Gravitational Waves – FCC connection

7th FCC Workshop

Annecy, Jan. '24

Germano Nardini

University of Stavanger

LISA CONSORTIUM

Results from **ArXiv:2403.xxxxx**

C. Caprini, M. Lewicki, *E.Magde, M. A. Merchand*, GN, M. Pieroni, *A. Robert-Pol*, R. Jinno, *V. Vaskonen*

for the

LISA Cosmology Working Group

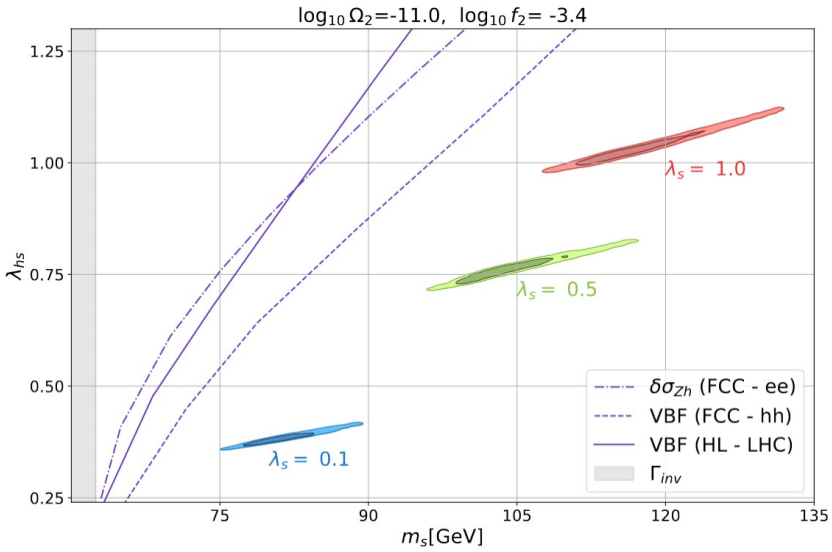
New branch of the CosWG tool “SGWBinner”:

…, GN, *M. Pieroni*, … et al. **ArXiv:1906.09244, 2009.11845**

Take-home message

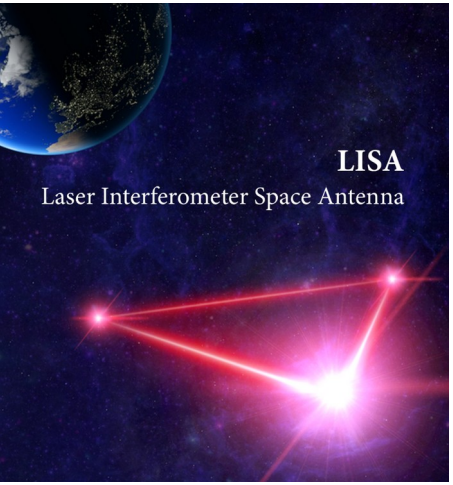
- LISA will precisely reconstruct or bound the Stochastic Grav.Wave Background (SGWB) that several BSM predict
- The reconstruction binds some effective (thermodynamic) parameters of these BSM models
- Once you assume a specific BSM model, LISA binds the parameter space (more precisely than what I guessed)
- First SGWB measurement in ~2037.

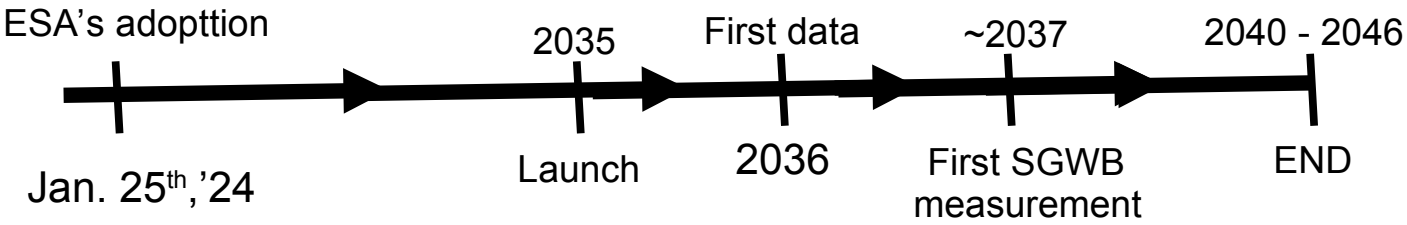
  Synergy with FCC



LISA vs FCC timeline

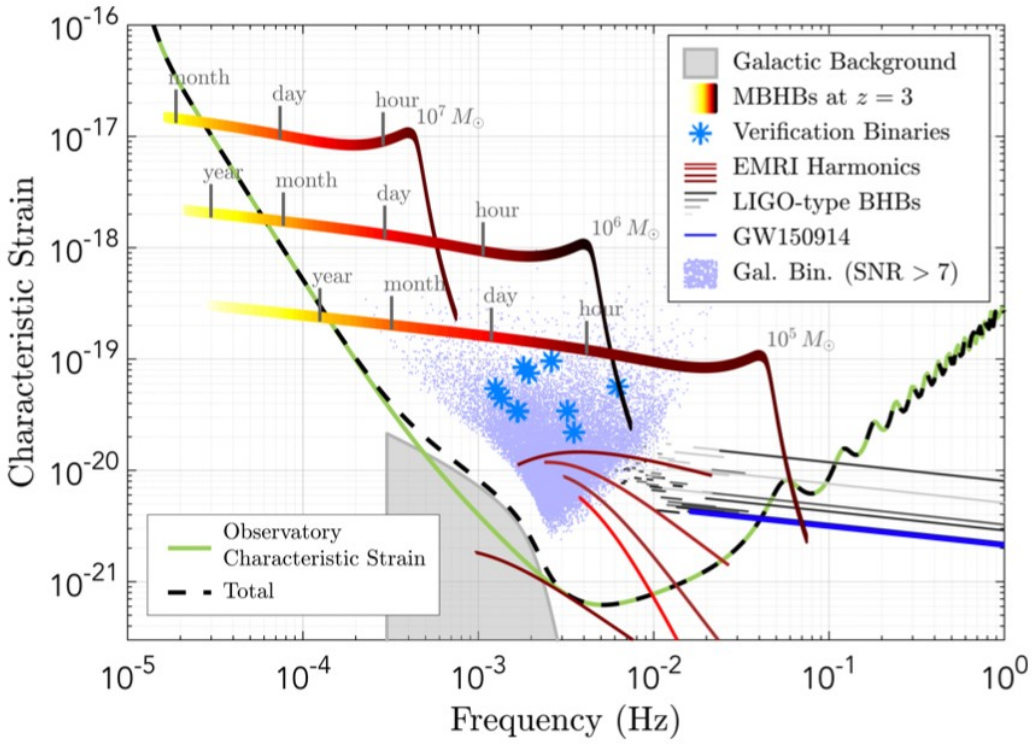
Contracts now
Building spacecrafts + Ground segment
Prototyping pipelines (~2029), validating main ones





