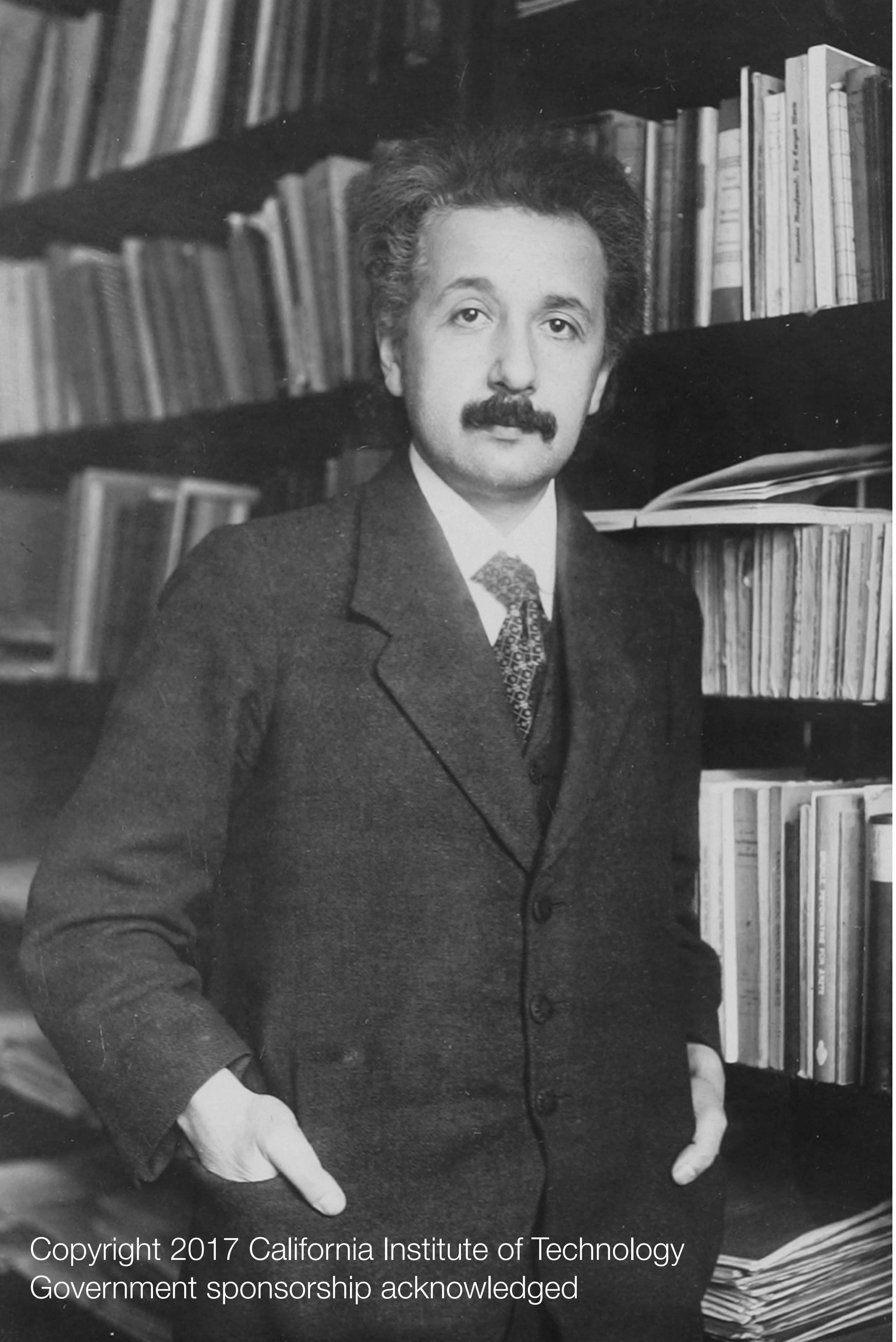
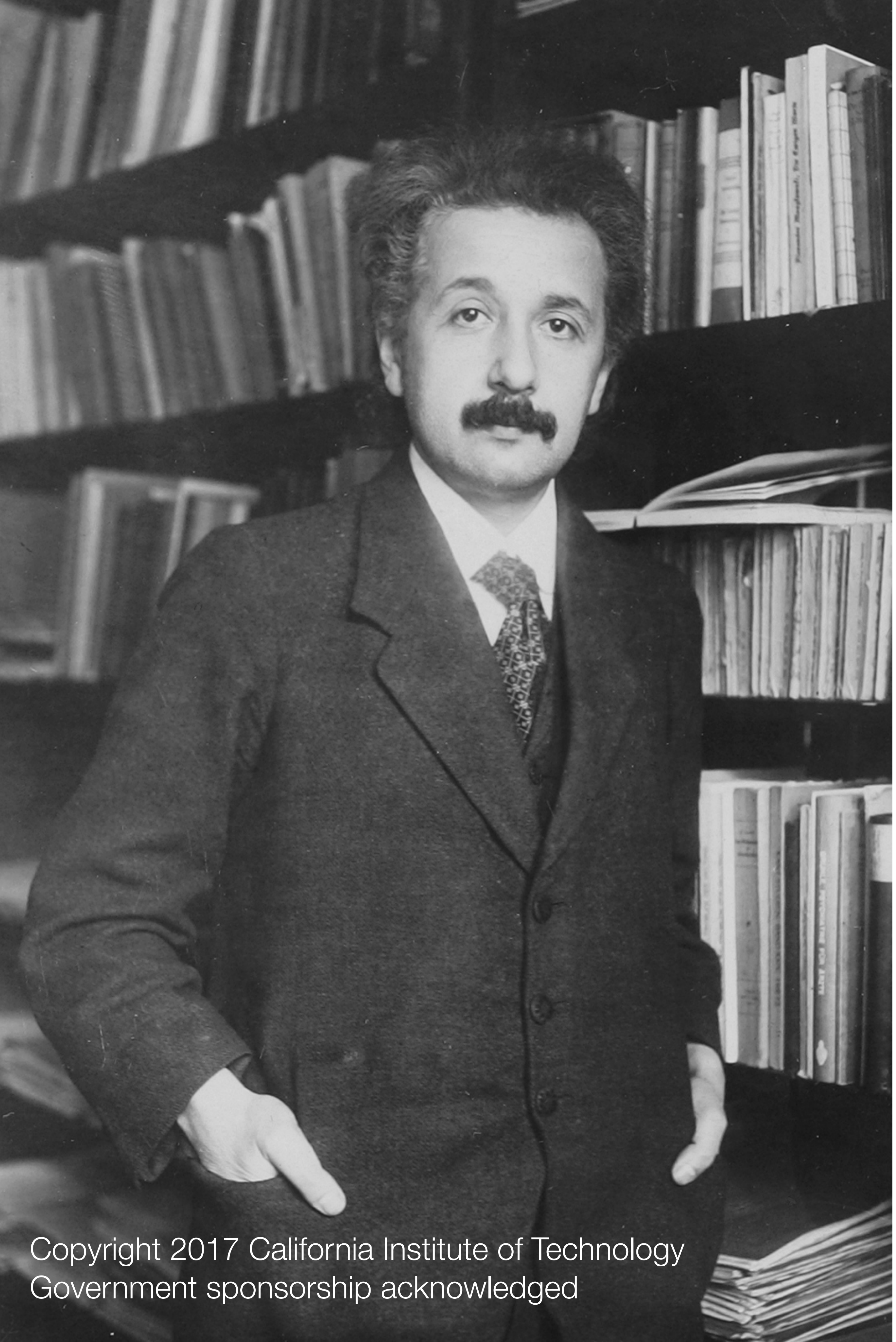


Gravitational waves from binary black holes across the spectrum

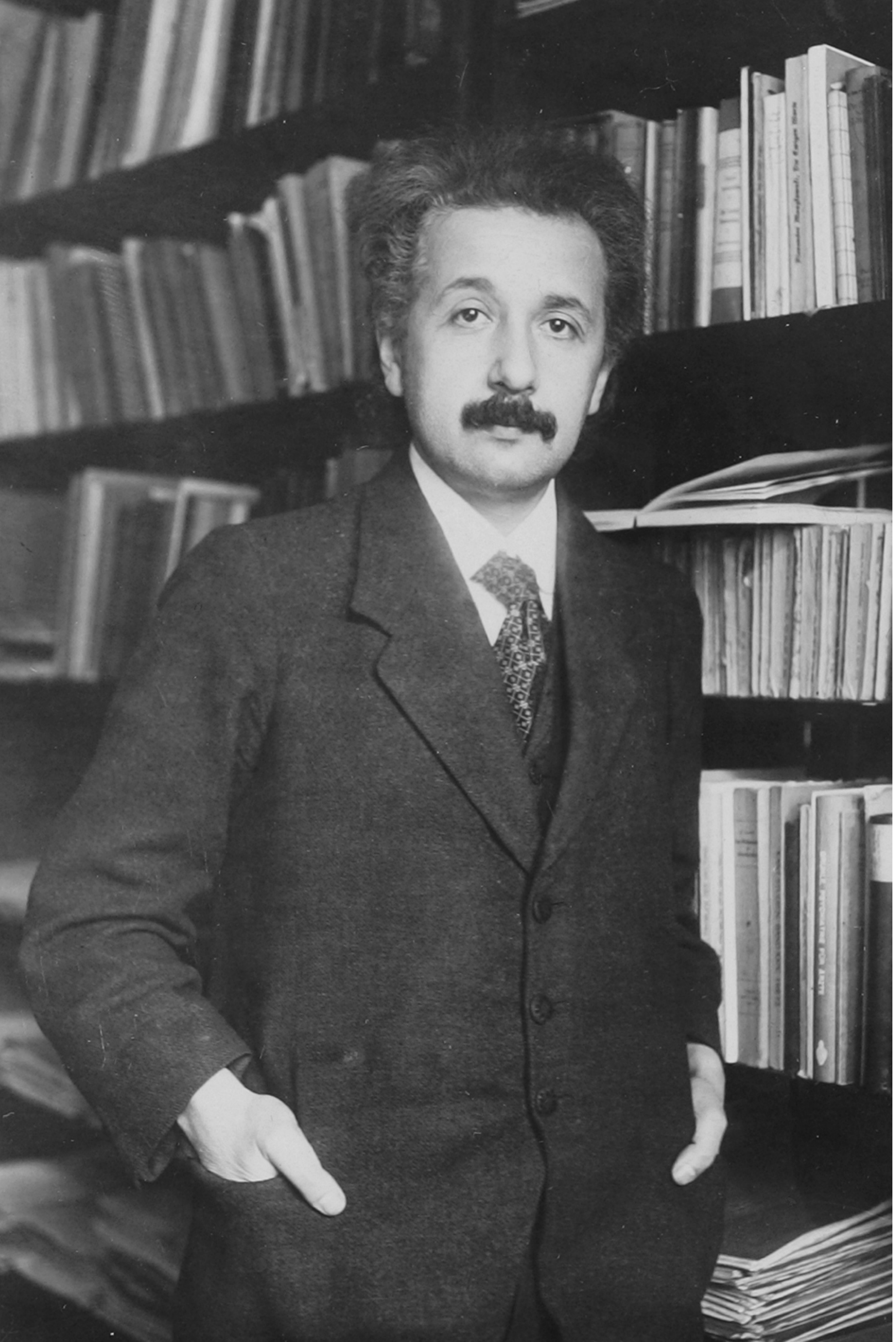
Michele Vallisneri
Jet Propulsion Laboratory
California Institute of Technology

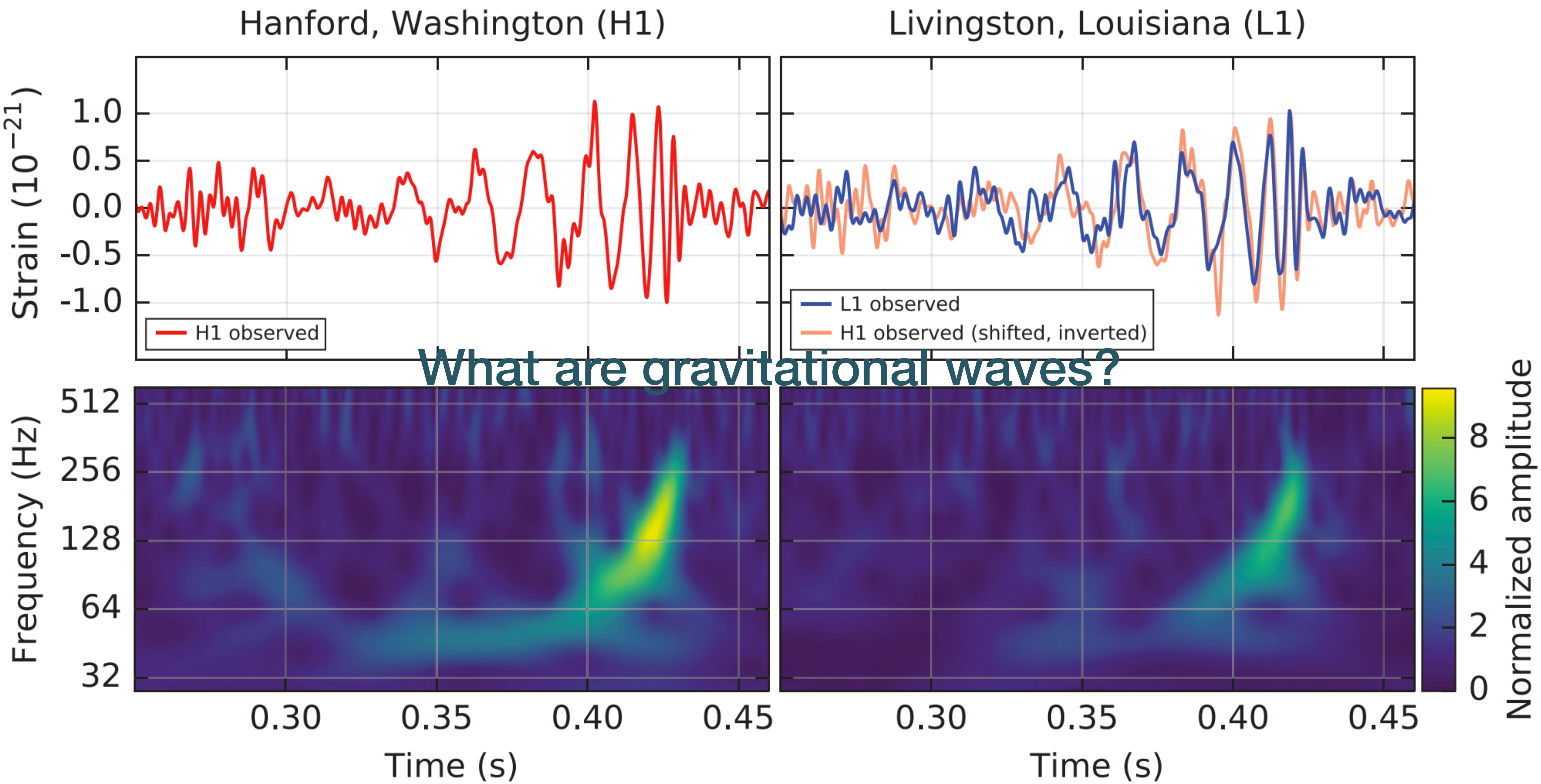
LIGO Scientific Collaboration

NANOGrav



1915: GR
1916: GWs; Schwarzschild metric
1919: Eddington's expedition
1939: gravitational collapse
1957: Chapel Hill conference
1960: Weber bars
1967: "black hole," no-hair theorem
1971: Cygnus X-1
1972: GW interferometer design
1974: PSR B1913+16
1990, 1999: LIGO approved, inaugurated
2002: Sgr A* as black hole
2002–2010: initial LIGO runs
2015: aLIGO; GW150914



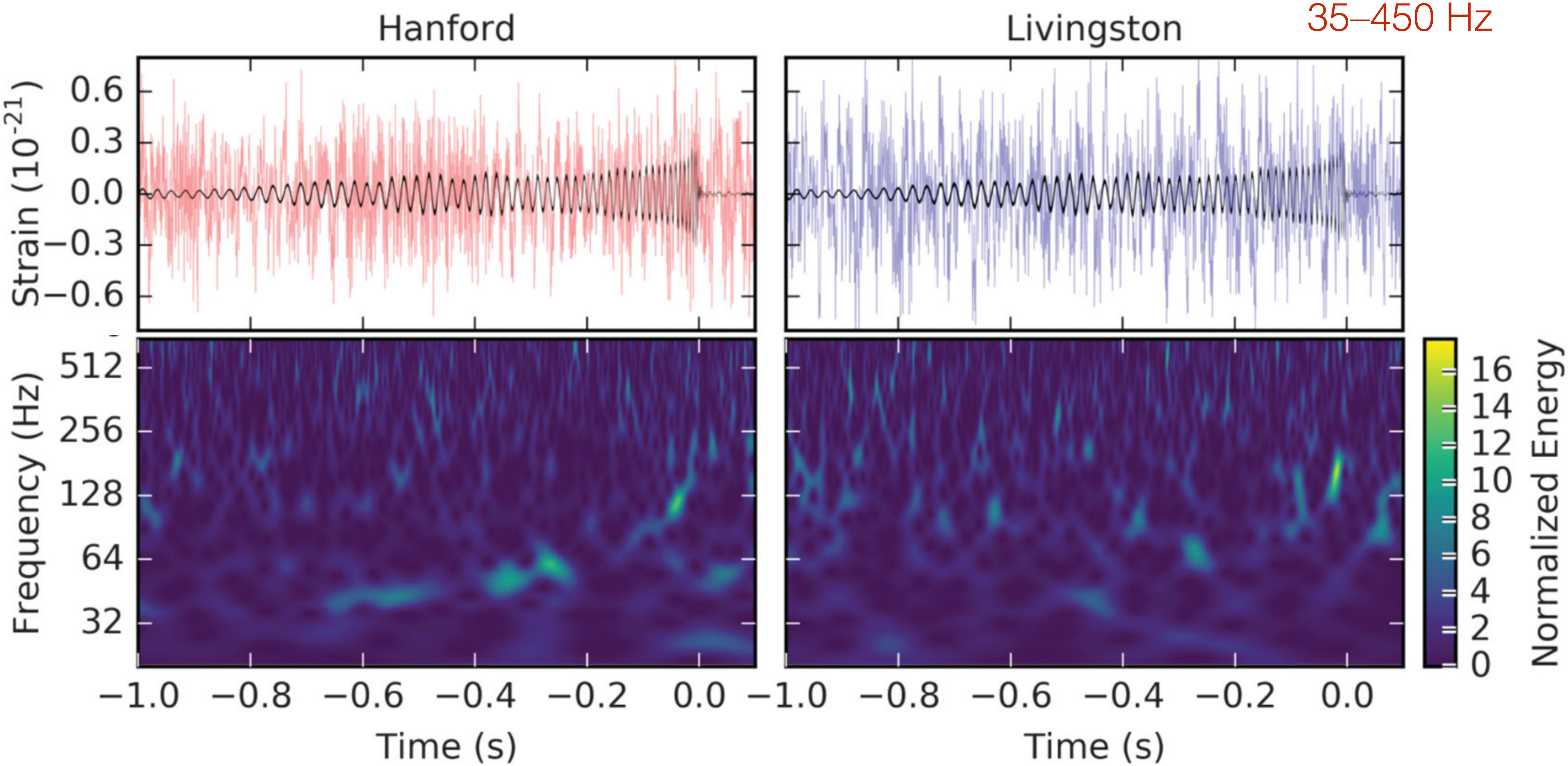


What are gravitational waves?

GW150914: detection and companion papers at papers.ligo.org

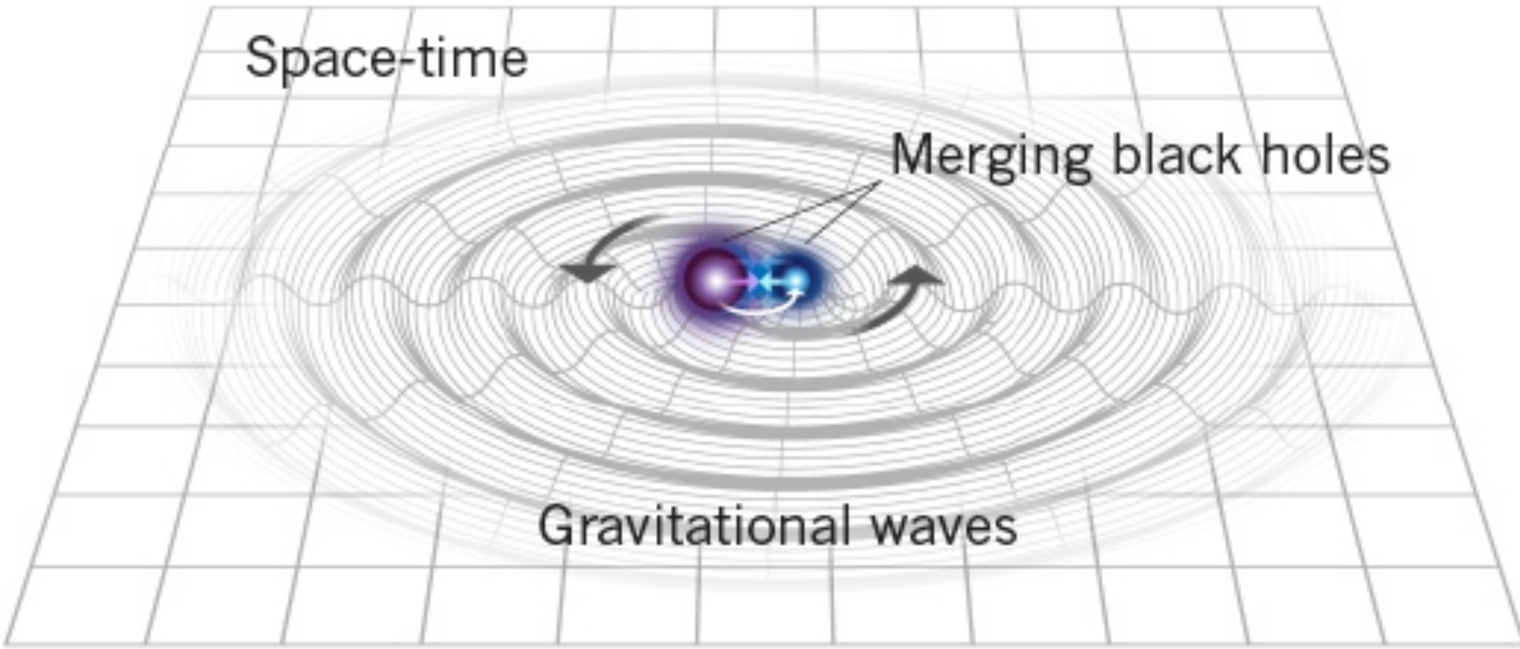
[LVC 2016]

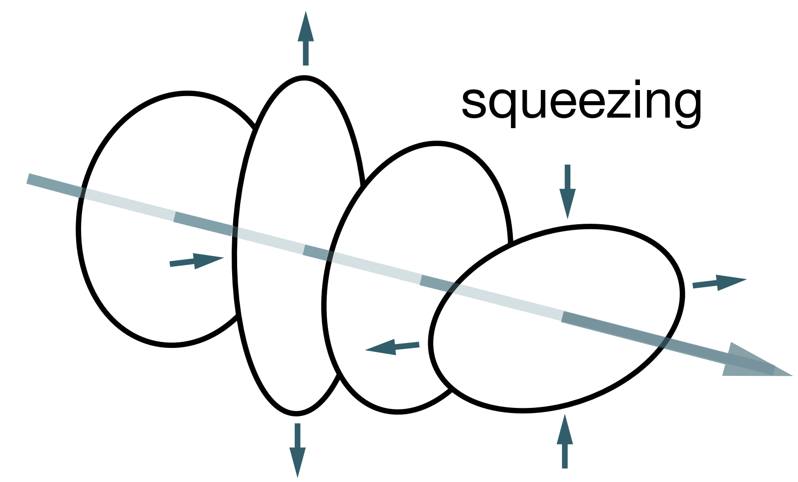
55 cycles over 1 s
35–450 Hz



GW151216: see PRL and O1 BBH paper

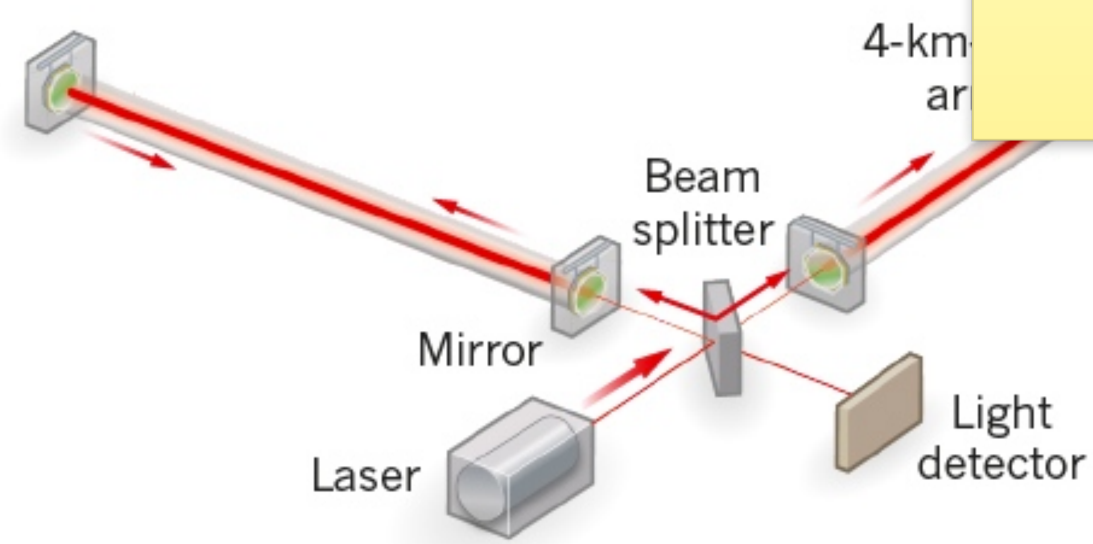
[LVC 2016]

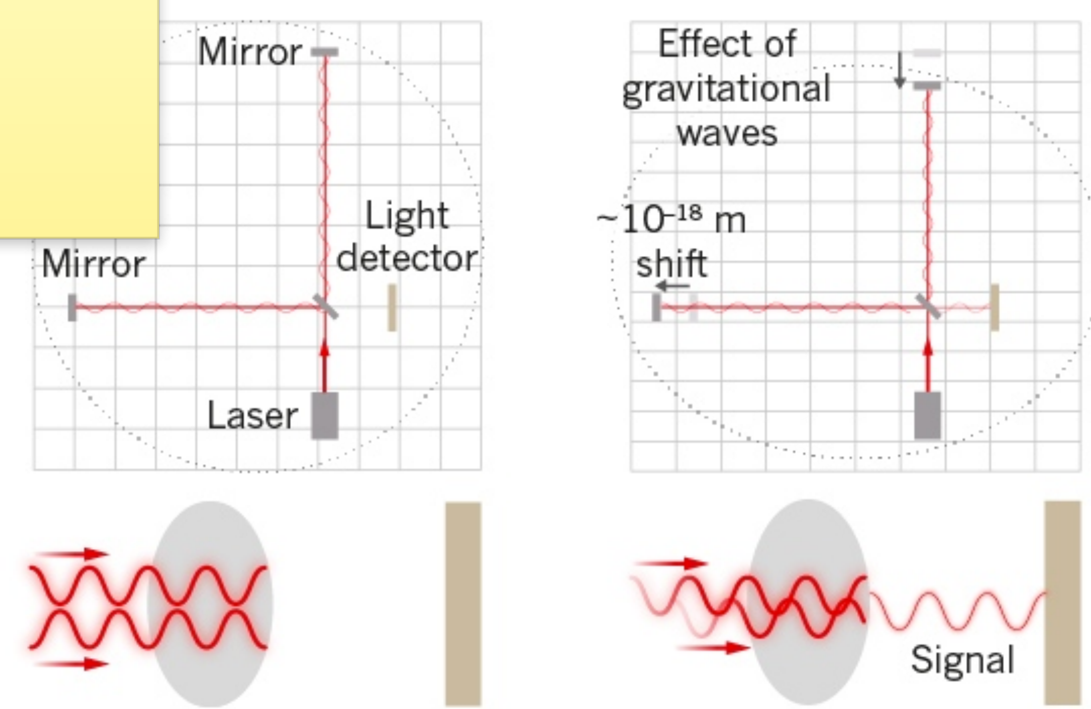




$$\Box \bar{h}^{\alpha\beta} = -16\pi\tau^{\alpha\beta}$$

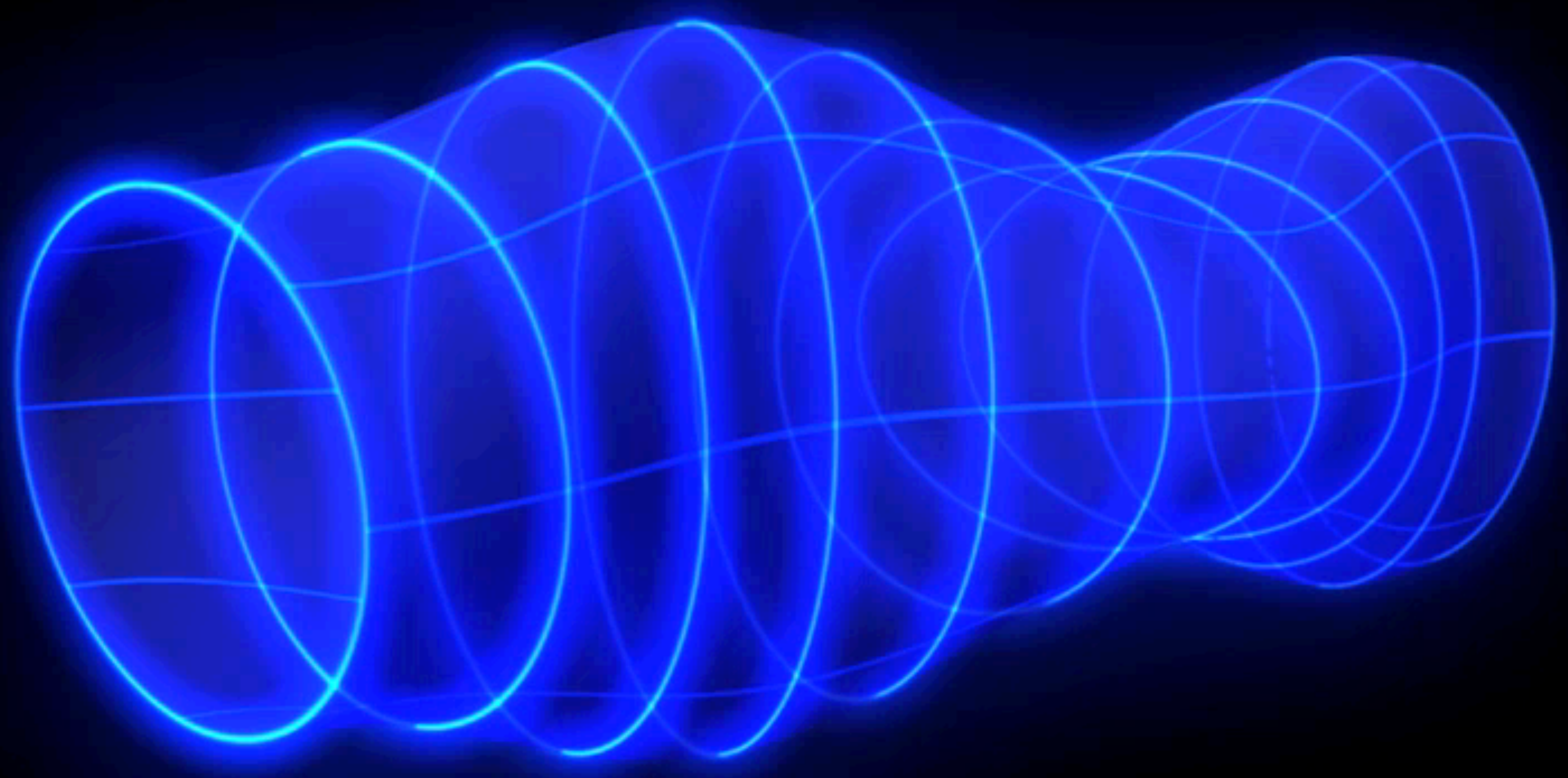
To first approximation… indeed, in the linearized approximation…





