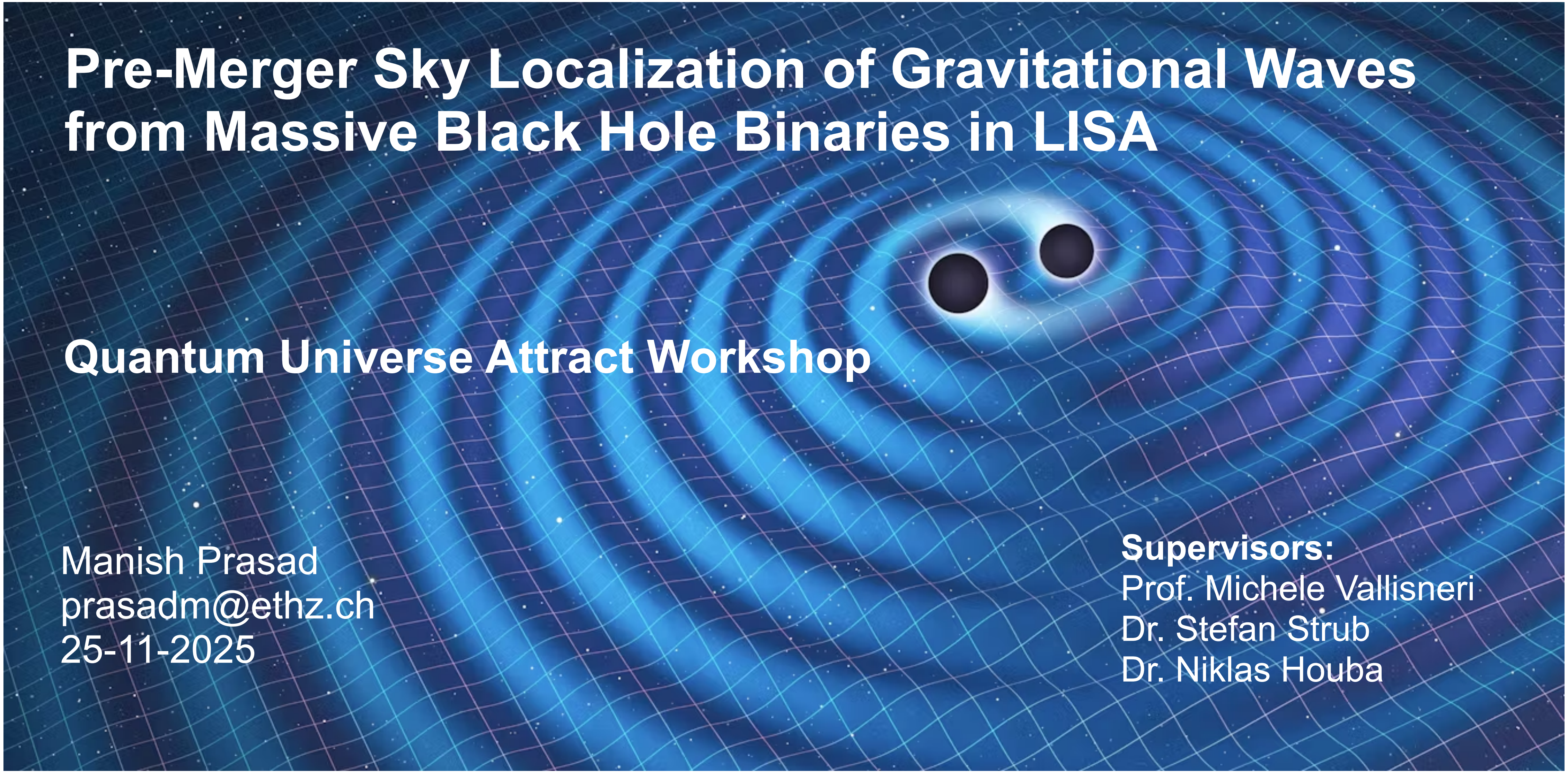
Pre-Merger Sky Localization of Gravitational Waves from Massive Black Hole Binaries in LISA



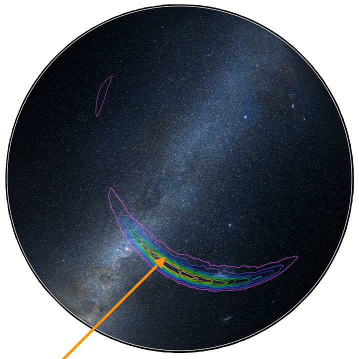
Quantum Universe Attract Workshop

Manish Prasad
prasadm@ethz.ch
25-11-2025

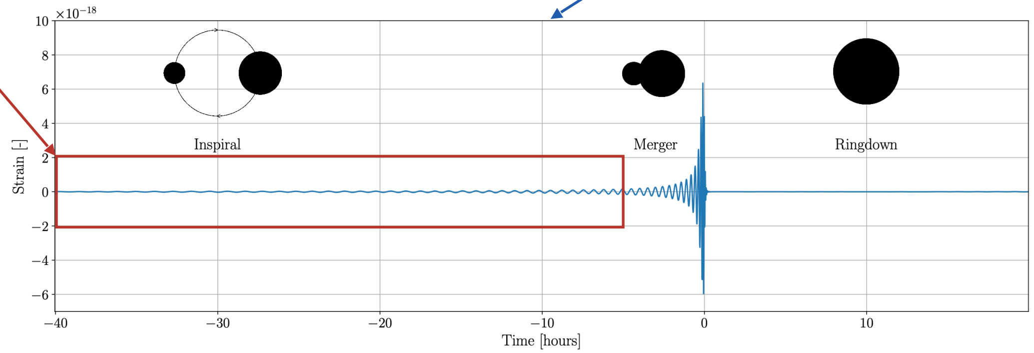
Supervisors:
Prof. Michele Vallisneri
Dr. Stefan Strub
Dr. Niklas Houba

ETH zürich
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG
DESY.
CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE
QUANTUM UNIVERSE ATTRACT. WORKSHOP

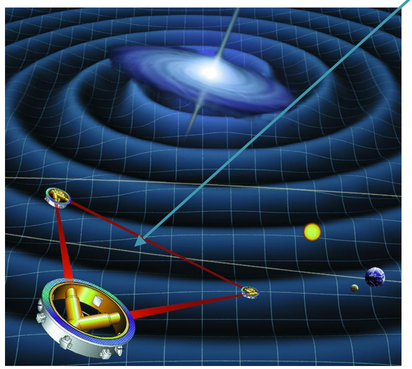
Black holes with individual masses $\sim 10^5 M_\odot$



Pre-Merger Sky Localization of Gravitational Waves from Massive Black Hole Binaries in LISA



A gravitational wave signal with the time of the merger is set to t = 0

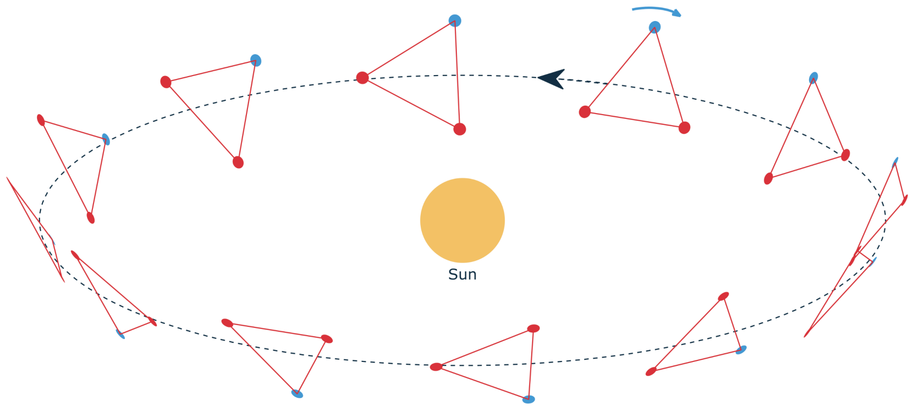


Motivation? Multi-Messenger Astronomy with Gravitational Waves

The Potential of Multi-Messenger Astronomy with LISA

Future with LISA

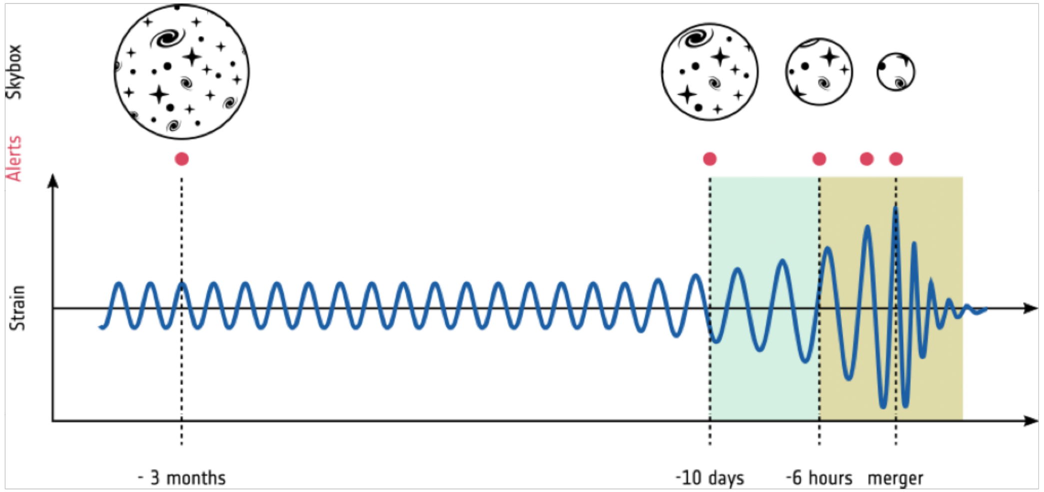
- Massive black hole binaries (MBHSs) visible for weeks to months before the merger.
- Signals only last for seconds to minutes in current ground based detectors.
- Enables early warning for telescopes to prepare coordinated electromagnetic follow-ups before the merger.
- **Scientific Opportunities:**
  - Trace the origins, growth, and merger history of massive black holes.
  - Identify electromagnetic counterparts of the pre-merger and post-merger phases.
  - Probe how accretion proceeds in the violently evolving spacetime of an MBHB merger.



