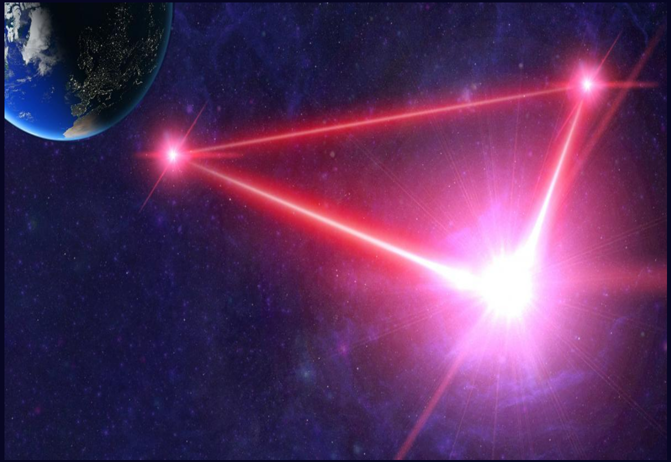
Glitch systematics on the observation of massive black-hole binaries with LISA



Alice Spadaro, R. Buscicchio, D. Vetrugno, A. Klein, D. Gerosa, S. Vitale, R. Dolesi, W. J. Weber, M. Colpi

arXiv:2306.03923

September 4th 2023 - Trieste

XXV SIGRAV Conference on General Relativity and Gravitation

UNIVERSITY OF BIRMINGHAM | GRAVITATIONAL WAVE ASTRONOMY

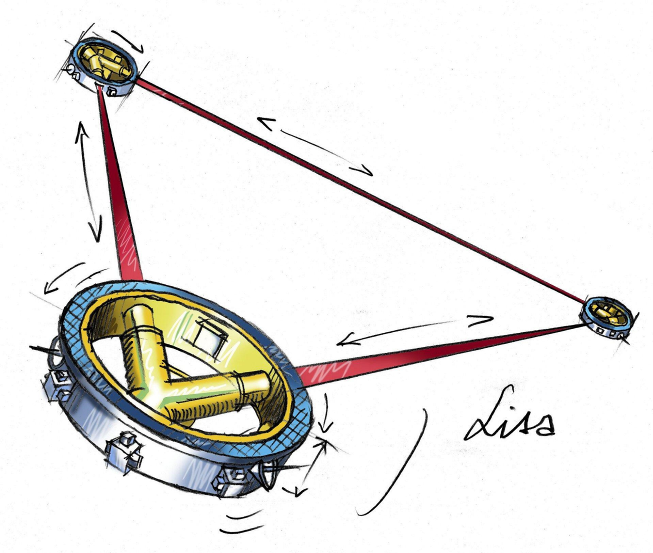
European Research Council, Established by the European Commission

INFN

ASI Agenzia Spaziale Italiana

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

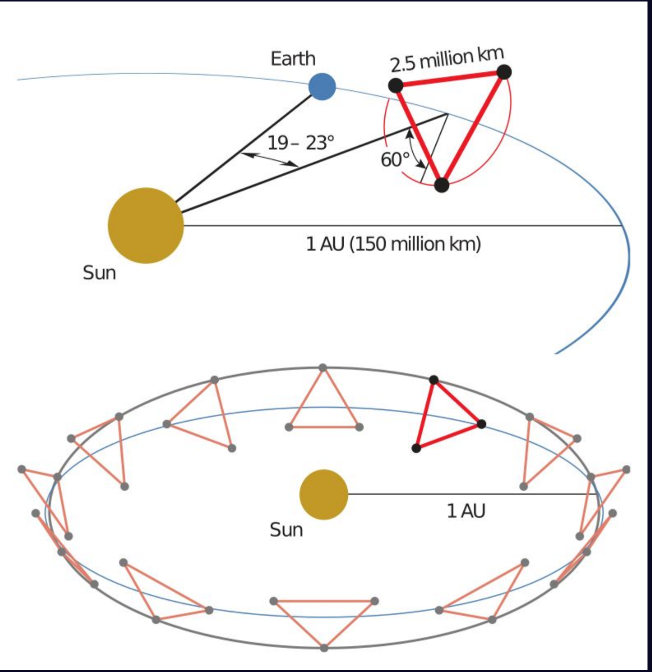
Contents



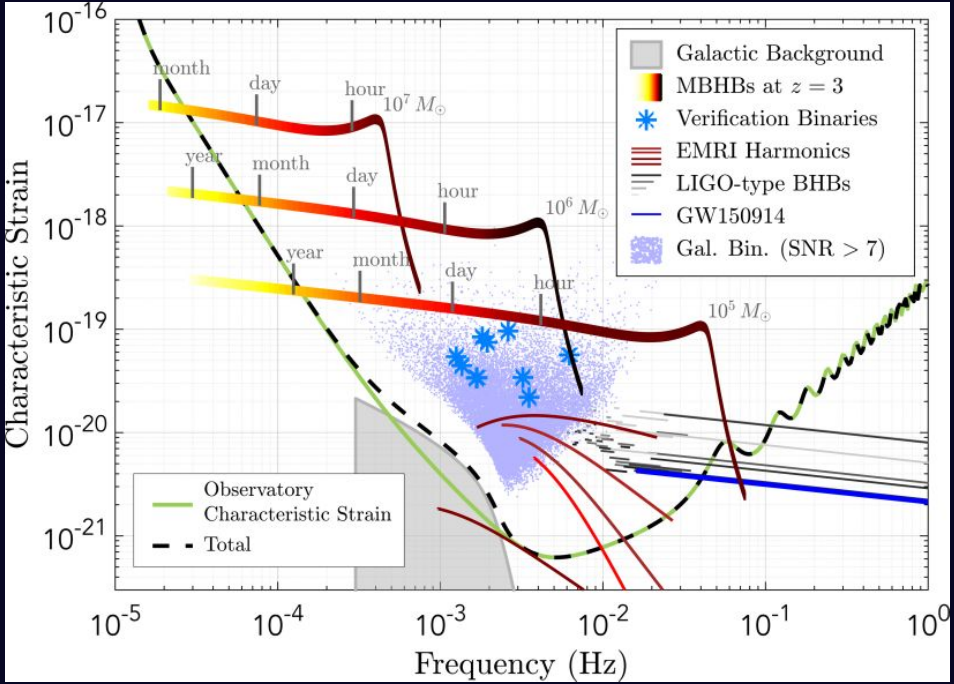
credits: ESA-C. Vijoux

LISA & Astrophysics

- ESA mission planned to be launched in ~2034
- Gravitational-waves detection from space



[1702.00786] Laser Interferometer Space Antenna



[1702.00786] Laser Interferometer Space Antenna

Monochromatic sources + drifting sources + chirping sources…and more

→ LISA: astronomical observatory of unprecedented range!

LISA & Astrophysics

- ESA mission planned to be launched in ~2034
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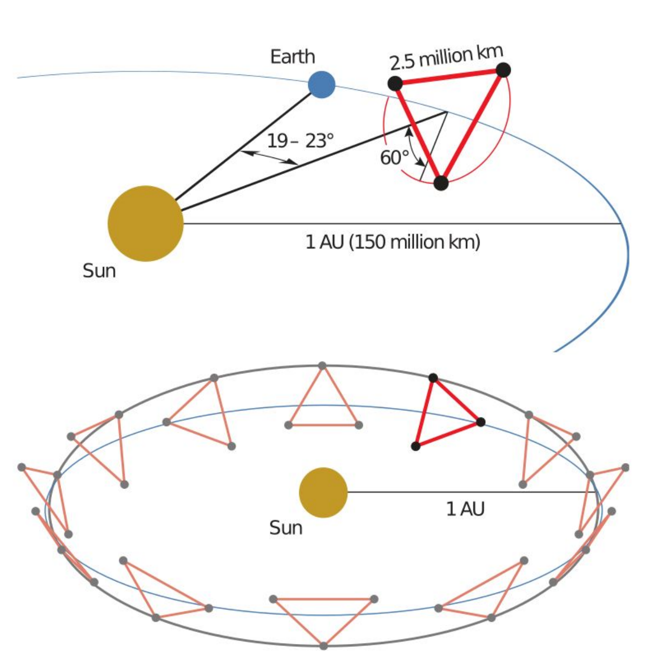

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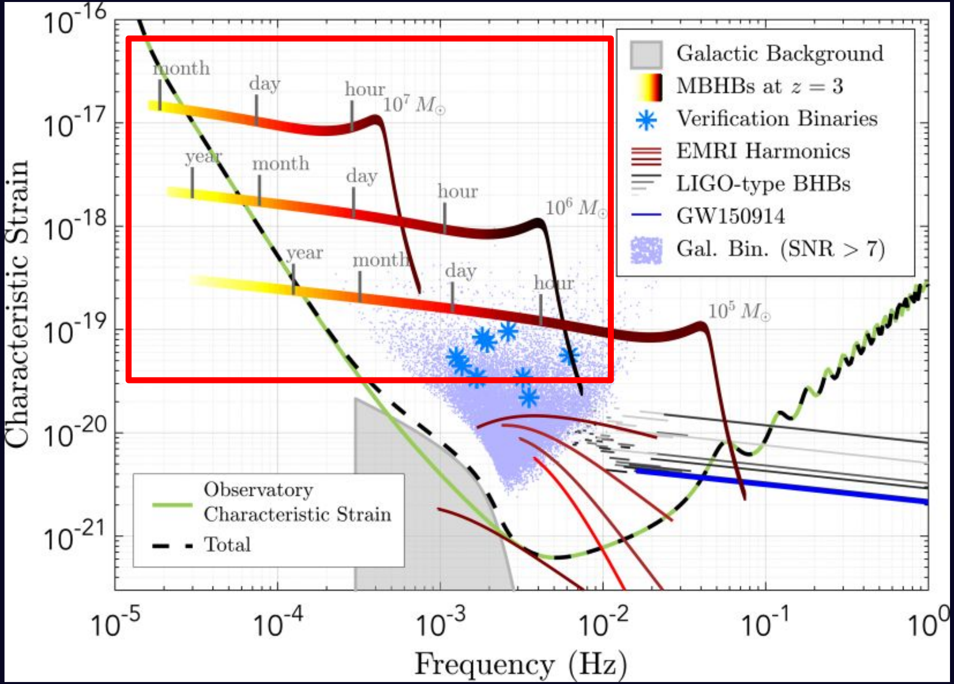