[Useful to be flexible]

LISA

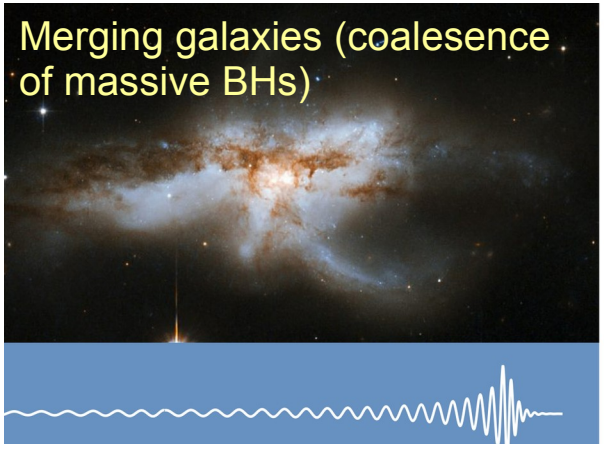


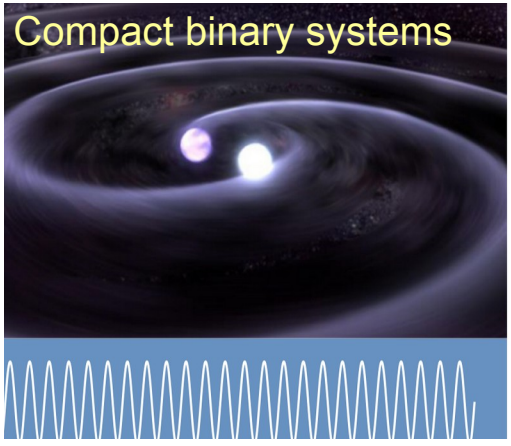
O(10^4) resolv. galac. binaries

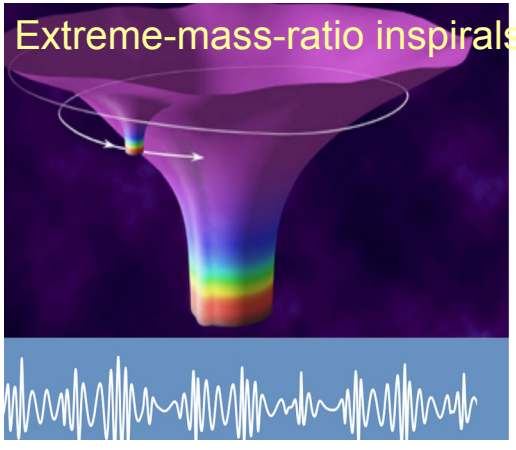
O(10) extragal. BBHs of 10^0–10^2 $M_\odot$

O(1 - 10) extreme mass-ratio inspirals

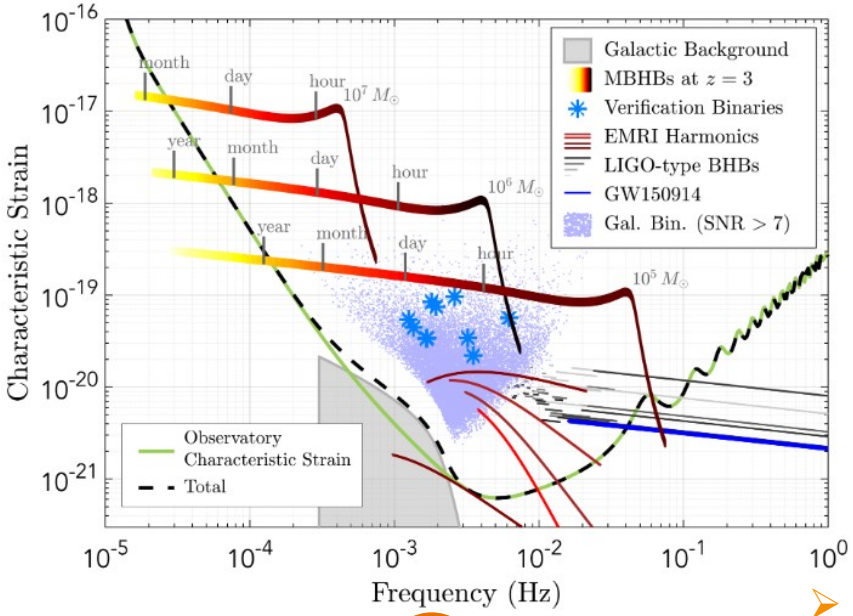
O(10 - 100) merging BBHs of 10^5–10^8 $M_\odot$



