Interplay among gravitational waves, dark matter and collider signals within singlet extended type-II seesaw scenario

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- Motivations,

to consider the singlet extended type-II seesaw model:

- Provide an cold Dark Matter candidate (the additinal singlet)

  → Possible signals at the Dark Matter Direct Detection experiments

- Extended Higgs sector → First-order EW Phase transition

  → Solution to Matter-Antimatter asymmetry

  → Stochastic Gravitational Waves from Higgs Bubble Collisions in FOEWPT and Plasma Motion

- Provide tiny mass to neutrinos

- Probing the Extended Higgs Sector: through the heavy Higgs Searches (coming from the triplet sector) and the precision Studies of h_{SM} at LHC

Singlet extended type-II seesaw model

Fields		$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$\otimes Z_3$
Complex Scalar DM	$S = \frac{1}{\sqrt{2}}(h_s + i a_s)$	1	1	0	$e^{i\frac{2\pi}{3}}$
Scalar Triplet	$\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \frac{1}{\sqrt{2}}(h_t + i a_t) & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$	1	3	2	1
Higgs doublet	$H = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h_d + i a_d) \end{pmatrix}$	1	2	1	1

$$\begin{aligned} V(H,\Delta) = & -\mu_H^2 (H^\dagger H) + \lambda_H (H^\dagger H)^2 \\ & + \mu_\Delta^2 \mathrm{Tr}\left[\Delta^\dagger \Delta\right] + \lambda_1 \left(H^\dagger H\right) \mathrm{Tr}\left[\Delta^\dagger \Delta\right] + \lambda_2 \left(\mathrm{Tr}[\Delta^\dagger \Delta]\right)^2 \\ & + \lambda_3 \,\mathrm{Tr}[\left(\Delta^\dagger \Delta\right)^2] + \lambda_4 \left(H^\dagger \Delta \Delta^\dagger H\right) + \left[\mu \left(H^T i\sigma^2 \Delta^\dagger H\right) + h.c.\right] \end{aligned}$$

$$H = \begin{pmatrix} G^+ \\ \frac{h_d + v_d + i a_d}{\sqrt{2}} \end{pmatrix}$$

$$\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \frac{h_t + v_t + i a_t}{\sqrt{2}} & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

$$V^{\rm DM} = \mu_S^2 \, |S|^2 + \lambda_S |S|^4 + \frac{\mu_3}{3!}\left(S^3 + S^{*3}\right) \; + \lambda_{SH} H^\dagger H (S^* S) + \lambda_{S\Delta} \,\mathrm{Tr}\left[\Delta^\dagger \Delta\right] (S^* S)$$

$$\mathrm{S} = \mathrm{h}_s + i a_s$$

- Some interesting mass relations

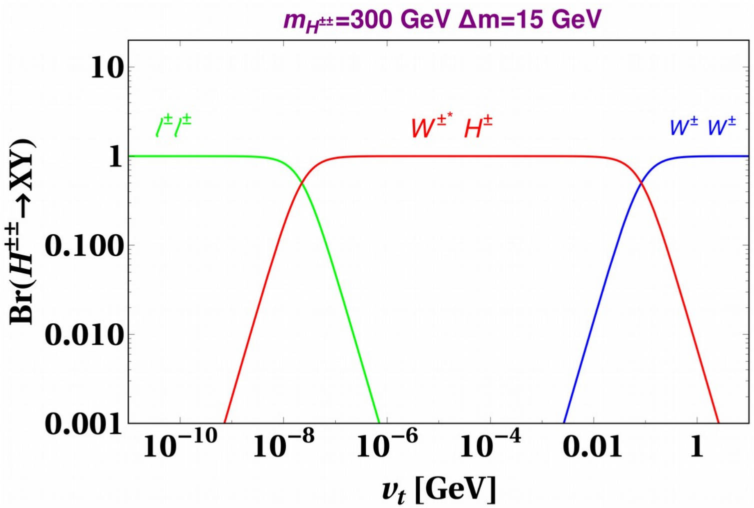
$$\left(m^2_{H^{\pm\pm}} - m^2_{H^{\pm}}\right) \approx -\frac{\lambda_4 v_d^2}{4} \; ; \; \left(m^2_{H^{\pm}} - m^2_{A^0}\right) \approx -\frac{\lambda_4 v_d^2}{4} \; ; \; m_{H^0} \approx m_{A^0} \approx M_\Delta \qquad \left[M_\Delta^2 = \frac{\mu v_d^2}{\sqrt{2} v_t}\right]$$

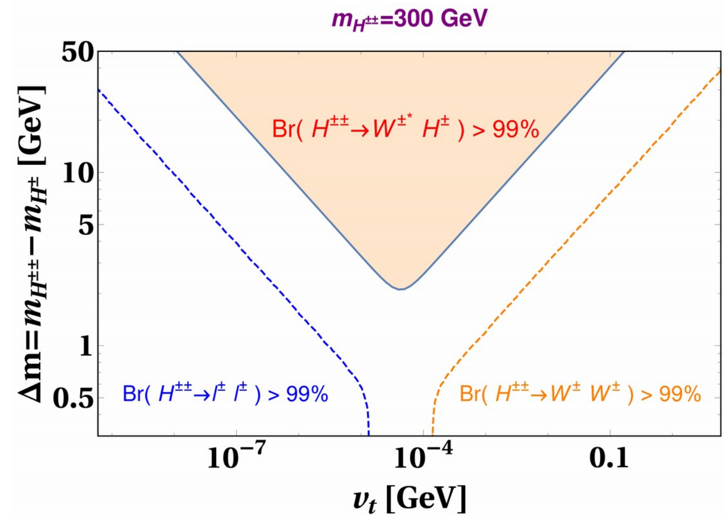
- Two types of mass hierarchy among different components of the triplet scalar depending on the sign of λ_4

  - when λ_4 is negative: $m_{H^{\pm\pm}} > m_{H^{\pm}} > m_{H^0,A^0}$,
  - when λ_4 is positive: $m_{H^{\pm\pm}} < m_{H^{\pm}} < m_{H^0,A^0}$.

