Probing First-Order Phase Transitions at LISA

CATCH 22+2

Dublin, May '24

LISA CONSORTIUM

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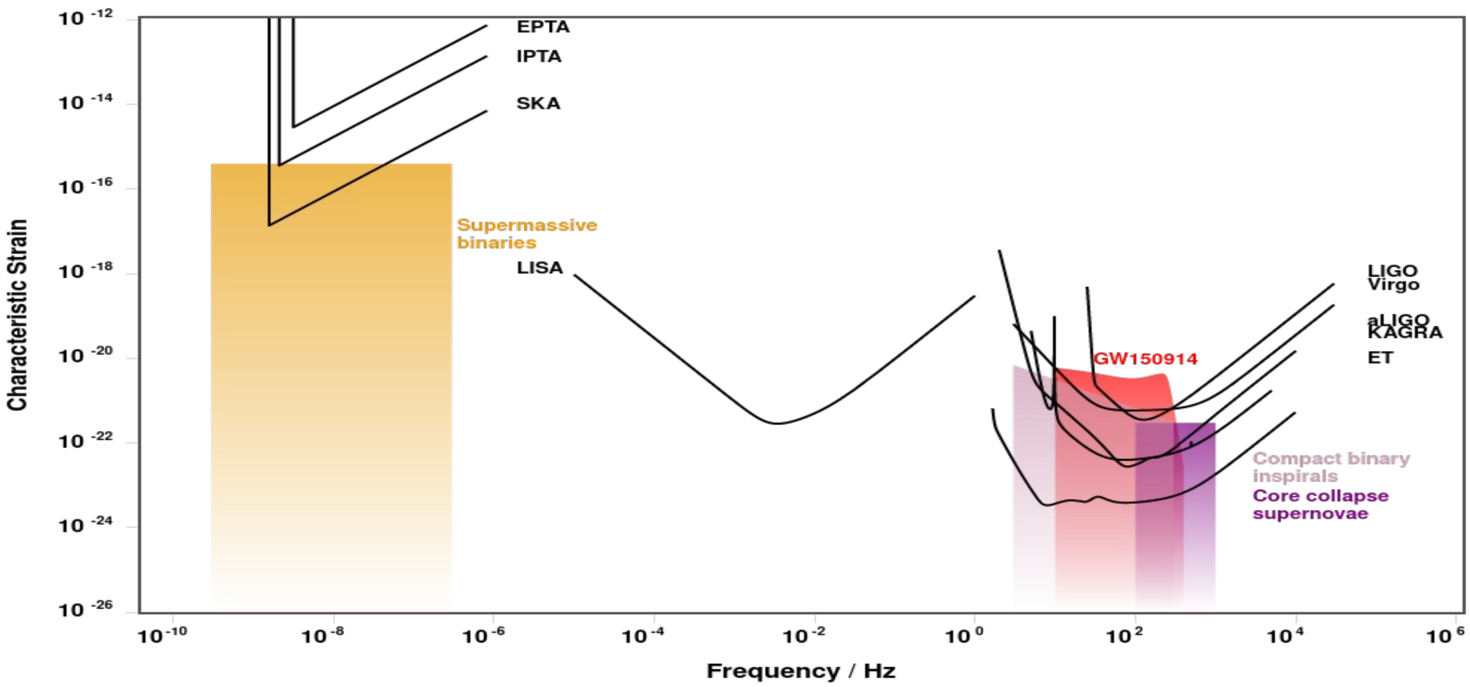
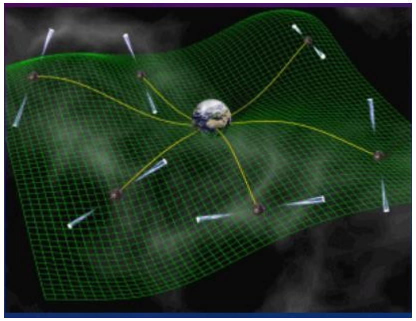
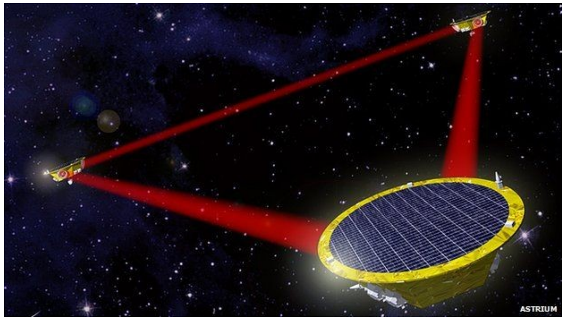
Existing Gravitational Waves Detectors

Pulsar timing arrays: GWs with 10^{-9}–10^{-6} Hz

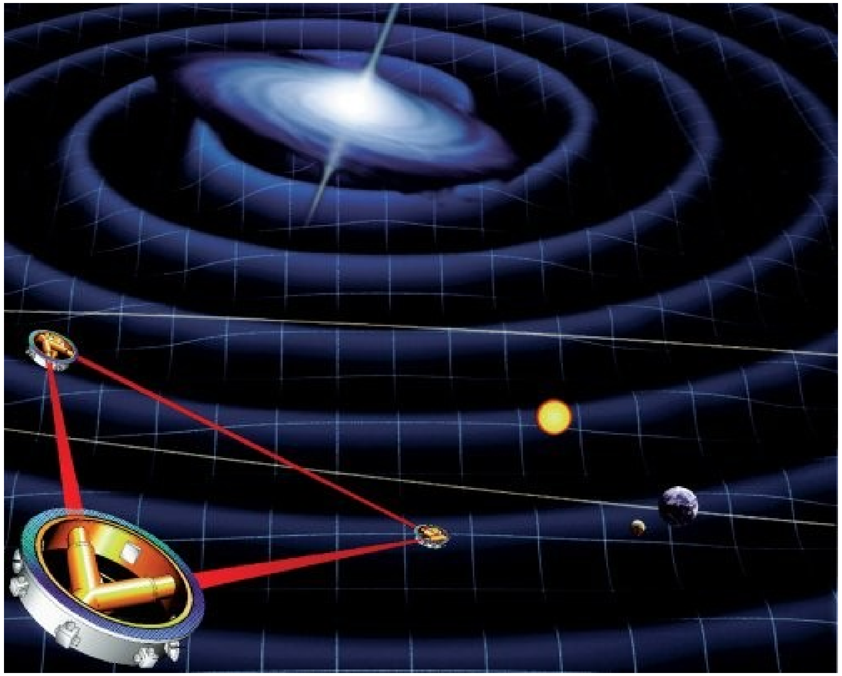
Ground-based interferometers: GWs with 10^{0}–10^{4} Hz

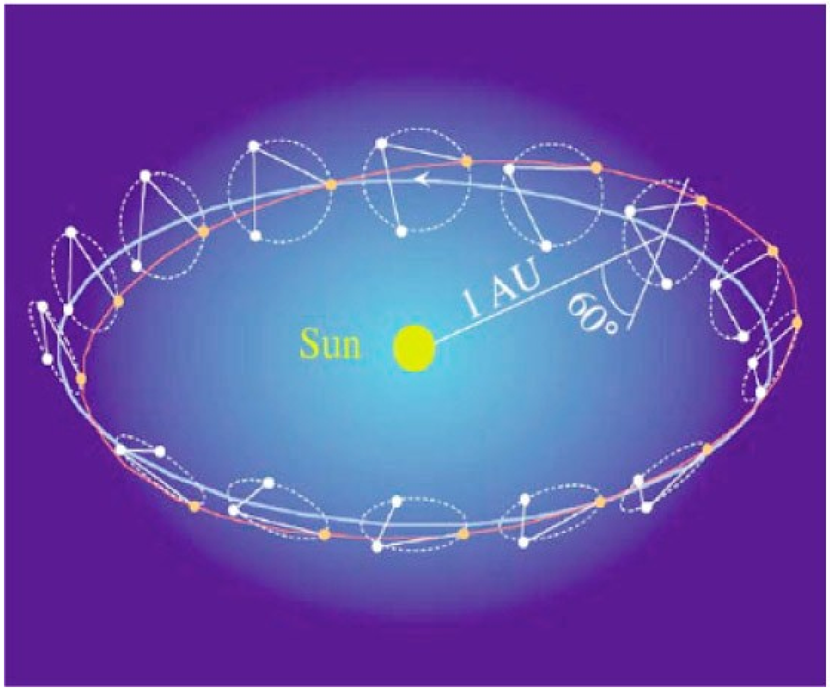






Laser Interferometer Space Antenna (LISA)