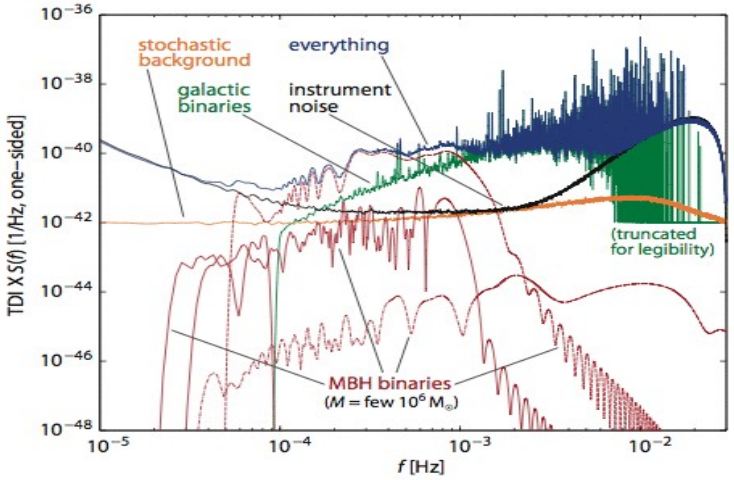


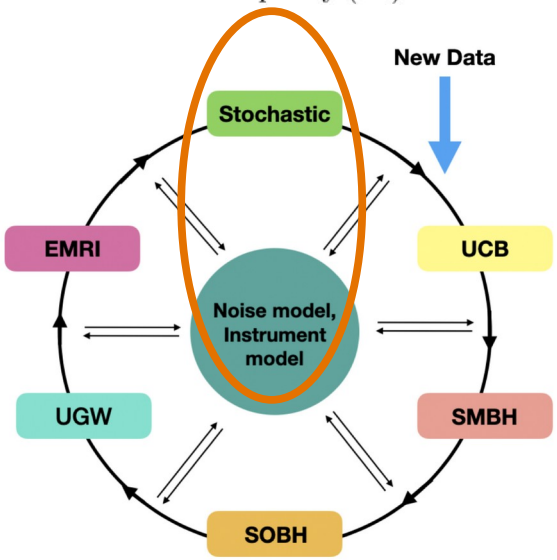


LISA: resolv. binaries + unresol. binar + como SGWB + noise



LISA is a signal-dominated experiment





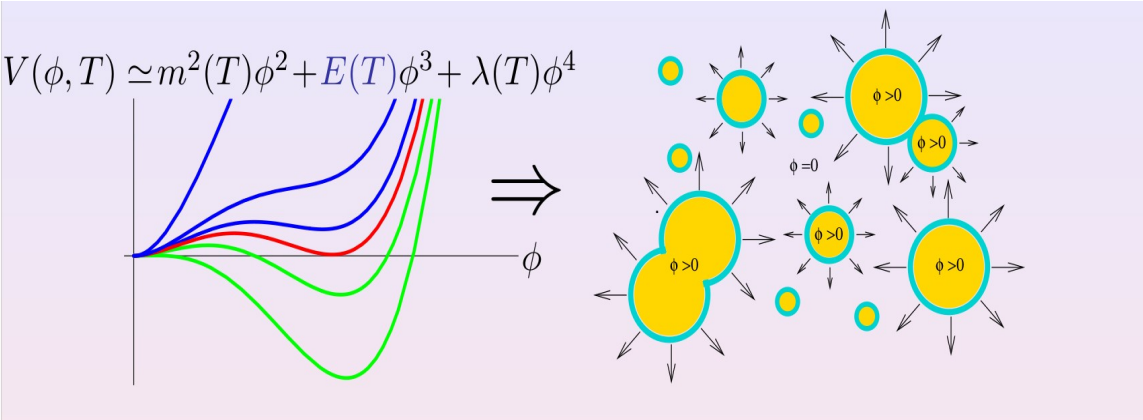
- Reconstruct and subtract the astro. events with their waveforms. Only possible for the loud events.
- The leftover contains:
  - **The (faint) unresolved binaries**
  - **The instrumental noise**
  - **The primordial SGWB**
  - (Mismatches in the waveforms, large correlations in the posteriors, ...)

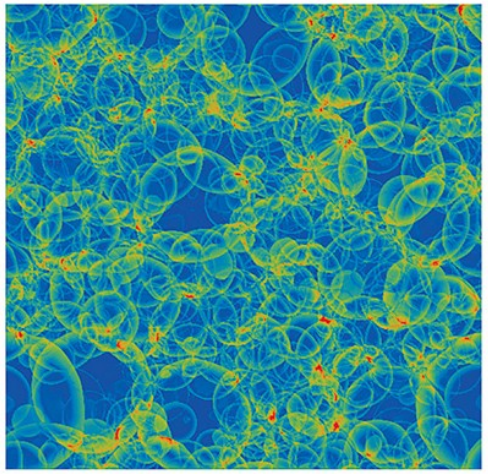
Iterative global fit.
Computational expensive!!! ***Simplified test: 50.000$***

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

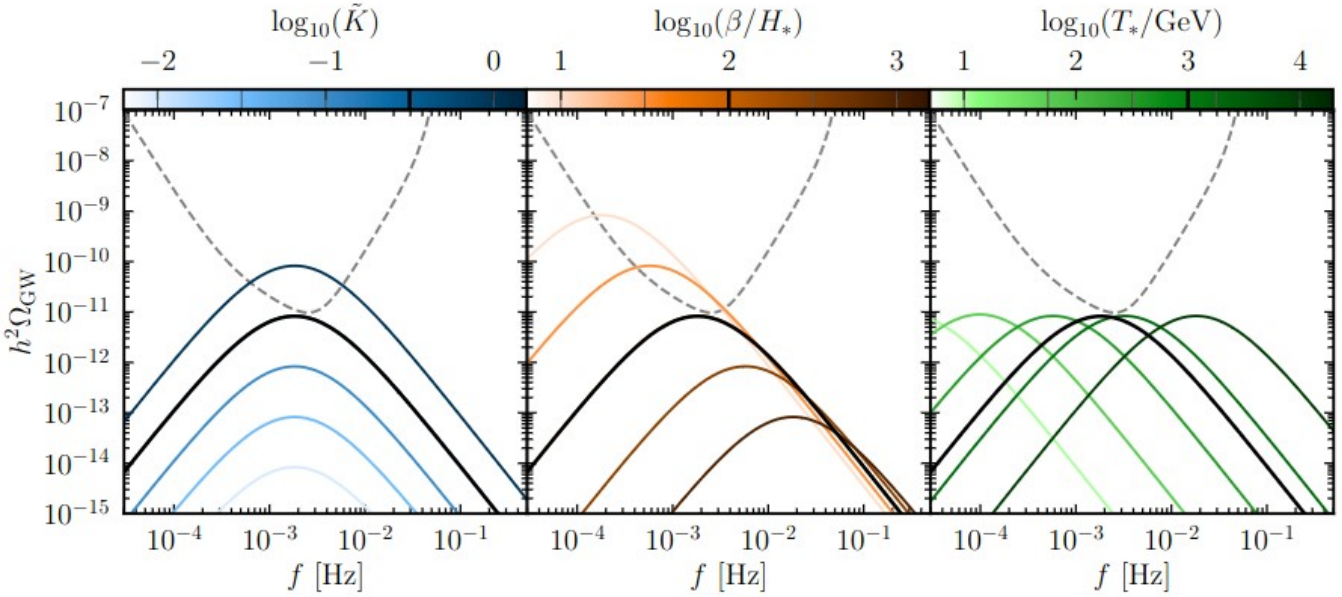
κ_i : efficiency factor of each contribution (bubble wall, sound wave, turbulence)

