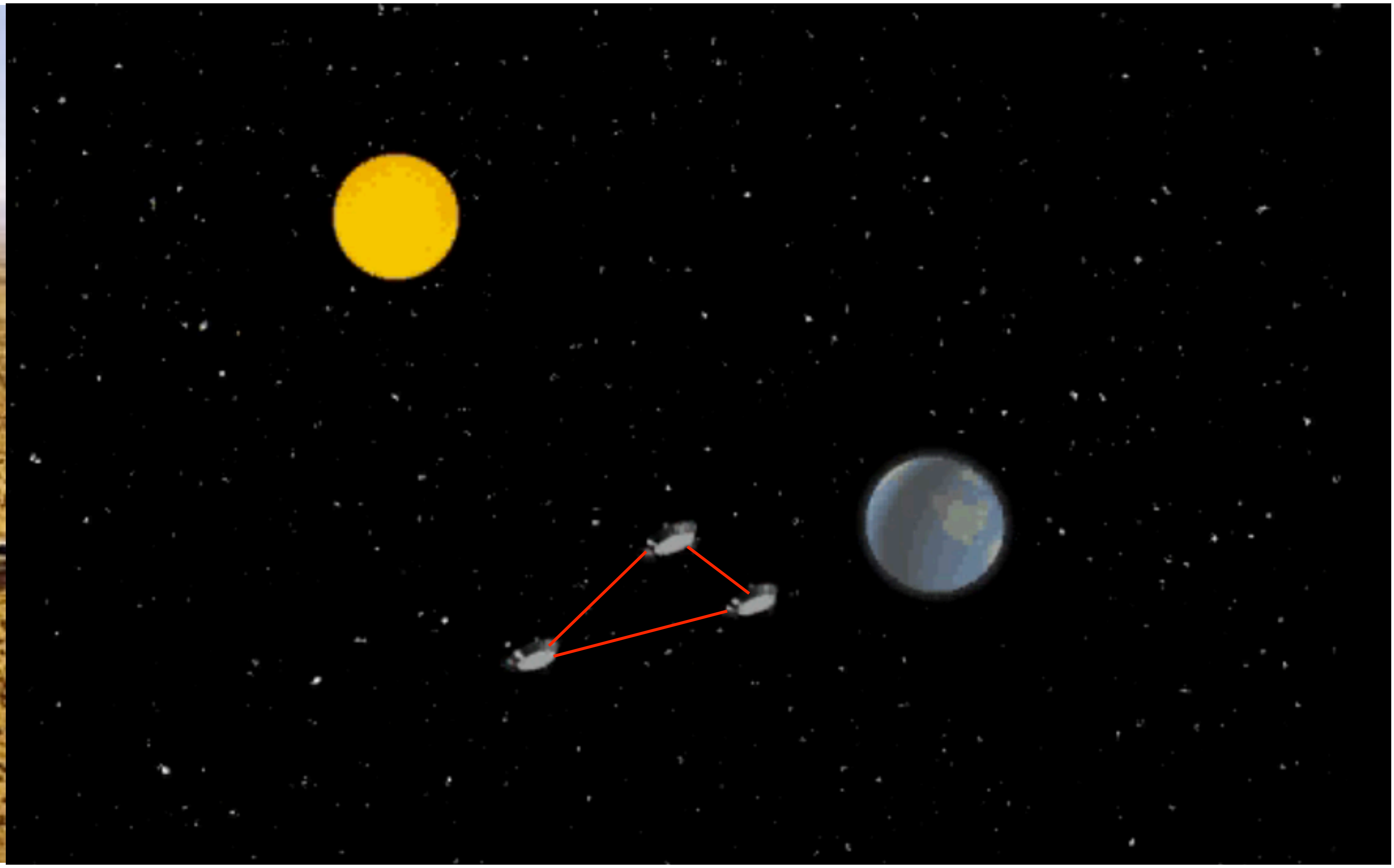
LIGO — LISA
LINKS



MONTANA STATE UNIVERSITY

Neil J. Cornish

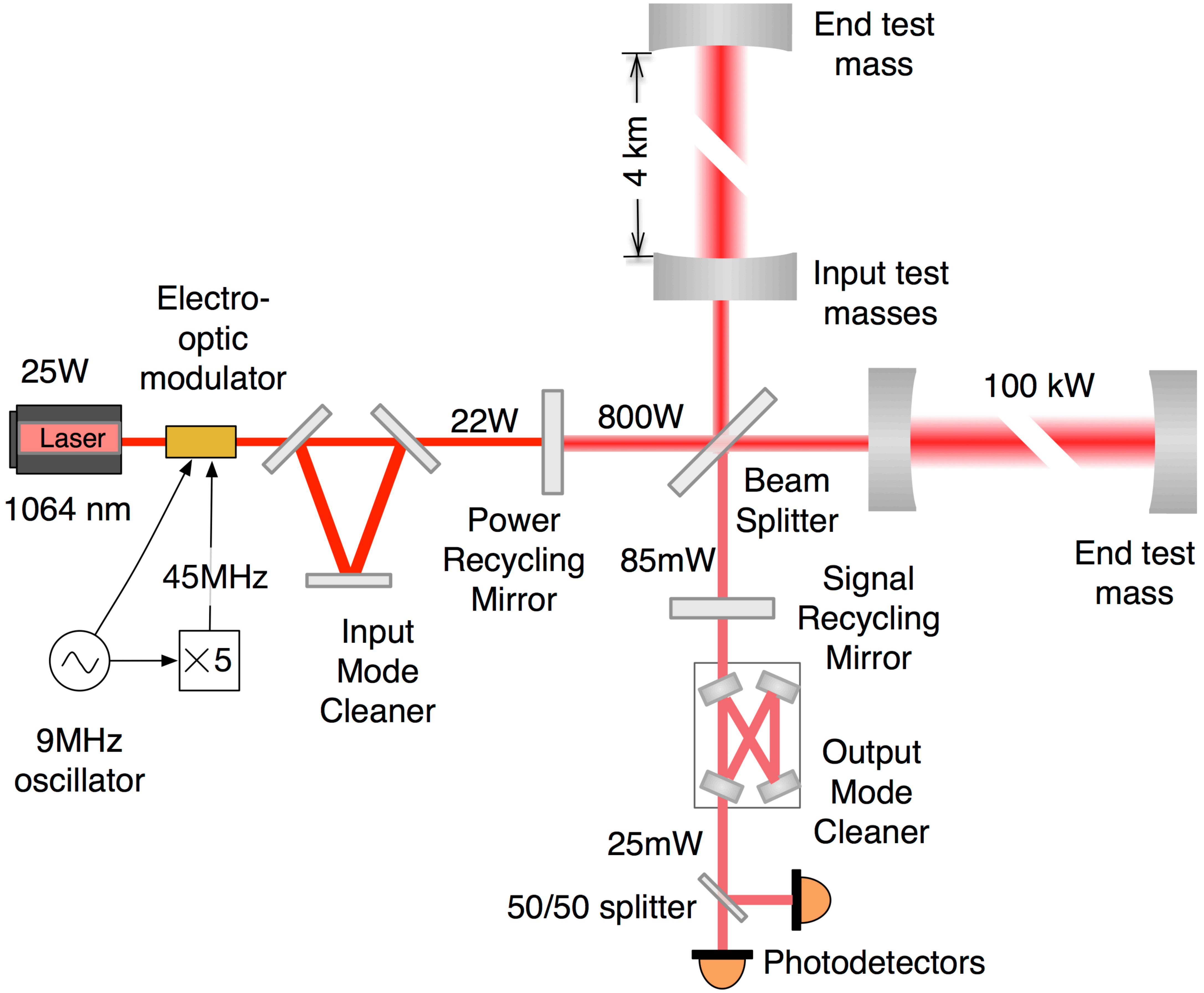
eXtreme Gravity Institute

Outline

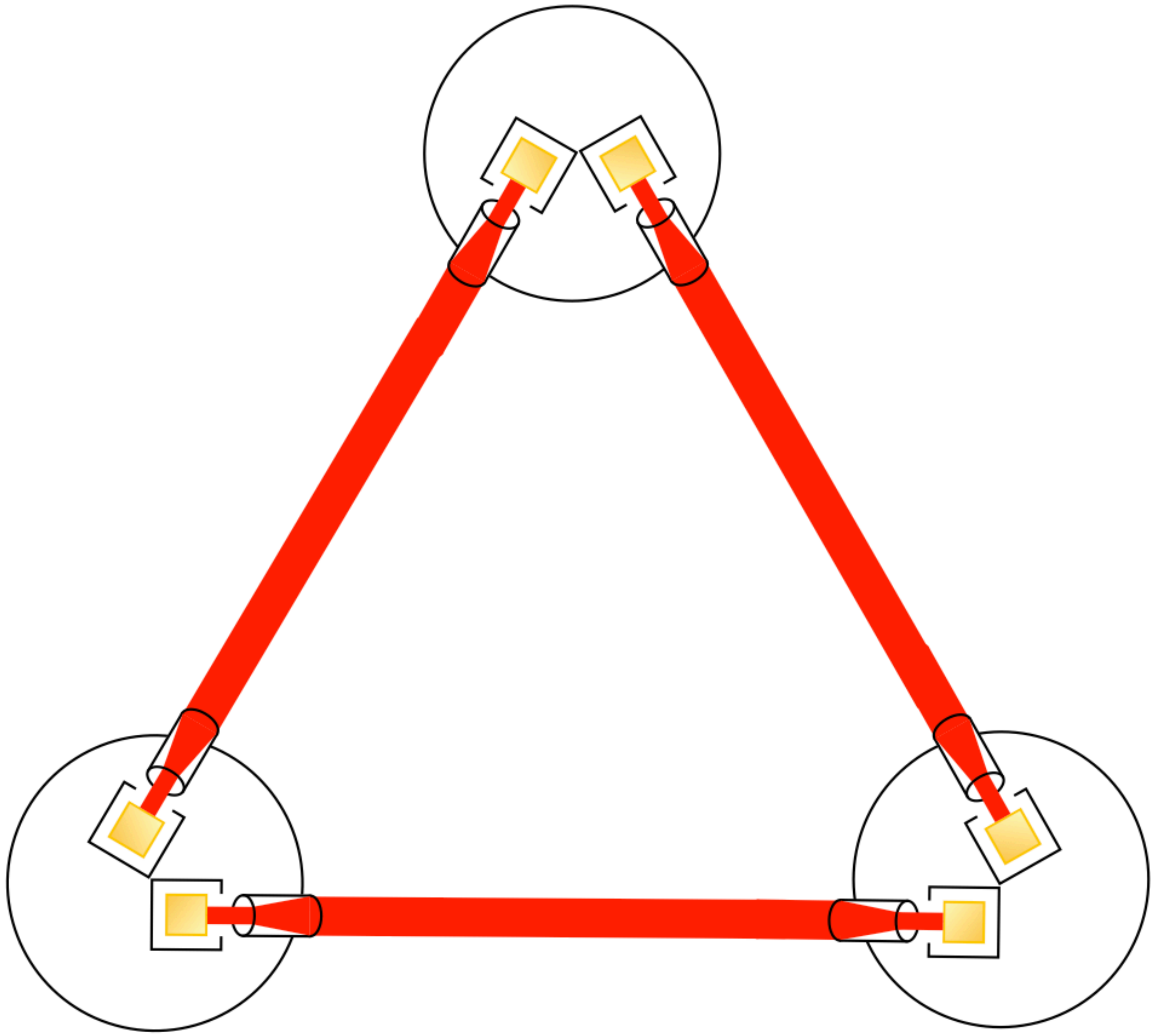
- Instruments - similarities and differences
- Sources & Science - similarities and differences
- Analysis - similarities and differences

Instruments

LIGO

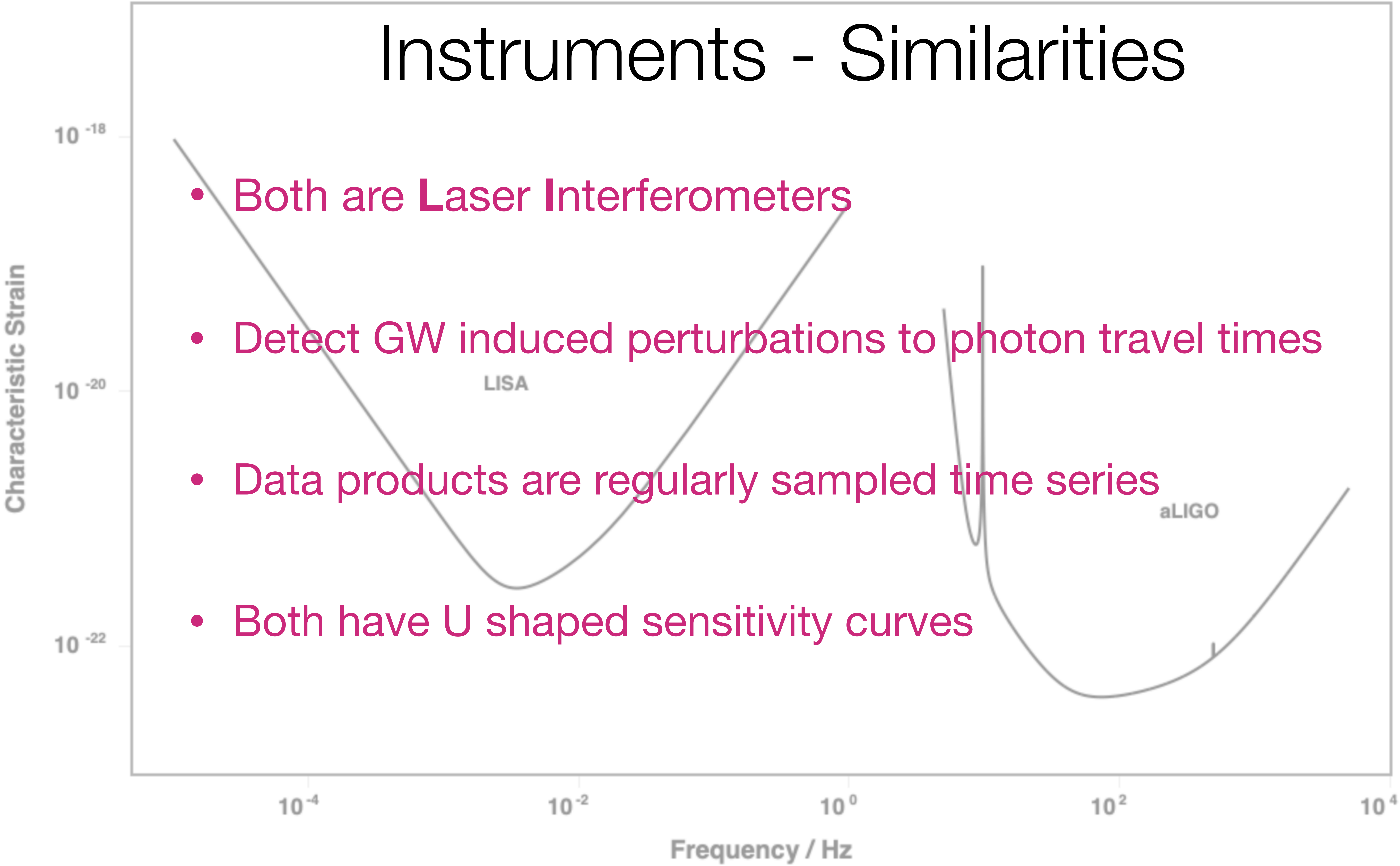


LISA



Instruments - Similarities

- Both are **L**aser **I**nterferometers
- Detect GW induced perturbations to photon travel times
- Data products are regularly sampled time series
- Both have U shaped sensitivity curves



Instruments - Differences

LIGO

Ground based, repair and upgrade

High power, resonant cavity, optical spring

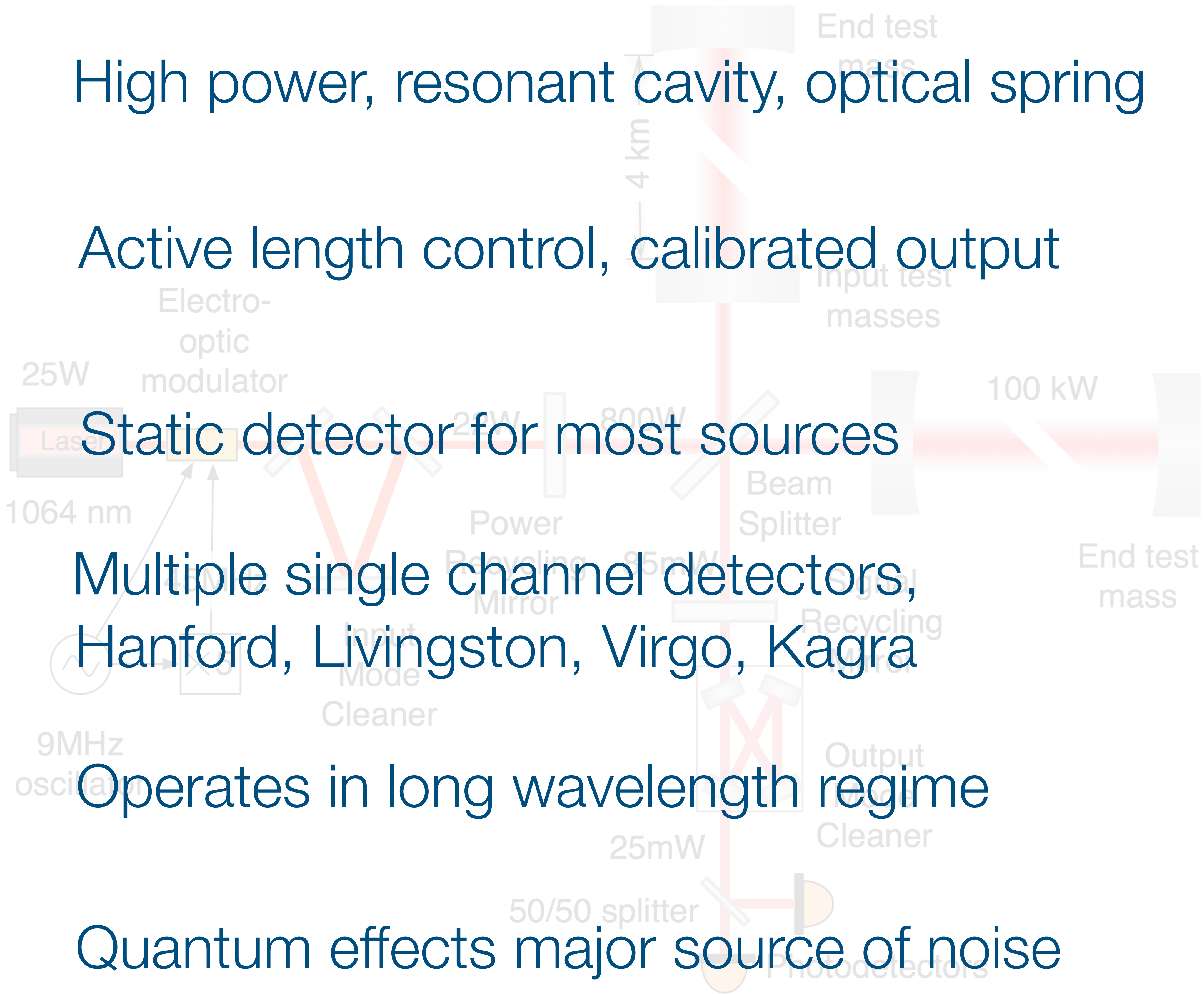
Active length control, calibrated output

Static detector for most sources

Multiple single channel detectors, Hanford, Livingston, Virgo, Kagra

Operates in long wavelength regime

Quantum effects major source of noise



LISA

Space based, one shot to get it right

Low power, single pass

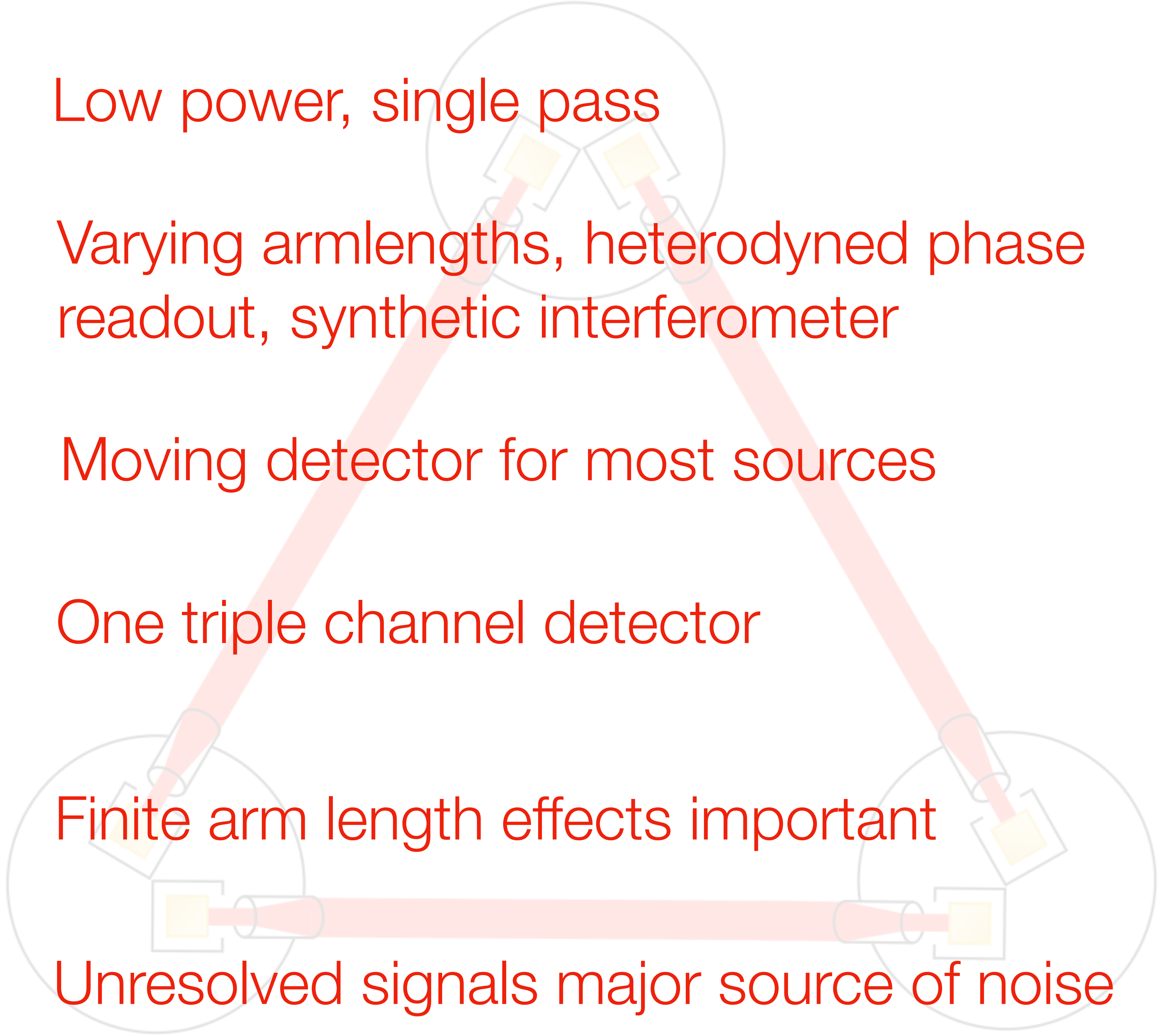
Varying armlengths, heterodyned phase readout, synthetic interferometer

