

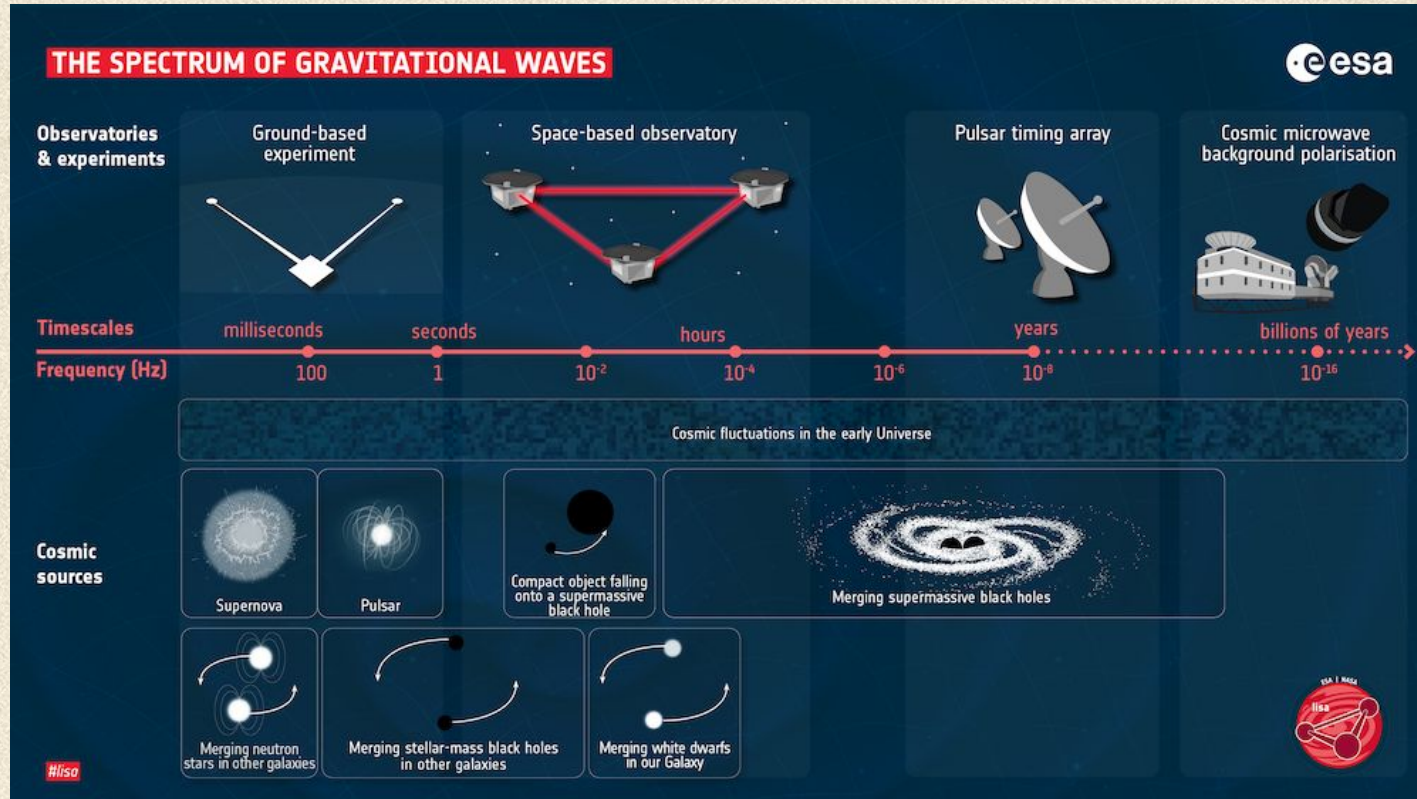
# Perspectives for low frequency gravitational waves astronomy

LISA and Pulsar Timing Array

Stas Babak, 5-6 October, 2026



# Gravitational wave landscape



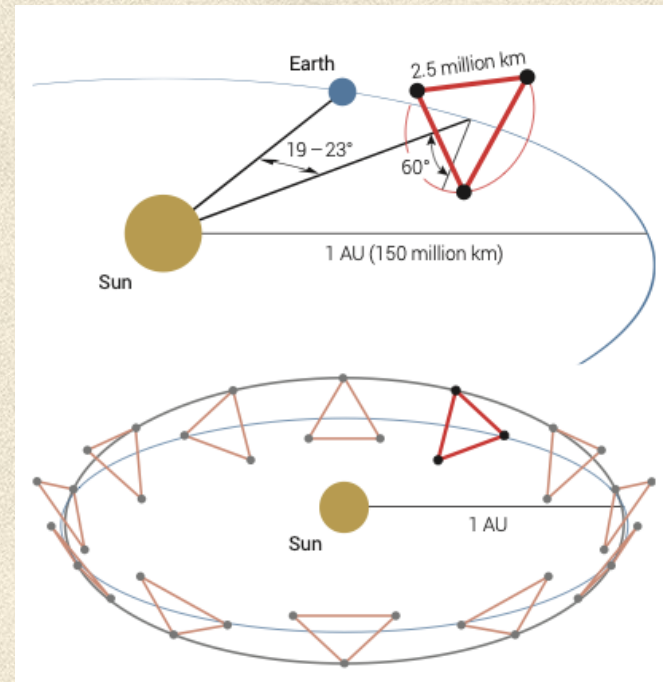
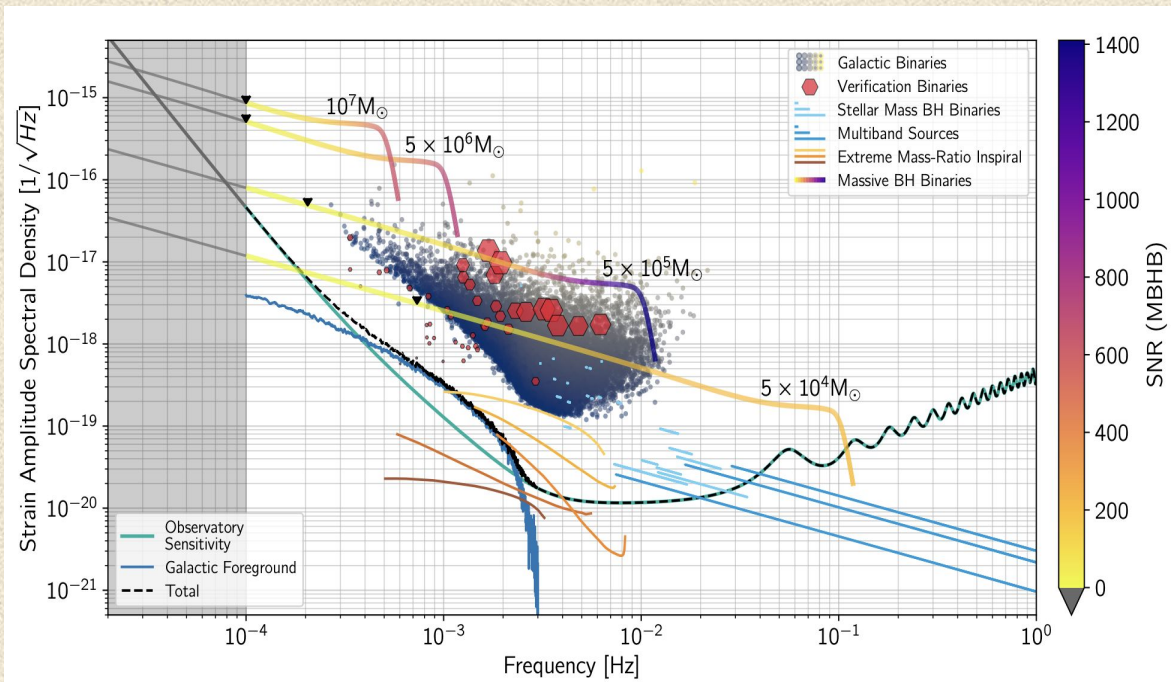
# LISA is not LIGO in space