Schematic depiction of the LISA's heliocentric orbit. (Figure from Copli et al., 2024)

Low Latency Alert Pipeline (LLAP)

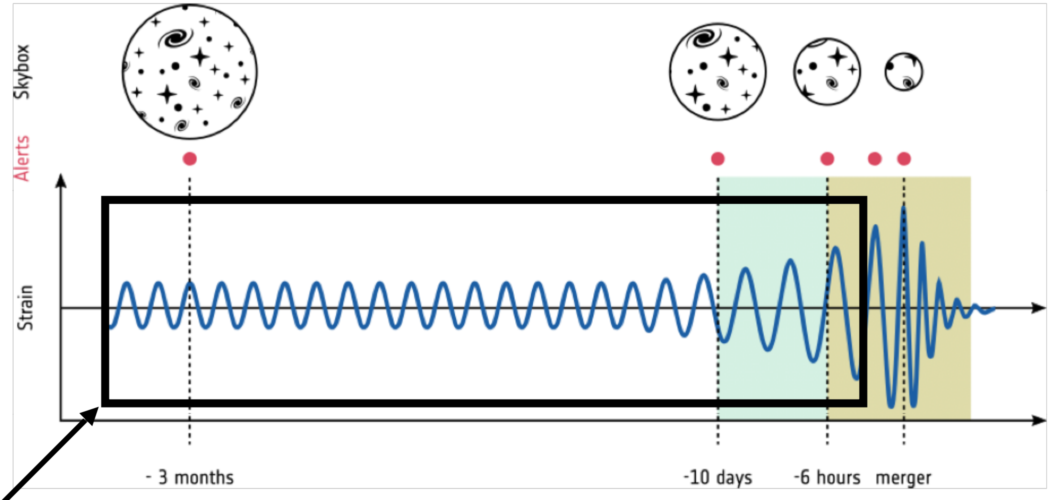
- Operate in real time to detect high-value transients like MBHBs.
- With time, sky localization uncertainty decreases.
- Send alerts to the astronomy observatories.



Schematic of LLAP. (Figure from Copli et al., 2024)

My Thesis: Pre-Merger Sky Localization of MBHBs

- Developed a pre-merger framework for MBHBs to estimate:
  - Sky localization
  - Merger time
- Use simulated LISA data using only the pre-merger data in the analysis.



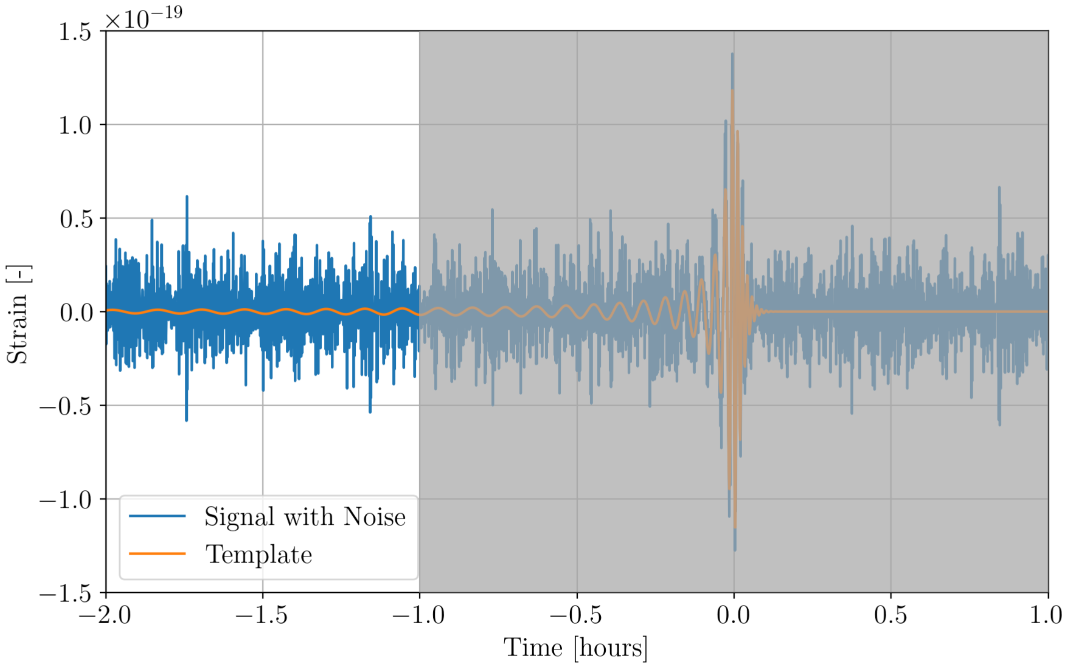
Schematic of LLAP. (Figure from Copli et al., 2024)

Pipeline

Parameter Estimation:
How do we get information about the sources from GW data?

- **Template matching:** cross-correlating detector data with theoretical GW templates.
- Waveforms for MBHBs depend on 11 parameters: $\theta_{\mathrm{MBHB}} = \{m_1, m_2, a_1, a_2, D_L, \phi, \iota, \lambda, \beta, \psi, t_c\}$

  - m_1 = Mass of the first black hole
  - m_2 = Mass of the second black hole
  - a_1 = Spin of the first black hole
  - a_2 = Spin of the second black hole
  - D_L = Luminosity distance
  - ϕ = Phase
  - ι = Inclination of the system
  - λ = Ecliptic longitude
  - β = Ecliptic latitude
  - ψ = Polarization angle
  - t_c = Coalescence time

