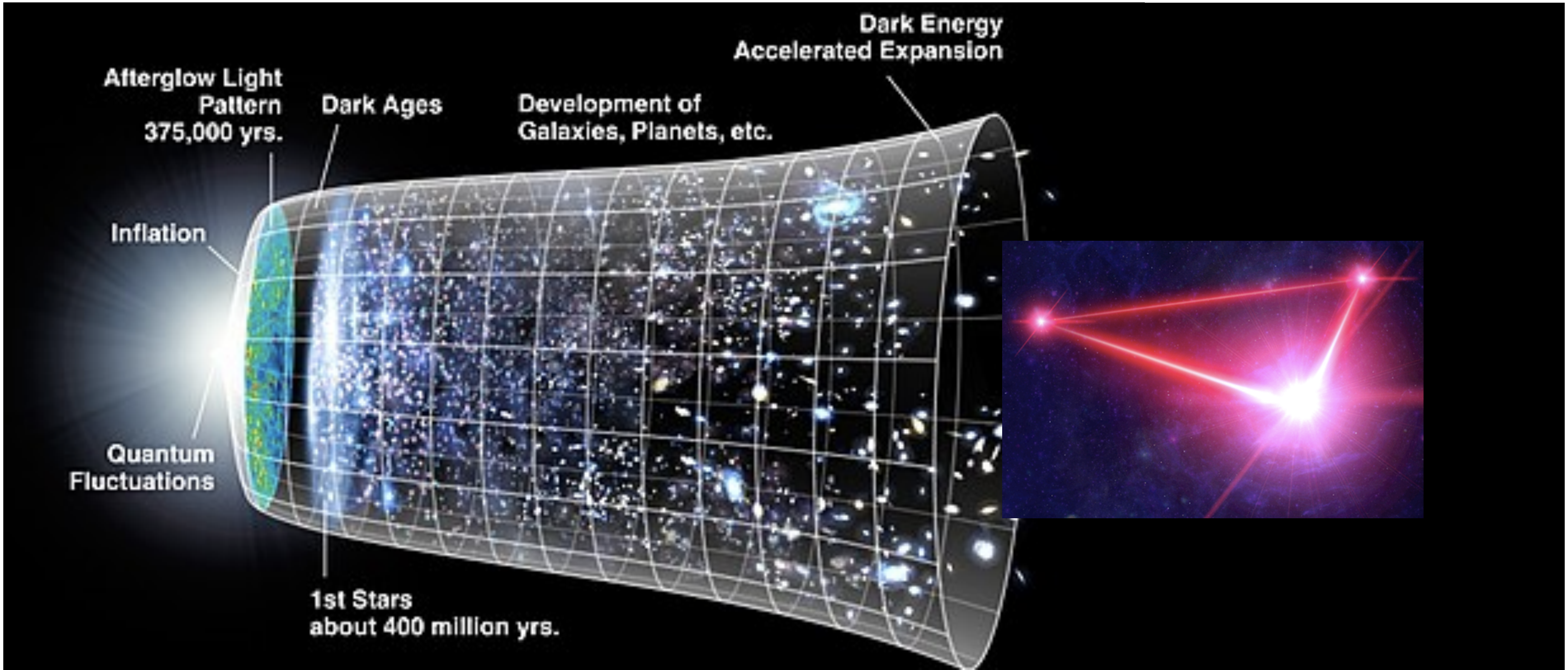
Cosmology with LISA

Chiara Caprini
University of Geneva & CERN



Summary

- LISA has been initially conceived as a GW astrophysics observatory, it has not been designed to do cosmology

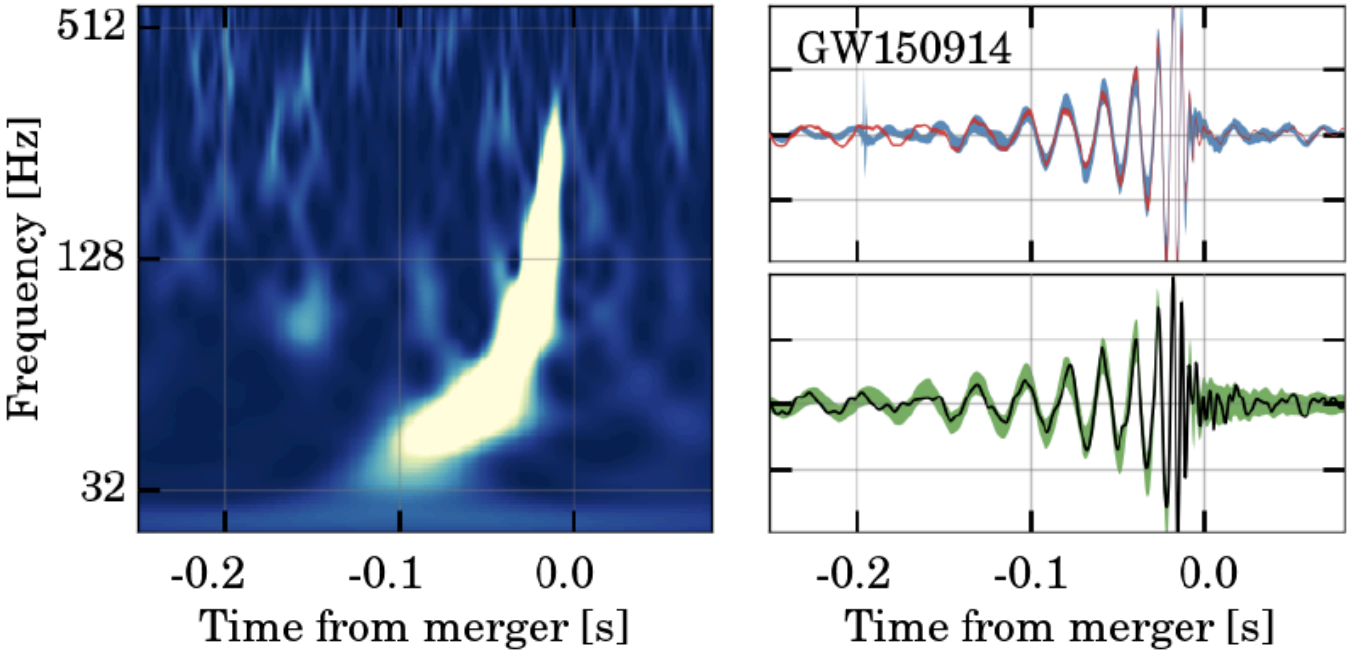
- However, it can provide new information on a variety of scales: from the Galaxy to Hubble scales, from the present time to the very early universe -> therefore it can be used as a cosmological observatory as well

- LISA can test the *late time universe* through the observation of the GW emission from compact binaries, and measure cosmological parameters

- LISA can test the *gravitational interaction*, and constrain modifications to General Relativity in the cosmological context

- LISA can test the *very early universe* through the detection of a stochastic GW background and therefore, indirectly, test high energy physics scenarios

GW emission from the inspiral of a binary system



LIGO/Virgo arXiv:1811.12907

$$M_c = \frac{(m_1\, m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

$$\boxed{f(\tau) = \frac{1}{\pi}\left(\frac{G\, M_c}{c^3}\right)^{-5/8}\left(\frac{5}{256\,\tau}\right)^{3/8}}$$

τ time to coalescence

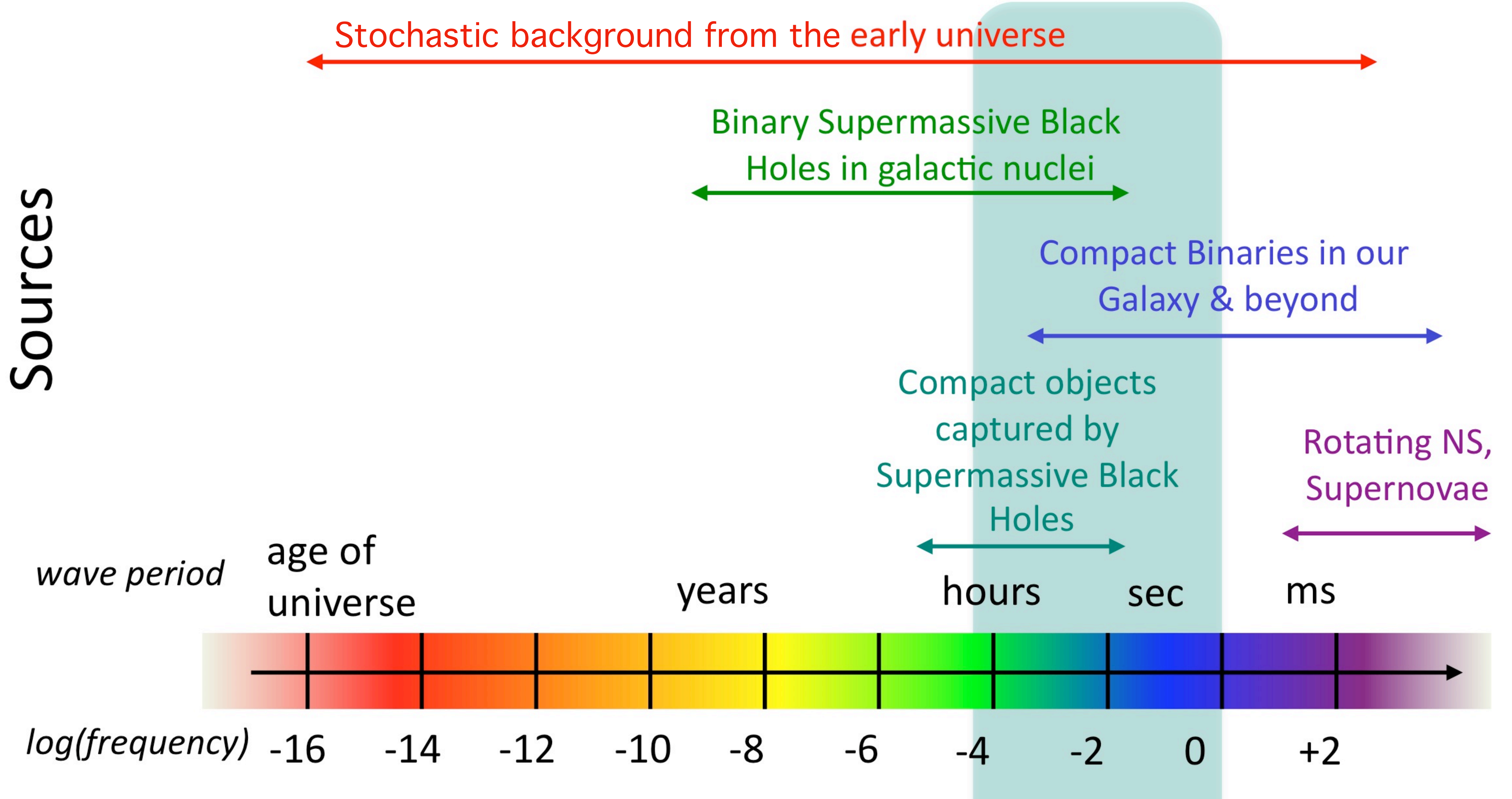
$$M_c = 25\,\mathrm{M}_\odot \qquad \tau = 0.2\,\mathrm{sec} \qquad \longrightarrow \qquad f = 37\,\mathrm{Hz}$$

$$M_c = 25\,\mathrm{M}_\odot \qquad \tau = 10\,\mathrm{year} \qquad \longrightarrow \qquad f = 0.01\,\mathrm{Hz}$$

$$M_c = 10^6\,\mathrm{M}_\odot \qquad \tau = 1\,\mathrm{hour} \qquad \longrightarrow \qquad f = 1\,\mathrm{mHz}$$

$$M_c = 10^9\,\mathrm{M}_\odot \qquad \tau = 10^5\,\mathrm{year} \qquad \longrightarrow \qquad f = 7 \cdot 10^{-9}\,\mathrm{Hz}$$

The Gravitational Wave Spectrum



Sources

Stochastic background from the early universe

Binary Supermassive Black Holes in galactic nuclei

Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

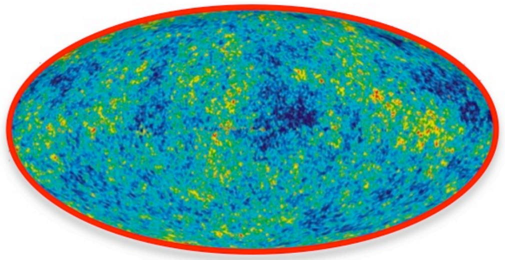
Rotating NS, Supernovae

wave period age of universe | years | hours | sec | ms

log(frequency) -16 | -14 | -12 | -10 | -8 | -6 | -4 | -2 | 0 | +2

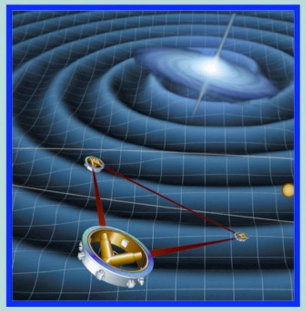
Detectors

Cosmic microwave background polarization



Pulsar Timing

Space Interferometers



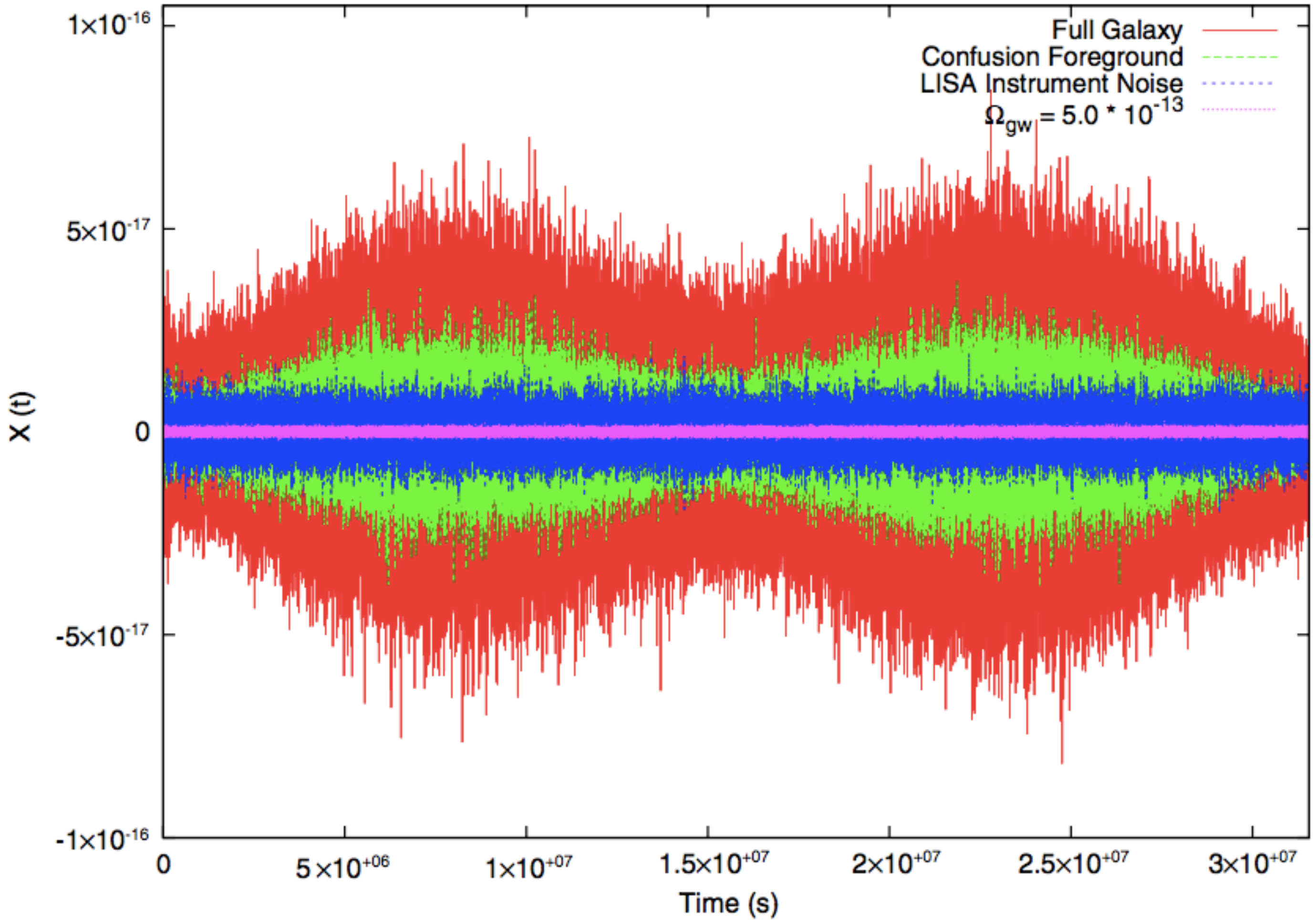
Terrestrial interferometers

NASA Goddard Space Flight Center

Stochastic gravitational wave background

the superposition of sources that cannot be resolved individually

- binaries too numerous and with too low SNR to be individually resolved
- signals from the primordial universe typically with too small correlation scale (*about horizon at the time of production*) with respect to the detector resolution



Adams and Cornish, 1307.4116

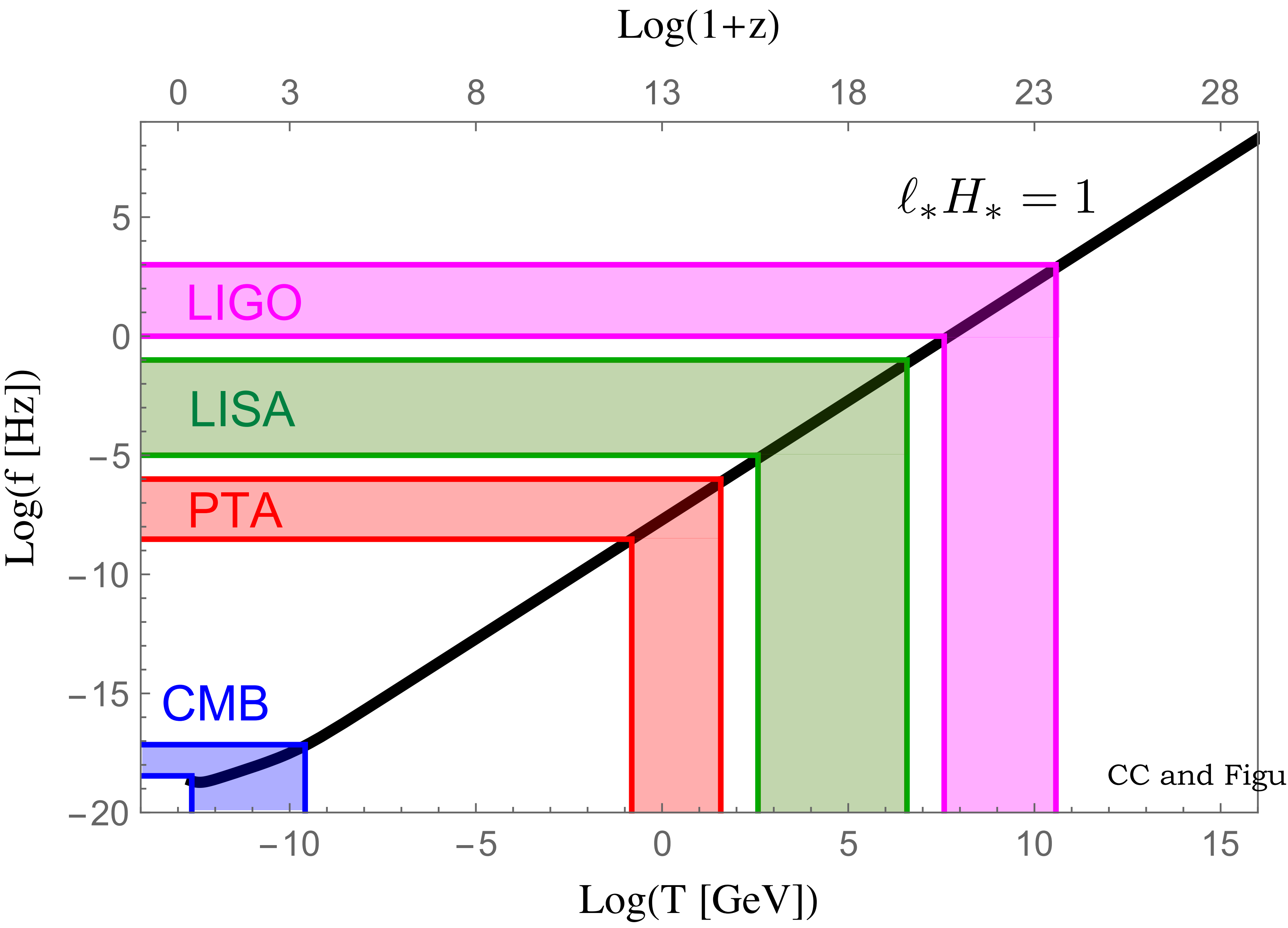
Potential of GW detectors to probe the primordial universe

Localised source

$$\boxed{f_* \sim \frac{1}{\ell_*} \geq H_*}$$

$$f = f_* \frac{a_*}{a_0} = \frac{1.65 \times 10^{-7}}{\ell_* H_*} \left(\frac{g(T_*)}{100}\right)^{1/6} \frac{T_*}{\text{GeV}} \,\text{Hz}$$

