GW experiments and collider synergies: unveiling first-order phase transitions

2025 Biejing Particle Physics and Cosmology Symposium

(Beijing, Sept. `25)

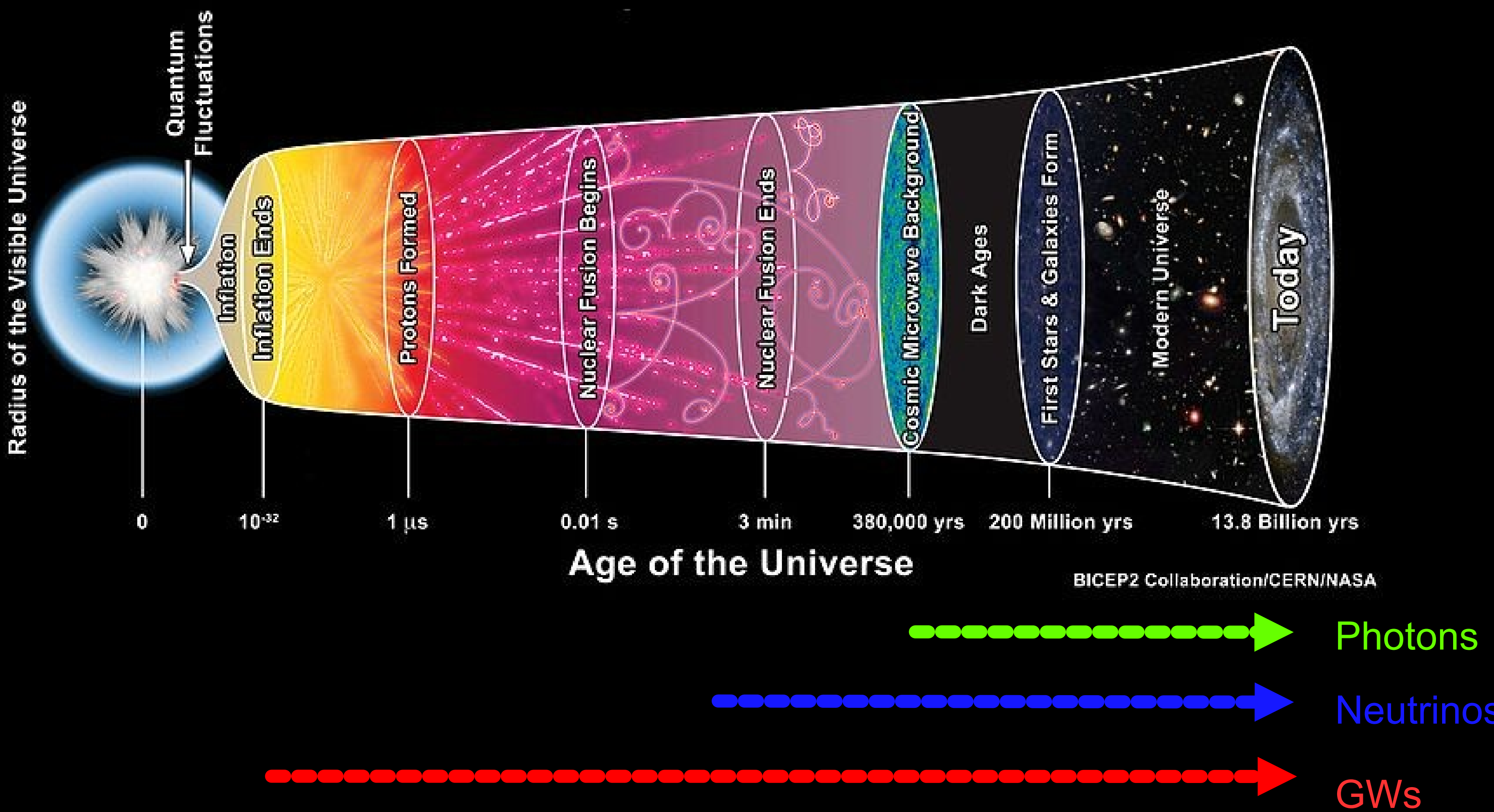
Many results from
LISA CosWG (Caprini, Jinno, Lewicki, Madge, Merchand, GN, Pieroni, Roper Pol, Vaskonen) ‘24

Germano Nardini

University of Stavanger

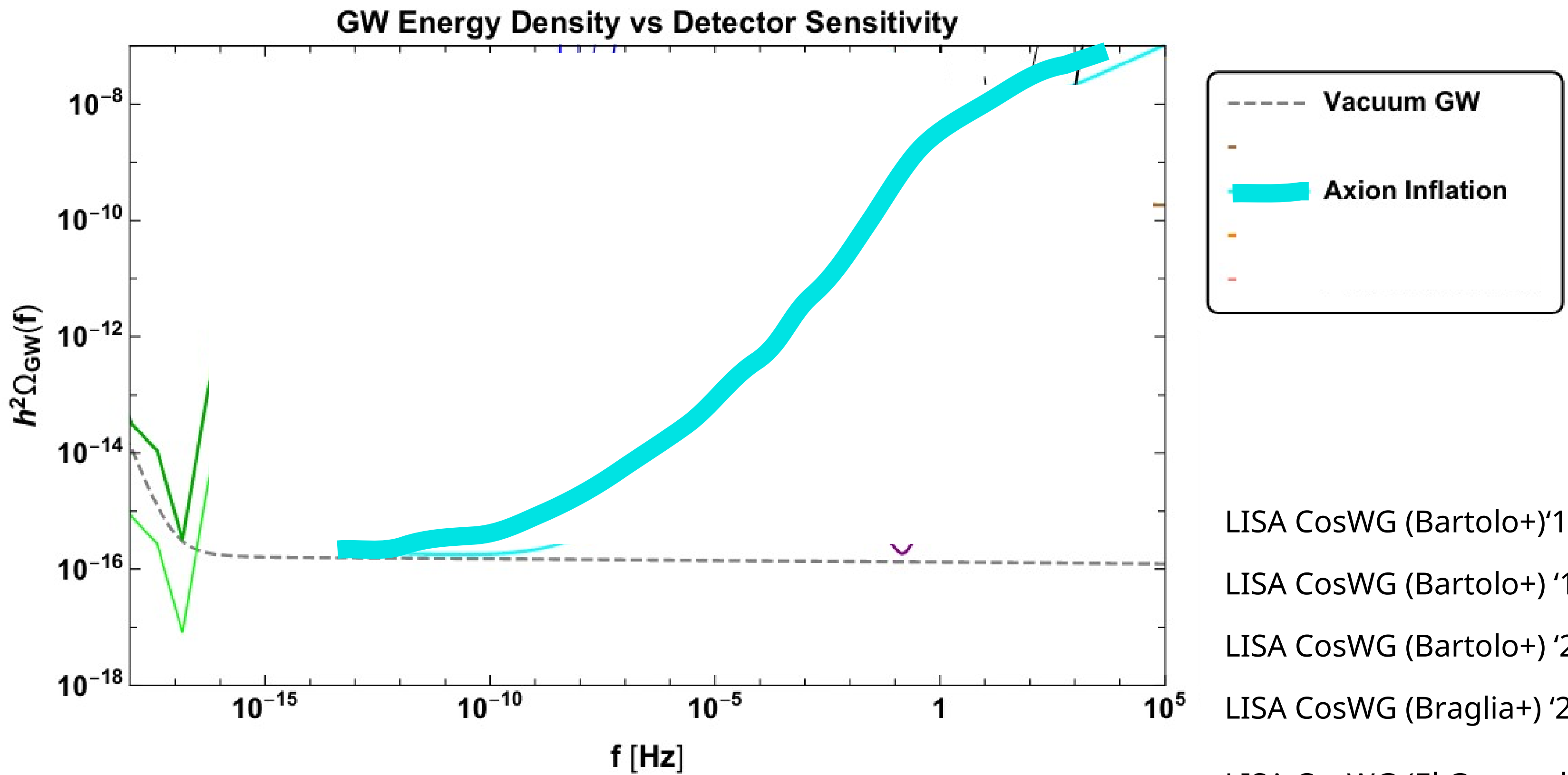
Why is SGWB search so exciting for fundamental physics?

A **source-independent** **direct** probe of the pre-BBN universe



SGWB from the inflationary epoch

- **Inflation**: standard single-field slow-roll, inflation with spectators, preheating, … very model dependent!
  - Signal from vanilla scenario is very small



LISA CosWG (Bartolo+)'16

LISA CosWG (Bartolo+) '18

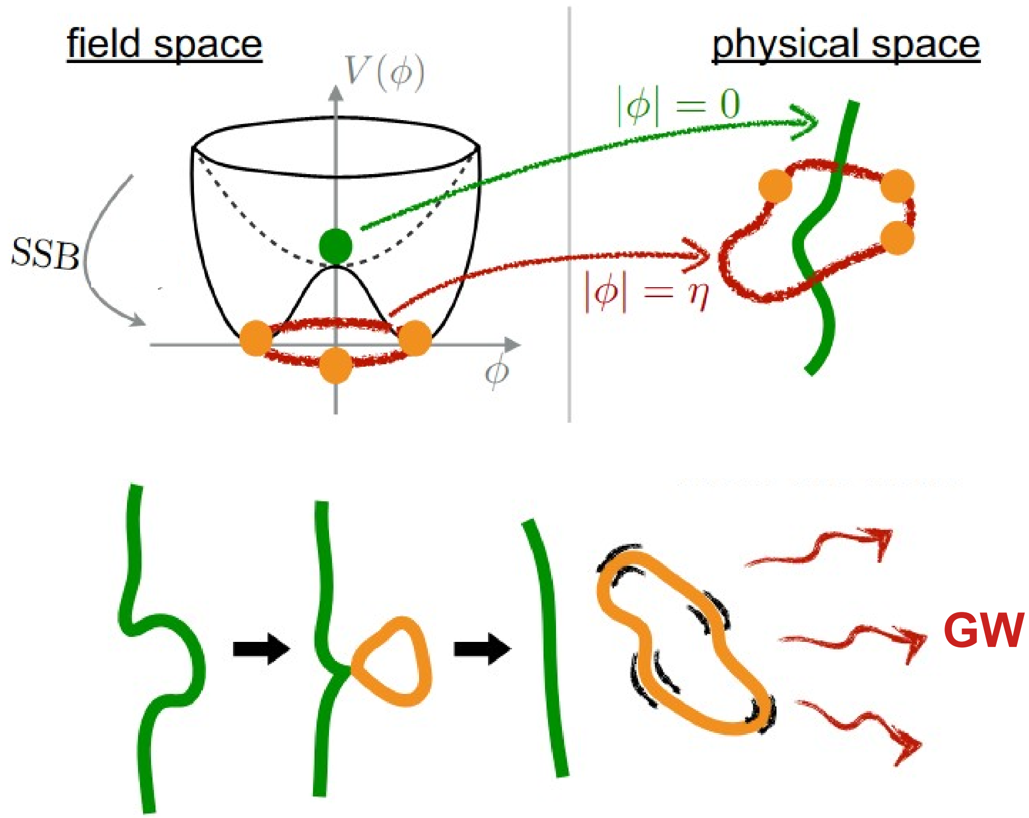
LISA CosWG (Bartolo+) '22

LISA CosWG (Braglia+) '24

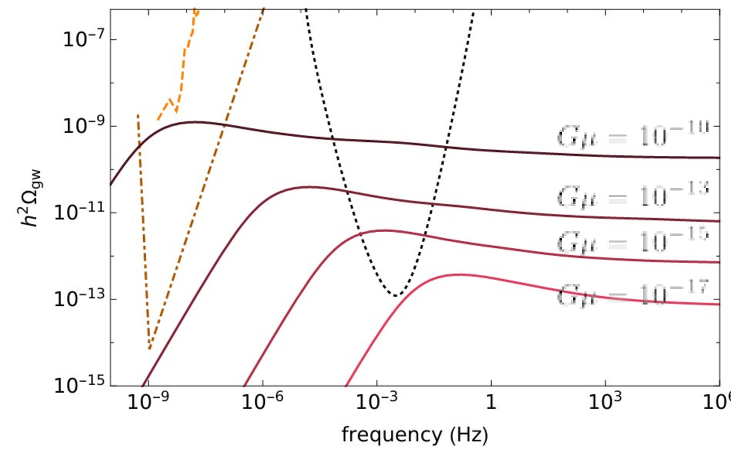
LISA CosWG (El Gammal+) '25

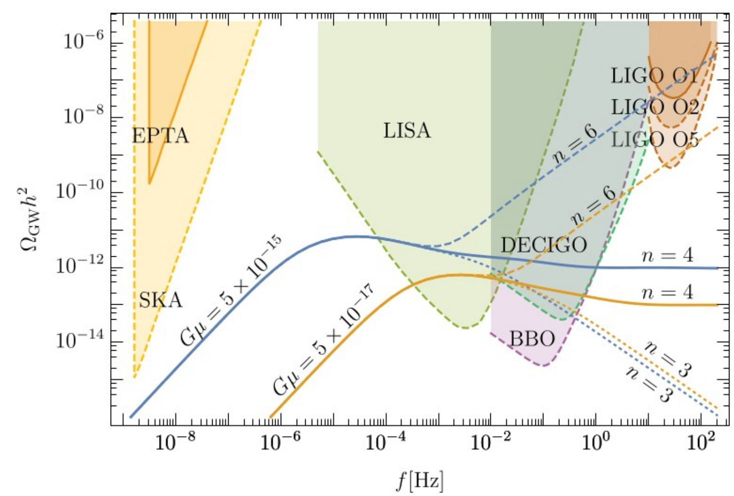
GWs from symmetry breaking (cosmic strings)

Cosmic strings: stable 1-dim. topological objects from (topologically non-trivial) spontaneous symmetry breakings



[credits: P. Simakachorn]



