Search for cosmological phase transitions through their gravitational wave signals

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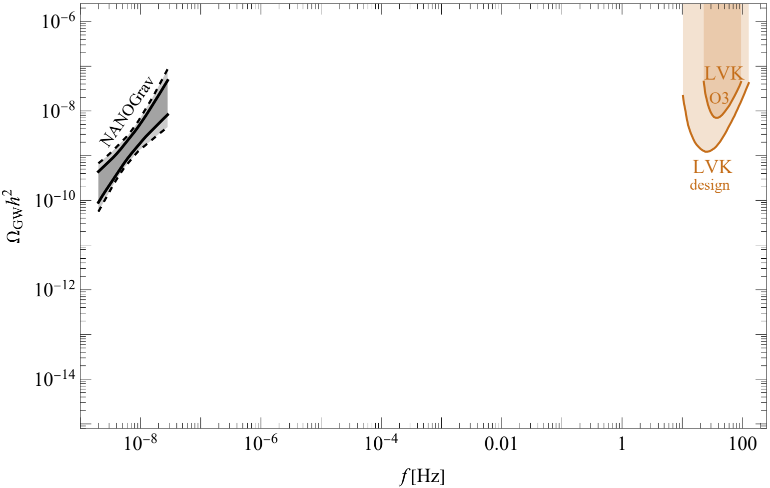
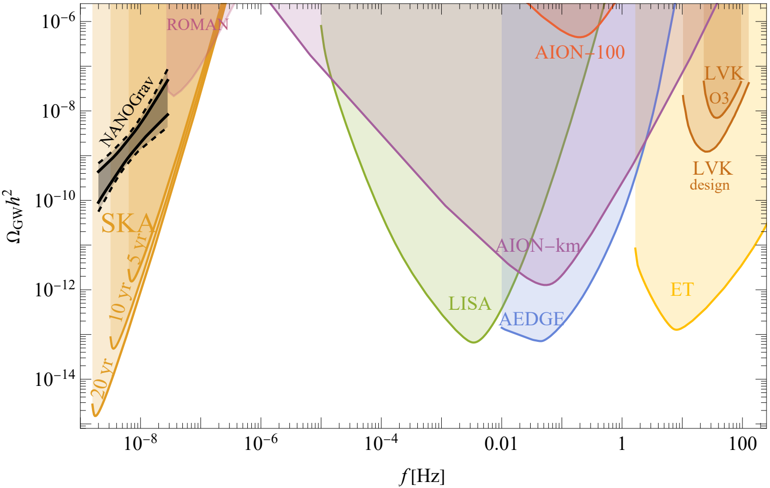
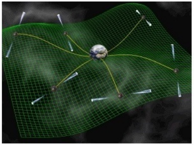


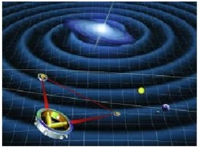
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
$\Omega_{\rm GW} h^2$
NANOGrav
LVK
O3
LVK
design
10^{-8}
10^{-6}
10^{-4}
0.01
1
100
f [Hz]





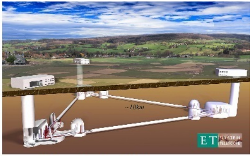
Pulsar Timing

[David Champion/NASA/JPL]



LISA

wiki/Laser_Interferometer_Space_Antenna



Einstein Telescope

www.et-gw.eu

Gravitational waves from a very strong PT

- Strength of the transition

$$\alpha \approx \frac{\Delta V}{\rho_R} \gg 1$$

- Reheating temperature

$$T_{\rm reh} \approx \left(\frac{30}{\pi^2}\frac{1}{g_*}\Delta V\right)^{\frac{1}{4}}$$

- Characteristic scale

$$\Gamma \propto e^{-\frac{S_3(T)}{T}} = e^{\beta\,(t-t_0)} \Longrightarrow \frac{\beta}{H} = T\frac{d}{dT}\left(\frac{S_3(T)}{T}\right)\Big|_{T=T_p}$$

