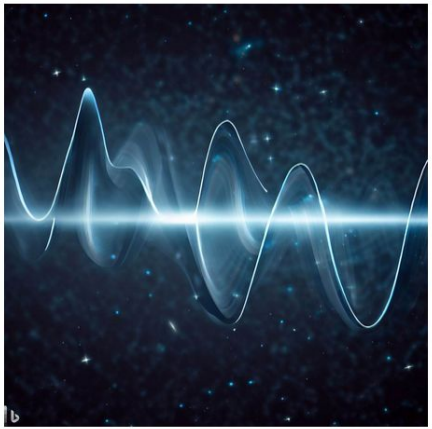
Christmas party: 4+1 questions and a toast

GRAF: Gravitational-waves data and global fit

R.Buscicchio
Univ. of Milano-Bicocca
2023/12/29

The “mission”

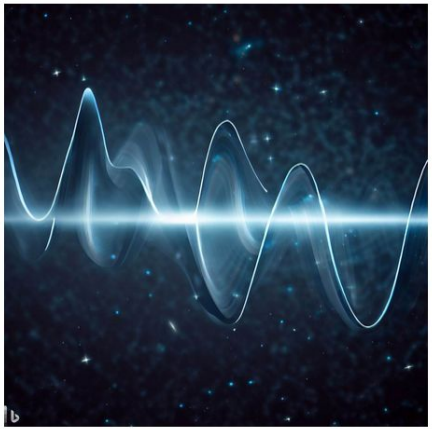
GRAF



The objective of GRAF (GRAvitational global fit) is the development of **new models** and **analysis techniques** for **high-precision** measurements of gravitational-waves

The “mission”

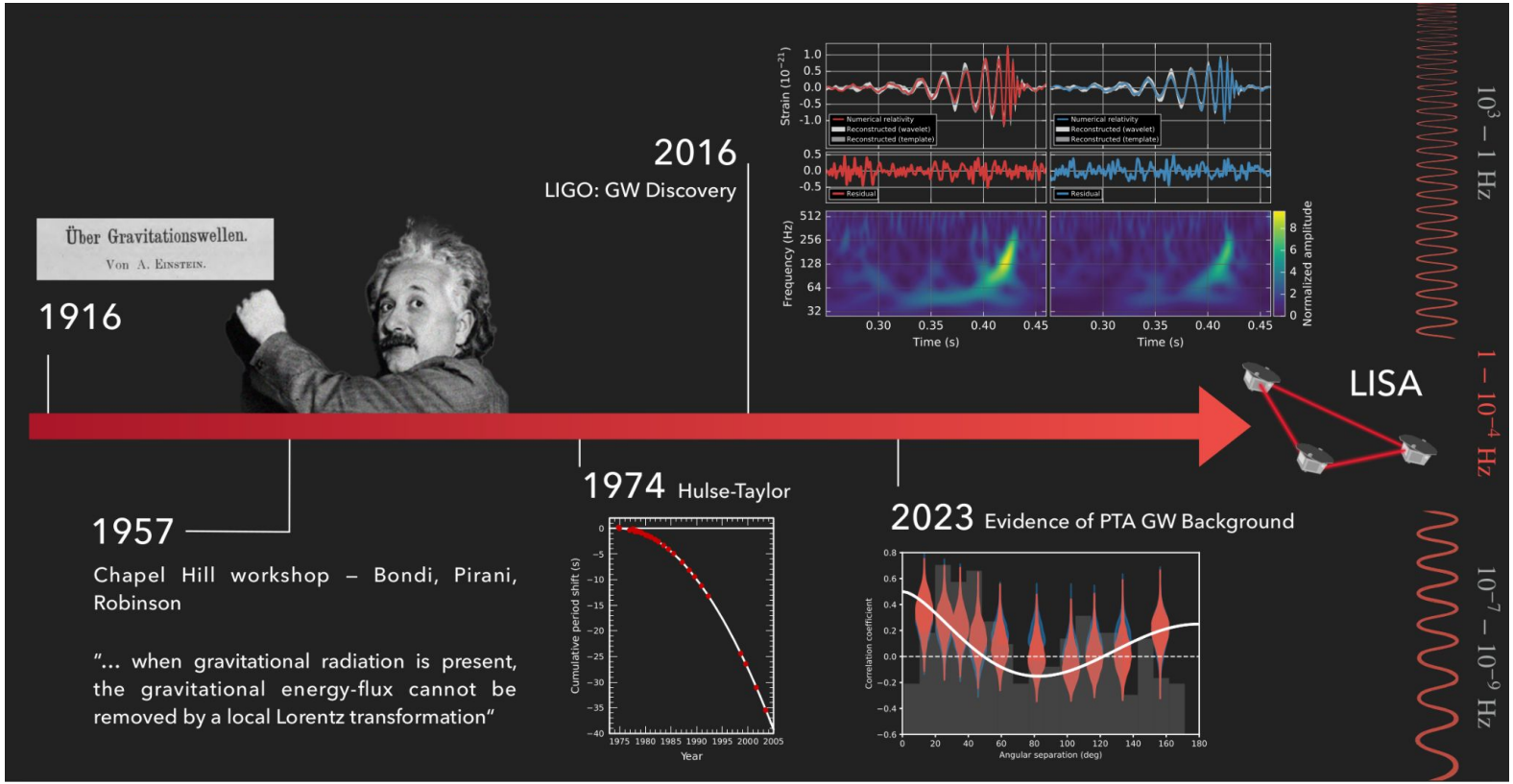
GRAF



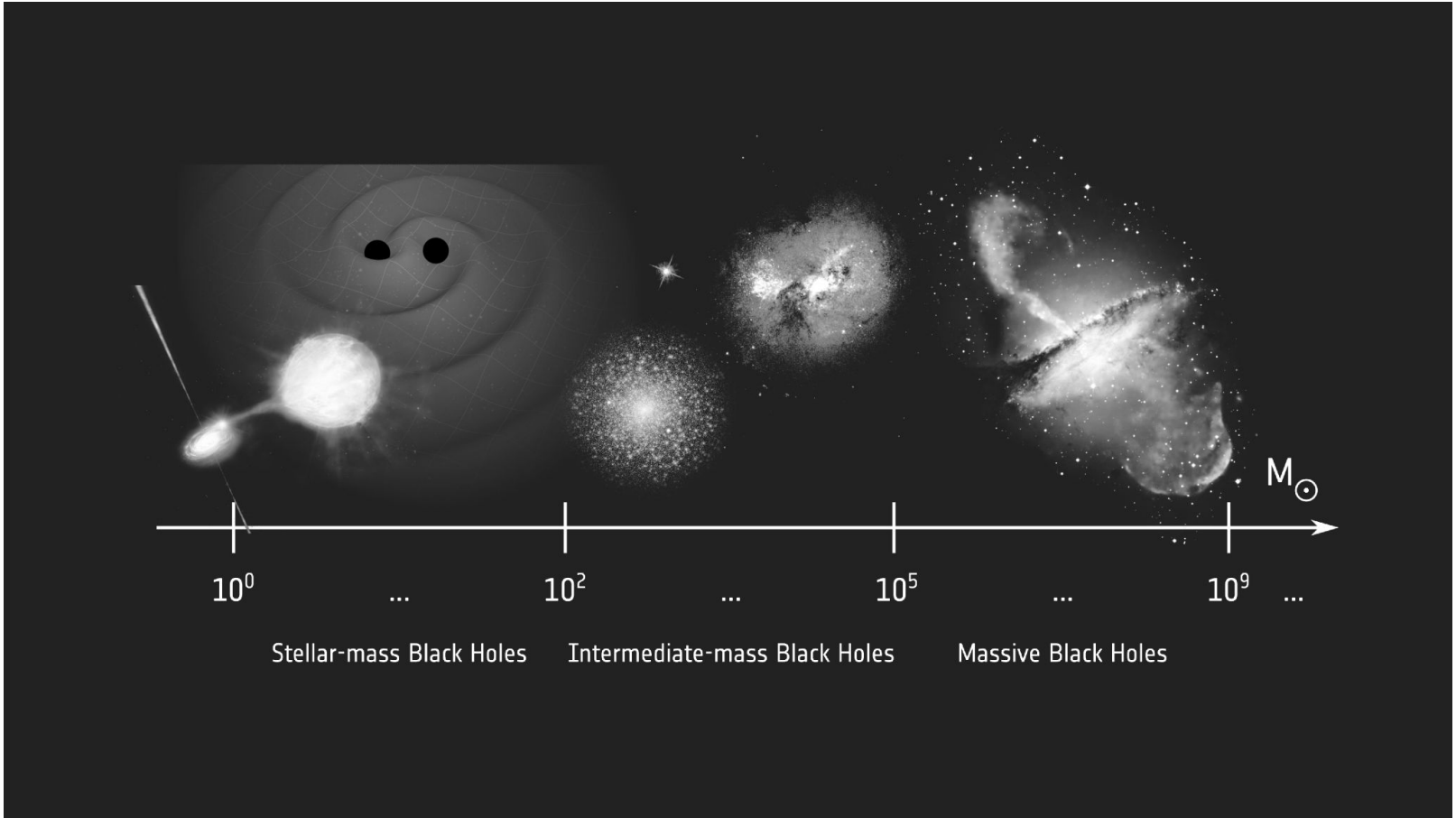
The objective of GRAF (GRAvitational global fit) is the development of new **models** and **analysis techniques** for **high-precision** measurements of gravitational-waves

Why?

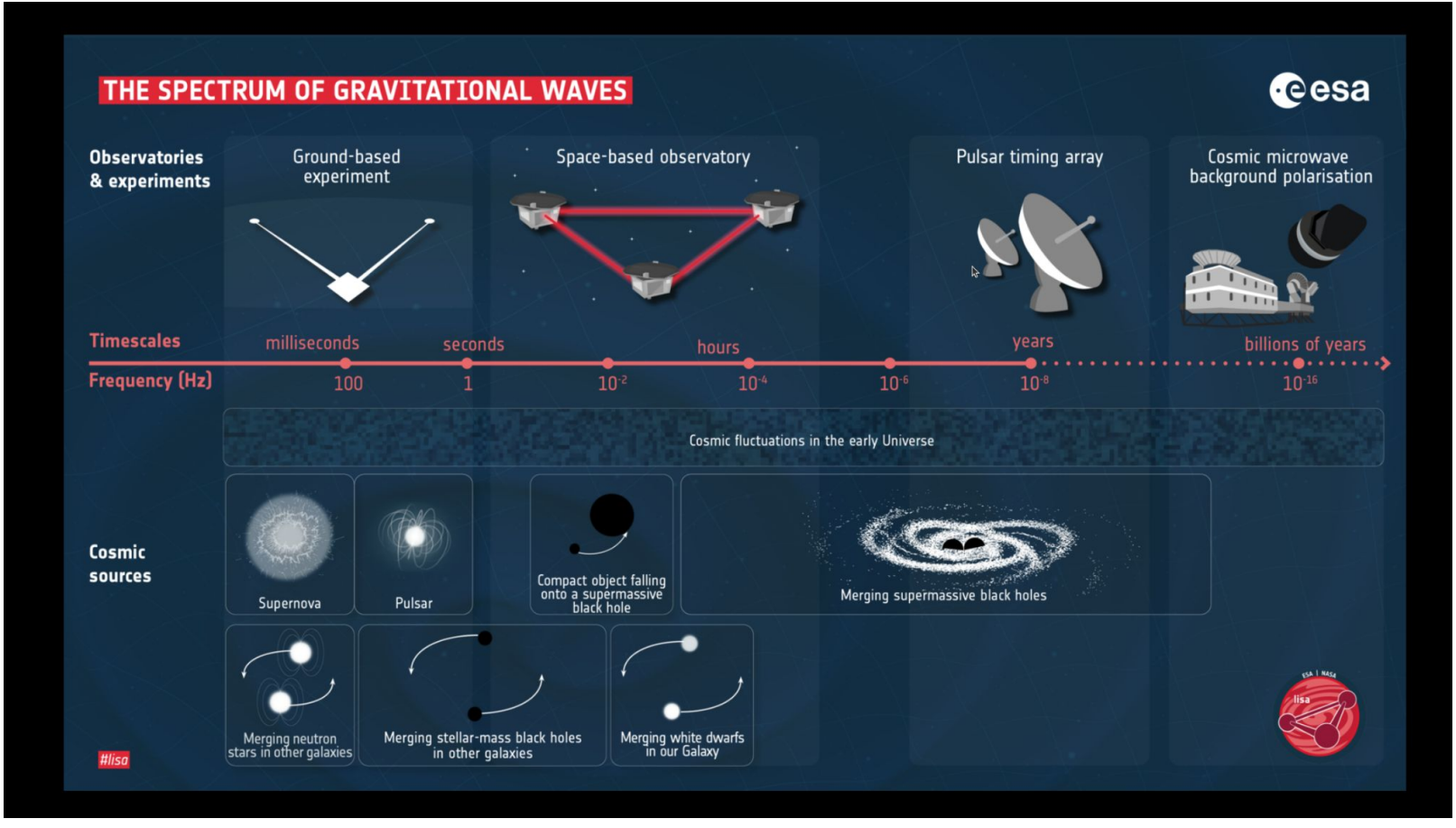
Gravitational waves are real!



