Gravitational Waves – Future Colliders

LFC24

SISSA, Sept. '24

LISA CONSORTIUM

Germano Nardini

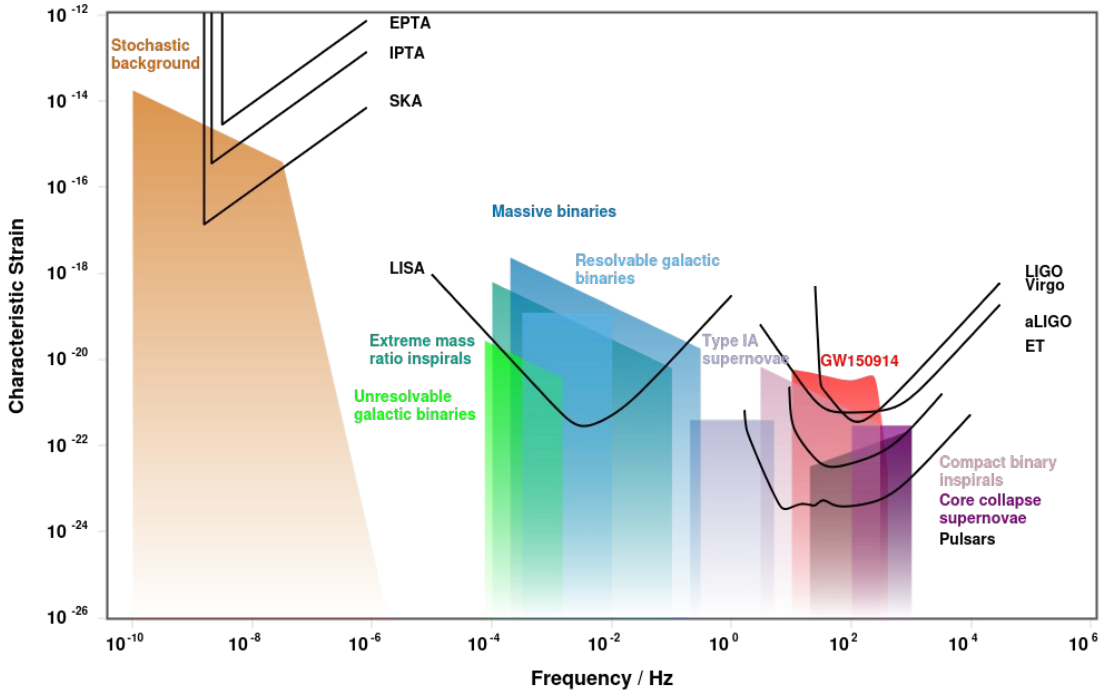
University of Stavanger

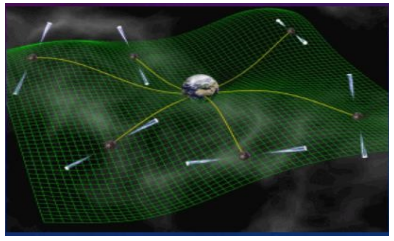
Gravitational Waves Detectors

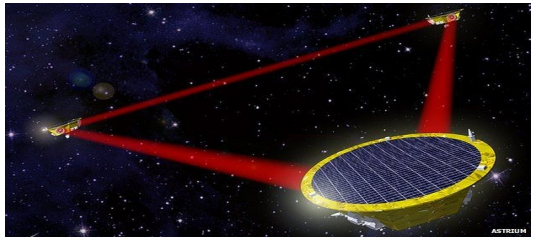
Pulsar timing arrays: GWs with 10^{-9}–10^{-6} Hz

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

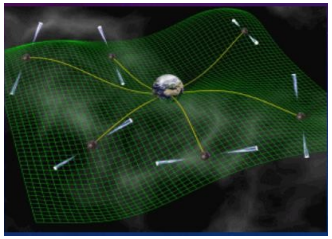
Ground-based interferometers: GWs with 1–10^{4} Hz







GW experiment and FCC timelines



SGWB 4-sigma hint — Jun.'23

~2026 — IPTA joint analysis

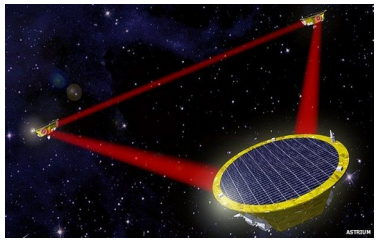
~2030 — SKA

LVK GWTC-3 — 2021

~2024 — GWTC-4

O5 — ~2030

~2040 — ET



ESA's adopttion — Jan. 25th,'24

2035 — Launch

First data — 2036

~2037 — First SGWB announcement

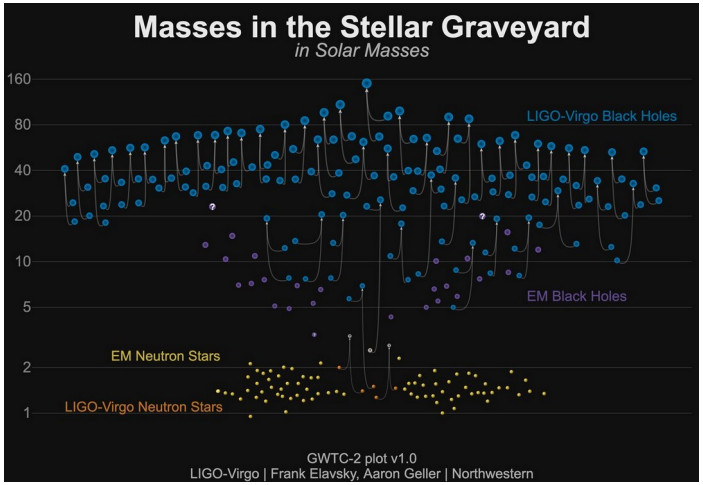
2040 / 2046 — END

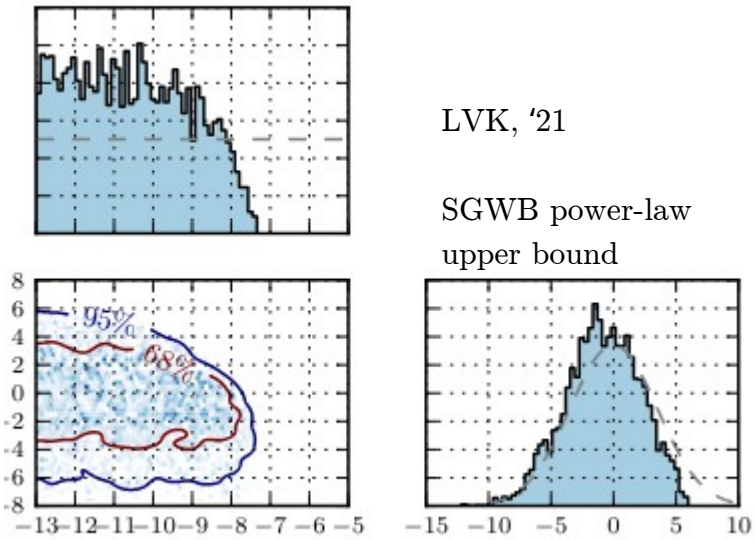
~2029 — HL-LHC

~2040 — FCC-ee

BSM status at GW experiments (brutally brief and biased)