Moving detector for most sources

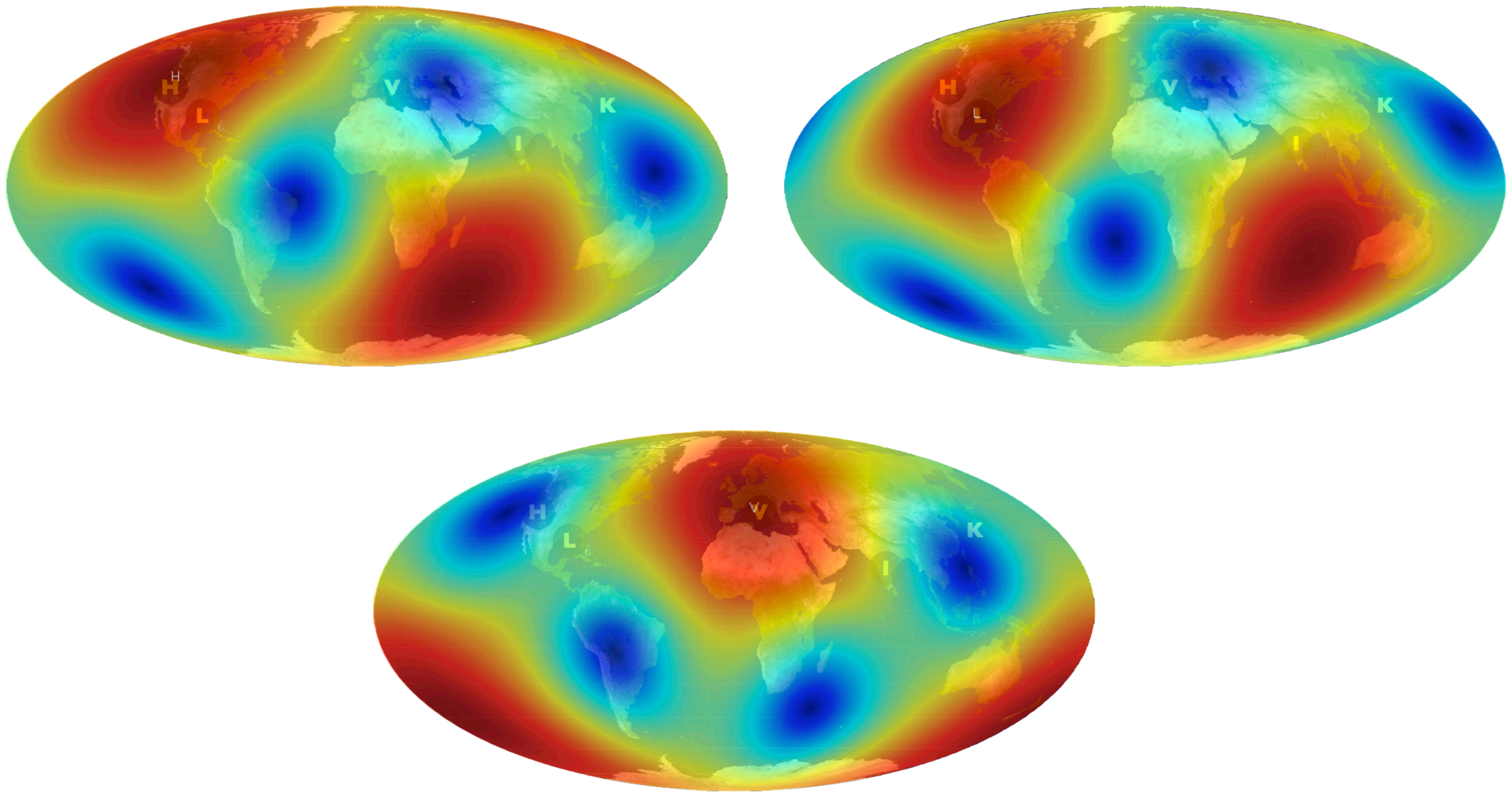
One triple channel detector

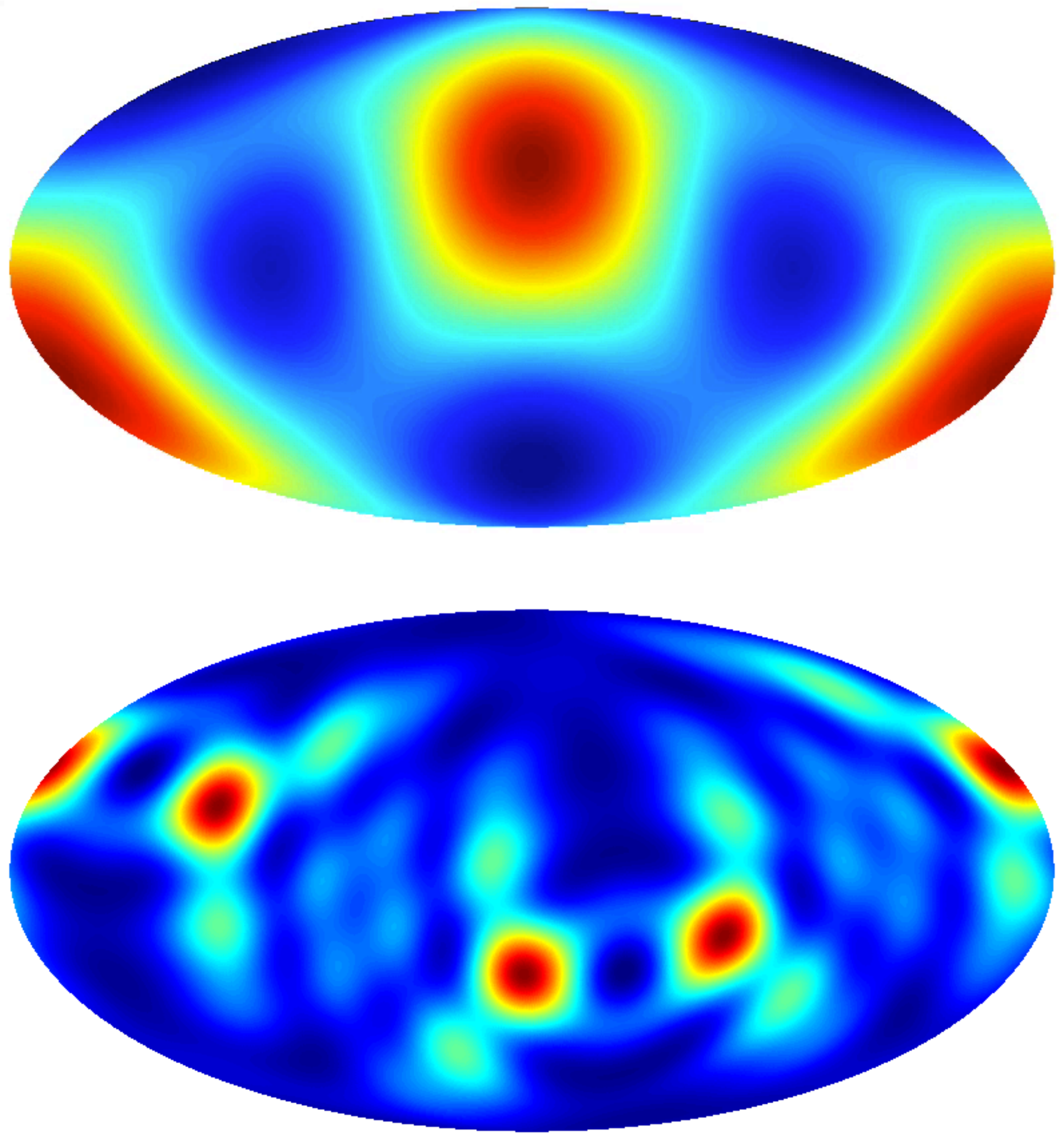
Finite arm length effects important

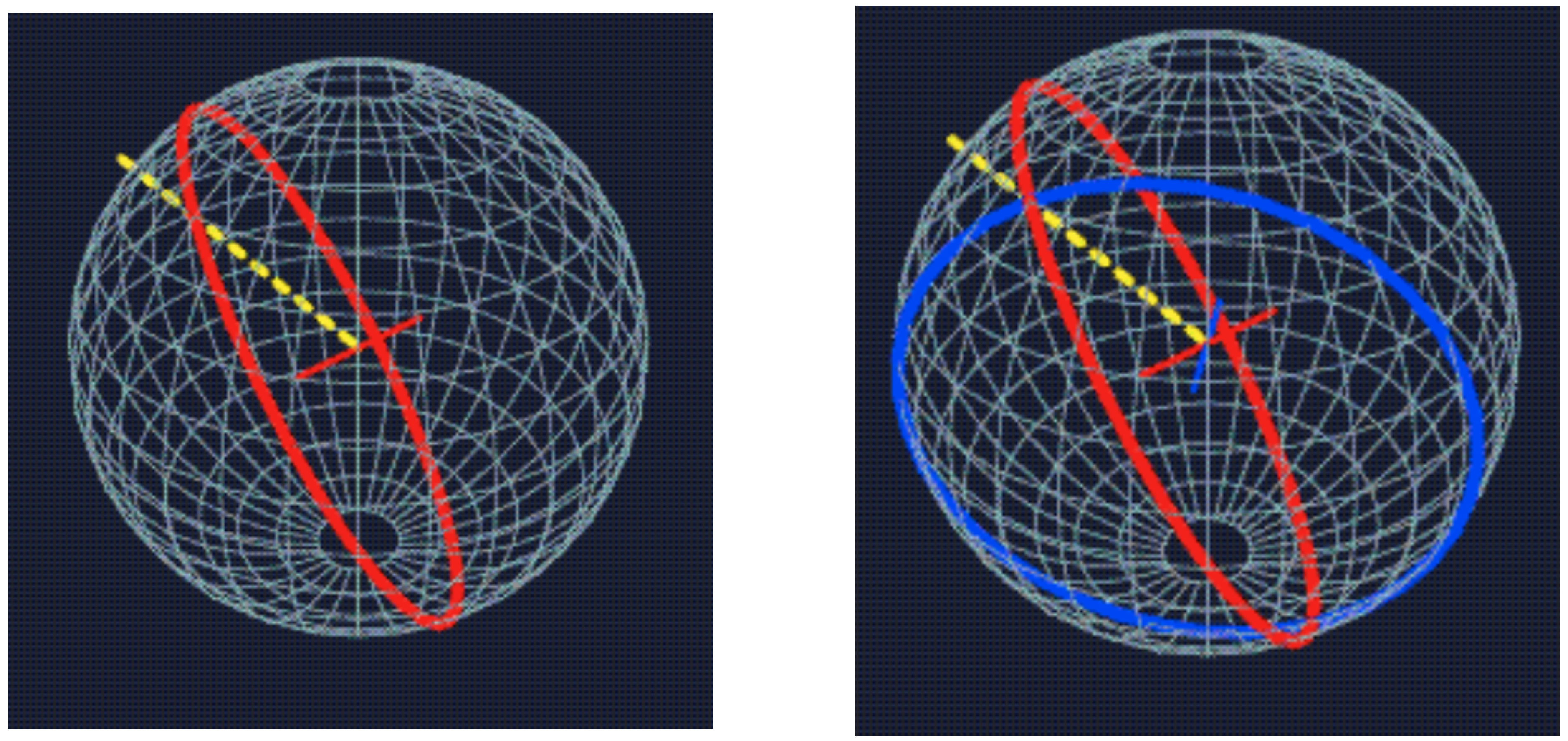
Unresolved signals major source of noise

