Gravitational waves physics - status and prospects

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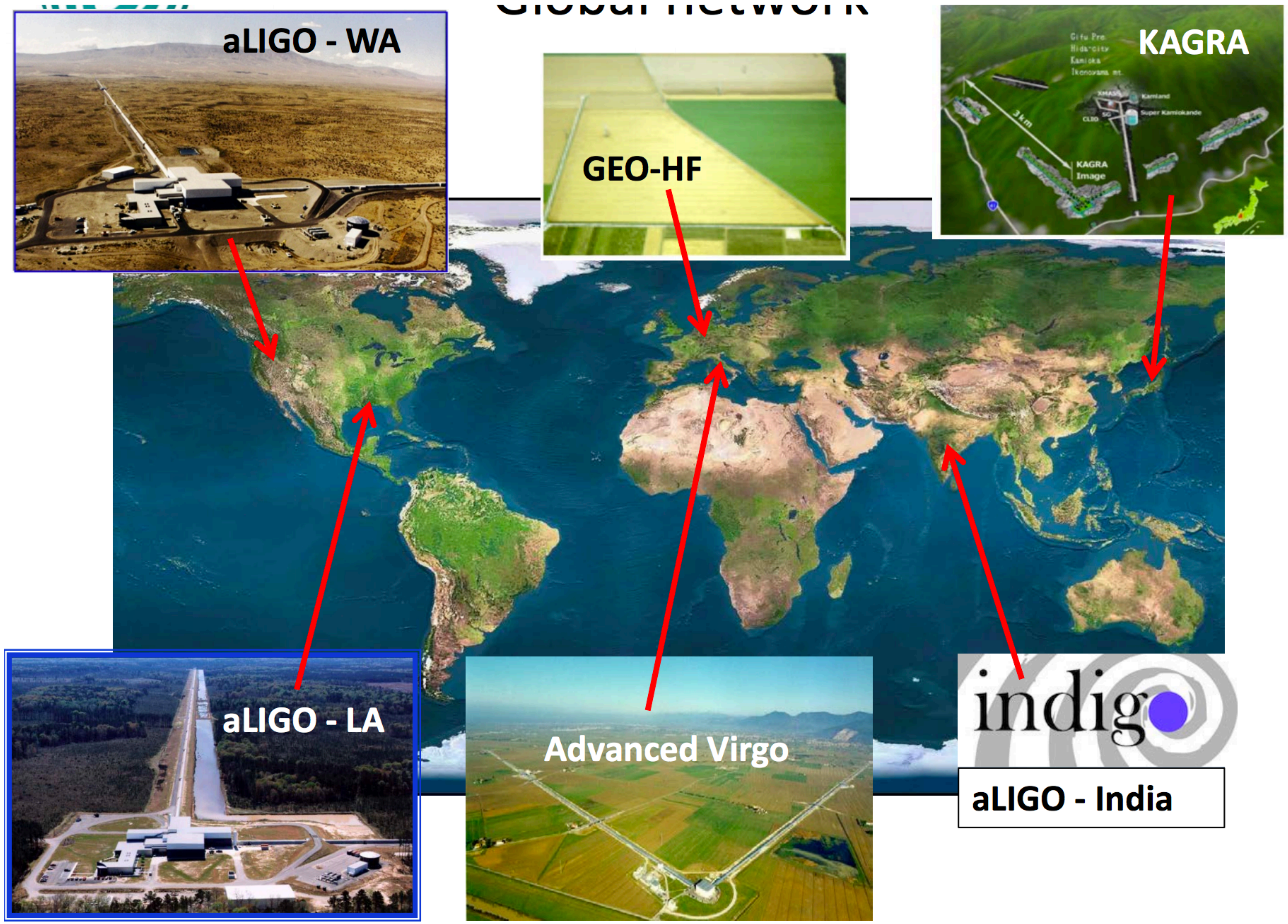
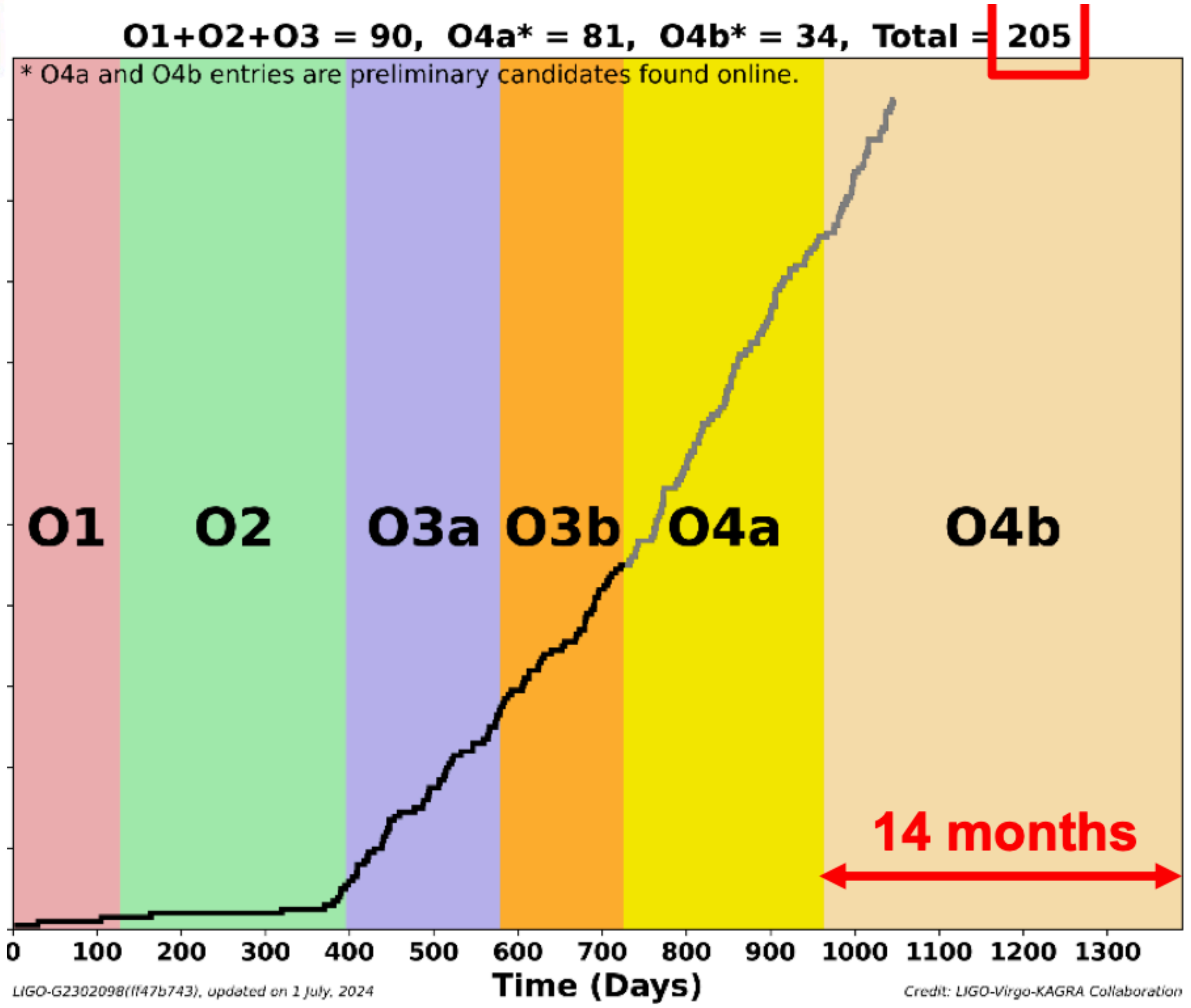
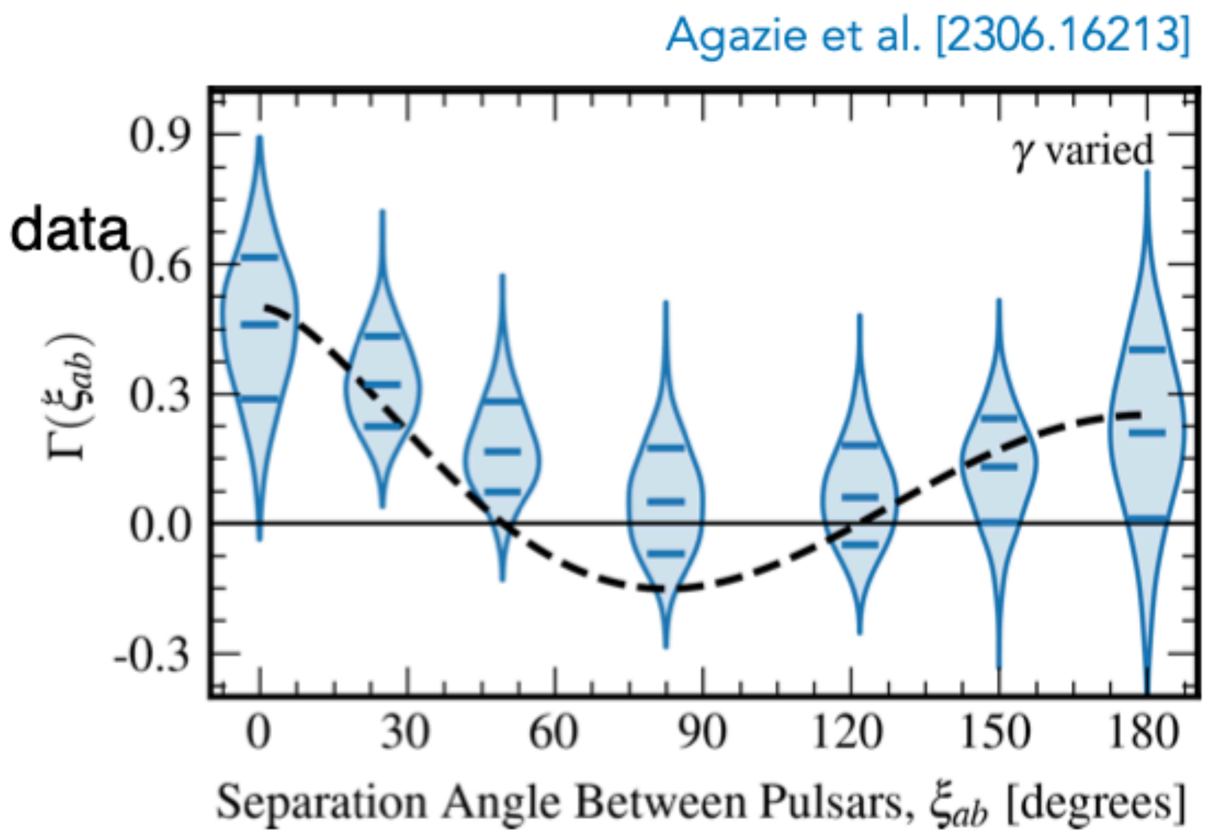
Where are we now - ground-based



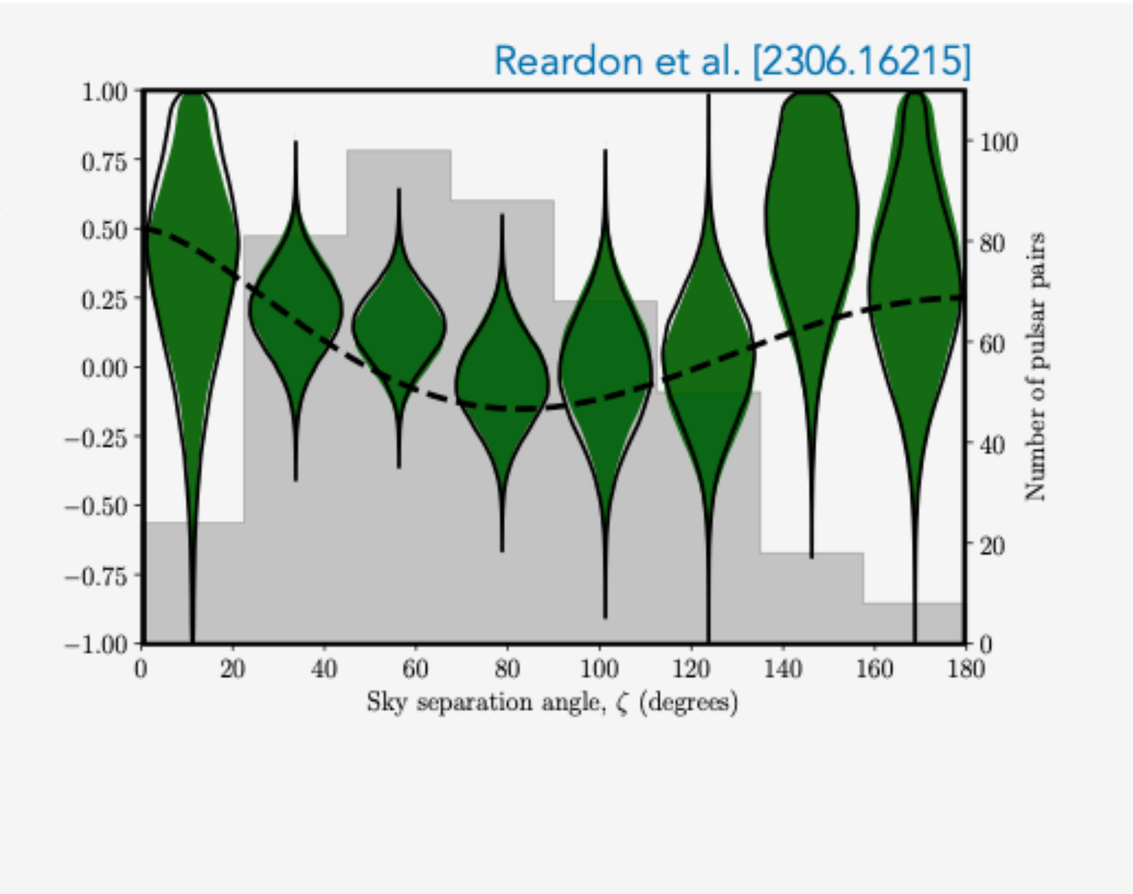


Where are we now - PTA

NANOGRav:
68 pulsars, 16 yrs of data
$\sim 3-4\sigma$ significance



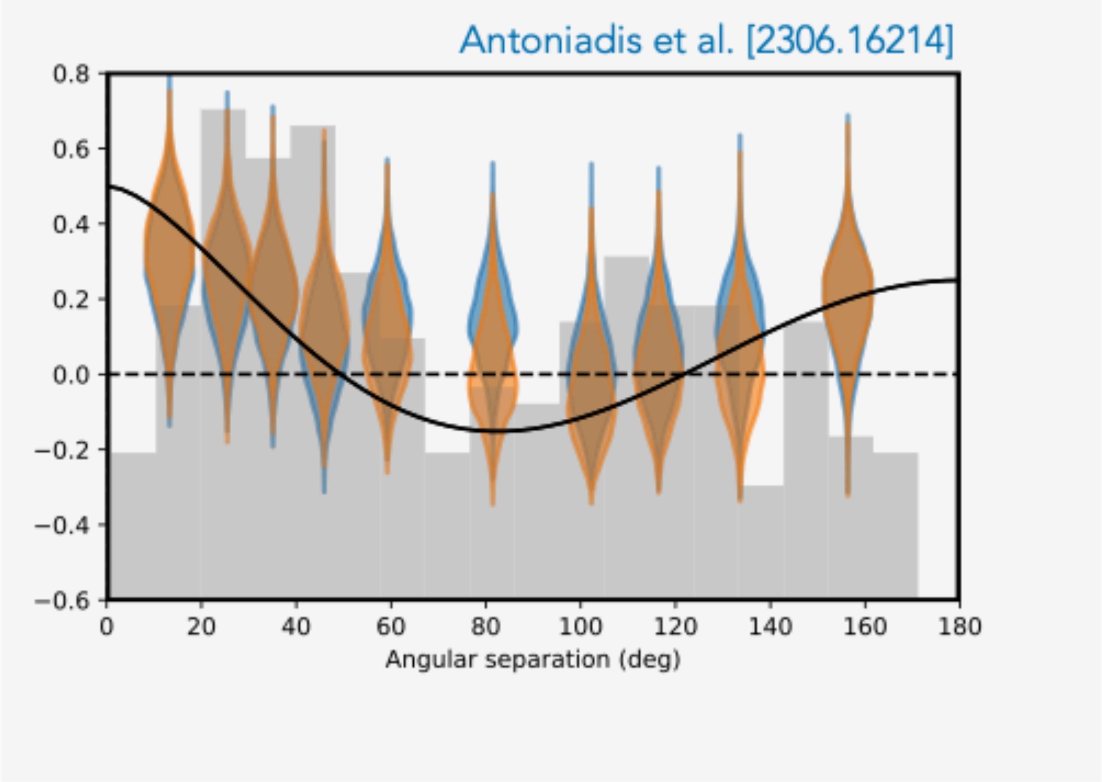
PPTA:
32 pulsars, 18 yrs of data
$\sim 2\sigma$ significance



First Detection of a SGWB

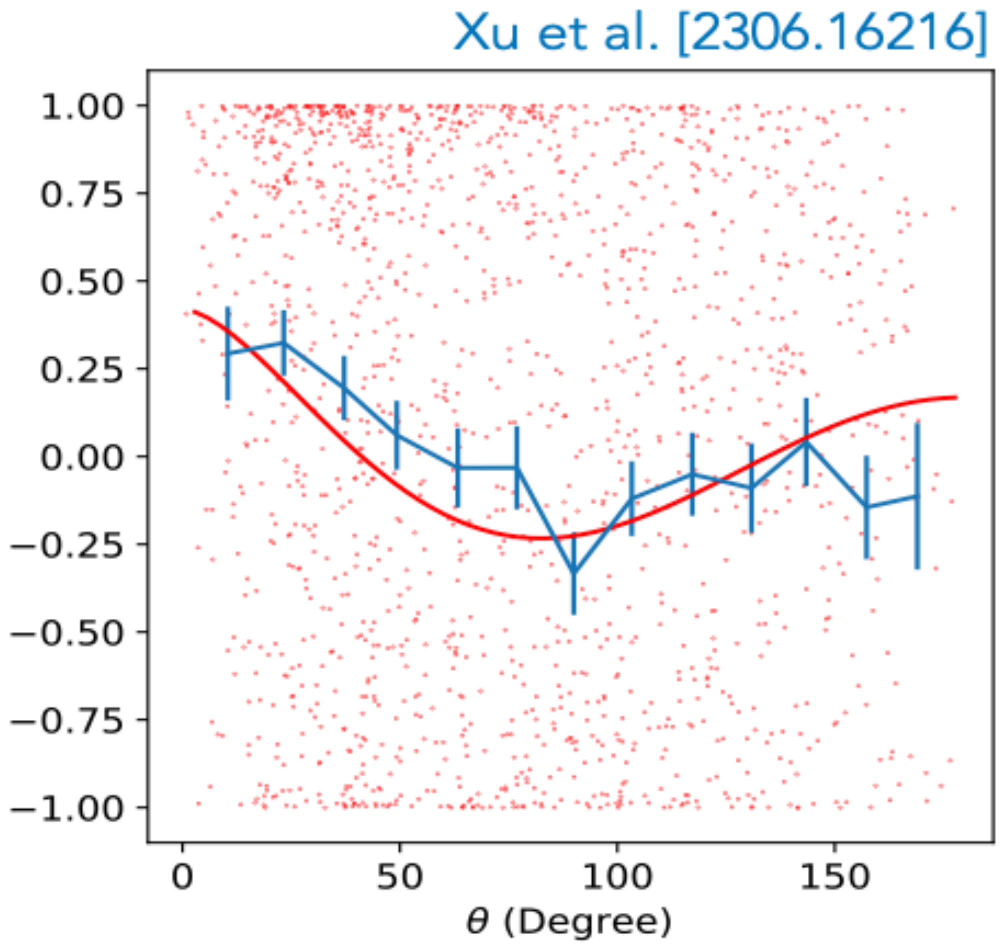
EPTA+InPTA:
25 pulsars, 24 yrs of data

$\sim 3\sigma$ significance

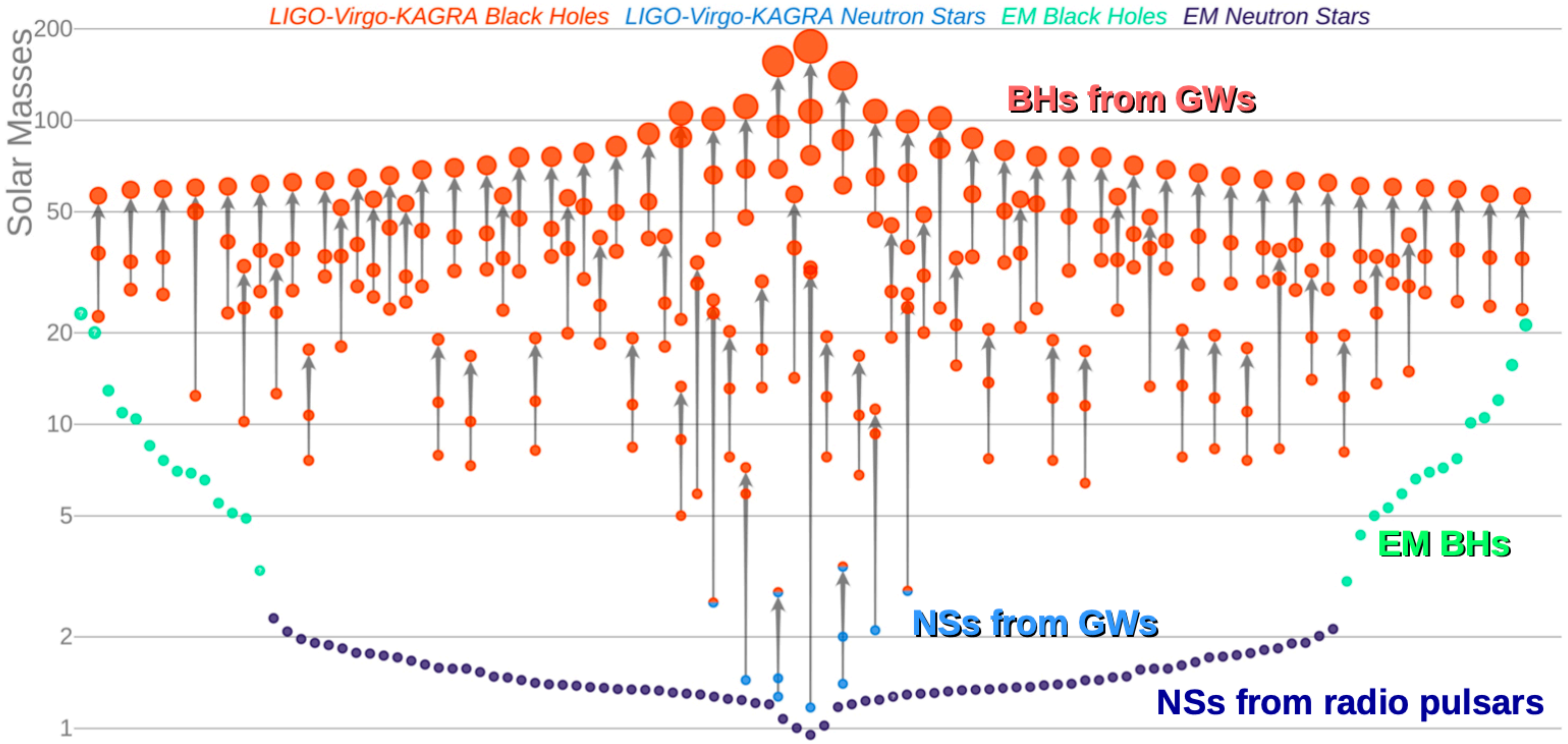


CPTA:
57 pulsars, 3 yrs of data

$\sim 4.6\sigma$ significance



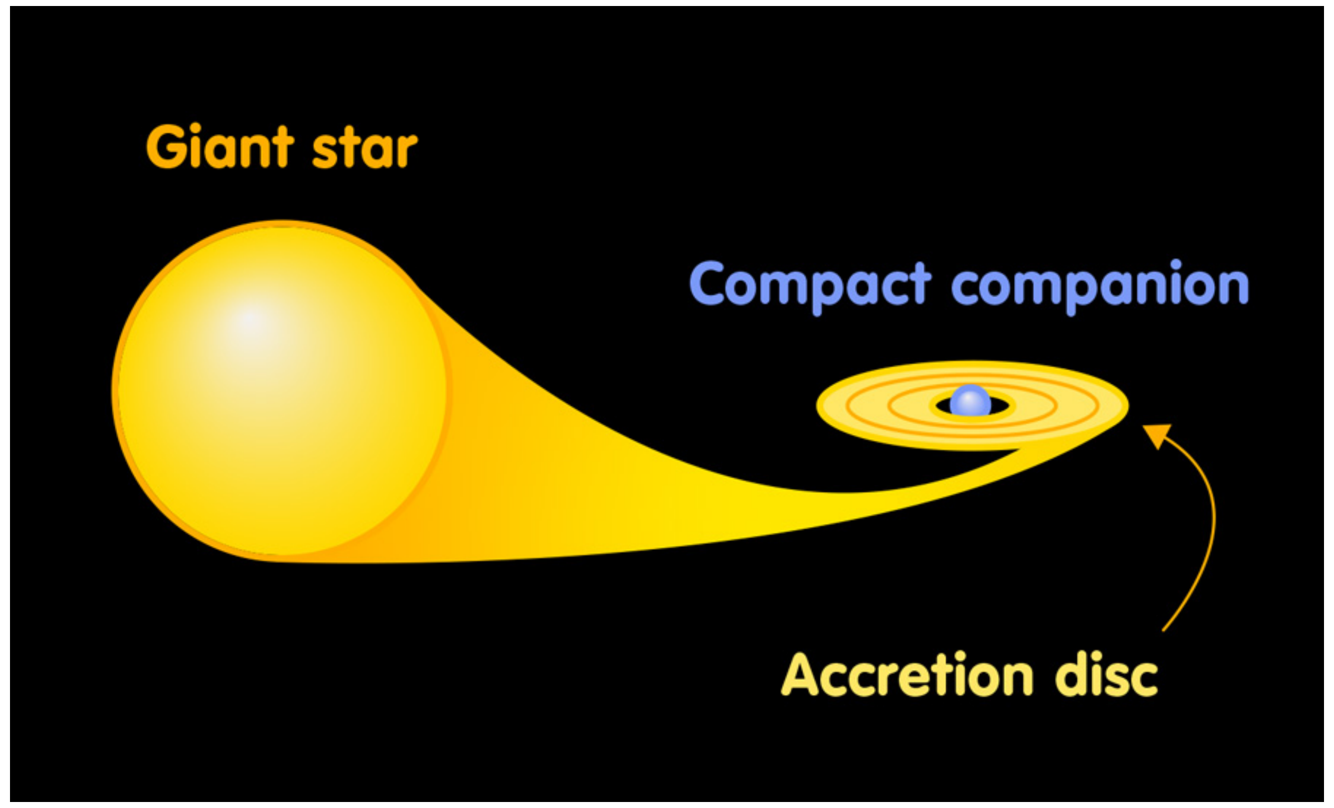
The GW Universe



credit: LIGO-Virgo-KAGRA | A. Geller | Northwestern

Where do BHs come from?