LVK



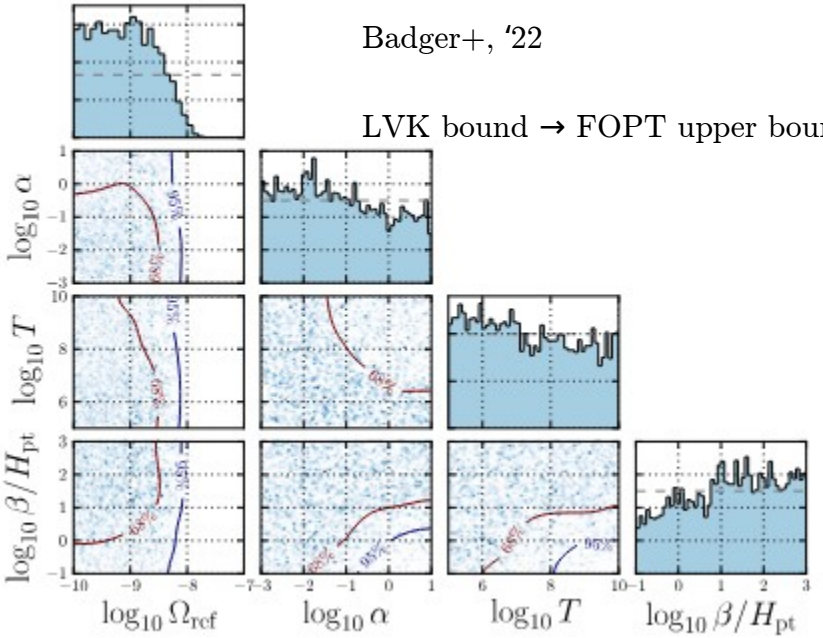


Amplitude

Tilt

LVK, ‘21

SGWB power-law upper bound



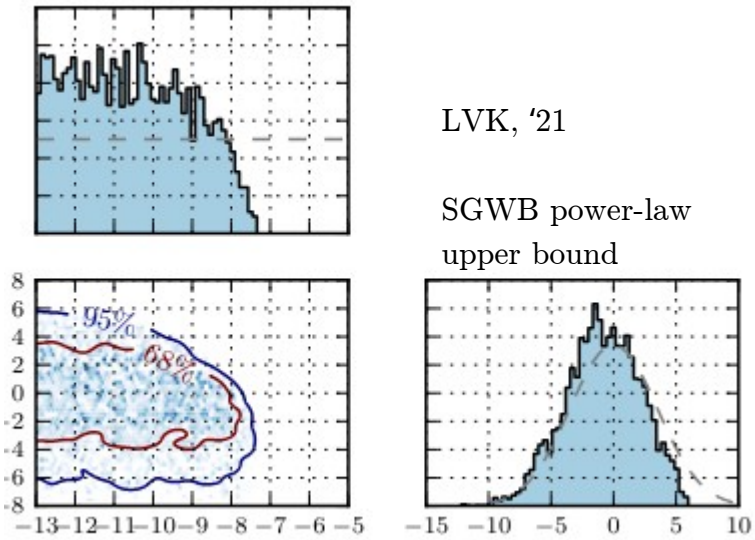
Badger+, ‘22

LVK bound → FOPT upper bound

BSM status at GW experiments (brutally brief and biased)

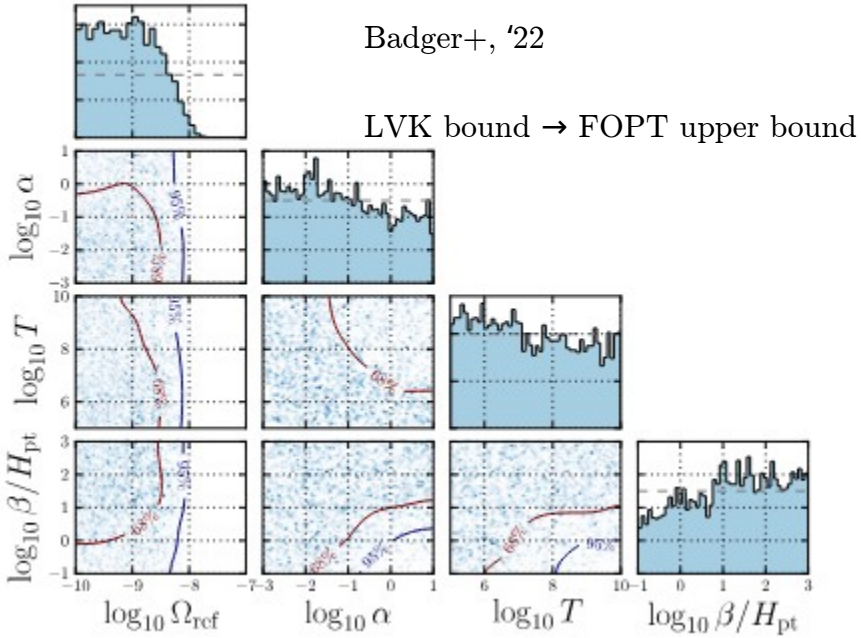
LVK

- 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

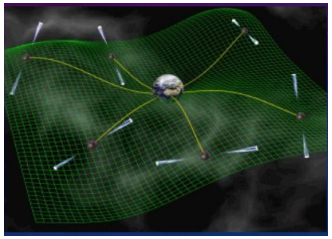
SGWB power-law upper bound



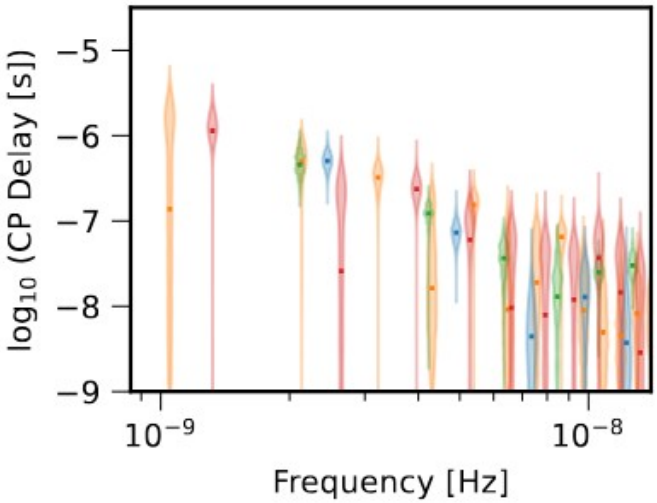
Badger+, ‘22

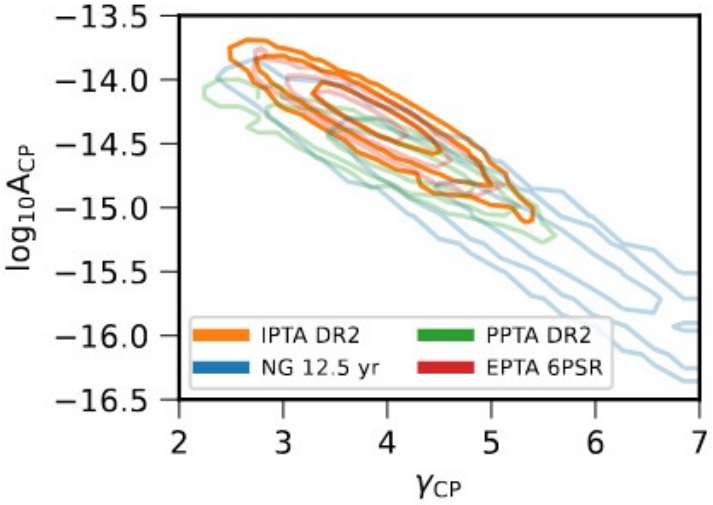
LVK bound → FOPT upper bound

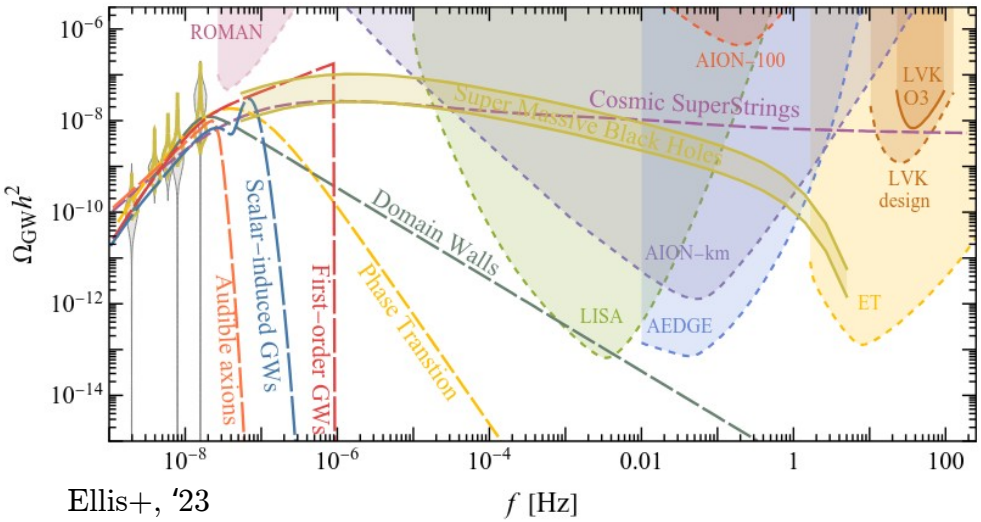
BSM status at GW experiments (brutally brief and biased)



