Parameter estimation for inspiralling MBH binaries in LISA

Alberto Mangiagli (APC, Paris)

In collaboration with: Antoine Klein, Matteo Bonetti, Alberto Sesana, Michael Katz, Sylvain Marsat, Stanislav Babak, Marta Volonteri, Monica Colpi

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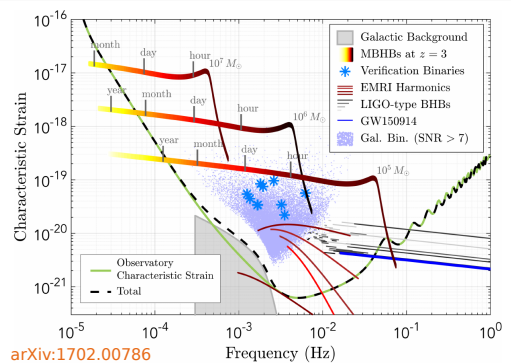
Overview



arXiv:1702.00786

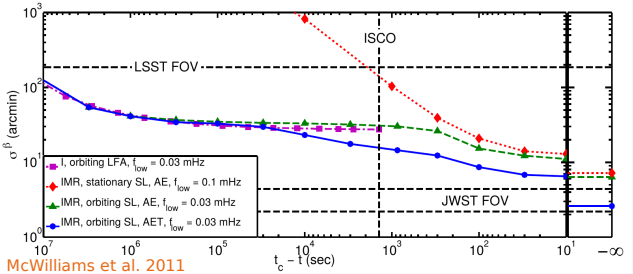
MBHBs are key sources for Multi-Messenger Astrophysics

- Detected weeks before coalescence → early warnings
- Likely occurring in gas-rich environment → EM counterparts
- At least $\simeq 10$ events per year expected → statistics

Parameter estimation

Science outcomes depends on LISA ability to estimate source parameters

1. **MCMC** (Babak et al.2010, Marsat et al.2020)
   - Bayesian formalism
   - Computational expensive → few selected cases
2. **Fisher matrix** (Vecchio 2004, Lang&Hughes 2008, Kocsis et al.2008, Klein et al.2016)
   - Reproduce MCMC results only in the high-SNR limit
   - Computational cheap → large parameter space



McWilliams et al. 2011

Main idea

Problems

- old LISA design in past inspiral studies
- Both methods require computational time

Aims (AM+20 PRD102, 084056)

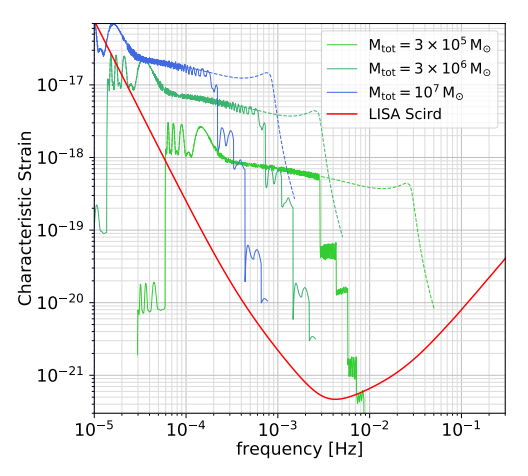
- Performance of current LISA design for *'on the fly'* estimates
- Analytical formulae to describe how parameter estimates improve during the inspiral $\rightarrow \Delta\Omega = \mathcal{F}(\mathrm{t_c}, \mathrm{M_{tot}}, \mathrm{z})$?