- Small amount of data
- Data dominated by GW sources (overlapping in time and frequency)
  - Number of sources – parameter
- GW wavelength  $\sim$  detector size
  - Complicated response
- Armlength is not constant
  - Time-delay interferometry
- Strong long-lived source
  - Noise is non-stationary
- Sky position: Doppler + triangulation
- Glitches
- Have to work out of box
- Huge amount of data
- Rare transient (usually non-overlapping) sources
- GW wavelength  $\gg$  detector size
  - Simple response
- Constant armlength
  - Requires calibration
- Long-lived sources are weak
  - Noise locally stationary
- Sky position for transients: triangulation
- Glitches
- Can fix problems by getting inside



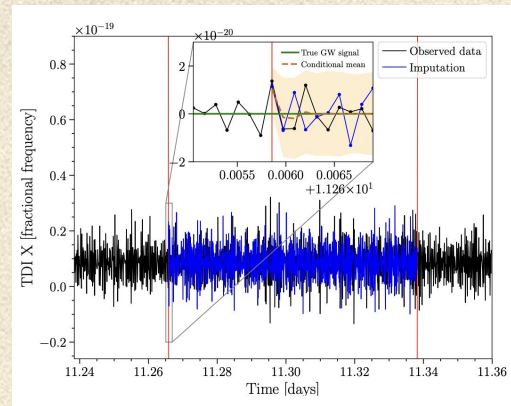
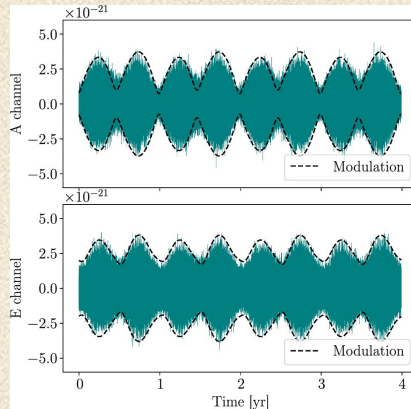
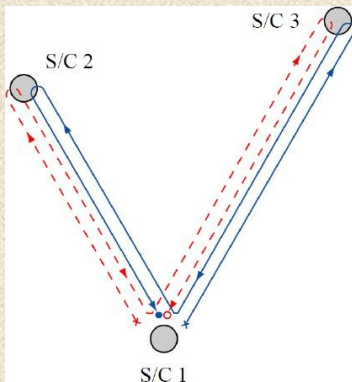
N. Cornish

# LISA sources



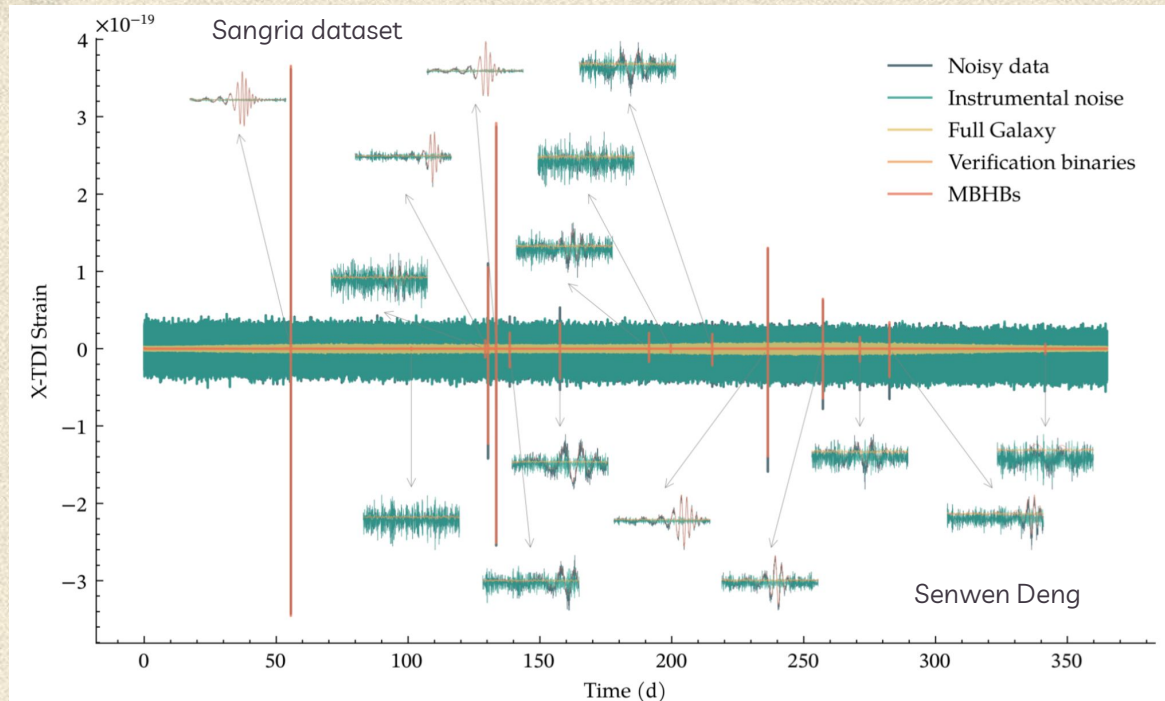
# Challenges in LISA

- Arms are function of time:
  - Not trivial procedure to cancel laser frequency noise: Time delay interferometry
  - Makes noise non-stationary
- Population of Galactic sources create anisotropic and non-stationary foreground
  - We will use time-frequency approach, assuming that the noise properties are smoothly & slowly changing in time
- Gaps in the data (scheduled and not)
  - Time-frequency formulation helps
  - Filling the gaps



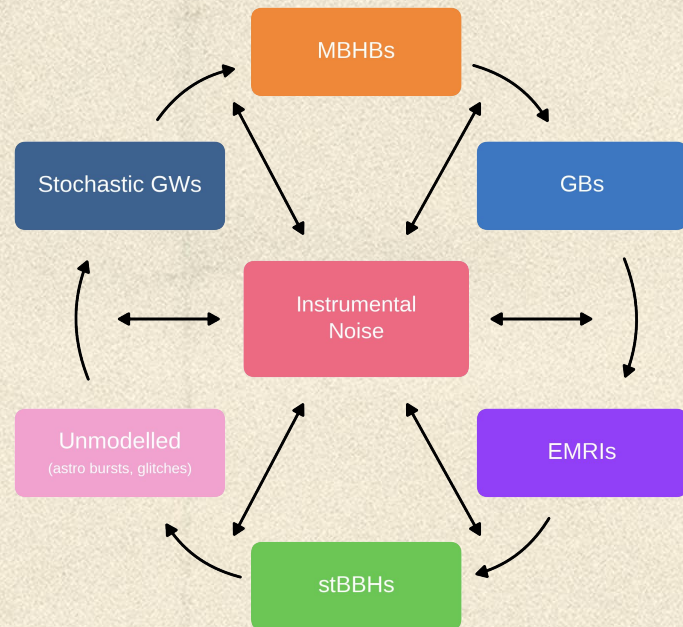
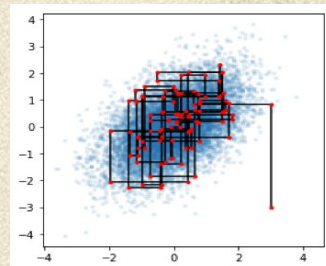
# Challenges in LISA: data analysis

