Gravitational waves and cosmology

Progress on Old and New Themes in Cosmology
(PONT), 14–18 April 2014

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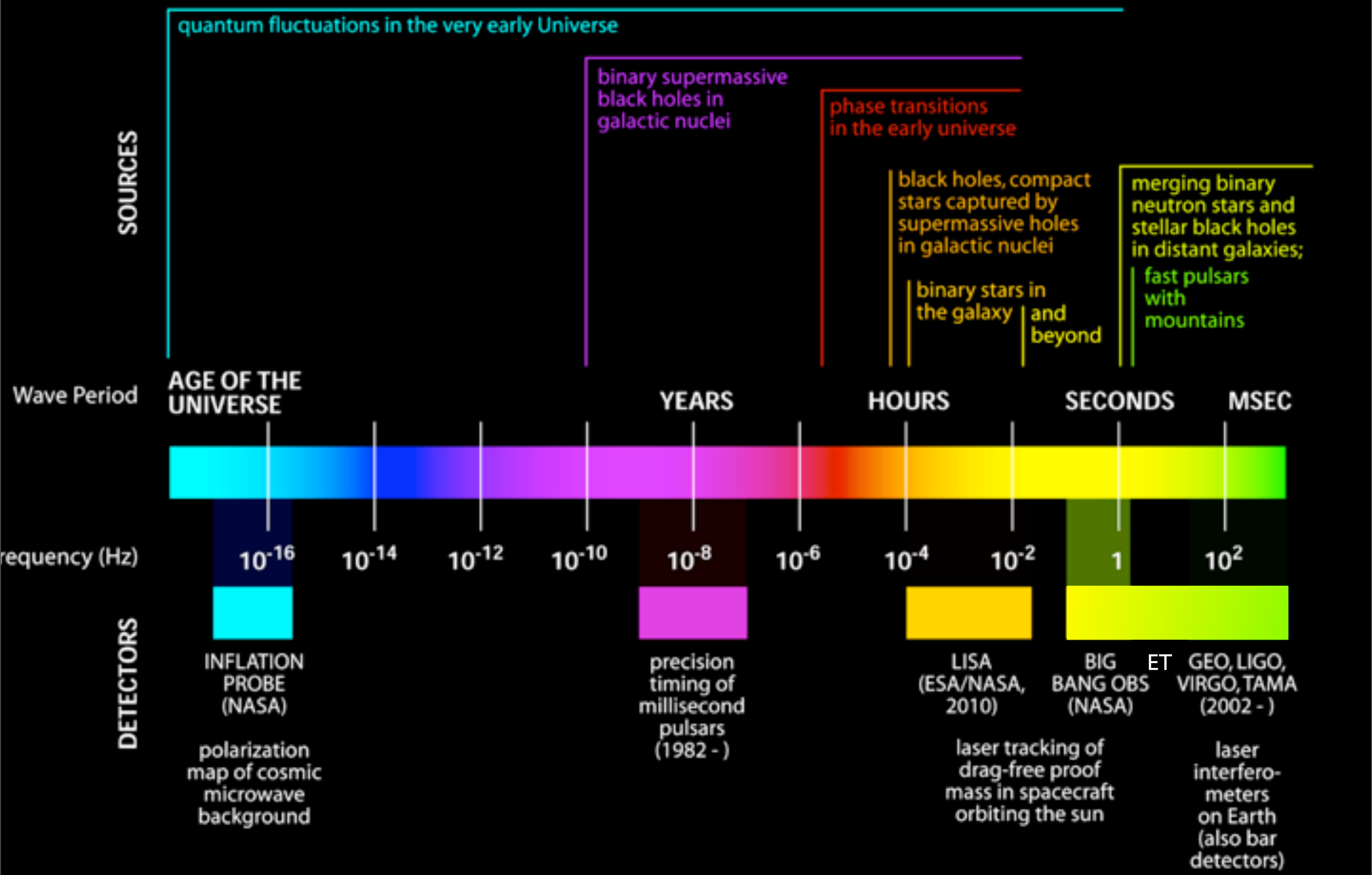
PRIFYSGOL CAERDYDD

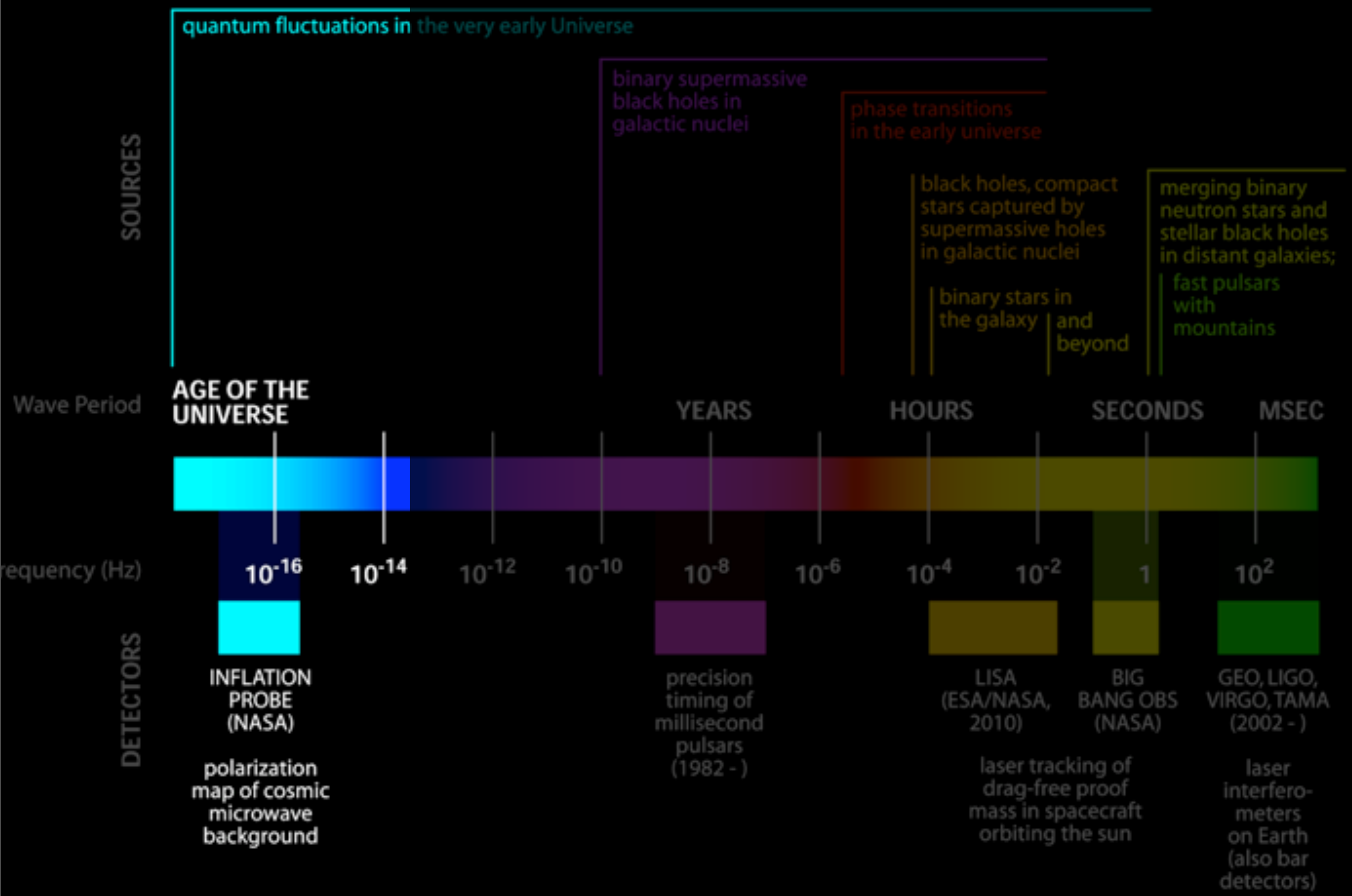
Outline

- Upcoming detectors and space missions
  - opportunities to observe gravitational waves from 1 to 10^8 solar mass sources
- Binary inspiral sources
  - Why are they standard candles or “sirens”?
  - How can they be used for cosmography?
  - Learning about black hole seeds
- Cosmological backgrounds

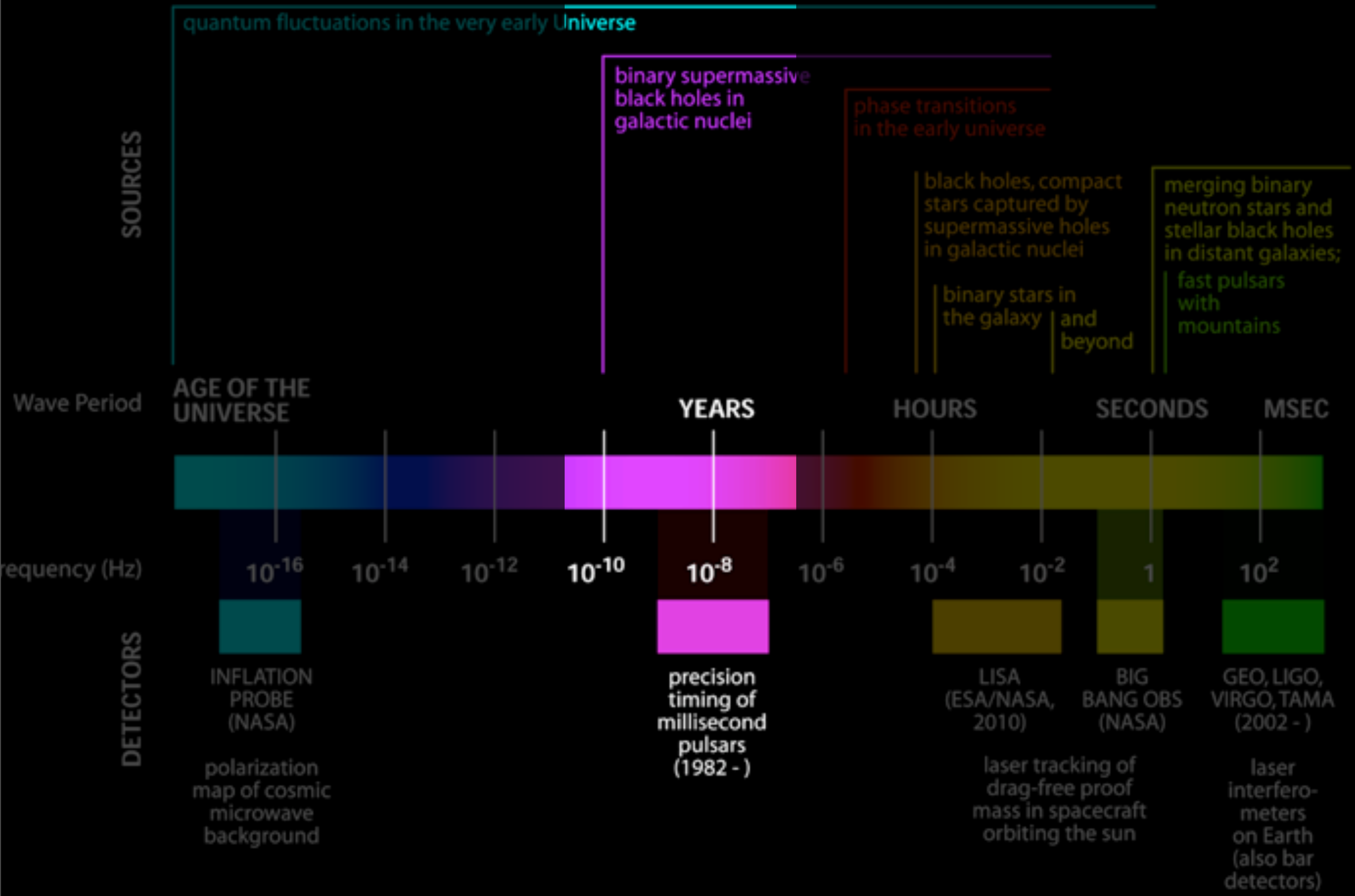
THE GRAVITATIONAL WAVE SPECTRUM



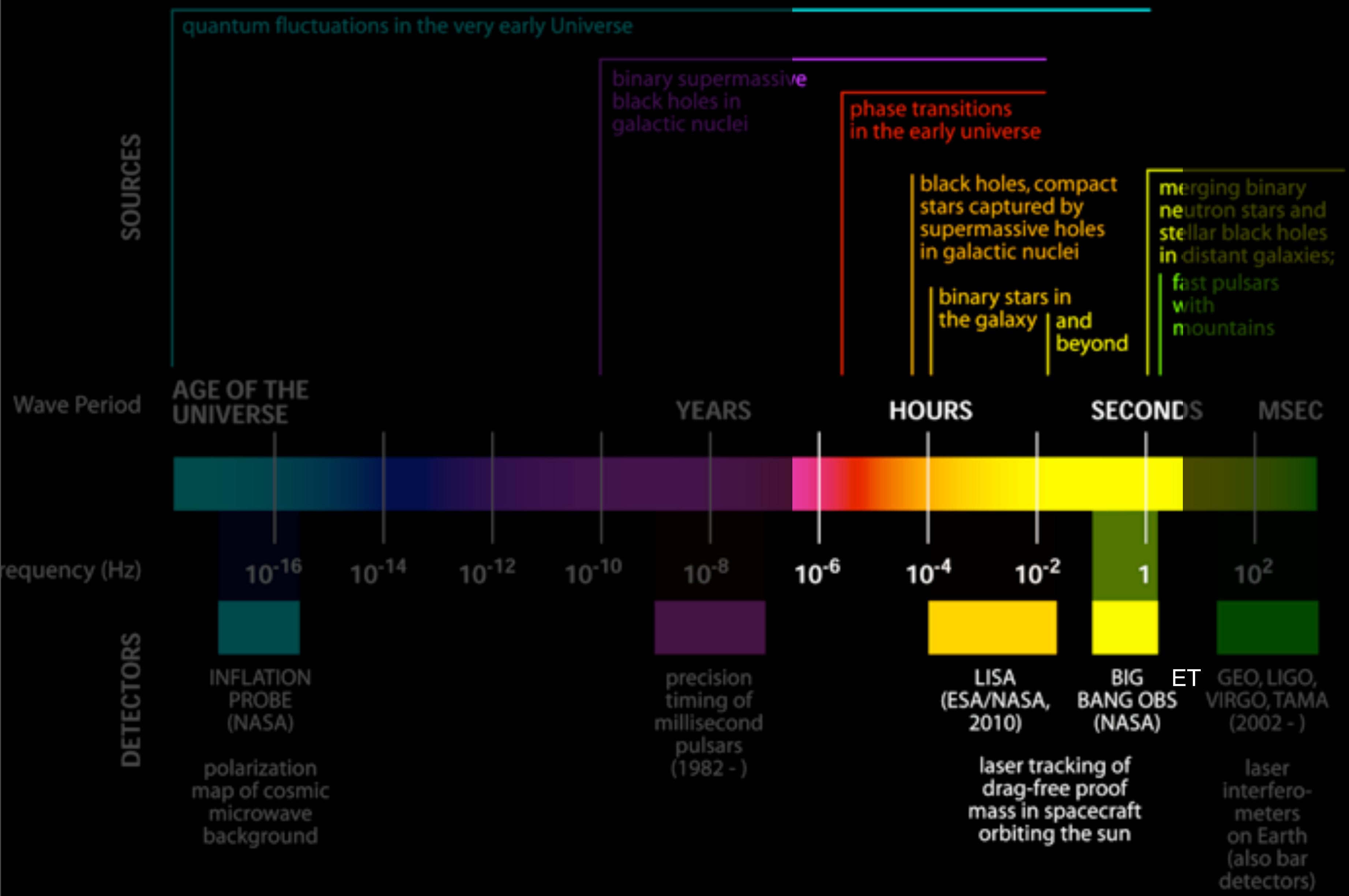
Ultra Low Frequency



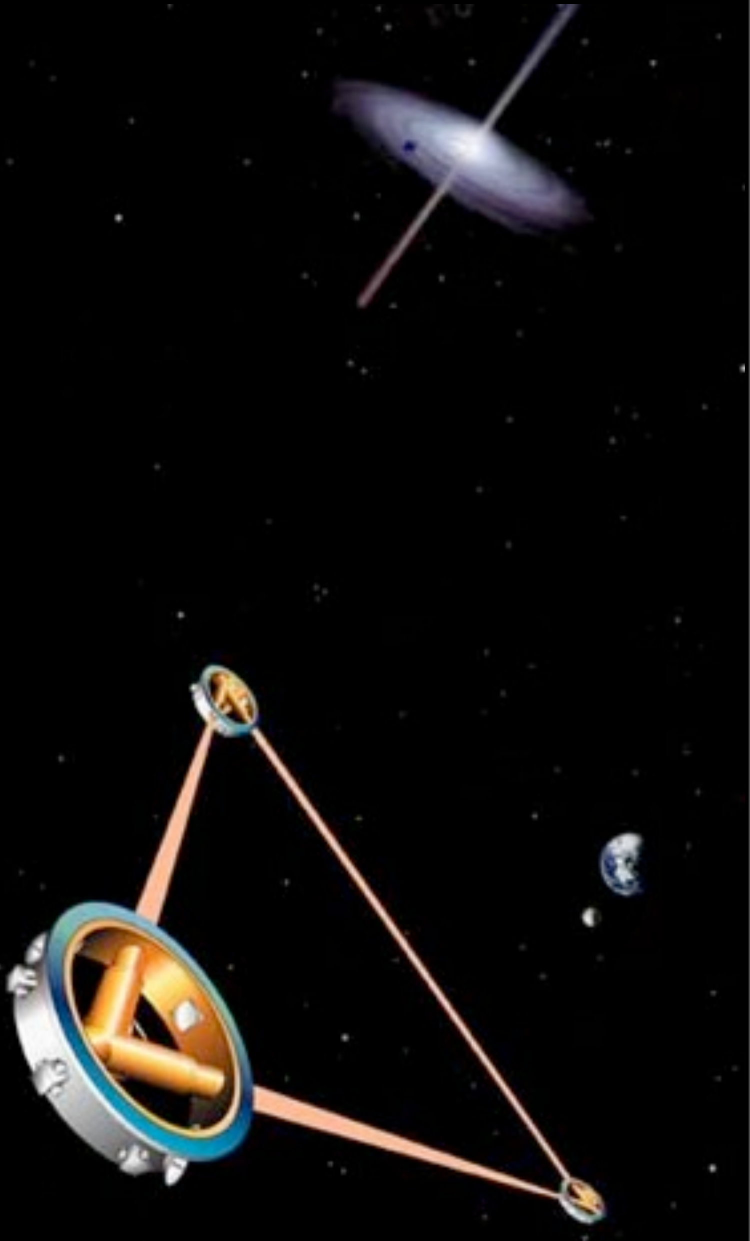
Very Low Frequency



Low Frequency

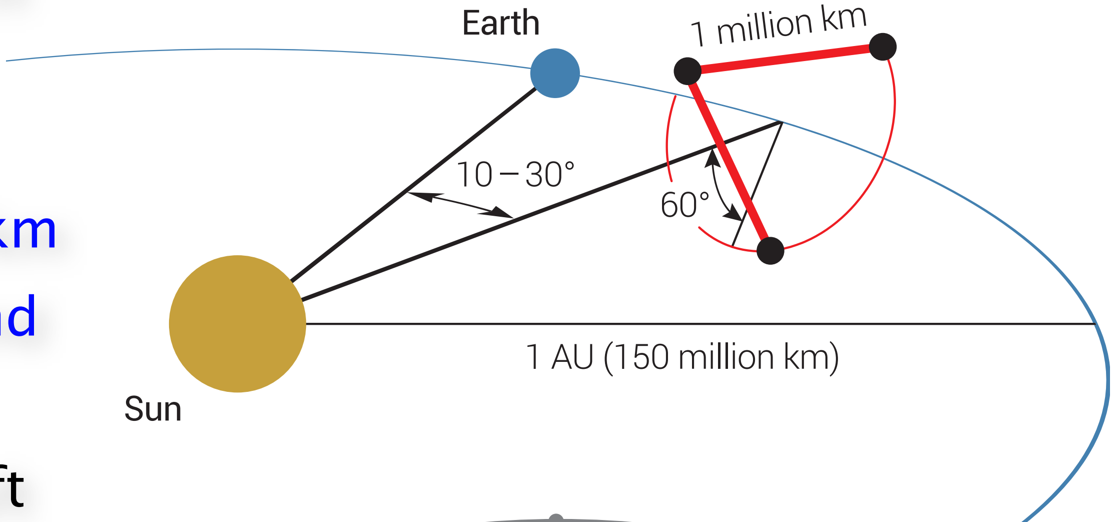


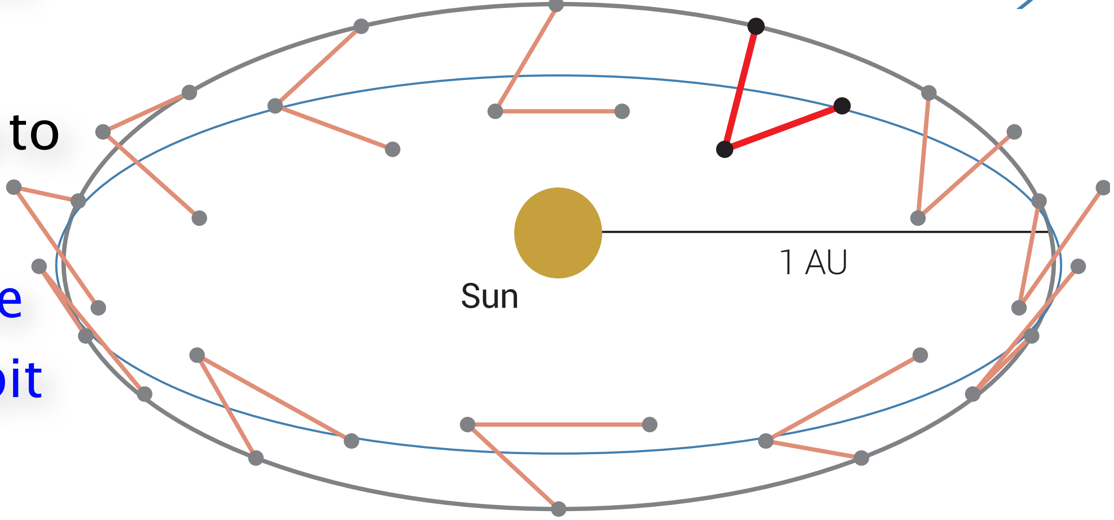
LISA: Laser Interferometer Space Antenna



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

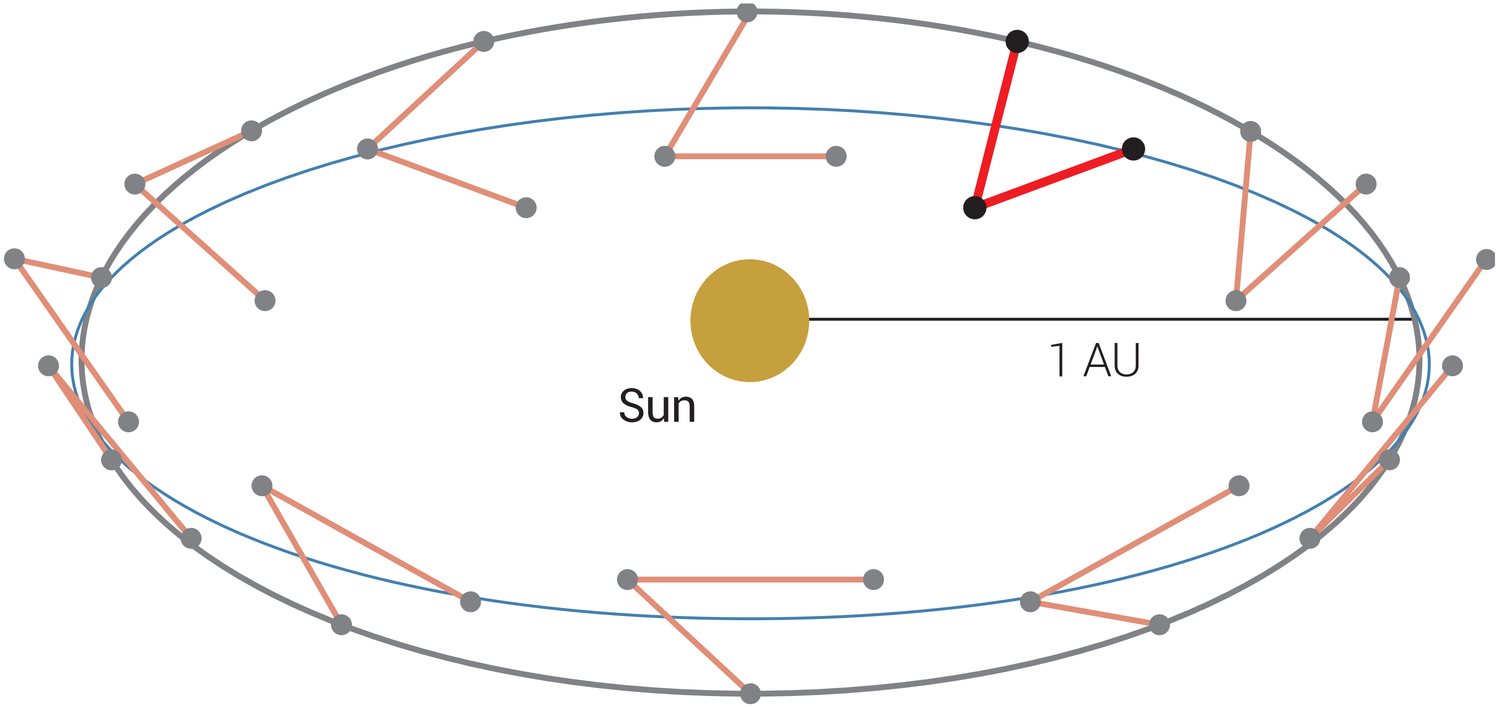




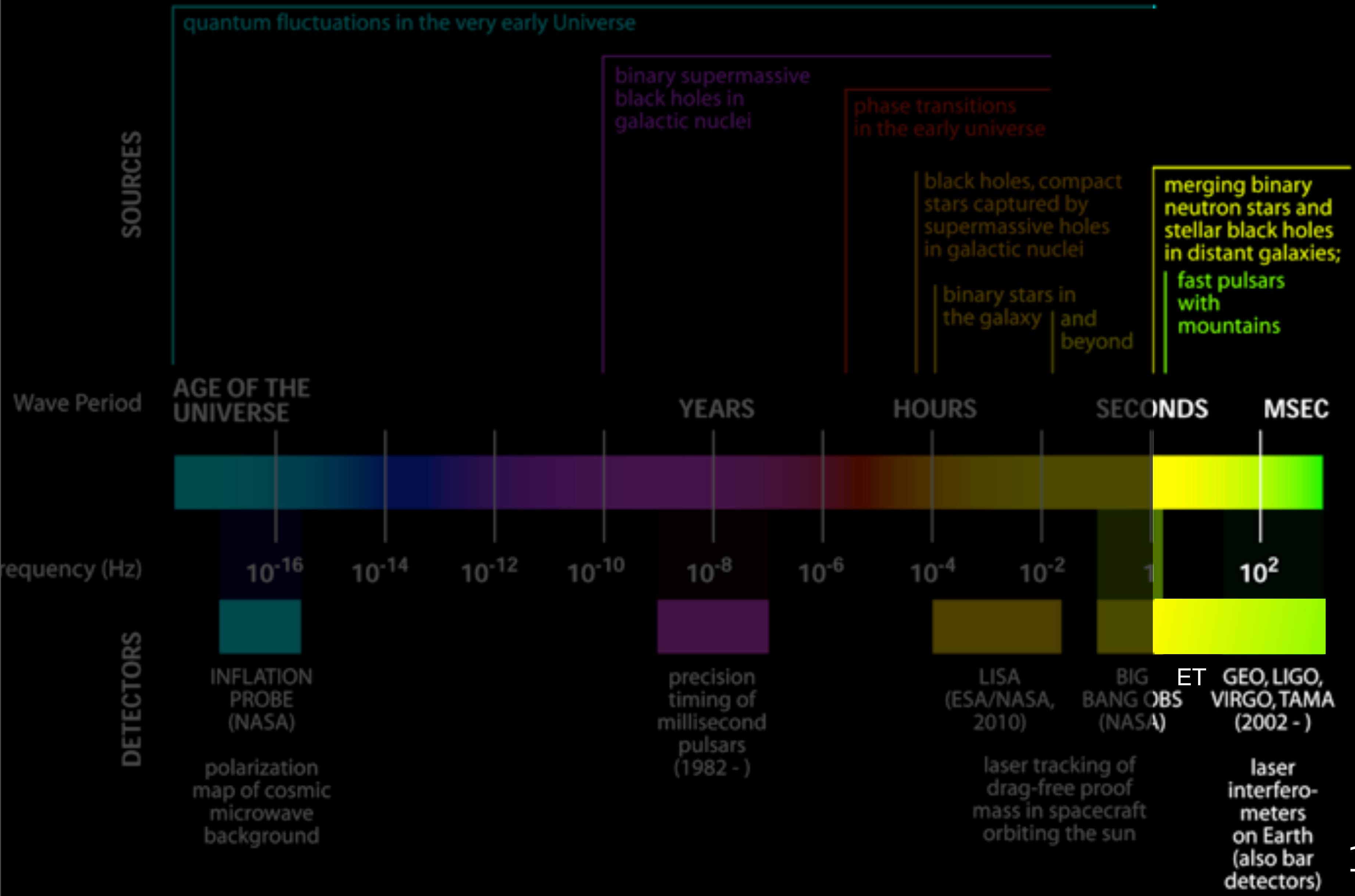
THE GRAVITATIONAL UNIVERSE

A General Science Theme addressed by the *eLISA* Survey Mission observing the entire Universe