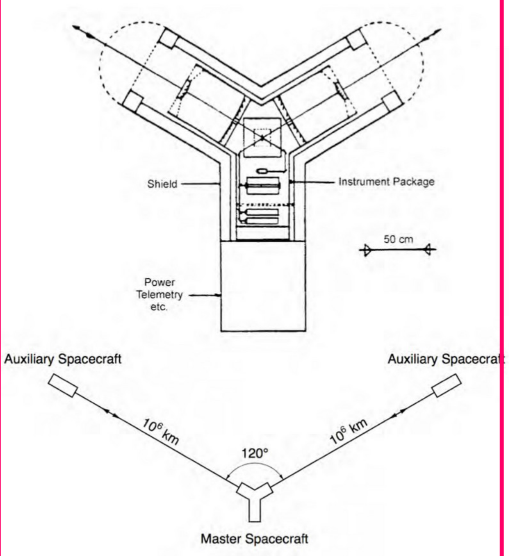




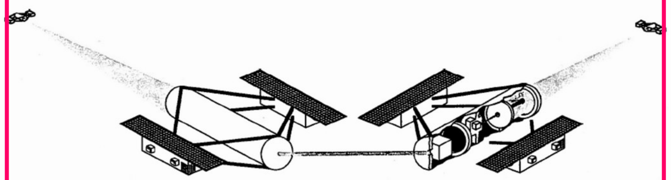
- LISA is kind of a scaled-up version of two LIGO detectors
- Three arms that are 2.5 million km long, with masses at their extrema following Earth in free fall
- The relative displacements of free-fall masses are measured by means of laser interferometry
- A GW passing through LISA displaces the free-fall masses
- Taking data for at least 3.7 (but expected ~10) years

LISA: a tribute to the "ancestors"

1981: LAGOS

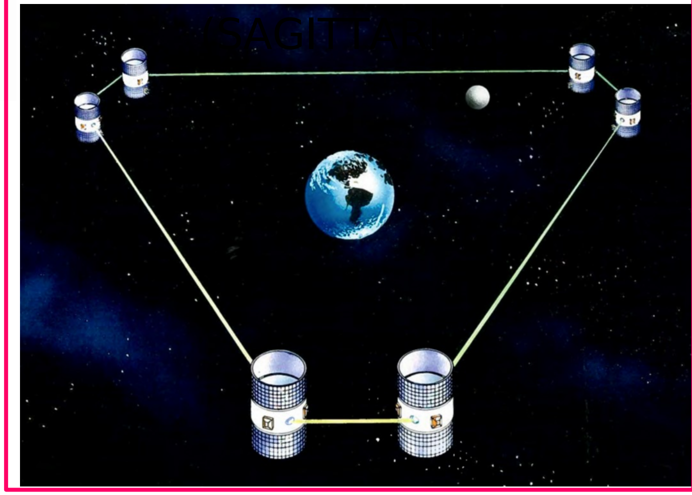


1983: LISA

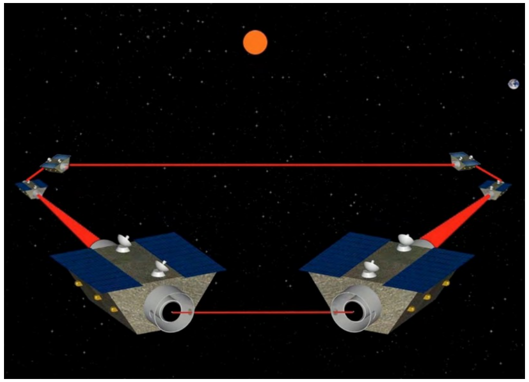


1993: SAGITTARIUS

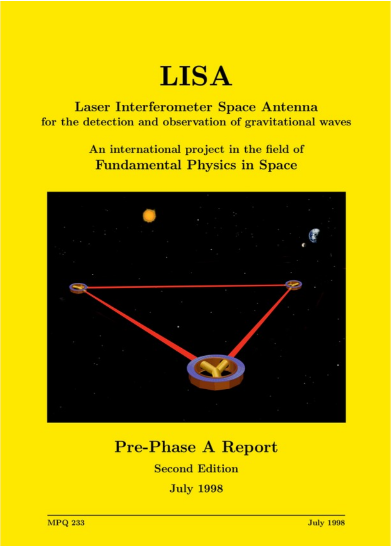
Spaceborne Astronomical Gw Interferometer To Test Aspects of Relativity and Investigate Unknown Sources



1993: LISAG



1998: LISA



LISA

Laser Interferometer Space Antenna
for the detection and observation of gravitational waves

An international project in the field of
Fundamental Physics in Space

Pre-Phase A Report
Second Edition
July 1998

MPQ 233 July 1998

- LIGO in space with Gm-long arms
- LIGO mirrors replaced by free falling masses
- Relative displacements of the masses measured by means of interferometry

LISA: recent past

ESA selects L3 science theme:

“The Gravitational Universe”

2013

2016

Results from LISA PathFinder

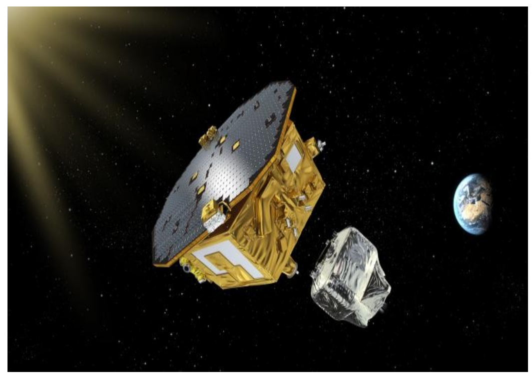
& GW150914 announcement

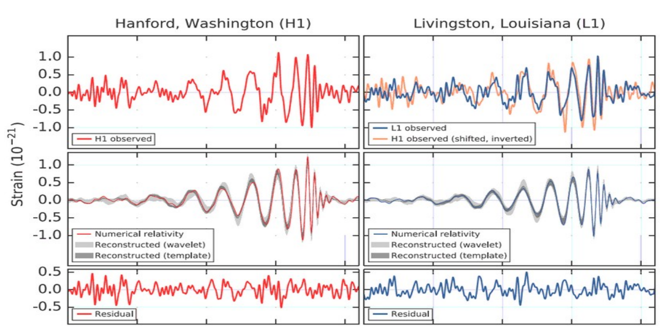
Series of papers “Science with the space-based interferometer eLISA/LISA”