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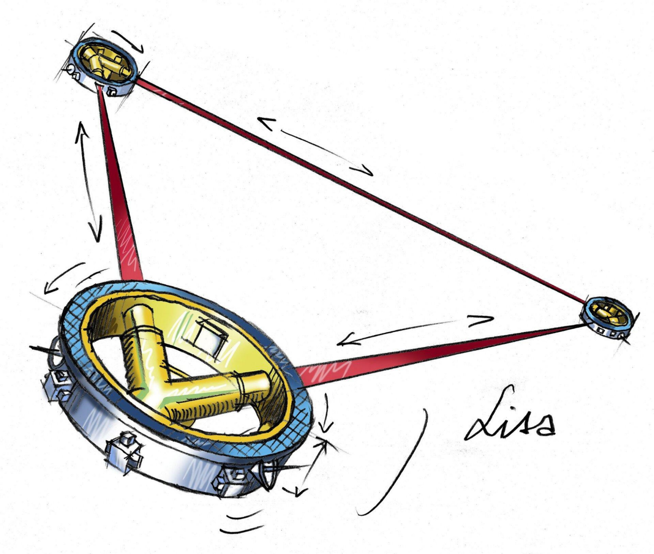
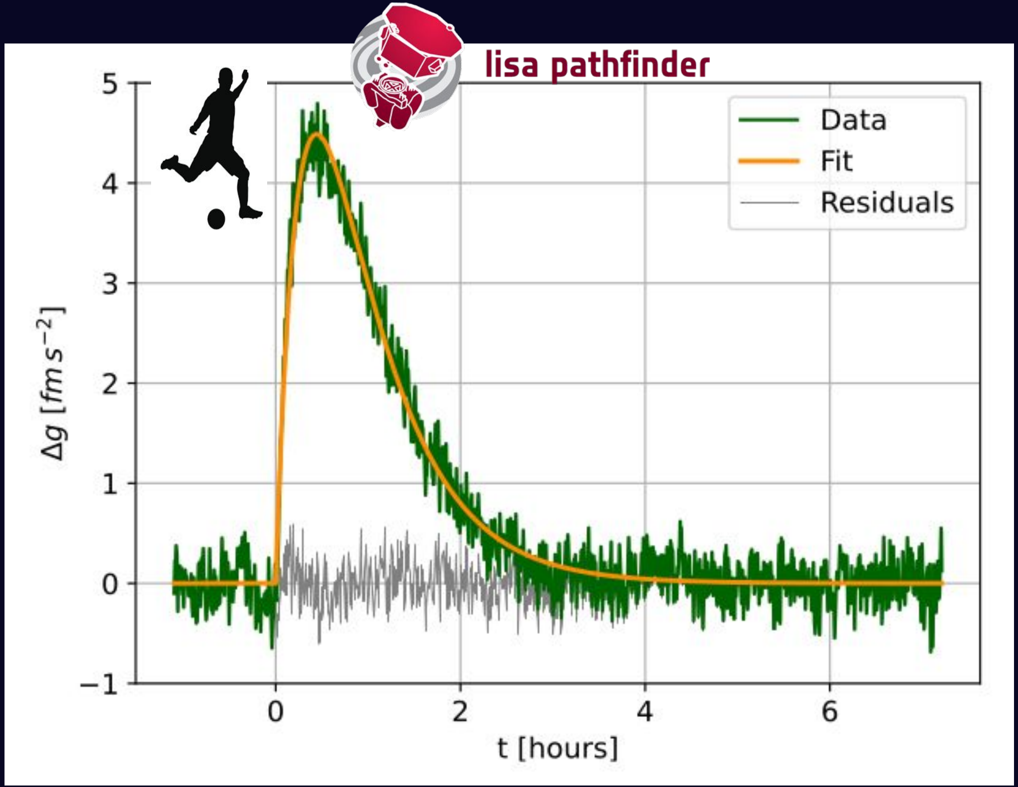


credits: ESA-C. Vijoux

Glitches in LISA



[2205.11938] Transient acceleration events in LISA Pathfinder data: properties and possible physical origin

- One-sided model

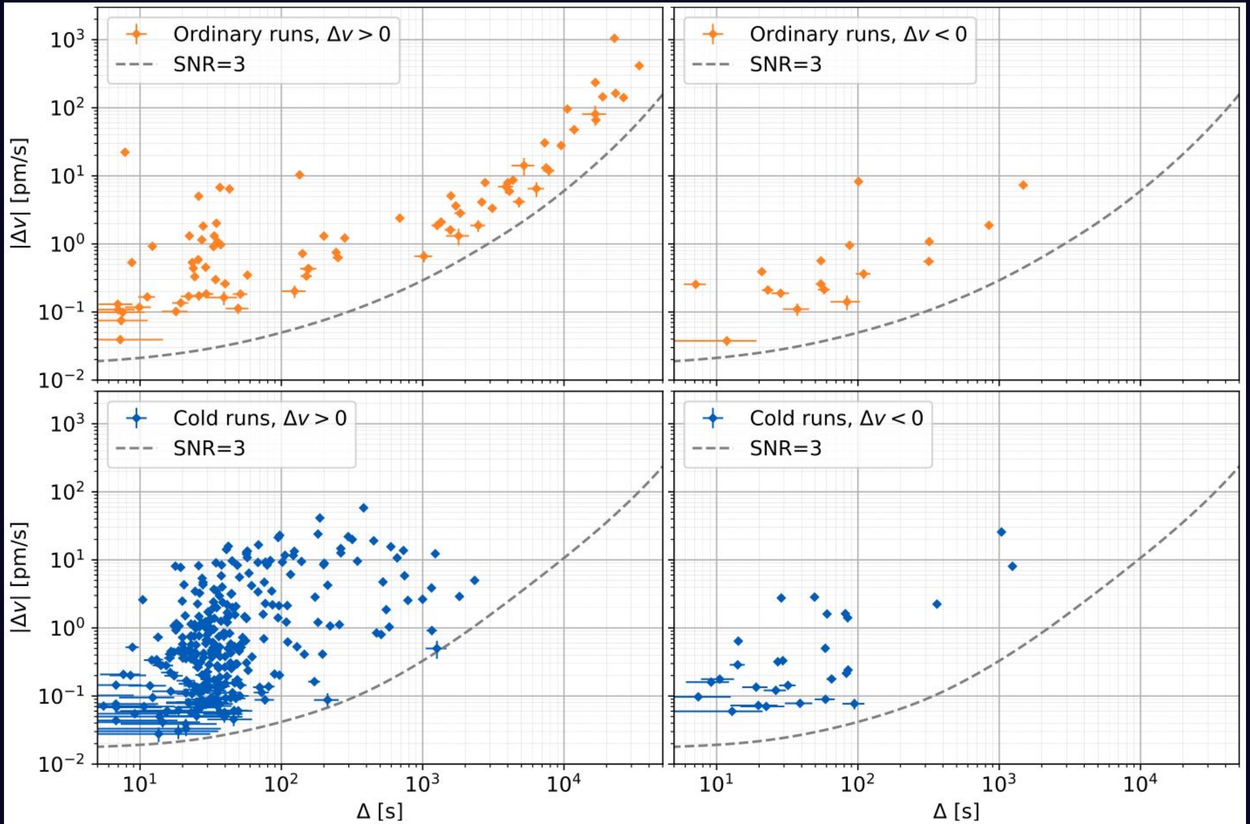
$$g(t) = \frac{\Delta v}{\tau_1 - \tau_2}\left(e^{-\frac{t-t_0}{\tau_1}} - e^{-\frac{t-t_0}{\tau_2}}\right)\Theta(t-t_0)$$

- Exponential shapelet model

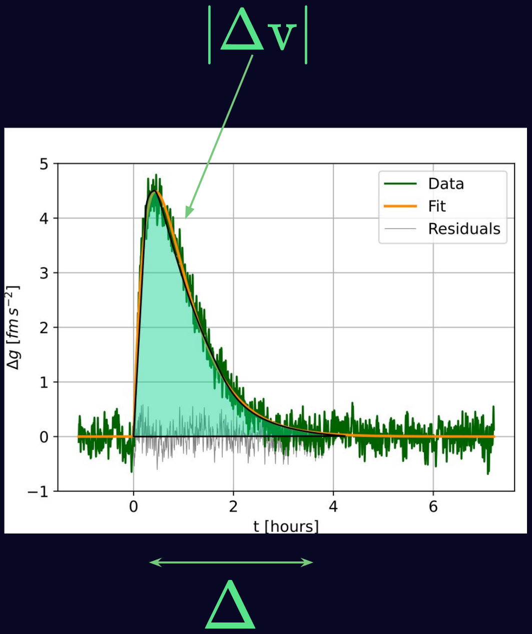
$$g(t) = \sum_{i=1}^{P} \alpha_i \psi_n\left(\frac{t-\tau_i}{\beta_i}\right)$$

$$\psi_n(t) = c_n \frac{2t}{n} e^{\frac{-t}{n}} L^1_{n-1}\left(\frac{2t}{n}\right)\Theta(t)$$

Population of LPF glitches



[2205.11938] Transient acceleration events in LISA Pathfinder data: properties and possible physical origin



