LISA and the future of gravitational wave science

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Outline

- Introduction: gravitational wave astronomy
- Status of LIGO/Virgo
- Future ground-based detectors
- The LISA mission
- Targets of LISA
- Challenges for the data analysis of LISA
- Counterparts for MBHBs, GW cosmology and tests of GR in LISA

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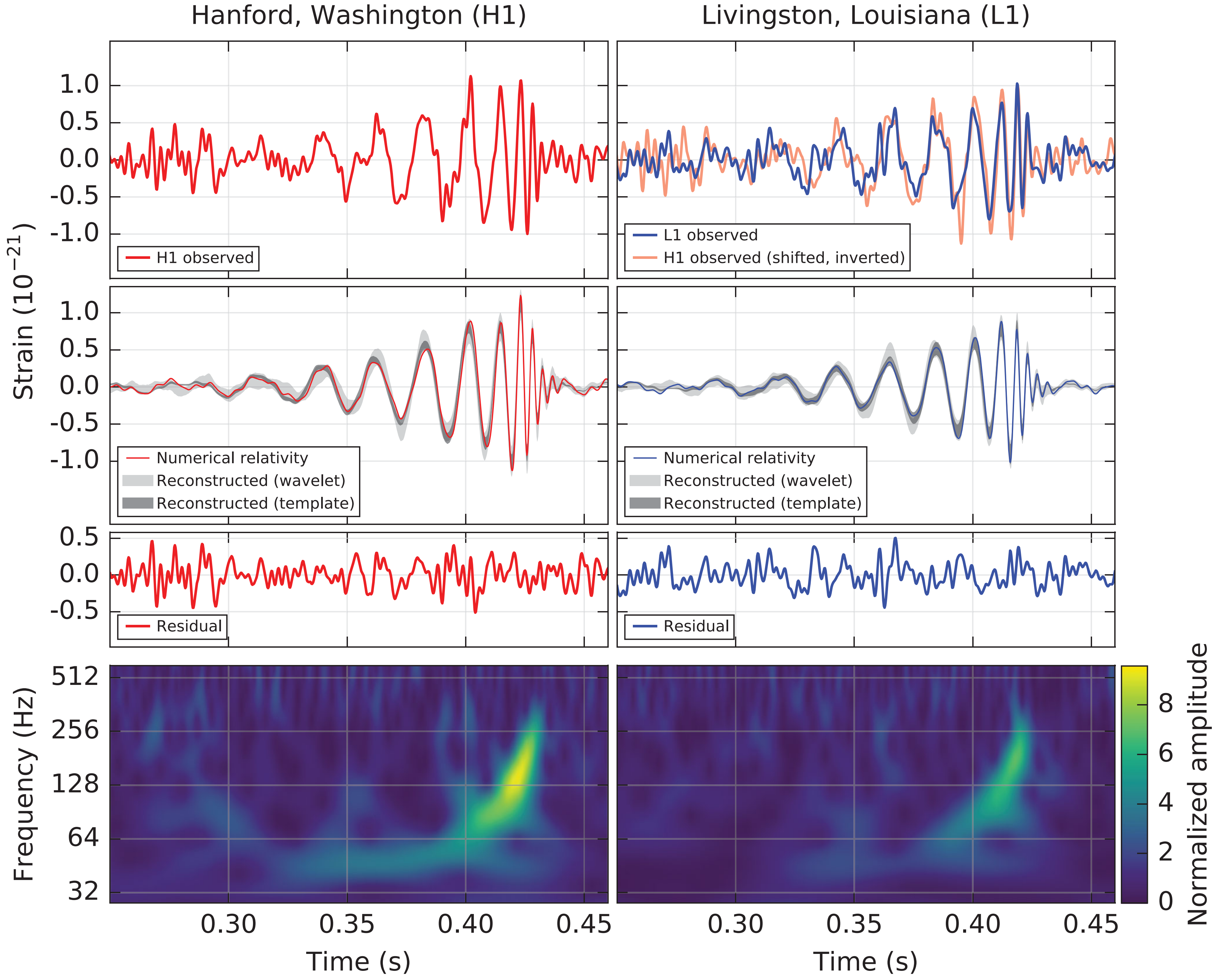
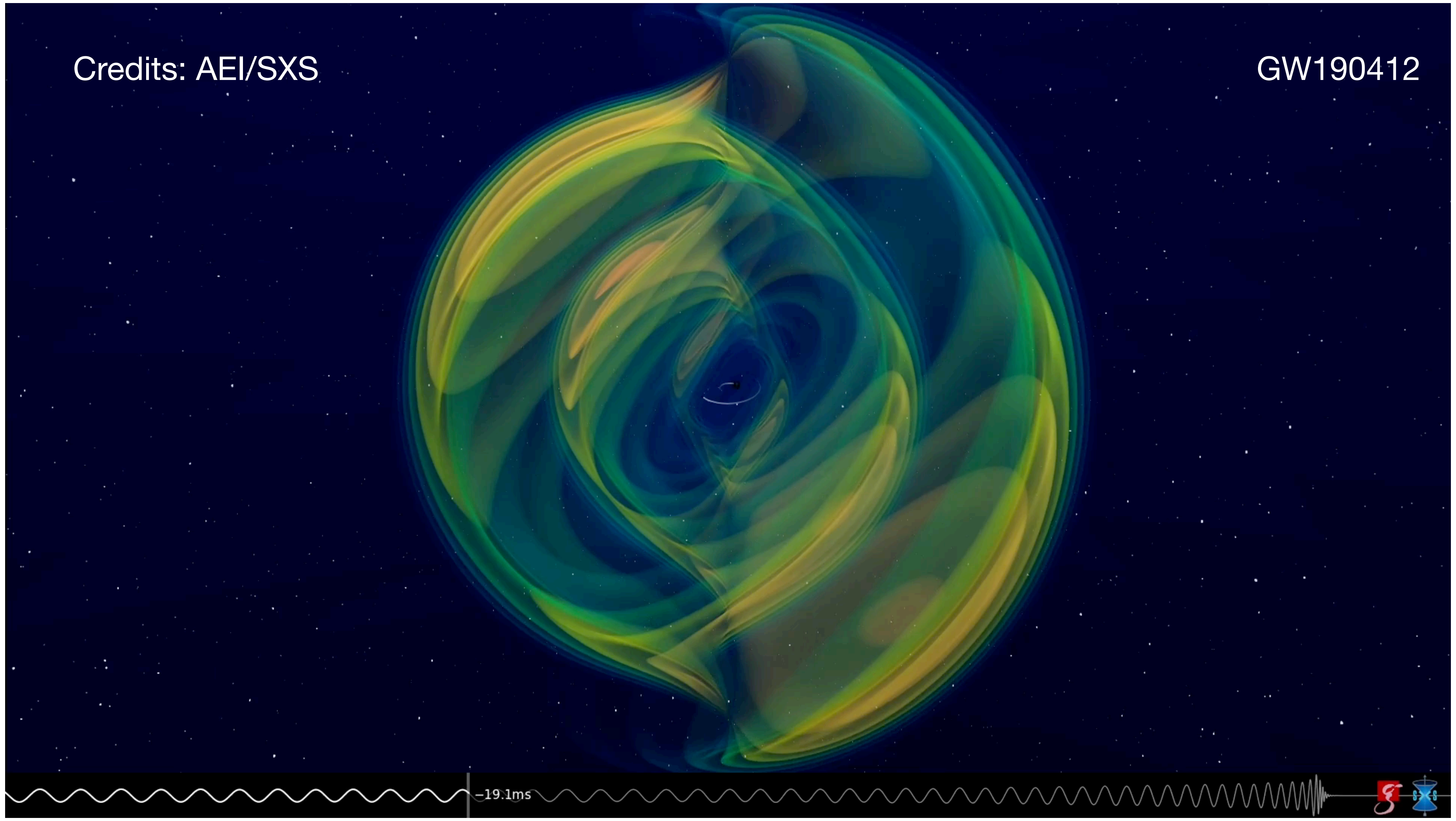
GW150914: first direct detection of gravitational waves

GW150914: Network SNR: 24 !

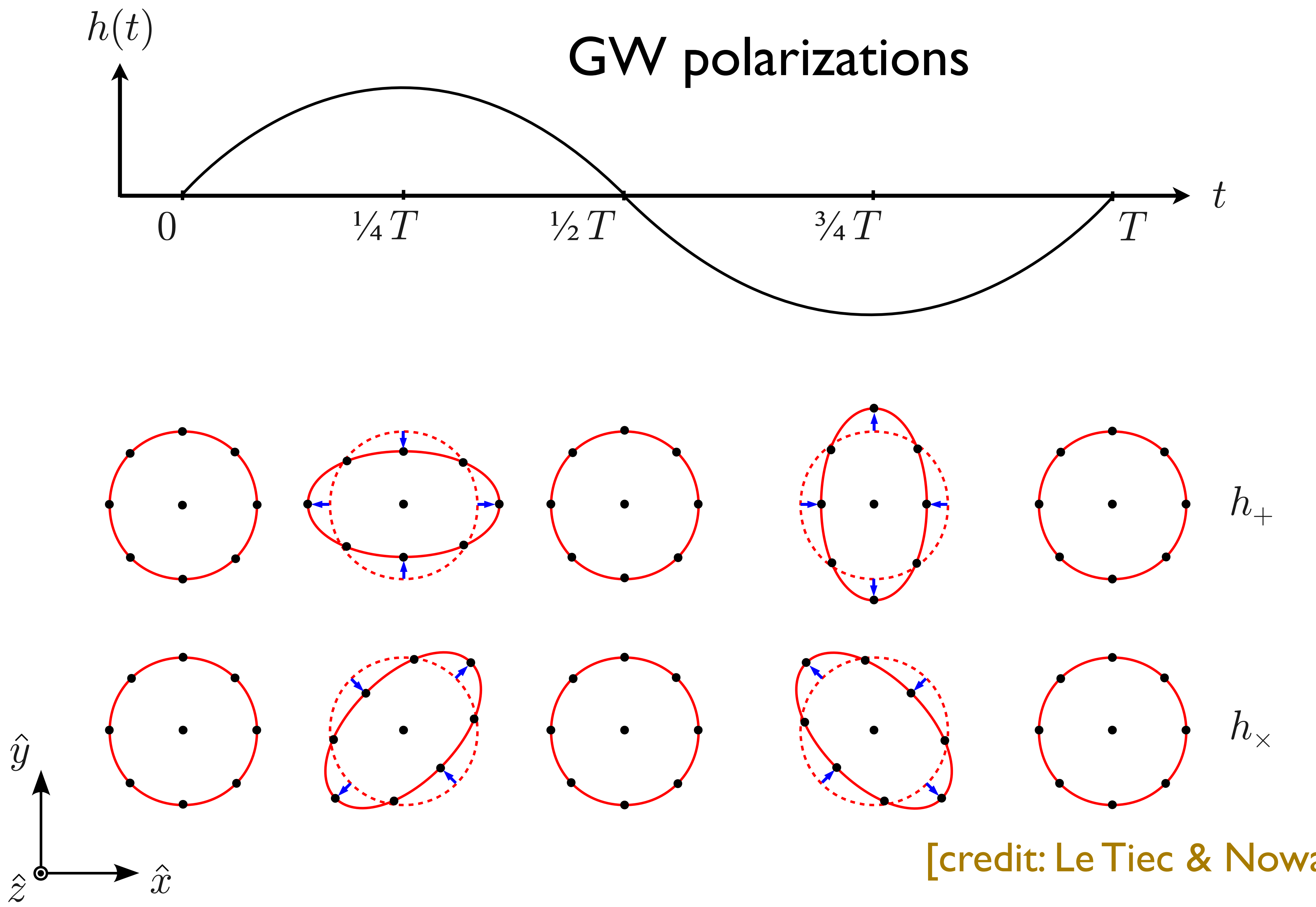


2017 Nobel Prize in Physics: R. Weiss, B. C. Barish, K S. Thorne

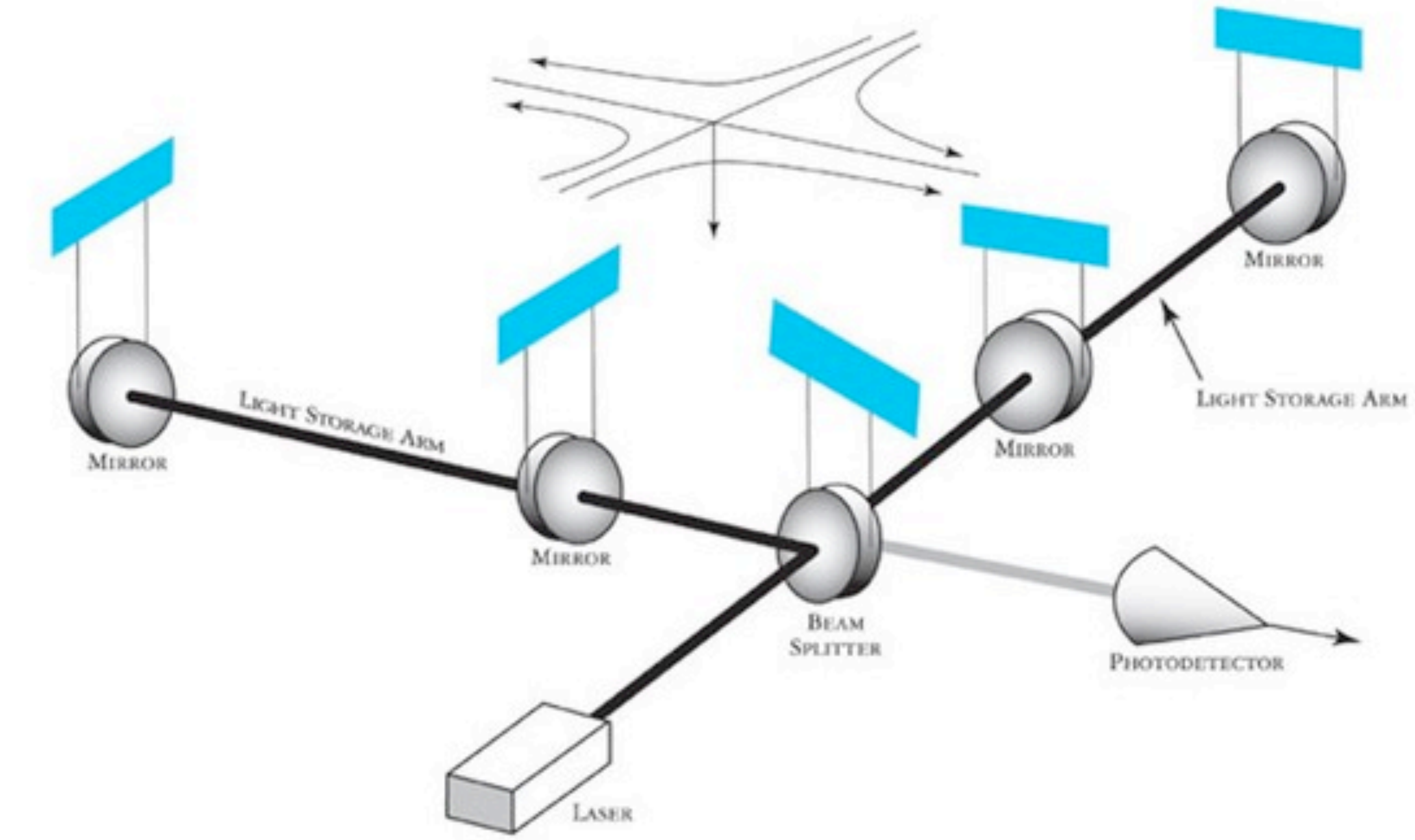


NR simulation for a BHNS system

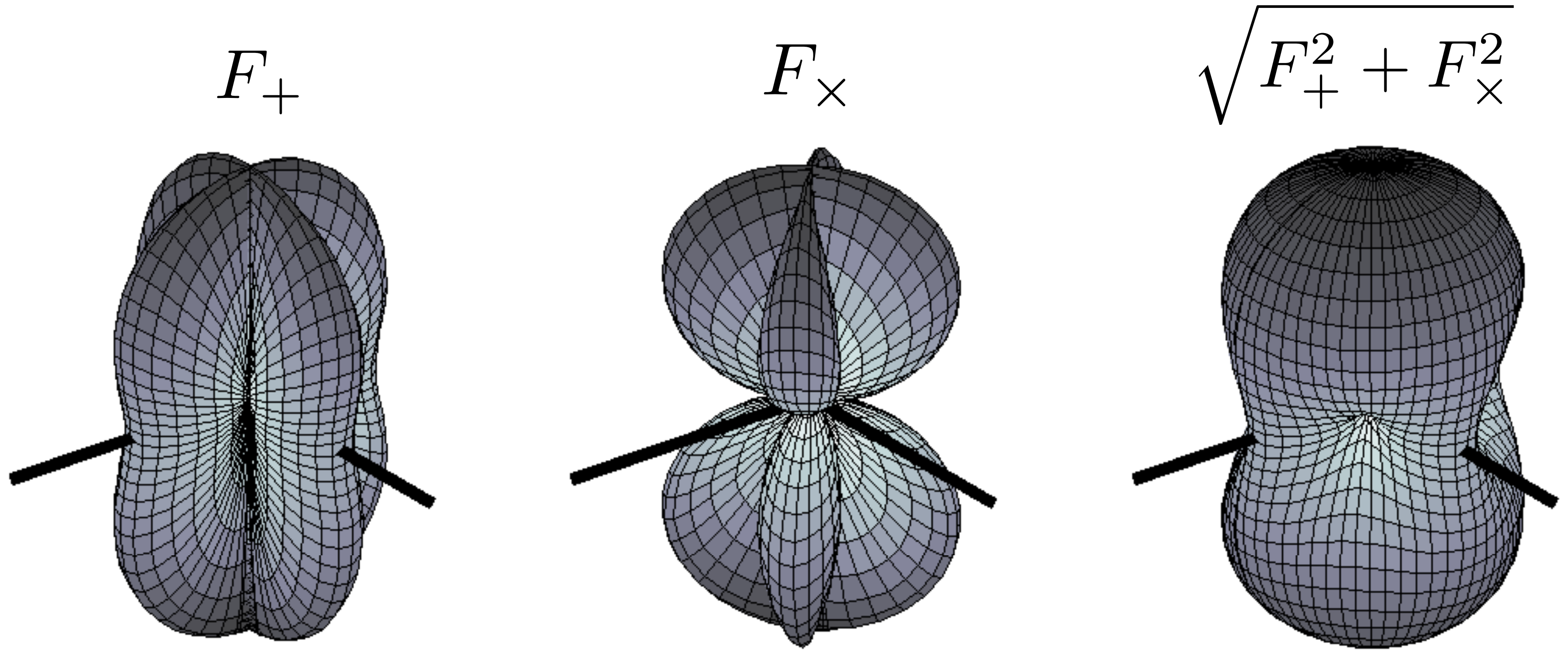
GW Signals: polarizations and strain



[credit: Le Tiec & Nowak 2016]



[credit: LIGO]



[credit: LVK 2007]

Response of an interferometer:

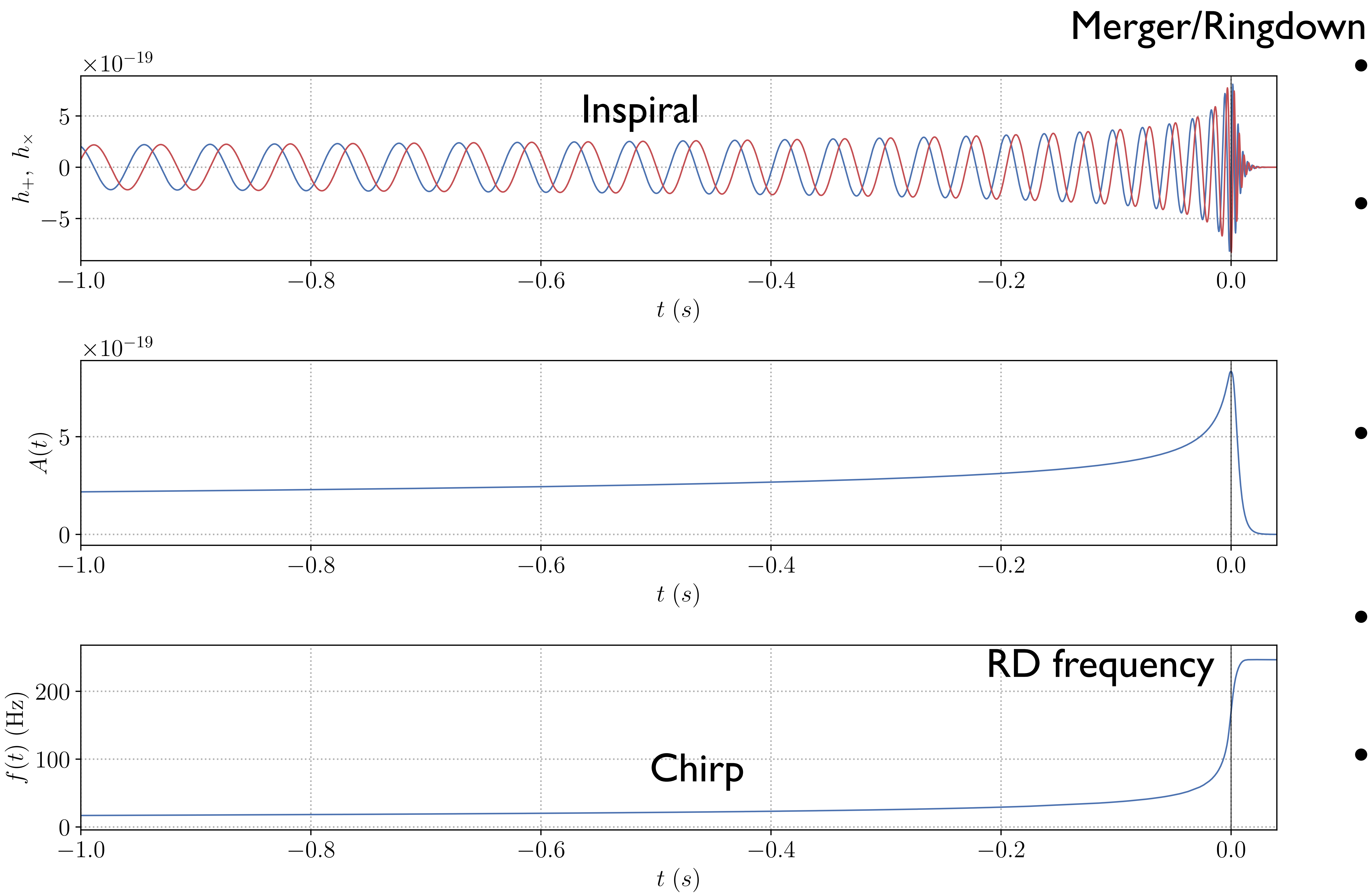
$$h = F_+ h_+ + F_\times h_\times$$

$F_{+,\times}(\theta, \phi, \psi)$ pattern functions, depend on sky and polarization

All-sky detectors 'listening' to the gravitational universe

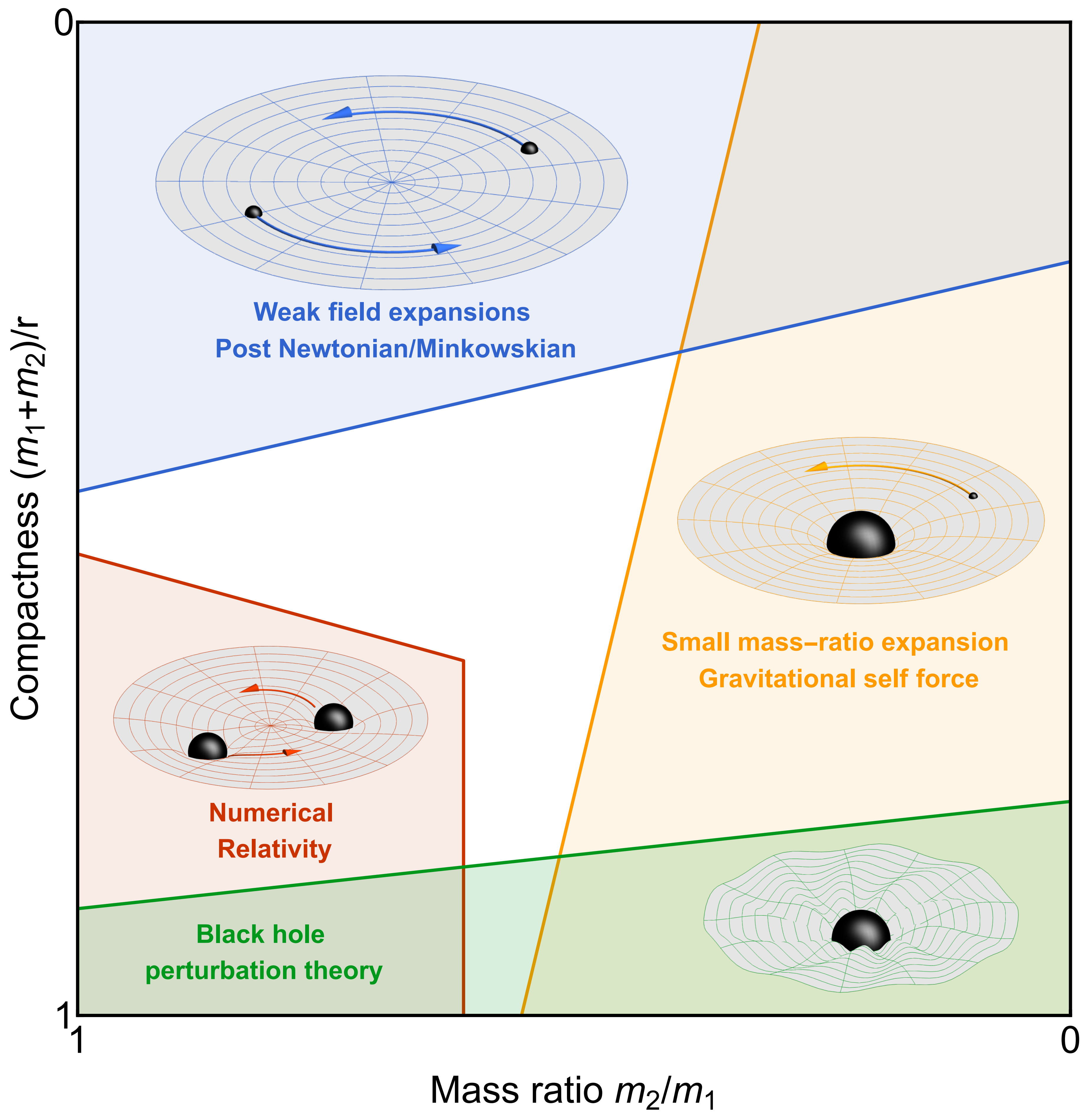
Compact Binary Coalescences - Lexikon

BBH: binary black hole
BNS: binary neutron star



- Dominant frequency: $$f = 2 f_{\mathrm{orb}}$$
- Chirp mass: $$\mathcal{M}_c = \frac{m_1^{3/5} m_2^{3/5}}{(m_1 + m_2)^{1/5}}$$
- Inspiral frequency:
$$\omega_{\mathrm{orb}}(t) = \left(\frac{G\mathcal{M}_c}{c^3}\right)^{-5/8} \left(\frac{5}{256}\frac{1}{t_c - t}\right)^{3/8}$$
- BBH scale invariance:
$$G = c = 1 \qquad t \to t/M \qquad f \to Mf \qquad h \to rh/M$$
- End of inspiral:
$$r_{\mathrm{ISCO}} = 6M \qquad f_{\mathrm{ISCO}} = 1/6^{3/2}/(\pi M)$$
- Effect of cosmology:
$$M \to (1+z)M \qquad 1/r \to 1/d_L$$

Waveform modelling



Analytic approaches (PN/PM)

- analytic perturbative results for the inspiral phase
- recent progress on post-Minkowskian side, hyperbolic orbits

Self-force, small mass ratios (SF)

- analytic/numerical results for the extreme mass ratio limit
- recent progress on 2nd order SF, and comparable-mass limit

Numerical relativity (NR)

- costly full-GR 4D simulations, limited to merger and few orbits
- only reference for merger-ringdown signals
- recent progress on high mass ratio and modified gravity

Combination of analytical/ numerical approaches

Crucial and active field of study

Noise and signal

Noise autocorrelation in the stationary case:

$$C(t,t') = \langle n(t) n(t') \rangle$$
$$C(t,t') = C(0, t'-t) \equiv C(t'-t)$$

Noise PSD as the FT of the autocorrelation:

$$\frac{1}{2} S_n(f) = \int d\tau \, C(\tau) e^{-2i\pi f \tau}$$

Introduce a noise-weighted inner product:

$$(a|b) \equiv 4\mathrm{Re} \int_0^{+\infty} \frac{df}{S_n(f)} \tilde{a}(f) \tilde{b}^*(f)$$

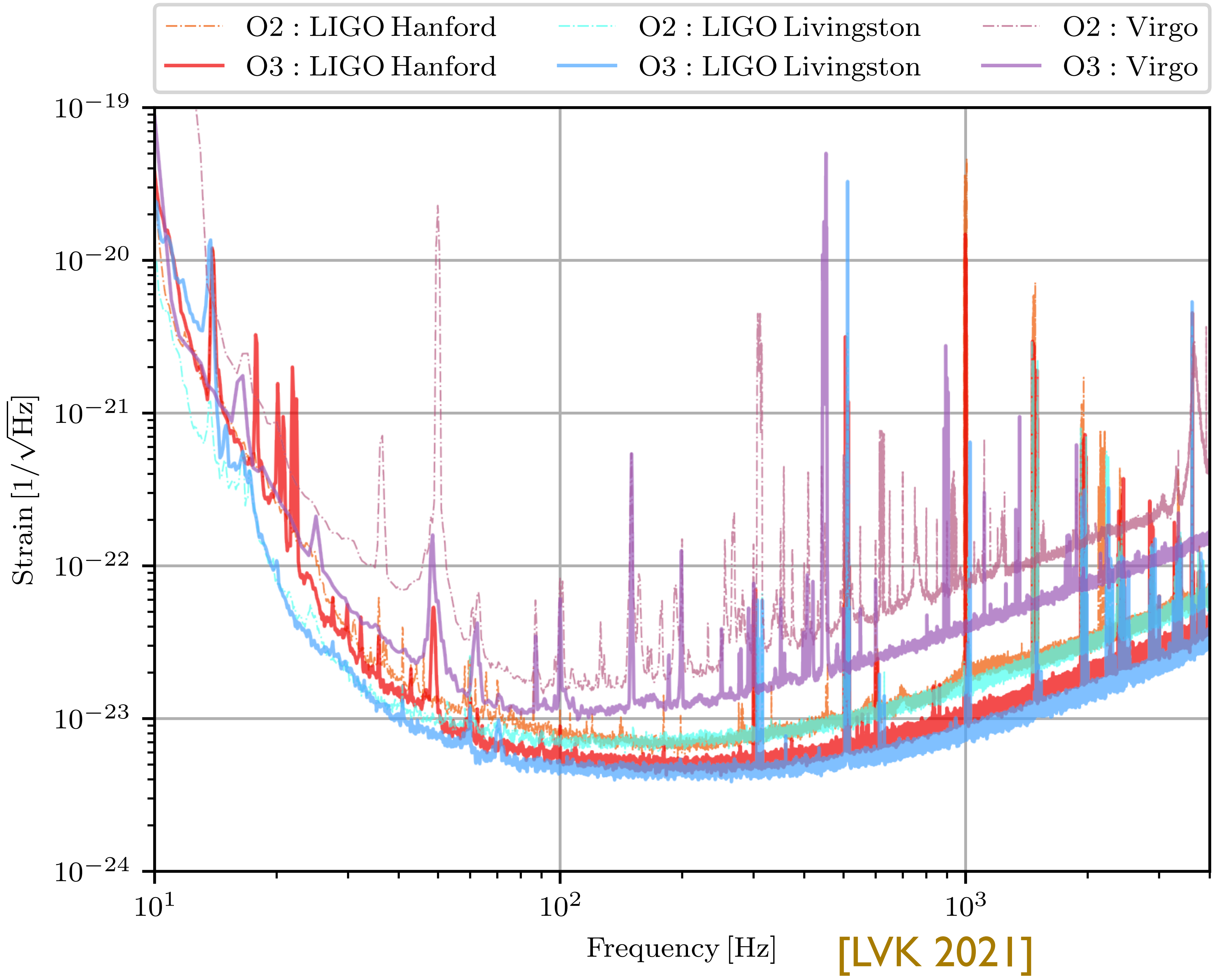
Optimal Signal-to-Noise ratio:

$$\mathrm{SNR}^2 = (h|h)$$

Matched filter SNR comparing template to data:

$$\rho^2 = (h|d)$$

Example of real instrumental PSDs (instr. lines, …)



[LVK 2021]

Bayes theorem and posterior distribution

Bayes theorem

Likelihood $p(d|\theta, M) = \mathcal{L}(d|\theta, M)$

Posterior distribution

$$p(\theta|d, M) = \frac{p(d|\theta, M)p(\theta|M)}{p(d|M)}$$

Prior distribution

- a priori knowledge of parameters

- target of the analysis
- multidim. distribution, discrete samples

θ inferred params (17 for GW source)
d data (observed data in detector)
M model (context, assumptions)

Evidence $$p(d|M) = \int d\theta \, p(d|\theta, M)p(\theta|M)$$

- normalization of the posterior
- important for model comparison

Idealized data likelihood (Whittle)

For a **stationary Gaussian** process: independence FD, diagonal covariance

$$\ln \mathcal{L}(\theta) = -\frac{1}{2}(h(\theta) - d|h(\theta) - d)$$

(Noise-weighted) norm of residuals between template and data

Hierarchical inference

Infer hyperparameters affecting the whole population (population model, cosmology, modified gravity)

$$p(\Lambda|\{d\}) \propto p(\Lambda) \prod_{i=1}^{N_{\rm GW}} \frac{1}{\xi(\Lambda)} \int d\theta \, \mathcal{L}(d_i|\theta, \Lambda)p(\theta|\Lambda)$$

Selection effect: Malmquist bias, louder events more likely to be detected

$$\xi(\Lambda) = \int d\theta p_{\rm det}(\theta, \Lambda)$$

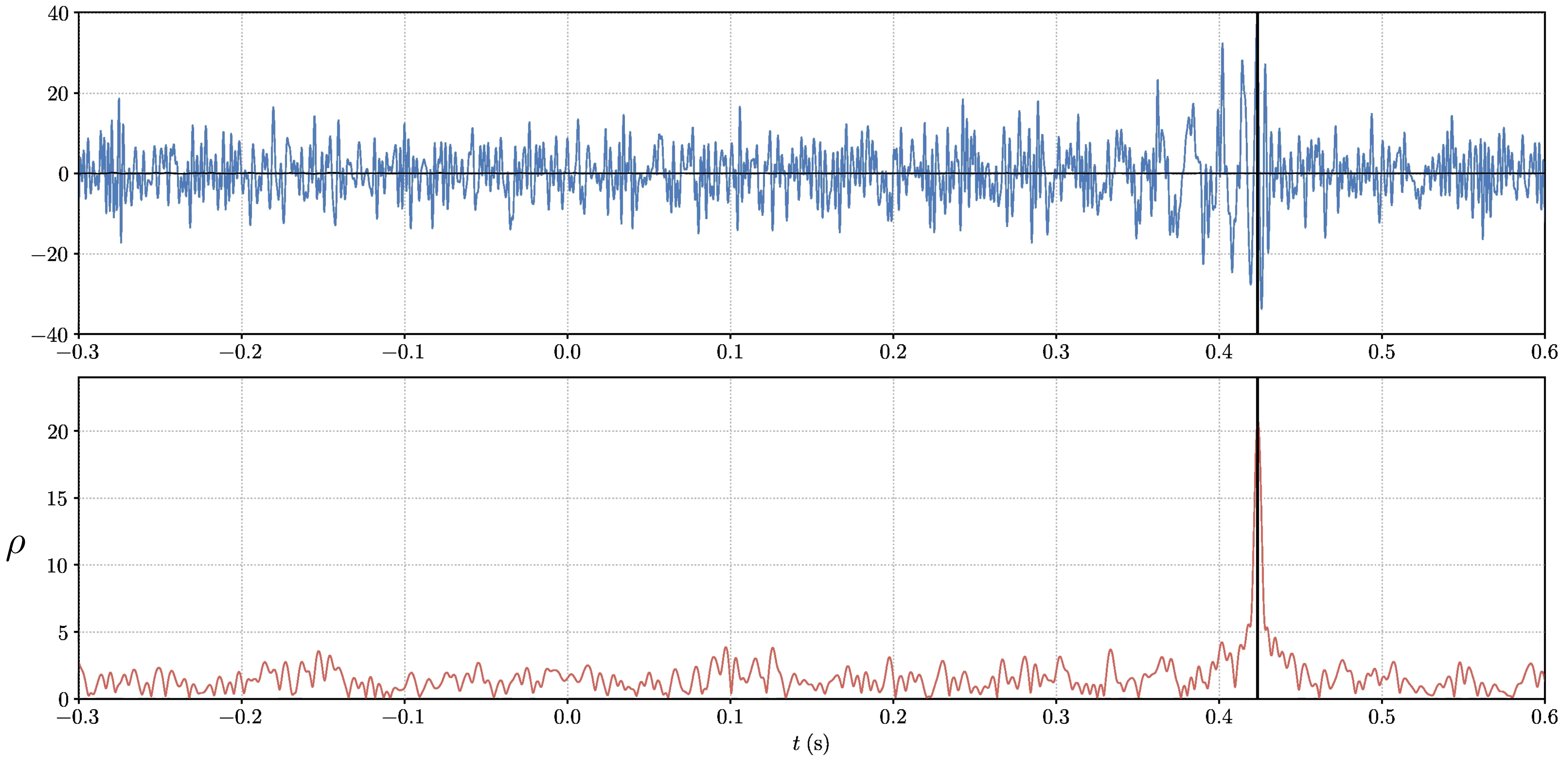
$$p_{\rm det}(\theta, \Lambda) = \int_{x > {\rm thres.}} dx \, \mathcal{L}(x|\theta, \Lambda)$$

Matched filtering example

Example: trying a fixed template

Optimize over phase: $\max_{\alpha} \mathrm{Re}\left(e^{i\alpha} h|s\right) = |(h|s)|$

Optimize over time: $\int df\, e^{2i\pi f \Delta t} \tilde{h}\tilde{s}^* / S_n = \mathrm{IFFT}(\tilde{h}\tilde{s}^*/S_n)$



