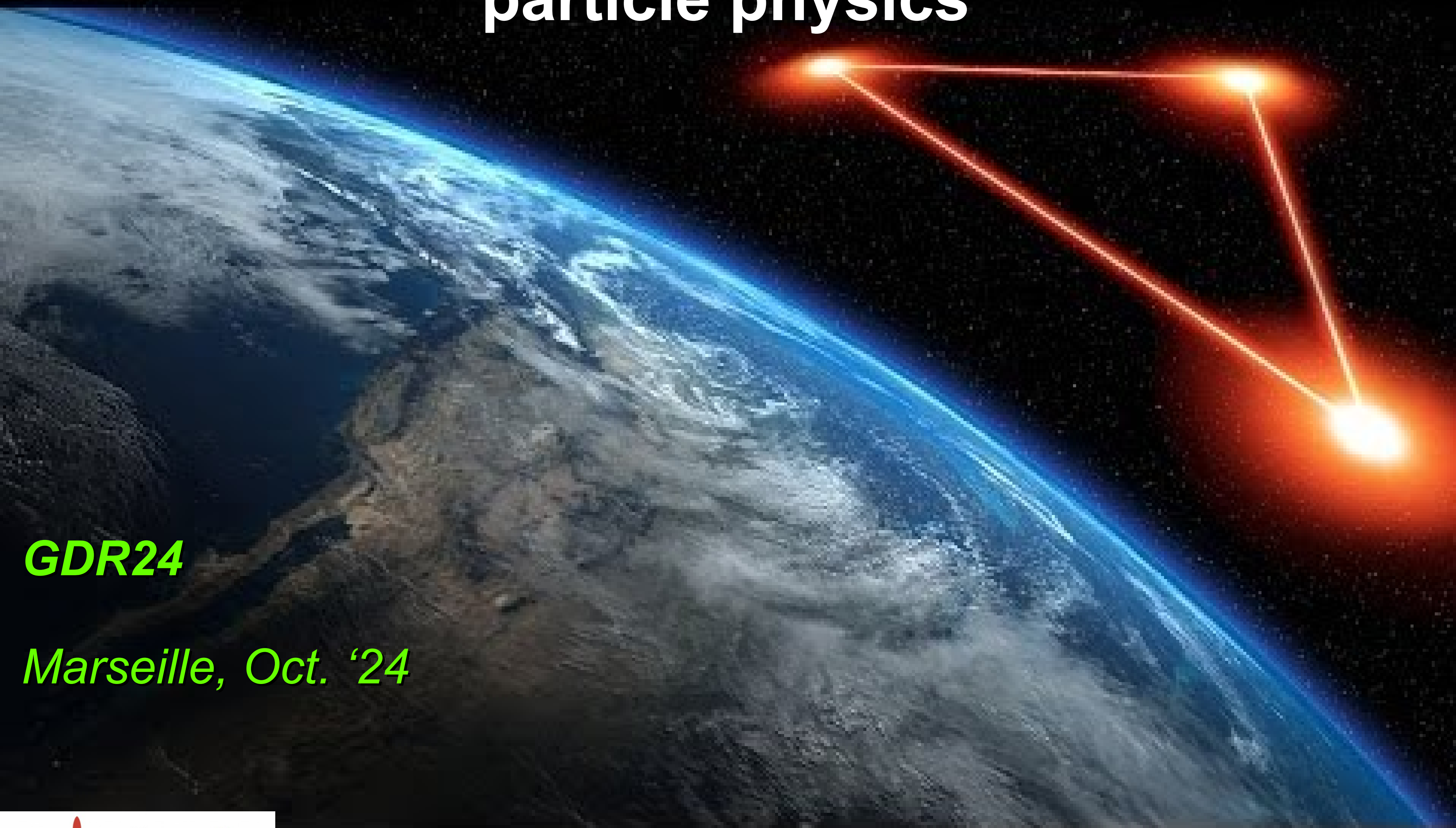
LISA as a probe of particle physics



GDR24

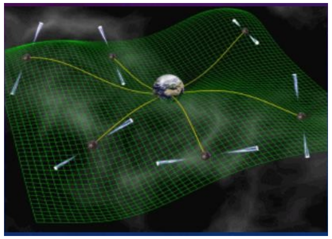
Marseille, Oct. '24

Germano Nardini

University of Stavanger

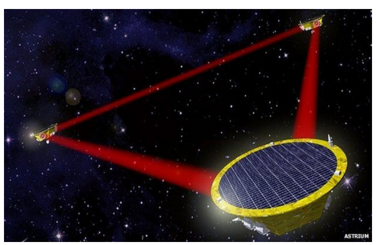
LISA CONSORTIUM

GW experiment and potential-collider timelines



SGWB 4-sigma hint — Jun.'23
~2026 — IPTA joint analysis
~2030 — SKA

LVK GWTC-3 — 2021
~2024 — GWTC-4
O5 — ~2030
~2040 — ET

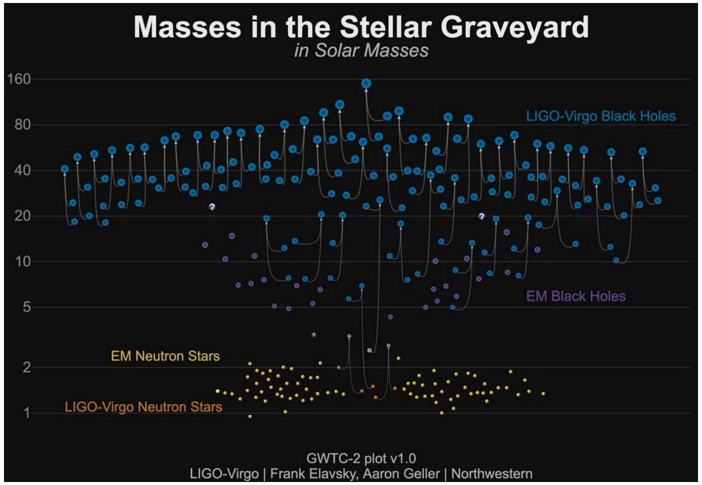


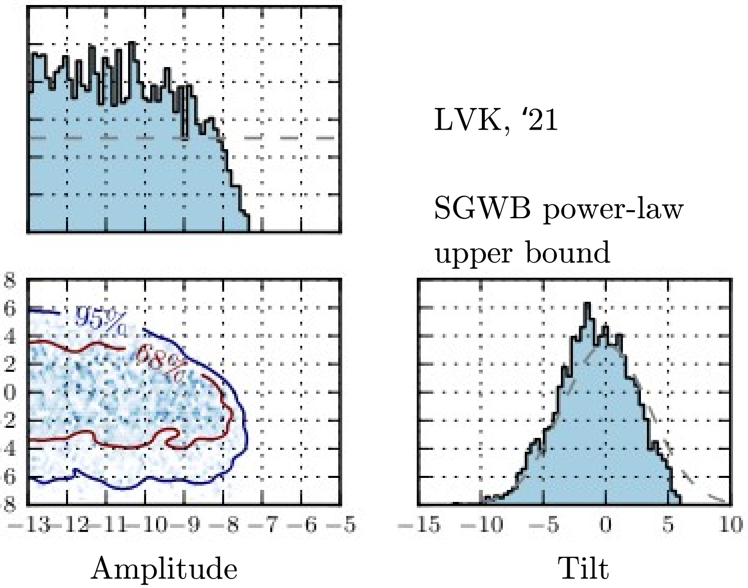
ESA's adoption — Jan. 25th,'24
2035 — Launch
First data — 2036
~2037 — First SGWB announcement
2040 / 2046 — END

~2029 — HL-LHC
~2040 — FCC-ee

BSM status at GW experiments (brutally brief and biased)

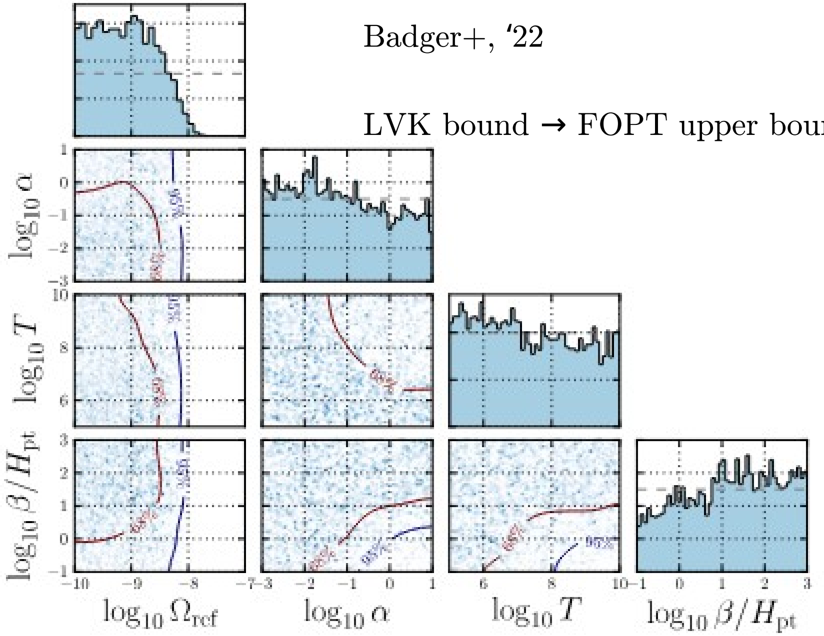
LVK





LVK, '21

SGWB power-law upper bound



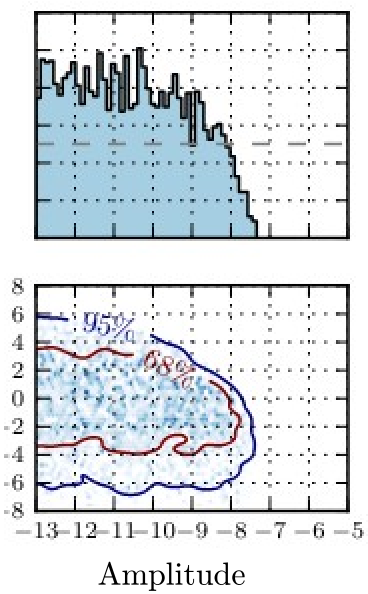
Badger+, '22

LVK bound → FOPT upper bound

BSM status at GW experiments (brutally brief and biased)