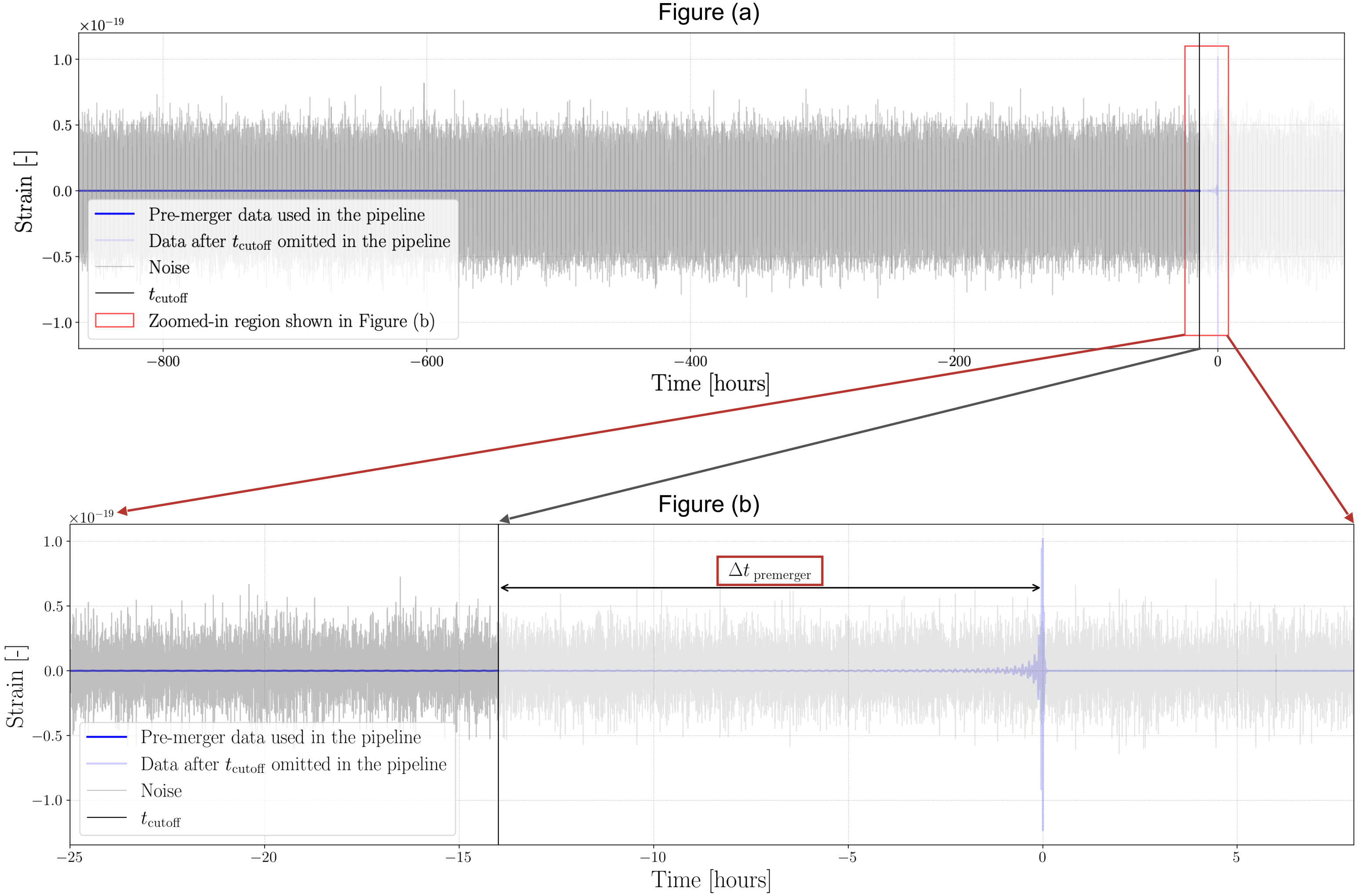


A schematic of template matching

Simulating Pre-Merger LISA Data

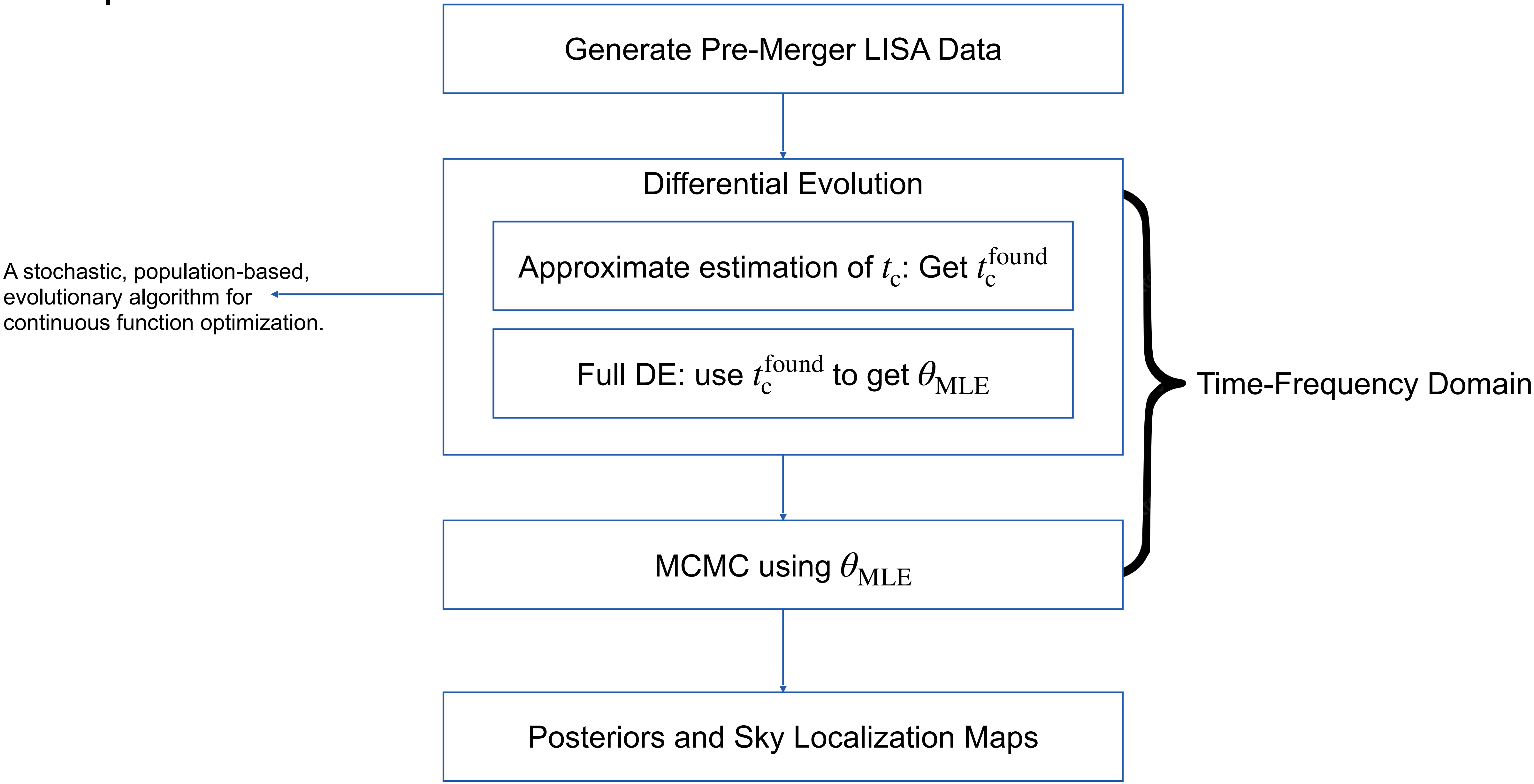
Assumptions:

- Stationary Gaussian Noise
- Equal and time-invariant arm lengths
- No gaps in the data
- No glitches
- Only one MBHB signal + noise



Time-domain representation of the MBHB signal, with the merger time set to t = 0. Waveform was generated using BBHx (Katz et al., 2021)

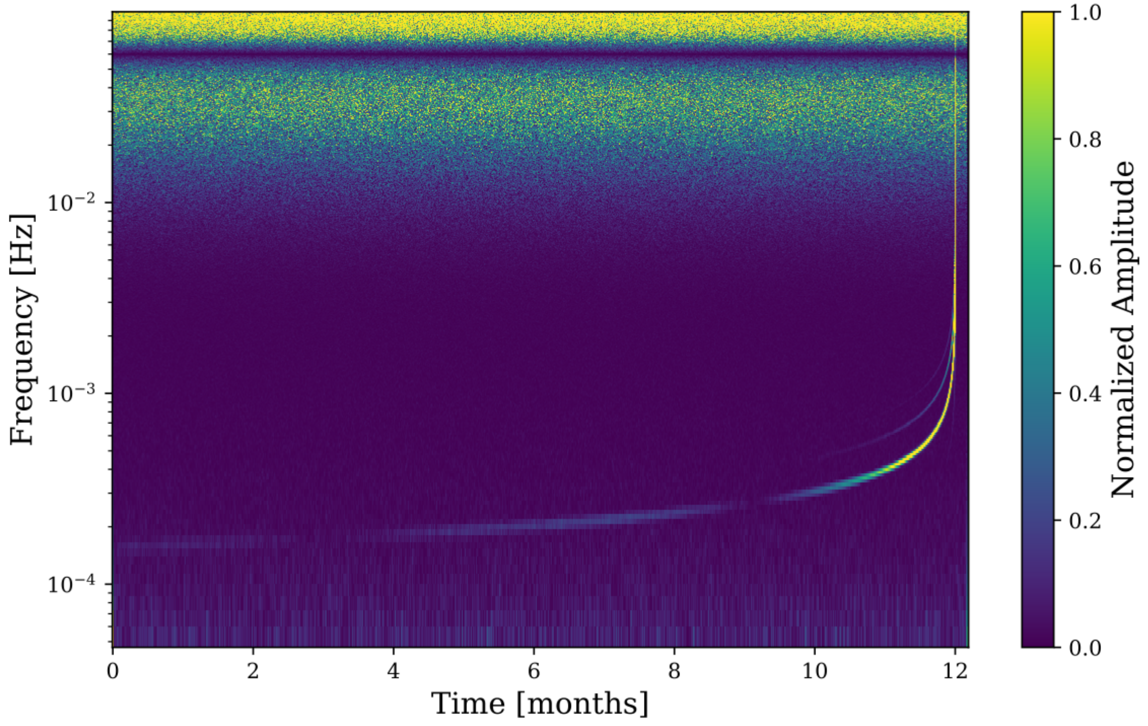
Pipeline


Generate Pre-Merger LISA Data
Differential Evolution
Approximate estimation of t_c: Get t_c^{found}
Full DE: use t_c^{found} to get θ_{MLE}
A stochastic, population-based, evolutionary algorithm for continuous function optimization.
MCMC using θ_{MLE}
Time-Frequency Domain
Posteriors and Sky Localization Maps

Time-Frequency Domain

Modulation in the time-frequency domain:

- This modulation arises from the changing orientation of LISA during its orbit.
- These modulations encode directional information about the source.
- This allows the sky localization to improve over time as LISA accumulates data from different viewing geometries.



A gravitational wave signal from an MBHB with individual masses of $10^5 M_\odot$ each, in the time-frequency domain.

Results

Results

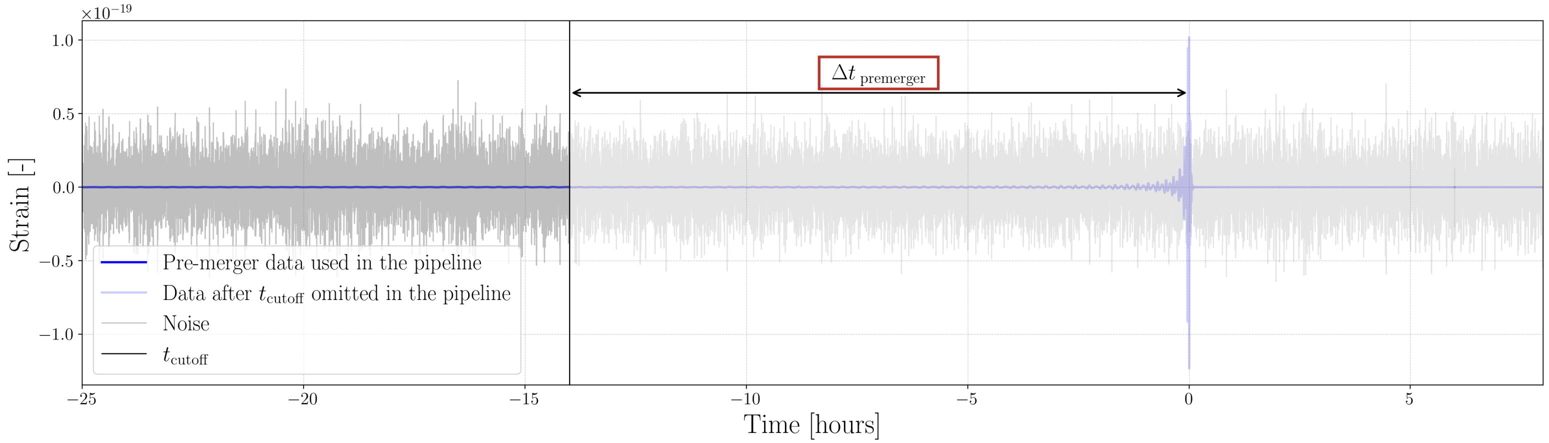
(Signal-to-noise ratio with the merger included)

Simulation Setup:

- Observation time = 36 days

Test Cases:

Test Case	Full SNR	$\Delta t_{\text{premerger}}$
Test Case 1	1865	10 Hours
		14 Hours
Test Case 2	1988	10 Hours
		14 Hours



