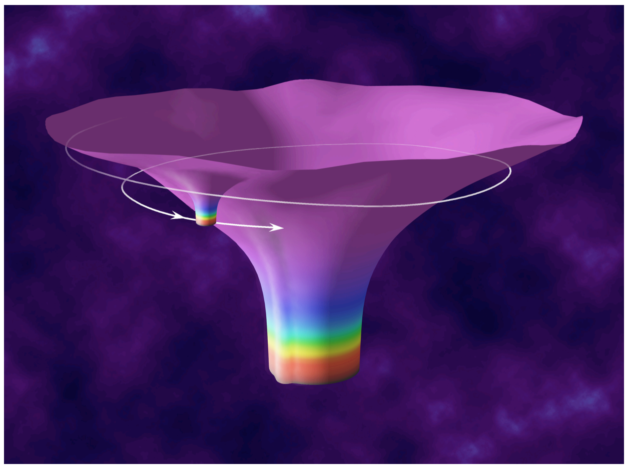
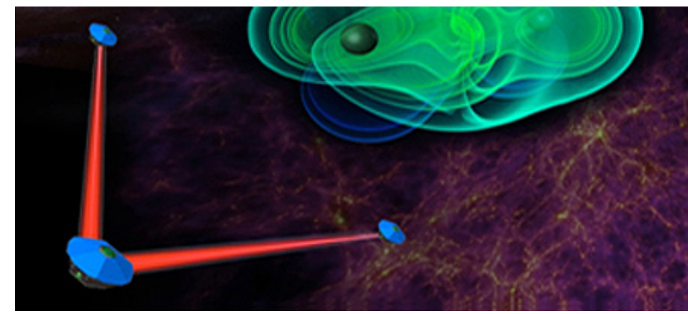
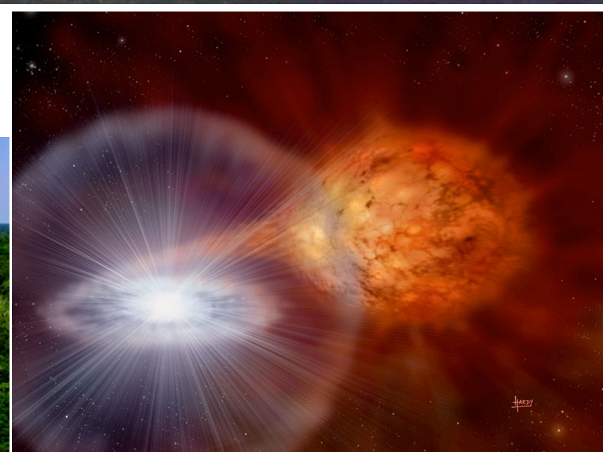
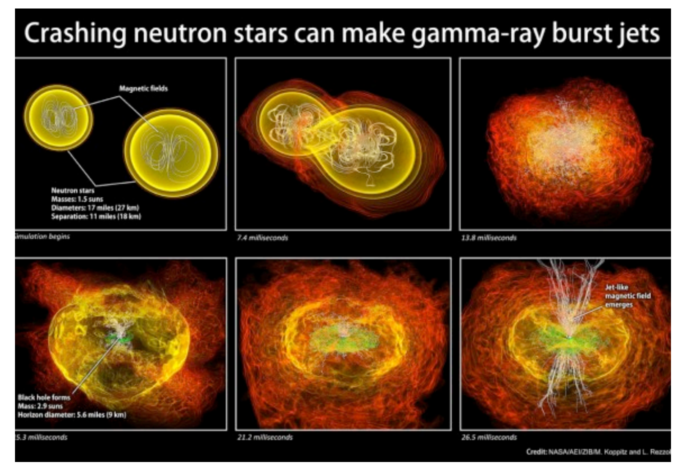
Gravitational Wave Astrophysics

Using gravitational waves as a tool for observing the universe









The role of space instruments in maximizing the potential of GWs for astronomy

Scott A. Hughes with John G. Baker and Matthew Benacquista

NASA Astrophysics Roadmap, 6 May 2013

Summary of this talk

Once directly measured, gravitational waves will evolve into an outstanding tool for observing dense, dynamical, and often dark sectors of our universe ... a tool for *astronomy* as well as for physics.

Space instrumentation will be critical:

* Necessary to directly detect gravitational waves in one of the most important and interesting frequency bands,

* Provides complementary "electromagnetic" views which enabling multimessenger studies of many gravitational-wave sources.

The basic basics

Gravitational radiation *necessary* in any relativistic theory of gravity: Need a mechanism to causally communicate changes in the gravitational field.

In general relativity, tidal fields ("curvature") play a role similar to electric and magnetic fields in electrodynamics … radiation will take the form of tidal gravitational field propagating from source.

Leading radiation *quadrupolar*: monopole violates conservation of energy, dipole violates conservation of momentum.

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

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

Critical properties

G/c^4 is very small! Need large m, large v to get strong radiation — compact object dynamics make best sources.

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

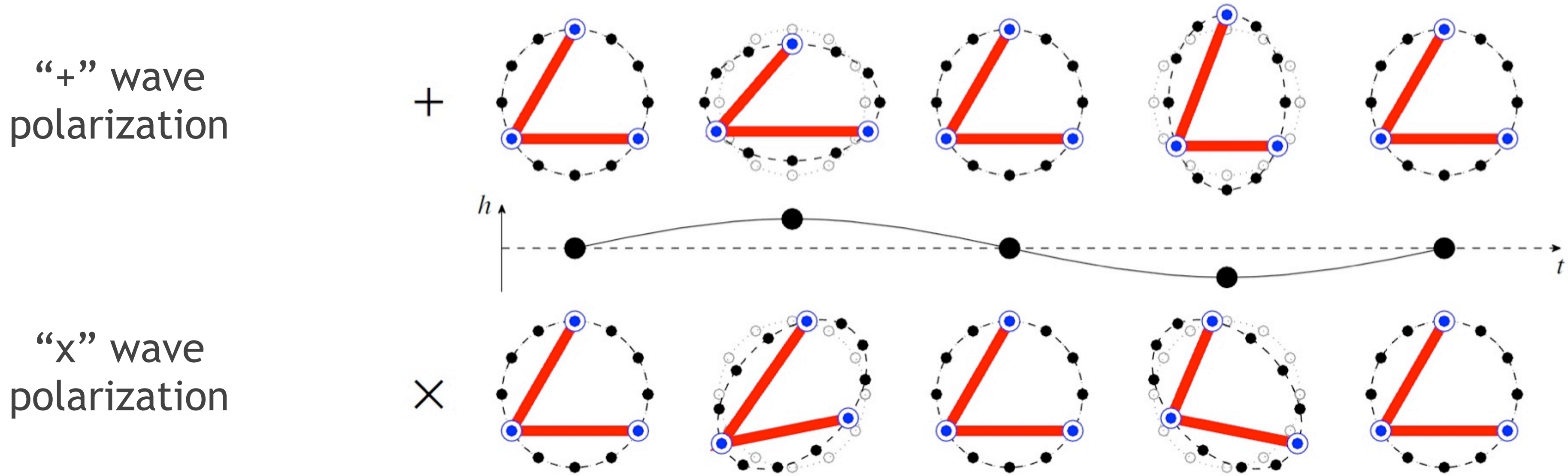
$$\simeq \frac{2G}{c^4}\frac{1}{r} \times mv^2$$

Reflects the fundamental weakness of gravity ... makes GWs challenging to measure directly, but means they do not suffer extinction or scattering: Propagate from source to us largely unimpeded.

Gravitational wave observable has $1/r$ falloff with distance ... similar to directly measuring (coherent) electric or magnetic field rather than an (incoherent) EM energy flux.

Detection

Acts as an oscillating tidal field:



Can be measured by precisely timing light travel between inertial masses: During stretch/squeeze, light takes more/less time for round trip.

Key to gravitational wave detection is good clock (e.g., pulsars, or timing standard of a high-quality laser) and good inertial reference frame.

Contrast: GWs versus EM

* Directly measured quantity has $1/r$ falloff (coherent GW amplitude) versus $1/r^2$ for many telescopes ... relatively short pathway from detecting nearby sources to detecting cosmological sources.

