Leptophilic Dark Matter from Gauged Lepton Number

Phenomenology and Gravitational Wave Signatures

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Gauged Lepton Number

SM + RH ν + $U(1)_\ell$ gauge group — Schwaller, Tait, Vega-Morales (2013)

- $U(1)_\ell$ gauge boson $Z' \rightsquigarrow Z - Z'$ mixing
- anomaly cancellation: two generations of SM vector-like fermions $\rightsquigarrow$ 4 additional fermions: e_4^-, e_5^-, ν_4, ν_{DM}
- L spontaneously broken by scalar ϕ with $L_\phi = 3$ $\rightsquigarrow h - \phi$ mixing, $m_{Z'} \simeq 3 g_L v_\phi$

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LEP II:

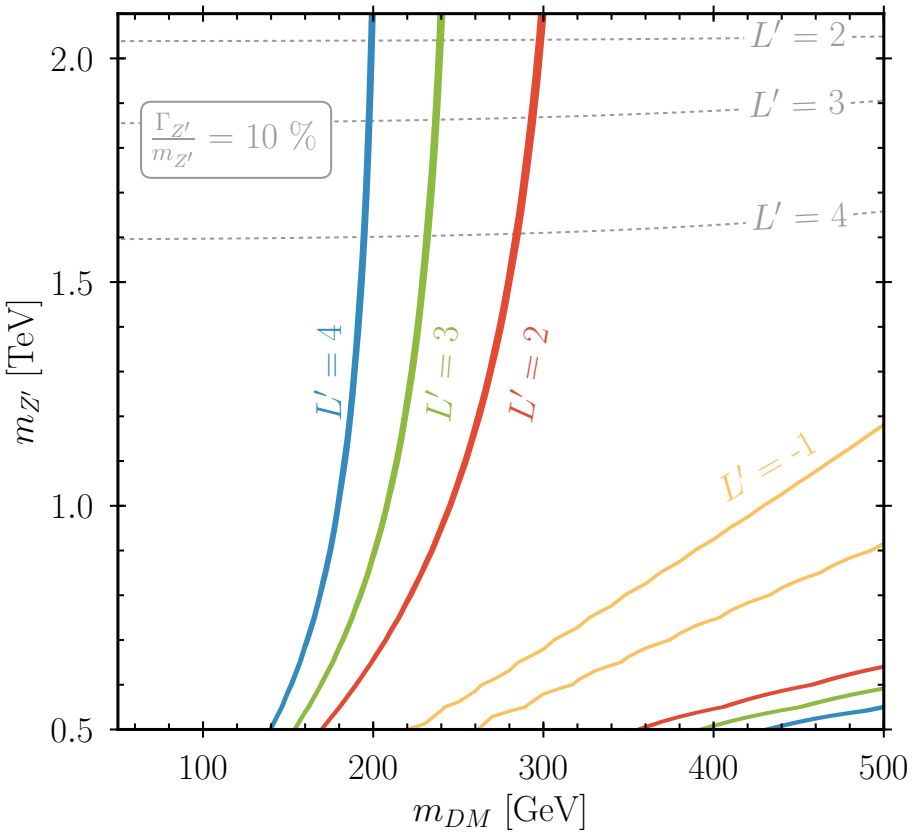
$v_\phi > 1700$ GeV, $m_{Z'} > 209$ GeV

LHC:

- Higgs searches
- signal strengths: Higgs mixing, $h \to \gamma\gamma$

Dark Matter

DM candidate: mostly SM singlet, chiral couplings to Z'



