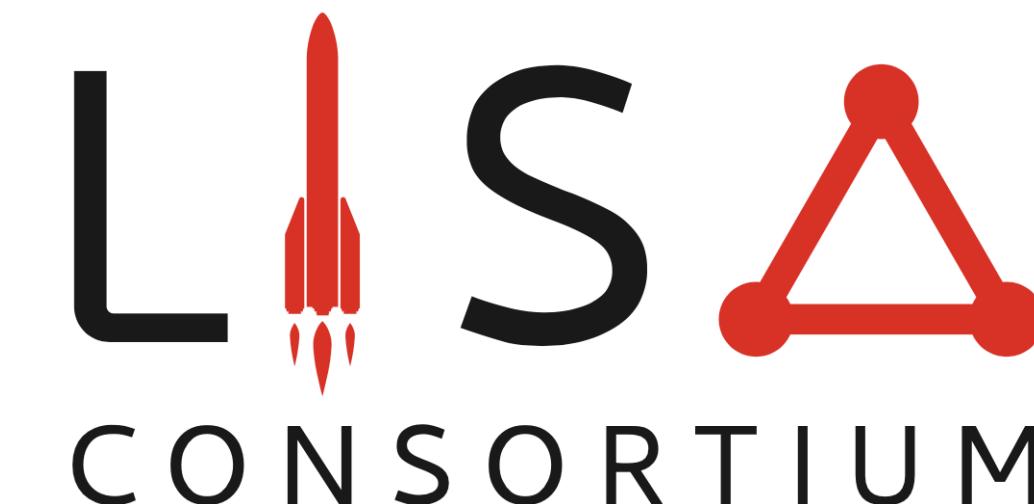


Massive black hole mergers observed by LISA and their localization

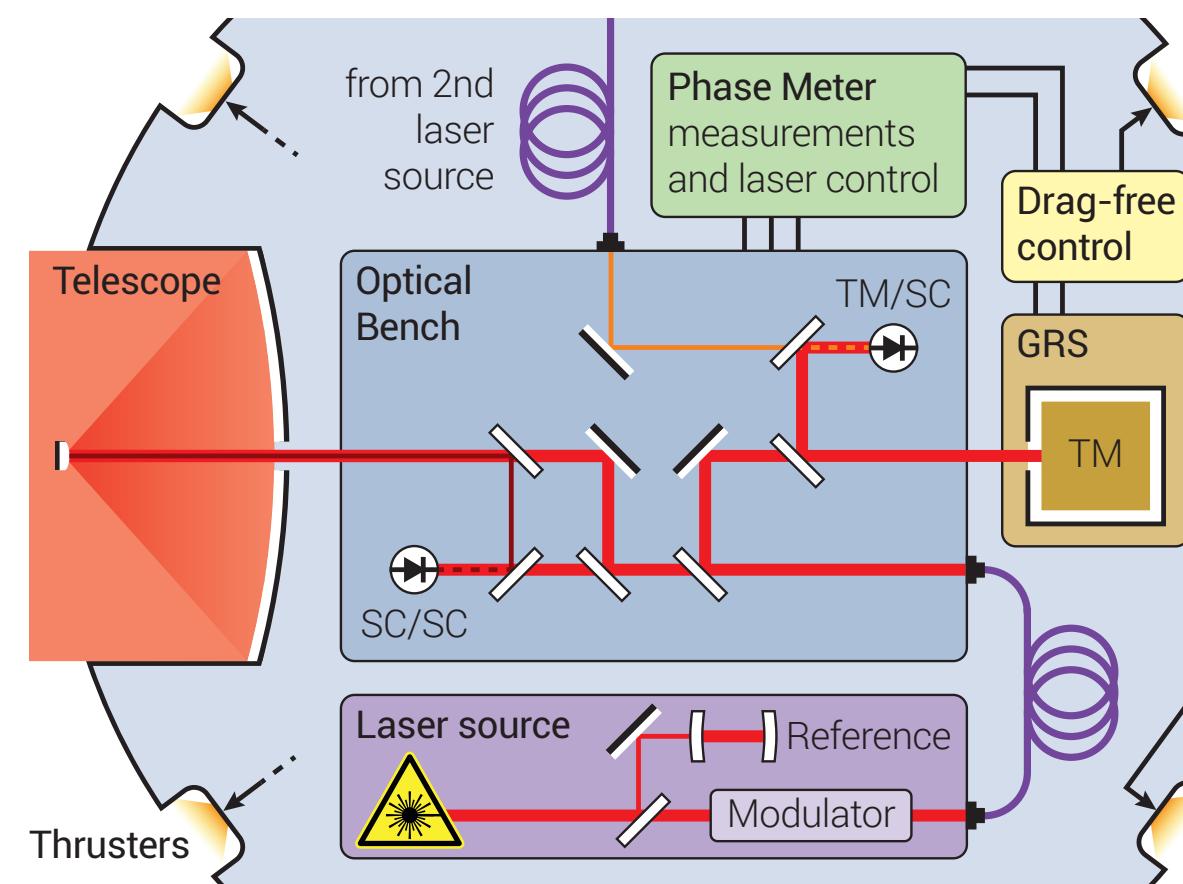
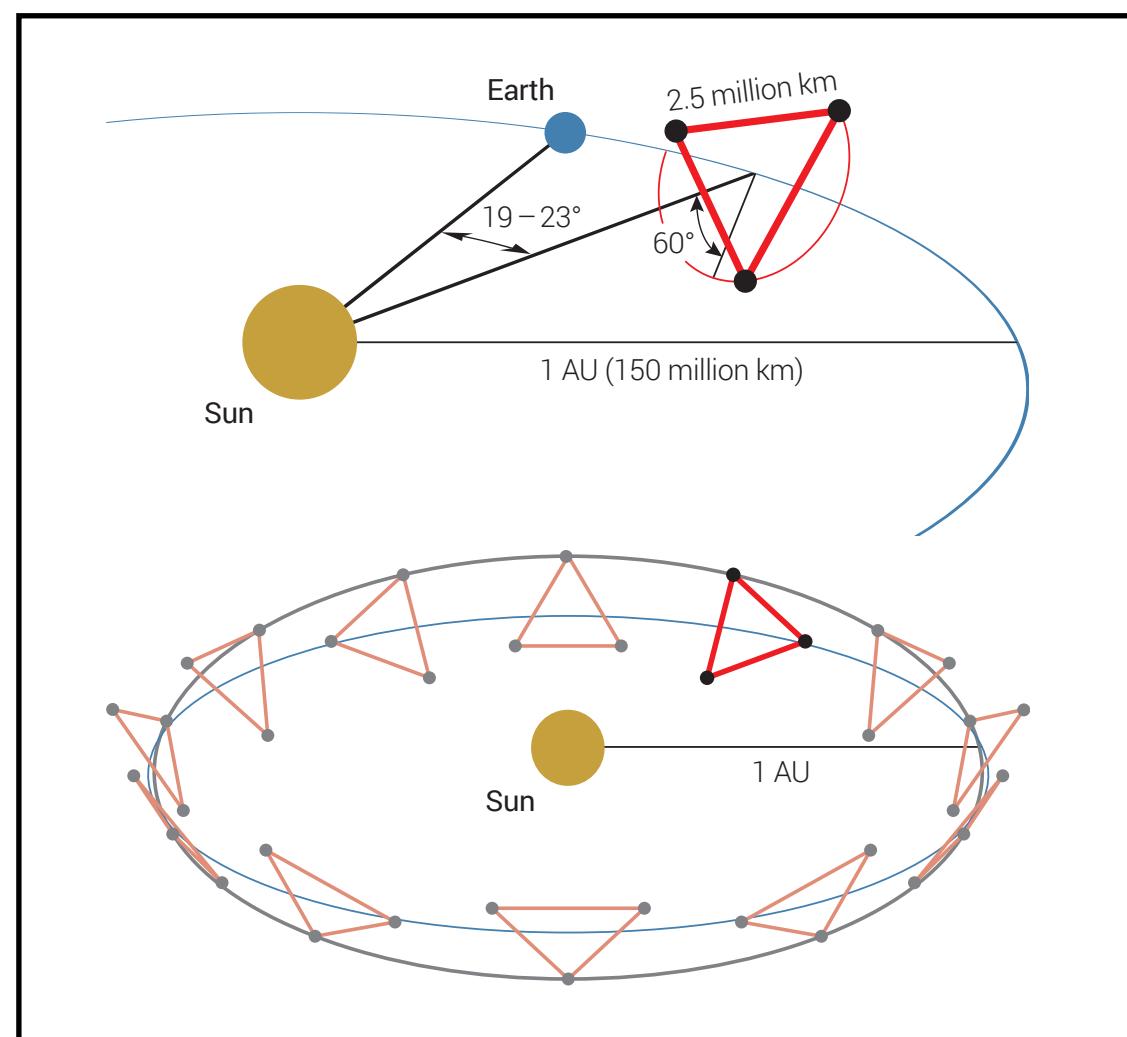
Sylvain Marsat (L2IT,Toulouse)



in collaboration with J. Baker (NASA GSFC), T. Dal Canton (LAL), S. Babak (APC), A. Toubiana (APC), M. Katz (AEI), A. Mangiagli (APC), H. Inchauspé (APC), R. Cotesta (J. Hopkins), ...

The LISA mission

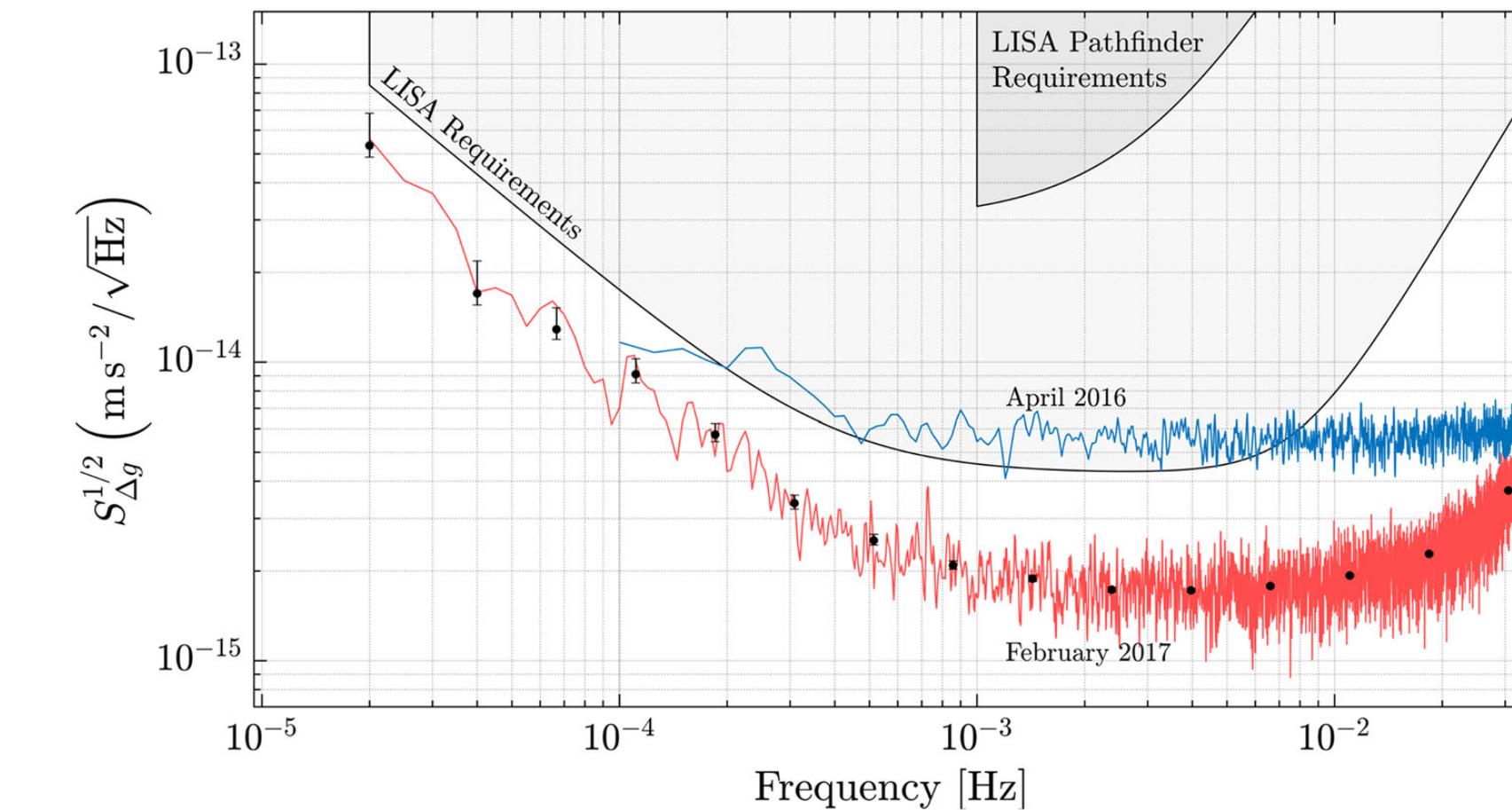
LISA instrument



Status

- Provisional launch date around 2034
- Successfully finished phase A, entering phase B I

Success of LISA pathfinder !



Specificities of LISA response

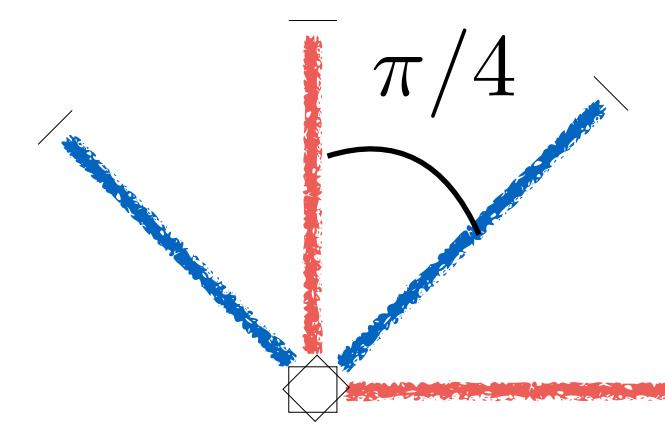
Features in the instrument response that give us the localization:

Time and frequency-dependency

Time: motion of LISA on its orbit

Frequency: departure from long-wavelength

Low-f approximation: **two LIGO-type detectors** in motion [Cutler 1997]
High-f: more complicated



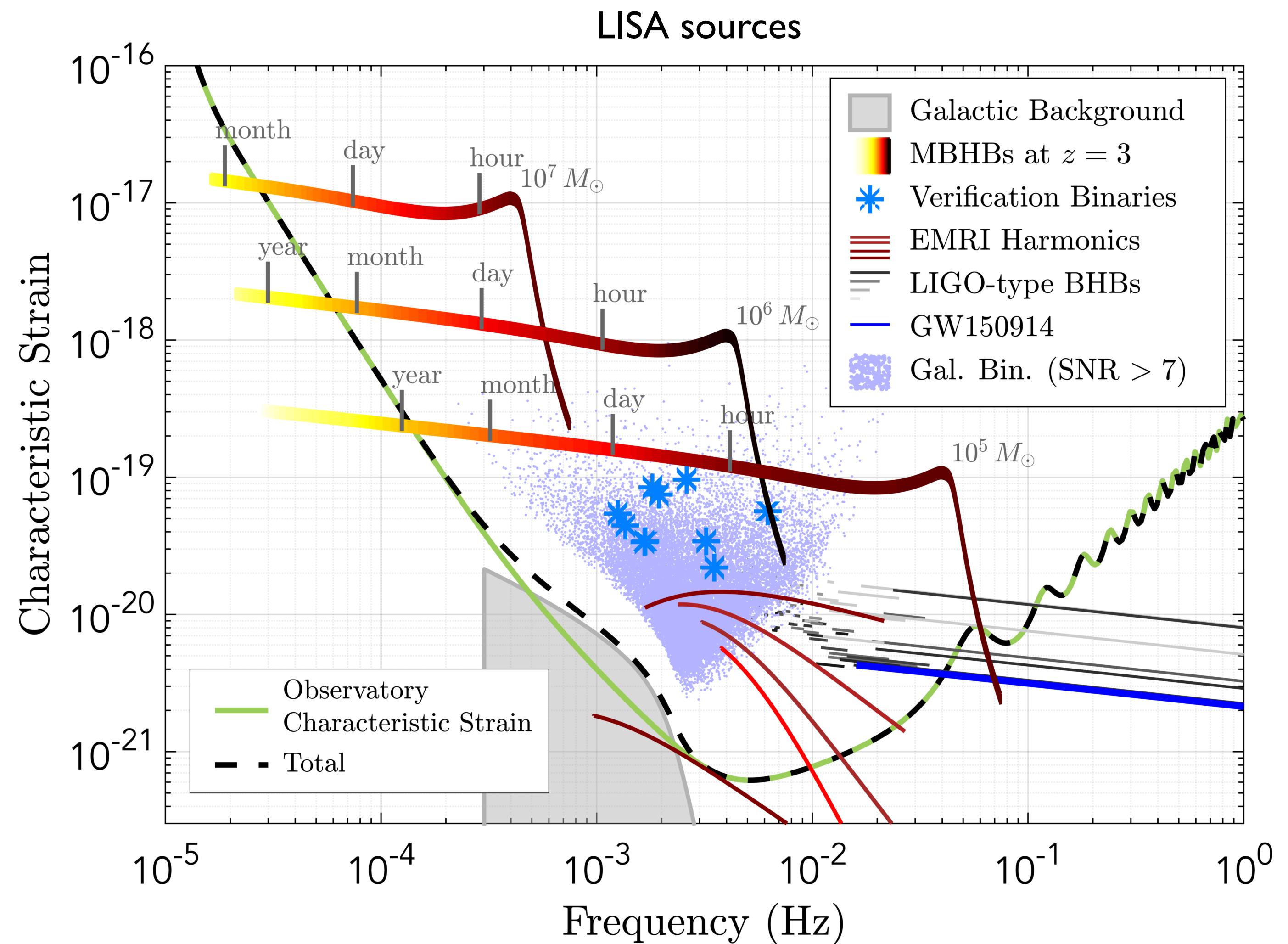
Data acquisition, low-latency [Preliminary, in discussion]

- Scheduled gaps: ~5hrs every 15 days, longer gaps ~1/year
- Unscheduled gaps
- Target duty cycle > 75%
- Protected periods: 6 days continuous operations
- Data downlink: 8hrs every day
- Real-time data downlink ?

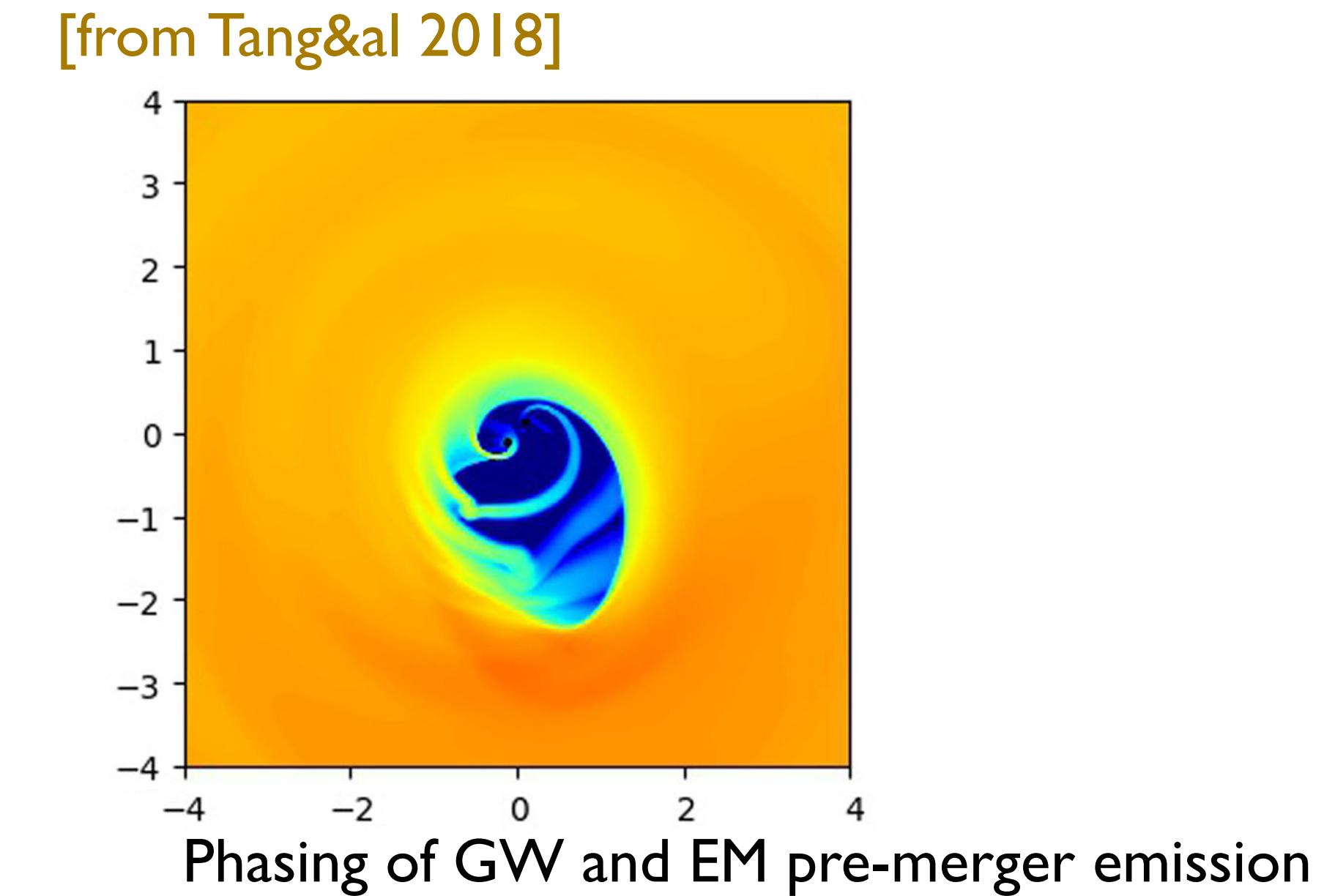
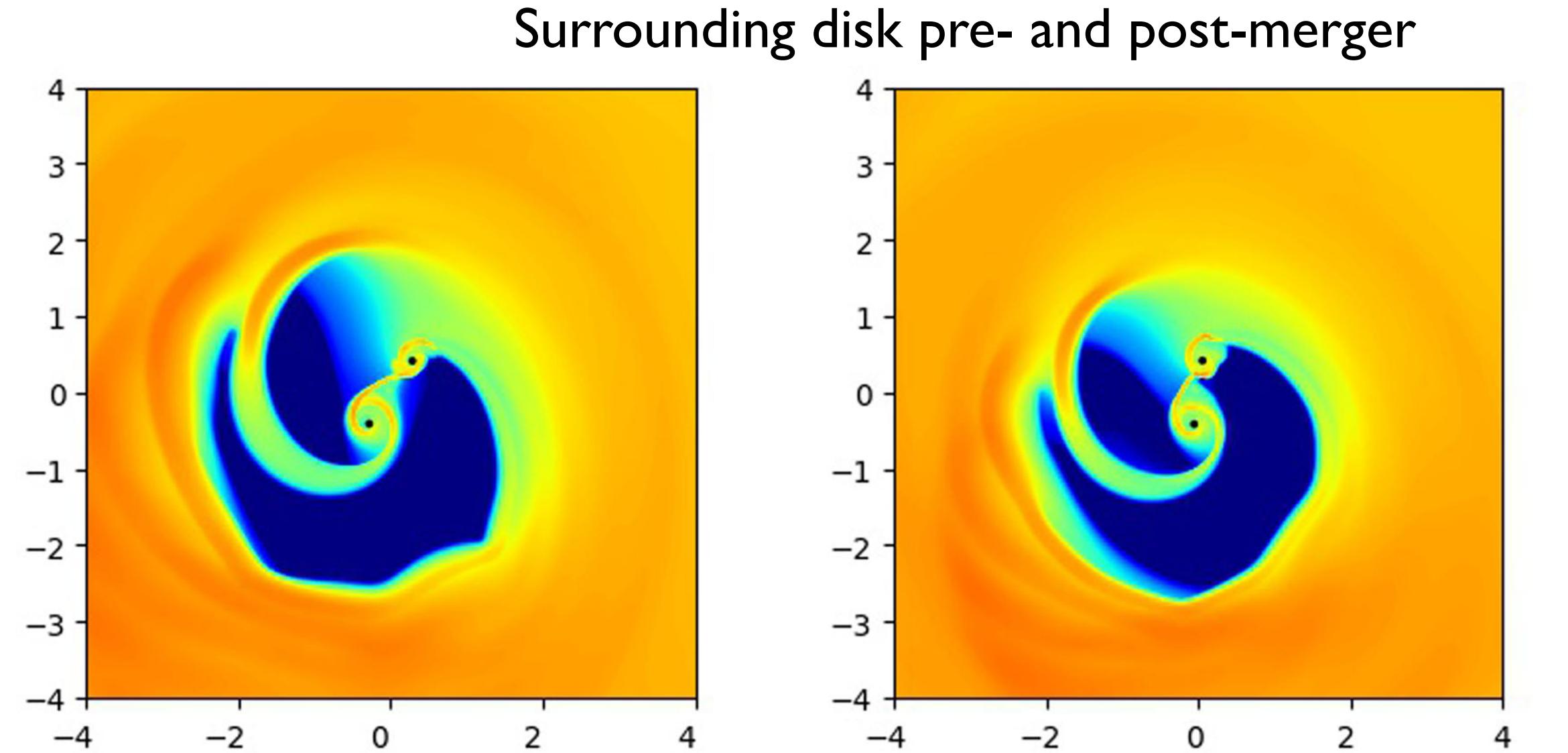
The LISA sources

A rich landscape at low frequencies

- **MBHBs:** massive black hole binaries **primary candidates** for EM counterparts
- **EMRIs:** extreme mass ratio inspirals (tidal disruption EM counterpart ?)
- **GBs:** galactic binaries, e.g. white dwarfs
- **SBHBs:** stellar-mass black hole binaries
- + astrophysical and cosmological stochastic backgrounds, other transients (TDE)



Electromagnetic counterparts from MBHB mergers



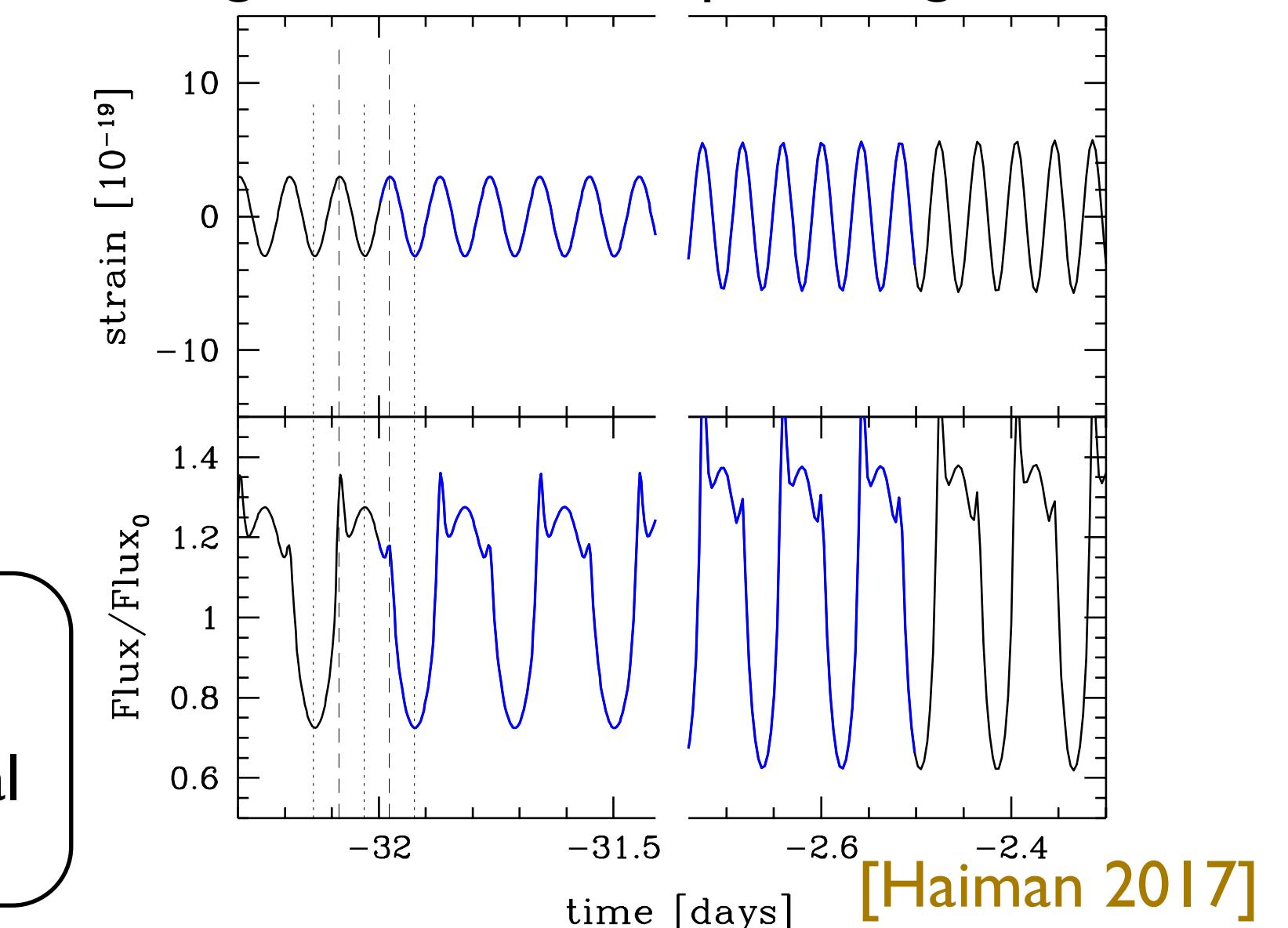
Pre-merger emission

- Circumbinary disk, lump
- Minidisks
- Accretion streams
- Emission lines

[Review: Bogdanovic&al 2021]

Post-merger emission

- Shocks close to merger
- Formation of jets
- Effect of mass-energy loss
- GW recoil kick
- Reorientation of AGN jet

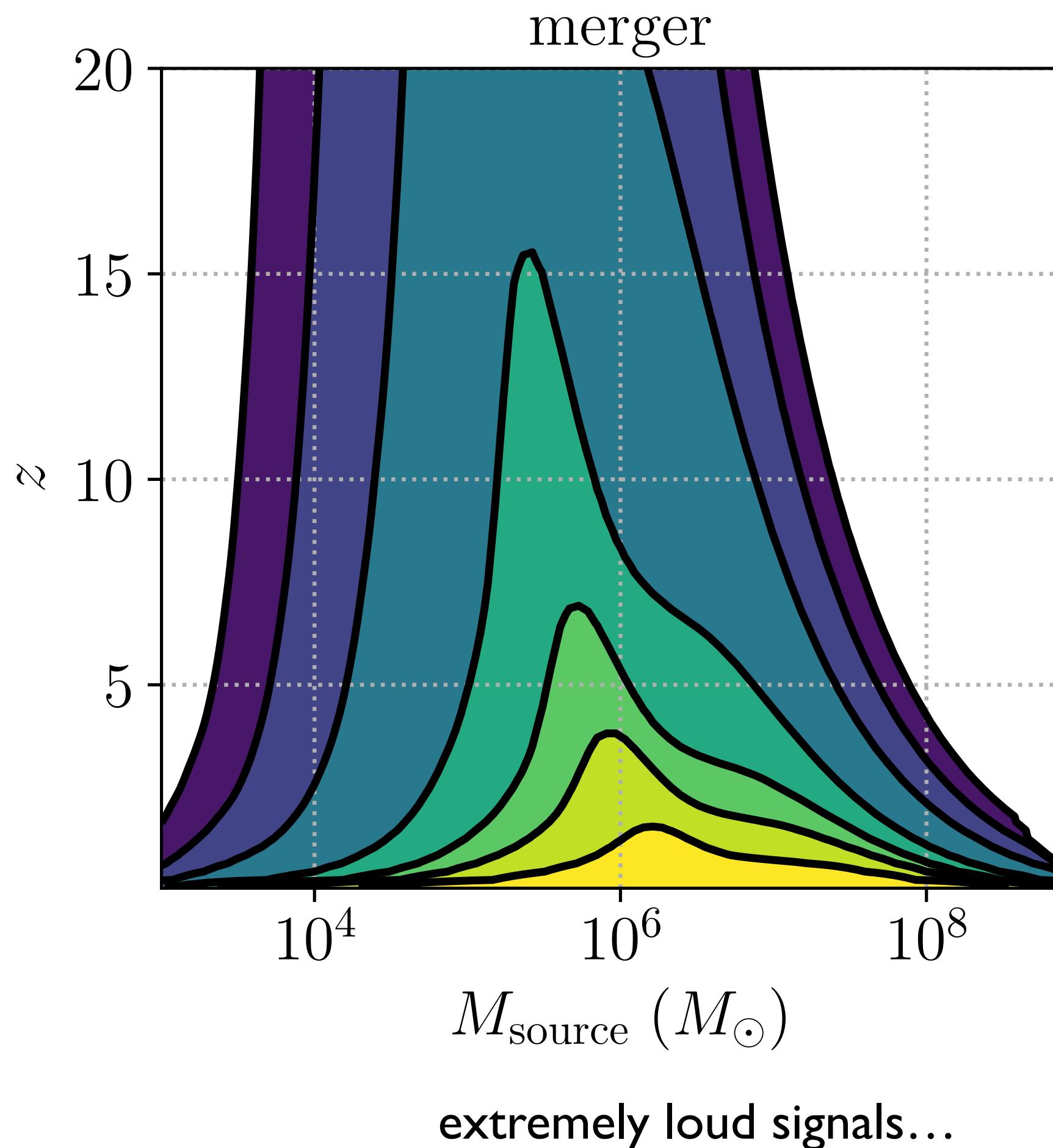


Active area of research
Multiwavelength counterparts: X, optical, radio
Future instruments: Athena, LSST, SKA

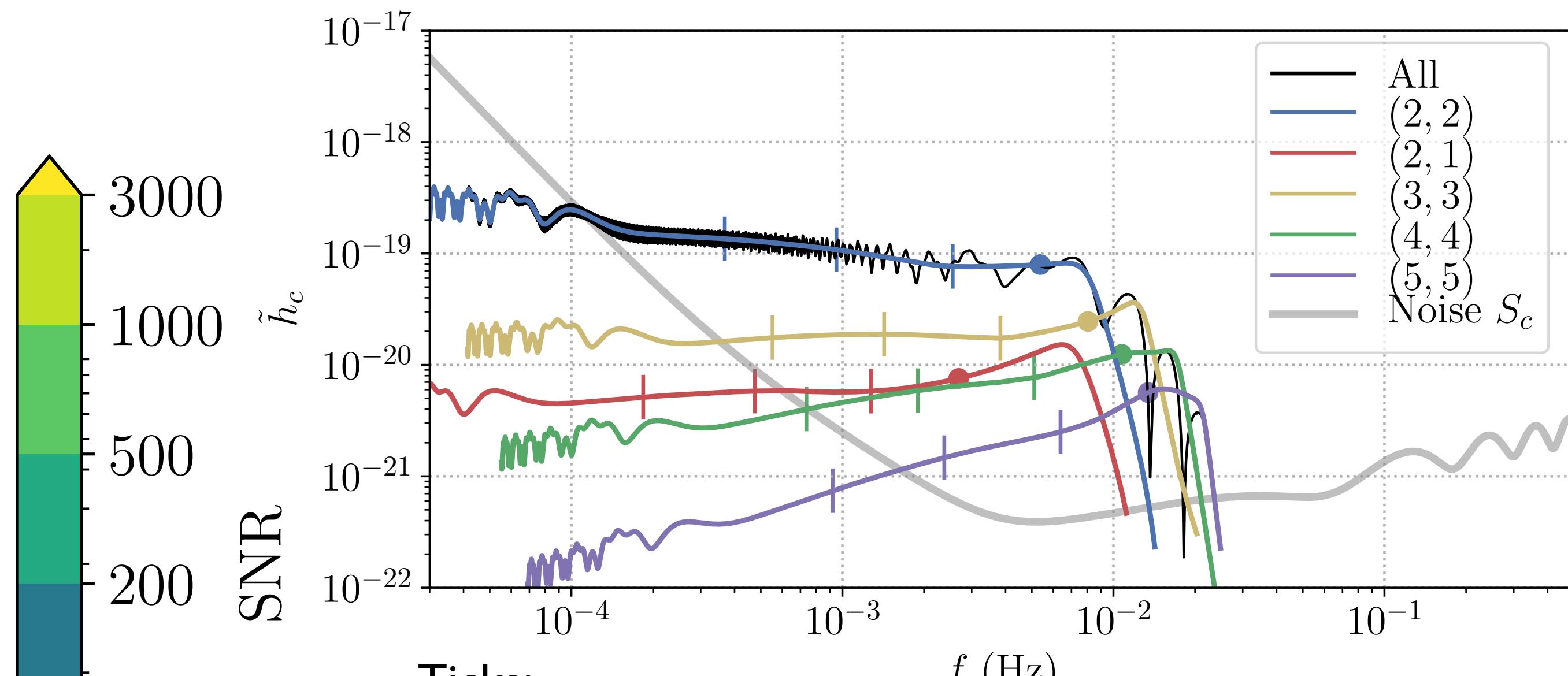
LISA MBHB
localization crucial

Massive black hole binaries

MBHB SNR contours post-merger



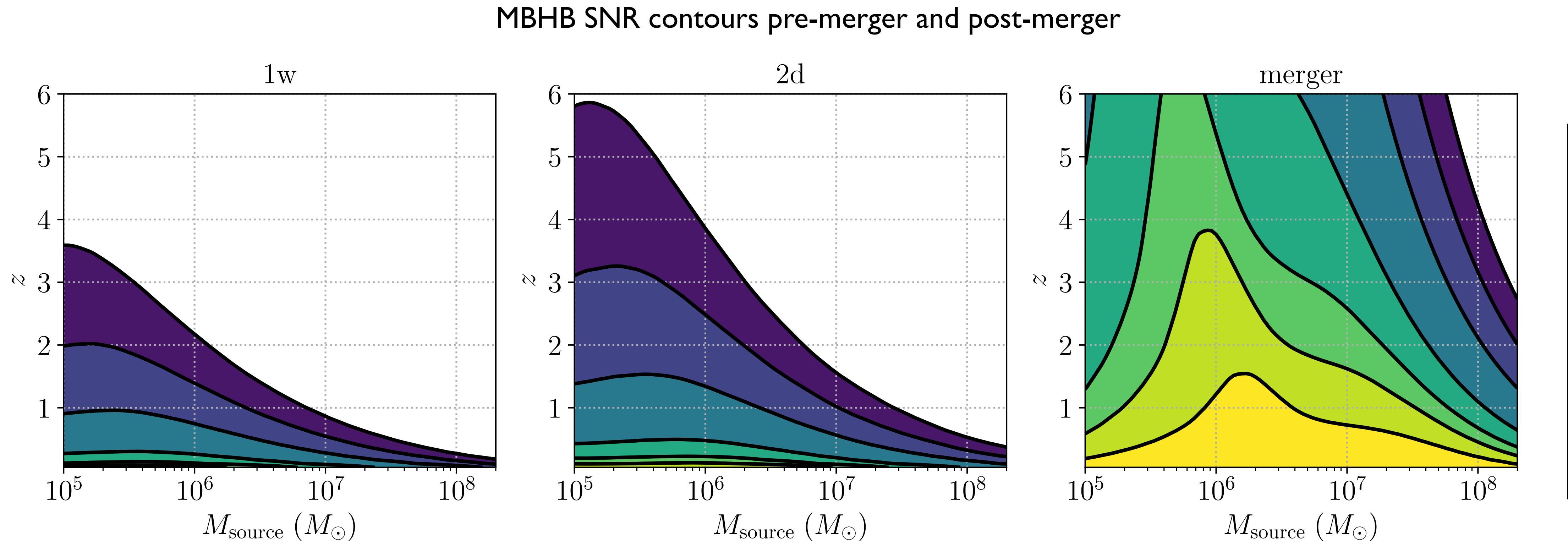
Example MBHB GW signal with higher harmonics



