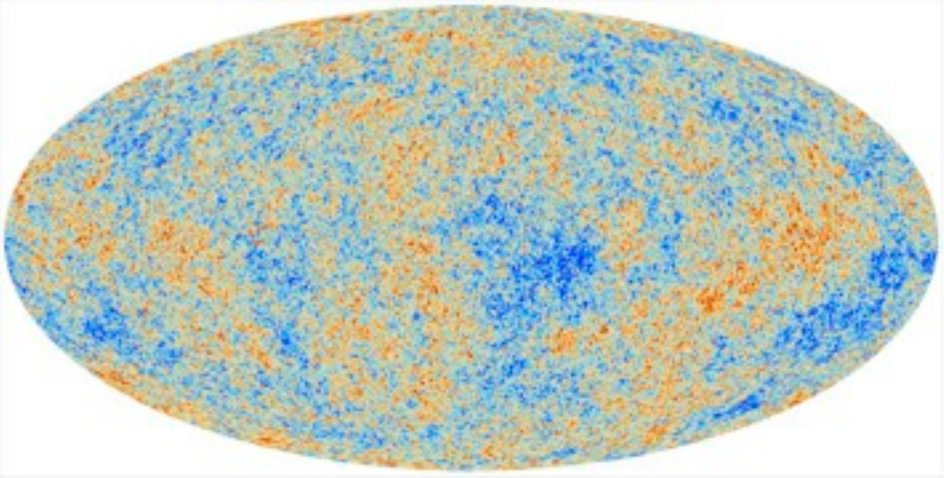
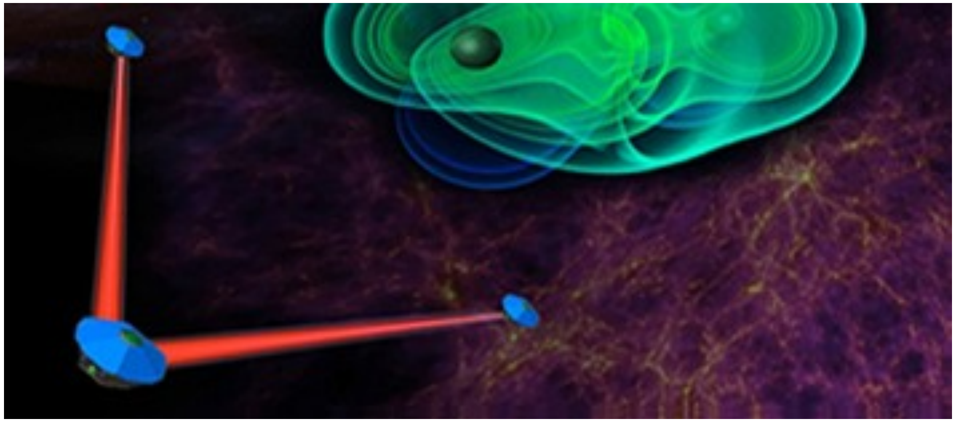
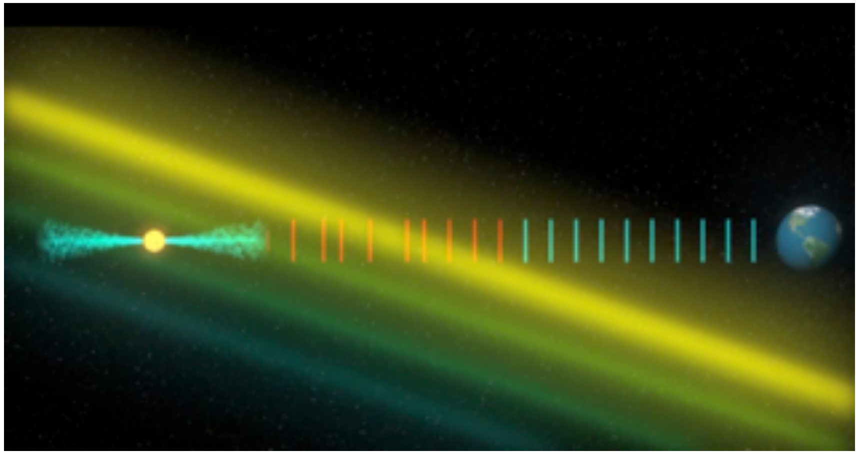
Gravitational Wave Cosmology







How will we be able to exploit direct gravitational wave measurements for cosmology? What will this bring us?

Outline

- Basics: What gravitational waves are and how to measure them
- Why: The potential importance of GWs for astronomy and cosmology, broadly speaking
- How: Ongoing and upcoming efforts to measure GWs
- Specifics: Several ways in which GWs can bring us cosmologically important data.
  - Relic waves (direct imprint of inflation)
  - Precise distances ("standard sirens")
  - Early growth of black holes (tracer of early structure)

Basic basics

Gravitational radiation *necessary* in any relativistic gravity theory: Must causally communicate changes in the gravitational field.

GR: Tides ("curvature") play role similar to electric and magnetic fields in E&M … radiation takes form of propagating tidal gravitational force.

Leading radiation *quadrupolar*: monopole protected by energy conservation; dipole protected by conservation of momentum.

$$h = \frac{2G}{c^4}\frac{1}{r}\frac{d^2Q}{dt^2}$$

$$\simeq \frac{2G}{c^4}\frac{1}{r} \times mv^2$$

Indirect measurement

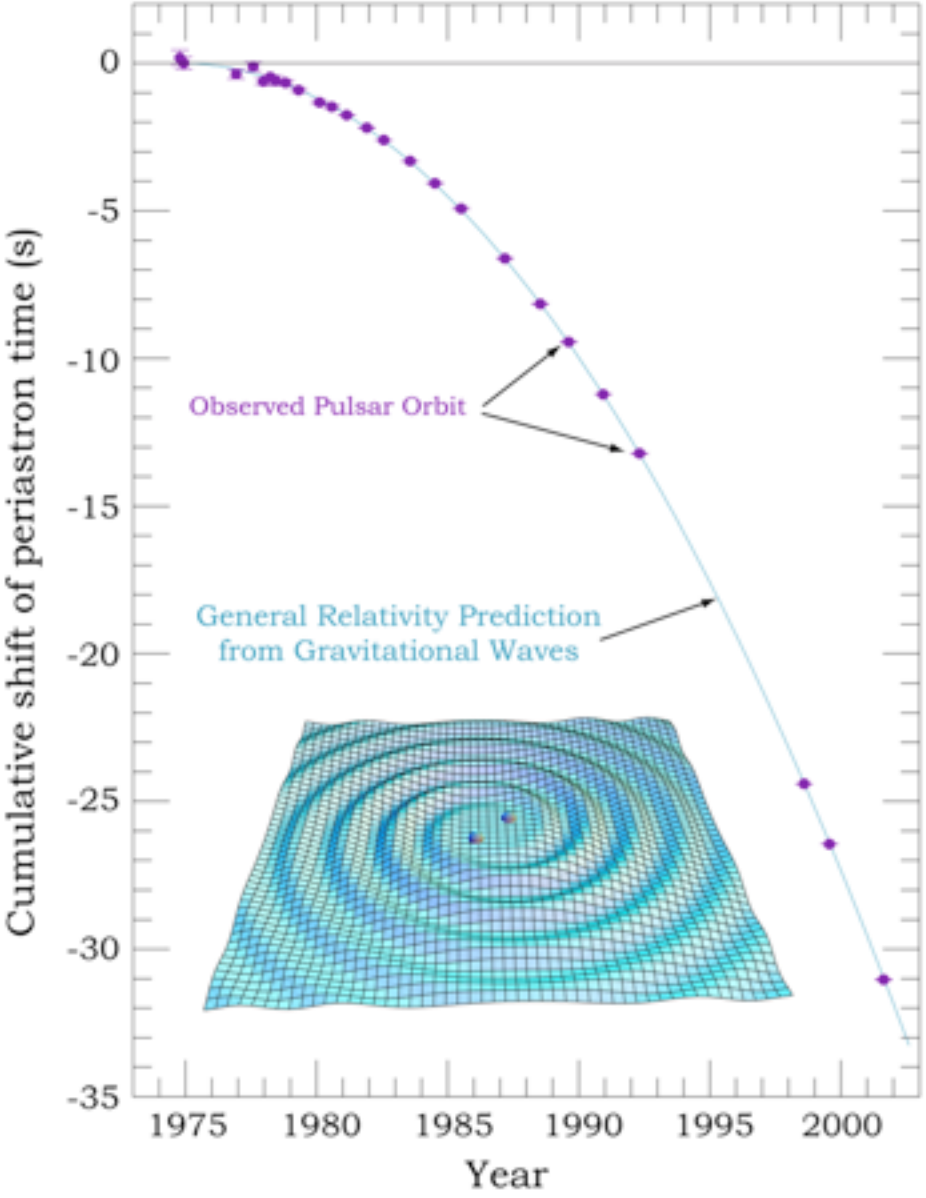
Binary stars with rapidly varying quadrupole moment lose energy due to GWs.

First one discovered in 1975; detailed study over decades showed orbit decay at

exactly

the rate predicted for GW emission.

Several such systems now known, all agree with GWs.



Direct measurement

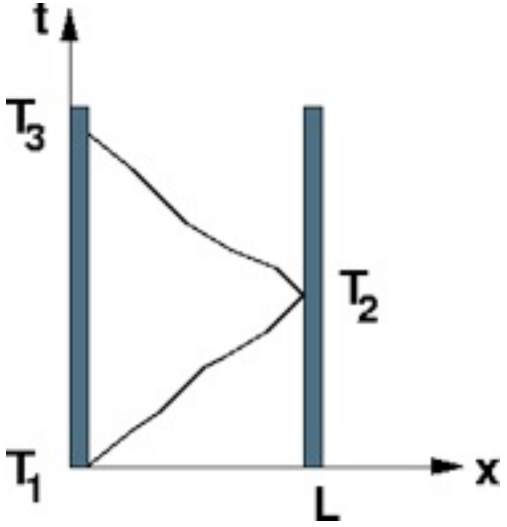
The GW is an oscillation in spacetime, has an impact on propagation of light:

$$ds^2 = -c^2 dt^2 + [1 + h(t, x)]\, dx^2 = 0$$

Speed of light in this coordinate system:

$$\frac{dx}{dt} = \frac{c}{\sqrt{1 + h(t, x)}}$$

Imagine mirrors that fall freely in this spacetime. Bounce light, record time between bounces.



Scott A. Hughes, MIT

Topics in Astroparticle and Underground Physics, 9 Sep 2013

Direct measurement

The GW *h* is an oscillation in spacetime, has an impact on propagation of light:

$$ds^2 = -c^2 dt^2 + [1 + h(t,x)]\,dx^2 = 0$$

Interval between bounces:

$$\Delta T = \int \frac{dx}{dx/dt} \simeq \frac{1}{c}\int \left[1 - \frac{1}{2}h(t,x)\right] dx$$

GW enters as oscillation in interval (Bondi 1957).

Magnitude of effect

Size of effect for interesting astrophysical sources can be estimated using

$$h \simeq \frac{G}{c^4}\frac{2mv^2}{r}$$

Magnitude of effect

Size of effect for interesting astrophysical sources can be estimated using

$$h \simeq \frac{G}{c^4}\frac{2mv^2}{r}$$

Typical sources have *m* ~ several Msun to several million Msun; v ~ 0.1 speed of light; *r* ~ 100s of Mpc to multiple Gpc:

Magnitude of effect

Size of effect for interesting astrophysical sources can be estimated using

$$h \simeq \frac{G}{c^4} \frac{2mv^2}{r}$$

Typical sources have *m* ~ several Msun to several million Msun; v ~ 0.1 speed of light; *r* ~ 100s of Mpc to multiple Gpc:

