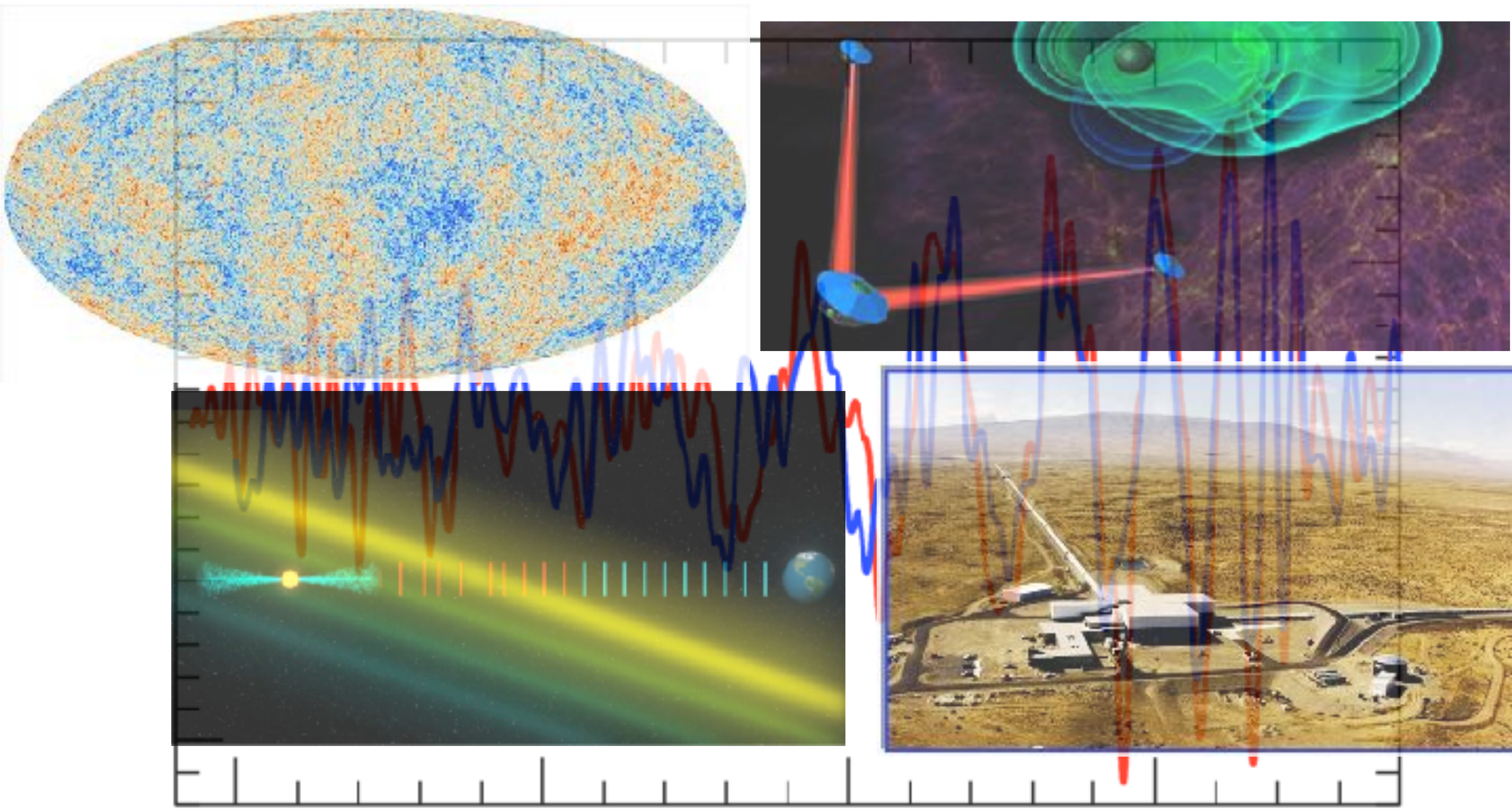
Gravitational wave probes of cosmological physics



Scott A. Hughes, MIT

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

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(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 $50 M_\odot$ for initial LIGO interferometers, $100 M_\odot$ 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 $100 M_\odot - 700 M_\odot$ out to ~ 200 Mpc for initial LIGO interferometers, and in the mass range of $\sim 200 M_\odot$ to $\sim 3000 M_\odot$ 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 ~ 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 $(200 \div 300)$ km s^{-1}.

The rate of NS mergers is $\sim 2 \times 10^{-5}$ yr^{-1} for a galaxy with constant astration rate of 4 $M_\odot$ yr^{-1} (and $M_{min} = 0.1\,M_\odot$ 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 ~ 200 yr for the first generation GWR detectors (which are expected to be sensitive up to ~ 25 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

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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.**"

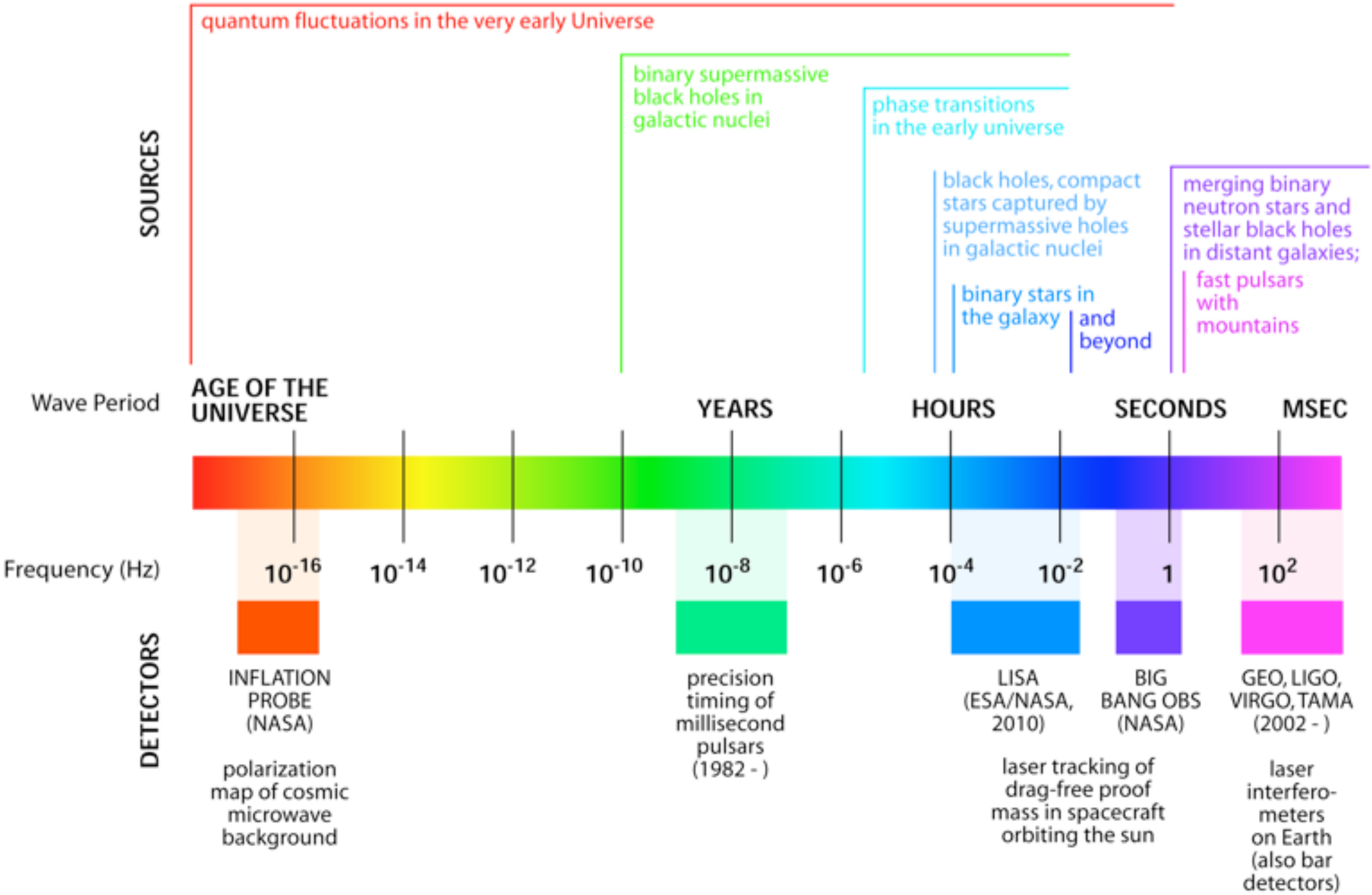
(Comment by Kip Thorne on our draft manuscript, sometime in late ***1996***.)

