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The Science of Gravitational Waves with Space Observatories

J.I. Thorpe
NASA Goddard Space Flight Center

Talk Outline

I. Gravitational Waves - What, Where, Why, & How?

II. The "classic" LISA mission

III. Science with LISA

IV. Current concepts & opportunities

Gravitational Waves

what?

where?

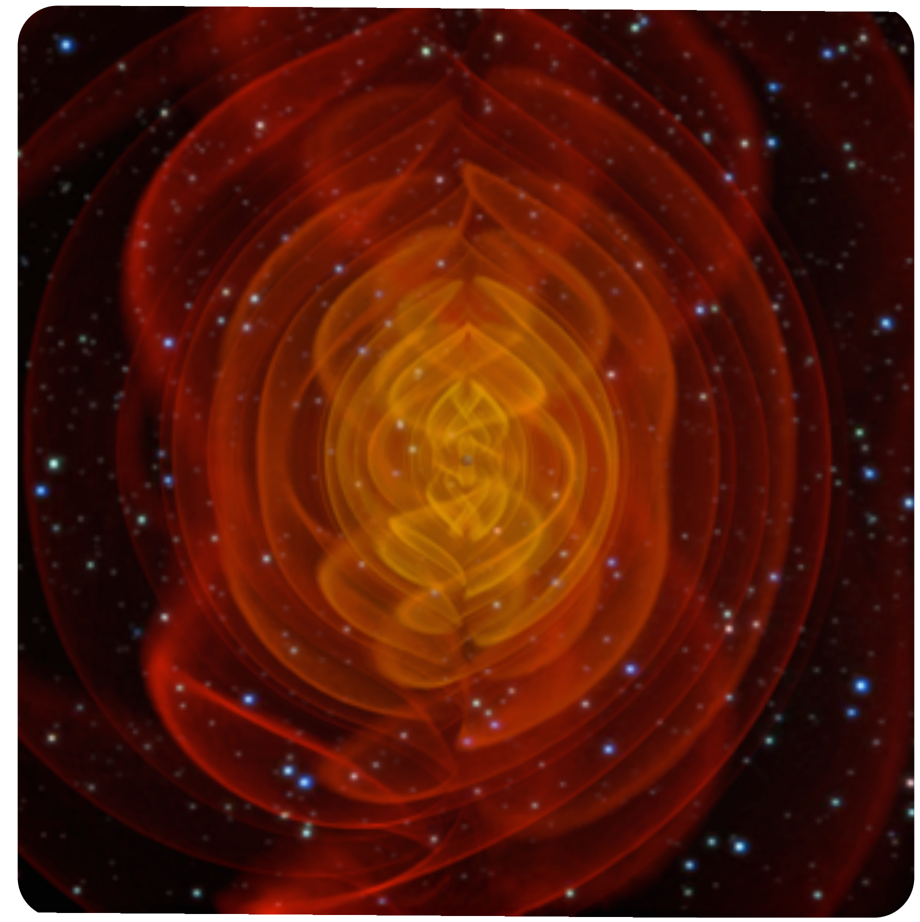
how?

why?

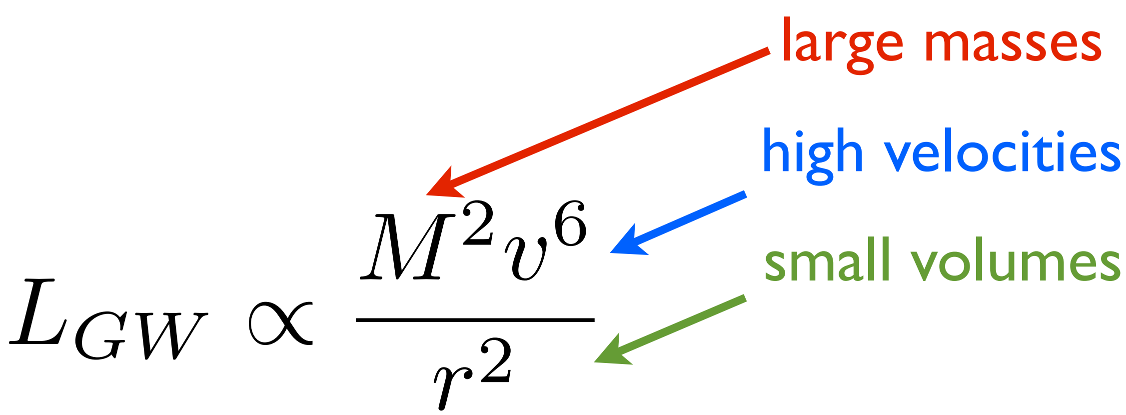
What are Gravitational Waves?

Dynamical part of spacetime

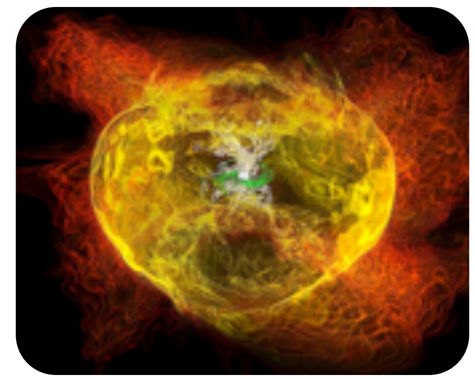
- Wave solutions to vacuum Einstein equations
- curvature pertubations to background metric
- Propagate at the speed of light
- carry energy & momentum
- have two polarizations

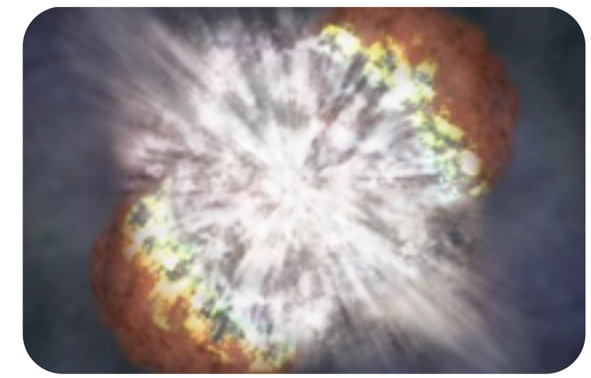


Where do they come from?



Formation of compact objects





Compact objects in binaries

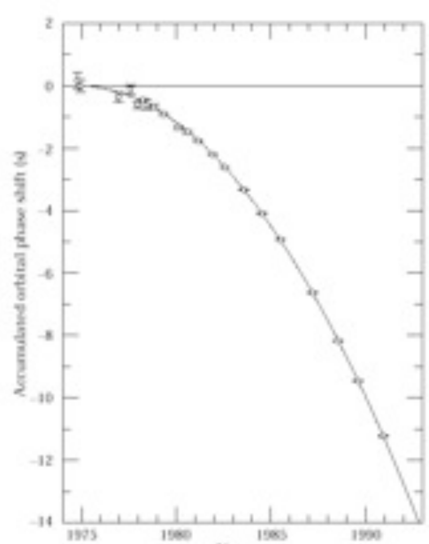
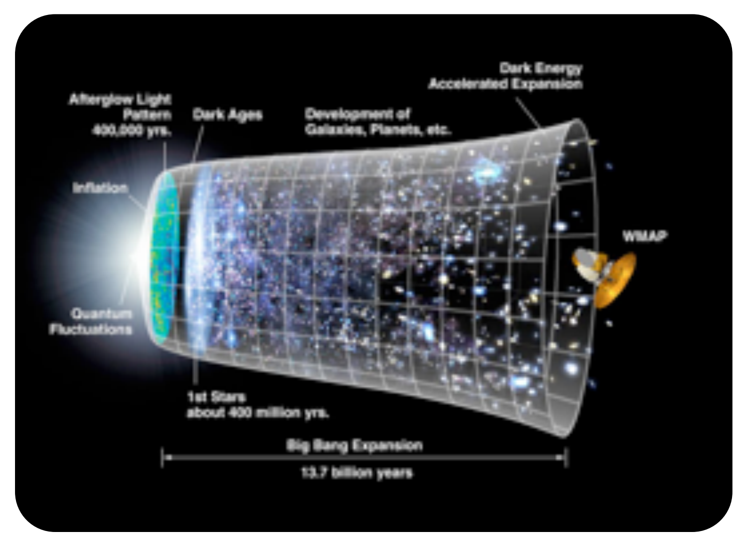
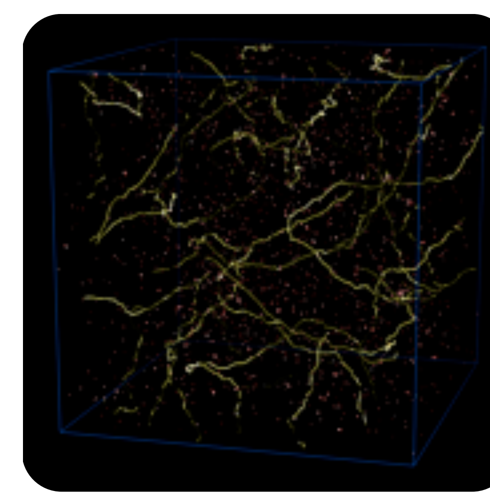


Figure 14.1: Accumulated shift of the times of periastron passage in the PSR 1913+16 system, relative to an assumed orbit with a constant period. The parabolic curve represents the general relativistic prediction, modified by Galactic effects, for orbital period decay from gravitational radiation damping forces.