Parameter space

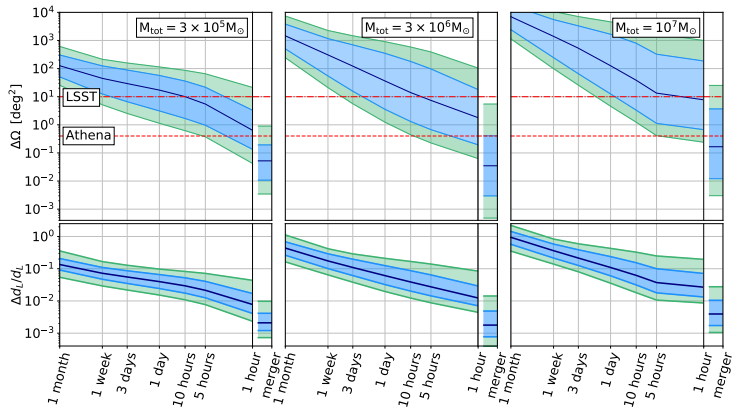
- $\mathrm{M_{tot}} = 10^5, 3\times10^5, 5\times10^5, 7.5\times10^5, 10^6, \ldots, 3\times10^7 \mathrm{M}_\odot$
- $z = 0.1$, 0.3, 0.5, 1, 2, 3, 4
- 1 month, 1 week, 3 days, 1 day, 10 hrs, 5, hrs and 1 hr from merger
- $\mathrm{N} = 10^4$ realizations

Examples of simulated signals

- Fisher matrix with inspiral precessing waveform (Klein et al. 2014)
- PhenomC to rescale $\Delta\Omega$ and Δd_L at merger



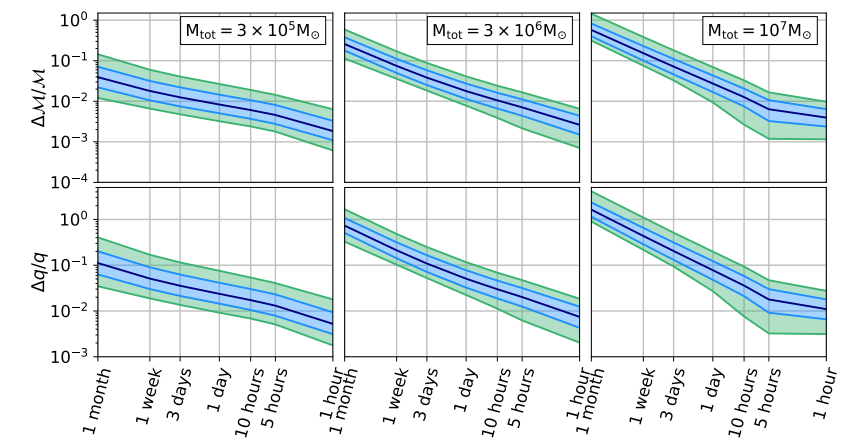
Sky position and d_L uncertainties at $z = 1$



$\Delta\Omega \simeq$ telescope FOV only close to merger $\begin{cases} < 10\,\mathrm{hrs} & \boxed{\text{LSST}} \\ \mathrm{merger} & \boxed{\text{Athena}} \end{cases}$

Large distributions $\rightarrow$ strong dependence from true binary position

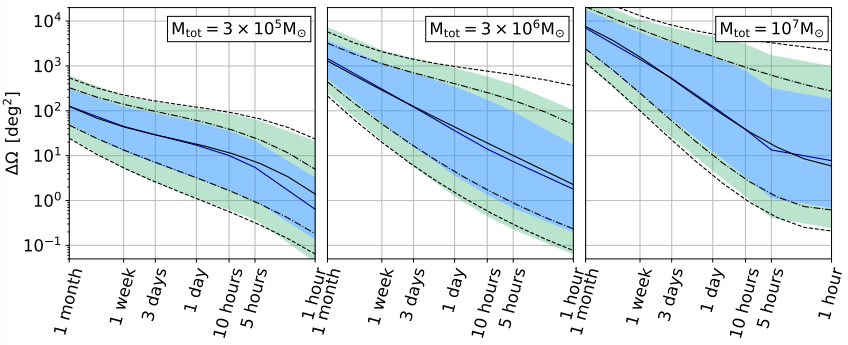
Chirp mass and mass ratio uncertainties at $z = 1$



Chirp mass and mass ratio are determined to $< 10\%$ at 1 week before merger for light and intermediate systems

