Probing Early Universe Supercooled Phase Transitions with Gravitational Wave Data

ET Symposium - May 8, 2023

Charles Badger*, Bartosz Fornal, Katarina Martinovic, Alba Romero, Kevin Turbang, Huai-Ke Guo, Alberto Mariotti, Mairi Sakellariadou, Alexander Sevrin, Feng-Wei Yang, and Yue Zhao

Motivation and Goals

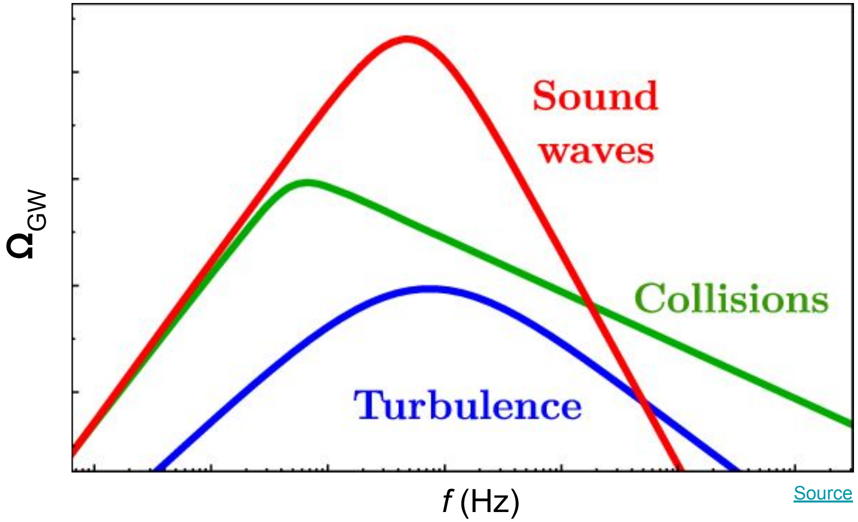
- Want to constrain particle physics (PP) models beyond Standard Model (BSM) using GW data.
- First order phase transitions (FOPT) are a generic feature of BSM theories - could use as a bridge between GW data analysis and PP phenomenological studies.
- Understand the outlook for future runs and detectors.

Talk mainly based off work in Phys. Rev. D **107**, 023511.

First order phase transitions

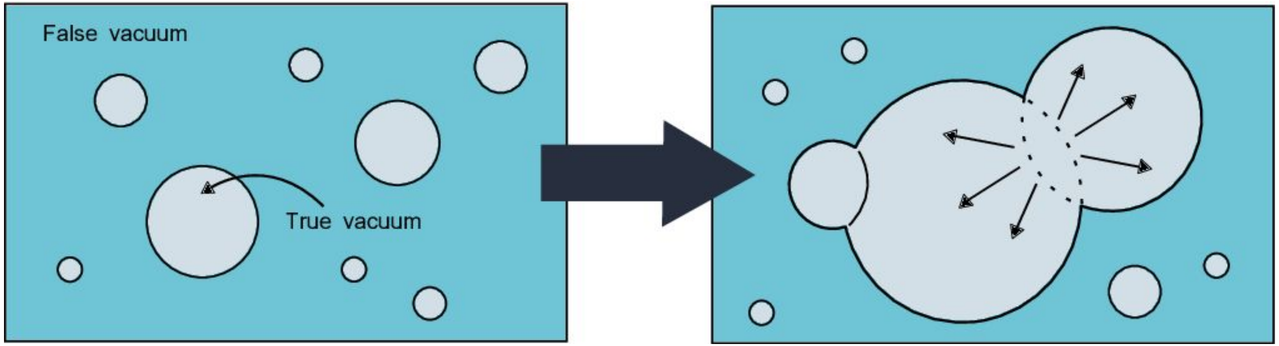
A generic feature of extended Standard Model (SM) theories with new physics in baryogenesis, dark matter, and more.

Can characterize the FOPT GW spectra with a broken power law ansatz.



Source

Supercooled FOPT take place when nucleation temperature is much smaller than the symmetry breaking scale, leading to amplified GW signals.



