LISA CosWG-24-01

GWs from first-order PTs in LISA

reconstruction pipeline and physics interpretation

Eric Madge (IFT-UAM/CSIC)

based on:

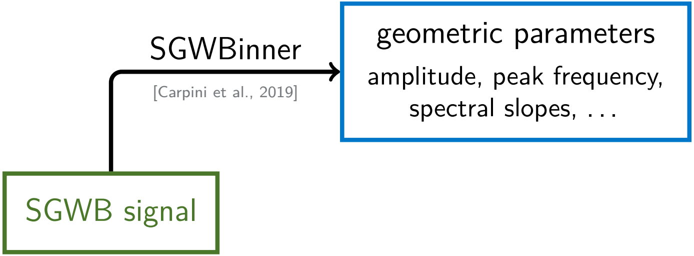
C. Caprini, R. Jinno, M. Lewicki, E.M., M. Merchand, G. Nardini, M. Pieroni, A. Roper Pol and V.Vaskonen

JCAP **10** (2024) 020; arXiv:2403.03723 [astro-ph.CO]

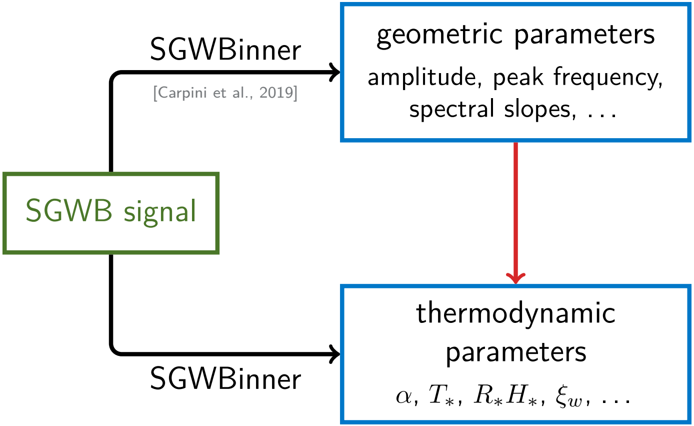
Parameter reconstruction for cosmological phase transitions

SGWB signal

Parameter reconstruction for cosmological phase transitions



Parameter reconstruction for cosmological phase transitions



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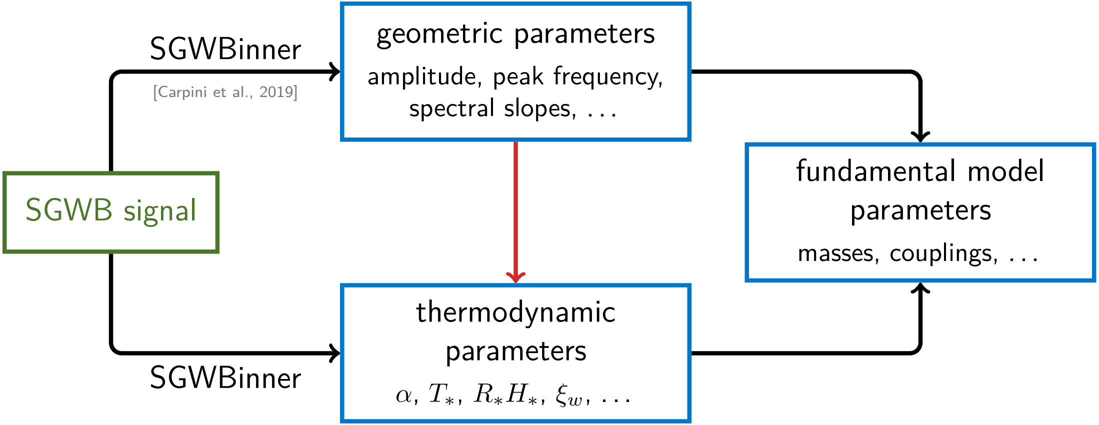
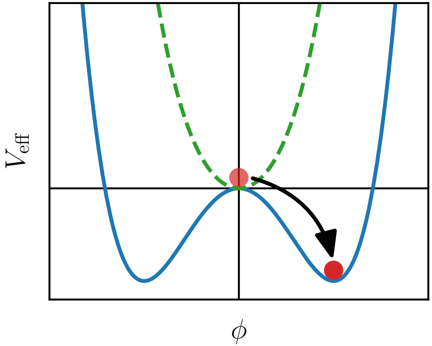


Cosmological phase transitions

- thermal corrections typically restore spontaneously broken symmetries at high temperatures
  $\Longrightarrow$ symmetry breaking phase transition
- can be crossover or first-order