Gravitational waves and their detection

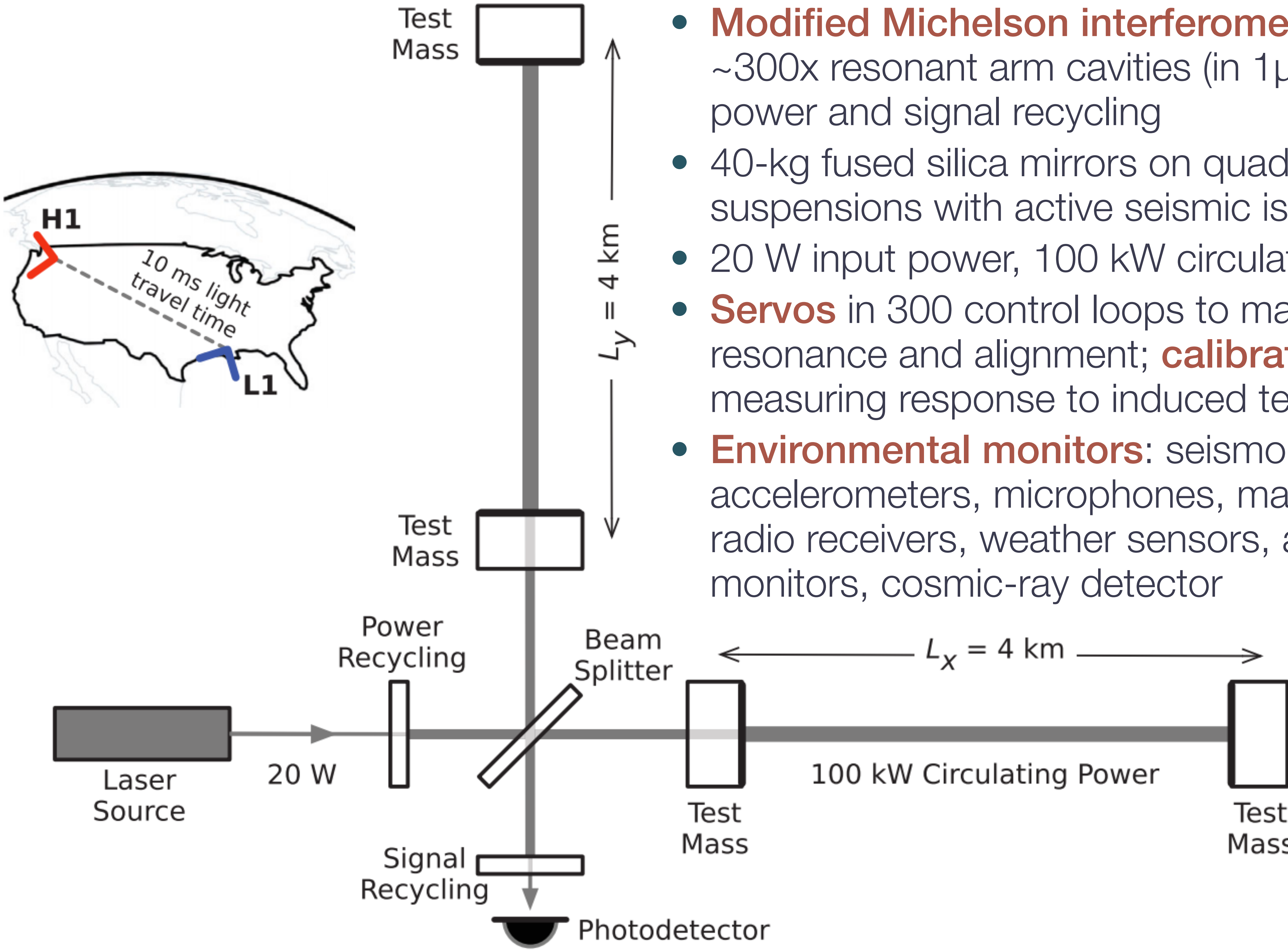
[Nature 2016]



GWs are transverse and traceless tidal fields

[ESA 2016]

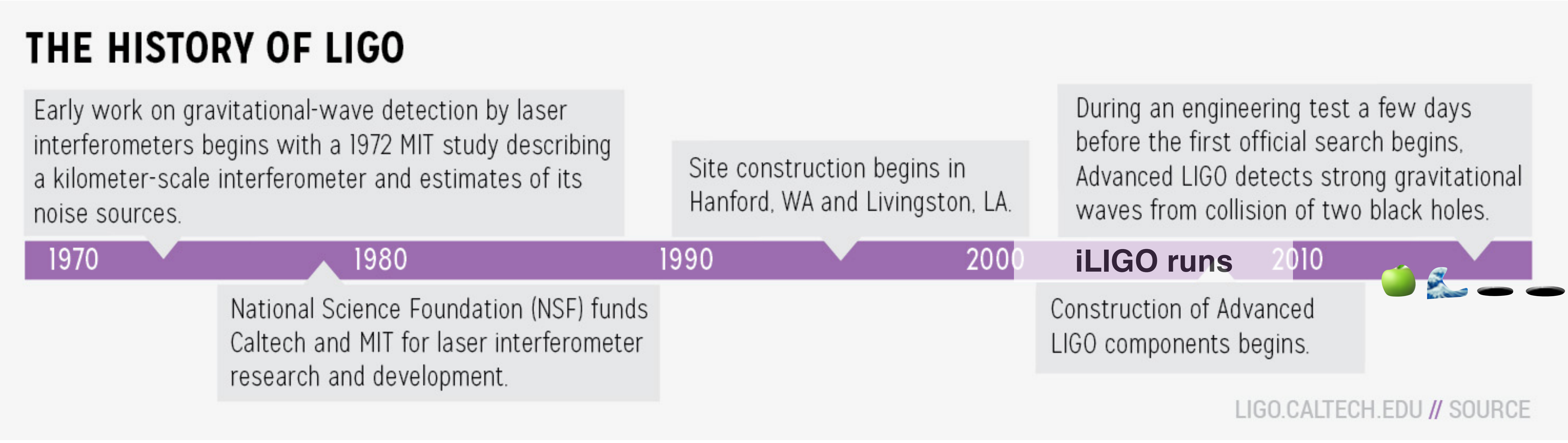
- **Modified Michelson interferometer** with ~300x resonant arm cavities (in 1μPa vacuum), power and signal recycling
- 40-kg fused silica mirrors on quadruple-pendulum suspensions with active seismic isolation
- 20 W input power, 100 kW circulating in O1
- **Servos** in 300 control loops to maintain resonance and alignment; **calibration** achieved by measuring response to induced test-mass motion
- **Environmental monitors**: seismometers, accelerometers, microphones, magnetometers, radio receivers, weather sensors, ac-power line monitors, cosmic-ray detector

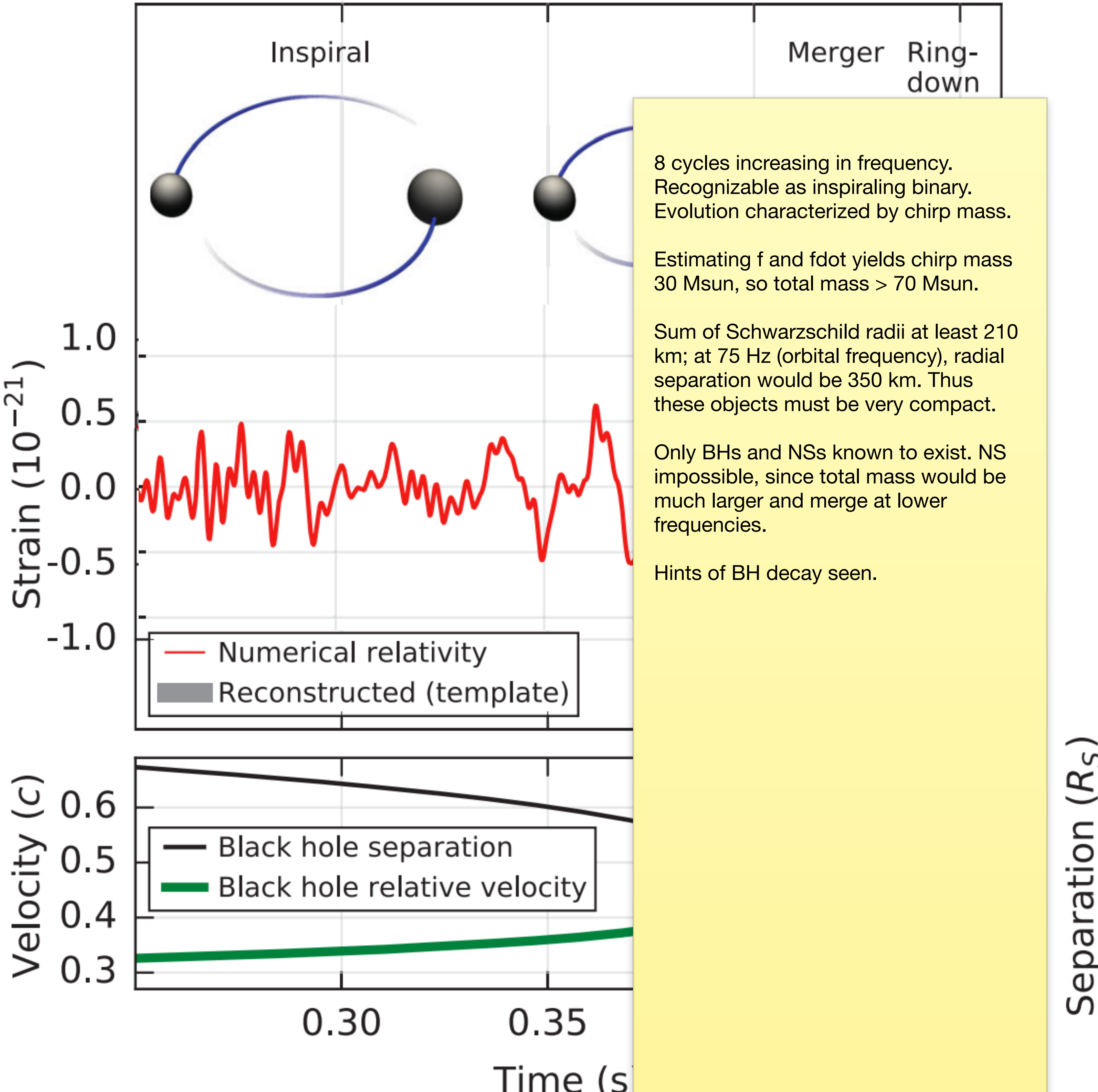


The LIGO observatories

[LVC 2016]

Advanced LIGO & Advanced Virgo





$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$
$$= \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

8 cycles increasing in frequency. Recognizable as inspiraling binary. Evolution characterized by chirp mass.

Estimating f and fdot yields chirp mass 30 Msun, so total mass > 70 Msun.

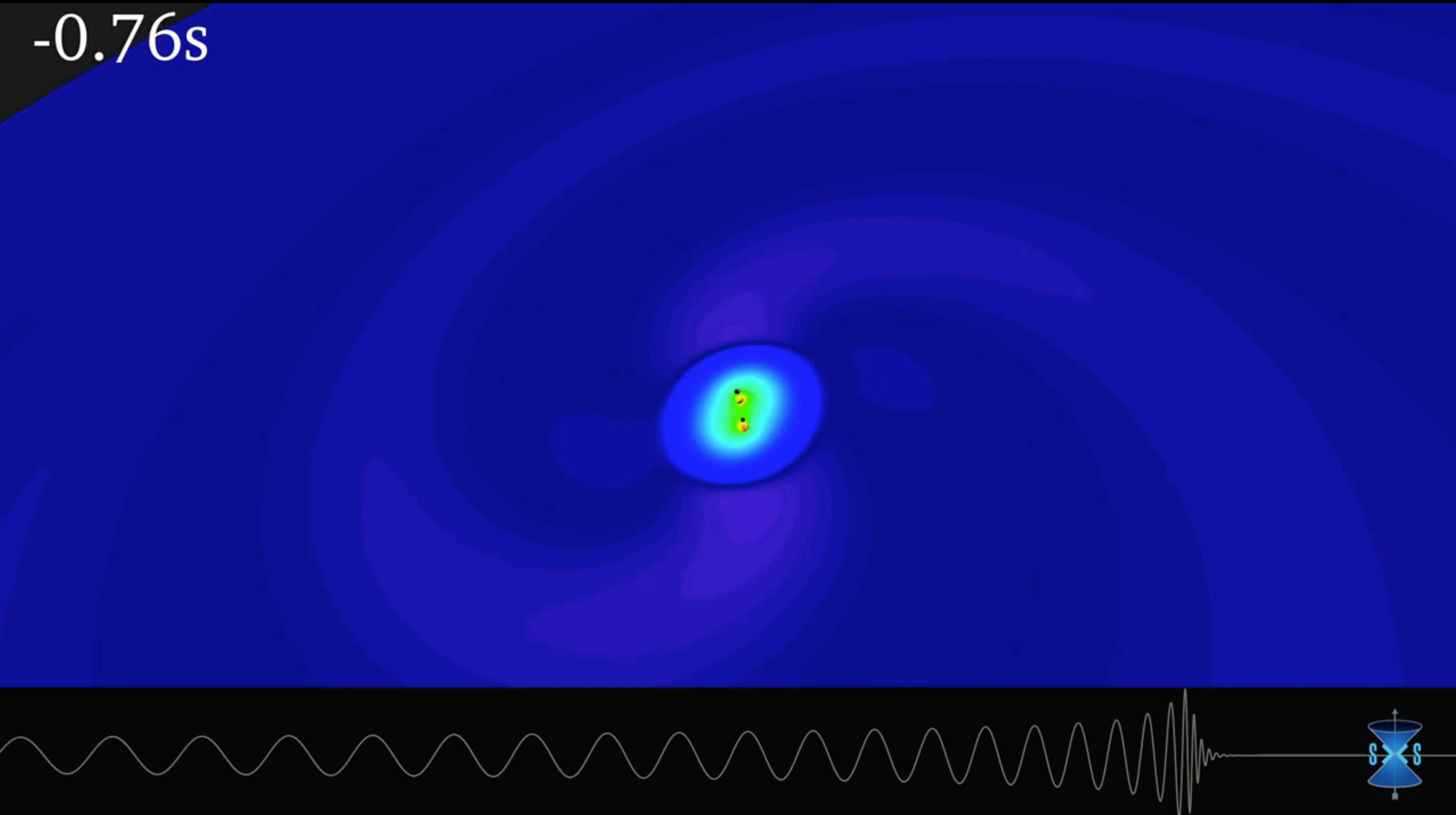
Sum of Schwarzschild radii at least 210 km; at 75 Hz (orbital frequency), radial separation would be 350 km. Thus these objects must be very compact.

Only BHs and NSs known to exist. NS impossible, since total mass would be much larger and merge at lower frequencies.

Hints of BH decay seen.

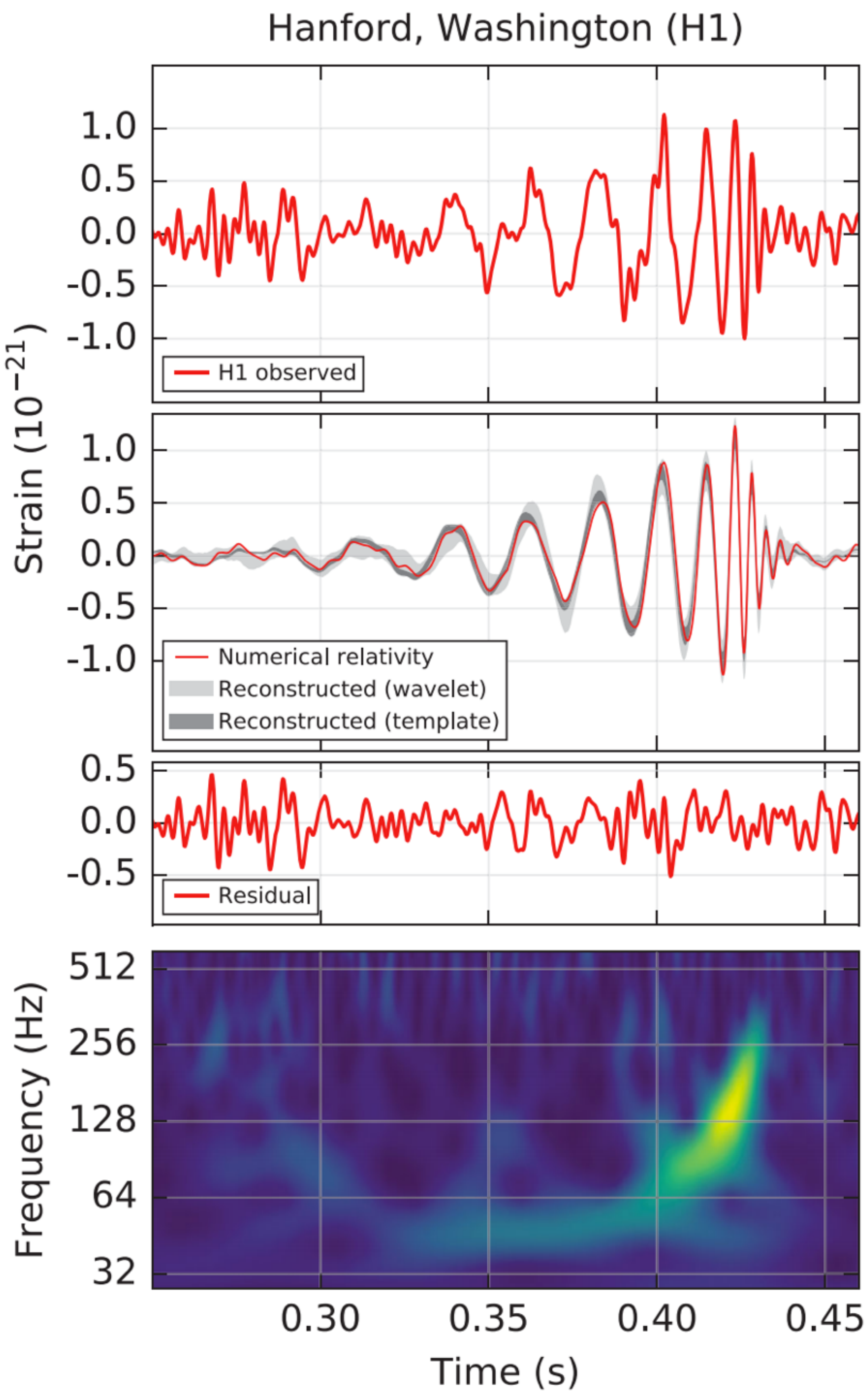
GW150914: nd ringdown

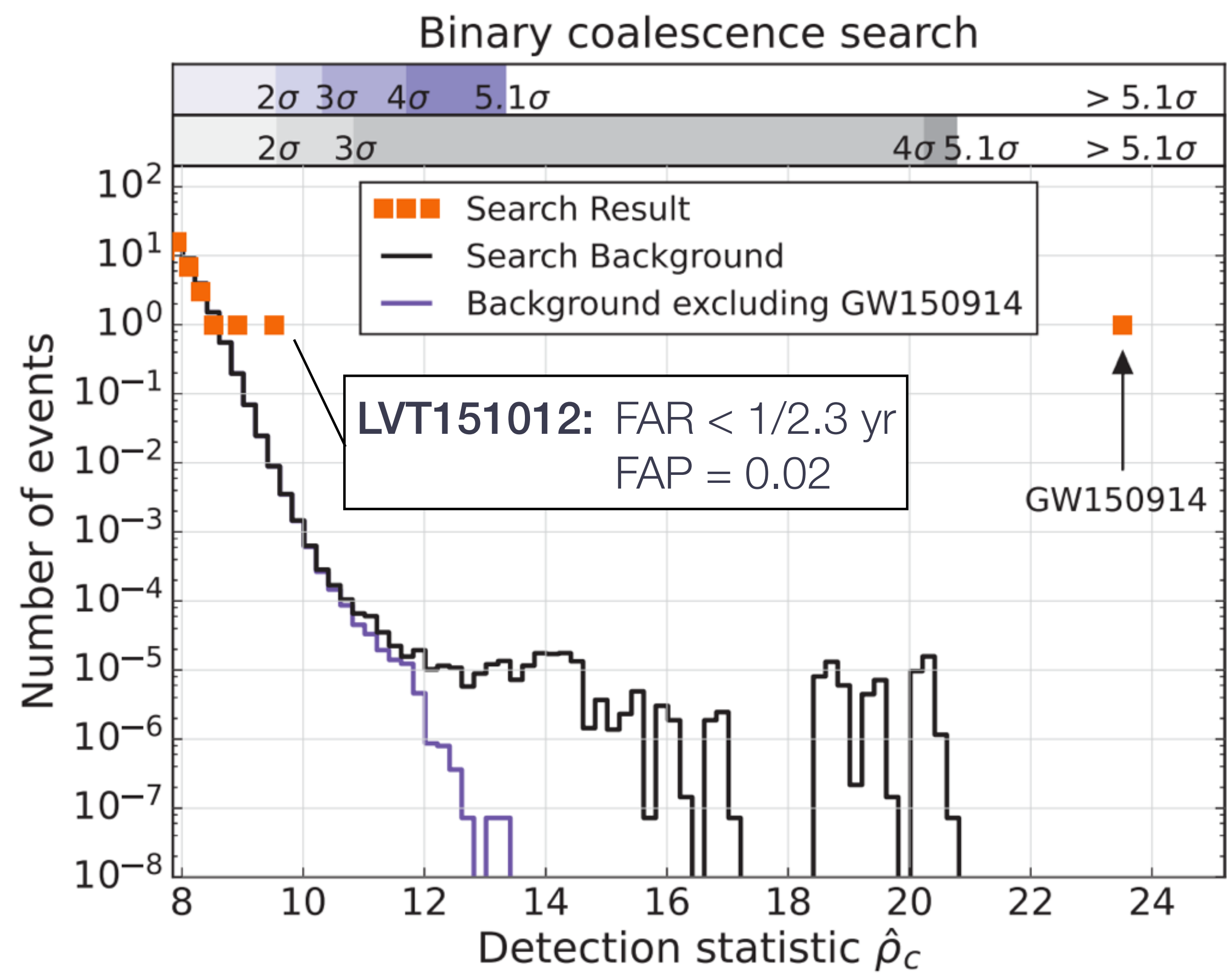
[LVC 2016]



GW150914: numerical relativity simulation

[SXS collaboration 2016]

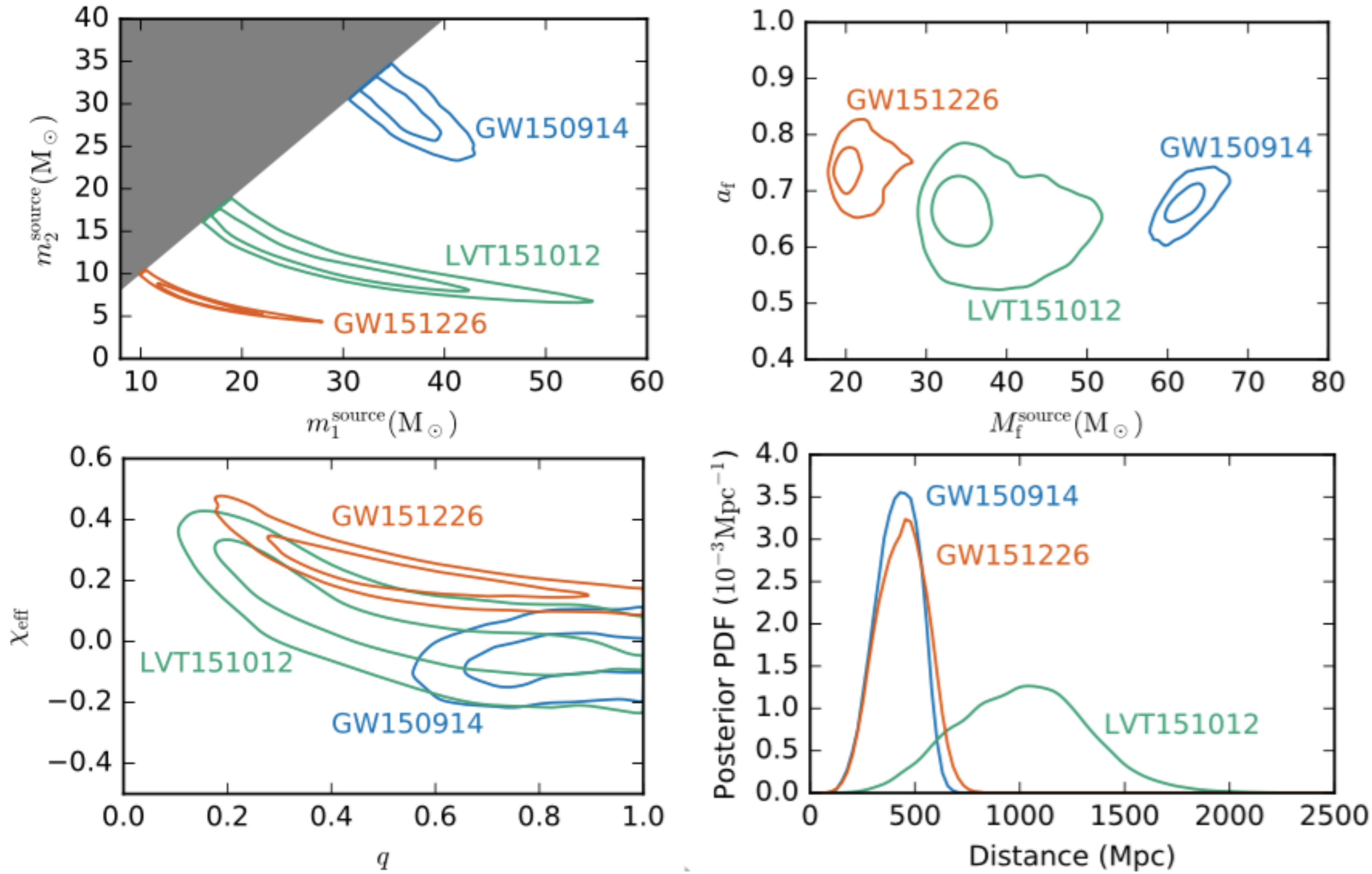




- Binaries with masses 1–99 M⊙, total mass < 100 M⊙, dimensionless spin < 0.99
- 250,000 PN and EOB signal templates. Matched-filter SNR + χ^2 statistic
- Measured on 608,000-yr background, false-alarm rate < 1 in 203,000 yr (2×10^{-7} false alarm = 5.1σ)

GW150914: matched-filter inspiral search

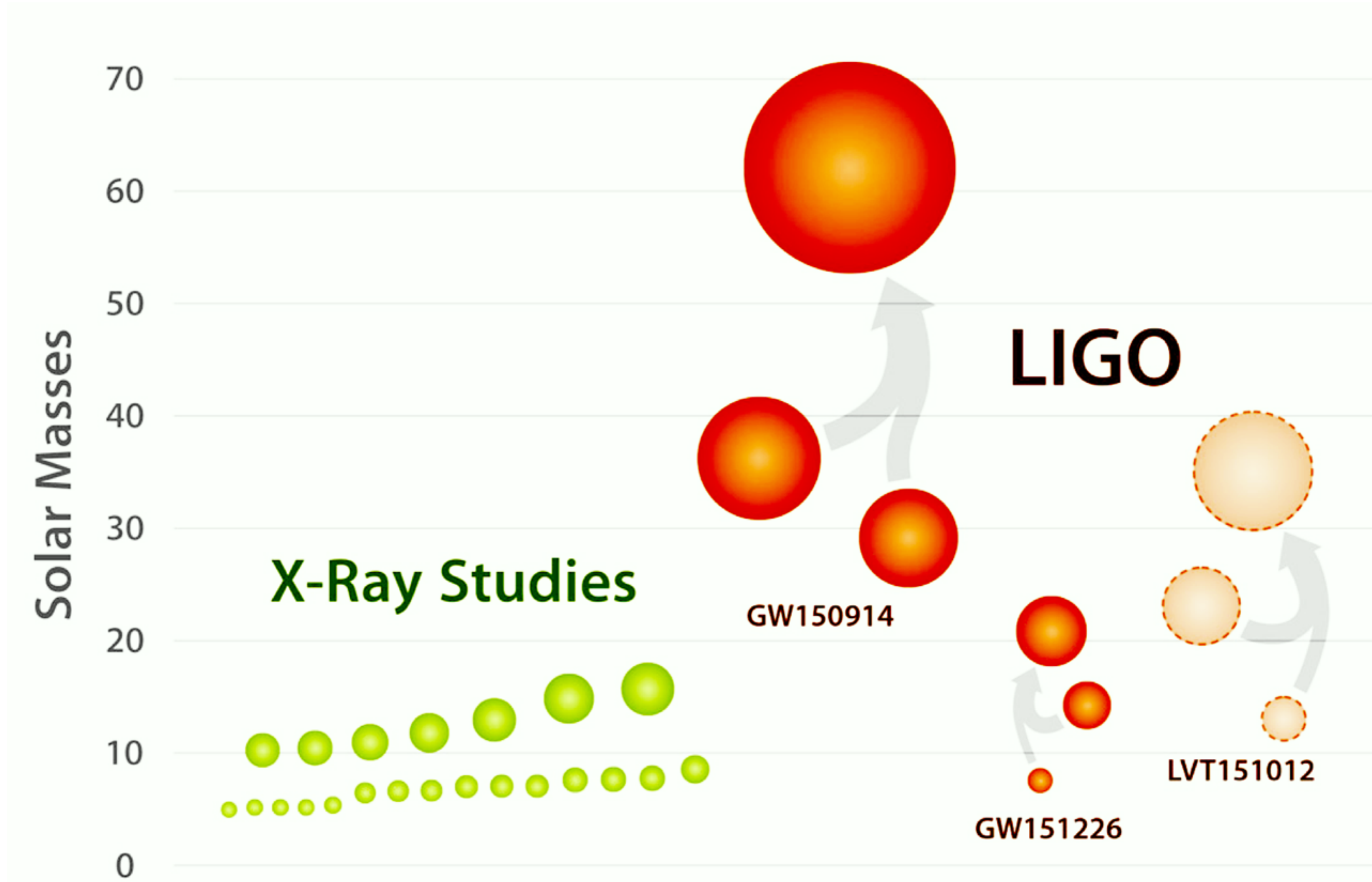
[LVC 2016]



	SNR	solar masses	effective spin	D/Mpc	z
GW150914	23.7	36 + 29		420	0.1
LVT151012	9.7	23 + 13		1000	0.2
GW151226	13	14 + 7.5	0.2	440	0.1

LIGO O1 BBH: parameter estimation

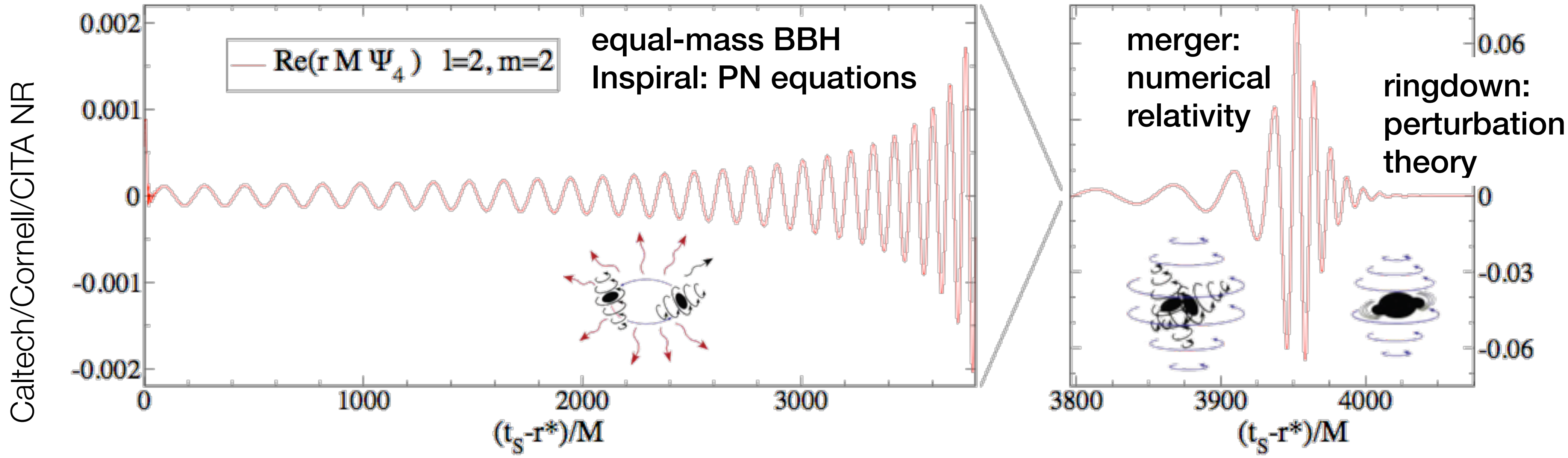
[LVC 2016]



- Primordial: density fluctuations after Big Bang
- Pop III: first massive stars (1% of stars in Universe)
- Pop II/I: classic field binary evolution (90%)
- Pop II/I: rapid rotation (homogeneous evol.) (10%)
- Pop II/I: dynamical formation in globular clusters (0.1%)
- Exotic: e.g., single-star core splitting

