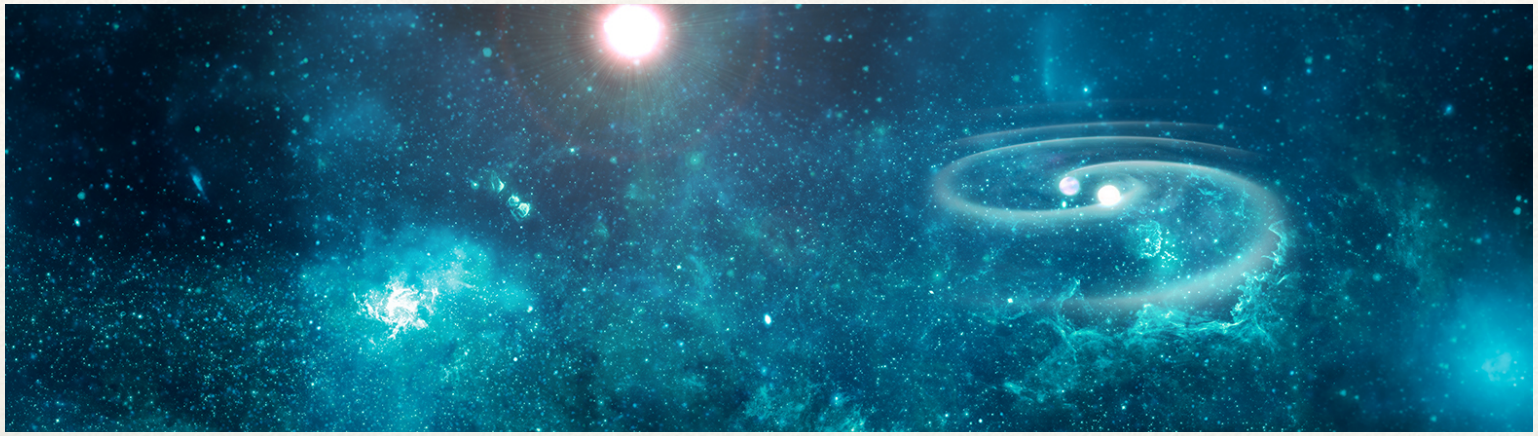
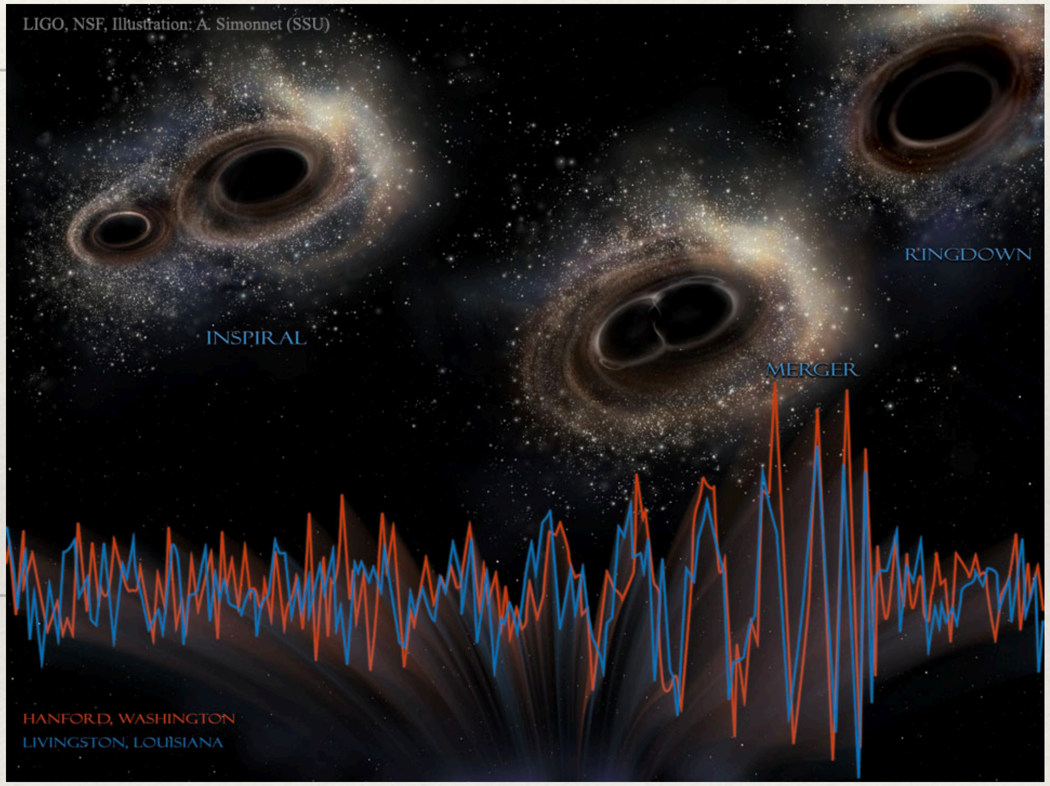
Stanislav (Stas) Babak.
AstroParticule et Cosmologie, CNRS (Paris)

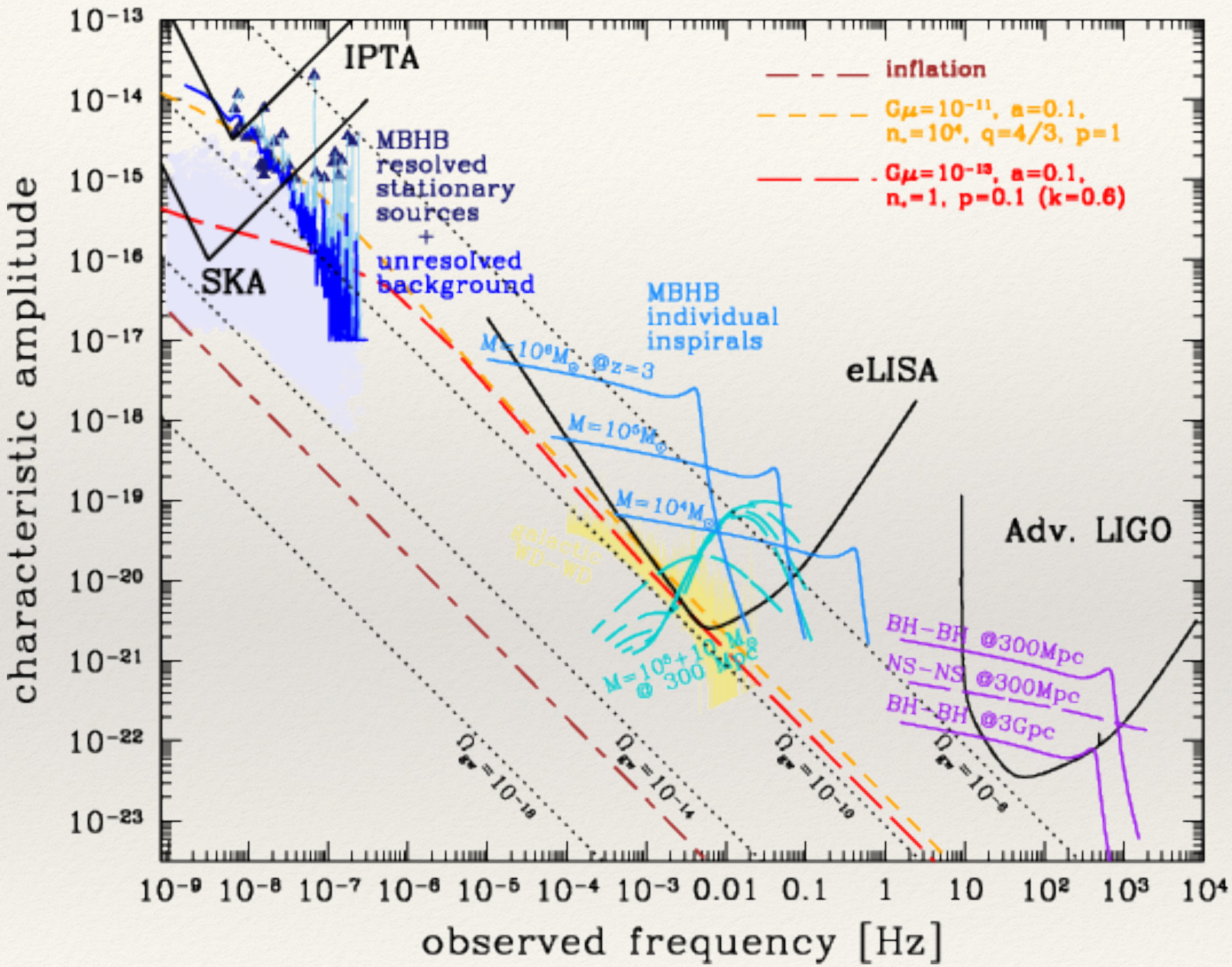


LISA: detecting gravitational waves from space.



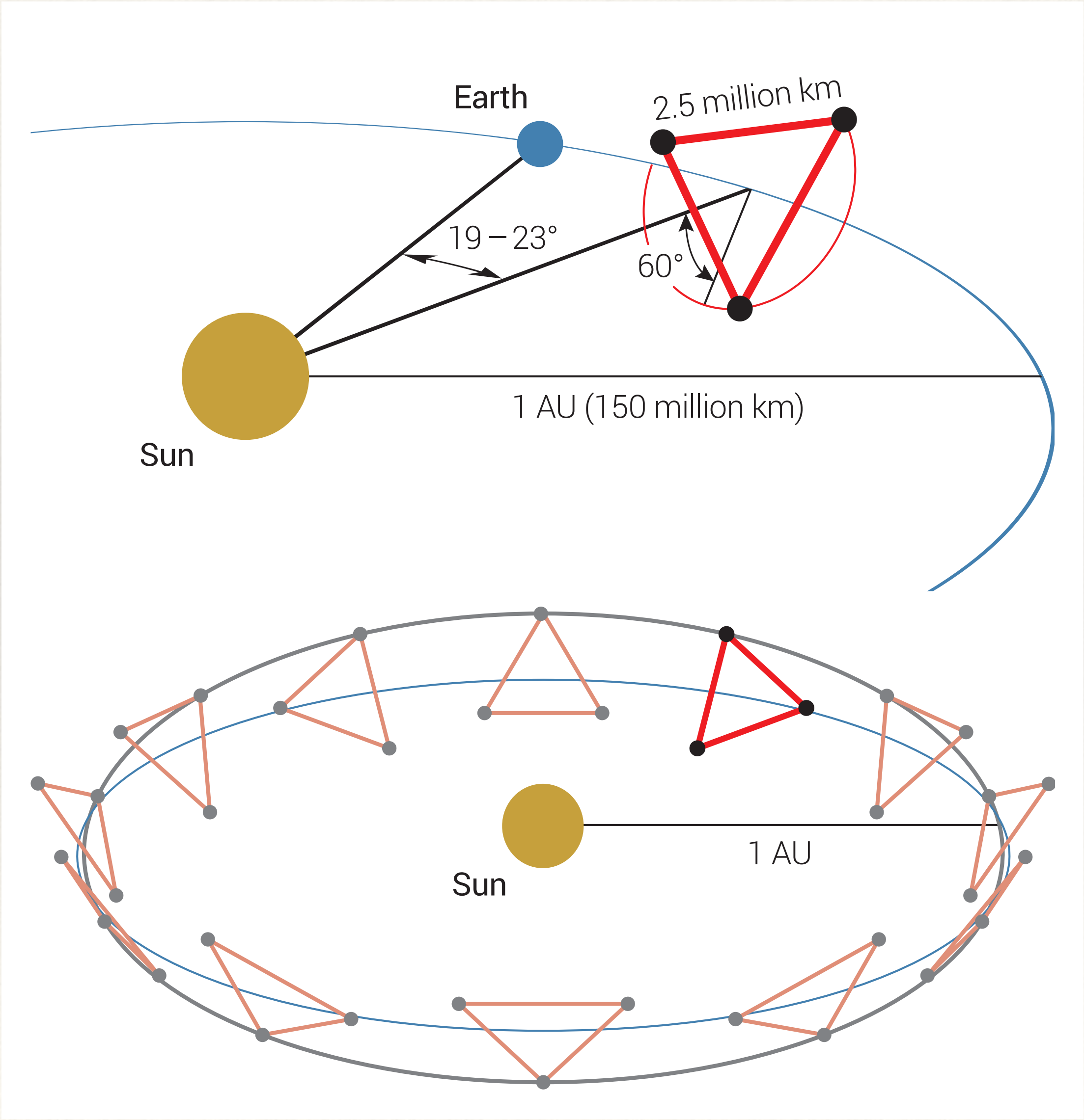
ISAPP, 7-17 June 2021

GW landscape

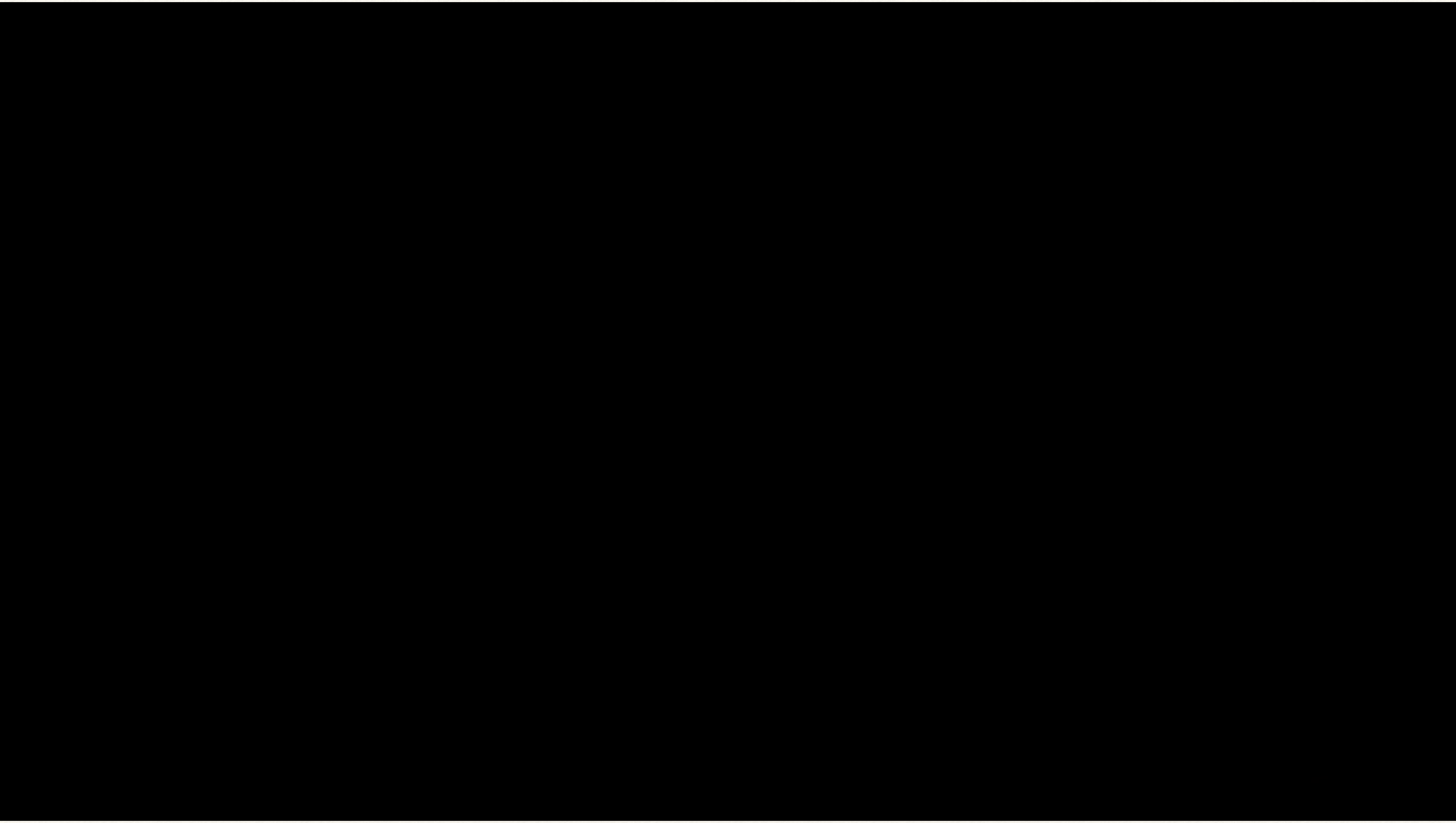


LISA: Laser Interferometric Space Antenna

- LISA: GW observatory in space: The launch date 2034. Leading by European Space Agency.
- LISAPathfinder - Technological mission to prove the technical readiness of LISA - fantastic results, order of magnitude better than minimum requirement

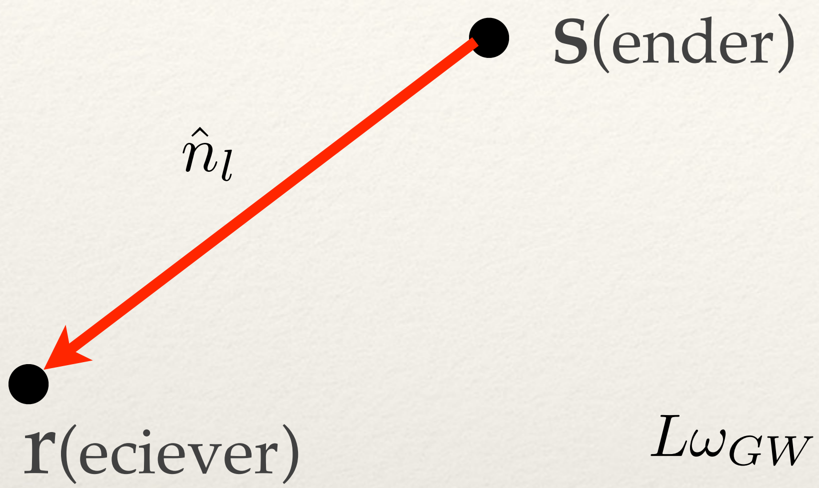


LISA (cartoon) - LISA as it was before 2010



LISA

Principle of measurement



LISA: three satelites in free falling orbits around the sun, constellation forms equelateral triangle

L1~L2~L3= 2.5 mln. km.

Operates in freq. range 0.1 mHz - 0.1 Hz.

Exchange laser light - measurement of the proper distance between satelites .

$L\omega_{GW} = 1 \quad \to \; f_{GW} \approx 20 mHz$ Long wavelength is not applicable

We cannot cover the detector by LIF, use “TT” frame: in this frame GW can be seen as affecting the phase (or frequency) of the laser light.

$$\frac{\Delta\nu}{\nu_0} = \frac{n_l^i n_l^j \Delta h_{ij}}{2(1 - \hat{k}.\hat{n}_l)}$$

Change in laser freq. due to GWs → $\Delta\nu$

unperturbed freq. of a laser → ν_0

$\Delta h^{ij} = h^{ij}(t_s) - h^{ij}(t_r)$ → Δh_{ij}

direction of GW propagation → $\hat{k}$

$$t = t_r, \;\; t_s = t - |\vec{R}_r(t) - \vec{R}_s(t_s)| \approx t - |\vec{R}_r(t) - \vec{R}_s(t)| \approx L_l$$

Detection of GWs in TT-frame

$$\lambda^{GW} \approx L, \quad \omega_{GW} L \approx 1$$

We cannot set the LIF covering the whole detector, but we can introduce LIF for the background curvature . This is the case for LISA and PTA. We use TT-gauge:

$$g_{\mu\nu} = \eta_{\mu\nu} + h^{TT}_{\mu\nu} + O(h^2)$$

Consider the wave propagating in z-direction

$$ds^2 = dt^2 + [1 + h_+(t - z)]dx^2 + [1 - h_+(t - z)]dy^2 + dz^2$$

Mirrors are moving along geodesics. In TT frame the coordinate distance does not change (but the proper distance does) $d\hat{x}^2 = g_{xx}dx^2$

Need to consider equation of propagation of e/m signal $g^{\alpha\beta}\phi^l_{,\alpha}\phi^l_{,\beta} = 0$

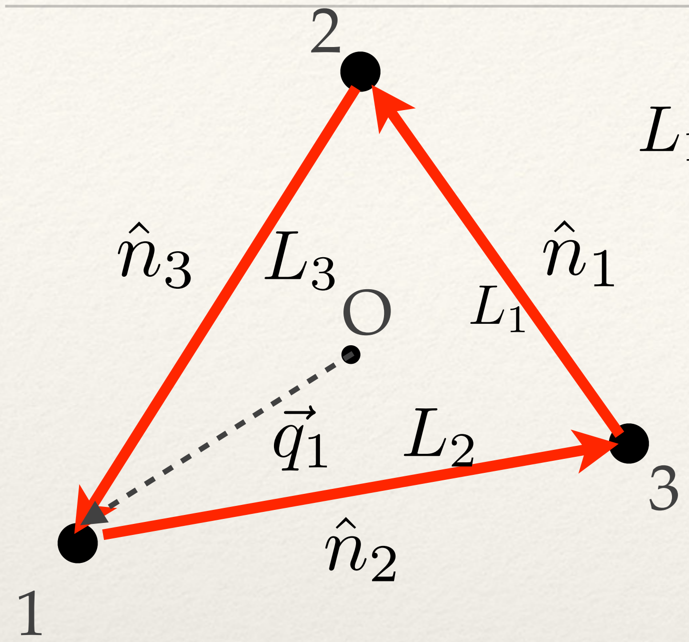
The phase difference for the round trip is

$$\Delta\phi_l = \phi_l|_x - \phi_l|_y = -\nu_l \left[-2(L^{(0)}_x - L^{(0)}_y) + \frac{1}{2}H(t - 2L^{(0)}_x) + \frac{1}{2}H(t - 2L^{(0)}_y) - H(t) \right]$$

$$H(t) = \int_0^t h(t')dt'$$

$$\omega_{GW} L \ll 1 \longrightarrow \Delta\phi^l \approx 2\nu_l(L^{(0)}_x - L^{(0)}_y + L^{(0)}h_+(t))$$

LISA



$L_1 \approx L_2 \approx L_3 \approx L$ — but not exactly!