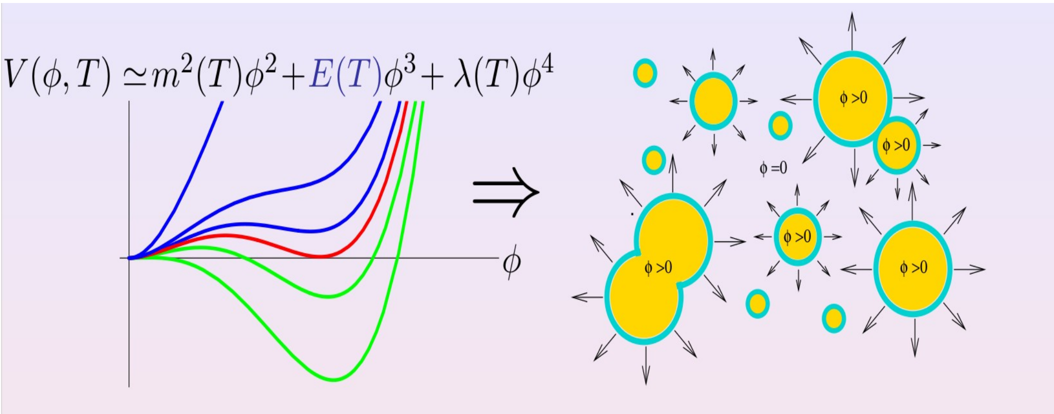


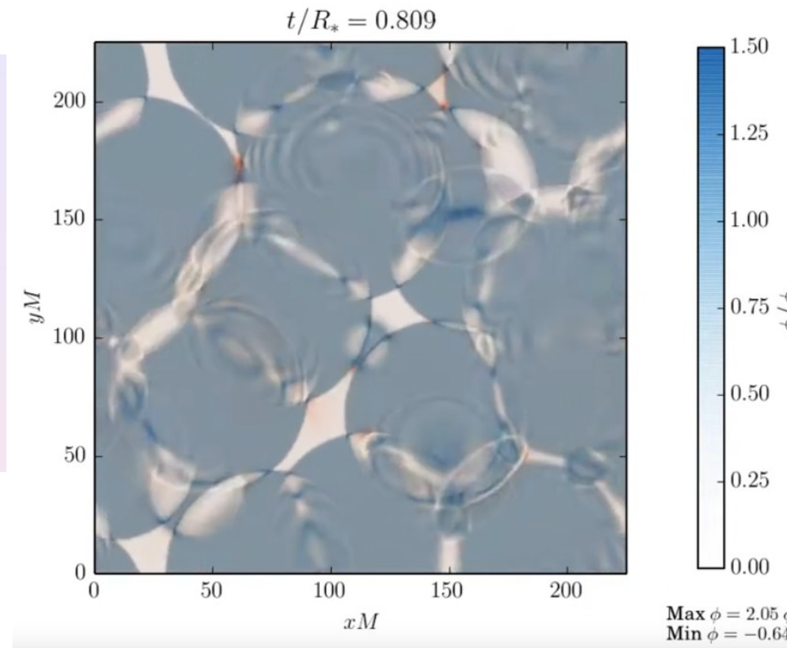
LISA CosWG (Blanco Pillado+) ‘20

LISA CosWG (Blanco Pillado+) ‘24

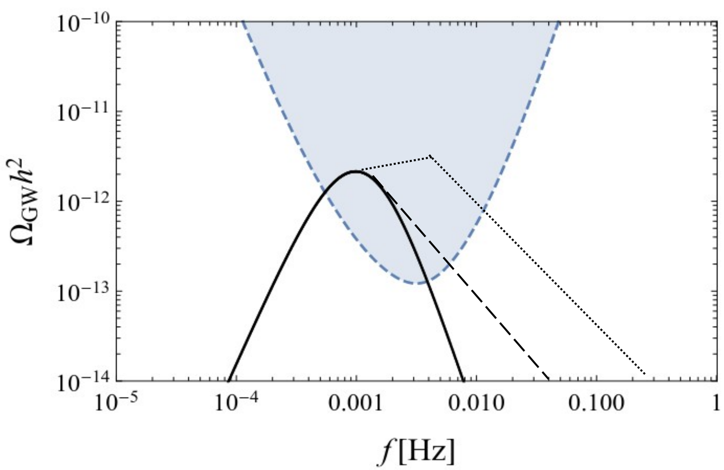
GWs from symmetry breaking (bubble nucleation)

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





[credits: D. Cuttings and M. Hindmarsh]



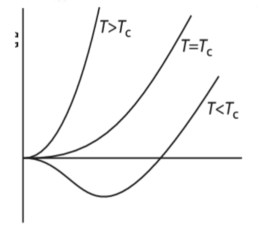
LISA CosWG (Caprini+) ‘15

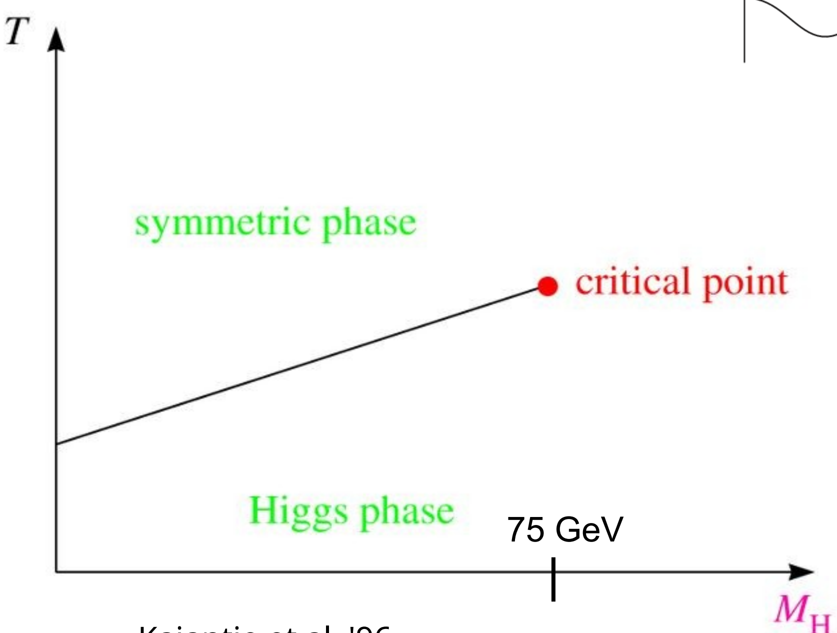
LISA CosWG (Caprini+) ‘19

LISA CosWG (Caprini+) ‘24

First-order phase transitions in SM particle physics/cosmology ?

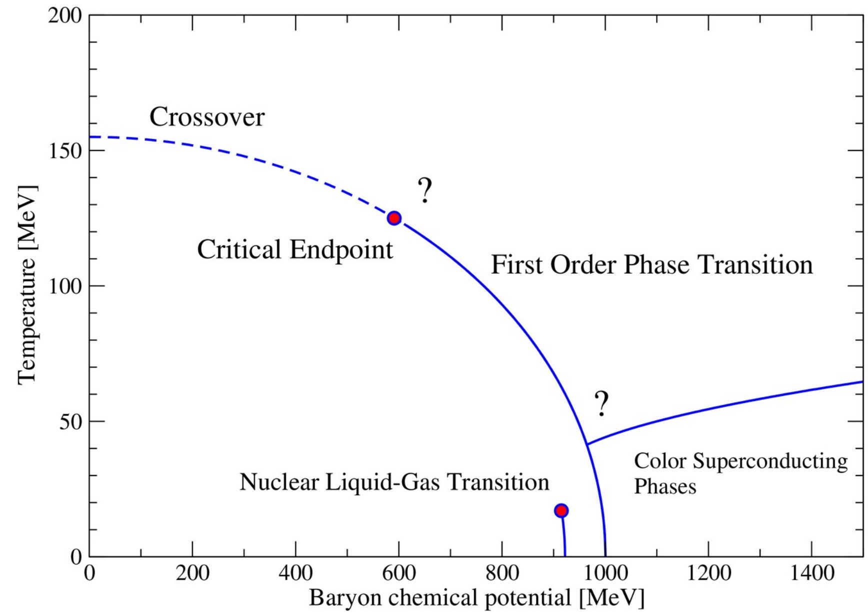
EW





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

QCD

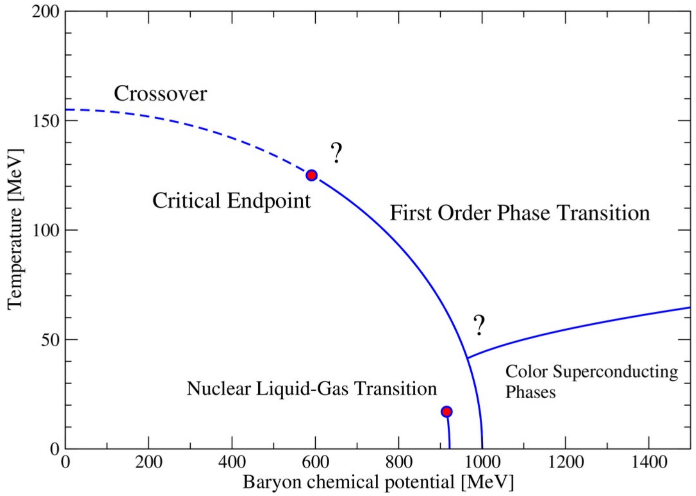


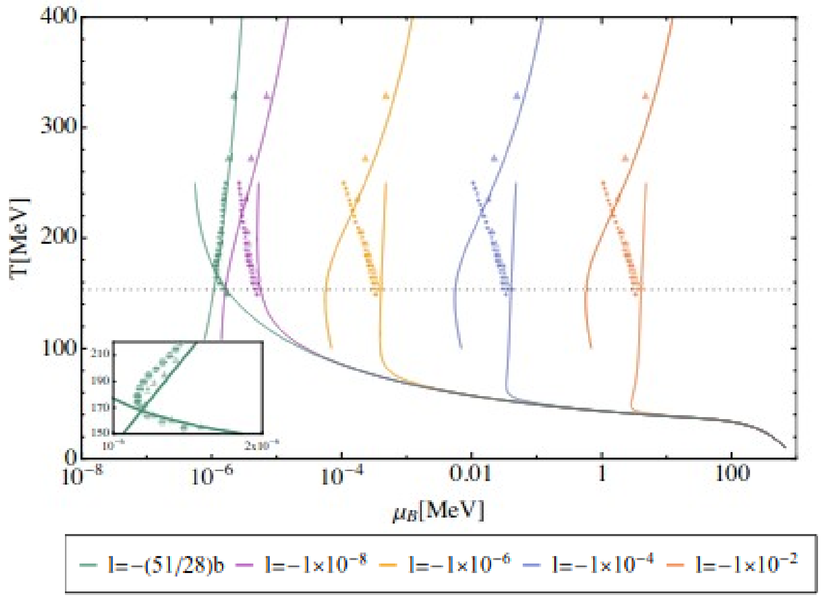
Aoki et al. ‘06
Wigas et al. ‘18
Gunkel et al. ‘21

No FOPT in the SM of particles/cosmology, but ...

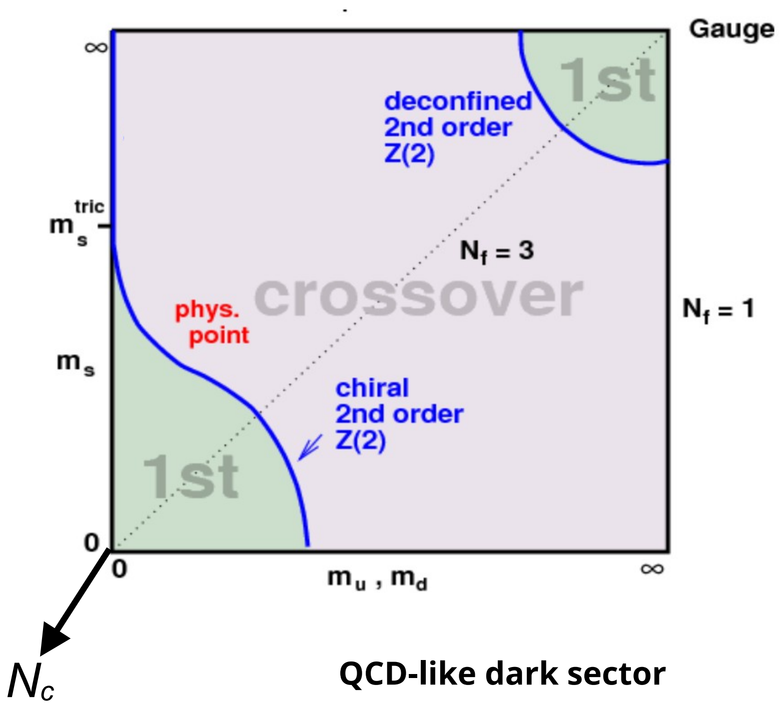
First-order phase transitions in SM particle physics/cosmology ?

QCD



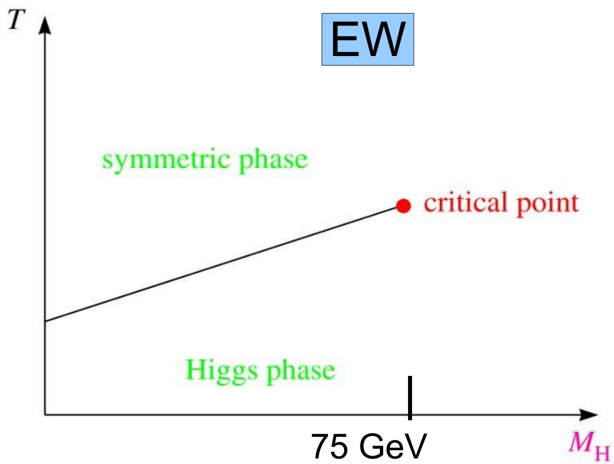


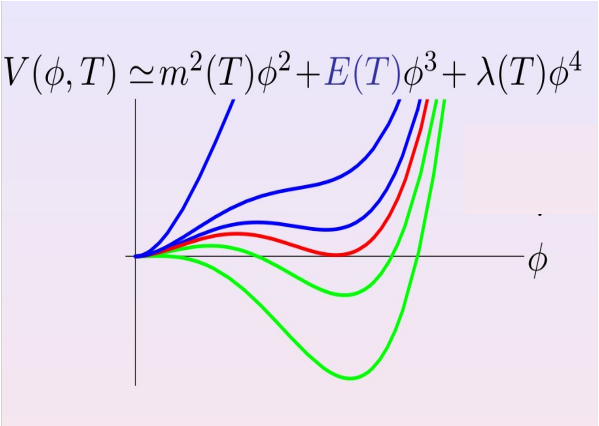
Large lepton asymmetry
Schwarz+Stuke '10, Wigas+ '18



QCD-like dark sector
Brown+ '90, Springer '23

First-order phase transitions in SM particle physics/cosmology ?





- EW-sector extensions: the barrier can be achieved via:
  - Temp. radiative corrections with scalar interactions, or/and
  - new dynamical fields (i.e. scalars) coupled to the Higgs

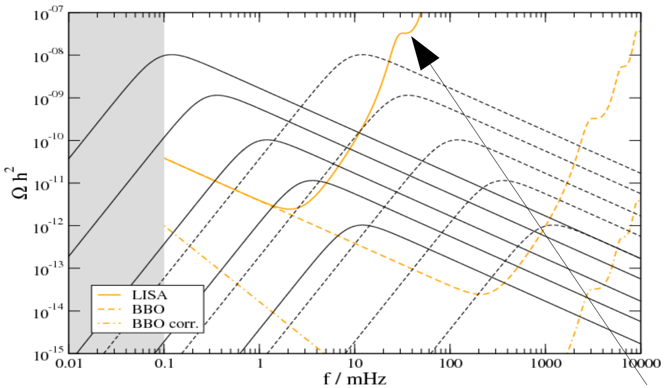
New TeV-scale scalars

- New fermions → no large T-effects → no large barrier → no 1st order
- Very heavy fields → Boltzmann suppressed and small low-energy effects → no 1st order'
- New largely-coupled fields → Large T effects but also changes in collider pheno
- New dynamical scalar fields → Mixing → Higgs signal strengths + heavy-Higgs pheno
- New dynamical scalar fields with negligible mixing (due to symmetry) → rather clean

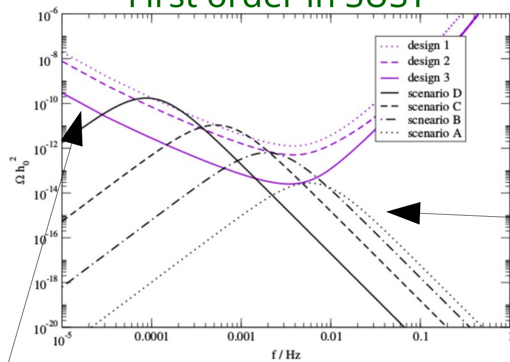
- Beyond EW-sector extension: extra scalar sector in hidden sectors, at high scales, …

Examples of EW-scale BSM with loud FOPT GW signal

First order in Randall Sundrum



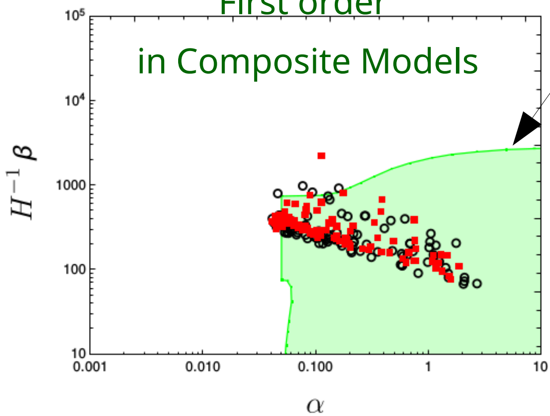
First order in SUSY



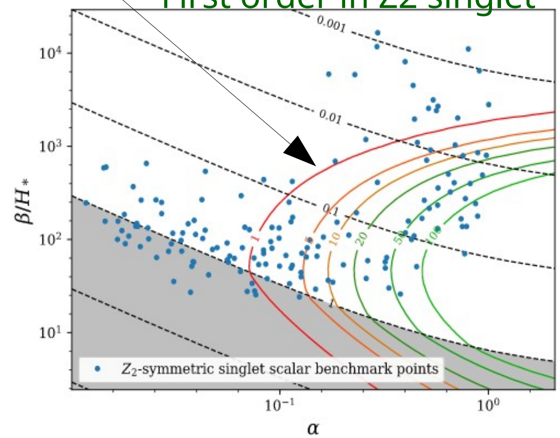
SGWB signal above sensitivity

LISA sensitivy region

First order in Composite Models



First order in Z2 singlet



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

But also 2HDM, B-L model , …. all talks here!!!