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

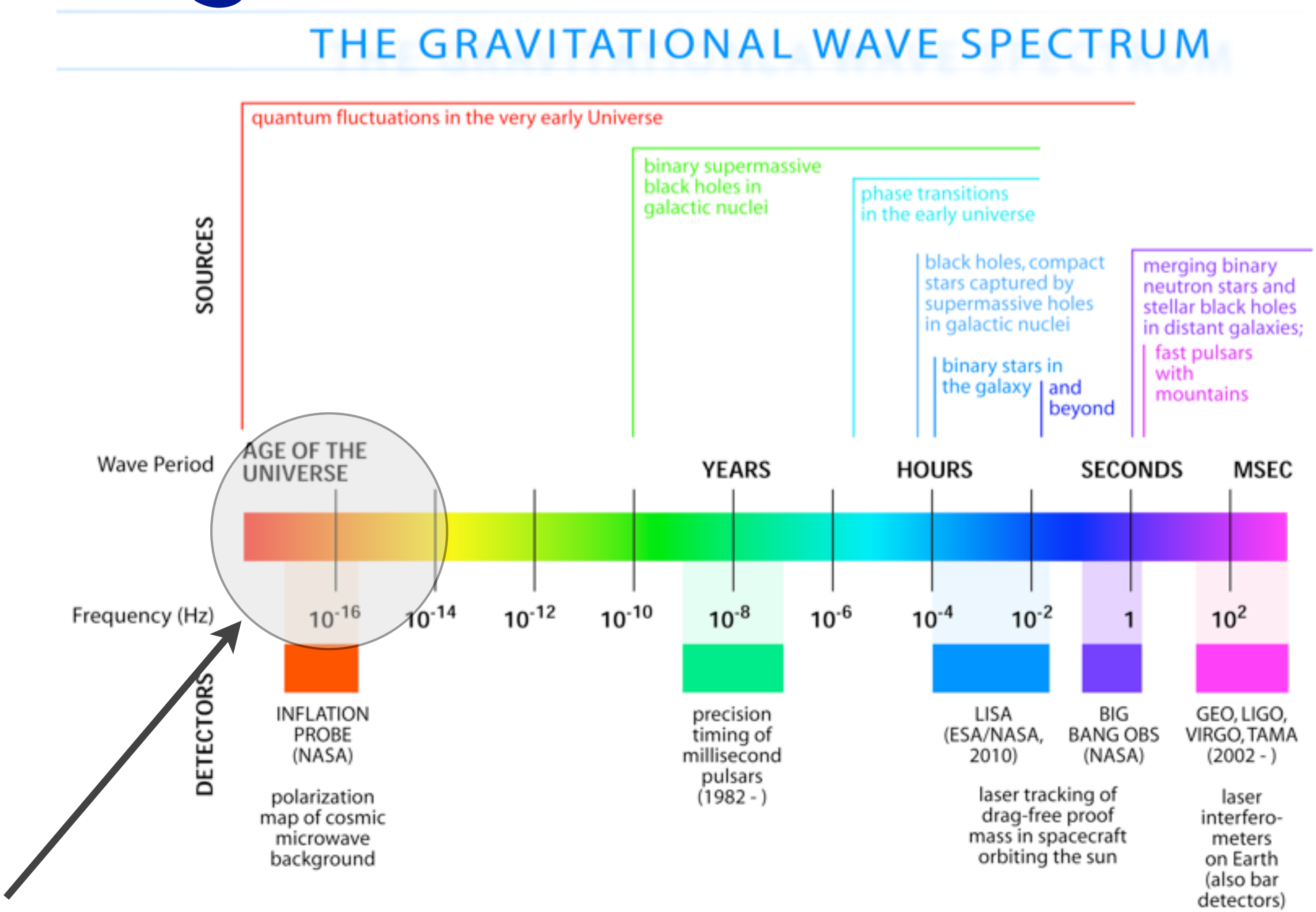
GWs as cosmological probes: Outline

- Basics: Gravitational wavebands; programs for measuring waves in different bands.
- Relics: The possibility of GWs as a direct imprint of processes in the early universe.
- Structure growth: Tracking the evolution of the first black holes as a way of tracing the growth of the earliest galaxies and large-scale structures
- Precise distances: Using binary sources as standard “sirens” to precise measure cosmological distances.

THE GRAVITATIONAL WAVE SPECTRUM



Programs to measure GWs



Lowest *f*: Detector is plasma at recombination. GWs acting on plasma have unique signature on polarization of photons that begin free-streaming.

Hubble-scale GWs

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

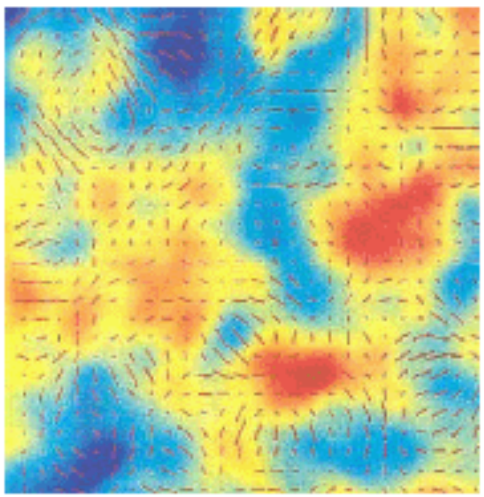
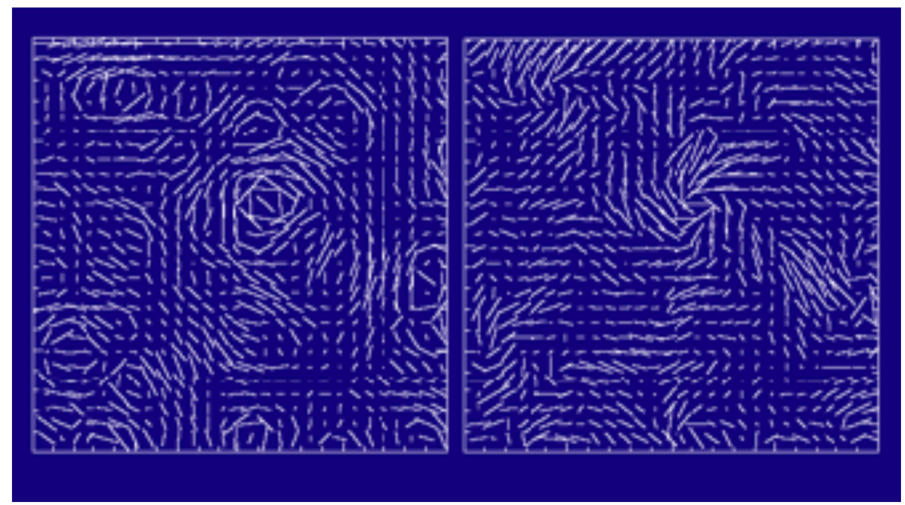


Image by Wayne Hu
http://background.uchicago.edu/~whu/intermediate/Polarization/polar5.html



Even parity polarization modes

Odd parity polarization modes

Hubble-scale GWs

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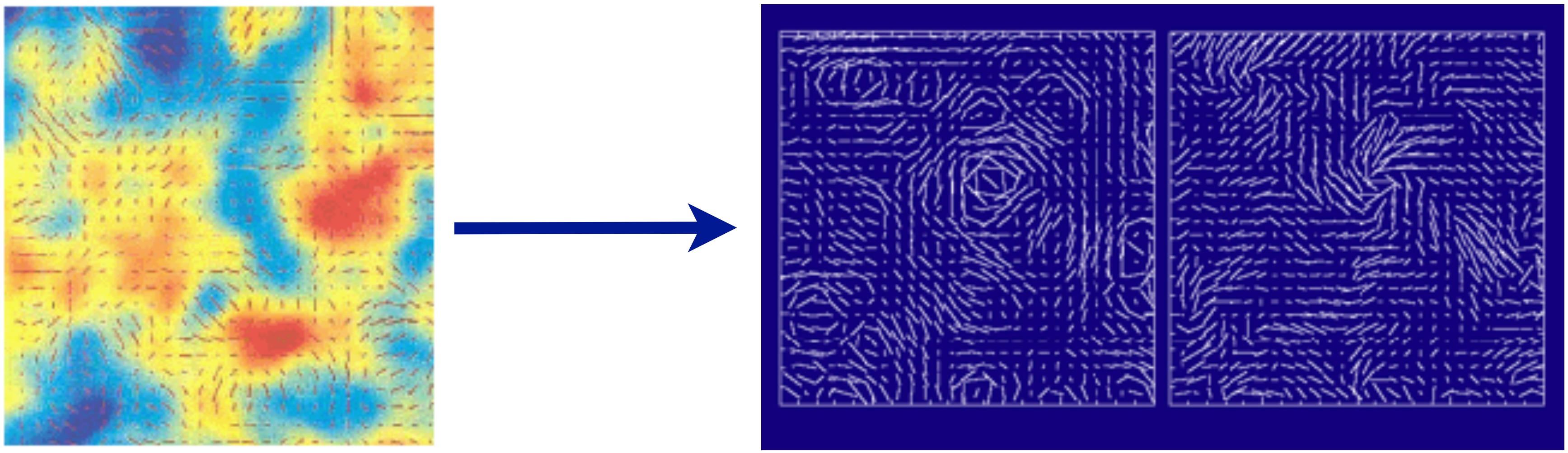

Even parity (*E*-modes): Due to fluctuations in the inflaton (with a subdominant contribution from spacetime fluctuations — ie, GWs).