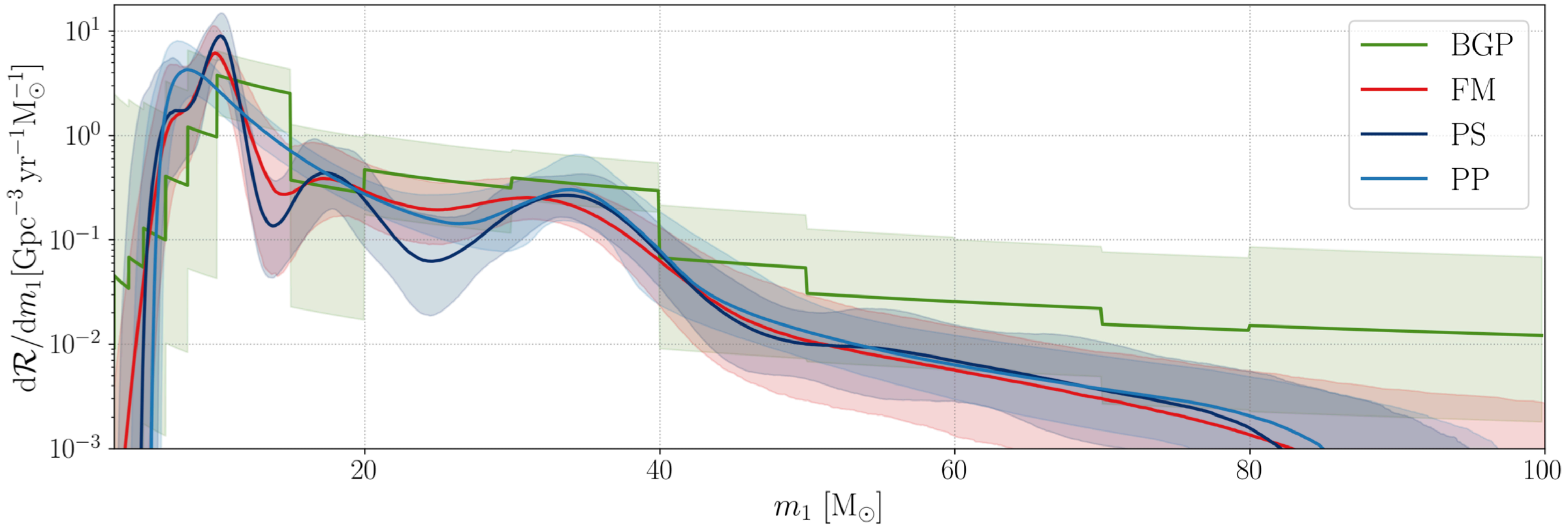
- Isolated/Field
  - common envelope
  - stable mass transfer
- Dynamical/Cluster
  - globular cluster
  - young star clusters
  - AGN disk

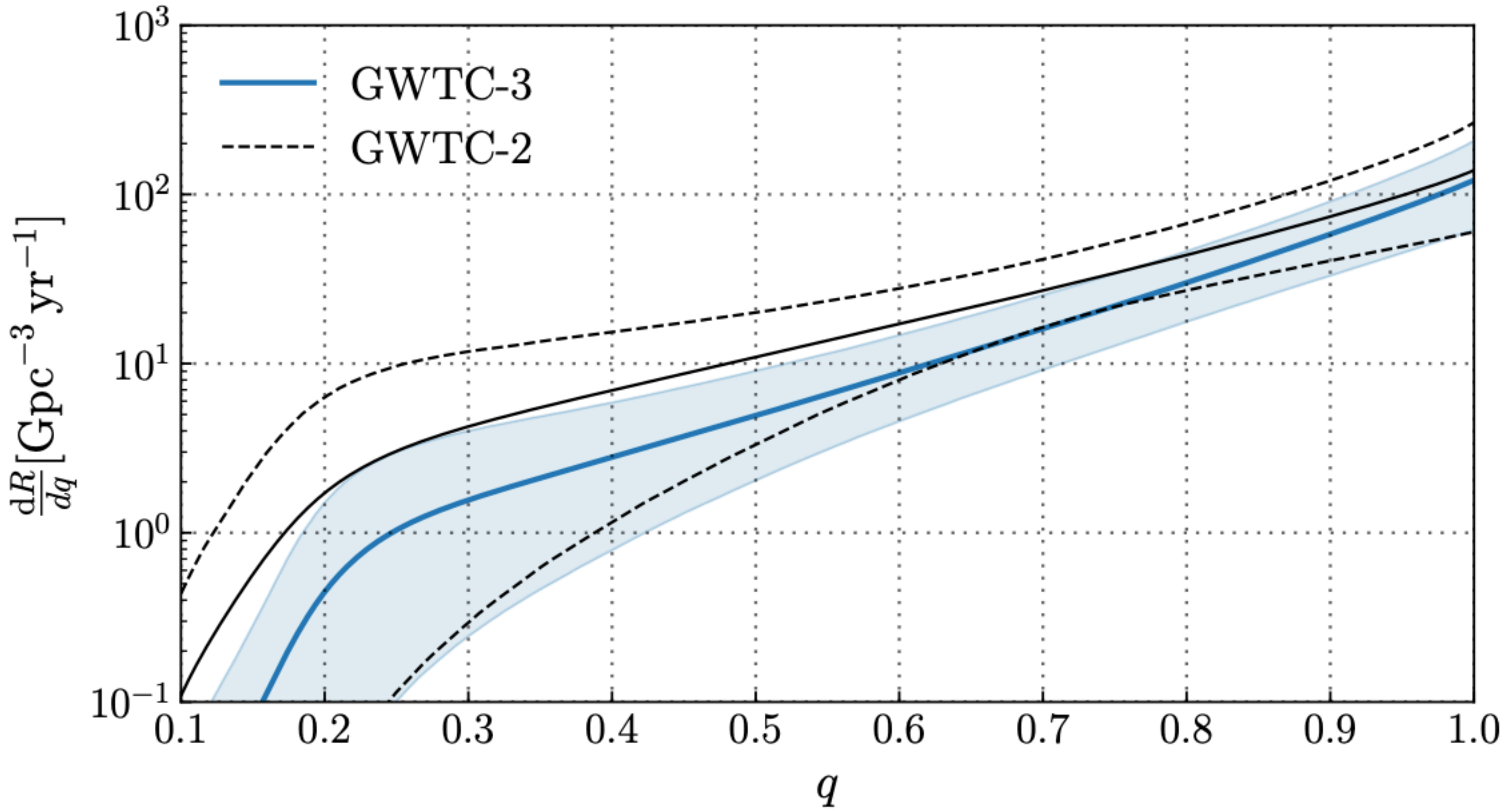


- Primordial black holes
- Triples/quadruples
- Hierarchical

Mass distribution

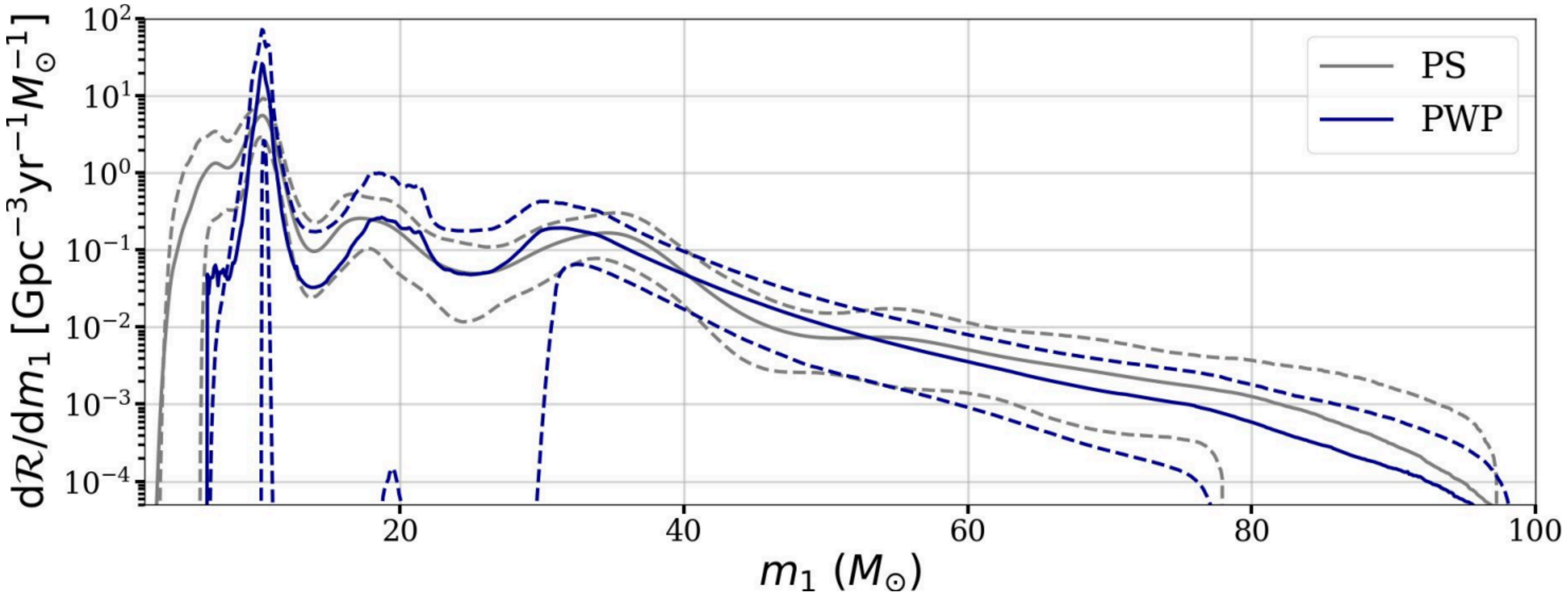
- LVK phenomenological modeling
- Primary mass modelled as a power-law plus peak (Fishbach & Holz 2017, Talbot & Thrane 2018)
- Preference for equal mass
  - But $p(q) \sim q^{\alpha}$

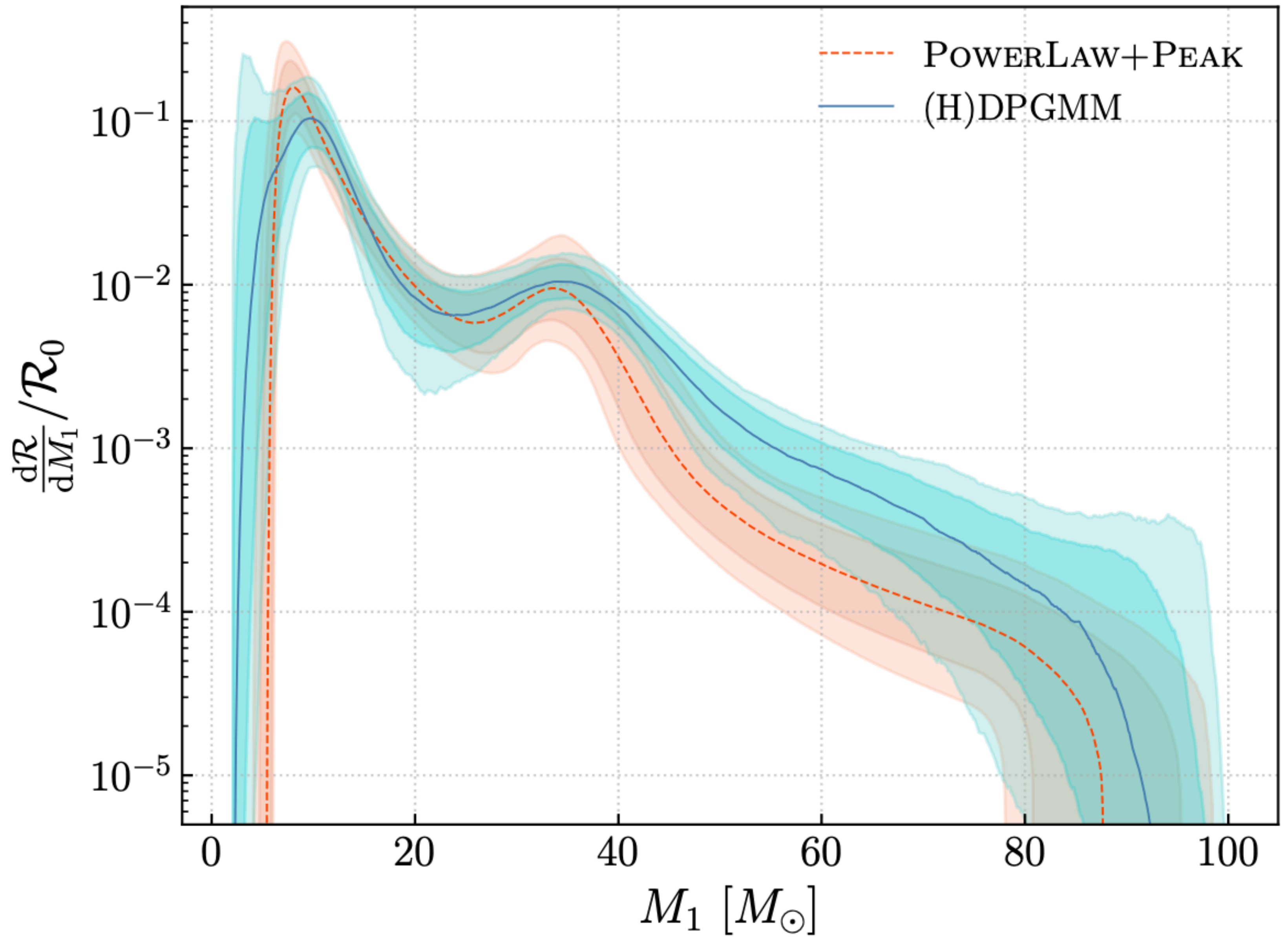




Mass distribution

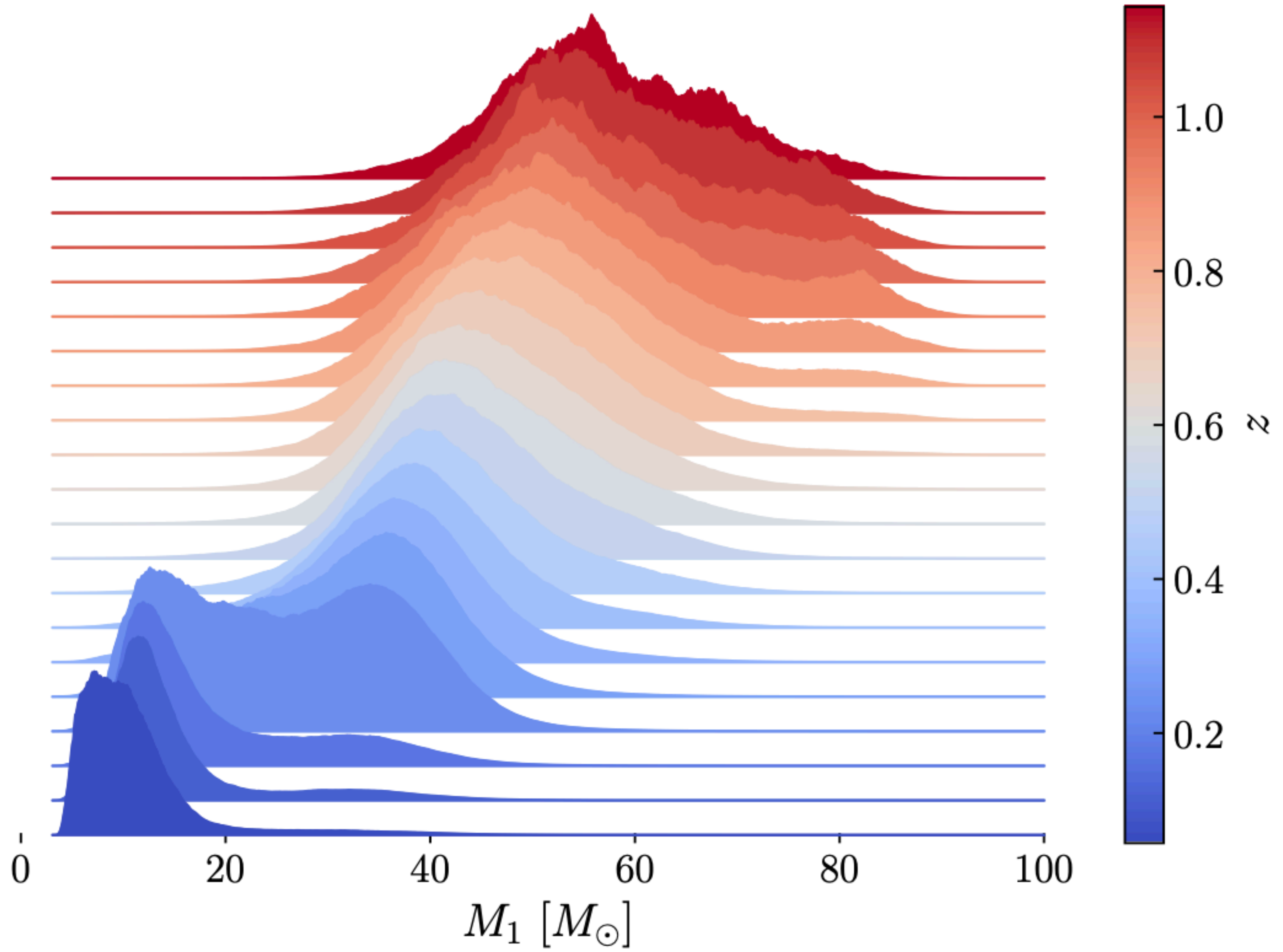
- Substructure (Farah+ 2023, Edelman+ 2022, Tiwari & Fairhurst 2021)
  - Reversible Jump MCMC on piece-wise power law (Toubiana+2023)
- Hierarchy of Dirichlet Process Gaussian Mixture Models (Rinaldi & Del Pozzo 2022, Rinaldi + 2023)





Mass tomography

- Primary mass evolves with redshift (Rinaldi + 2023)
  - Low-z sources have $m_1 < 20M_\odot$, in agreement with X-ray binaries (Özel+2010, Farr+2011)
  - For $z > 0.4$ most sources have $m_1 > 20M_\odot$
  - Selection biases?



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GW as standard sirens

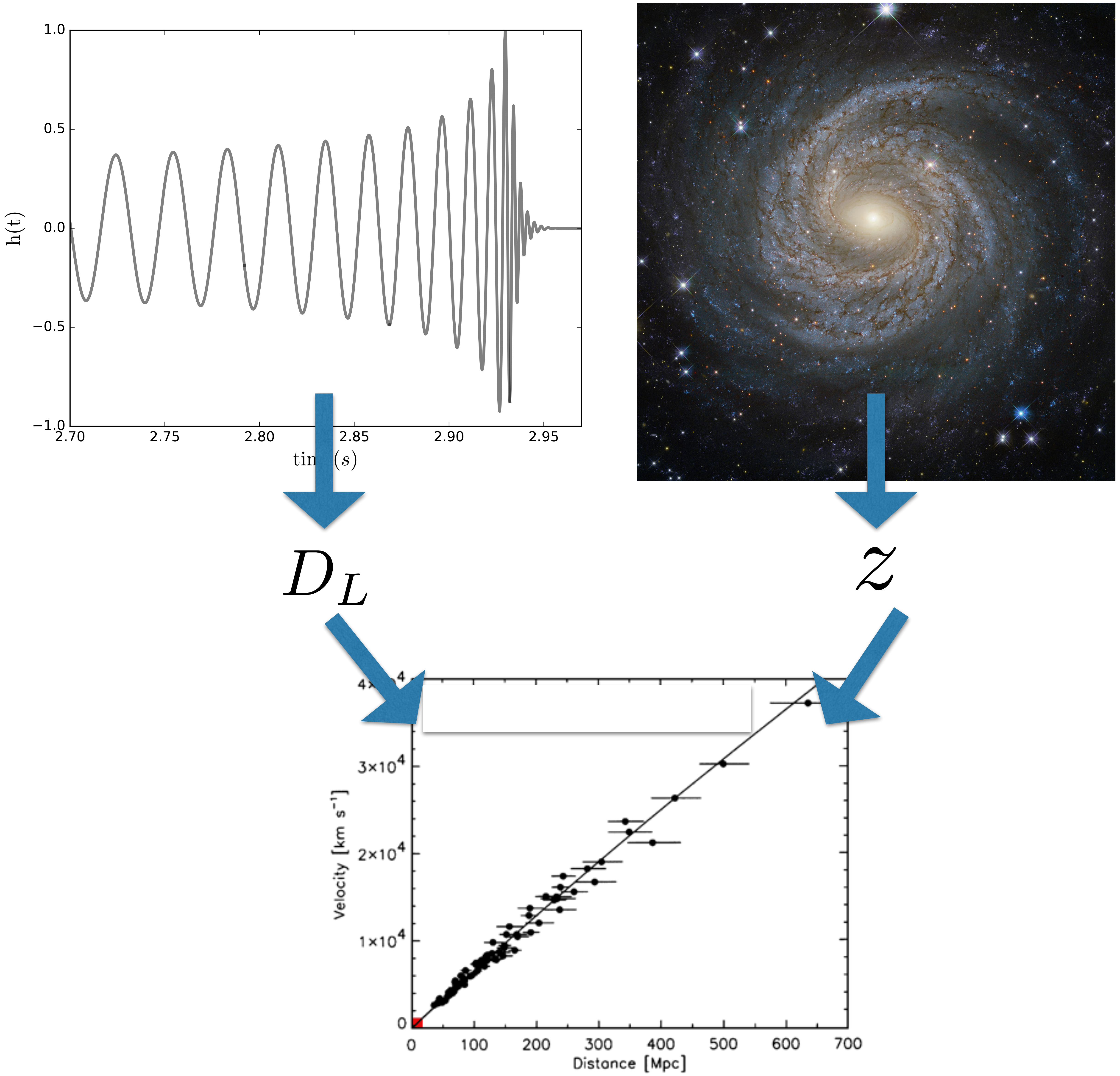
- GW are self-calibrating sources

$$h \sim D_L^{-1}$$

  - Direct measurement of luminosity distance

- Complemented with redshift information
  - EM counterpart
  - Host galaxy

- Determination of cosmological parameters



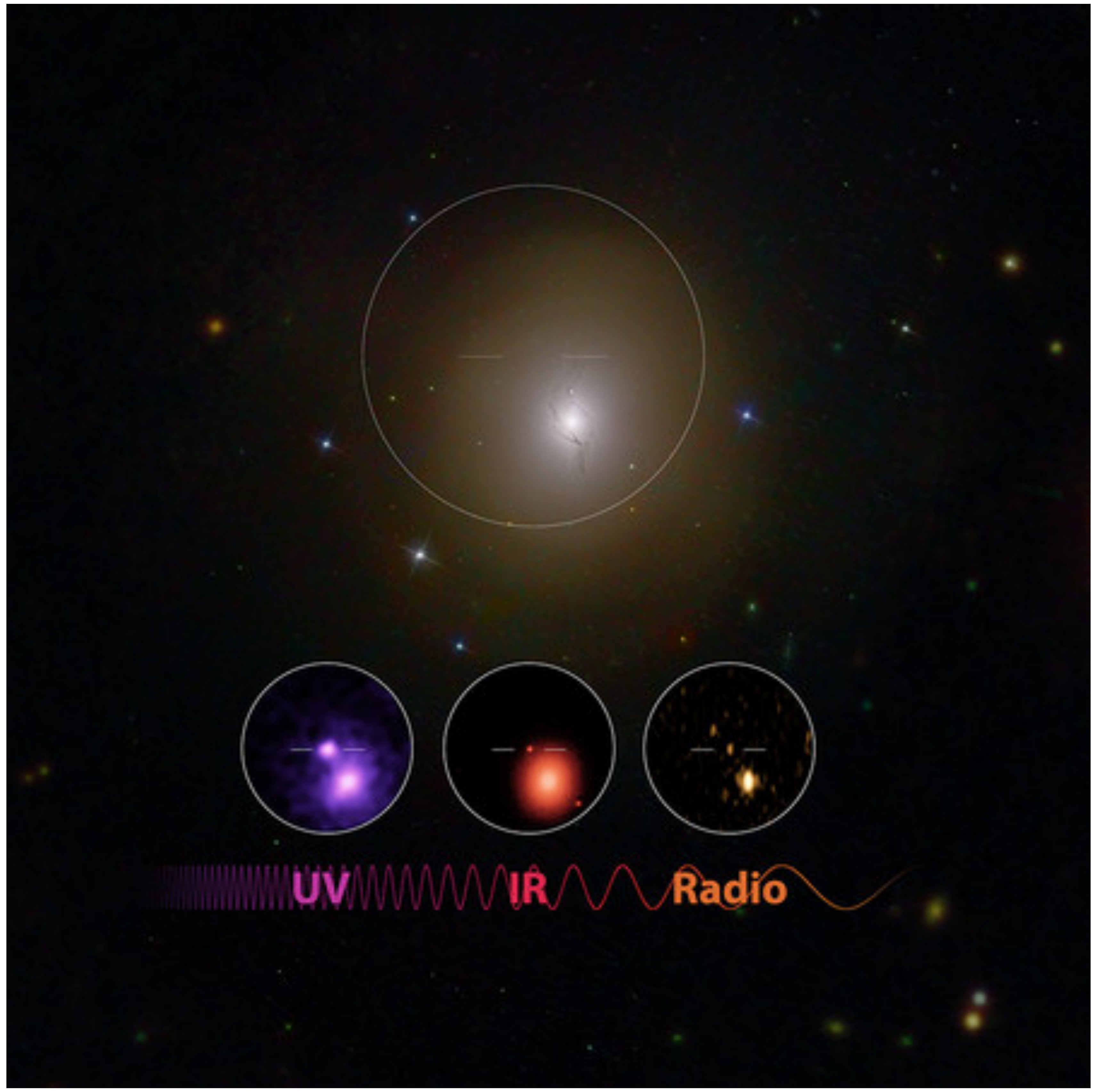
EM counterpart identification

- Optical/infrared/UV counterpart
  - kilonova (LVK, arXiv:1710.05833)
  - speed of GW (LVK, arXiv:1710.05834)