$\frac{\Delta\nu}{\nu_0} \to y_{slr}$ — for a single link

Consider GW signal from a binary system

$$y_{slr}^{GW} = -i\frac{\omega L}{2} A_l(\iota, \psi, \theta_s, \phi_s) e^{i\Phi(t-\hat{k}.\vec{R}_0)} e^{-i\omega\hat{k}.\vec{q}_r} Sinc\left[\frac{\omega L}{2}(1-\hat{k}.\hat{n}_l)\right] e^{-i\frac{\omega L}{2}(1-\hat{k}.\hat{n}_l)}$$

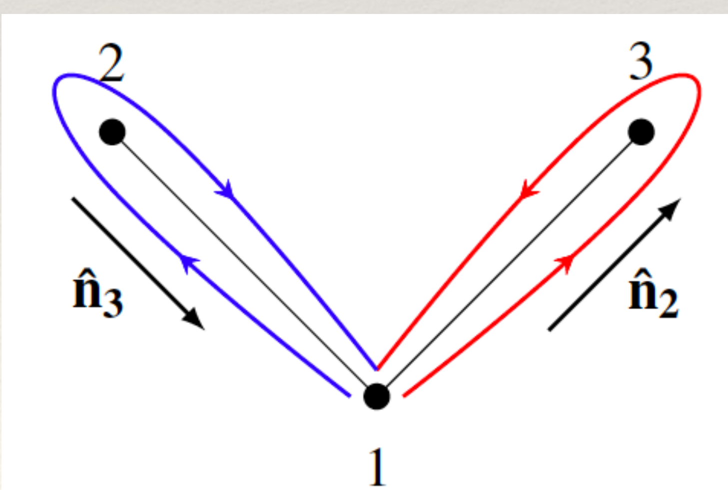
- A_l Amplitude of GW times antenna beam function
- Sinc — zero of sinc function gives freq. of GW signal which cannot be measured (f-n of sky position) - wiggles in the sensitivity at high frequencies
- Phase: $t - \hat{k}.\vec{R}_0(t)$ Doppler modulation (dominant) due to relative motion of the detector and the source

LISA

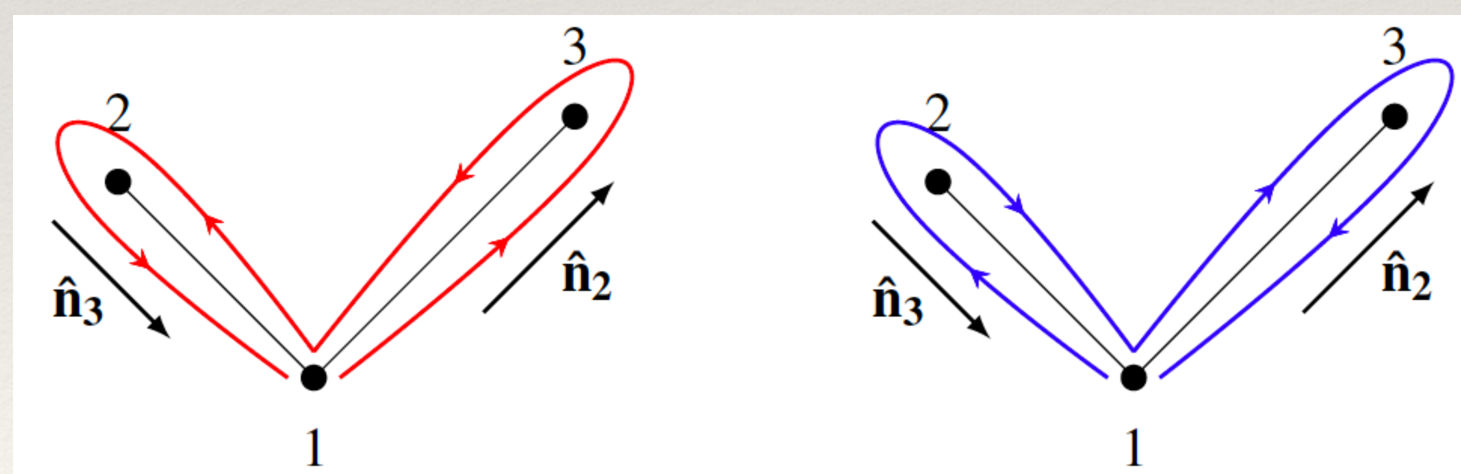
- The localization of the sources in the sky comes from the Doppler modulation of the phase and from the amplitude modulation (time dependent antenna beam f-n)
- The term(s) dependent on the position of each spacecraft explicitely (q-vectors): important at very high frequency: constellation "feels" GW propagation

- The biggest problem is the laser frequency noise: orders of magnitude higher than other noise sources

TDI — Time Delay Interferometry: technique which we apply to cancel the laser noise (in post-processing the data)



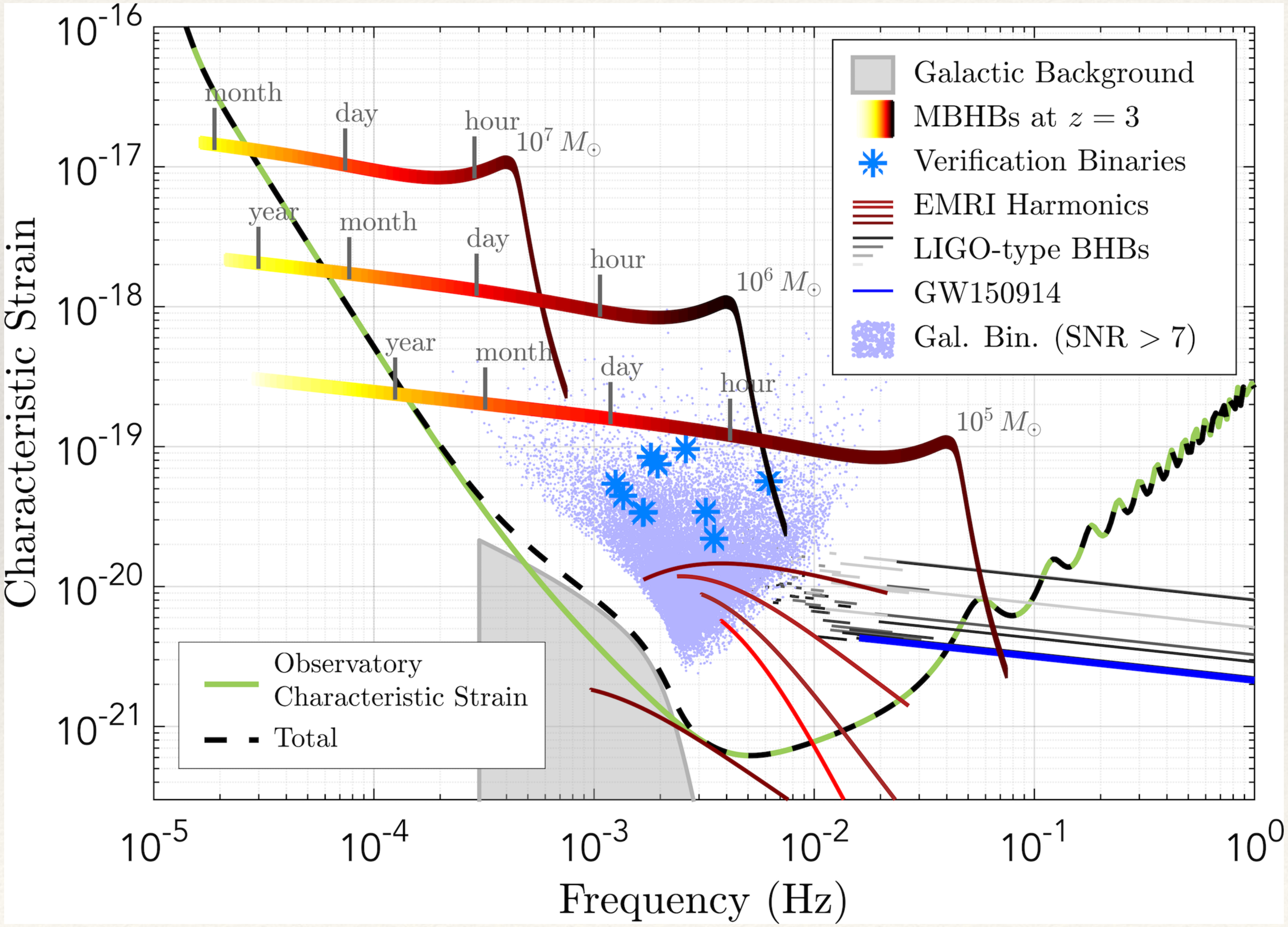
Equal arm Michelson



Unequal arm Michelson

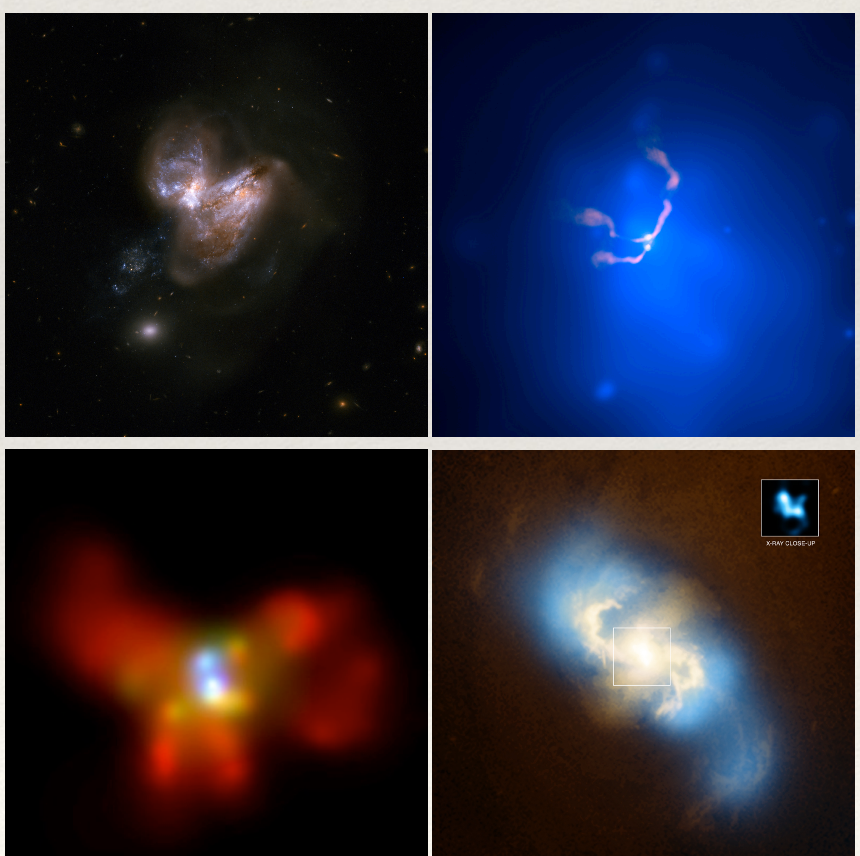
GW sources in LISA band

- GW signals in LISA are strong and long-lived.
- LISA data will contain thousands of GW signals simultaneously: need to separate and characterize them
- Non-stationary noise

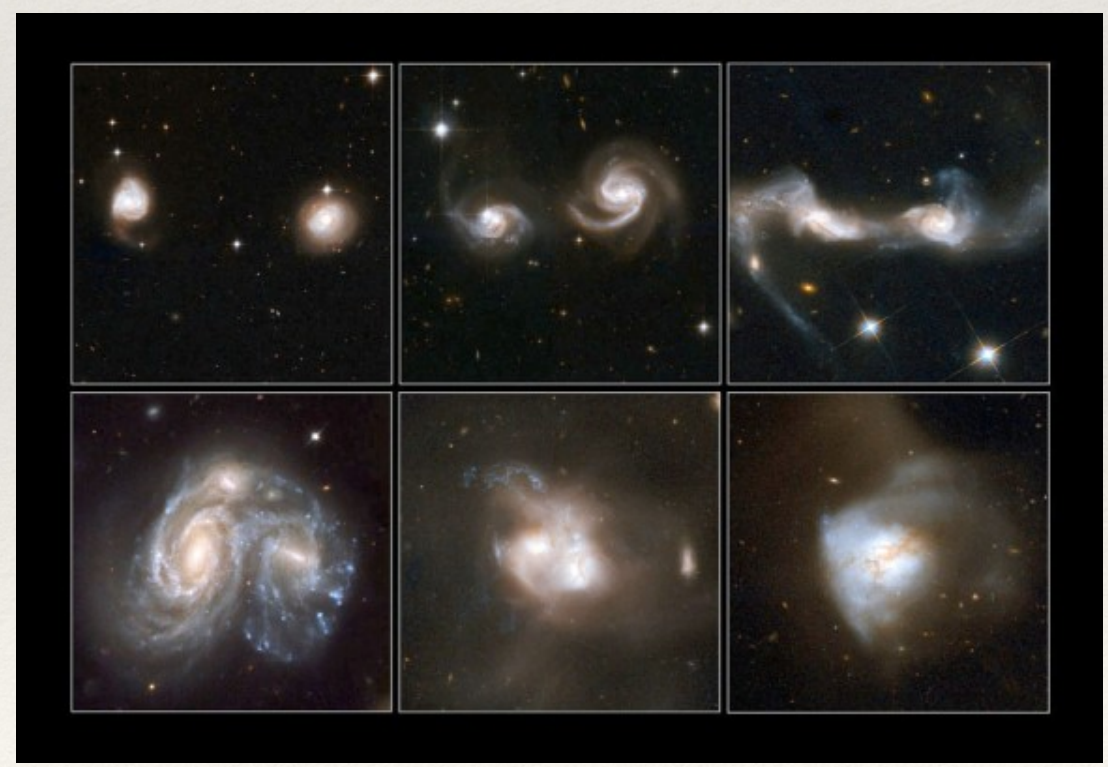


LISA sources

- We believe that all galactic nuclei host Massive Black Holes: Milky Way has 4 mln. solar mass BH
- Galaxies merge: we can form Massive Black Hole Binary (MBHB) system
- We need stars and gas to bring MBHs close together for GW to be efficient (binary is merging within Hubble time)



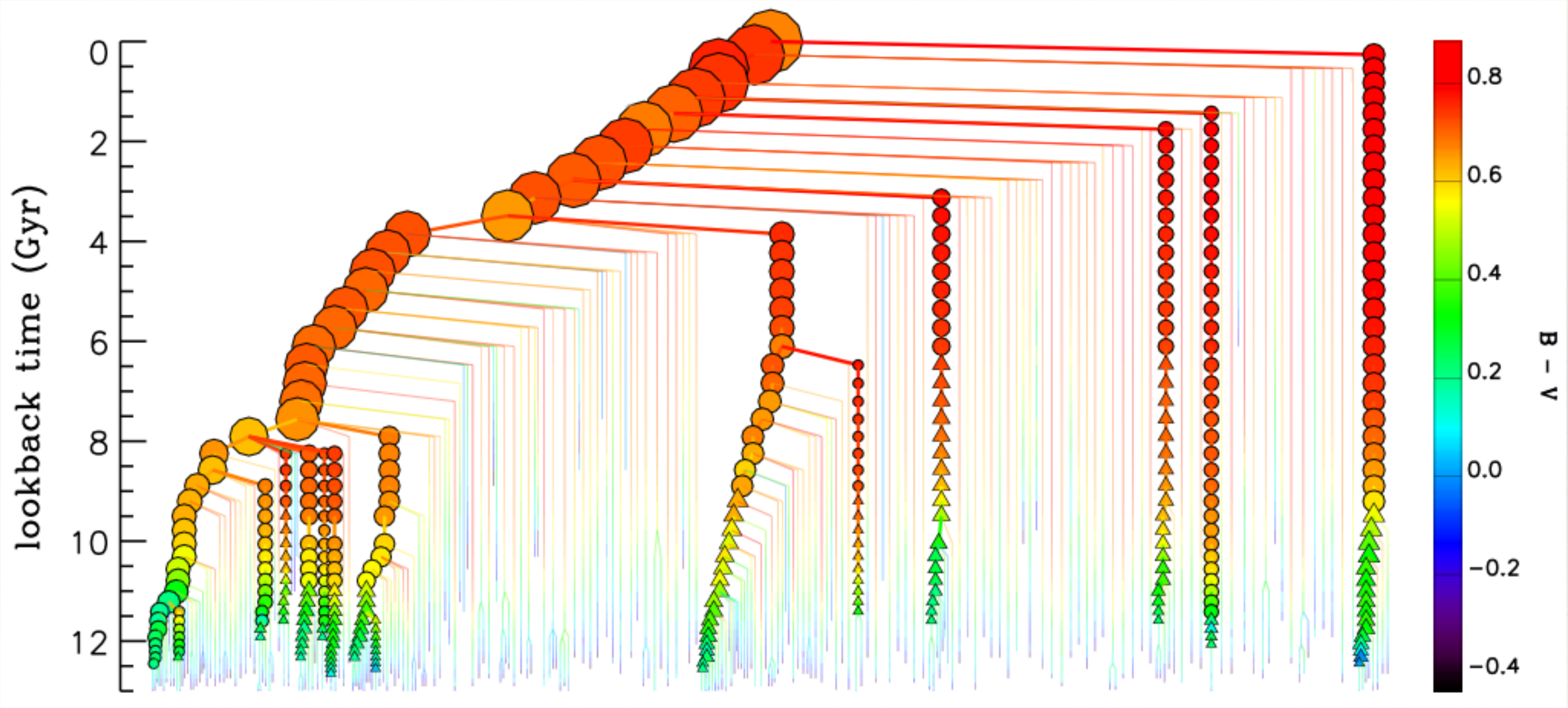
[Credits: Hassinger+, VLA, Chandra , NASA]



[Image: Hubble telescope]

LISA sources: MBHB

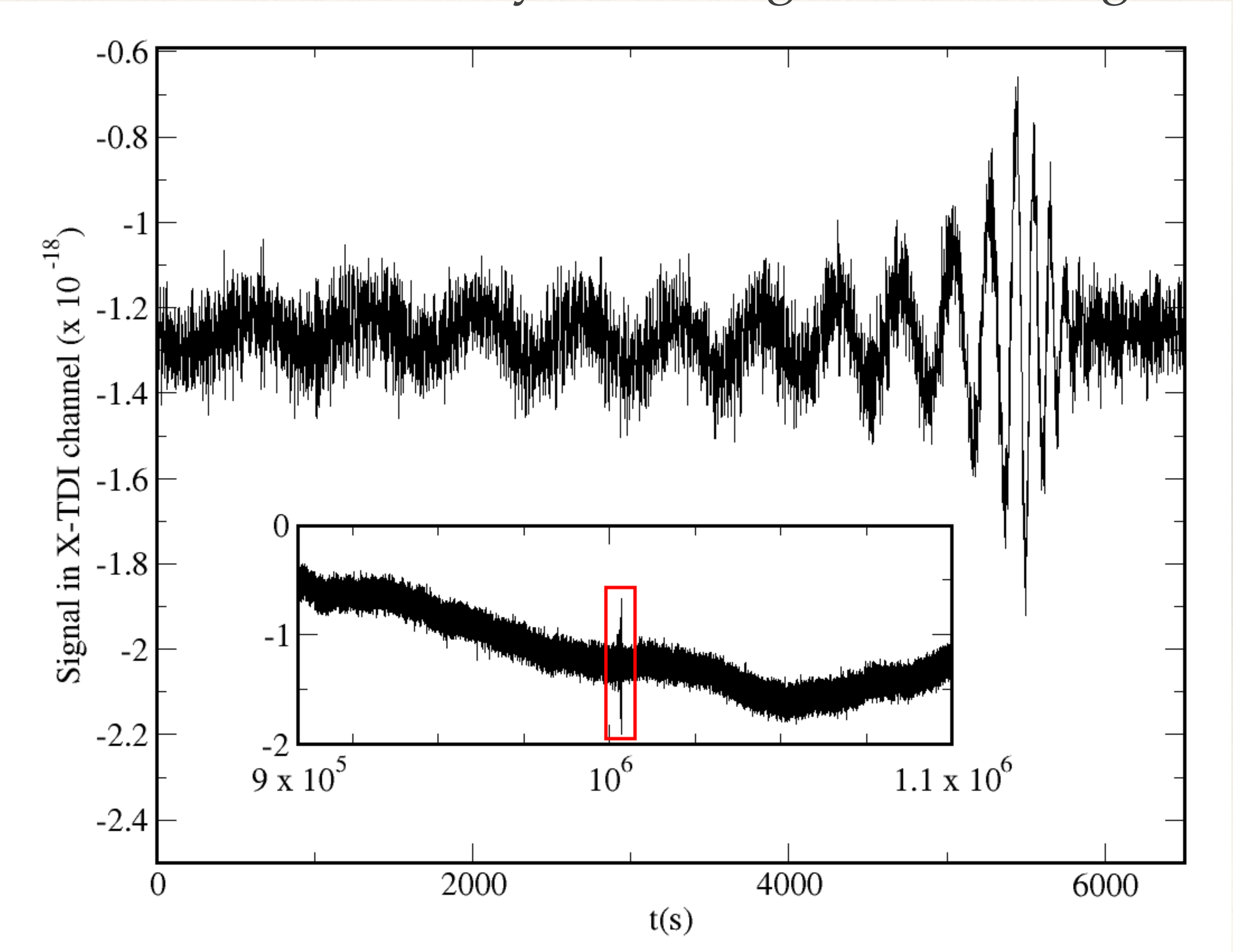
MBHs are formed from the initial BH seed. Those seeds could be "light" remnant of the first generation of stars or "heavy" from the direct collapse of a giant gas cloud. BHs accumulated the mas through gas accretion and merging.