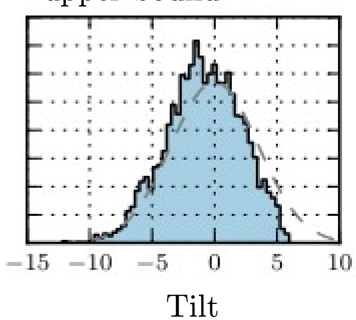
LVK

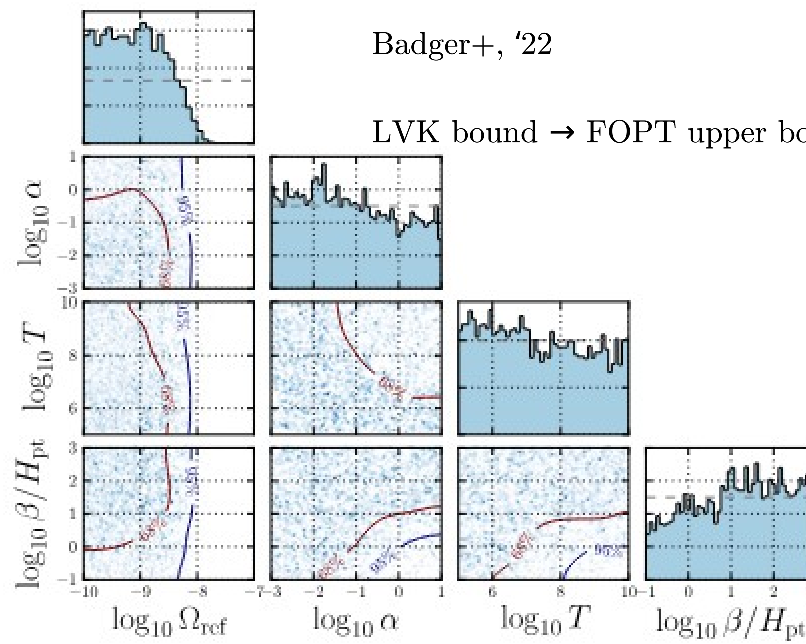
- Observations compatible with “expected” astronomy
- Recast observations give weak upper bounds on BSM physics at ~$10^{6\text{-}10}$ GeV
- Likely, no huge progress before ET due to the soonish-emerging binary foreground



LVK, ‘21

SGWB power-law upper bound

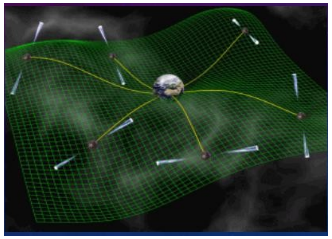




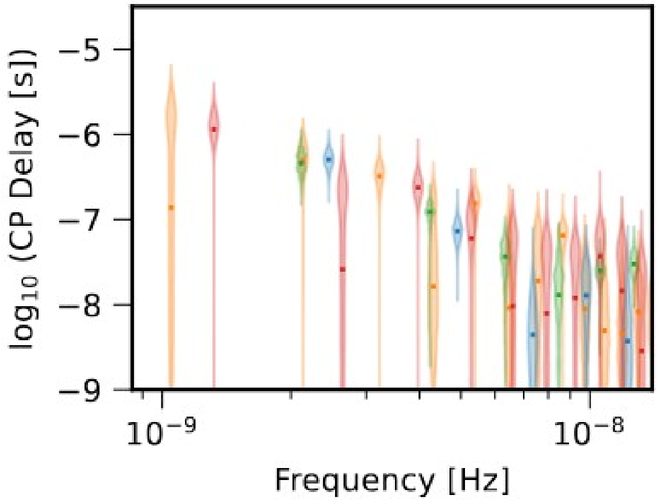
Badger+, ‘22

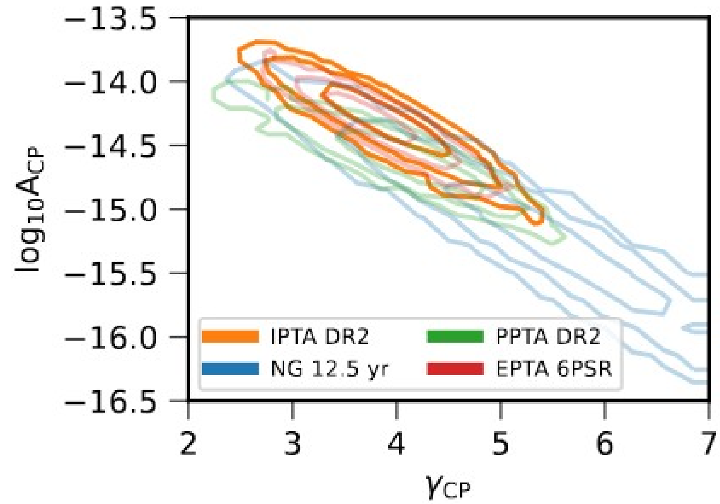
LVK bound → FOPT upper bound

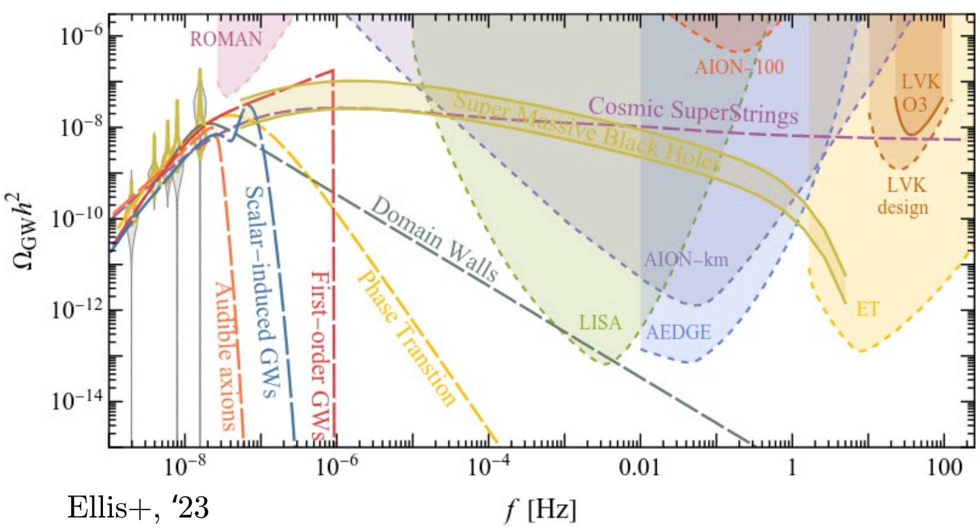
BSM status at GW experiments (brutally brief and biased)