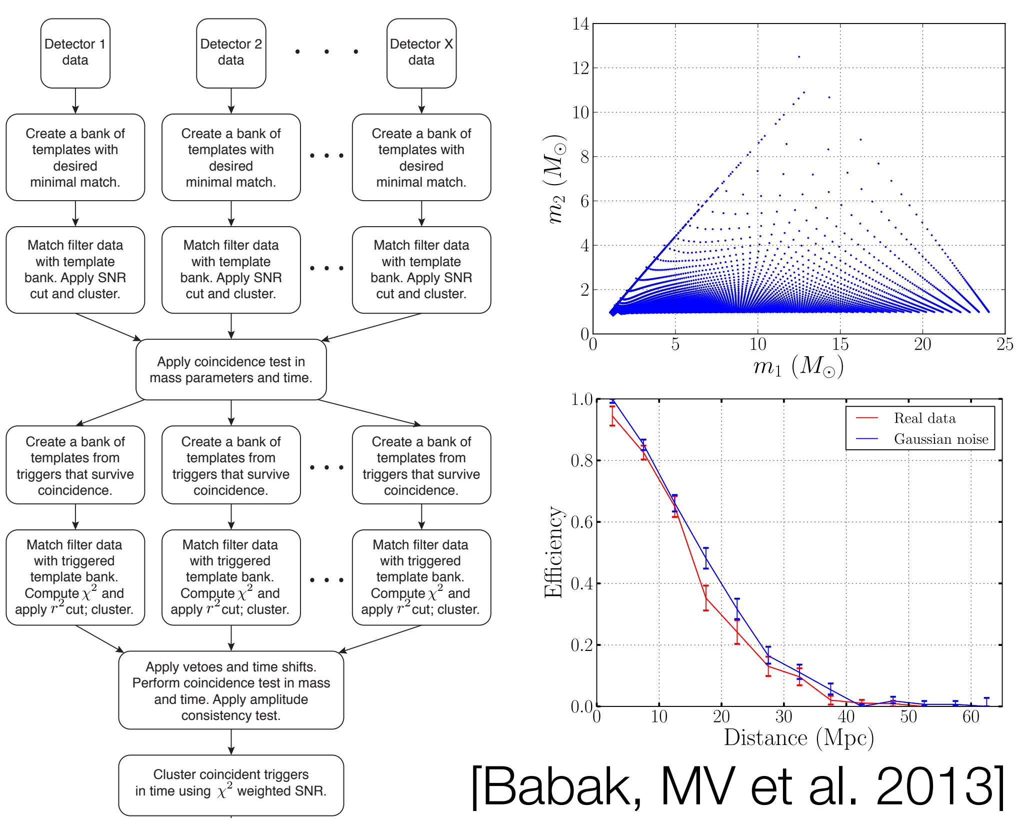
Origin of massive GW150914-like BHs

[LVC 2016, Belczynski 2016]



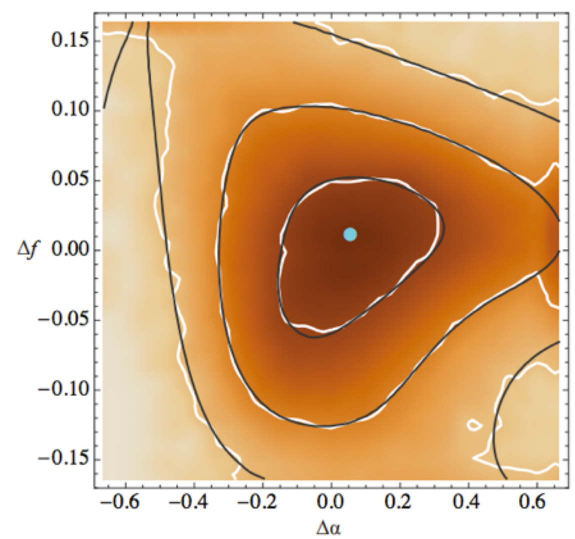
waveform models

GW searches



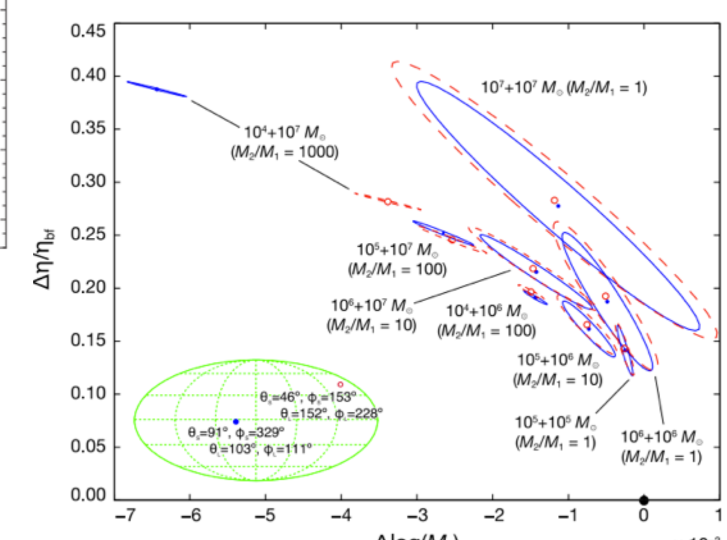
[Babak, MV et al. 2013]

statistical inference

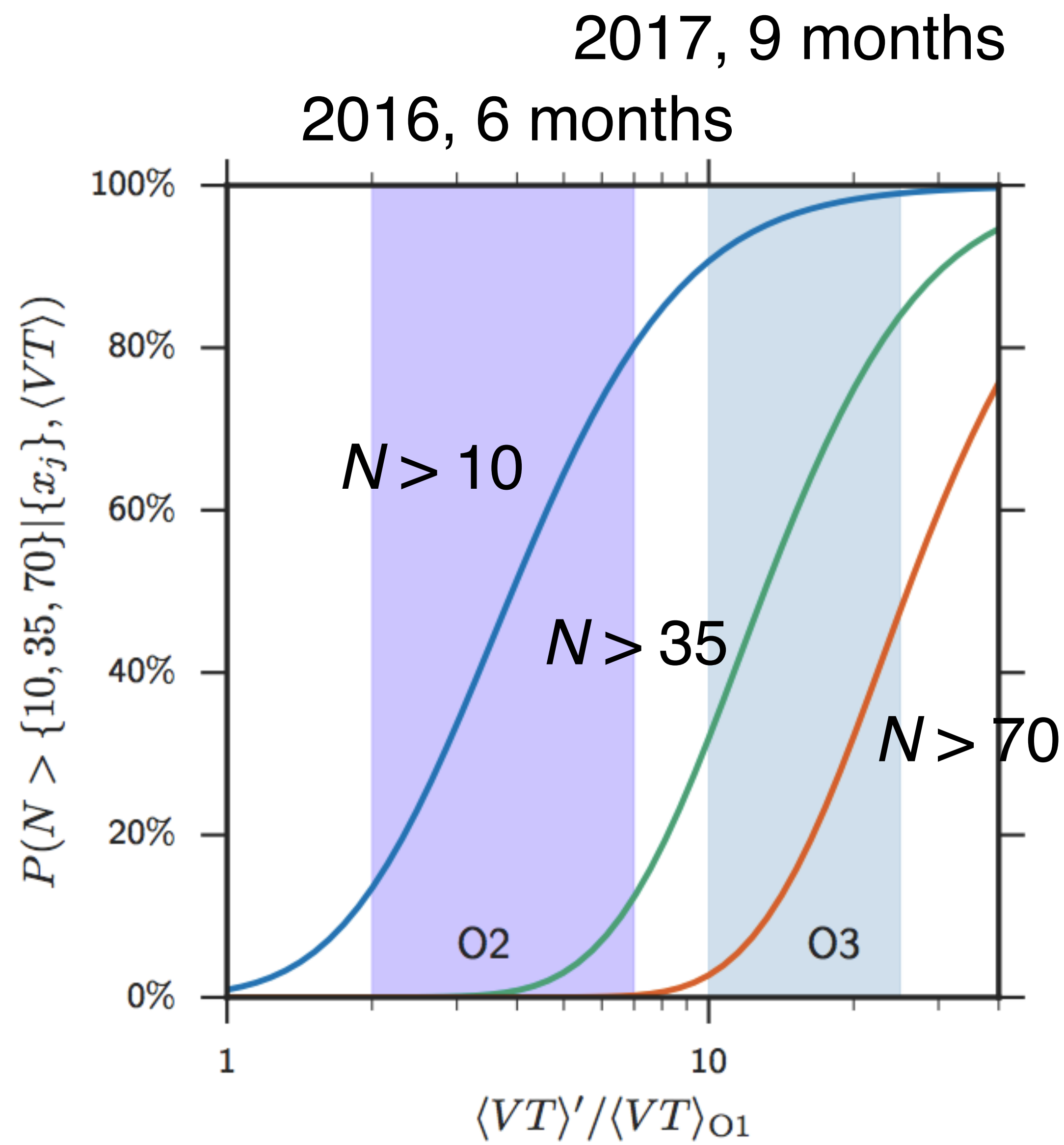


[MV 2008, 2012]

[Cutler & MV 2007]



Mass distribution	$R/(\mathrm{Gpc}^{-3}\mathrm{yr}^{-1})$		
	PyCBC	GstLAL	Combined
Event based			
GW150914	$3.2^{+8.3}_{-2.7}$	$3.6^{+9.1}_{-3.0}$	$3.4^{+8.6}_{-2.8}$
LVT151012	$9.2^{+30.3}_{-8.5}$	$9.2^{+31.4}_{-8.5}$	$9.4^{+30.4}_{-8.7}$
GW151226	35^{+92}_{-29}	37^{+94}_{-31}	37^{+92}_{-31}
All	53^{+100}_{-40}	56^{+105}_{-42}	55^{+99}_{-41}
Astrophysical			
Flat	31^{+43}_{-21}	30^{+43}_{-21}	30^{+43}_{-21}
Power Law	100^{+136}_{-69}	95^{+138}_{-67}	99^{+138}_{-70}



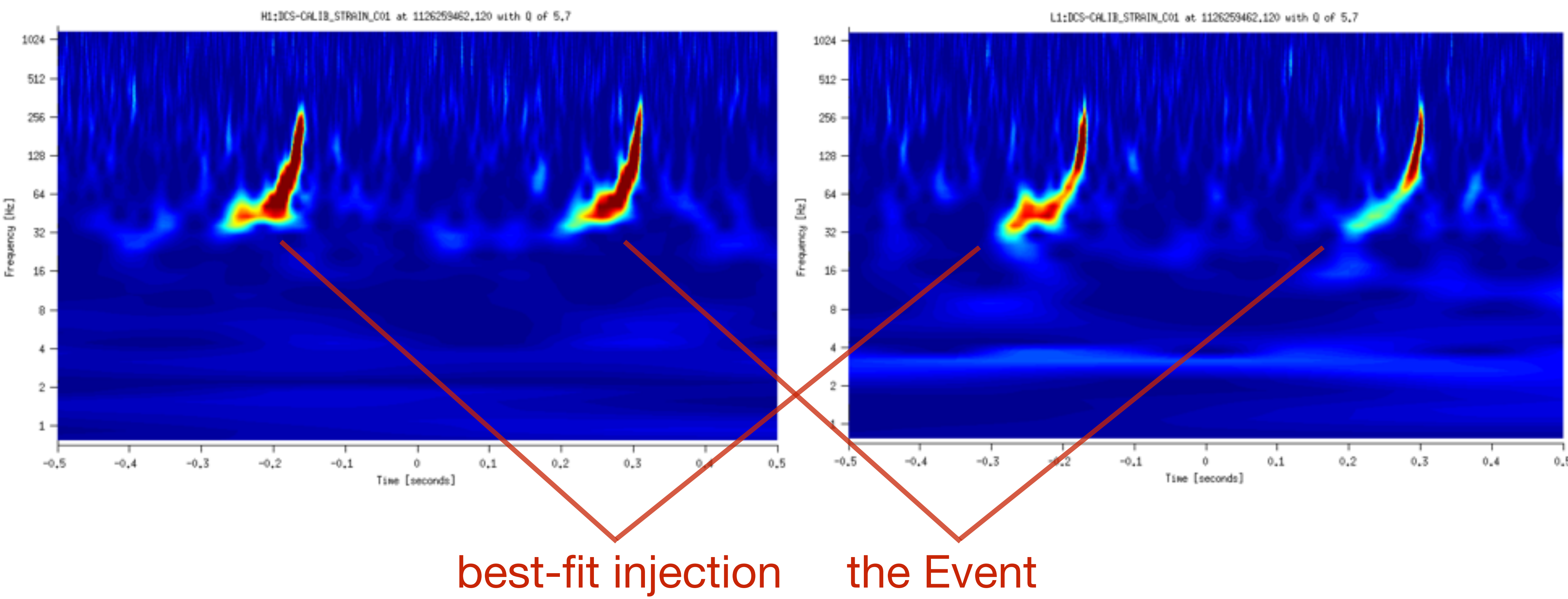
GW150914 and GW151226: merger rate estimates

[LVC 2016]

- **Consistency**: useful sanity checks, hard to interpret statistically. P values are possible with much work. But would we ever believe an inconsistent result?
- **Parametric tests**: constraints on GR "constants" (PN coefficients, graviton mass)—useful proxies for increasing resolving power, but again hard to interpret. Apparent violations may focus our search for new physics.
- **Alternative theories**: new physics will be established by model comparison of GR with fully predictive alternative theories. (However, it is a problem to establish Bayesian priors for alternative gravity, and for alternative-gravity parameters.)

A hierarchy of tests of GR with GW observations

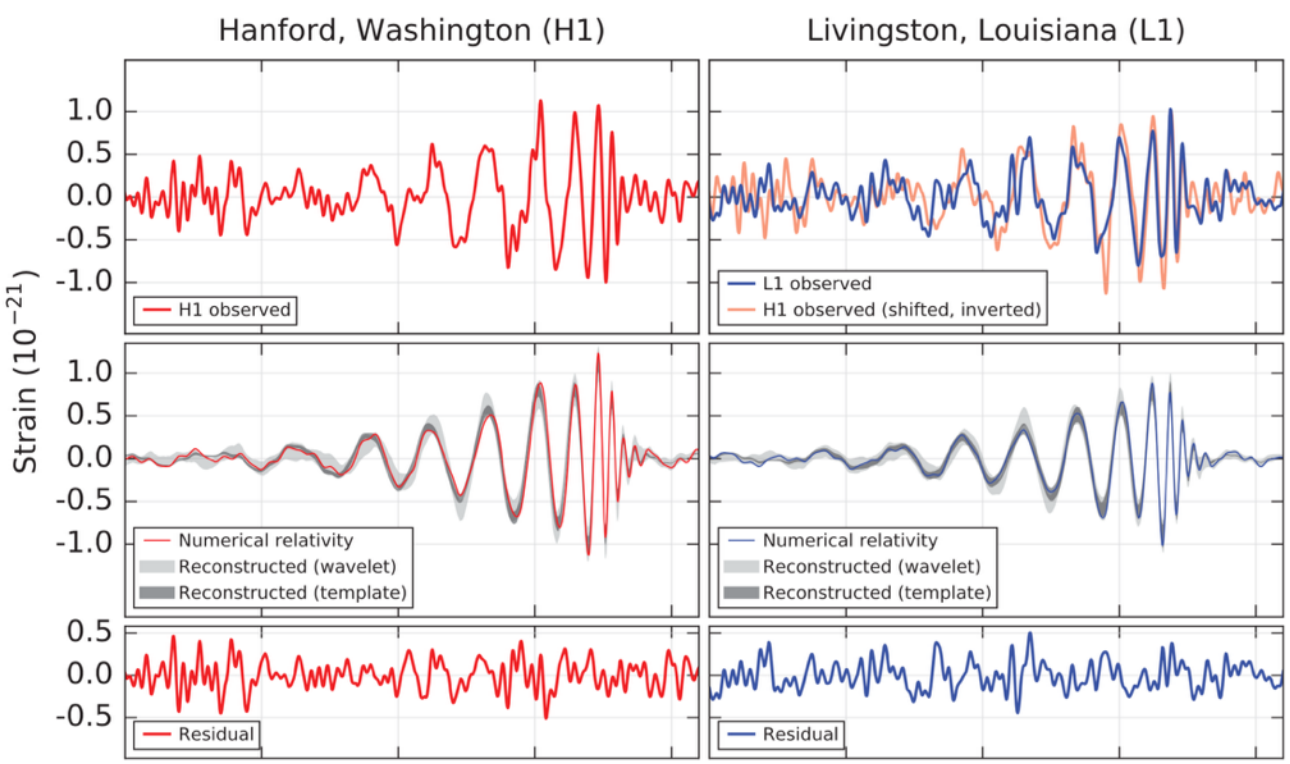
[MV in preparation]

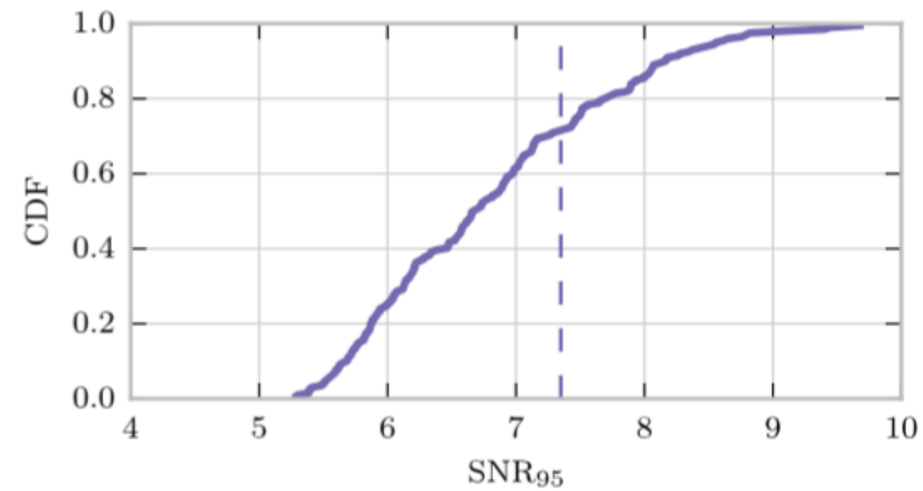


“Consistency” test: residual

[B. Allen 2016]

an actual null-hypothesis test (with *P*-value 0.3), which implies that GR prediction is verified to 4%; i.e., no GR violations above 4% of waveform





SNR in coherent burst analysis of data residual after subtracting best-fit GW150914 waveform

$$\mathrm{SNR}^2_{\mathrm{res}} = \frac{1-\mathrm{FF}^2}{\mathrm{FF}^2}\mathrm{SNR}^2_{\mathrm{det}}$$

Fitting Factor: parameter-maximized waveform overlap

$$\mathrm{SNR}_{\mathrm{res}} \leq 7.3 \Rightarrow \mathrm{FF} \geq 0.96$$

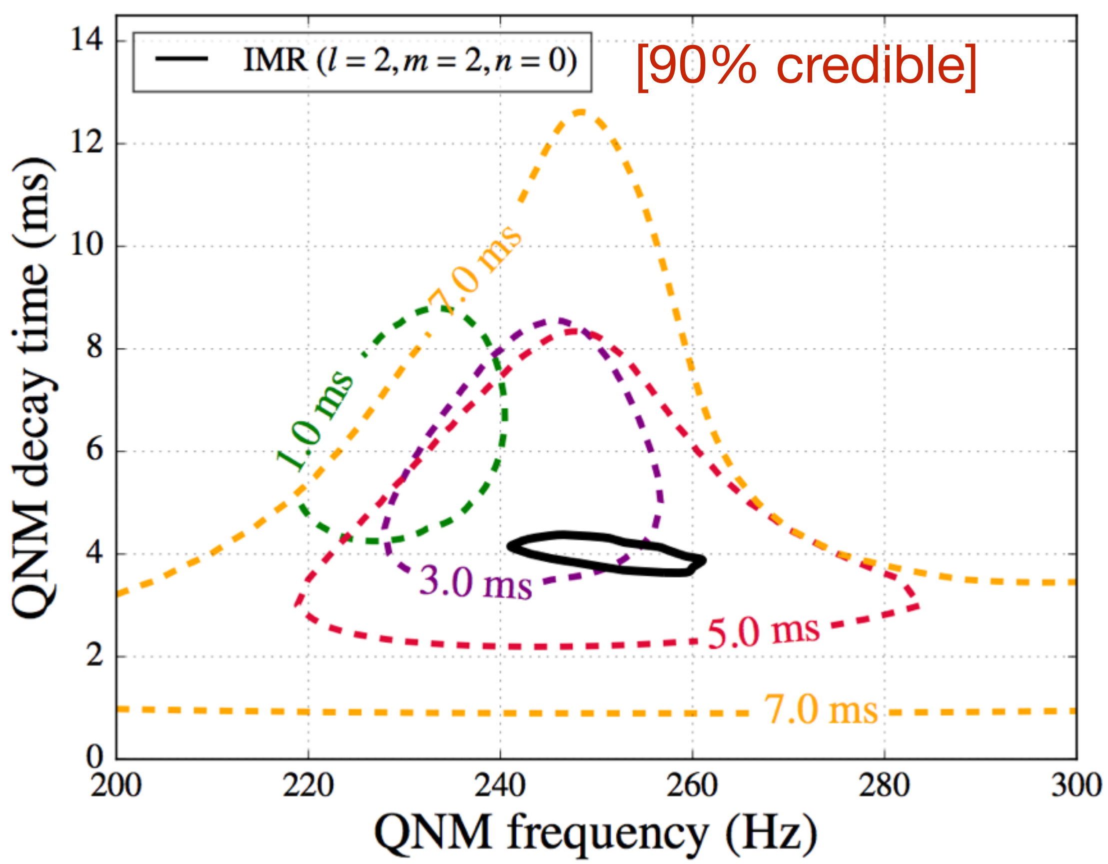
(for violations not absorbed by physical parameters)

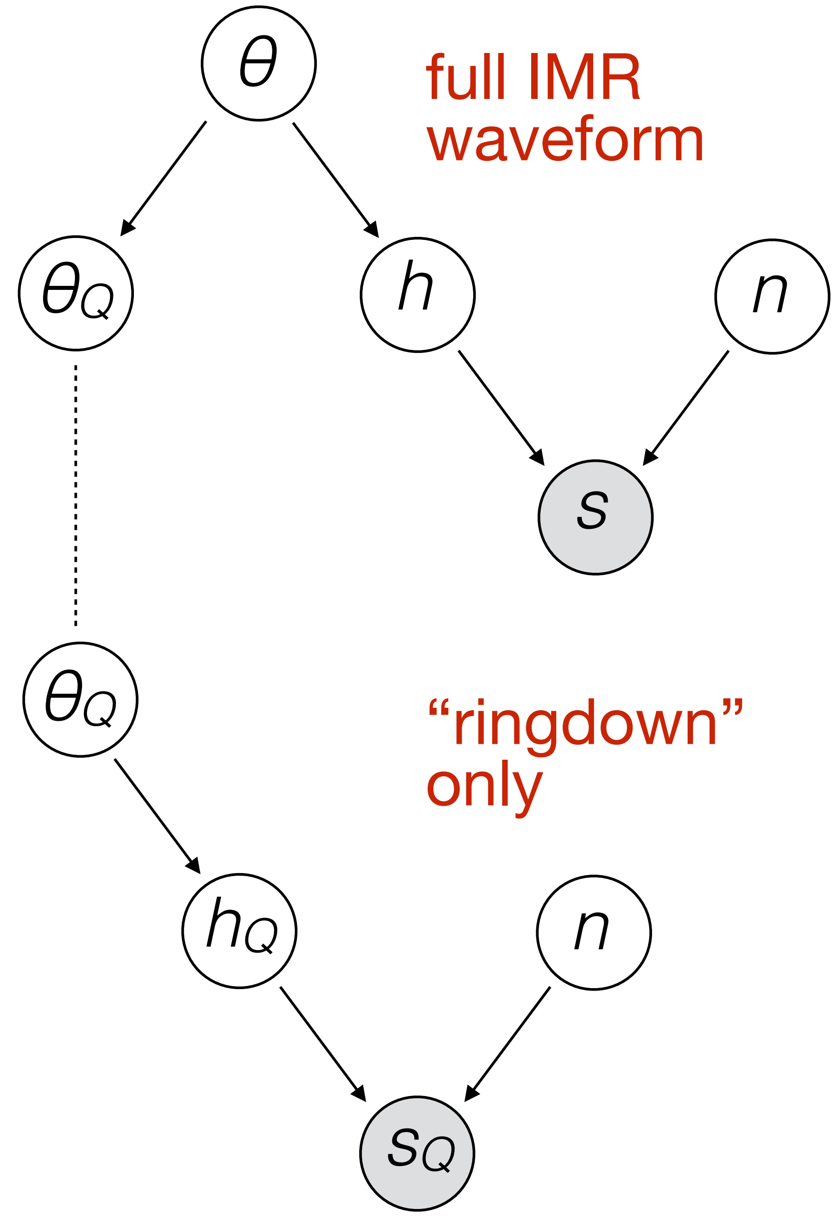
“Consistency” test: residual

[LVC 2016]

answers question: if we estimate QNM parameter directly and compare them with values deduced from the preferred binary parameters, are the resulting estimates “consistent”?

single quasi-normal mode





“Consistency” test: quasinormal modes

[LVC 2016]

answers question: what are the preferred values of individual waveform coefficients in a set of hypothetical theories in which each in turn is free?

Theoretical Effect	Theoretical Mechanism	Theories	ppE b	Order	Mapping
Scalar Dipolar Radiation	Scalar Monopole Field Activation	EdGB [140, 142, 149, 150]	-7	-1PN	$\beta_{\rm EdGB}$ [140]
	BH Hair Growth	Scalar-Tensor Theories [59, 151]	-7	-1PN	$\beta_{\rm ST}$ [59, 151]
Anomalous Acceleration	Extra Dimension Mass Leakage	RS-II Braneworld [152, 153]	-13	-4PN	$\beta_{\rm ED}$ [141]
	Time-Variation of G	Phenomenological [137, 154]	-13	-4PN	$\beta_{\dot{G}}$ [137]
Scalar Quadrupolar Radiation Scalar Dipole Force Quadrupole Moment Deformation	Scalar Dipole Field Activation due to Gravitational Parity Violation	dCS [140, 155]	-1	$+2$PN	$\beta_{\rm dCS}$ [146]
Scalar/Vector Dipolar Radiation Modified Quadrupolar Radiation	Vector Field Activation due to Lorentz Violation	EA [109, 110], Khronometric [111, 112]	-7 -5	-1PN 0PN	$\beta_{\text{Æ}}^{(-1)}$ [113] $\beta_{\text{Æ}}^{(0)}$ [113]
Modified Dispersion Relation	GW Propagation/Kinematics	Massive Gravity [156–159]	-3	$+1$PN	$\beta_{\rm MDR}$ [145, 156]
		Double Special Relativity [160–163]	$+6$	$+5.5$PN	
		Extra Dim. [164], Horava-Lifshitz [165–167],	$+9$	$+7$PN	
		gravitational SME ($d=4$) [179]	$+3$	$+4$PN	
		gravitational SME ($d=5$) [179]	$+6$	$+5.5$PN	
		gravitational SME ($d=6$) [179]	$+9$	$+7$PN	
		Multifractional Spacetime [168–170]	3–6	4–5.5PN	

[Yunes, Yagi, Pretorius 2016]

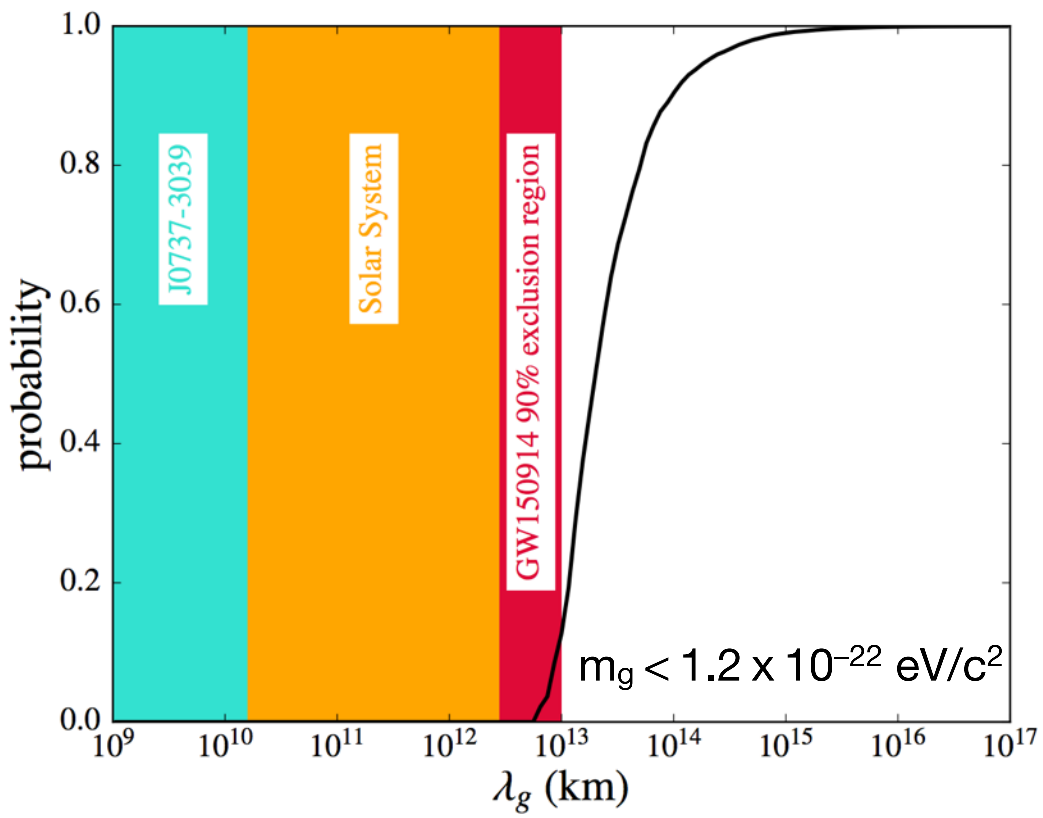
$$h(f) = \frac{1}{D}\frac{\mathcal{A}}{\sqrt{\dot{F}}} f^{2/3} e^{i\Psi(f)}$$

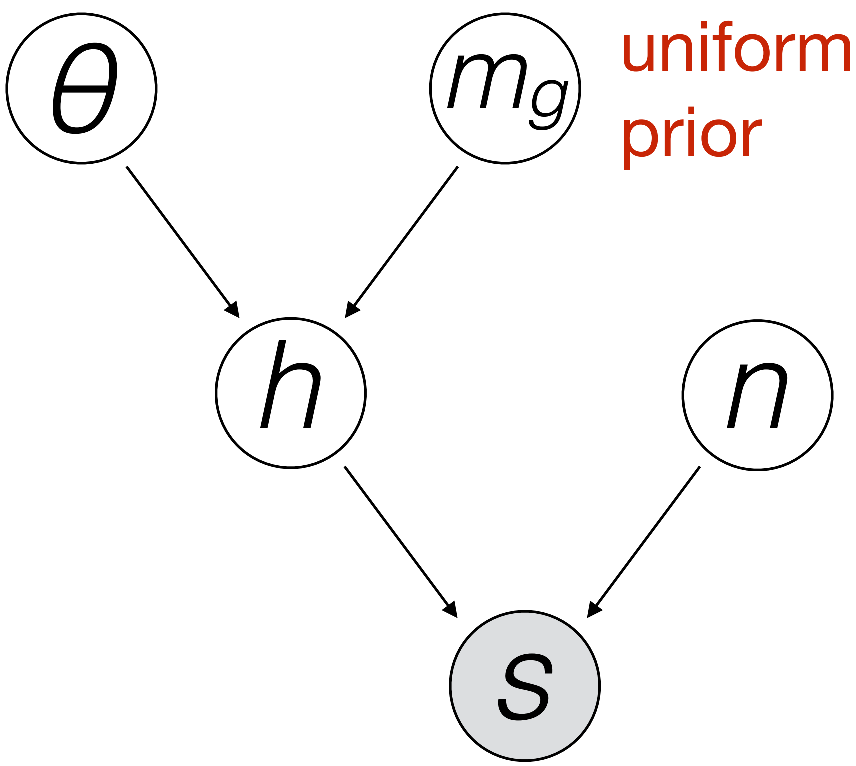
$$\Psi(f) = \sum_i \left[\psi_i + \psi_{il}\log f\right] f^{(i-5)/3} + \Phi^{\rm MR}[\beta_i, \alpha_i]$$

Parametric test: PN coefficients

[LVC 2016]

answers question: what is the preferred value of the "dispersion" m_g in a hypothetical theory of gravity where it is a free parameter?





$$h(f) = \frac{1}{D}\frac{\mathcal{A}}{\sqrt{\dot{F}}} f^{2/3} e^{i\Psi(f)}$$

$$\Psi(f) = \sum_i \left[\psi_i + \psi_{il}\log f\right] f^{(i-5)/3} + \Phi^{\mathrm{MR}}[\beta_i, \alpha_i]$$