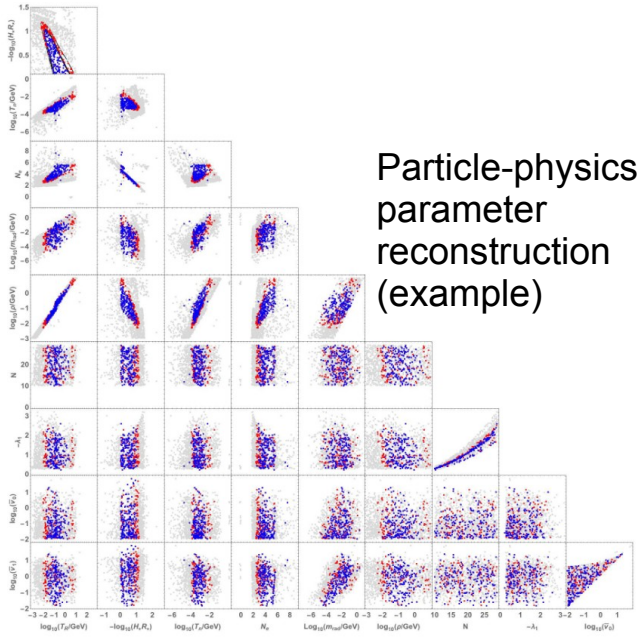
PTA







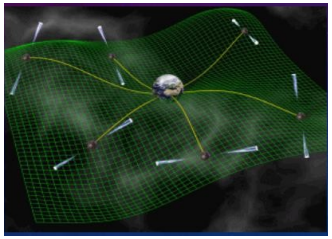
Ellis+, '23



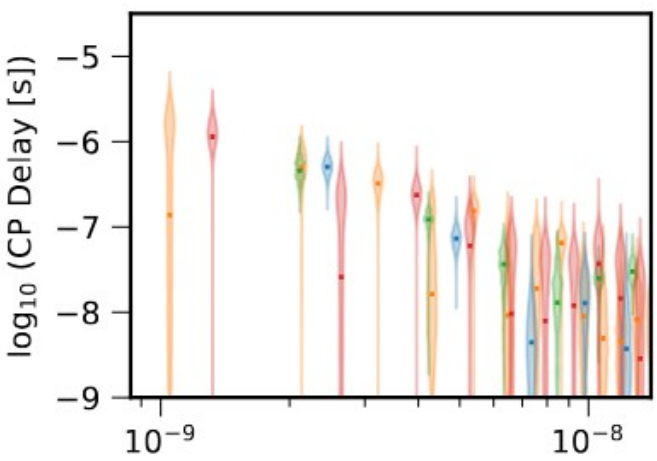
Particle-physics parameter reconstruction (example)

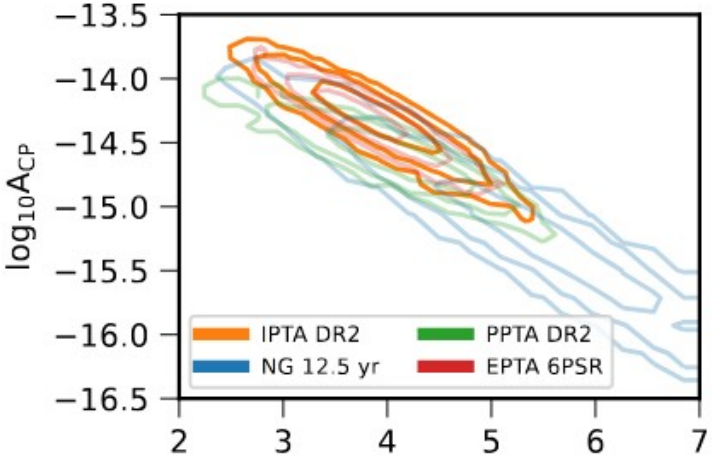
Megias+GN+Quiros, '23

BSM status at GW experiments (brutally brief and biased)



PTA





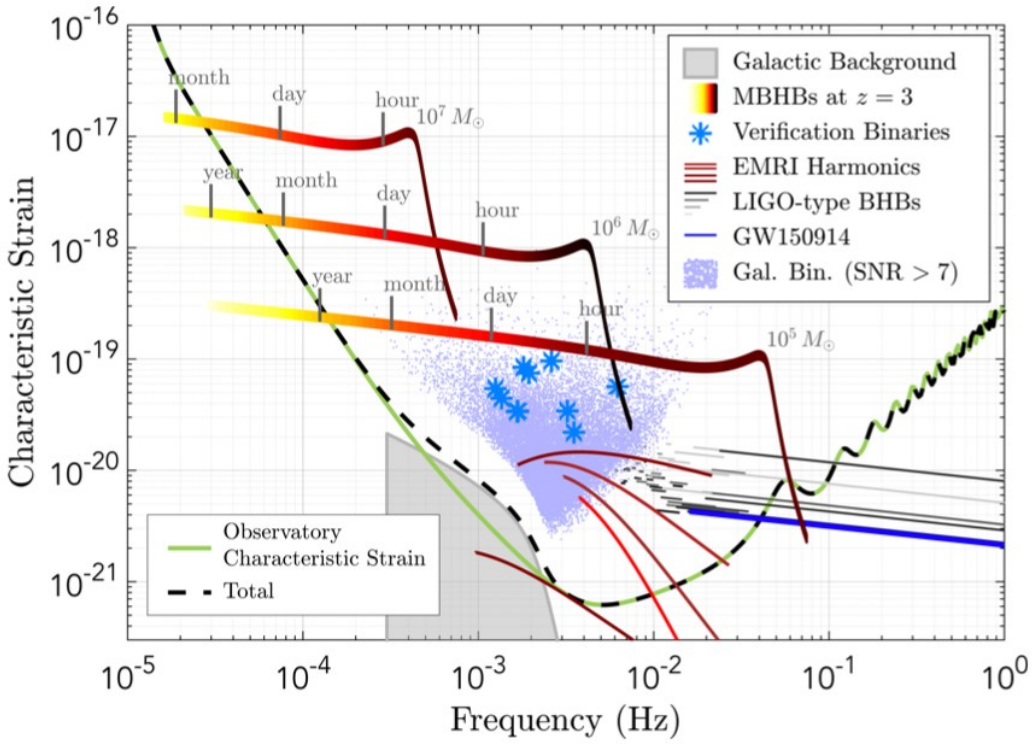
MAYBE A BSM HINT, MAYBE NOT

- 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

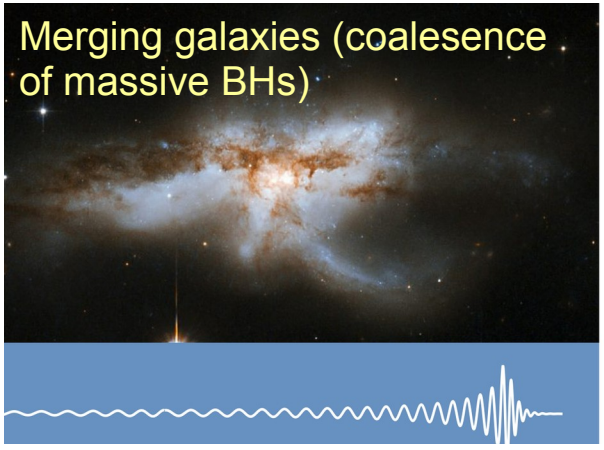


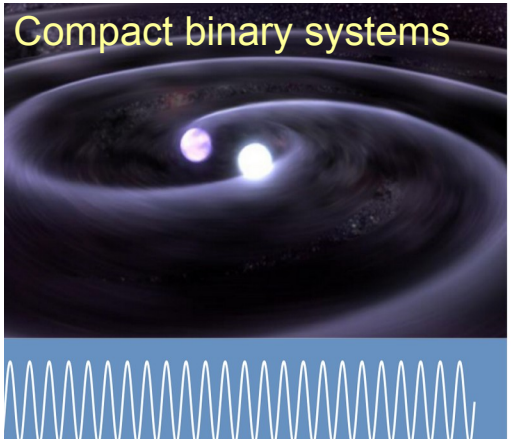
O(10^4) resolv. galac. binaries

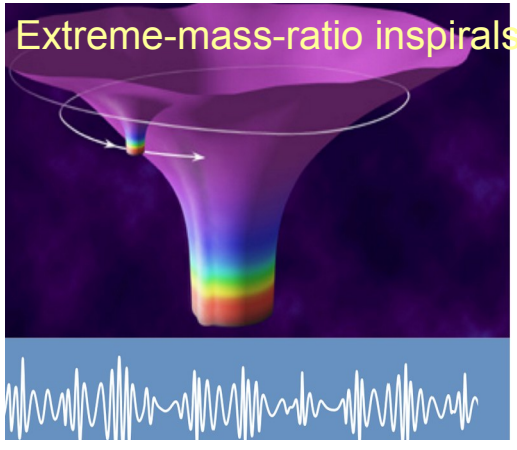
O(10) extragal. BBHs of 10^0–10^2 $M_\odot$