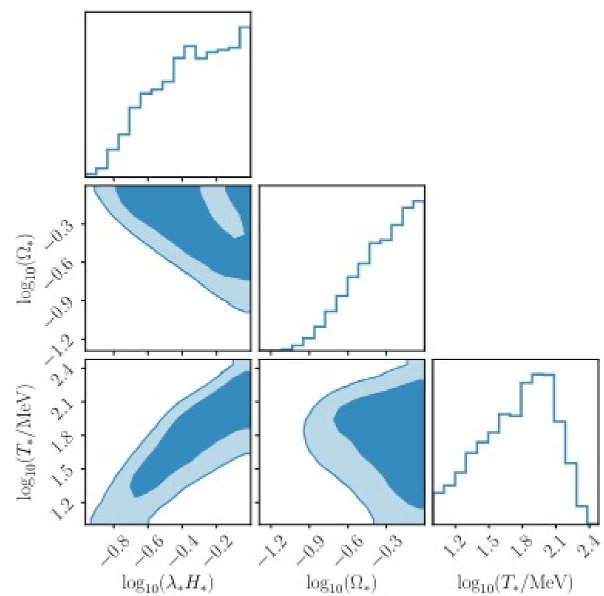
PTA





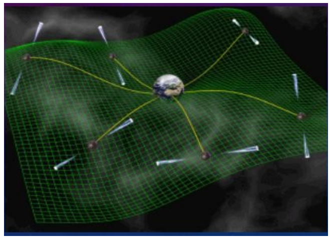


Ellis+, ‘23

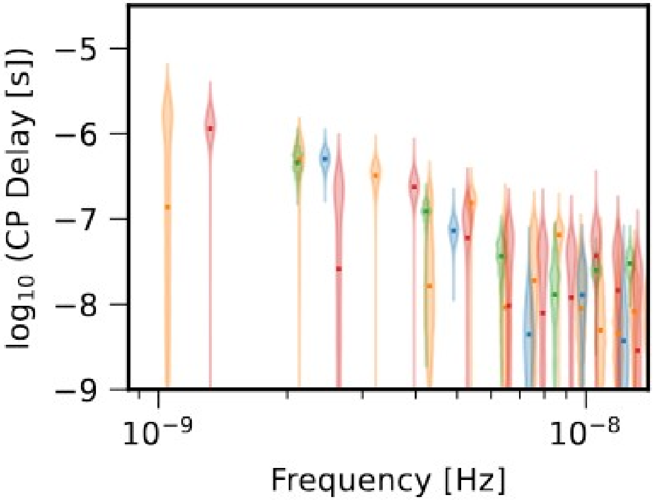


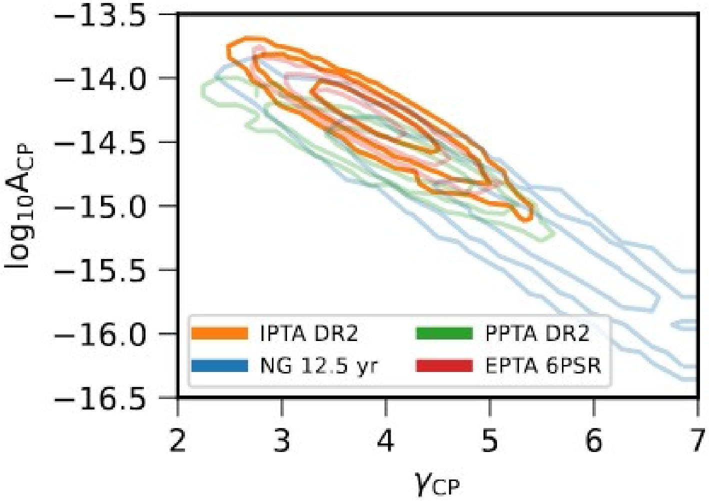
EPTA Coll., ‘23

BSM status at GW experiments (brutally brief and biased)



PTA





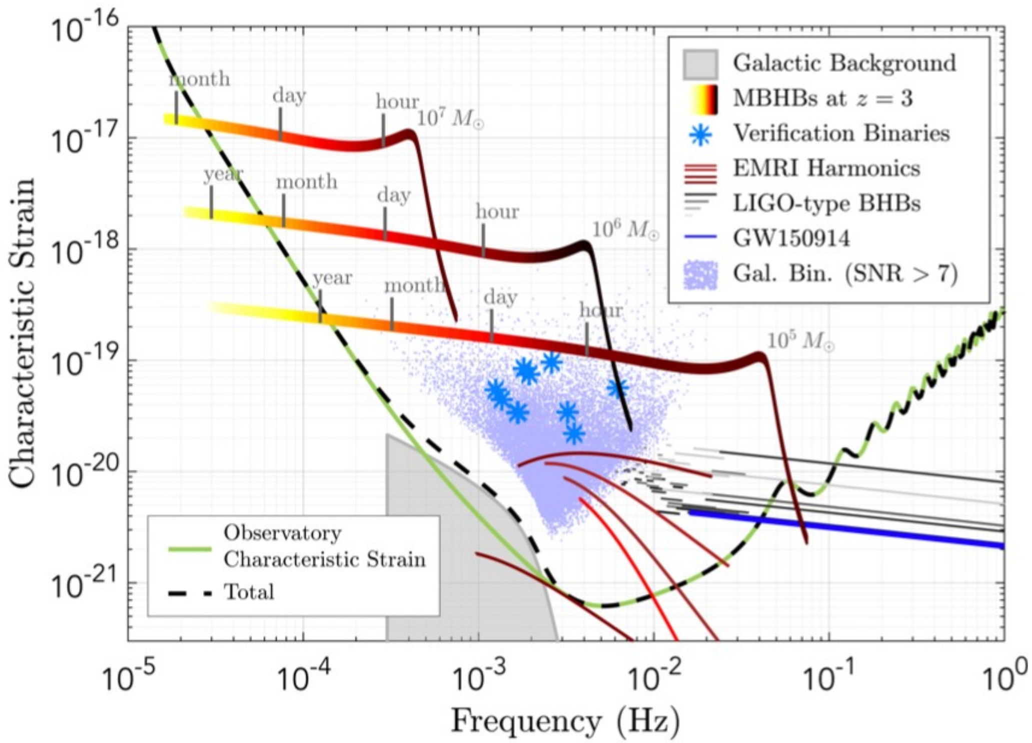
MAYBE A BSM HINT, MAYBE NOT

- Compatible with SMBBH-only SGWB
  (non-circular binaries with environmental effects)

- A few sub-threshold SMBBHs + SMBBH SGWB
  (anisotropic contribution boosts the signal at some frequencies + weaker SGWB)

- If no BSM hint, low progress on BSM physics
  (you need to dig out the BSM signal from a strong SOBBH SGWB)

What about LISA?   The mission targets

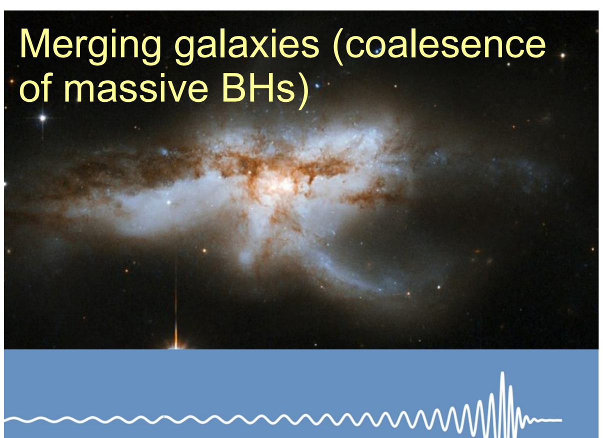


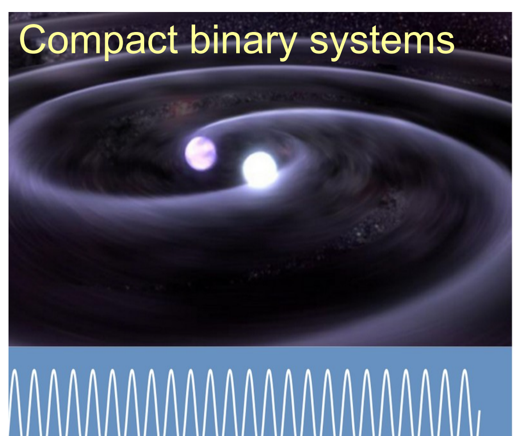
O(10^4) resolv. galac. binaries

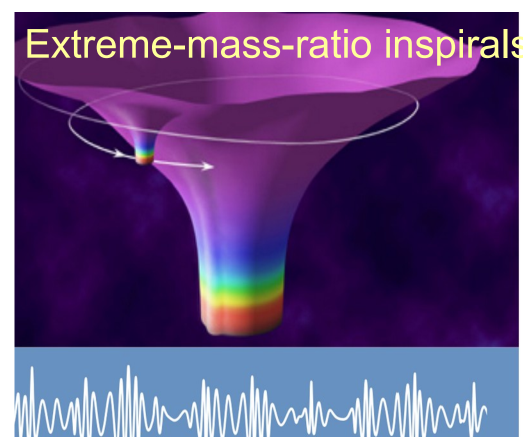
O(10) extragal. BBHs of 10^0–10^2 $M_\odot$

