Towards a Spanish LISA Global Fit Pipeline

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Institute of Space Sciences
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CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
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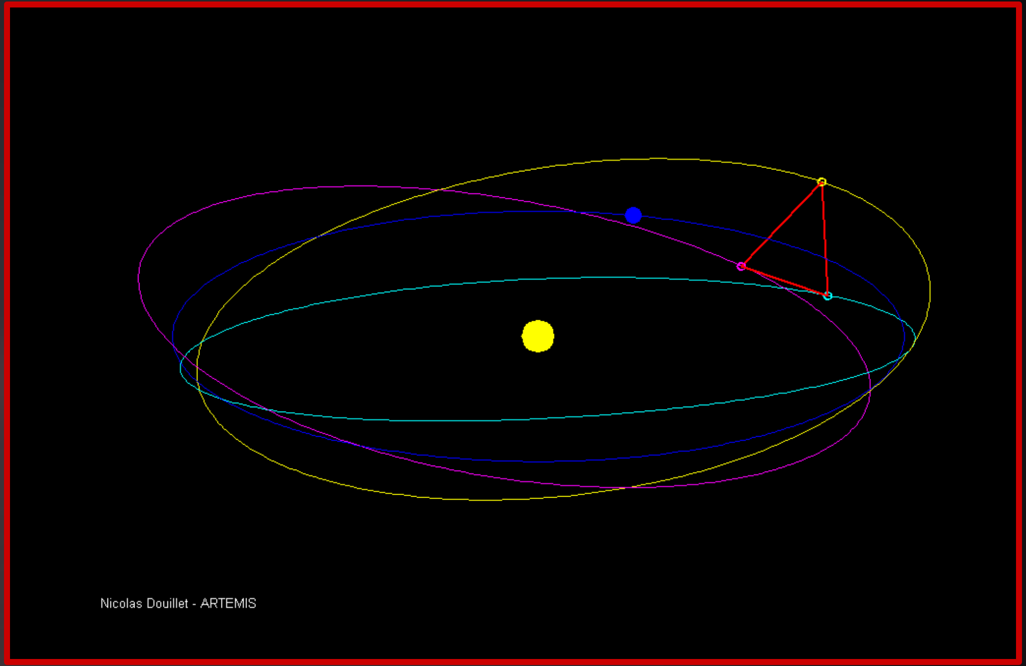
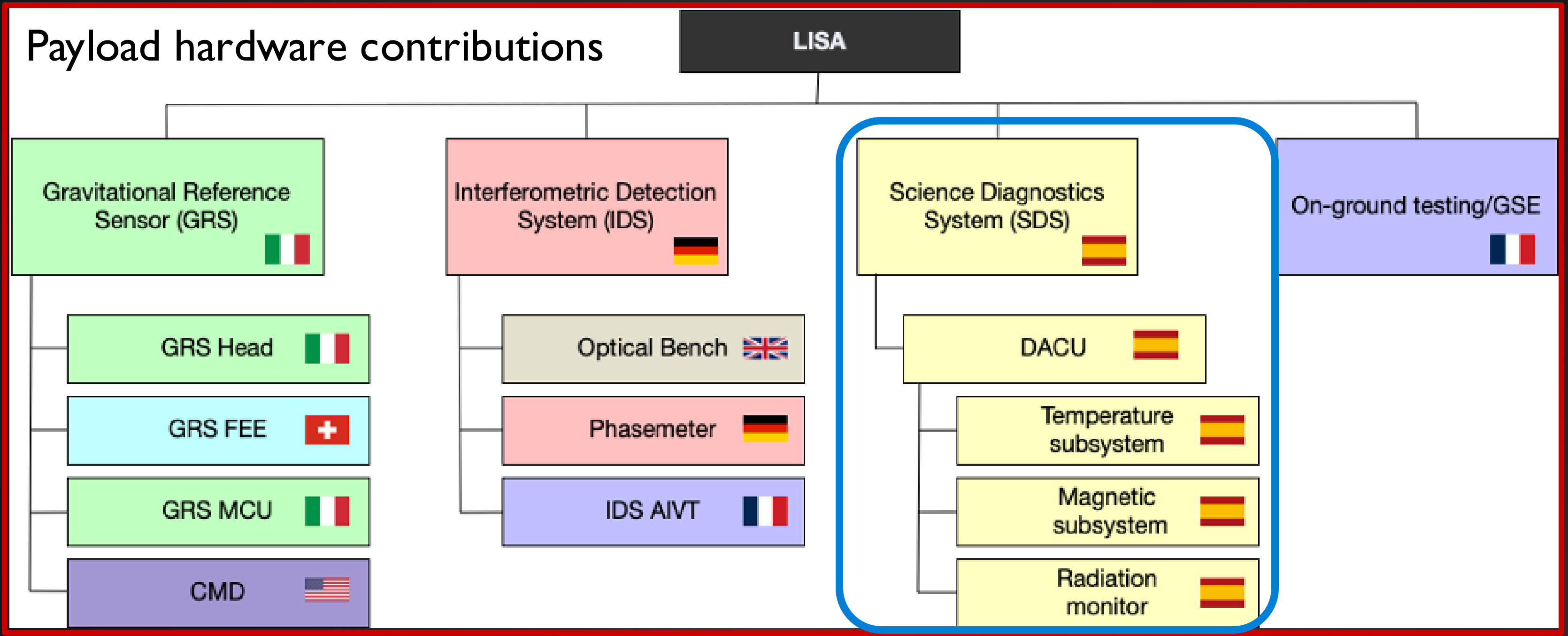
The LISA mission

