First results from a LISA end-to-end simulation and analysis pipeline

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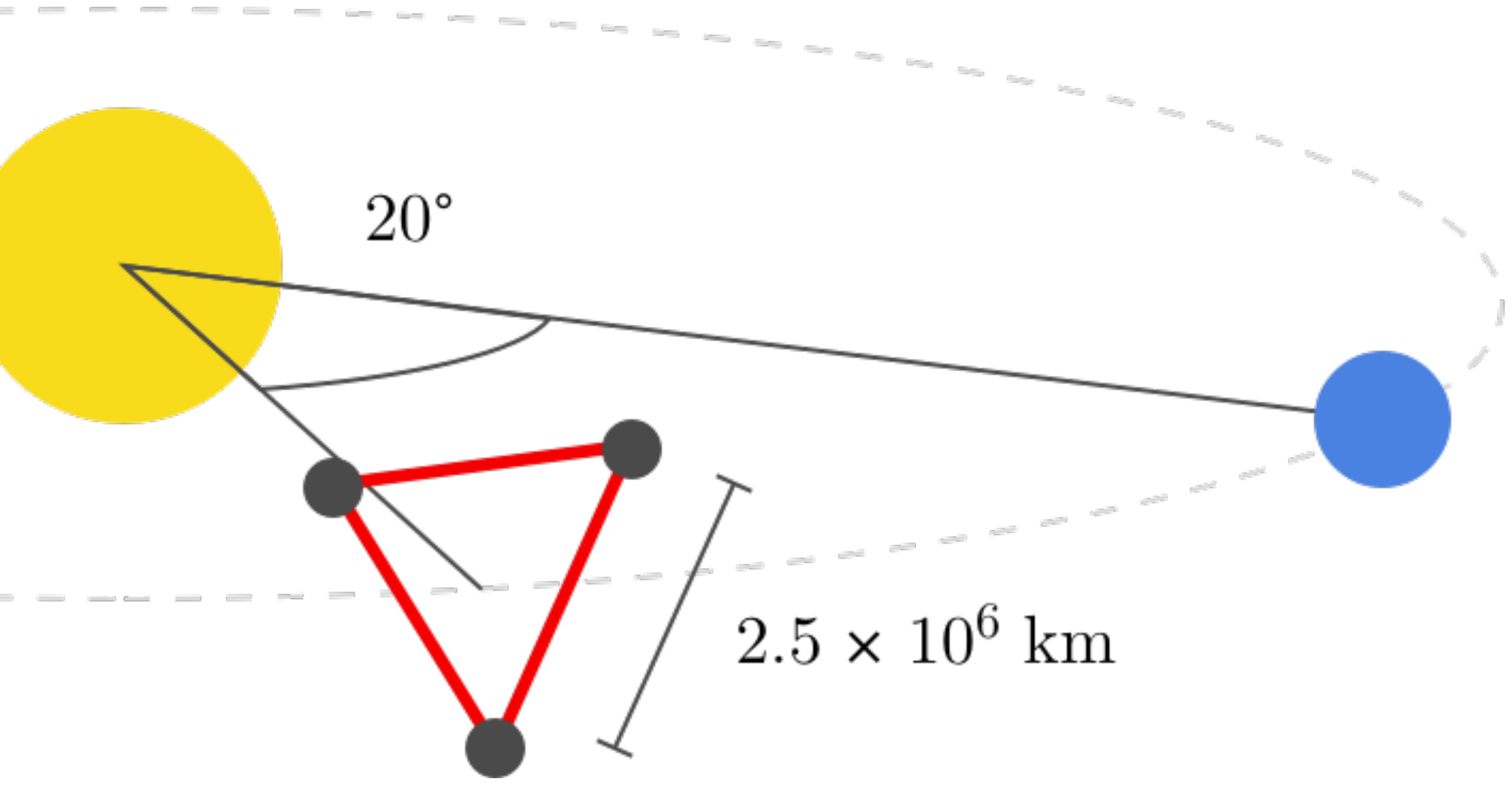
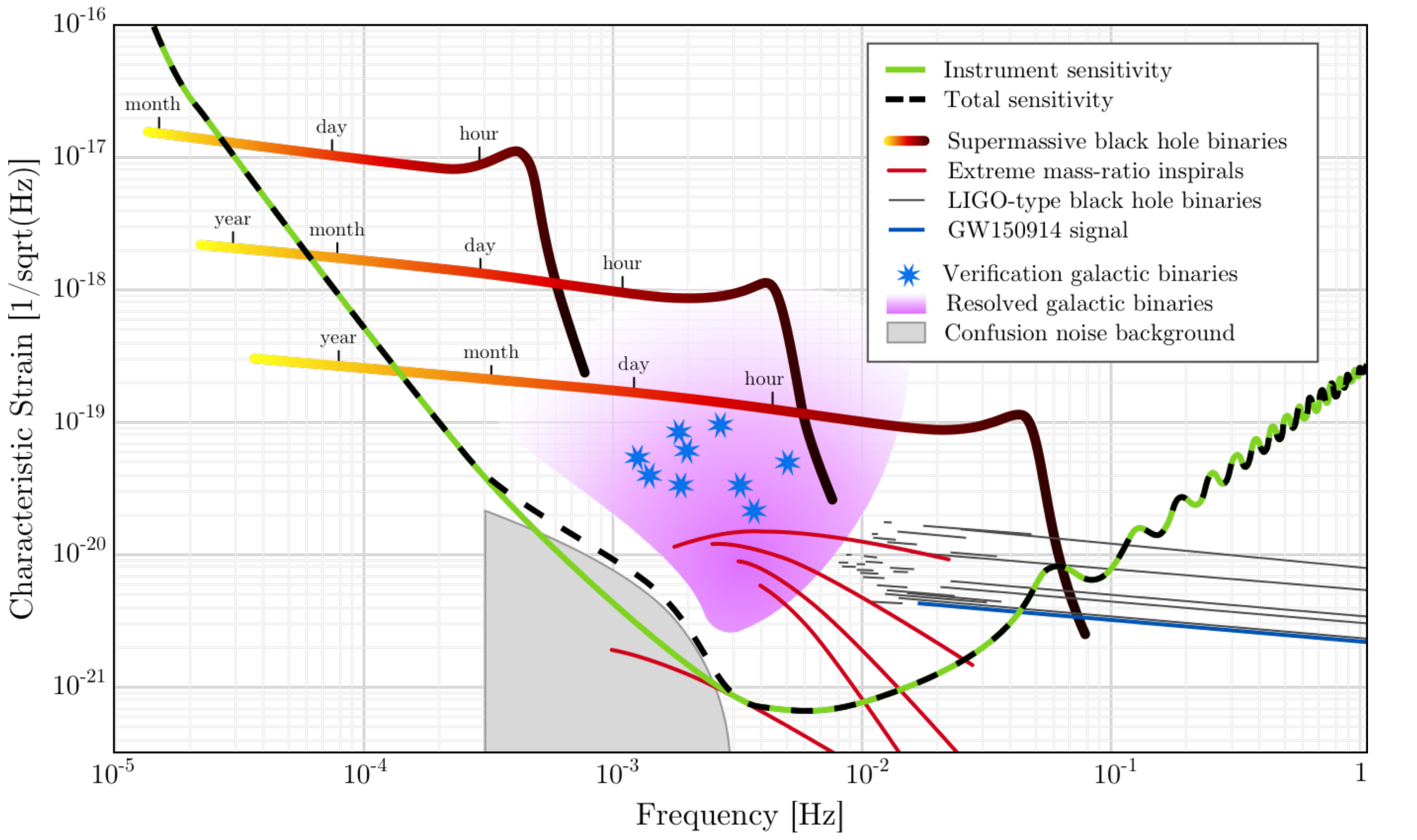
Context