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

SGWB from a FOPT : templates

(for bubble coll.)

SGWB from relativistic bubbles ($\xi_w \simeq 1; \quad \kappa = 1$) $\rightarrow$ Broken Pow. Law SGWB



Simulations hint to the geometric-param. template

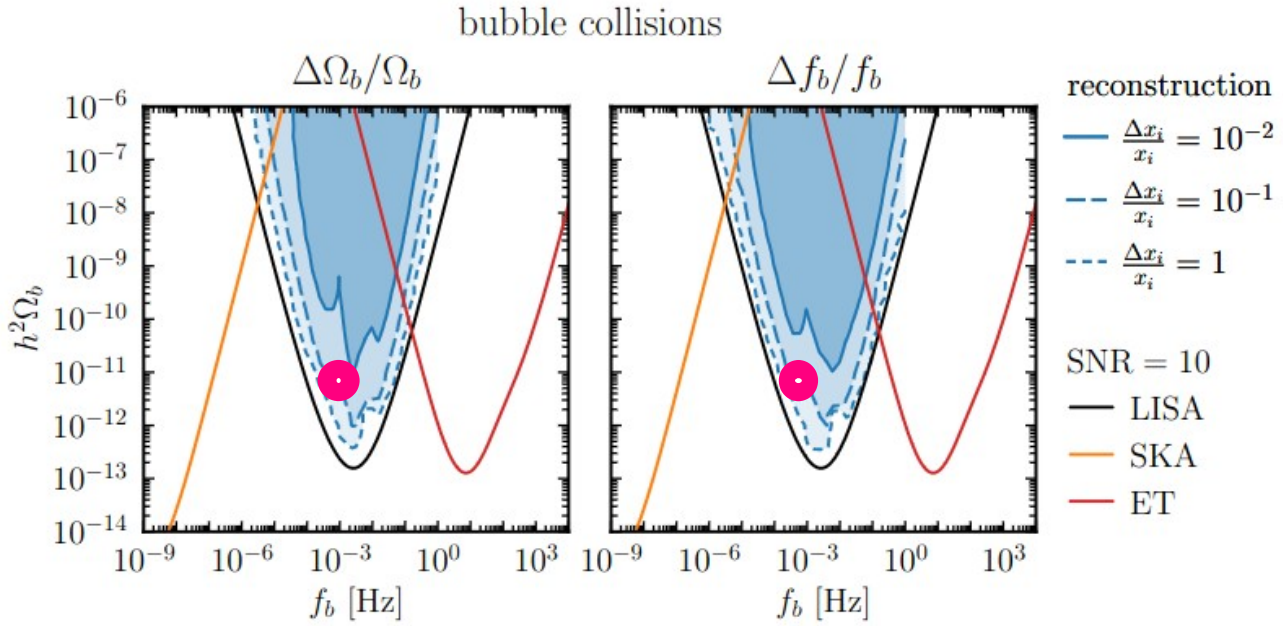
$$\Omega_{\mathrm{GW}}^{\mathrm{BPL}}(f) = \Omega_b \left(\frac{f}{f_b}\right)^{n_1} \left[\frac{1}{2} + \frac{1}{2}\left(\frac{f}{f_b}\right)^{a_1}\right]^{\frac{n_2 - n_1}{a_1}}$$

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

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

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

SGWB from relativistic bubbles ($\xi_w \simeq 1; \quad \kappa = 1$) $\rightarrow$ Broken Pow. Law SGWB