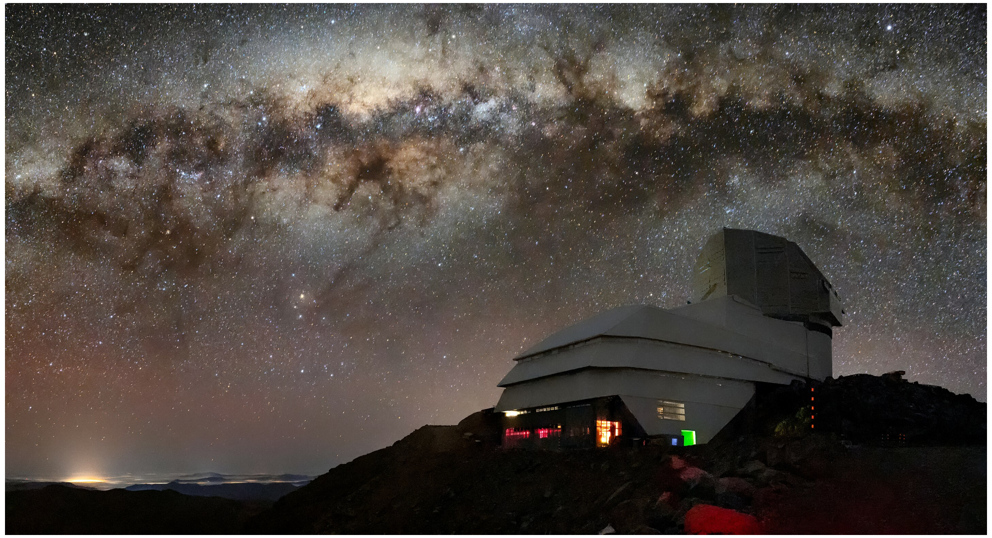
Time-domain representation of the MBHB signal, with the merger time set to t = 0.
Waveform was generated using BBHx (Katz et al., 2021)

Quantifying the Feasibility of Multi-Messenger Astronomy

- The LSST or the Rubin Observatory can be used for multi-messenger followups.
- Field of View of 9.6deg^2.
- For each test case, the 90% credible sky-localization area A_{90} was calculated, and then used to estimate:

$$N_{\text{pointings}} = \frac{A_{90}}{9.6}$$

where $N_{\text{pointings}}$ represents the number of telescope pointings required to image the localization region.

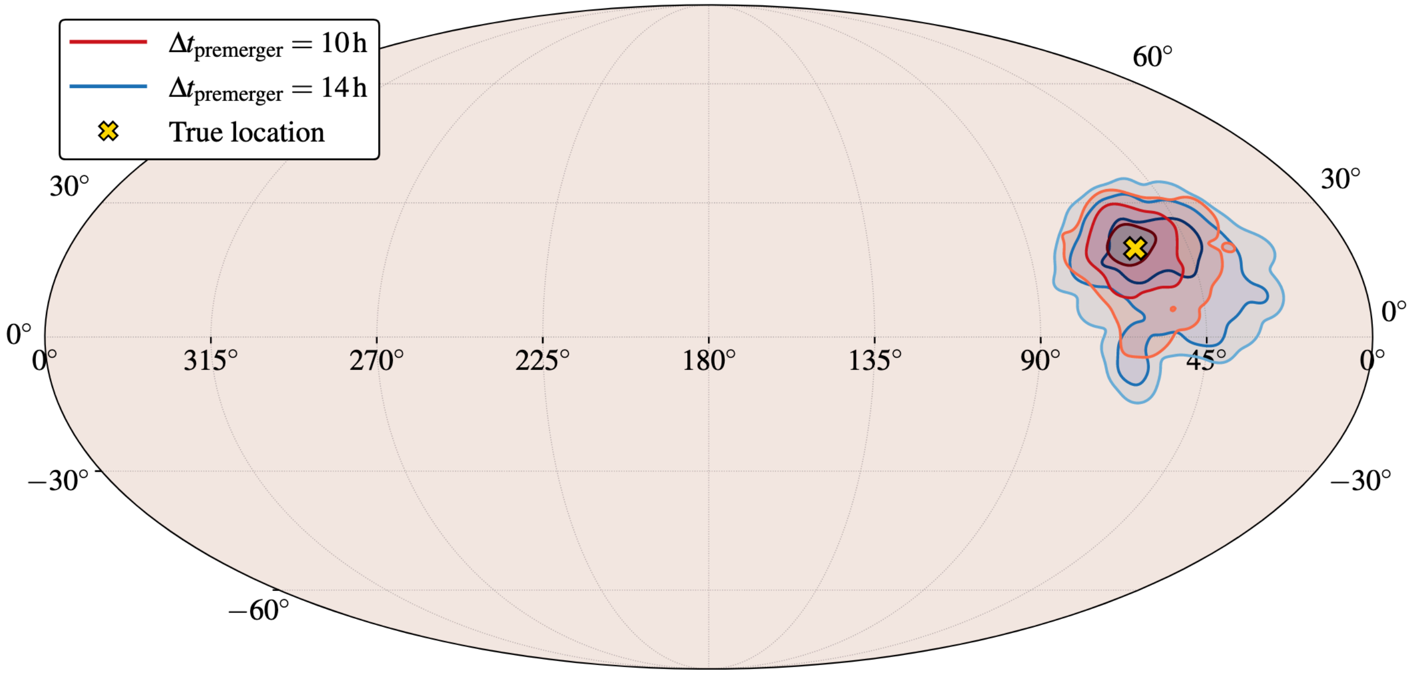


Vera C. Rubin Observatory (2023). Credit: Rubin Observatory/ NSF/AURA/B. Quint

Test Case 1: MBHB with a Full SNR of 1865

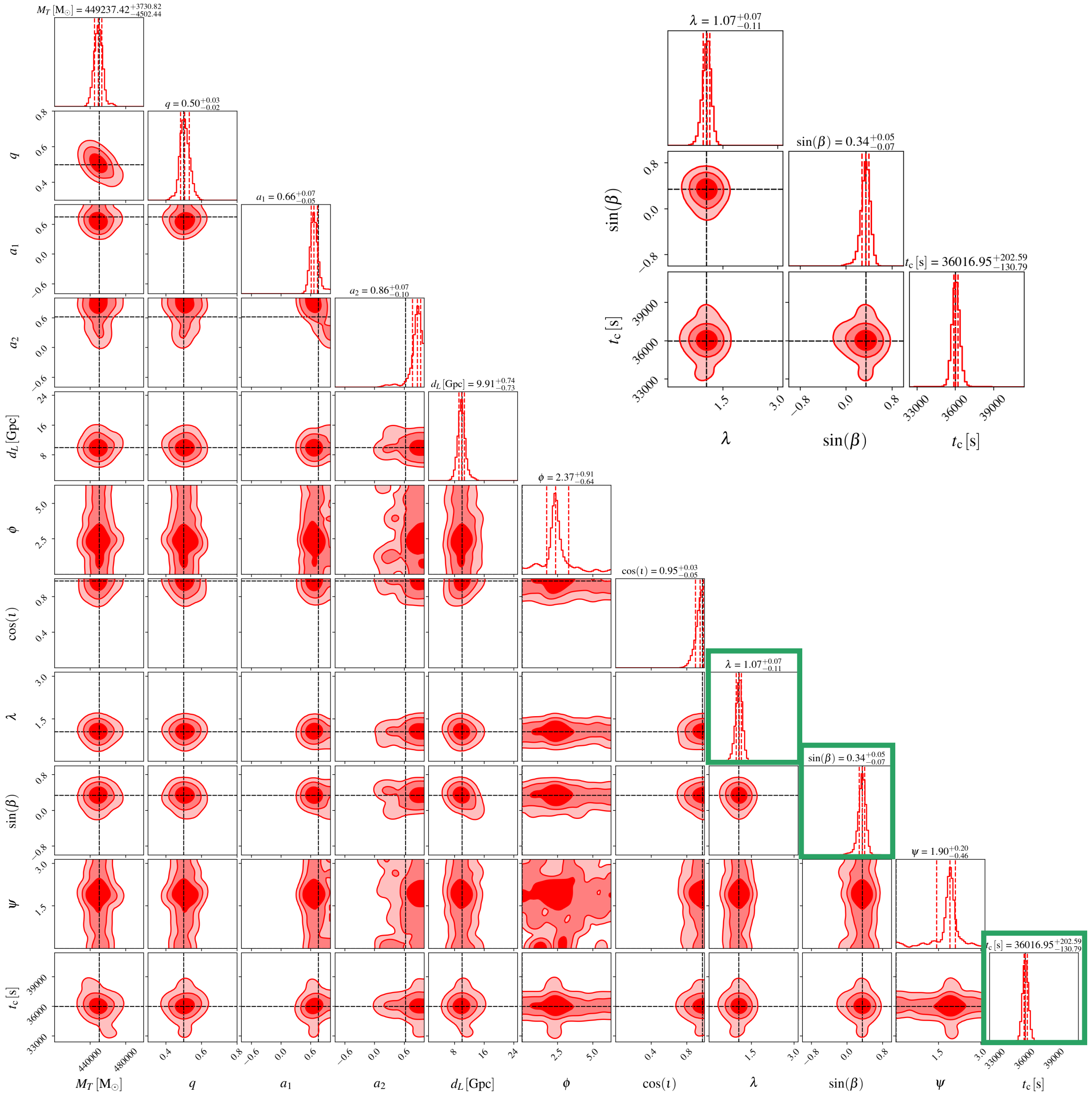
$\Delta t^{\mathbf{true}}_{\text{premerger}}$	$\Delta t^{\mathbf{found}}_{\text{premerger}}$
$10\text{h} = 36000\text{s}$	$36016^{+203}_{-131}\text{s}$
$14\text{h} = 50400\text{s}$	$50135^{+211}_{-286}\text{s}$

- As $\Delta t_{\text{premerger}}$ is changed from 14 to 10 hours the sky localization improves.
- $N_{\text{pointings}}$ reduces from 74 to 25.