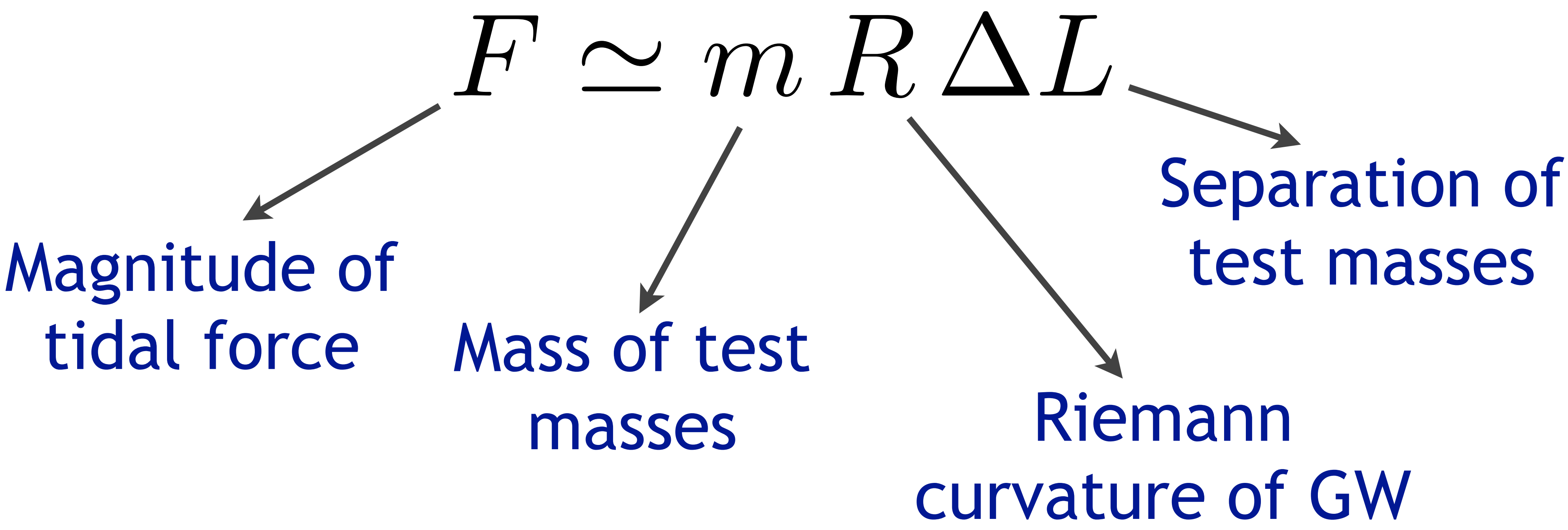
$$h \sim 10^{-21} - 10^{-23}$$

Not as bad as you might guess

Recall GW acts as a *tide*: Can convert GW *strain* to tidal *force*. Gives a good sense of challenge for isolating from noise:

Not as bad as you might guess

Recall GW acts as a *tide*: Can convert GW *strain* to tidal *force*. Gives a good sense of challenge for isolating from noise:



$$F \simeq m\,R\,\Delta L$$

Magnitude of tidal force

Mass of test masses

Riemann curvature of GW

Separation of test masses

Not as bad as you might guess

Recall GW acts as a *tide*: Can convert GW *strain* to tidal *force*. Gives a good sense of challenge for isolating from noise:

$$F \simeq m R \Delta L$$

Plug in

$$R \simeq \omega^2 h$$

Not as bad as you might guess

Recall GW acts as a *tide*: Can convert GW *strain* to tidal *force*. Gives a good sense of challenge for isolating from noise:

$$F \approx 1\,\mathrm{picoNewton} \left(\frac{m}{10\,\mathrm{kg}}\right) \left(\frac{f}{100\,\mathrm{Hz}}\right)^2 \left(\frac{4000\,\mathrm{m}}{\Delta L}\right) \left(\frac{h}{10^{-22}}\right)$$

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

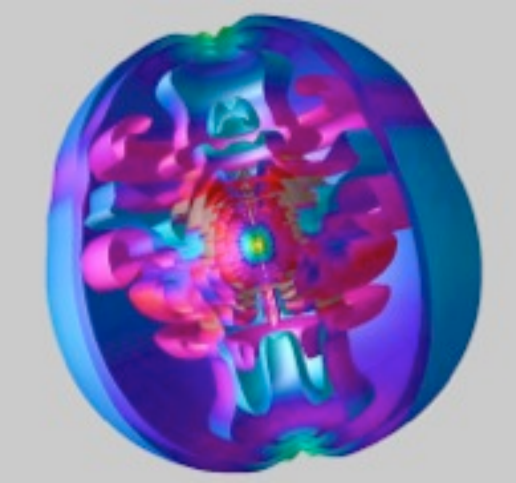
Measuring GWs requires isolating from forces of this magnitude in chosen frequency band.

What we gain

Weakness of GWs is a curse as we try to measure them ... but it becomes a *blessing* when we begin to interpret the information that a measured wave carries.

Reason: Waves barely interact with matter as they propagate from their source.

Carry a “pristine” map of source dynamics.

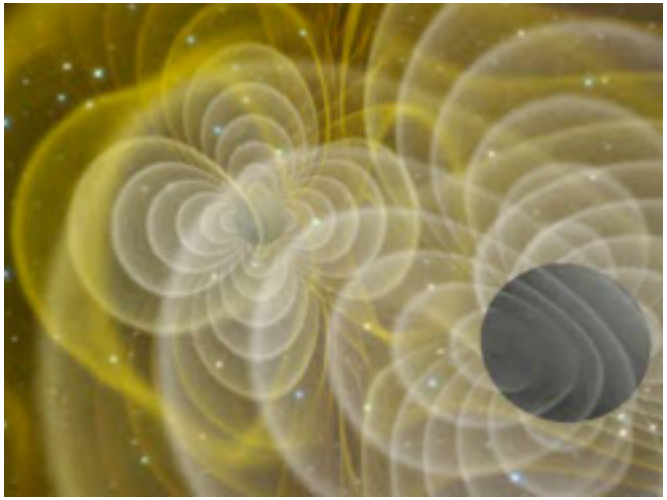


Inner engine of supernovae: Directly imprinted on core collapse waveform

What we gain

Weakness of GWs is a curse as we try to measure them ... but it becomes a *blessing* when we begin to interpret the information that a measured wave carries.

Reason: Waves barely interact with matter as they propagate from their source. Carry a “pristine” map of source dynamics.

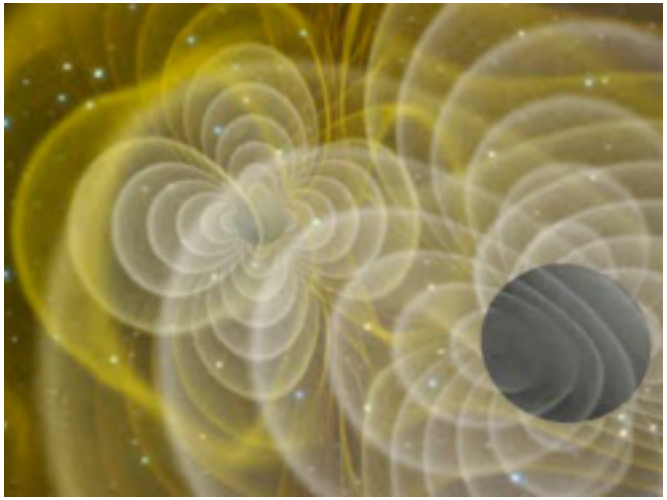


Gravitational dynamics of interacting black holes likewise imprinted on GWs.

What we gain

Weakness of GWs is a curse as we try to measure them ... but it becomes a *blessing* when we begin to interpret the information that a measured wave carries.

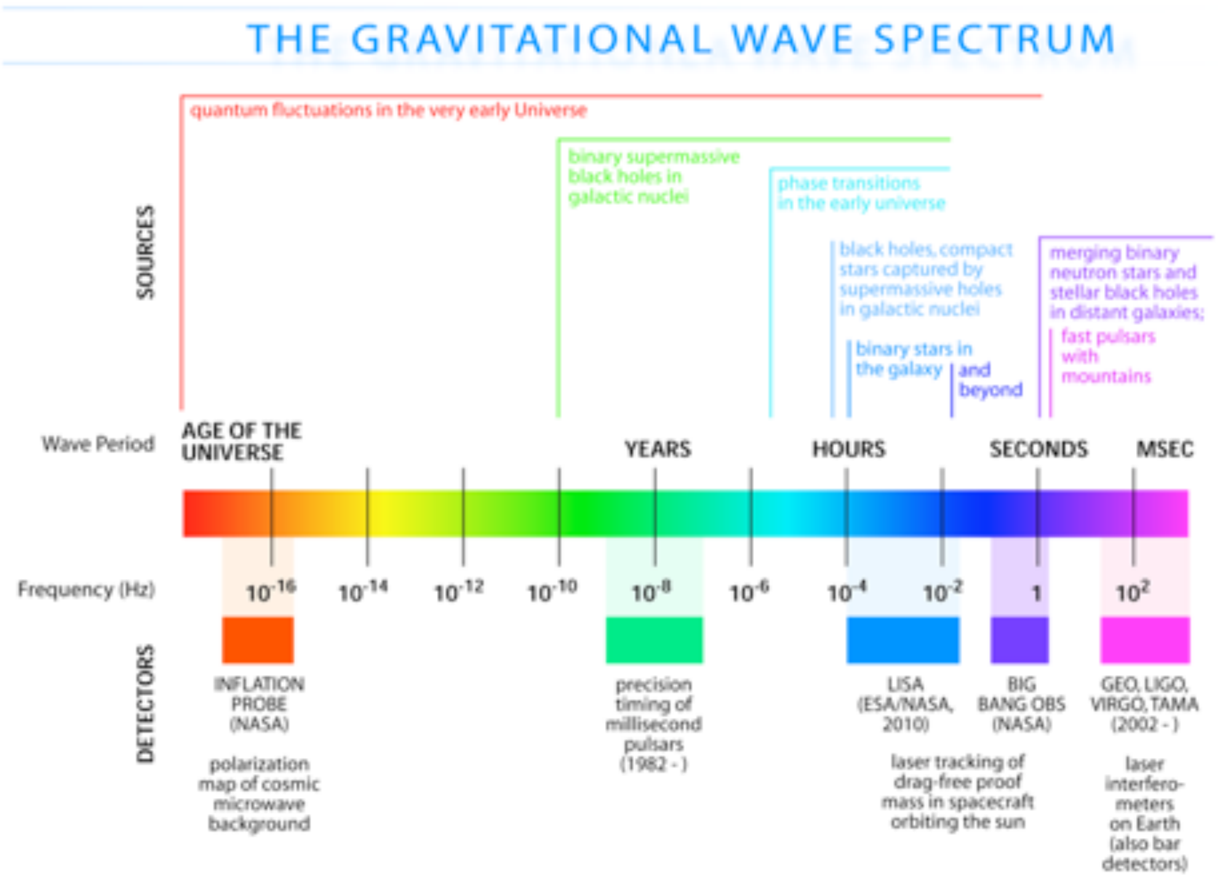
For cosmology, only strong effect on waves is gravitational lensing ... propagate unimpeded from very early redshifts to our detectors.



Gravitational dynamics of interacting black holes likewise imprinted on GWs.

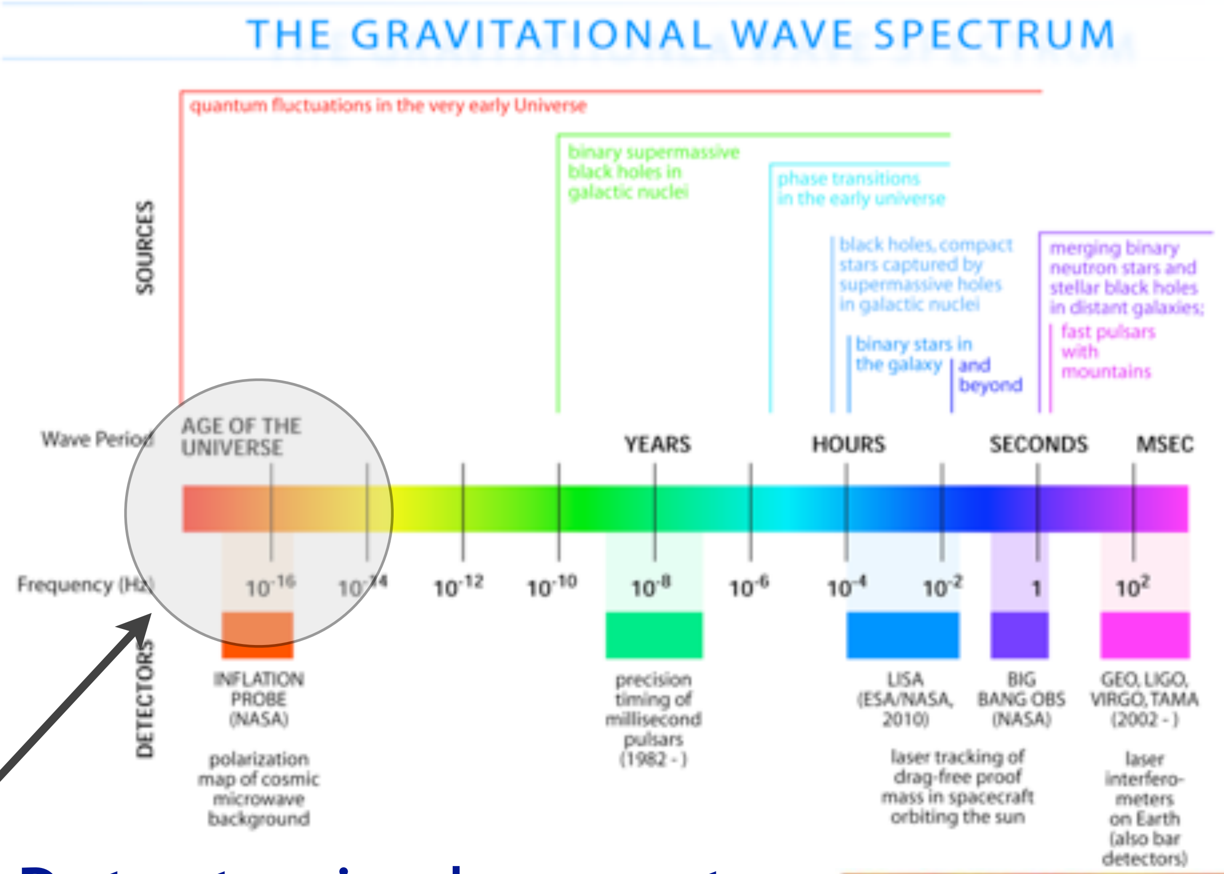
Programs to measure GWs

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

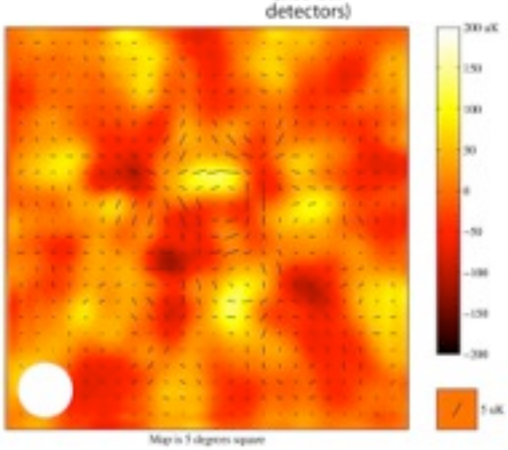


Programs to measure GWs

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



Lowest frequencies: Detector is plasma at recombination. Tidal GWs imprint unique signature in polarization of photons that begin free-streaming at that time.



