15

Seeds of black holes seen in galaxies like Milky Way … measurement traces the assembly of black holes and the galaxies that host them.

Massive black hole science

Galaxies were built hierarchically: Big galaxies assembled through repeated mergers of subunits.



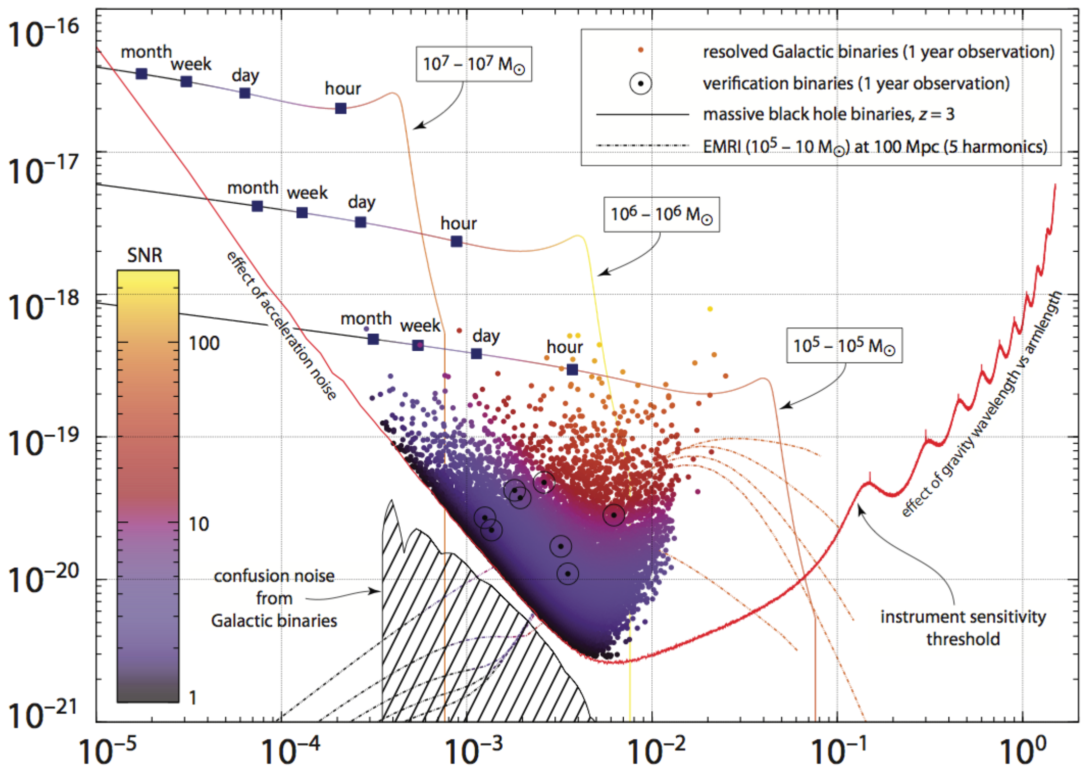
Crown jewel of low-frequency GW band!

Signal stands above almost all foreground and noise sources, even for high redshift sources.

Same basic waveform as what LIGO has seen, but frequencies scaled down and duration scaled up, both by about 4 or 5 orders of magnitude.

Massive black hole science

Galaxies were built hierarchically: Big galaxies assembled through repeated mergers of subunits.