- Space-based GW observatory
- 3 spacecrafts in an interferometer configuration
- Arm length: 2.5M km
- Heliocentric orbit behind Earth
- ESA-led, with NASA as junior partner
- Estimated launch: ~2035
- Estimated adoption: in 3 days!



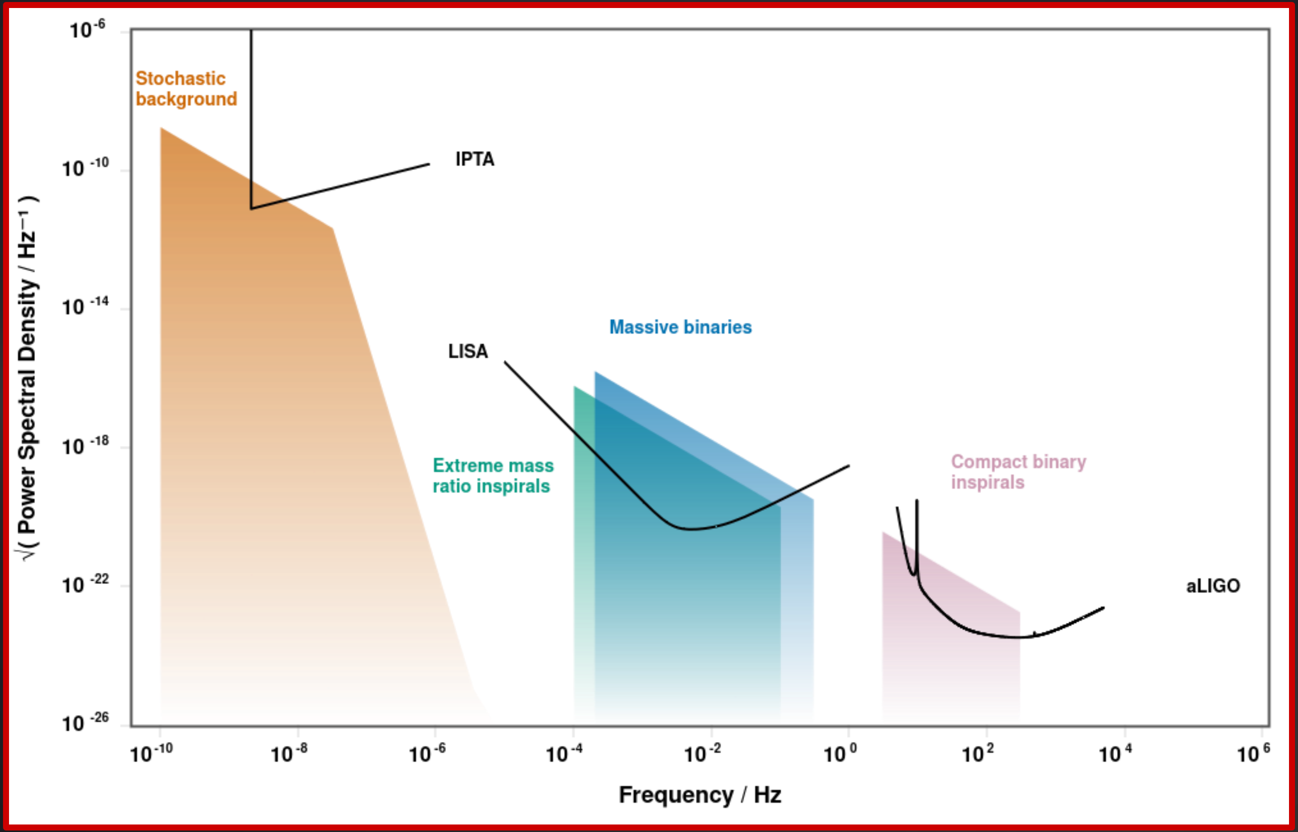
Spanish contribution to LISA



(source: ESA)