* GW detectors are naturally all sky ... quadrupolar antenna patterns of detectors very broad.

* Corollary: Localization with GWs is often poor. Need multiple detectors, or long lived sources so modulation from detector motion (from rotation of Earth [terrestrial] or orbit around sun [space]) encodes sky position ... or, partner with telescopes that get positions much than GW instrument.

Natural path for development

First direct detections likely in the next ~5 years by ground-based detectors or pulsar timing (or both).

What comes next?

All-sky sensitivity, $1/r$ nature of observable, and relatively poor localization suggest that GWs may quickly reach their confusion limit ... best path to improve their astronomy is ***improving their ability to pin down source position***.

Can regard GWs right now as analogous to radio astronomy c. 1937 (1st telescope built, has not yet detected anything) ... what must we to do to move toward where radio telescopes are today?

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Ground-based detectors will be limited by number of sites — plans to expand that well underway.

Hope (expect?) that optical and high-energy transients will do much to enable localization of GW sources!

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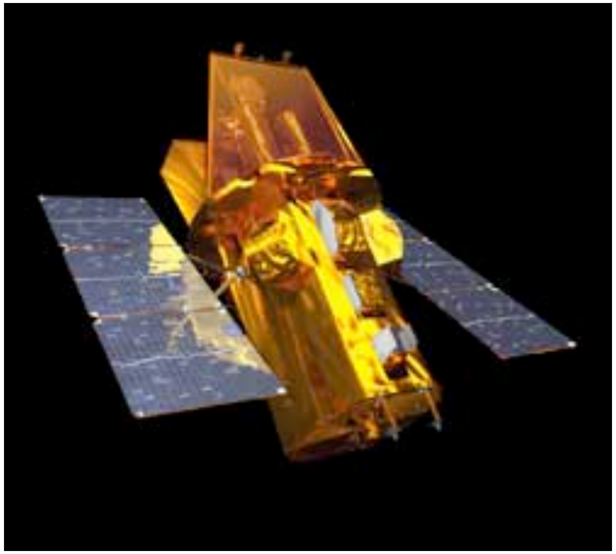
Swift,



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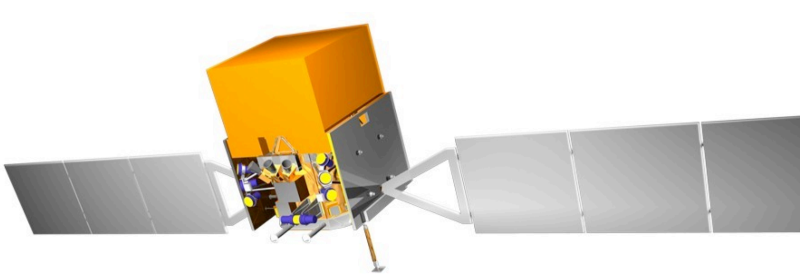
Fermi,



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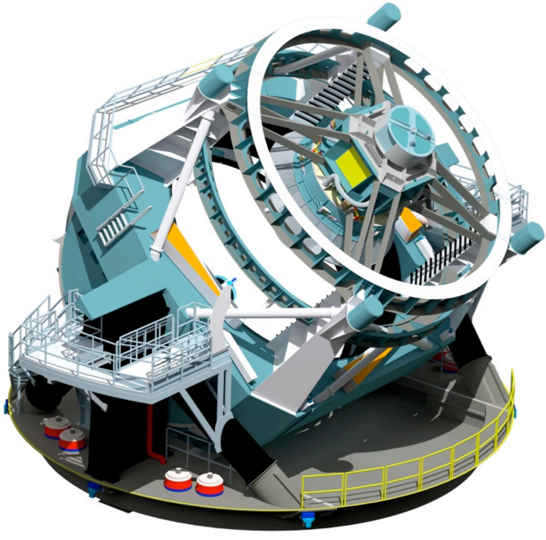
LSST: Perfect examples of instruments that will augment GWs for astro.



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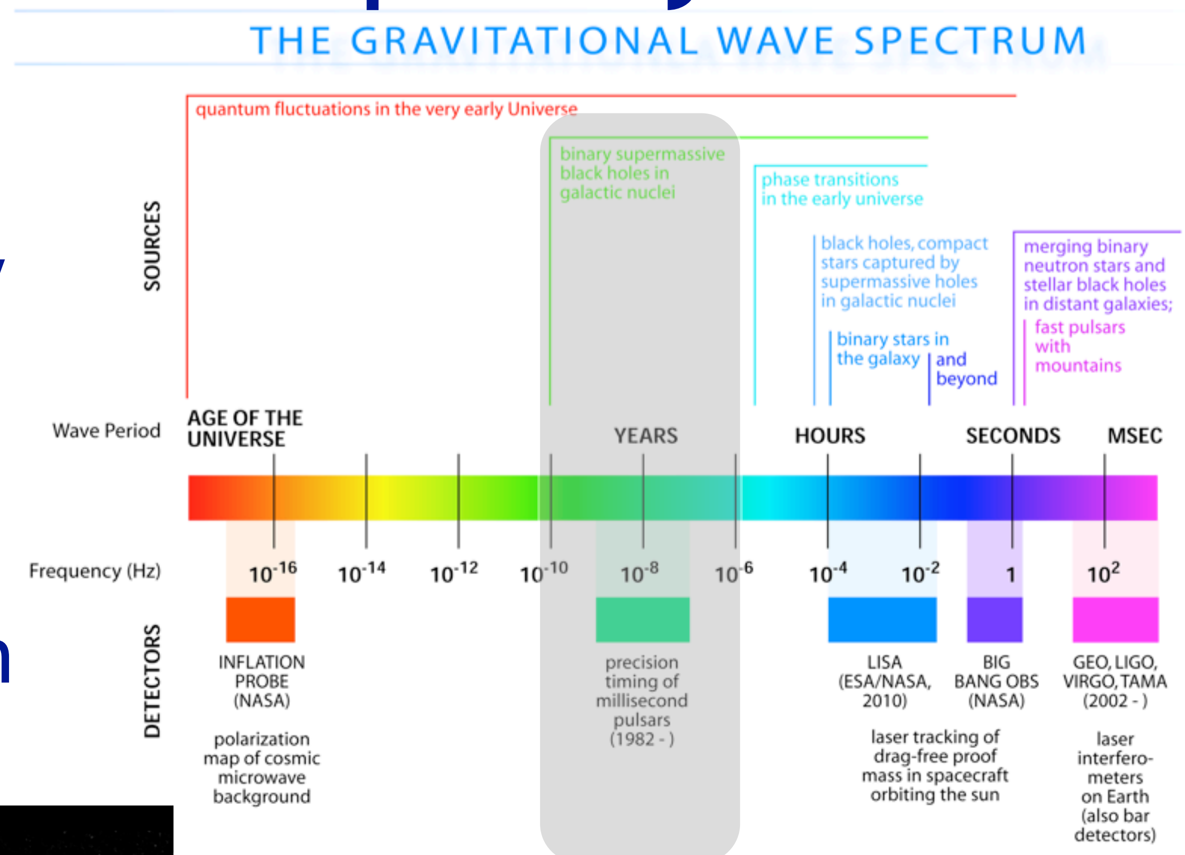
Space-based detectors limited by their ability to measure waveform polarizations, mission duration.