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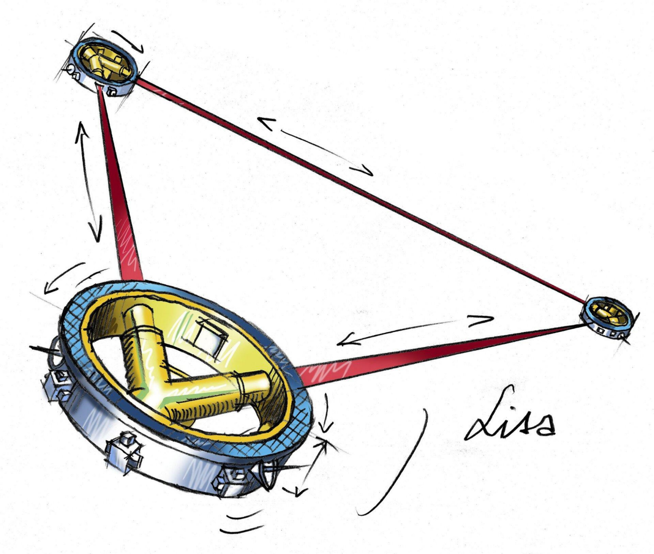
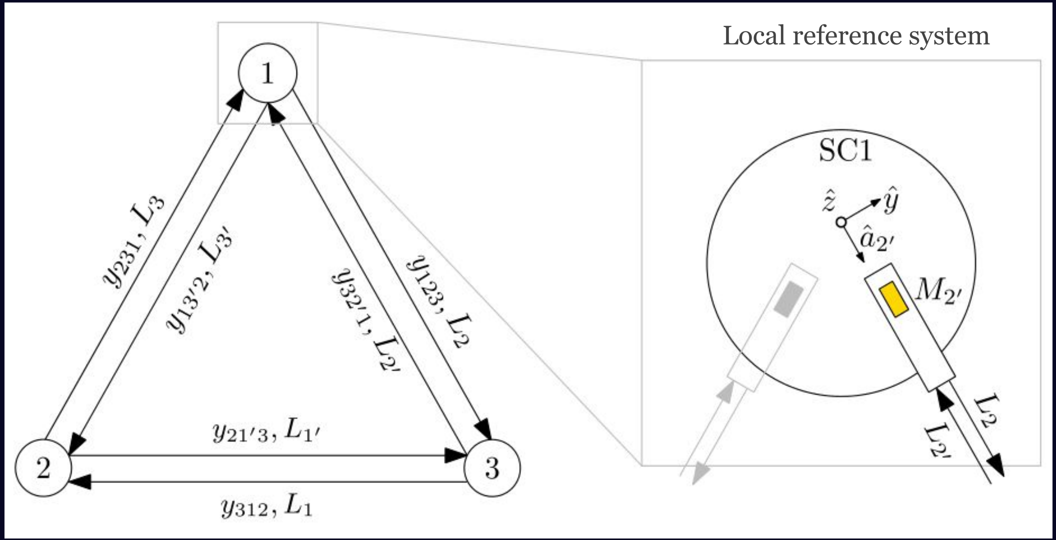


credits: ESA-C. Vijoux

LISA response to glitches



- True reflection impossible ($P_{RX} \sim 100$ pW)

  six laser links

- Two test masses in each spacecraft

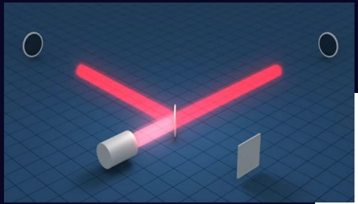
- Single-link response $\frac{\Delta L(t)}{L} = \int_{t_0}^{t} ds \frac{\Delta\omega(s)}{\omega_l} = y(t)$

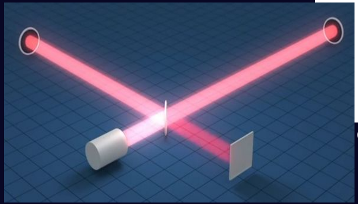
Time Delay Interferometry (TDI)

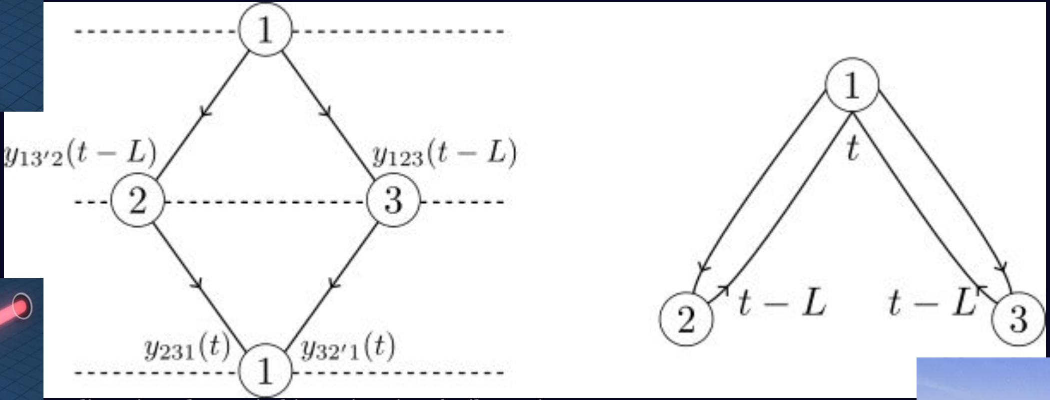
Post-processing technique to reduce laser phase noise → Combination of delayed phase measurements

↓

Two variables to synthesize physical interference







credits: Riccardo Buscicchio, University of Milano-Bicocca

$$M_X = \underbrace{y_{231}(t) + y_{13'2}(t-L)} - \underbrace{y_{32'1}(t) - y_{123}(t-L)}$$

Interferometric variables

LIGO Livingston, US

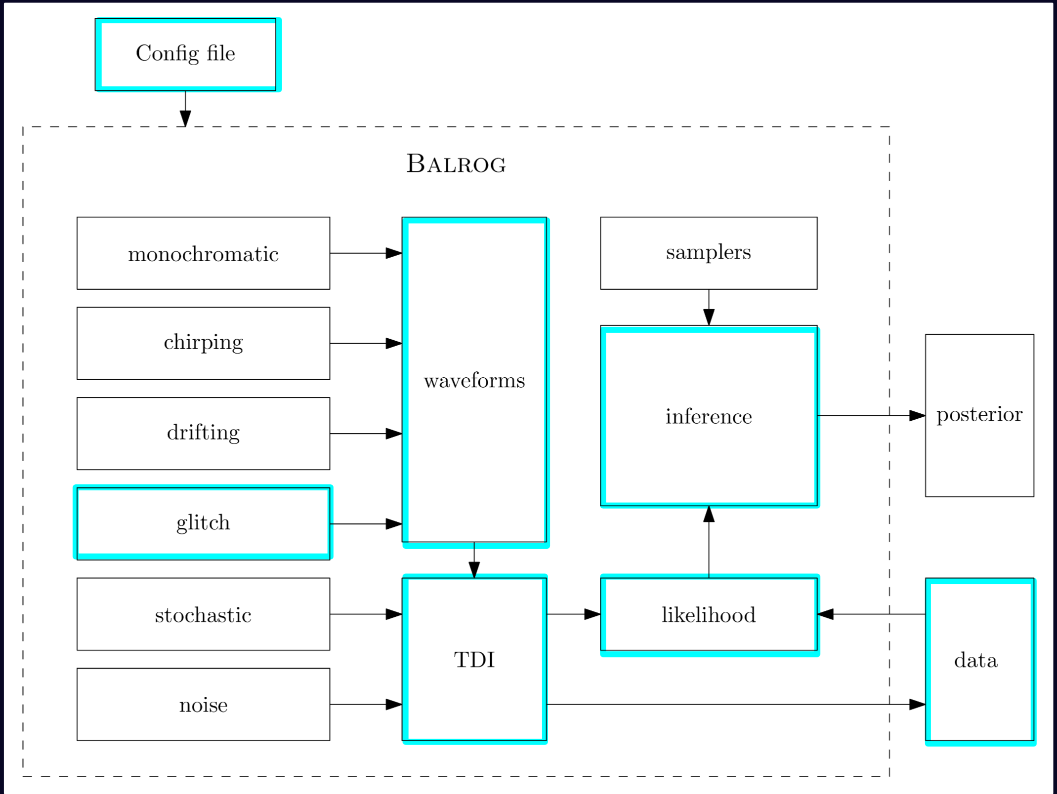
credits:Caltech/MIT/LIGO Lab

The Balrog code

- Collaboration: *Institute for Gravitational Wave Astronomy*, Univ. of Birmingham (UK)

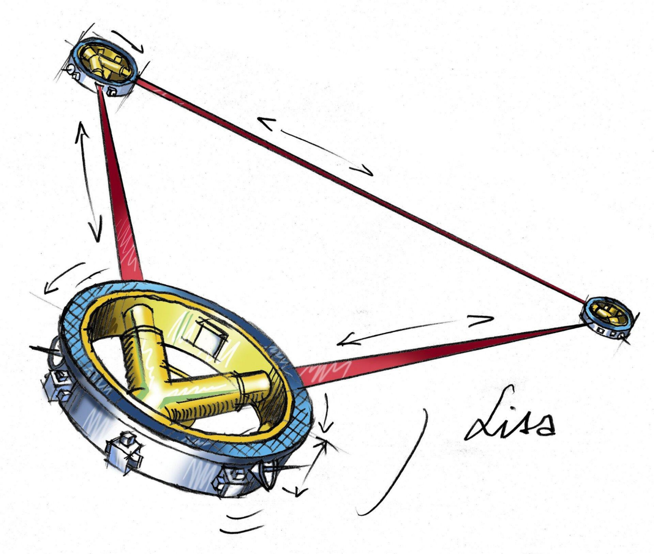
credits: Riccardo Buscicchio, University of Milano-Bicocca

- Modular code → Data generation / Parameter estimation
- Multi-sources parameter inference
- Stochastic samplers