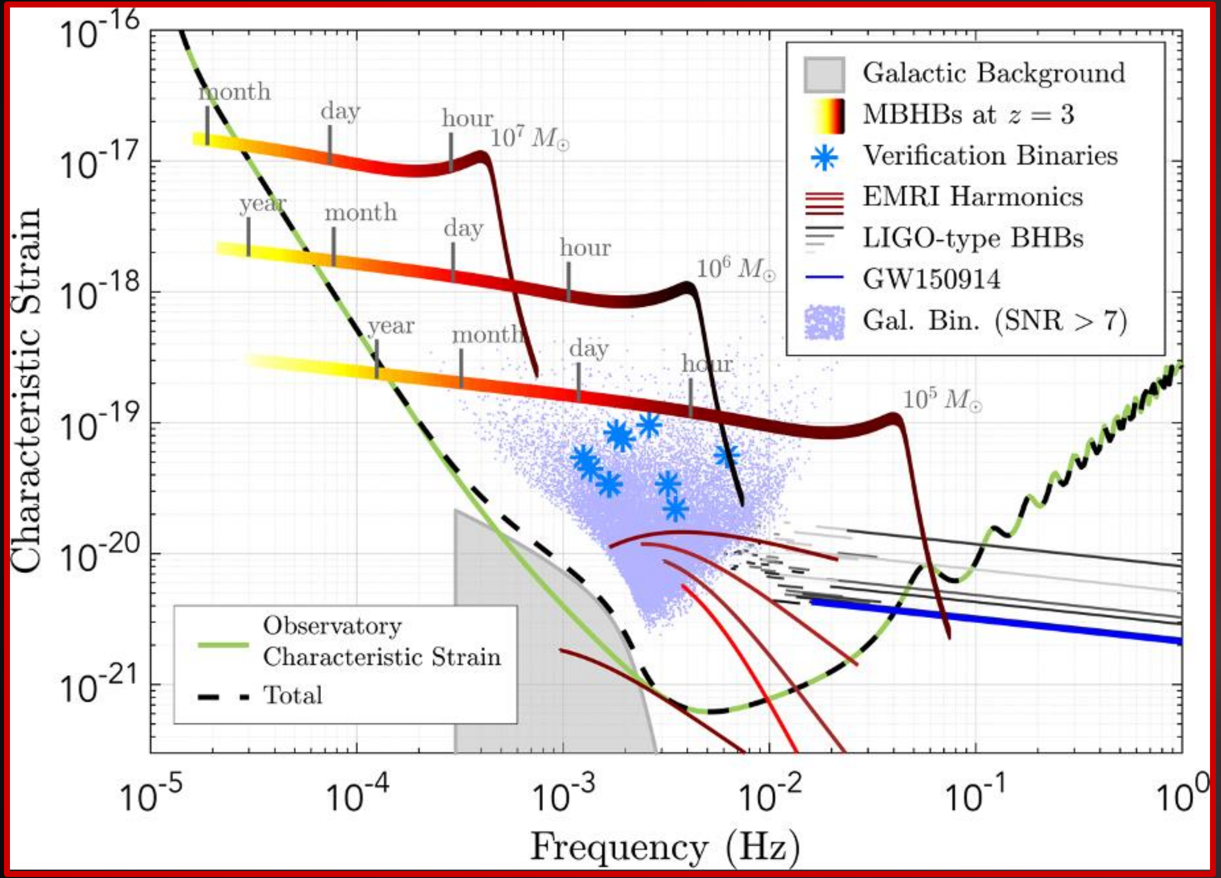
- In the ground segment, Spain is committing to:
  - Establishing a Data Processing Centre (DPC)
  - Developing and running a Global Fit pipeline