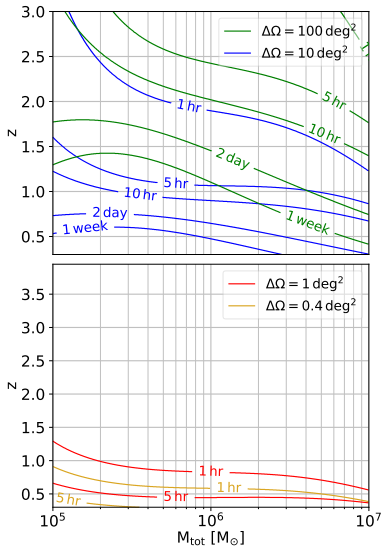
Analytical fits

Few input parameters → Time left before merger, $\mathrm{M_{tot}}$ and z $\log_{10} \Delta X = c_1 + c_2\, y + \cdots \rightarrow$ polynomial with 20 coefficients



Fits for $\begin{cases} \mathrm{M_{tot}} \in [10^5, 10^7]\, \mathrm{M}_\odot \\ z \quad \in [0.3,\ 3] \end{cases}$

Time left before merger



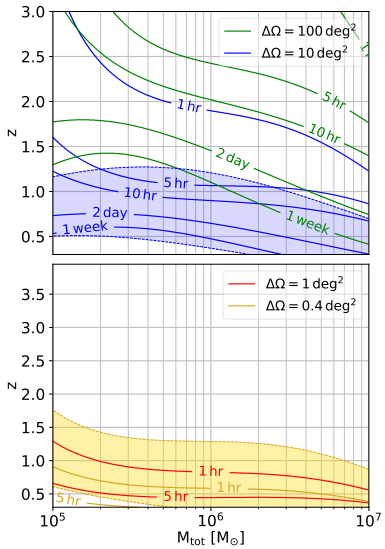
For $\mathrm{M_{tot}} = 10^6 \mathrm{M}_\odot$:

- $10\,\mathrm{deg}^2 \begin{cases} 5\,\mathrm{hrs} & \rightarrow z < 1 \\ 1\,\mathrm{week} & \rightarrow z < 0.5 \end{cases}$
- $100\,\mathrm{deg}^2 \begin{cases} 5\,\mathrm{hrs} & \rightarrow z \lesssim 2.4 \\ 1\,\mathrm{week} & \rightarrow z < 1 \end{cases}$

For all masses:

- $\Delta\Omega < 1\mathrm{deg}^2$ close to merger
- Large uncertainties

Time left before merger



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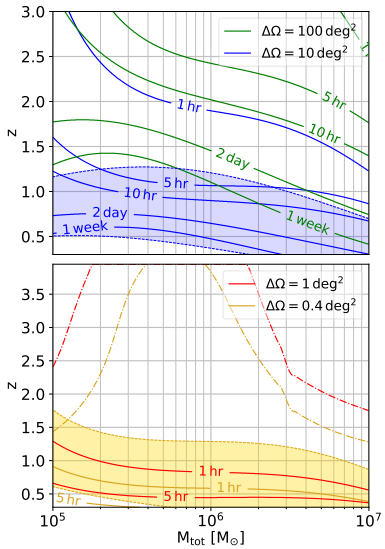

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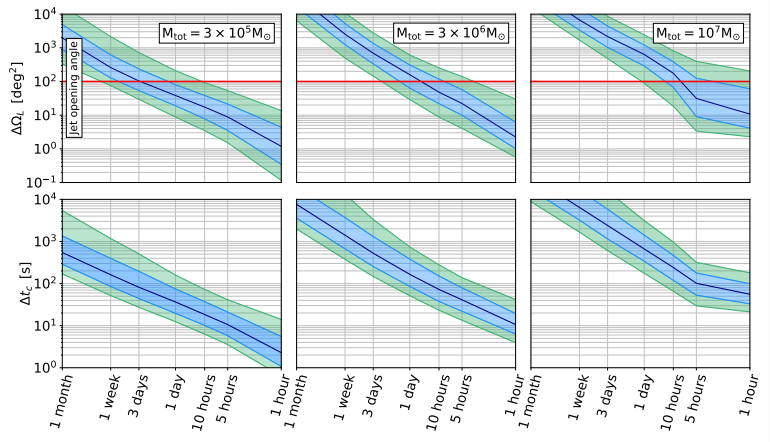
Angular momentum and coalescence time