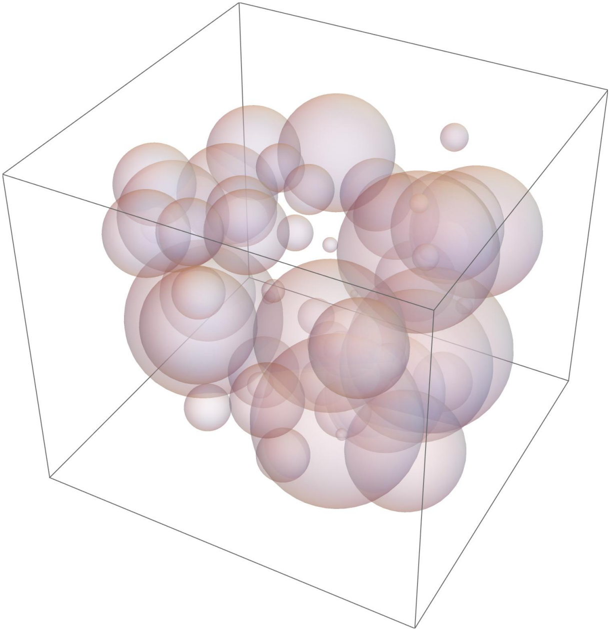
- Amplitude of the spectrum

$$\Omega_{\rm p} \propto \left(\frac{\alpha}{\alpha+1}\right)^2 \left(\frac{\beta}{H}\right)^{-2}$$

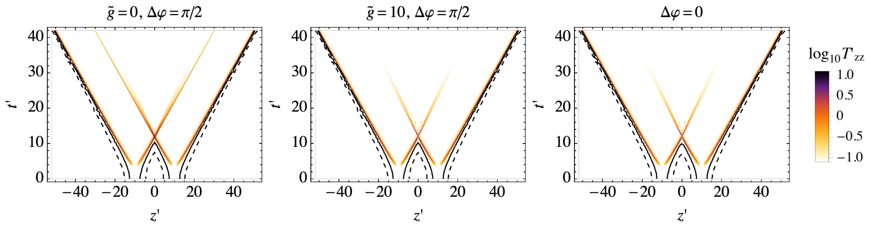
- Peak frequency

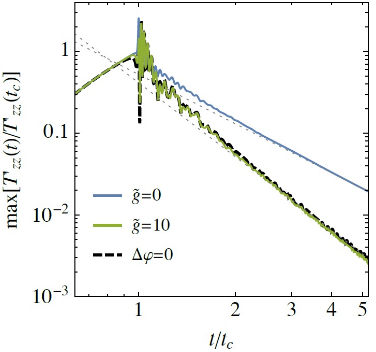
$$f_p \propto T_{\rm reh}\frac{\beta}{H}$$

Strong transitions: computation of the GW spectrum



Abelian Higgs Model: Energy Scaling





- scaled gauge coupling:

$$\tilde{g} = \frac{gv^2}{\sqrt{\Delta V}}$$

- Global Symmetry breaking:

$$T_{zz} \propto R^{-2}$$

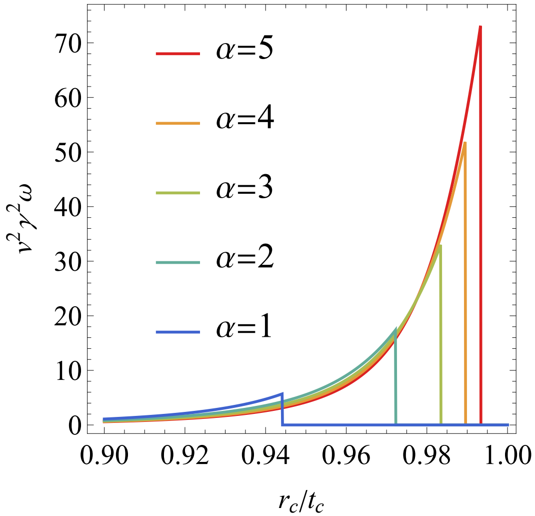
- Gauge Symmetry breaking:

$$T_{zz} \propto R^{-3}$$

ML, Ville Vaskonen arXiv: 2007.04967

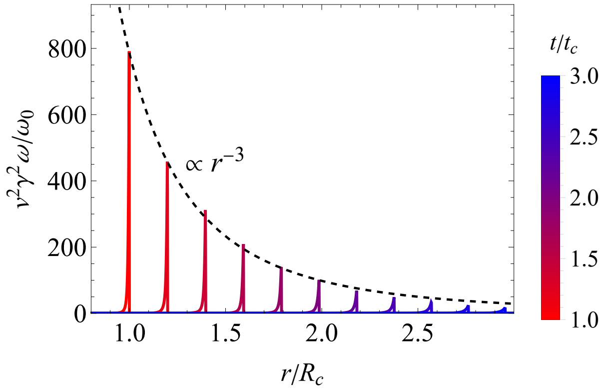
Fluid Shells

- Plasma profiles for $v_w \gtrsim v_J$



Fluid Shell Evolution

- Plasma profile evolution with $\alpha = 20$ and $\gamma_w = 50$



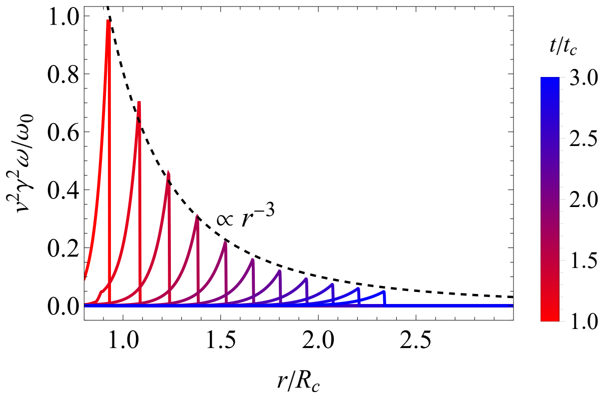
- Fluid shells with $\alpha \gg 1$:

$$T_{zz} \propto R^{-3}$$

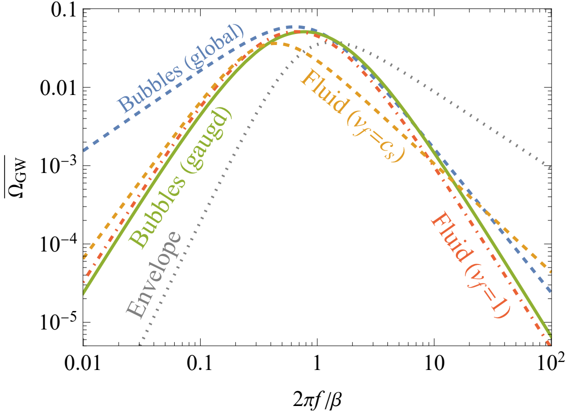
ML, Ville Vaskonen arXiv:2208.11697

Fluid Shell Evolution

- Plasma profile evolution with $\alpha = 0.5$ and $\gamma_w = 3$



ML, Ville Vaskonen arXiv:2208.11697



- Resulting spectrum:

$$\overline{\Omega_{GW}} = \frac{A\,(a+b)^c}{\left[b\left(\frac{f}{f_p}\right)^{-\frac{a}{c}} + a\left(\frac{f}{f_p}\right)^{\frac{b}{c}}\right]^c}$$

	Bubbles		Fluid
	Global($T \propto R^{-2}$)	Gauged ($T \propto R^{-3}$)	$v_{\rm shell} = 1$
$100\,A$	5.93 ± 0.05	5.13 ± 0.05	5.14 ± 0.04
a	1.03 ± 0.04	2.41 ± 0.10	2.36 ± 0.09
b	1.84 ± 0.17	2.42 ± 0.11	2.36 ± 0.09
c	1.91 ± 0.29	1.45 ± 0.34	3.69 ± 0.48
$2\pi f_p/\beta$	1.33 ± 0.19	0.64 ± 0.09	0.66 ± 0.04

ML, Ville Vaskonen arXiv: 2208.11697

ML, Ville Vaskonen, arXiv: 2007.04967

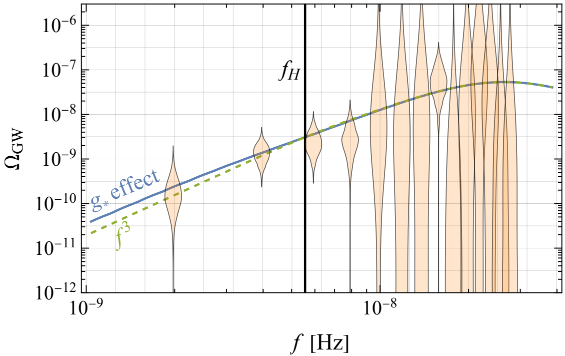
- Spectrum today

$$\Omega_{\rm GW}(f,T_*)h^2 \approx 1.6\times 10^{-5} S_H(f, f_H(T_*)) \left[\frac{\beta}{H}\right]^2 \frac{A(a+b)^c}{\left(b\left[\frac{f}{f_p}\right]^{-\frac{a}{c}} + a\left[\frac{f}{f_p}\right]^{\frac{b}{c}}\right)^c}$$