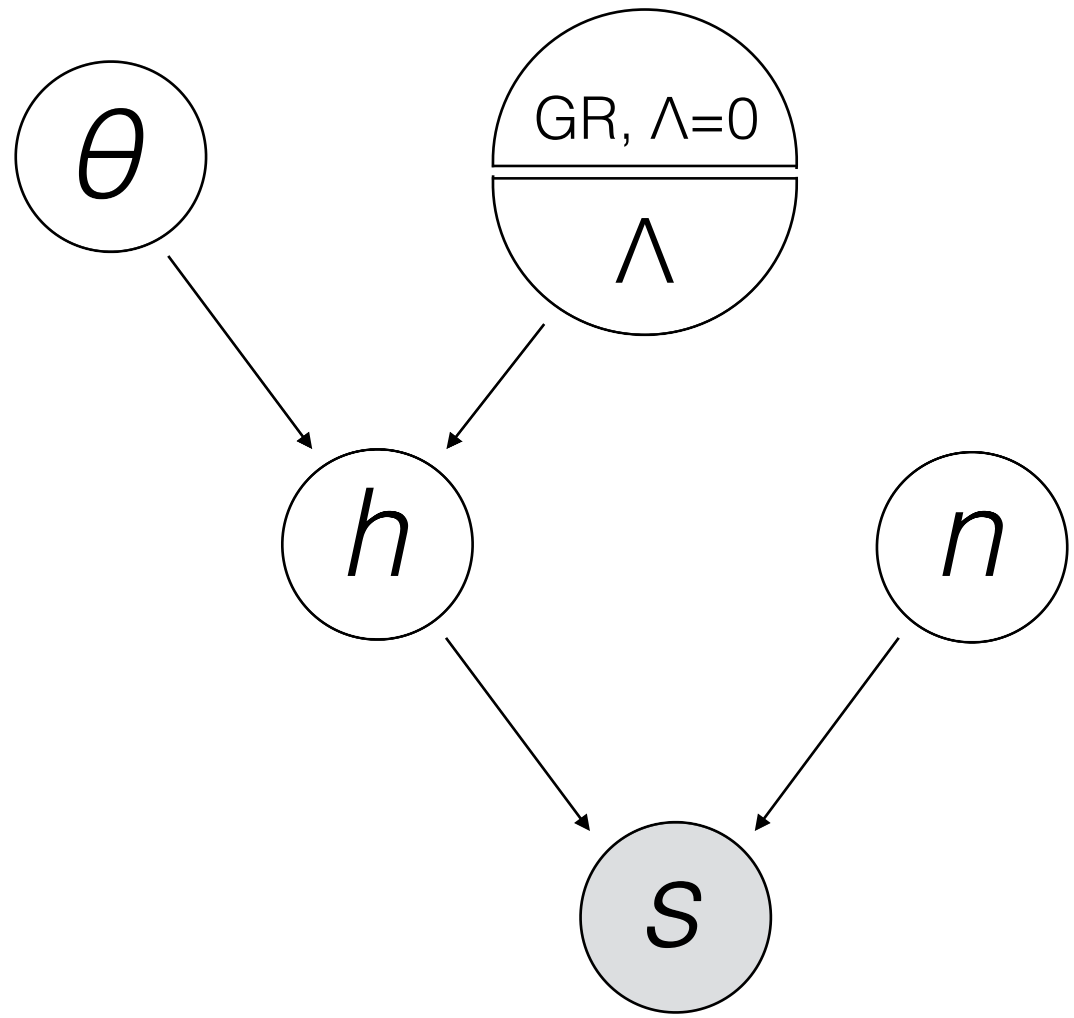
$$\frac{v_{\mathrm{g}}^2}{c^2} = 1 - \frac{m_{\mathrm{g}}^2 c^4}{E^2}$$

$$\delta\Psi(f) = \frac{\pi D c}{\lambda_g^2 (1+z) f}$$

Parametric test: graviton mass

[LVC 2016]

new physics follows from establishing an **anomaly**: we need to obtain convincing evidence that the data prefers an alternative theory of gravity over GR

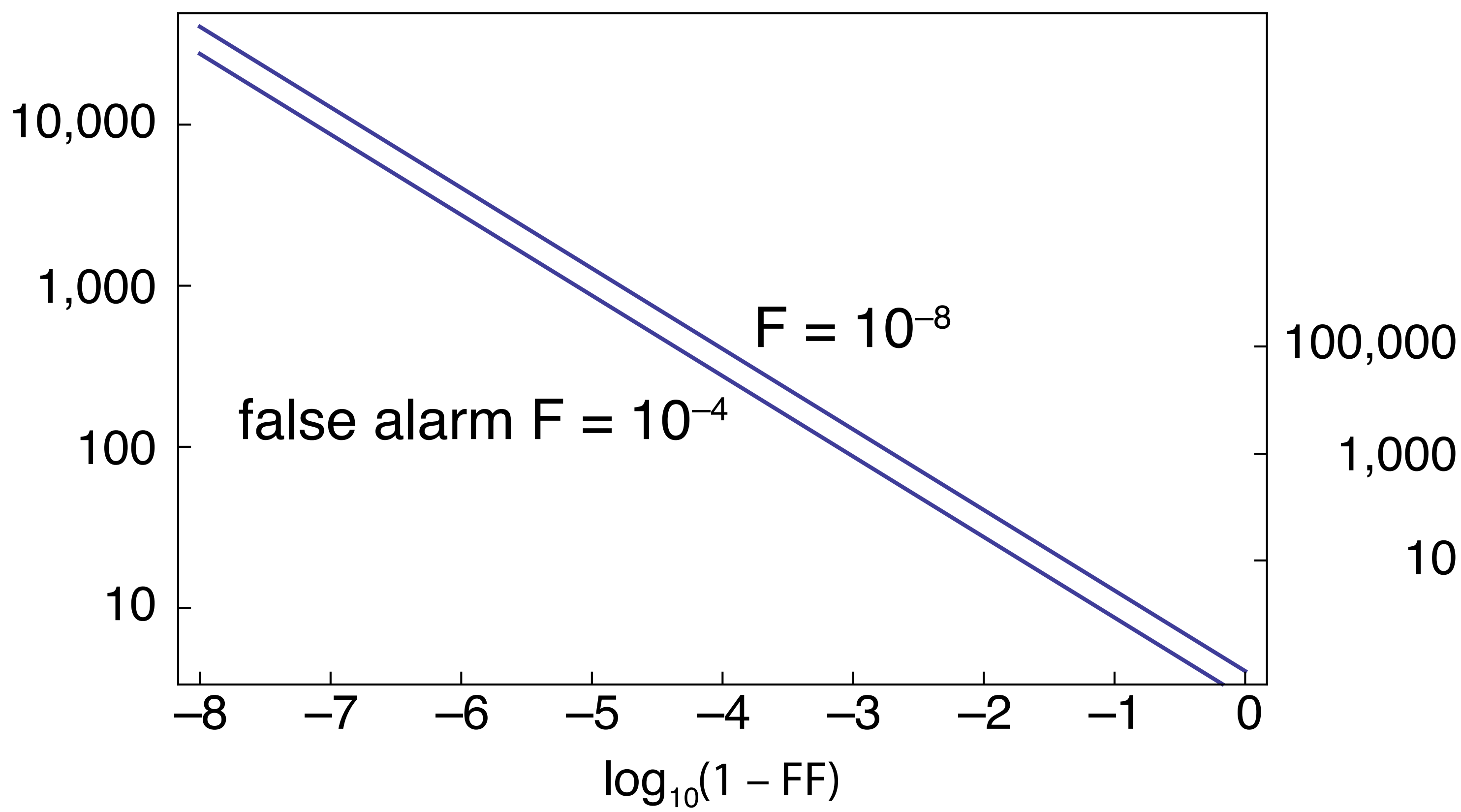


Detecting alternative gravity

[LVC 2016]

for a fixed false-alarm rate, we ask what **SNR** is needed to detect AG with 50% probability as a function of **fitting factor FF**, using the Bayesian odds ratio as “detection” statistic.

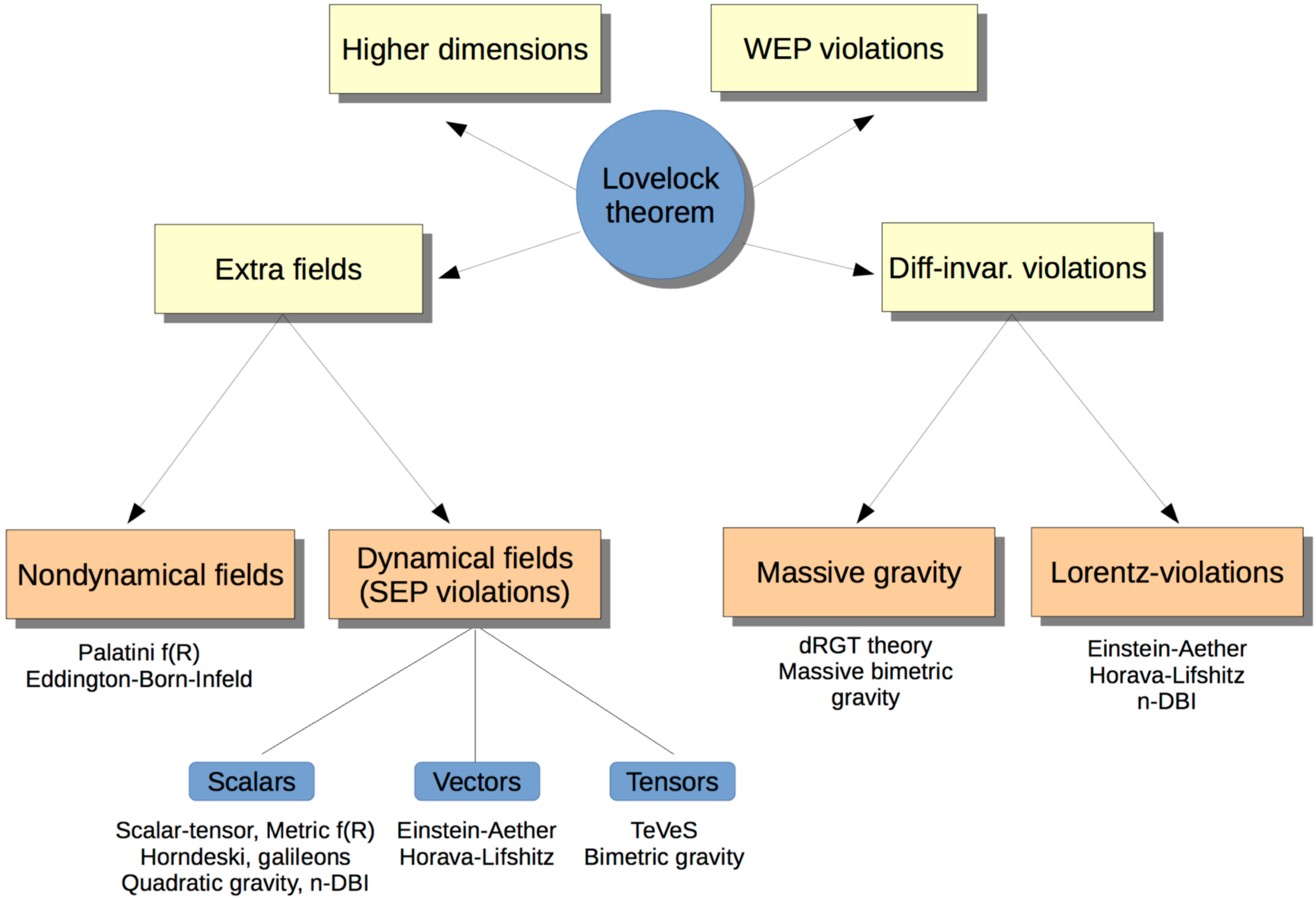
SNR
to detect AG



events
to yield SNR

Detection SNR limits GR test sensitivity

[MV 2012]



Modified theories of gravity

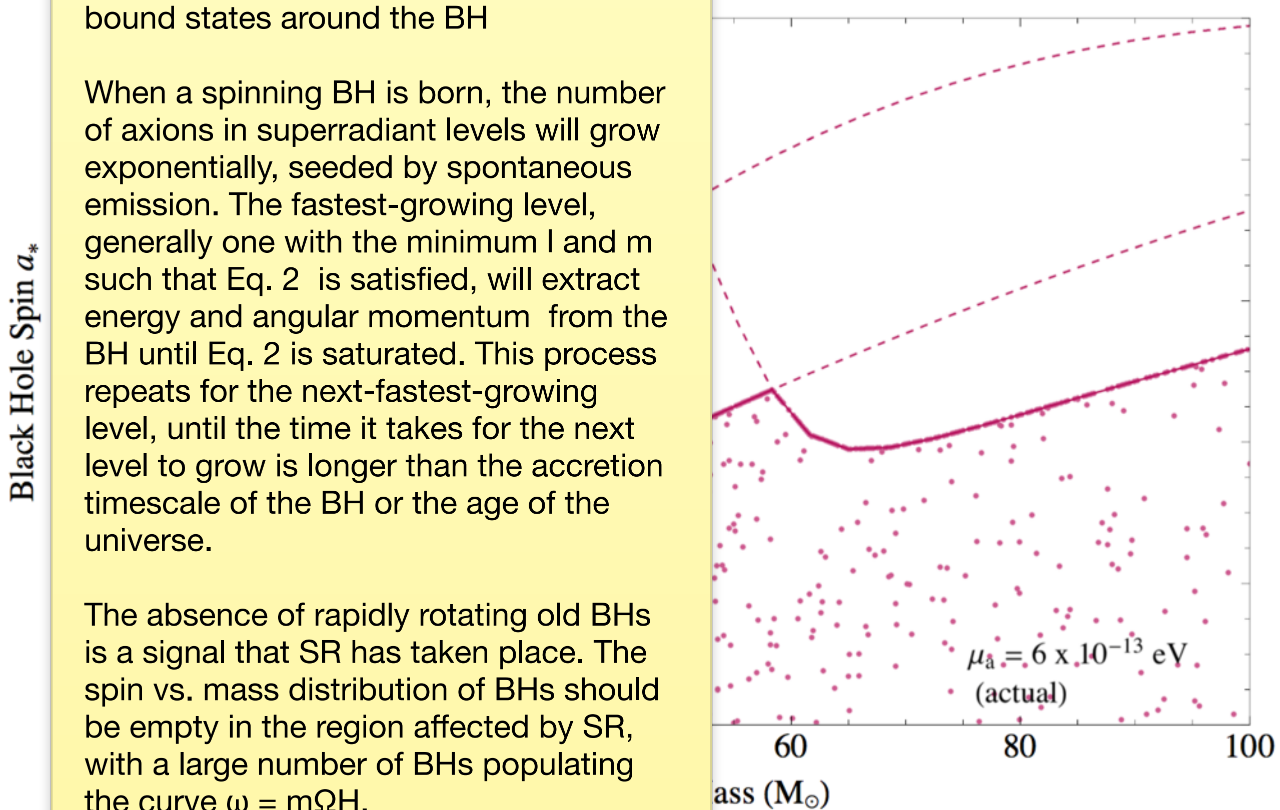
[Berti et al. 2016]

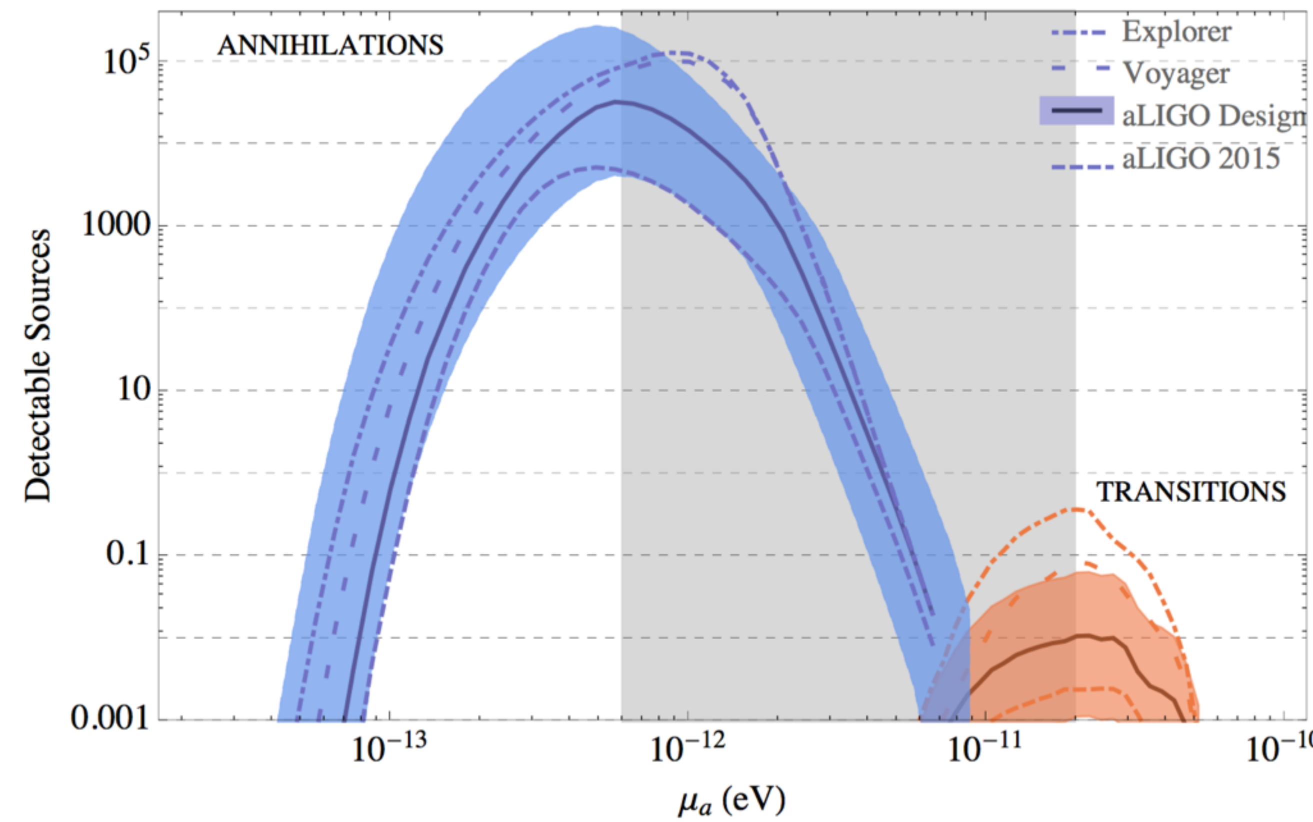
Axions with Compton wavelength large compared to the size of the BH have an approximately hydrogenic spectrum of bound states around the BH

When a spinning BH is born, the number of axions in superradiant levels will grow exponentially, seeded by spontaneous emission. The fastest-growing level, generally one with the minimum l and m such that Eq. 2 is satisfied, will extract energy and angular momentum from the BH until Eq. 2 is saturated. This process repeats for the next-fastest-growing level, until the time it takes for the next level to grow is longer than the accretion timescale of the BH or the age of the universe.

The absence of rapidly rotating old BHs is a signal that SR has taken place. The spin vs. mass distribution of BHs should be empty in the region affected by SR, with a large number of BHs populating the curve ω = mΩH.

Direct emission: two axions can annihilate into a single graviton of energy 2mu_A, creating a quasi monochromatic emission.





$$\mu_a \left(1 - \frac{\alpha^2}{2n^2}\right)$$

$$h_{ann} \approx 6 \times 10^{-23} \left(\frac{\alpha}{0.3}\right)^7 \left(\frac{a_*}{0.9}\right)\left(\frac{M_{BH}}{60 M_\odot}\right)\left(\frac{1\,\mathrm{Mpc}}{d}\right)$$

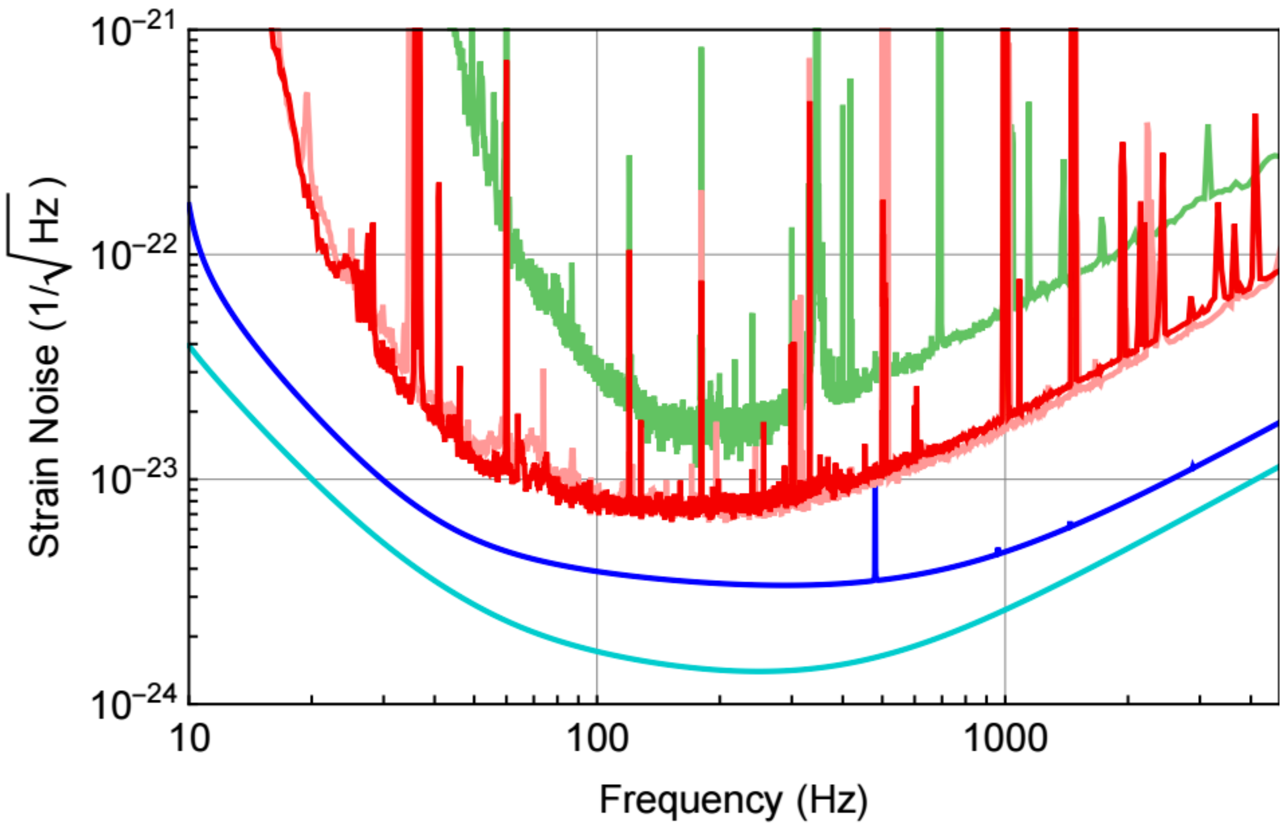
$$\Omega_H$$

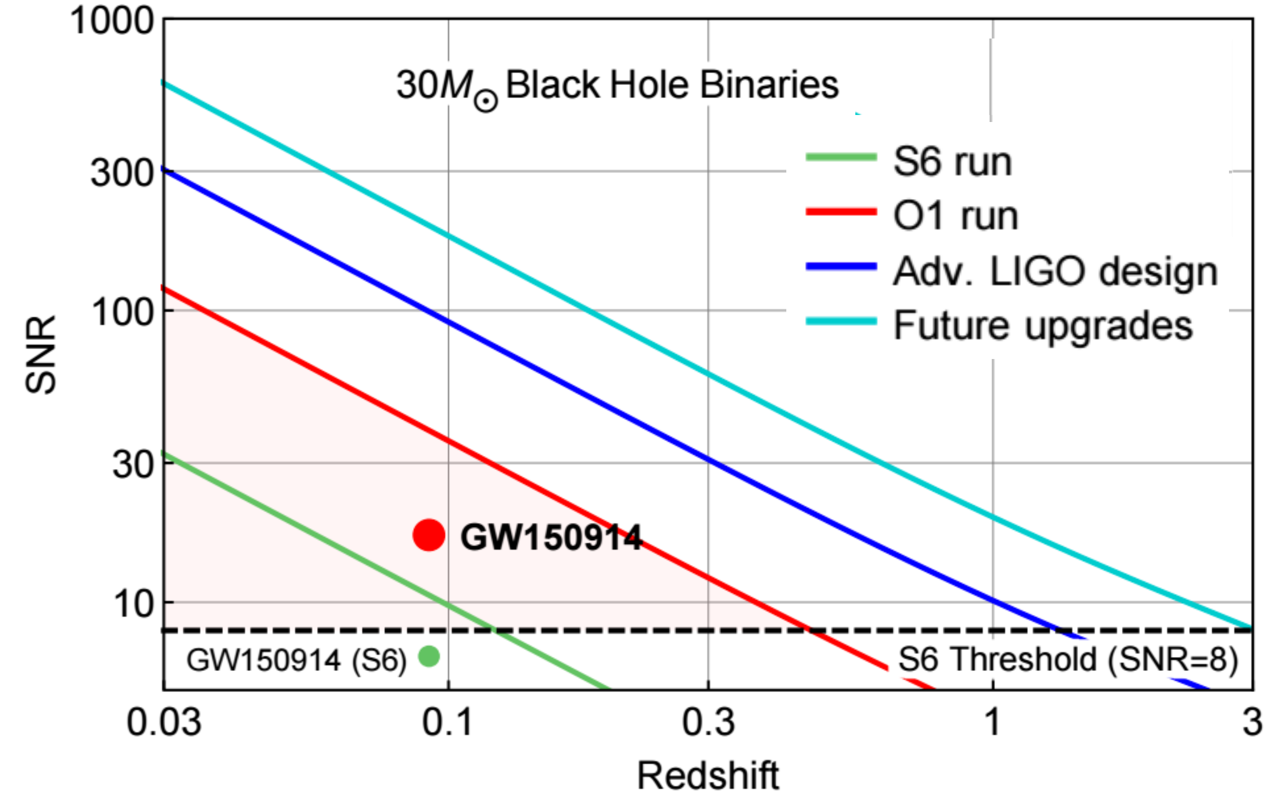
$$\tau_{ann} \approx 0.1 \text{ yr} \left(\frac{0.3}{\alpha}\right)^{15} \left(\frac{0.9}{a_*}\right)\left(\frac{M_{BH}}{60 M_\odot}\right)$$

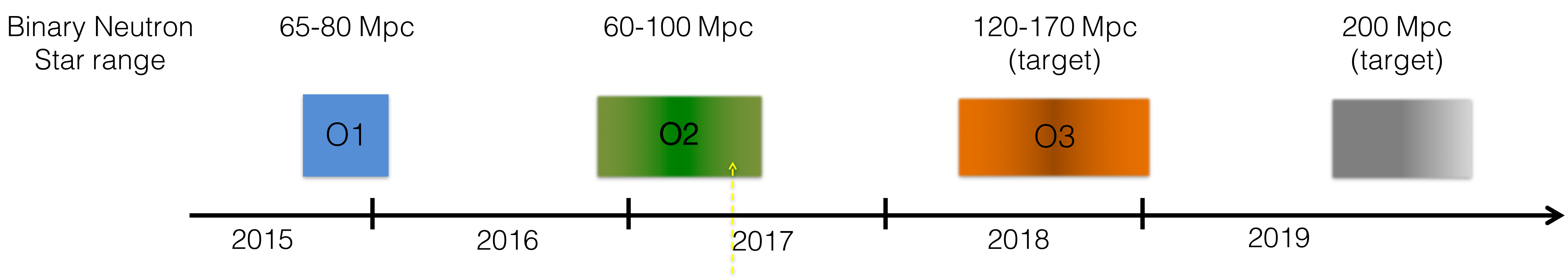
$$\Omega_H = \frac{1}{2r_g} \frac{a_*}{1+\sqrt{1-a_*^2}}$$

GWs from superradiant axions in gravitational “atoms”

[Arvanitaki et al. 2016]

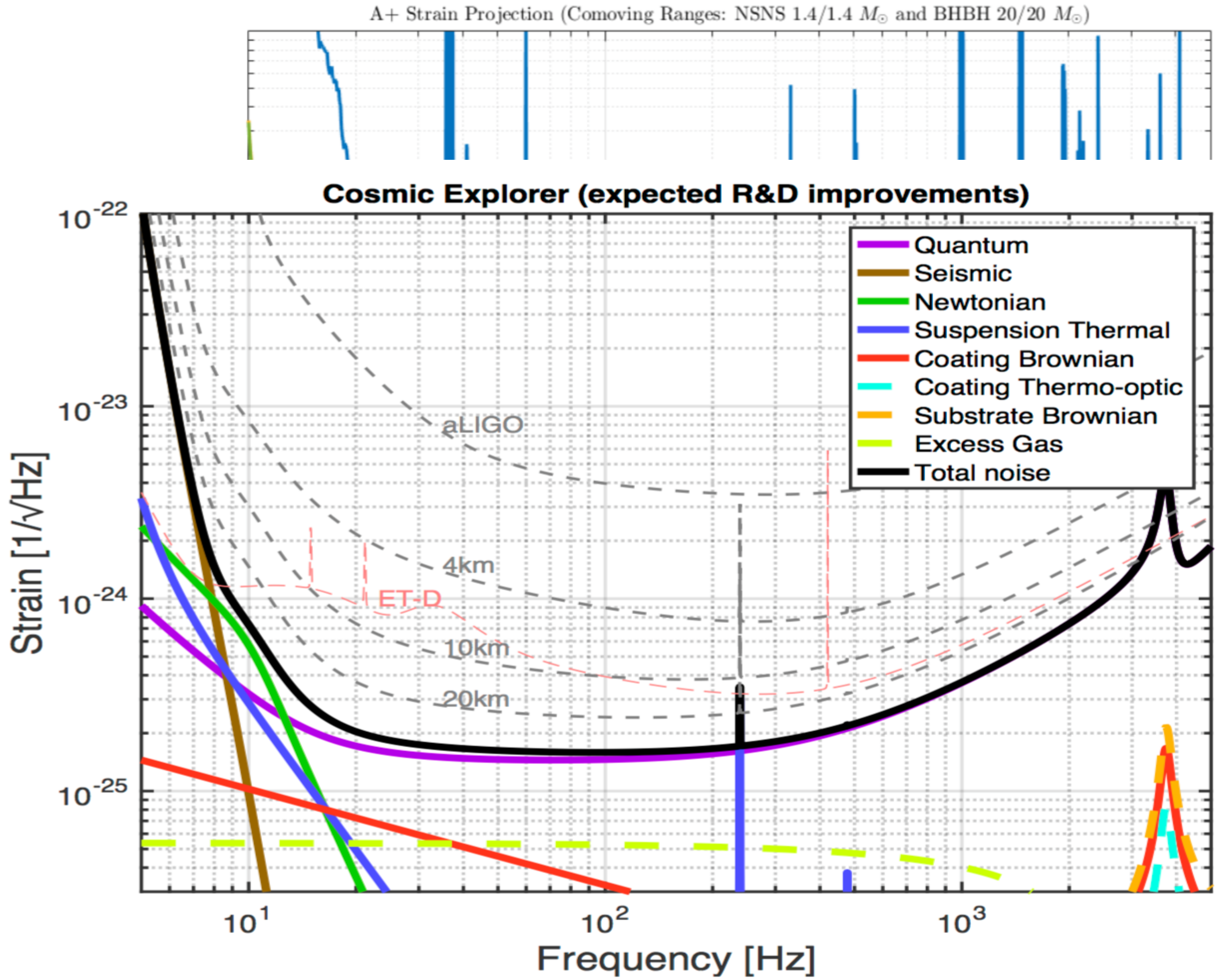






Advanced LIGO roadmap

[LVC 2016, 2017]