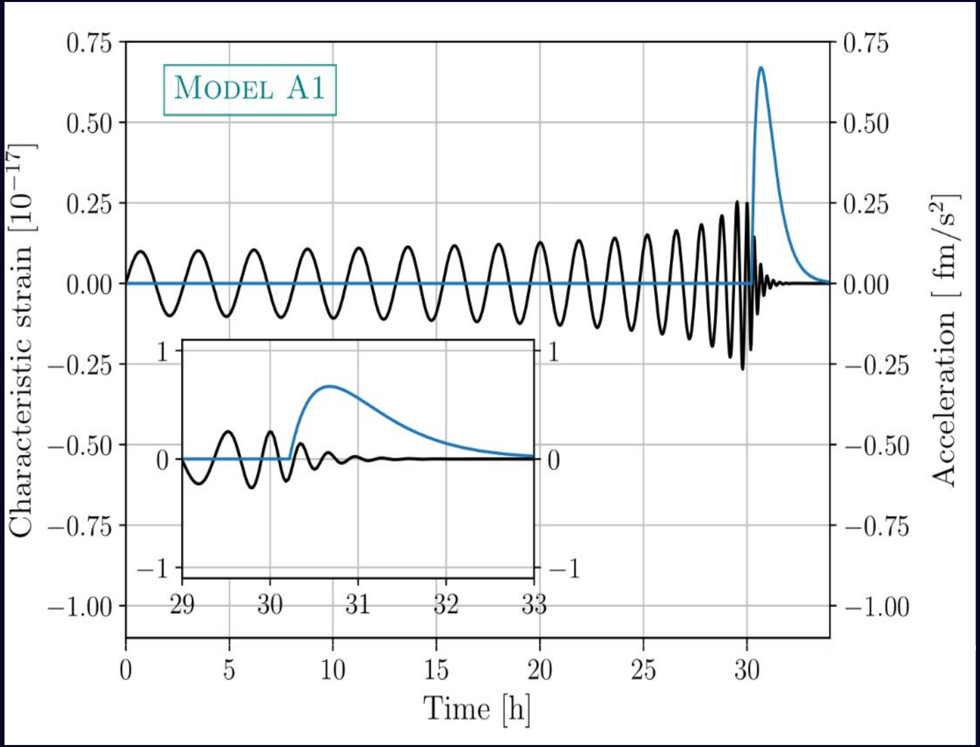
credits: Balrog developers

Contents



credits: ESA-C. Vijoux

The joint scenario



- Short-lived massive black-hole binary signal

  $M = 6 \times 10^7 M_\odot$

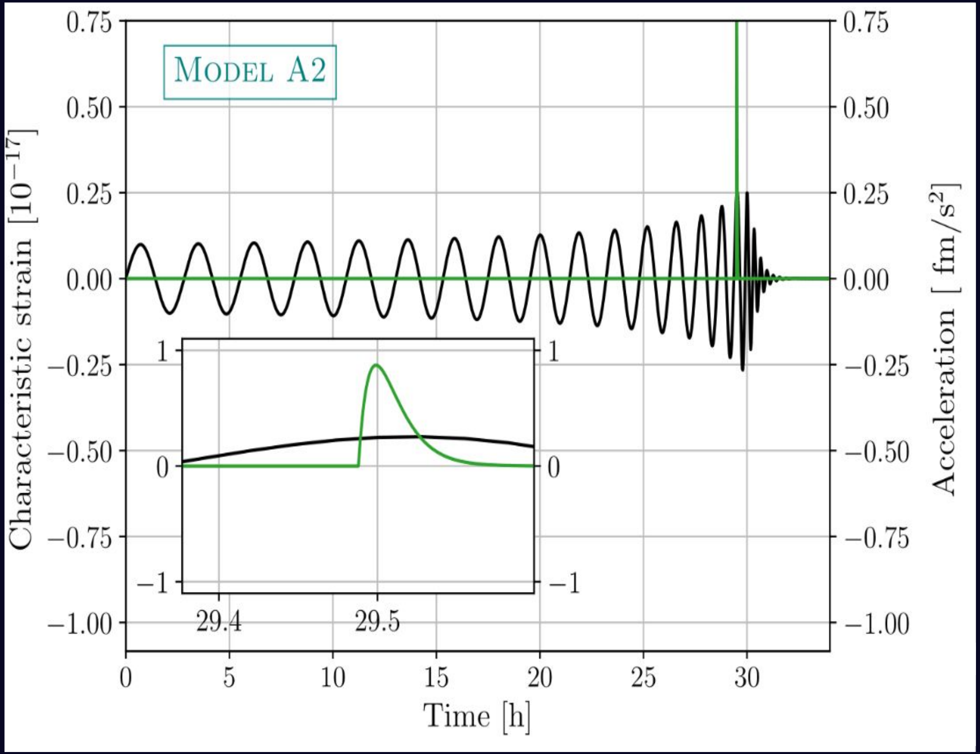
  $z = 5$

  $t_m = 30h$

- Three different glitches:

  1. Long ($3300\,\mathrm{s}$)

The joint scenario



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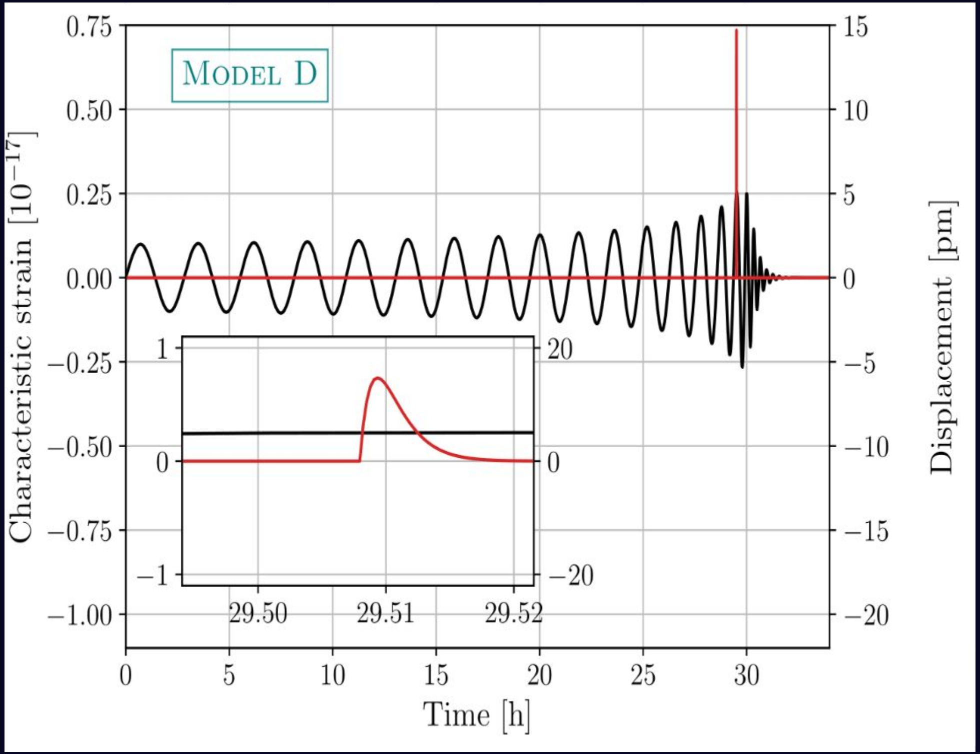
  2. Moderate ($40\,\mathrm{s}$)

The joint scenario



- Short-lived massive black-hole binary signal

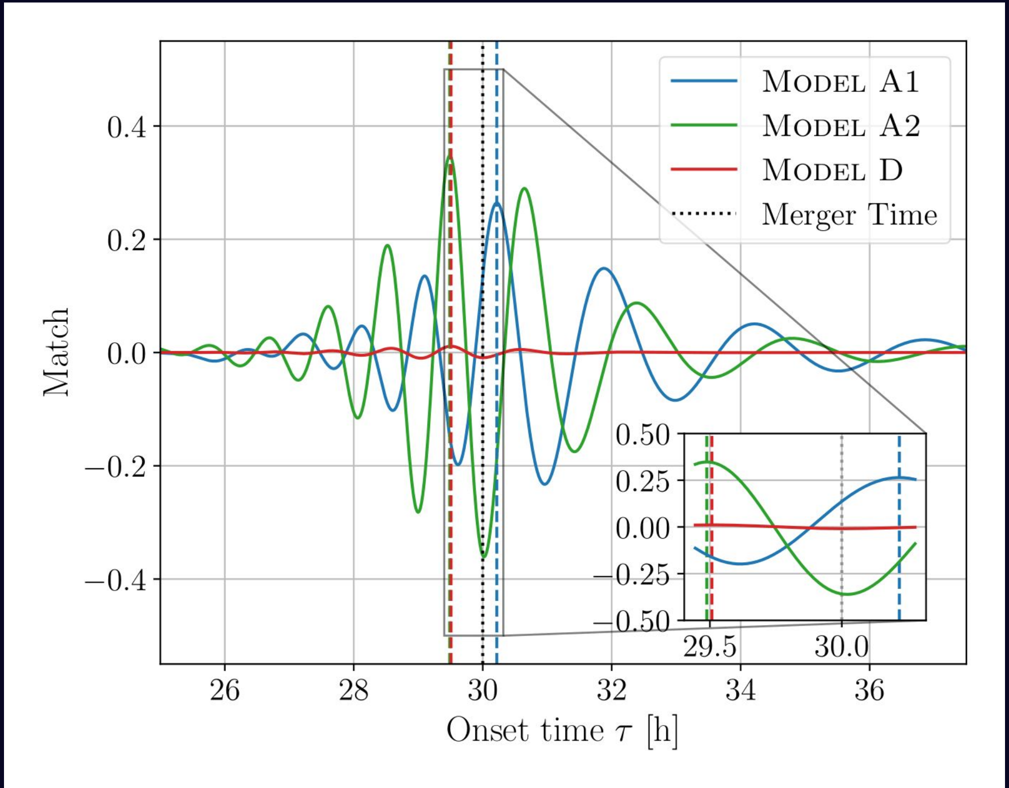
  $M = 6 \times 10^7 M_\odot$

  $z = 5$

  $t_m = 30h$

- Three different glitches:
  1. Long ($3300\,\mathrm{s}$)
  2. Moderate ($40\,\mathrm{s}$)
  3. Short ($5\,\mathrm{s}$)