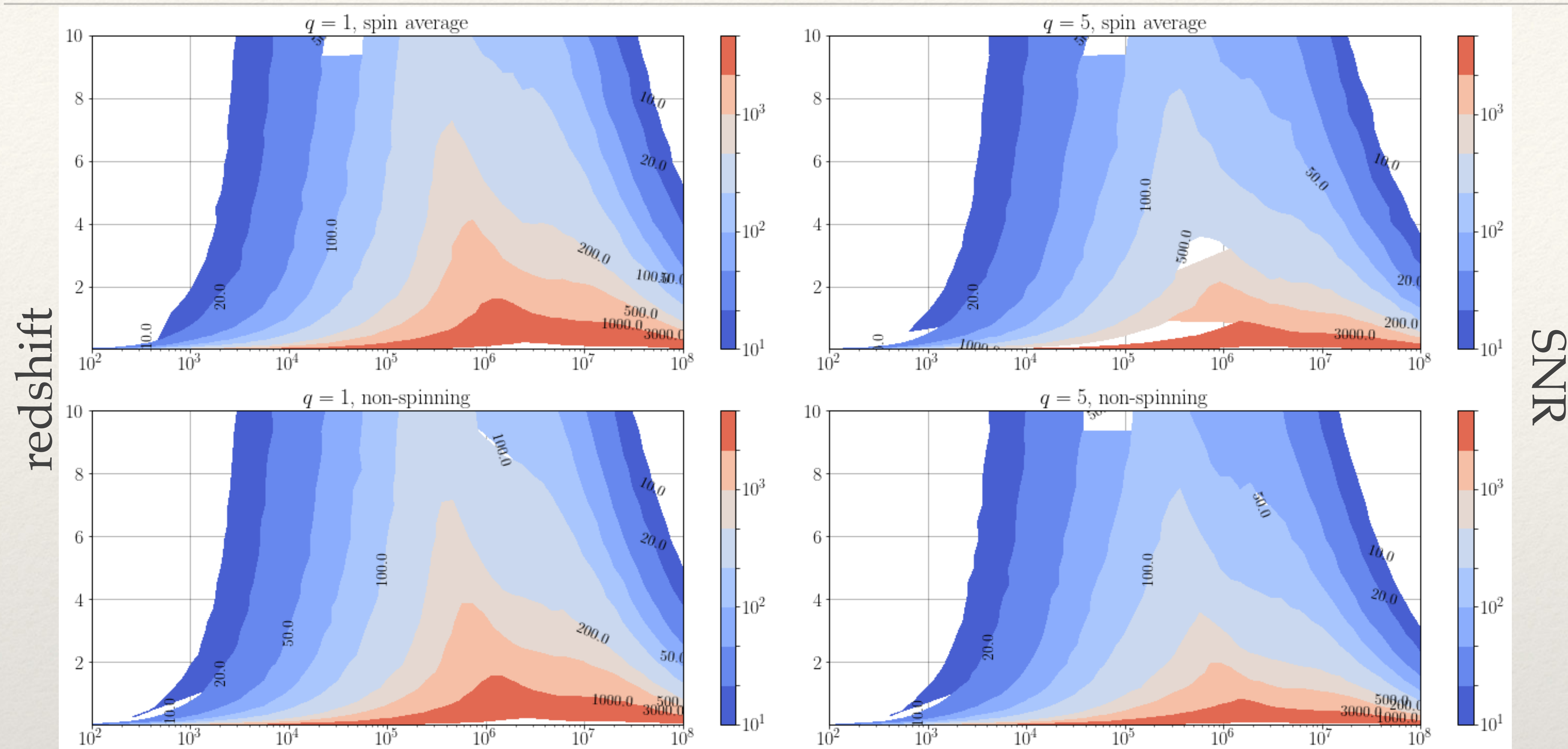
[Credits: Gabriella De Lucia]

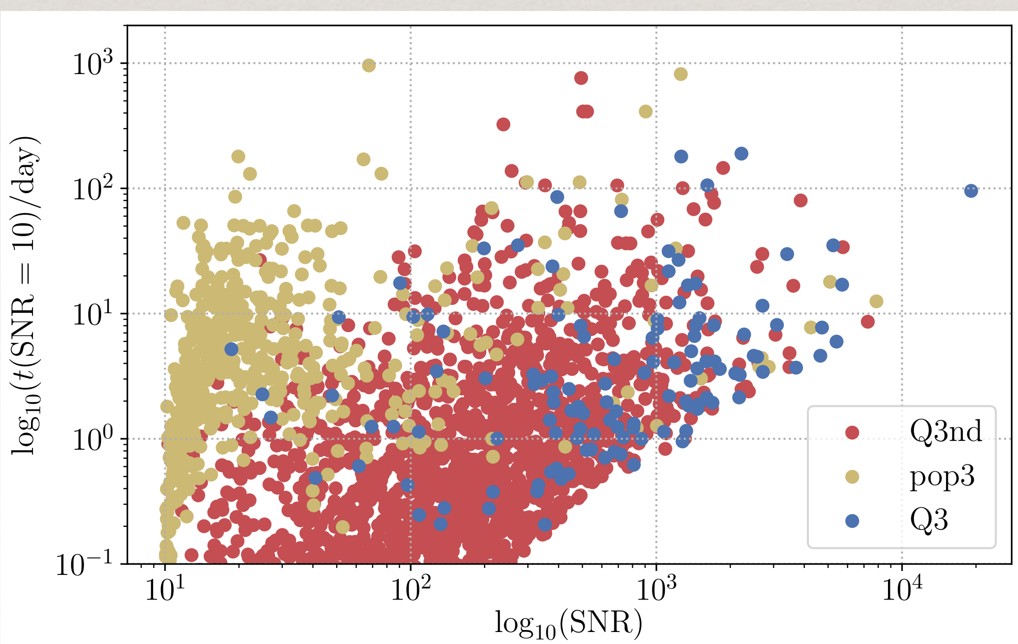
LISA: GW signal from MBHB

The signal from MBHB is similar to what we have observed in LIGO (scaled up in the amplitude and streched in time). GW signal from MBHB is expected to be the strongest signal (seen by eye in the simulated data). Imposes stringent demands on the accuracy of GW signal modelling



Detecting GW signal from MBHBs



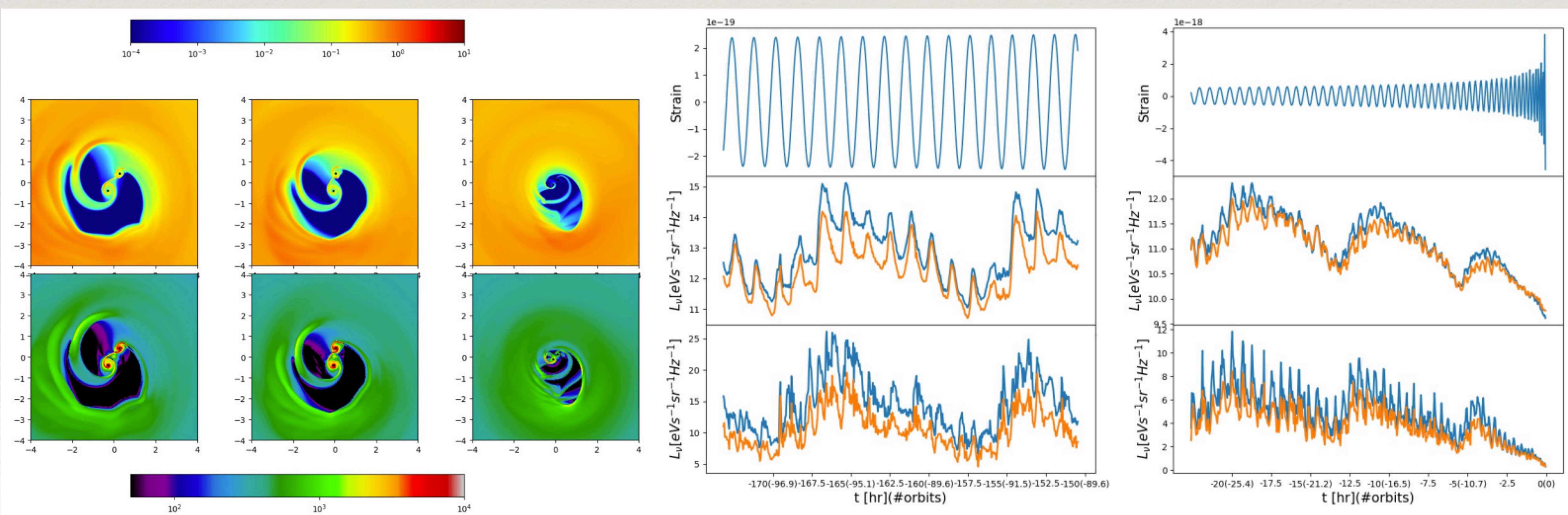


- Merger is very strong: detectable throughout the unverse in mass range $M = 10^4 - 10^7\, M_\odot$
- Detectable part of the signal lasts few hours - few months
  - pop3 - light seed from first stellar population
  - Q - heavy seed from direct collapse of gaseoud cloud
    - Q3d - delayed MBHs merger from galactic collisions
    - Q3nd - no delay between galaxy collisions and MBHBs merger

Pre-merger e/m signal

X-ray emission during the late stages of the inspiral (days to hours before final merger) comes from:

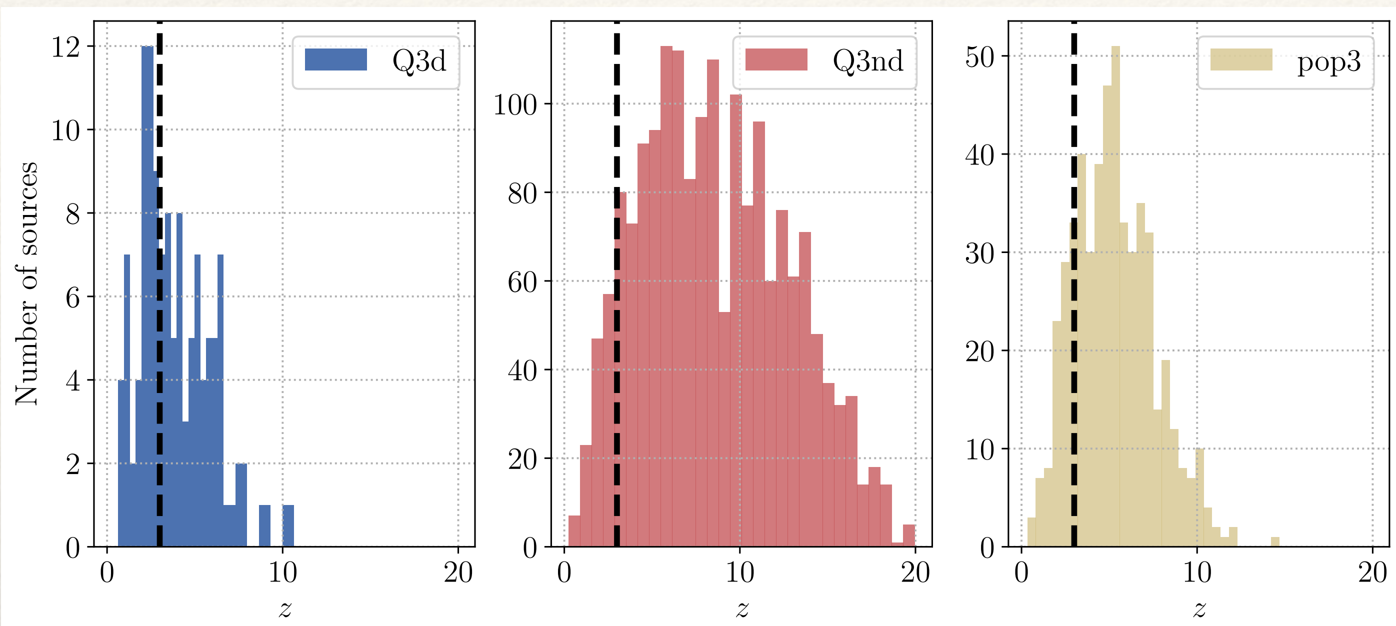
- Circumbinary disc:
  - X-ray emission in soft x-rays (≤1keV)
- Mini-discs around black holes
  - Hard x-ray emission (≥10keV) from accretion of minidiscs individually onto each black hole
- Interaction of circumbinary and mini discs:
  - Accretion of circumbinary disc onto mini-discs via optically thick streams
  - Thermal radiation dominated by the inner edge of thecircumbinary disc, producing soft x-rays (~2keV)
- X-ray emission shows clear modulation on timescales as short as a few hours



lisa Y. Tang+, MNRAS 2018

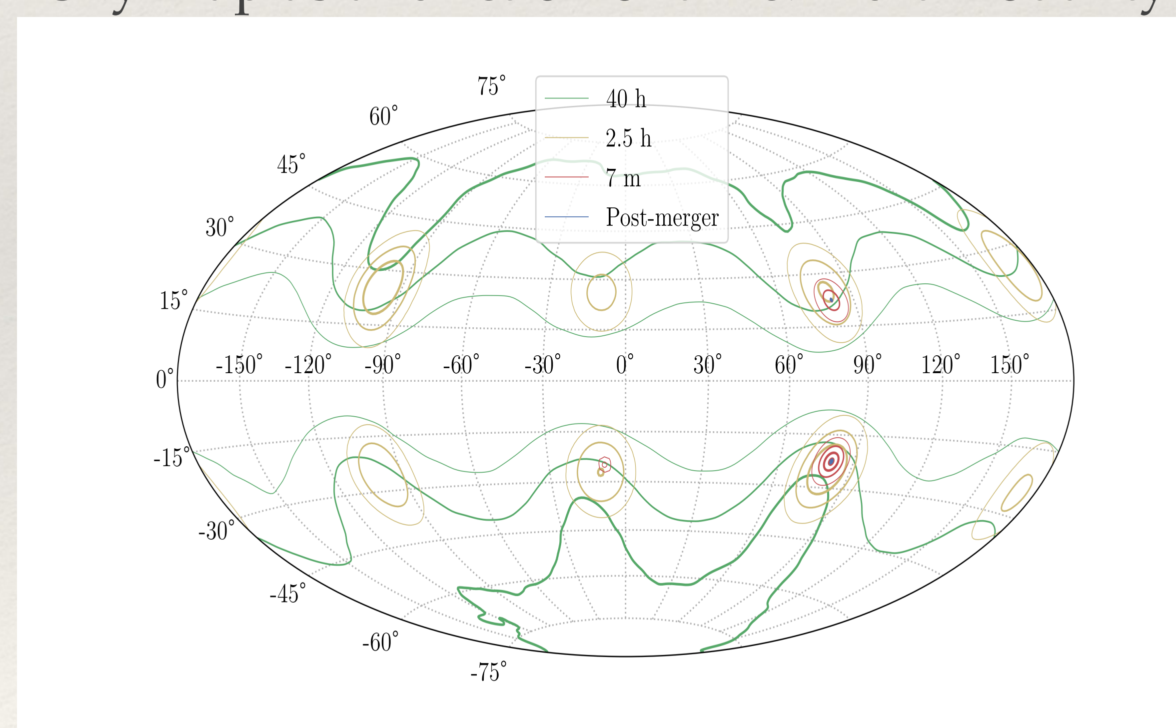
Observing MBHBs

- Different populations have different characteristic: help to dientangle and solve inverse problem: given the LISA observation what vcan we infer about the evolution of MBHBs: how they were born? how they accumulated its mass



Simultaneous (multimessanger) observations of MBHB: GW + e/m. Need to localize the source in the sky to point telescopes: pre-merger is weak signal, not enough info - up to 8 modes on the sky - improvement as we approach merger. Necessitiy to follow the signal in the real time

Sky map as a function of time: multimodality

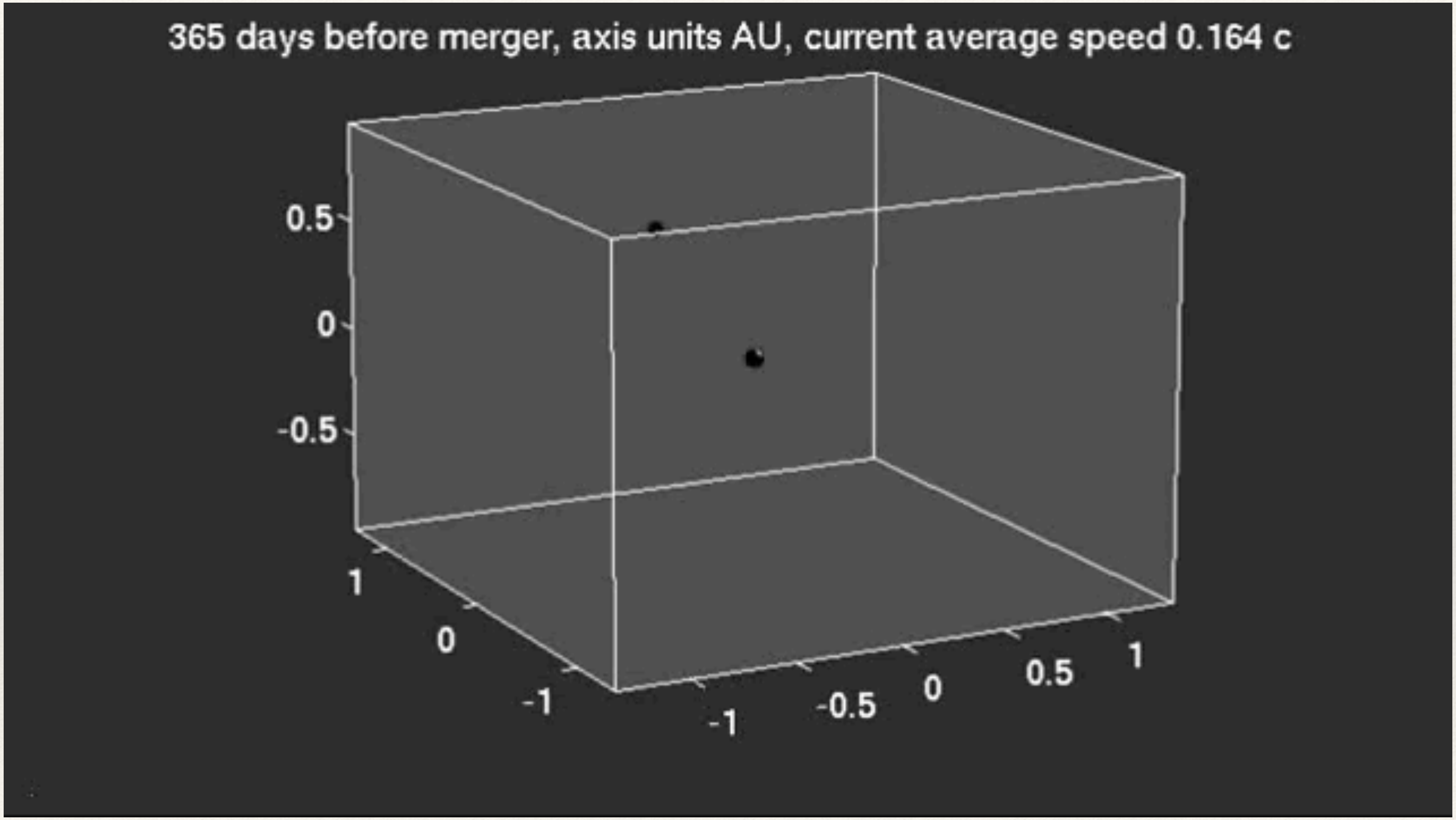


Marsat+2020

EMRIs (extreme mass ratio inspirals)

- Massive BHs in galactic nuclei surrounded by stars and gas with quite high density
- MBH could capture a compact object (BH, NS, WD) which is thrown on a very eccentric orbit (due to N-body interaction). The orbit shrinks and circularizes due to grav. radiation.
- EMRI: binary system with extreme mass ratio of component 10^{-7} - 10^{-5}
- Compact object revolves 10^6 orbits in the proximity of MBH before the plunge.