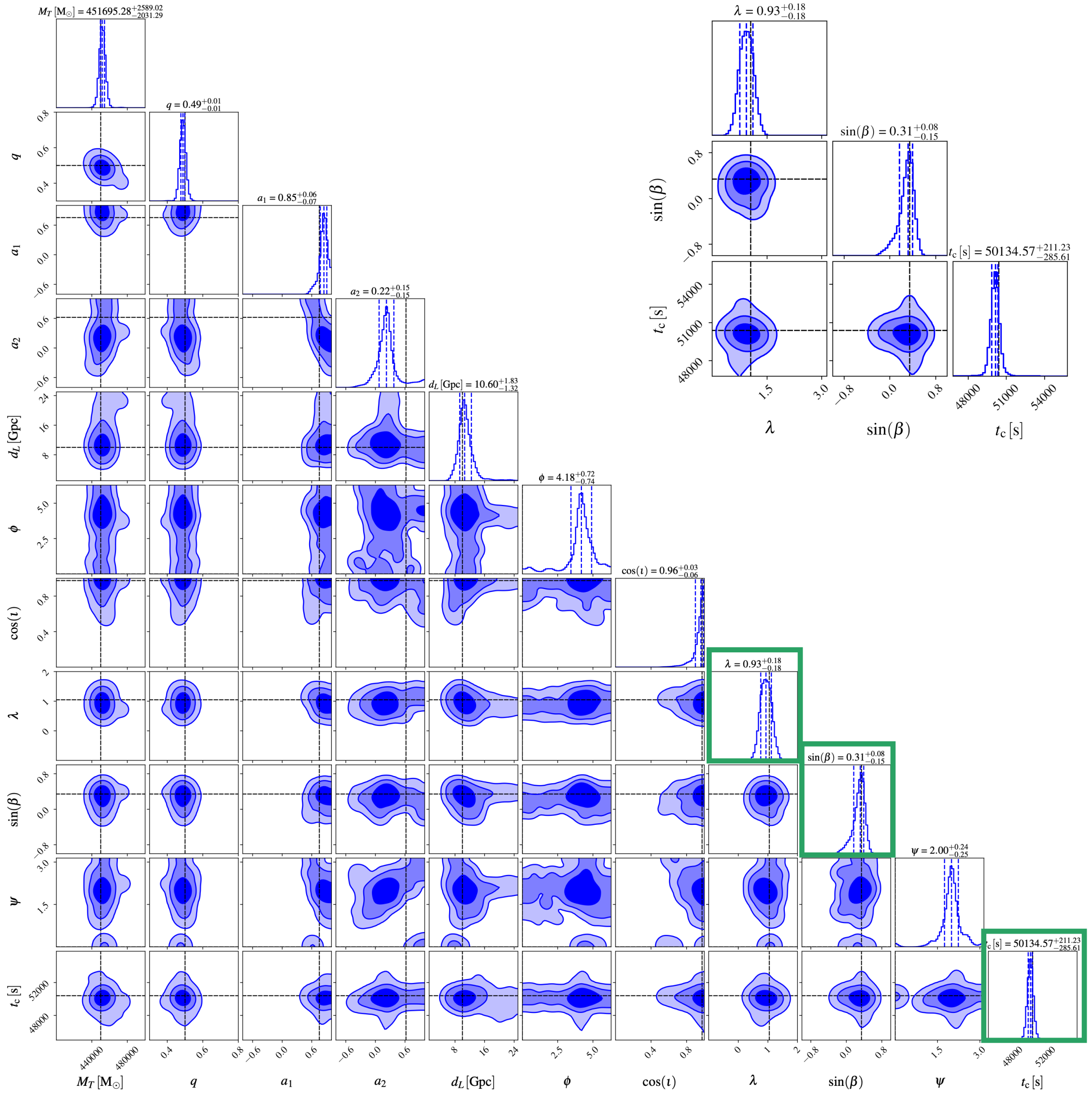


The contours show the 1σ, 2σ, and 3σ credible regions of the sky localization for $\Delta t_{\text{premerger}}$ = 10 hours in red and 14 hours in blue. The true location is indicated with a yellow ×.

Test Case 1: MBHB with a Full SNR of 1865



Corner plot of all parameters for 10 Hours Pre-Merger

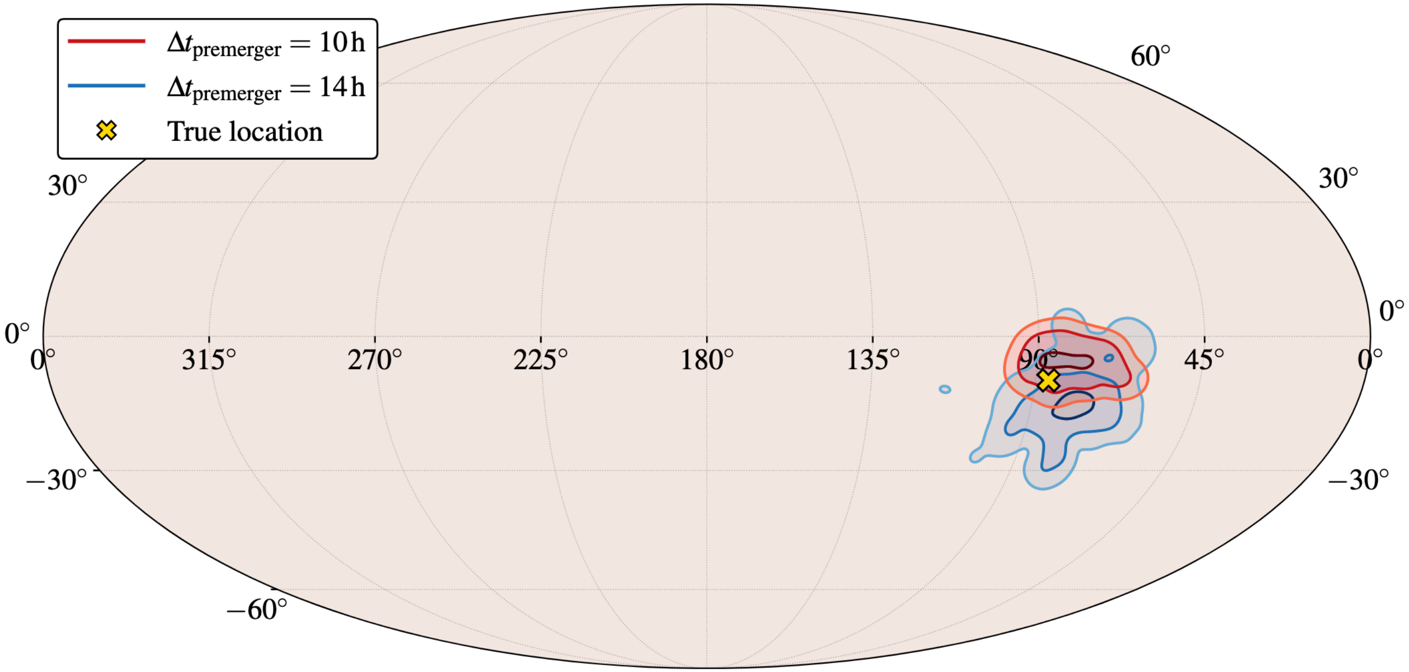


Corner plot of all parameters for 14 Hours Pre-Merger

Test Case 2: MBHB with a Full SNR of 1988

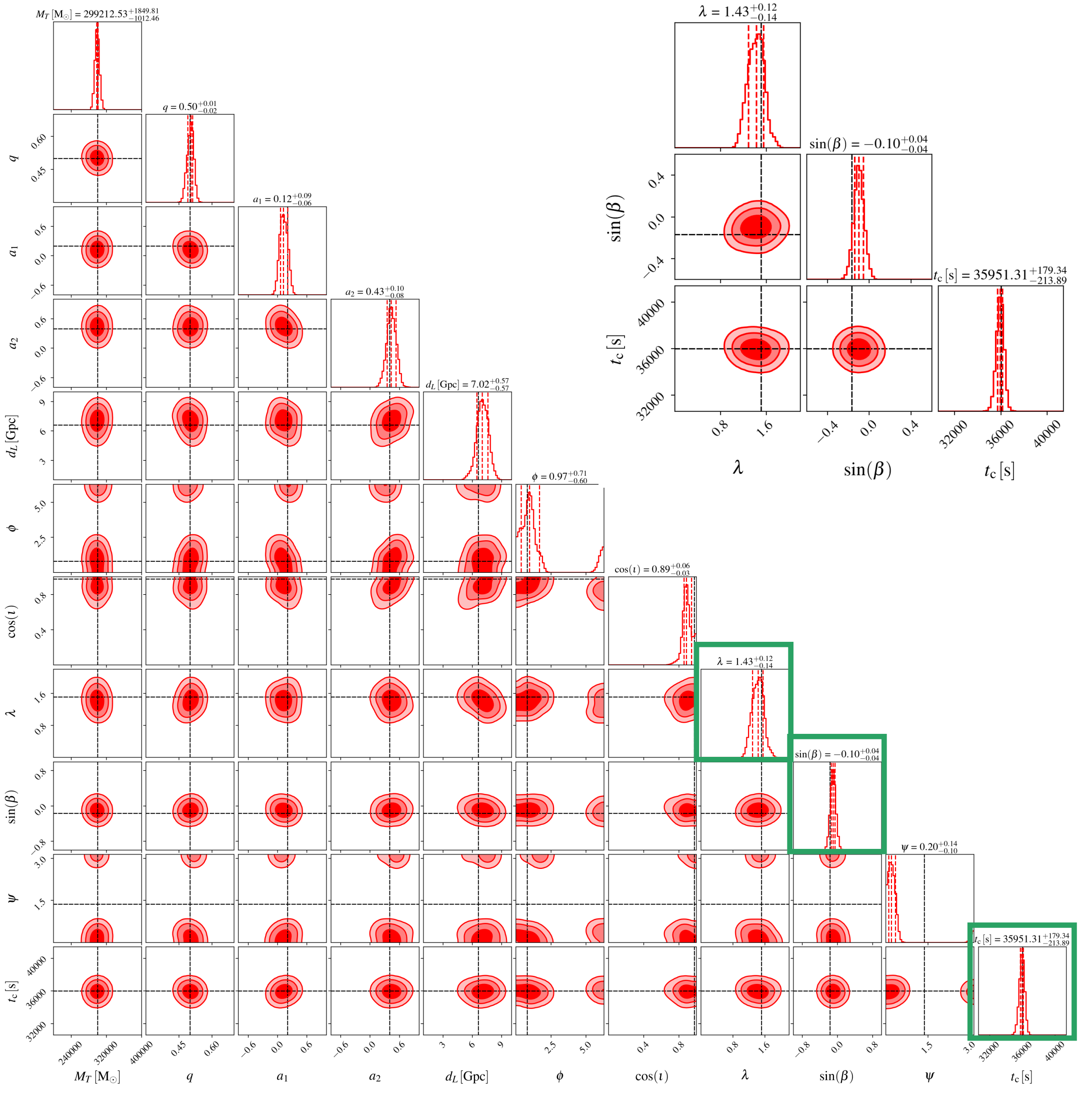
$\Delta t^{\mathbf{true}}_{\mathrm{premerger}}$	$\Delta t^{\mathbf{found}}_{\mathrm{premerger}}$
$10\mathrm{h} = 36000\mathrm{s}$	$35951^{+179}_{-214}\mathrm{s}$
$14\mathrm{h} = 50400\mathrm{s}$	$50127^{+249}_{-143}\mathrm{s}$