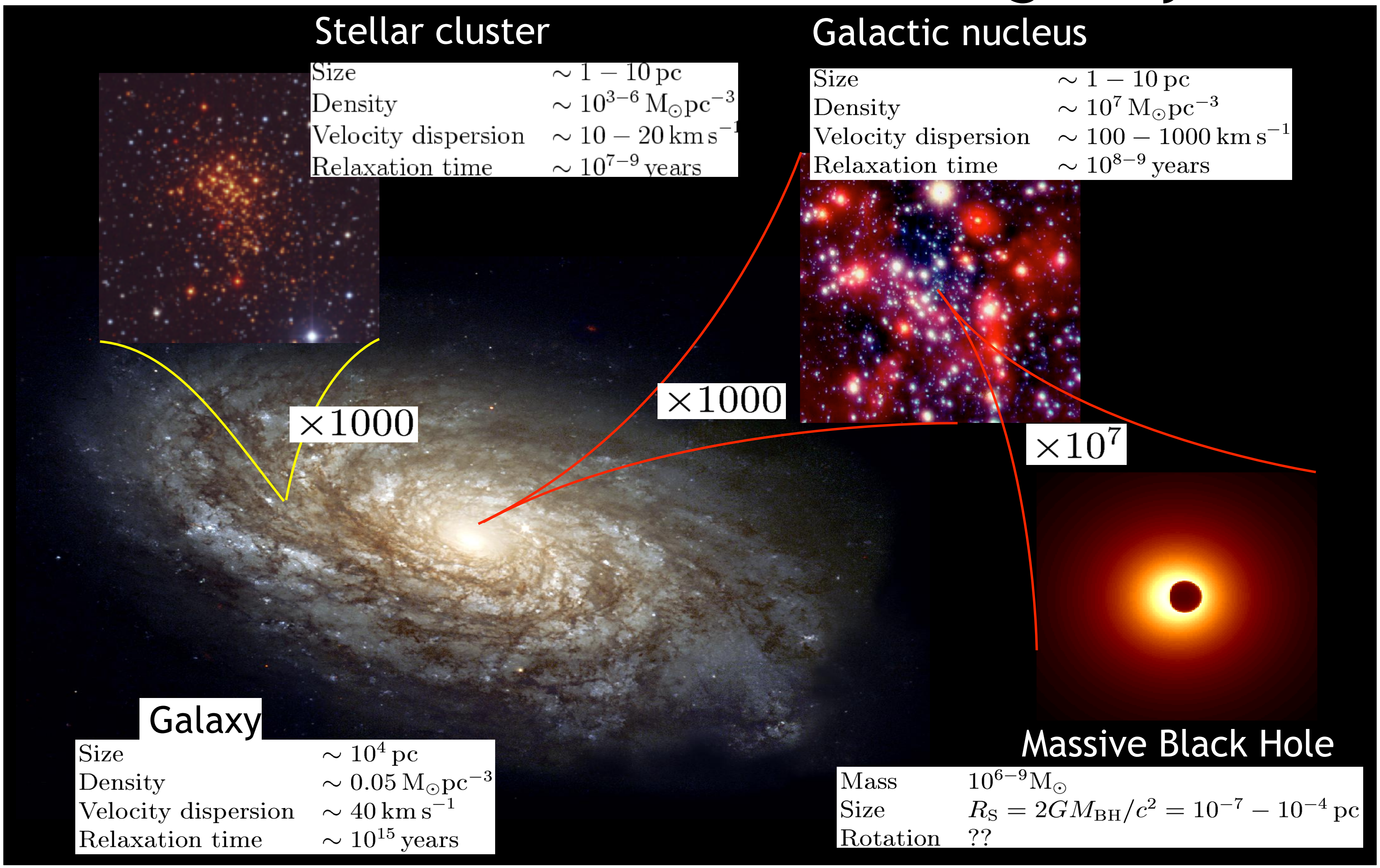


Coherent integration of events over time that they are in band yields SNR ~ 10^2 – 10^3, enabling highly precise source characterization.

Same basic waveform as what LIGO has seen, but frequencies scaled down and duration scaled up, both by about 4 or 5 orders of magnitude.

Extreme mass ratio inspirals ("EMRIs")

Capture of stellar mass compact objects onto relativistic orbits of black holes in galaxy cores.