O(1 - 10) extreme mass-ratio inspirals

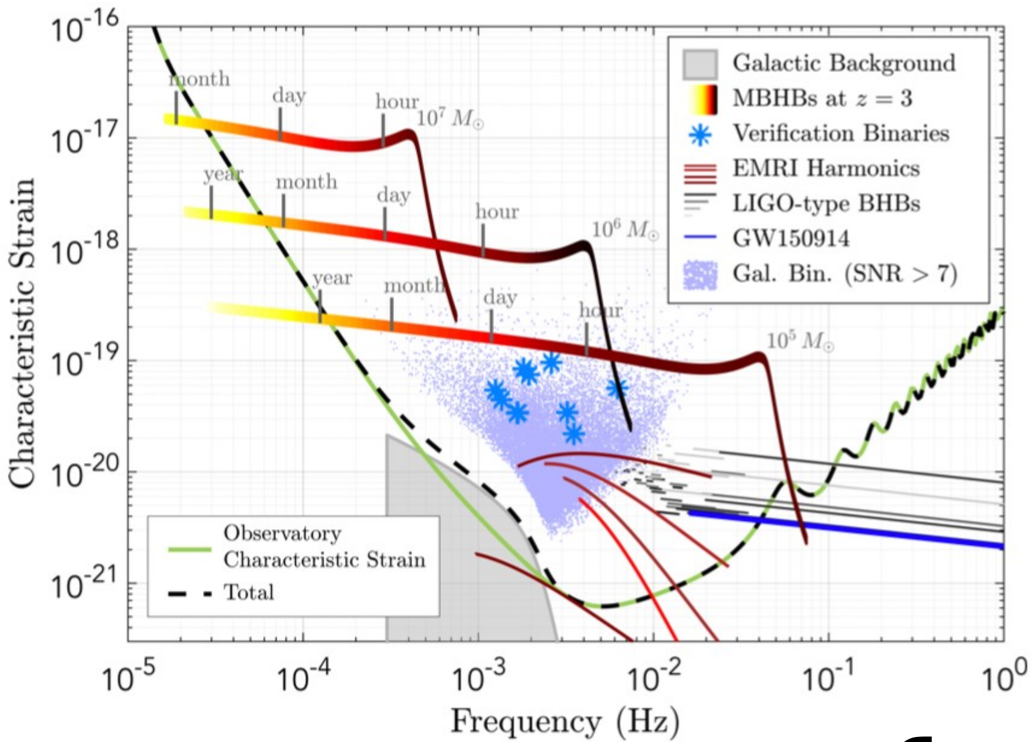
O(10 - 100) merging BBHs of 10^5–10^8 $M_\odot$

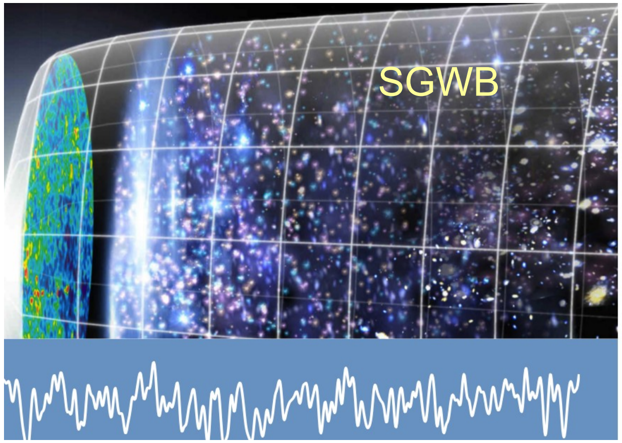






What about LISA? The mission targets



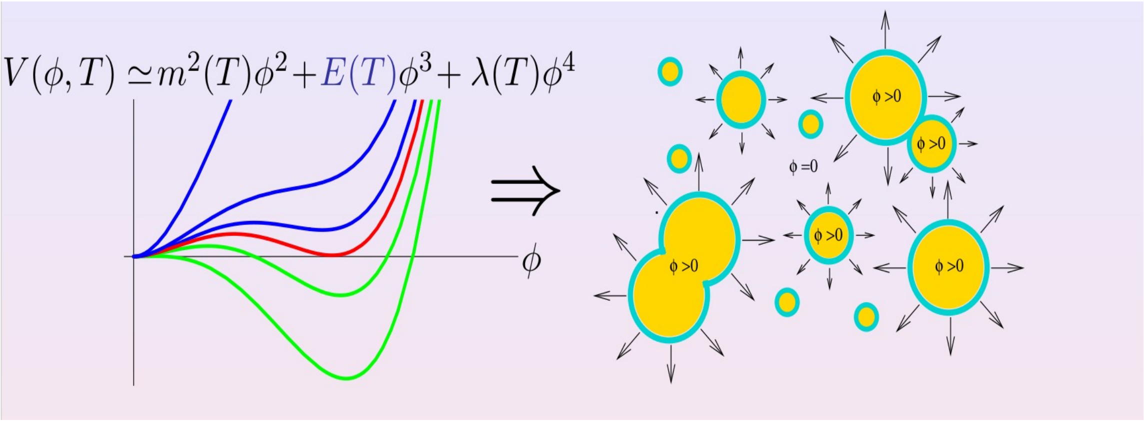


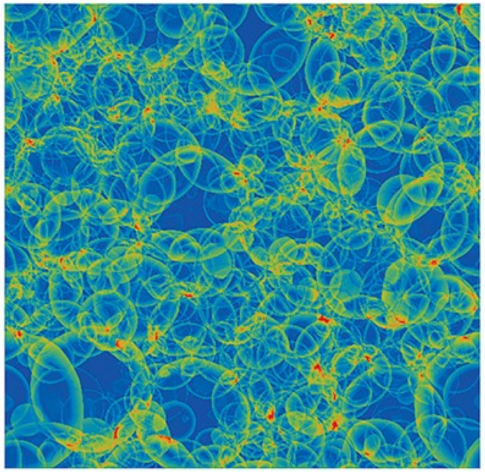
SGWB
- Astronomical sources
  - Galactic binaries
  - Extra-Gal. binaries
- Cosmological sources
  - Cosmic strings, Domain walls
  - FOPT, Inflation

SGWB from a first-order phase transition (FOPT)

Some BSM models predict that, in the hot universe, some symmetries break via FOPTs

FOPT → Many bubbles in a Hubble volume → Isotropic SGWB





<u>Parameters</u>:

$K(\alpha)$: approx. max. energy that can be converted into GW radiation

β/H : inverse duration of the phase transition

T_* : universe temperature when bubbles collide

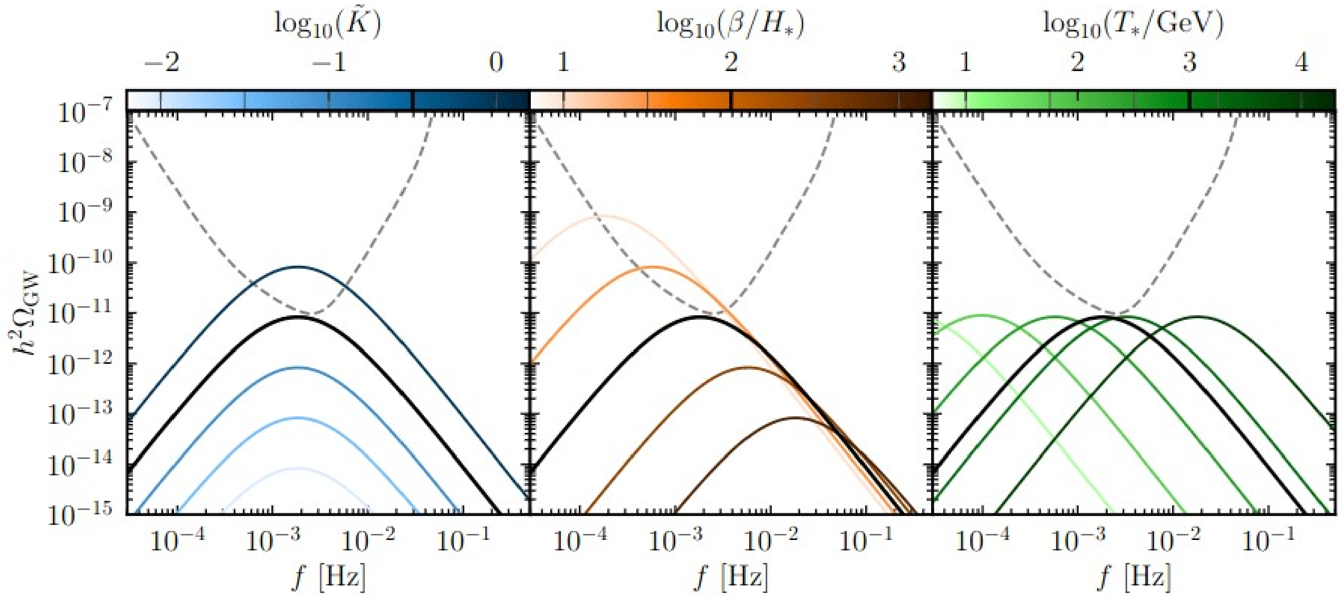
ξ_w : bubble wall velocity

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

LISA CosWG (C.Caprini+...+GN+) '15 ; '19

SGWB from a FOPT : templates (for bubble coll.)

