Gravitational Astronomy: The Big Picture

International Centre for Theoretical Sciences

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What are Gravitational Waves?

In Newton's law of gravity the gravitational field satisfies the Poisson equation:

$$\nabla^2\Phi(t,\mathbf{X}) = 4\pi G\rho(t,\mathbf{X})$$

Gravitational field is described by a scalar field, the interaction is instantaneous and no gravitational waves.

In general relativity for weak gravitational fields, i.e.

$$g_{\alpha\beta} = \eta_{\alpha\beta} + h_{\alpha\beta}, \quad |h_{\alpha\beta}| \ll 1$$

in Lorentz gauge, i.e. $\bar{h}^{\alpha\beta}{}_{,\beta} = 0$, Einstein's equations reduce to wave equations in the metric perturbation:

$$\left(-\frac{\partial^2}{\partial t^2} + \nabla^2\right)\bar{h}^{\alpha\beta} = -16\pi T^{\alpha\beta}.$$

Here $\bar{h}_{\alpha\beta} = h_{\alpha\beta} - \frac{1}{2}\eta_{\alpha\beta}\eta^{\mu\nu}h_{\mu\nu}$ is the trace-reverse tensor.

Gravitational Wave Observables

- **Luminosity** $=$ Asymmetry factor x $(v/c)^{10}$

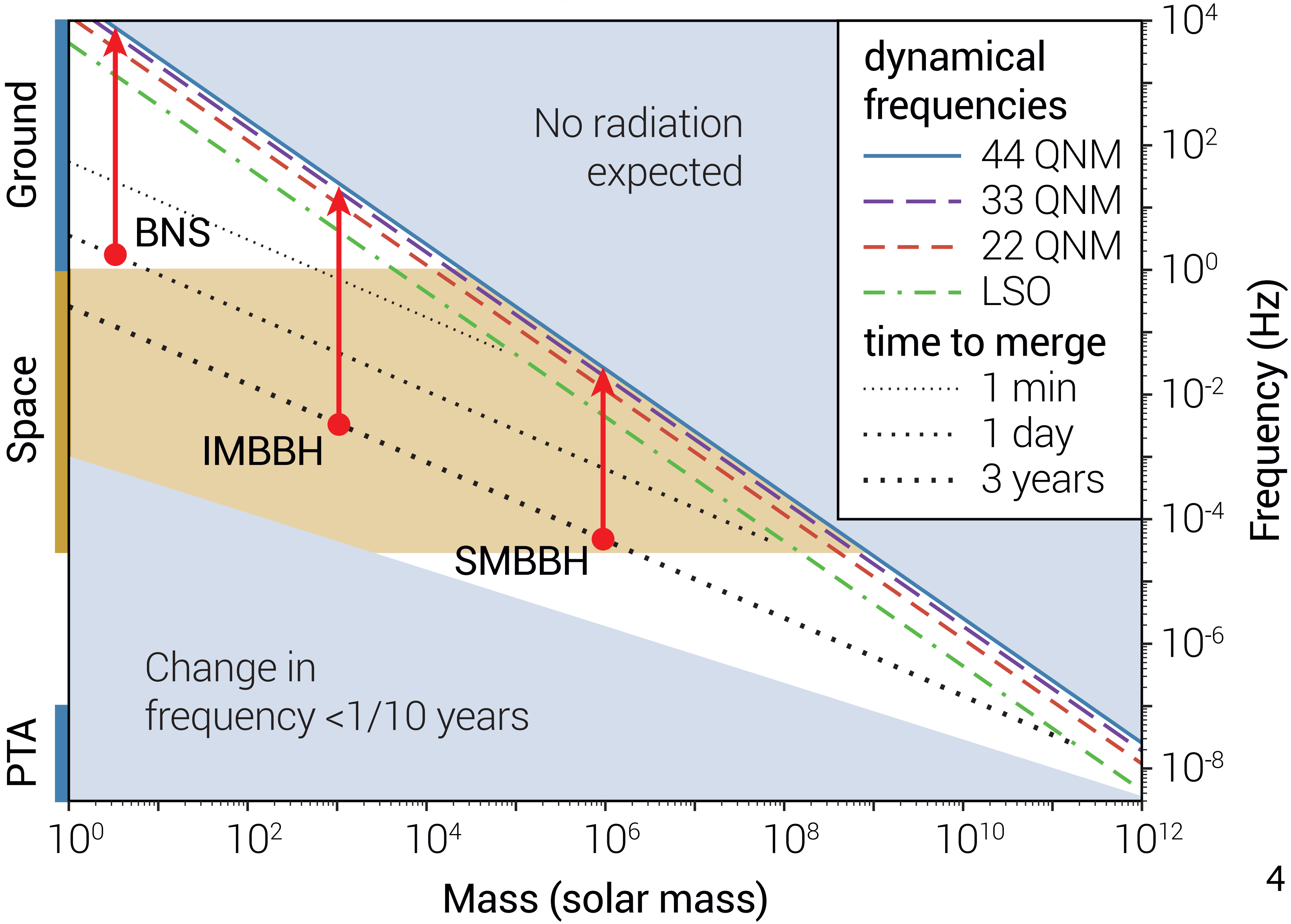
  $=$ Asymmetry factor x $(M/R)^5$

  - A strong function of velocity: During merger a binary black hole in gravitational waves outshines the entire Universe in light
- **Amplitude** from a source of size R at a distance D is

$$h = (\text{Asymmetry factor})\ (M/D)\ (M/R)$$

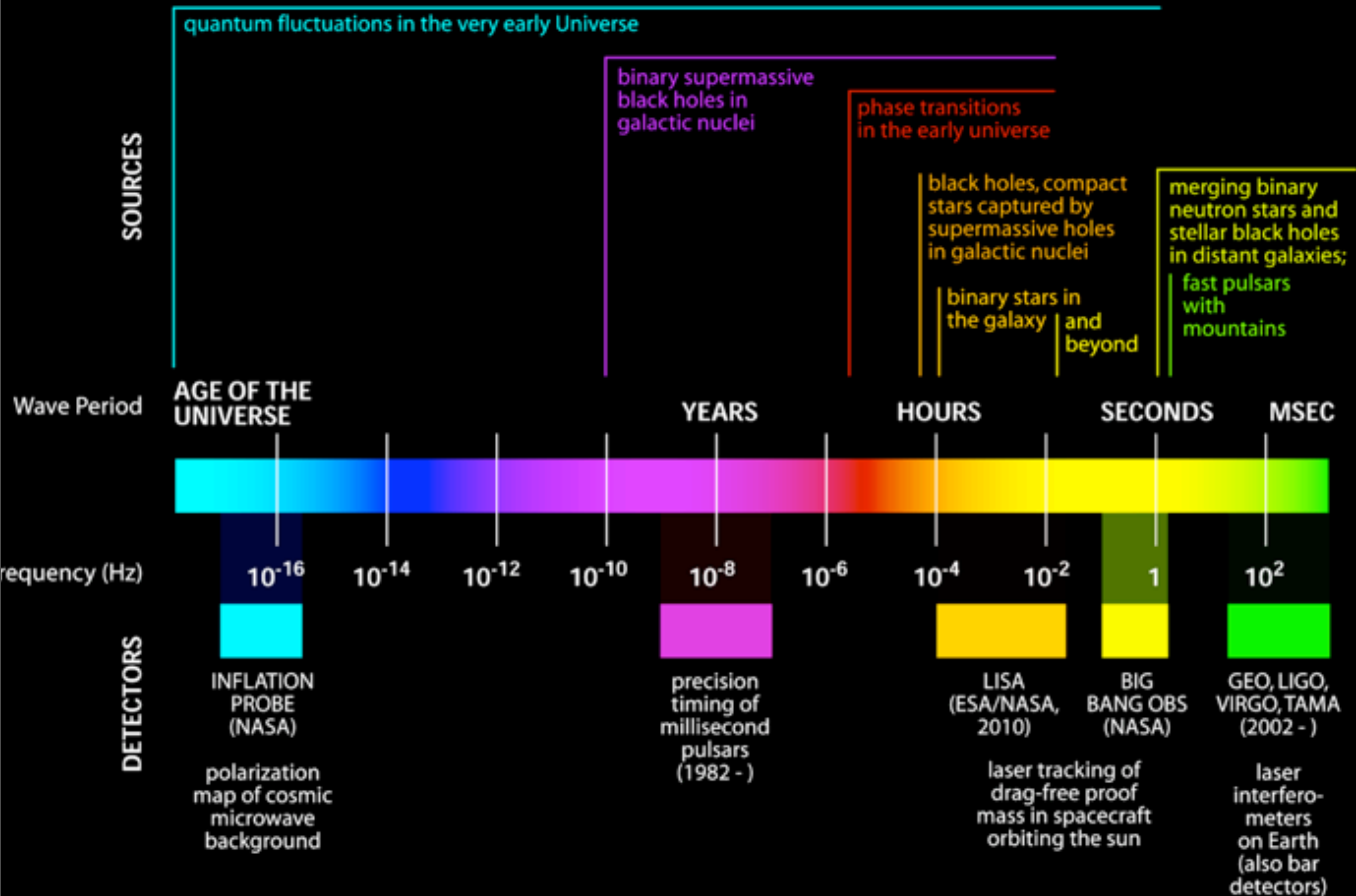
- Gravitational wave detectors are essentially detectors of neutron stars and black holes
- **Frequency** of the waves is the dynamical frequency $f \sim \sqrt{G\rho}$
  - For binaries dominant gravitational-wave frequency is twice the orbital frequency: A binary of 20 solar masses merges at a frequency of 200 Hz
- **Polarization** is determined from a network of detectors
  - A single detector is sensitive only to a linear combination of the two polarizations

Frequency–Mass Diagram For Compact Binaries

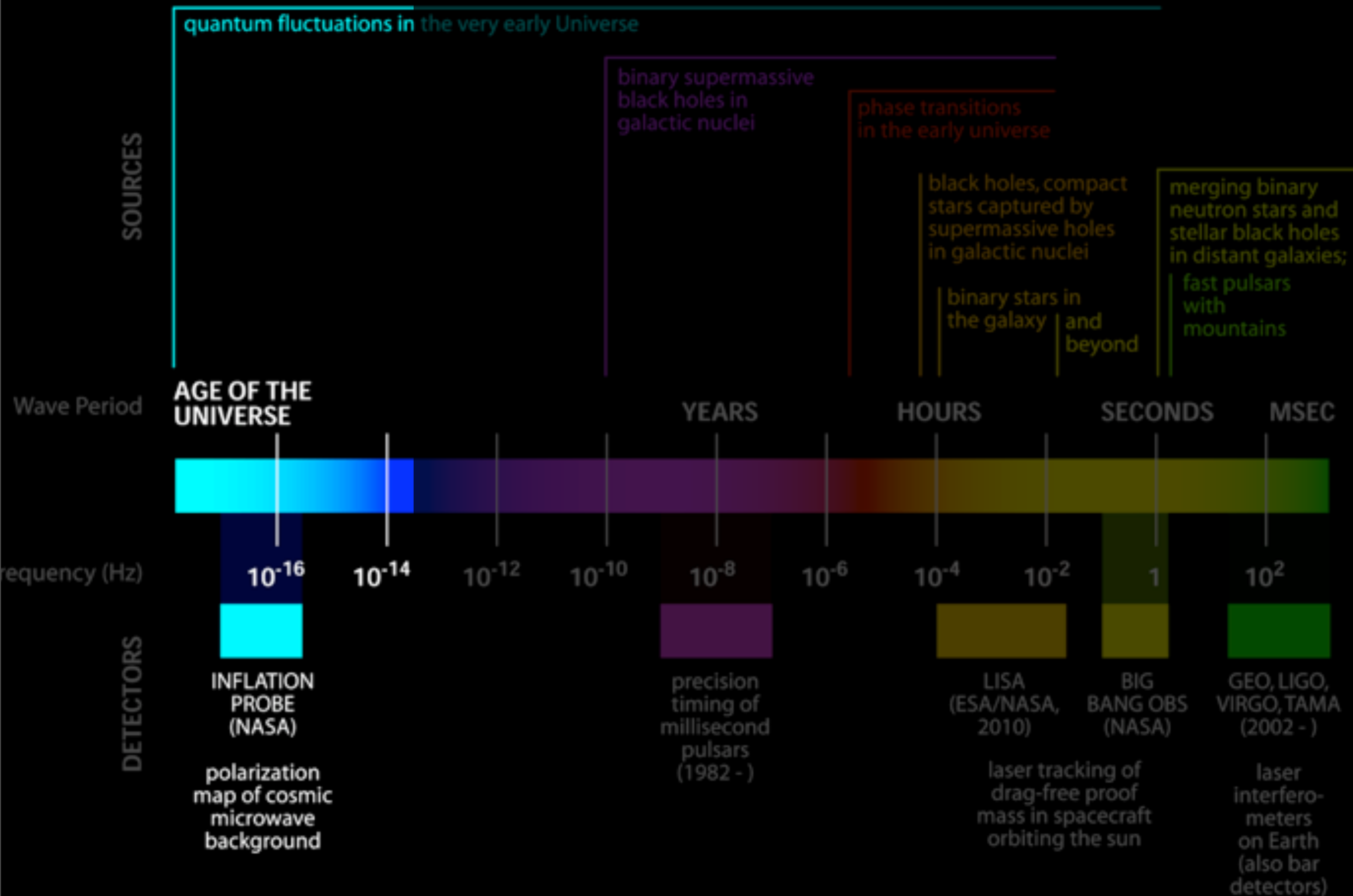


Wednesday, 26 June 2013

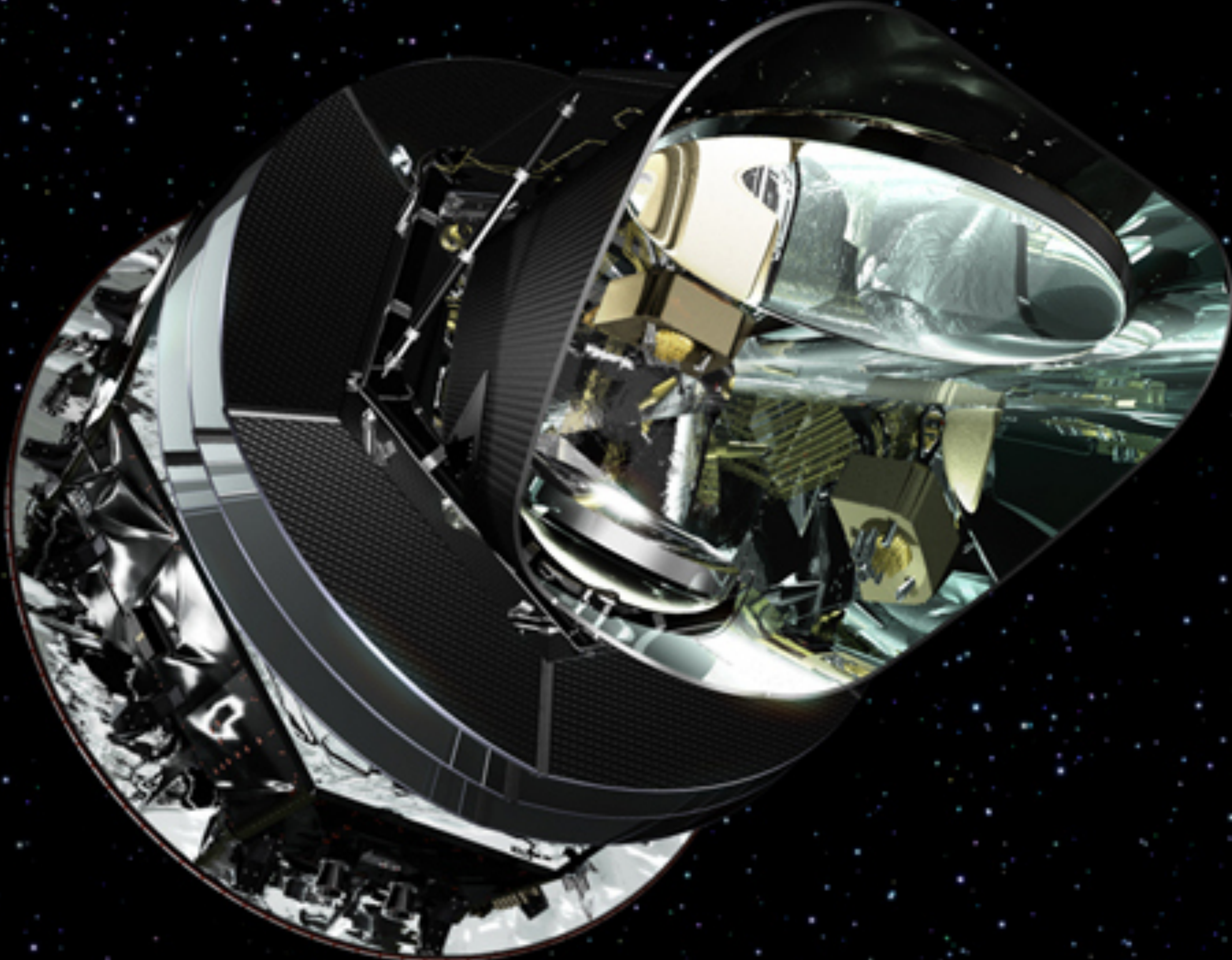
Overview of the Talk



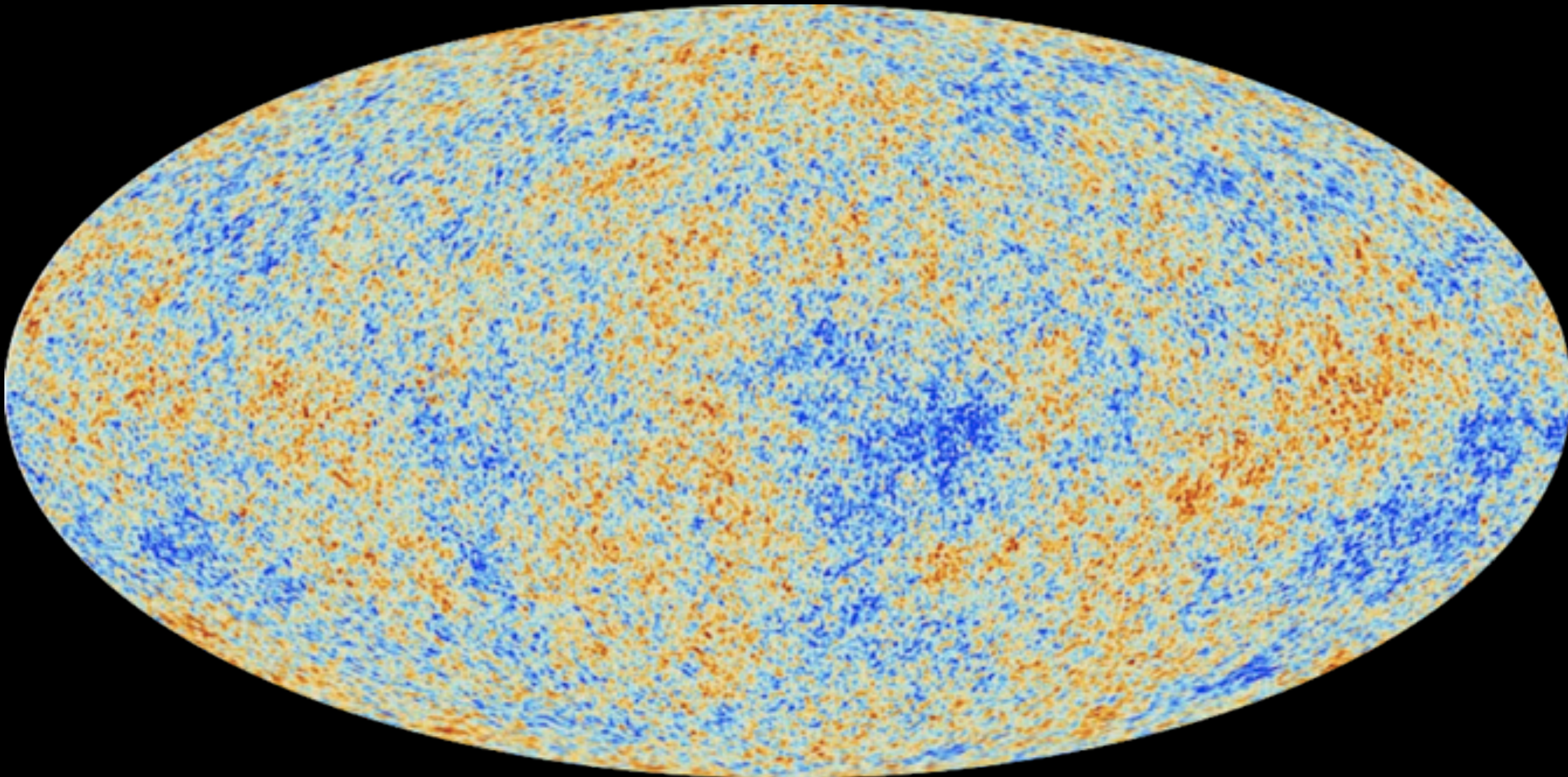
Ultra Low Frequency



Planck Satellite

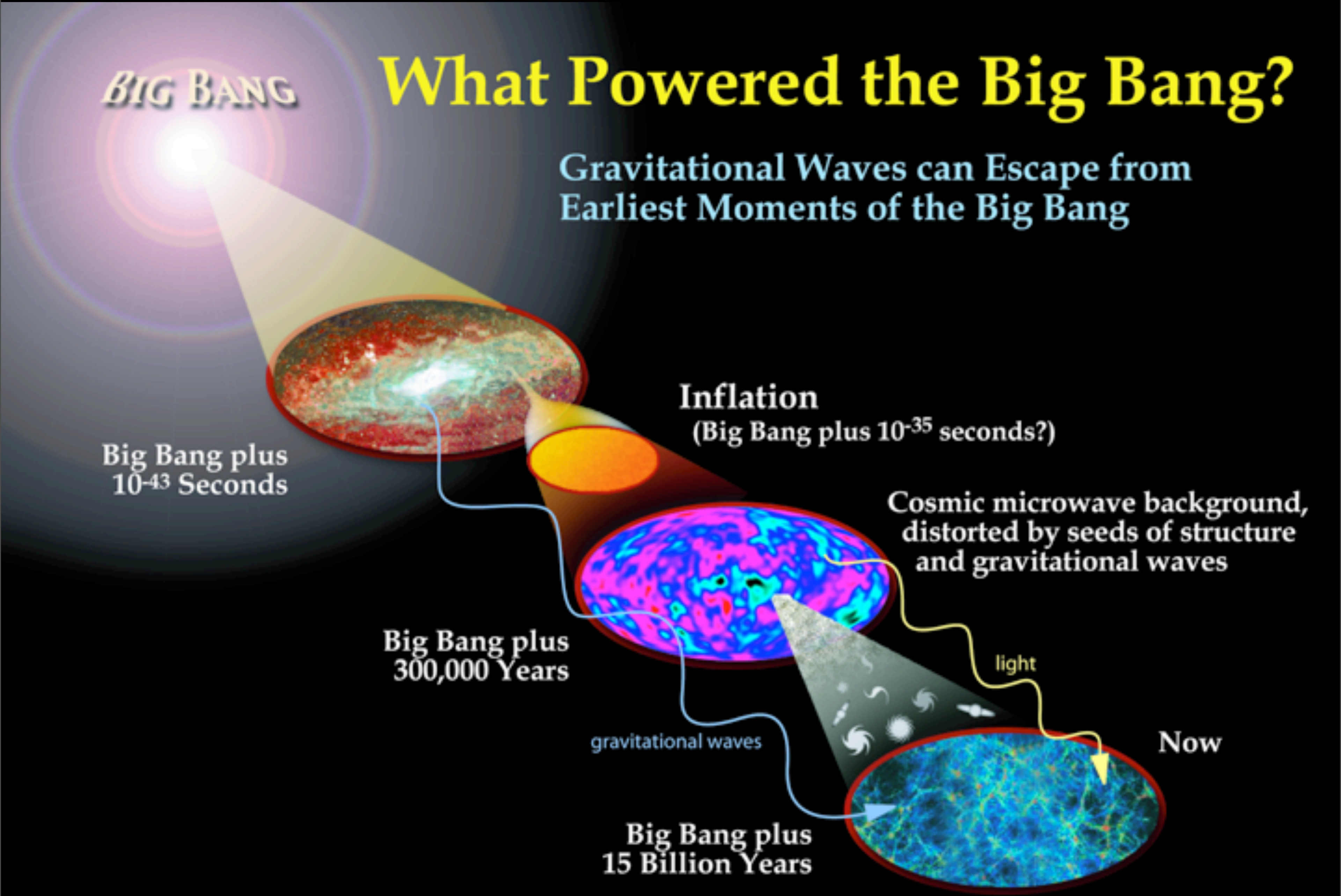


Planck Temperature Fluctuations



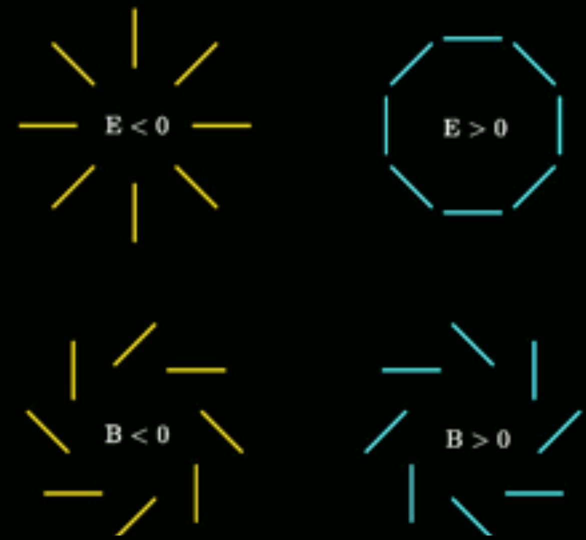
What Powered the Big Bang?