Mass scales


$M_\odot$
10^0
...
10^2
...
10^5
...
10^9
...
Stellar-mass Black Holes
Intermediate-mass Black Holes
Massive Black Holes

Timescales


THE SPECTRUM OF GRAVITATIONAL WAVES
esa
Observatories & experiments
Ground-based experiment
Space-based observatory
Pulsar timing array
Cosmic microwave background polarisation
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
10-2
10-4
10-6
10-8
10-16
Cosmic fluctuations in the early Universe
Cosmic sources
Supernova
Pulsar
Compact object falling onto a supermassive black hole
Merging supermassive black holes
Merging neutron stars in other galaxies
Merging stellar-mass black holes in other galaxies
Merging white dwarfs in our Galaxy
#lisa
lisa

Alberto Sesana et al.

Pulsar timing arrays, Galaxy & supermassive black holes coevolution

Strong involvement in DR2, ongoing projects:

- pulsar selection (Alberto)
- preparation of the data WP1 (Golam)
- noise analysis WP2 (Aurelien)
- analysis WP3 (Golam Aurelien)

Suite of DA tools, implementing several NS algorithms in Enterprise (paper accepted)

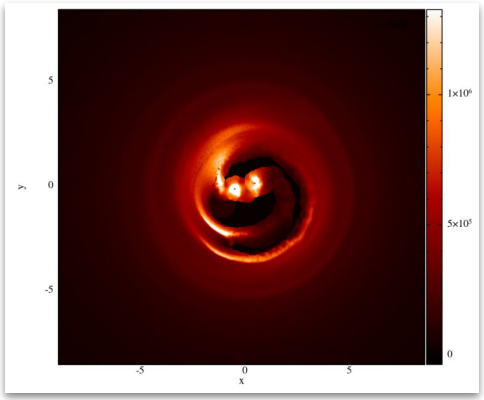
- inference WP3 (Matteo, Alessia)
- Extension of Chen+19, including model variance (in progress)

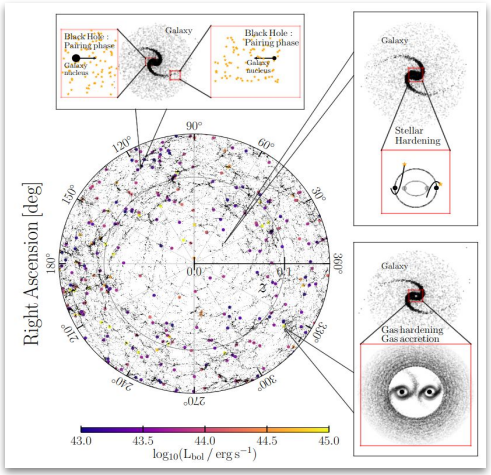
-Two master students (Serena, Giulia) recently finished (paper in preparation)
-Three new master students working on PTA analysis (Beatrice, Irene, Sara)
-Nataliya joined the group as a visiting fellow with a DFG fellowship

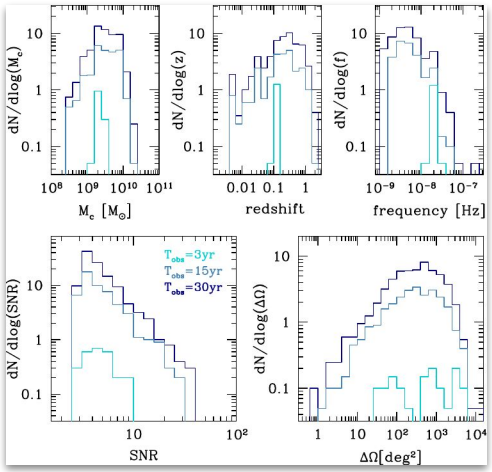
- MBHB population models (Izquierdo – Villalba+ 21, 22a, 22b, 22c)
- Creating mock universes to assess:
  - GWB SNR
  - CGW statistics
  - multimessenger

- Dynamics of MBHBs in stellar and gaseous environments (Bortolas+ 21, Gualandris+22, Franchini +21, 22)
- Hardening in realistic galaxies (PhD Federica)
- EM counterparts characterization (PhD Fabiola)

- EMRIs and SGWB for LISA (Federico, now @ Uninsubria)
- EMRIs and SGWB for LISA (Manuel, now @ L2I, Toulouse)







Davide Gerosa et al.

Gravitational-wave phenomenology and data exploitation

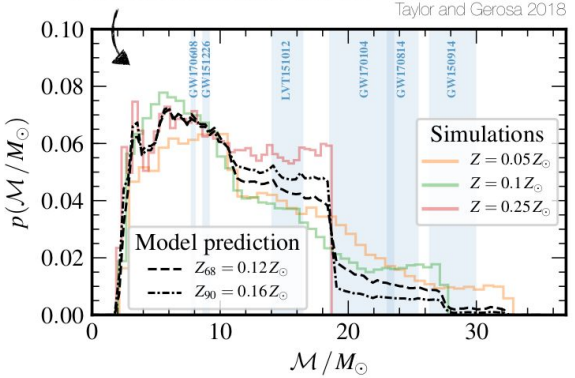
- How do black-hole binaries form and get together?
- What's their gravitational-wave emission pattern?
- What are current GW data (not) telling us? How do we get that information out?

Group research lines:

- **Astrophysical** modeling of GW sources
- **Theoretical** calculations in relativistic dynamics
- **Computational** applications to BH physics
- **Data analysis** and Bayesian statistics
- **Machine learning** tools

Machine learning and hierarchical Bayesian analysis to infer the lives of stars from black-hole binary data

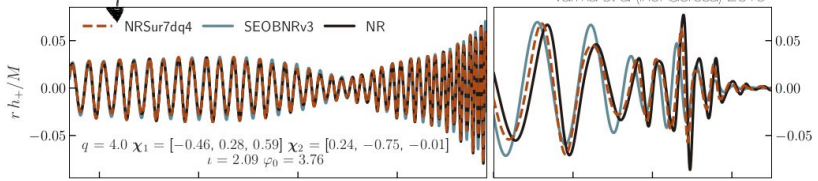
Taylor and Gerosa 2018



Accurate modeling is crucial for LIGO/Virgo **today** and even more so for LISA and Einstein Telescope **tomorrow**!

Emulation of numerical-relativity simulations to analyze gravitational-wave signals

Varma et al (incl Gerosa) 2019



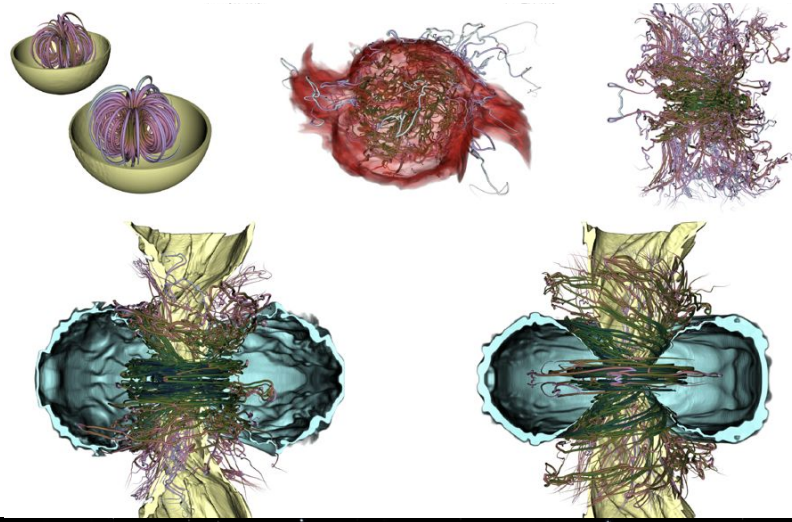
Grants

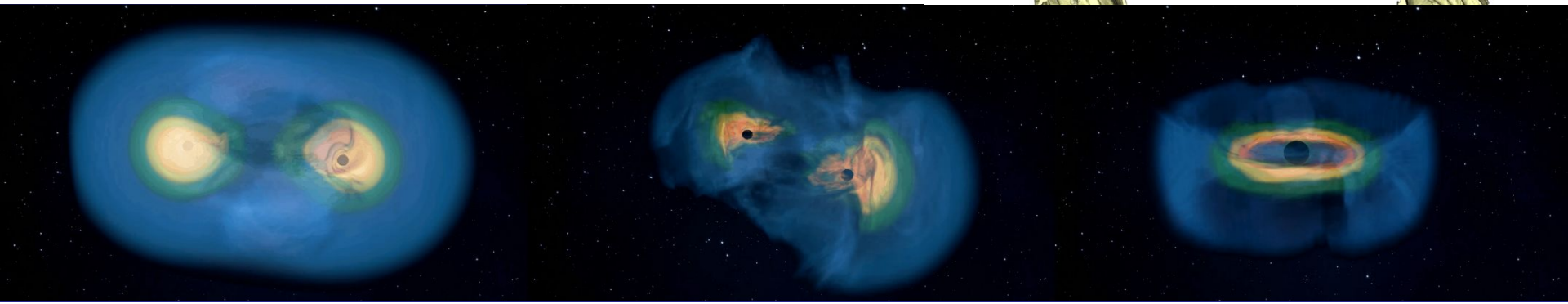
- **ERC** Starting Grant (*GWmining*)
- Marie Curie fellowship (*StochRewind*)
- Cariplo Foundation
- PRIN (with GSSI L'Aquila)
- (3 pending Marie Curie proposals)

Bruno Giacomazzo et al.

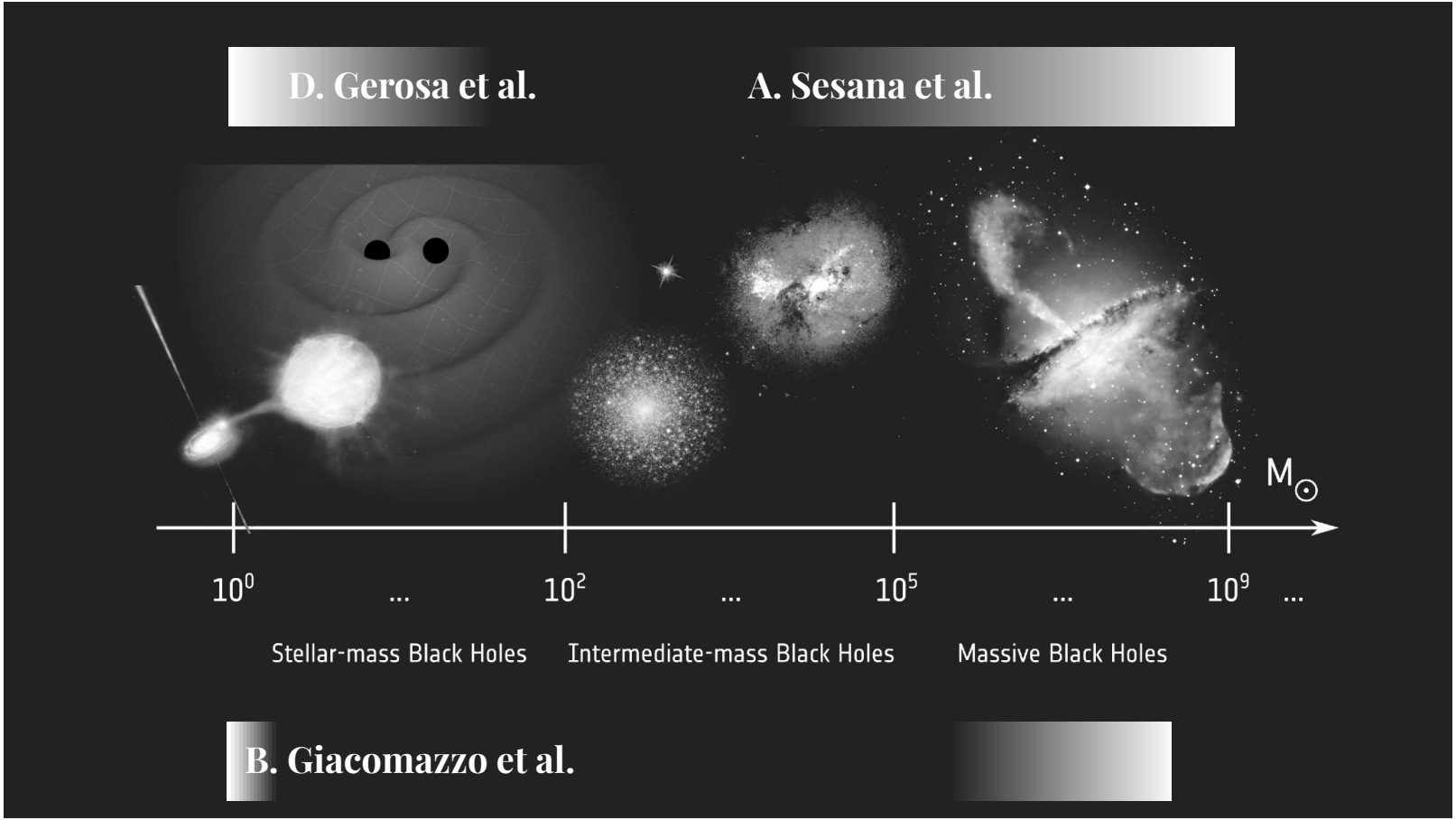
Numerical relativity

- Binary Neutron Star Mergers
- Accretion onto Supermassive Black Hole Binaries (postdoc F. Cattorini)
- Code Development for General Relativistic MagnetoHydroDynamics
- GRANTS: PRIN 2024 -2026 (with Padova and Trento)