BSM leading to "relativistic bubbles" ($\xi_w \simeq 1$; $\kappa = 1$; free β/H , T_* , K)
→ SGWB broken power-law shape



Simulations hint to the geometric-param. template

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

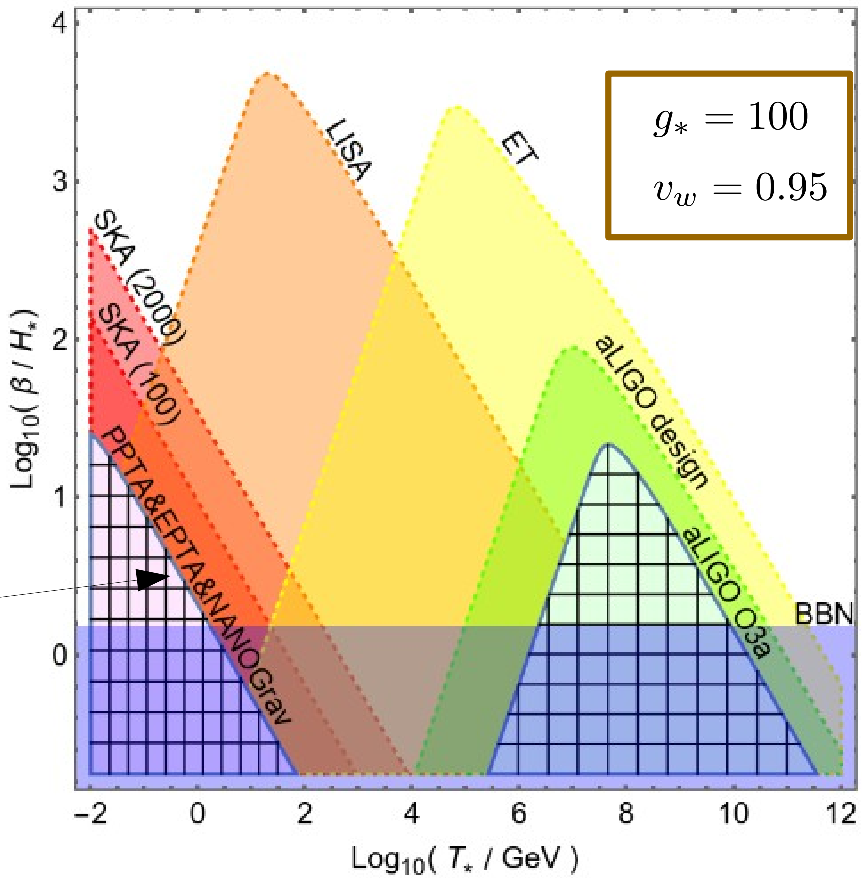
$n_1 = 2.4\,,\quad n_2 = -2.4\,,\quad a_1 = 1/2$ Lewicki+Vaskonen, '23, Cutting+,'18

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

SGWB from a FOPT : parameter reach (for bubble coll.)

BSM leading to “relativistic bubbles” $(\xi_w \simeq 1; \quad \kappa = 1; \quad$ free $\beta/H\,,\ T_*\,,\ K\,)$

→ SGWB broken power-law shape



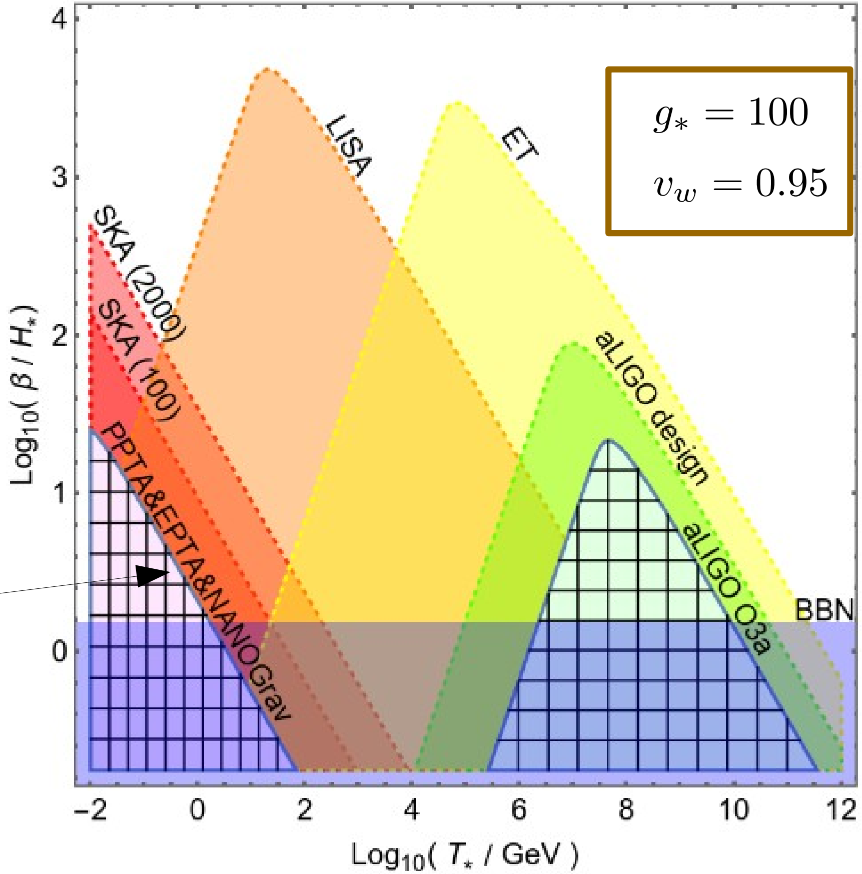
If no FOPT SGWB signalin PTA

Taking SNR > 10 as detection/non-detection criterion

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

SGWB from a FOPT : parameter reach (for bubble coll.)

BSM leading to “relativistic bubbles” $(\xi_w \simeq 1; \quad \kappa = 1; \quad$ free $\beta/H\,, \; T_*\,, \; K\,)$
$\rightarrow$ SGWB broken power-law shape



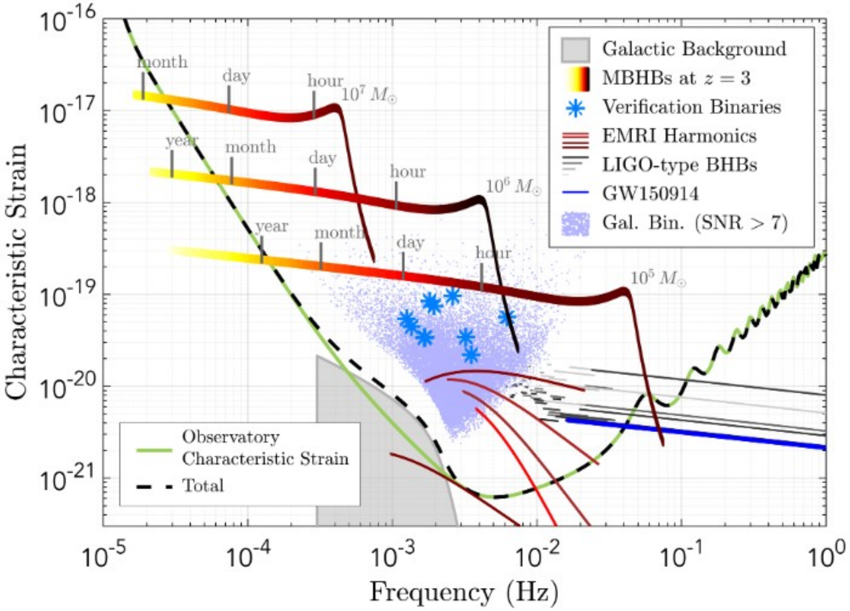
Taking SNR > 10 as detection/non-detection criterion

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

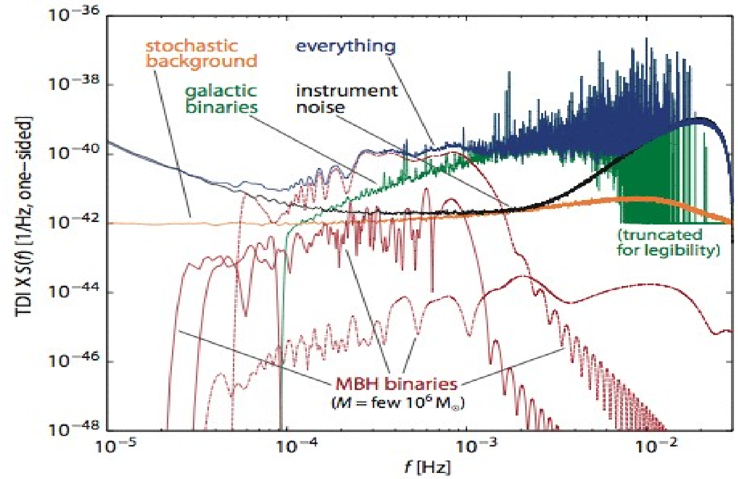
```
If no FOPT SGWB
signalin PTA
```

Knowing the parameter reach is nice,
but
it is the reconstruction accuracy that matters in understanding the underlying physics

SGWB from a FOPT : **LISA** search based on template



LISA is a signal-dominated experiment

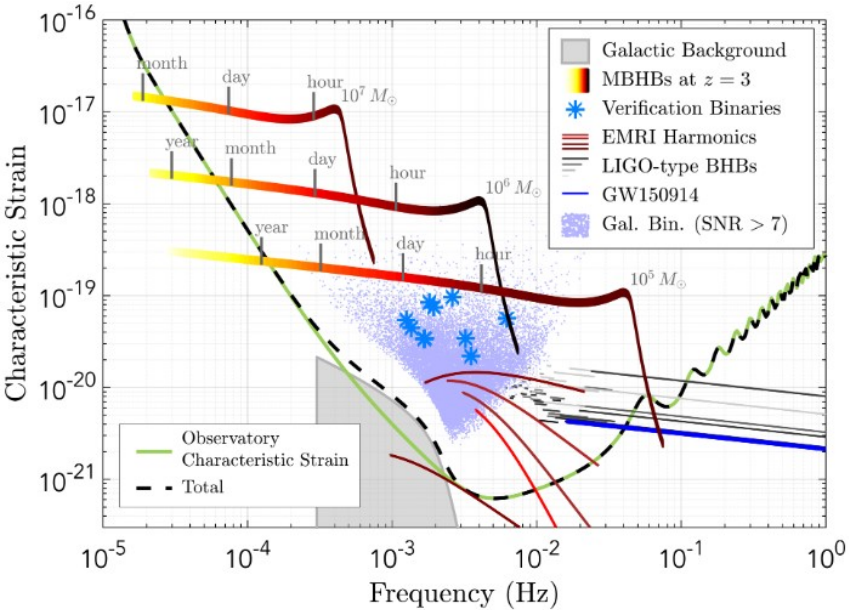


- Too many parameters to fit.