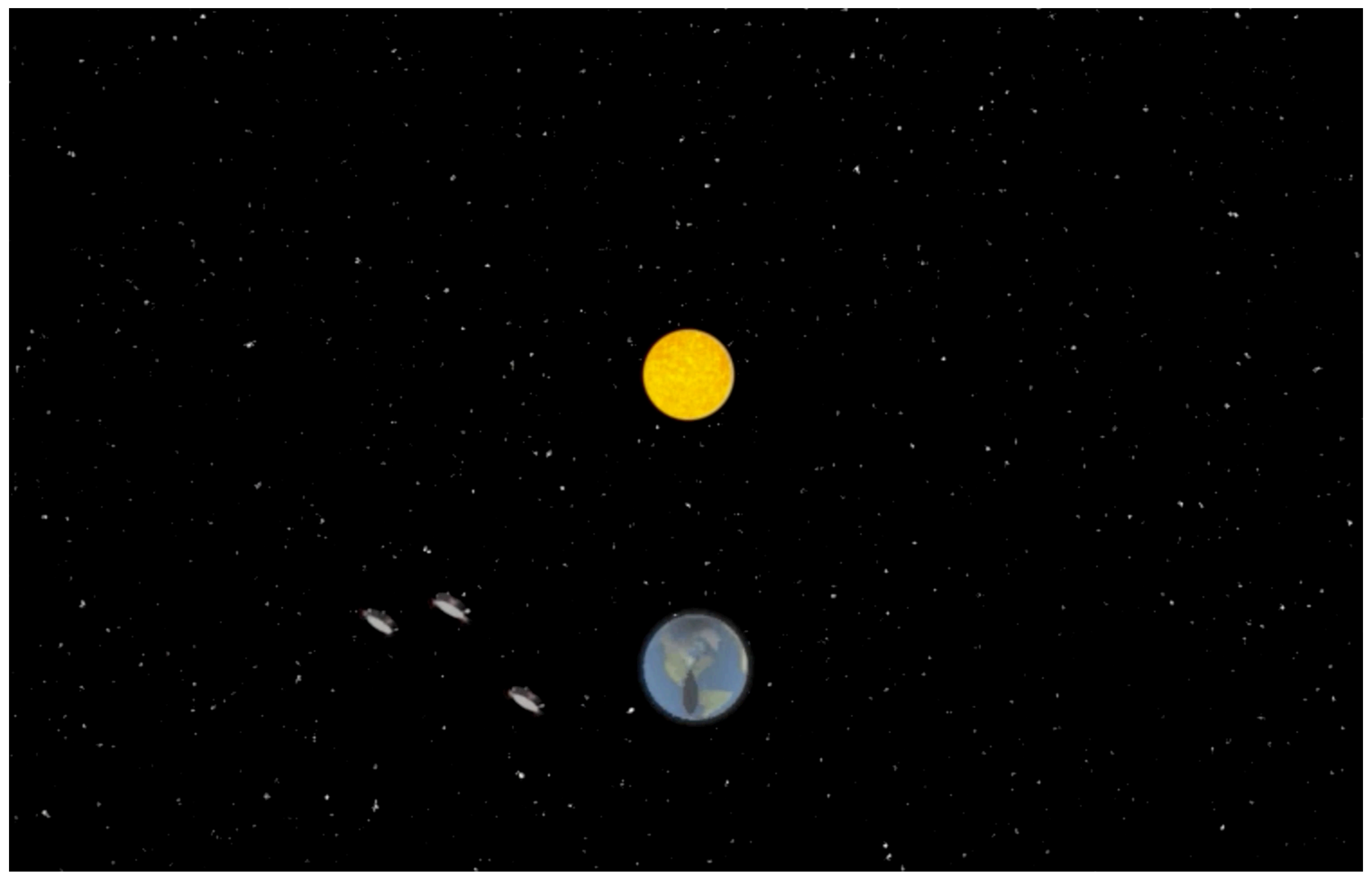


Source Localization



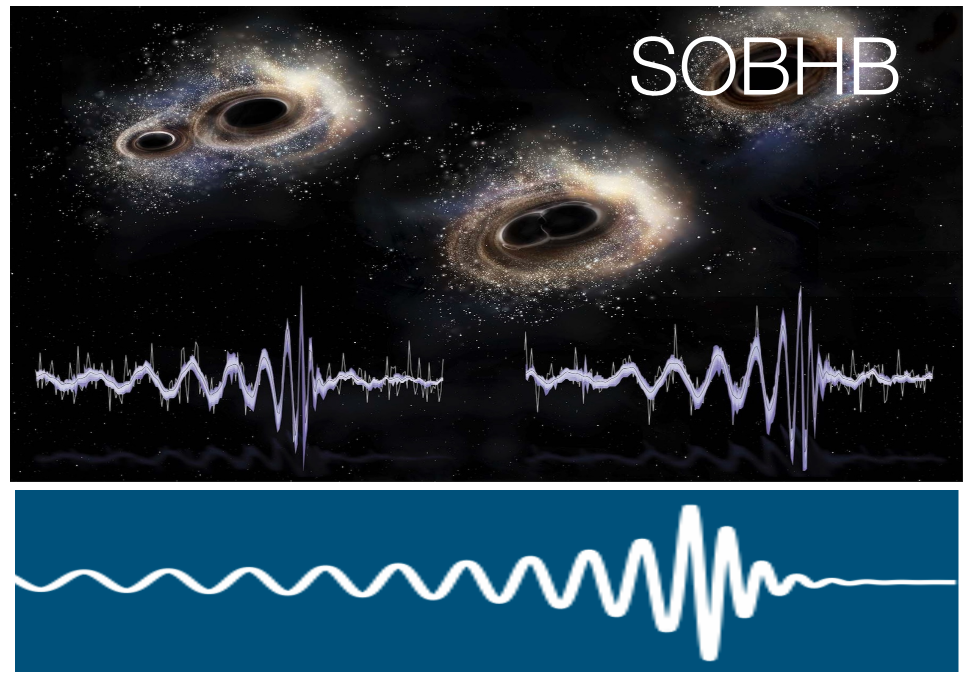


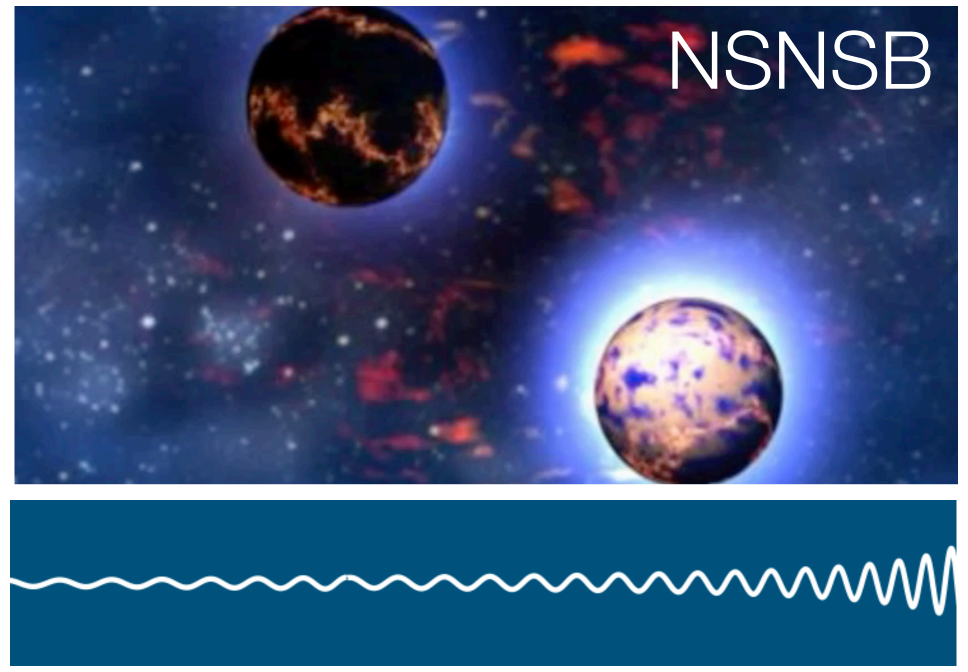


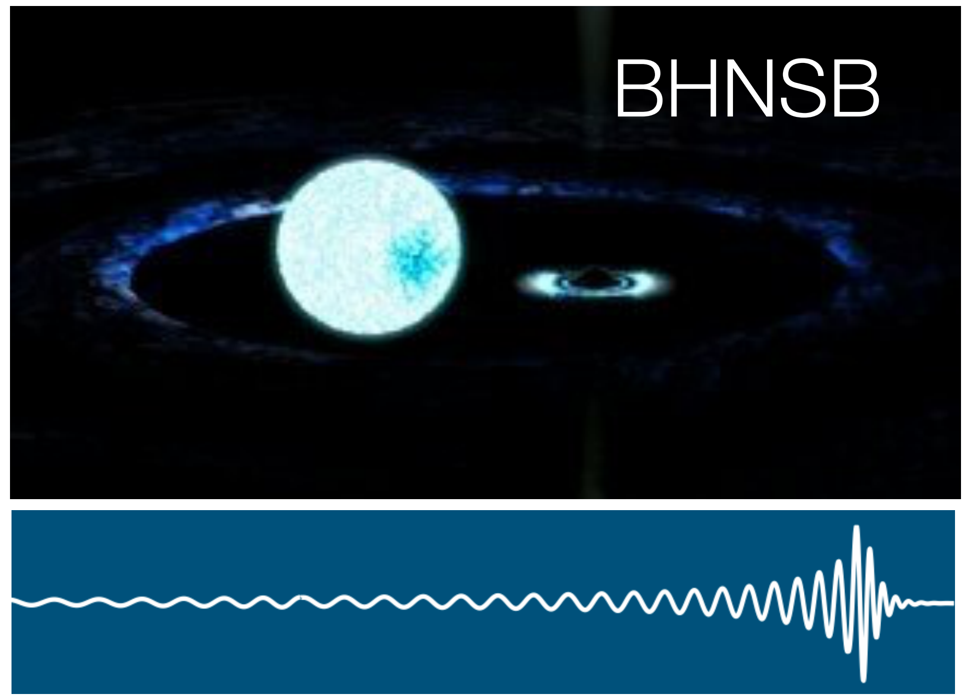


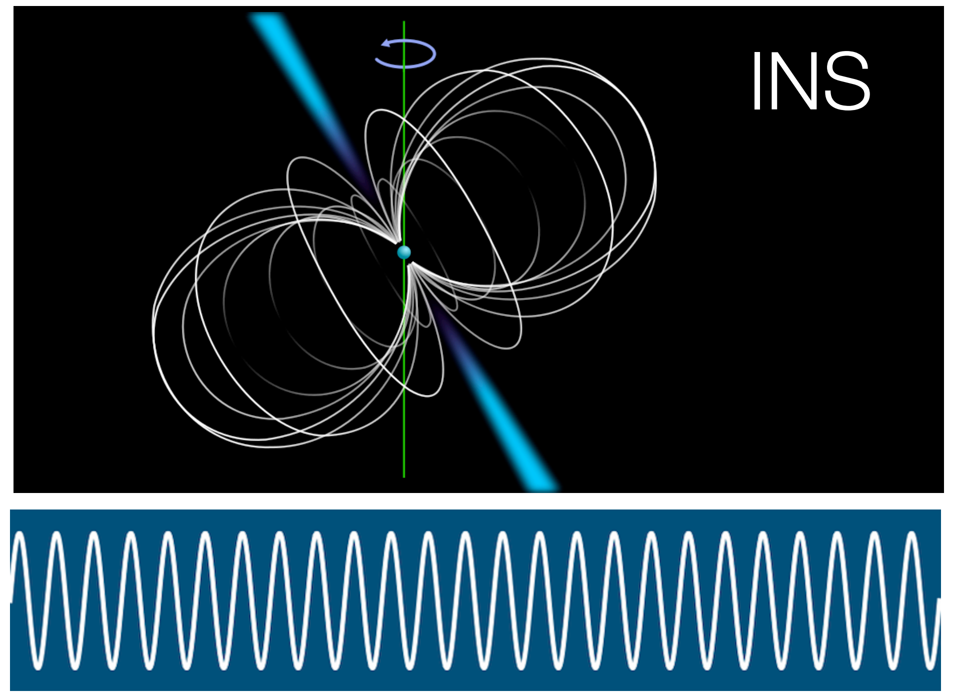
Sources and Science

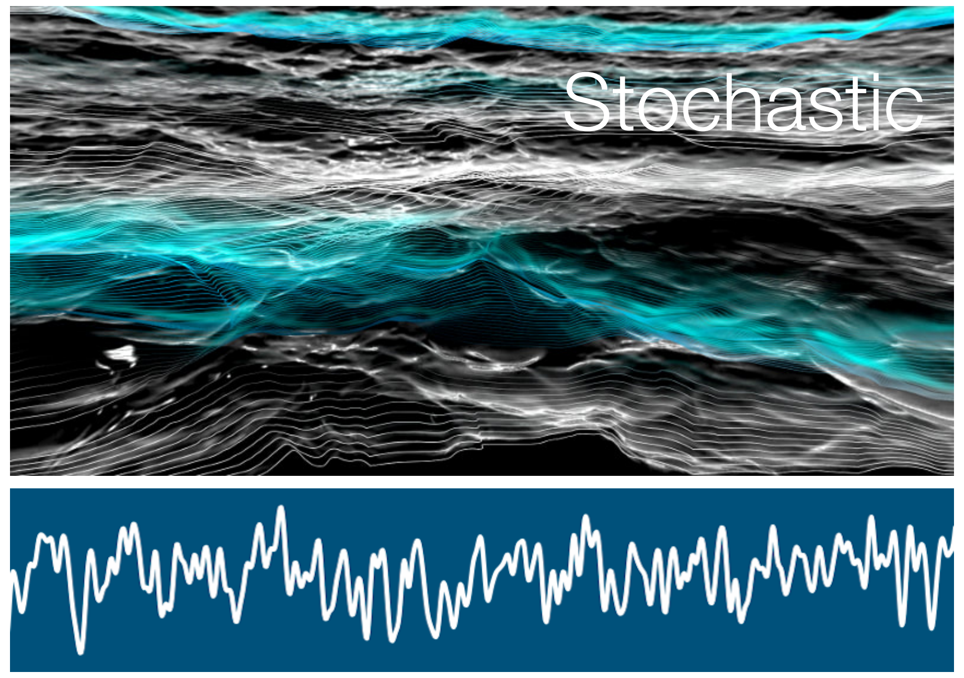
LIGO

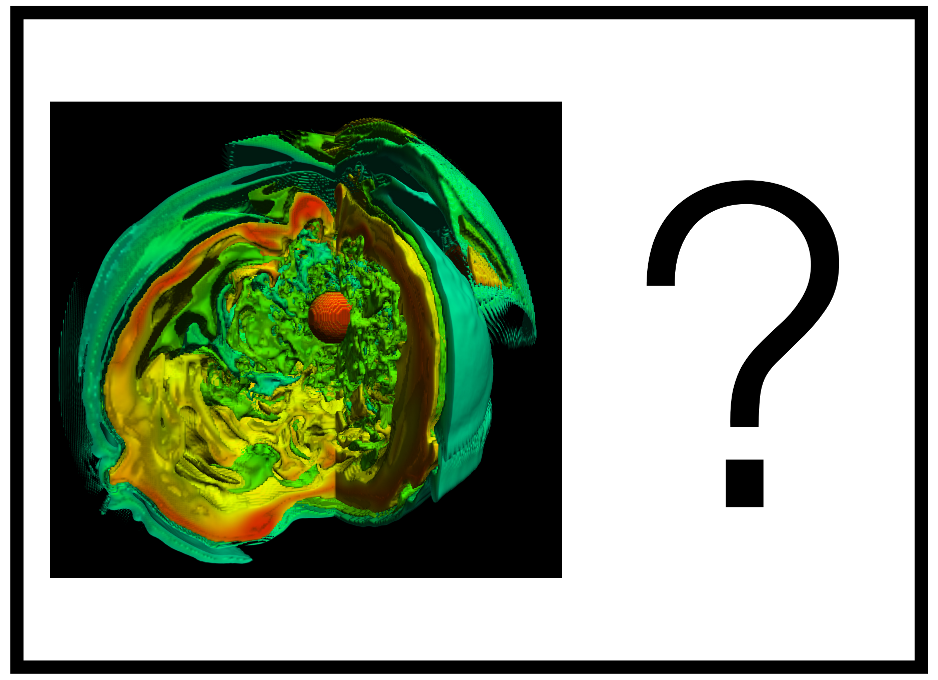




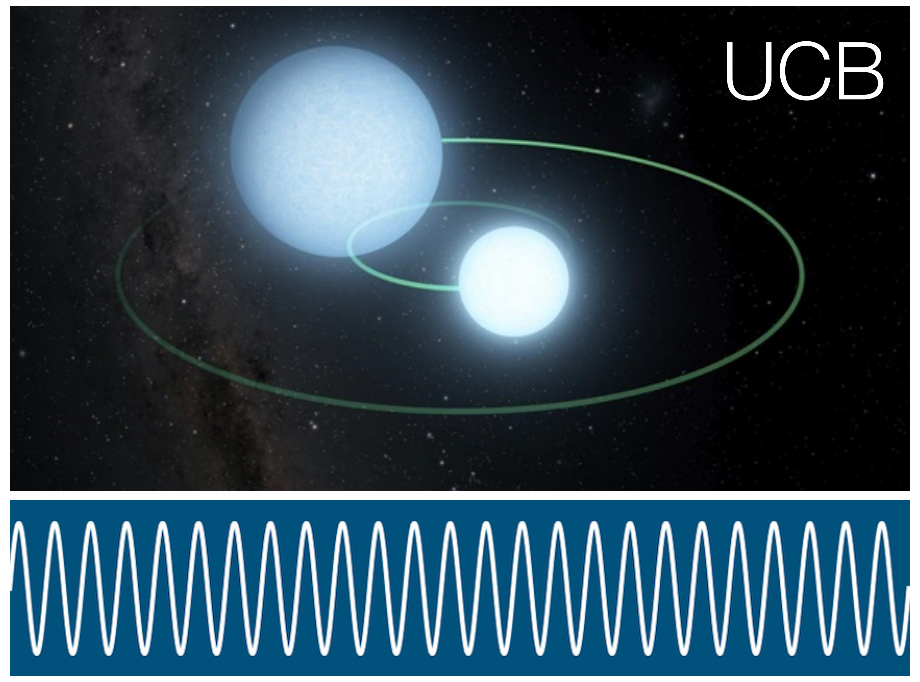


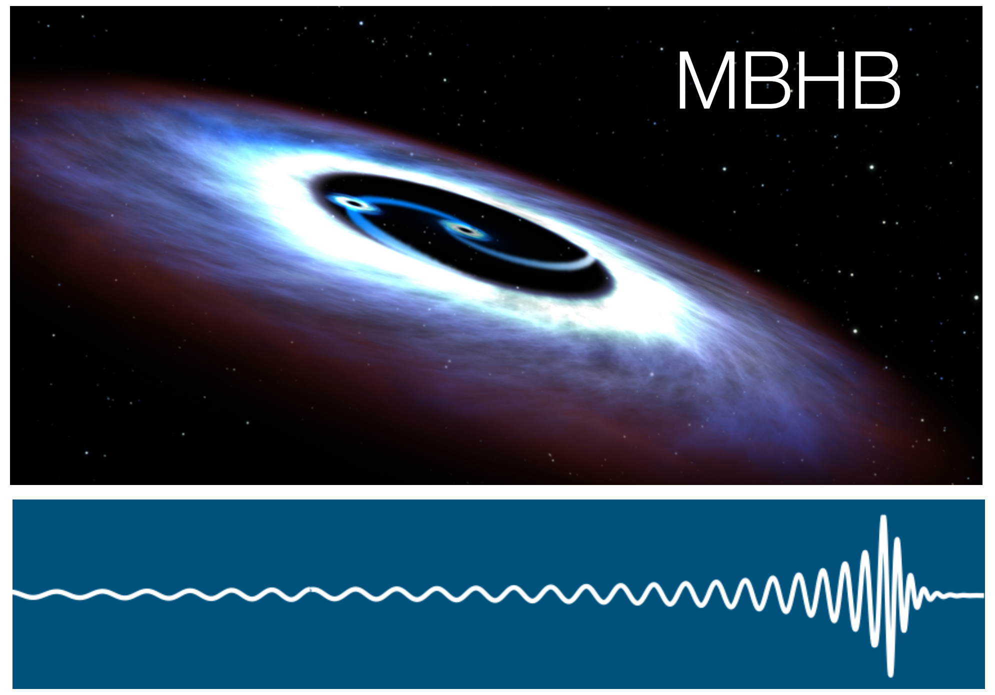


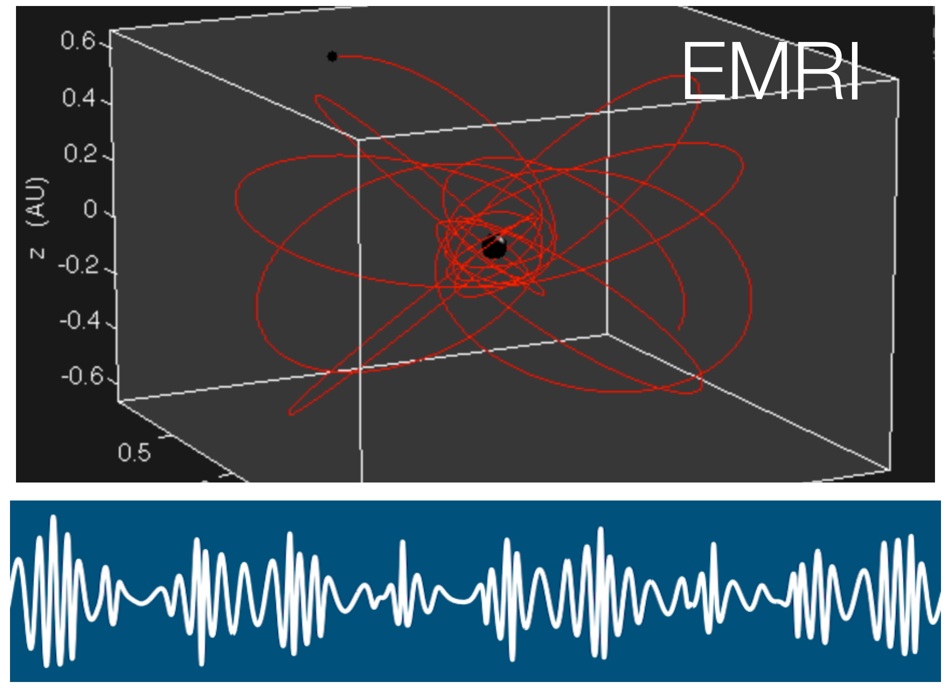


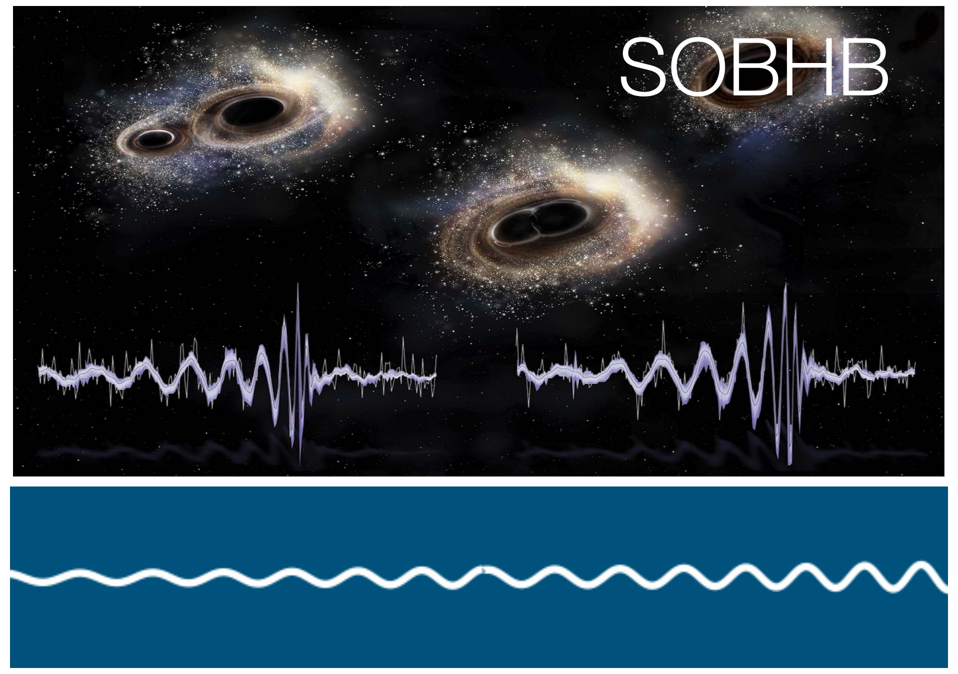


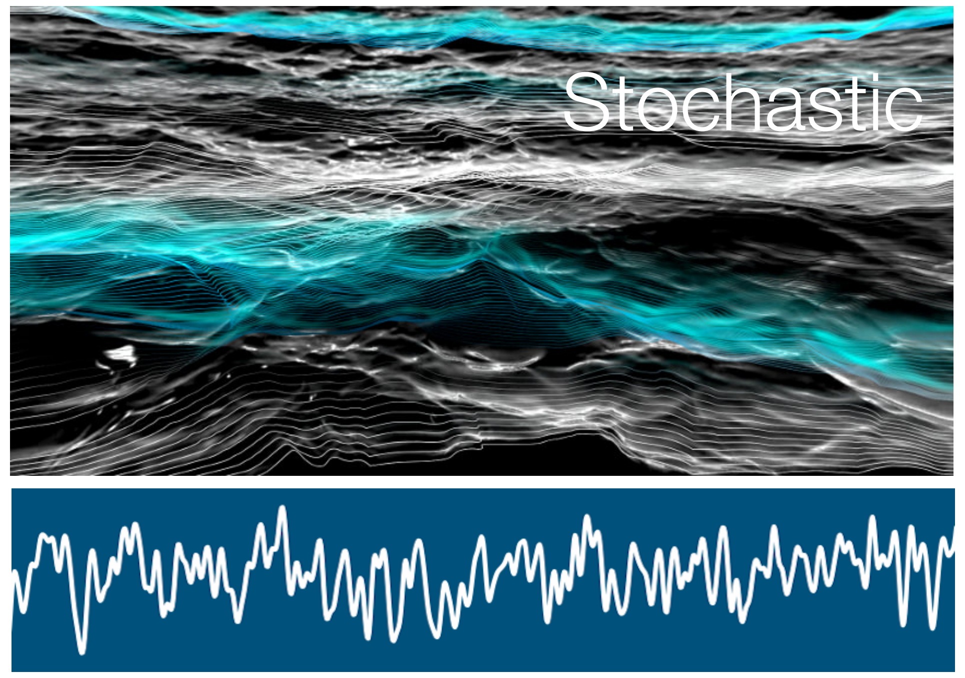
LISA

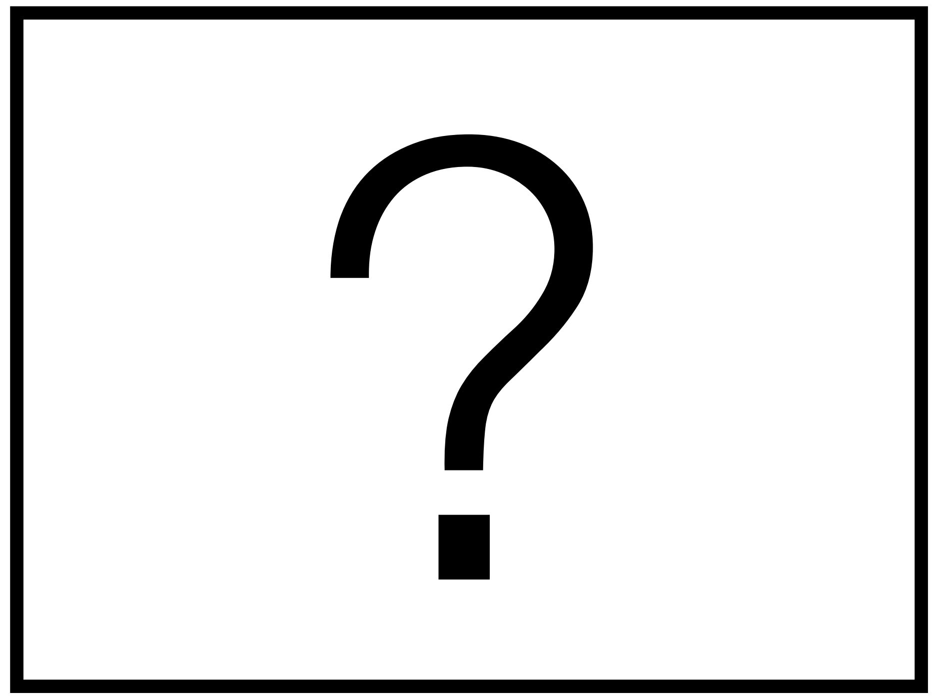




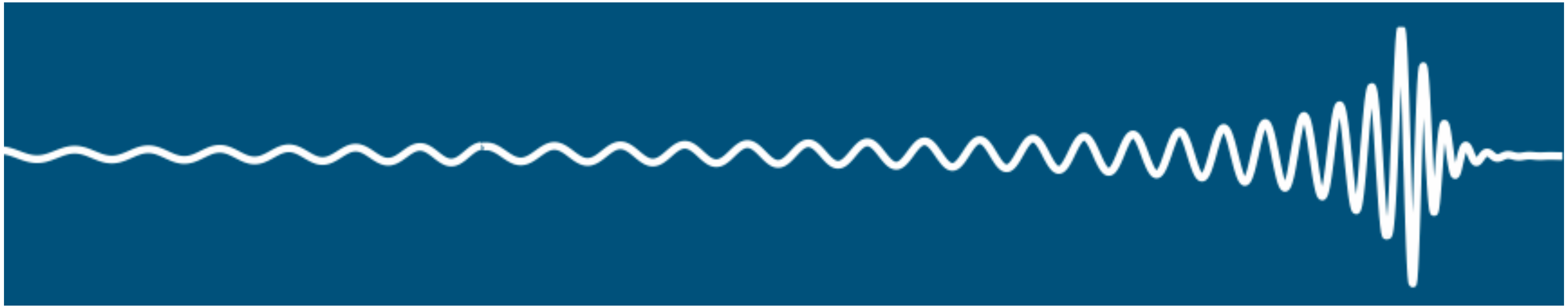








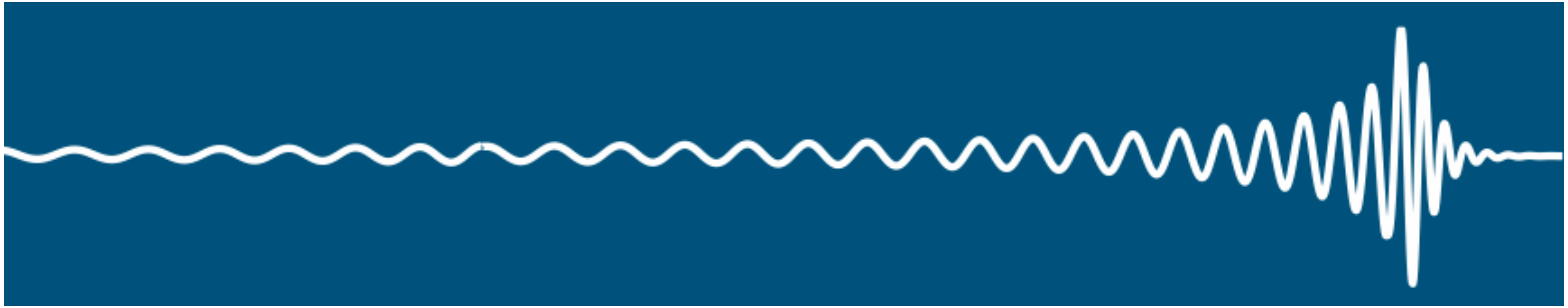
Black Hole Mergers



Isolated black hole merger waveforms for LISA are just rescaled versions of the LIGO waveforms

$$t_{\rm LISA} = t_{\rm LIGO} \left(\frac{M_{\rm LISA}}{M_{\rm LIGO}} \right)$$

Black Hole Mergers



Key difference - typically many more cycles in-band for LISA

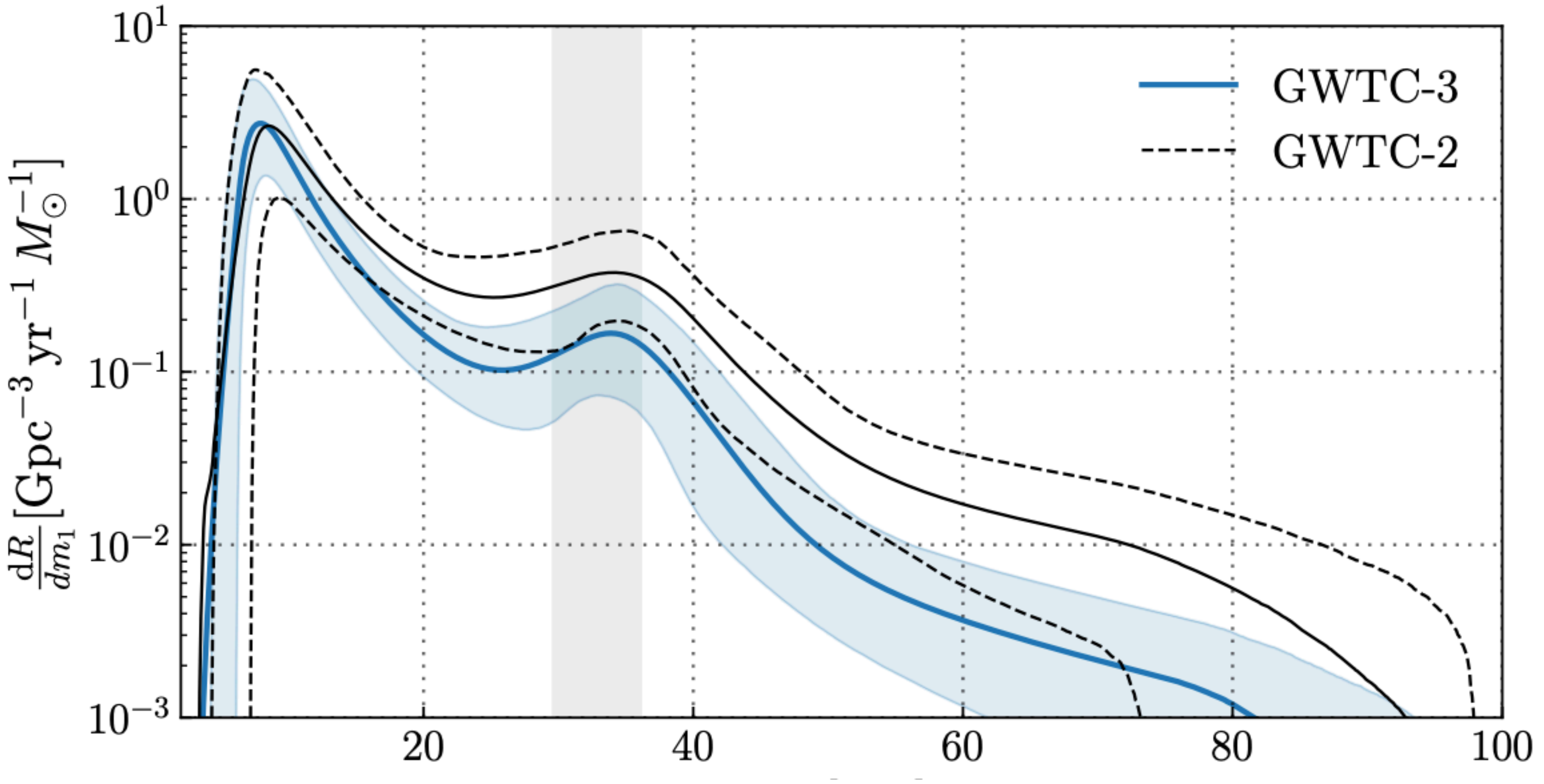
$$N_{\rm LISA} = 8.4 \times 10^3 \left(\frac{10^5 M_\odot}{\mathcal{M}} \frac{10^{-4}{\rm Hz}}{f_0} \right)^{5/3}$$

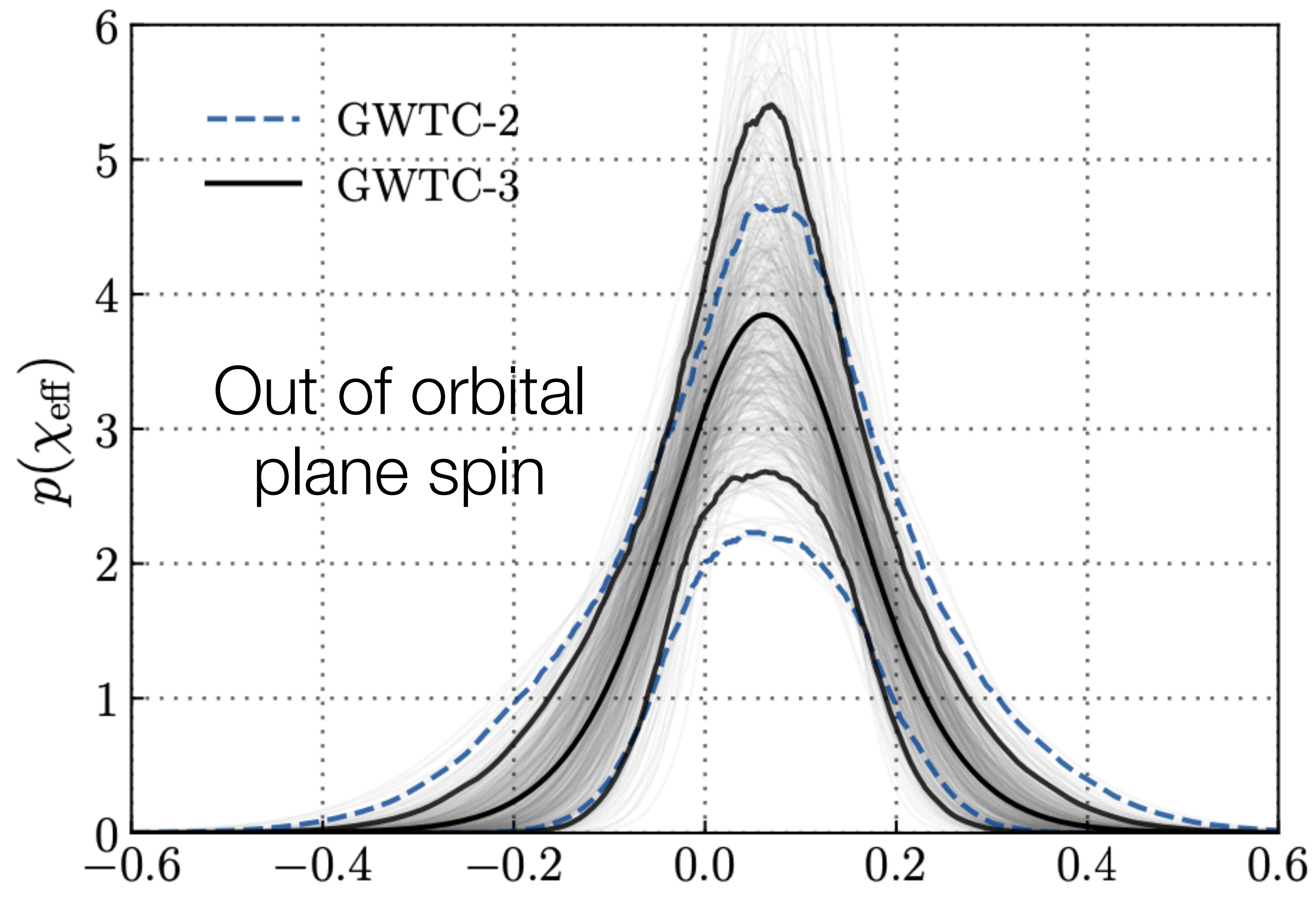
$$N_{\rm LIGO} = 4.6 \left(\frac{30 M_\odot}{\mathcal{M}} \frac{30{\rm Hz}}{f_0} \right)^{5/3}$$