Hubble-scale GWs

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

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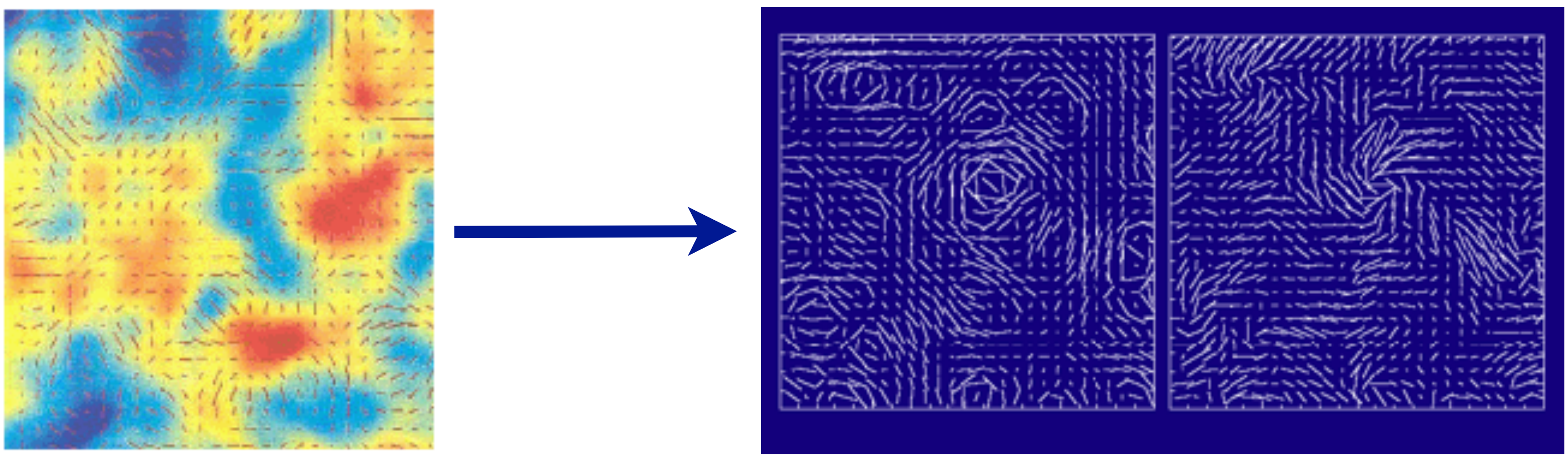
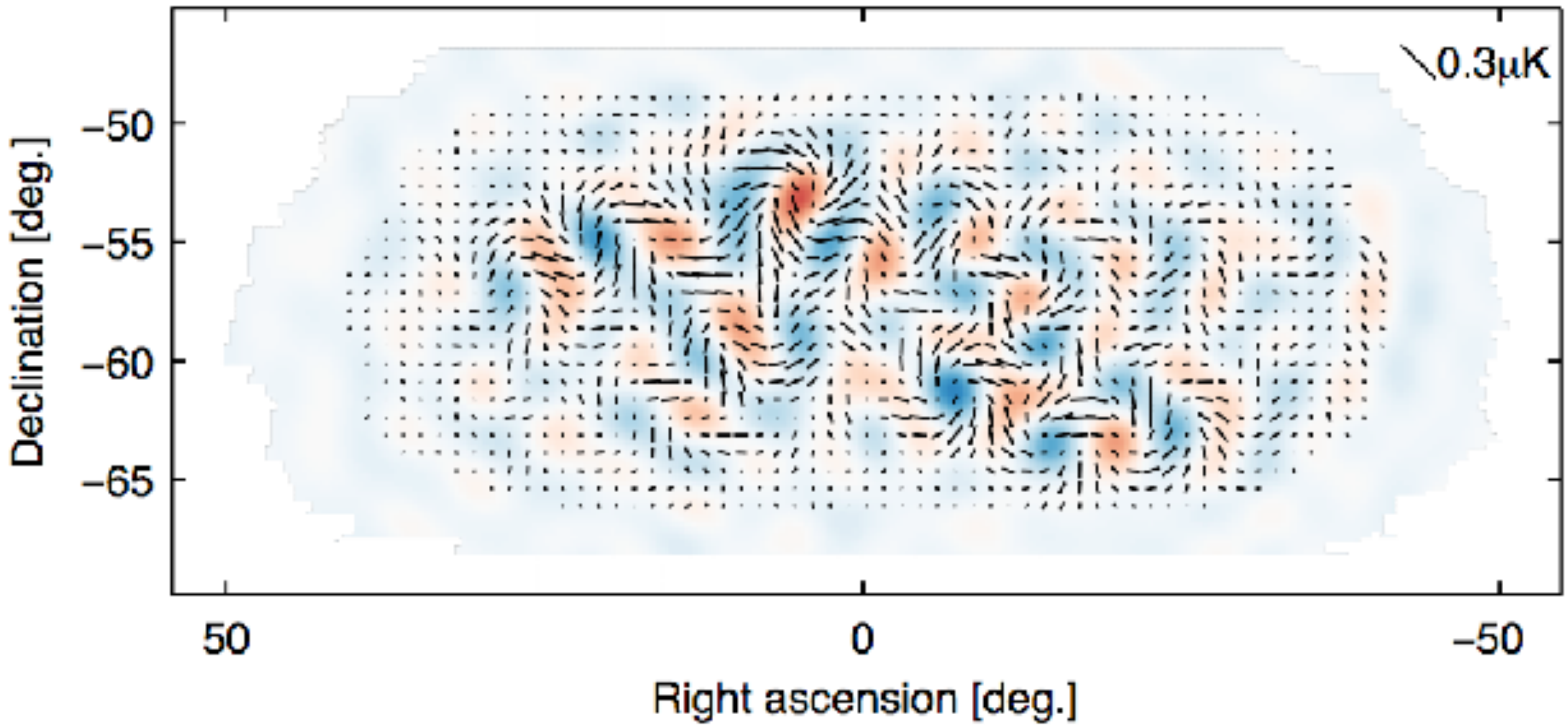


Odd parity (*B*-modes): ***Fundamentally*** arise only from spacetime fluctuations — GWs.

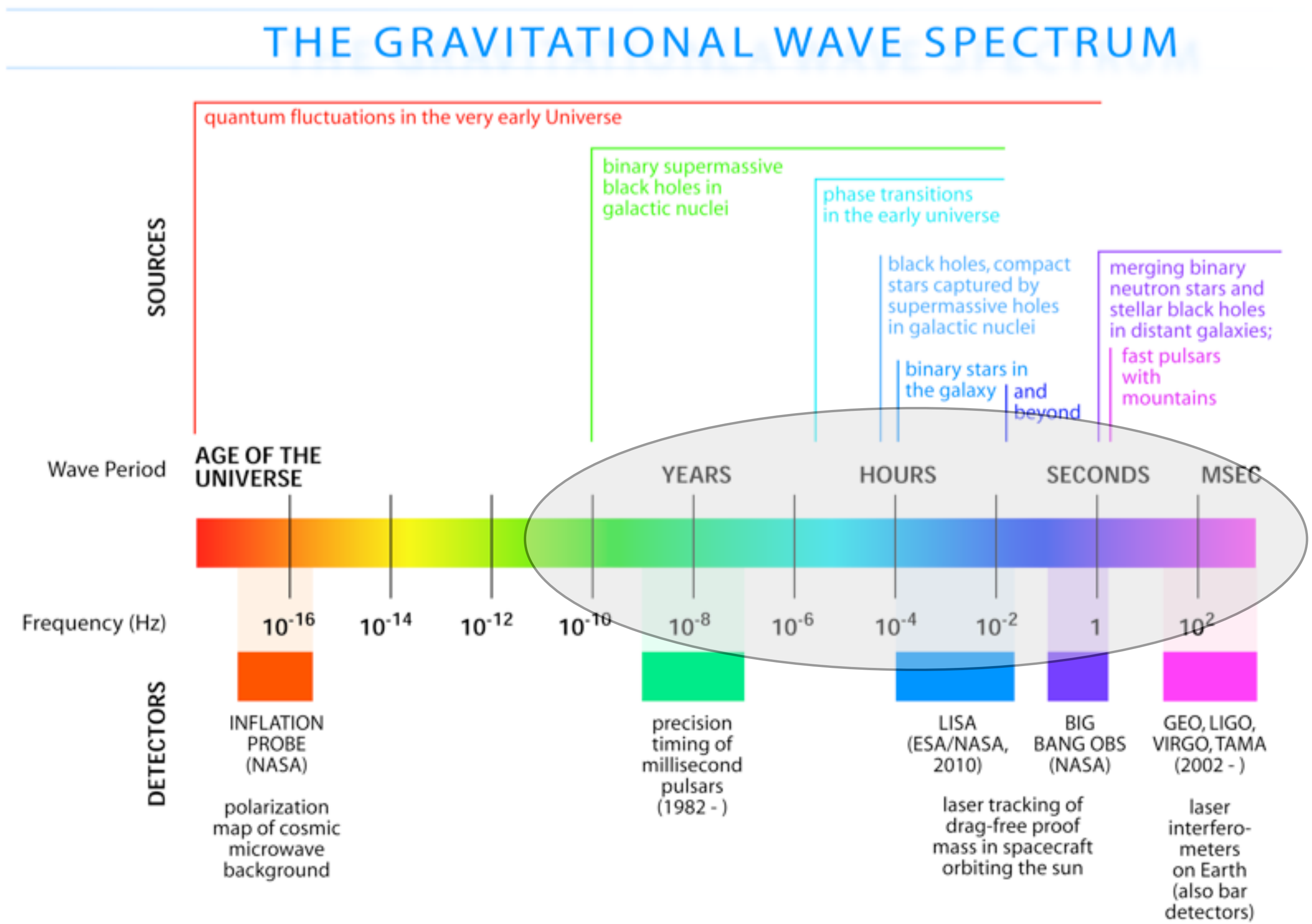
(Also arise from gravitational lensing, which turns *E*-modes into *B*-modes. Signal describing mass distribution ... but noise for GWs.)