$\Delta\Omega_L \lesssim 100\,\mathrm{deg}^2$ only for light and intermediate systems

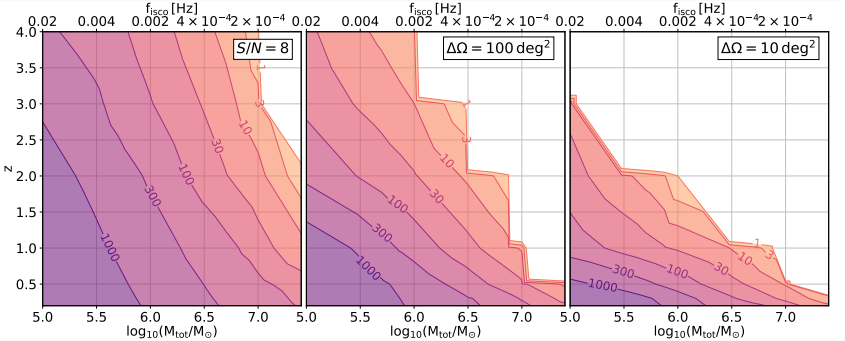
$\Delta t_c \lesssim 3$ hrs even for heavy systems

Periodicity

MBHBs are localized within $100\,\mathrm{deg}^2$ 2 days before merger up to $z \simeq 1.5$

$\downarrow$

Large number of GW cycles before merger



Possible EM periodicity for light and nearby systems?

Conclusion

Parameter estimation 'on the fly' for LISA MBHBs:

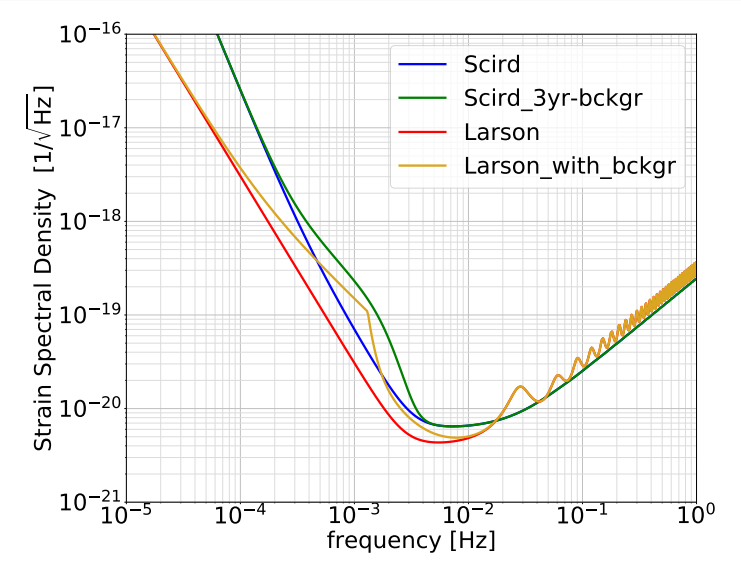
- Systems with $\mathrm{M_{tot}} \simeq 10^6\,\mathrm{M_\odot}$ are localized within $\Delta\Omega \simeq 100\,\mathrm{deg}^2$ up to $z \simeq 1.5$ 2 days before merger
- MBHBs between $3 \times 10^5\,\mathrm{M_\odot}$ and $10^6\,\mathrm{M_\odot}$ are localized to $\lesssim 0.4\,\mathrm{deg}^2$ up to $z \simeq 3$ when the full signal is included and spend a large number of cycles in band
- MBHBs with $\mathrm{M_{tot}} \simeq 10^7\,\mathrm{M_\odot}$ are poorly localize during the inspiral but their position is constrained to $\Delta\Omega \simeq 1\,\mathrm{deg}^2$ with merger and ringdown up to $z \simeq 1.5$
- Large uncertainties (especially in the sky position)
- Luminosity distance, chirp mass and mass ratio are constrained to percent precision at the end of inspiral