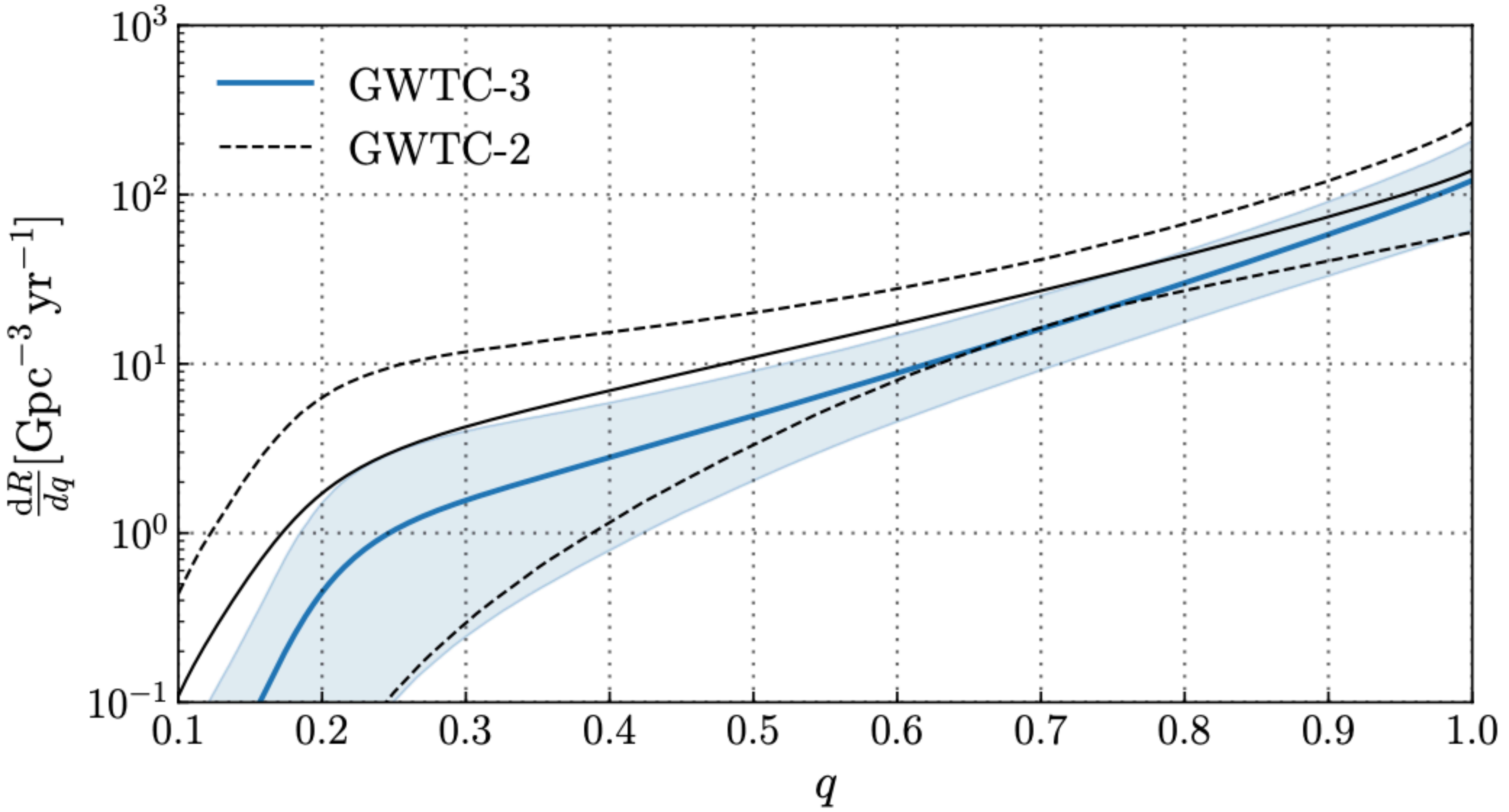
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1

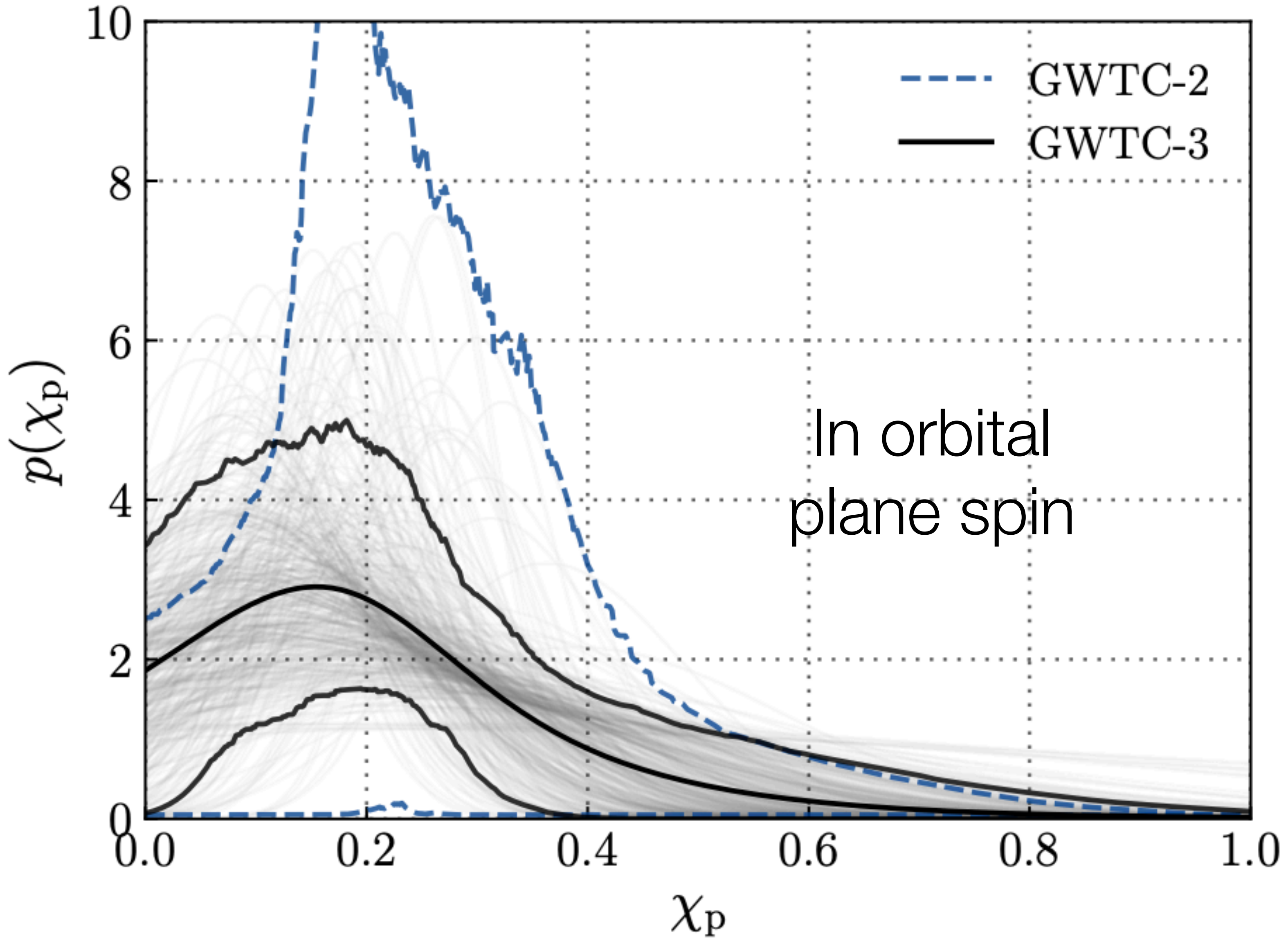
LIGO SOBHB Mass & Spin distributions

Majority of systems near equal mass, low-spin, quasi-circular orbits









[LIGO/Virgo 2111.03634]

Binary Black Hole Mergers

LIGO

Stellar Mass $2M_\odot \rightarrow 200M_\odot$

Mostly near equal mass

Moderate S/N ~ $10 \rightarrow 30$

Dry mergers, vacuum GR

Unlikely to have EM counterparts

Mostly low spins, aligned spins

Mostly (all?) quasi-circular orbits

LISA

Very Massive $10^3 M_\odot \rightarrow 10^8 M_\odot$

Large mass ratios likely the norm

High S/N ~ $10 \rightarrow 10^4$

Wet mergers, environmental effects

Likely to have EM counterparts

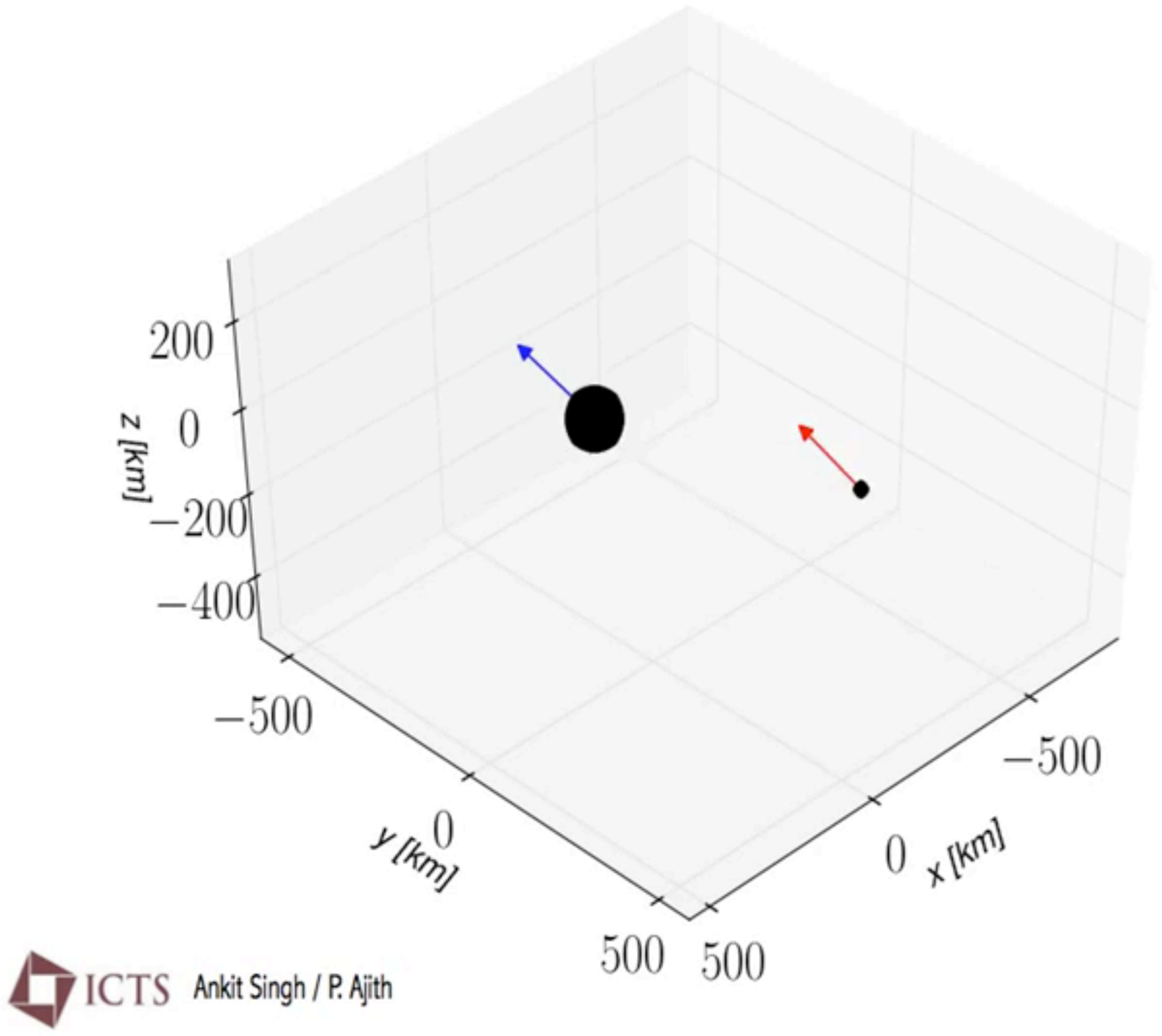
Many scenarios predict spin precession

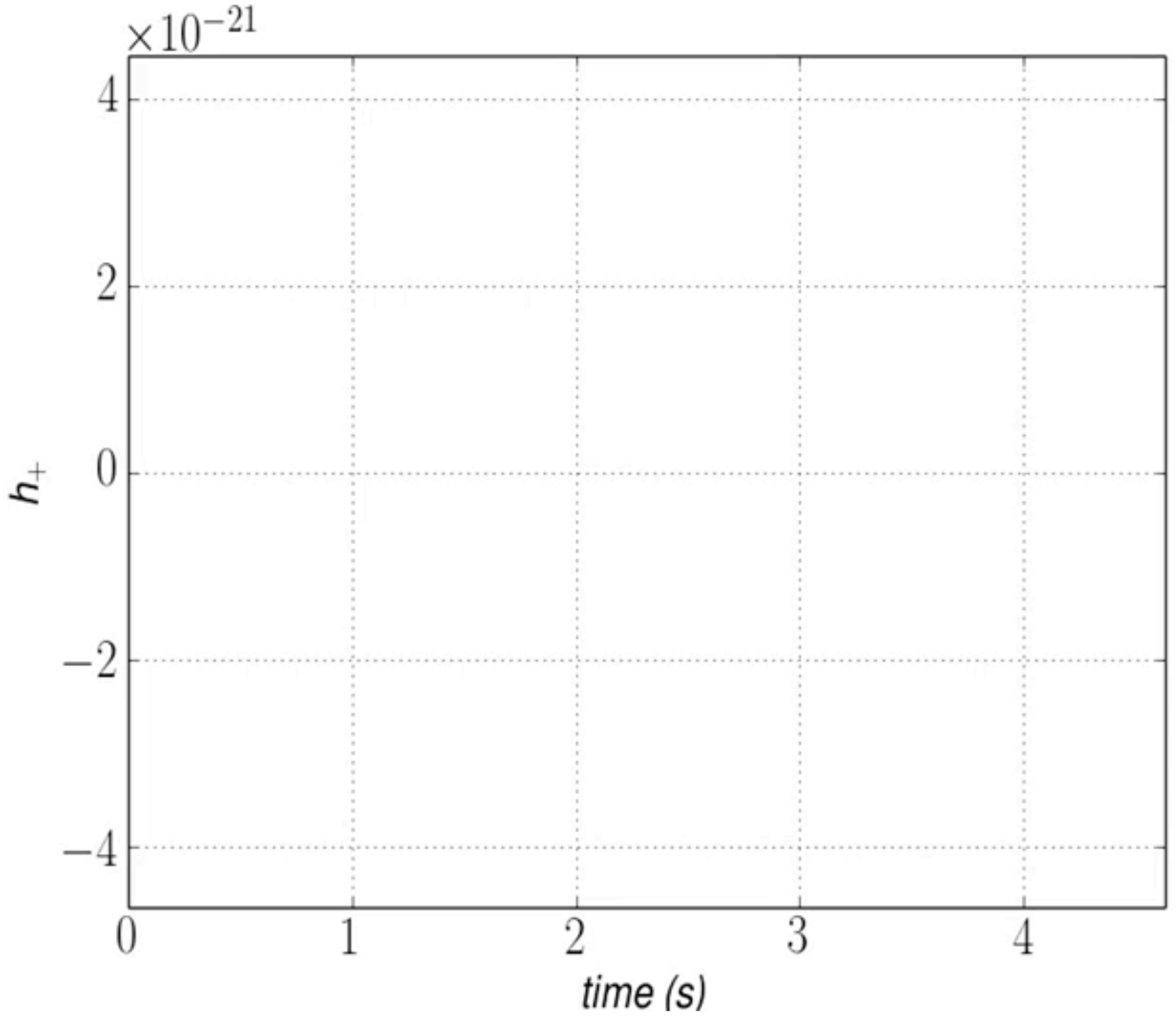
Many scenarios predict orbital eccentricity

LISA Binary Black Hole Mergers

$$N_{\rm LISA} = 8.4 \times 10^3 \left(\frac{10^5 M_\odot}{\mathcal{M}} \frac{10^{-4}\rm Hz}{f_0} \right)^{5/3}$$

$$\tau_{\rm orb} < \tau_{\rm orb\ prec} < \tau_{\rm spin\ prec} < \tau_{\rm decay}$$



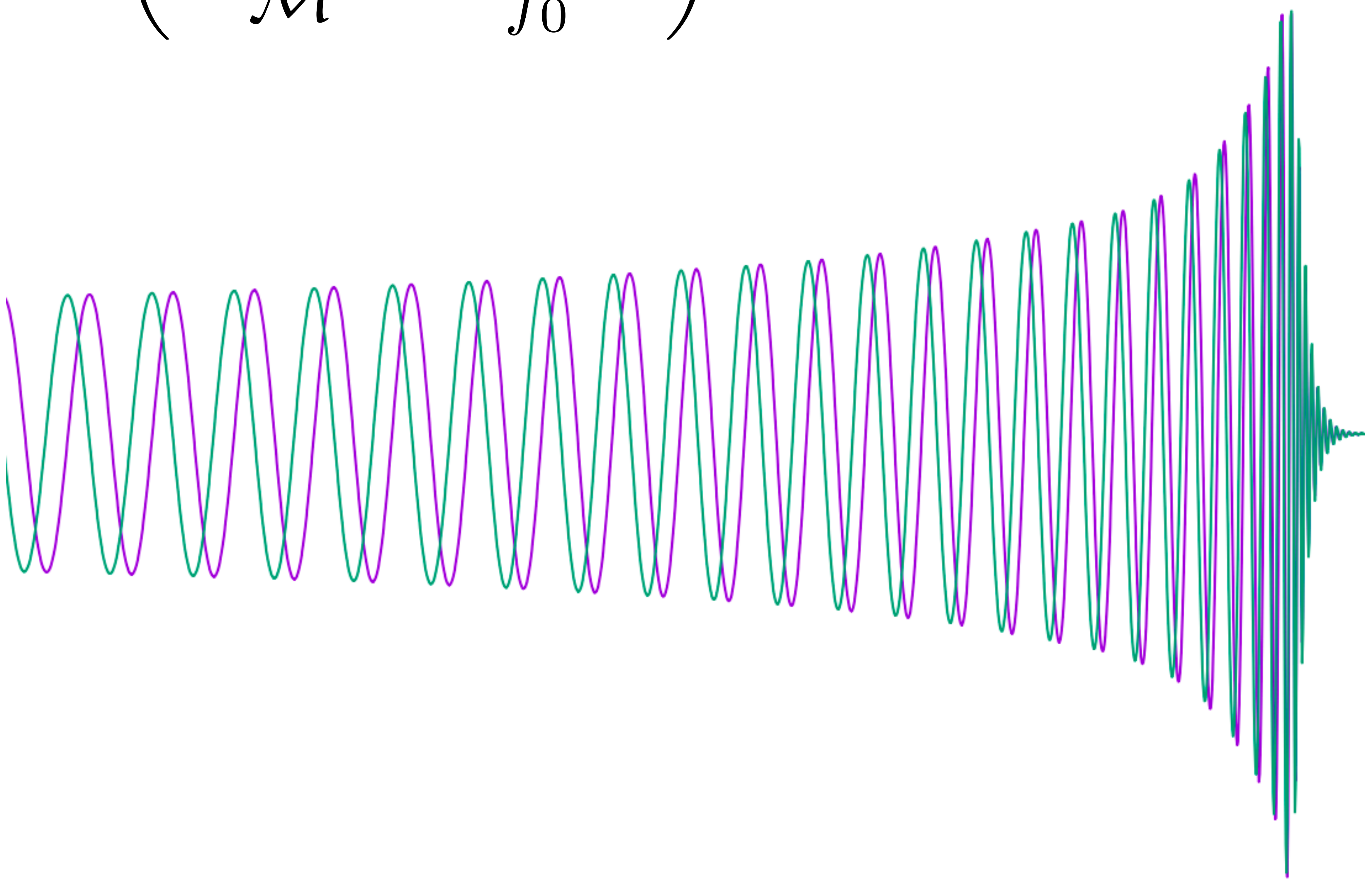


Large number of cycles and high S/N makes it easier to detect spin precession and orbital eccentricity

LISA Binary Black Hole Mergers

$$N_{\mathrm{LISA}} = 8.4 \times 10^3 \left(\frac{10^5 M_\odot}{\mathcal{M}} \frac{10^{-4}\mathrm{Hz}}{f_0} \right)^{5/3}$$

$$\mathrm{E[MM]} = \frac{D-1}{2\,(\mathrm{S/N})^2}$$



Large number of cycles and high S/N makes it easier to detect deviations from GR

But… waveform accuracy requirements are much higher for LISA

Analysis: Detection and Characterization

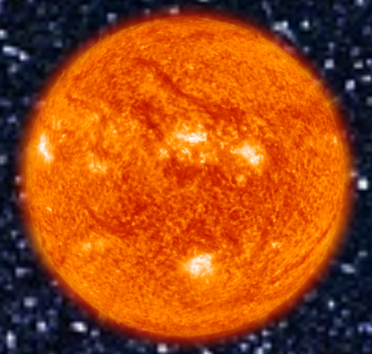
LIGO

- Short duration, non overlapping
- Low Latency Search
  - Maximum likelihood inspired
  - Analyze short time segments
  - Grid based search, simple templates
- Longer latency Bayesian follow up
- Also Continuous Wave, Un-modeled and Stochastic searches

LISA

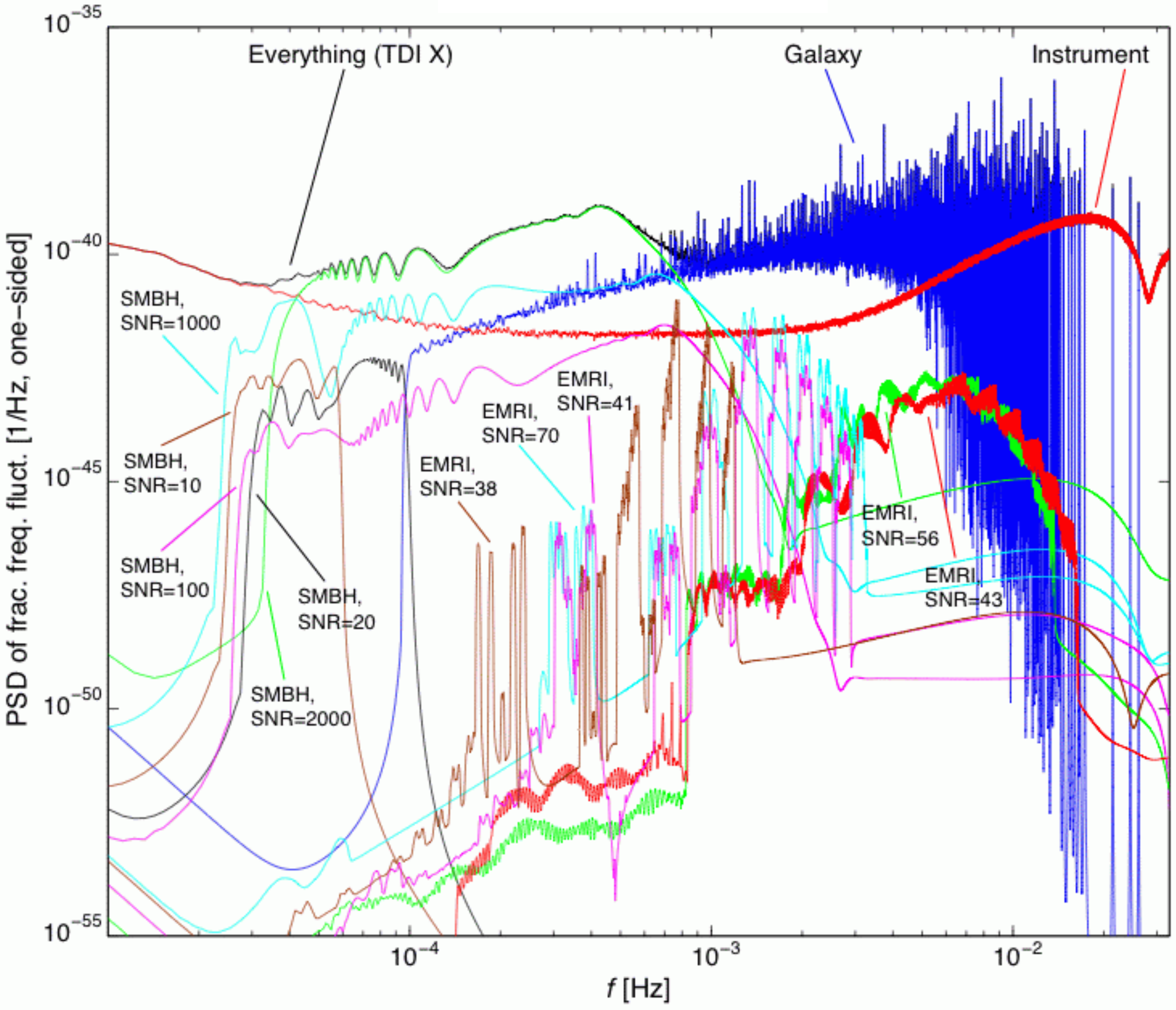
- Millions of overlapping signals
- High dimensional search space
  - Grid based searches impractical
  - Stochastic search methods
- Signal duration often comparable to mission lifetime
- Need a Global Fit: Binaries of all kinds, stochastic signals and un-modeled signals. All together