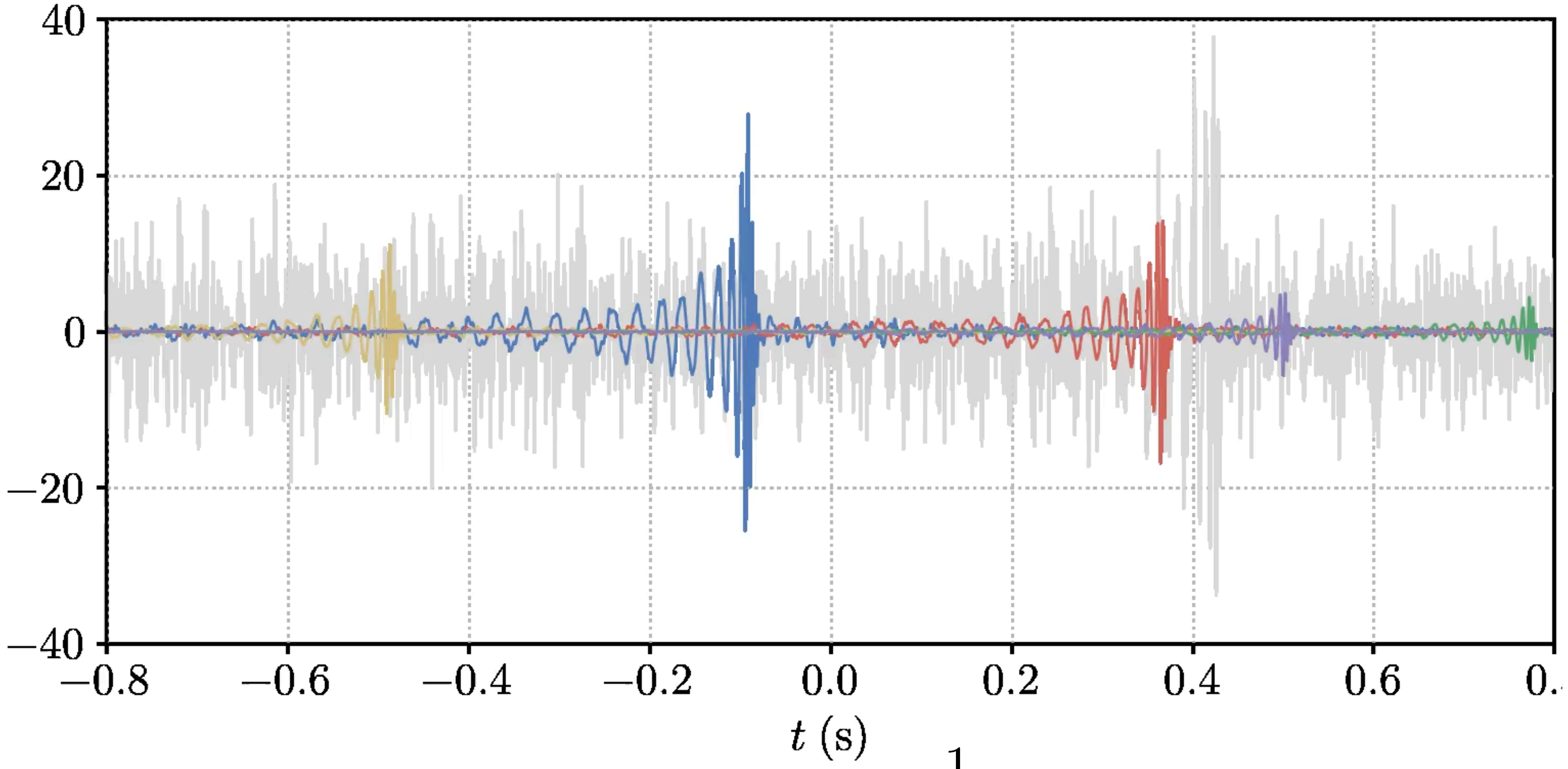
In reality, detector noise has strong outliers (glitches):

- use custom detection statistics penalizing outliers
- use carefully constructed template banks covering the parameter space
- exploit coincidence between independent detectors for detection confidence
- use real detector data in time slides to assess significance of coincidence
- triggers are assessed by their False-Alarm Rate (FAR)

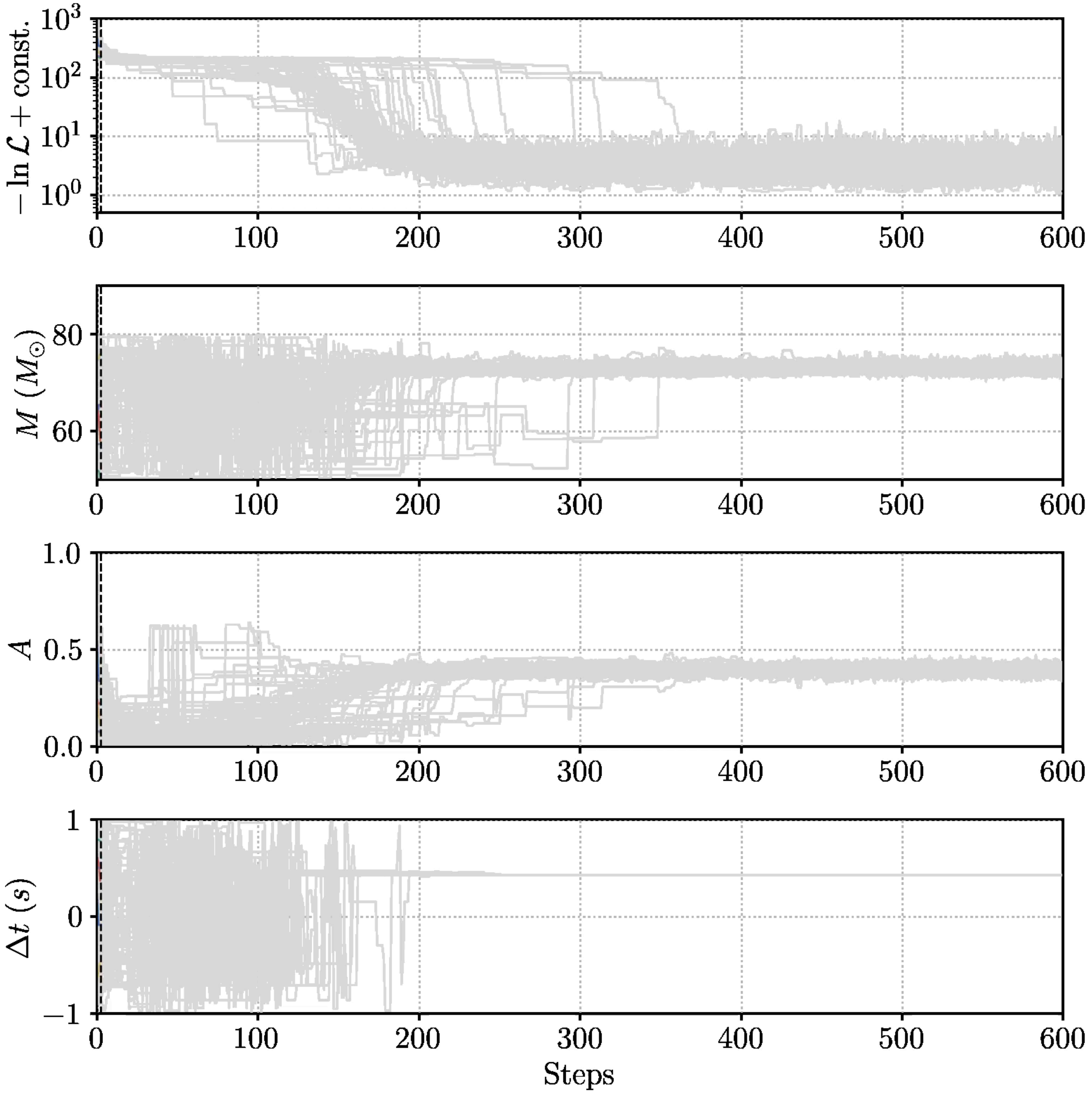
Matched filtering and coincidence state-of-the-art for LVK

GW Parameter Estimation example

Sample waveforms (5 random walkers)



Trace plot

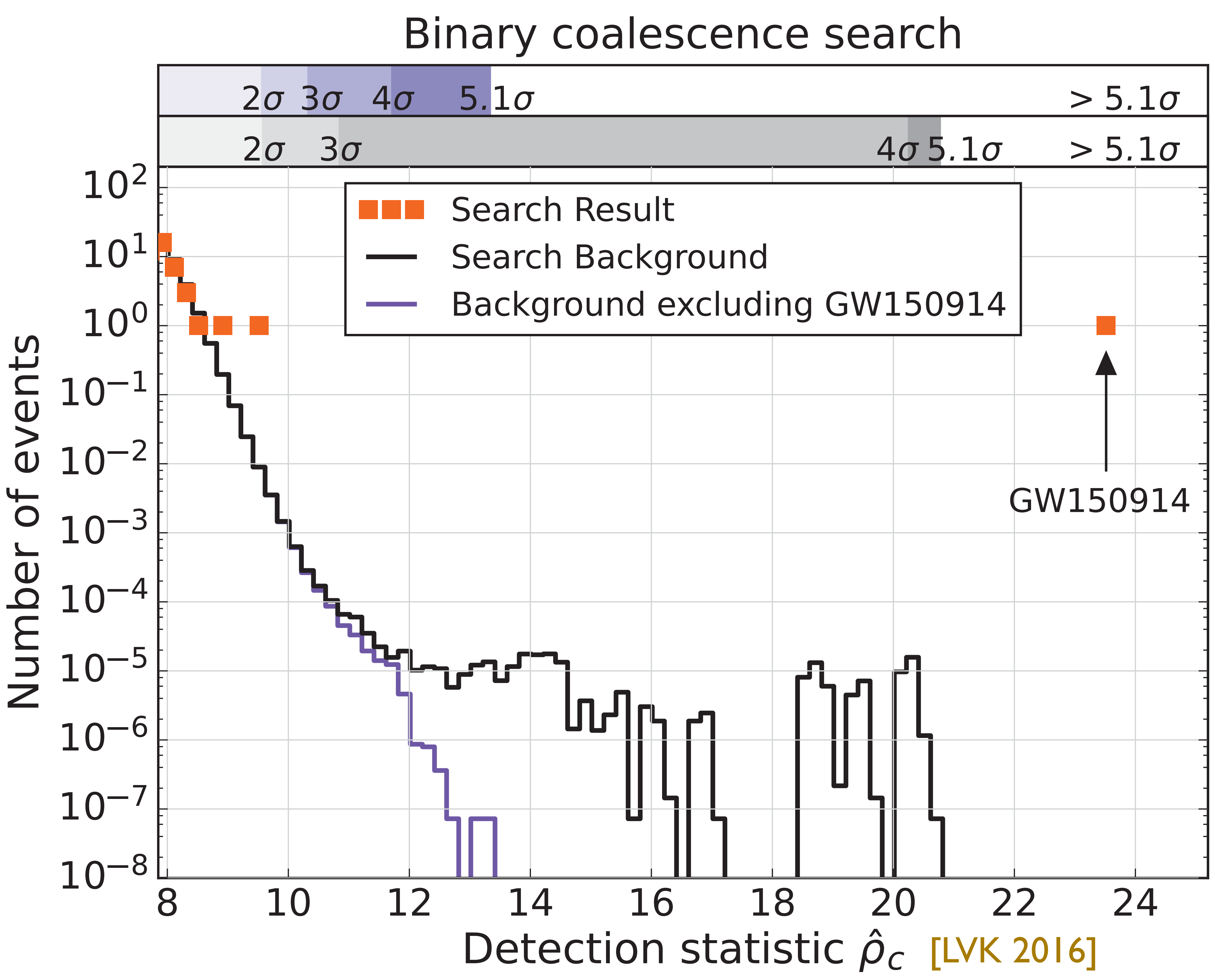


$$\ln\mathcal{L}(\theta) = -\frac{1}{2}(h(\theta) - d|h(\theta) - d)$$

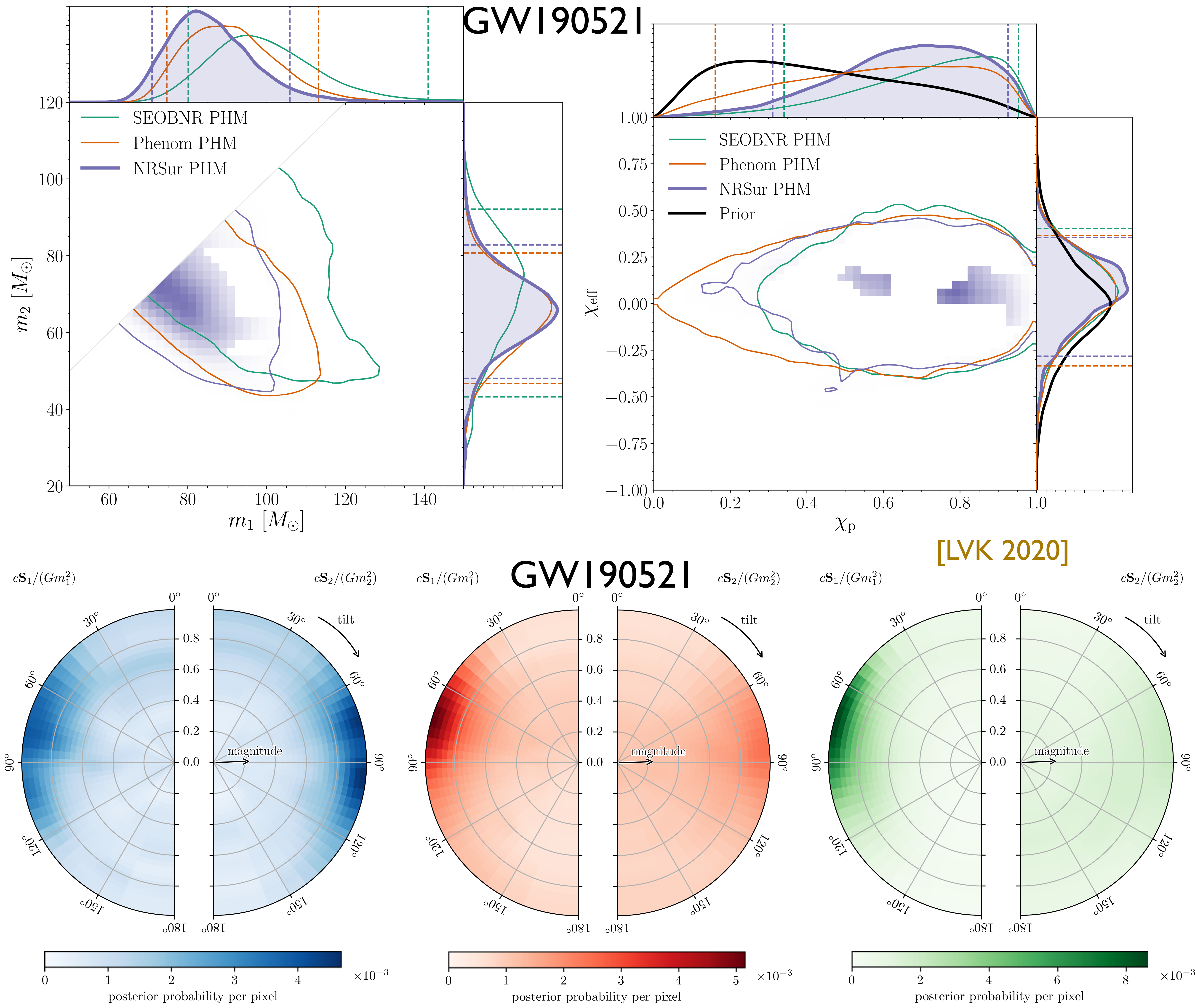
In reality:

- need millions of likelihood evaluations, cost intensive
- need to explore up to 17d parameters
- Nested Sampling
- Metropolis-Hastings MCMC (with Parallel Tempering and custom proposals)
- Machine learning techniques appearing

Examples of LVK results



[LVK 2016]



[LVK 2020]

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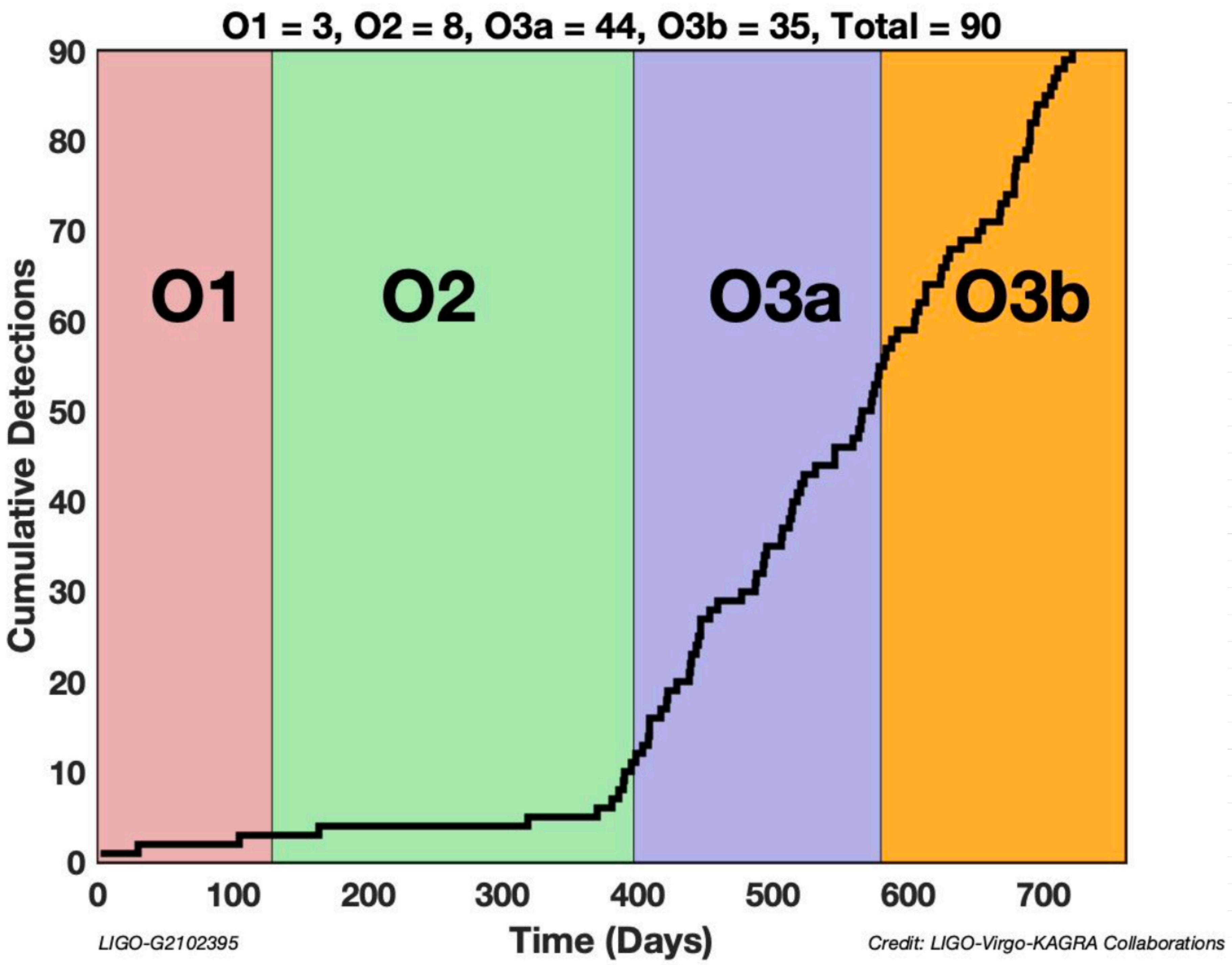
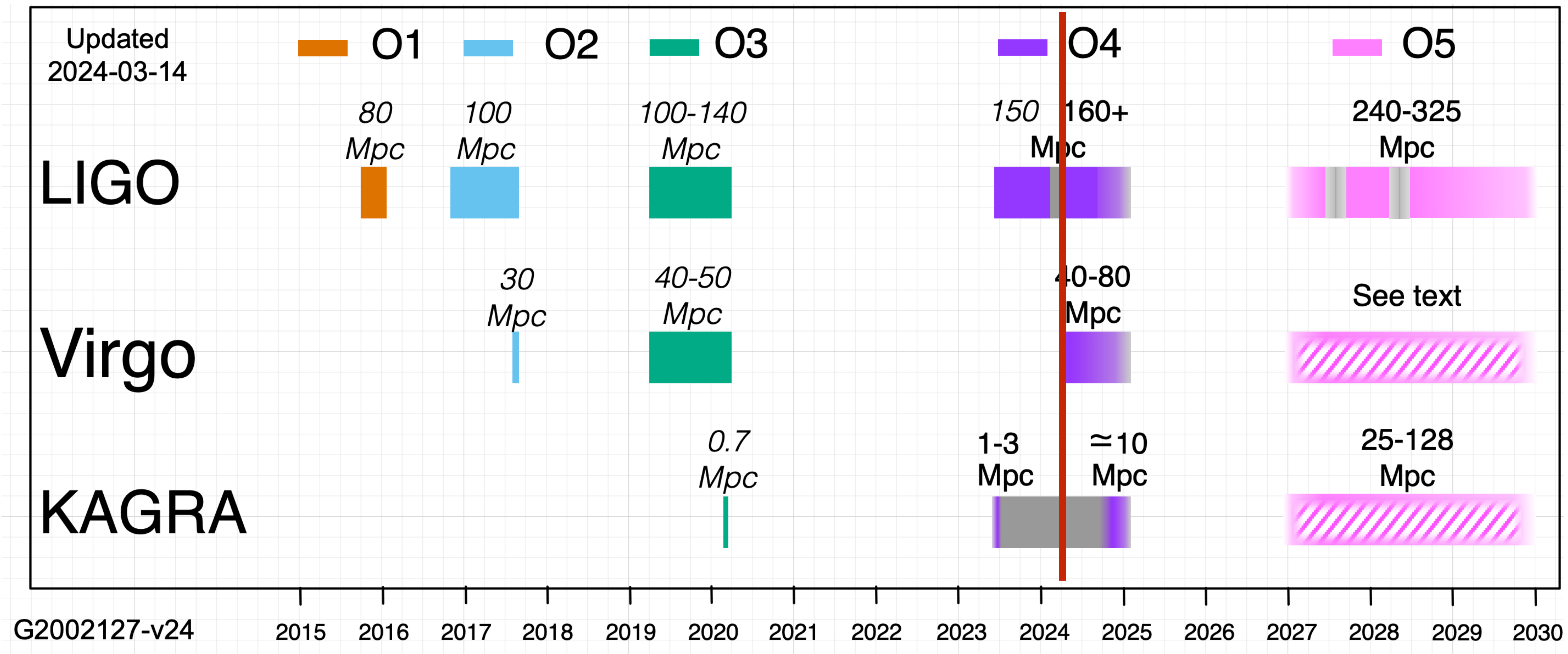
The gravitational wave spectrum

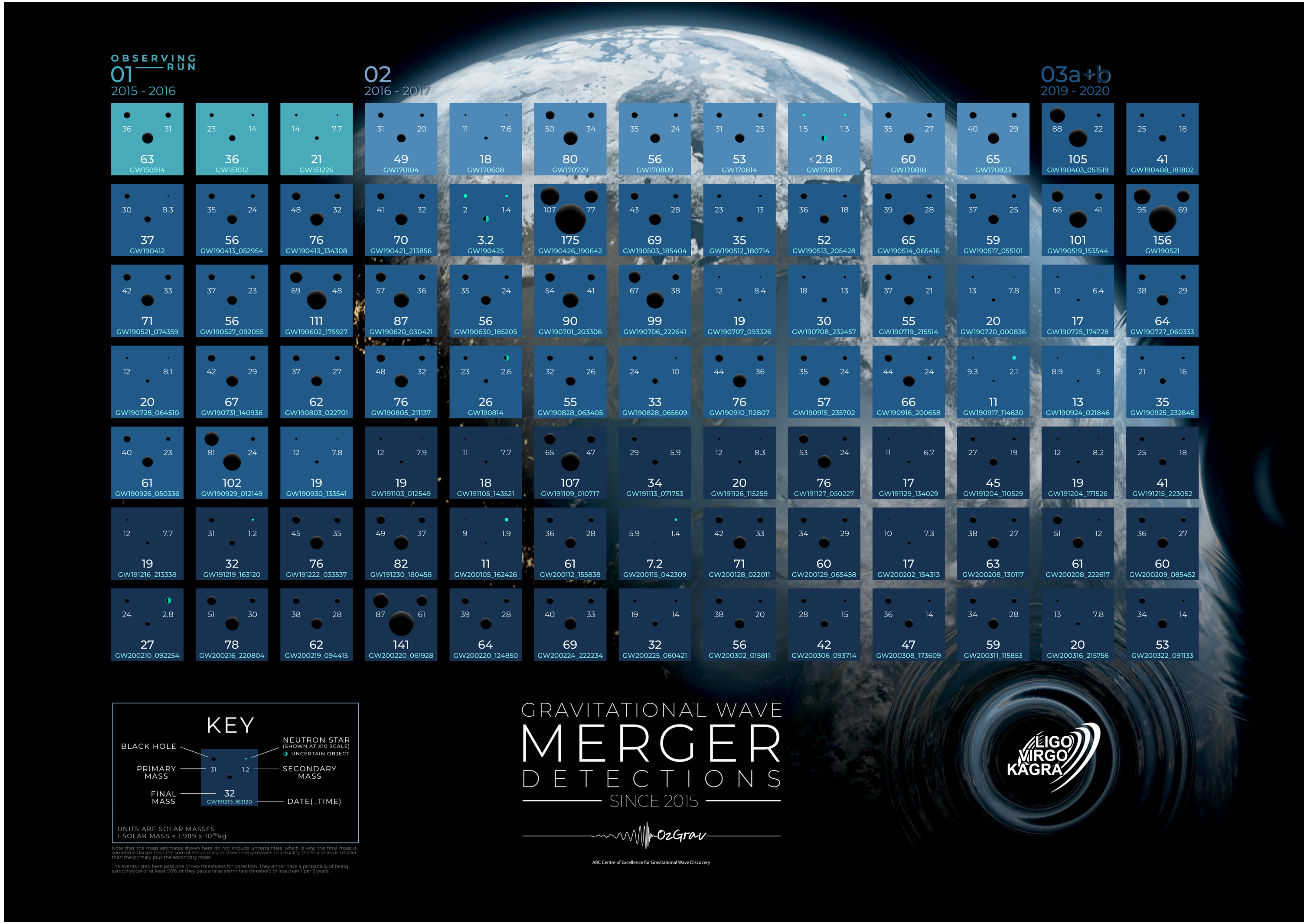


Detection horizons in Mpc for BNS

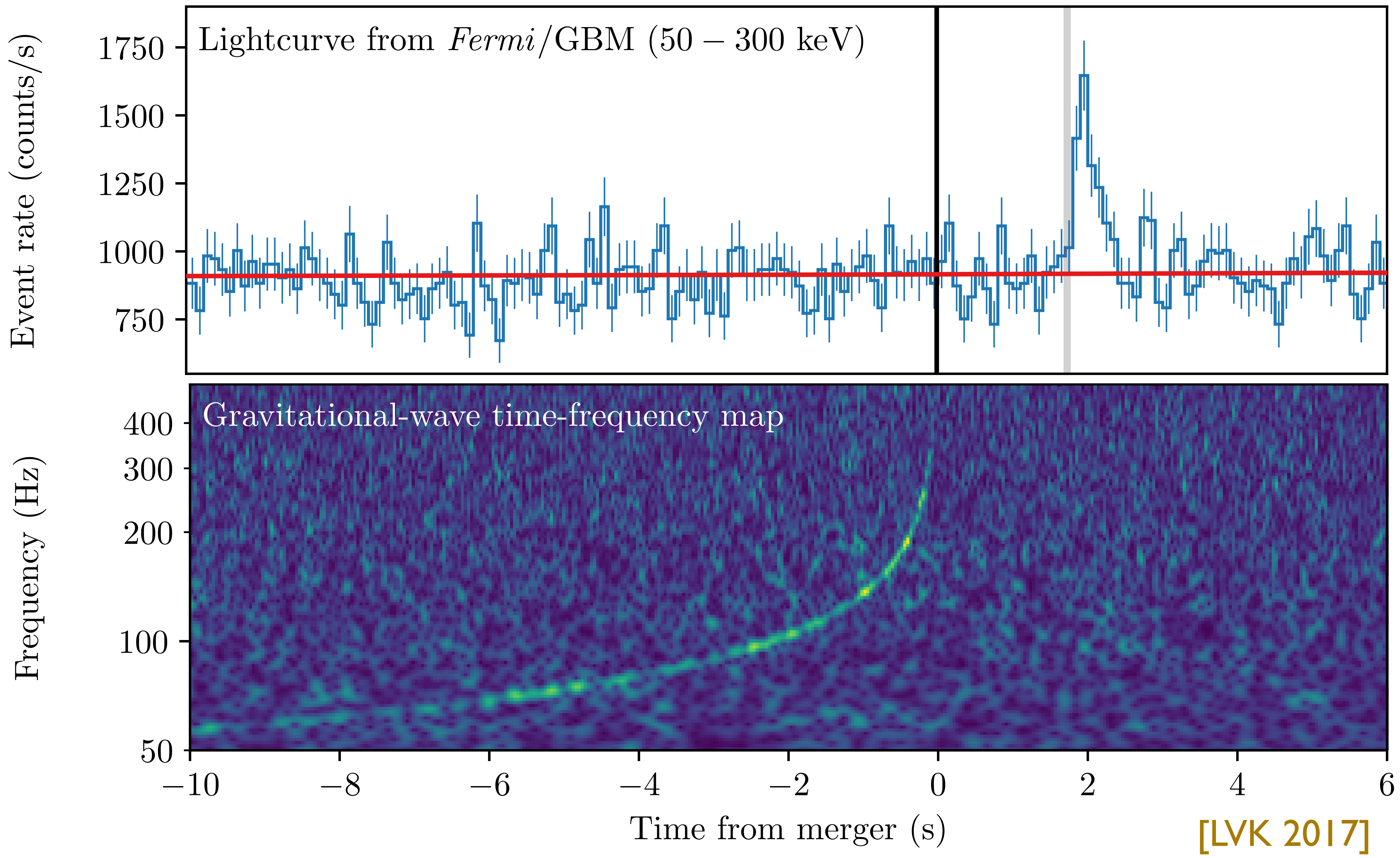


Gravitational wave science: from discovery science to a new astronomy

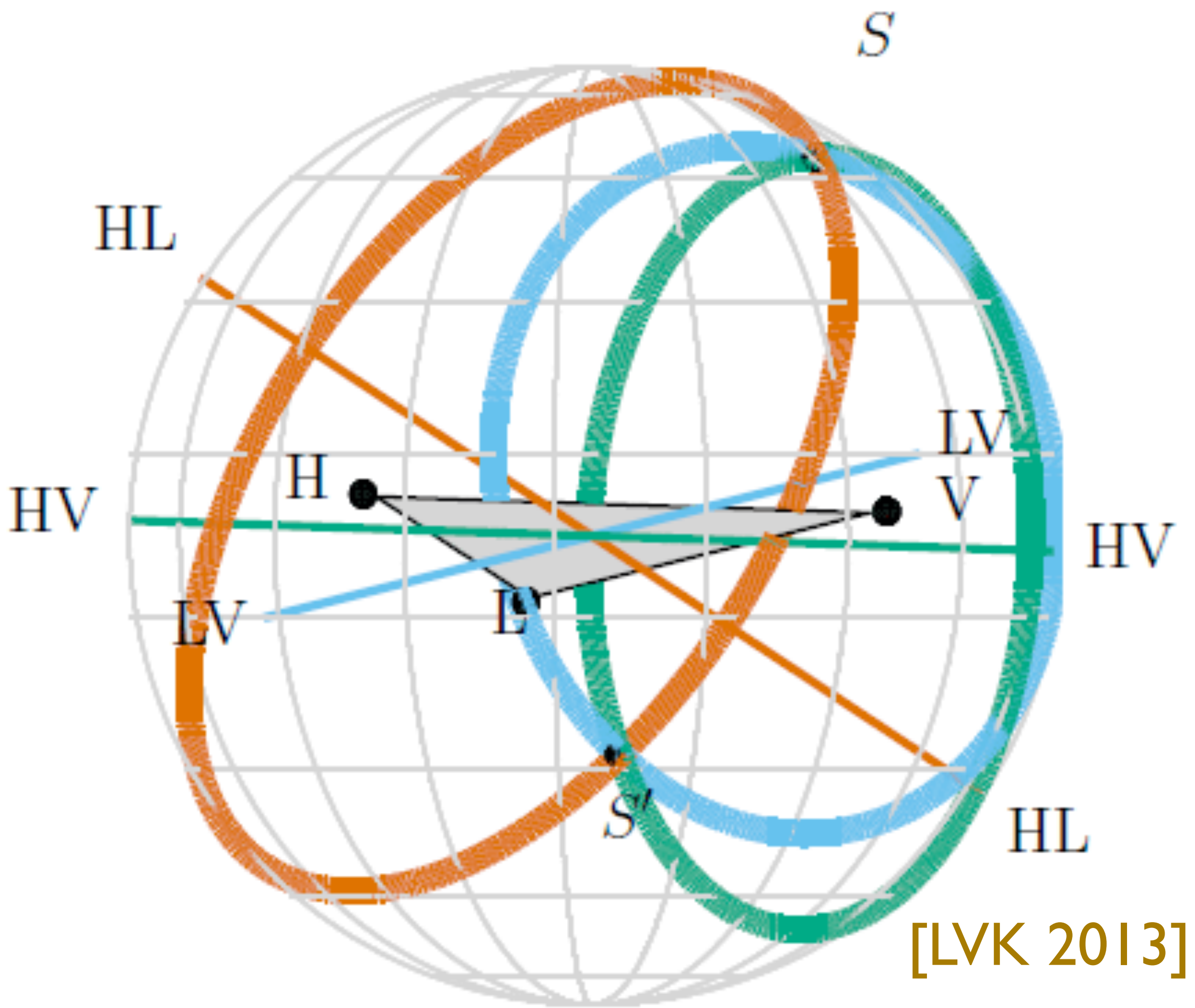
CBC detections



GW170817: a BNS merger and a kilonova



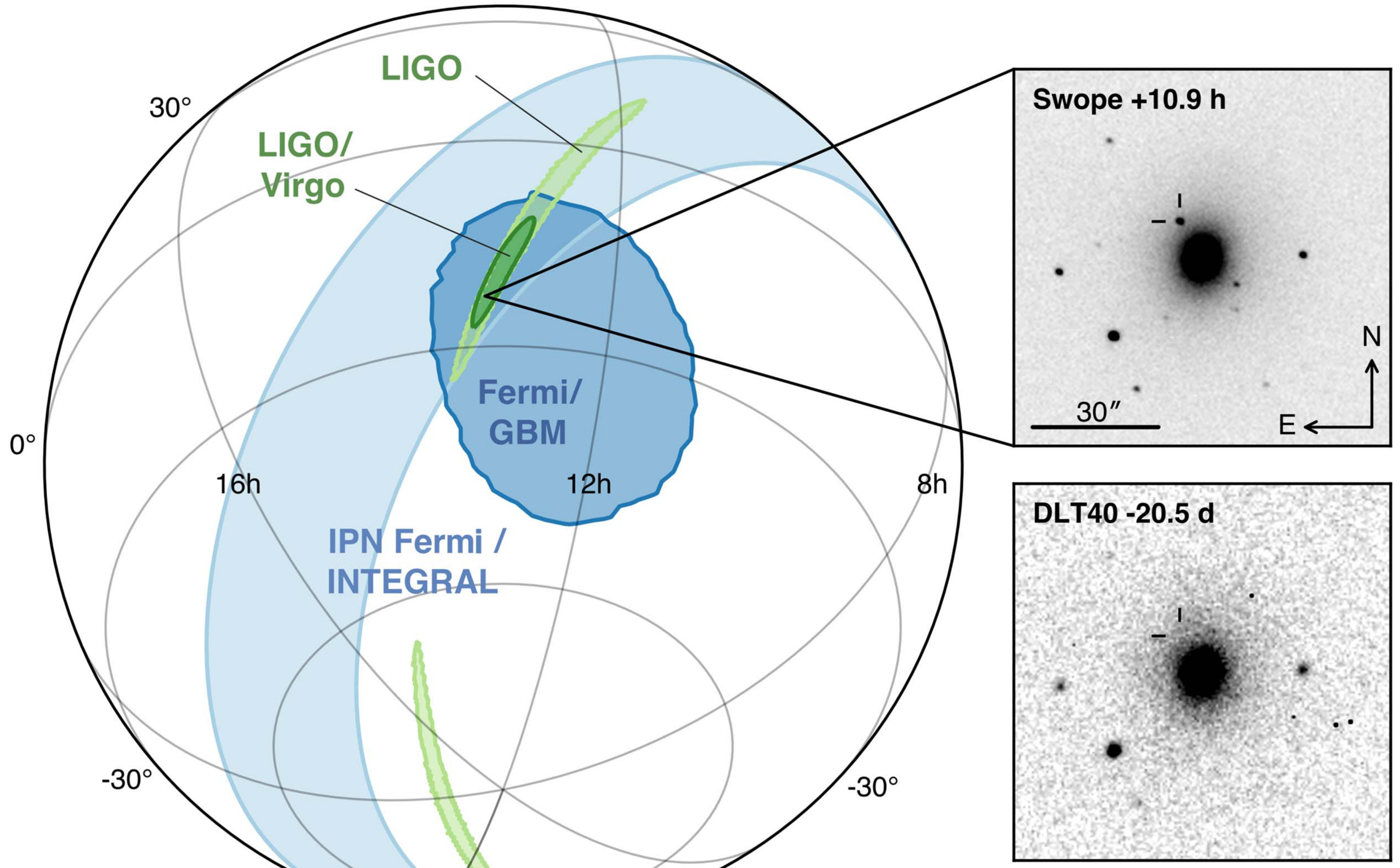
[LVK 2017]



[LVK 2013]