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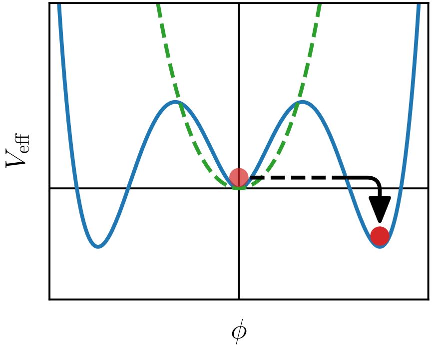

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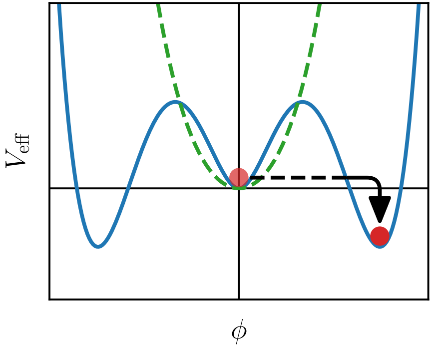
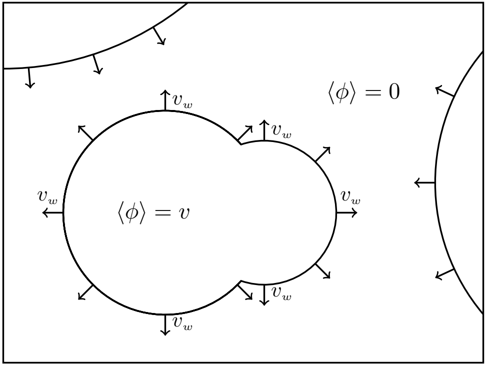


GW production:

1. vacuum bubble collisions



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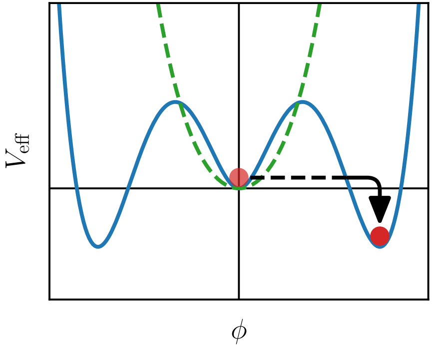

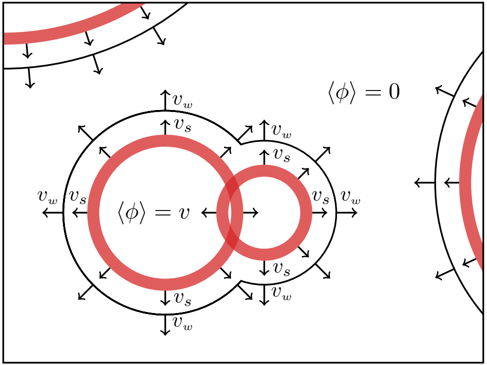

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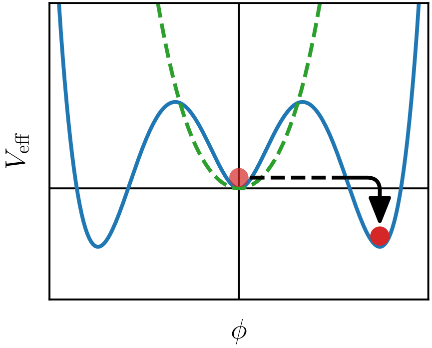

GW production:

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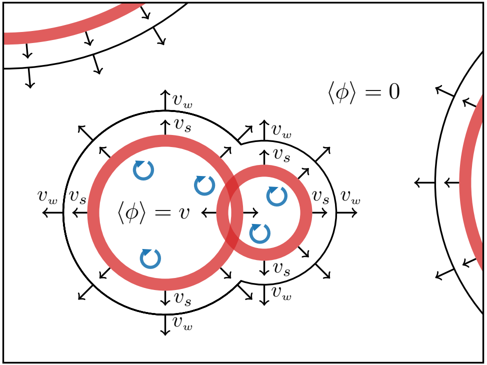
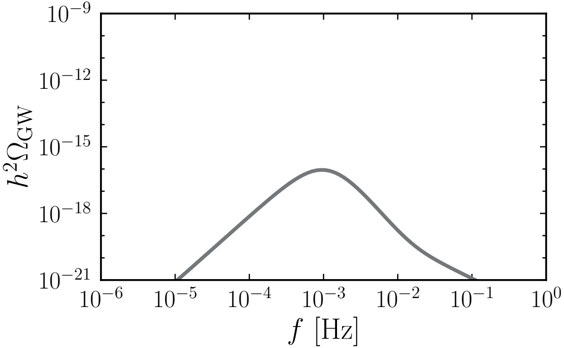
3. turbulence and vortical motion



Phase transition parameters (thermodynamic parameters)

Phase transitions can be characterized in terms of four parameters that determine the corresponding gravitational wave spectrum:



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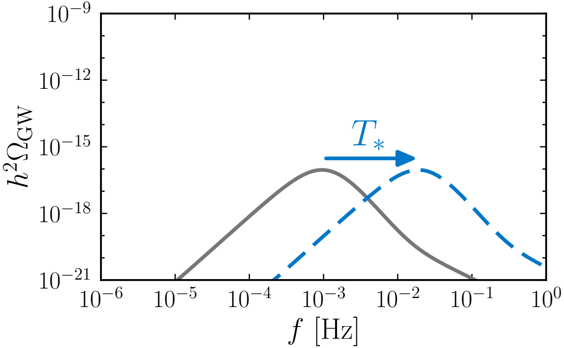
$$\Gamma(T_n) \simeq H^4(T_n)\,, \qquad P_f(T_p) \simeq 0.71$$



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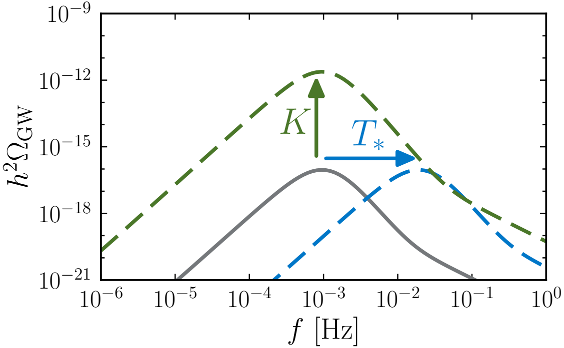
$$\alpha = \frac{\rho_{\rm vac}}{\rho^*_{\rm rad}} \simeq \frac{\Delta V_{\rm eff}}{\rho^*_{\rm rad}}\,, \qquad K = \frac{\alpha}{1+\alpha}$$



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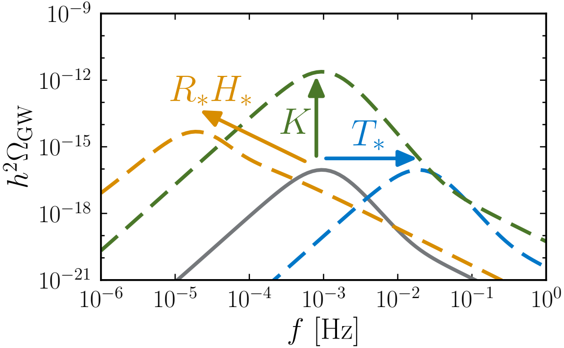

$$\Gamma(t) = \Gamma_* \exp\left(\beta_*(t-t_*)\right)\,, \qquad R_* = (8\pi)^{1/3}\frac{\max(\xi_w, c_s)}{\beta_*}$$

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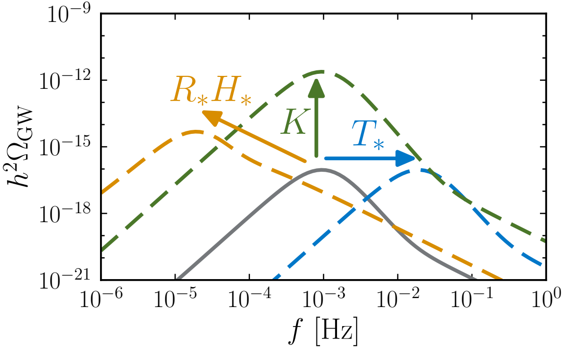
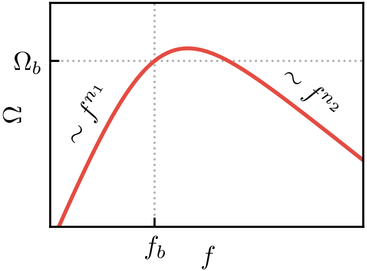
- bubble wall velocity ξ_w, here: $\xi_w \sim 1$



Templates

broken power-law

$$\Omega_b \mathcal{N}\left(\frac{f}{f_b}\right)^{n_1}\left[1+\left(\frac{f}{f_b}\right)^{a_1}\right]^{\frac{n_2-n_1}{a_1}}$$



- bubble collisions: [Lewicki & Vaskonen, 2023]
  $(n_1, n_2, a_1) = (2.4, -2.4, 4)$

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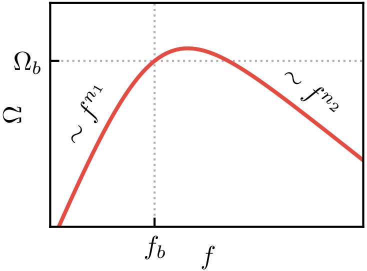