Many models with different pheno!

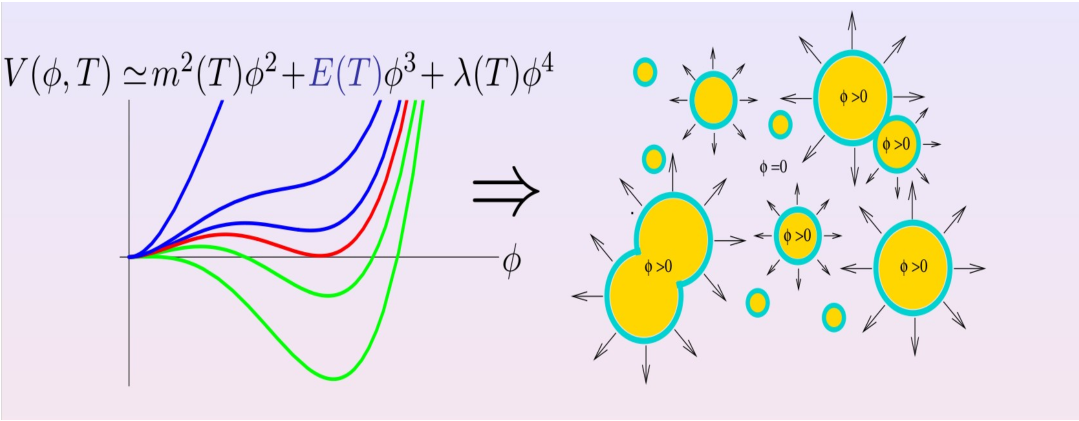
More examples in:
LISA CosWG (Caprini+)'16
LISA CosWG (Caprini+.)'20

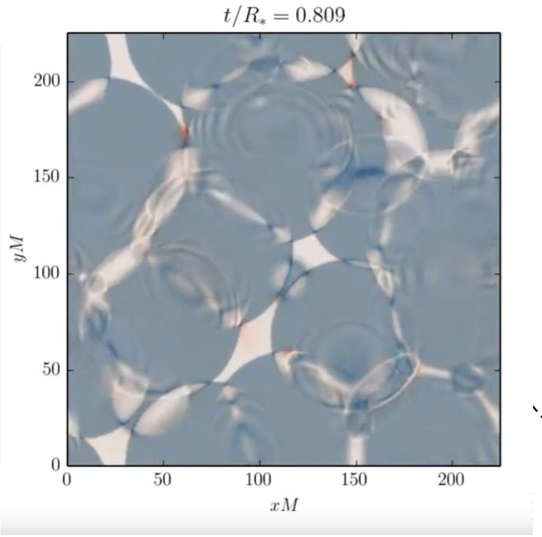
FOPT GW signal = stochastic GW background (SGWB)

Contrary to LVK events detected so far, the GW signal from the early-universe is (in first approximation)

- sourced by events that are intrinsically *non-localized and uniformly distributed* in the sky dome
  → **isotropic** signal

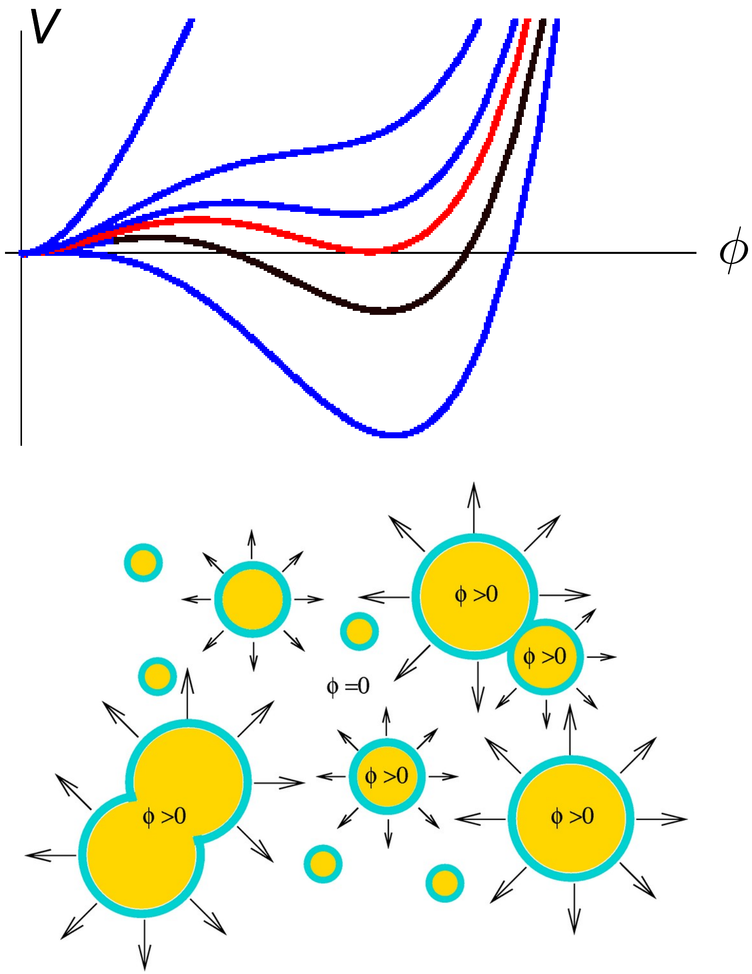
- sourced by a *huge* number of *uncorrelated* events
  → **Gaussian stochastic** signal

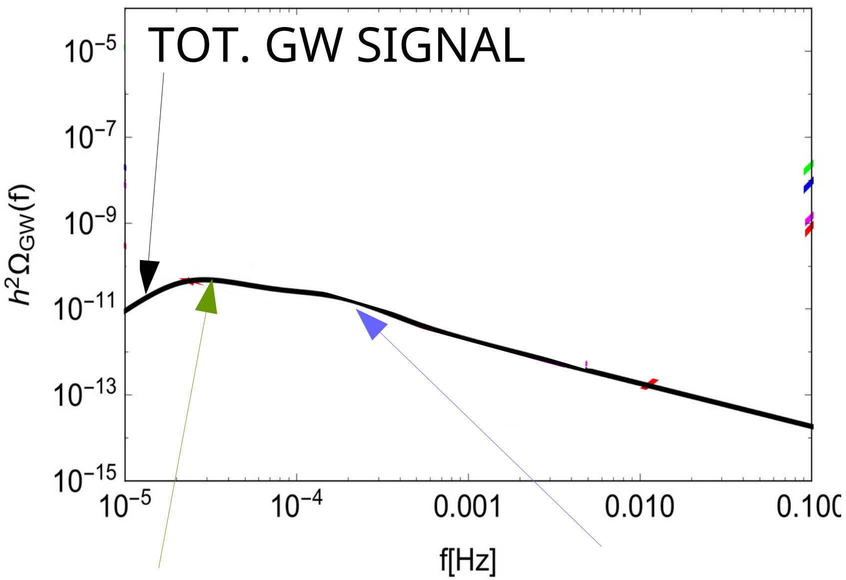




FOPT SGWB signal: frequency shape

When the transition is of first order...





Main peak due to **SOUND WAVES CONTRIBUTION** and/or **BUBBLE COLLISION CONTRIBUTION**

M.Hindmarh,S.Huber, K.Rummukainen,D.Weir,'13,'15

Peak due to **TURBULENCE CONTRIBUTION**

P.Binetruy+,'12
Roper Pol+, ‘22

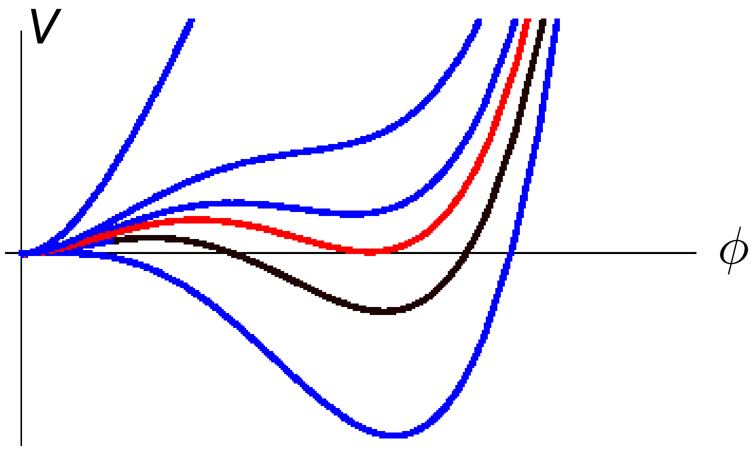
LISA CosWG (Caprini+) ‘15

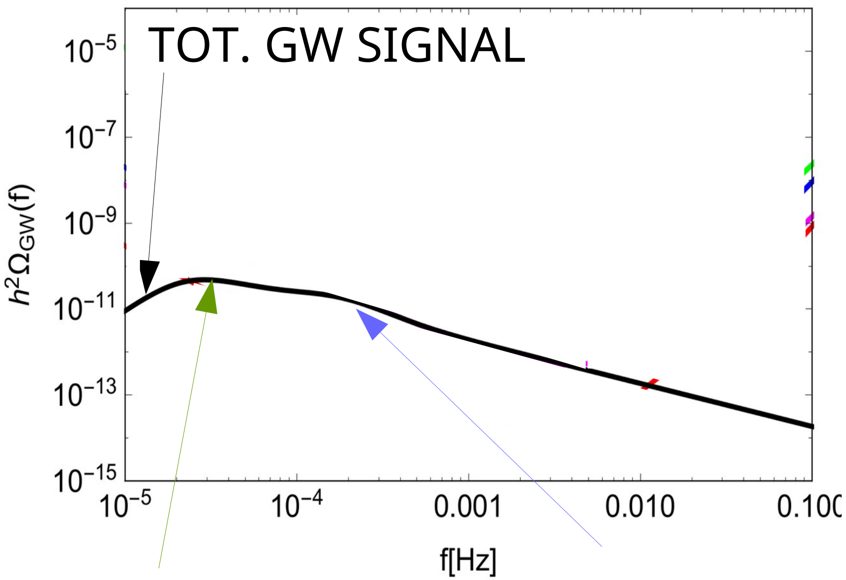
LISA CosWG (Caprini+) ‘19

LISA CosWG (Caprini+) ‘24

FOPT SGWB signal: frequency shape

When the transition is of first order...





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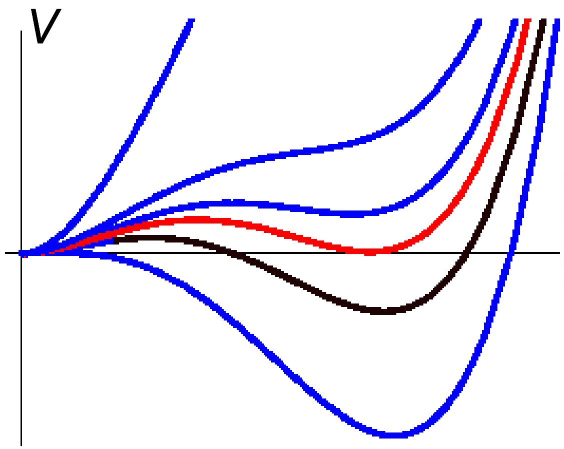
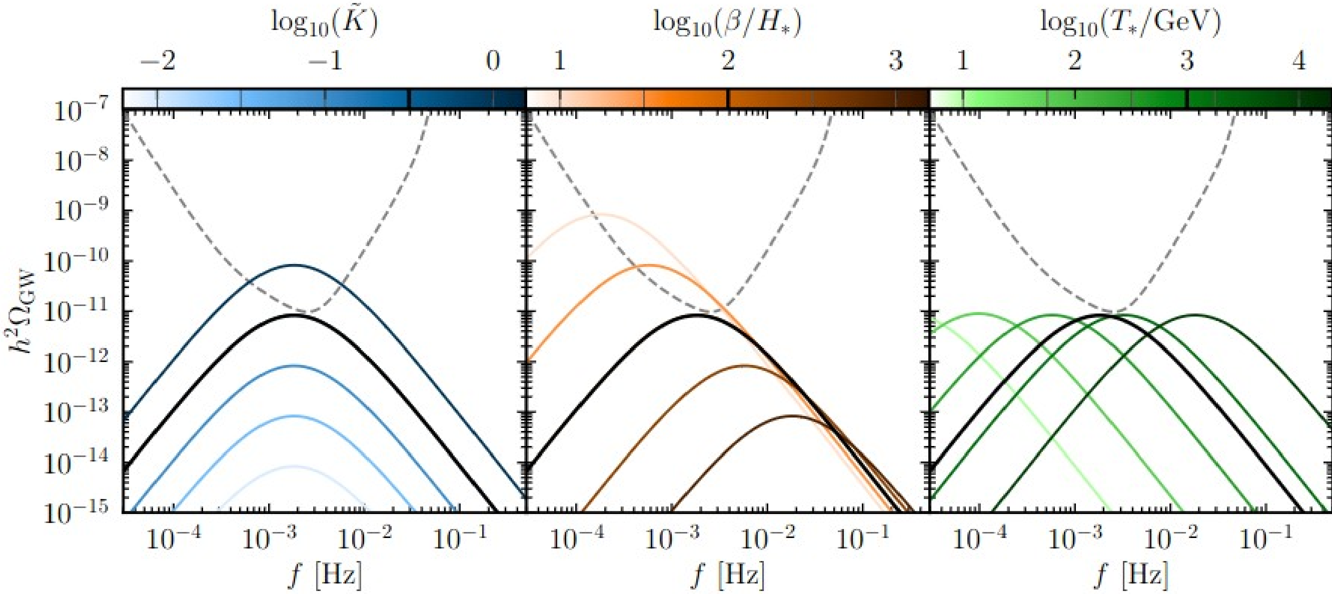
$$\left.\begin{matrix} K(\alpha) \\ \beta/H \\ T_* \\ \xi_w \\ \kappa_i \end{matrix}\right\}$$ thermodyn.-parameter inputs