Big Bang



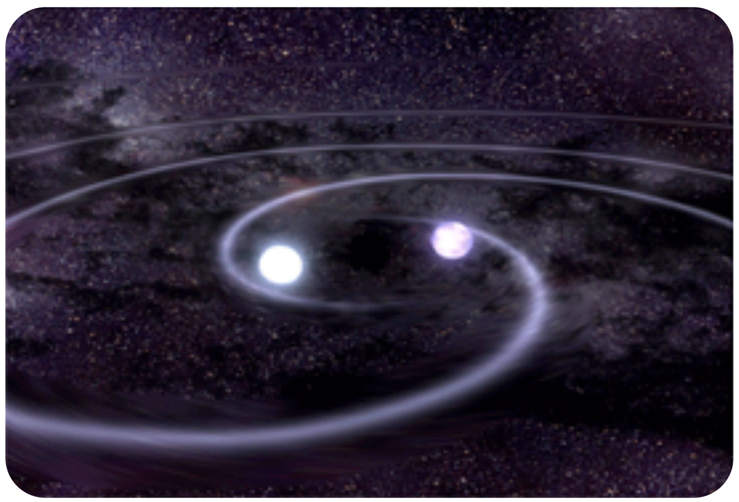
Cosmic Strings?



LBNL

Binary inspirals & merger

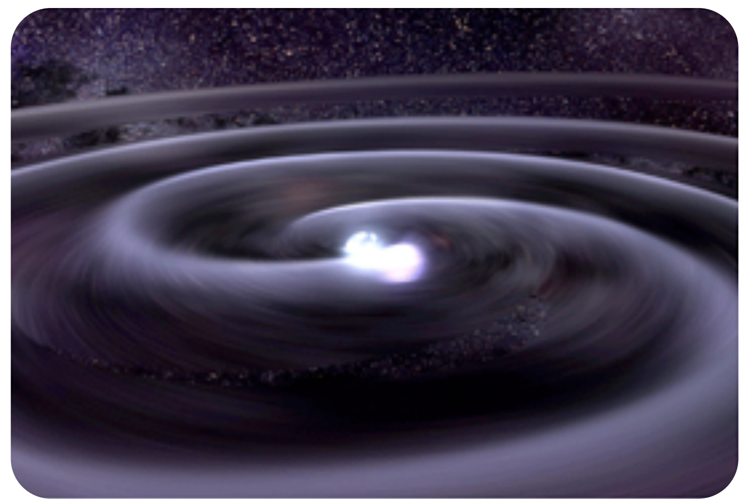
Early Inspiral



- GWs carry away energy
- Adiabatic shrinking of the binary
- Analytically tractable

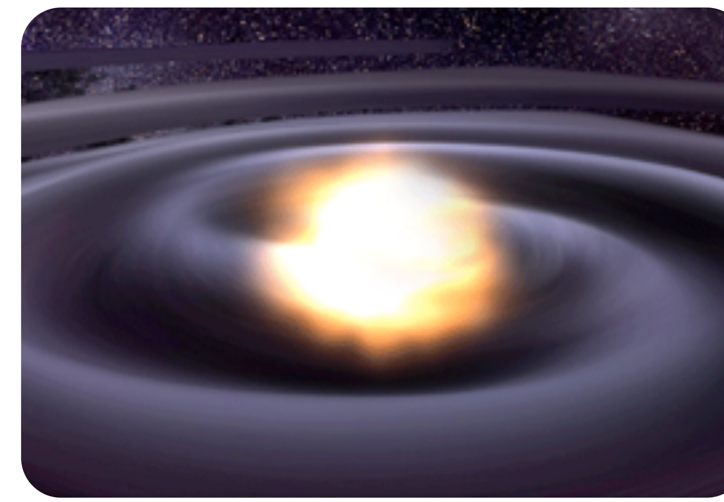
$$a(t) = a_0 \left(1 - t/\tau\right)^{1/4}$$

Late Inspiral



- exponential increase in L
- More complex physics
  - GR orbital effects
  - tides & mass-transfer

Merger



- merger of compact object(s)
- formation of new object
- physics more difficult

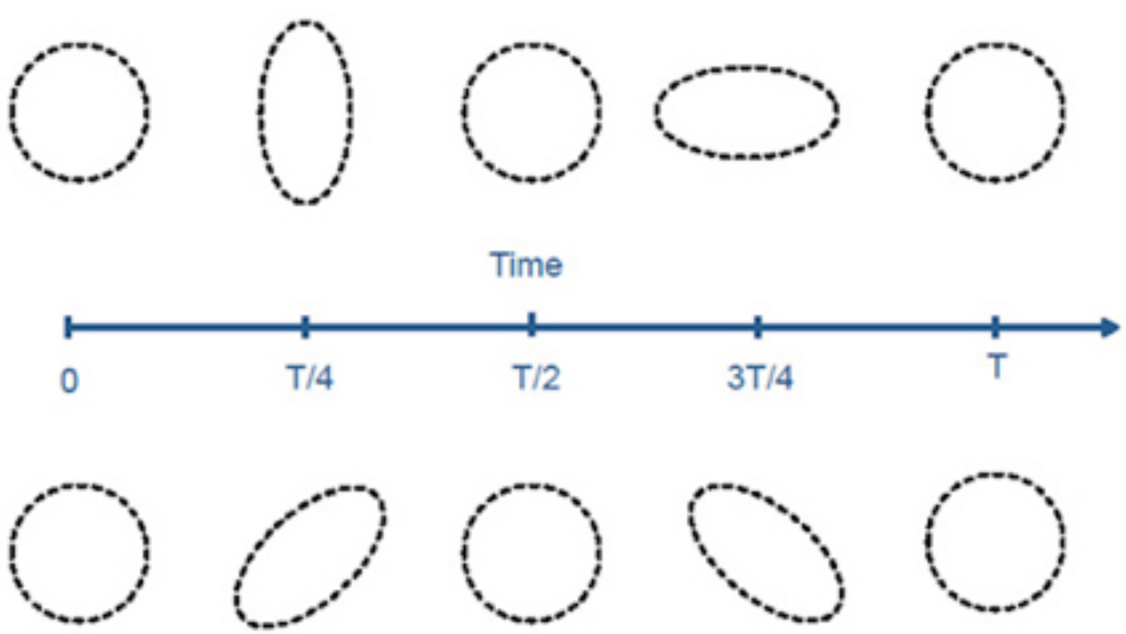
Detecting Gravitational Waves

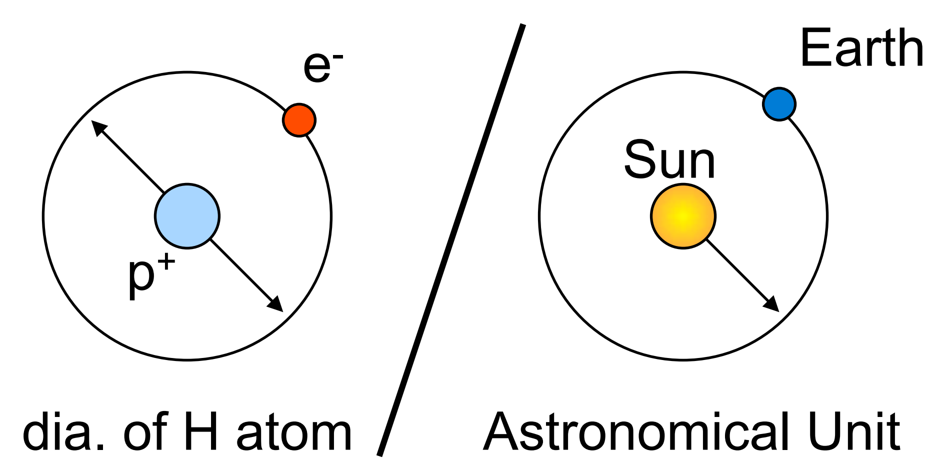
- Oscillating tidal distortions
- Displacement scales with separation
- Two polarizations