- Define, $\Delta m = m_{H^{\pm\pm}} - m_{H^{\pm}}$

Heavy doubly charged Higgs decay modes



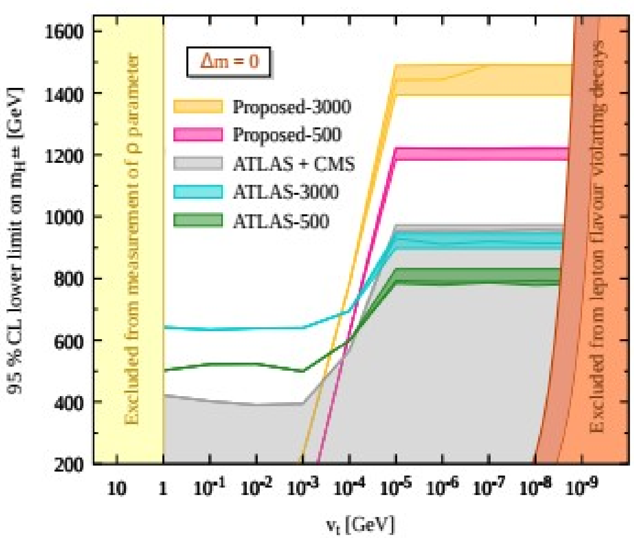


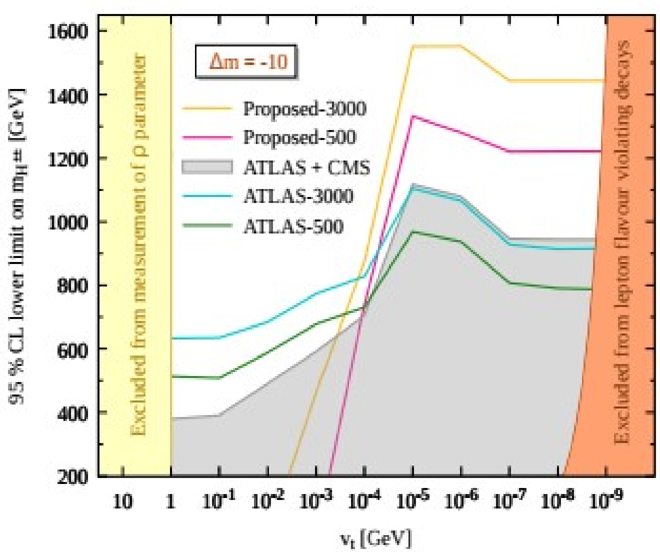
LHC constraints depends on

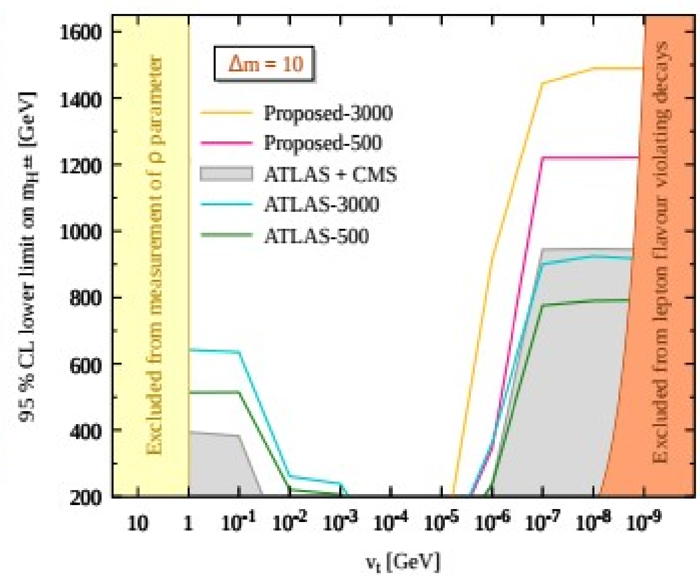
$$\Delta m, v_t \text{ and } m_{H^{\pm\pm}}$$

Constraints after recasting LHC data

arxiv:2108.10952



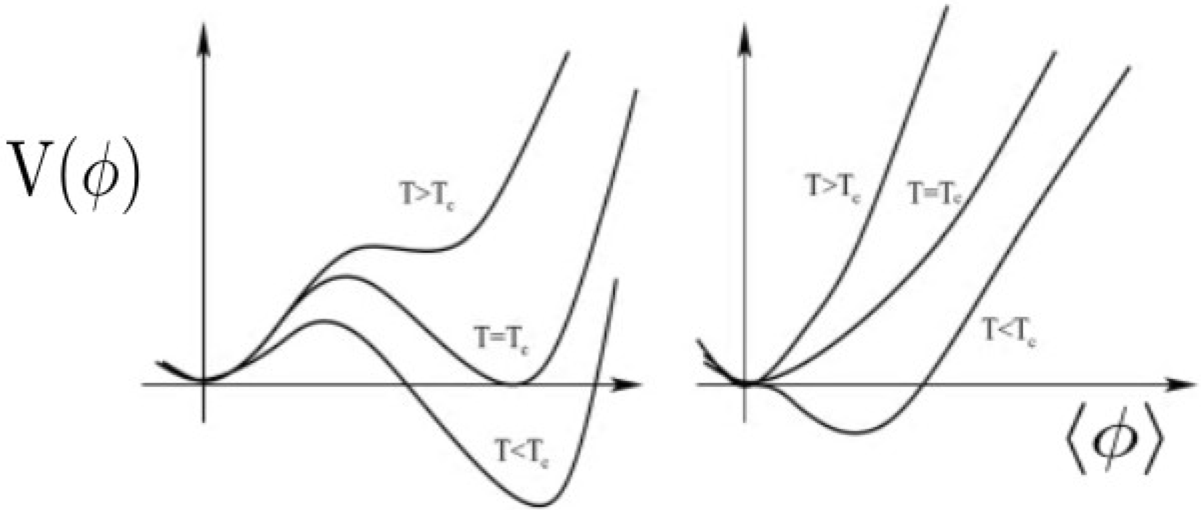




LHC will be unable to constrain $10\text{GeV} < \Delta m < 40\text{GeV},\ 10^{-5}\text{GeV} < v_t < 10^{-3}\text{GeV}$ and $m_{H^{\pm\pm}} > 200\text{GeV}$ region, even with $3\,\text{ab}^{-1}$ of integrated luminosity data, from its canonical searches.