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\rm EM}} \leqslant +7 \times 10^{-16}$$

$$\Delta v = v_{\rm GW} - v_{\rm EM}$$

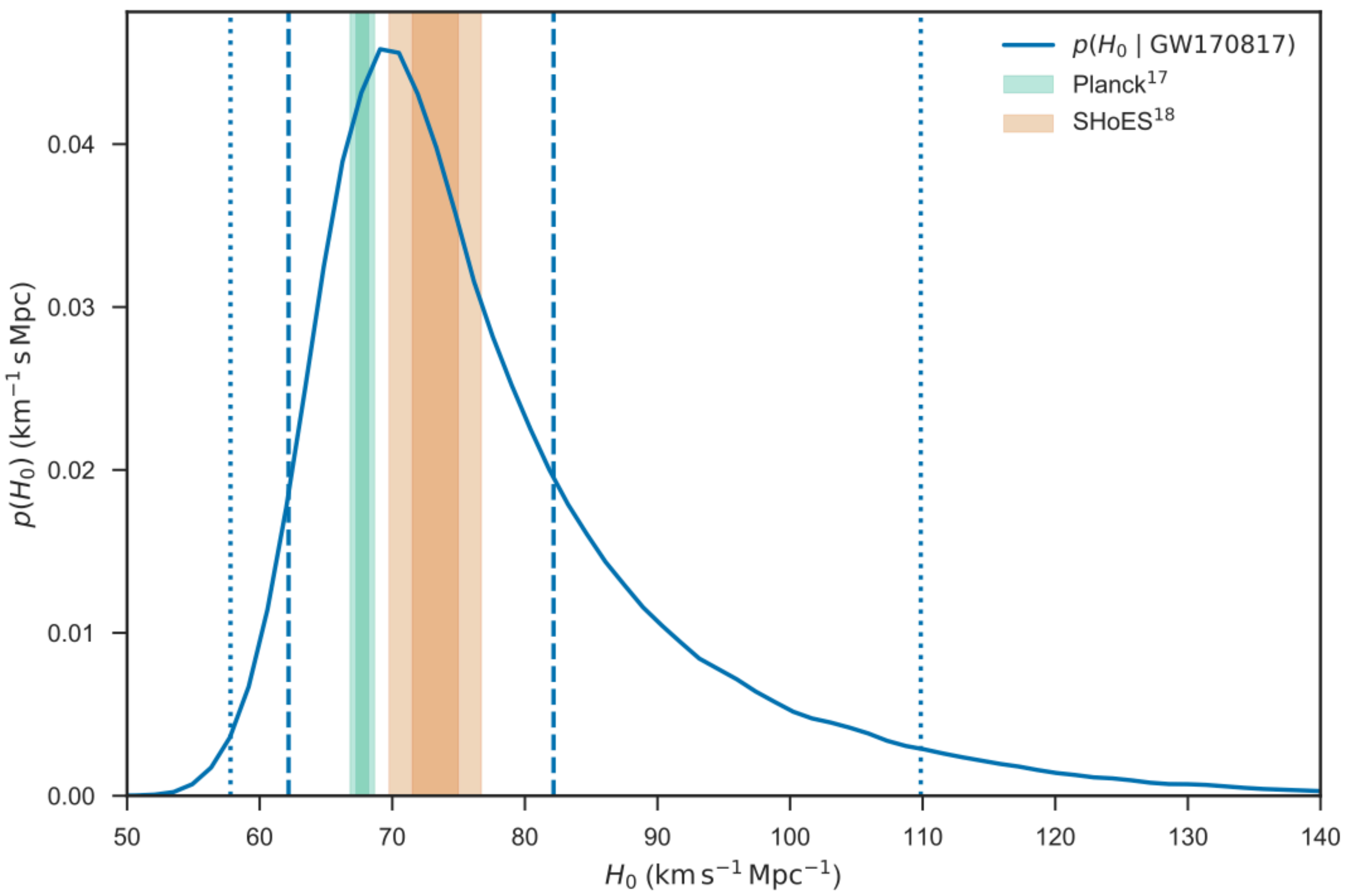
- EoS constraints, jet morphology, …



H0 from GW170817

- Spectroscopic redshift from NGC 4993
- First "non-distance-scale-ladder" H_0 measurement

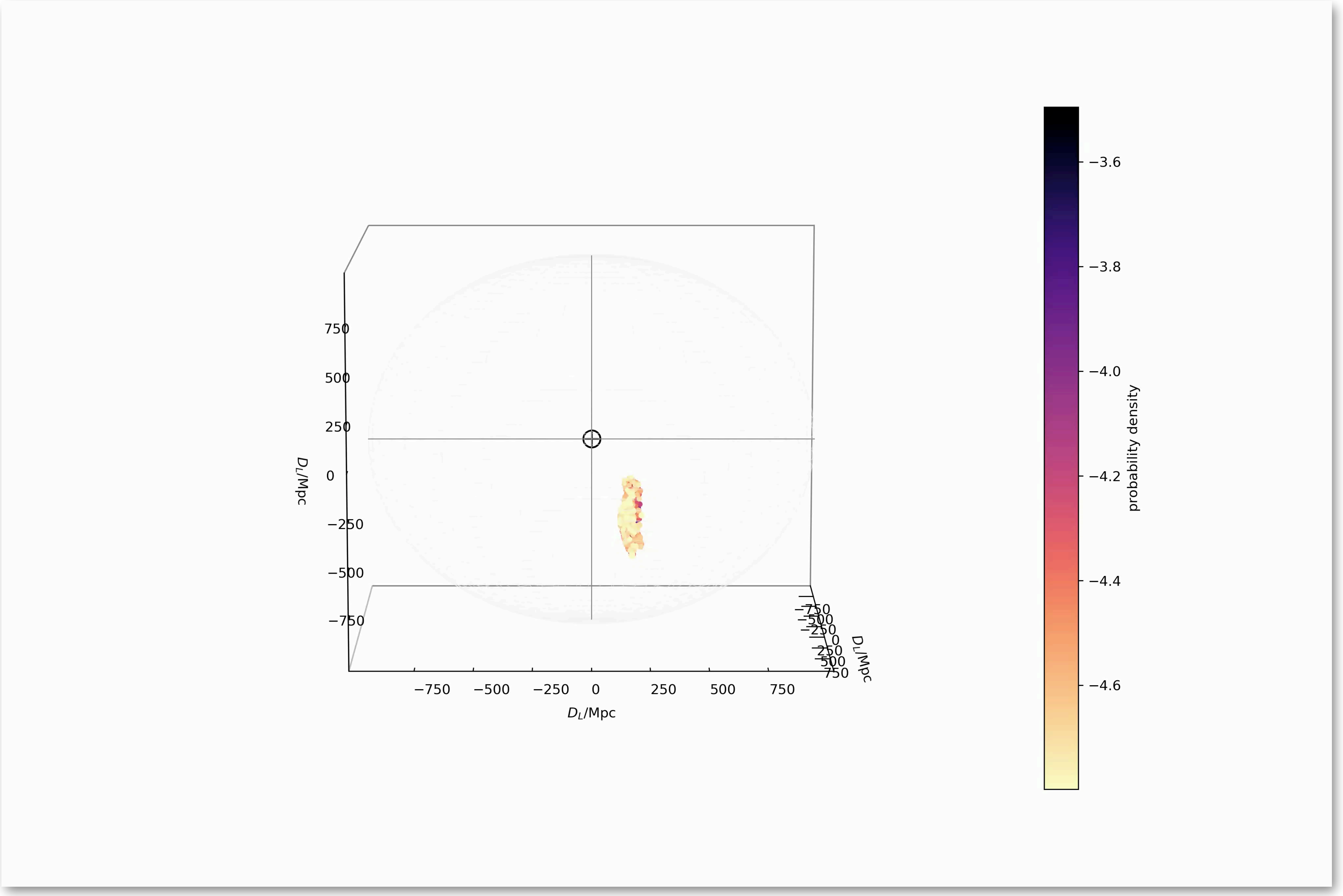
$$H_0 = 70^{+12}_{-8}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

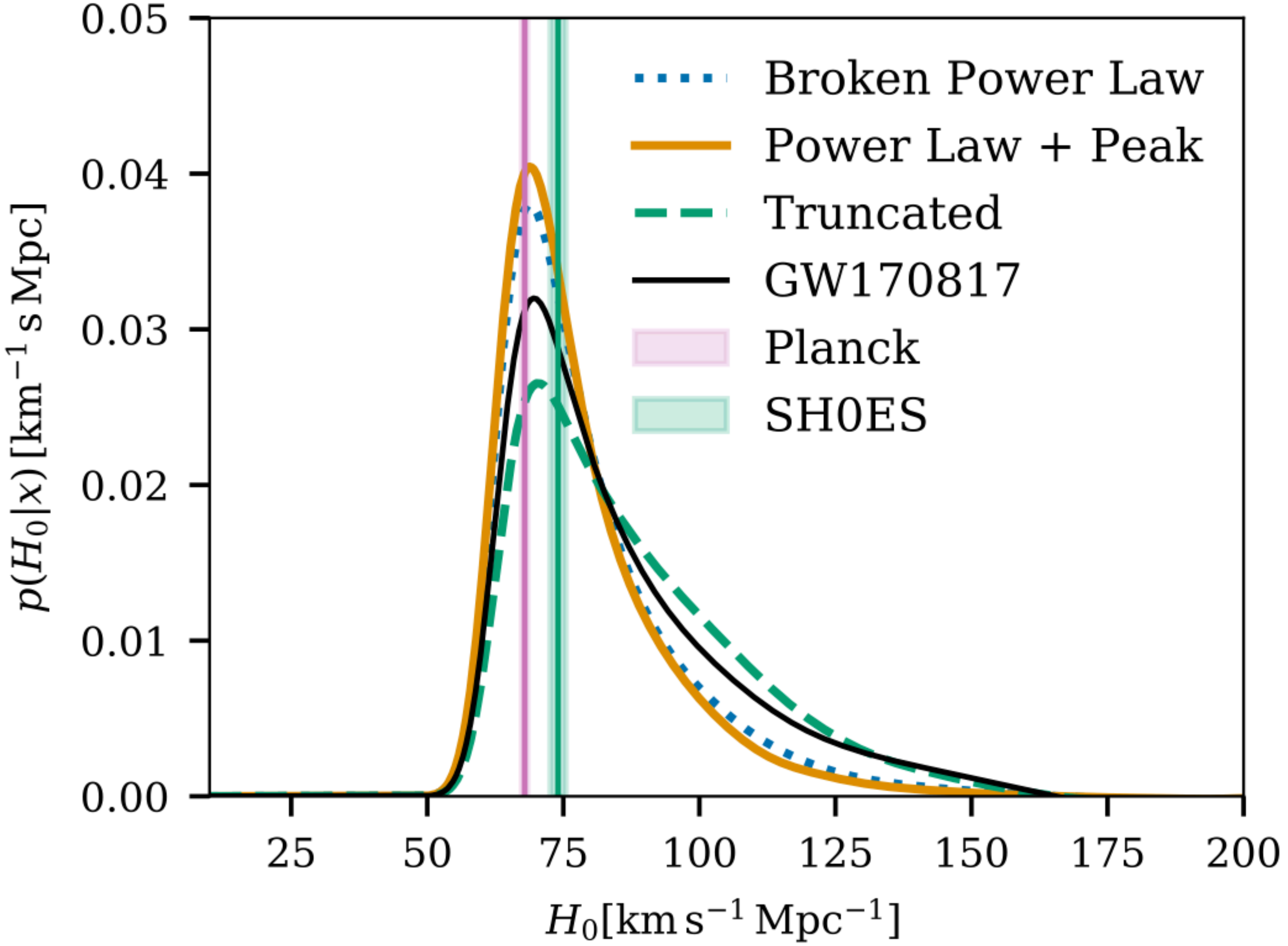


LVK, arXiv:1710.05835

Cosmology

- H_0 not just from GW170817, BBH bring information too
  - Statistical association method (e.g. DP, arXiv:1108.1317)

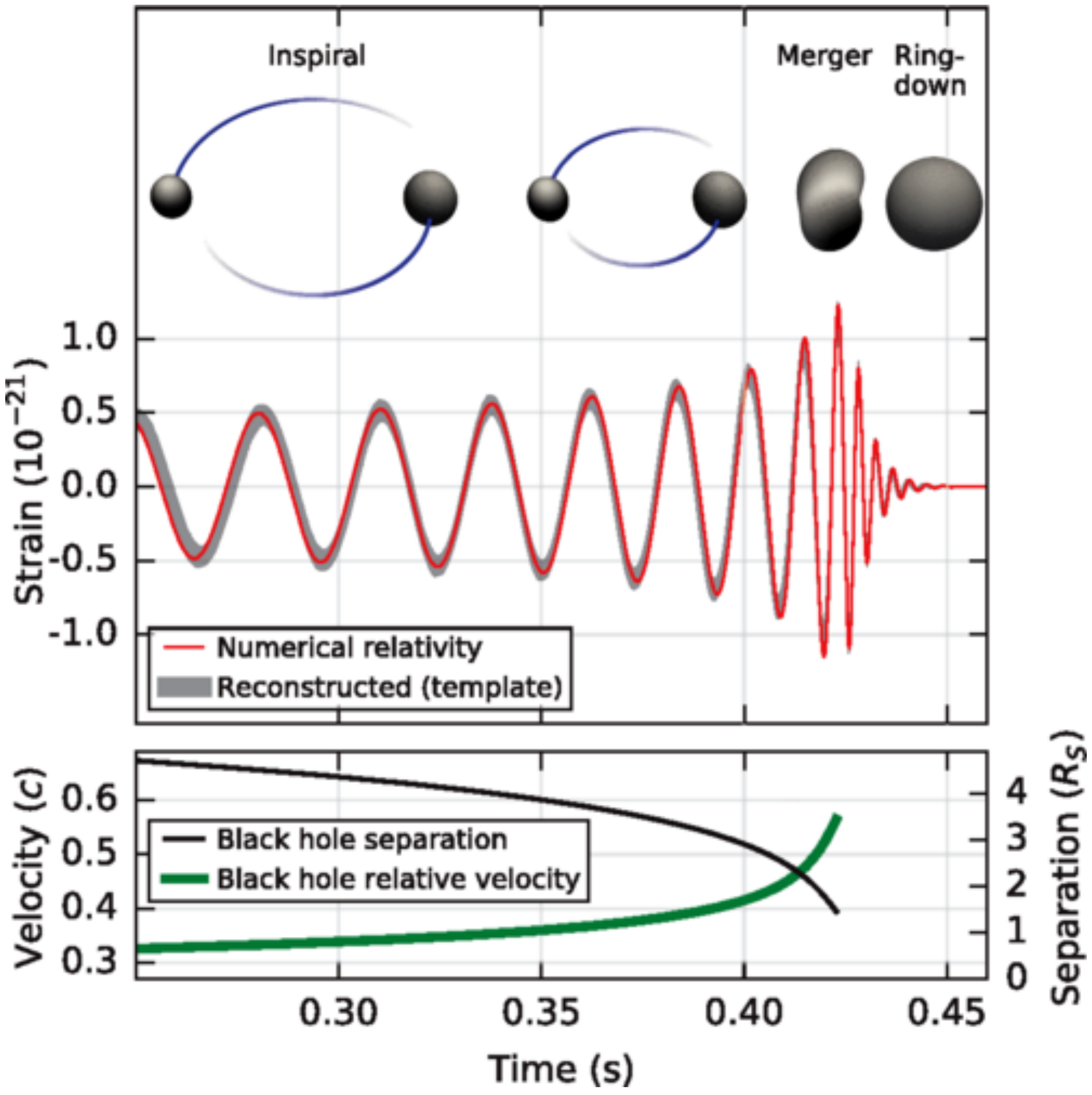




LVK, arXiv:2111.03604

Fundamental physics

- In GR, gravitational waves (GW) are wave solutions to Einstein's equations generated from accelerating masses, propagating at the speed of light
- Shape of GW signal carries information about
  - binary dynamics and component nature
  - non-linear dynamics of space-time
  - final object nature



LVC, arXiv:1602.03837

Gravitational strong-field

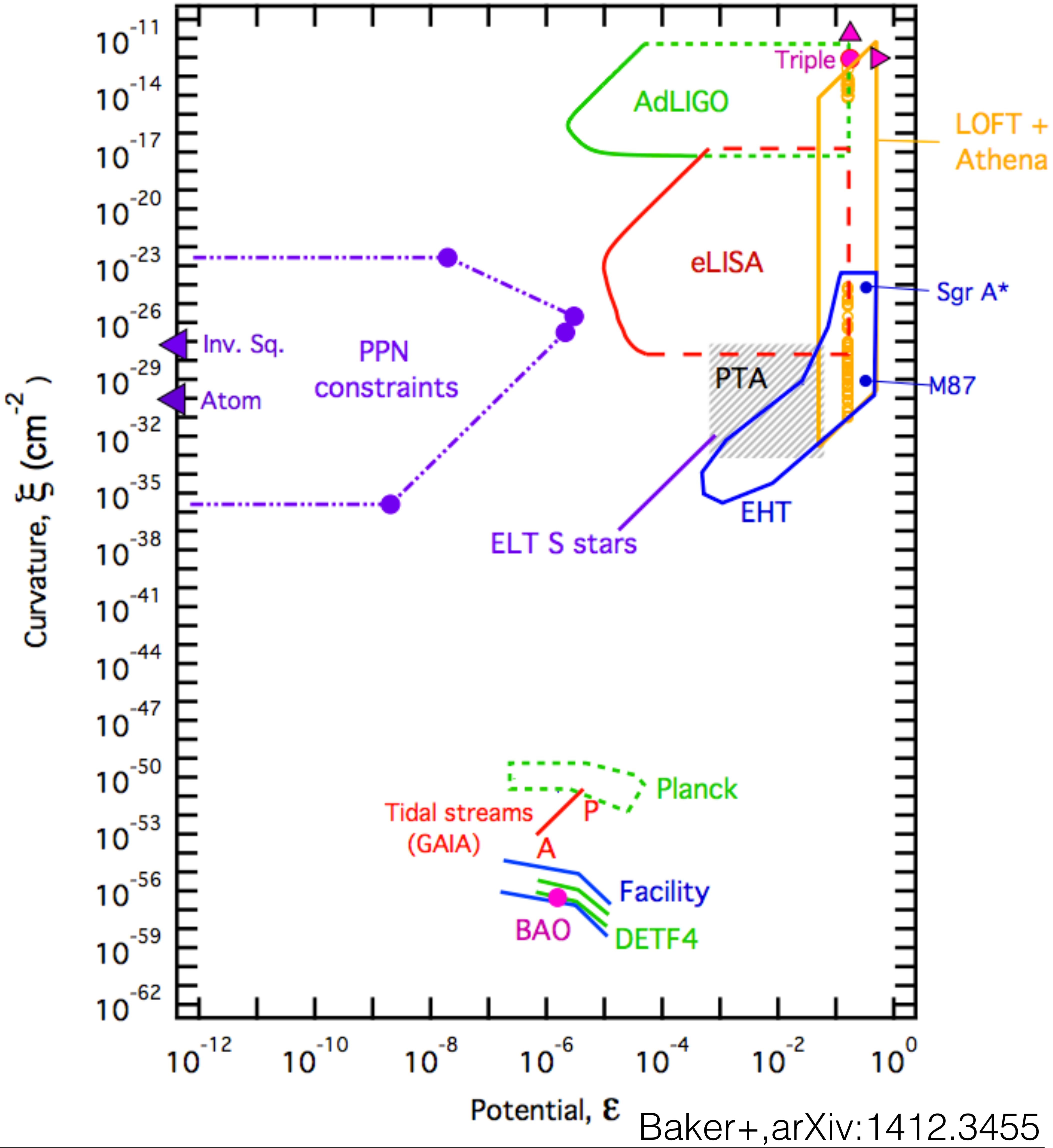
- Field strength

$$\epsilon = \frac{GM}{c^2 R}$$

- Curvature (Kretschmann scalar)

$$\xi = (R_{\alpha\beta\gamma\delta} R^{\alpha\beta\gamma\delta})^{1/2}$$

- Gravitational waves from binary black holes are the optimal probes



Baker+,arXiv:1412.3455

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GW in alternative gravity

- Alternative to GR can introduce extra-fields, curvature terms, challenge GR pillars, …
- Almost no full solution in non-GR known (but see Okounkova et al, arXiv:1705.07924)
- GW phase is modified:
  - non-GR action (extra fields, higher curvature, …): no full non-linear description, only post-Newtonian
  - Propagation (Lorentz violations, graviton mass, …): GR-like BBH dynamics, but modified GW propagation
  - non-GR BHs (extra-fields, exotic objects):
    - Anomalous quadrupole moments
    - ringdown spectrum
    - Echoes
    - Dark matter
    - …

Theory	Field content	Strong EP	Massless graviton	Lorentz symmetry	Linear $T_{\mu\nu}$	Weak EP	Well-posed?
Extra scalar field							
Scalar-tensor	S	✗	✓	✓	✓	✓	✓ [34]
Multiscalar	S	✗	✓	✓	✓	✓	✓ [38]
Metric $f(R)$	S	✗	✓	✓	✓	✓	✓ [40, 41]
Quadratic gravity							
Gauss-Bonnet	S	✗	✓	✓	✓	✓	✓?
Chern-Simons	P	✗	✓	✓	✓	✓	✗✓? [44]
Generic	S/P	✗	✓	✓	✓	✓	?
Horndeski	S	✗	✓	✓	✓	✓	✓?
Lorentz-violating							
Æ-gravity	SV	✗	✓	✗	✓	✓	✓?
Khronometric/ Hořava-Lifshitz	S	✗	✓	✗	✓	✓	✓?
n-DBI	S	✗	✓	✗	✓	✓	?
Massive gravity							
dRGT/Bimetric	SVT	✗	✗	✓	✓	✓	?
Galileon	S	✗	✓	✓	✓	✓	✓?
Nondynamical fields							
Palatini $f(R)$	–	✓	✓	✓	✗	✓	✓
Eddington-Born-Infeld	–	✓	✓	✓	✗	✓	?
Others, not covered here							
TeVeS	SVT	✗	✓	✓	✓	✓	?
$f(R)\mathcal{L}_m$	?	✗	✓	✓	✓	✗	?
$f(T)$	?	✗	✓	✗	✓	✓	?