The LISA frequency band

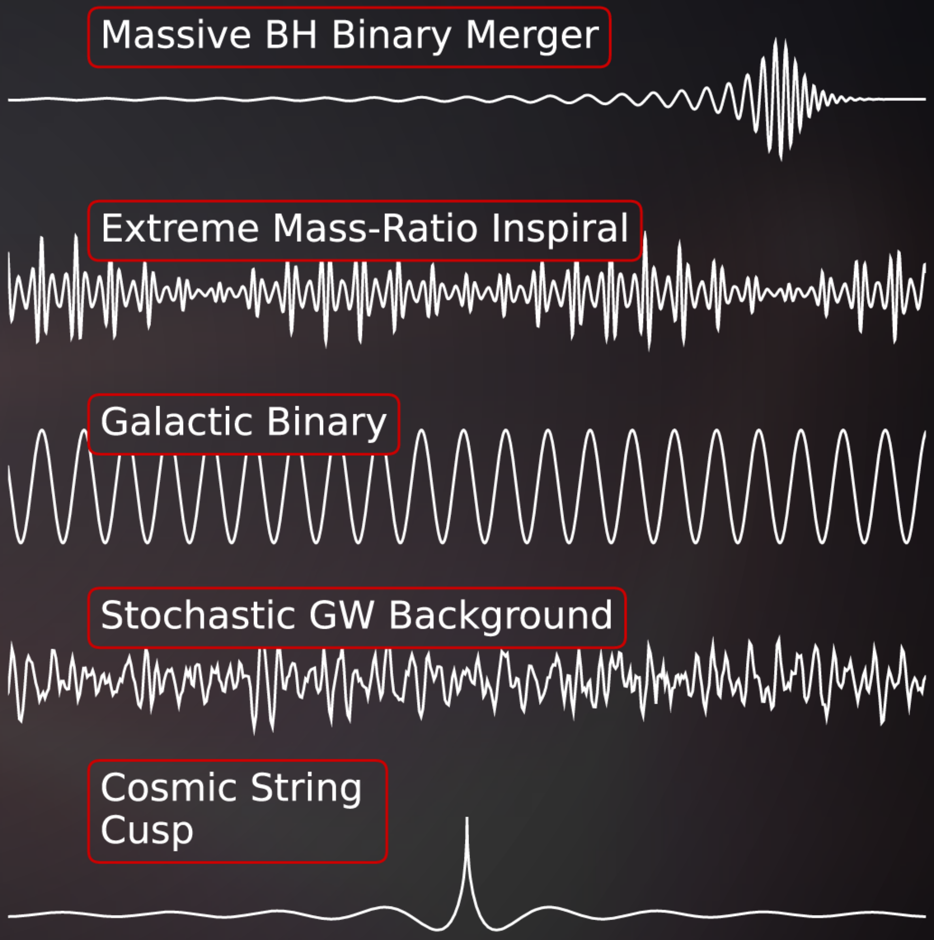


(source: C. Moore et al., gwplotter.com)

GW sources in LISA



(source: K. Danzmann et al., LISA mission proposal, arXiv:1702.00786)



LISA Science Objectives

- SO1: Study the formation and evolution of compact binary stars and the structure of the Milky Way Galaxy
- SO2: Trace the origins, growth and merger histories of massive Black Holes
- SO3: Probe the properties and immediate environments of Black Holes in the local Universe using EMRIs and IMRIs
- SO4: Understand the astrophysics of stellar-mass Black Holes
- SO5: Explore the fundamental nature of gravity and Black Holes
- SO6: Probe the rate of expansion of the Universe with standard sirens
- SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics
- SO8: Search for GW bursts and unforeseen sources