Here’s why


D. Gerosa et al.
A. Sesana et al.
M⊙
10^0
...
10^2
...
10^5
...
10^9
...
Stellar-mass Black Holes
Intermediate-mass Black Holes
Massive Black Holes
B. Giacomazzo et al.

A comparison

Ground based (2G)

+

(+noise)

Space based

+

+

(+noise)

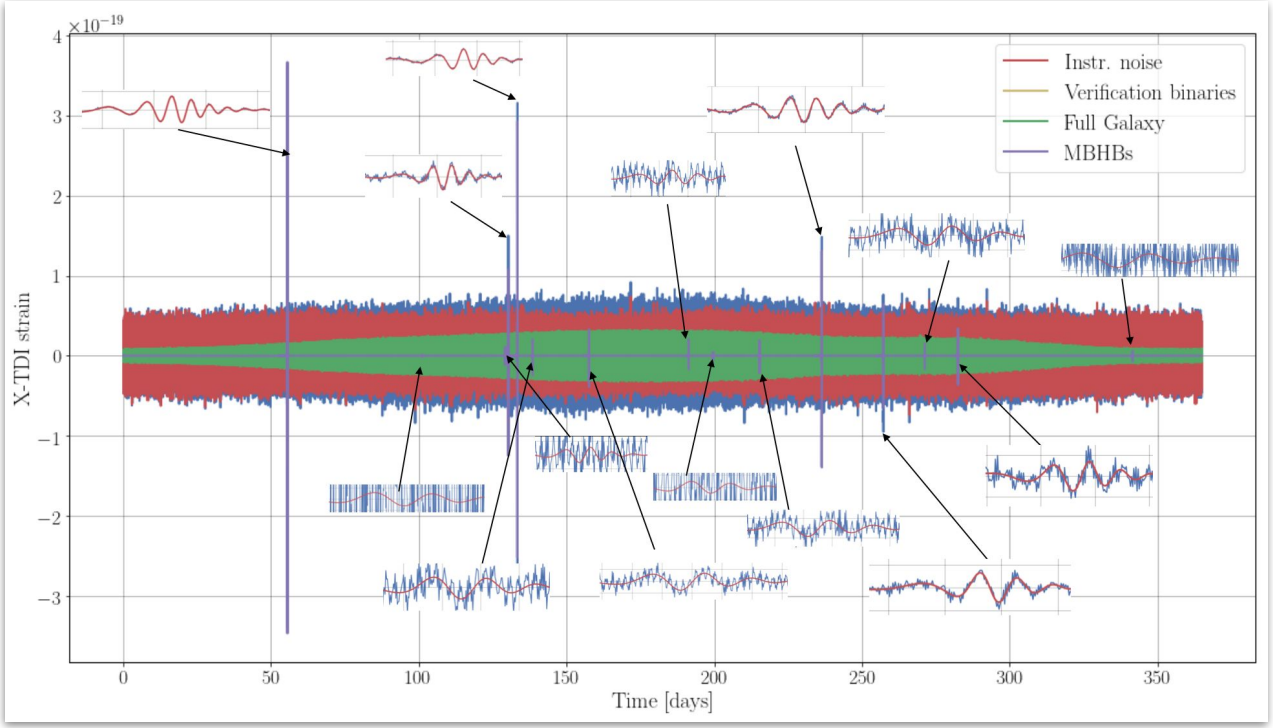
Pulsar Timing Array

+

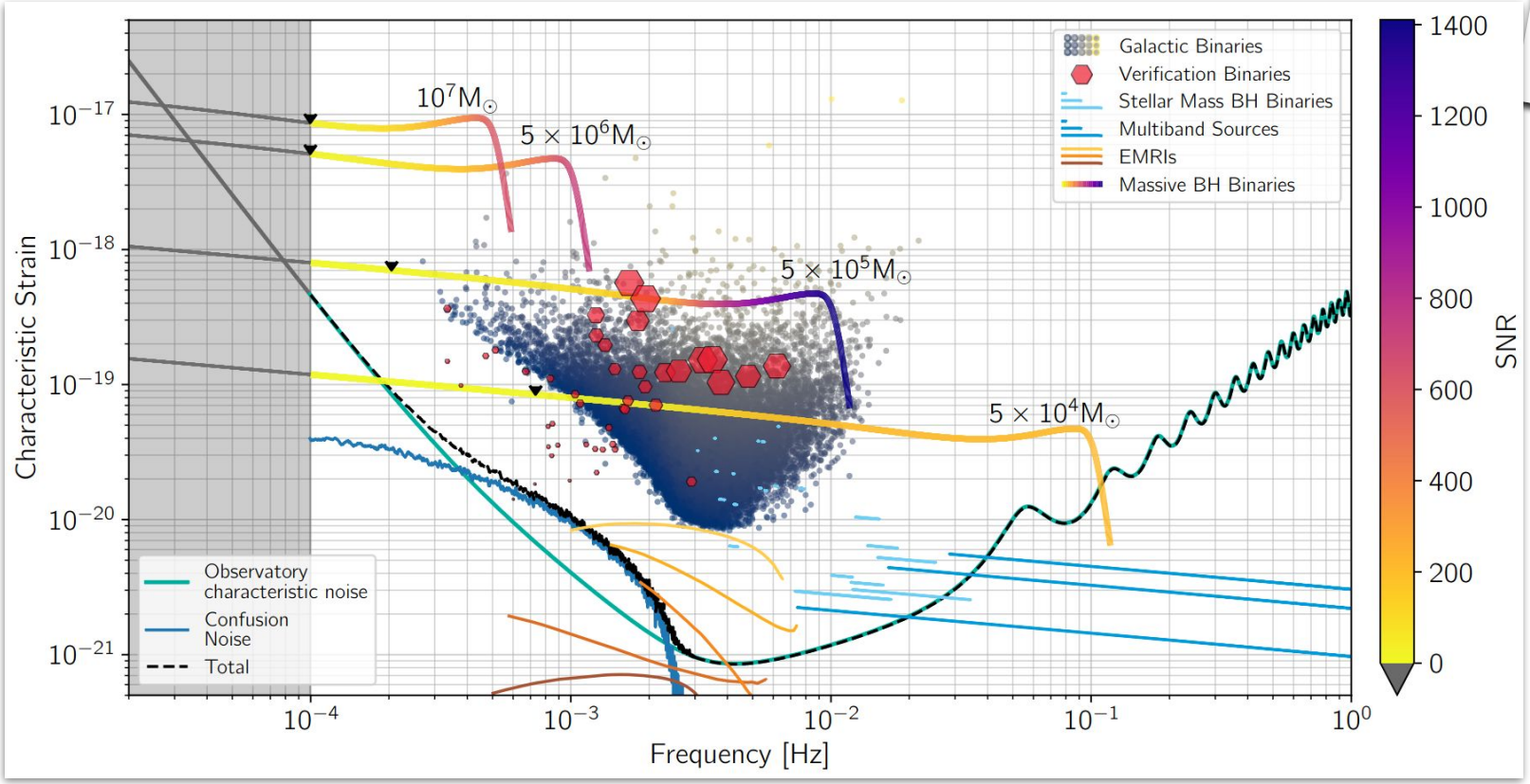
(+noise)

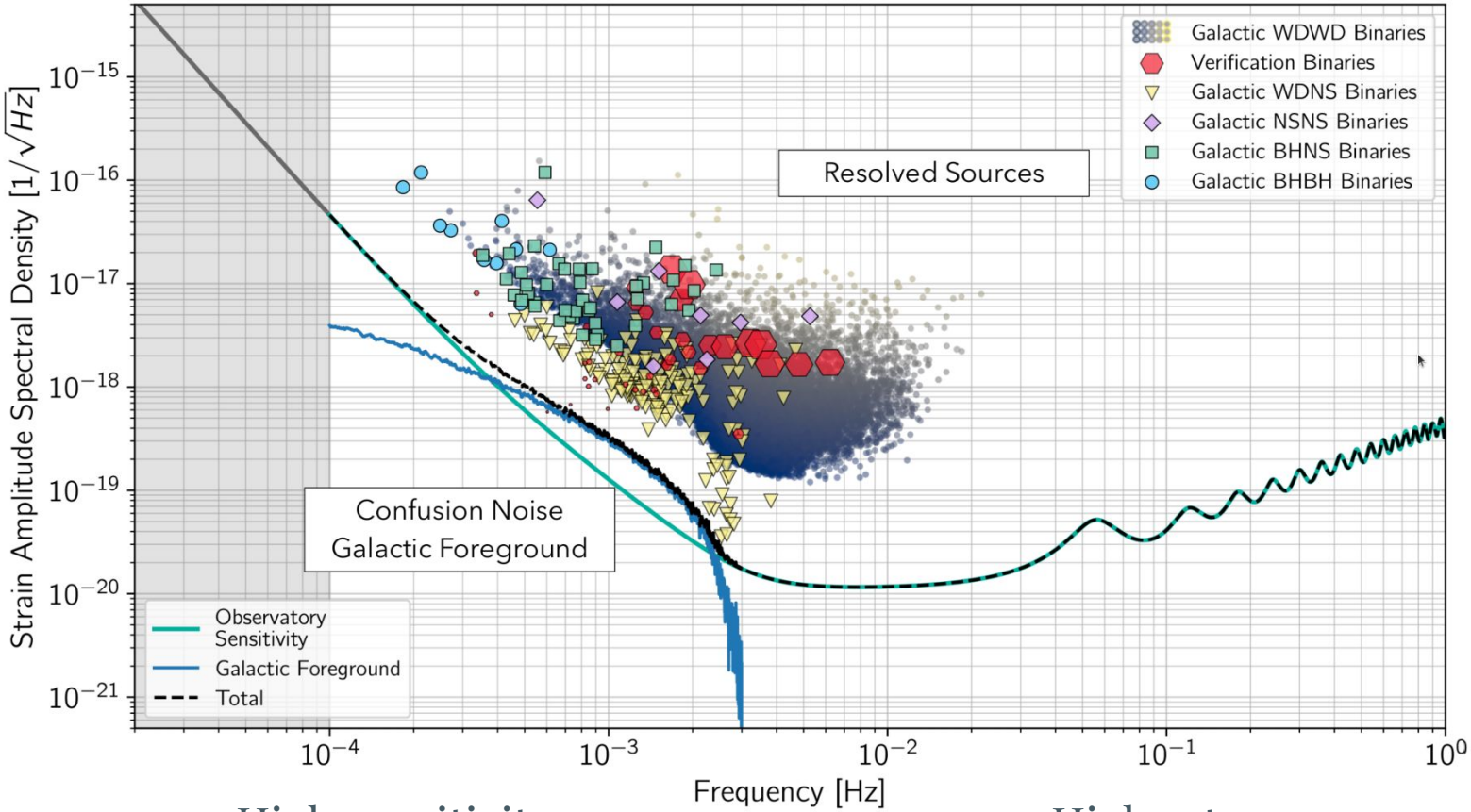
The dataset

A few solos, a concert, and a rave party..together!



