XXIV SIGRAV Conference
on General Relativity and Gravitation
Urbino - 2021/09/08

Bayesian parameter estimation of stellar-mass black-hole binaries with LISA

[arXiv: 2106.05259](https://arxiv.org/abs/2106.05259)
Phys. Rev. D 104, 044065

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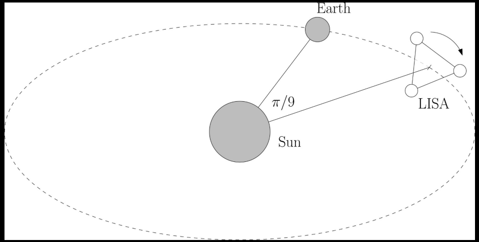
Agenzia Spaziale Italiana

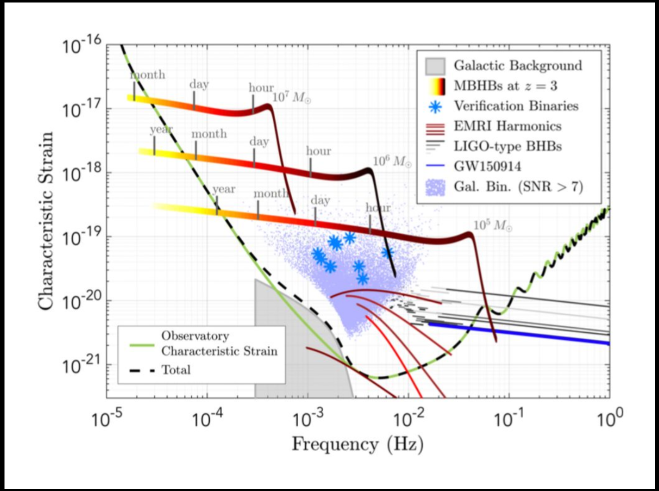
The Mission(s)

LISA: a bright (sources) future ahead

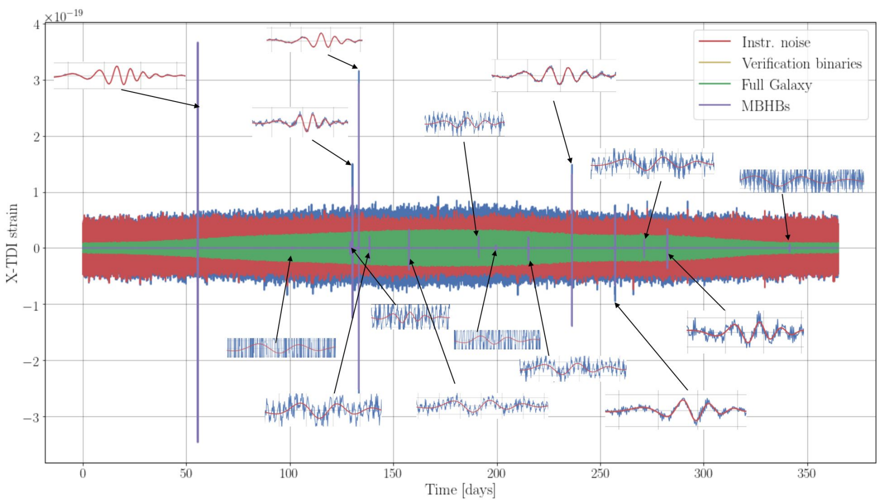


(+noise)

(+noise)



LISA-L3 Mission proposal



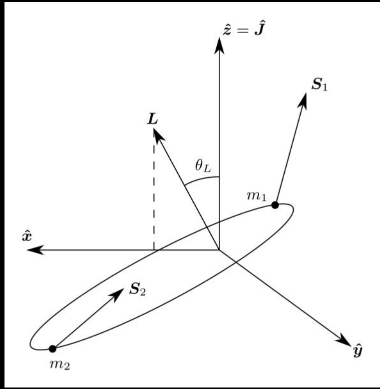
credits: courtesy of LISA Data Challenge working group

Stellar mass black hole binaries

What we know? What we expect?