Source

Models

Broken power-law

- BC: $n_1 = 3$, $n_2 = -1$, $\Delta = 4$
- SW: $n_1 = 3$, $n_2 = -4$, $\Delta = 2$
- Free parameters: peak amplitude $\mathbf{\Omega}_*$, peak frequency f_*

Phenomenological model

- When supercooled, have $\alpha >> 1$, $T_{RH} >> T_n$, $v_w \sim 1$
- Free parameters: FOPT duration H_n/β, reheating temperature T_{RH}

Overlaying CBC foreground $\mathbf{\Omega}_{CBC}(f) = \mathbf{\Omega}_{ref}\,(f\,/\,25\text{ Hz})^{2/3}$

Model 1

- Minimal $U(1)_{B-L}$ SM extension by introducing two new bosonic fields
- Can be incorporated into SO(10) grand unification
- Parametrize with gauge boson mass $m_{Z'}$ and $U(1)_{B-L}$ gauge coupling g

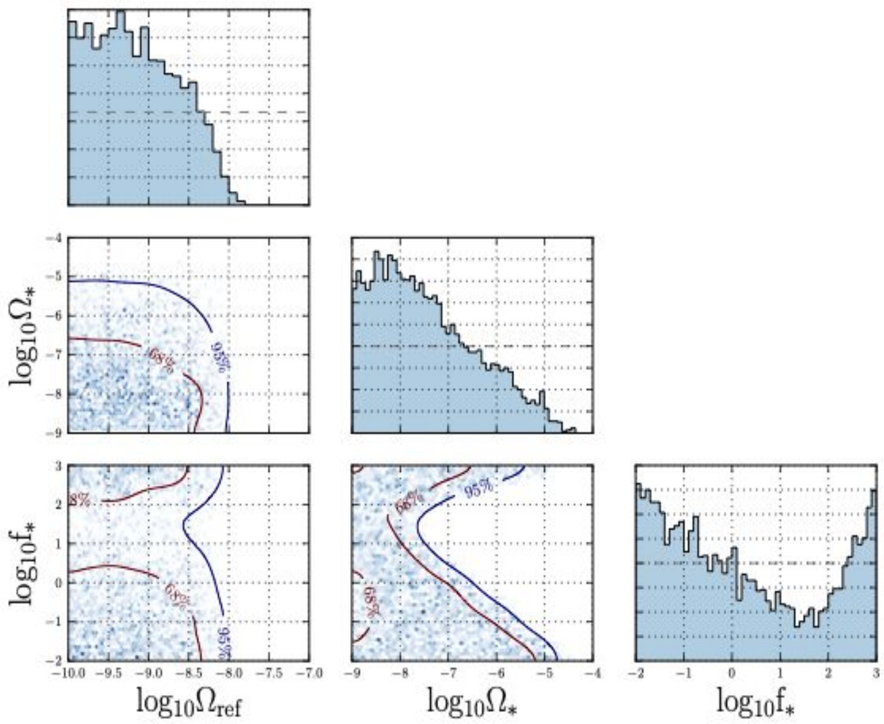
Model 2

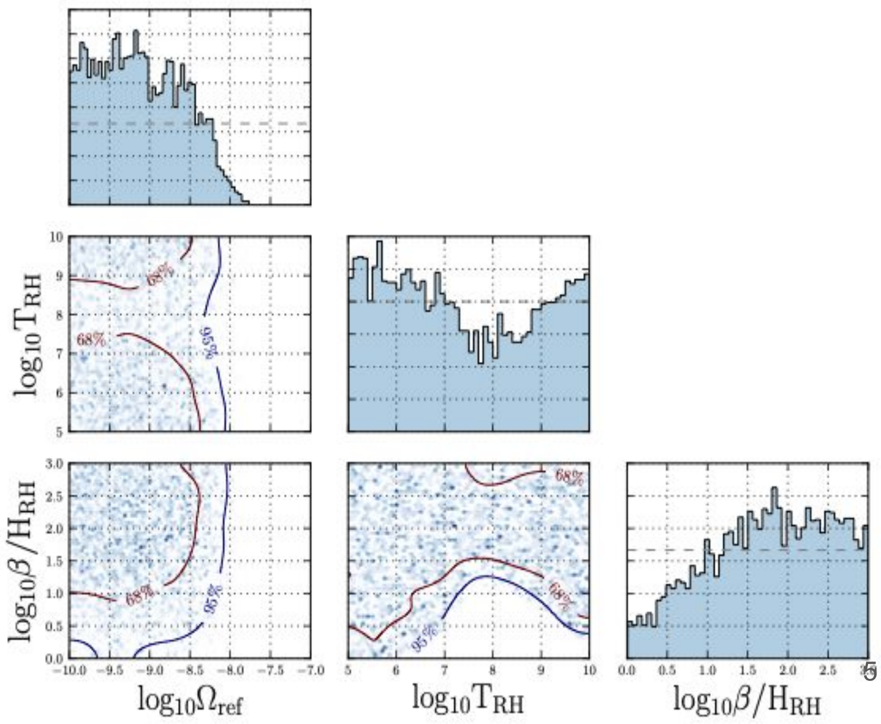
- Radiatively broken U(1) Peccei-Quinn symmetry by introducing two complex scalar fields
- Solves strong CP problem, introduces dark matter candidate (axion)
- Parameterize with potential strength λ and minimum of potential F