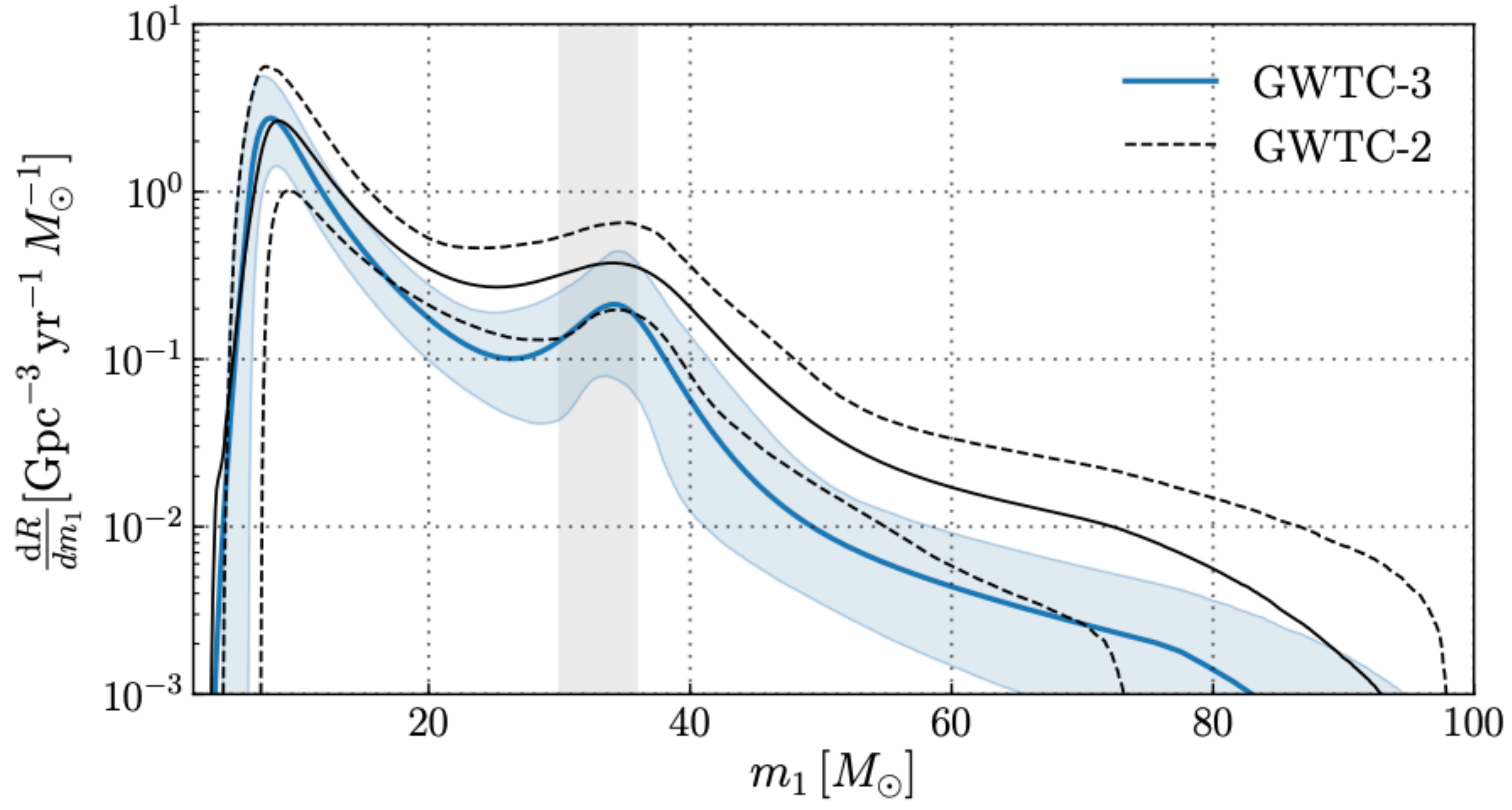
Multimessenger astronomy:

- wealth of data on BNS mergers, heavy element synthesis, etc…
- constrain the speed of GWs !
- standard siren for GW cosmology



GW170817

Population inference

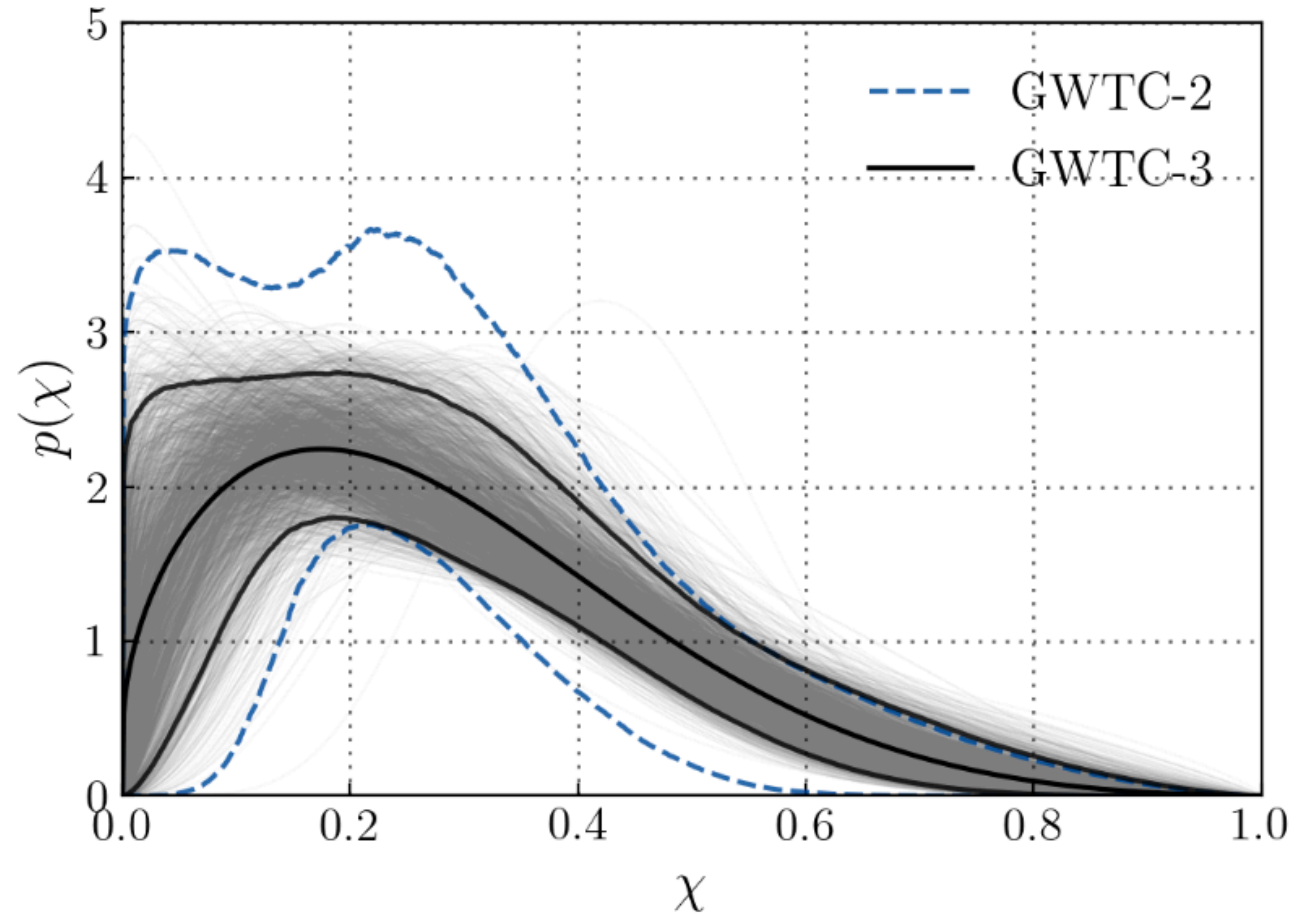


Hierarchical population inference:

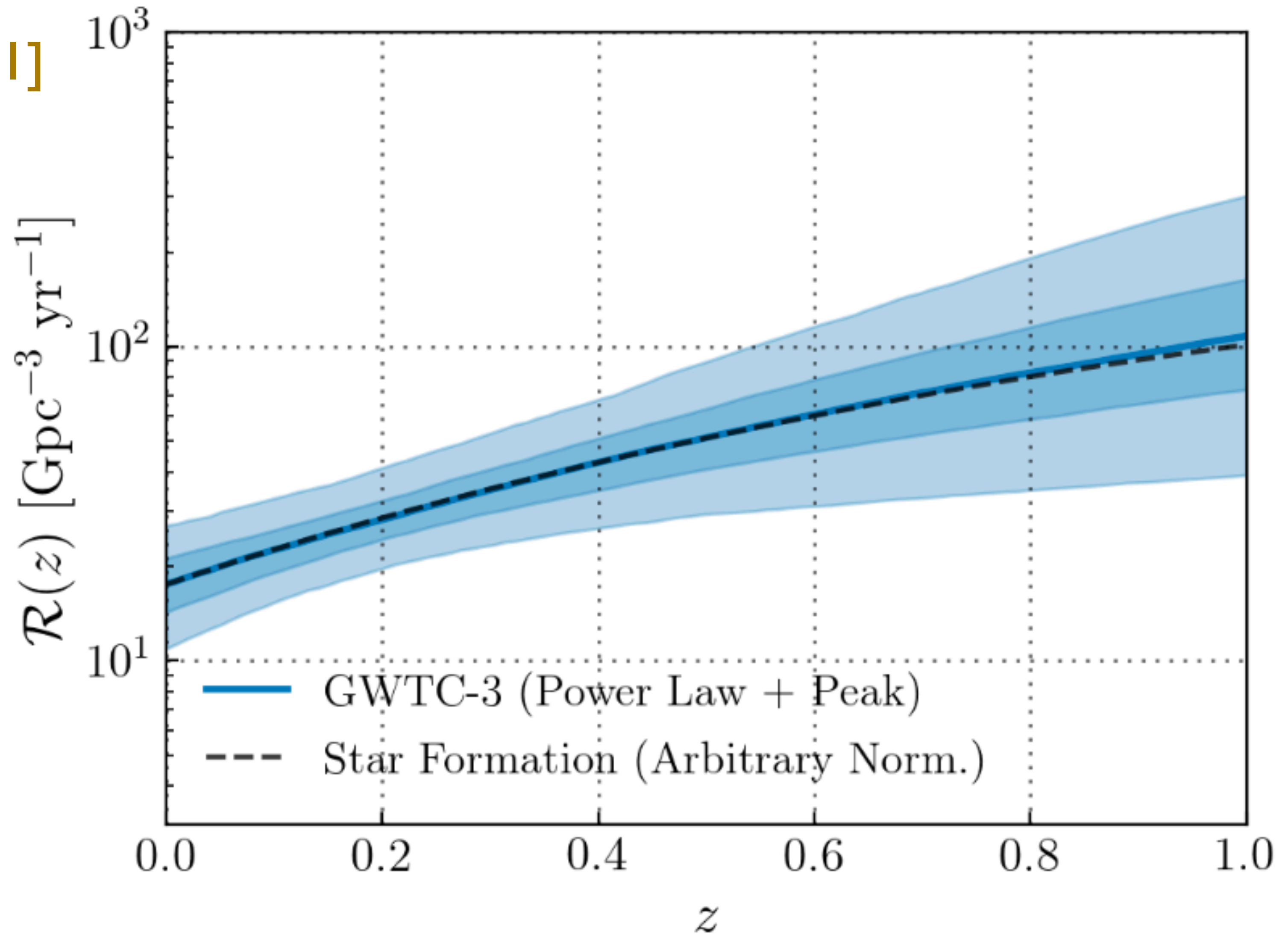
- BBH mass spectrum
- BBH spin distribution
- Rate evolution with z

Exceptional events:

- massive BBH
- BH-NS events
- Mass gap between NS/BH

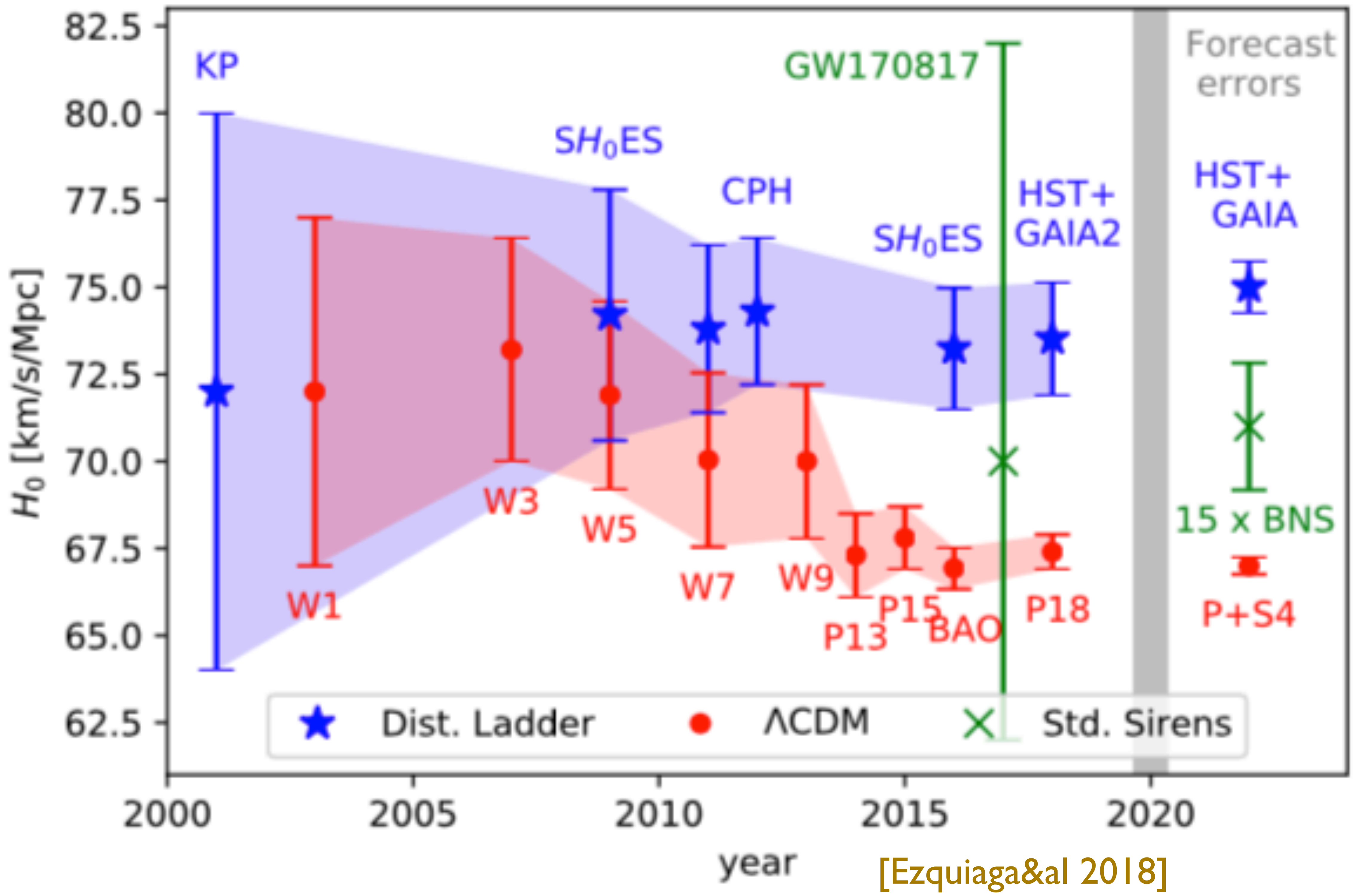


[LVK 2021]



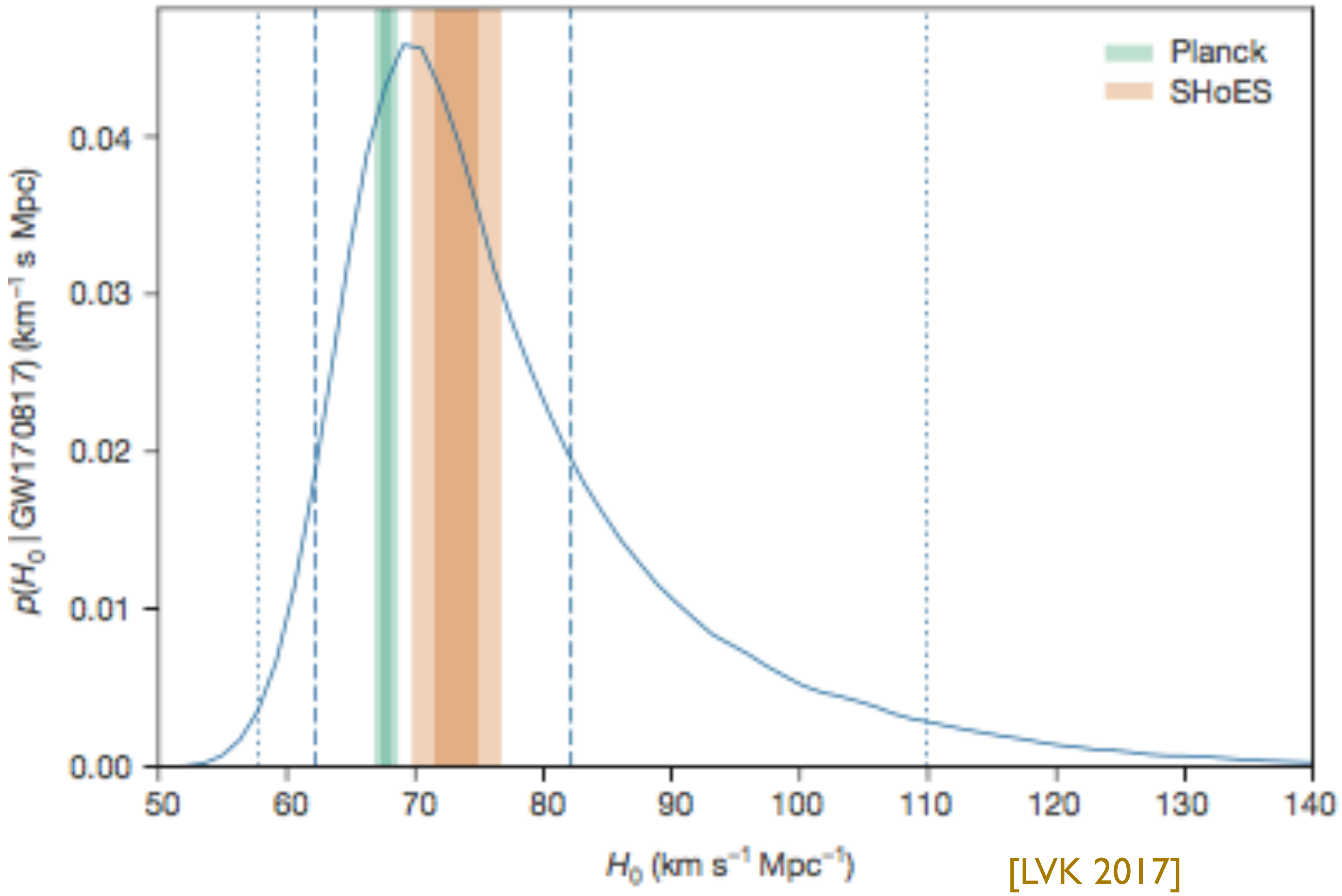
Gravitational wave cosmology

Hubble tension



[Ezquiaga&al 2018]

GW170817 as standard siren



[LVK 2017]

GW propogation at cosmological distances:

$M \to (1+z)M$ Measurement of redshifted masses M_z

$1/r \to 1/d_L$ Measurement of luminosity distance d_L

How to get redshift information:

- spectrum of EM counterpart (standard siren, GW170817)
- correlate with catalogs of galaxies (dark sirens)
- source-frame mass feature (spectral sirens), e.g. mass gap
- non-gravitational physics: in BNS

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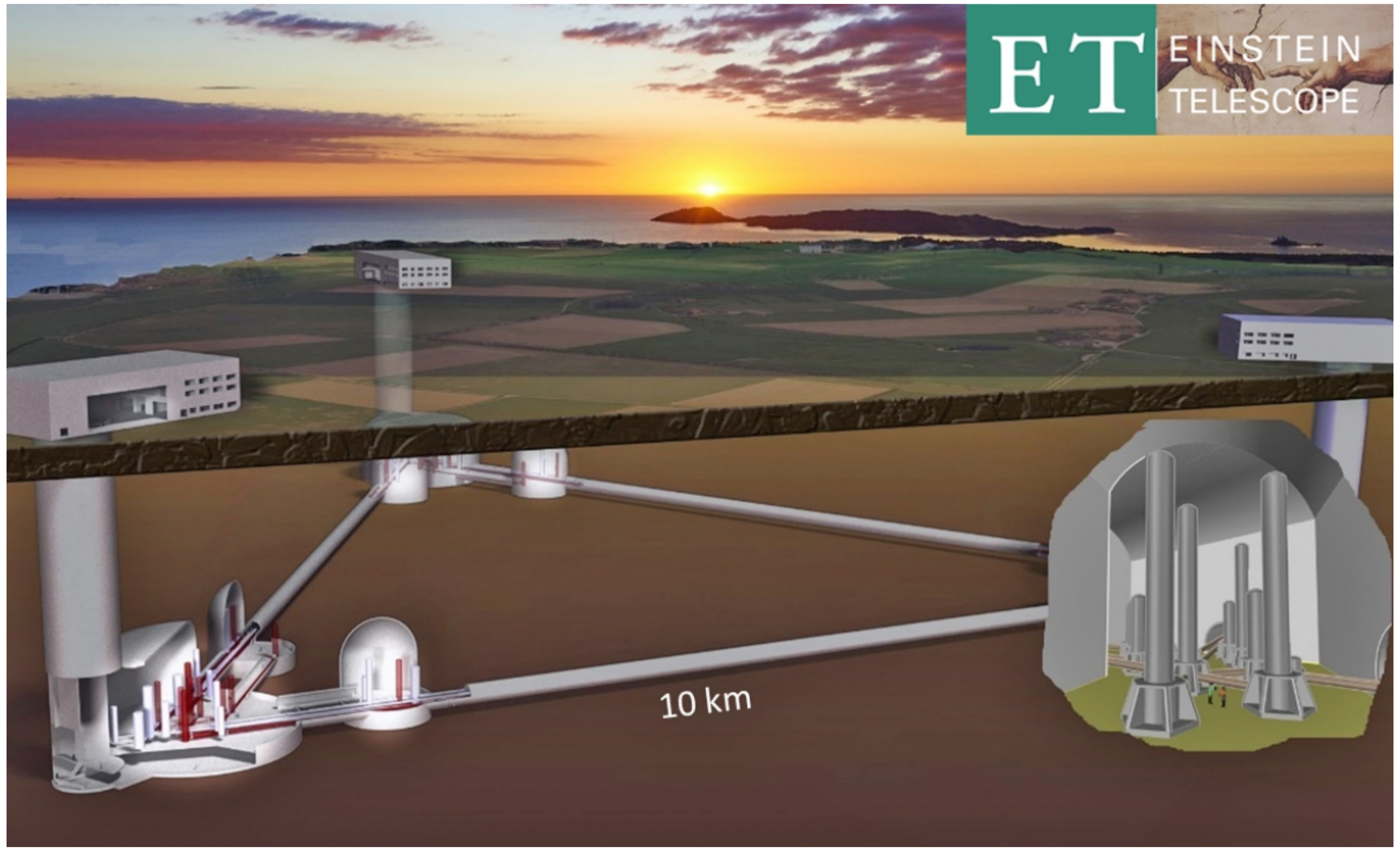
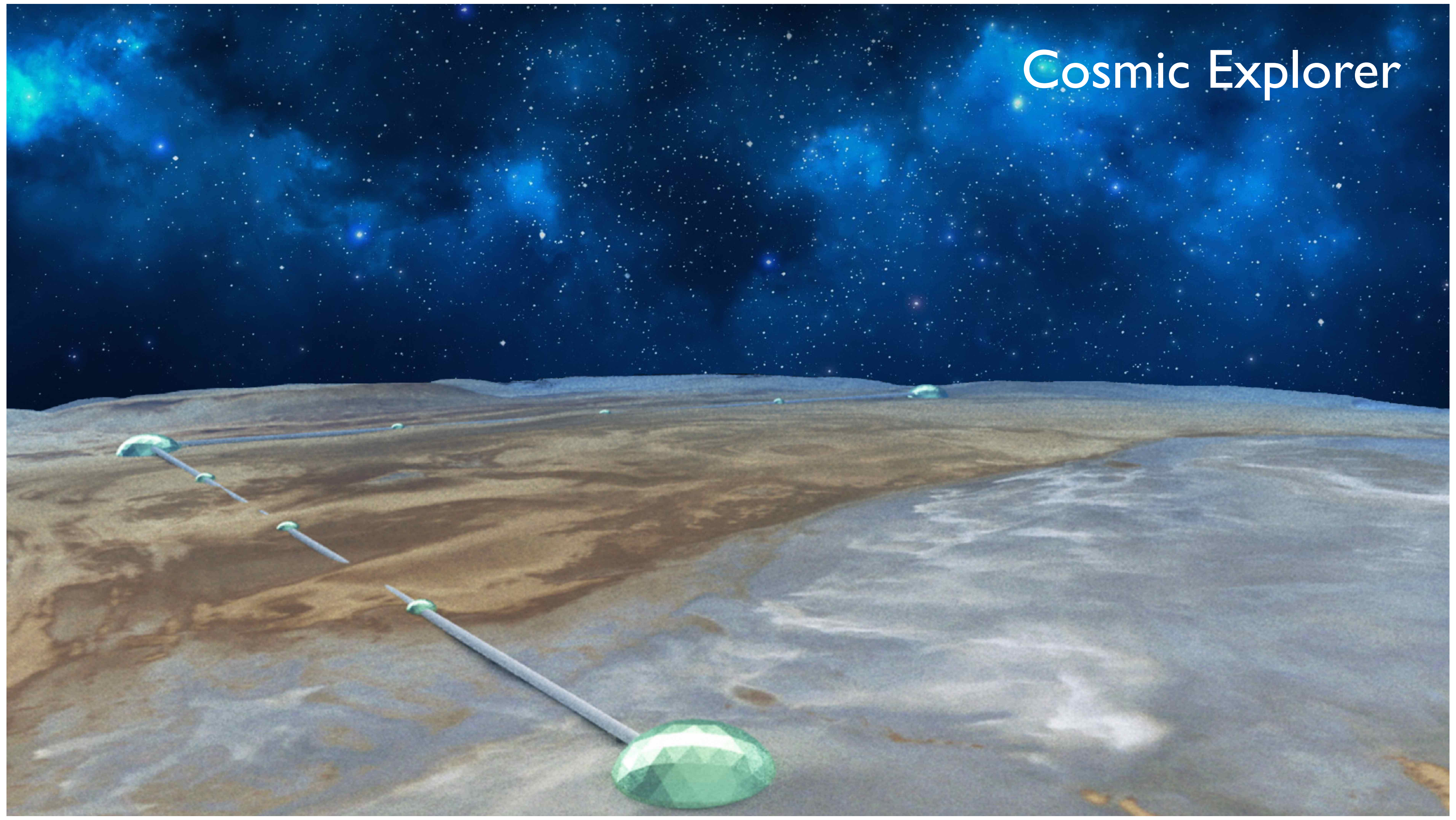
3G detectors - 2030-2040

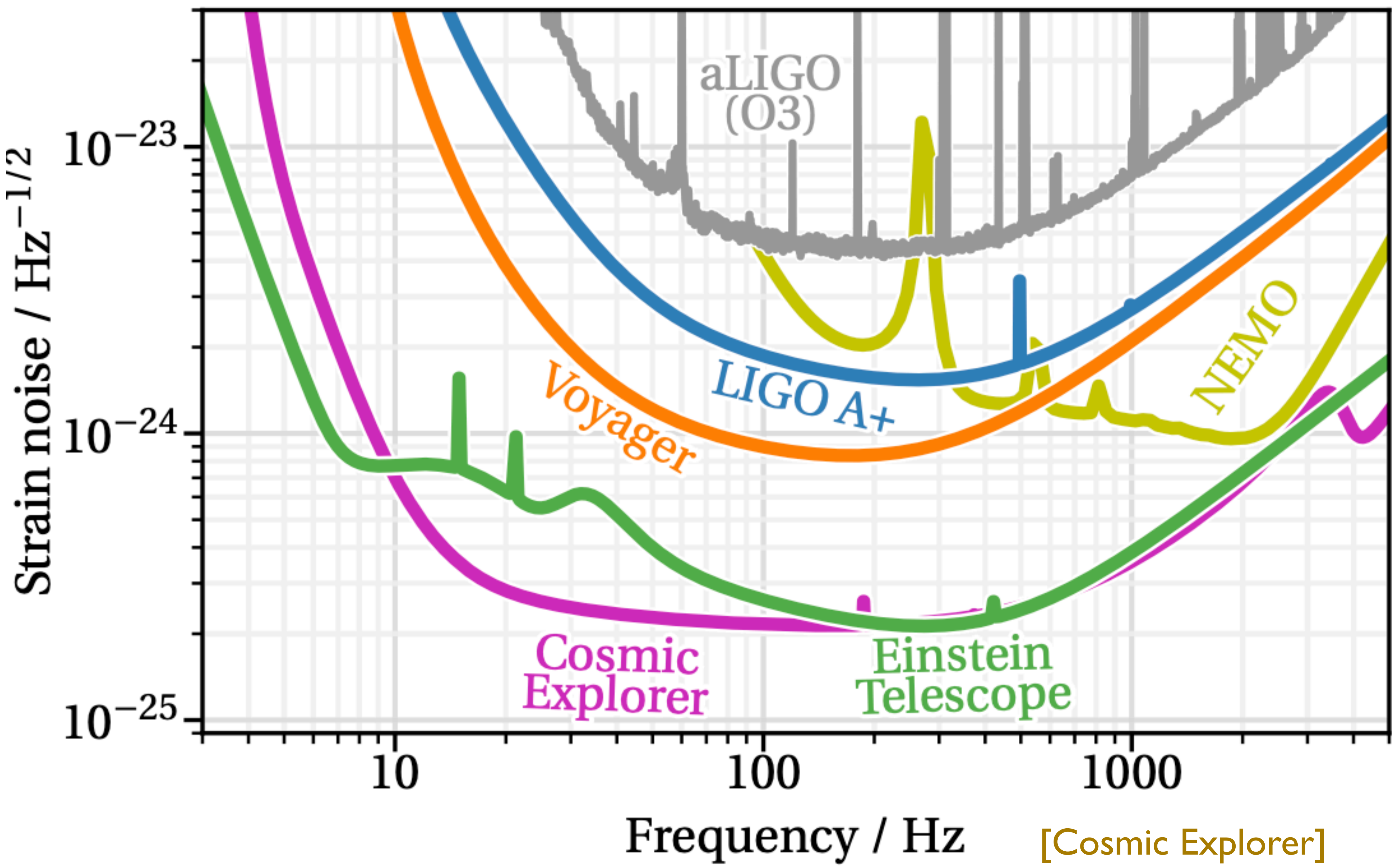


Einstein Telescope:
- 10km armlengths
- triangle design
- underground setting
- cryogeny

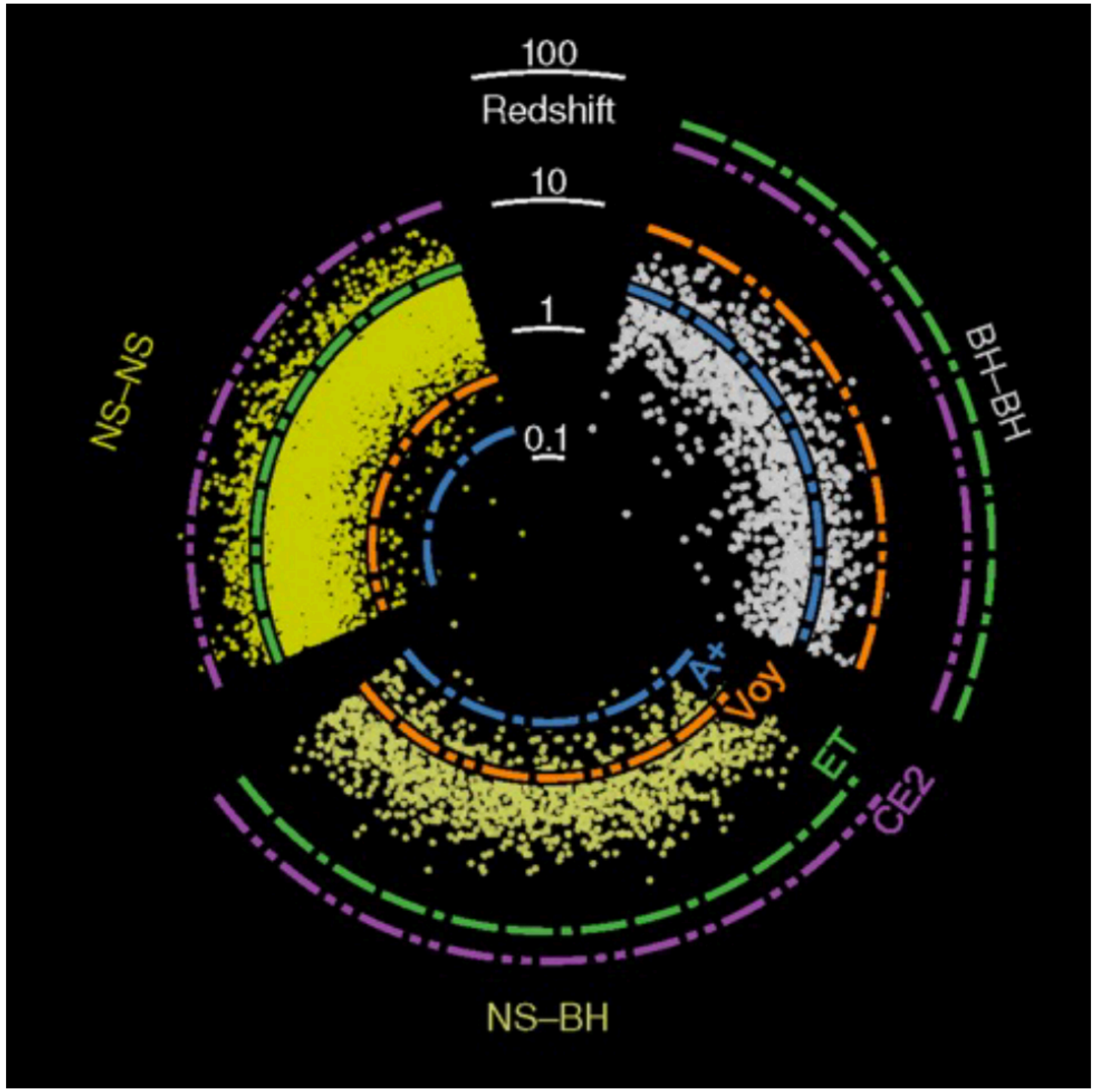


Cosmic Explorer:
- 40km armlengths
- L-shape design
- 2 detectors proposed

3G detectors



[Cosmic Explorer]



[Cosmic Explorer]

Events/yr (low-median-high):

- BBH: 60k-90k-150k
- BNS: 300k-1000k-3000k

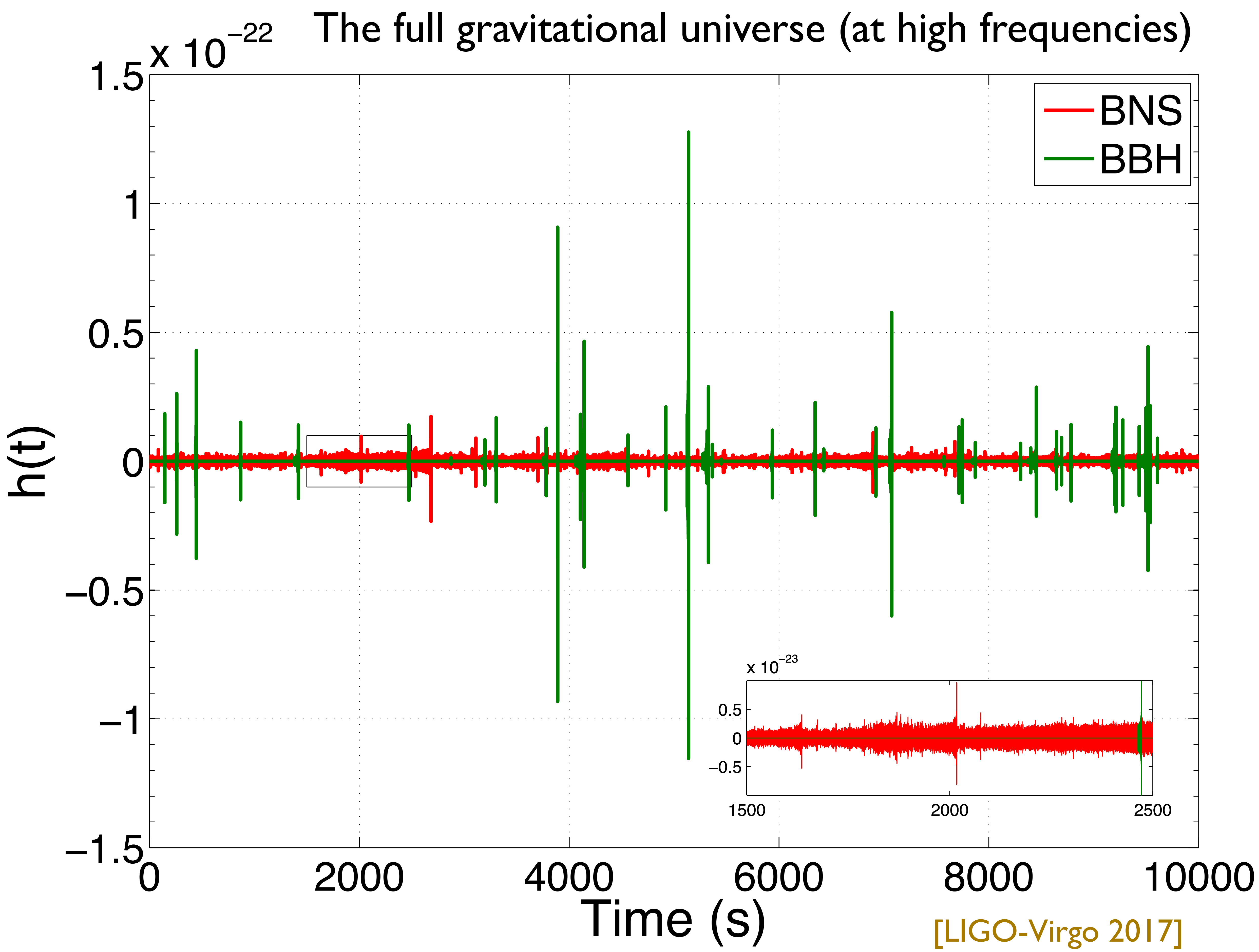
Detections (2 CE+1ET):

- BBH: 93%
- BNS: 35%

[Samajdar&al 2021]

GW astronomy on a massive scale !