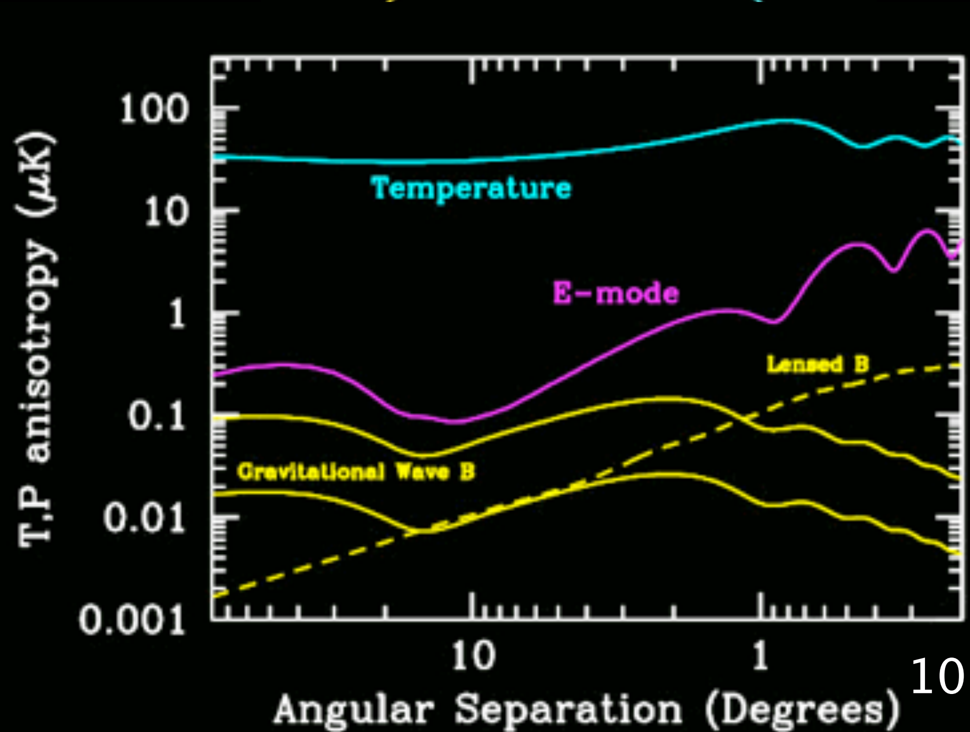
Gravitational Waves can Escape from Earliest Moments of the Big Bang



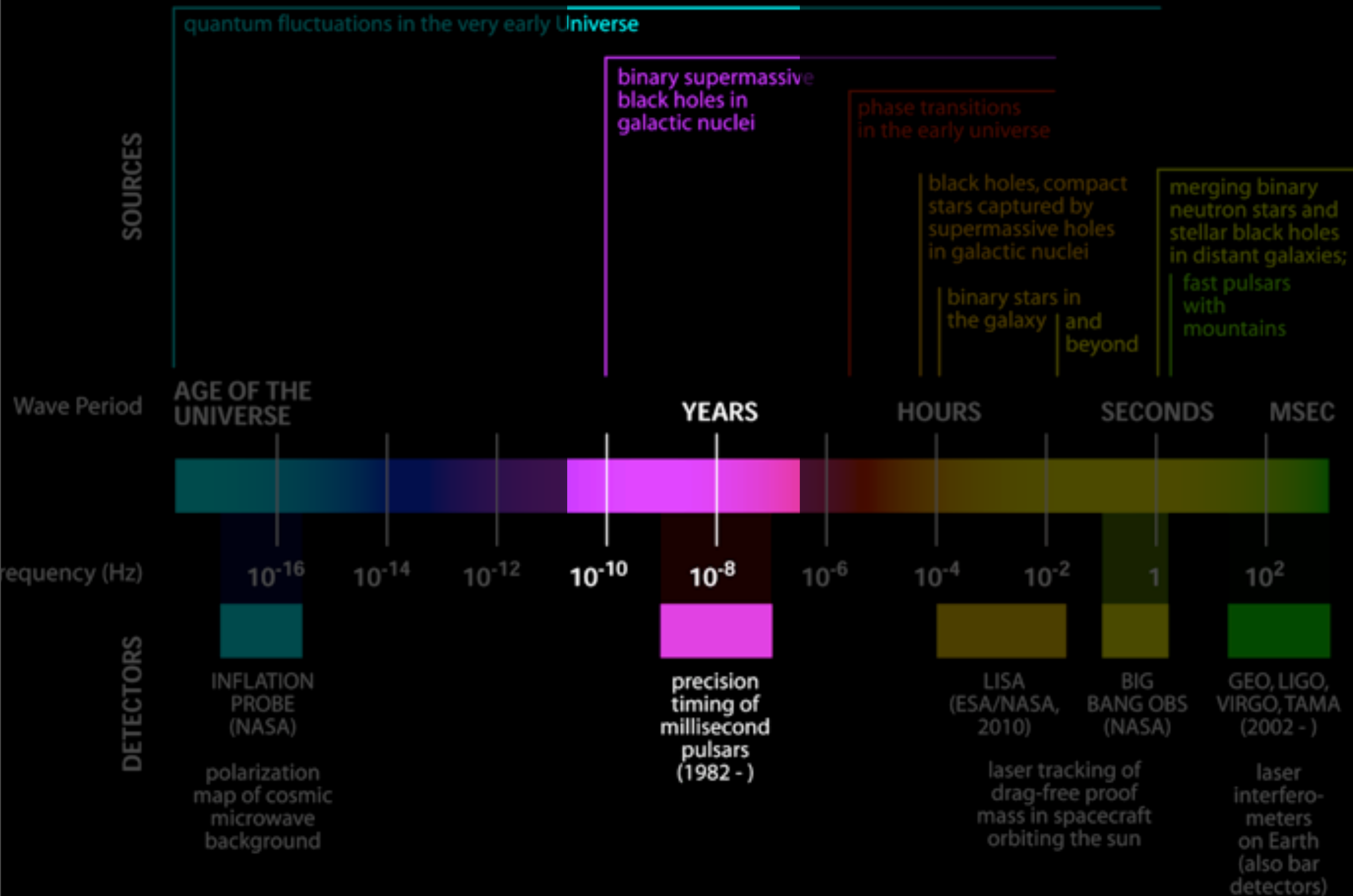
Primordial Background and New Physics

- Horizon scale stochastic radiation
- Gravitational waves can cause
  - Temperature anisotropies as well as specific polarization modes in CMB photons
- Detection can determine the energy scale of inflation
  - Larger the energy scale greater is the strength of the background
- New physics
  - Need to have extra dimensions required by string theory



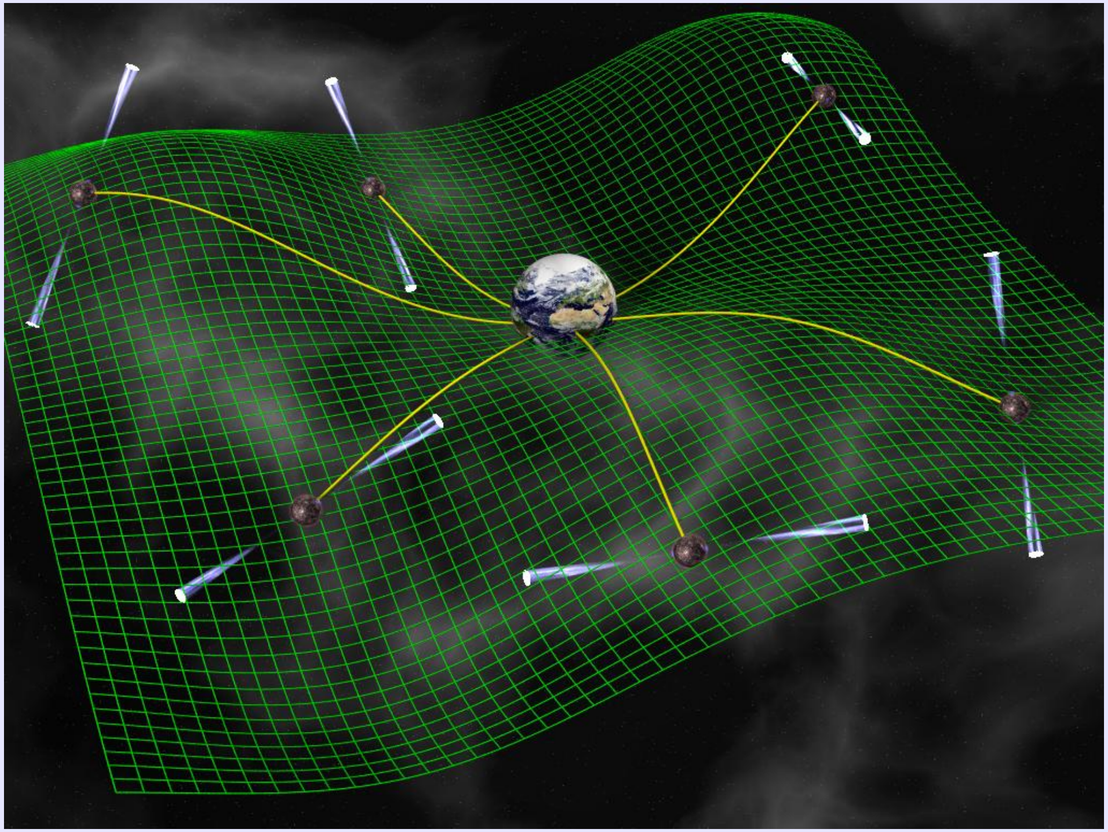


Very Low Frequency



Pulsar timing arrays:
Use millisecond pulsars (MSPs) to detect gravitational waves

Pulsar Timing Array: a galactic-scale gravitational wave detector.



Sensitive to very low frequency (~nHz) grav waves.

Pulsar Timing Arrays around the world:

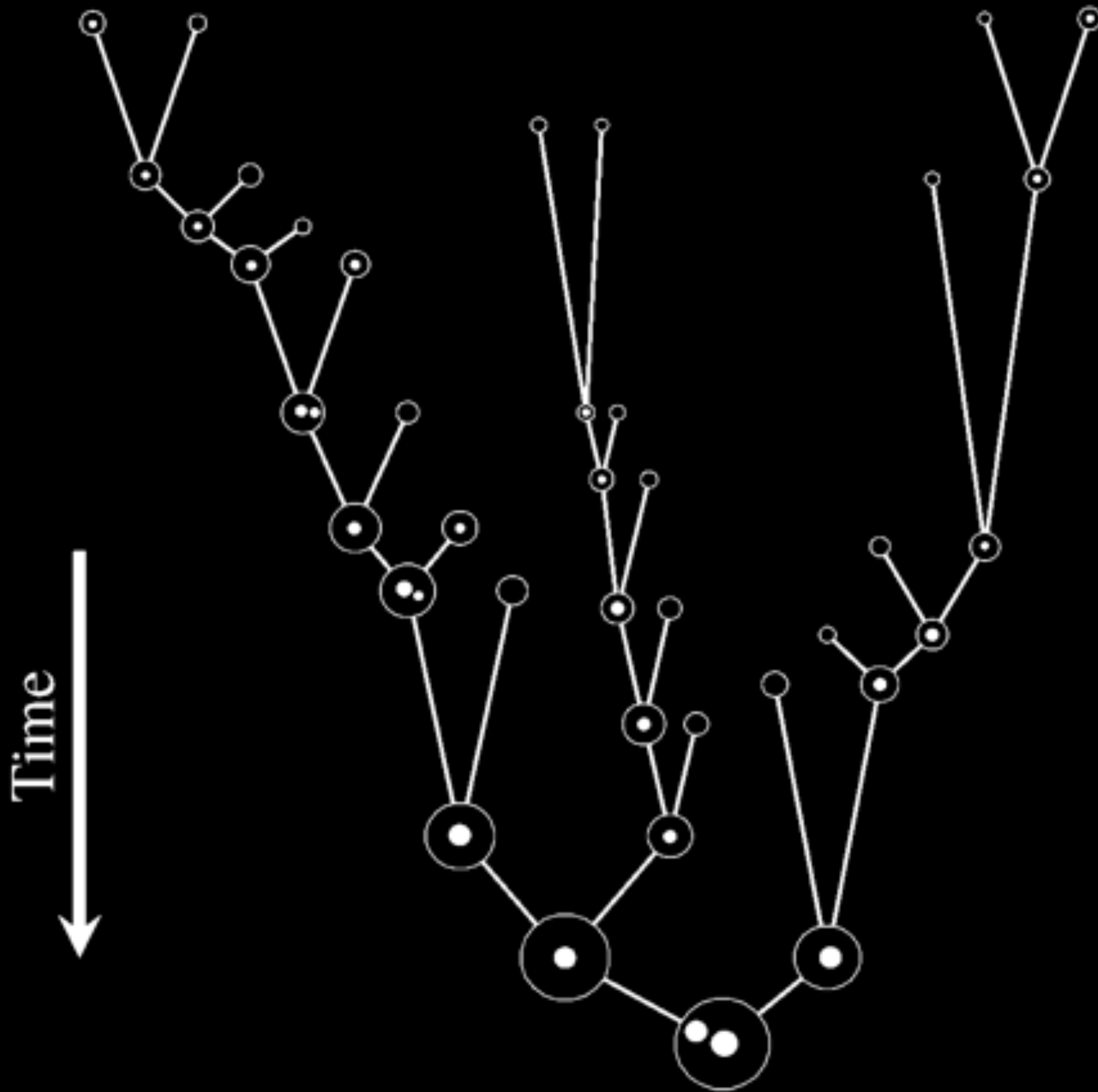
Parkes Pulsar Timing Array (PPTA)

European Pulsar Timing Array (EPTA)

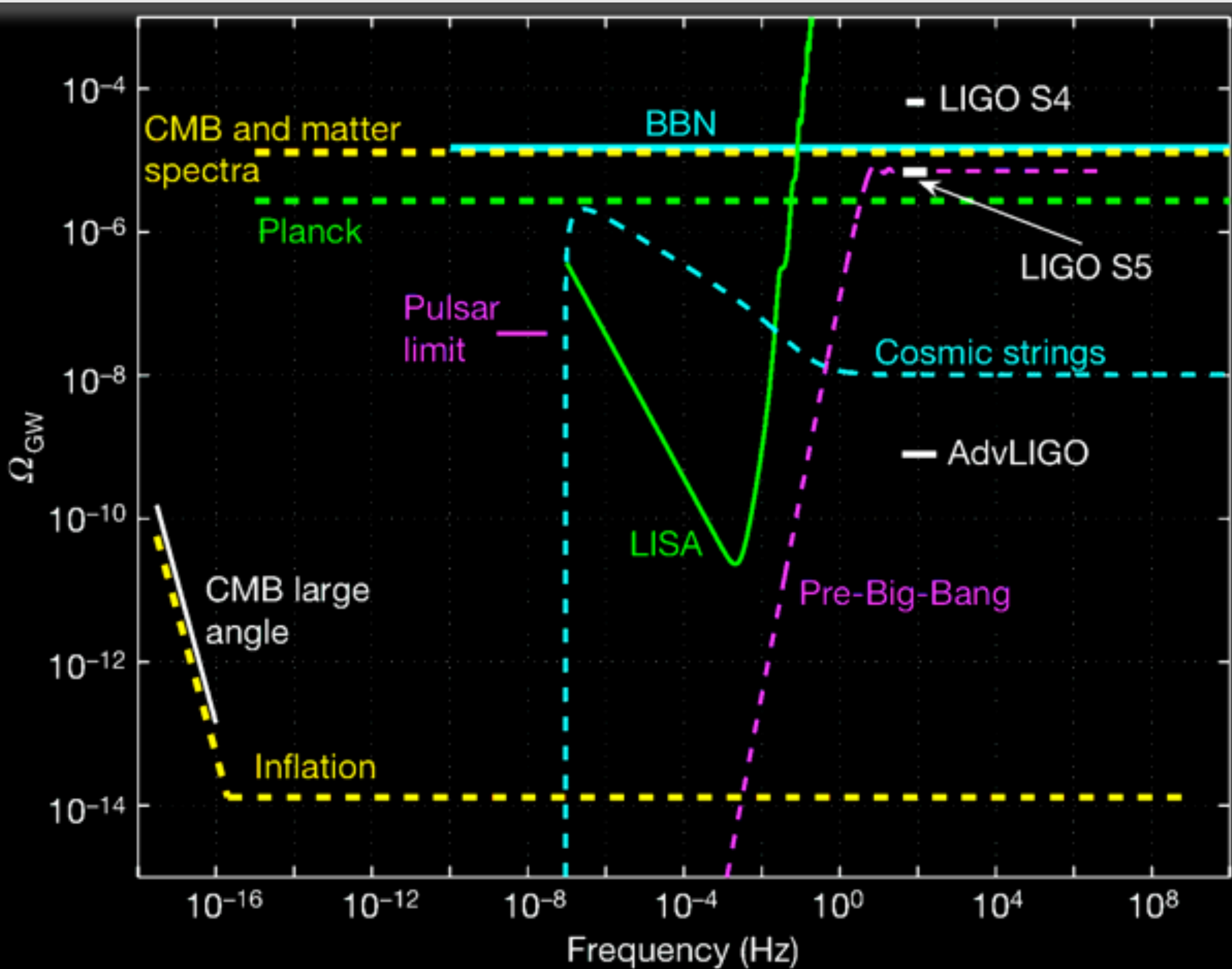
North American Nanohertz Observatory for Gravitational Waves (NANOGrav)

In combination, International Pulsar Timing Array (IPTA)!

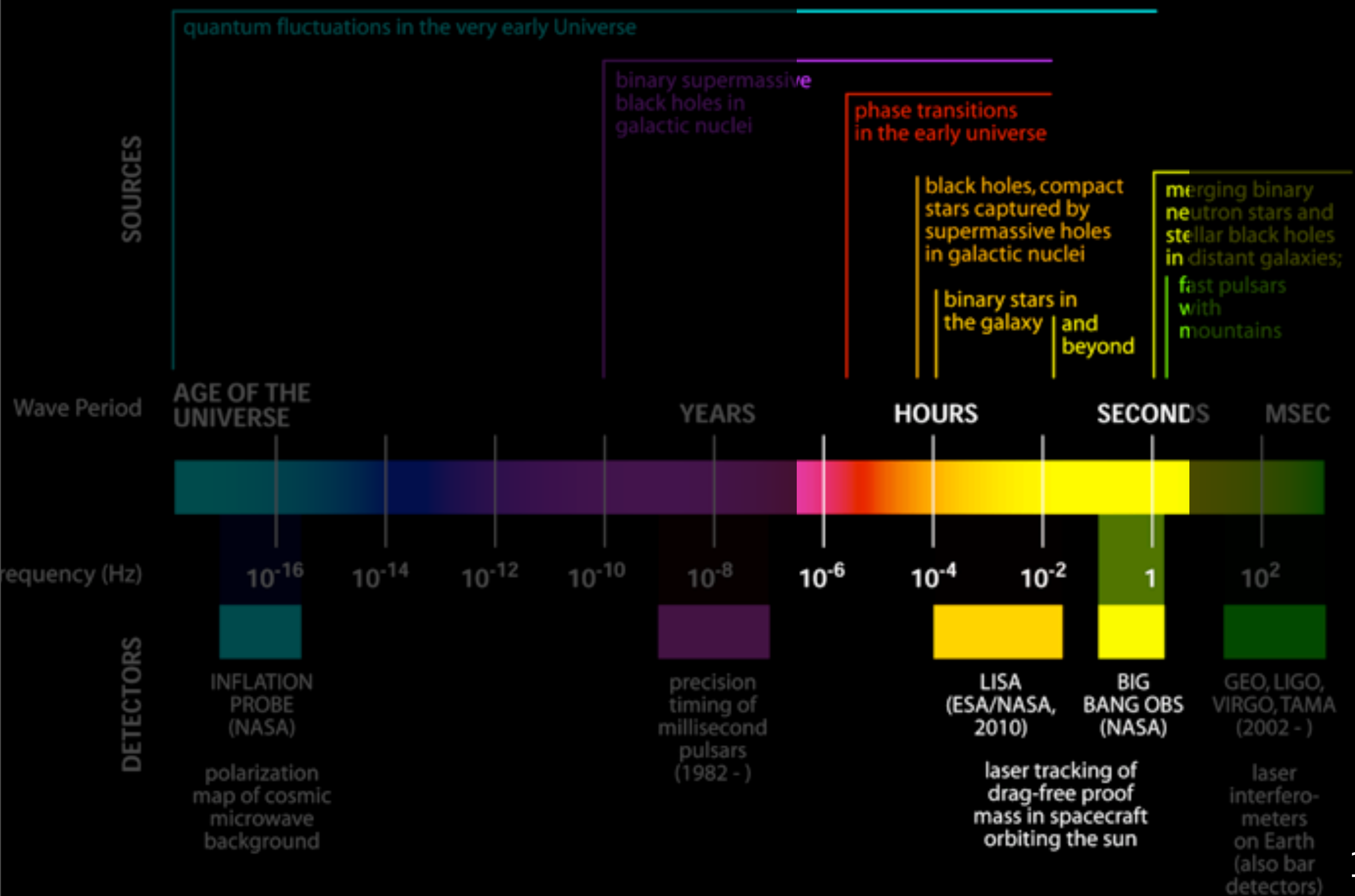
Black Holes Undergo Frequent Merger



Upper Limits on GW Stochastic Background



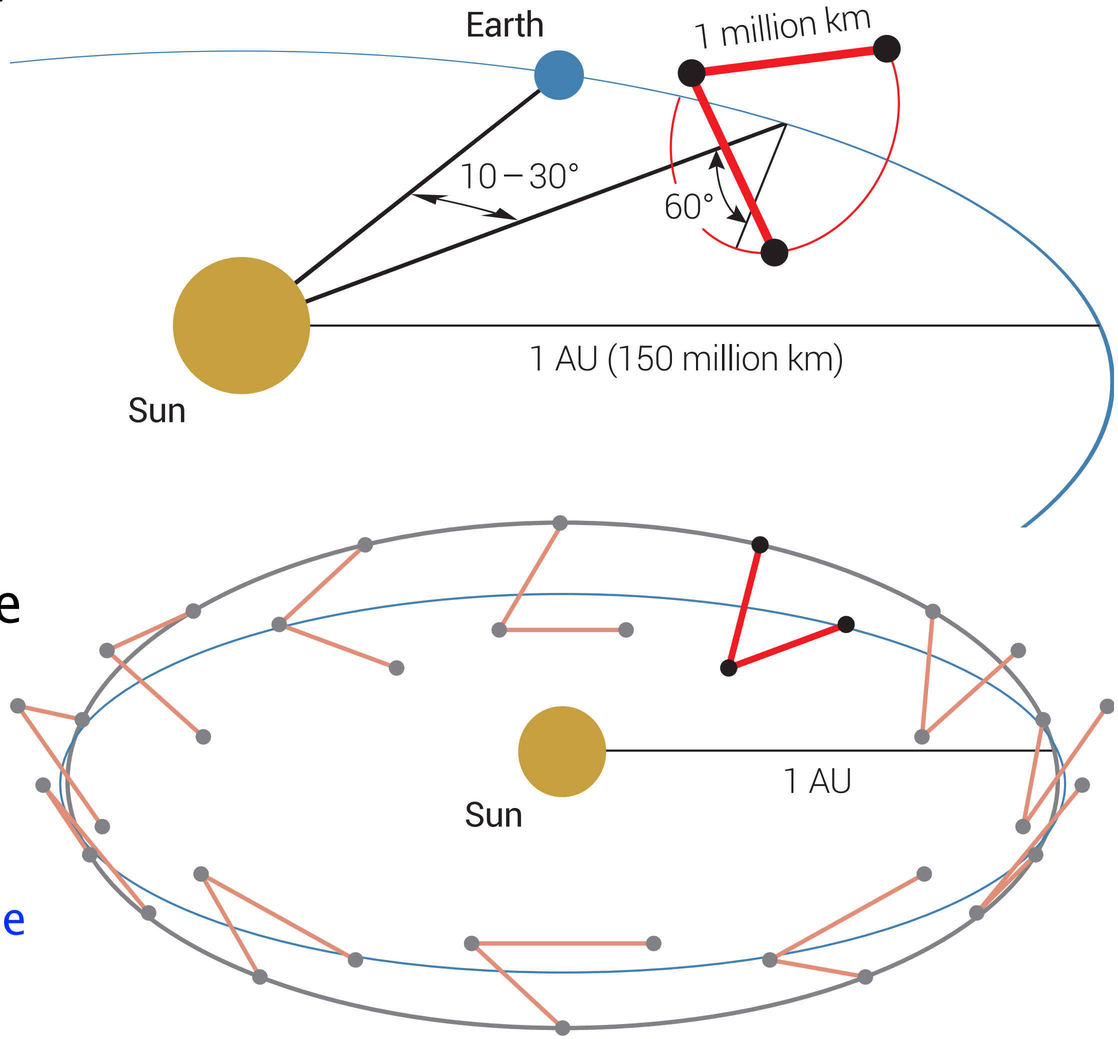
Low Frequency



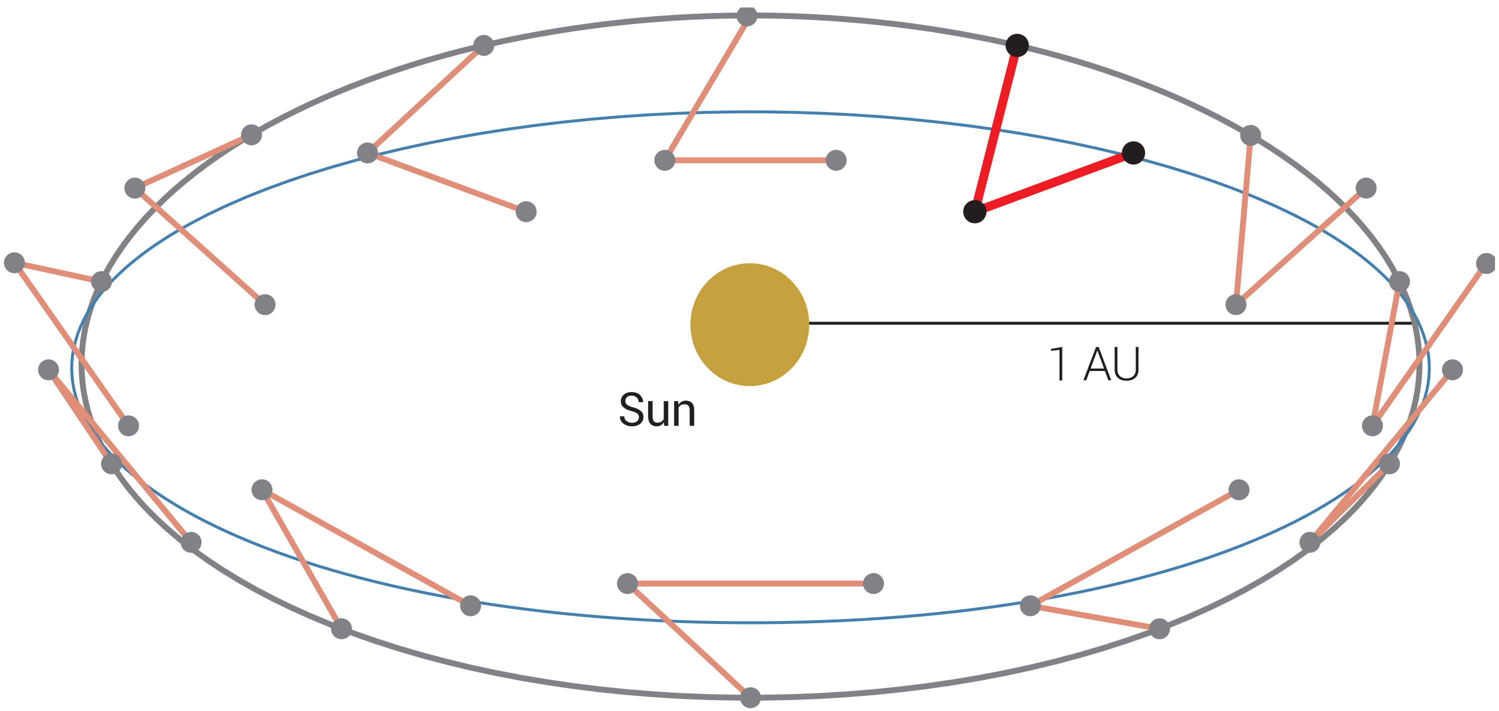
LISA: Laser Interferometer Space Antenna