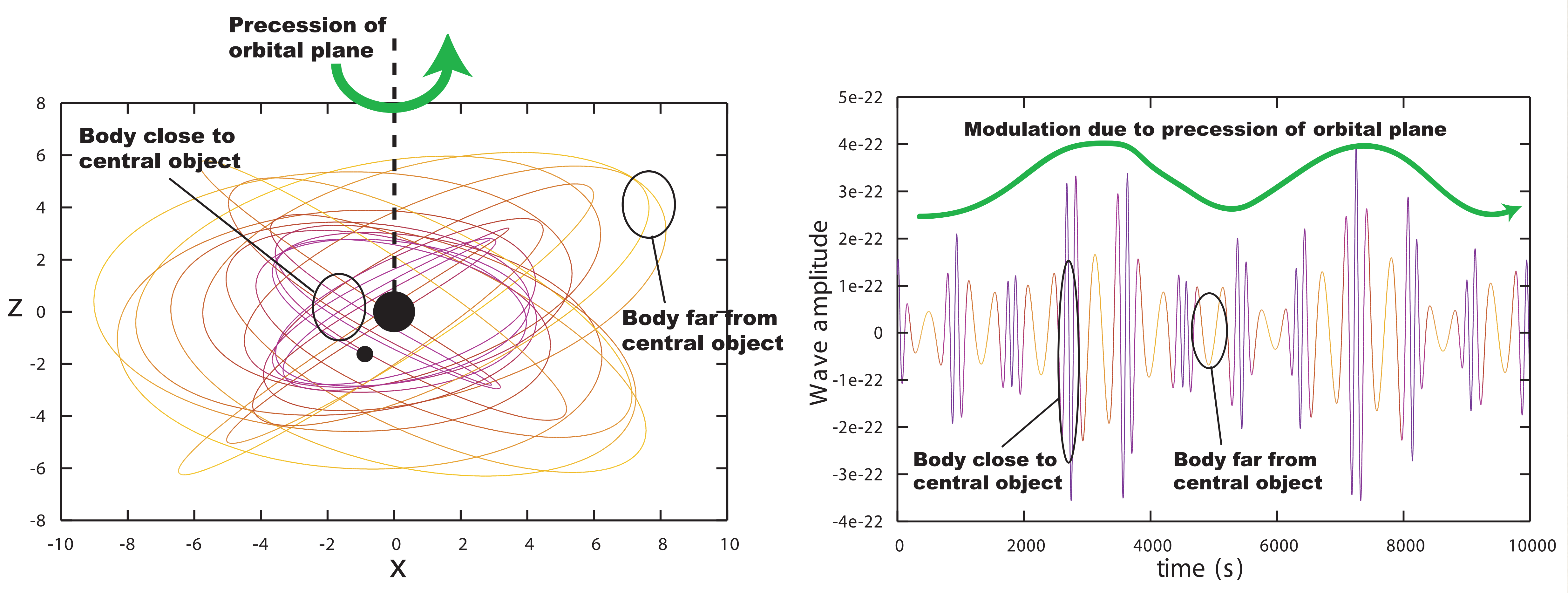
EMRI



[Credits: S Draco, CalTech]

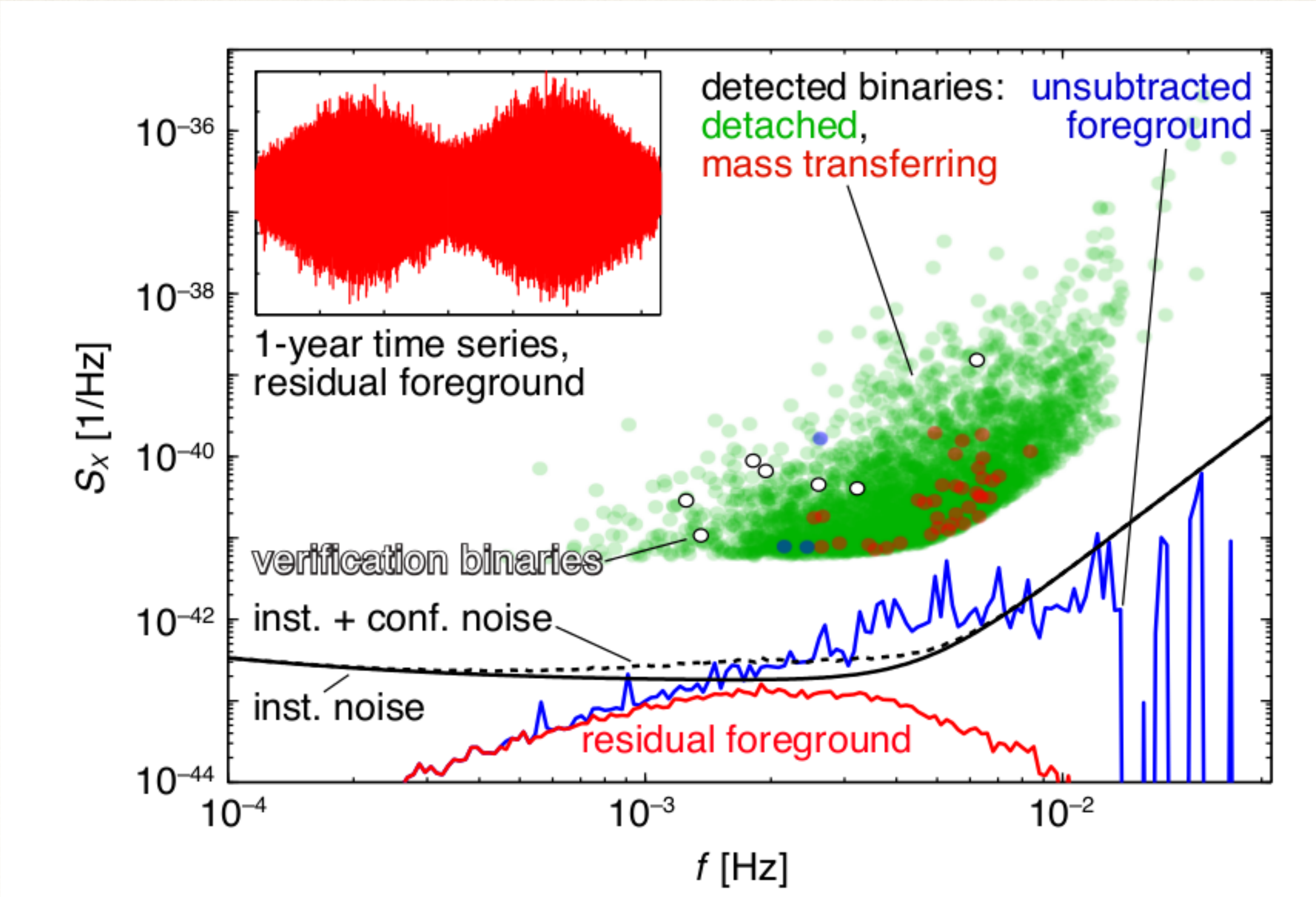
EMRI

- Orbital motion: (almost) elliptical with a strong relativistic precession + orbital precession due to spin-orbital coupling
- Signal is very rich in structure (hard to detect but gives a lot of information.
- Ultra-precise parameter determination (if detected). Can map spacetime of a heavy object: holiodesy



Galactic white dwarf binaries

- We expect to have 10^7 WD binaries all emitting GWs in the LISA band, only 10^4 can be resolved individually, other form stochastic GW signal (foreground)
- GW signal is almost monochromatic
- Verification binaries: known from current e/m observations (+GAIA,+ LSST)



Verification Galactic binaries

- There are few dozen of GBs observed in e/m.
- Can measure orb. period, sky position, distance: guaranteed sources in the LISA's band
- More verification binaries are being discovered (ZTF, GAIA, LSST)

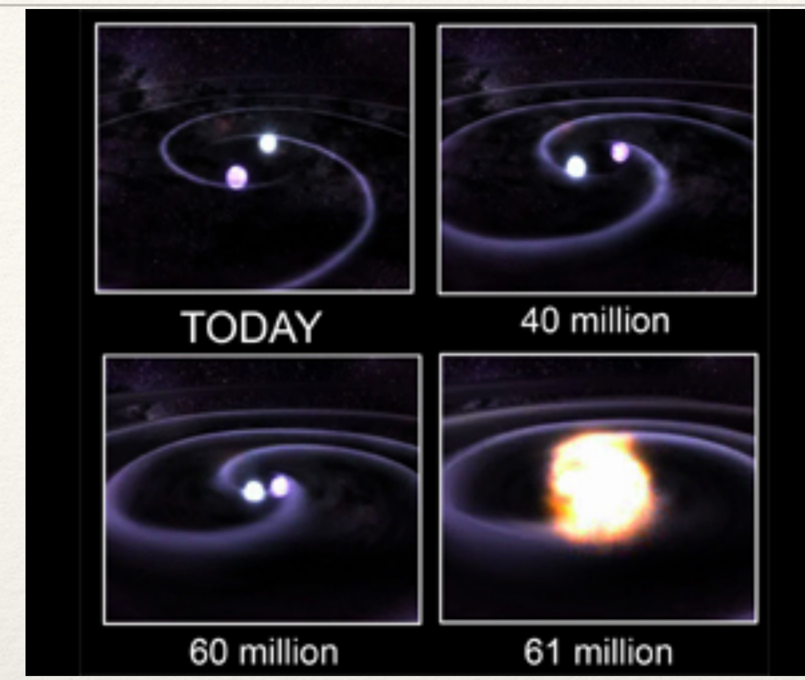
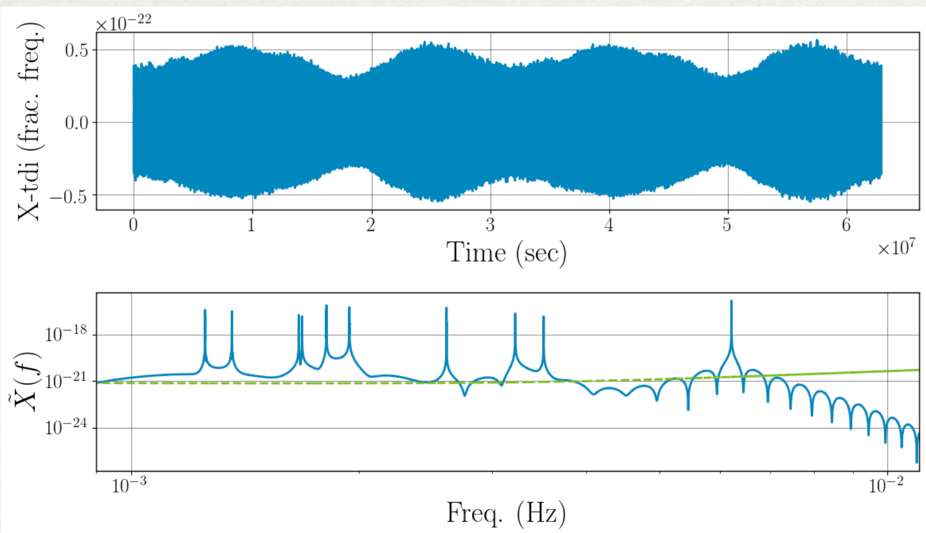
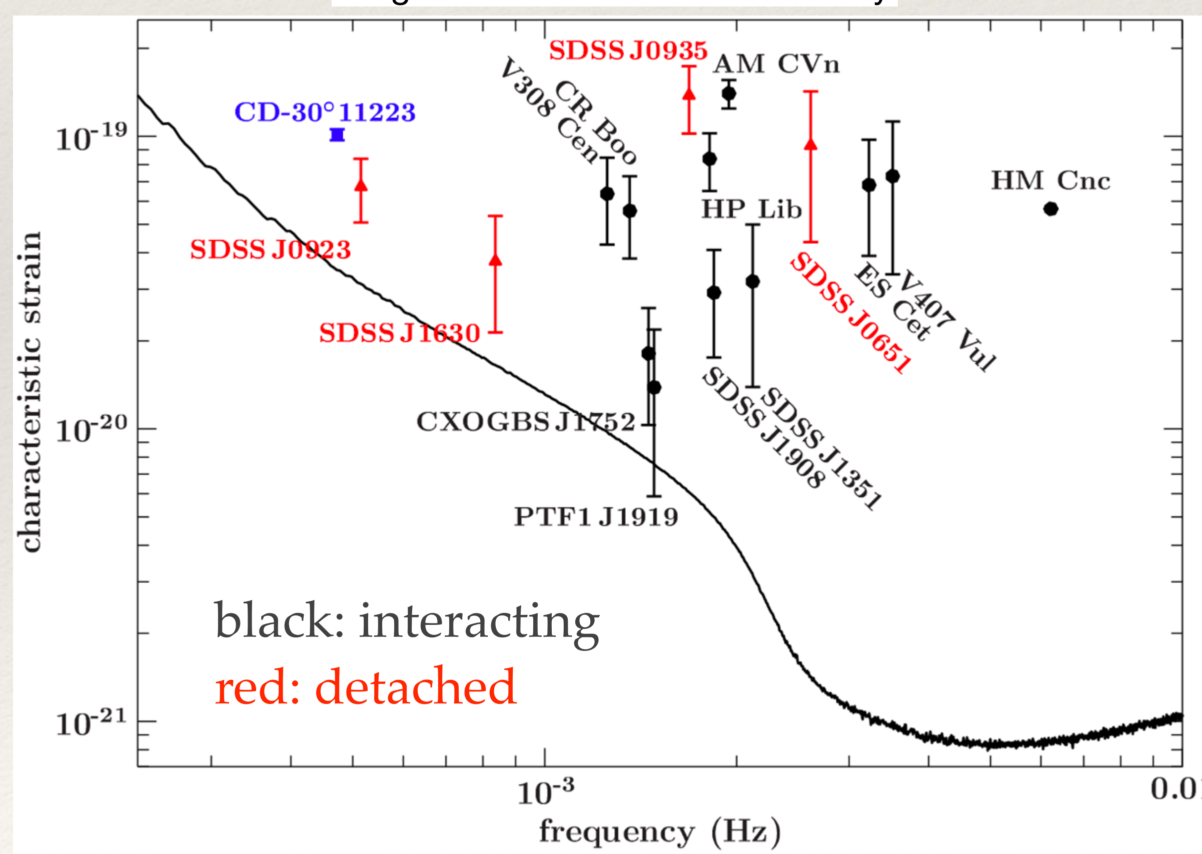


Image Credit: NASA/GSFC/D.Berry.





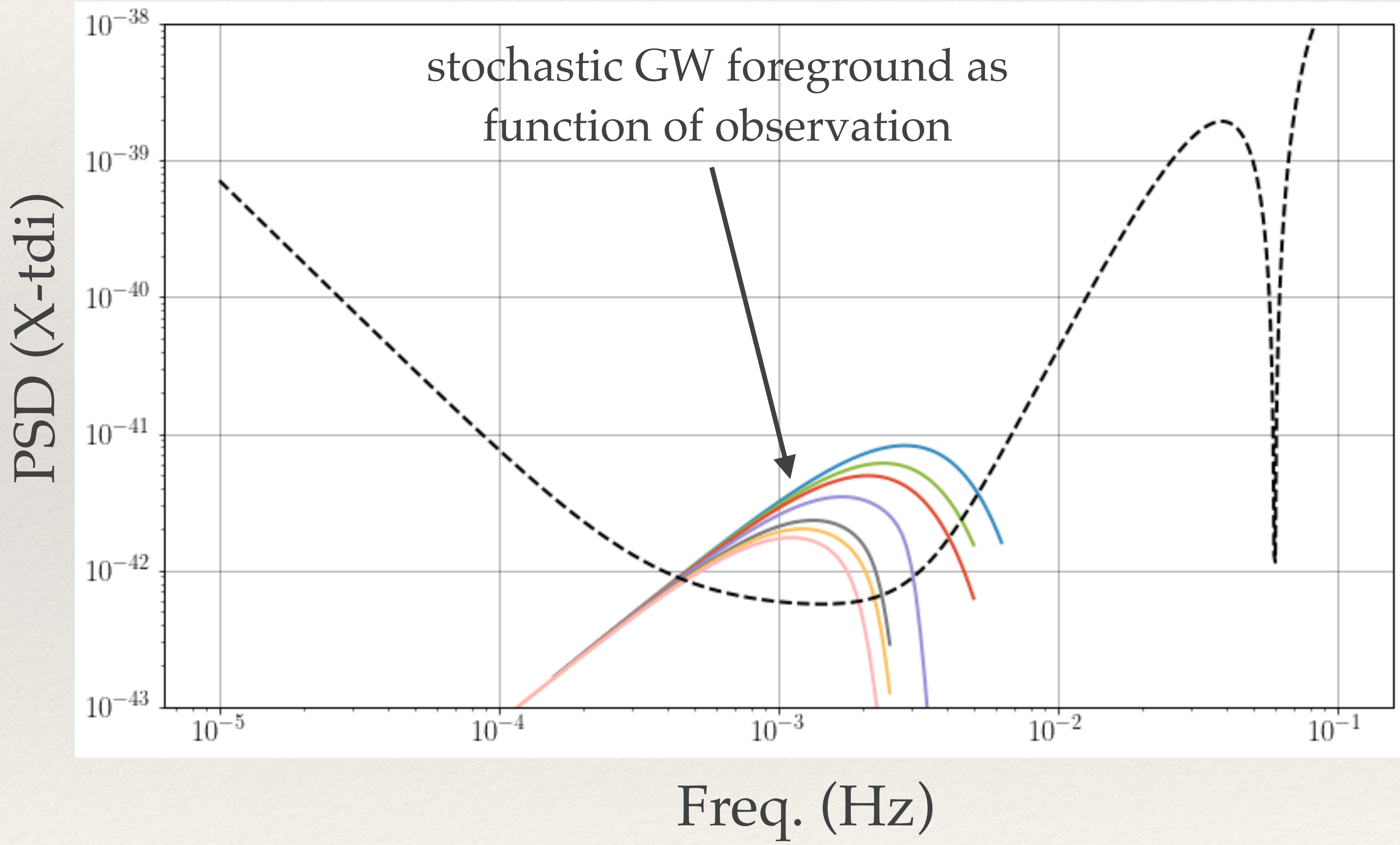
credits: G. Nelemans

Detecting GBs as function of time

Data comes continuously (daily): the signal-to-noise grows as $\sqrt{T}$ we start resolving previously unresolved signals

Observation duration	Max number of detectable source
10 days	156
3 months	1984
6 months	3818
1 year	7116
2 years	13103
5 years	25488
7 years	31150
10 years	40023

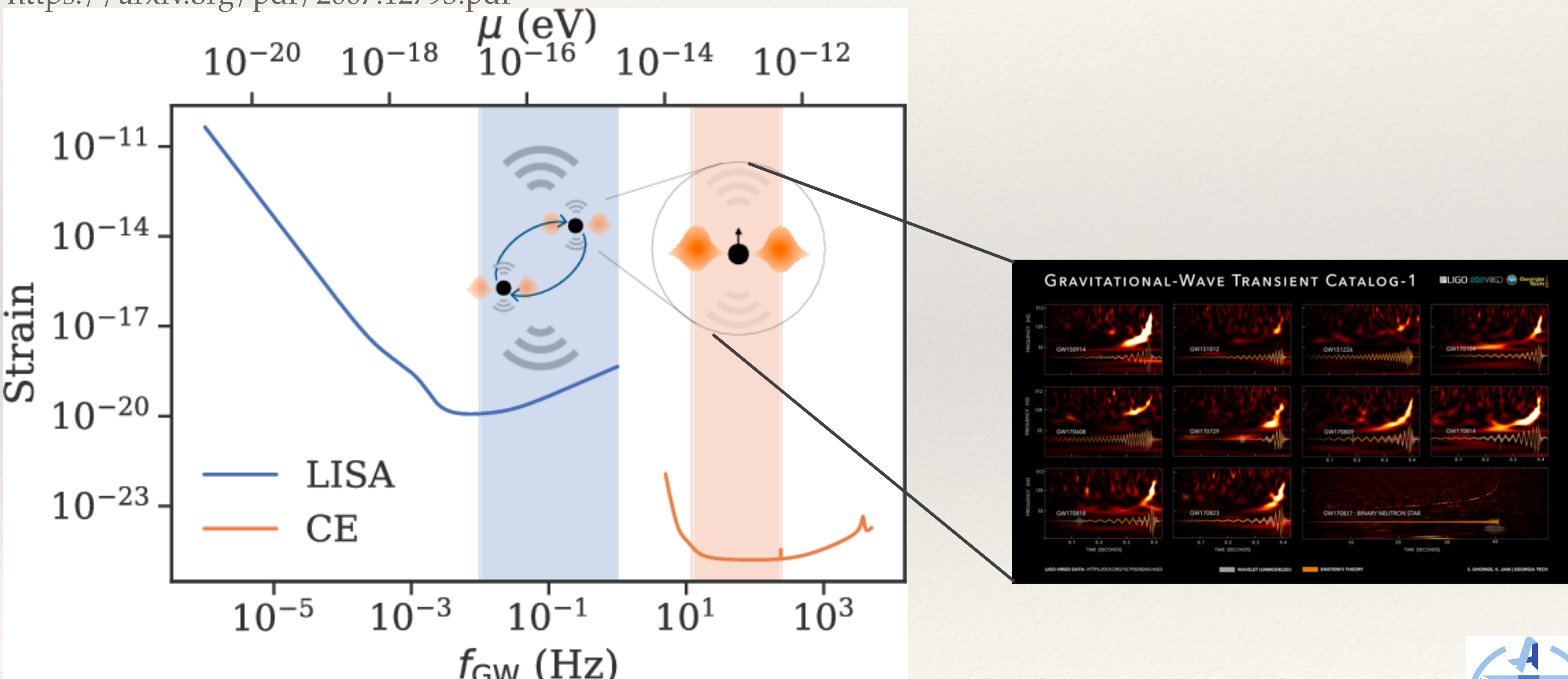
[Karnesis+ e-Print: 2103.14598]



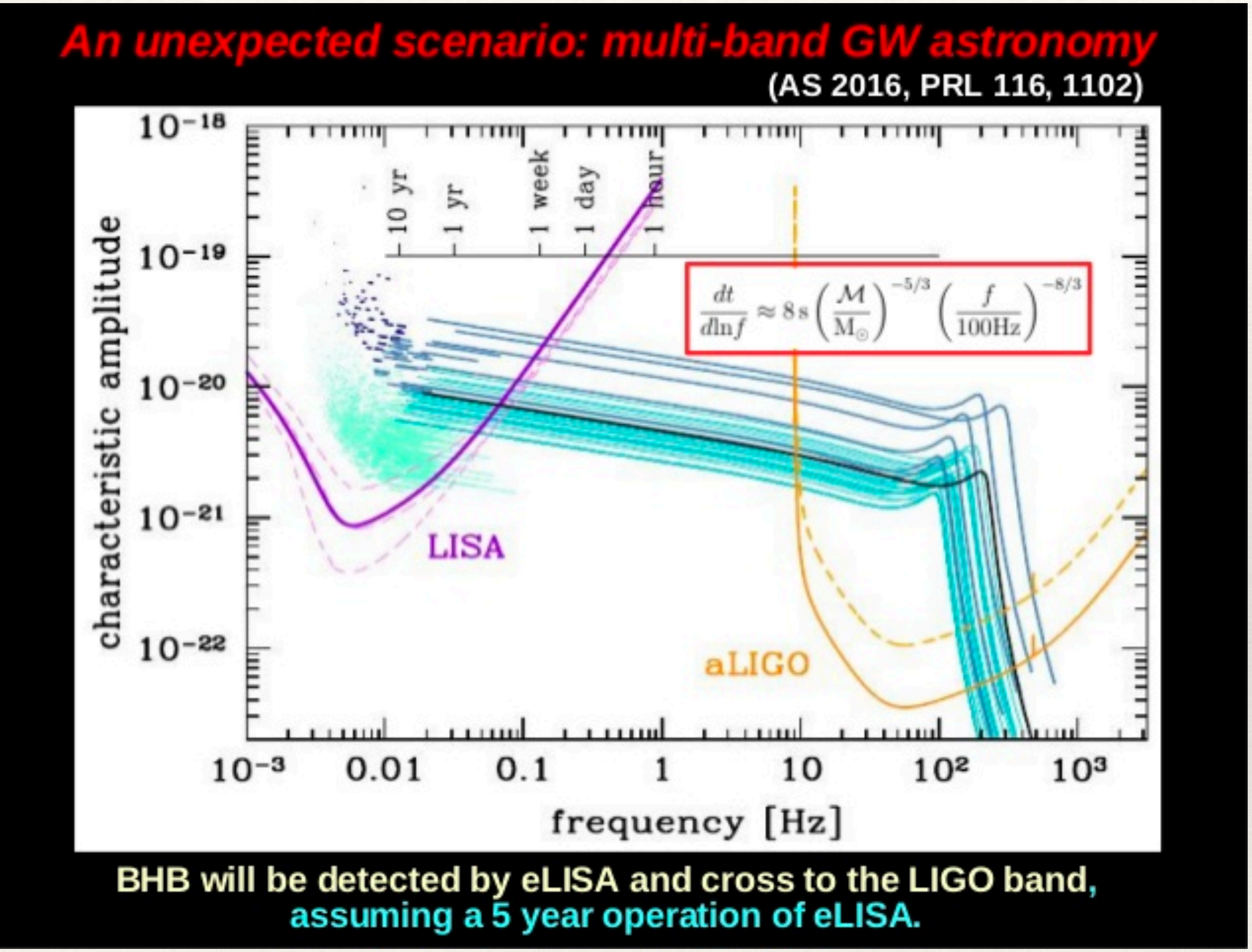
Stellar mass black hole binaries

- Stellar mass black hole binaries: SBBH — the same black holes which merger we observe with LIGO-Virgo. If consider those binaries 5-50 years in the past (slow inspiral) they emit in the LISA's band

https://arxiv.org/pdf/2007.12793.pdf



Stellar mass black hole binaries



A. Sesana PRL 2016

Multi-band observations: some binaries will be first observed/ detected by LISA and then 5-10 years later re-appear and merge in the band of ground-based detectors (Einstein Telescope, Cosmic Explorer)