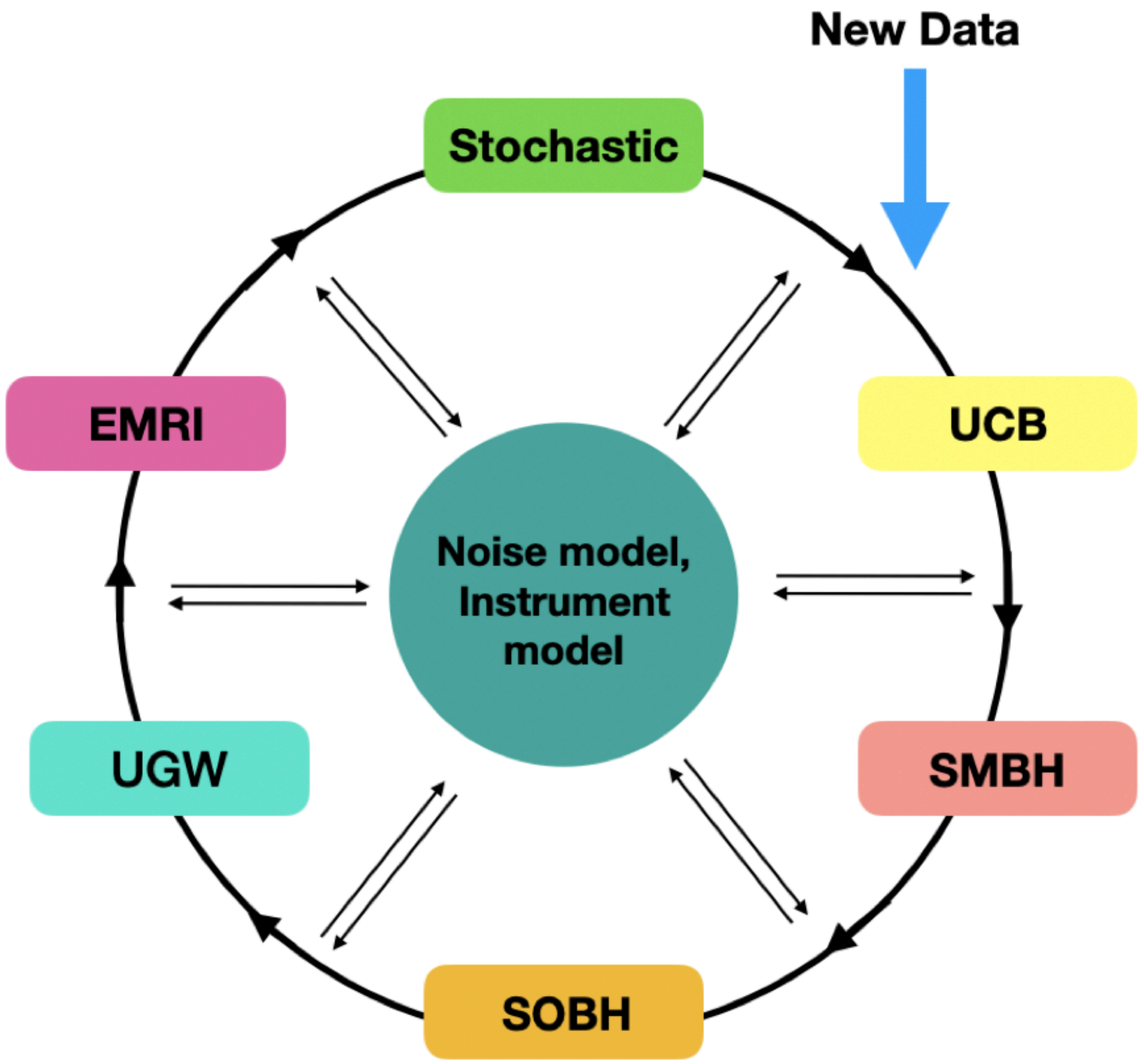
LISA is not LIGO in Space



- Millions of overlapping signals
- Unknown number of detectable sources
- Non-stationary and non-Gaussian noise
- Data gaps and disturbances
- Time varying instrument response
- Complex signals, multiple harmonics

LISA Global Fit - Simultaneously fitting tens of thousands of signals and noise



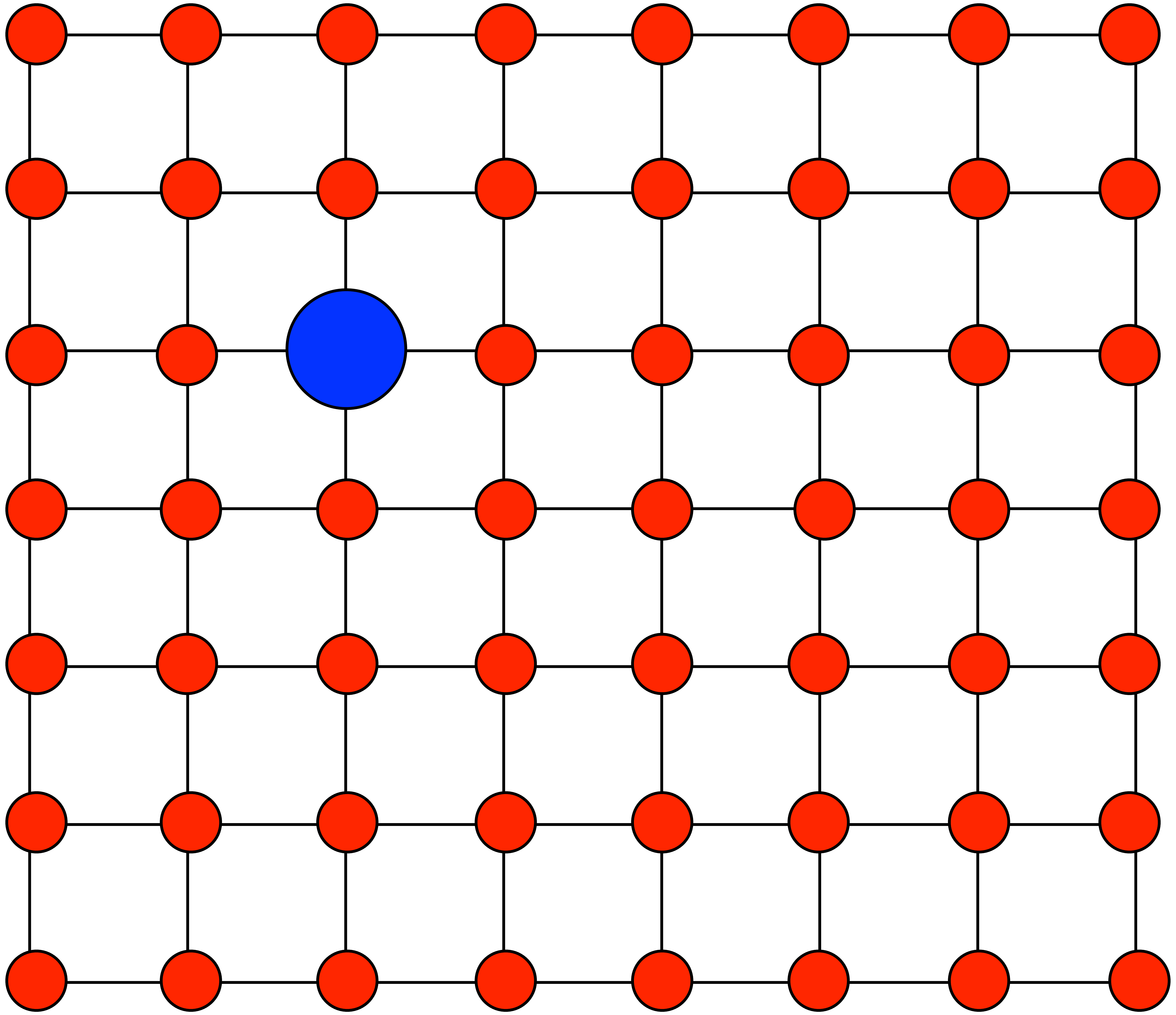


~200,000 parameter fit

Analysis: Detection

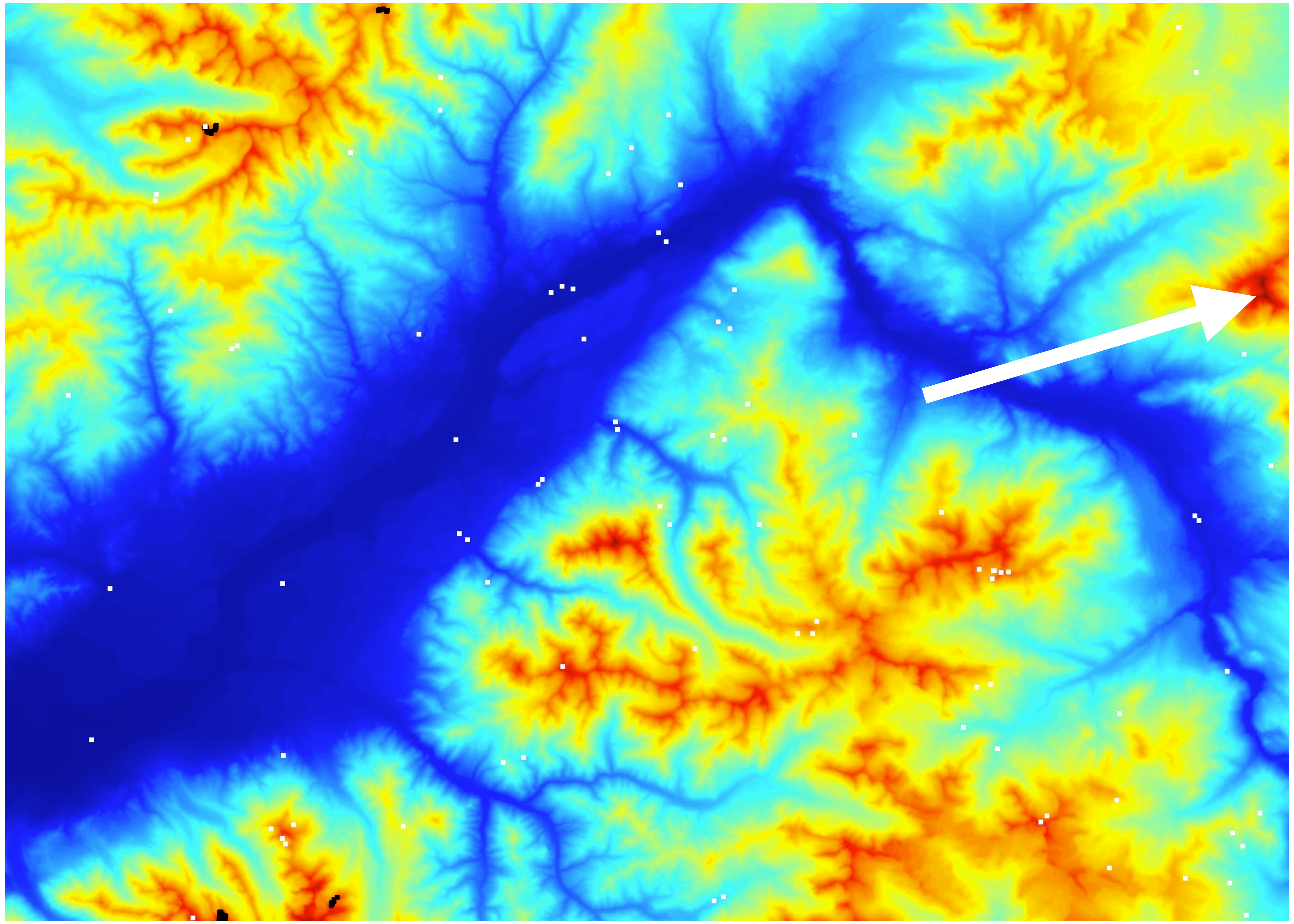
LIGO

Template grid, max likelihood inspired

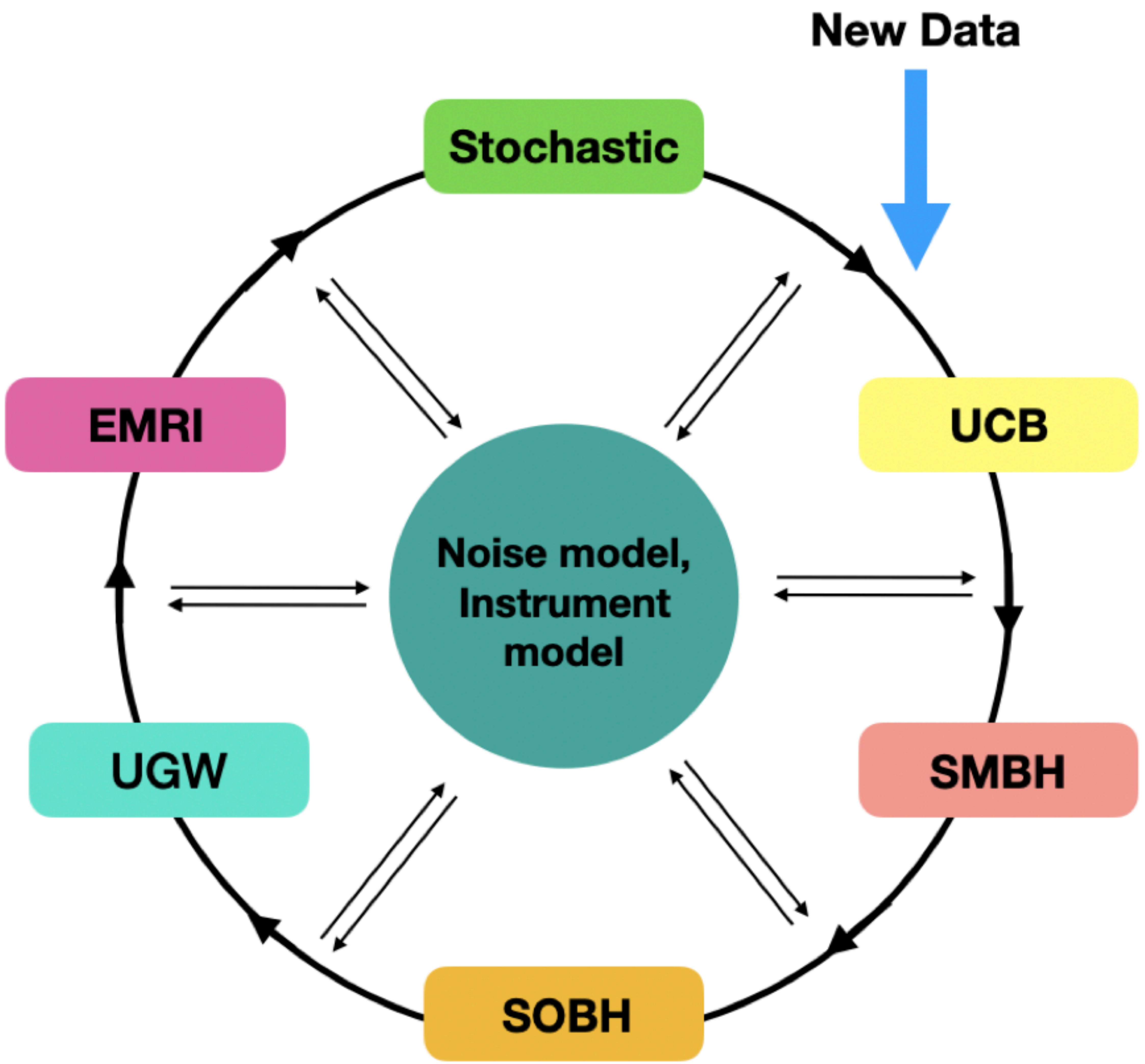


LISA

Semi-coherent, likelihood based stochastic search

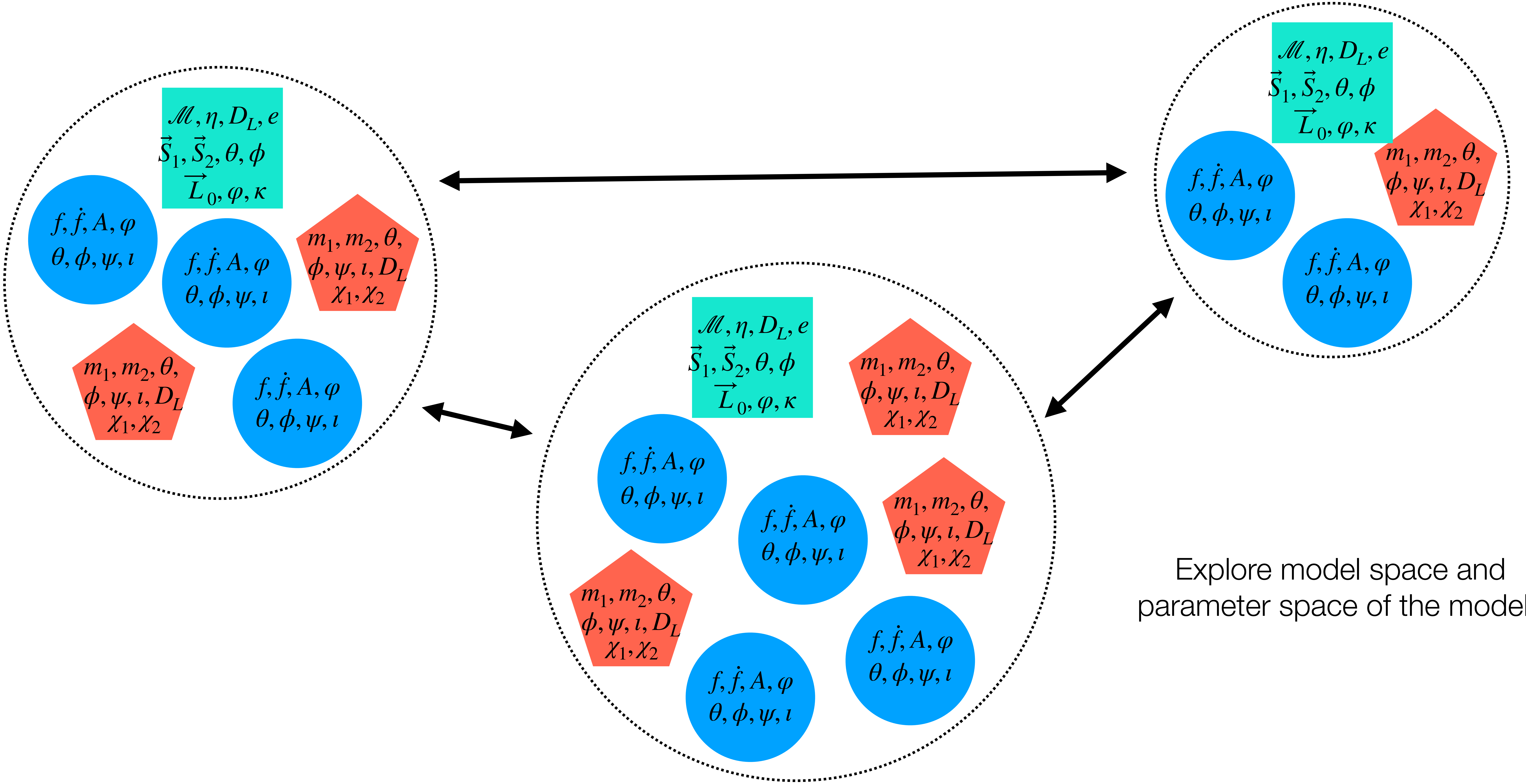


LISA Global Fit



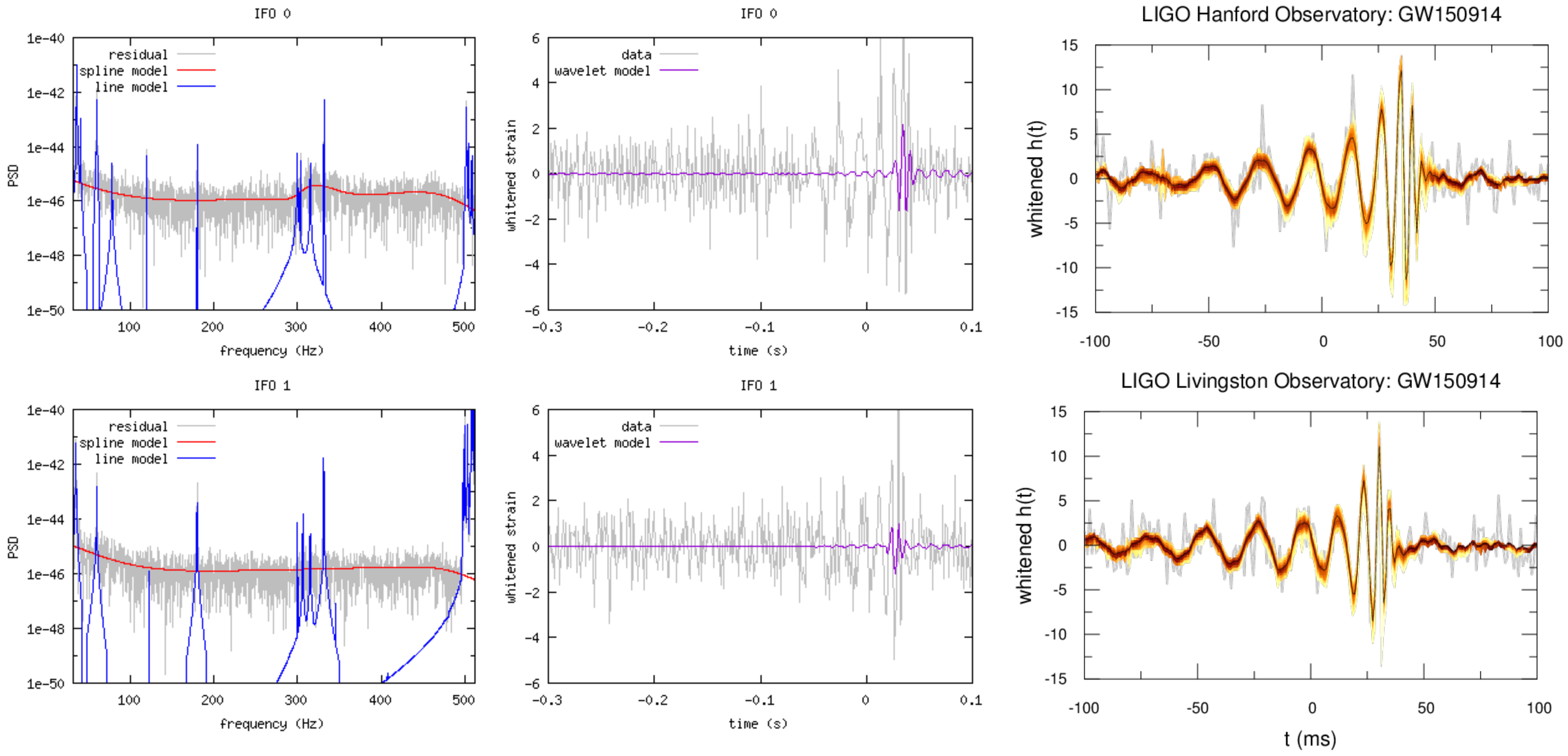
- Transdimensional Markov Chain Monte Carlo (RJMCMC)
- Blocked Updates - update each component of the signal/ noise model in multiple sweeps
- Only pass residuals - decouples the analysis types
- Update the fit every few days as new data arrives