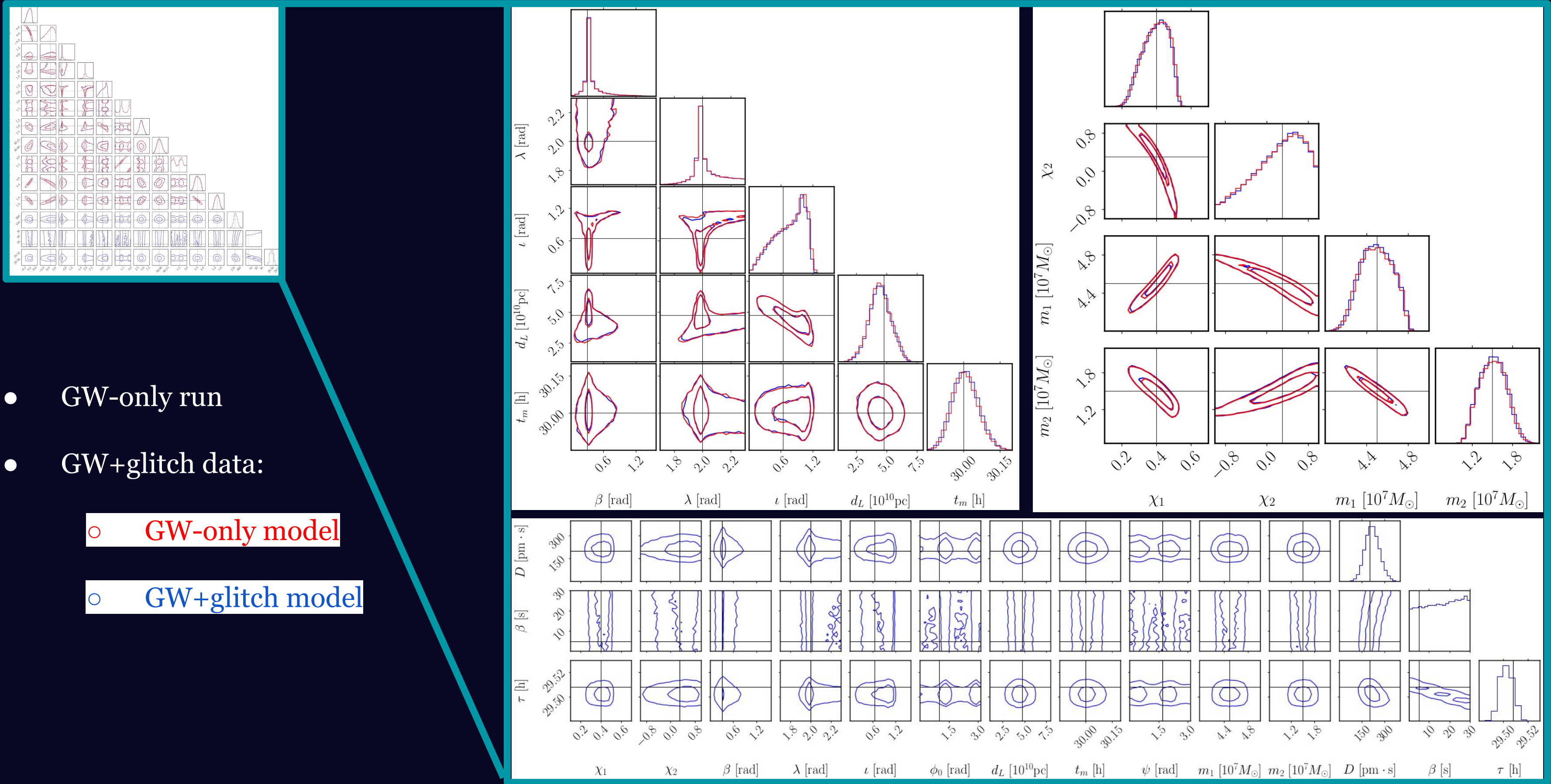
Signal match



Maximum match between massive black-hole (h) and glitch (g) waveforms

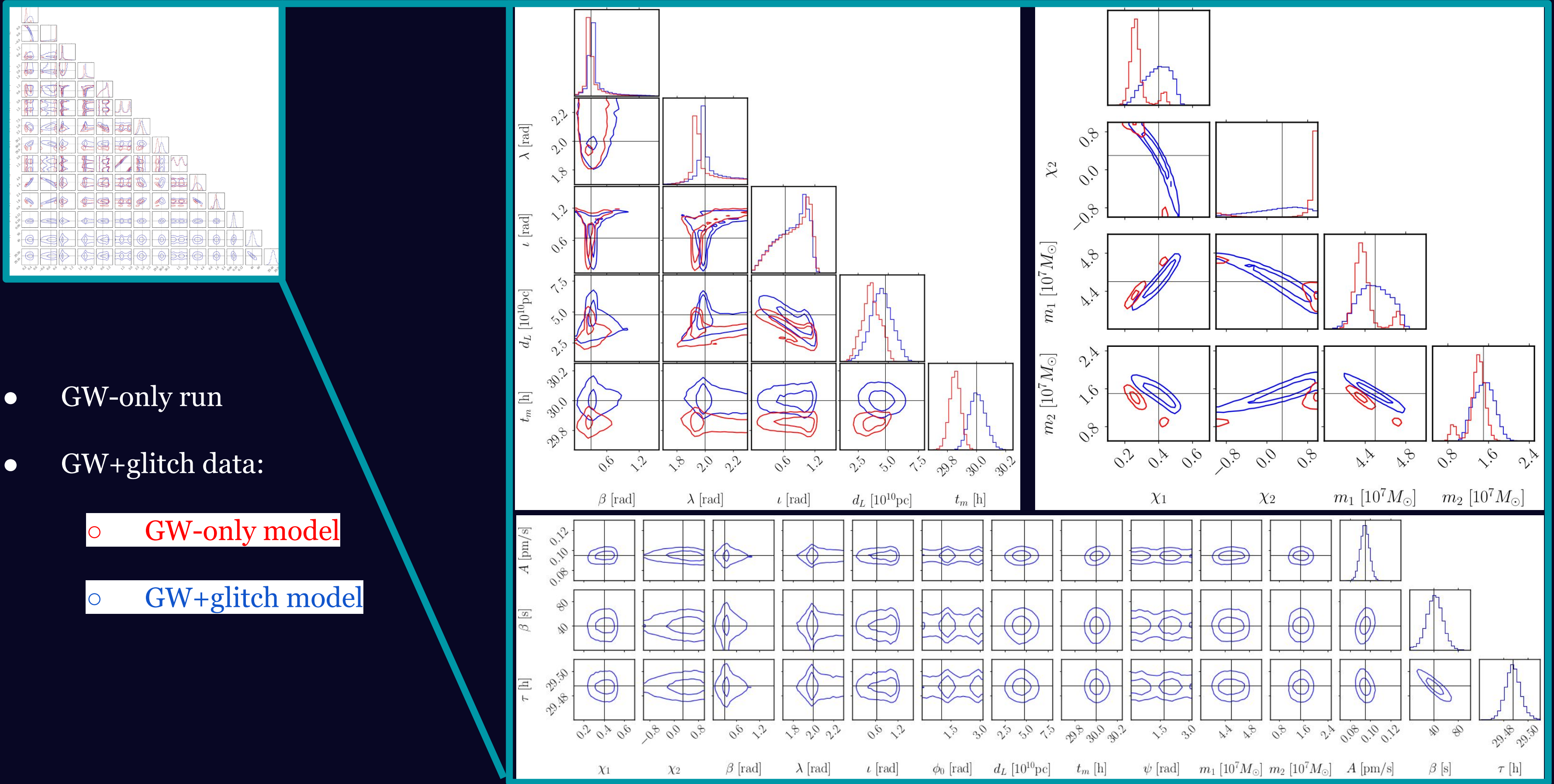
$$M(h, g) = \frac{(h|g)}{(h|h)^{1/2}(g|g)^{1/2}}$$

Parameter inference (short glitch)



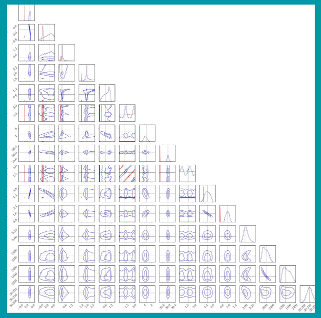
- GW-only run
- GW+glitch data:
  - GW-only model
  - GW+glitch model

Parameter inference (moderate glitch)