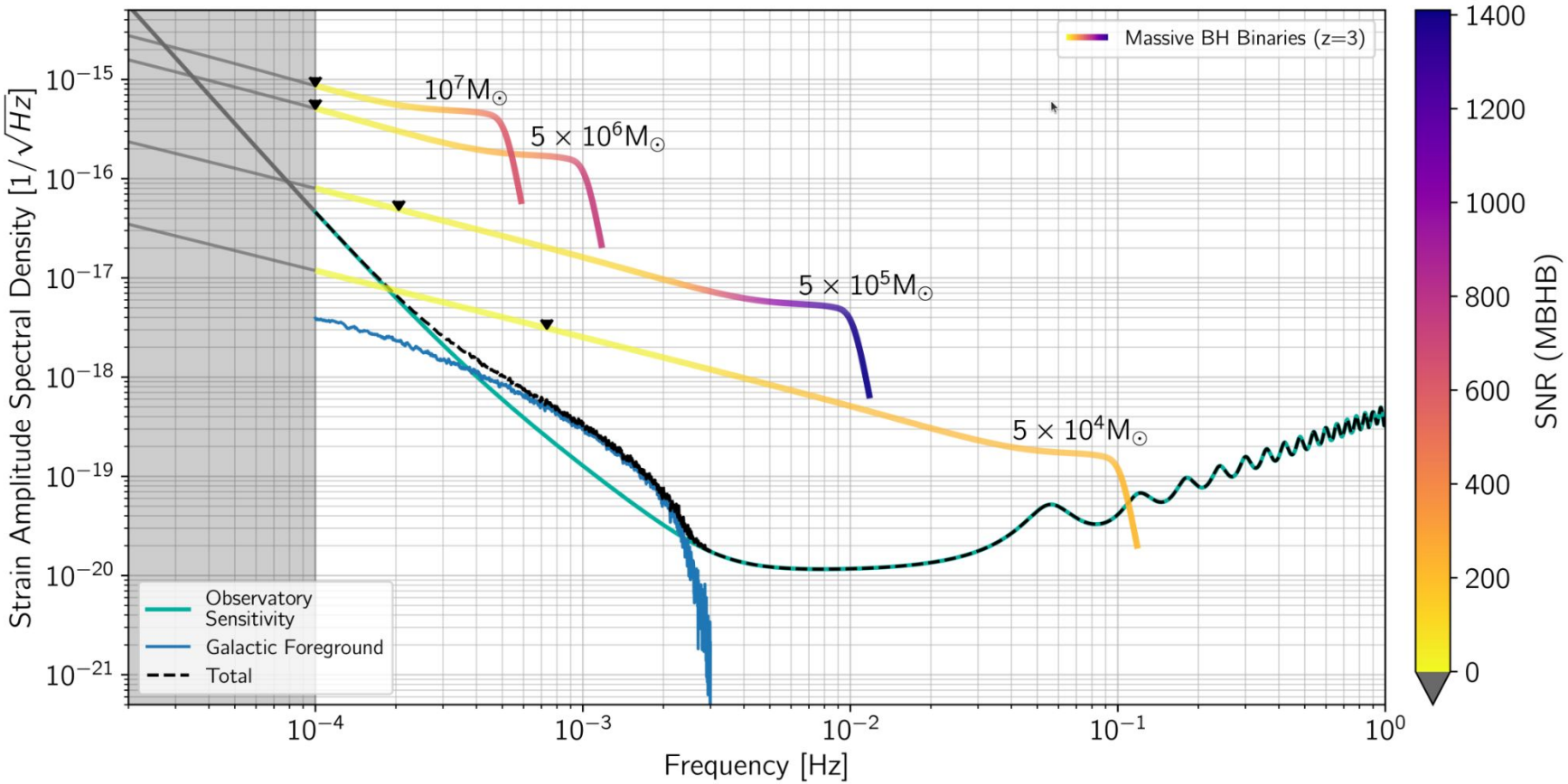
The dataset
A spectral view

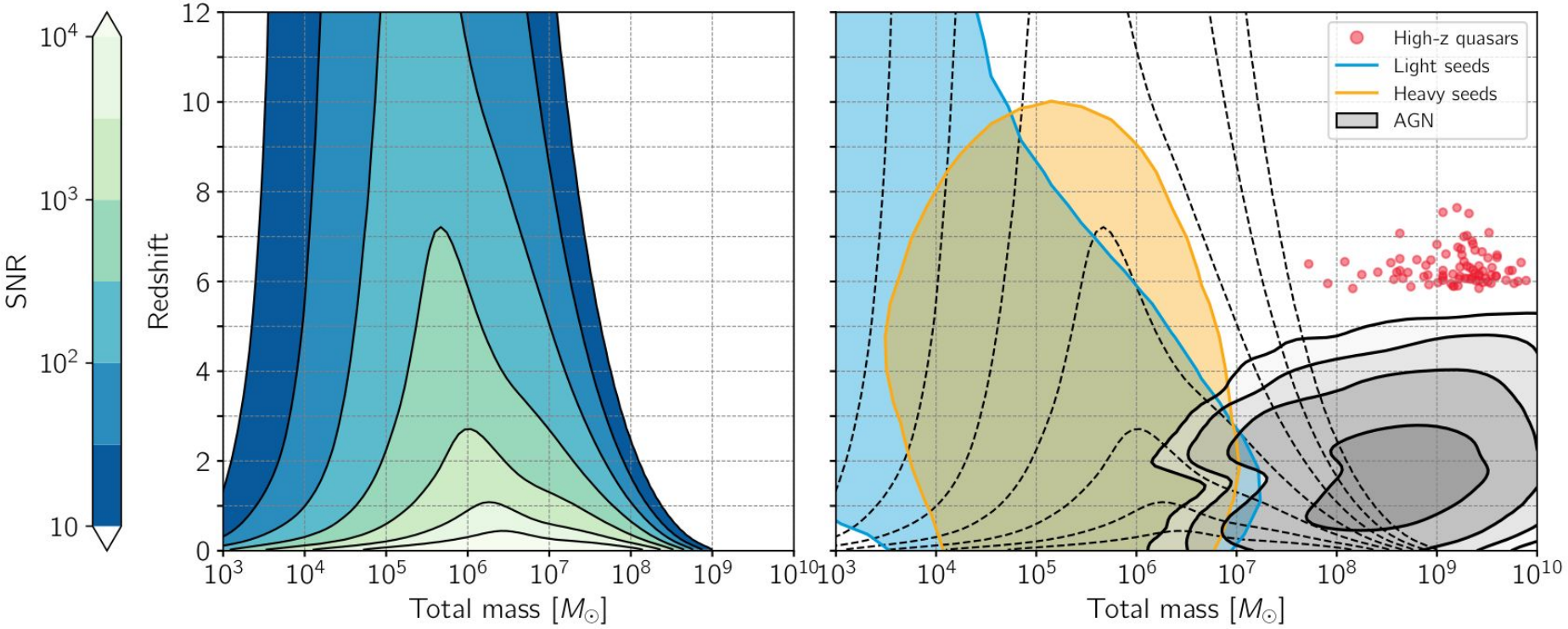




High sensitivity → High rate

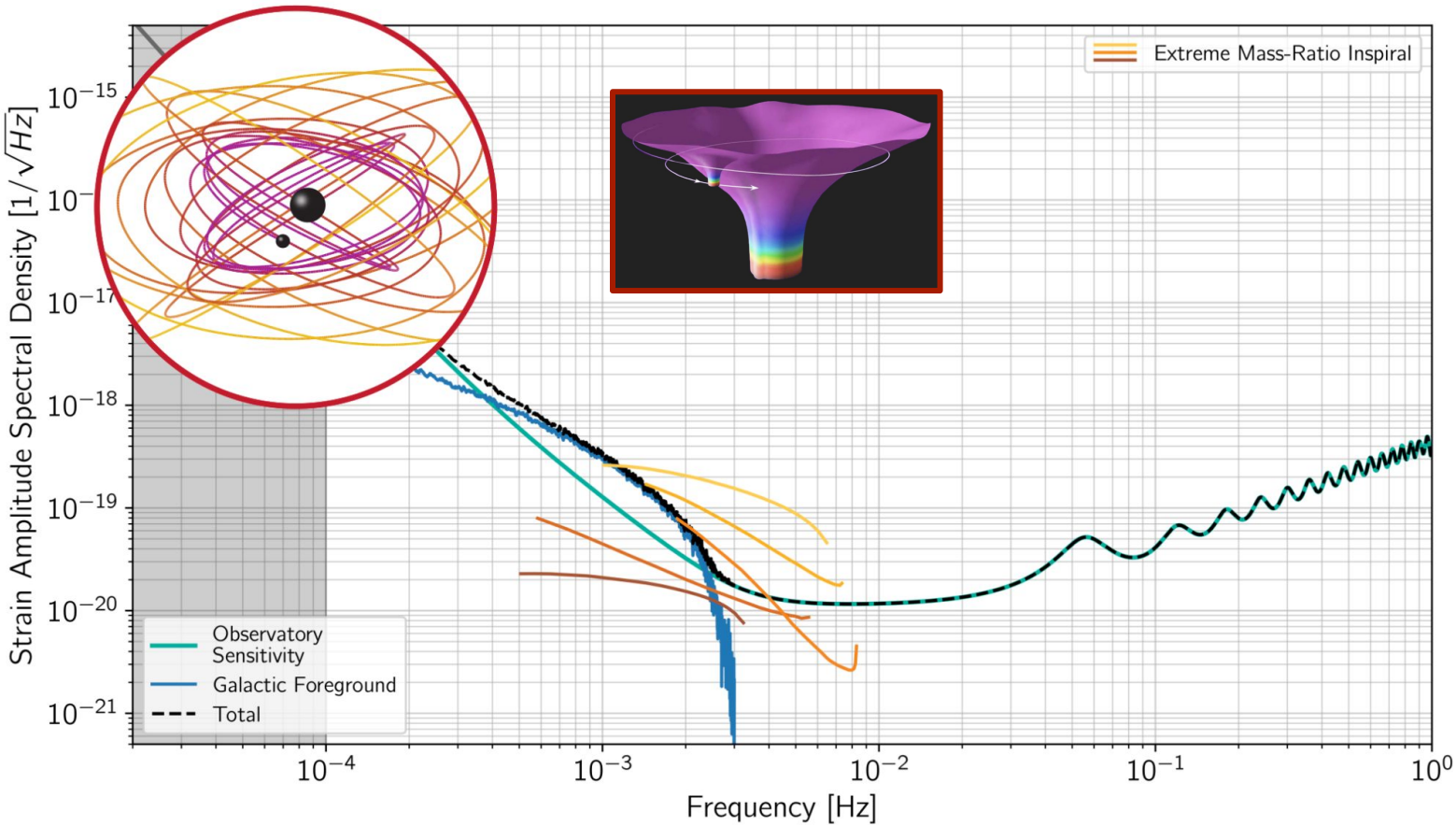
TRACE THE ORIGINS, GROWTH AND MERGER HISTORIES OF MASSIVE BLACK HOLES





High sensitivity → High SNR

TRACE THE ORIGINS, GROWTH AND MERGER HISTORIES OF MASSIVE BLACK HOLES

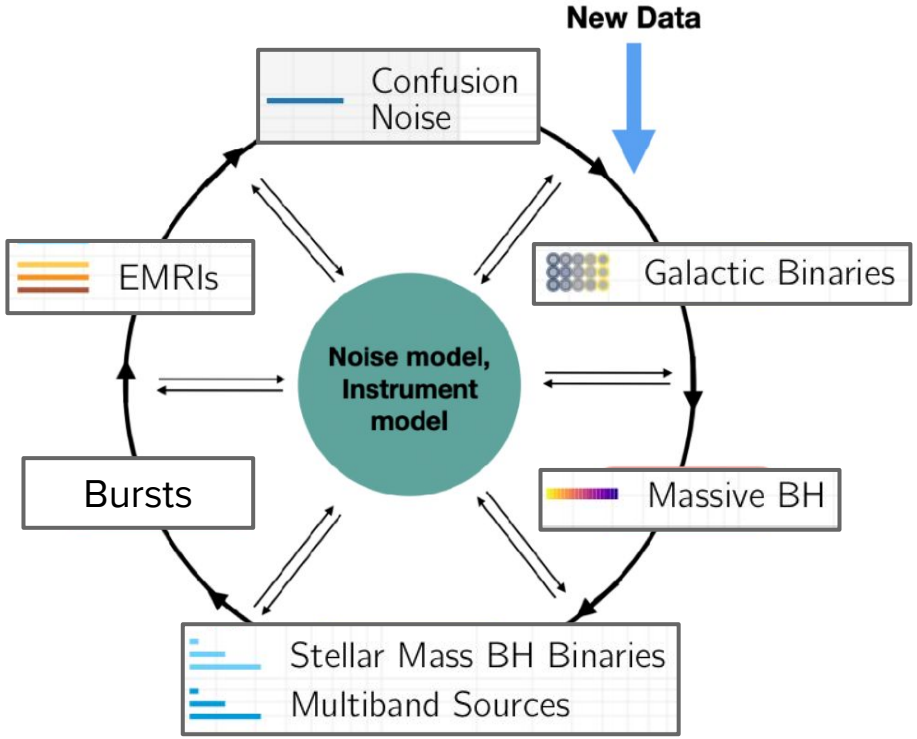


LOGIC OF THE DATA PROCESSING

- Analysis of all signals and noises together => global analysis
- Flexibility: first data of this kind => novel analysis challenge
  - Multiple approaches, multiple pipelines
  - Quick development from prototyping to production (devOps)
- Multiple steps approach with iterations between steps because data products are very interconnected:
  1. Reduce dominant noises (Time Delay Interferometry) and partial correction on instrument artefacts => L1 data
  2. GW sources extraction + better understanding of noises and instrument with multiple pipelines => L2 data
  3. Cross-check, combination, merging of L2 data to produce catalogs + associated scientific products => L3 data
- Publication of the data L0.5, L1, L2 et L3 simultaneously with a unique official version of L3 (SMP)
- Long prototyping phase; already started (2005-2011: MLDC, 2017-now: LDC)