The data is signal dominated. We need to detect and characterise (parameter estimation) all of them simultaneously present in the data



# LISA global fit

- We assume that the GWs of different type weakly correlate with each other
  - (block) Gibbs sampling approach: works *efficiently* work weakly correlated components
- Within sources of the same type we use parallelisation if (we think) sources are not-correlated
- Population of binaries could be observed as resolved (individual sources) and unresolved (stochastic) sources: the informative prior connects them [Toubiana & Gair 2026, Criswell+ 2025, 2026]



# Pre-merger search for MBHBs

## Peeling off overlapping black-hole binaries

### 1 • Search the data

**BBH-3** (SNR 3356) found before its merger at 3201 h

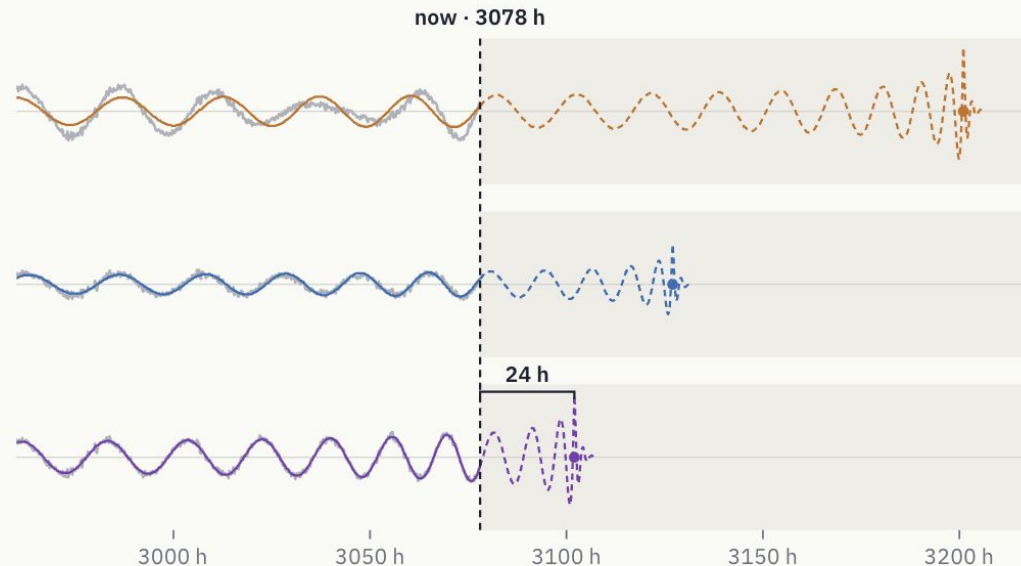
### 2 • Subtract BBH-3

**BBH-2** (SNR 2098) emerges; merger at 3127 h

### 3 • Subtract BBH-2, -3

**BBH-1** (SNR 339) found 24 h before its merger at 3102 h

Grey: data · colour: found signal · dashed: not yet observed

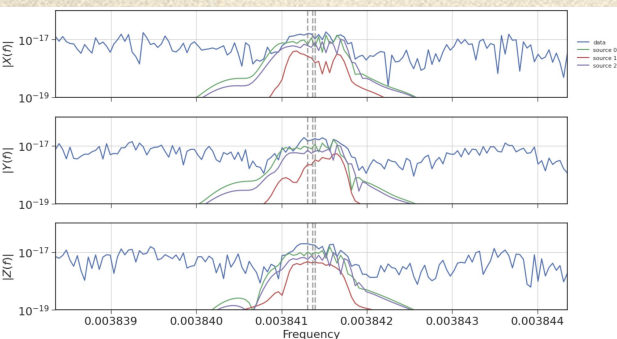


1. We first detect (pre-merger) MBHB-4,
2. then detect (after subtracting MBHB-4) MBHB-3,
3. after subtracting MBHB-3,4 we detect MBHB-2 24 hours before the merger

# Trans-dimensional sampling

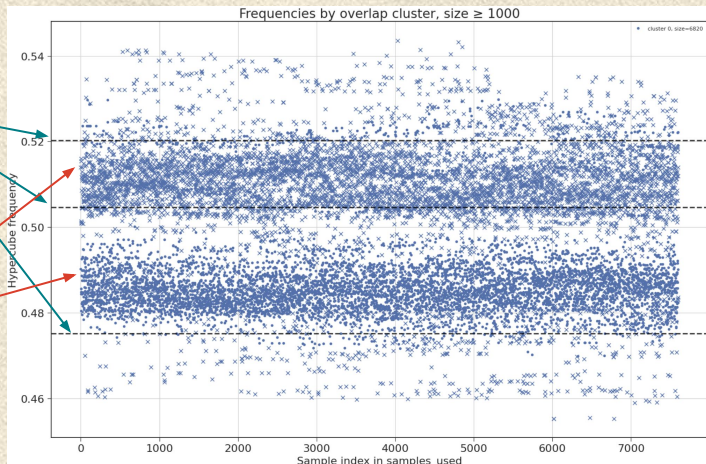
Number of sources is random variable to infer from the data

Three Galactic binaries, close in freq.

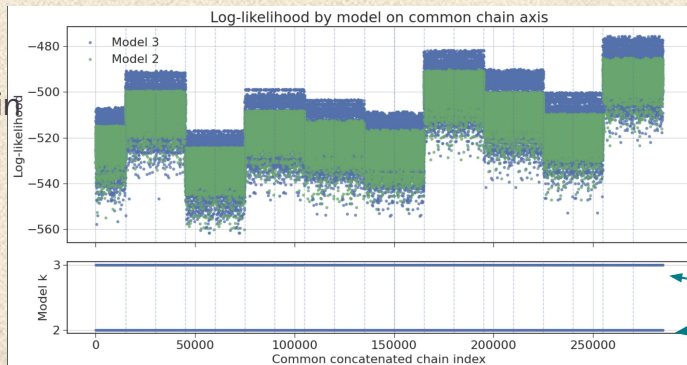


Frequencies of true GBs

Frequencies of M2 GBs (2-sources)



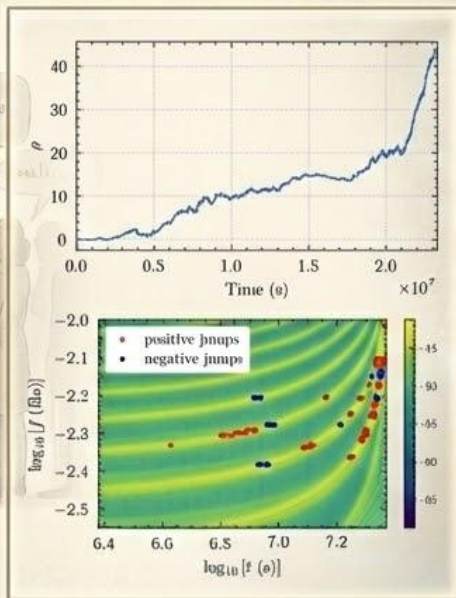
We are testing for 1, 2, 3 sources in the data: Bayes factors