O(1 - 10) extreme mass-ratio inspirals

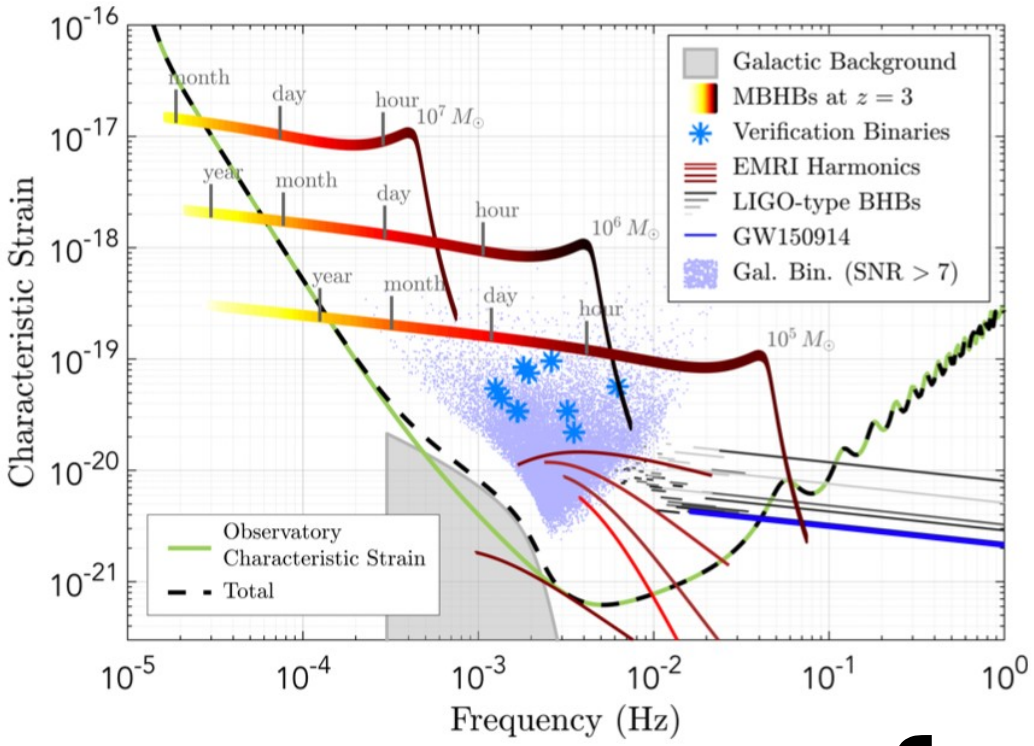
O(10 - 100) merging BBHs of 10^5–10^8 $M_\odot$

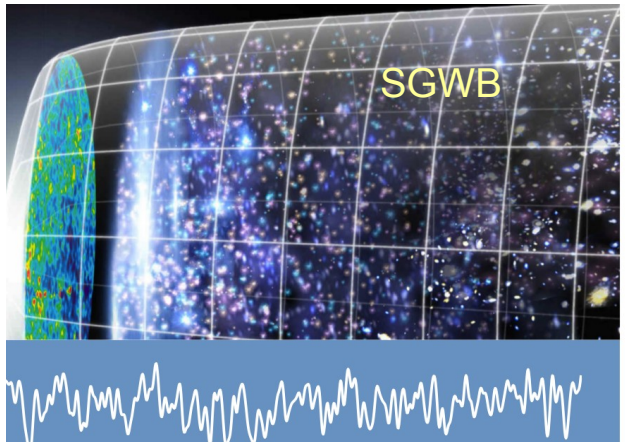






What about LISA? The mission targets





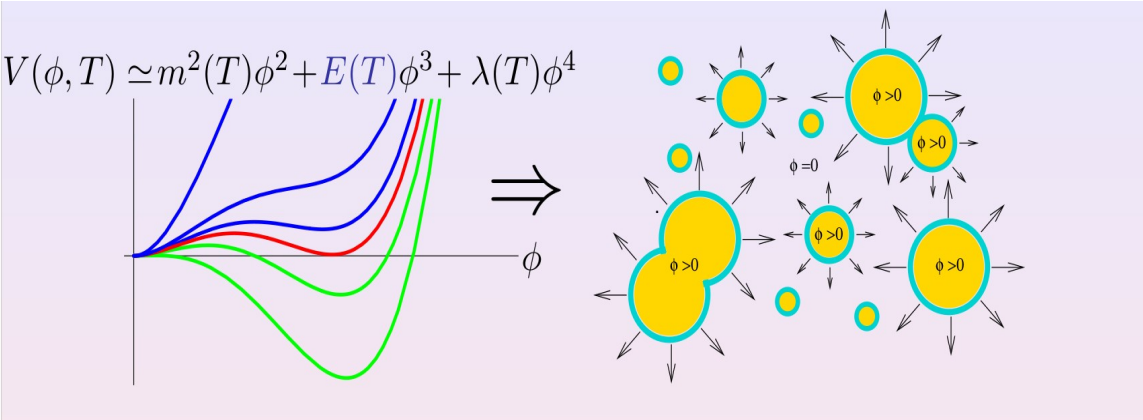
SGWB

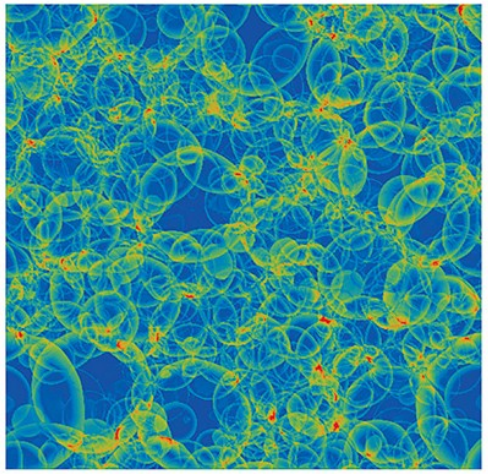
- Astronomical sources
  - Galactic binaries
  - Extra-Gal. binaries
- Cosmological sources
  - Cosmic strings, Domain walls (Notari's talk)
  - FOPT **(this talk** +Stelzl's**),** Inflation
  - Superradiance (e.g. due to axions; Biekotter's talk)

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





Parameters:

$K(\alpha)$: approx. max. energy that can be converted in 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)

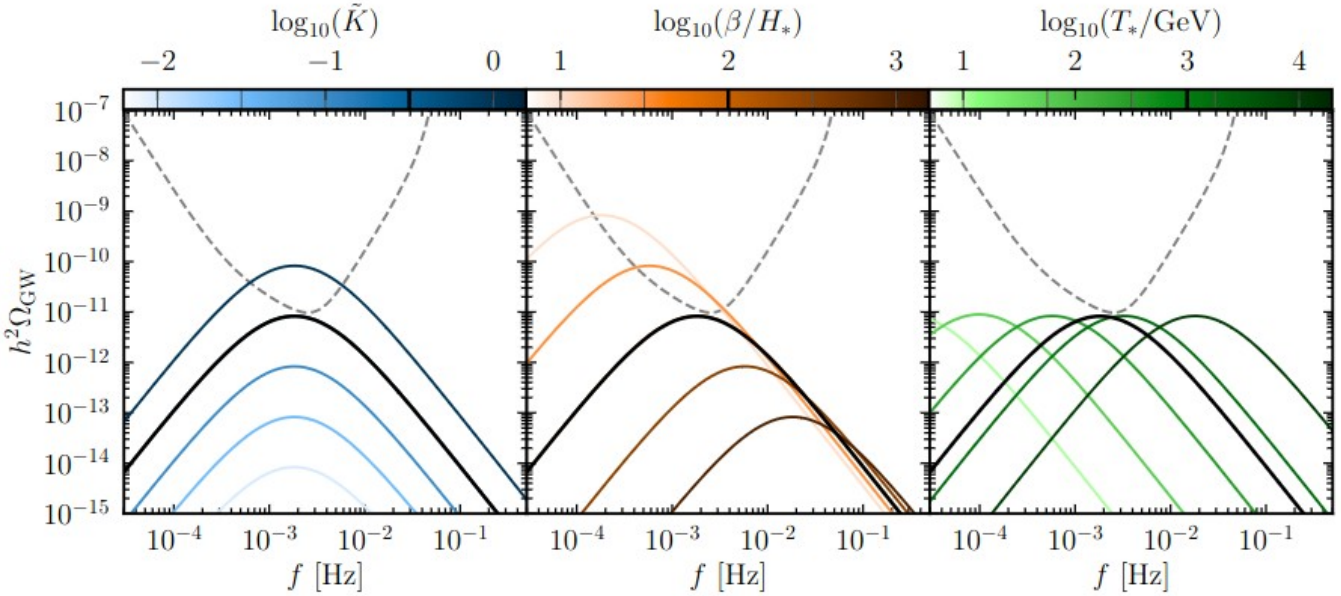
LISA CosWG (C.Caprini+...+GN+) '15 ; '19