LISA CosWG (Caprini+) '24

FOPT SGWB signal: frequency shape in bubble coll. regime





$$f_{peak} \sim \mathrm{mHz}\left(\frac{\beta/H}{100}\right)\left(\frac{T_*}{100\mathrm{GeV}}\right)$$

$$h_0^2\Omega_{peak} \sim 10^{-10} K^2(\alpha)\left(\frac{100}{\beta/H}\right)^2\left(\frac{\alpha}{\alpha+1}\right)^2$$

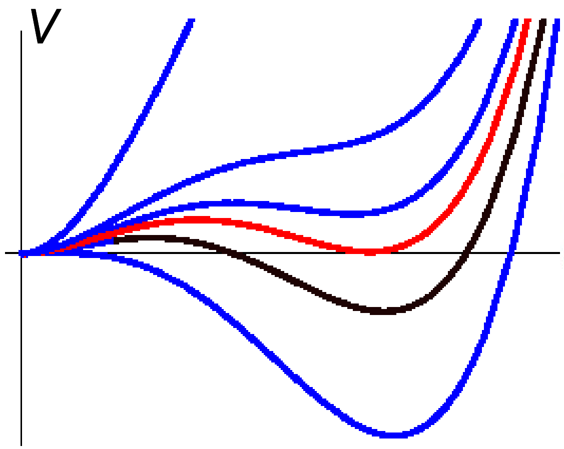
$K(\alpha)$
β/H
T_*
$\xi_w \simeq 1$
$\kappa_i \simeq (1,0,0)$

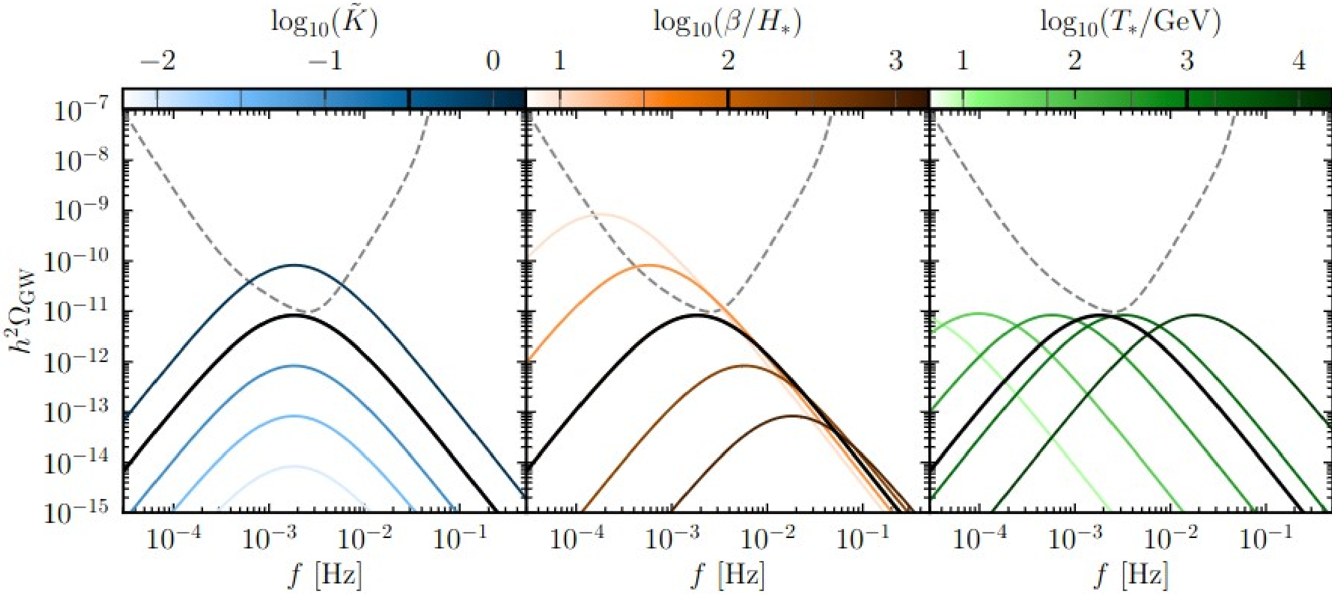
} Inputs for the BUBBLE WALL thermodyn.-parameter templates

- 2 out 5 thermodyn. param. fixed for bubble collisions

LISA CosWG (Caprini+) '24

FOPT SGWB signal: frequency shape in bubble coll. regime





$$f_{peak} \sim \text{mHz}\left(\frac{\beta/H}{100}\right)\left(\frac{T_n}{100\text{GeV}}\right) \qquad h_0^2\Omega_{peak} \sim 10^{-10}K^2(\alpha)\left(\frac{100}{\beta/H}\right)^2\left(\frac{\alpha}{\alpha+1}\right)^2$$

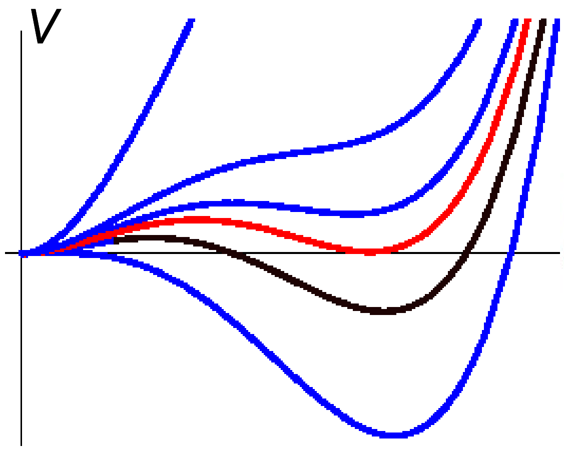
$$\Omega_{\rm GW}^{\rm BPL}(f) = \Omega_b\left(\frac{f}{f_b}\right)^{n_1}\left[\frac{1}{2}+\frac{1}{2}\left(\frac{f}{f_b}\right)^{a_1}\right]^{\frac{n_2-n_1}{a_1}}$$

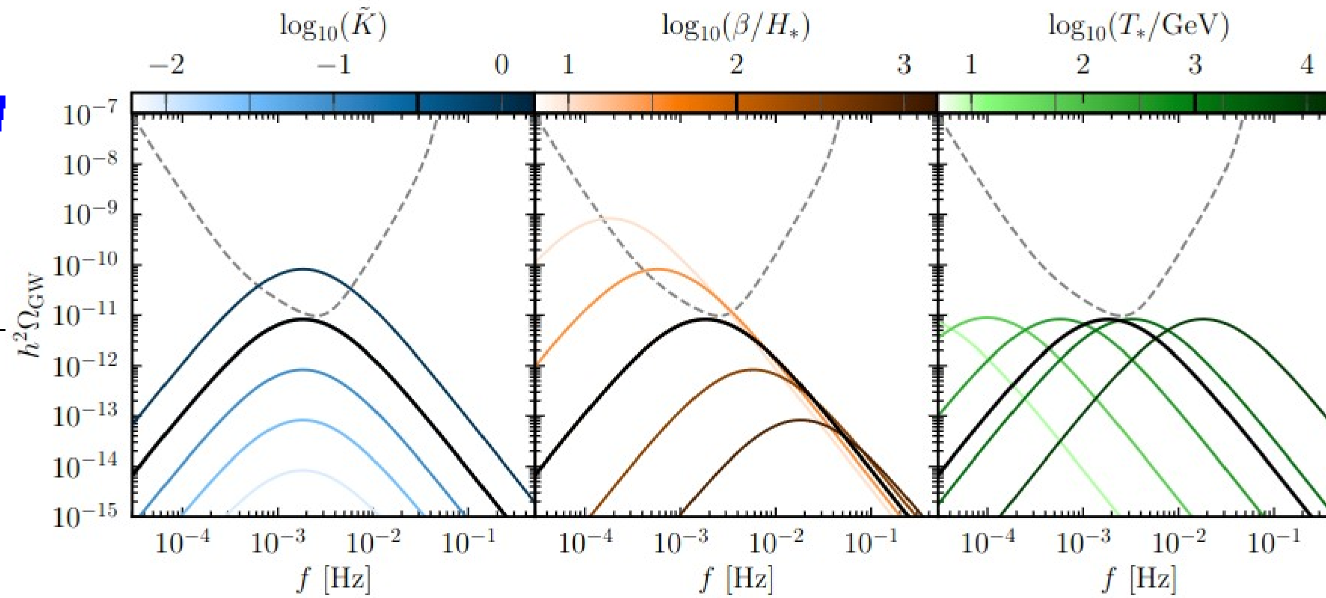
$$n_1 = 2.4\,,\quad n_2 = -2.4\,,\quad a_1 = 1/2$$

Inputs for the BUBBLE WALL geometric.-parameter templates $\begin{cases} f_b \\ \Omega_b \end{cases}$

LISA CosWG (Caprini+) ‘24

FOPT SGWB signal: frequency shape in bubble coll. regime





$$f_{peak} \sim \mathrm{mHz}\left(\frac{\beta/H}{100}\right)\left(\frac{T_n}{100\mathrm{GeV}}\right) \qquad h_0^2\Omega_{peak} \sim 10^{-10}K^2(\alpha)\left(\frac{100}{\beta/H}\right)^2\left(\frac{\alpha}{\alpha+1}\right)^2$$

$K(\alpha)$
β/H
T_*
$\xi_w \simeq 1$
$\kappa_i \simeq (1,0,0)$

} Inputs for the BUBBLE WALL thermodyn.-parameter templates

Inputs for the BUBBLE WALL geometric.-parameter templates {

f_b
Ω_b

Degeneracies !!!

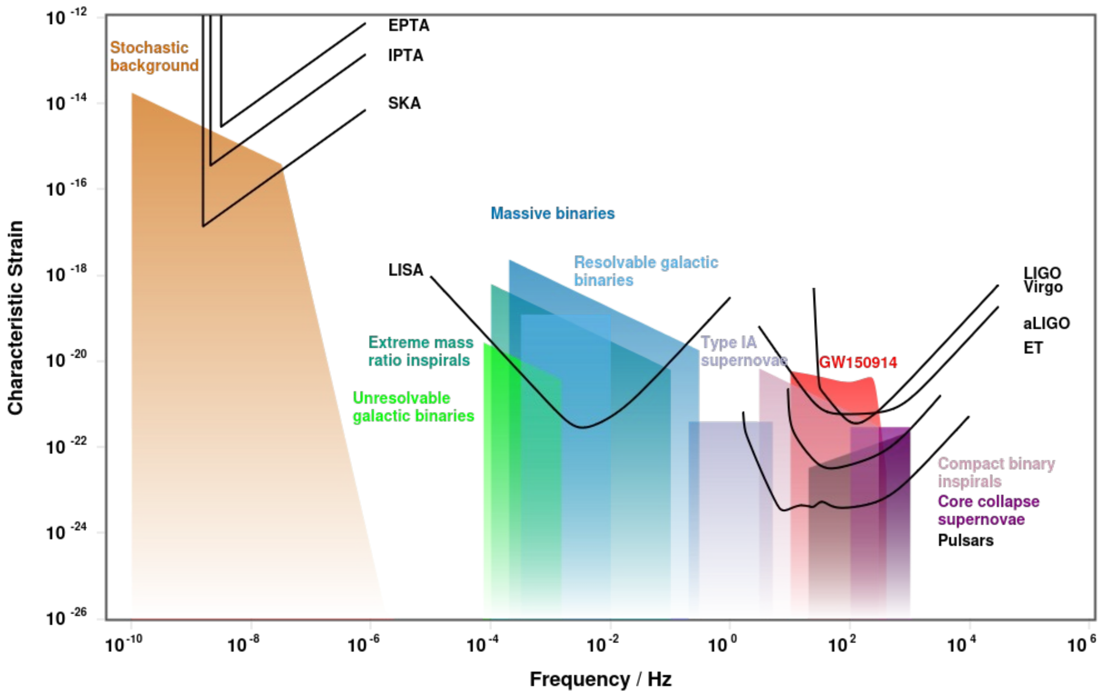
LISA CosWG (Caprini+) ‘24

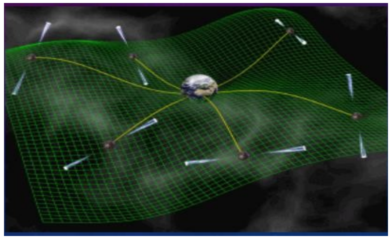
Gravitational Waves Detectors

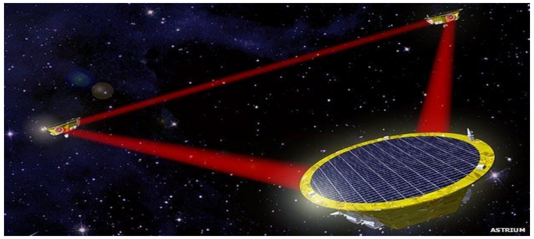
Pulsar timing arrays: GWs with 10^{-9}–10^{-6} Hz

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

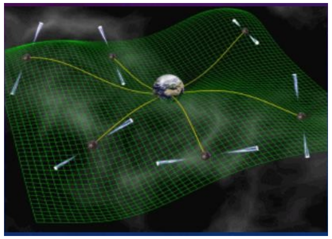
Ground-based interferometers: GWs with 1–10^{4} Hz