eLISA

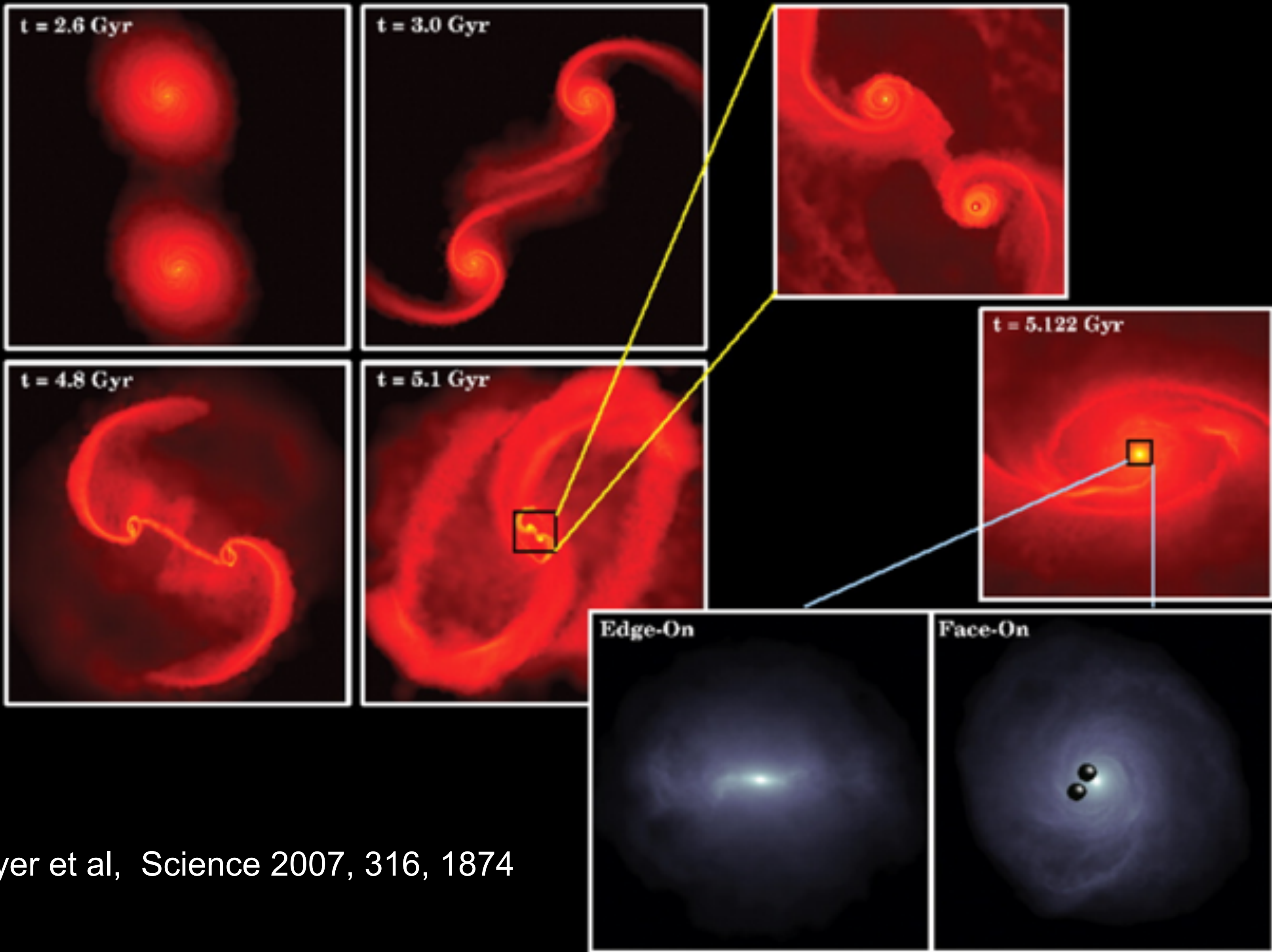
- Consists of 3 spacecraft in heliocentric orbit
  - Distance between spacecraft ~ 1 million km
  - 10 to 30 degrees behind earth
- The three eLISA spacecraft follow Earth almost as a rigid triangle entirely due to celestial mechanics
  - The triangle rotates like a cartwheel as craft orbit the sun



eLISA Survey Mission



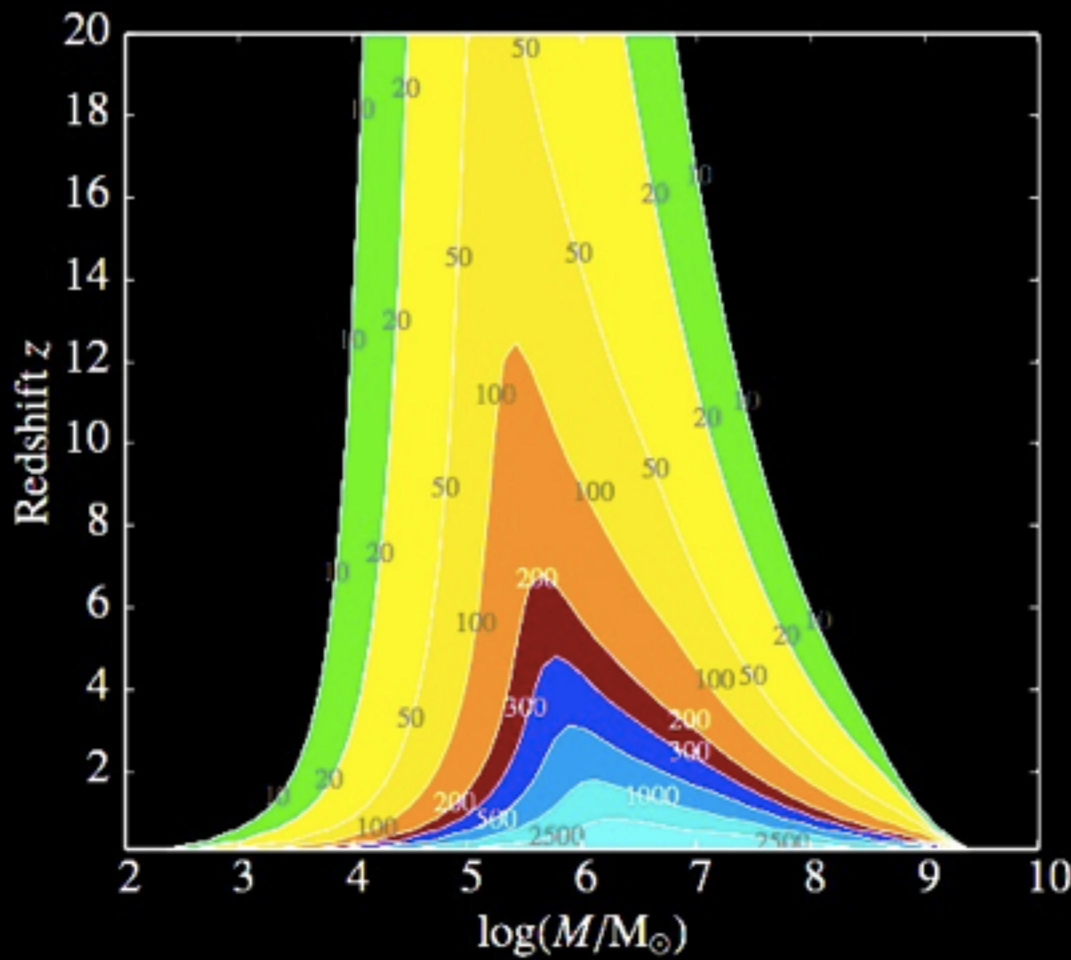
Growth of Supermassive Black holes



Mayer et al, Science 2007, 316, 1874

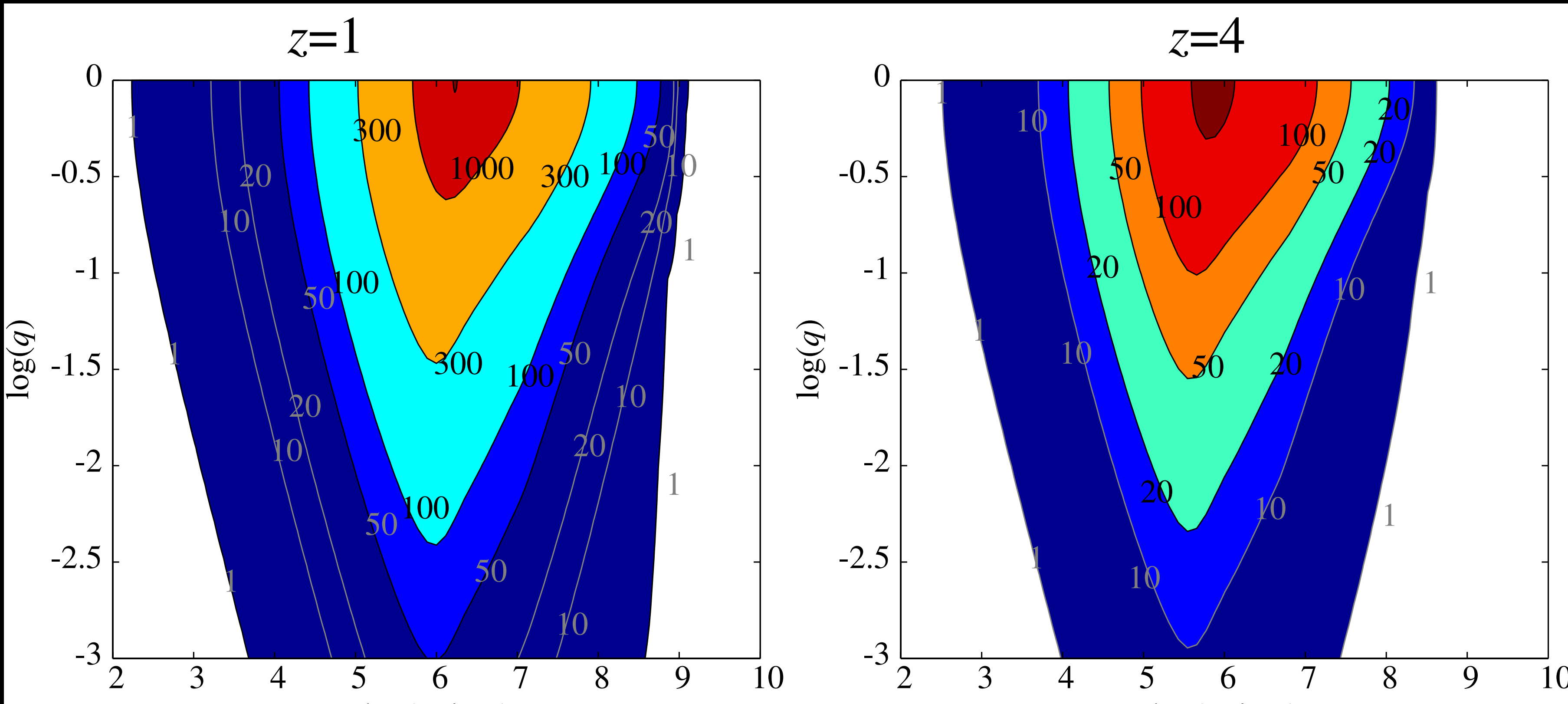
Visibility of SMBBH in eLISA

- Plot shows SNR contours as a function of intrinsic total mass and redshift
- Cosmological redshift makes binaries appear more massive than they actually are
- Even at z=20 SNRs can be pretty large



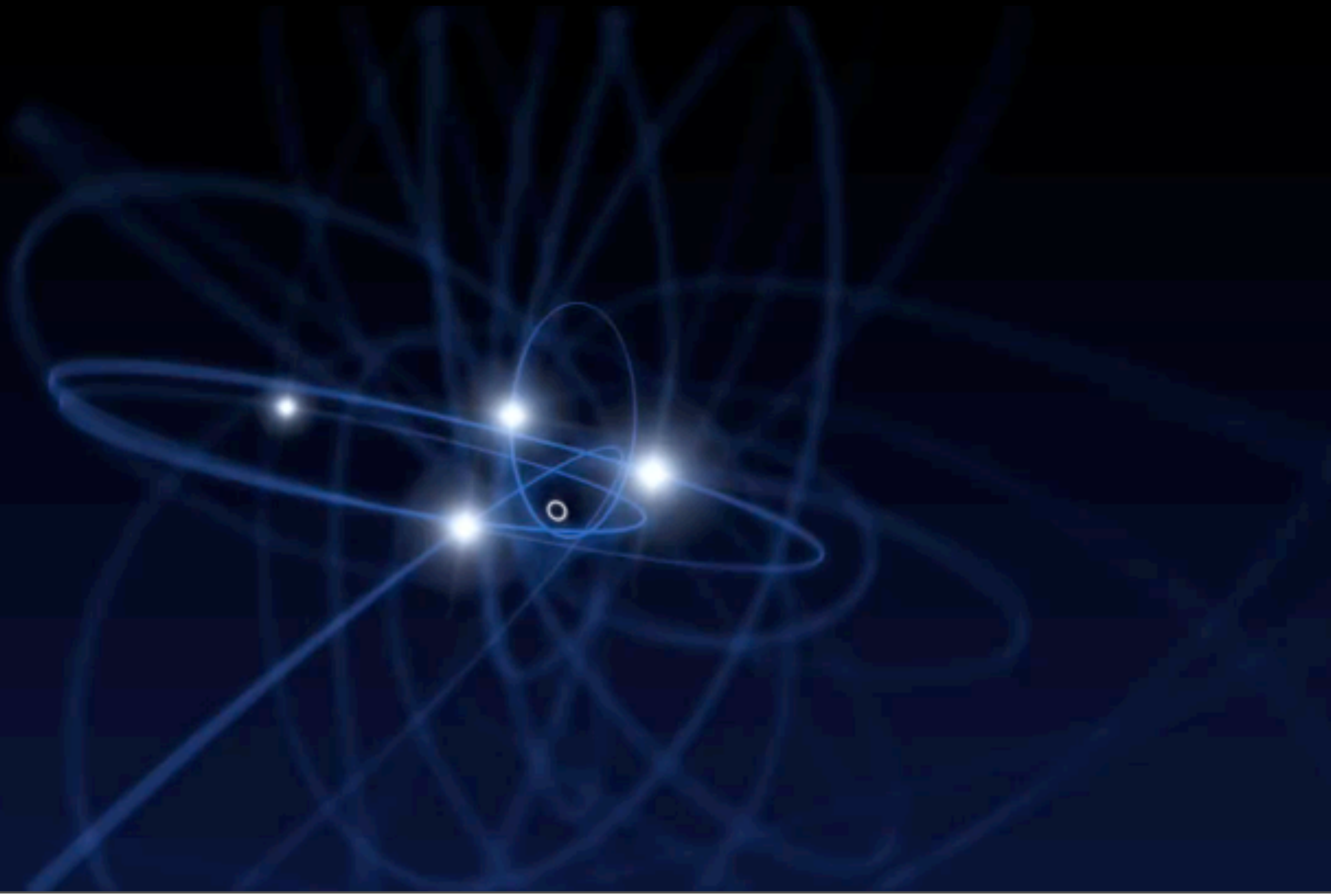
Understanding Black Hole Populations

- Masses can be measured to an accuracy of 0.1% to 1%
- Absolute errors in dimensionless spin in the range 0.01 to 0.1
- For sources within z=1 distance could be measured to within 1 to 10%

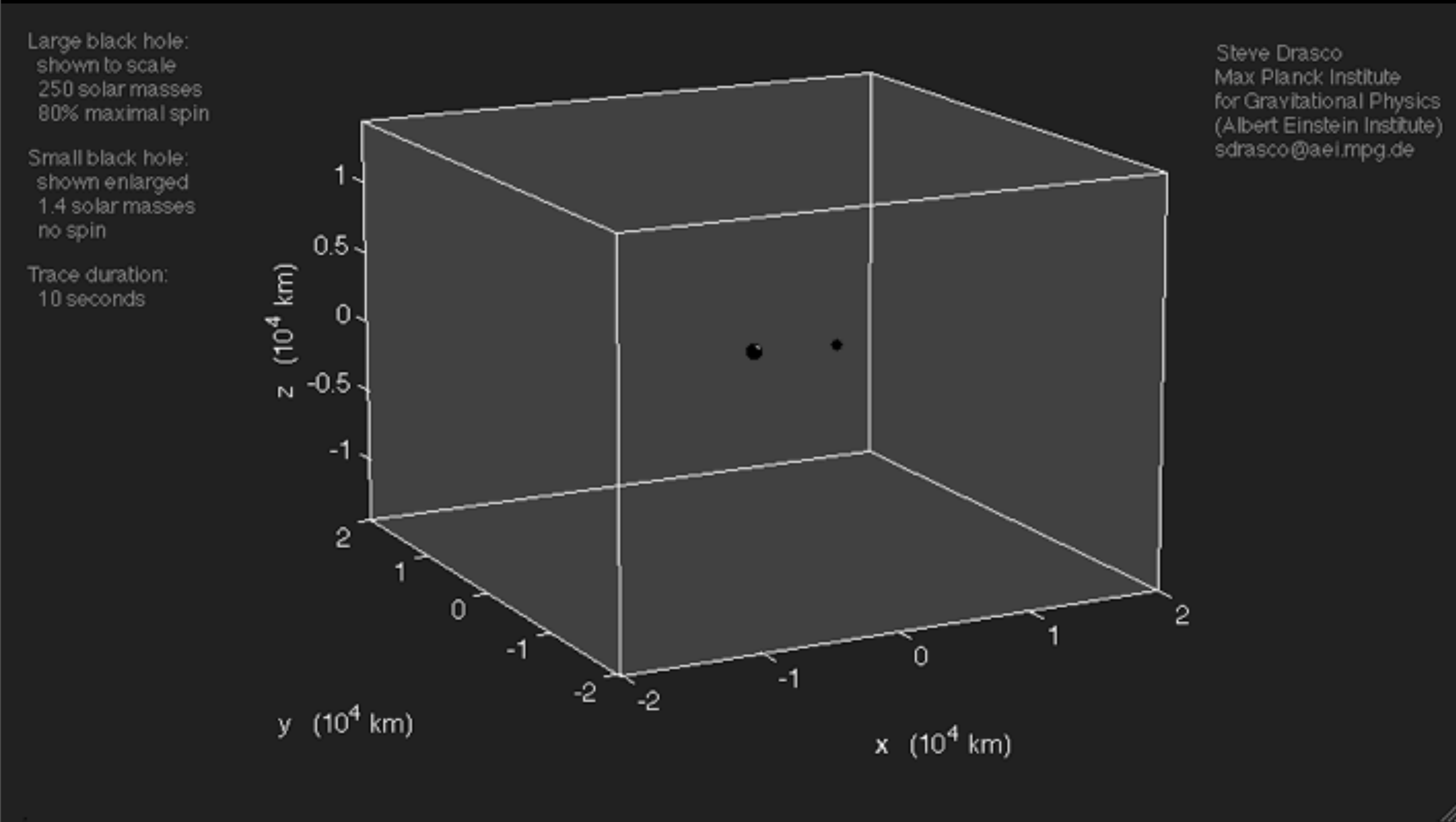


Slide from E. Berti

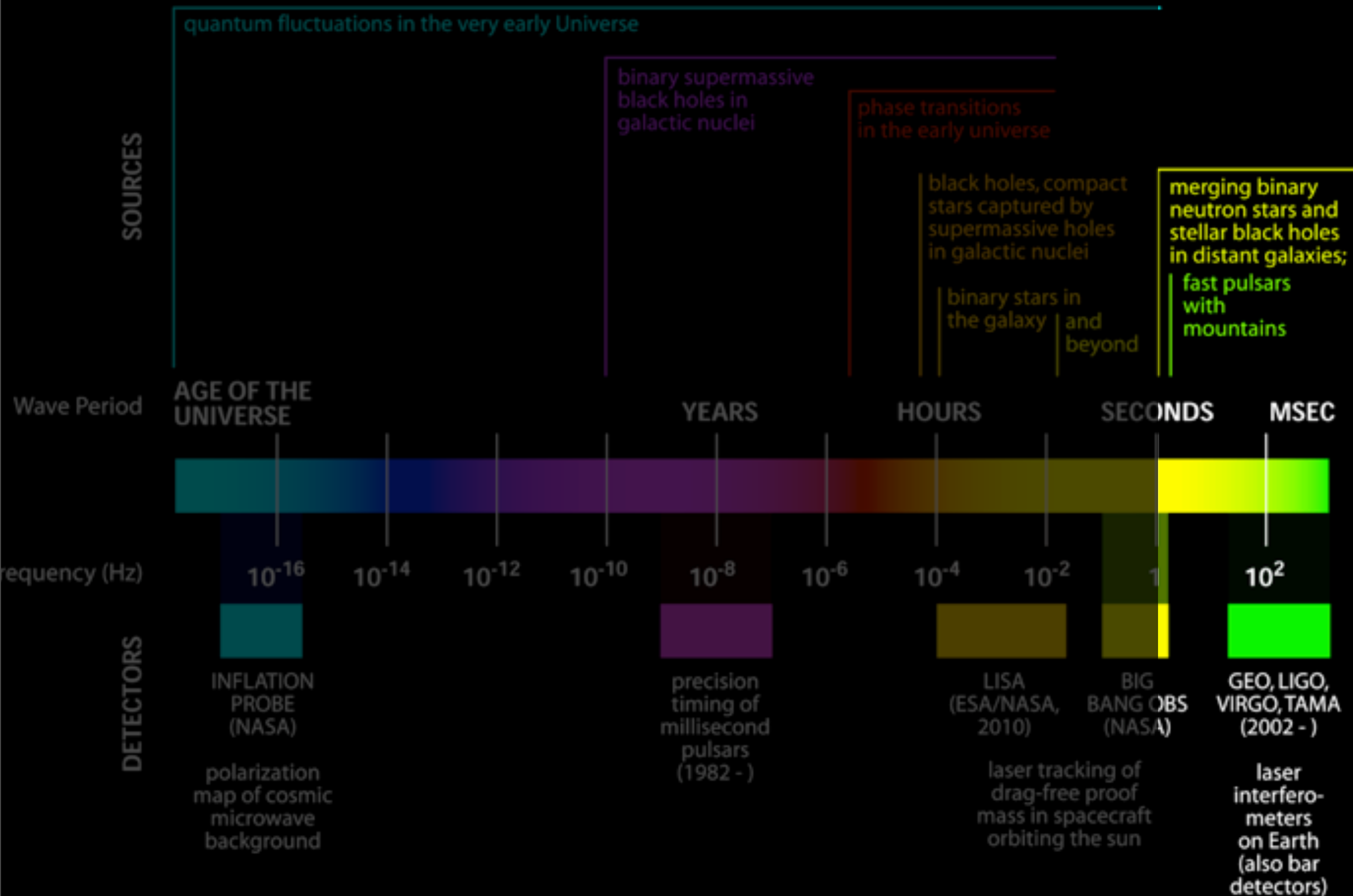
Milky Way's black hole – a 4 million solar mass monster