Results: O3 PE Results

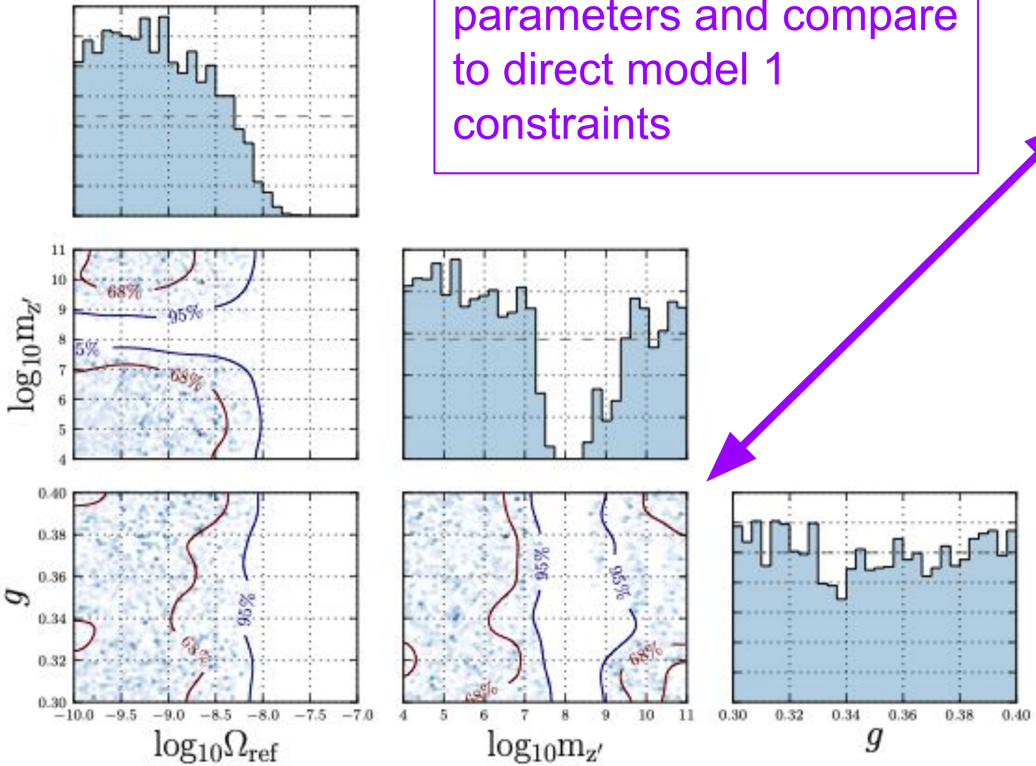
Conduct a parameter estimation (PE) on O3 data assuming a Ω_{CBC} + Ω_{FOPT} GWB model.

Example: Constraints on BC GWB for BPL and Pheno model.