Programs to measure GWs

More specifically, use the fact that CMB polarization can be decomposed by parity:

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

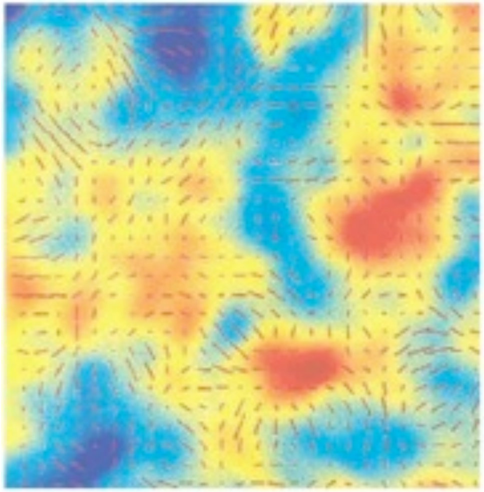
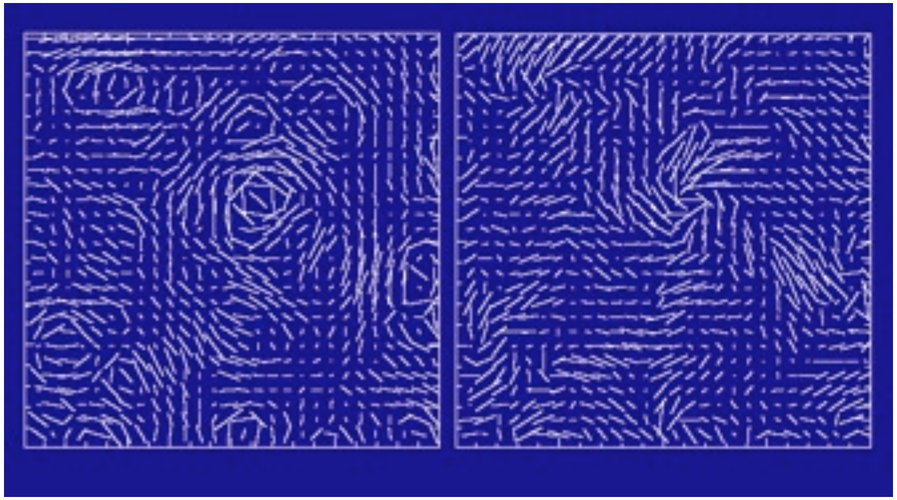


Image by Wayne Hu
http://background.uchicago.edu/~whu/intermediate/Polarization/polar5.html



Even parity polarization modes

Odd parity polarization modes

Programs to measure GWs

More specifically, use the fact that CMB polarization can be decomposed by parity:

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

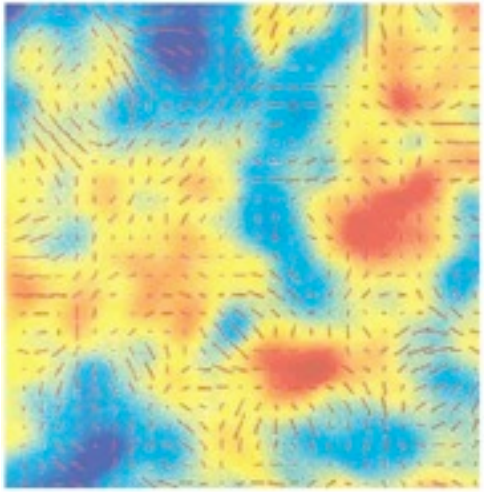
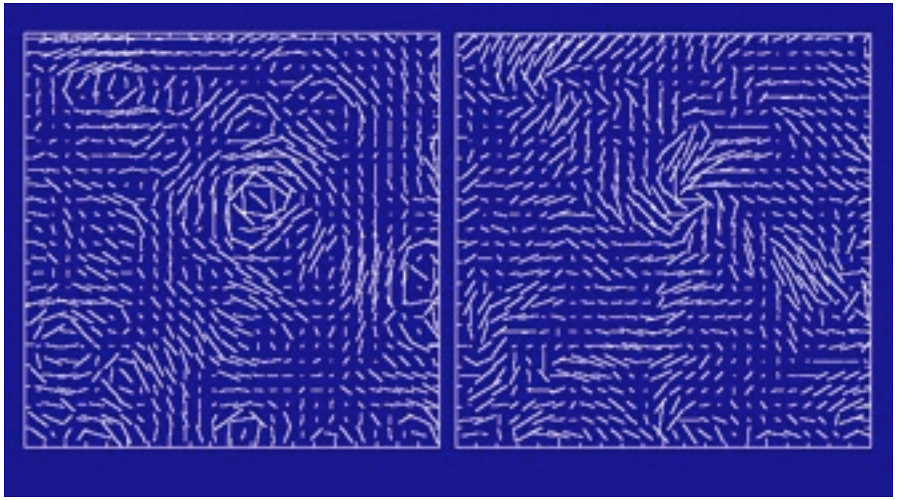


Image by Wayne Hu
http://background.uchicago.edu/~whu/intermediate/Polarization/polar5.html



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

Programs to measure GWs

More specifically, use the fact that CMB polarization can be decomposed by parity:

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

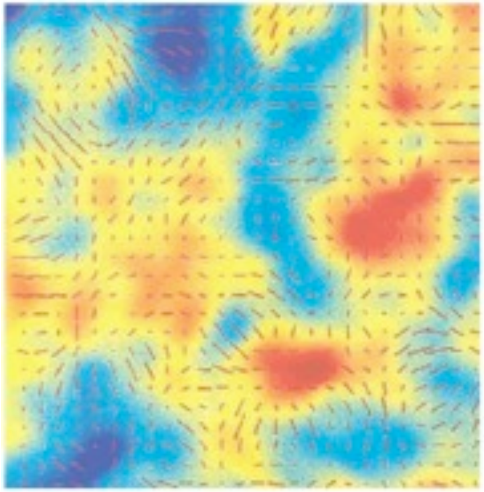
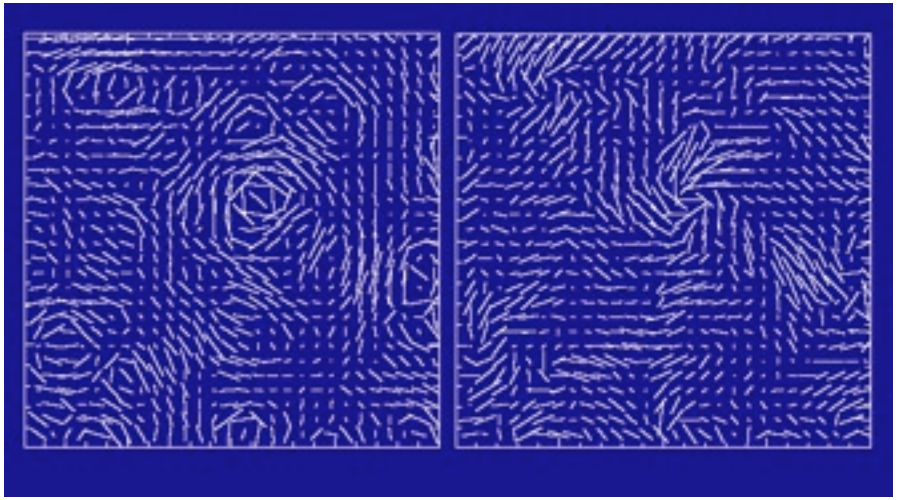


Image by Wayne Hu
http://background.uchicago.edu/~whu/intermediate/Polarization/polar5.html



Odd parity (*B*-modes): 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.)

Programs to measure GWs

More specifically, use the fact that CMB polarization can be decomposed by parity:

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

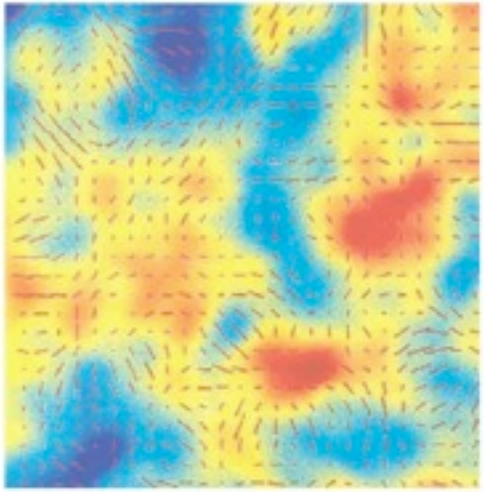
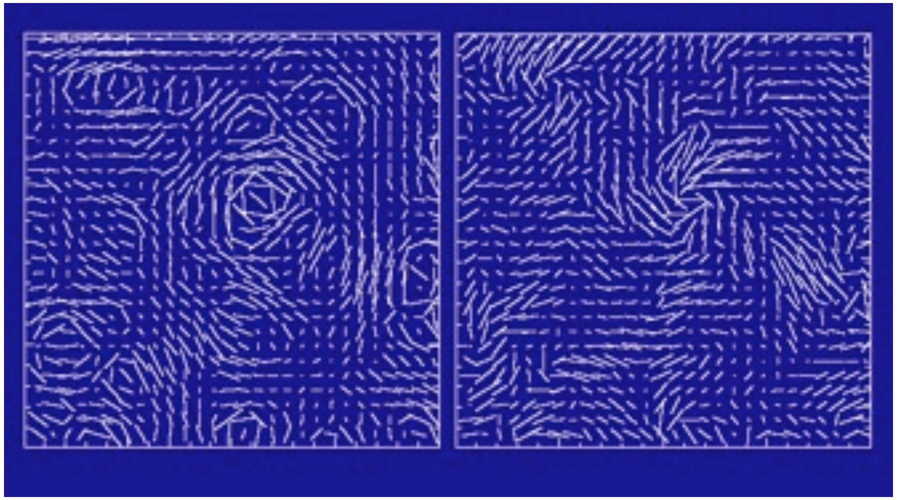


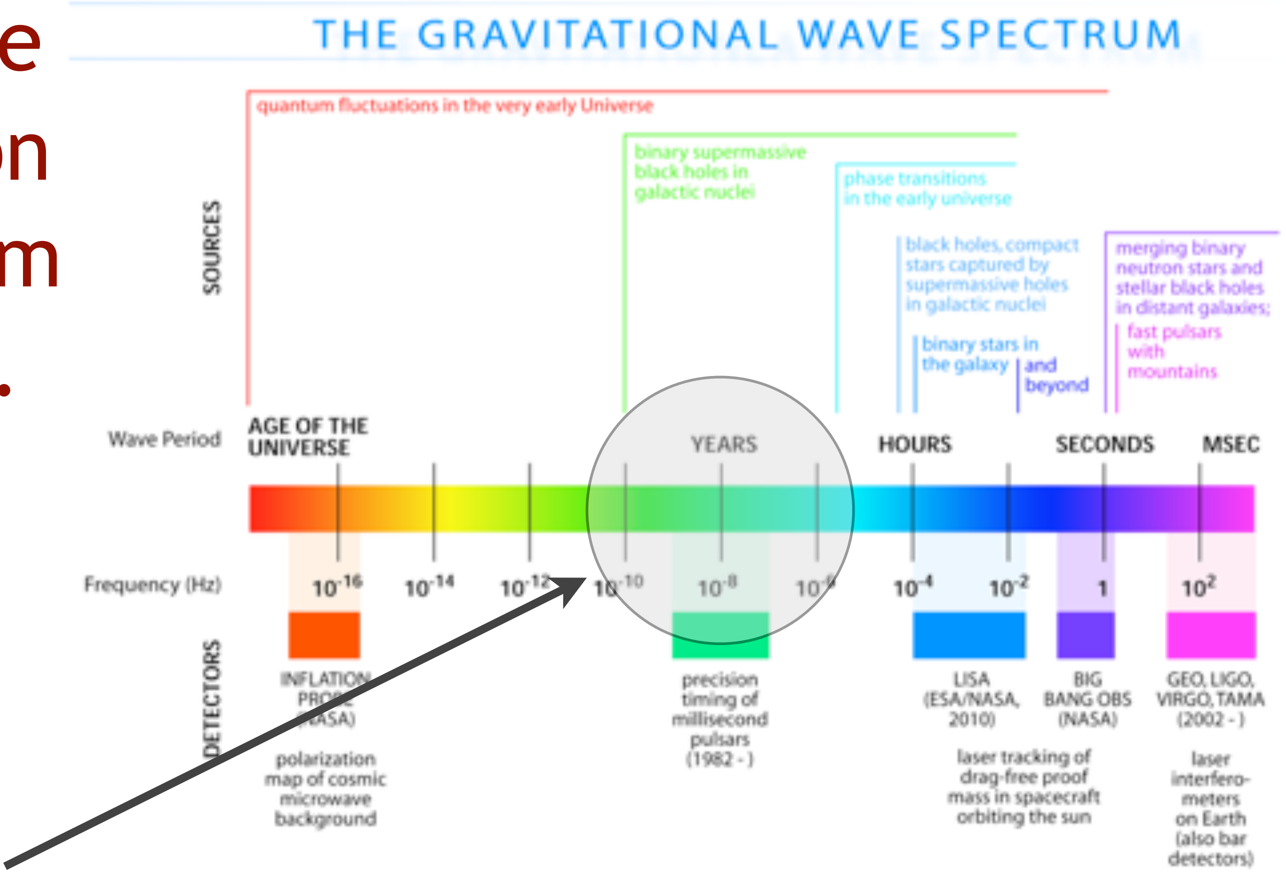
Image by Wayne Hu
http://background.uchicago.edu/~whu/intermediate/Polarization/polar5.html