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



Other bands: Look for effect of coherent space-time oscillations.

Highest f: Ground-based detectors

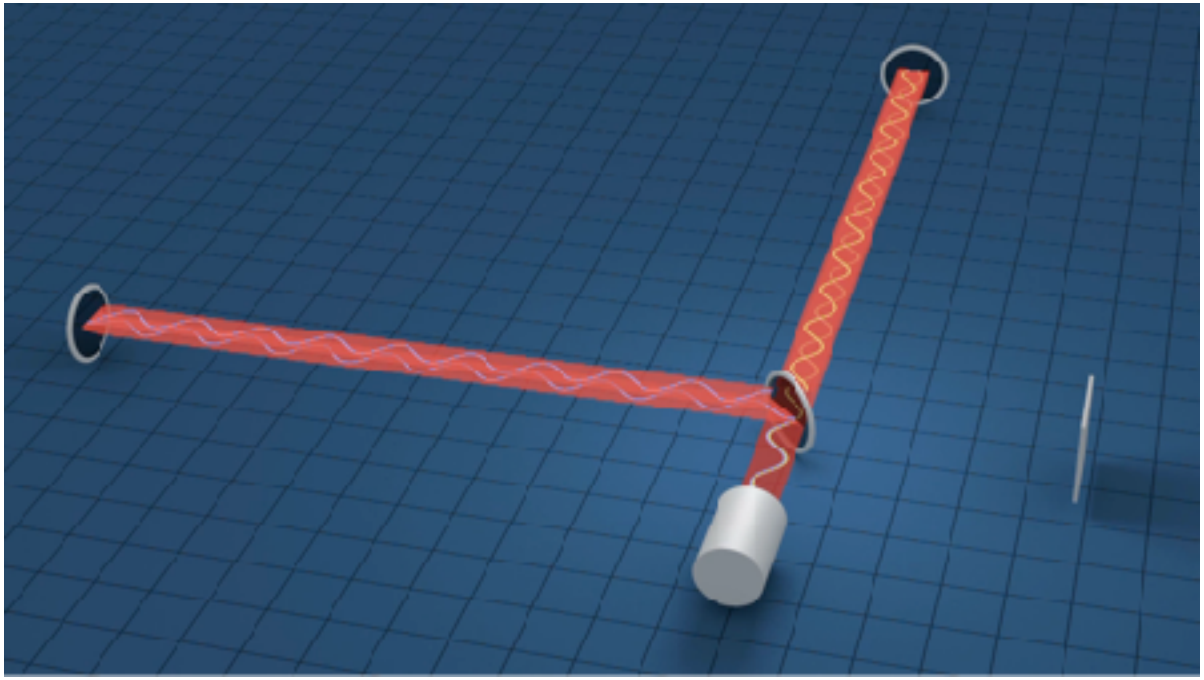
Three large-scale facilities operating: Hanford, WA & Livingston, LA (LIGO); and Pisa, Italy (Virgo).

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

Sensitive to GWs with amplitudes ~10^{-22}

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:

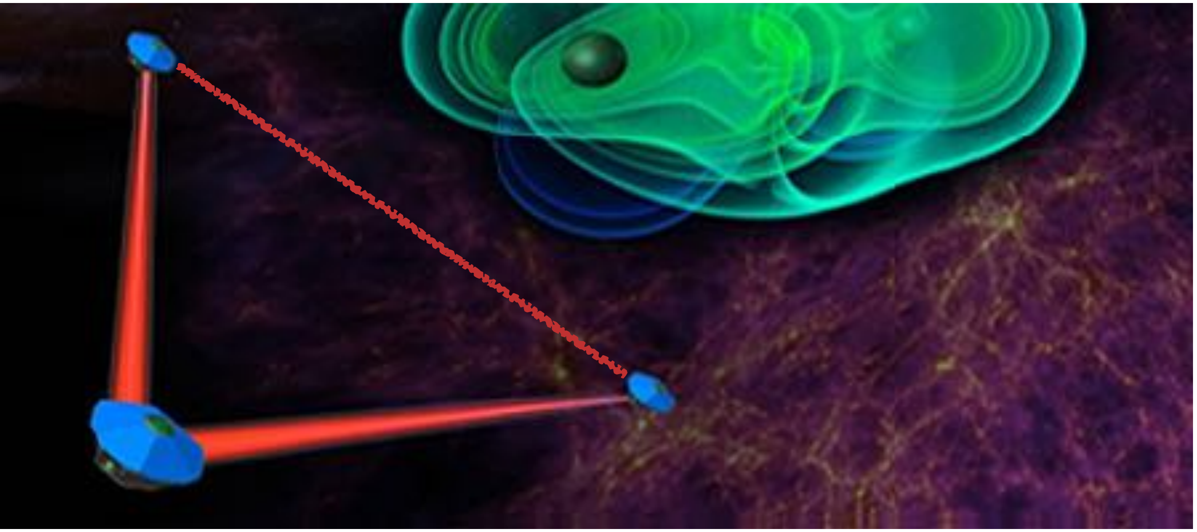
$$\Delta\Phi_{\rm GW} \simeq 2\mathcal{F} \times (hL) \times \frac{2\pi}{\lambda_{\rm laser}}$$

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.

Low *f*: Space-based detectors



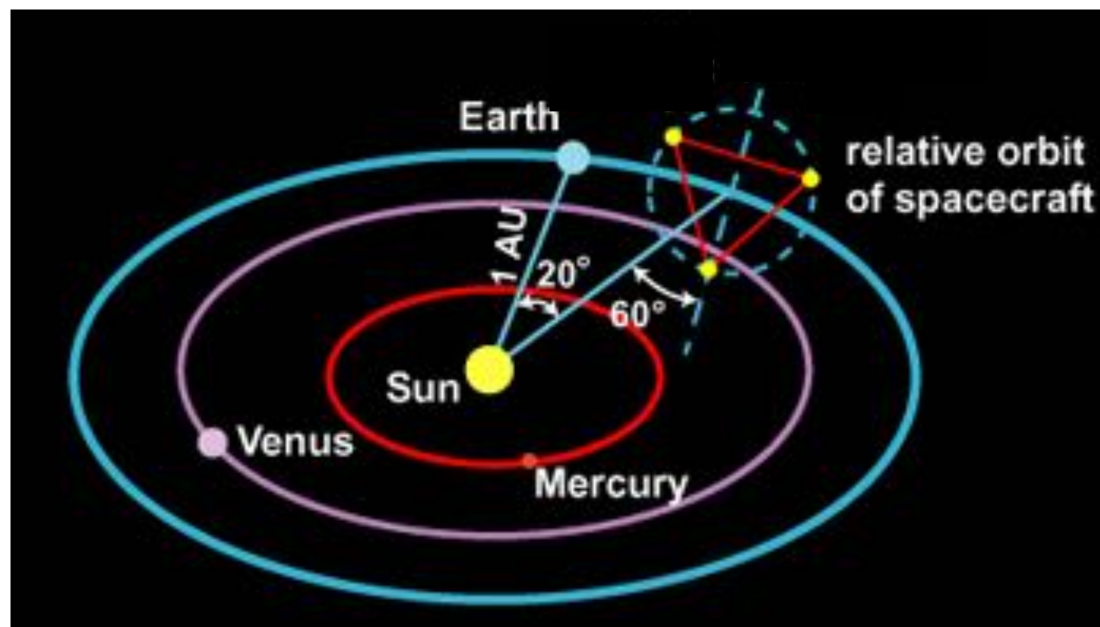
LISA: The 2.5 million km space interferometer.

ESA mission, selected in June. NASA involvement looks certain, details under development now.

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

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

A target-rich frequency band.