Trans-dimensional Inference

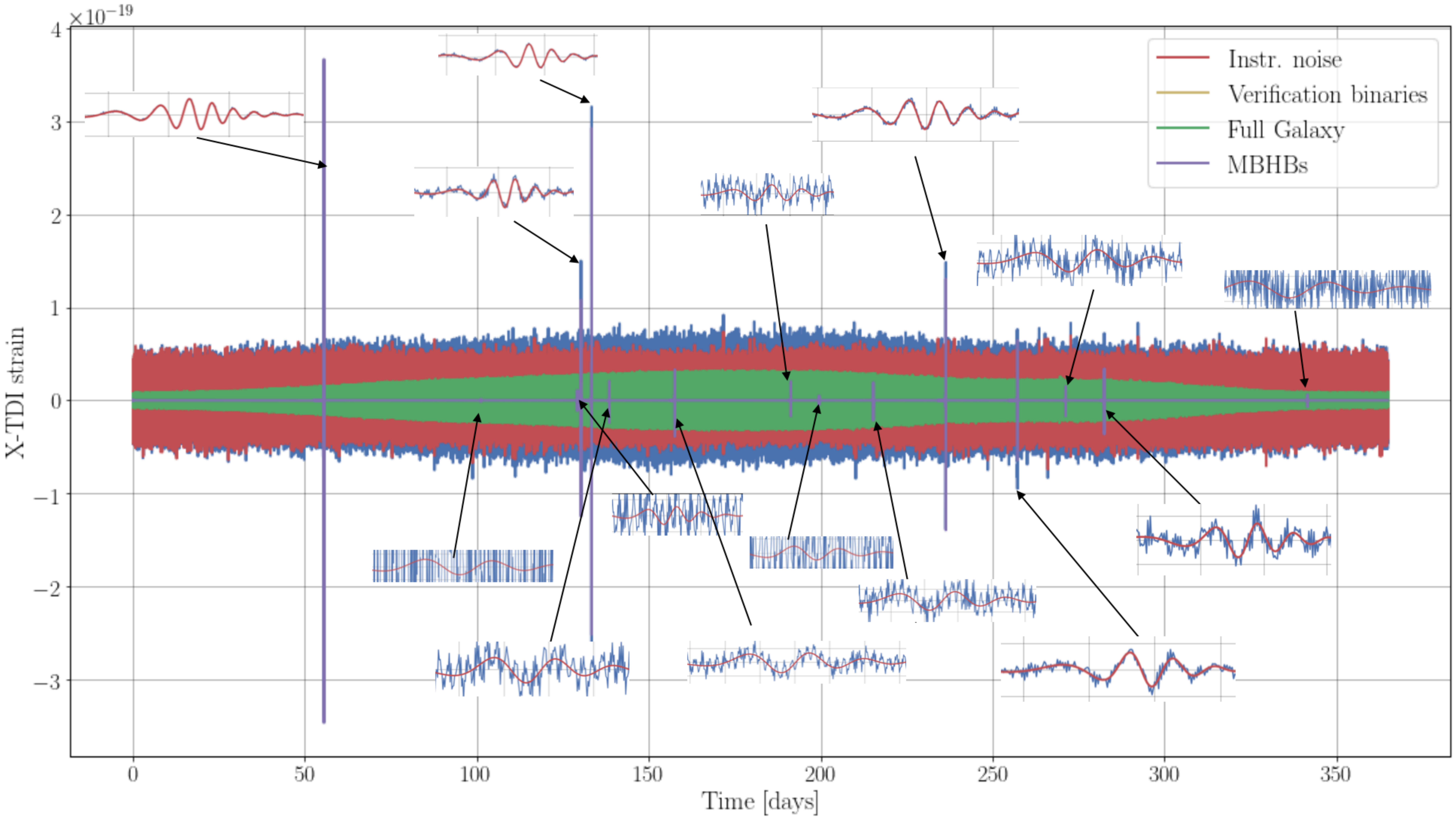


Explore model space and parameter space of the models

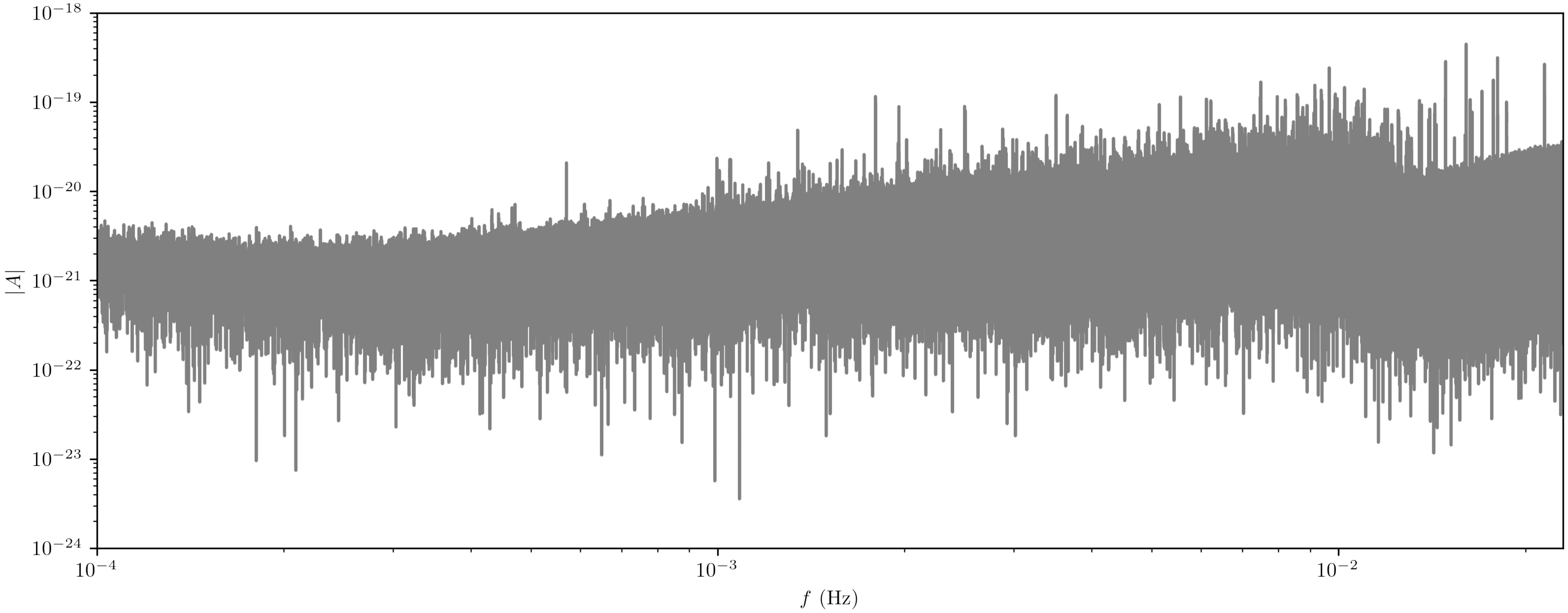
Example of LISA - LIGO crossover: BayesWave



LISA Data Challenge: Sangria Edition

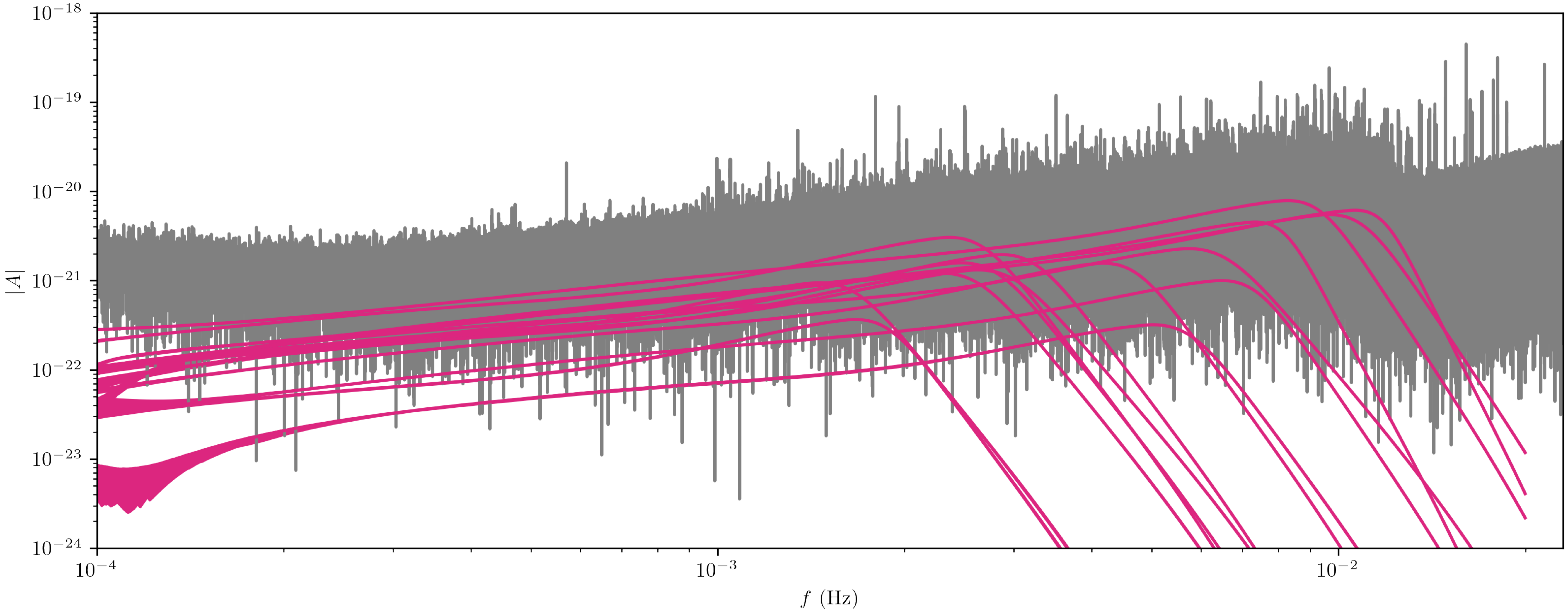


12 months of Sangria data - A TDI channel



[Litttenberg & Cornish, arXiv: 2301.03673]

12 months of Sangria data - A TDI channel



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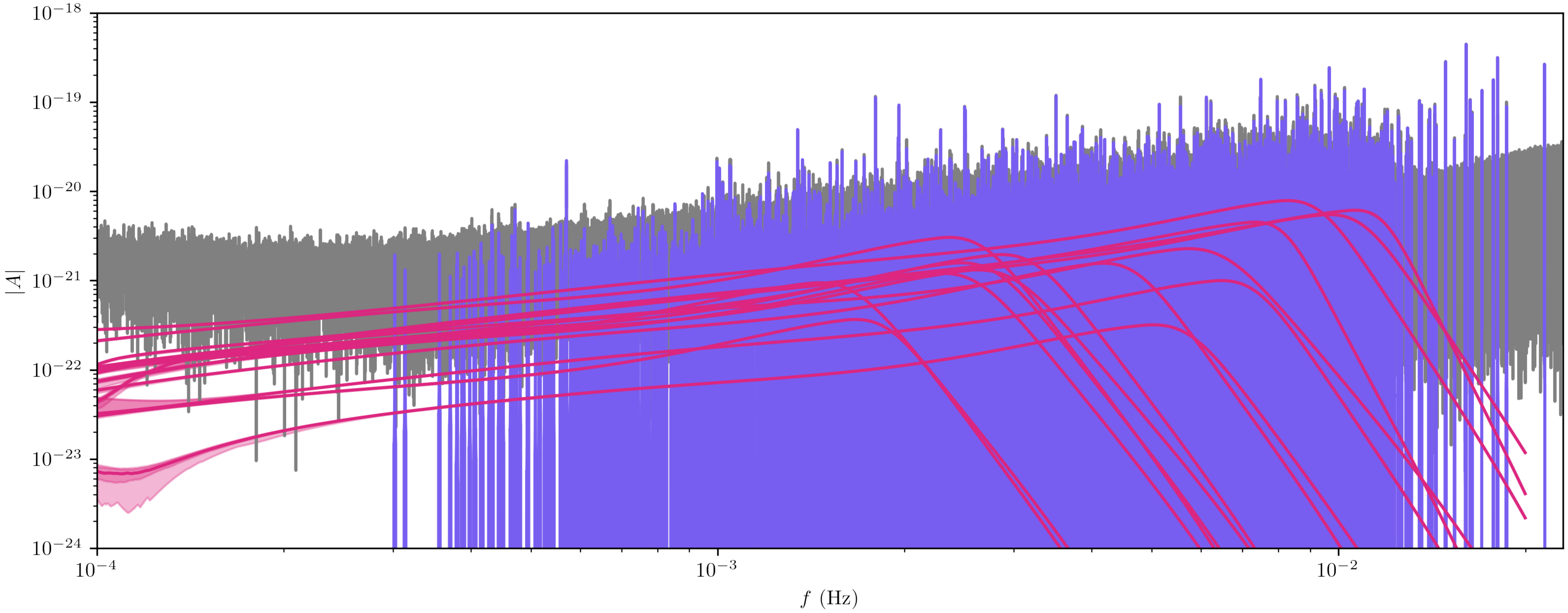

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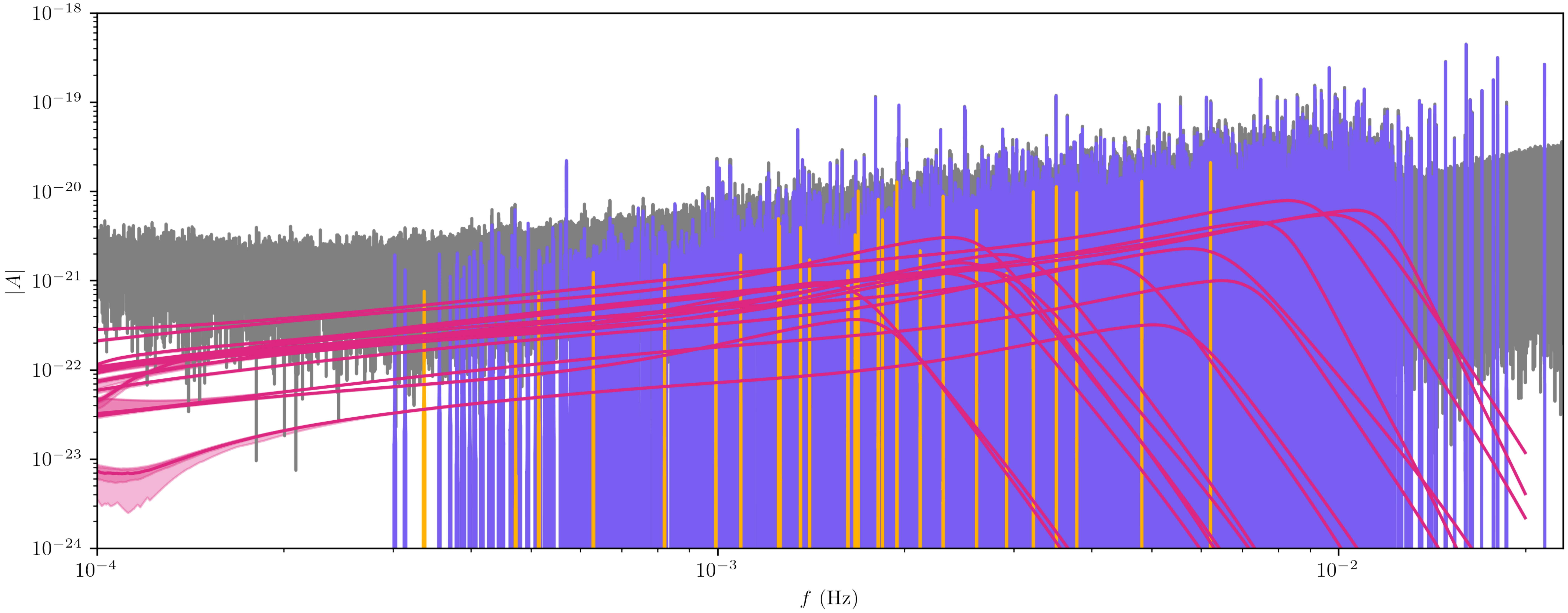

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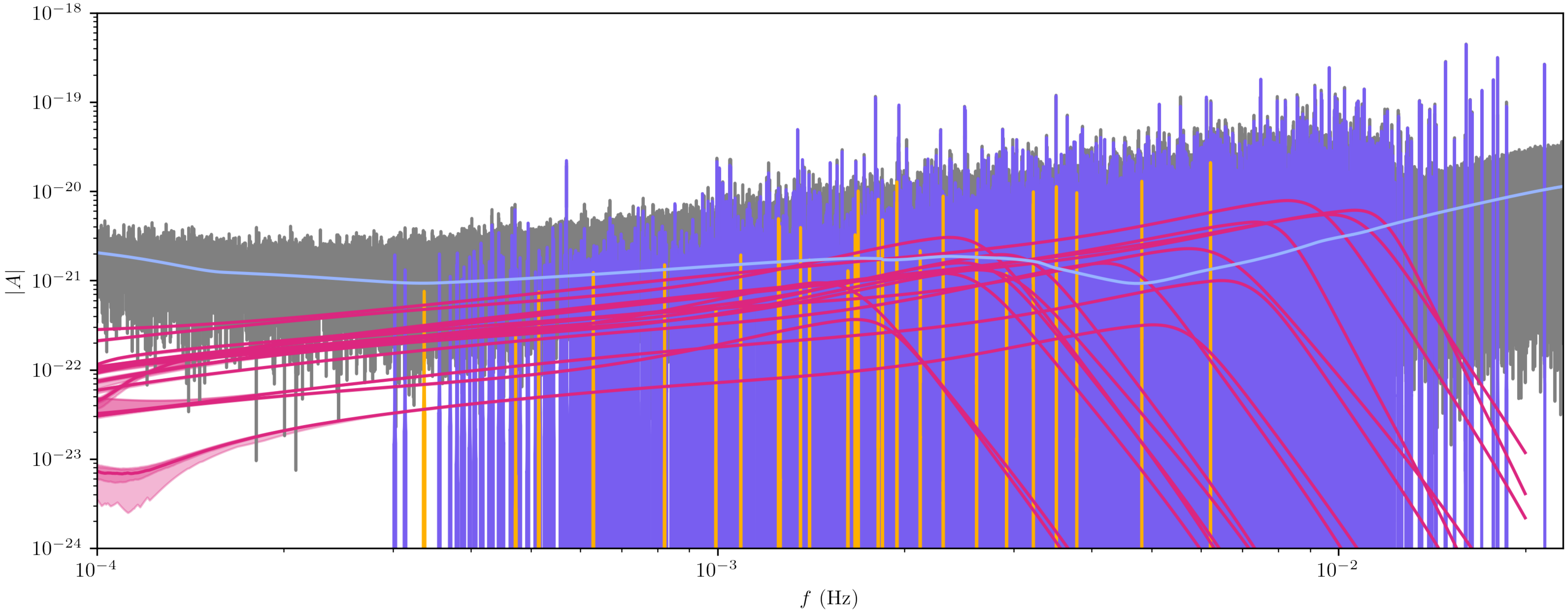
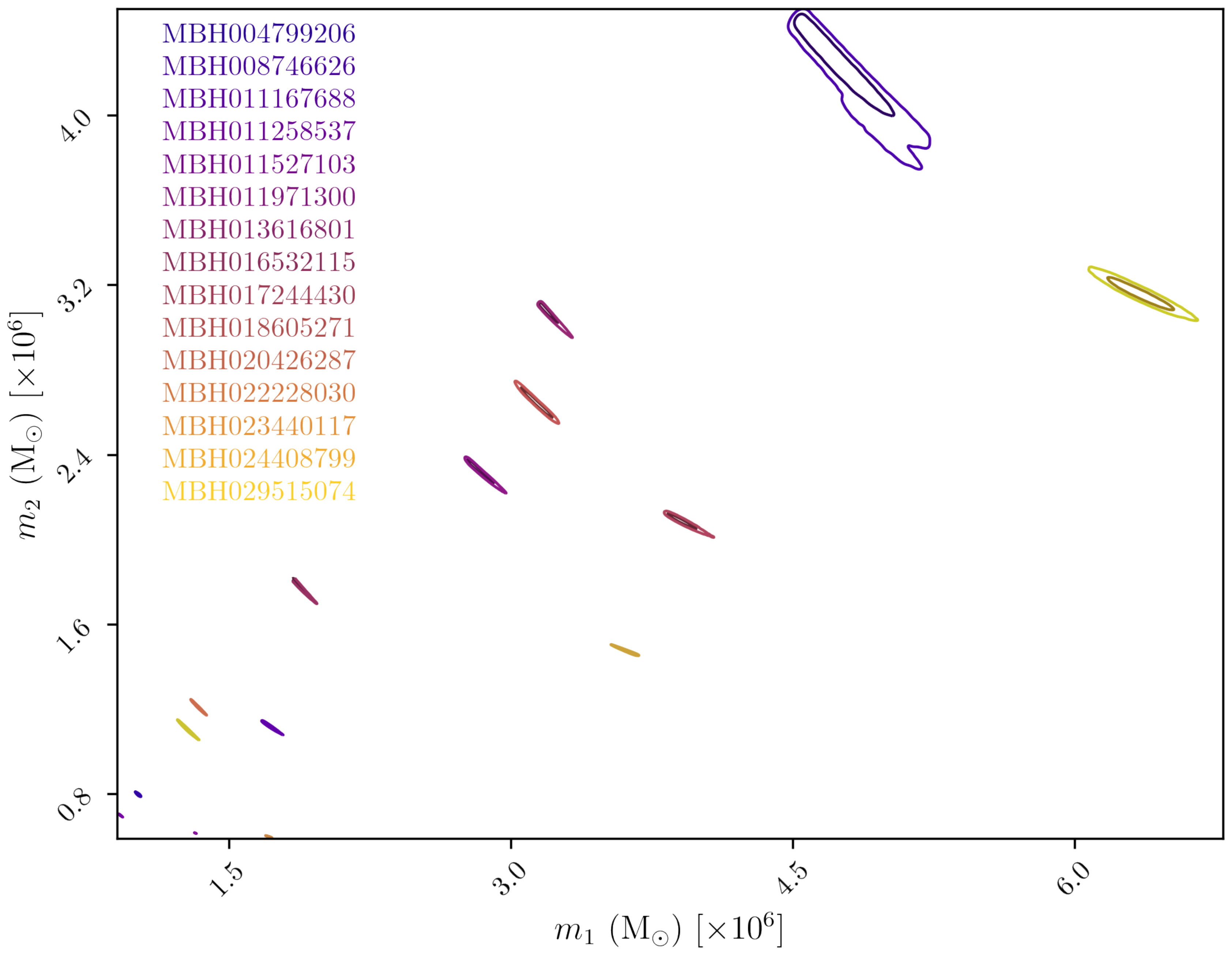
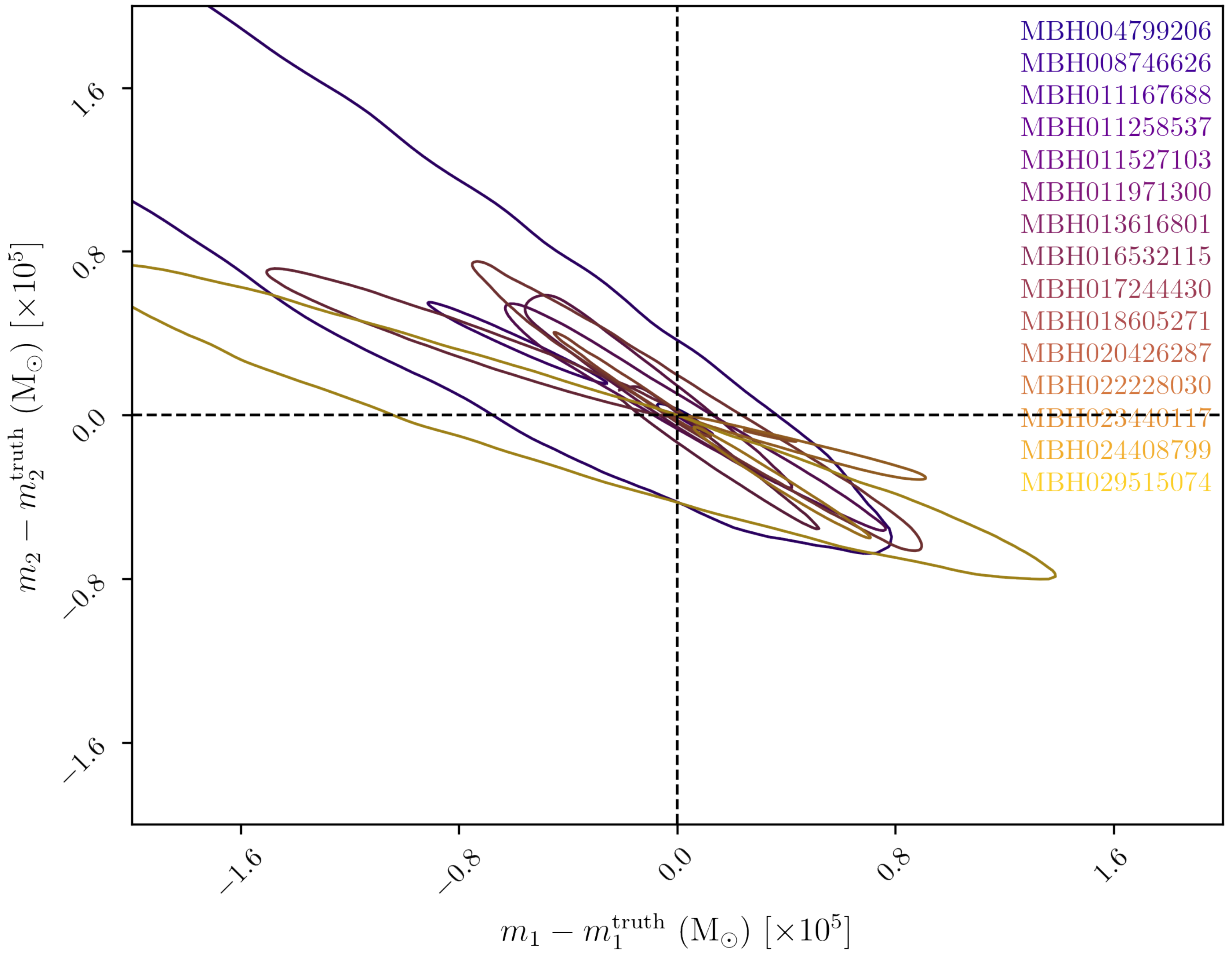
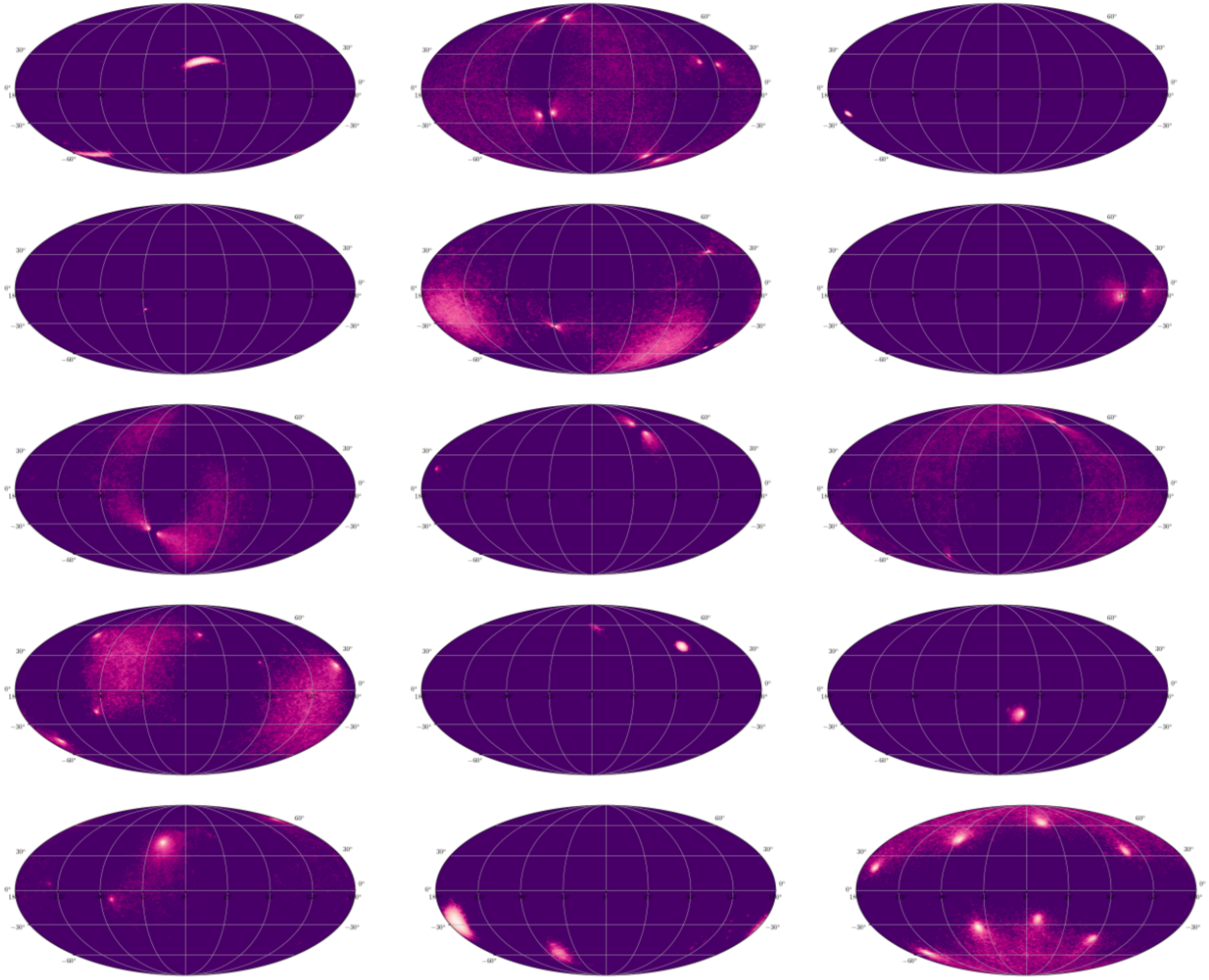