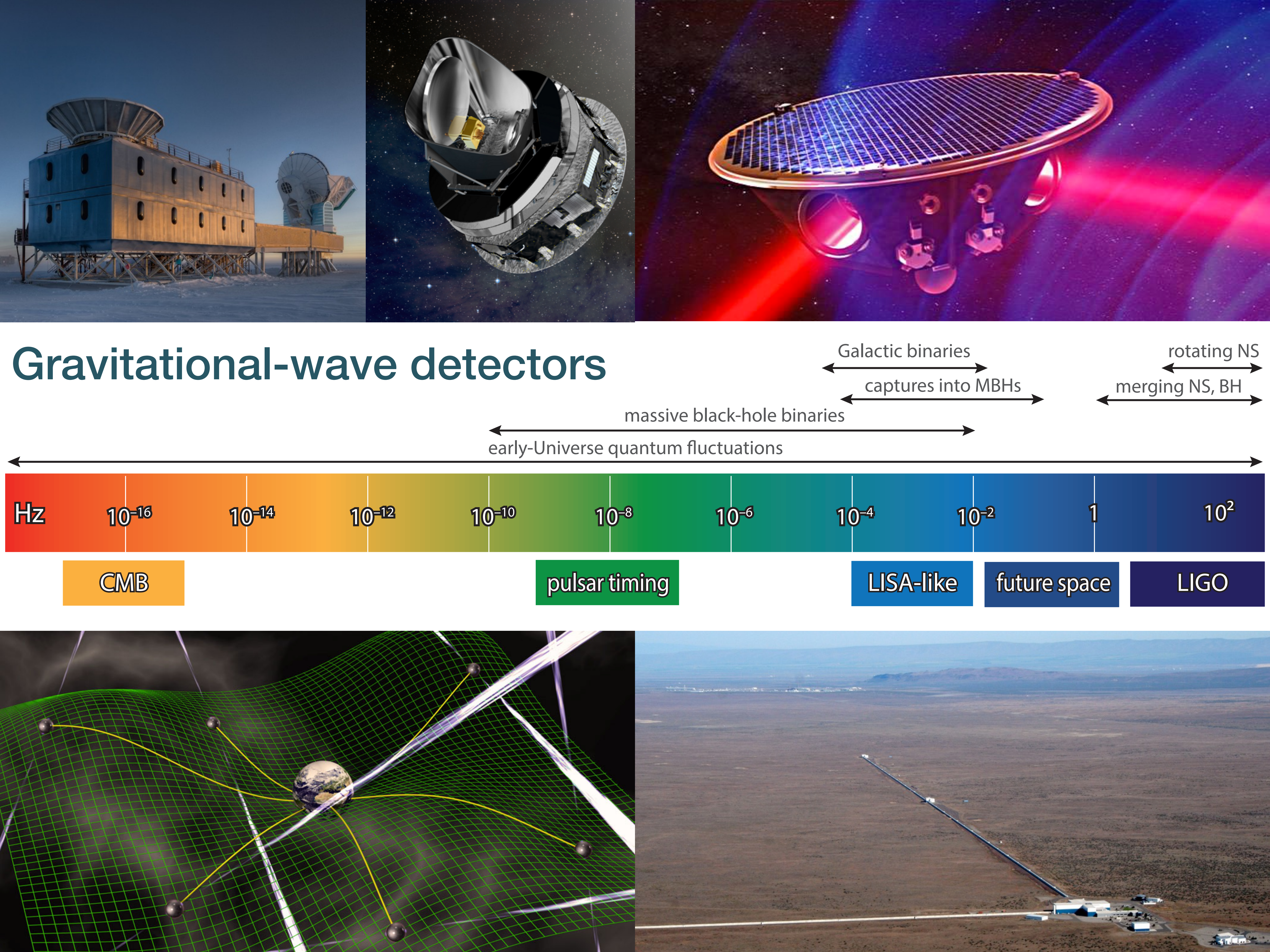


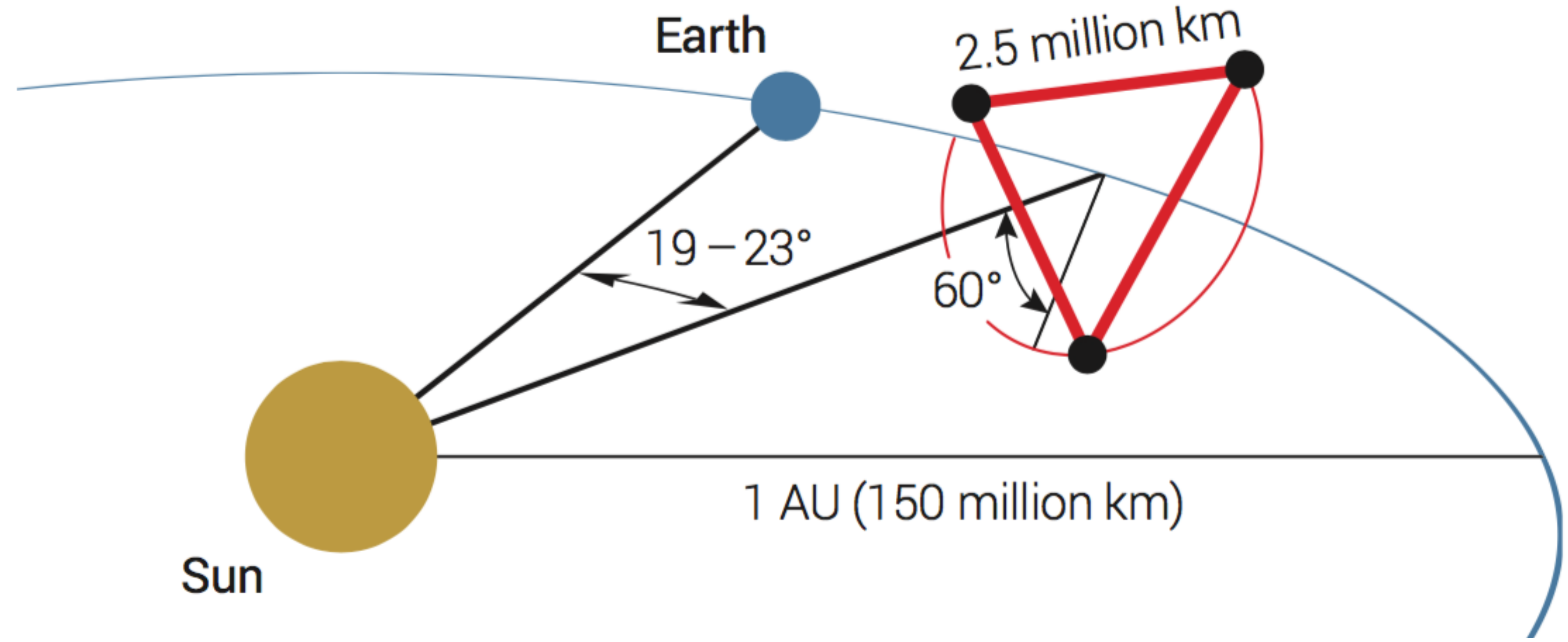
Adv. LIGO Plus (A+): x1.7 range increase over aLIGO
leverage existing technology and infrastructure

LIGO Voyager: x2 sensitivity broadband improvement
larger Si masses, cryogenic operation, shorter laser wavelength

Future LIGO enhancements

[LVC 2016]


Gravitational-wave detectors
Galactic binaries
rotating NS
captures into MBHs
merging NS, BH
massive black-hole binaries
early-Universe quantum fluctuations
Hz
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
CMB
pulsar timing
LISA-like
future space
LIGO



Concept selected: 4/2017
Phase 0 studies: by 9/2017
Industrial Phase studies: by 2020
Mission adoption: 2024
Phase B2/C/D/E1: 2025
Launch: 2033

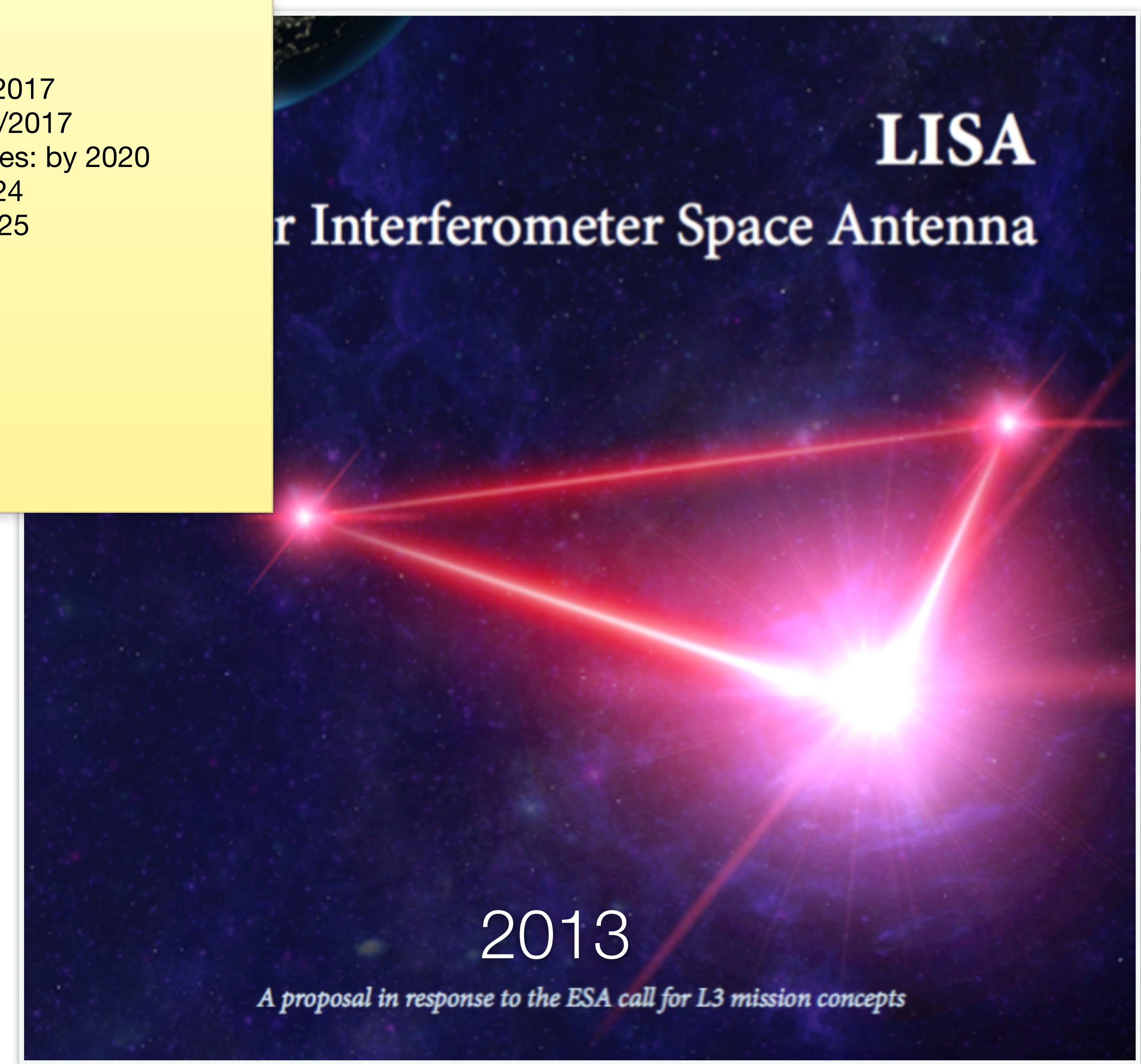
THE GRAVITATIONAL UNIV

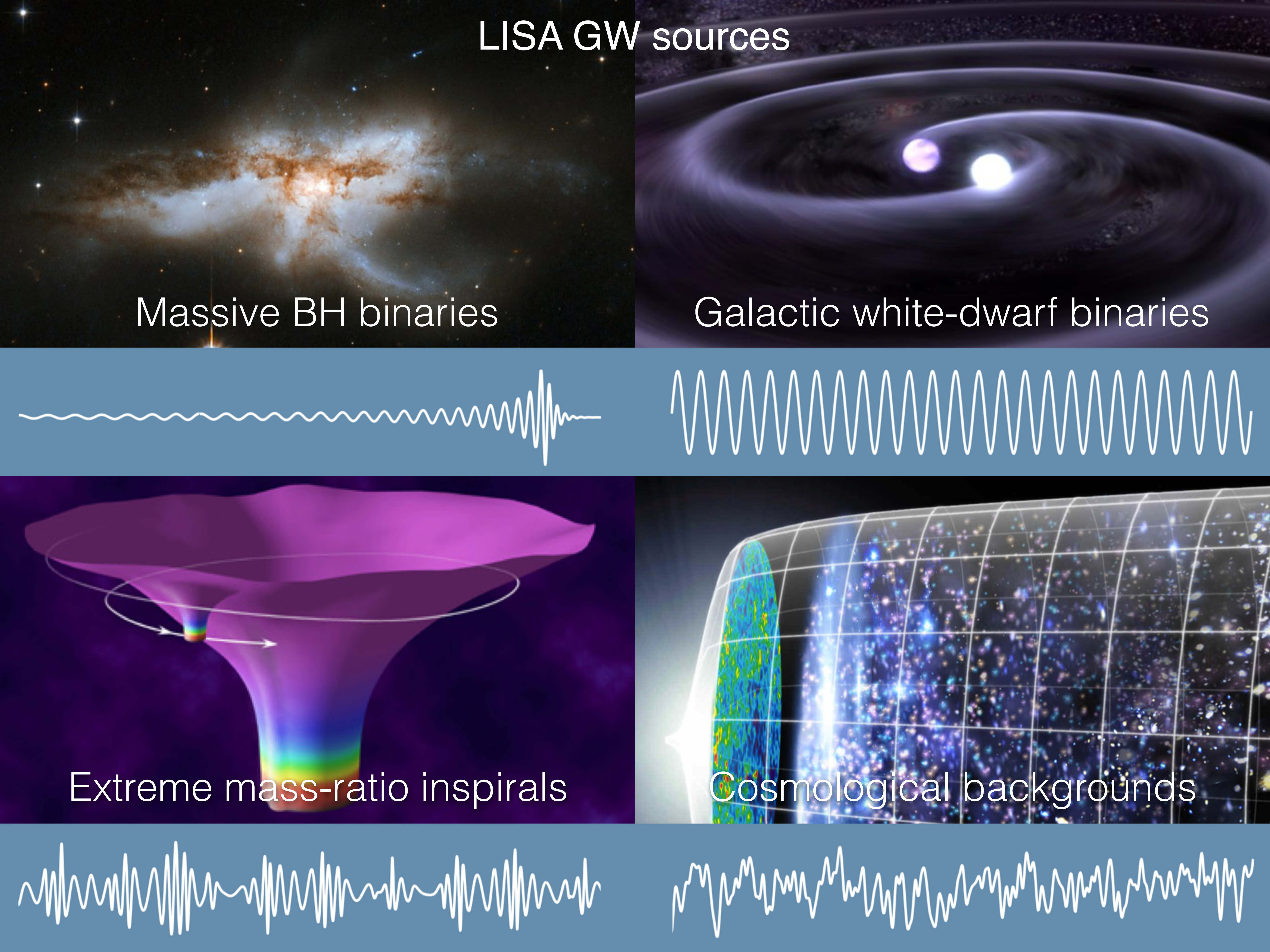
A science theme addressed by the *eLISA* mission observing the

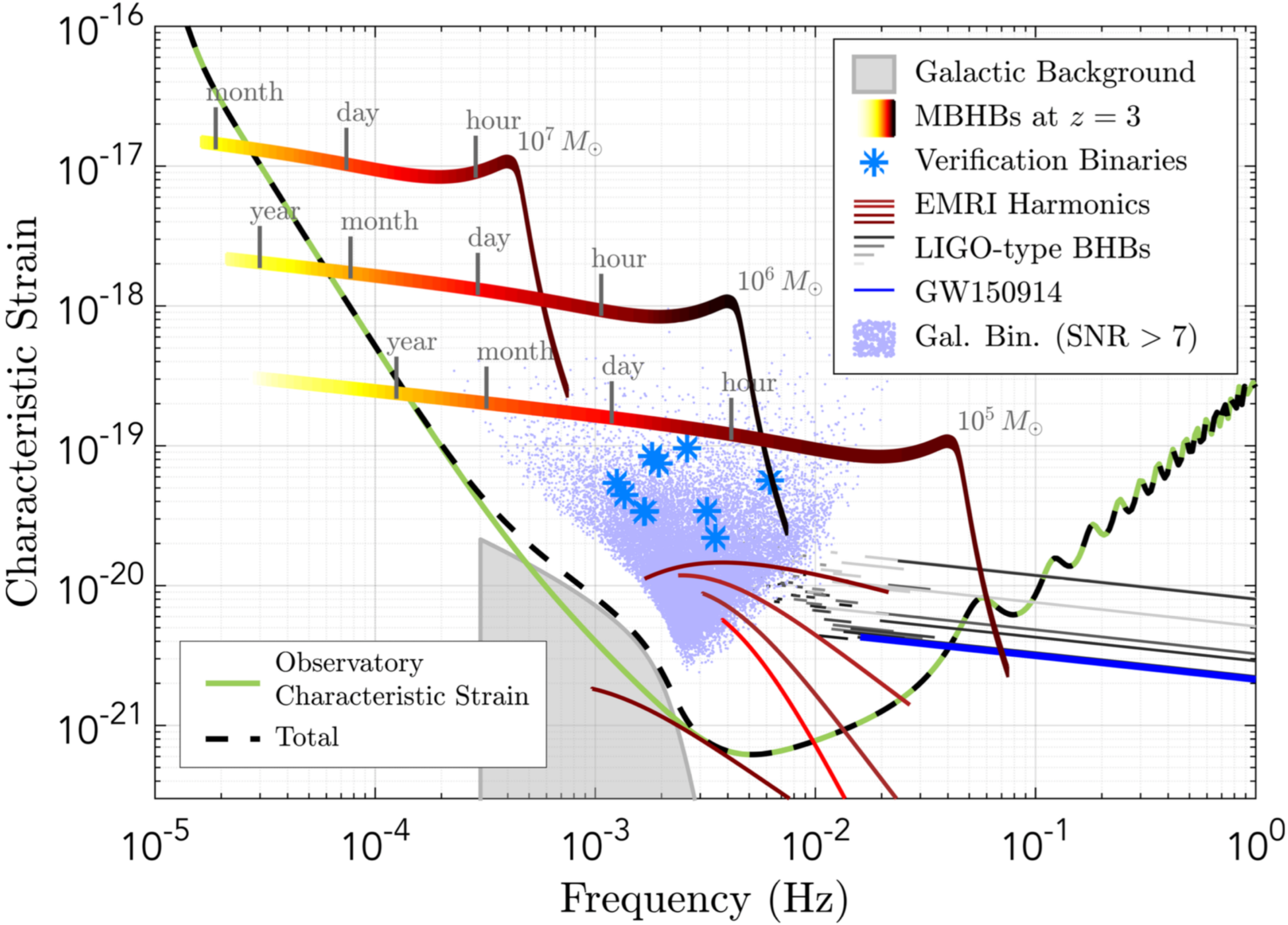
2017

Prof. Dr. Karsten Danzmann
Albert Einstein Institute Hannover
MPI for Gravitational Physics and
Leibniz Universität Hannover
Callinstr. 38

The last century has seen enormous progress in our understanding of the Universe. We know the life cycles of stars, the structure of galaxies, the remnants of the big bang, and have a general understanding of how the Universe evolved. We have come remarkably far using electromagnetic radiation as our tool for observing the Universe. However, gravity is the engine behind many of the processes in the Universe, and much of its action is dark. Opening a gravitational window on the Universe will let us go further than any alternative. Gravity has its own messenger: Gravitational waves, ripples in the fabric of spacetime. They travel essentially undisturbed and let us peer deep into the formation of the first seed black holes, exploring redshifts as large as z ~ 20, prior to the epoch of cosmic re-ionisation. Exquisite and unprecedented measurements of black hole masses and spins will

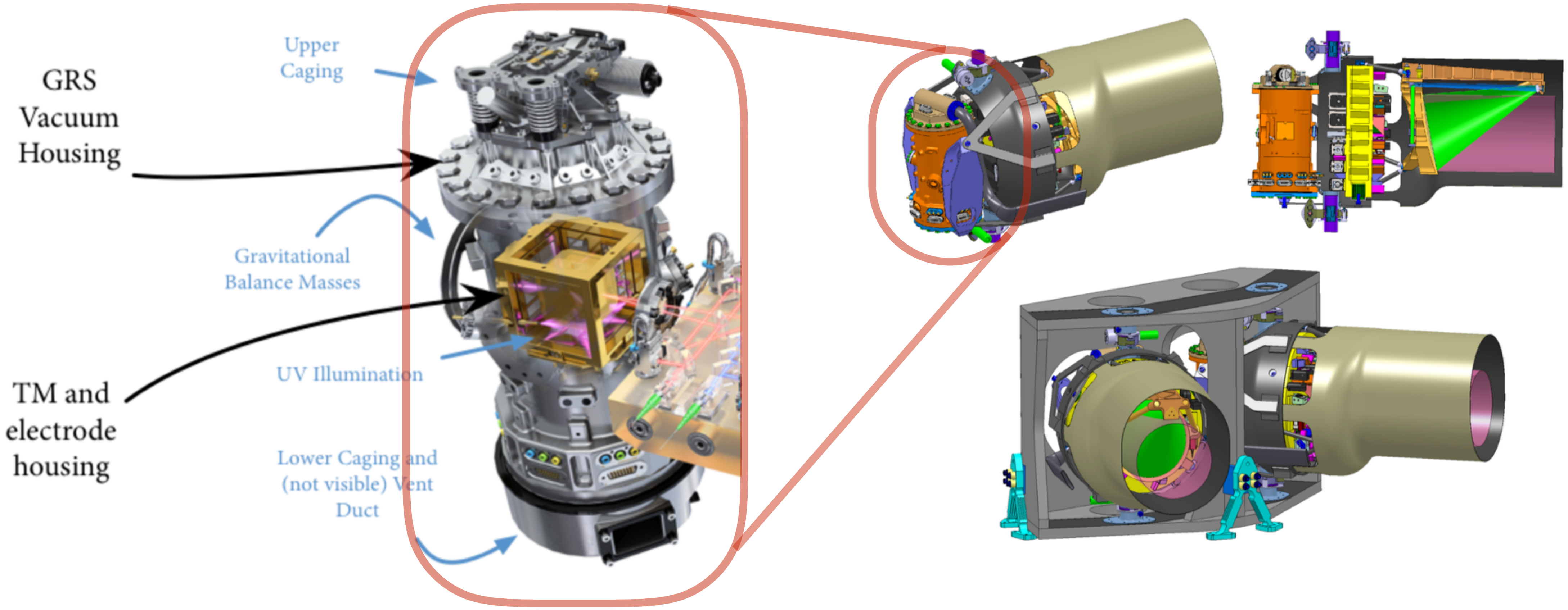


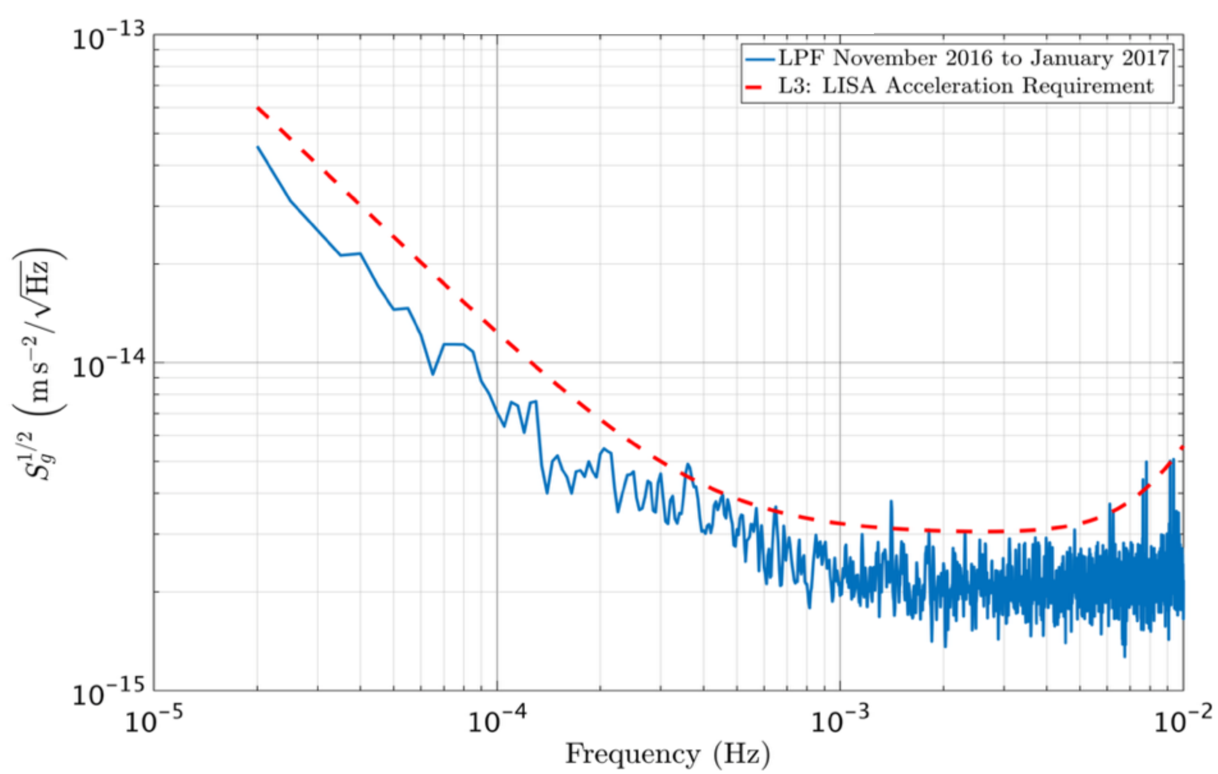

LISA GW sources
Massive BH binaries
Galactic white-dwarf binaries
Extreme mass-ratio inspirals
Cosmological backgrounds



LISA sensitivity and sources

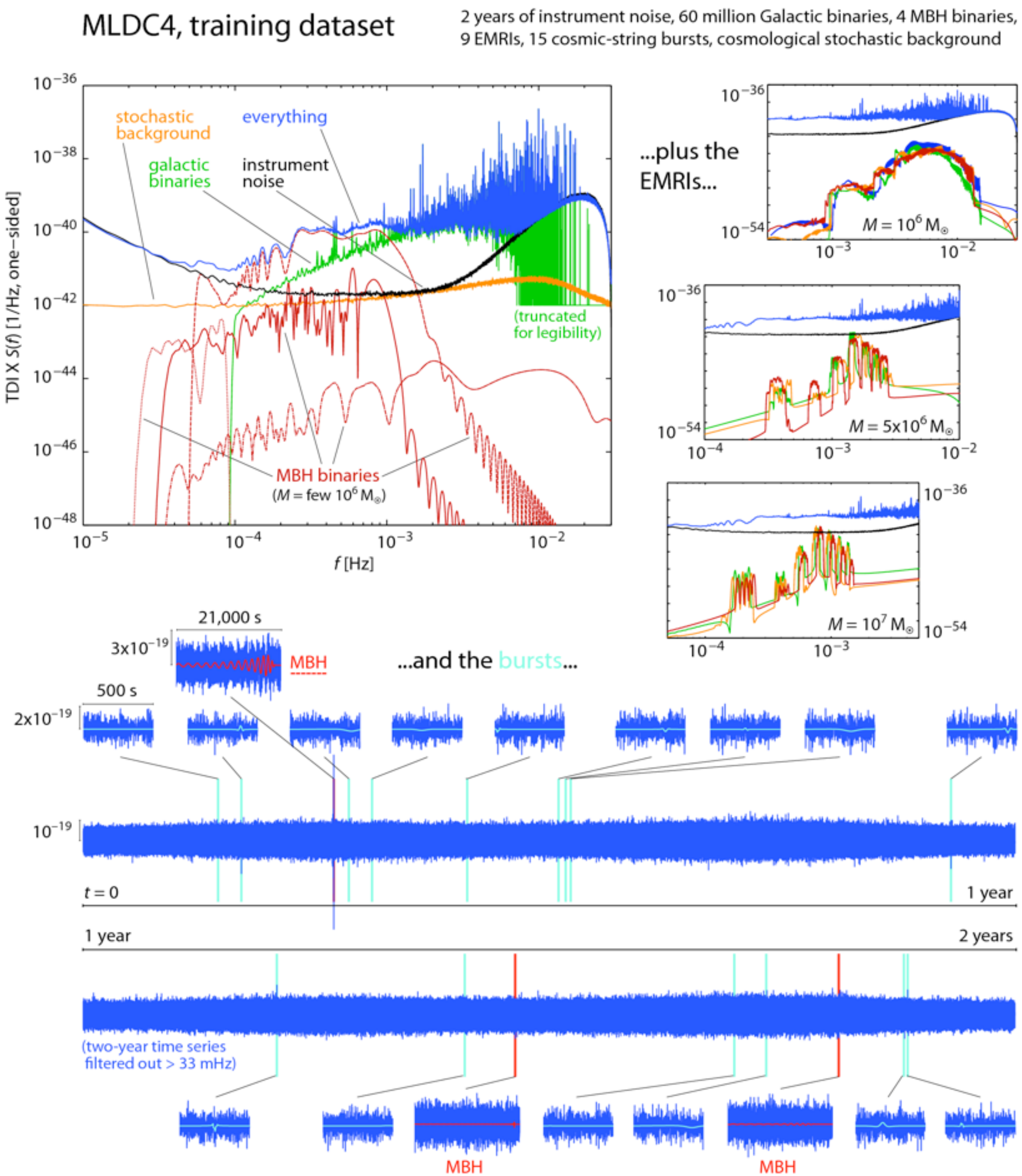
[LISA proposal 2017]





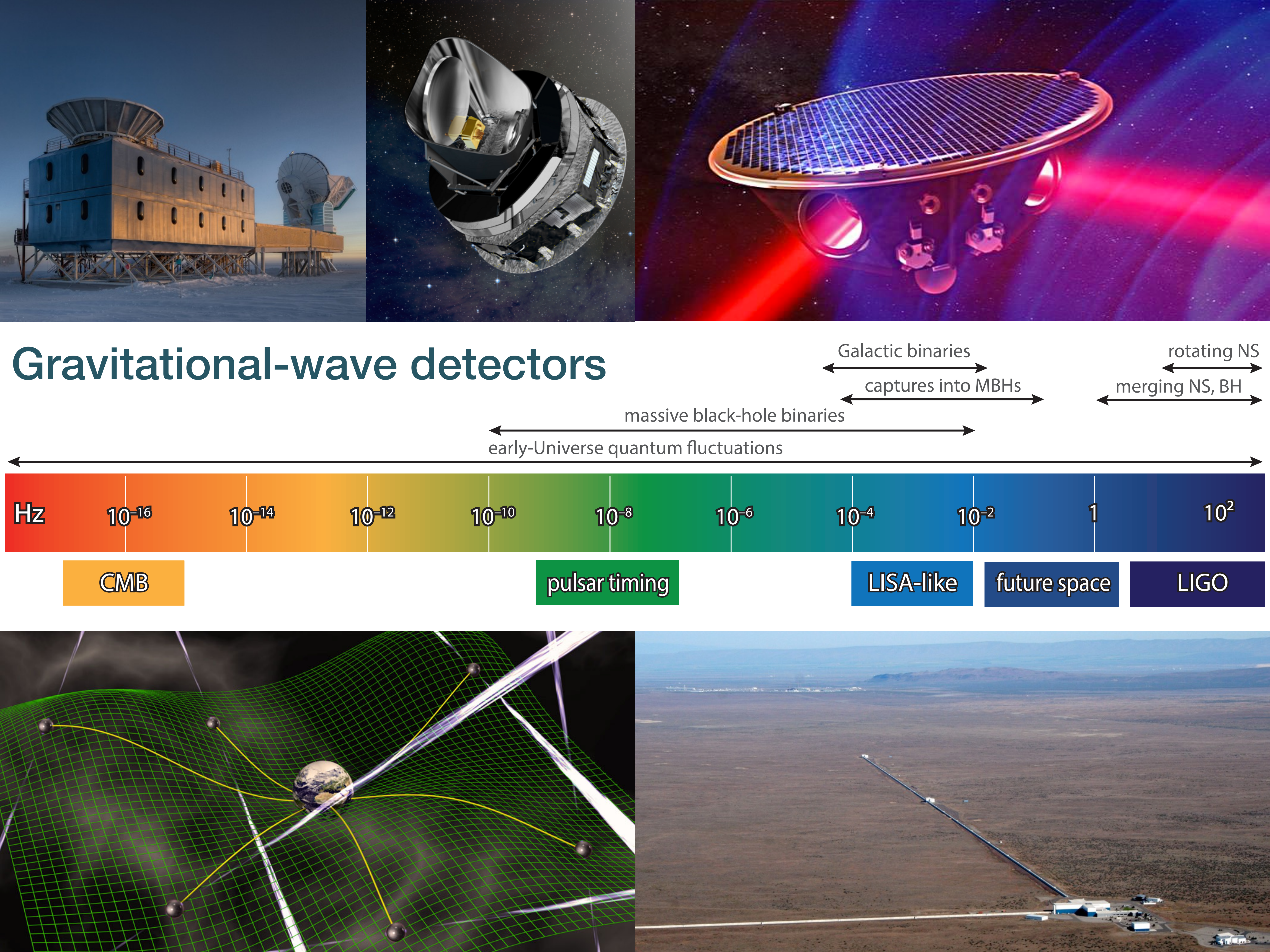
LISA payload and LPF performance

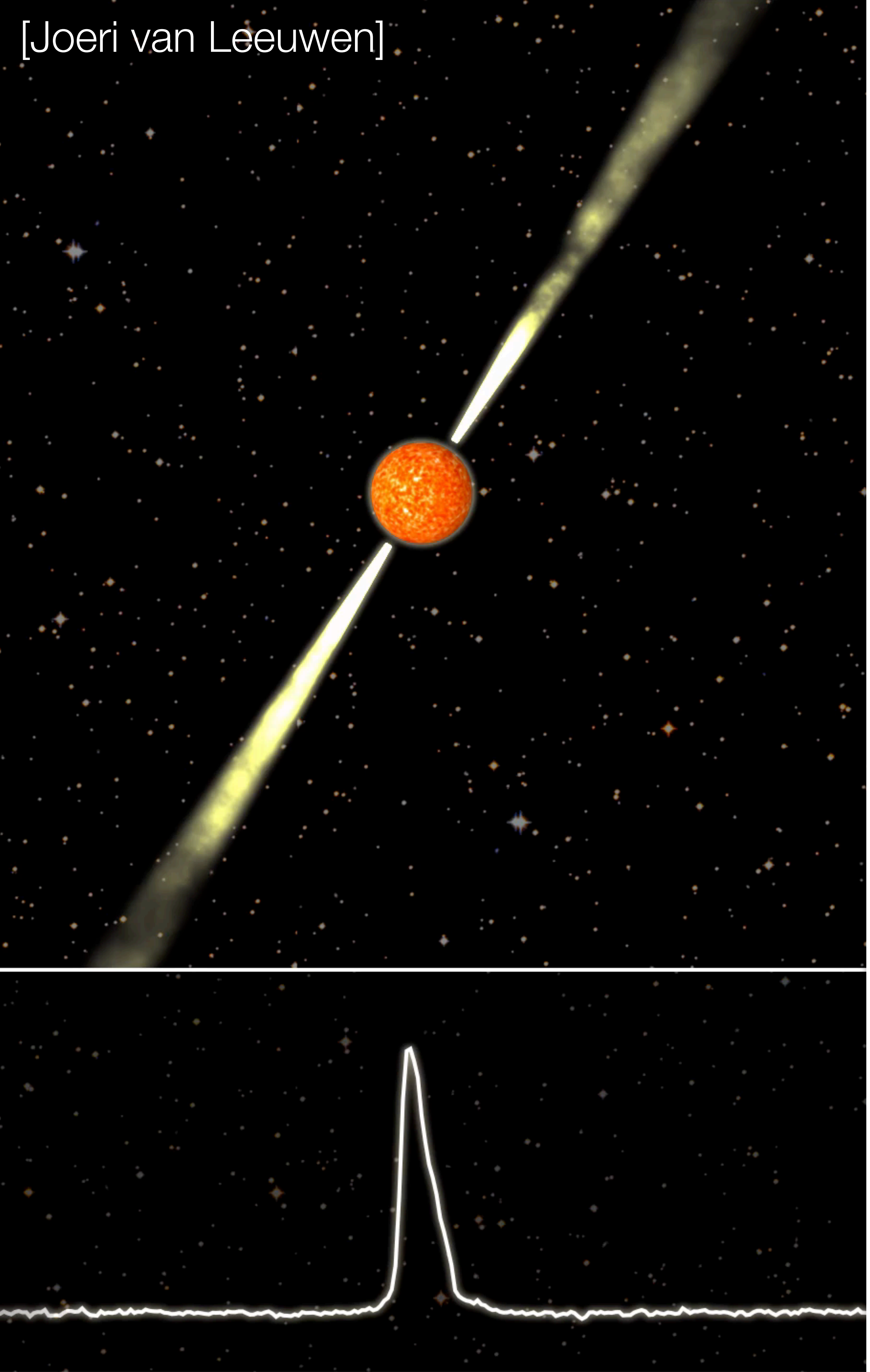
[LISA proposal 2017]