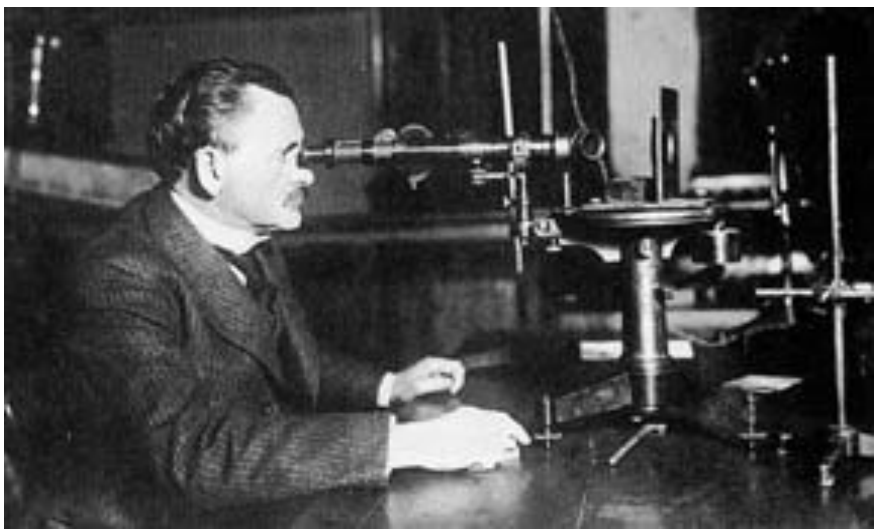
LISA metrology

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

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

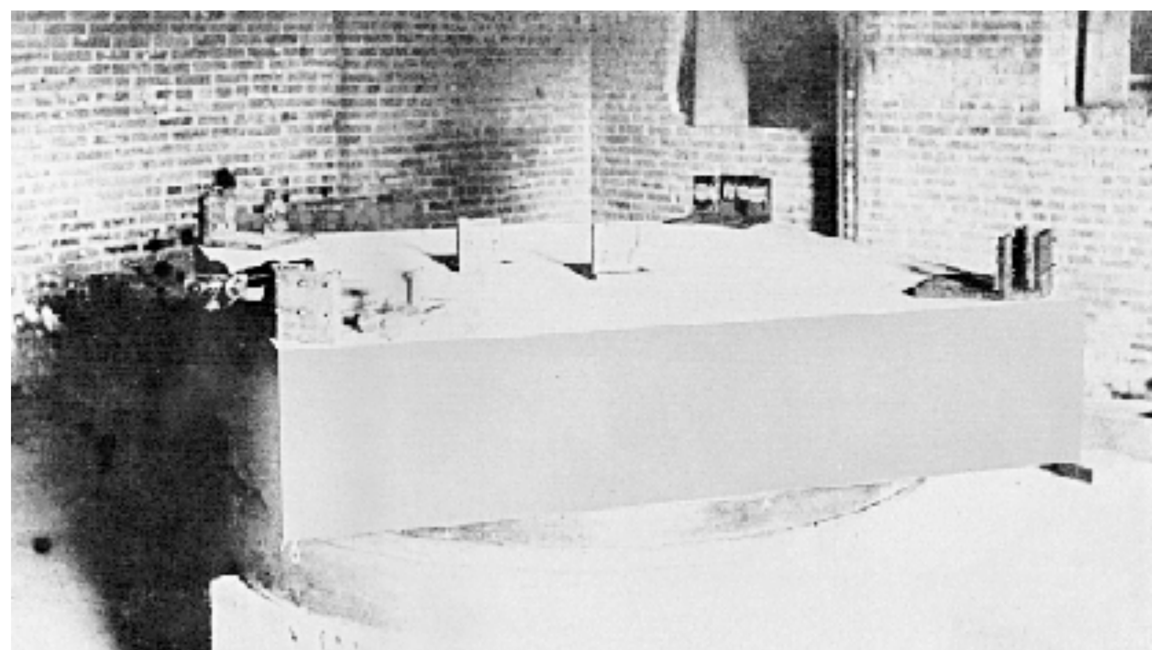
Ground: $h \lesssim 10^{-21}$, $L \sim$ kilometers: $\Delta L \lesssim 10^{-3}$ fm

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



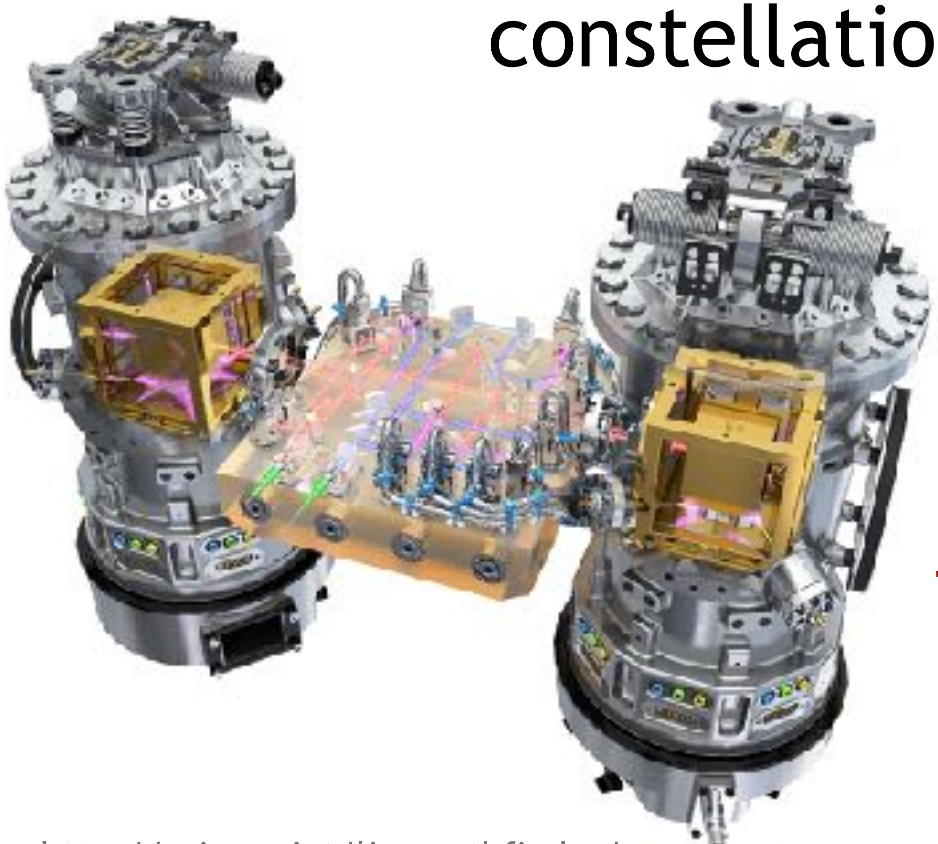
Measured at DC by eye.

About 2 orders 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

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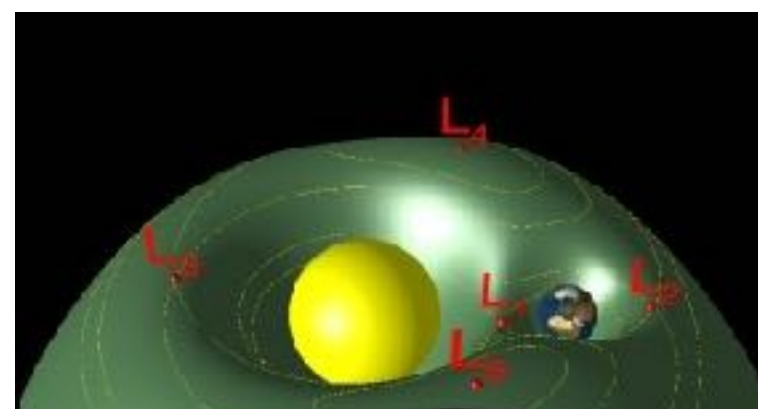
LISA Pathfinder: Testbed for technologies to demonstrate that free fall, control, and metrology can be done with the precision needed for LISA.

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



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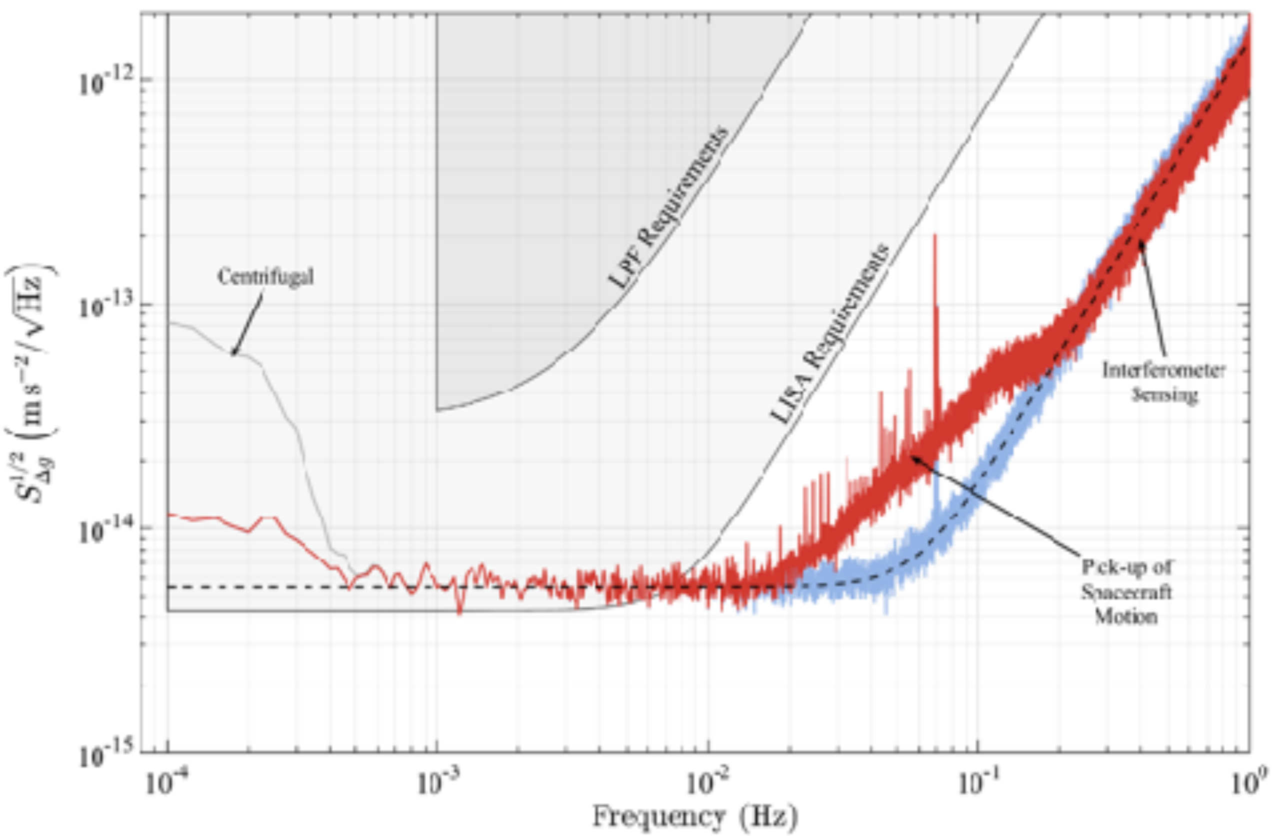