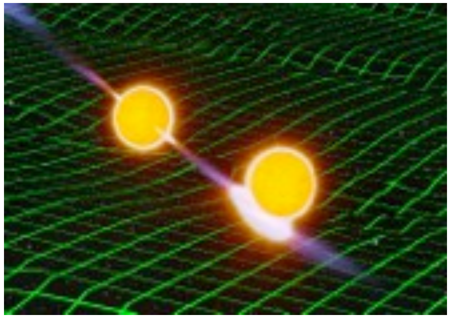


Direct detection of *B*-modes — plus detailed understanding of foregounds from lensing — measures GWs on longest lengthscales.

Programs to measure GWs

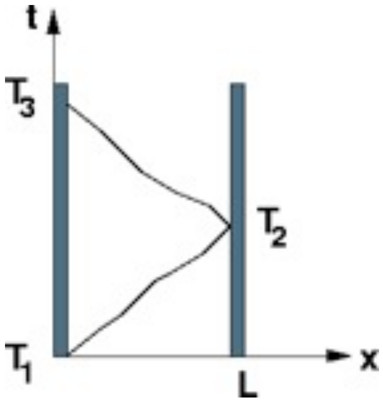
How you measure waves depends on where in spectrum you are probing.





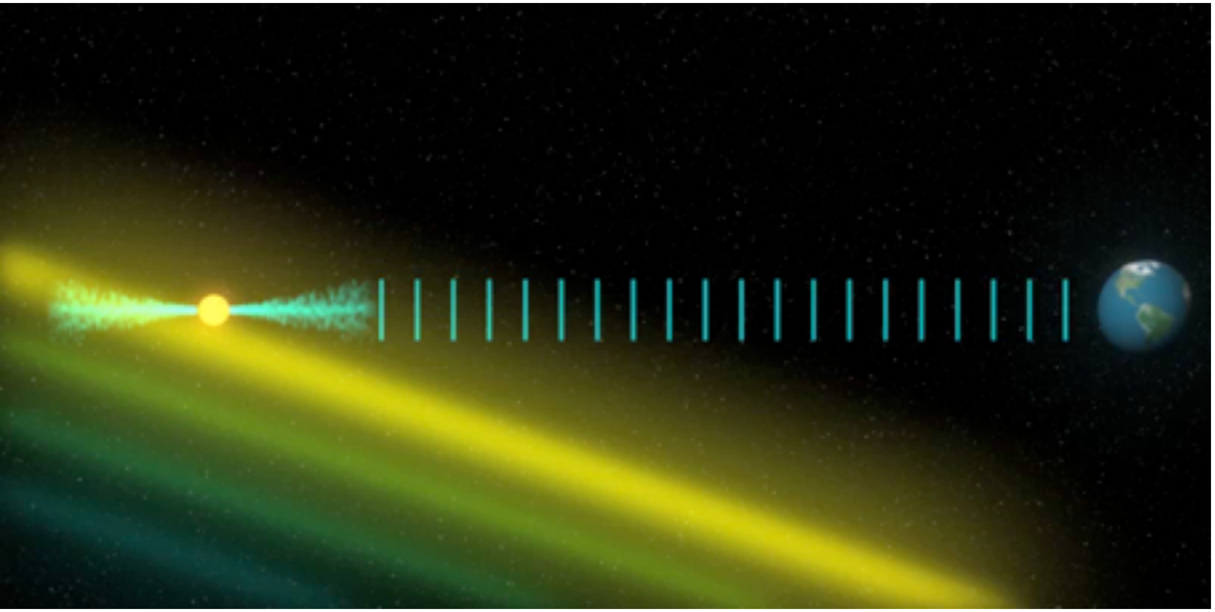
Year periods: Millisecond pulsars as light source, radio telescope as receiver. Enough pulsars & control of timing noise, can detect backgrounds!

Currently sets best limit.



NANOGrav (nanograv.org)

Developing network of pulsars with “nice” properties that can be used as clocks to detect GWs with periods of months to years.



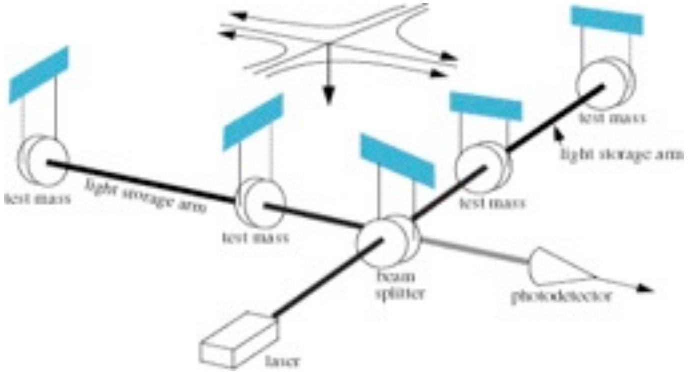
Movie courtesy Penn State Gravitational Wave Astronomy Group, http://gwastro.org

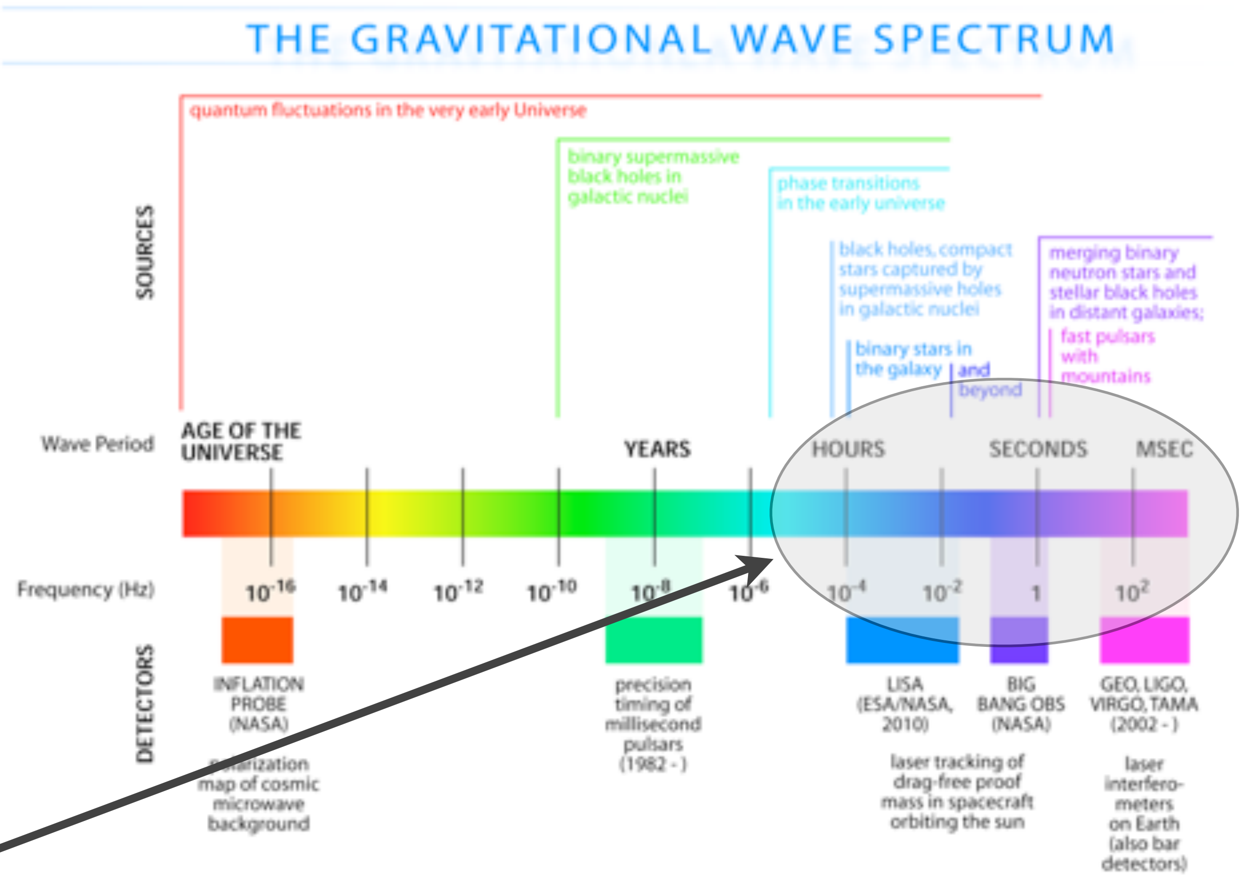
Presently: ~30 pulsars in network; set upper limit on a “stochastic background” of waves in this band.

Close to predictions of background from a population of cosmological black hole binaries.

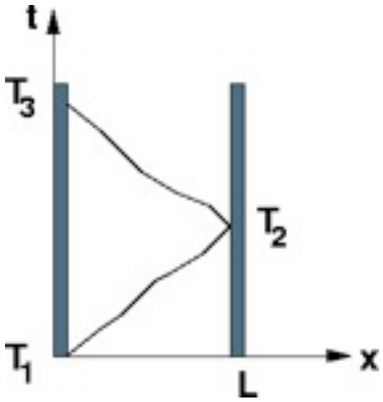
Programs to measure GWs

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





Hours to msec periods: Direct implementation of Bondi’s freely falling mirrors using laser interferometry.



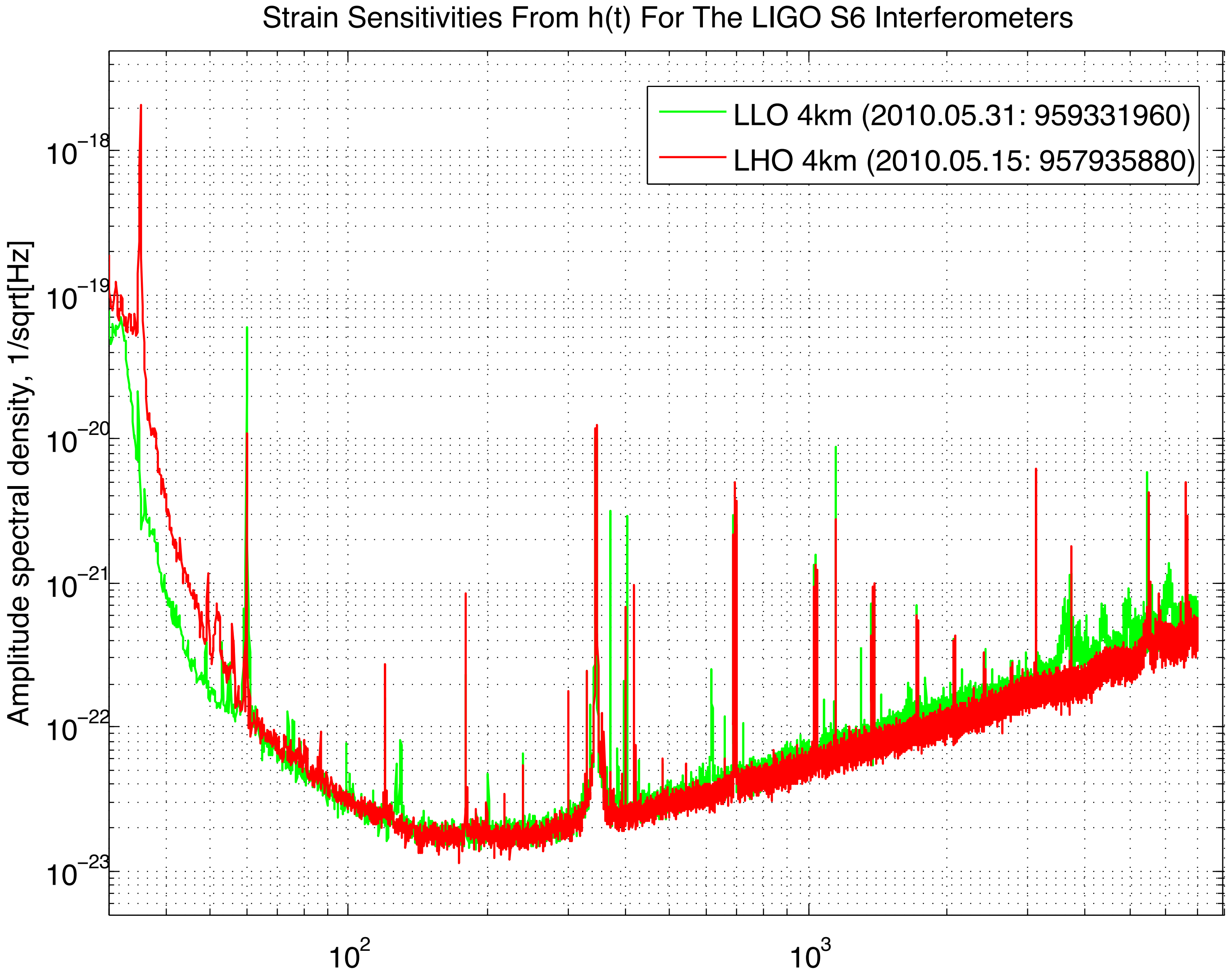
Ground-based detectors

Three large-scale facilities now 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.