- Many detections, more to come (O3b - O4)
- Evidence for aligned spins
- Evidence for unequal masses
- Signs for precession
- (No astrophysical foreground, yet)
- (No gravitational wave lensing, yet)
- (No eccentricity, yet)

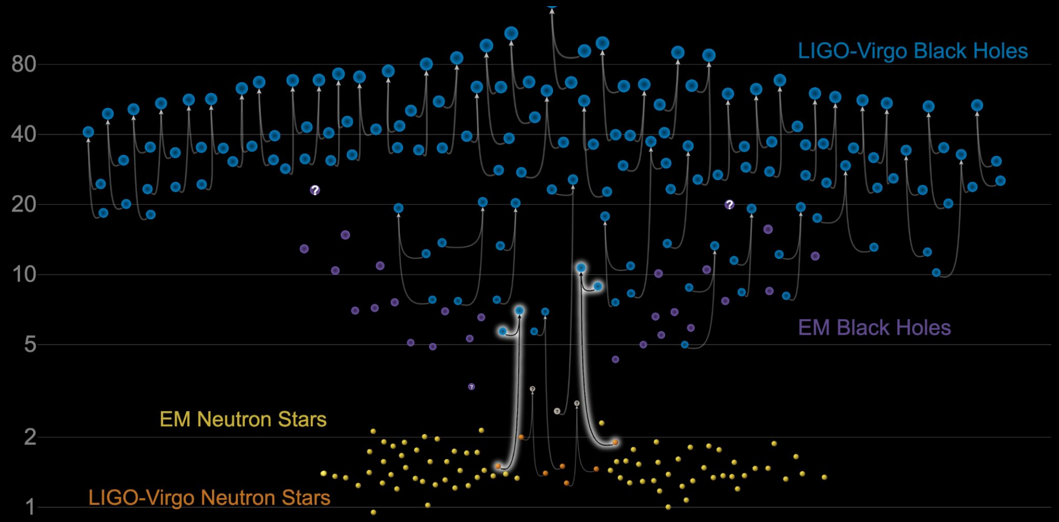
Ultimate source



Klein 2106.10291 ← **Why does it matter for LISA?**

Masses in the stellar graveyard

in Solar Masses

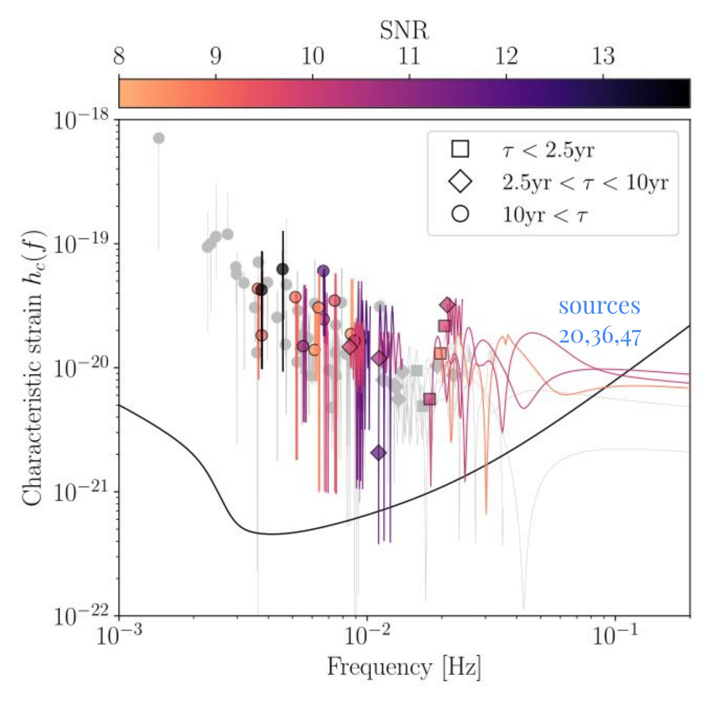


GWTC-2 plot v1.0

LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

The Sources

LDC dataset: stellar mass binary black holes (“Bright” set)



Recap

- 1 dataset, 66 sources, known injected parameters
- SNRs<14 (22 with SNR>8)
- Circular
- Aligned spins
- 13<Chirp mass<55
- Injected parameters, SNRs, merger time
- 2.5 year long mission ↠ orbital strain modulation
- 5 sources merging within LISA mission, (3 with SNR>8)
- 11-dimensional parameter space

And much more (see Challenge 2 - Sangria**)**

The Pipeline: BALROG

"A LISA Bayesian Parameter Estimation Routine for Tons of Objects, Simultaneously."