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

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

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

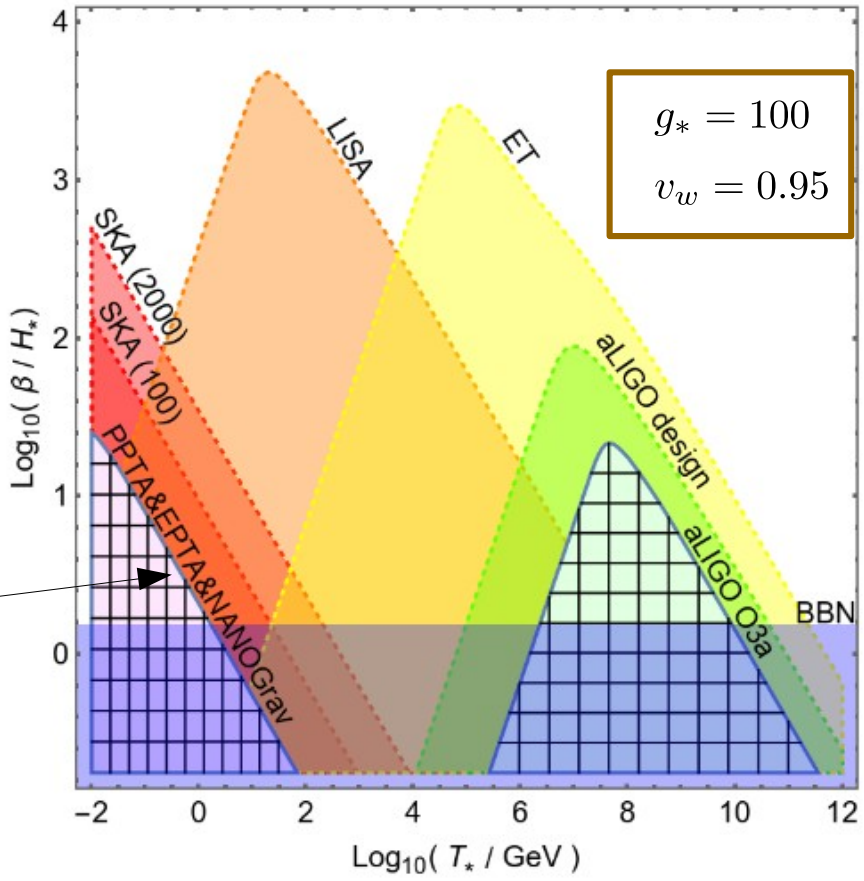
Param. reconstruction : 2 geom. vs 3 therm. param. DEGENERACY!

SGWB from a FOPT : parameter reach

(for bubble coll.)

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

→ 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” $(\xi_w \simeq 1;\quad \kappa = 1;\quad \text{free } \beta/H,\ T_*,\ K)$

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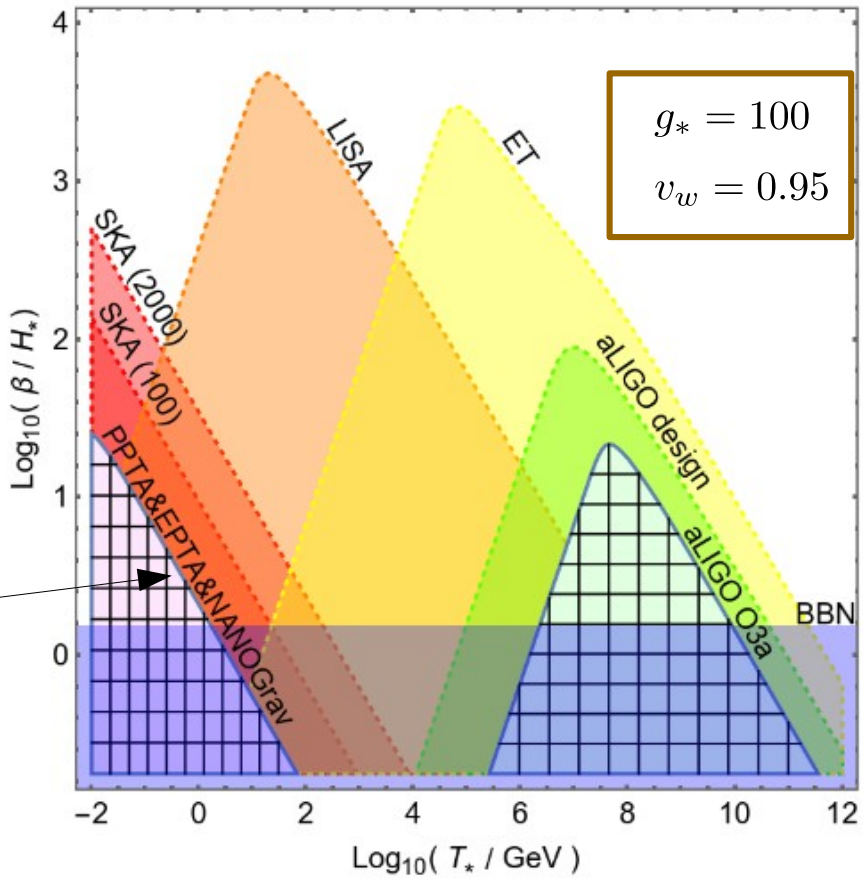


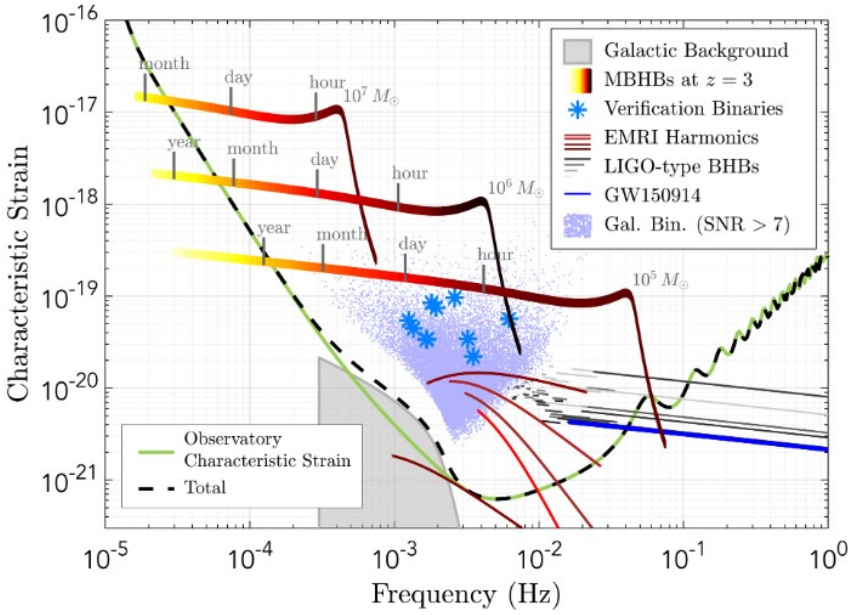
Taking SNR > 10 as detection/non-detection criterion