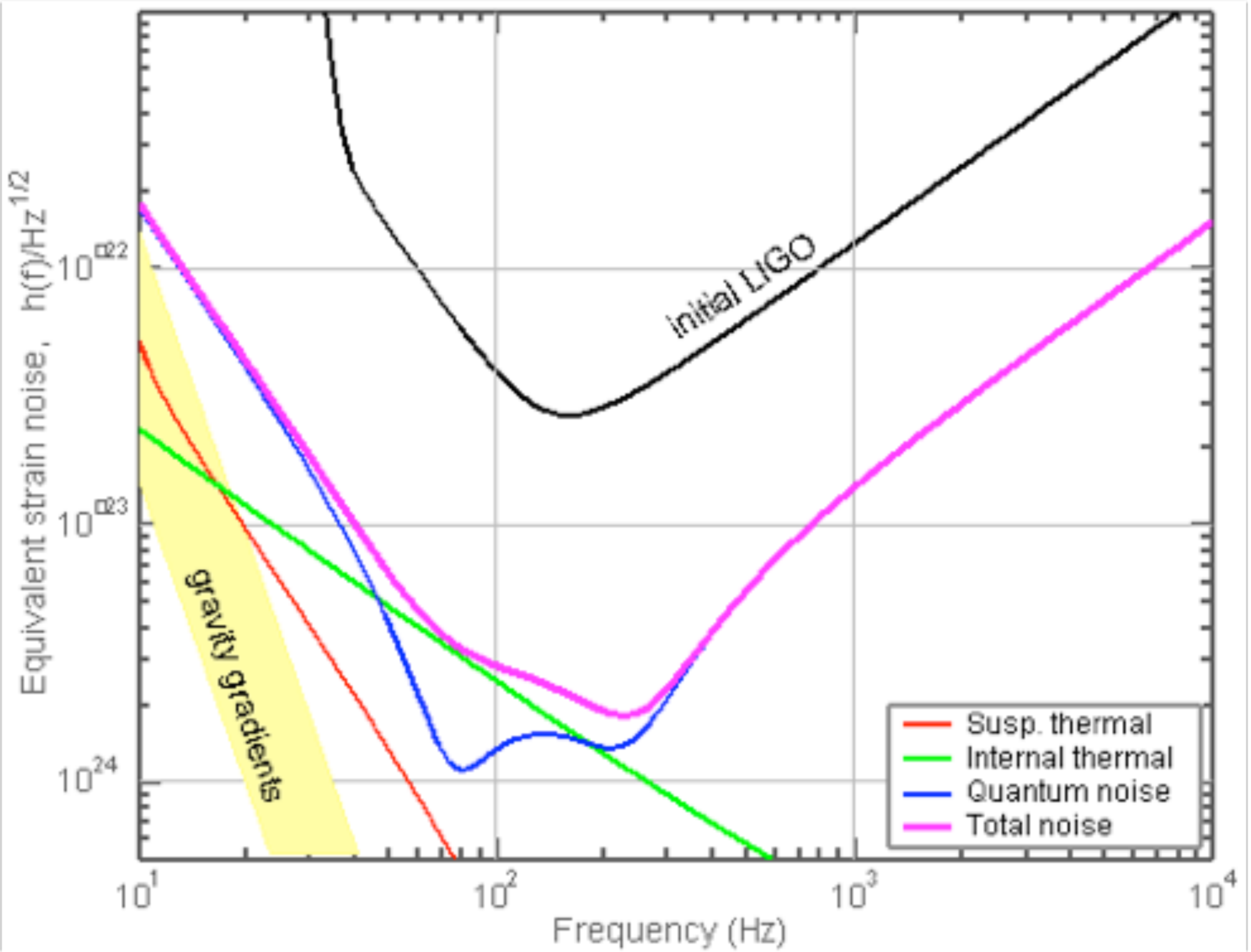
Recently completed initial runs ... undergoing upgrades to "advanced" sensitivity, to begin operations in 2015.

Initial detectors



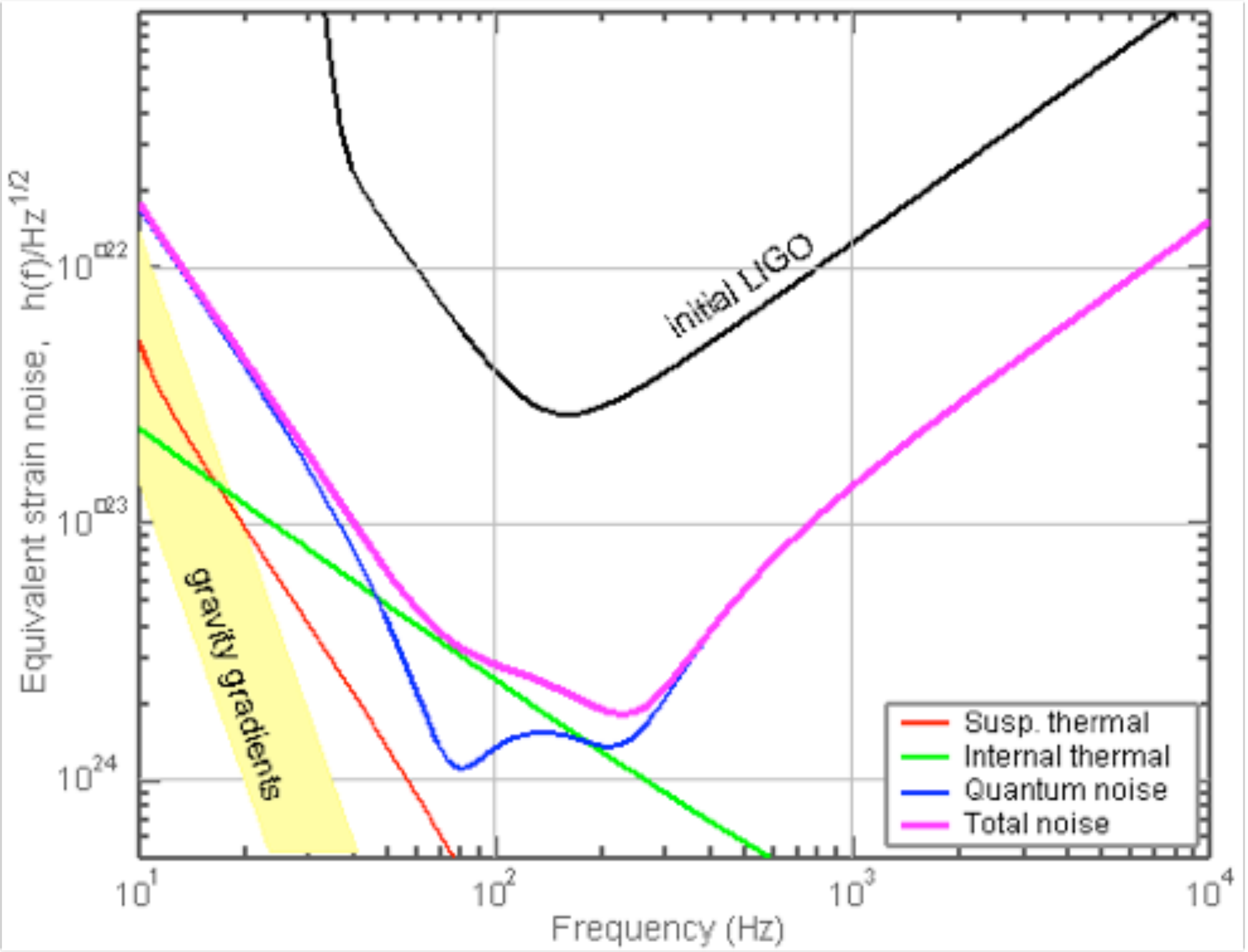
Sensitive to binary inspiral to ~20 Mpc.

Advanced detectors (2015)



By increasing laser power and mirror masses, can reach a detector with sensitivity essentially limited by the uncertainty principle.

Advanced detectors (2015)

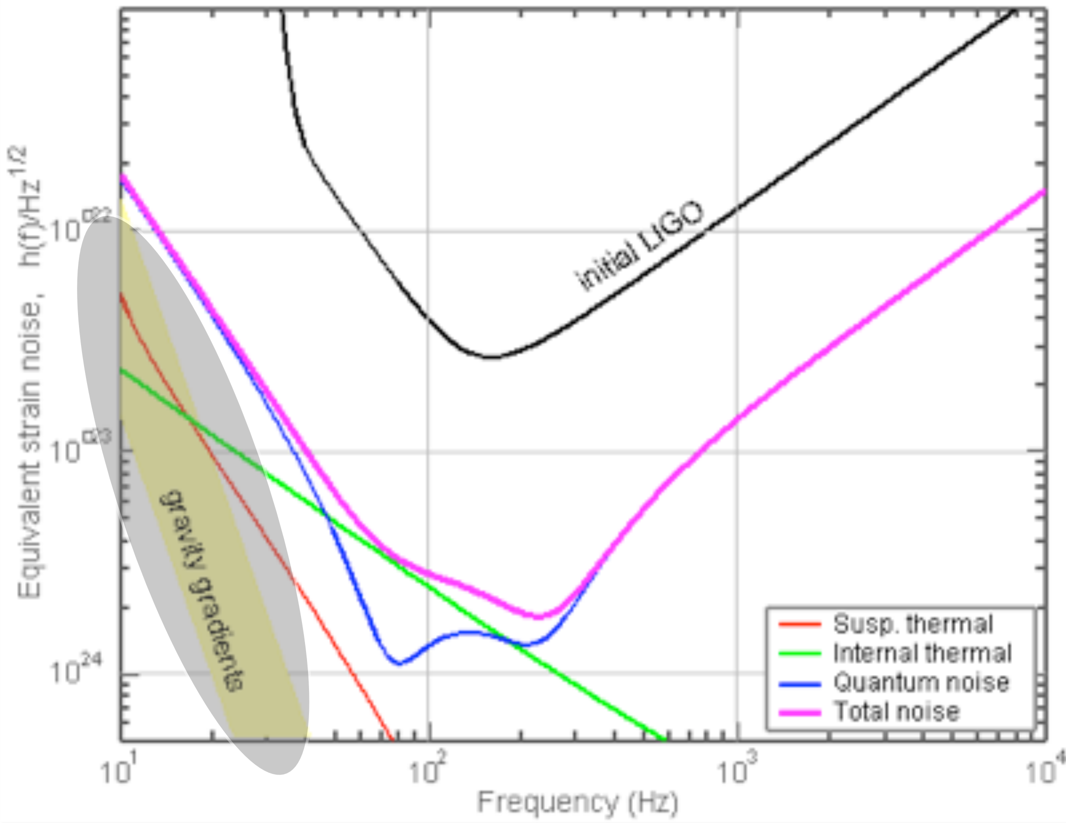


Reach to binary inspiral: A few hundred Mpc.

At this sensitivity, detections are expected.

Advanced detectors (2015)

Lowest frequency sensitivity limited by gravitational couplings to mass fluctuations in the local environment: “Newtonian noise.”