Characteristic frequency of the SGWB today

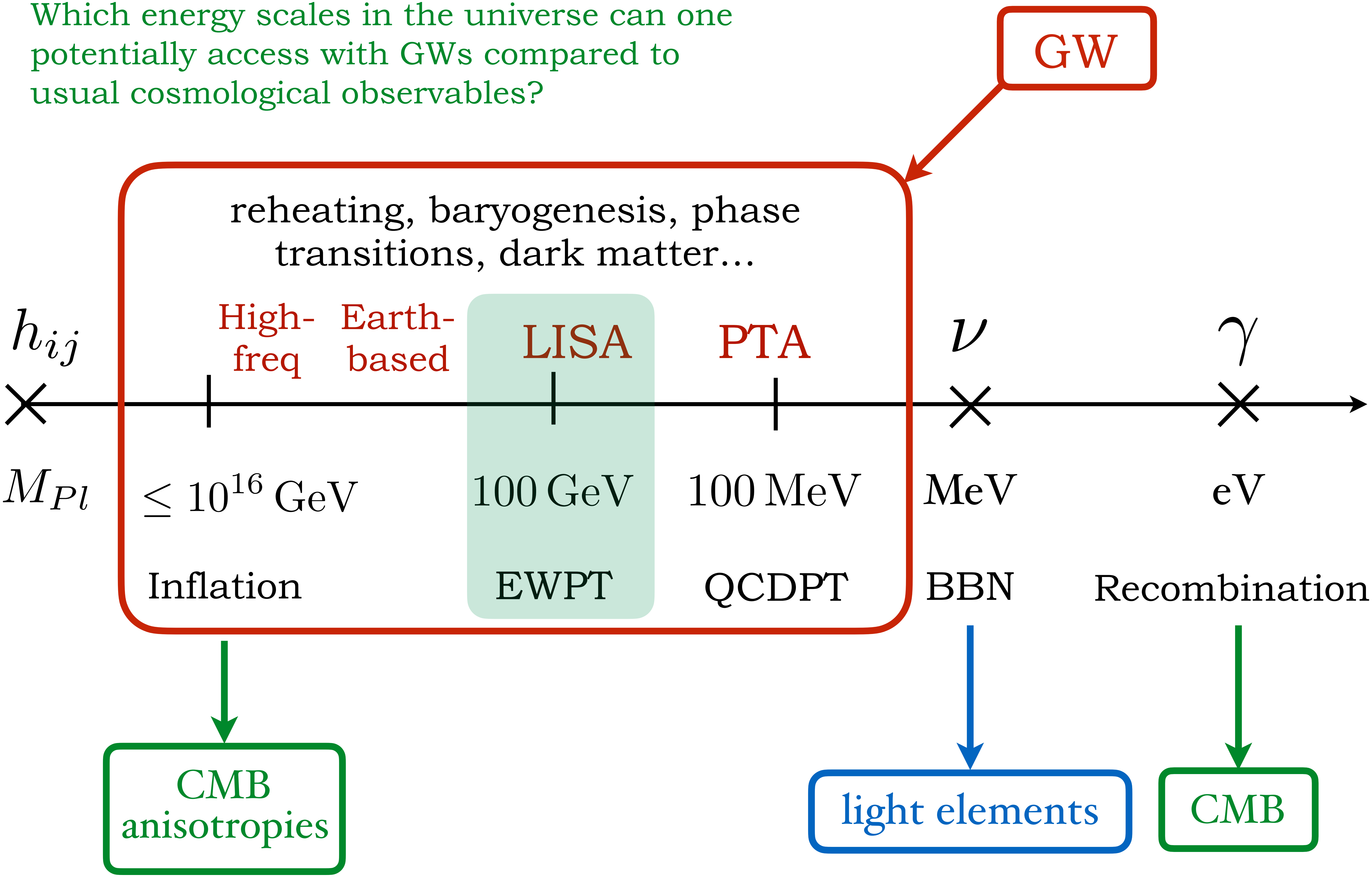


CC and Figueroa arXiv:1801.04268

Energy scale (temperature) in the early universe

Another kind of GW spectrum:

Which energy scales in the universe can one potentially access with GWs compared to usual cosmological observables?



GW

reheating, baryogenesis, phase transitions, dark matter…

h_{ij} High-freq Earth-based LISA PTA ν γ

M_{Pl} $\leq 10^{16}$ GeV 100 GeV 100 MeV MeV eV

Inflation EWPT QCDPT BBN Recombination

CMB anisotropies

light elements

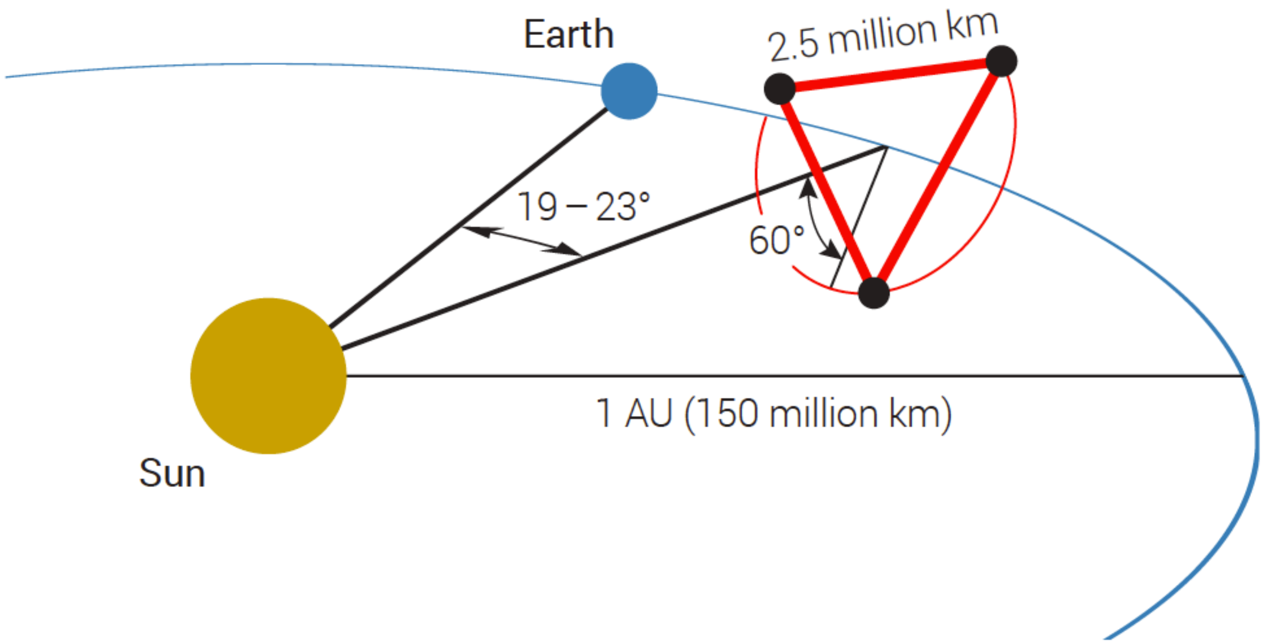
CMB

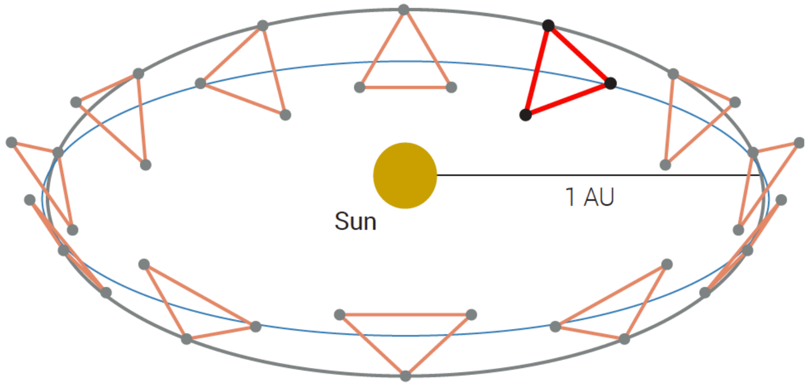
LISA: Laser Interferometer Space Antenna

GW detector in space:

- no seismic noise
- much longer arms than on Earth: 2.5 million km

frequency range of detection: $10^{-4}\,\mathrm{Hz} < f < 1\,\mathrm{Hz}$



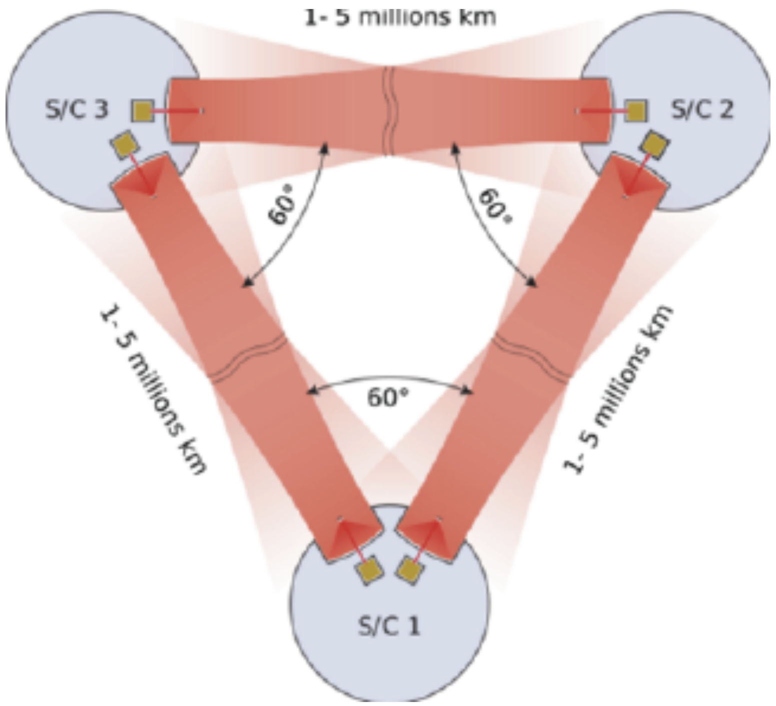


it is a survey instrument:

no pointing
continuous sky observation

LISA consortium arXiv:1702.00786

LISA: Laser Interferometer Space Antenna



- Two masses in free fall per spacecraft
- Objective: measure relative distance changes of 10^{-21} on 2.5 million km arms -> picometer displacement of masses
- Several sources of noise: laser, clocks, acceleration…
- Laser frequency noise reduced via Time Delay Interferometry

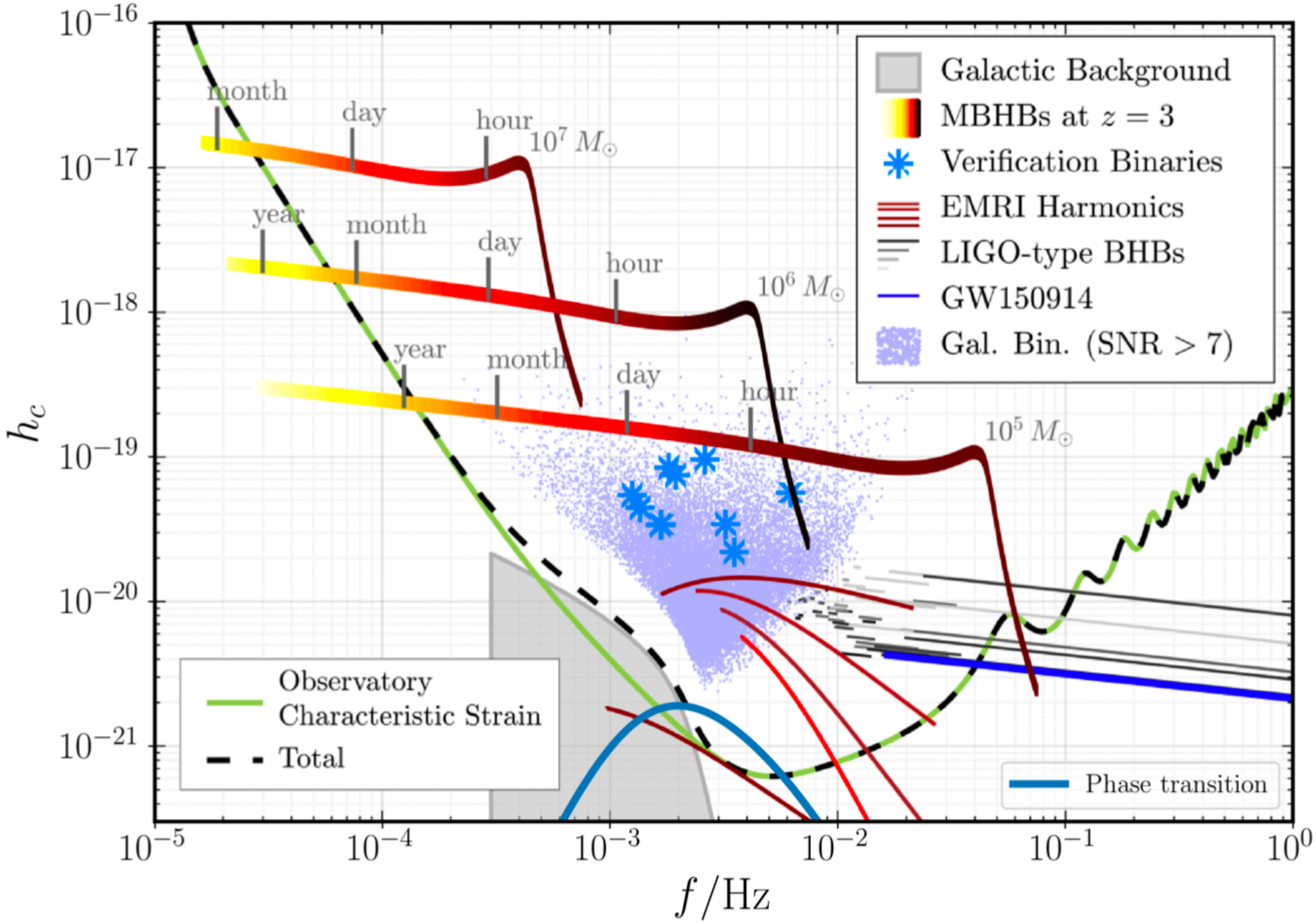
Schedule:

- autumn 2023: ESA mission adoption, science Red Book
- ~10 years: mission construction (definition, construction, integration, test, validation)
- ~2035: launch (Ariane 6)
- 1.5 years to get to orbit, 6-12 months for commissioning
- nominal mission duration ~4 years
- cost: ~1.3 B€

LISA consortium arXiv:1702.00786

What *we expect* LISA to detect
(It's a new window!)

Characteristic strain



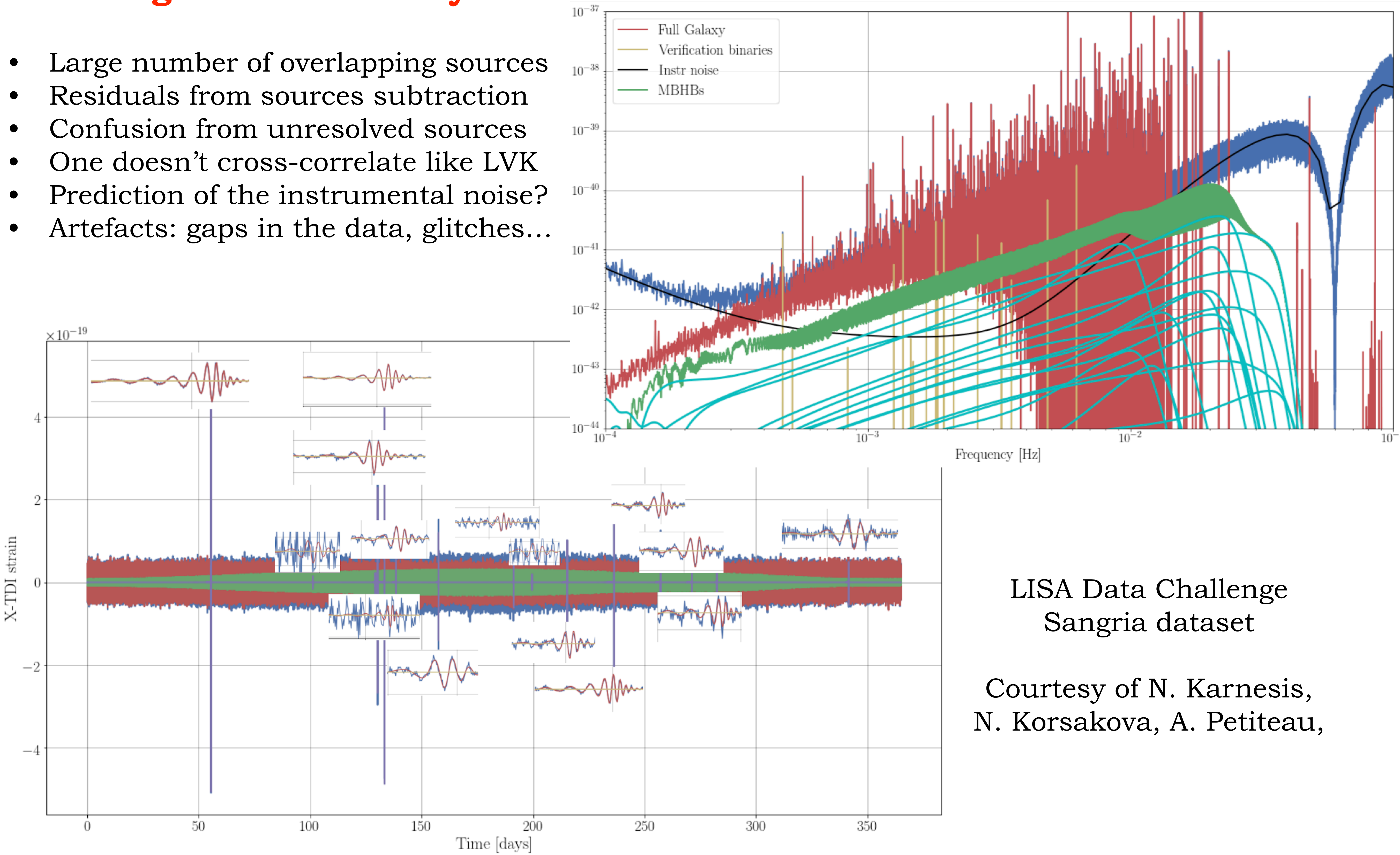
GW frequency today

LISA consortium arXiv:1702.00786
Hindmarsh et al arXiv:2008.09136

What we expect LISA to detect

Challenges for data analysis

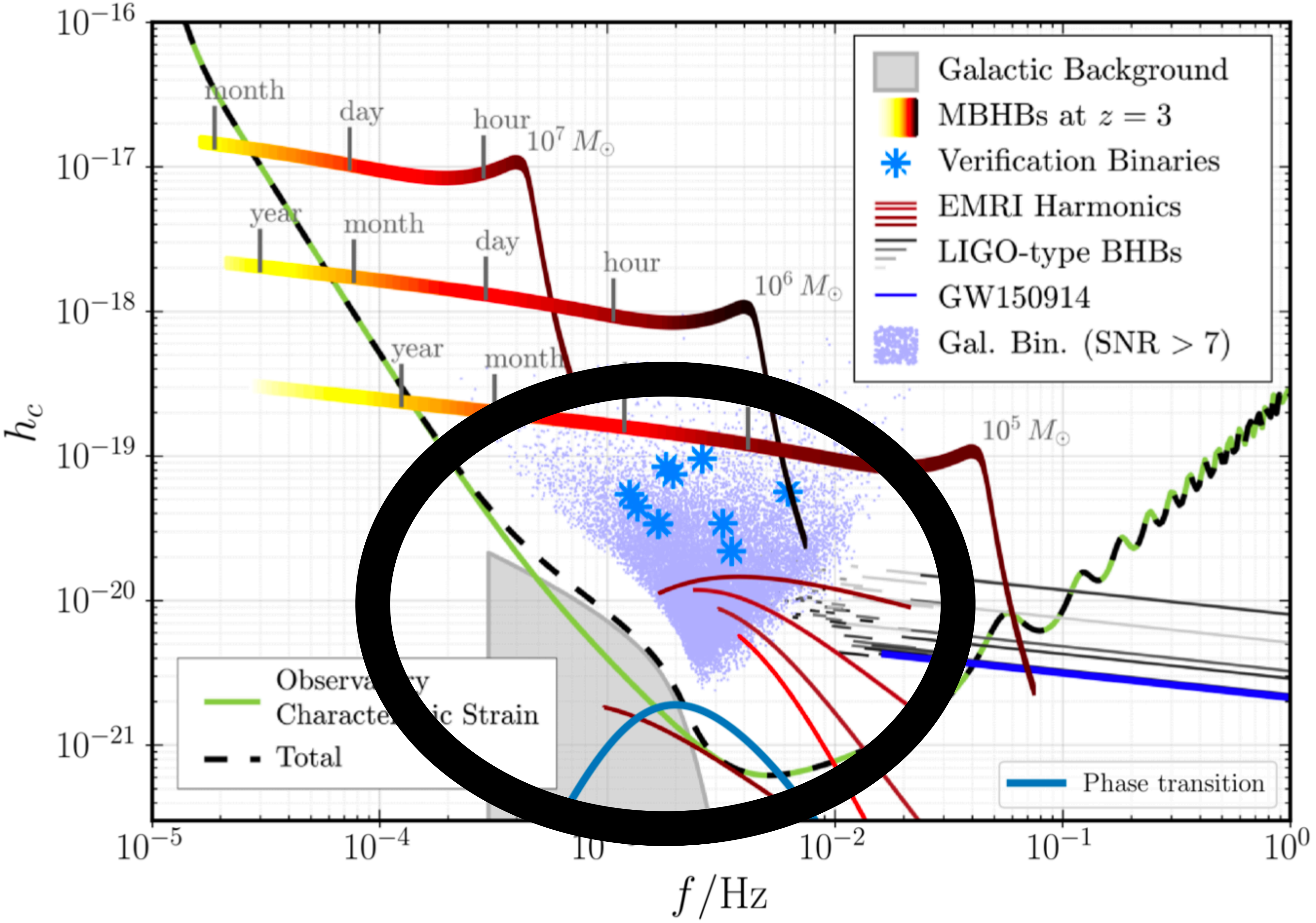
- Large number of overlapping sources
- Residuals from sources subtraction
- Confusion from unresolved sources
- One doesn't cross-correlate like LVK
- Prediction of the instrumental noise?
- Artefacts: gaps in the data, glitches…