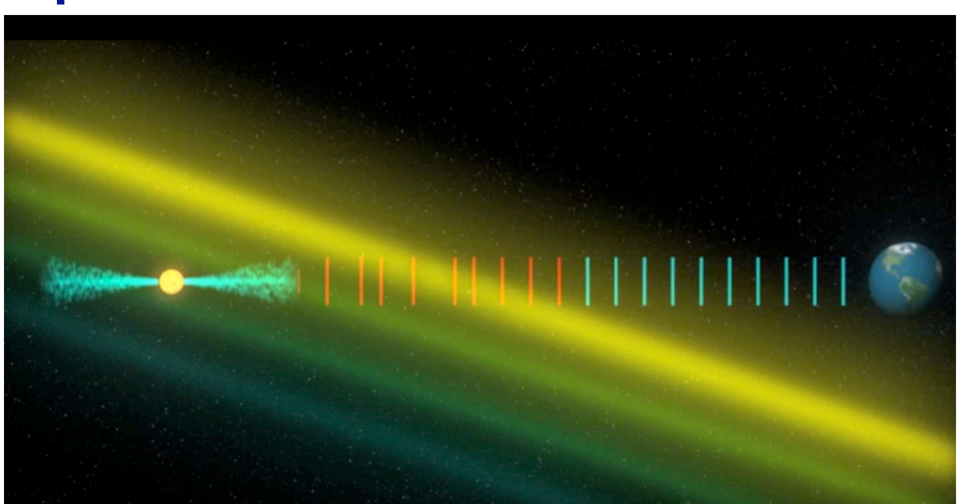
Looking forward: Think about missions that will get both GW polarizations, how to make the mission last as long as possible, other ways of improving source localization

Very low frequency

Frequencies: $(\text{years})^{-1}$ to $(\text{months})^{-1}$

Measure in this band by precision timing of millisecond pulsars: Pulsars are clocks, GWs cause coherent variation in pulse arrival times.



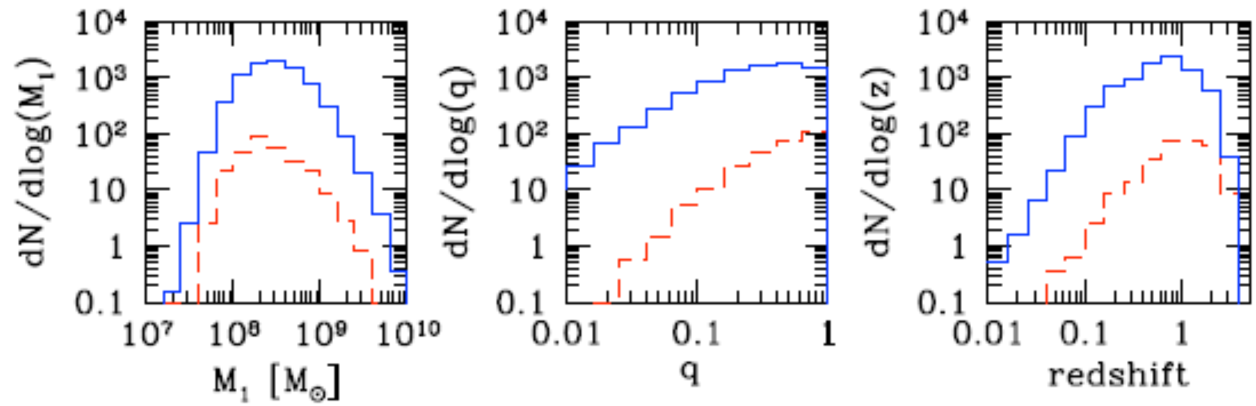


Still from pulsar timing movie courtesy Penn State Gravitational Wave Astronomy Group, http://gwastro.org

Build a network of pulsars, time them well, look for pulse variations with a particular angular distribution on the sky.

Very low frequency

Key source: Nearby ($z < 2$), high mass ($M > 10^8\ M_{sun}$) BH binaries.



Plot taken from Sesana et al, MNRAS 2012

Pulsar timing signal contains millions of sources, but is dominated by several hundred binaries. May be strong “foreground” sources whose positions can be determined and then followed up with other instruments.

Background teaches us about populations of merging black holes and host galaxies; individual sources allow study of merging binary. Only a few cycles per year ... but fantastic multimessenger studies if we get position.

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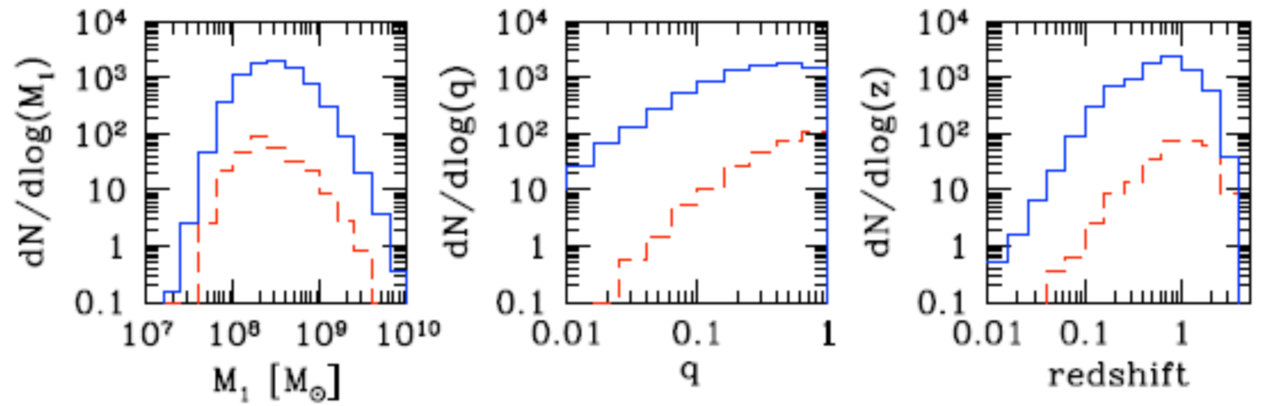

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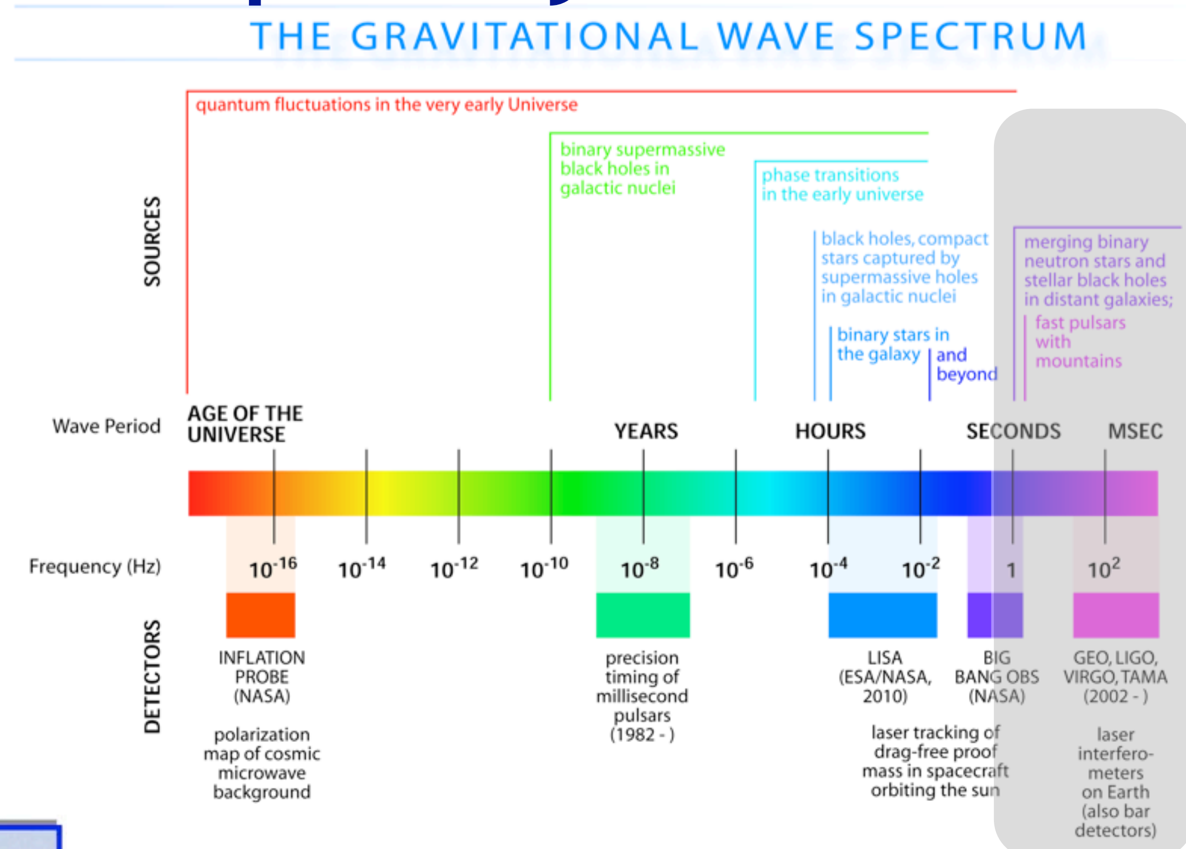
Critical player: Fermi Space Telescope. Many pulsars in timing array have been discovered in gamma rays, then found in radio data.