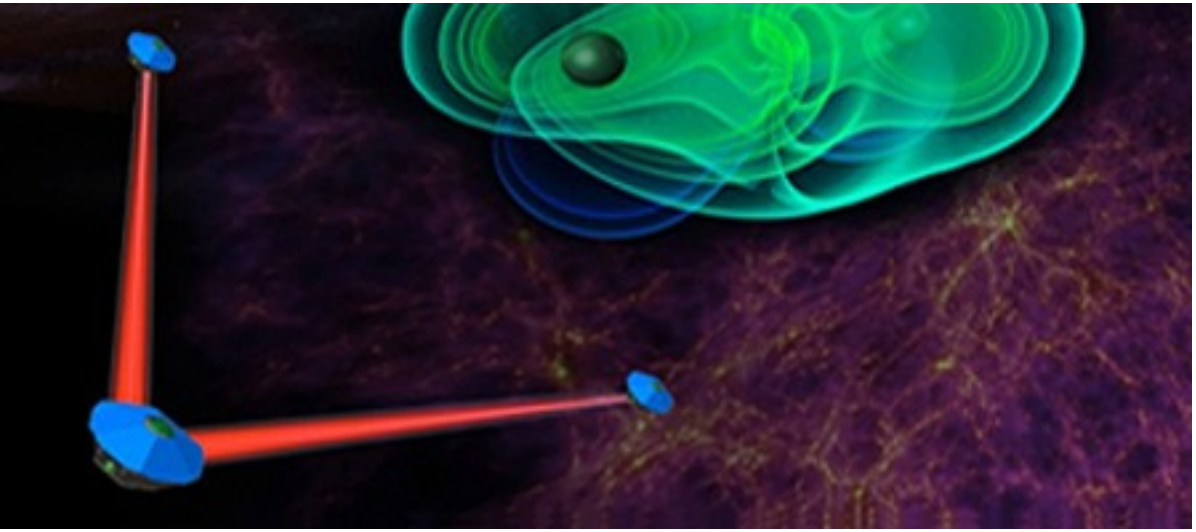
Part of the cure: **Go underground!**

Major sources of this noise are surface seismic modes, which sharply attenuate with depth.

Detailed discussion: Harms et al, arXiv:1308.2074

Worldwide network

eLISA



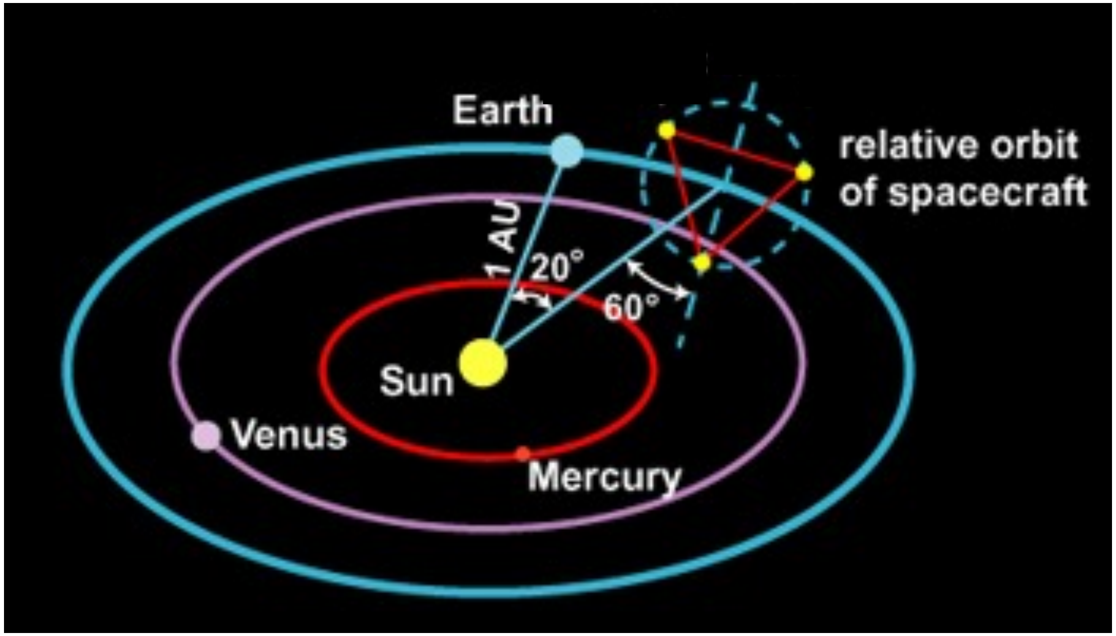
10^6 kilometer space-based interferometer.

ESA mission (?) for next decade, evolved from LISA concept.

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

$\sim 10^{-4}$ Hz < f < 0.1 Hz

Largely targets processes involving massive black holes.



Astrophysics and Cosmology

I: Relics from the early universe

Early universe "seeded" with spectrum of GWs … essentially zero-point fluctuations of spacetime.

Fluctuations evolve according to wave equation

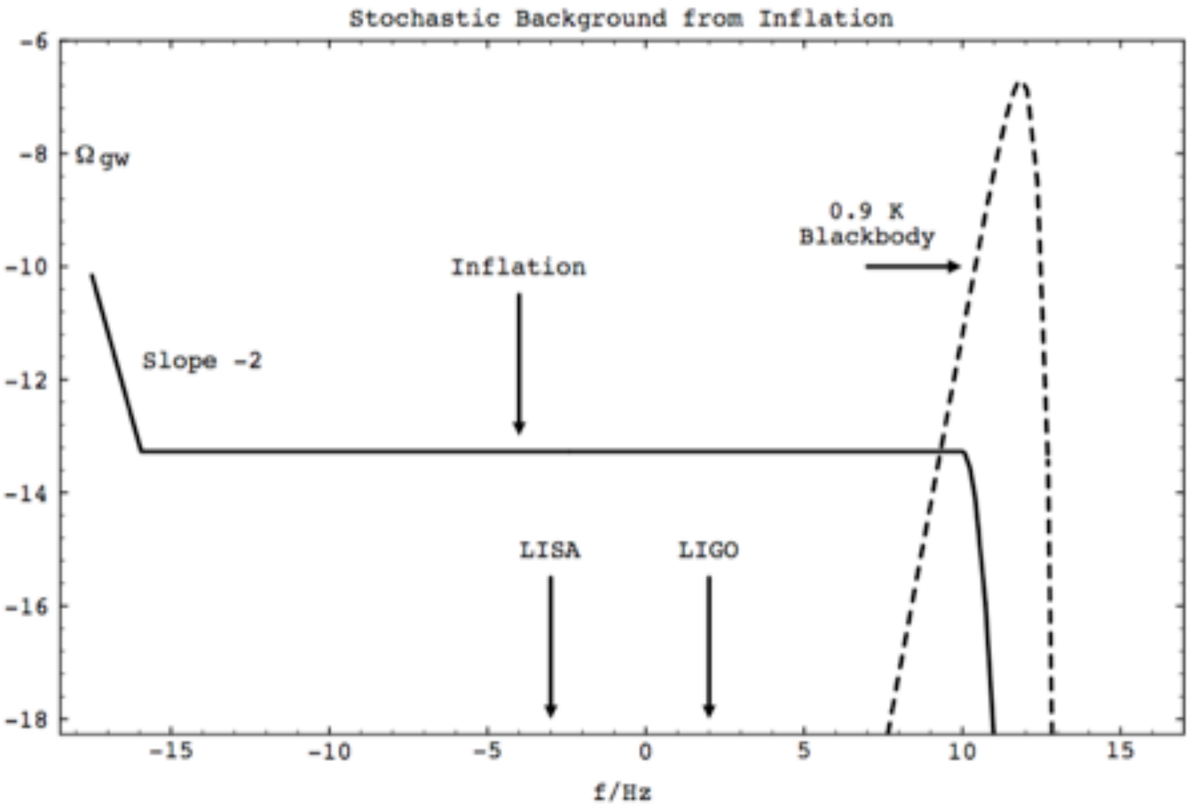
$$\frac{d^2\phi}{d\eta^2} + \frac{2}{a}\frac{da}{d\eta}\frac{d\phi}{d\eta} + k^2\phi = 0$$

where *Φ* parameterizes amplitude, *a* is universe's scale factor, *k* is wavenumber 2*π*/*λ*, and *η* is a time variable.

Evolution quite interesting in inflationary universe: Mode wavelength inflates while Hubble scale *a*/(*da*/*dt*) is constant. Mode amplitude is parametrically amplified until λ exceeds Hubble scale, then freezes.

I: Relics from the early universe

Start with a spectrum of zero-point fluctuations, end with a spectrum whose features encode properties of inflationary potential!

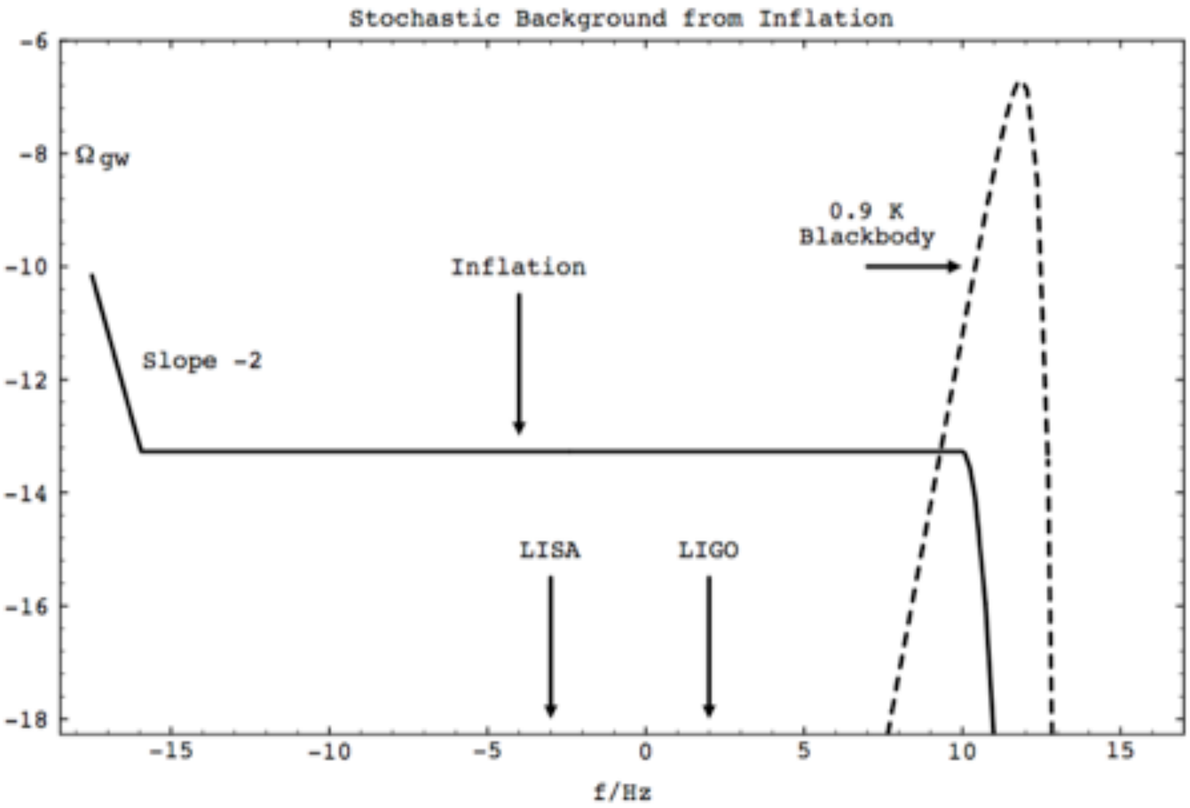


From B. Allen, gr-qc/9604033 (Proceedings of Les Houche School: Astrophysical sources of Gravitational Radiation)

Typical spectrum of inflationary waves: Rises as f^{-2} at low freq (waves that re-enter Hubble volume in matter dominated era), and is flat elsewhere.

I: Relics from the early universe

Start with a spectrum of zero-point fluctuations, end with a spectrum whose features encode properties of inflationary potential!