LISA Data Challenge
Sangria dataset

Courtesy of N. Karnesis,
N. Korsakova, A. Petiteau,

Compact binaries in the galaxy

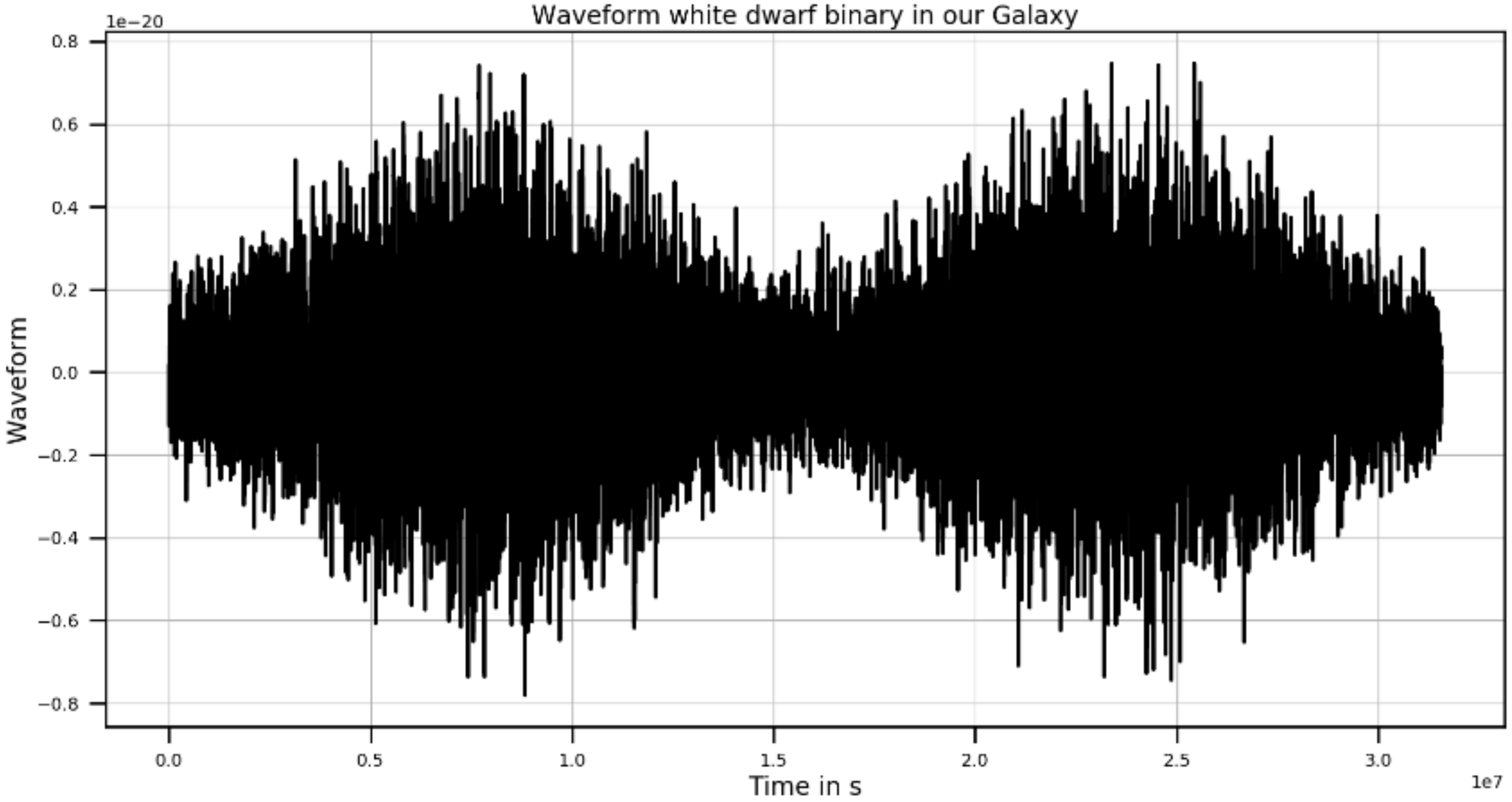


Compact binaries in the galaxy

- A large number of stars are in binary systems and evolve towards WD, NS and stellar BH binaires (expected 60 millions in the galaxy)
- Most are in the inspiral phase: quasi-monochromatic, permanent GW signal

$$M_c = 1\,M_\odot \quad \tau = 10^5\,\mathrm{y} \longrightarrow f = 3\,\mathrm{mHz}, \quad \dot{f} = 10^{-16}\,\mathrm{Hz/sec}$$

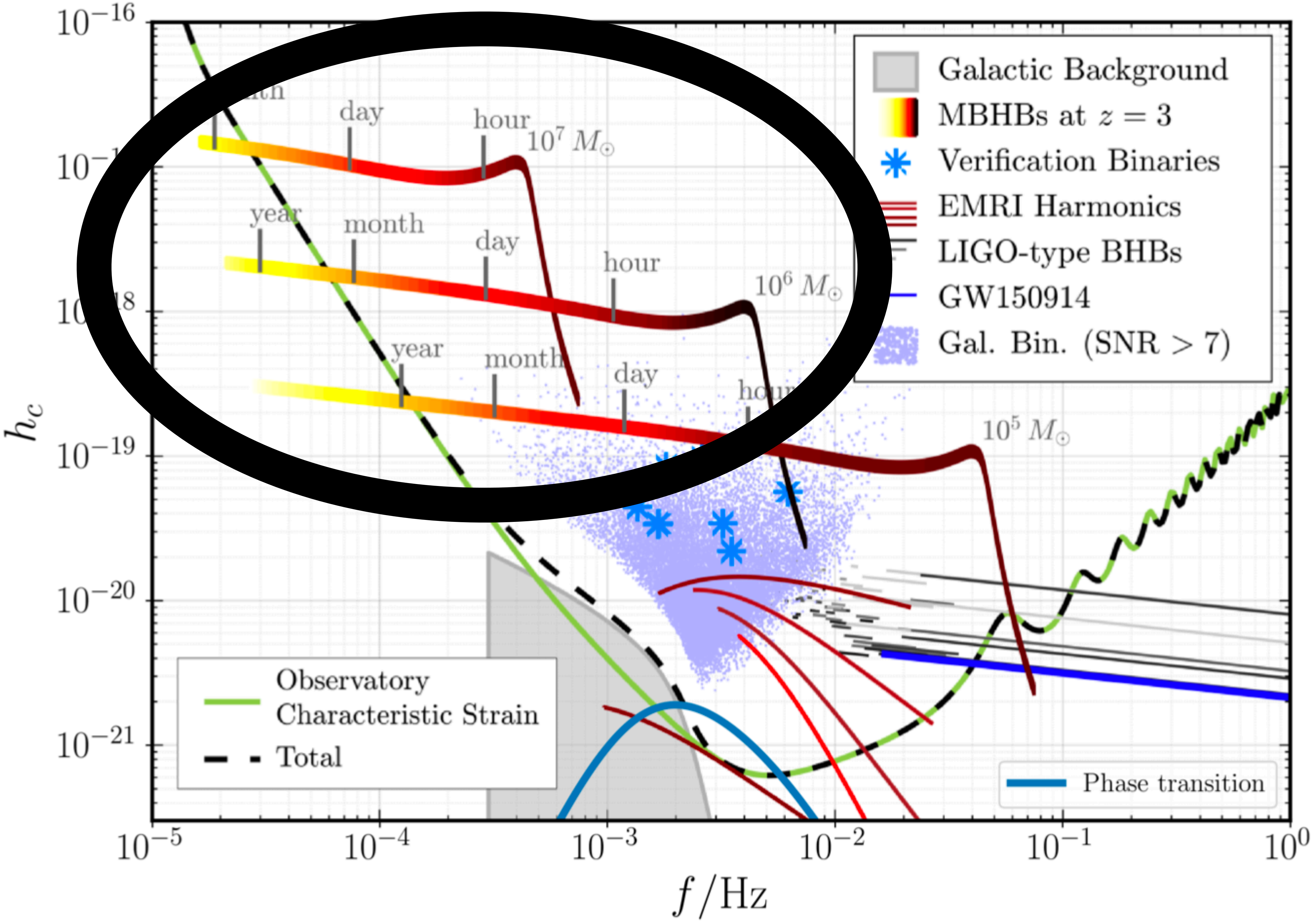
- ~ 20 known WD systems are guaranteed LISA sources: verification binaries
- Resolved binaries: ~ 25000 sources are expected with SNR 7-1000
- Stochastic foreground from sources with too low SNR, yearly modulated



Foreground for Cosmology

G. Boileau et al, arXiv:2105.04283

Massive black hole binaries



Massive black hole binaries

- MBH are indirectly observed in the centre of many galaxies. Galaxies collide -> MBH must exist in binaires

- The loudest LISA sources (Other than unexpected ones)
  - MBHB from $10^4\,M_\odot$ to $10^7\,M_\odot$: LISA detects the inspiral, merger, ringdown
  - Signal duration: from few hours to several months prior to merger
  - SNR up to few thousands
  - Up to z ~ 20!
  - Expected rates from few to 100 per year

- LISA will probe MBH formation and growth (accretion, mergers…)

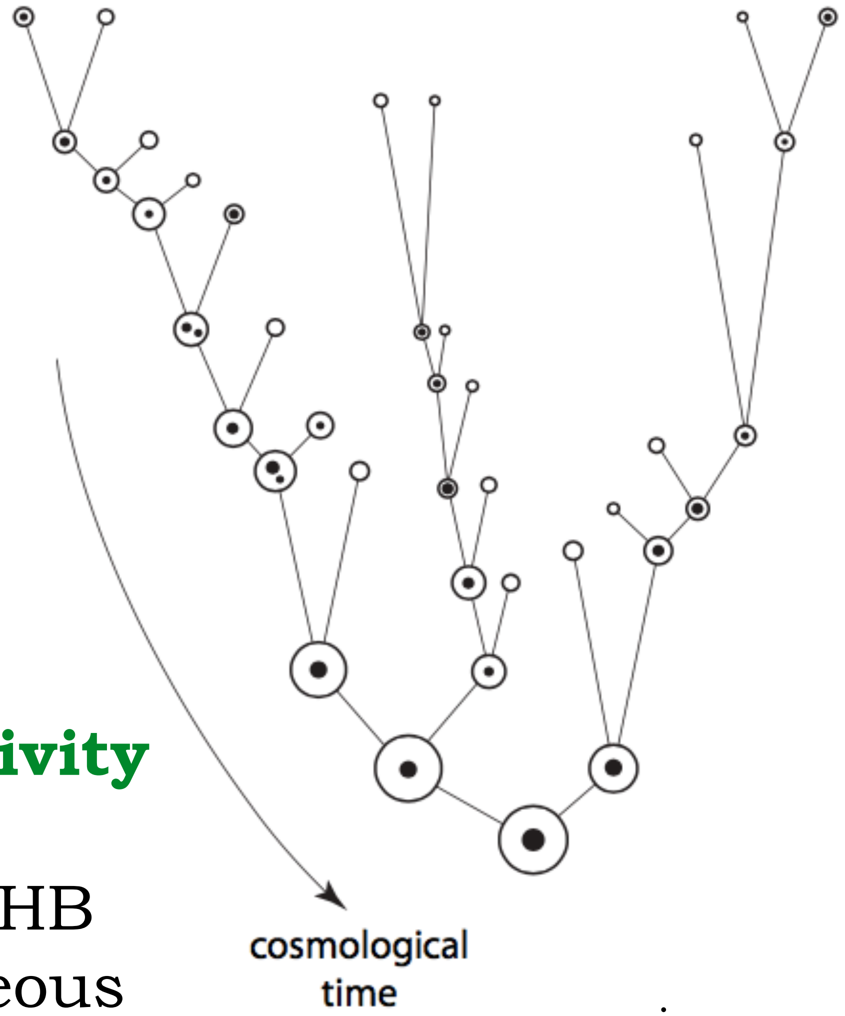


image: M. Volonteri

Cosmology:

- MBHB can be used to perform **tests of General Relativity**

- **EM counterparts and coincident GW detection:** MBHB are expected to have counterparts if they occur in gaseous disks at the centre of galaxies (very uncertain rate)

Massive black hole binaries

MBHB can be used as standard sirens to measure cosmological parameters

$$h_+(\tau,\theta,\varphi) = \frac{4}{d_L(z)}(G\,\mathcal{M}_c)^{5/3}[\pi f(\tau)]^{2/3}\left(\frac{1+\cos^2\theta}{2}\right)\cos(2\Phi(\tau))$$

$$h_\times(\tau,\theta,\varphi) = \frac{4}{d_L(z)}(G\,\mathcal{M}_c)^{5/3}[\pi f(\tau)]^{2/3}\,\cos\theta\,\sin(2\Phi(\tau))$$

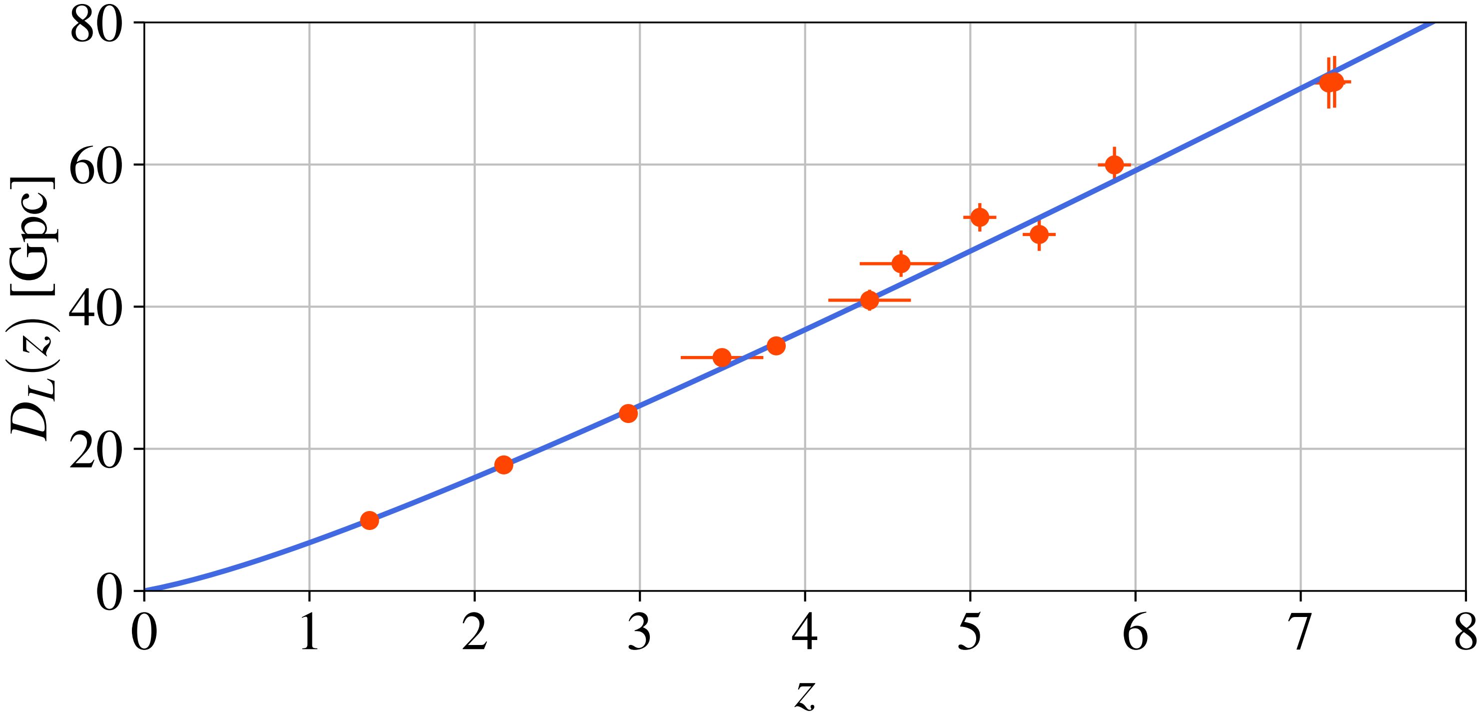
$$\mathcal{M}_c = (1+z)M_c$$

$$d_L(z) = (1+z)\,\mathcal{G}\left(\int_0^z \frac{dz'}{H(z')}\right)$$

Redshifted chirp mass
degeneracy among the redshift and the true chirp mass

- Measurement of the luminosity distance: no calibration needed, EASY AND DIRECT

- Measurement of the redshift: IMPOSSIBLE BY GW EMISSION ONLY



Courtesy of A. Mangiagli

Massive black hole binaries

MBHB can be used as standard sirens to measure cosmological parameters

- In order to infer the redshift from the detection of an EM counterpart of the MBHB one must select events with good sky localisation (few!)
- The nature of the EM counterpart at merger is unclear
- Weak lensing (and peculiar velocity) error affect the measurement of d_L

Our approach

- Step 0: simulated catalogues of massive BH binaries (E. Barausse)

- Step 1: LISA parameter estimation (error on sky localisation and d_L)
    - Bayesian code LISAbeta (S. Marsat)

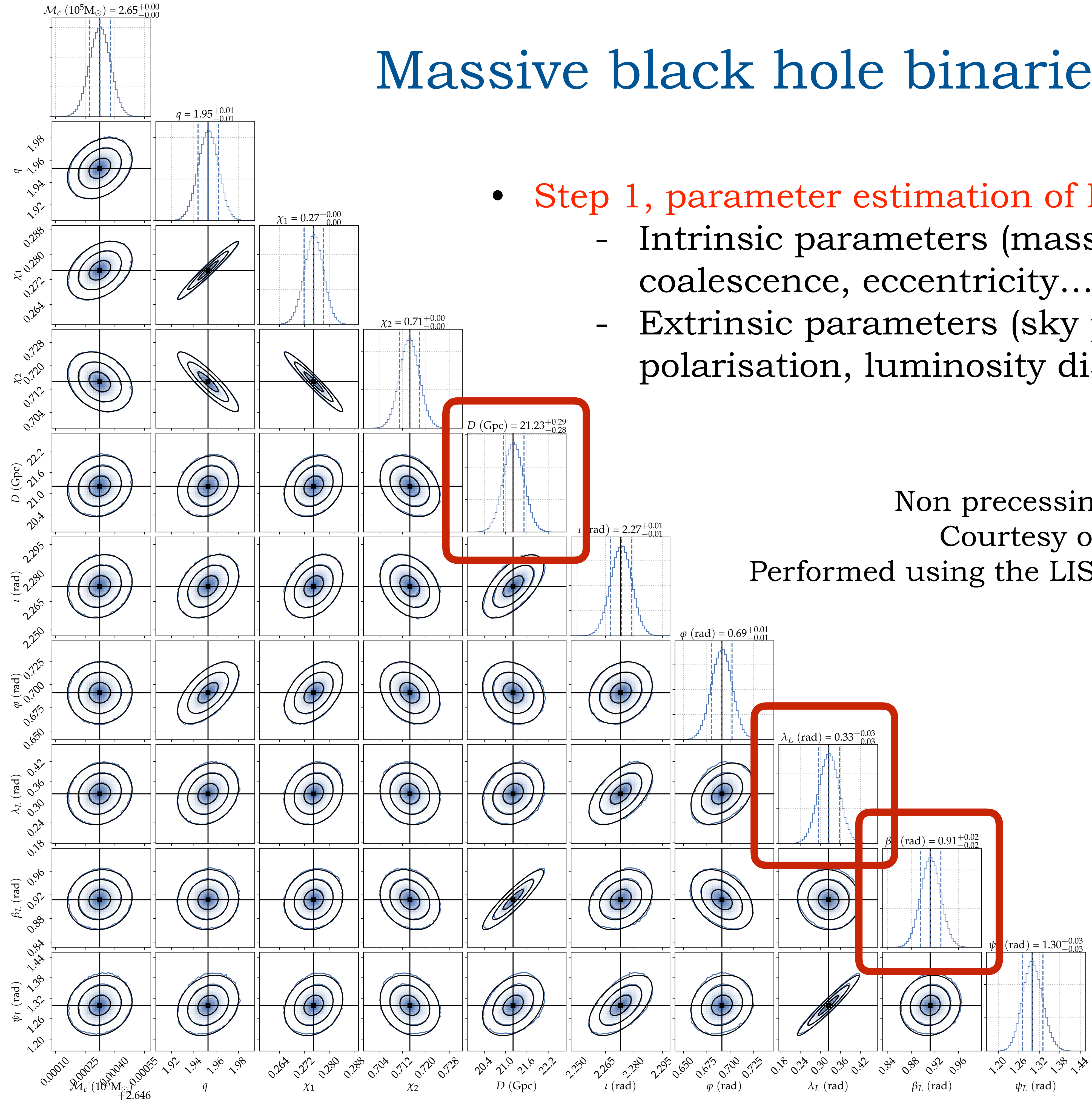
- Step 2: model of the EM counterpart and detection strategy (redshift error)
    - Detection of the host galaxy with LSST
    - Localisation of a radio counterpart with SKA and detection of the host galaxy with ELT (for the redshift information)
    - Localisation of a X-ray counterpart with Athena and detection of the host galaxy with ELT (for the redshift information)