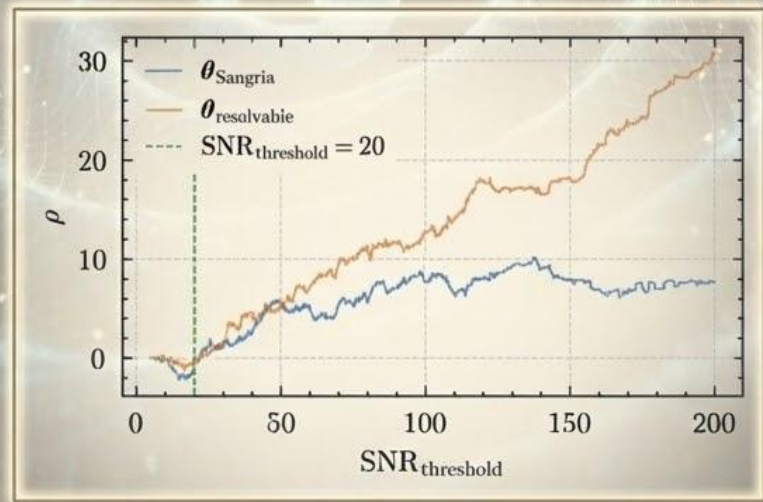
Bayes factor = 1  
comparing 2 and 3 sources

# Correlations: Chat between EMRIs and GBs

- They do not talk to each other, but EMRI like a tourist in a crowd on the main square: hear some words here and there and sometimes they random combination make sense
  - Overlap (correlation) between an EMRI and a single GB is very small (could be amplified by a GB's amplitude)
  - Correlation: cumulative effect of interaction of EMRI with many (resolvable) strong GBs

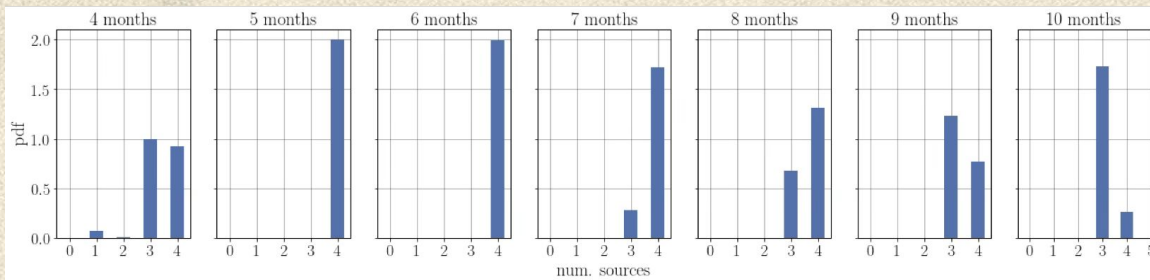


<https://arxiv.org/abs/2509.20062>

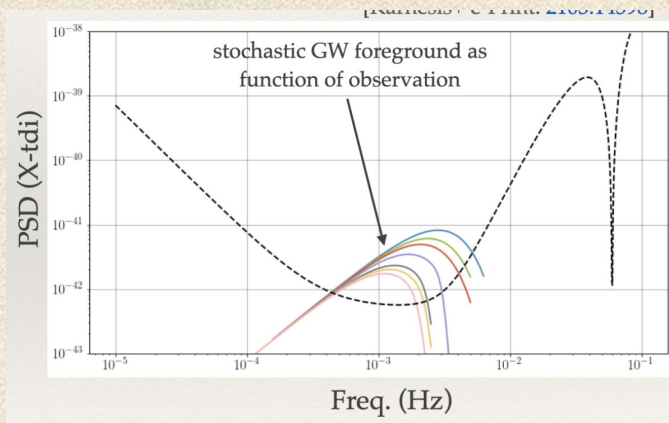
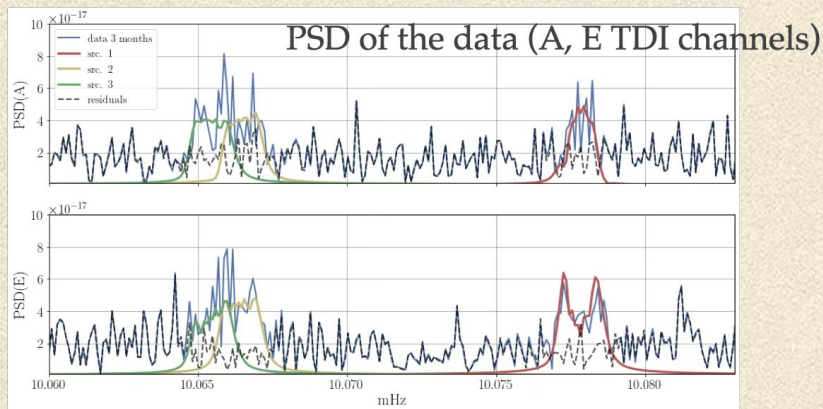


# Time iterative analysis: GBs

- Take a narrow band next to 10mHz: 3 GW signals
- Perform time-data adaptive (4 months, 5 months, ... 10 months) search
- Consider 4 models: 1 GW source, 2 GW sources, 3 GW source, 4 GW sources