small amplitudes

linear in source distance

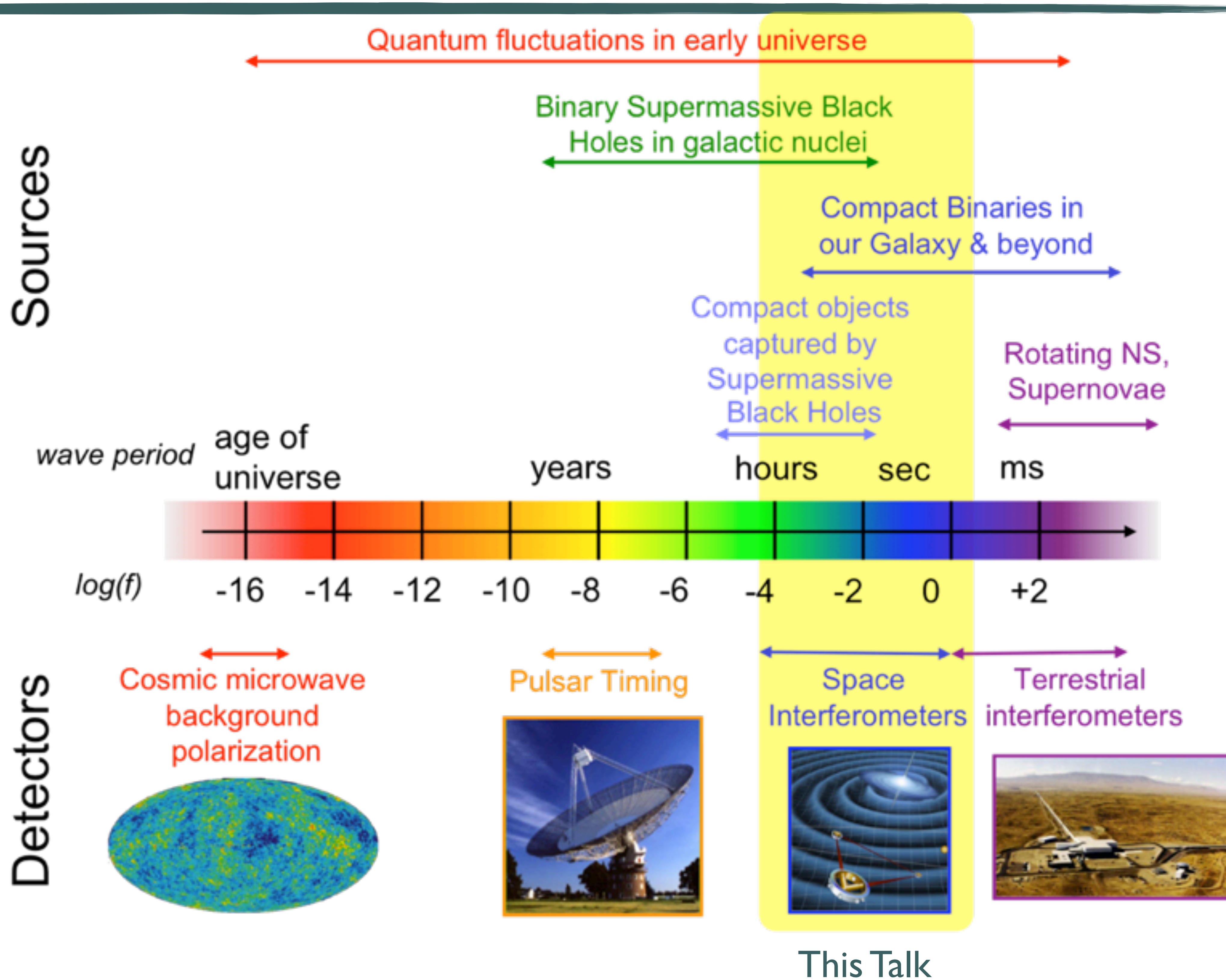
$$h \equiv \frac{\delta L}{L} \propto \frac{G^2}{c^4} \frac{1}{D} \frac{M^2}{r}$$



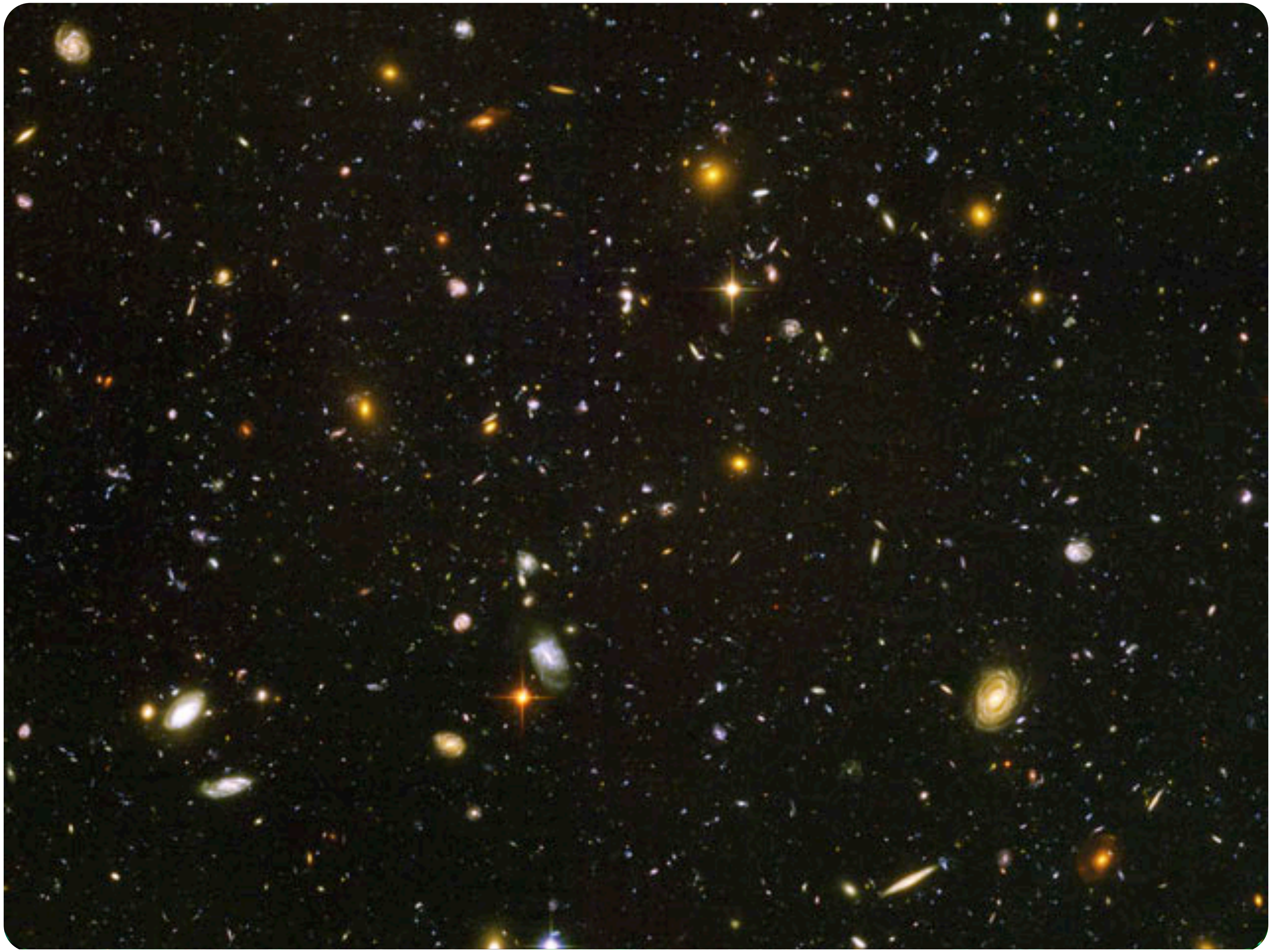


$$h \sim 10^{-21}$$

The Gravitational Wave Spectrum



Welcome to the jungle...



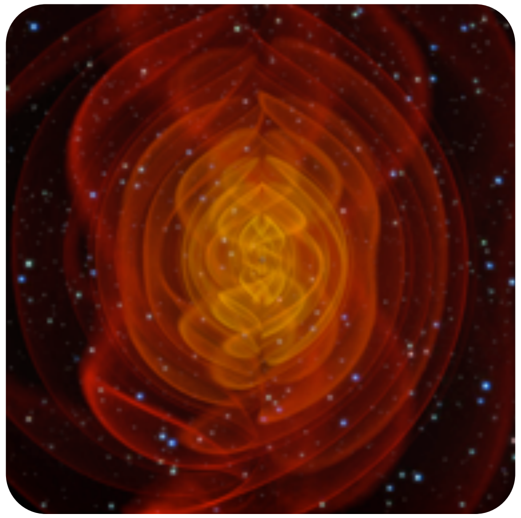
Seeing and Hearing the Universe

Electromagnetic Waves

- Tell us about atoms & molecules
- Often absorbed/modified in transit
- Hard to determine distance
- Easy to determine sky location
- Easy to measure redshift

Gravitational Waves

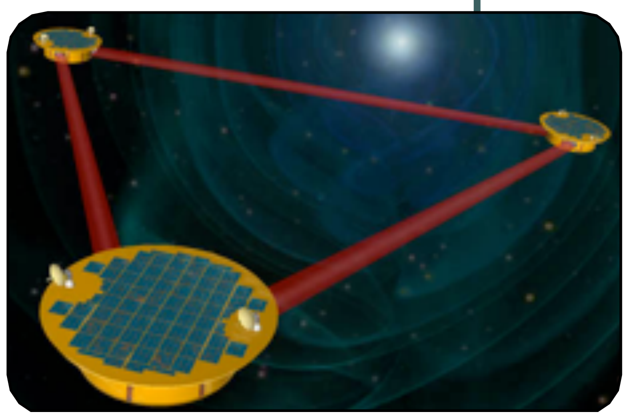
- Tell us about (large) masses
- Travel directly to us
- Easy to determine distance
- Hard to determine sky location
- Impossible to measure redshift



LISA

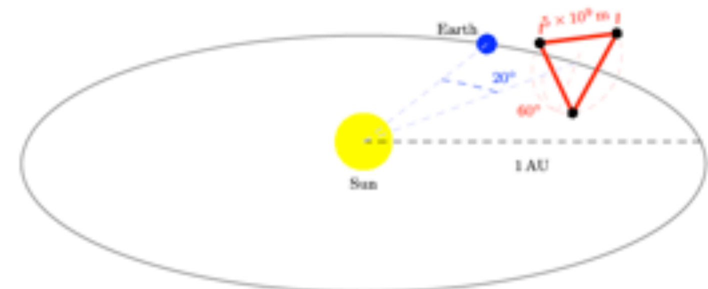
LISA Mission Concept

Triangular constellation of three identical spacecraft.