LISA in one (busy) slide

- ESA-led **space-based mHz GW observatory** with launch planned in the mid-2030s





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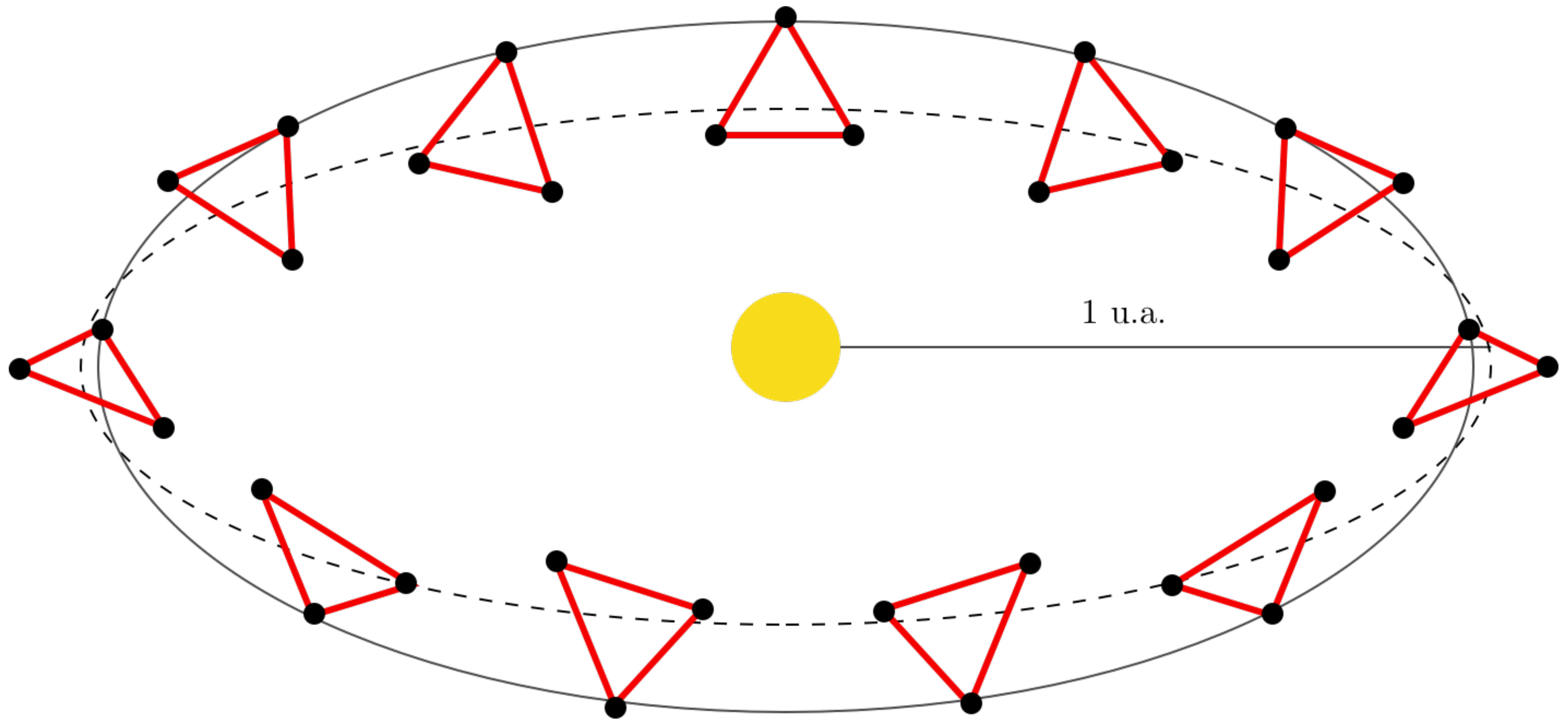