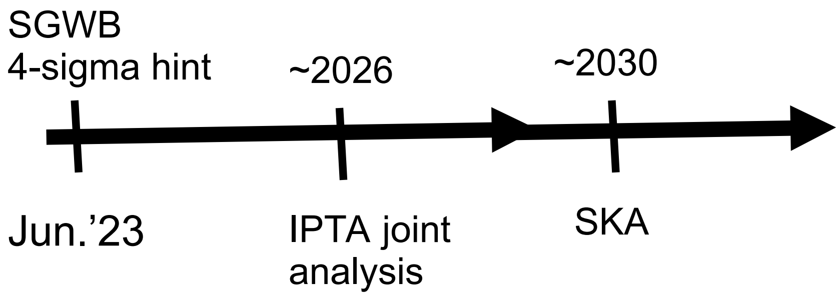


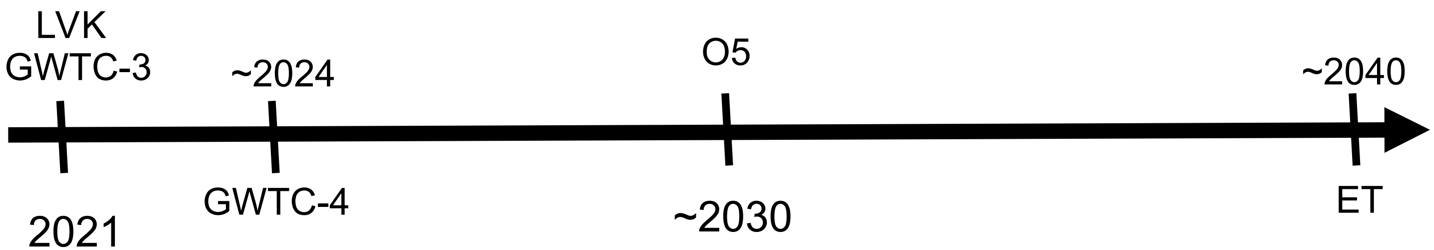


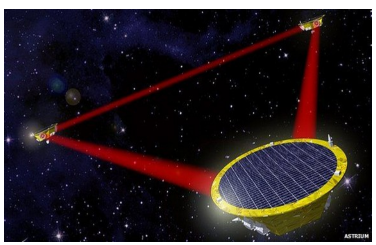


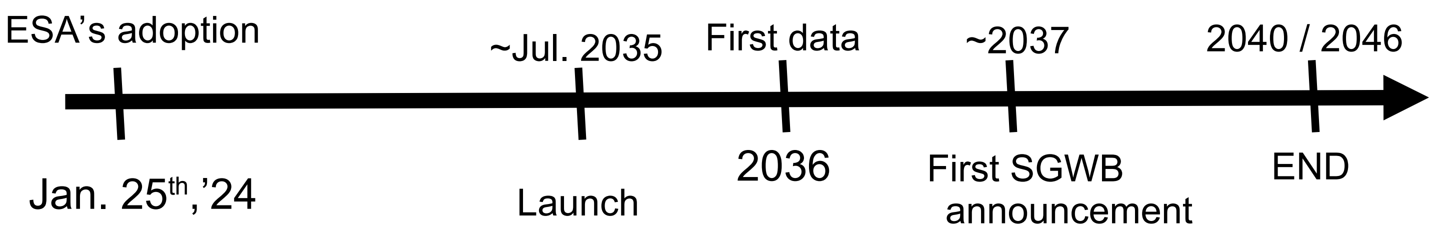
GW experiment and FCC timelines

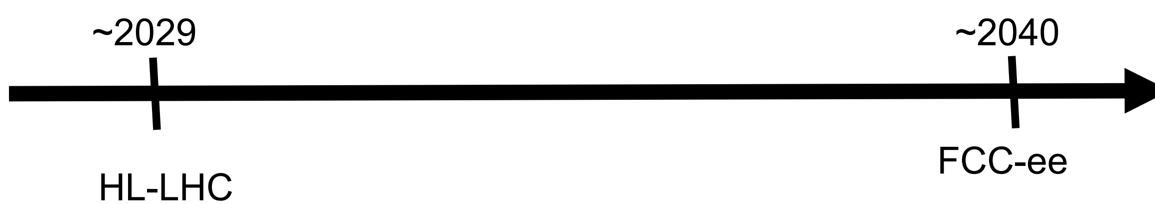








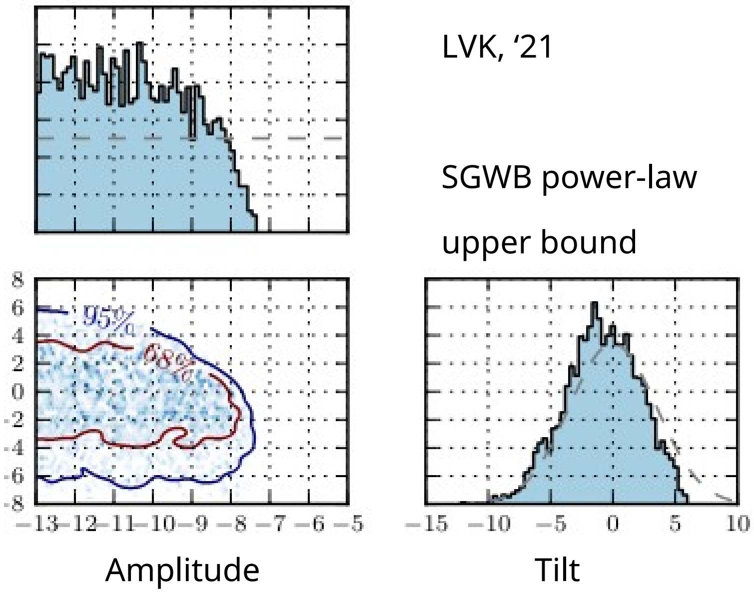




SGWB status at Hz experiments (brutally brief and biased)

LVK

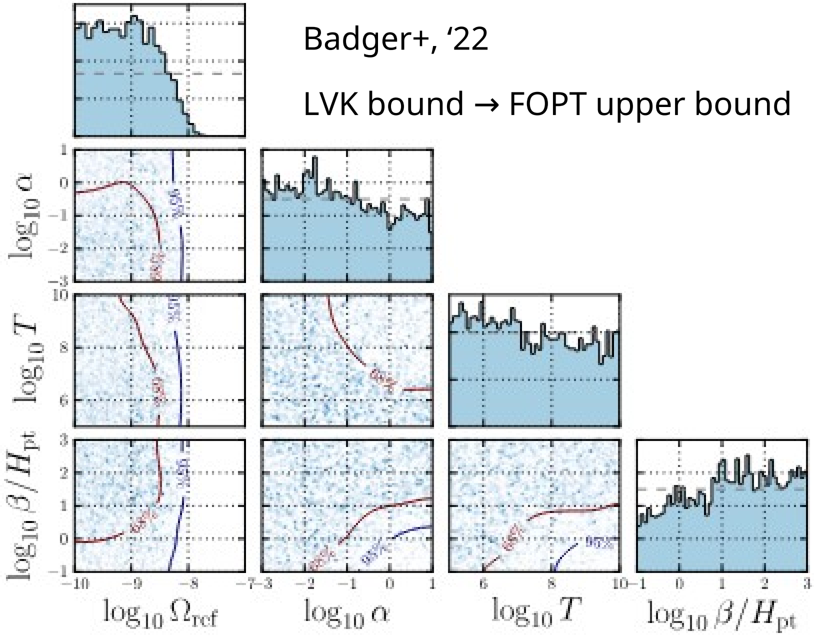
- Observations compatible with "expected" astronomy
- Recast observations give weak upper bounds on BSM physics at $\sim 10^{6\text{-}10}$ GeV
- Likely, no huge progress before ET due to the soonish-emerging binary foreground



LVK, '21

SGWB power-law

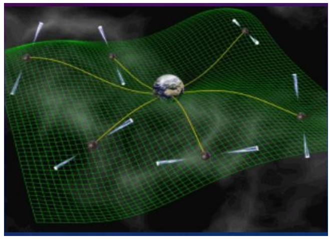
upper bound



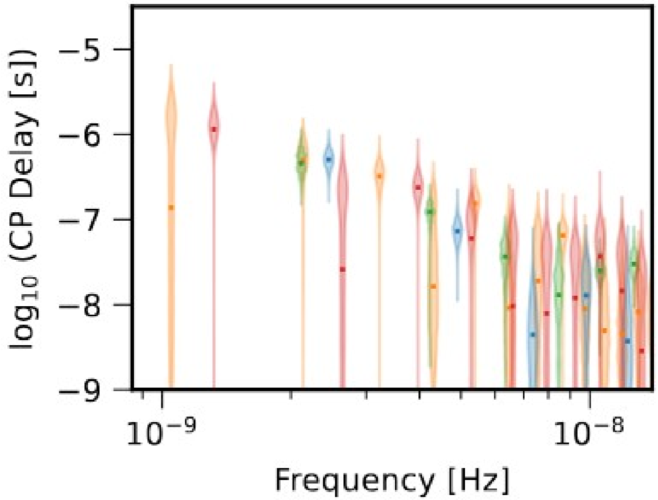
Badger+, '22

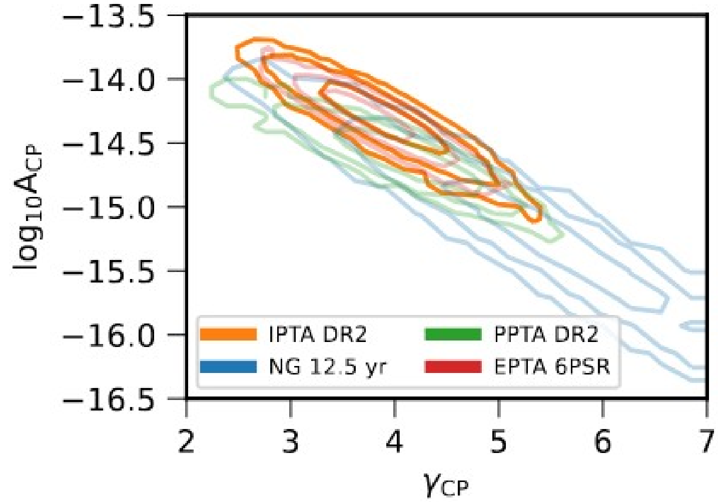
LVK bound → FOPT upper bound

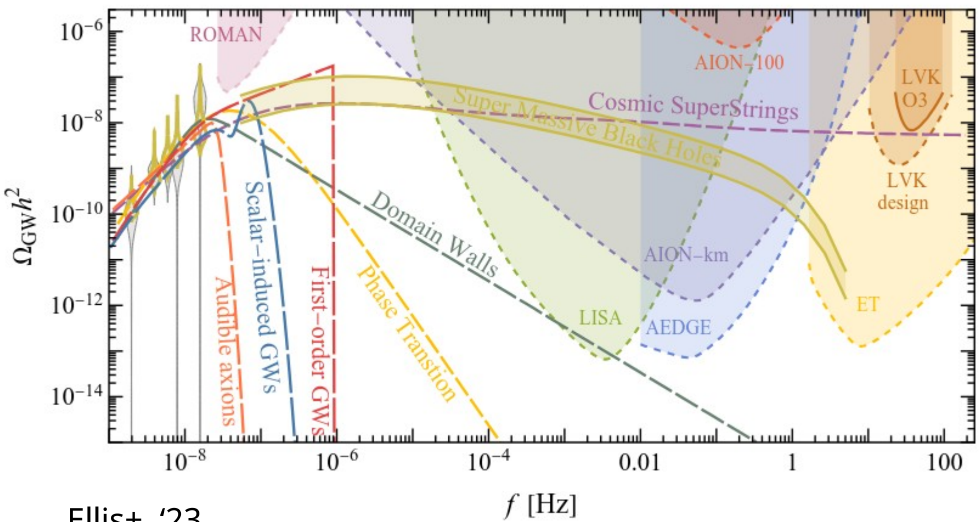
SGWB status at nHz experiments (brutally brief and biased)



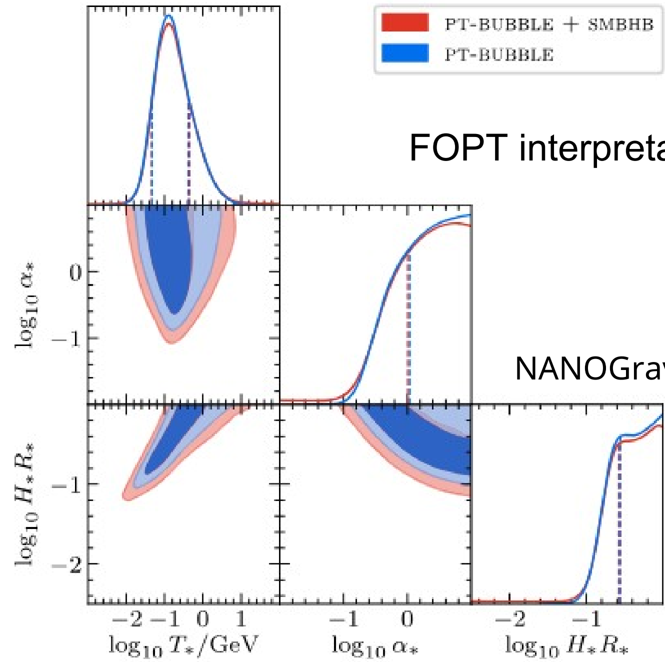
PTA







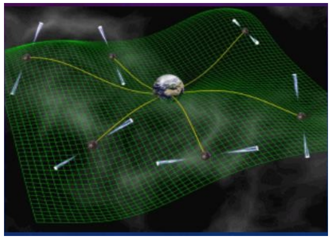
Ellis+, '23



FOPT interpretation

NANOGrav. '23

SGWB status at nHz experiments (brutally brief and biased)



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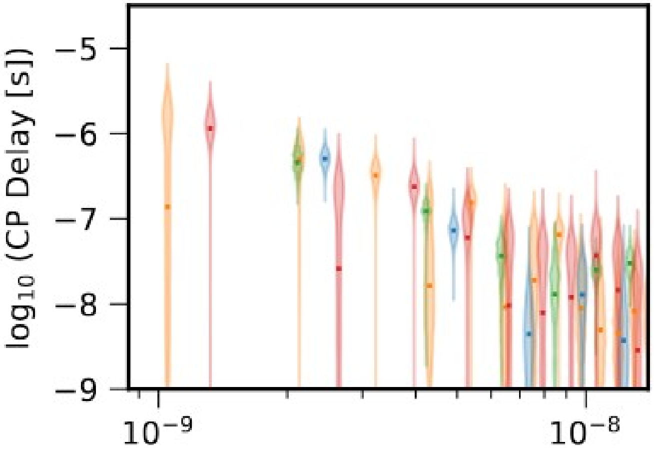
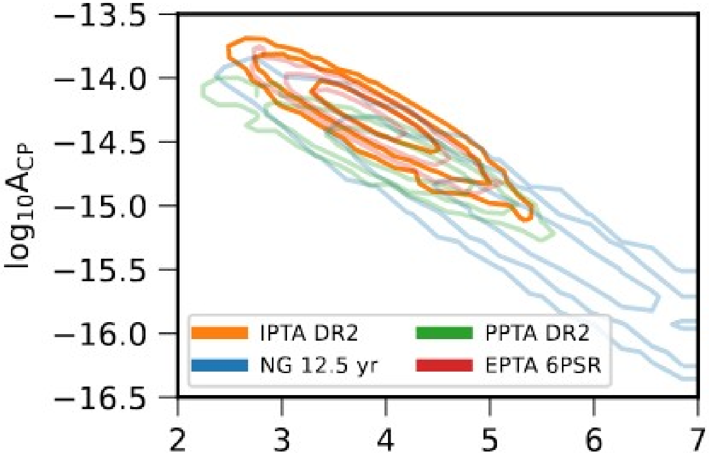
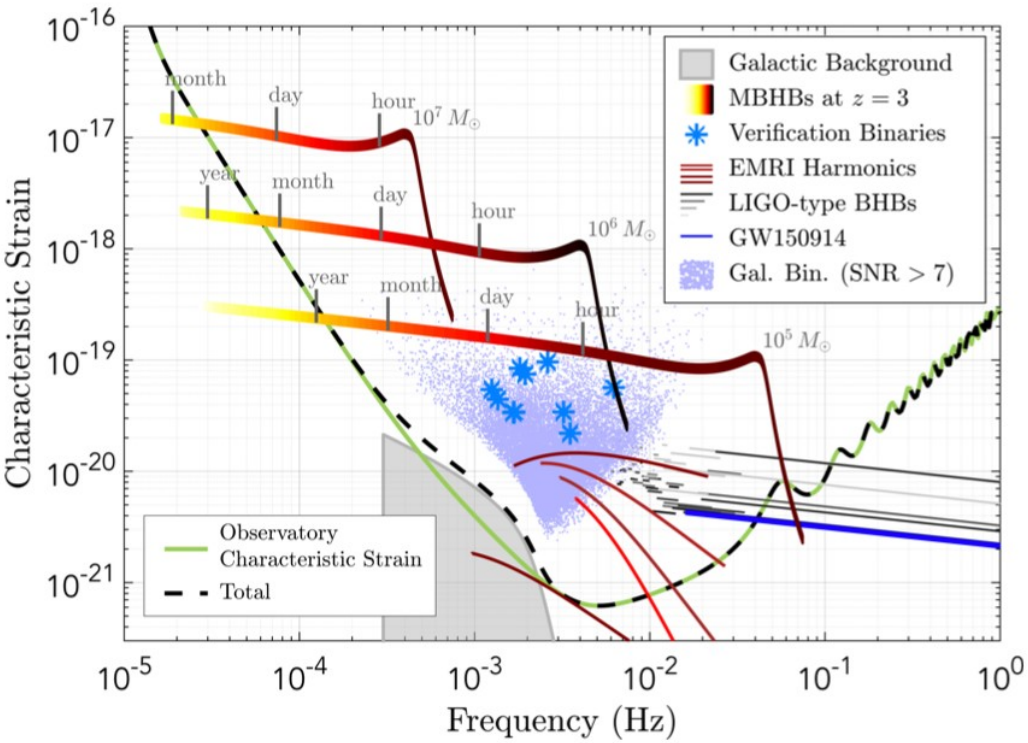