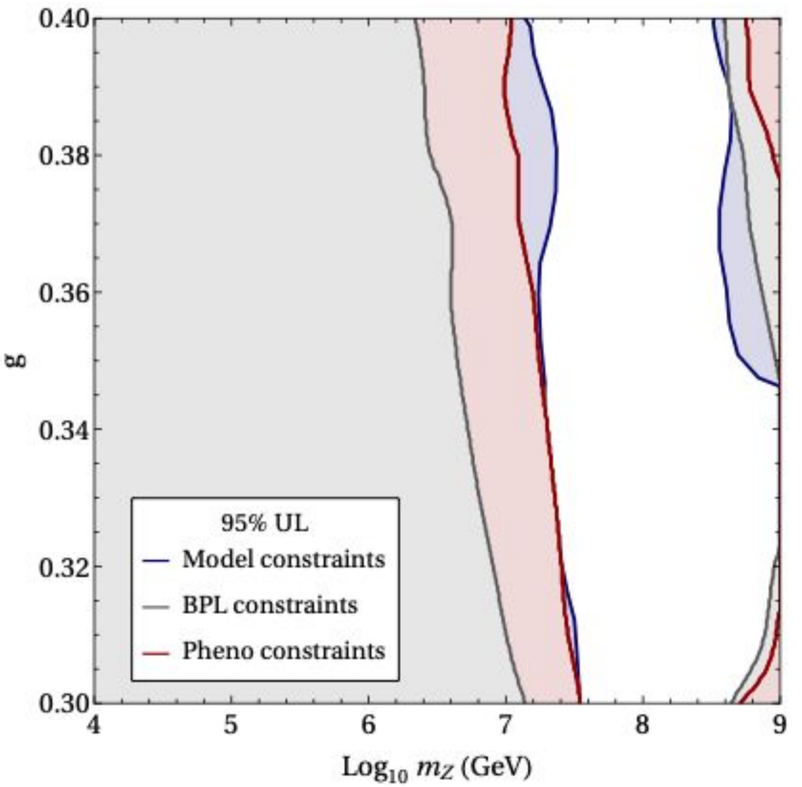




Results: O3 PE Results



Can convert BPL, pheno constraints to model 1 parameters and compare to direct model 1 constraints