relic density: $h^2\Omega_{\mathrm{DM}} = 0.1198 \pm 0.0015$

Dark Matter

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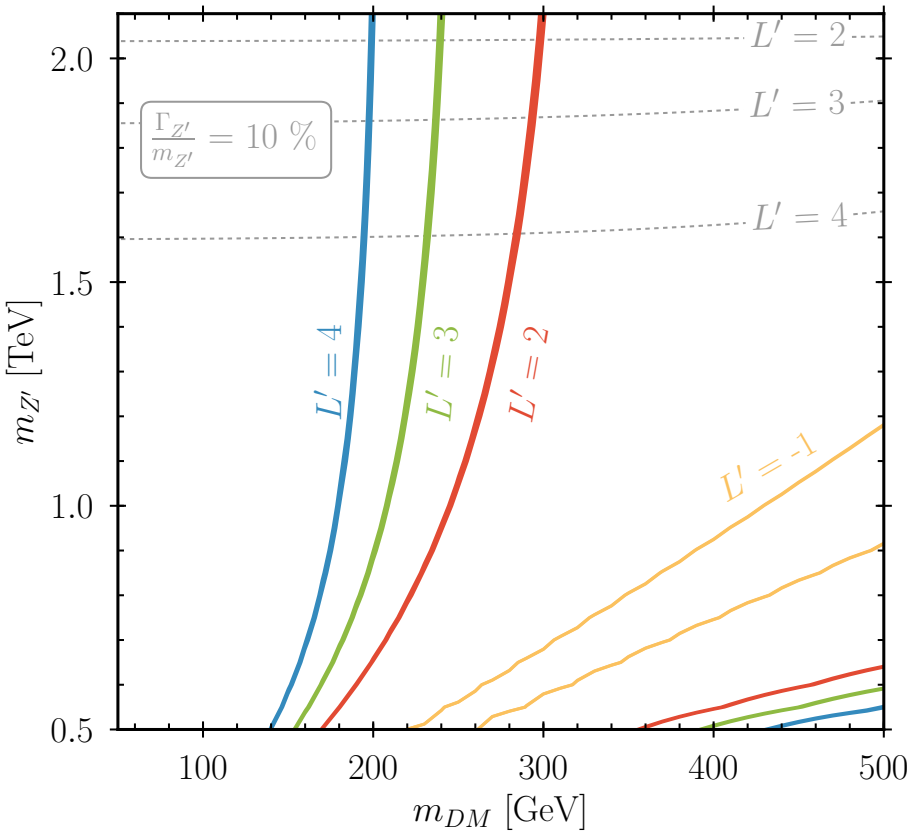
direct detection: $\sin(\theta_{\mathrm{DM}}) \lesssim 0.02$, $\sin(\xi) \lesssim 10^{-4}$, $\sin(\theta_H) \lesssim 0.25$



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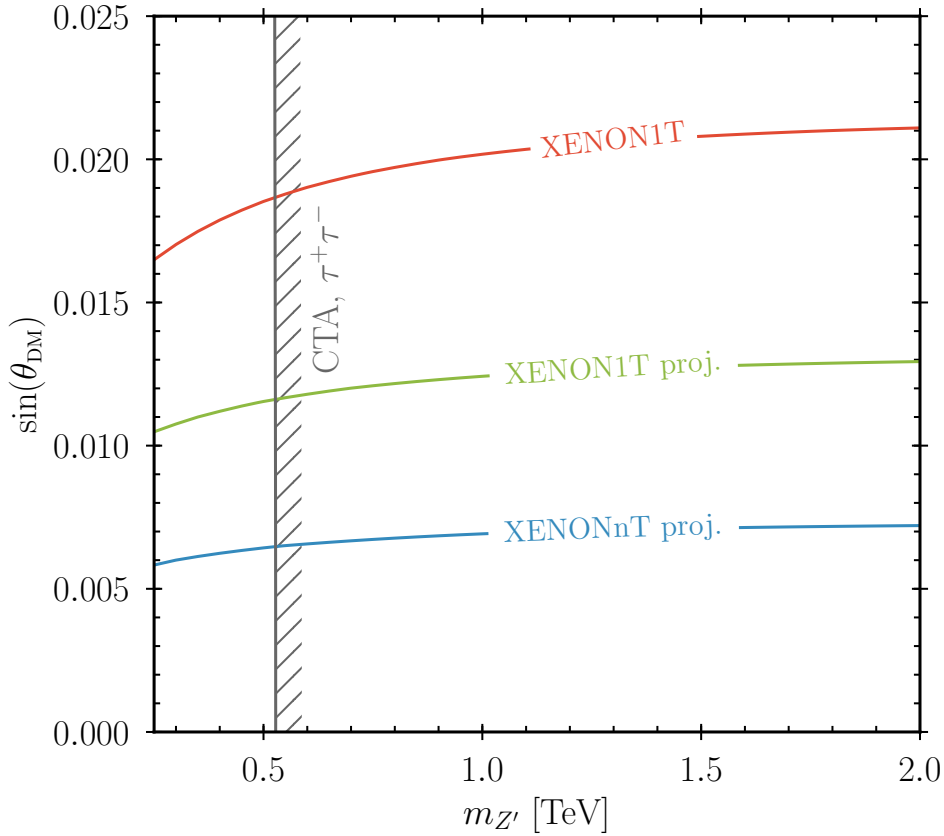

direct and indirect detection constraints ($L' = 2$)