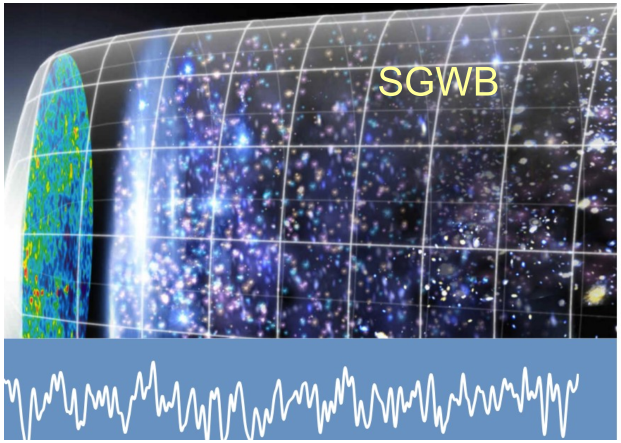


MAYBE A BSM HINT, MAYBE NOT

- 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 mHz experiments ? LISA mission targets



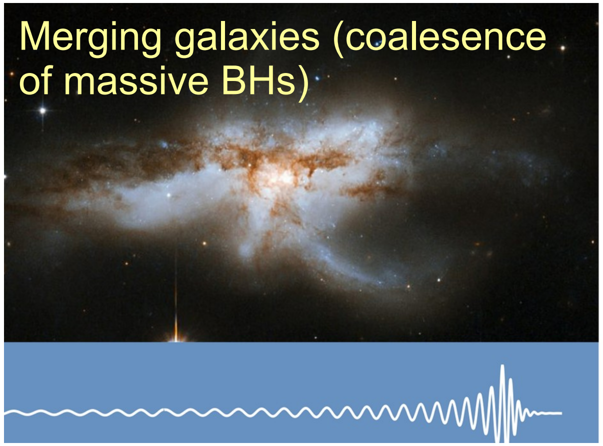


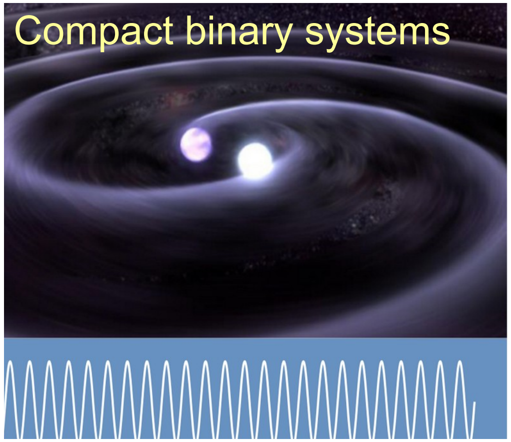
O(10^4) resolv. galac. binaries

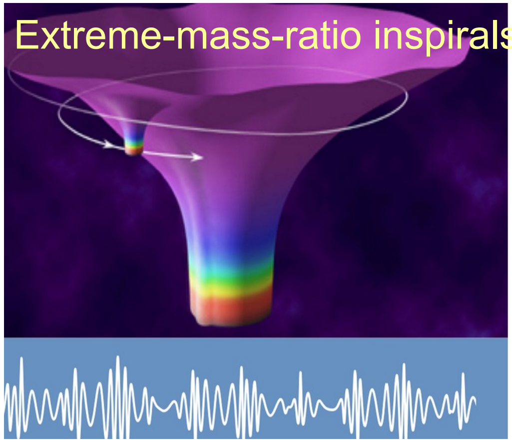
O(10) extragal. BBHs of 10^0–10^2 $M_\odot$

O(1 - 10) extreme mass-ratio inspirals

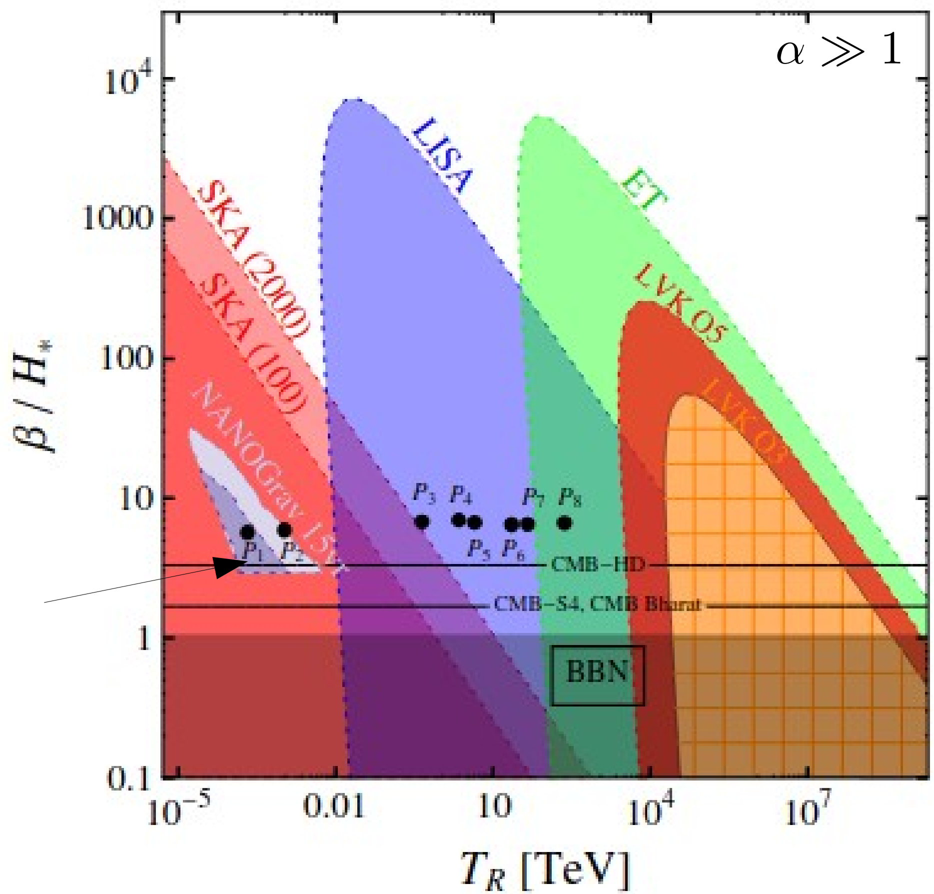
O(10 - 100) merging BBHs of 10^5–10^8 $M_\odot$







SGWB from a FOPT : parameter reach in bubble coll. regime



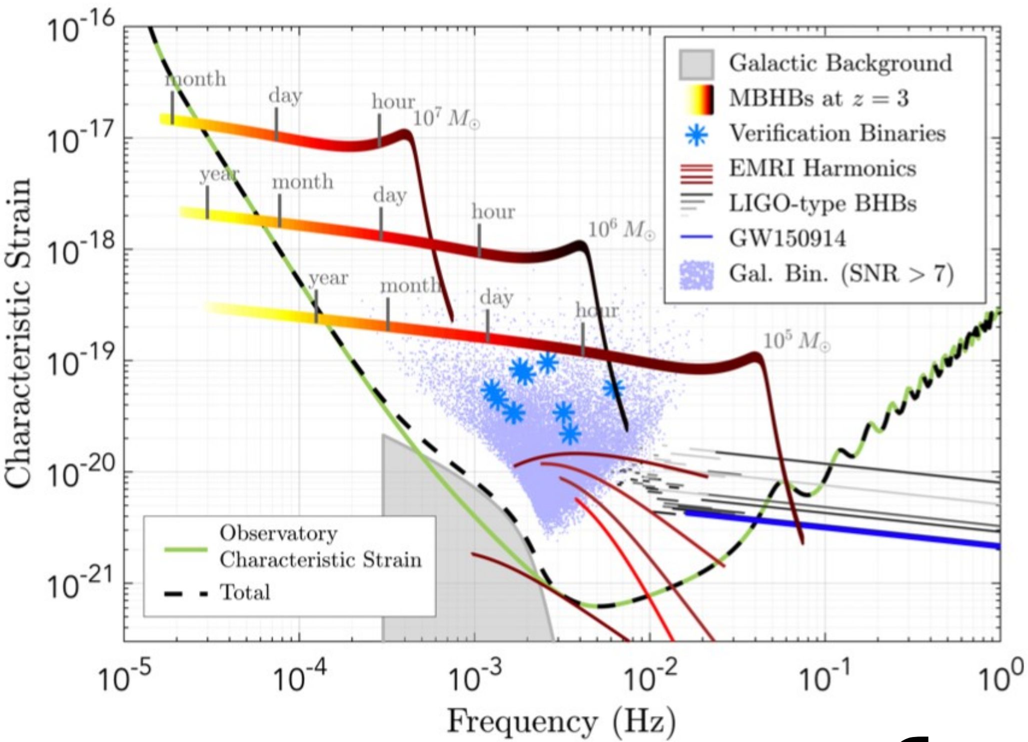
Current PTA signal

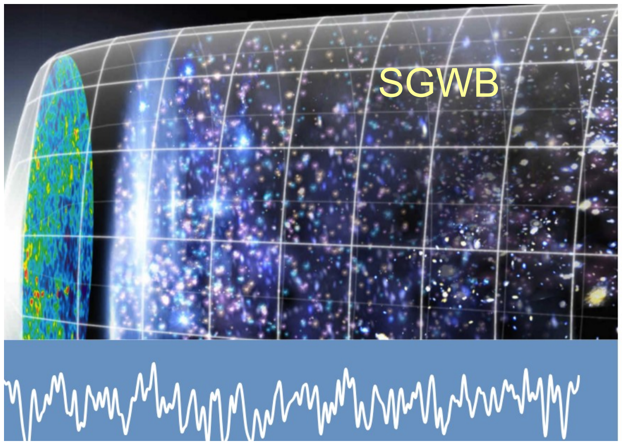
Taking SNR > 10 as detection/non-detection criterion

(Goshal) Megias, GN, Quiros, '18, ('24)
LISA CosWG (P. Auclair+) '22

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

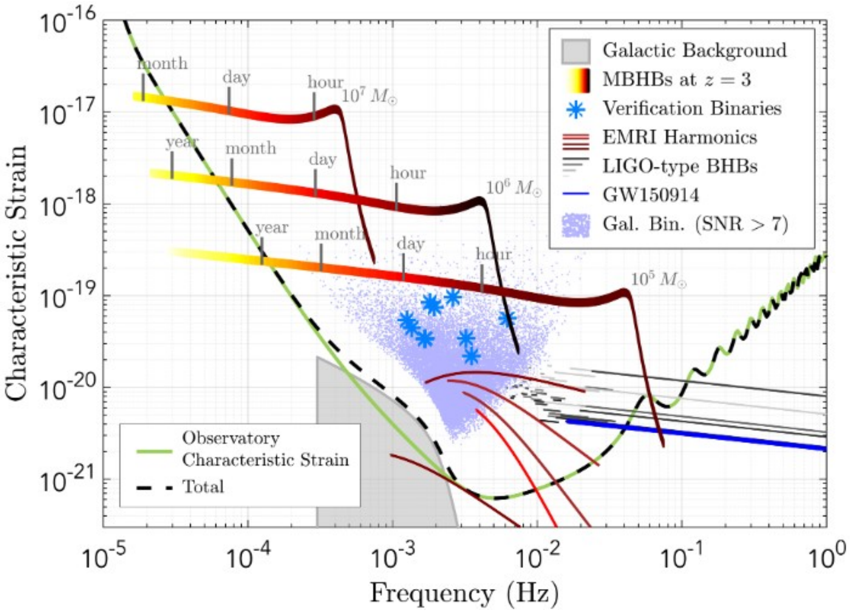
SGWB reconstruction at LISA



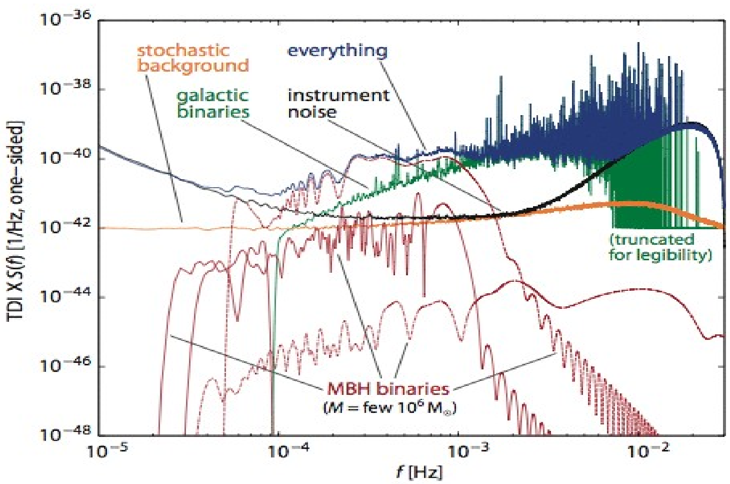


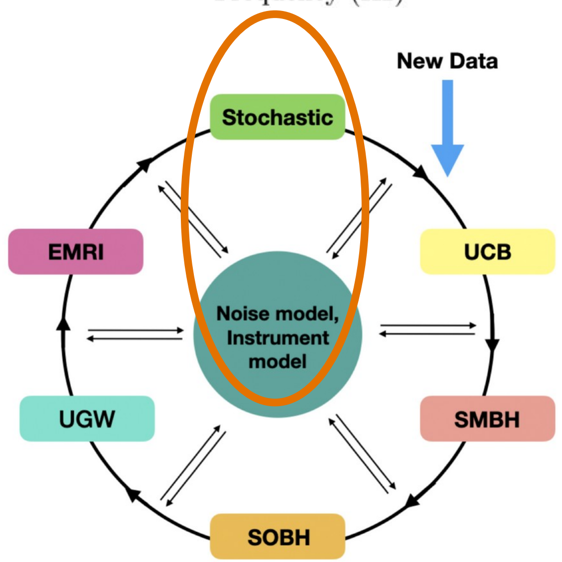
SGWB
- Astronomical sources
  - Galactic binaries
  - Extra-Gal. binaries
- Cosmological sources
  - Cosmic strings, Domain walls, **FOPT**, Inflation, ….

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



LISA is a signal-dominated experiment



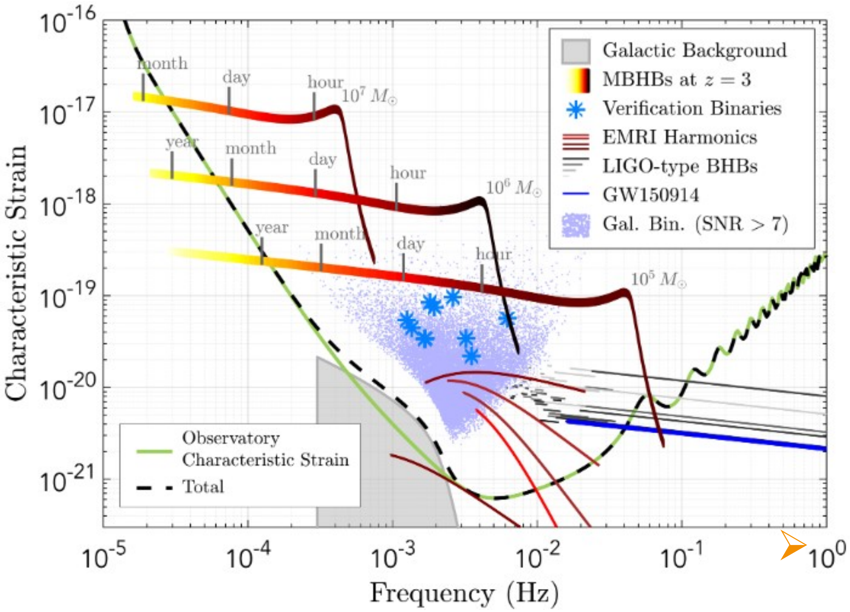


- Too many parameters to fit.
- Heavy-memory waveforms.