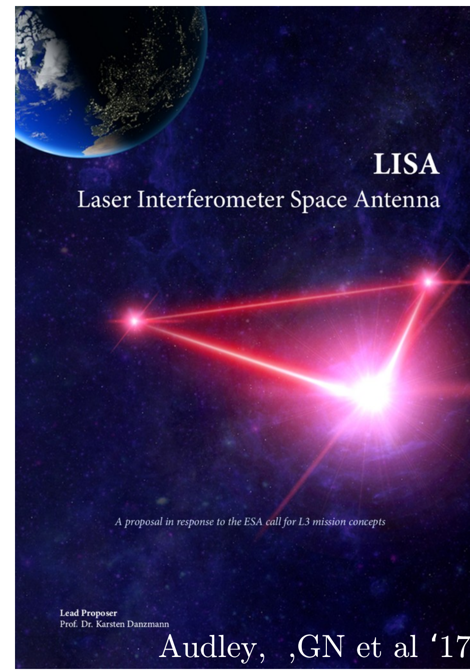
ESA L3 call

2017

Many developments

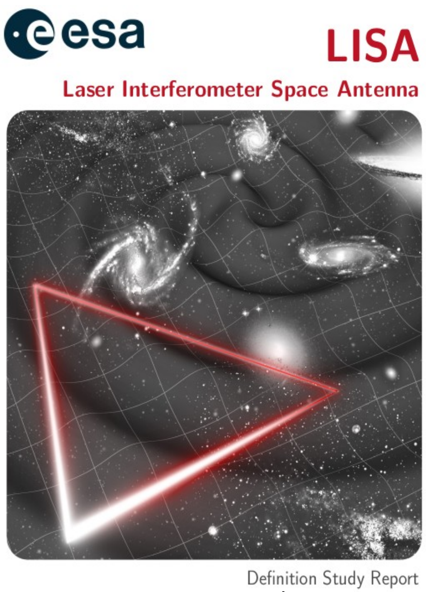






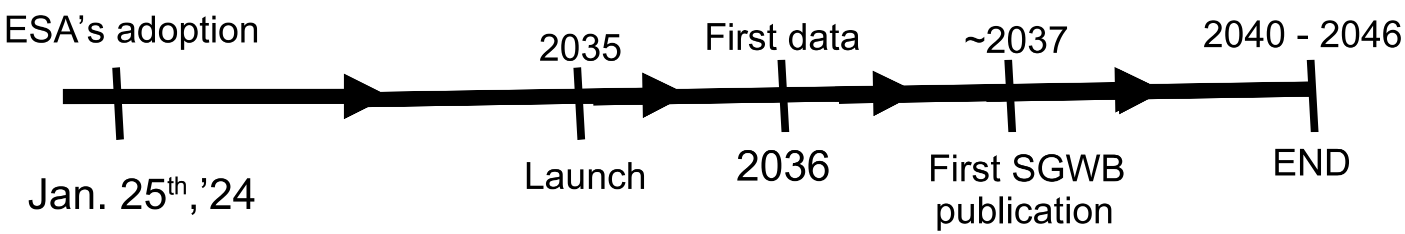
Audley, ,GN et al ‘17

LISA: now and future



Colpi, ...,GN et al '17

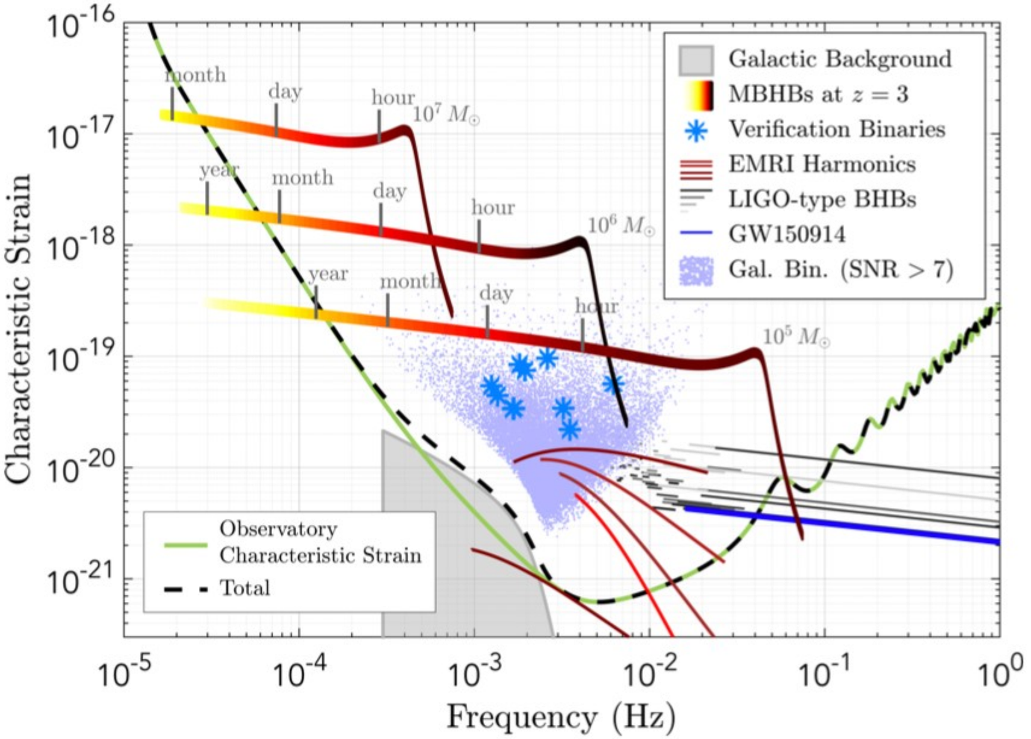
Contracts now
Building spacecrafts + Ground segment
Prototyping pipelines (~2029), validating main ones



- **Now**:
  - signing contracts with industries
  - sharping the country commitments

- Interested in contributing with data analysis, computational resources, wave forms, software&hardware engineering, … ? Contact an author coming from your country

Astrophysical sources in LISA



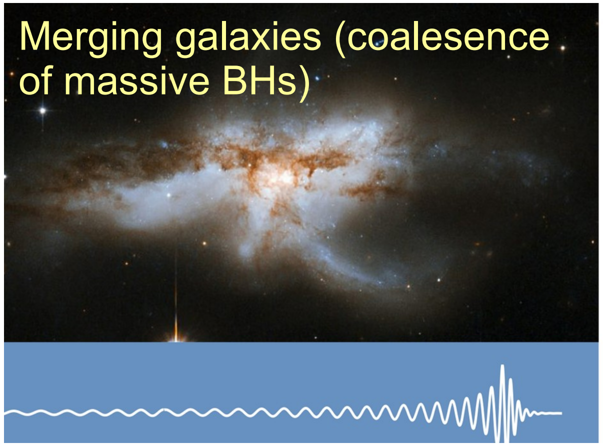
Individually <u>resolved</u> sources:

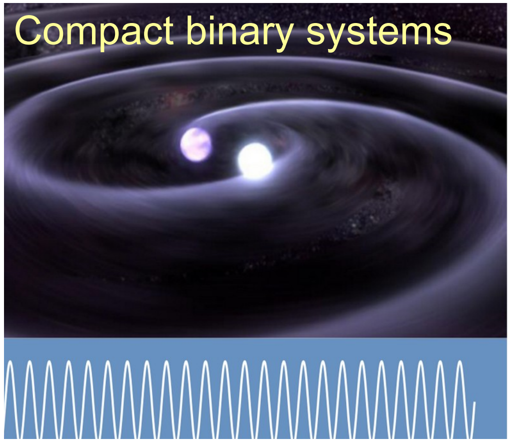
O(10^4) resolv. galac. binaries

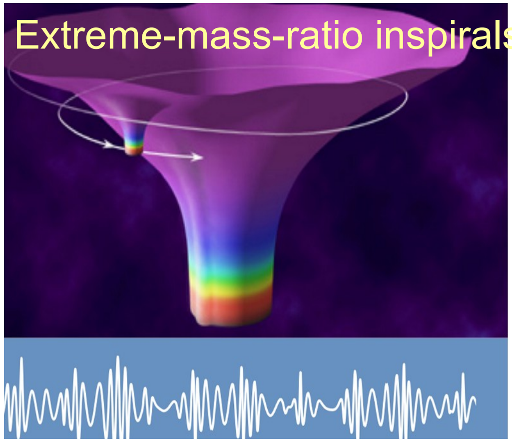
O(10) extragal. BBHs of 10^0–10^2 $M_\odot$