Higher harmonics strong
at merger (break
degeneracies)

Data analysis simulations
still missing precession,
eccentricity

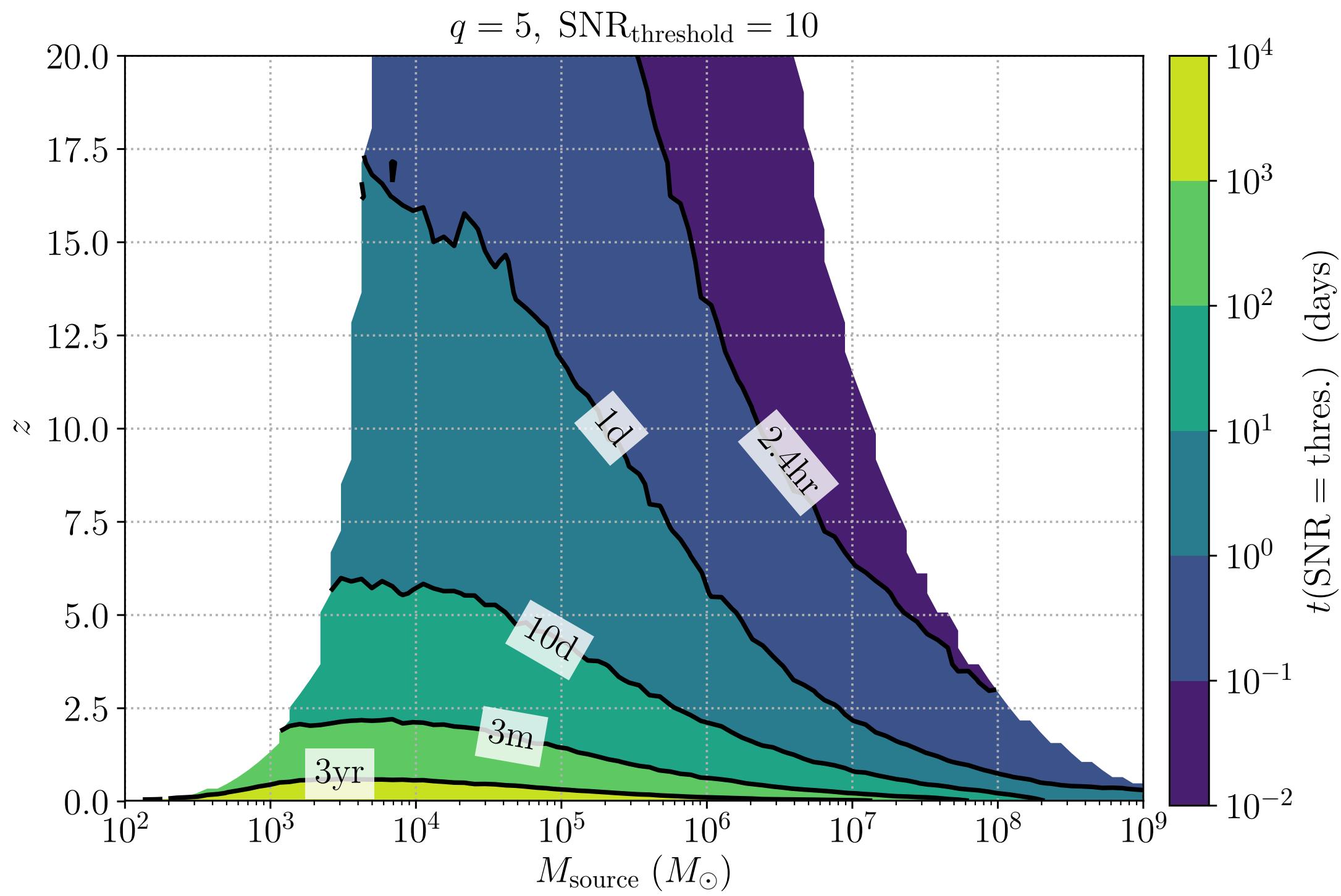
MBHB signals are merger-dominated in SNR



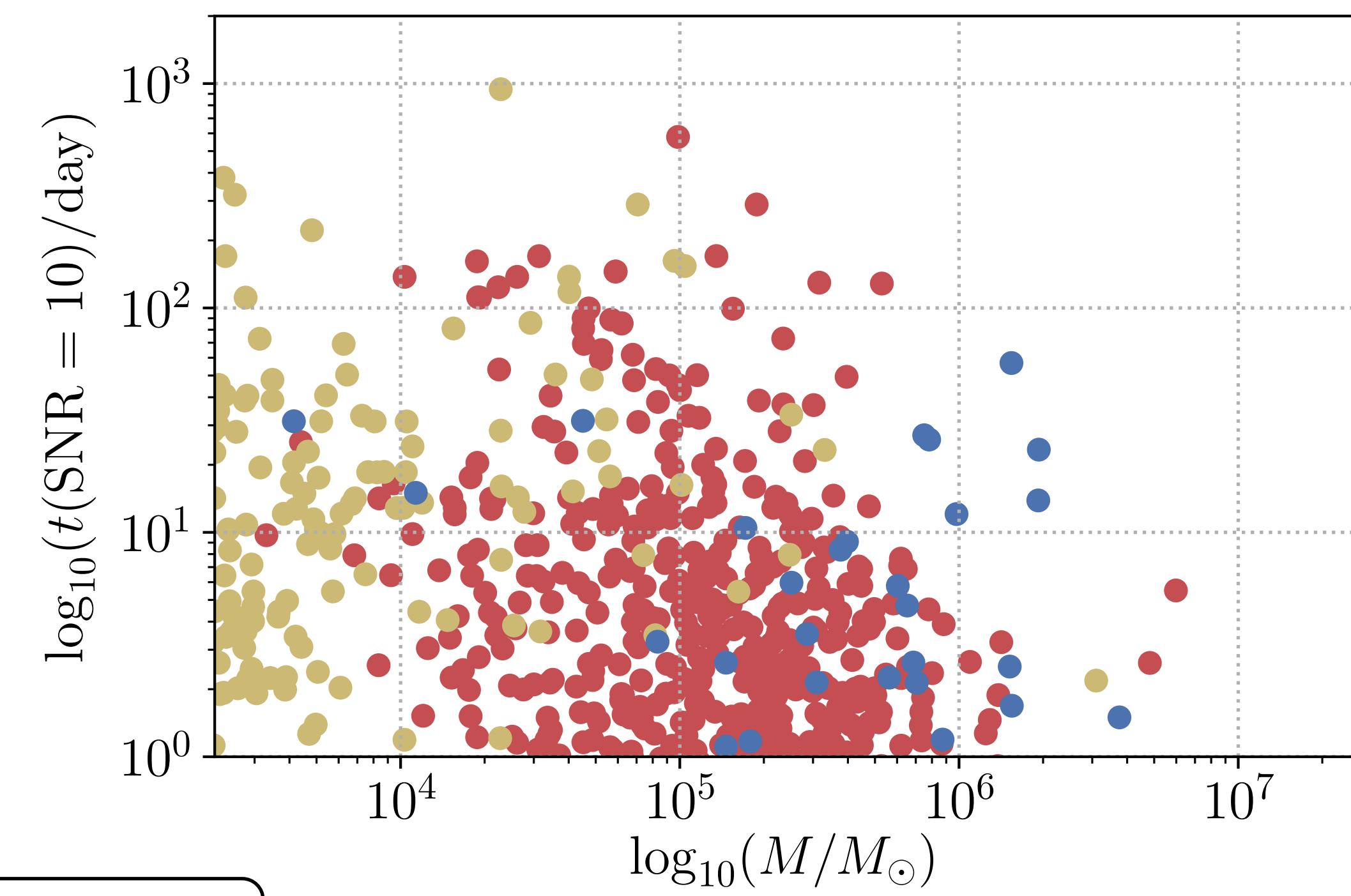
Most of the SNR accumulates
in the last hours before merger

The length of MBHB signals

- How long before merger can we detect the signal ?
- SNR=10 to claim detection



- Astrophysical models [Barausse 2012]:
- Heavy seeds - delay
 - Heavy seeds - no delay
 - PopIII seeds - delay

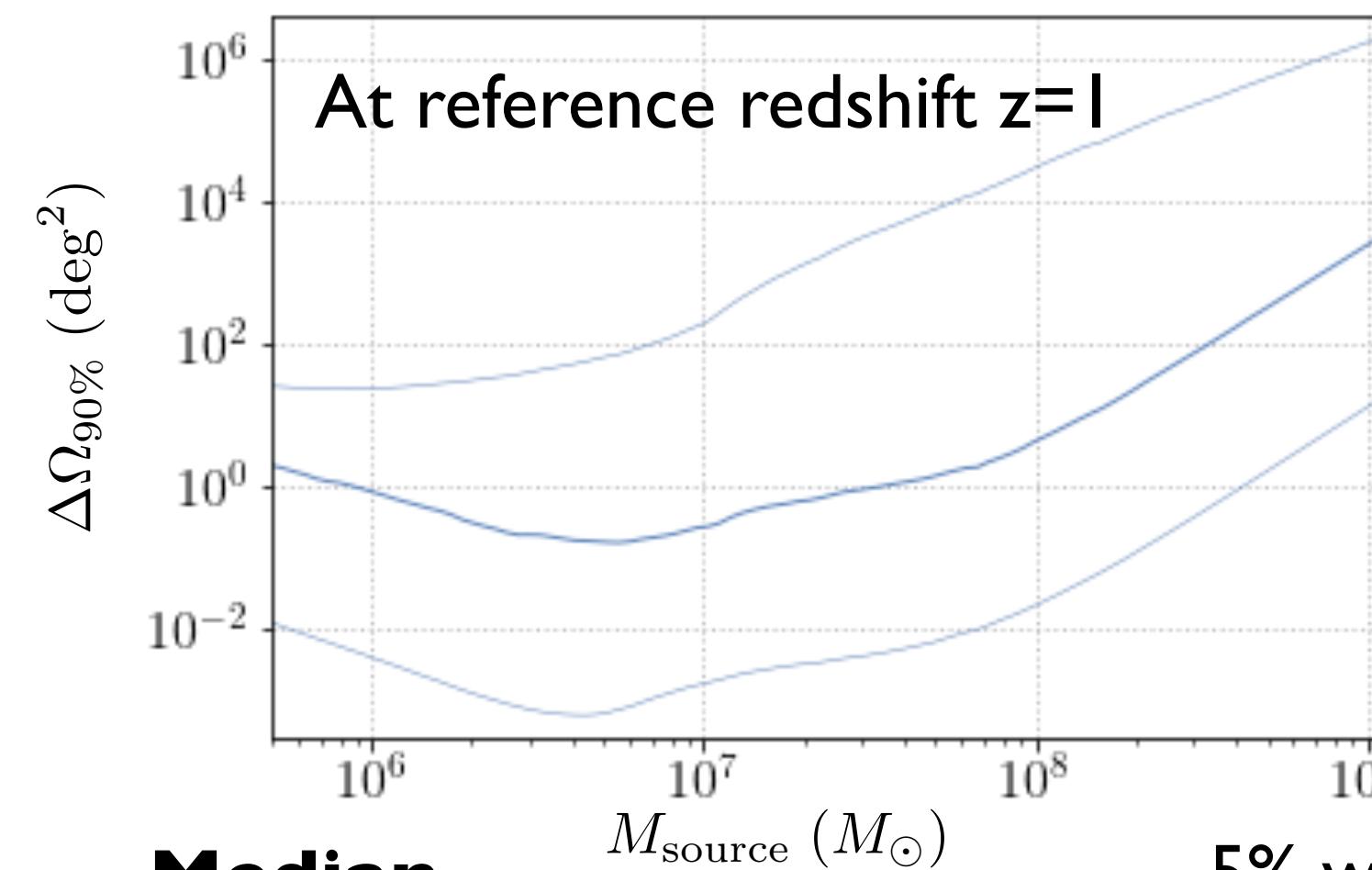


MBHB detected signals:
Bulk shorter than ~10days
Tail extending to ~3months

MBHB localization at merger

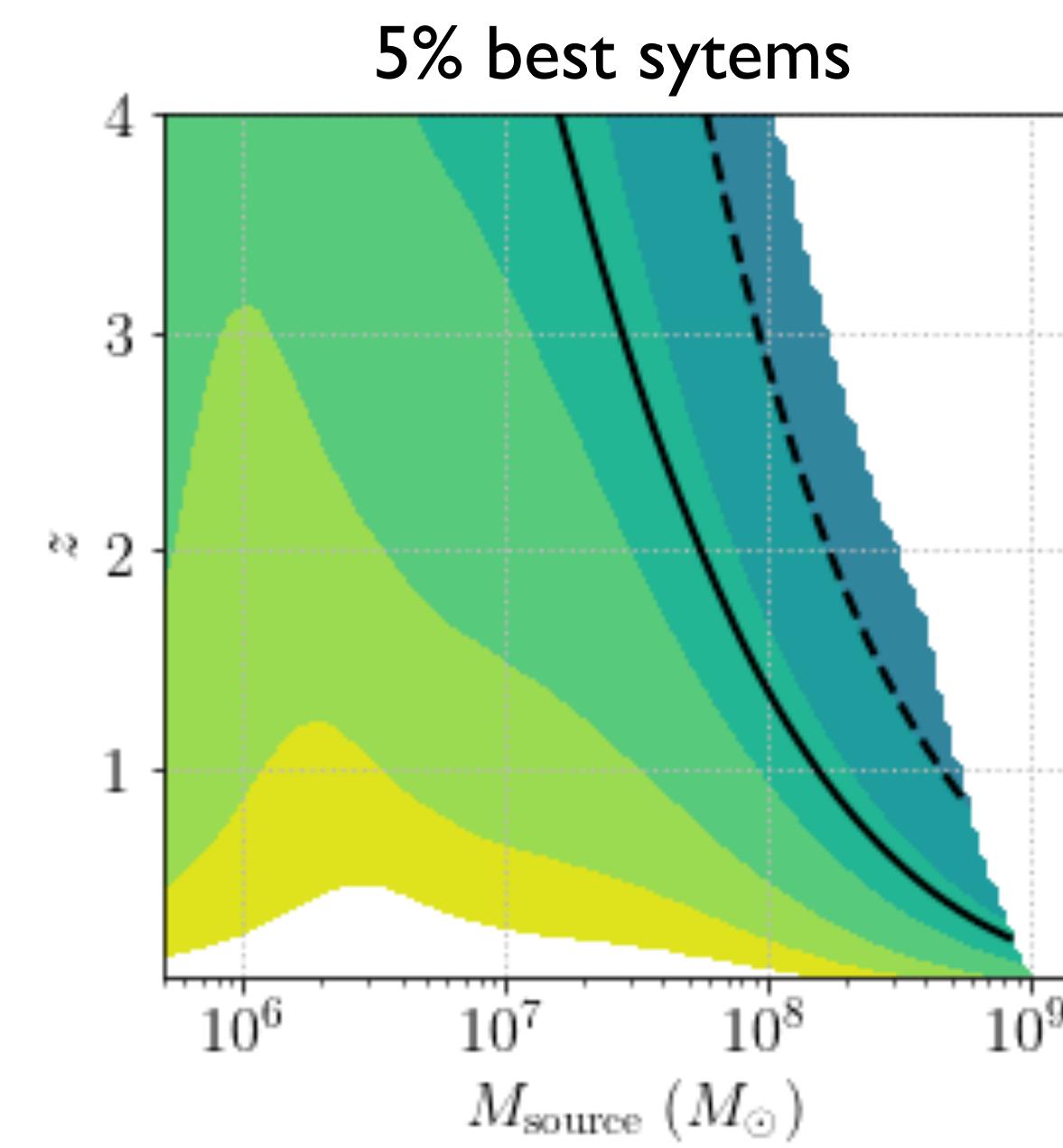
Fisher matrix analysis (with merger and HM)

Randomizing over mass ratio, spin, orientation

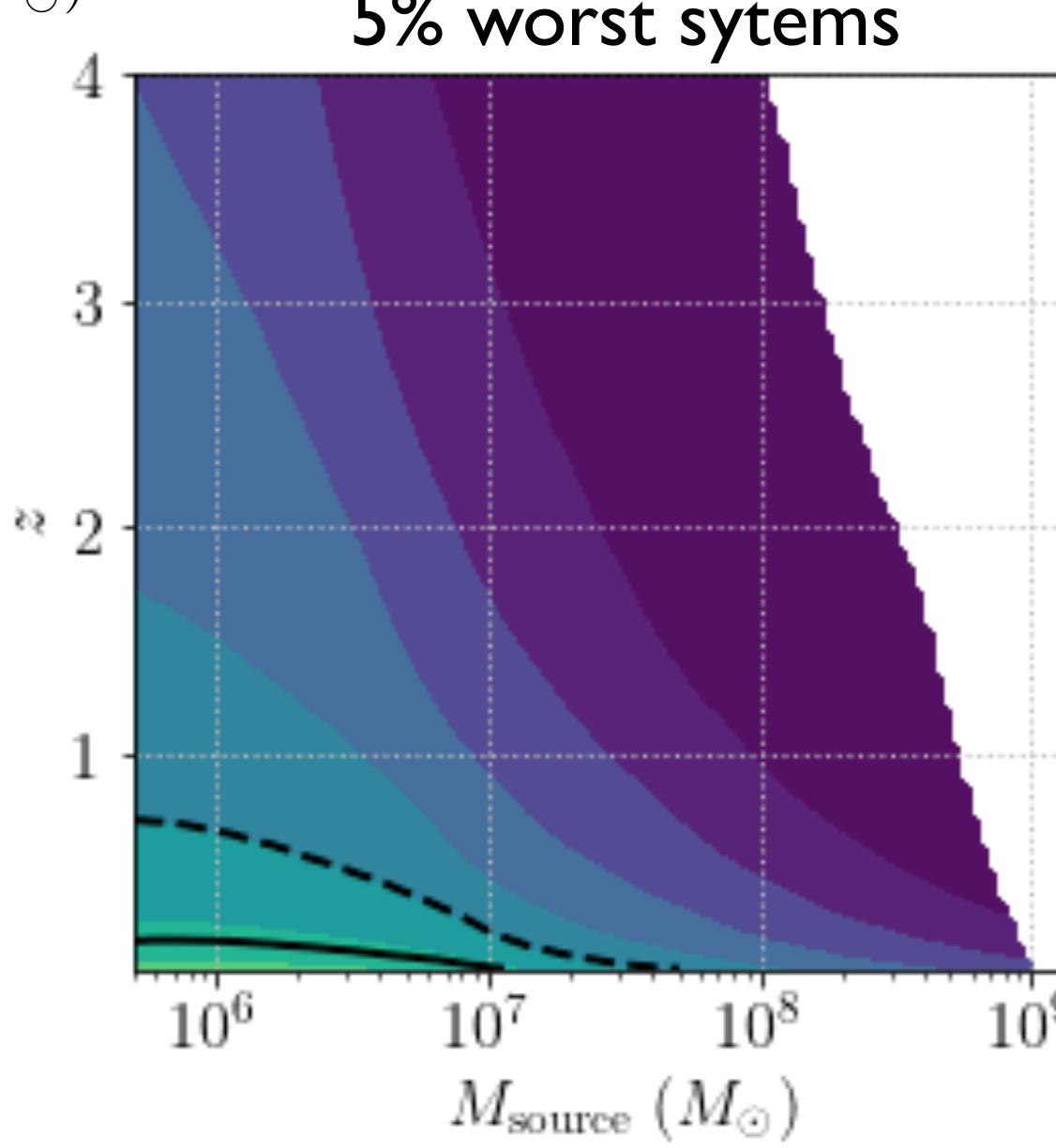
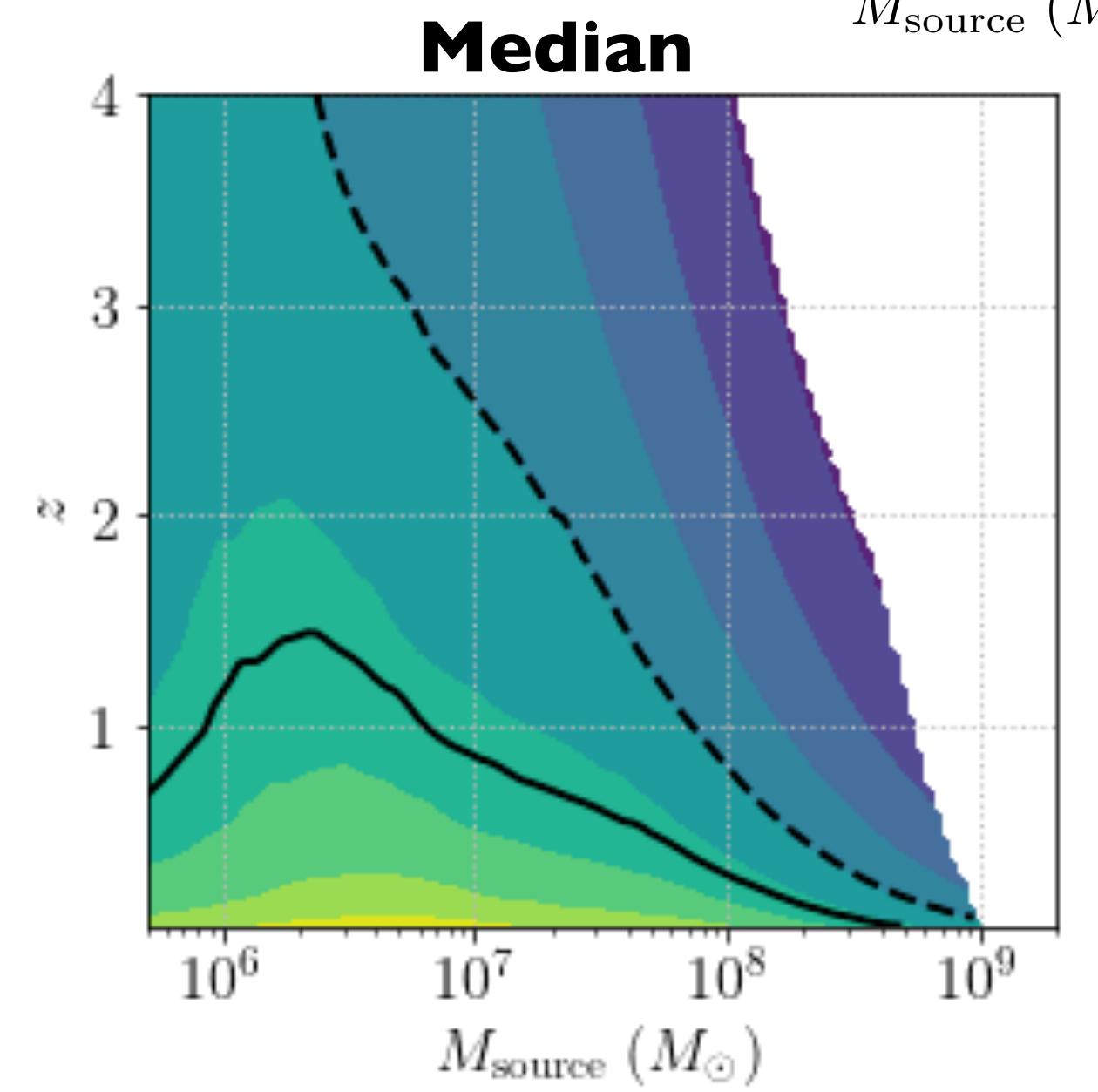


[Preliminary]

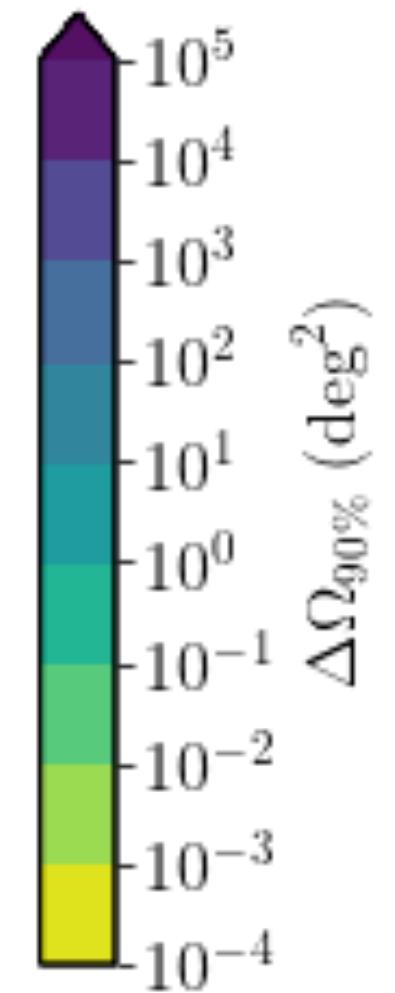
Large variations of sky localization depending on orientation !



[See also McGee&al2018, Mangiagli&al 2020]



- - 10 sq. deg. : LSST field of view
— 0.4 sq. deg.:Athena Wide Field Imager

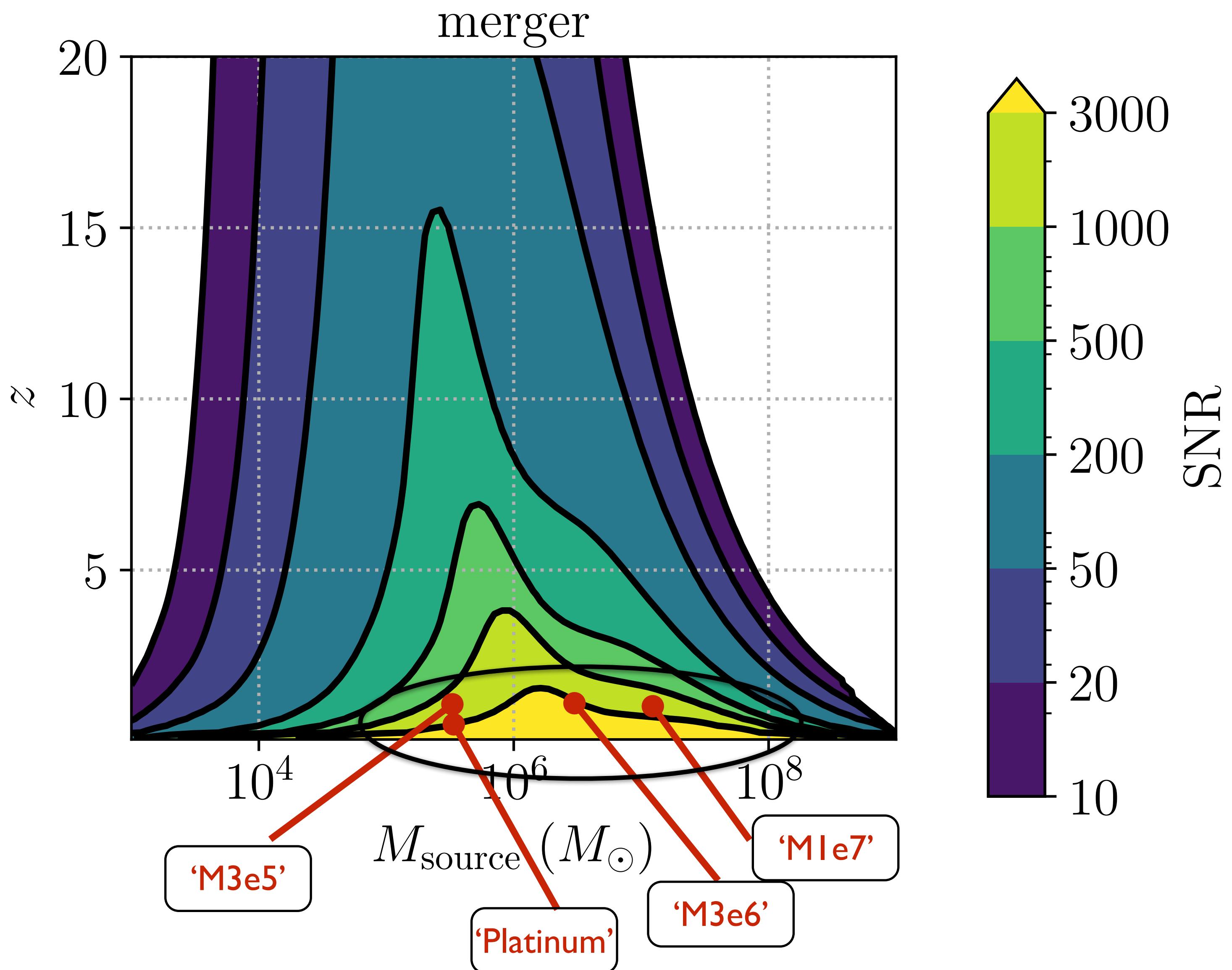


[Preliminary]

Example MBHB signals: ‘golden’ sources

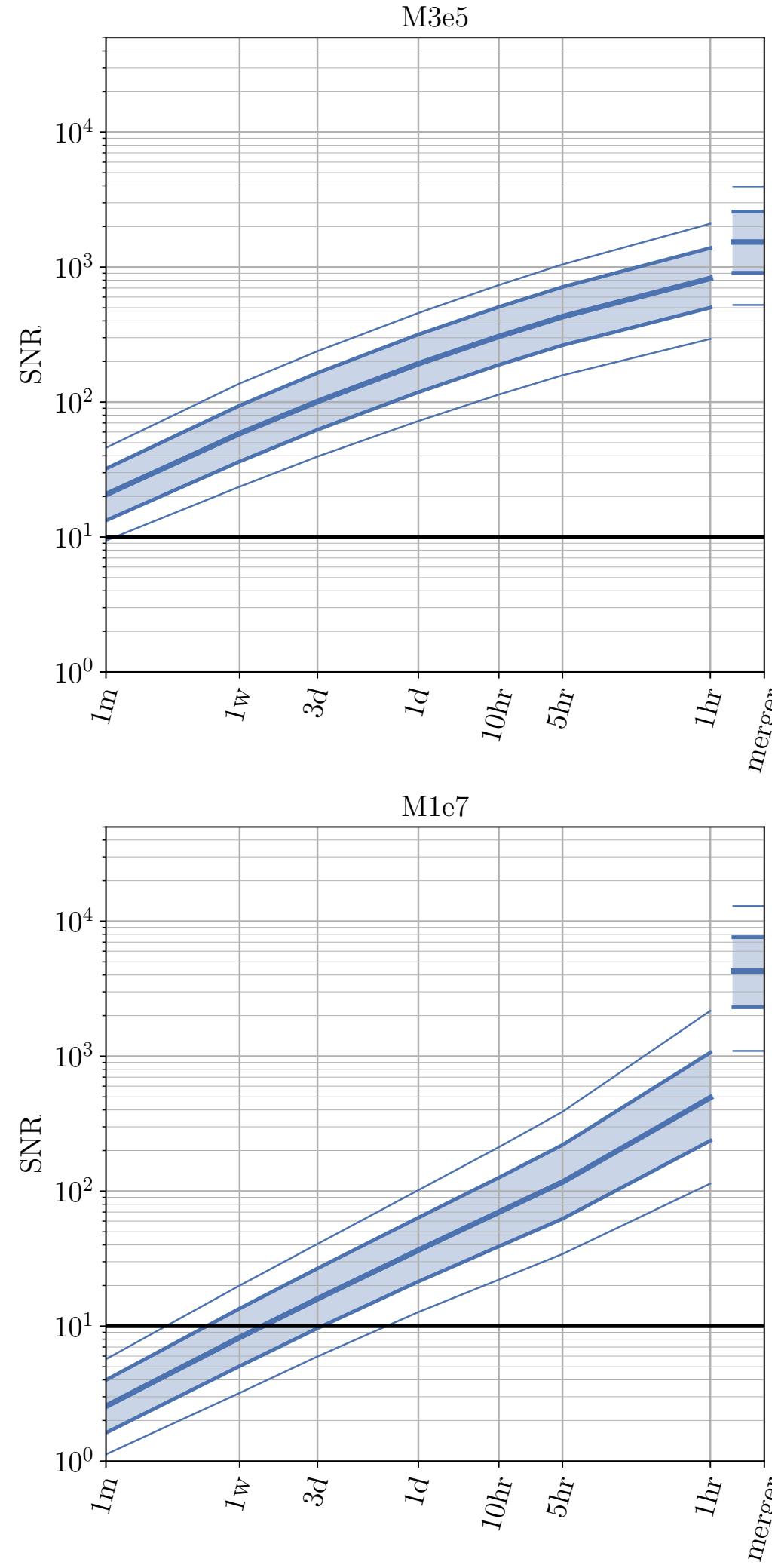
Examples of good candidate systems
for an advance localization :

- M3e5 z=1
- M3e6 z=1 (‘Gold’)
- M1e7 z=1 (‘Heavy’)
- M3e5, **z=0.3** (‘Platinum’)



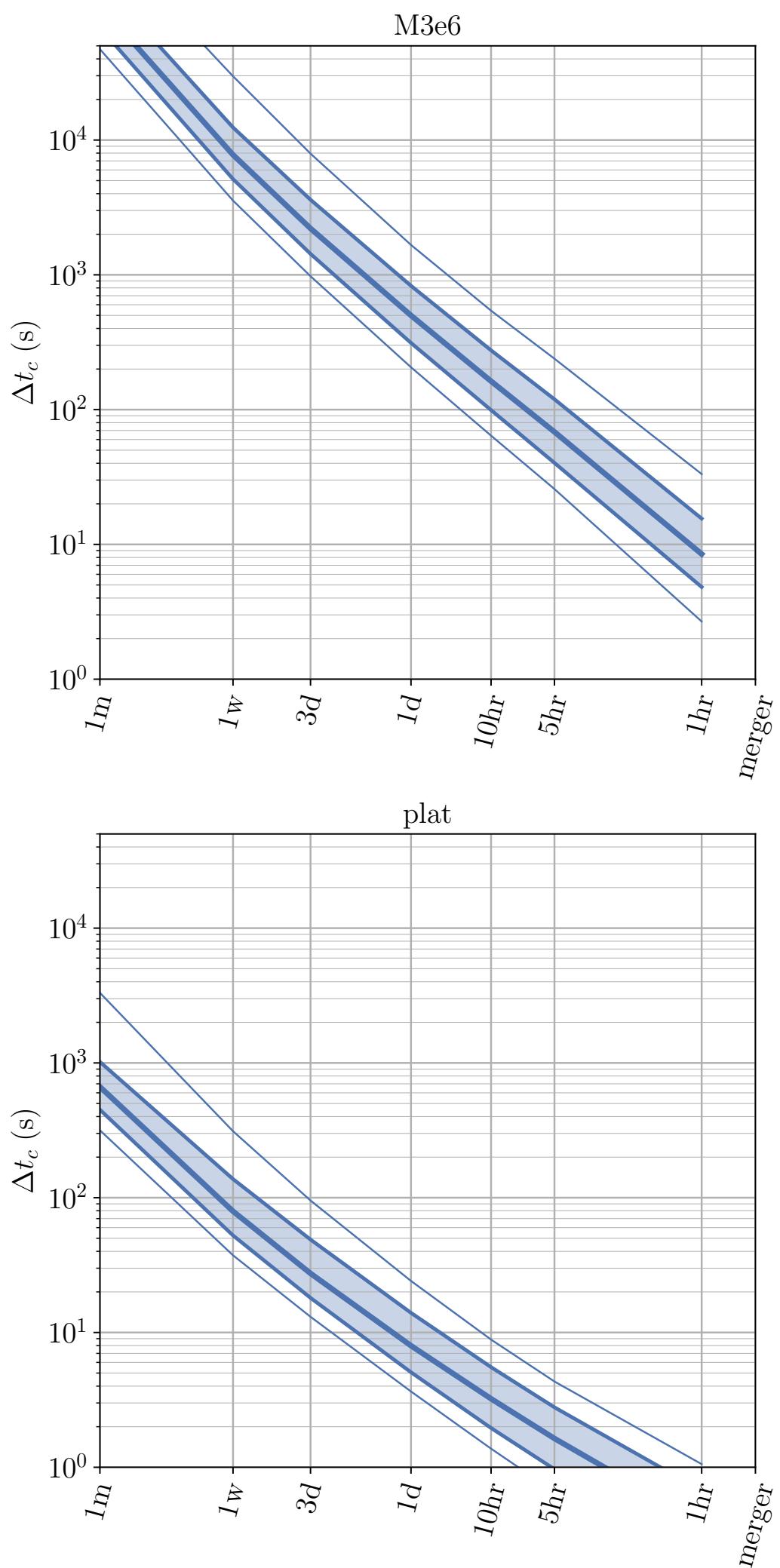
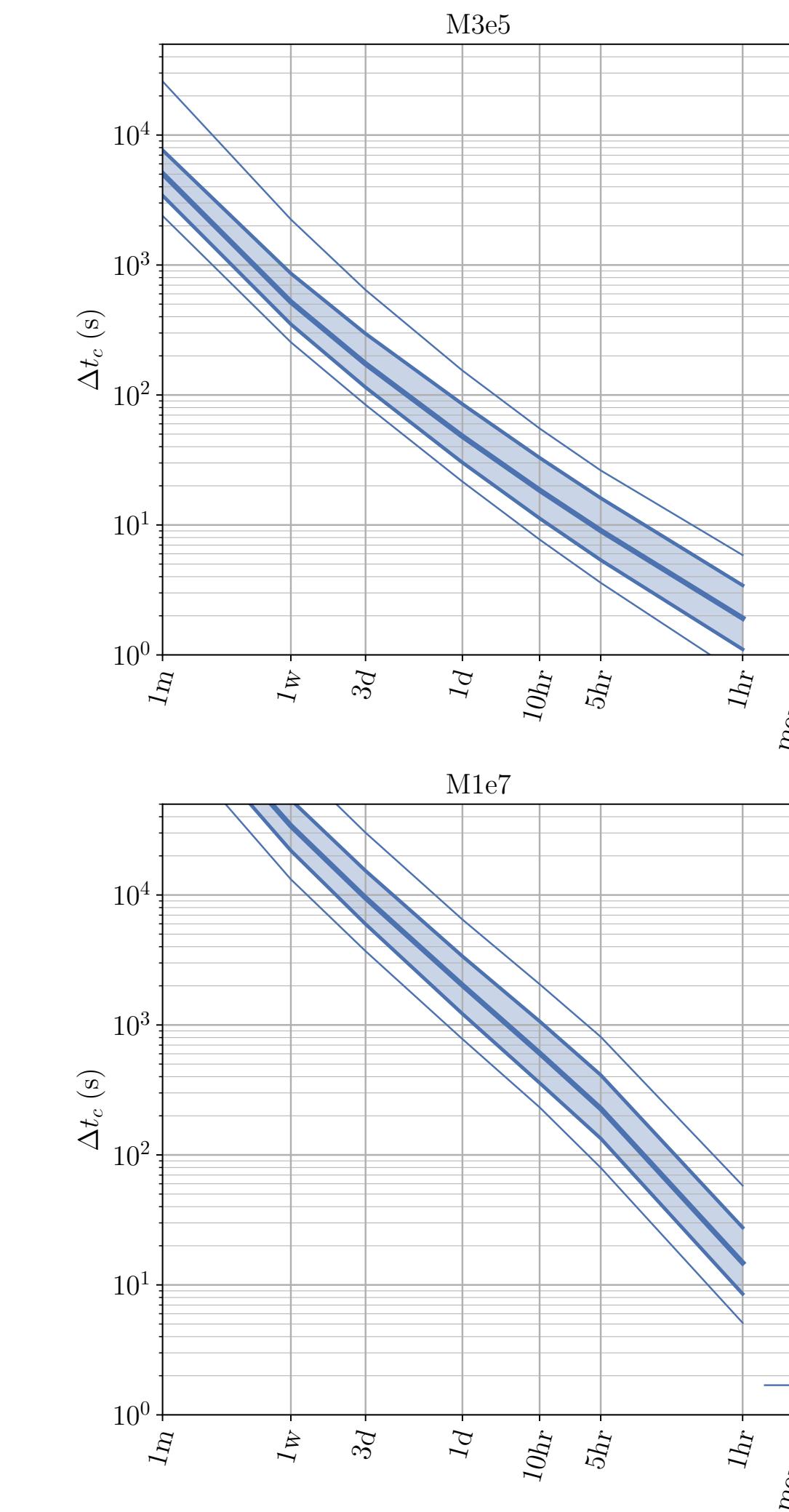
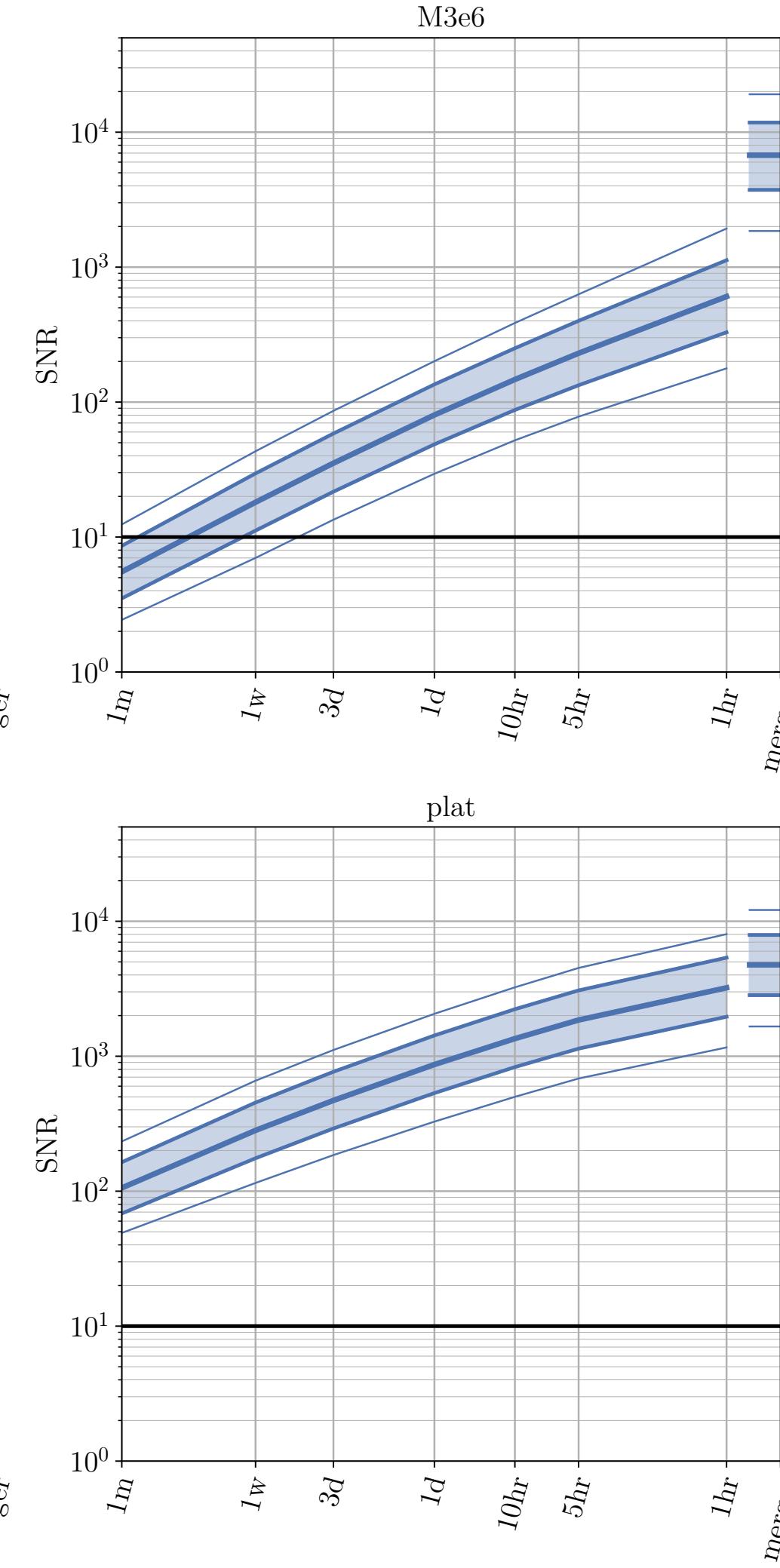
Early detection for ‘golden’ sources

SNR pre-merger and early detection



[See also Mangiagli&al 2020]

Time of coalescence measurement error



Early detection easy for
golden sources

Allows protected observation periods

Pre-merger analysis: can we localize well enough for EM observatories ?