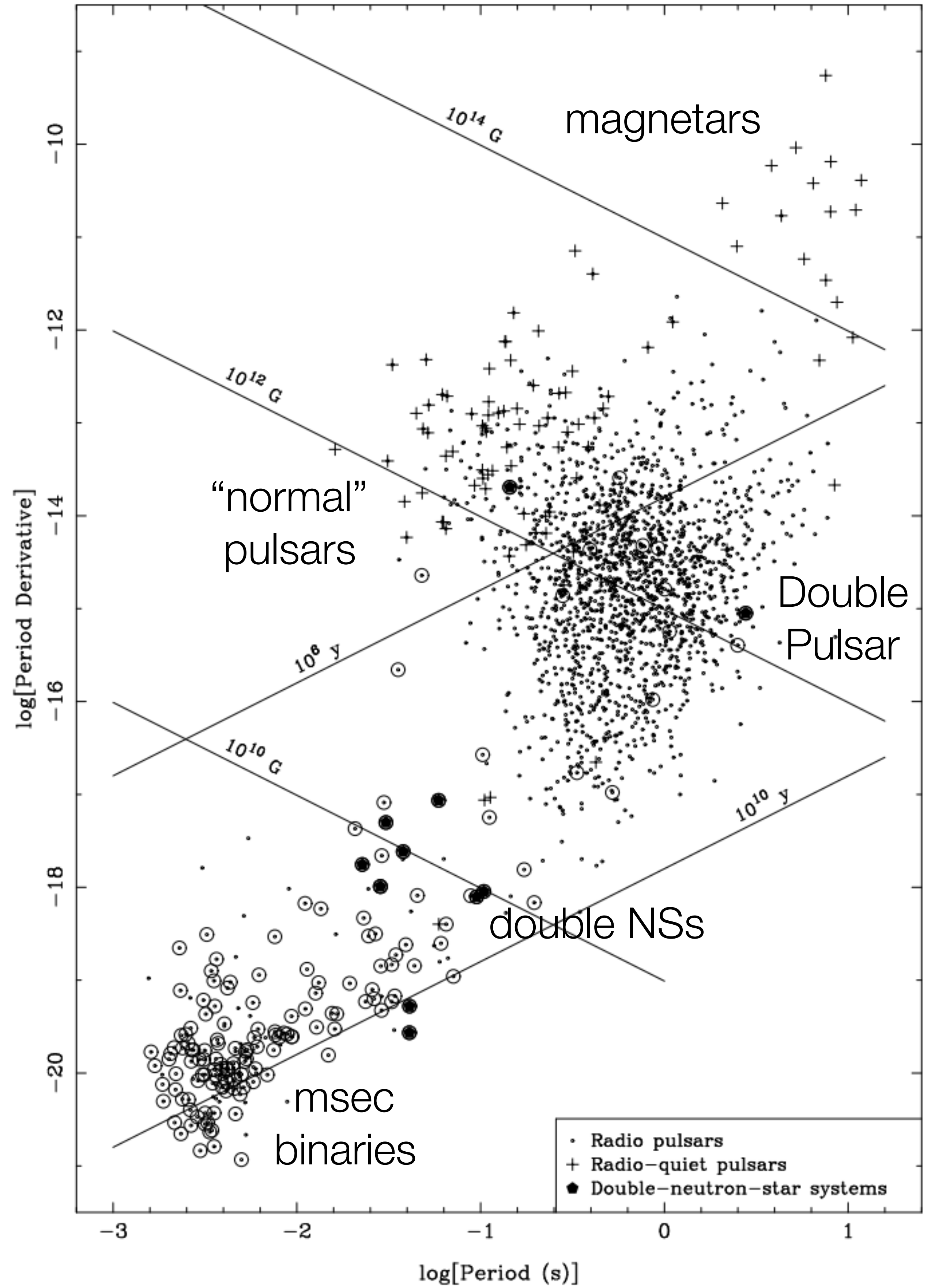


The LISA science analysis

[MV 2011]


Gravitational-wave detectors
Galactic binaries
captures into MBHs
massive black-hole binaries
early-Universe quantum fluctuations
rotating NS
merging NS, BH
Hz
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
CMB
pulsar timing
LISA-like
future space
LIGO



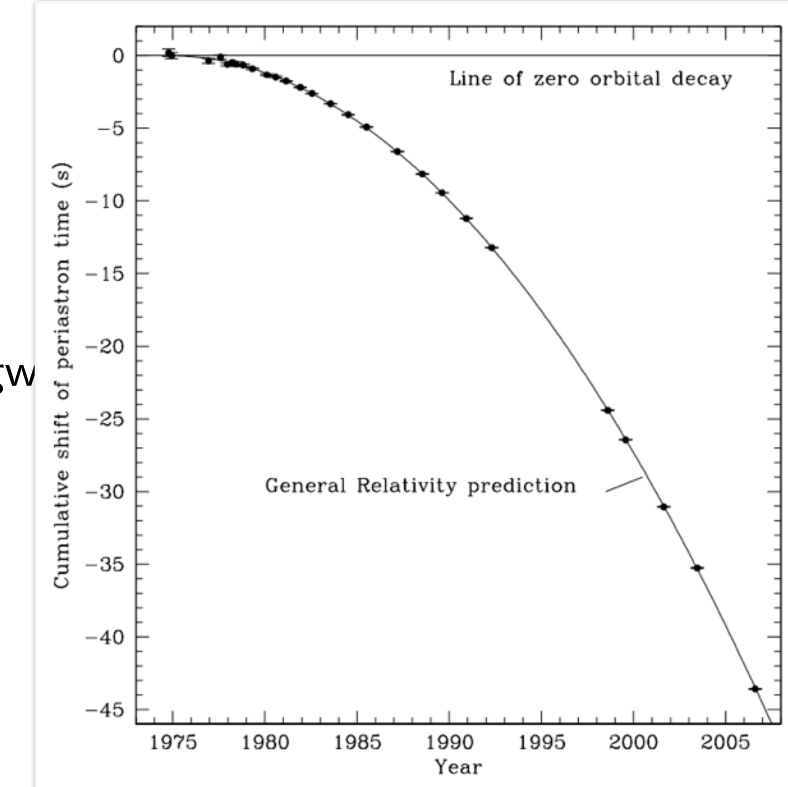


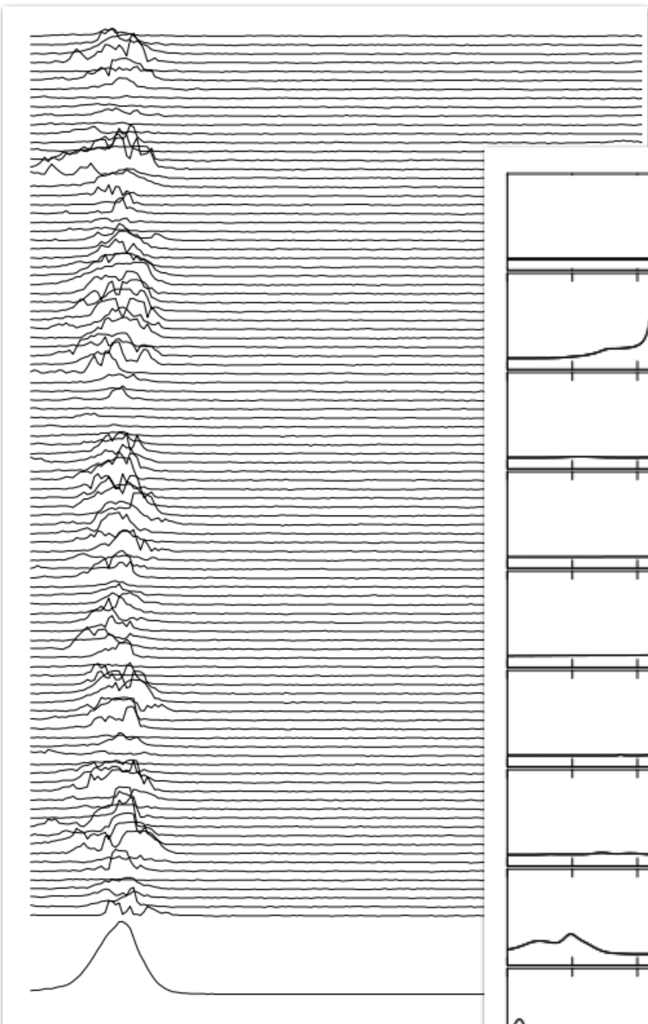
pulsars: Nature's precision clocks

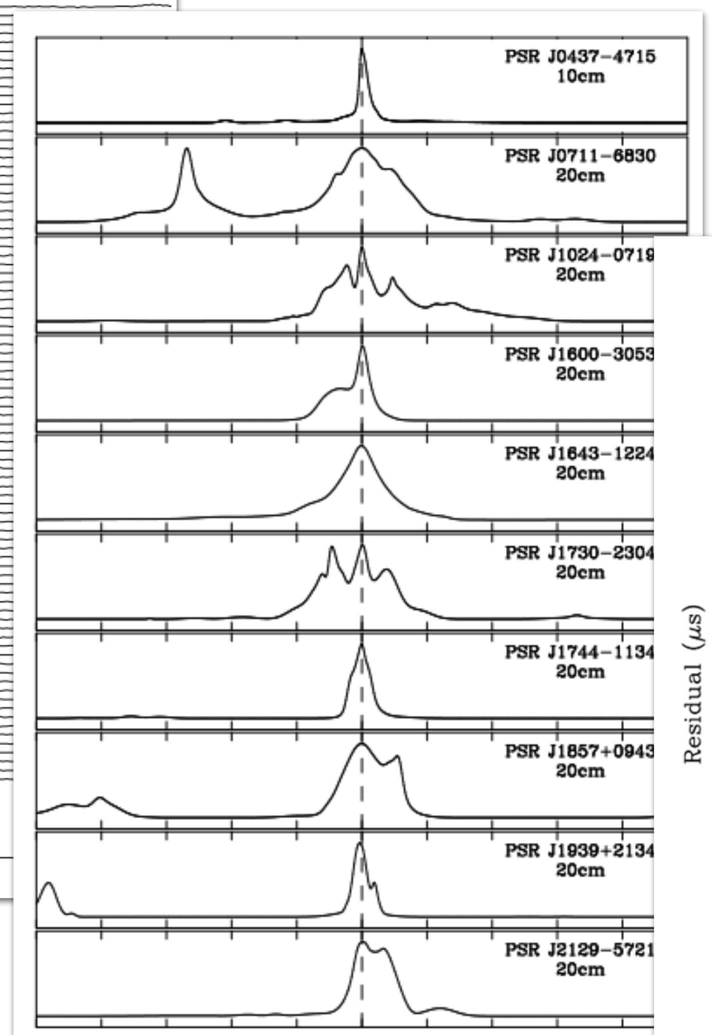
[Manchester 2015]

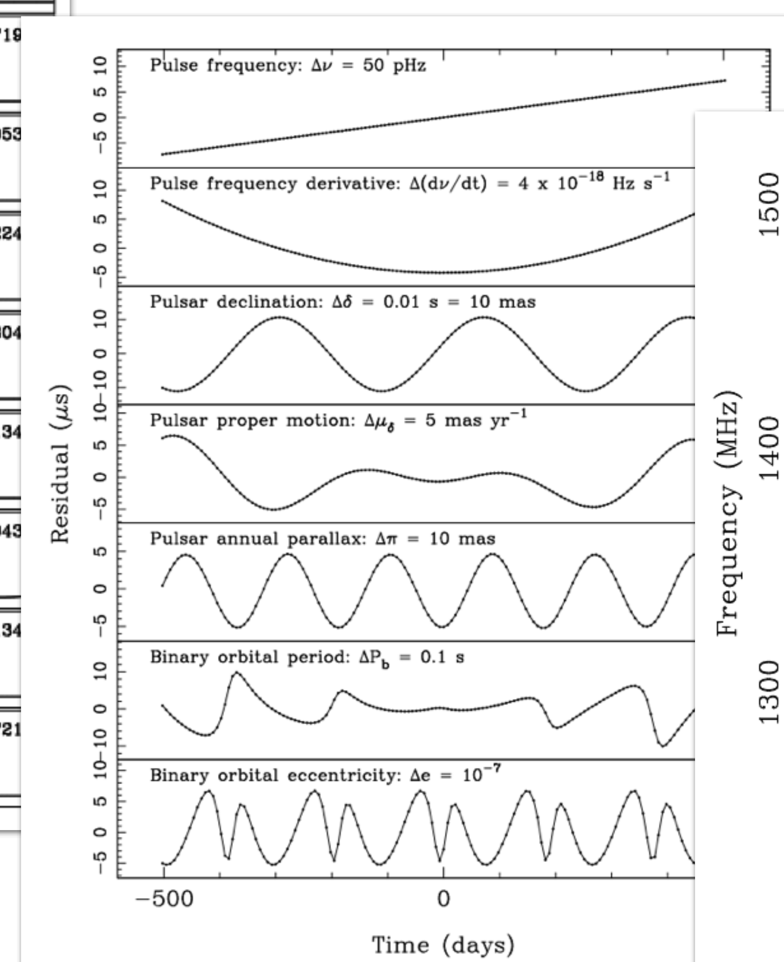
Pulsar-timing multiphysics

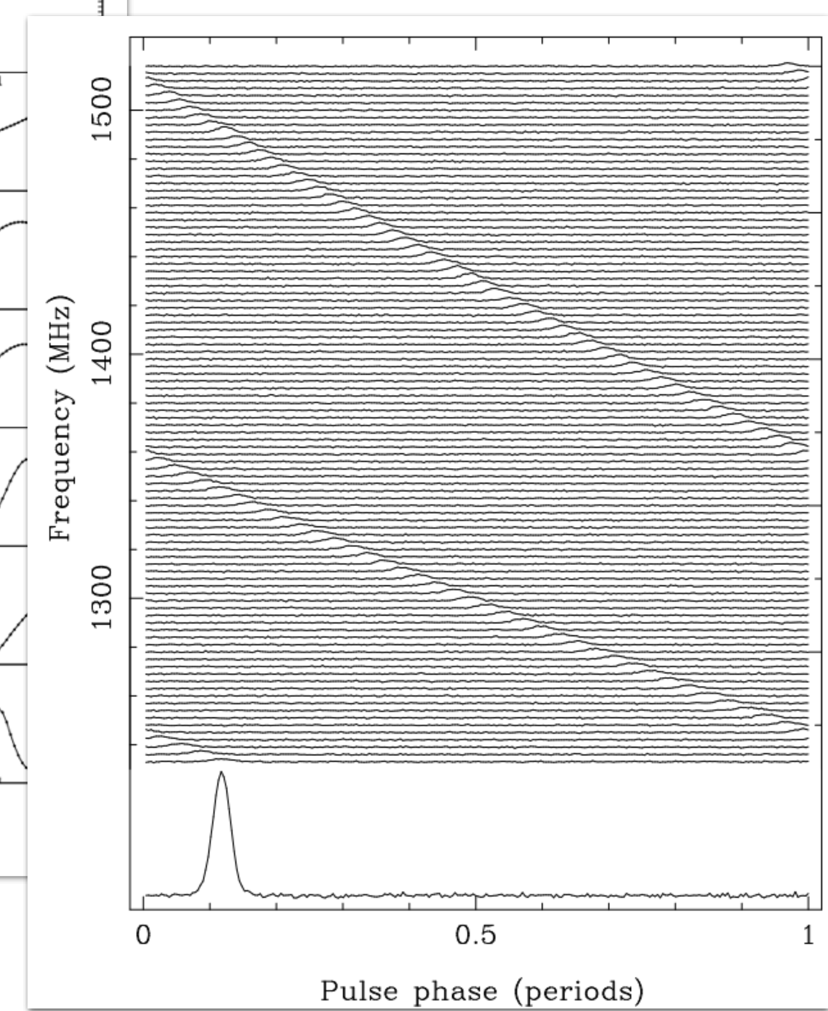
$$L_{12} = L_{12}^{\text{no gw}}$$





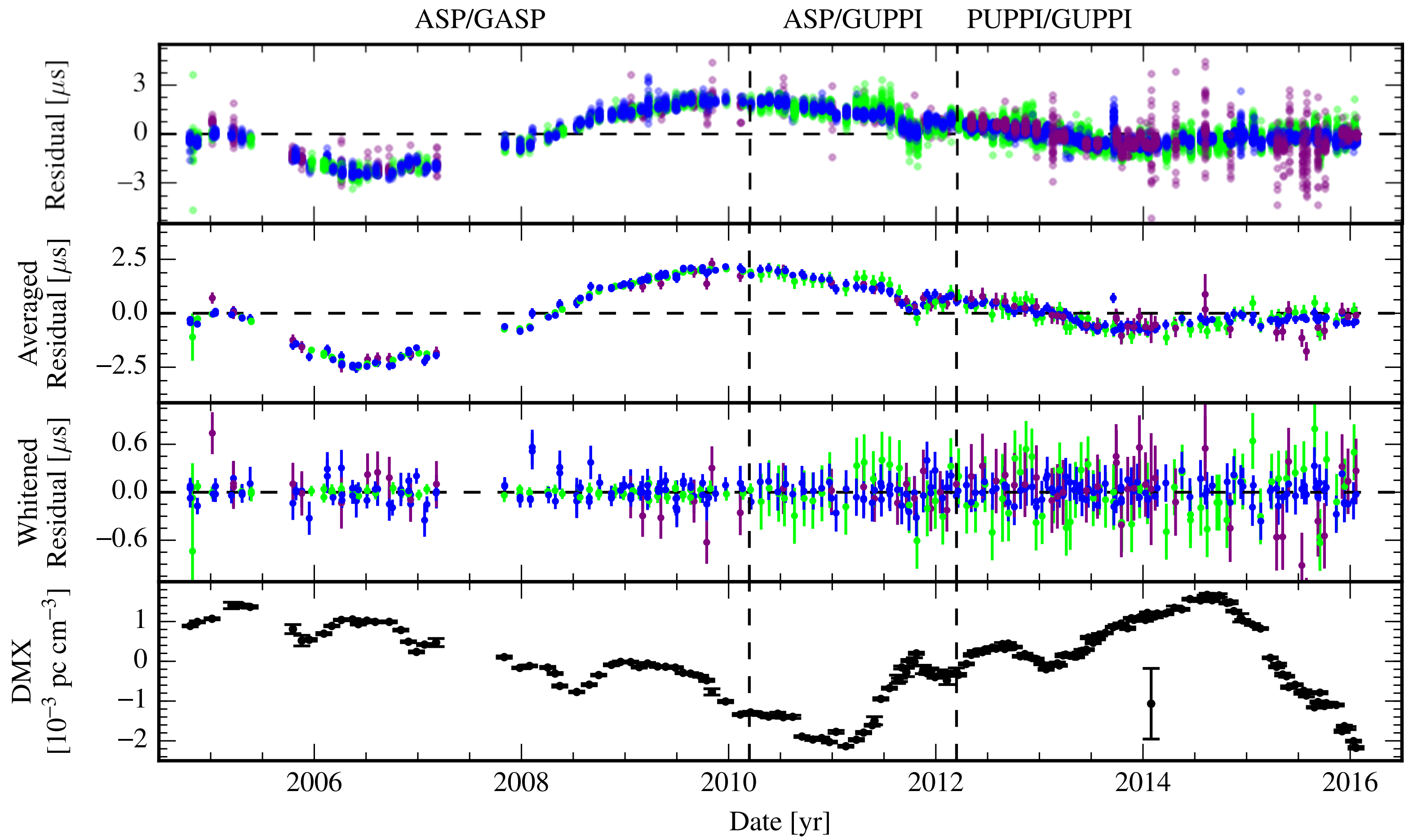






[Stairs 2003, Manchester 2013, Manchester 2015, You et al. 2007, Weisberg et al. 2010]

J1909-3744



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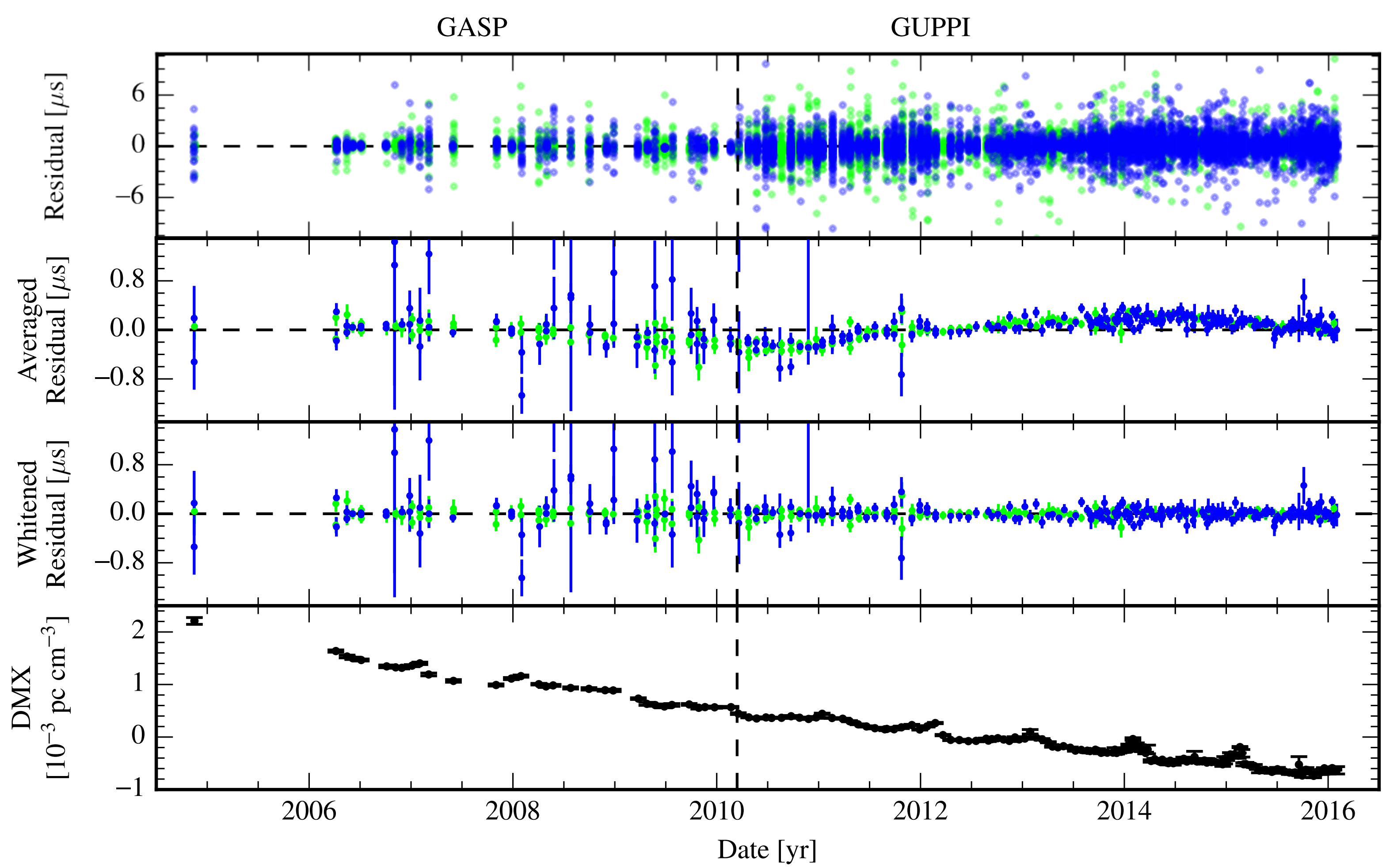
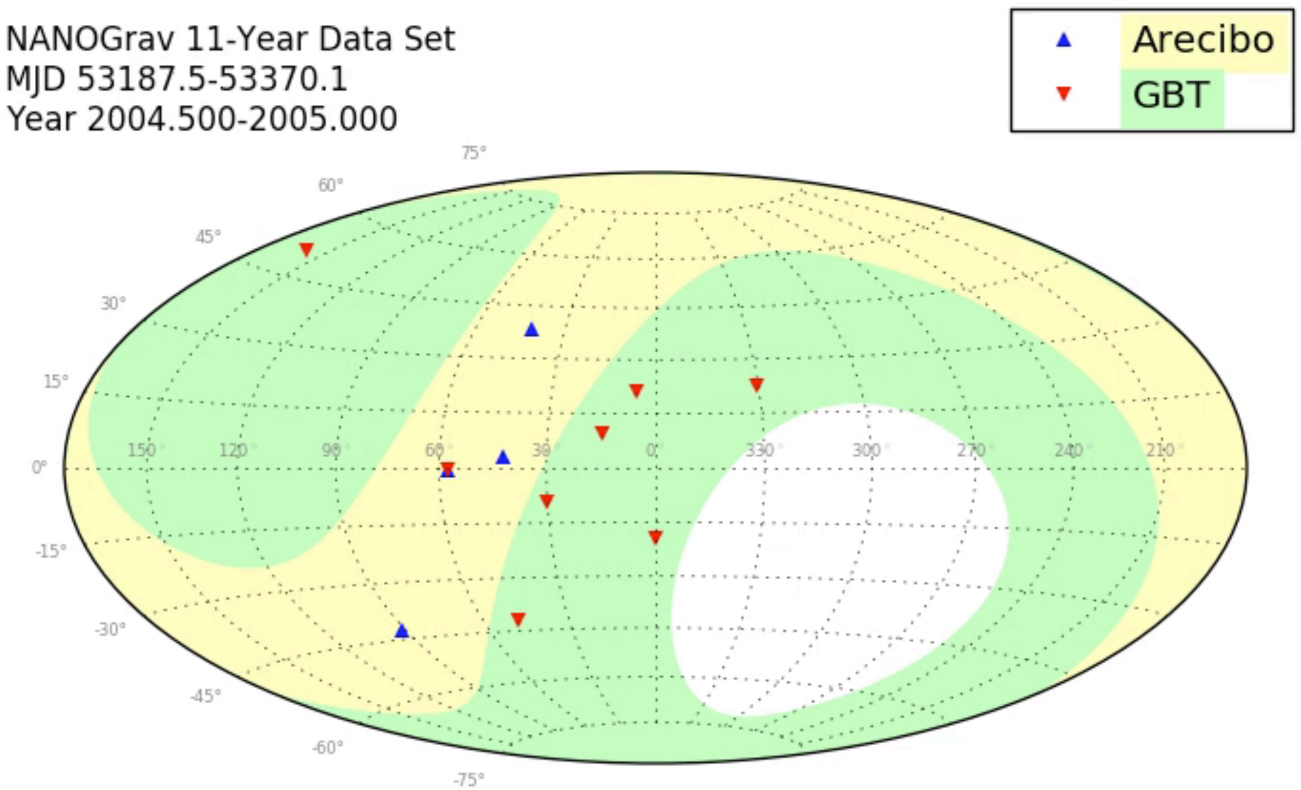
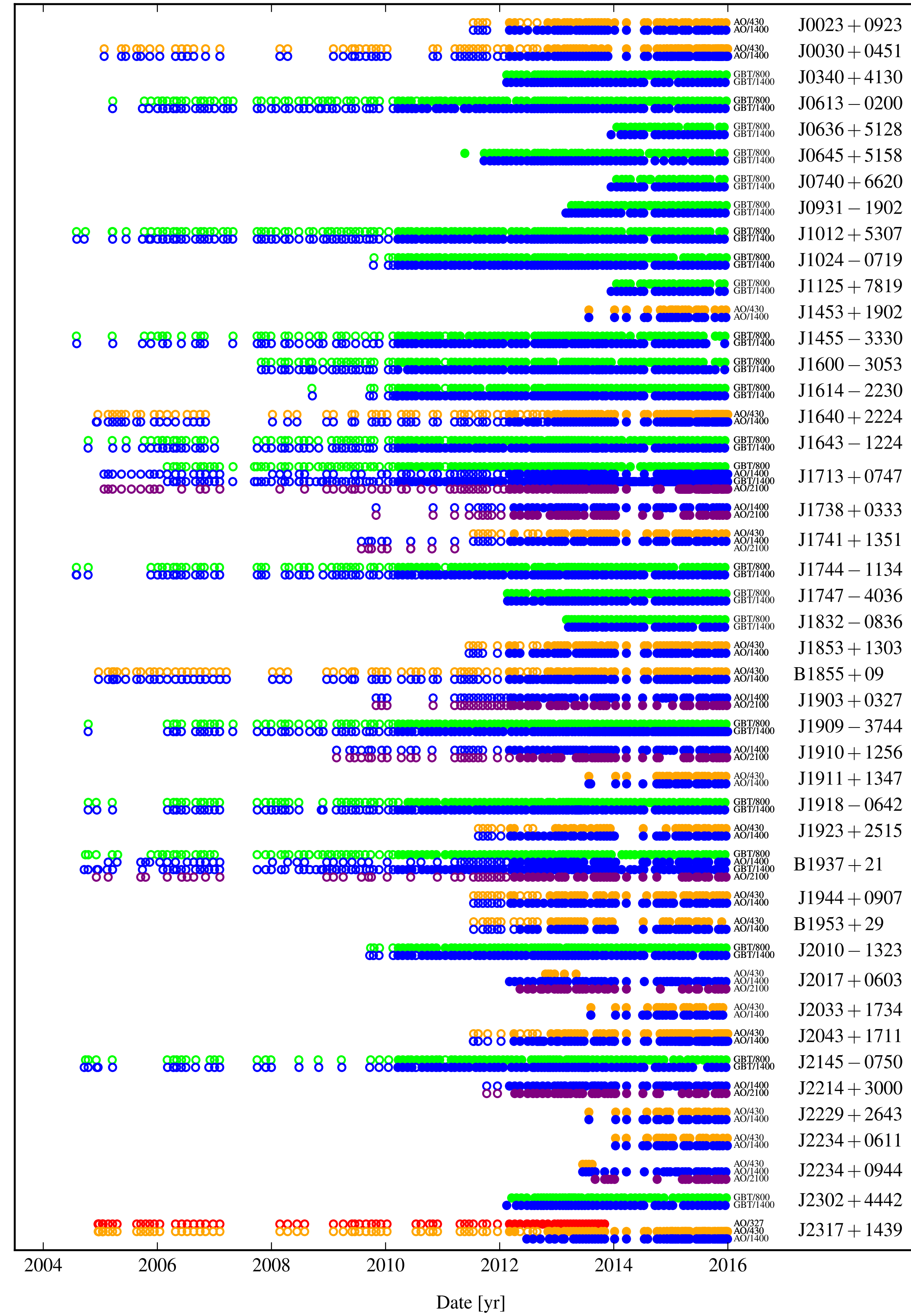


[NANOGrav soon]