LISA Ground Segment

L0 data

Raw phasemeter data

L1 data

Time-Delay Interferometry

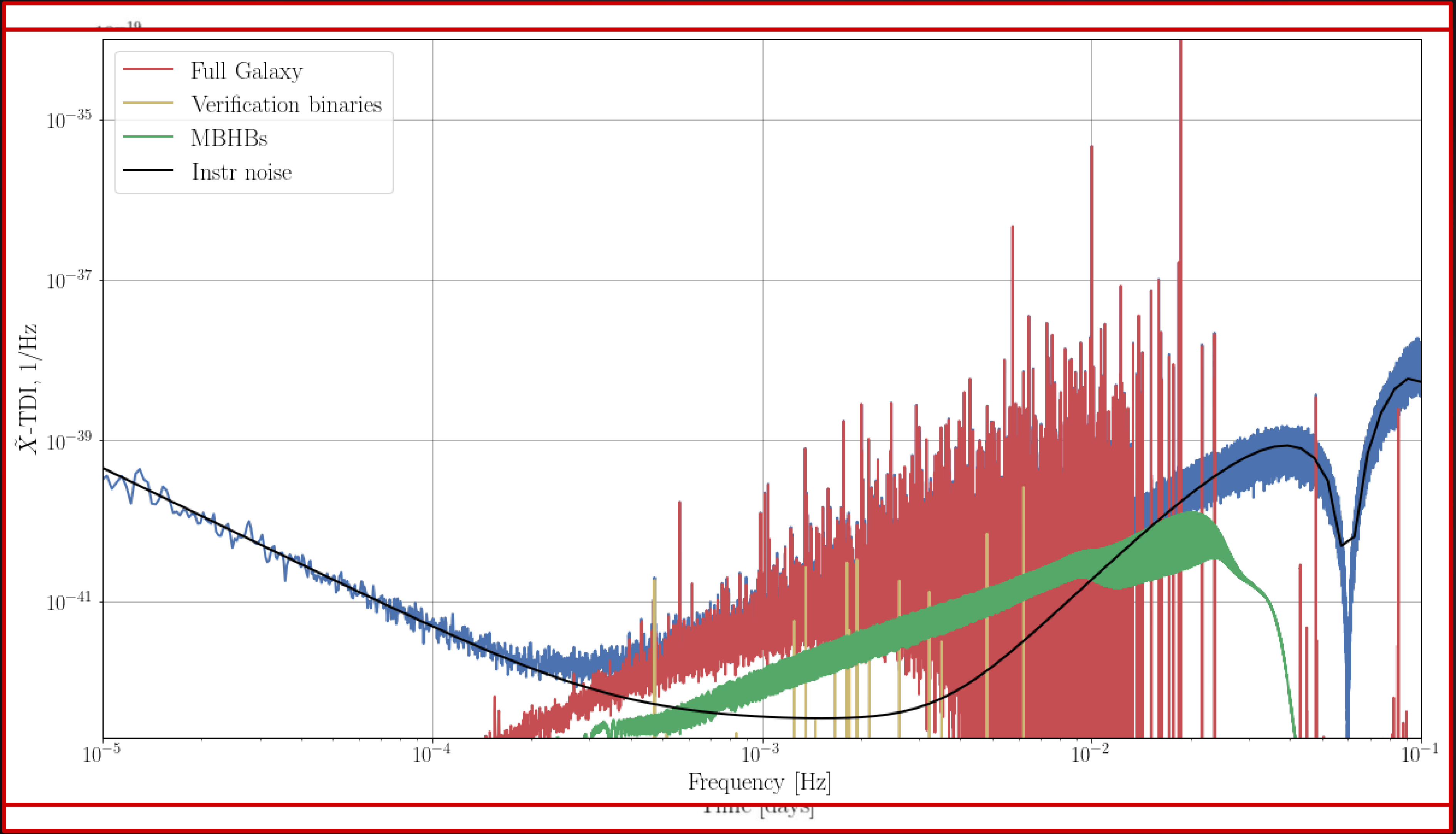
L2 data

Identified source waveforms

L3 data

Source catalogs for astrophysicists

The LISA Data Challenges



Fundamentals of GW data analysis

- Our signal is $\mathbf{d}(t;\boldsymbol{\theta}) = \mathbf{h}(t;\boldsymbol{\theta}) + \mathbf{n}(t)$

  deterministic
  depends only on $\boldsymbol{\theta}$

  realization of a
  random process

- If we assume $\mathbf{n}(t) = \mathbf{d}(t) - \mathbf{h}(t;\boldsymbol{\theta})$ is a Gaussian, stationary random process:

$$p(\mathbf{n} = \mathbf{n}_0) \propto \exp\left[-\frac{1}{2}\,(\mathbf{n}_0|\mathbf{n}_0)\right] = \exp\left[-\frac{1}{2}\,(\mathbf{d}-\mathbf{h}|\mathbf{d}-\mathbf{h})\right]$$

with $(\mathbf{a}|\mathbf{b}) = 2\int_0^\infty \frac{\tilde{\mathbf{a}}^*(f)\tilde{\mathbf{b}}(f)+\tilde{\mathbf{a}}(f)\tilde{\mathbf{b}}^*(f)}{S_n(f)}\,\mathrm{d}f.$

$$\mathrm{SNR}[\mathbf{h}] \simeq \sqrt{(\mathbf{h}|\mathbf{h})}$$

$$\rho(\mathbf{h};\mathbf{d}) = \frac{(\mathbf{h}|\mathbf{d})}{\sqrt{(\mathbf{h}|\mathbf{h})}}$$