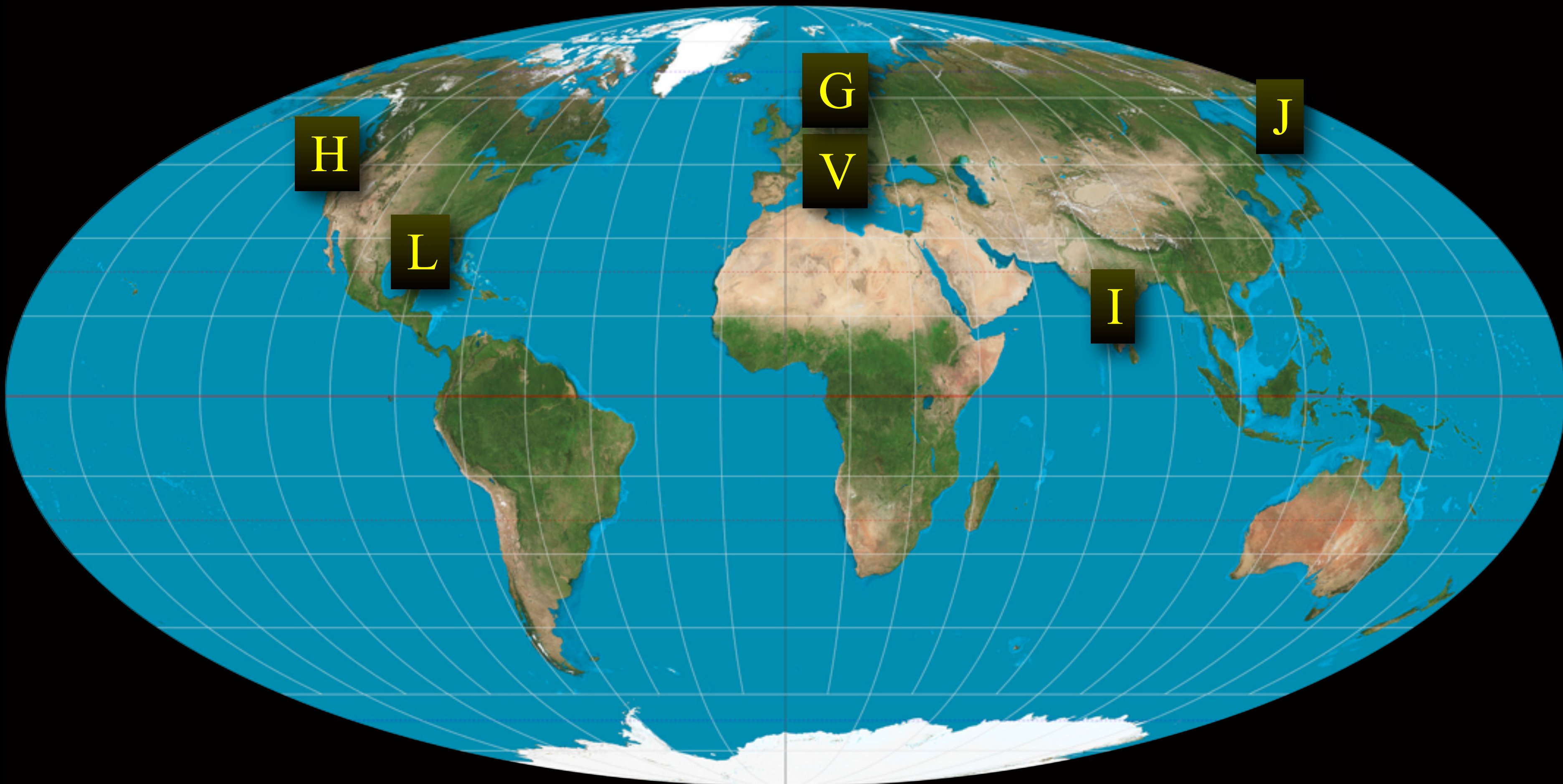
Measuring the Kerr Geometry



High Frequency



World Network of Gravitational Wave Detectors



- Between 2006–2010 larger detectors took 2 years worth of data at unprecedented sensitivity levels
- No detections so far but beginning to impact astrophysics

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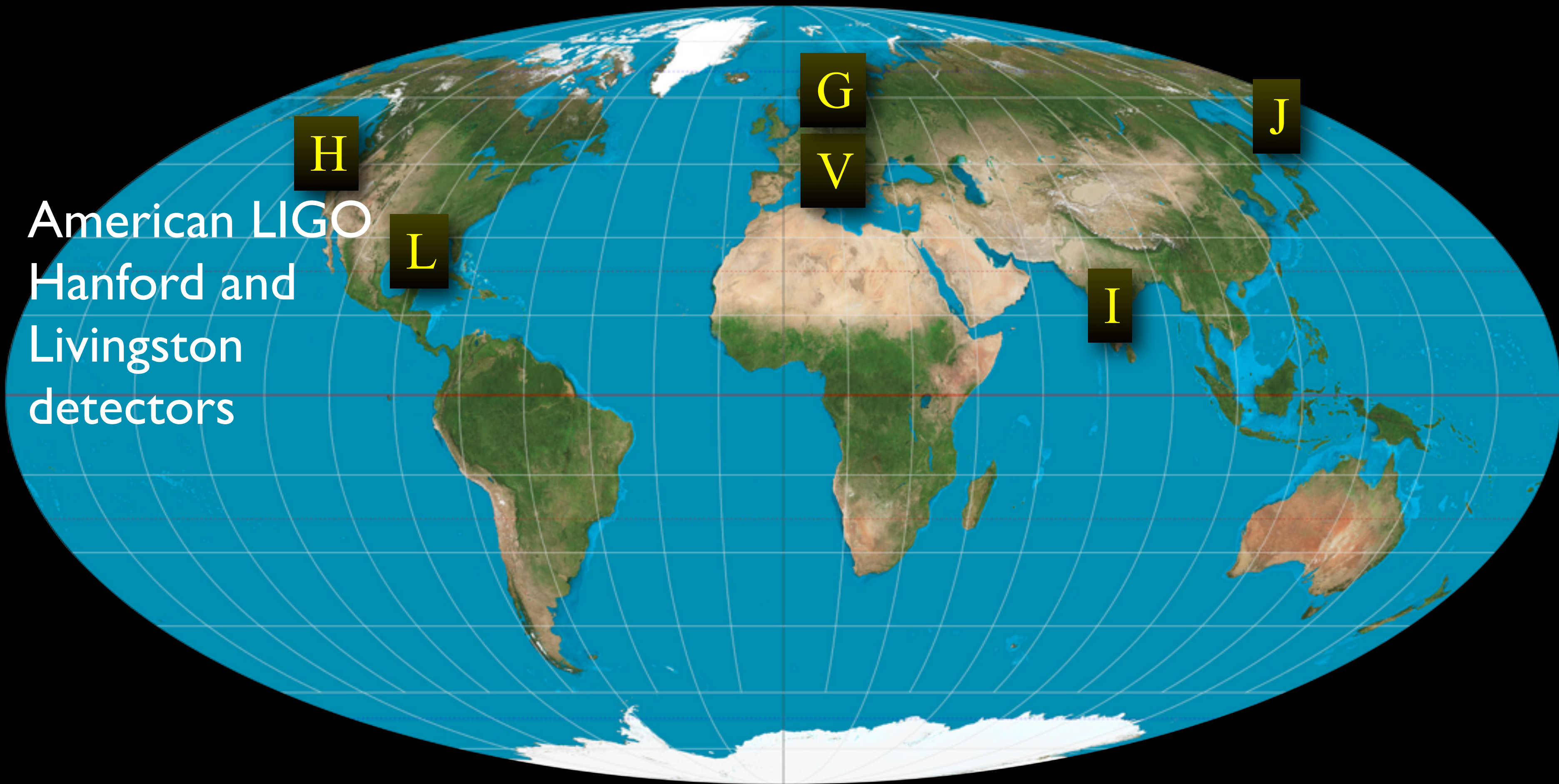

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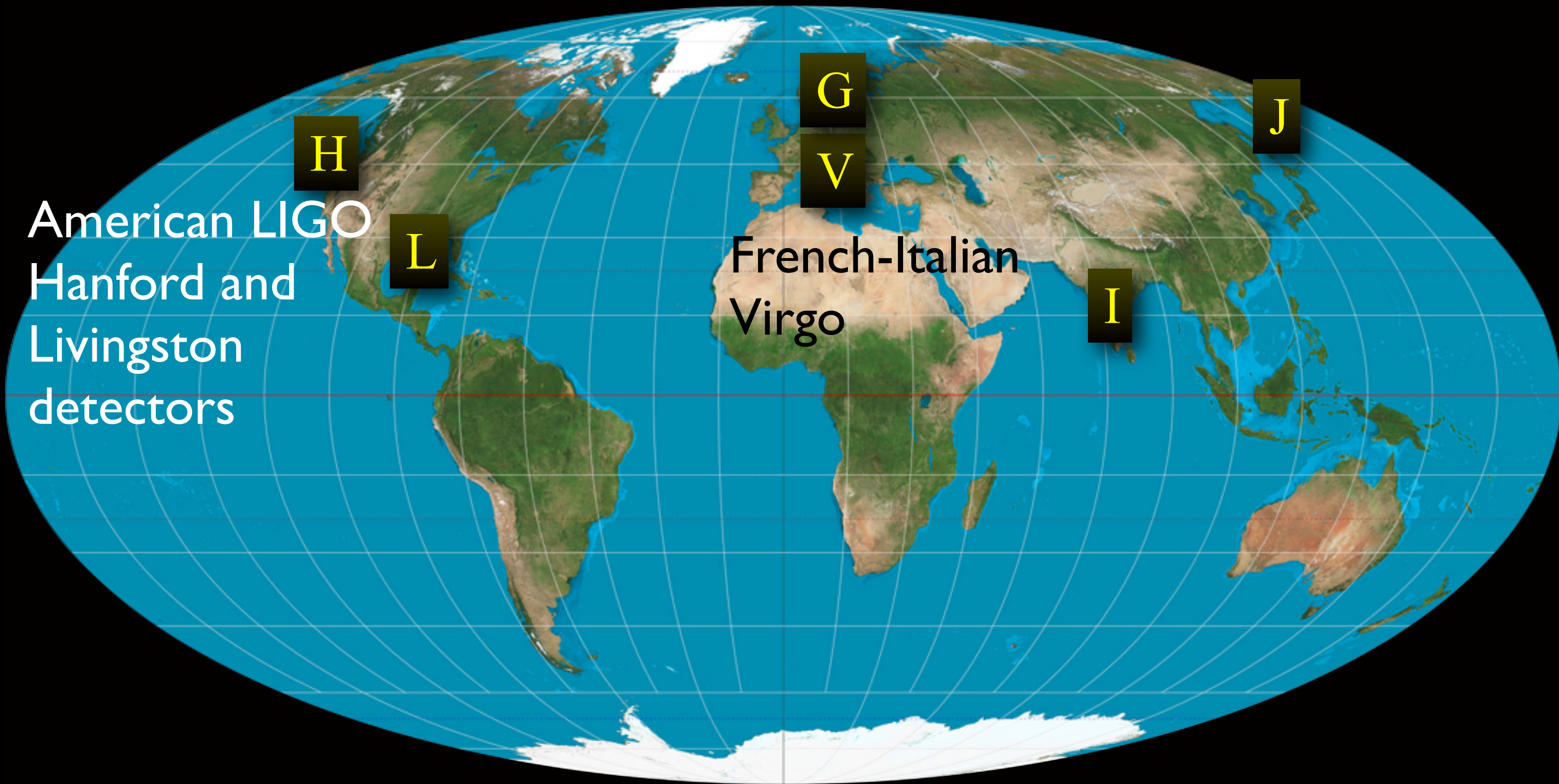

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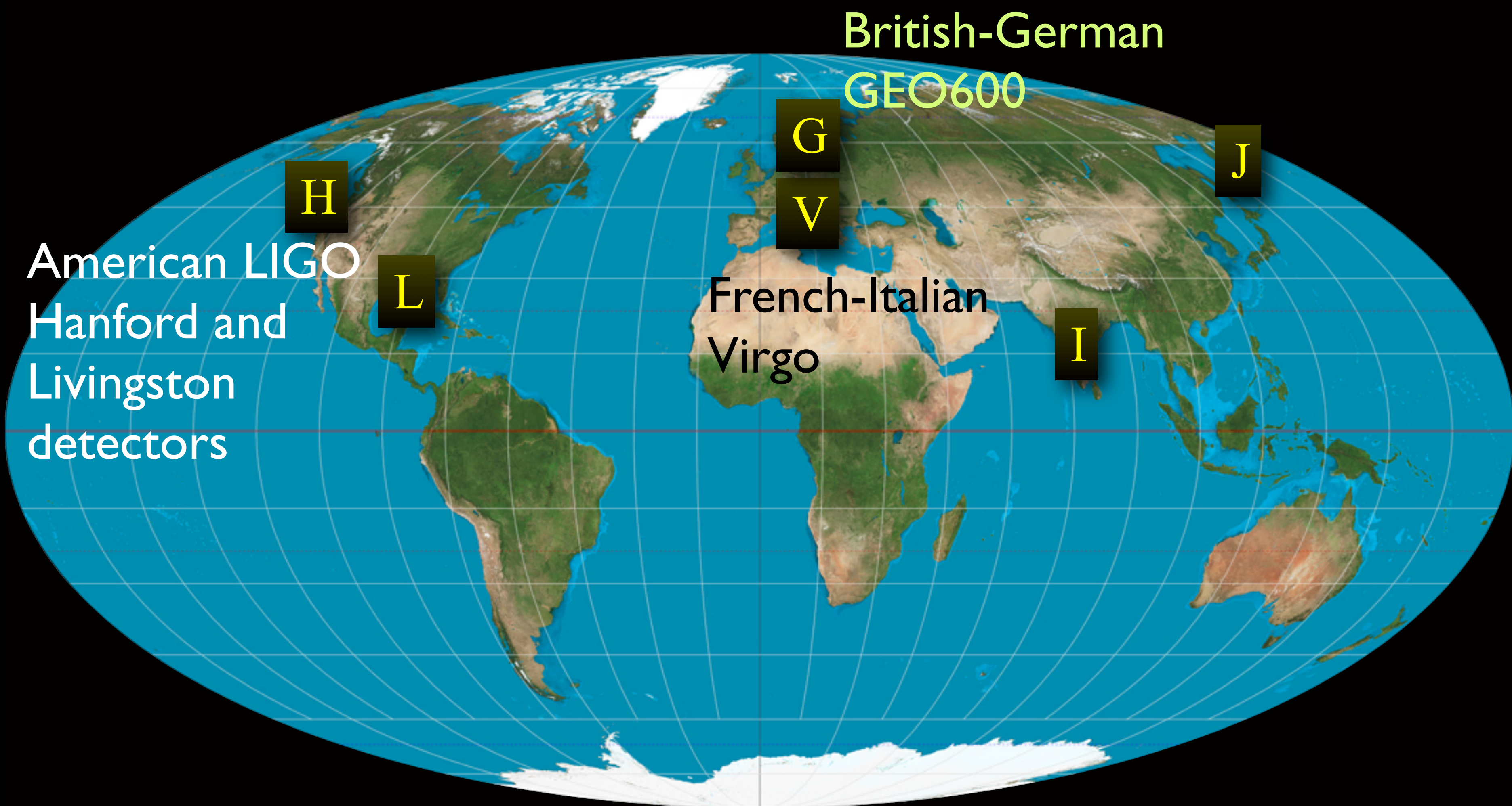

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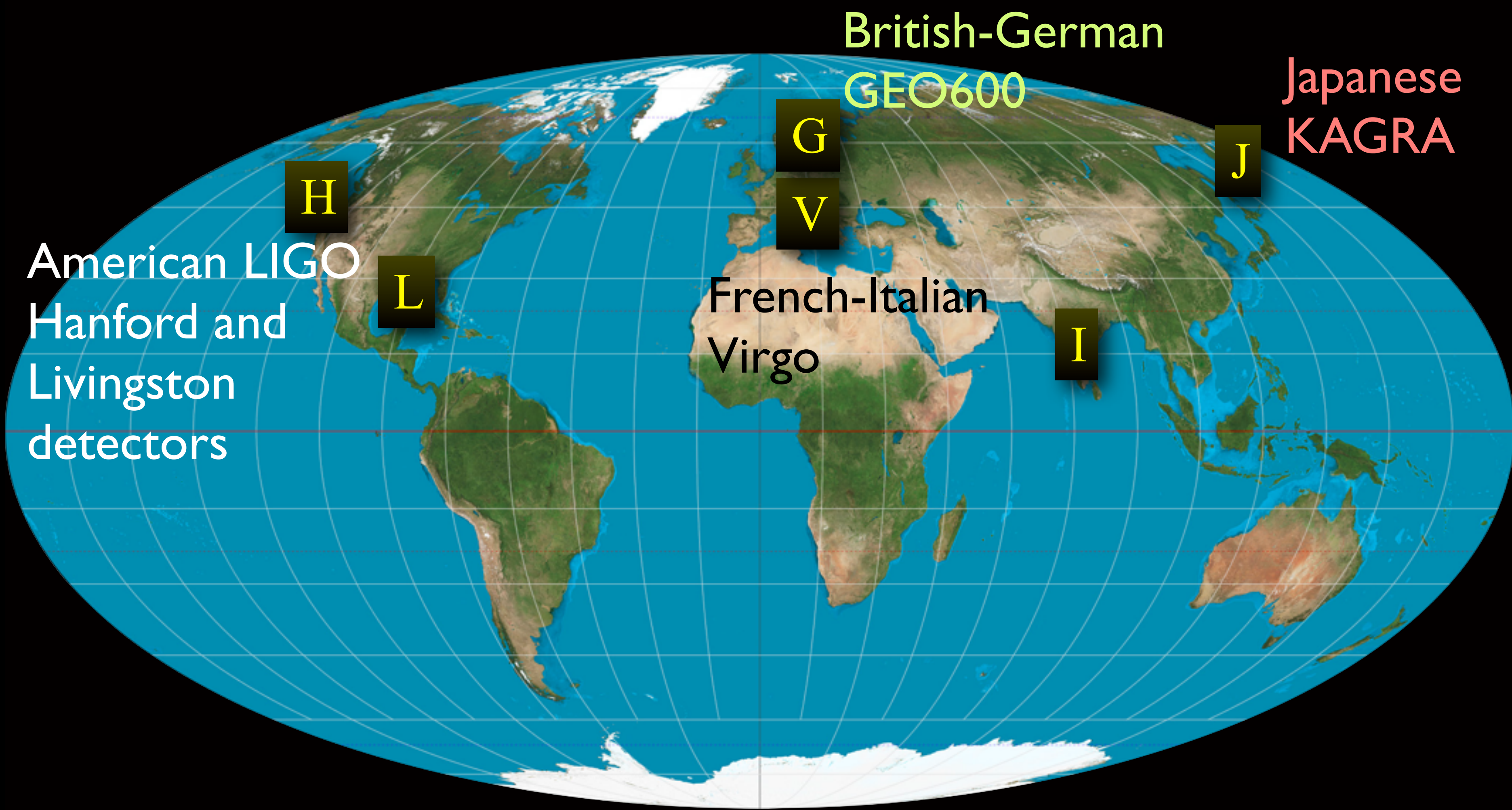

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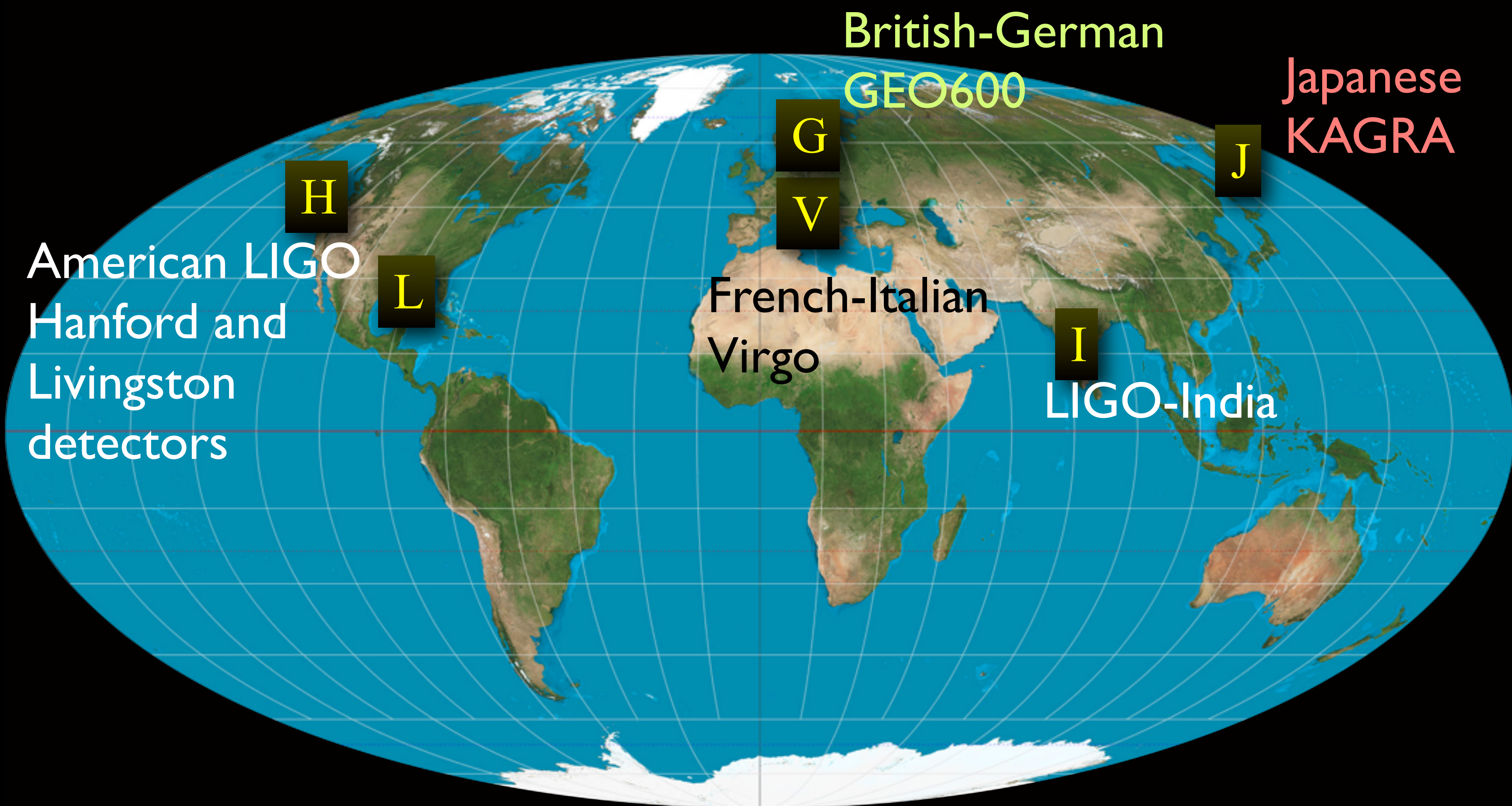

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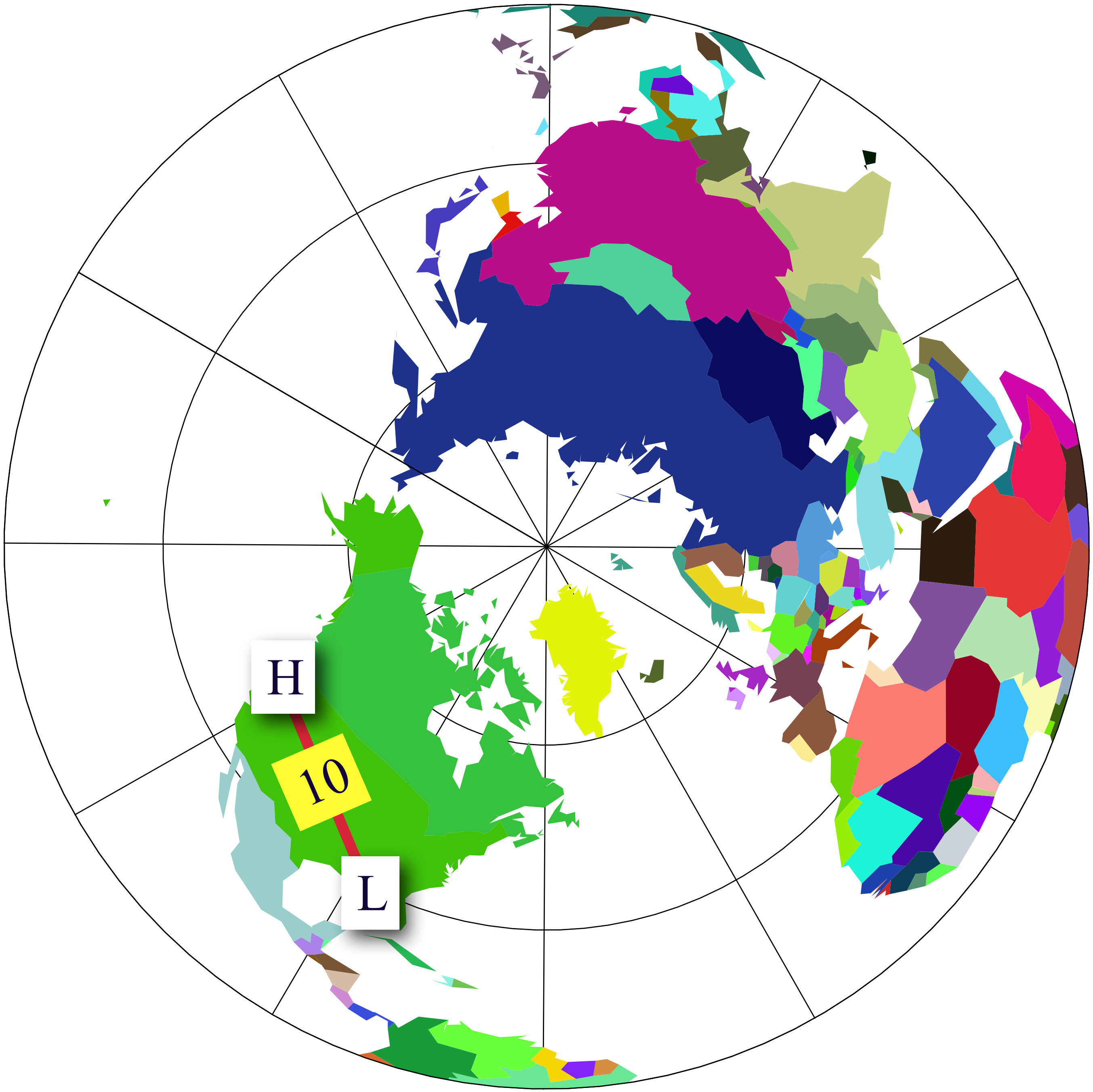
Advanced Detectors:

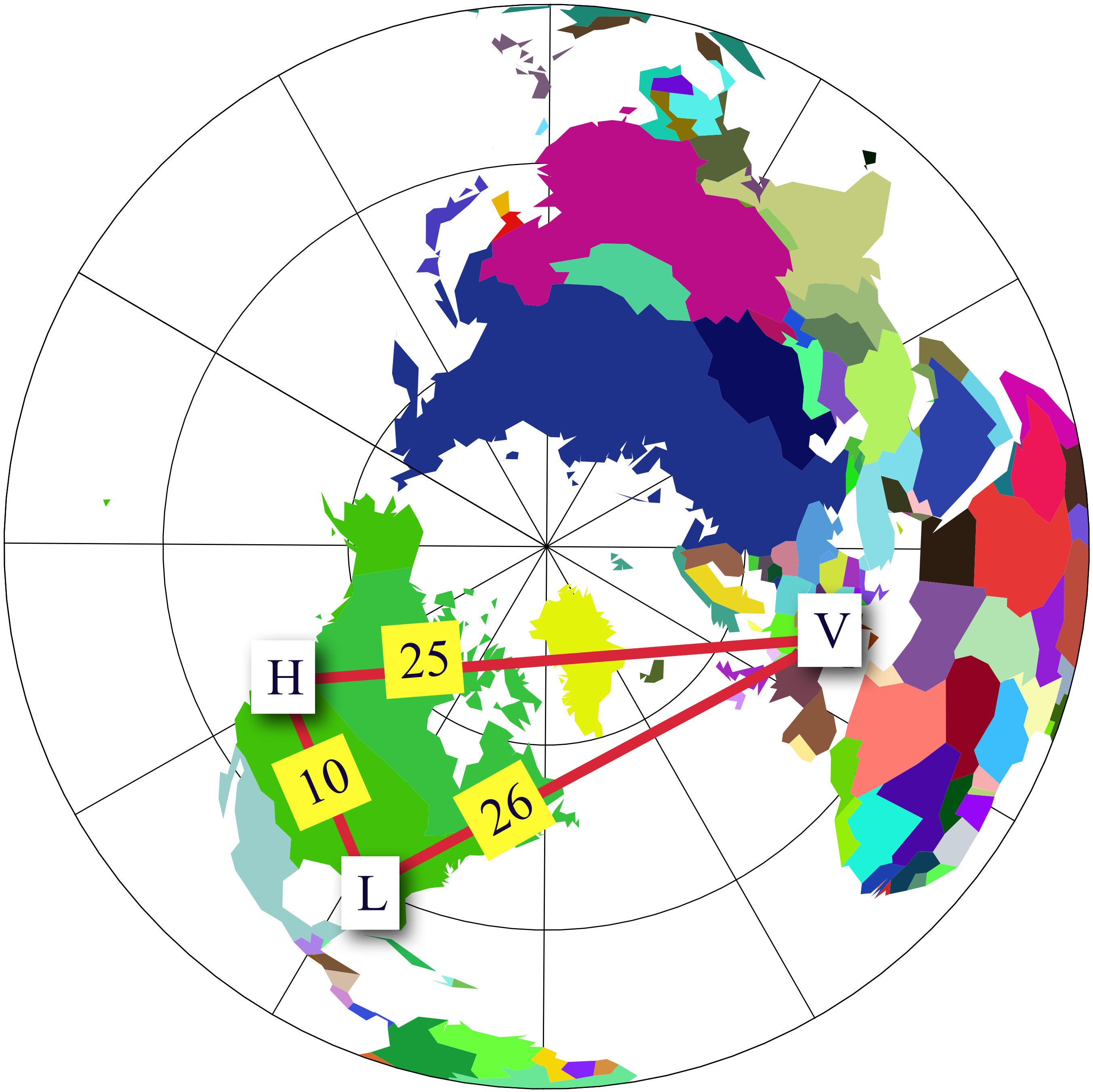
Ca 2015–2025

Detector Networks 2015-



Baselines

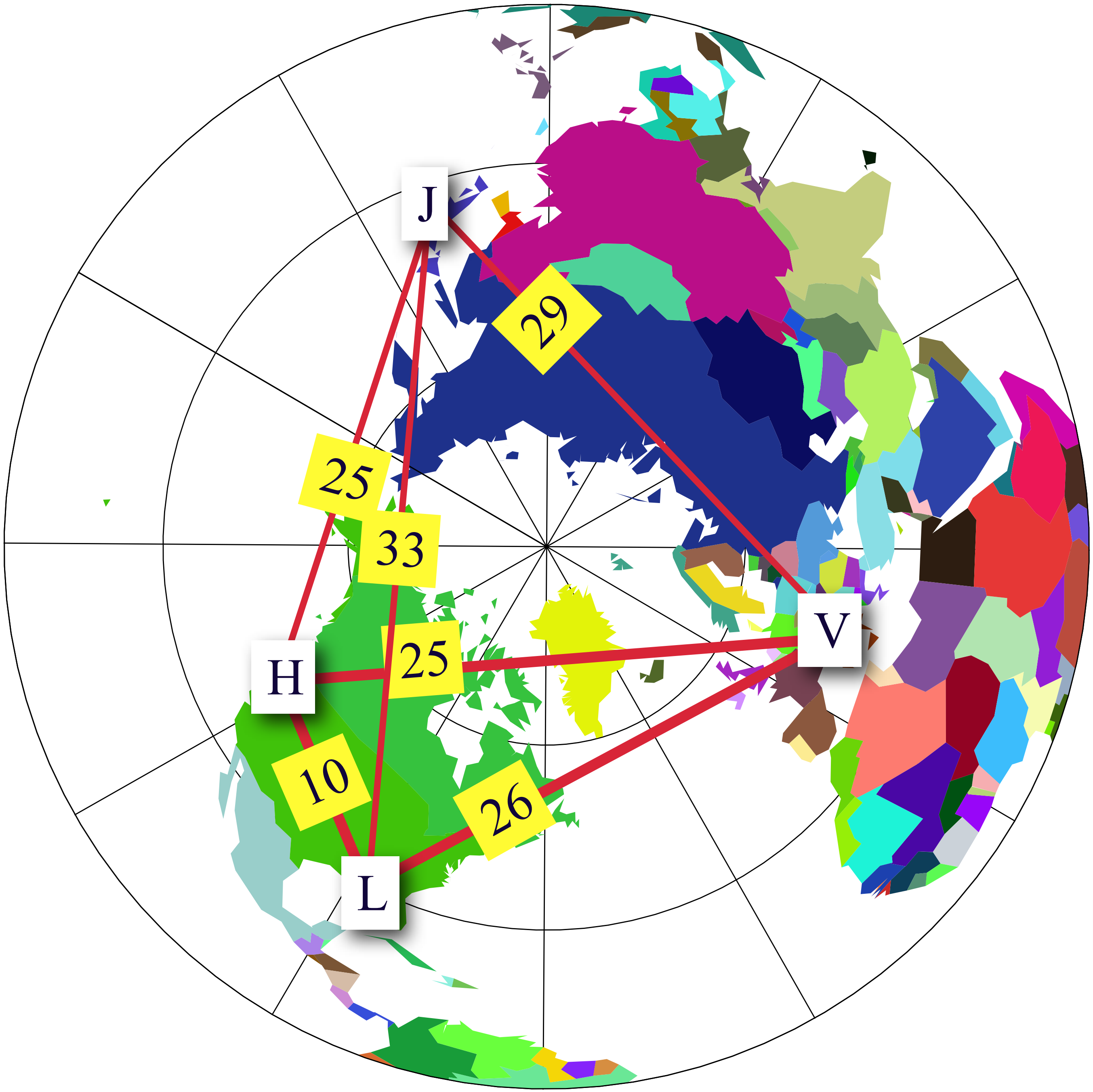
in light travel time (ms)



Detector Networks 2016-

Baselines

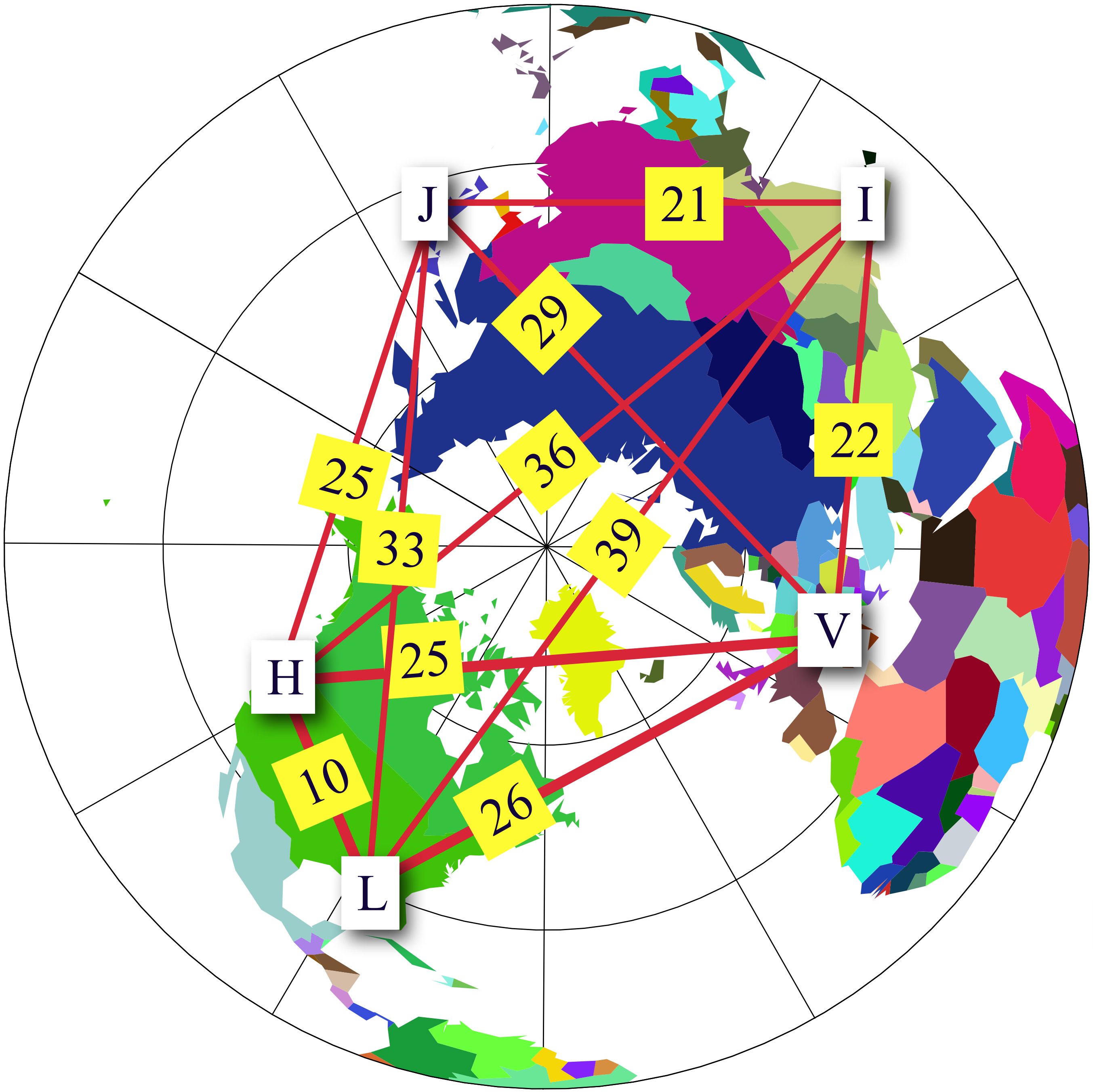
in light travel time (ms)



Detector Networks 2018-

Baselines

in light travel time (ms)



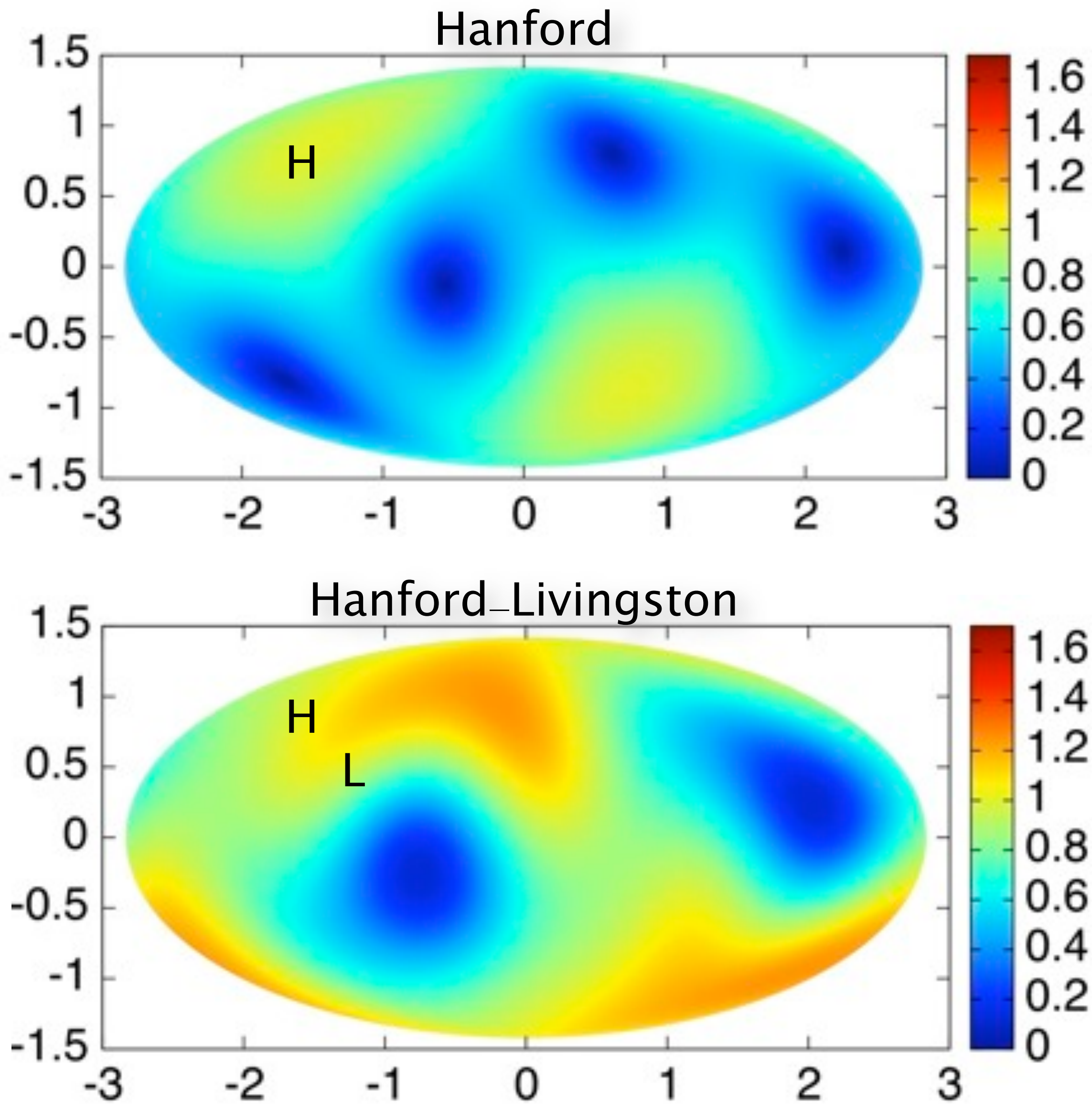
Detector Networks 2022-

Baselines

in light travel time (ms)

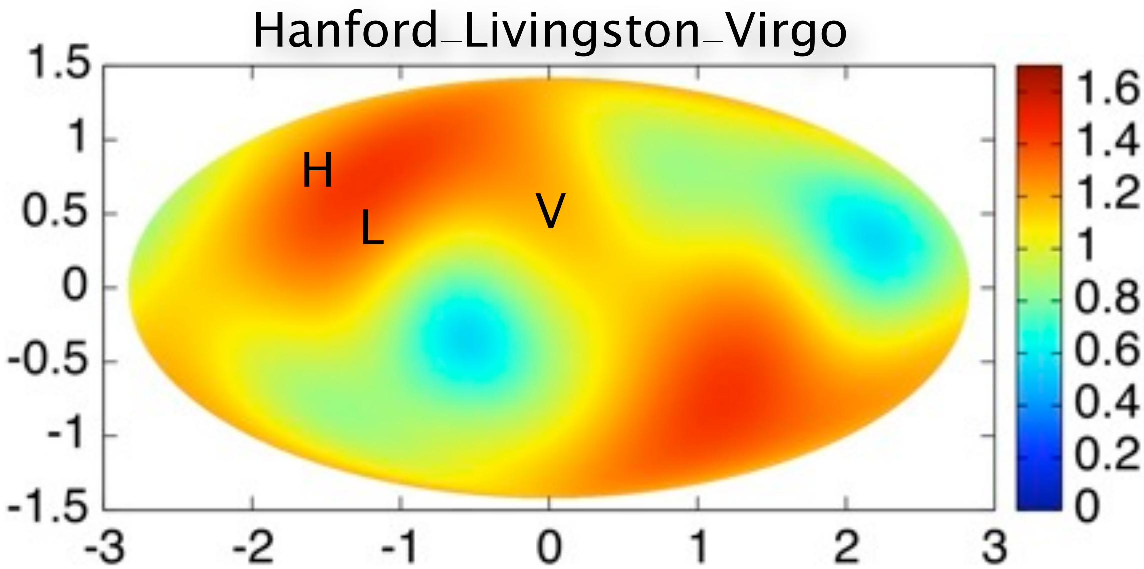
Detector Beam Pattern Function

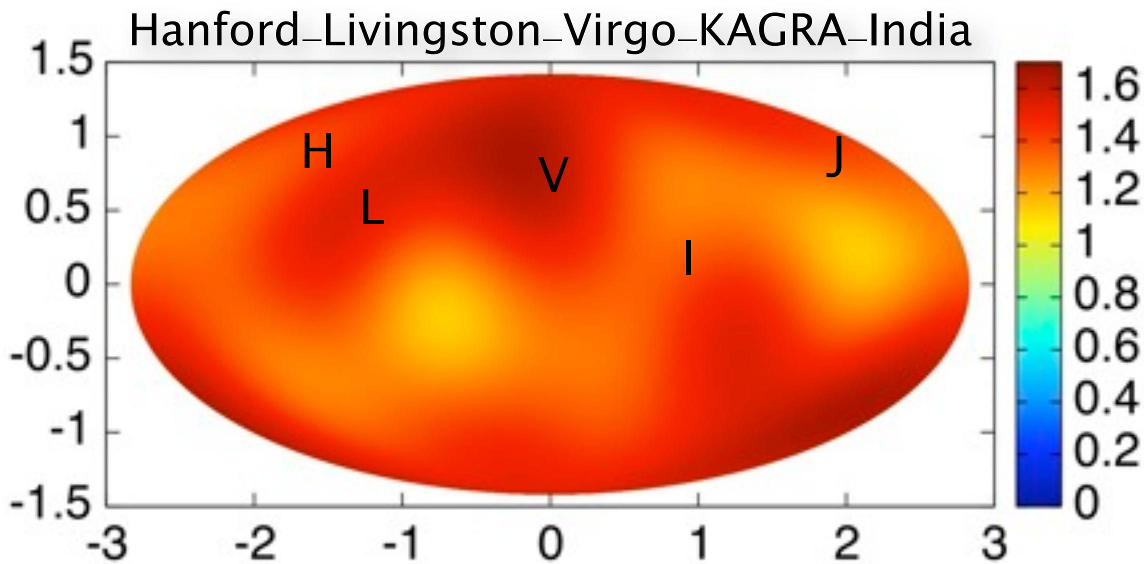
- Gives the sensitivity of a detector to sources at different parts of the sky
- For a single detector the beam is a quadrupole
- For a network of 5 or more globally distributed detectors the pattern can essentially become isotropic



Challenge of Gravitational Wave Searches

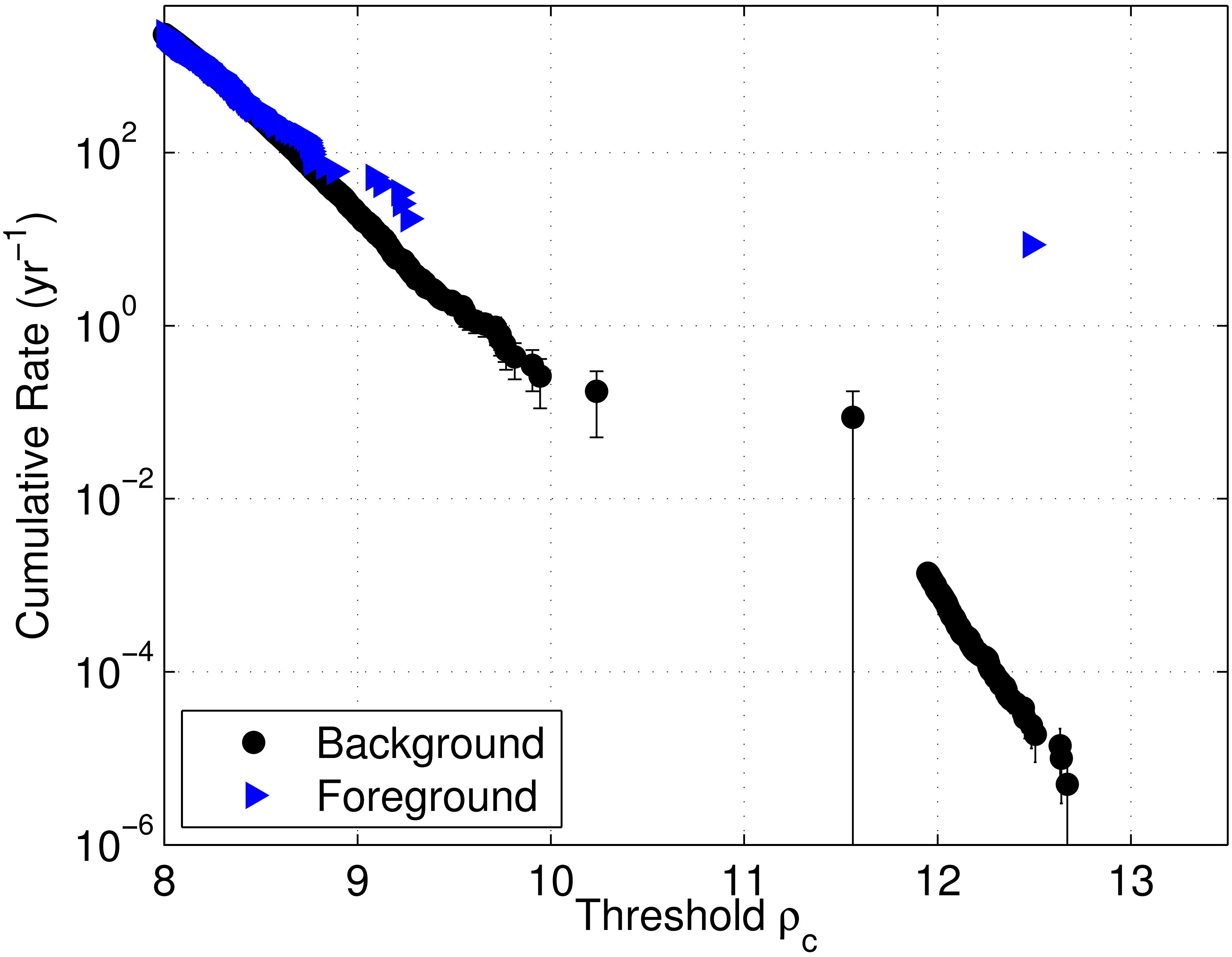
- A network of gravitational wave detectors is always on and sensitive to most of the sky
- Signals can be milliseconds long or last for years
- Multiple signals could be in band but with different amplitudes
- We can integrate and build SNR by coherently tracking signals in phase



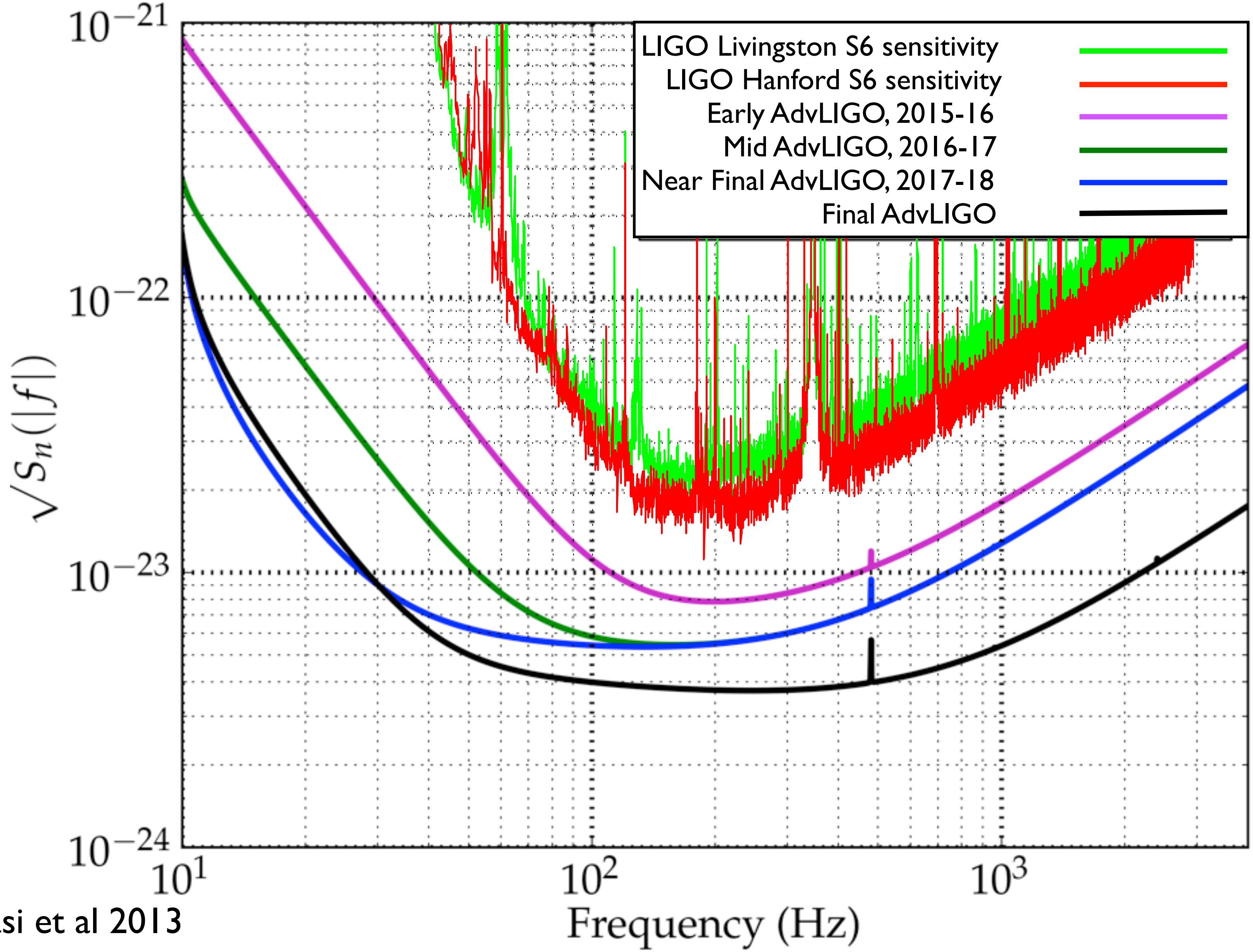


How confident our detections are likely to be?