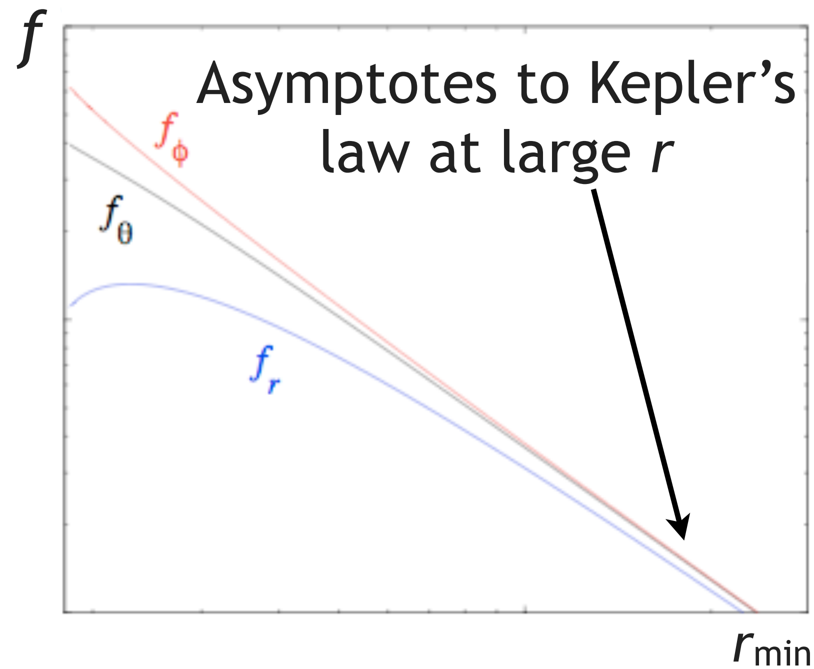


EMRI setting, courtesy Marc D. Freitag

Relativity view

Special limit of two-body problem: One body far more massive than other. Binary dominated by large black hole … GWs encode its properties.

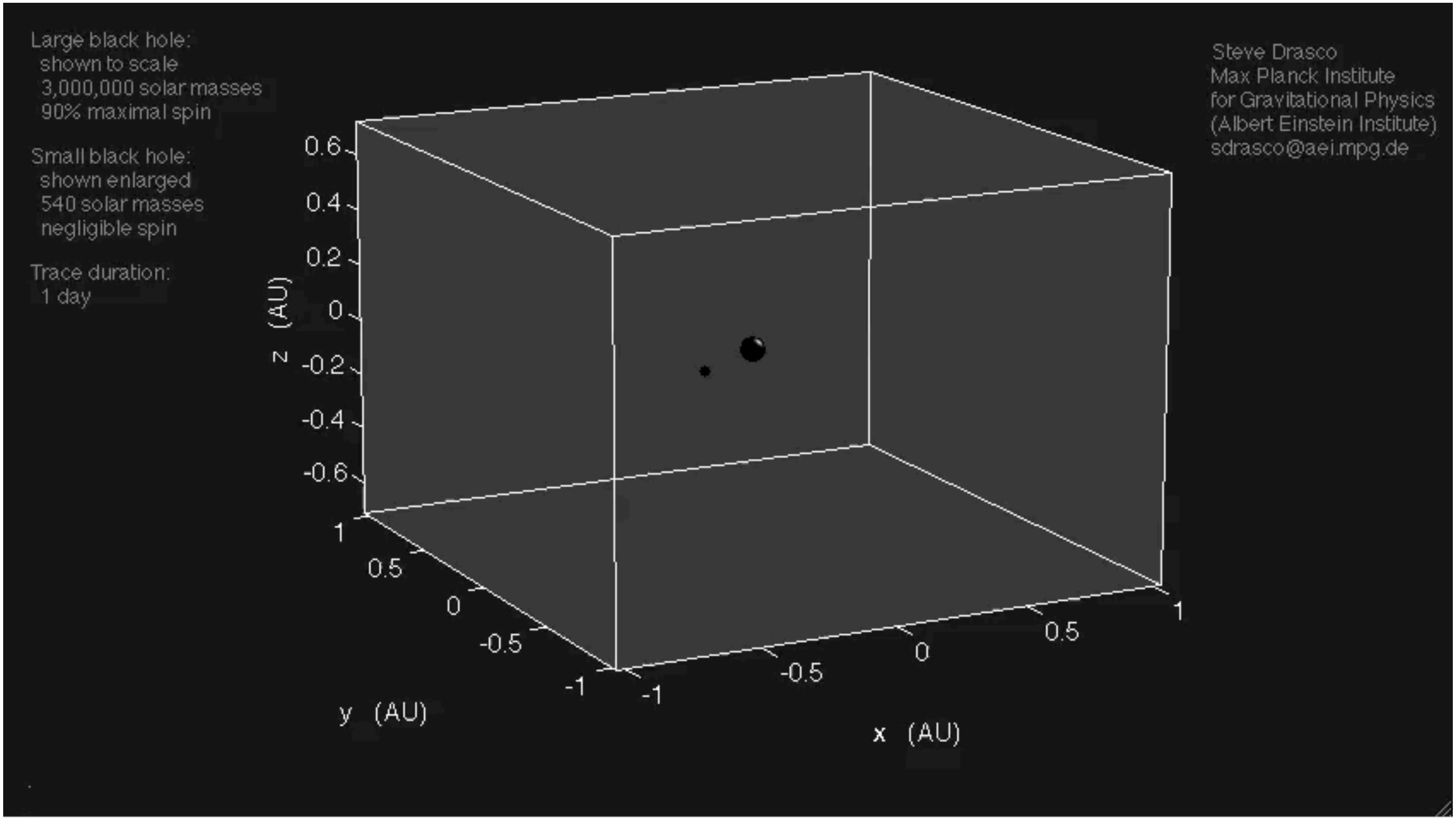
Short timescales: Small body follows "textbook" black hole orbit … triperiodic, highly non-Newtonian motion.