3G detectors



[LIGO-Virgo 2017]

- Popcorn nature of combined signals
- Superposition problem

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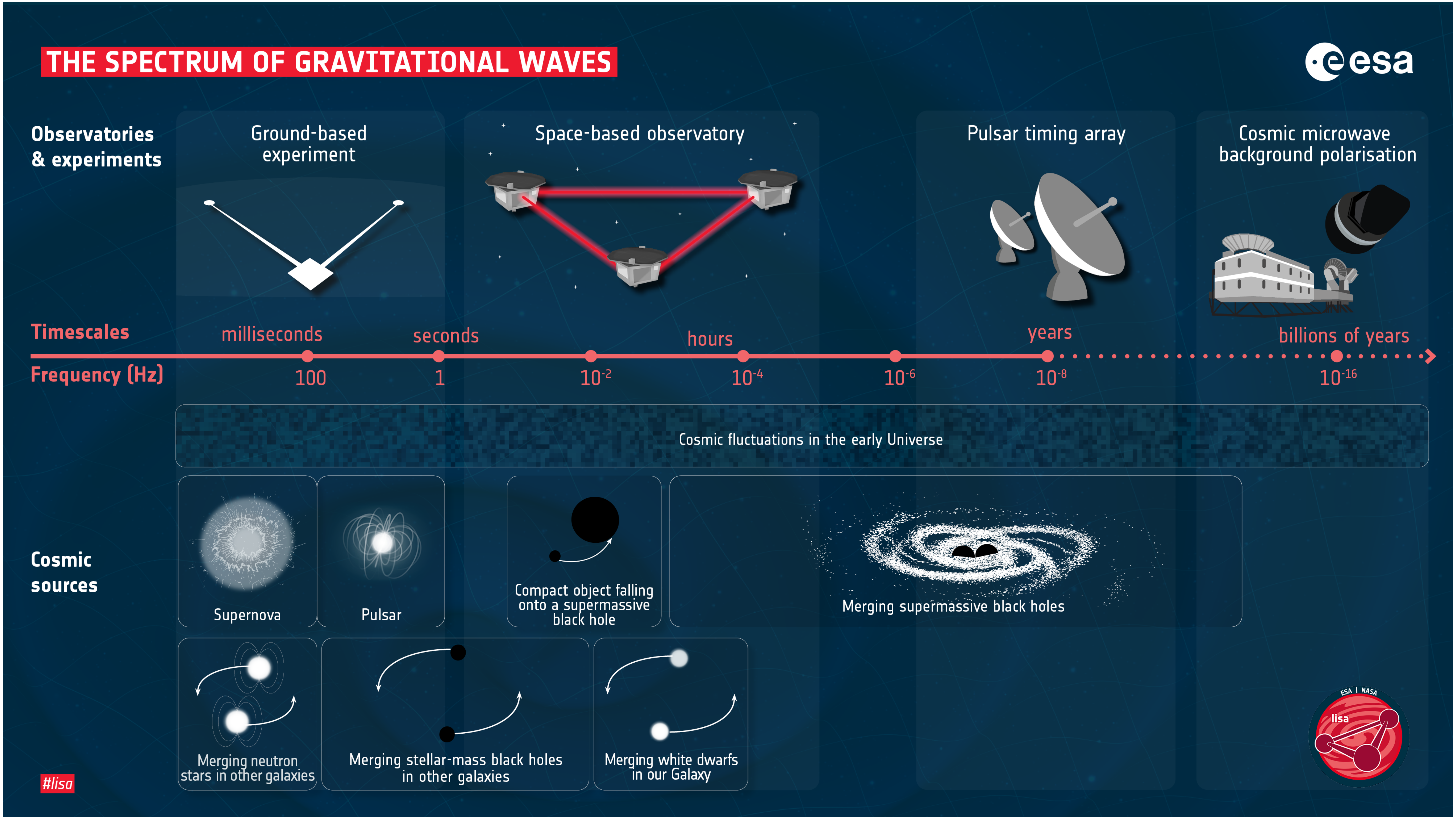
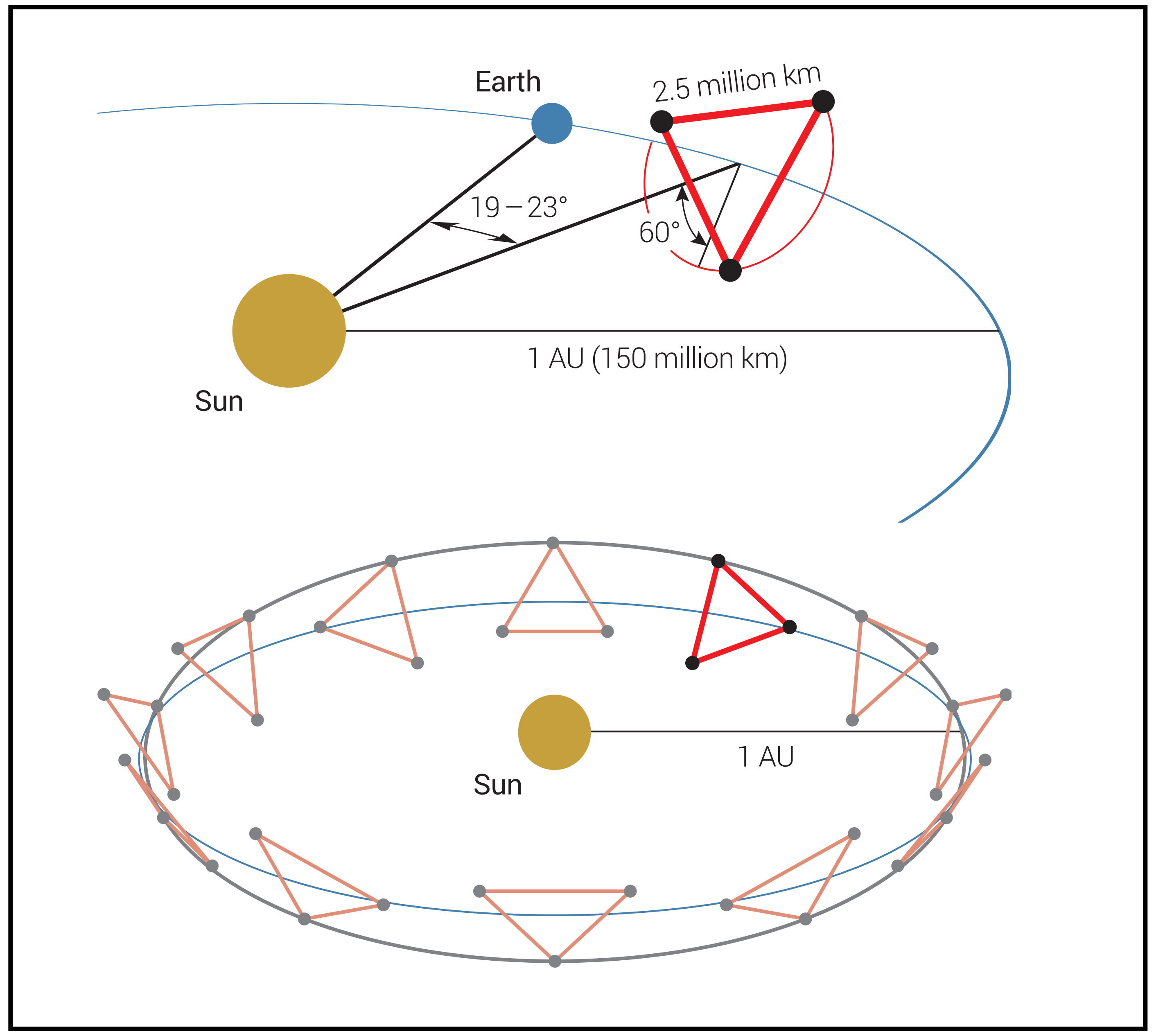
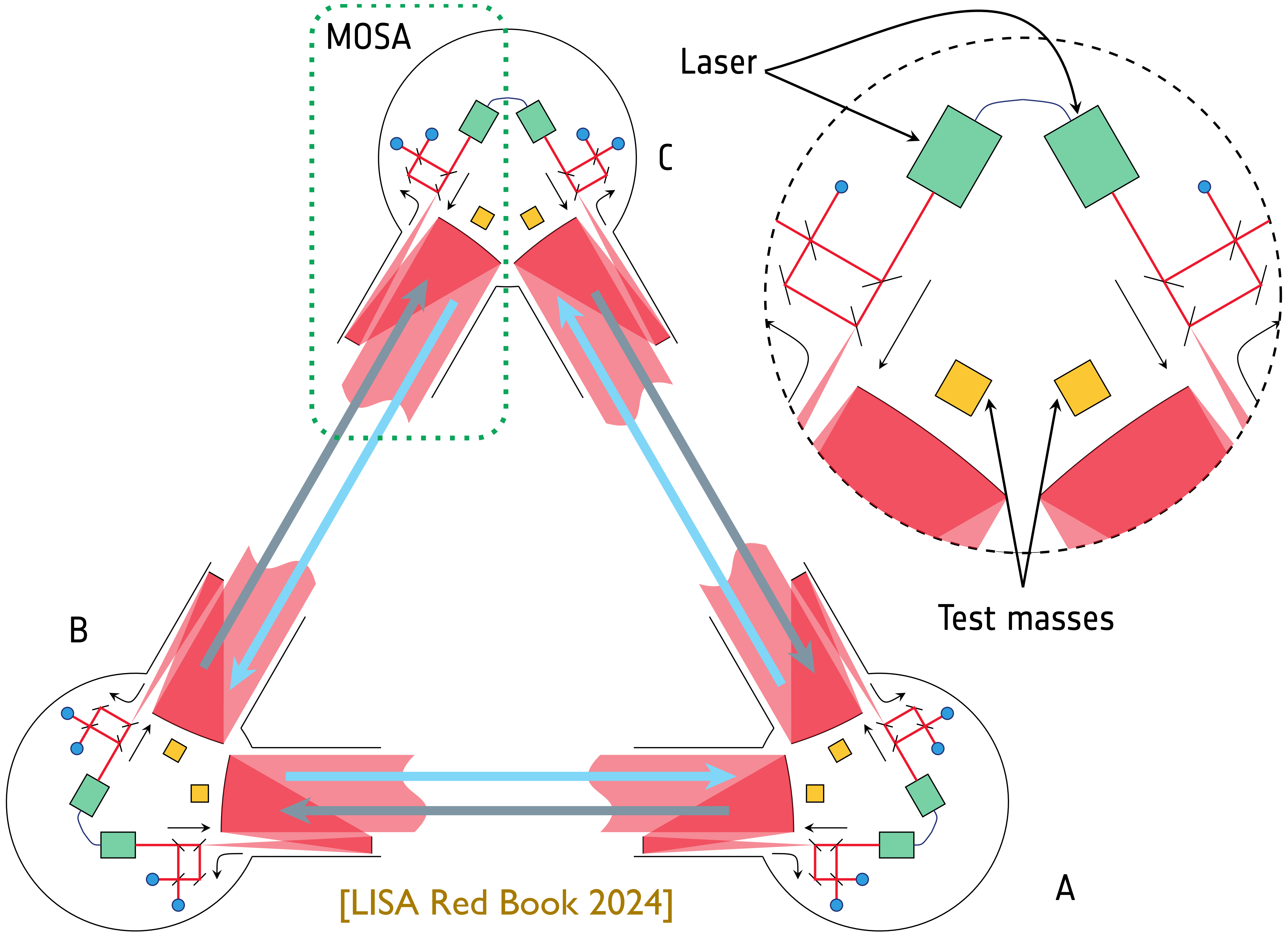
The gravitational wave spectrum



LISA instrument concept





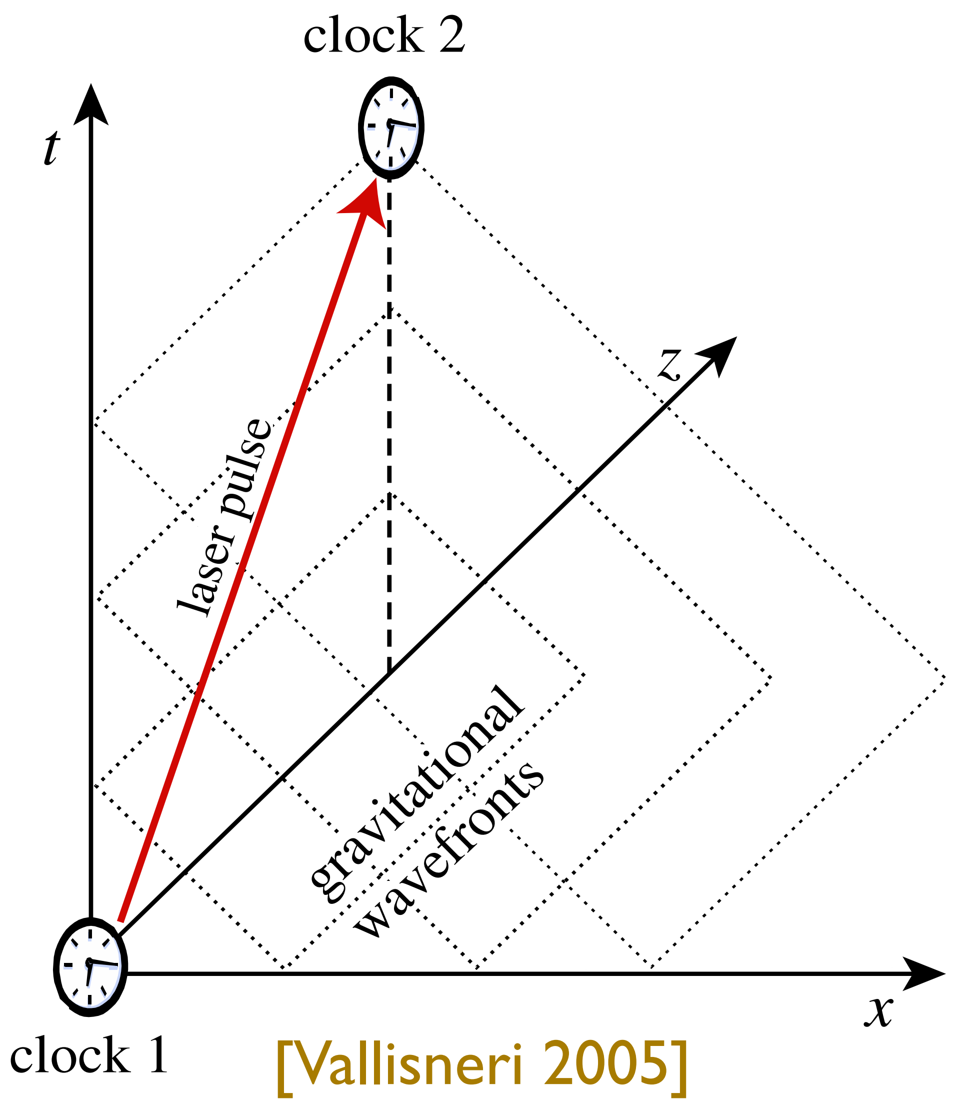
[LISA Red Book 2024]

An extremely ambitious mission:

- 2.5 million km armlength
- 6 laser links
- test masses shielded from the environment
- success of technological demonstrators: LISA pathfinder, Grace Follow-on
- provisional launch 2035

Mission adoption by ESA 2024-01

LISA measurement principle



[Vallisneri 2005]

From spacecraft s to spacecraft r through link l: $y = \Delta\nu/\nu$

$$y_{slr} = \frac{1}{2}\frac{1}{1-\hat{k}\cdot n_l} n_l \cdot (h(t_s) - h(t_r)) \cdot n_l$$

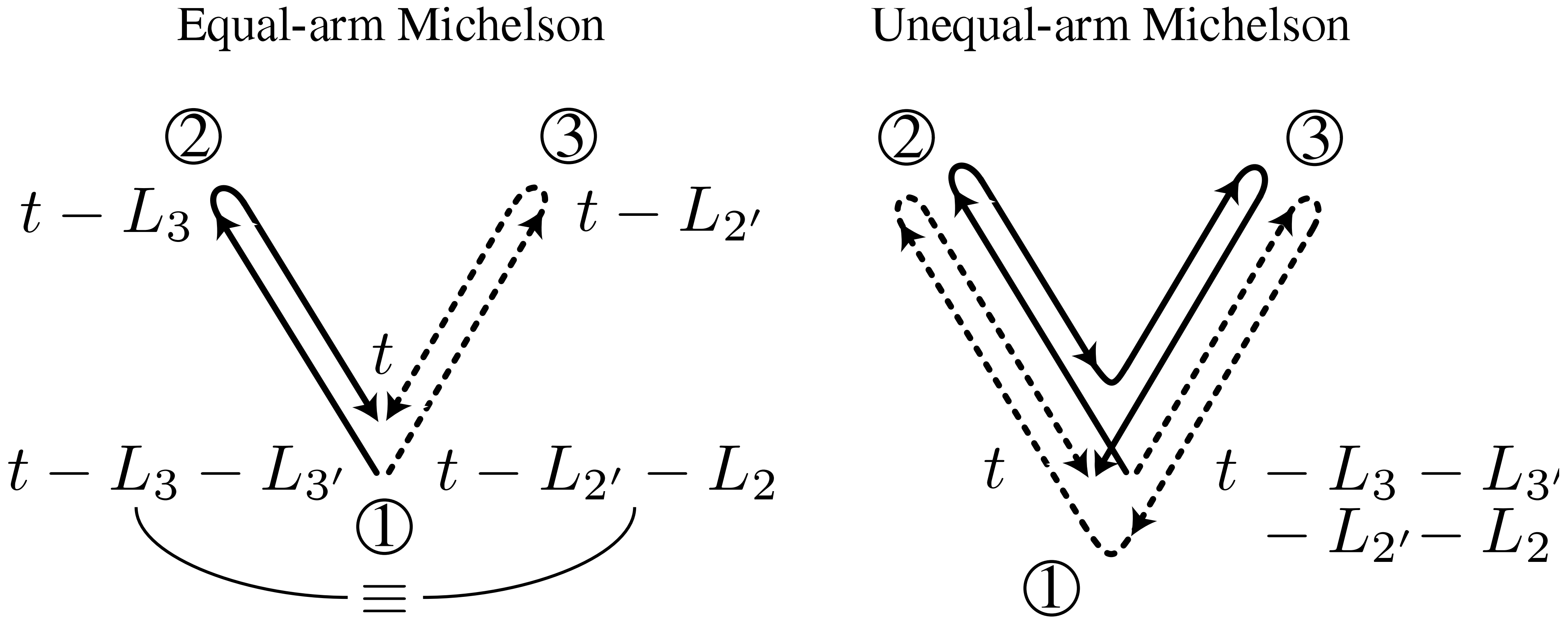
Response time and frequency-dependent:

$$\mathcal{T}_{slr} = \frac{i\pi f L}{2} \mathrm{sinc}\left[\pi f L \left(1 - k \cdot n_l\right)\right] \exp\left[i\pi f \left(L + k \cdot (p_r + p_s)\right)\right] n_l \cdot P \cdot n_l(t_f)$$

Doppler delay from orbit, change in orientation

Analogous to 2 LIGO in motion at low frequencies only

Time-delay interferometry (TDI)



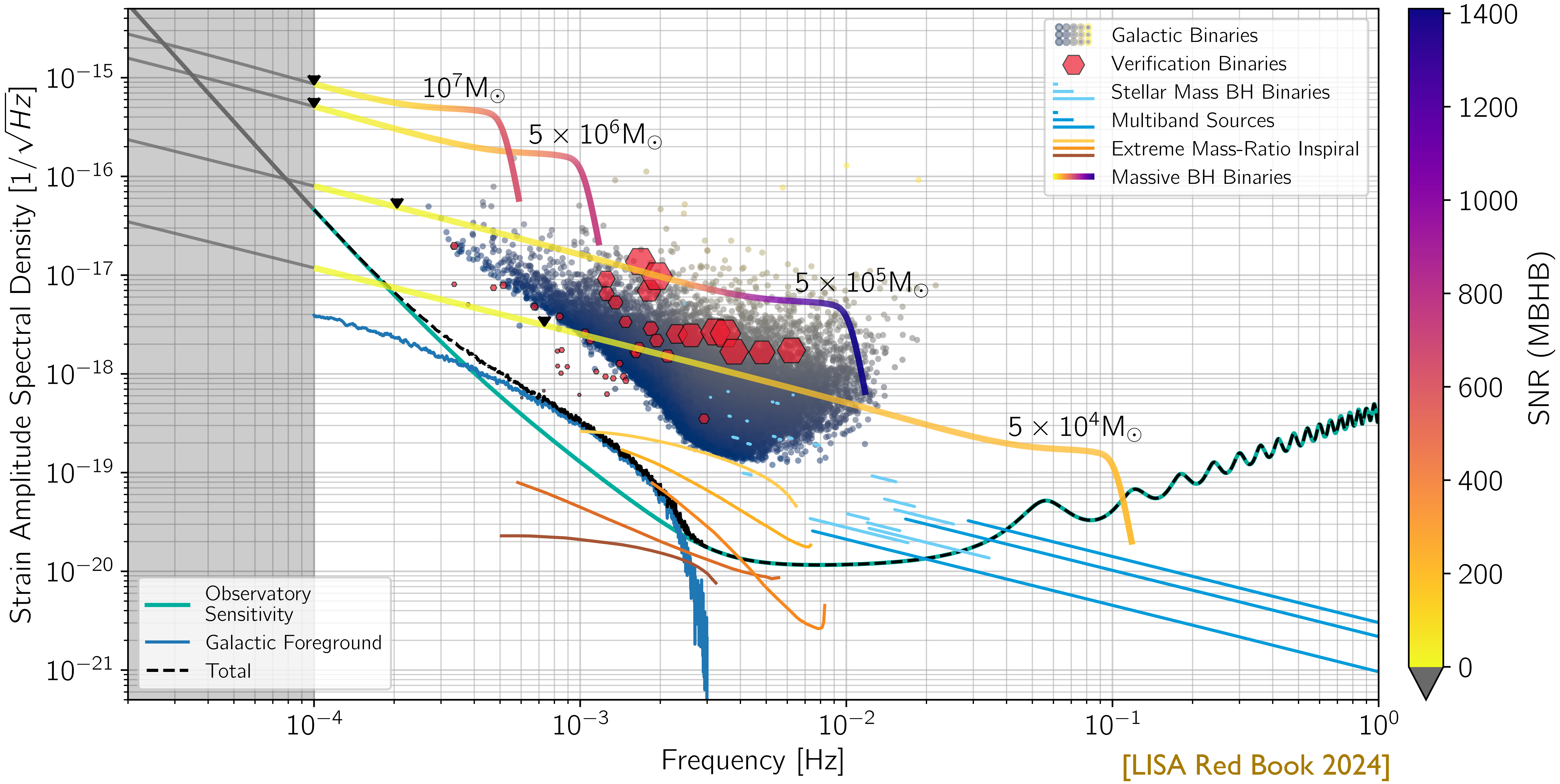
Cancelling laser noises in post-processing, from phasemeter measurements

+ refinements for unequal arms, moving constellation

$$X_1^{\rm GW} = \underbrace{\left[(y_{31}^{\rm GW} + y_{13,2}^{\rm GW}) + (y_{21}^{\rm GW} + y_{12,3}^{\rm GW})_{,22} - (y_{21}^{\rm GW} + y_{12,3}^{\rm GW}) - (y_{31}^{\rm GW} + y_{13,2}^{\rm GW})_{,33}\right]}_{X^{\rm GW}(t)}$$
$$- \underbrace{\left[(y_{31}^{\rm GW} + y_{13,2}^{\rm GW}) + (y_{21}^{\rm GW} + y_{12,3}^{\rm GW})_{,22} - (y_{21}^{\rm GW} + y_{12,3}^{\rm GW}) - (y_{31}^{\rm GW} + y_{13,2}^{\rm GW})_{,33}\right]_{,2233}}_{X^{\rm GW}(t-2L_2-2L_3) \simeq X^{\rm GW}(t-4L)} .$$

Panorama of LISA sources

- Galactic binaires (WD/WD), quasi monochromatic, form foreground
- Massive Black Hole Binaries (MBHBs) loud merger-dominated signals
- Extreme Mass Ratio Inspirals (EMRIs) small compact object falling in a MBH
- Stellar-mass Black Hole Binaries (SBHBs)
- + GW stochastic backgrounds (astrophysical, cosmological)
- + cosmic strings, unforeseen sources ?



[LISA Red Book 2024]

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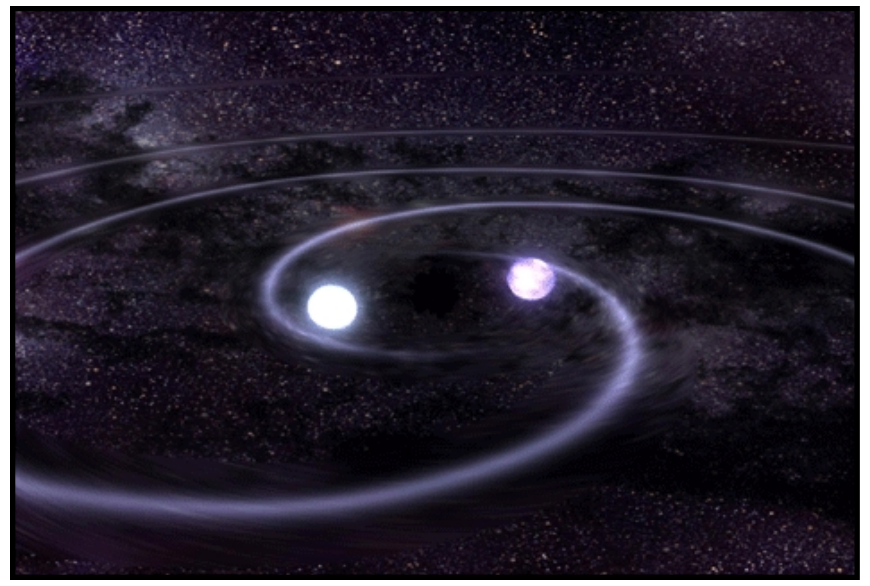
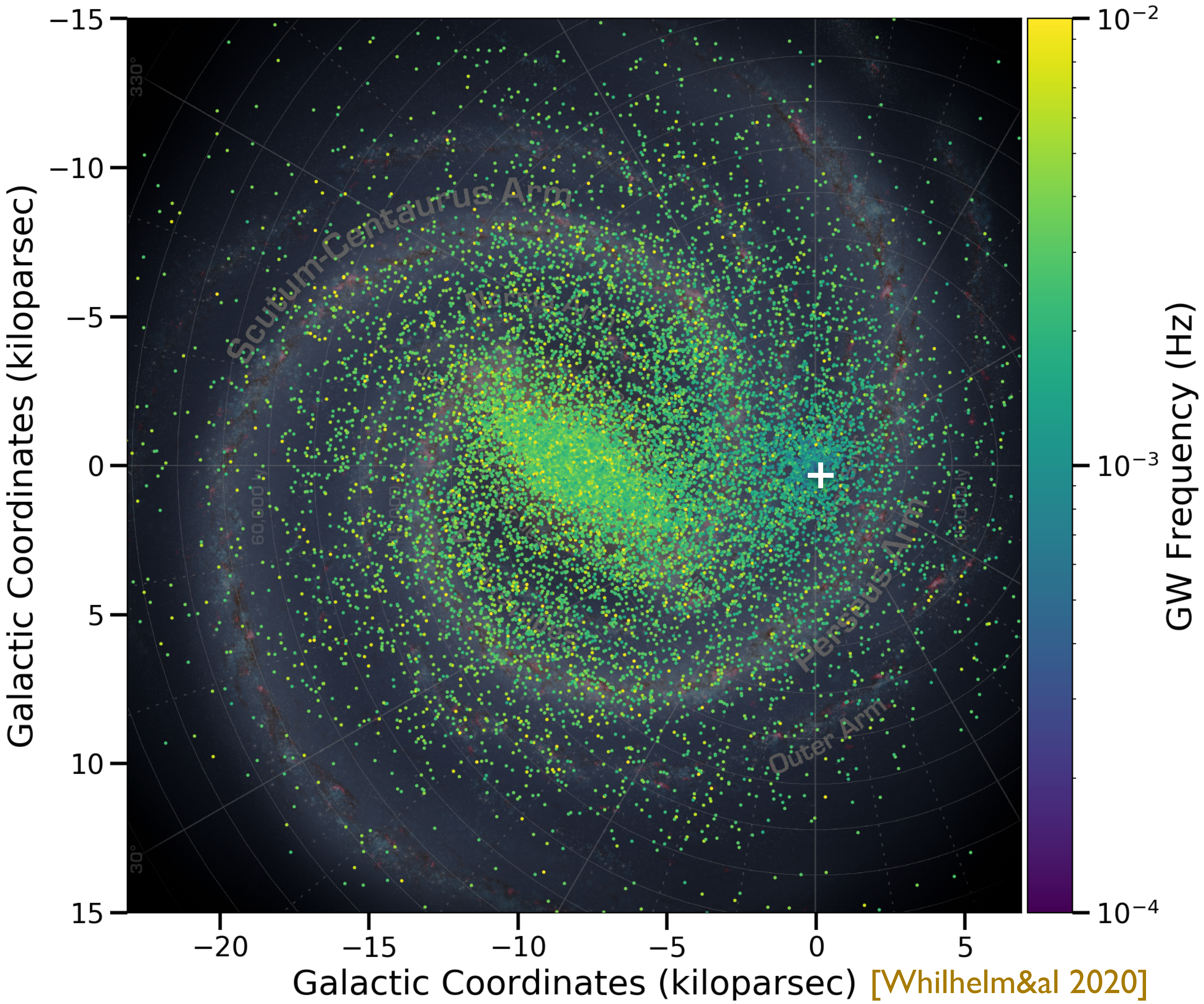
LISA sources: Galactic Binaries



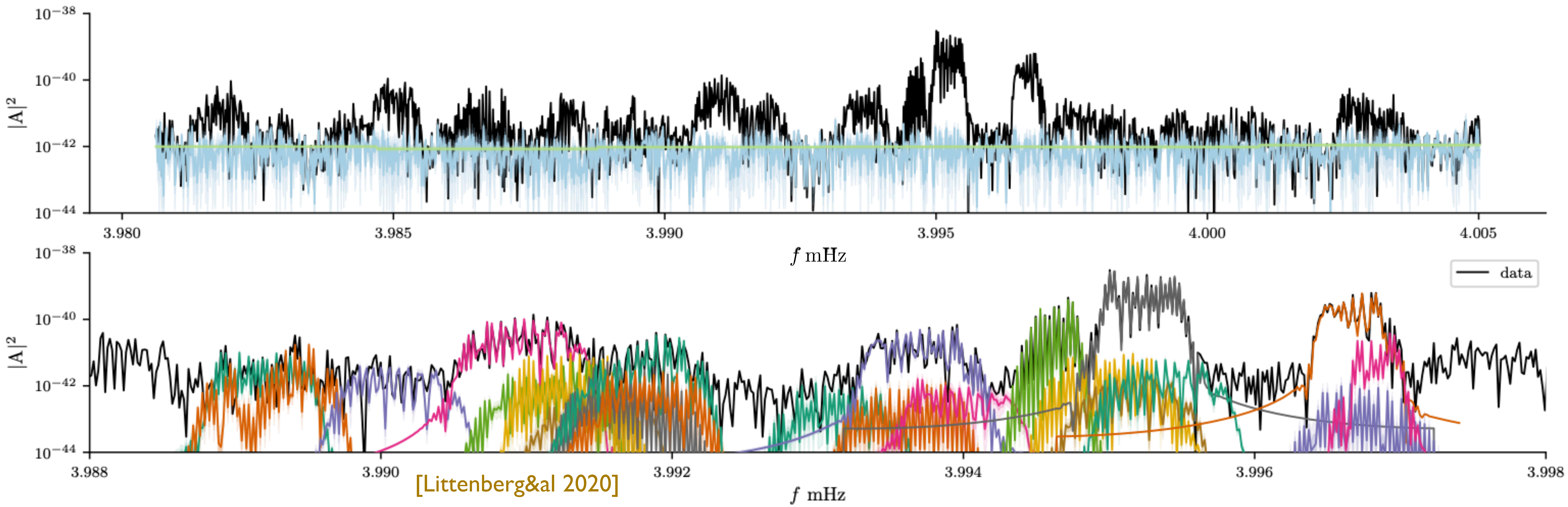
- Full galaxy: ~20 million systems !
- Mostly WD-WD, some other compact objects
- About ~20000 individually resolvable
- Form a (non-stationary) background
- Verification binaries



[Whilhelm&al 2020]

- How do binary stars evolve ?
- What is the WD/NS/BH merger rate in the Milky Way ?
- What is the structure of the Milky Way beyond the Galactic Center ?