The Big Dog Event

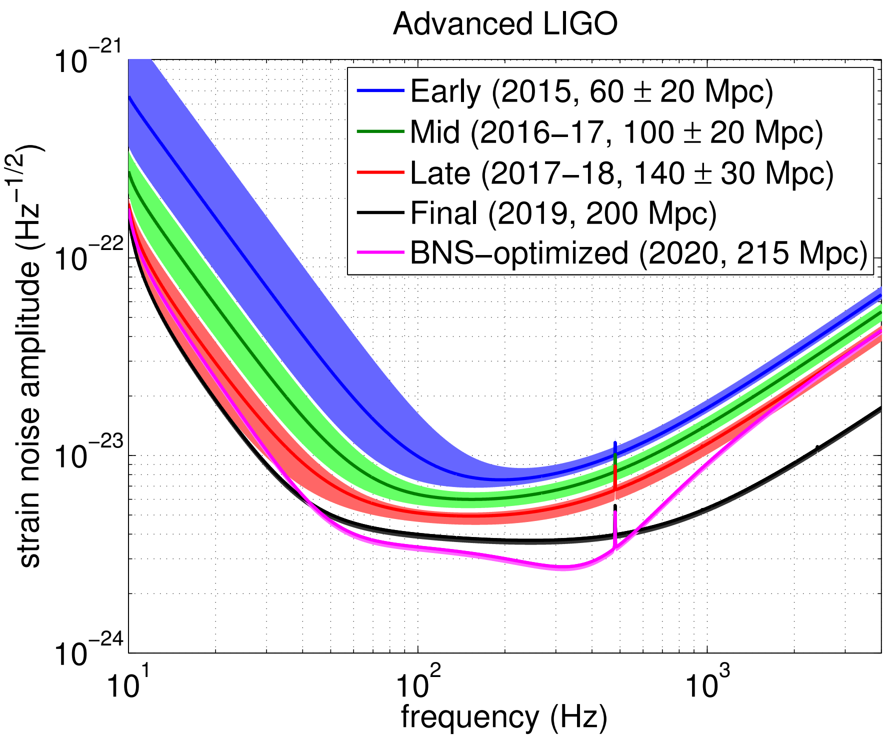


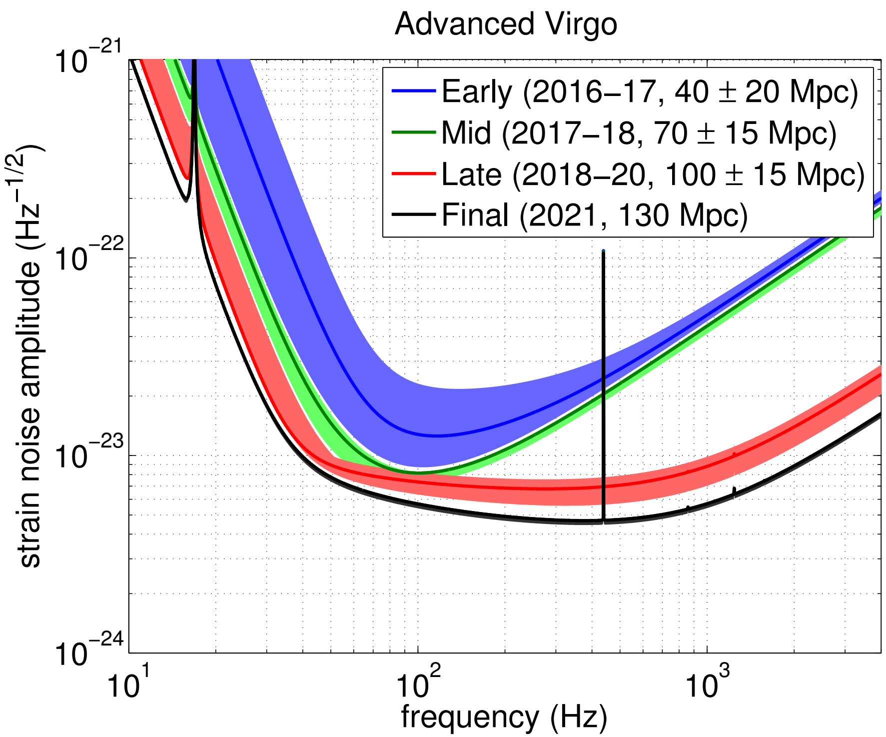
Advanced LIGO Sensitivity



Aasi et al 2013

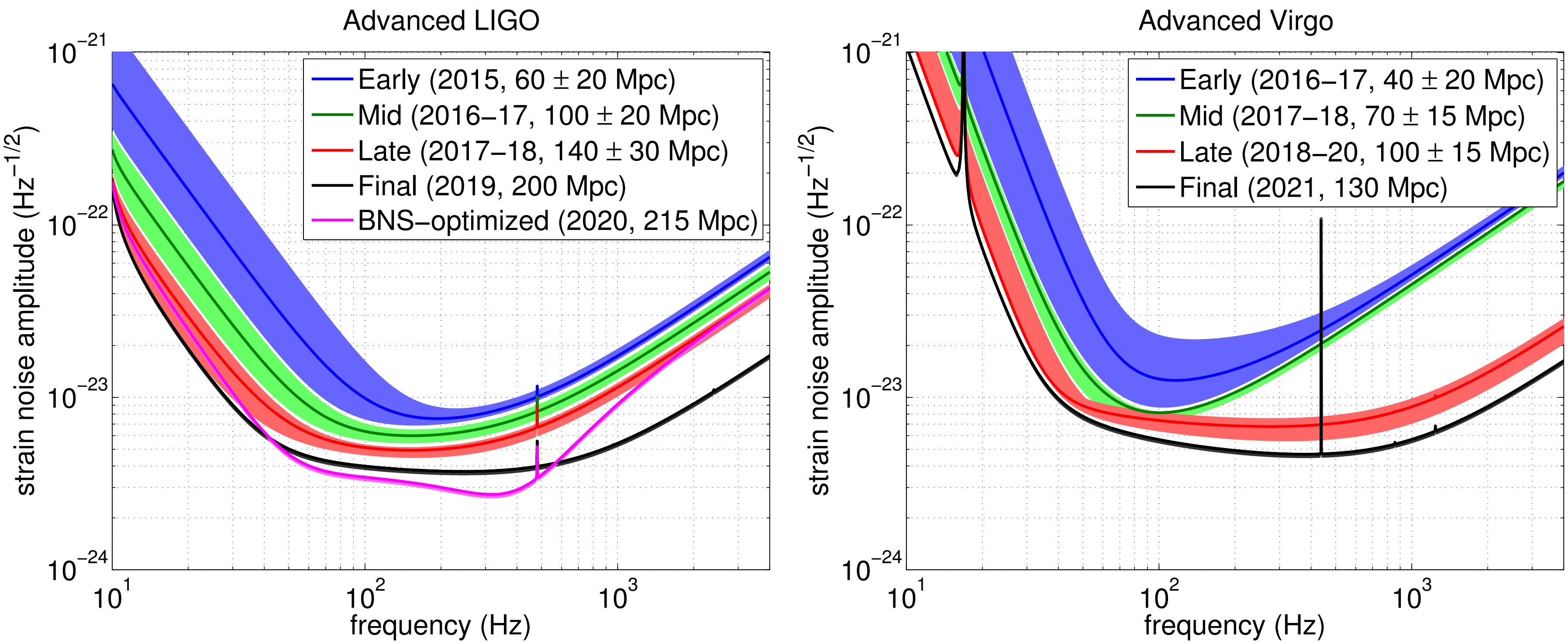
Advanced Detectors: Schedule and Sensitivity





Epoch	Run Duration	BNS range (Mpc) LIGO	Virgo	Number of Detections	Median Area (deg^2)	% localized within 5 deg^2	20 deg^2
2015	3 months	60 ± 20	—	0.0004 - 3	2000	-	-
2016–17	6 months	100 ± 20	40 ± 20	0.006 - 20	70	2	15
2017–18	6 months	140 ± 30	70 ± 15	0.02 - 70	84	1	12
2019+	(per year)	200	100 ± 15	0.2 - 200	31	5	37
2022+ (India)	(per year)	200	130	0.4 - 400	11	19	73

Advanced Detectors: Schedule and Sensitivity



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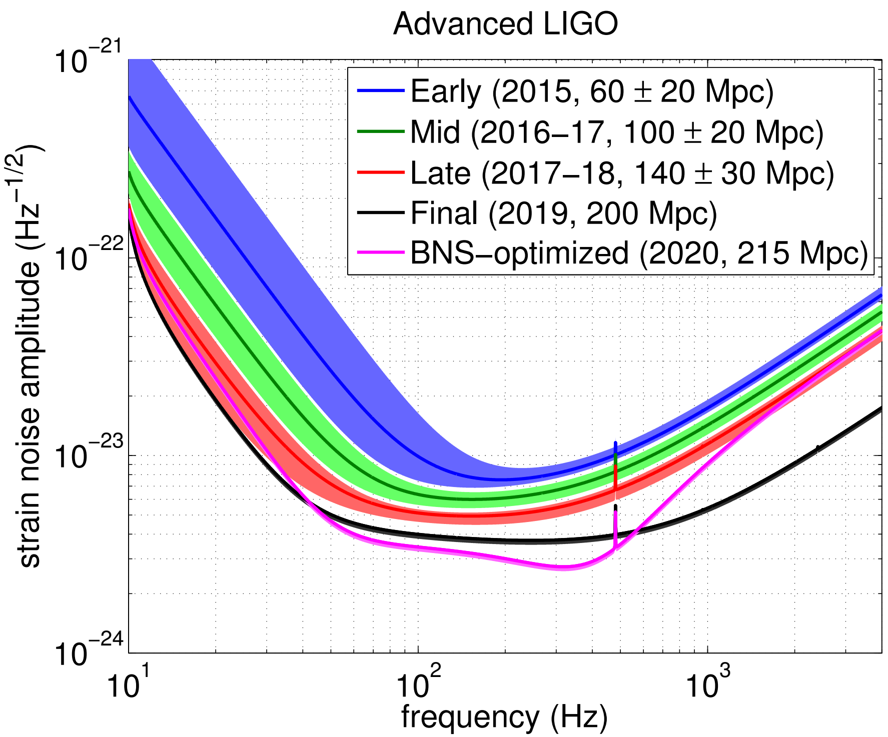

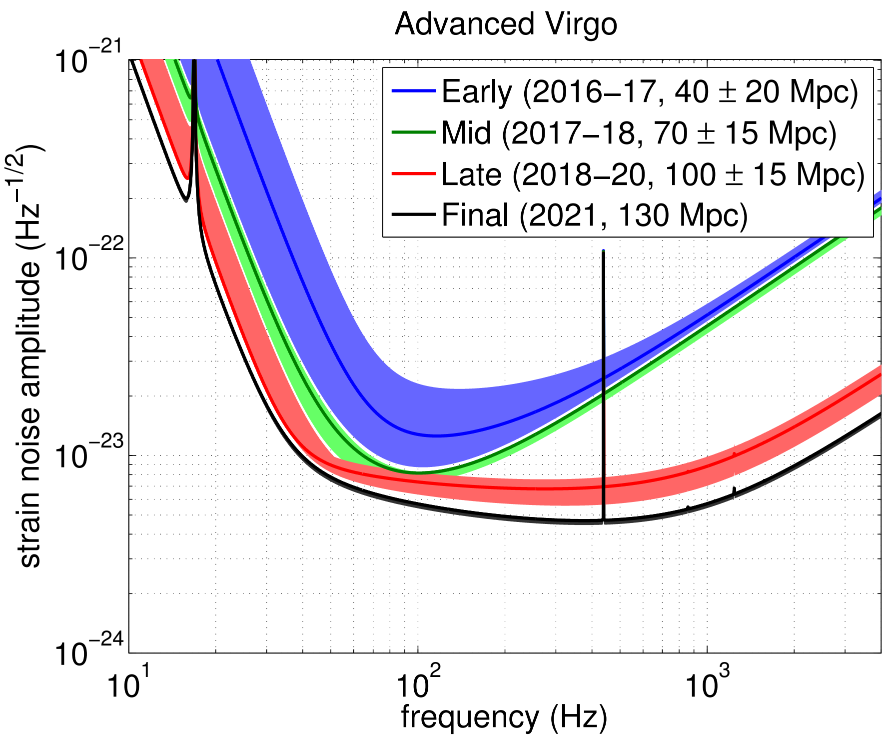

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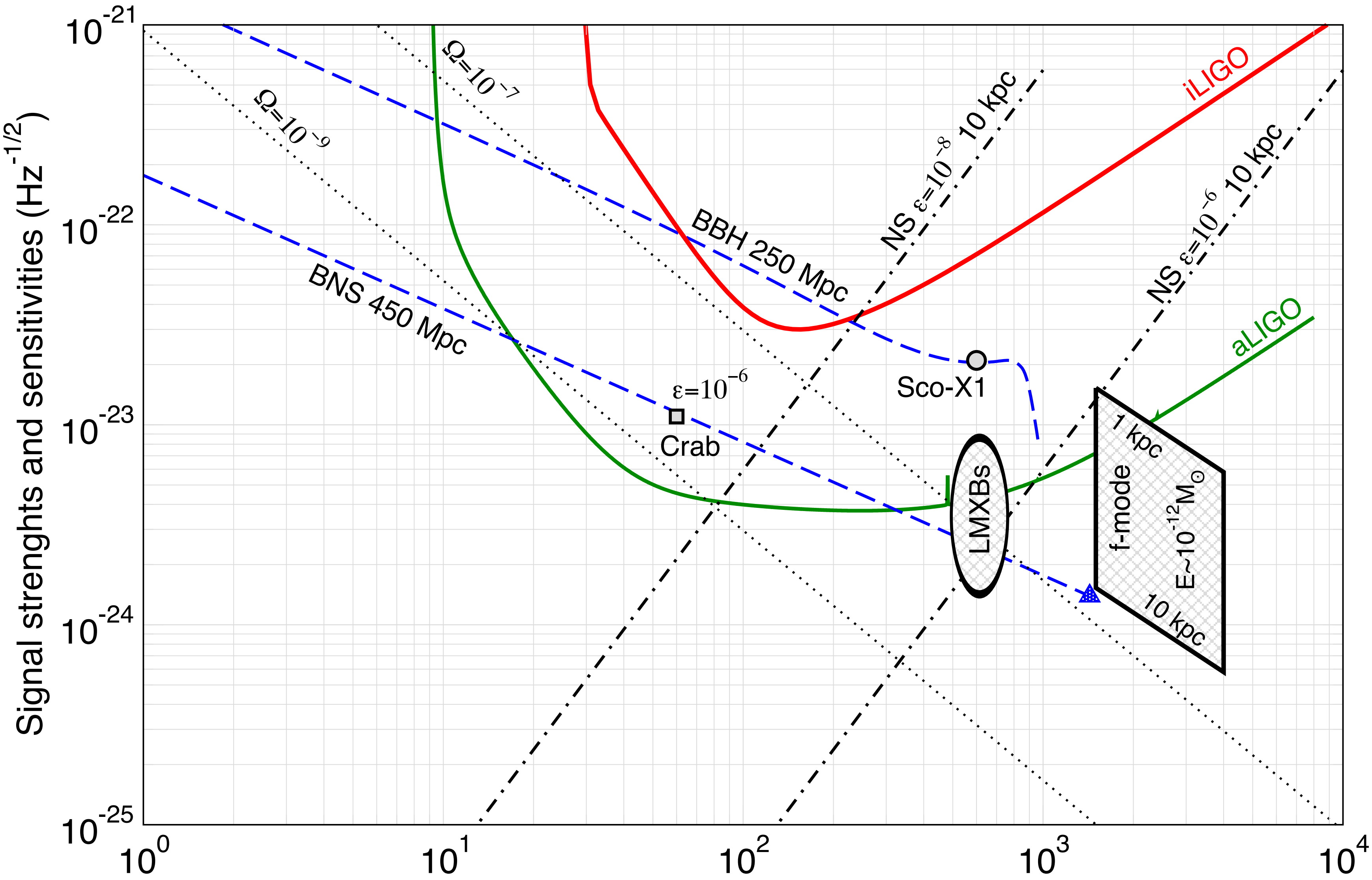
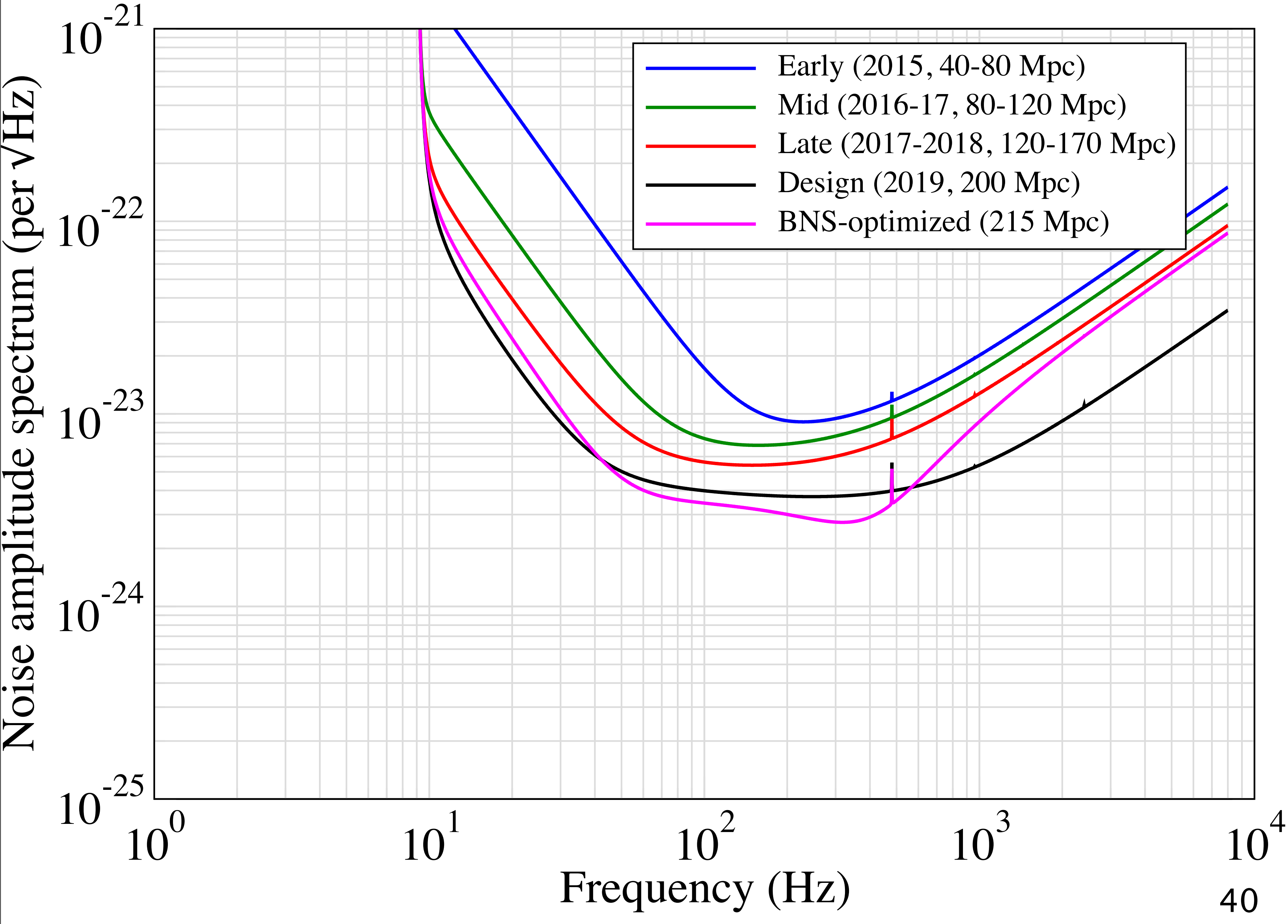
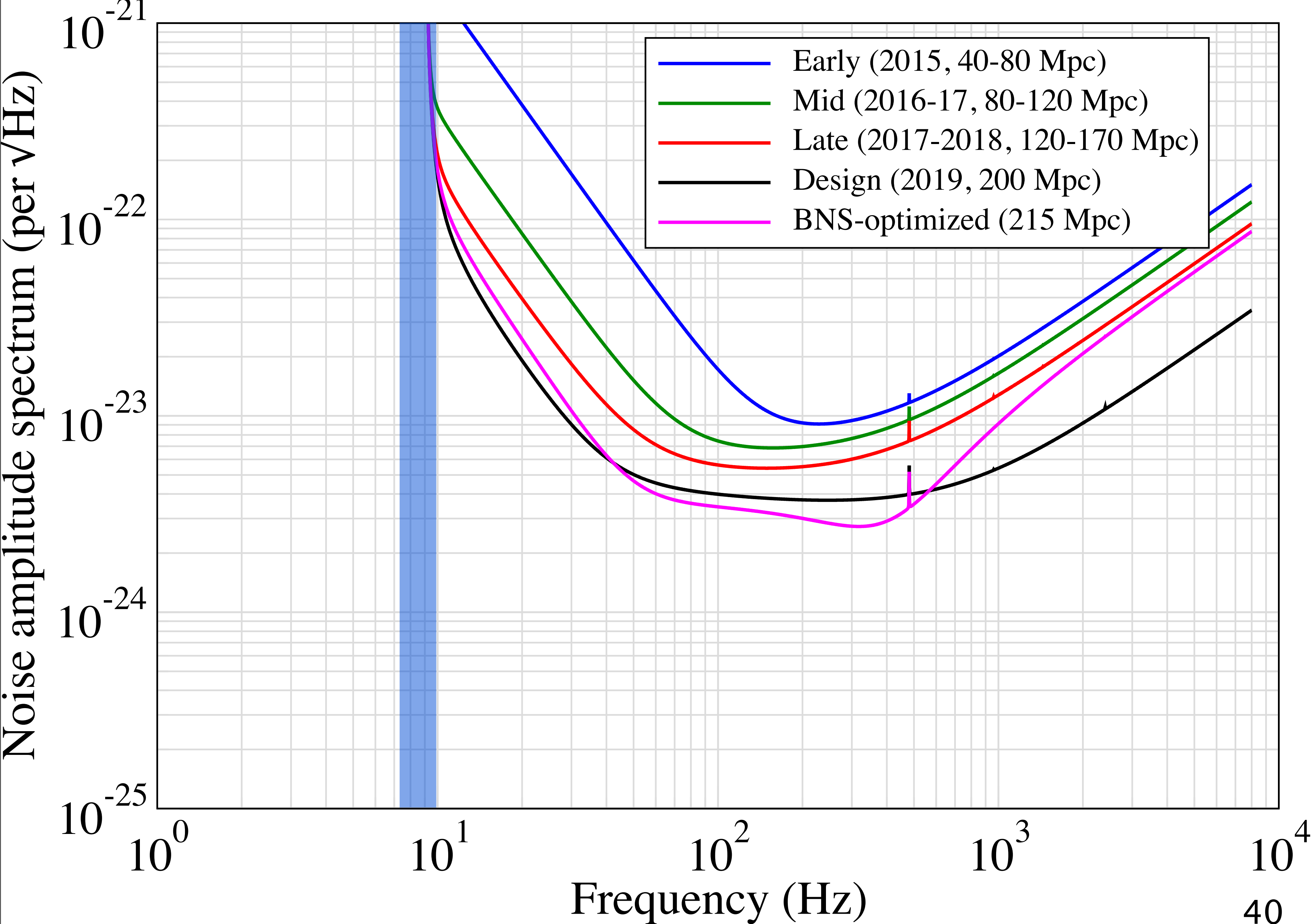
Aasi et al 2013 (arXiv:1304.0670)

Sources in advanced detectors



Beyond Advanced Detectors:
Einstein Telescope


Early (2015, 40-80 Mpc)
Mid (2016-17, 80-120 Mpc)
Late (2017-2018, 120-170 Mpc)
Design (2019, 200 Mpc)
BNS-optimized (215 Mpc)
Noise amplitude spectrum (per √Hz)
Frequency (Hz)
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}