Probability of having N-sources in the data using different data duration



# Pulsar Timing Array



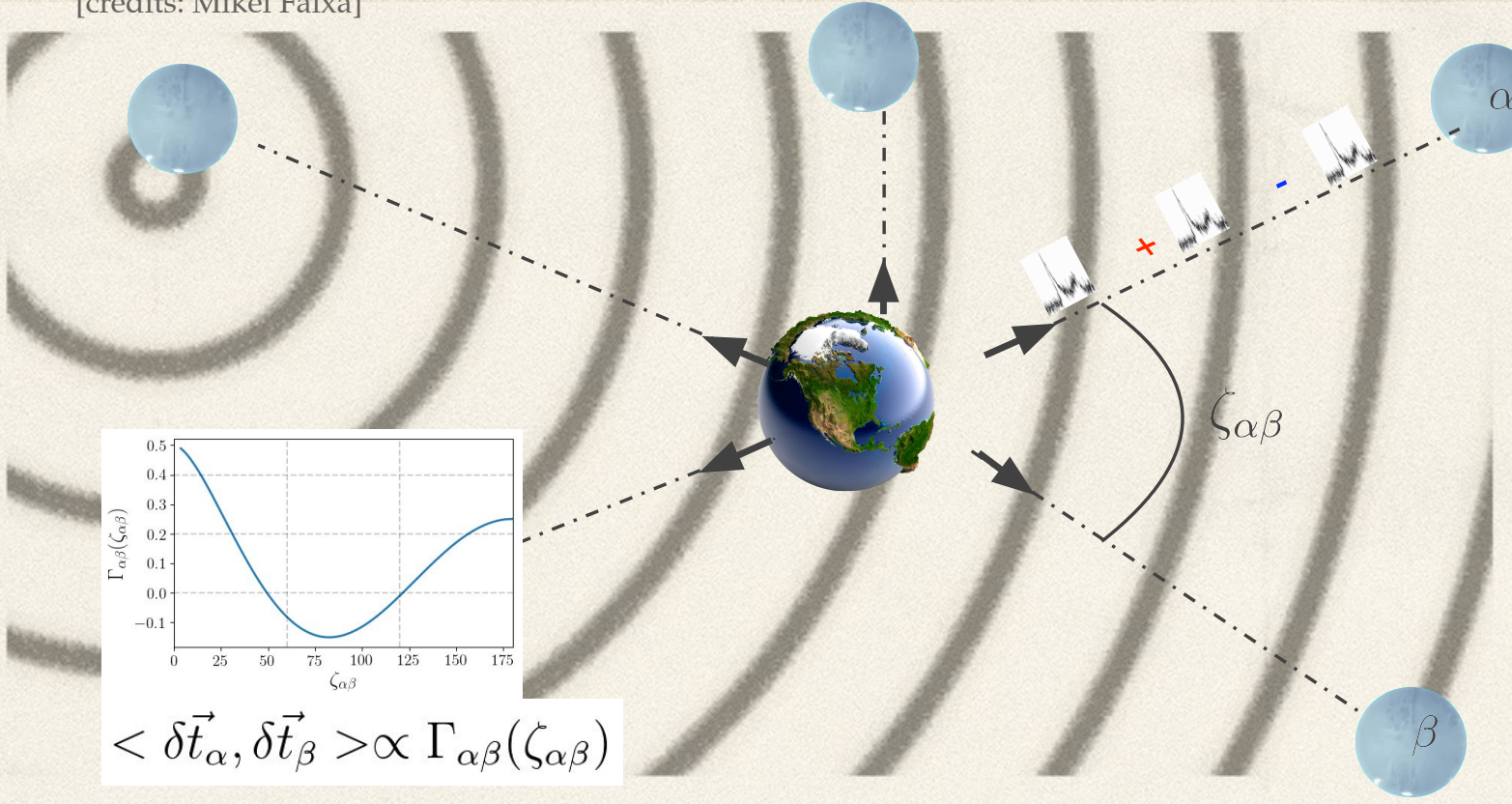
# Modelling PTA data

- We measure time of arrival (ToA) radio pulses: the difference between expected and measured ToAs = *residuals*
- Timing model: deterministic model for the residuals:
  - interaction of e/m (radio) with interstellar medium
  - Pulsar spin-down
  - Propagation delays: Shapiro, Romer
  - Proper motion, orbital motion (pulsars in binaries), sky position
- Noise modelling:
  - White noise: measurement (mostly)
  - Red noise:
    - Individual to each pulsar
    - Common process but independent
    - Variation in dispersion and scattering (Radio-freq. Dependent → “chromatic”)
  - Error in ephemerides
- GW signal....

# Pulsar Timing Array



[credits: Mikel Falxa]

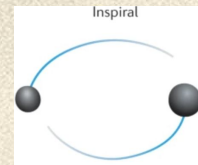


$$\langle \delta \vec{t}_{\alpha}, \delta \vec{t}_{\beta} \rangle \propto \Gamma_{\alpha\beta}(\zeta_{\alpha\beta})$$



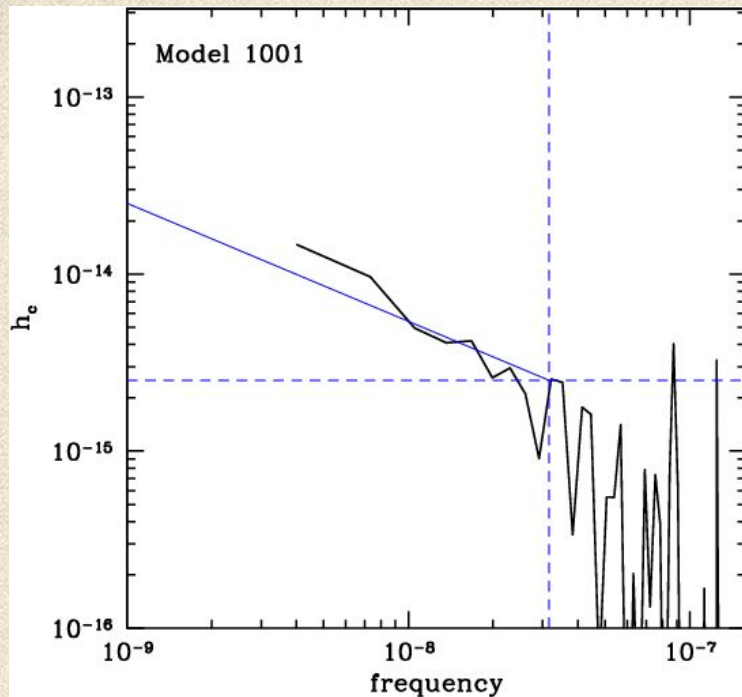
# Individual GW sources: CGW

- Particularly massive and close binary could be detected individually: continuous and small evolution in frequency
- Strategy: all-sky search with simplistic model -> follow up candidates relaxing simplified assumptions on the reduced prior range

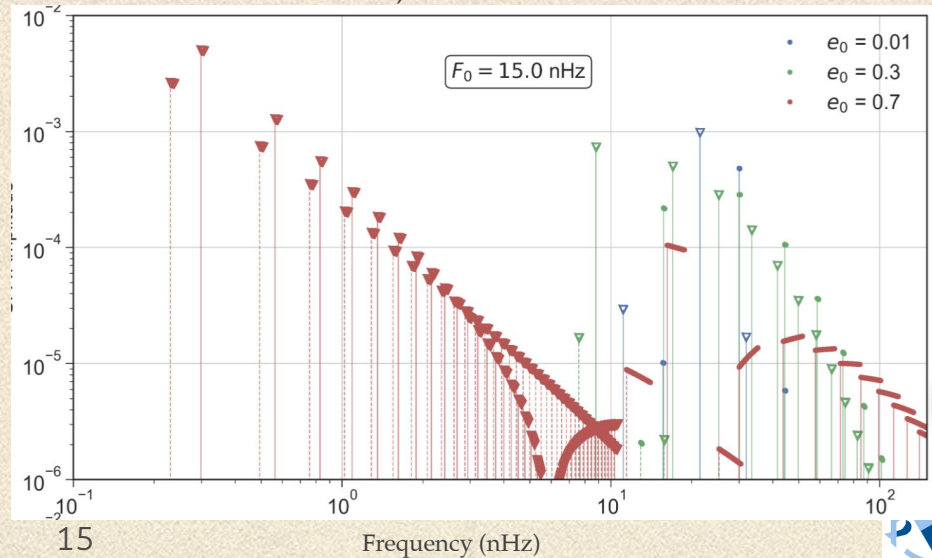


[NG: 2306.16222]

[EPTA+InPTA: 2306.16226]



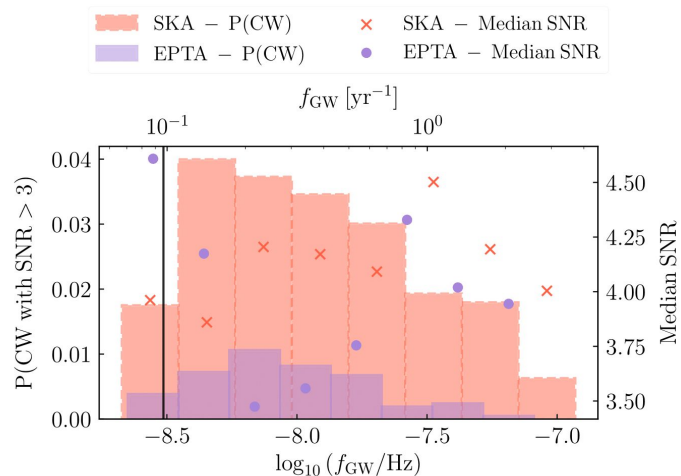
Manzini & Babak 2025, 2511.19611



# Expectations based on Horizon-AGN



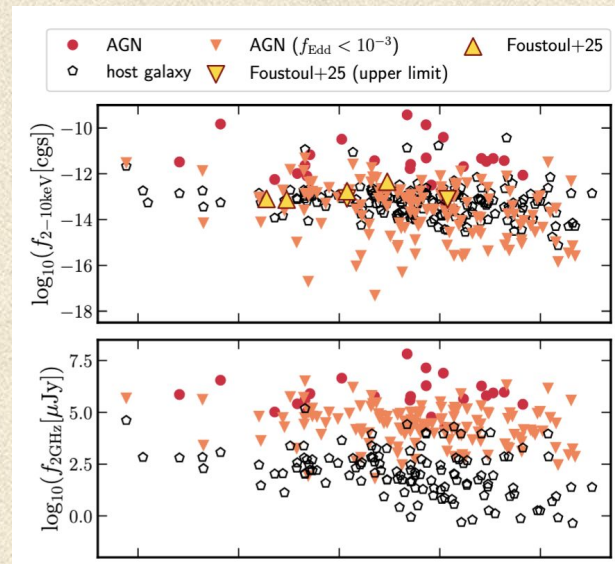
[Quelquejey+ 2025]