Birmingham (UK)

Focus on parameter estimation for:

- Multiple sources (simultaneously)
- Multiple source types: currently chirping and monochromatic binaries
- Python design, core Cythonized waveforms
  (see Klein A. **2106.10291** EFPE waveform for SOBBH)
- Interface with multiple samplers
- Fully containerized
- Built alongside LDC for noise generation, compatibility, testing, conventions

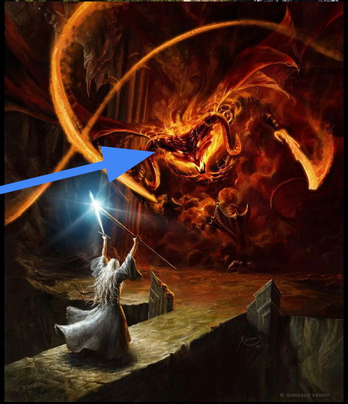
$$\ln \mathcal{L}(d \mid \boldsymbol{\theta}) = -\sum_k \frac{\langle d_k - h_k(\boldsymbol{\theta}) | d_k - h_k(\boldsymbol{\theta}) \rangle_k}{2} + \text{ cons}$$

$$\langle a \mid b \rangle_k = 2 \int_0^{+\infty} \mathrm{d}f \, \frac{\tilde{a}(f)\tilde{b}^*(f) + \tilde{a}^*(f)\tilde{b}(f)}{S_k(f)}$$

$$\tilde{X}_{1.5-\mathrm{g}}(f) \approx \left(1 - e^{-4\pi i f L}\right) \tilde{X}_{\mathrm{RAA}}(f)$$

\+ Clenshaw-Curtis quadrature to speed up waveform evaluation

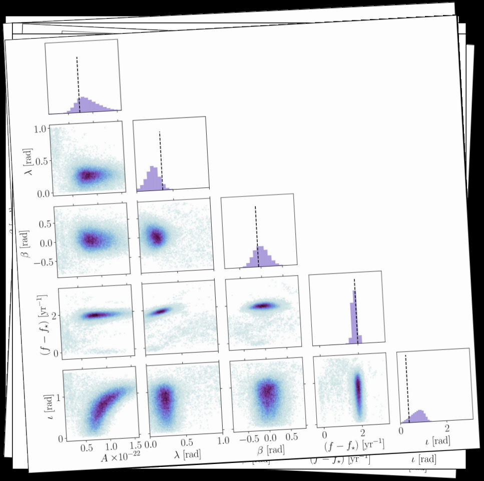
Balrog

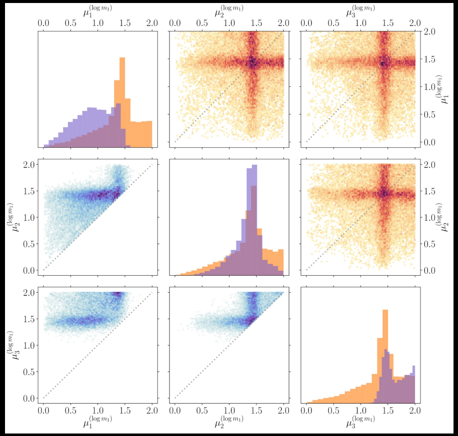


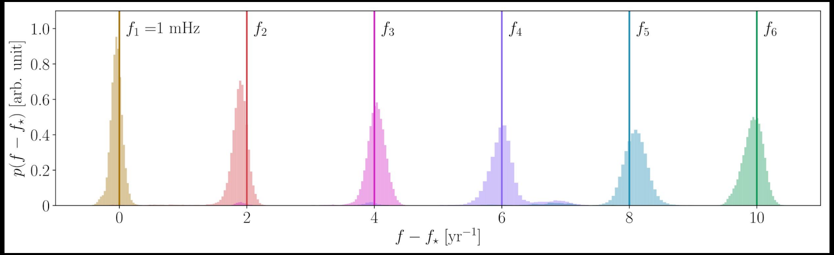
Previous episodes

Appeared previously in...