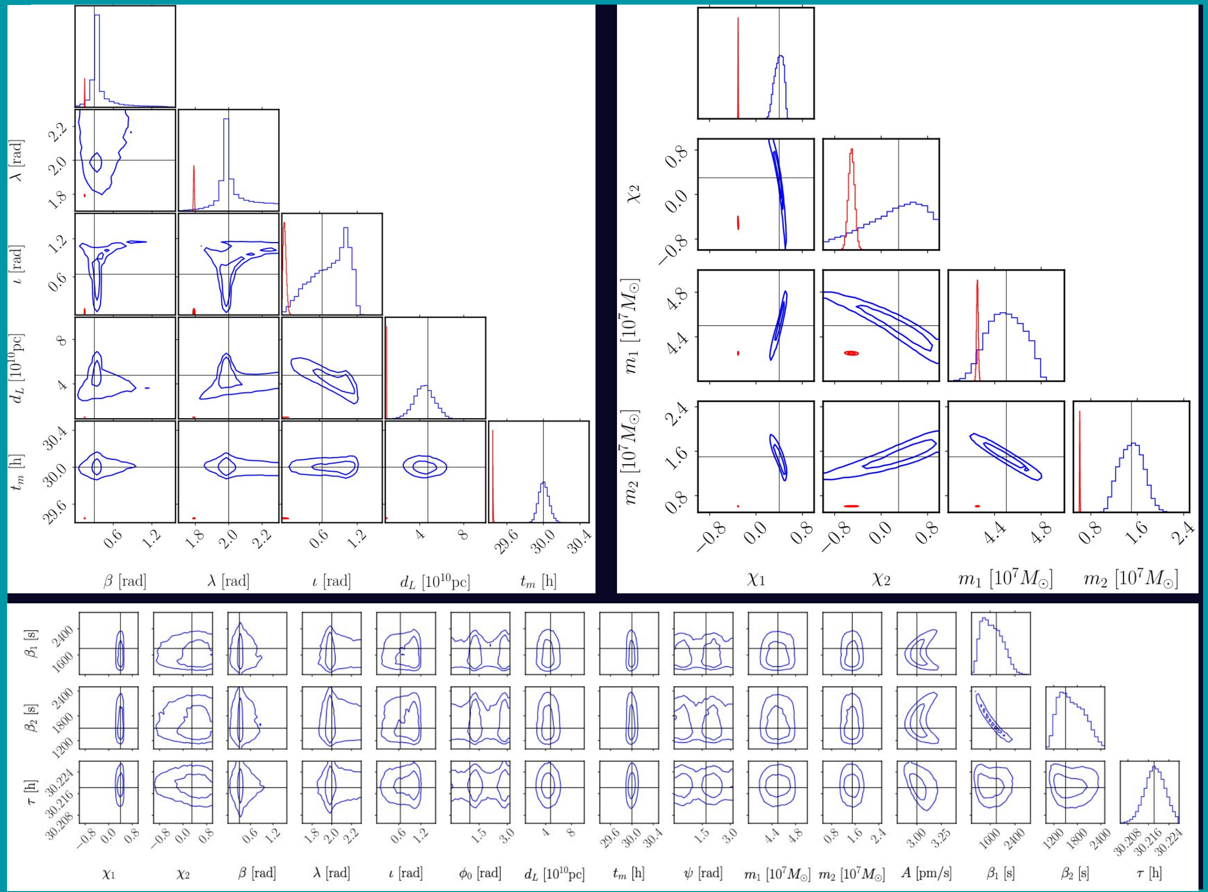


- GW-only run
- GW+glitch data:
  - GW-only model
  - GW+glitch model

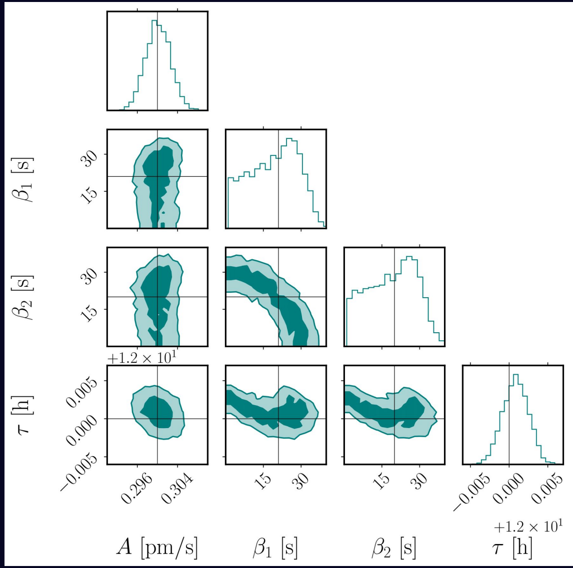
Parameter inference (long glitch)

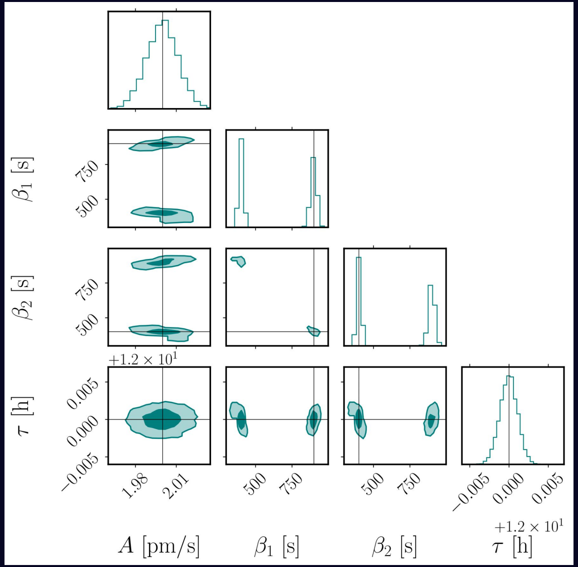


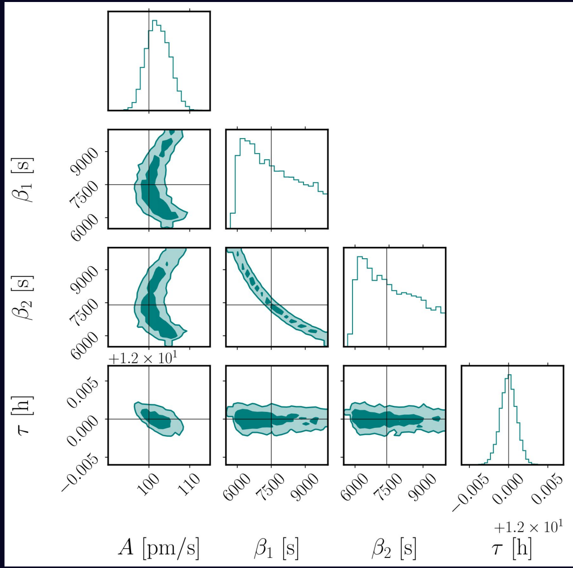
- GW-only run
- GW+glitch data:
  - GW-only model
  - GW+glitch model



Glitch analysis



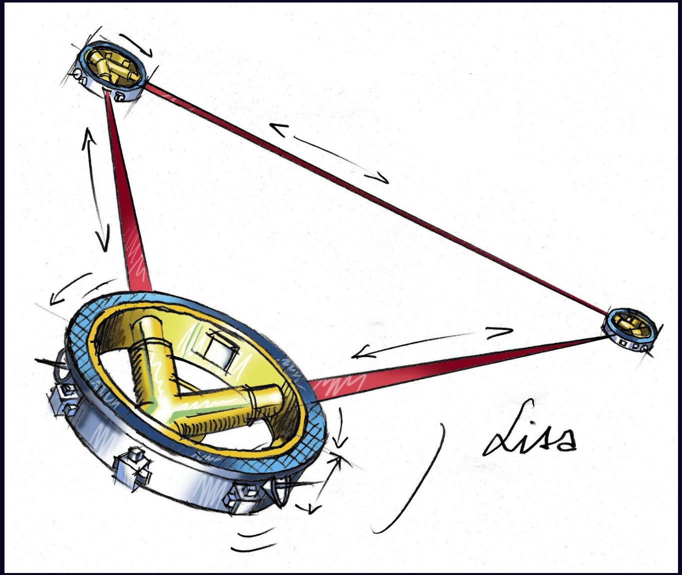




Conclusions

Our work:

- modeling (bonus: acceleration TDI)
- extending Balrog to include glitches
- studying contamination of GW sources
- large campaign of glitch characterization in LISA



credits: ESA-C. Vijoux

Future developments:

- Systematic study with different sources and glitches

Thanks for your attention!

From ground to space

Ground-based detectors **VS** Space-based detectors

same detection principle but…

LIGO

↓

physical interferometry

LISA

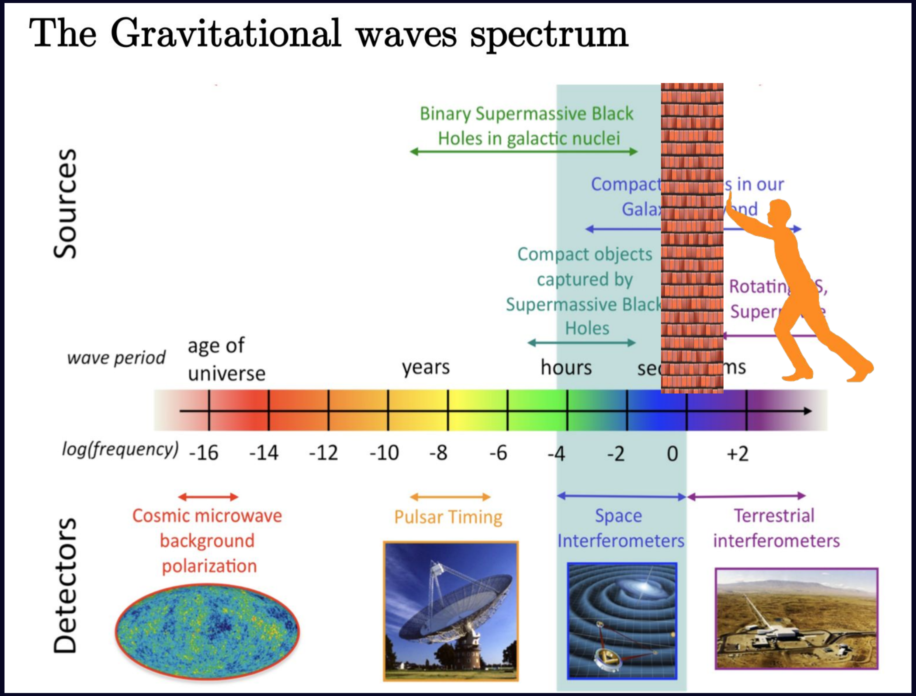
↓

Transponder mode
and
Time Delay Interferometry (TDI)

LISA timeline

2017: ESA's Large class mission

2022: LISA mission moves to final design phase



credits: NASA

Massive black-hole science

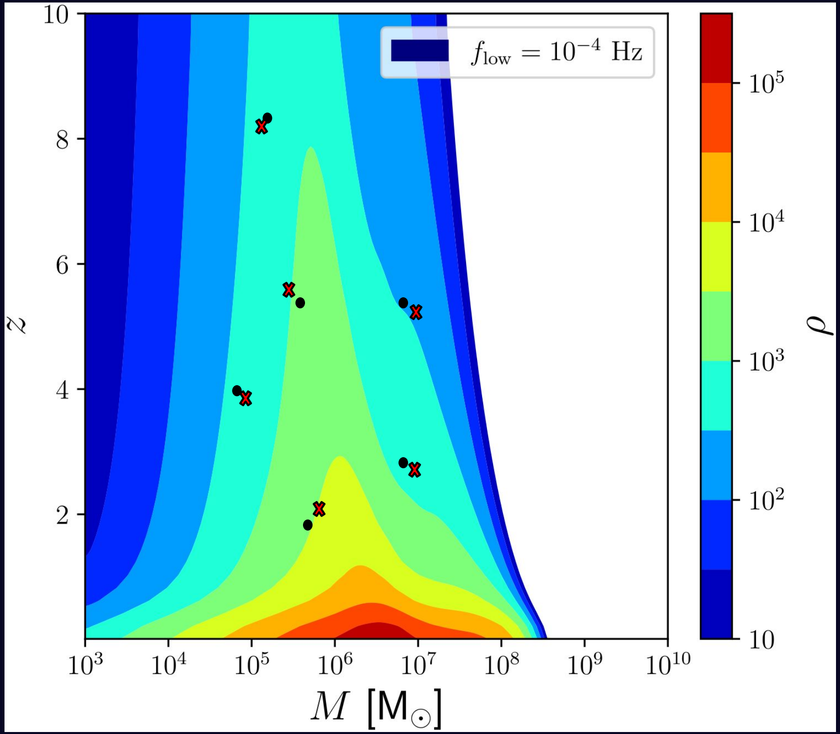


Figure adapted from Steinle at al. 2023

- Wide range of masses $f_{merge} \sim 10^4\ Hz \frac{M_\odot}{M}$
- High SNR and redshift $h_{merge} \sim 10^{-20} \frac{M}{M_\odot} \frac{Mpc}{D}$