First order electroweak phase transition and production of gravitational waves:

Dine, Kusenko, 0303065



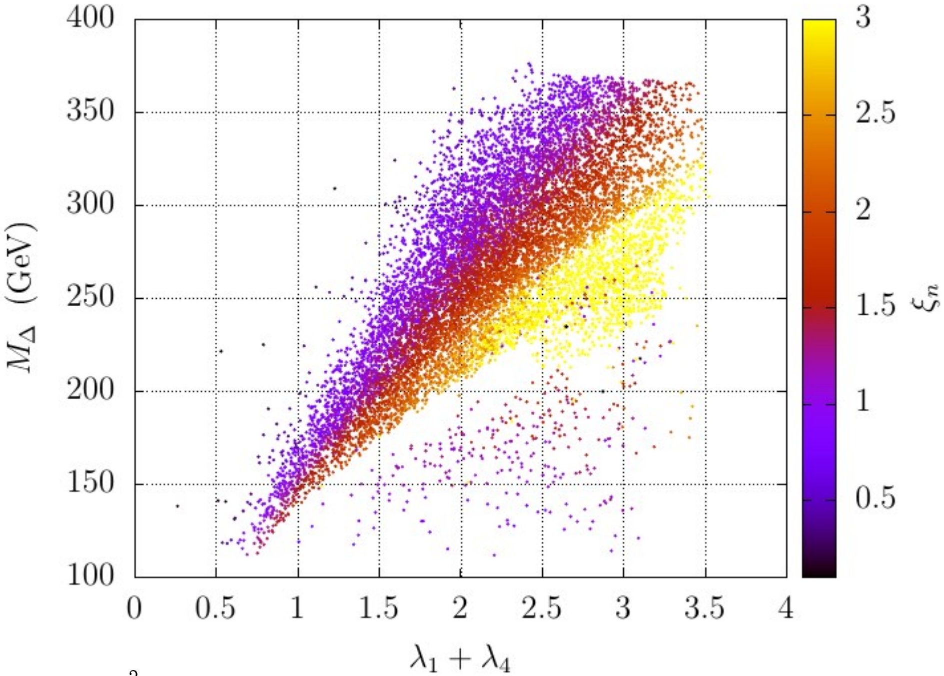
First order → Second order

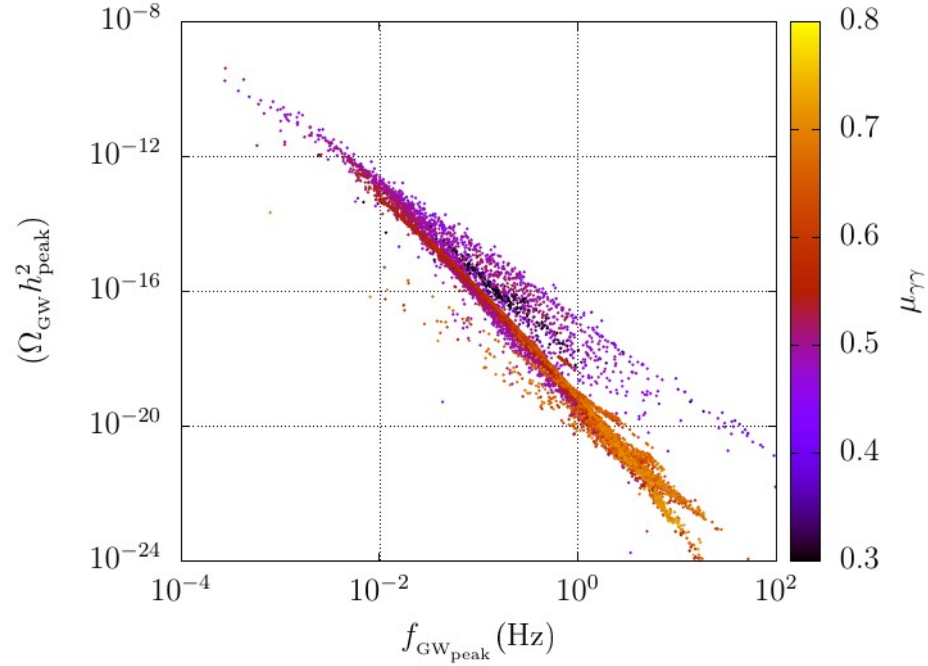
m_h ⟶

⟵ Additional new scalars
(add cubic terms in the potential)

- Phases are seperated by potential barrier at finite temperature
- Broken (true vacuum) phase bubbles nucleates and expand
- They eventually merge/collide ⟶ anisotropic stress ⟶ sources of gravitational waves signal
  also, from the subsequent plasma motion

FOEWPT preferred region





$[M_\Delta^2 = \frac{\mu v_d^2}{\sqrt{2} v_t}]$

- FOEWPT prefers relatively larger quartic couplings and smaller Higgs states.
- The precision study of $h_{\rm SM} \to \gamma\gamma$ decay mode excludes most of the region, which are otherwise allowed from the canonnical searches at the LHC, that can generate stochastic gravitational waves

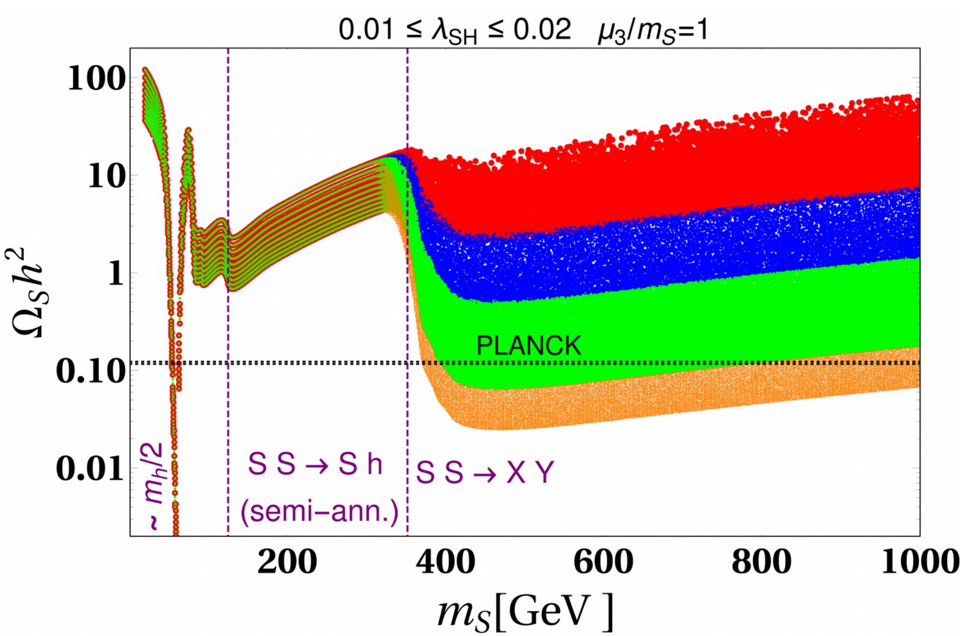
Dark sector :

$$V^{\rm DM} = \mu_S^2\,|S|^2 + \lambda_S|S|^4 + \frac{\mu_3}{3!}\left(S^3 + S^{*3}\right) + \lambda_{SH}H^\dagger H(S^*S) + \lambda_{S\Delta}\,{\rm Tr}\left[\Delta^\dagger\Delta\right](S^*S)$$