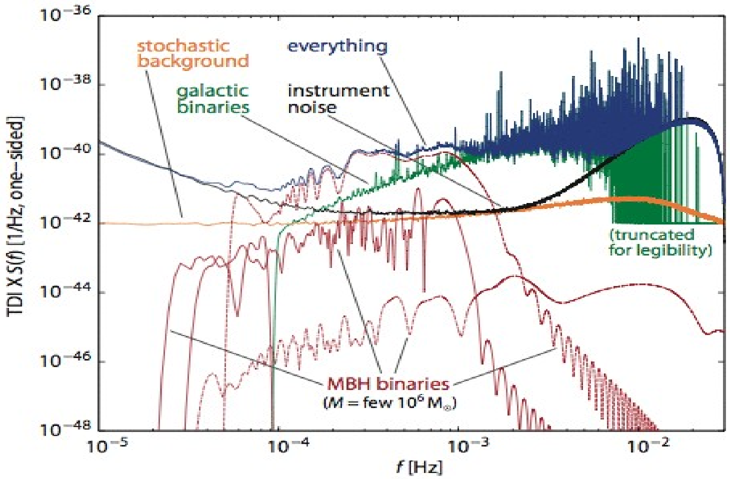
- Heavy-memory waveforms.

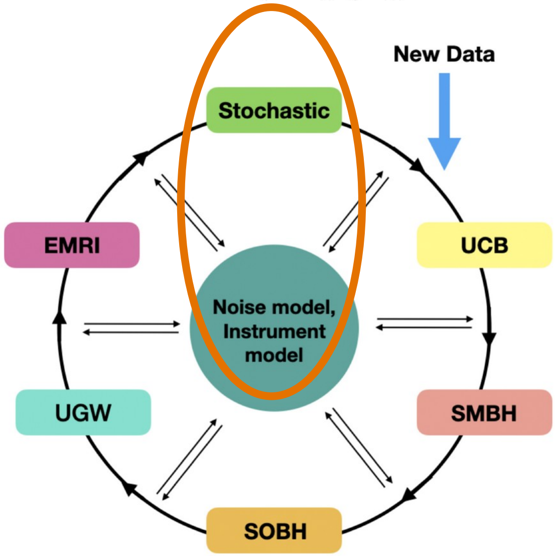
  No hope to reach convergence in the parameter estimate by standard methods

SGWB from a FOPT : **LISA** search based on template



LISA is a signal-dominated experiment



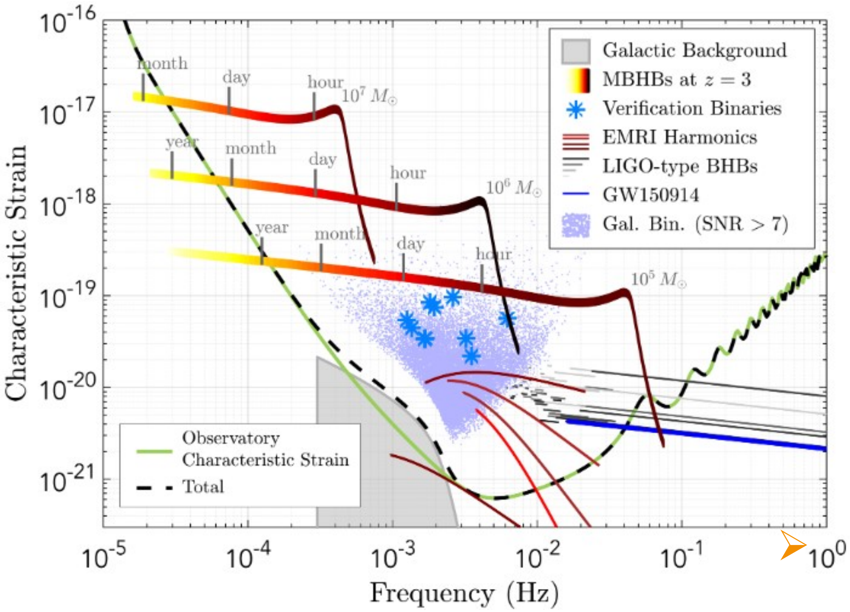


- Too many parameters to fit.
- Heavy-memory waveforms.

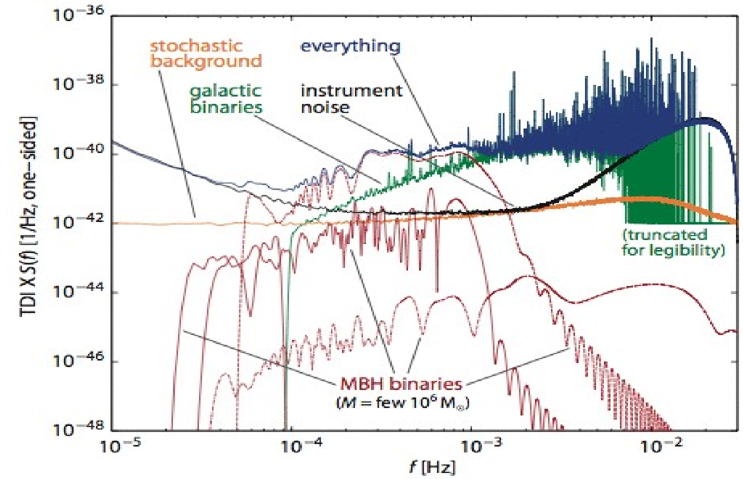
No hope to reach convergence in the parameter estimate by standard methods

Iterative global fit.
Computational expensive!!!   Simplified test: 50.000$

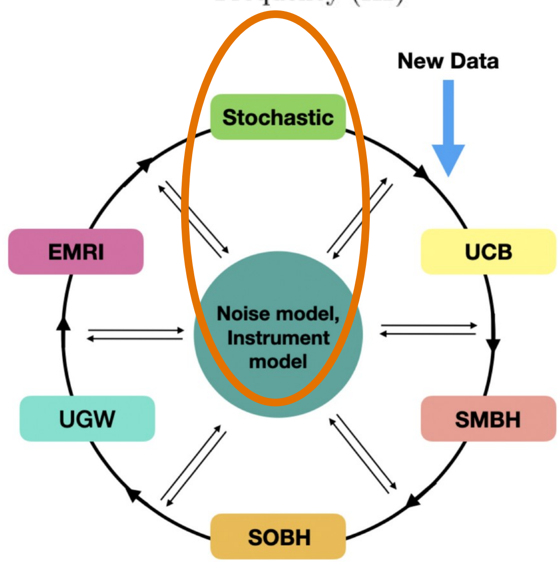
SGWB from a FOPT : **LISA** search based on template



LISA is a signal-dominated experiment



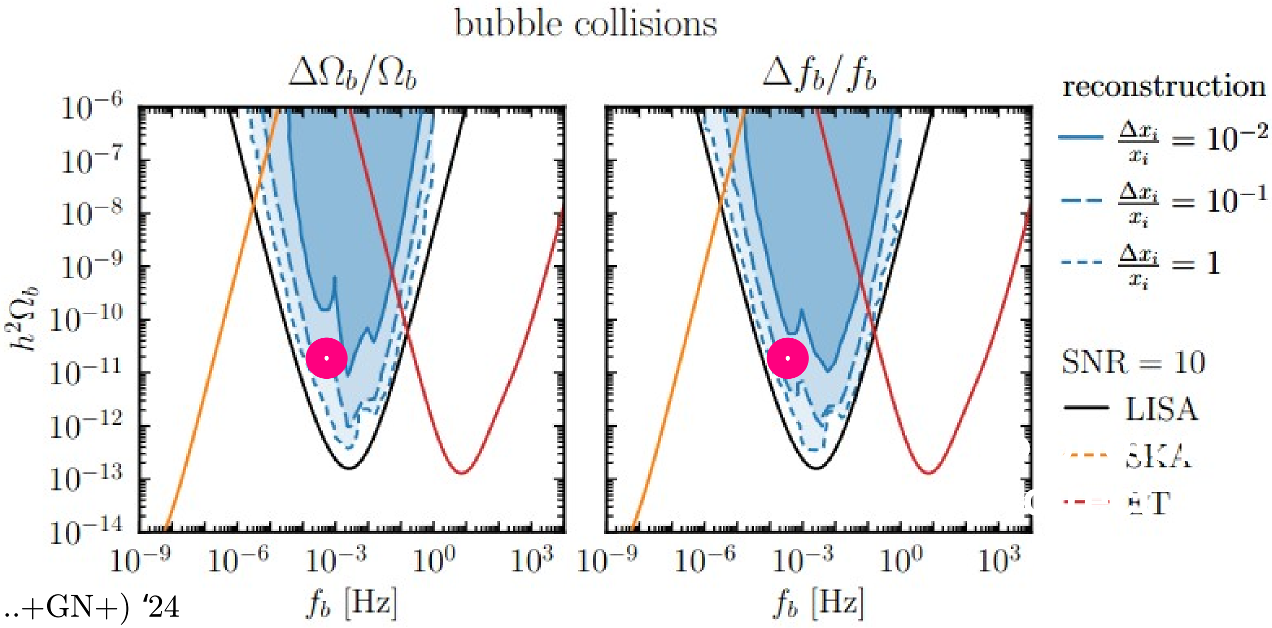
- We build the search and run it on data with
  - **The (faint) unresolved binaries**
  - **The instrumental noise**
  - **The FOPT SGWB**