As $\Delta t_{\mathrm{premerger}}$ is changed from 14 to 10 hours, $N_{\mathrm{pointings}}$ reduces from 19 to 15.

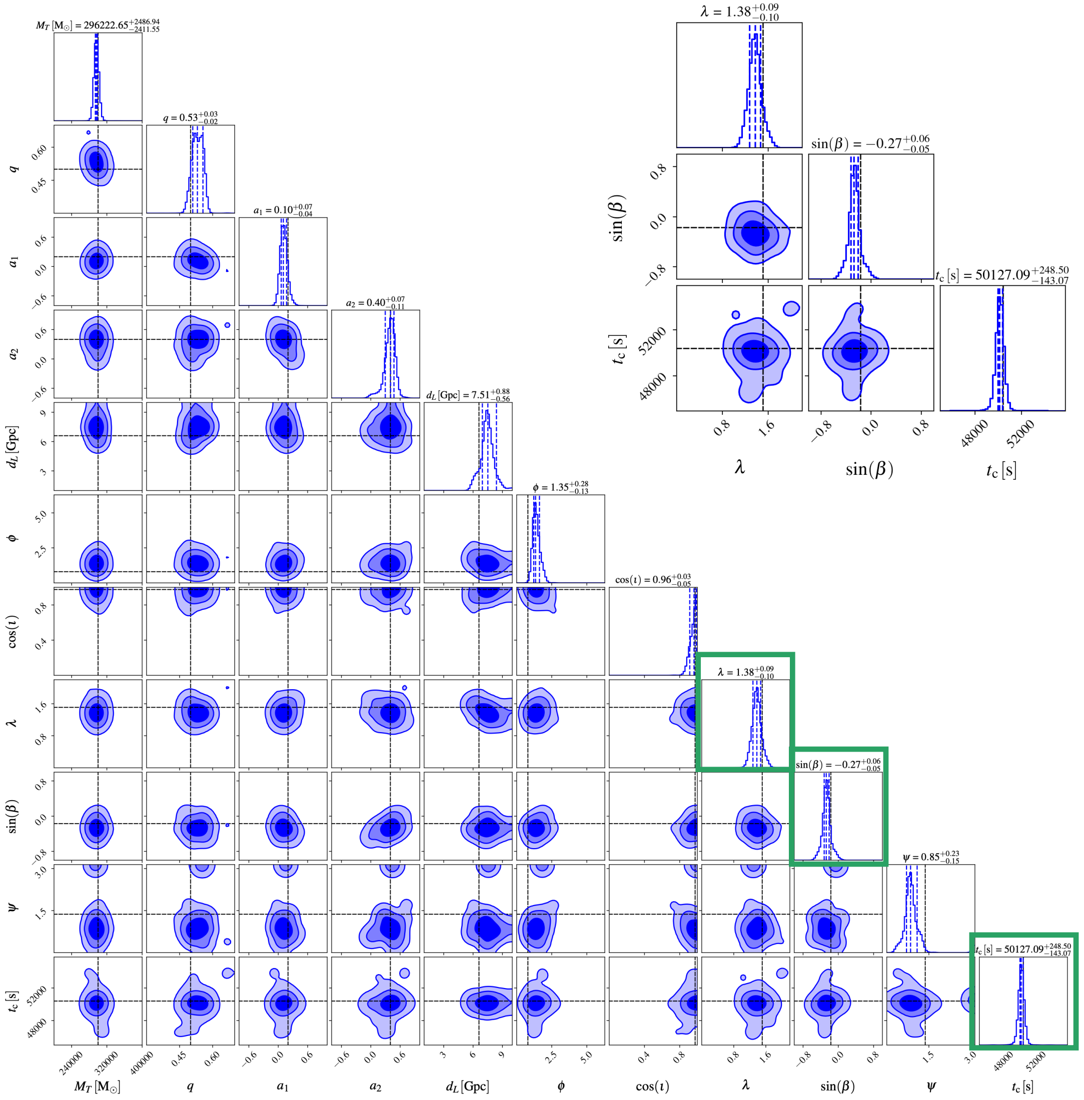


The contours show the 1σ, 2σ, and 3σ credible regions of the sky localization for $\Delta t_{\mathrm{premerger}}$ = 10 hours in red and 14 hours in blue. The true location is indicated with a yellow ×.

Test Case 2: MBHB with a Full SNR of 1988



Corner plot of all parameters for 10 Hours Pre-Merger



Corner plot of all parameters for 14 Hours Pre-Merger

Conclusion

Conclusion

Key Results

- Sky localization improves as $\Delta t_{\text{premerger}}$ reduces from 14 hours to 10 hours.
- Corresponds to 15-75 Rubin Observatory fields, showing feasibility for optical follow-ups.
- The pipeline also provides posterior estimates for the complete set of source parameters.

Computational Performance

- Using GPUs on the HPCs of the Swiss National Supercomputing Centre, total runtime ~ 4.5 hours.
- For a 10 hour (14 hour) pre-merger signal, it leaves roughly 5.5 hours (9.5 hours) until the merger for issuing early-warning alerts.
- Framework can provide real-time sky localization alerts for LISA's Low-Latency Alert Pipeline.

ETH zürich

Thank you for listening!

Any questions?

Special Thanks to:

ETH zürich | IPA Institute for Particle Physics and Astrophysics

CSCS Centro Svizzero di Calcolo Scientifico Swiss National Supercomputing Centre

ESA | NASA lisa

UHH Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

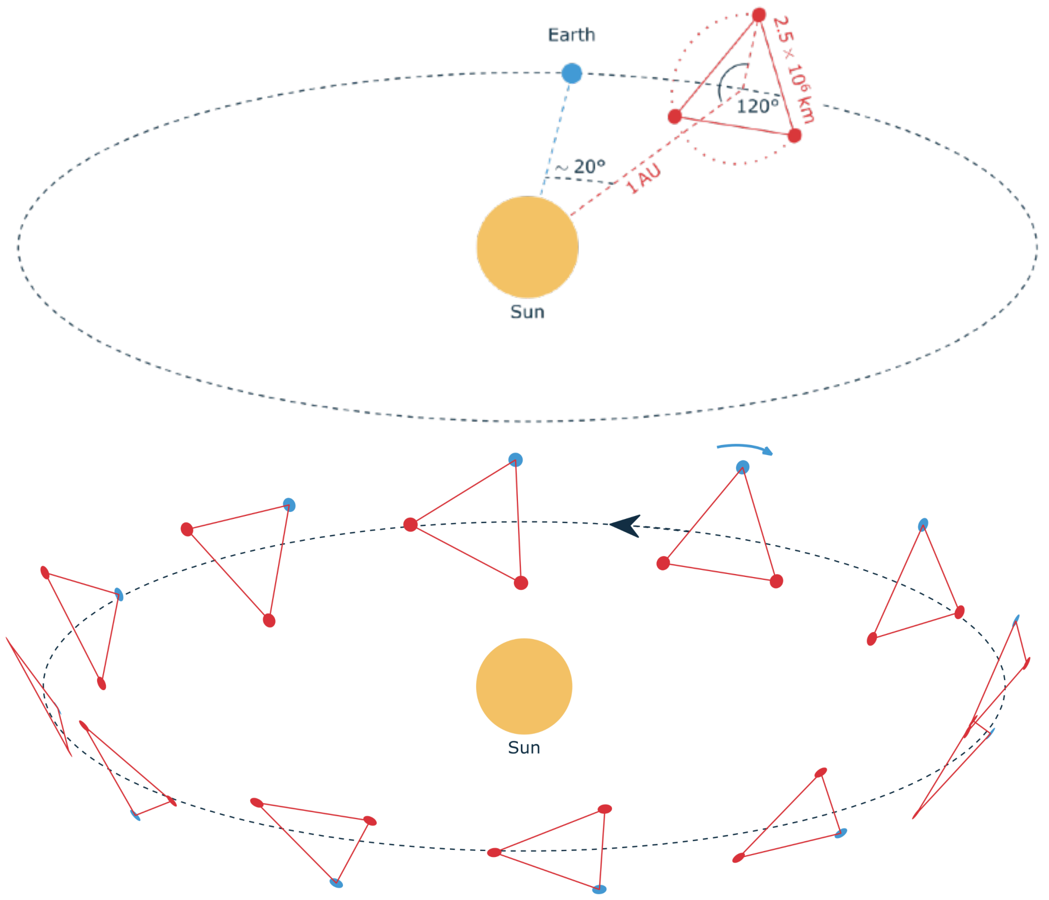
QUANTUM UNIVERSE ATTRACT. WORKSHOP

DESY.