O(1 - 10) extreme mass-ratio inspirals

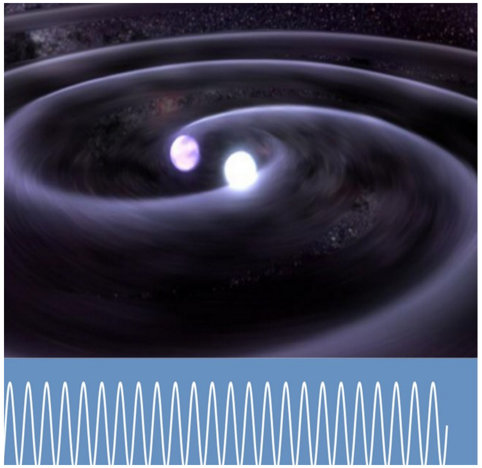
O(10 - 100) merging BBHs of 10^5–10^8 $M_\odot$

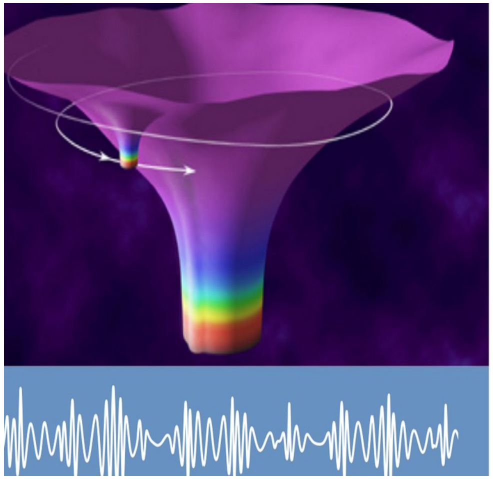


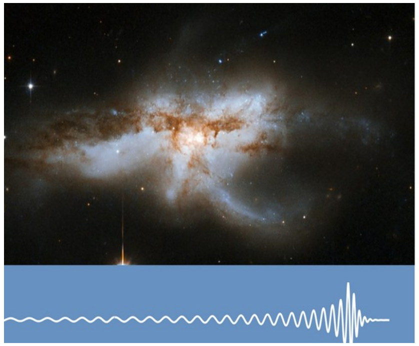


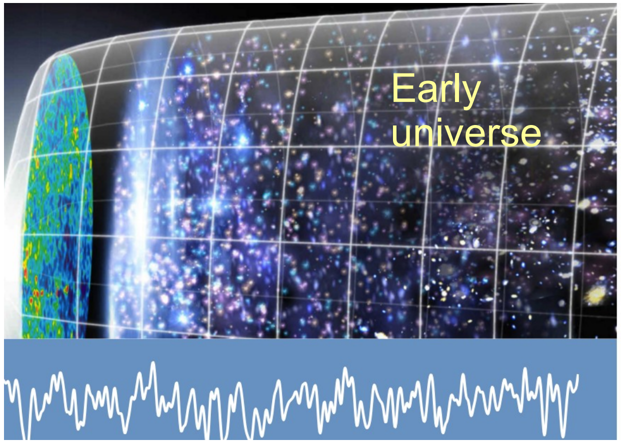


Science objectives









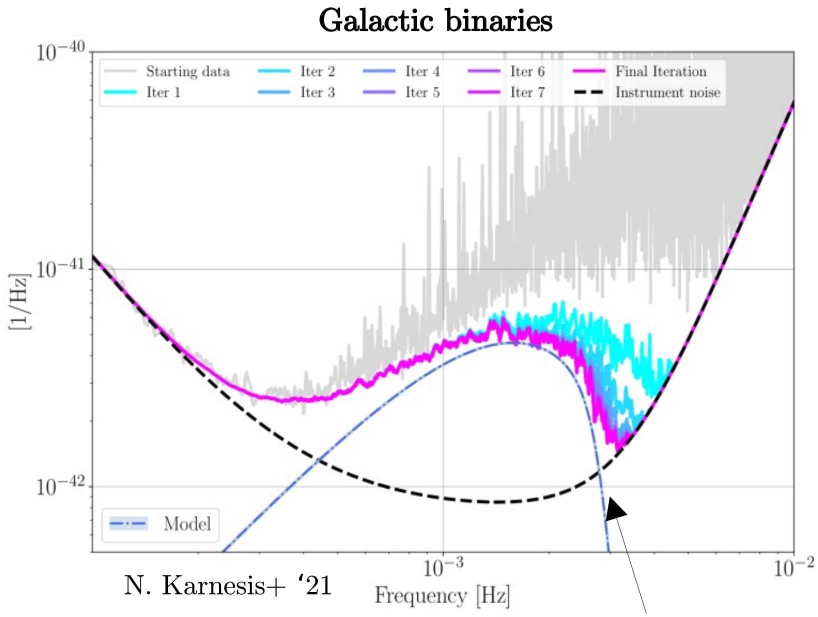
- Formation and evolution of the astro. population
- Primordial black holes ?
- BBH signatures of DM ?
- Tests of GR
- Measurement of cosmol. parameters
- Characterize the stochastic GW background (SGWB)

No science objective “surprises” but reasonably prepared to them

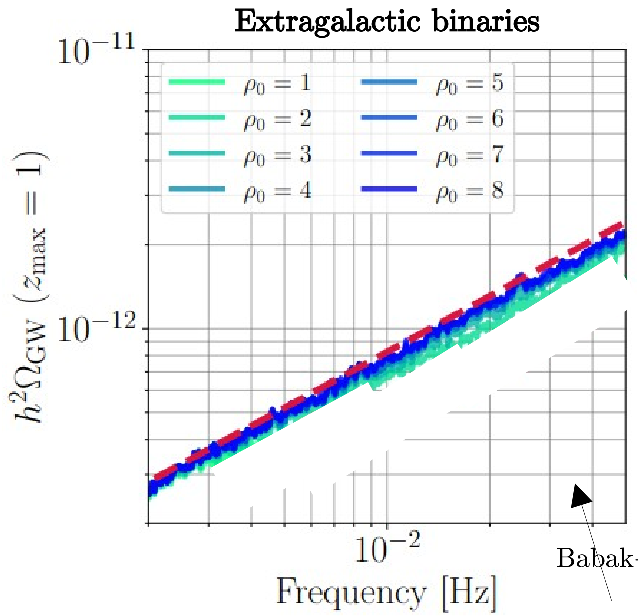
SGWB `sources': noise, unresolved binaries, cosmo SGWB

> **Instrumental noise**: its stochastic (Gaussian) component is known only within some margins, but its frequency shape "can" be parametrized → noise template.

> **Unresolved binaries**: from the total population, only the brightest sources can be individually resolved. The remaining overall signal is stochastic.



N. Karnesis+ '21



Babak+GN+. '23

Overall signal of unresolved galactic binaries

↓

Template for galactic unresolv. sources (a few param. dependence)

Overall signal of unresolved extragalactic binaries with $\rho_0 = SNR \gtrsim 4$