Berti+,1501.07274

Self-consistency approach

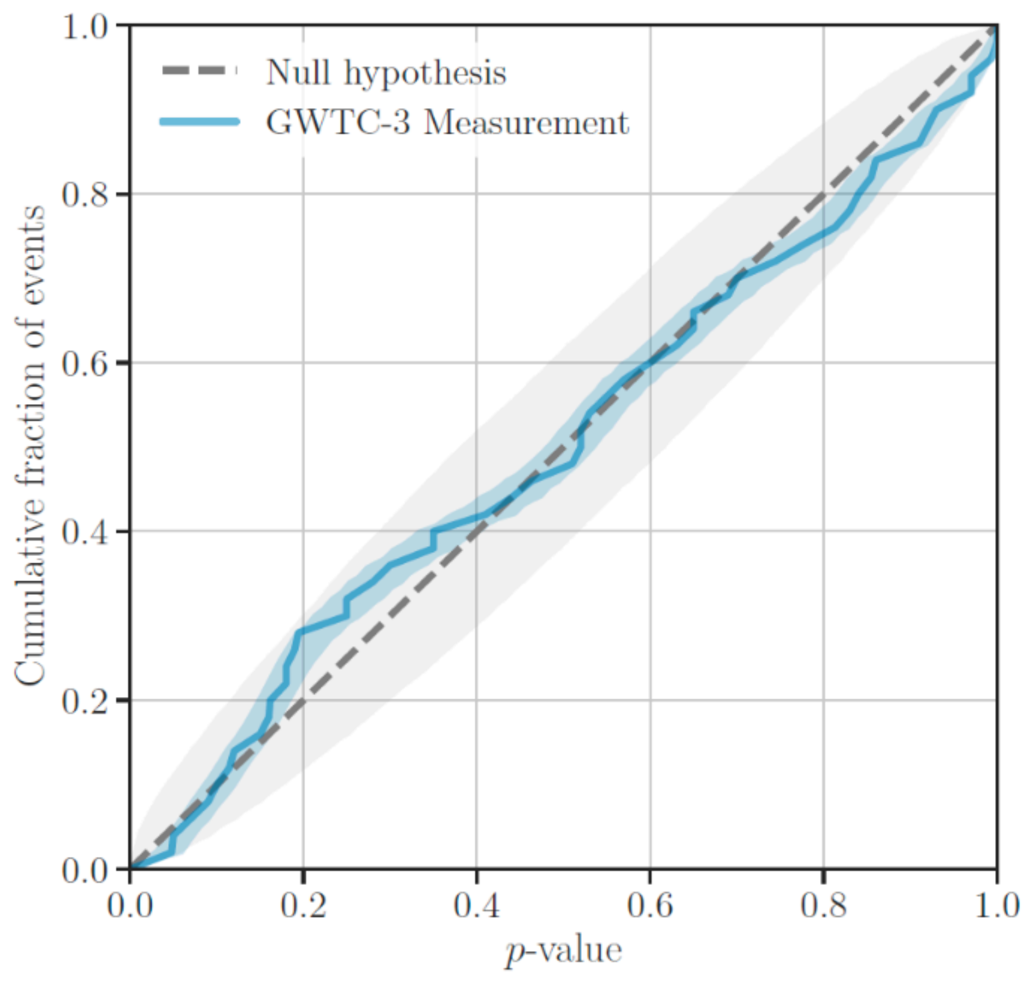
- Multitude of potential extensions
  - Modelling limitations imply agnosticism
- Assume we know GR
  - overall and self-consistency checks
  - perturb around the GR expectation and let the data speak
  - GW generation, propagation and polarizations, BH ringdown hypothesis, post-merger echoes

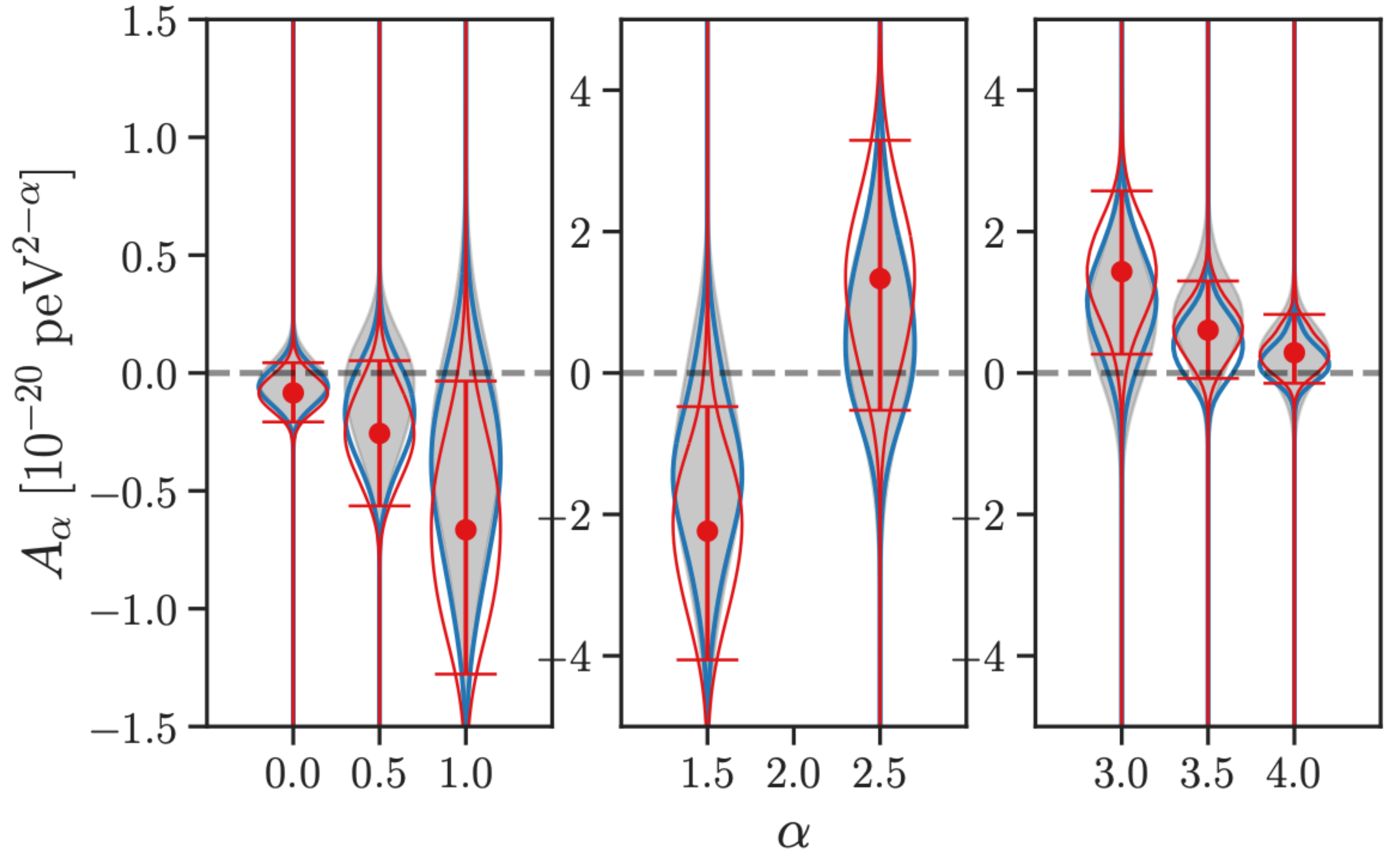
Event	Tests performed							
	RT	IMR	PAR	SIM	MDR	POL	RD	ECH
GW191109_010717	✓	–	–	–	–	✓	✓	✓
GW191129_134029	✓	–	✓	✓	✓	–	–	✓
GW191204_171526	✓	–	✓	✓	✓	✓	–	✓
GW191215_223052	✓	–	–	–	✓	✓	–	✓
GW191216_213338	✓	–	✓	✓	✓	✓	–	✓
GW191222_033537	✓	–	–	–	✓	✓	✓	✓
GW200115_042309	✓	–	✓	–	–	–	–	✓
GW200129_065458	✓	✓	✓	✓	✓	✓	✓	✓
GW200202_154313	✓	–	✓	–	✓	–	–	✓
GW200208_130117	✓	✓	–	–	✓	✓	–	✓
GW200219_094415	✓	–	–	–	✓	✓	–	✓
GW200224_222234	✓	✓	–	–	✓	✓	✓	✓
GW200225_060421	✓	✓	✓	✓	✓	✓	–	✓
GW200311_115853	✓	✓	✓	–	✓	✓	✓	✓
GW200316_215756	✓	–	✓	✓	–	–	–	✓

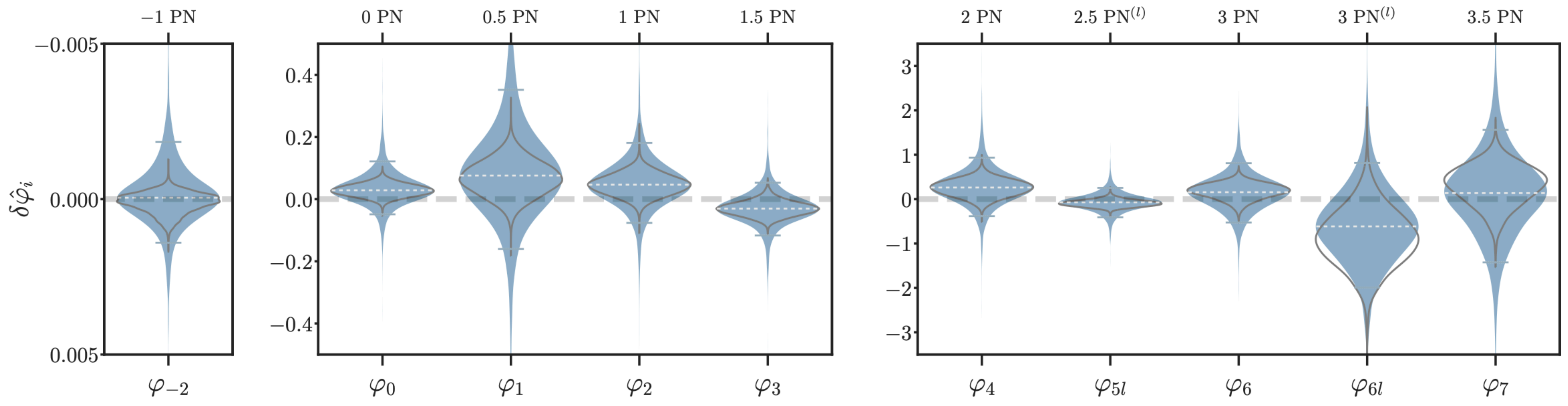
LVK, arXiv:2112.06861

GR tests

- consistency tests of predictions vs data
- consistency checks of GW emission model using different data portions (inspiral-merger-ringdown)
- tests of GW generation
- Remnant properties
- tests of GW propagation







LVK, arXiv:2112.06861

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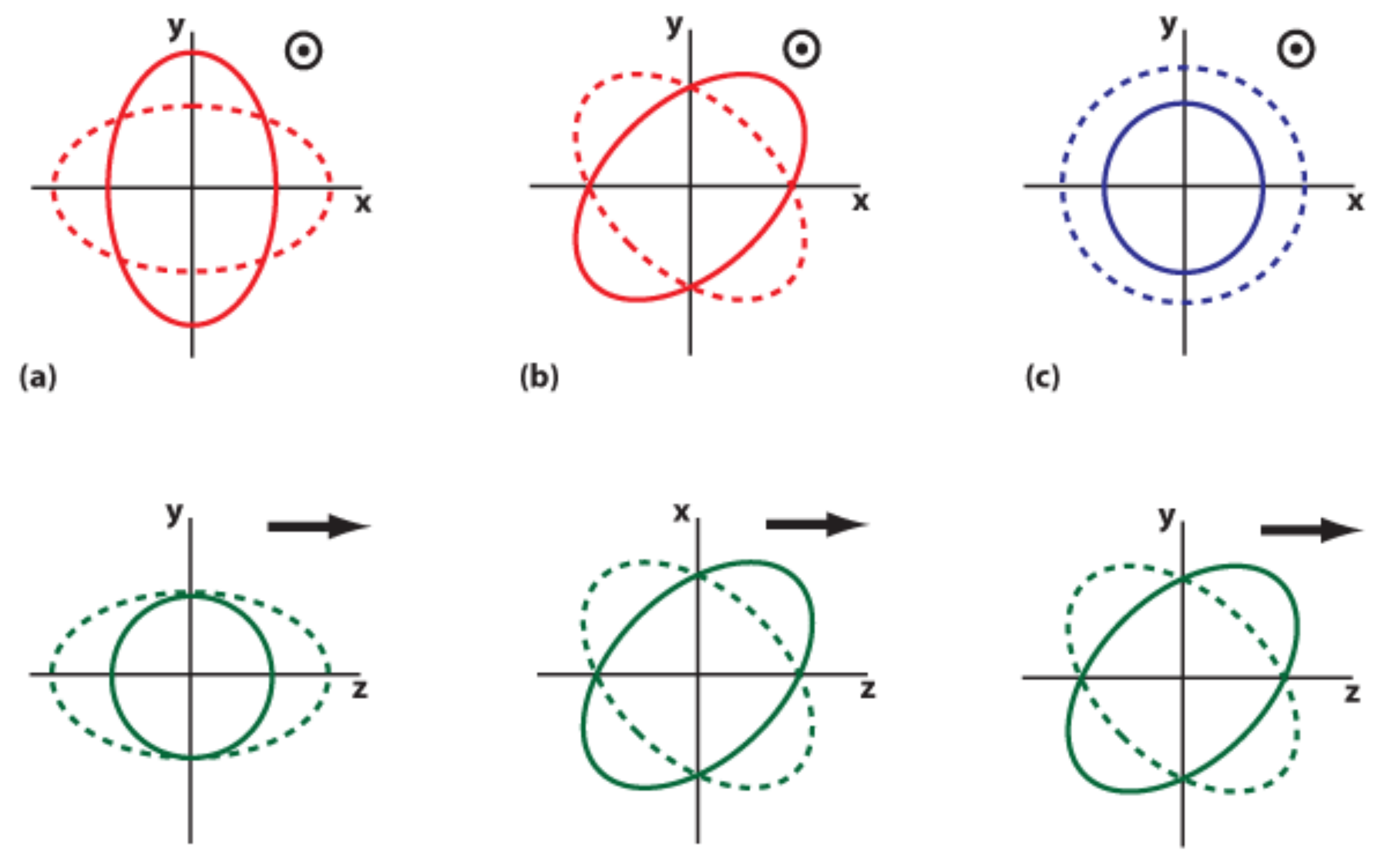
Gravitational wave polarisation states

LIGO VIRGO KAGRA

Will, arXiv:1403.7377

- Gravitational waves in general relativity are transverse, tensorial waves
- Extensions to general relativity predict up to six polarisation states
  - Two transverse tensor states
  - Two longitudinal vector states
  - Two scalar states, one longitudinal and one "breathing"



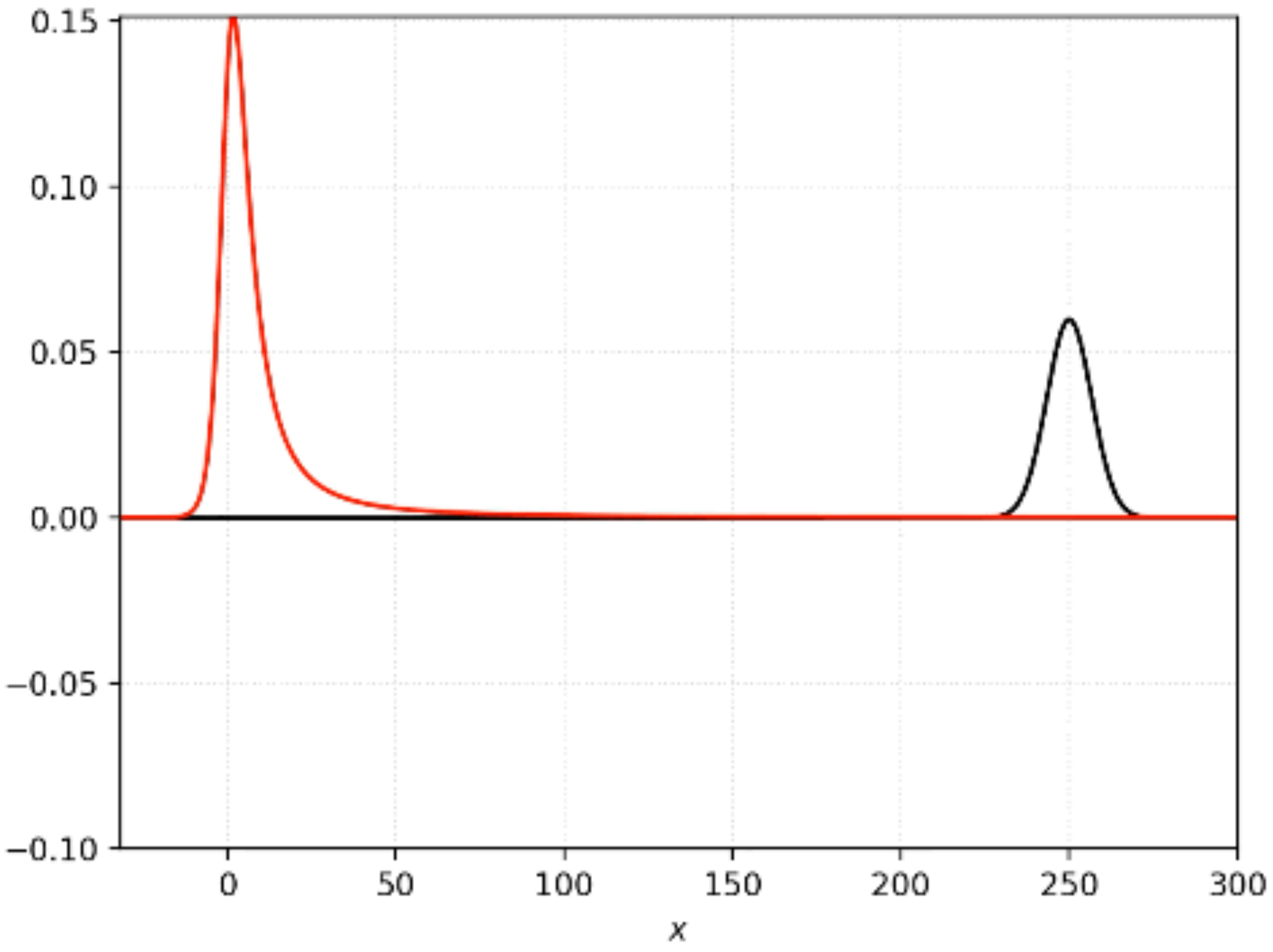
Theory	+	x	x	y	b	l
General Relativity	allowed	allowed	forbidden	forbidden	forbidden	forbidden
GR in noncompactified 4/6D Minkowski	allowed	allowed	allowed	allowed	allowed	allowed
Einstein-Æther	allowed	allowed	allowed	allowed	allowed	allowed
5D Kaluza-Klein	allowed	allowed	allowed	allowed	allowed	forbidden
Randall-Sundrum braneworld	allowed	allowed	forbidden	forbidden	forbidden	forbidden
Dvali-Gabadadze-Porrati braneworld	allowed	allowed	depends	depends	depends	depends
Brans-Dicke	allowed	allowed	forbidden	forbidden	allowed	allowed
f(R) gravity	allowed	allowed	forbidden	forbidden	allowed	allowed
Bimetric theory	allowed	allowed	allowed	allowed	allowed	allowed
Four-Vector Gravity	forbidden	forbidden	allowed	allowed	forbidden	forbidden

Nishizawa et al., Phys. Rev. D 79, 082002 (2009) [except G4v & Einstein-Æther]. allowed / depends / forbidden

Ringdown

- BH responds to perturbations by "ringing" (Vishveshawara 70, Press 71, Ruffini et al, 72, Chandrasekhar 75)

- Quasi-normal modes excited by light-ring crossing (Goebel 72)



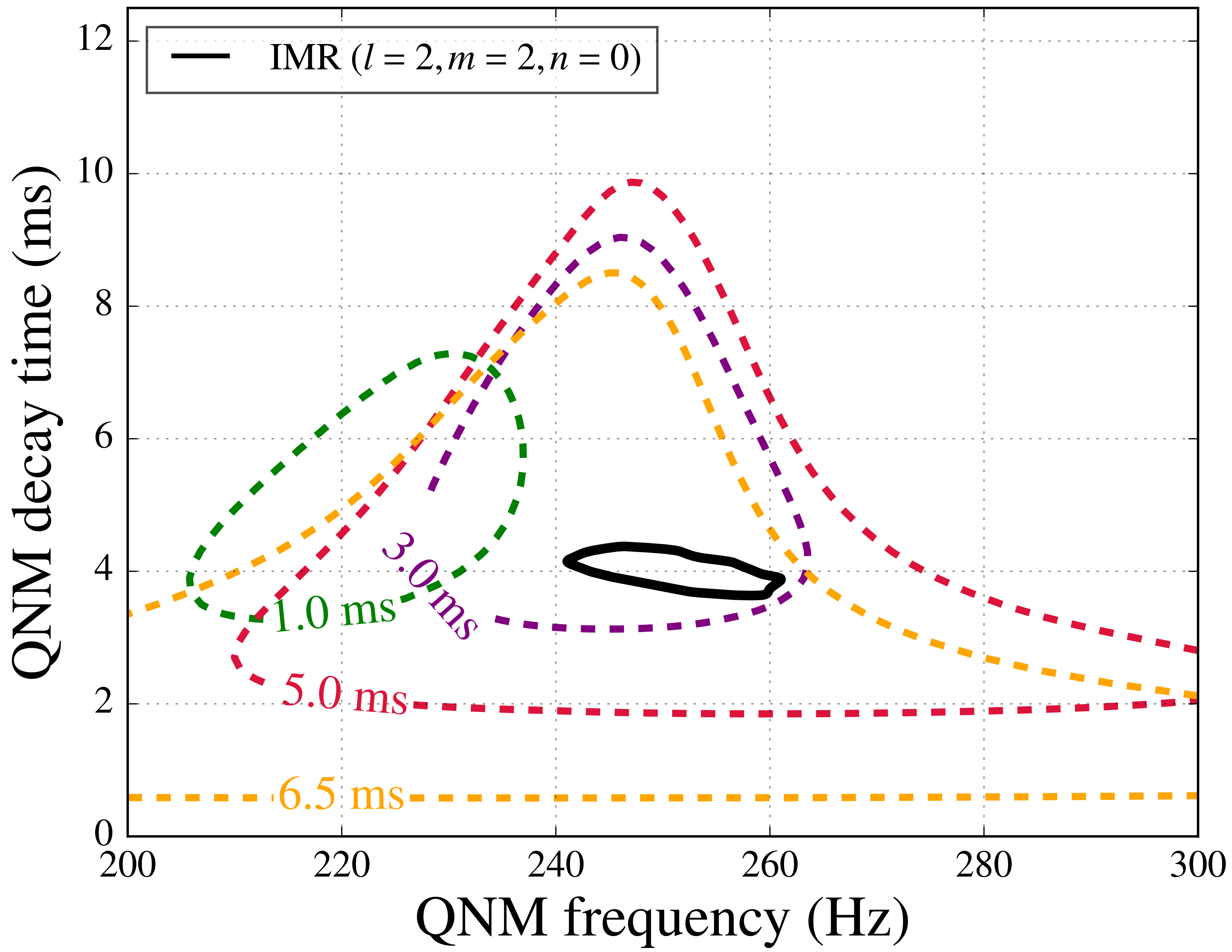
The nature of the final object

- Simple waveform:

$$h(t) = \sum_{nlm} A_{nlm} e^{-\frac{t-t_0}{\tau_{nlm}}} \cos(\omega_{nlm}(t-t_0)+\varphi_{nlm})$$

- Central frequencies ω_{nlm} and decay times τ_{nlm} are functions of BH mass and spin only (manifestation of the BH uniqueness hypothesis, Berti et al, arXiv:0512160)