One ring to fit them all

Blocked-Gibbs sampling

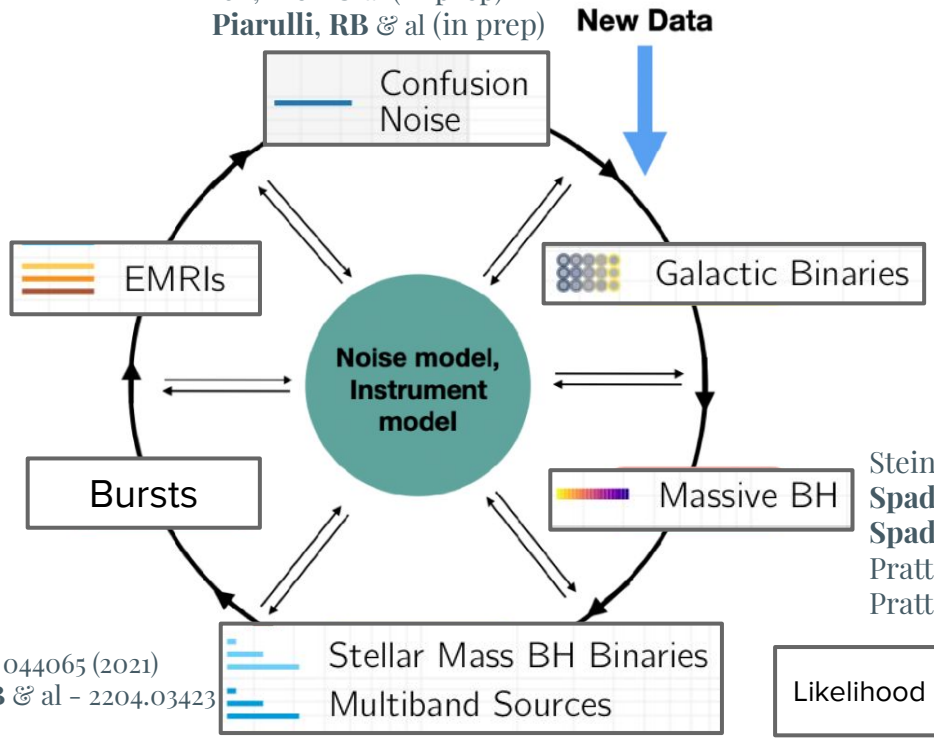


- Monochromatic (DWDs) ✅
- Drifting sources (BBHs) ✅
- Chirping sources (SMBBHs) ✅
- Instrumental artifacts (Glitch) ✅
- Multiband sources ✅
- Polichromatic (EMRIs)
- Unresolvable (SGWBs) ✅

“Riccardo Buscicchio et al.”

My dowry

Pozzoli, **RB** & al 2311.12111
RB, Klein& al (in prep)
Piarulli, **RB** & al (in prep)



Single, circular:
Roebber, **RB**+ ApJL, 894.2 L15 (2020)
Korol+ (incl **RB**) A&A 638, A153 (2020)
Multiple, circular:
RB+ PRD 100, 084041 (2019)
Verification:
Finch & al MNRAS, 522 (2023)
Eccentric:
Moore+ 2310.06568

Steinle & al (incl. **RB**) MNRAS 525 (2023)
Spadaro, **RB** & al 2306.03923 (in press PRD)
Spadaro, RB, Izquierdo & al (ongoing)
Pratten & al Phys. Rev. D 107, 123026 (2023)
Pratten & al 2307.13026

RB & al PRD 104, 044065 (2021)
Klein, Pratten, **RB** & al - 2204.03423

Likelihood Interpolators	**RB**, El Gammal+ (ongoing)
Forward modelling	**RB**, Bhardwaj+ (ongoing)

“Riccardo Buscicchio et al.”

My dowry

“**A** **L**ISA **B**ayesian **E**stimation **R**outine for **T**ons of **O**bjects, **S**imultaneously”

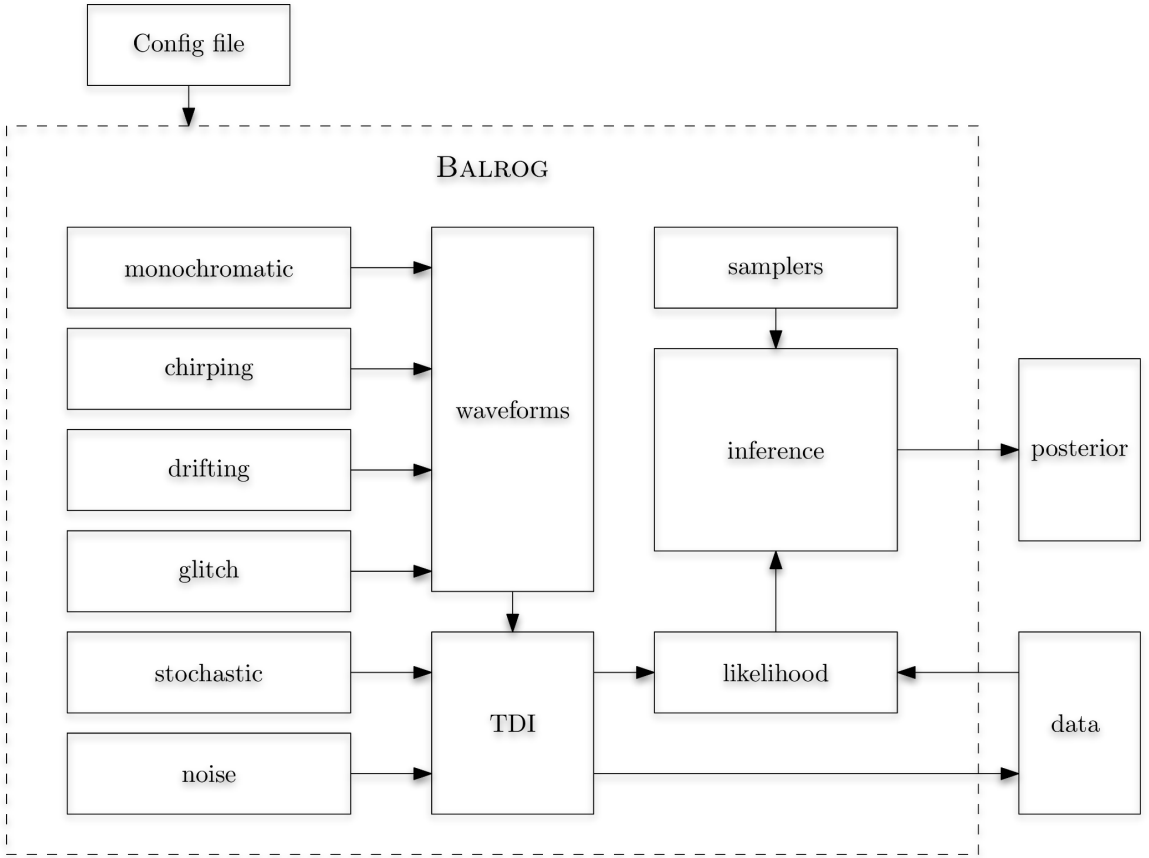
Active development with:

- Univ. of Birmingham
- Univ. of Stavanger

Collaborative projects with:

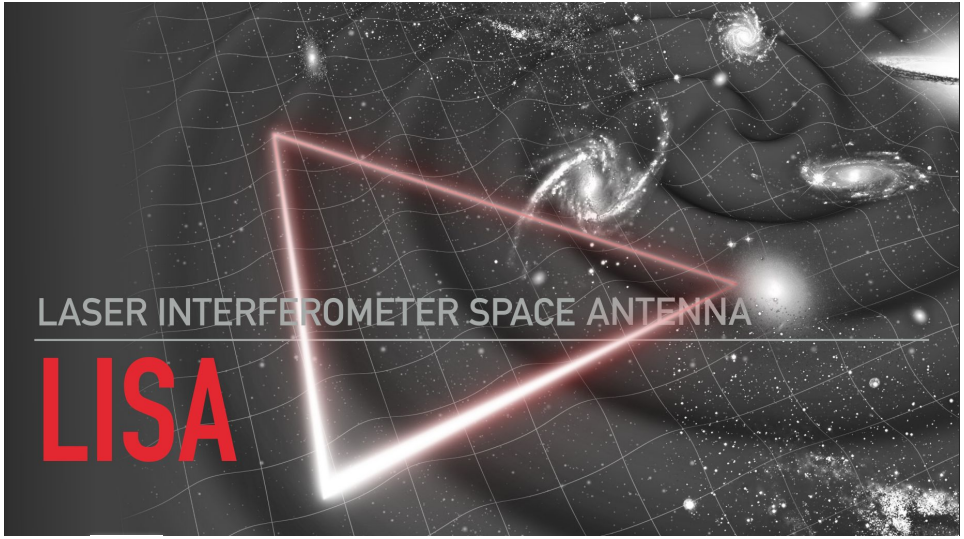
- Univ. of Pisa
- AEI (Berlin)
- MPA (Garching)
- APC (Paris)
- GRAPPA (Amsterdam)

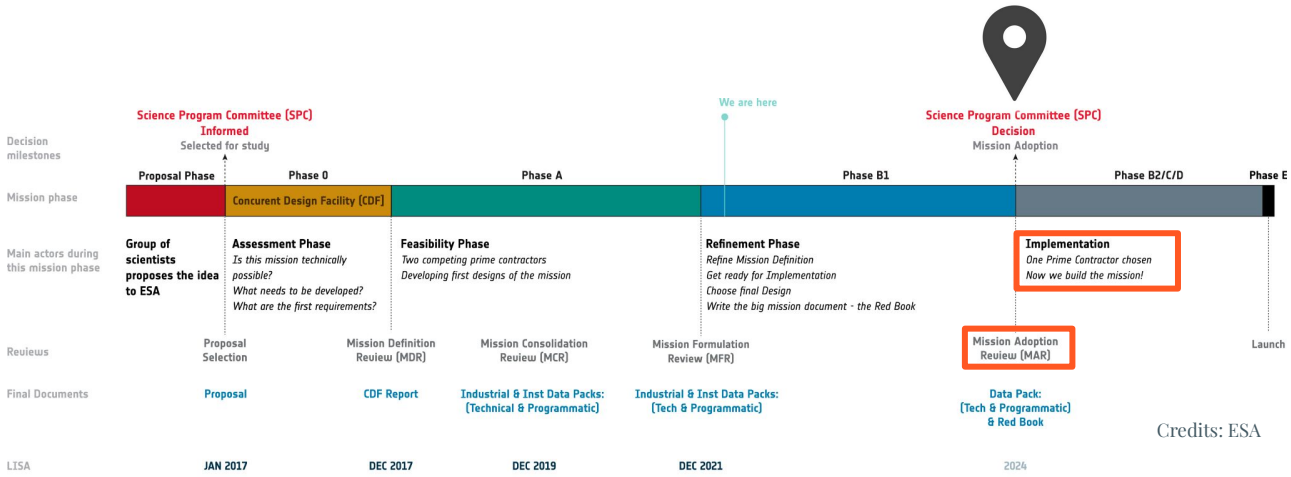
Stay tuned for the public release, due Spring 2024