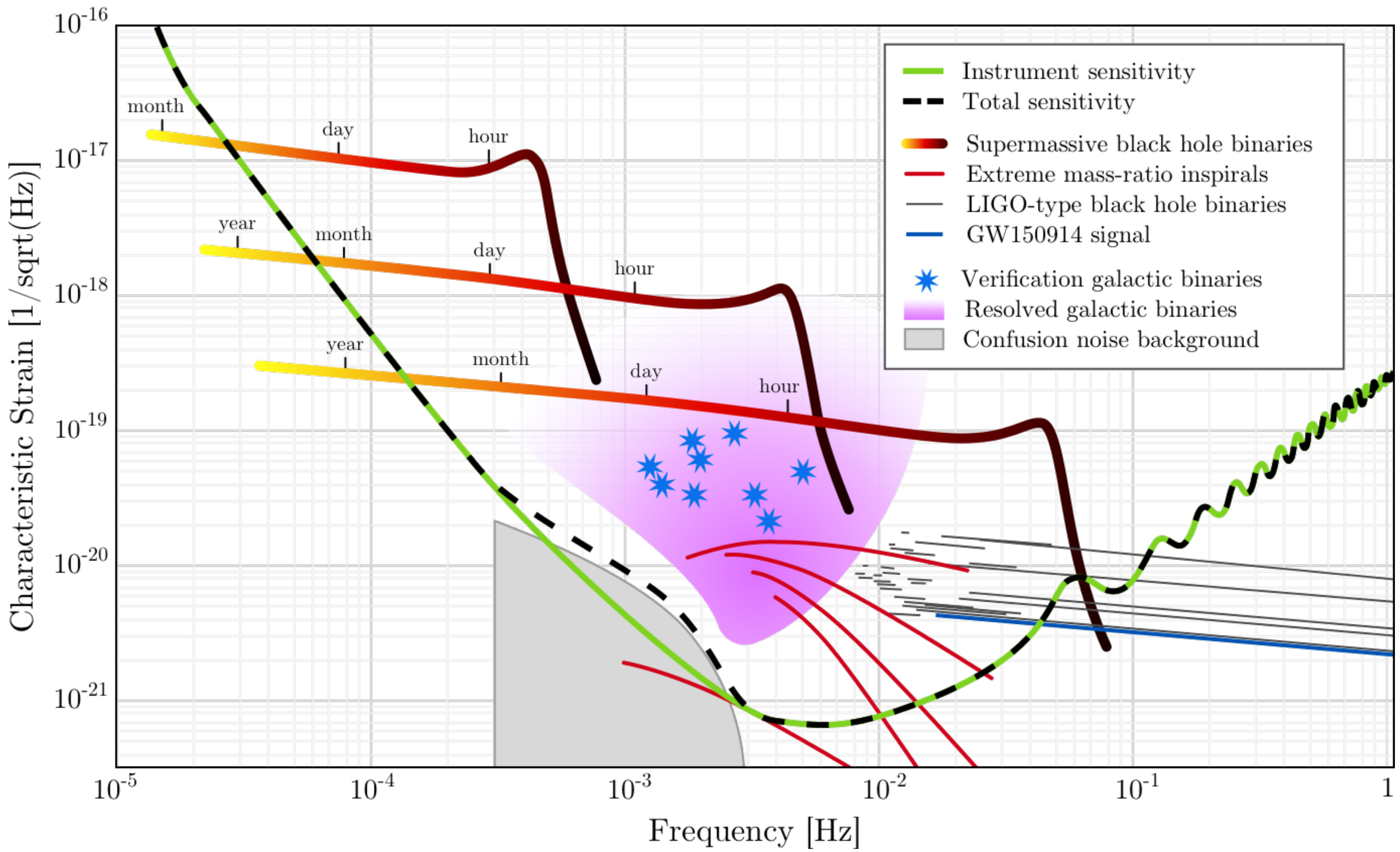

LISA in one (busy) slide

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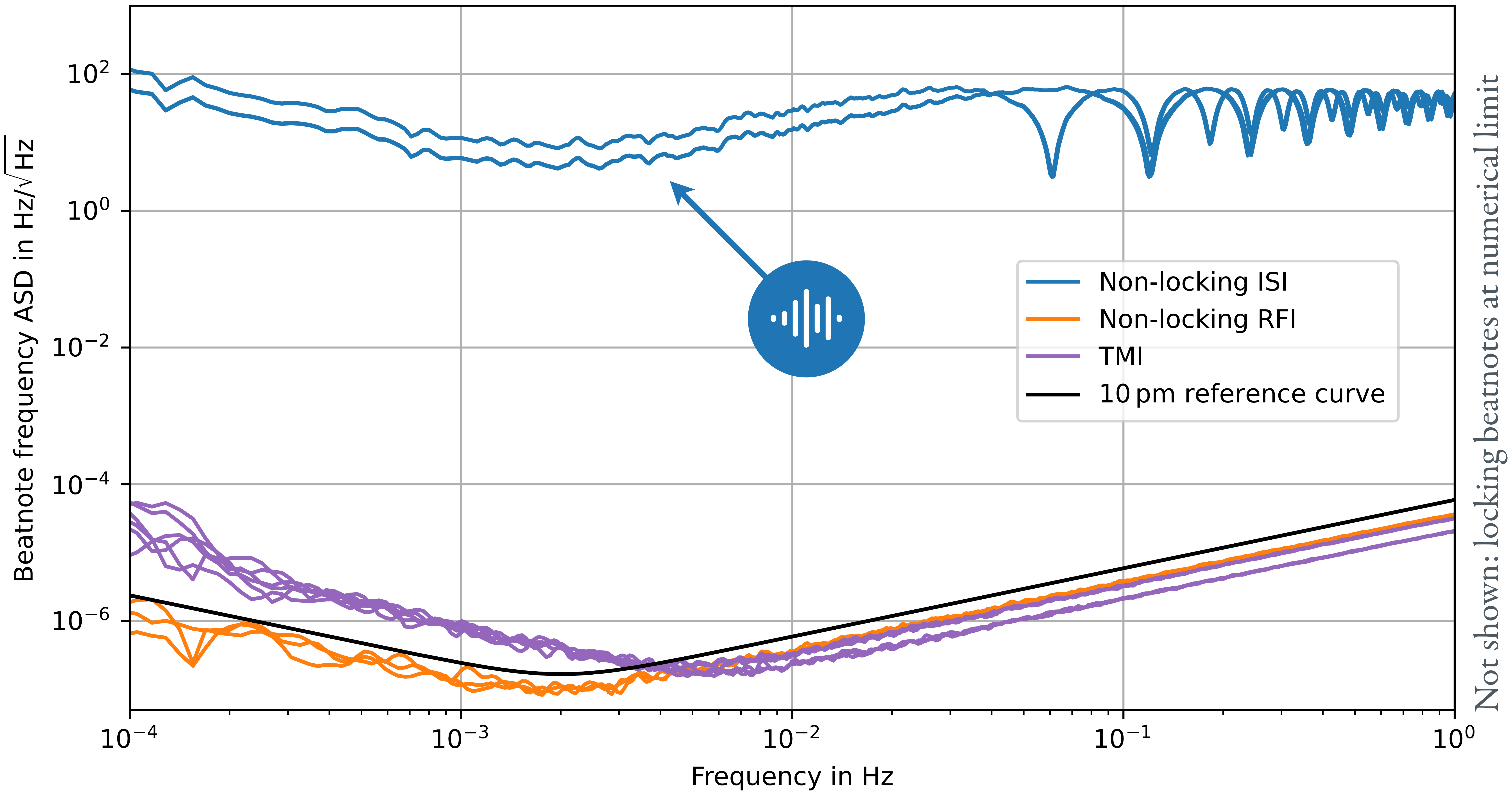
Some challenges for data analysis