The phenomenology of DM depends on

$$\{m_S,\ \mu_3,\ \lambda_{SH},\ \lambda_{S\Delta}\}$$

$$\{M_\Delta = 367.7\ {\rm GeV},\ v_t = 3.3\times10^{-4}\ {\rm GeV},$$
$$\lambda_1 = 3.92,\ \lambda_2 = 0.1,\ \lambda_3 = 0,\ \lambda_4 = -0.989\}$$

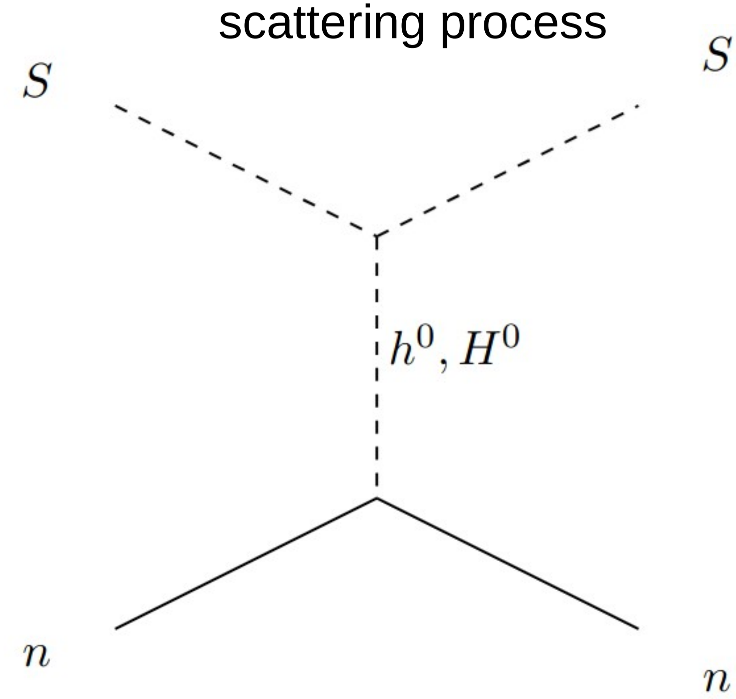


Variation of relic density as a function of DM mass

$0.01 \leq \lambda_{S\Delta} \leq 0.04$ (Red)

$0.04 < \lambda_{S\Delta} \leq 0.1$ (Blue)

spin-independent DM-nucleon scattering process

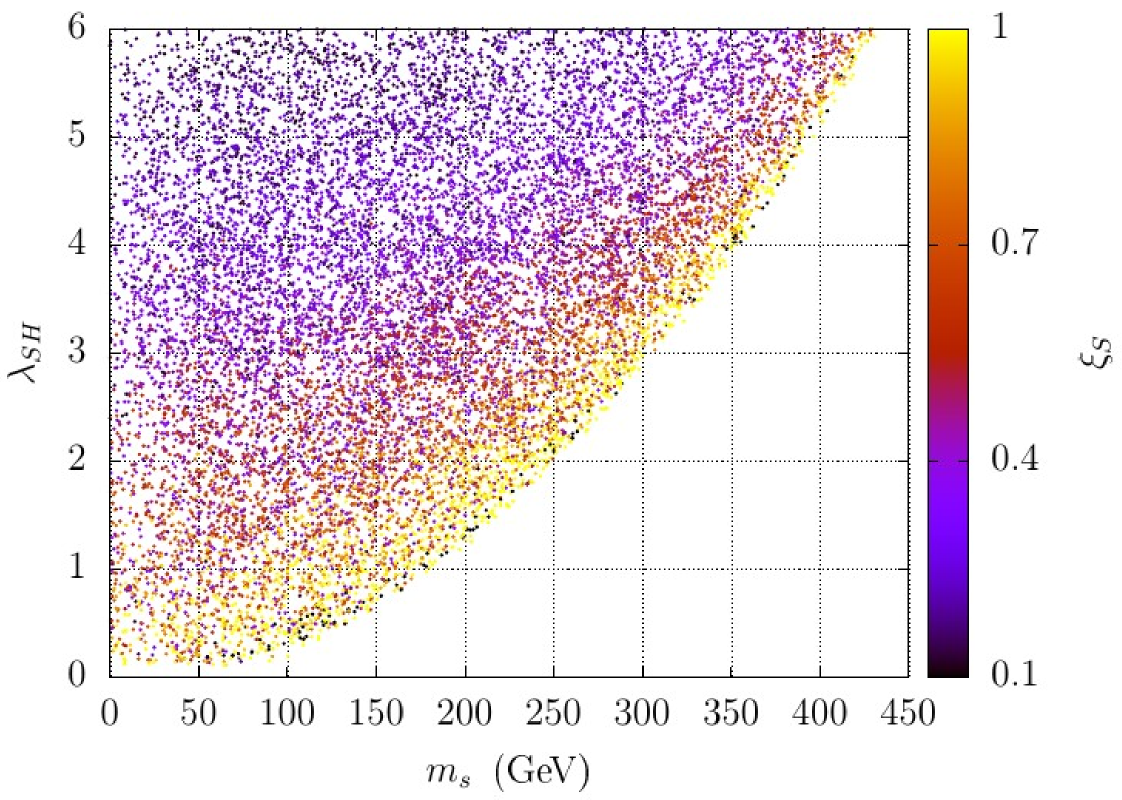


λ_{SM} controls the crosssection

H^0- mediated process is suppressed by v_t and mixing angle

$\lambda_{S\Delta}$ is a free parameter in SI cros-section but, control relic density for $m_S > m_\Delta$

First order Phase transition in the Dark sector



FOEWPT in the dark sector prefers relatively larger quartic couplings (λ_{SH}) and smaller dark matter mass.