Multiple sources

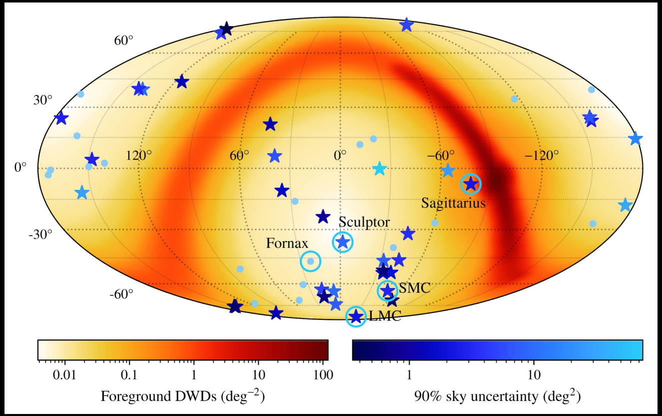




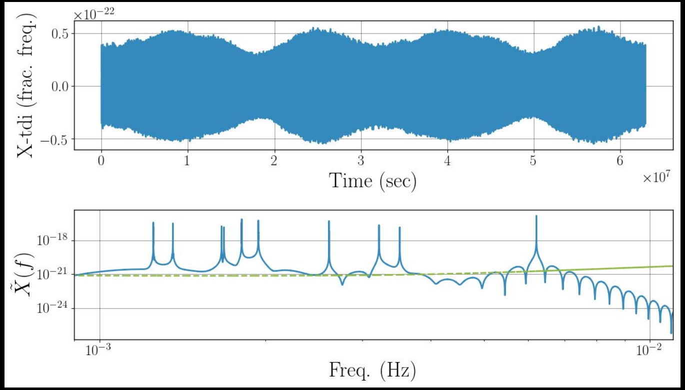


Buscicchio & al. PRD.100.084041(2019)

DWD in Milky Way Satellites



Roebber, **RB** & al. ApJL, 894, 2, L15 (2020)
Korol, **RB** & al. A&A 638, A153 (2020)

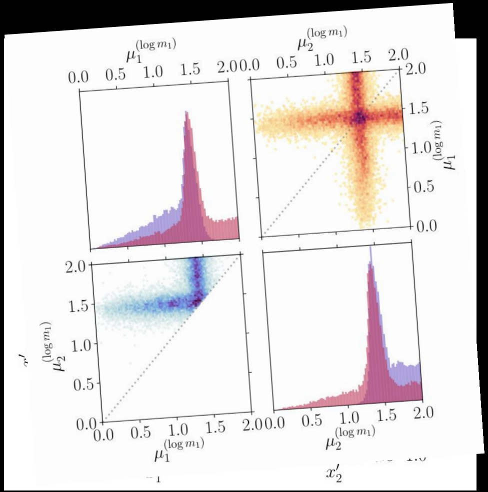


LDC-1.3 **Birmingham** submission:
Verification binaries

Pipeline structure

Brief summary of a 4-year long work

Handling excess multimodality



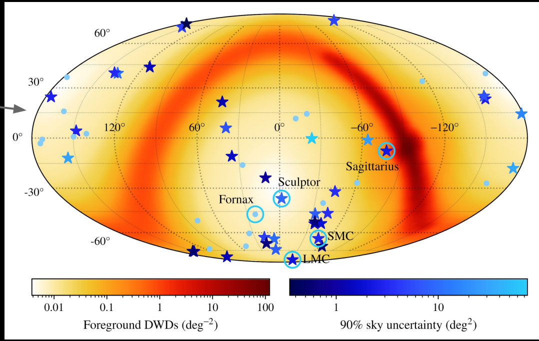
Handling evidence (nested sampling)

K	$\log Z_{\mathcal{T}}$	$\log Z_{\mathcal{C}}$
1	-74.76 ± 0.09	
2	-78.37 ± 0.05	-78.30 ± 0.05
3	-81.82 ± 0.09	-81.66 ± 0.08
4	-84.58 ± 0.06	-84.2 ± 0.1