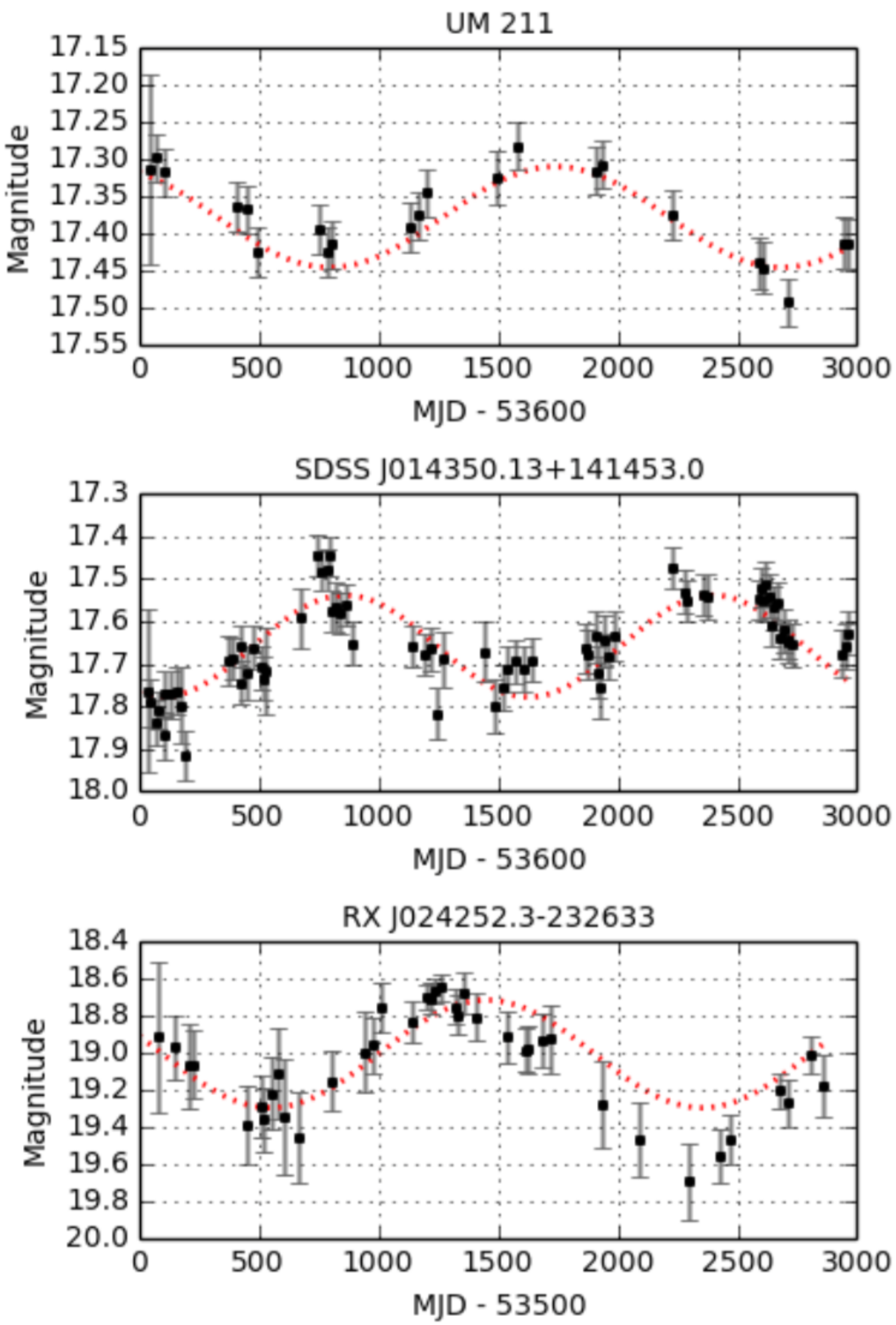
Pulsar-timing arrays [Foster and Backer 1990]



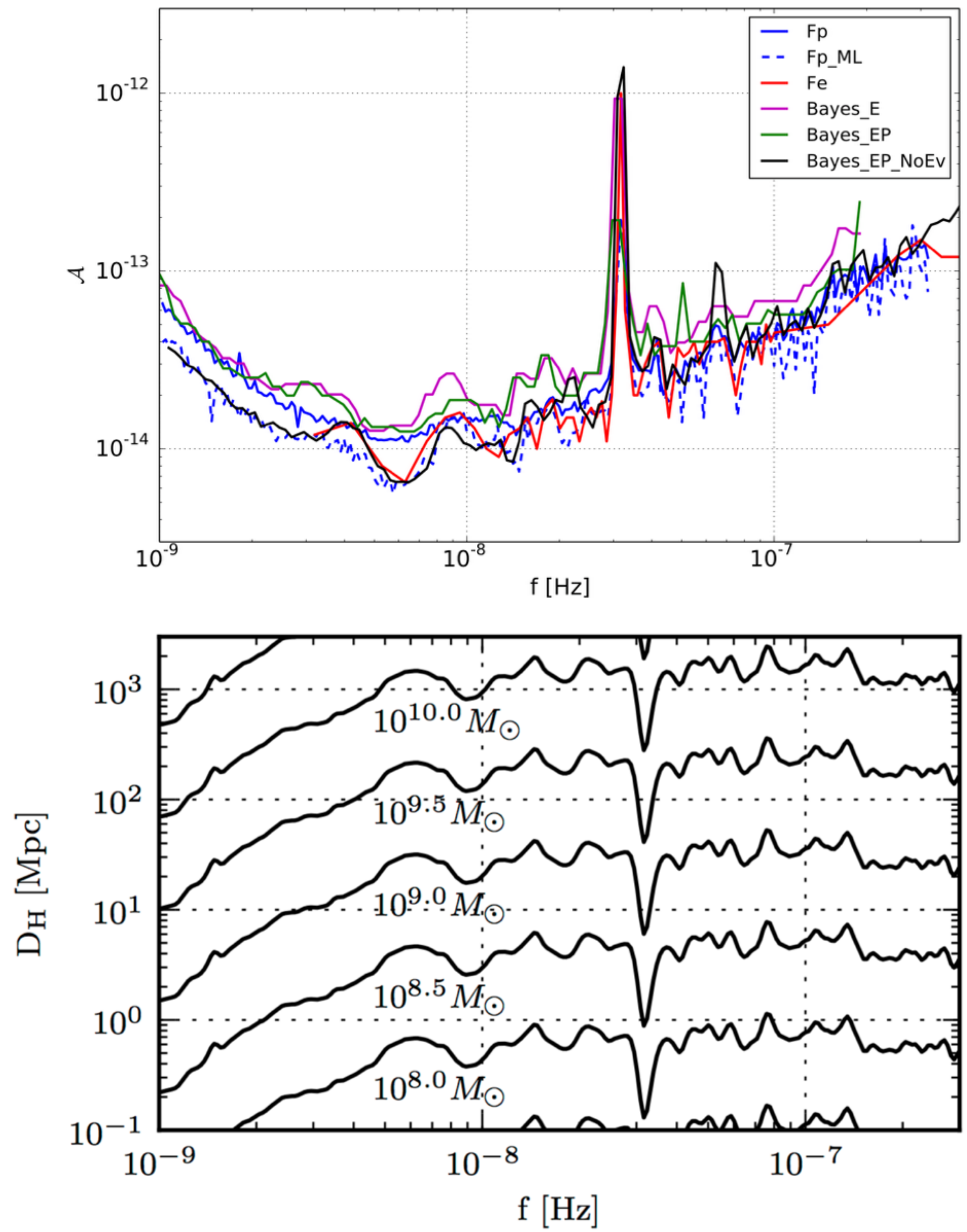


[Nice 2016, NANOGrav soon]

Pulsar science: individual SMBH binaries

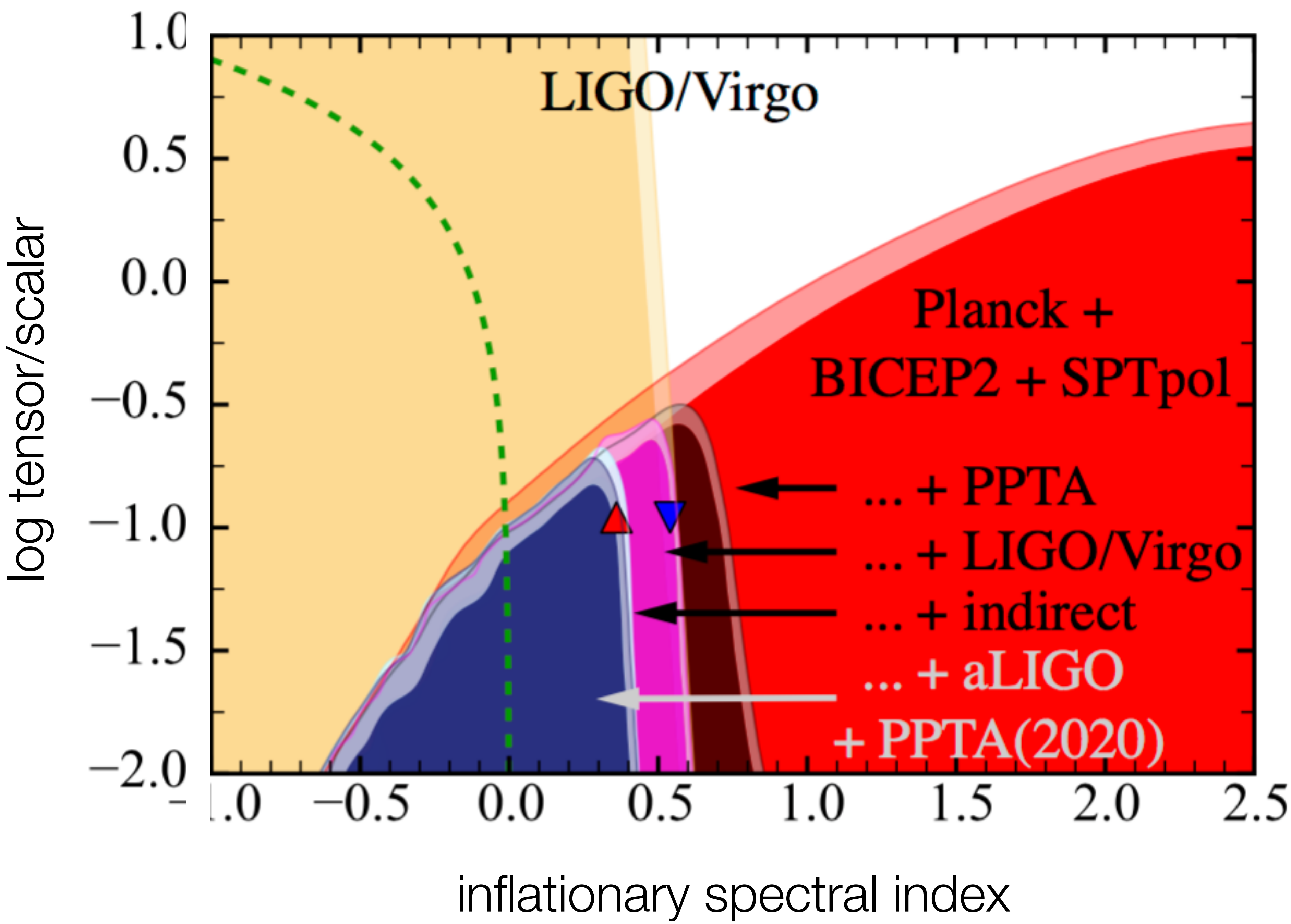


[Graham et al. 2015]



[Babak et al. 2016]

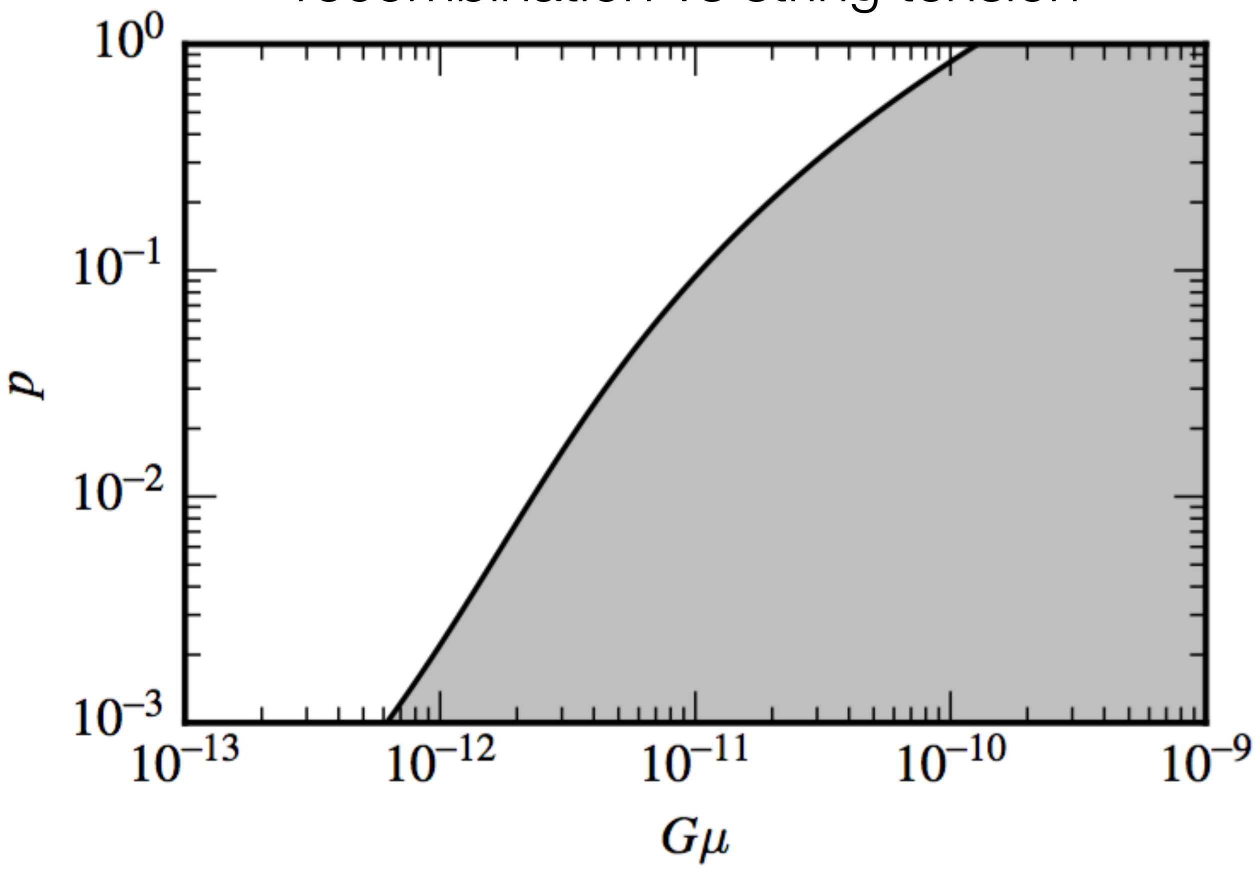
Pulsar science: relic radiation



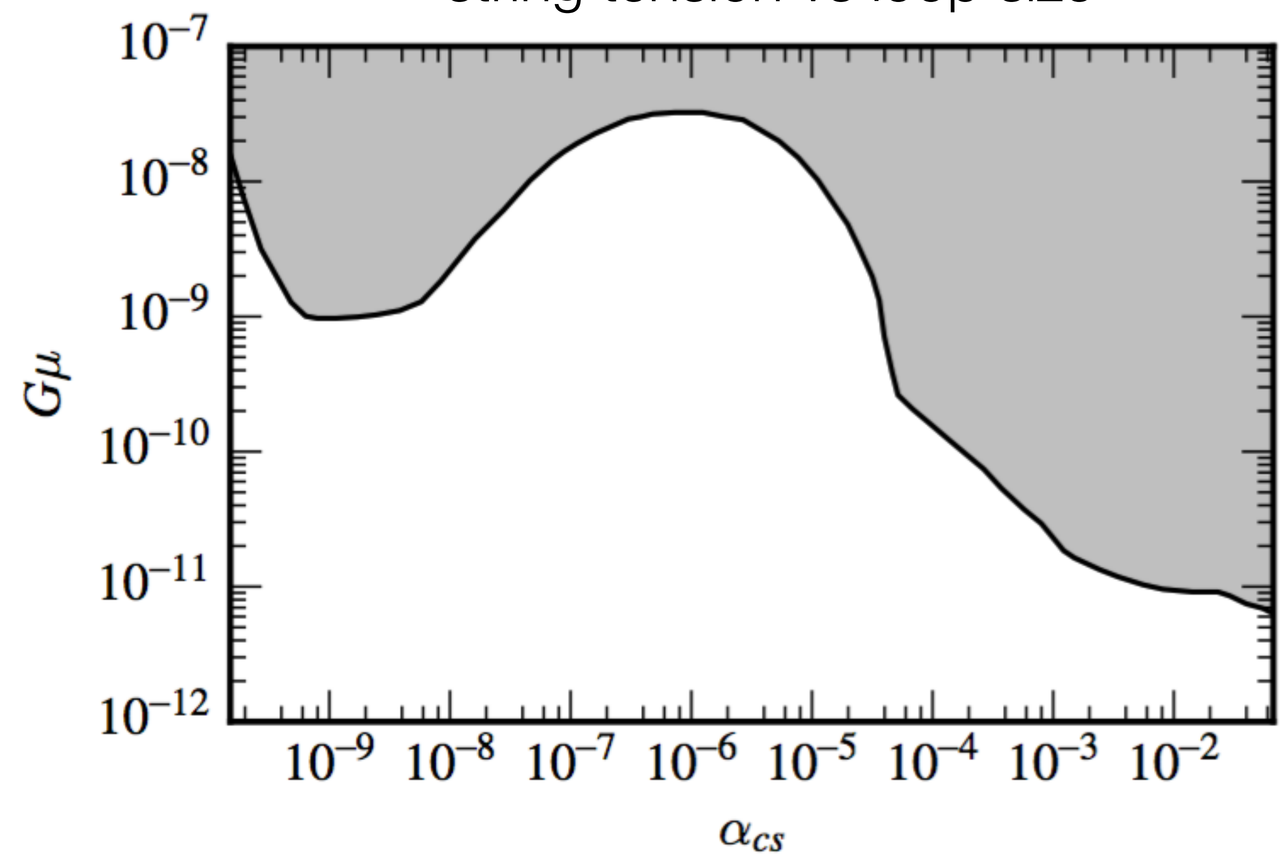
[Lasky et al. 2016]

Pulsar science: cosmic strings

recombination vs string tension



string tension vs loop size



[NANOGrav 2016]

$$\Omega_{\rm gw}(f) = \frac{1}{\rho_c}\frac{d\rho_{\rm gw}(f)}{d\ln f}$$

$$\frac{d\rho_{\rm gw}(f)}{d\ln f} = \frac{\pi}{4} f^2 h_c^2(f) = \int_0^\infty dz \, \frac{dn}{dz}\frac{1}{1+z} \left.\frac{dE_{\rm gw}}{d\ln f_r}\right|_{f_r = f(1+z)}$$

$$h_c^2(f) = \frac{4}{\pi f^2}\int_0^\infty dz \int_0^\infty d\mathcal{M} \, \frac{d^2 n}{dz d\mathcal{M}} \frac{1}{1+z} \frac{dE_{\rm gw}(\mathcal{M})}{d\ln f_r}$$

$$\frac{dE_{\rm gw}}{d\ln f_r} = \frac{\pi^{2/3}}{3}\mathcal{M}^{5/3} f_r^{2/3}$$

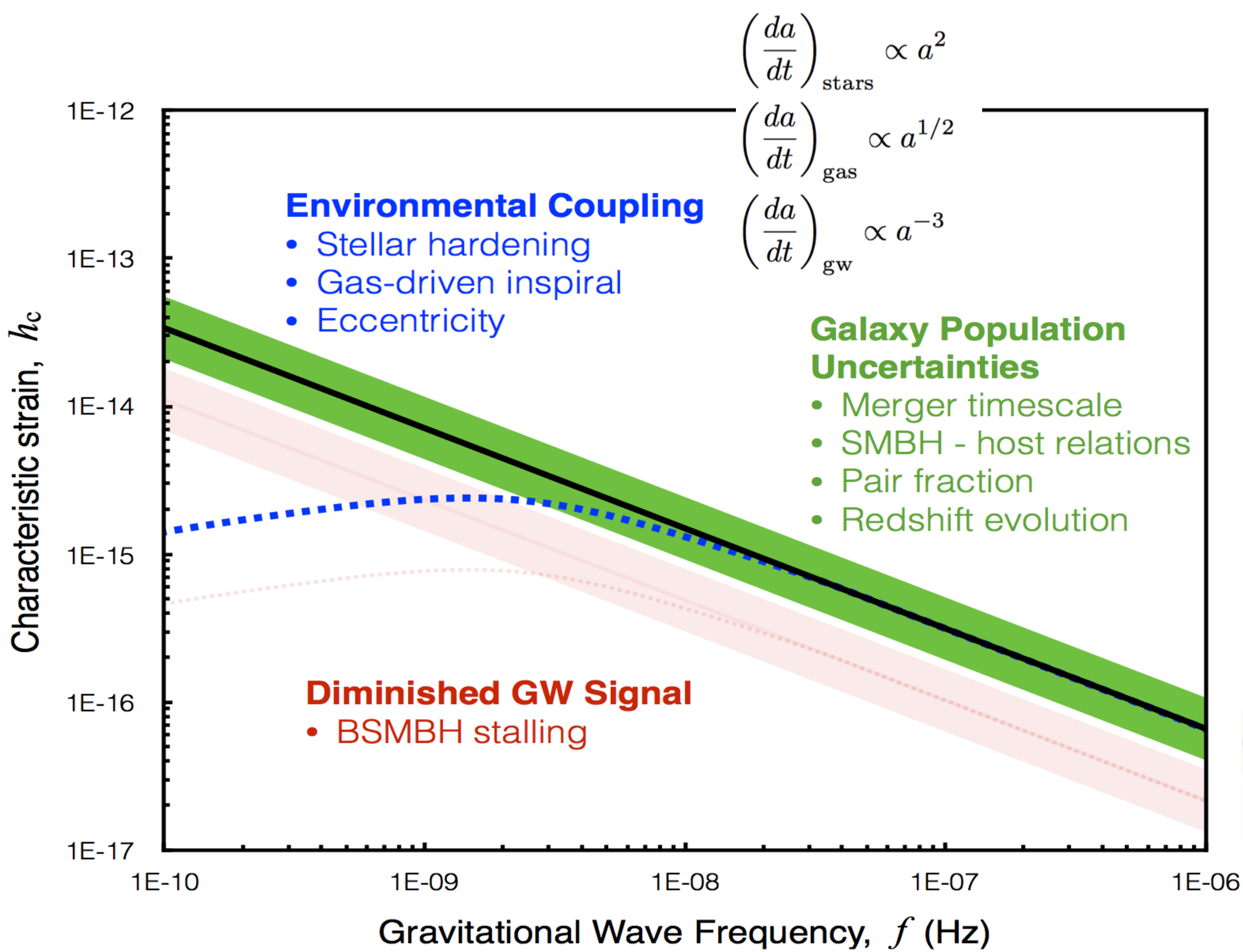
$$h_c(f) = h_{\rm 1yr}\left(\frac{f}{\rm yr^{-1}}\right)^{-2/3}$$

$$h = \frac{8\pi^{2/3}}{10^{1/2}}\frac{\mathcal{M}^{5/3}}{d_L(z)} f_r^{2/3}$$

$$\frac{df_r}{dt_r} = \frac{96}{5}\pi^{8/3}\mathcal{M}^{5/3} f_r^{11/3}$$

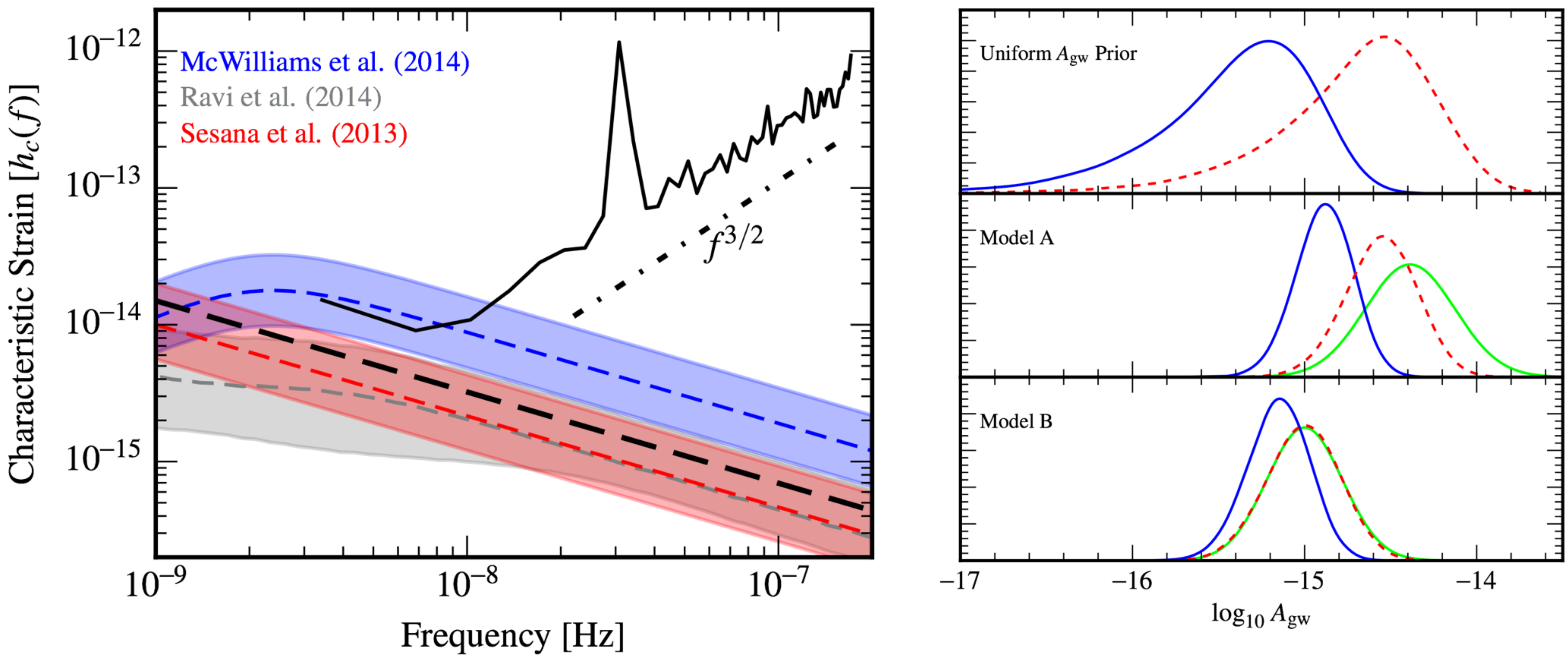
Stochastic background from SMBH mergers

[Phinney 2001, Sesana et al. 2008]



Stochastic background from SMBH mergers

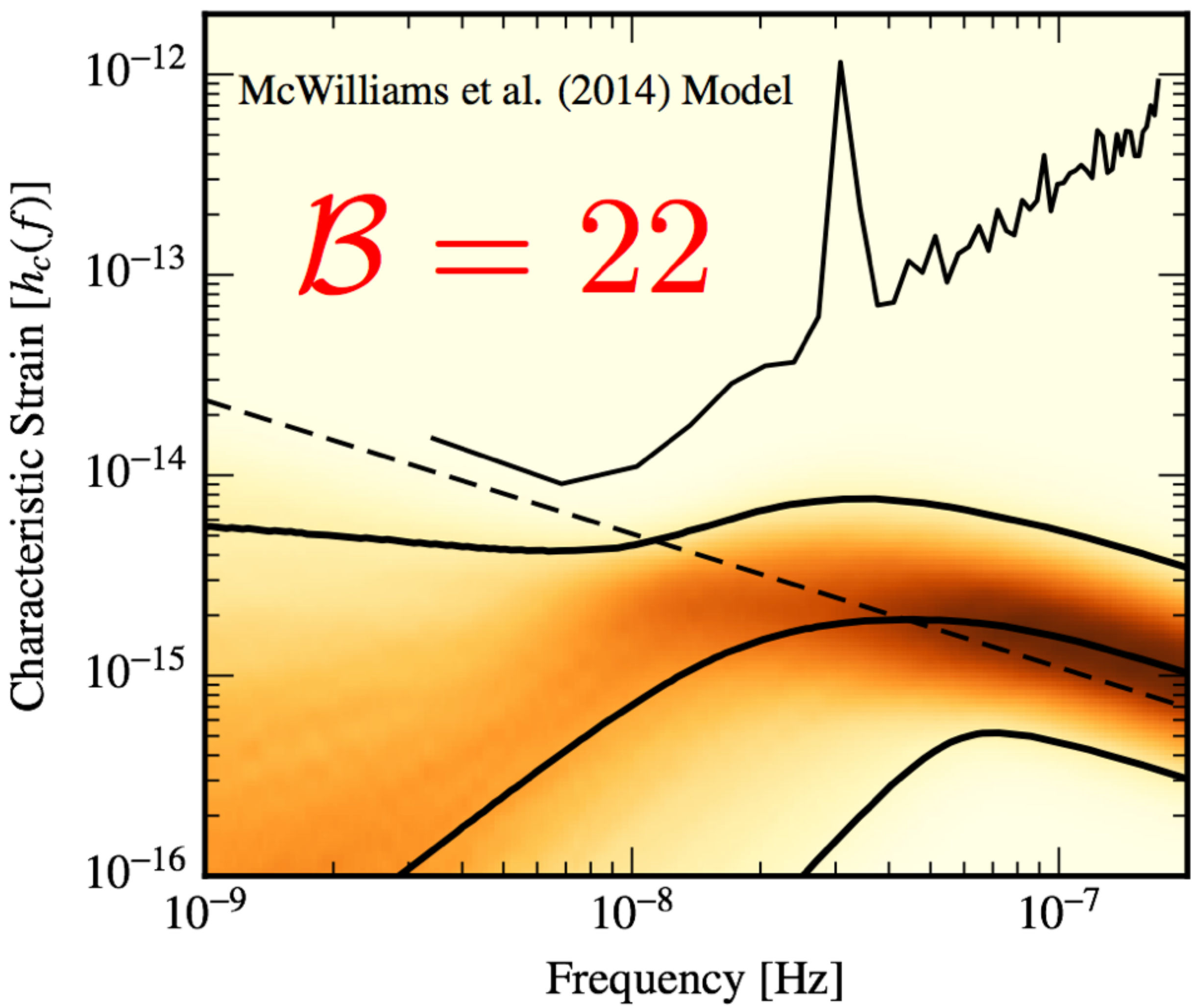
[Sesana et al. 2012, Ravi et al. 2014, Burke-Spolaor 2015]

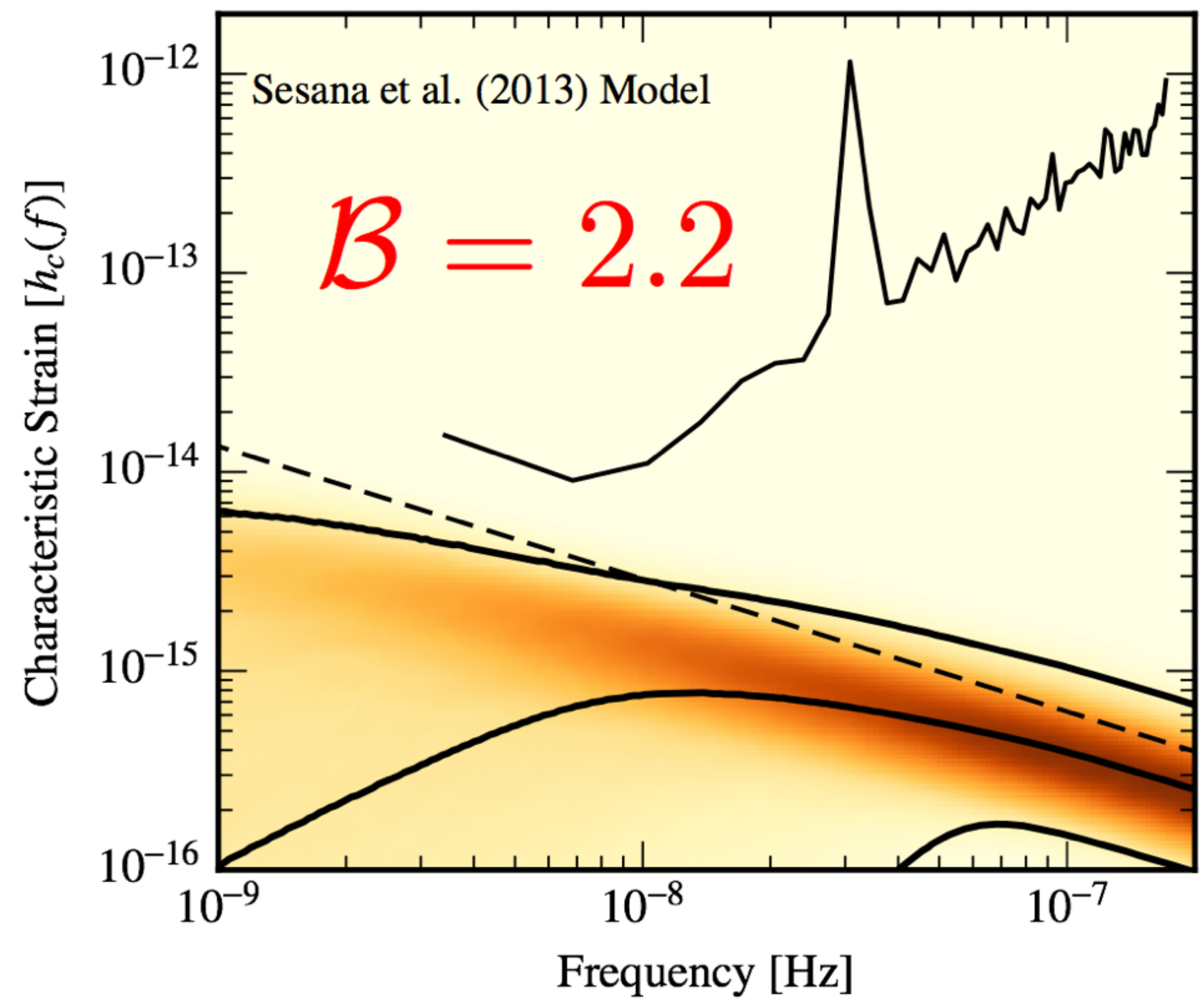


Isotropic SMBH background: NANOGrav 9-year analysis

[NANOGrav 2016]

$$h_c(f) = A \frac{(f/f_{\mathrm{yr}})^{\alpha}}{\left(1+(f_{\mathrm{bend}}/f)^{\kappa}\right)^{1/2}}$$