Frequencies agree with Kepler for weak field orbits … become distinct in strong field, as curvature splits the "Kepler line."

Relativity view

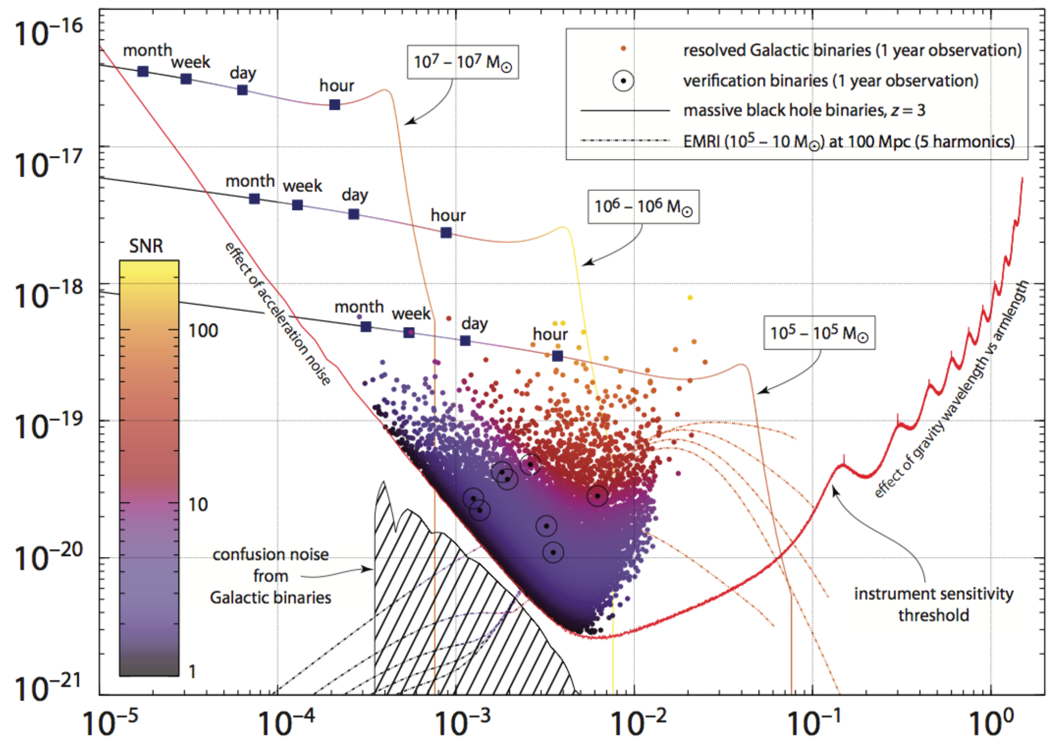
Long timescales: Backreaction of radiation drives inspiral, evolves through a sequence of orbits with continually changing radius and eccentricity.



EMRIs as targets in this band

If we can coherently follow phase over ~10^5 orbits, obtain integrated SNR ~ (a few) x 10 – 100.

Good SNR plus large phase precisely weighs source: Expect both masses and large BH's spin to be measured with ~10^{-4} precision.