Model selection

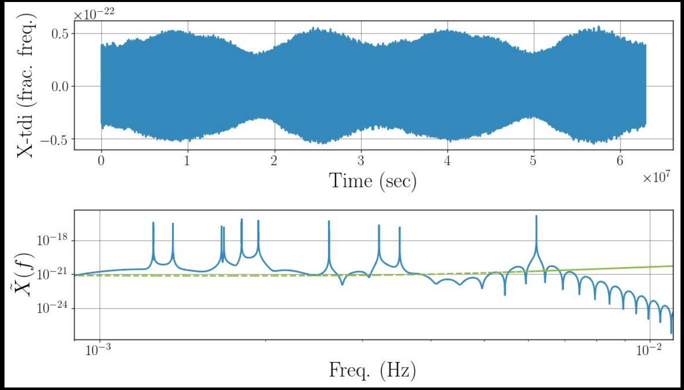
Handling injection recovery campaigns

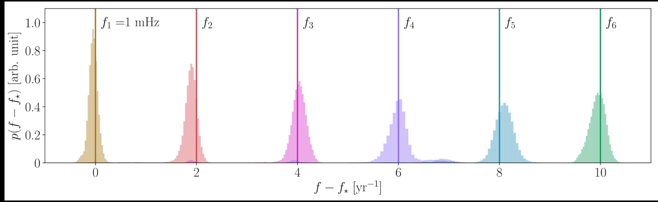
DWD in Milky Way Satellites



Roebber, **RB** & al. ApJL, 894, 2, L15 (2020)
Korol, **RB** & al. A&A 638, A153 (2020)

Handling multiple flavours of TDIs





Handling multiple sources, multiple source-type, simultaneously.

Bayesian inference (computationally)

Multi-stage process:

- Individual source PE, noiseless datasets, on 3.5 PN Taylor F2, restricted to aligned spins, circular binaries
  ↣ Diagnosing sources' confusion, waveform mismatches ↞

- Iterative PE with pre-determined recipe for prior adjustment on $\mathcal{M}_c, f_0, \sin b, l$
  ↣ Proxy for search-informed priors ↞

- Stopping criterion: informative, clean, non-railing, posteriors
  ↣ After 3 iterations at most (1 for the SNR>8 "recovered") ↞

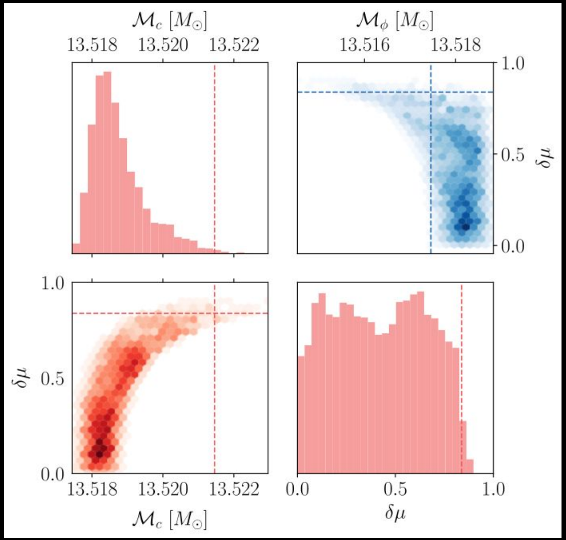
- Run on LDC-1 dataset

Bayesian inference (computationally)

Sources baby-sitting:

- All SNR 22 sources automatically processed

  » The injection campaign manager worked well «



- A couple with SNR 7.9 ones were interesting, but unclean posteriors (see Section III.C of the paper).
  Flagged as undetected.

  » SNR 8 is our choice «

- Source 5, 20 triaged, unbiased in single source dataset

  » Confusion under investigation «

- Source 16 unconstrained mass difference, gives biased marginals in chirp mass (see also Toubiana & al. PRD.102.124037)

  » Projection effect, PN-driven reparametrization gives milder biases «

Bayesian inference (parameter estimation)