Selected by ESA for L3 launch in 2034



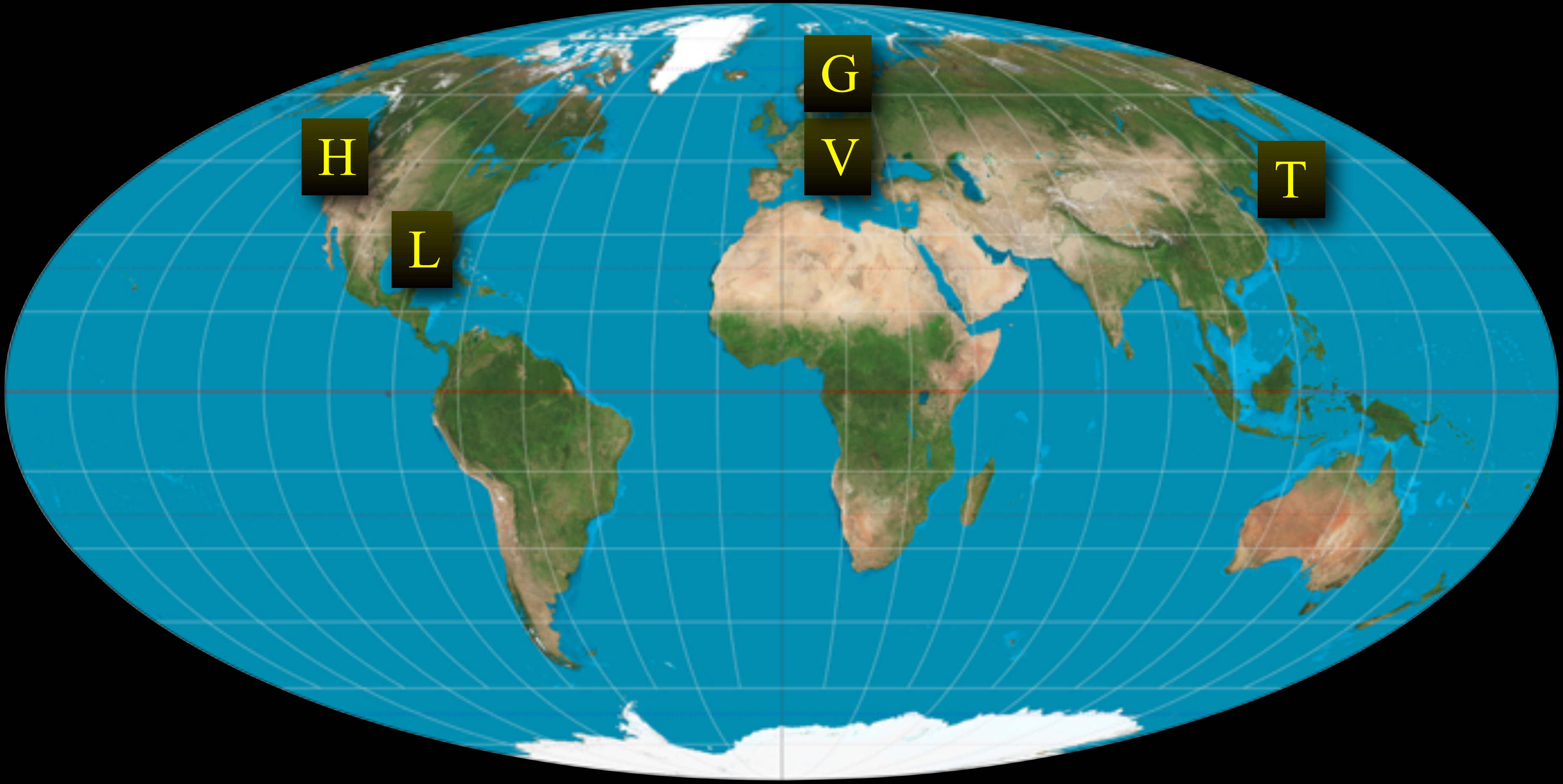
High Frequency



Initial Interferometers

Ca 2002–2010

Initial Interferometer Network



- 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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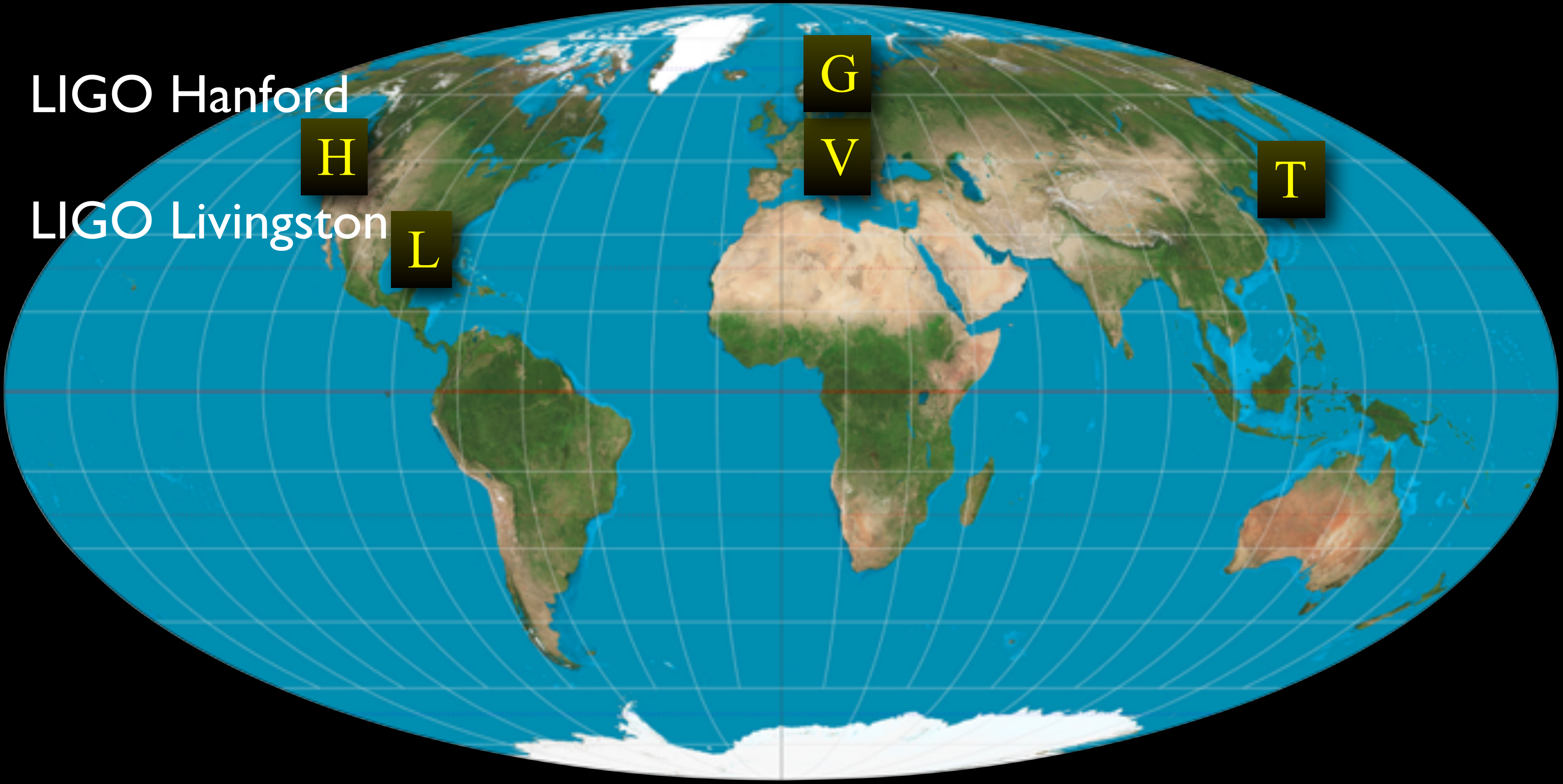

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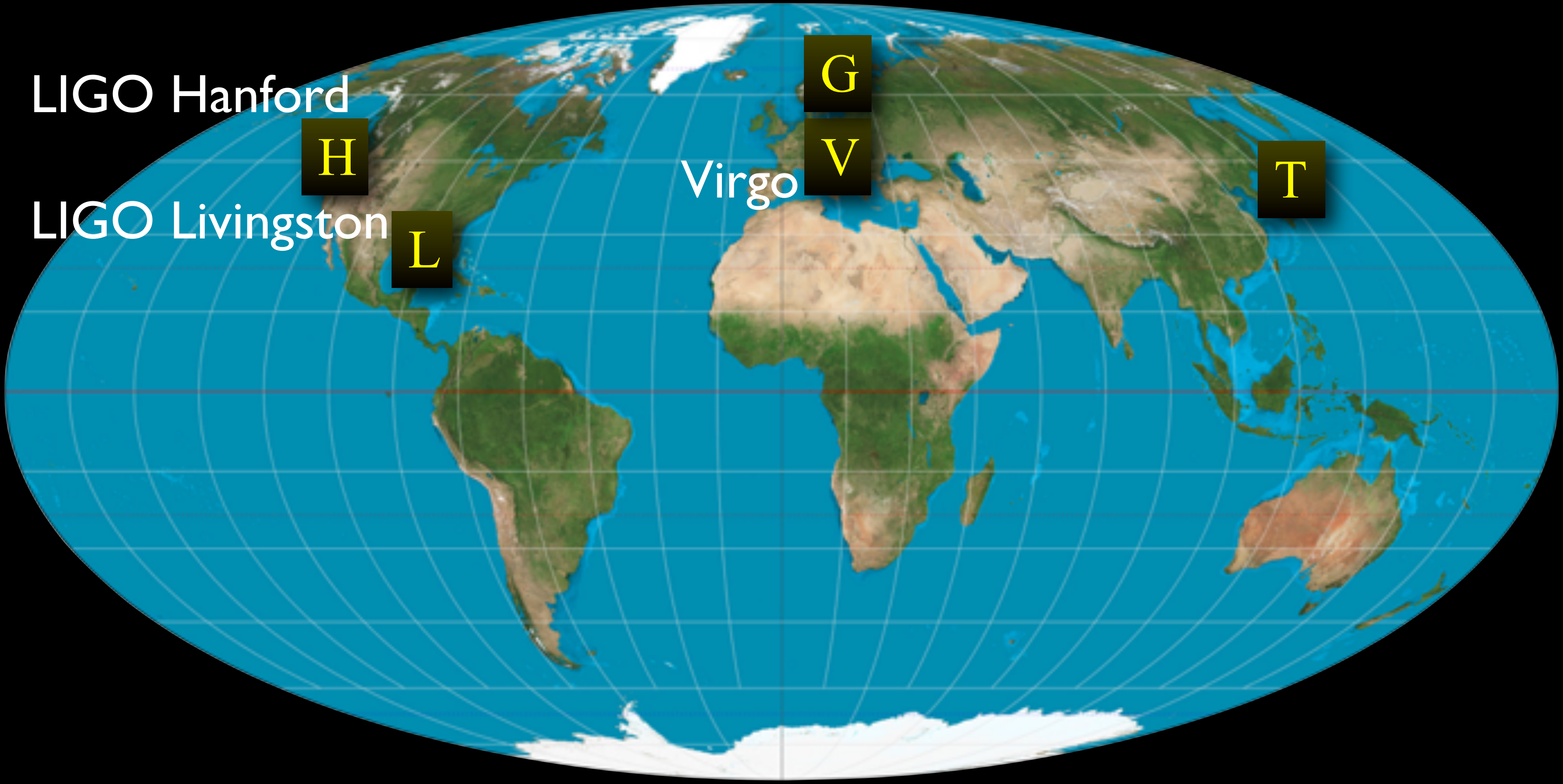

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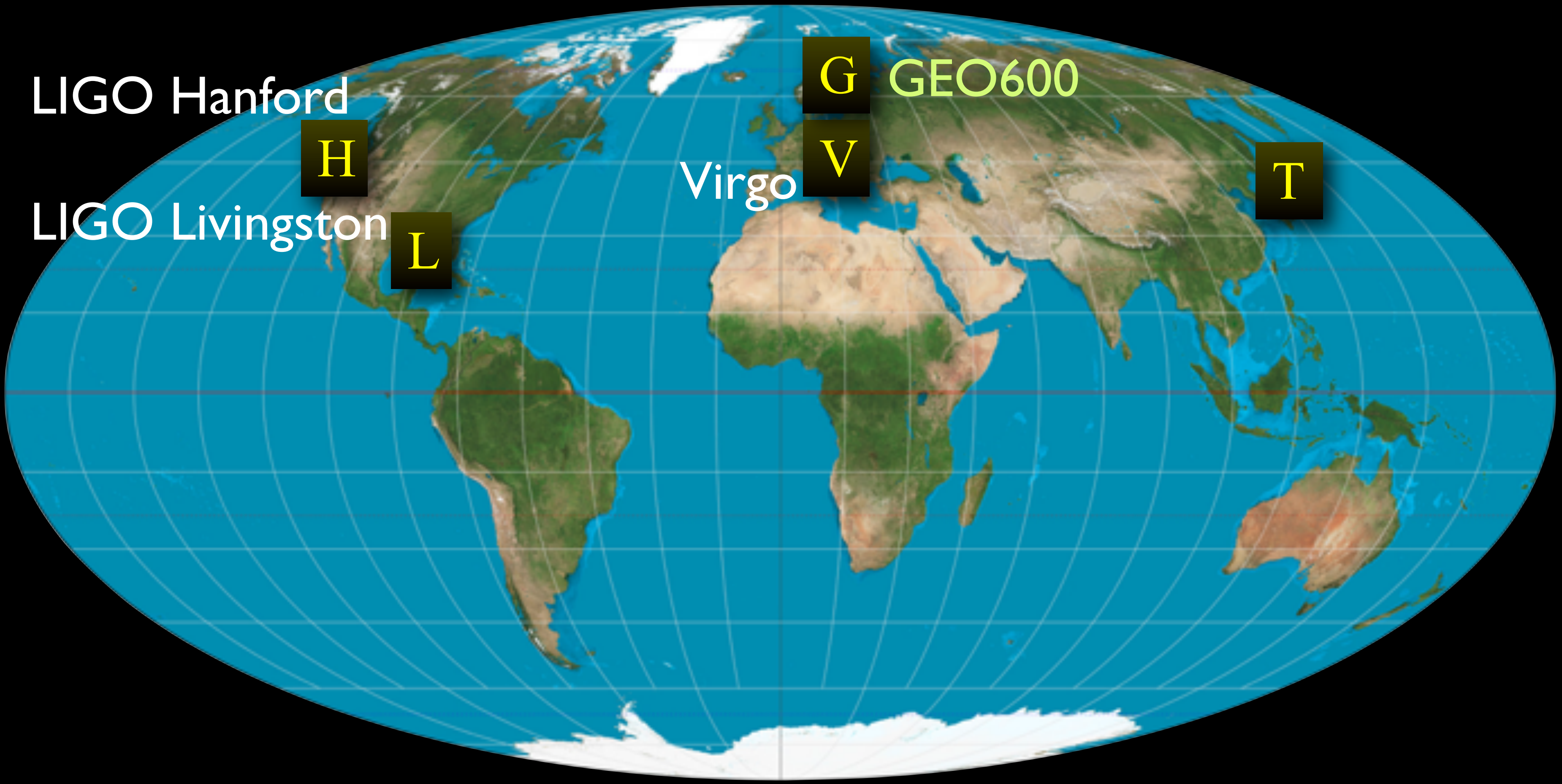

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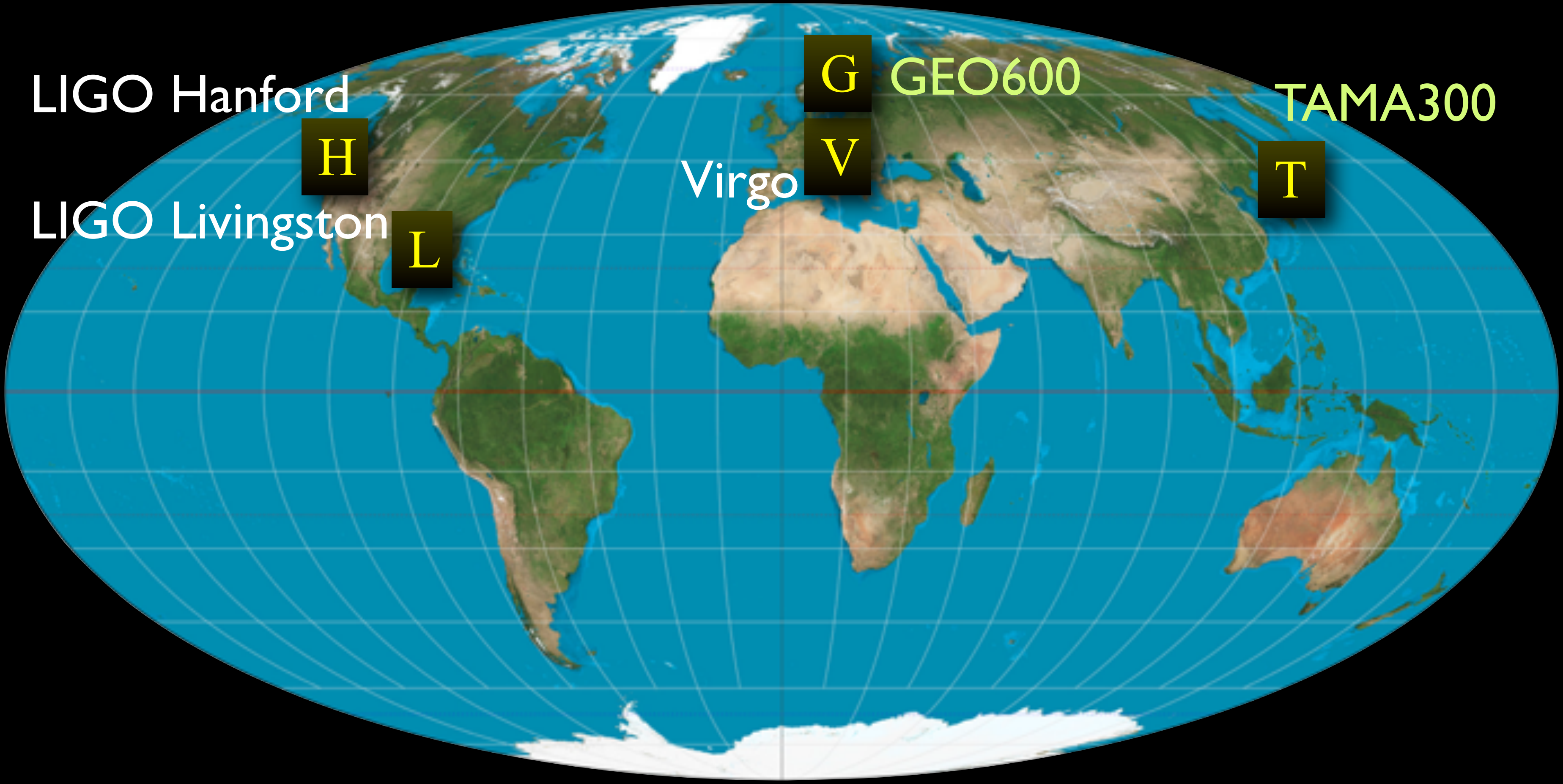

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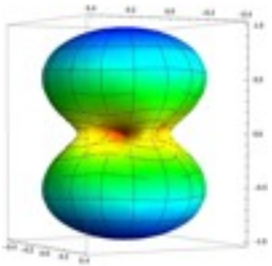
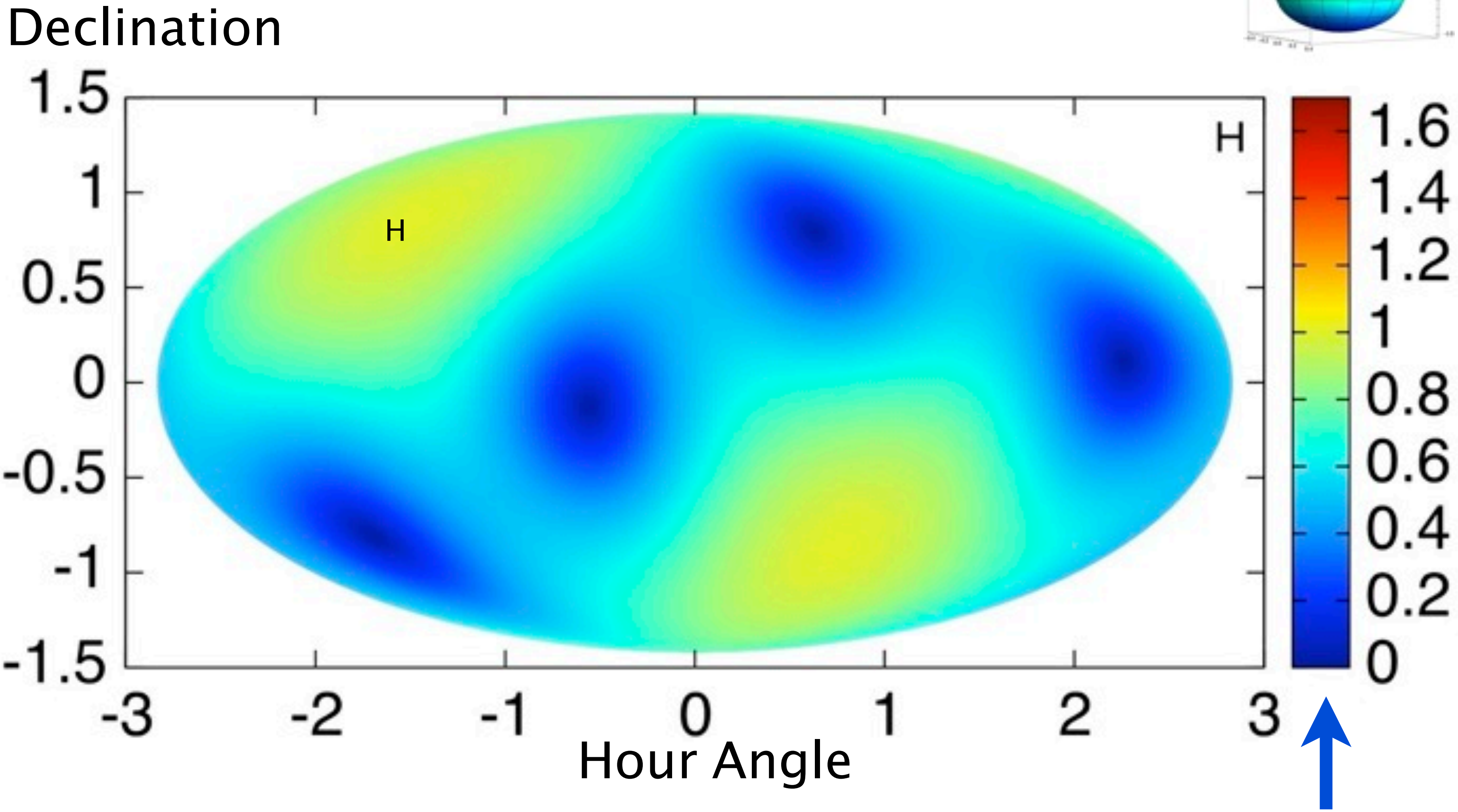
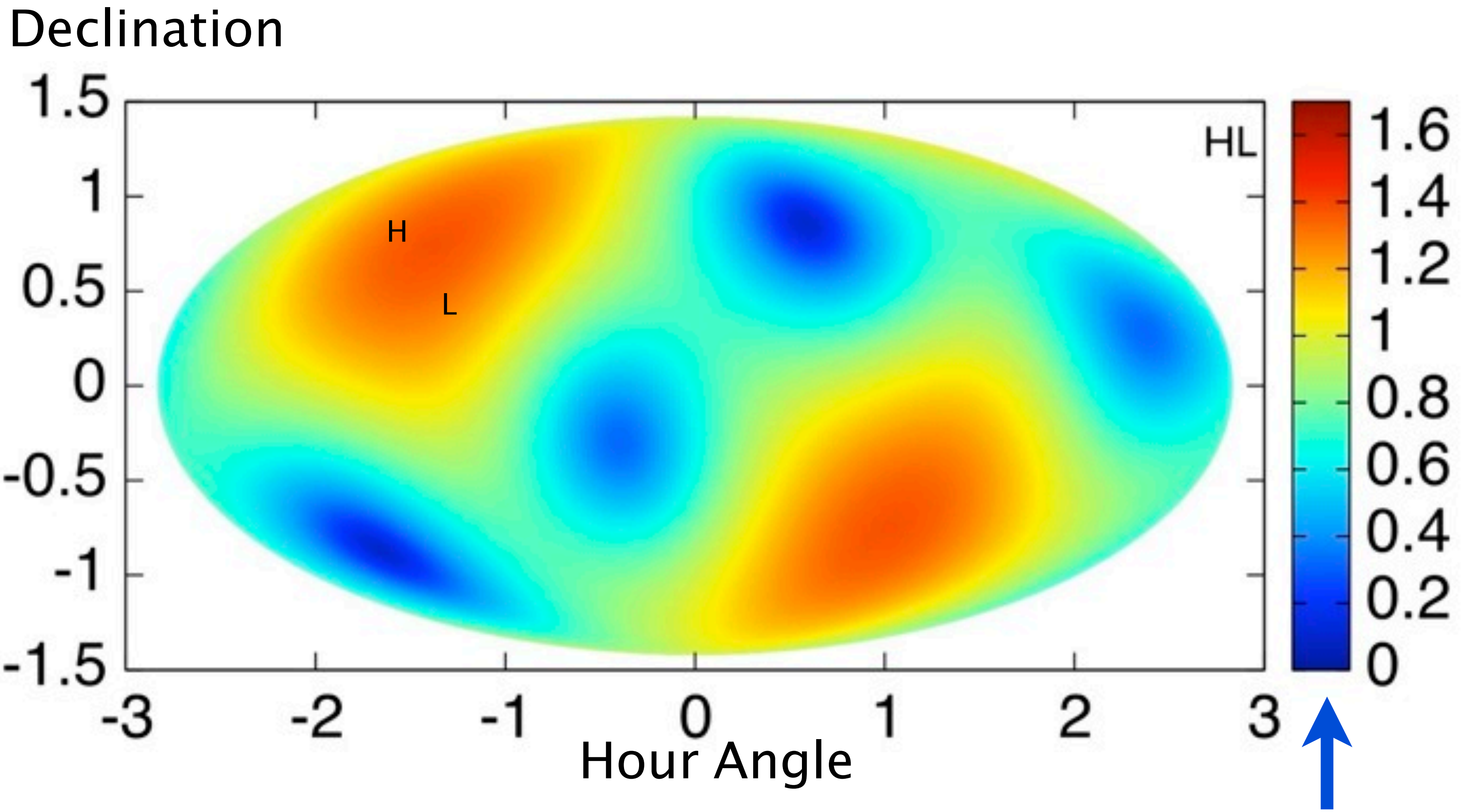
Sky CoverageLIGO_Hanford





Gives the distance reach in different directions relative to the maximum distance reach for sources overhead with respect to the interferometer

Sky Coverage of HL



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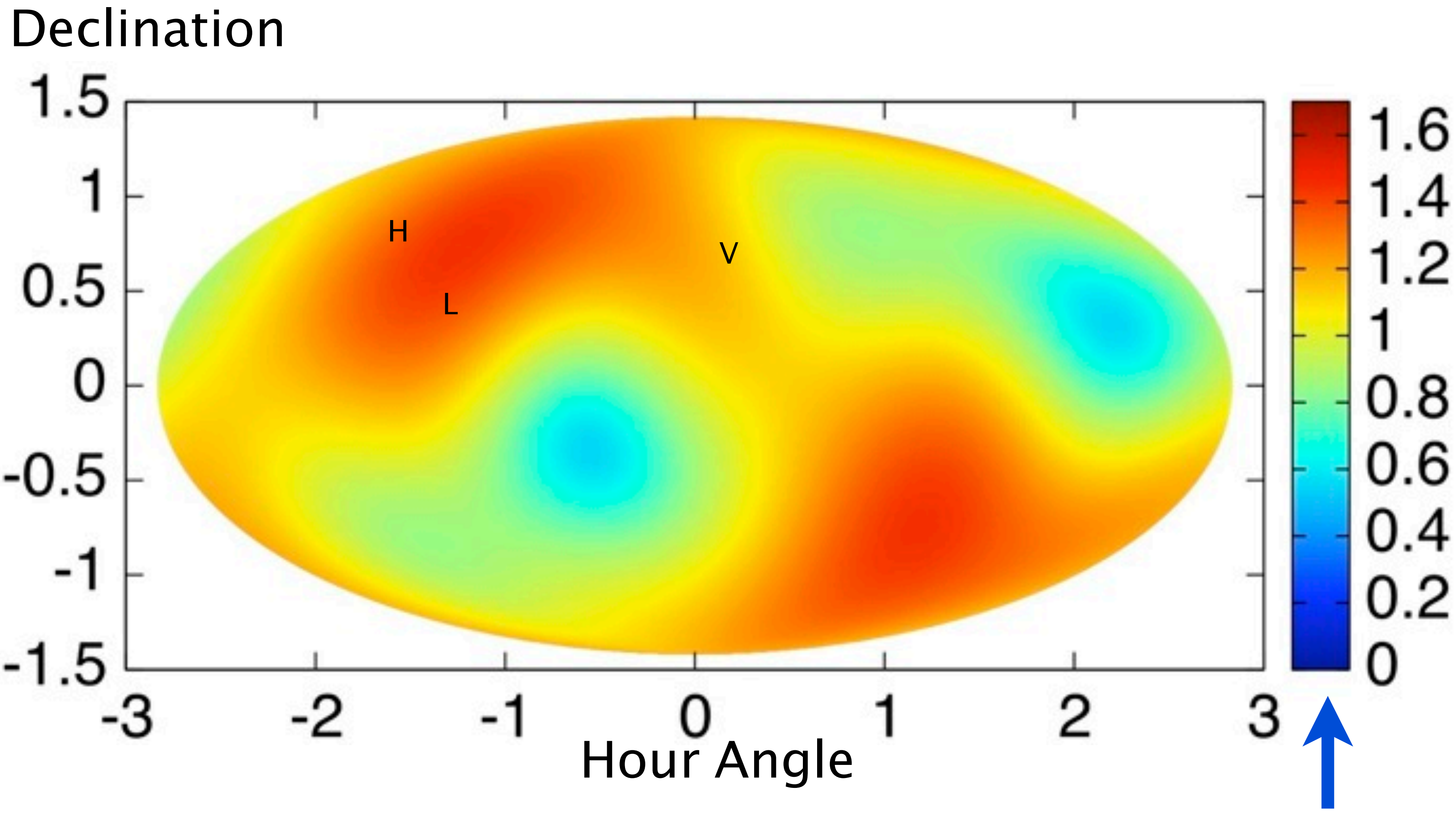
Sky Coverage of HLV