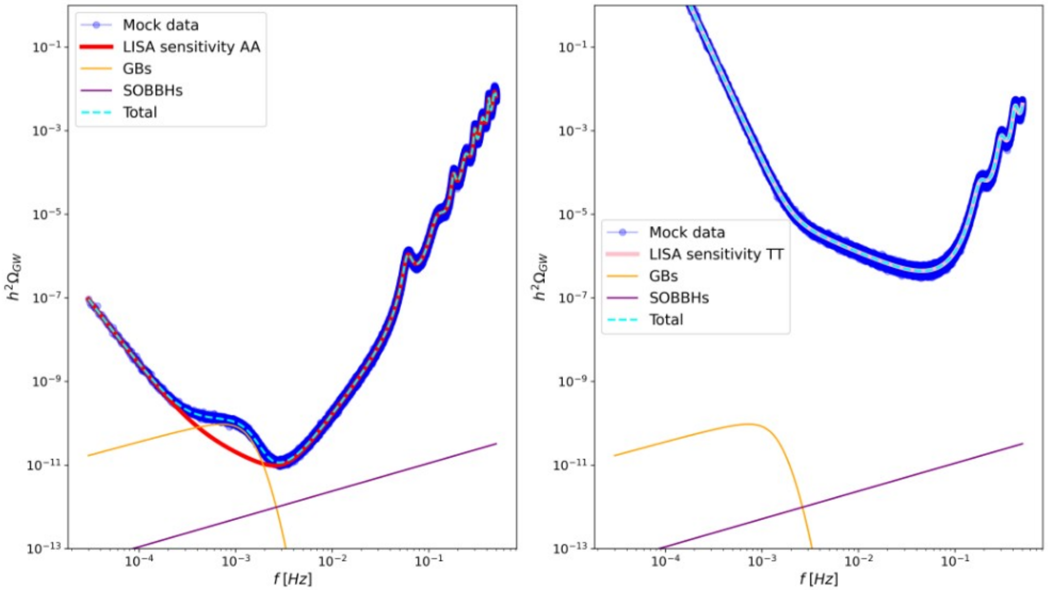
↓

Template for extragalactic unresolv. sources (a power law)

SGWB `sources’: noise, unresolved binaries, cosmo SGWB

- **Instrumental noise**: its stochastic (Gaussian) component is known only within some margins, but its frequency shape “can” be parametrized → noise template.

- **Unresolved binaries**: from the total population, only the brightest sources can be individually resolved. The remaining overall signal is stochastic.



Simulated data including noise + unresolved-binaries

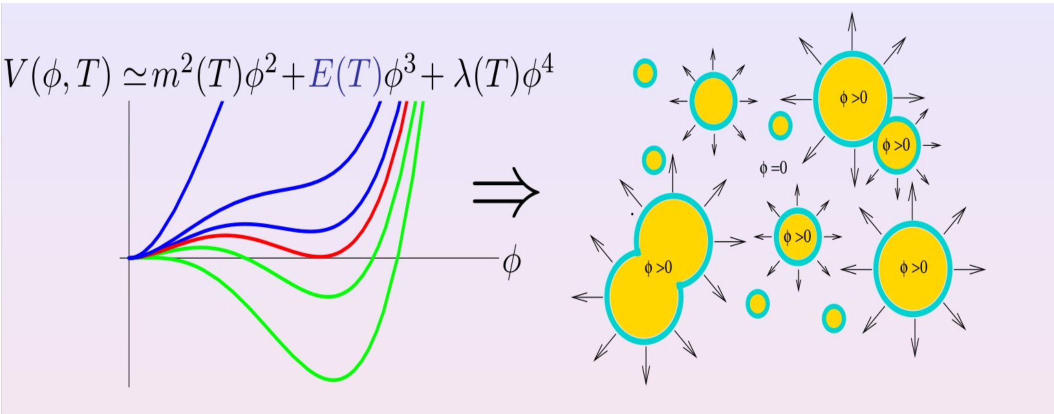
based on **templates**

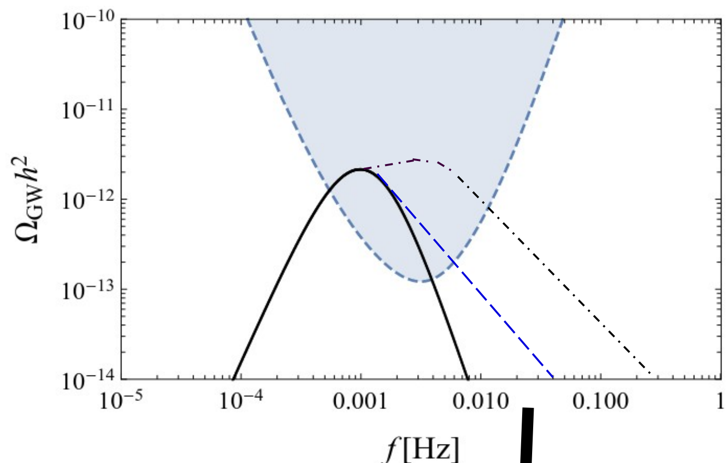
in **two** (of the three) LISA channels

Cosmological SGWB: First-order phase transition
(but also some scenarios of cosmic strings, inflation, ….)

Details in many previous talks

First-order phase transitions: bubbles produced in spontaneous symmetry breakings via tunnelings or thermal jumps





Templates for FOPT sources
(broken power law OR double broken power law OR sum of the two)

Parameters:

α : approx. max. energy that can be converted in GW radiation

β/H : duration of the phase transition

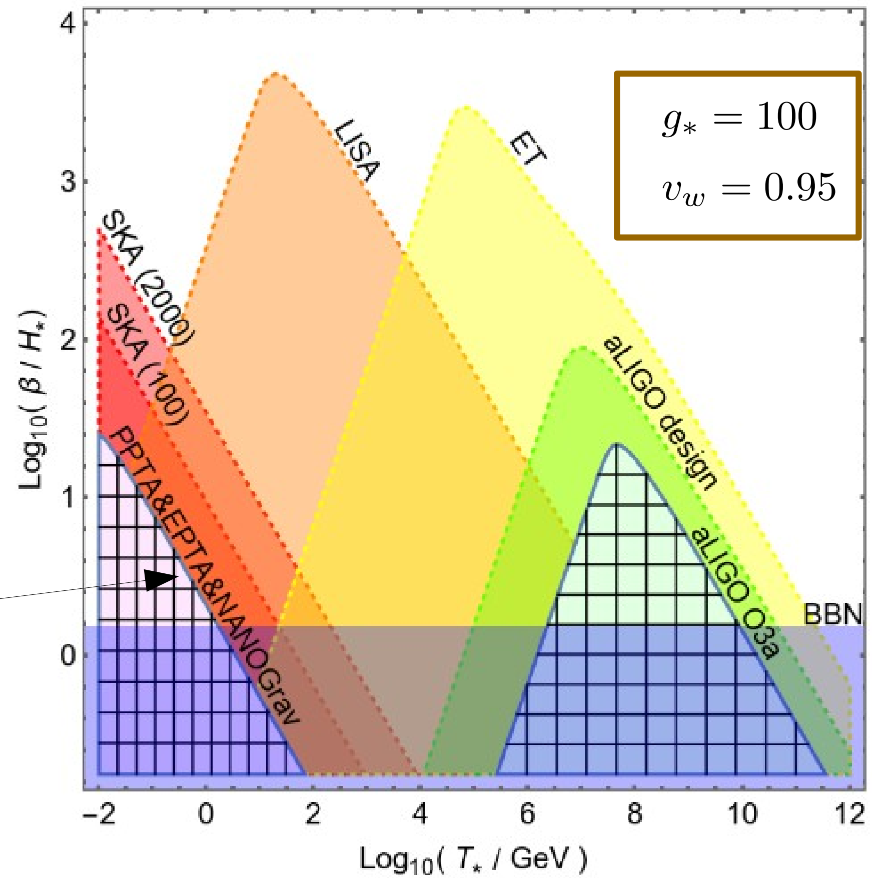
T_* : universe temperature when bubbles collide

v_w : bubble wall velocity

κ_i : efficiency factor of each contribution (bubble wall, sound wave, turbulence)

LISA CosWG (C.Caprini, ..., GN et al.) '15
LISA CosWG (C. Caprini, .., GN et al.) '19
LISA CosWG (P.Auclair, .. , GN et al.) '22

1st-Order-PT parameter space (with old template)