Stellar mass black hole binaries

A. Toubiana+2020

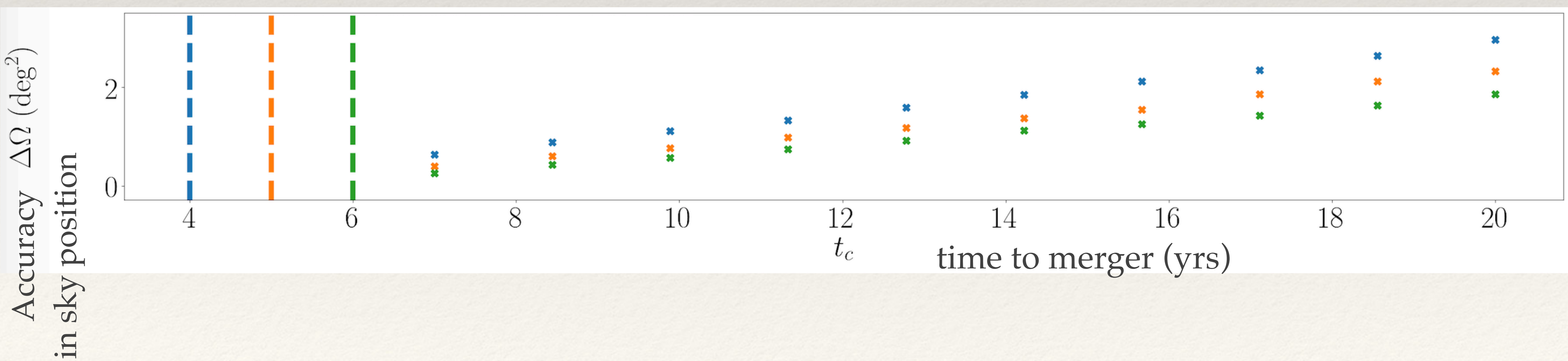
	B	m_g
System 1	$< 2\ 10^{-11}$	$< 6\ 10^{-25}$
System 2	$< 9\ 10^{-11}$	$< 4\ 10^{-25}$
System 3	$< 1\ 10^{-10}$	$< 5\ 10^{-25}$
Current constraints	$< 4 \times 10^{-2}$	$< 8 \times 10^{-23}$

Constraint on dipolar radiation

Constraint on graviton mass

- SBBH - multiband observations: amazing laboratories for testing General Relativity theory

- We can detect and estimate sky position of those sources years before they merge: pre-merger multimessanger observations



Expected event rate in LISA

- LISA's minimum mission time is 6 years (expected at 75% duty cycle), consumables up to 10 years

- MBHB : high uncertainties in the event rate - from few to few hundreds per year

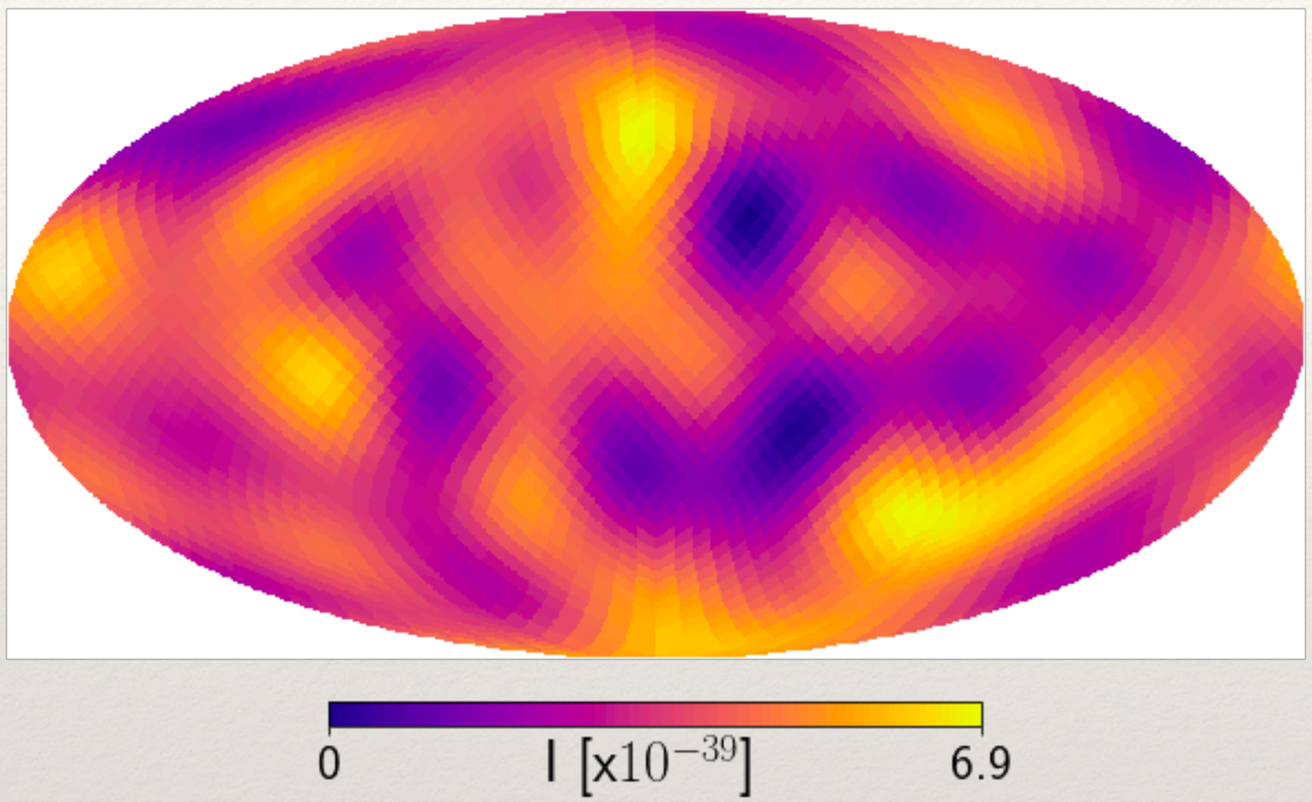
- EMRIs: even more uncertain - from few to few thousands of detectable GW signals per year.

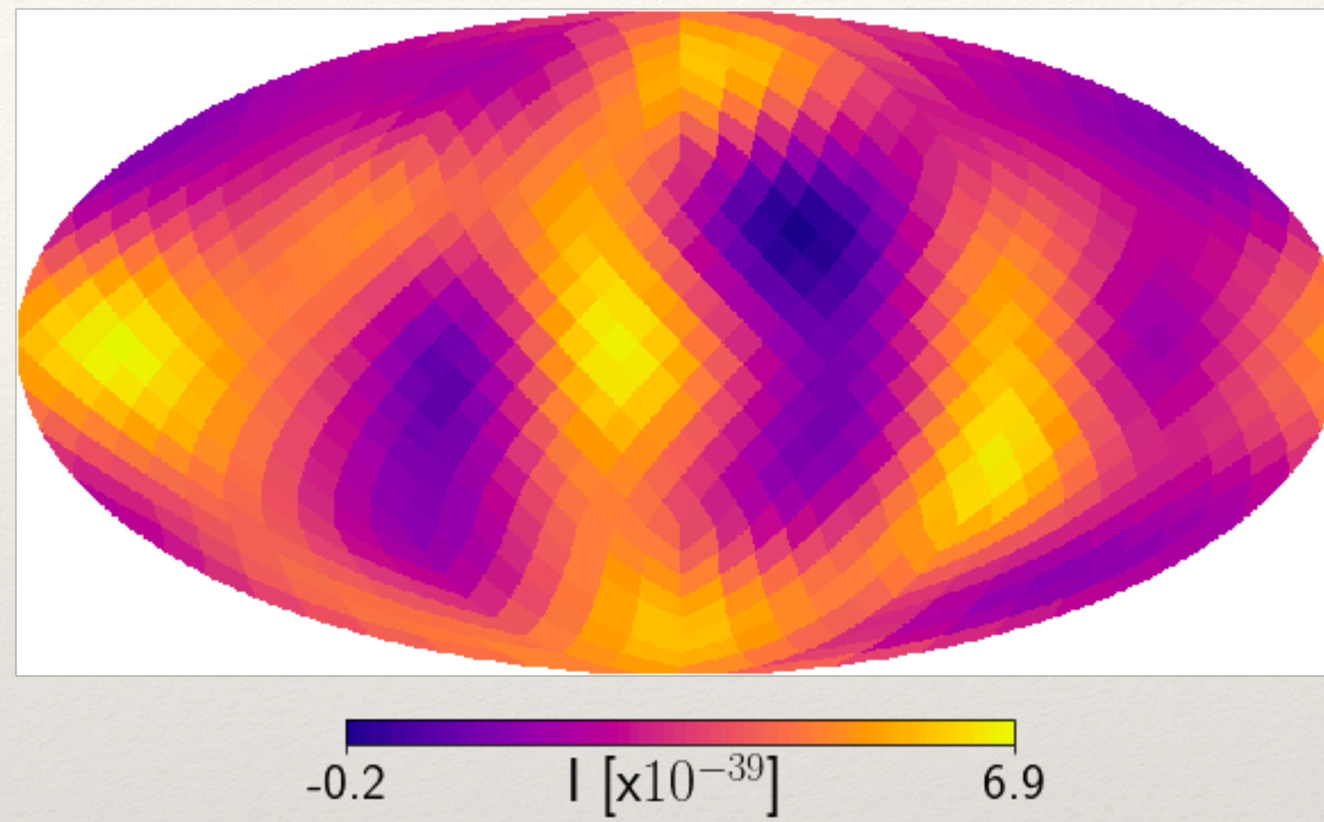
- GW signal from solar mass BBH (LIGO/VIRGO sources). We expect to observe about 10 sources: GW signal first observed in LISA and then 5-10 years later with the ground based detectors.

- Possible detection of the stochastic GW signal from energetic processes in the early Universe.

Stochastic GW signal

Reconstruction of Anysotropy



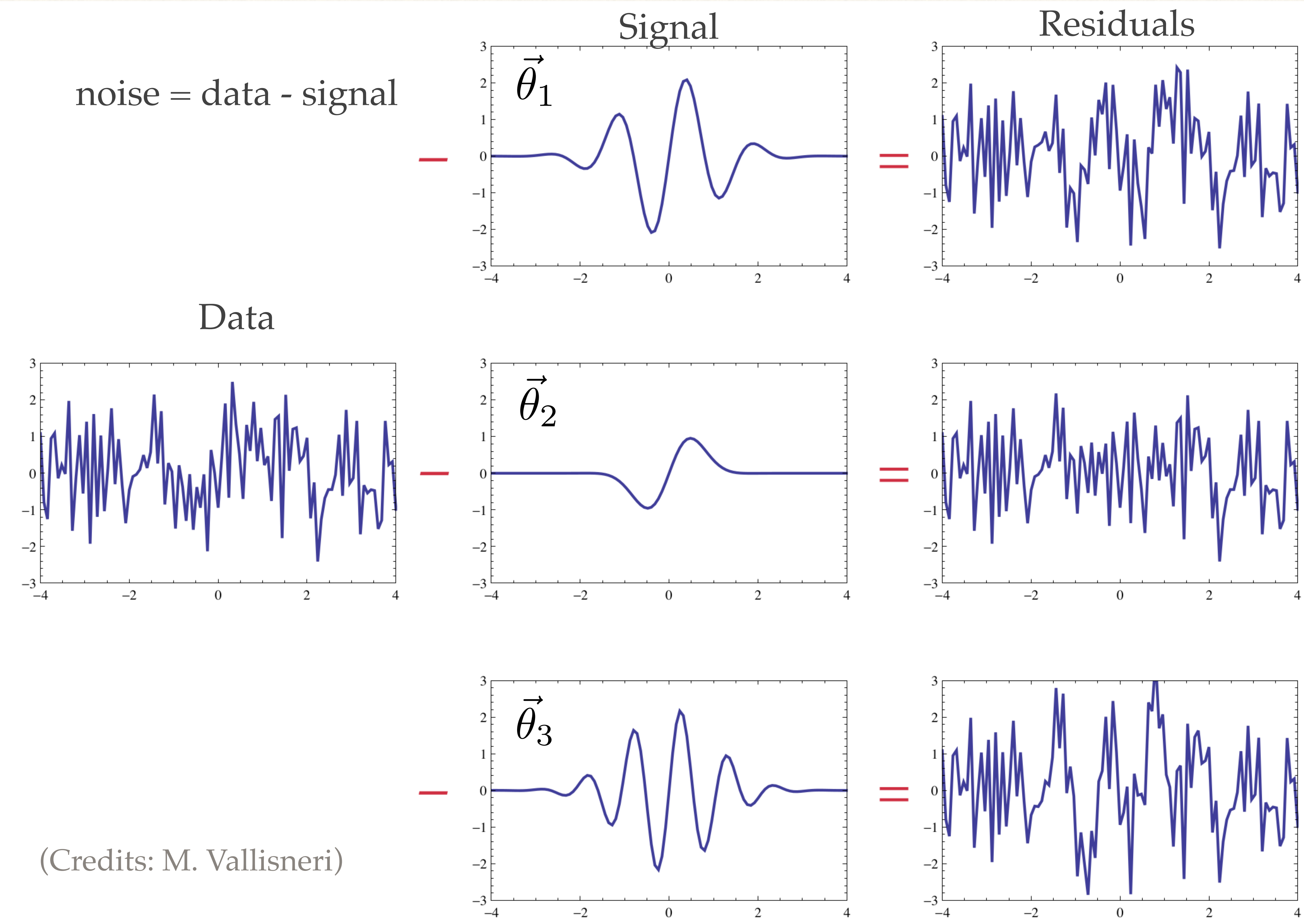


Smoothing on small scales (complete loss of sensitivity at l~ 15)

[Contaldi+ (2006)]

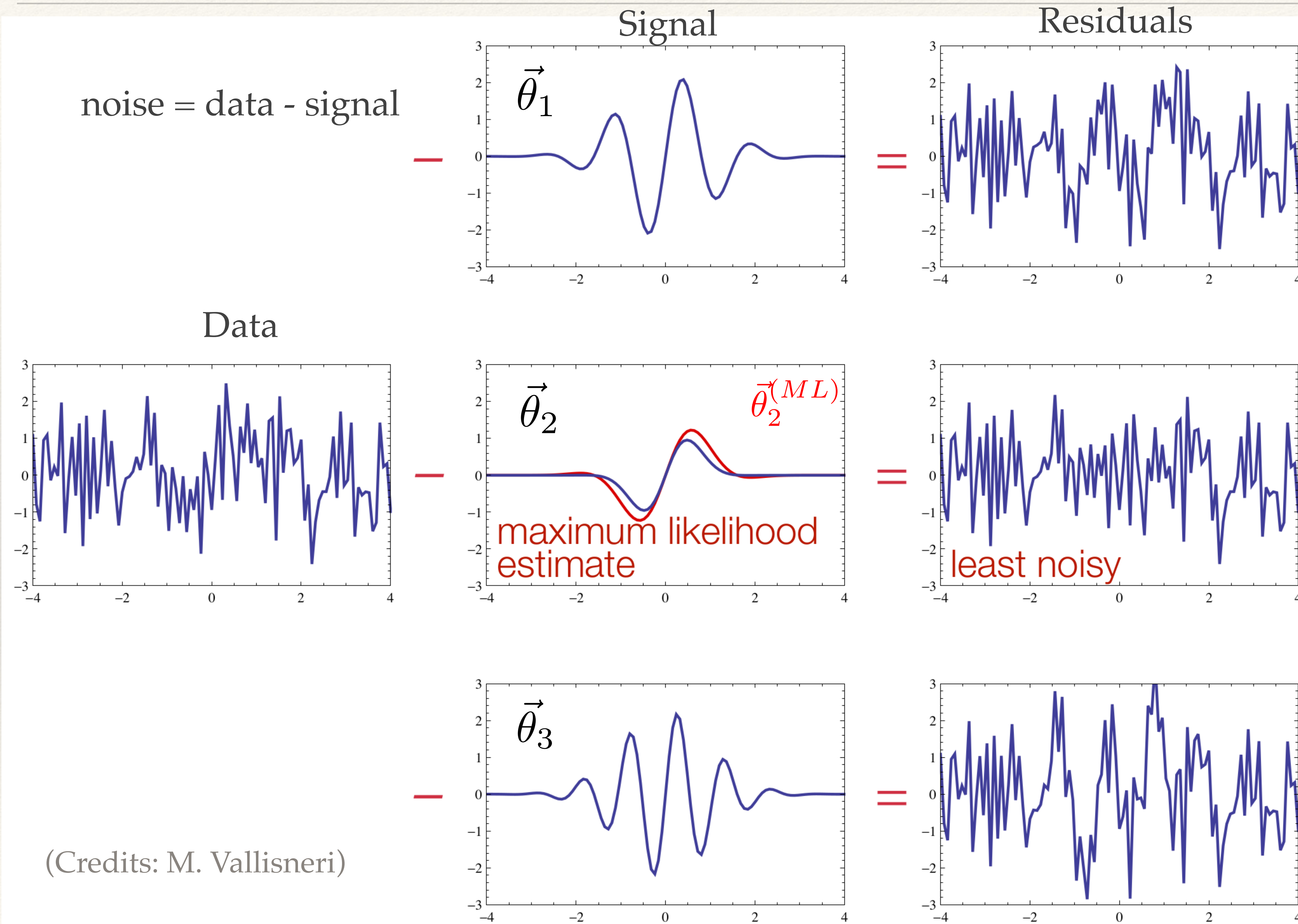
lisa

Matched filtering and parameter estimation



(Credits: M. Vallisneri)

Matched filtering and parameter estimation



(Credits: M. Vallisneri)

Bayesian approach: parameter estimation

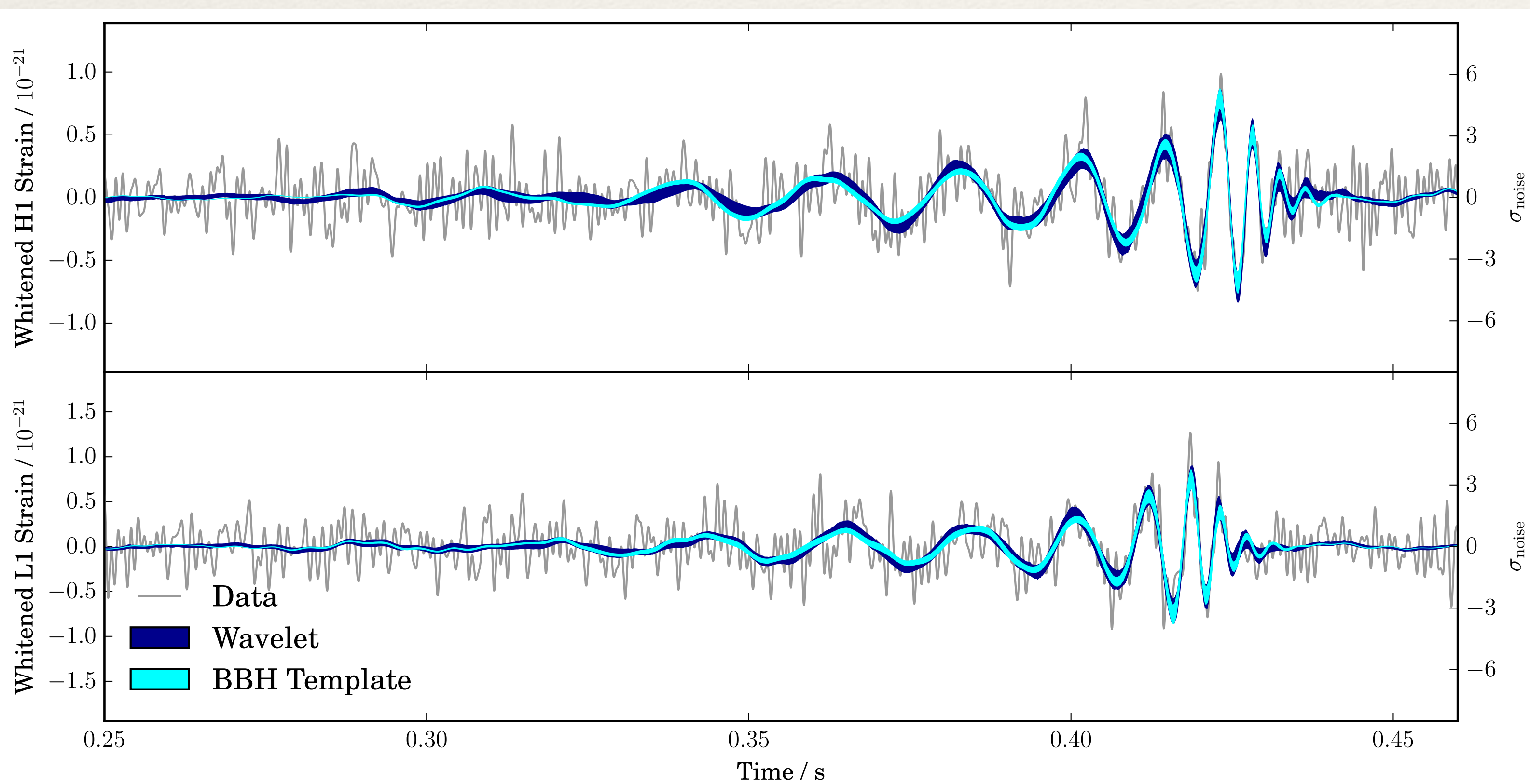
Likelihood

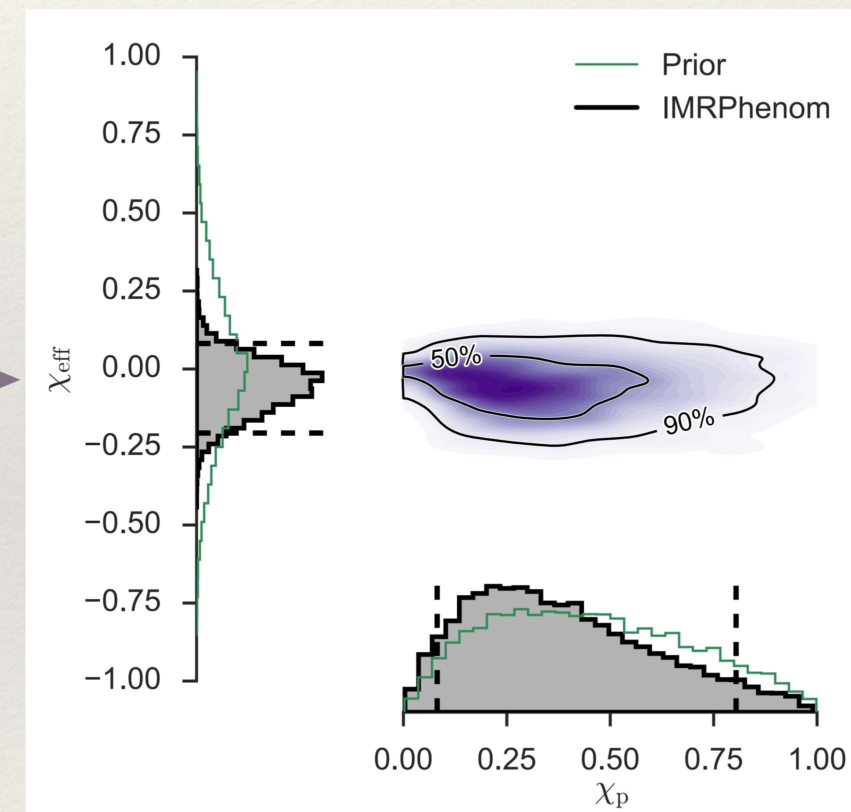
Prior

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

Posterior

Evidence





[GW150914, LSC+VIRGO PRL (2016)]