geometrical-param. template

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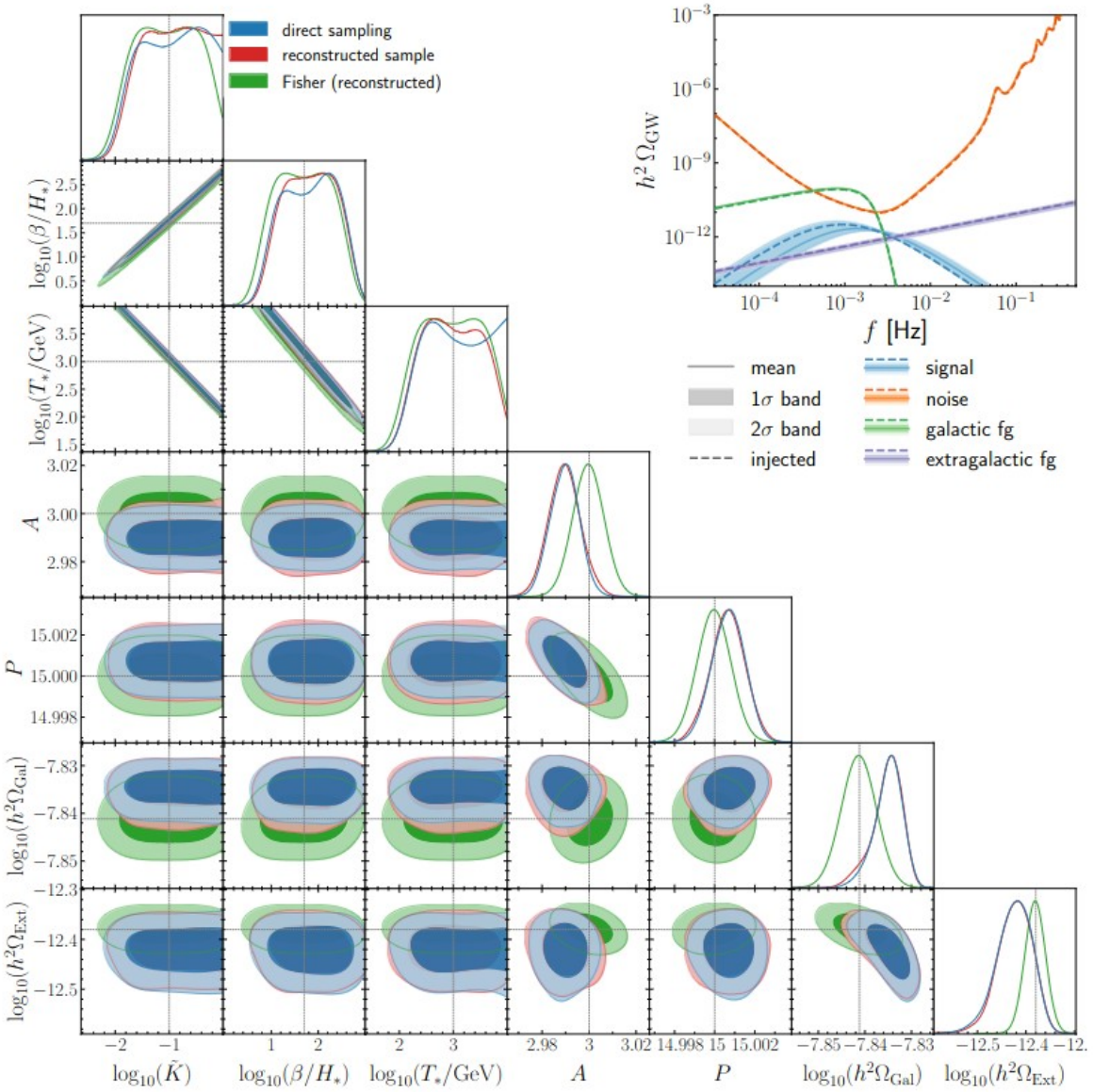


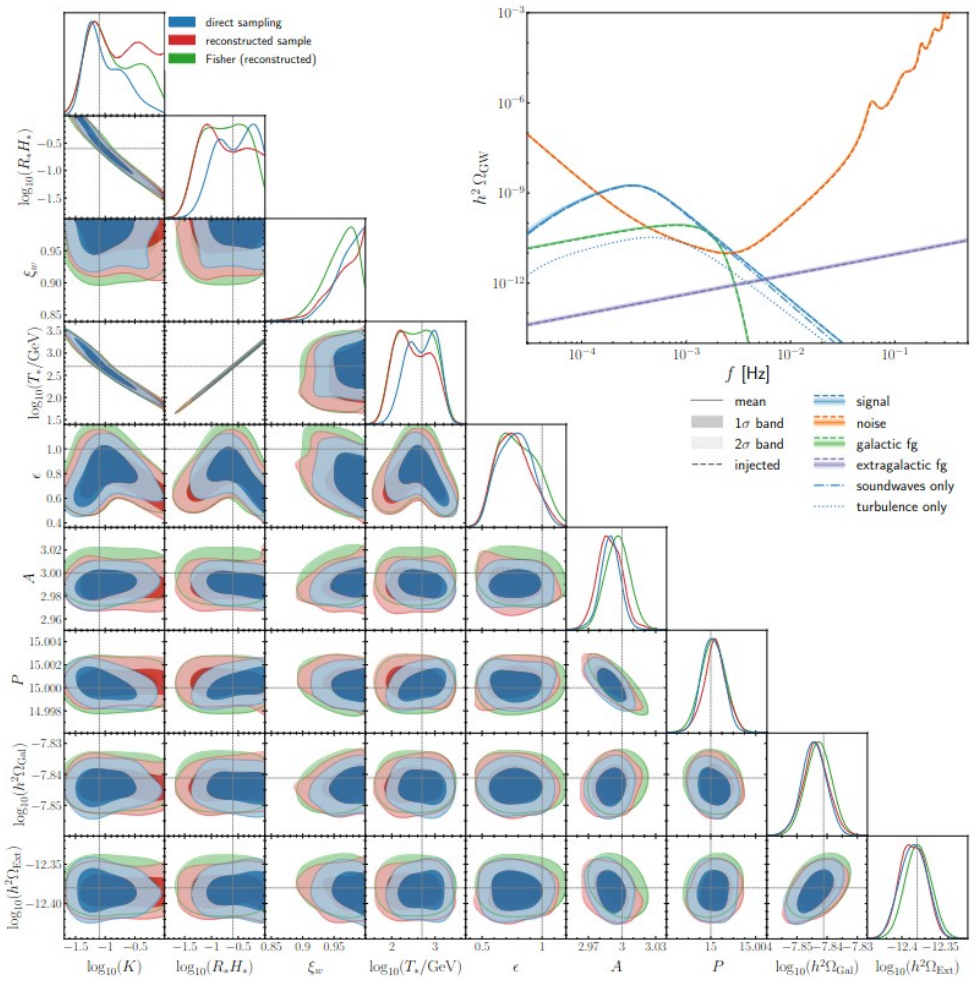
SGWB from a FOPT : templates

(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



Summary so far

Assumptions:

- Data = Noise + Unresolved sources + FOPT SGWB
  (no leakage from resolved binaries)
- Template for injection = template for reconstruction
  (no theor. error in signal predictions)
  (noise simulator works well)