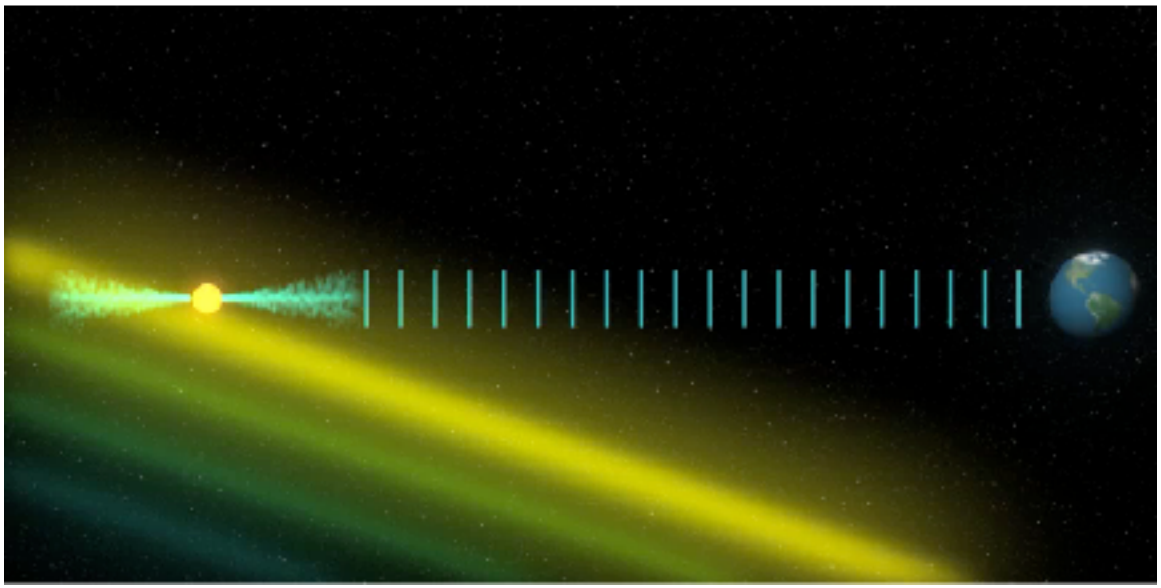
Figure 1 of Armano et al, Phys. Rev. Lett. **116**, 231101 (2016).

Results significantly exceeded mission specifications.

LISA is within reach.

Very low *f*: Pulsar Timing Arrays

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

About 50 pulsars now monitored by several collaborations (EPTA [Europe], NANOGrav [US], PPTA [Australia])

No direction detections yet; have set upper limits on a “stochastic background” of waves in this frequency band.

GWs from cosmic relics

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:

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

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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

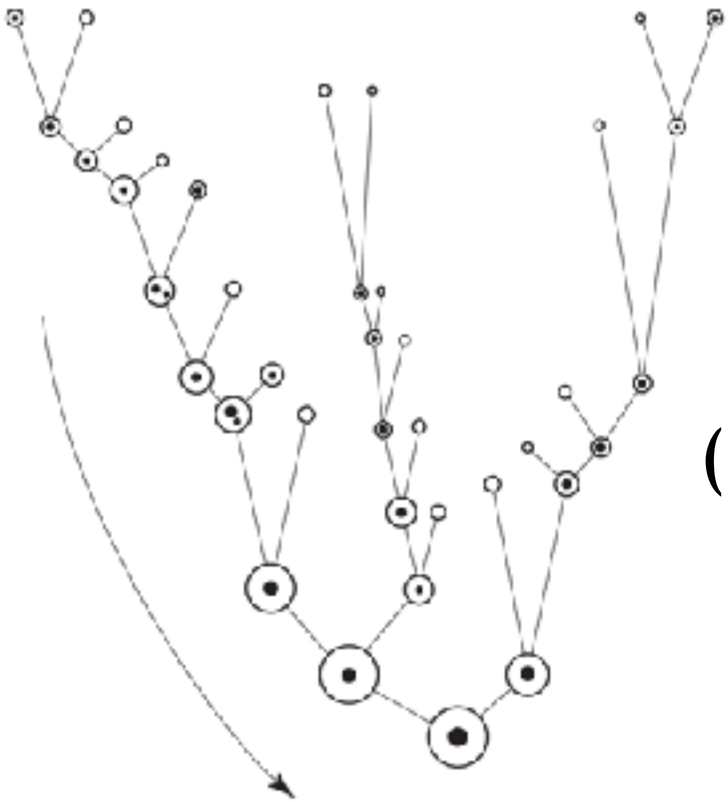
[Caprini et al, JCAP **4**, 001 (2016)]

GWs and the growth of early black holes

Black holes in the early universe

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

Quasars tell us that large black holes have existed since the earliest cosmic times.



Tell us that massive black hole mergers should be common over universe's history. Events with

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

will be in band of LISA, and detectable out to $z \sim 15 - 20$.

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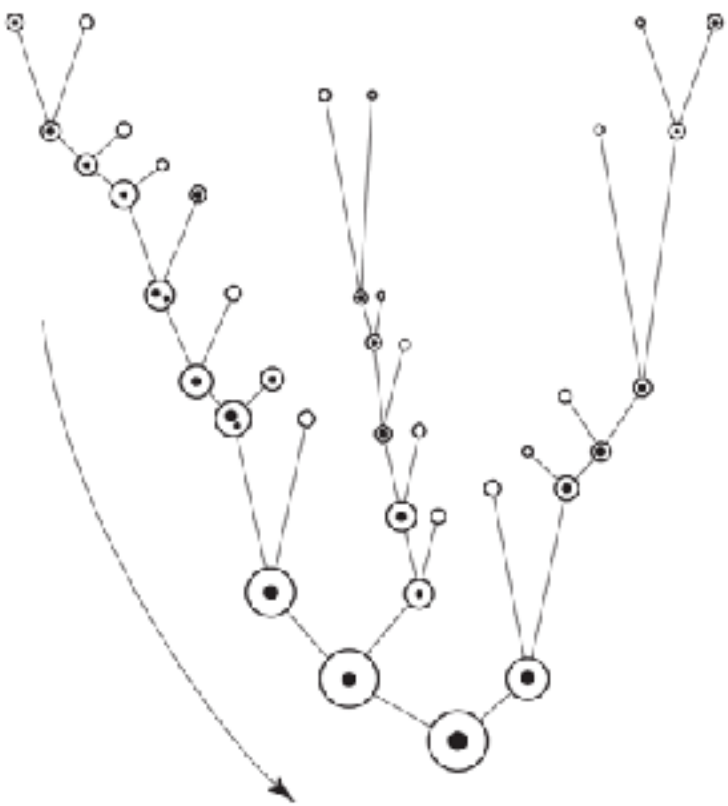


Very different populations probed by LISA and by PTAs:

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

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

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

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

Astronomy of merging BHs

Signal in band for months to years; measured with signal-to-noise of several tens to several hundreds.

Many cycles in band plus high SNR means LISA can characterize binaries with high precision: Expect to measure BH masses and spins, as well as distance to binary very accurately.