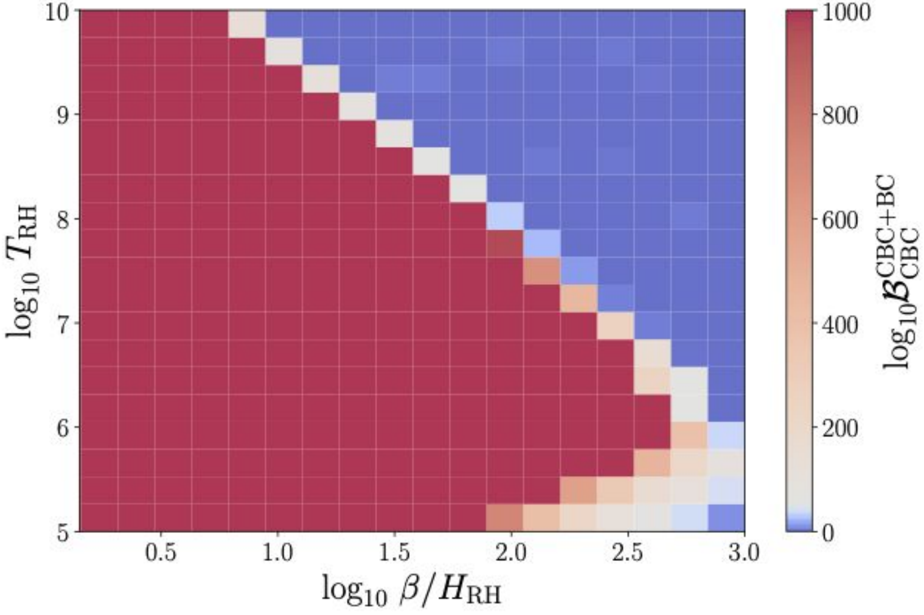


Constraints match!
→ Can use BPL and pheno constraints for <u>any</u> PP model

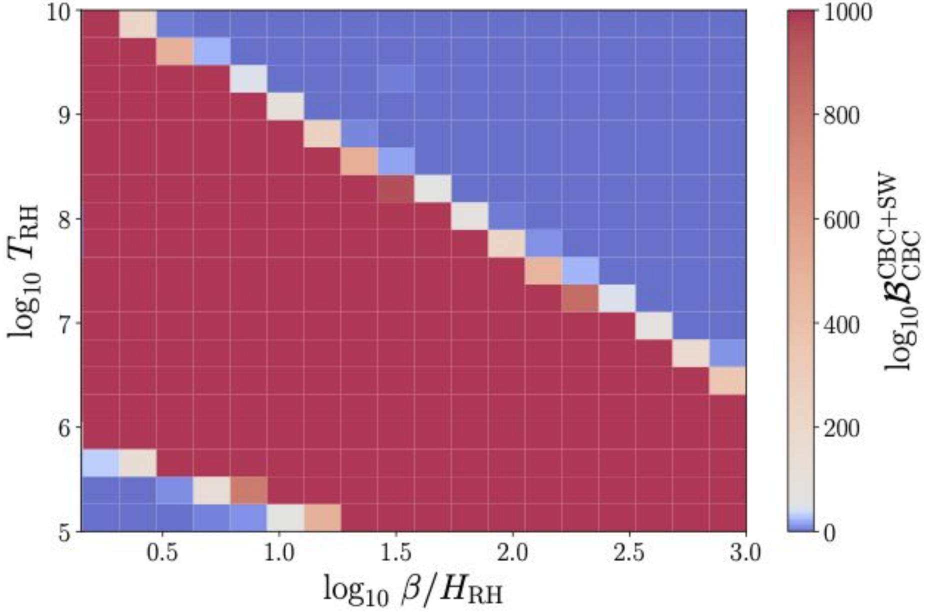
Outlook: 3G GW detectors

A 3G network of ET + 2 CEs can probe an even larger portion of FOPT parameter space.

Bubble collisions

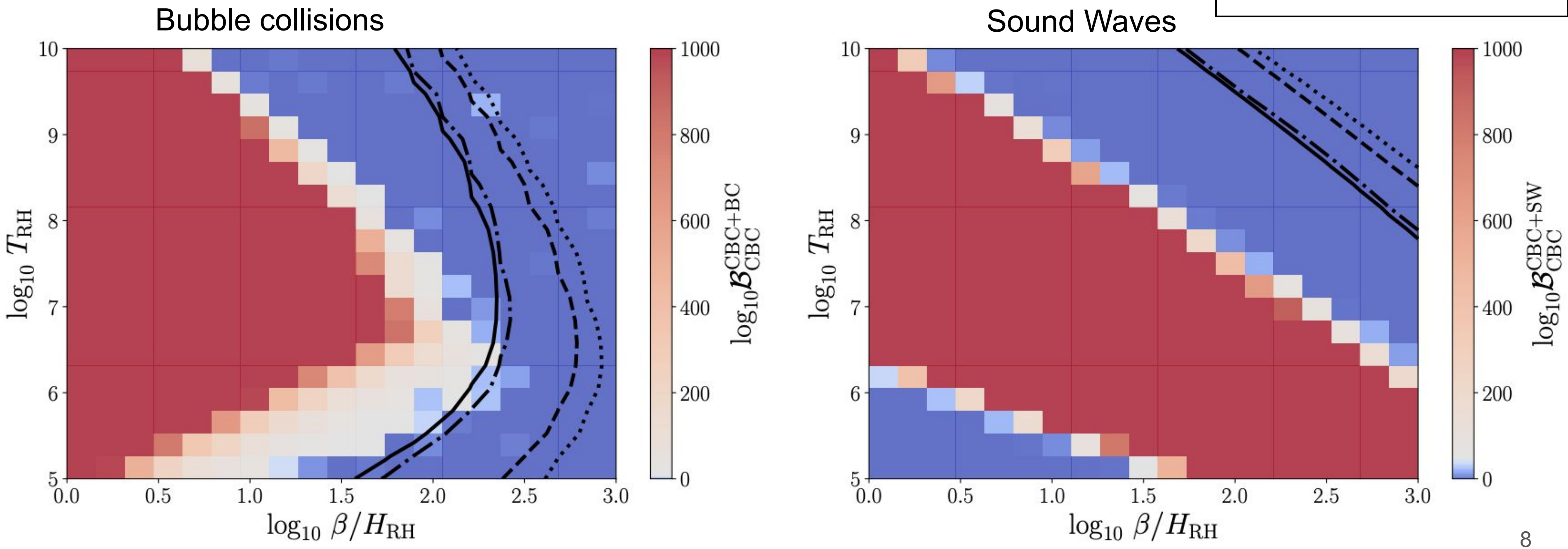


Sound Waves



Outlook: 3G GW detectors

Choice of ET configuration changes detectability as well. Detection threshold of $\log_{10} B = 8$ plotted.



Conclusions

- Can translate GW data constraints to particle physics models.
- Such constraints placed on supercooled FOPT model constraints from O3 data.
- 3G detectors can explore large portions of FOPT parameter space.
- ET configuration matters!

Thank you! Questions?