- **Laser frequency instabilities swamp the measurements**



Some challenges for data analysis

- **Laser frequency instabilities swamp the measurements**
  - Orbital dynamics cannot maintain equal arm lengths
  - Laser noise many orders of magnitude above expected signals
  - TDI synthesizes equal-arm interferometer measurements on ground
  - Requires good knowledge of inter-spacecraft distances

Some challenges for data analysis

- **Laser frequency instabilities swamp the measurements**
- **Heterodyne interferometry**
  - Orbital dynamics implies high spacecraft relative motion
  - Results in time-varying Doppler-shifts of laser beams, i.e., beating interferometric signals
  - Main interferometric data are beatnote rapidly-evolving phases frequencies
  - GWs (and noises) as 100 nHz signals in these MHz frequencies

Some challenges for data analysis

- **Laser frequency instabilities swamp the measurements**
- **Heterodyne interferometry**
- **Measurements made in different time frames**
  - The spacecraft experience different proper times (Sun's gravitational potential)
  - They each host a clock, used to drive the phasemeter (sampling and frequency reference)
  - Clocks are not actively synchronize, so they have (in-band) jitter and (long-term) drifts
  - Needs to estimate a relationship between the onboard clock times and a global time, then carefully resynchronize the measurements (very stringent requirements from TDI)

Some challenges for data analysis

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- **Heterodyne interferometry**
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- And others…
- The analysis pipeline will include an L0-L1 step for these algorithms

- **Test the integration of** (a first version of) **the L0-L1-L2 sections**

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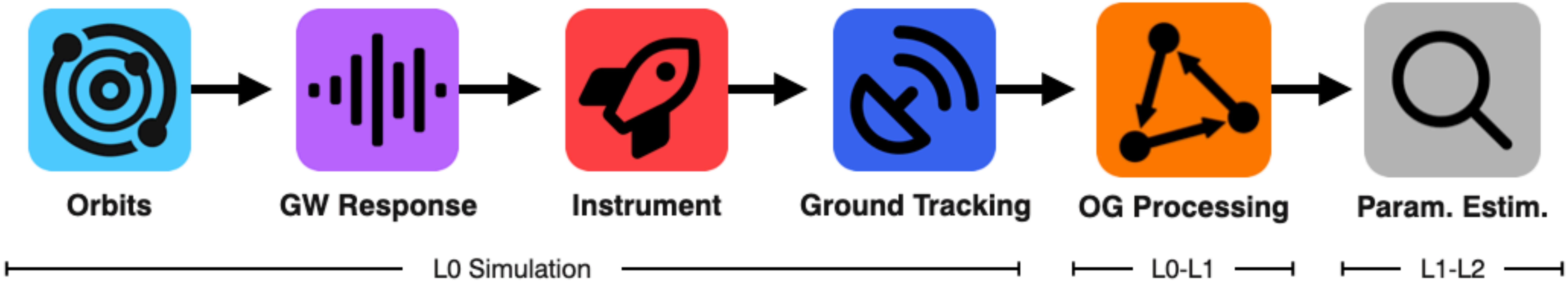
Method

Purpose and method

- **Simple configuration to test interplays and interfaces**
  - Incrementally increase complexity to study the impact of instrumental effects
- **Figures of merit as performance indicators on L1 and L2**
- Results of a study carried out for the Mission Adoption Review



Simulation of L0 data

- **Full time-domain simulations with LISA Simulation Suite**
- Keplerian orbits (spacecraft state vectors, proper times, light travel times) [Bayle+22]
- Simple (almost monochromatic) Galactic binary signal
  - Bright verification binary (scaled to keep SNR irrespect. of sim. size) [Kupfer+23]
  - Response on a single laser link as frequency shift [Bayle+23]
- Instrumental simulation [Bayle+22,BayleHartwig23]
  - Propagation of modulated laser beams and coupling with GW signals and noises (laser noise, test-mass and readout noises, other subdominant noises)
  - Interferometric beatnotes, including clock effects and simple onboard processing
  - Other measurements (sideband beatnotes, spacecraft ranging, time couples)
  - Simulation performed at 16 Hz, telemetry at 4 Hz
- Ground observation of spacecraft