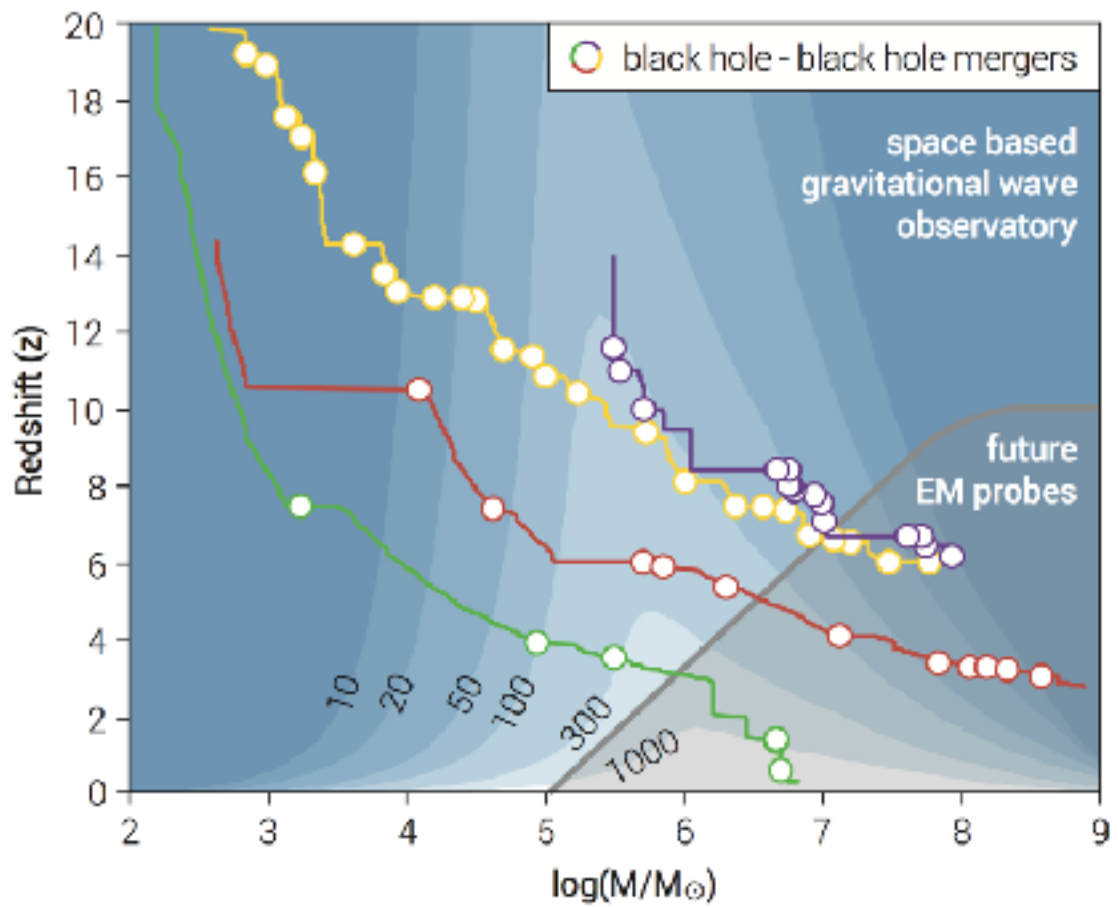
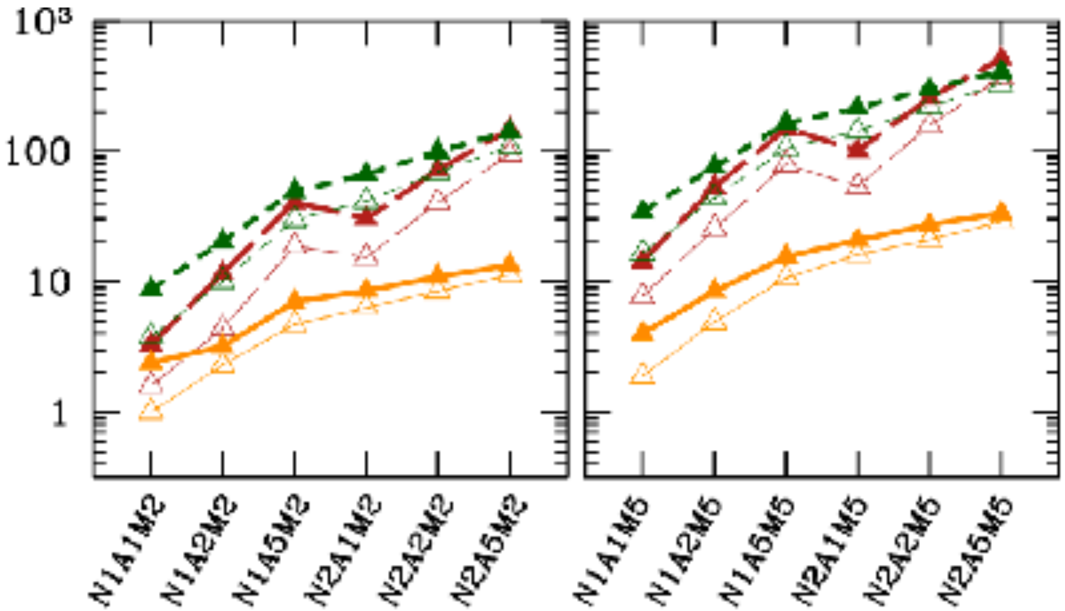


Figure 2, *The Gravitational Universe*, arXiv:1305.5720

What LISA will measure

Example: Mass measurement accuracy.



Number of events in which masses are measured to better than 1% accuracy.

Ref: Klein et al [1511.05581; Phys Rev **93**, 024003 (2016)], Fig 8

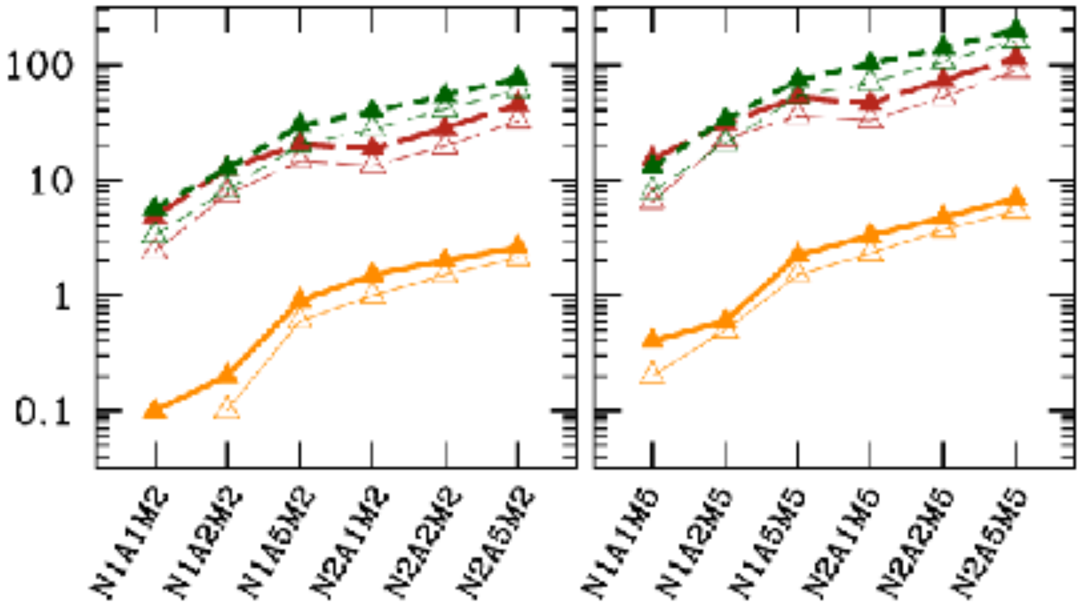
Left: 2-year mission; right: 5-year mission.

Horizontal axis: Detector configurations.

Tracks: Models for initial seeds, accretion history.

What LISA will measure

Example: Spin measurement accuracy.



Number of events in which Kerr parameter is measured with error $\delta a < 0.01$.

Ref: Klein et al [1511.05581; Phys Rev **93**, 024003 (2016)], Fig 9

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What LISA will measure

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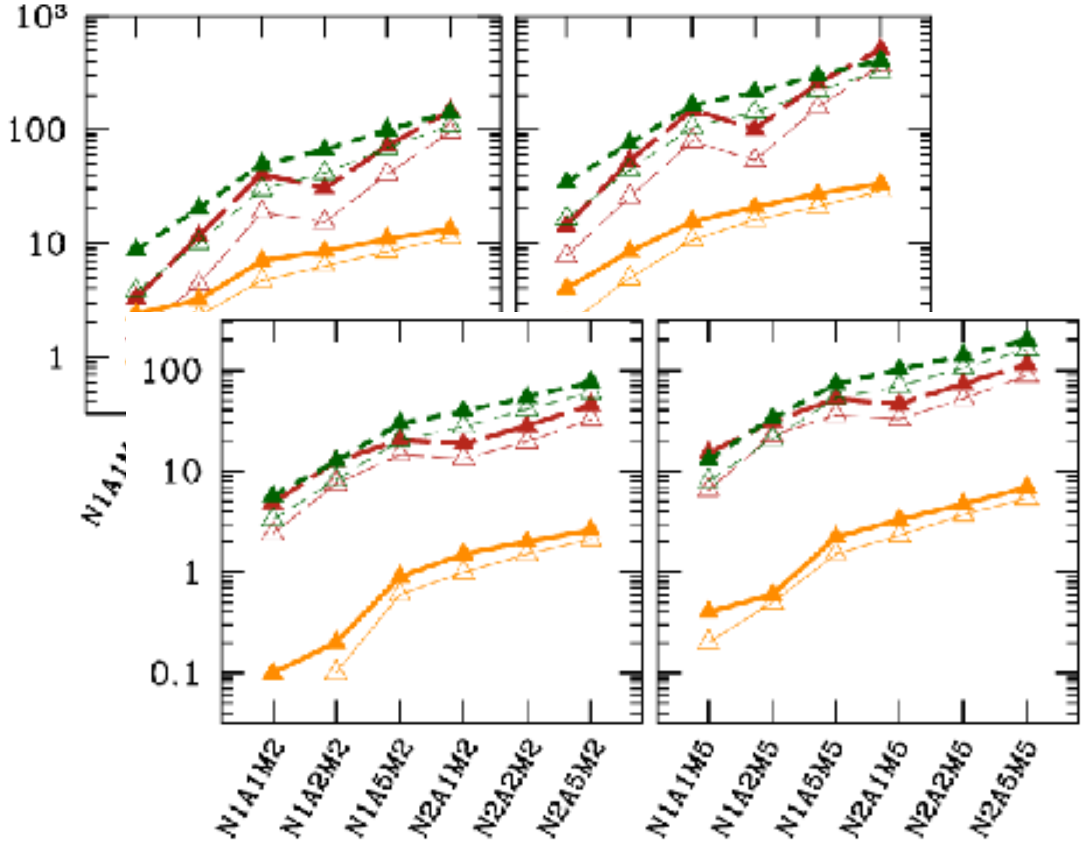

These studies used a simulated population of black holes which form binaries … **the majority of which come from redshift z > 5.**

LISA will be an outstanding instrument for studying early growth of black holes and their host structures.