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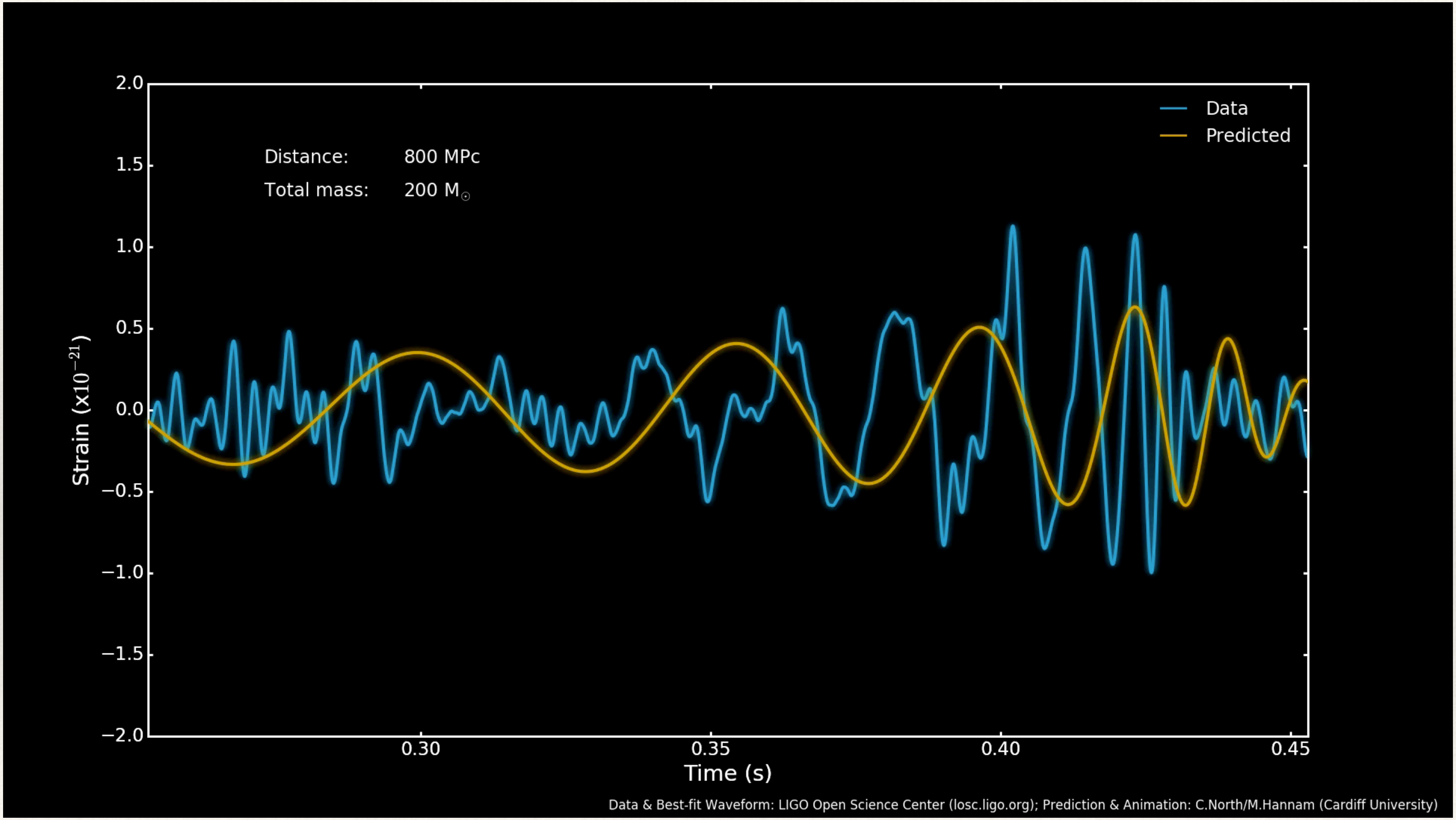
GW data analysis



Bayesian approach: model selection

- Sometimes we have several competing models: Are BHs spining? Is GR or an alternative theory? Is there one GW signal in the data or more?

$$P(M_i|d) = \frac{P(d|M_i)\pi(M_i)}{p(d)}$$

Probability of model M_i given observational data d

likelihood

prior

$$P(\vec{\theta}_i|M_i, d) = \frac{P(d|\vec{\theta}_i, M_i)\pi(\vec{\theta}_i)}{p(d|M_i)}$$

posterior

evidence

Odds ratio: which model is preferred

$$O_{a,b} = \frac{p(M_a|d)}{p(M_b|d)} = \frac{p(d|M_a)}{p(d|M_b)} \frac{\pi(M_a)}{\pi(M_b)}$$

$$p(d|M_i) = \int d\vec{\theta}_i \; p(d|\vec{\theta}_i, M_i)\pi(\vec{\theta}_i)$$

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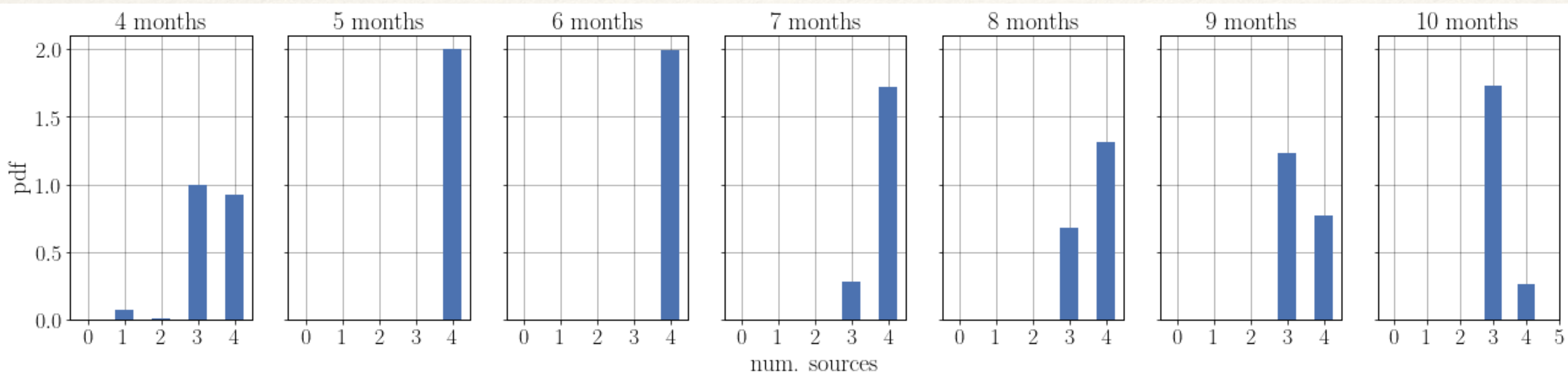
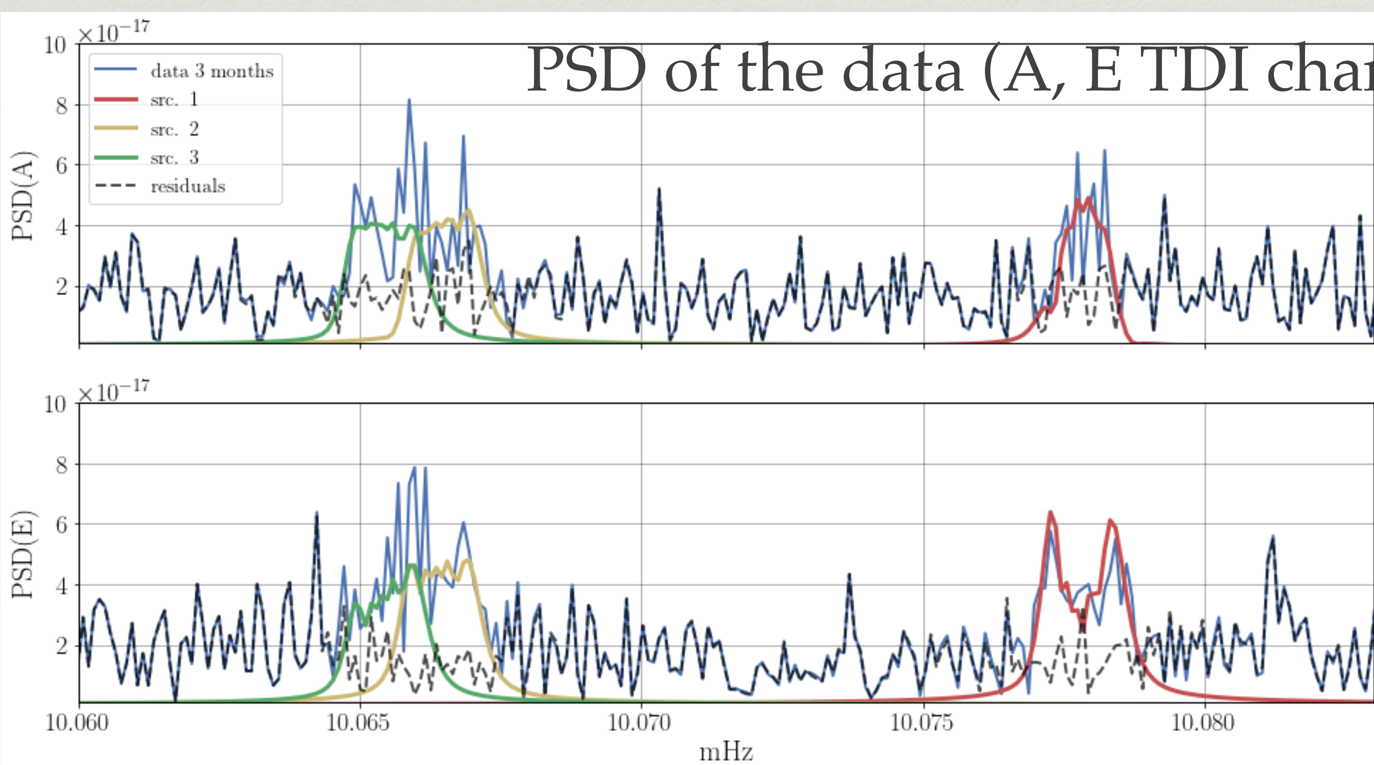
Identifying number of sources

- Take a narrow band next to 10mHz: 3 GW signals
- Perform time-data adaptive (4 months, 5 months, … 10 months) search
- Consider 4 models: 1 GW source, 2 GW sources, 3 GW source, 4 GW sources



Probability of having N-sources in the data using different data duration



PSD of the data (A, E TDI channels)

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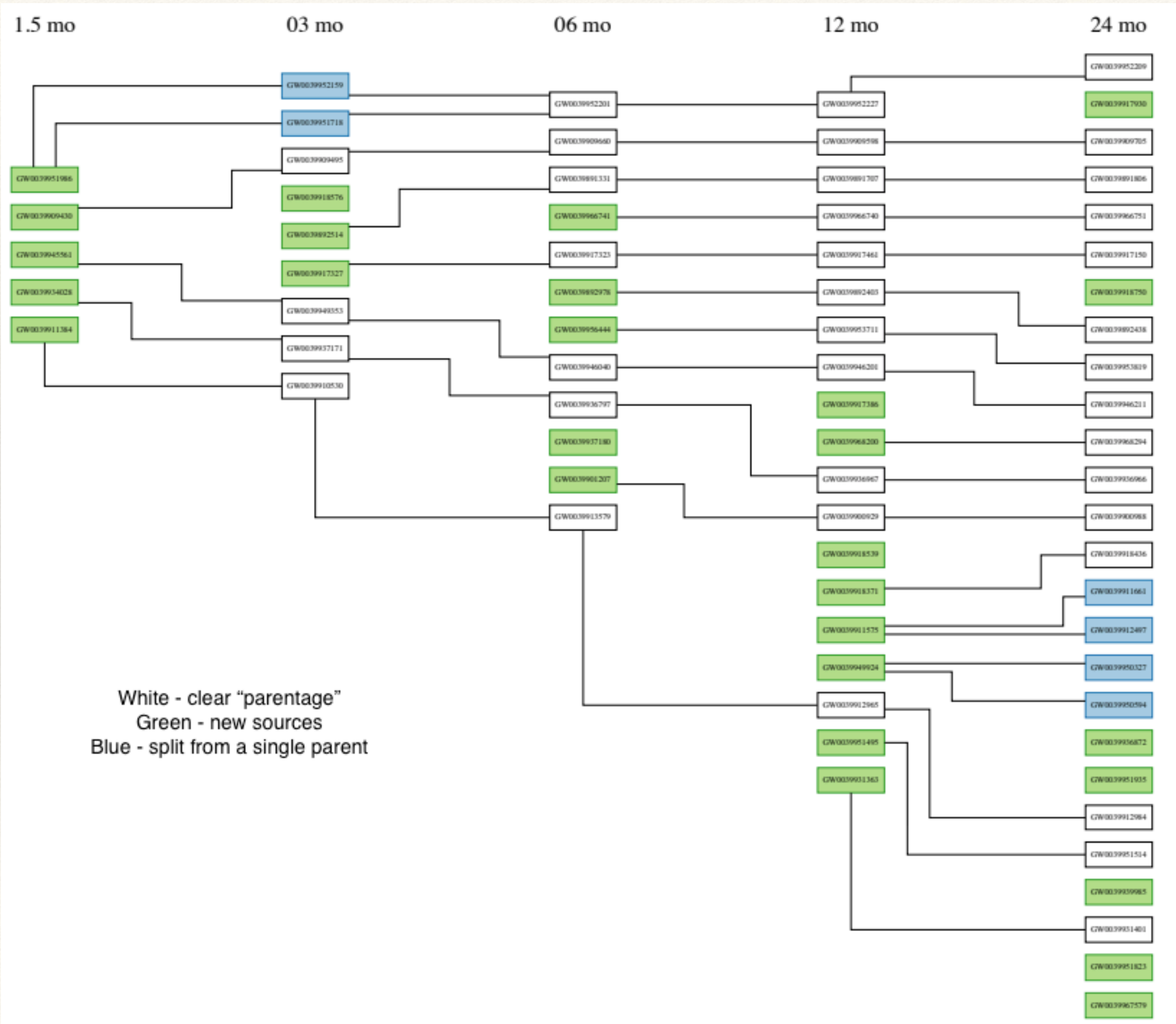
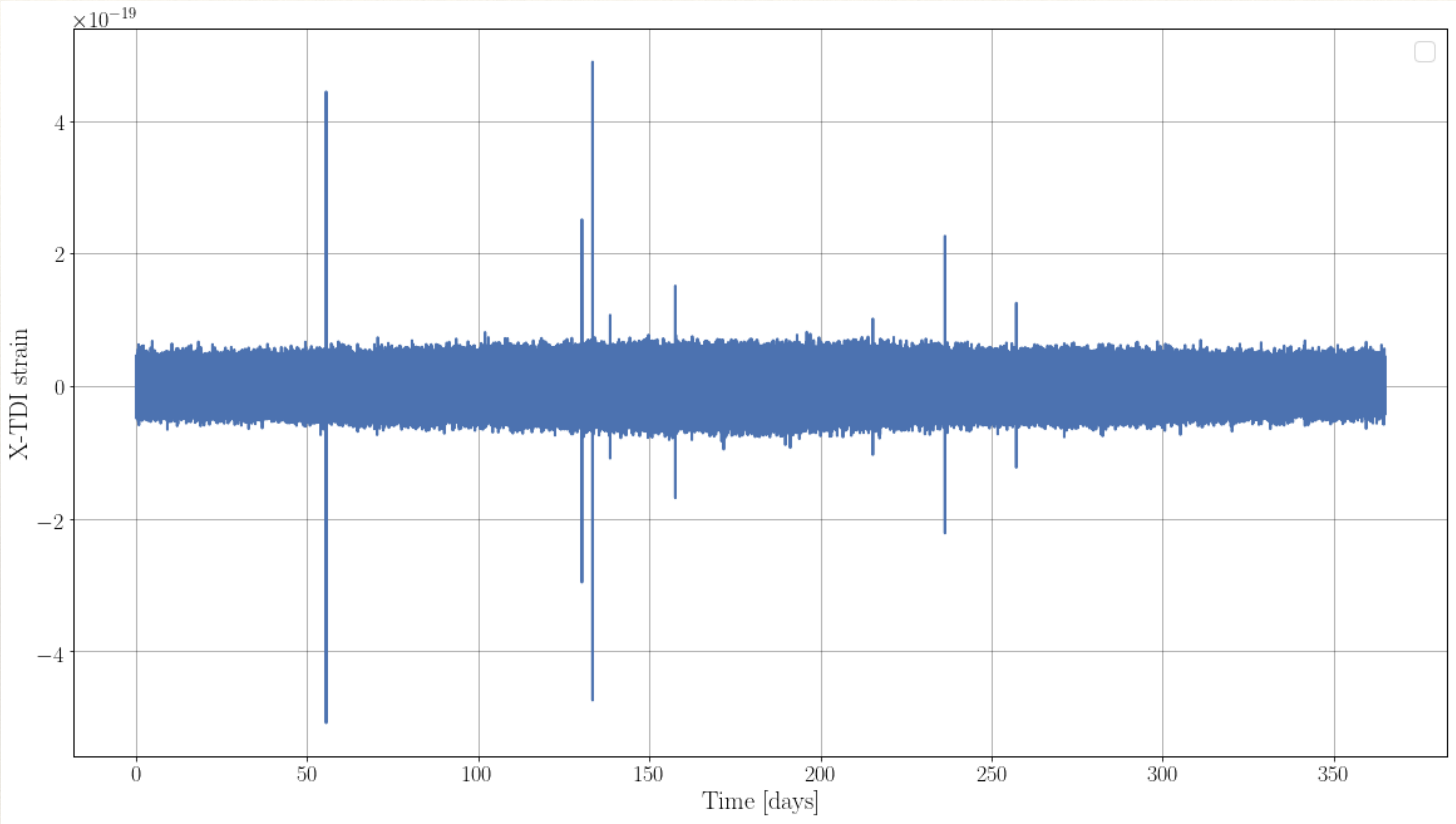
Time-evolving catalogue building



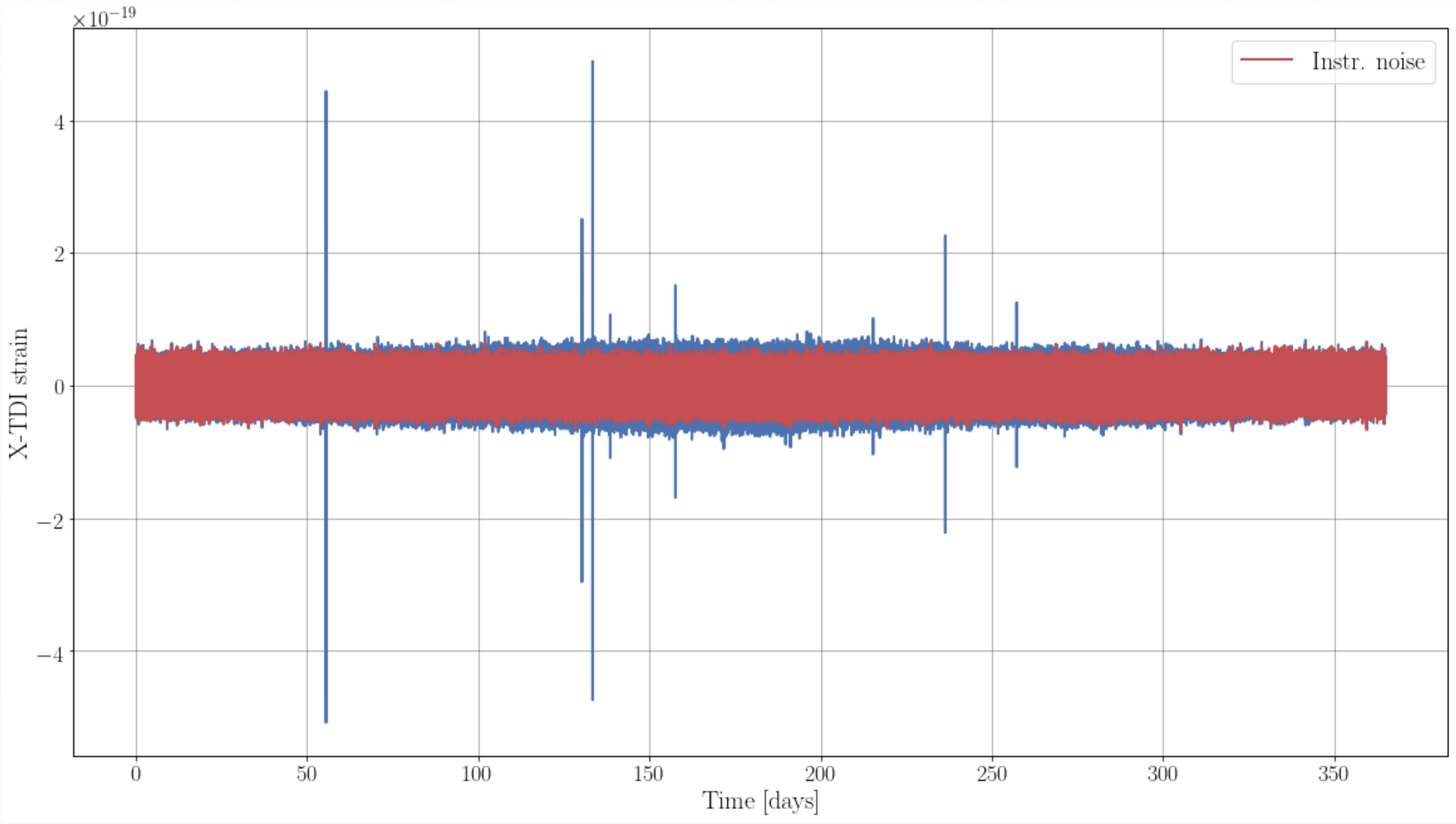
[Littenberg+ PRD, 2020]

Number of sources is a random variable: building catalogue of sources?