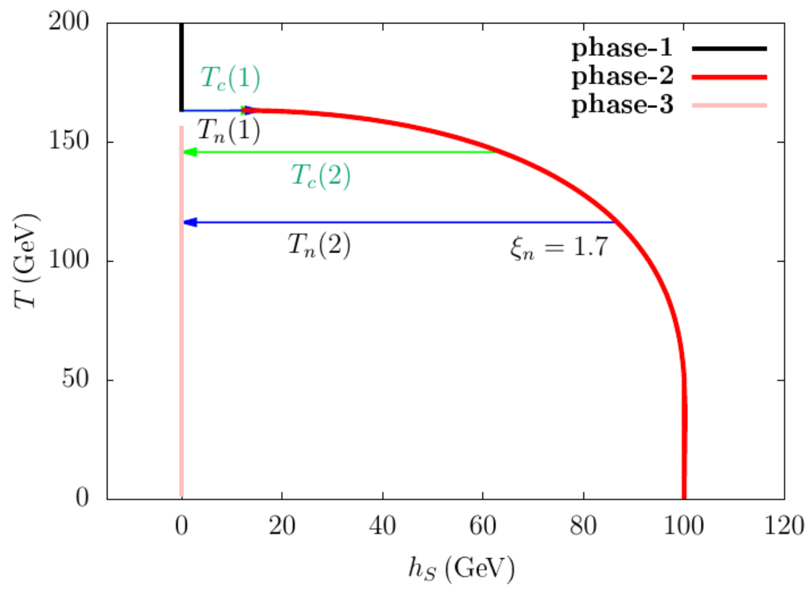
→ Correlation with Spin-independent Dark matter direct detection

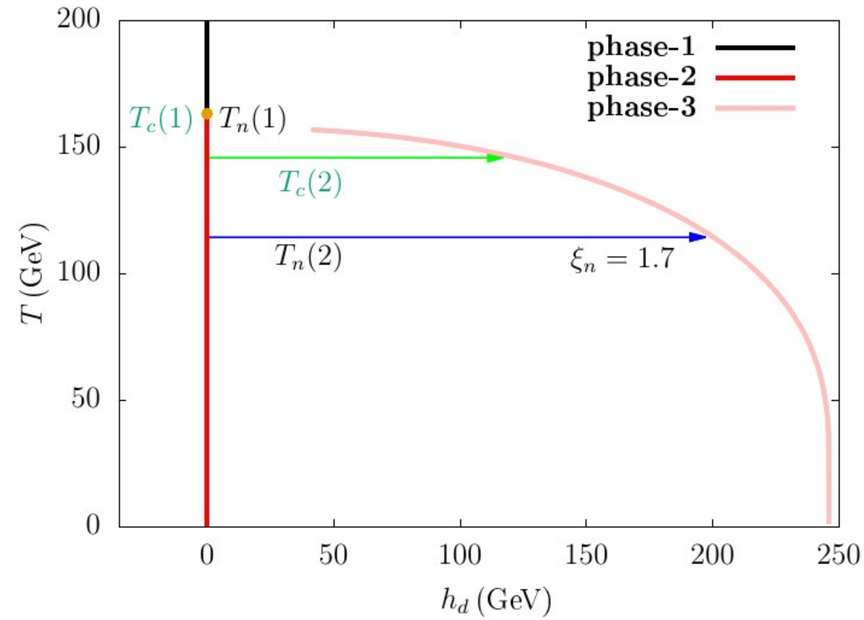
Benchmark scenario

BM No		T_i (GeV)	$\{h_d, h_t, h_s\}_{\rm false}$	$\xrightarrow[\text{type}]{\text{Transition}}$	$\{h_d, h_t, h_s\}_{\rm true}$ (GeV)	$\gamma_{\rm EW}$
BP3	T_c	163.2	{0, 0, 0}	FO	{0, 0, 14.8}	
		145.7	{0, 0, 63.6}	,,	{78.9, 0, 0}	
	T_n	163.1	{0, 0, 0}	,,	{0, 0, 15.1}	
		116.3	{0, 0, 86.7}	,,	{197.3, 0, 0}	1.7

Input/Observables	BP3
λ_1	0.17
λ_4	-0.30
M_Δ	193.2
v_t (GeV)	4.5×10^{-4}
μ_3 (GeV)	-100.8
λ_{SH}	1.2
λ_{ST}	6.9
λ_{ST}	2.17
m_{DM}	252.2
$m_{H^{++}}$ (GeV)	215.3
m_{H^+} (GeV)	204.5
$m_{H^0 \sim A^0}$ (GeV)	193.2
m_h (GeV)	125
$\sin\theta_t$ (GeV)	8.0×10^{-6}
Ωh^2	4.3×10^{-5}
$\xi_{\rm DM}\, \sigma^{\rm SI}_{\rm DD}$ (cm^2)	7.1×10^{-47}
SNR (LISA)	<< 1