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double broken power-law

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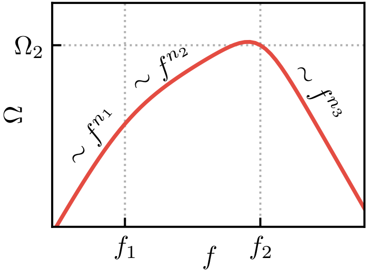
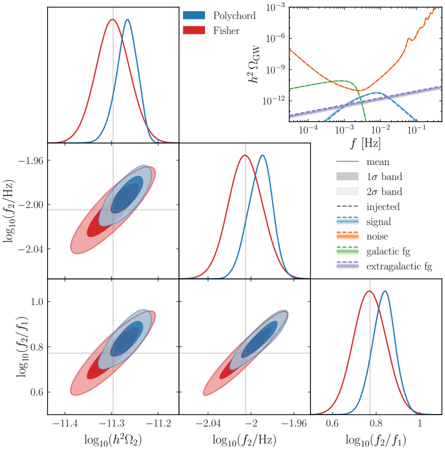


- sound waves: [Jinno et al., 2023]
  $(n_1, n_2, n_2, a_1, a_2) = (3, 1, -3, 2, 4)$
- MHD turbulence: [Roper Pol et al., 2022]
  $(n_1, n_2, n_2, a_1, a_2) = (3, 1, -\frac{8}{3}, 4, 2.15)$

Geometric parameter reconstruction



$$h^2\Omega_2 = 5\times 10^{-12},\ f_2 = 10\,\mathrm{mHz},\ \frac{f_2}{f_1}\approx 6$$

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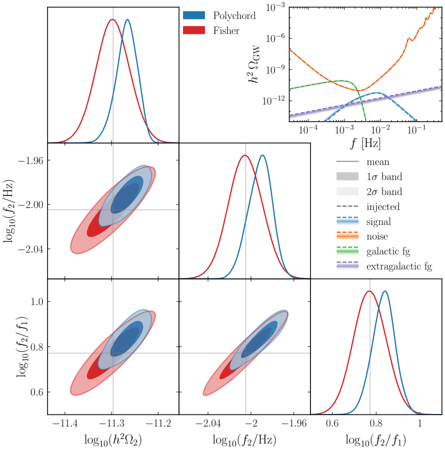

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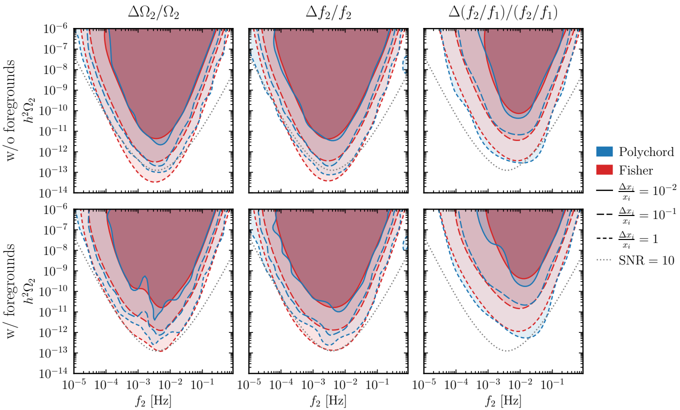


$(n_1,\ n_2,\ n_3,\ a_1,\ a_2) = (3,\ 1,\ -3,\ 2,\ 4)$

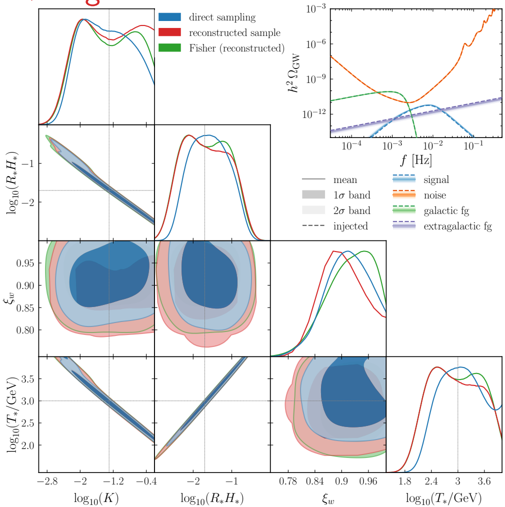
Reconstructing thermodynamic parameters

soundwaves:

3 geom. params.: $\Omega_2,\ f_2,\ f_1$

4 therm. params.: $K,\ H_*R_*,\ \xi_w,\ T_*$

$\Longrightarrow$ degenerate



$K = 0.05,\ R_*H_* = 0.02,\ \xi_w = 1,\ T_* = 1$ TeV

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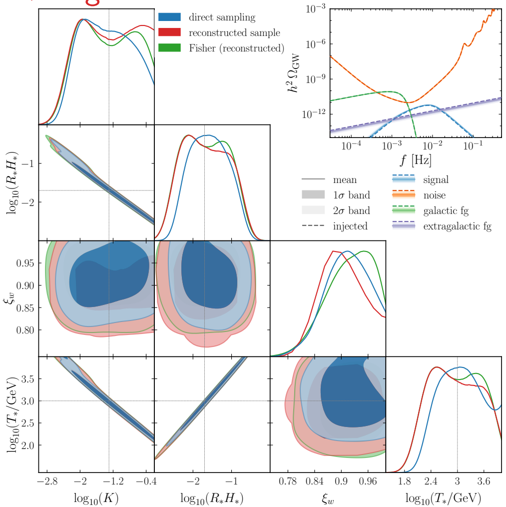
soundwaves + turbulence:

$\Longrightarrow$ additional parameter: ε

$\Longrightarrow$ degeneracy broken?



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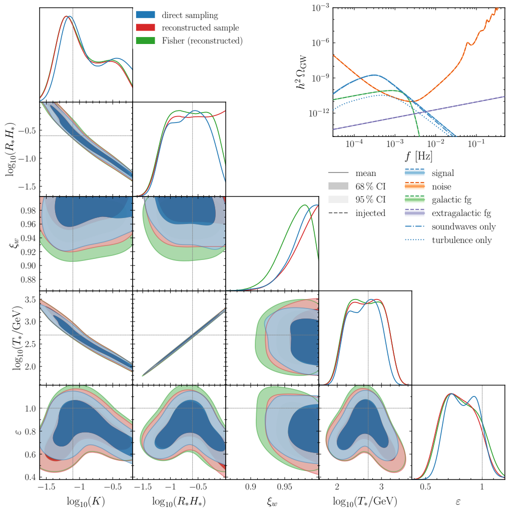

$K = 0.08,\ R_*H_* = 0.25,\ \xi_w = 1,\ T_* = 500$ GeV, $\varepsilon = 1$

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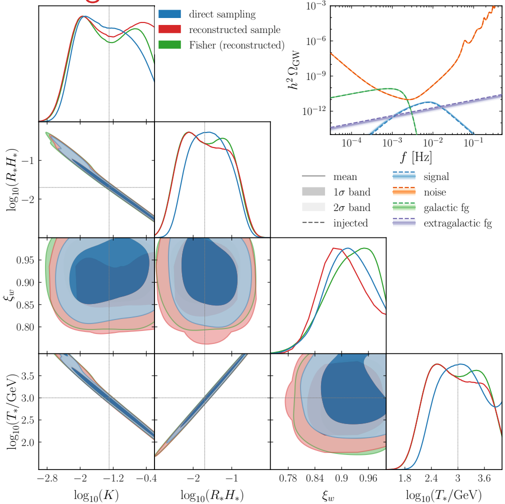

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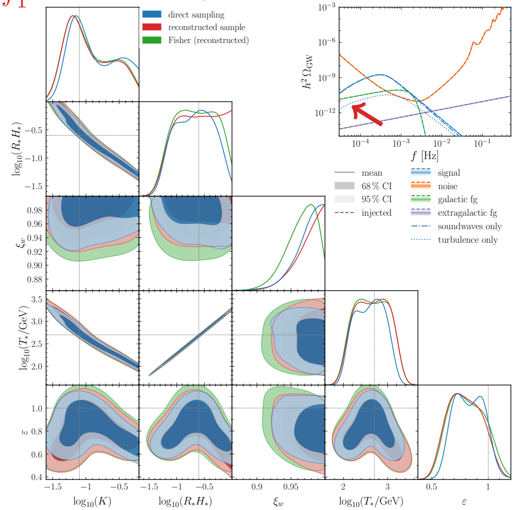
$f_1^{\rm turb}$ hidden $\Longrightarrow$ not reconstructed!



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calculation of PT parameters from fundamental model parameters is expensive

$\Longrightarrow$ direct parameter inference not a good option

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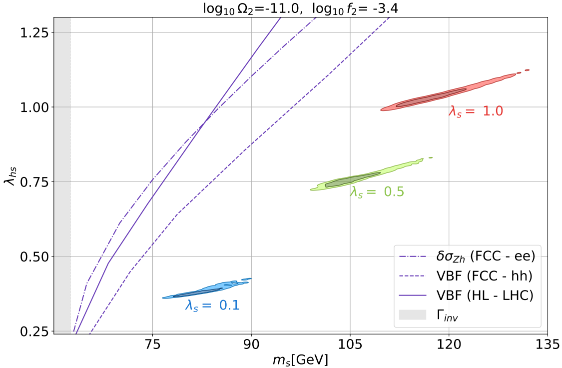
3. Interpolate on grid to convert geometric parameters to model parameters