Analytical fits for parameter estimates

- Valid for $\mathrm{M_{tot}} \in [10^5, 10^7]\,\mathrm{M_\odot}$ and $z \in [0.3, 3]$
- Independent fits for uncertainties at merger
- Fits also for d_L, chirp mass and mass ratio
- Data available on Github (amangiagli/Fits-for-parameter-estimation-of-MBHBs-in-LISA)

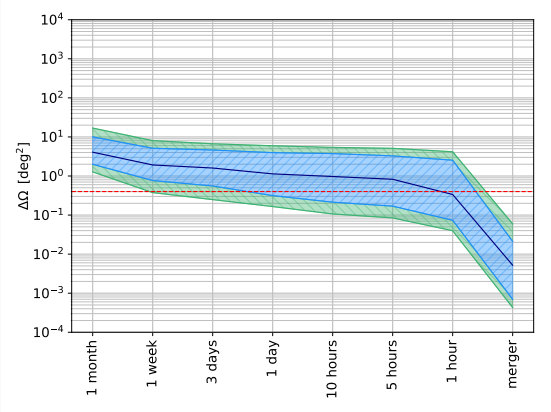
Thanks

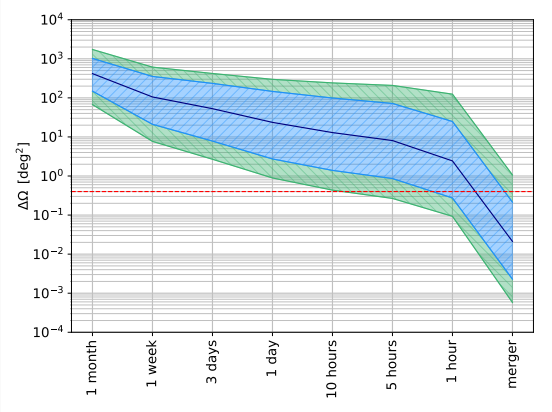
Backup slides



Backup slides

For a MBHB with $\mathrm{M_{tot}} = 10^6 \mathrm{M}_\odot$, $z = 1$





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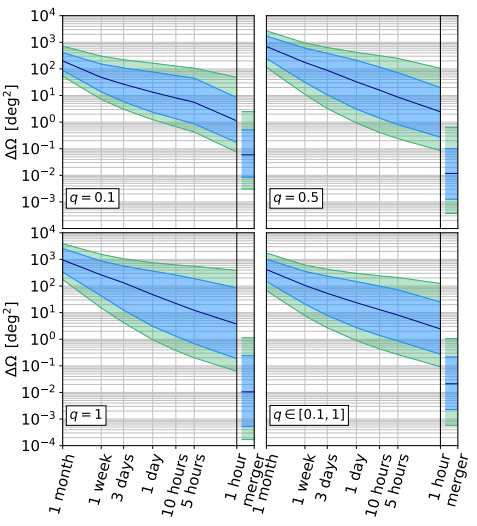

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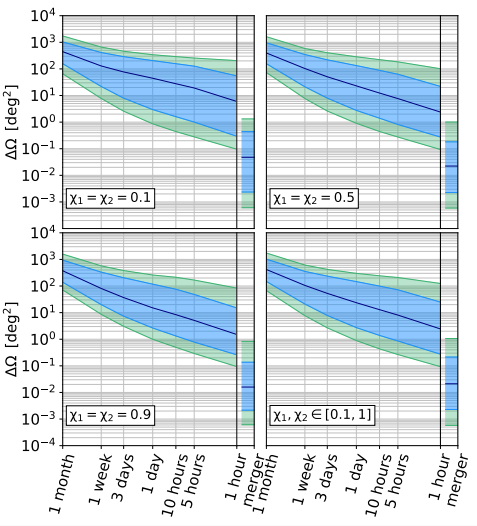