Spare slides

Explicit models

Broken power-law (BPL)

$$\Omega_{\rm bpl}(f) = \Omega_* \left(\frac{f}{f_*}\right)^{n_1} \left[1 + \left(\frac{f}{f_*}\right)^{\Delta}\right]^{(n_2 - n_1)/\Delta}$$

- Bubble Collisions: $n_1 = 3$, $n_2 = -1$, $\Delta = 4$
- Sound Waves: $n_1 = 3$, $n_2 = -4$, $\Delta = 2$

- Free parameters: peak amplitude $\mathbf{\Omega}_*$, peak frequency f_*

Phenomenological (Pheno)

$$h^2\Omega_{\rm bc}(f) \approx \frac{(4.88\times10^{-6})\,(f/f_{\rm bc})^{2.8}}{1+2.8\,(f/f_{\rm bc})^{3.8}} \left(\frac{H_{\rm RH}}{\beta}\right)^2 \left(\frac{100}{g_*}\right)^{\frac{1}{3}}$$

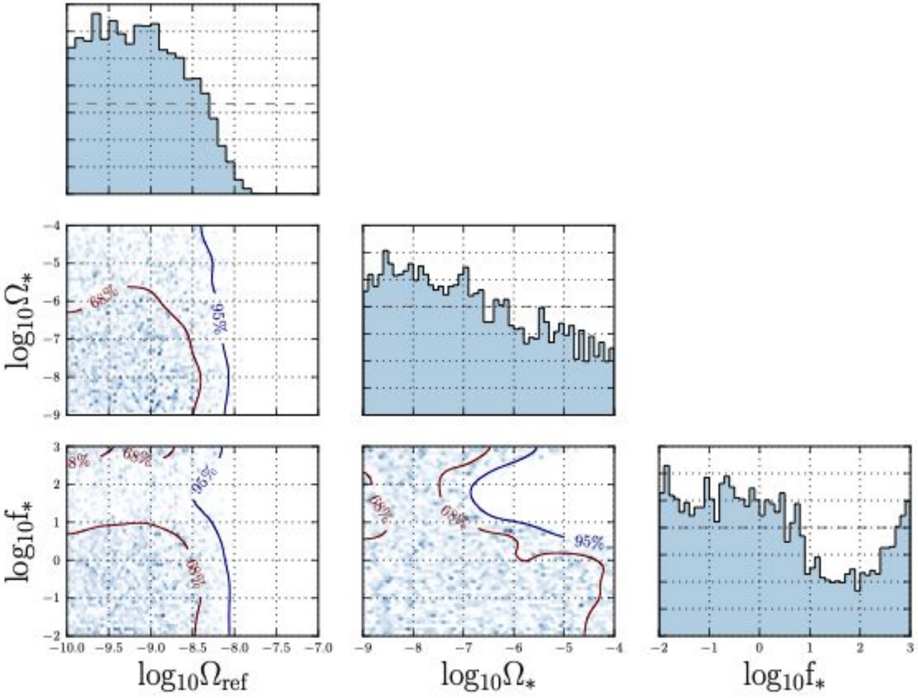
$$f_{\rm bc} \approx (3.7\times10^{-5}\ {\rm Hz}) \left(\frac{g_*}{100}\right)^{\frac{1}{6}} \left(\frac{\beta}{H_{\rm RH}}\right) \left(\frac{T_{\rm RH}}{1\ {\rm TeV}}\right)$$