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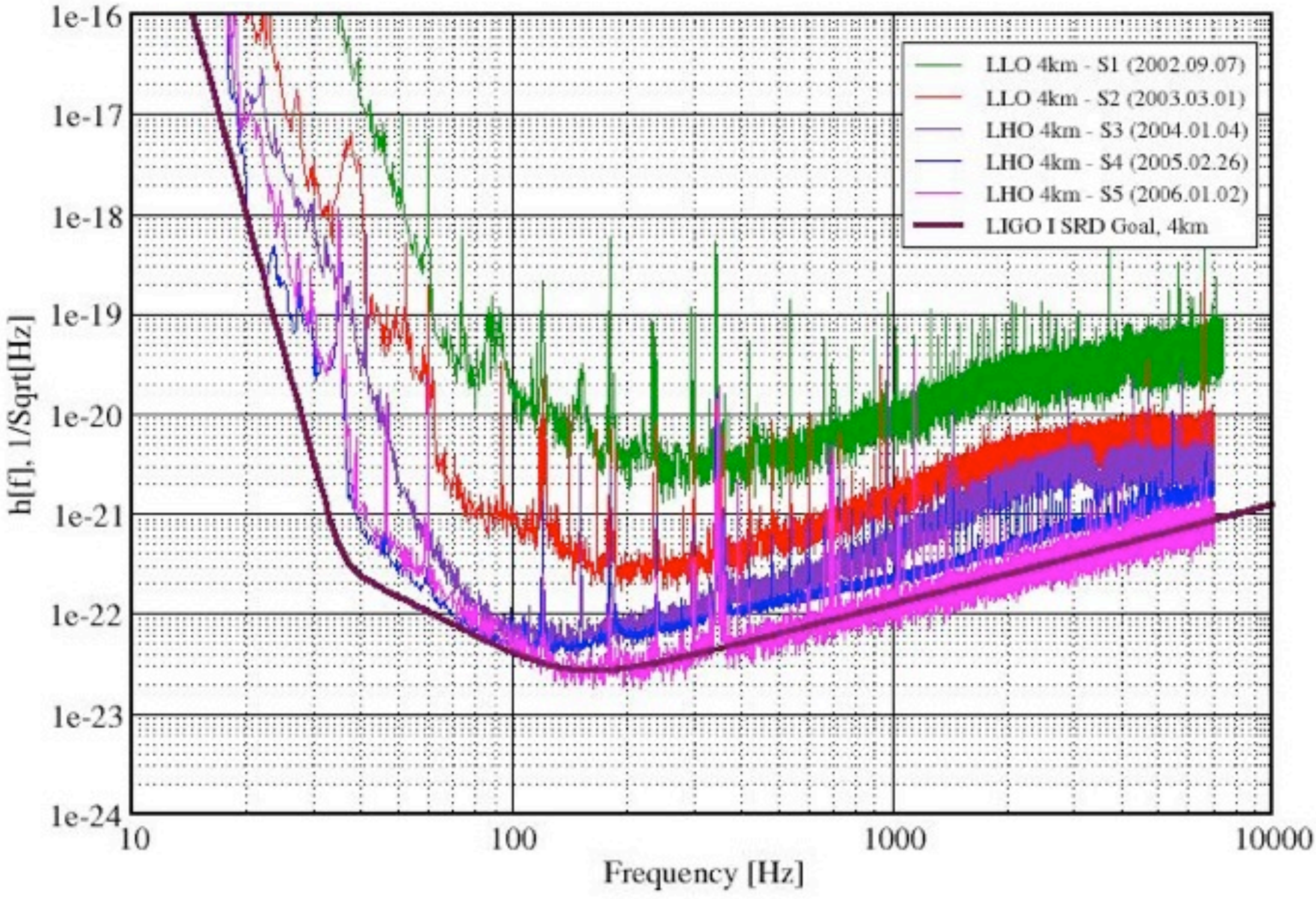
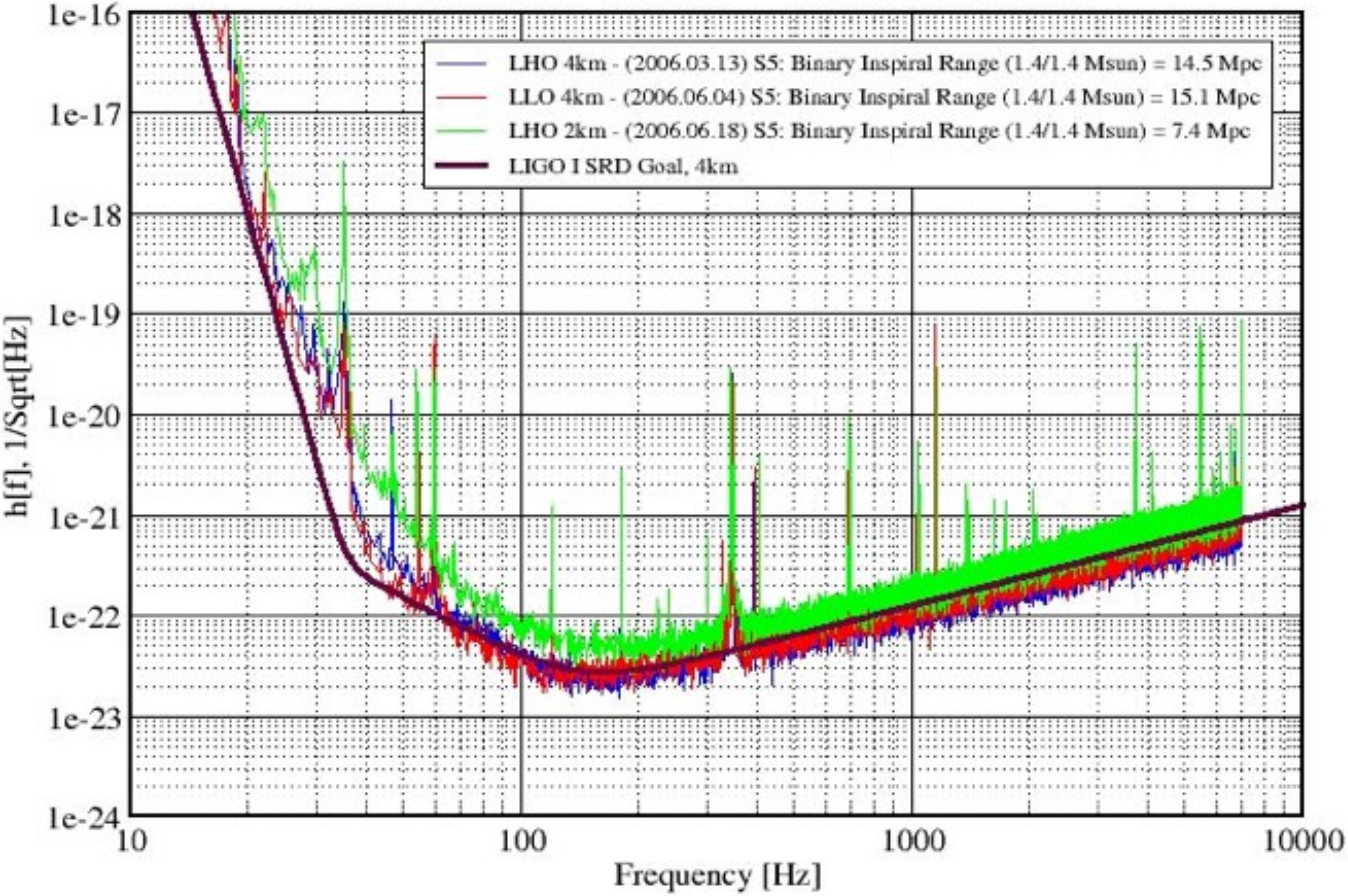
Initial LIGO / Virgo Sensitivity

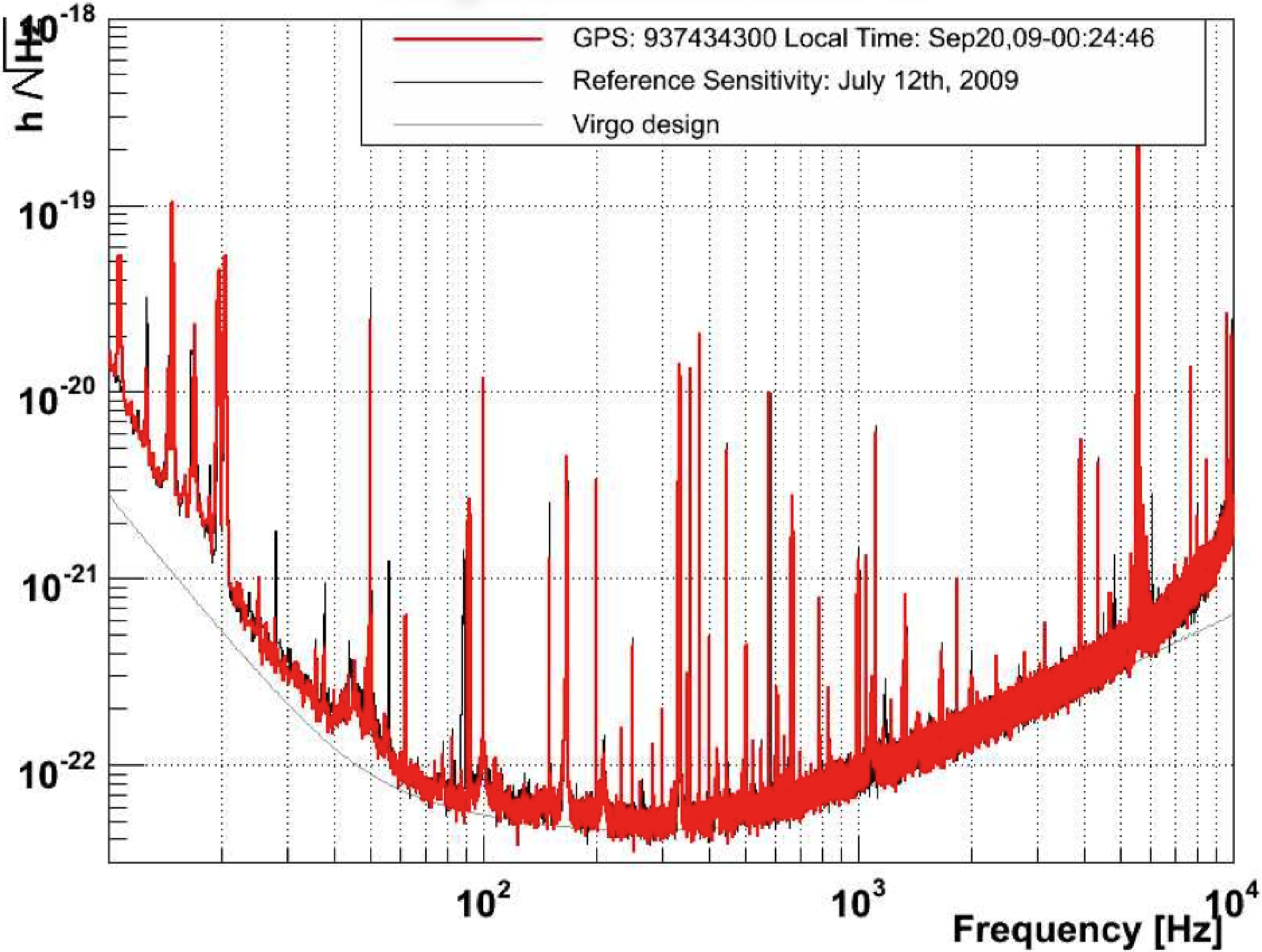
Initial LIGO Sensitivity 2002–2006



Design goal reached in 2006



Virgo Science Run_2

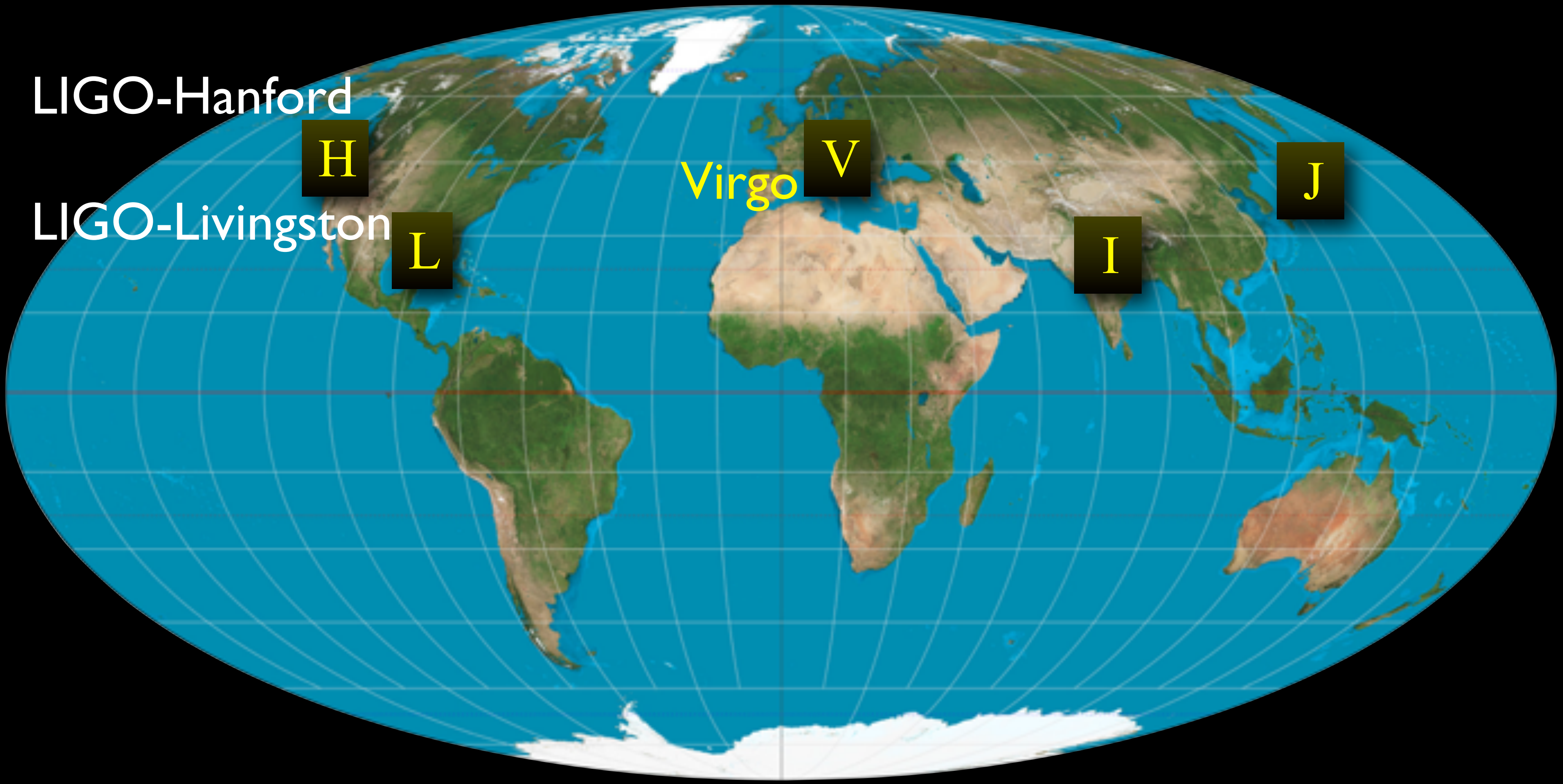


Highlights from initial detectors

- Beating the spin-down limit on the strength of gravitational waves from of the crab pulsar
  - Crab pulsar emits less than 1% of its rotational energy into gravitational waves
- Improved upper limits on the strength of stochastic backgrounds around 100 Hz
  - Better than BB nucleosynthesis limit
- Providing indirect evidence that certain extra-Galactic short GRBs are SGRs
  - First detection of a magnetar outside the Milky Way
- Follow-up of hundreds of short and hard gamma-ray burst events

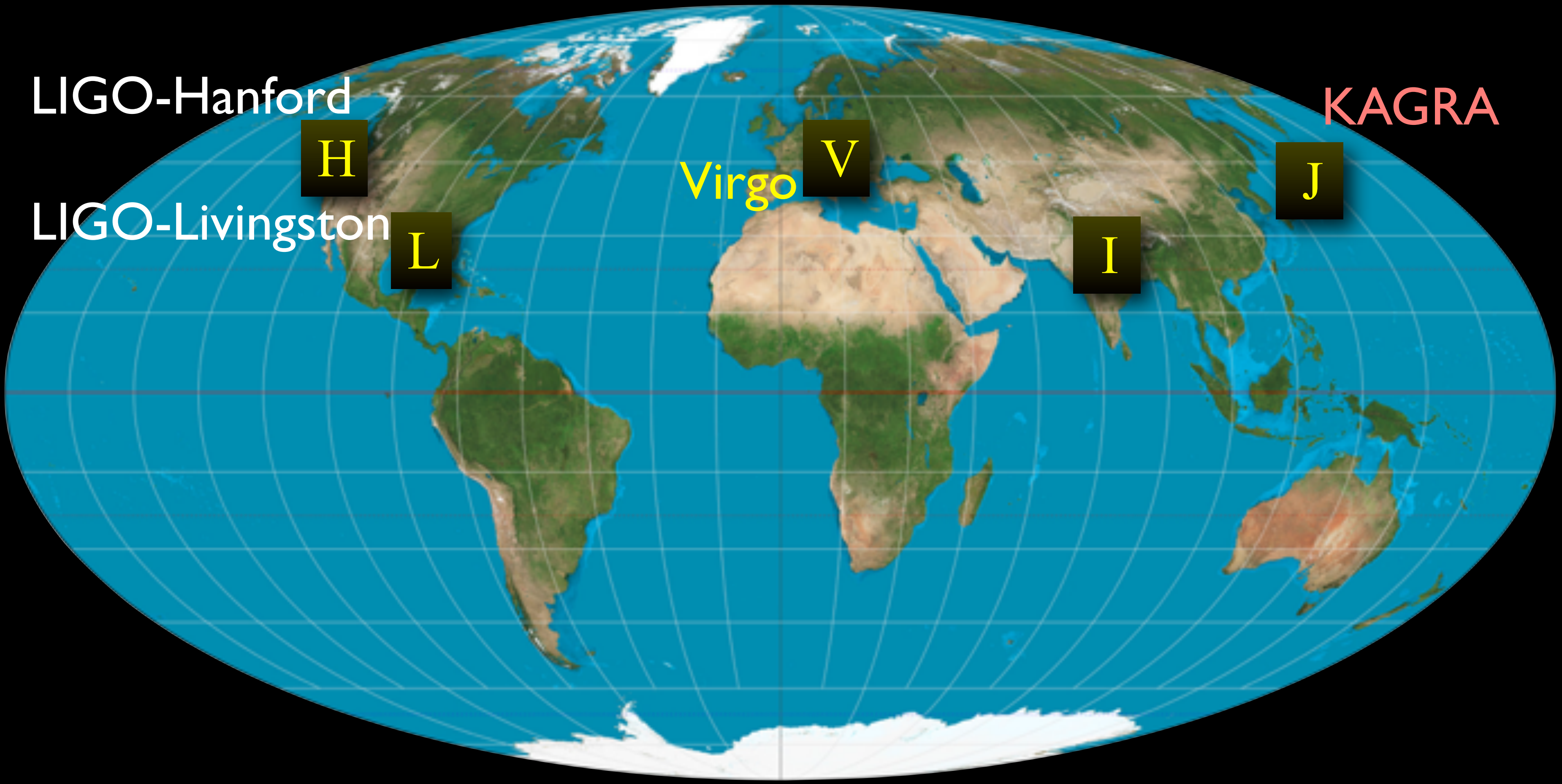
Advanced Detectors:
Ca 2015–2025

Advanced Detector Network



Between 2015–2022 five large detectors should become operational

Advanced Detector Network



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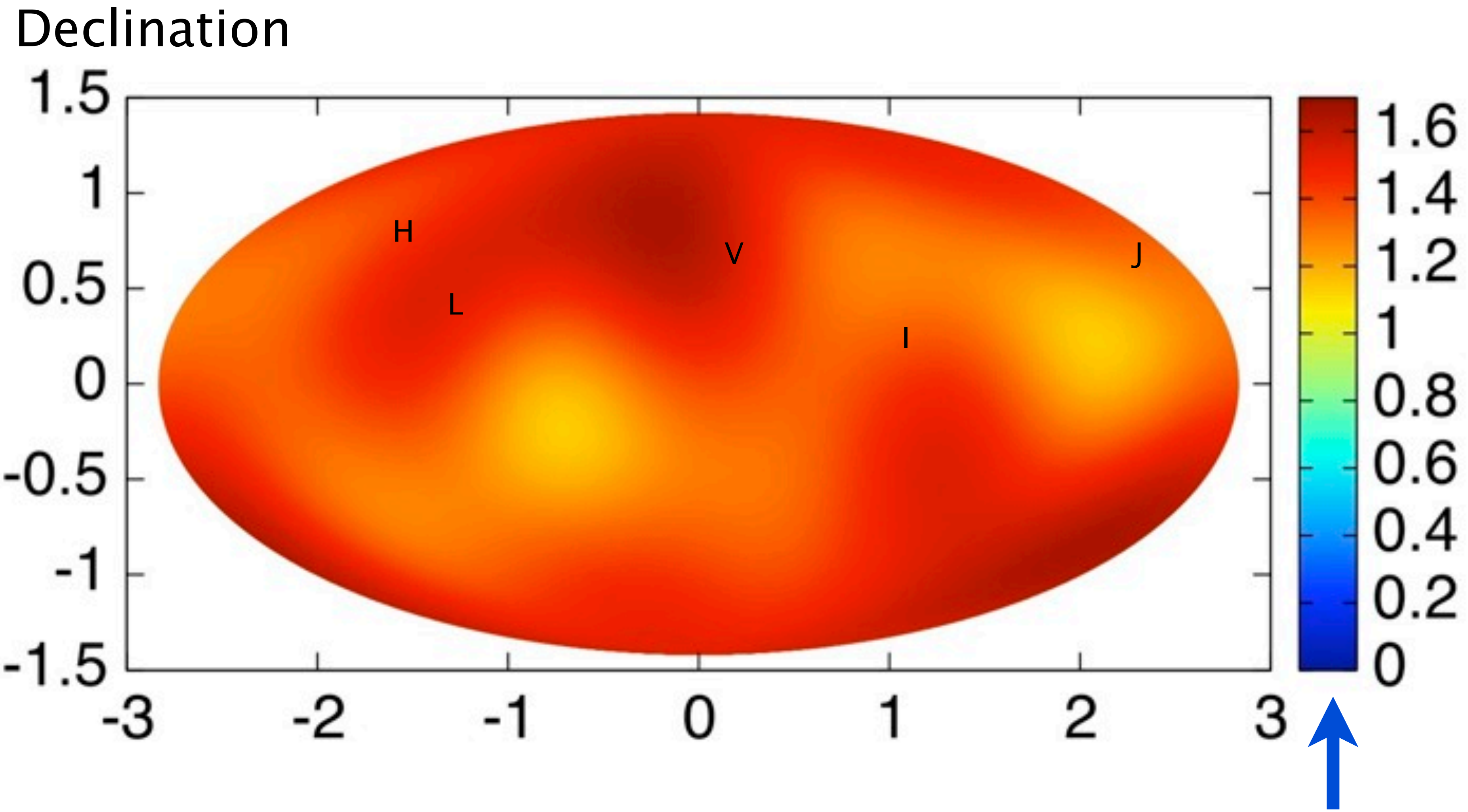

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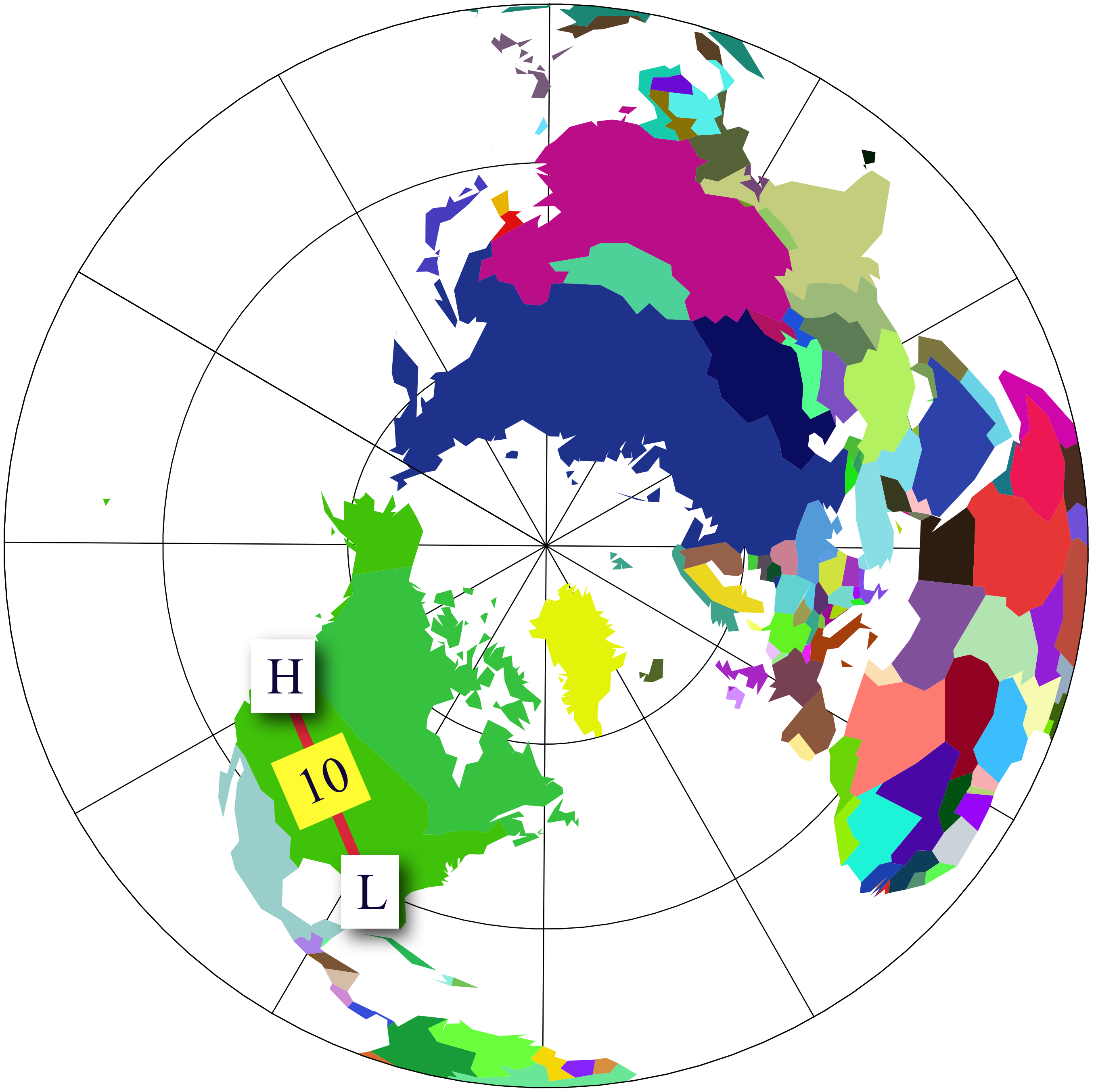
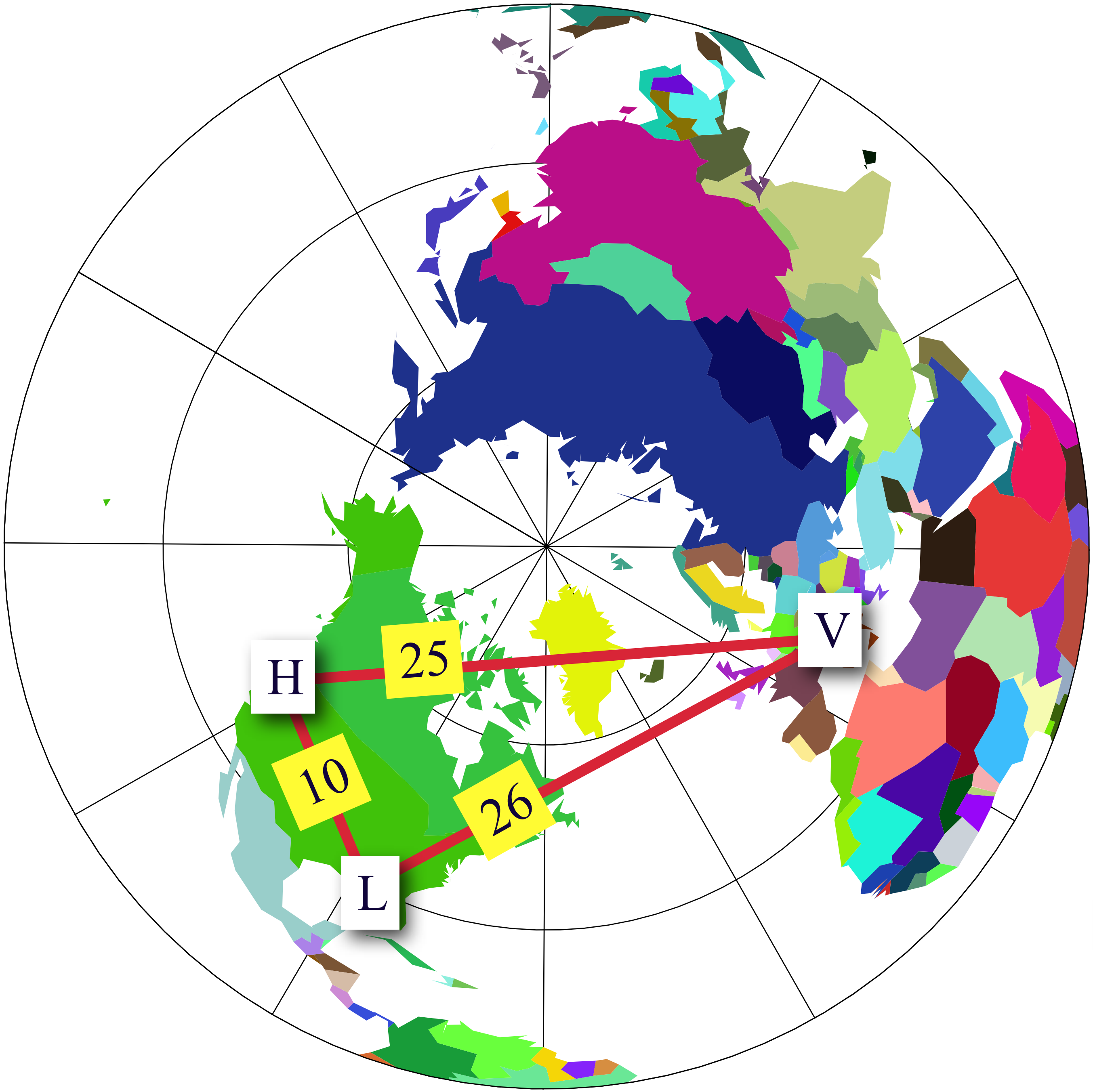
Detector Networks 2015-