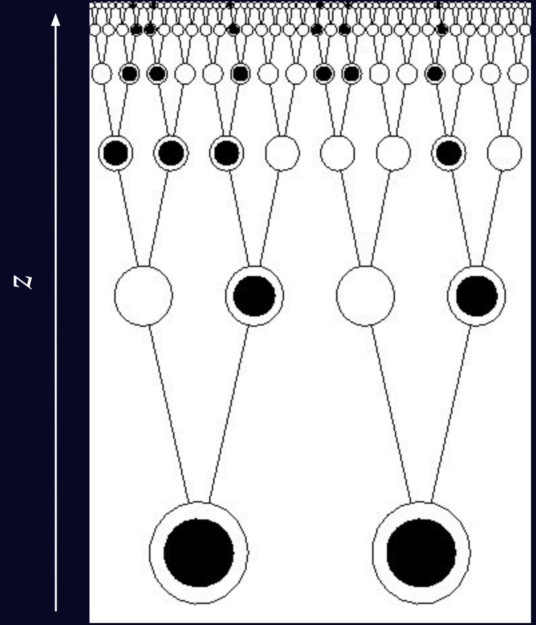
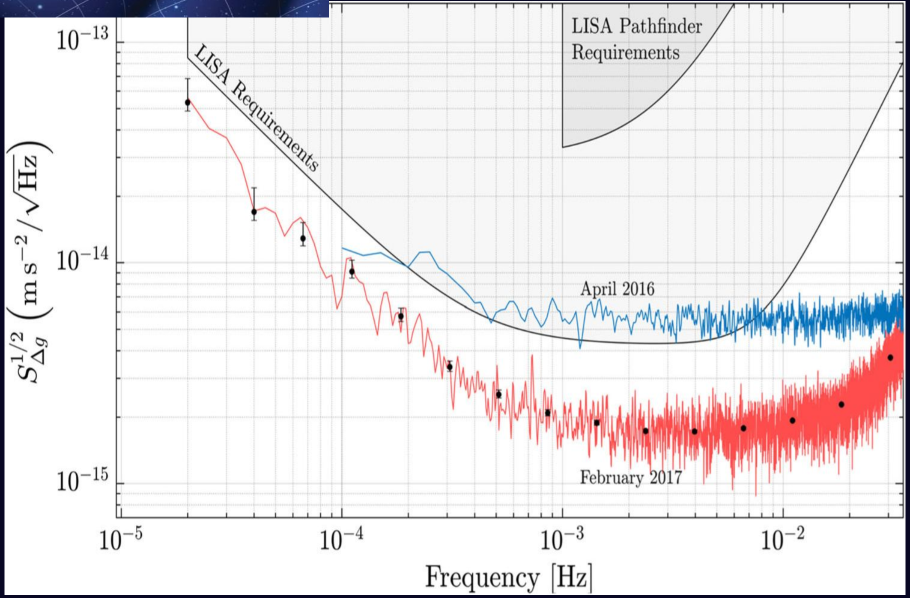


Figure adapted from Schnittman at al. 2007

- Trace the origin, growth and merger history of massive black holes

LISA Pathfinder (LPF) mission

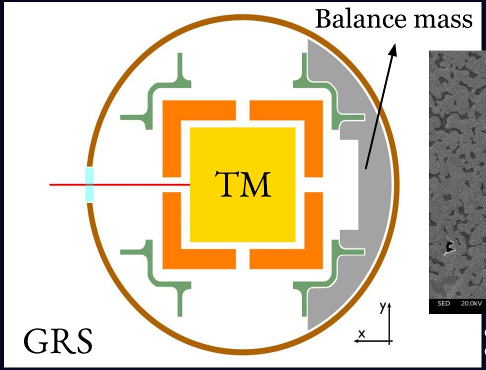
LPF exceeded all the expectations!



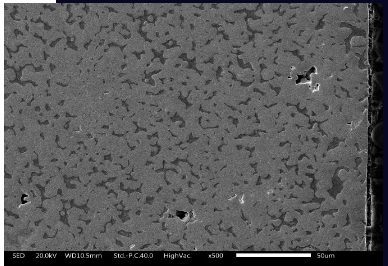
Outgassing phenomena from the balance mass

↓

Physical origin of noise transients: **glitches**!



https://arxiv.org/pdf/2205.11938.pdf



credits: Eleonora Castelli, PhD thesis, University of Trento

Two kinds:

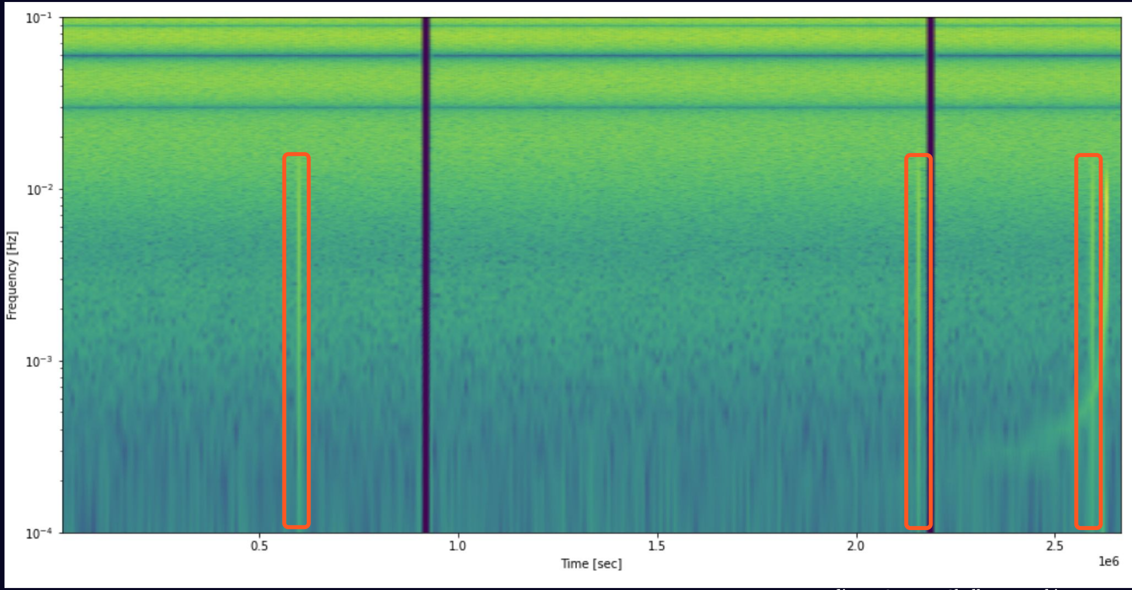
- Forces acting on test masses (TMs)
- Transients in the interferometer readout

LISA Data Challenges

- Open, collaborative effort to tackle scientific questions in the LISA data analysis
- Organized by the LISA Consortium
- Spritz challenge: joint characterization of GW signals and glitches

LISA CONSORTIUM

credits: ESA

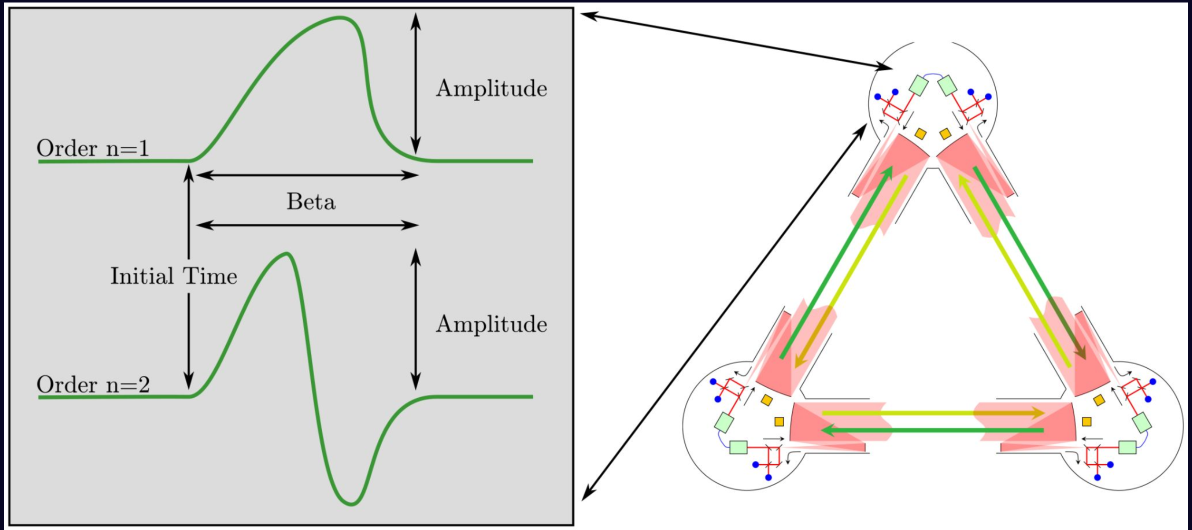


credits: LISA Data Challenge working group

Glitch-only analysis

Model selection:

- Number of components and shapelet order
- Number of glitches
- Injection point



credits: Riccardo Buscicchio, University of Milano-Bicocca

credits: LISA Assessment Study Report / ESA

Identification of the correct transient model trough Bayes factors

Bayesian statistics

Posterior probability

Likelihood function

Prior

$$p(\boldsymbol{\theta}|d) = \frac{\mathcal{L}(d|\boldsymbol{\theta}) \cdot \pi(\boldsymbol{\theta})}{\mathcal{Z}}$$

Evidence

$$d = n + g$$

Stationary and Gaussian noise

Model selection: $BF_{12} = \frac{\mathcal{Z}_{M_1}}{\mathcal{Z}_{M_2}}$

Run summary (GW+glitches)

ID	Injection		Recovery		$\log_{10} \mathcal{Z}$	Figure	Table
	Glitch Model	GW Source	Glitch Model	GW Source			
1	✗	✓(acceleration TDI)	✗	✓(acceleration TDI)	-35.27		
2	✗	✓(displacement TDI)	✗	✓(displacement TDI)	-35.19		
3	A1	✗	A1	✗	-14.0		
4	A2	✗	A2	✗	-9.1		
5	D	✗	D	✗	-8.8		
6	A1	✓	✗	✓	-14537.8	4	III
7	A2	✓	✗	✓	-296.5	5	IV
8	D	✓	✗	✓	-48.8	6	V
9	A1	✓	A1	✓	-46.8	4	III
10	A2	✓	A2	✓	-43.9	5	IV
11	D	✓	D	✓	-40.8	6	V
12	✗	✓	A1	✓	-75.0		
13	✗	✓	A2	✓	-44.1		
14	✗	✓	D	✓	-52.2		