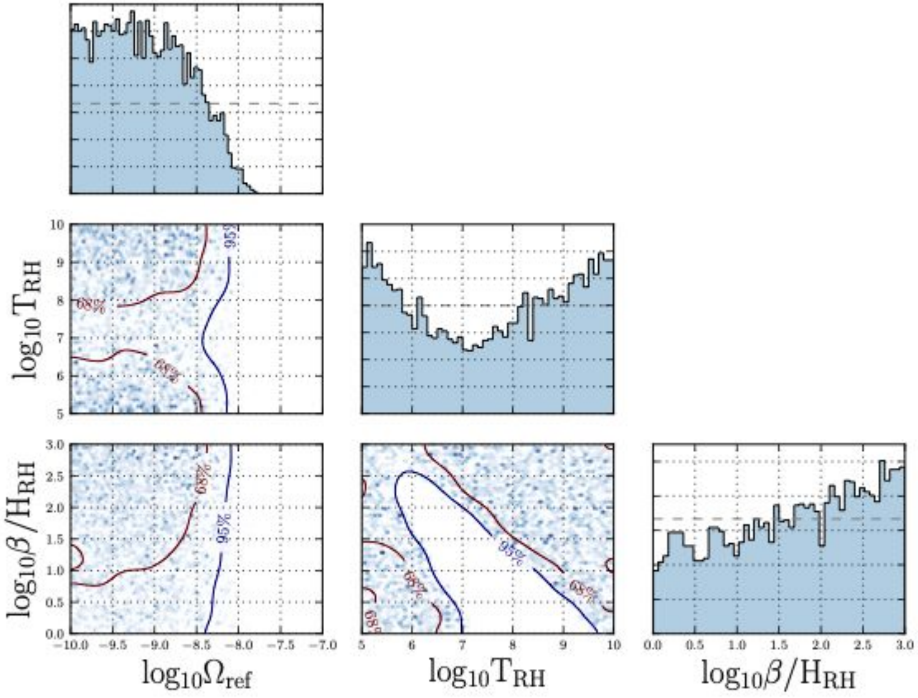
$$h^2\Omega_{\rm sw}(f) \approx \frac{(1.86\times10^{-5})\,(f/f_{\rm sw})^{3}}{\left[1+0.75\,(f/f_{\rm sw})^{2}\right]^{7/2}} \left(\frac{H_{\rm RH}}{\beta}\right) \left(\frac{100}{g_*}\right)^{\frac{1}{3}},$$

$$f_{\rm sw} \approx (1.9\times10^{-4}\ {\rm Hz}) \left(\frac{g_*}{100}\right)^{\frac{1}{6}} \left(\frac{\beta}{H_{\rm RH}}\right) \left(\frac{T_{\rm RH}}{1\ {\rm TeV}}\right)$$

- Free parameters: FOPT duration H_n/β, reheating temperature $T_{\rm RH}$

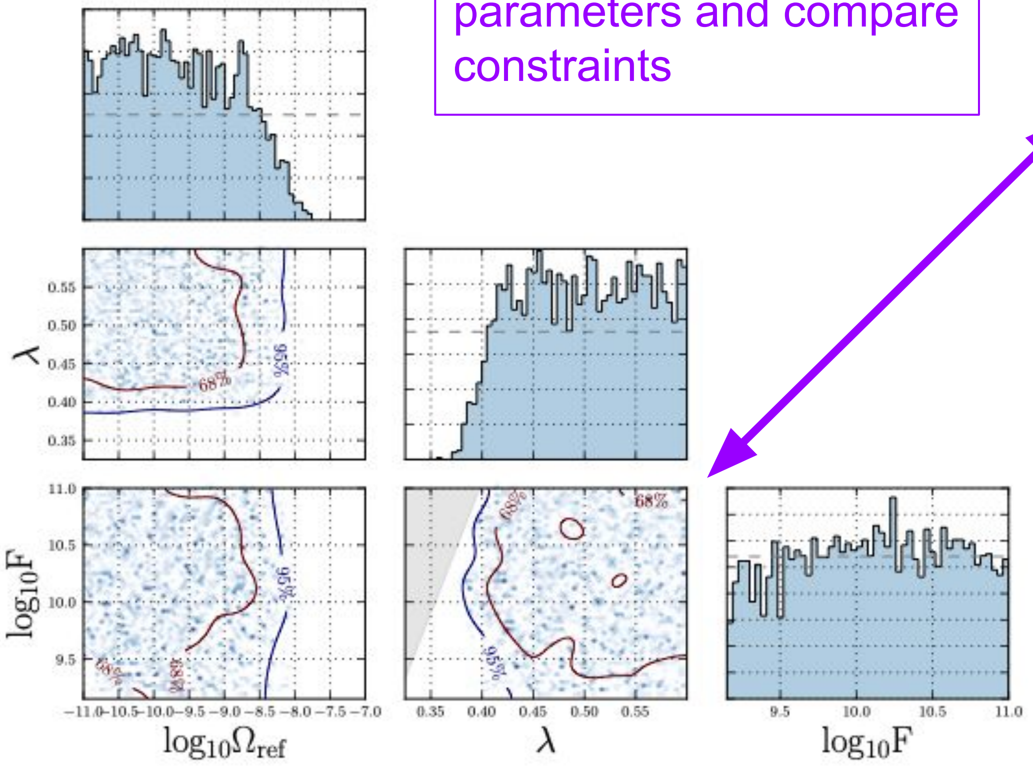
Results - O3 (SW BPL / Pheno)