Parameter reconstruction

gauge singlet extension w/ Z_2

$$V(H,s) \supset \frac{\mu_s^2}{2}\, s^2 + \frac{\lambda_s}{4}\, s^4 + \frac{\lambda_{hs}}{2}\, s^2 H^\dagger H$$

GWs predominantly produced by sound waves



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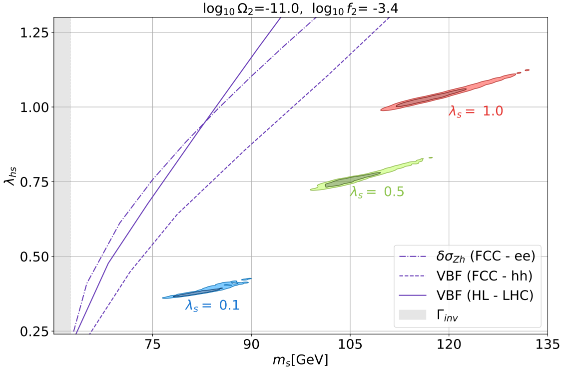
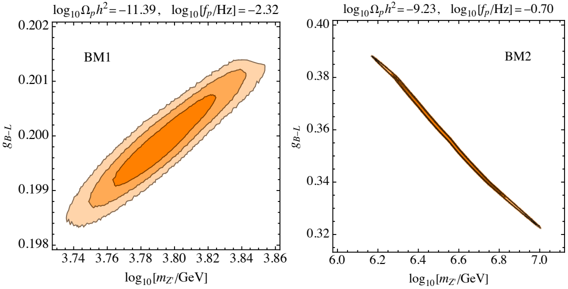


classically conformal $U(1)_{B-L}$

$$V(H,\phi) \supset \lambda_\phi \left(\phi^\dagger\phi\right)^2 - \lambda_p \left(H^\dagger H\right)\left(\phi^\dagger\phi\right)$$

supercooled PT

$\Longrightarrow$ bubble collision / fluid shells



Conclusions

- for the geometric parameters (amplitude, peak/break frequencies, . . .), we can estimate the reach using Fisher analysis
- the reconstruction of thermodynamic parameters of cosmological phase transitions (α, H_*R_*, T_*, . . .) suffers from degeneracies
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Conclusions

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Thank you for your attention!

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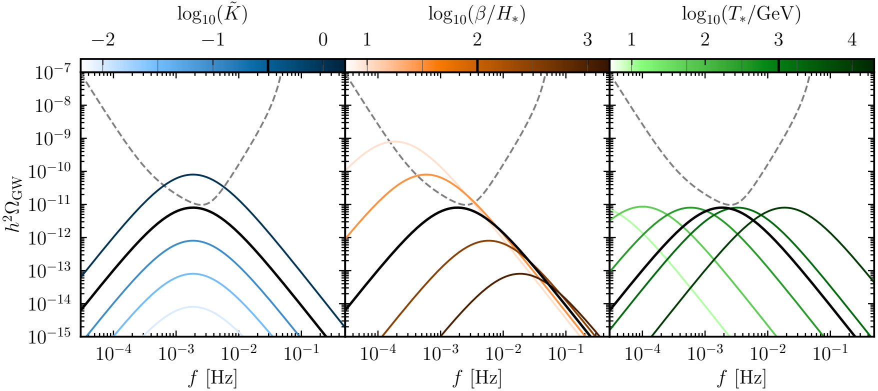
backup slides

Very strong transitions ($\alpha \gg 1$)

Koskwsky, Turner & Watkins, 1992; Kosowsky & Turner, 1993; Huber & Konstandin, 2008; Bodeker & Moore, 2009, 2017; Weir, 2016; Jinno & Takimoto, 2017, 2019; Konstandin, 2018; Lewicki & Vaskonen, 2020, 2023; ...

GWs from vacuum bubble collisions or highly relativistic fluid shells

$$h^2\Omega_b \propto \underbrace{\tilde{K}^2}_{\tilde{K}=\frac{\alpha}{1+\alpha}} \left(\frac{H_*}{\beta}\right)^2 \qquad f_b \propto T_* \, \frac{\beta}{H_*}$$