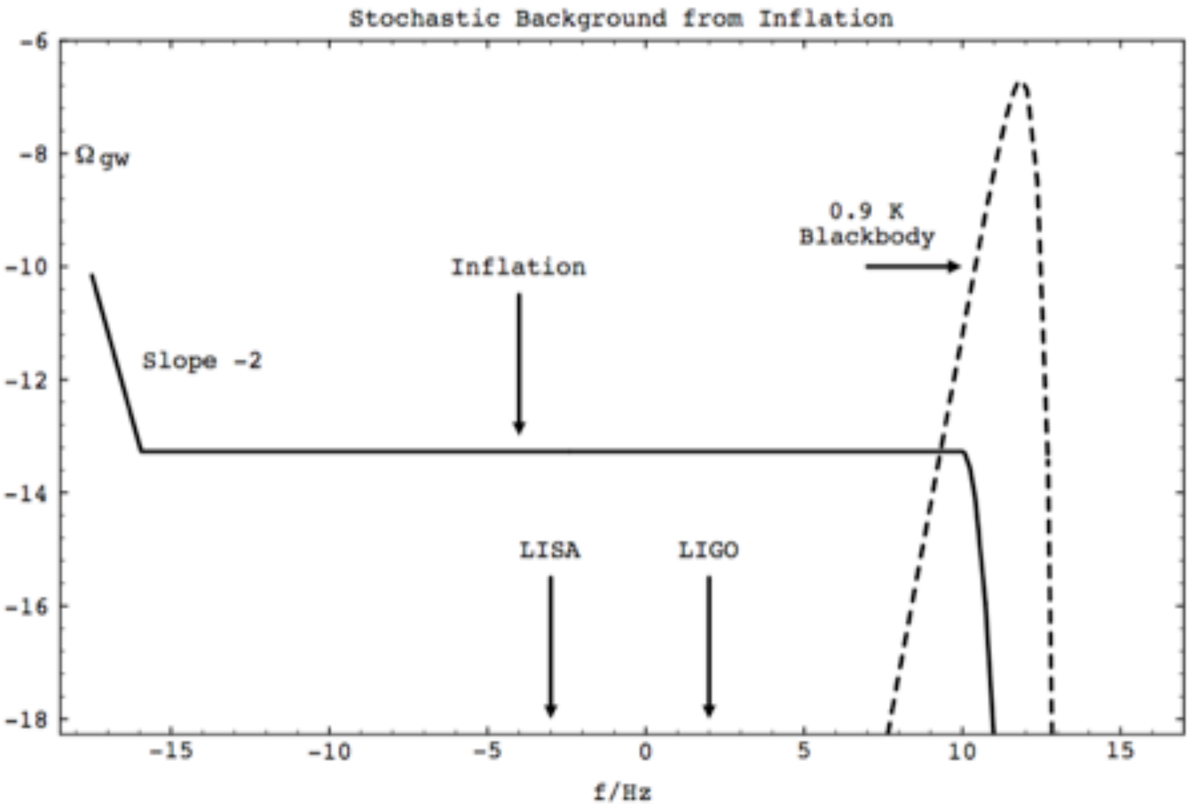
From B. Allen, gr-qc/9604033 (Proceedings of Les Houche School: Astrophysical sources of Gravitational Radiation)

Level of the spectrum directly encodes the inflationary potential!

Measurement of these waves called “smoking gun” of inflation, especially if it can be done at multiple *f*.

I: Relics from the early universe

Start with a spectrum of zero-point fluctuations, end with a spectrum whose features encode properties of inflationary potential!



From B. Allen, gr-qc/9604033 (Proceedings of Les Houche School: Astrophysical sources of Gravitational Radiation)

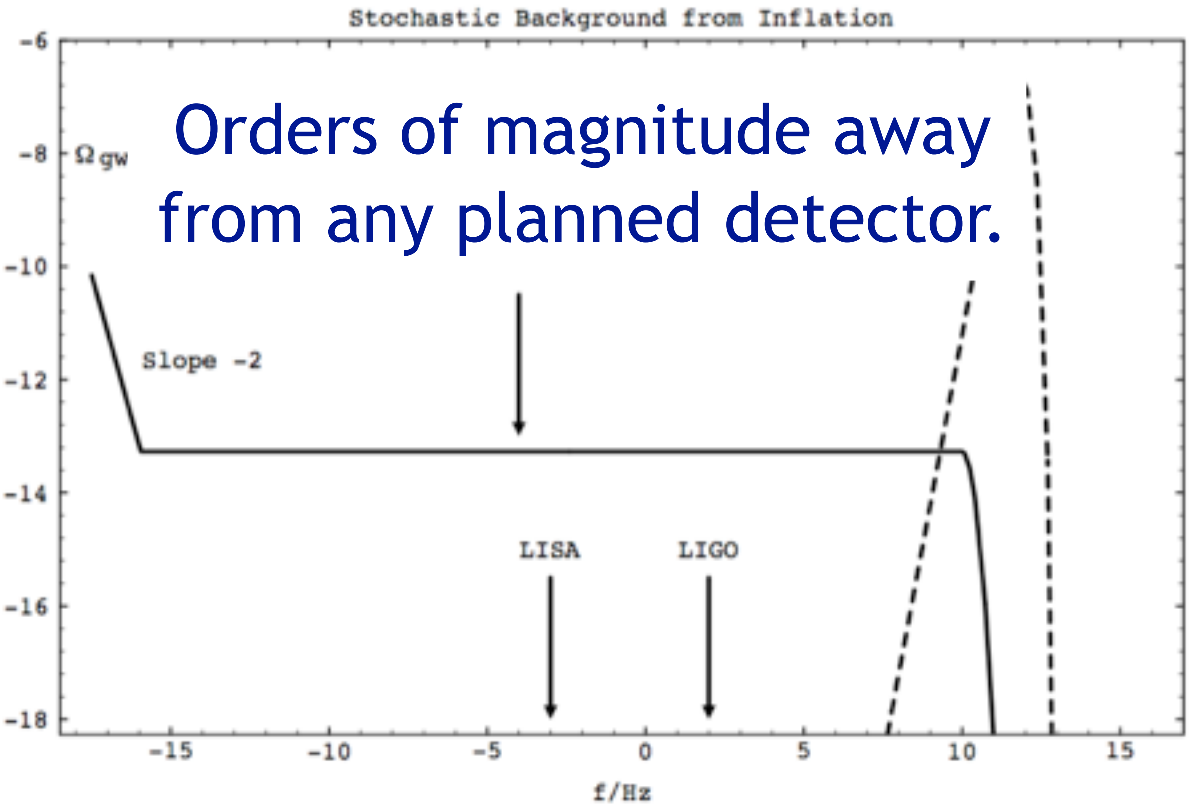
Level of the spectrum directly encodes the inflationary potential!

Extremely challenging.

At lowest frequencies, requires detangling lensed *E* modes from “primordial” *B* modes

I: Relics from the early universe

Start with a spectrum of zero-point fluctuations, end with a spectrum whose features encode properties of inflationary potential!



Orders of magnitude away from any planned detector.

From B. Allen, gr-qc/9604033 (Proceedings of Les Houche School: Astrophysical sources of Gravitational Radiation)

Level of the spectrum directly encodes the inflationary potential!

Extremely challenging.

Higher *f*: must measure weak stochastic GWs ... typically masked by more prosaic sources.

II: Precision distances

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

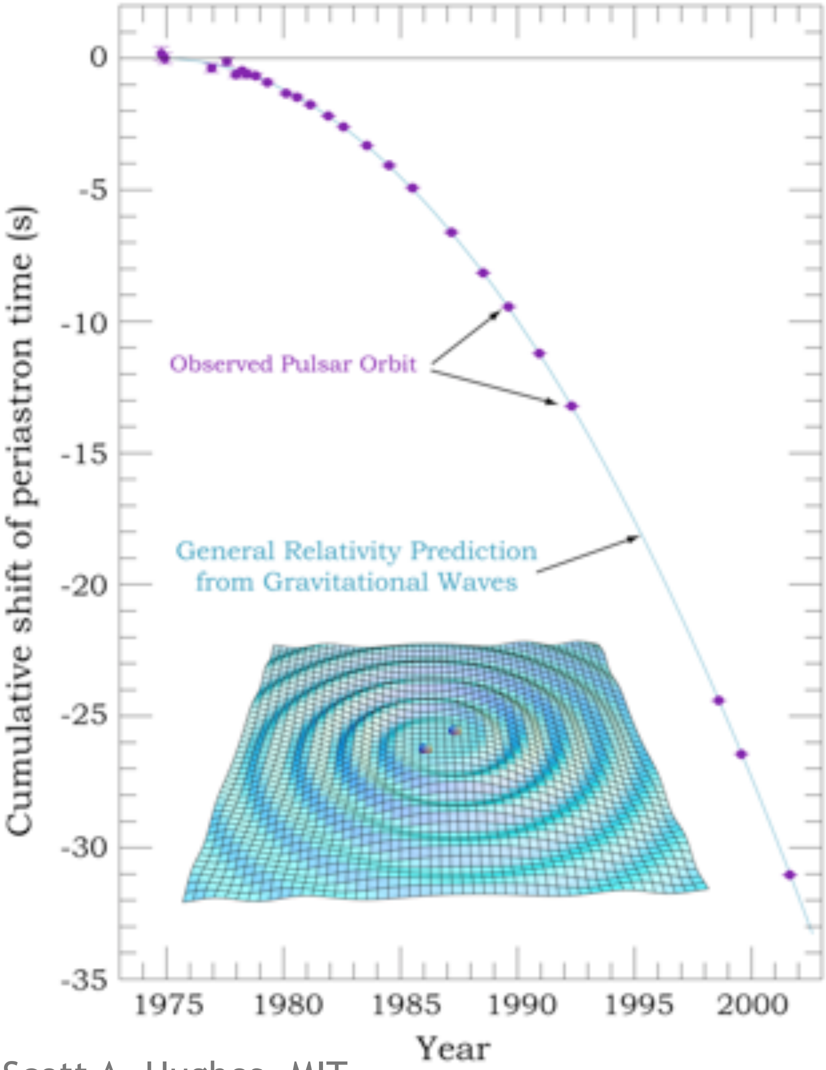
Perfect candle: Simple radiator (e.g., dipole) in which the radiative moment evolves in a slow, predictable way.

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

Read off ω from radiation. If we could read off time-changing dipole moment, easy to get distance.

II: Precision distances

Binary coalescence *is* this “perfect” standard candle!



Rate at which frequency changes determined by binary’s mass quadrupole ... observing “chirp” measures this moment.

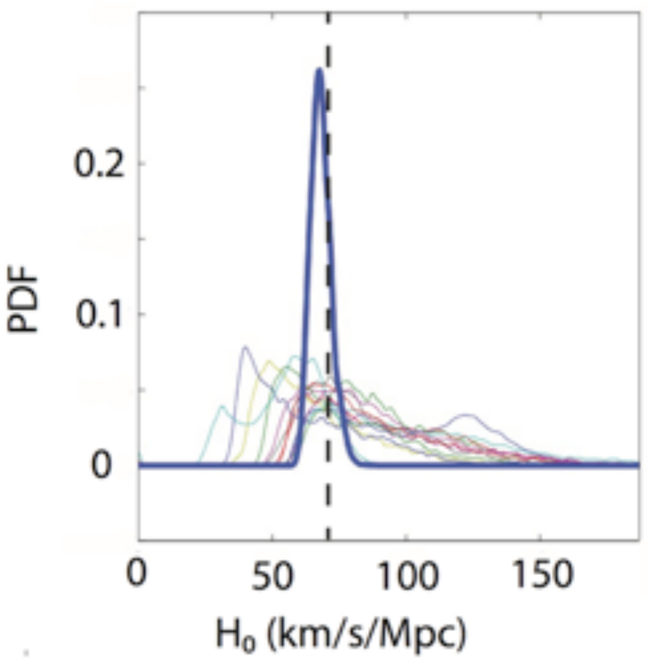
Measuring both GW polarizations determines angular factors.

Distance to binary is then fixed by measured amplitude of the wave.

II: Precision distances

Binary coalescence *is* this “perfect” standard candle!

GW distance plus “electromagnetic” redshift allows us to determine cosmology ... with *very* different systematics from other techniques.



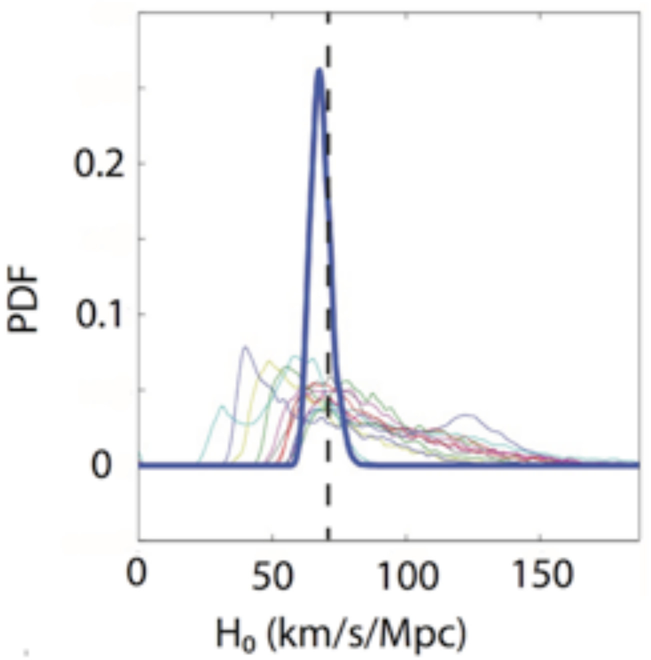
Recent work (Nissanke et al, arXiv: 1307.2638) examines how well GW plus EM counterpart determines Hubble:

About 10 events needed for H_0 to be competitive with other methods ... could help resolve tension between methods.

II: Precision distances

Binary coalescence *is* this “perfect” standard candle!

GW distance plus “electromagnetic” redshift allows us to determine cosmology ... with *very* different systematics from other techniques.