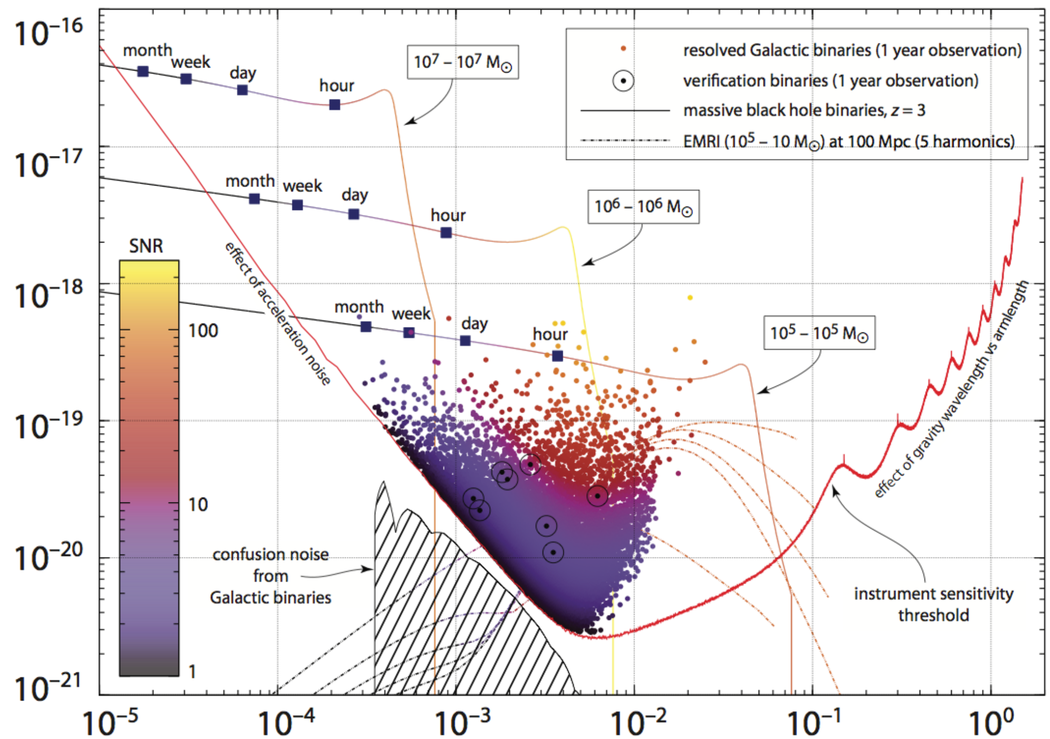
EMRIs as targets in this band

If we can coherently follow phase over ~10^5 orbits, obtain integrated SNR ~ (a few) x 10 – 100.

Test "Kerr-ness" of the large BH's spacetime by checking that spacetime multipoles have form that Kerr metric demands:

$$M_\ell + iS_\ell = M(ia)^\ell$$

$$M_0 = M \qquad S_1 = aM \qquad M_2 = -a^2 M$$



EMRIs as targets in this band

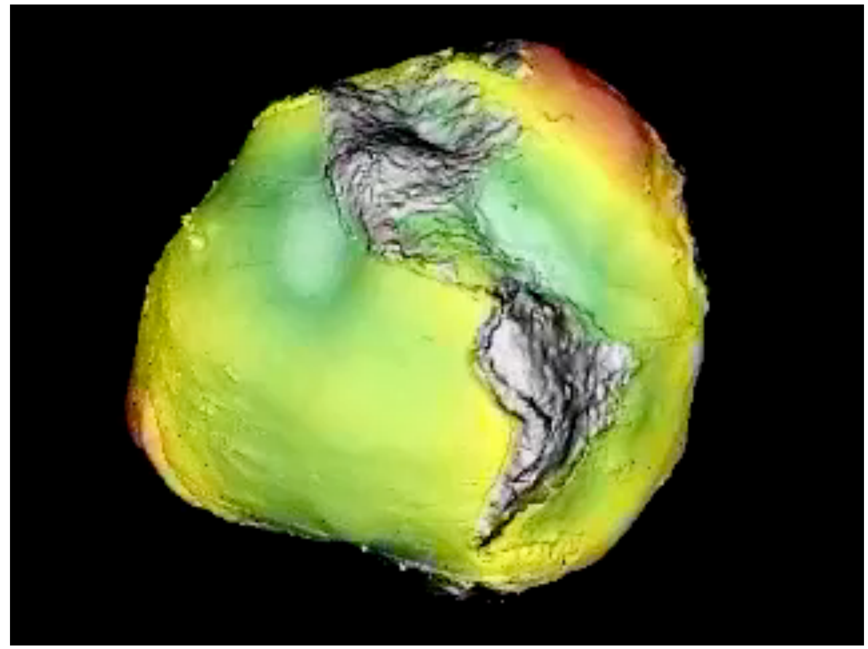
If we can coherently follow phase over ~10^5 orbits, obtain integrated SNR ~ (a few) x 10 – 100.

Test "Kerr-ness" of the large BH's spacetime by checking that spacetime multipoles have form that Kerr metric demands:

$$M_\ell + iS_\ell = M(ia)^\ell$$

$M_0 = M \quad S_1 = aM \quad M_2 = -a^2 M$

Geodesy for black holes?