Isotropic SMBH background: NANOGrav 9-year analysis

[NANOGrav 2016, Sampson et al. 2015]

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REPORT

Gravitational waves from binary supermassive black holes missing in pulsar observations

R. M. Shannon[1,2,*], V. Ravi[3,*], L. T. Lentati[4], P. D. Lasky[5], G. Hobbs[1], M. Kerr[1], R. N. Manchester[1], W. A. Coles[6], Y. Levin[5], M. Bailes[3], N. D. R. Bhat[2], S. Burke-Spolaor[7], S. Dai[1,8], M. J. Keith[9], S. Osłowski[10,11], D. J. Reardon[5], W. van Straten[3], L. Toomey[1], J.-B. Wang[12], L. Wen[13], J. S. B. Wyithe[14], X.-J. Zhu[13]

+ Author Affiliations

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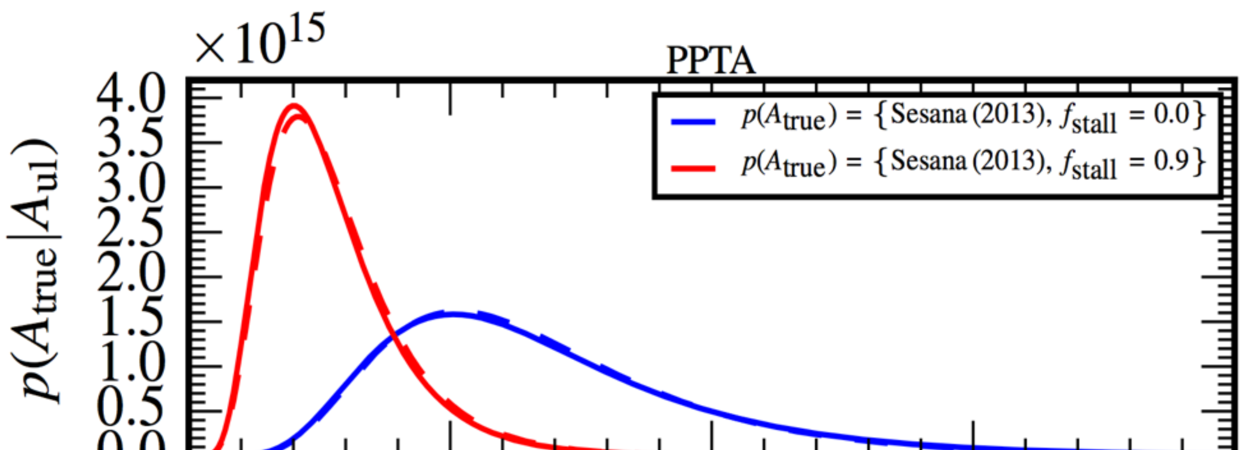
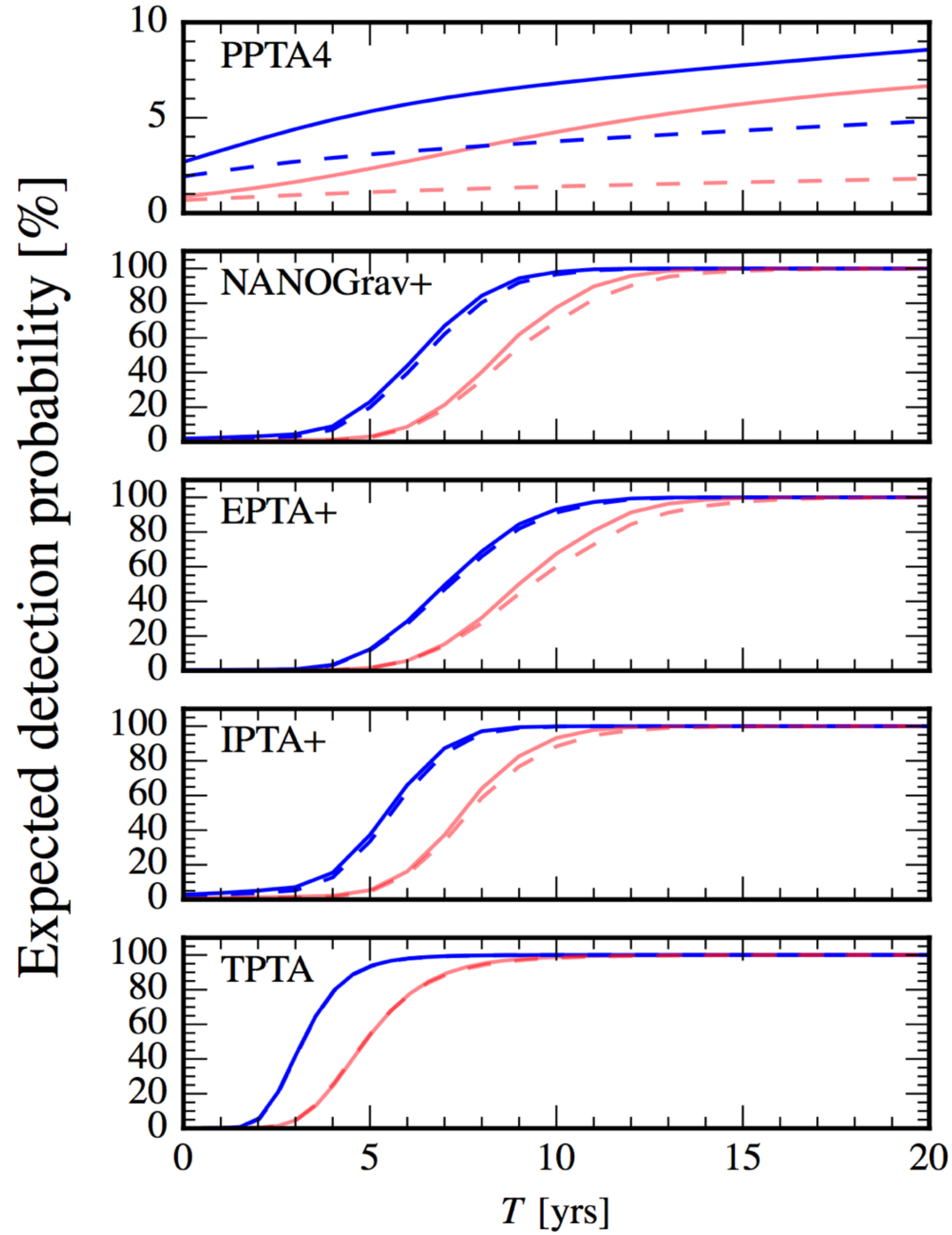
Science 25 Sep 2015:
Vol. 349, Issue 6255, pp. 1522-1525
DOI: 10.1126/science.aab1910



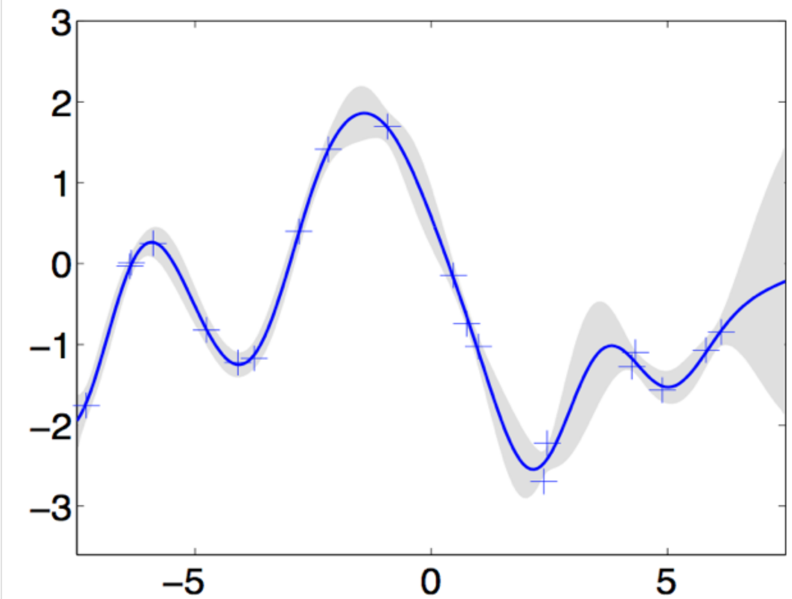


Detection probability given the PPTA limit

[Taylor, Vallisneri, et al. 2015]

A PTA noise *model*: everything is a Gaussian process

timing residuals = radiometer noise (white) + timing-model errors + jitter noise (white, epoch) + DM + timing noise (red) + GWs



Basis picture
Search over basis coefficients and hyperparameters

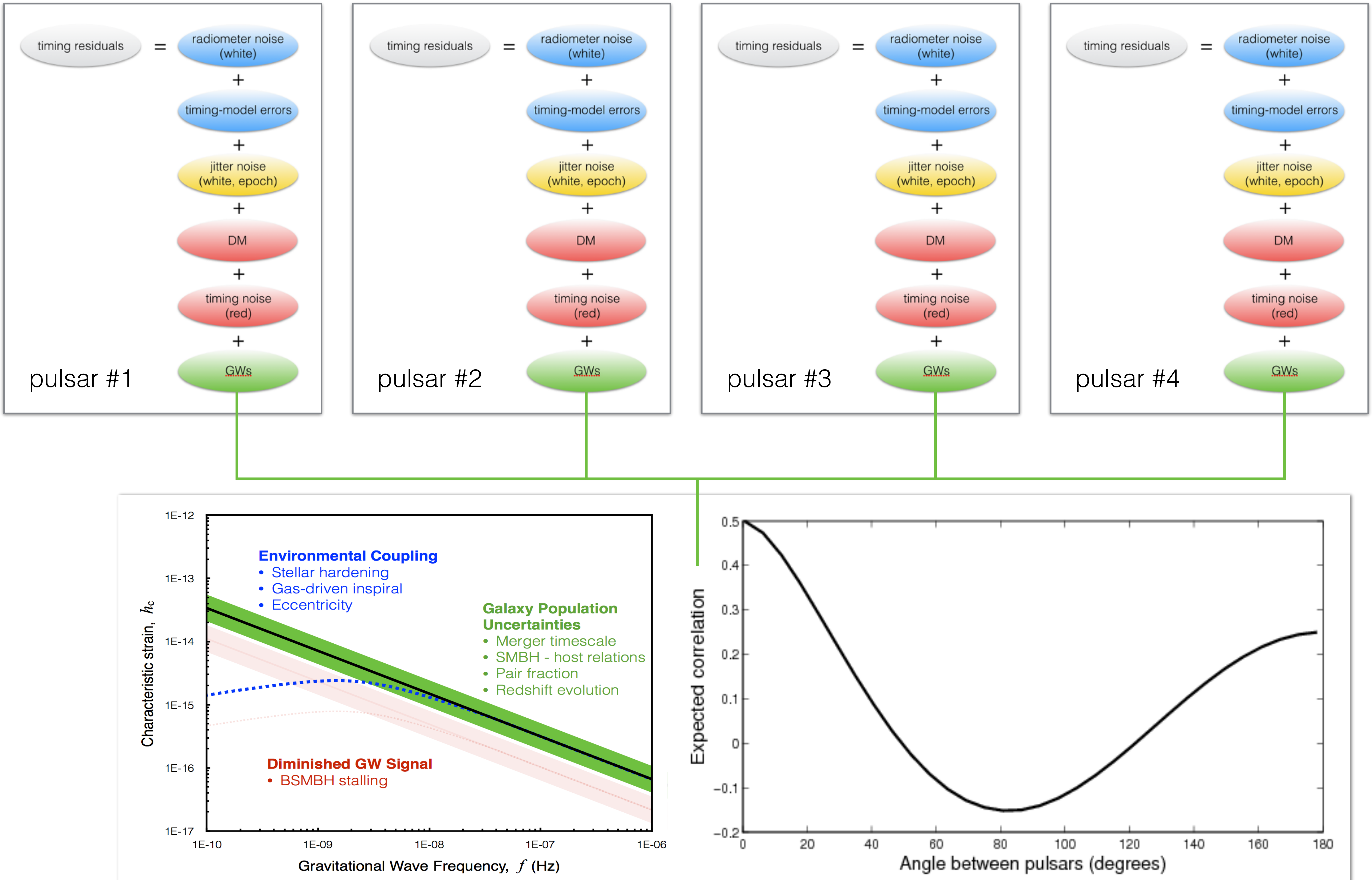
$$y_{\rm gp} = F a$$
$$p(a) \propto e^{-a^T \Phi(\theta)^{-1} a/2}$$

Kernel picture
Marginalize over basis coefficients, search over hyperparameters

$$p(y_{\rm gp}) \propto e^{-y_{\rm gp}^T K(\theta)^{-1} y_{\rm gp}/2}$$
$$K(\theta) = F \Phi(\theta) F^T$$

van Haasteren & MV
PRD 90, 104012 (2014)

Stochastic GWs as correlated Gaussian process

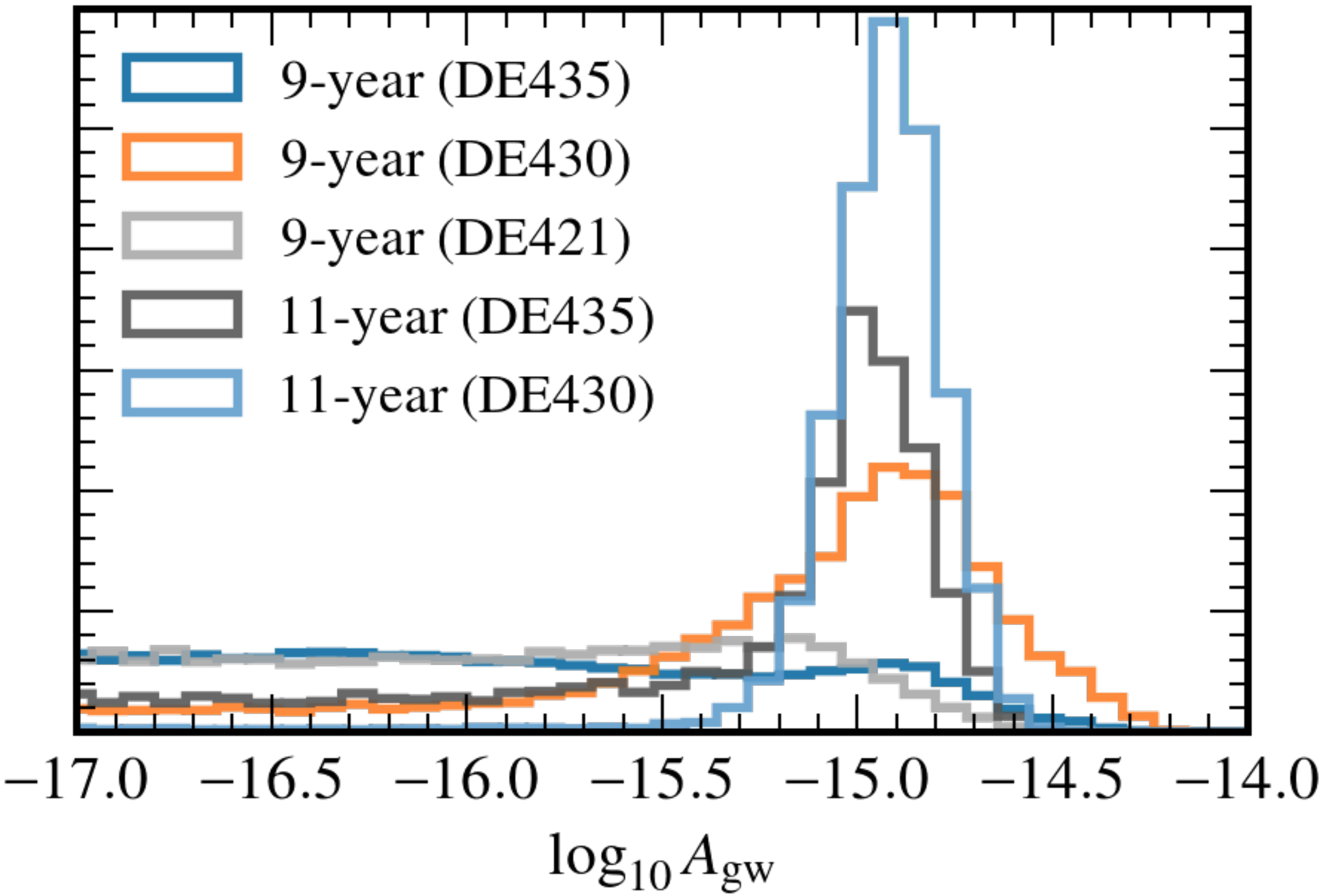


[Burke-Spolaor 2015]

[Jenet et al. 2015]

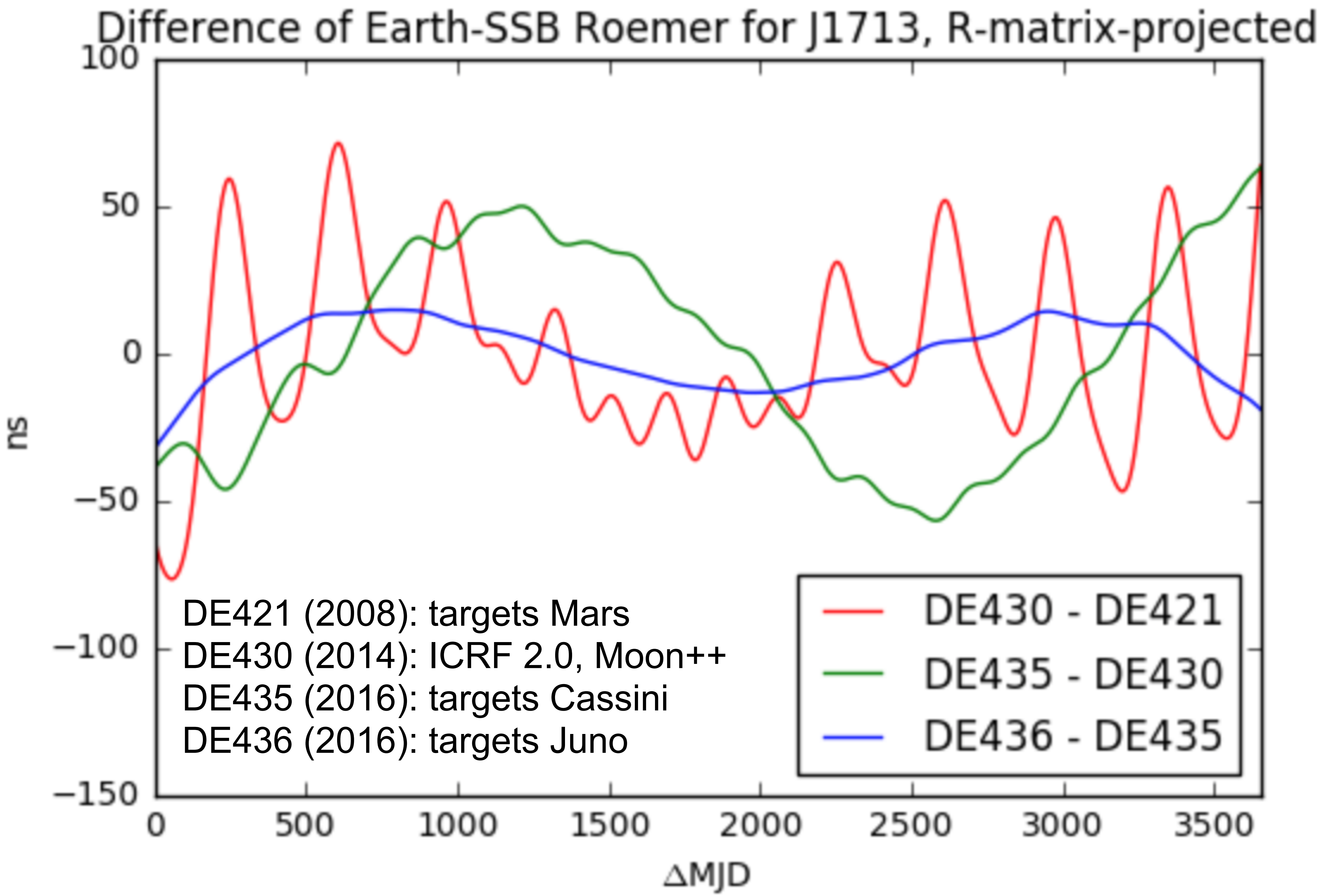
GWB amplitude posteriors

[NANOGrav 2017, PRELIMINARY]



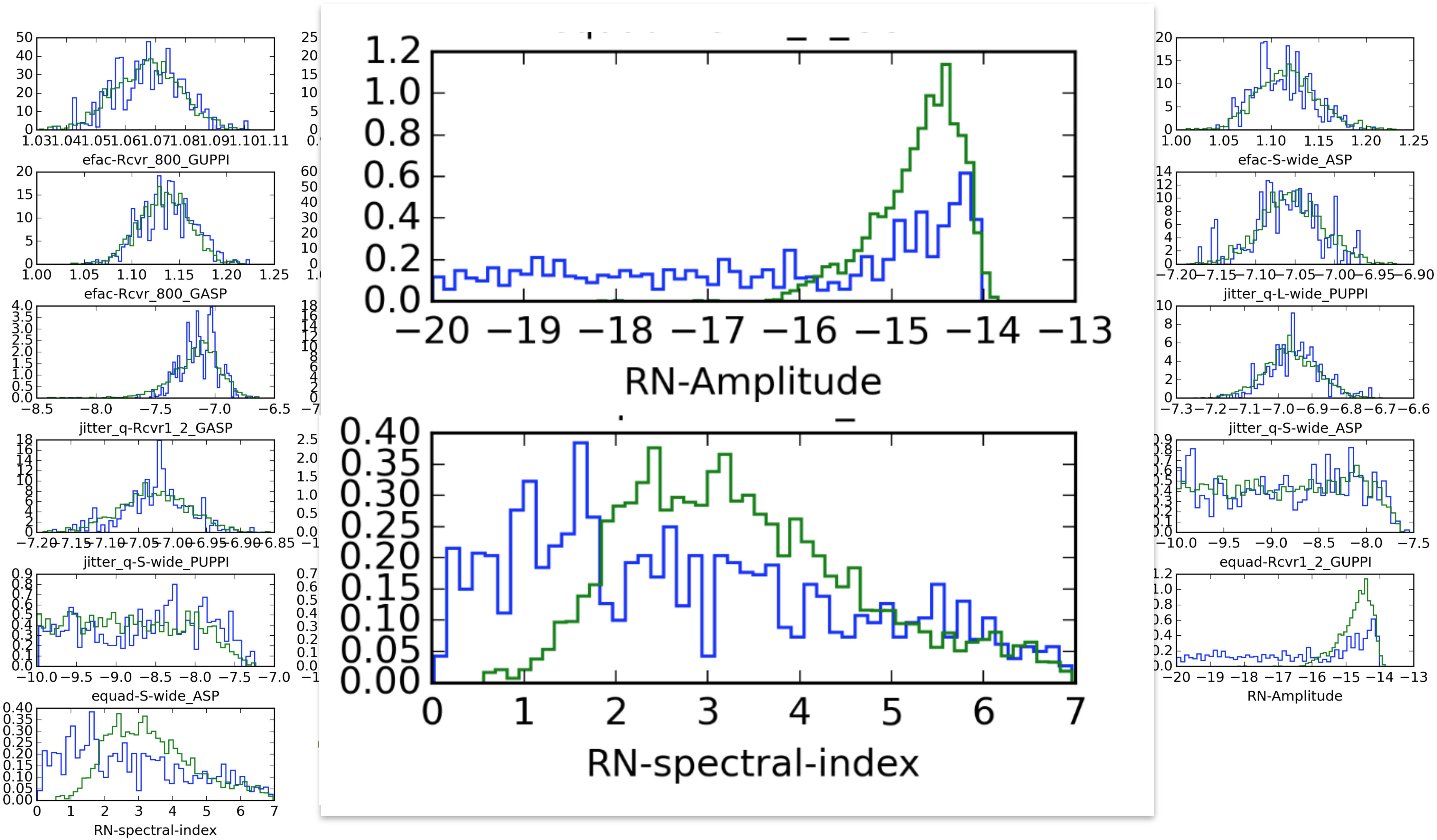
Ephemeris systematics

[NANOGrav 2017, PRELIMINARY]



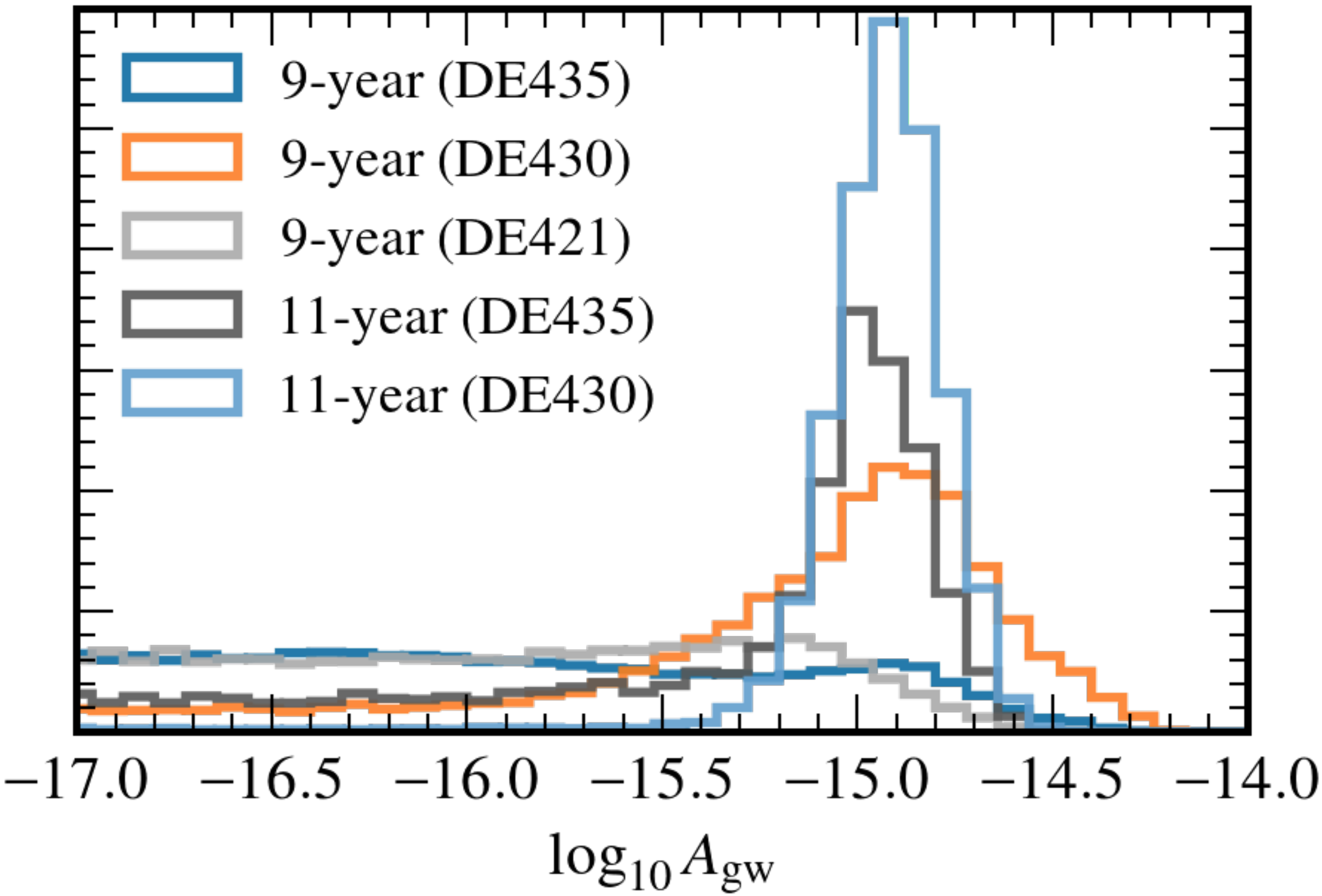
J1713+0747 noise model

[NANOGrav 2017, PRELIMINARY]



GWB amplitude posteriors

[NANOGrav 2017, PRELIMINARY]

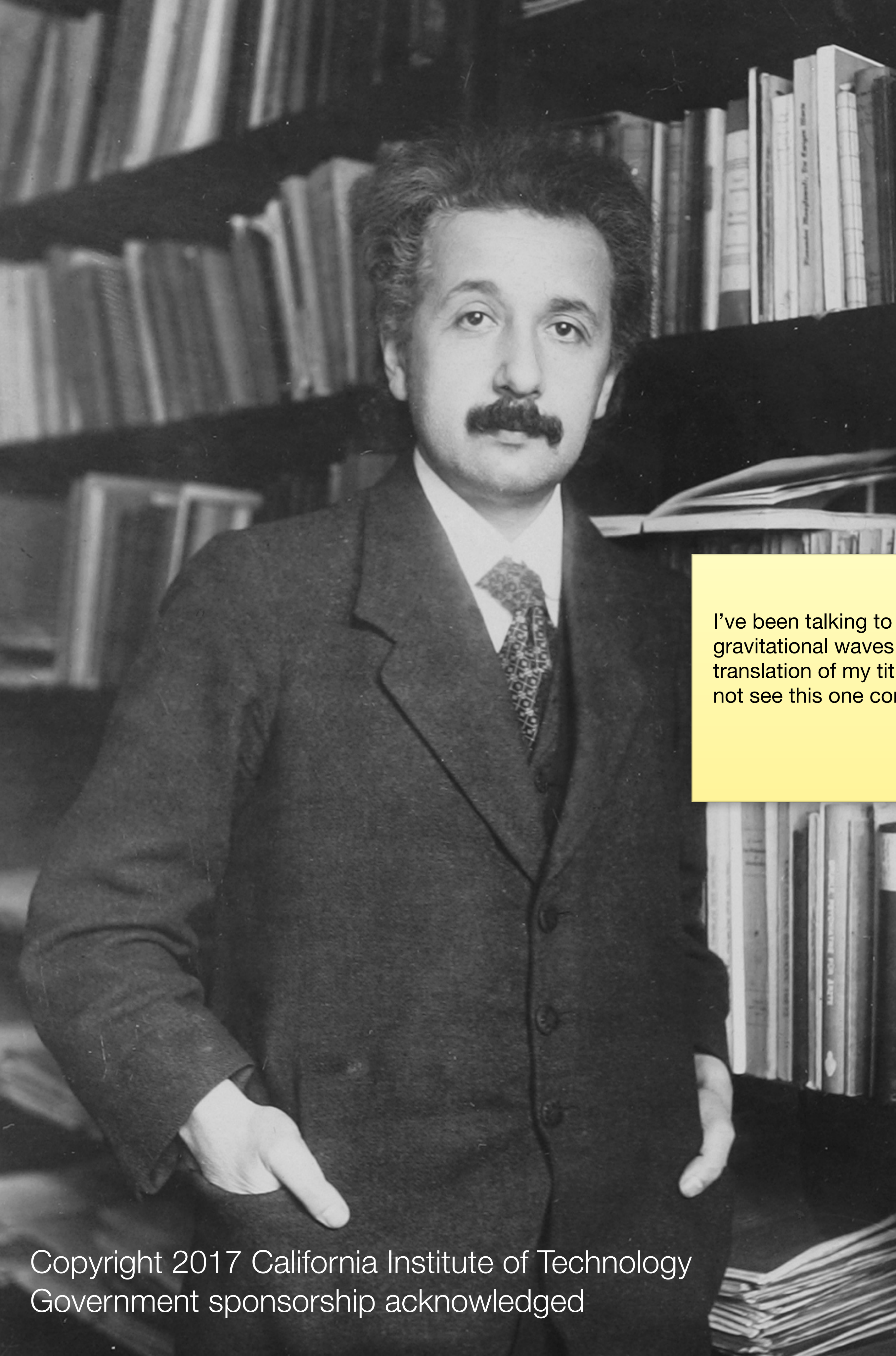


PTA outlook

Fitting that pulsars, after indirectly confirming the presence of GWs by loss of energy, should offer a way to measure them directly.

- GW detection with PTAs offers a very beaut challenge: building a detector the size of ou nature's most precise clocks, millisecond pu
- Barring surprises (cosmic strings, nonstandard relic radiation, GW memory from early-Universe events), PTAs will observe first the stochastic background from the cosmological population of supermassive black-hole binaries in Galactic nuclei.
- Improvements in sensitivity are limited by the increasing span of datasets and by the continued discovery of new pulsars.
- The most recent upper limits on the background are in tension with theoretical expectations, suggesting “last-parsec” physics, or faulty assumptions. Nevertheless, if theoretical models are correct, detection is expected within 10 years.
- Establishing confident detection requires sophisticated statistical techniques and superior control of systematics. Unfortunately, recent hints of a signal seem to be subsiding.

Gravitational waves from binary black holes across the spectrum



I've been talking to schoolkids about gravitational waves, so I'm providing a translation of my title. I bet Einstein did not see this one coming, either.

Michele Vallisneri
Jet Propulsion Laboratory
California Institute of Technology

LSC LIGO Scientific Collaboration

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