- First observation: GW150914

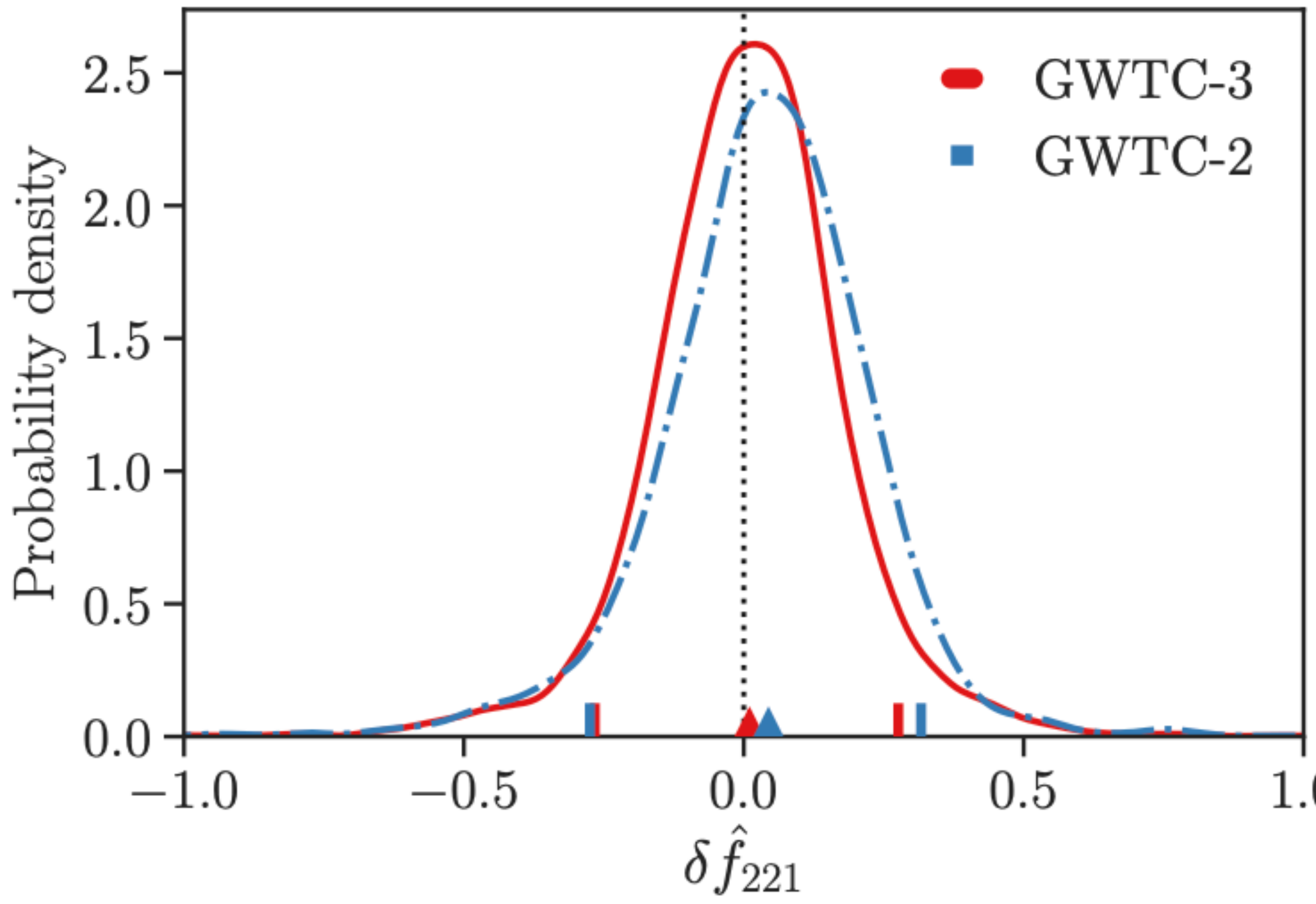


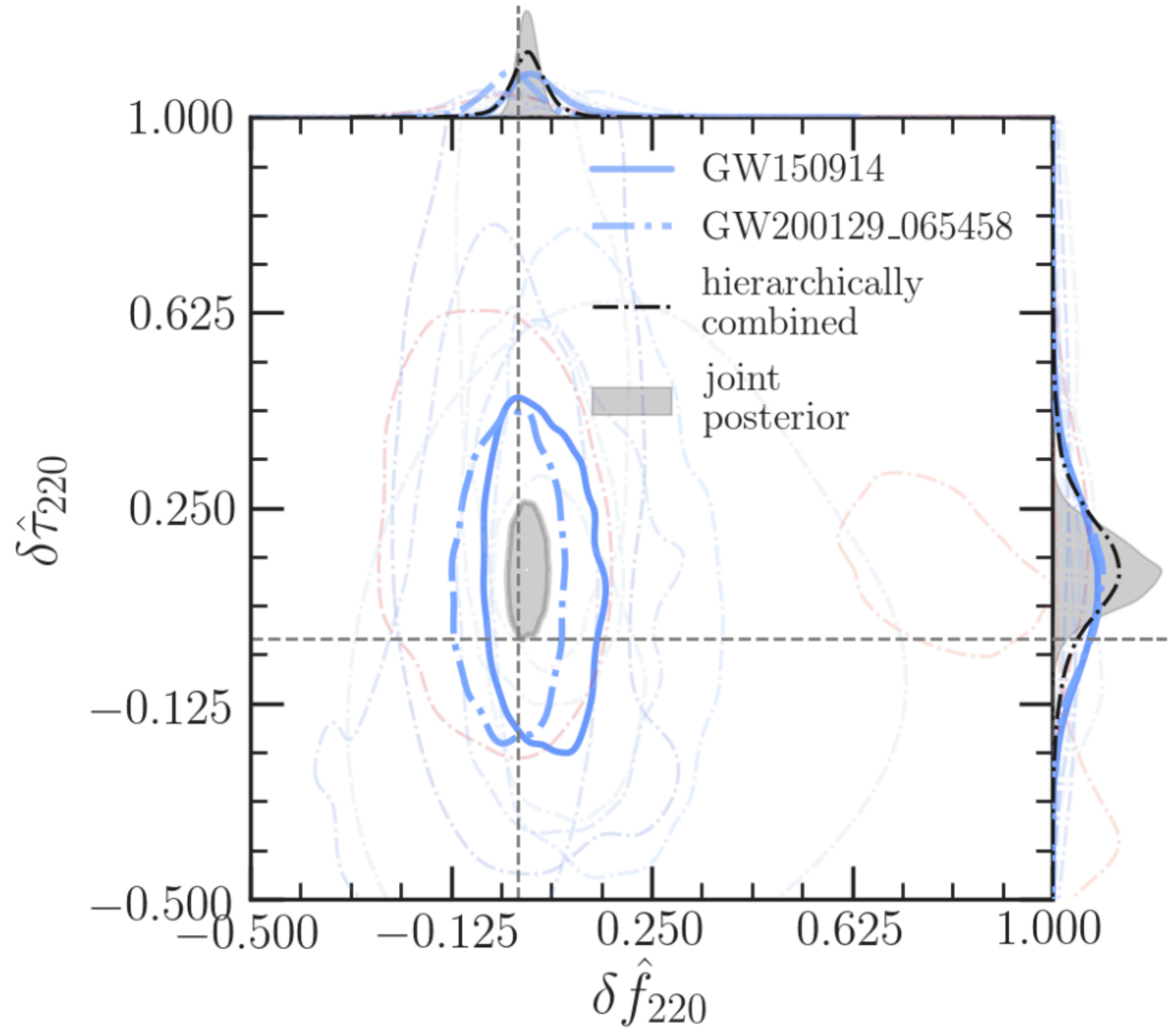
LVC,arXiv:1602.03841

GWTC-3 Ringdown

- Ringdown observed in several BBH remnants
  - pyRing (Carullo et al, arXiv:1902.07527): ringdown only time domain analysis
  - pSEOBNR (Ghosh et al, arXiv:2104.01906): modified SEOBNR waveform
- Independent determination of final parameters
- Tests of BH uniqueness

$$\log B_{GR,nGR} \sim 1$$

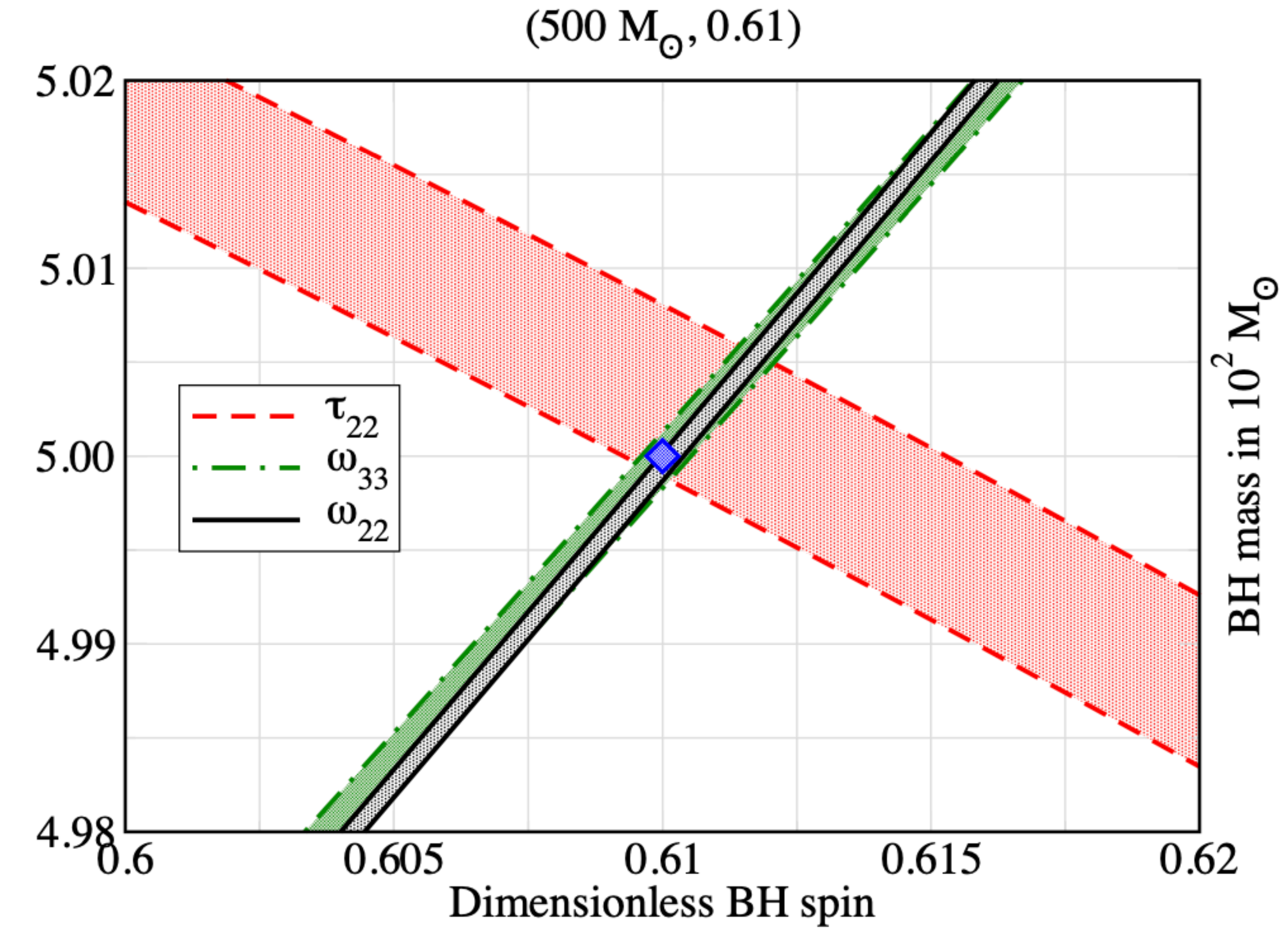


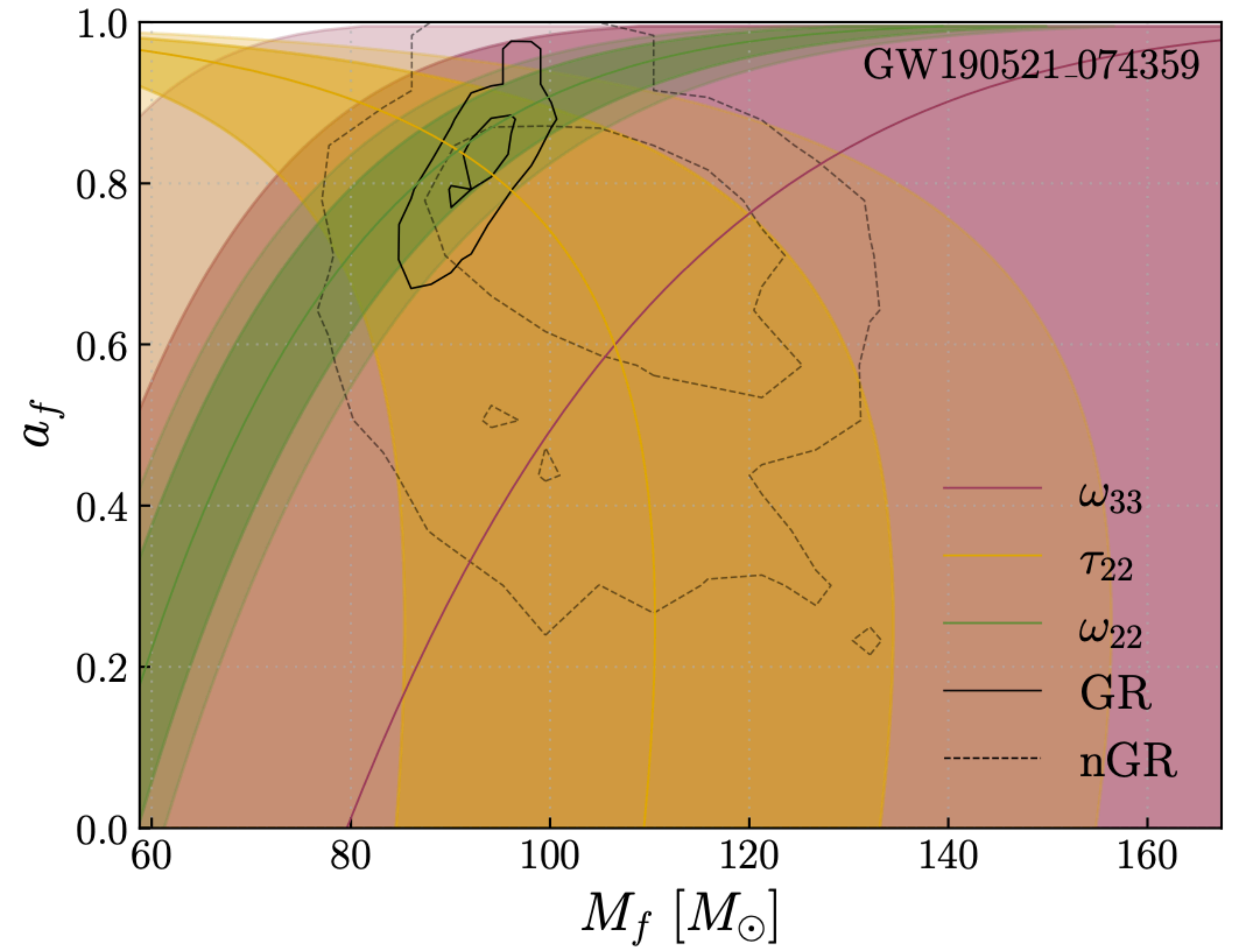


Higher angular modes

- As the number of detected events will increase, so will the possibility of detecting $l > 2, \quad m \neq 2$ modes
- Multi-mode BH spectroscopy
  - Smoking gun for violations of BH uniqueness theorems

Gossan et al, arXiv:1111.5819

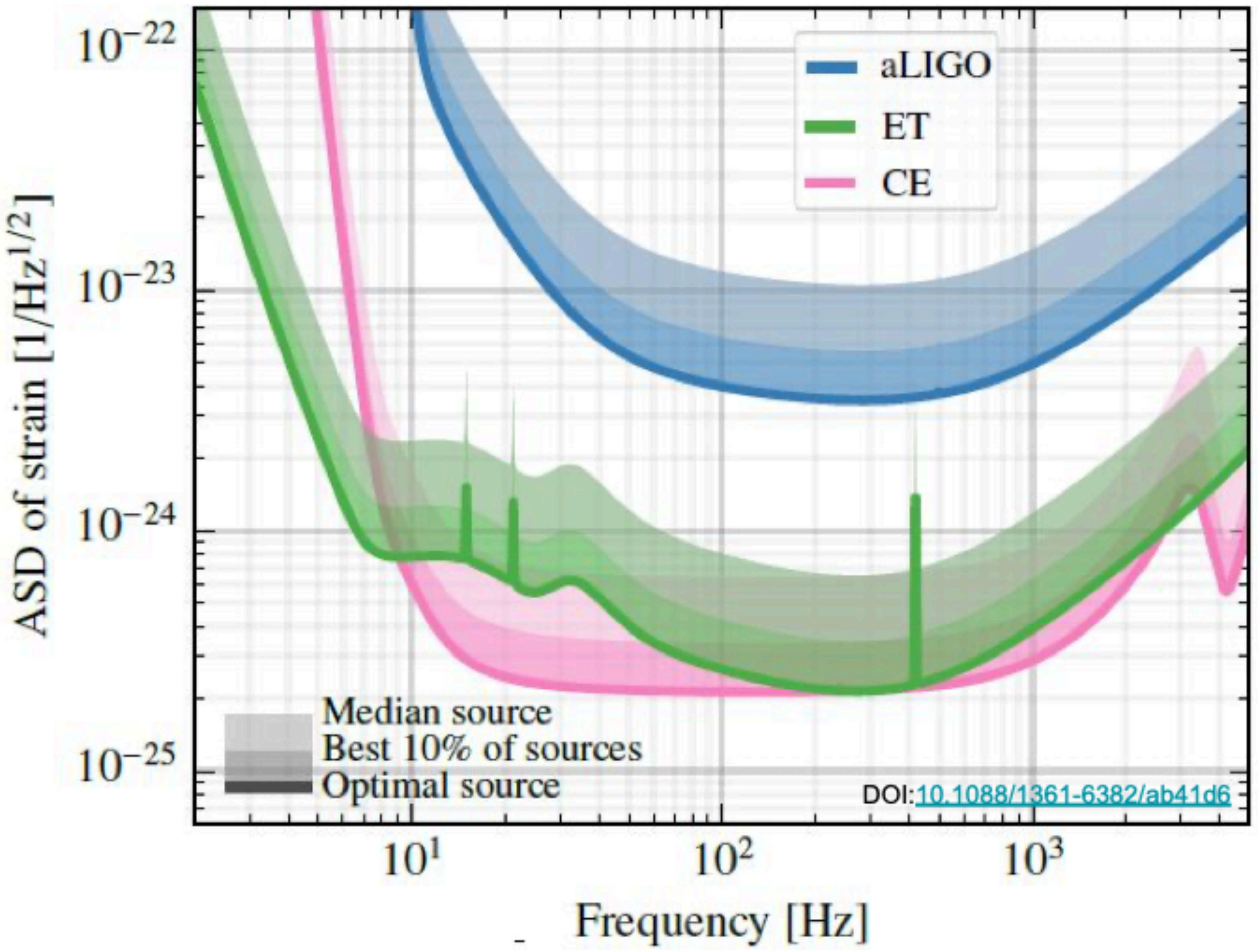


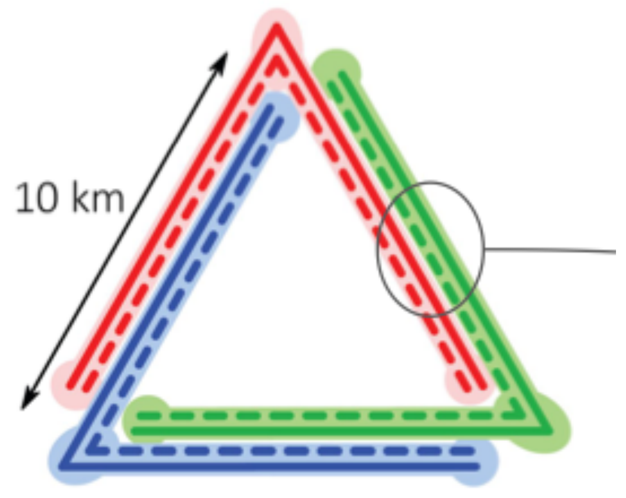


Gennari et al, arXiv:2312.12515

Einstein telescope

- EU proposal for 3rd generation detector
  - 10 km arm length, underground
  - Triangular configuration
    - Redundancy





ET Design Report Update 2020

Einstein telescope

- Different configurations being evaluated
  - Arm length
  - 1 triangle vs 2 L-shaped
- O(10^5 - 10^6) compact binary coalescences per year

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Science with the Einstein Telescope: a comparison of different designs

Marica Branchesi[1,2], Michele Maggiore[3,4], David Alonso[5], Charles Badger[6], Biswajit Banerjee[1,2], Freija Beirnaert[7], Enis Belgacem[3,4], Swetha Bhagwat[8,9], Guillaume Boileau[10,11], Ssohrab Borhanian[12]

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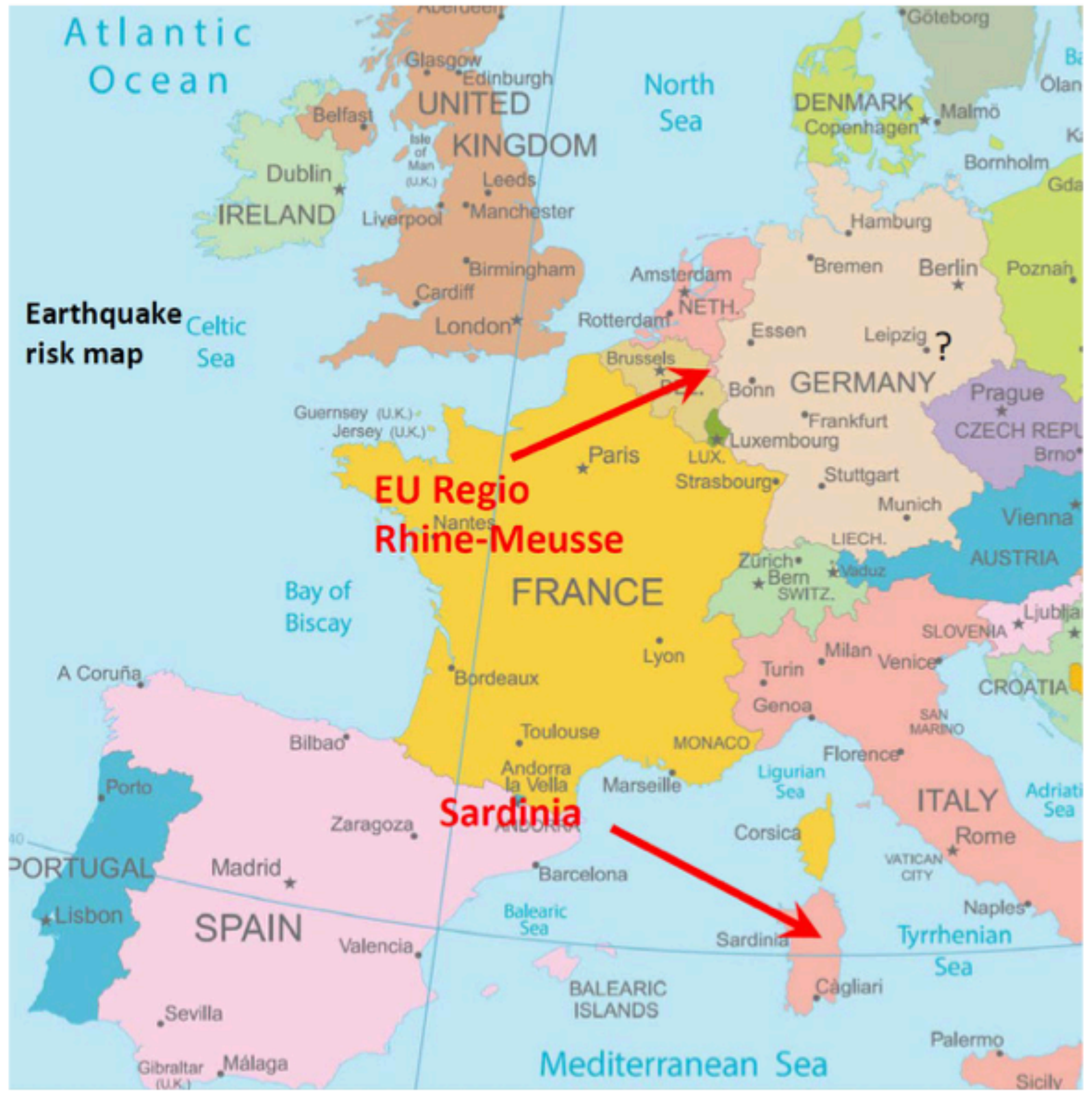
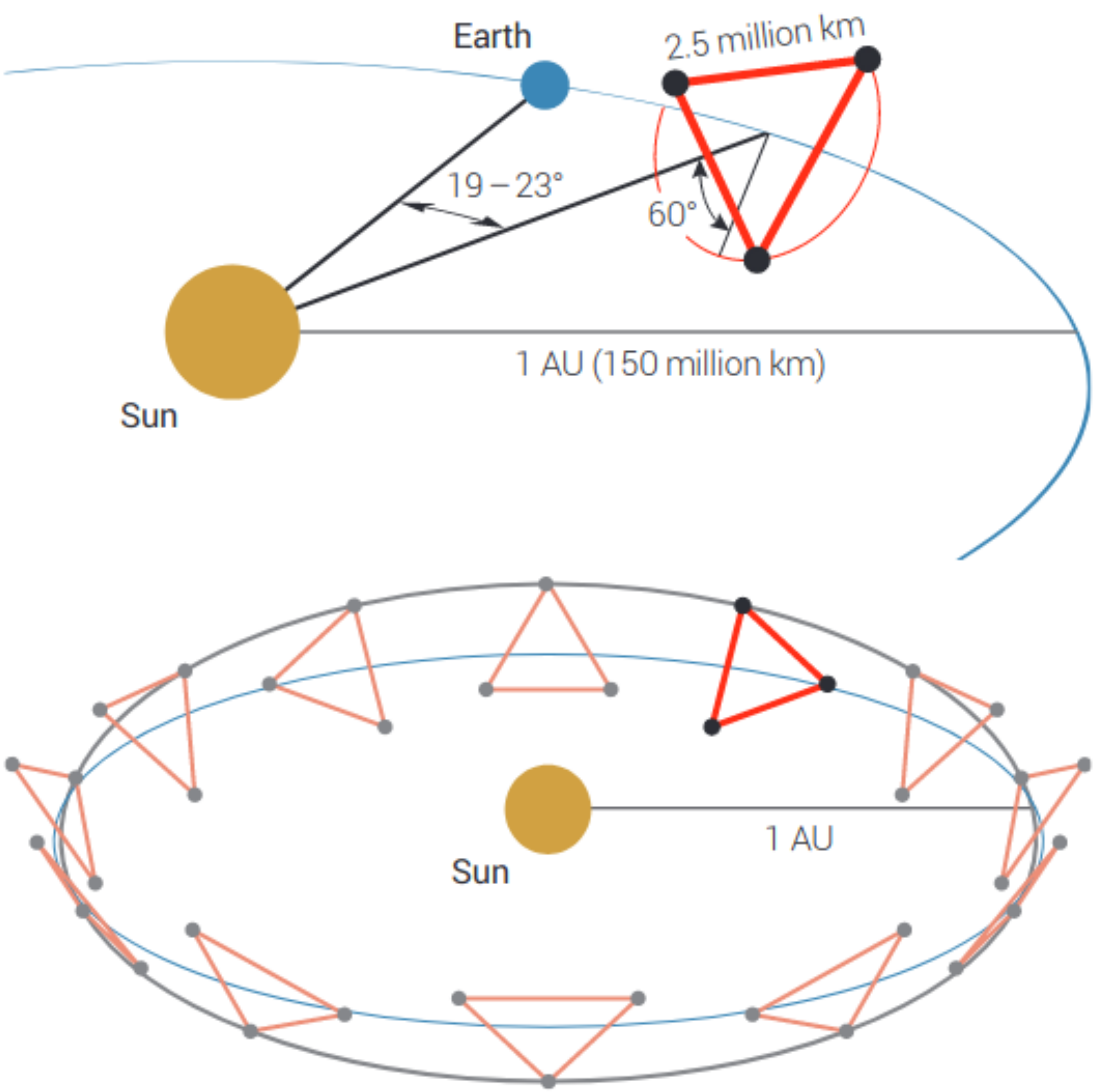
- 197 pages
- 75 authors