Search surrogate

Priors uniform

$$\delta\mu = (m_1 - m_2)\,/\,(m_1 + m_2)$$

[0,0.9]

$$A_L = (1+\cos\iota)/\sqrt{2D_L}$$

$$A_R = (1-\cos\iota)/\sqrt{2D_L}$$

twice the true distance of the optimally oriented

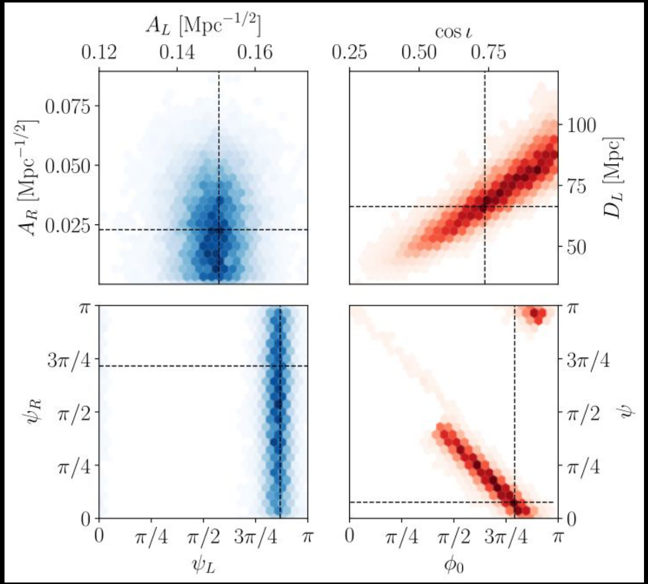
$$\psi_{L,R} = \phi_0 \pm \psi$$

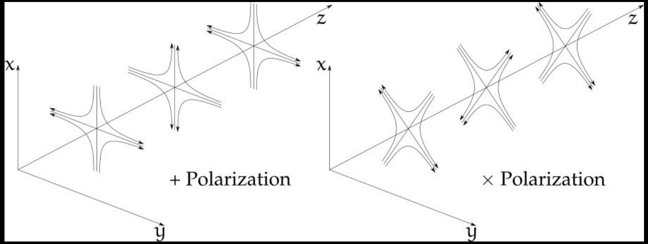
full space

$$\chi_{1,\ell}, \chi_{2,\ell}$$