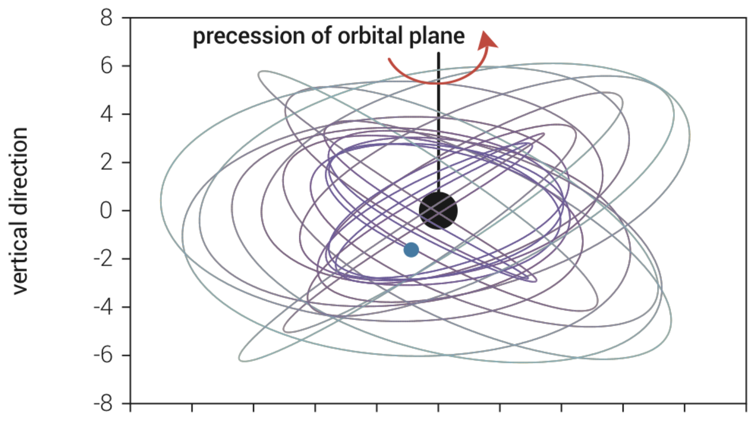


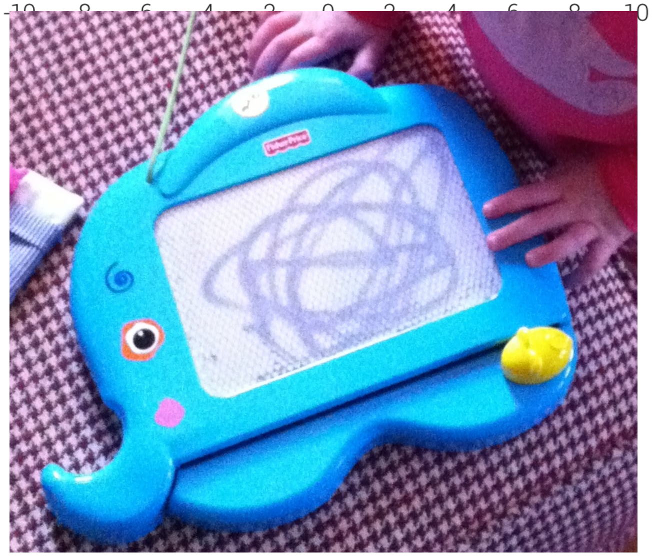
GRACE gravity model

Theoretical challenge: Achieving science these sources promise will require models with precision to remain phase coherent with data for ~10^5 orbits.

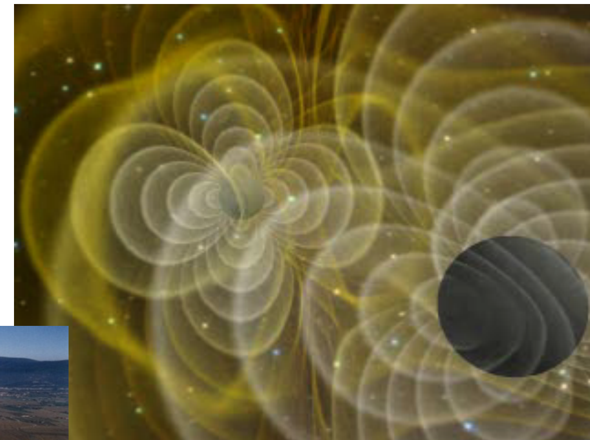
EMRIs as targets in this band

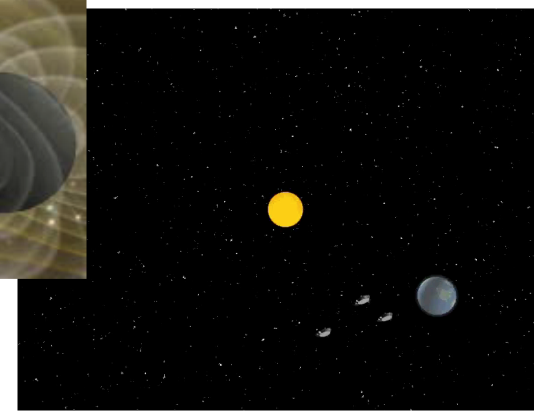
Theoretical program to model these sources underway now … need intense program to develop models with precision we need.





14 Sept 2015:
The end of the beginning





Advanced LIGO's first observing run has validated the promise of gravitational wave astronomy … but represents just part of a wide GW spectrum.

Much more to come … soon.