Here: sky area of main mode of the posterior

LISA-EM synergy

- 10 sq. deg. : LSST field of view
- 0.4 sq. deg.: Athena Wide Field Imager

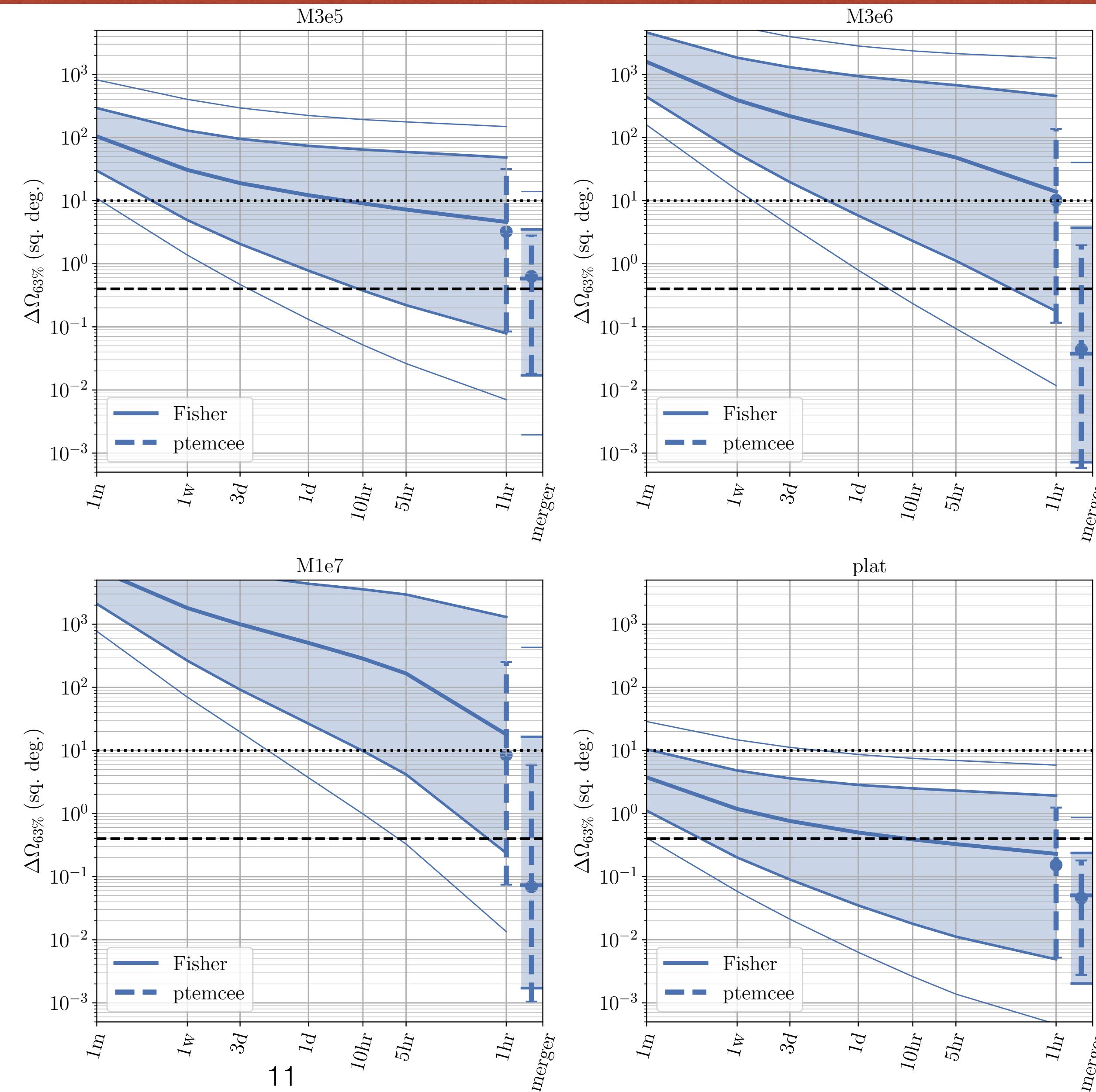
Fisher-MCMC comparison

[See also Mangiagli&al 2020]

- Fisher matrices: 10000 random parameters
- MCMC (ptemcee): 100 random PE runs

Advance localization
challenging, much better
post-merger

Large dispersion in sky
area, ~4 orders of
magnitude



Preliminary

LSST

Athena

LSST

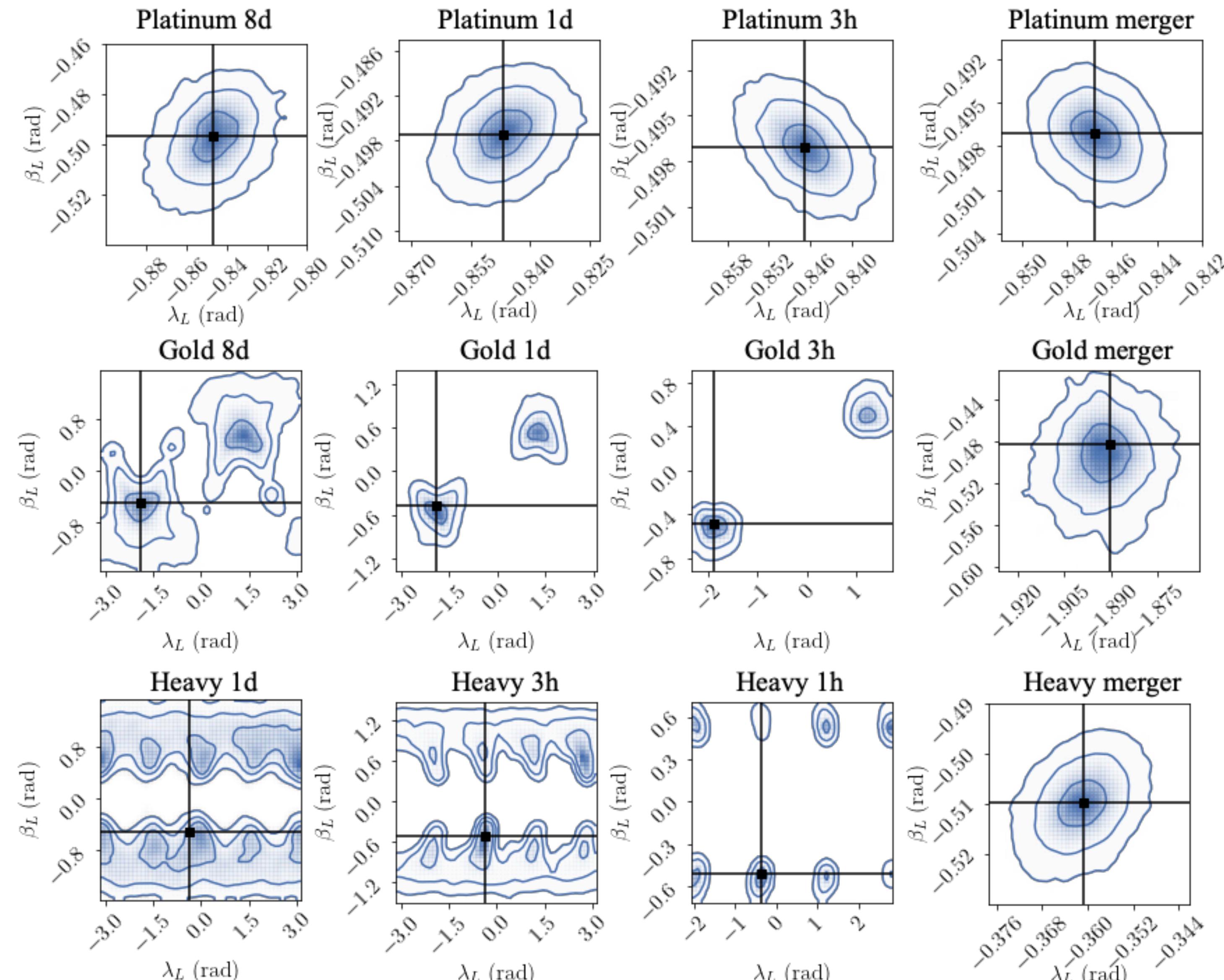
Athena

Localization of ‘golden’ MBHB sources: degeneracies

Bayesian sky localization cutting at different times

- ‘Gold’: M3e6, z=1
- ‘Heavy’: M1e7, z=1
- ‘Platinum’: M3e5, z=0.3

- Wide range of multimodalities dep. on parameters
- Post-merger localization unimodal



[Preliminary]

Conclusion and outlook

Highlights

- LISA localization capabilities for MBHBs crucial for multimessenger science
- Many MBHB systems might be short, subset of low-z events could be observed for months
- MBHB signals are merger-dominated, post-merger localization can be very good
- Pre-merger localization can be challenging, except for the very best events
- Degeneracies in the sky position can occur, notably pre-merger

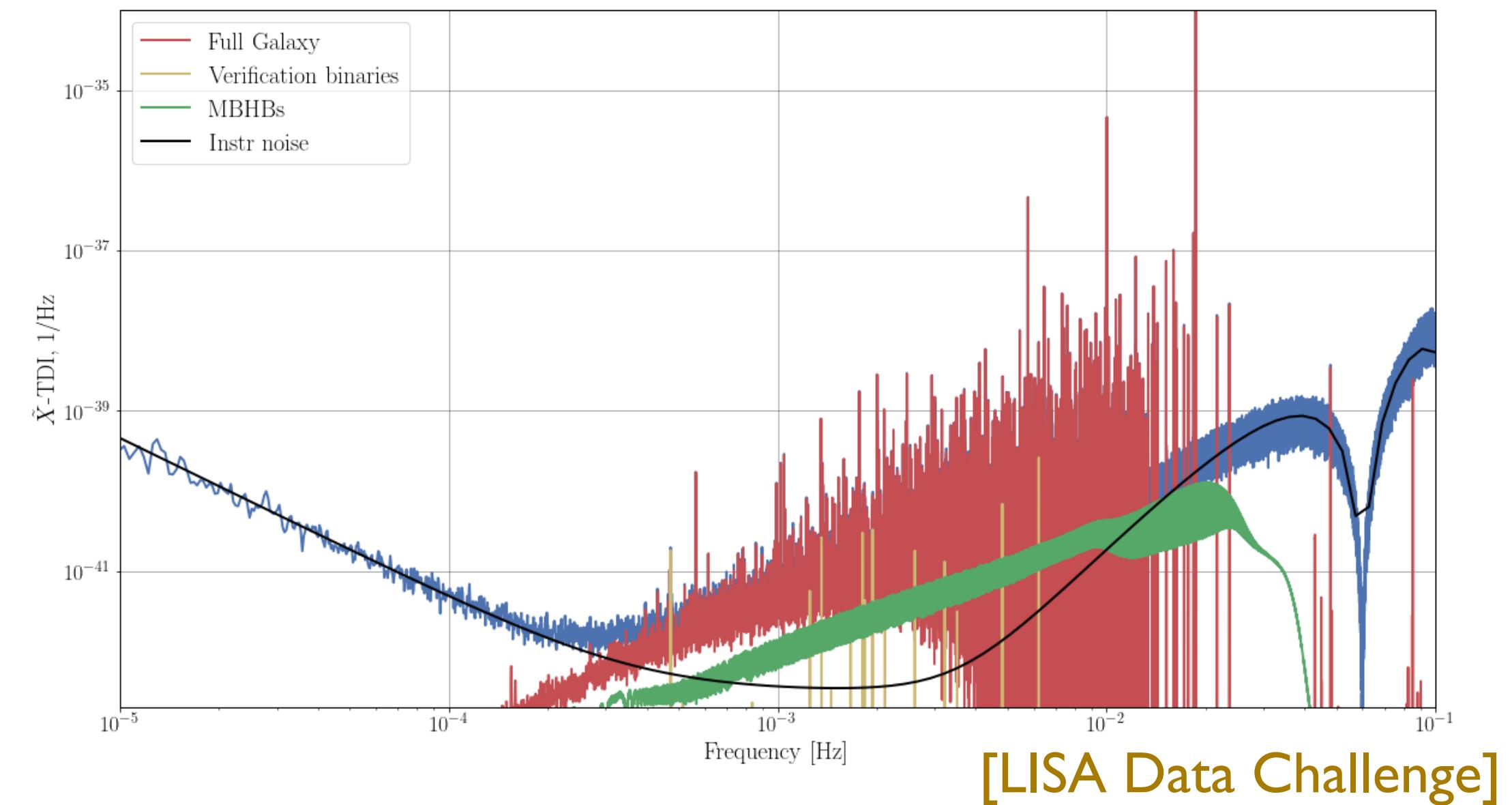
Outlook

- Better explore LISA's localization capability across the parameter space
- More realistic analysis: superposition of multiple signals, realistic noise, data gaps, glitches...
- More realistic waveforms: precession and eccentricity

LDC-2: source superposition and global analysis

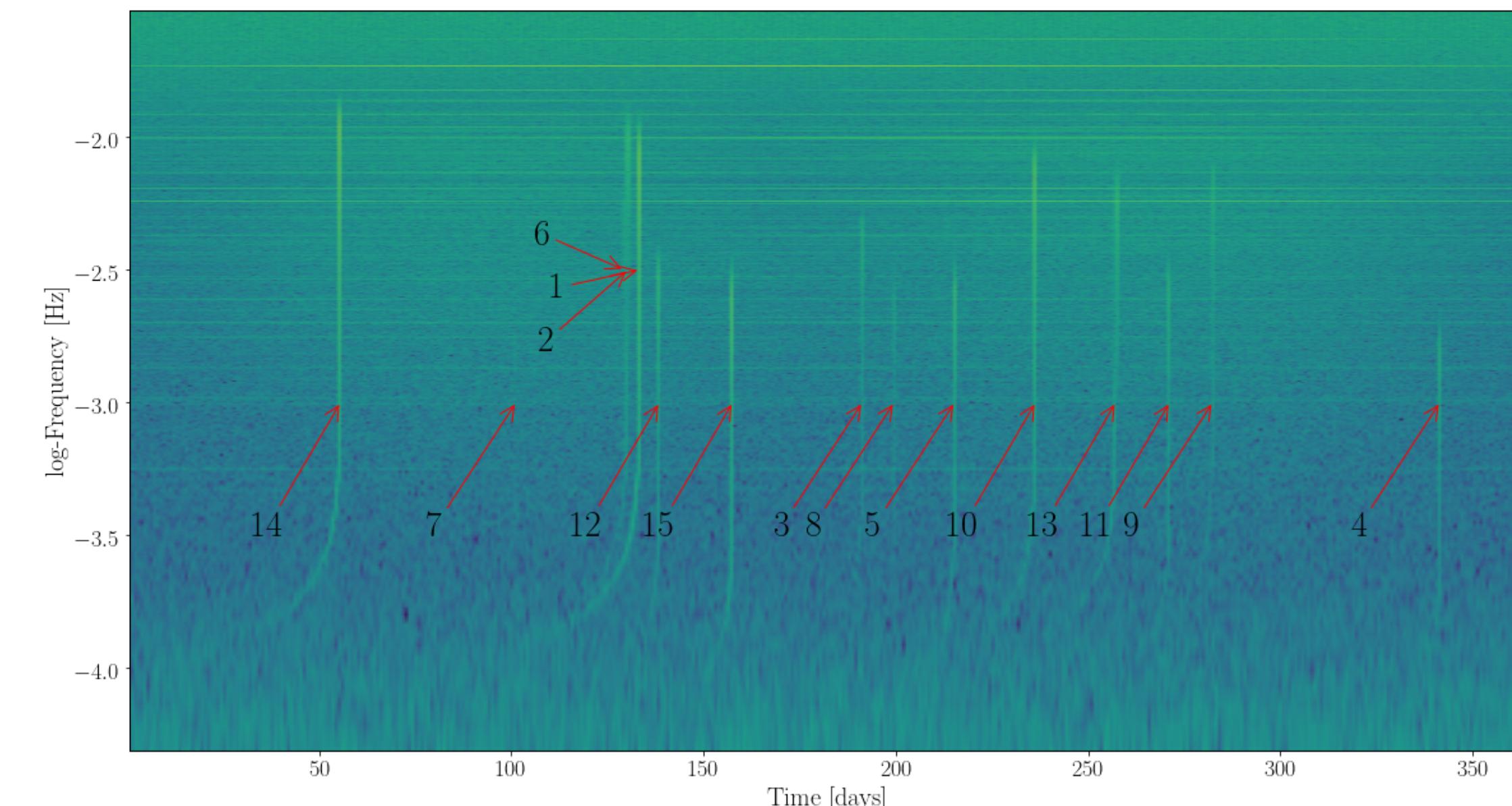
LISA Data analysis challenges

- Superposition of many sources, with a population of GBs also forming a stochastic background -> Global fit
- High SNR for MBHBs, waveform systematics important
- EMRI waveform models
- Data gaps
- Glitches, instrumental non-stationarity



LISA Data Challenge 2 ‘Sangria’

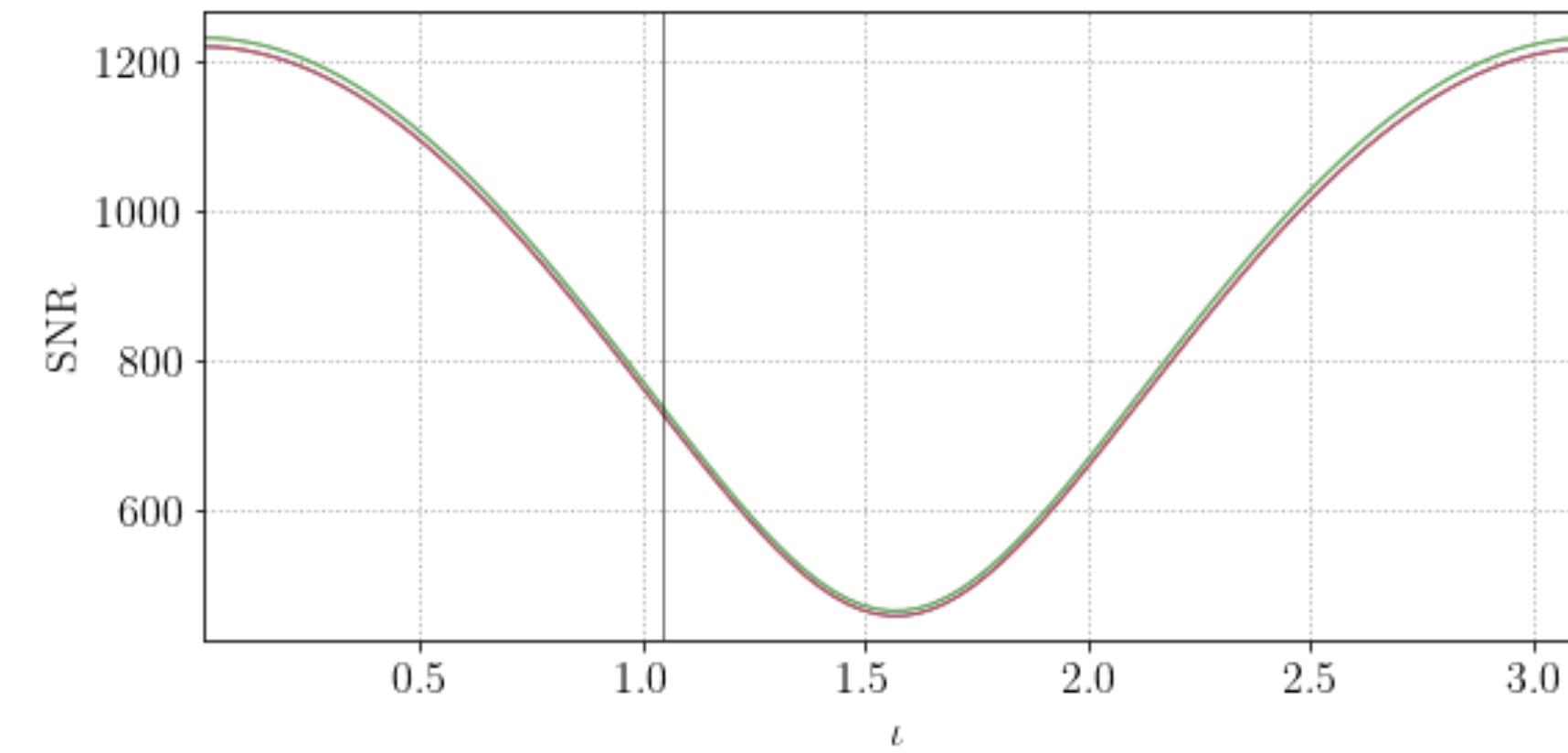
- ~10 massive black holes
- Population of galactic binaries (~10000 resolved)
- Unknown noise level



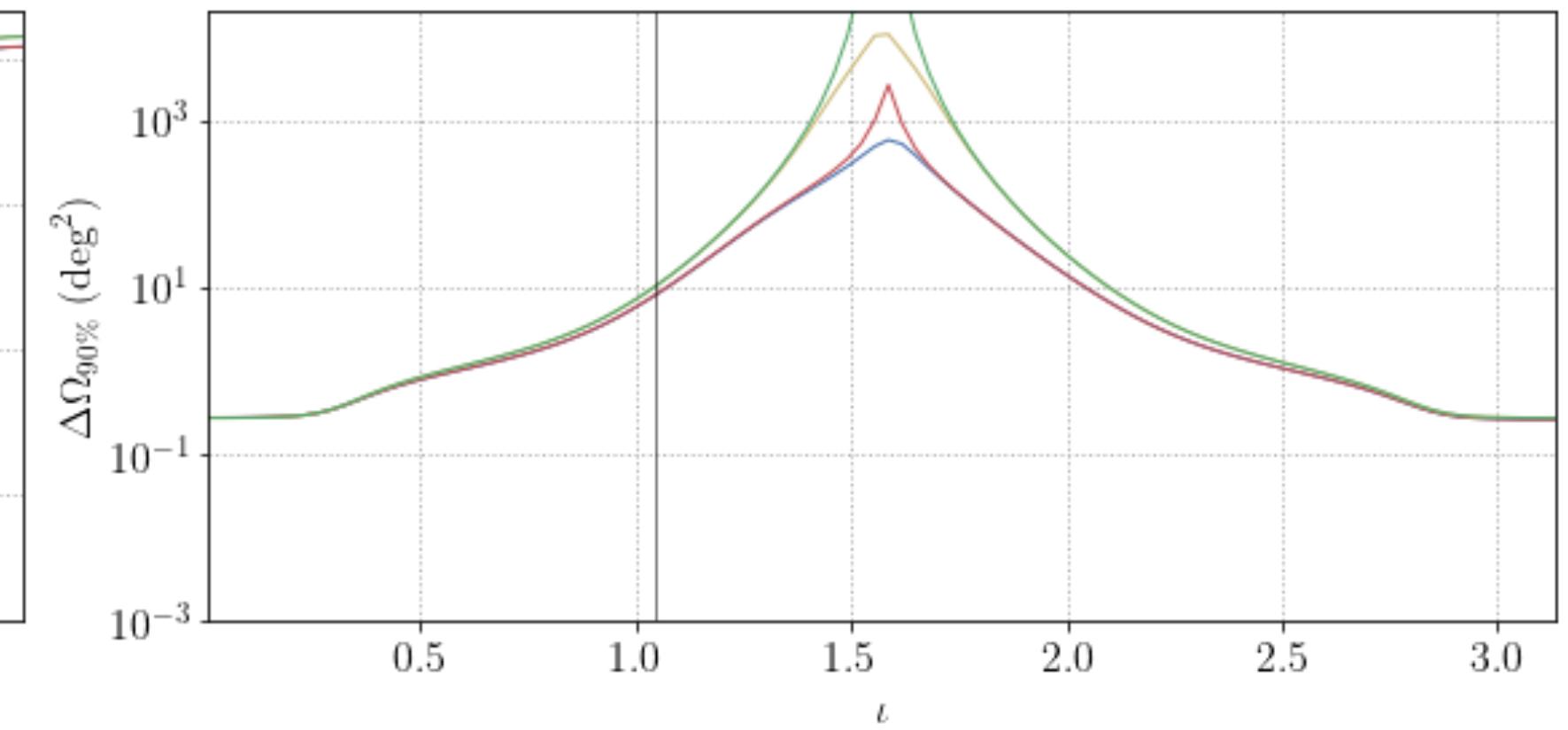
Sky area: which parameters are the most important ?

What are the dominant parameters determining the sky area error ?

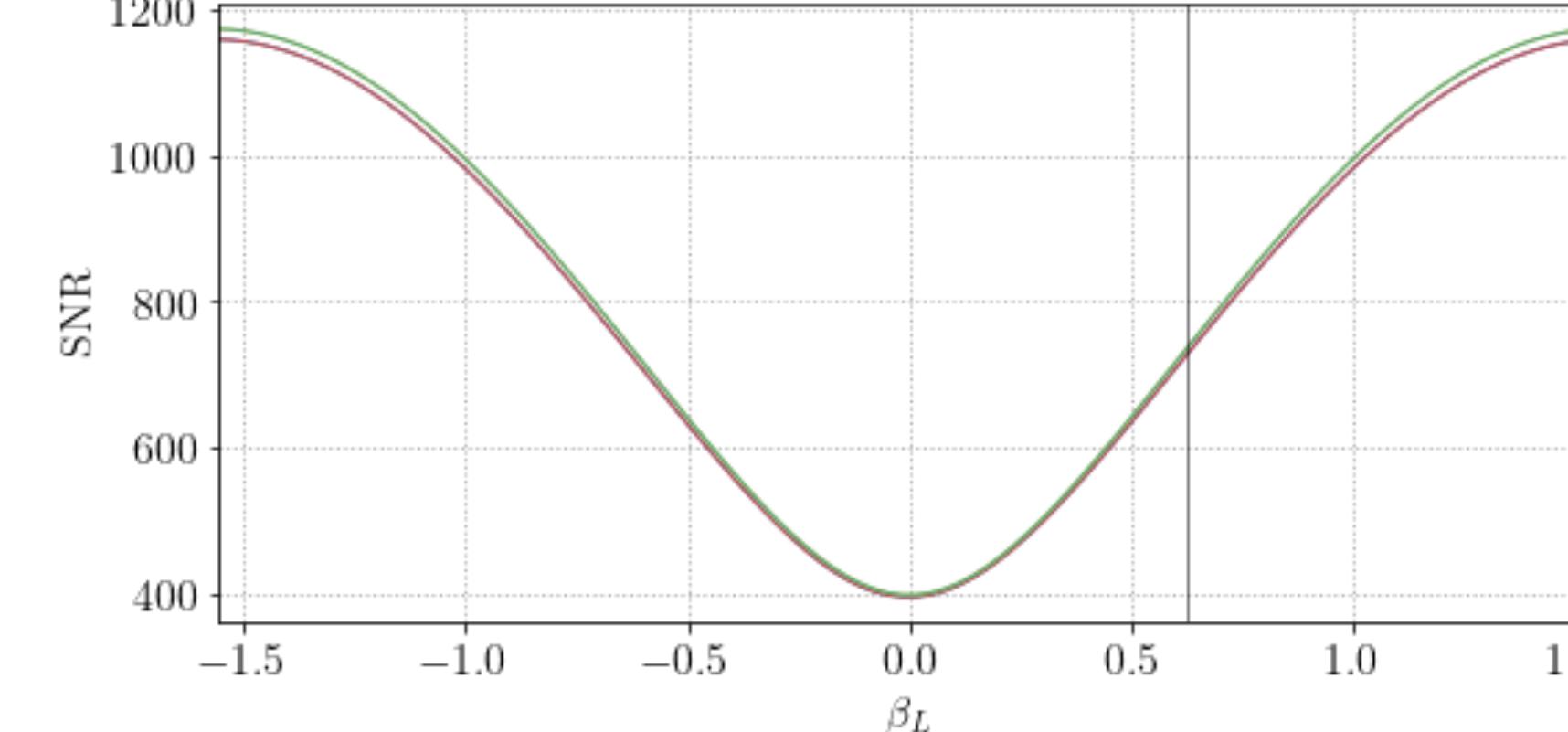
Large dispersion in sky area, ~4 orders of magnitude



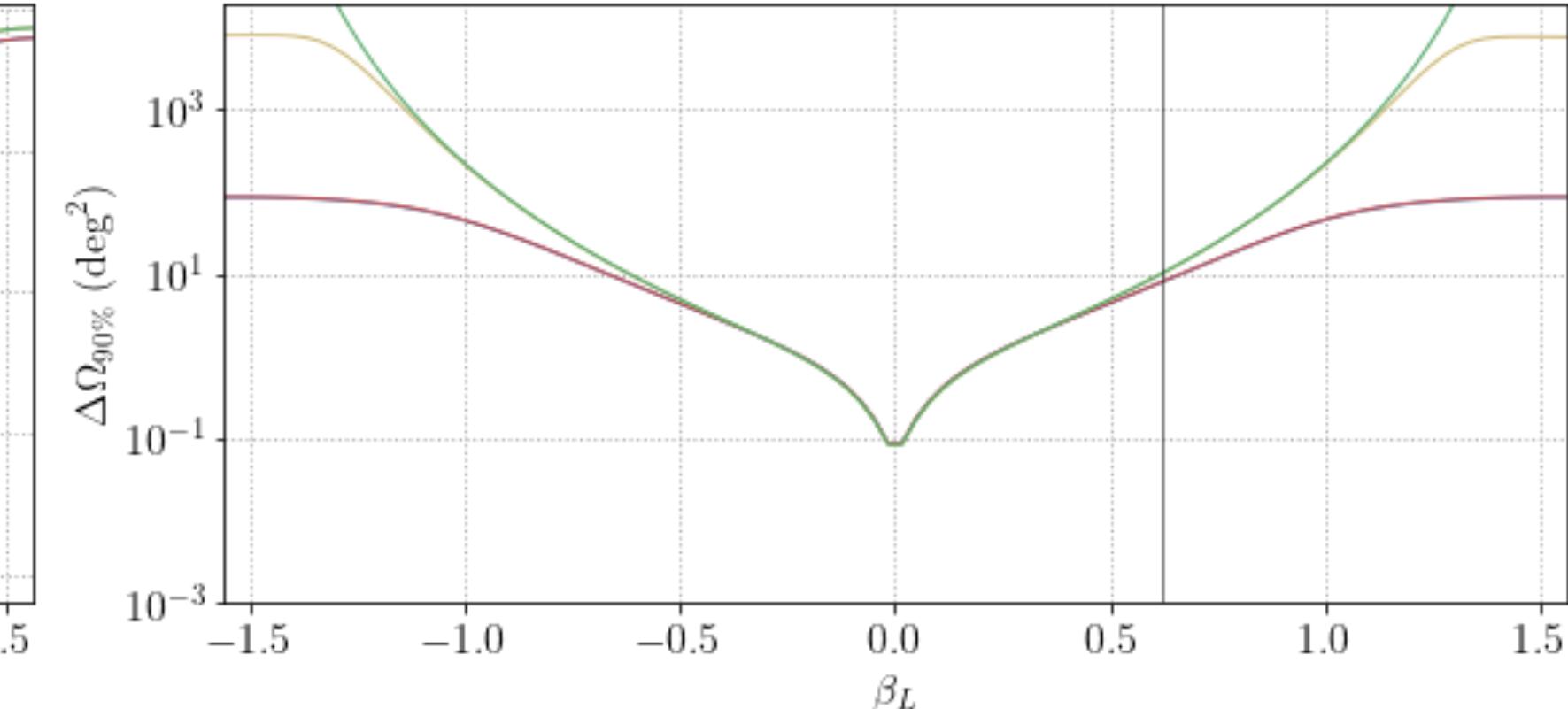
Inclination



Inclination and L-frame latitude dominant parameters to determine sky area



Latitude in the LISA-frame



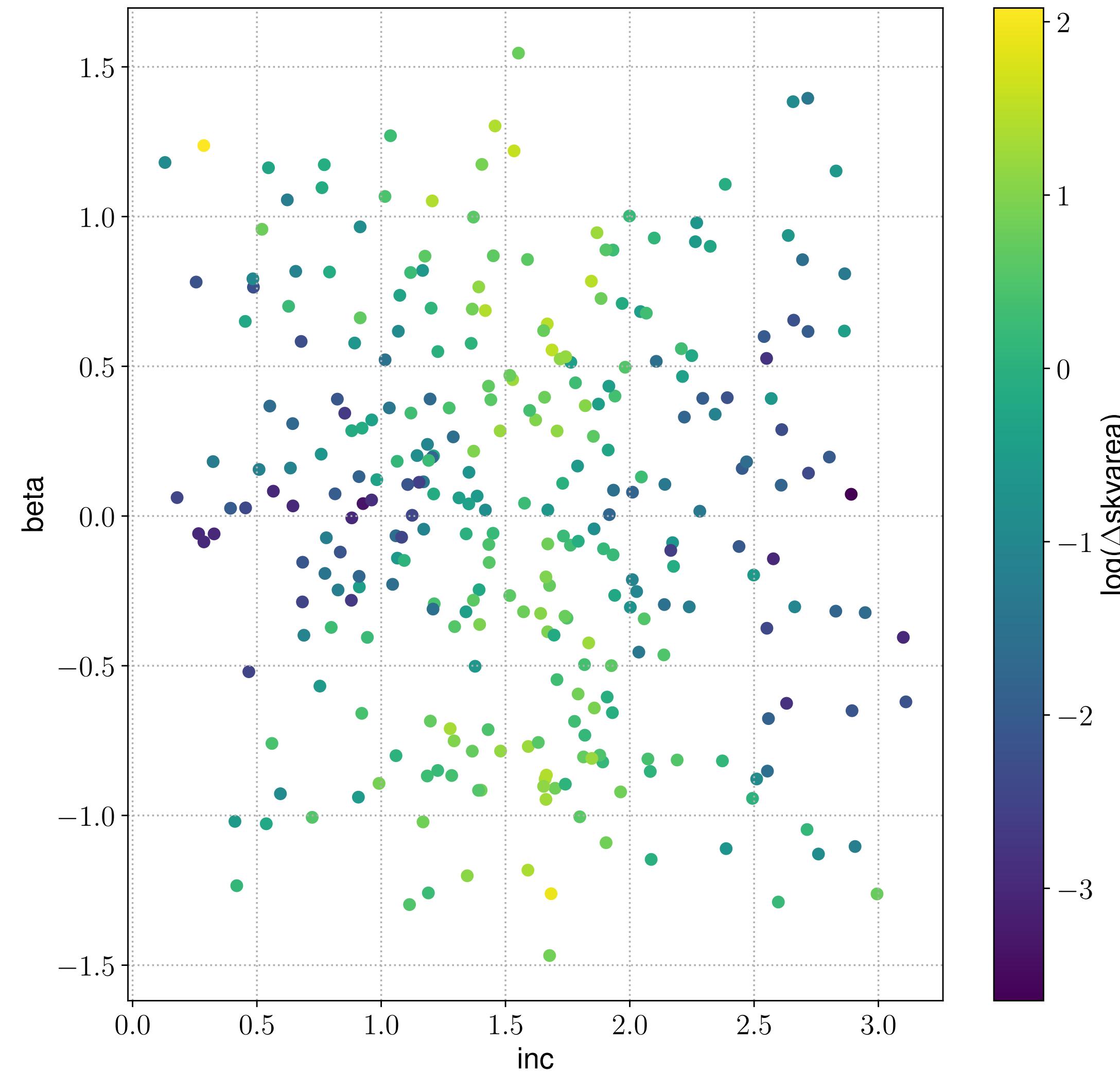
Trend goes against SNR !