- Step 3: construction of the Hubble diagram

Tamanini et al, arXiv:1601.07112
Mangiagli et al, arXiv:2207.10678

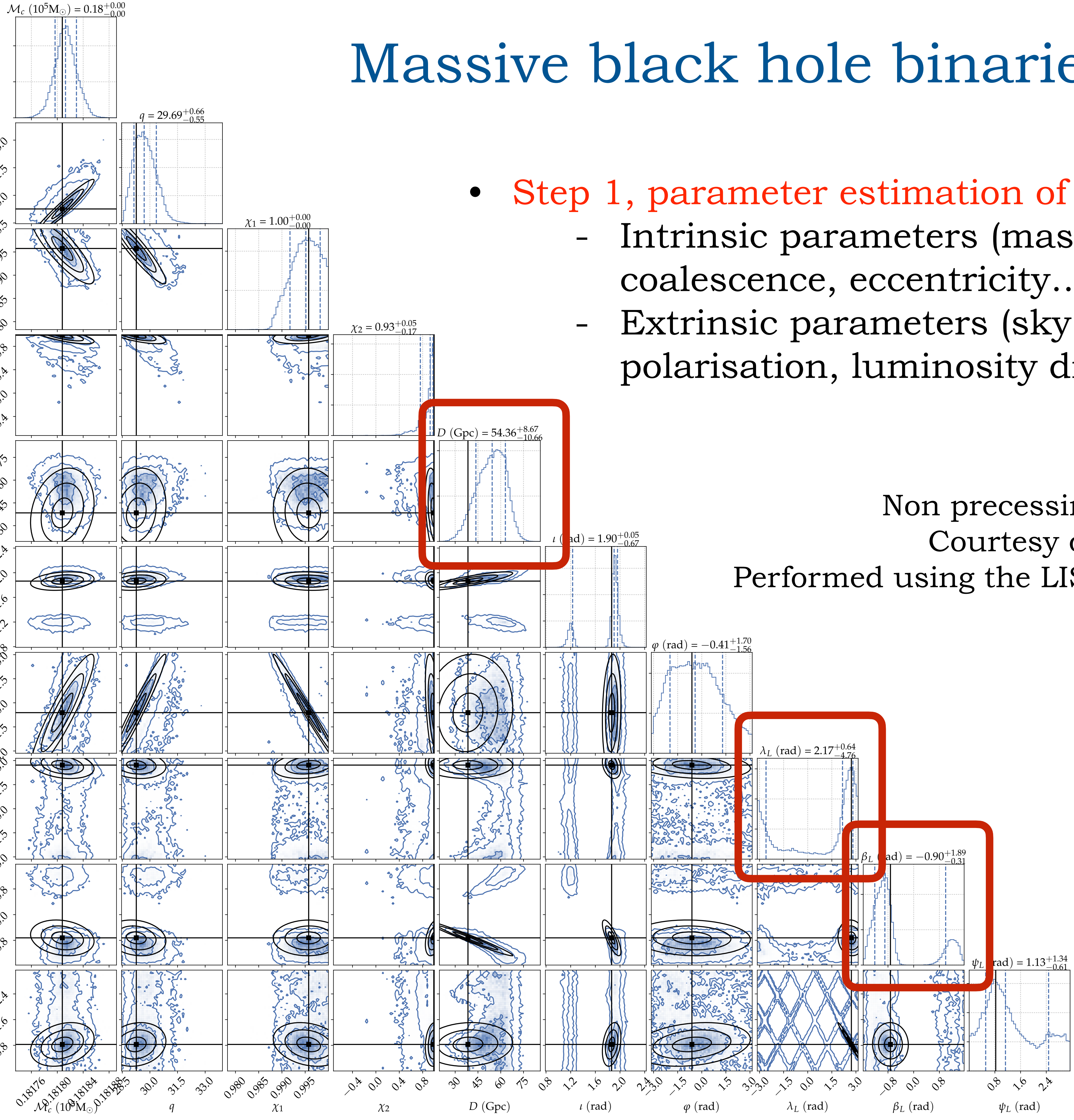
Massive black hole binaries

- Step 1, parameter estimation of MBHB systems:
  - Intrinsic parameters (masses, spins, phase at coalescence, eccentricity…)
  - Extrinsic parameters (sky position, inclination, polarisation, luminosity distance…)



Non precessing circular binary
Courtesy of A. Mangiagli
Performed using the LISAbeta code, S. Marsat et al

Massive black hole binaries



- Step 1, parameter estimation of MBHB systems:
  - Intrinsic parameters (masses, spins, phase at coalescence, eccentricity…)
  - Extrinsic parameters (sky position, inclination, polarisation, luminosity distance…)

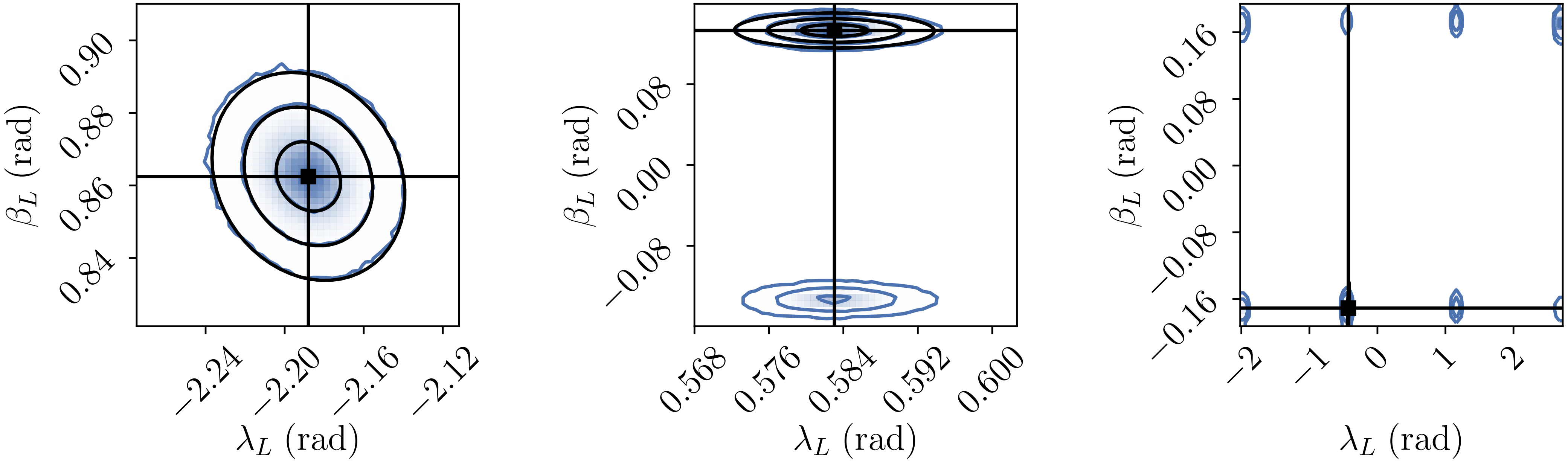
Non precessing circular binary
Courtesy of A. Mangiagli
Performed using the LISAbeta code, S. Marsat et al

Massive black hole binaries

- Step 1, parameter estimation of MBHB systems:
    - Intrinsic parameters (masses, spins, phase at coalescence, eccentricity…)
    - Extrinsic parameters (sky position, inclination, polarisation, luminosity distance…)

Non precessing circular binary
Courtesy of A. Mangiagli
Performed using the LISAbeta code, S. Marsat et al

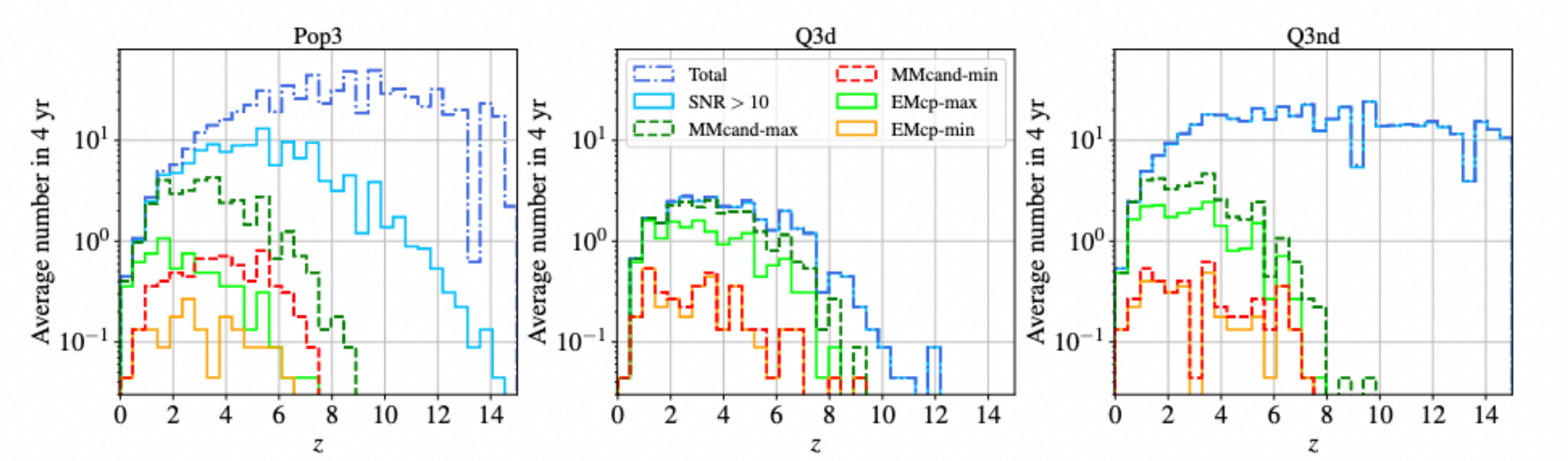
Some events are multi-modal in the sky position and need to be treated separately

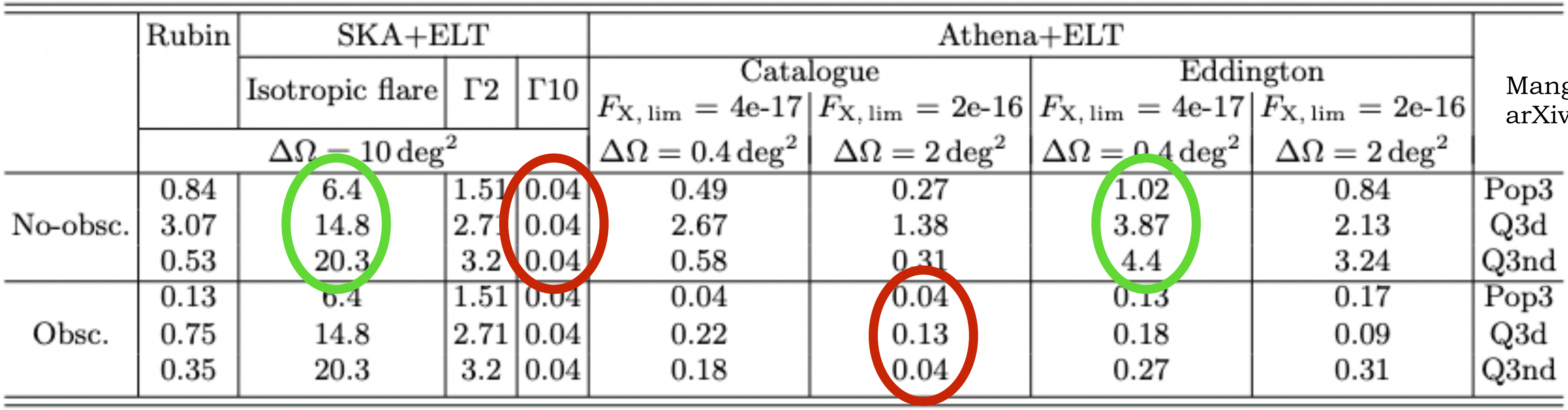


Massive black hole binaries

- Step 2, construction of the EM counterpart and its detection strategy:

- After applying the sky localisation cut, the number of standard sirens is quite low
- It depends heavily on the MBHB astrophysical generation model and on the EM detection channel
- The events cluster at high redshift 2 < z < 5





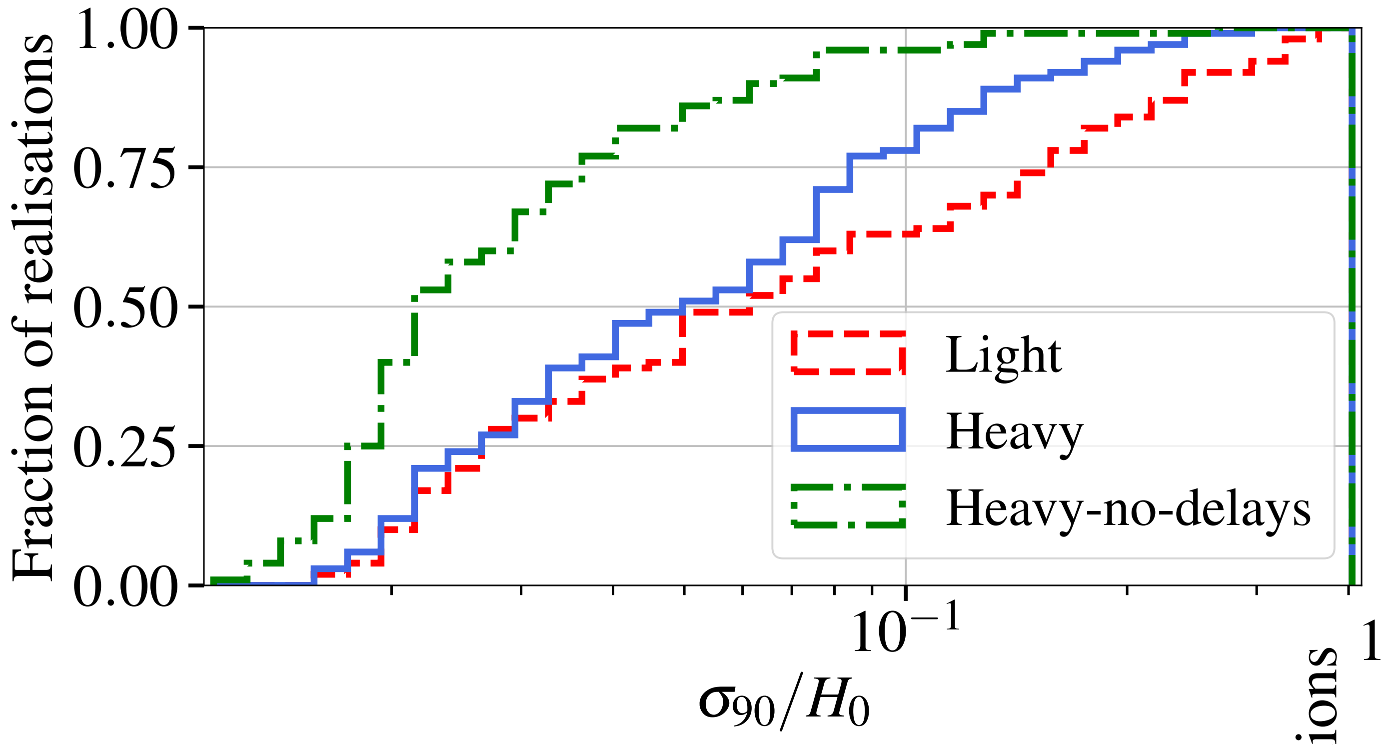
	Rubin	SKA+ELT			Athena+ELT				
		Isotropic flare	Γ2	Γ10	Catalogue		Eddington		
					$F_{\mathrm{X,\,lim}} = 4\text{e-}17$	$F_{\mathrm{X,\,lim}} = 2\text{e-}16$	$F_{\mathrm{X,\,lim}} = 4\text{e-}17$	$F_{\mathrm{X,\,lim}} = 2\text{e-}16$	
	$\Delta\Omega = 10\,\mathrm{deg}^2$				$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 2\,\mathrm{deg}^2$	$\Delta\Omega = 0.4\,\mathrm{deg}^2$	$\Delta\Omega = 2\,\mathrm{deg}^2$	
No-obsc.	0.84	6.4	1.51	0.04	0.49	0.27	1.02	0.84	Pop3
	3.07	14.8	2.71	0.04	2.67	1.38	3.87	2.13	Q3d
	0.53	20.3	3.2	0.04	0.58	0.31	4.4	3.24	Q3nd
Obsc.	0.13	6.4	1.51	0.04	0.04	0.04	0.13	0.17	Pop3
	0.75	14.8	2.71	0.04	0.22	0.13	0.18	0.09	Q3d
	0.35	20.3	3.2	0.04	0.18	0.04	0.27	0.31	Q3nd

Mangiagli et al,
arXiv:2207.10678

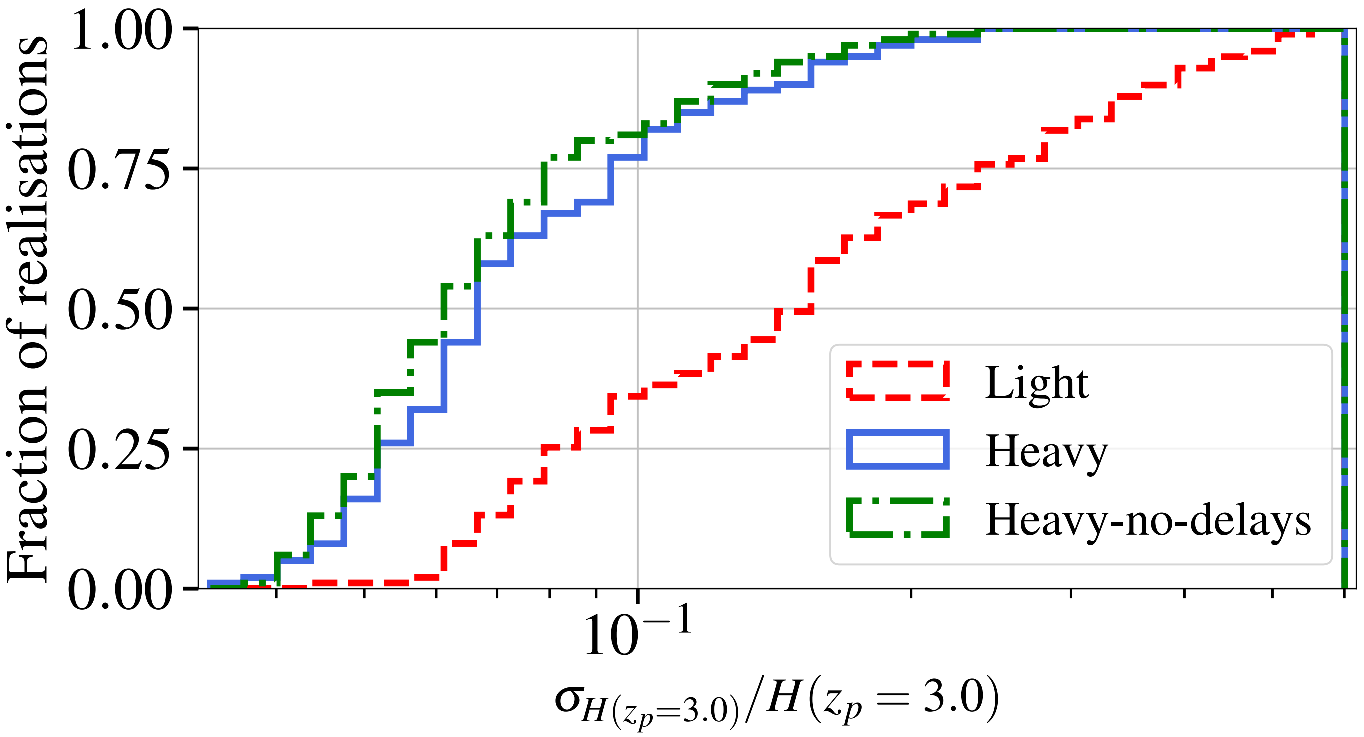
Massive black hole binaries

The uncertainty of cosmological measurement with MBHB standard sirens
is difficult to forecast!