- Simplifications:
  - We neglect the likelihood correlations/systematics with the transient sources
  - Same template model for injection and recovery (no. theory systematics)

LISA FOPT search: forecast (for bubble coll.)

BSM leading to "relativistic bubbles" ($\xi_w \simeq 1$; $\kappa = 1$; free β/H, T_*, K)
→ SGWB broken power-law shape



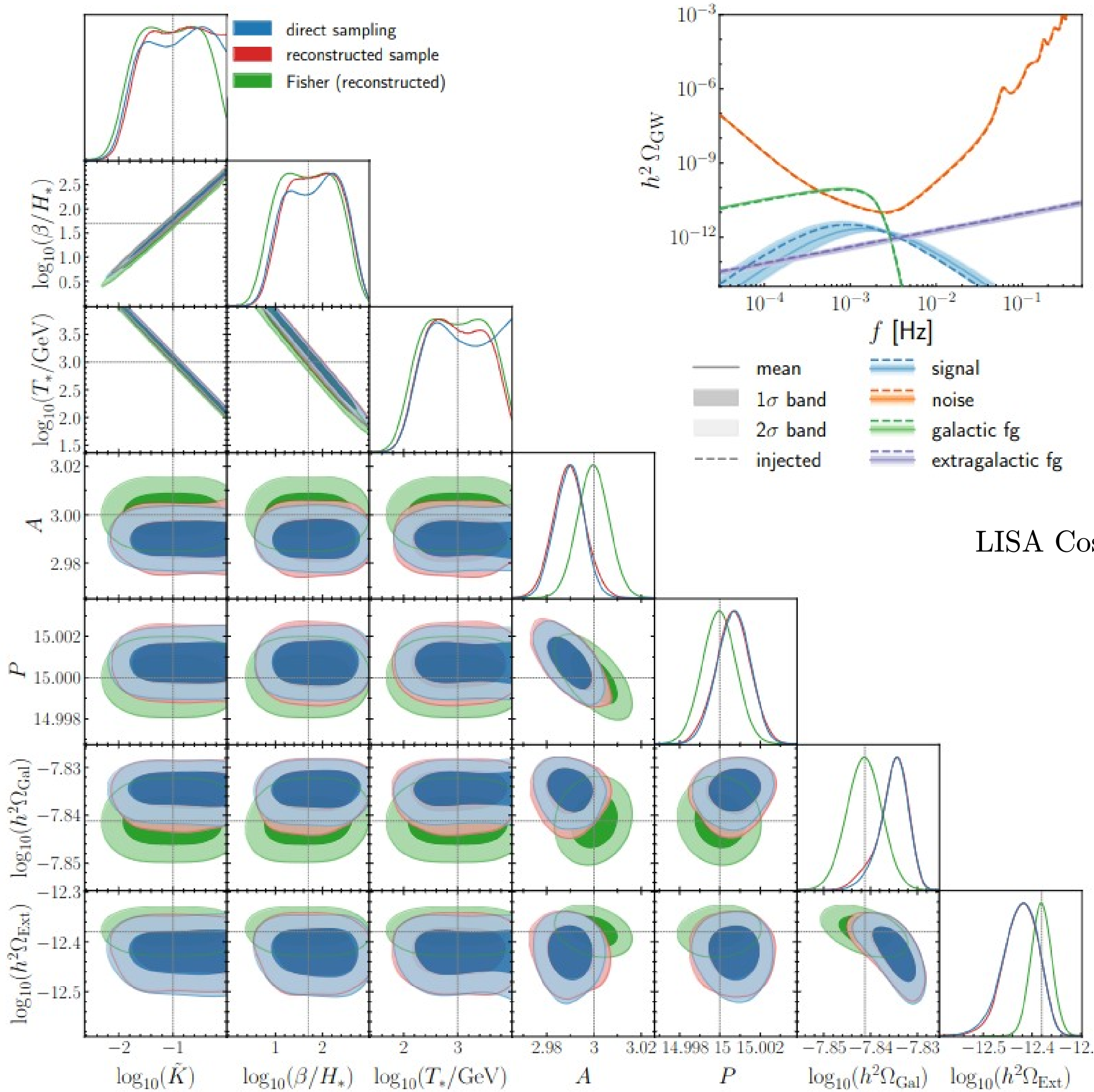
LISA CosWG (Caprini+...+GN+) '24

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

$$n_1 = 2.4\,, \quad n_2 = -2.4\,, \quad a_1 = 1/2$$

LISA FOPT search: forecast for benchmark (for bubble coll.)

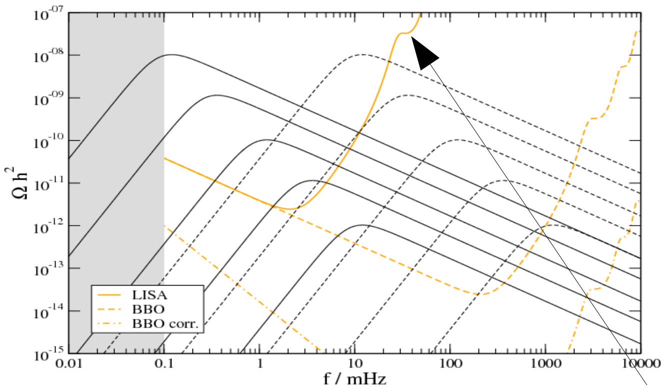
Noise + astro. SGWB + FOPT thermodynamic parameters



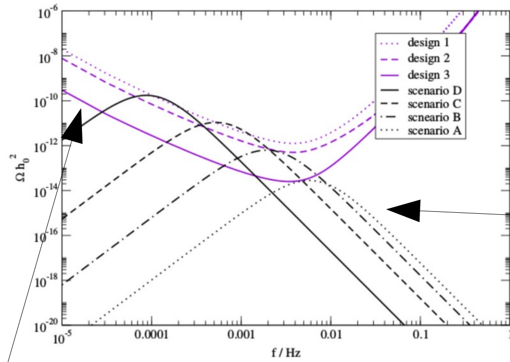
LISA CosWG (Caprini+...+GN+) '24

What BSM behind the FOPT SGWB ? A multitude

First order in Randall Sundrum



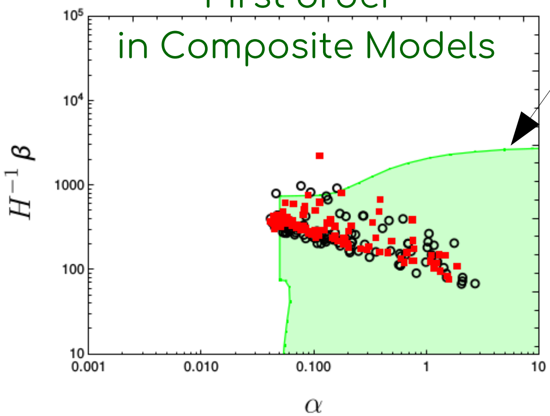
First order in SUSY



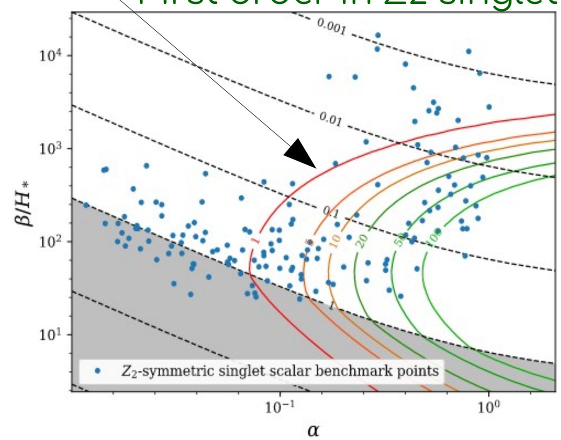
SGWB signal above sensitivity

LISA sensitivy region

First order in Composite Models



First order in Z2 singlet



But also 2HDM, B-L model , dark sector, ….