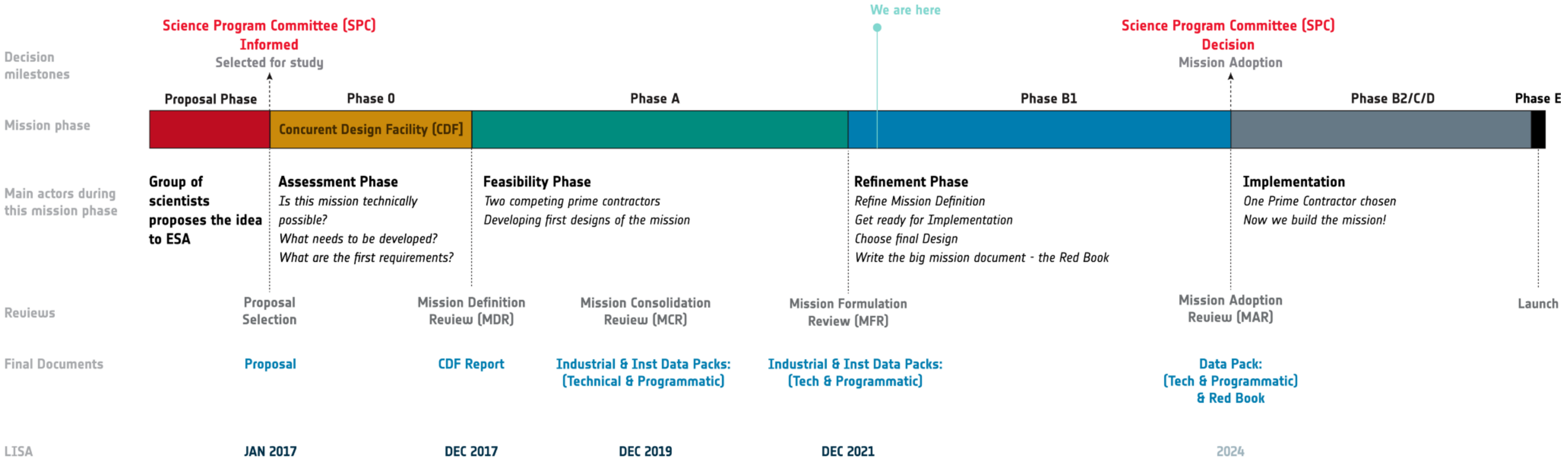
LISA

- Long baseline: 2.5 Mkm
- Sensitivity bucket ~ mHz
- Mission duration: 4 to 10 years
- Dominating laser phase noise: synthetic interferometry (TDI)
- LISA Red Book: arXiv:2402.07571



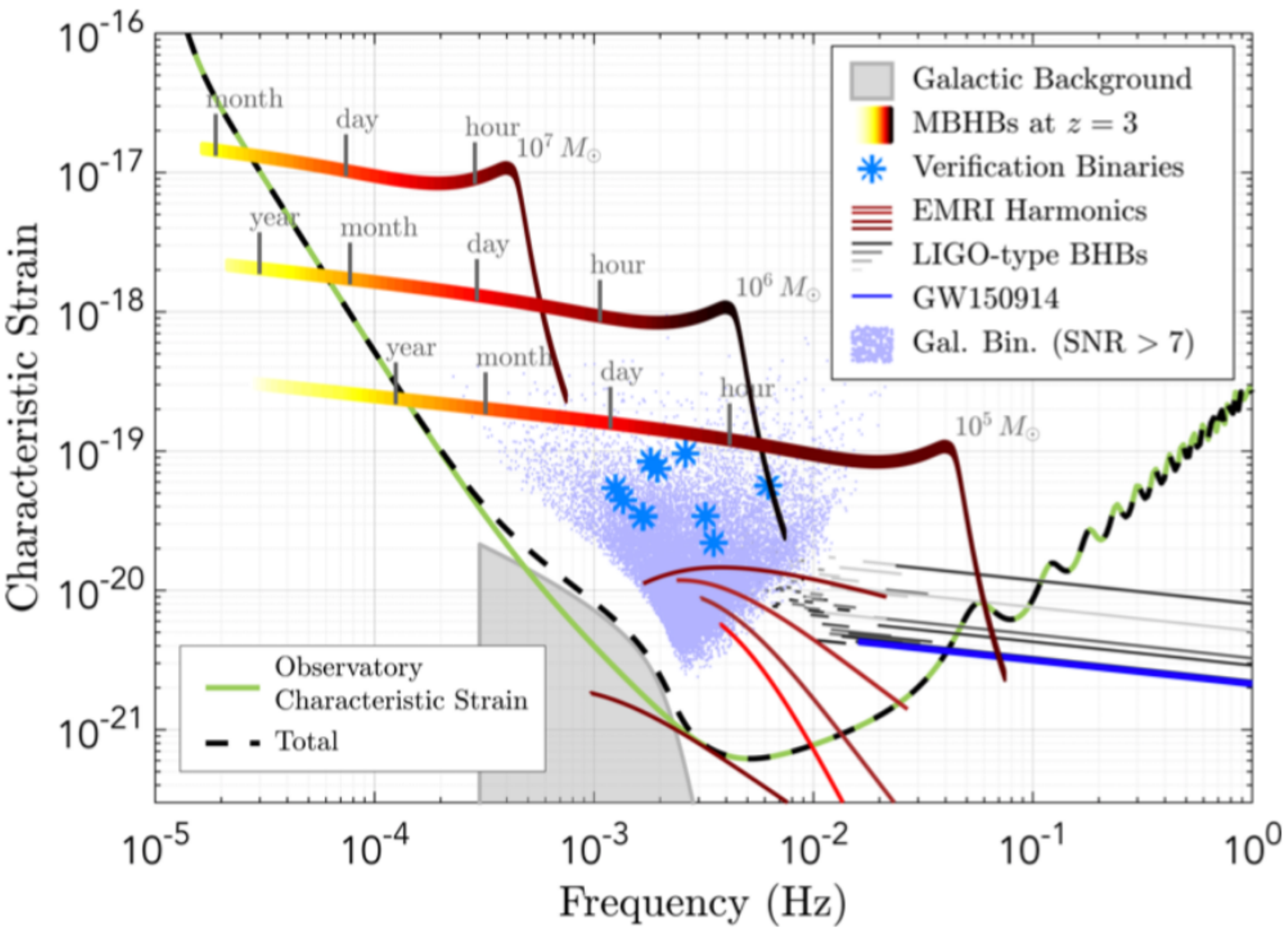
LISA Mission Status

- Mission Formulation Review ✓
- Towards Mission Adoption
  - Consortium reshaping
    Performance Experts, Data Analysis Experts Groups
- Redbook
- Launch expected in 2034



LISA sources

- Several classes of compact binaries expected
  - Supermassive black hole binaries (SMBH)
  - Stellar mass black hole binaries (sBH)
  - Double white dwarfs
  - Extreme mass ratio inspirals
- Stochastic signals
  - Astrophysical background
  - Cosmological background



GW data analysis

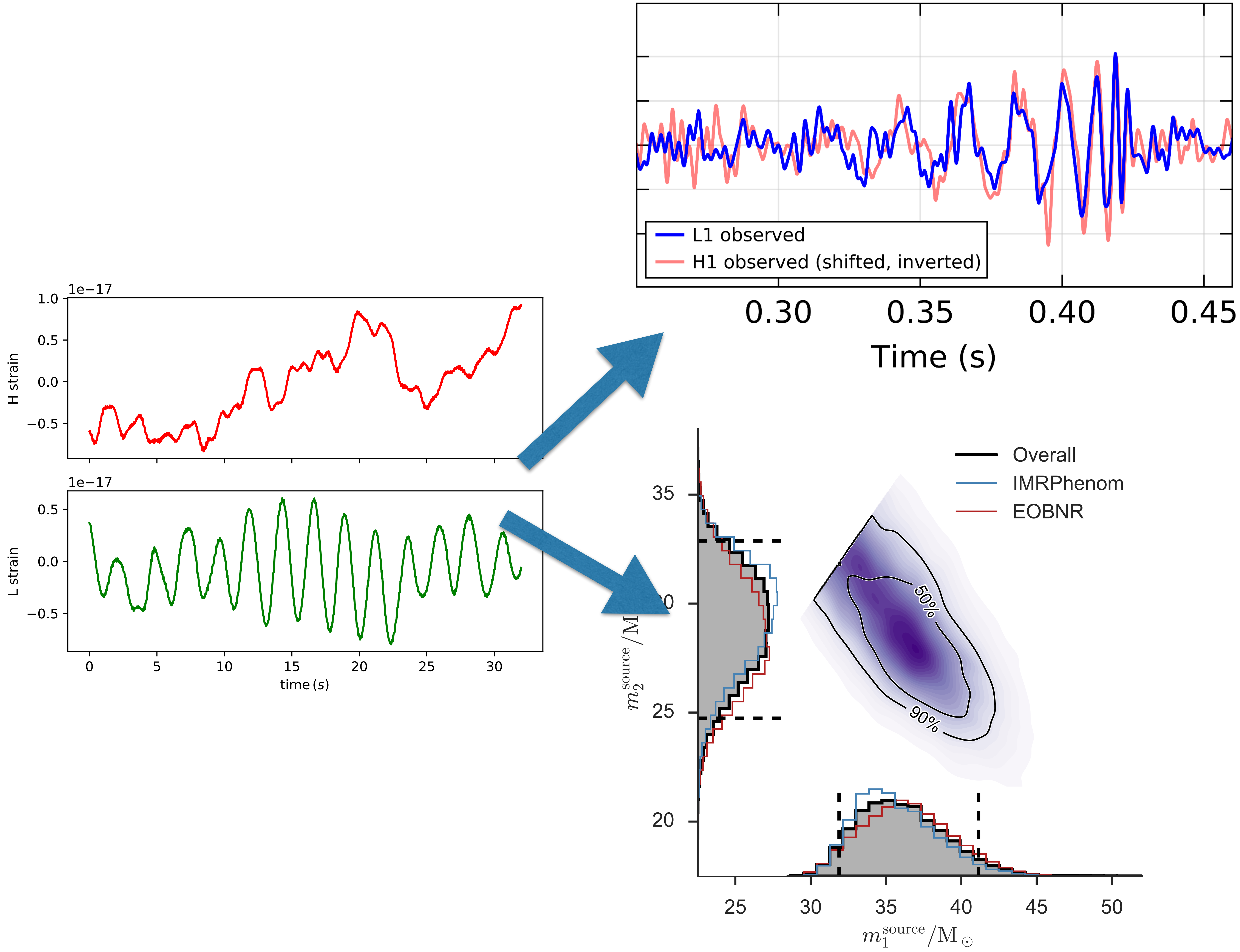
- GW data analysis relies on Bayes Theorem

- Parameter estimation:

$$p(\theta|DHI) = p(\theta|HI)\frac{p(D|\theta HI)}{p(D|HI)}$$

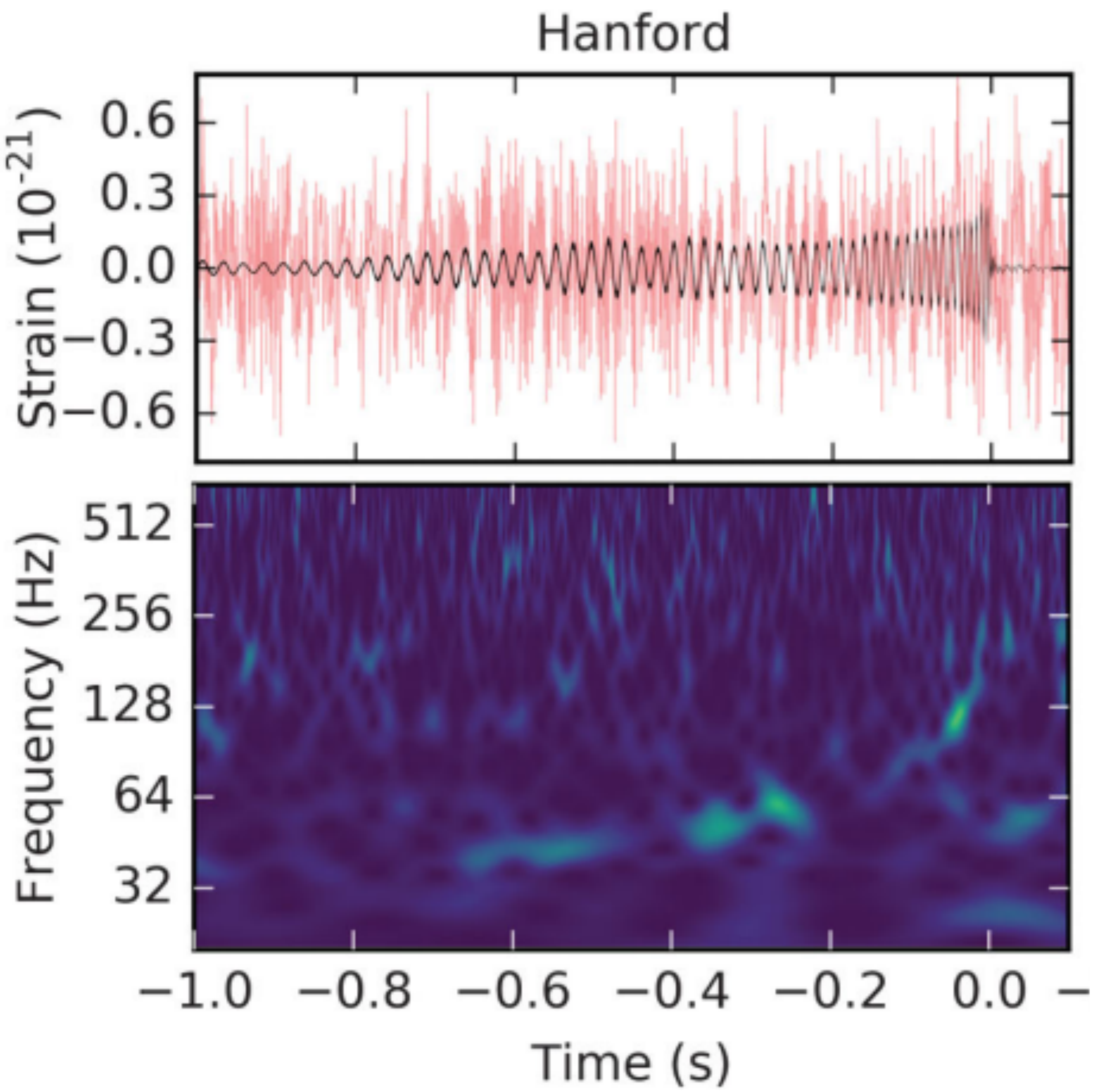
- Model selection:

$$O_{12} = \frac{p(H_1|I)p(D|H_1 I)}{p(H_2|I)p(D|H_2 I)} = \frac{p(H_1|I)}{p(H_2|I)} B_{12}$$



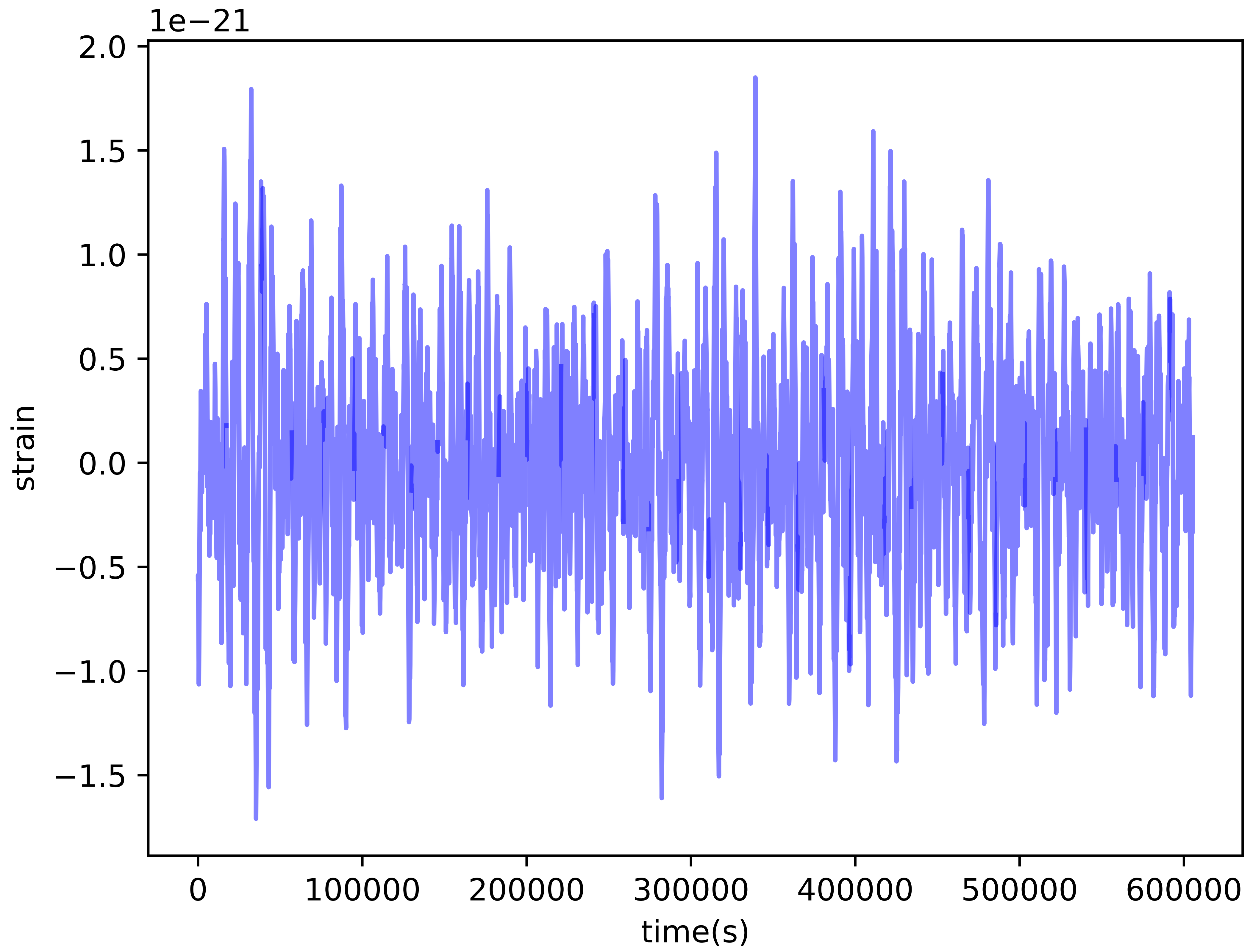
Noise-dominated detectors

- Gravitational wave events are rare
- Noise dominated detectors
  - We can search for events with matched filtering
  - Noise properties can be determined independently



Signal-dominated detectors

- Signal dominated detector
  - Unknown and unspecified sources are present at all times
- No clear access to noise properties



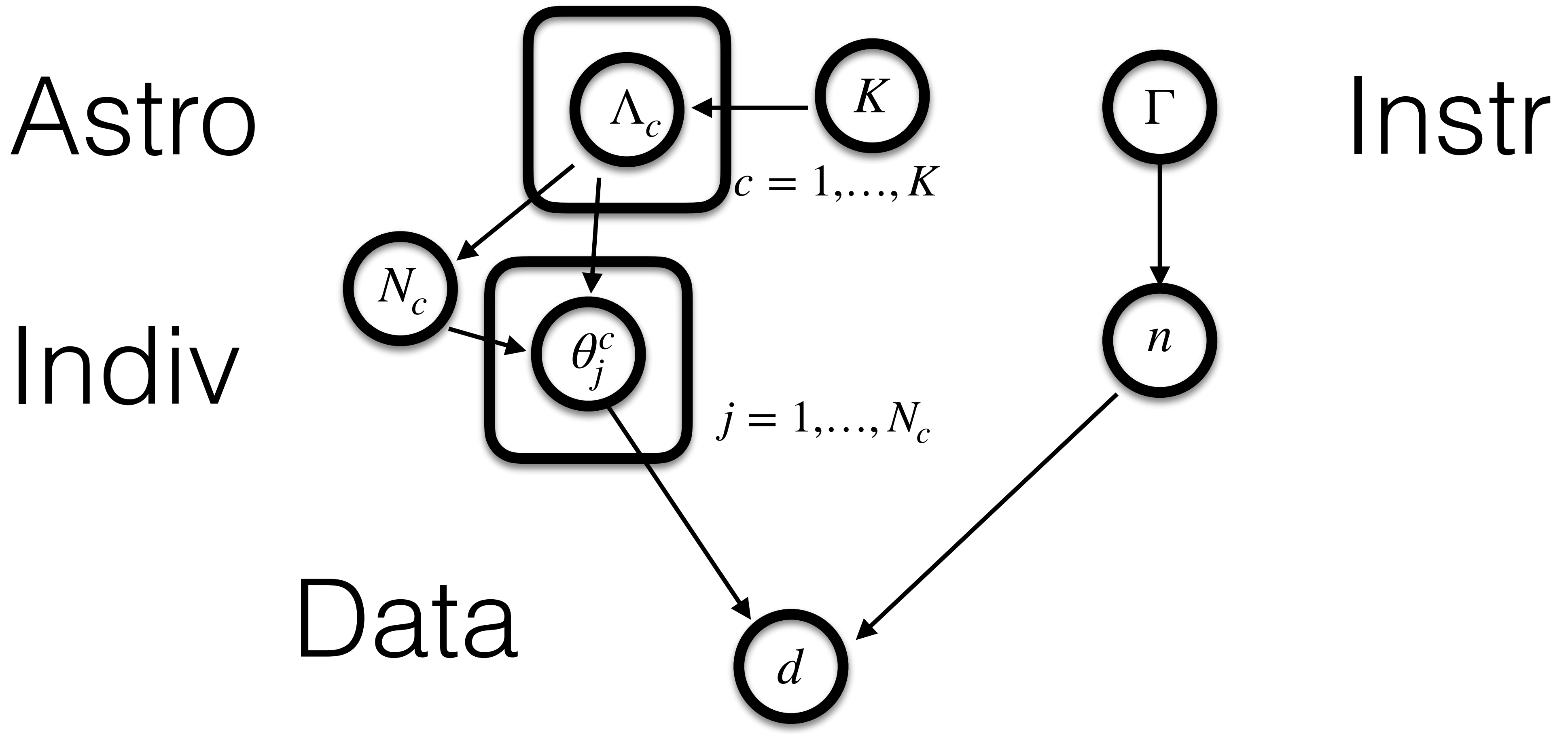
The LISA data analysis problem

- The data model

$$d(t) = n(t) + \sum_{c=1}^{K} \sum_{j=1}^{N_c} h_j^c(t; \theta_j^c)$$

- with K the (unknown) number of classes of signals (e.g. $c = \mathrm{SMBH}, \mathrm{sBH}, \mathrm{EMRI}, \ldots$) and N_c is the unknown number of signals per class

- The challenge is to estimate the joint posterior for all sources, their numbers and their astrophysical distributions, jointly with the detector and noise models