Simulation of L0 data

Reference GW signal

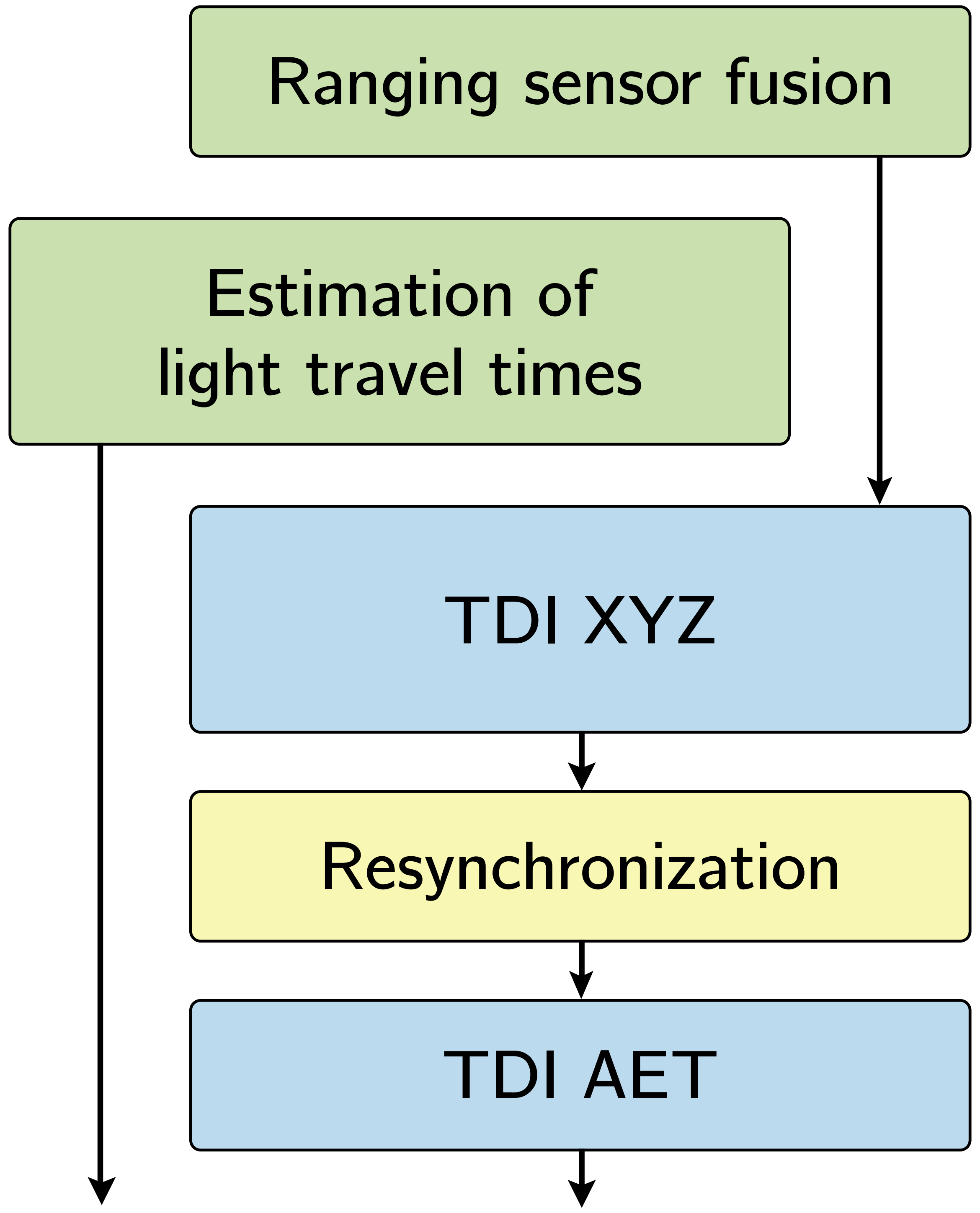
Parameter	Reference value
Strain amplitude	$A = 6.3 \times 10^{-23}$
Frequency	$f_0 = 3.5 \times 10^{-3}\,\mathrm{Hz}$
Frequency derivative	$\dot{f} = 5.6 \times 10^{-17}\,\mathrm{Hz\,s^{-1}}$
Initial phase	$\phi_0 = \pi/3$
Inclination	$\iota = \pi/3$
Polarization angle	$\psi = \pi/4$
Ecliptic latitude	$\beta = 0.82$
Ecliptic longitude	$\lambda = 5.15$

L0 dataset content

Quantity	Symbol	Unit	Cadence
6 ISI carrier beatnote freq.	$\mathrm{isi}_{ij,\mathrm{c}}^{\hat{\tau}_i}(\tau)$	Hz	4 Hz
6 RFI carrier beatnote frequencies	$\mathrm{rfi}_{ij,\mathrm{c}}^{\hat{\tau}_i}(\tau)$	Hz	4 Hz
6 TMI carrier beatnote frequencies	$\mathrm{tmi}_{ij,\mathrm{c}}^{\hat{\tau}_i}(\tau)$	Hz	4 Hz
6 ISI upper sideband beatnote freq.	$\mathrm{isi}_{ij,\mathrm{sb}}^{\hat{\tau}_i}(\tau)$	Hz	4 Hz
6 RFI upper sideband beatnote freq.	$\mathrm{rfi}_{ij,\mathrm{sb}}^{\hat{\tau}_i}(\tau)$	Hz	4 Hz
6 ISI MPRs	$\mathrm{MPR}_{ij}^{\hat{\tau}_i}(\tau)$	s	4 Hz
3 spacecraft reconstructed positions	$\mathbf{x}_i^t(\tau)$	m	$10^{-5}\,\mathrm{Hz}$
3 spacecraft reconstructed velocities	$\mathbf{v}_i^t(\tau)$	$\mathrm{m\,s^{-1}}$	$10^{-5}\,\mathrm{Hz}$
6 time correlations	$\Delta\hat{\tau}_i^t(\tau)$	s	$1\,\mathrm{day}^{-1}$

L0-L1 pipeline

- Use L0 total beatnote frequencies and apply synchronization after computing TDI [Hartwig+22]
- Combine auxiliary measurements and ground-based observations to estimate the delays to be applied in TDI, as well as drifts between clocks
- Resynchronize combinations on a global time frame, where the templates are generated



Quantity	Symbol	Units	Cadence
2^{nd}-gen. Michelson TDI combinations	$X^t(\tau), Y^t(\tau), Z^t(\tau)$	Hz	4 Hz
6 reconstructed LTTs	$\mathrm{LTT}^t_{ij}(\tau)$	s	$1\,\mathrm{day}^{-1}$
3 spacecraft reconstructed positions	$\mathbf{x}^t_i(\tau)$	m	$1\,\mathrm{day}^{-1}$
3 spacecraft reconstructed velocities	$\mathbf{v}^t_i(\tau)$	m	$1\,\mathrm{day}^{-1}$
3 reconstructed time correlations (deviations)	$\Delta\hat{\tau}^t_i(\tau)$	s	$1\,\mathrm{day}^{-1}$