- Multiple data channels? The inner product then becomes:

$$(\mathbf{a}|\mathbf{b}) = 2\sum_{i,j}\int_0^\infty \mathrm{d}f\; \tilde{\mathbf{a}}_i^*(f)[\mathbf{S}_n(f)^{-1}]^{ij}\tilde{\mathbf{b}}_j(f)\,.$$

(it simplifies to a sum over streams if the channels are independent, e.g. TDI AET)

Bayesian inference

Likelihood $\log p(\,\mathbf{d}\mid\boldsymbol{\theta}\,) = \sum_{n=\{A,E,T\}} 2\,(\,\mathbf{h}(\boldsymbol{\theta})\mid\mathbf{d}\,)_n - (\,\mathbf{h}(\boldsymbol{\theta})\mid\mathbf{h}(\boldsymbol{\theta})\,)_n$

integrals!

forward simulations!

$$p(\,\boldsymbol{\theta}\mid\mathbf{d}\,) = \frac{p(\,\mathbf{d}\mid\boldsymbol{\theta}\,)\,p(\boldsymbol{\theta})}{p(\mathbf{d})}$$

Prior

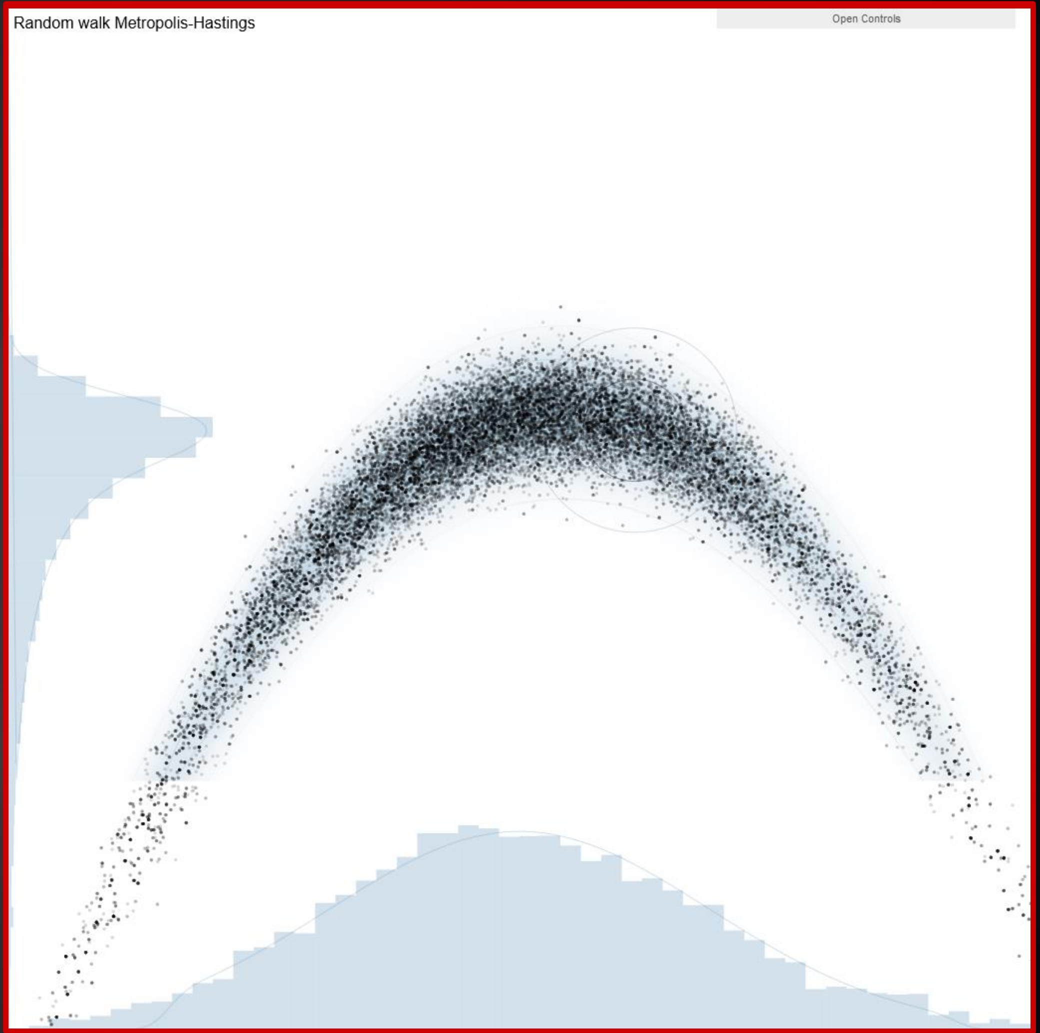
Posterior

Evidence

$$p(\mathbf{d}) = \int p(\,\mathbf{d}\mid\boldsymbol{\theta}\,)\,d\boldsymbol{\theta}$$