Sky area: which parameters are the most important ?

Set of MCMC PE runs at a fixed $z=1$,
randomizing over masses, spins and extrinsic
params

Large dispersion in sky
area, ~4 orders of
magnitude

Inclination and L-frame
latitude dominant
parameters to determine
sky area



Pre-merger localization: role of instrumental response for ‘golden’ systems

Here: main mode sky area

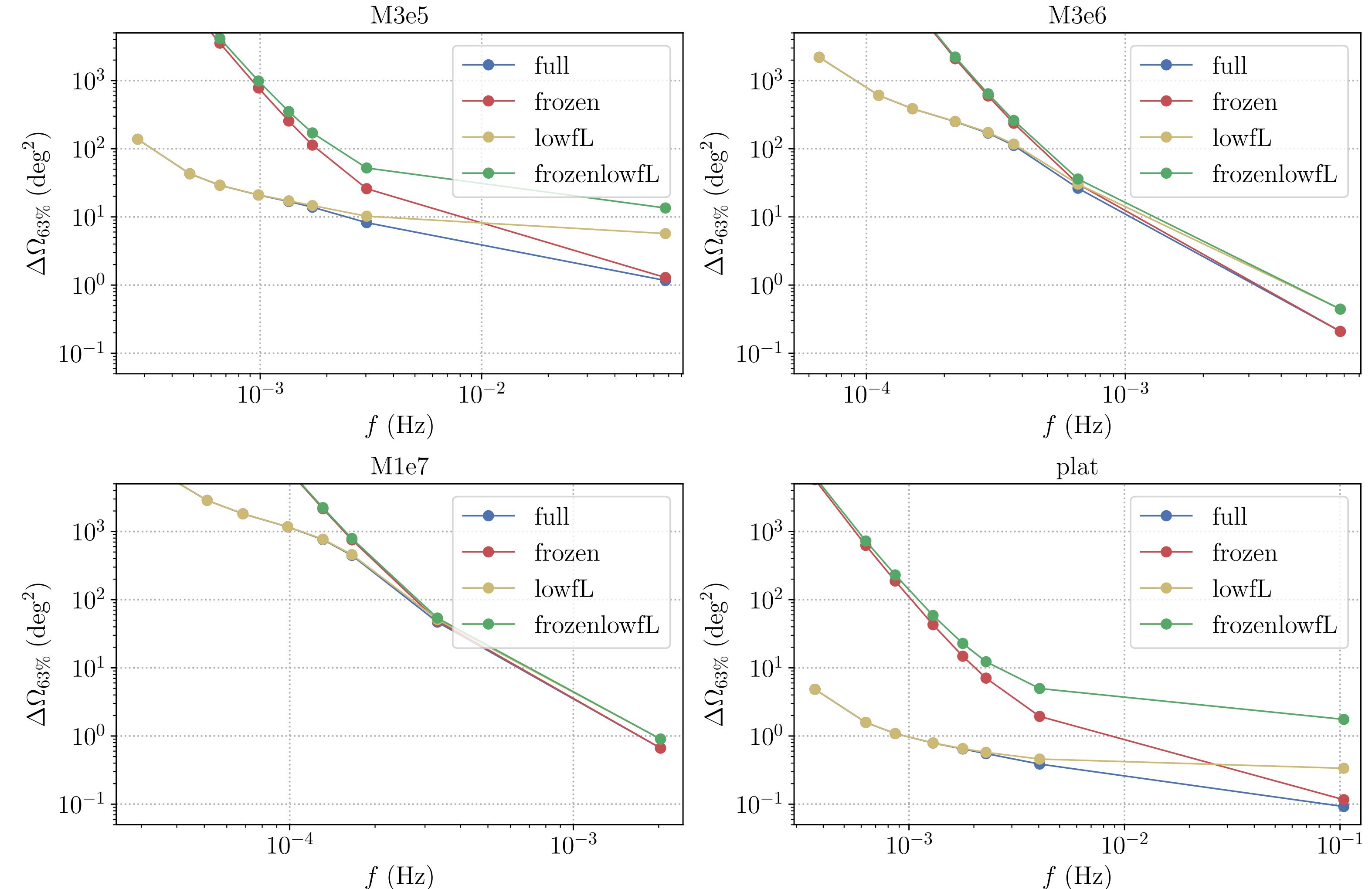
Response (signal with HM here):

- ‘Full’: keep all terms
- ‘Frozen’: ignore LISA motion
- ‘Low-f’: ignore f-dependency
- ‘Frozen Low-f’: ignore both

For low masses, best candidates for advance localization:

- Localization from the LISA motion saturates reaching merger
- Localization from high-f effects dominates at merger

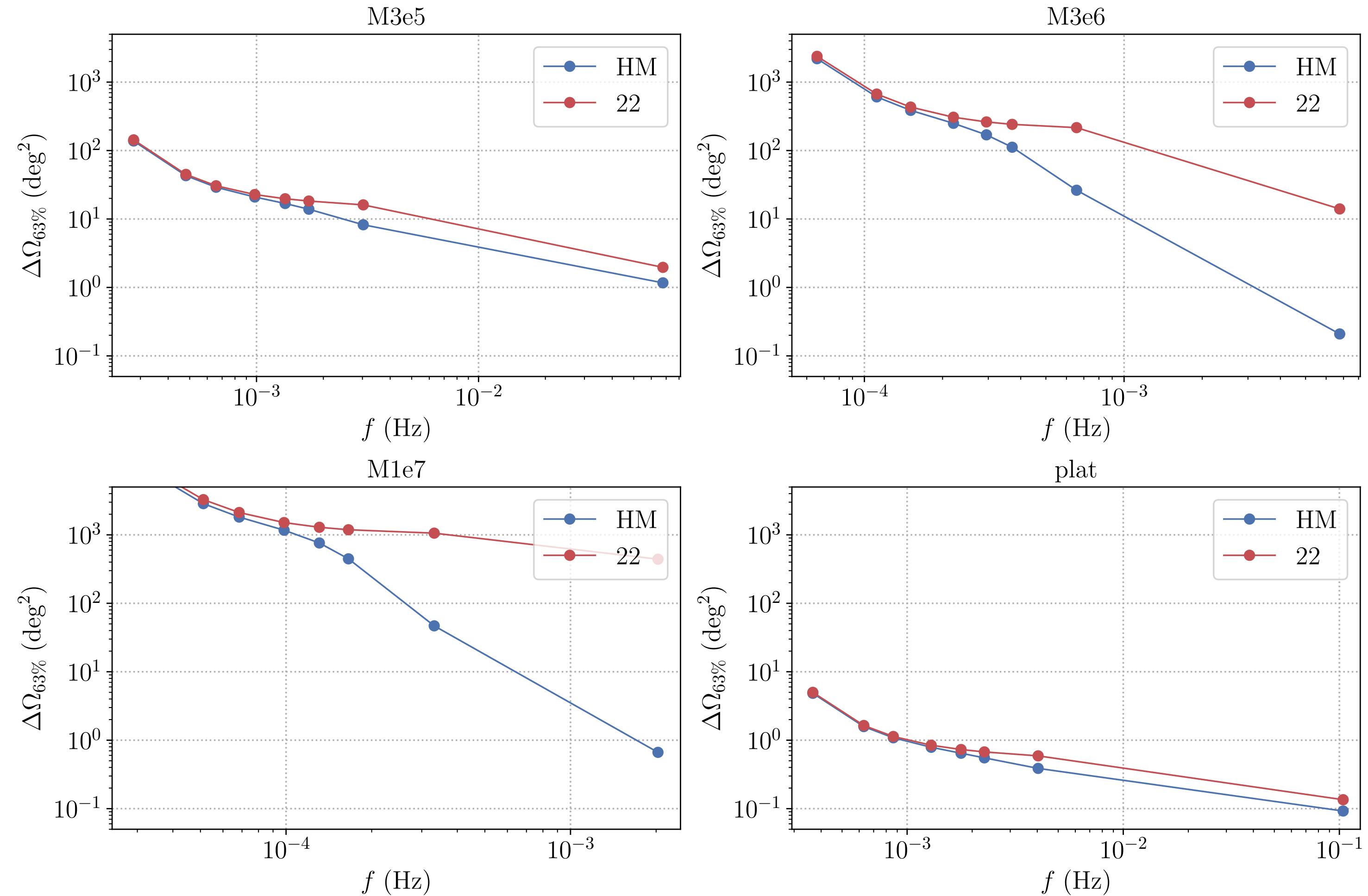
For high masses, HM at merger convey most of the information



Pre-merger localization: role of HM for ‘golden’ systems

Here: main mode sky area

Higher modes become
most important at
merger and for high mass



Pre-merger analysis: likelihood with decomposed response

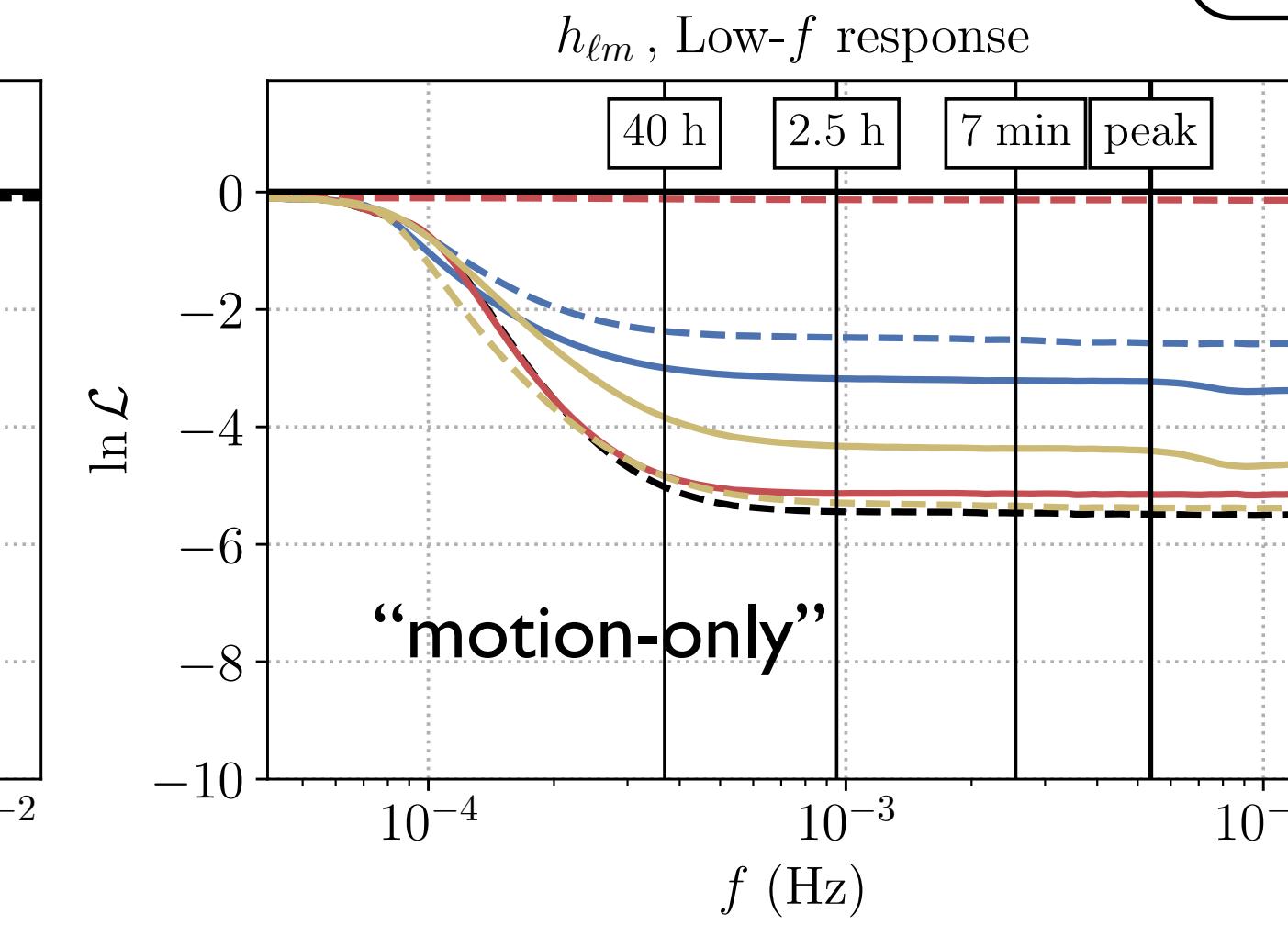
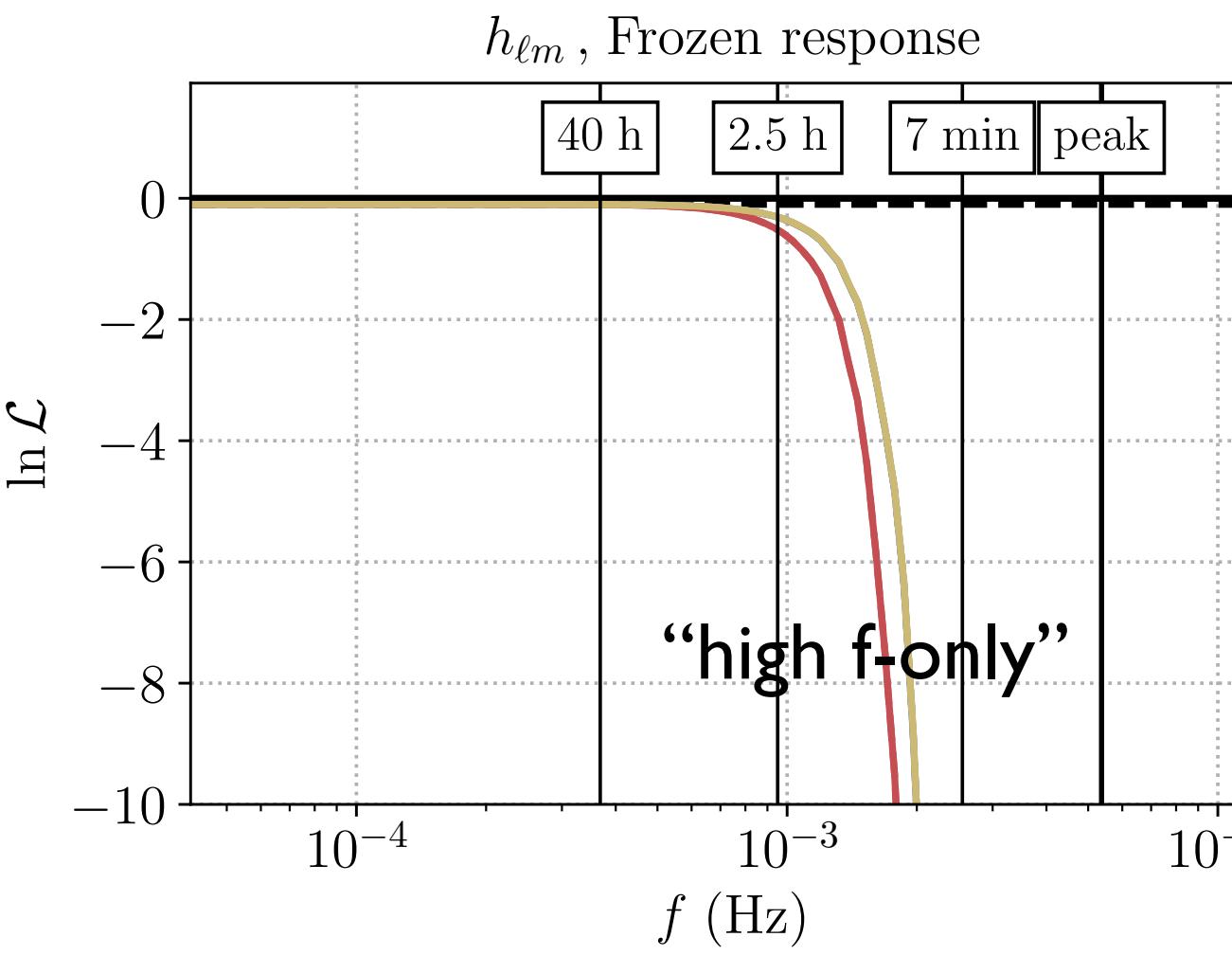
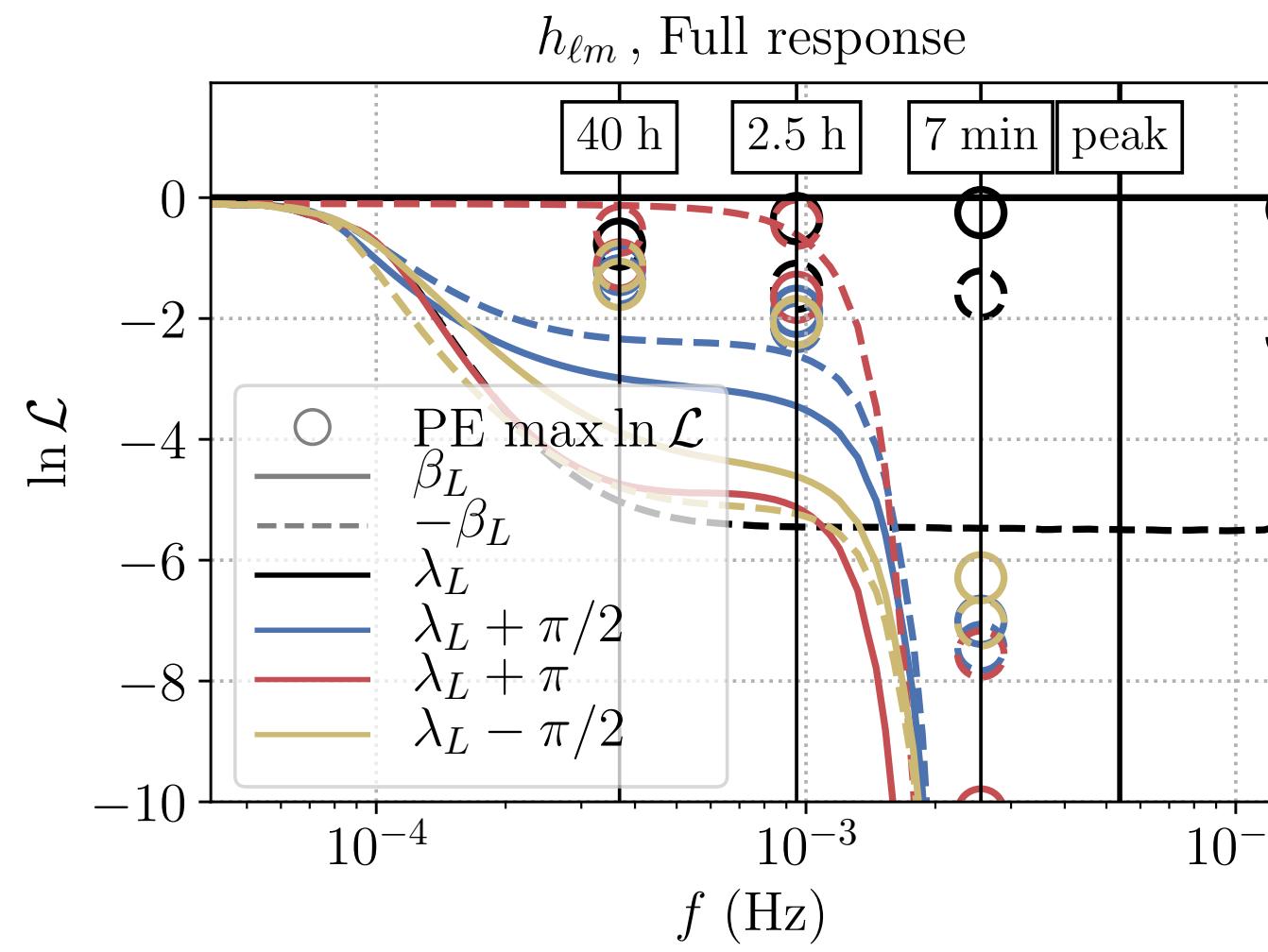
Degeneracy breaking for 8 sky maxima

Instrument response:

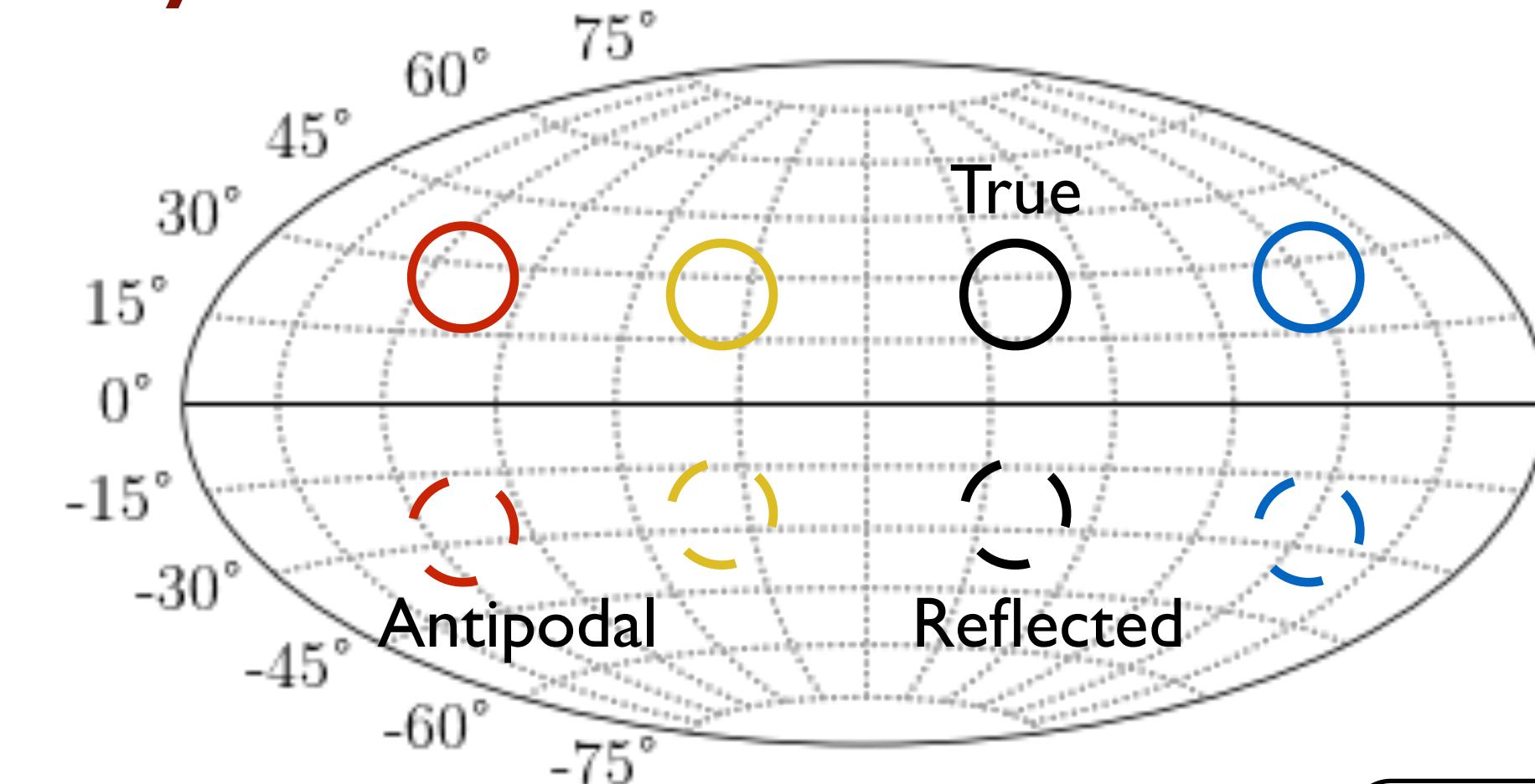
- ‘Full’: keep all terms
- ‘Frozen’: ignore LISA motion
- ‘Low-f’: ignore f-dependency
- ‘Frozen Low-f’: ignore both

$$\text{Likelihood: } \ln \mathcal{L}(d|\theta) = - \sum_{\text{channels}} \frac{1}{2} (h(\theta) - d | h(\theta) - d)$$

Approximate degeneracy measure: likelihood at the other sky positions



Sky modes L-frame

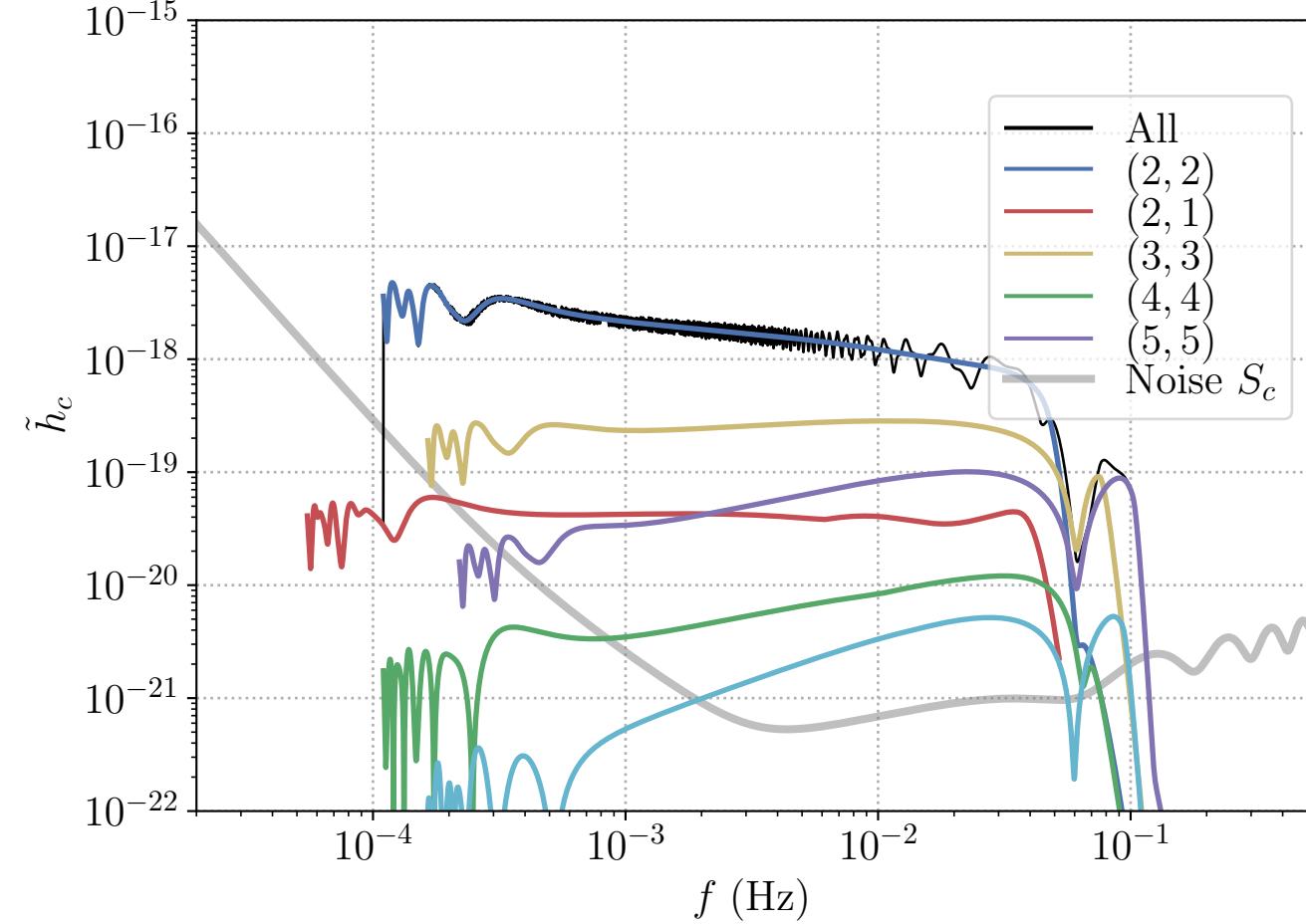


LISA/Athena candidates

‘Platinum’

$$M_{\text{source}} = 3 \times 10^5 M_{\odot}, z = 0.3$$

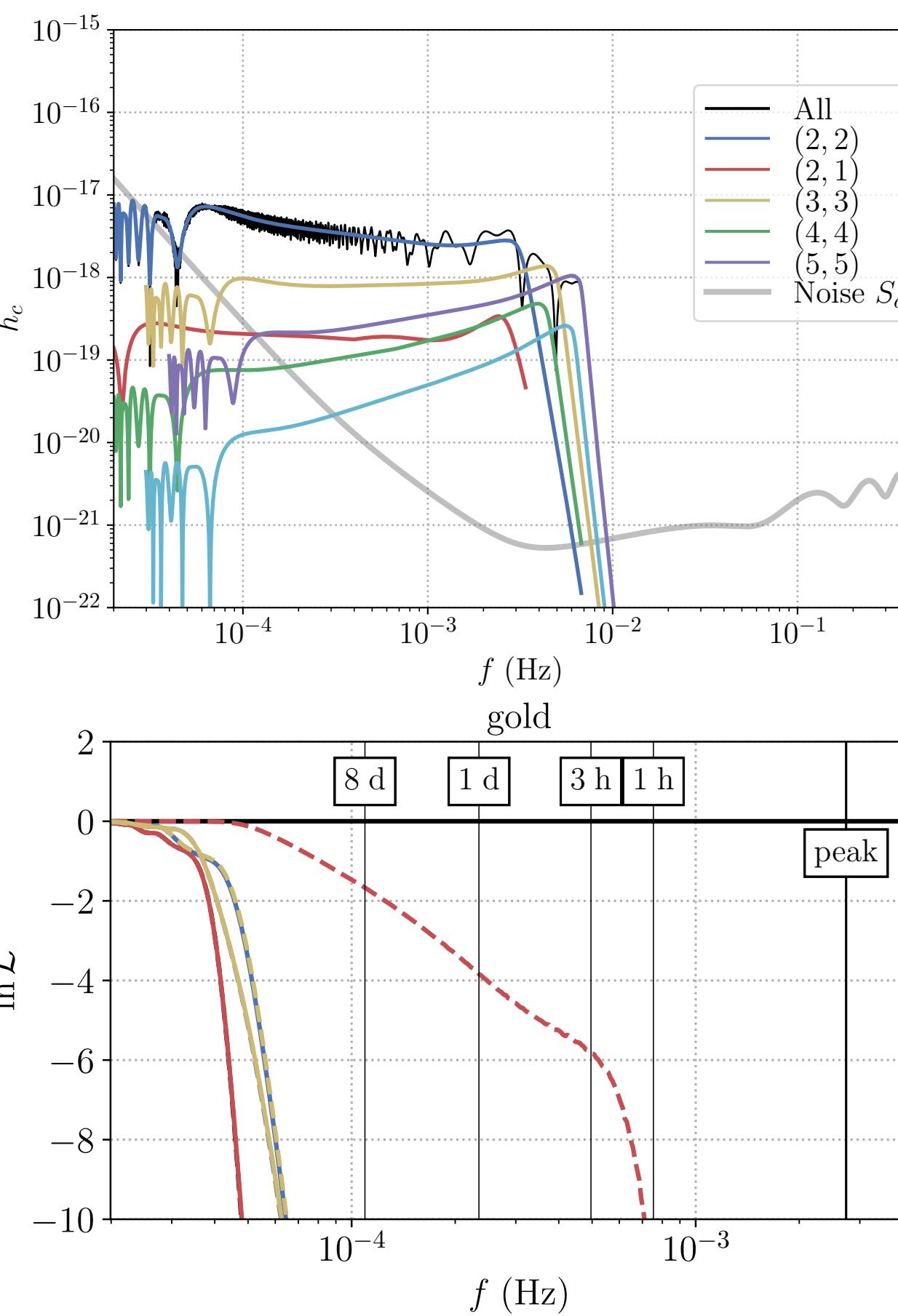
- Very long: >1yr
- Localization unimodal early on, no sky degeneracies



‘M3e6’

$$M_{\text{source}} = 3 \times 10^6 M_{\odot}, z = 1$$

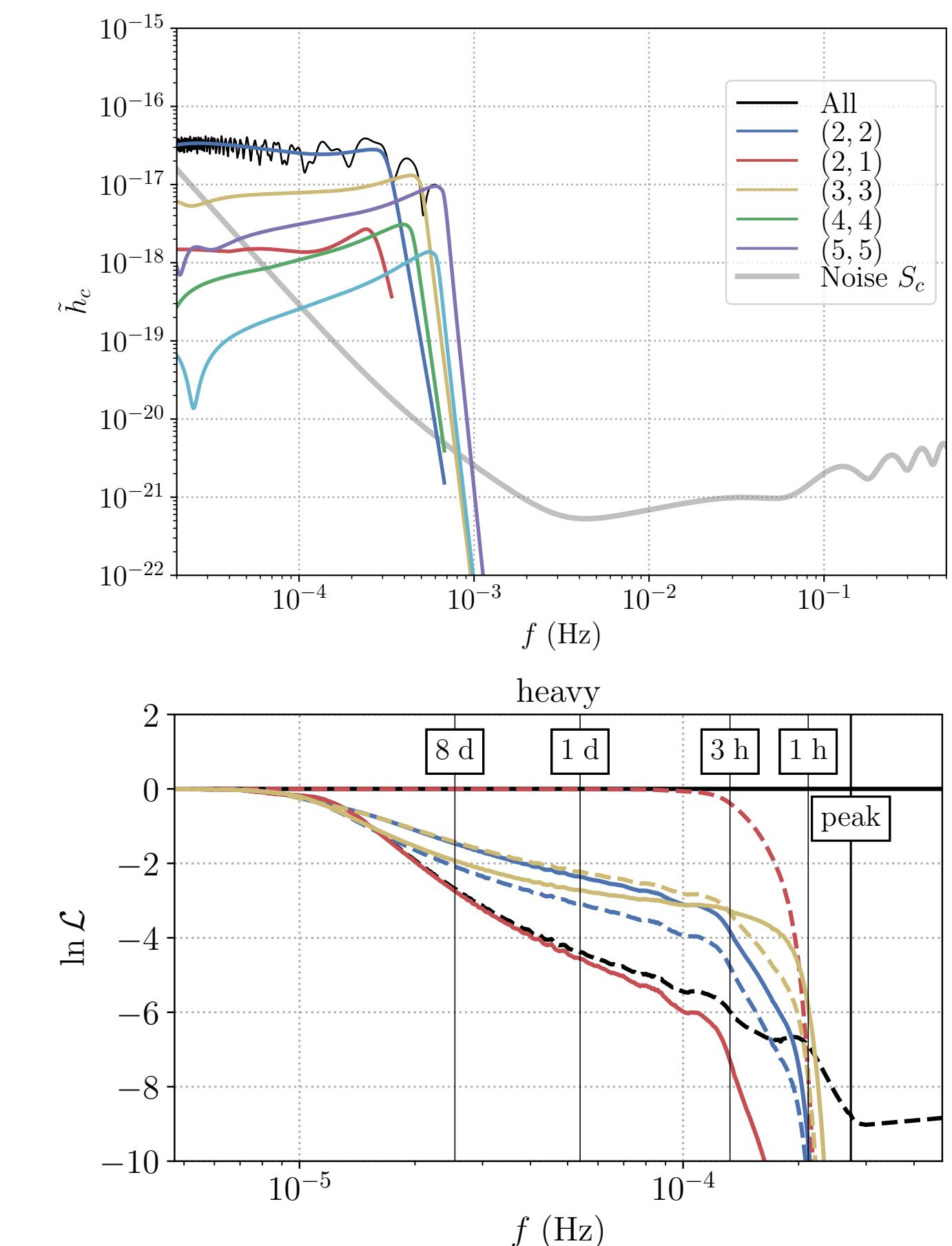
- Observable for ~2w



‘M1e7’

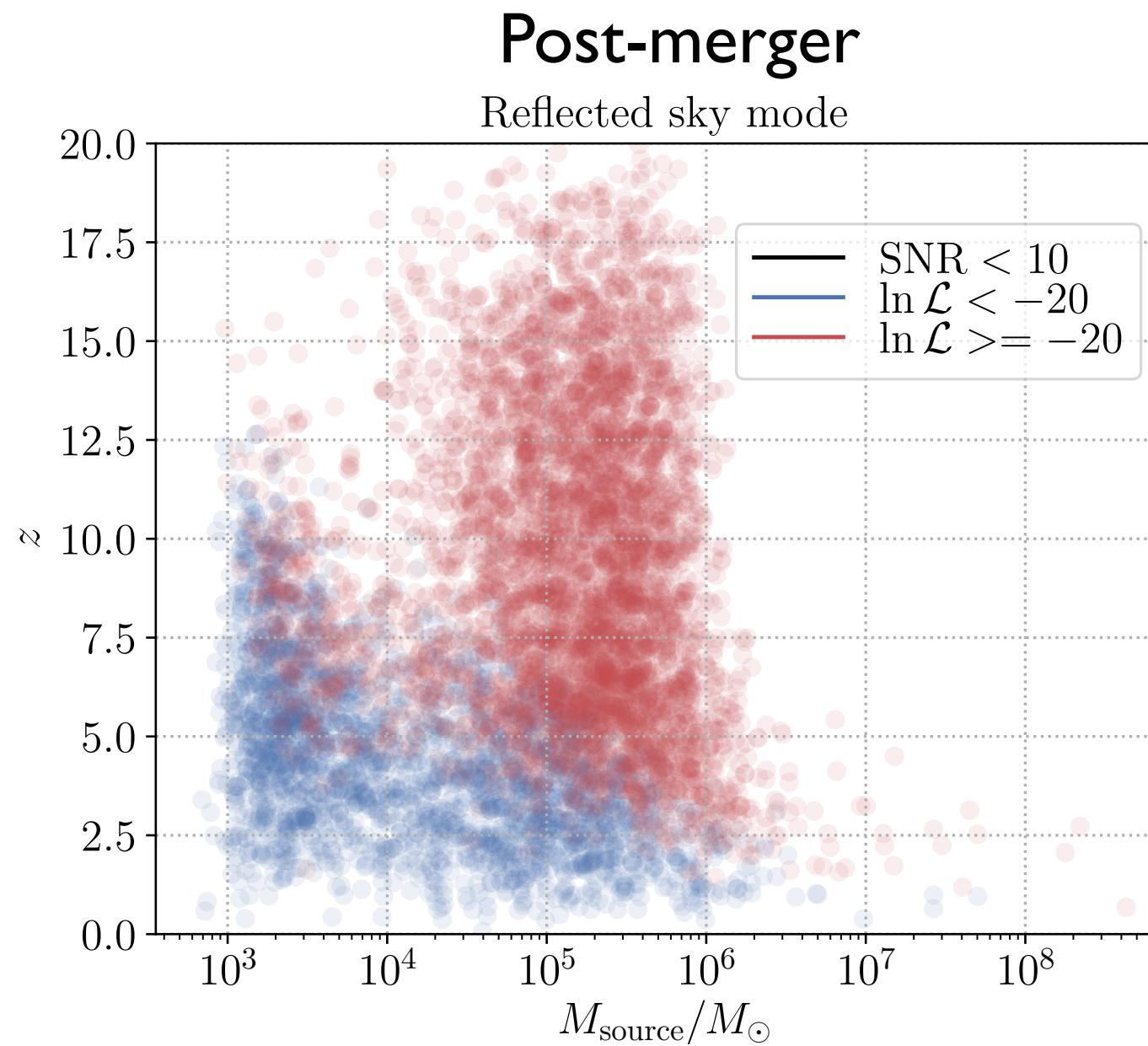
$$M_{\text{source}} = 3 \times 10^7 M_{\odot}, z = 1$$