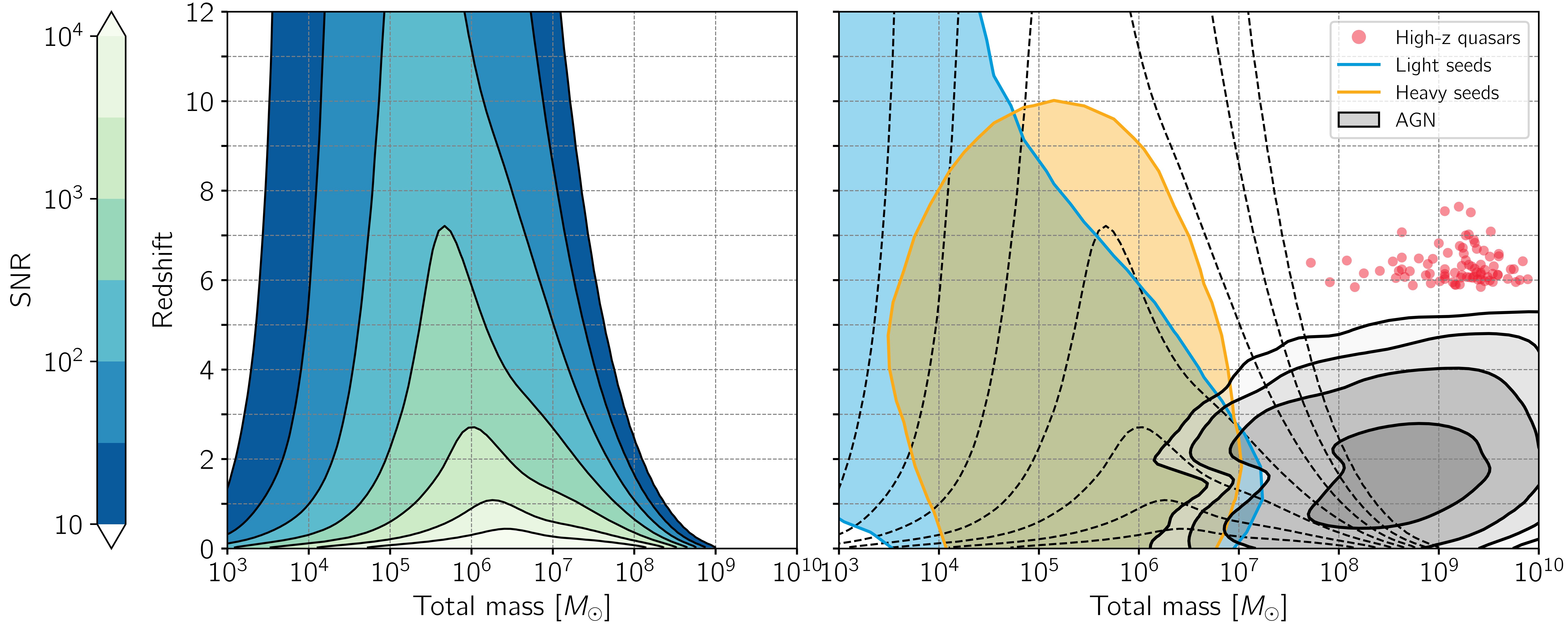
LISA sources: Galactic Binaries



[Littenberg&al 2020]

- Quasi-monochromatic GW emitters
- Modulation by LISA motion (sidebands in Fourier-domain)
- **Superposition/confusion** of signals in Fourier-domain
- Form a (non-stationary) **foreground** for all other sources
- Verification binaries useful for data analysis

LISA sources: Massive Black Hole Binaries



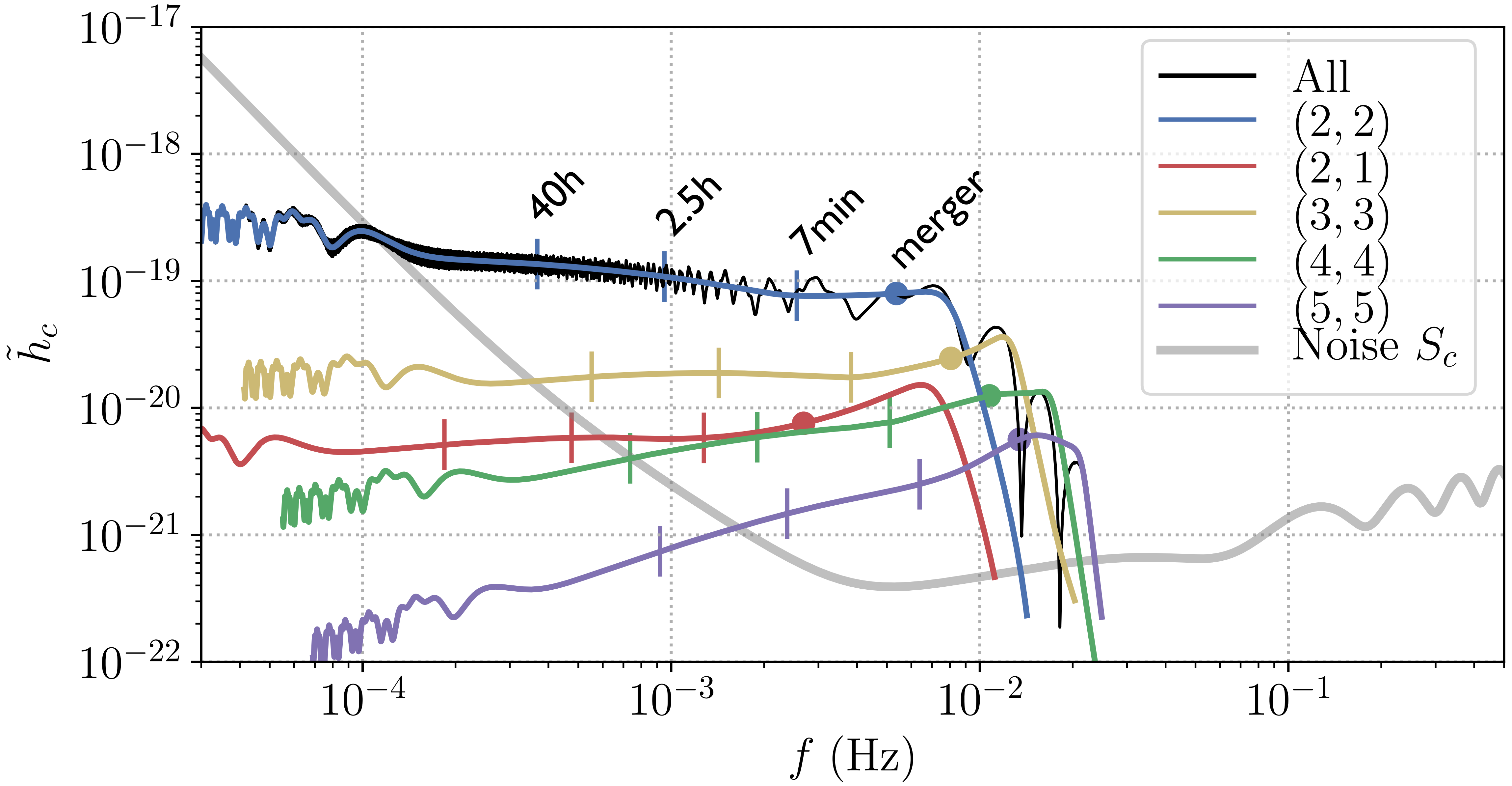
- MBH grow from seeds (light? massive?) through both mergers and accretion
- MBHBs very loud for LISA, detectable to cosmic dawn
- Rates uncertain, from ~1/yr to ~100/yr

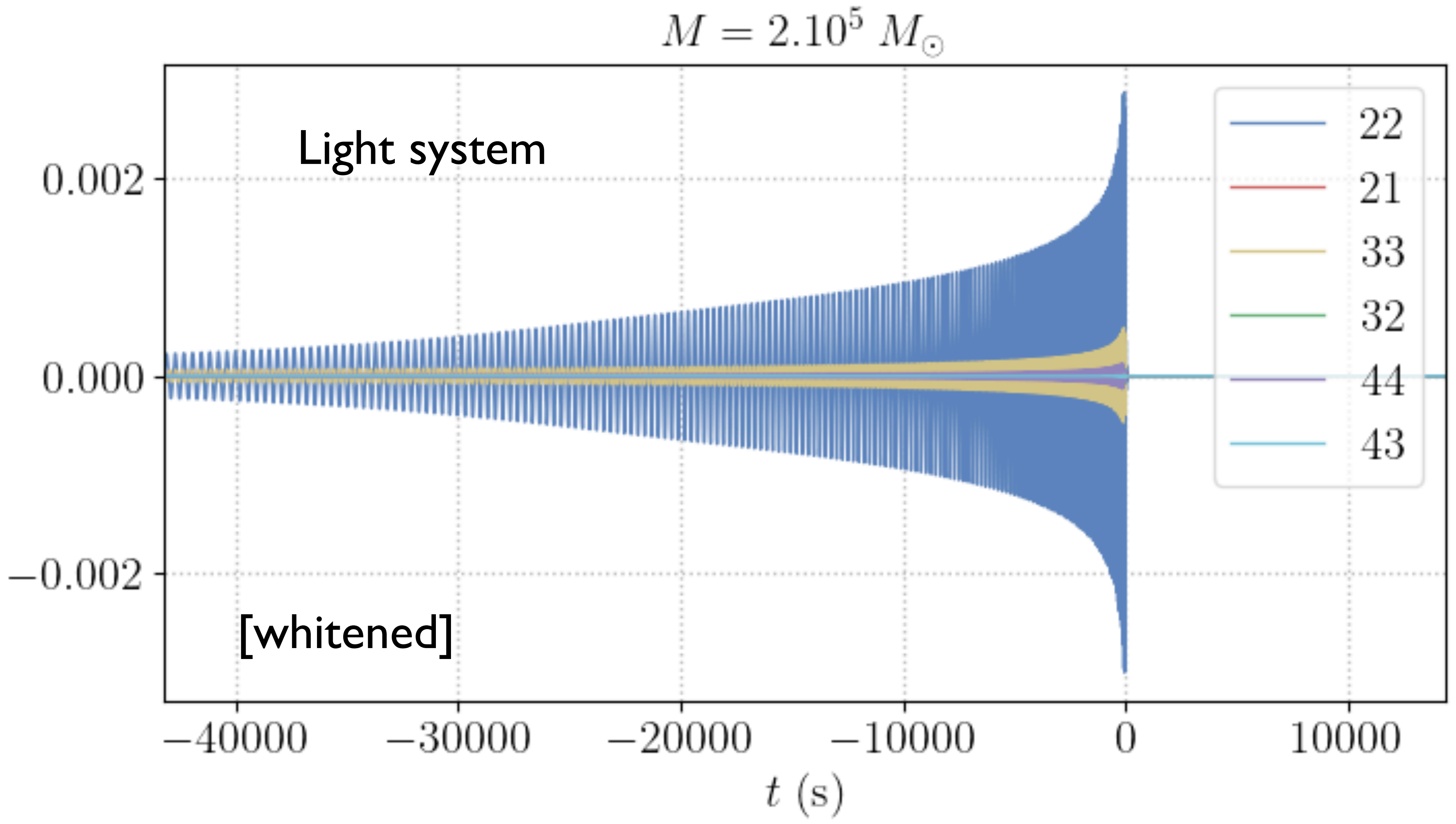
- What are the seeds of Massive Black Holes ?
- What is their population and how do they grow ?
- Identify host galaxies of MBHBs in EM
- Test General Relativity predictions for the signals

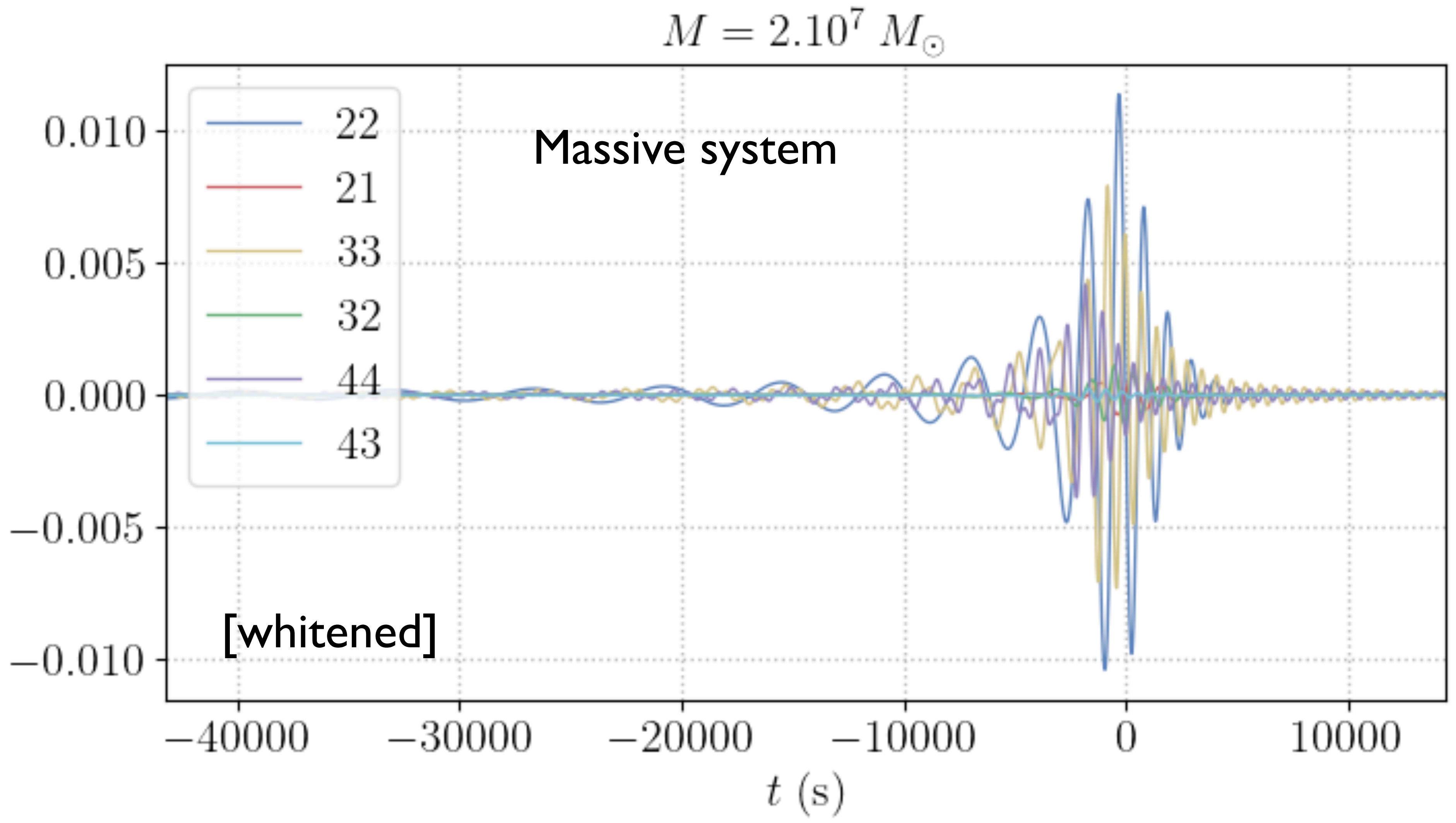
LISA sources: Massive Black Hole Binaries

- Very loud signals, merger-dominated
- All subdominant details in the waveform matter !
- Higher harmonics (m*orbital frequency) are crucial and break degeneracies
- Precession (misaligned spins) and eccentricity could be important

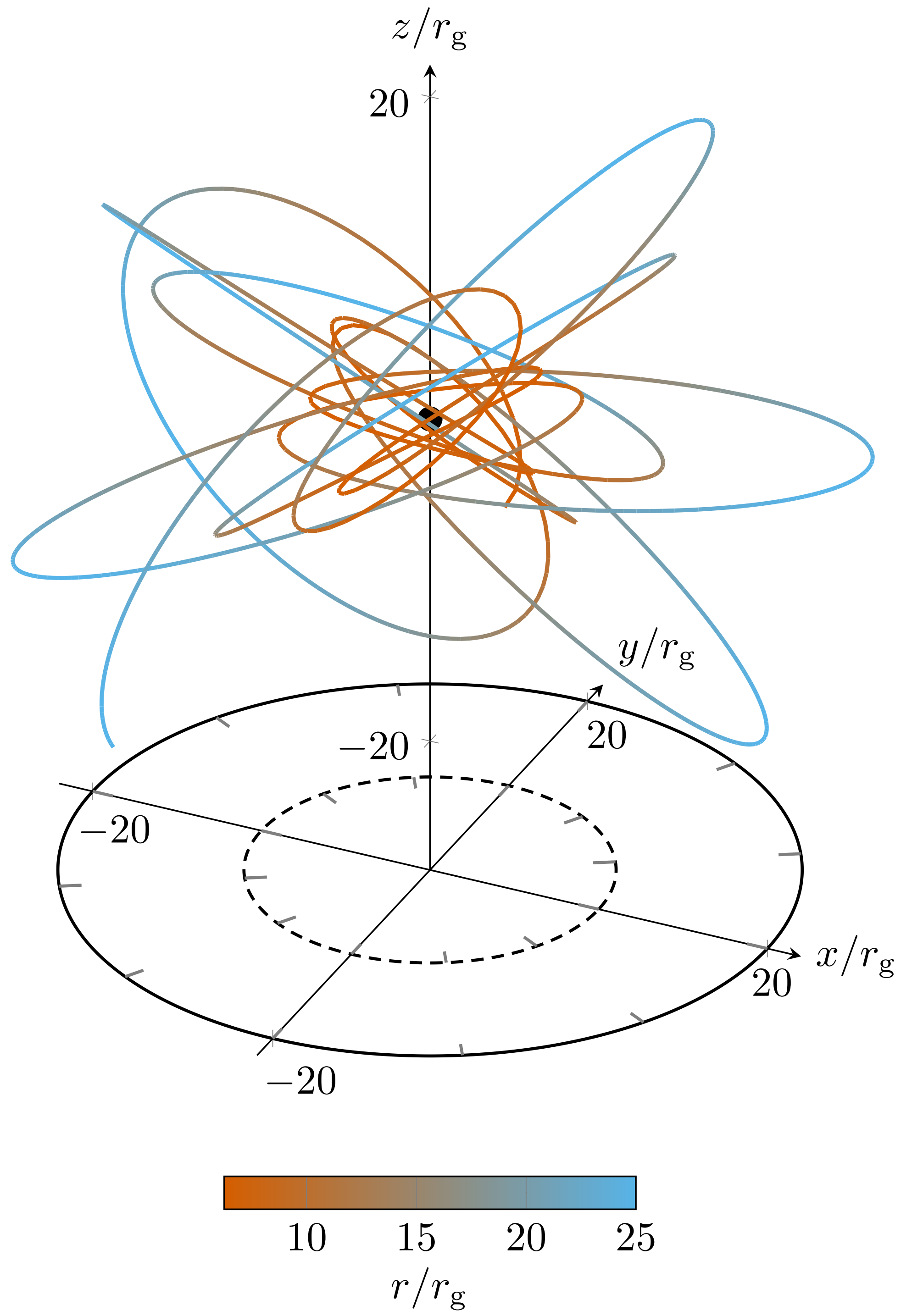
Example MBHB signal with higher harmonics



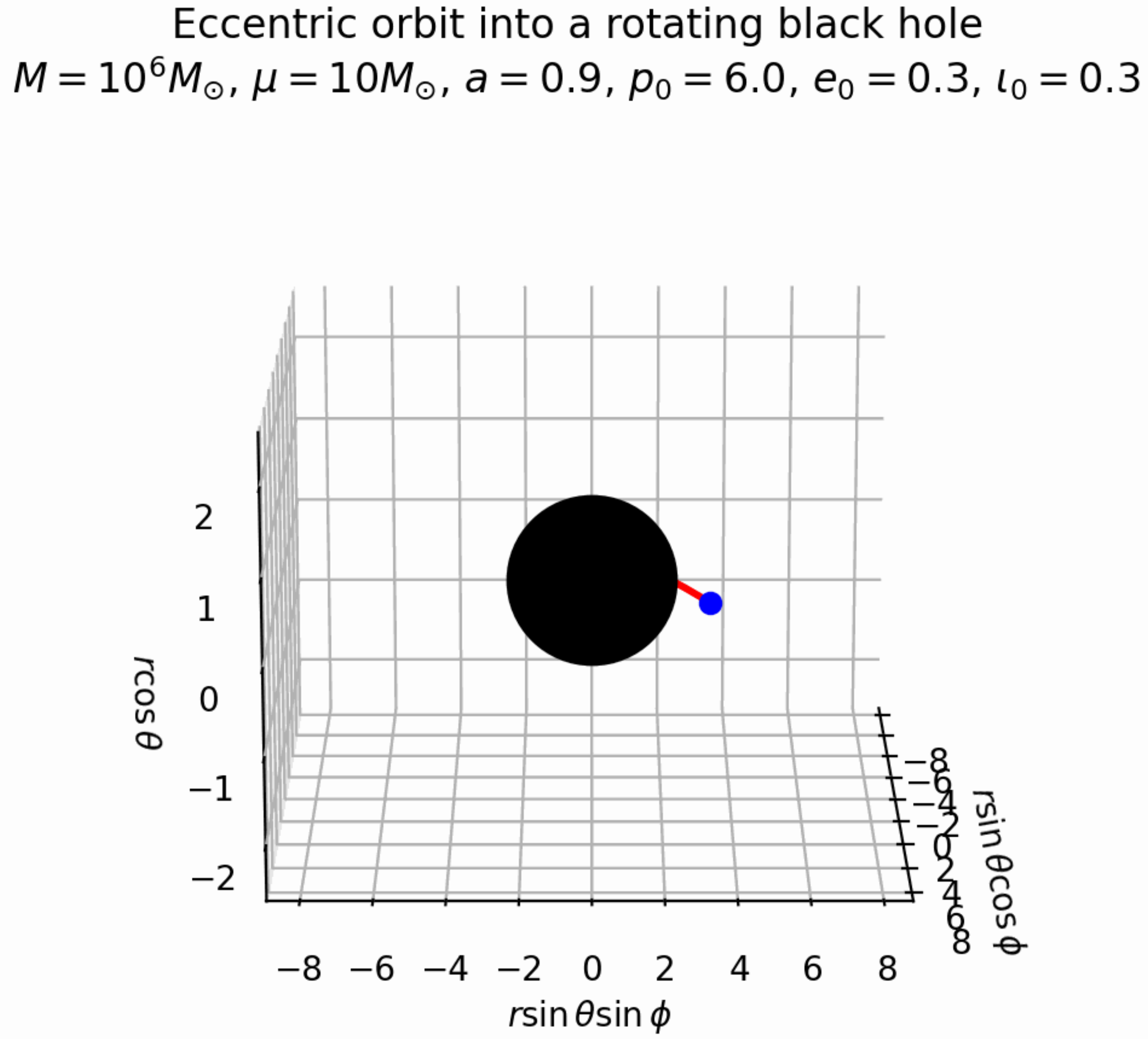




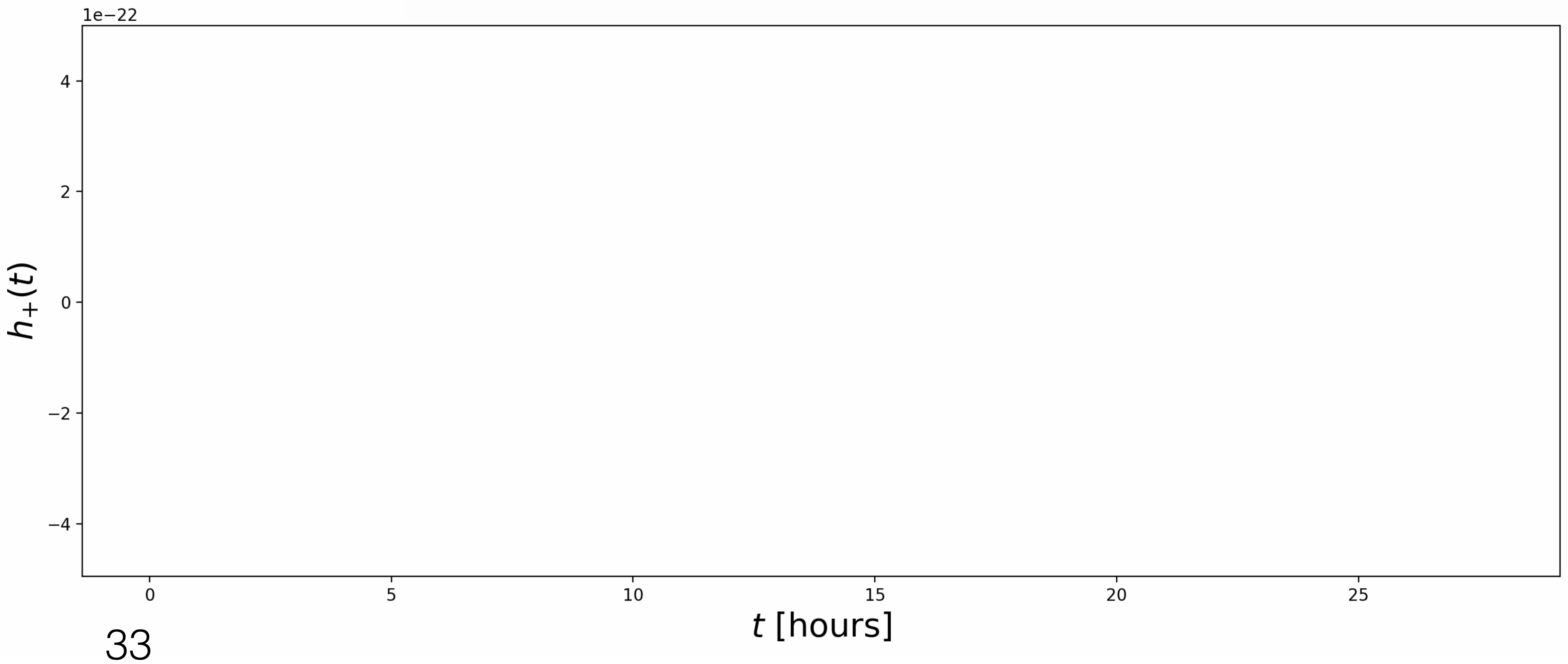
LISA sources: Extreme Mass Ratio Inspirals



- Dynamical capture of a compact object by a MBH can form a direct plunge or an EMRI
- EMRIs can be detected to z=1-2
- Rates **very** uncertain, from ~1/yr to ~1000/yr

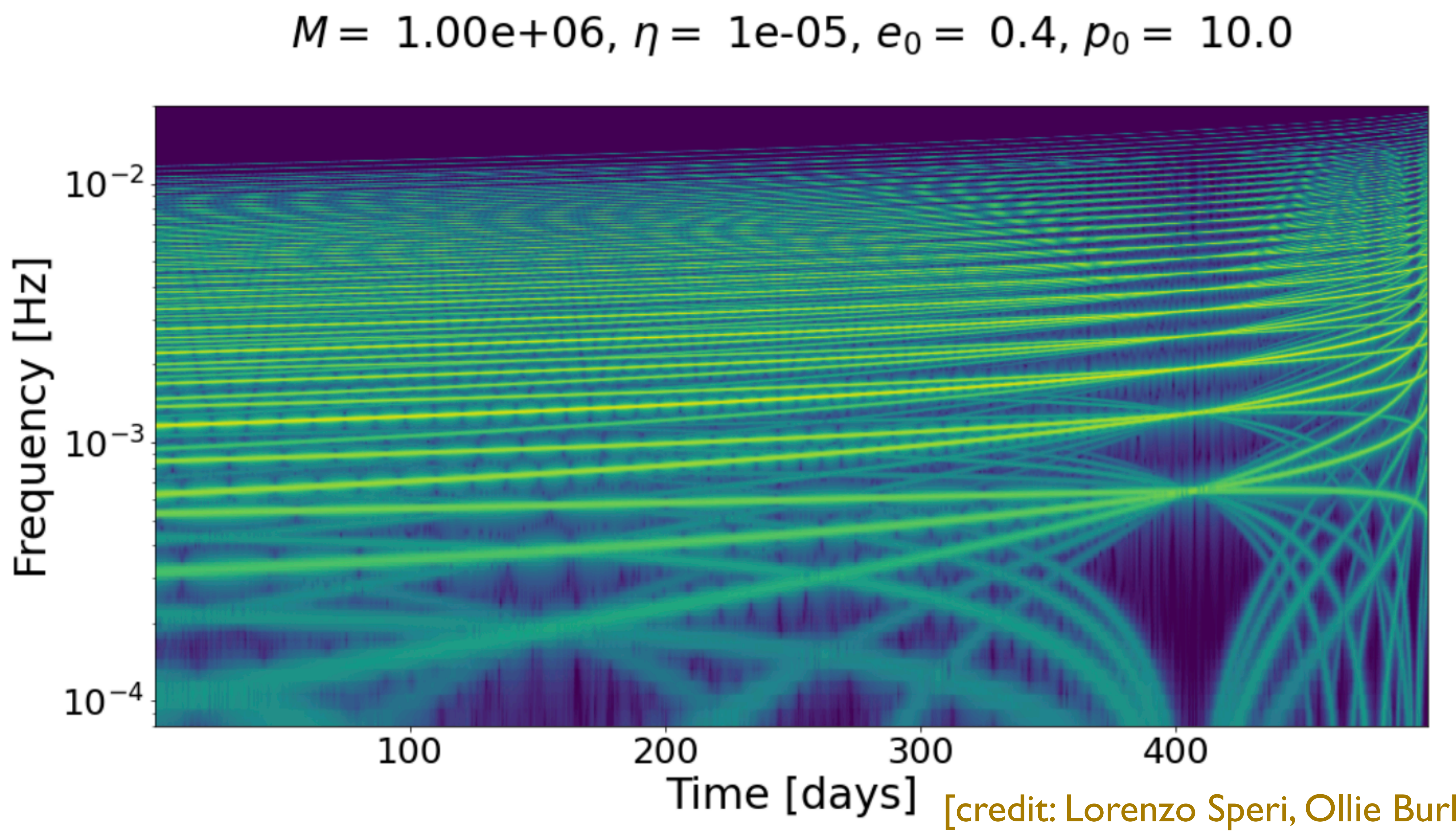


[credit: Burke&Speri]

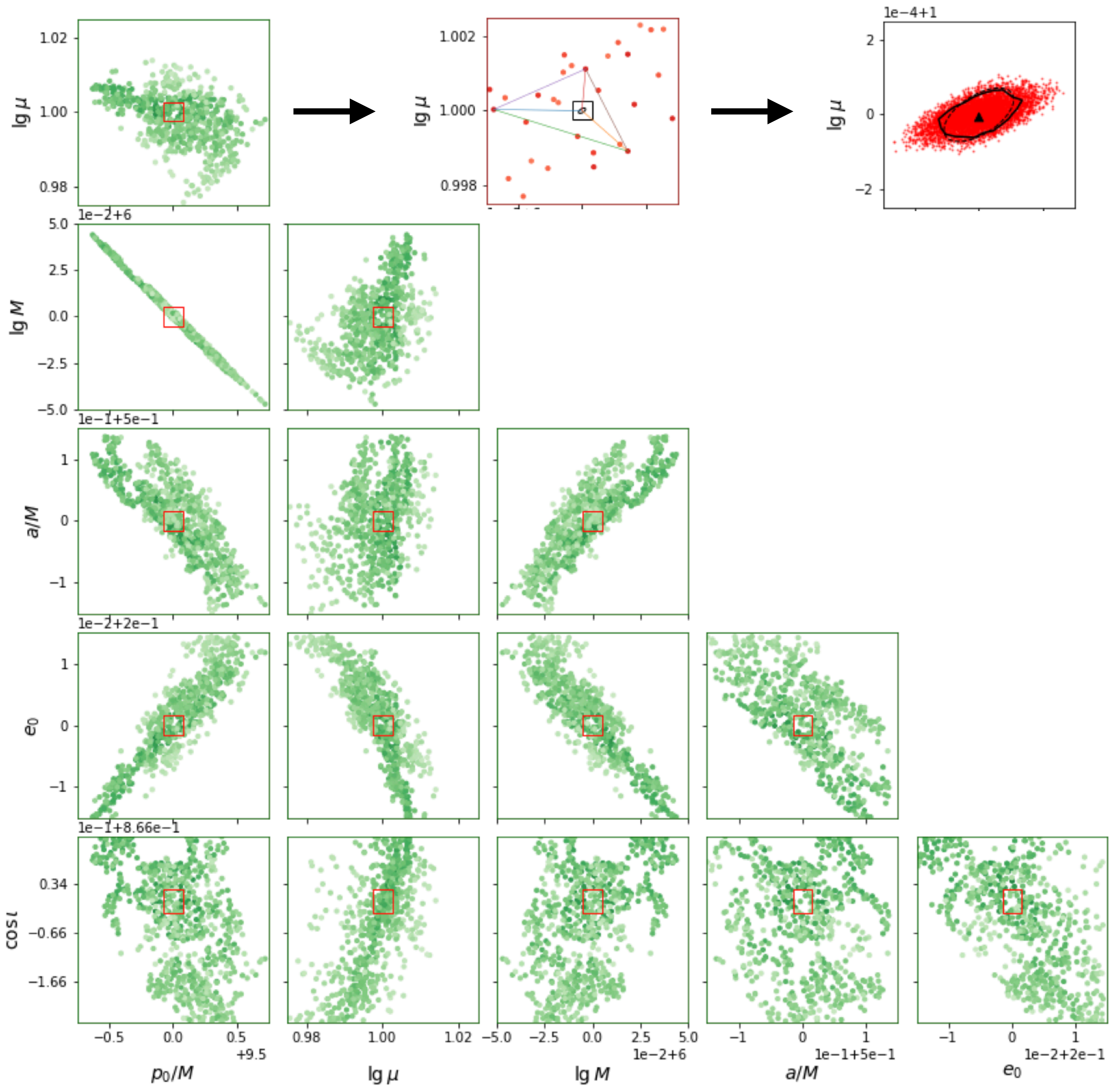


- What is the population of (individual) Massive Black Holes ?
- How do EMRIs form, in what environment ?
- Test General Relativity predictions for the signals

LISA sources: Extreme Mass Ratio Inspirals



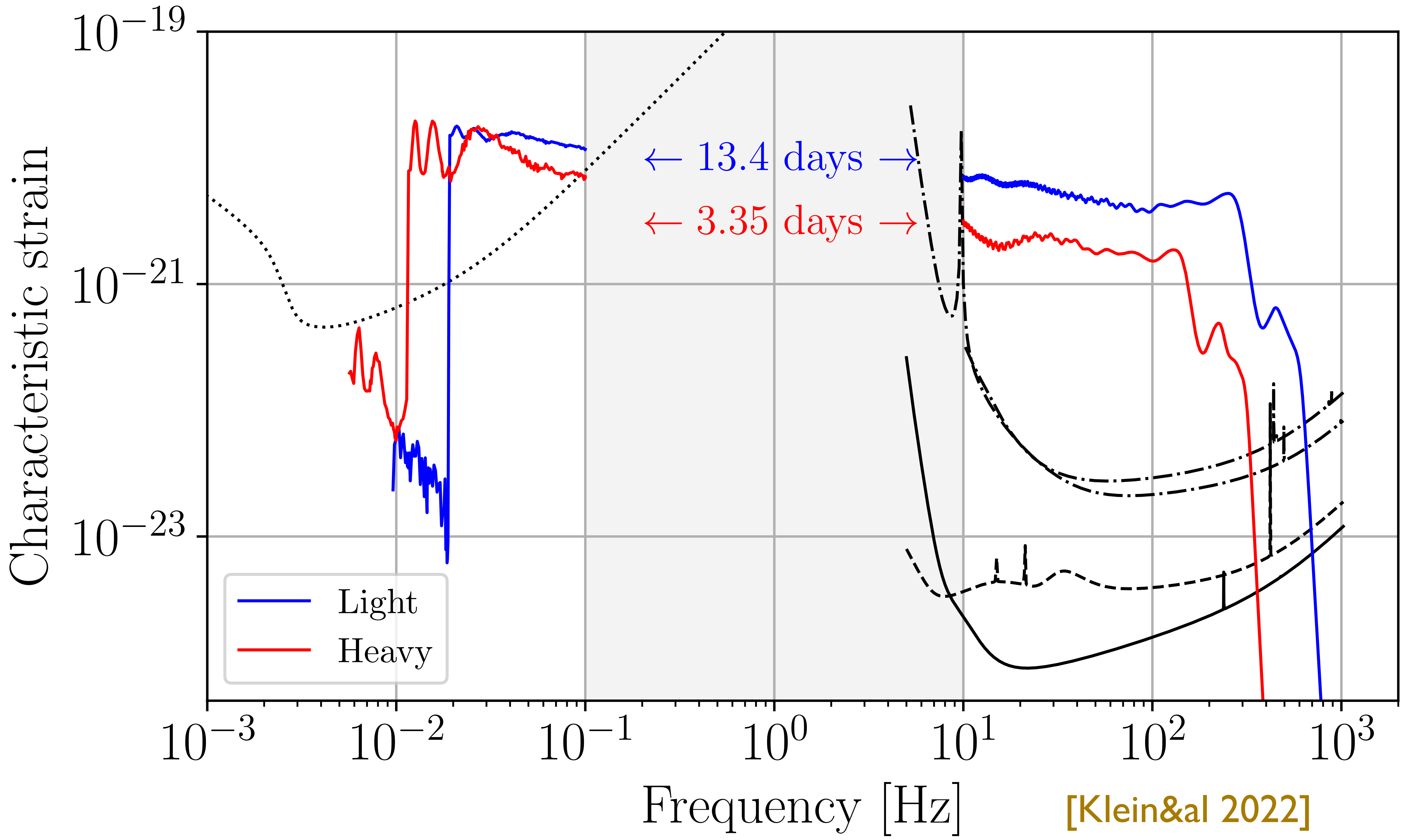
[credit: Lorenzo Speri, Ollie Burke]



[Chua&al 2021]

- Extremely complex signals, modelled in perturbative GR (frontier: 2nd order self-force)
- Long-lived signals, large number of orbits — exquisite parameter estimation
- Very rich harmonic structure
- Difficult to detect on its own (cannot use template banks !)
- Strong multimodality in parameter space

LISA sources: Stellar-mass Black Hole Binaries



[Klein&al 2022]

- What is the formation channel of stellar-mass BHBs ?
- What is their environment ?
- Test General Relativity predictions for the signals

- Same BBH as observed by LIGO/Virgo
- Long-lived signals, large number of orbits, very far from merger
- Difficult to detect on its own (cannot use template banks !)
- Could probe the presence of eccentricity, signature of the formation channel
- Possibility of **multiband detection** with ground instruments
- Rates low, signals barely detectable (but later detection on ground allows an archival search)

[LISA Red Book 2024]

	sBHB type	definition	$\langle N \rangle$	90 % confidence	no sBHB (%)
SI 4.1	detected	SNR > 8	4.9	0.4 – 9.8	2.2
	archival	$5 <$ SNR < 8 & $t_c < 15$ yr	5.6	0.8 – 10.0	1.4
SI 4.3	multiband	SNR > 8 & $t_c < 15$ yr	1.5	0 – 3.8	26.7
		SNR > 8 & $t_c < 4.5$ yr	0.4	0 – 1.4	67.7

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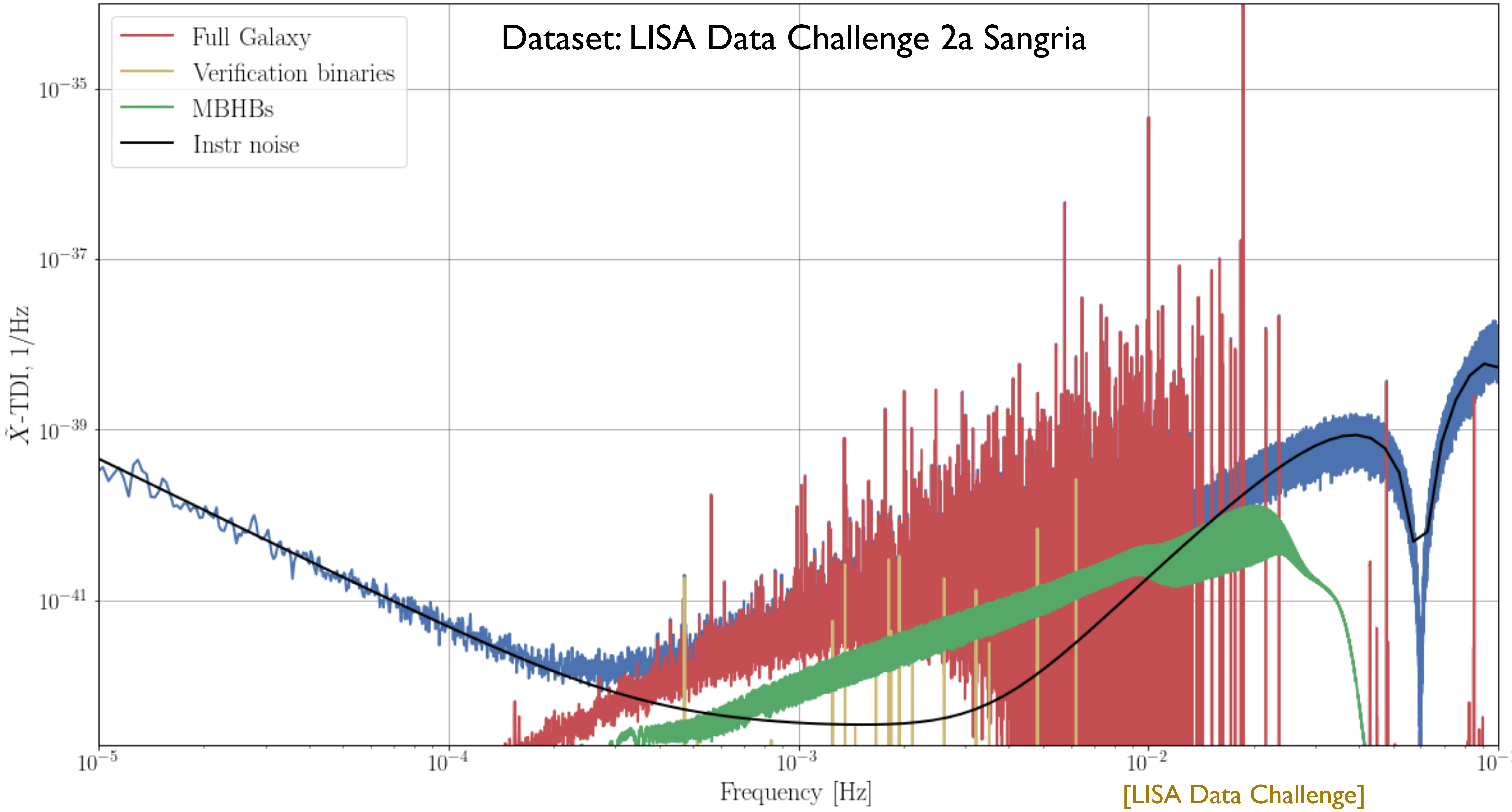
LISA data in frequency-domain