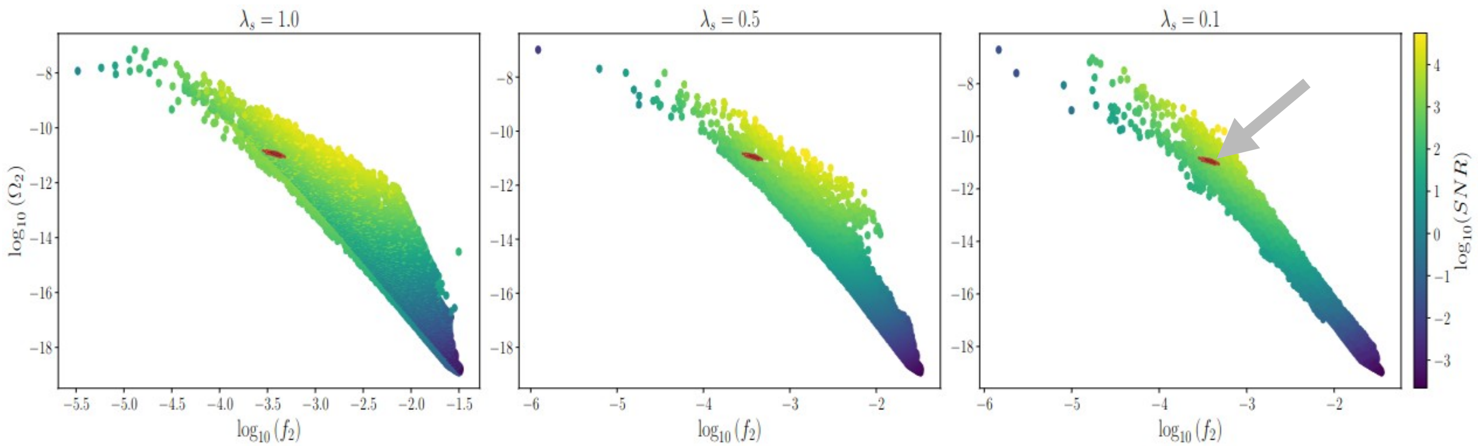
Many models with different pheno!

Figs. from:
Konstandin, GN et al.'10
Huber, GN et al.'15
Chala, GN et al.'16

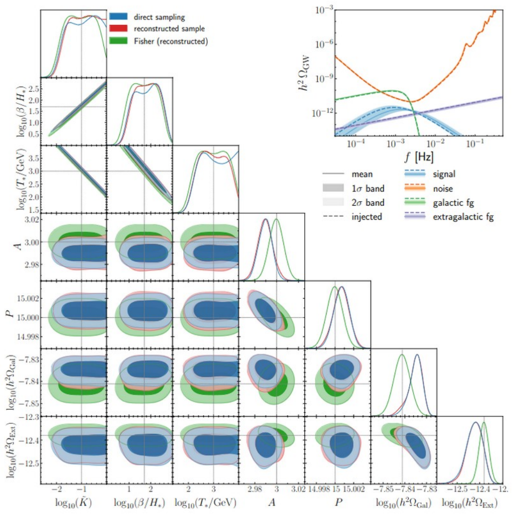
More examples in:
LISA CosWG (Caprini, ..., GN et al.)'16
LISA CosWG (Caprini, ..., GN et al.)'20

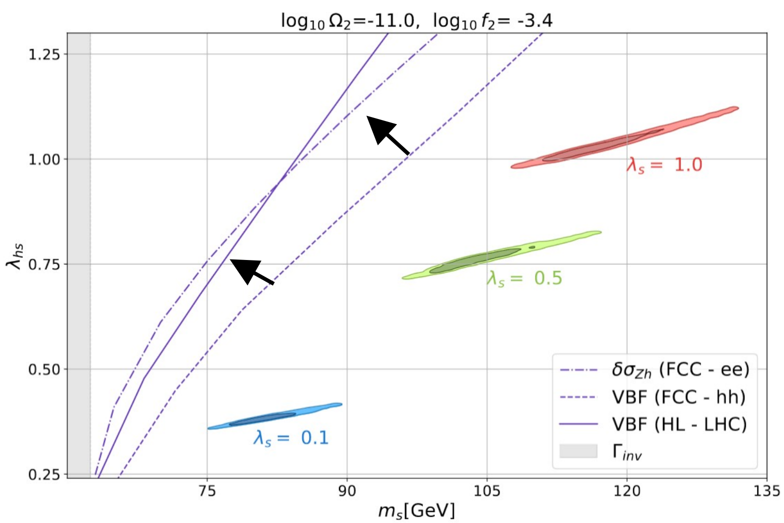
If nature is described by the Z_2 singlet model ...

- FOPT SGWB parameter region compatible with the Z_2 singlet model

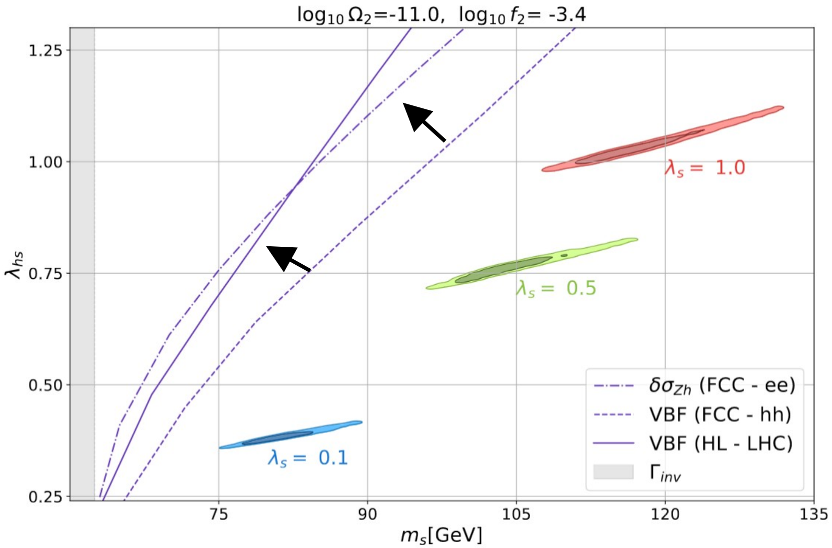


- LISA detection benchmark recast into the Z_2 singlet model



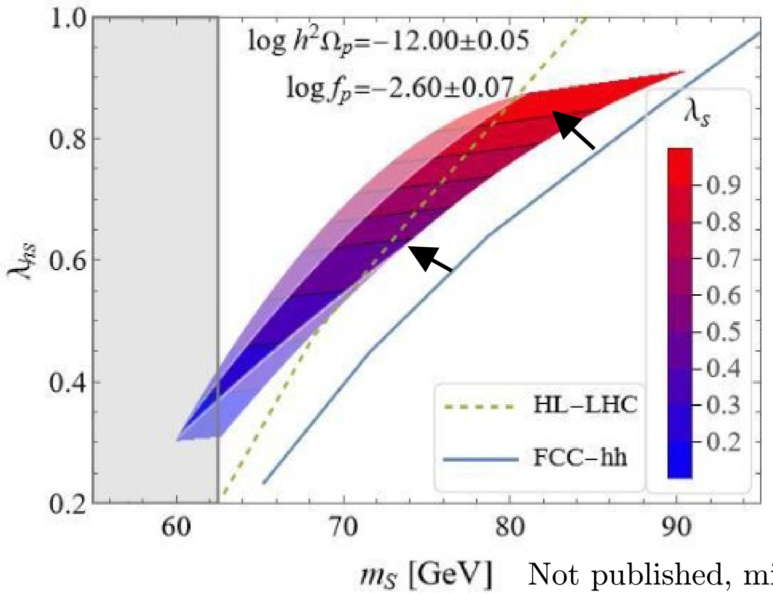


If nature is described by the Z_2 singlet model ...



LISA CosWG (Caprini+...+GN+) '24

For collider bounds: Craig+,14 ; Ellis+,'18



Not published, minor mistakes

- Synergy/complementarity between LISA and colliders
- LISA reconstruction accuracy rather good
- This accuracy allows for some model selection (benchmark and model dependent conclusion)

Singlet is just an example. In general:

- *Does the synergy efficiently break degeneracies ?*
- *Ways to improve the FCC design if LISA sees the signal in ~2036 ?*

Conclusions and outlook

- An observation of a primordial SGWB would be a BSM proof (inflation, cosmic strings, phase transitions, ...)
- LISA can accurately reconstruct a FOPT signal
- Results based on some simplifications. Need to test results with more realistic simulations (although expensive)
- Signal interpretation done only for two BSM models. Rationale can be followed for other models.
- Clear synergy/complementarity with future colliders
- Next goals:
  - Quantify the realistic LISA accuracy of SGWB measurements
  - Quantify model-selection capabilities with LISA + colliders

Gravitational Waves Detectors

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

Space-based interferometers: GWs with 10^{-5}–1 Hz

Ground-based interferometers: GWs with 1–10^{4} Hz