$$l, \sin b \qquad \mathcal{M}_c, f_0$$

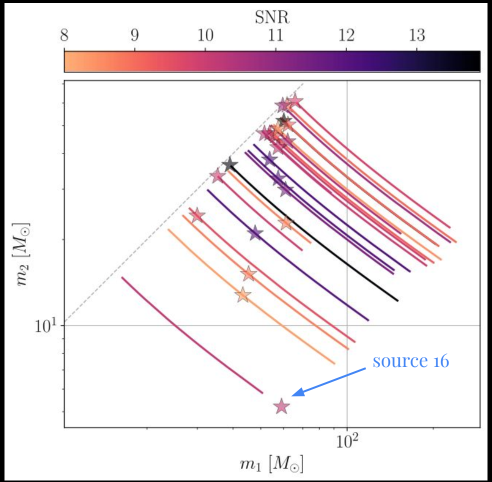
Iteratively adjusted

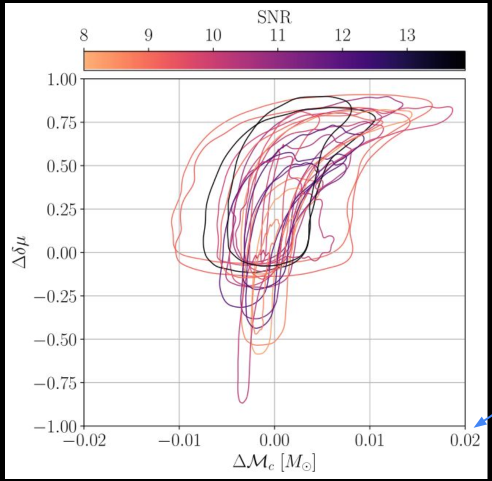


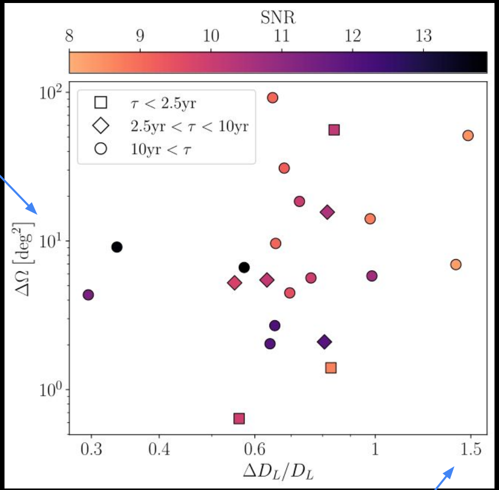


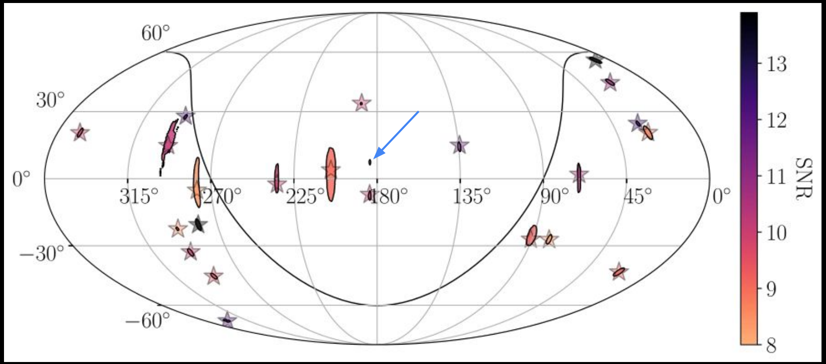
The Good, the Bad and the Ugly

(and where to find them)



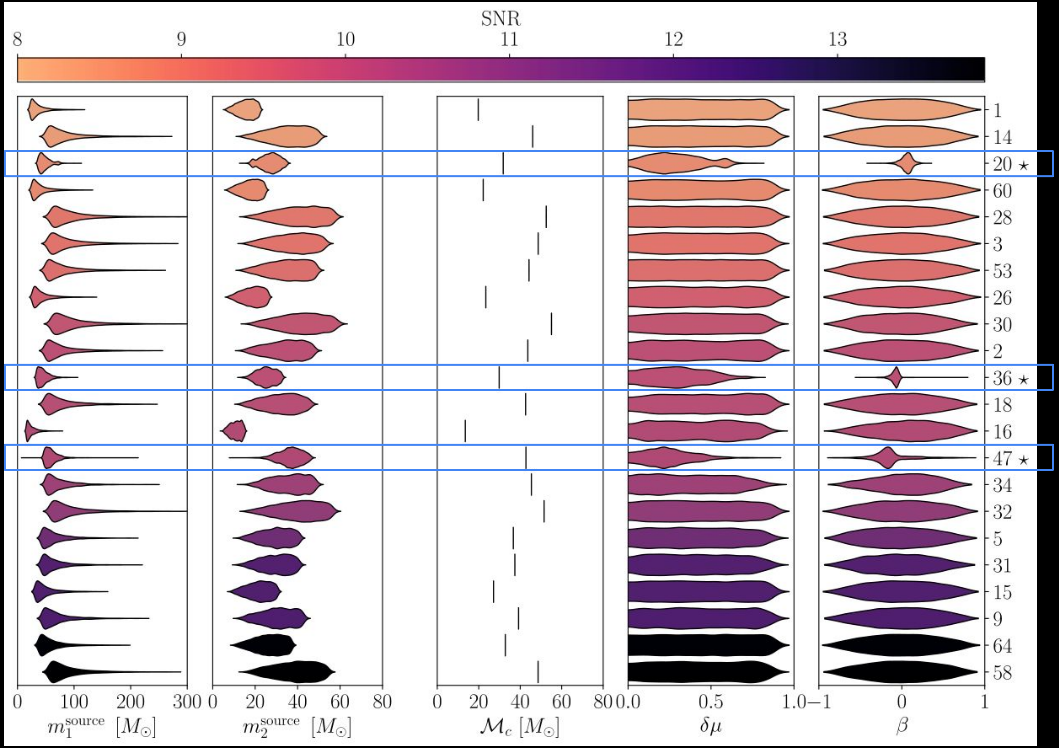






Violins

22 sources recovered (SNR>8)