- Observable for ~2d



Multimodality of the sky localization: astrophysical catalogs

[Preliminary]

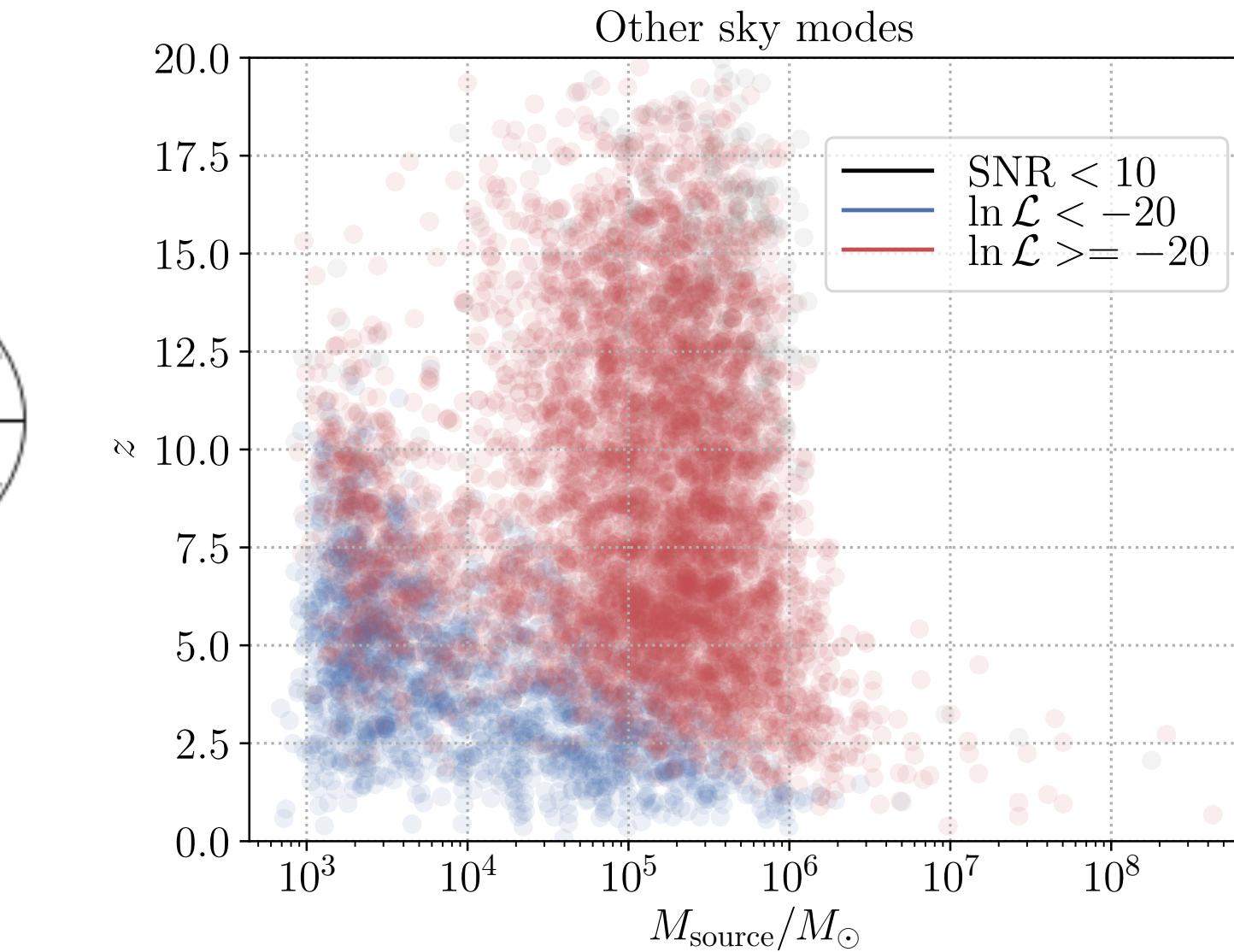
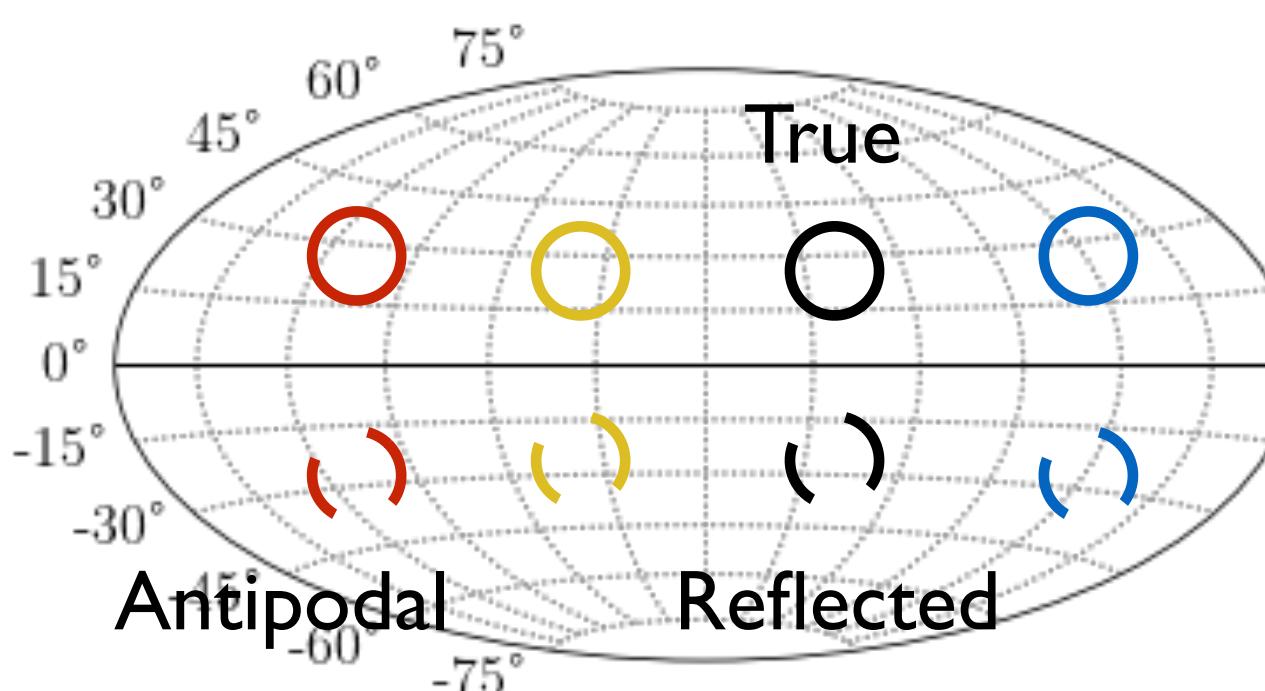
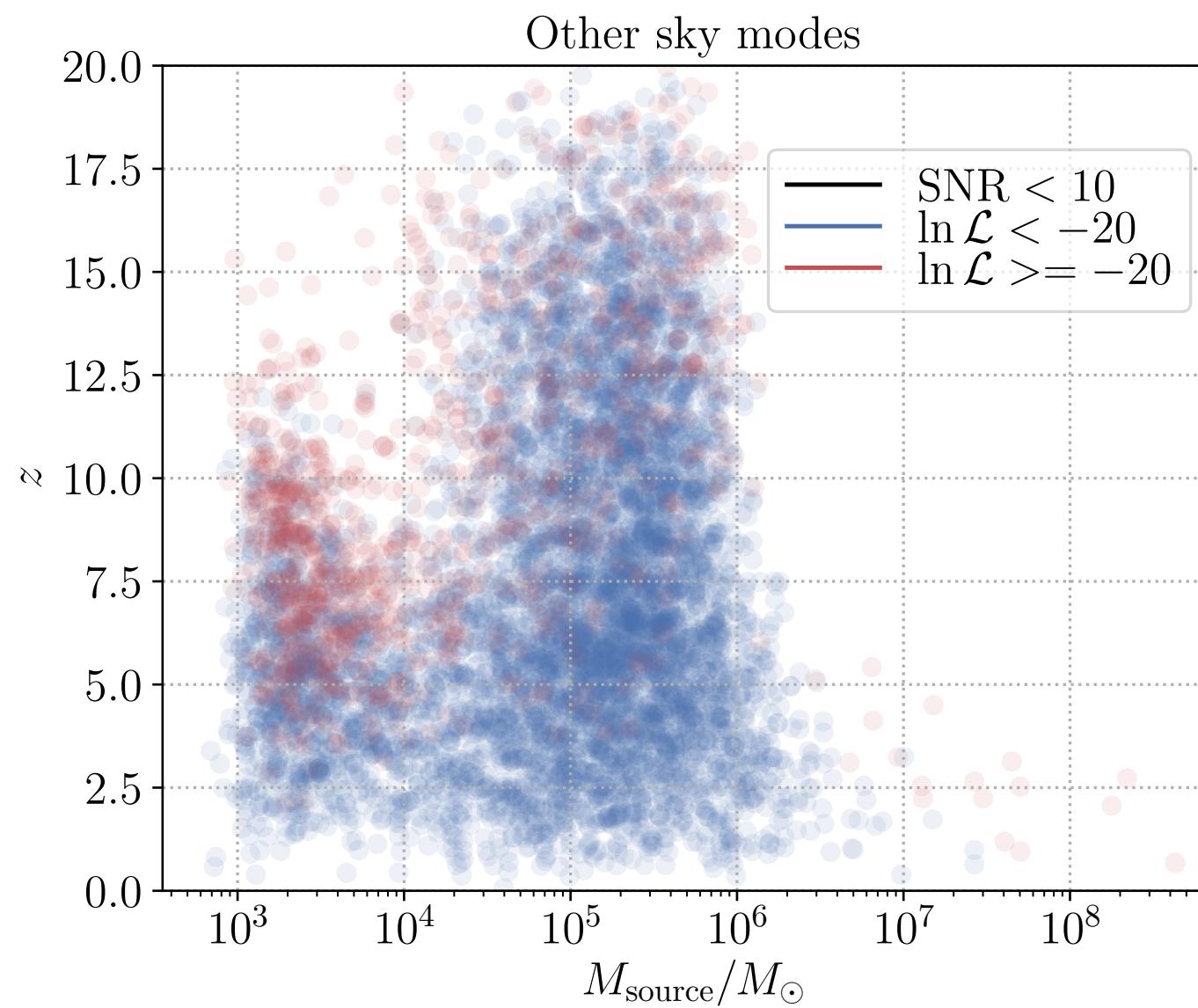
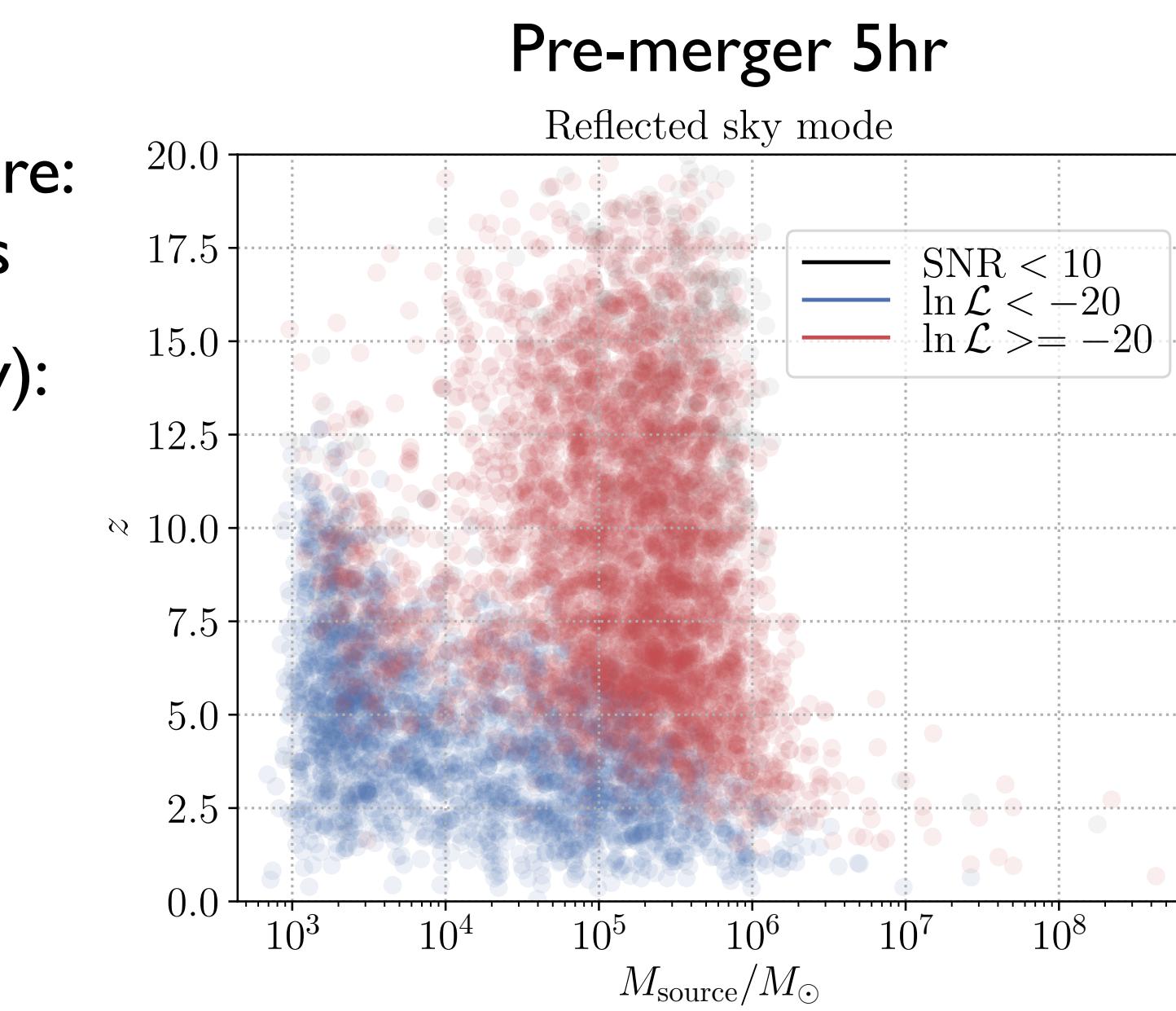


Approximate degeneracy measure:
likelihood at the other sky positions

Threshold used here (a bit arbitrary):

$$\ln \mathcal{L} > -20$$

Blue: presumably not degenerate
Red: presumably degenerate

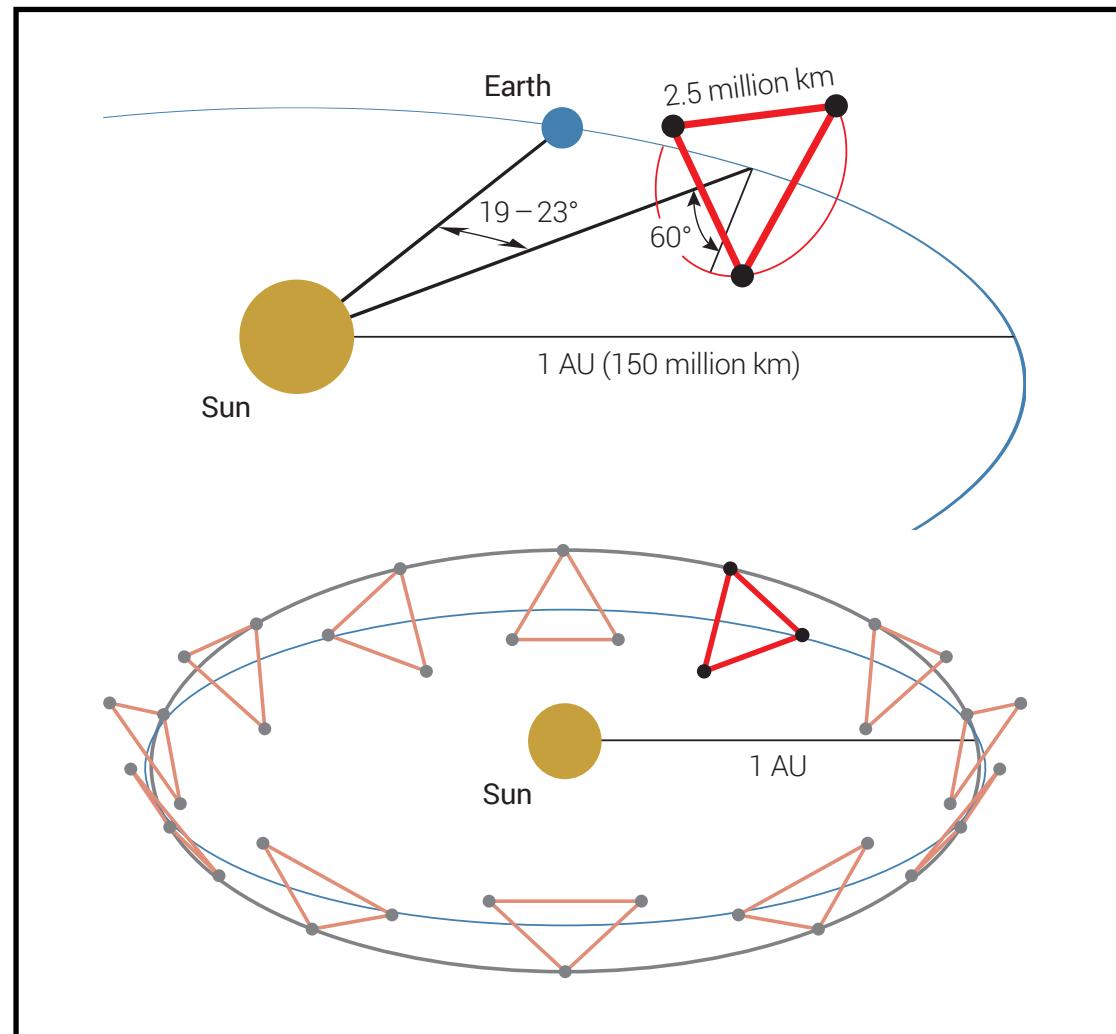


- **Signals and instrument response**
- The crucial role of higher harmonics
- Understanding LISA's localization capabilities
- Understanding multimodality in the sky position

LISA instrumental response

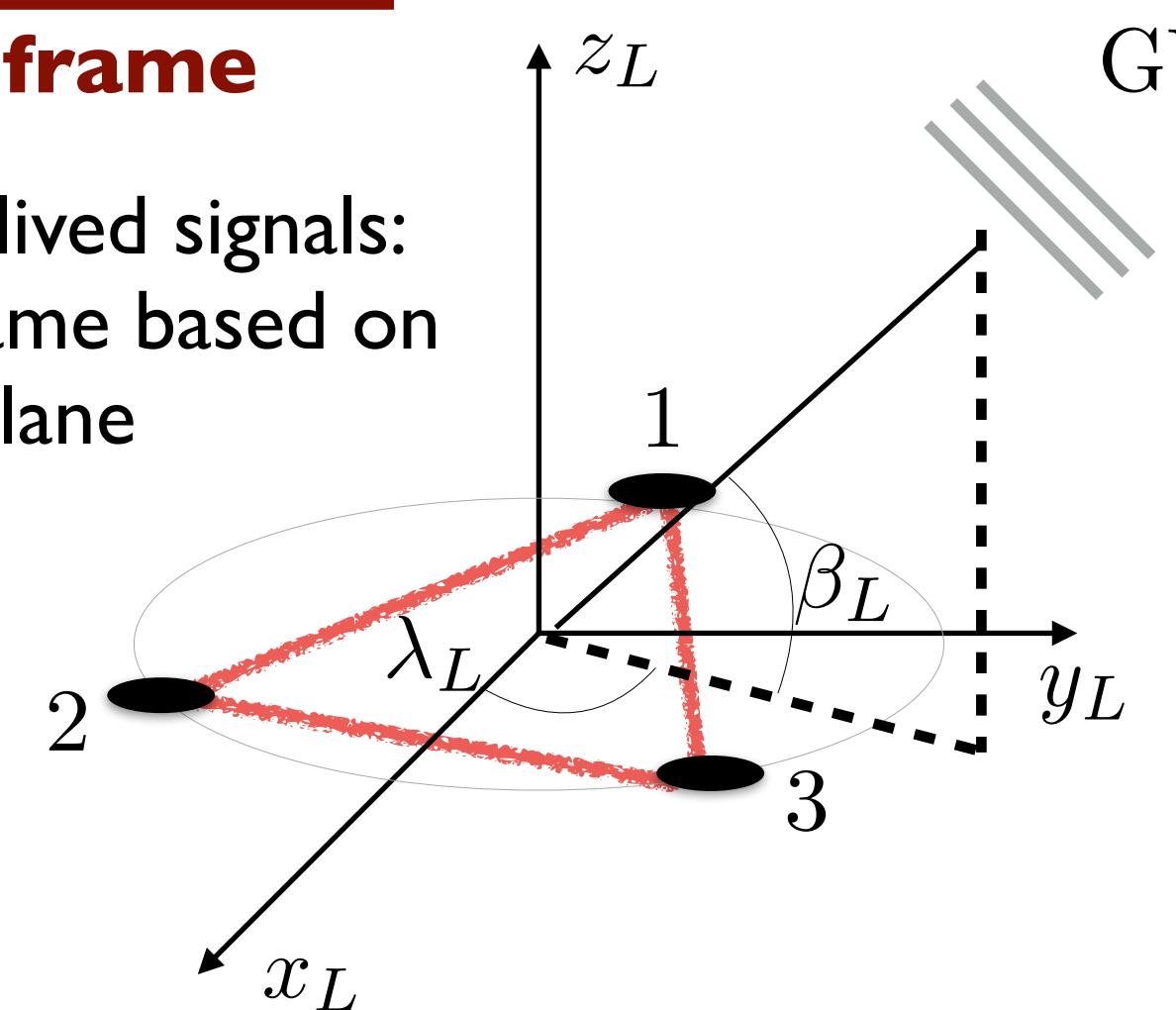
LISA orbits

SSB-frame: global view of the orbits



LISA frame

Short-lived signals:
use frame based on
LISA plane



Response

From spacecraft s to spacecraft r
through link s: $y = \Delta\nu/\nu$

$$y_{slr} = \frac{1}{2} \frac{1}{1 - \hat{k} \cdot n_l} n_l \cdot (h(t_s) - h(t_r)) \cdot n_l$$

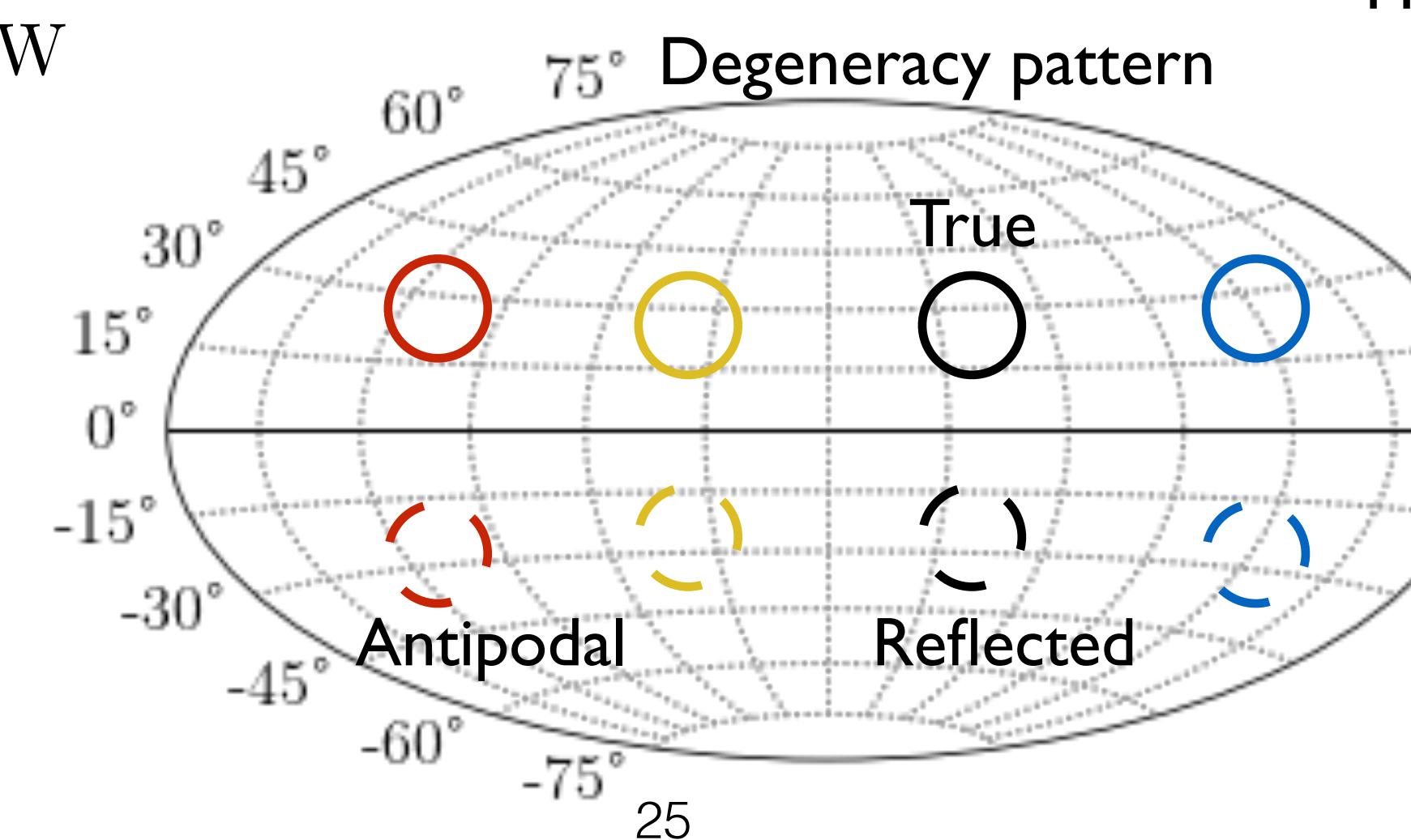
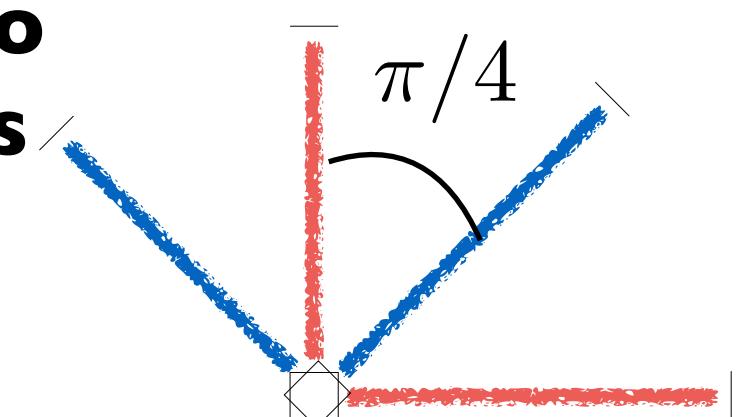
+ Time-delay
interferometry (TDI)

Fourier-domain (separation of timescales [Marsat-Baker 2018])

$$\mathcal{T}_{slr} = \frac{i\pi f L}{2} \text{sinc} [\pi f L (1 - k \cdot n_l)] \exp [i\pi f (L + k \cdot (p_r + p_s))] n_l \cdot P \cdot n_l(\mathbf{t}_f)$$

Time and frequency-dependency
Time: motion of LISA on its orbit
Frequency: departure from long-wavelength

Low-f approximation: two
LIGO-type detectors
in motion [Cutler 1997]
High-f: more complicated



Pre-merger analysis: decomposing the instrument response

Decomposing the response

$$\mathcal{T}_{slr} = \frac{i\pi f L}{2} \text{sinc} [\pi f L (1 - k \cdot n_l)] \exp [i\pi f (L + k \cdot (p_r + p_s))] n_l \cdot P \cdot n_l(\mathbf{t}_f)$$

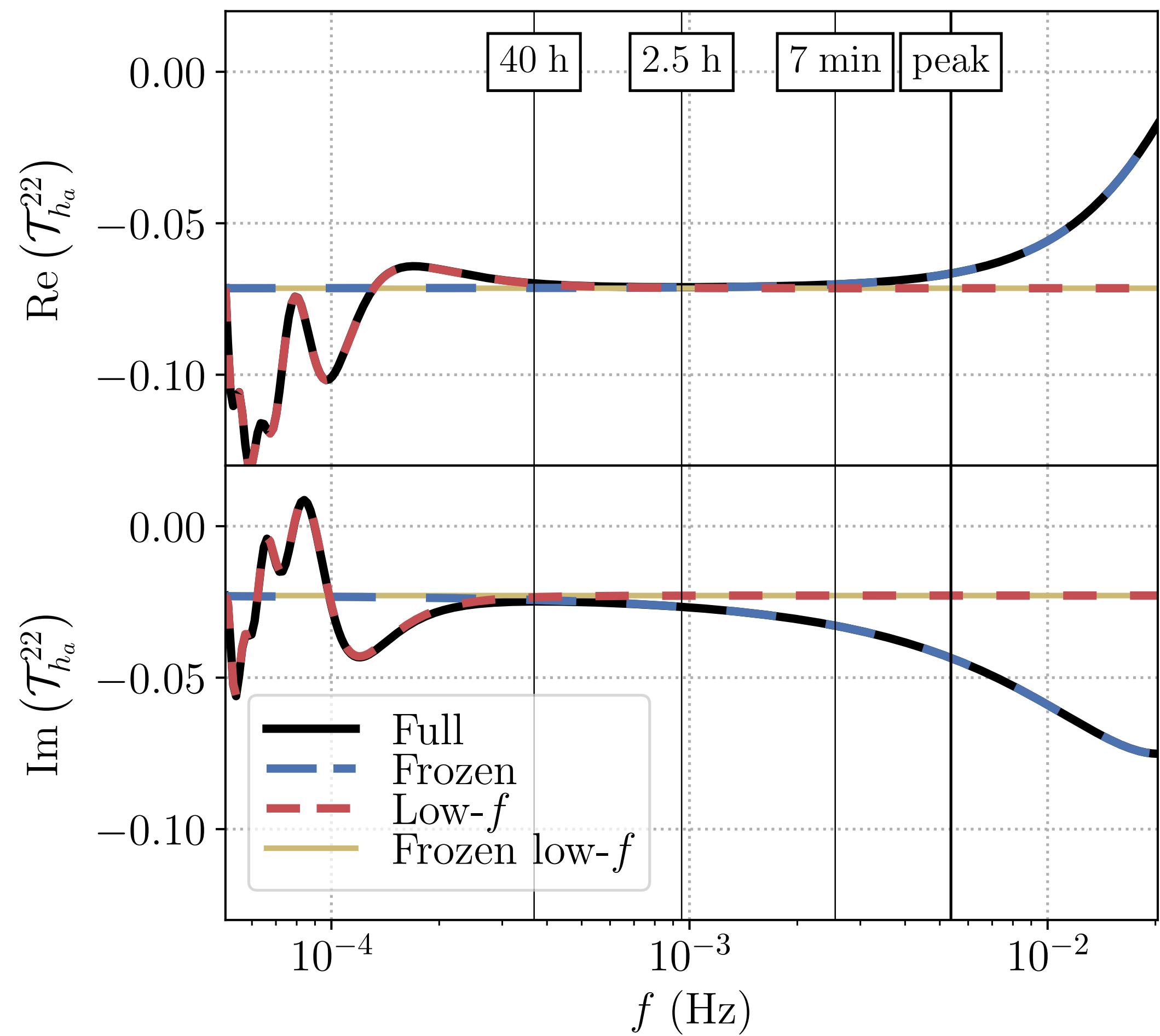
+ Doppler phase: $\exp [2i\pi f k \cdot p_0(\mathbf{t}_f)]$

Time and frequency-dependency in transfer functions

Time: motion of LISA on its orbit

Frequency: departure from long-wavelength approx.

- Response:
- ‘Full’: keep all terms
 - ‘Frozen’: ignore LISA motion
 - ‘Low-f’: ignore f-dependency
 - ‘Frozen Low-f’: ignore both



Outline

- Signals and instrument response
- **The crucial role of higher harmonics**
- Understanding LISA's localization capabilities
- Understanding multimodality in the sky position

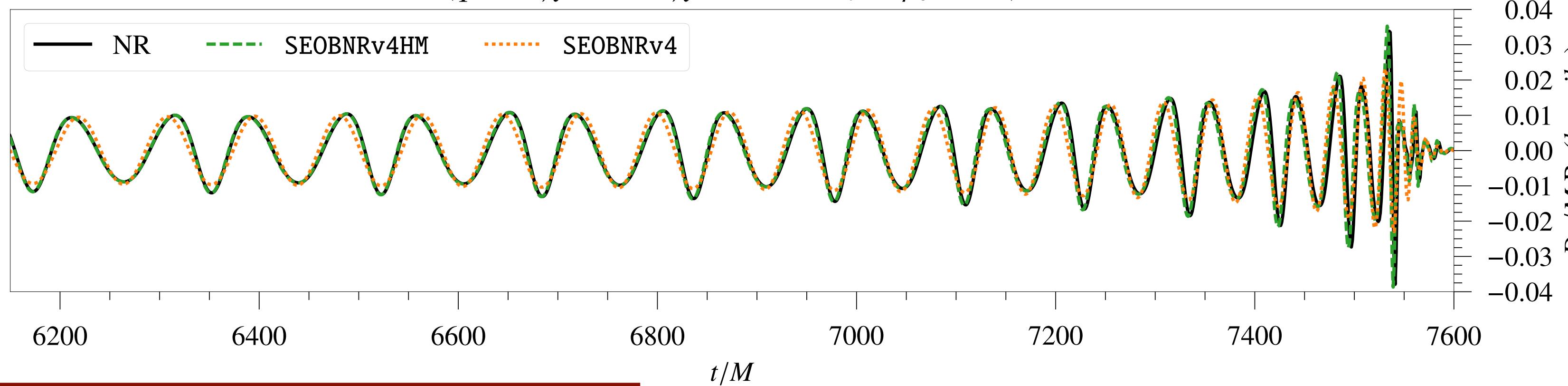
Higher harmonics in GW signals

Higher harmonics hlm

$$h_+ - ih_x = \sum_{\ell \geq 2} \sum_{m=-\ell}^{\ell} {}_{-2}Y_{\ell m}(\iota, \varphi) h_{\ell m}$$

Example in time domain:

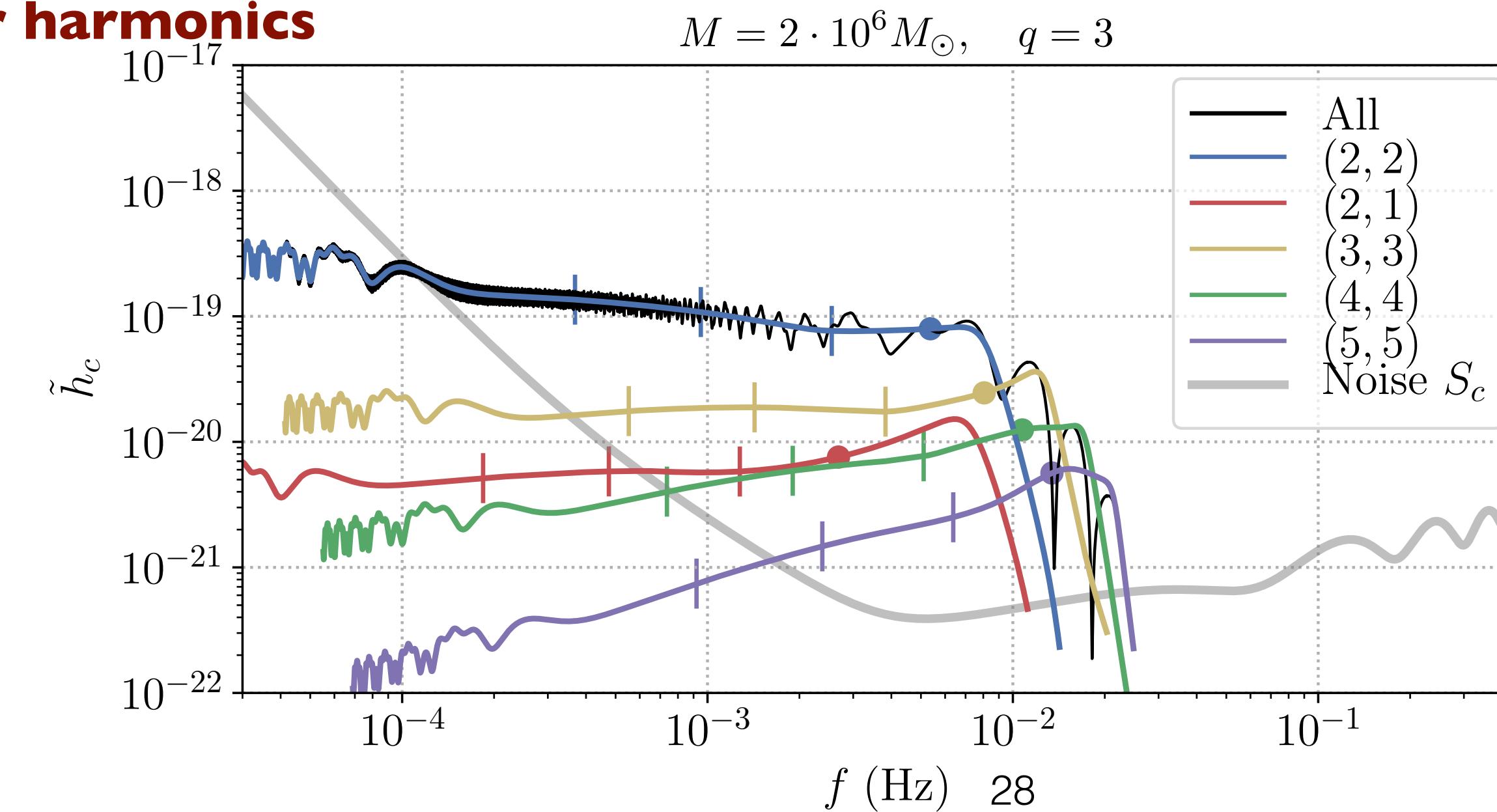
$(q = 8, \chi_1 = 0.5, \chi_2 = 0, \iota = \pi/2, \varphi_0 = 1.2)$



- Dominant harmonic h_{22}
- Higher modes stronger at merger/ringdown
- Higher modes more important for high q and edge-on