Markov Chain Monte Carlo (MCMC)

- Random number generation that can follow an arbitrary distribution *eventually*
- Propose points, then accept/reject with some criterion
- Large zoo of algorithms, some more suitable than others depending on situation
- Lots of evaluations of the likelihood ⇒ potentially slow



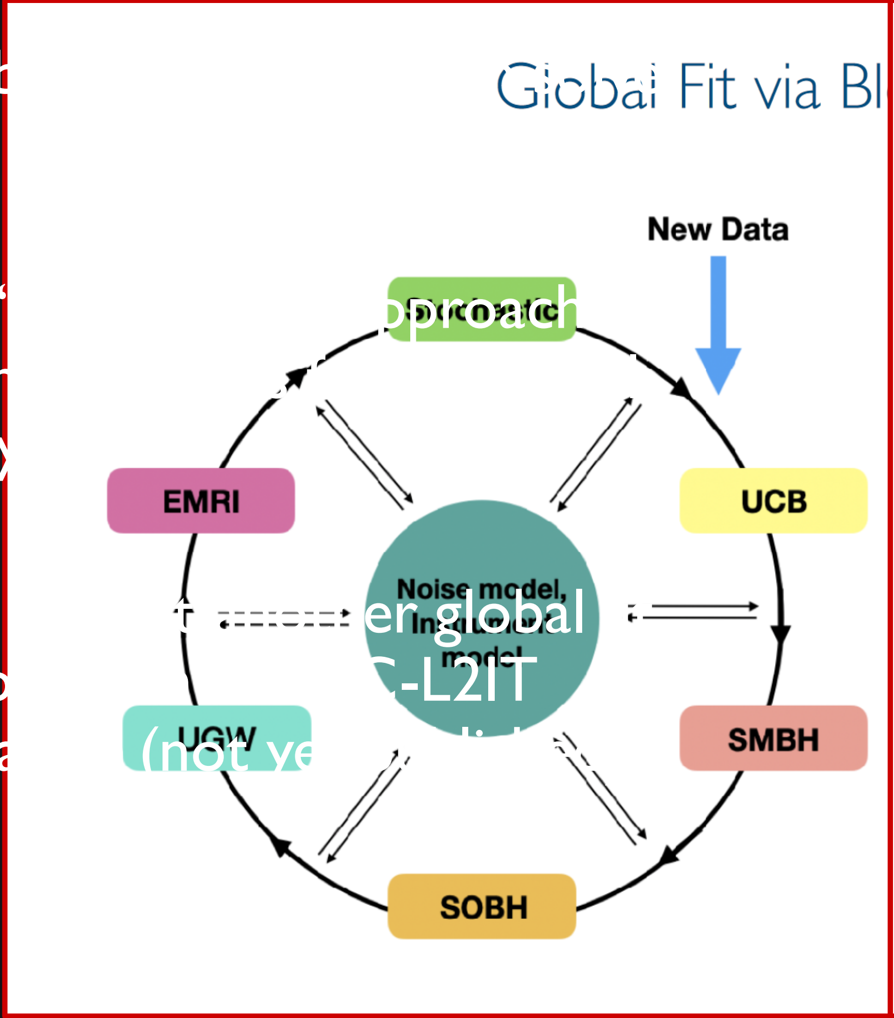
(source: Chi Feng, *The Markov Chain Monte Carlo Interactive Gallery*)