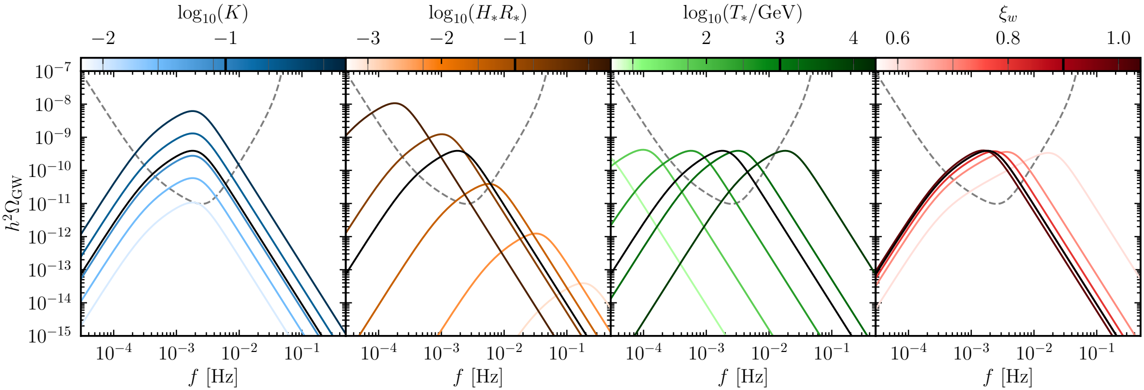


Sound waves

[Hindmarsh et al., 2013, 2015, 2017; Cutting, Hindmarsh & Weir, 2020; Hindmarsh & Hijazi, 2019; Jinno, Konstandin & Rubira, 2019; Jinno et al., 2023; . . .]

$$h^2\Omega_2 \propto K^2\,(H_*\tau_{\rm sw})\,(H_*R_*) \qquad f_1 \propto T_*\,(H_*R_*)^{-1} \qquad f_2 \propto T_*\,(H_*R_*)^{-1}\,\frac{\xi_w}{\xi_w - c_s}$$

soundwave lifetime $H_*\tau_{\rm sw} = \max\left[1,\; H_*R_*/\sqrt{\tfrac{4}{3}K}\right]$

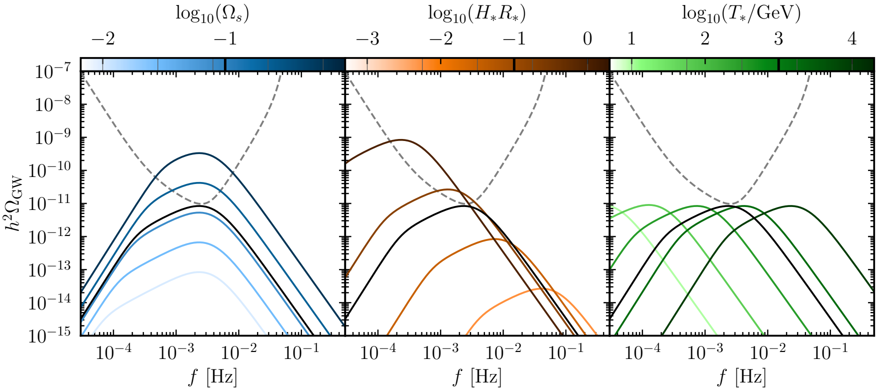


Magnetohydrodynamic turbulence

[Caprini, Durrer & Servant, 2009; Roper Pol et al., 2022; Auclari et al, 2022; Roper Pol et al., 2023]

$$h^2\Omega_2 \propto \Omega_s^2 \, (H_* R_*)^2 \qquad f_1 \propto \Omega_s^{\frac{1}{2}} \, T_* \, (H_* R_*)^{-1} \qquad f_2 \propto T_* \, (H_* R_*)^{-1}$$

total energy in turbulent motion $\Omega_s = \varepsilon \, K$

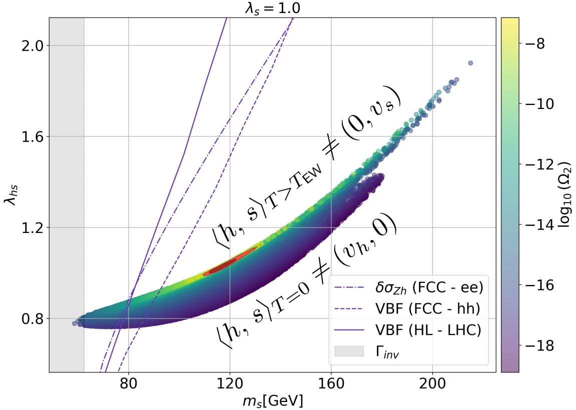


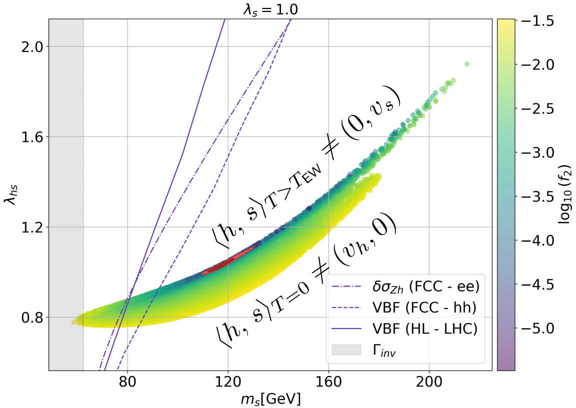
Gauge singlet extension with Z_2 symmetry