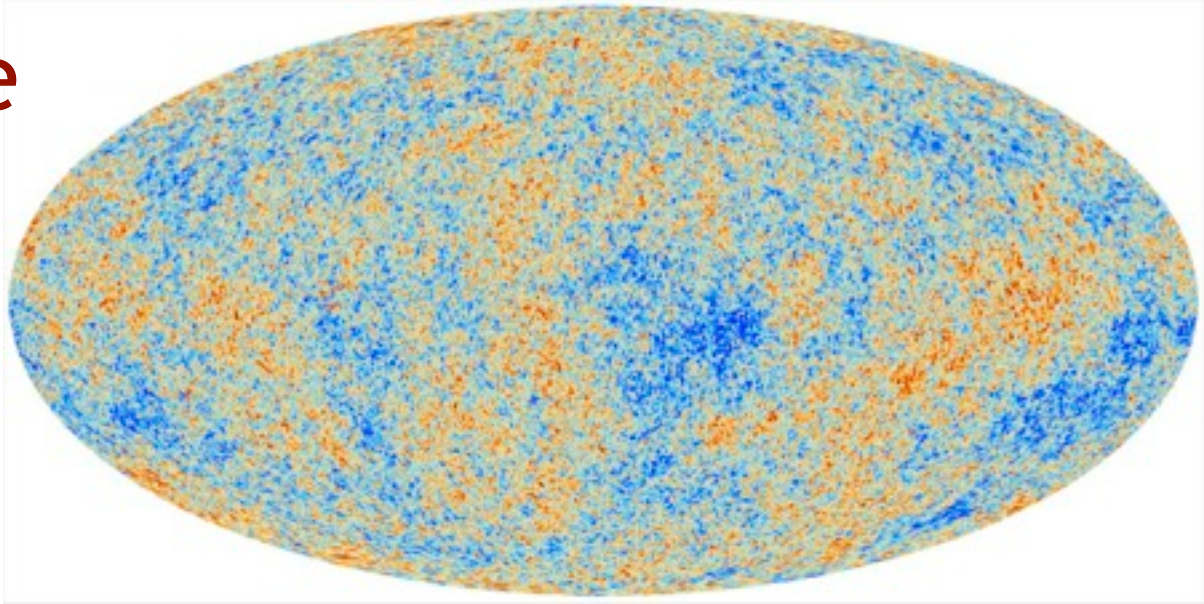


Recent work (Nissanke et al, arXiv: 1307.2638) examines how well GW plus EM counterpart determines Hubble:

Need close coordination between GW facilities and (wide spectrum) electromagnetic telescopes.

III: The growth of cosmic structure

Cosmic microwave background gives first glimpse of the universe’s largest structures

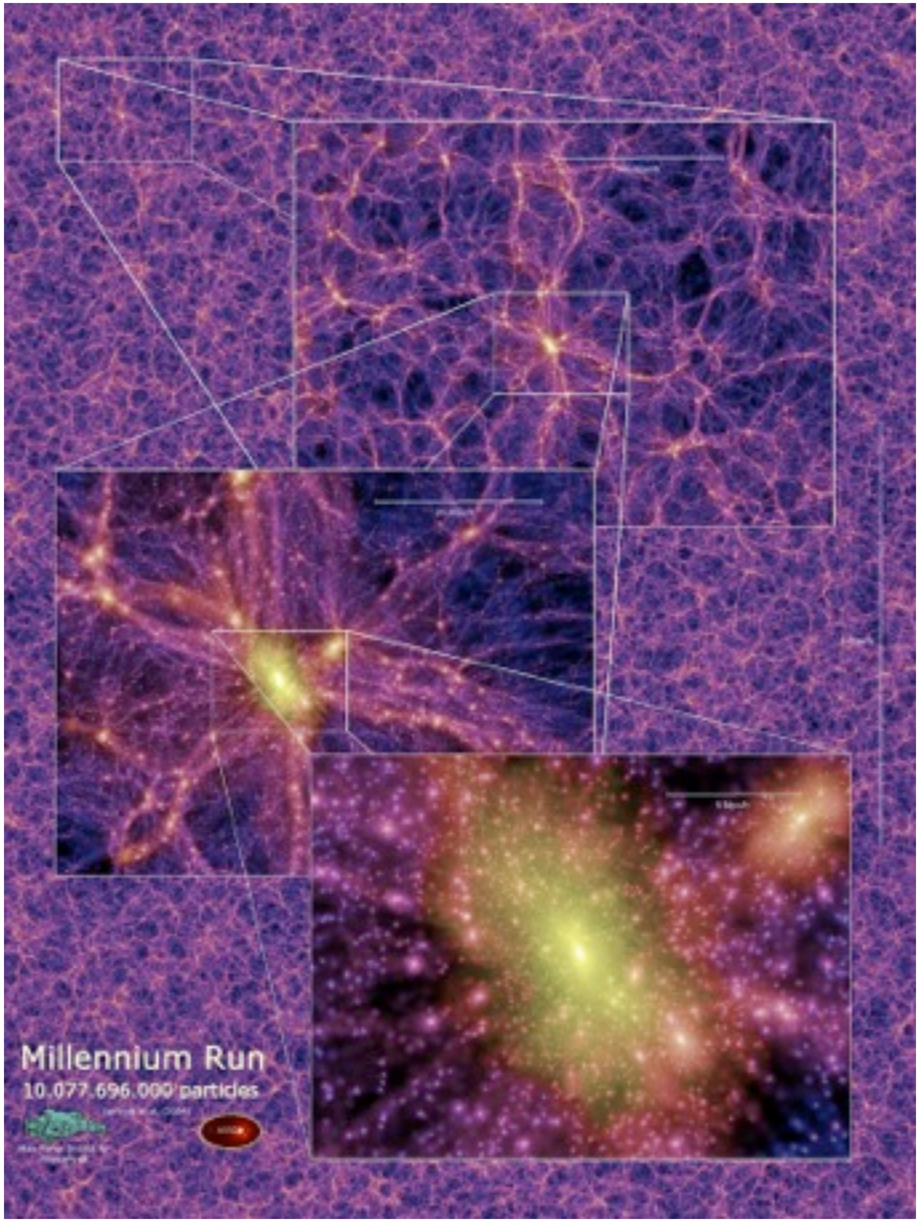


Gravity grows overdensities: A slight overdensity at z = 1100 will become progressively more dense as that region attracts more matter to itself.

III: The growth of cosmic structure

As overdensities become massive, they attract other overdensities into themselves ... find a hierarchical network of *mergers* building the first galaxies and clusters.

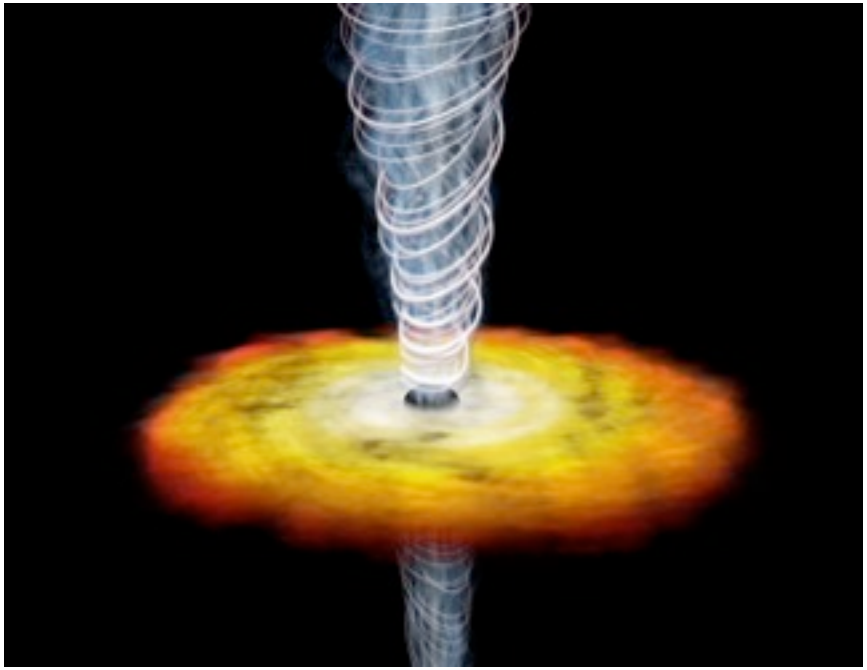
Galaxies and their host halos merge often, especially at moderate to high redshift.



http://www.mpa-garching.mpg.de/galform/virgo

III: The growth of cosmic structure

High redshift quasars show that massive black holes have existed in merging structures from early in universe's history.

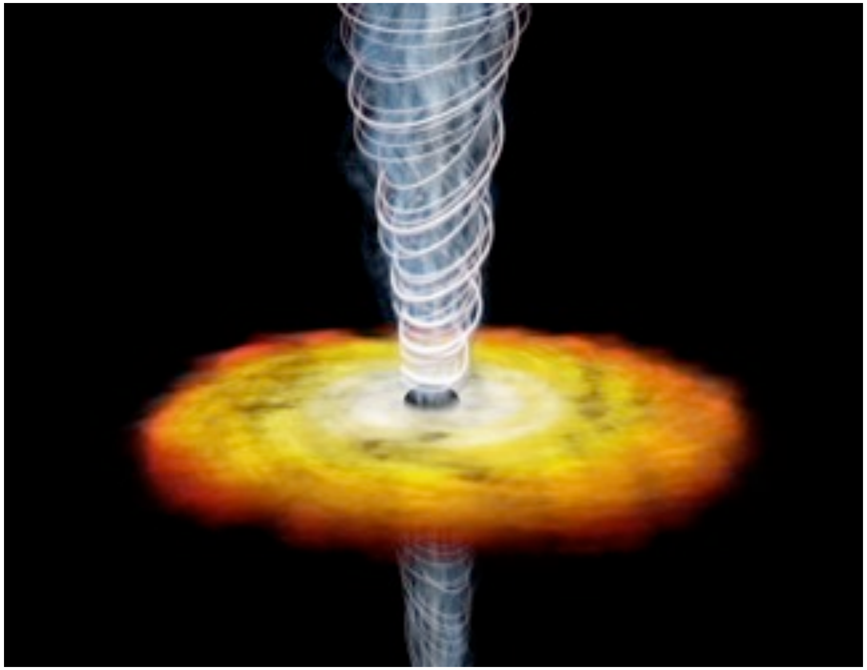


Most extreme example known: ULAS J1120+0641 at $z = 7.085$ … luminosity and line widths imply $M_{BH} \sim 5 \times 10^9\ M_\odot$.

Early structures host BHs; structures merge; BHs come together, forming binaries … strong GW radiators.

III: The growth of cosmic structure

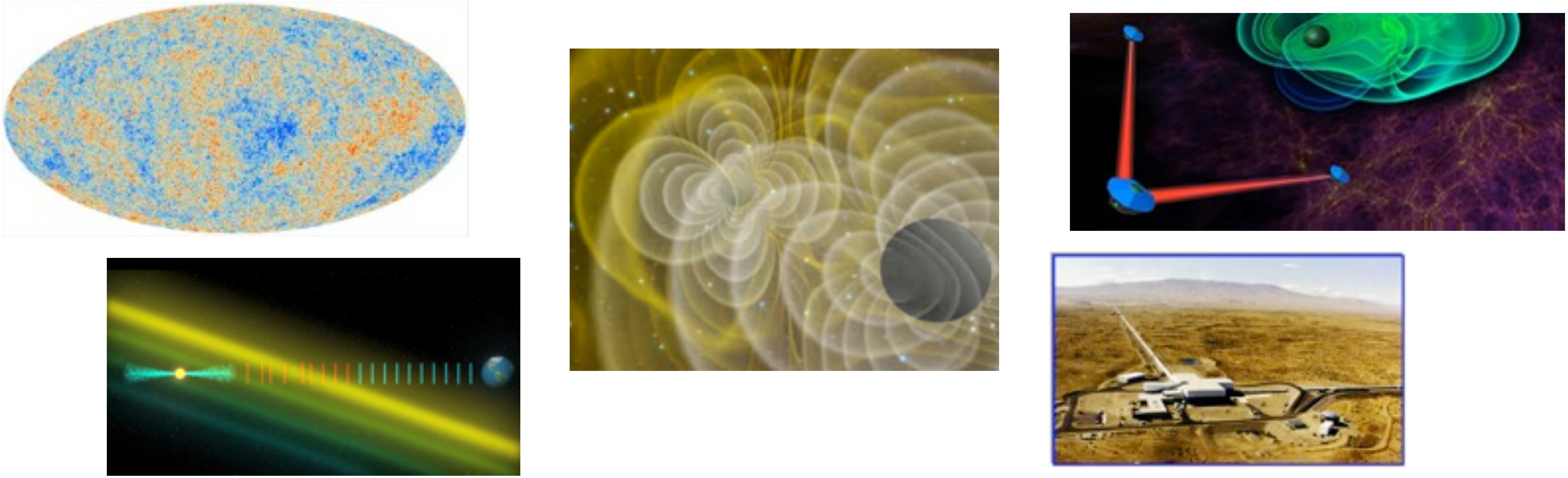
High redshift quasars show that massive black holes have existed in merging structures from early in universe's history.



Most extreme example known: ULAS J1120+0641 at $z = 7.085$ ... luminosity and line widths imply $M_{BH} \sim 5 \times 10^9\ M_{\odot}$.

Binaries formed this way targets for space detectors (eLISA) ... measuring their GWs will let us directly track mergers and growth of structure at high redshift.

Conclusion



Gravitational waves: On cusp of inaugurating new tools for astronomy and astrophysics.

Operations of advanced ground-based detectors begins in 2015 … expect the fun to begin in earnest in the years to follow.