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

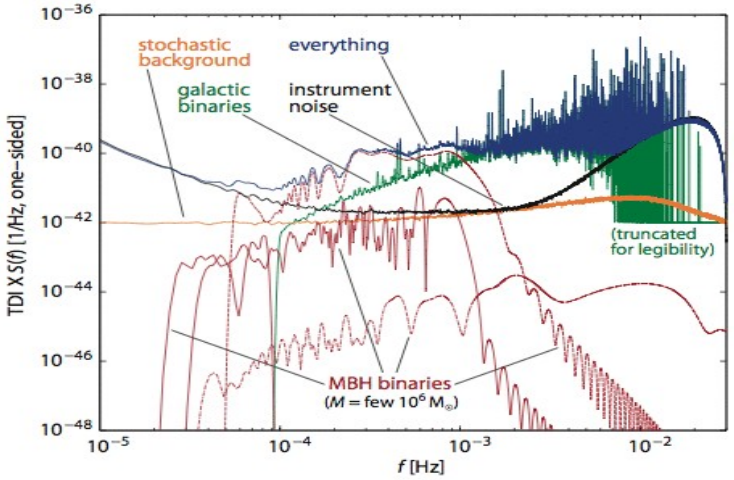
If no FOPT SGWB signalin PTA

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



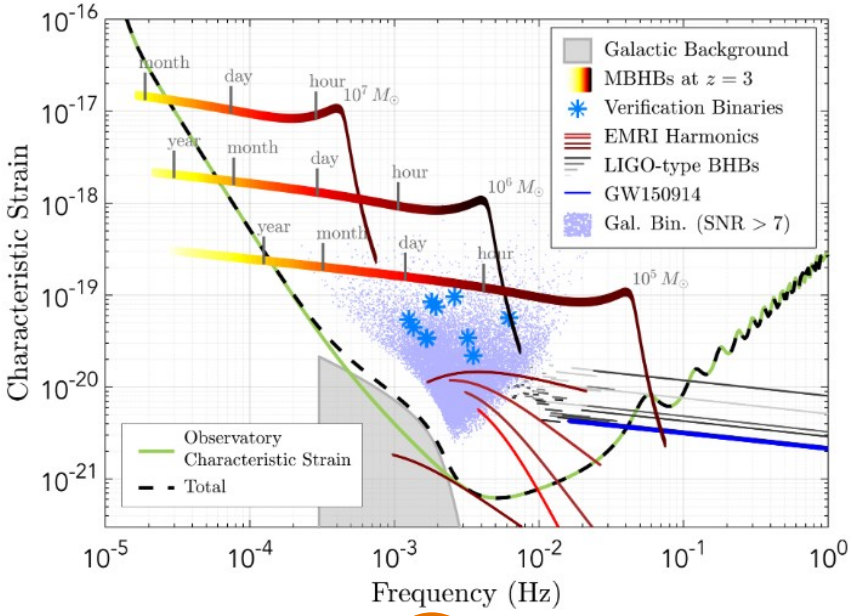
LISA is a signal-dominated experiment



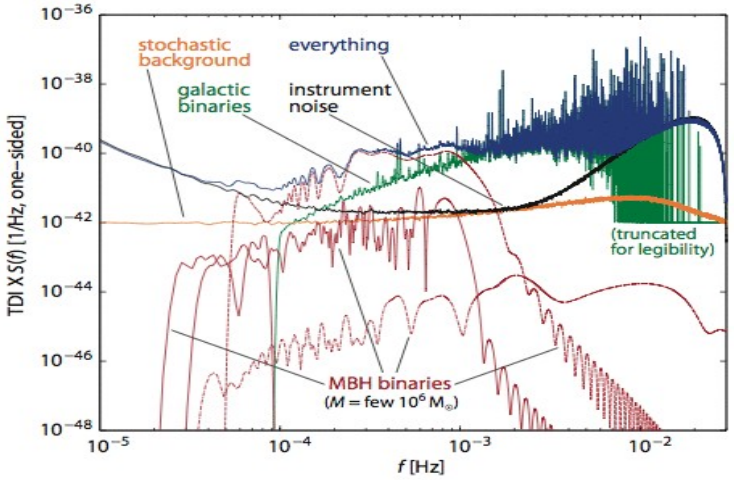
- Too many parameters to fit.
- Heavy-memory waveforms.

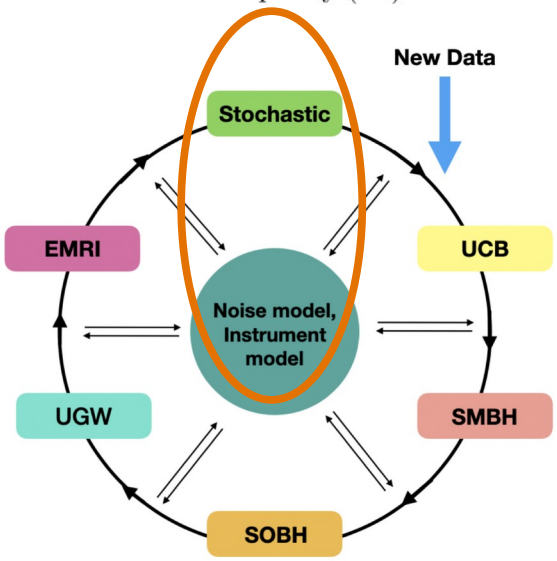
No hope to reach convergence in the parameter estimate by standard methods

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



LISA is a signal-dominated experiment



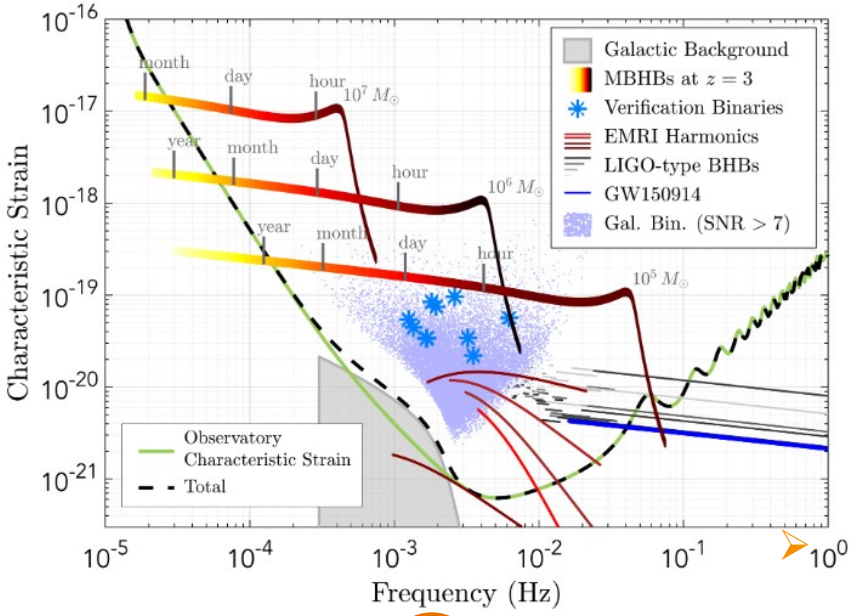


- Too many parameters to fit.
- Heavy-memory waveforms.

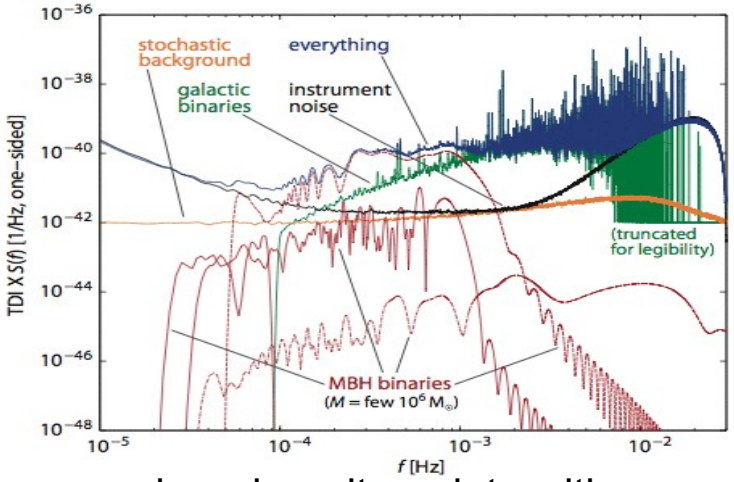
No hope to reach convergence in the parameter estimate by standard methods

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

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

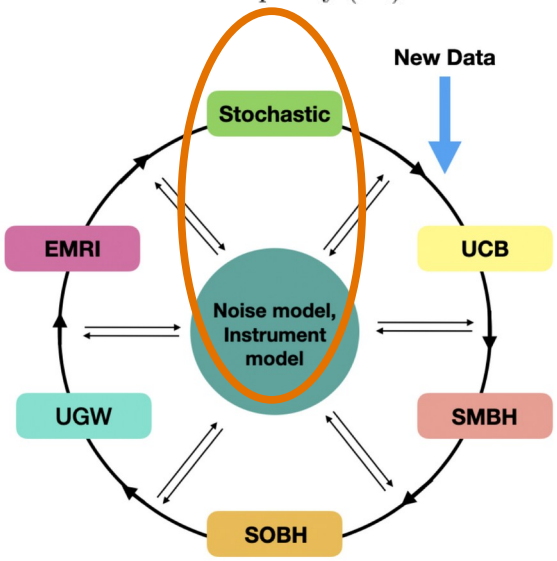


LISA is a signal-dominated experiment



We build the search and run it on data with

- **The (faint) unresolved binaries**
- **The instrumental noise**
- **The FOPT SGWB**