- Probability of finding at least one CGW
- Median SNR of CGW (in case of detection)
- Current PTA: 10-15 % chance to detect individual SMBHB,
- SKA: 30-40% chance to detect individual SMBHB (>5 years of observation)

Prospectives of e/m identification of SMBH

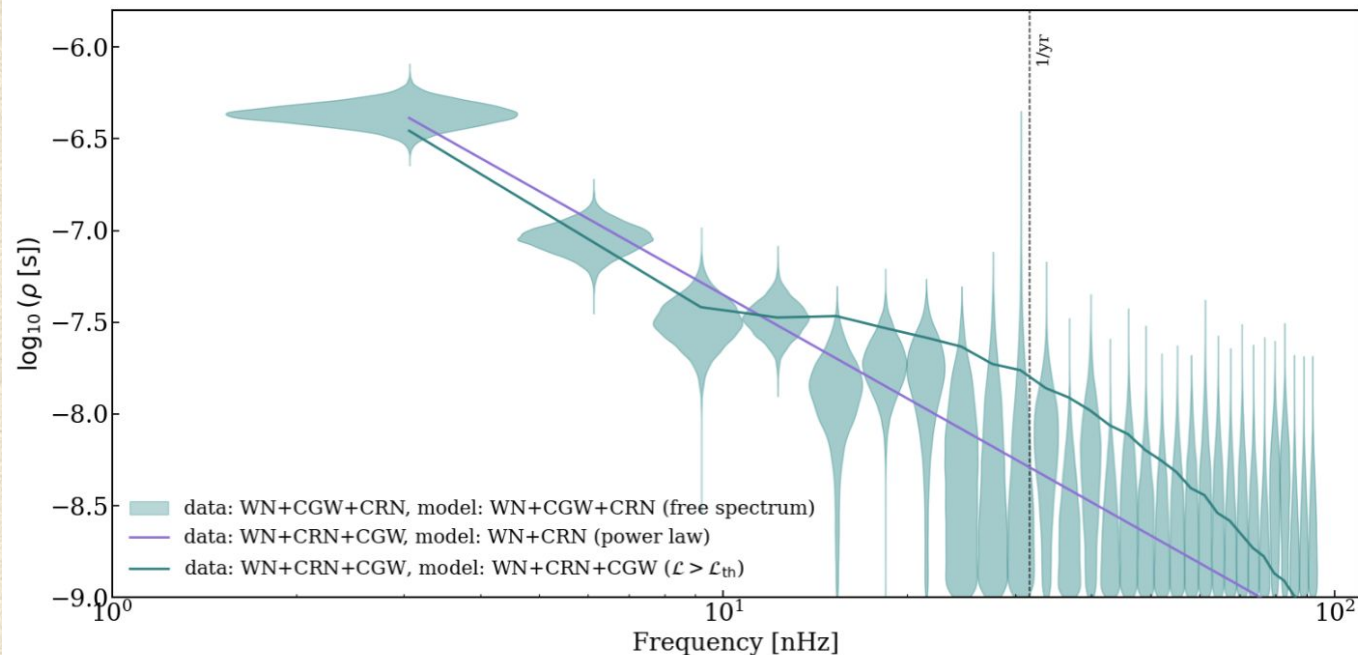
- If there is a gas: AGN (faint)
- Most likely to see (outshine the host galaxy) in radio(X-ray)



# Correlation between SGWB and eCGW



- CGW is covariant (correlated) with the stochastic GW background (SGWB)
  - Easier to disentangle individual sources at high(-ish) frequency (white-noise dominated regime)
  - Need PTA (many pulsars) to get the sky position and (potentially) individual masses



# Global fit in PTA

We need global fit in PTA:

- timing model + noise modeling + GWs.
- Uncertainty in the composition of the noise components
- Pulsar-specific choices.
- Current data: many pulsars & long observations
- Data combinations
  - Accurate and fast way of combining data from many radio telescopes?
  - Timing model evolution, unreliable observations with small error-bar.
- Significance estimation?
  - Sky shuffle, phase shuffle

## IPTA DR3 dimensions



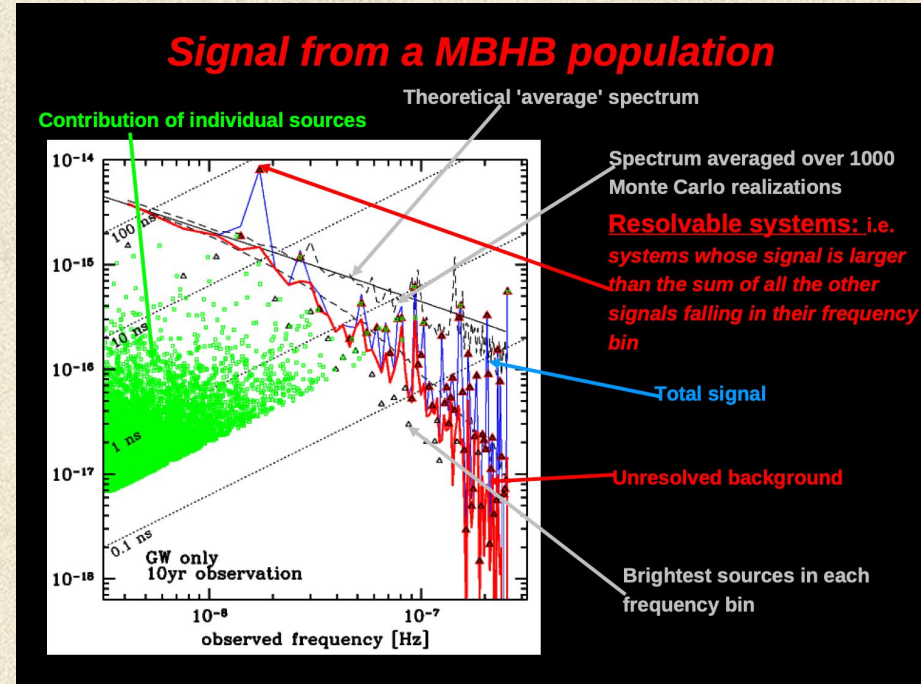
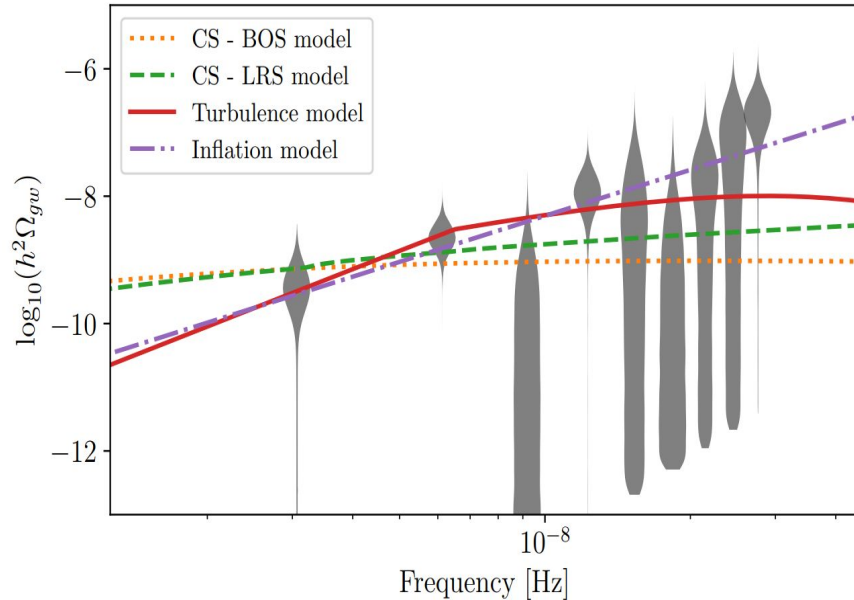
- In total **121** pulsars in full DR3;
  - The biggest / most sensitive PTA dataset ever made !!