Since the number of EM counterparts is low for the nominal mission duration (4 years), the errors (high) are dominated by statistical fluctuations in the realisations
The constraints also depend much on the MBHB formation channel



High redshift is more interesting!
(matter only)



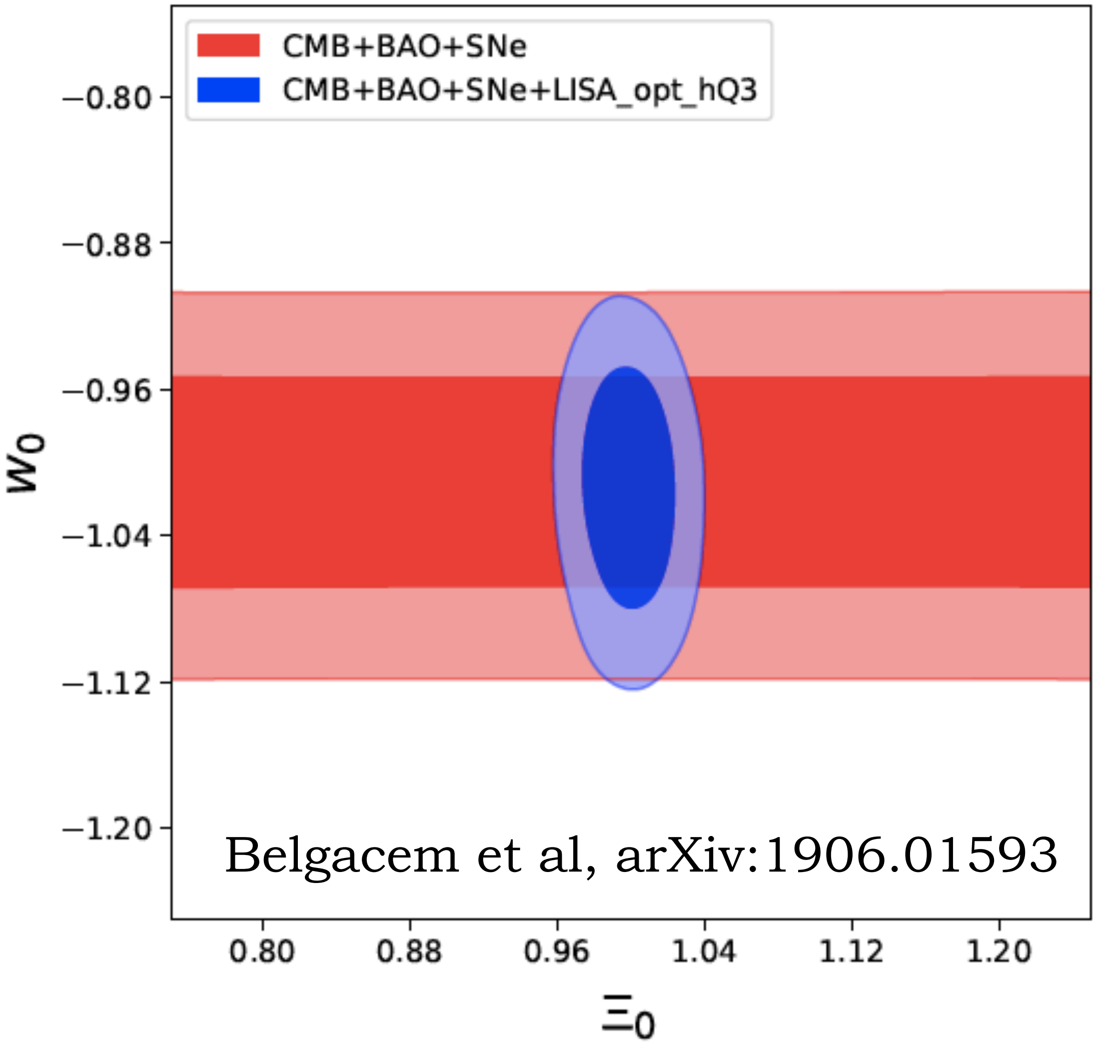
Mangiagli et al, in preparation
-> more in A. Magiangli's talk

Massive black hole binaries

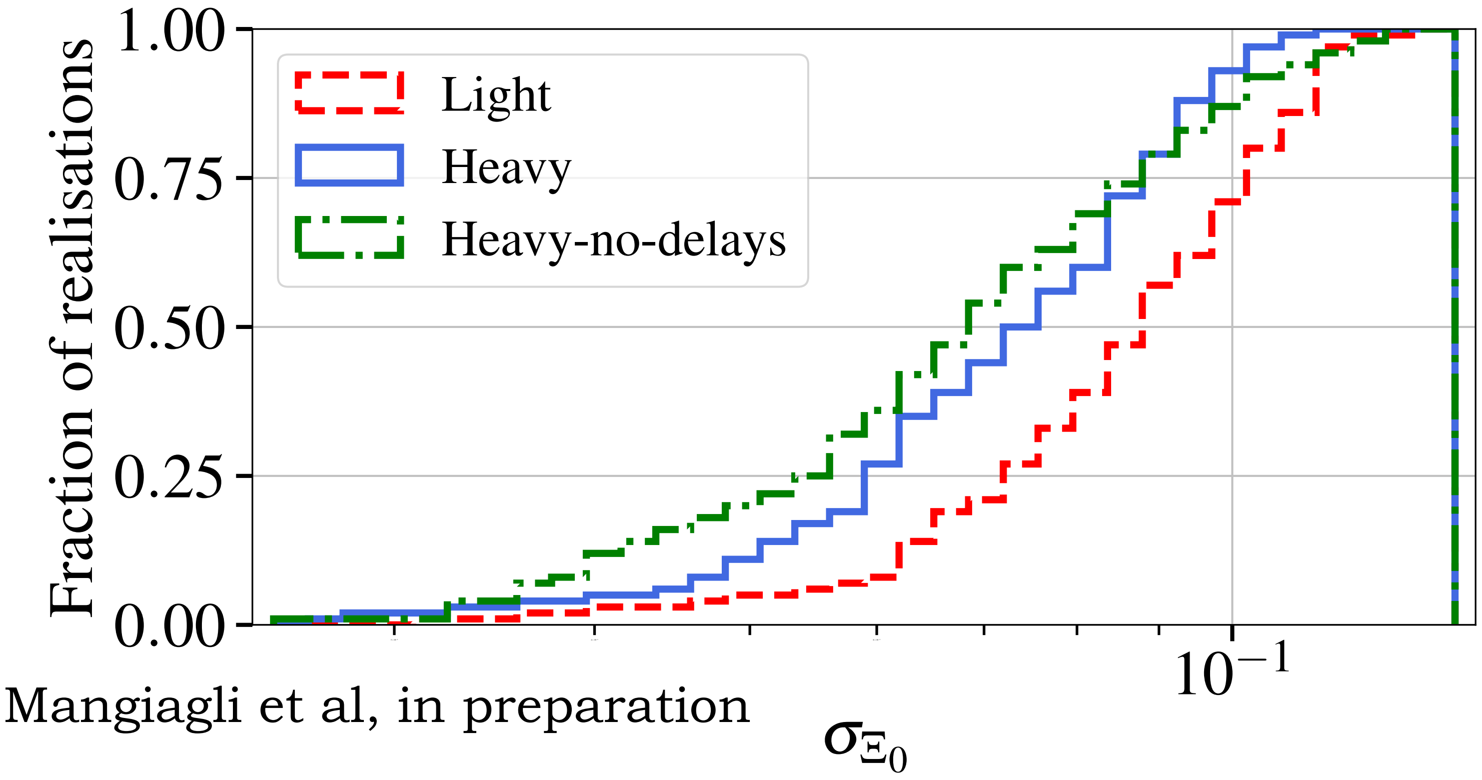
MBHB with LISA: more constraining power on "unconventional" cosmologies?

$$\tilde{h}''_A + 2\mathcal{H}[1-\delta(\eta)]\tilde{h}'_A + k^2\tilde{h}_A = 0$$

general parametrisation: $$\frac{d_L^{\rm gw}(z)}{d_L^{\rm em}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$

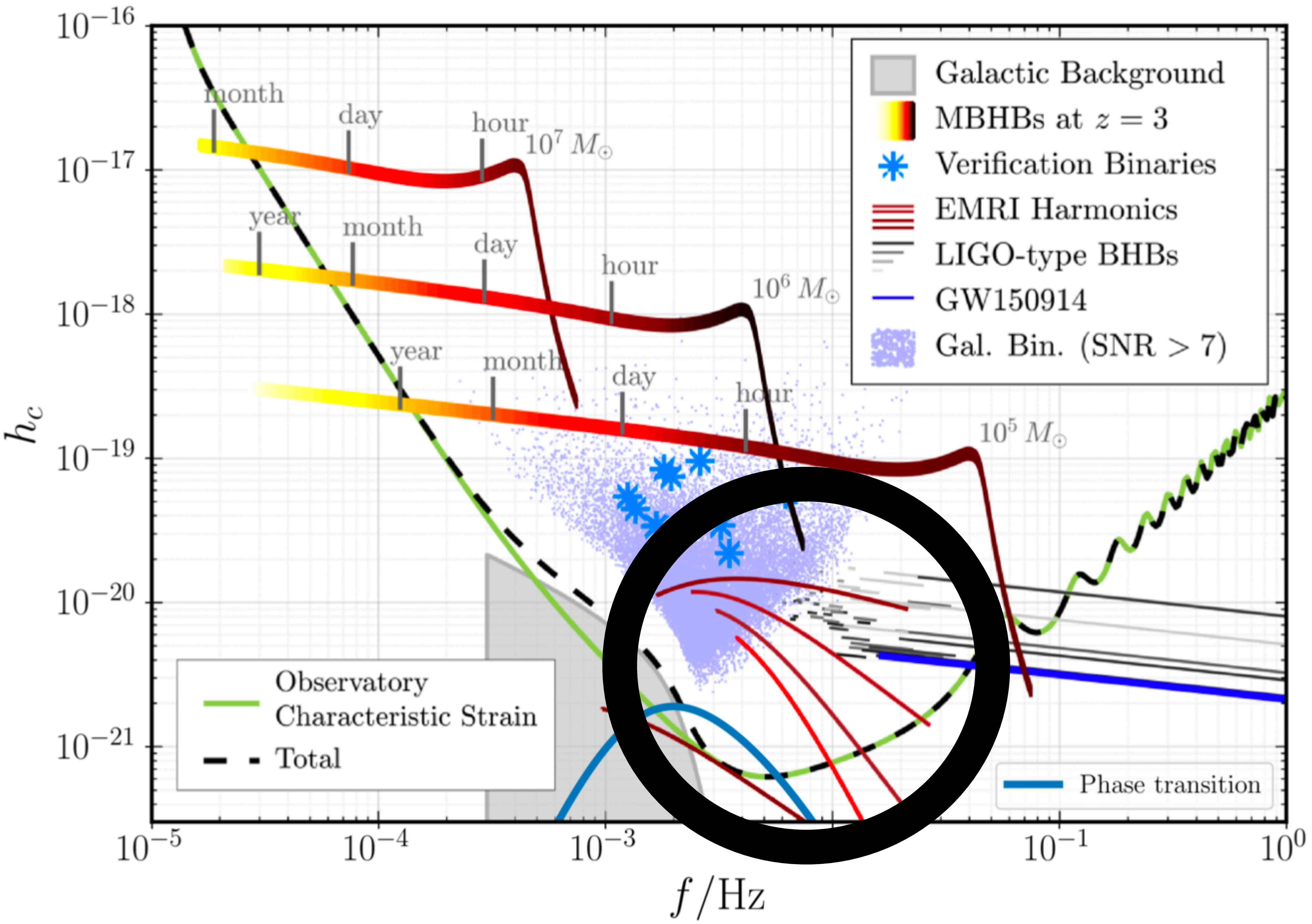


Belgacem et al, arXiv:1906.01593



Mangiagli et al, in preparation

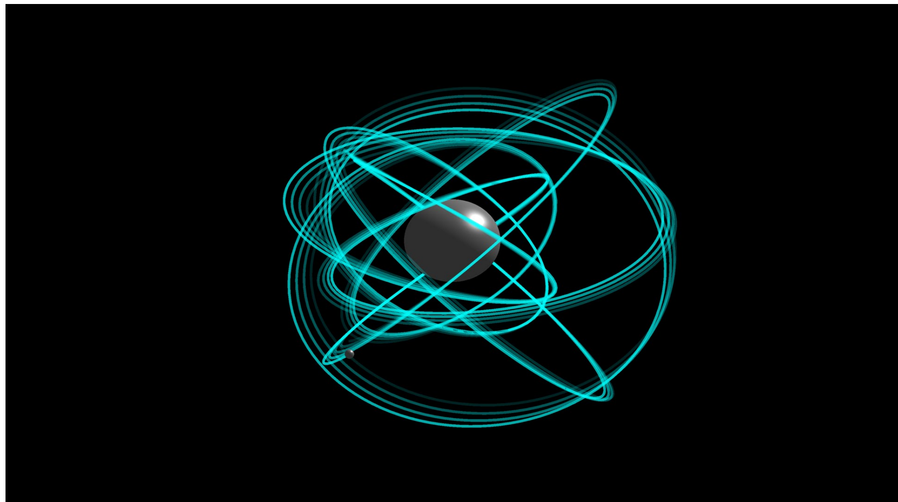
Extreme mass ratio inspirals



Extreme mass ratio inspirals

- Binaries for which the masses of the two objects are very different $10^{-7} < q < 10^{-4}$
- The waveforms are complex and the rates are highly uncertain
- The SNR can be as high as few hundreds
- They remain in band for a long time, longer as q decreases
- They can give rise to an unresolved background
- They offer the opportunity to map the full BH population of the Universe
- And to study the environment of galaxy centres (including the Milky Way)
- They can be used to perform tests of General Relativity

Cosmology: dark sirens

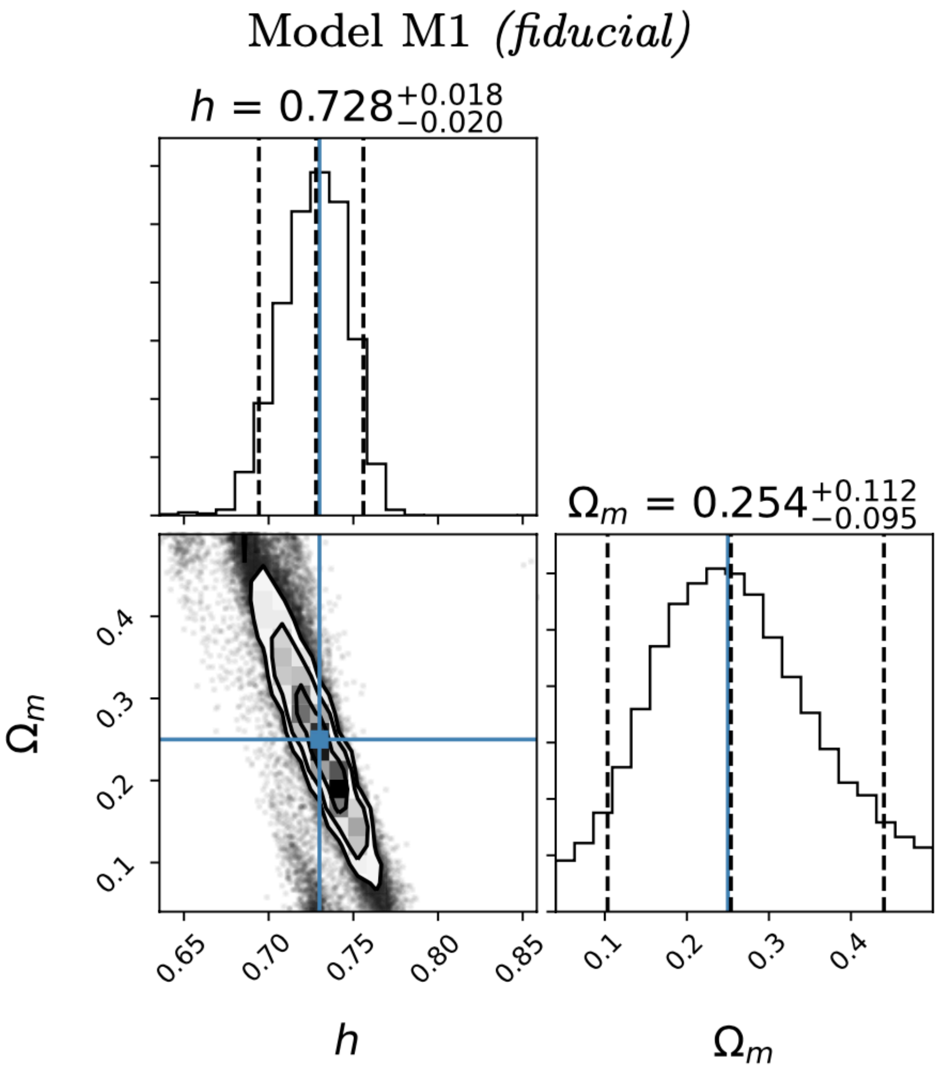


Extreme mass ratio inspirals

Dark sirens: sources for which no counterpart is expected, **statistical method**
cross-correlation with galaxy catalogues to infer the redshift from the luminosity distance measurement

- EMRIs with SNR>100 can be used for cosmology
  Results depend on the rates, which are uncertain

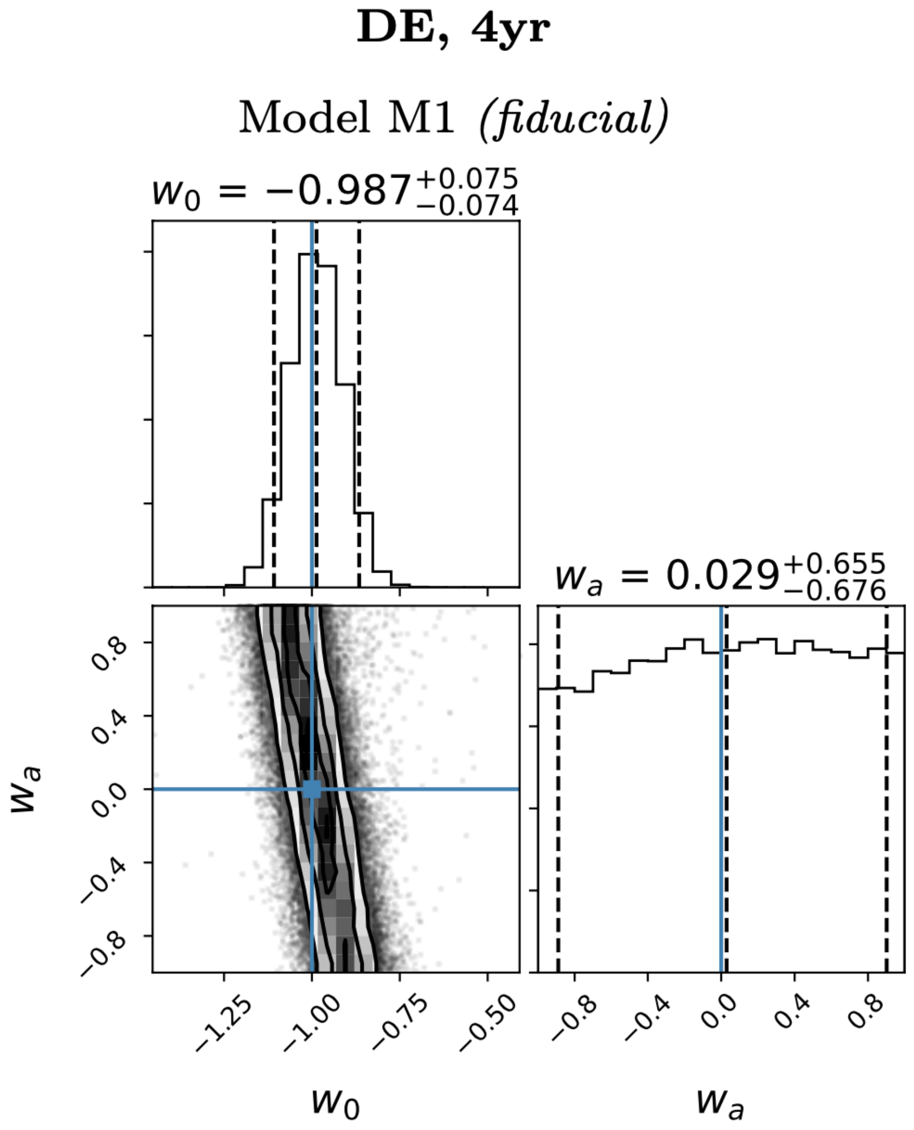
Laghi et al, arXiv:2102.01708



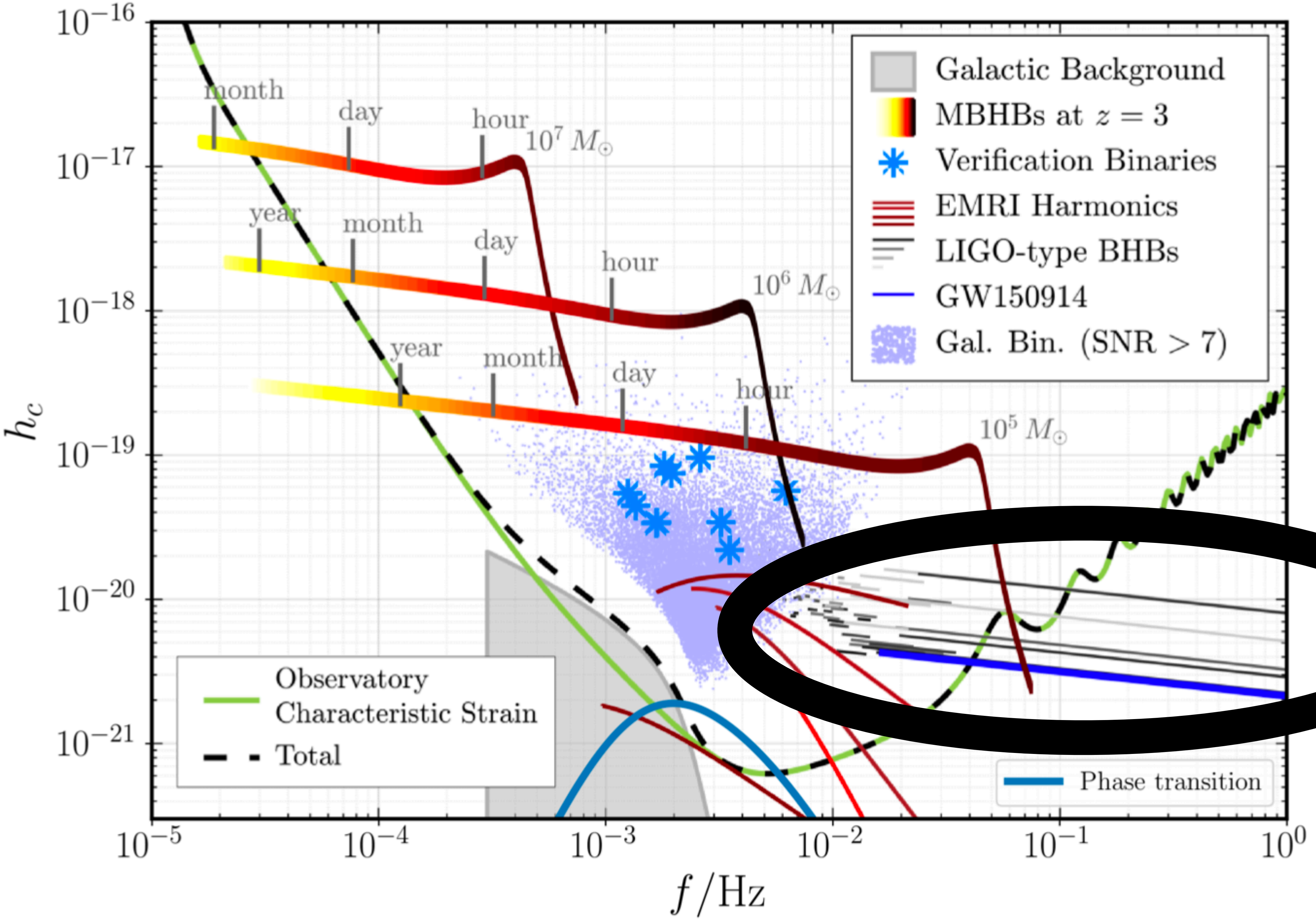
A 4-year LISA mission can provide:

3% constraints on H_0

7% constraints on w_0



Black hole binaries of tents of solar masses



Black hole binaries of tents of solar masses

- Merging BHBs are observed regularly by Earth-based interferometers

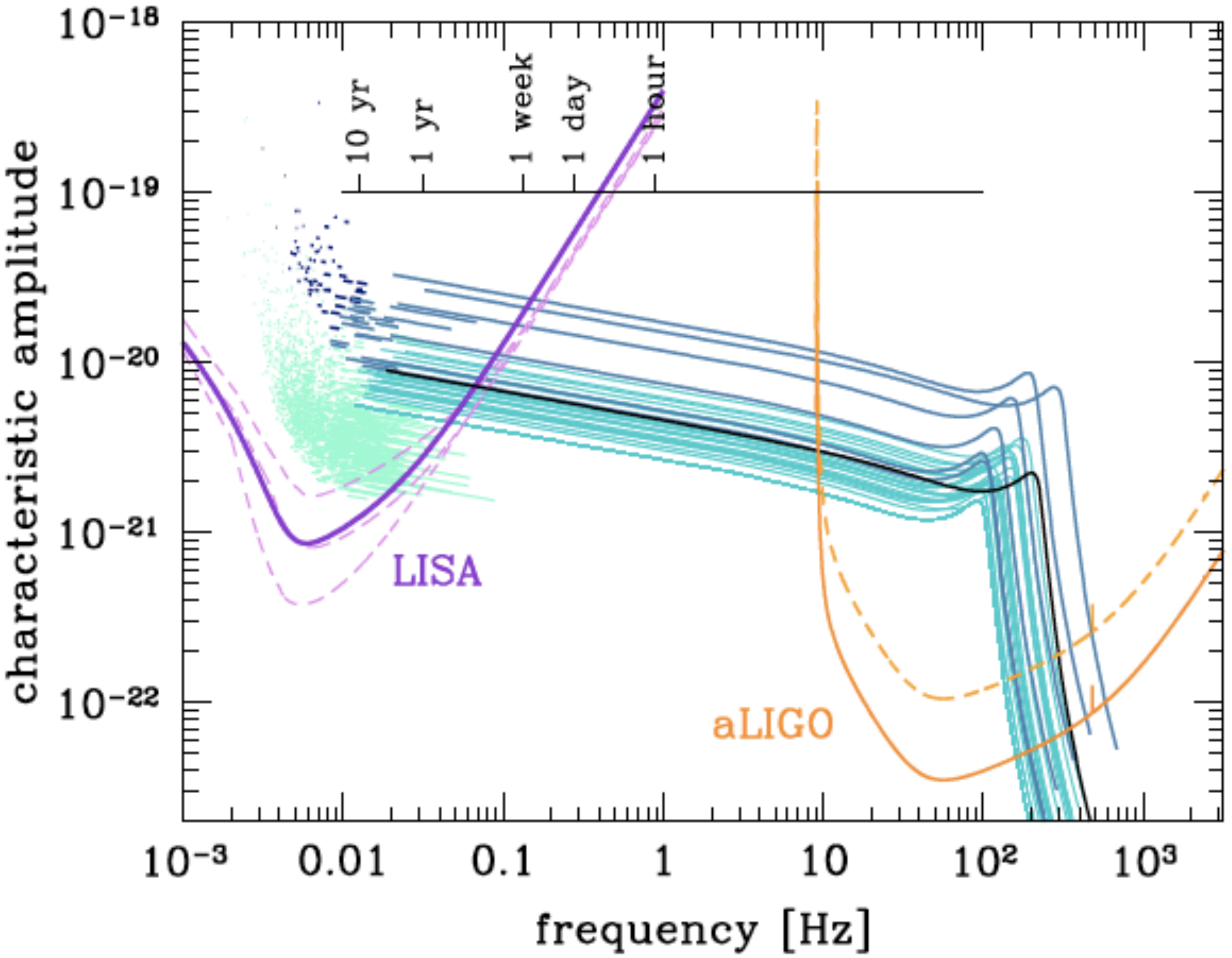
- Earlier in the inspiral phase, they can emit in the LISA band

$$M_c = 25\, M_\odot \quad \tau = 10\,\mathrm{y} \longrightarrow f = 0.01\,\mathrm{Hz}, \quad \dot{f} = 10^{-11}\,\mathrm{Hz/sec}$$

- Most of them will be quasi-monochromatic sources during the mission duration

- Some of them will be caught late enough in the inspiral phase, and will evolve to merge in the Eart-based interferometer band within a reasonable number of years

A Sesana arXiv:1702.04356



Cosmology:

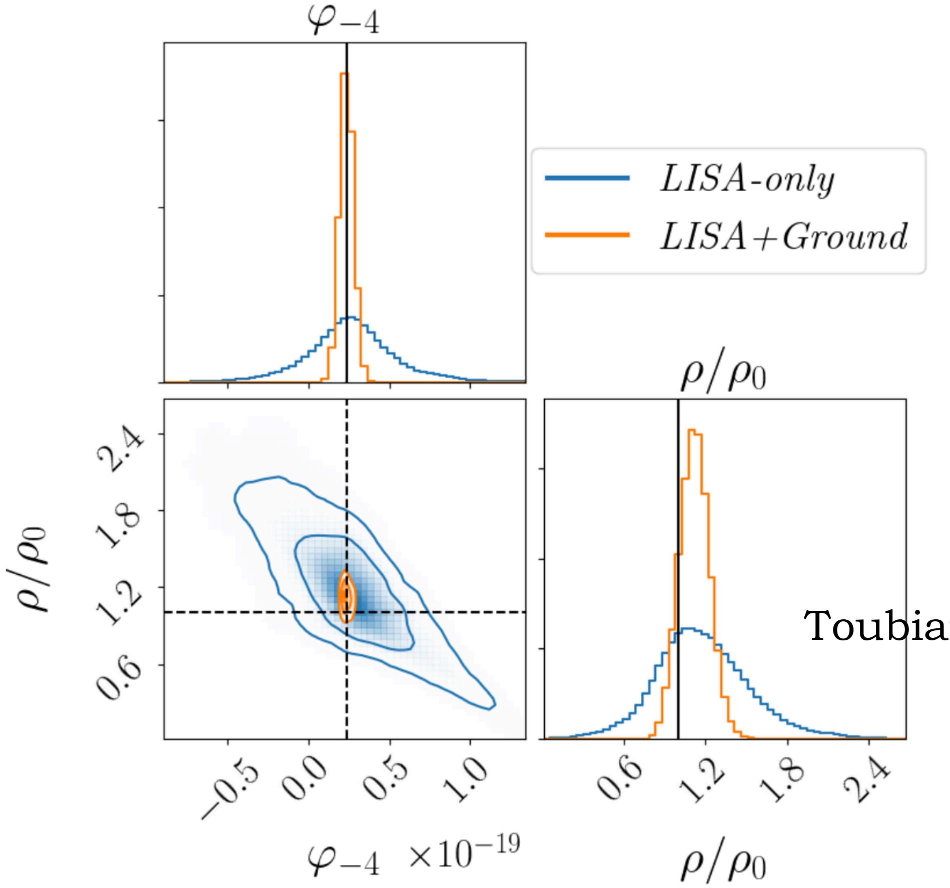
- The science that can be done with them depends on their number
- **Tests of General Relativity**
- **Dark sirens?**
- **Stochastic GW background**

Black hole binaries of tents of solar masses

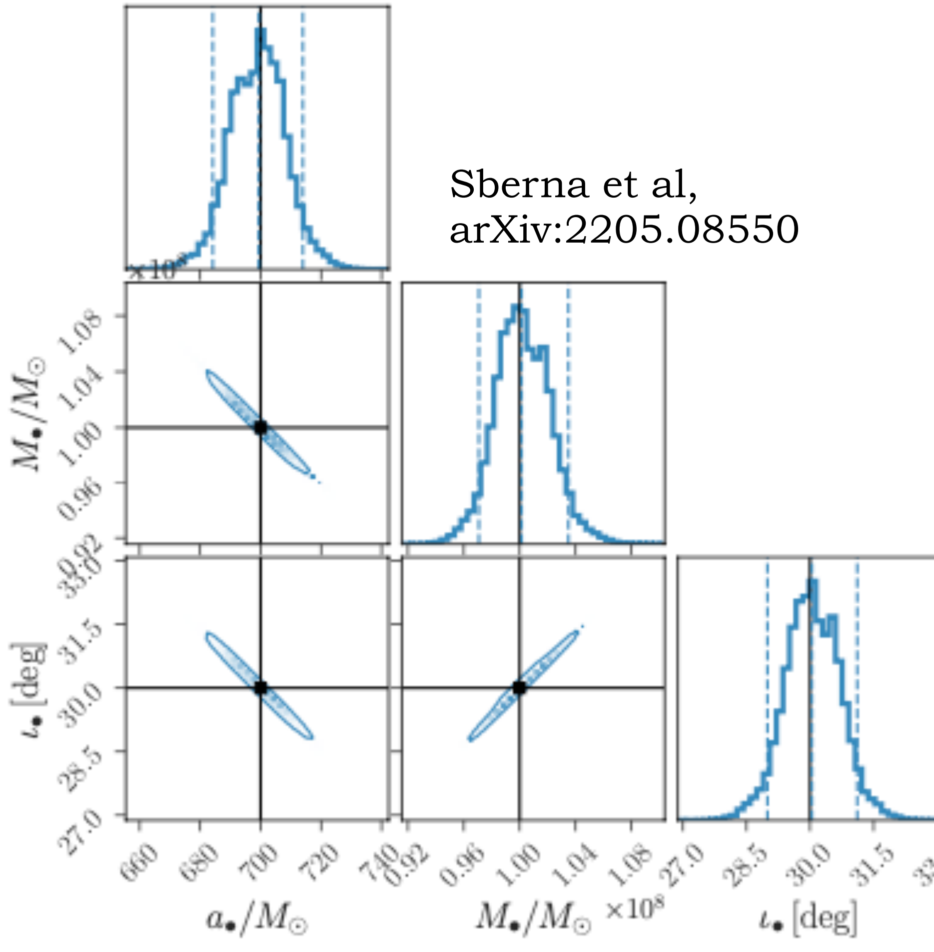
- LISA will measure precisely many cycles in their waveform: sensitive to external effects causing waveform modifications such as dephasing

$$1 + z = \frac{a_O}{a_S}\left[1 + (\mathbf{v}_S - \mathbf{v}_O)\cdot\mathbf{n} + \psi_O - \psi_S - \int_{t_S}^{t_O} dt(\dot{\phi} + \dot{\psi})\right]$$

- Study the population characteristics:
  - binary location and formation channel (peculiar acceleration, doppler modulation…)
  - binary environment (accretion, dynamical friction…)
- If the SOBHB orbits a MBH: dephasing due to Doppler modulation and Shapiro time delay provides access to the central MBH parameters
- Tests of General Relativity (variation of G, speed of GWs…)



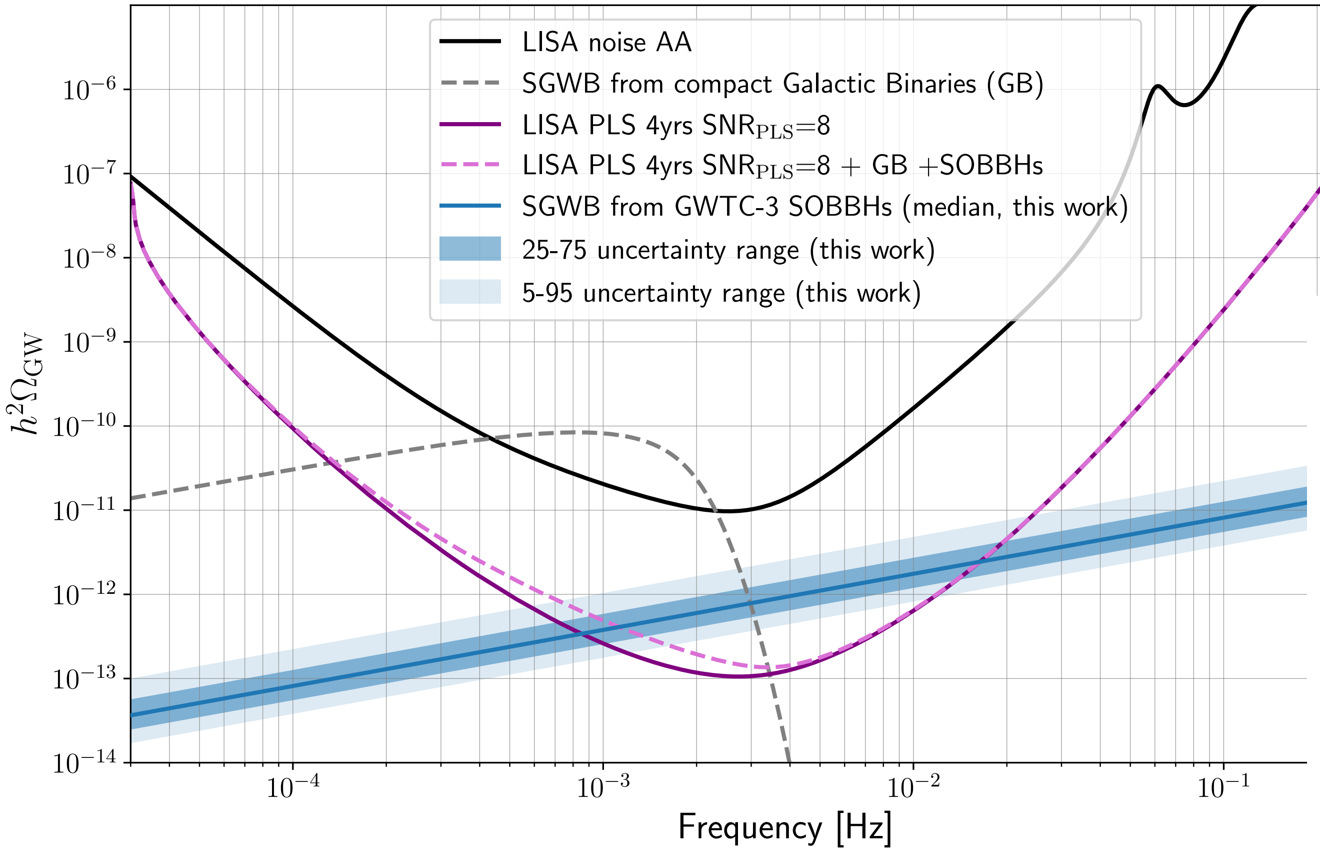
Toubiana et al, arXiv:2010.06056
GW190521-like source



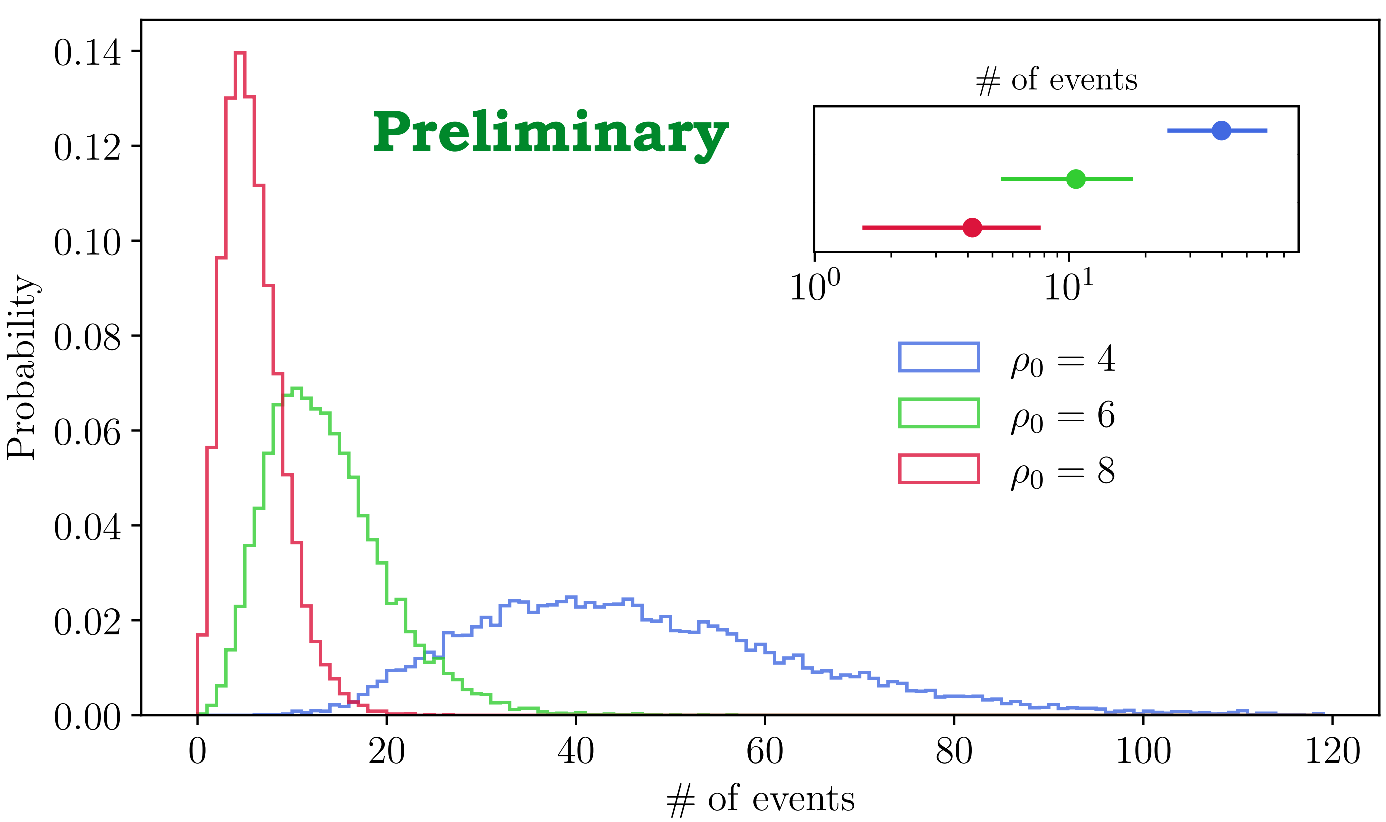
Sberna et al,
arXiv:2205.08550

Black hole binaries of tents of solar masses

- The science that can be done with them depends on the number of resolved sources
- The rest (unresolved ones) generates a Stochastic GW Background
- On must estimate both at the same time via iterative subtraction
- Resolved: closer to merger and to us; SGWB: distant and inspiralling
- Expected about 10 resolved in 4 years of mission, a few multi-band
- Very much depends on the high-z population characteristics