EXTRA SLIDES

Laser Interferometer Space Antenna (LISA)

- LISA is a space-based gravitational wave detector being developed by the ESA in collaboration with NASA.
- Millihertz frequency window ($10^{-4} - 1\text{Hz}$).
- **Configuration:**
  - Three spacecraft.
  - Triangular configuration with a distance of $2.5 \times 10^6\text{km}$ between the spacecraft.
  - The constellation trails Earth by roughly 20° in a heliocentric orbit.
  - Laser links measure changes in distances between the spacecraft.
- Will detect thousands of overlapping signals from various sources:
  - Massive Black Hole Binaries (MBHBs)
  - Extreme Mass-Ratio Inspirals
  - Stellar-Mass Black Hole Binaries
  - Galactic Binaries
  - Stochastic Gravitational Wave Background



Schematic depiction of the LISA constellation, its heliocentric orbit, and its cartwheel-like rotation.
(Figure from Copli et al., 2024)

How LISA Measures Gravitational Waves

Laser Interferometry

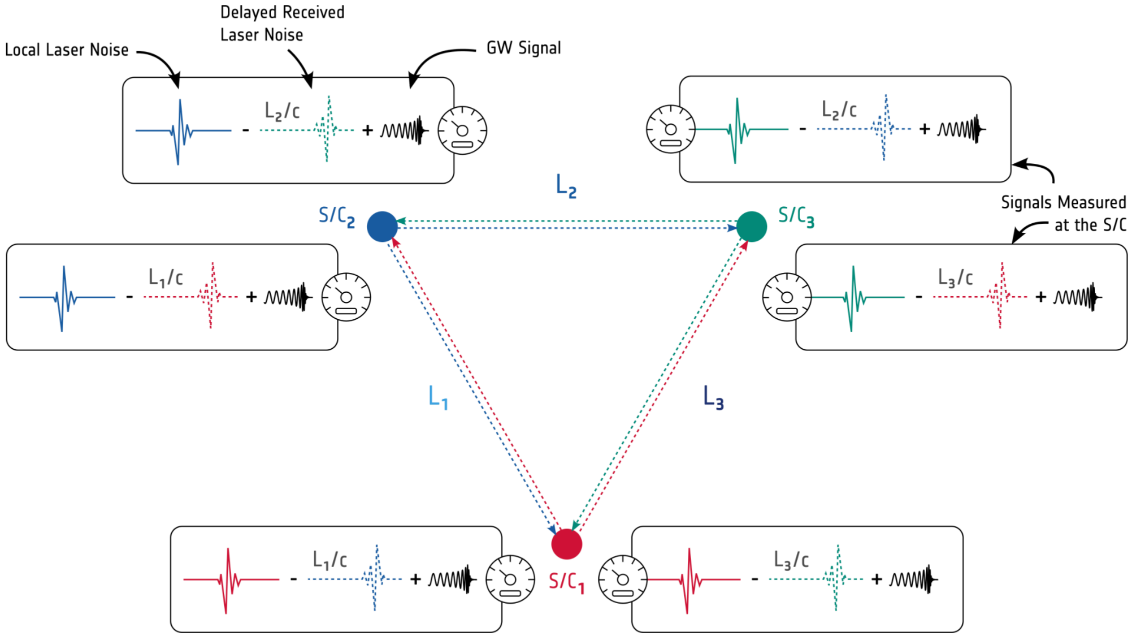
- Each spacecraft interferes local laser with received signal from other spacecraft.
- 6 Doppler measurements (one per laser link).

Time-Delay Interferometry (TDI)

- Combines these 6 measurements with precise time delays.
- Forms measurements mostly free from laser frequency noise.
- Converted into three observables: X, Y , and Z.
- Three orthogonal combinations: A, E and T

$$A = \frac{1}{\sqrt{2}}(Z - X), E = \frac{1}{\sqrt{6}}(X - 2Y + Z), T = \frac{1}{\sqrt{3}}(X + Y + Z)$$

- Under the assumptions of **equal arm lengths** and **stationary noise**, the channels are uncorrelated with the instrument noise.



Schematic representation of TDI in LISA; local laser (solid) and the received signal contains a time-delayed copy of the distant spacecraft's laser noise (dashed signal) and a GW signal. Figure from Copli et al., 2024

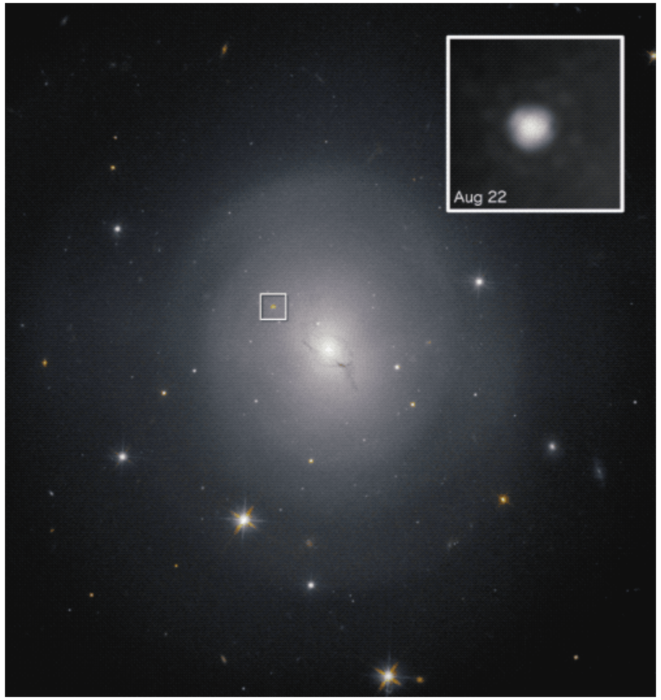
Importance of Multi-Messenger Astronomy

GW170817: First binary neutron star merger

- Detected by LIGO-Virgo-KAGRA and Fermi & INTEGRAL spacecraft.
- Gamma ray burst GRB170817A in the Galaxy NGC 4993.
- Science:
  - Physics of the origin of heavy elements.
  - Confirmed short gamma-ray bursts.
  - And many more…
- Only confirmed multi-messenger gravitational wave event till now.

One of the limitations of Ground-Based Detectors:

- Signals last only a few seconds (GW170817 ~ 100 seconds)

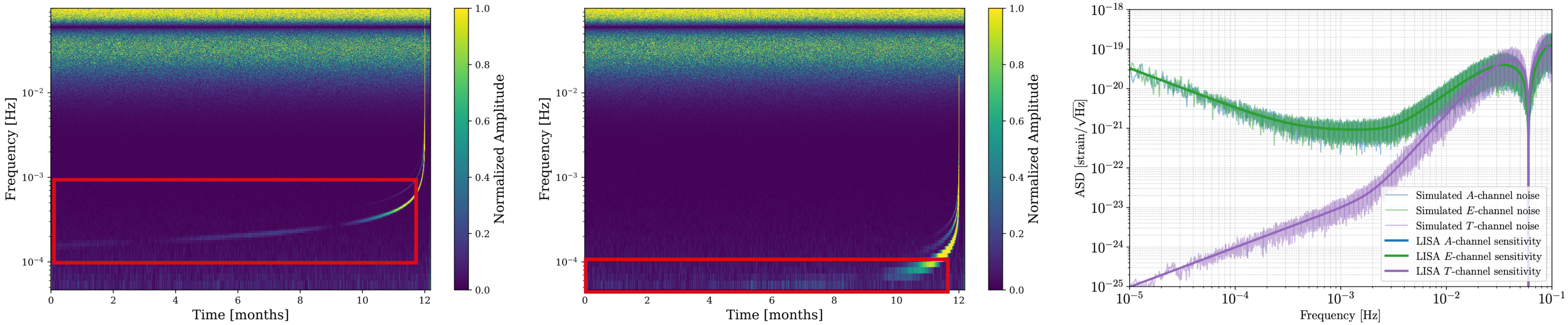


Hubble pictures of NGC 4993 with inset showing GRB 170817A over 6 days. Credit: NASA and ESA

Time-Frequency Domain

Time-Frequency Domain for MBHBs in Different Mass Ranges:

- More prominent for lower-mass systems $\sim 10^5 \mathrm{M}_\odot$ than for higher-mass systems $\sim 10^6 \mathrm{M}_\odot$.
- The inspiral of the lower-mass systems is between $10^{-3} - 10^{-4}\mathrm{Hz}$, while for higher masses it falls below $10^{-4}\mathrm{Hz}$.
- LISA noise is also higher at these low frequencies, causing the modulation to be increasingly buried in noise for these higher mass systems.



Time-frequency domain representations of MBHBs with individual masses of left: $10^5 \mathrm{M}_\odot$ each, and middle: $10^6 \mathrm{M}_\odot$ each, with noise included. Right: the LISA sensitivity curves and noise in the A, E and T channels.