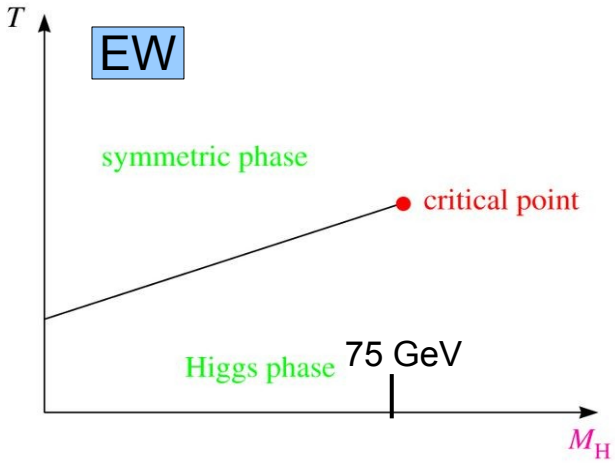
These assumptions are not showstoppers, but require more expensive and cumbersome tests

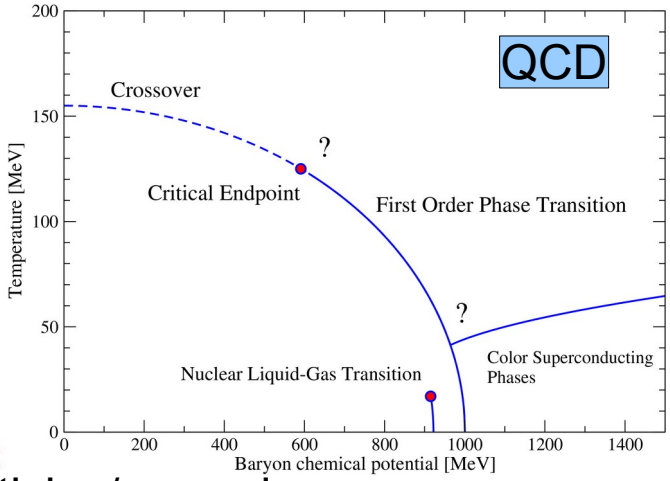
Result:

- Excellent constraints on geometric parameters
- Excellent constraints on thermodyn. parameters, but degeneracies

…. this implies interesting constraints on BSM models!!!

Model building for SGWB





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

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

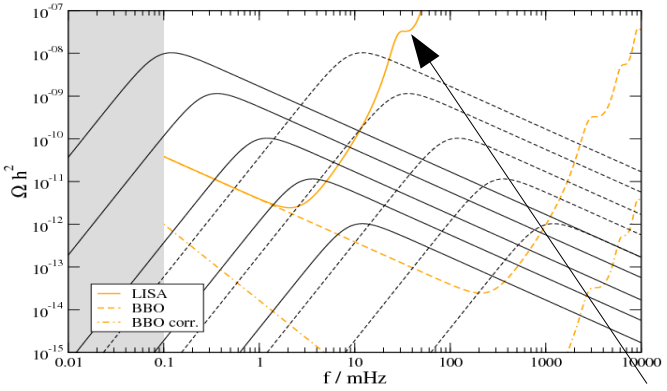
- No FOPT in the SM of particles/cosmology
- Conceivable in hidden sectors, at high scales, or EW extensions
- For EW extensions, need for a barrier via temp. radiative corrections or/and dynamical fields in the EW sector.
  New TeV-scale scalars

Some rationales for EW FOPT:

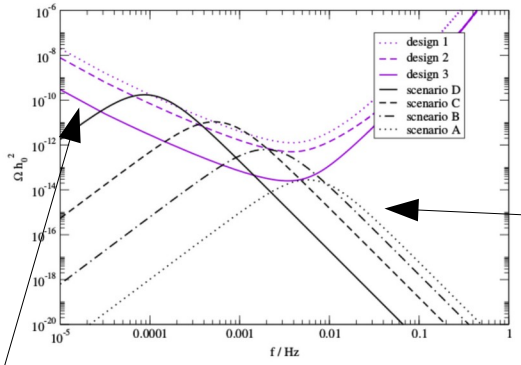
- New color fields → Large T effects but also Higgs gluon fusion changes
- New dynamical scalar fields → Mixing → Higgs signal strengths
- New fermions → no large T-effects → no large barrier → no 1st order
- Very heavy fields → Boltzmann suppressed and small low-energy effects