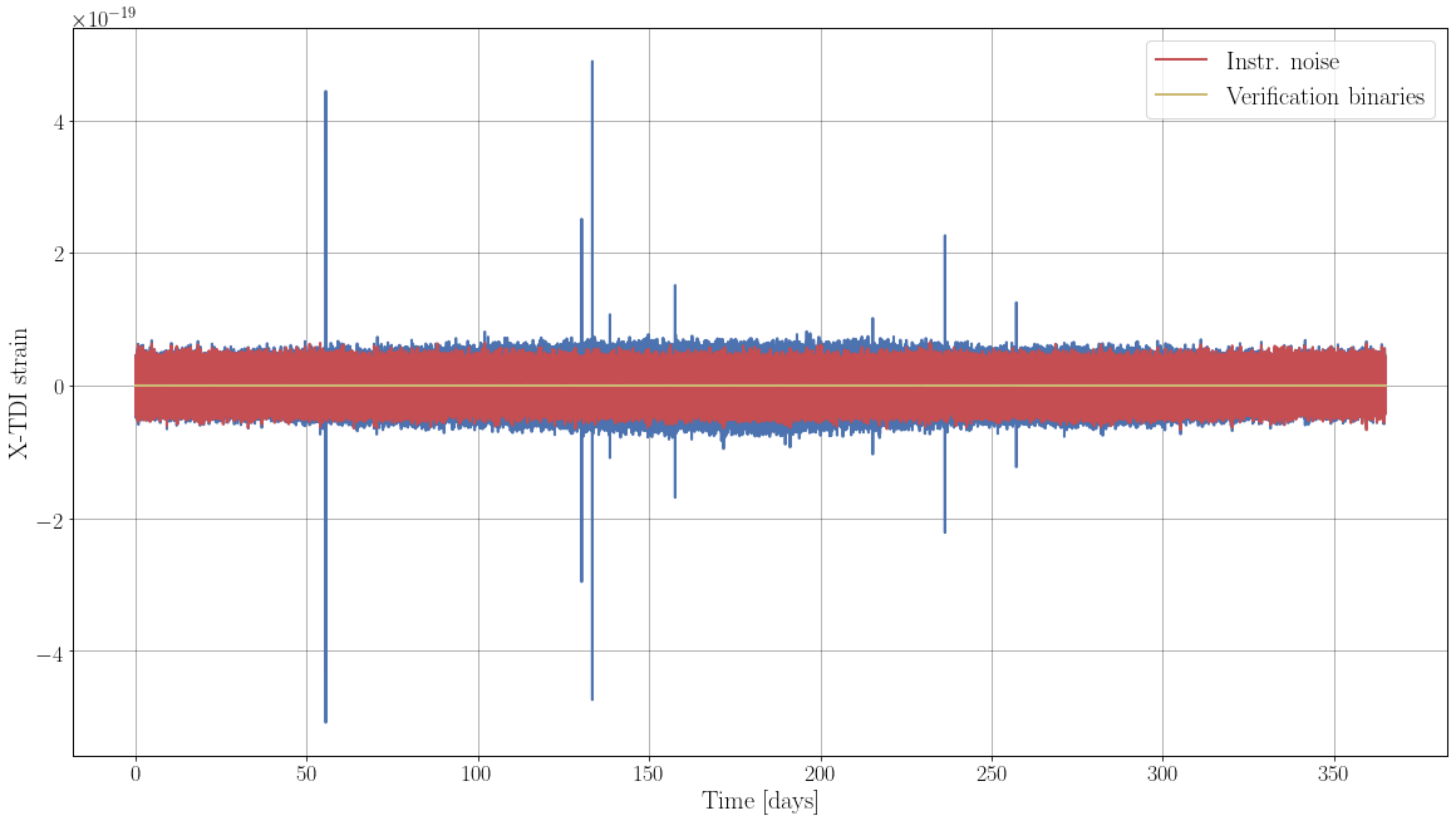
Simulated LISA data in time domain



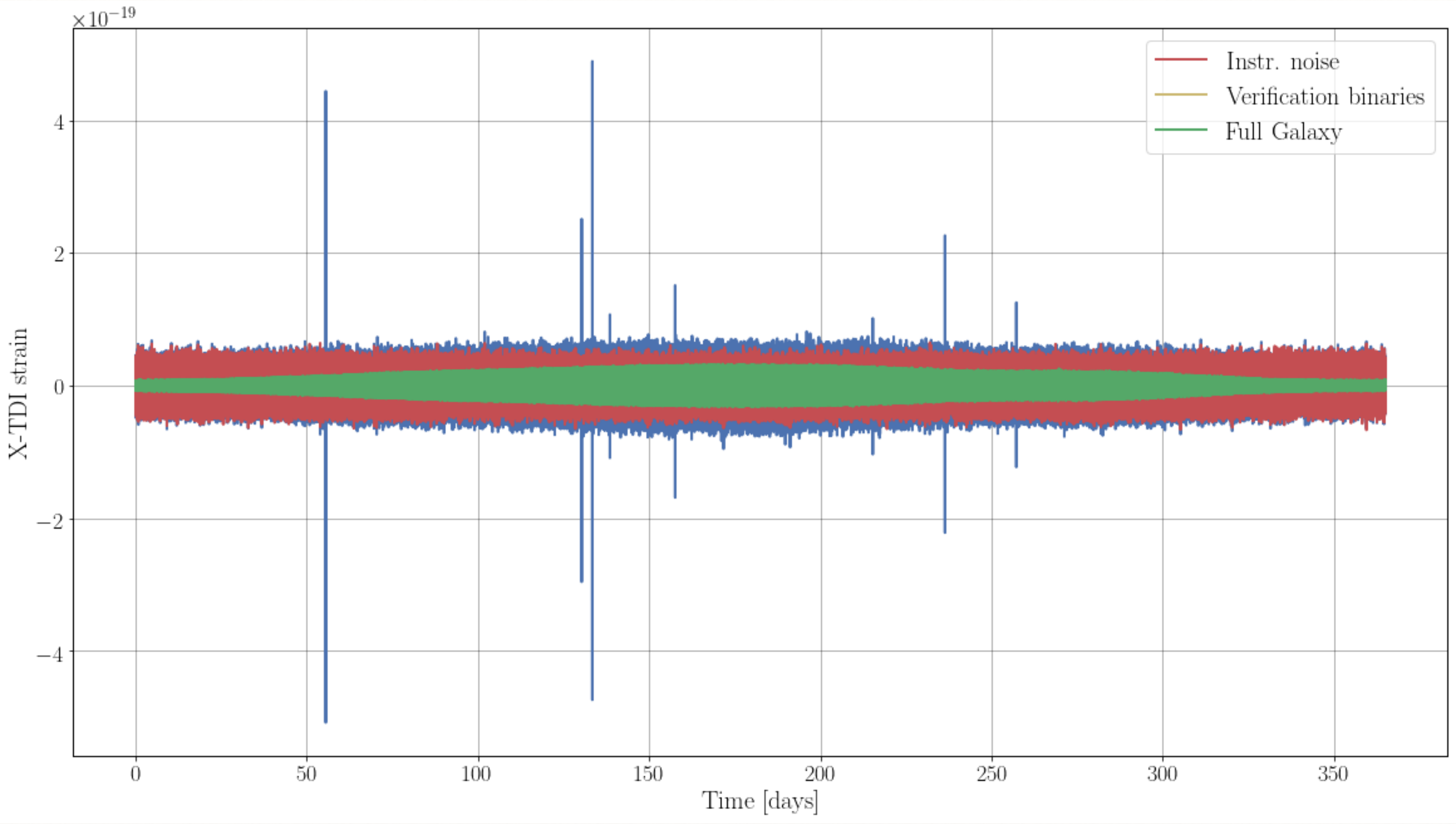
Simulated LISA data in time domain



Simulated LISA data in time domain

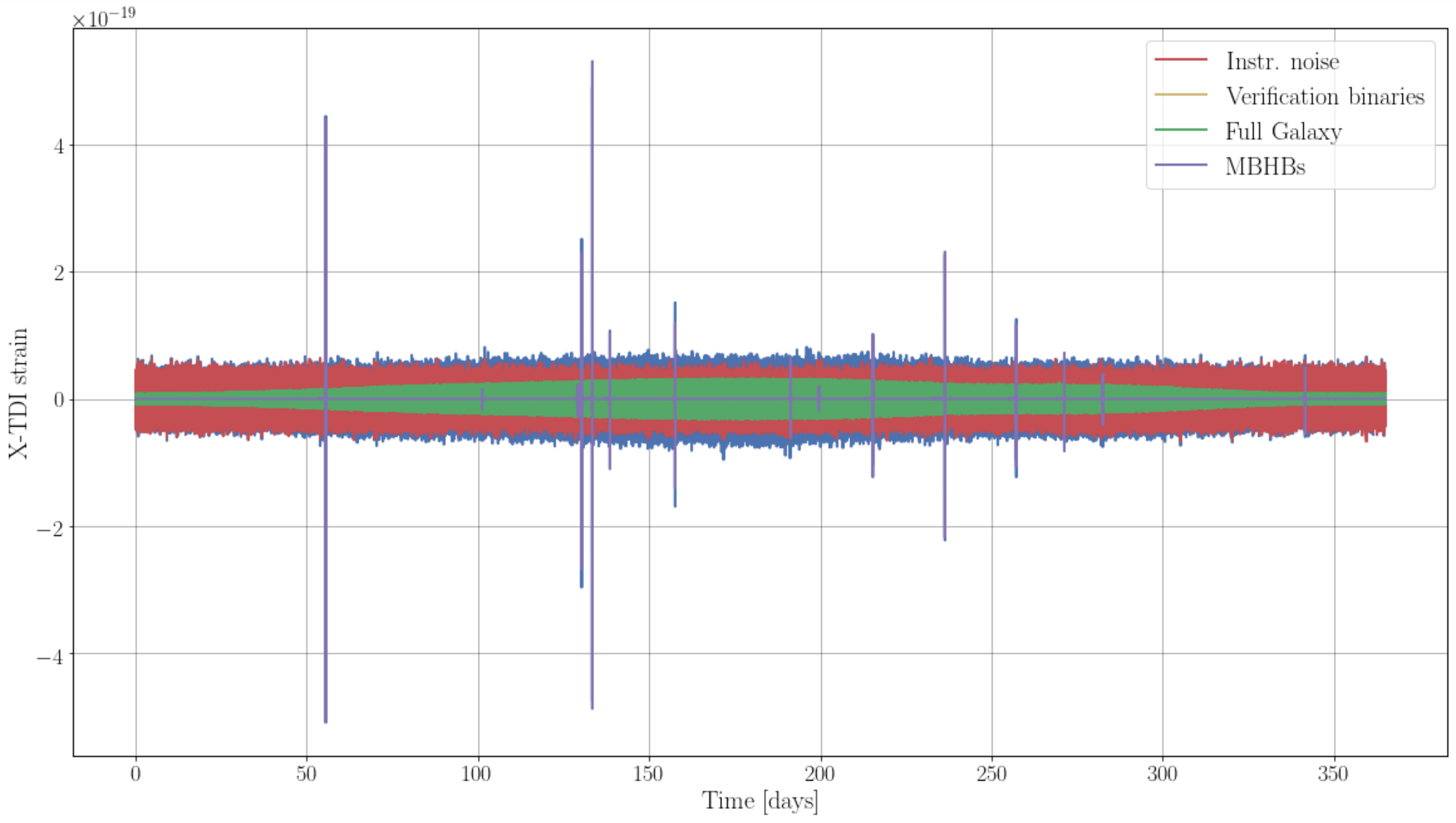


Simulated LISA data in time domain



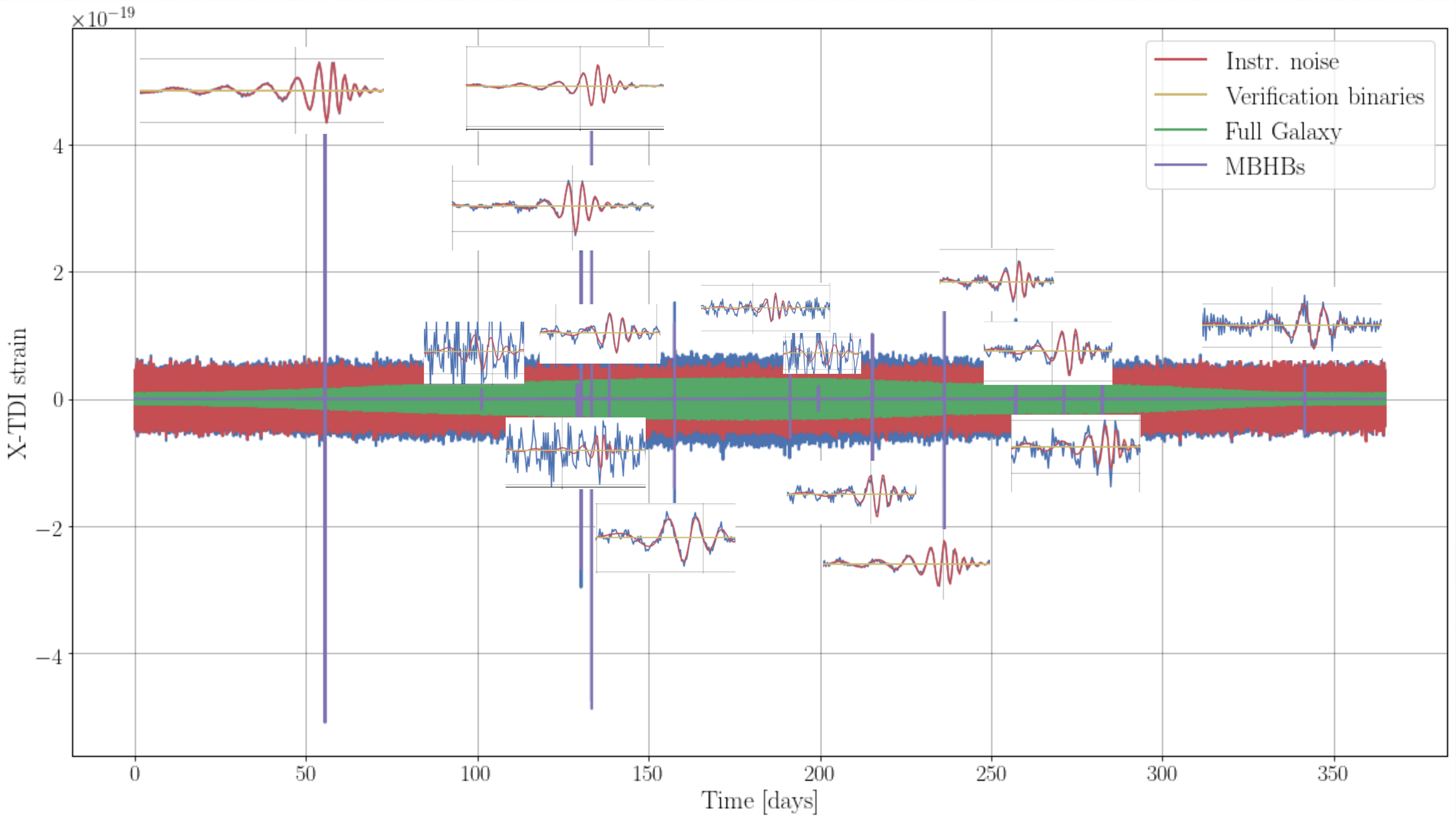
lisa

Simulated LISA data in time domain



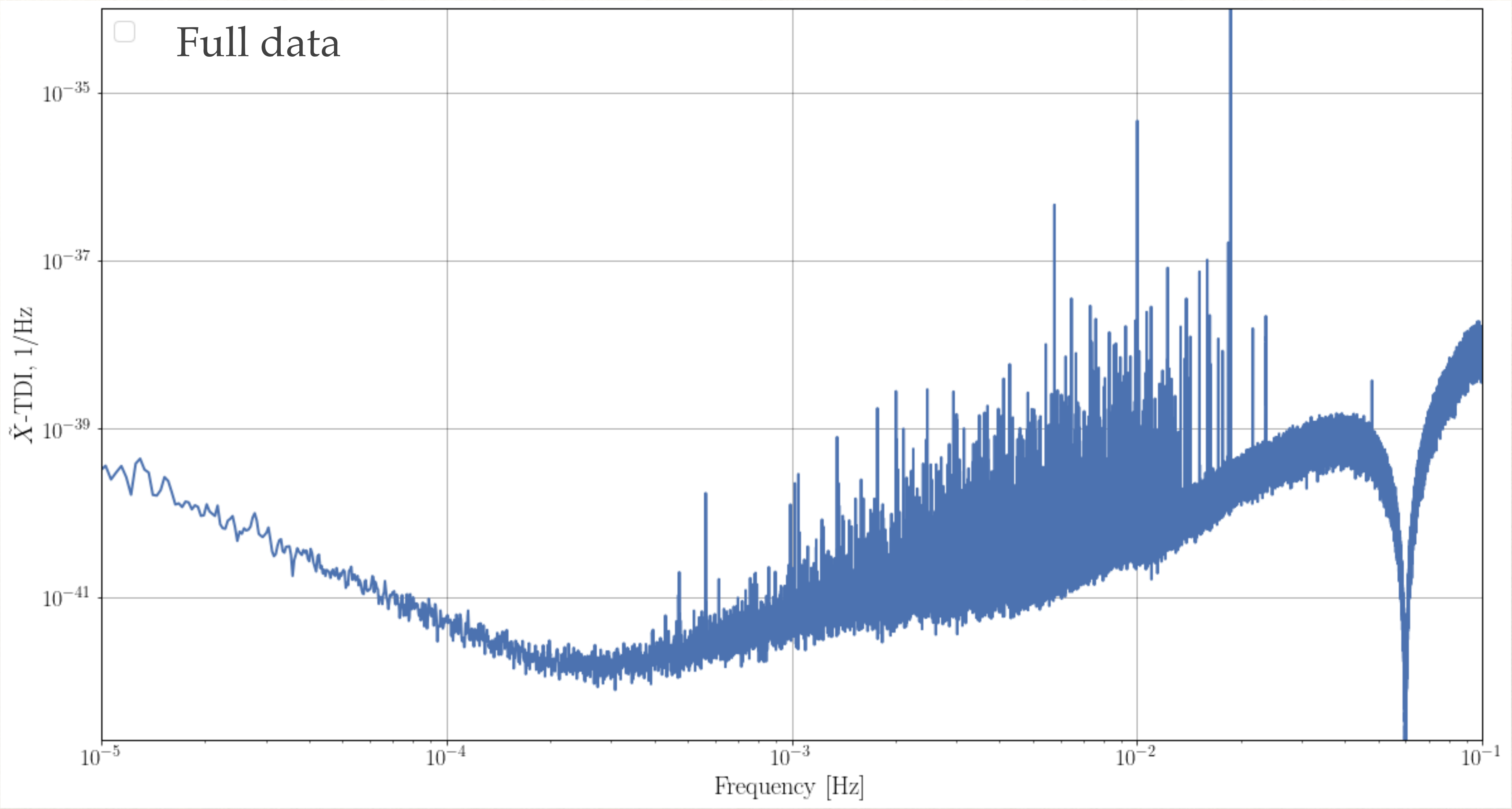
lisa

Simulated LISA data in time domain



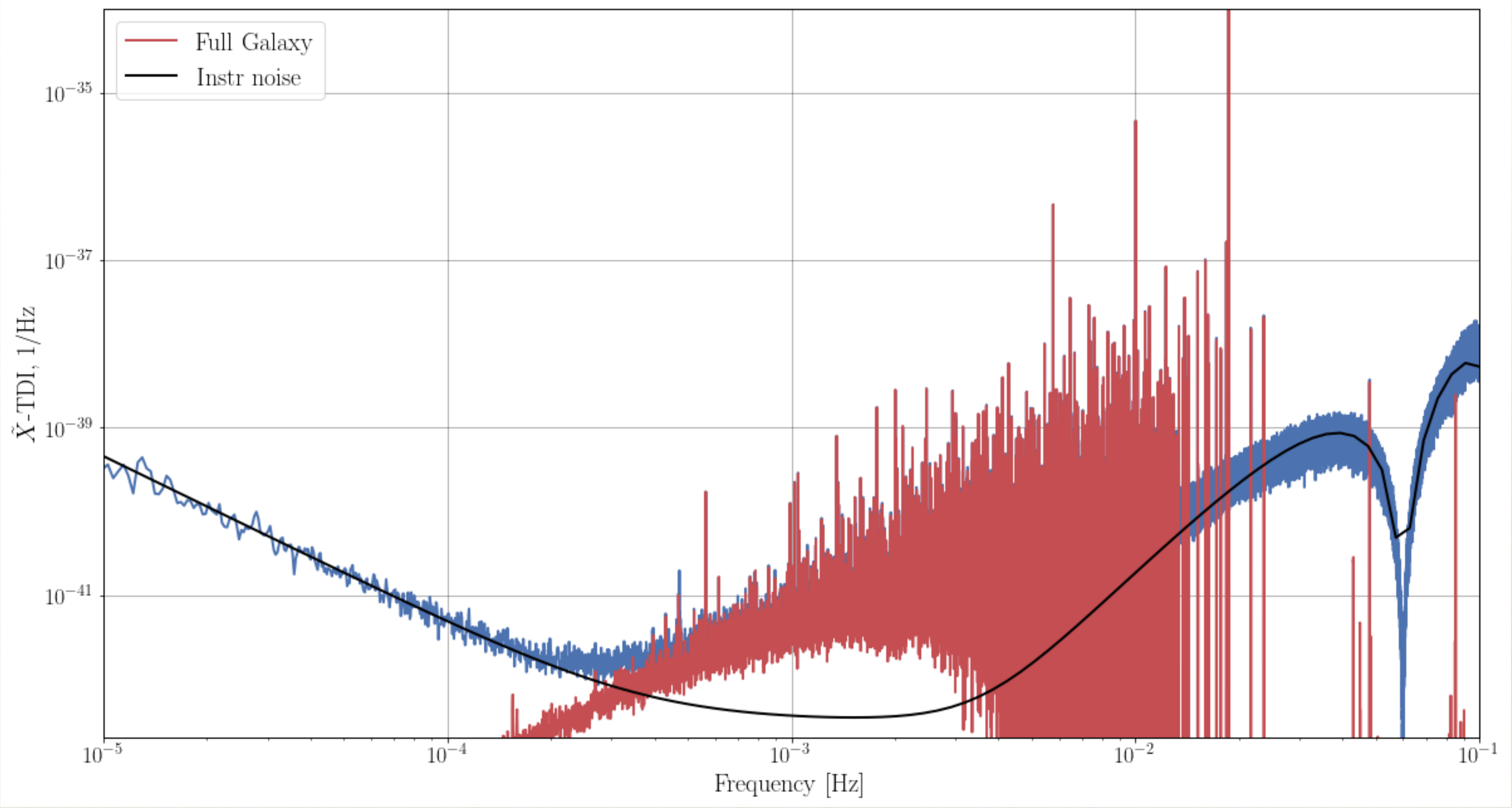
lisa

Simulated LISA data in frequency domain



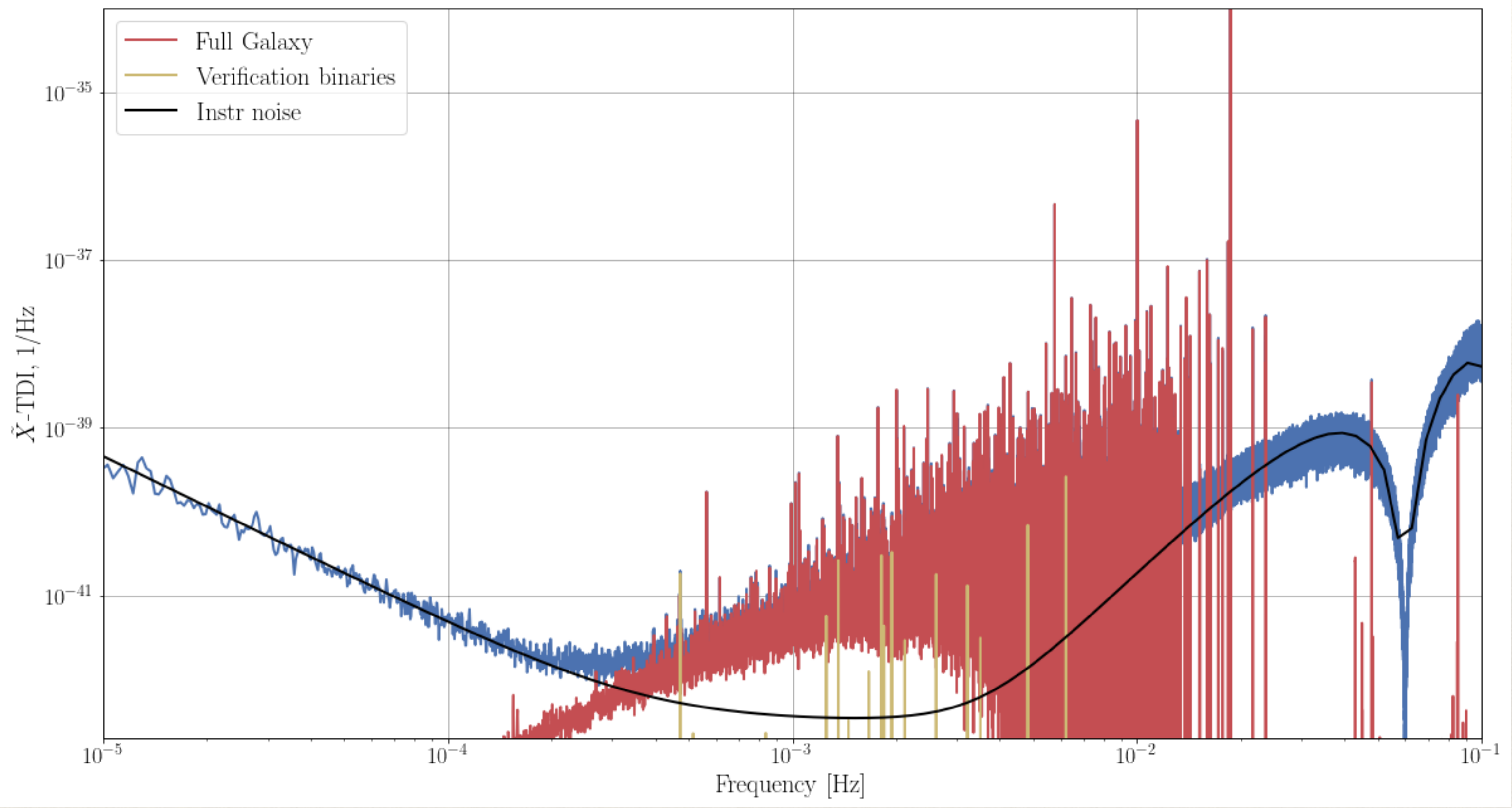
lisa

“Sangria” in frequency domain



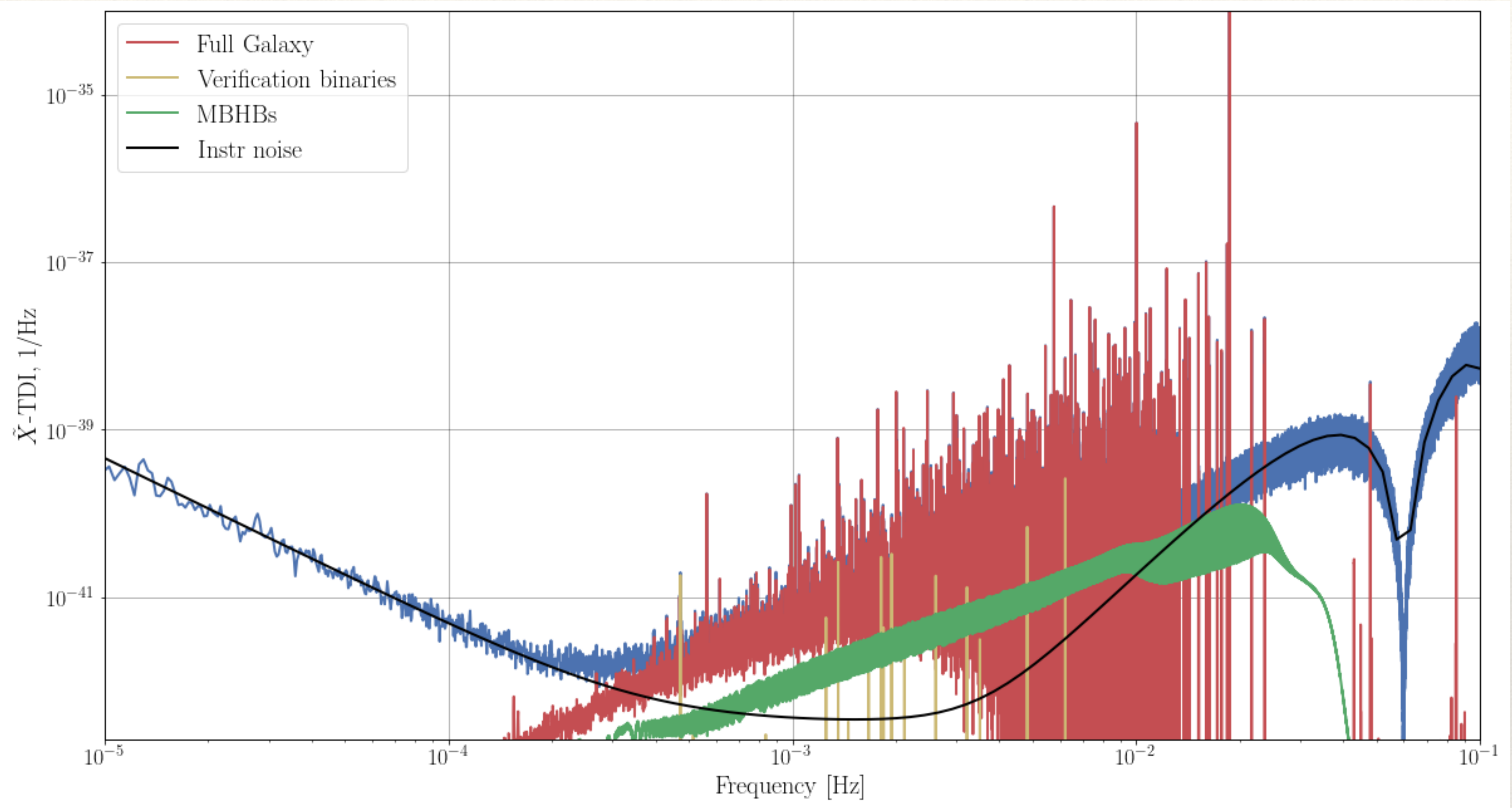
lisa

“Sangria” in frequency domain



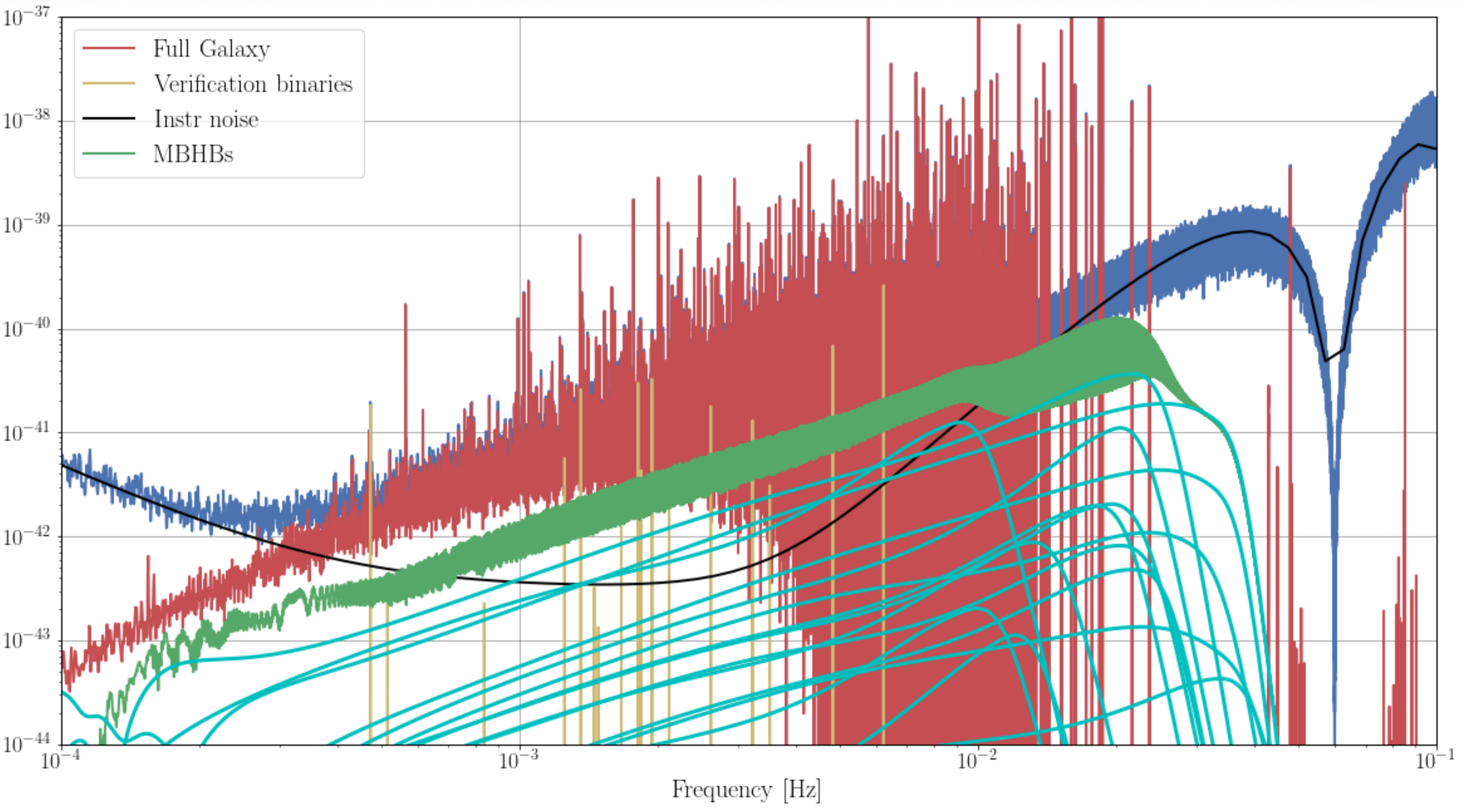