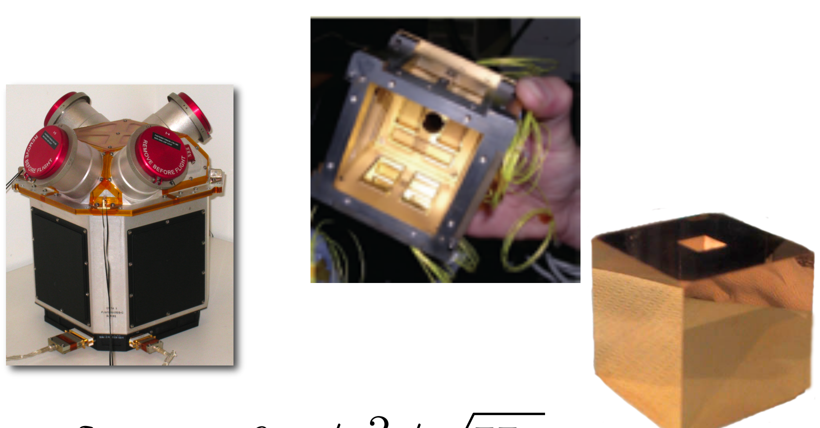
(redundancy + polarization)

Passively-stable, Earth-trailing heliocentric orbit .



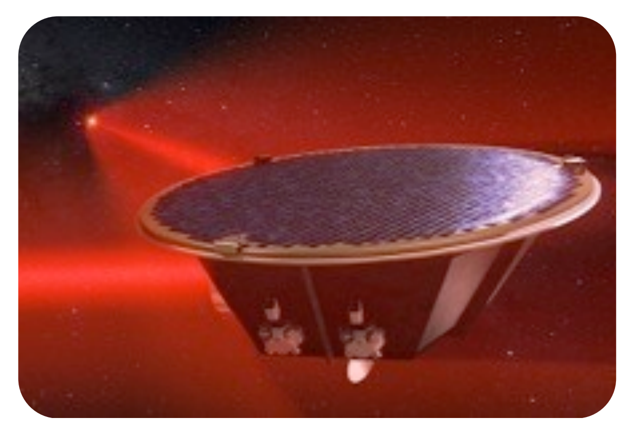
(Arm length = 5 Mkm)

Drag-free flight to realize ‘freely-falling’ test mass



$$\delta\tilde{a} \sim 3\,\mathrm{fm/s^2/\sqrt{Hz}}$$

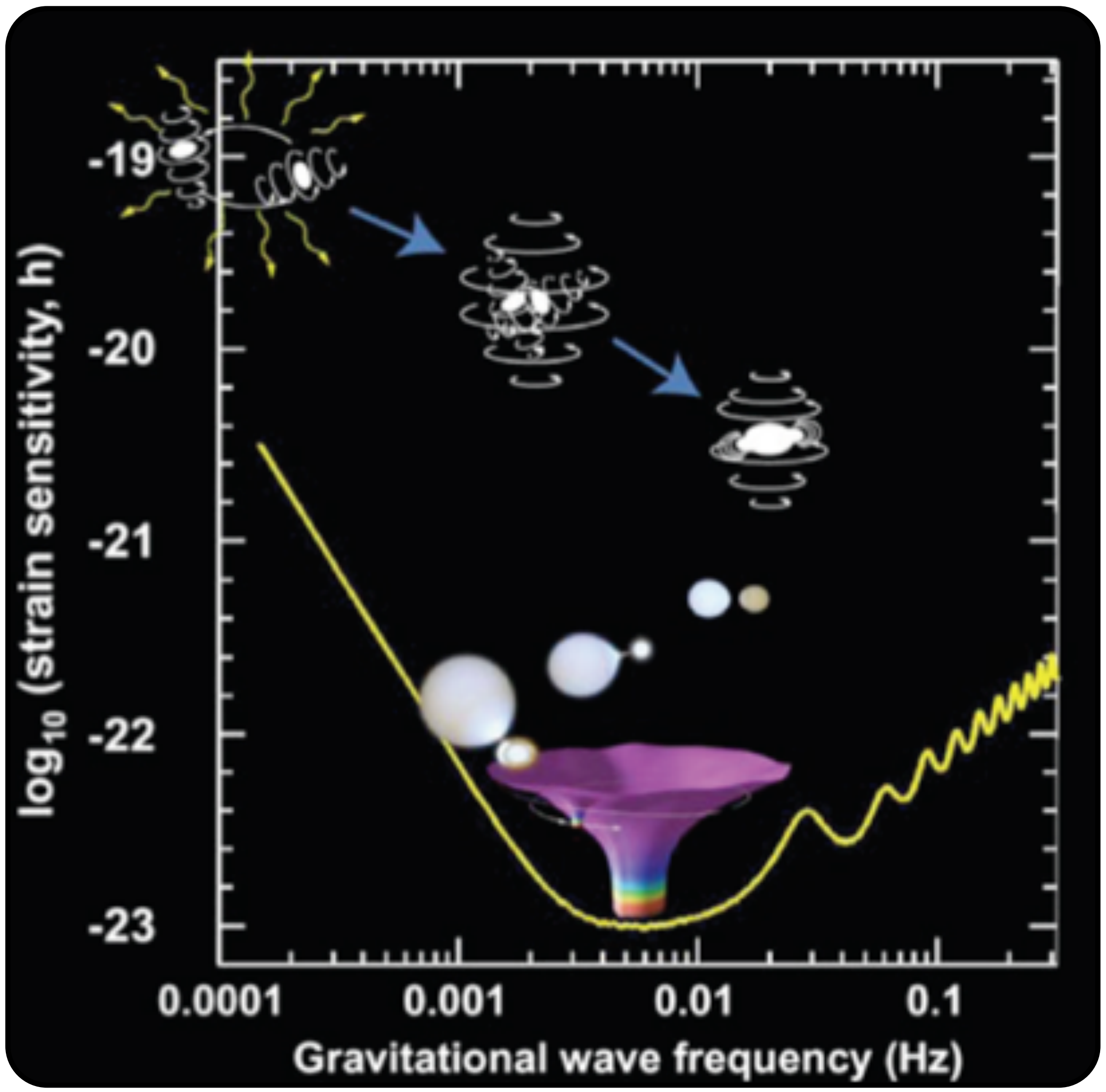
Heterodyne interferometry distance measurements



$$\delta\tilde{x} \sim 10\,\mathrm{pm/\sqrt{Hz}}$$

LISA Science

LISA Sources



(S)MBH binaries
~30 yr^{-1}

(S)MBH capture of BHs
~10^2 yr^{-1}

Close binaries in Milky Way
~10^{6-7} total, ~10^4 resolved

Unknowns?

Structure Formation & Galaxy Evolution

Current Picture

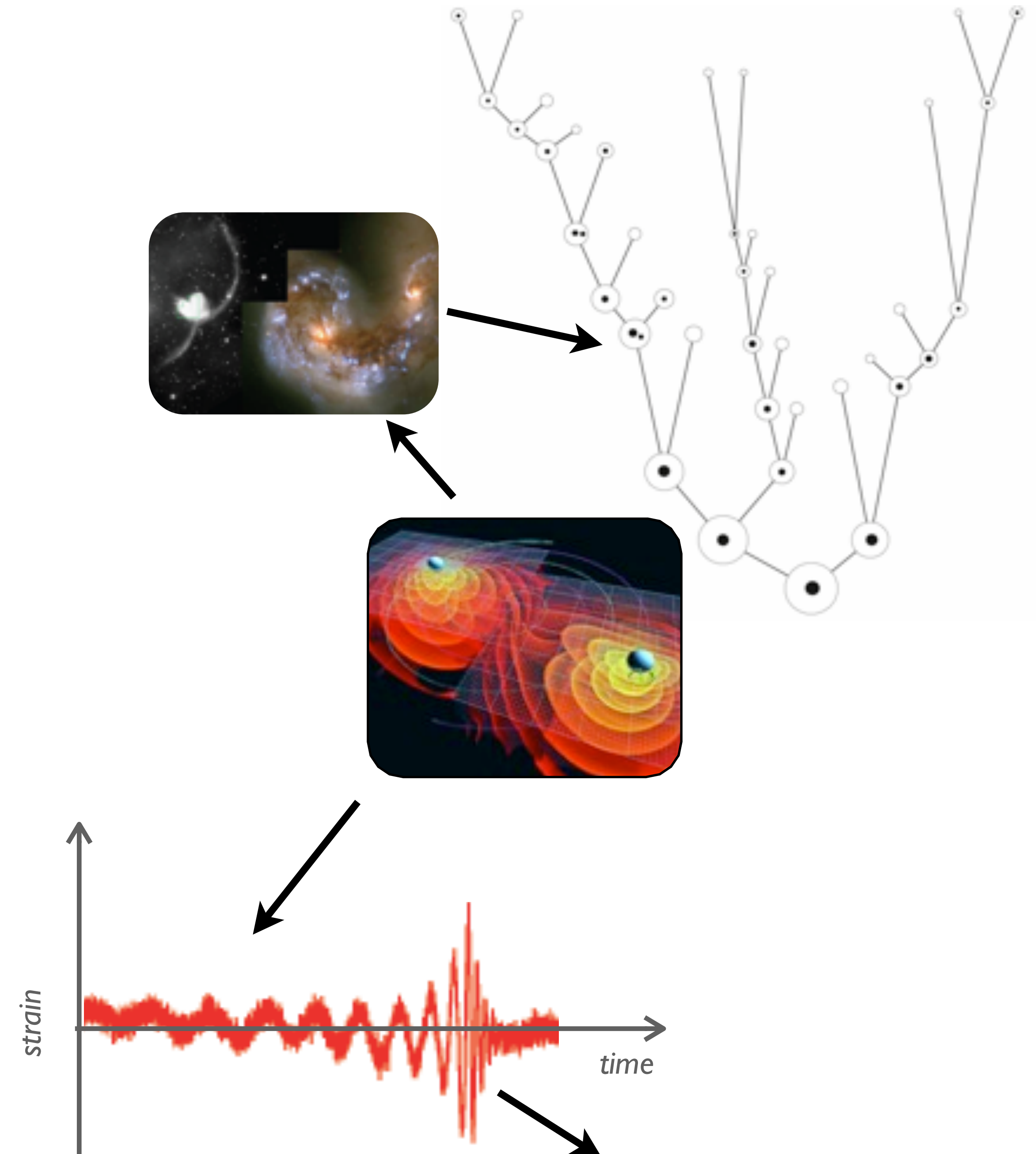
- galaxies formed hierarchically
- central black holes 'track' galaxy mass