Precise cosmic distance measures

Precision distances

Astronomical distances often determined using *standard candles*: Sources with known (**empirically calibrated**) luminosity. Compare measured brightness with intrinsic luminosity, infer distance.

A perfect standard candle: Simple radiator (e.g., dipole) in which the radiative moment evolves in a predictable way.

$$\frac{dE}{dA\,dt} = \frac{p(t)^2\omega^4}{8c^2}\frac{\sin^2\theta}{r^2}$$

Get ω from radiation. If we can also determine time-changing dipole moment, can infer distance.

Distance with binary GWs

Binary coalescence essentially **IS** such a "perfect" standard candle: Replace dipole with quadrupole, adjust power of frequency and coupling constant:

$$\frac{dE}{dA\,dt} = \frac{G}{8\pi c^5}\frac{\Omega(t)^6}{r^2}\mathcal{I}_{ij}(t)\mathcal{I}_{ij}(t)$$

Wonderful trick: **The evolution of the waveform allows us to self-consistently determine the source's time-evolving quadrupole moment.**

B. F. Schutz, Nature **323**, 310 (1986)

How it works in practice

Examine waves from a coalescing binary:

$$h = F_+ h_+ + F_\times h_\times$$

h is the waveform in a detector; antenna functions F_+ and $F_\times$ depend on sky position (θ, φ), polarization angle ψ.

Polarizations of binary GWs:

$$h_+ = \frac{2c}{D}(G\mathcal{M}/c^3)^{5/3}\Omega^{2/3}(1+\cos^2\iota)\cos\left[2\int\Omega(t)\,dt\right]$$

$$h_\times = \frac{4c}{D}(G\mathcal{M}/c^3)^{5/3}\Omega^{2/3}\cos\iota\sin\left[2\int\Omega(t)\,dt\right]$$

At leading order, frequency set by binary's "***chirp mass***":

$$\Omega(t) = \left[\frac{5}{256}\left(\frac{c^3}{G\mathcal{M}}\right)^{5/3}\frac{1}{(t_c - t)}\right]^{3/8}$$

$$\mathcal{M} \equiv \mu^{3/5}M^{2/5}$$

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$$h_\times = \frac{4c}{D}(G\mathcal{M}/c^3)^{5/3}\Omega^{2/3}\cos\iota\sin\left[2\int\Omega(t)\,dt\right]$$

Once chirp mass is known, and ***IF*** angles are known, **then distance to source is directly measured** with accuracy of roughly 1/SNR.

Distance … but not redshift

Binary's intrinsic parameters enter waveform as timescales:

Every mass *m* enters as time: $\tau_m = Gm/c^3$

Every spin *s* enters as time *squared*: $(\tau_s)^2 = Gs/c^5$

A binary with parameters (*m*, *S*) at redshift *z* has exactly the same phase evolution as a binary with parameters $[(1+z)m,\ (1+z)^2 S]$ at redshift 0.

Two ways to break z degeneracy

1. Assume cosmology. Use the GW-determined distance to infer redshift.

This is how redshift and "rest frame" parameters are inferred for GW events that have been announced so far.

Two ways to break z degeneracy

1. Assume cosmology. Use the GW-determined distance to infer redshift.

This is how redshift and "rest frame" parameters are inferred for GW events that have been announced so far.

2. Measure "electromagnetic" counterpart. Independently determine z (E&M) and D (GWs).

Combining GW distance with an "electromagnetic" z allows us to determine cosmology with *very* different systematics than other techniques.

B. F. Schutz, Nature **323**, 310 (1986)

D. E. Holz and S. A. Hughes, ApJ **629**, 15 (2005)

Standard "sirens"

High z standard sirens: Combine LISA measurement of BH mergers with optical identification of host galaxy. Map expansion over a range of epochs, perhaps giving precise data about onset of dark-energy dominance.

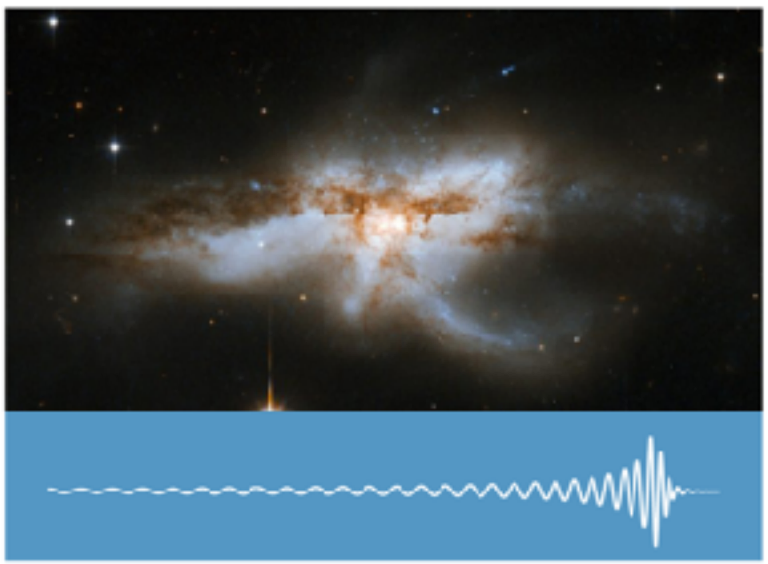


Figure 1, *The Gravitational Universe*, arXiv:1305.5720

Transition from matter to DE dominance?

Contribution of other radiation species?

Evolution of dark energy?

Standard "sirens"

Low z standard sirens: Combine LIGO measurement of binary inspiral with electromagnetic association (e.g., neutron star merger and short gamma ray burst or kilonova), yields measurement of Hubble expansion H_0.

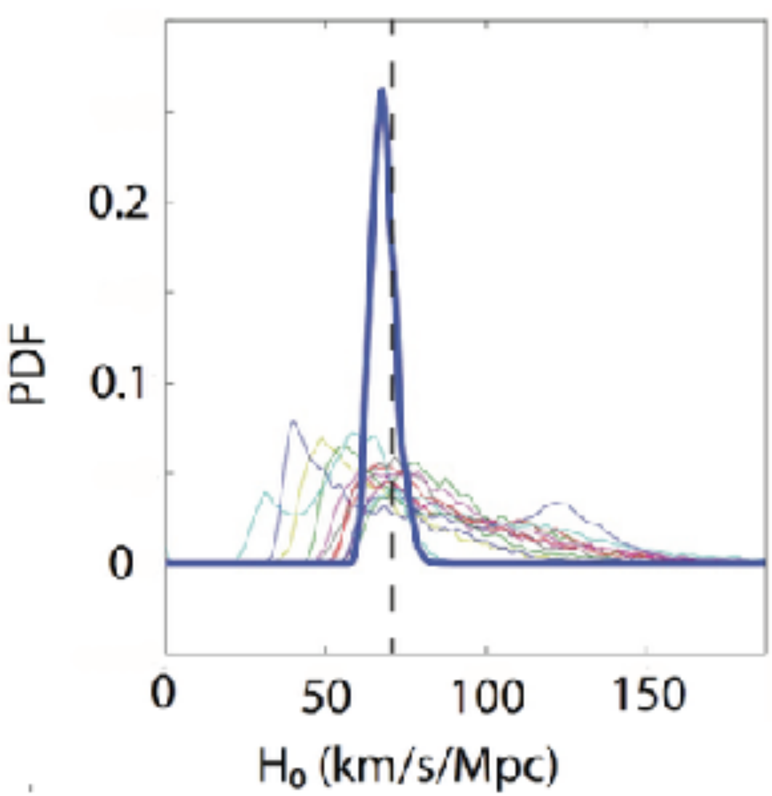


Figure 1 of arXiv:1307.2638

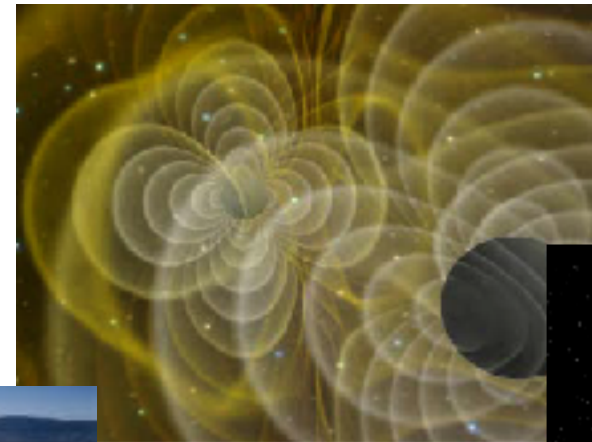
Work by Nissanke et al (arXiv: 1307.2638) finds it takes roughly 15 events to measure H_0 with few percent statistical error.

Different systematics could be useful for resolving tension between current values

(e.g., CMB value of 68.3 km/sec/Mpc vs Type Ia SN value of 73 km/sec/Mpc)

The end of the beginning






Advanced LIGO and Virgo are at last doing astronomy in the high-f GW spectrum. There's a lot more spectrum … and a lot of cosmology to do with these data.

More to come … soon!