[see e.g. Lewicki, Merchand, Zych (2022)
Ellis, Lewicki, Merchand, No, Zych (2023)]

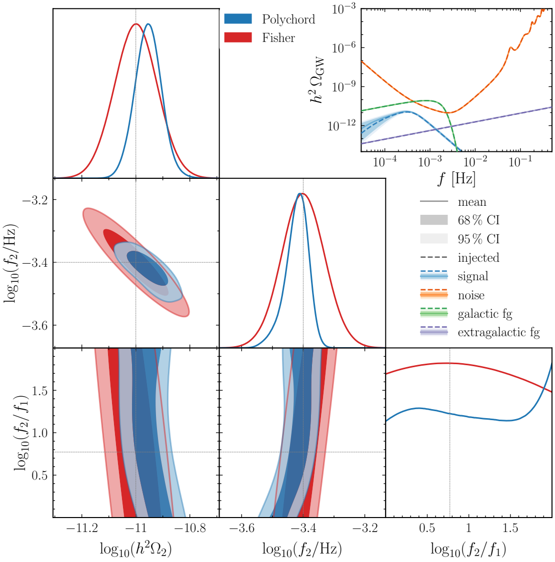
$$V(H,s) = -\mu_h^2\, H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \frac{\mu_s^2}{2}\, s^2 + \frac{\lambda_s}{4}\, s^4 + \frac{\lambda_{hs}}{2}\, s^2 H^\dagger H$$

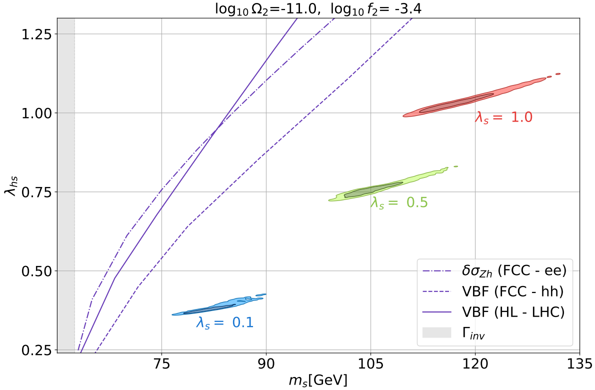
- 2-step transition: $\langle h,\, s\rangle = (0,0) \;\rightarrow\; (0, v_s) \;\rightarrow\; (v_h, 0)$
- GWs predominantly produced by sound waves





Gauge singlet parameter reconstruction



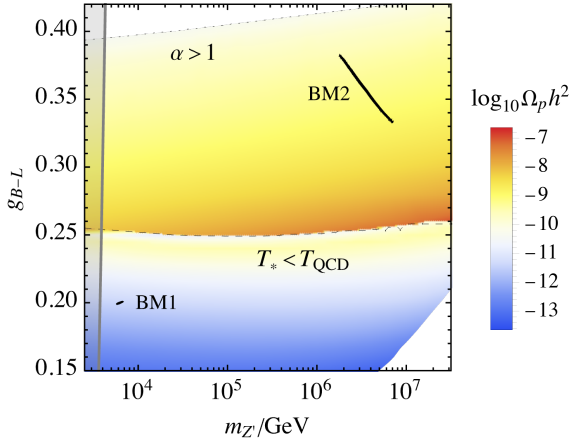


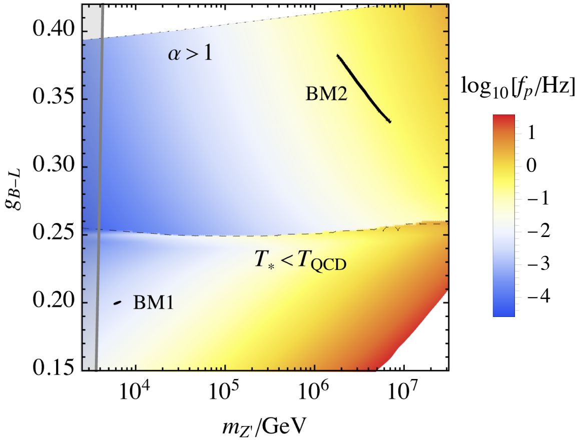
Classically conformal $U(1)_{B\text{-}L}$ model

[see e.g. Jinno, Takimoto (2009)
Marzo, Marzola, Vaskonen (2019)
Ellis, Lewicki, No, Vaskonen (2019)]

$$V(H,\phi) = \lambda_H \left(H^\dagger H\right)^2 + \lambda_\phi \left(\phi^\dagger \phi\right)^2 - \lambda_p \left(H^\dagger H\right)\left(\phi^\dagger \phi\right)$$

supercooled PT $\Longrightarrow$ bubble collision / highly relativistic fluid shells





$U(1)_{B-L}$ parameter reconstruction