Baselines

in light travel time (ms)

Detector Networks 2016-



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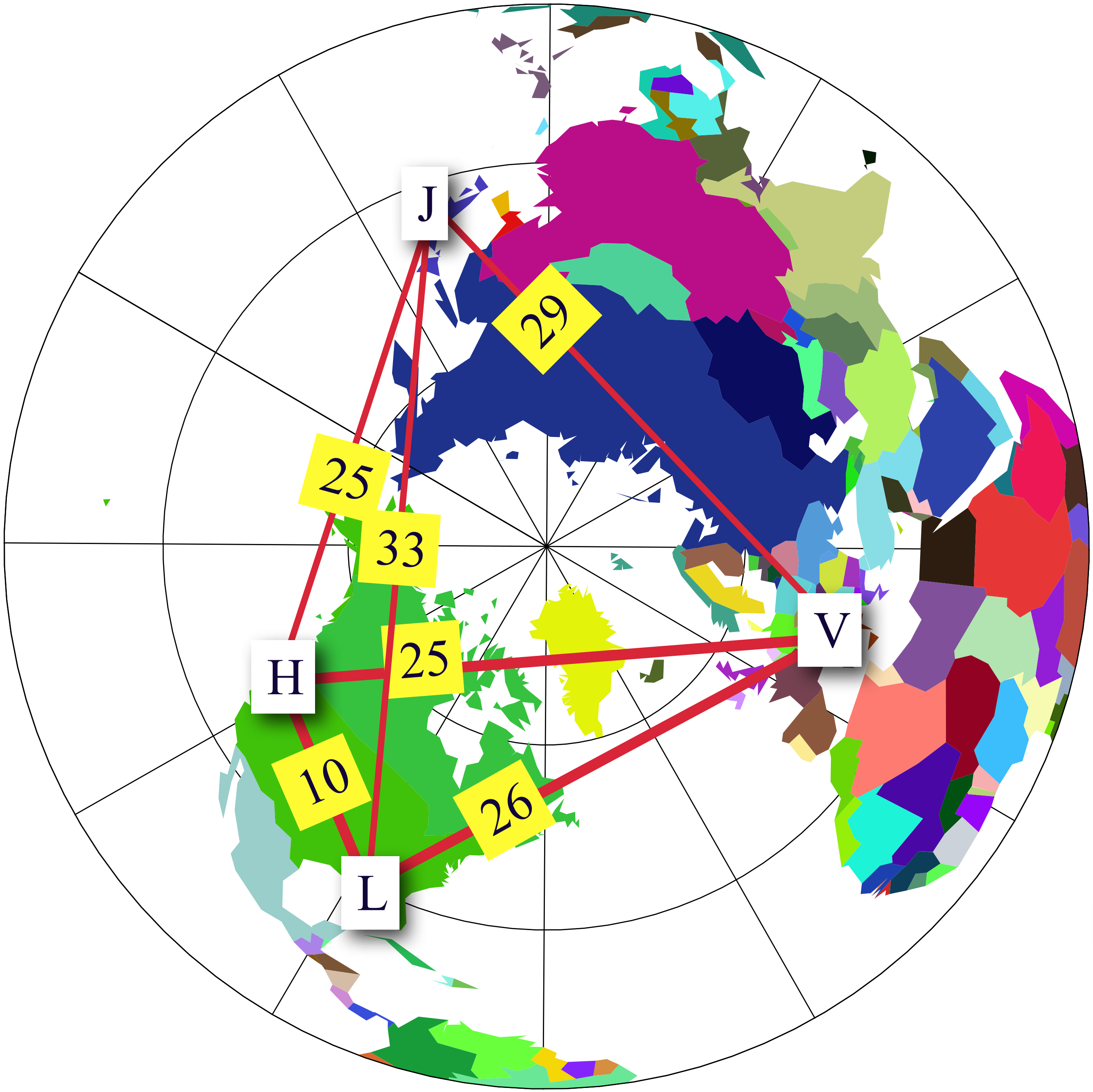

Detector Networks 2018-

Baselines

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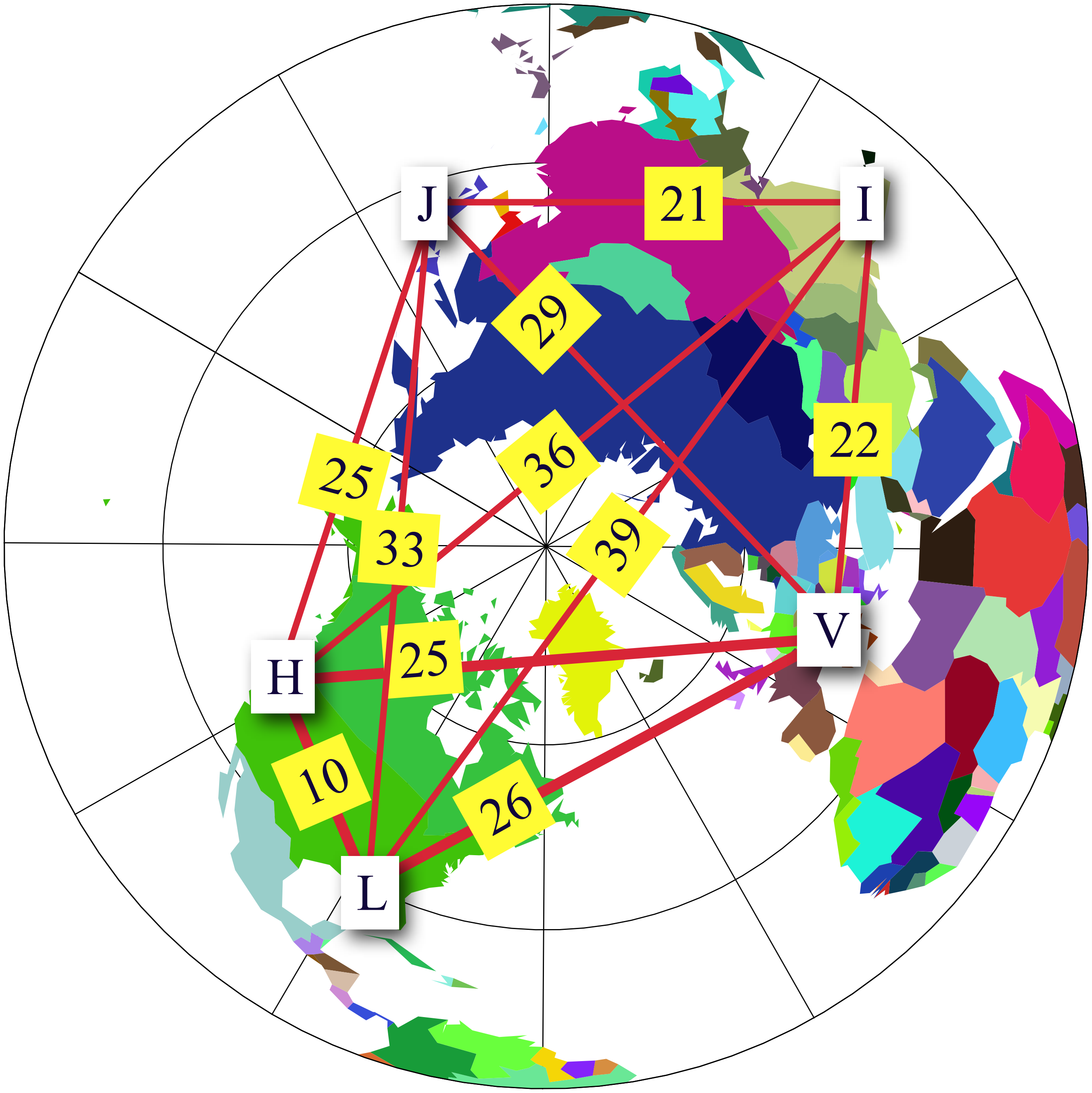
Detector Networks 2022-



Baselines

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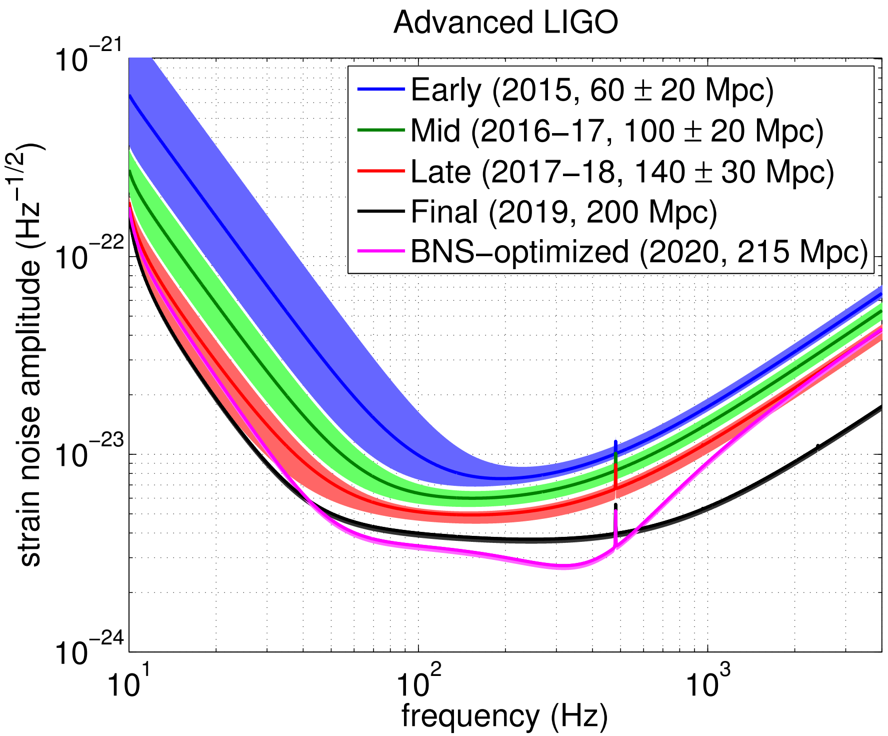
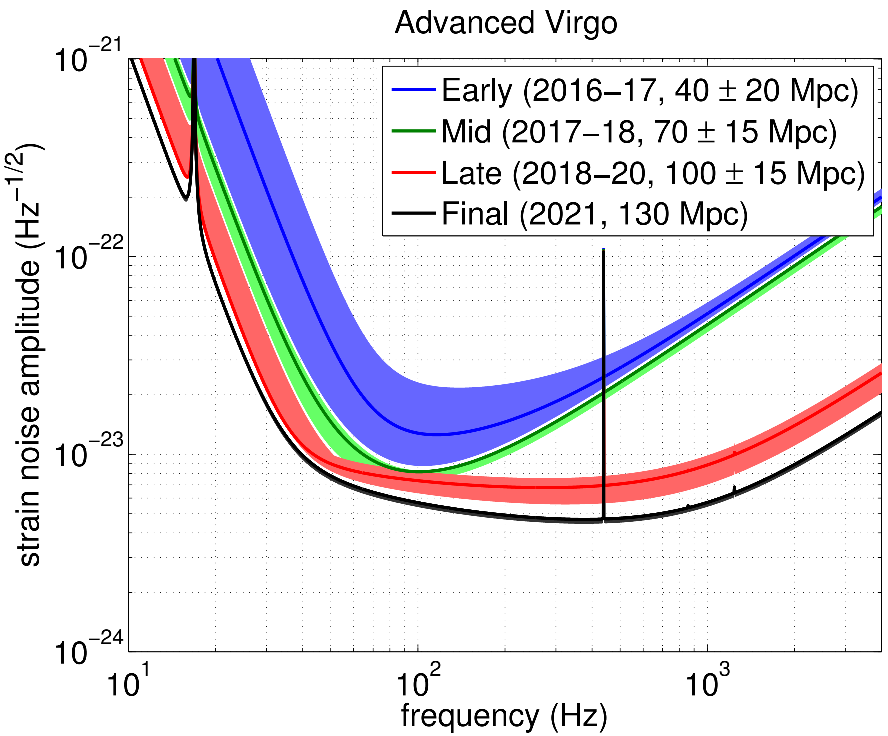
Advanced Detectors: Schedule and Sensitivity

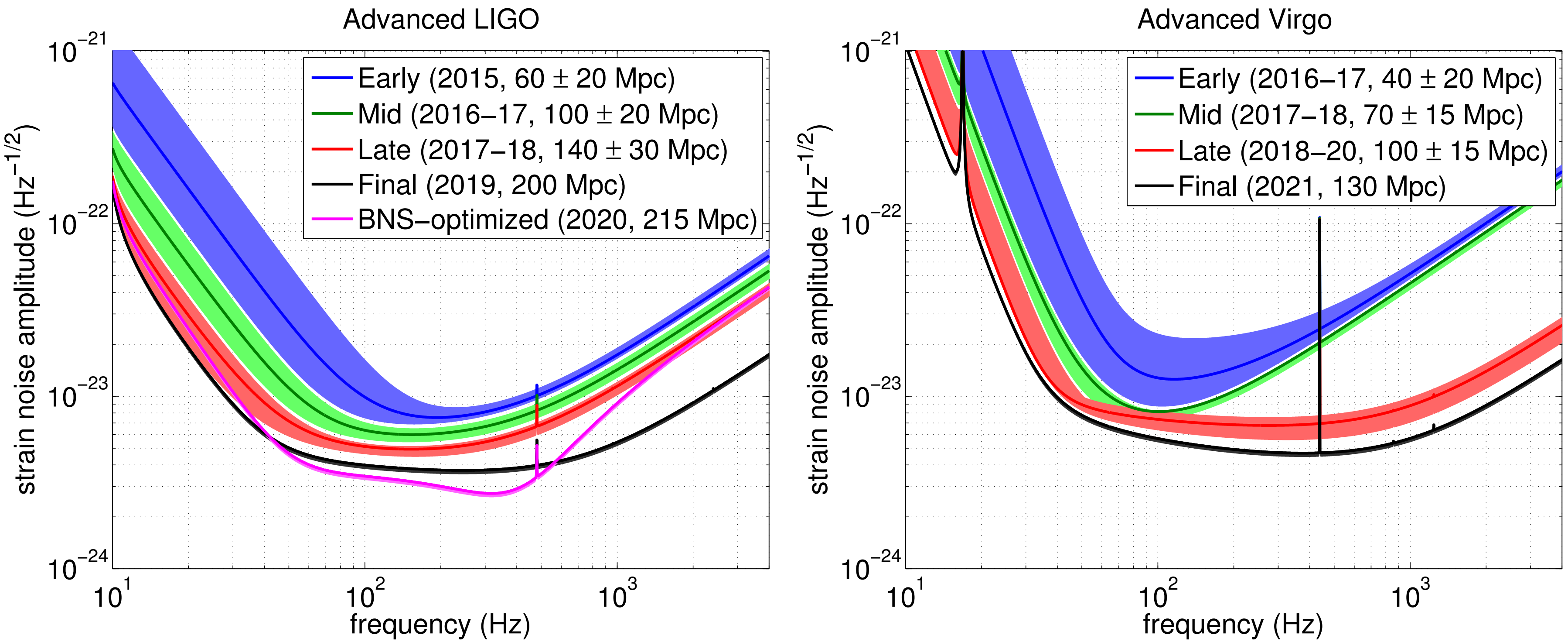




Epoch	Run Duration	BNS range (Mpc) LIGO	Virgo	Number of Detections	Median Area (deg^2)	% localized within 5 deg^2	20 deg^2
2015	3 months	60 ± 20	—	0.0004 - 3	2000	-	-
2016–17	6 months	100 ± 20	40 ± 20	0.006 - 20	70	2	15
2017–18	6 months	140 ± 30	70 ± 15	0.02 - 70	84	1	12
2019+	(per year)	200	100 ± 15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

Aasi et al 2013 (arXiv:1304.0670)

Advanced Detectors: Schedule and Sensitivity



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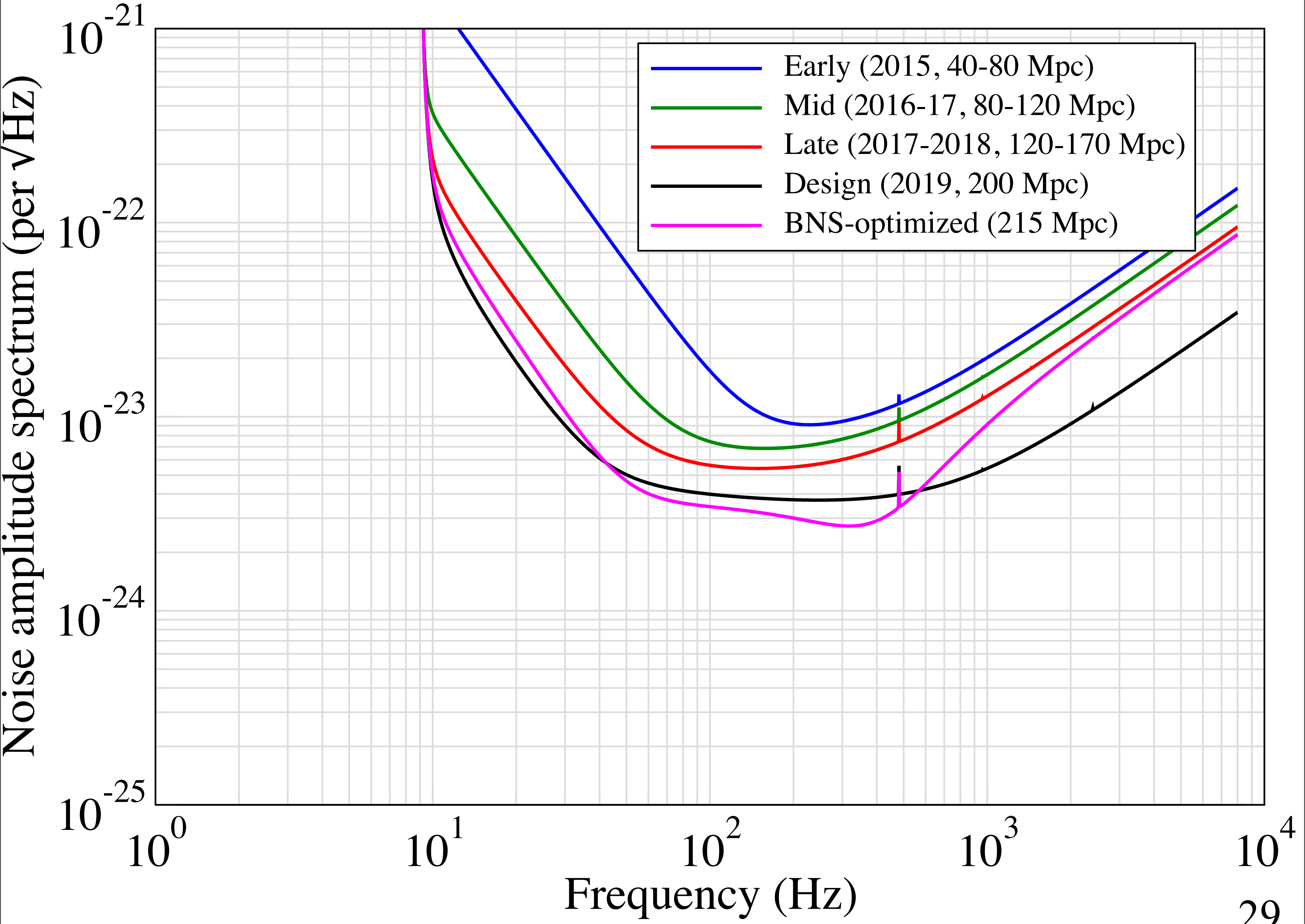
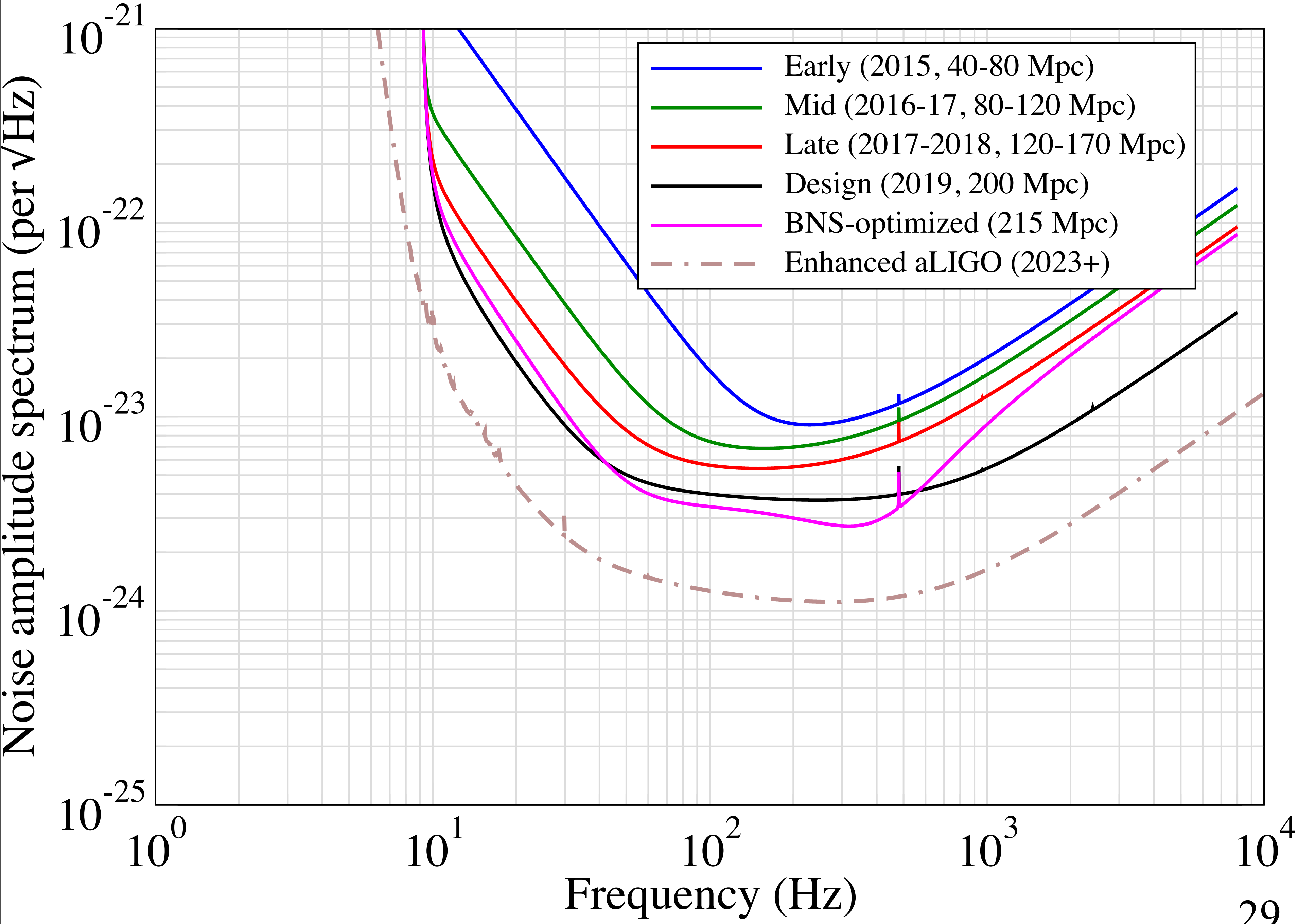


Early (2015, 40-80 Mpc)
Mid (2016-17, 80-120 Mpc)
Late (2017-2018, 120-170 Mpc)
Design (2019, 200 Mpc)
BNS-optimized (215 Mpc)
Noise amplitude spectrum (per √Hz)
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
Frequency (Hz)
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}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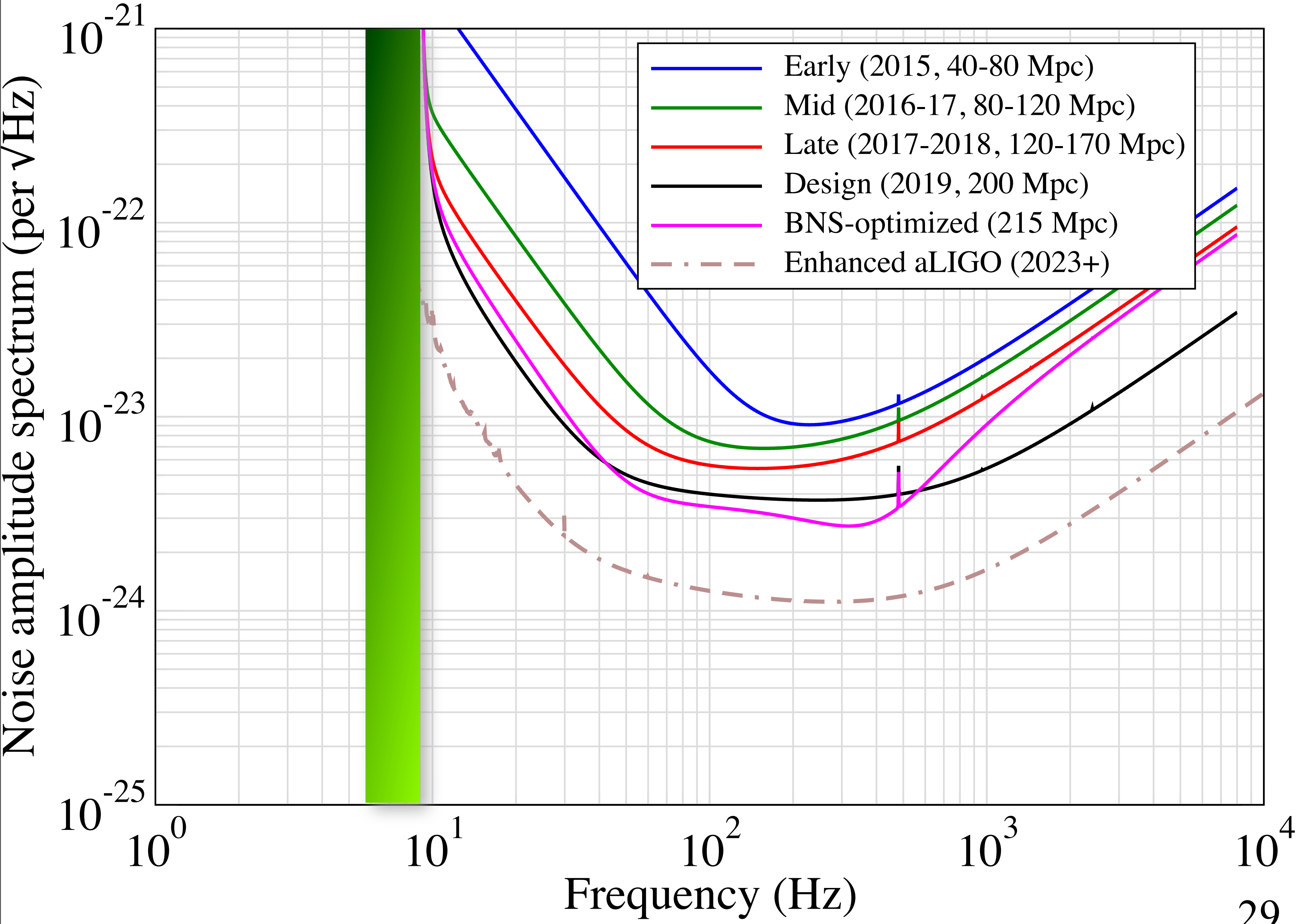
Enhanced aLIGO (2023+)