Open questions

- seed BH population
- BH growth (merger vs. accretion)
- BH merger rate ('stalled' binaries?)

GW approach

- measure statistical sample of merging binaries
- compare mass/mass ratios/spins vs. distance with model predictions



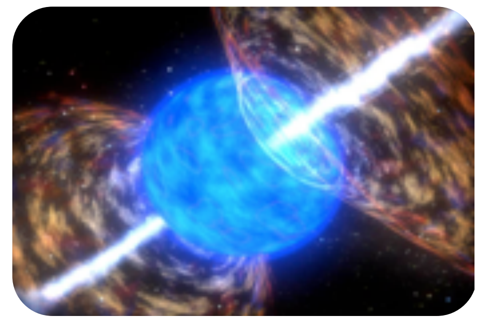
$M_1,\ M_2,\ \chi_1,\ \chi_2,\ ,D_L\ldots$

Powerful events

SN Ia

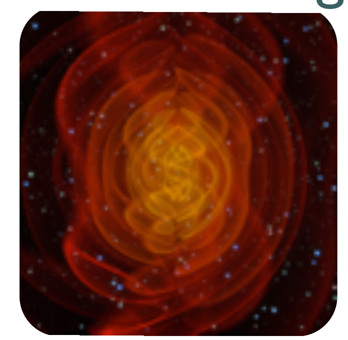
$L_{peak} \sim 10^{43}$ erg/s

GRB



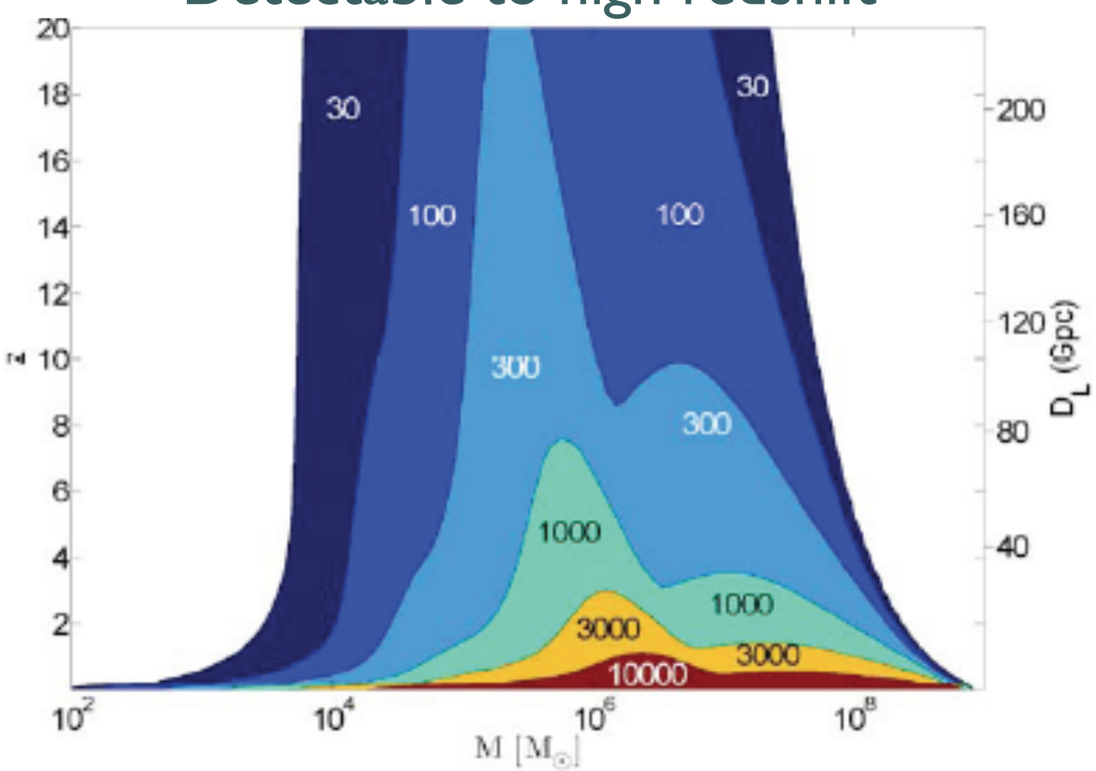
$L_{peak} \sim 10^{53}$ erg/s

BH-BH merger

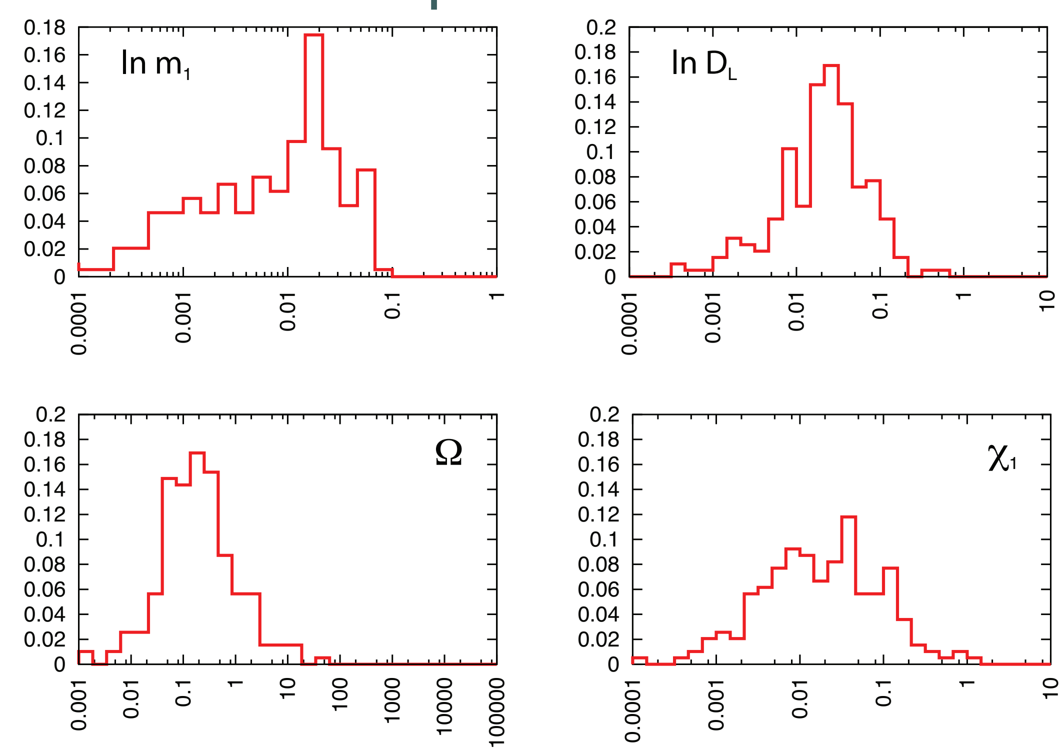


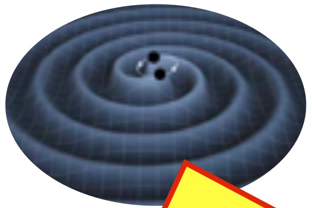
$L_{peak} \sim 10^{56}$ erg/s

Detectable to high redshift



Precision parameter estimation





Cosmology with 'Standard Sirens'