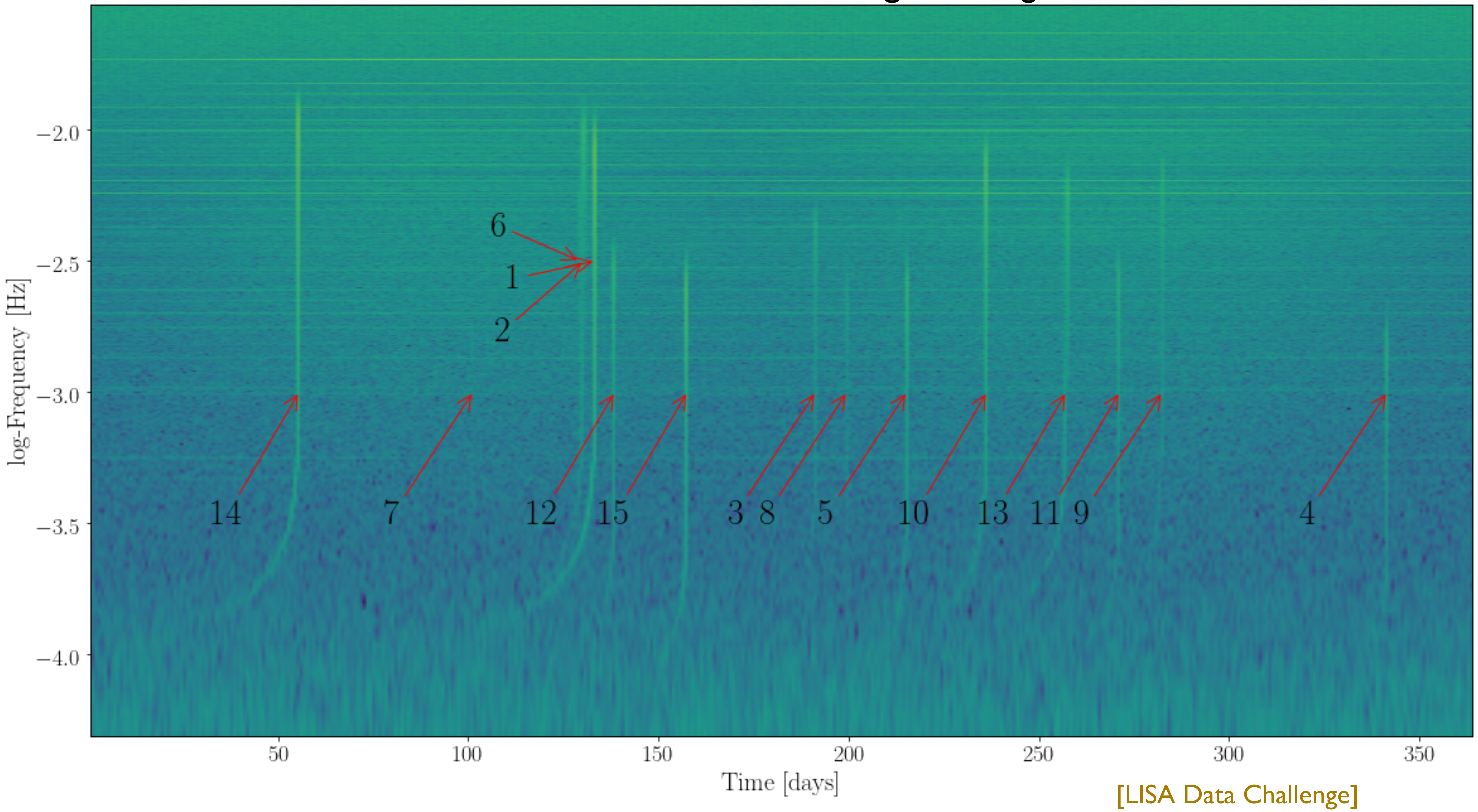


[LISA Data Challenge]

- **MBHBs**: loud and merger-dominated, localized in time but extended in frequency
- **GBs**: continuous signals very local in frequency, both individually resolvable and building up a background

LISA data in time-frequency domain

Dataset: LISA Data Challenge 2a Sangria

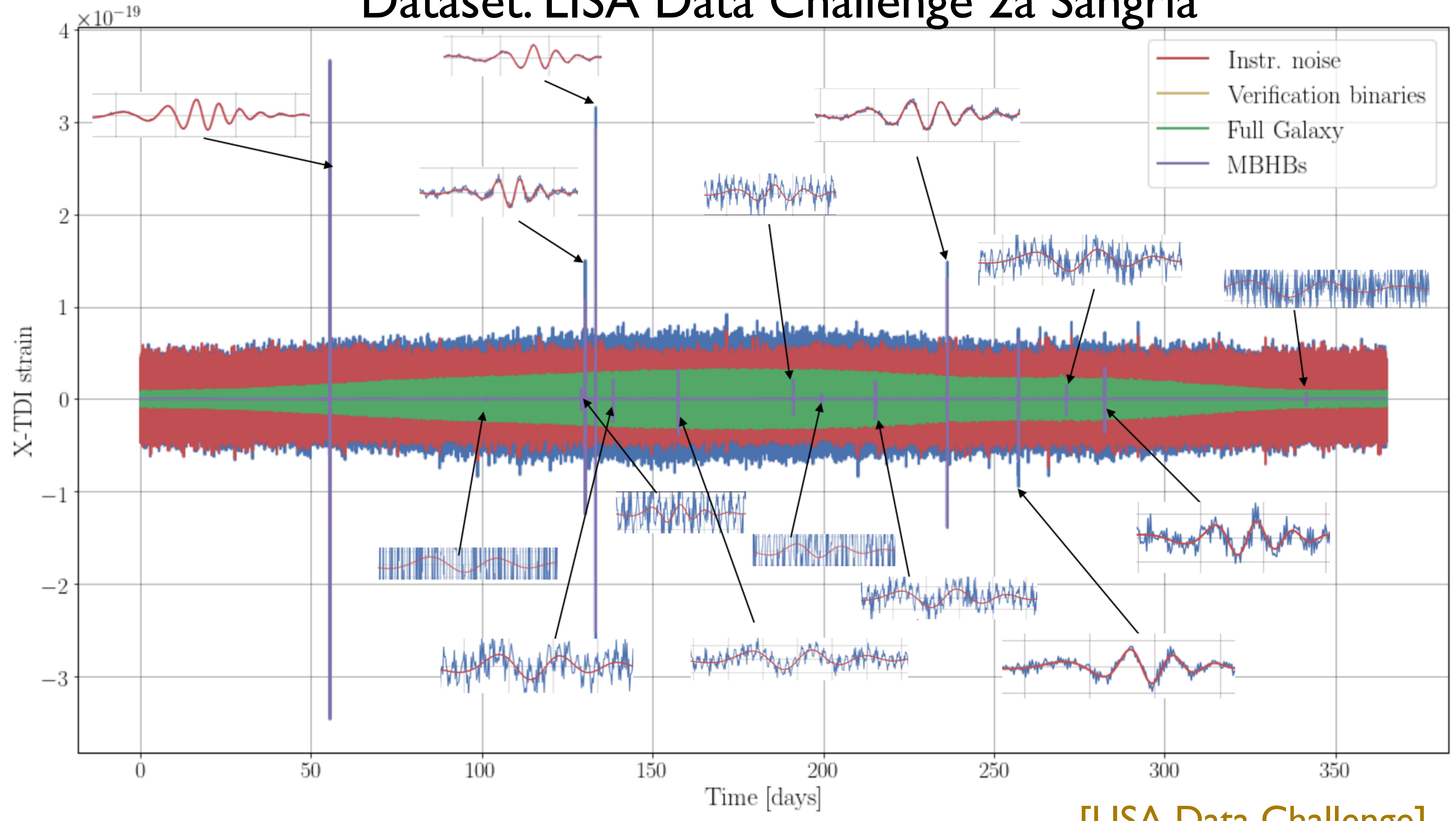


[LISA Data Challenge]

- **MBHBs**: loud and merger-dominated, localized in time but extended in frequency
- **GBs**: continuous signals very local in frequency, both individually resolvable and building up a background

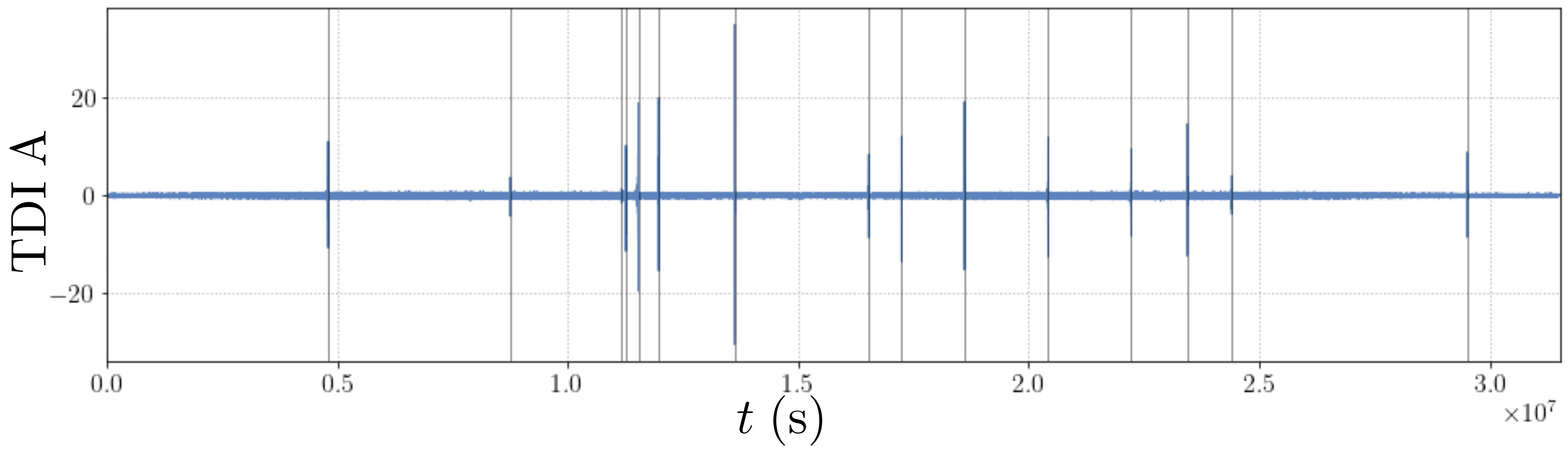
LISA data - band-passed, whitened in time domain

Dataset: LISA Data Challenge 2a Sangria

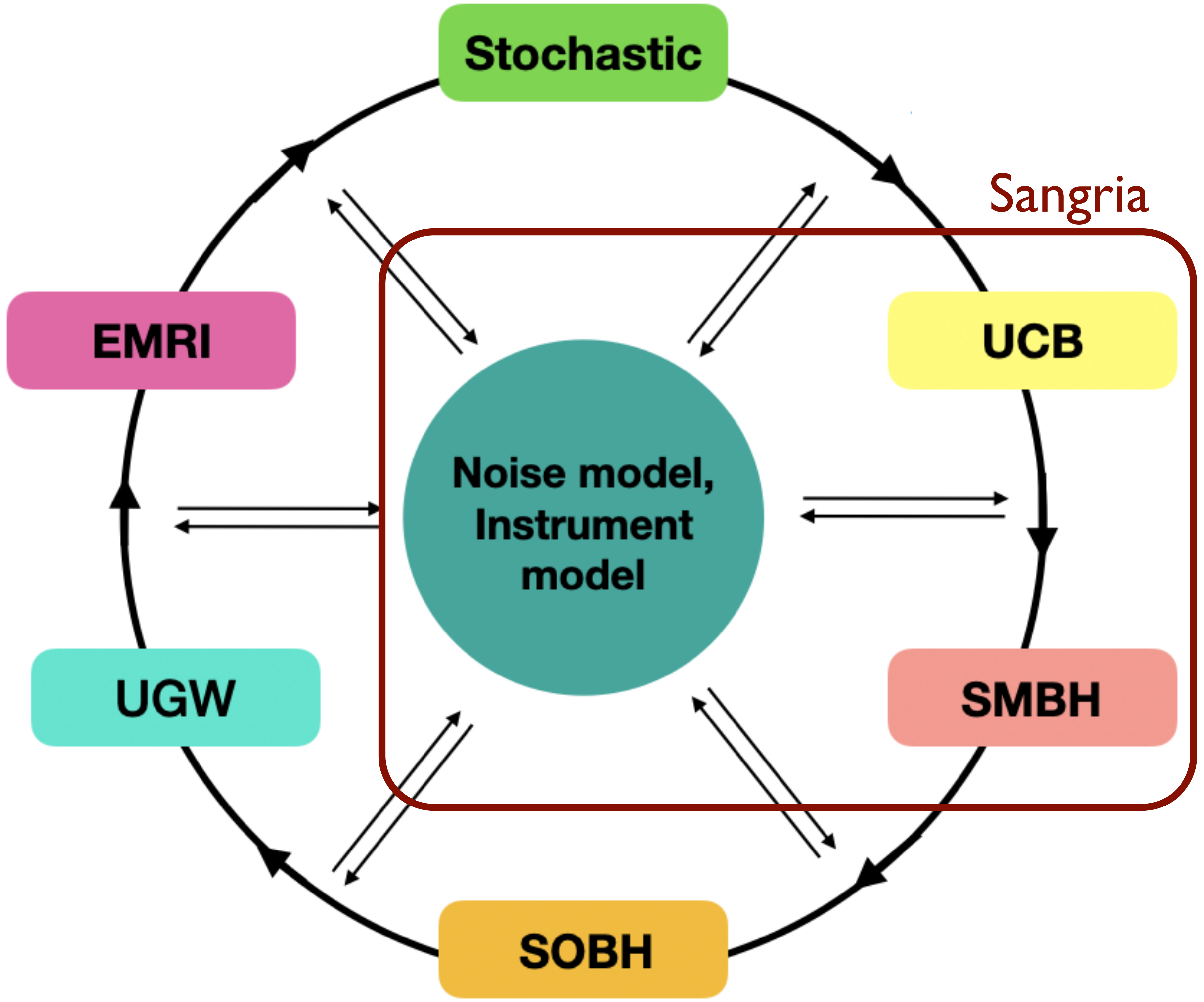


[LISA Data Challenge]

Whitened, band-passed data



LDC Sangria: first steps of a global fit



[credit: Cornish]

Source superposition: a first approach

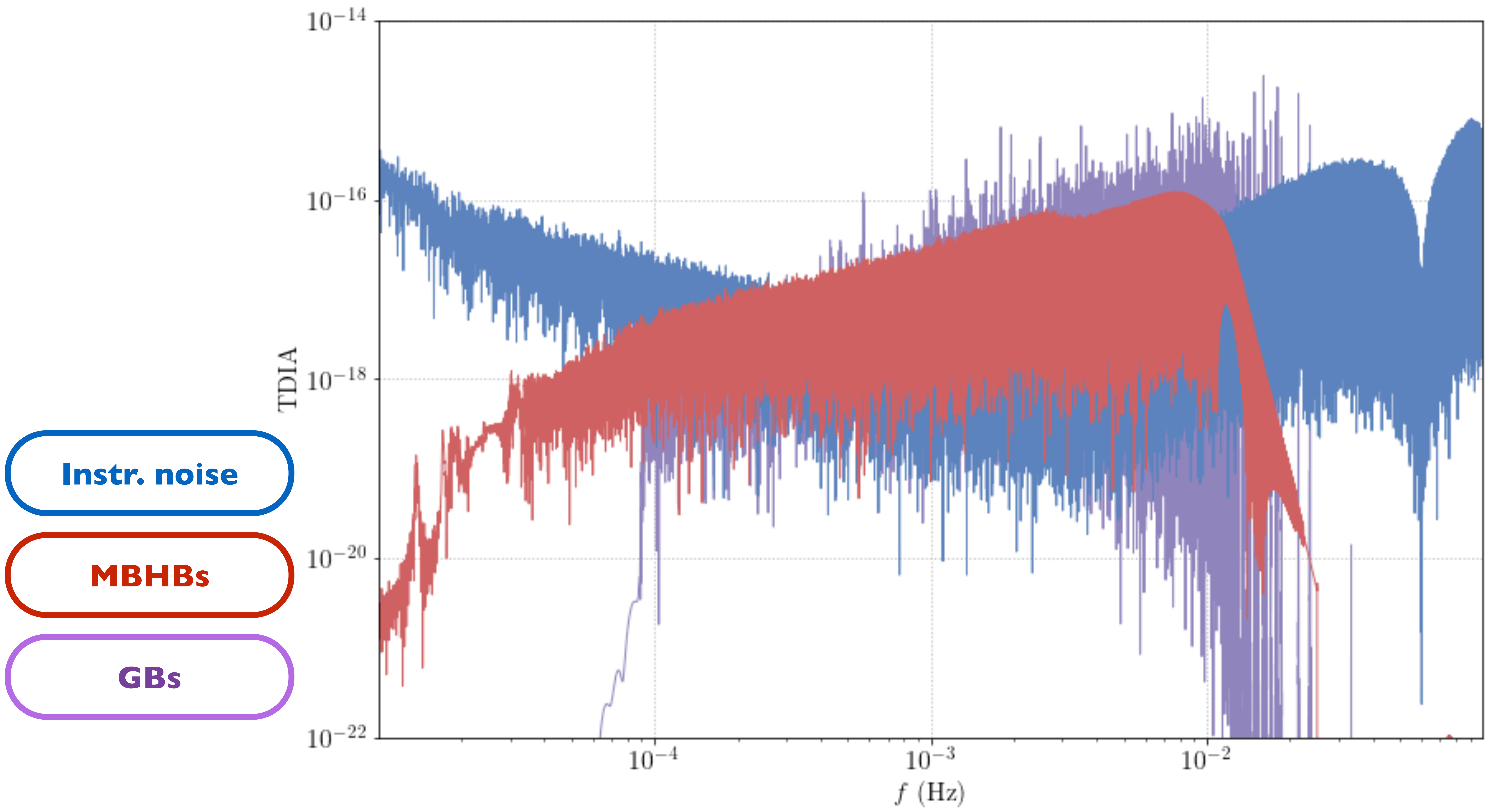
- Most classes of sources superpose in time or frequency, but signals should be approximately orthogonal
- Instrument noise level is also unknown a priori
- Problem intractable in full dimensionality…
- **Gibbs sampling** approach: sample/subtract each signal in succession, iterate the loop many times

Where to start the loop ?

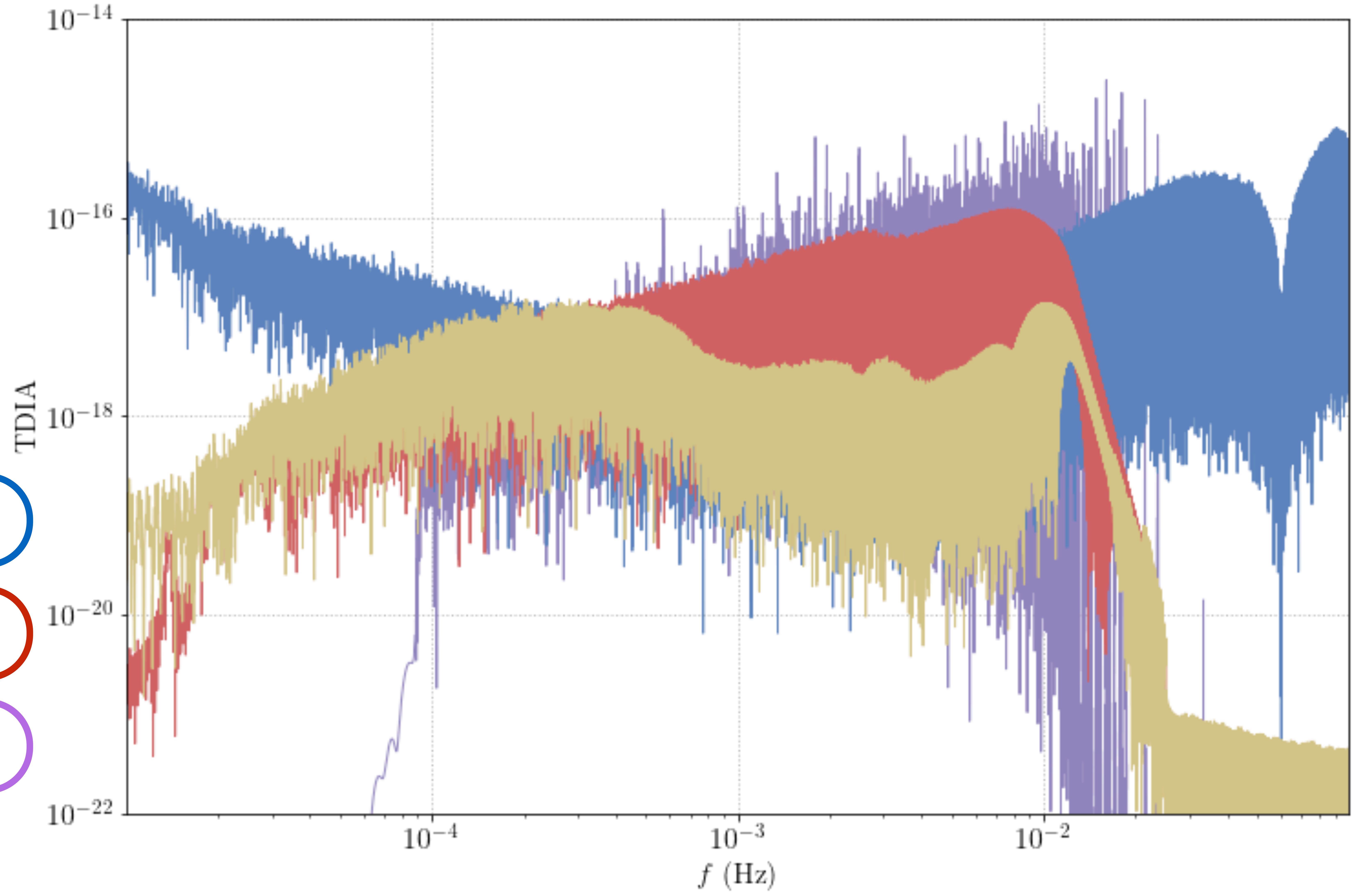
- MBHB analysis with full galaxy / GB analysis with full MBHBs are typically biased
- Some form of signal subtraction seems to be required

LISA data analysis will require a **global fit** of all signals
This global fit can be modular

LDC Sangria: first steps of a global fit



LDC Sangria: first steps of a global fit



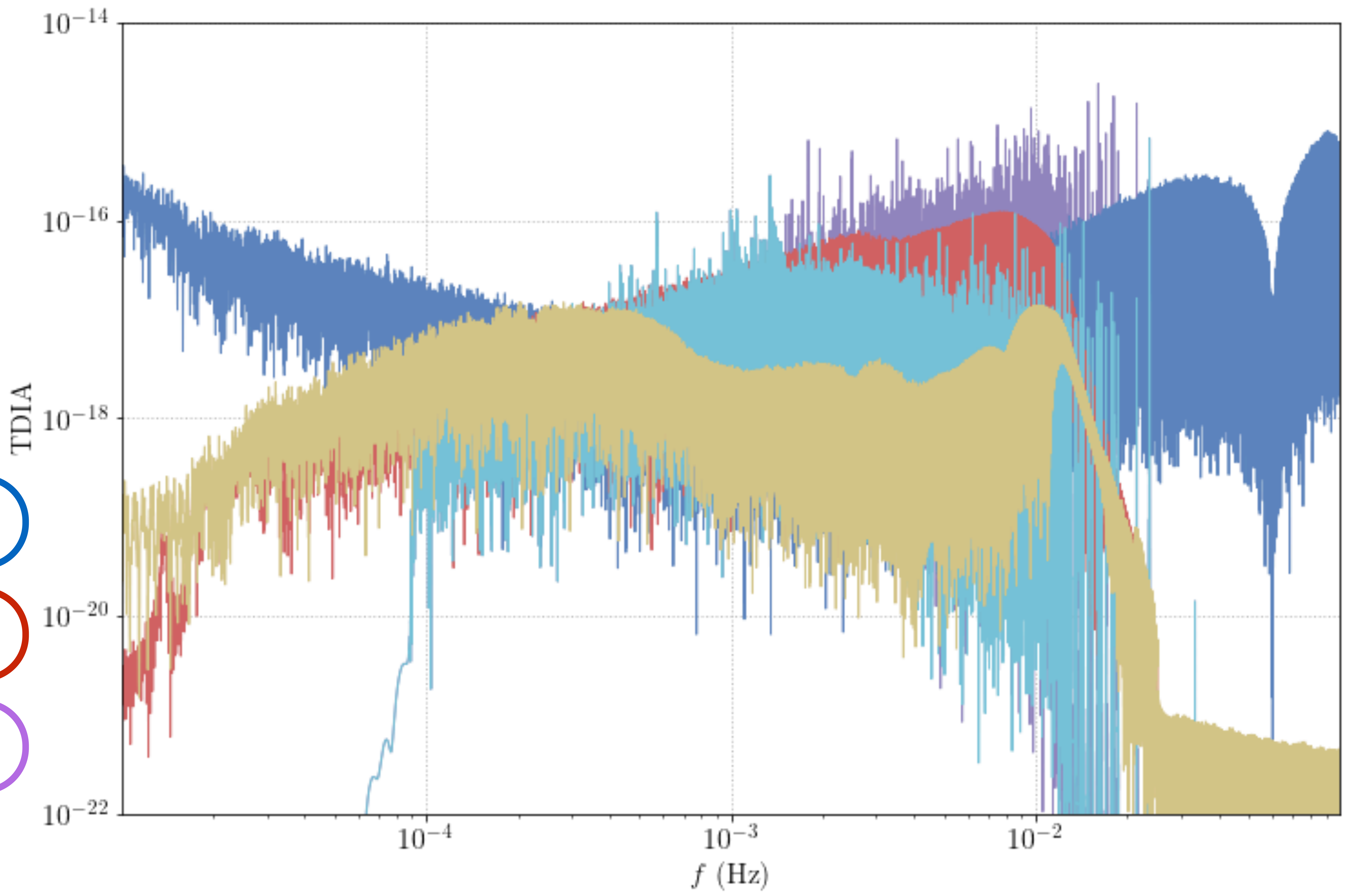
MBHBs
1st subtraction resid.

Instr. noise

MBHBs

GBs

LDC Sangria: first steps of a global fit



Instr. noise

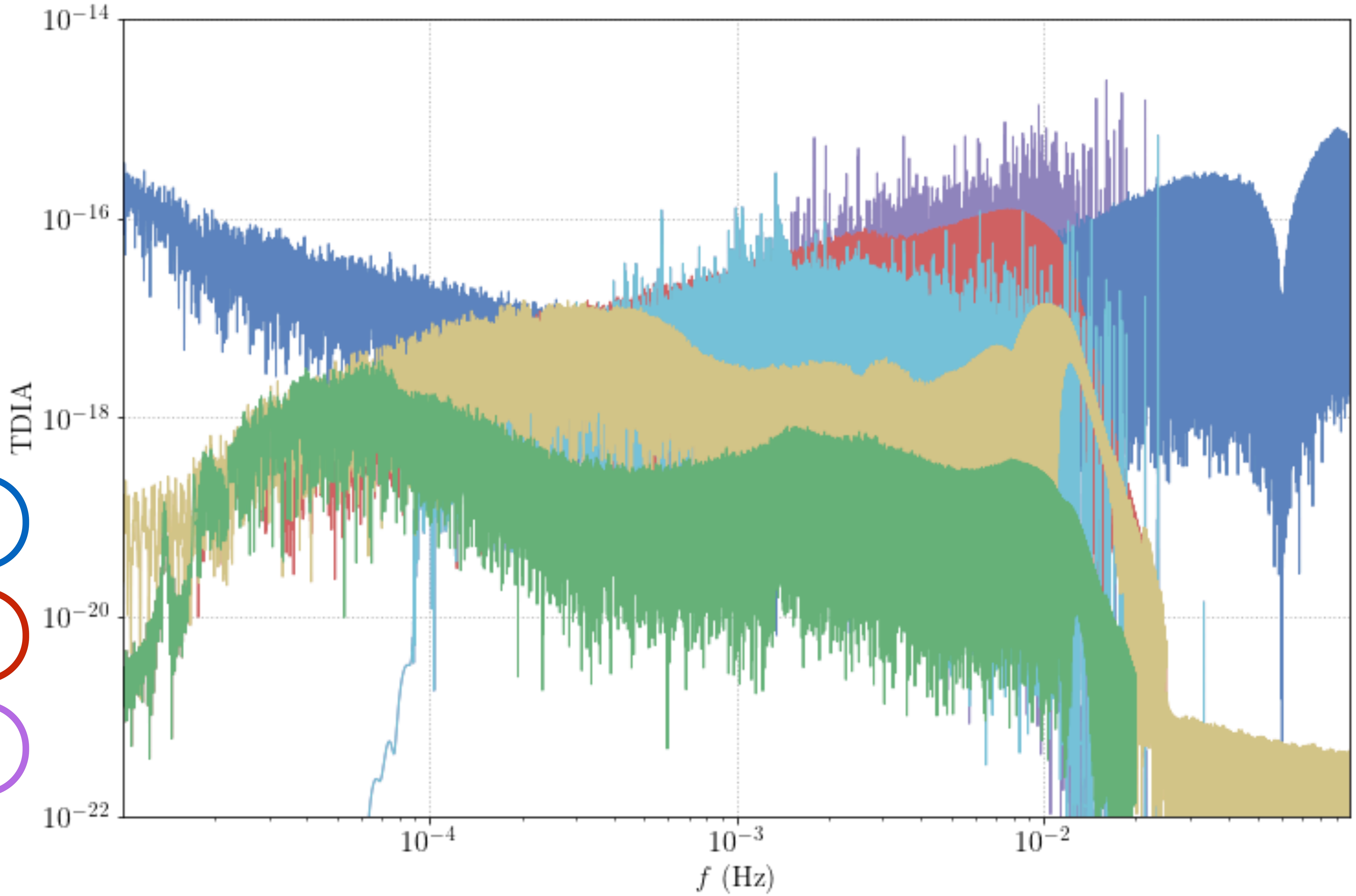
MBHBs

GBs

MBHBs
1st subtraction resid.

GBs
1st PE resid.

LDC Sangria: first steps of a global fit



Instr. noise

MBHBs

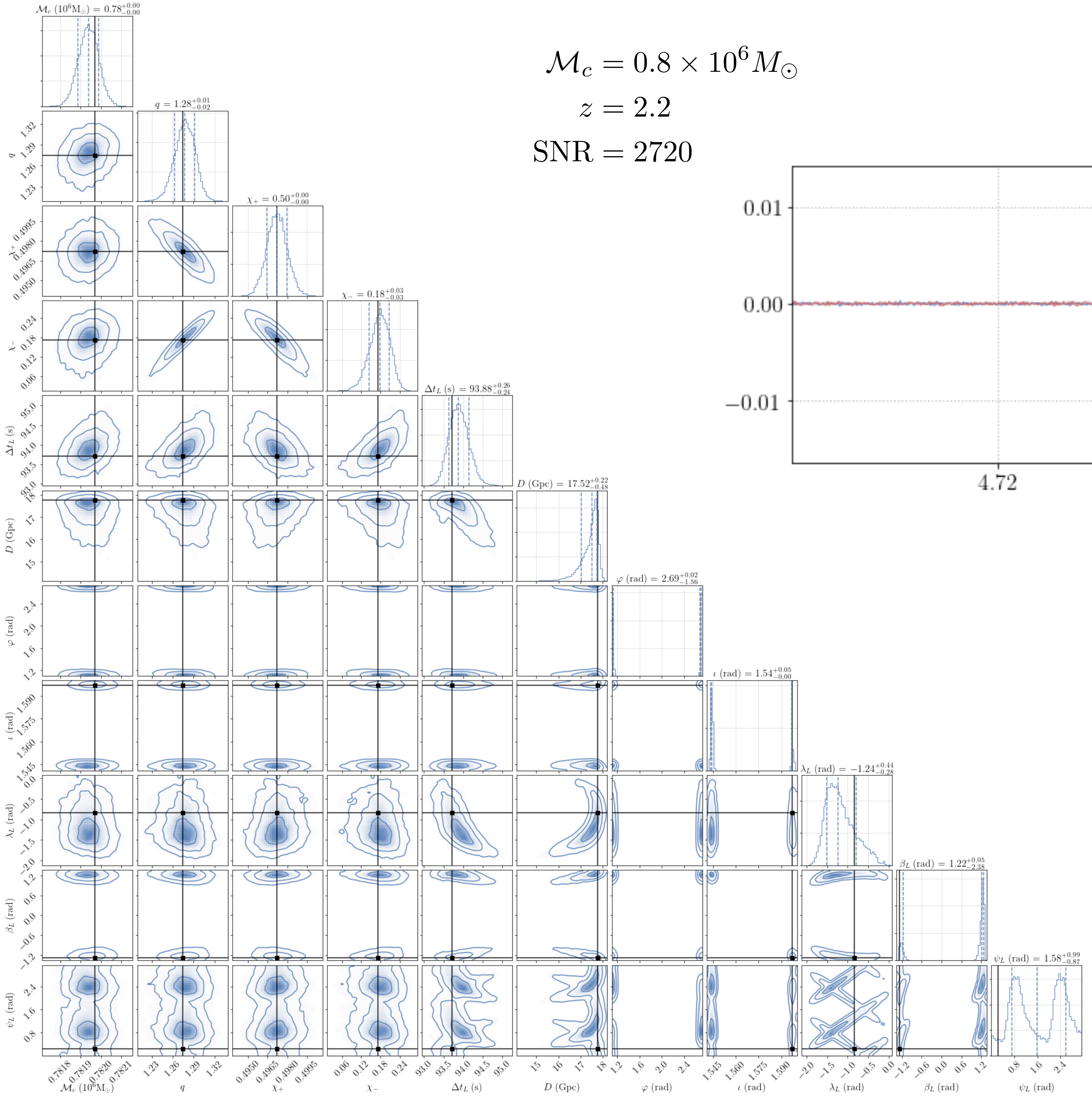
GBs

MBHBs
1st subtraction resid.

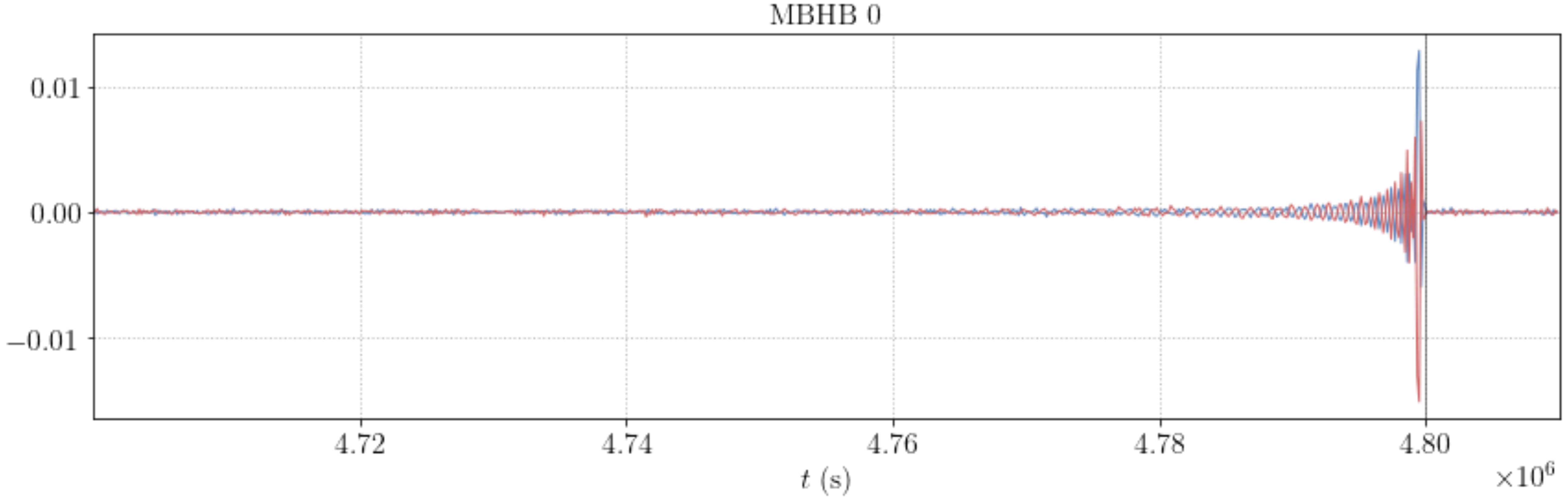
GBs
1st PE resid.

MBHBs
1st PE resid.