- Superhorizon modes

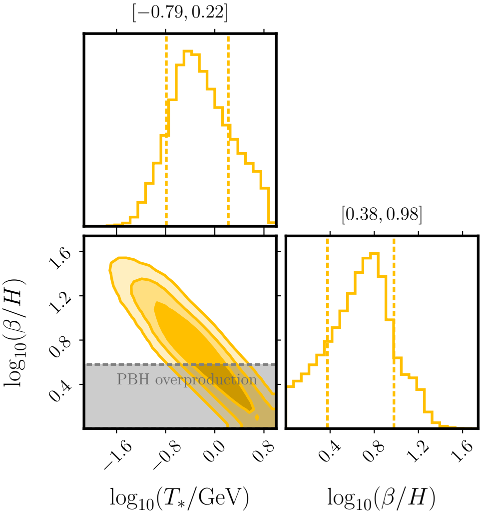
Gabriele Franciolini, Davide Racco, Fabrizio Rompineve arXiv: 2306.17136

$$f_H(T) = \frac{a(T)}{a_0}\frac{H(T)}{2\pi}\,, \quad S_H(f,f_H) = \left(1+\left[\frac{\Omega_{\rm CT}(f)}{\Omega_{\rm CT}(f_H)}\right]^{-\frac{1}{\delta}}\left[\frac{f}{f_H}\right]^{\frac{a}{\delta}}\right)^{-\delta}$$



Fit to NANOGrav

- Constraint from PBH overproduction $\beta/H \gtrsim 3.9$
  ML, Piotr Toczek, Ville Vaskonen arXiv: 2305.04924



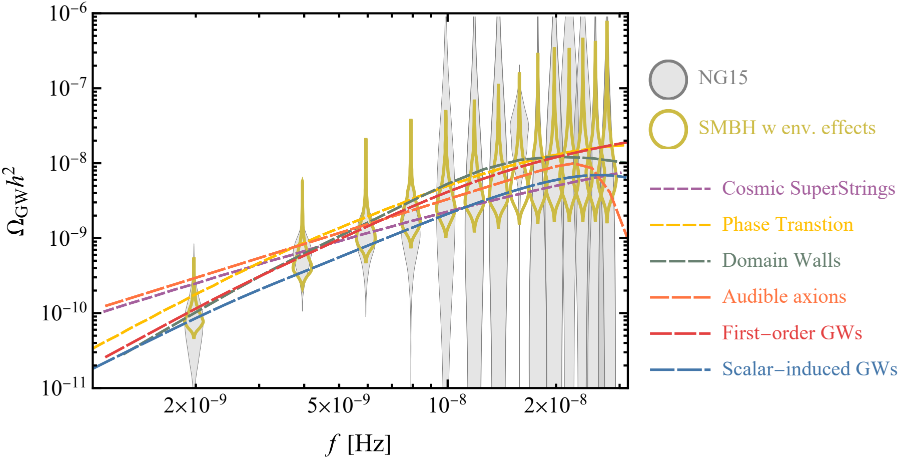
John Ellis et al. arXiv: 2308.08546

Results from Multi-Model Analysis (MMA)