LISA
Mission status

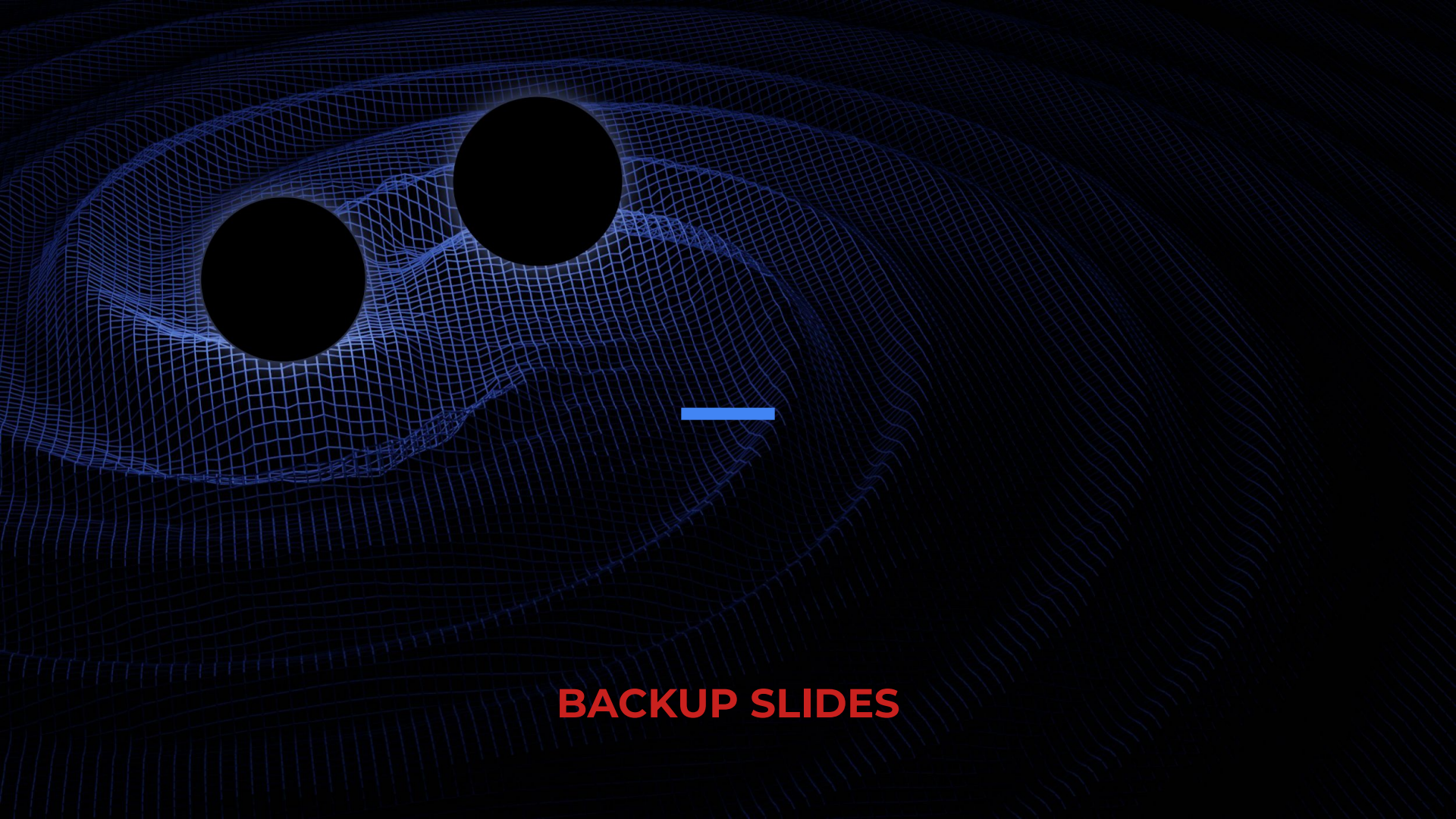
- Mission Formulation Review ✓
- Redbook ✓
- Mission Adoption (due early 2024)
- Launch expected in 2037





Credits: ESA

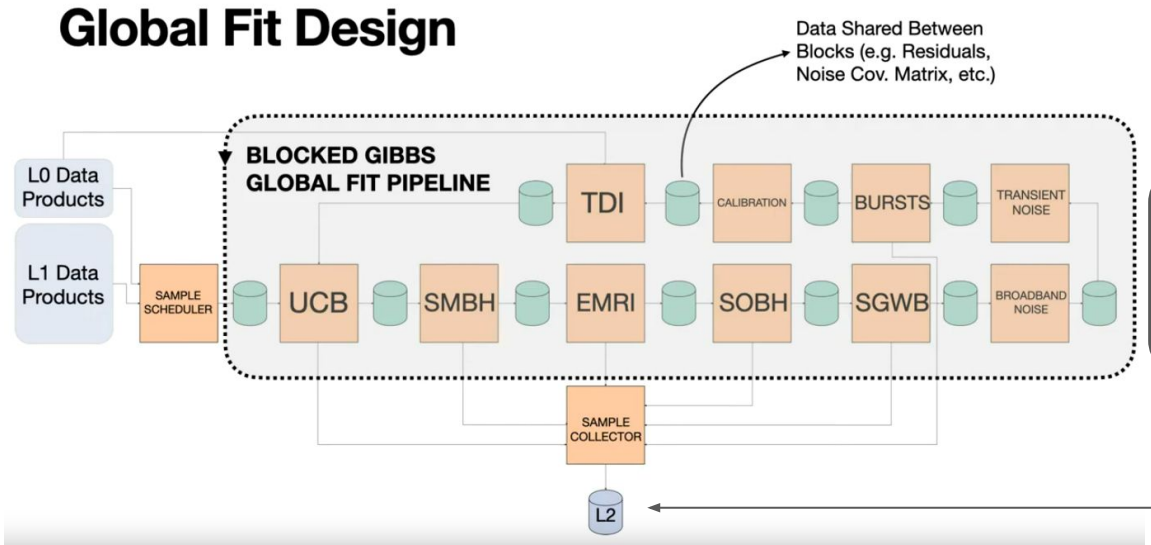

Thank you!



BACKUP SLIDES

Computational challenges

The elephant in the room



It's a logistic problem:
not heavily parallelizzable,
some blocks are very expensive
(30 to 100 cores for ~few months long parameter estimation)
Blocking strategy is crucial!

10 - 100 TB per catalogue

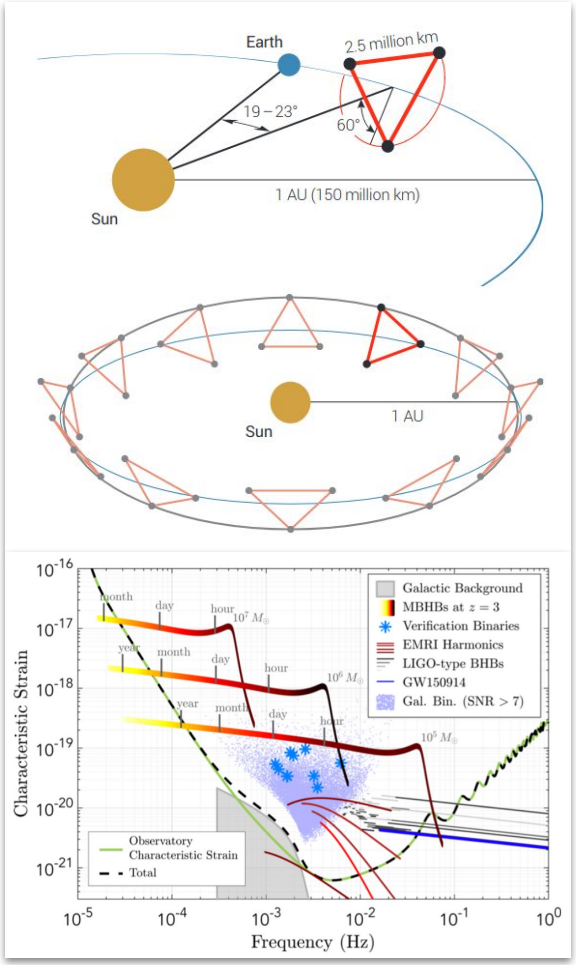
Designing a Global Fit Analysis for LISA (T. Lyttenberg)

Constellation

Key instrument features

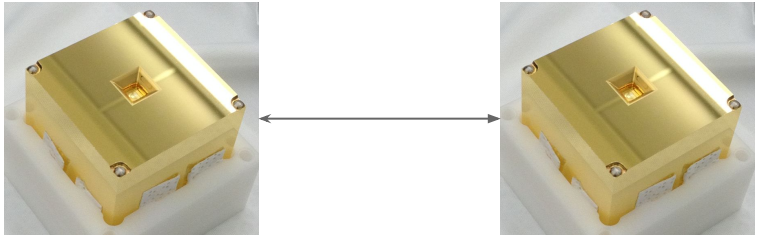
- Long baseline: 2.5 Mkm
- Sensitivity bucket ~ mHz
- Data on a stick:
  4 to 10 years-long
  science datastreams = O(10 GB)
- Dominating laser phase noise: synthetic interferometry
- Noise not enough under control: “null-channel”
- Source-rich sky: transient, persisting & overlapping sources
- Time dependent response: “new” wrt ground-based detectors
- Noise/Signal distinction is blurrier than ever: “confusion” noise