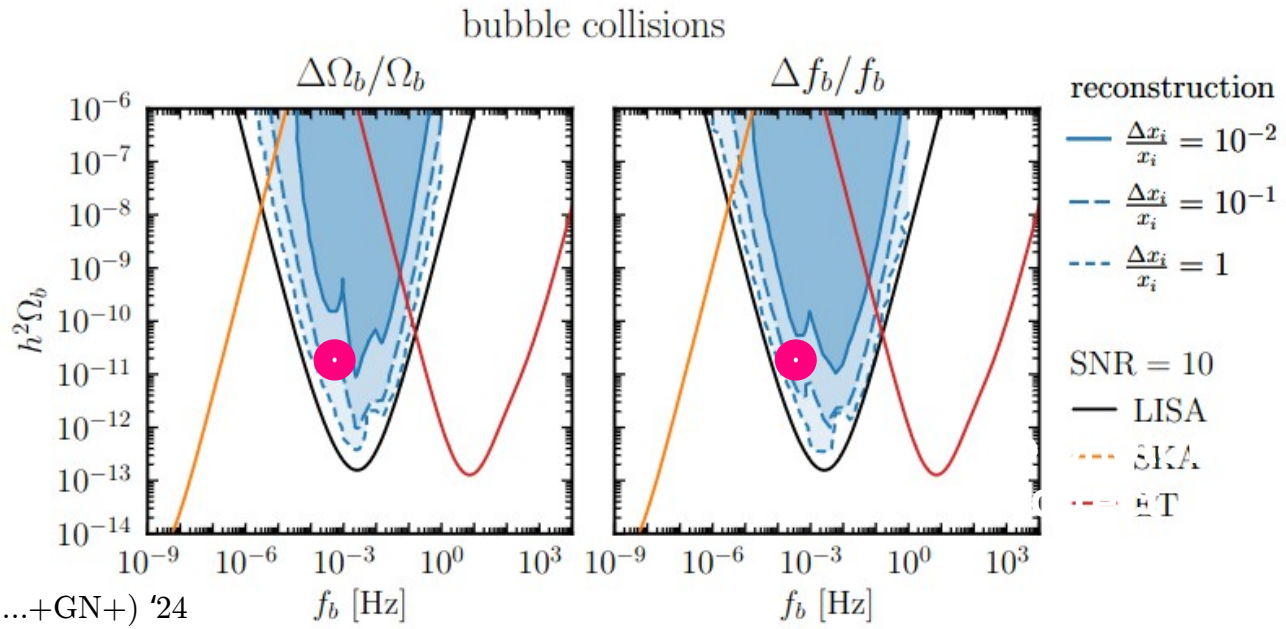


- Simplifications:
  - We neglect the likelihood correlations/systematics with the transient sources
  - Same template model for injection and recovery (no. theory systematics)

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



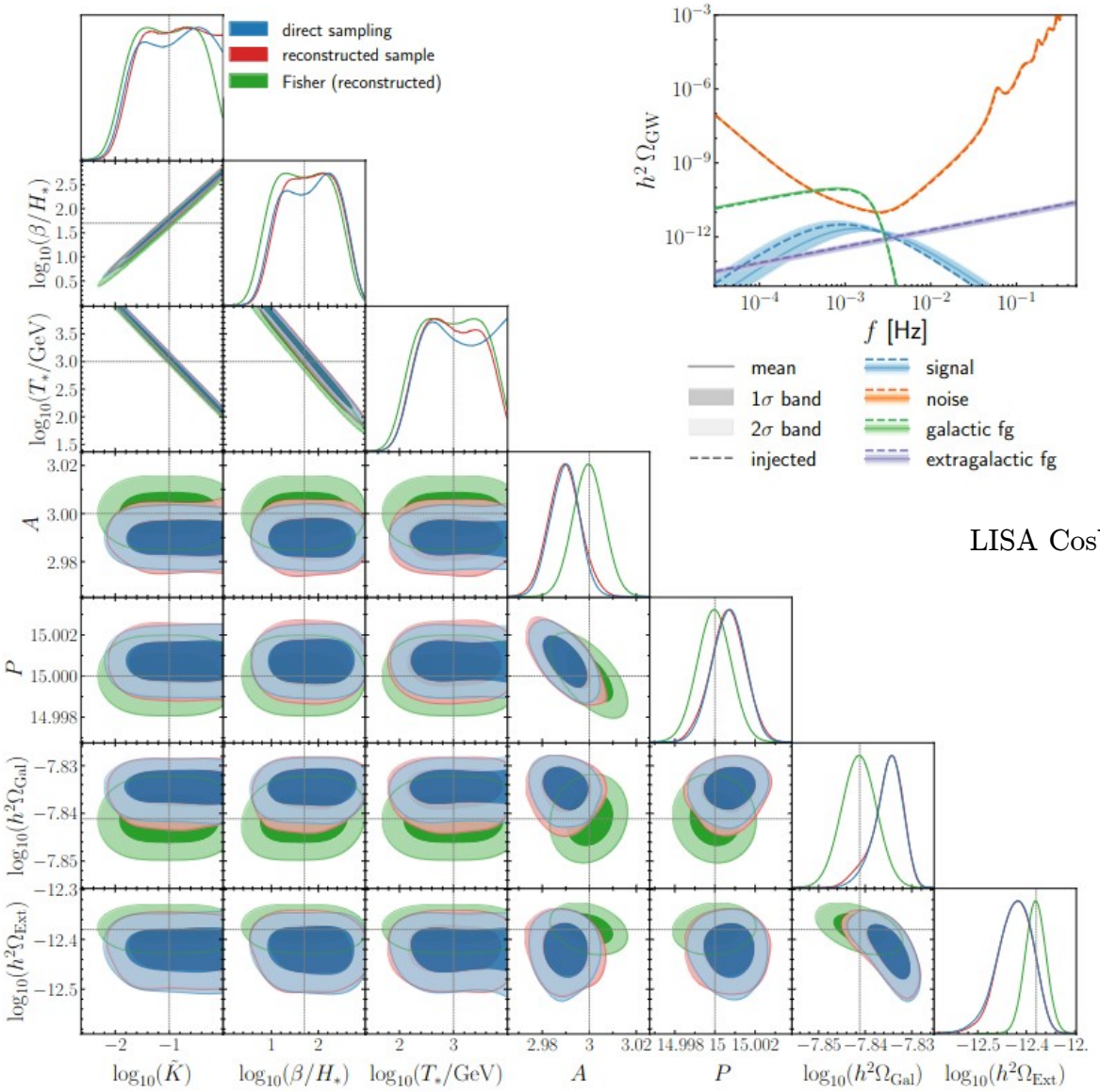
LISA CosWG (Caprini+...+GN+) ‘24

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

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

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

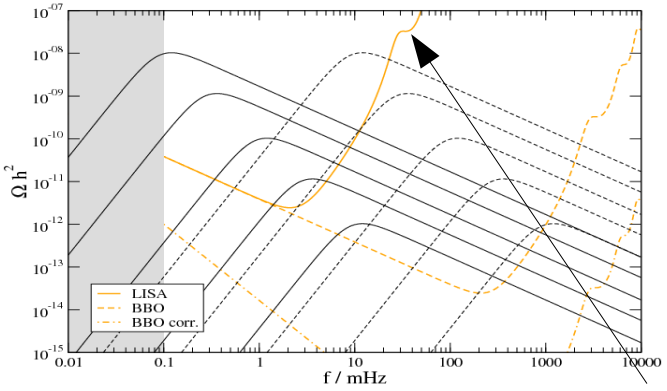
Noise + astro. SGWB + FOPT thermodynamic parameters