Parameter estimation

- **Assume Gaussian stationary test-mass and readout noises in Fourier XYZ**

$$d_i(t) = h_i(t) + n_i(t), \qquad p(\vec{\mathbf{d}}|\vec{\theta}) = \prod_k \frac{1}{\sqrt{(2\pi)^3 \det \mathbf{C}_{ij,k}}} \exp\left\{-\frac{1}{2}[\tilde{d}_{i,k} - \tilde{h}_{i,k}(\vec{\theta})]^\dagger \mathbf{C}^{-1}_{ij,k}[\tilde{d}_{j,k} - \tilde{h}_{j,k}(\vec{\theta})]\right\},$$

- Use 3-day simulation (memory constraints), and therefore equal constant arm approximation holds for response function and noise models

$$S_{XX}(\omega) = 64\sin^2(\omega L)\sin^2(2\omega L)(S_{\mathrm{OMS}}(\omega) + [3 + \cos(2\omega L)]S_{\mathrm{acc}}(\omega)),$$

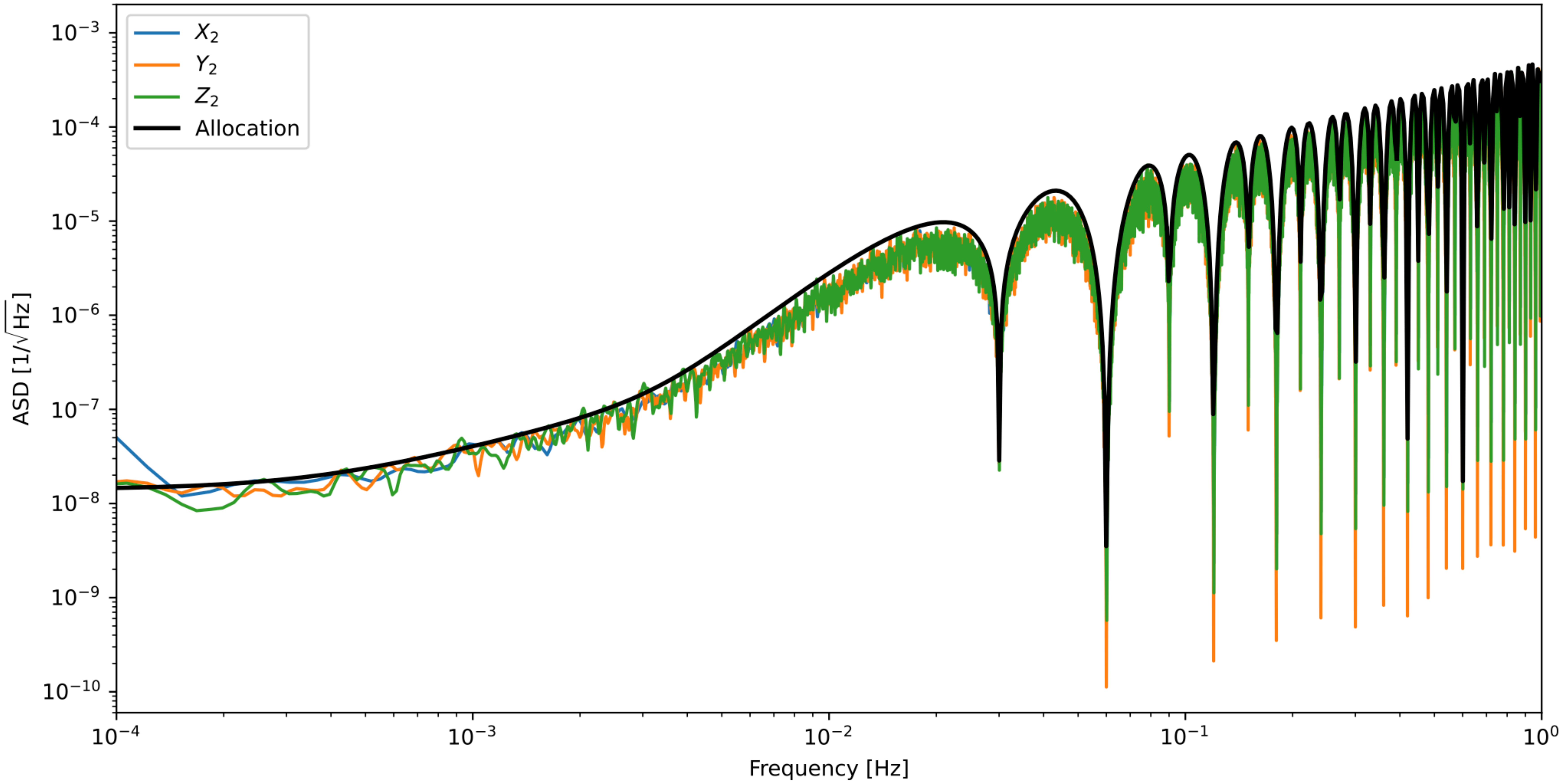
$$S_{XY}(\omega) = -16\sin(\omega L)\sin^3(2\omega L)(S_{\mathrm{OMS}}(\omega) + 4S_{\mathrm{acc}}(\omega)),$$

- **Templates computed with FastGB** [Cornish+07]
- Nessai [Williams21] as to sample posterior distributions using normalizing flows
- For rapid convergence, **we fix sky localization angles** (poorly constrained over 3 days)