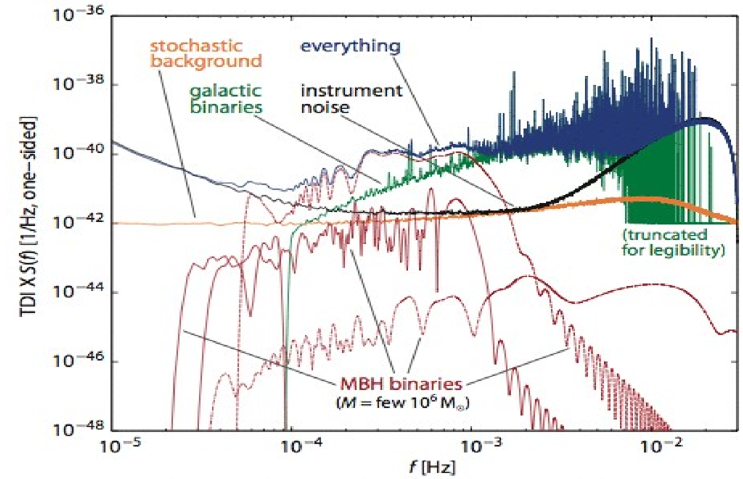
No hope to reach convergence in the parameter estimate by standard methods

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

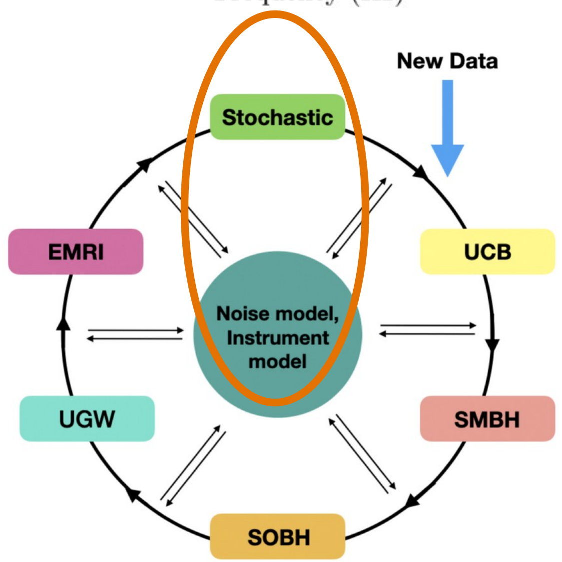
SGWB from a FOPT : **LISA** search based on template



LISA is a signal-dominated experiment

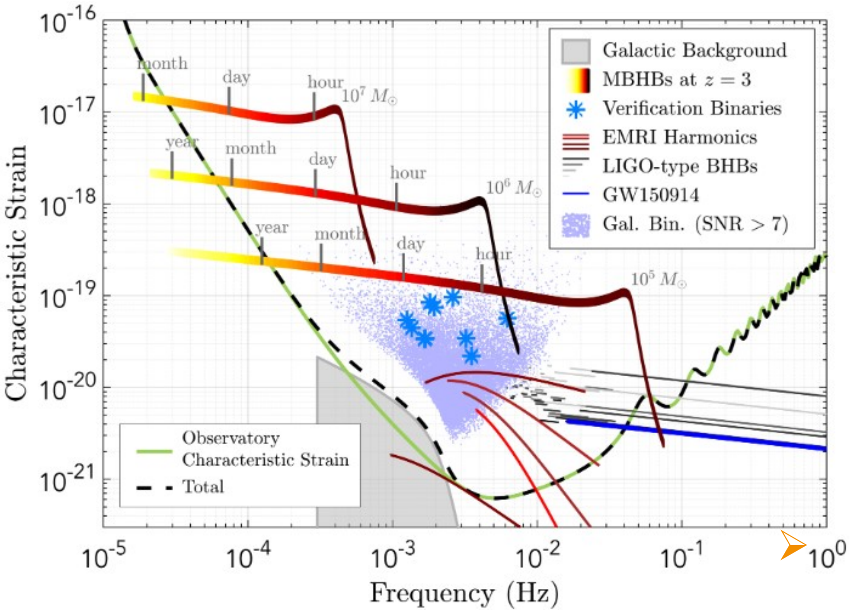


- We build the search and run it on data with
  - **The (faint) unresolved binaries**
  - **The instrumental noise**
  - **The cosmological SGWB**

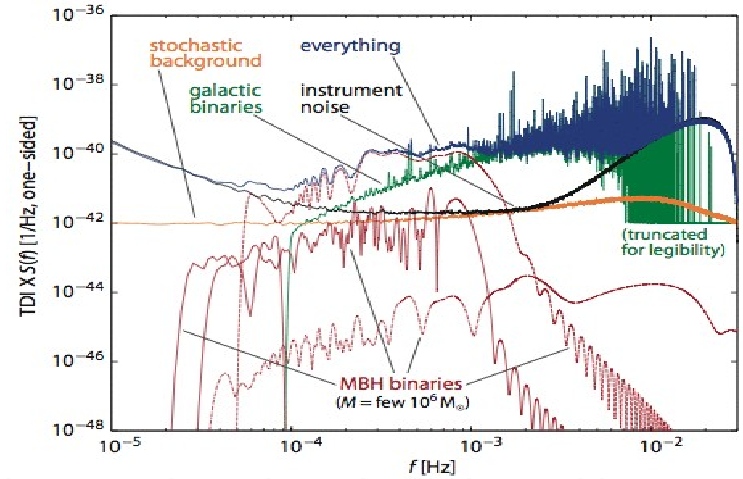


- Simplifications:
  - We neglect the likelihood correlations/systematics with the transient sources
  - Same template model for injection and recovery (no. theory systematics)

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



LISA is a signal-dominated experiment



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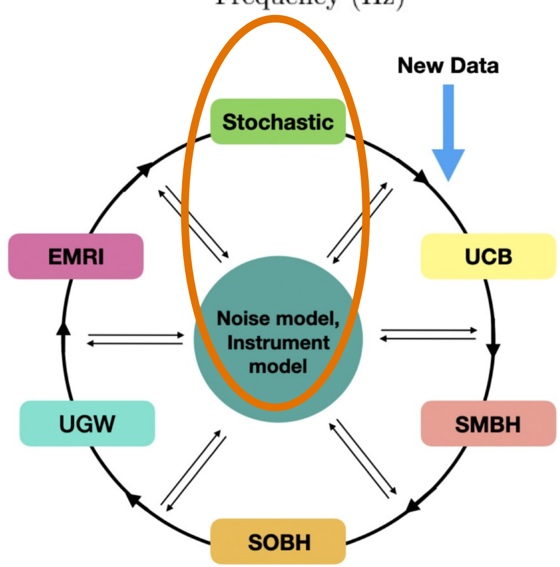


FOPT: LISA CosWG (Caprini+) '24

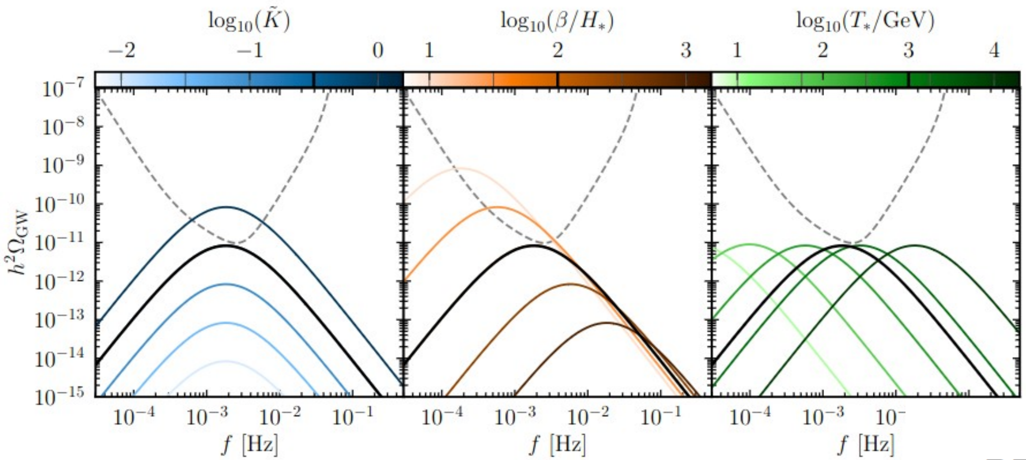
Cosmic strings: LISA CosWG (Blanco Pillado+) '24

Inflation: LISA CosWG (Braglia+) '24, LISA CosWG (El Gammal+) '25

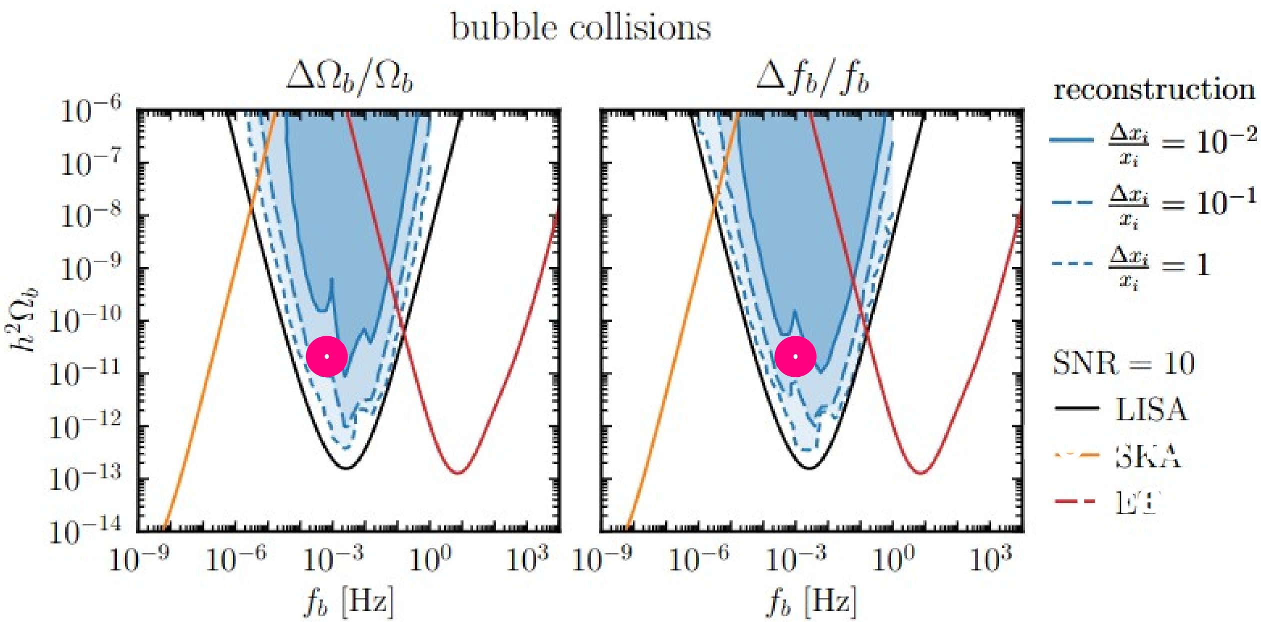
Agnostic searches: LISA CosWG (Caprini+) '19 LISA CosWG (Flauger+) '21

LISA reconstruction accuracy: FOPT in bubble coll. regime

Params of "Bubble coll. Regime" ($\xi_w \simeq 1$; $\kappa = 1$; free β/H, T_*, K)