Time-Frequency Inner Product

For d = data, h = template and $S_n(f)$ = the one sided Power Spectral Density

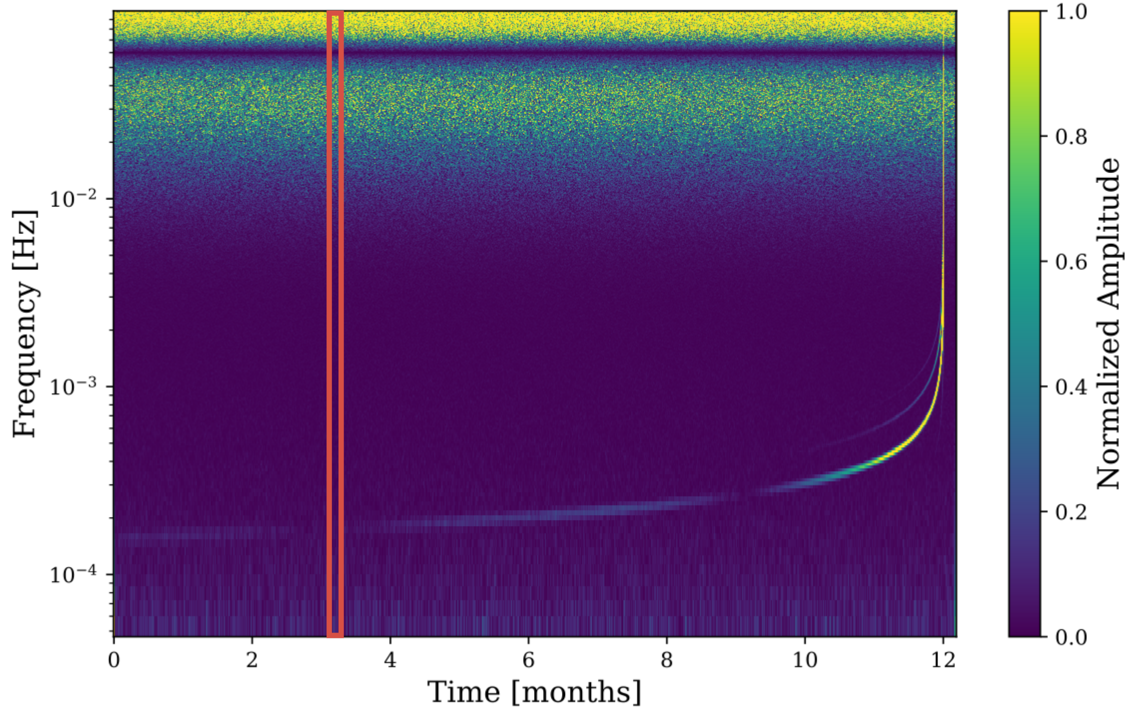
Frequency domain inner product:

$$\left\langle h, d \right\rangle = 4\mathrm{Re}\int_0^\infty \frac{\tilde{h}(f)\tilde{d}^*(f)}{S_n(f)}\mathrm{d}f$$

Time-frequency inner product:

$$\left\langle h, d \right\rangle_{\mathrm{TF}} \equiv \sum_{\tau=0}^{N-1} 4\mathrm{Re}\int_0^\infty \frac{\tilde{h}_\tau(f)\tilde{d}^*_\tau(f)}{\tilde{S}_n(f)}\mathrm{d}f,$$

where N = Number of time segments



Gravitational wave signal with noise from an MBHB with individual masses of $10^5 M_\odot$ each, in the time-frequency domain for the TDI-A channel.

Time-Frequency Likelihood

MBHB Parameters: $\theta = \{M_T, q, a_1, a_2, D_L, \phi, \cos\iota, \lambda, \sin\beta, \psi, t_\mathrm{c}\}$

Time-frequency Likelihood

$$\log\mathscr{L}(d \mid \theta)_{\mathrm{TF}} = -\frac{1}{2}\Big\langle d - h(\theta), d - h(\theta) \Big\rangle_{\mathrm{TF}}$$

Time-frequency SNR

$$\rho_{\mathrm{TF}} = \frac{\langle d \,|\, h(\theta')\rangle_{\mathrm{TF}}}{\sqrt{\langle h(\theta) \,|\, h(\theta')\rangle_{\mathrm{TF}}}}$$

- M_T = Total Mass
- q = Mass Ratio
- a_1 = Spin of the first black hole (aligned with the orbital angular momentum)
- a_2 = Spin of the second black hole (aligned with the orbital angular momentum)
- D_L = Luminosity distance
- ϕ = Phase
- $\cos\iota$ = Cosine of the inclination of the system
- λ = Ecliptic longitude
- $\sin\beta$ = Sine of ecliptic latitude
- ψ = Polarization angle
- t_c = Coalescence time

ETH zürich

Differential Evolution (DE)

DE is a stochastic, population-based, evolutionary algorithm for continuous function optimization

1. **Initialize a population:**
   - Create a population of size N, randomly chosen within the priors at generation G: $x_i^G, i = 1,2, \ldots, N$
2. **Mutation:**
   - For every vector i, select three other random vectors from the population.
   - Add the weighted difference of two of the three random vectors $x_{r_1}^G, x_{r_2}^G, x_{r_3}^G$ to the third to form a donor vector v_i^G:

   $$v_i^G = x_{r_1}^G + F \cdot (x_{r_2}^G - x_{r_3}^G)$$

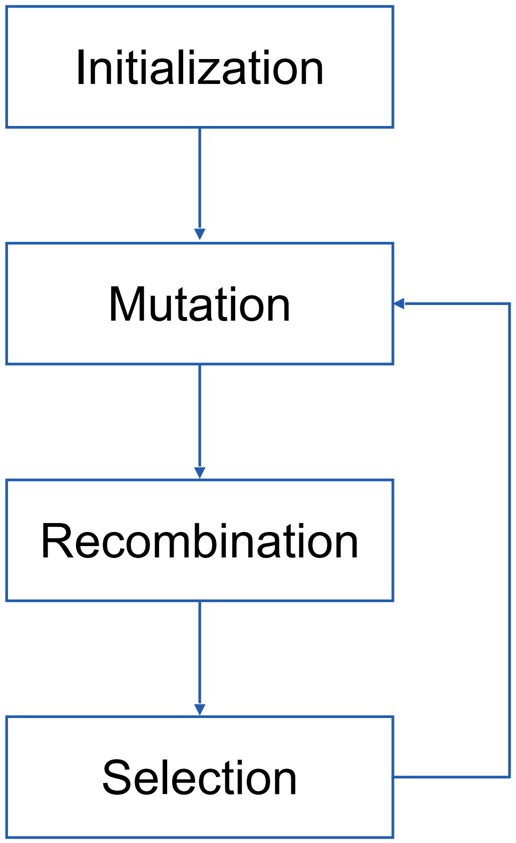
3. **Recombination / Crossover:**
   1. Define a crossover rate CR and create a candidate vector $u_{i_j}^G$ according to:

   $$u_{i_j}^G = \begin{cases} v_{i_j}^G, & \text{if rand}[0,1] < \text{CR} \\ x_{i_j}^G, & \text{otherwise} \end{cases}$$

4. **Selection:**
   1. For minimizing the function f, create a new population at generation $G+1$, x_i^{G+1} according to:

   $$x_i^{G+1} = \begin{cases} u_i^G, & \text{if} f(u_i^G) < f(x_i^G) \\ x_i^G, & \text{otherwise} \end{cases}$$

Repeat steps 2 through 4 until a pre-defined stopping condition is met.



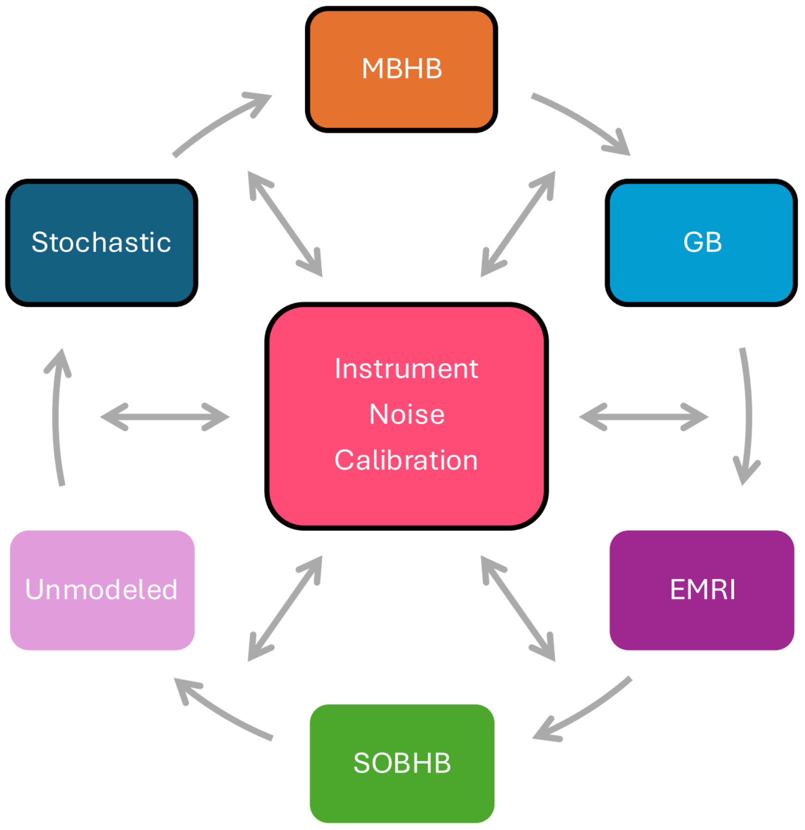
Differential Evolution (DE)

- DE is a stochastic, population-based, evolutionary algorithm for continuous function optimization
- DE was used to maximize ρ_{TF}
- ρ_{TF} does not depend on D_{L}
- DE was used to find the parameters $\theta' = \theta - \{D_{\mathrm{L}}\}$
- D_{L} was analytically calculated using:

$$D_L = \frac{\langle h(\theta') \,|\, h(\theta') \rangle_{\mathrm{TF}}}{\langle d \,|\, h(\theta') \rangle_{\mathrm{TF}}}$$

LISA Global Fit

1. LISA we can see signals that last for months or even years
2. The data will be GW dominated, meaning that we do not have a time segment without a detectable GW signal
3. Sources in LISA:
    1. Massive black hole binaries (MBHBs)
    2. Galactic (and extra-Galactic) white dwarf binaries (GBs)
    3. Stellar-origin black hole binaries (SOBHB)
    4. Extreme mass ratio inspires (EMRI)
    5. Stochastic GW signal from the energetic processes in the early Universe
    6. Maybe something else that's unmodeled?



M. L. Katz, et al., 2025
Deng et. al., 2025

LISA Global Fit