| Dataset        | Number of pulsars | Time span | Frequency range |
|----------------|-------------------|-----------|-----------------|
| EPTA DR2       | 25                | 24.5 yr   | 283 – 5107 MHz  |
| NANOGrav 15-yr | 68                | 15.9 yr   | 302 – 3988 MHz  |
| PPTA DR3       | 24                | 18.1 yr   | 704 – 4032 MHz  |
| InPTA DR1      | 15                | 3.5 yr    | 300 – 1460 MHz  |
| MeerKAT DR2    | 83                | 4.5 yr    | 856 – 1712 MHz  |
| CHIME DR1      | 11                | 2.5 yr    | 400 – 800 MHz   |
| LOFAR+NenoFar  | 17                | 9.6 yr    | 35 – 190 MHz    |
| IPTA DR3       | 121               | ~25 yr    | ~30 – 5000 MHz  |

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# Interpretation

PTAs observe an emerging GW signals: what is it? Is it stochastic or CGW? What sources it?

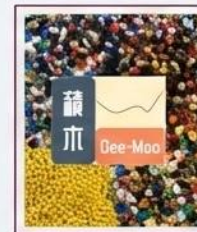
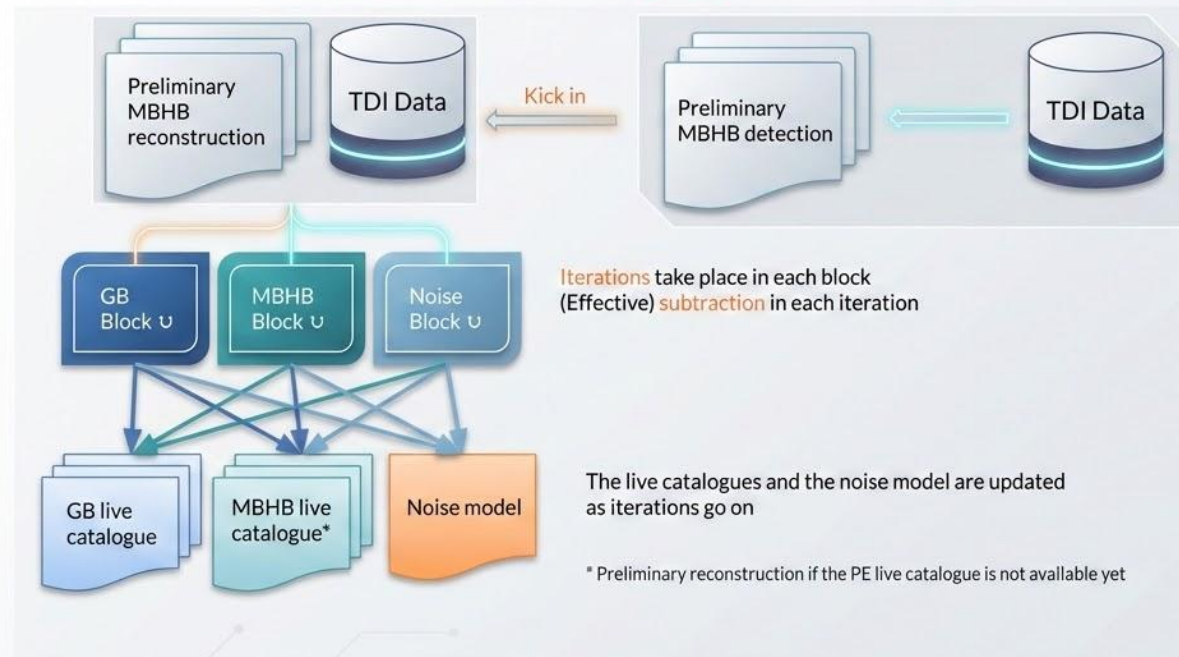


[Credits: Hippolyte Quelquejay]

# Summary

- LISA is reality, launch is 2035 (= tomorrow)
  - Simulated data increasing in realism
  - Many data analysis and post-analysis interpretation challenges
  - Get into the game now!
- PTA
  - IPTA and EPTA new data is ready for analysis
  - Continuous GW signal from individual binaries
  - Interpretation of the stochastic GW signal
  - SKA is coming next

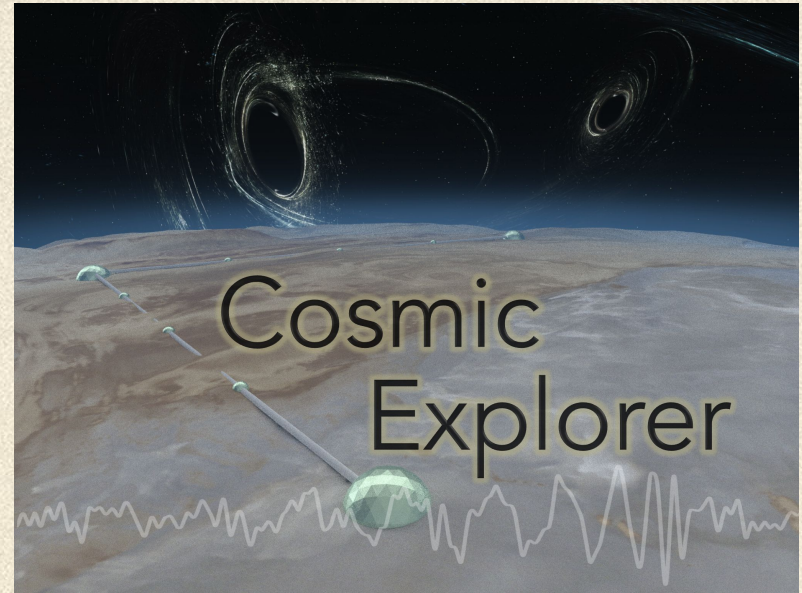
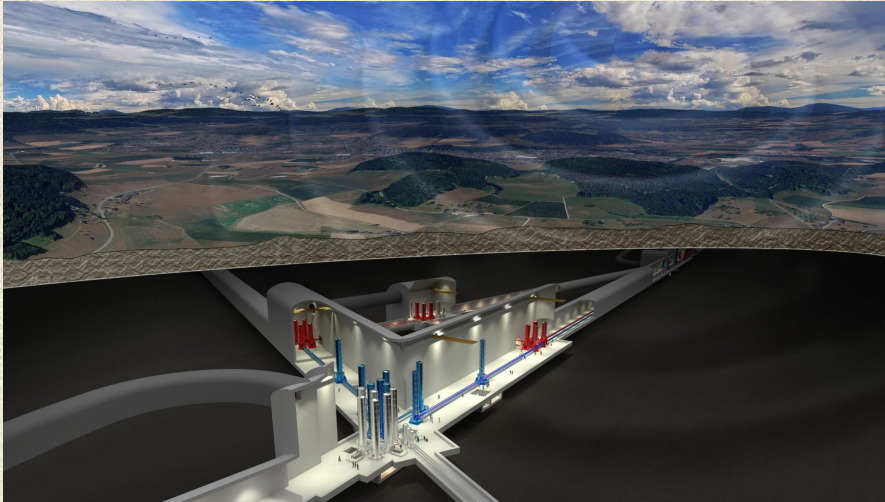
# Global fit pipeline (Gee-Moo)