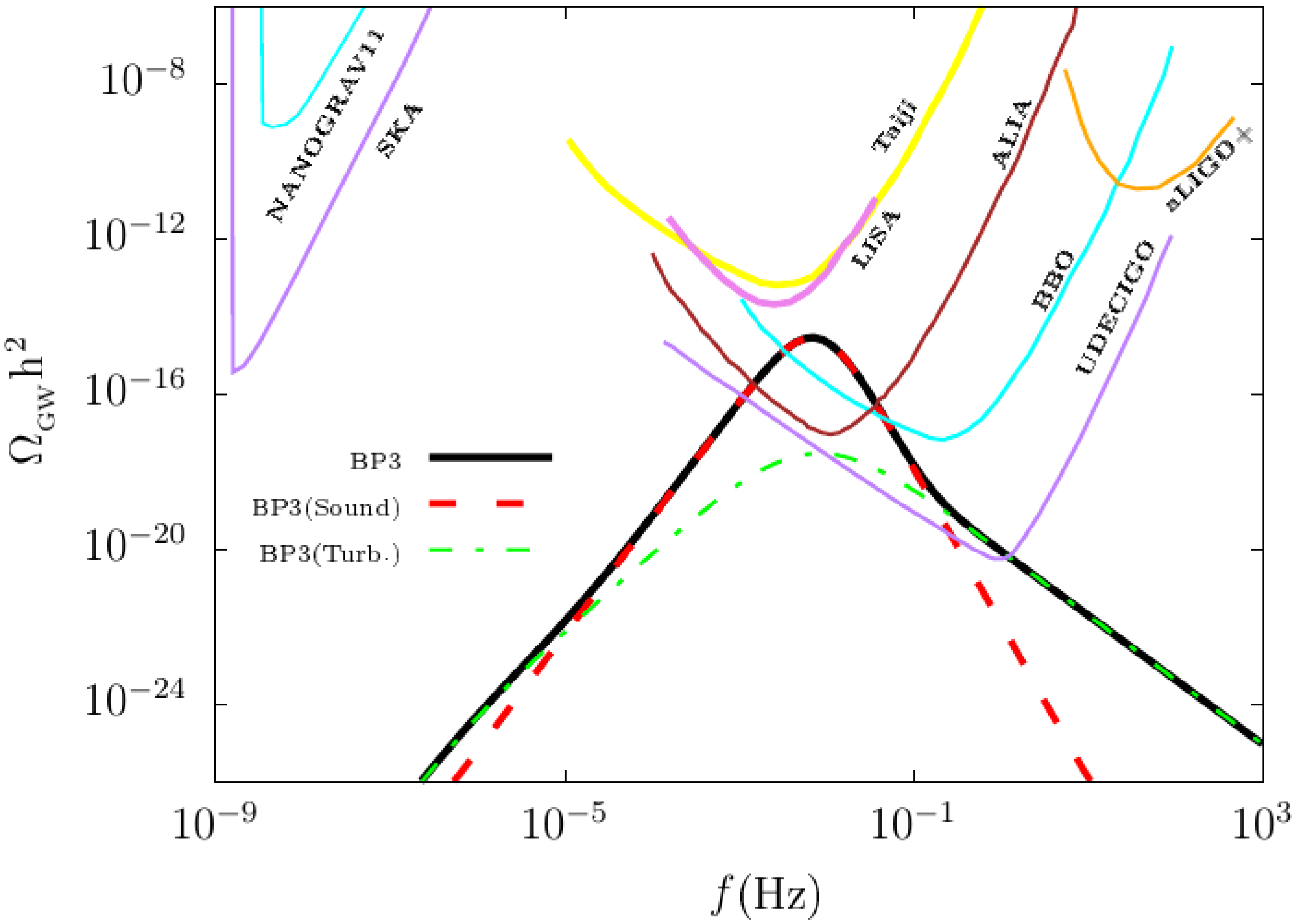
Phase flows with temperature





Benchmark scenario

T_n (GeV)	α	β/H_n
163.1	2.3×10^{-4}	4.8×10^{6}
116.3	0.027	312.7



The peak of GW spectrum lies within the sensitivity of various future proposed GW experiments

Conclusion

Explore DM, LHC physics, and FOPT-produced GW interplay at the electroweak scale.

Point out triplet sector parameter space that can modify the Higgs potential in such a way that it can produce an FOEWPT satisfying constraints coming from the direct heavy Higgs search at the LHC.

However mostly that region is excluded from the the precision measurement of the di-photon decay rate of the observed 125 GeV Higgs boson at the LHC.

Such a correlation limits GW detection in proposed detectors due to FOEWPT in specific parameter space.

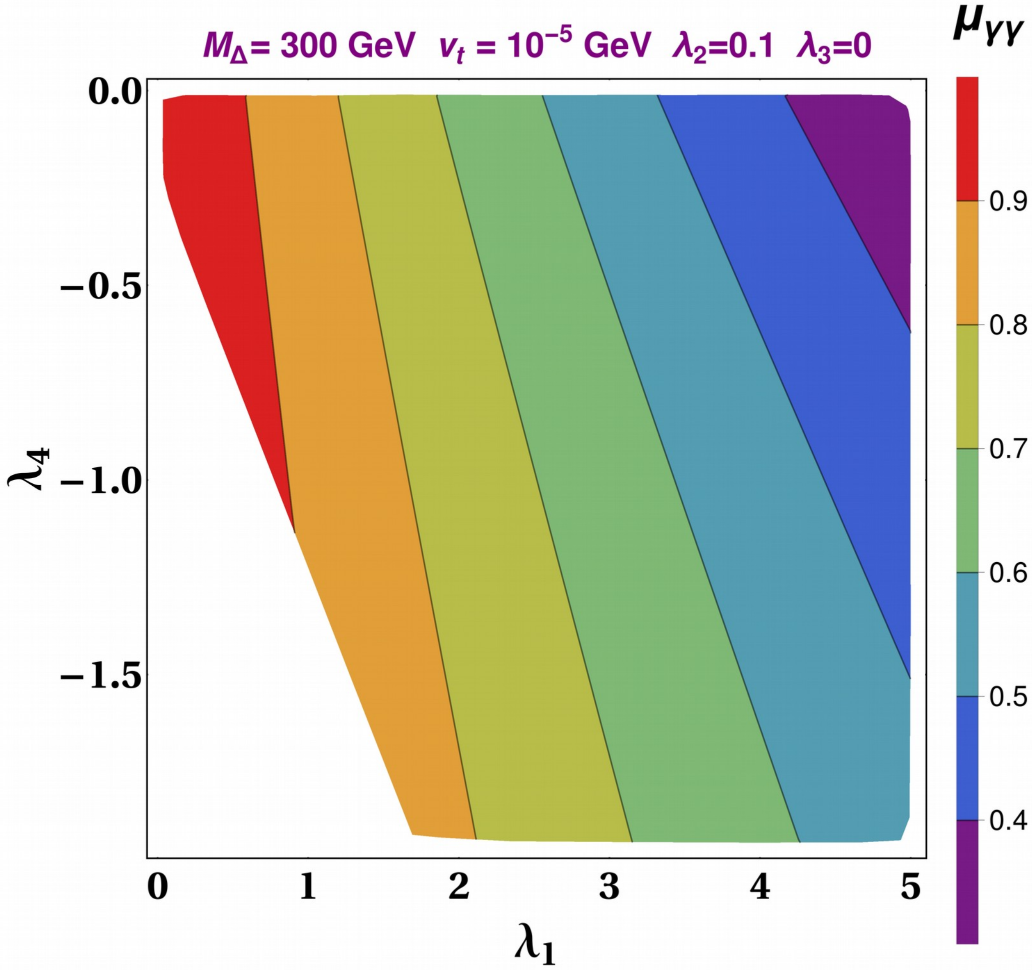
FOPT in the singlet-direction parameter space is either excluded by recent DMDD-SI limits or will be probed in the near future, corresponding to significantly underabundant DM.

The absence of new physics at the HL-LHC and various DMDD experiments in future would severely limit the prospects of detecting GW at future GW experiments from this scenario.