Model building for SGWB

First order in Randall Sundrum



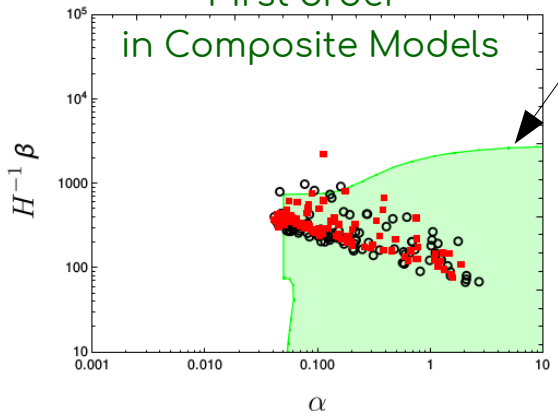
First order in SUSY



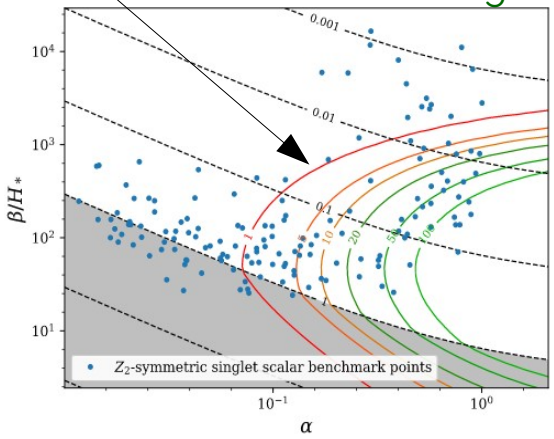
SGWB signal above sensitivity

LISA sensitivy region

First order in Composite Models



First order in Z2 singlet



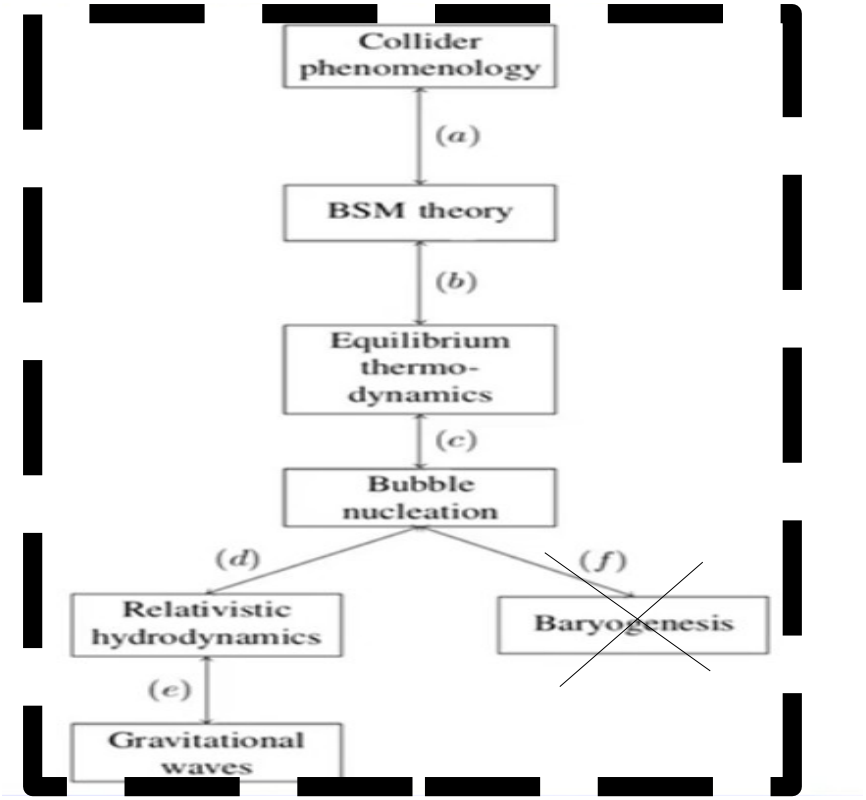
But also 2HDM, B-L model , ….

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

LISA – FCC connection program

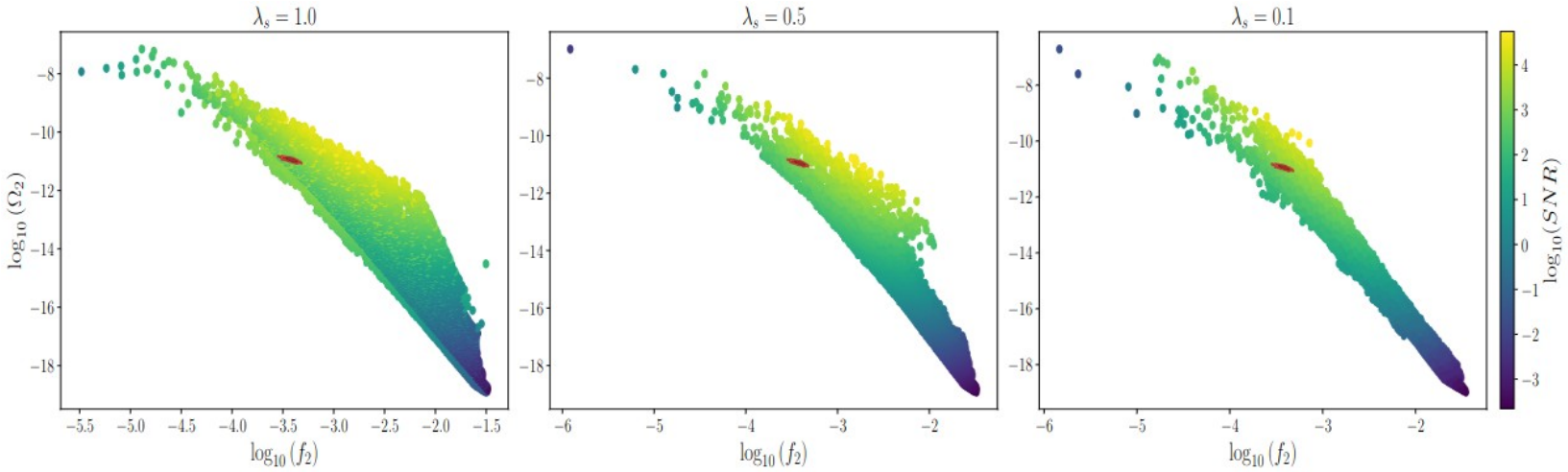


When running the program, we can be more ambitious than "there is a signal in FCC/LISA"

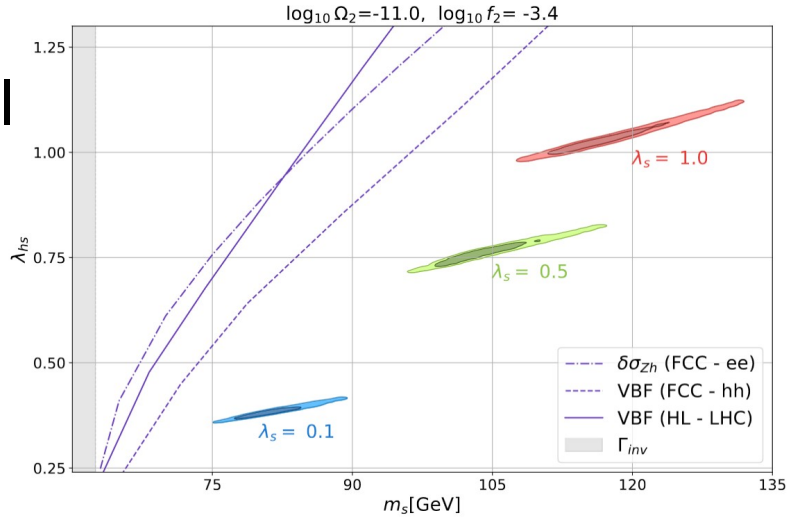
- What are the constraints on the Lagrangian parameters that we will obtain?
- Will the reconstructions allow us to do decent model selection?