If no SGWB signal
from FOPT in PTA

Taking SNR > 10 as detection/non-detection criterion

E. Megias, GN, M. Quiros, ‘18
LISA CosWG (P. Auclair, …, GN et al.) ‘22

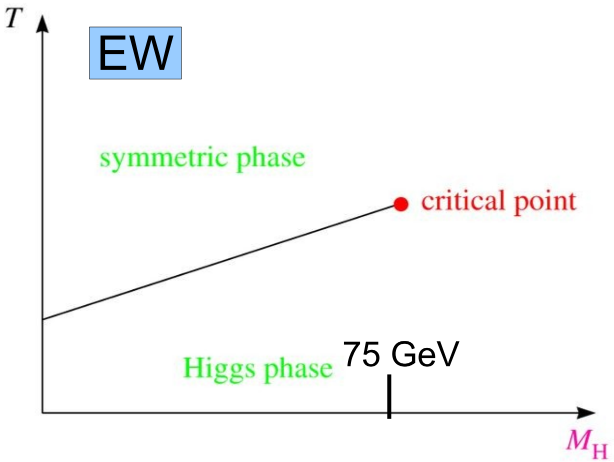
Synergies among GW detectors

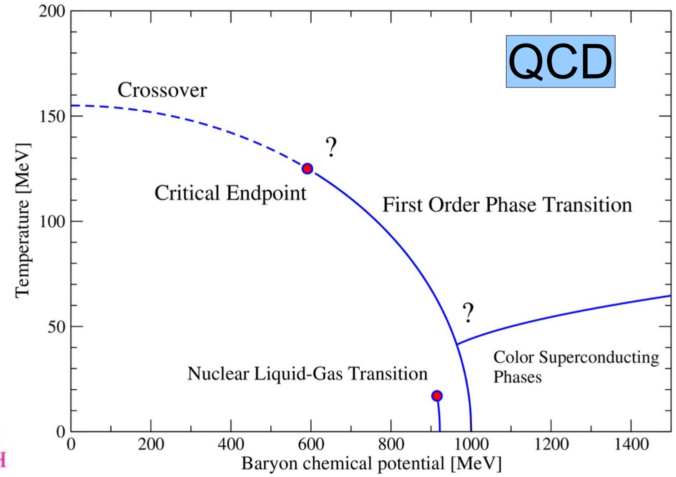
Parameters:

α : approx. max. energy that can be converted in GW radiation
β/H : duration of the phase transition
T_R : universe temperature when bubbles collide
v_w : bubble wall velocity
κ_i : efficiency factor of each contribution (**bubble wall**, sound wave, turbulence)

Model building for FOPT

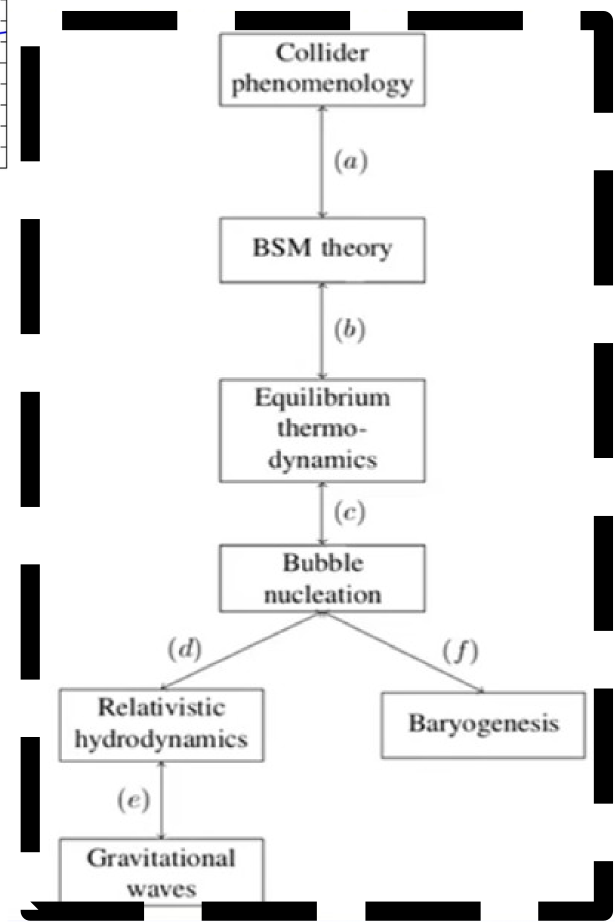
Synergies with FCC





Kajantie et al. '96
Karsh,Neuhaus,Patkos '96
Csikor,Fodor,Hietger '98

Gunkel et al. '21
Wigas, Oldengott + Bielefeld '18



- No FOPT in the SM of particles/cosmology
  - Conceivable in hidden sectors, at high scales, EW extensions, …

FOPT signal = BSM physics

FOPT detection

We have:

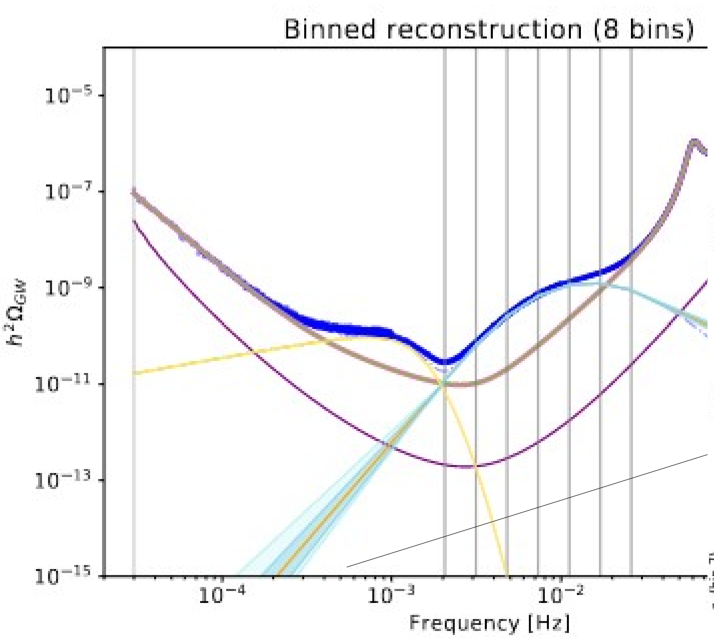
- waveforms for resolvable binaries (guaranteed but omitted here)
- the template for the noise (guaranteed signal)
- the templates for the astrophysical SGWBs (guaranteed signal)
- the template for the FOPT SGWB (possible signal)

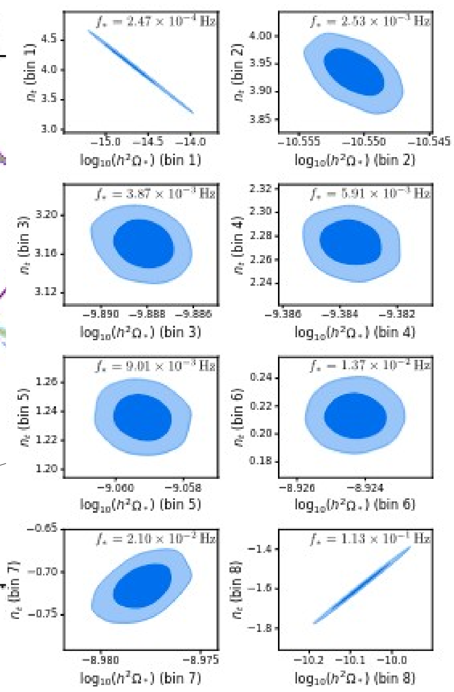
Now, let's assume THERE IS A FOPT SGWB IN THE LISA FREQUENCY BAND.

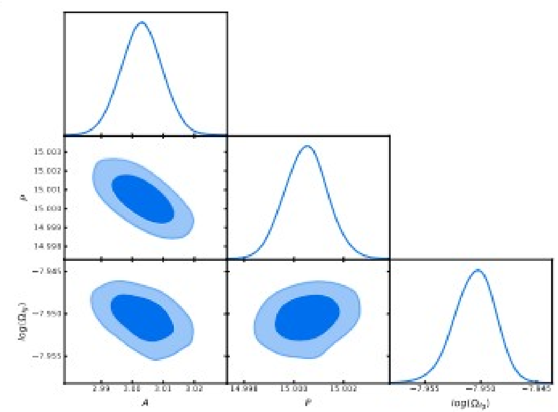
How well can we detect the FOPT signal ?