Scenario	Best-fit parameters	ΔBIC
GW-driven SMBH binaries	$p_{\rm BH} = 0.25$	6.0
GW + environment-driven SMBH binaries	$p_{\rm BH} = 1$, $\alpha = 3.8$ $f_{\rm ref} = 12$ nHz	(BIC = 53.9)
Cosmic (super)strings	$G\mu = 2 \times 10^{-12}$, $p = 6.3 \times 10^{-3}$	-1.2
Phase transition	$T_* = 0.4$ GeV, $\beta/H = 5.5$	-4.9
Domain walls	$T_{\rm ann} = 0.79$ GeV, $\alpha_* = 0.026$	-5.7
Scalar-induced GWs	$k_* = 10^{7.6}$/Mpc $A = 0.08$, $\Delta = 0.28$	-2.1
First-order GWs	$\log_{10} r = -16$, $n_{\rm t} = 2.9$ $T_{\rm rh} = 0.35\,{\rm GeV}$	-2.0
"Audible" axions	$m_a = 3.1 \times 10^{-11}\,{\rm eV}$, $f_a = 0.87\,M_{\rm P}$	-4.2

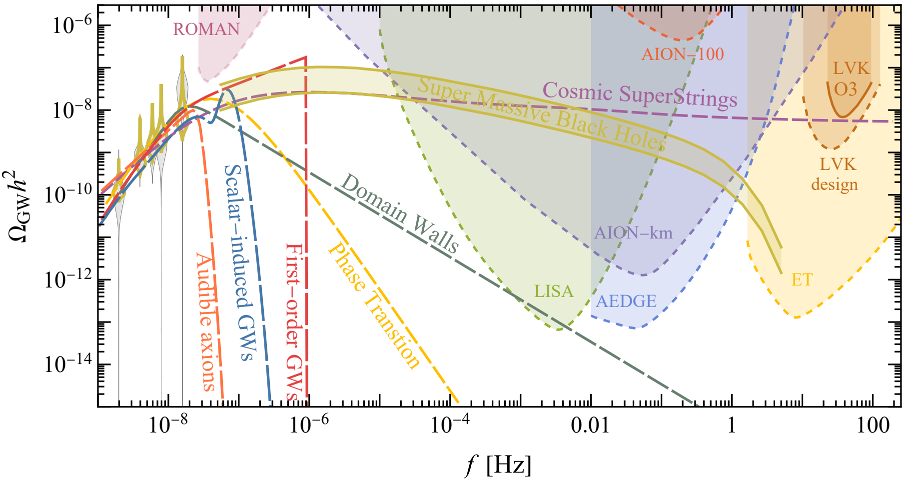
For each model, we tabulate their best-fit values, and the Bayesian information criterion $BIC \equiv -2\Delta\ell + k \ln 14$ relative to that for the purely SMBH model with environmental effects that we take as the baseline. The quantity in the parentheses in the third column shows the ΔBIC for the best-fit combined SMBH+cosmological scenario.

Best Fits to NANOGrav including SMBH



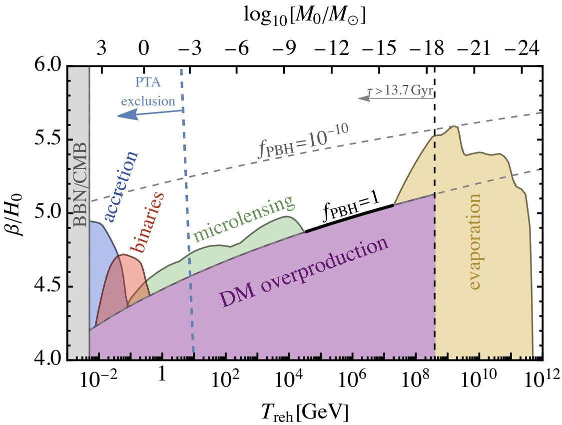
John Ellis et al. Phys.Rev.D 109 (2024) 2, 023522 arXiv: 2308.08546