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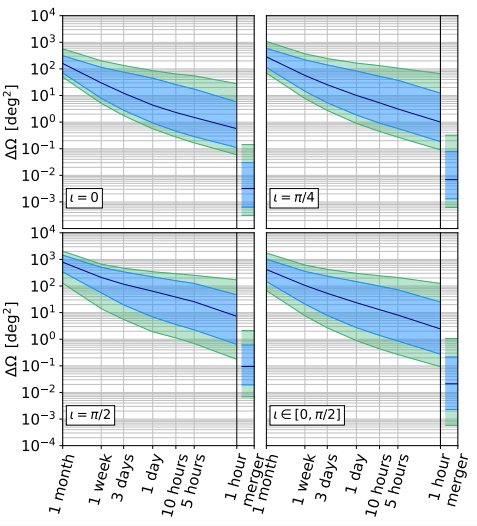

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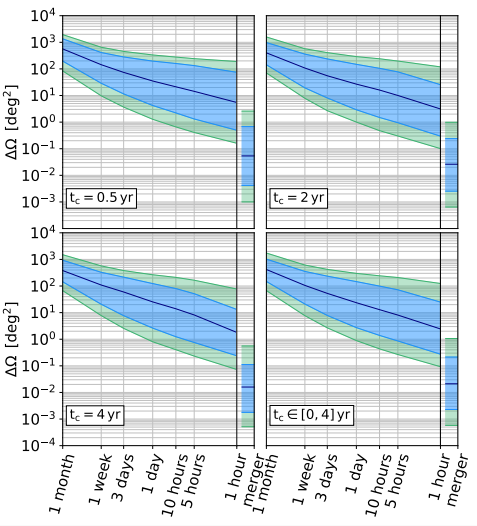

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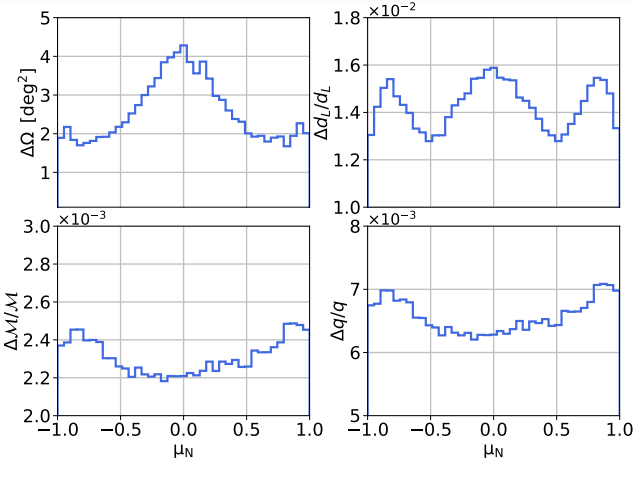
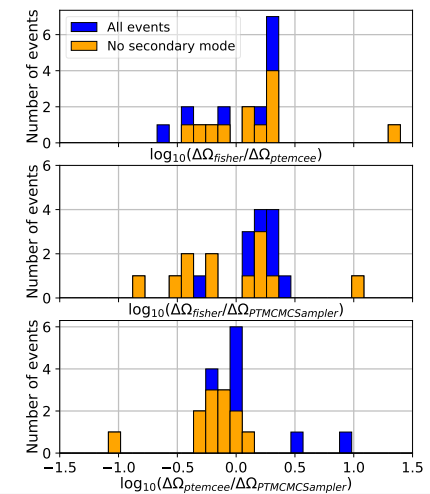


Backup slides

Fisher matrix vs *MCMC* simulations

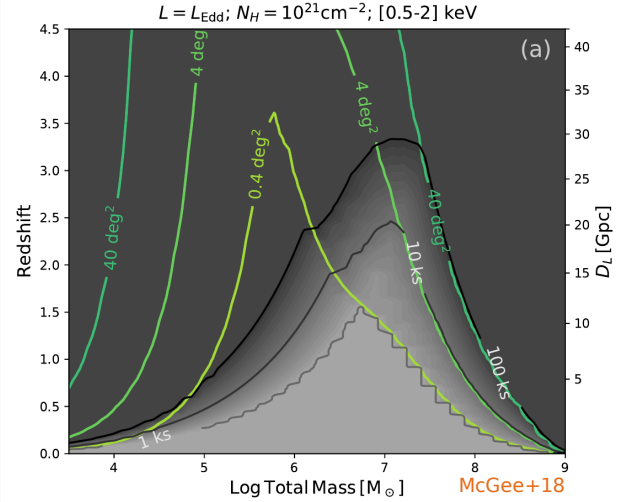


Compare subsample of 20 systems with $\Delta\Omega < 10\,\mathrm{deg}^2$ at 5 hours before merger:

- Similar results for *fisher* vs *MCMC*
- Differences between *MCMC* implementations are similar with the one from *fisher*

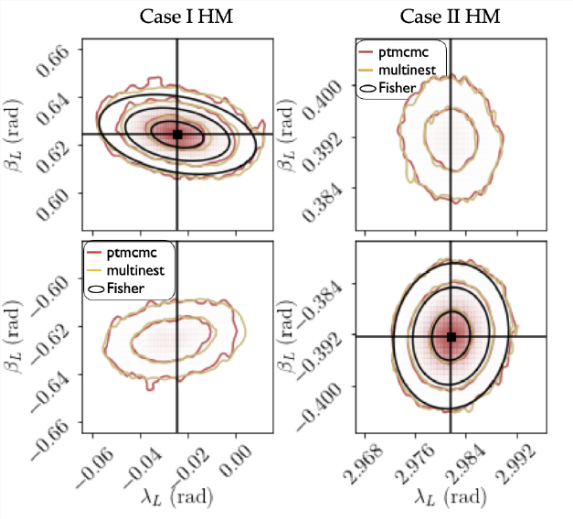
Backup slides

Joint LISA+Athena observation



Backup slides

Multimodal sky position posterior (Marsat+ 20)



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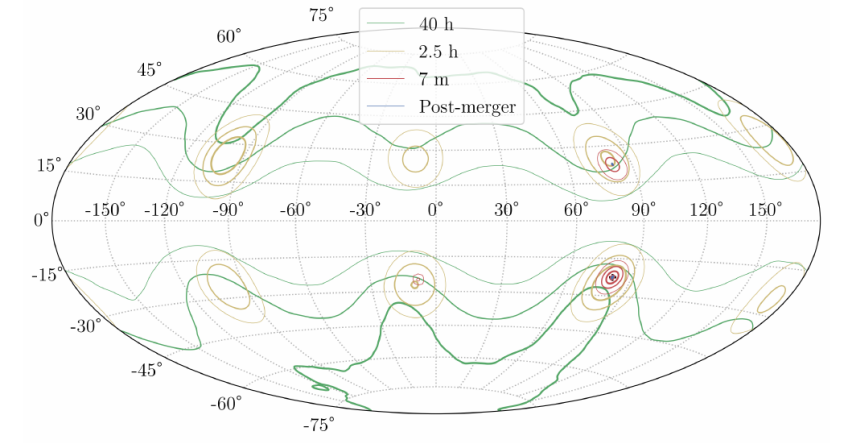

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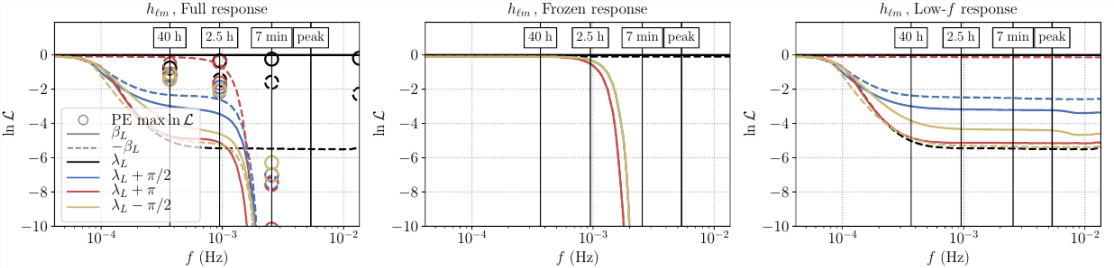

Backup slides

Ringdown parameter estimation with higher harmonics (Baibhav+ 20)