Results

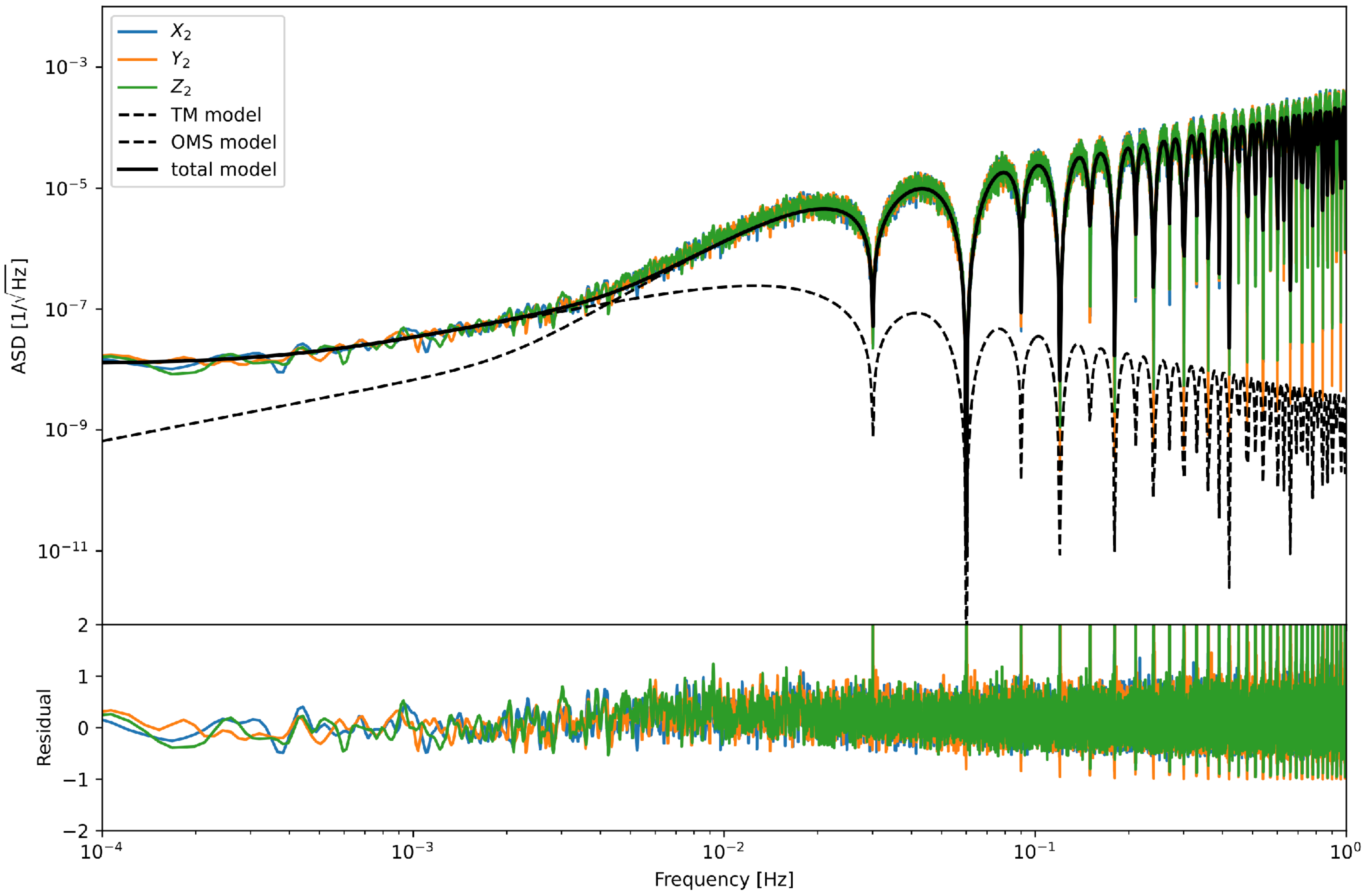
Noise suppression performance

- Check that the various noises included in the simulation are reduced by the L0-L1 pipeline to below the global noise allocation budget