LDC Sangria MBHB example



$$\mathcal{M}_c = 0.8 \times 10^6 M_\odot$$
$$z = 2.2$$
$$\mathrm{SNR} = 2720$$

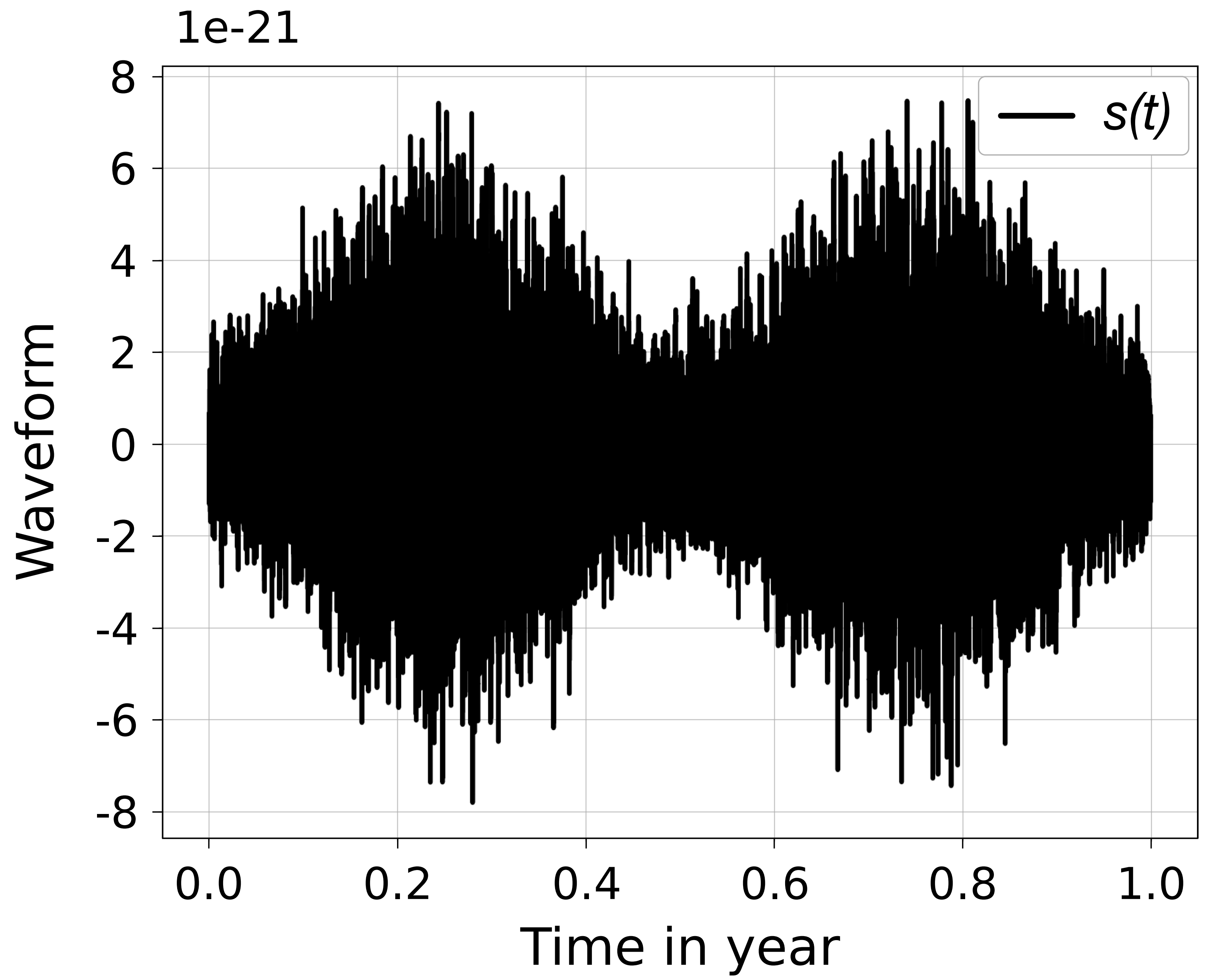


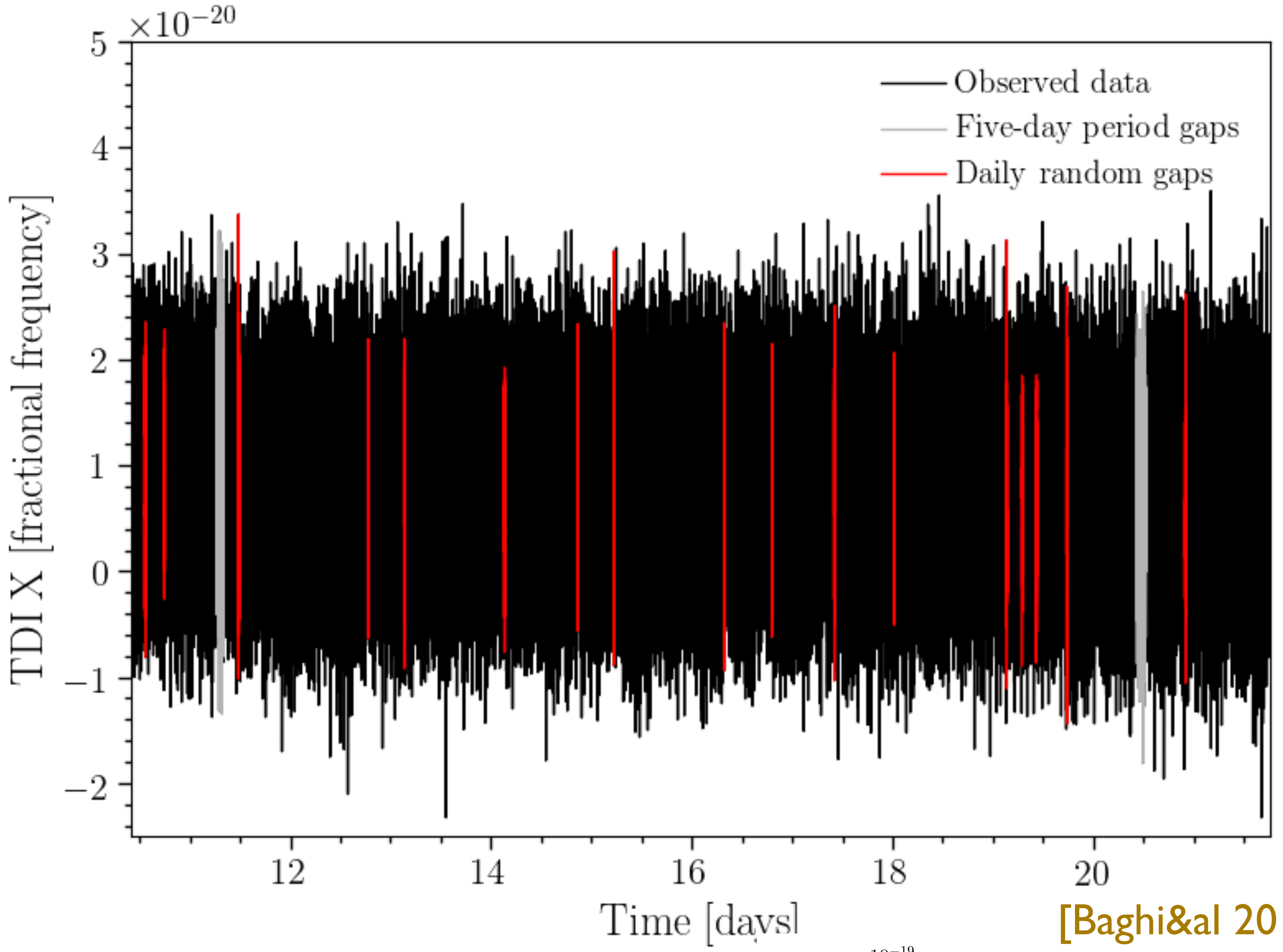
LISA Data Challenge 2a (global fit) successfully passed

Global fit prototypes (to date !):

- Marshall/Montana
- APC/L2IT
- AEI Potsdam

LISA: non-stationarity and gaps





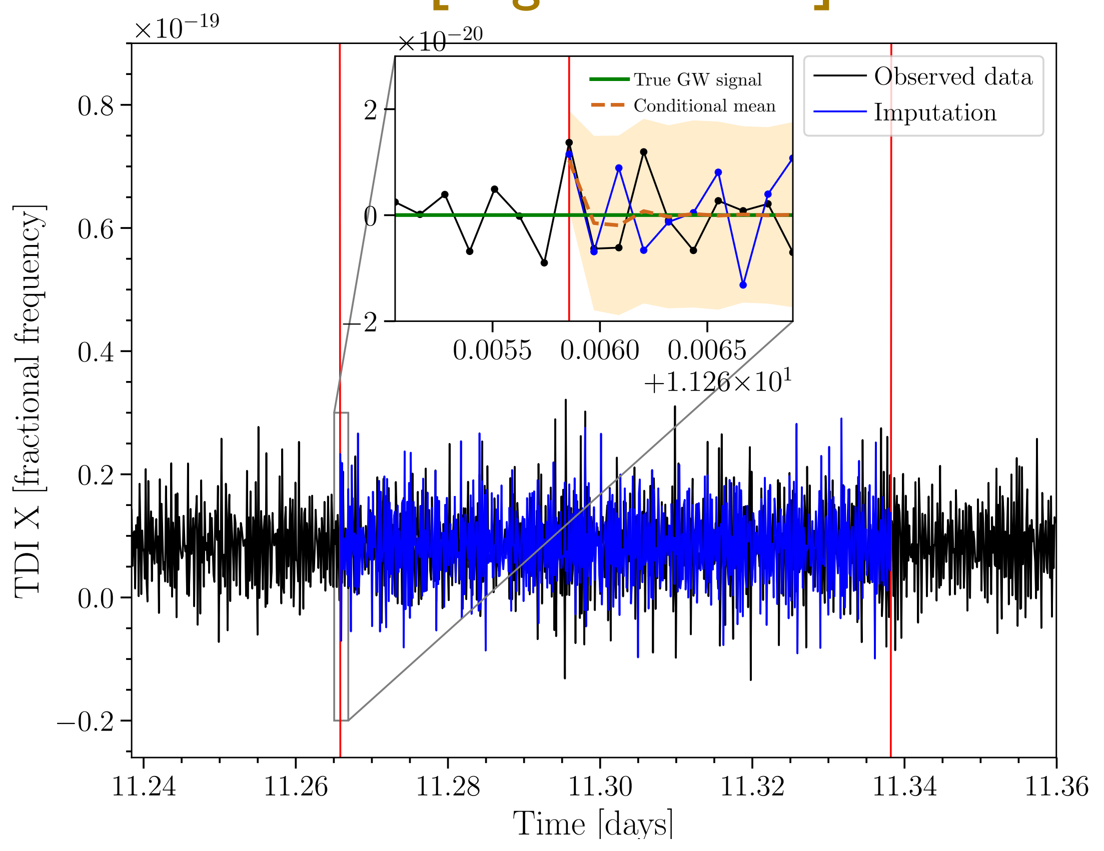
[Baghi&al 2019]

Non-stationarity

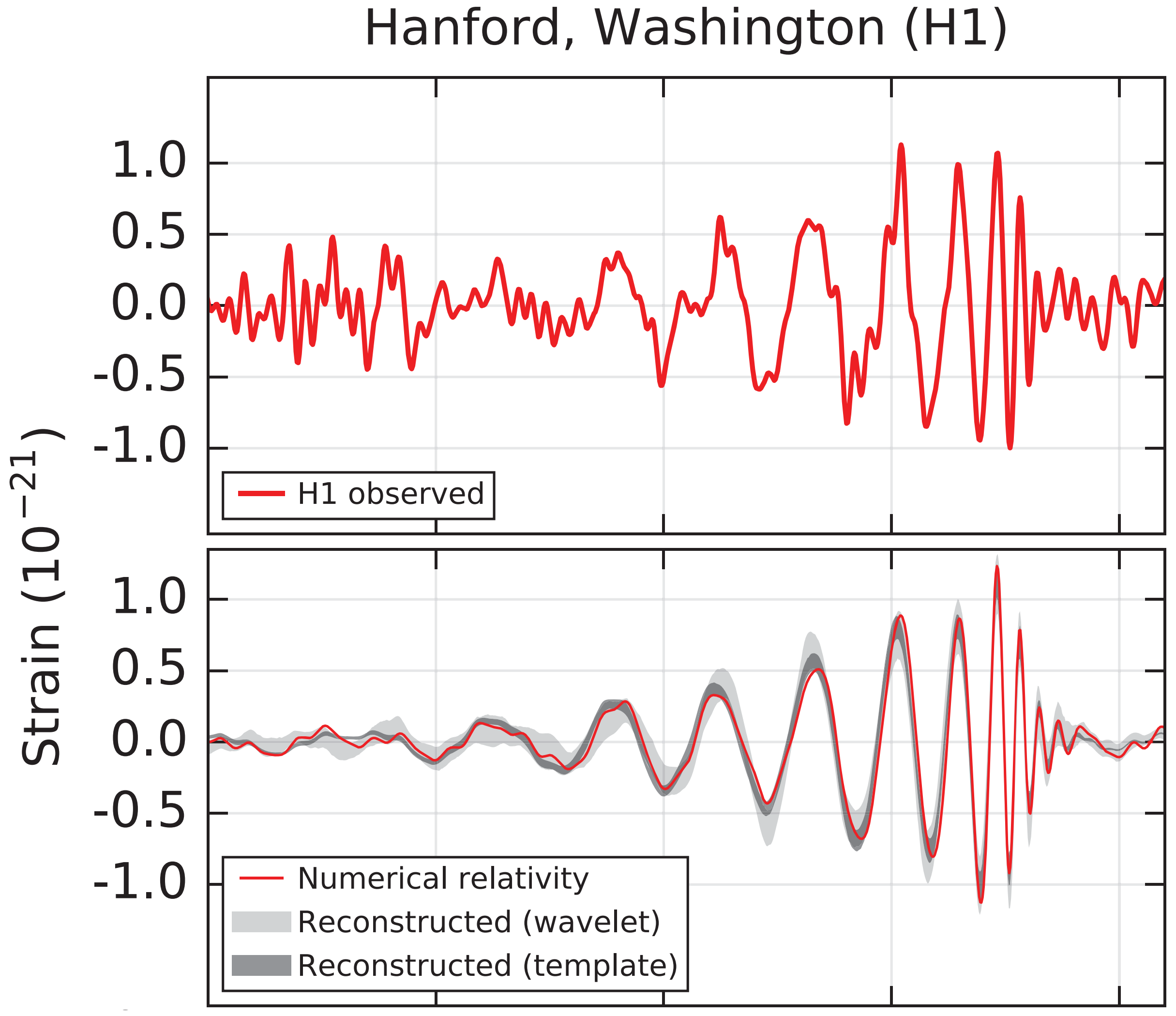
- Non-stationarity background from double WD in the galaxy
- Instrumental non-stationarity over long times
- Glitches (as seen in LISA Pathfinder)

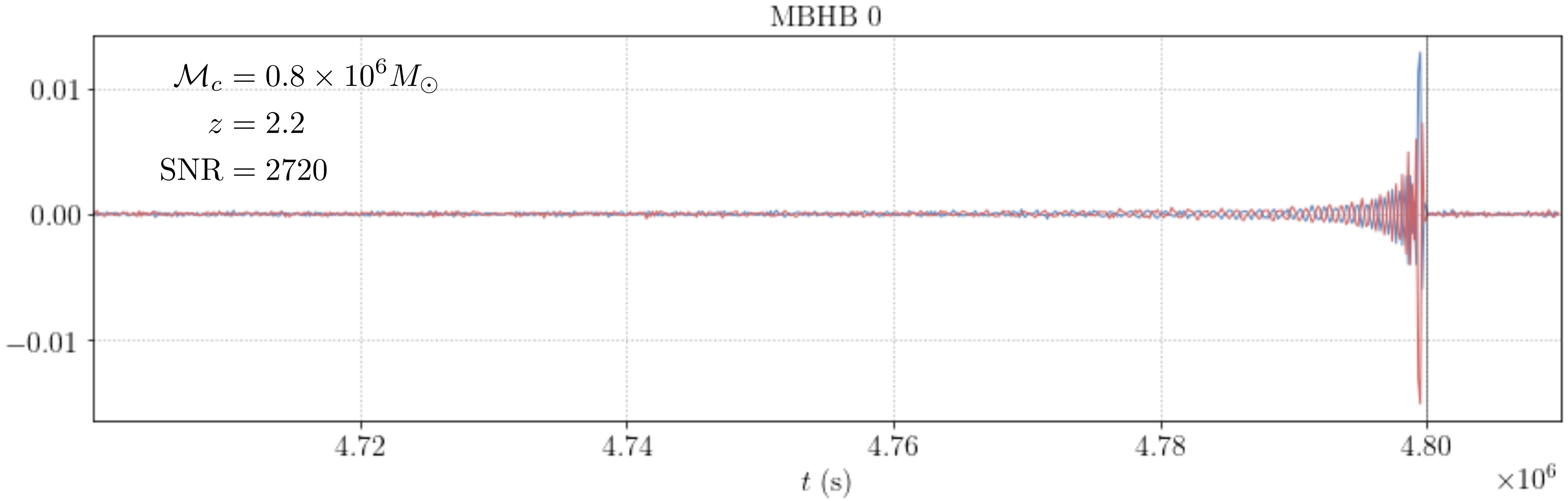
Data gaps

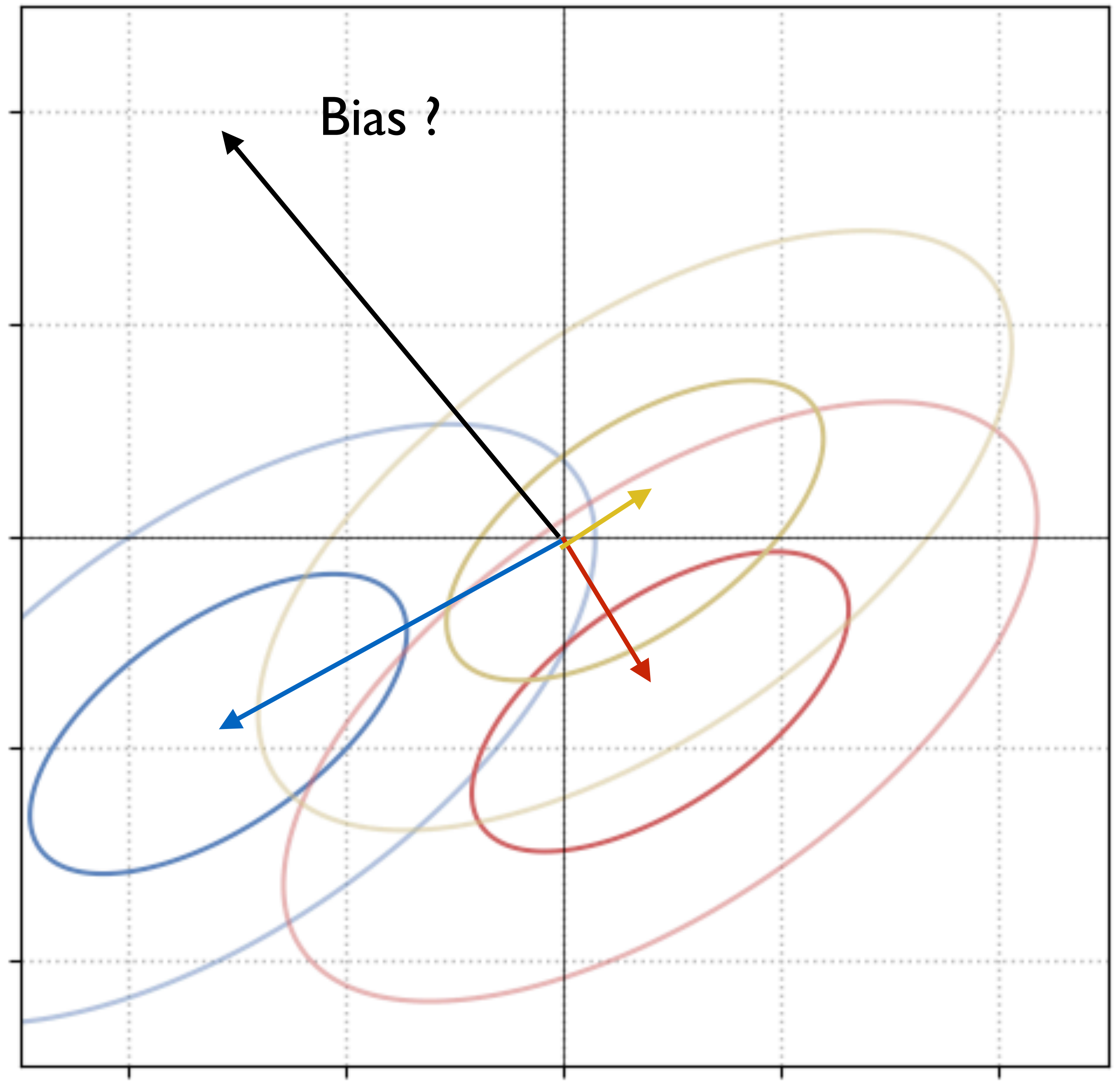
- Both scheduled and unscheduled
- Mask/taper data ?
- Inpainting methods ?



High-precision gravitational wave astronomy: waveform systematics ?







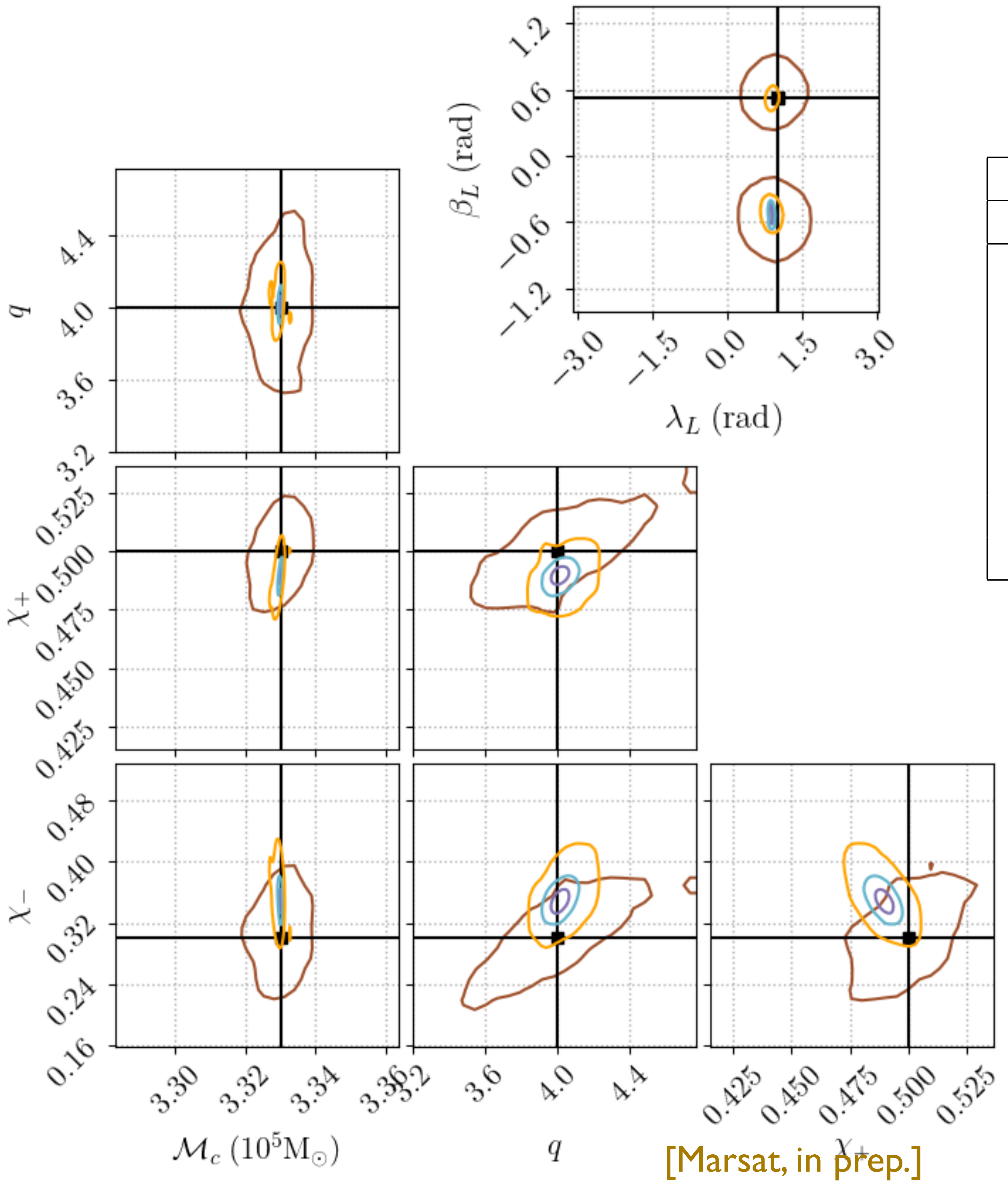
For different noise realizations:

- peak of the posterior moves around by the size of the statistical errors
- width of posterior unaffected (in this approx.)

$$h_{\rm model} = h_{\rm GR} + \delta h$$

- For very strong signals, width of posteriors shrinks like 1/ SNR
- The best-fit parameters for the model are **biased** from the true values
- Does this bias become larger that statistical errors ?

MBHB waveform systematics: intrinsic parameters



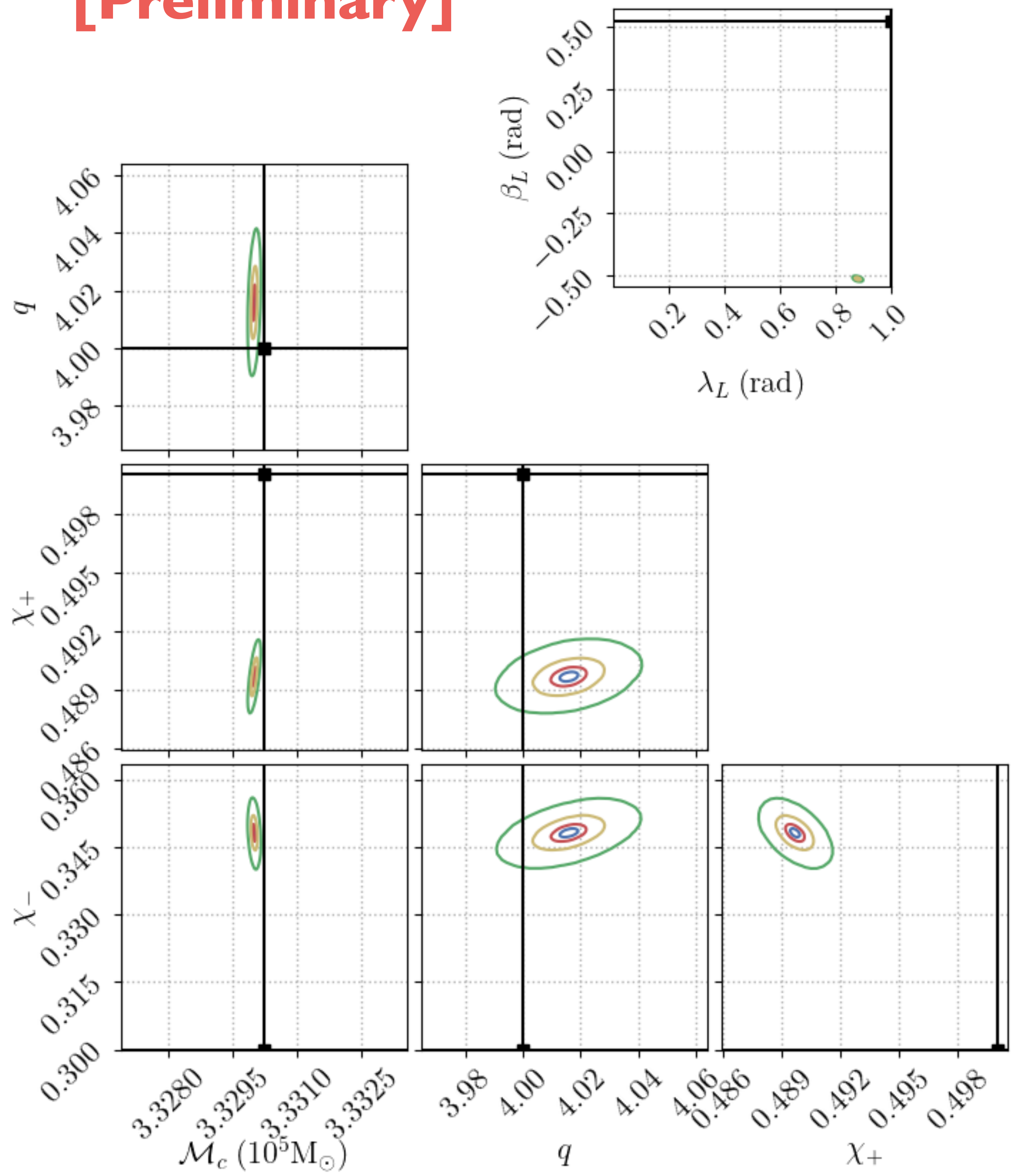
[Marsat, in prep.]

- Injection: NRHybSur3dq8
- Template: PhenomXHM

$M_z = 10^6\ M_\odot$	
z	SNR
0.32	7610
0.57	3804
1.0	1902
1.76	951
3.11	475
5.59	237
10.21	118
18.97	59

- Current waveform models are insufficient for LISA signals
- Waveforms may have to include waveform errors, to be marginalized

[Preliminary]



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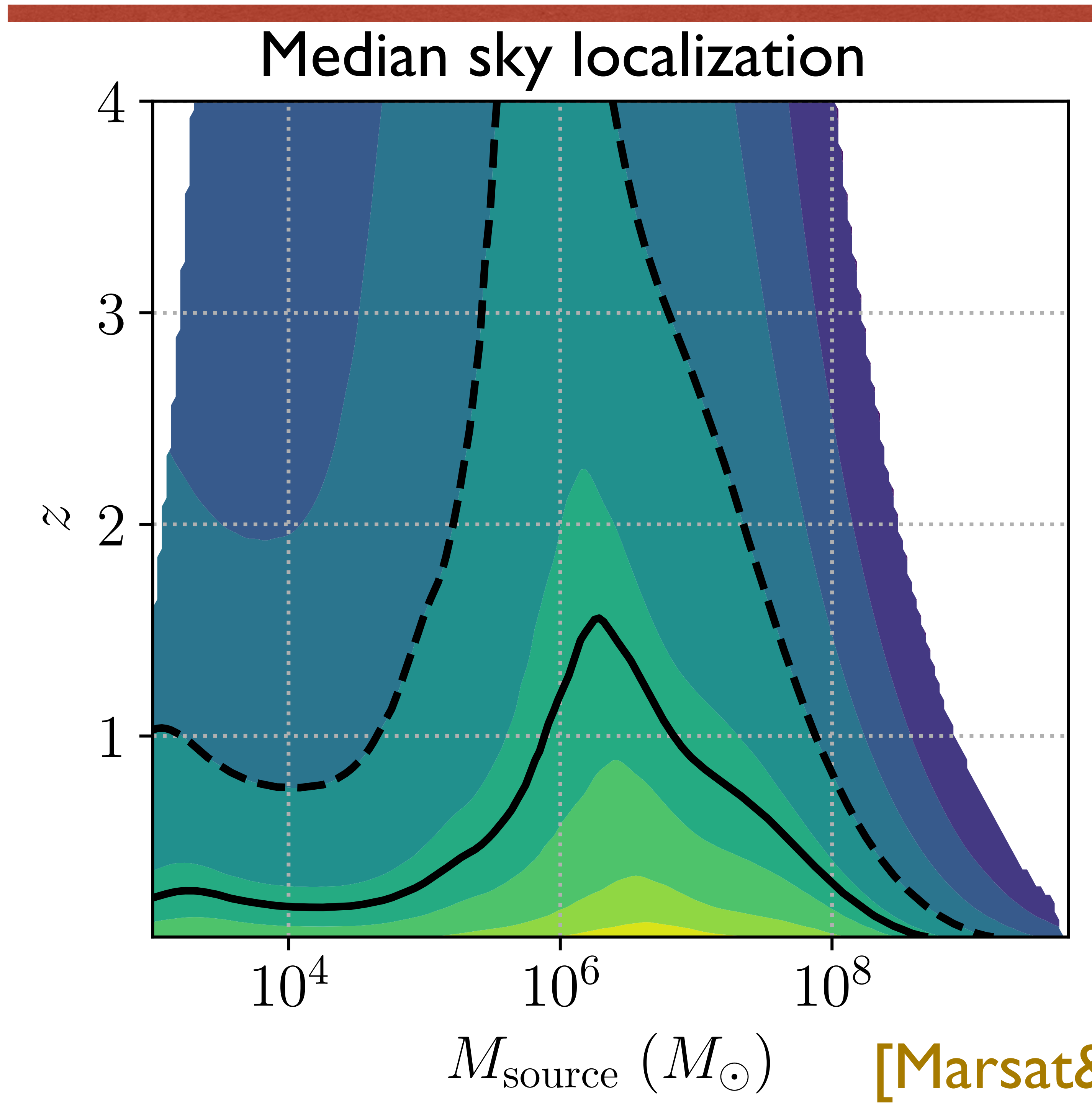
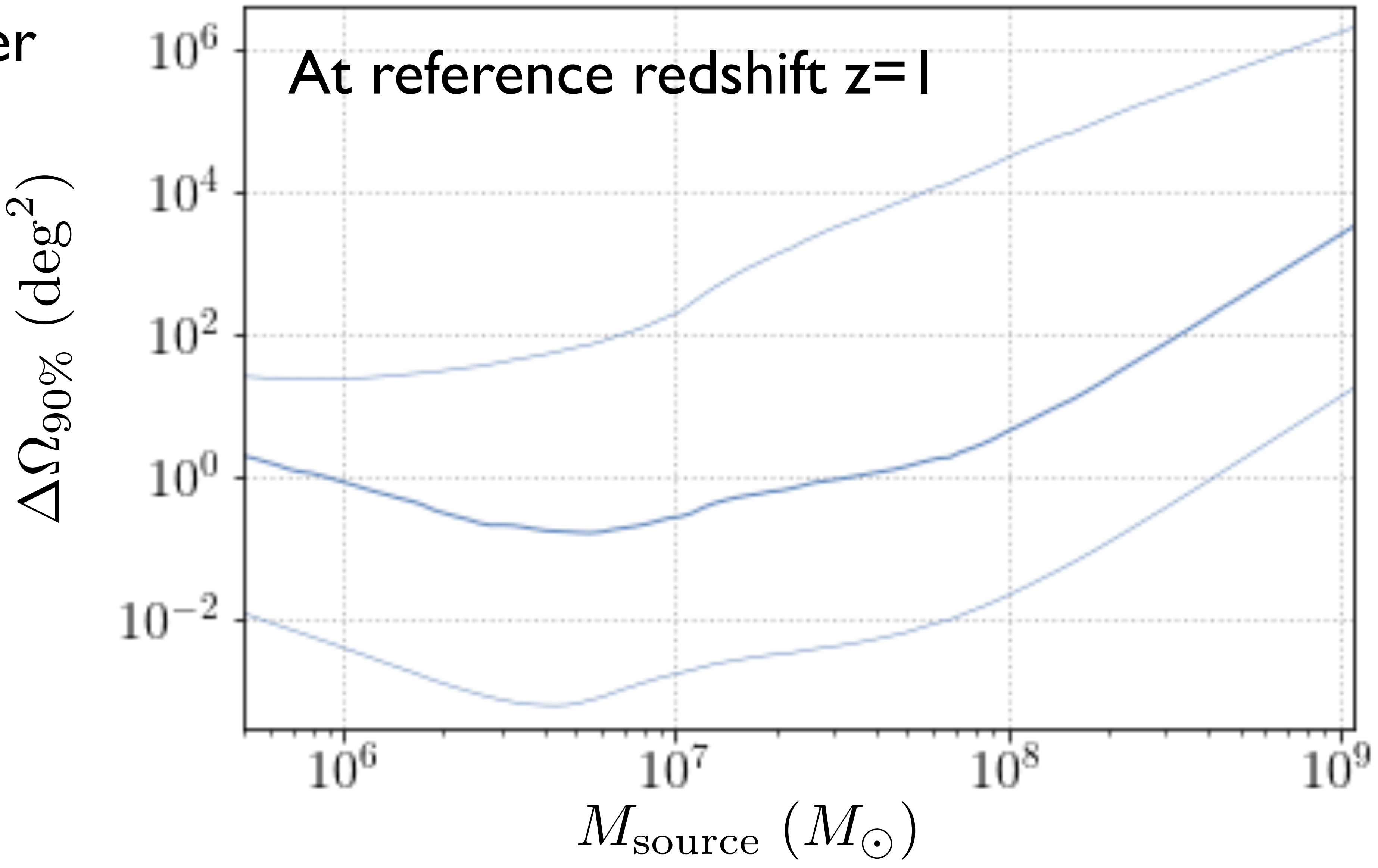
MBHB sky localization at merger

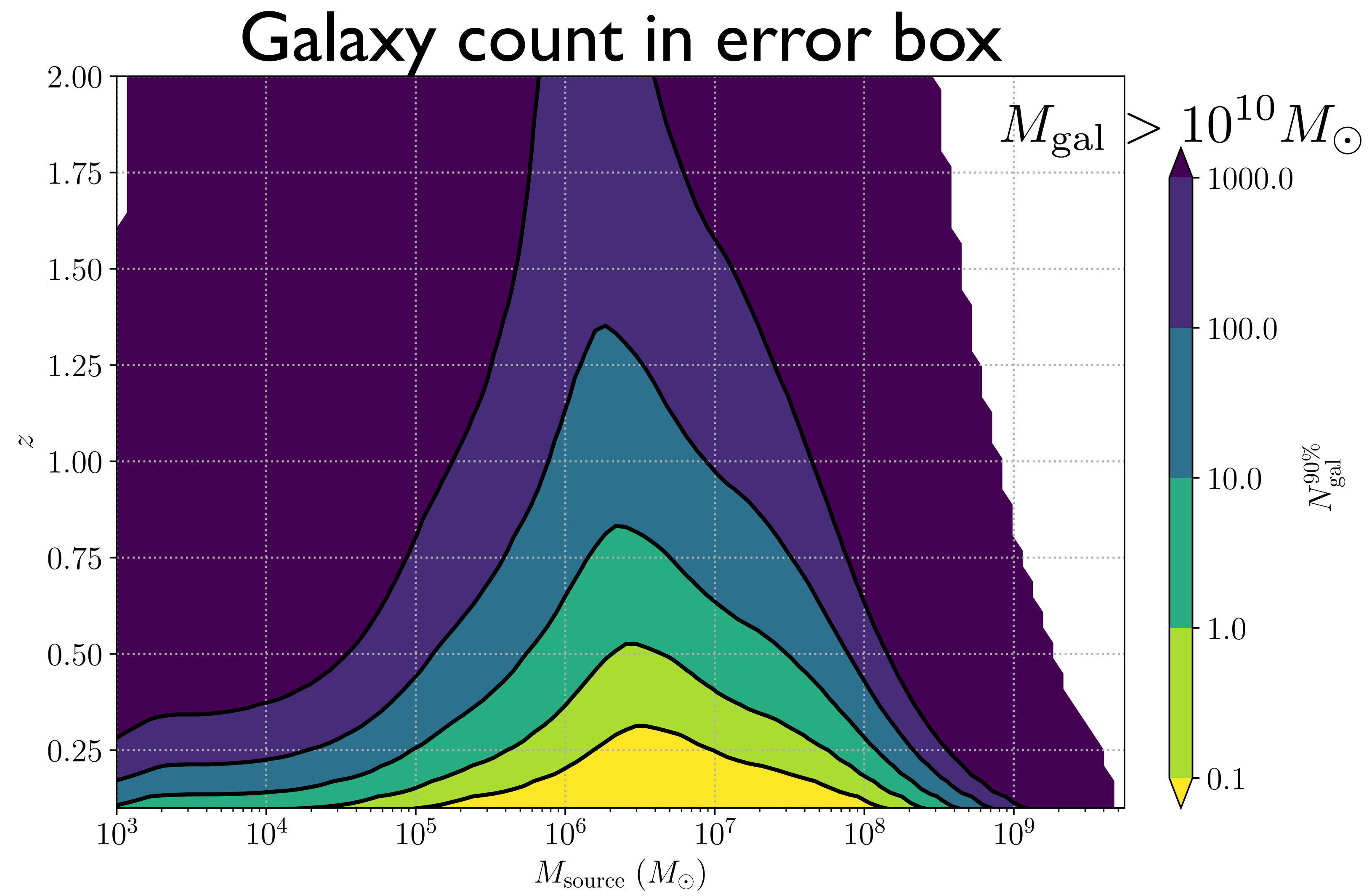


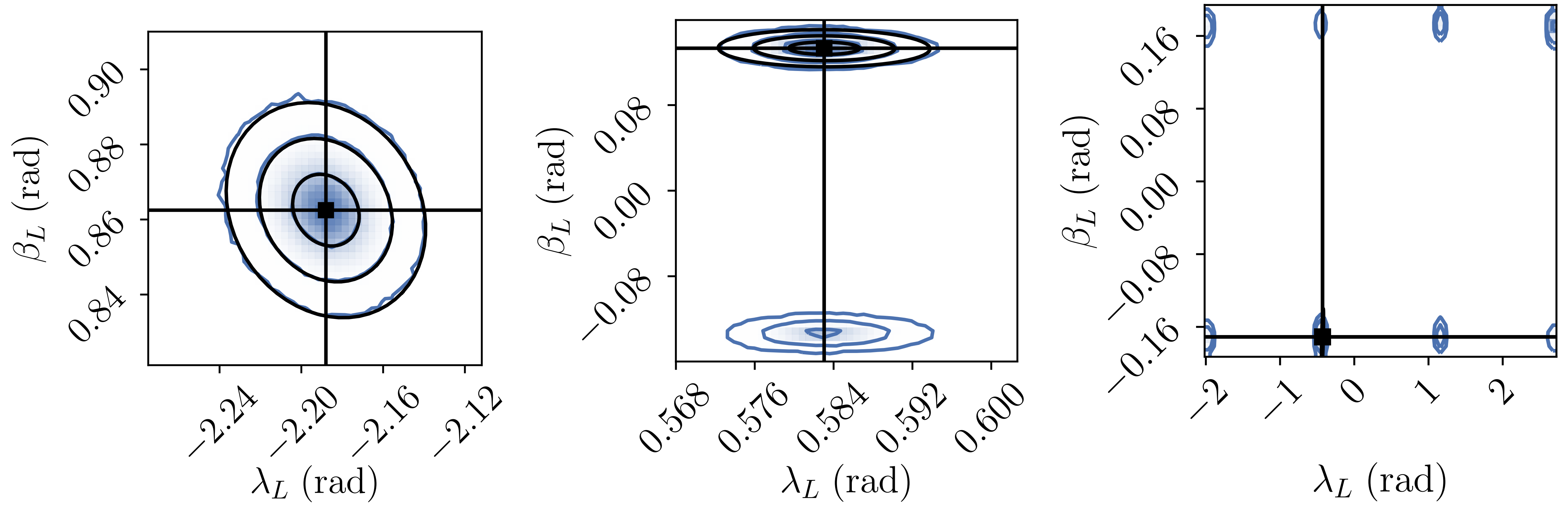
- - 10 sq. deg. : LSST field of view
— 0.4 sq. deg.: Athena Wide Field Imager



Large variations of sky localization depending on orientation

[Marsat&al, in prep.]