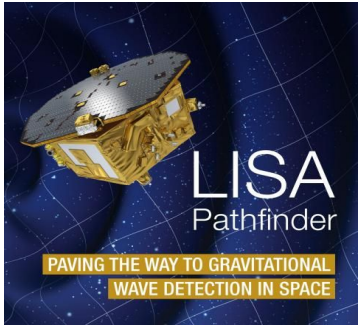
credits: LISA Proposal L3 ESA mission



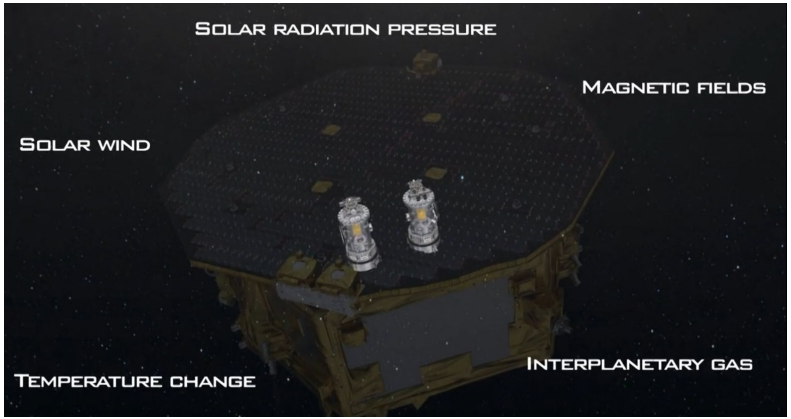
LISA pathfinder

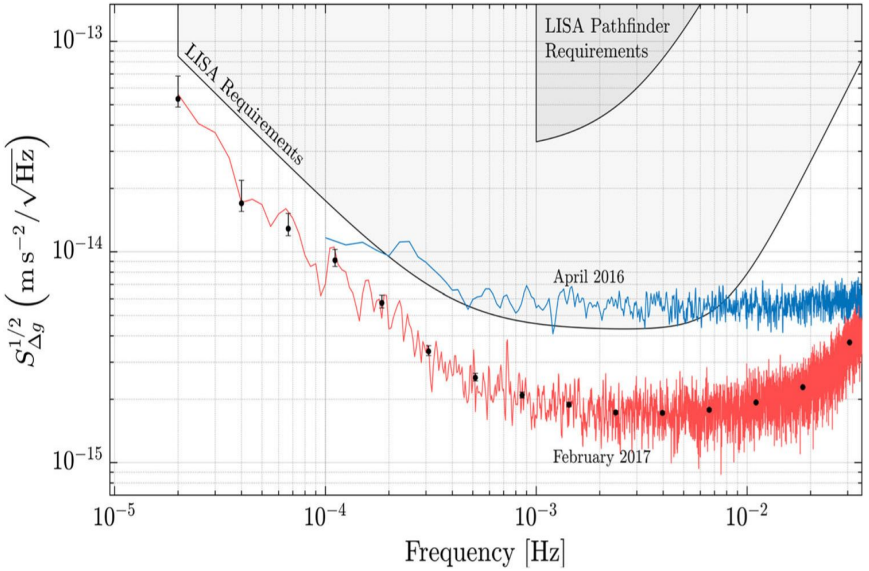
Some optimism





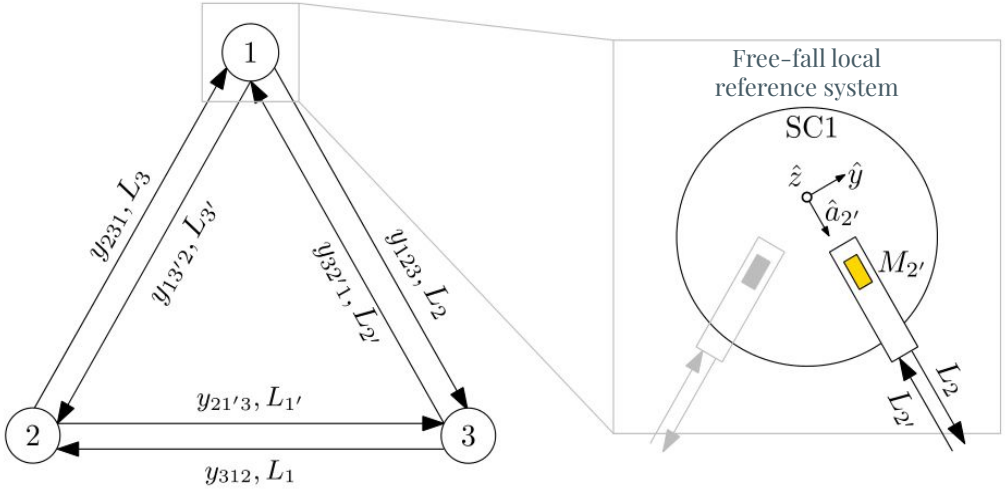
credits: LPF collaboration

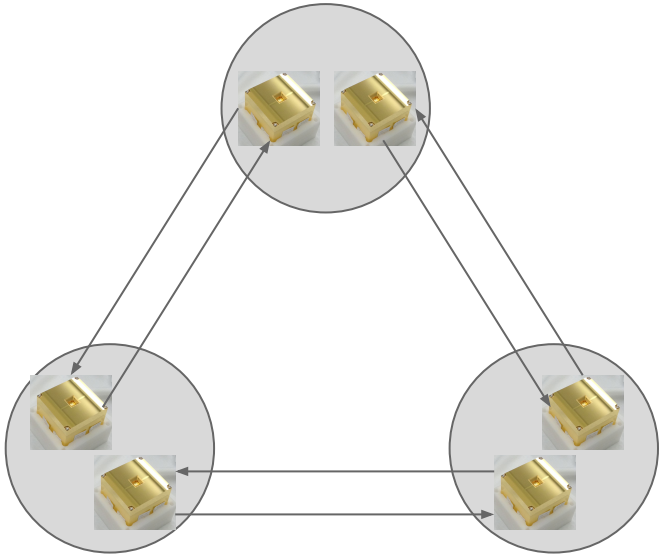




LISA pathfinder

The observable(s)





- Physical interferometry unfeasible (telescope incoming power 100 pW)
- Post-processing technique to combine 6 independent “link” into equivalent interferometers
- Individual observable: individual phase (or frequency)

$$\delta\nu(t) = (1/2\pi)d\phi/dt$$

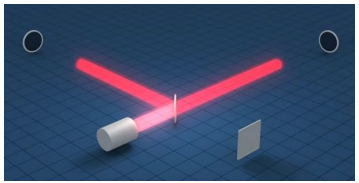
Time delay interferometry

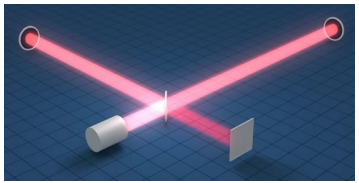
The path found

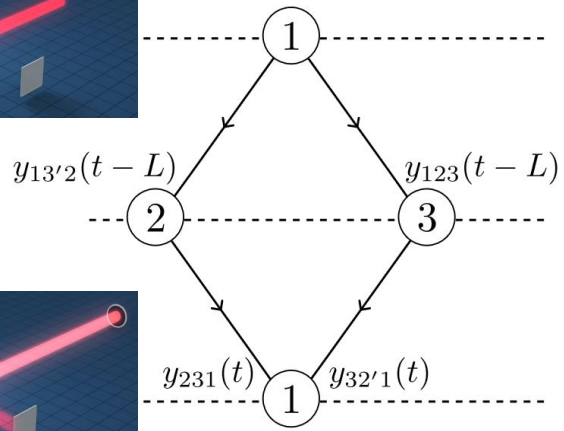
GW effect on a single link. But: laser frequency noise-dominated.

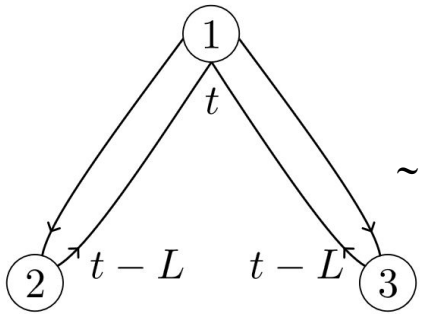
$$\Delta L(t) = \frac{1}{2}\frac{\hat{r}^a(t)\hat{r}^b(t)}{1-\hat{\mathbf{k}}\cdot\hat{\mathbf{r}}(t)}\int_{u-\Delta u}^{u} h_{ab}(u')du' \longrightarrow \frac{\Delta L(t)}{L} = \frac{1}{2}\hat{r}^a(t)\hat{r}^b(t)\int_{-\infty}^{\infty}\tilde{h}_{ab}(f)\mathcal{T}(f,t,\hat{\mathbf{k}})e^{2\pi i f(t-\Delta t)}df$$

Combine multiple links together. How?









~

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

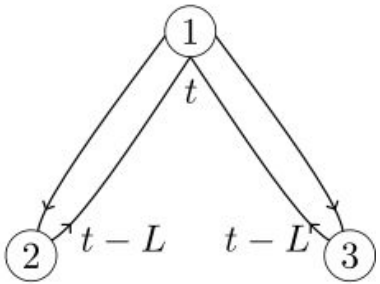
Time delay interferometry

The path found

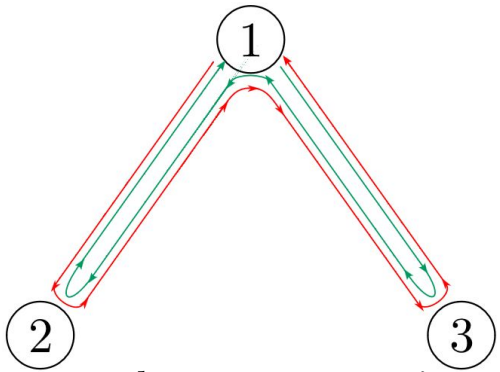
GW effect on a single link. But: laser frequency noise-dominated.

$$\Delta L(t) = \frac{1}{2}\frac{\hat{r}^a(t)\hat{r}^b(t)}{1-\hat{\mathbf{k}}\cdot\hat{\mathbf{r}}(t)}\int_{u-\Delta u}^{u} h_{ab}(u')du' \longrightarrow \frac{\Delta L(t)}{L} = \frac{1}{2}\hat{r}^a(t)\hat{r}^b(t)\int_{-\infty}^{\infty}\tilde{h}_{ab}(f)\mathcal{T}(f,t,\hat{\mathbf{k}})e^{2\pi i f(t-\Delta t)}df$$

Combine multiple links together. How?



a TDI “generation”



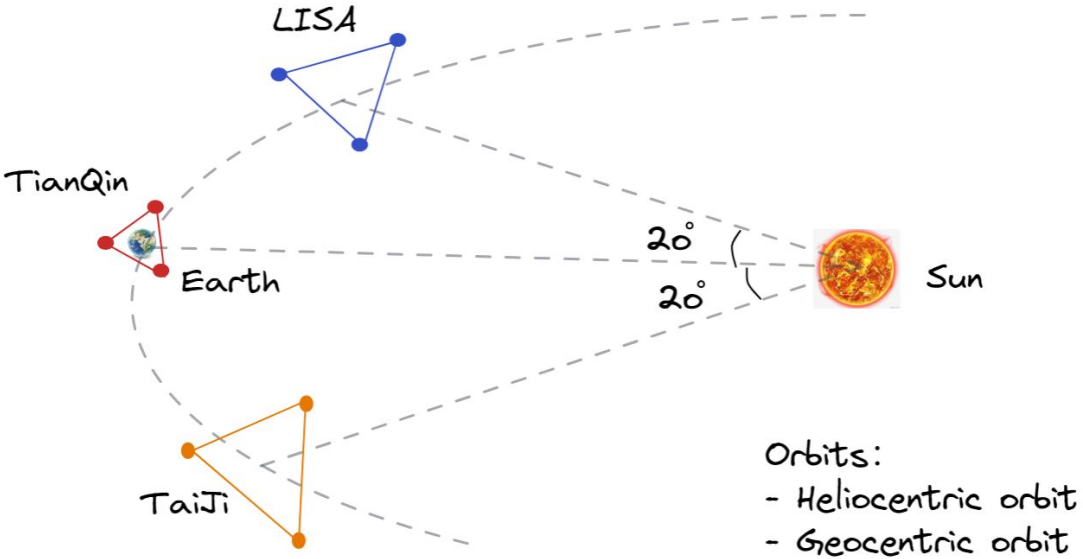
another TDI “generation”

...a never ending story...

Tinto, M., Dhurandhar
Time-delay interferometry.
Living Rev Relativ 24, 1
(and many others)

LISA's good company

太极计划 and 天琴计划



Schematic of the spacecraft's orbit in the SSB coordinate system.

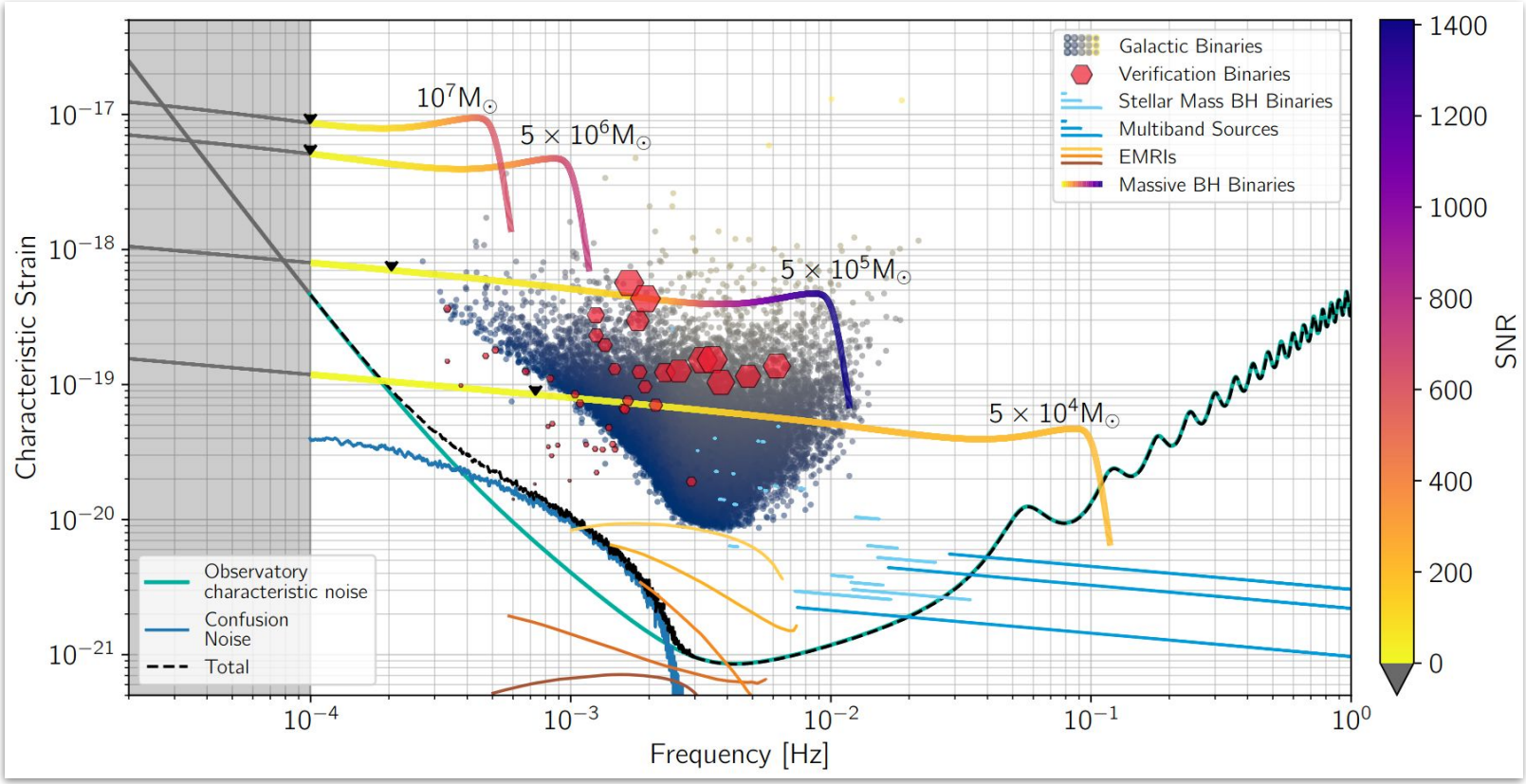
[gr-qc] 2309.15020

Relevant for:

- source localization
- SGWBs
- improved false alarm vetoing

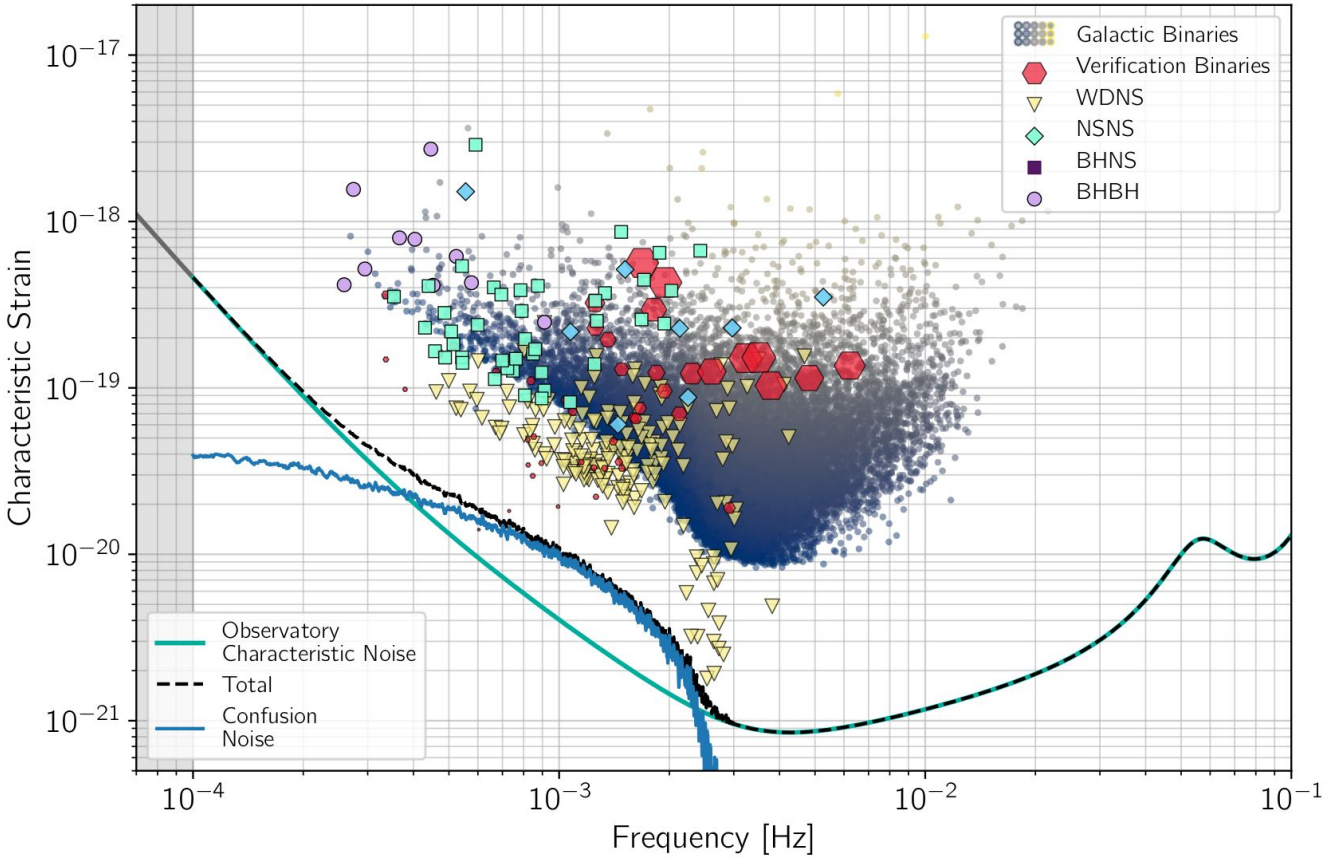
Expected sources

An astrophysical zoo



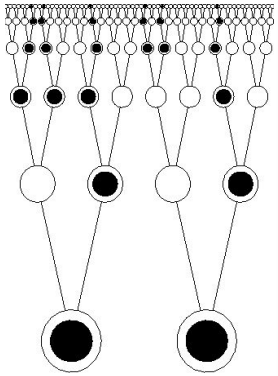
Expected sources

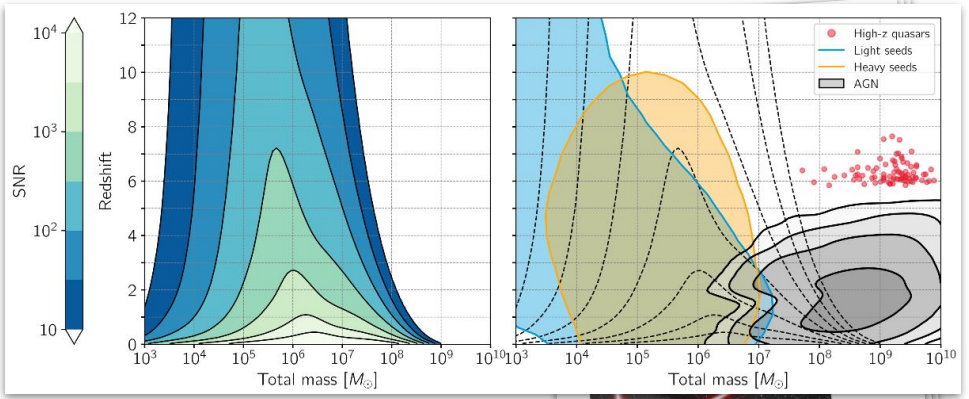
An astrophysical zoo

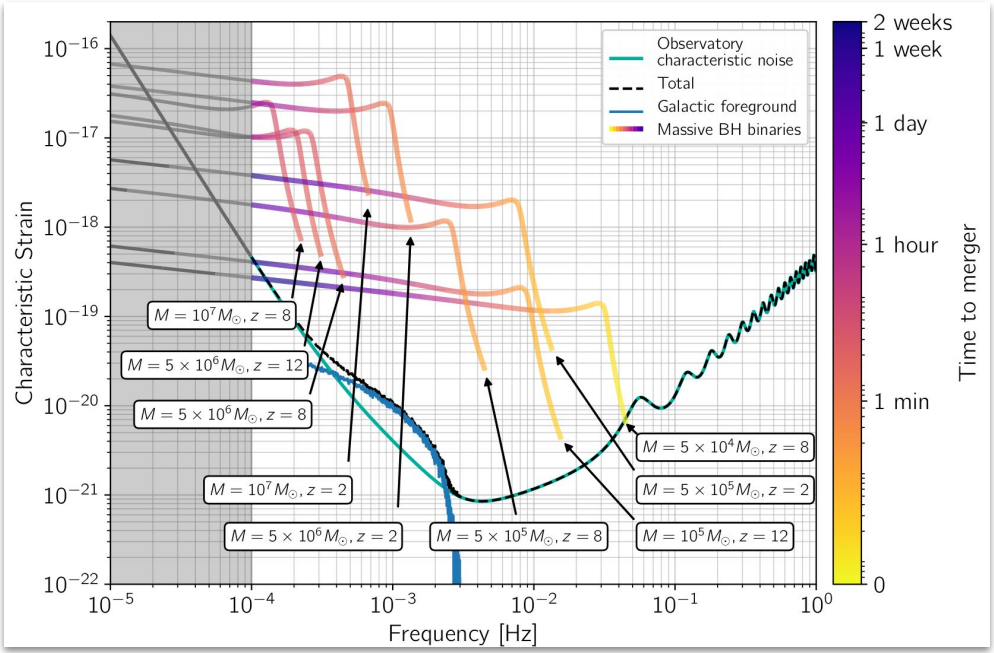


Expected sources

An astrophysical zoo

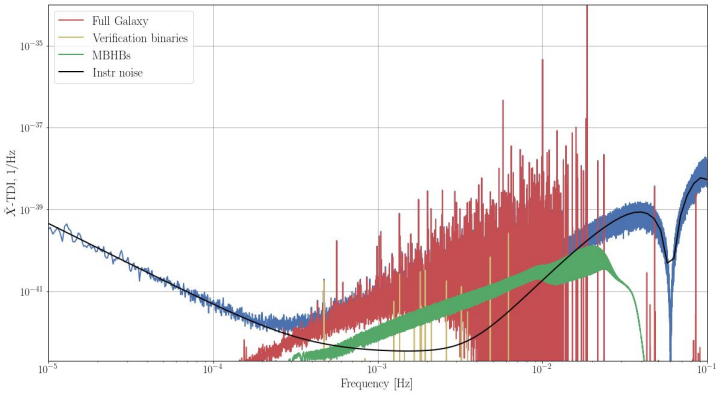




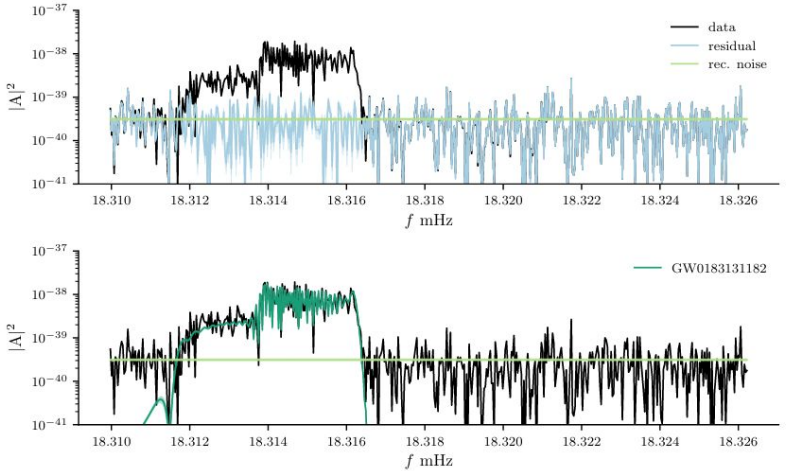


Double White Dwarfs

Get rid of resolvable ones..



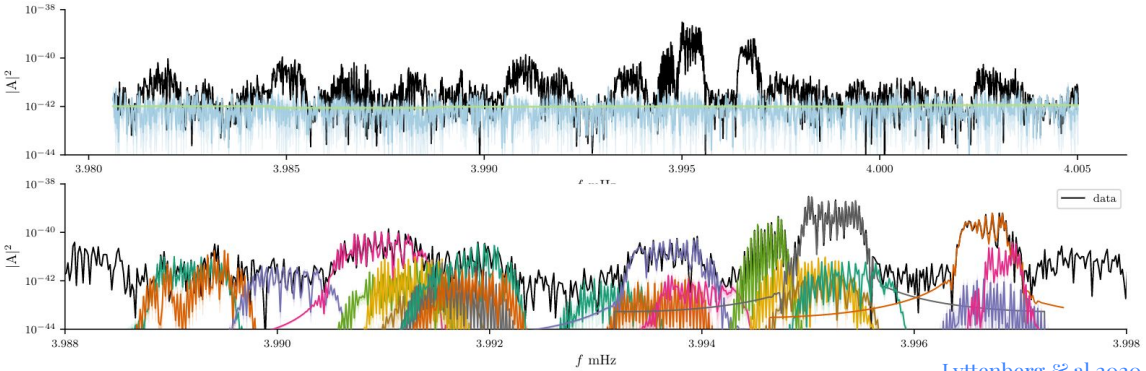
LISA Data Challenge



Lyttenberg & al. 2020

[more here]

[and here]



Lyttenberg & al 2020

Double White Dwarfs

...this is what you are left with.

RB, Klein, & al. (in prep)