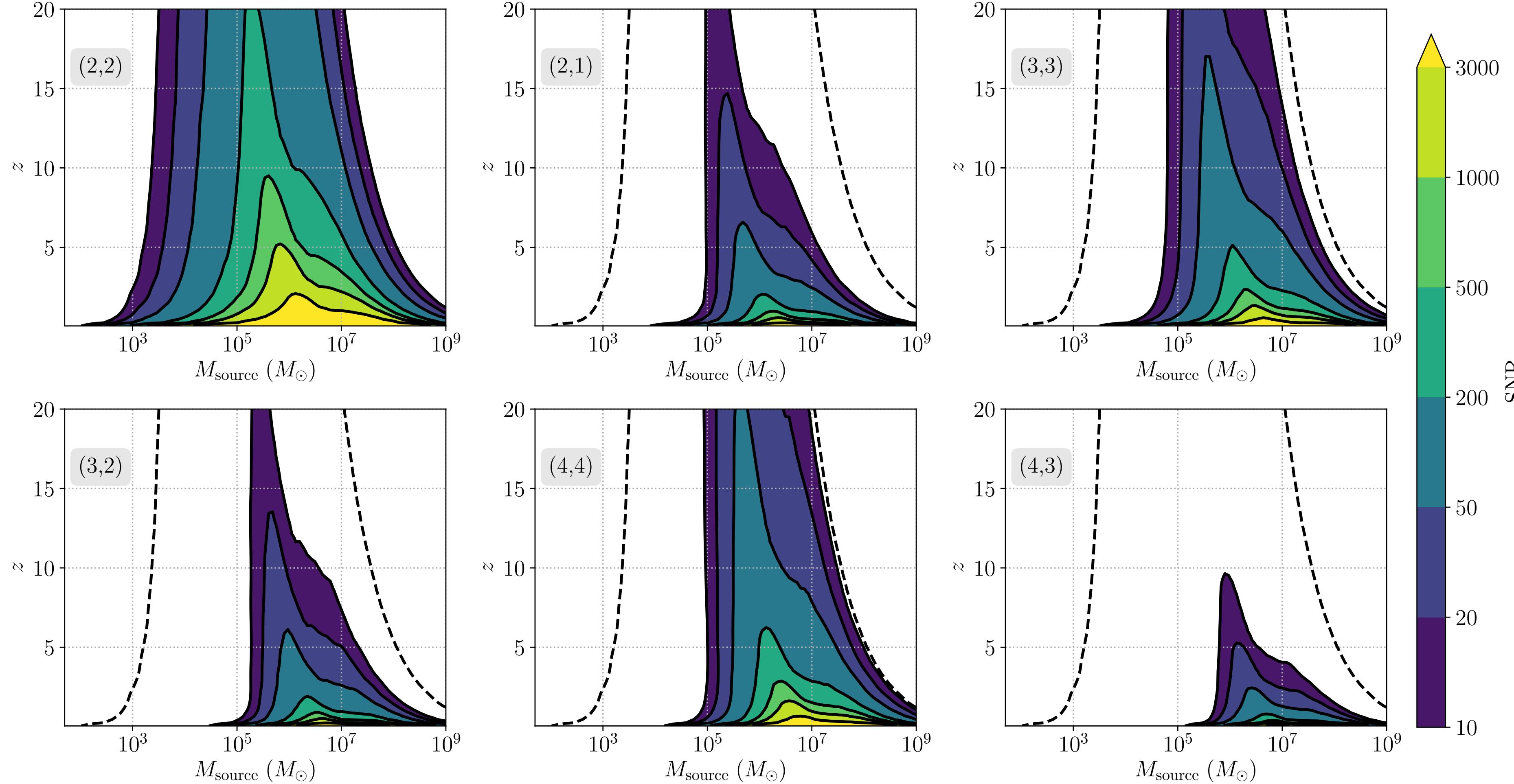
MBHB with higher harmonics

- Ticks:
- SNR/64 (40h)
 - SNR/16 (2.5h)
 - SNR/4 (7min)
 - merger



The SNR of higher harmonics

PhenomHM, $q=5$, averaging over spins and orientations



'Mode SNR':

$$\sqrt{(s_{\ell m} | s_{\ell m})}$$

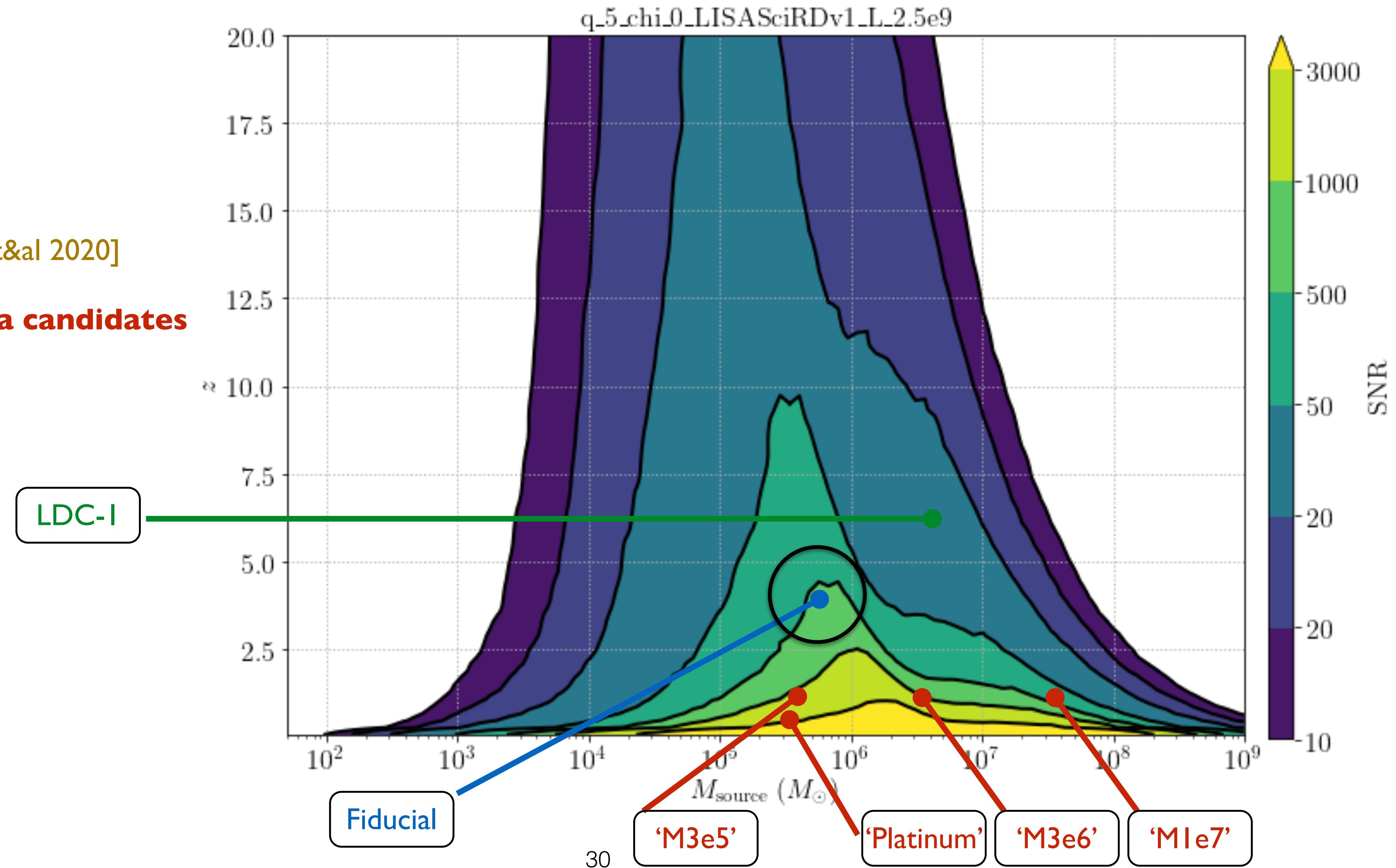
Cross-terms not negligible

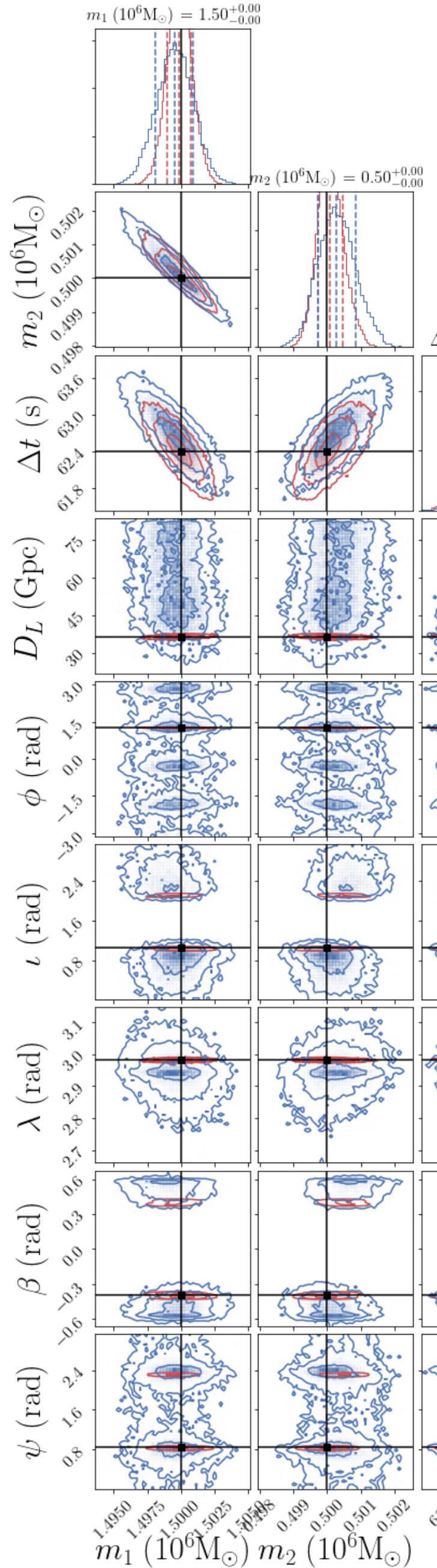
$$\sum_{(\ell m) \neq (\ell' m')} (s_{\ell m} | s_{\ell' m'})$$

Example MBHB signals

Systems:

- Fiducial [Marsat&al 2020]
- **LISA/Athena candidates**
- LDC-I

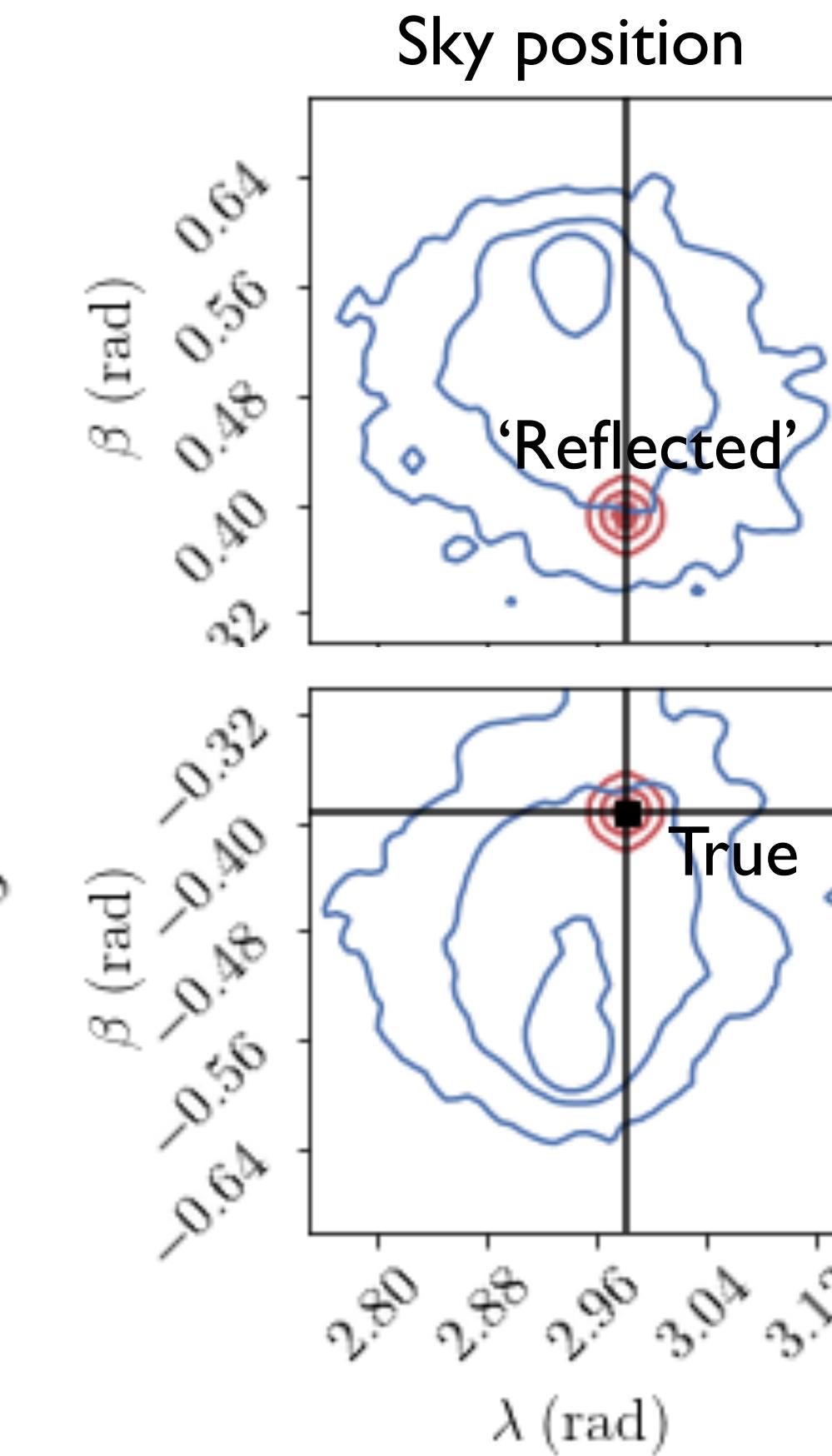
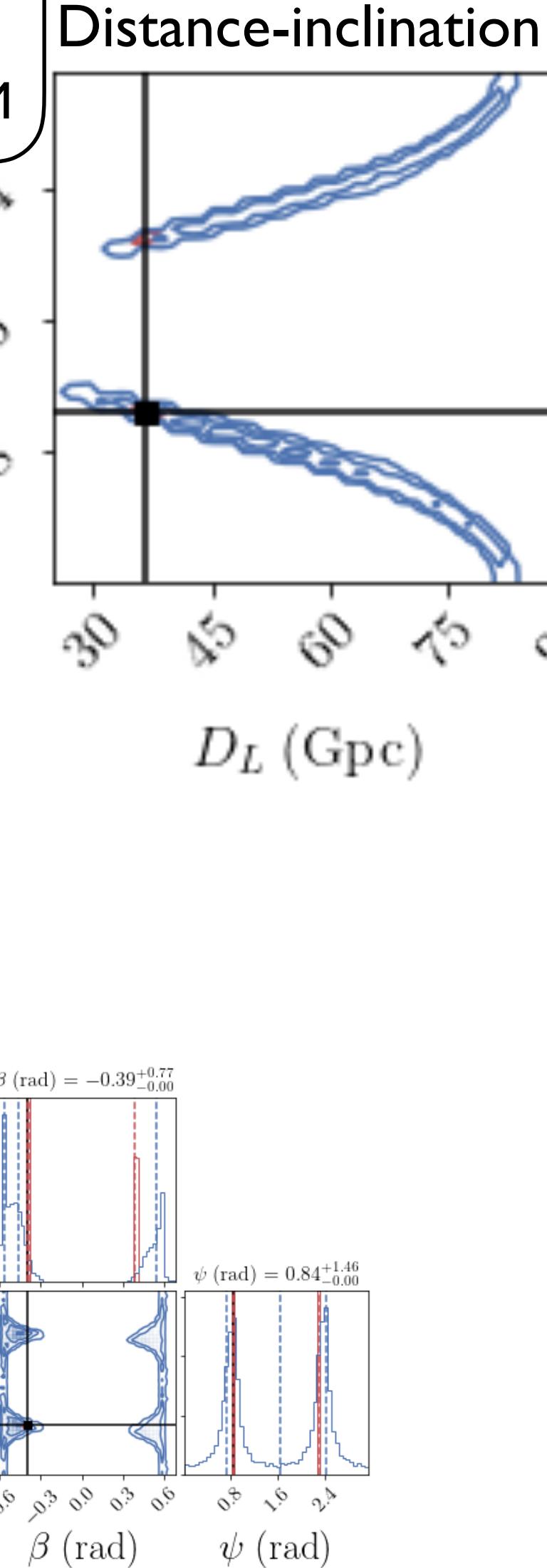




Fiducial system:

MBHB PE 22 vs HM: degenerate case

■ injection
— ptmcmc 22
— ptmcmc HM



Higher harmonics
crucial in breaking
degeneracies

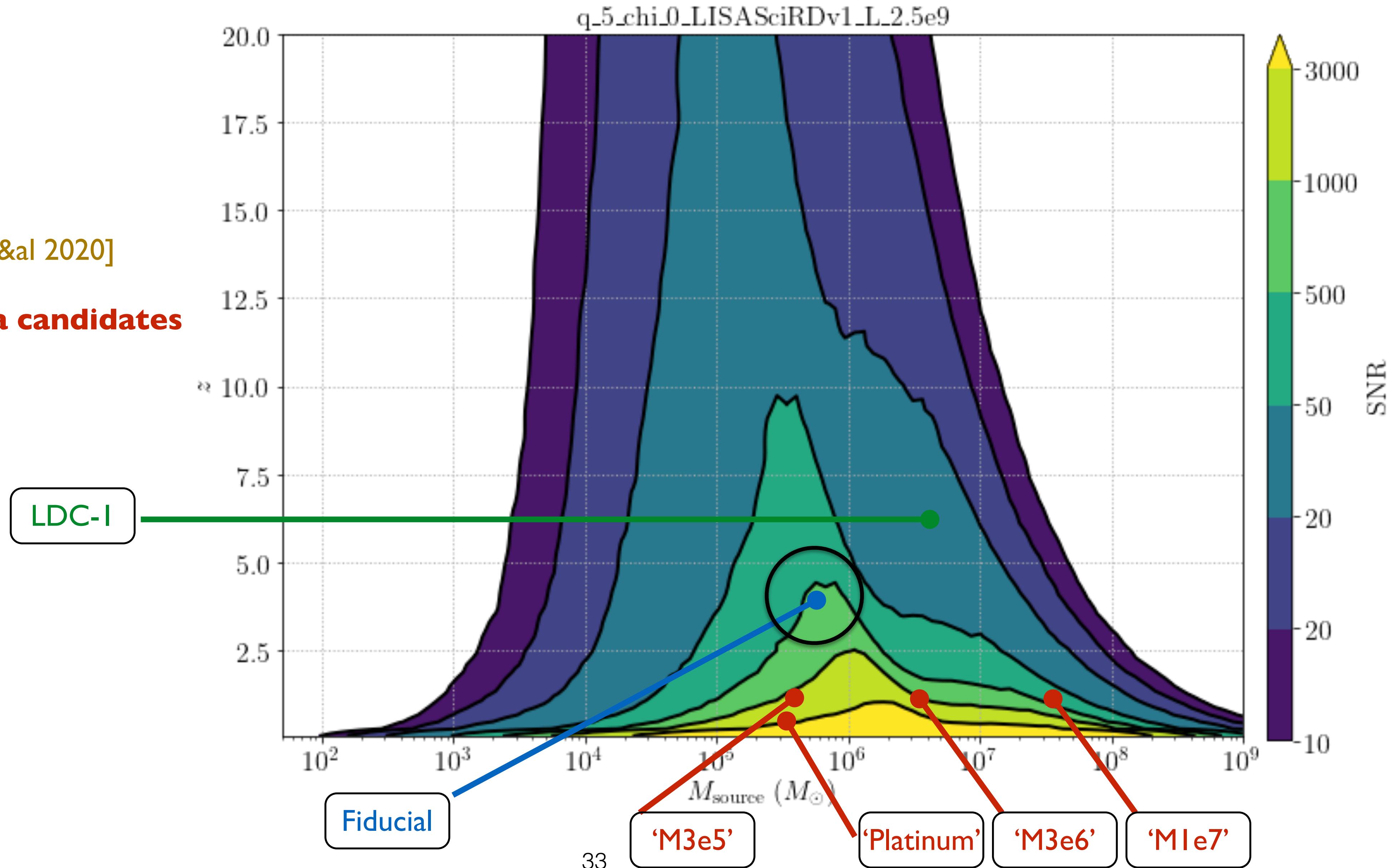
Outline

- Signals and instrument response
- The crucial role of higher harmonics
- **Understanding LISA's localization capabilities**
- Understanding multimodality in the sky position

Example MBHB signals

Systems:

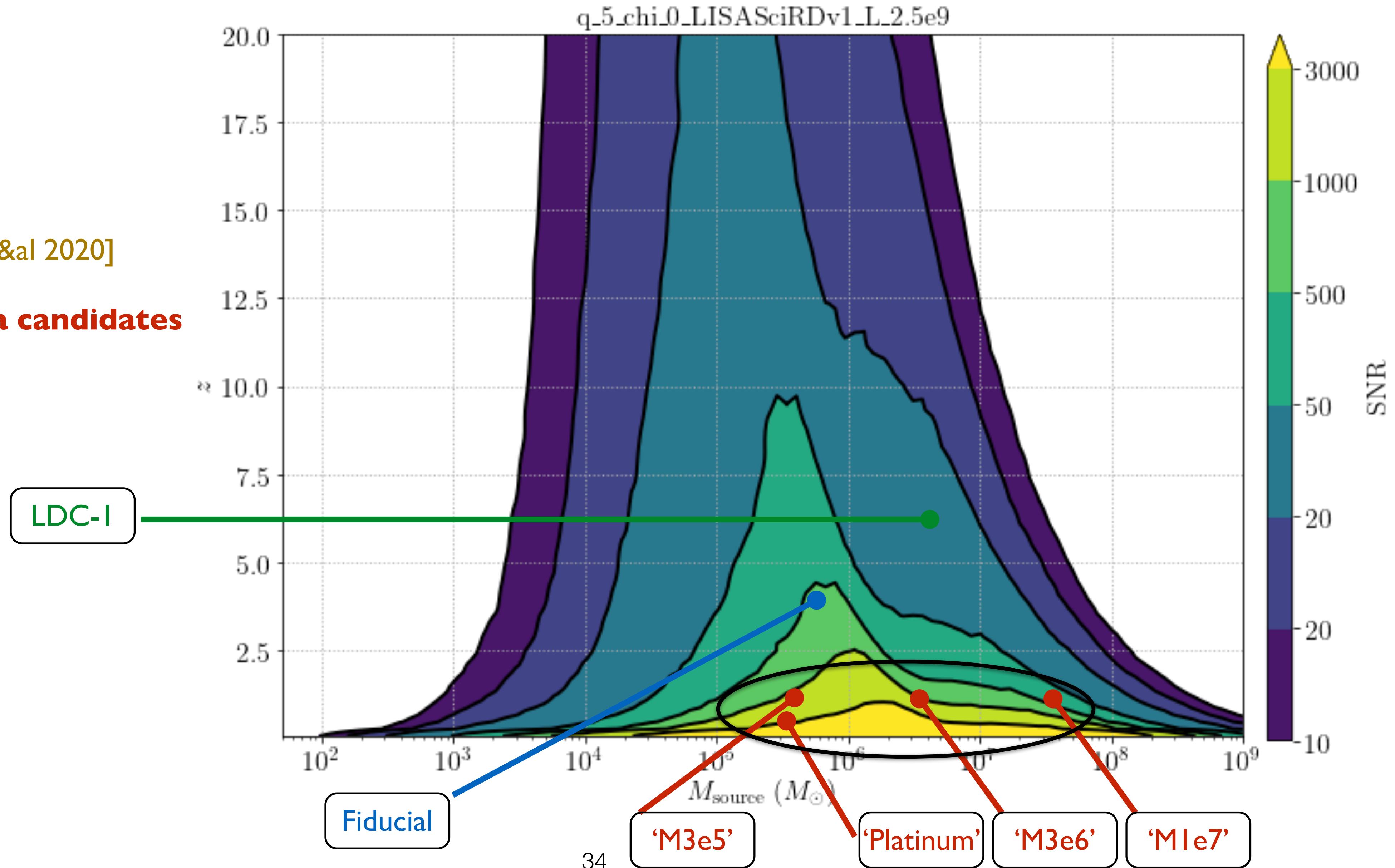
- Fiducial [Marsat&al 2020]
- **LISA/Athena candidates**
- LDC-I



Example MBHB signals

Systems:

- Fiducial [Marsat&al 2020]
- **LISA/Athena candidates**
- LDC-I



Pre-merger localization: role of response for ‘golden’ systems

Here: main mode sky area

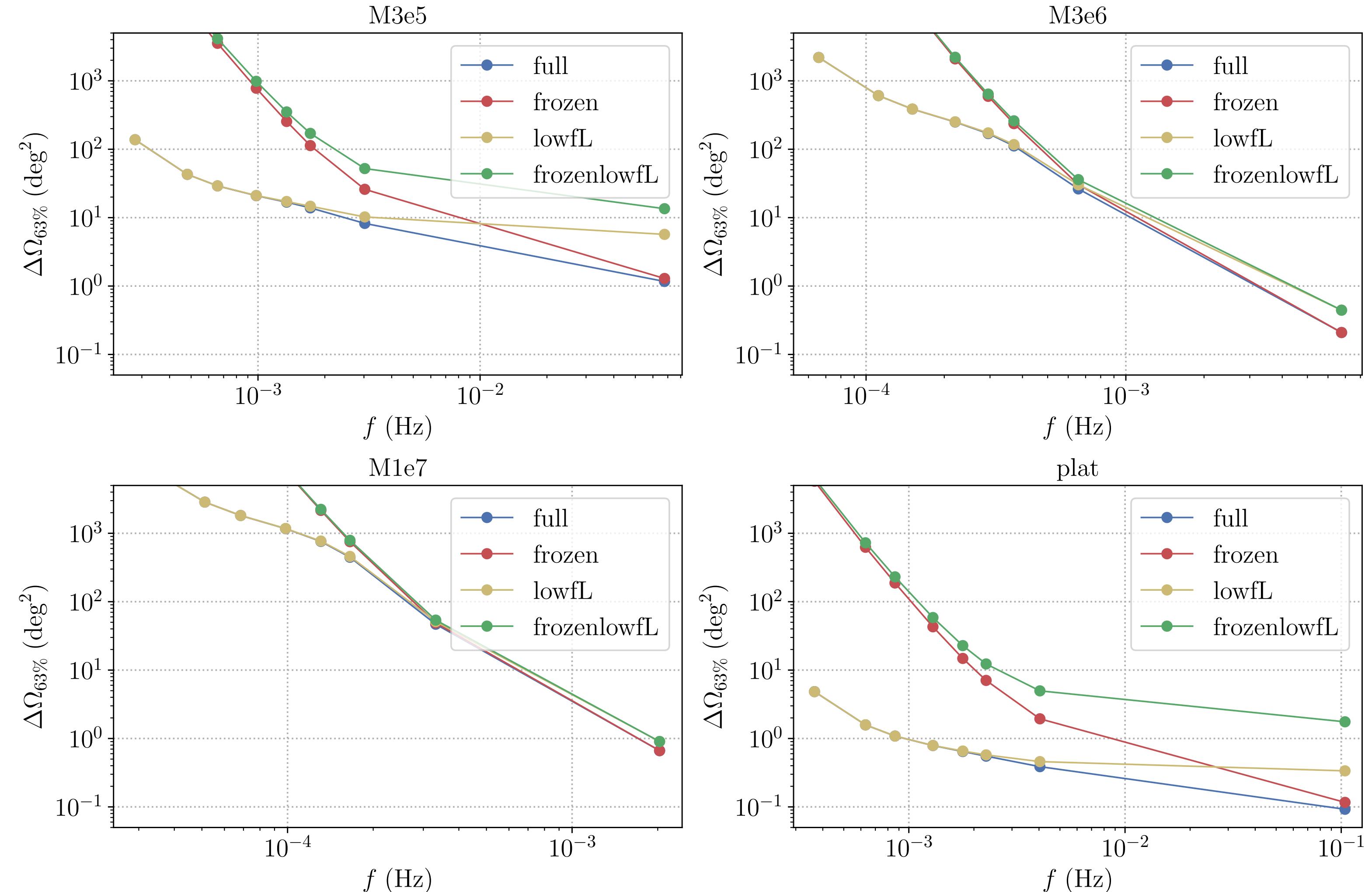
Response (signal with HM here):

- ‘Full’: keep all terms
- ‘Frozen’: ignore LISA motion
- ‘Low-f’: ignore f-dependency
- ‘Frozen Low-f’: ignore both

For low masses, best candidates for advance localization:

- Localization from the LISA motion saturates reaching merger
- Localization from high-f effects dominates at merger

For high masses, HM at merger convey most of the information



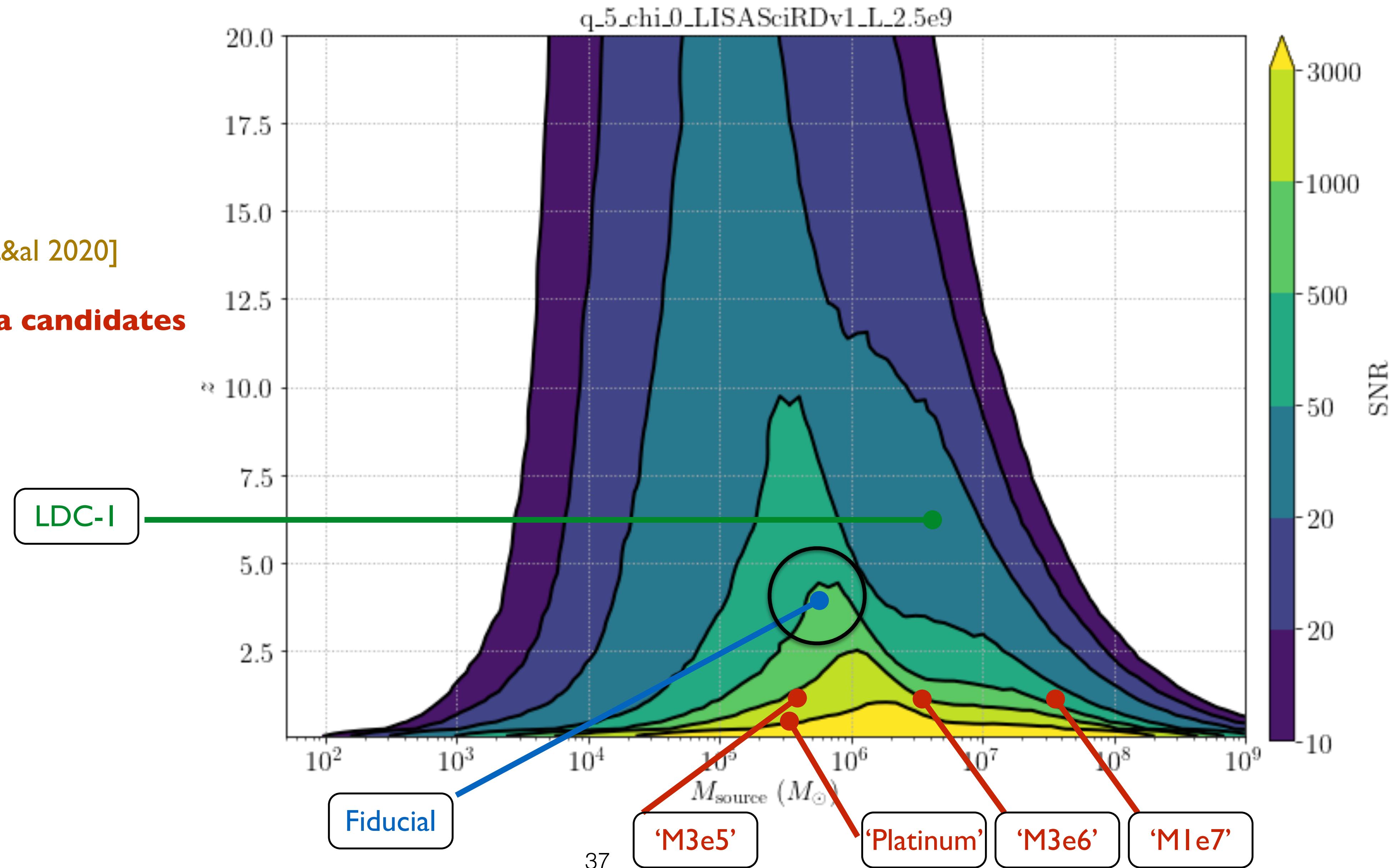
Outline

- Signals and instrument response
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- **Understanding multimodality in the sky position**

Example MBHB signals

Systems:

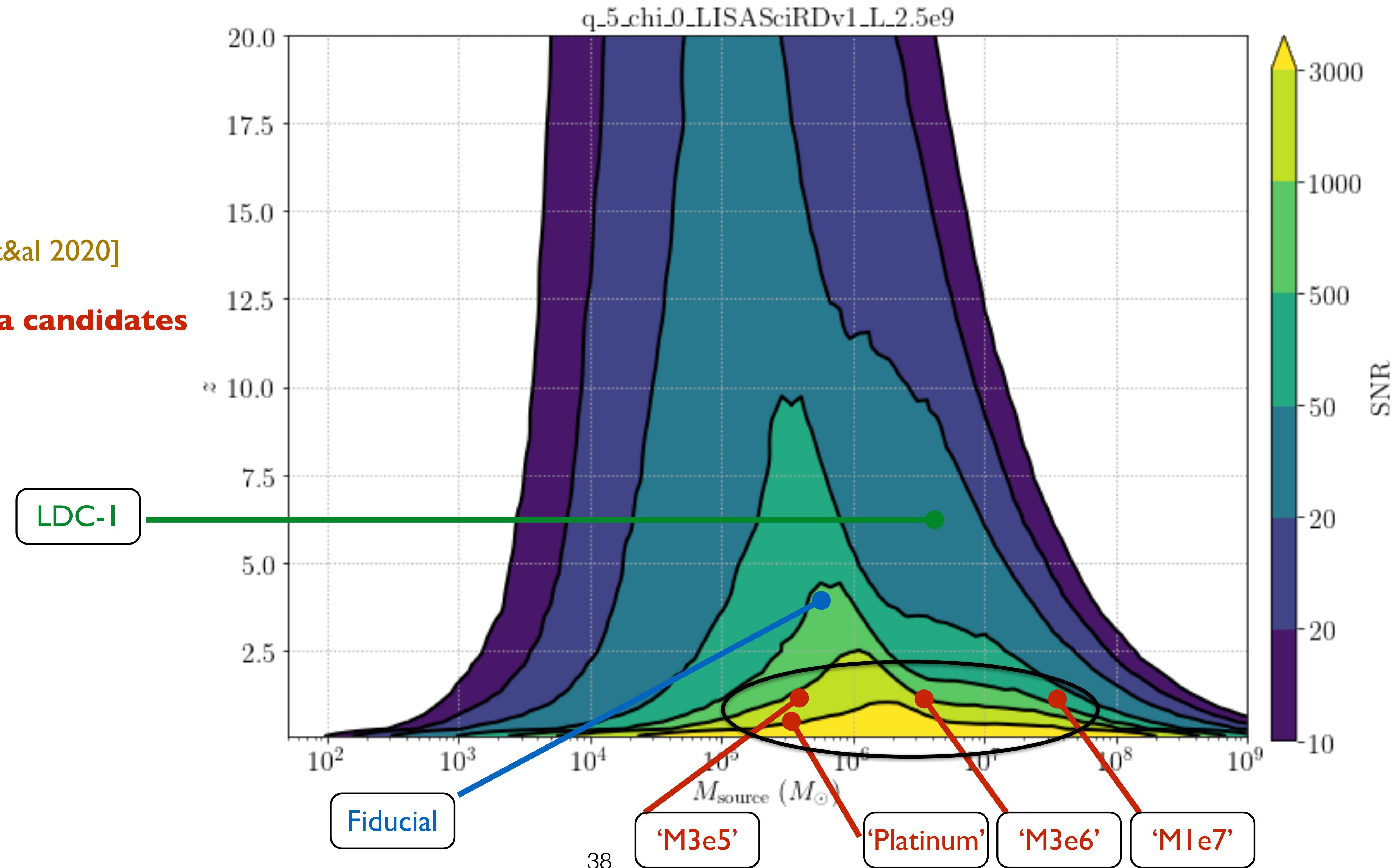
- Fiducial [Marsat&al 2020]
- **LISA/Athena candidates**
- LDC-I



Example MBHB signals

Systems:

- Fiducial [Marsat&al 2020]
- **LISA/Athena candidates**
- LDC-I

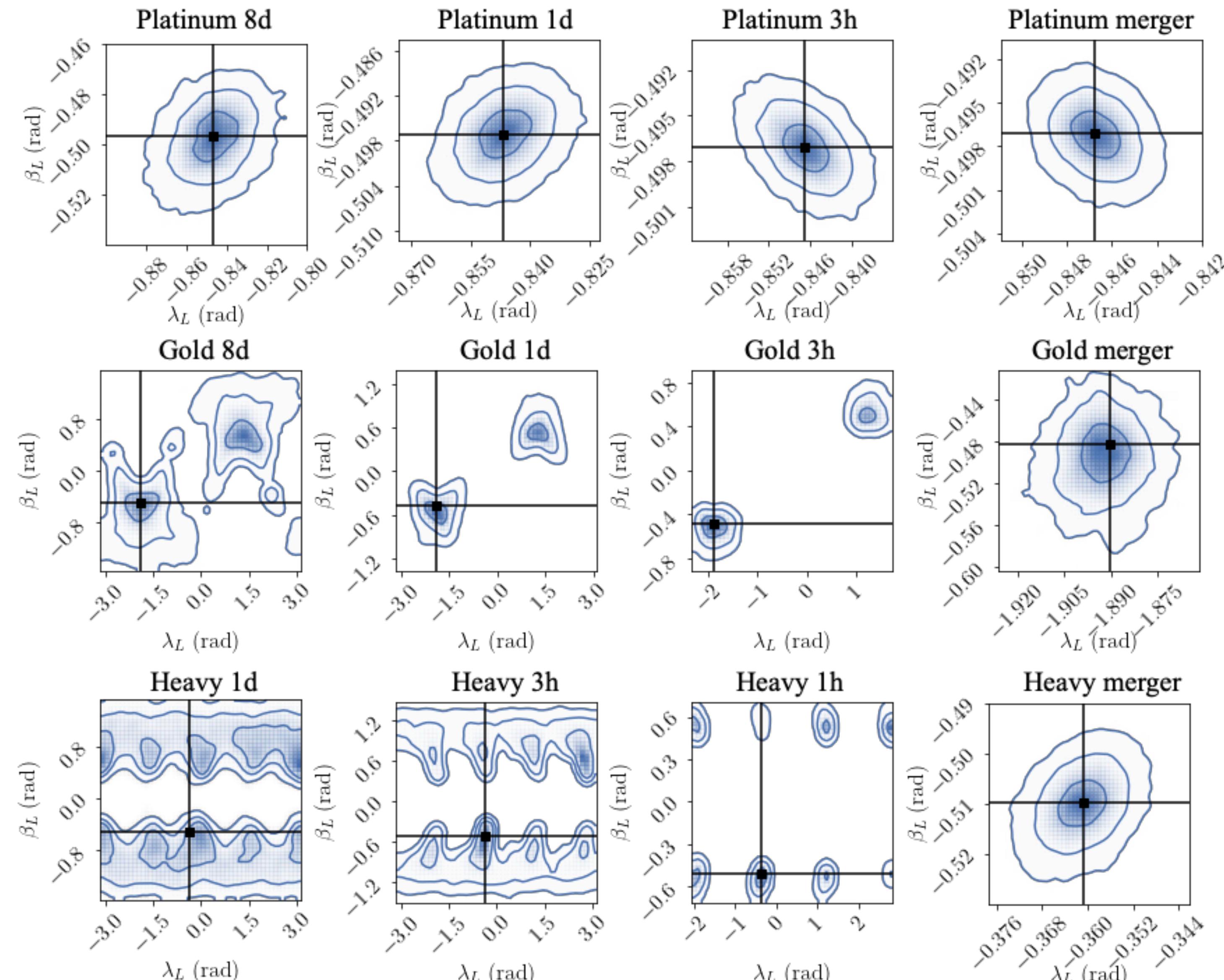


Localization of LISA/Athena candidates

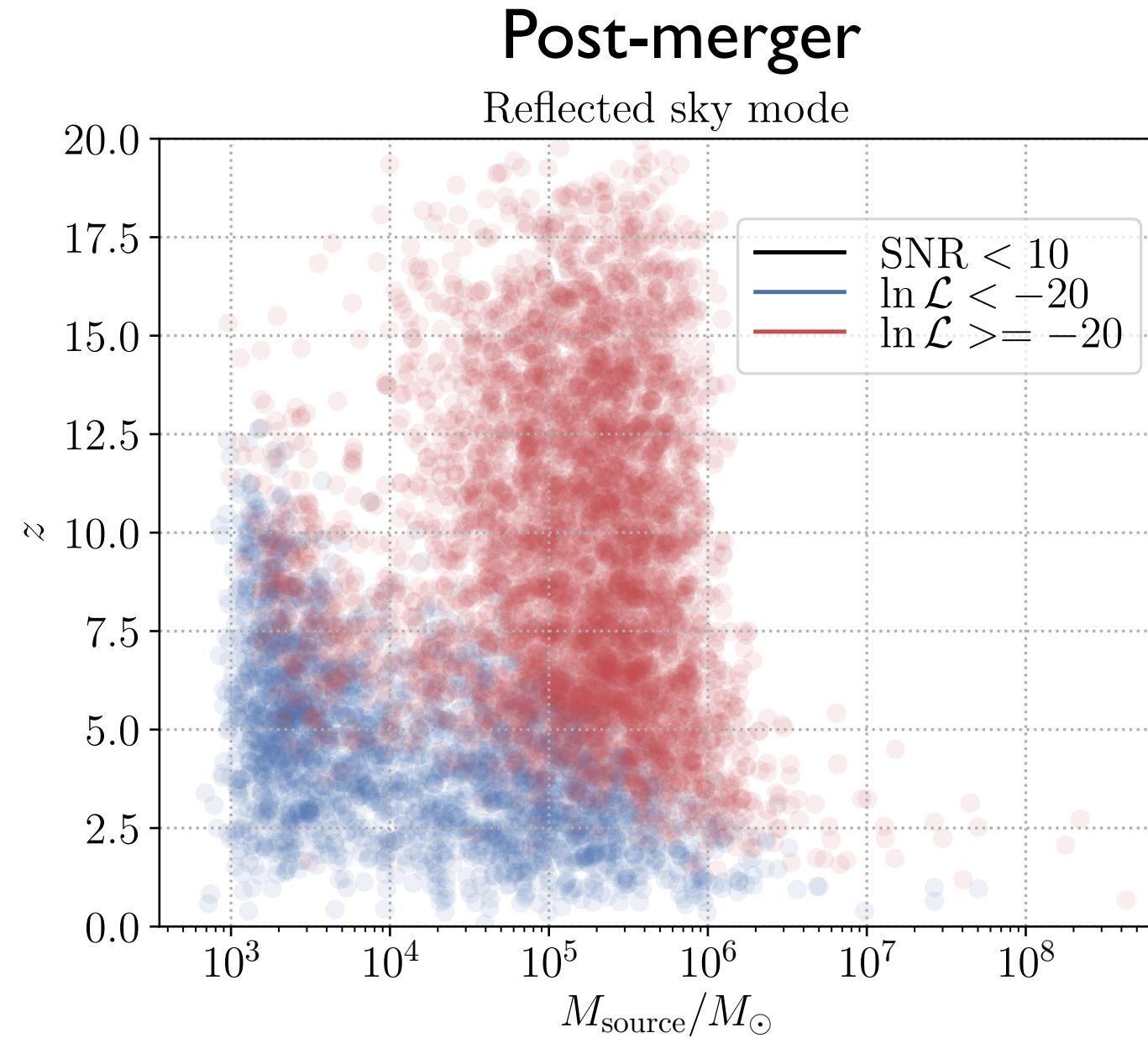
Bayesian sky localization
(on different time stamps)

- ‘Gold’: M3e6, $z=1$
- ‘Heavy’: M1e7, $z=1$
- ‘Platinum’: M3e5, $z=0.3$

- Wide range of multimodalities dep. on parameters
- Post-merger localization unimodal



Multimodality of the sky localization: astrophysical catalogs

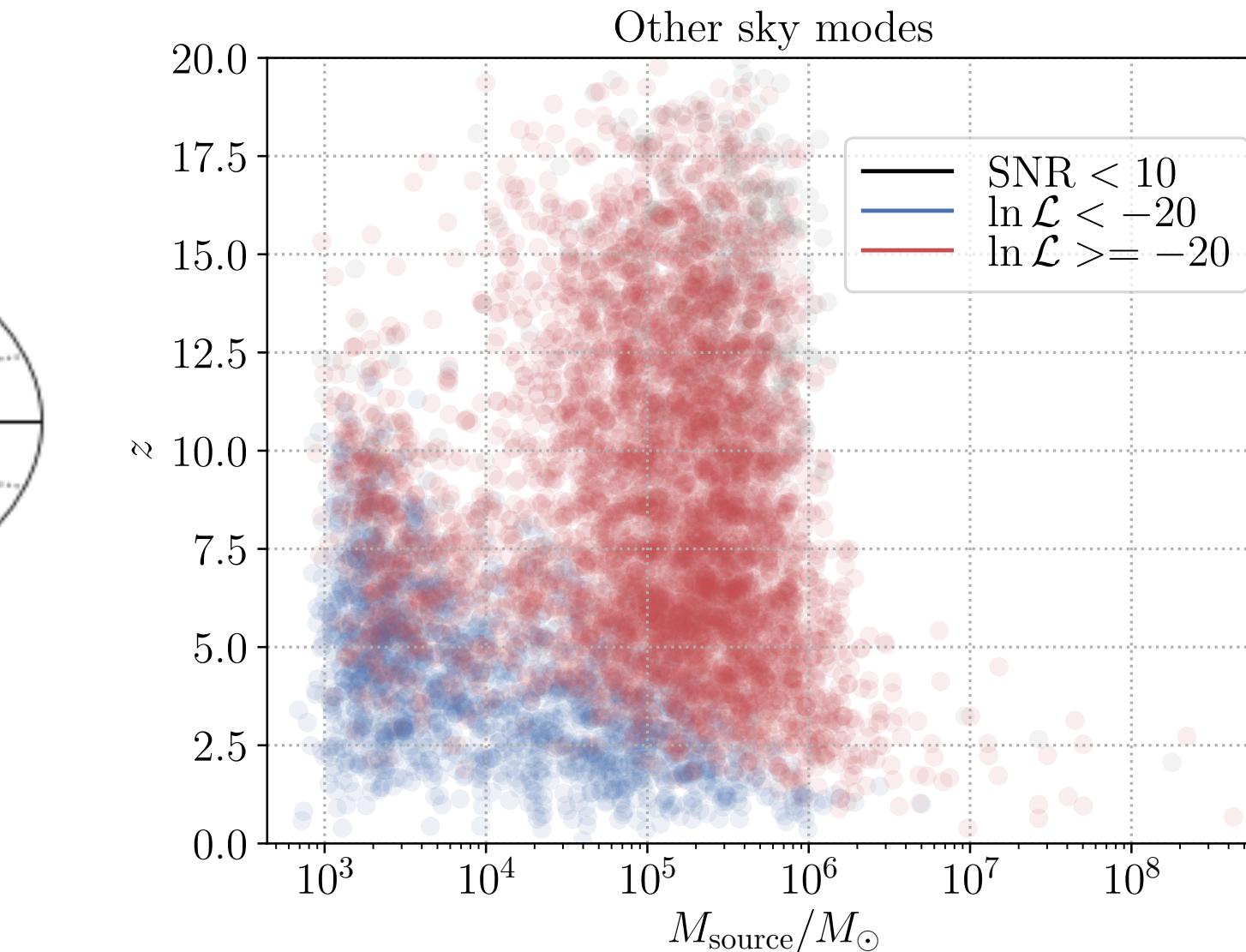
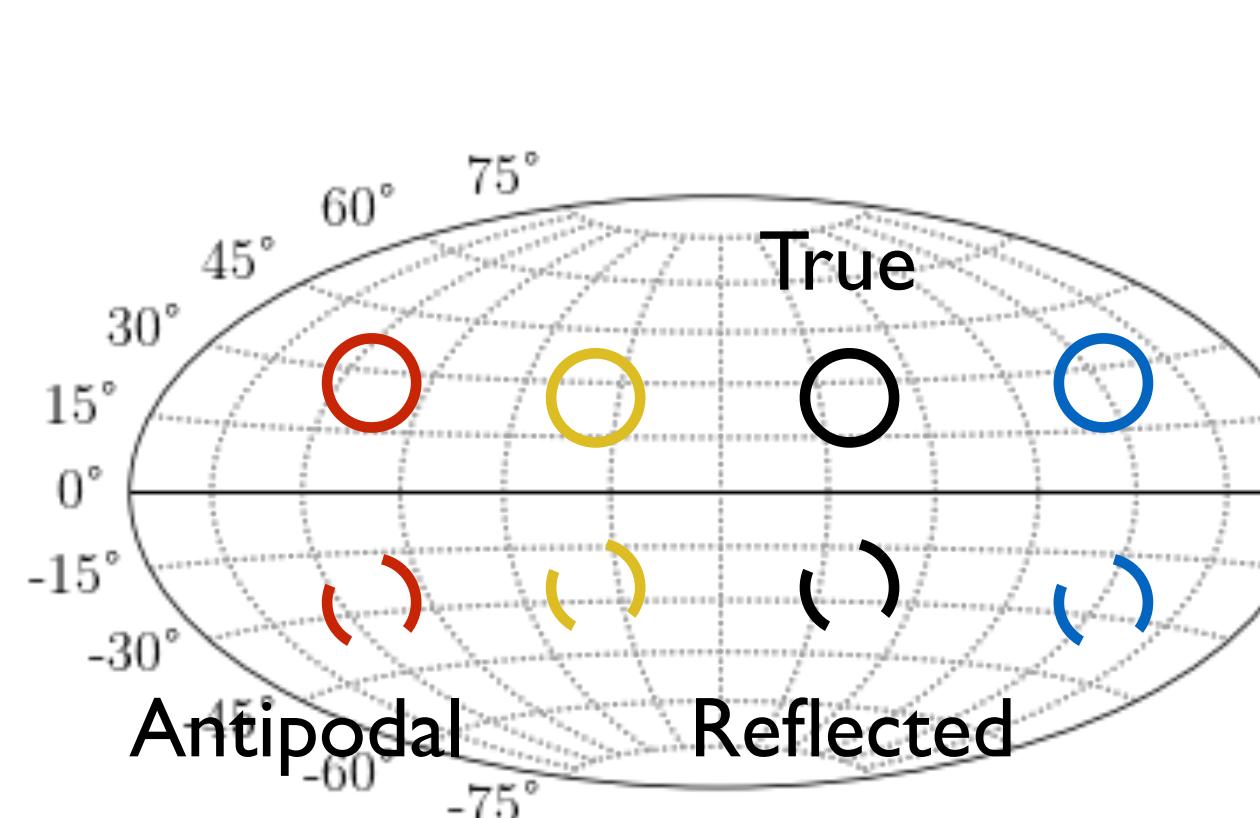
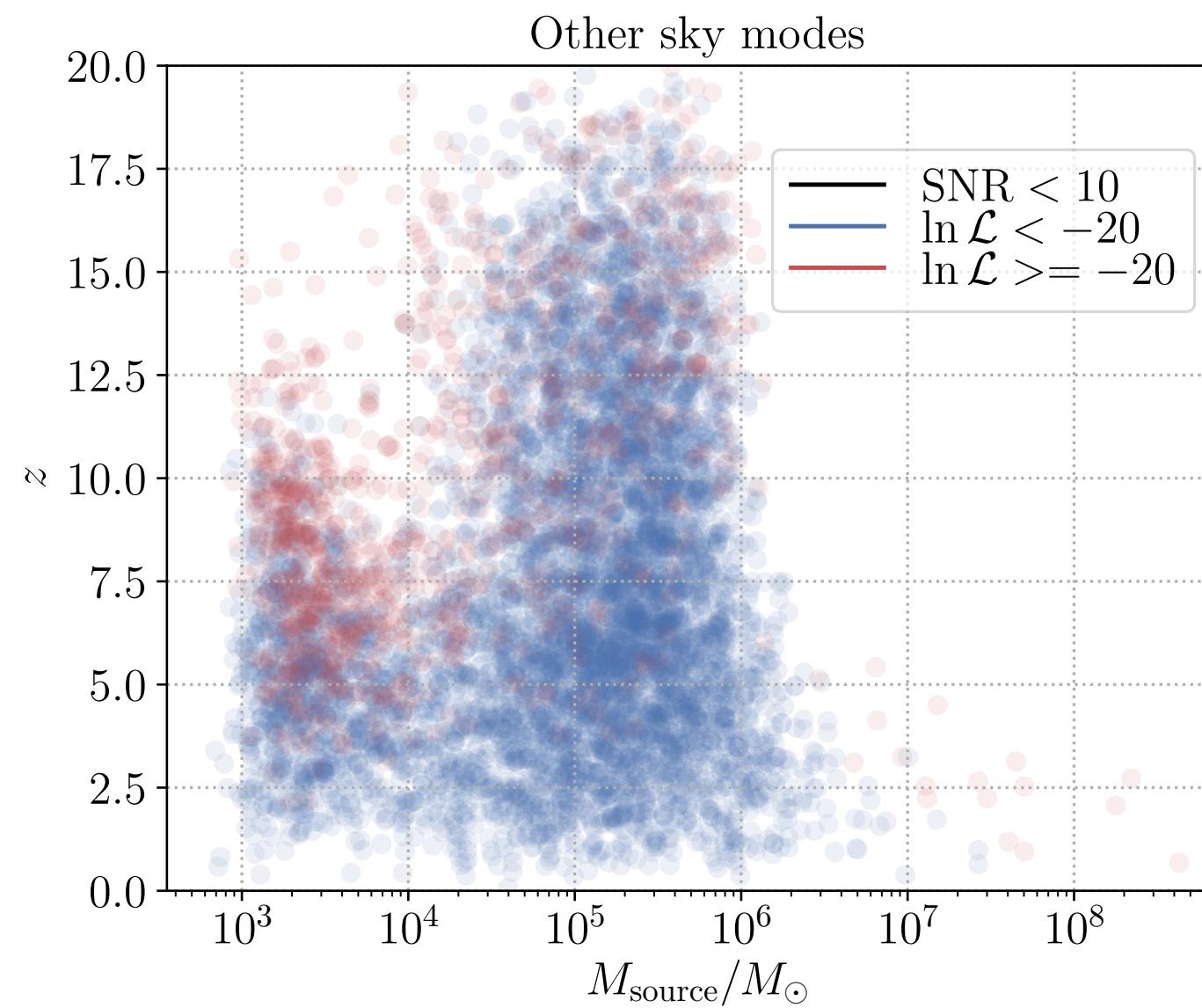
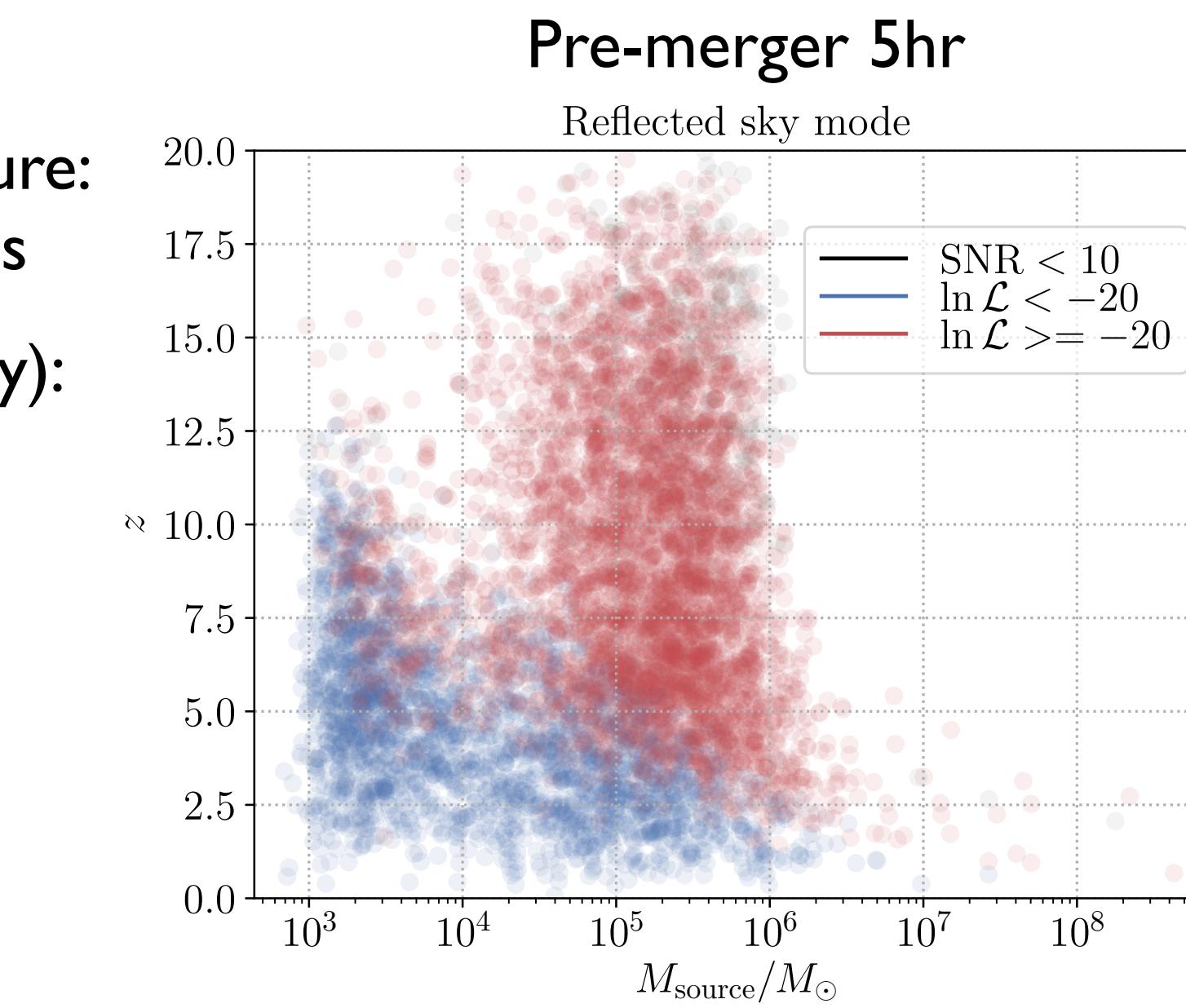


Approximate degeneracy measure:
likelihood at the other sky positions

Threshold used here (a bit arbitrary):

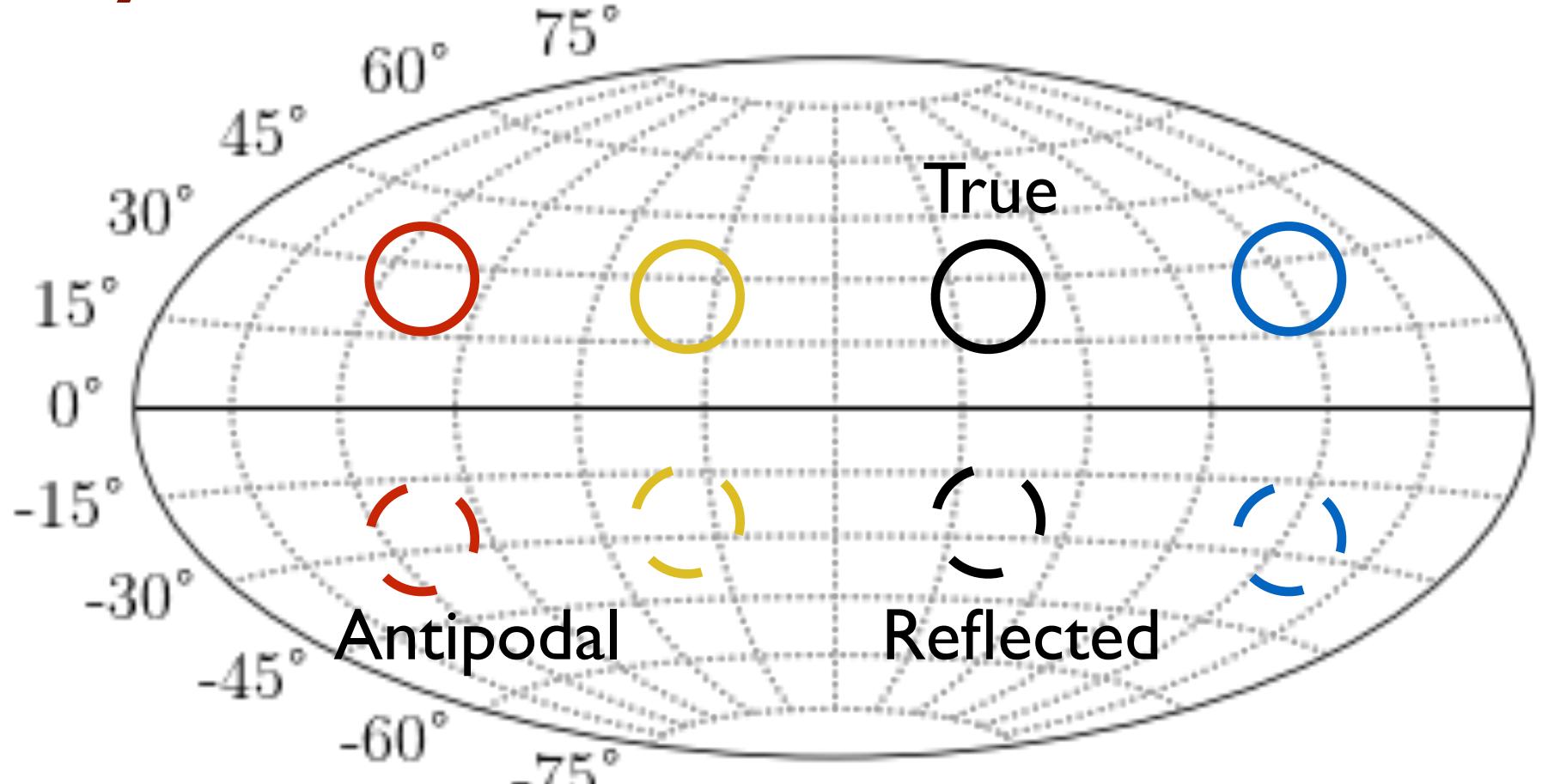
$$\ln \mathcal{L} > -20$$

Blue: presumably not degenerate
Red: presumably degenerate



Multimodality of the sky localization: a likelihood estimator ?

Sky modes L-frame

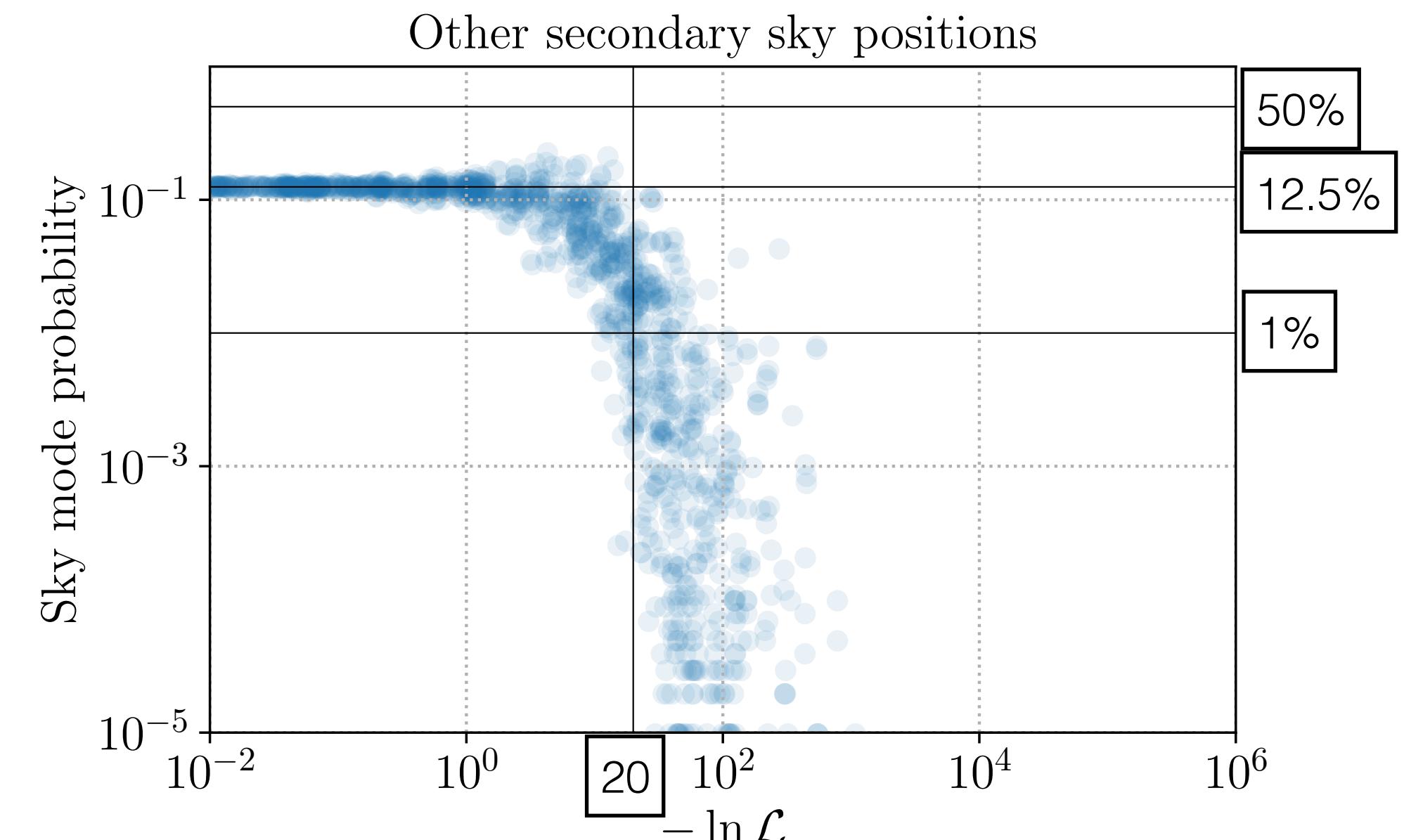
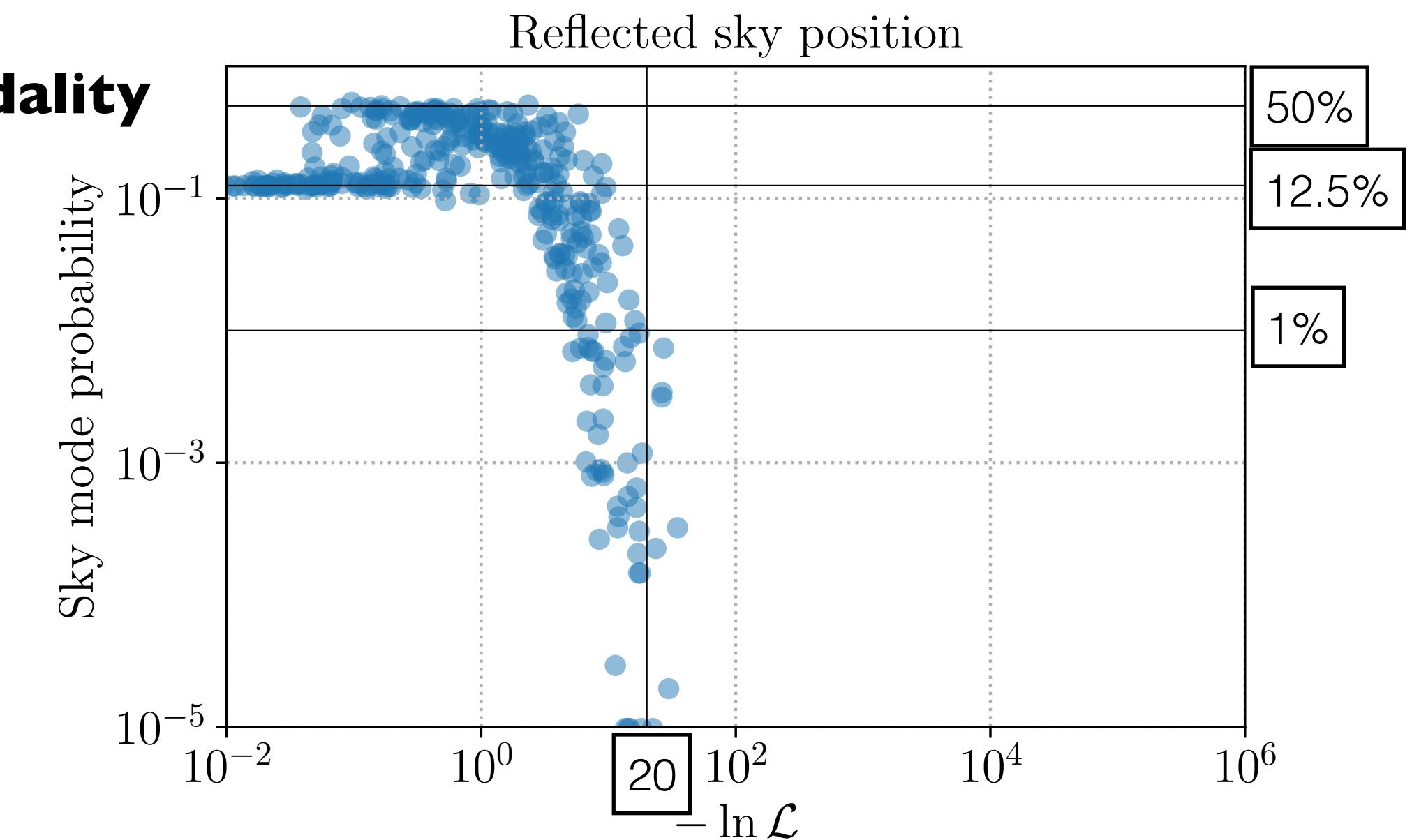


400 post-merger PE runs
at ‘boundary’ of multimodality

Point-like estimate of multimodality: likelihood at the sky modes.

Relation to posterior probability weights from actual (expensive) sampling ?

Dispersion in this relation; thresholding approximate



Conclusion and outlook

Highlights

- Bayesian tools for fast PE of MBHB signals
- Explored the LISA parameter recovery of MBHBs
- Analyzed role of higher harmonics in breaking parameter space degeneracies
- Analyzed features of the instrumental response and breaking of multimodal sky degeneracies

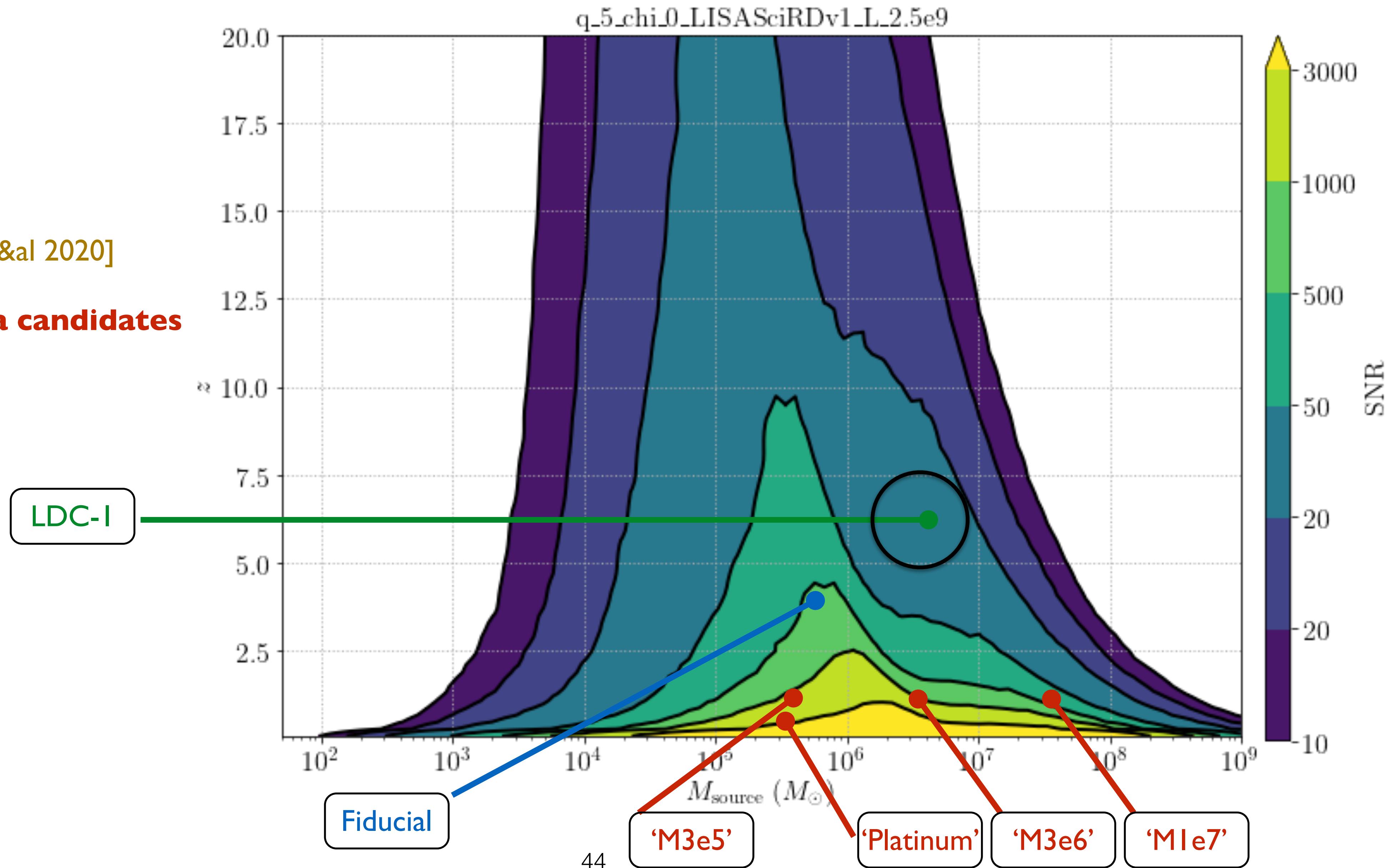
Outlook

- Explore LISA's localization capability across the parameter space
- More realistic analysis: multiple signals, realistic noise
- More realistic waveforms: precession and eccentricity

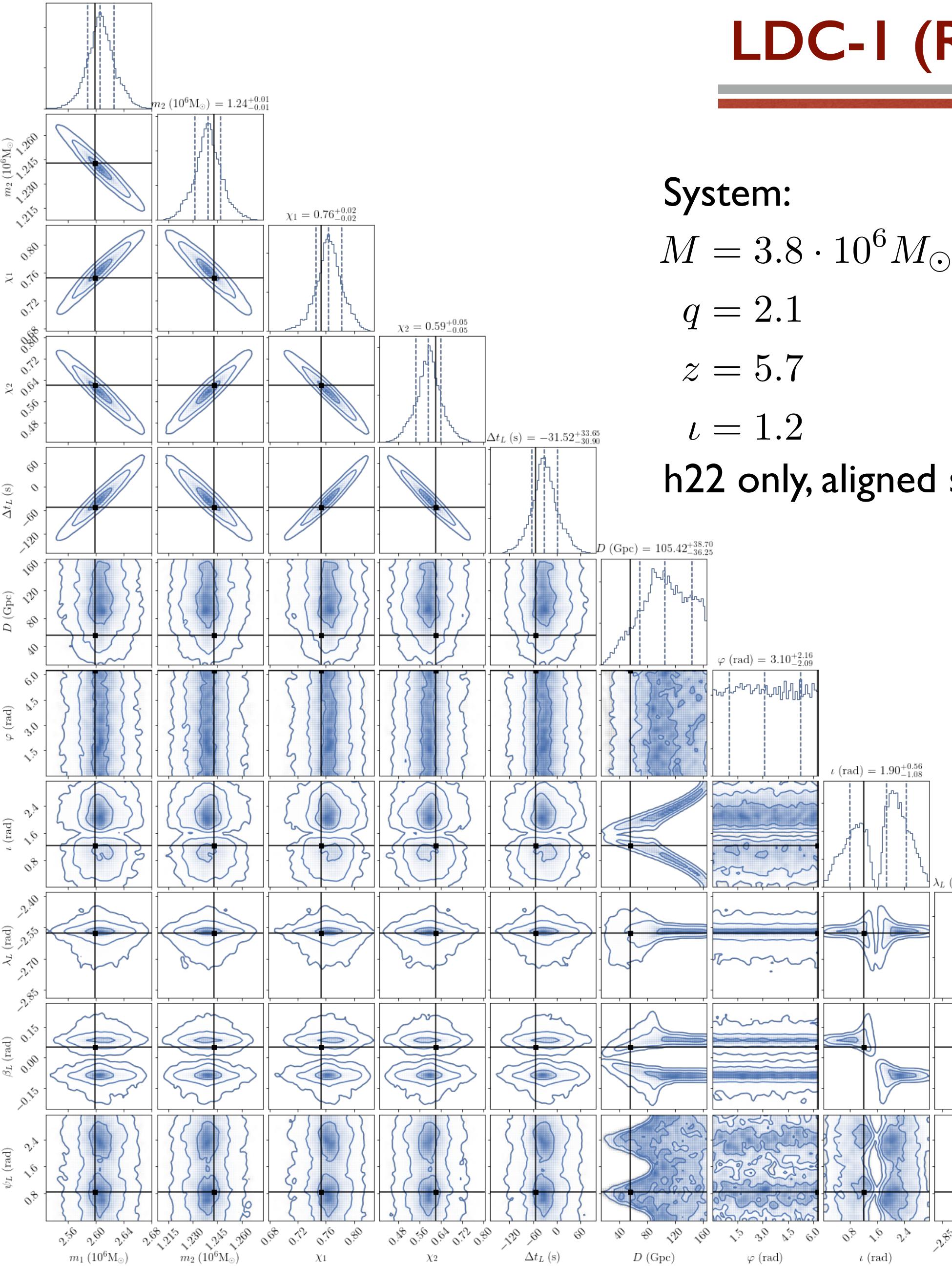
Example MBHB signals

Systems:

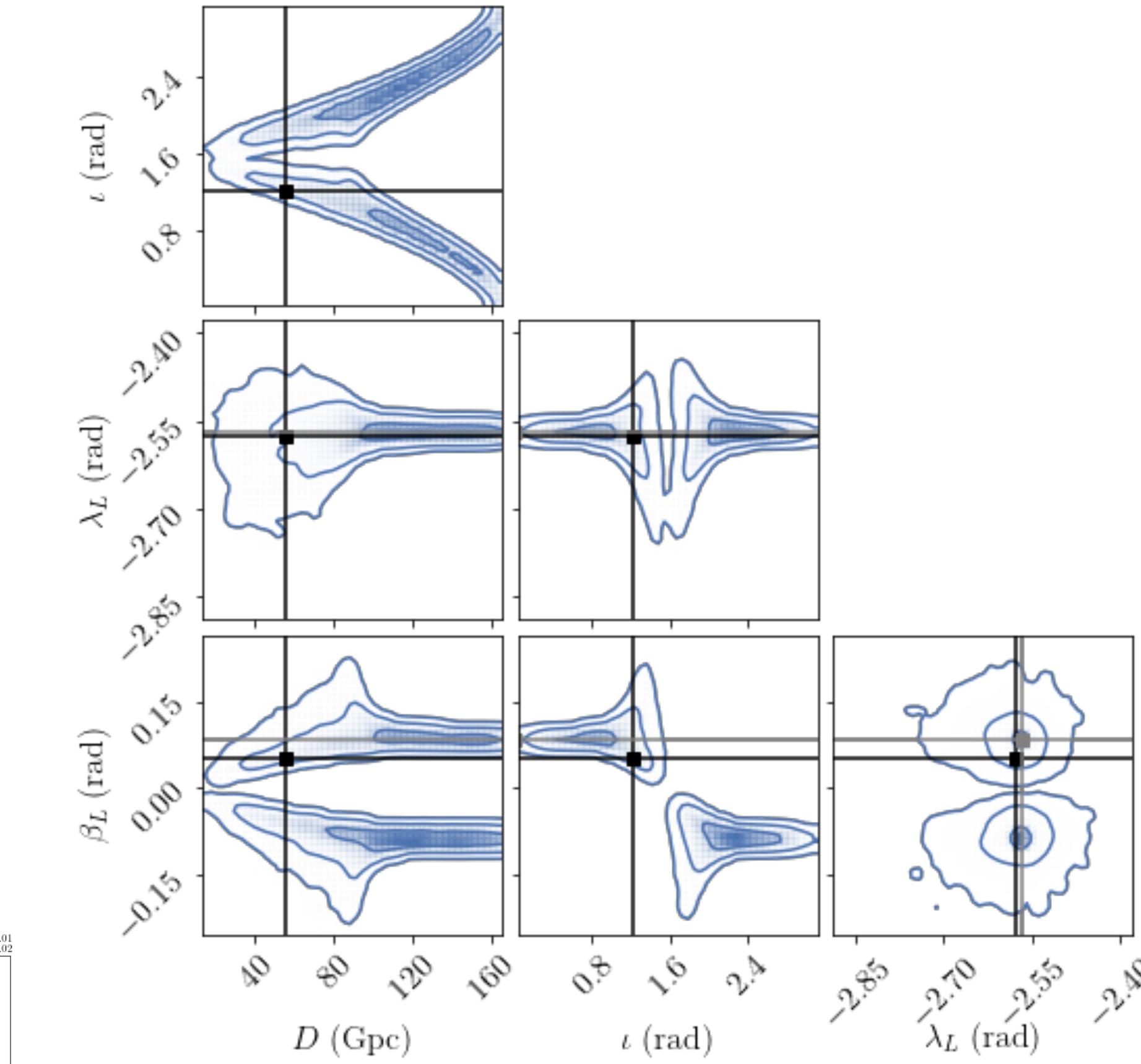
- Fiducial [Marsat&al 2020]
- **LISA/Athena candidates**
- LDC-I



$$m_1 (10^6 M_\odot) = 2.61^{+0.02}_{-0.02}$$



LDC-I (Radler) results

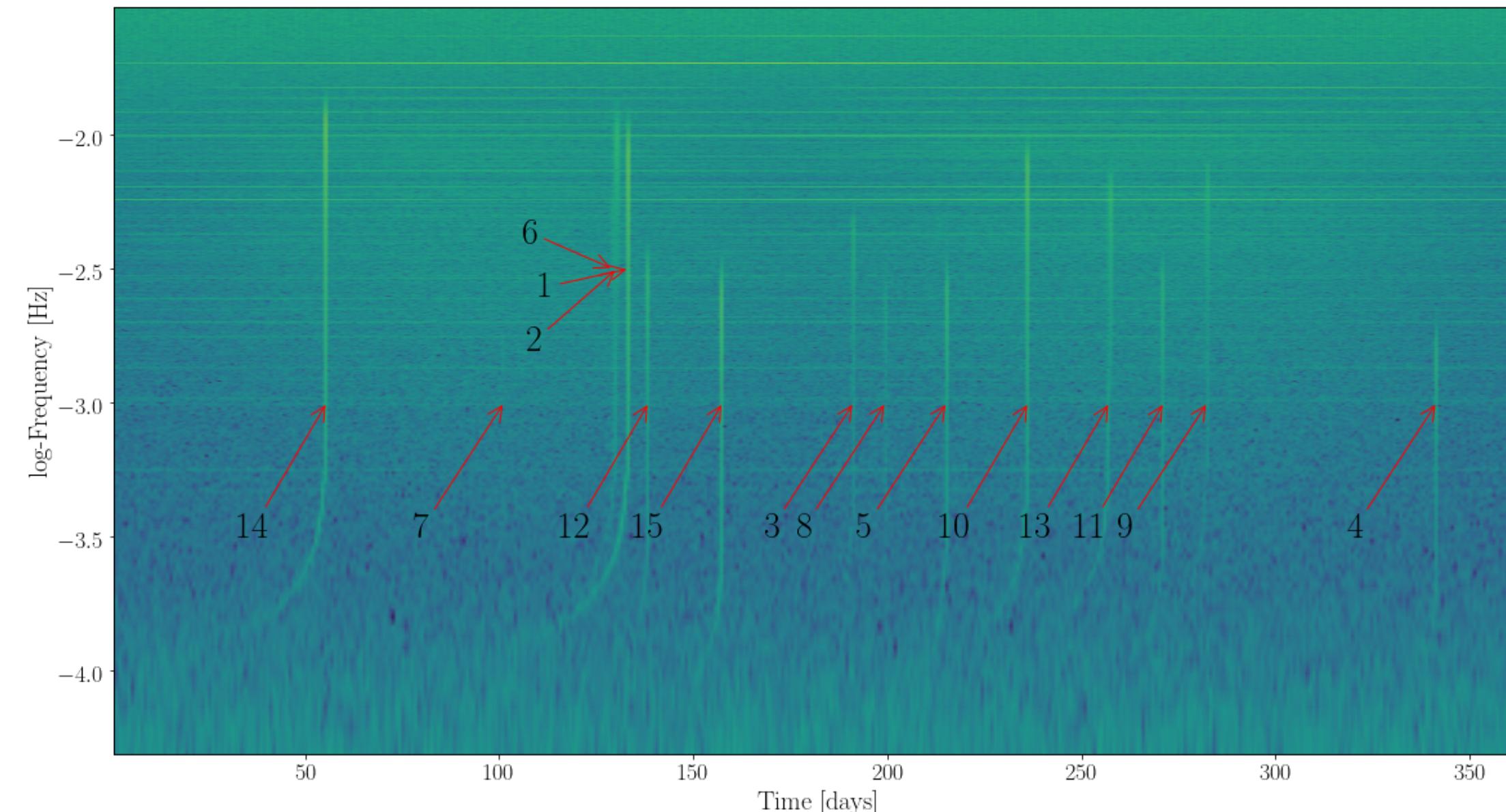
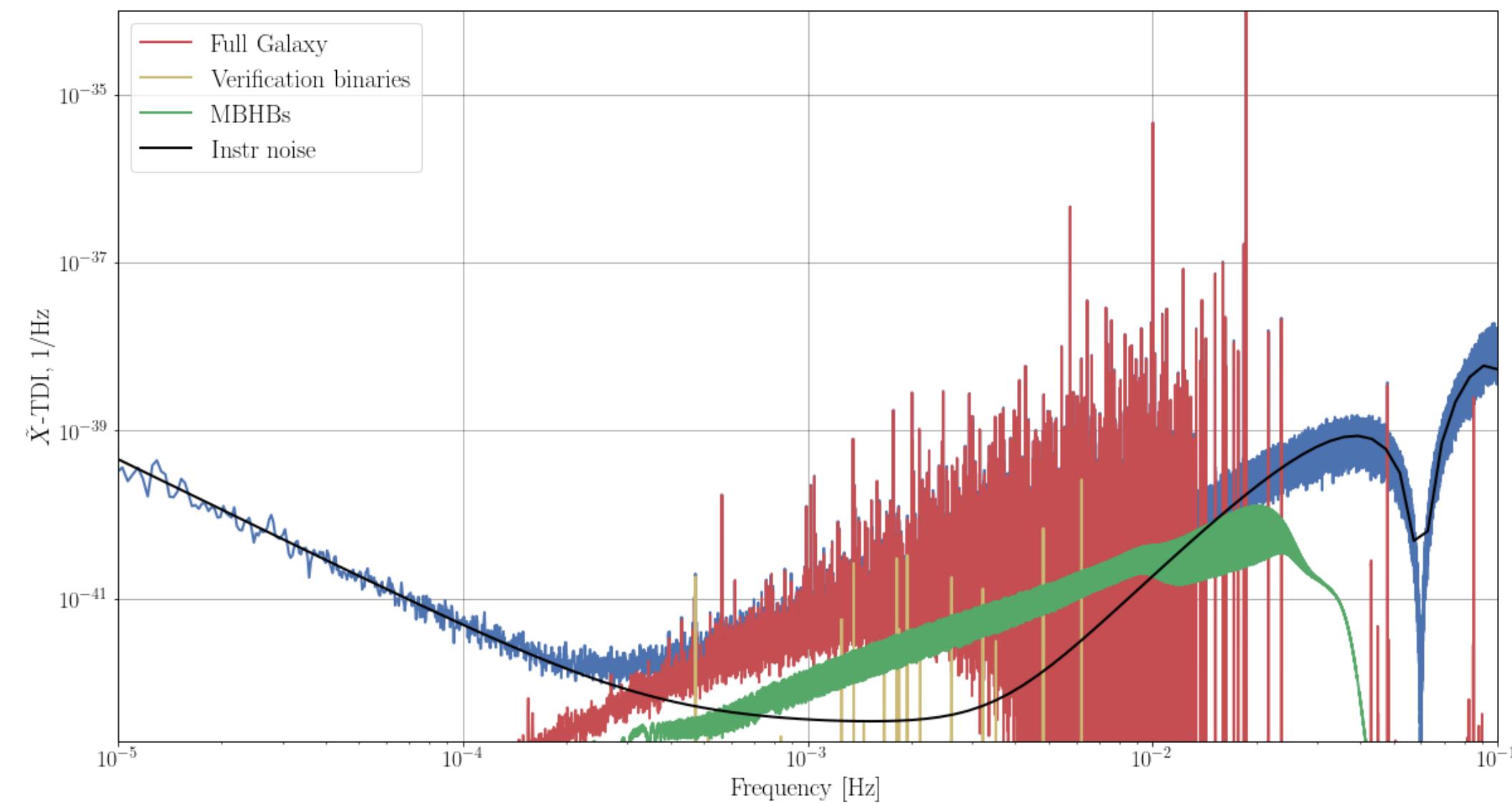


Strong 22-mode degeneracies,
multimodal sky (reflected)
Use this knowledge to sample !

LDC-2: source superposition and global analysis

LDC-2 ‘Sangria’

- ~10 massive black holes
- Population of galactic binaries (~ 10000 resolved)
- Unknown noise level



Pre-merger analysis: accumulation of information with time

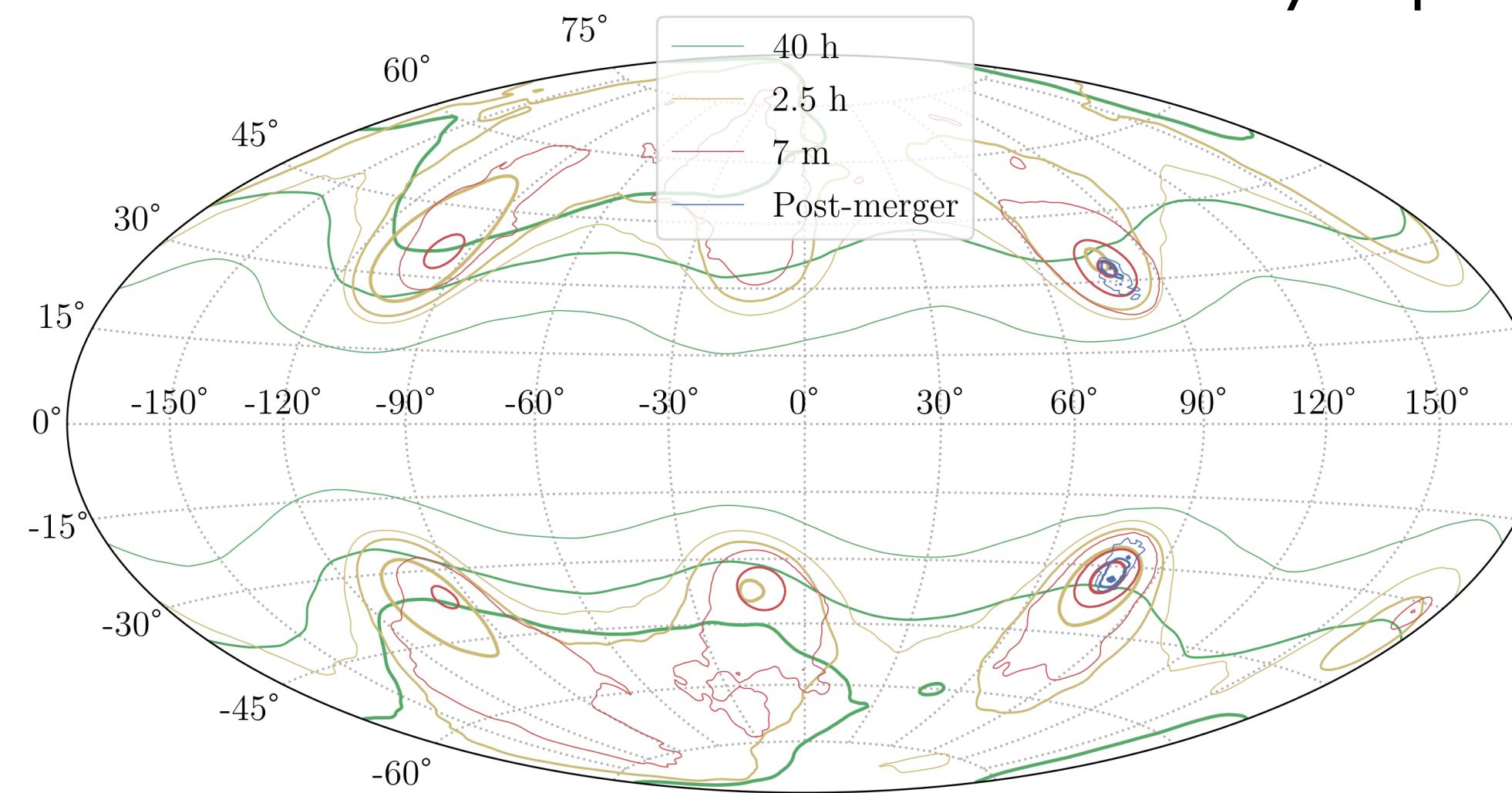
Method

- Represent a cut in time-to-merger by a cut in frequency, becomes inaccurate at merger

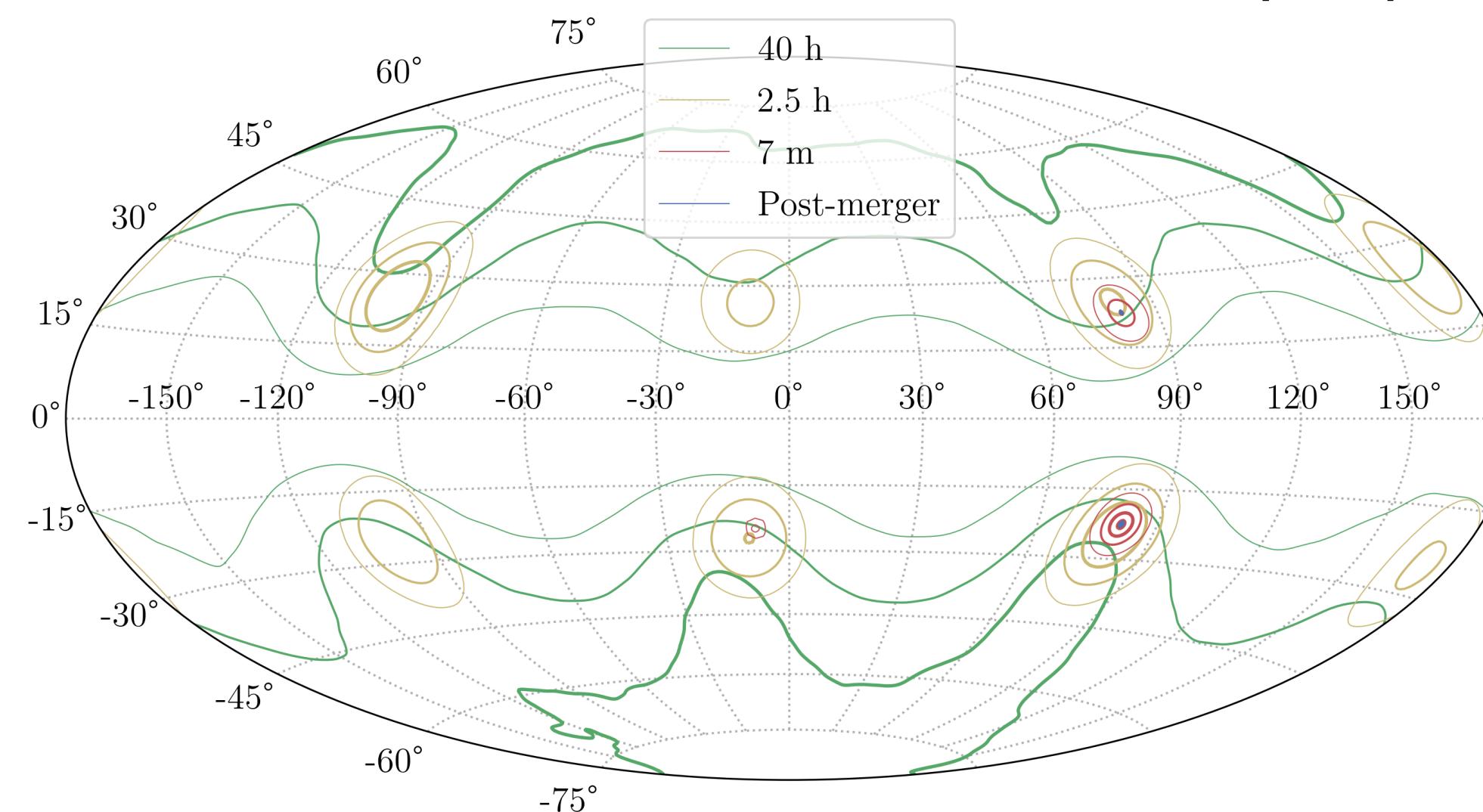
SNR-based time cuts:

SNR	DeltaT
10	40h
42	2.5h
167	7min
666	-

LISA-frame sky map 22



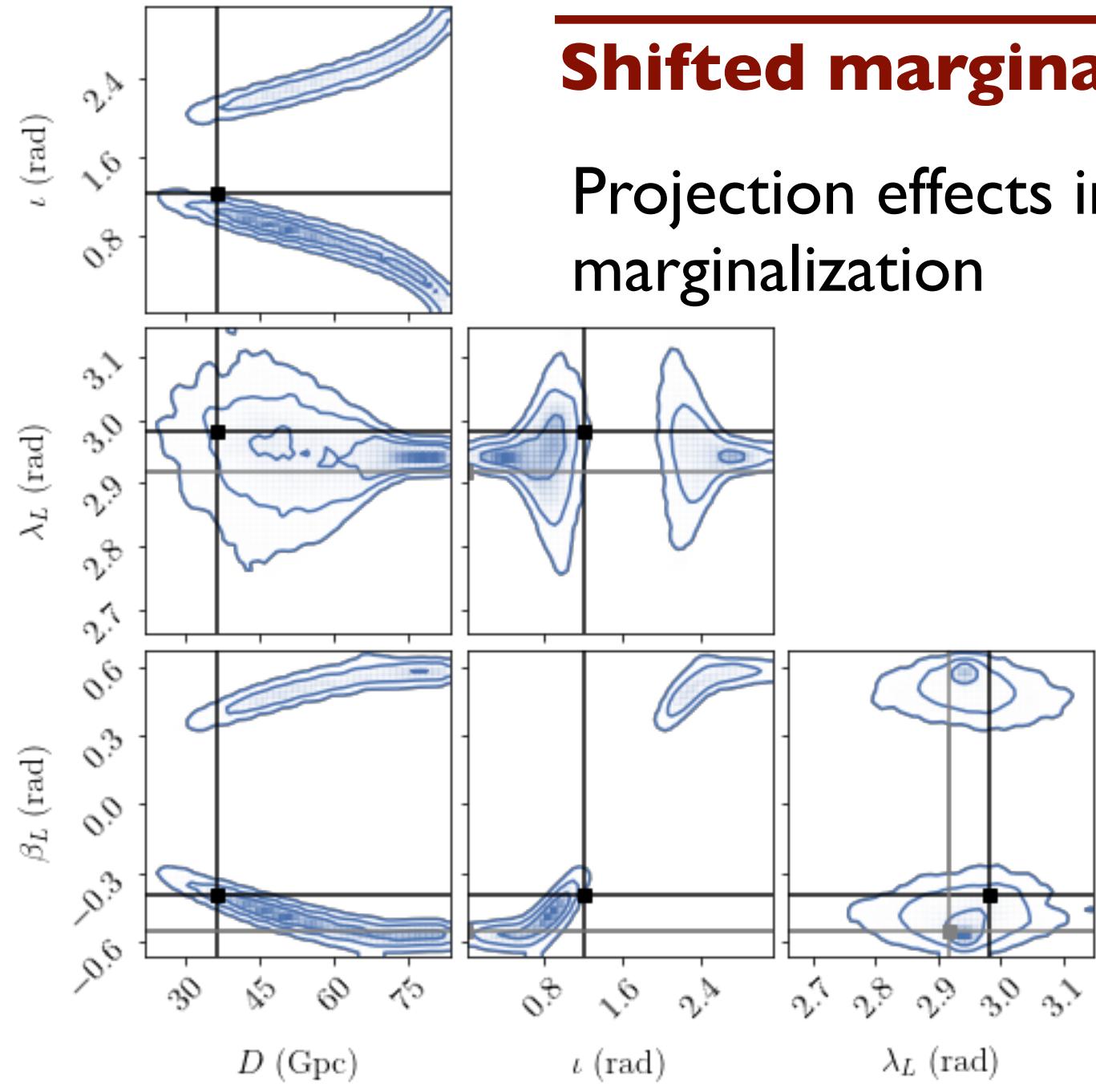
LISA-frame sky map hm



8-maxima sky degeneracy
only broken shortly before merger

2-maxima sky degeneracy
survives after merger ('Reflected')

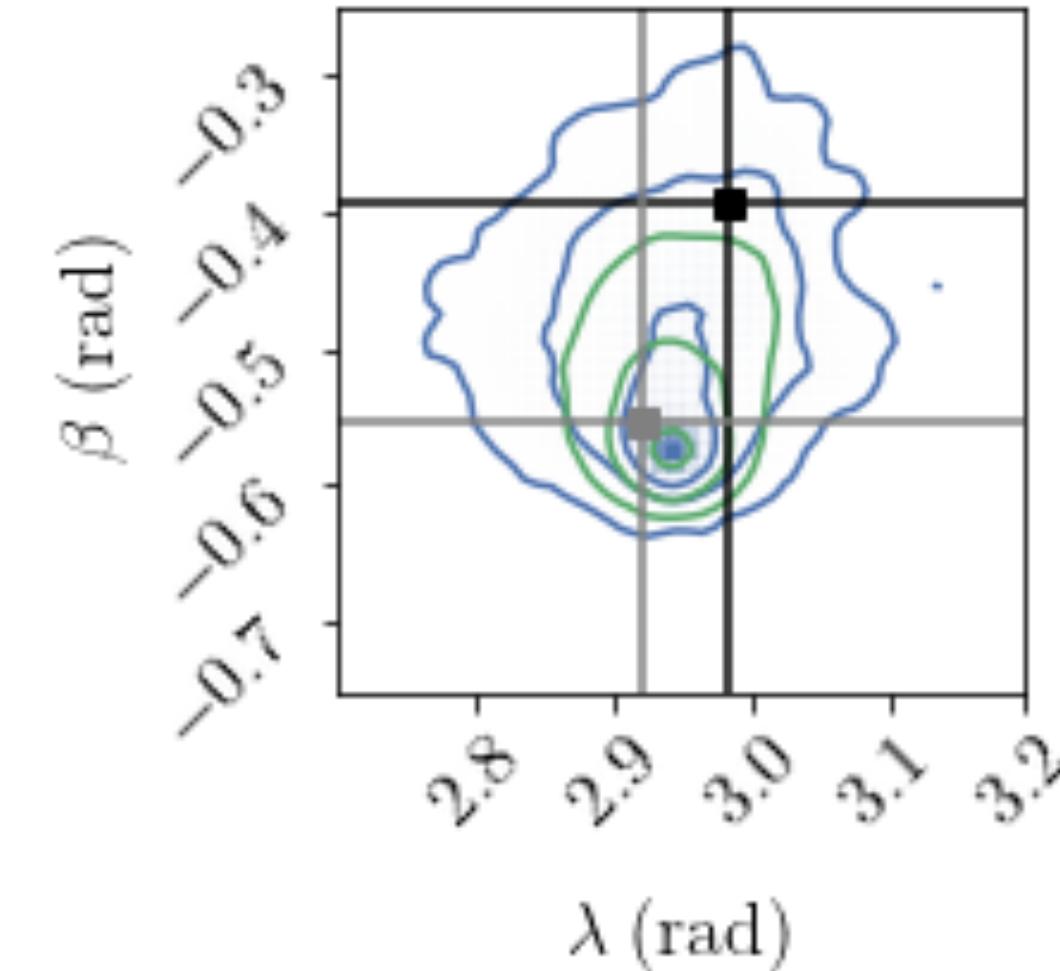
Understanding degeneracy breaking by higher harmonics



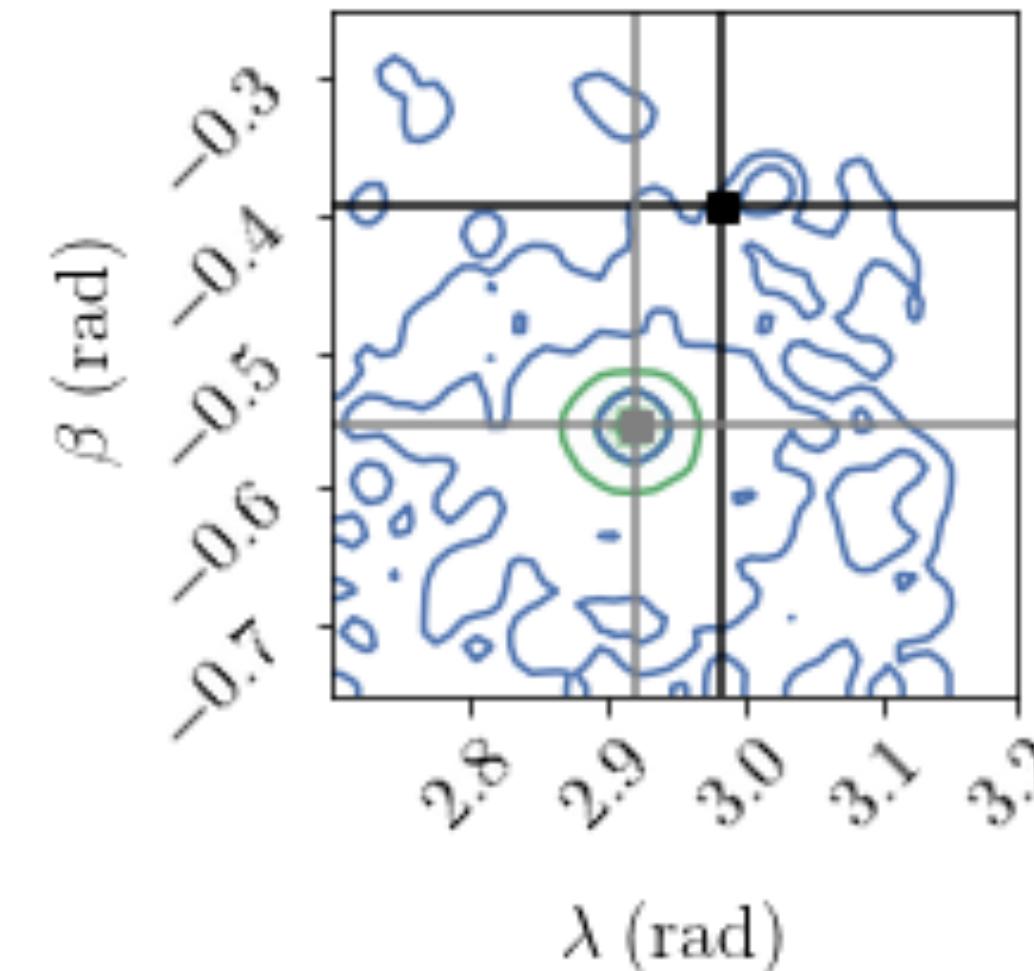
Shifted marginal sky posterior

Projection effects in marginalization

Sky zoom (h22), full response



Sky zoom (h22), no LISA motion and no high-f



- injection
- ptmcmc 22
- multinest 22
- analytic degeneracy

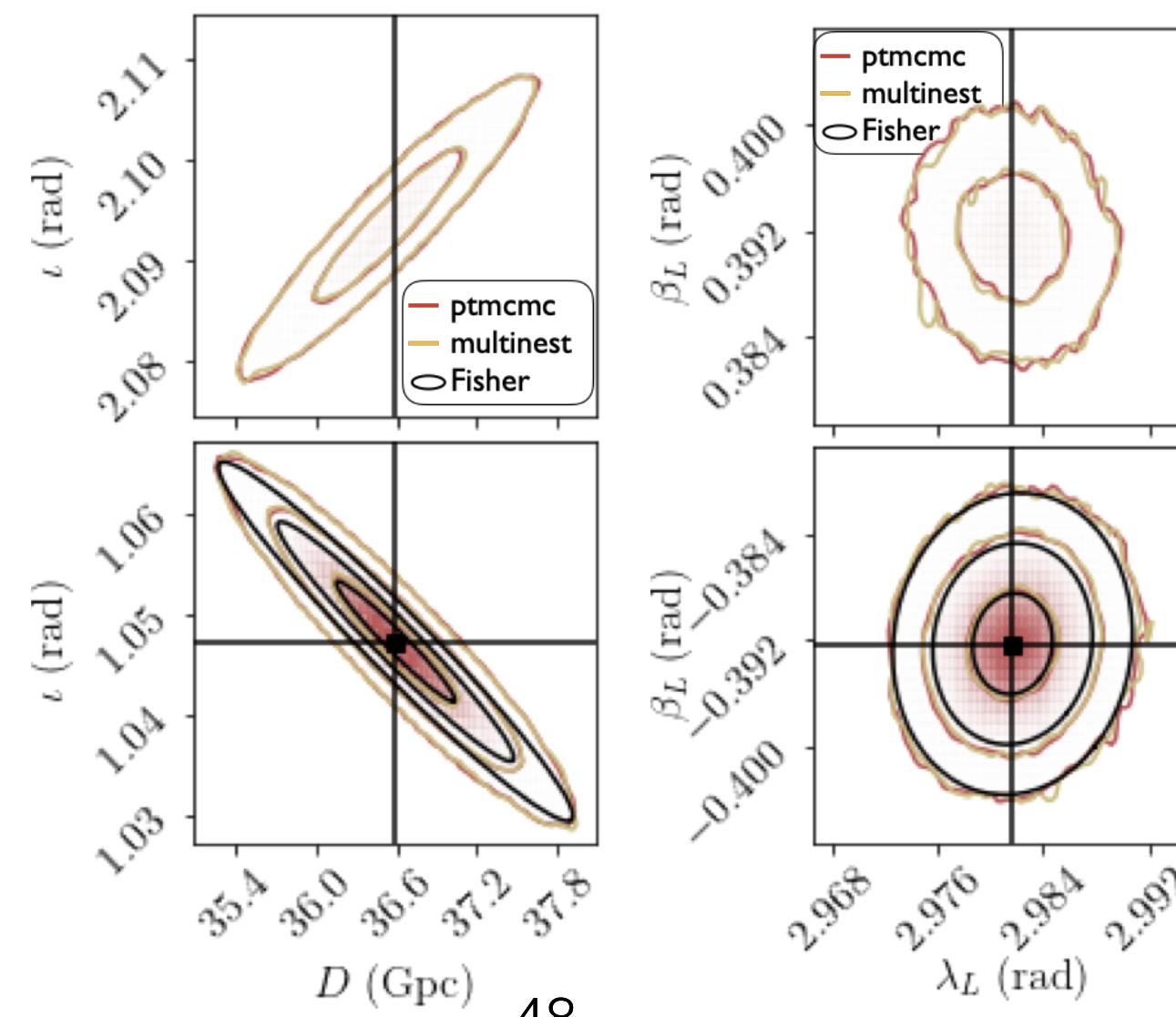
The role of higher harmonics

$$h_+ - ih_\times = \sum -_2 Y_{\ell m}(\iota, \varphi) h_{\ell m}$$

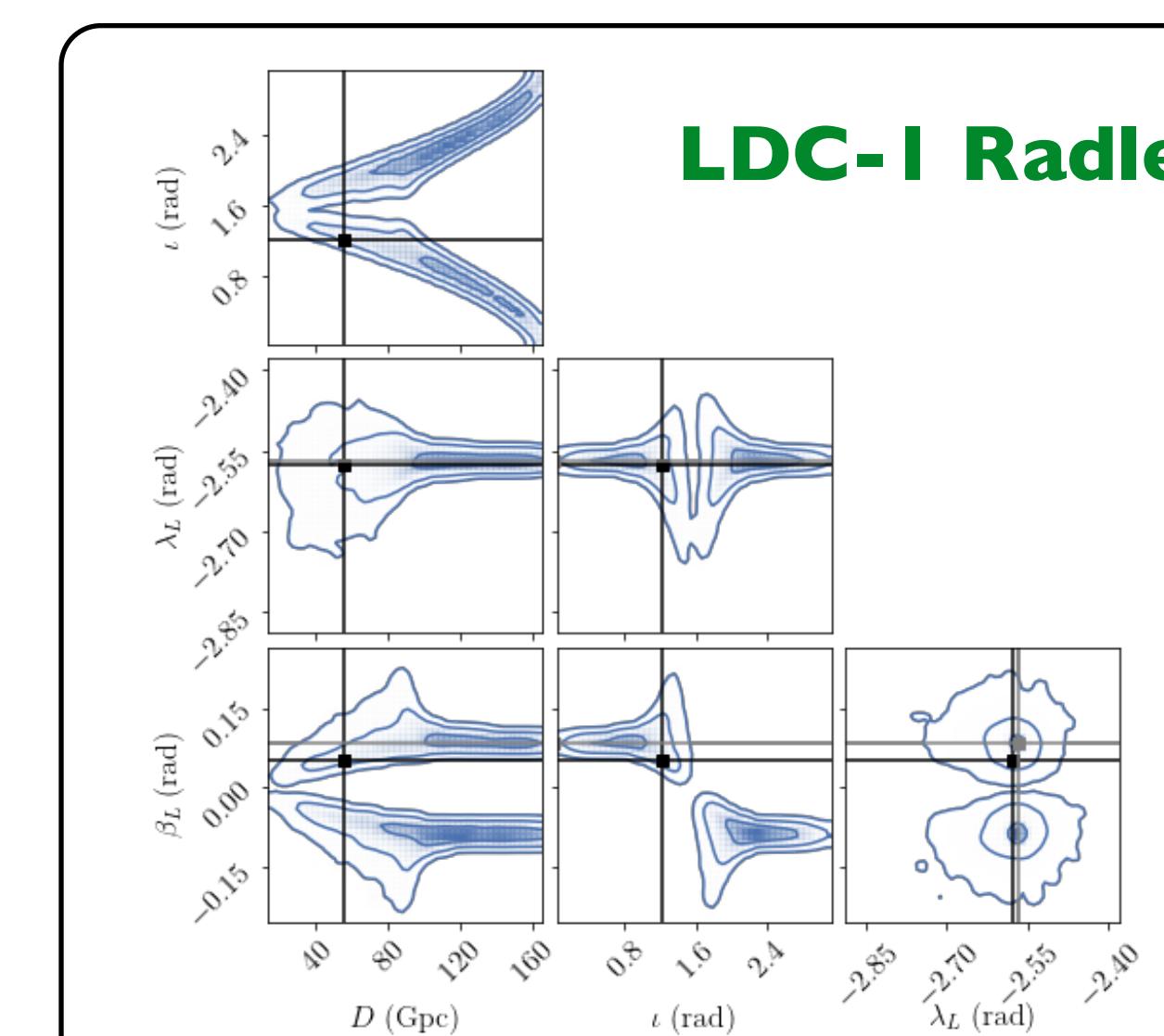
$$-_2 Y_{\ell m}(\iota, \varphi) = -_2 Y_{\ell m}(\iota, 0) e^{im\varphi}$$

When measuring several modes $h_{\ell m}$:

- Distance/inclination degeneracy broken
- Phase independently measured
- Better sky localization (caveat: edge-on, see [Katz&al 2020])



LDC-I Radler



Bayesian methodology

Bayesian analysis

$$\text{Posterior: } p(\theta|d) = \frac{\mathcal{L}(d|\theta)p_0(\theta)}{p(d)}$$

$$\text{Likelihood: } \ln \mathcal{L}(d|\theta) = - \sum_{\text{channels}} \frac{1}{2} (h(\theta) - d | h(\theta) - d)$$

$$\text{Data: signal+noise } d = s + n$$

- PE example: 0-noise simulation, n=0
- LDC: noise included

Samplers:

- MultiNest: Nested Sampling
- Parallel Tempering MCMC, differential evolution

Millions of likelihoods
needed

Computational performance of
waveforms/likelihoods crucial

Waveforms

$$h_+ - i h_\times = \sum_{\ell,m} {}_{-2}Y_{\ell m}(\iota, \varphi) h_{\ell m}$$

- PE example: EOBNRv2HM (Non-spinning model, includes modes (22, 21, 33, 44, 55) + Reduced Order Model (ROM) for sub-ms evaluation)
- LDC: PhenomD (22, spins aligned)

Accelerated likelihoods

$$(h_1|h_2) = 4\text{Re} \int df \frac{\tilde{h}_1(f)\tilde{h}_2^*(f)}{S_n(f)}$$

Likelihood for n=0:

- Sparse grids: amplitude/phase and response
- Cubic spline representation 300-800 pts
- **Cost: h22: 1-2ms, 5 modes hlm: 15ms**

Likelihood with noise:

- Downsample for a short MBHB signal
- **Cost: h22: 3-5ms**

Example MBHB signals

Systems:

- Fiducial [Marsat&al 2020]
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