Multi-messenger

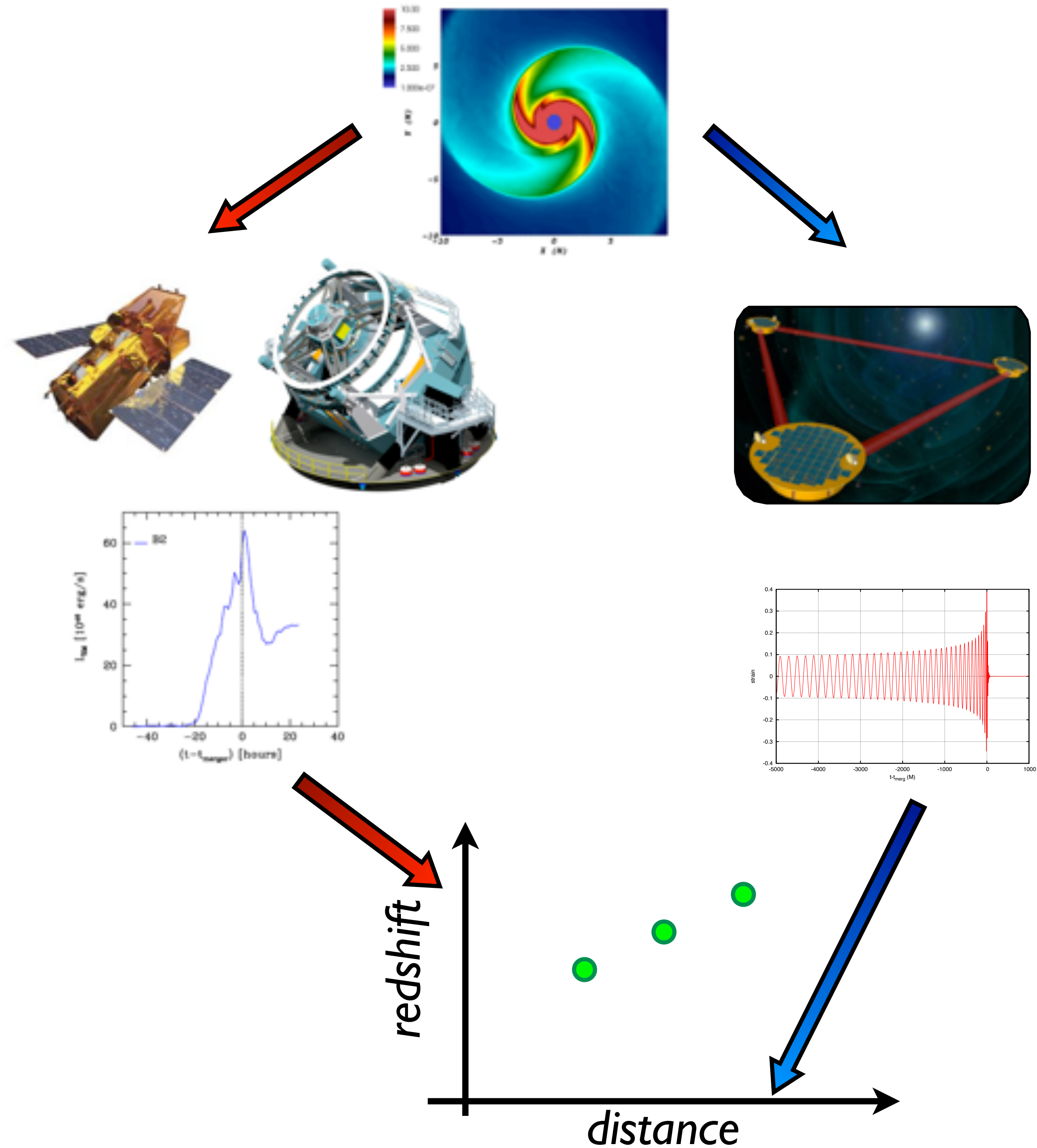
Binary merger waveform *directly* encodes luminosity distance

- intrinsic error < 0.1%
- weak-lensing limits ~3%

EM counterpart provides redshift

- identify host galaxy
- 3D error box + merger time

Lower statistics but different systematics than SN approach



Extreme Mass Ratio Inspirals

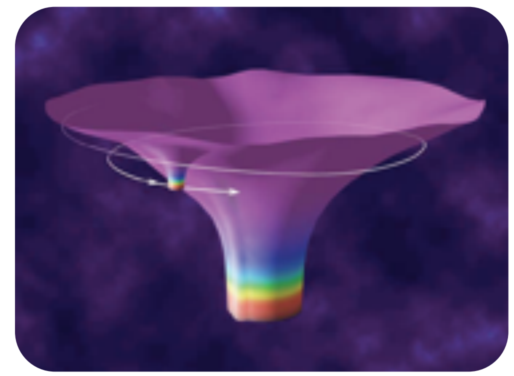
Capture of stellar-remnant BH by central BH.

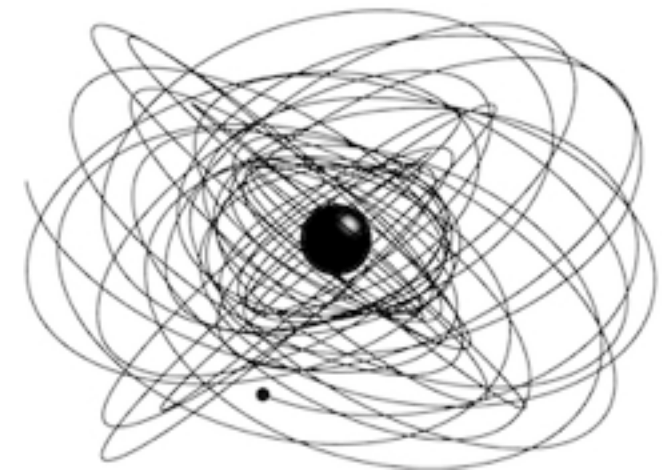
Complex, long-lived orbits

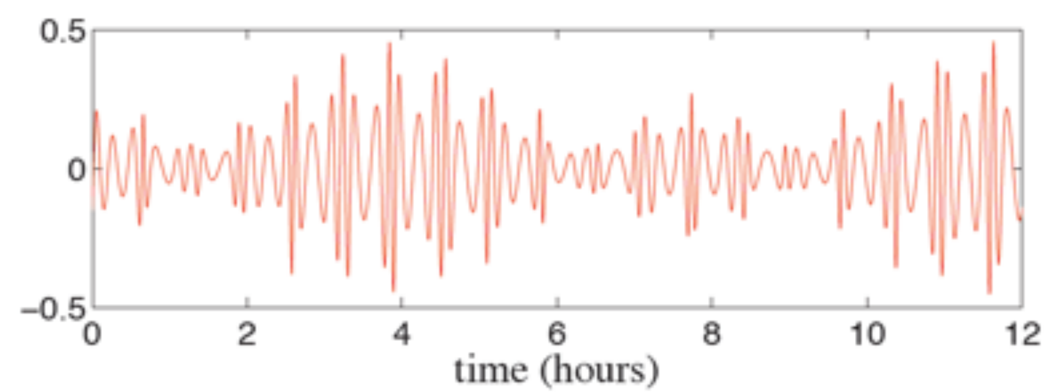
- ~10^5 cycles measured: precision parameter estimation!
- Need templates & search strategy

Tests of GR

- small BH acts as "indestructible" test particle mapping out spacetime of large BH.





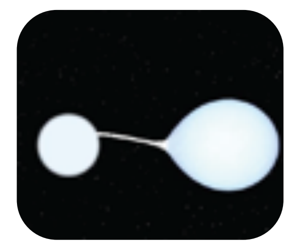


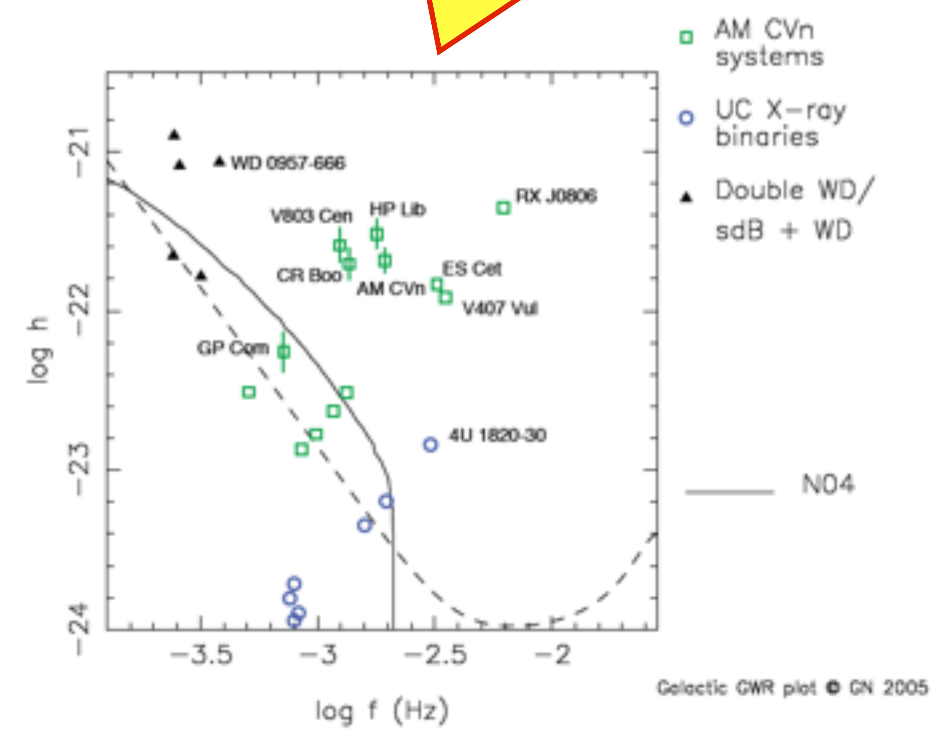
Binaries in our backyard

Multi-messenger

'Ultra-compact' binaries with WD, NS, or BH members

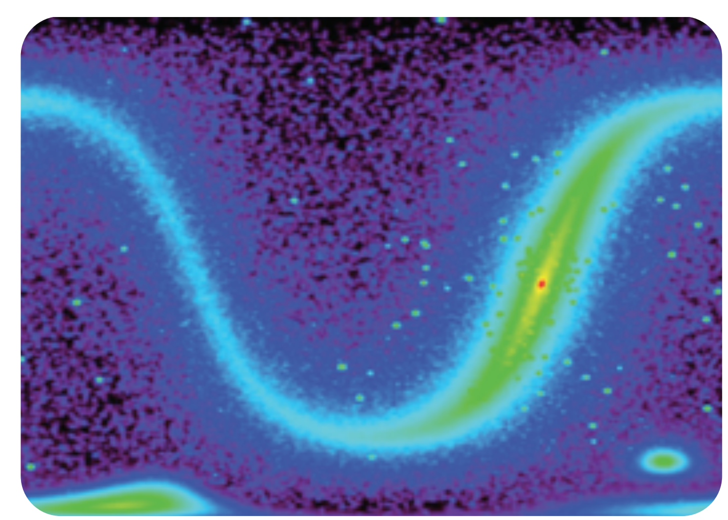
- ~10^6 in our galaxy within LISA band.
- ~10^4 resolvable
- ~10 already known
- Detectable in LMC, SMC and (possibly) nearby galaxies