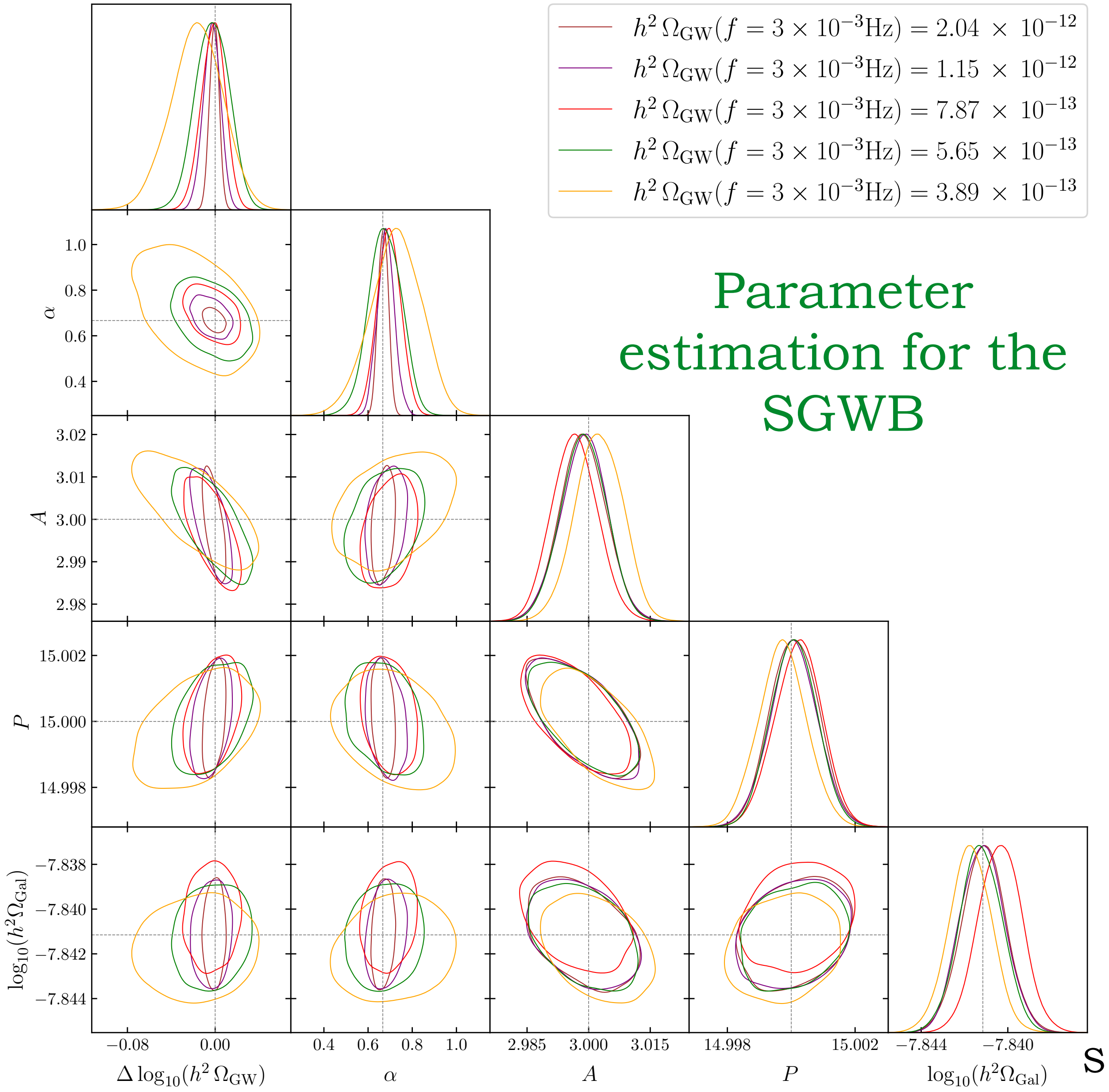
S. Babak et al, arXiv:2304.06368



J. Torrado, N. Karnesis, et al, in preparation

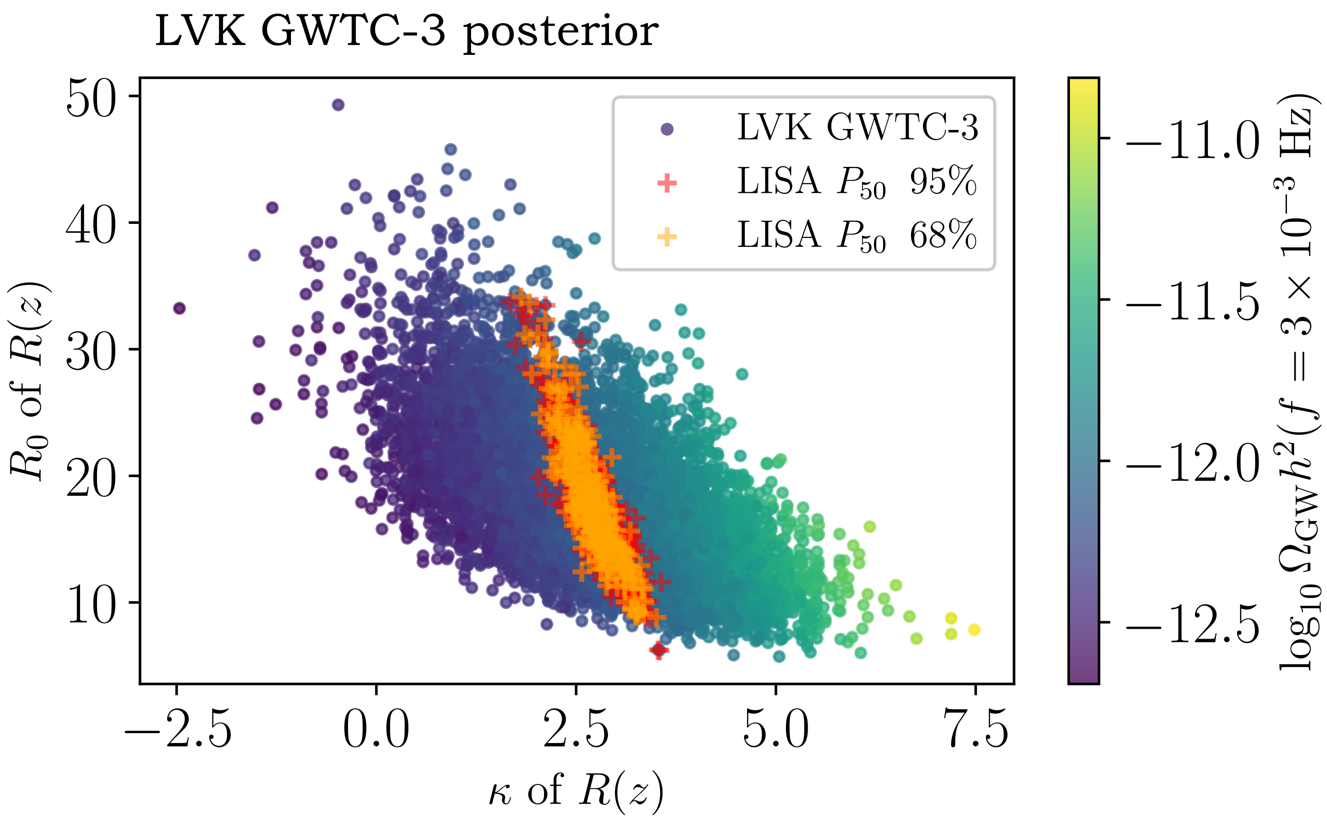
Black hole binaries of tents of solar masses

- The science that can be done with them depends on the number of resolved sources
- The rest (unresolved ones) generates a Stochastic GW Background
- On must estimate both at the same time via iterative subtraction
- Resolved: closer to merger and to us; SGWB: distant and inspiralling
- Expected about 10 resolved in 4 years of mission, a few multi-band
- Very much depends on the high-z population characteristics



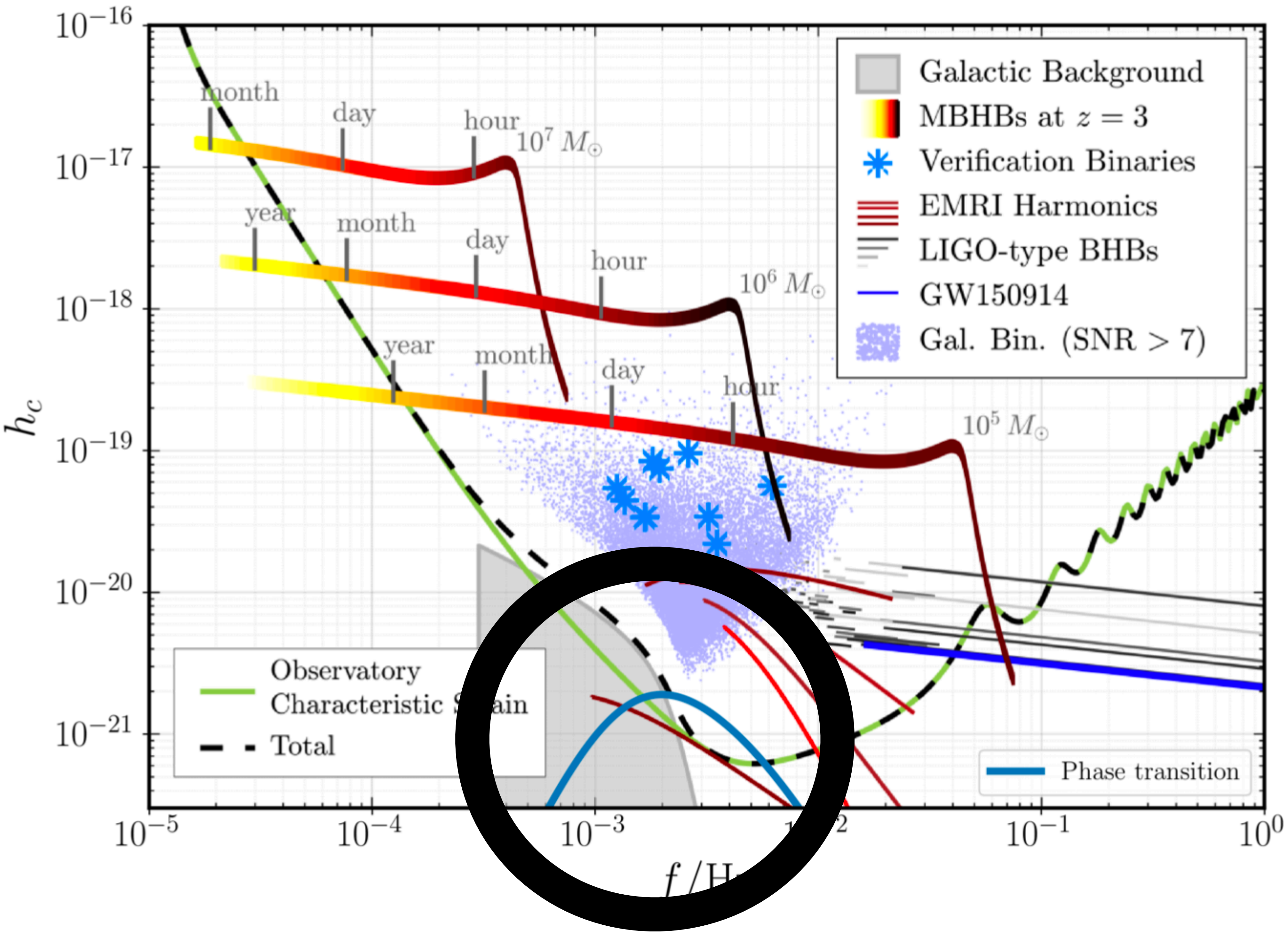
Parameter estimation for the SGWB

The SGWB detection with LISA is expected to be informative of the population characteristics


LVK GWTC-3 posterior

S. Babak et al, arXiv:2304.06368

The stochastic GW background



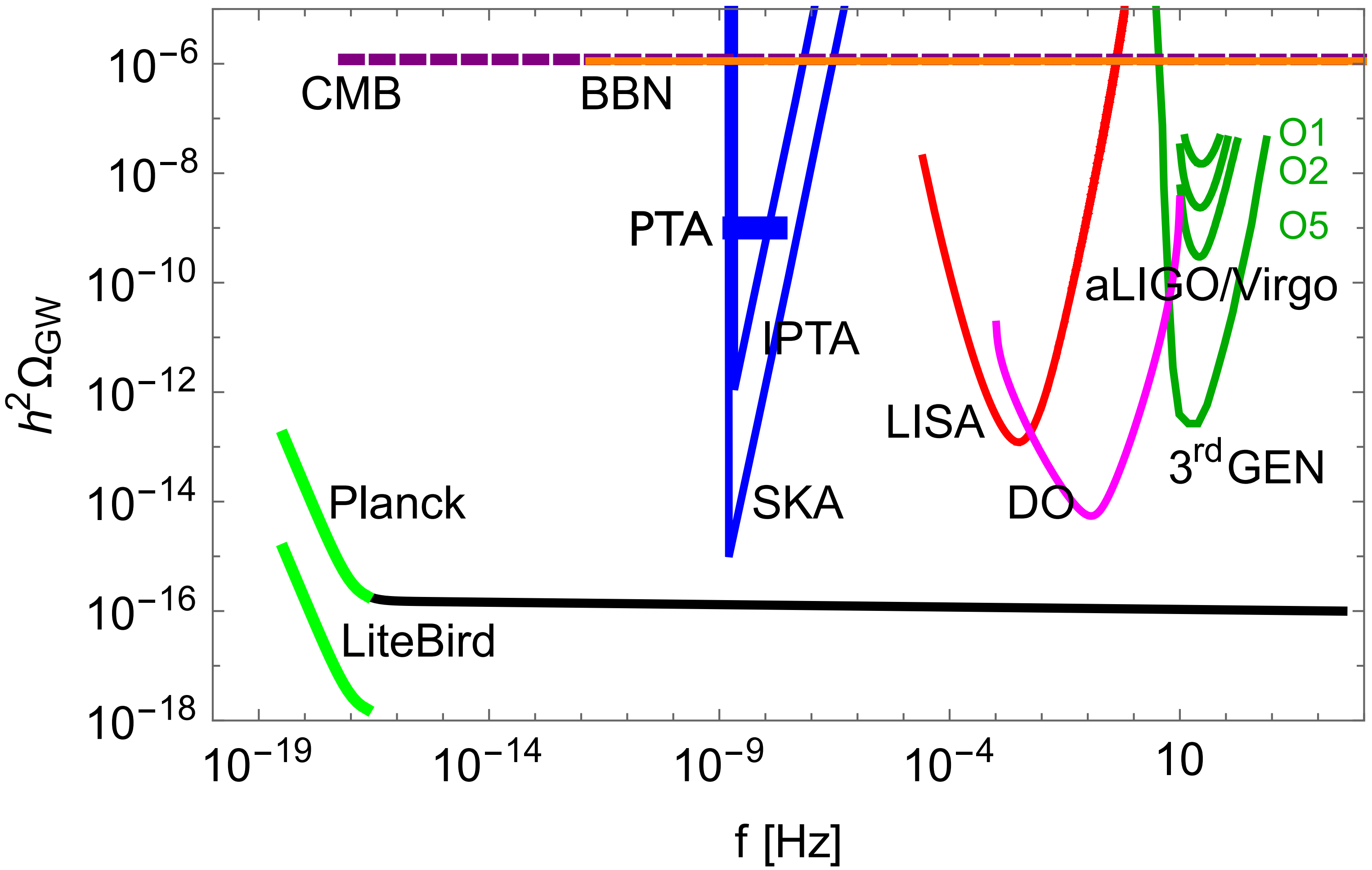
The stochastic GW background

- Foreground from astrophysical sources (galactic binaries, stellar mass BHB, EMRIs…)

- Background from the very early universe

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = 0$$

Amplification pf quantum tensor fluctuations during inflation… but not only



$$V^{1/4} \sim 10^{16}\,\mathrm{GeV}$$

$$n_T \simeq -2\epsilon$$

The stochastic GW background

- Foreground from astrophysical sources (galactic binaries, stellar mass BHB, EMRIs…)

- Background from the very early universe

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = \boxed{16\pi G\,\Pi_{ij}^{TT}}$$

Possible sources of tensor anisotropic stress in the early universe:

- Scalar field gradients $\Pi_{ij} \sim [\partial_i\phi\partial_j\phi]^{TT}$
- Bulk fluid motion $\Pi_{ij} \sim [\gamma^2(\rho + p)v_i v_j]^{TT}$
- Gauge fields $\Pi_{ij} \sim [-E_i E_j - B_i B_j]^{TT}$
- Second order scalar perturbations, Π_{ij} from a combination of $\partial_i\Psi, \partial_i\Phi$
- …

The stochastic GW background

- Foreground from astrophysical sources (galactic binaries, stellar mass BHB, EMRIs…)

- Background from the very early universe

$$\ddot{h}_{ij} + 3H\,\dot{h}_{ij} + k^2\,h_{ij} = \boxed{16\pi G\,\Pi_{ij}^{TT}}$$

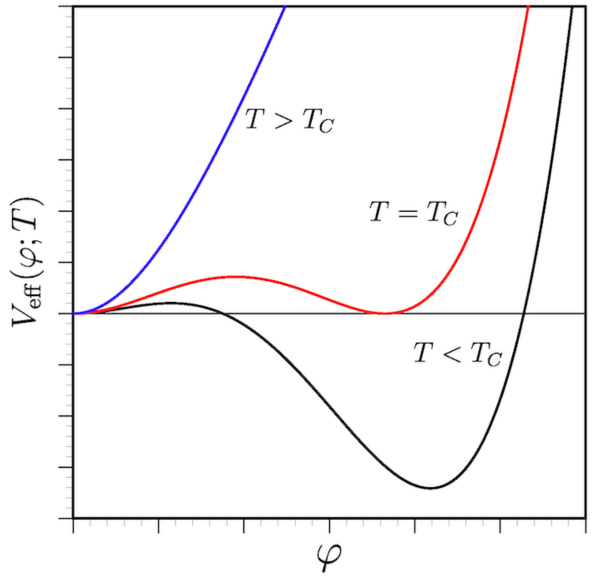
Possible sources of tensor anisotropic stress in the early universe:

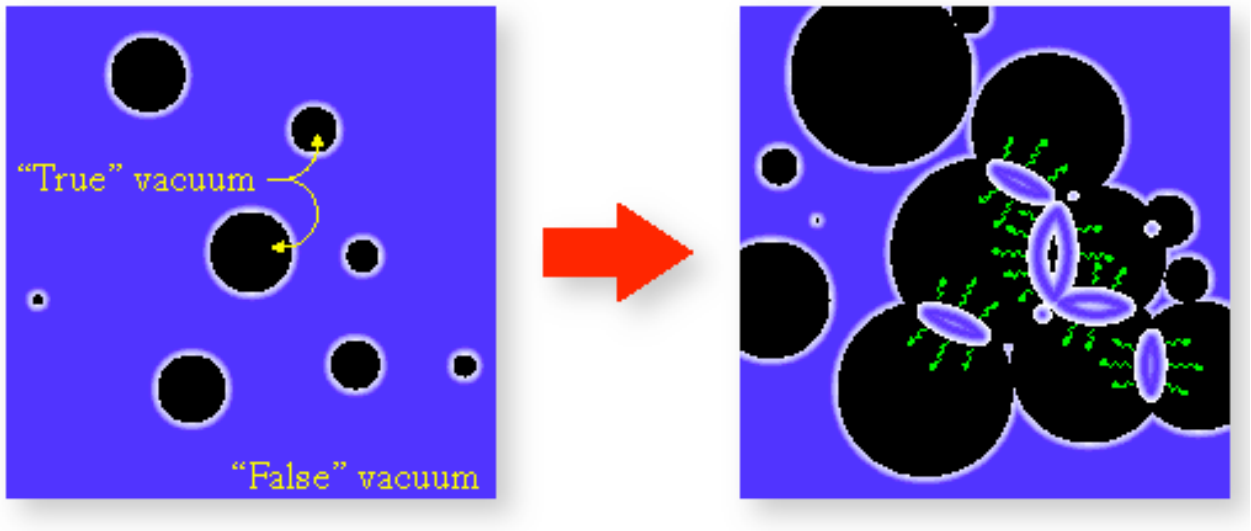
- *Inflation*:
  - quantum tensor fluctuations at second order
  - tensor modes from additional fields (scalar, gauge…)
  - GWs rated to primordial Black Holes
  - preheating
  - modifications of gravity

- *Other phase transitions*:
  - stable topological defects (in particular strings)
  - bubble wall collisions from a first order phase transition
  - bulk fluid motion (compressional and vortical)
  - magnetic fields

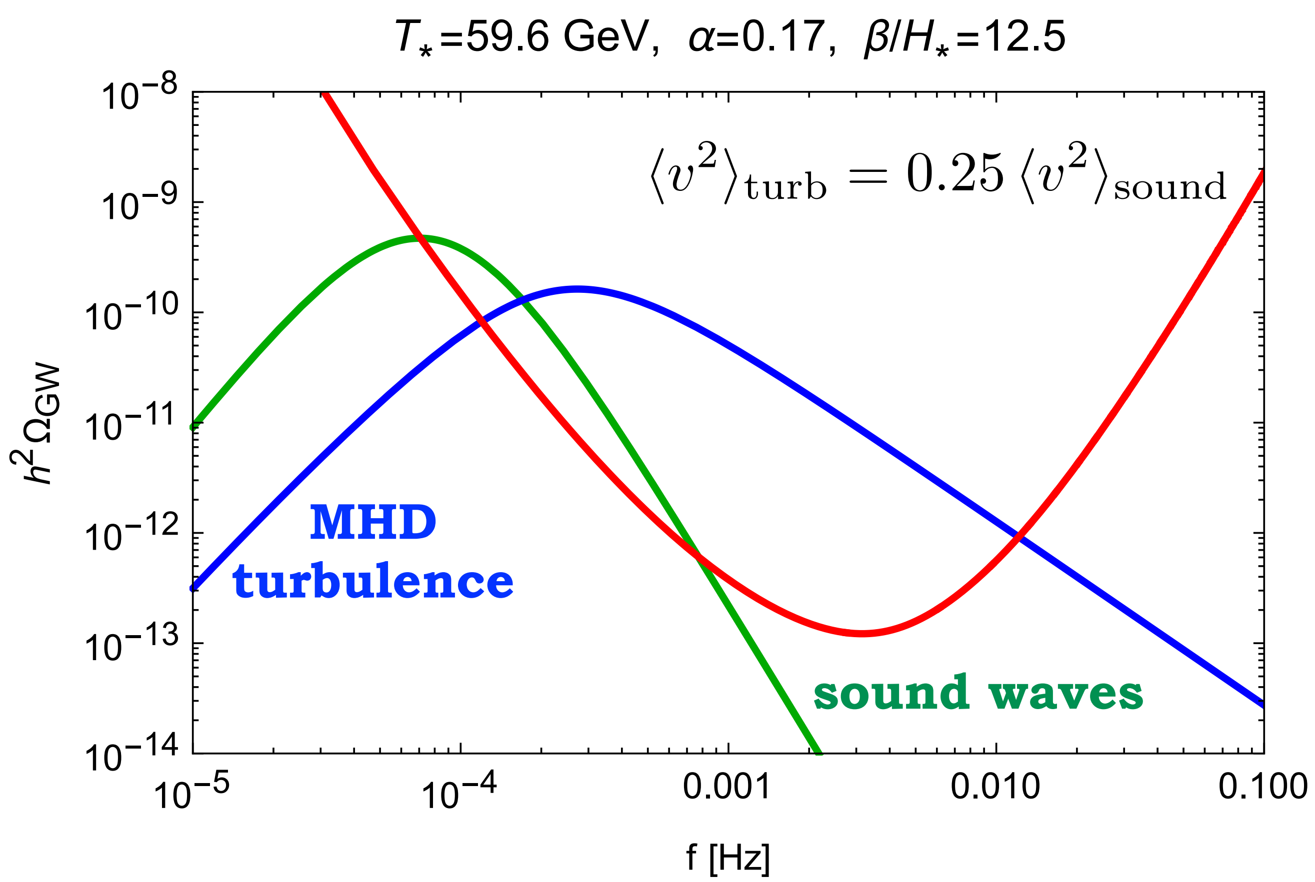
The stochastic GW background

- Strong scientific case for LISA: the **Electroweak Phase Transition**
- Frontier between tested physics and new physics
- Can be first order in scenarios Beyond the Standard Model of particle physics
- Connections with baryon asymmetry, dark matter: LISA could act as a **probe of Beyond Standard Model physics, complementary to colliders**
- In some BSM scenarios joint detection at LISA and LHC/FCC possible
- Definite prediction of the SGWB signal not yet available: complicated non-linear problem!