Near future: NASA's Deep Space Network adapted to use for this: Gaps in "normal" DSN use (a few hours every few days) being looked at for radio pulsar measurements for this purpose.

High frequency

Frequencies: several Hz up to about 1 kHz (human audio)

Measure using laser interferometry: Precise timing of light traveling in beam tubes of interferometer.

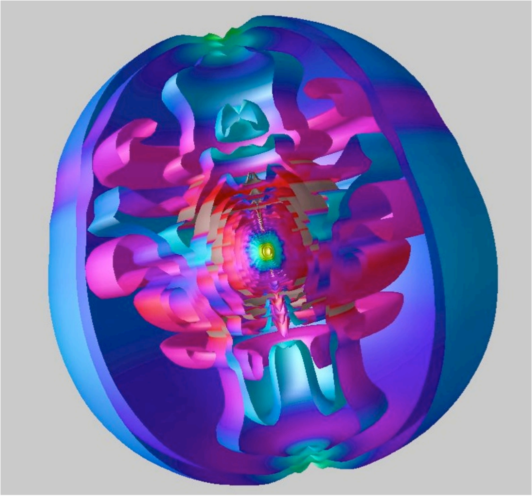


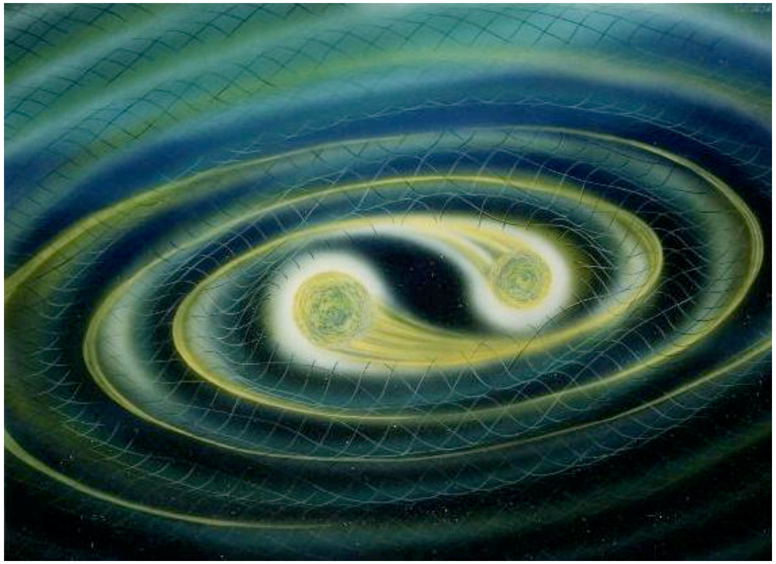
World-wide network of sites beginning operations with advanced sensitivity around 2015 … widely expect first detections in next few years.

High frequency

Sources: Dynamics of relativistic, compact, stellar-mass objects — neutron stars and black holes.

Core collapse of massive stars in nearby galaxies





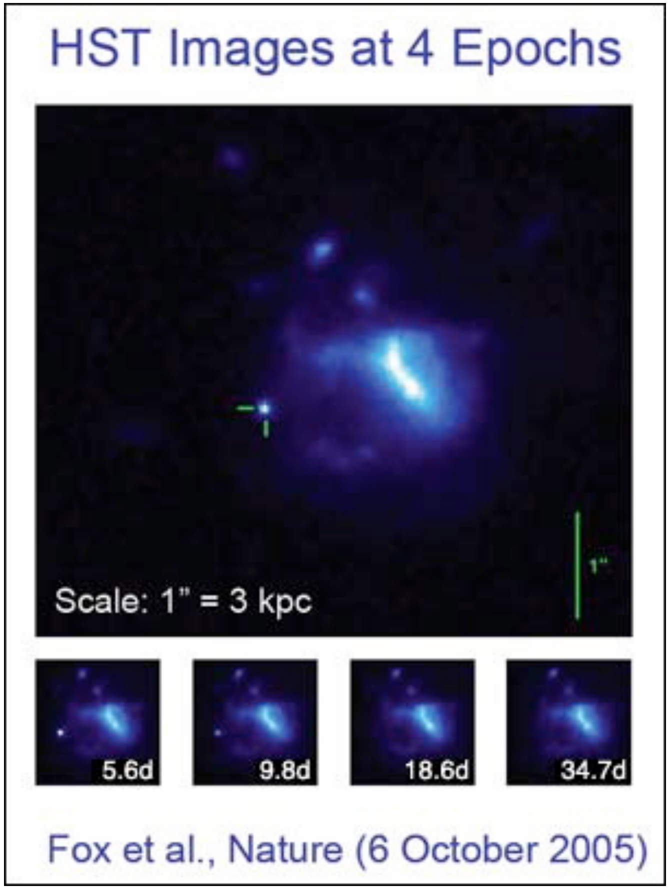
Coalescence of compact binaries (neutron star-neutron star; neutron star-black hole; black hole-black hole)

High frequency

Sources: Dynamics of relativistic, compact, stellar-mass objects — neutron stars and black holes.

Many of these events likely to have a counterpart in photons: Can determine, for example, how many short GRBs are associated with binary coalescence.

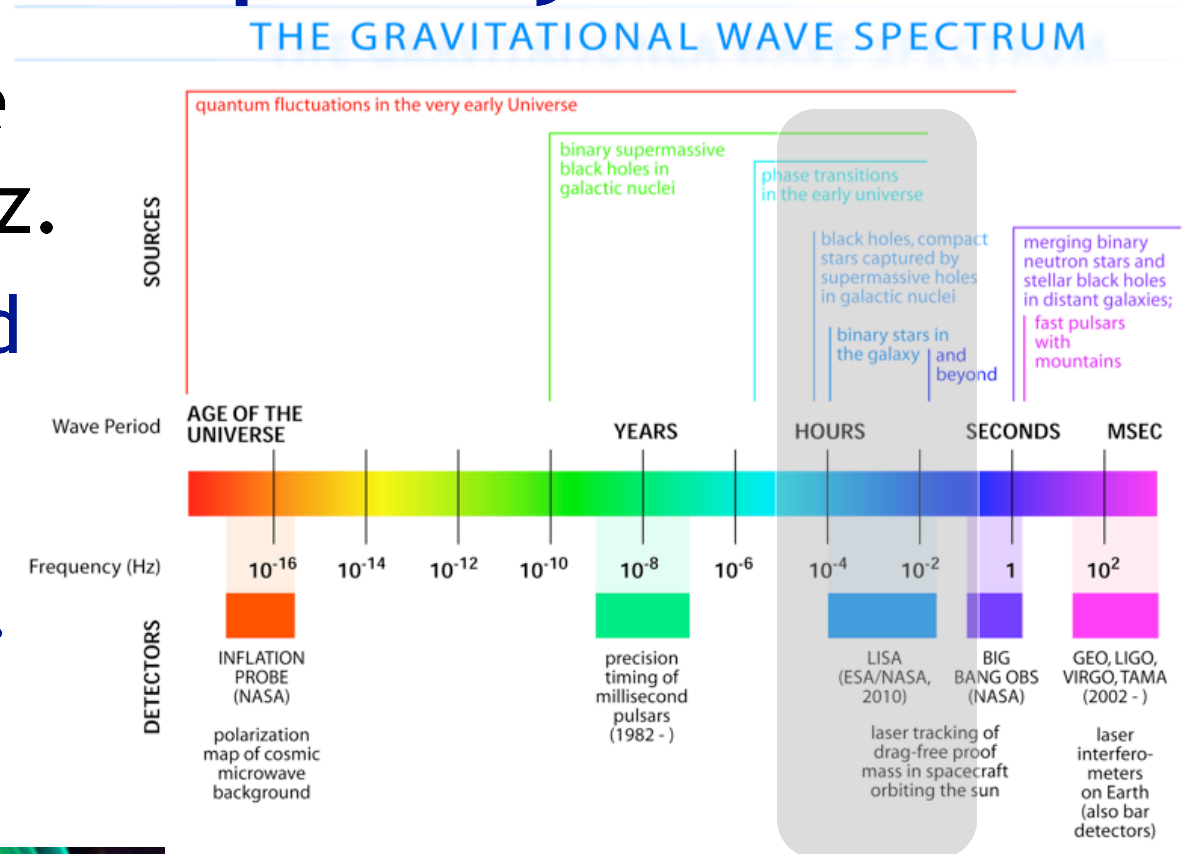
Need space instruments to find counterparts: Wide field, rapid response to short-lived high-energy transients.