[Litttenberg & Cornish, arXiv: 2301.03673]

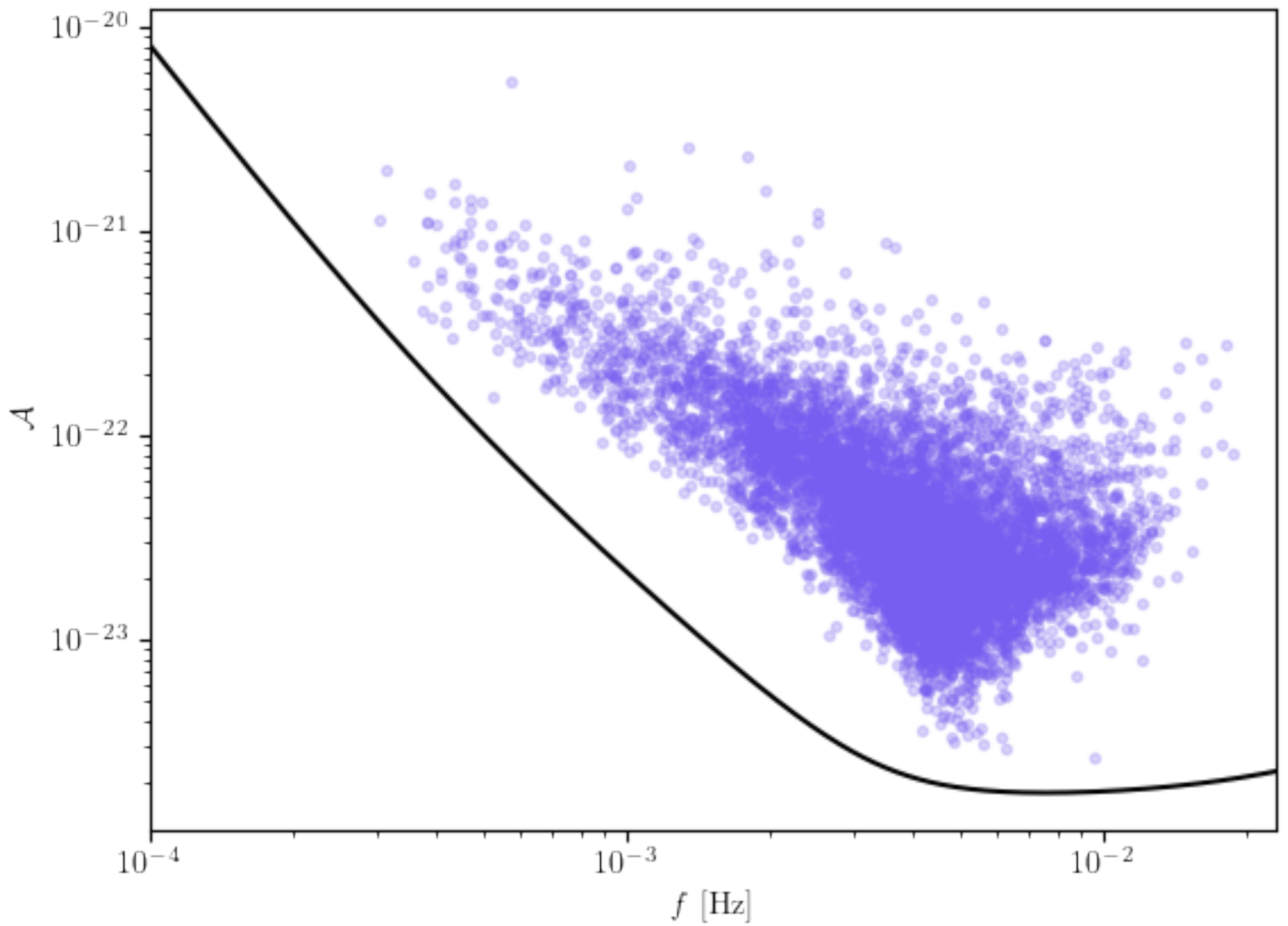
12 months of Sangria data - MBHBs



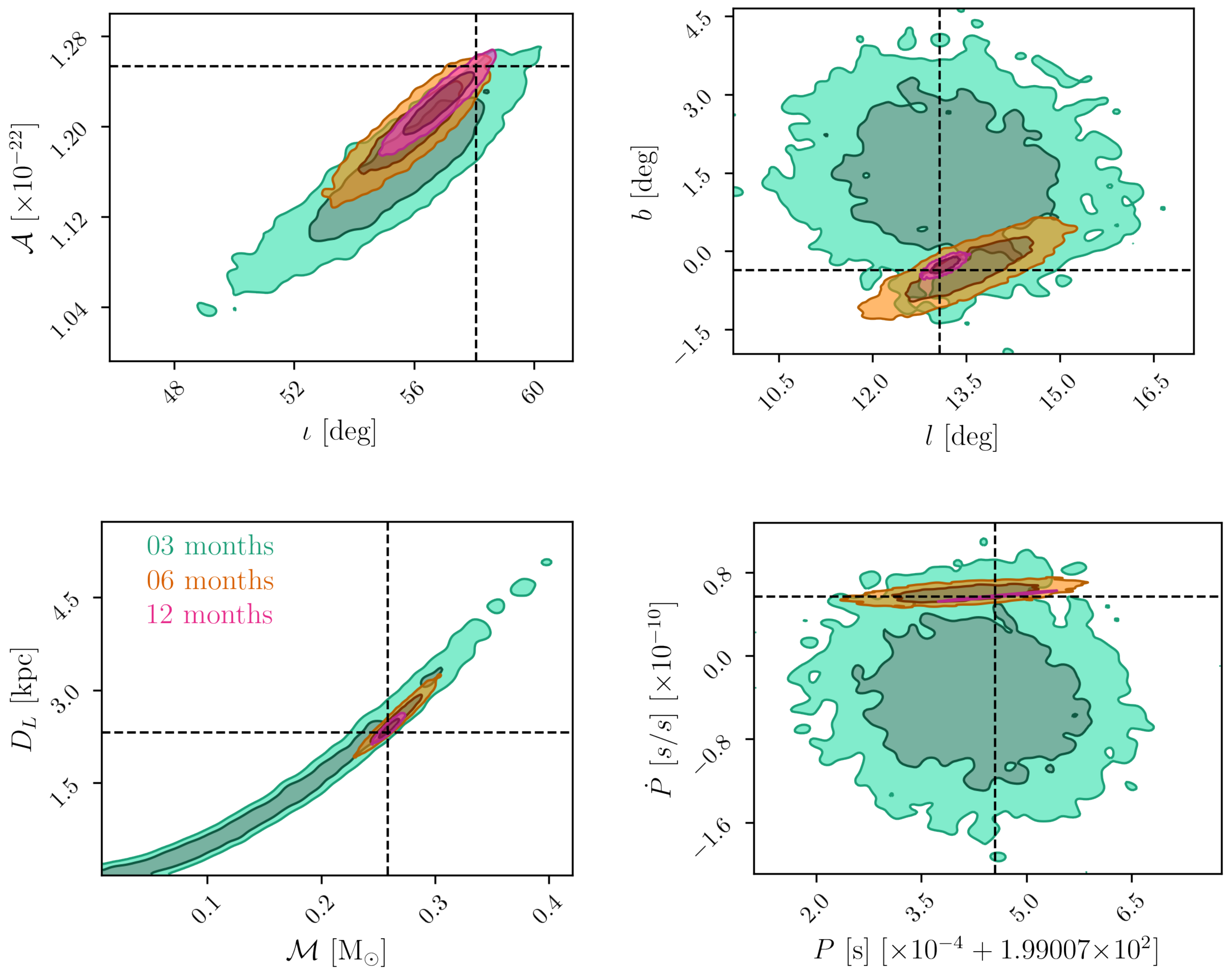




Sangria data - Galactic Binaries



All candidate UCB sources at 12 months



Example of how a source resolves with time

LIGO - LISA Source Catalogs

Both are probabilistic - quote probabilities that a putative signal is astrophysical

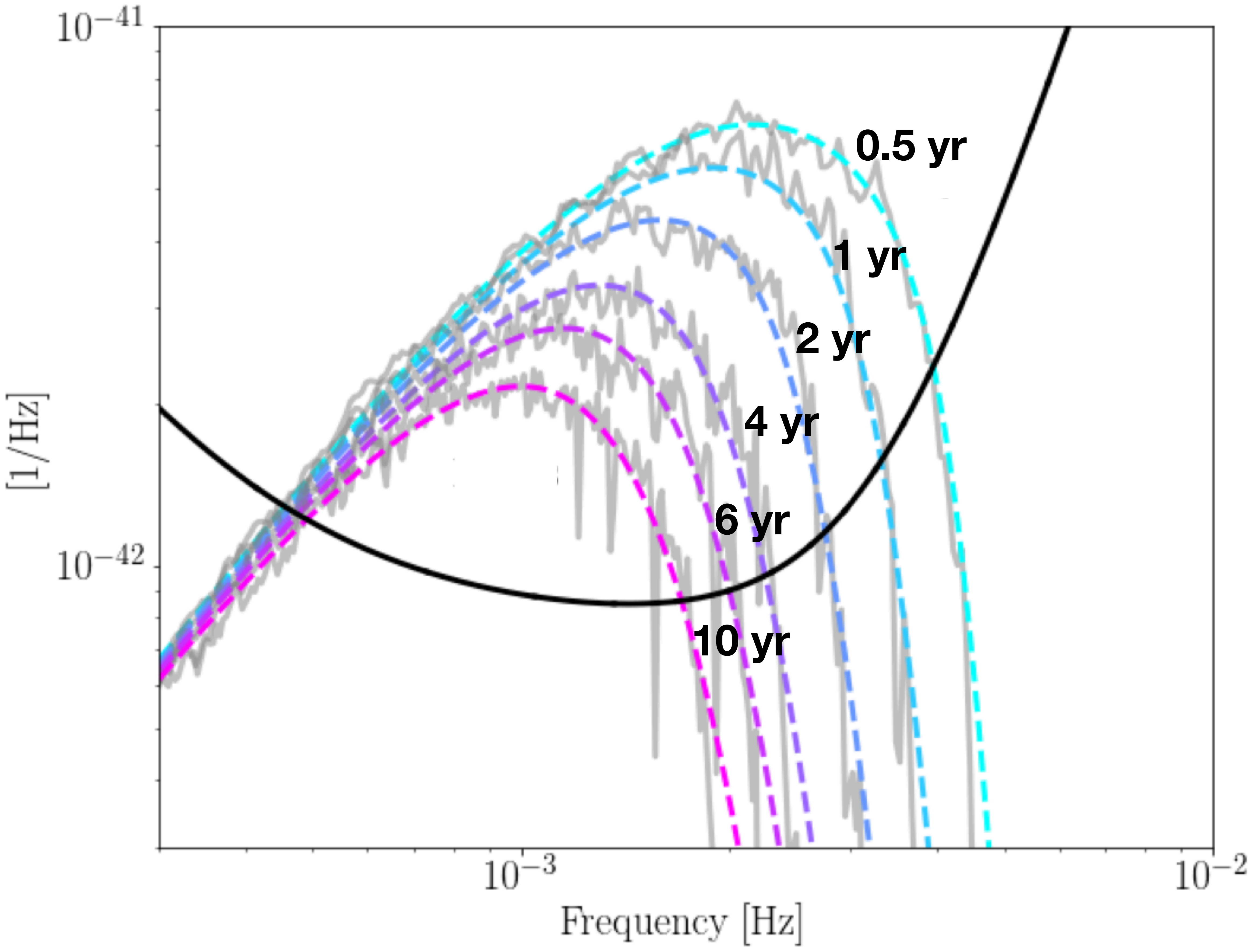
Name	$\mathbf{FAR}_{\min}$ (yr^{-1})	$p_{\rm astro}$	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	**First appears in**
GW150914	$< 1 \times 10^{-5}$	> 0.99	$35.6^{+4.7}_{-3.1}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.7}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	[13]
GW151012	7.92×10^{-3}	> 0.99	$23.2^{+14.9}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.1}_{-1.2}$	$0.05^{+0.31}_{-0.20}$	[14]
GW151226	$< 1 \times 10^{-5}$	> 0.99	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.5}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	[15]
GW170104	$< 1 \times 10^{-5}$	> 0.99	$30.8^{+7.3}_{-5.6}$	$20.0^{+4.9}_{-4.6}$	$21.4^{+2.2}_{-1.8}$	$-0.04^{+0.17}_{-0.21}$	[16]
GW170608	$< 1 \times 10^{-5}$	> 0.99	$11.0^{+5.5}_{-1.7}$	$7.6^{+1.4}_{-2.2}$	$7.9^{+0.2}_{-0.2}$	$0.03^{+0.19}_{-0.07}$	[17]
GW170729	1.80×10^{-1}	0.98	$50.2^{+16.2}_{-10.2}$	$34.0^{+9.1}_{-10.1}$	$35.4^{+6.5}_{-4.8}$	$0.37^{+0.21}_{-0.25}$	[2]
GW170809	$< 1 \times 10^{-5}$	> 0.99	$35.0^{+8.3}_{-5.9}$	$23.8^{+5.1}_{-5.2}$	$24.9^{+2.1}_{-1.7}$	$0.08^{+0.17}_{-0.17}$	[2]
GW170814	$< 1 \times 10^{-5}$	> 0.99	$30.6^{+5.6}_{-3.0}$	$25.2^{+2.8}_{-4.0}$	$24.1^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.12}$	[18]
GW170817	$< 1 \times 10^{-5}$	> 0.99	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	[19]
GW170818	$< 1 \times 10^{-5}$	> 0.99	$35.4^{+7.5}_{-4.7}$	$26.7^{+4.3}_{-5.2}$	$26.5^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	[2]
GW170823	$< 1 \times 10^{-5}$	> 0.99	$39.5^{+11.2}_{-6.7}$	$29.0^{+6.7}_{-7.8}$	$29.2^{+4.6}_{-3.6}$	$0.09^{+0.22}_{-0.26}$	[2]
GW190408_181802	$< 1 \times 10^{-5}$	> 0.99	$24.6^{+5.1}_{-3.4}$	$18.4^{+3.3}_{-3.6}$	$18.3^{+1.9}_{-1.2}$	$-0.03^{+0.14}_{-0.19}$	[4]
GW190412_053044	$< 1 \times 10^{-5}$	> 0.99	$30.1^{+4.7}_{-5.1}$	$8.3^{+1.6}_{-0.9}$	$13.3^{+0.4}_{-0.3}$	$0.25^{+0.08}_{-0.11}$	[20]
GW190413_134308	1.81×10^{-1}	0.99	$47.5^{+13.5}_{-10.7}$	$31.8^{+11.7}_{-10.8}$	$33.0^{+8.2}_{-5.4}$	$-0.03^{+0.25}_{-0.29}$	[4]
GW190421_213856	2.83×10^{-3}	> 0.99	$41.3^{+10.4}_{-6.9}$	$31.9^{+8.0}_{-8.8}$	$31.2^{+5.9}_{-4.2}$	$-0.06^{+0.22}_{-0.27}$	[4]
GW190425_081805	3.38×10^{-2}	0.78	$2.0^{+0.6}_{-0.3}$	$1.4^{+0.3}_{-0.3}$	$1.44^{+0.02}_{-0.02}$	$0.06^{+0.11}_{-0.05}$	[21]
GW190503_185404	$< 1 \times 10^{-5}$	> 0.99	$43.3^{+9.2}_{-8.1}$	$28.4^{+7.7}_{-8.0}$	$30.2^{+4.2}_{-4.2}$	$-0.03^{+0.20}_{-0.26}$	[4]
GW190512_180714	$< 1 \times 10^{-5}$	> 0.99	$23.3^{+5.3}_{-5.8}$	$12.6^{+3.6}_{-2.5}$	$14.6^{+1.3}_{-1.0}$	$0.03^{+0.12}_{-0.13}$	[4]
GW190513_205428	$< 1 \times 10^{-5}$	> 0.99	$35.7^{+9.5}_{-9.2}$	$18.0^{+7.7}_{-4.1}$	$21.6^{+3.8}_{-1.9}$	$0.11^{+0.28}_{-0.17}$	[4]

GW190929_012149	1.55×10^{-1}	0.87	$80.8^{+33.0}_{-33.2}$	$24.1^{+19.3}_{-10.6}$	$35.8^{+14.9}_{-8.2}$	$0.01^{+0.34}_{-0.33}$	[4]
GW190930_133541	1.23×10^{-2}	>0.99	$12.3^{+12.4}_{-2.3}$	$7.8^{+1.7}_{-3.3}$	$8.5^{+0.5}_{-0.5}$	$0.14^{+0.31}_{-0.15}$	[4]
GW191105_143521	1.18×10^{-2}	>0.99	$10.7^{+3.7}_{-1.6}$	$7.7^{+1.4}_{-1.9}$	$7.82^{+0.61}_{-0.45}$	$-0.02^{+0.13}_{-0.09}$	[1]
GW191109_010717	1.80×10^{-4}	>0.99	65^{+11}_{-11}	47^{+15}_{-13}	$47.5^{+9.6}_{-7.5}$	$-0.29^{+0.42}_{-0.31}$	[1]
GW191127_050227	2.49×10^{-1}	0.49	53^{+47}_{-20}	24^{+17}_{-14}	$29.9^{+11.7}_{-9.1}$	$0.18^{+0.34}_{-0.36}$	[1]
GW191129_134029	$<1\times10^{-5}$	>0.99	$10.7^{+4.1}_{-2.1}$	$6.7^{+1.5}_{-1.7}$	$7.31^{+0.43}_{-0.28}$	$0.06^{+0.16}_{-0.08}$	[1]
GW191204_171526	$<1\times10^{-5}$	>0.99	$11.9^{+3.3}_{-1.8}$	$8.2^{+1.4}_{-1.6}$	$8.55^{+0.38}_{-0.27}$	$0.16^{+0.08}_{-0.05}$	[1]
GW191215_223052	$<1\times10^{-5}$	>0.99	$24.9^{+7.1}_{-4.1}$	$18.1^{+3.8}_{-4.1}$	$18.4^{+2.2}_{-1.7}$	$-0.04^{+0.17}_{-0.21}$	[1]
GW191216_213338	$<1\times10^{-5}$	>0.99	$12.1^{+4.6}_{-2.3}$	$7.7^{+1.6}_{-1.9}$	$8.33^{+0.22}_{-0.19}$	$0.11^{+0.13}_{-0.06}$	[1]
GW191222_033537	$<1\times10^{-5}$	>0.99	$45.1^{+10.9}_{-8.0}$	$34.7^{+9.3}_{-10.5}$	$33.8^{+7.1}_{-5.0}$	$-0.04^{+0.20}_{-0.25}$	[1]
GW191230_180458	5.02×10^{-2}	0.95	$49.4^{+14.0}_{-9.6}$	37^{+11}_{-12}	$36.5^{+8.2}_{-5.6}$	$-0.05^{+0.26}_{-0.31}$	[1]
GW200105_162426	2.04×10^{-1}	0.36	$8.9^{+1.2}_{-1.5}$	$1.9^{+0.3}_{-0.2}$	$3.41^{+0.08}_{-0.07}$	$-0.01^{+0.11}_{-0.15}$	[10]
GW200112_155838	$<1\times10^{-5}$	>0.99	$35.6^{+6.7}_{-4.5}$	$28.3^{+4.4}_{-5.9}$	$27.4^{+2.6}_{-2.1}$	$0.06^{+0.15}_{-0.15}$	[1]
GW200115_042309	$<1\times10^{-5}$	>0.99	$5.9^{+2.0}_{-2.5}$	$1.44^{+0.85}_{-0.29}$	$2.43^{+0.05}_{-0.07}$	$-0.15^{+0.24}_{-0.42}$	[10]
GW200128_022011	4.29×10^{-3}	>0.99	$42.2^{+11.6}_{-8.1}$	$32.6^{+9.5}_{-9.2}$	$32.0^{+7.5}_{-5.5}$	$0.12^{+0.24}_{-0.25}$	[1]
GW200129_065458	$<1\times10^{-5}$	>0.99	$34.5^{+9.9}_{-3.2}$	$28.9^{+3.4}_{-9.3}$	$27.2^{+2.1}_{-2.3}$	$0.11^{+0.11}_{-0.16}$	[1]
GW200202_154313	$<1\times10^{-5}$	>0.99	$10.1^{+3.5}_{-1.4}$	$7.3^{+1.1}_{-1.7}$	$7.49^{+0.24}_{-0.20}$	$0.04^{+0.13}_{-0.06}$	[1]
GW200208_130117	3.11×10^{-4}	>0.99	$37.8^{+9.2}_{-6.2}$	$27.4^{+6.1}_{-7.4}$	$27.7^{+3.6}_{-3.1}$	$-0.07^{+0.22}_{-0.27}$	[1]
GW200209_085452	4.64×10^{-2}	0.95	$35.6^{+10.5}_{-6.8}$	$27.1^{+7.8}_{-7.8}$	$26.7^{+6.0}_{-4.2}$	$-0.12^{+0.24}_{-0.30}$	[1]
GW200219_094415	9.94×10^{-4}	>0.99	$37.5^{+10.1}_{-6.9}$	$27.9^{+7.4}_{-8.4}$	$27.6^{+5.6}_{-3.8}$	$-0.08^{+0.23}_{-0.29}$	[1]
GW200224_222234	$<1\times10^{-5}$	>0.99	$40.0^{+6.9}_{-4.5}$	$32.5^{+5.0}_{-7.2}$	$31.1^{+3.2}_{-2.6}$	$0.10^{+0.15}_{-0.15}$	[1]
GW200225_060421	$<1\times10^{-5}$	>0.99	$19.3^{+5.0}_{-3.0}$	$14.0^{+2.8}_{-3.5}$	$14.2^{+1.5}_{-1.4}$	$-0.12^{+0.17}_{-0.28}$	[1]
GW200302_015811	1.12×10^{-1}	0.91	$37.8^{+8.7}_{-8.5}$	$20.0^{+8.1}_{-5.7}$	$23.4^{+4.7}_{-3.0}$	$0.01^{+0.25}_{-0.26}$	[1]
GW200311_115853	$<1\times10^{-5}$	>0.99	$34.2^{+6.4}_{-3.8}$	$27.7^{+4.1}_{-5.9}$	$26.6^{+2.4}_{-2.0}$	$-0.02^{+0.16}_{-0.20}$	[1]