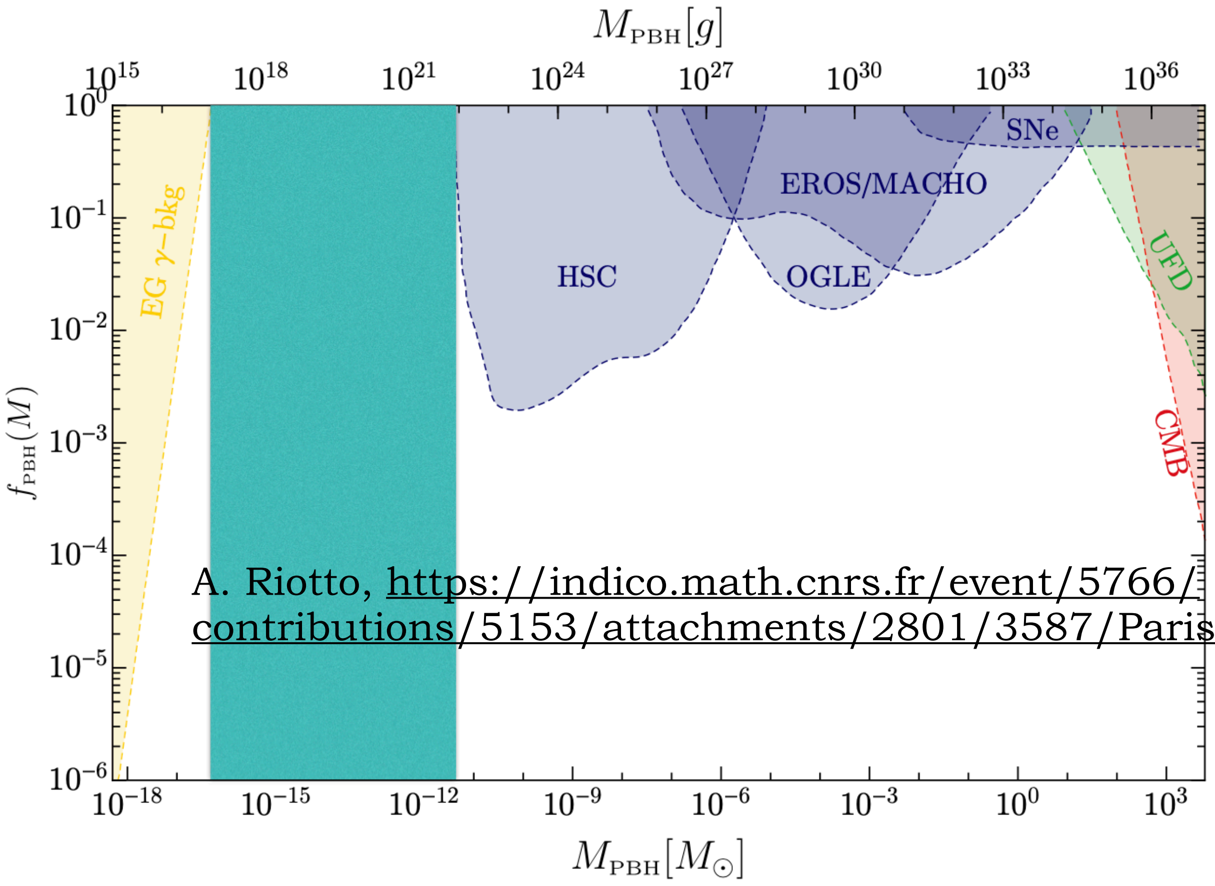


One example of GW signal from the EWPT: "Higgs portal" scenario



The stochastic GW background

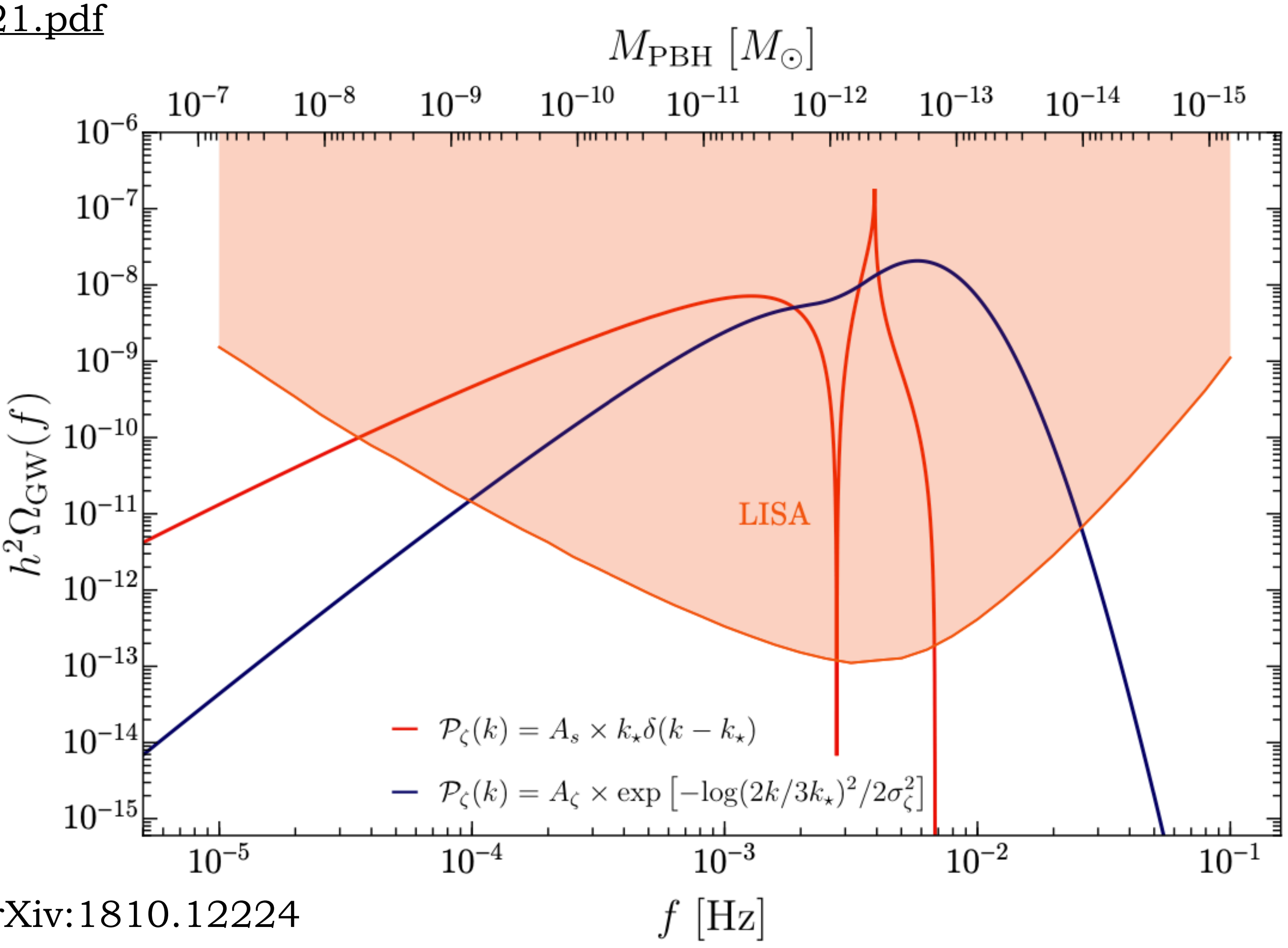
Primordial black holes: GW signal from second order scalar perturbations



A. Riotto, https://indico.math.cnrs.fr/event/5766/contributions/5153/attachments/2801/3587/Paris2021.pdf

There is a mass window for which PBH can still constitute the whole of the dark matter

If one wants to produce PBH in this mass range, one also has an observable SGWB in LISA by second order scalar perturbations

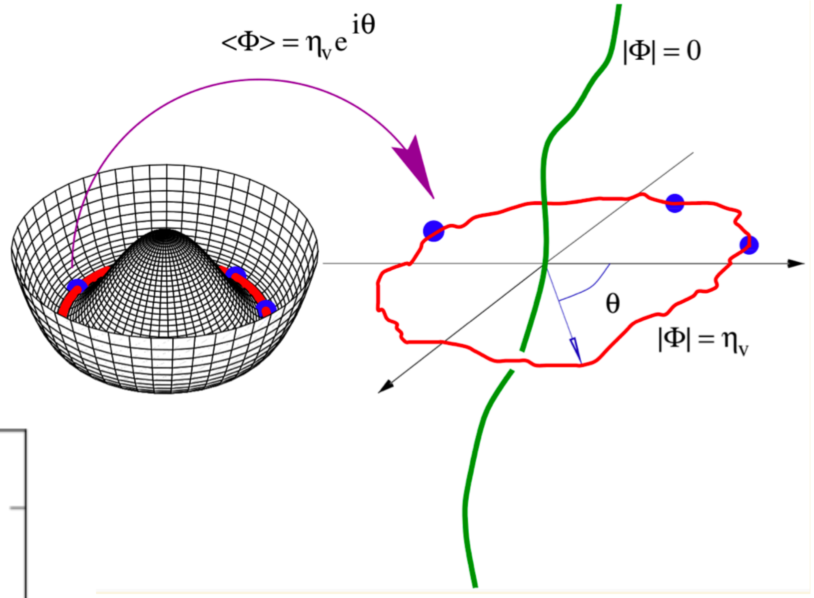


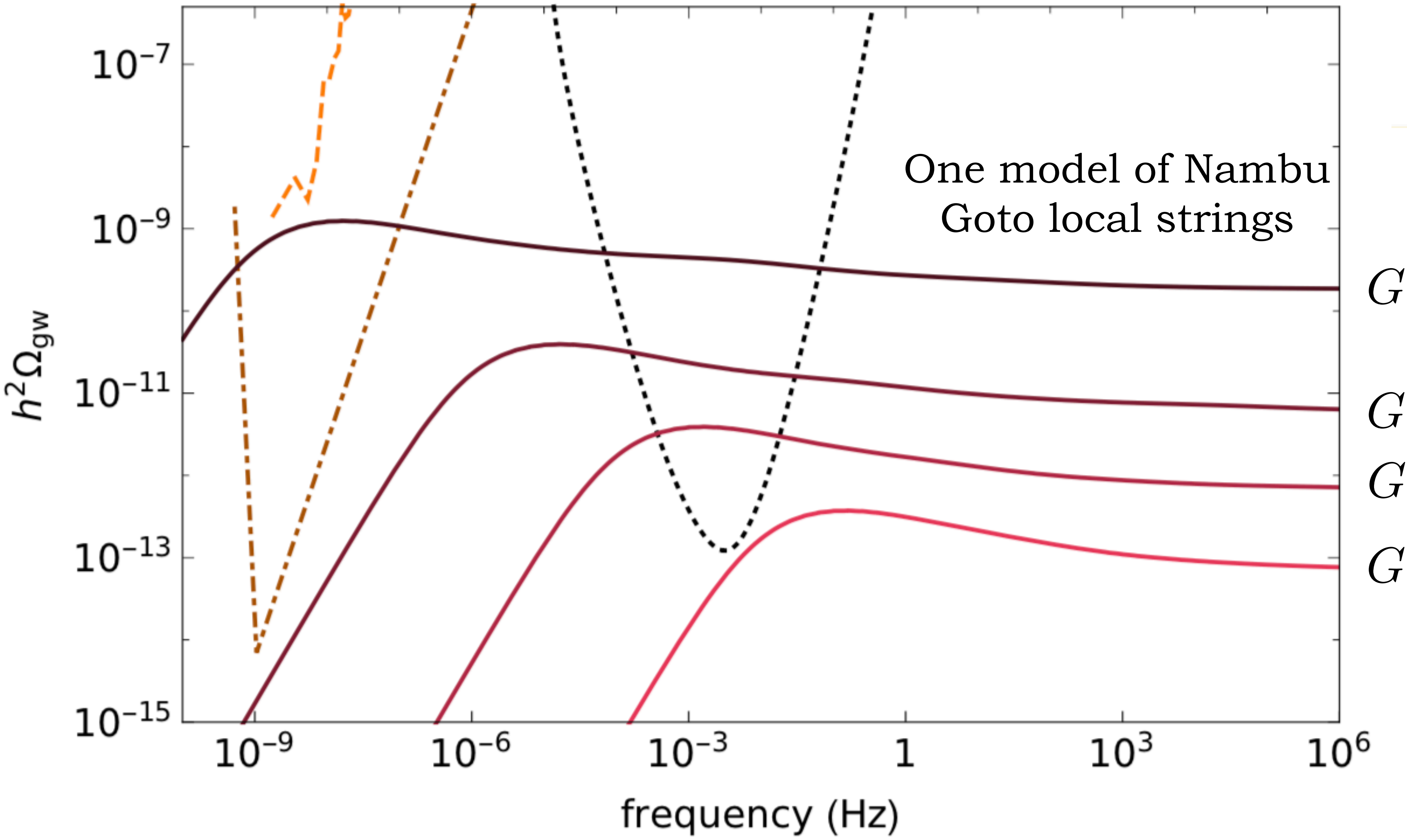
N. Bartolo et al, arXiv:1810.12218, arXiv:1810.12224

The stochastic GW background

Cosmic strings (or other kind of topological defects) are non-trivial field configurations left-over after the phase transition has completed

A network of cosmic strings can emit GWs
(though the results are very model dependent)





One model of Nambu Goto local strings

$G\mu = 10^{-10}$

Present PTA sensitivity

$G\mu = 10^{-13}$

$G\mu = 10^{-15}$

$G\mu = 10^{-17}$

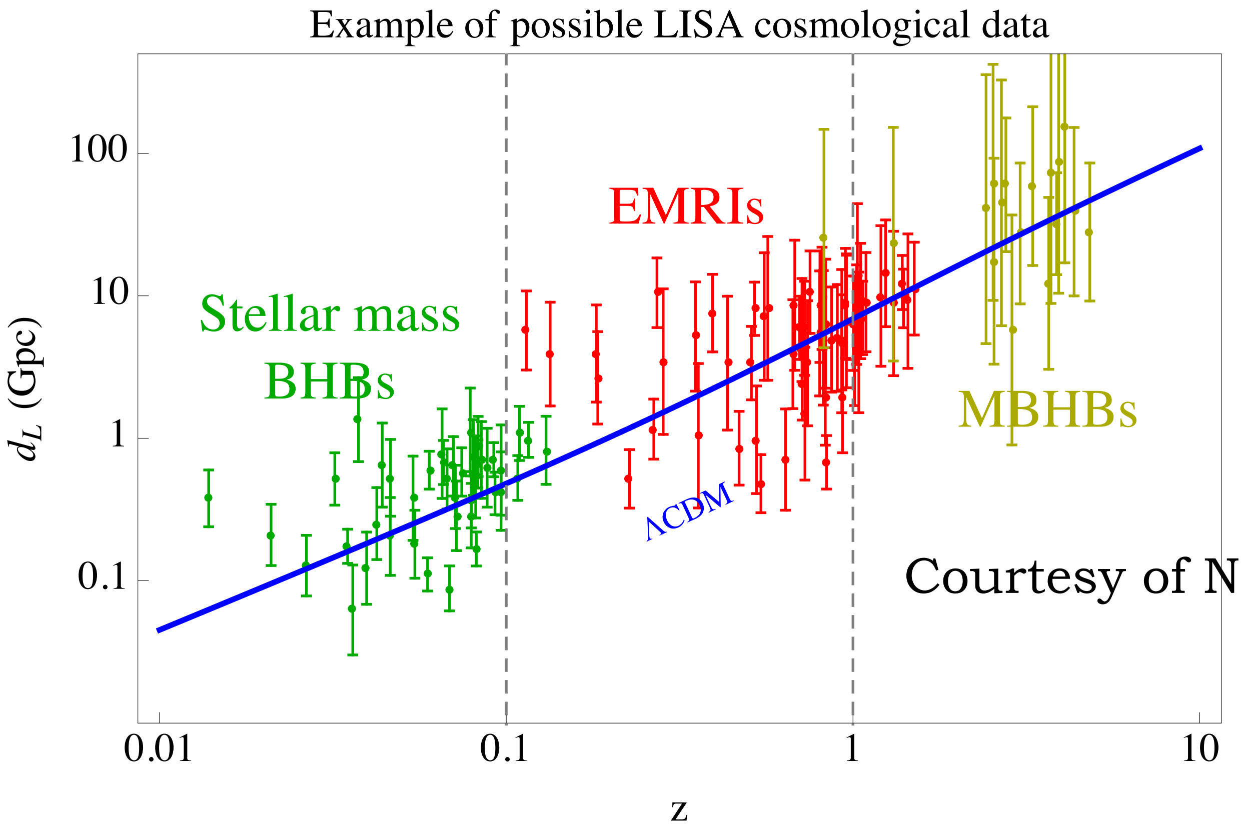
LISA constraints

Conclusions

- For not having been designed to do cosmology, LISA performs pretty well!

Constraining late universe expansion with sirens

- Not directly competitive with standard cosmological surveys (SNIa, BAO, CMB…) at least for the nominal mission duration of about 4 years
- However, the measurement of luminosity distance is direct and independent on EM emission (different systematics)
- Potential of constraining the universe at high redshift (modified gravity scenarios, early/interacting DE…)
- Several categories of sources: MBHBs, EMRIs, Stellar Mass BHBs, at different redshift: possibility of combining the measurement and improve the constraints
- Exploit features in the mass distribution of the sources



Courtesy of N. Tamanini

Conclusions

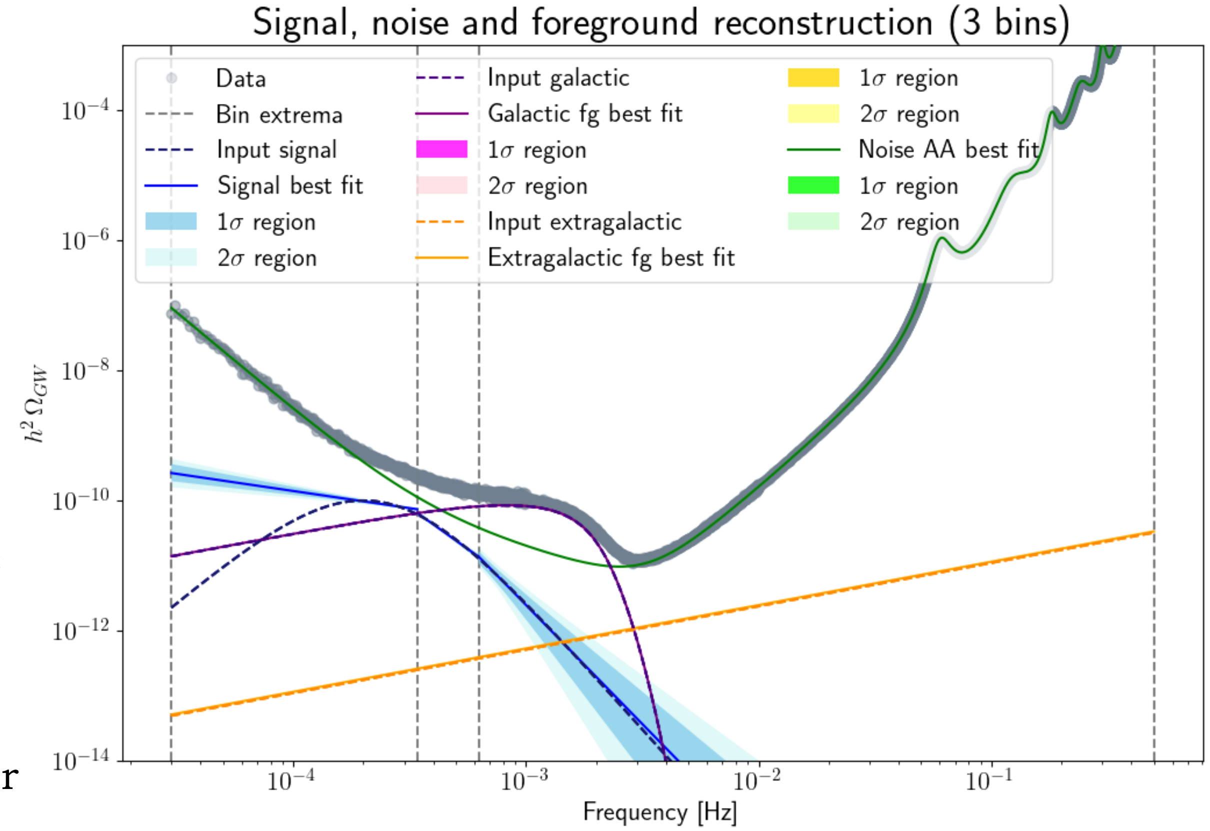
- For not having been designed to do cosmology, LISA performs pretty well!

Constraining early universe and high energy physics with SGWBs

- SGWBs from the primordial universe might seem speculative but their potential to probe fundamental physics is great and amazing discoveries can be around the corner
- Physics beyond the SM: many proposals of signals, interesting constraining power
- LISA has especially three very motivated science cases (in my opinion):
    - SGWB at the EW scale, complementary to particle colliders
    - SGWB from II order perturbations when PBH can be the totality of DM
    - SGBW from cosmic strings in coincidence with PTA
- Concerning inflation, direct SGWB detection can be useful to probe another range of scales (and of the inflationary potential), much smaller than CMB

- The detection is very challenging!
  In general, one must control:

- Prediction of spectral shapes -> the only handle to identify the SGWB origin
- Foreground from astrophysics sources
- Decent understanding of the instrument noise
- Residuals from the global fit of LISA sources



LISA Red Book, SGWBinner