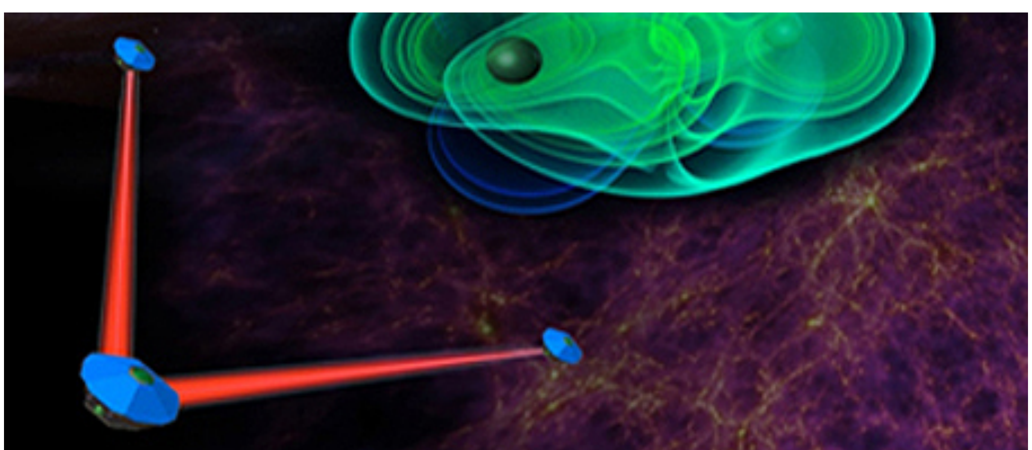


Low frequency

Frequencies: Inverse hours up to about 1 Hz.

Interferometry needed to measure these waves … but Earth too noisy in this band. ***Must*** go into space.





Space antenna like eLISA designed to measure waves in this band.

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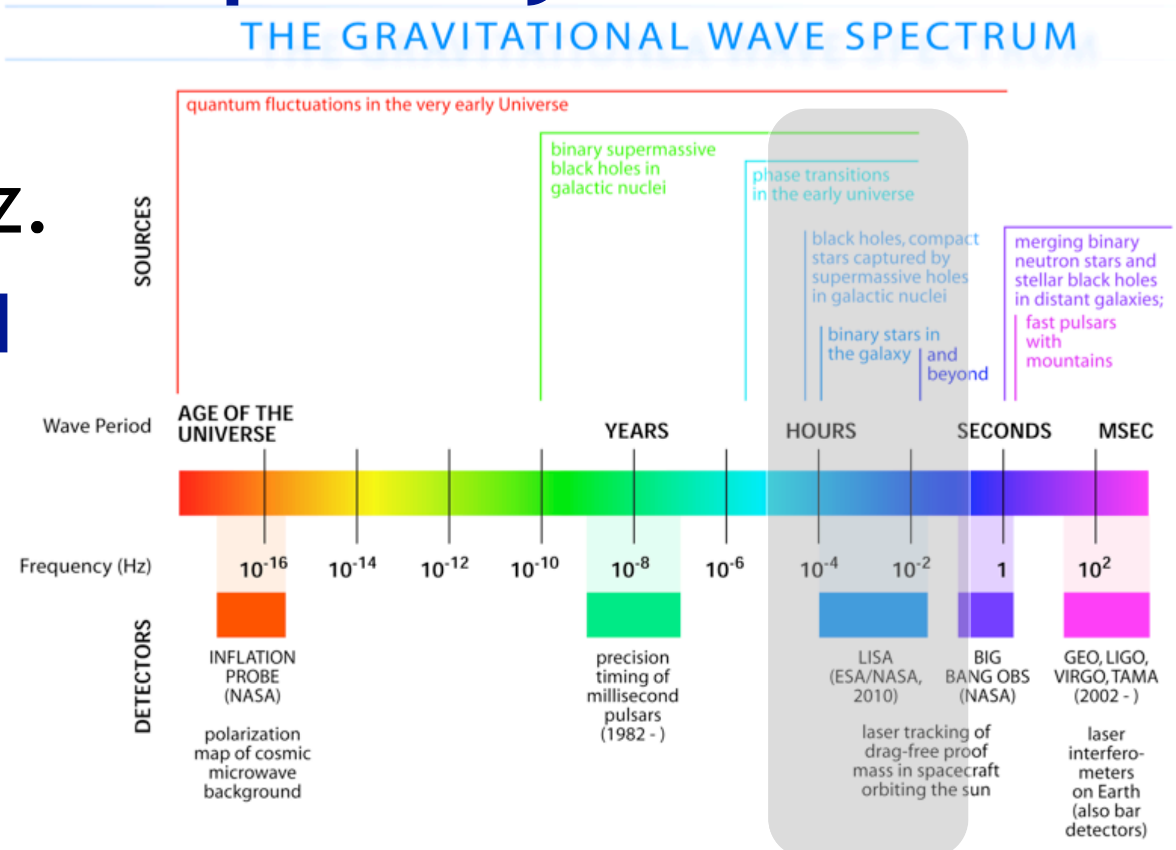
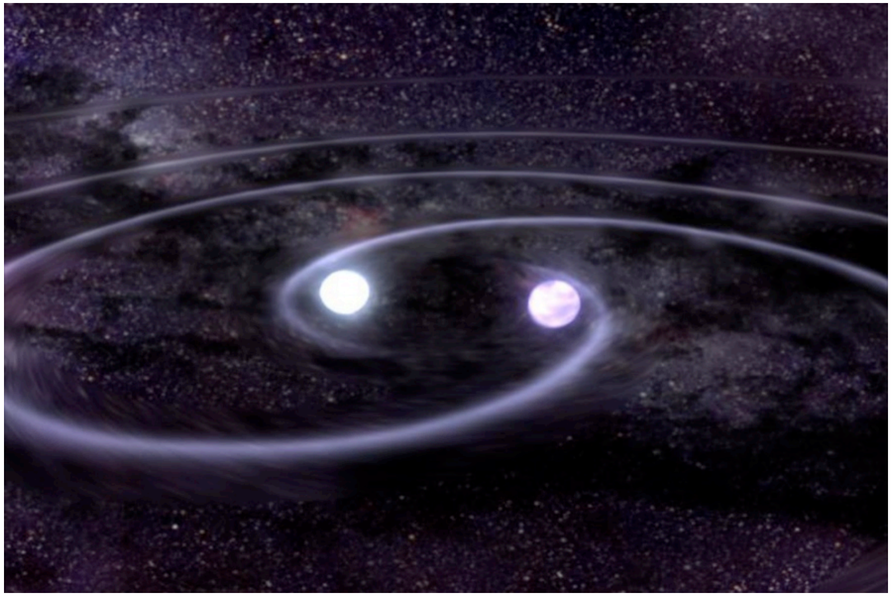


Especially rich gravitational-wave spectrum: Many sources (galactic binaries and processes involving ~10^6 M_{sun} black holes), long-lived signals (months or years).

Stellar population surveys

Millions of binary stars in our galaxy with orbital periods of tens of minutes to about an hour.