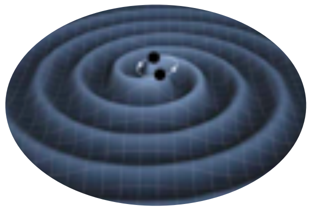




Science applications

- compact object demographics
- binary physics (mass transfer)
- fundamental physics
- galactic structure
- globular clusters

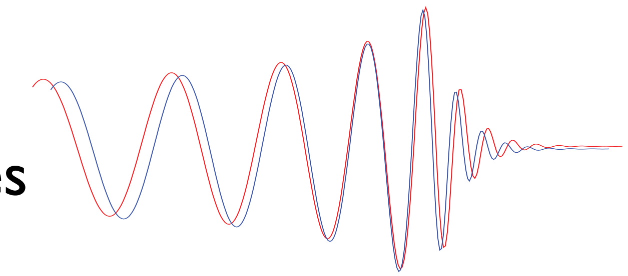




An astrophysical laboratory for gravity research

Binary (S)MBH merger

- Compare observed waveforms with templates

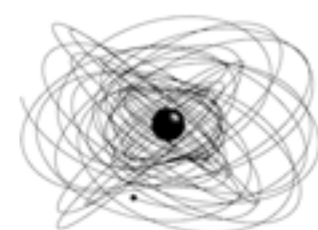


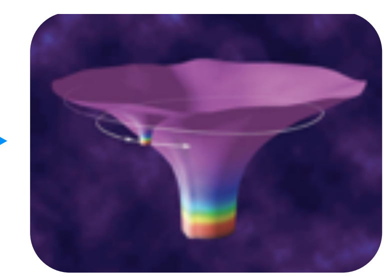
- modal analysis of ring-down

$$(M,\ \chi)_1 \stackrel{?}{=} (M,\ \chi)_2$$

EMRIs

- Map geodesics & compare with Kerr metric





Galactic Binaries

- compare EM & GW signals to constrain graviton mass

See Living Reviews Article arXiv:1212.5575 [gr-qc]

Discovery Space

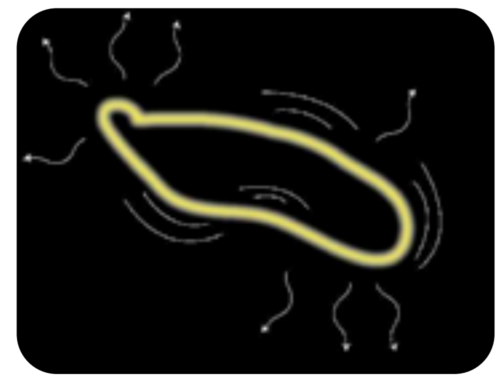
‘Exotic’ physics

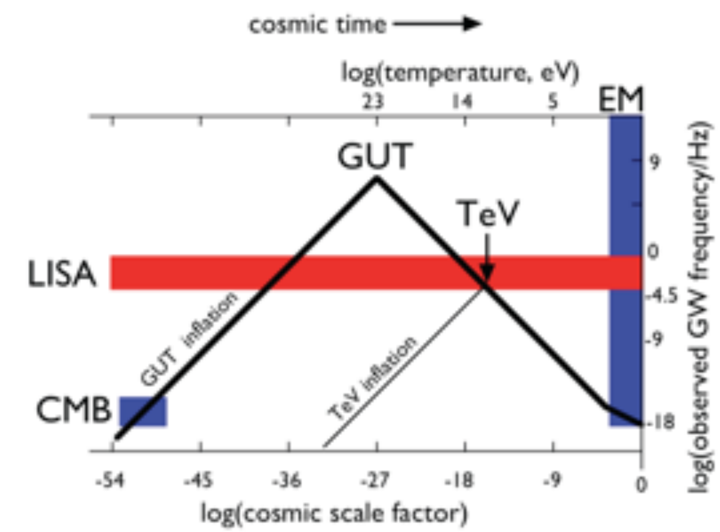
- Inflation (certain models)
- cosmic strings
- vacuum bubble nucleation
- electroweak physics
- branes