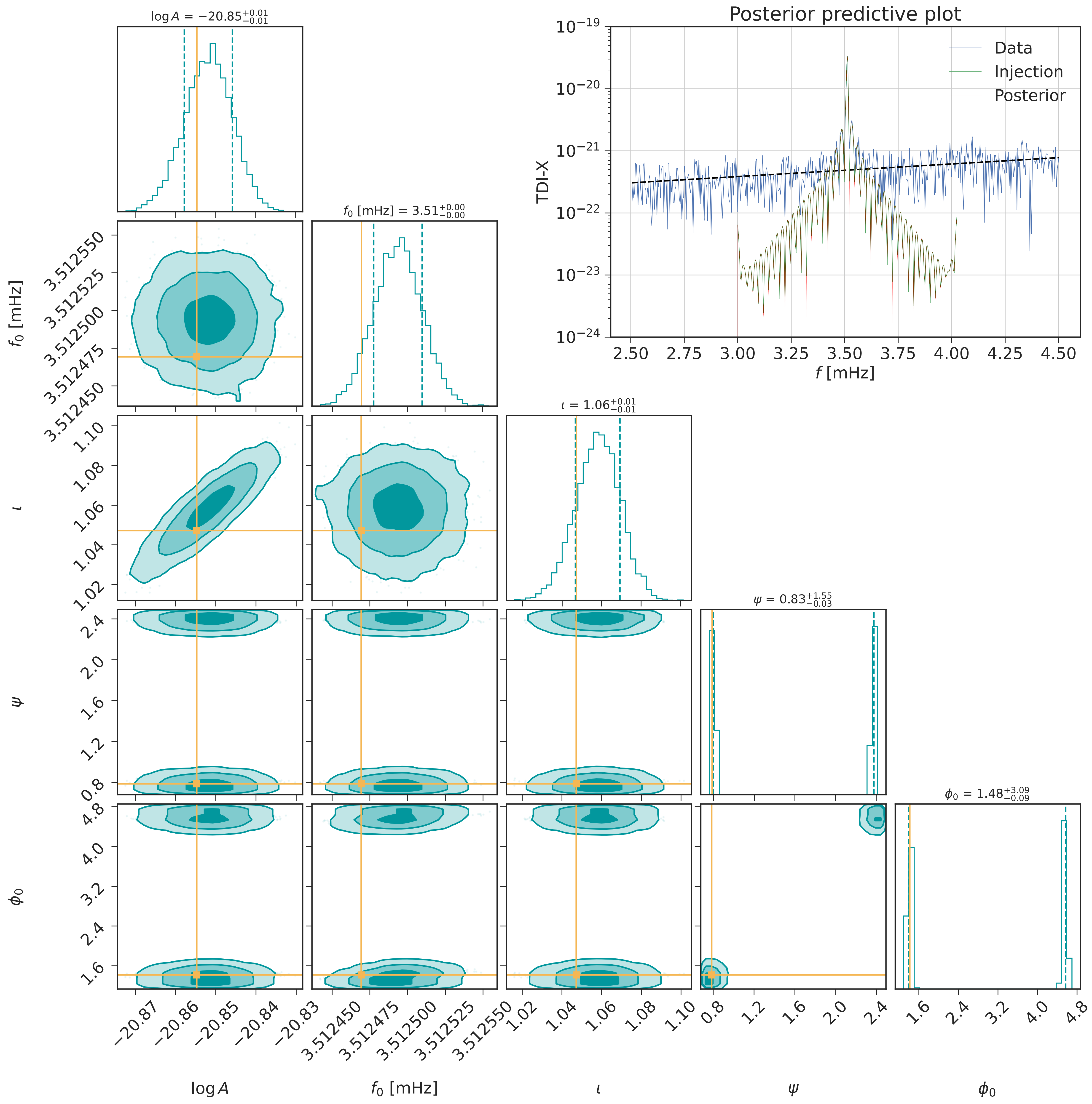
Noise modeling performance

- Check that our noise model (stationary test-mass and readout noises) describes the noise-only L1 dataset sufficiently well



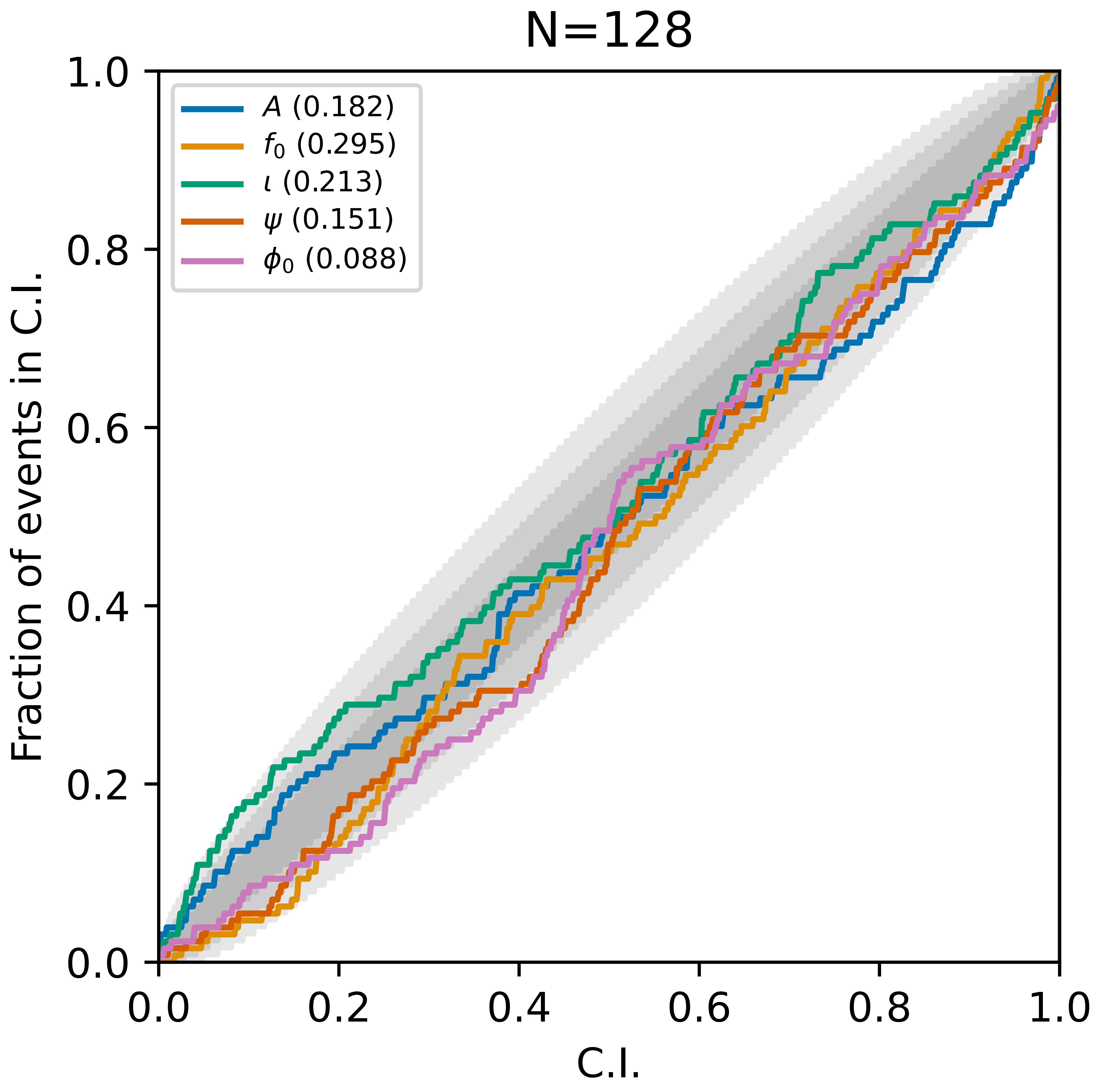
Posterior distributions

- Injected values lie in the bulk of the posteriors for all parameters
  - Sky localization angles and source frequency derivative fixed to their true values and not represented here
- Correlations are as expected
  - Strong positive correlation between amplitude and inclination angle
  - Weak correlation between frequency and phase
  - Degenerate modes for phase and polarization angle



Analysis model consistency

- p-p plot built from 128 injections
- Confirms that obtained posteriors are consistent with the data, i.e., that our assumptions regarding the performance of the instrument are in agreement with the simulations
- Excursions of phase and inclination angles to 3σ not worrying but will be investigated



Takeaways and outlook

- We developed an end-to-end demonstration pipeline to integrate and validate critical methods used in LISA data processing and source parameter estimation
- **All performance indicators for L1 and L2 data are in the green**
  - The L0-L1 pipeline is able to reduce noise to below the requirements
  - We are able to obtain reasonable param. posteriors for a single bright Galactic binary
  - Our analysis model provides a good description of our data
- This work will be continued and the pipeline will be used to systematically explore the impact of individual noise sources and modeling errors; in particular we want to
  - Simulate longer datasets
  - Estimate all parameters, including sky localization and binary frequency derivative
  - Include more noise terms in the simulation (in particular tilt-to-length effects)
  - Perform studies on other types of sources