Ultracompact binaries are progenitors for many important objects:



* Millisecond pulsars
* LMXBs
* Type Ia supernovae

Critical to high-energy astrophysics ... but much remains poorly understood about their formation (e.g., common envelope evolution, tidal coupling, mass transfer) and population (spatial density & distribution, connection to star formation or dynamical formation)

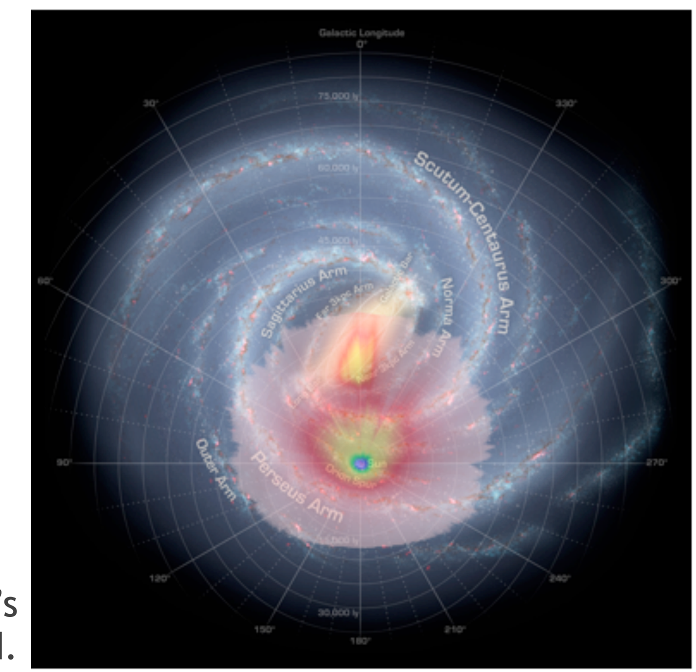
Need more data!!

Optical surveys will provide information to rectify this situation in part ... combining with GW information would be ideal.

Limitations of electromagnetic surveys:

* Magnitude limits
* Crowding
* Extinction
* Mostly visible when members interact.

Example: GAIA. Will do excellently for nearby, long-period binaries ... but magnitude limit only allows it to find binaries within 1 kpc, and crowding limits ability in disk and toward bulge.



Spitzer *GLIMPSE* model of Milky Way, with GAIA's predicted stellar catalog superimposed.

GWs and galactic binaries

Low-frequency GW observations — in concert with electromagnetic surveys — perfect tools for this.

Strengths of GW observations excellent complement to EM weaknesses:

* Gets short-period systems
* Detached systems (before mass transfer) not a problem

* Covers entire galaxy
* Only crowding is in frequency space.

BUT: * Poorer angular resolution.

Complementarity of two approaches: Calibrate selection effects for sources seen both ways; joint catalogs allow probe of common envelope evolution (which sources survive, which don't).

GW wish list

Most analyses done for galactic binary science have used instrument like eLISA to define sensitivity ... what is the wish list to go beyond this?

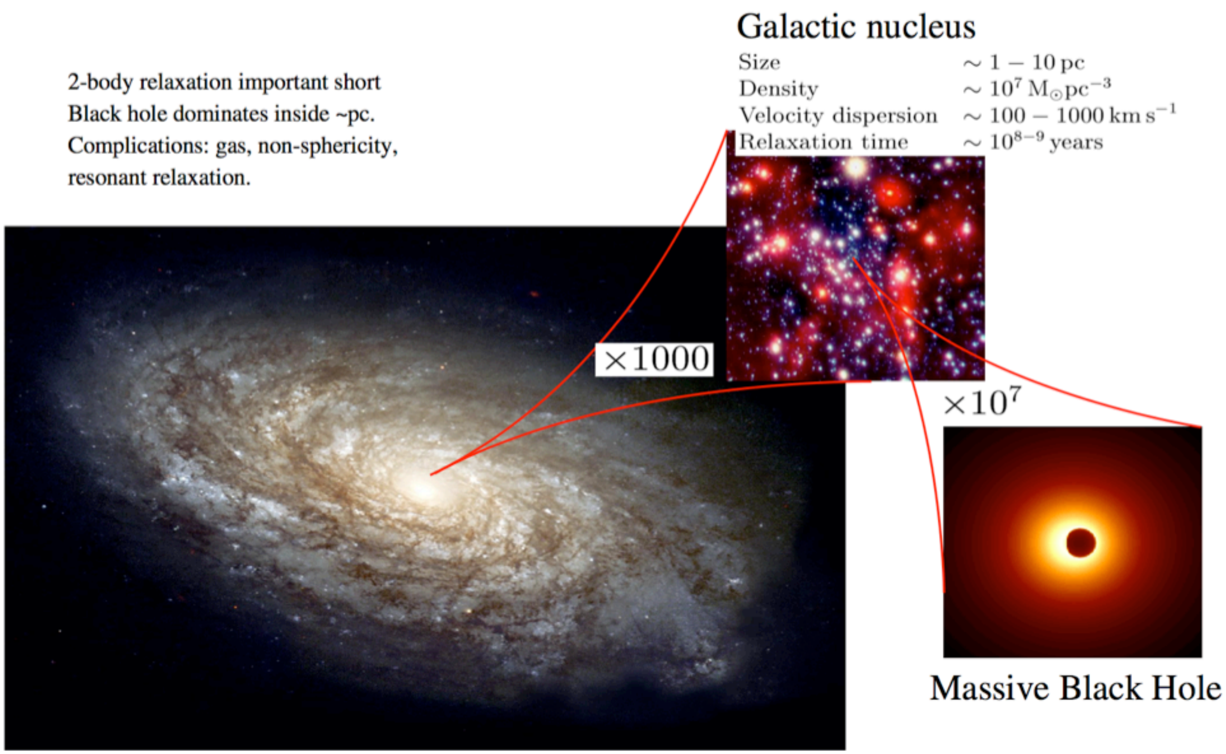
* Better angular resolution: Significantly improves ability to match sources between EM and GW catalogs.

* Broader bandwidth: Push the sources we can measure down to lower frequency.

* Finer spectral resolution/longer observations: frequency evolution reveals tidal effects, other dissipative mechanisms; with improved angular resolution, may enable study of extragalactic binaries.

Probing innermost galaxy cores

Using "small" (~1 - 10 M_{sun}) compact bodies captured onto relativistic orbits of galaxy center BH (~10^6 M_{sun})



Signal "visible" to z ~ 0.5. In the band of low-frequency detectors for about 1 year, small body orbits about 10^4 - 10^5 times before plunging into large BH.

Events rare per galaxy ... but enough of a range that we expect tens to hundreds in a multiyear mission.