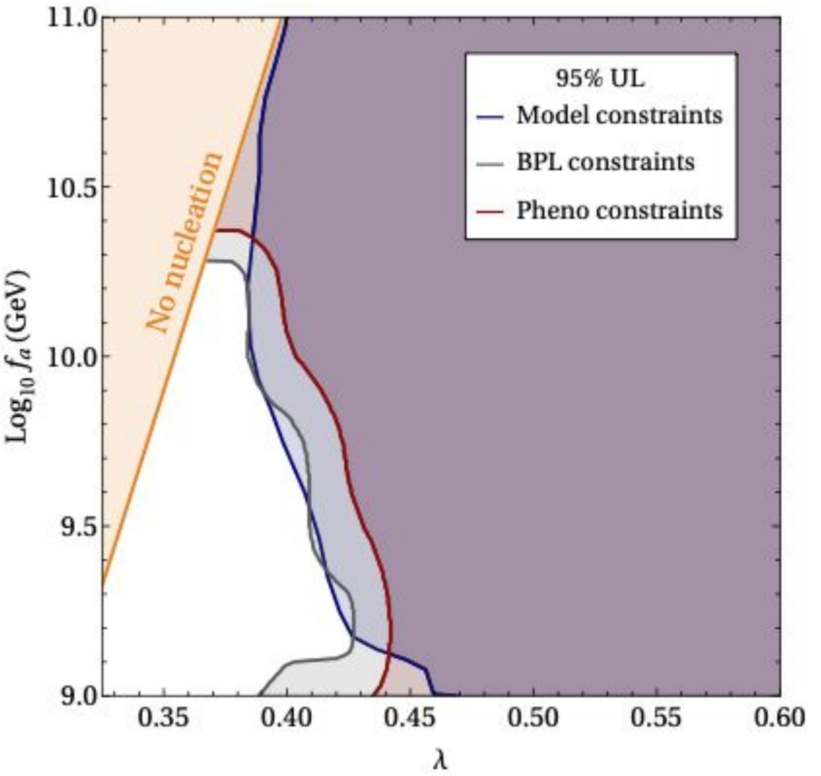




Results - O3 model 2

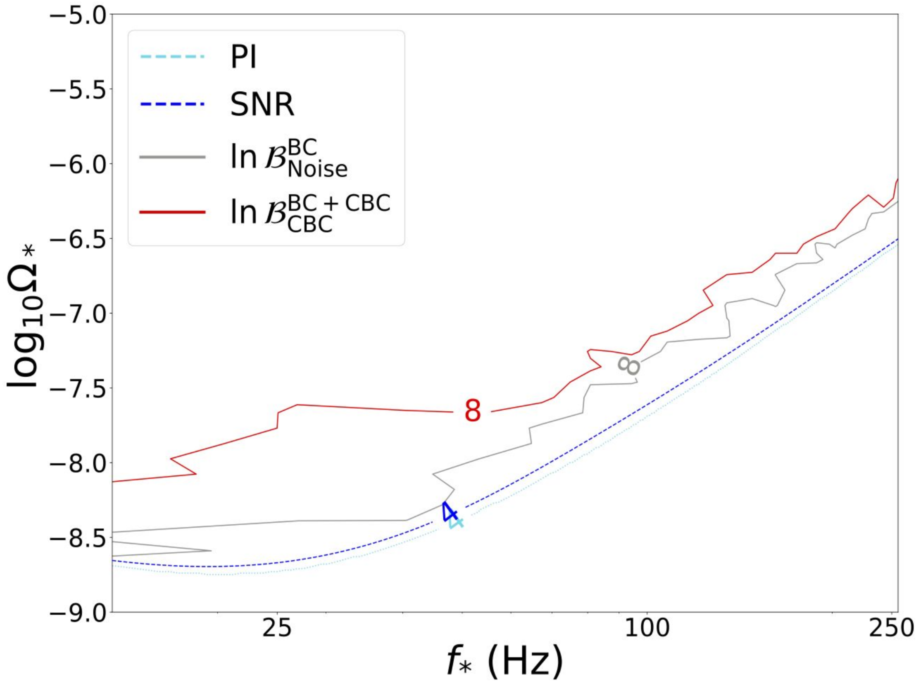
Can convert BPL, pheno constraints to model 2 parameters and compare constraints





Results - O4 outlook

Bubble Collisions - BPL



Sound Waves - BPL