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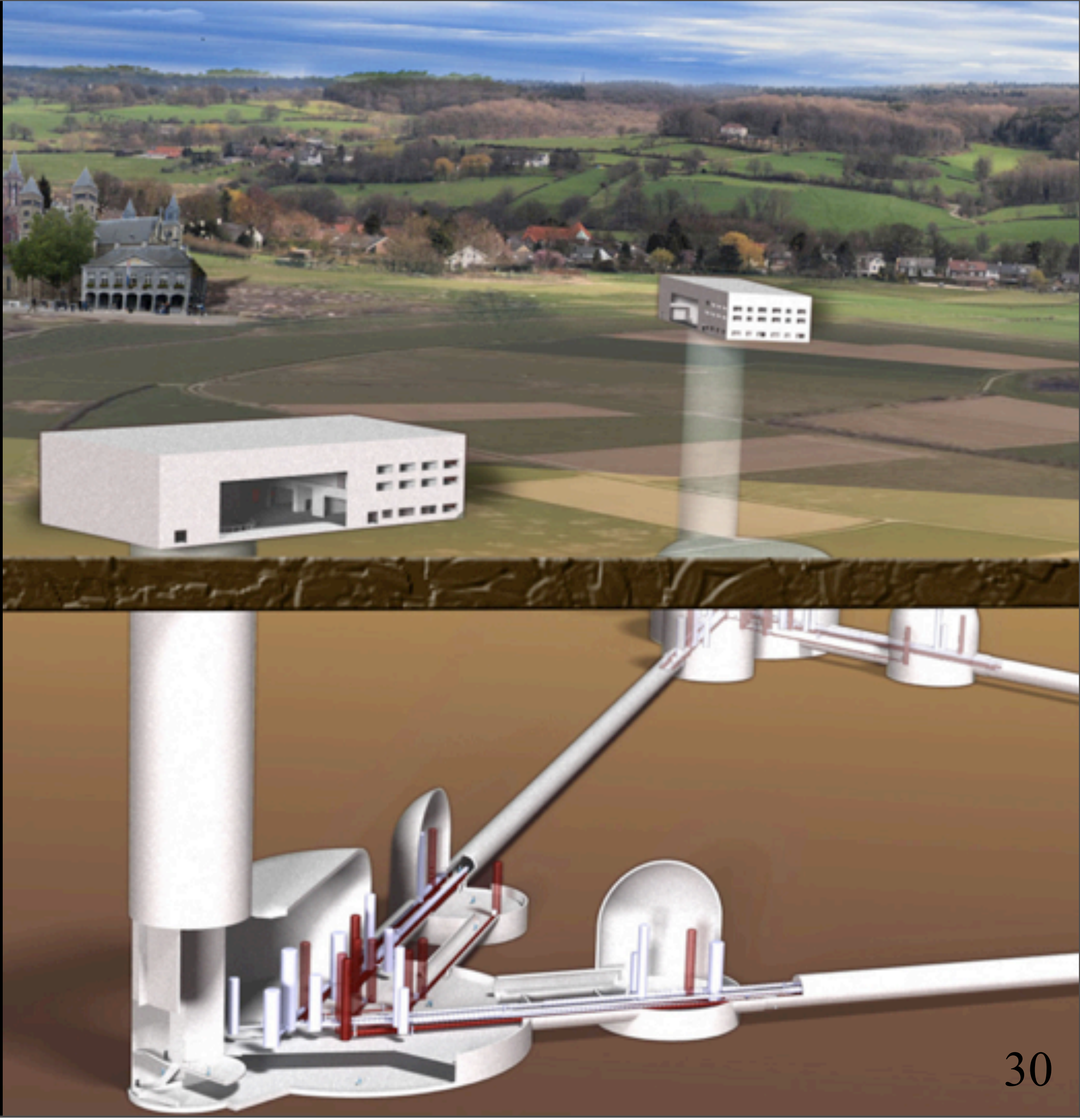
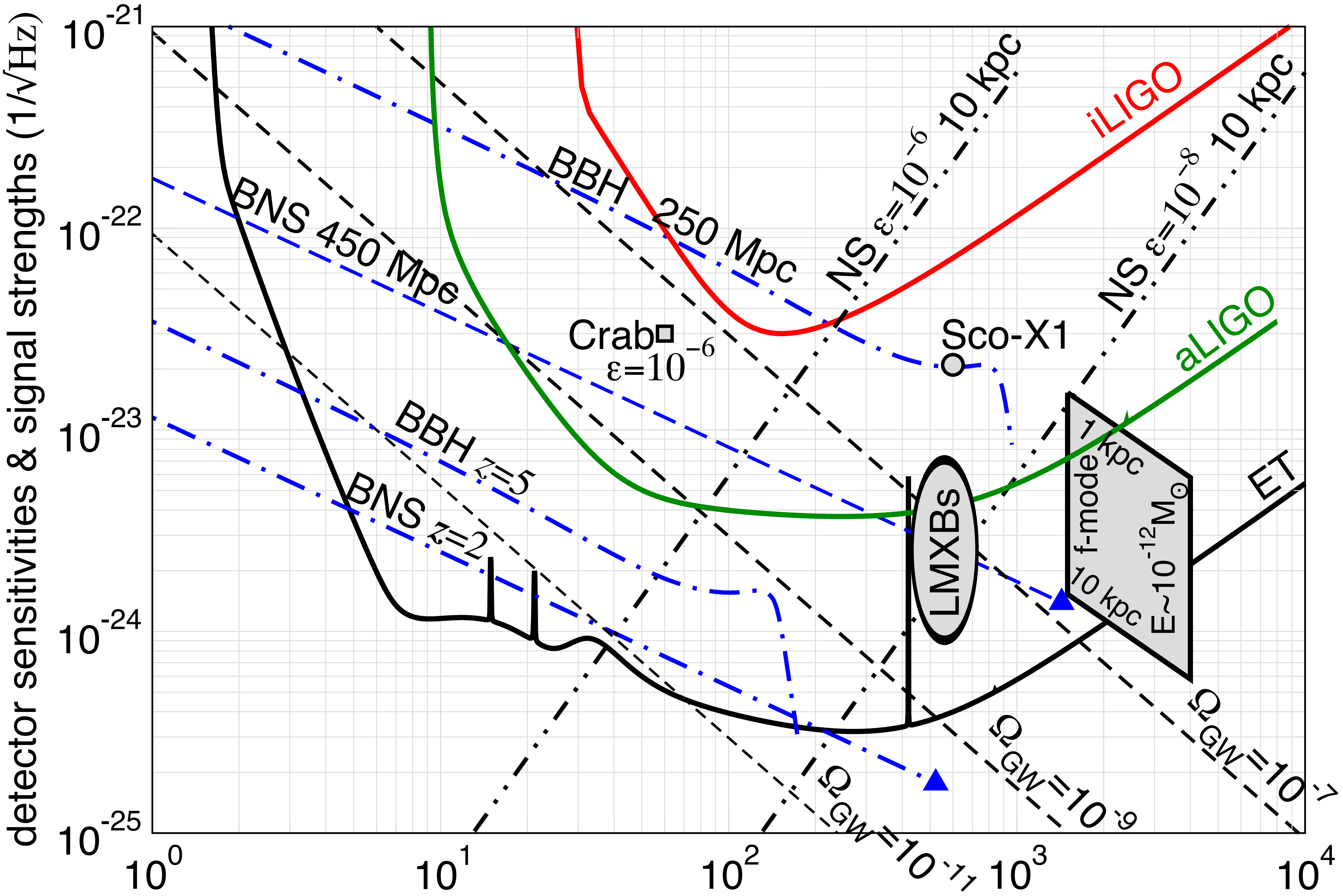
2008–2011
European
Conceptual
Design Study

2013–2016
ET R and D

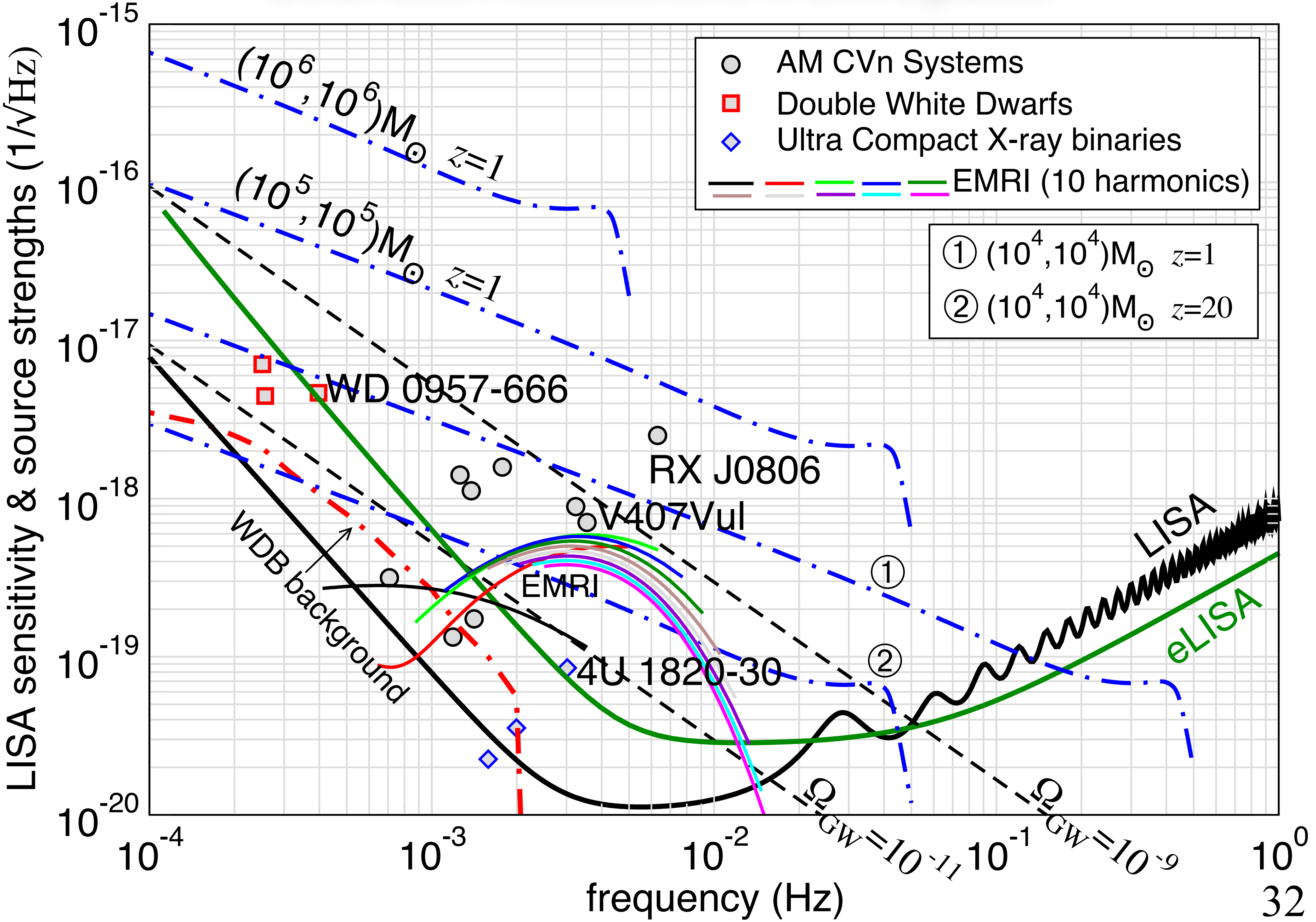
Underground
detectors
should have
Significant
reduction in
gravity
gradient noise



Sources Accessible to Ground

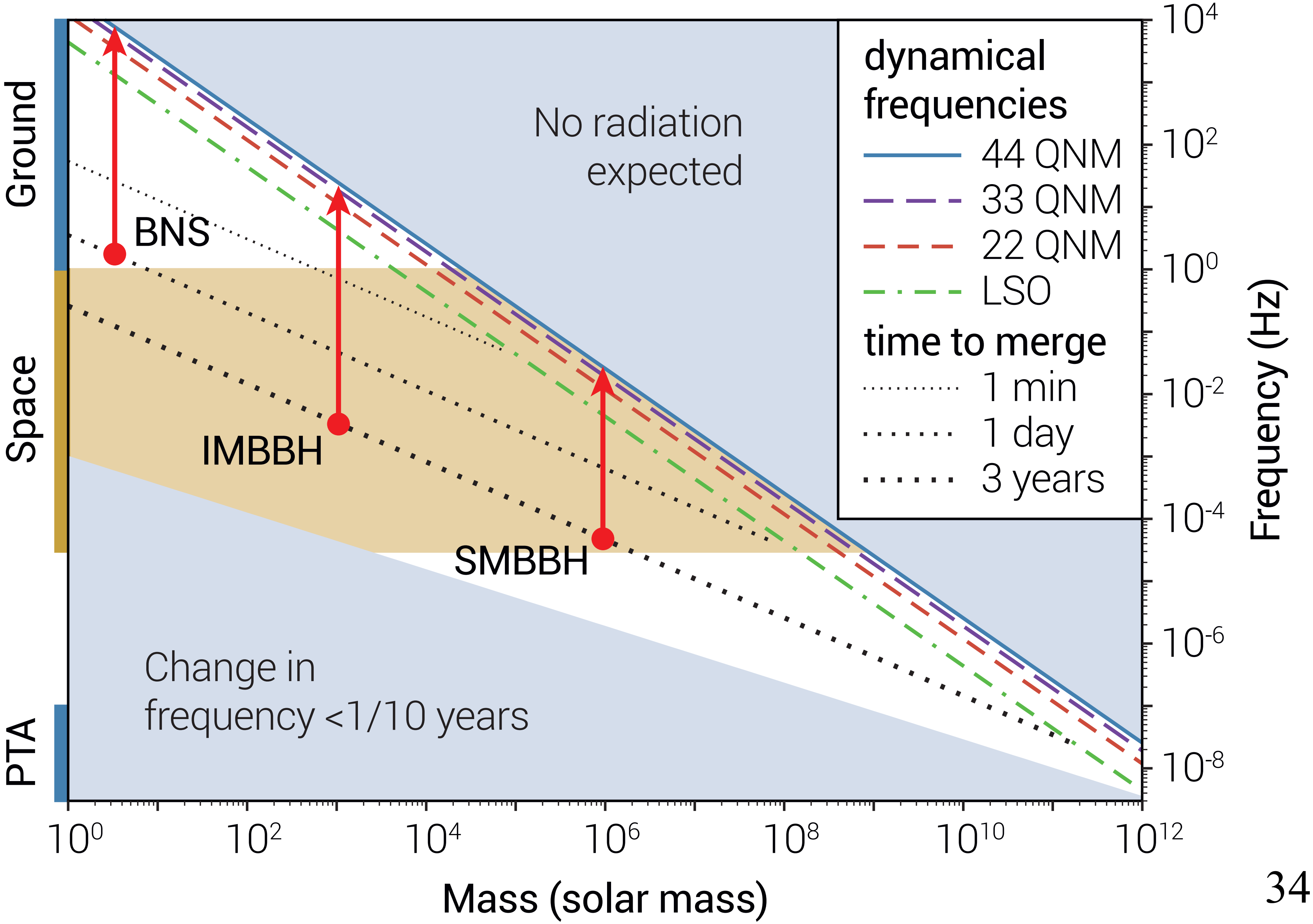


Sources Accessible from Space



Binary Inspiral Sources of Gravitational Waves

Frequency_Mass Diagram For Compact Binaries



Binary inspiral sources of gravitational waves

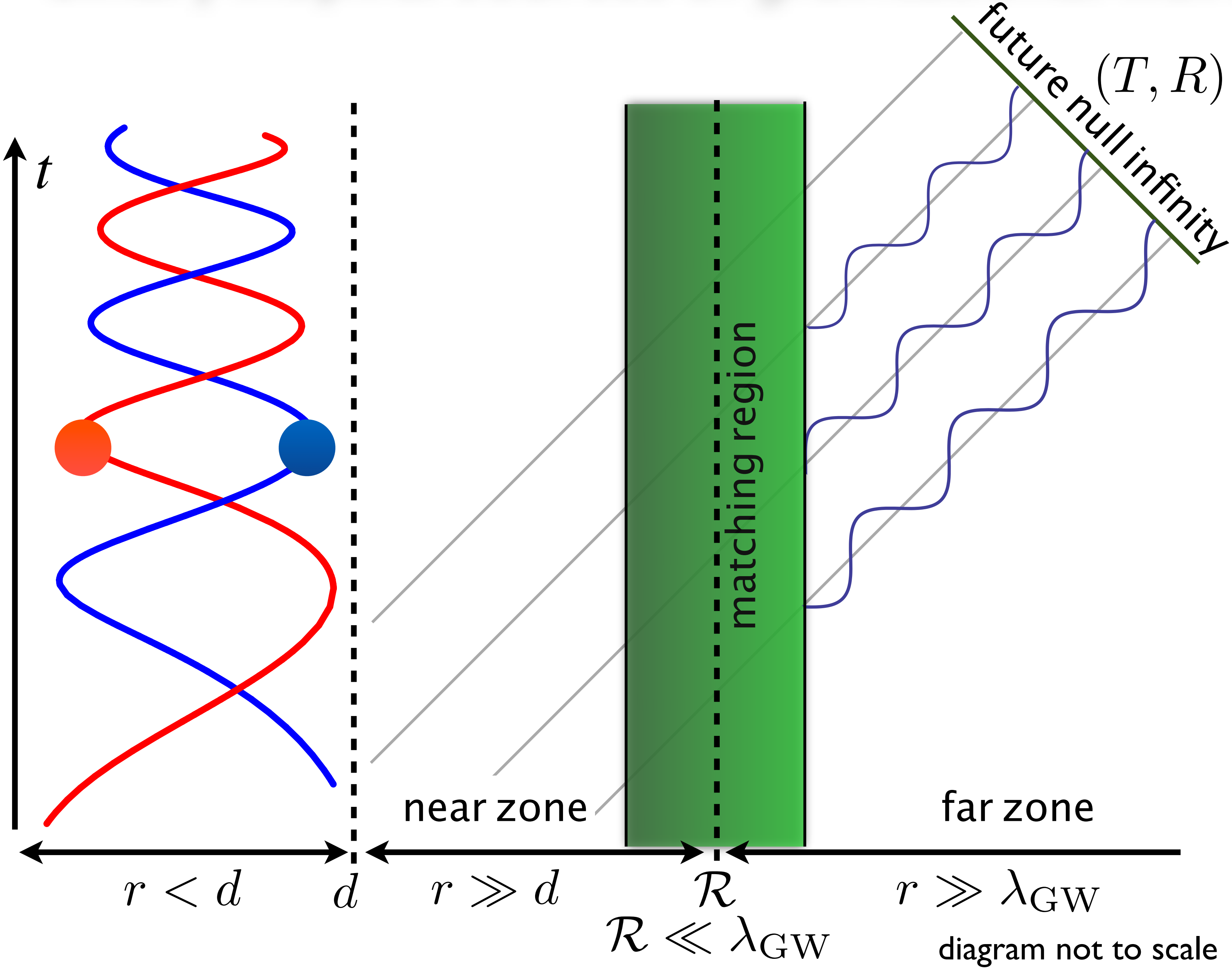
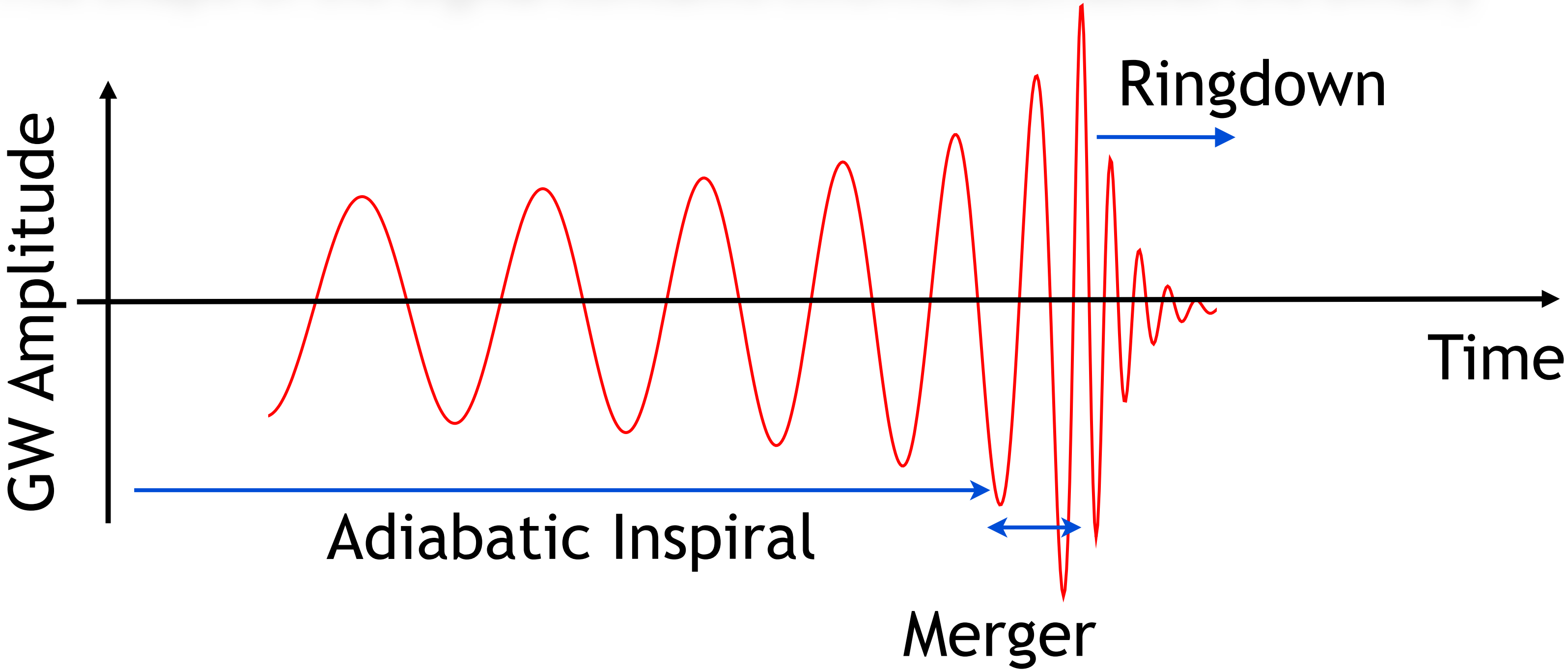


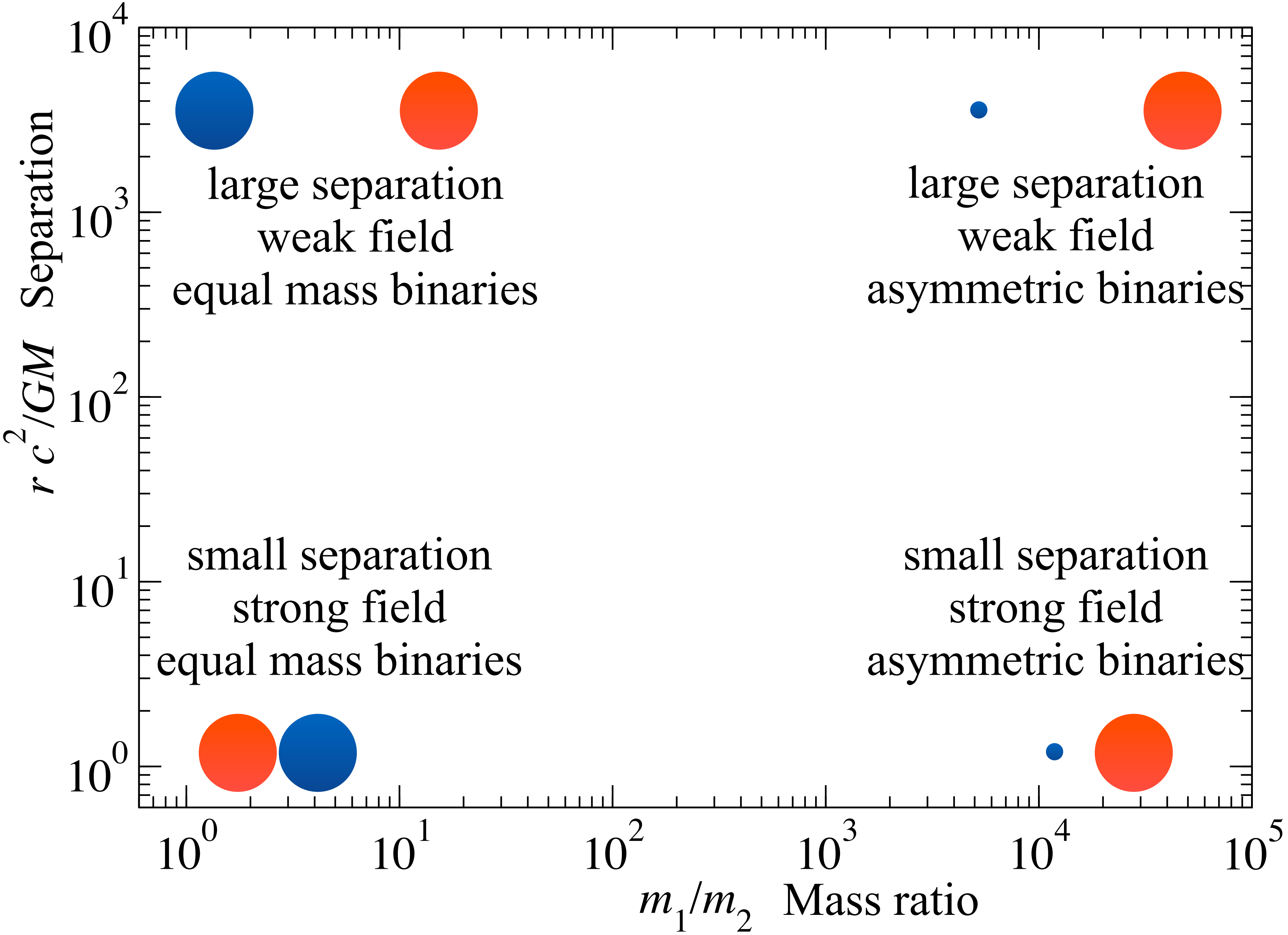
diagram not to scale

Binary black hole dynamics

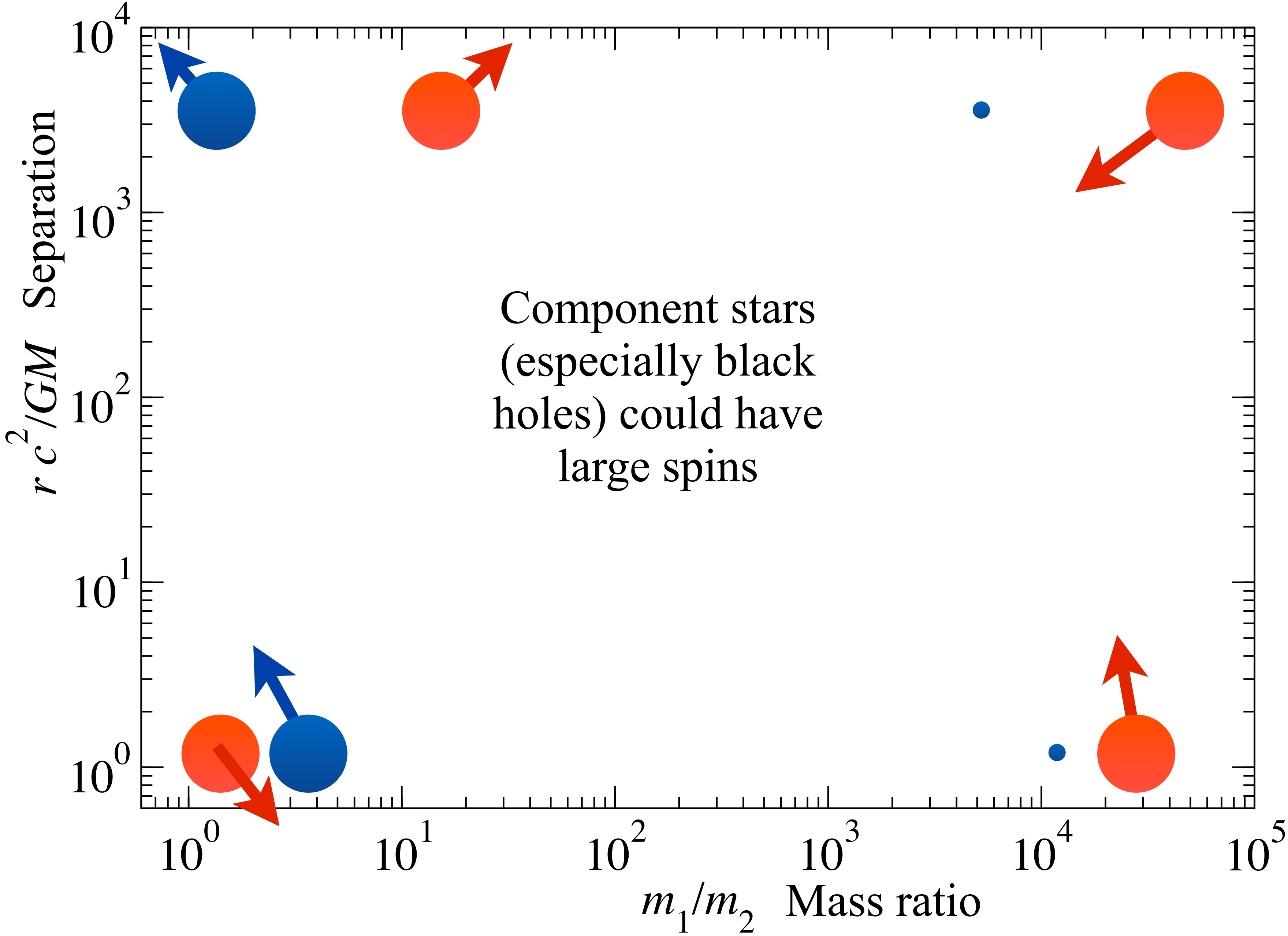
- The signal from a binary black hole is characterized by
  - slow adiabatic inspiral – the two bodies slowly spiral in towards each other; dynamics well described by post–Newtonian approximation
  - fast and luminous merger phase; requires numerical solutions to Einstein equations
  - rapid ringdown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