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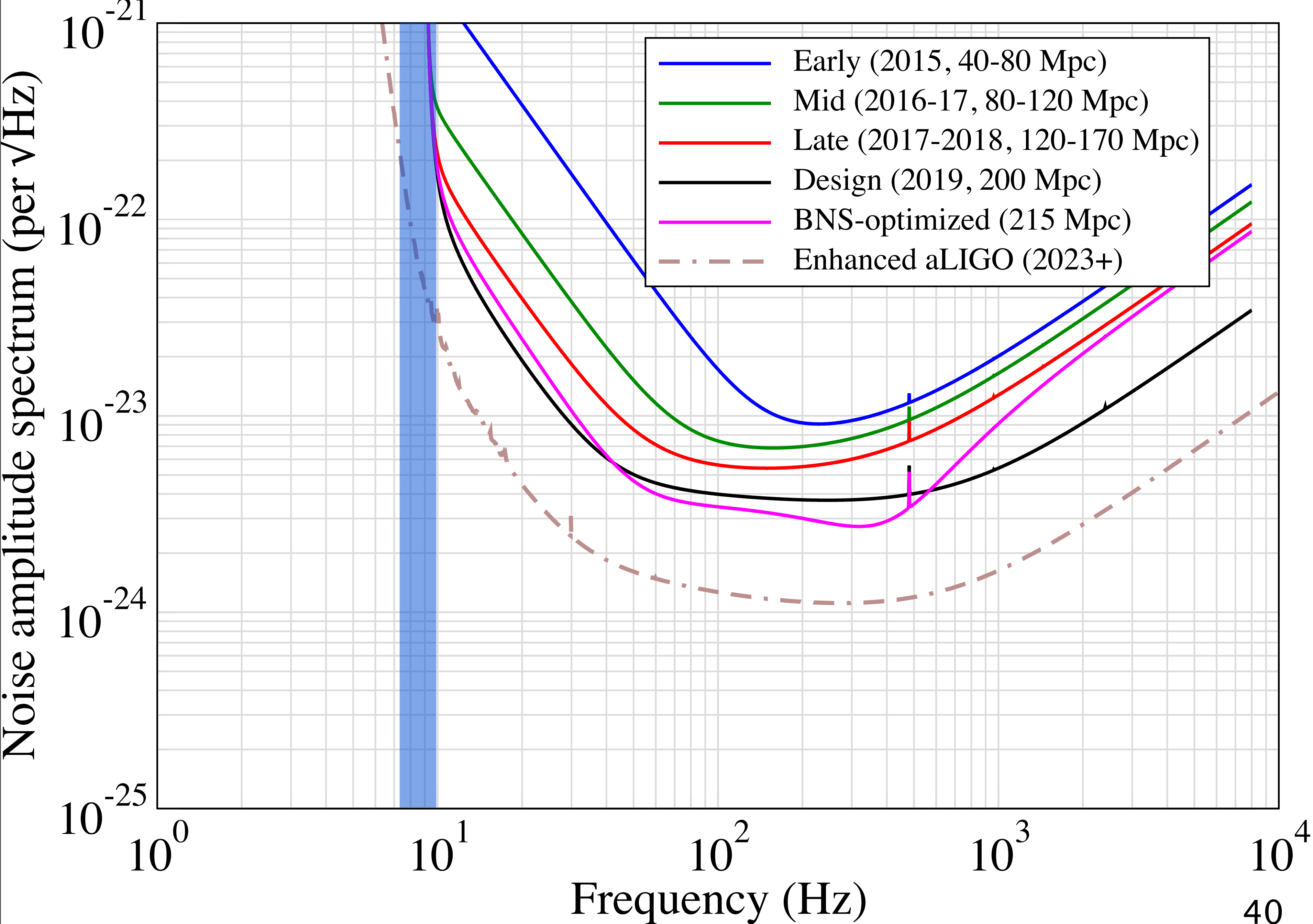

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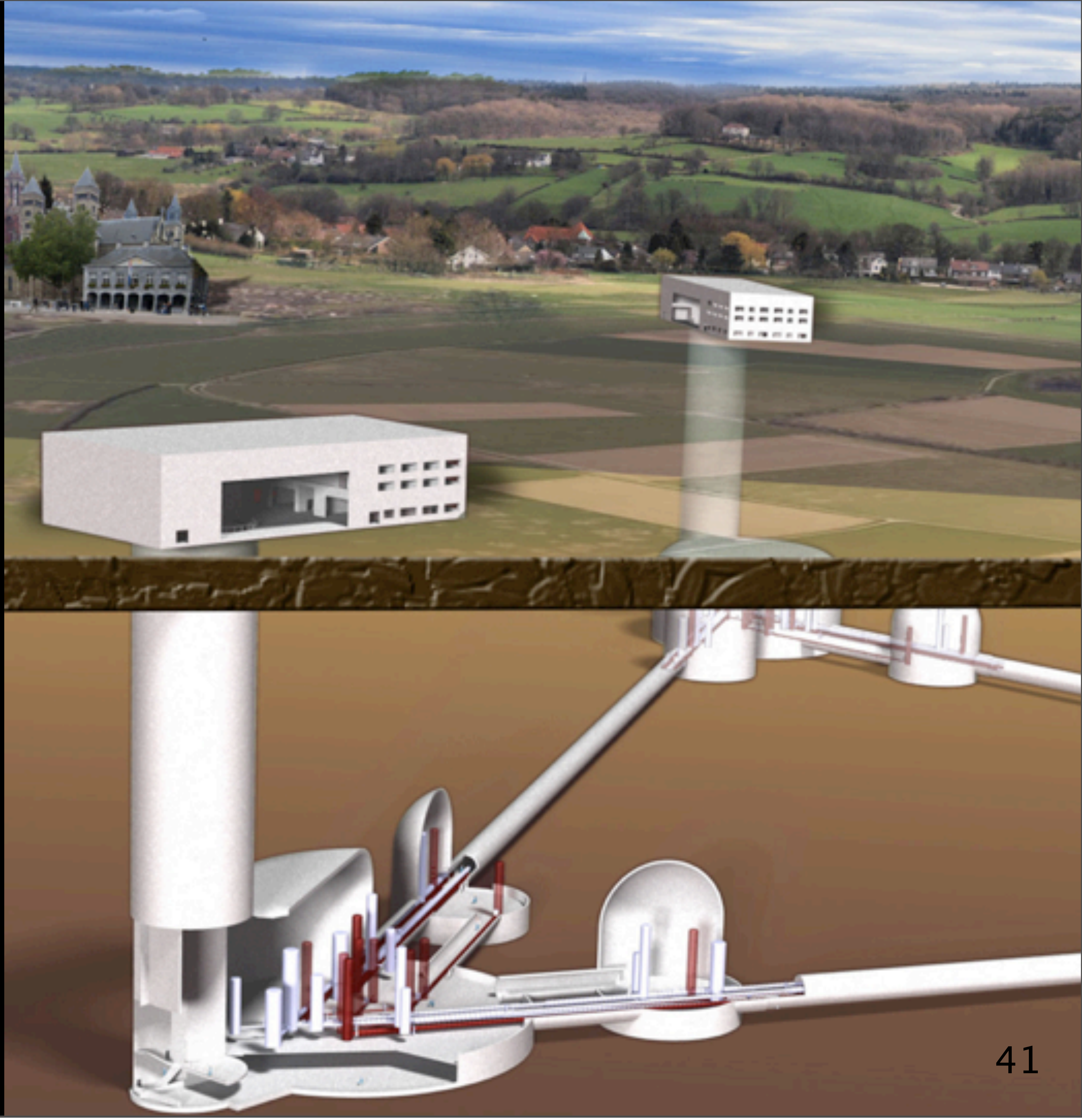
Design (2019, 200 Mpc)
BNS-optimized (215 Mpc)
Enhanced aLIGO (2023+)

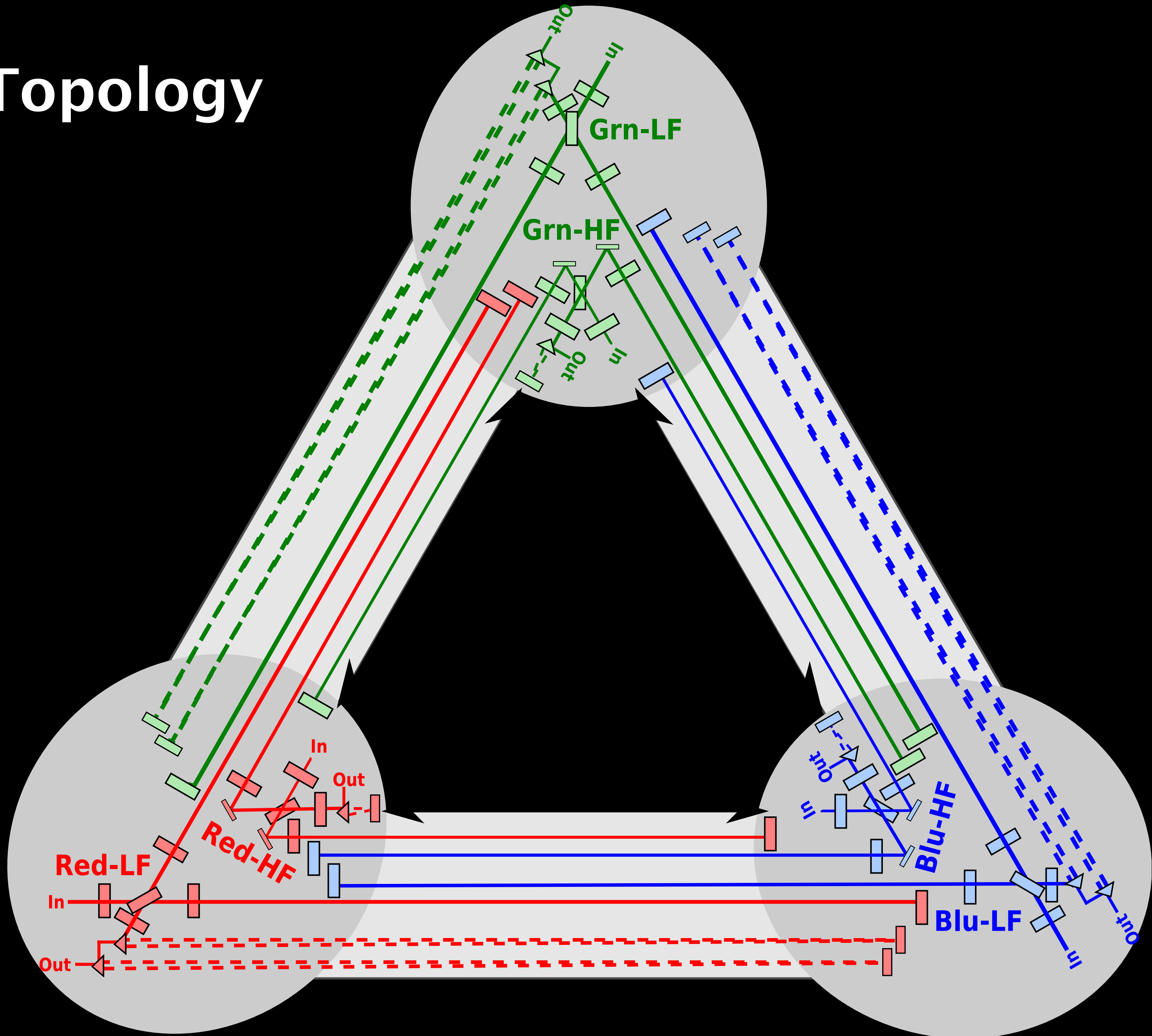
2008–2011
European
Conceptual
Design Study

2013–2016
ET R&D

Underground
detectors
should have
Significant
reduction in
GG



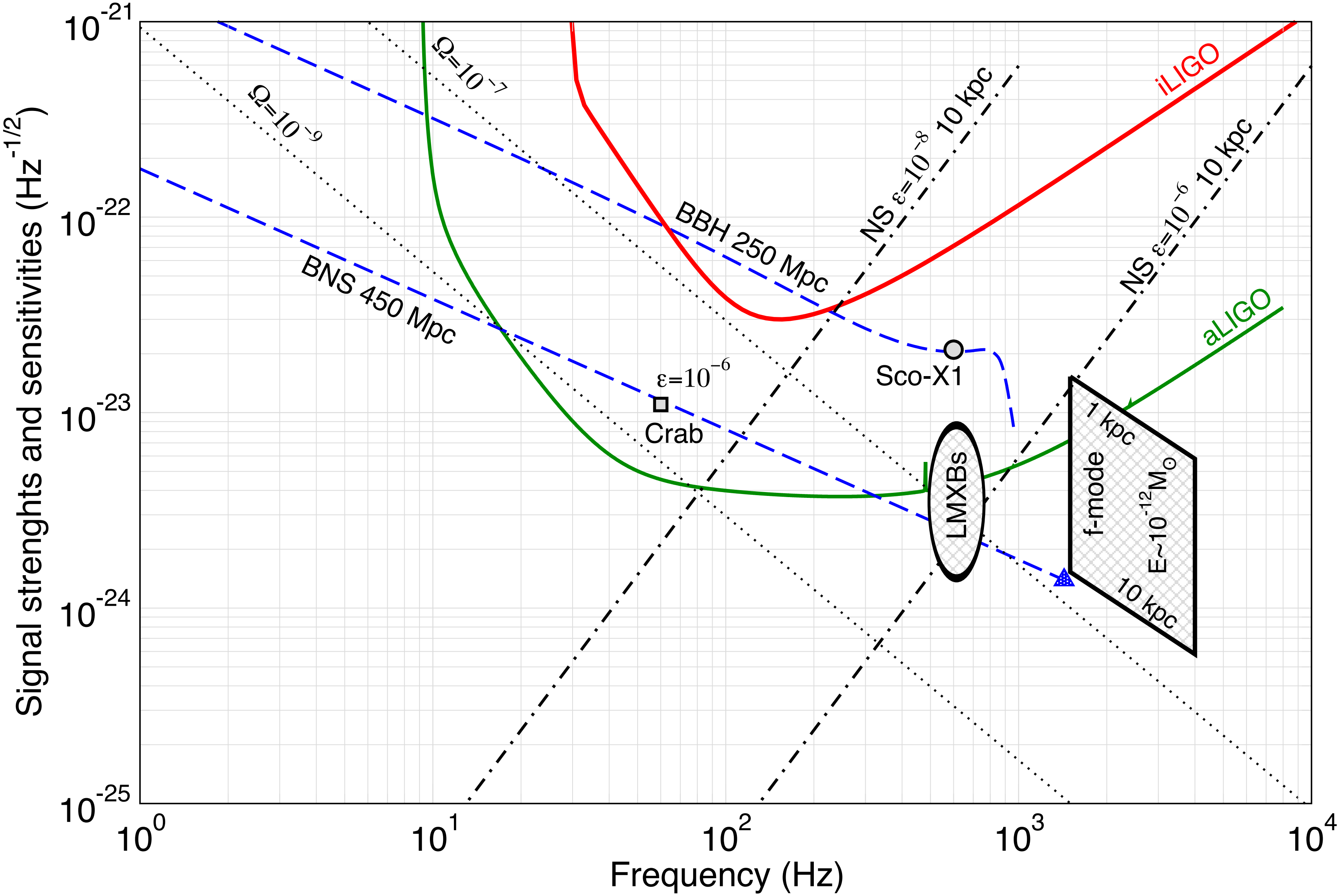
ET Topology



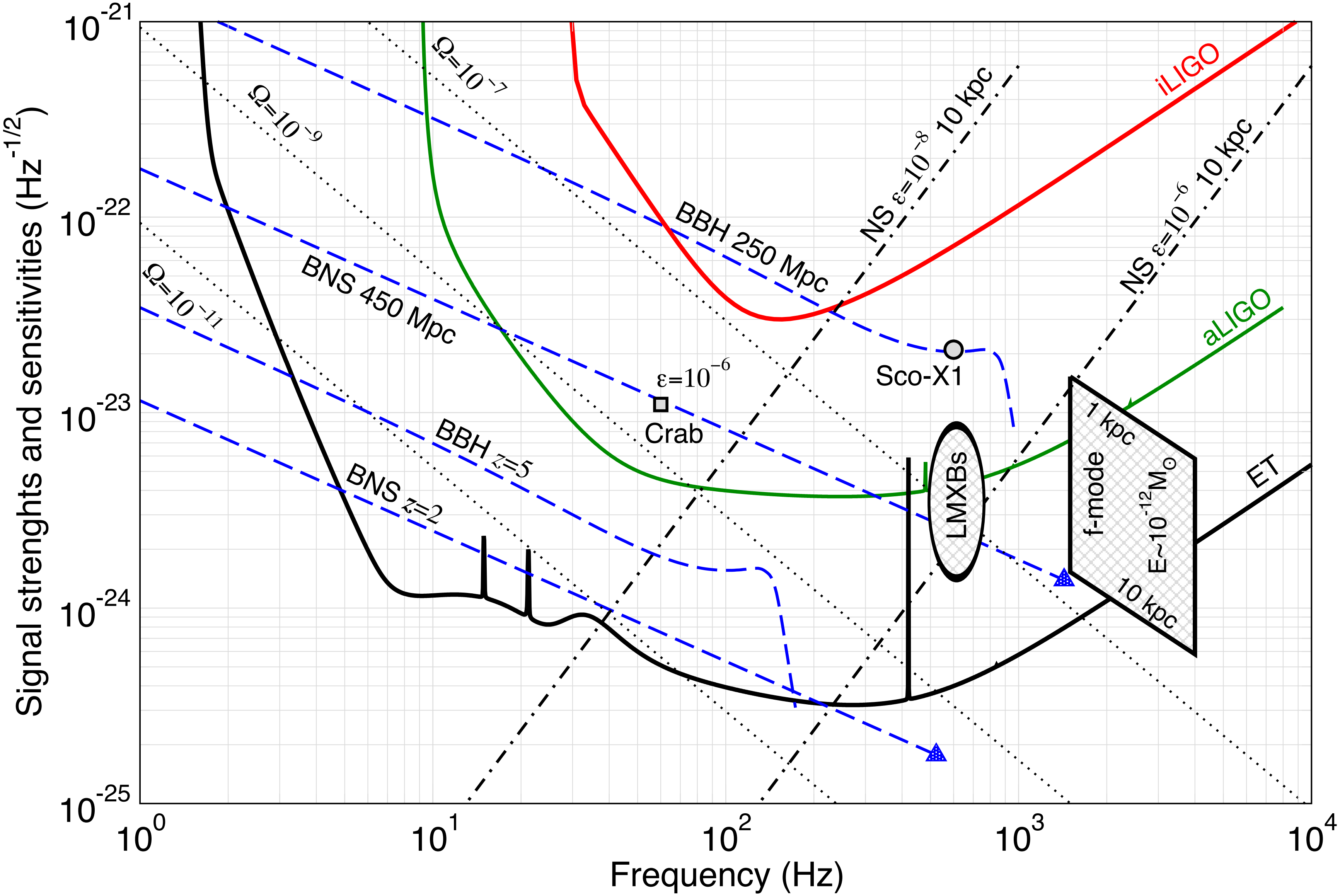
ET's Null Stream

- Given a network of (two collocated and three or more non–collocated) detectors it is possible to construct a linear combination of the responses that is completely devoid of any gravitational waves
  - For detectors that are not collocated different linear combinations are required for different directions on the sky
- For ET the linear combination is the same for all directions on the sky
  - It is just the sum of the responses from the three triangular detectors
  - This is called the null stream and contains no gravitational wave signals
  - Extremely useful for understanding detector noise

Sources in advanced detectors



Sources in ET

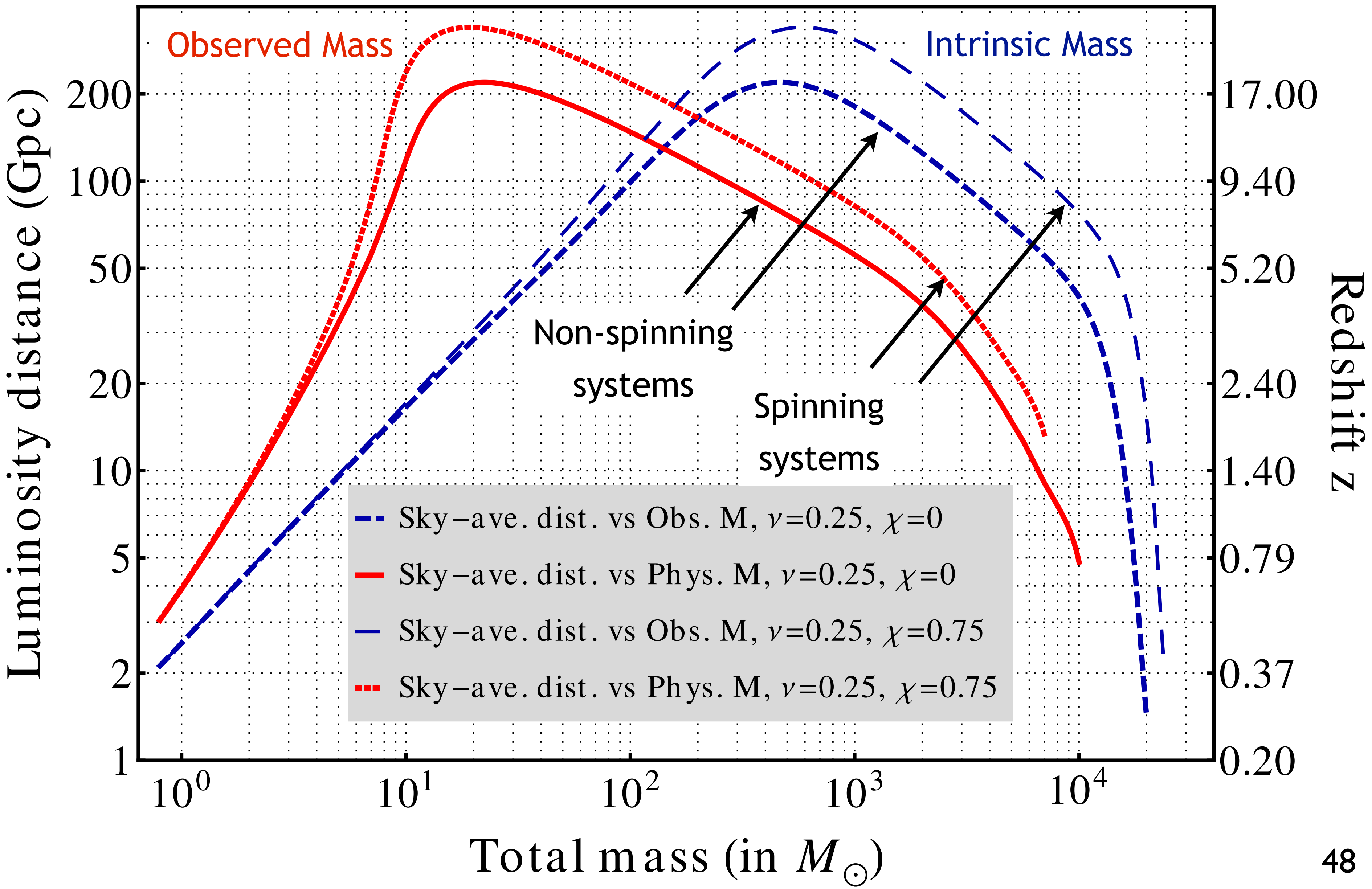


Fundamental Physics, Astrophysics and Cosmology with Ground Based Detectors

Cosmology

- Cosmography
  - Strengthen existing distance calibrations at high z
  - Calibration–free measurements of distance and cosmological parameters
- Black hole seeds
  - Black hole seeds could be stellar mass or intermediate mass black holes
  - Explore hierarchical growth of central engines of black holes
- Anisotropic cosmologies
  - In an anisotropic Universe the distribution of H on the sky should show residual quadrupole and higher–order anisotropies
- Primordial gravitational waves
  - Quantum fluctuations in the early Universe produce a stochastic b/g
- Production of GW during early Universe phase transitions
  - Phase transitions, pre–heating, re–heating, etc., could produce detectable stochastic GW

Probing black hole mergers at z ~ 10–20



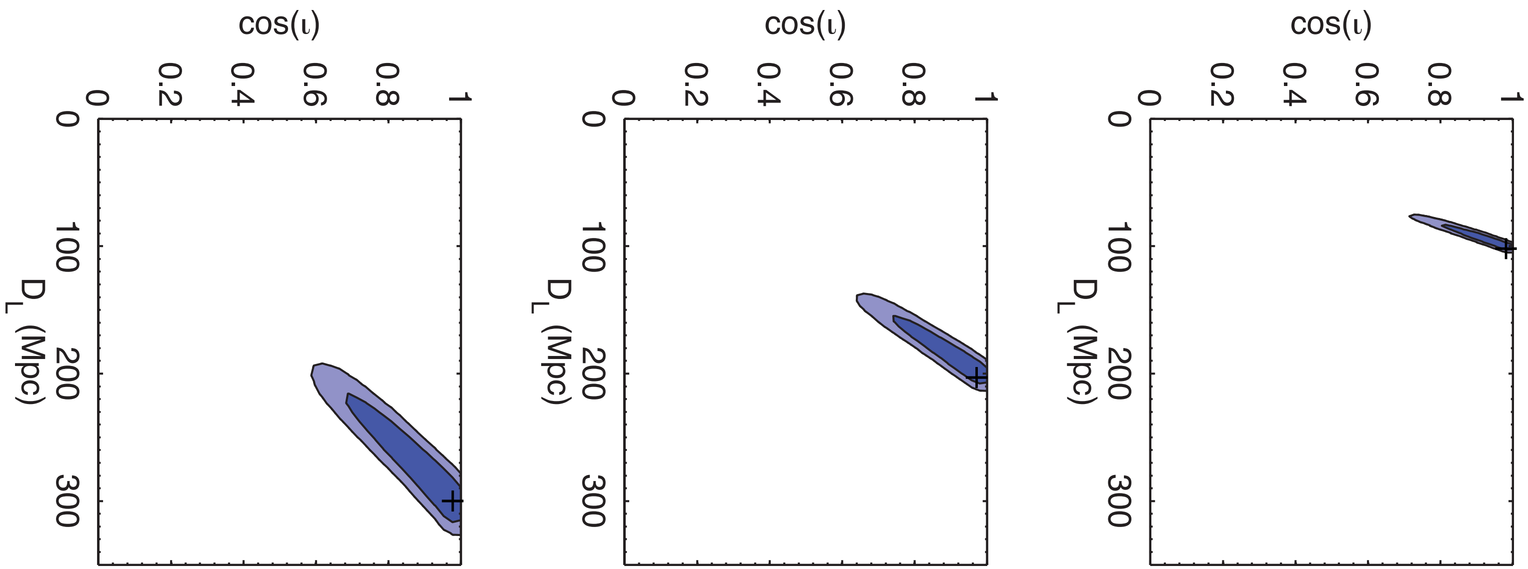
Hubble Constant from Advanced Detectors

EXPLORING SHORT GAMMA-RAY BURSTS AS GRAVITATIONAL-WAVE STANDARD SIRENS

Samaya Nissanke[1,2], Scott A. Hughes[2], Daniel E. Holz[3], Neal Dalal[1], Jonathan L. Sievers[1]