Best Fits to NANOGrav including SMBH



John Ellis et al. Phys.Rev.D 109 (2024) 2, 023522 arXiv: 2308.08546

Slow transitions produce PBHs

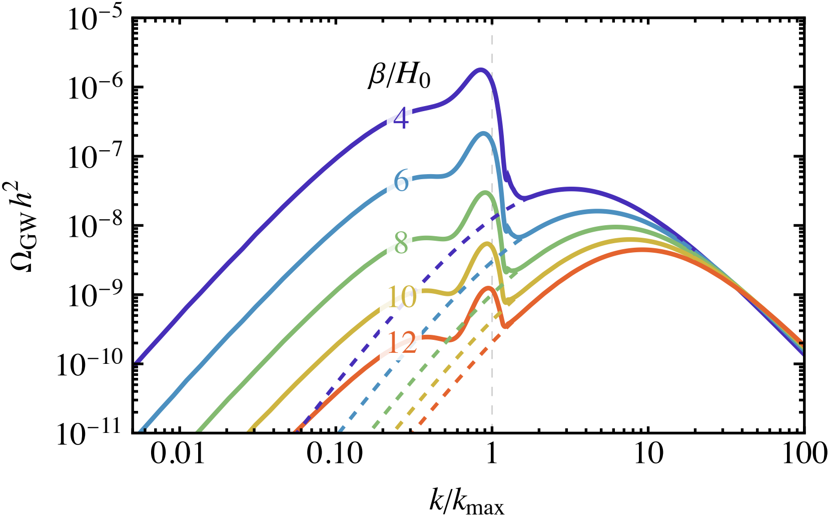


- Mass and abundance of PBHs

$$M_0 \approx 0.05 M_\odot \left[\frac{100}{g_*}\right]^{\frac{1}{2}} \left[\frac{T_{\rm reh}}{\rm GeV}\right]^{-2}, \; f_{\rm PBH} = 2.8\times 10^9 \exp\left[-0.246 e^{\beta/H_0}\right] \frac{g_*}{g_{*s}} \frac{T_{\rm reh}}{\rm GeV}$$

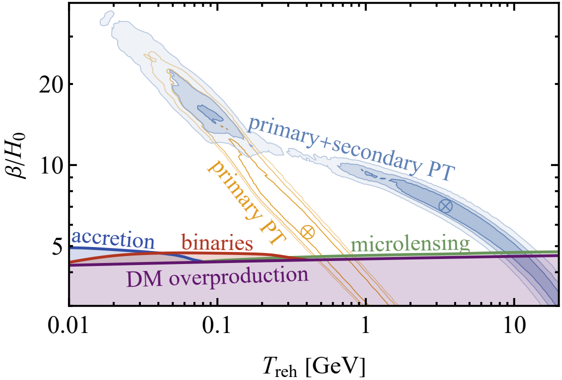
ML, P. Toczek and V. Vaskonen, arXiv:2402.04158

Secondary GWs dominating for slow transitions



ML, P. Toczek and V. Vaskonen, arXiv:2402.04158

Secondary GWs: Impact on PTA fits



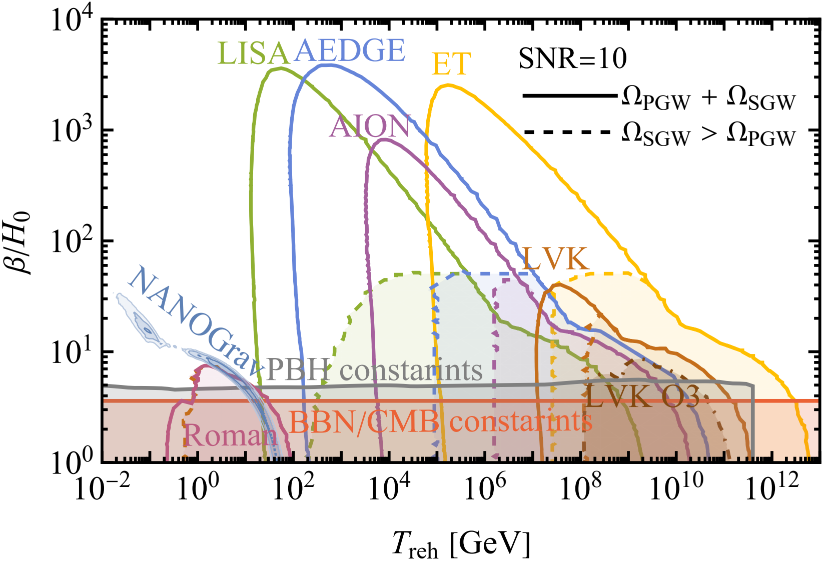
- Best fit with primary vs primary+secondary GWs

  $T_{\rm reh} = 0.4\,\text{GeV}$ $\quad$ $T_{\rm reh} = 3.4\,\text{GeV}$

  $\beta/H = 5.5$ $\quad$ $\beta/H = 7.0$

ML, P. Toczek and V. Vaskonen, arXiv:2402.04158

Secondary GWs: Detection prospects



ML, P. Toczek and V. Vaskonen, arXiv:2402.04158

Conclusions

- Very strong transitions ($\alpha \gg 1$) produce the same GW spectrum regardless of whether the main source is collisions of bubble or motion of the plasma.
- A very strong phase transition is one of the best explanations for the current PTA data.
- If the transition is also slow ($\beta/H \lesssim 10$) a secondary GW contribution will dominate the spectrum and a large population of PBH can be created.