Huge Parameter Space and Strong Field Dynamics



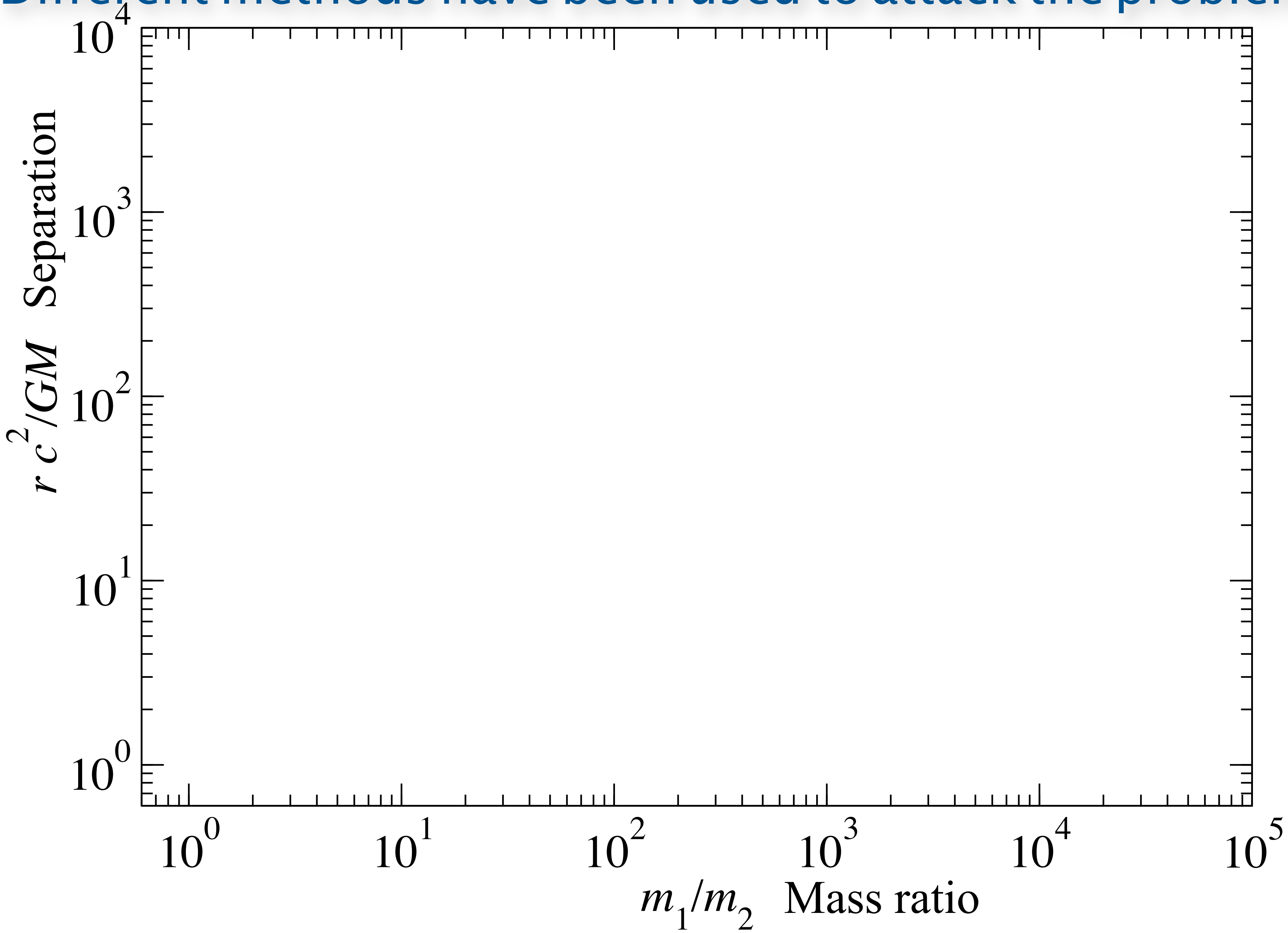
Spins cause frame dragging and orbital plane precession



Component stars (especially black holes) could have large spins

Dynamics completely governed by General Relativity:

Different methods have been used to attack the problem



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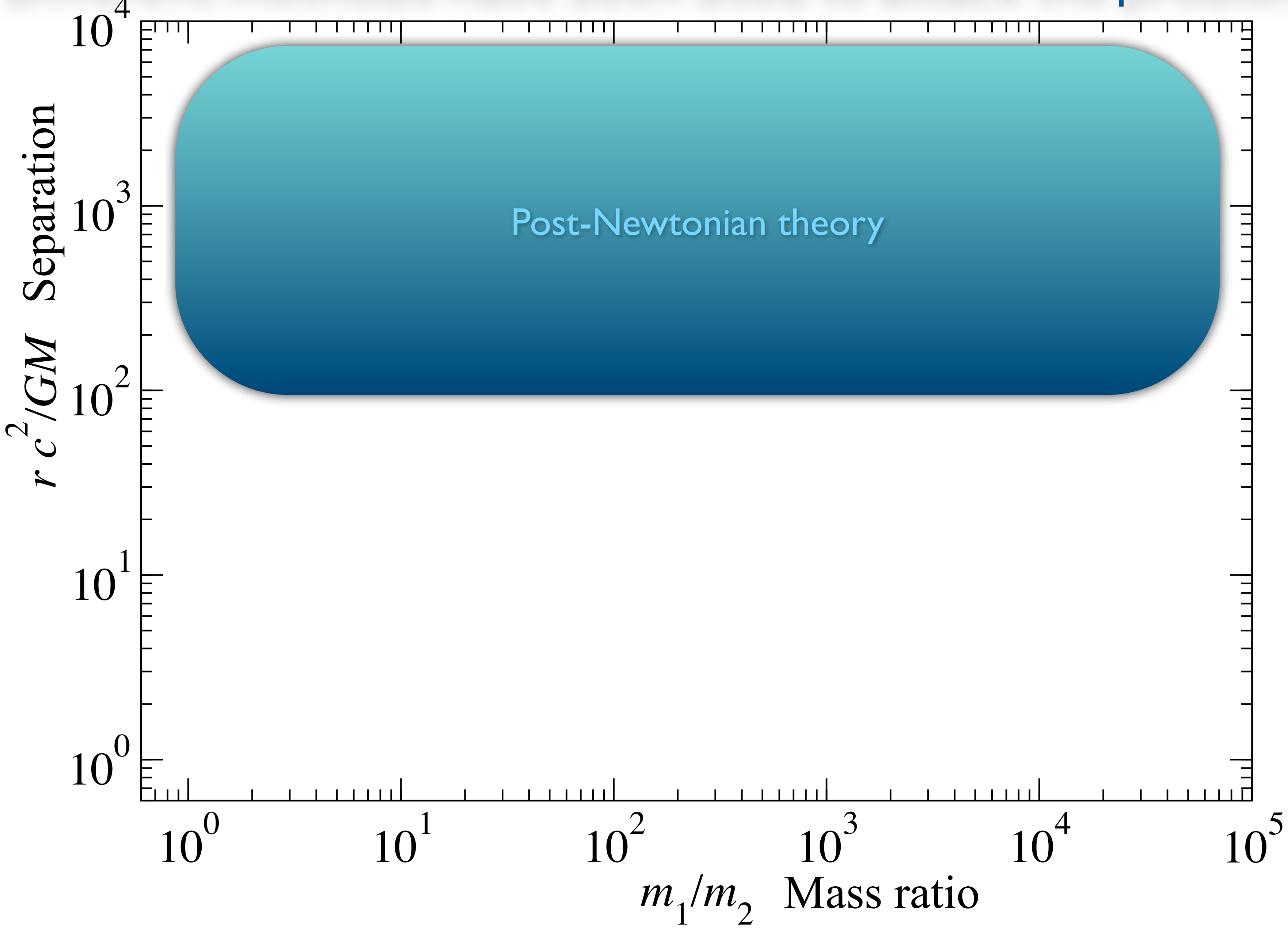

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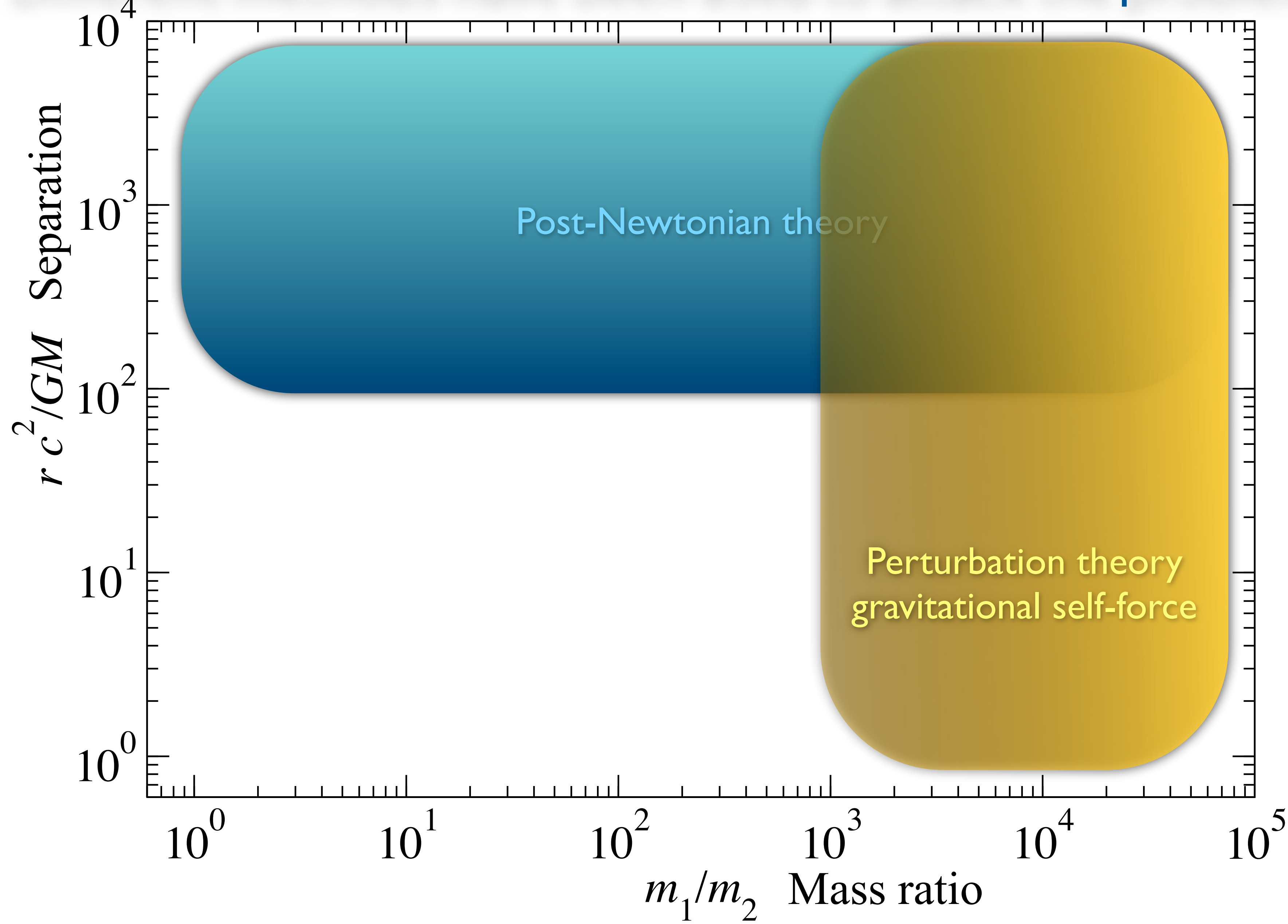

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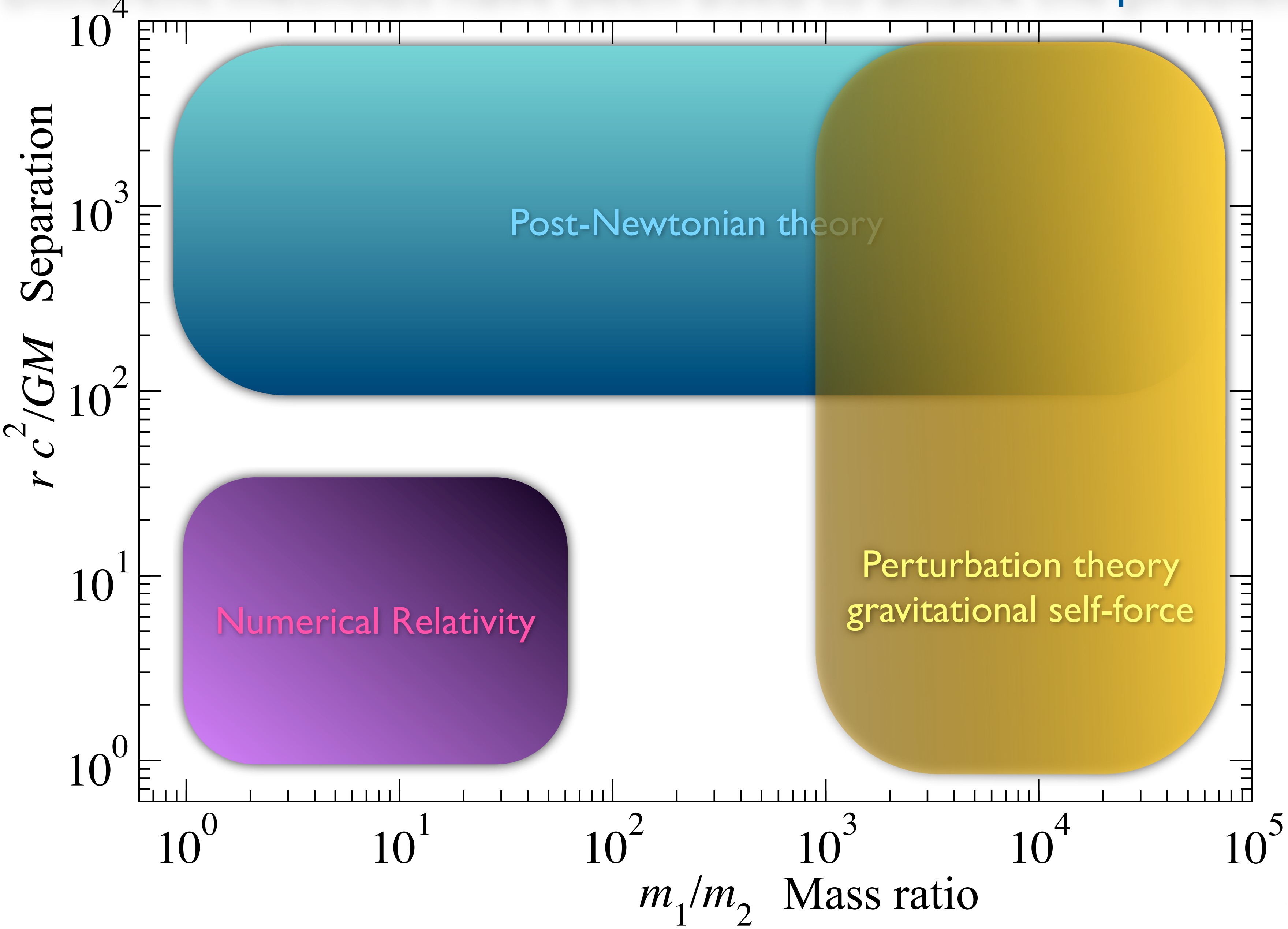

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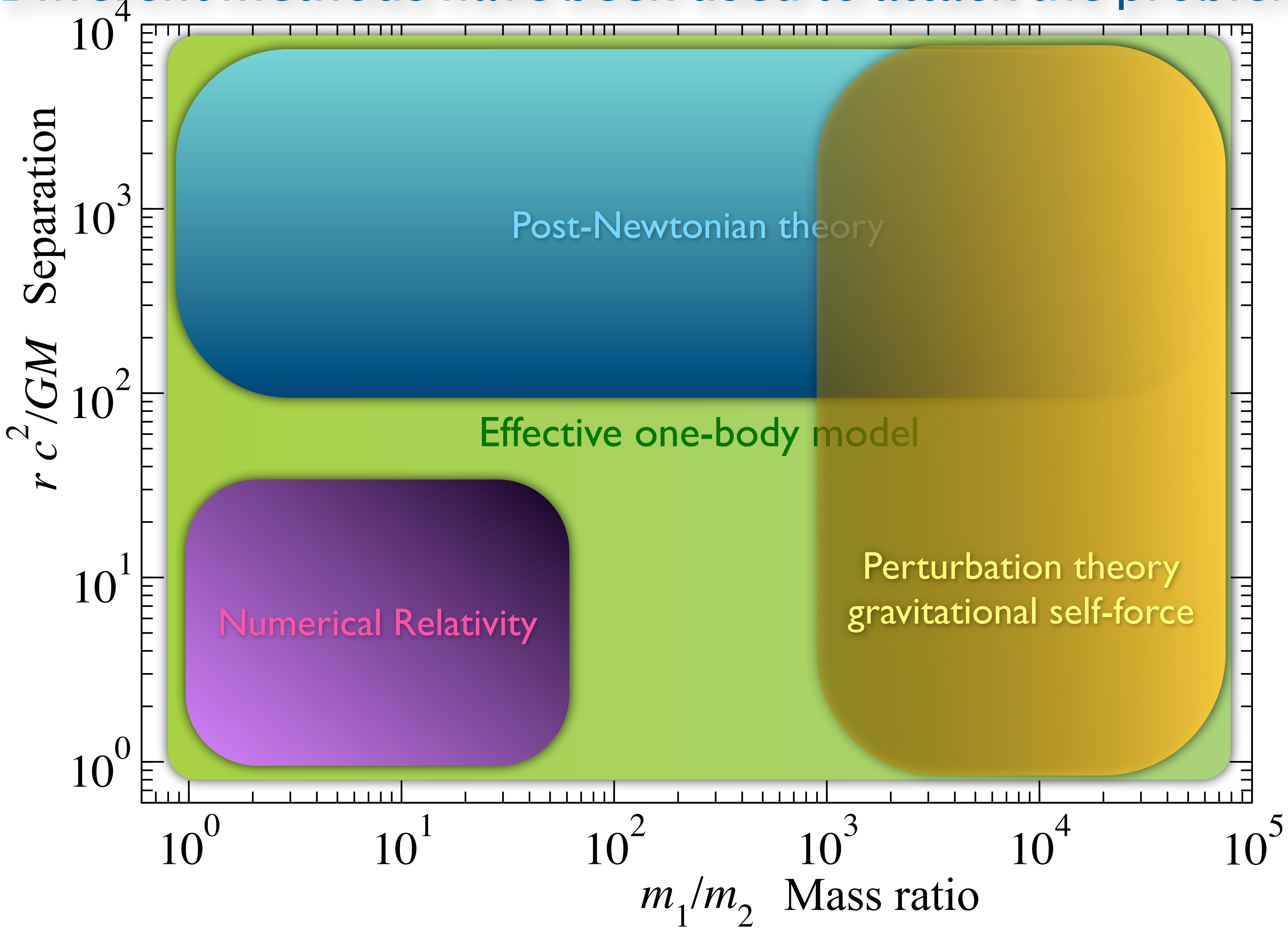
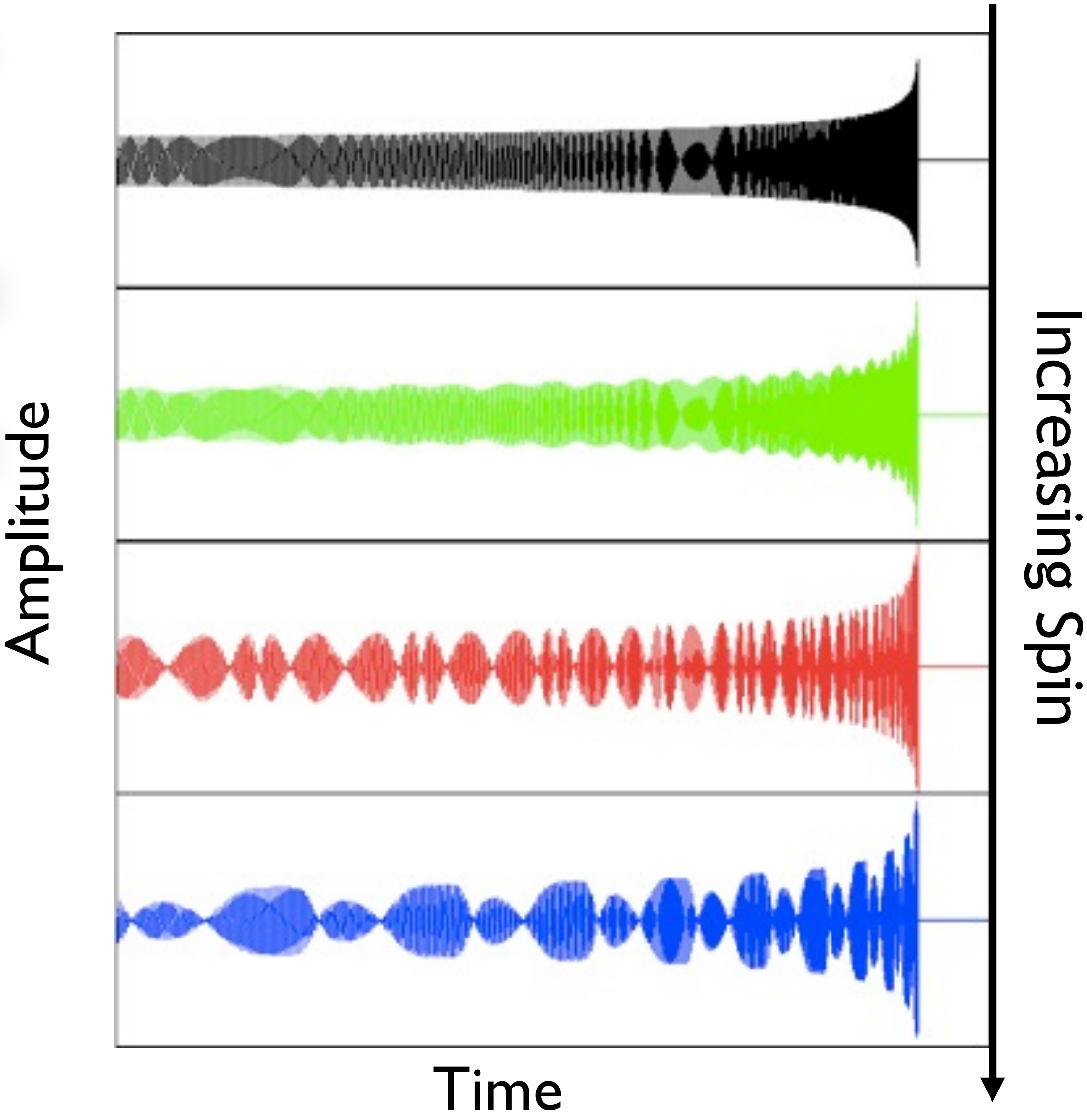


Inferring Distance from GW Observations

- 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
- To infer the distance we need to be able to measure all the parameters and the source's redshift

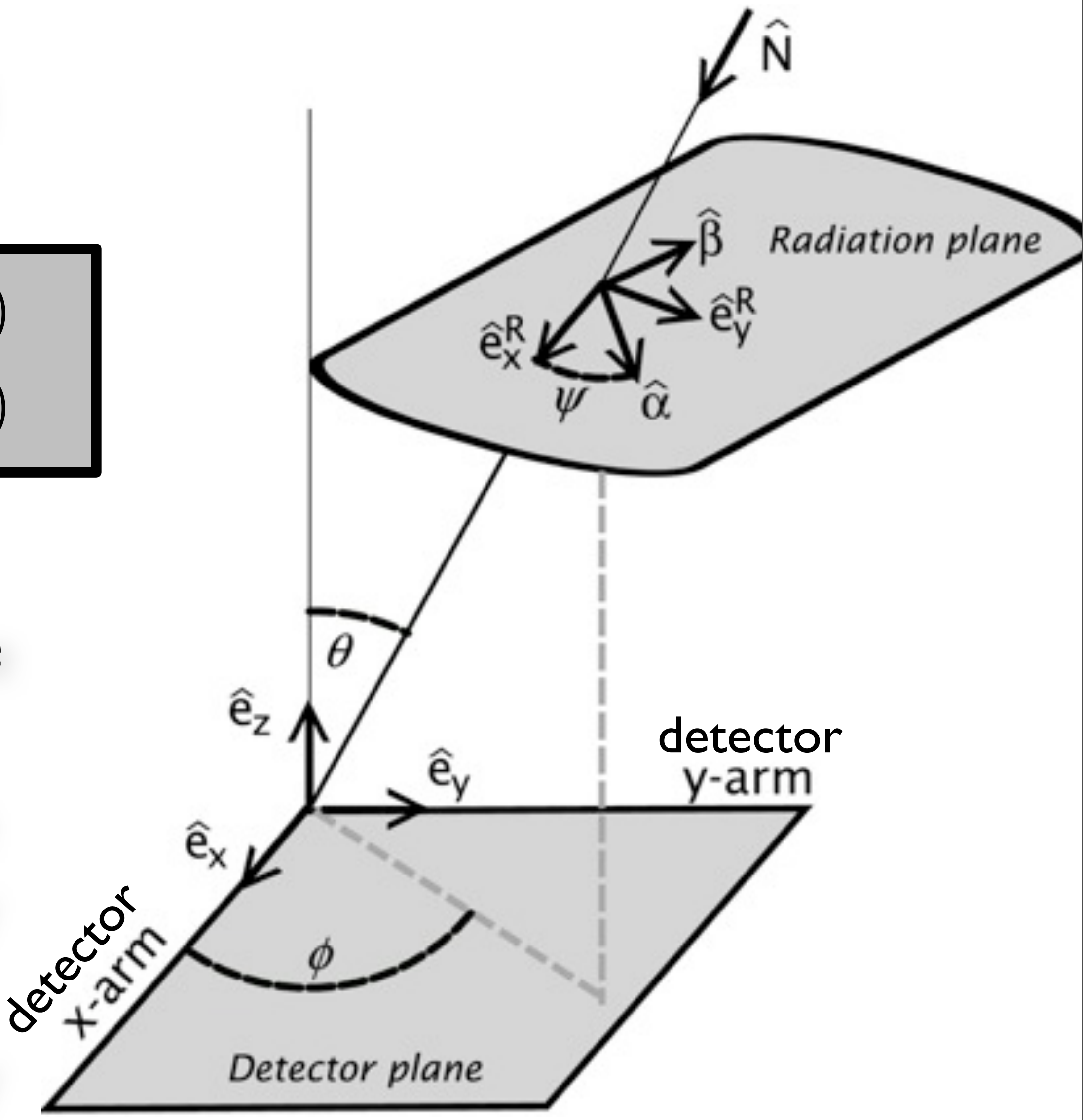


What do gravitational wave detectors measure?

- A combination of the two polarizations called antenna response:

$$h(t) = F_+(\theta,\varphi,\psi)h_+(t) + F_\times(\theta,\varphi,\psi)h_\times(t)$$

- So a net work of 3 or more detectors would be needed to measure the source direction; but we can also measure binary masses, their spins and orientation of the binary



BSS and Schutz 2009

Why are inspirals Standard Sirens

Why are inspirals standard sirens?

- Luminosity distance D can be inferred if one can measure:
  - the flux of radiation F and
  - absolute luminosity L:

$$D = \sqrt{\frac{L}{4\pi F}}$$

- Flux of gravitational waves depends on the amplitude of gravitational waves measured by our detectors
- Absolute luminosity can be inferred from the rate $\dot{f}$ at which the frequency of a source changes
  - Not unlike Cephied variables except that $\dot{f}$ is completely determined by general relativity
- Therefore compact binaries are self–calibrating standard sirens

Schutz Nature1986

What do we actually measure?