Thank you

Backup slides

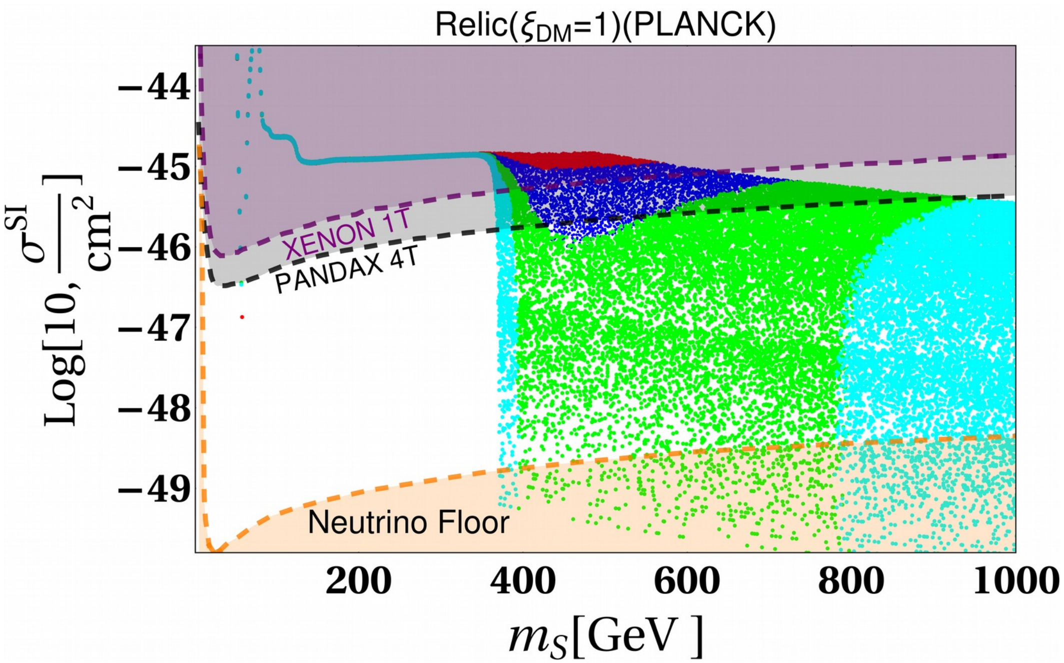
Variation of the signal strength $\mu_{\gamma\gamma}$ in the $\lambda_1 - \lambda_4$ plane

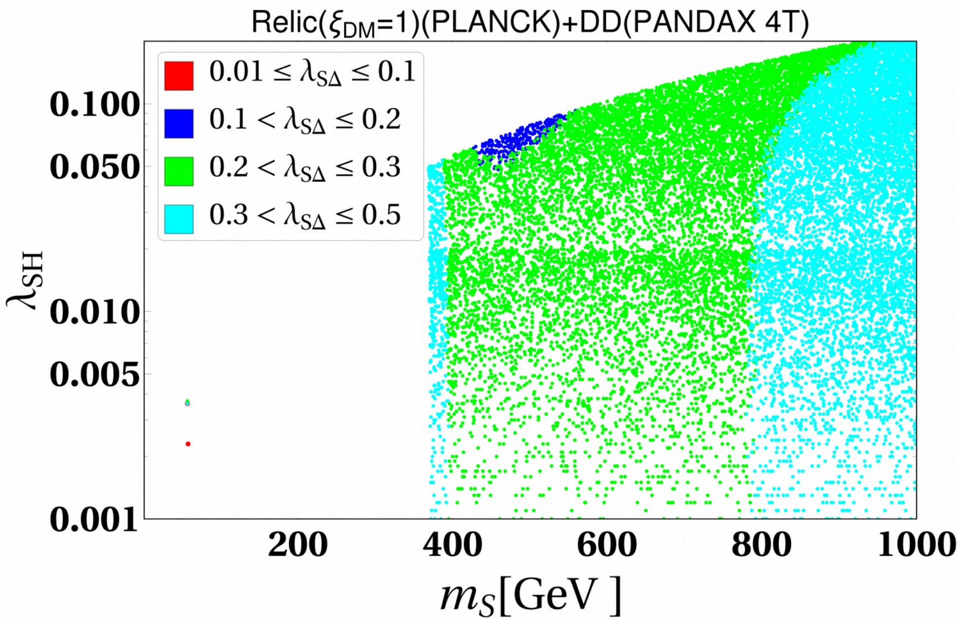


The signal strength parameter of $\mathrm{h}^0 \to \gamma\gamma$ channel is defined as

$$\mu_{\gamma\gamma} = \frac{\Gamma^{\mathrm{N}P}[h^0 \to \gamma\gamma]}{\Gamma^{\mathrm{S}M}[h^0 \to \gamma\gamma]}$$

Spin-independent DM-nucleon scattering cross-section, $\sigma_{\rm DD}^{\rm SI}$, for relic density allowed (PLANCK) parameter space as a function of DM mass (m_S)





Gravitational waves from FOPT

The dynamics of the nucleated bubbles generated from FOPT could generate stochastic background of gravitational waves (GW).

It is caused mainly by three mechanisms namely,

(i) bubble collisions,

(ii) sound waves induced by the bubbles running through the cosmic plasma

(iii) Magnetohydrodynamic turbulence induced by the bubble expansions in the cosmic plasma.

$$\Omega_{\rm GW}h^2 \simeq \Omega_\phi h^2 + \Omega_{\rm sw}h^2 + \Omega_{\rm turb}h^2$$

sourced by
collisions of bubble walls

Kosowsky, et. al., PRL 69 (1992) 2026;
PRD 45 (1992) 4514
Huber, Konstandin, JCAP 0809 (2008) 022

sourced by
plasma sounds waves
(usually the dominent one)

Hindmarsh, et. al., PRL 112 (2014) 041301;
Hindmarsh, Hijazi, JCAP 12 (2019) 062

sourced by
plasma turbulence

Gogoberidze, et. al., PRD 76 (2007) 083002
Caprini, at. al., JCAP 0912 (2009) 024

The contribution of bubble collision may be ignored since long-lasting sound waves during and after the FOPT contribute mostly to the production of gravitational waves, followed by MHD turbulence.

Observables for GW calculation from FOPT

Important quatities:

$$\alpha = \frac{\rho_{\rm vac}}{\rho^*_{\rm rad}} = \frac{1}{\rho^*_{\rm rad}}\left[T\frac{\Delta \dot{V}(T)}{\dot{T}} - \Delta V(T)\right]\Bigg|_{T_n}$$

→ Related to the energy budget of the FOPT

$$\beta = -\frac{dS_3(T)}{dt}\Big|_{t_n} \simeq H_n T_n \frac{d(S_3(T)/T)}{dT}\Big|_{T_n}$$

→ Related to the inverse duration of the transition

v_w → the wall-velocity of the expanding bubble

T_n → Nucleation Temperature

Decay rate $\Gamma(T) \approx T^4 \exp\left(-\frac{S_3(T)}{T}\right)$

O(3) symmetric action

$$S_3(T) = 4\pi \int dr r^2 \left[\frac{1}{2}\left(\frac{d\phi}{dr}\right)^2 + V(\phi, T)\right]$$

For this work, we consider v_w value 1.