Cosmo SGWB agnostic reconstruction
i.e. *would you trust theorist's cosmo. templates? :-)*

- Still requires templates for noise and astro. SGWB
- Cosmo. SGWB reconstruction as power law in small bins with optimized width (start with many bins, and merge them not to overfit)
- Source identification from the agnostic reconstruction of freq. shape
- Check whether it looks like one of your FOPT template or what





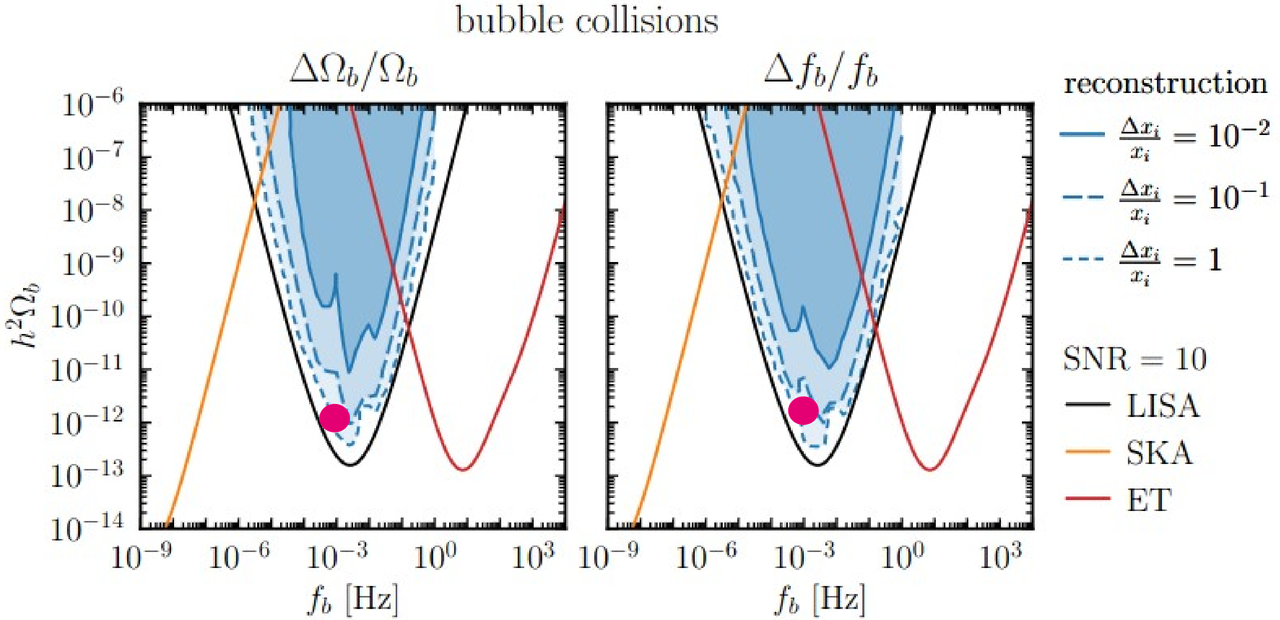


(c)

Flauger, Karnesis, GN, Pieroni et al '20; Caprini, …, GN, Pieroni et al. '19

FOPT template-based recostruction (for bubble coll.)

Broken Pow. Law parameters



geometrical-param. template

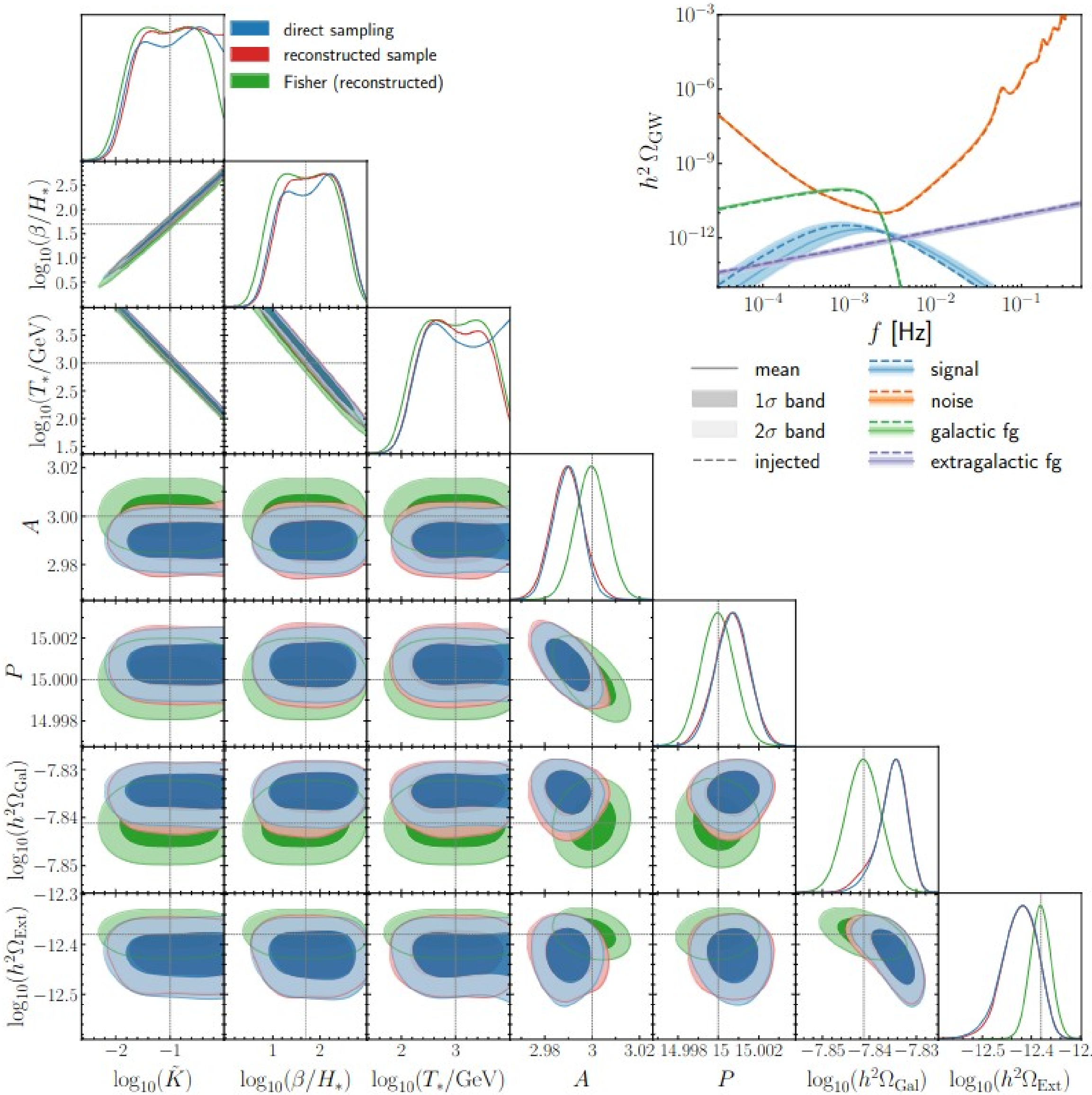
$$\Omega_{\rm GW}^{\rm BPL}(f) = \Omega_b \left(\frac{f}{f_b}\right)^{n_1} \left[\frac{1}{2} + \frac{1}{2}\left(\frac{f}{f_b}\right)^{a_1}\right]^{\frac{n_2-n_1}{a_1}}$$

$n_1 = 2.4\,,\quad n_2 = -2.4\,,\quad a_1 = 1/2$ Lewicki+Vaskonen, '23

Param. reconstruction : 2 geom. vs 3 therm. param. DEGENERACY!

FOPT template-based recostruction (for bubble coll.)