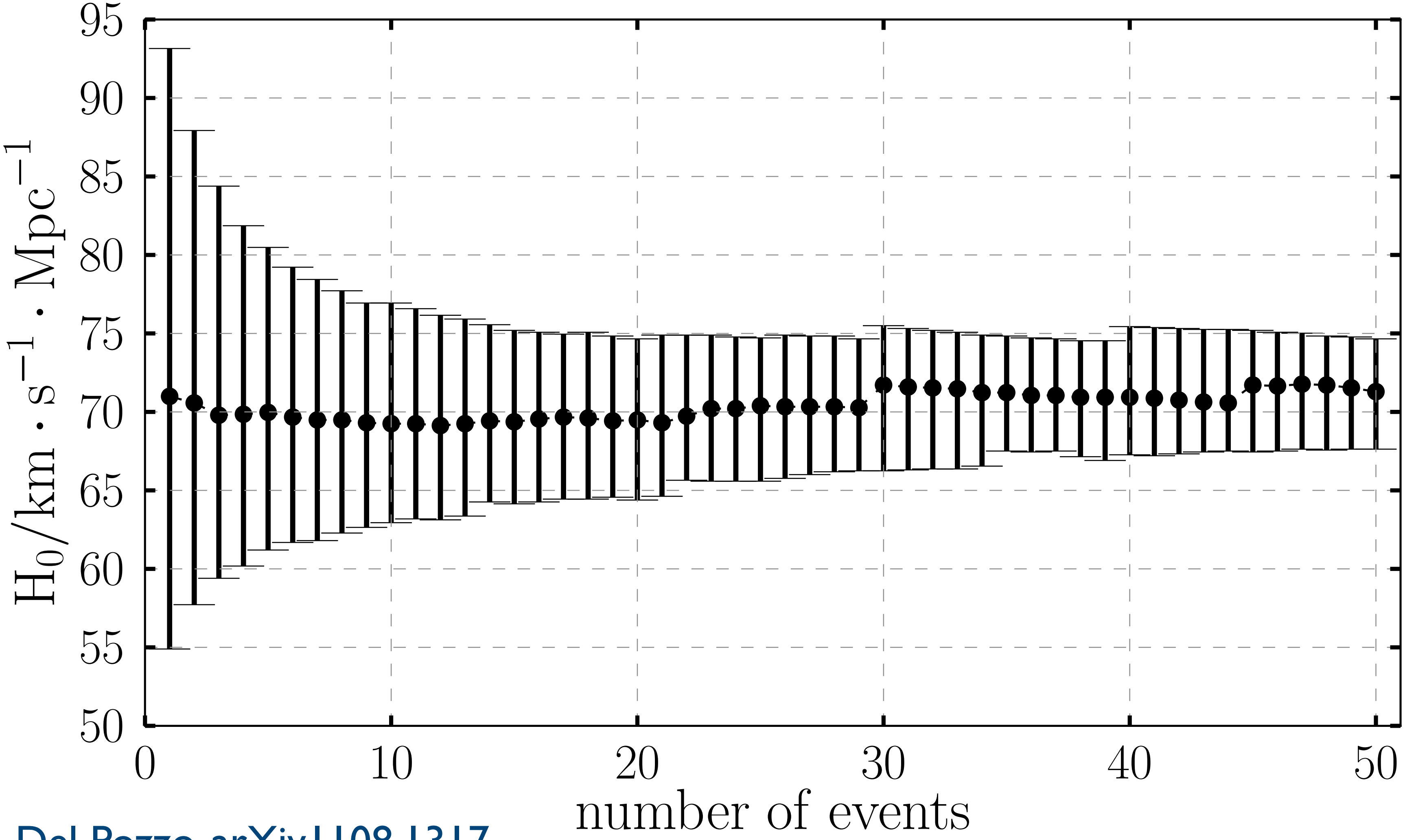
- We really only measure
  - the redshifted distance = luminosity distance $D_{\rm L} = D(1+z)$
  - blueshifted chirp mass $\mathcal{M}(1+z)$
- This means we cannot measure the source's redshift without EM identification
  - (at least that is what we thought until recently …)
- If we measure the source redshift we can deduce the intrinsic mass of the source and resolve redshift-mass degeneracy
- Distance is strongly correlated with the unknown orbital inclination of the source with respect to line-of-sight

Hubble Constant from Advanced Detectors without EM counterparts

- 25 events:
  - $H_0 = 69 \pm 3$ km s^{-1} Mpc^{-1} (~4% at 95% confidence)
- 50 events:
  - $H_0 = 69 \pm 2$ km s^{-1} Mpc^{-1} (~3% at 95% confidence)
- WMAP7+BAO+SnIa (Komatsu et al.,2011):
  - $H_0 = 70.2 \pm 1.4$ km s^{-1} Mpc^{-1} (~2% at 68% confidence)

Del Pozzo, arXiv1108.1317

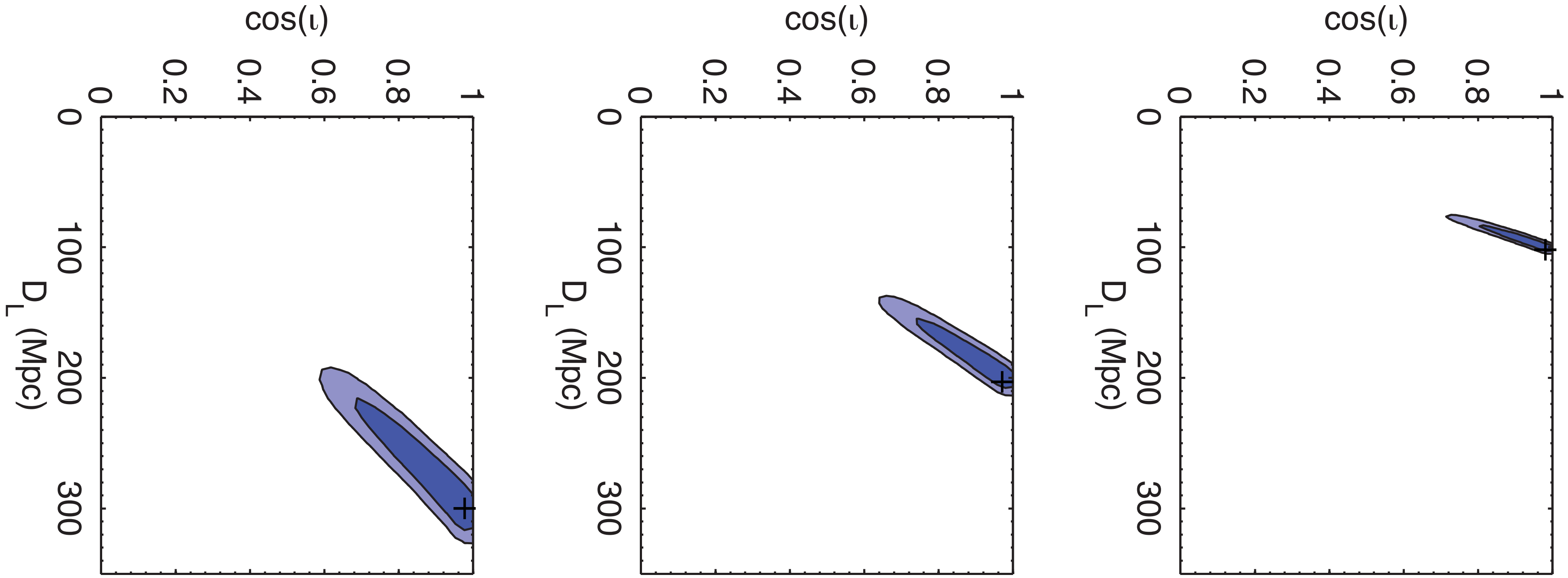
Error in H_0 with Catalogue Size



Del Pozzo, arXiv1108.1317

Hubble Constant from Advanced Detectors Assuming short_hard_GRBs are binary neutron stars

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,

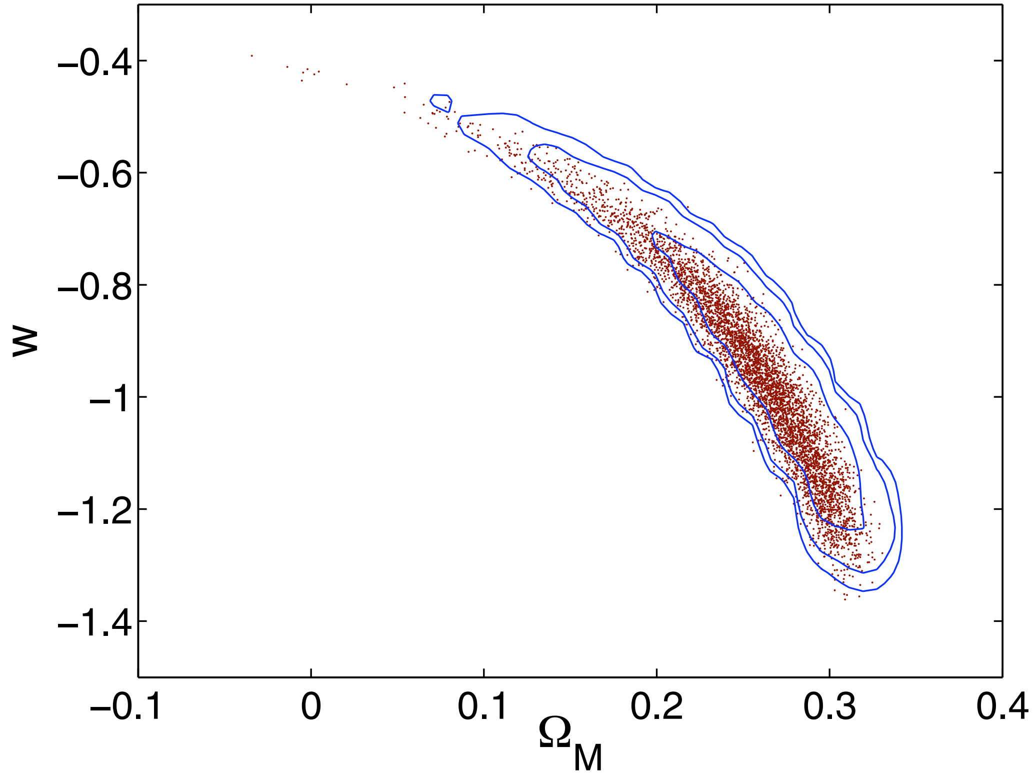


Nissanke et al 2009

ET: Measuring Dark Energy and Dark Matter

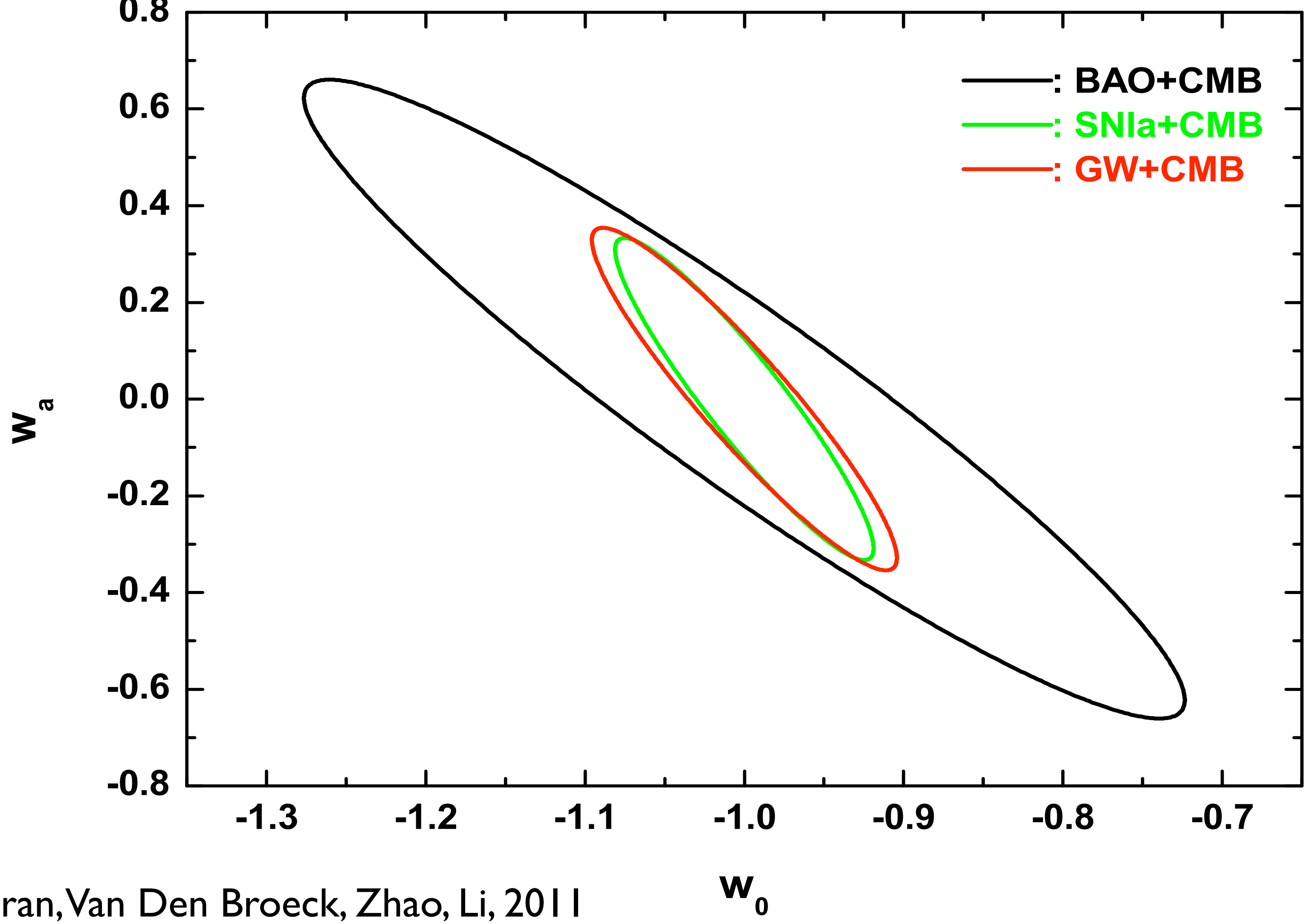
- ET will observe 100’s of binary neutron stars and GRB associations each year
- GRBs could give the host location and red-shift, GW observation provides D_L

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

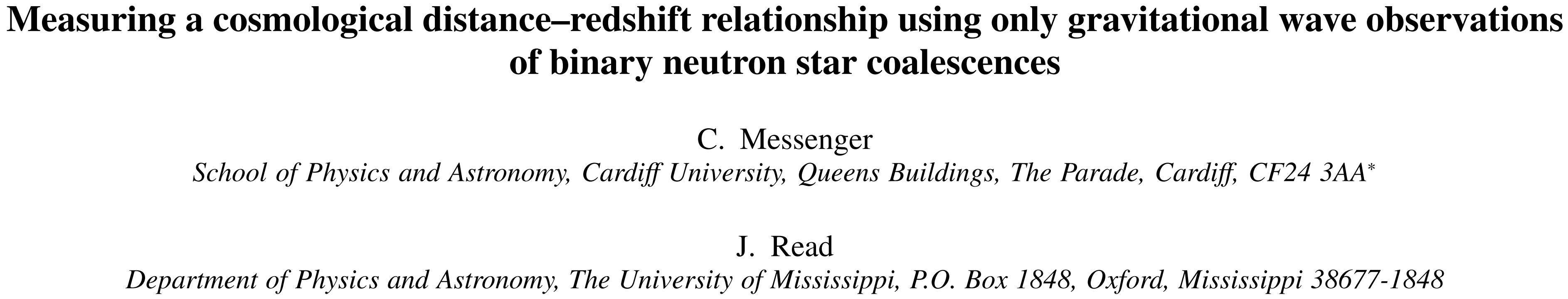


Measuring w and its variation with z

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



Baskaran, Van Den Broeck, Zhao, Li, 2011



Measuring a cosmological distance–redshift relationship using only gravitational wave observations of binary neutron star coalescences

C. Messenger
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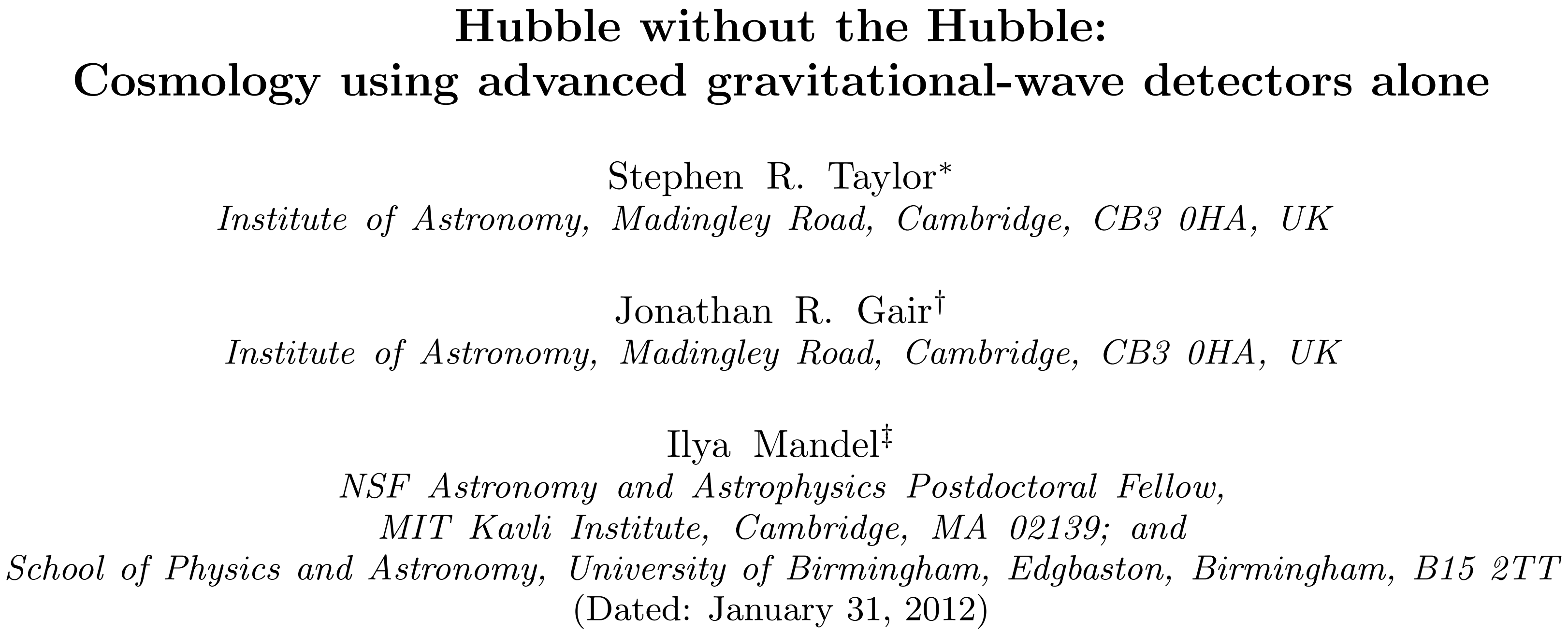
J. Read
Department of Physics and Astronomy, The University of Mississippi, P.O. Box 1848, Oxford, Mississippi 38677-1848



Hubble without the Hubble: Cosmology using advanced gravitational-wave detectors alone

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School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT
(Dated: January 31, 2012)

Messenger–Read Method:
Make use of the post–Newtonian Tidal Term

K. G. Arun, B. R. Iyer, B. S. Sathyaprakash, and P. A. Sundararajan, Phys. Rev. D, **71**, 084008 (2005), arXiv:gr-qc/0411146.

$$\Psi_{PP}(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \frac{3}{128\eta x^{5/2}} \sum_{k=0}^{N} \alpha_k x^{k/2}$$

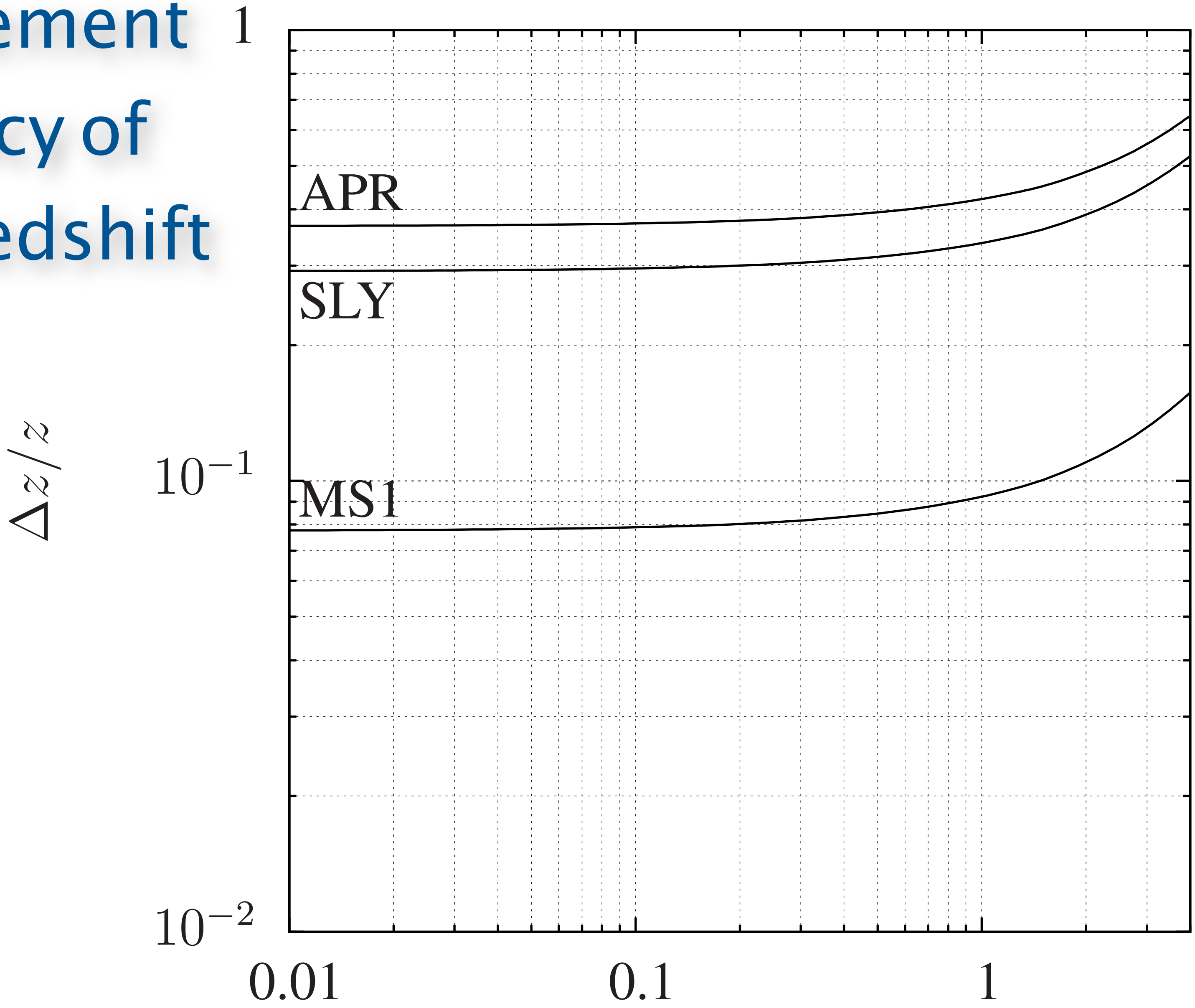
T. Hinderer, B. D. Lackey, R. N. Lang, and J. S. Read, Phys. Rev. D, **81**, 123016 (2010), arXiv:0911.3535 [astro-ph.HE].

$$\Psi^{\mathrm{tidal}}(f) = \sum_{a=1,2} \frac{3\lambda_a}{128\eta}\left[-\frac{24}{\chi_a}\left(1+\frac{11\eta}{\chi_a}\right)\frac{x^{5/2}}{M^5} - \frac{5}{28\chi_a}\left(3179 - 919\chi_a - 2286\chi_a^2 + 260\chi_a^3\right)\frac{x^{7/2}}{M^5}\right] \tag{3}$$

$$x = (\pi M f)^{2/3}$$

$$\lambda = (2/3)R_{\mathrm{ns}}^5 k_2$$

Measurement accuracy of source redshift



Messenger and Read, PRL, 2011

Cosmology with the lights off:

- Distribution of Chirp Mass

$$\mathcal{M} \sim N(\mu_c, \sigma_c^2),$$

$$\mu_c \approx 2(0.25)^{3/5}\mu_{\rm NS}, \quad \sigma_c \approx \sqrt{2}(0.25)^{3/5}\sigma_{\rm NS},$$

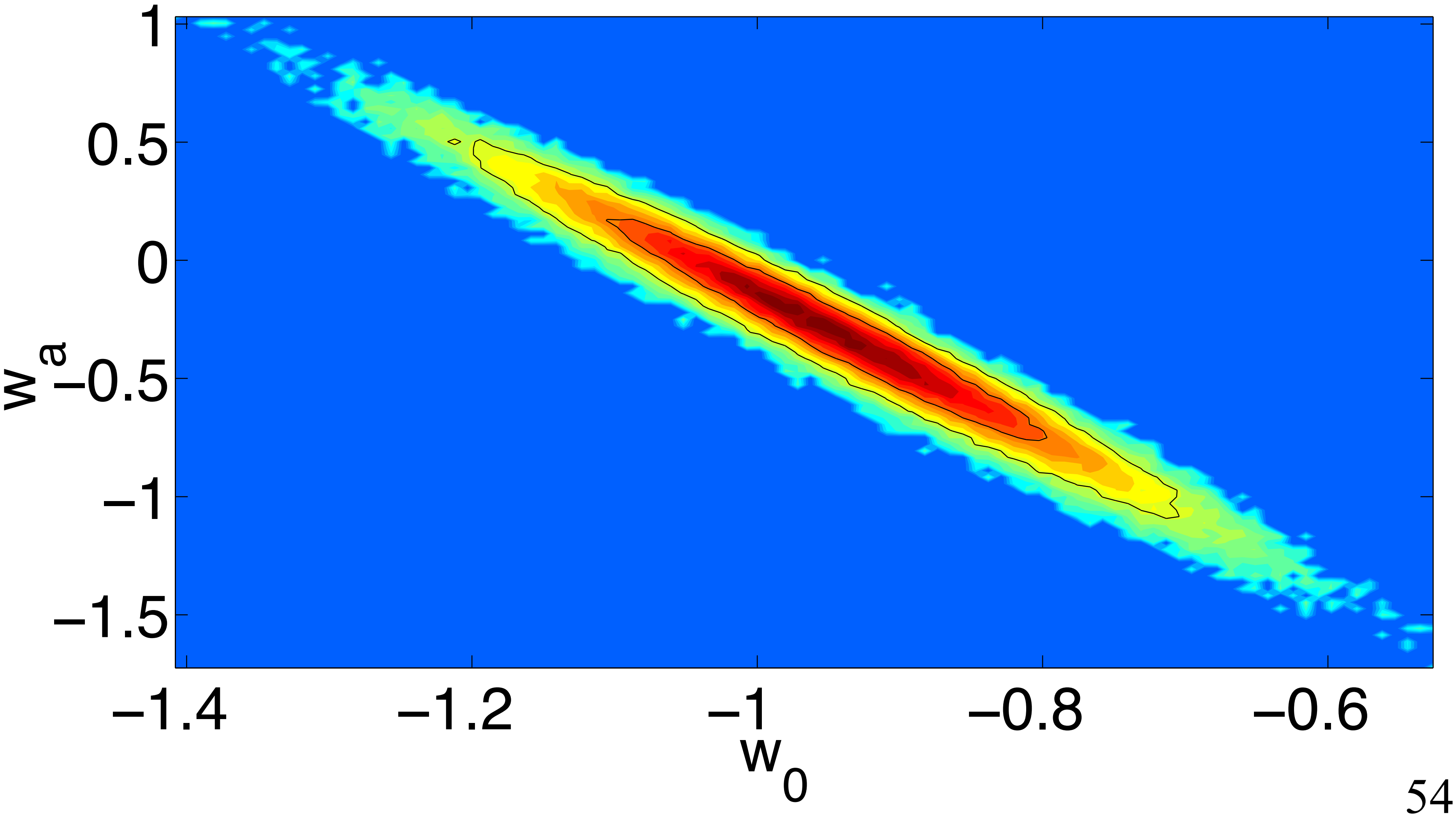
$$\mu_{\rm NS} \in [1.0, 1.5]M_\odot, \ \sigma_{\rm NS} \in [0, 0.3]M_\odot$$

$$w(a) = w_0 + w_a(1-a),$$

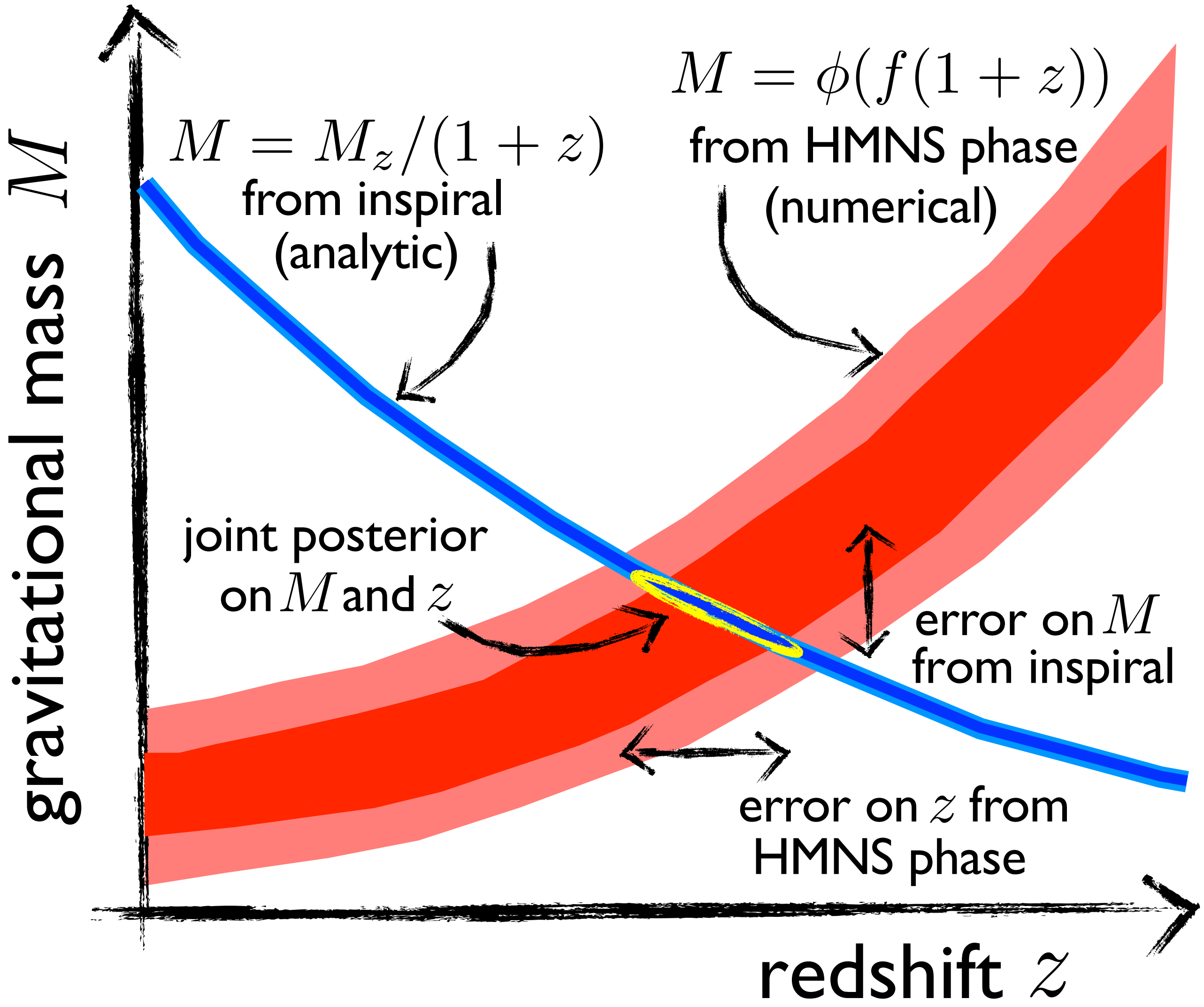
$$w(z) = w_0 + w_a\left(\frac{z}{1+z}\right).$$