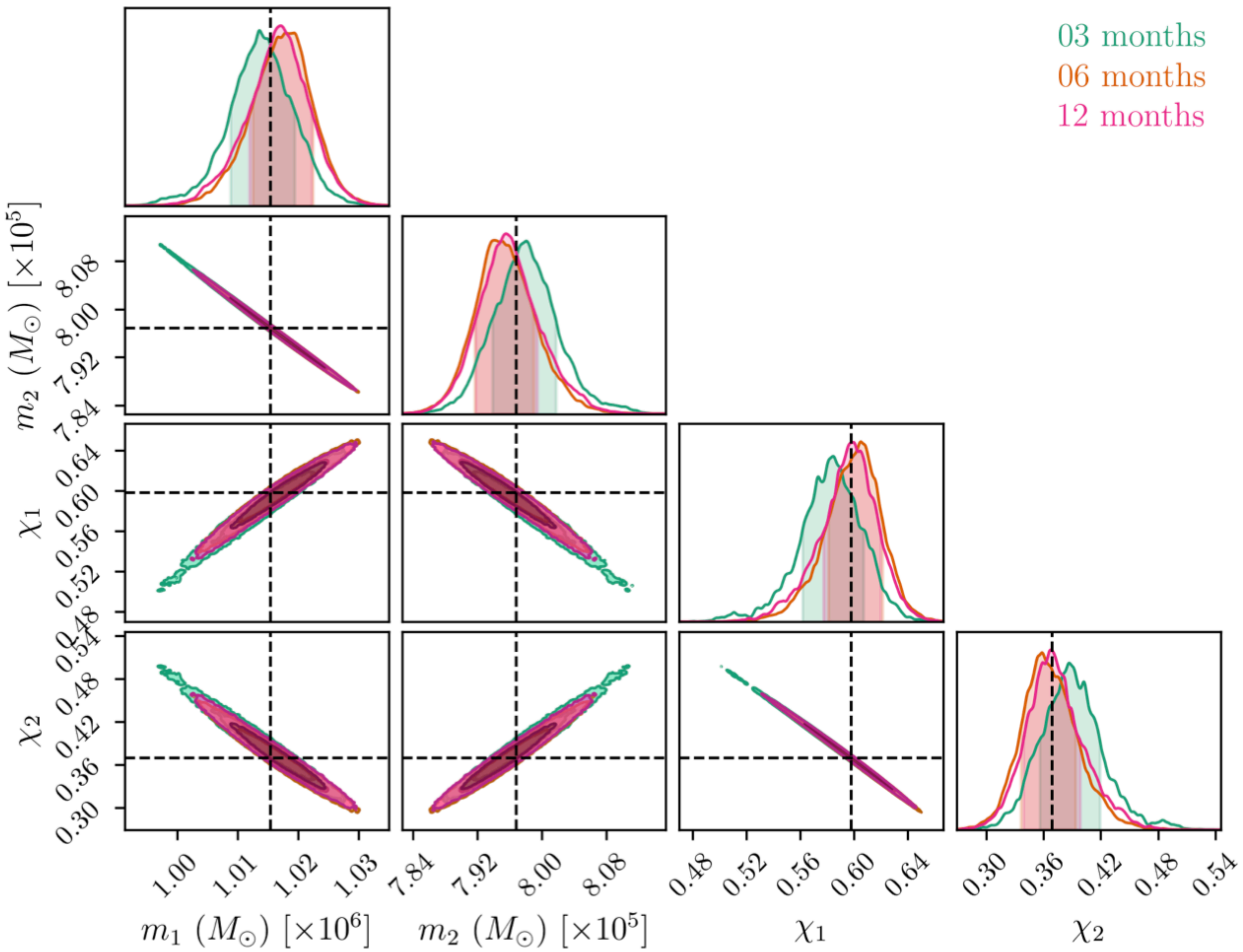
[LIGO/Virgo 2111.03634]

LIGO - LISA Source Catalogs

Both grow with time, but LISA catalogs can be atemporal



[Karnesis et al, arXiv: 2103.14598]



This MBHM merged in first 3 months. Posteriors continue to improve as confusion noise drops

Summary

LIGO heritage will be valuable for LISA

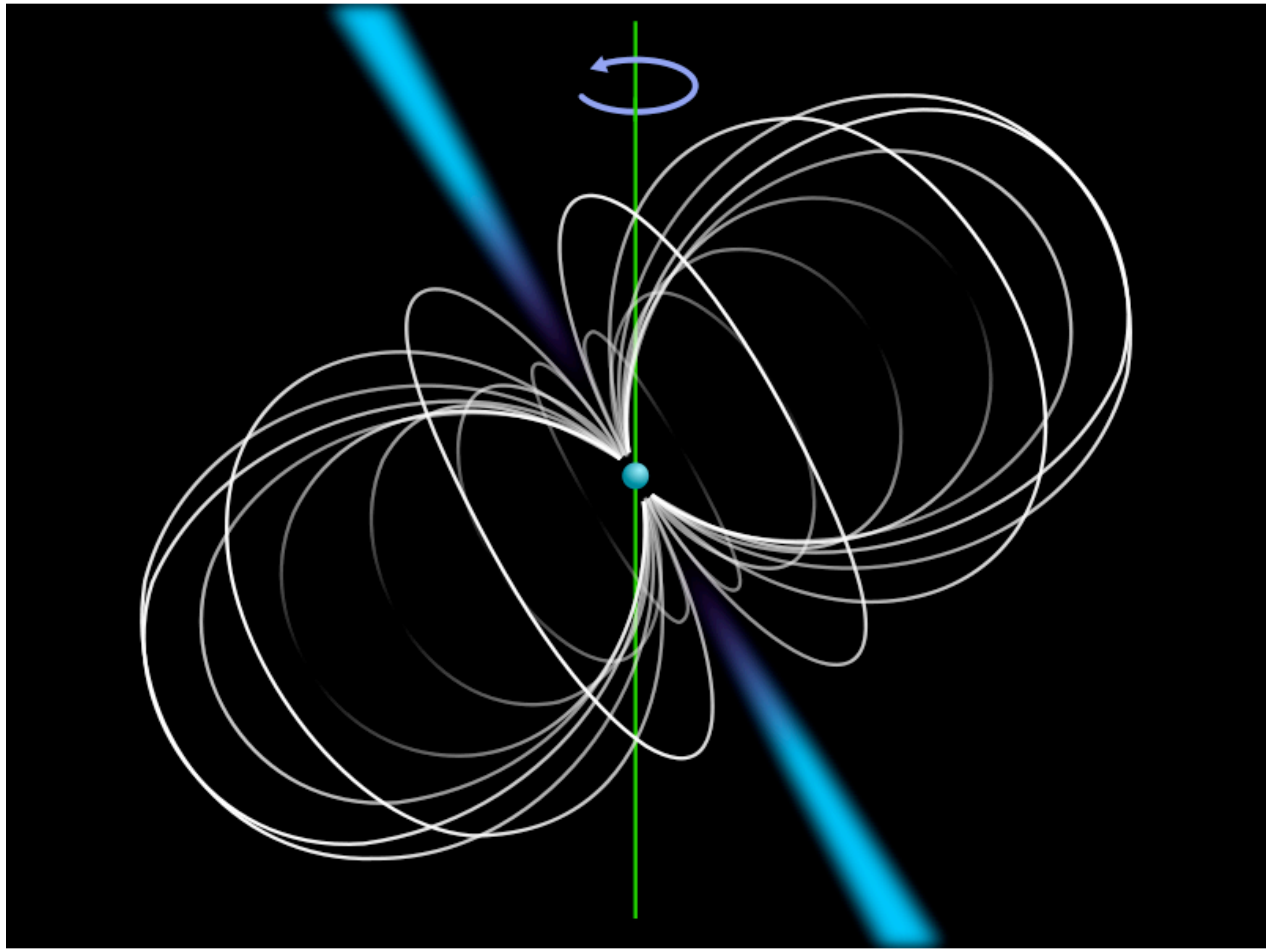
But….

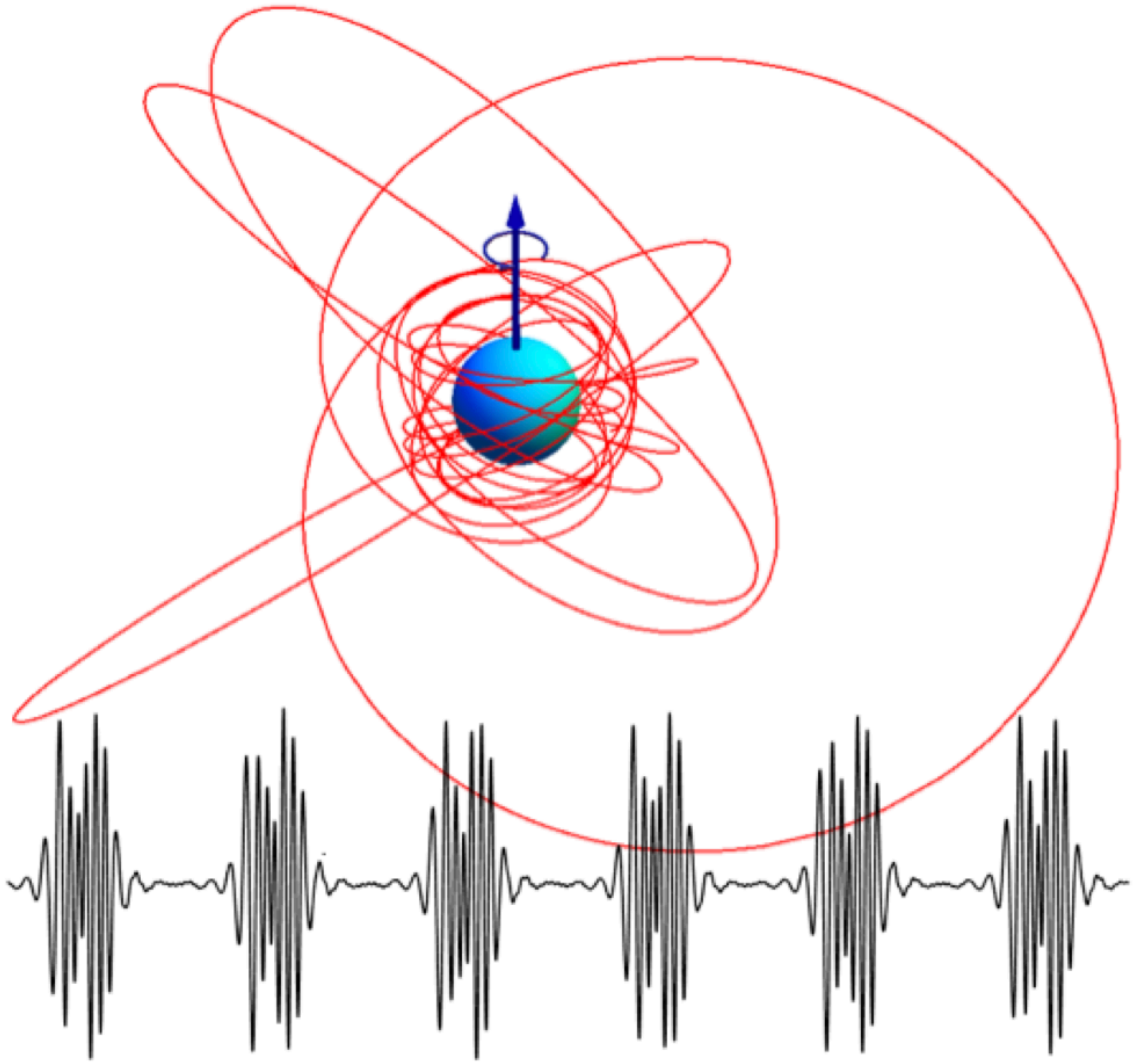
LISA science and analysis is significantly different

Much work to be done!

Extras

Links between LIGO CWs and LISA EMRIs





Simple signal - slowly chirping sinusoid

But…, modulated by Earth's orbit, huge number of cycles, $\sim 10^9$, low S/N per cycle, spread over large number of frequency bins , $\sim 10^5$

Complex signal - many evolving frequencies (or "voices"), large number of cycles, $\sim 10^5$, low S/N per cycle, spread over many voices

Cost of a coherent search

The cost of a coherent search scales as the observation time T to some power α, where α scales with the number of signal parameters D

$$\text{cost} \sim T^{\alpha}$$

Example: Detecting a chirping signal	$h(t) = A\cos(2\pi f_0 t + \pi \dot{f}_0 t^2 + \pi/3 \ddot{f}_0 t^3 + \phi_0)$
Signal-to-noise	$\text{SNR} \sim T^{1/2}$
Prior/Posterior volume ratio	$\frac{V}{\Delta V} \sim SNR^5\, T^6 \sim T^{8.5}$
Filter cost	$\sim T$
Search cost	$\sim T^{9.5}$

Semi-coherent searches

A semi-coherent search breaks up the analysis into N short segments $T_{\rm coh}$ with $T = N\,T_{\rm coh}$

$$\text{cost} \sim T^{\beta}\,T_{\rm coh}^{\alpha-\beta} \qquad \beta \sim 2$$

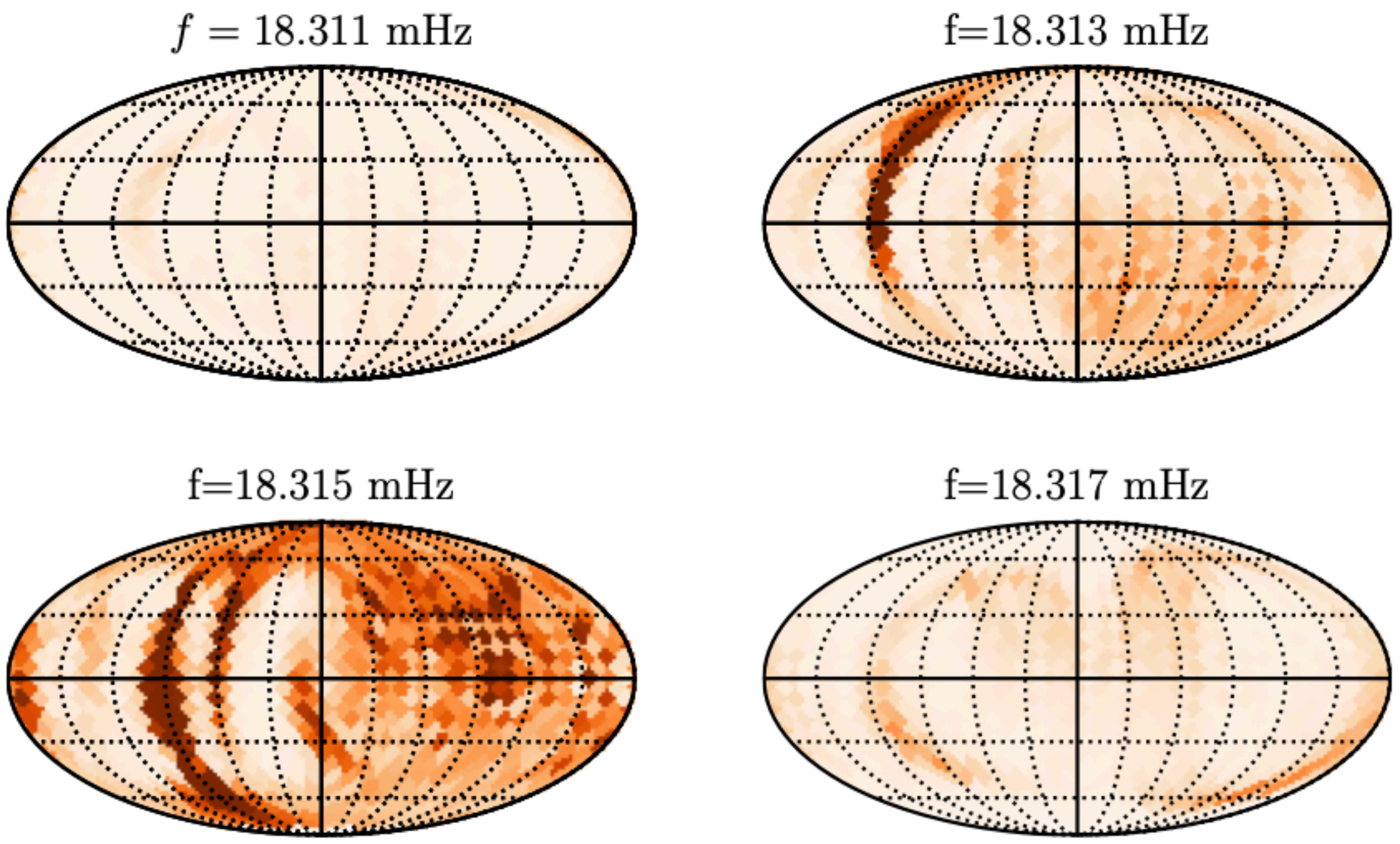
Semi-coherent searches can be much cheaper than fully coherent searches. But they are less sensitive

Minimum detectable amplitude for a coherent search $\quad h_{\rm min} \sim \dfrac{1}{T^{1/2}}$

Minimum detectable amplitude for a semi-coherent search $\quad h_{\rm min} \sim \dfrac{1}{T^{1/4}\,T_{\rm coh}^{1/4}}$

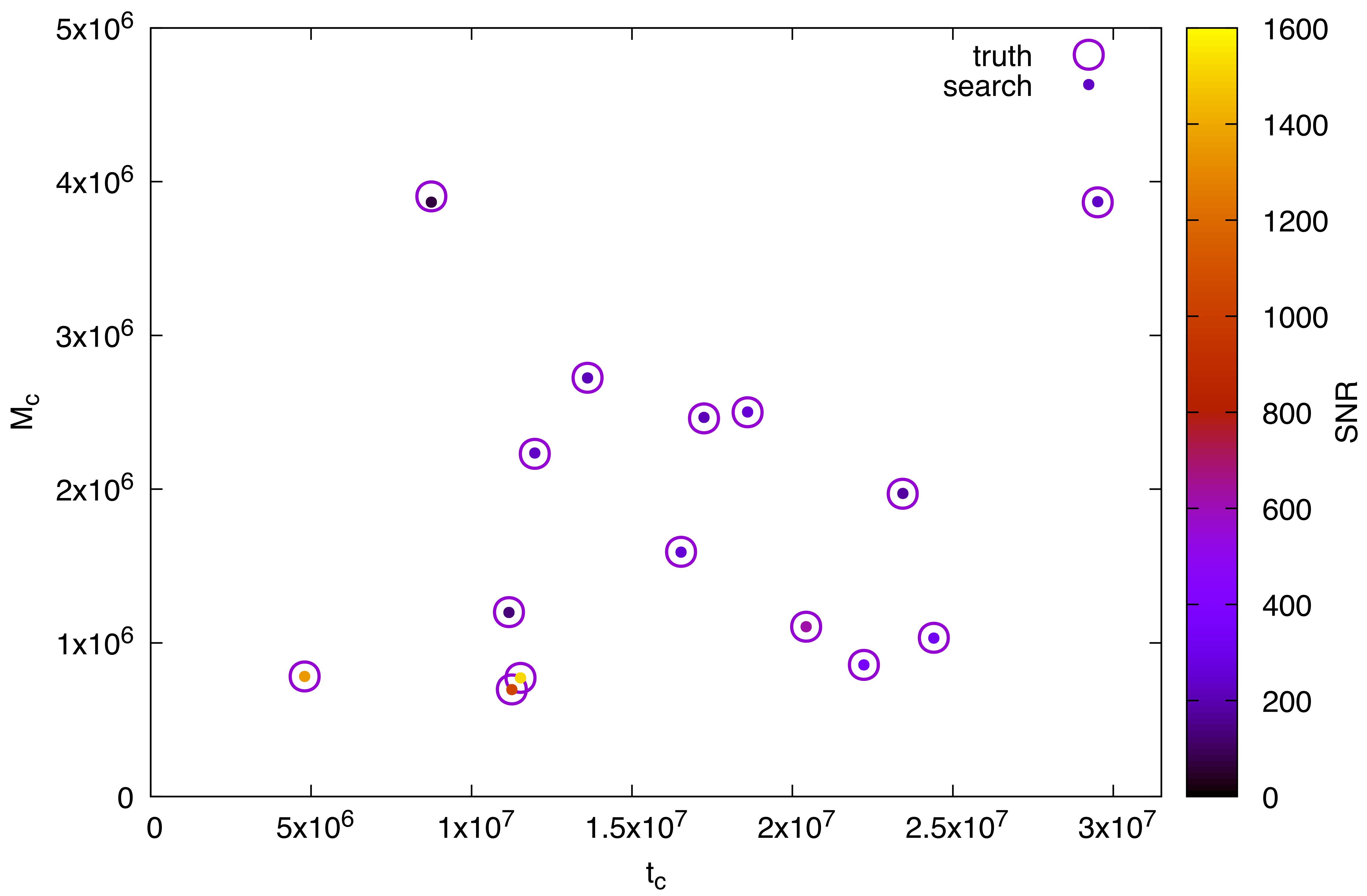
Low latency single-source search results used as proposals in global fit

F-statistic maps for GBs



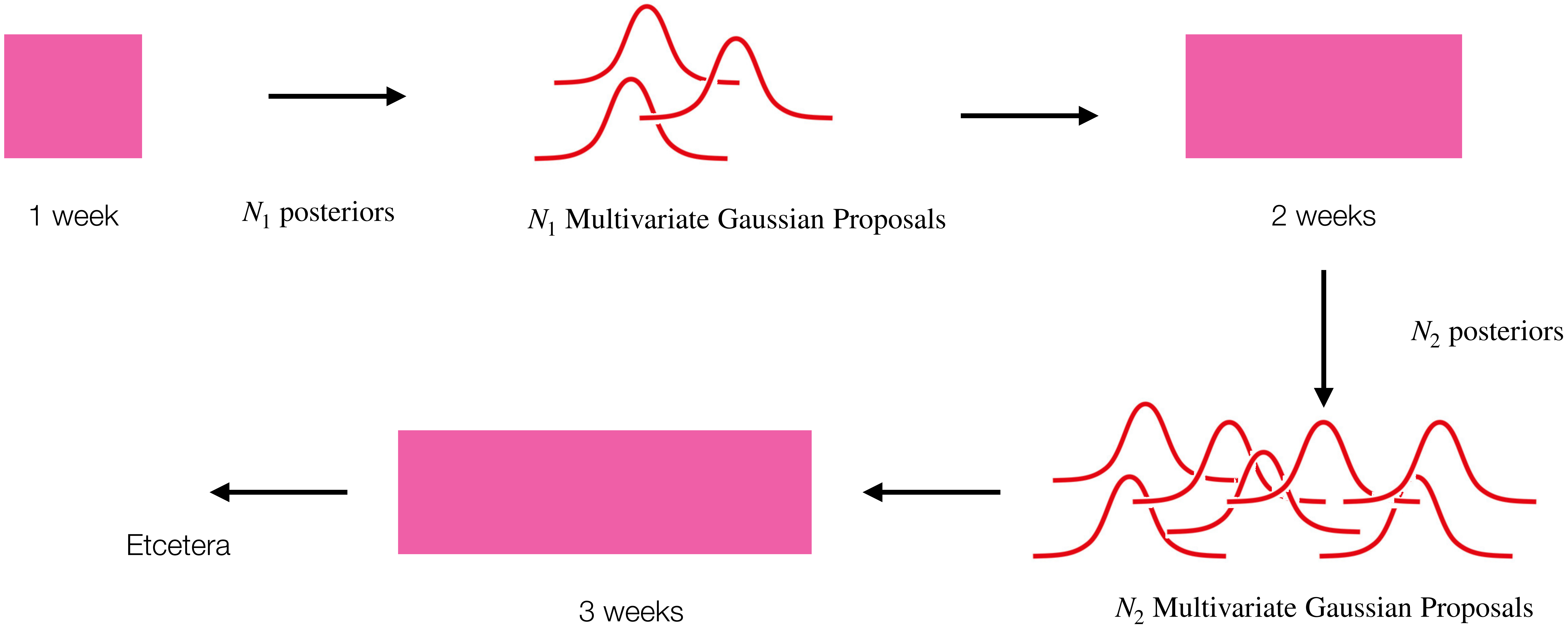
[Littenber, Cornish, Lackeos & Robson, arXiv:2004.08464]

Low latency BH search



[Cornish, arXiv: 2110.06238]

Building up the solution - "time annealing"



Building up the solution - “time annealing”