The problem in a nutshell

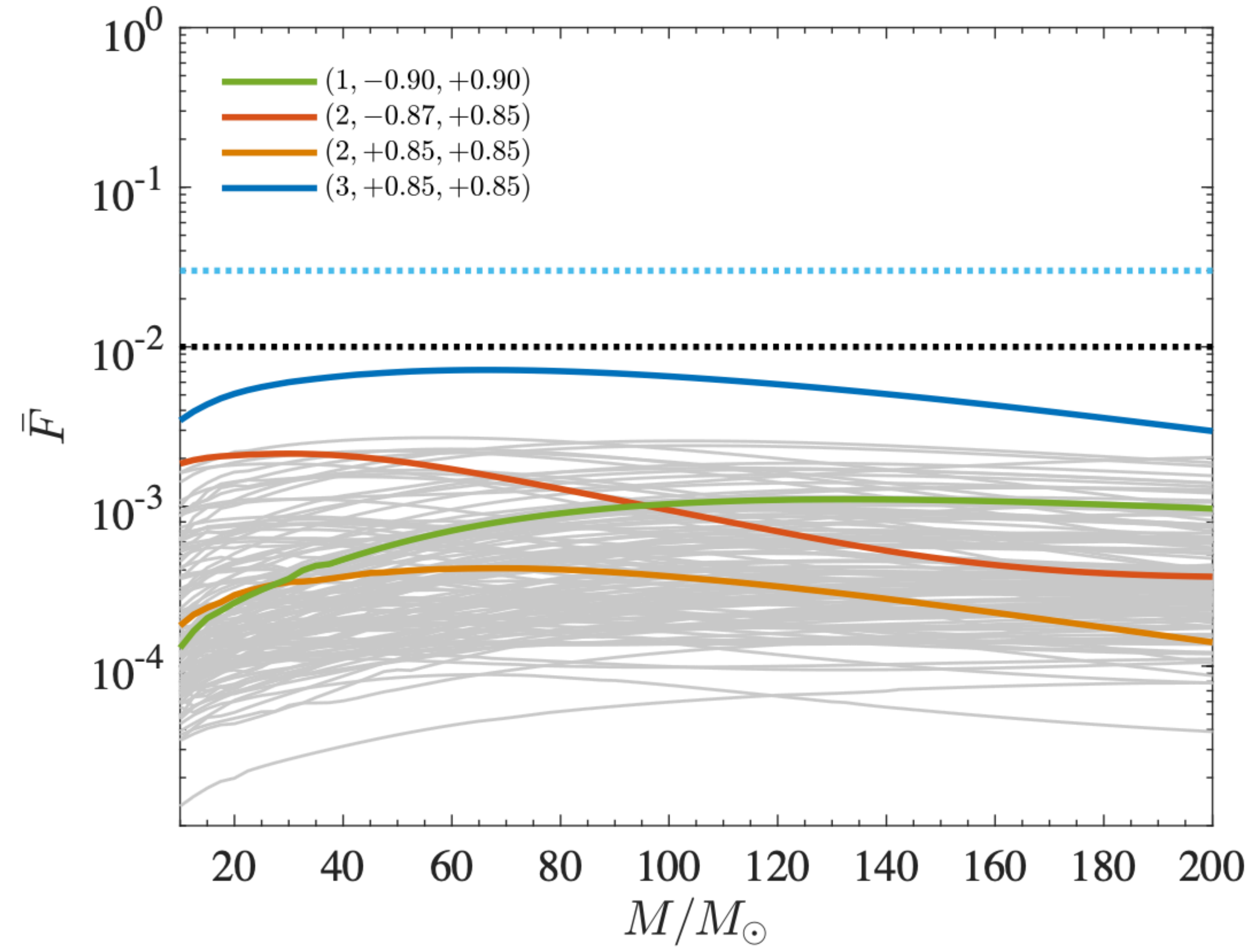
Noise-dominated

Signal-dominated

Challenges - Waveforms

Waveforms

- Monochromatic (DWDs) ☑
- Drifting sources (BBHs) ☑
- Chirping sources (SMBBHs) ☑
- Unresolvable (SGWBs) ☑
- Instrumental artifacts (Glitch) ☑
- Multiband sources ☑
- Polichromatic (EMRIs) ongoing



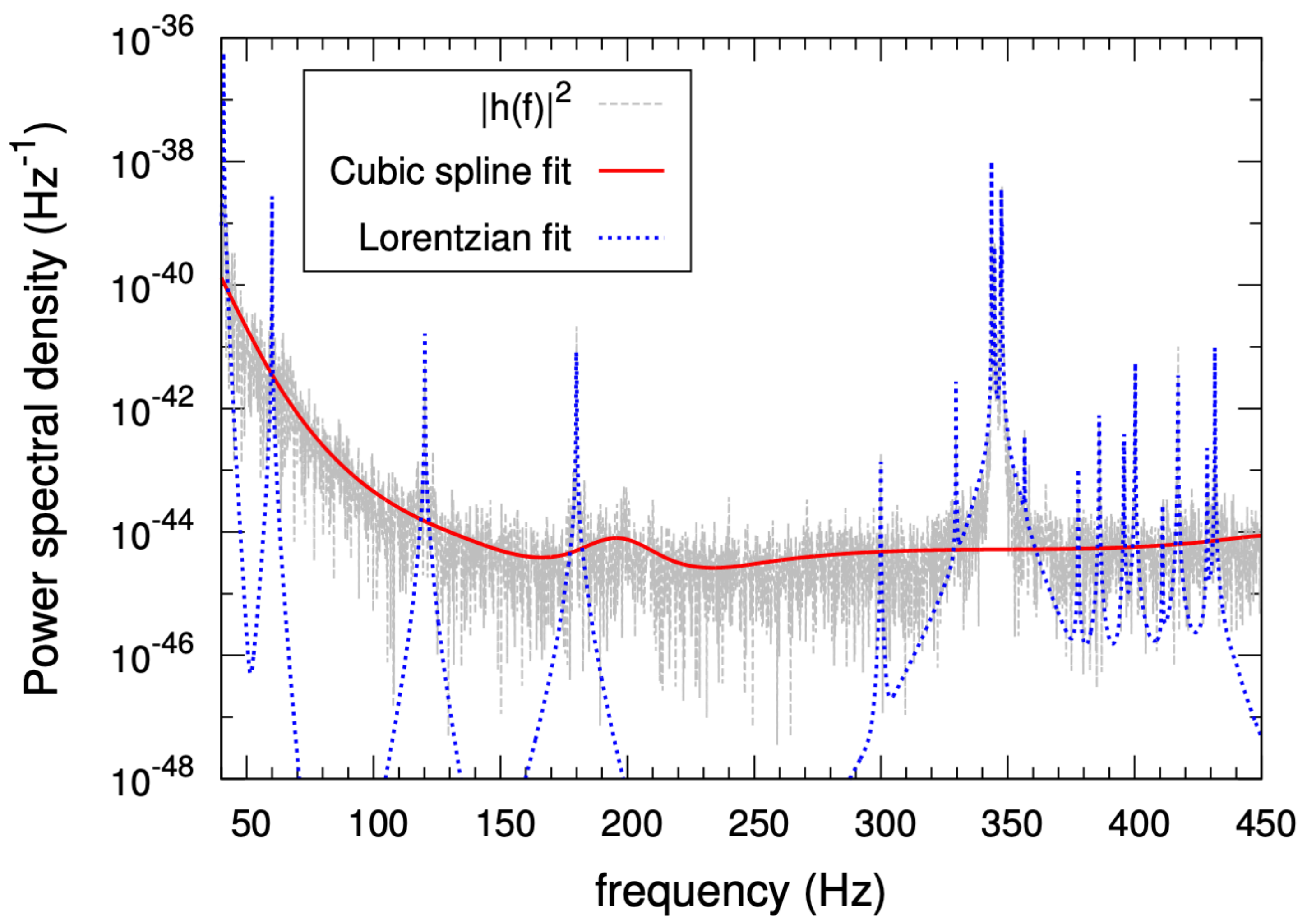
Good enough for $\mathrm{SNR} \simeq 10^3 - 10^4$?

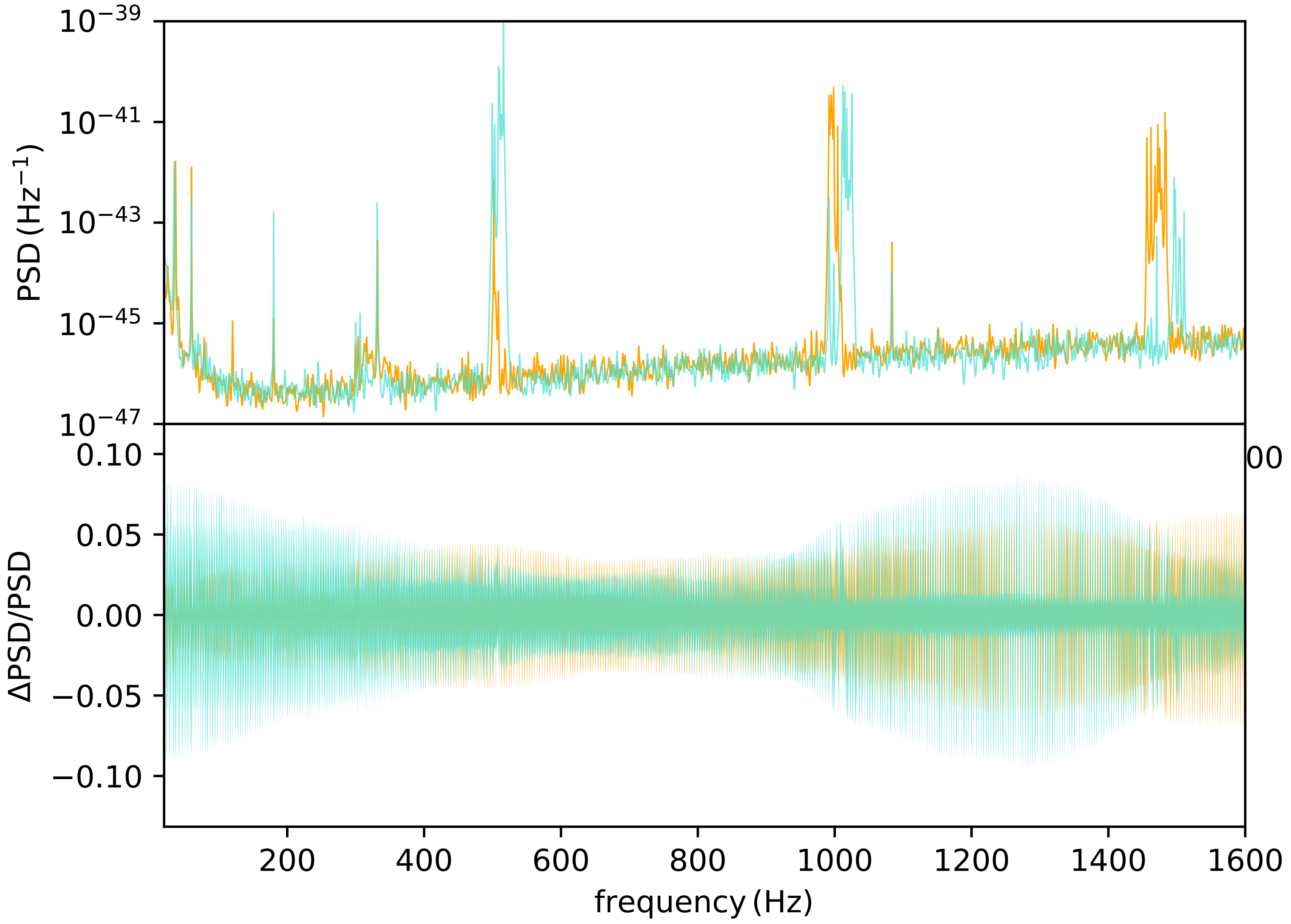
Efficient enough?

Nagar et al, arXiv:1806.01772

Challenges - Noise

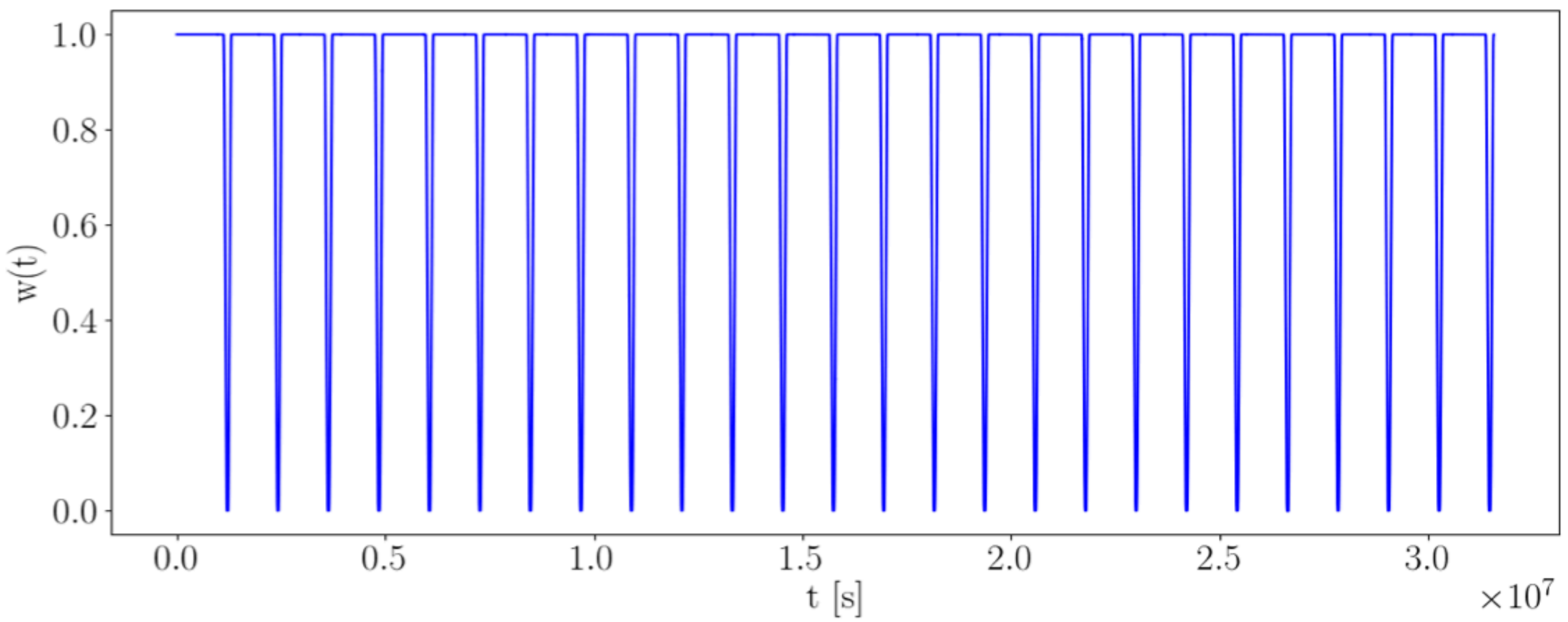
- Noise modelling is difficult
  - No "off-source" estimation
- Marginalise over noise properties?
  - Simultaneously model signal(s) and noise
  - BayesLine (Littenberg & Cornish, arXiv:1410.3852)
  - MAXENT (Martini et al, arXiv:2106.09499)
- Computationally expensive



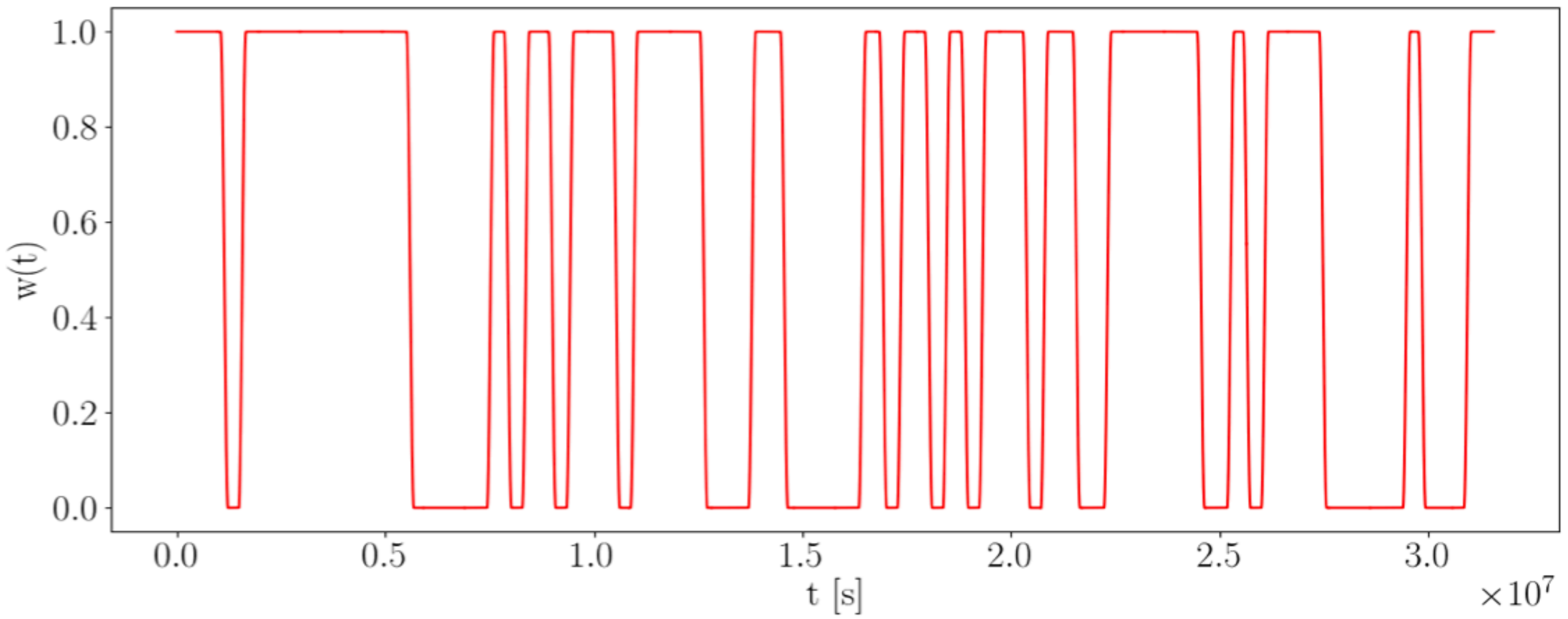


Challenges - Data gaps and glitches

- Data taking will not be continuous
  - Scheduled interruptions
  - Glitches
- Complicated windowing?
  - Large computation cost (e.g. Burke et al arXiv:2502.17426)
- Time domain analysis?



(a) Full distribution of Scheduled gaps



(c) Full distribution of Unscheduled gaps

Dey et al, arXiv:2104.12646

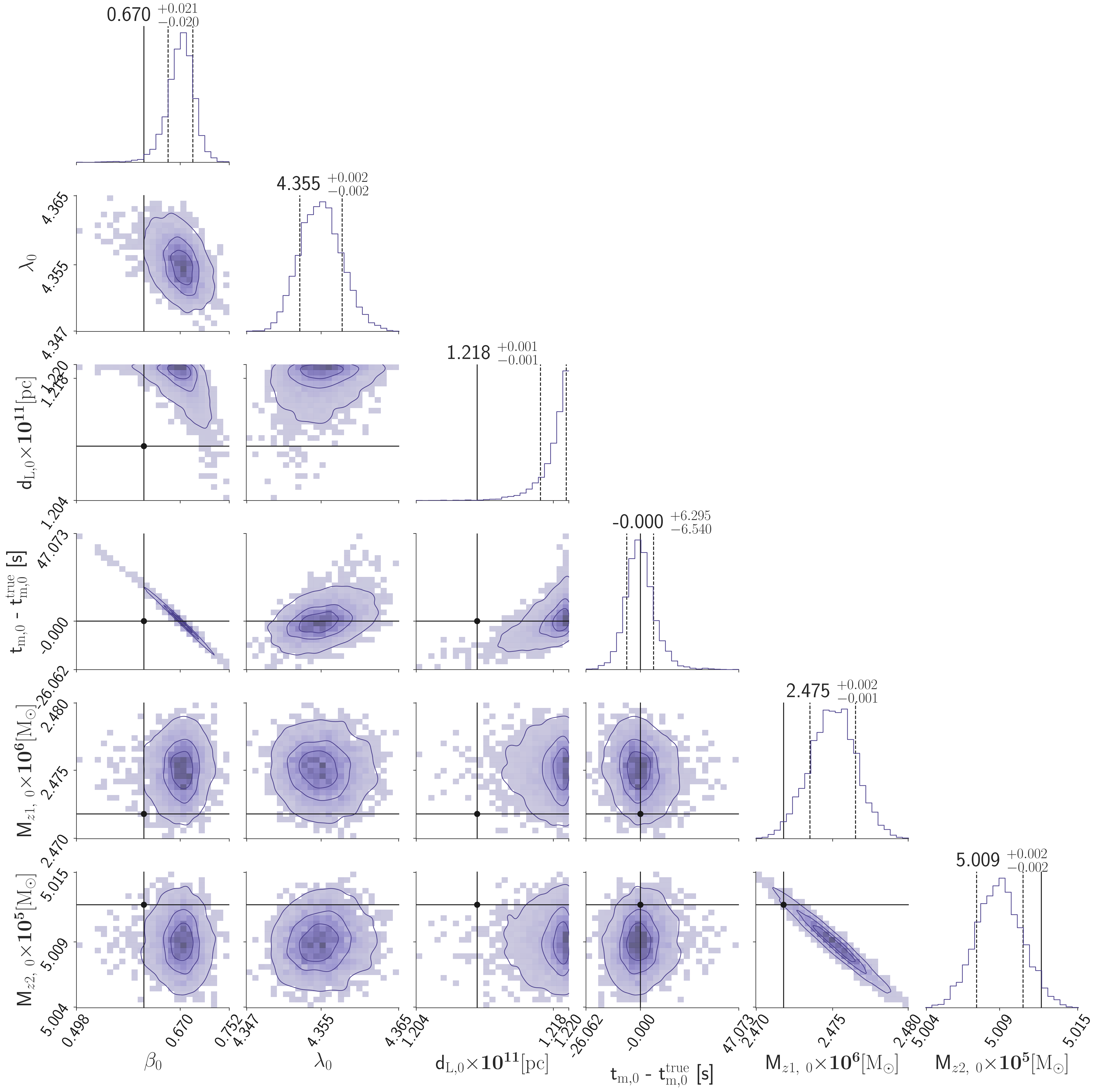
Challenges - overlapping signals

- Unknown number of sources but one recovered source

$$\log \mathscr{L}(\mathbf{d} \equiv \mathbf{h}_0 + \mathbf{h}_1 | \boldsymbol{\theta}_0) \approx -\frac{1}{2}(\mathbf{d} - \mathbf{h}(\boldsymbol{\theta}_0) | \mathbf{d} - \mathbf{h}(\boldsymbol{\theta}_0)) =$$

$$\approx -\frac{1}{2}\underbrace{(\mathbf{h}_1|\mathbf{h}_1)}_{\mathrm{SNR}_1^2} + \underbrace{(\mathbf{h}_0|\mathbf{h}_1)}_{O_{01}\,\mathrm{SNR}_0\,\mathrm{SNR}_1}$$

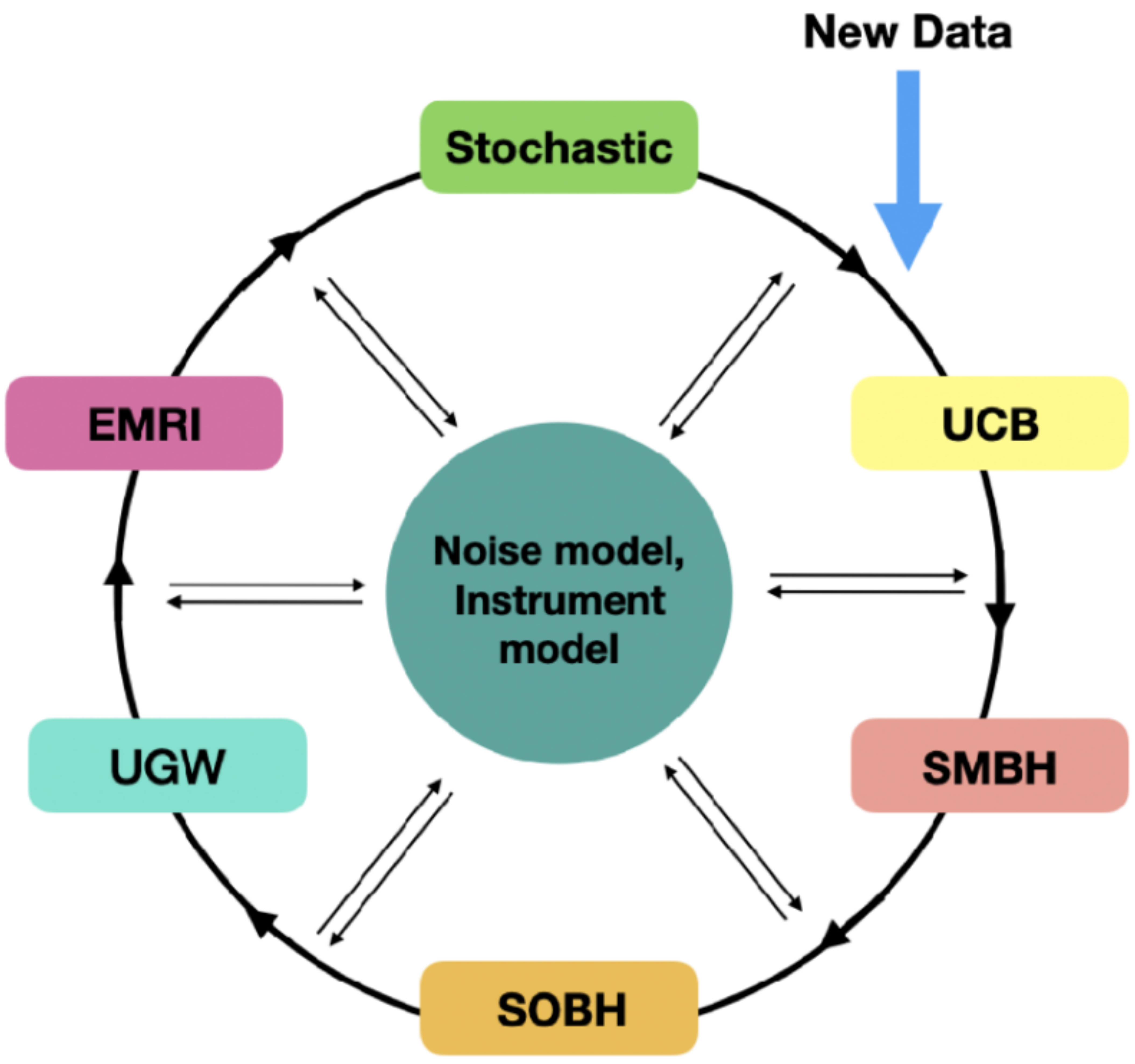
- Non-negligible bias in recovered parameters
  - Consequences for astrophysics, cosmology and fundamental physics