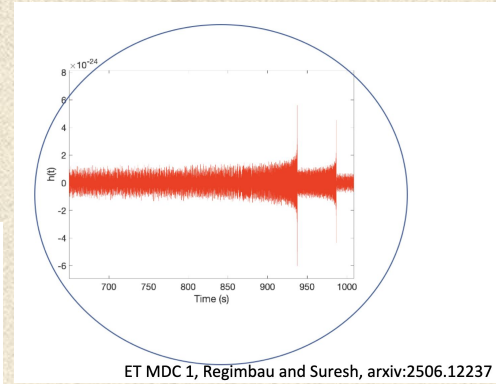
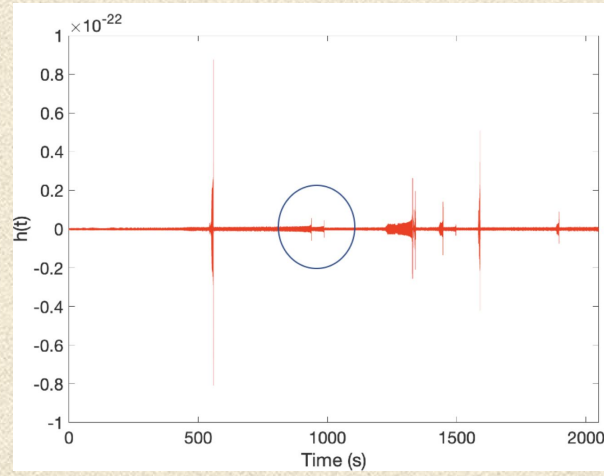
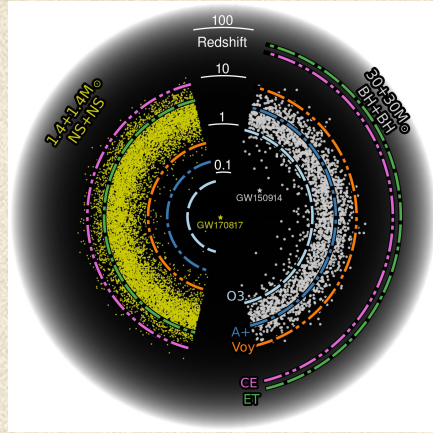
-  Several stages
-  Search for the "candidates"
-  Initiate the candidate/block
-  Maintain the "live catalogue" of sources and noise

# New generation of ground-based detectors: generation-X

Einstein Telescope



- What search means
- Significance
- BNS merger – a lot of info: eos, (model dependent) measure of intrinsic mass -> cosmology
- Multimessenger – early detection – challenge in source dominated data
- Very sensitive device – GW background → foreground.
- Population study
- Multi-band observations
  - LISA (inspiral) → ground based (merger)
  - Ground based (merger) → archival search in LISA data
-



## Binary neutron stars: detections and impact

| What CE delivers                                                                              | Scientific impact                                                                                                         |
|-----------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| BNS out to $z \approx 2$ with one CE (three A#: $z \approx 0.3$ )                             | Merger rates and delay times across the star-formation peak → history of heavy-element enrichment                         |
| Hundreds of BNS per year at SNR > 100 (two CE)                                                | Precise masses and spins → NS mass function across cosmic time and environments; binary-evolution physics                 |
| BNS to $z \approx 2$ localized to < 10 deg <sup>2</sup> ; nearby ones to < 1 deg <sup>2</sup> | Hosts and counterparts at scale → link progenitors to r-process outflows and jets; short-GRB origins beyond $z \approx 2$ |
| Alerts minutes before merger                                                                  | Light from the first moments: early kilonova, jet launch, possible FRB from a collapsing hypermassive NS                  |
| Thousands of BNS per year with < 10% distance errors                                          | $H_0$ to < 1% in under a year, independent of the distance ladder → handle on the Hubble tension and dark energy          |

Source: Cosmic Explorer white paper to the NSF MPSAC ngGW subcommittee (CE-P2300018-v3, June 2023); Fisher-matrix forecasts

Confidence in unmodelled and burst signals (§1.3, §3.2). For supernovae, magnetar flares, glitch-induced f-modes and other poorly modelled transients, "it is crucial to have multiple GW observatories to provide confidence through coincident detection". The authors use this as an argument for several XG detectors.

## Dense matter: measurements and impact

| What CE delivers                                                       | Scientific impact                                                                                                         |
|------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------|
| NS radii to < 100 m per event; ~10 m over the population               | Mass–radius and pressure–density relation of cold matter above nuclear density; features can reveal QCD phase transitions |
| Post-merger kHz signal, ~1 per year at SNR > 5 (A#: ~500 yr)           | First view of hot, rotating, magnetized dense matter beyond the reach of colliders; a test for deconfined quarks          |
| Prompt collapse vs. surviving remnant                                  | Threshold mass for collapse → maximum NS mass; sharper kilonova and supernova-engine models                               |
| Tidal deformability across thousands of BNS                            | Unexplained scatter with mass, age or environment would signal dark matter in NS cores                                    |
| Continuous waves from dozens of pulsars, f-modes, a Galactic supernova | Cold EOS of other NS populations, crust elasticity, viscosity, internal fields; proto-neutron-star EOS                    |

Source: CE white paper (CE-P2300018-v3, June 2023); Fisher forecasts assume the APR4 EOS; waveform systematics not included

- at  $z = 10$  seen by a single XG detector would be essentially unlocalized, with a distance error of about 50%. That translates into a redshift error of  $\pm 4$  and, because of the mass–redshift degeneracy, about a 40% error on the source-frame masses. High-redshift population studies therefore require at least two XG detectors, and good localization of most sources requires three.
- Early warnings, such as 10 BNS detected 300 s before merger with  $\Delta\Omega < 10 \text{ deg}^2$ , require low-latency detection and localization.
- Waveform systematics. (common with LISA for BBHs)
- Overlapping signals. With roughly  $10^5$  BBH and many more BNS in band per year, signals overlap.
- Long in-band durations. BNS signals last hours below 10 Hz, which raises the cost of searches and parameter estimation.
- Noise artefacts. Non-stationary noise and glitches.
- Computational cost. Bayesian inference for millions of events per year.
- Global fitting. Separating resolvable sources from the residual background, a ground-based analogue of the LISA global fit.