Taylor, Gair, Mandel 2011, 2012

Measuring dark energy EoS and its variation with redshift



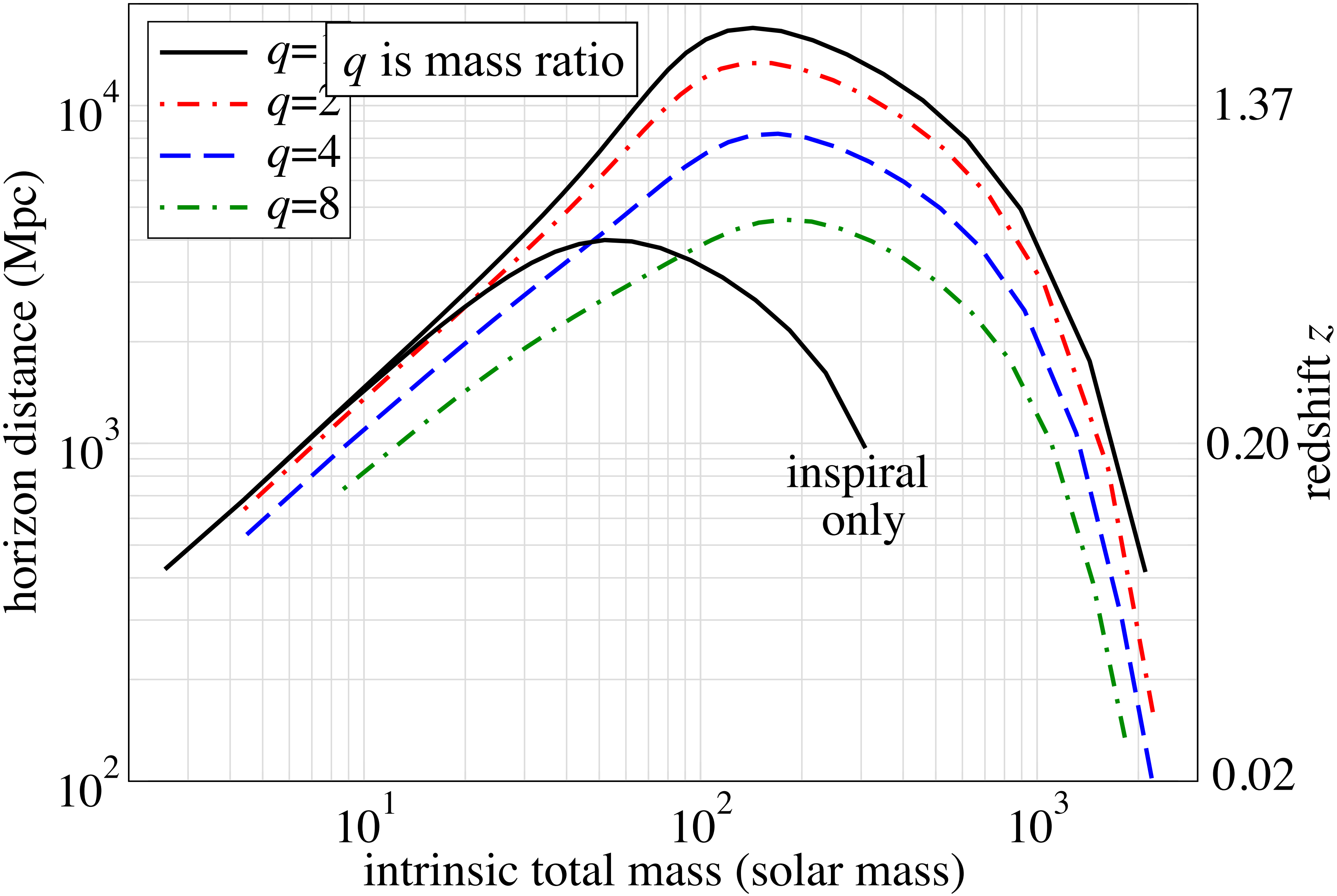
Host redshifts from gravitational wave observations



Messenger, Takami, Gossan, Rezzzolla, BSS, 2014

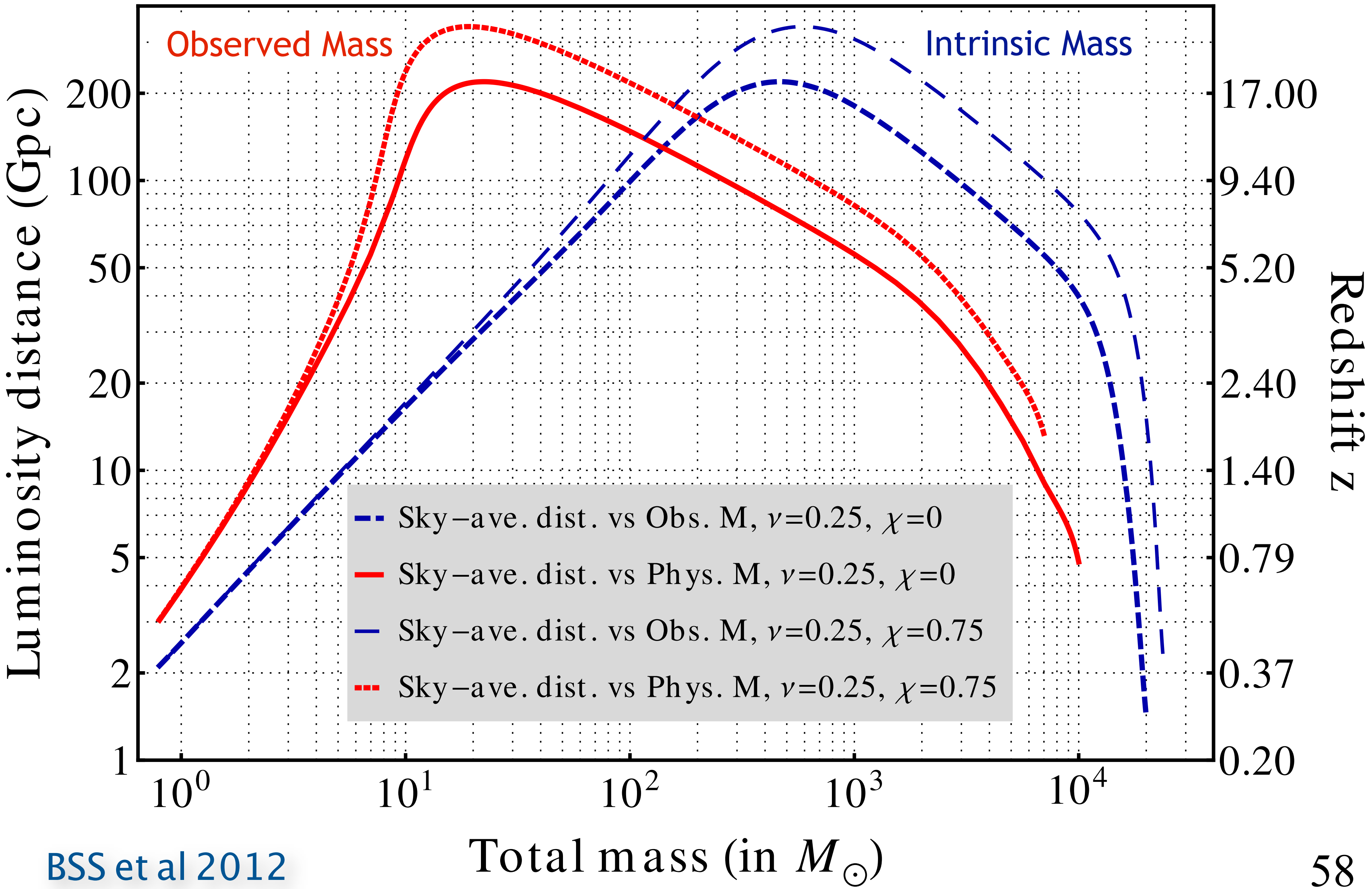
Black Hole Demographics

Advanced LIGO Distance Reach to Binary Coalescences



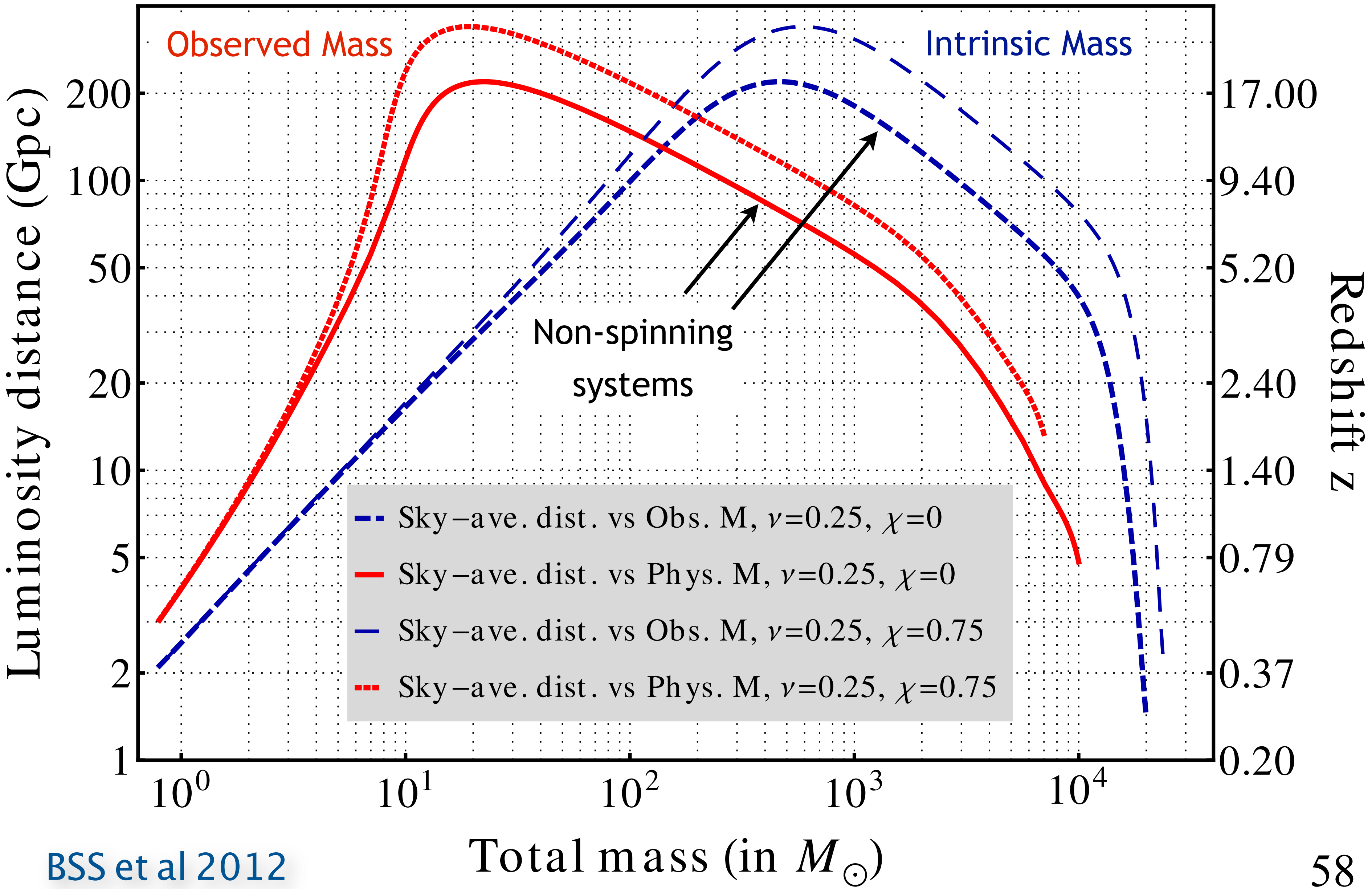
Buonanno and BSS 2014

ET Distance Reach to Coalescing Binaries



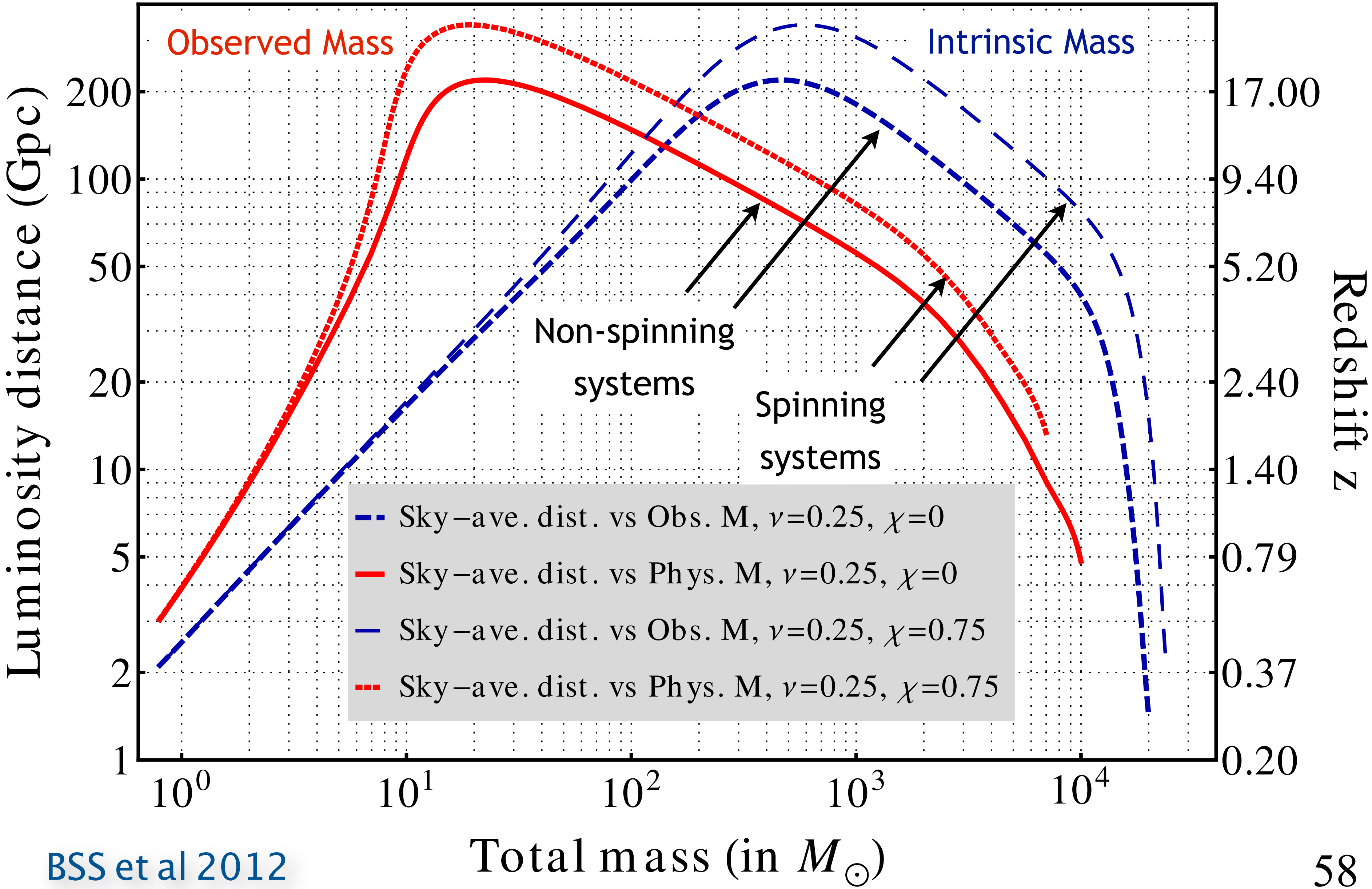
BSS et al 2012

ET Distance Reach to Coalescing Binaries



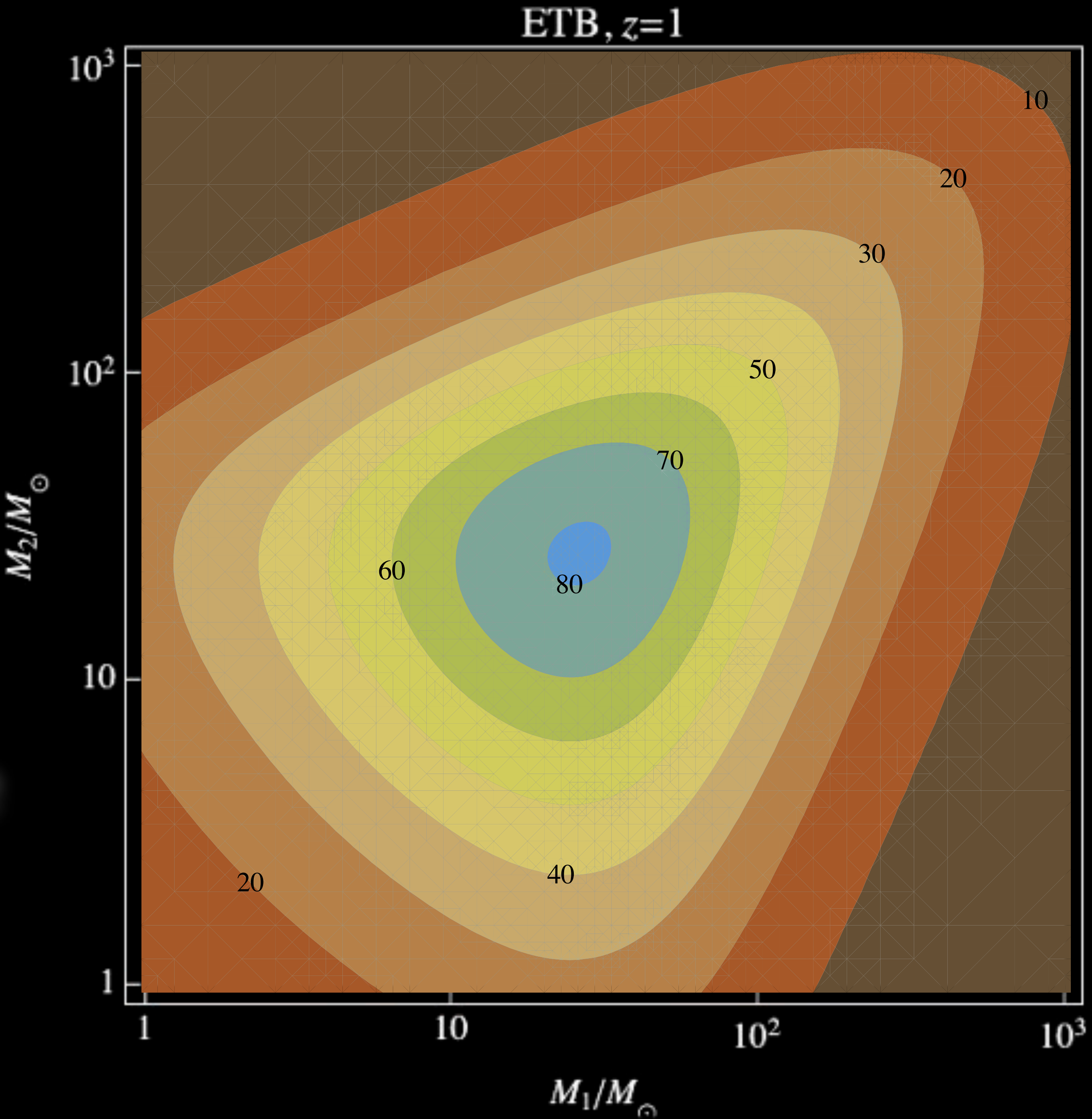
BSS et al 2012

ET Distance Reach to Coalescing Binaries



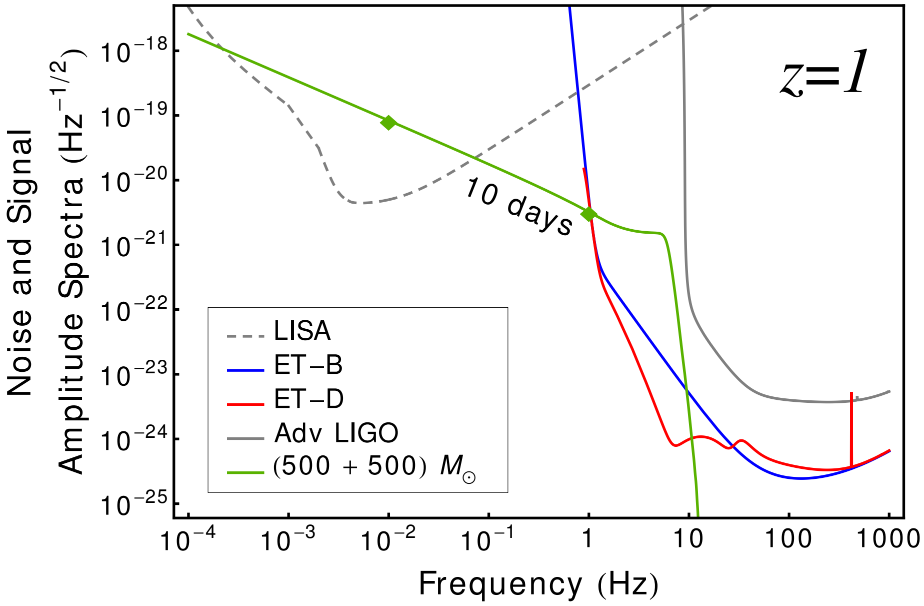
BSS et al 2012

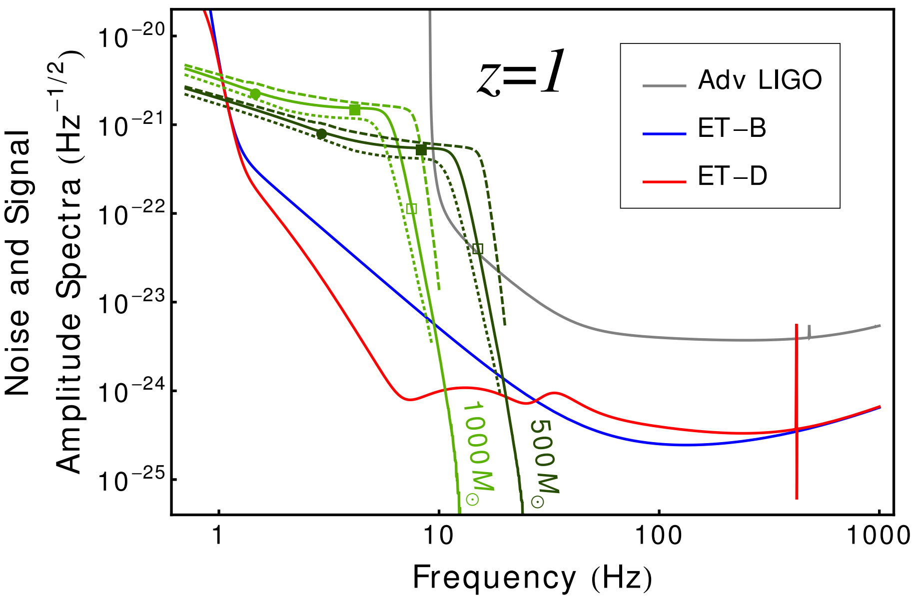
Visibility of Binary Inspirals in Einstein Telescope



Observing Intermediate–mass Black Hole Binaries

- Ultra–luminous X–ray sources might be hosting black holes of mass one thousand solar masses
- 100 solar mass black holes could be seeds of galaxy formation
- ET could observe black hole populations at different red–shifts and resolve questions about black hole demographics

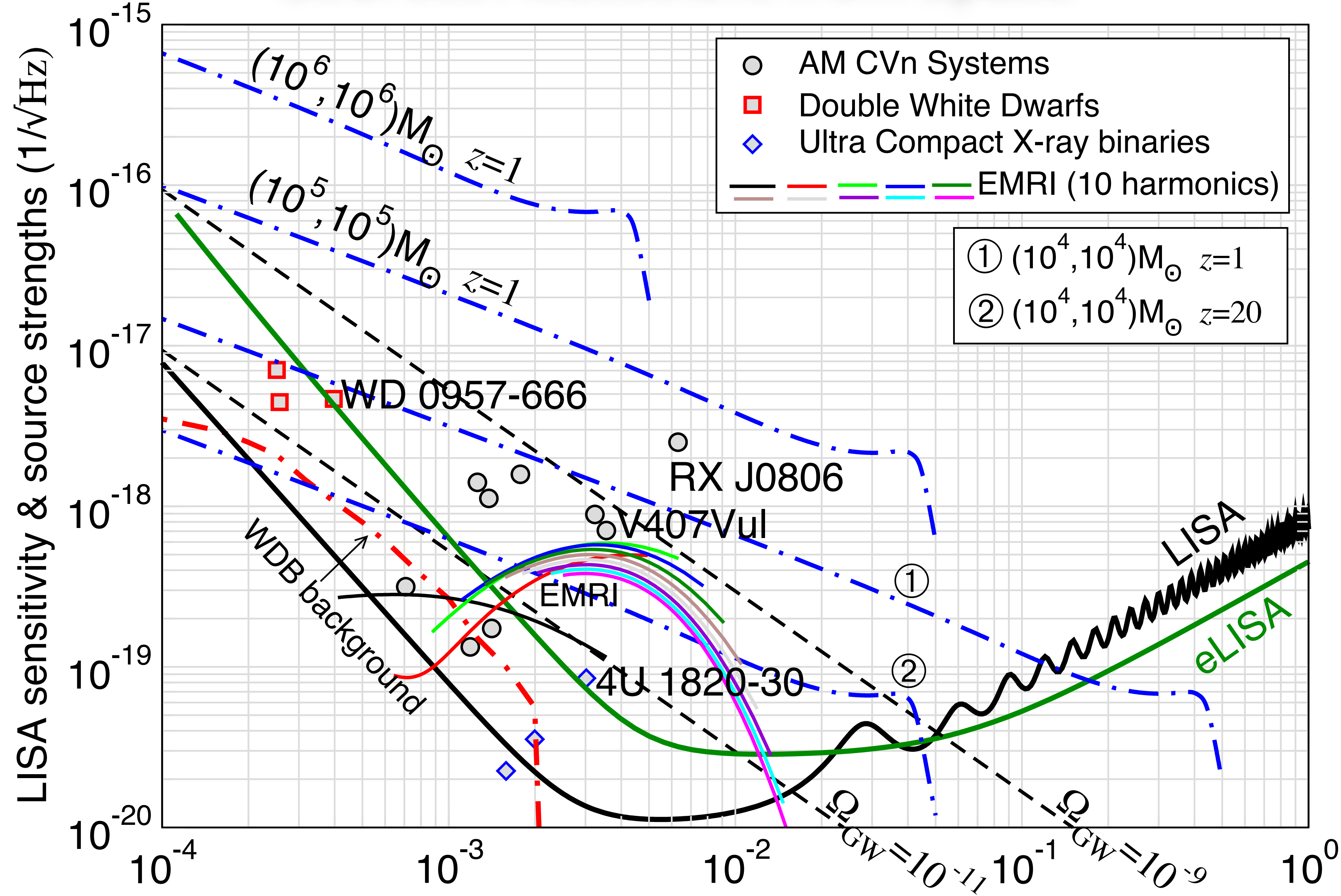




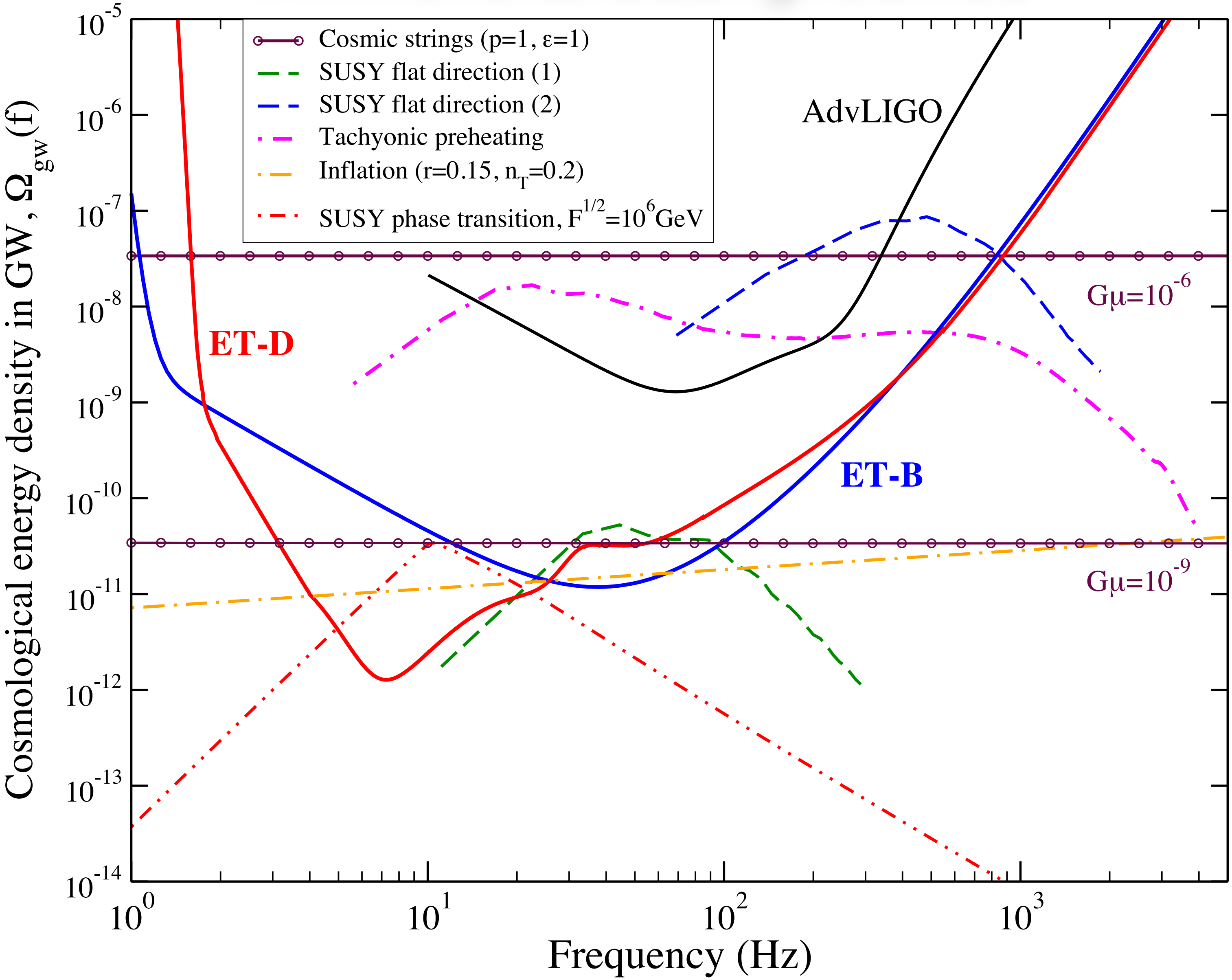
Slide Curtsey: L. Santamaria

Gravitational Wave Backgrounds

Sources Accessible from Space



Primordial Backgrounds



Abernathy et al 2011

GW observations tell us about …

- Cosmography
  - Verify cosmic distance ladder, strengthen existing calibrations at high z
  - Measure the Hubble parameter, dark matter and dark energy densities, dark energy EoS w, variation of w with z
- Black hole seeds
  - Confirm the nature black hole seeds, their masses and demographics
  - 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 produces stochastic b/g
- Production of GW during early Universe phase transitions
  - Phase transitions, pre–heating, re–heating, etc., could produce detectable stochastic GW