Draft version April 7, 2009

is further augmented by a factor of 1.12. At this rate, we find that *one* year of observation should be enough to measure H_0 to an accuracy of $\sim 1\%$ if SHBs are dominated by beamed NS-BH binaries using the "full" network of LIGO, Virgo, AIGO, and LCGT—admittedly,



ET: Measuring Dark Energy and Dark Matter

- ET will observe 100's of binary neutron stars and GRB associations each year
- GRBs could give the host location and red-shift, GW observation provides D_L

Class. Quantum Grav. **27** (2010) 215006 B S Sathyaprakash *et al*

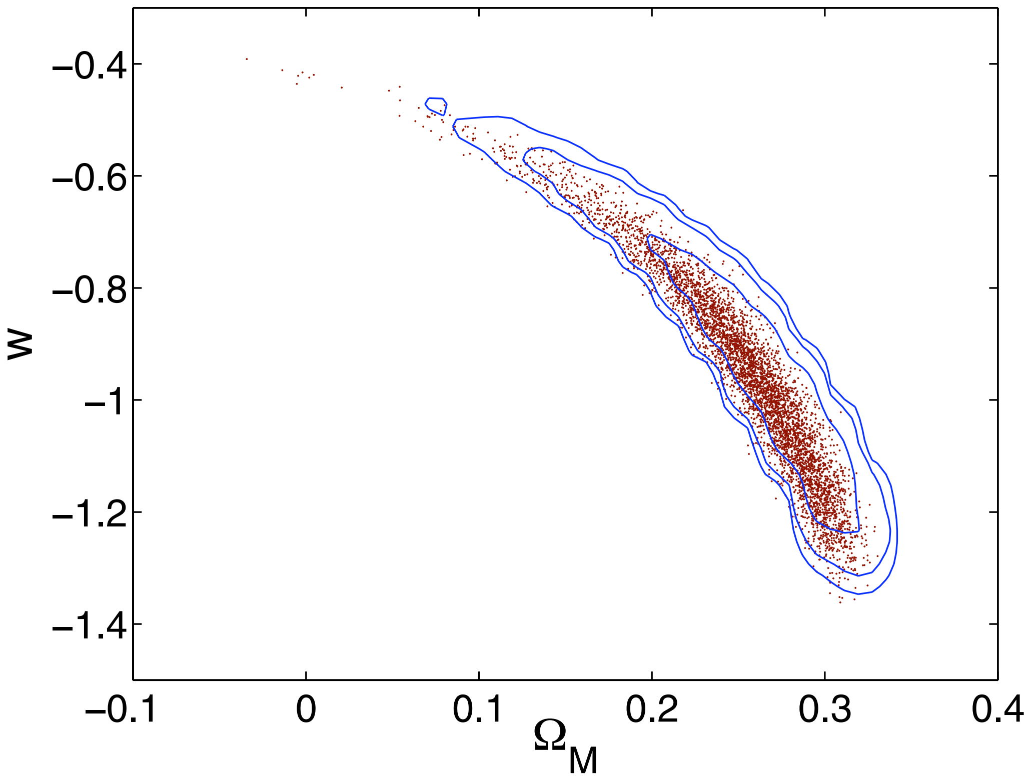
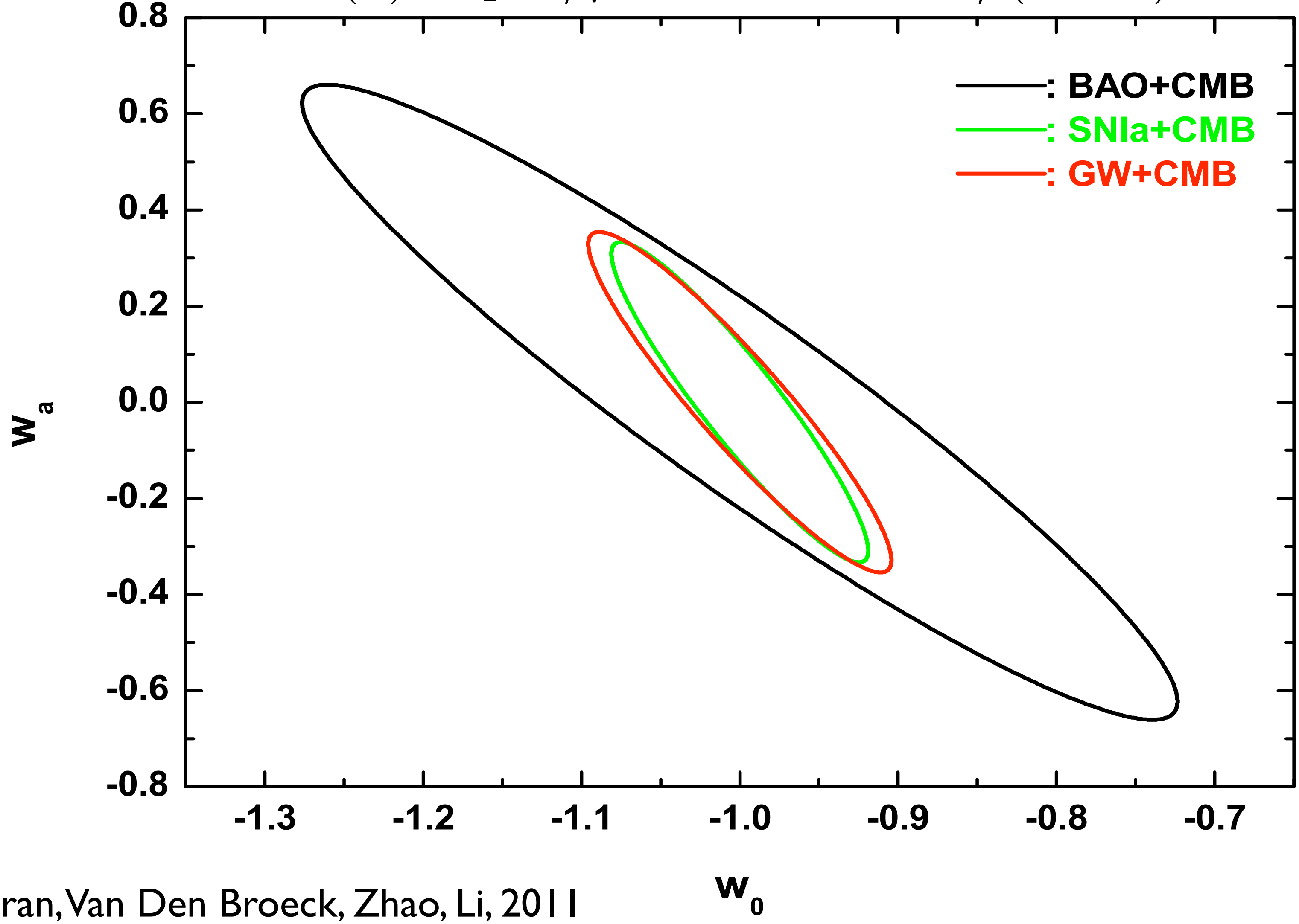


Figure 3. Scatter plot of the retrieved values for (Ω_Λ, w), with 1-σ, 2-σ and 3-σ contours, in the case where weak lensing is not corrected.

Measuring w and its variation with z

$$w(z) \equiv p_{de}/\rho_{de} = w_0 + w_a z/(1+z)$$



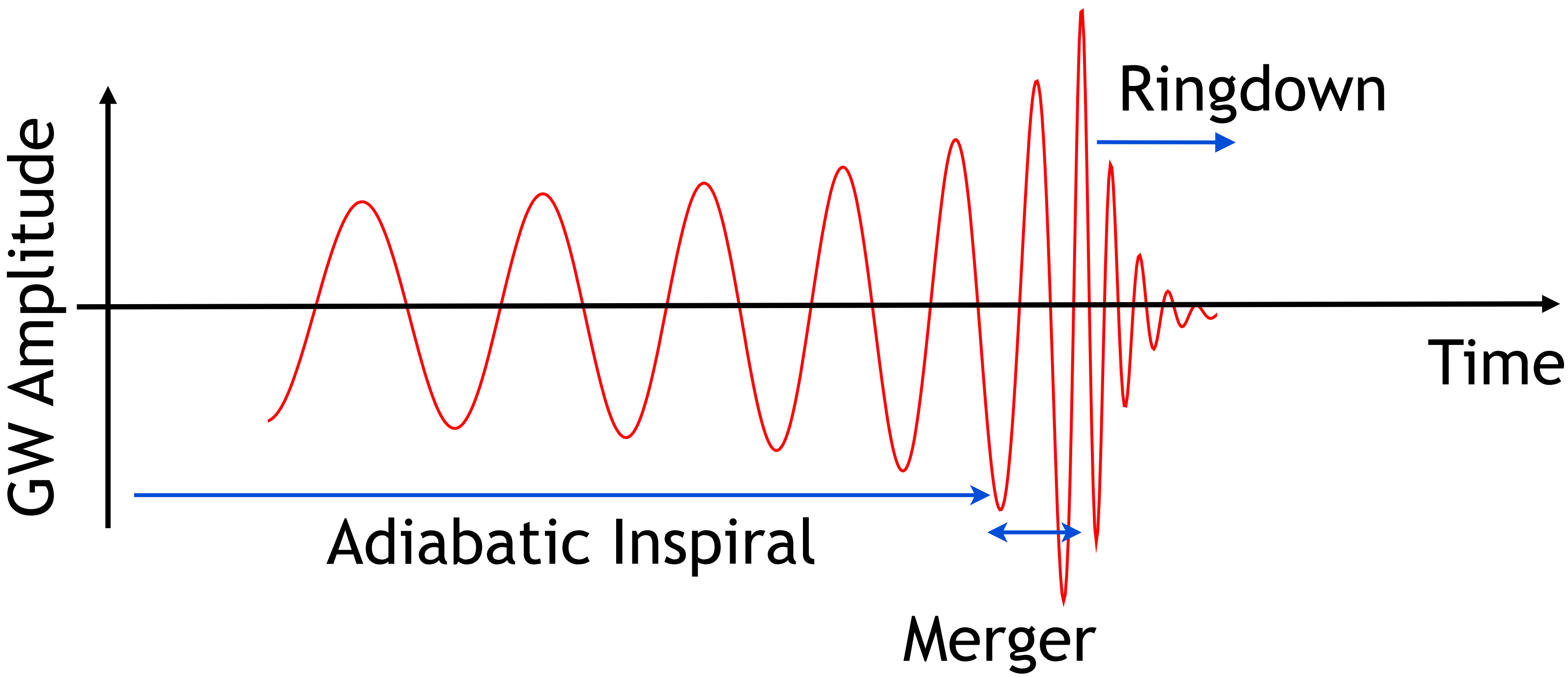
Baskaran, Van Den Broeck, Zhao, Li, 2011

Fundamental Physics

- The two body problem in general relativity
- Properties of gravitational waves
  - Testing GR beyond the quadrupole formula
  - How many polarizations are there?
  - Do gravitational waves travel at the speed of light?
- EoS of dark energy
  - Black hole binaries are standard candles/sirens
- EoS of supra-nuclear matter
  - Signature of EoS in GW emitted when neutron stars merge
- Black hole no-hair theorem and cosmic censorship
  - Are BH (candidates) of nature BH of general relativity?
- An independent constraint/measurement of neutrino mass
  - Delay in the arrival times of neutrinos and gravitational waves

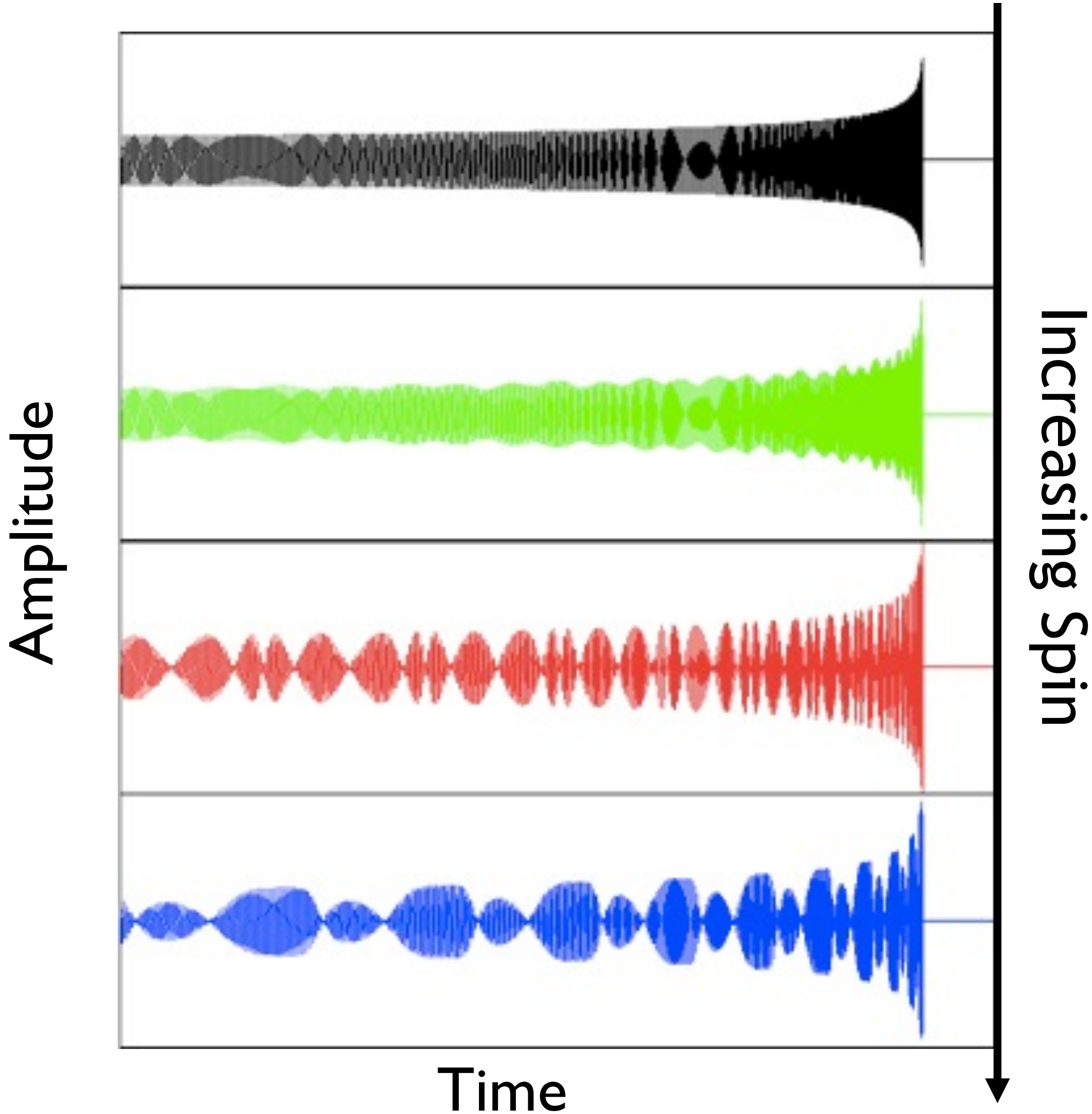
Binary black hole dynamics

- The signal from a binary black hole is characterized by
  - slow adiabatic inspiral – the two bodies slowly spiral in towards each other; dynamics well described by post–Newtonian approximation
  - fast and luminous merger phase; requires numerical solutions to Einstein equations
  - rapid ringdown phase; newly black hole emits quasi–normal radiation
- The shape of the signal contains information about the binary



Binary black hole waveforms

- The shape of the signal is determined by masses, spins and eccentricity
- The amplitude and arrival times in different detectors are determined by the distance, direction, polarization and inclination



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Testing Black Hole No_Hair Theorem

- Deformed black holes are unstable; they emit energy in their deformation as gravitational waves
  - Superposition of damped waves with many different frequencies and decay times
  - In Einstein's theory, frequencies and decay times all depend only on the mass M and spin j of the black hole
- Measuring two or modes would constrain Einstein's theory or provide a smoking gun evidence of black holes
  - If modes depend on other parameters (e.g., the structure of the central object), then test of the consistency between different mode frequencies and damping times would fail
- The amplitude of the modes cary additional information about what caused the deformity

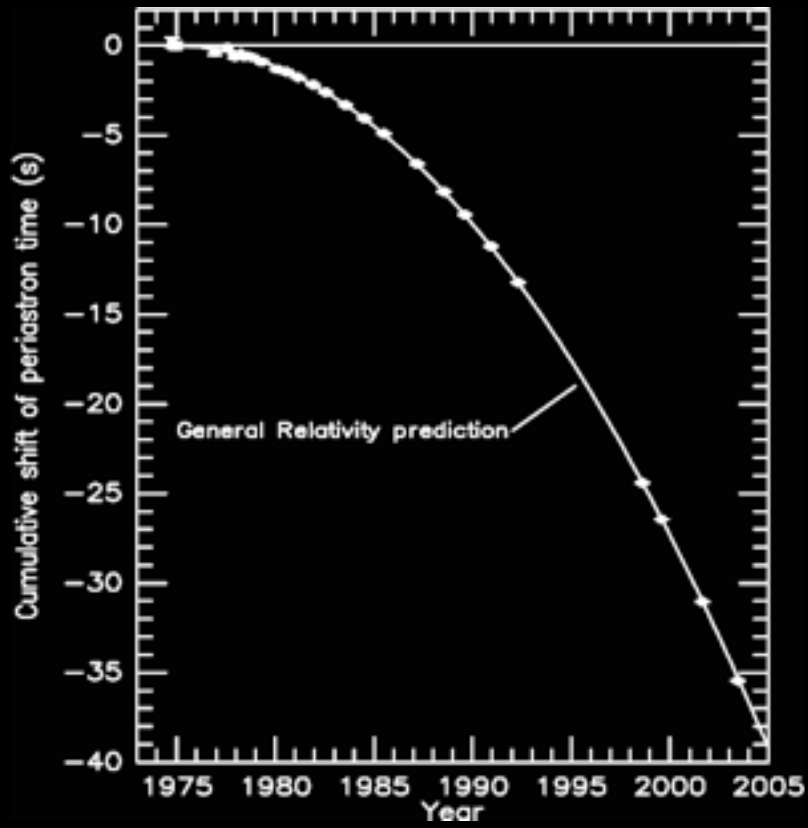
Dreyer et al (2004), Berti, Cardoso, Will (2006), Berti Cardoso, Cardoso, Cavaglia (2007)

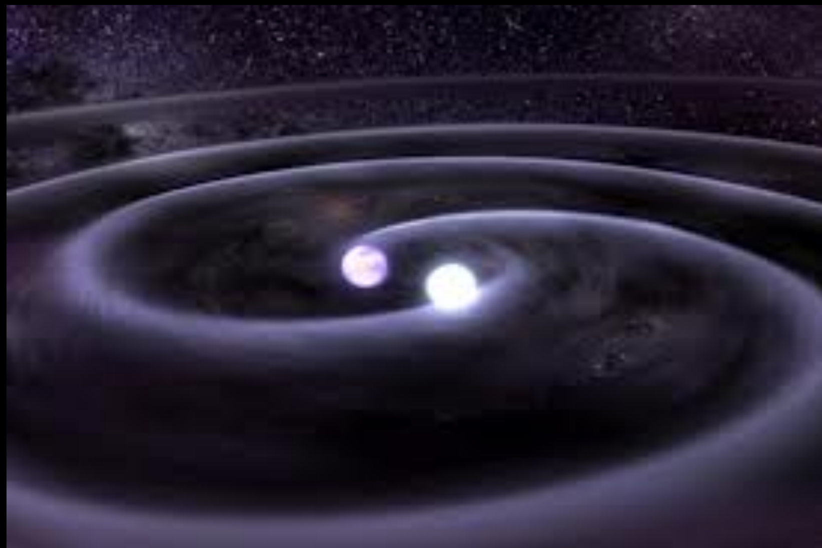
Astrophysics

- Unveiling progenitors of short–hard GRBs
  - Understand the demographics and different classes of short–hard GRBs
- Understanding Supernovae
  - Astrophysics of gravitational collapse and accompanying supernova?
- Evolutionary paths of compact binaries
  - Evolution of compact binaries involves complex astrophysics
- Finding why pulsars glitch and magnetars flare
  - What causes sudden excursions in pulsar spin frequencies and what is behind ultra high–energy transients of EM radiation in magnetars
- Ellipticity of neutron stars as small as 1 part in a billion (10μm)
  - Mountains of what size can be supported on neutron stars?
- NS spin frequencies in LMXBs
  - Why are spin frequencies of neutron stars in low–mass X–ray binaries bounded?
- Onset/evolution of relativistic instabilities
  - CFS instability and r–modes

Binary Neutron Stars

- These are systems we know exist and we should see them
- Rates are highly uncertain
  - Advanced detectors could see events in the range 0.5 to 400 per year
- Observed event rates will constrain models of formation and evolution of compact binaries
- Can measure masses and spins and possibly equation of state of supra-nuclear matter





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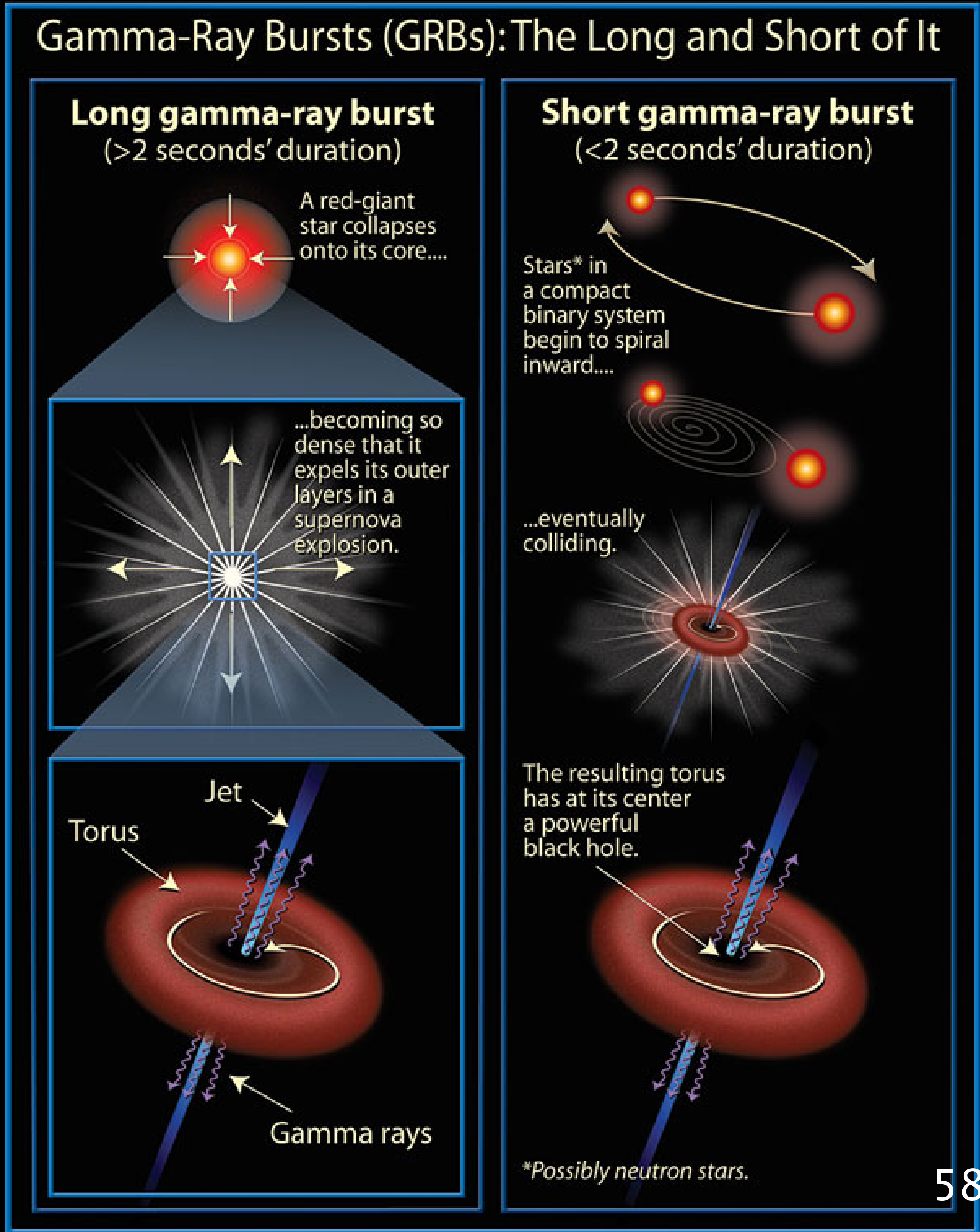
Progenitors of GRBs

- What causes these giant explosions?
- What are the different classes of GRBs?
- Synergy between EM and GW Astronomy
  - Distances measured with GW
  - Redshift measured with EM
  - Could potentially be very useful for cosmography

See SB's talk on July 5



Gravitational Astronomy

- We expect gravitational waves to be detected before the end of this decade
  - Detections could come from either Pulsar Timing Arrays or interferometers
- Scientific potential of future detectors, eLISA and ET, is huge
- Fundamental Physics
  - Is the **nature of gravitational radiation** as predicted by Einstein?
  - Is Einstein theory the **correct theory** of gravity?
  - Are black holes in nature **black holes of GR** and are there **naked singularities?**
- Astrophysics
  - What is the nature of **gravitational collapse?**
  - What is the origin of **gamma ray bursts?**
  - What is the **structure of neutron stars** and other compact objects?
- Cosmology
  - How did **massive black holes at galactic nuclei** form and evolve?
  - What is dark energy?
  - What phase transitions took place in the early Universe?
  - What were the **physical conditions** at the big bang and what role did quantum gravity in the early evolution of the Universe