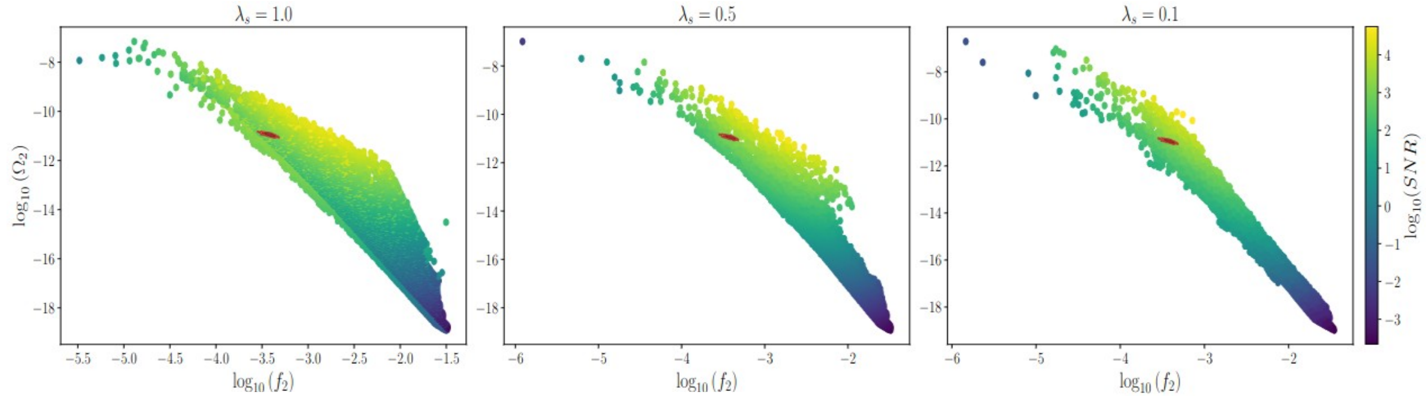
Broken Pow. Law parameters → **Thermodyn. parameters**

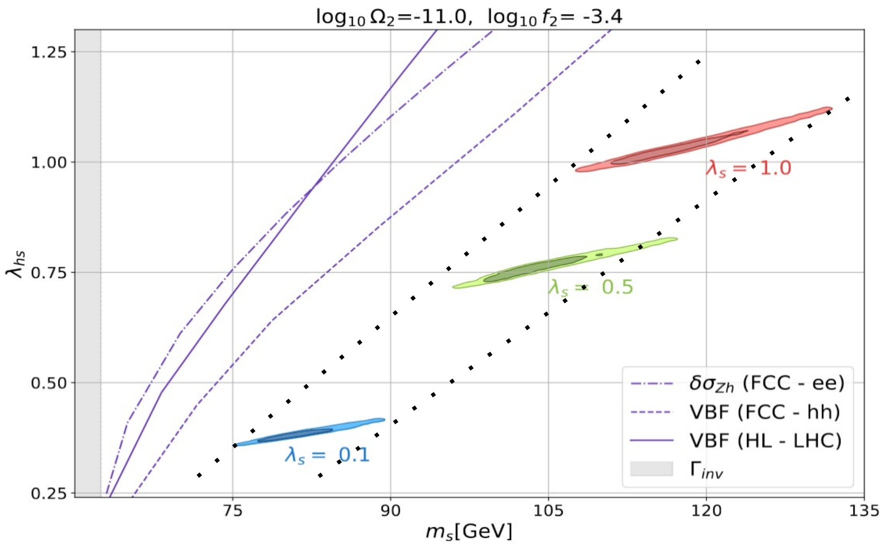


FOPT template-based recostruction (for bubble coll.)

Broken Pow. Law param. → Thermodyn. param. → **Particle physics param.**

Assume BPL signal $\log_{10}\Omega_2$=-11.0, $\log_{10} f_2$= -3.4 is detected, and you map it to the Z_2 singlet model





Proof of principle

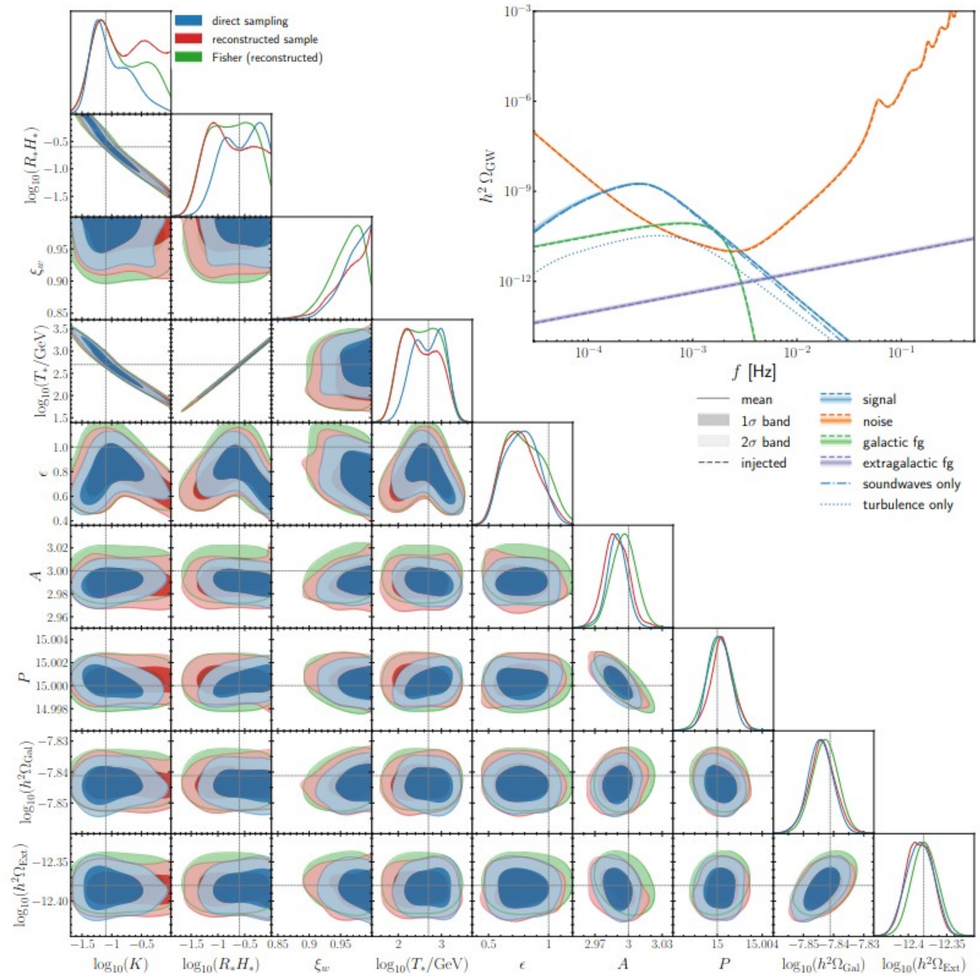
(If theoretical errors are subdominant. True in 10yr?)

For other FOPT SGWB dynamics [(for sound waves and/or turbulence)]

SGWB from sound waves → Double Broken Pow. Law

SGWB from turbul. → slightly diff. Double Broken Pow. Law

Similar rationale



LISA CosWG (Caprini, Jinno, Lewicki, Madge, Merchand, GN, Pieroni, Pol, Vaskonen)'24

Conclusions

- The FOPT detection would be a proof of BSM physics

- Accurate primordial SGWB reconstruction (or bound) requires accurate modelling of:
  - the signal of the unresolvable binaries in LISA
  - the LISA noise

  Effort of several communities

- If such an accurate knowledge will be achieved, LISA can reconstruct the parameters of reasonably strong primordial SGWBs at O(1%) level or better

- Reconstruction with 1% accuracy is useless if not accompanied by theoretical predictions/interpretation having the same accuracy

- LISA flies in ~1 decade, but prioritization, science feasibility and prototyping happen in the next ~5 years. Industry contracts are now!