Rosso, Buscicchio, DP in preparation

Challenges - Algorithms

- Block Gibbs sampling
  - Sample each “block” independently, conditioned on everything else
    - Reversible-Jump MCMC
  - Iterate and hope it converges

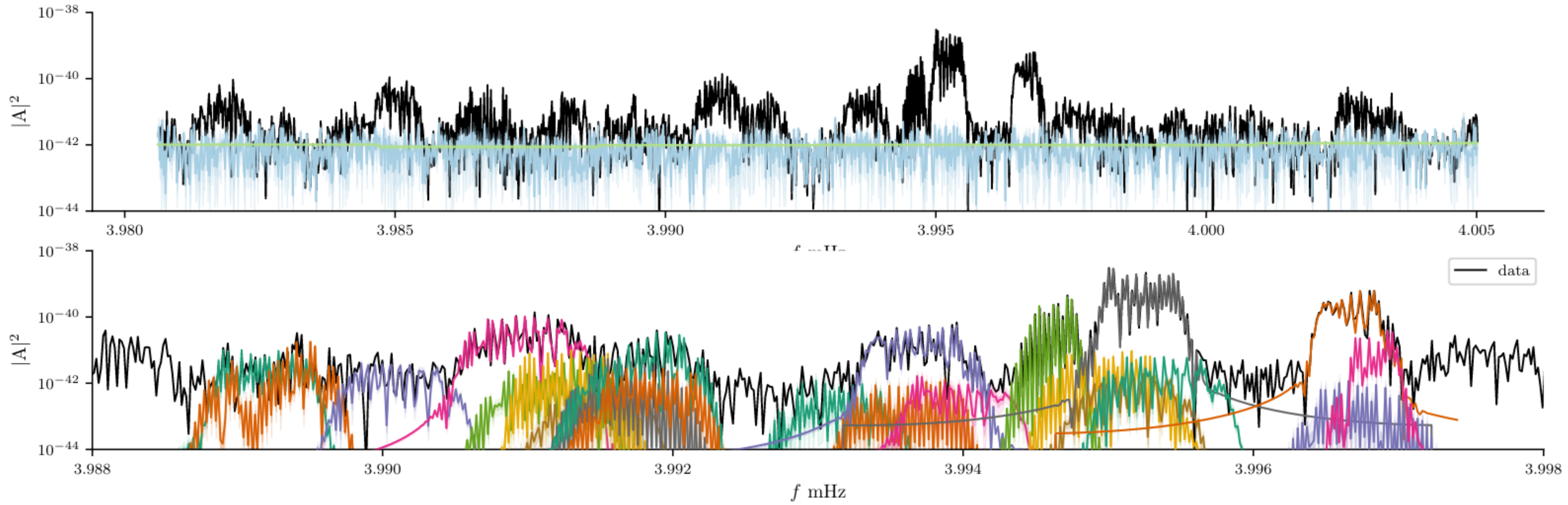


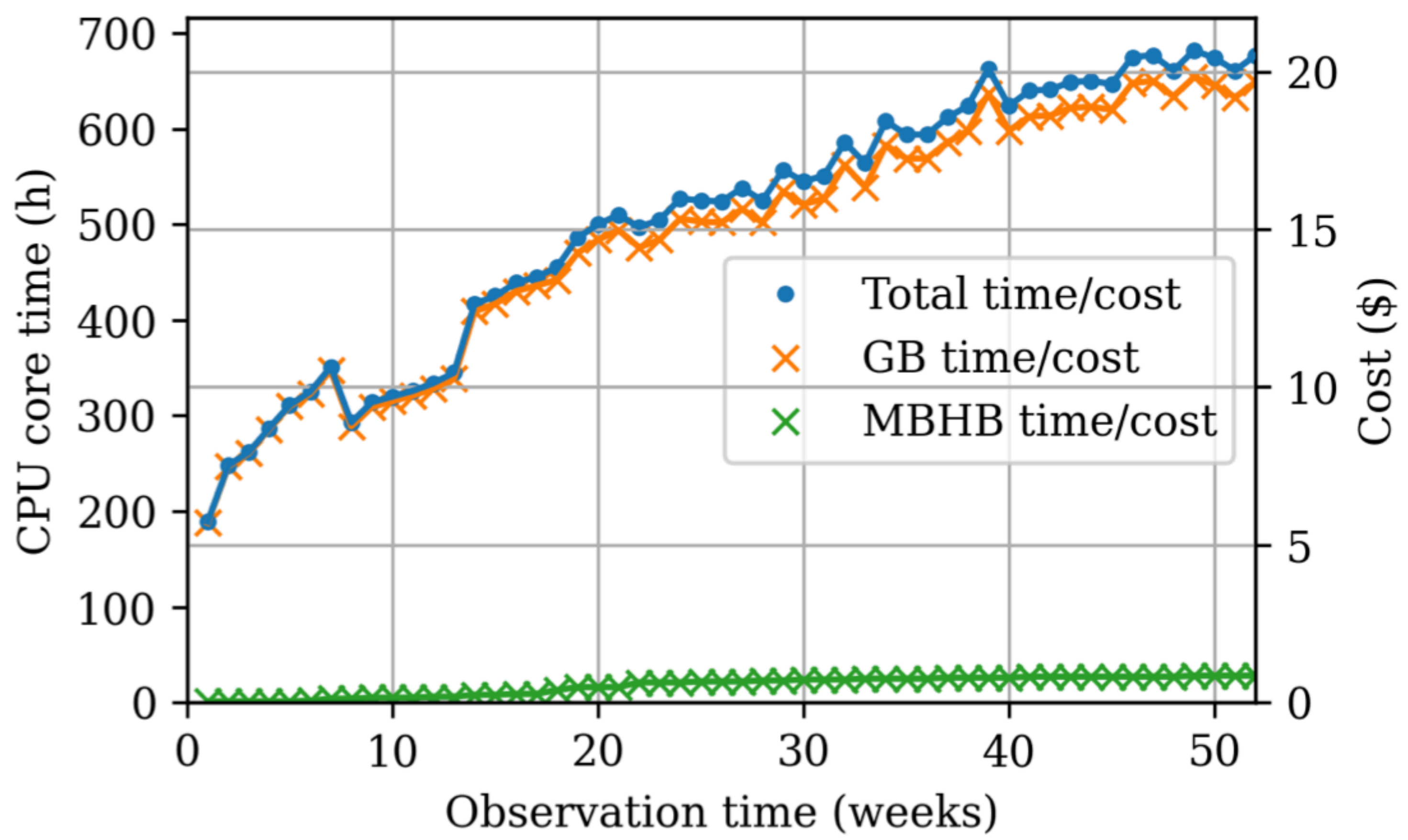
Littenberg et al, arXiv:2004.08464

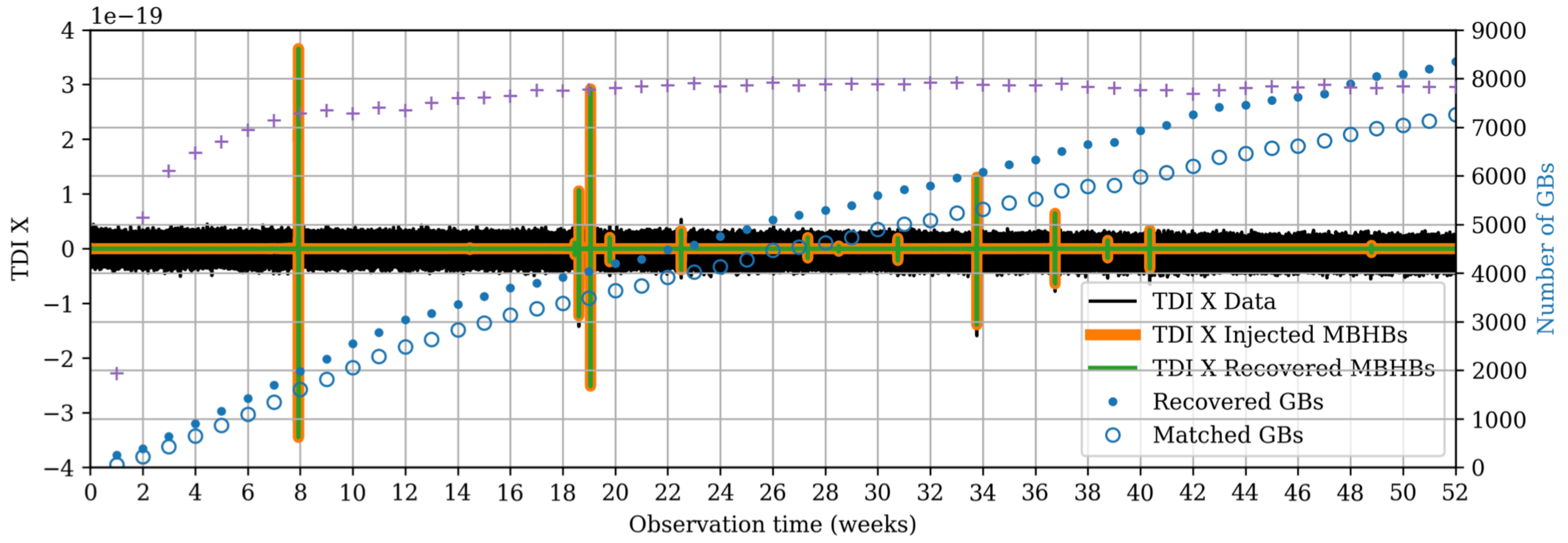
Where do we stand?

Littenberg et al, arXiv:2004.08464
Littenberg & Cornish, arXiv:2301.03673

- A few prototype analyses focusing on DWD+SMBH
  - Encouraging results
  - VERY expensive
- Still many simplifying assumptions







Strub et al, arXiv:2403.15318

LISA DDPC

- Distributed Data Processing Centre
- Responsible for the preparation, and analysis of LISA data at (almost) all levels
  - from the TDI combinations to the generation of the final catalogue
- Funded by the National Agencies (ASI for Italy)

Source type	CPU-hours	Scratch volume	Informative volume
Galaxy	(180-250)K	(260-2000)GB	120GB
MBHBs	(1.2-300)K	(5-50)TB	(0.6-6)GB
EMRIs	(4-6)M	(16-24)TB	(12-20)GB
SBBHs	14M	100TB	200MB
Noise	(0.5-3)K	(50-260)GB	(1-5)GB

Per year of data	CPU-hours	Scratch volume	Informative volume
#1 With SBBH	30M	500TB	160GB
#1 without SBBH	17M	225TB	160GB
#2 with SBBH	(14.5-52.5)M	500TB	160GB
#2 without	(7.5-15)M	225TB	160GB
Low-latency	550K	52TB	6GB

Italian contributions (to date)

- ASI:
  - Responsible for the Italian DCC
  - Supporting DDPC activities through a contract with University of Trento (3 LISA DA-dedicated postdocs: 1 UNIMIB, 1 SISSA, 1 UniPi)
- Universities:
  - Main actors so far: UNIMIB, SISSA, Pisa (DA), Trento (HW), Roma 2 (starting)
- INAF:
  - Interested in joining the DDPC

CTMCMC

- Continuous time MCMC algorithms are Markov processes where the transitions are governed by Poisson distribution

$$p(\Omega_i) \sim e^{-\lambda_i}$$

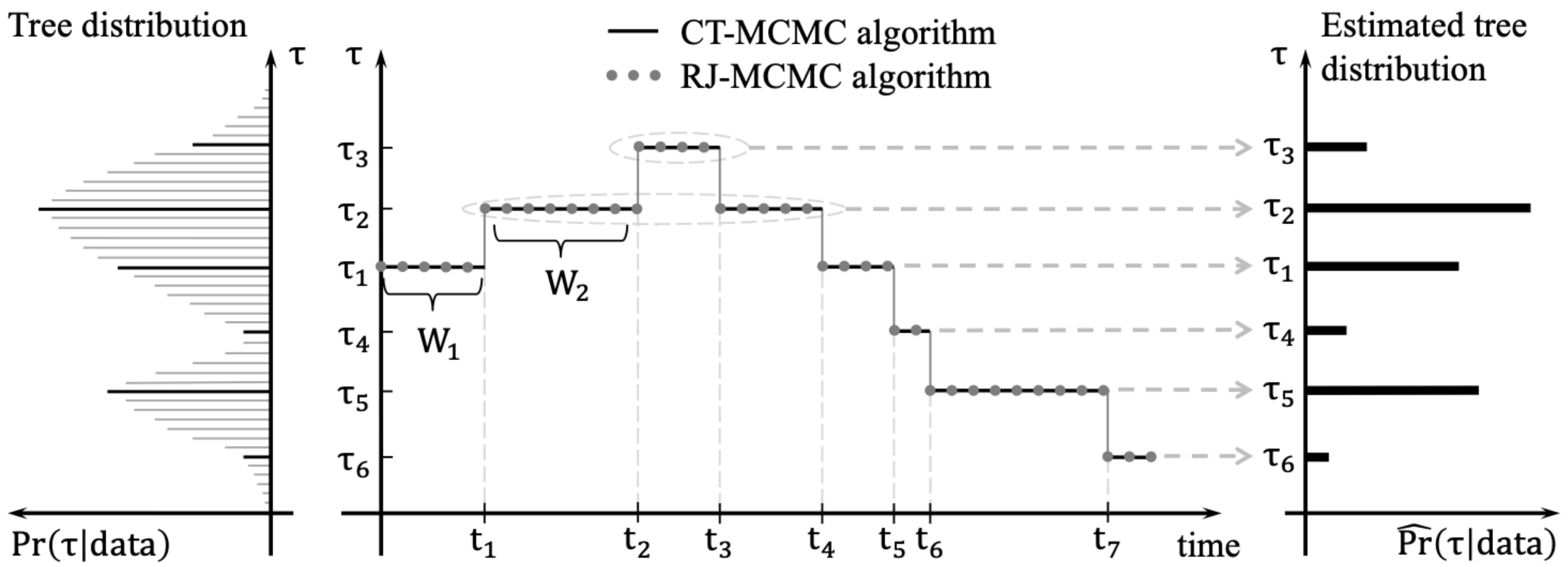
- Hence, for a given (arbitrary) number of states

$$p(\prod_i \Omega_i) \sim e^{-\sum_i \lambda_i}$$

- At any given fixed time, the chain is in state Ω_j with probability

$$p_j = \frac{\lambda_j}{\sum_k \lambda_k}$$

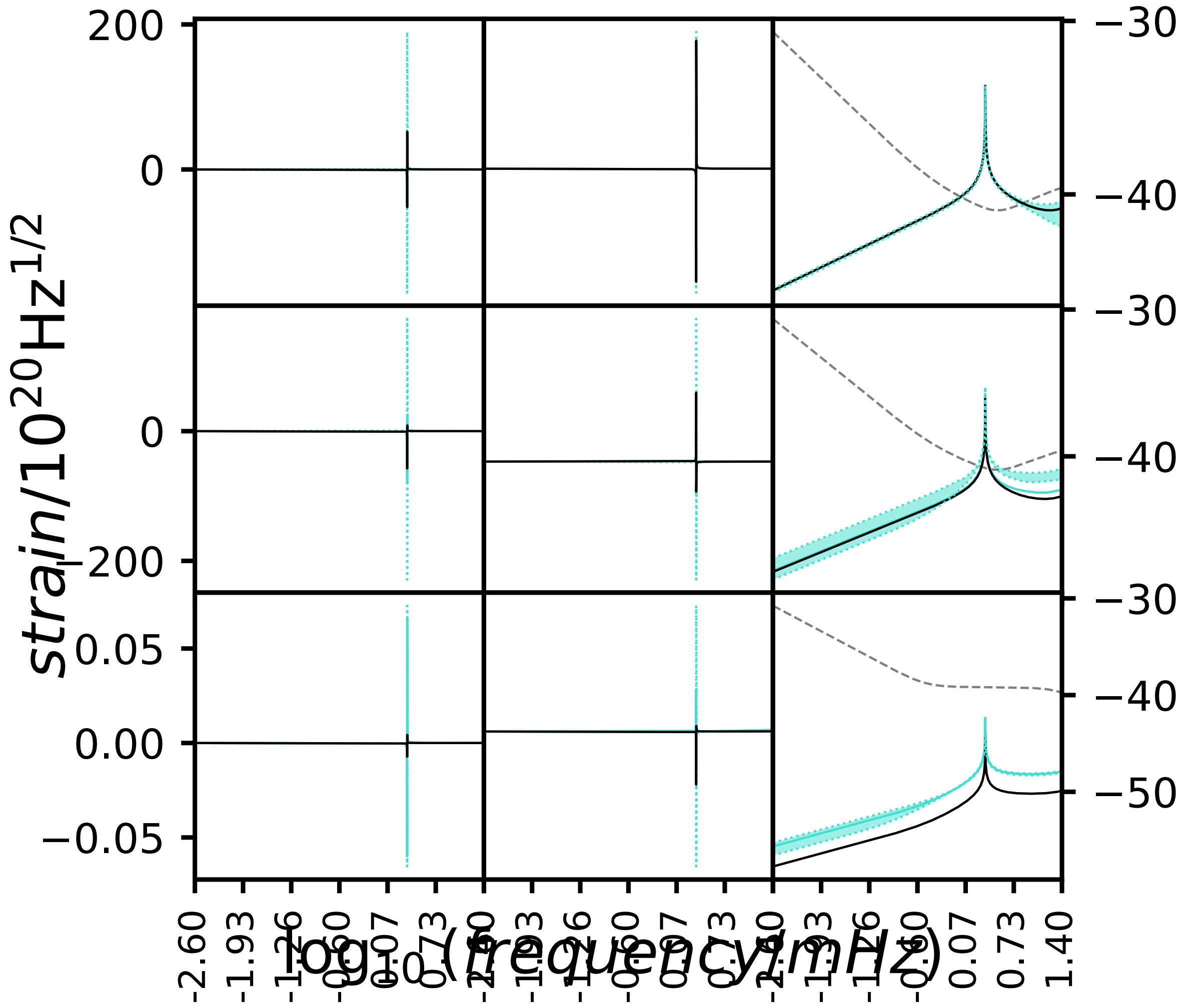
- If we define the states Ω_j as "there are j signals with parameters $\{\theta\}_j$", all we need to do is to estimate the associated rate parameters

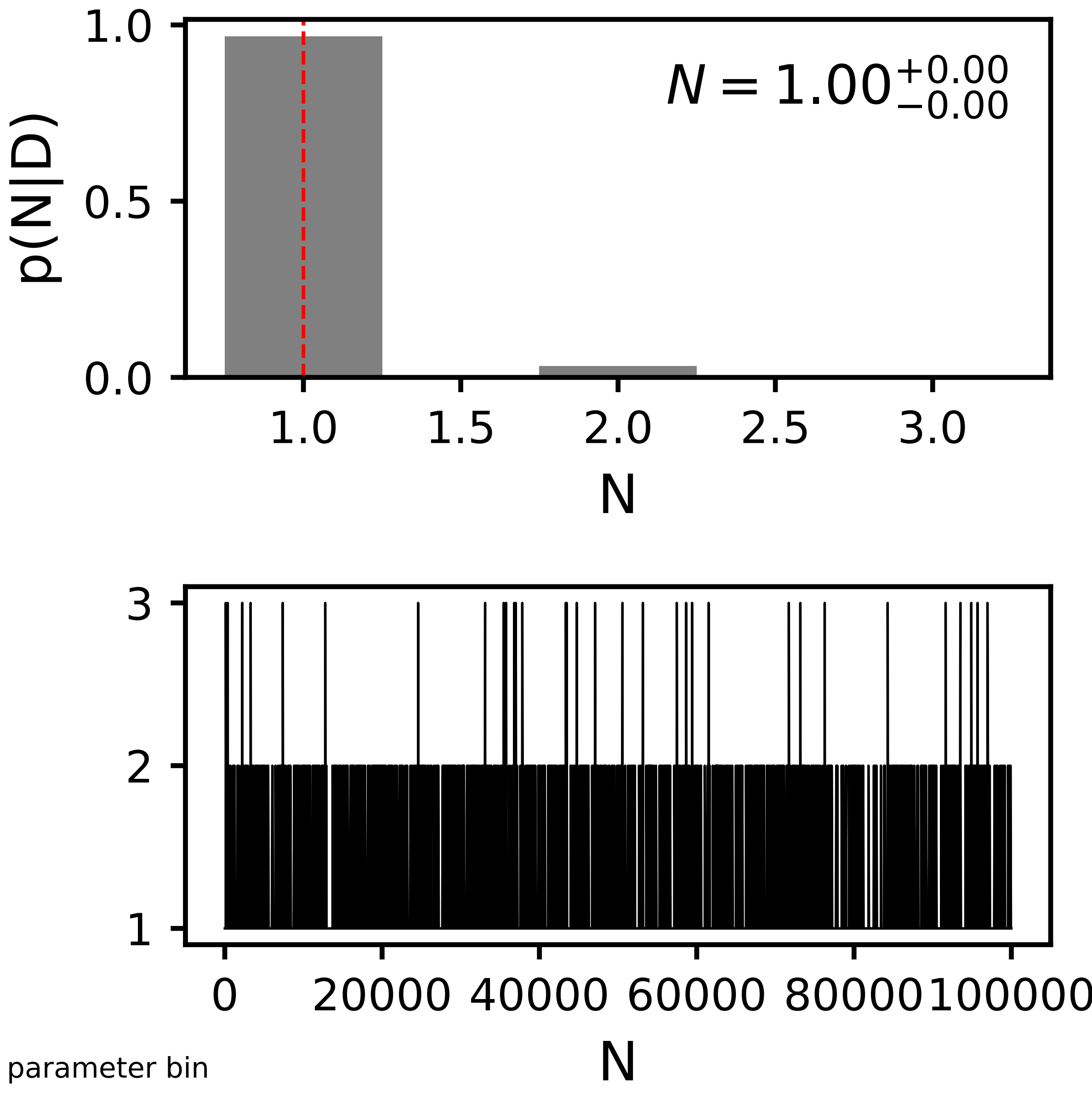


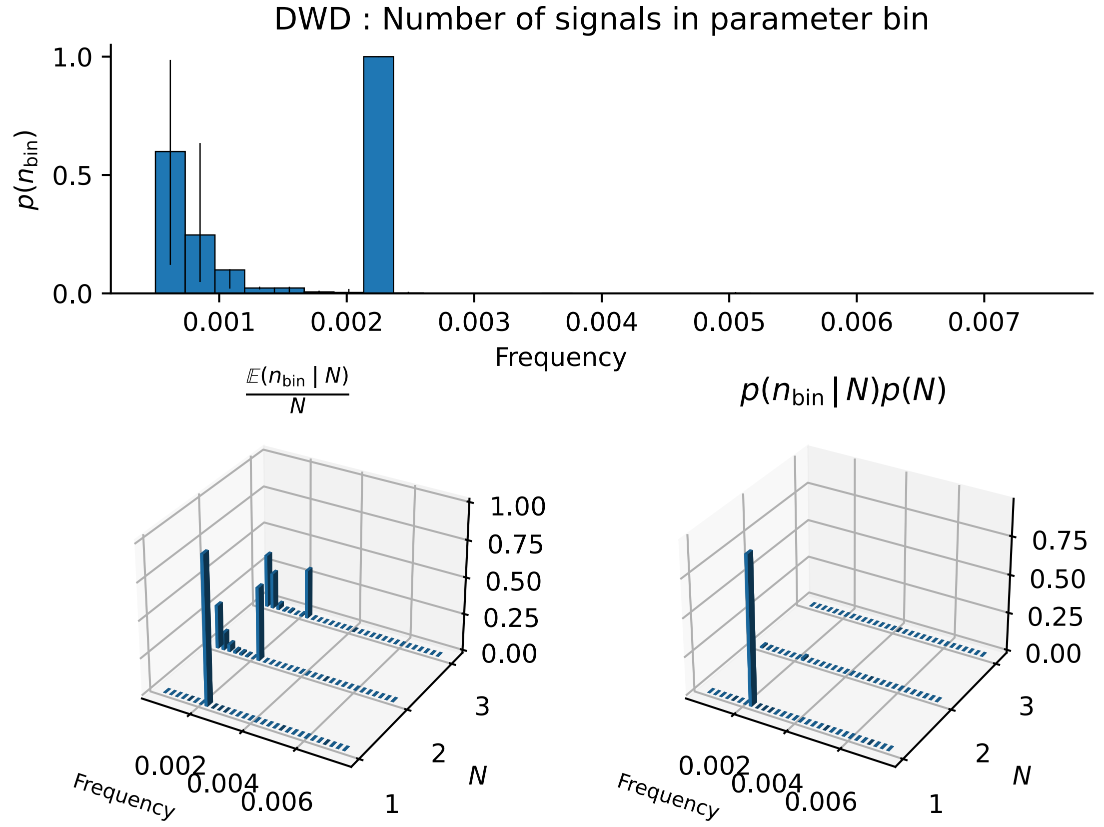
CTMCMC

Dipartimento di Fisica "E. Fermi" Università di Pisa
Istituto Nazionale di Fisica Nucleare

Astorino, Buscicchio, Valbusa Dall'Armi, DP, Pomper, in preparation







- Idea is to associate the probability of a state* to the time the chain spent in that state $p(\prod_j \Omega_j | D) \propto \{\tau\}_j$

*: a state is a given number of sources per class with a given set of parameters

Conclusions

- Virgo and LIGO are paving the way for GW astrophysics
  - Several novel results in many different sub-fields
- Next generation detectors present several challenges that need to be overcome
  - Modelling
  - Computational
- A conversation between the LISA and INFN communities has started
  - Joint informal workshop held on 27th Feb 2025