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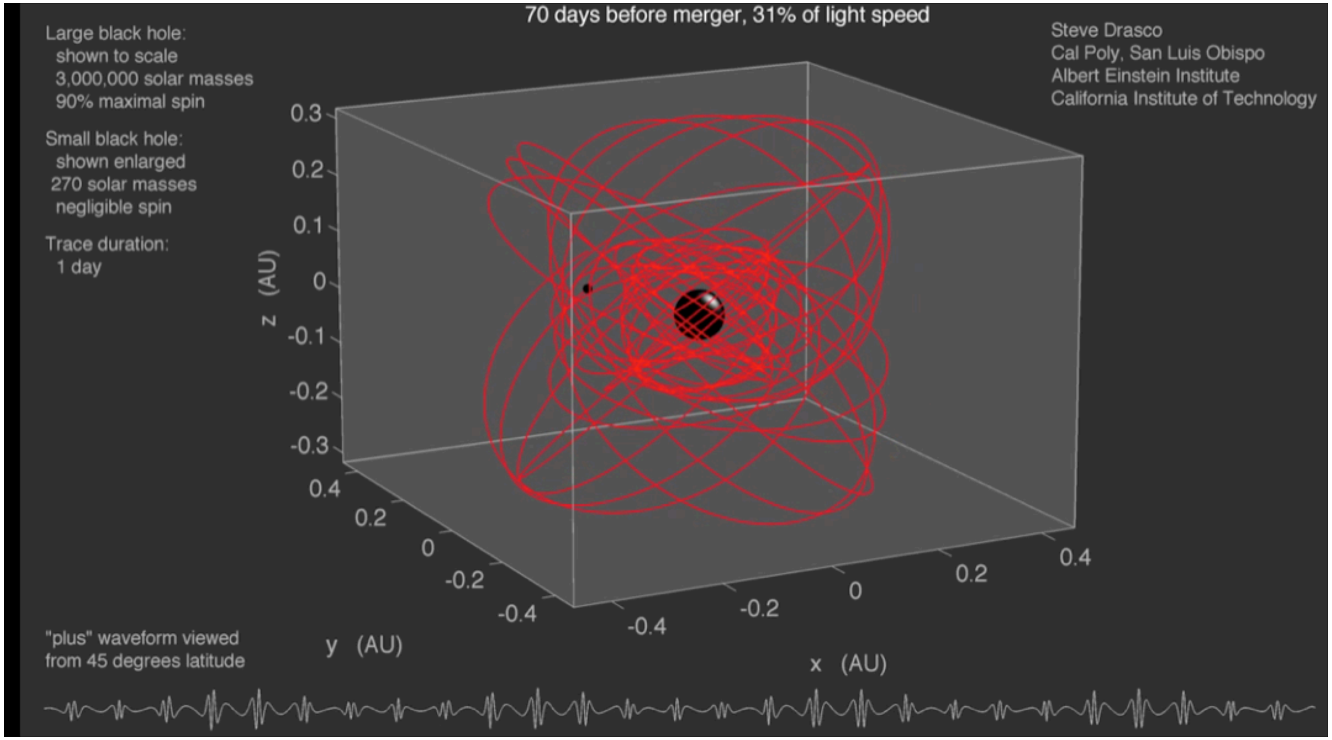
Strong-field orbital dynamics produces ornate signal as small body undergoes precessions (periapsis & orbital plane).



Still from animation by Steve Drasco; red trace shows orbital path of an inclined and eccentric orbit in the deep strong field of a rapidly rotating Kerr black hole.

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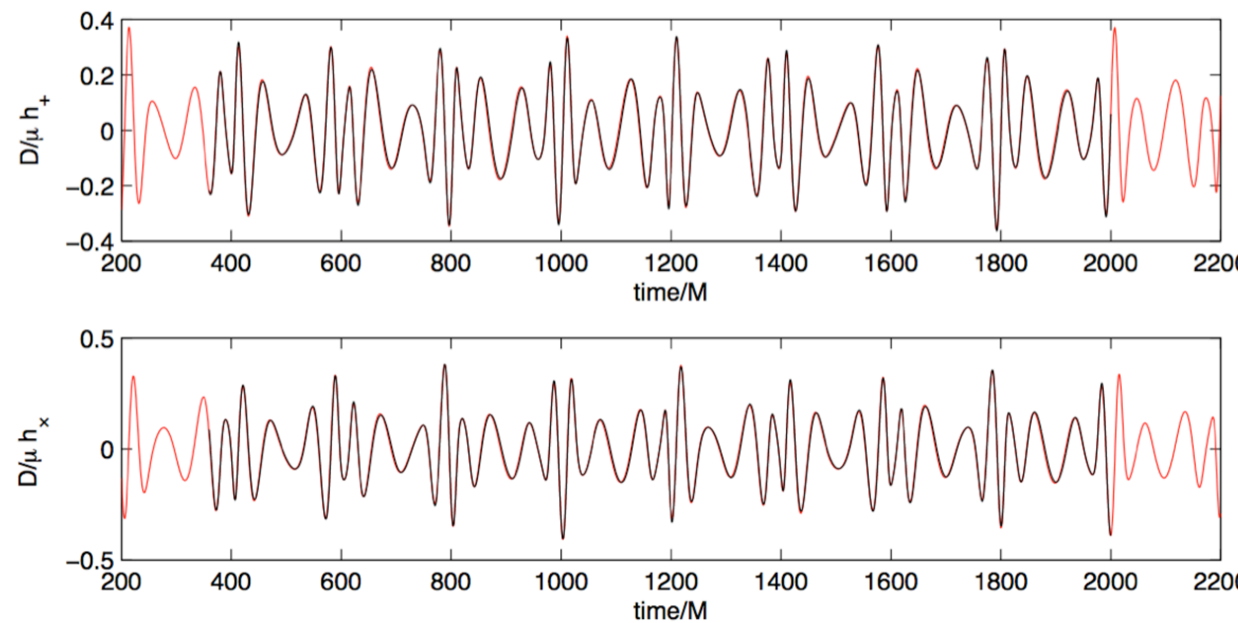


These precessions and the orbital evolution encode the nature of the spacetime; yields precise measurements of the large black hole's mass and spin, of the initial orbital geometry, and of the small body's mass.

Astrophysical payoff of extreme mass ratio inspiral measurements

* High precision sample of nearby quiescent central black holes: Will get excellent information about masses and spins of black holes for those events.

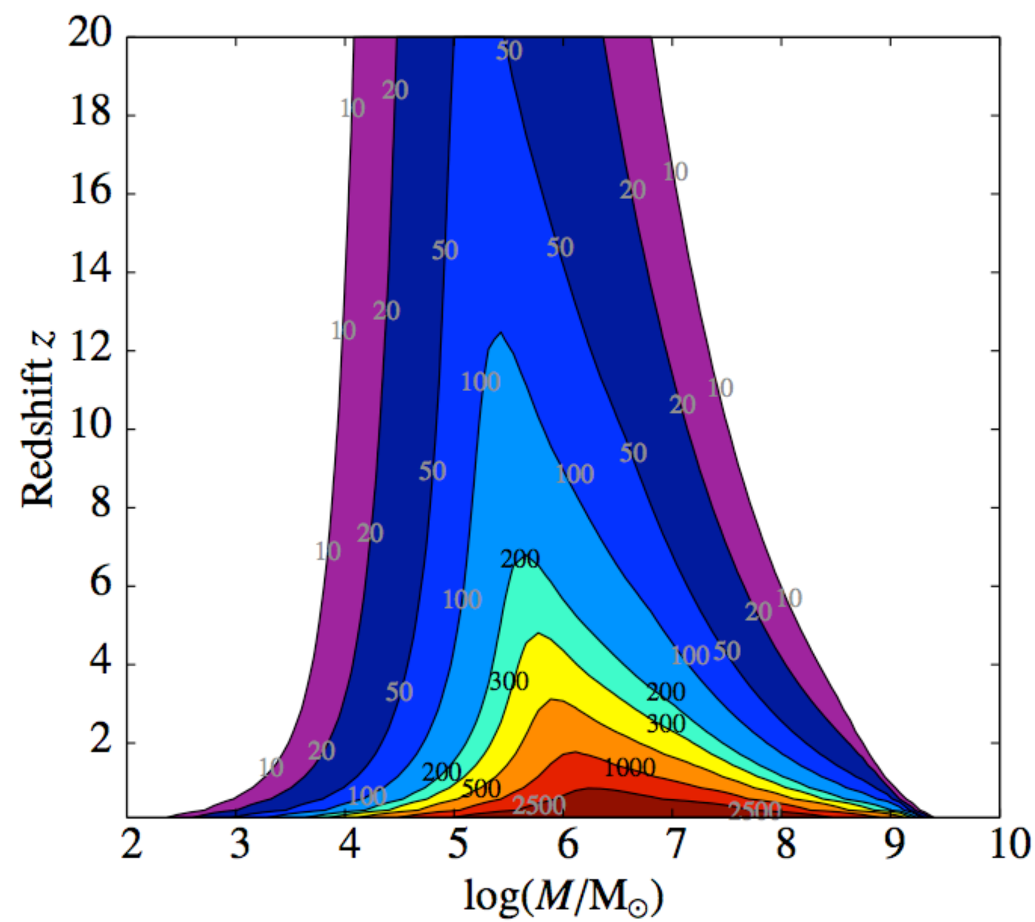
* Probes stellar population of galaxy centers. Measurements reveal mass of inspiralling object; event rate will calibrate the behavior of stars in the cluster around the black hole. Like studying the S-stars in the Milky Way center in a population of galaxies beyond ours.

Cosmological history of black holes

Using binaries in which each member is a BH of mass ~10^6 M_{sun}, formed following the merger of galaxies or in the assembly and buildup of galaxies.