Sky multimodality (< 8 modes) is also possible at moderate z

Pre-merger localization: can we locate the source in advance ?

LISA-EM synergy ?

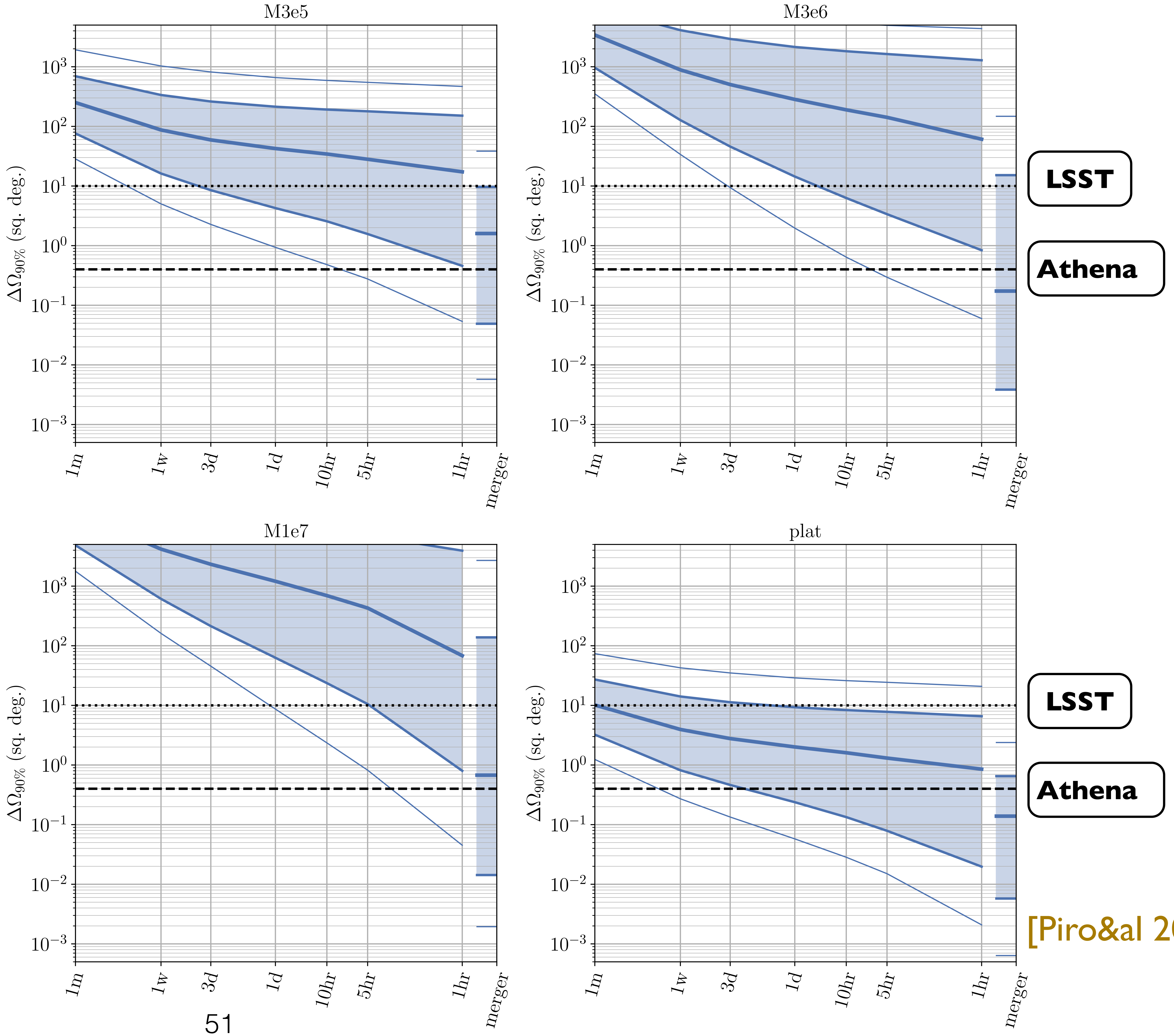
- 10 sq. deg. : LSST field of view
- 0.4 sq. deg.: Athena Wide Field Imager

Fisher matrix, sky area of main mode of the posterior (+MCMC full PE on a subset)

Only a 'platinum' system (M=1e5, z=0.3) can be localized well in advance of the merger

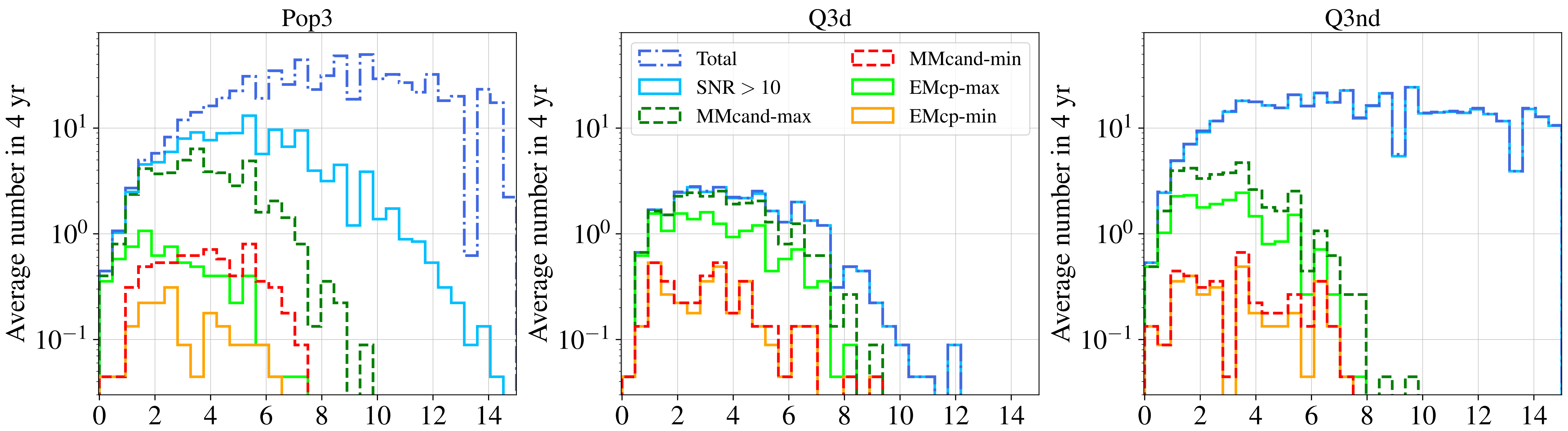
Advance localization challenging, much better post-merger

Large dispersion in sky area, ~4 orders of magnitude

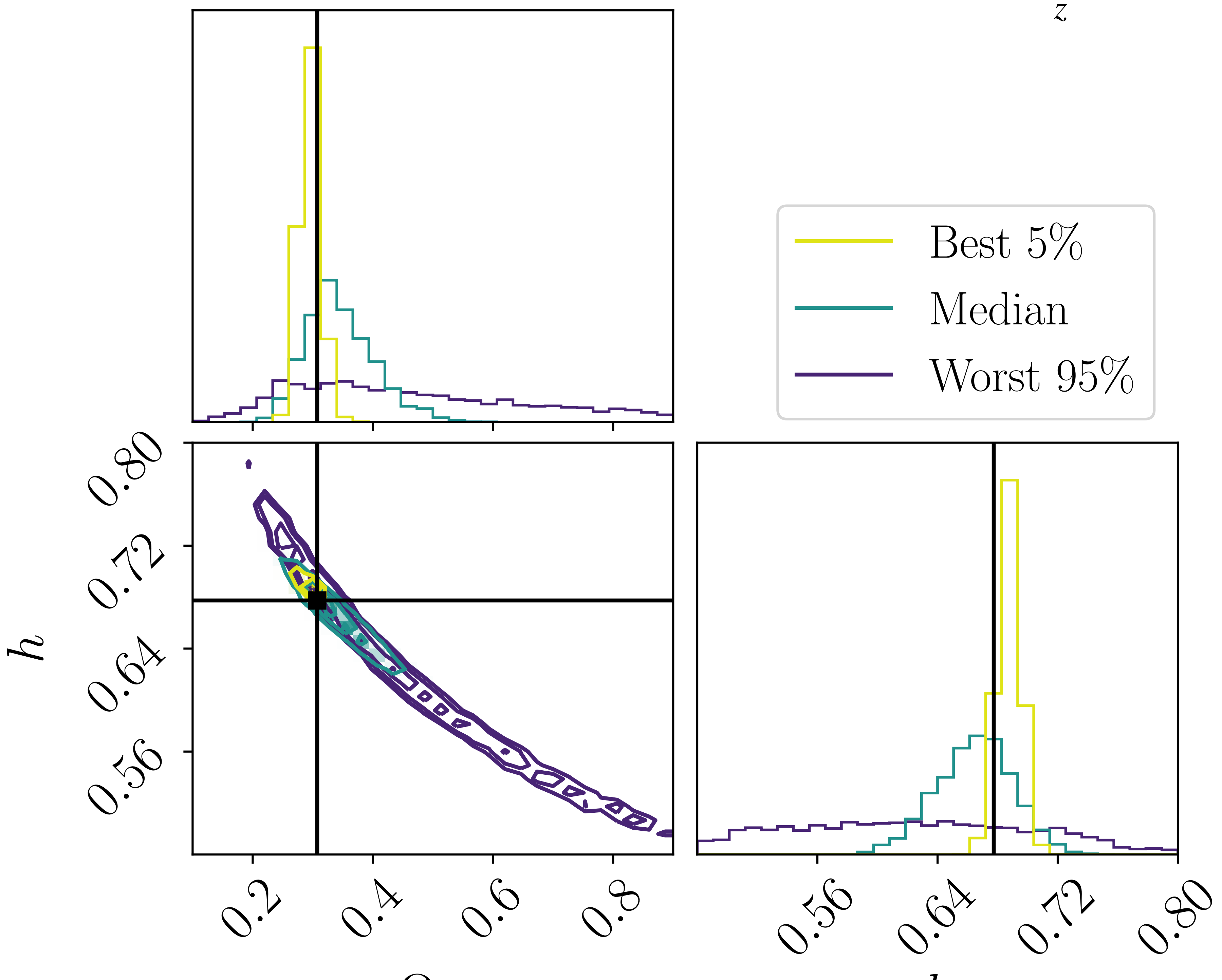


[Piro&al 2022]

Gravitational wave cosmology with LISA MBHBs

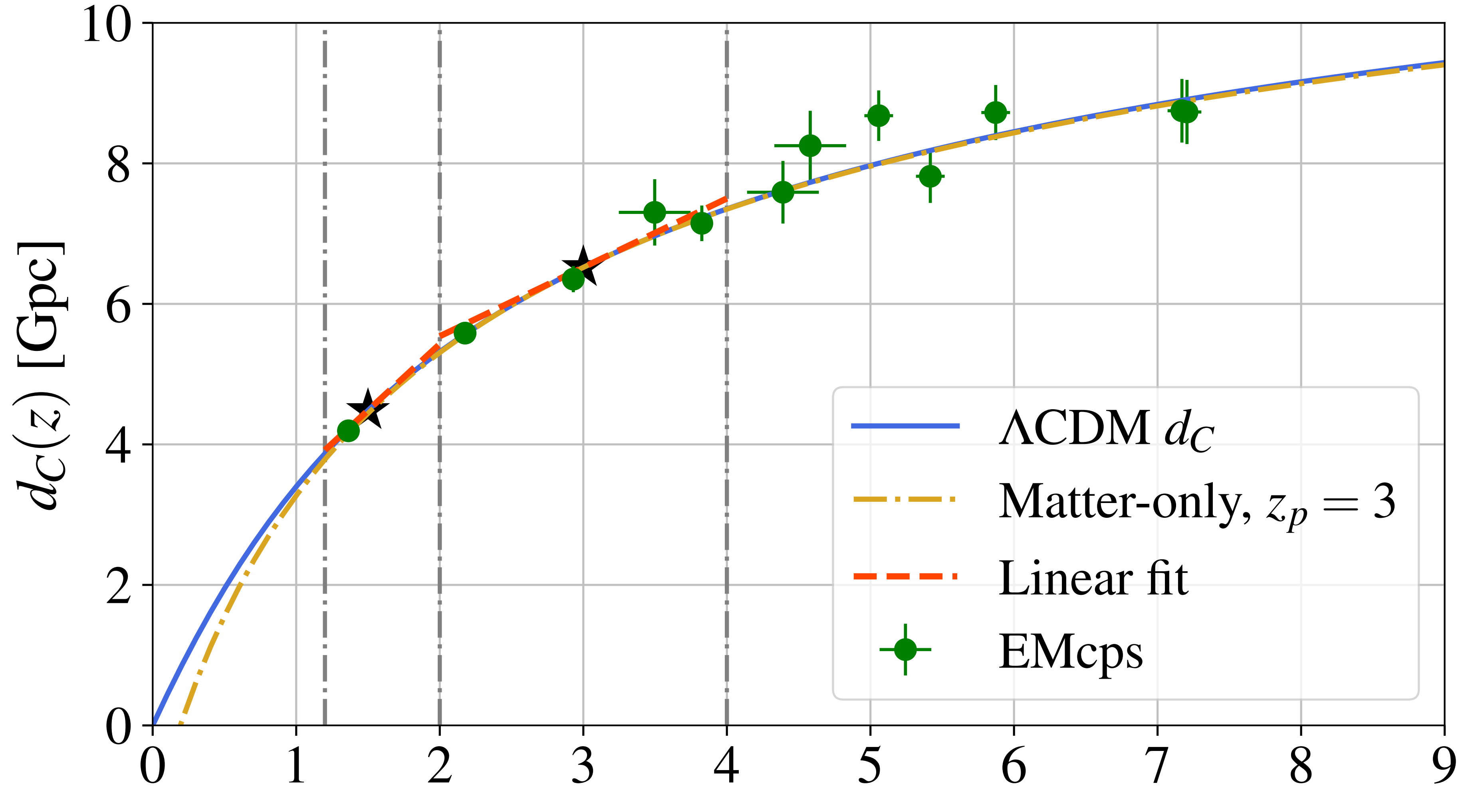


[Mangiagli&al 2022]



[Mangiagli&al 2023]

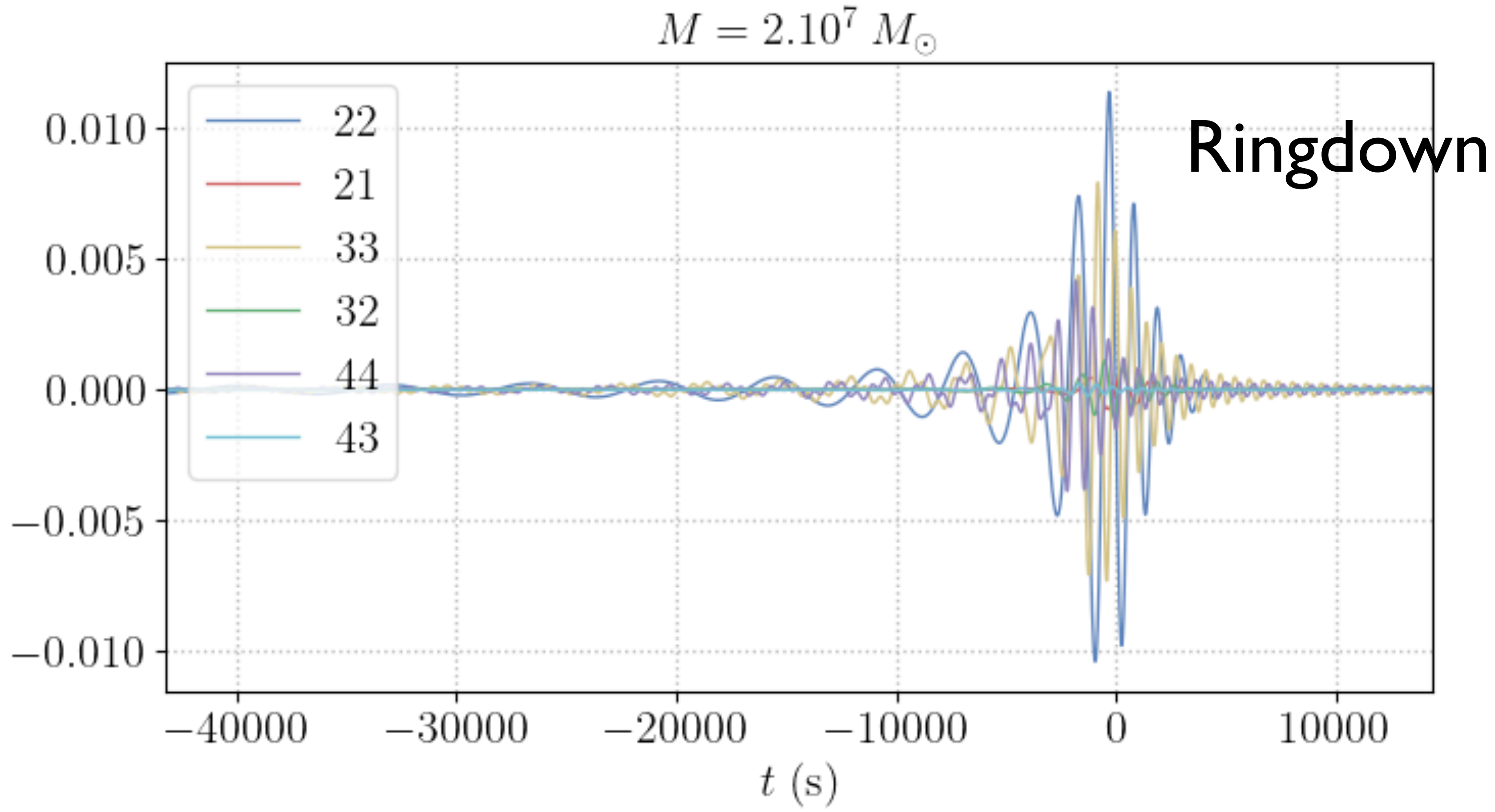
Still preliminary:
variability, confusion
Better emission models
needed



[Mangiagli&al 2023]

LISA standard sirens would be few, but could provide high-z information

Black hole Ringdown Spectroscopy with LISA



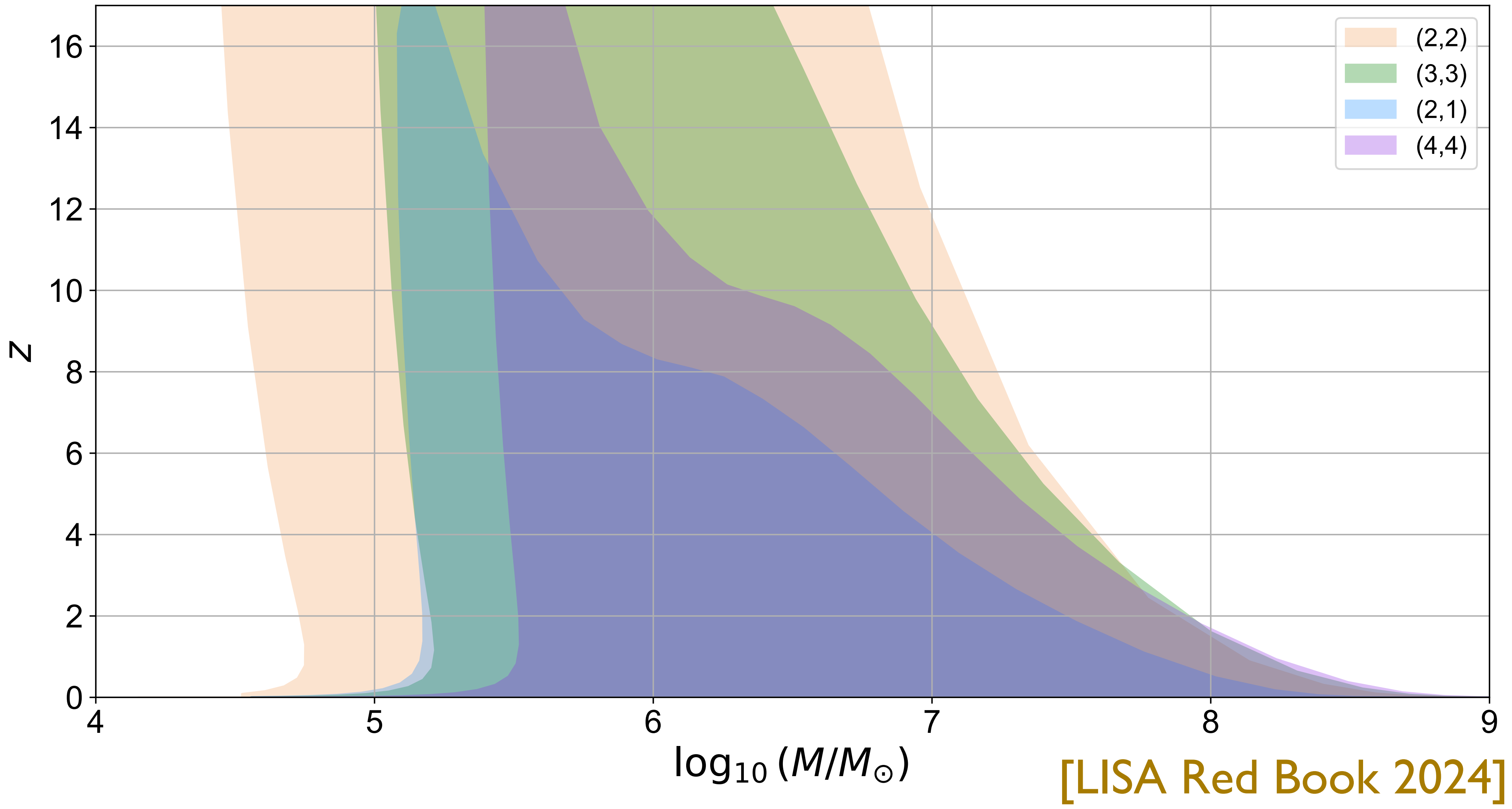
Ringdown signal: superposition of Qasi-Normal Modes

$$h \sim \sum_{\ell,m,n} A_{\ell m n} e^{-t/\tau_{\ell m n}} e^{i\omega_{\ell m n} t}$$

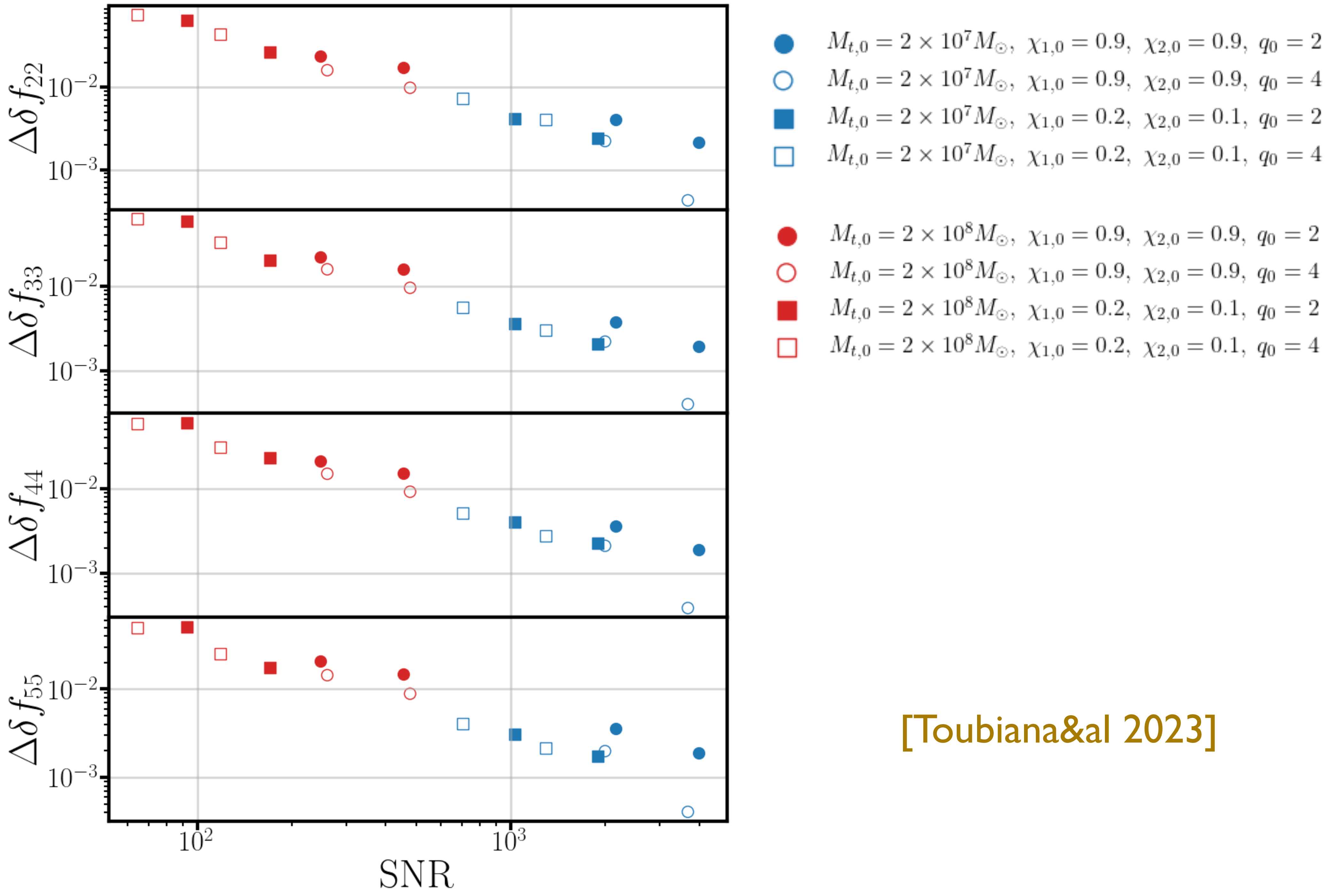
The frequencies and damping times are all functions of (M_f, χ_f) the mass and spin of the remnant
Signature of GR !

The measurement of more than one QNM allows to test the nature of black holes

LISA horizon (SNR=8) of individual QNMs

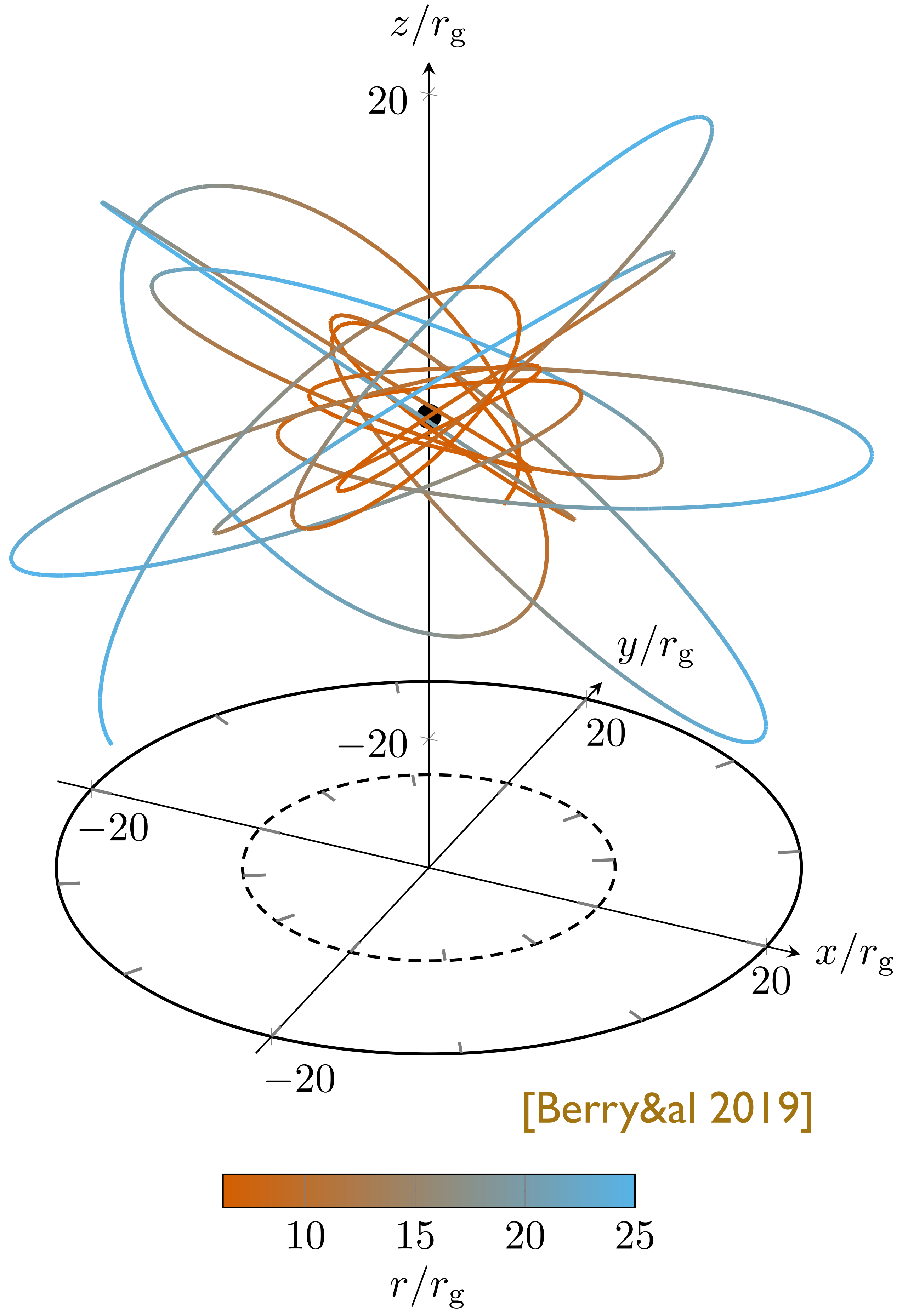


[LISA Red Book 2024]

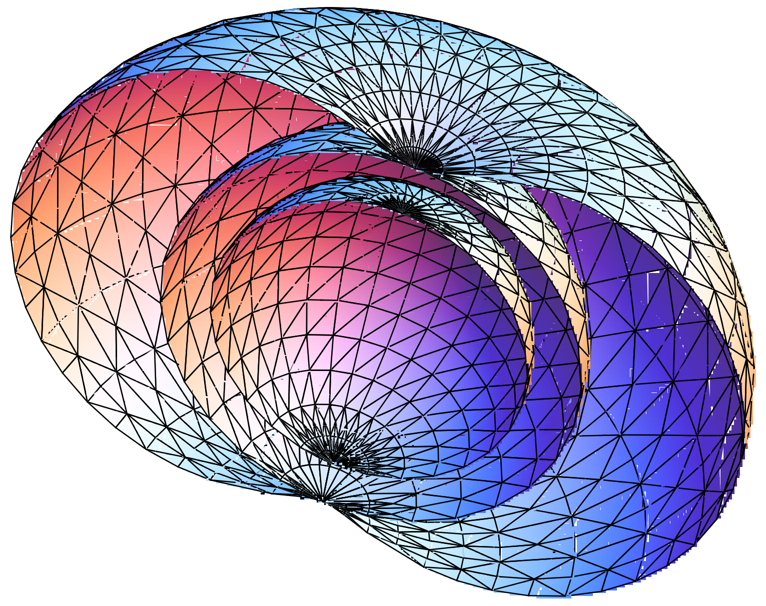


[Toubiana&al 2023]

EMRIs as probes of the BH spacetimes



[Berry&al 2019]



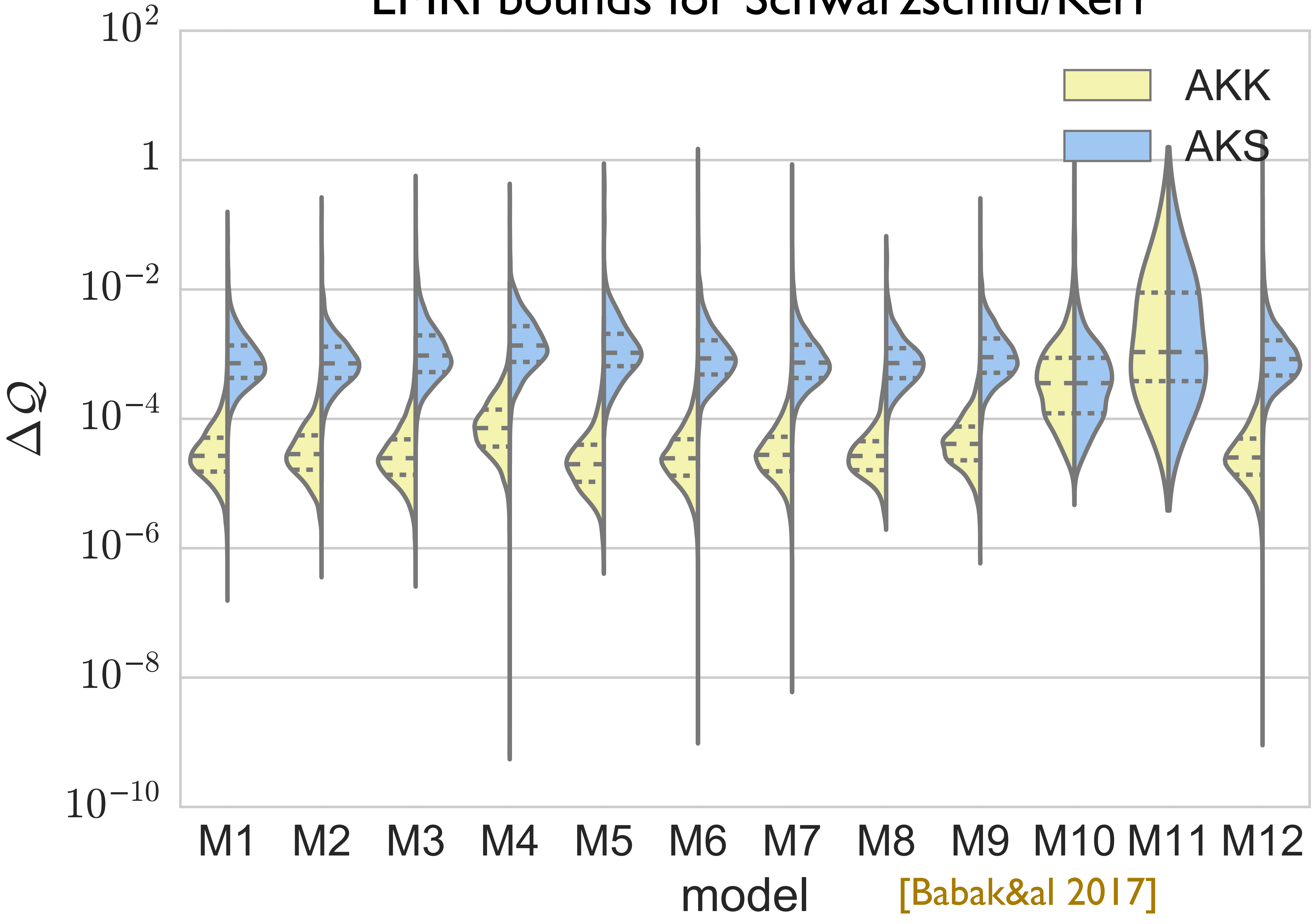
Kerr spacetime multipolar structure:

$$M_l + iS_l = M(ia)^l$$

In particular, spin-induced quadrupole Q(a)

Can test for a deviation of Q (simulated with approximate waveforms so far)

EMRI bounds for Schwarzschild/Kerr



[Babak&al 2017]

Current LVK bounds: ~few units

EMRI signals can probe deep into the structure of the Kerr spacetime