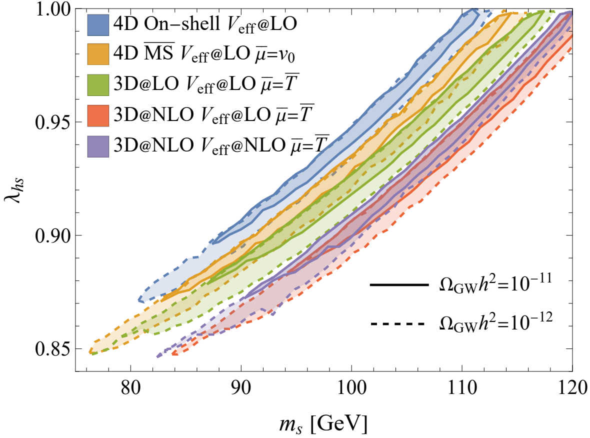
Thank you for your attention!

Backup Slides

Theoretical uncertainty on the parameter space

- Standard Model with an additional singlet scalar

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

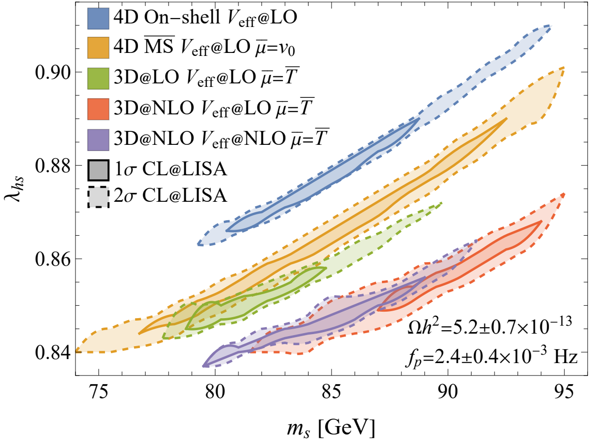


ML, Marco Merchand, Laura Sagunski, Philipp Schicho, Daniel Schmitt arXiv:2403.03769

Theoretical uncertainty on the parameter reconstruction

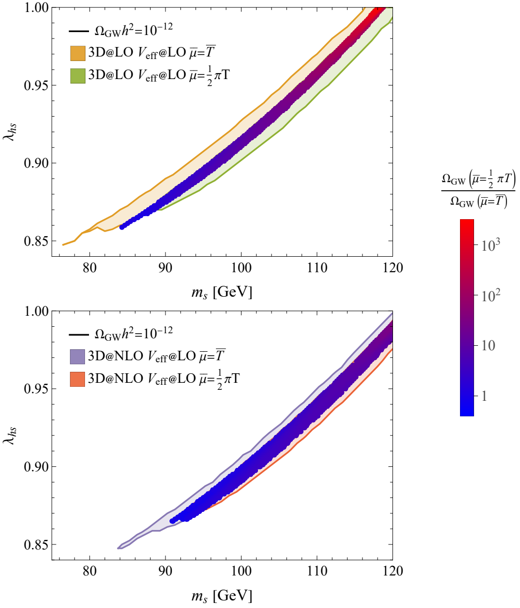
- Standard Model with an additional singlet scalar

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



ML, Marco Merchand, Laura Sagunski, Philipp Schicho, Daniel Schmitt arXiv:2403.03769

Theoretical uncertainty on the parameter space



ML, Marco Merchand, Laura Sagunski, Philipp Schicho, Daniel Schmitt arXiv:2403.03769

Conclusions II

- Large errors on the GW spectra for individual parameter points corresponds to small $O(1\%)$ error on the reconstructed model parameters
- These small reconstruction errors would still dominate the experimental uncertainties for any detectable spectra