Examples from the LISA side

If a BPL signal $\log_{10}\Omega_2$=-11.0, $\log_{10} f_2$= -3.4 is detected, then what ?



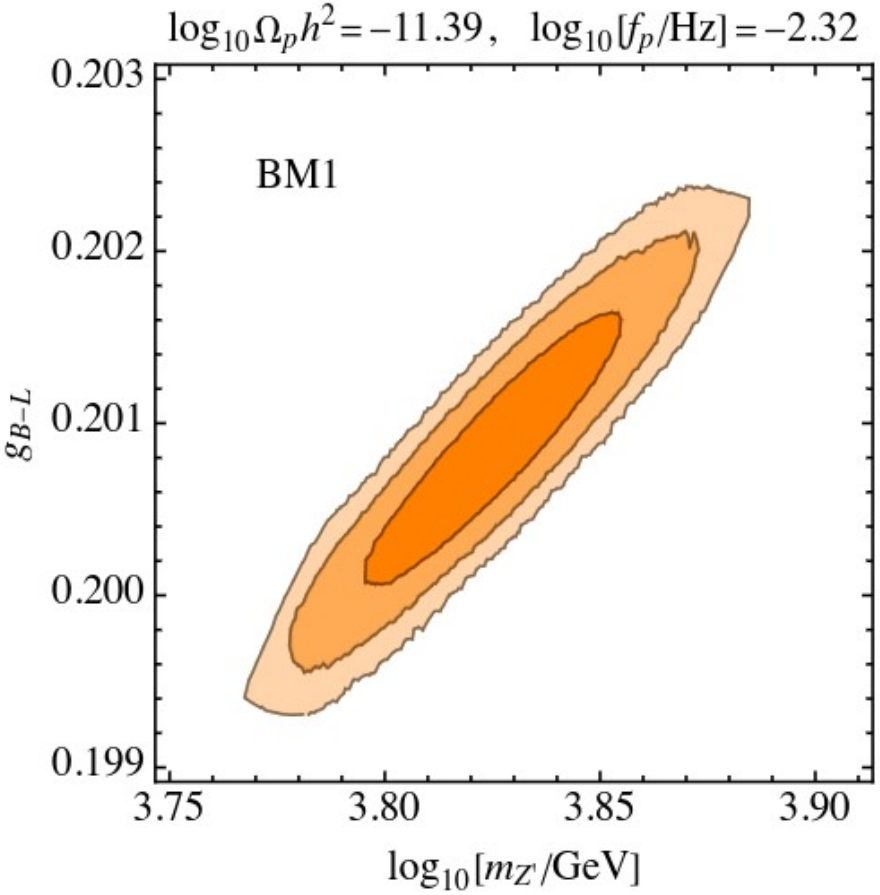
Z_2 singlet model



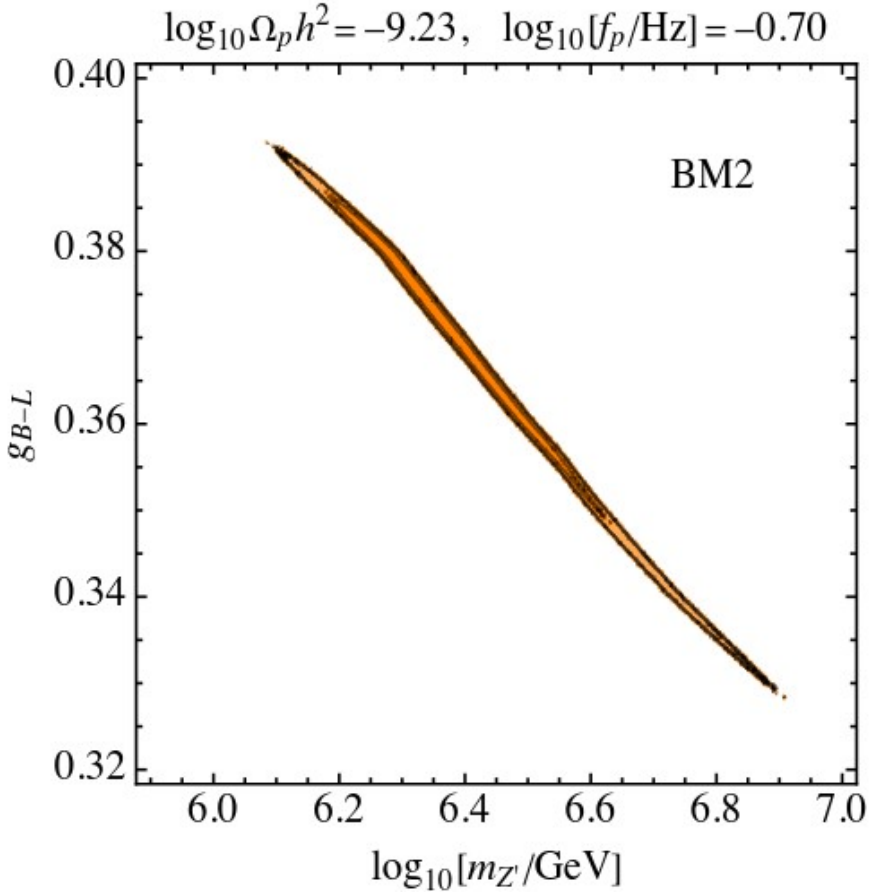
Examples from the LISA side

$U(1)_{B-L}$ model

Compatible with Z2 singlet region



Incompatible with Z2 singlet region



Conclusions (personal view)

- LISA mission is adopted. First SGWB measurements in ~2037
- LISA can reconstruct the model's parameter space
- FCC after LISA. Useful to allow some flexibility in energy (or similar) to explore
  the hints from LISA (or others experiments)
- Does addressing the following questions help strength the FCC science case and check our preparedness?
  - If LISA see a given hint, what to do at the FCC? And if LISA does not?
  - If FCC see hints, can we perform model selection ? How well do we bind the Lagrangian parameters?