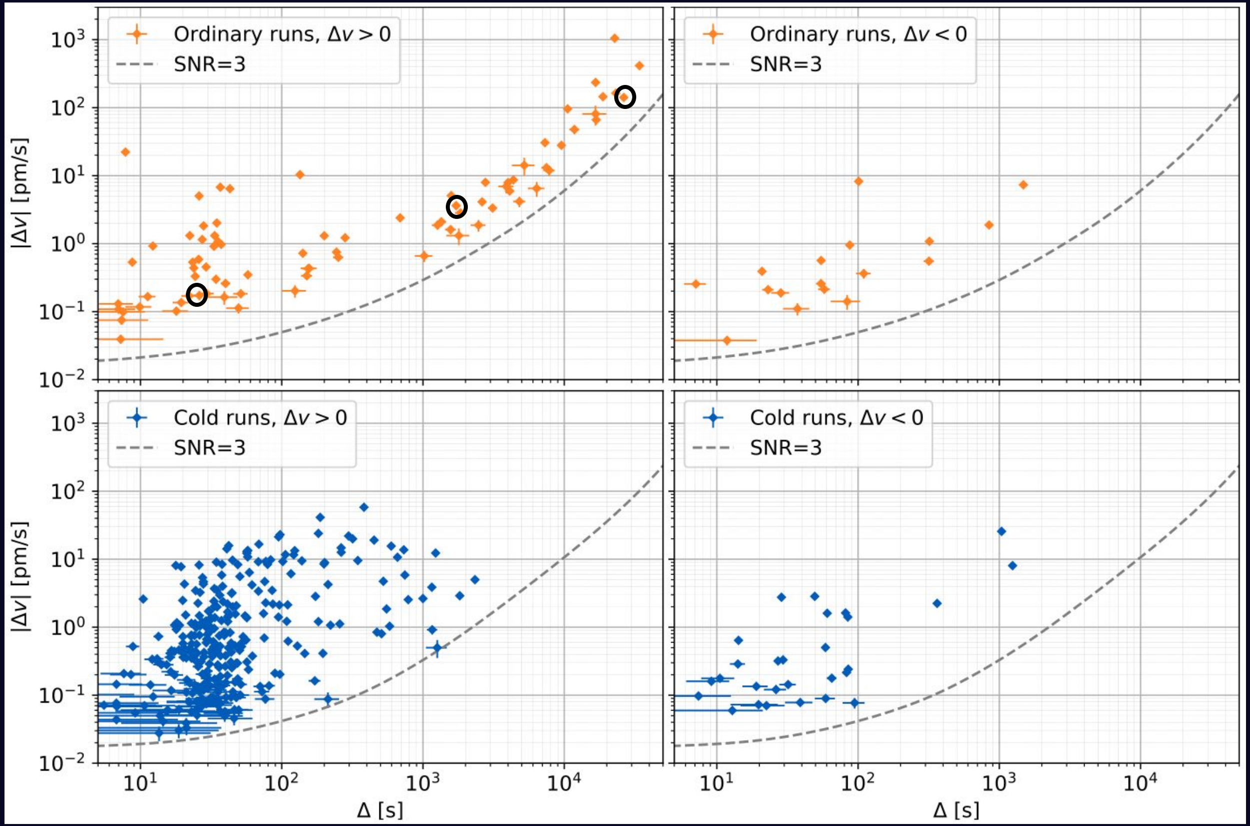
Parameter estimation results (GW+glitches)

	MBHB											Model A1			
ID	m_{1z} $[10^7 M_\odot]$	m_{2z} $[10^7 M_\odot]$	t_m [h]	χ_1	χ_2	d_L [Gpc]	ι [rad]	β [rad]	λ [rad]	ϕ [rad]	ψ [rad]	A [pm/s]	β_1 [s]	β_2 [s]	τ [h]
	4.5	1.5	30.0	0.4	0.3	47.6	0.6	0.30	2.0	1.0	1.7	3.0	1500.0	1800.0	30.21
9	$4.5^{+0.2}_{-0.2}$	$1.5^{+0.3}_{-0.3}$	$30.00^{+0.10}_{-0.08}$	$0.4^{+0.1}_{-0.1}$	$0.3^{+0.6}_{-1.0}$	44^{+15}_{-15}	$0.8^{+0.3}_{-0.6}$	$0.3^{+0.6}_{-0.1}$	$2.0^{+0.3}_{-0.1}$	$1.6^{+1.4}_{-1.3}$	$1.6^{+1.3}_{-1.4}$	$3.0^{+0.2}_{-0.1}$	1637^{+594}_{-417}	1647^{+584}_{-426}	$30.219^{+0.006}_{-0.006}$
6	$4.25^{+0.01}_{-0.01}$	$0.610^{+0.007}_{-0.007}$	$29.447^{+0.007}_{-0.002}$	$-0.308^{+0.005}_{-0.005}$	$-0.51^{+0.09}_{-0.09}$	$10.010^{+0.032}_{-0.009}$	$0.04^{+0.05}_{-0.03}$	$0.150^{+0.005}_{-0.005}$	$1.792^{+0.005}_{-0.005}$	$1.6^{+1.4}_{-1.4}$	$1.6^{+1.4}_{-1.4}$	✗	✗	✗	✗
	4.5	1.5	30.0	0.4	0.3	47.6	0.6	0.30	2.0	1.0	1.7	✗	✗	✗	✗
1	$4.5^{+0.2}_{-0.2}$	$1.5^{+0.3}_{-0.3}$	$30.01^{+0.09}_{-0.08}$	$0.4^{+0.1}_{-0.1}$	$0.3^{+0.6}_{-1.0}$	44^{+15}_{-14}	$0.8^{+0.3}_{-0.6}$	$0.3^{+0.6}_{-0.1}$	$2.0^{+0.2}_{-0.1}$	$1.6^{+1.5}_{-1.3}$	$1.6^{+1.3}_{-1.4}$	✗	✗	✗	✗

Run summary (glitches)

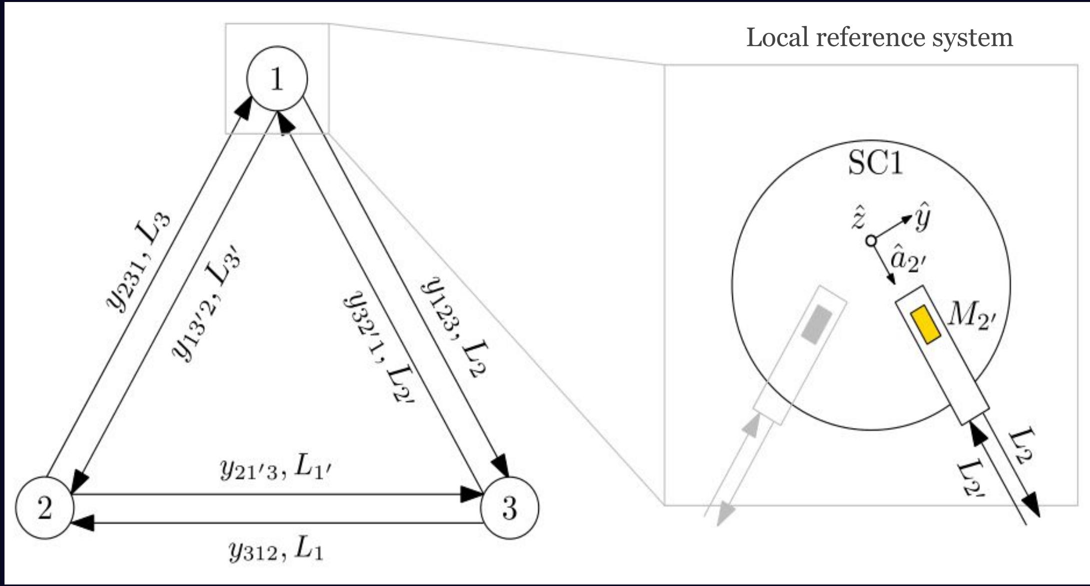
ID	Injection				Recovery				log-Evidence	Figure	Table
	Glitch 1		Glitch 2		Glitch 1		Glitch 2				
15	D(1, 1)	D(1, 2)	✗	✗	D(1, 1)	D(1, 2)	✗	✗	−16.1		VII
16					D(1, 1)	D(1, 3)	✗	✗	−18.0		
17					D(1, 2)	D(1, 3)	✗	✗	−20.1		
18					D(1, 1)	✗	✗	✗	−22.9		
19					D(1, 2)	✗	✗	✗	−23.9		
20					D(1, 3)	✗	✗	✗	−34.4		
21					D(1, 1)	D(1, 2)	D(1, 3)	✗	−17.0		
22	D(1, 1)	✗	✗	✗	D(1, 1)	✗	✗	✗	−15.2		VII
23					D(2, 1)	✗	✗	✗	−3650.20		
24					D(3, 1)	✗	✗	✗	−3650.18		
25					D(1′, 1)	✗	✗	✗	−224.1		
26					D(2′, 1)	✗	✗	✗	−3628.6		
27					D(3′, 1)	✗	✗	✗	−3640.8		
28	D(1, 2)	D(1, 3)	D(3, 1)	D(3, 2)	D(1, 2)	D(1, 3)	D(3, 1)	D(3, 2)	−34.8	9	VII
29	A2(1, 1)	✗	A2(2′, 2)	✗	A2(1, 1)	✗	A2(2′, 2)	✗	−15.9	8	VI
30	A1S(1)	✗	✗	✗	A1S(1)	✗	✗	✗	−13.6	7	VI
31	A1M(1)	✗	✗	✗	A1M(1)	✗	✗	✗	−18.0	7	VI
32	A1L(1)	✗	✗	✗	A1L(1)	✗	✗	✗	−16.6	7	VI

Glitch analysis



[2205.11938] Transient acceleration events in LISA Pathfinder data: properties and possible physical origin

Acceleration TDI



credits: Riccardo Buscicchio, University of Milano-Bicocca

- Inclusion of glitches in Bayesian inference framework

- Gravitational-wave signal rewritten as acceleration

$$g(t) = \frac{d}{dt^2}[y(t)]$$

freq. domain $\mathcal{F}[G_X] = (2\pi f)^2 \mathcal{F}[M_X]$