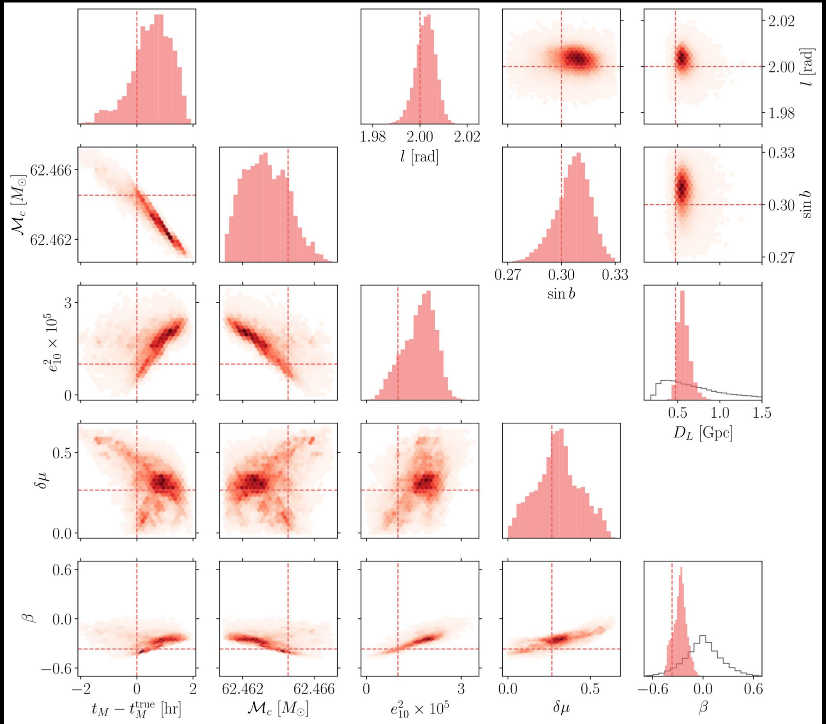
$$\beta = \sum_{i=1}^{2} \left(\mu_i + \frac{75\mu_j}{113} \right) \mu_i \chi_{i,\ell}$$

Spin and mass ratio posteriors from higher PN terms

Big Table with posterior point estimates and computational costs

Bonus content

Eccentric precessing run: SNR 15, GW190521-like, precessing 17-dimensional space, recovered eccentricity down to 3×10^{-3}



time to merger <1h

>1 point in parameter space investigation ongoing… **Stay tuned!**

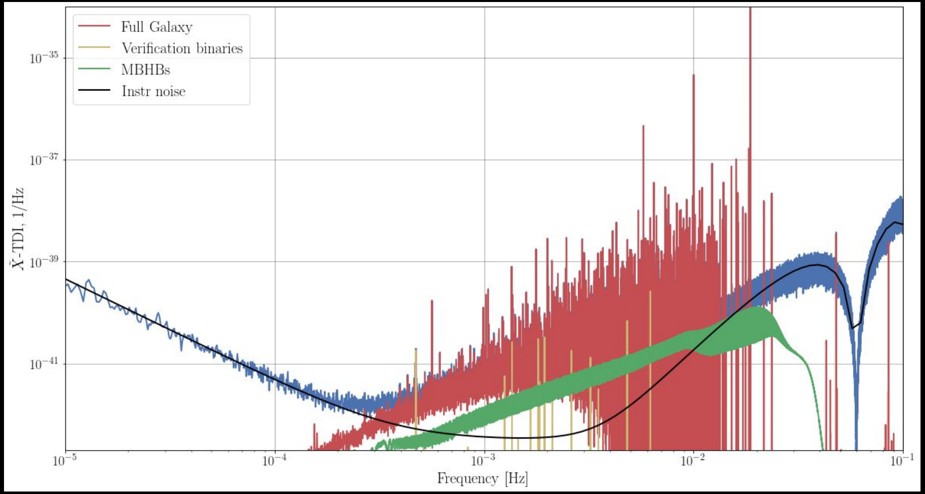
Where do we stand?

- Monochromatic sources (not this talk):
  - vastly tested and reliable for injection and recovery campaigns
  - successfully recovered LISA challenge white dwarfs verification sources
  - successfully recovered multiple ones, simultaneously

- Inspiralling sources (this talk):
  - successful recovery of challenge circular
  - successful recovery of an eccentric source (more to come..)

Where do we go?

- Chirping sources and sgwb (hopefully future talk):
  - Joint noise-signal inference: glitches, better instrument (see Eleonora's talk, tomorrow)
  - IMR waveforms for SMBBH: the big bright guys
  - Blind challenge: the pandora's box



Thanks

Follow-up questions, comments

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