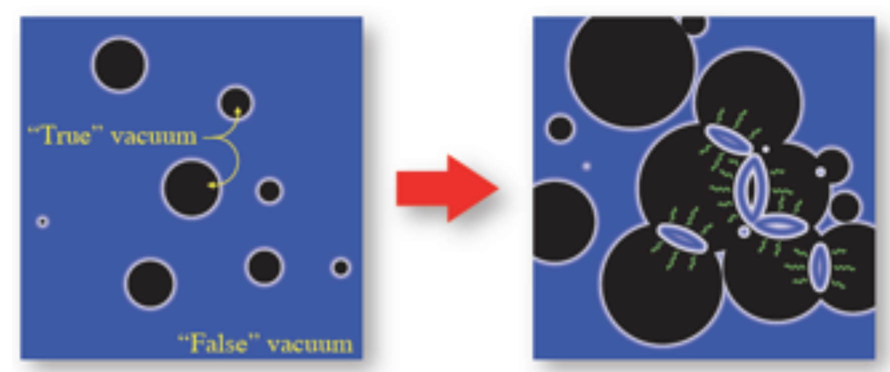
‘Exotic’ Astrophysics

- Intermediate-mass black holes

Unexpected sources



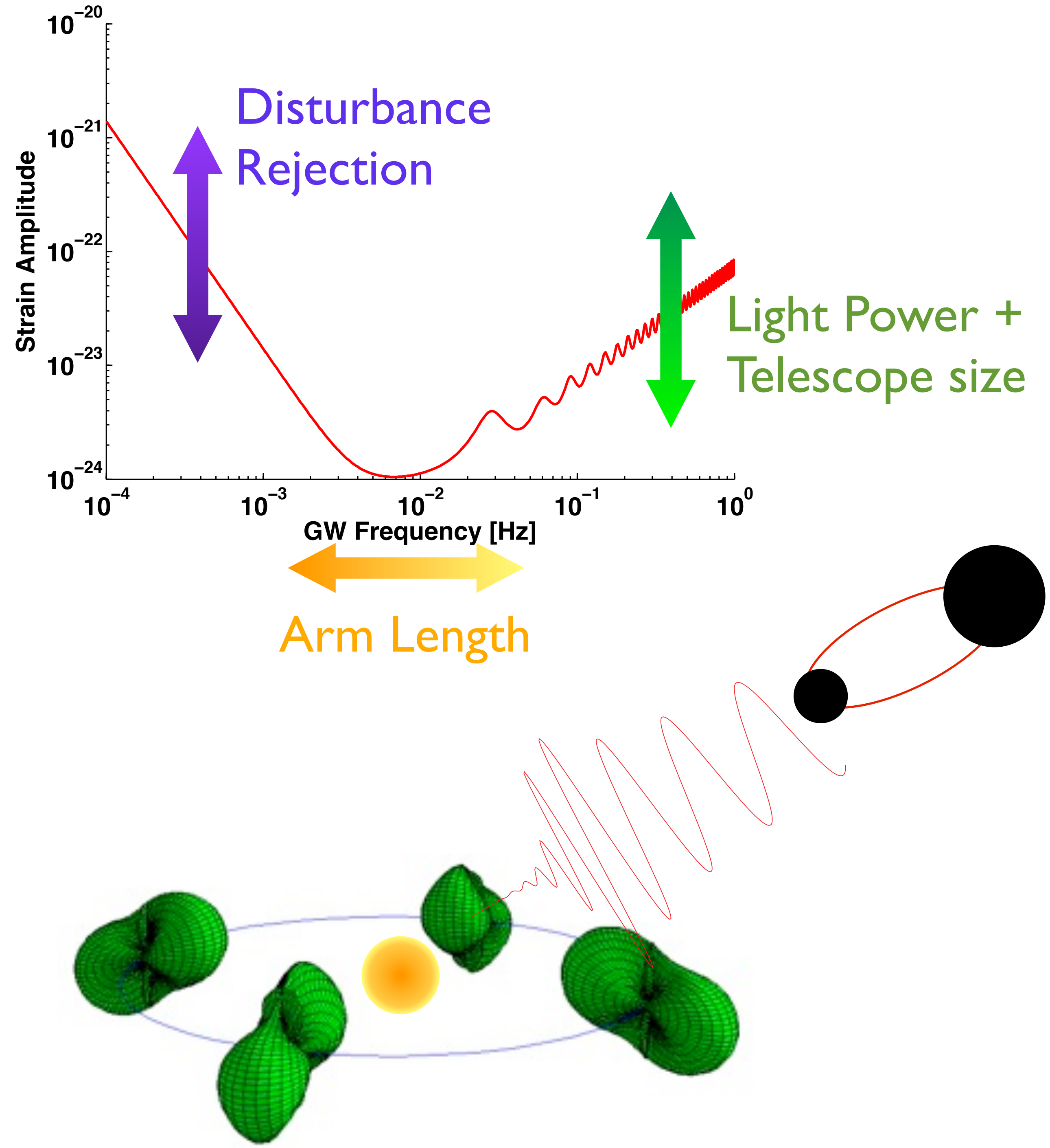




Current Landscape

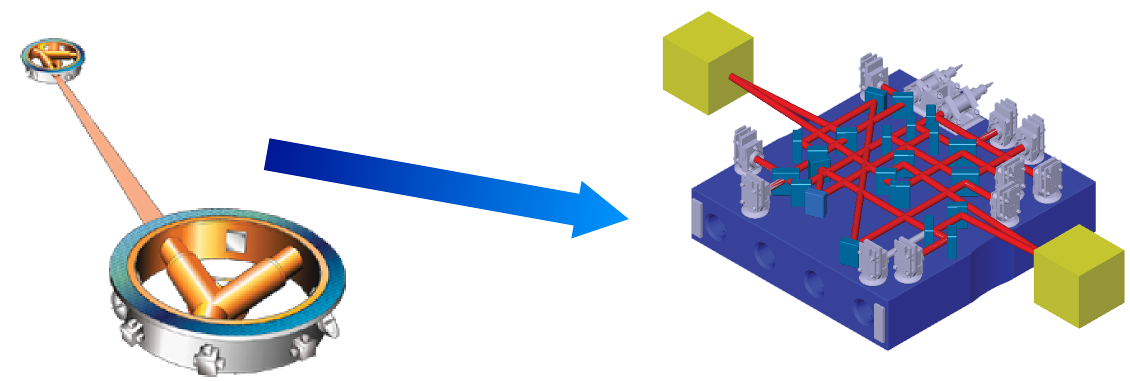
Science impact of design choices

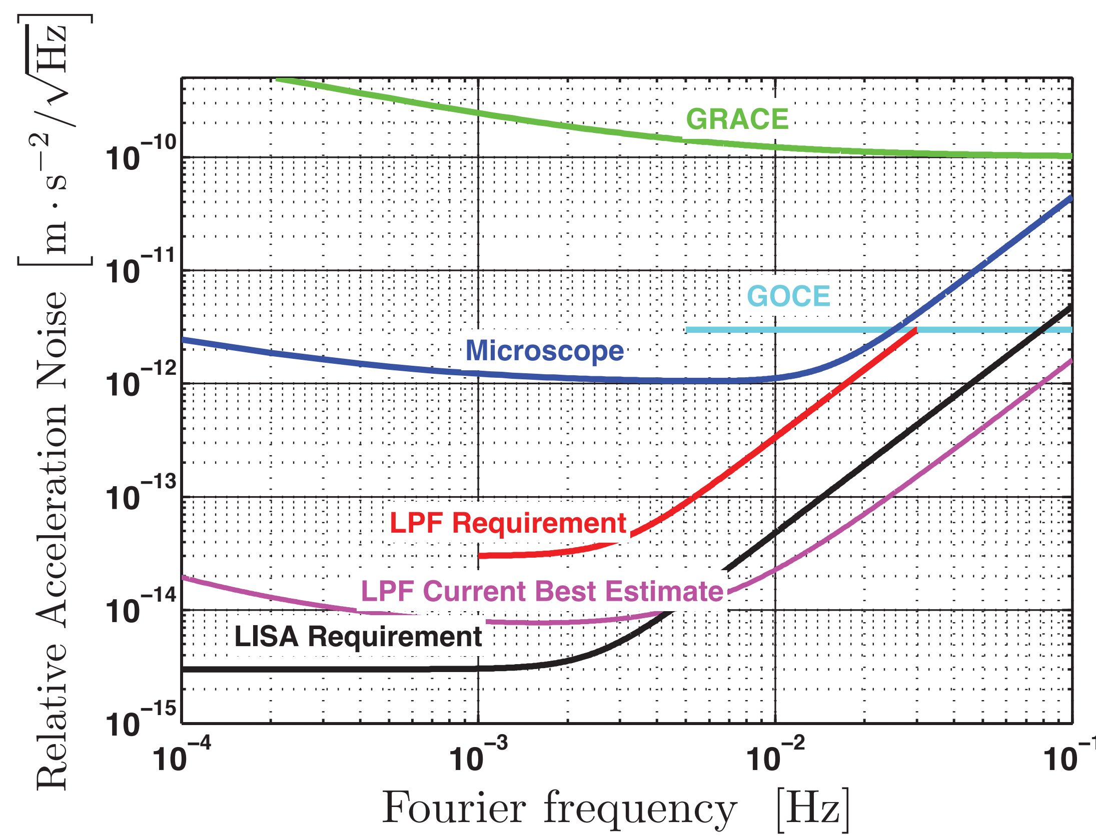
- Instrument choices affect instantaneous sensitivity (spectral response)
- Constellation configuration & orbit affect wavefront measurement (parameter estimation or ‘imaging’)
- Mission duration affects statistics & science associated with rare events
- Each of these affect mission cost

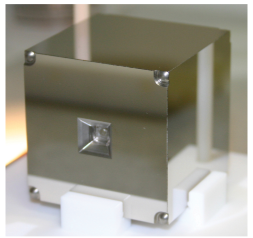
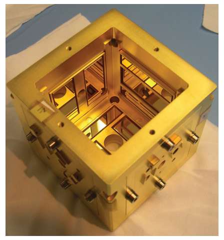
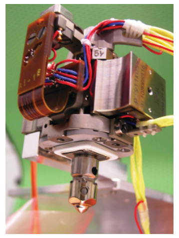
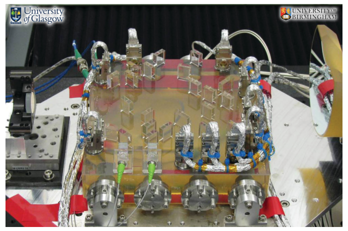
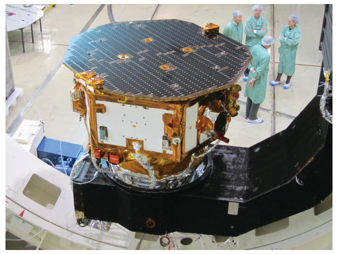
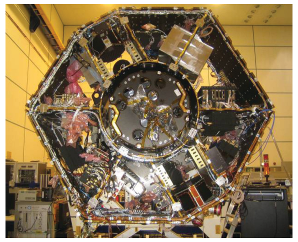


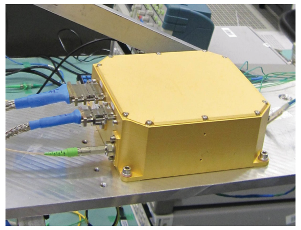
LISA Pathfinder

- Technology demonstrator for space-based GW detectors
- ESA lead, NASA-supplied thrusters & control laws
- Validate a physics-based model for disturbance reduction
- Late stages of integration & test, launch anticipated by 2015





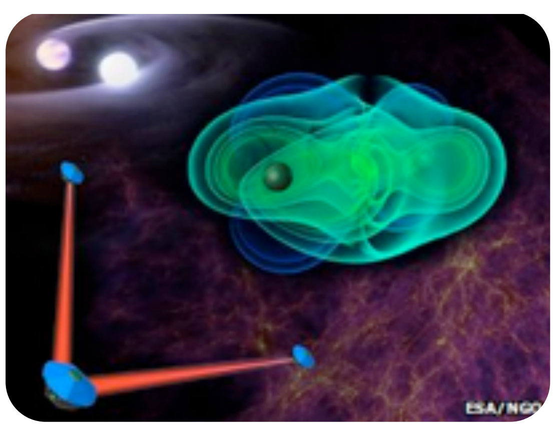









European Outlook

ESA call for Cosmic Visions L2 & L3 'Science Themes'

- Whitepapers due May 24th
- Theme Selection Nov. 2013
- Launches in 2028 & 2034
- International partnership at ~20%



eLISA Consortium (http://www.elisa-ngo.org/) organized to respond

- Will use 2-arm eLISA/NGO concept as strawman for whitepapers
- Refining science case
- Negotiating national roles & responsibilities
- Pursuing technology development

US outlook

2011-2012 NASA Mission Concept Study

- Explore trade space of science, cost, and risk
- community input + analysis + synthesis
- final report (http://pcos.gsfc.nasa.gov) in August 2012
- Findings (my interpretation):
    - LISA-like missions have an appropriate balance of science, cost, and risk
    - viable missions are all over ~$1B

Opportunities

- Minority partner in European mission
- Facility class mission (w/ or w/o partners) in the next decade
- Need to prepare *science and technology* for both possibilities

It's a Long Road...

2016?

Ground-based detectors