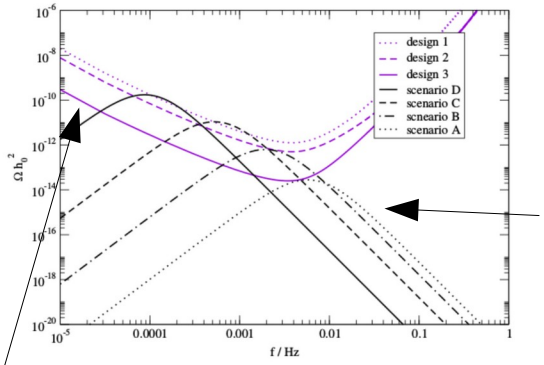
LISA CosWG (Caprini+...+GN+) '24

What BSM behind the FOPT SGWB ? A multitude

First order in Randall Sundrum



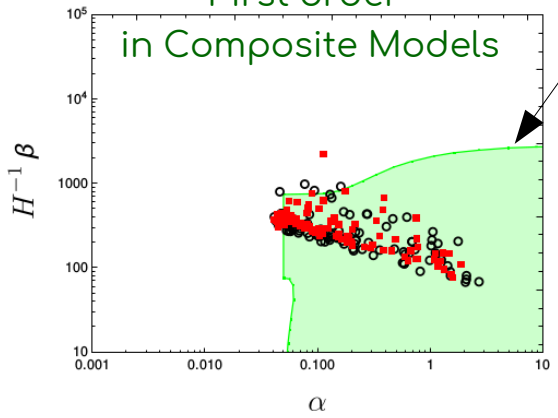
First order in SUSY



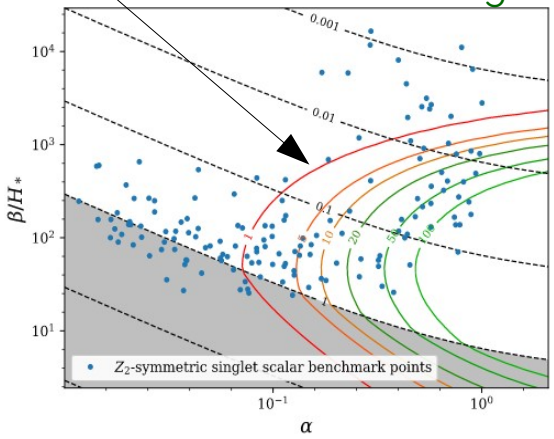
SGWB signal above sensitivity

LISA sensitivy region

First order in Composite Models



First order in Z2 singlet



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

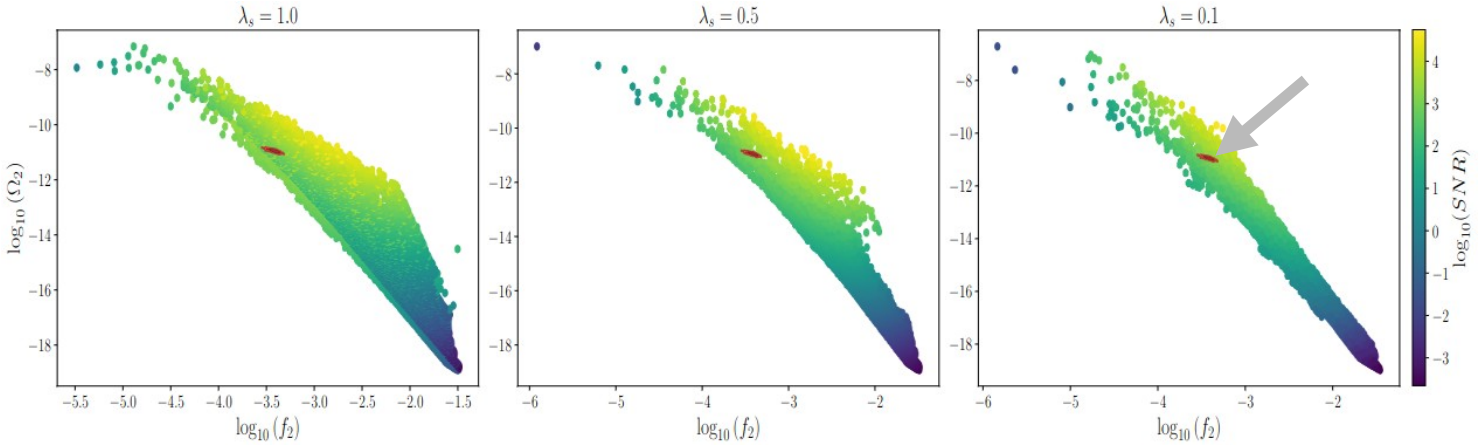
Many models with different pheno!

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

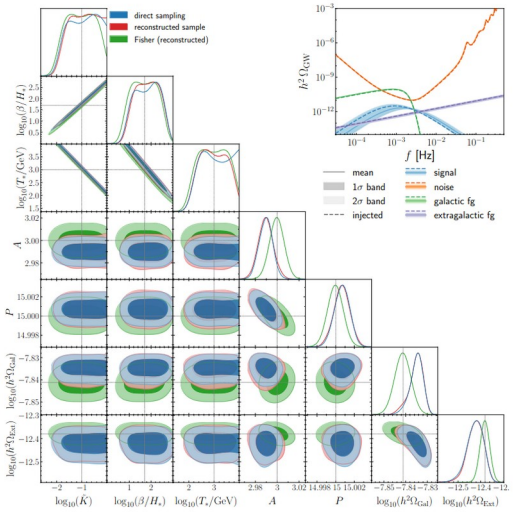
More examples in:
LISA CosWG (Caprini, ..., GN et al.)'16
LISA CosWG (Caprini, ..., GN et al.)'20

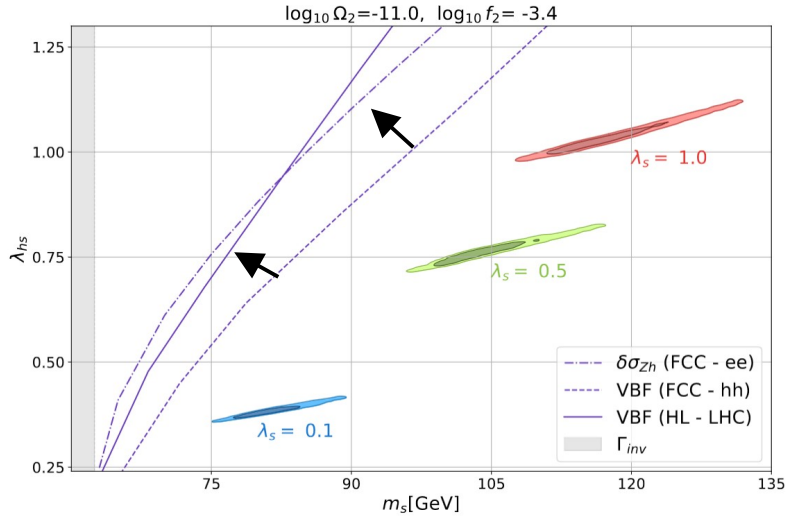
If nature is described by the Z_2 singlet model ...

- FOPT SGWB parameter region compatible with the Z_2 singlet model

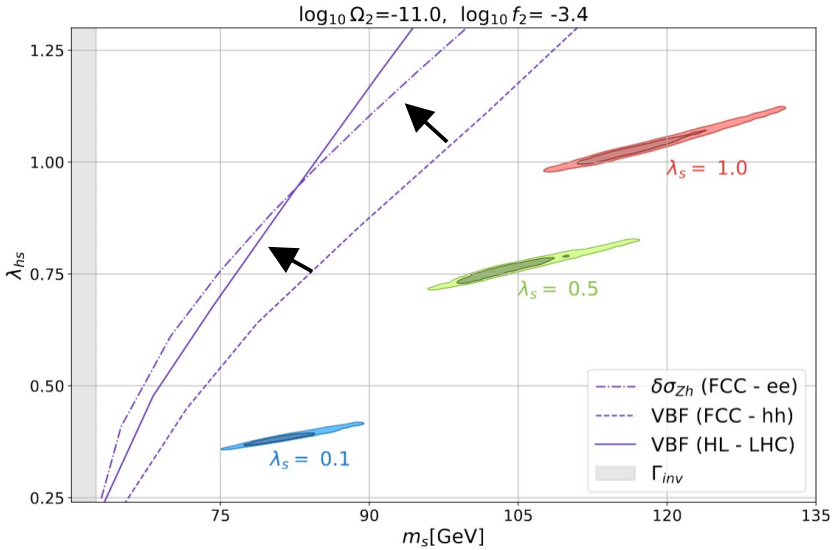


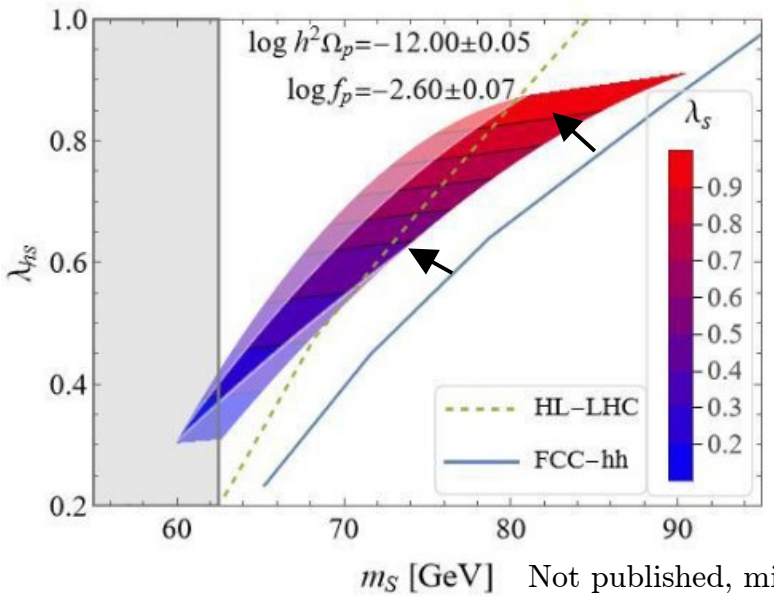
- LISA detection benchmark recast into the Z_2 singlet model





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

- LISA can accurately reconstruct a FOPT signal
- Results based on some simplifications. Need to test results with more realistic simulations (although expensive)
- Reconstruction interpretation done only for two BSM models. Rationale can be followed for other models (with caution to the par. space dimensionality)

- Clear synergy/complementarity with colliders. But IMO synergy should be quantified with an exhaustive list of representative models:.
  - How much does LISA constrain the param. space of a model? And the FCC? And LISA and FCC together ?
  - Is the achieved accuracy relevant? Breaks degeneracies? Helps for model selection?
  - Are there bottlenecks limiting the synergy? Feasible ways to improve them? Still on time to implement them if LISA sees a signal ?