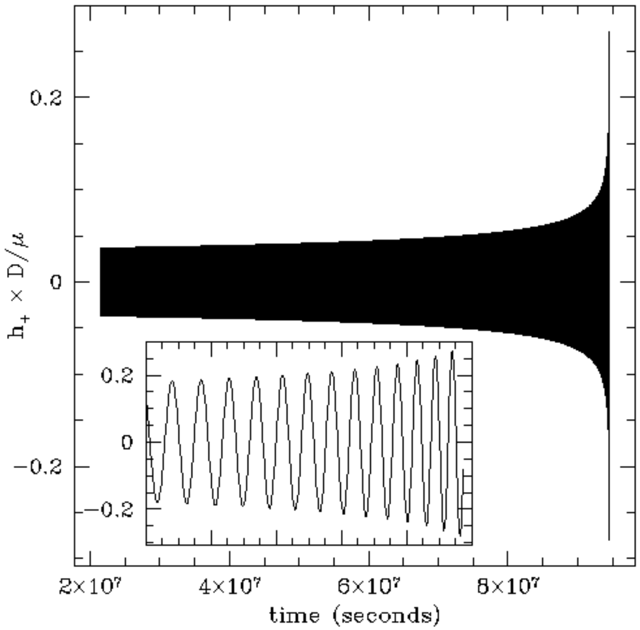
Reach of eLISA-type antenna to merging black holes: High SNR even for very high redshifts.

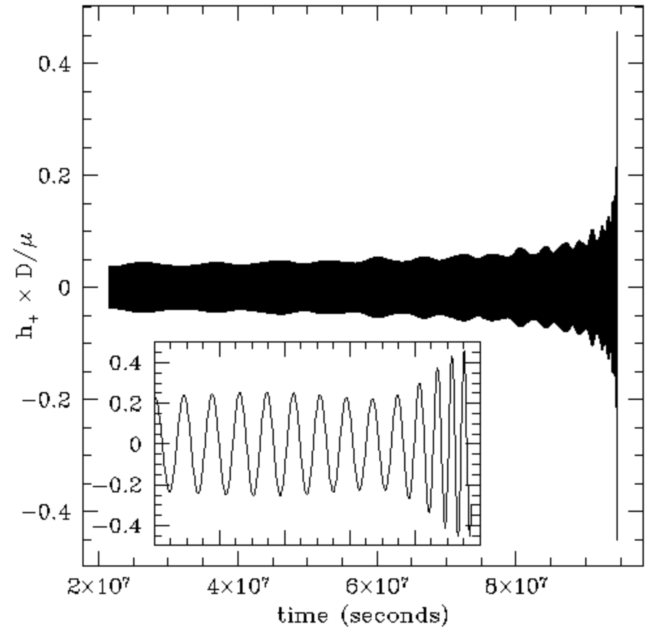
Such measurements trace the formation of the first high-redshift structures, complementing other high z probes (JWST, EOR)



Determines masses and spins

As with EMRIs, nature of the black holes is strongly imprinted on the waveform ... GW measurements make it possible to determine both mass and spin.



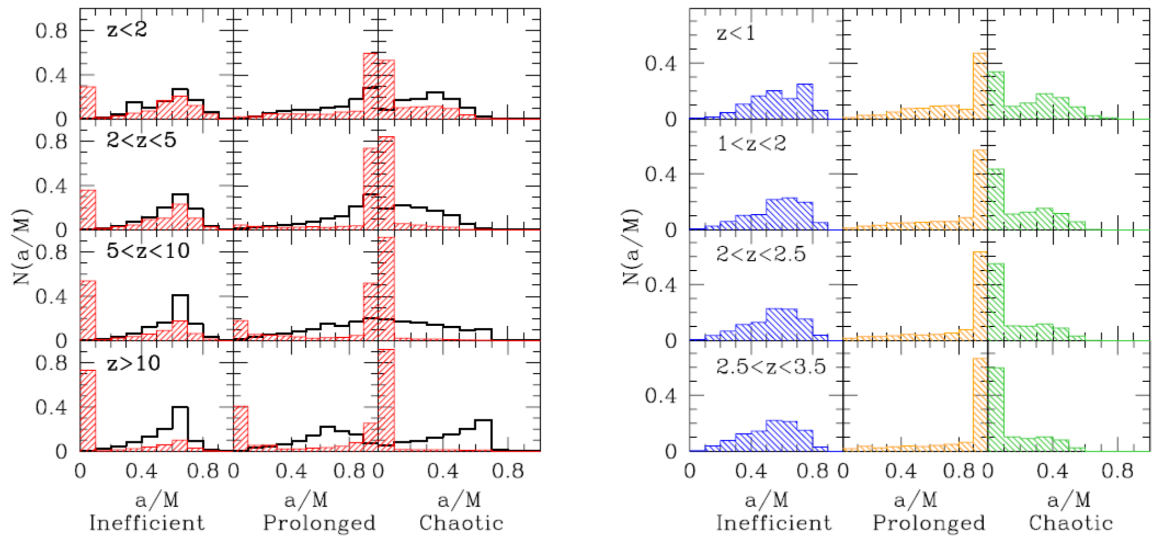


Left: Waveform for inspiral of non-rotating BHs.
Right: Waveform for inspiral of rapidly-rotating BHs.
Measured spin-induced modulations carry detailed, accurate information about the black holes.

Using knowledge of mass and spin

Mass and spin completely characterizes black holes; their co-evolution carries details about growth of cosmological black holes and their host structures.

Model showing results of different growth mechanisms: Mergers with inefficient accretion (left panel) tend to cluster at spin of 0.7; "prolonged" accretion (Bardeen-Petterson; center) produces spin-up; "chaotic" accretion (King-Pringle; right) produces spin-down.



From Berti & Volonteri 2008, ApJ 684, 822

Left panels: Black holes sampled by GW measurements.
Right panels: Full BH population in universe.

Using knowledge of mass and spin

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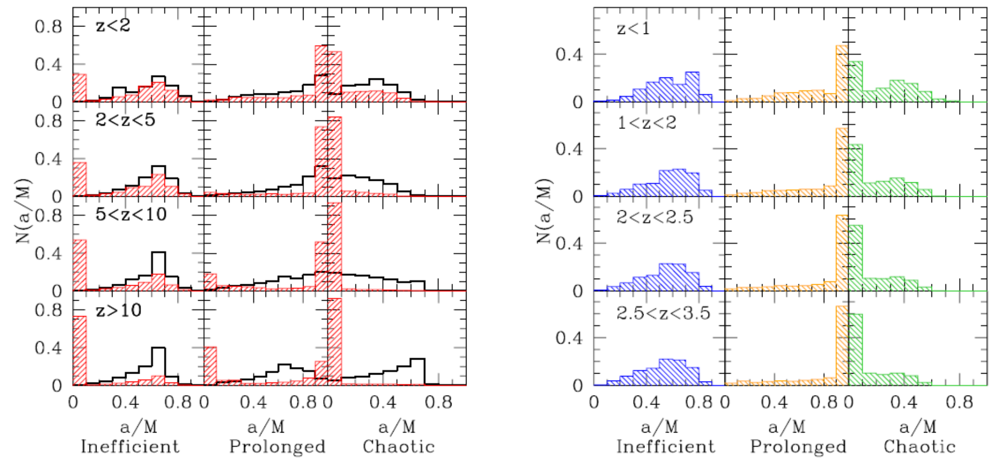
High z mergers likely associated with the formation of the first high-z quasars



GWs are a way to trace the early structure mergers which led to the formation of the first galaxies ... Combining with EM view of high redshift events (JWST, epoch of reionization) will give detailed data on the earliest cosmological structure growth.

Wish list

Detecting events and measuring masses/spins will enable much of high-z black hole science we. What can take us beyond that?

* Ability to measure both polarizations ... some proposed detectors only measure one of the two GW polarizations at each moment. Measuring both makes it possible to determine source distance, can infer redshift with knowledge of cosmology.

* Better localization: Accurate positions from waveform would greatly improve ability to combine GWs with electromagnetic data, such as epoch of reionization measurements.