Nucleation temperature:

One Higgs bubble per Horizon volume (on average)

$$N(T_n) = \int_{t_c}^{t_n} dt \frac{\Gamma(t)}{H(t)^3} = \int_{T_n}^{T_c} \frac{dT}{T}\frac{\Gamma(T)}{H(T)^4} = 1$$

Linde, Phys. Lett. B**100** (1981) 37; Nucl. Phys. B**216** (1983) 421

GW from sound waves

$$\Omega_{\rm sw}h^2 = 2.65\times10^{-6}\,\Upsilon(\tau_{\rm sw})\left(\frac{\beta}{H_\star}\right)^{-1} v_w \left(\frac{\kappa_v\alpha}{1+\alpha}\right)^2 \left(\frac{g_*}{100}\right)^{-\frac{1}{3}} \left(\frac{f}{f_{\rm sw}}\right)^3 \left[\frac{7}{4+3\left(\frac{f}{f_{\rm sw}}\right)^2}\right]^{\frac{7}{2}}$$

$$f_{\rm sw} = 1.9\times10^{-5}\,{\rm Hz}\left(\frac{1}{v_w}\right)\left(\frac{\beta}{H_\star}\right)\left(\frac{T_n}{100\ {\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$

Peak value

$$\Upsilon(\tau_{\rm sw}) = 1 - \frac{1}{\sqrt{1+2\tau_{\rm sw}H_*}}$$

due to the finite lifetime of the sound waves

$$\kappa_v \simeq \left[\frac{\alpha}{0.73+0.083\sqrt{\alpha}+\alpha}\right]$$

Fraction of energy from the PT converted into the bulk motion of the plasma

Note that, peak frequency proportinal with $\frac{\beta}{H_\star}$ and T_n

Hindmarsh et al., arXiv:2008.09136
Guo et al., JCAP 01 (2021)

GW power spectrum due to sound wave from beyond the bag model

Replace: $\frac{\alpha\kappa_\nu}{\alpha+1} \to \left(\frac{D\bar{\theta}}{4e_s}\right)\kappa_{\bar{\theta}}$

Giese, Konstandin and van de Vis, JCAP 07 (2020)

GW from MHD turbulence

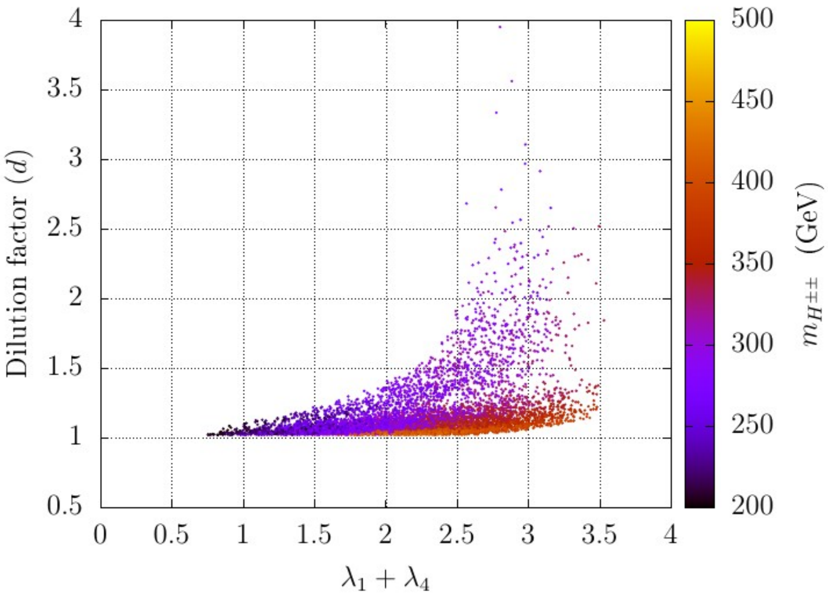
$$\Omega_{\rm turb}h^2 = 3.35\times10^{-4}\left(\frac{\beta}{H_*}\right)^{-1}\left(\frac{\kappa_{\rm turb}\alpha}{1+\alpha}\right)^{\frac{3}{2}}\left(\frac{100}{g_*}\right)^{\frac{1}{3}} v_w \frac{(f/f_{\rm turb})^3}{[1+(f/f_{\rm turb})]^{\frac{11}{3}}(1+8\pi f/h_*)}$$

$$f_{\rm turb} = 2.7\times10^{-5}\,{\rm Hz}\,\frac{1}{v_w}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\ {\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$

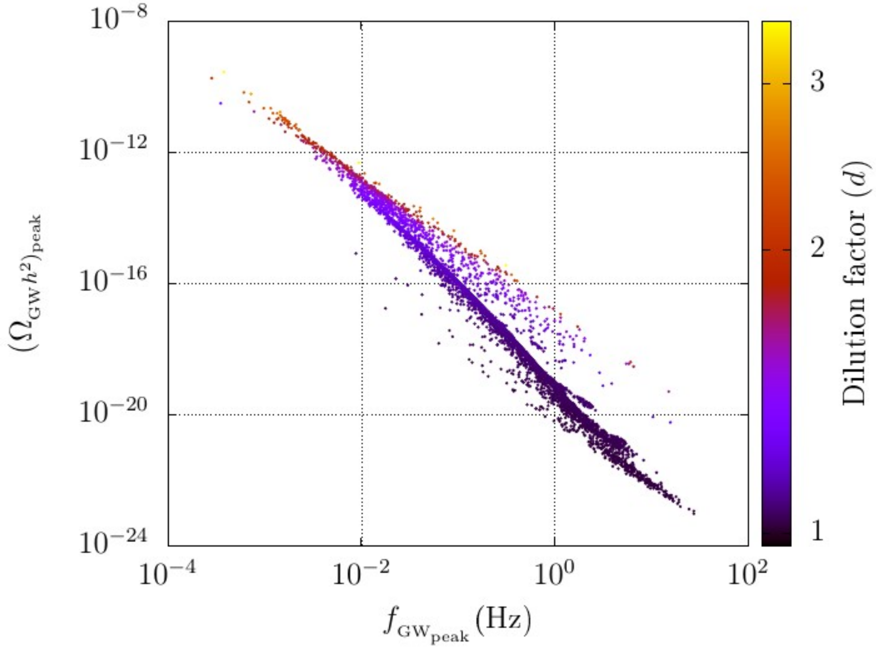
SNR

$$= \sqrt{\delta\times\mathcal{T}\int_{f_{min}}^{f_{max}} df\left[\frac{h^2\Omega_{\rm GW}(f)}{h^2\Omega_{\rm exp}(f)}\right]^2}$$

Dilusion of DM relic abundance



Correlation between Dilusion factor and gravitational waves intensity



arxiv:2212.11230