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

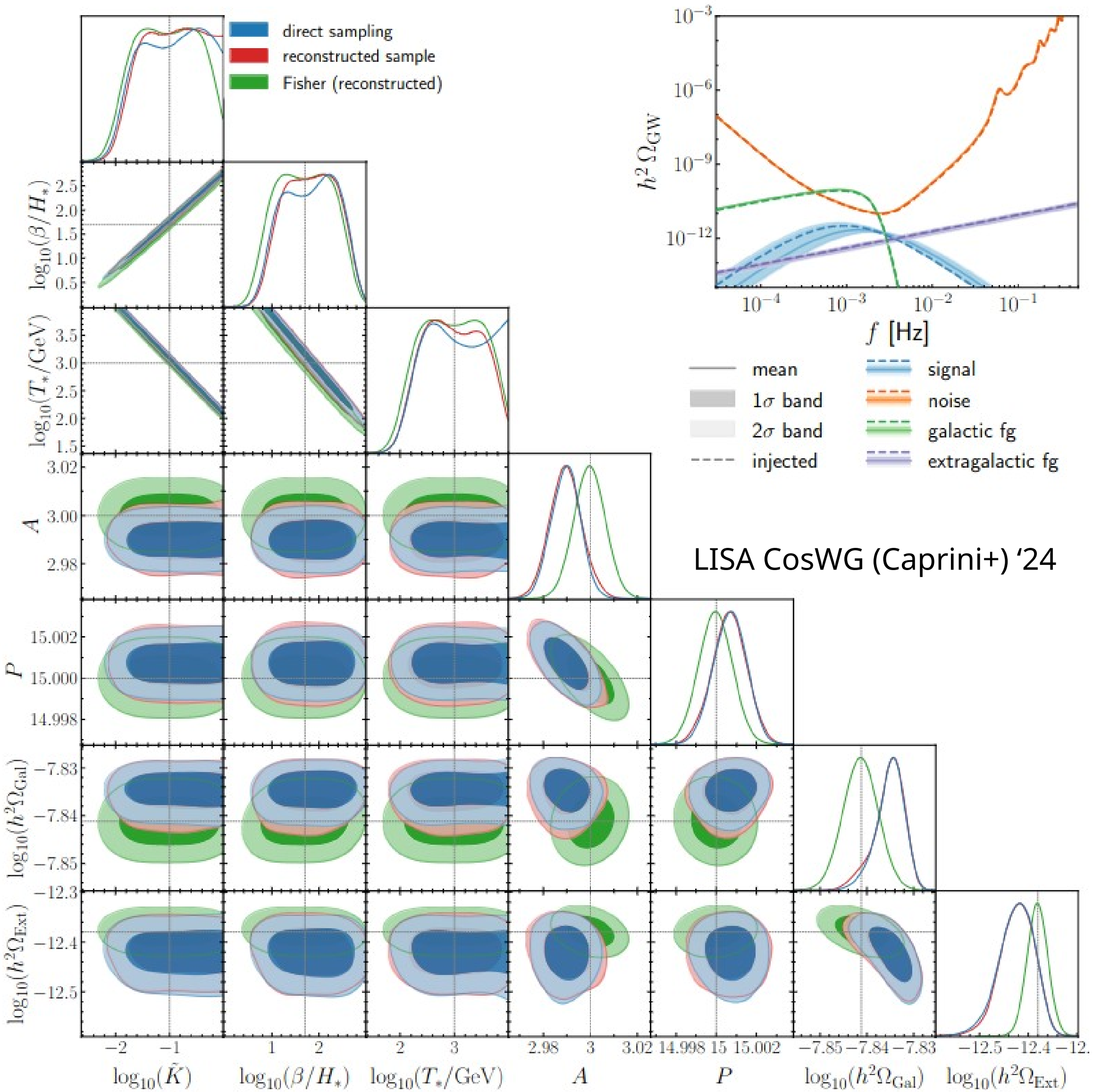


$n_1 = 2.4\,,\quad n_2 = -2.4\,,\quad a_1 = 1/2$

LISA CosWG (Caprini+) '24

LISA reconstruction accuracy: FOPT **in bubble coll. regime**

Noise + astro. SGWB + FOPT thermodynamic parameters

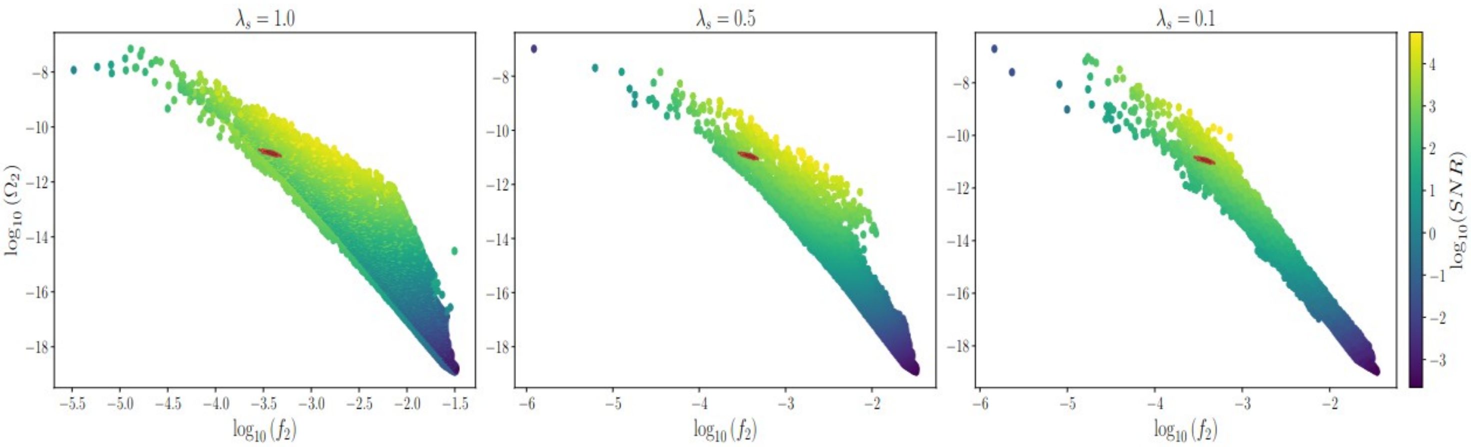


LISA CosWG (Caprini+) '24

See also:
Gowling+ '23
Hindmarsh+, '24

LISA detection recast if SM + Z_2 singlet

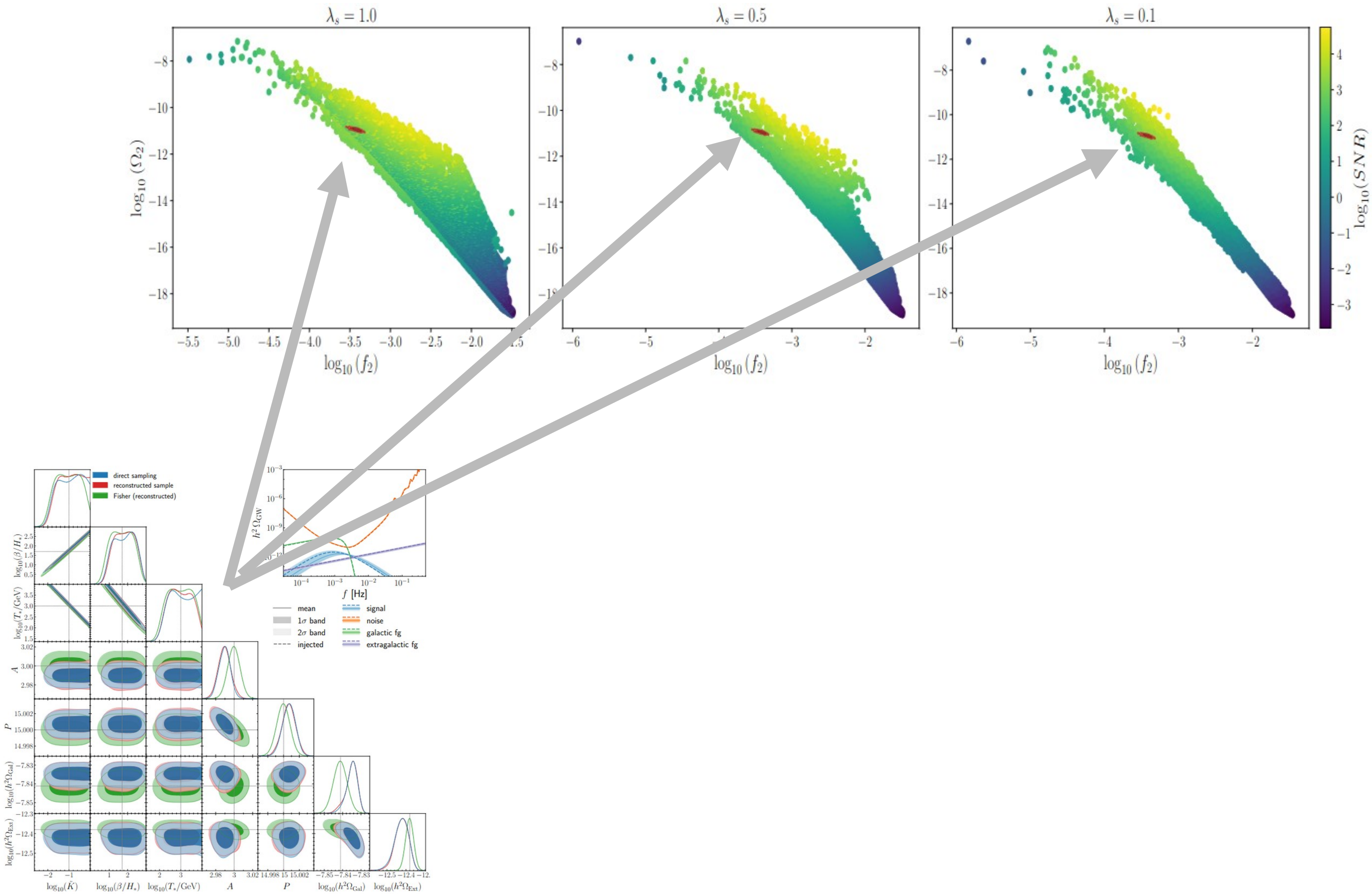
Z_2 singlet model's param. space predicting FOPT



$$-\mathcal{L} = \cdots - m_s^2 S^2 + \lambda_s S^4 + \lambda_{sh} S^2 |H|^2$$

LISA detection recast if SM + Z_2 singlet

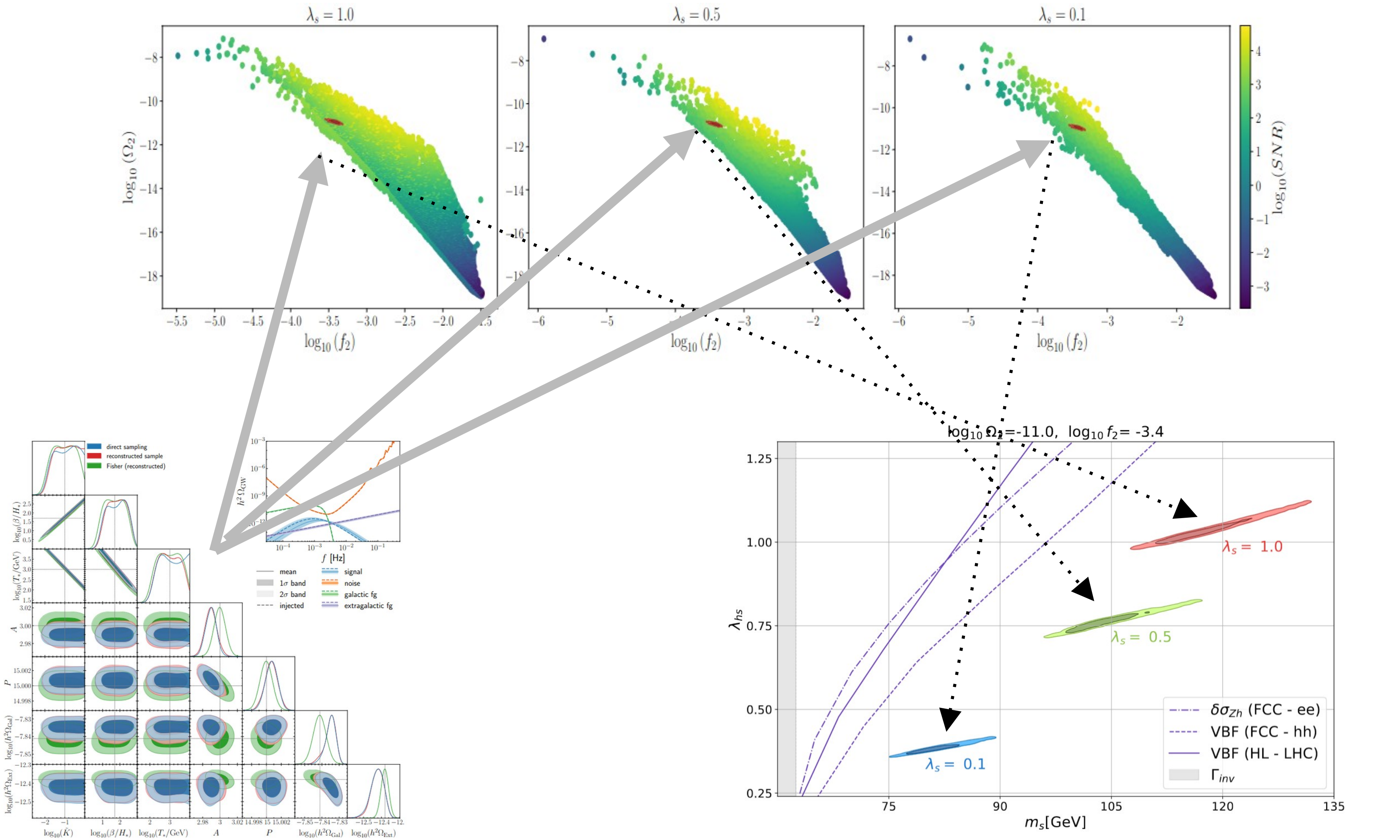
Z_2 singlet model's param. space predicting FOPT



$$h^2\Omega_b = 10^{-11} \qquad f_b = 10^{-3.4}\text{Hz}$$

$$-\mathcal{L} = \cdots - m_s^2 S^2 + \lambda_s S^4 + \lambda_{sh} S^2 |H|^2$$

LISA detection recast if SM + Z_2 singlet



$$h^2\Omega_2 = 10^{-11} \qquad f_2 = 10^{-3.4}\mathrm{Hz}$$

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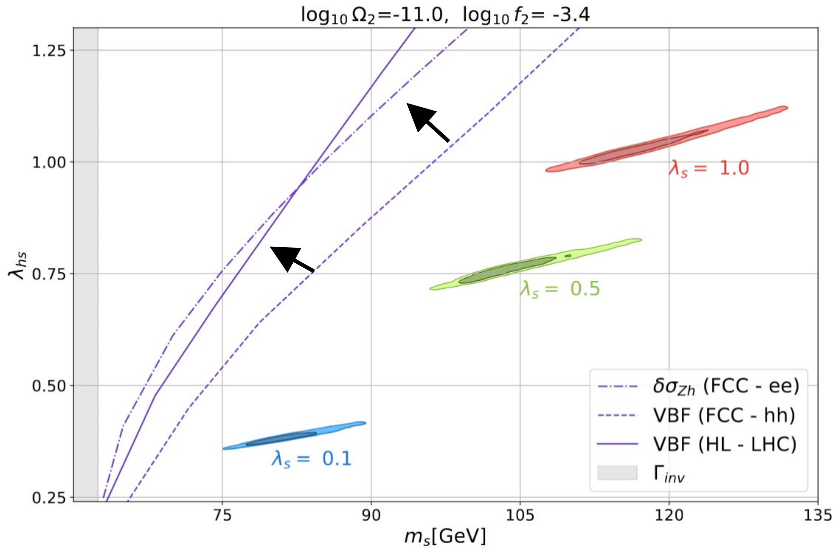
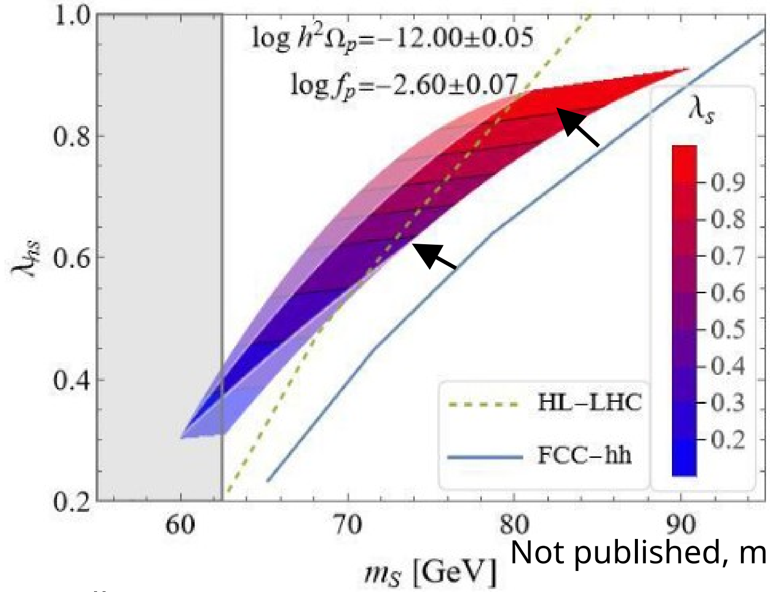
LISA detection recast if SM + Z_2 singlet





Not published, minor mistakes

LISA CosWG (Caprini+) ‘24 Collider bounds from: Craig+,14 ; Ellis+,’18

- Synergy/complementarity between LISA and colliders
- LISA reconstruction accuracy is rather good

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 priorities (TBD)

- PTA now, LVK soon, and LISA in 10 yr can probe FOPT at 10^{-5}–10^{8} TeV scale
- FOPT detection → BSM discovery
- LISA accurately reconstructs a FOPT signal from EW scale and above
  → great constraints on BSM parameters (assuming a model)
- Results based on simplifications. More realistic results in late 2026
  (official data challenge "Mojito")
- Reconstruction interpretation done only for a few BSM models. Rationale can be followed for other models

- Clear synergy/complementarity with colliders. With more models and FCC simulations:
  - ✓ How much does LISA constrain the param. space of a model?
    And the FCC? And LISA and FCC together ?
  - ✓ Are there "structural" bottlenecks limiting the synergy? Feasible ways to improve them? Still on time to implement them if LISA sees a signal ?

Conclusions and priorities (TBD)

- PTA now, LVK soon, and LISA in 10 yr can probe FOPT at 10^{-5}–10^{8} TeV scale
- FOPT detection → BSM discovery
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- Results based on simplifications. More realistic results in late 2026
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- Reconstruction interpretation done only for a few BSM models. Rationale can be followed for other models

- On the other hand, if we focus on the GW detection side only, the priorities IMO:
  1) Reduce the (systematic) errors of the geometrical template of the FOPT signal below the LISA reconstruction accuracy. Risky to correct it in the post-processing phase
  2) Reduce the (systematic) errors of the map “Thermody. Params. ↔ Geom. Params.”. Possible to change it in the post-processing phase.
  3) Mapping the Lagrangian params of a specific BSM setup to the SGWB spectrum