lisa

“Sangria” in frequency domain



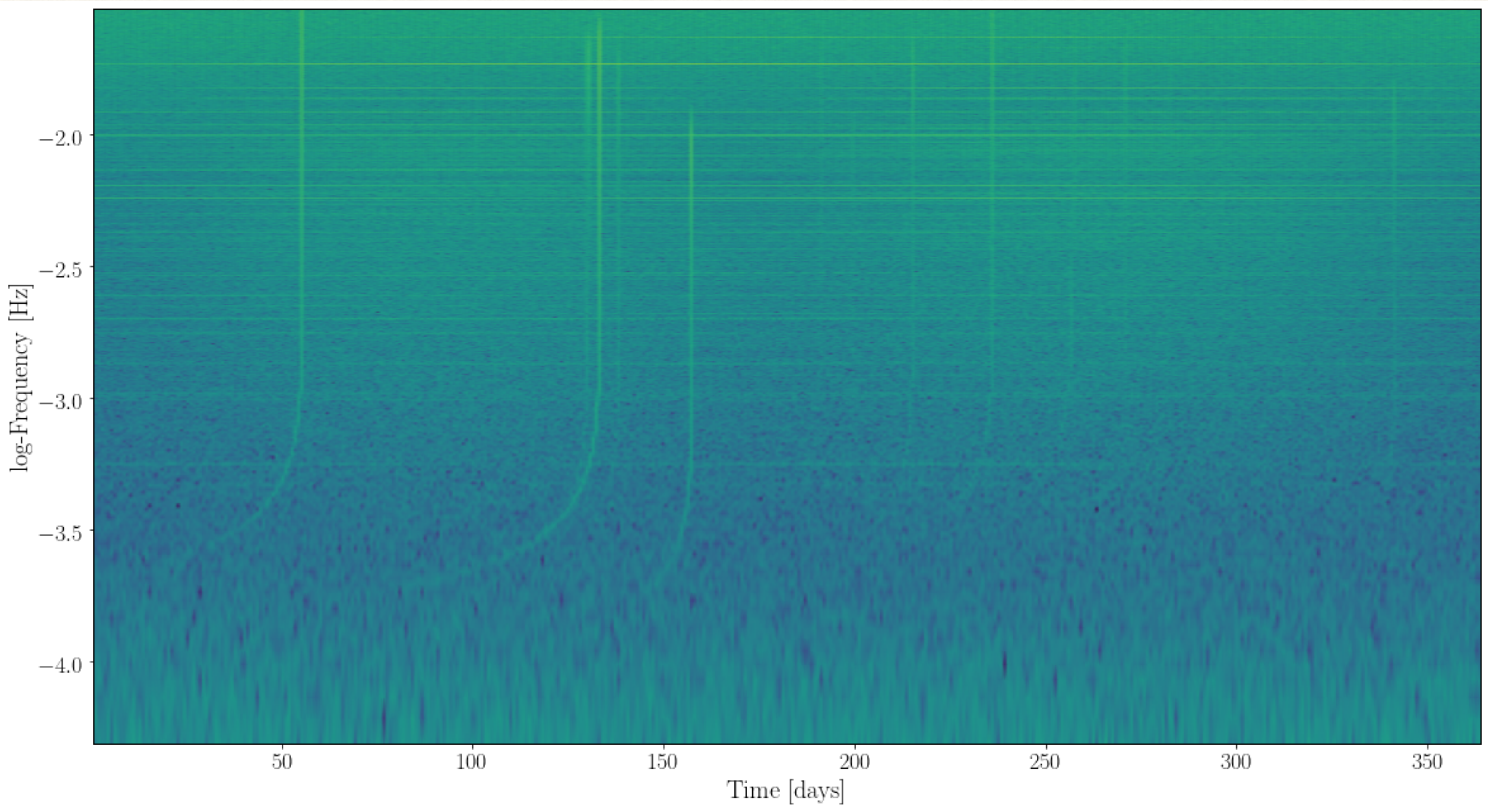
lisa

“Sangria” in frequency domain



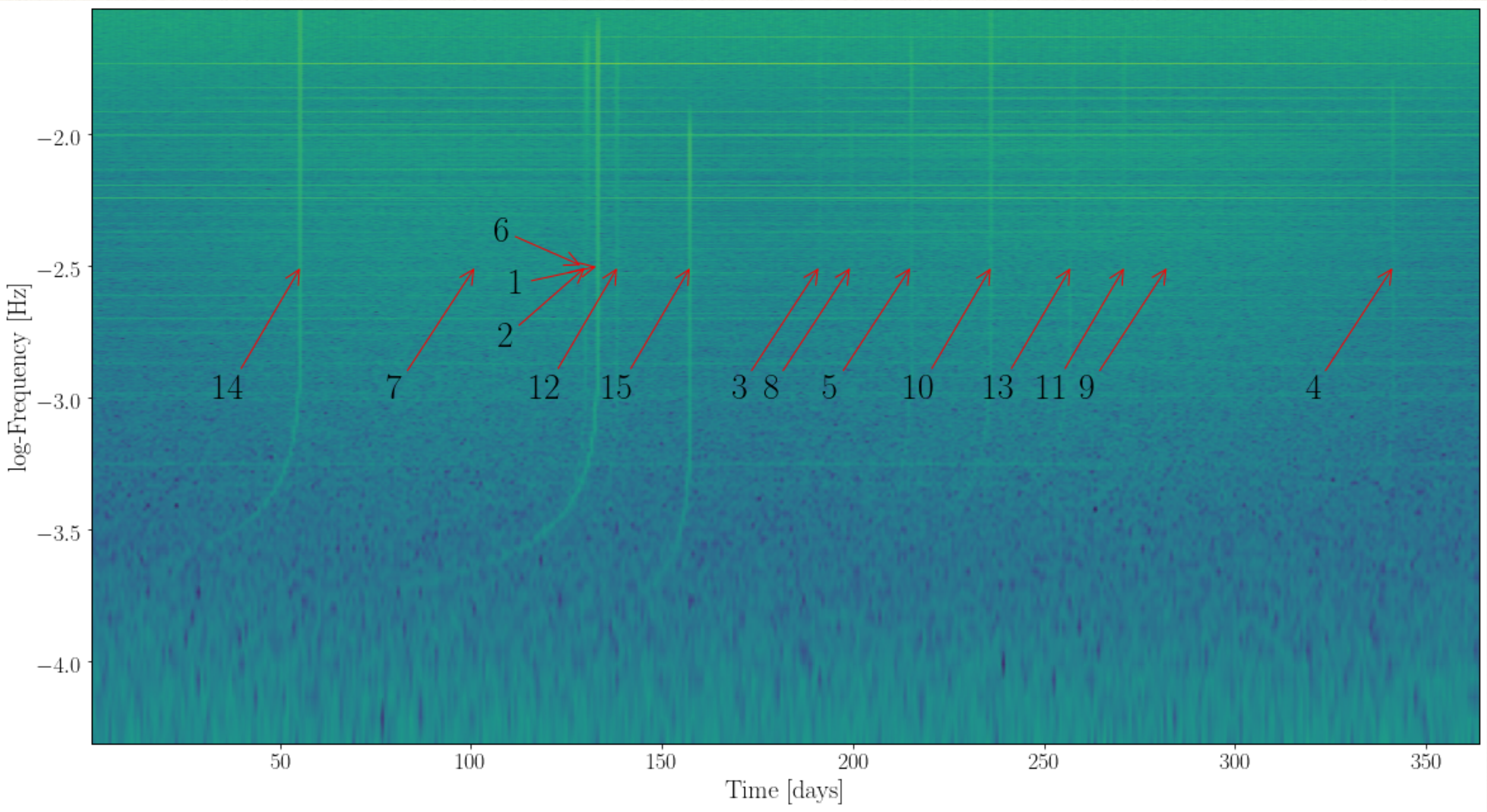
lisa

"Sangria" in time-frequency



lisa

“Sangria” in time-frequency



LISA: summary

- LISA: ESA lead mission to be launched in 2034 — your mission, your data
- Data is source dominated, GW signals are strong and long lived
- Possibility of simultaneous observations with ATHENA (X-Ray)
- Multi-band observations of stellar mass black holes
- Testing GR with amazing accuracy
- Looking at the hearts of galaxies far-far away
- Side science: exoplanets in white dwarf binaries, small celestial bodies near
- Earth orbit, helioseismology (g-modes of sun)