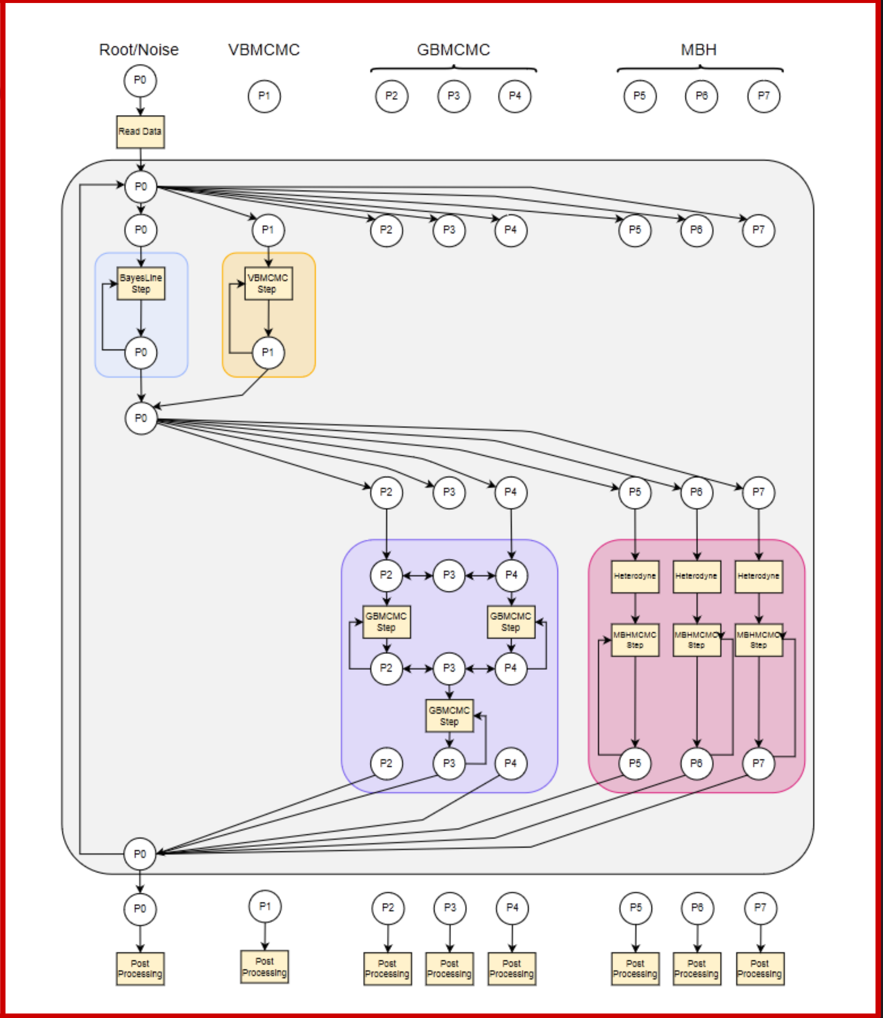
The need for a Global Fit

- In reality, our data will contain:
  - Non-stationary instrumental noise (+glitches, gaps)
  - $\mathcal{O}(10)$ MBHBs/year
  - $\mathcal{O}(10^7)$ GBs (!!!)
    - Of these, $\mathcal{O}(10^4)$ will be individually resolvable
    - There are 37 known GBs: verification binaries
  - $\mathcal{O}(1-1000)$ EMRIs
  - $\mathcal{O}(10^4)$ SBBHs
  - SGWBs
  - maybe some surprises...?
- Since one source may interfere with another, this all needs to be extracted and estimated, at once!

First Global Fit prototype

- First glob
  LDC2
- Kind of “ pproach
  combinin
  source ty
- There is t er global
  prototyp C-L2IT
  collabora (not ye





(source: T. Littenberg & N.Cornish, 2023)

(slide ~~stolen~~ graciously borrowed from: N. Cornish & T. Littenberg, “The LISA Global Fit @ Montana-MSFC”, Towards LISA catalogs workshop)

Computational requirements: the DDPC

- Based on LDC1 results, some studies have been made on the computational cost of 1 year of LISA analysis.
  - Assuming current techniques and usage of CPUs. Using GPUs may accelerate this.
  - Storage requirement is very high for intermediate data (*"scratch volume"*) but reasonable for the end products.
  - We need to account for potential bugs/recalibration and having alternative Global Fits as backup/reassurance ⇒ multiply all these numbers by a factor of ~6.
- We need to build a DDPC to analyse all this data.
- It is imperative that we find ways to increase the efficiency of data analysis! Either through "tricks" in existing algorithms or by using entirely new ones.

Requirements for analysis of 1 year of LISA data for individual sources

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

Table 2: Summary of the resources required for detection and characterization of all individually resolvable sources in 1 year of LISA data.

(source: S. Babak, "Computational cost and storage for L1, L2, L3 production", technical report ref. LISA-TN-001, 2021)

The Spanish LISA Data Analysis collaboration

- Currently beginning to take shape
- The plan: develop a Global Fit pipeline that uses more "experimental" ML techniques (+ all the tools/infrastructure needed to support it)
- Currently, we have collaborators from:

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UNIVERSITAT DE BARCELONA
IFIC
INSTITUT DE FÍSICA CORPUSCULAR

- Interested? Get in touch!

Thank you!