Effective Potential and Phase Transitions

effective Potential:

$$V_{\text{eff}}(\hat{h}, \hat{\phi}, T) = V_{\text{tree}}(\hat{h}, \hat{\phi}) + V_{\text{loop}}(\hat{h}, \hat{\phi}) + V_{\text{thermal}}(\hat{h}, \hat{\phi}, T)$$

finite-T corrections restore symmetry at high T

$\Longrightarrow$ symmetry breaking phase transition in the early universe

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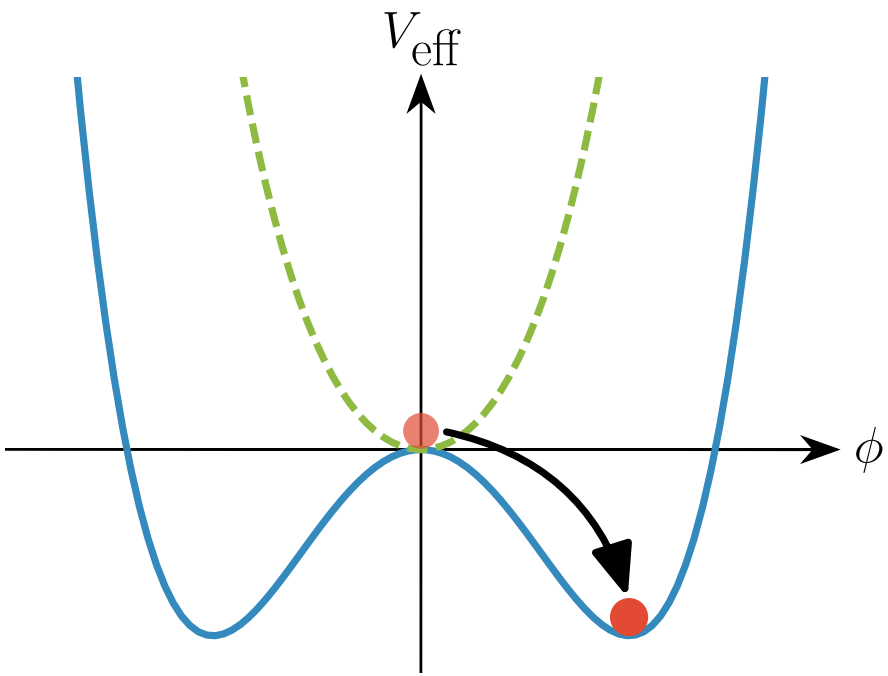
cross-over:



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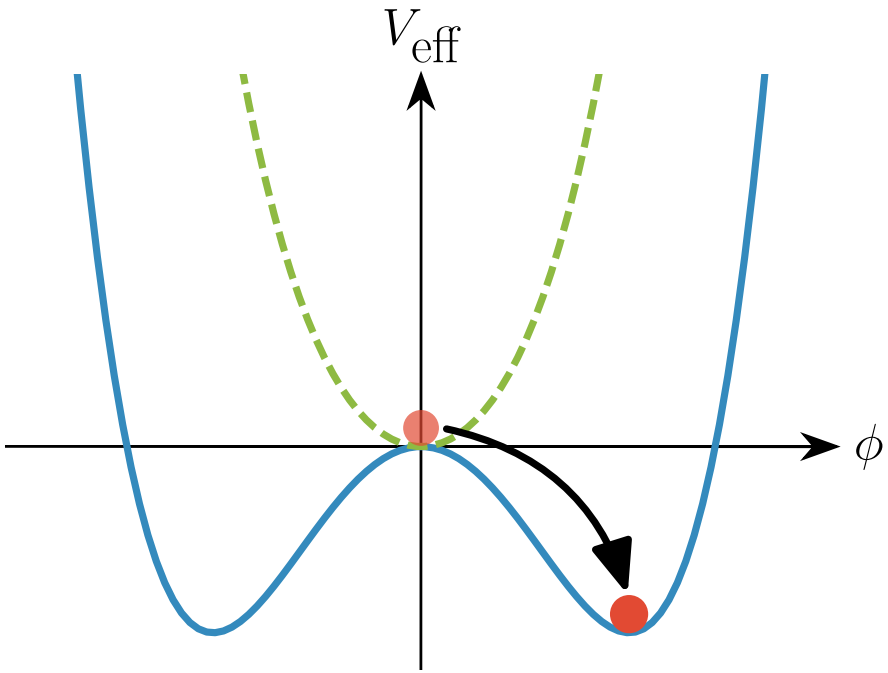
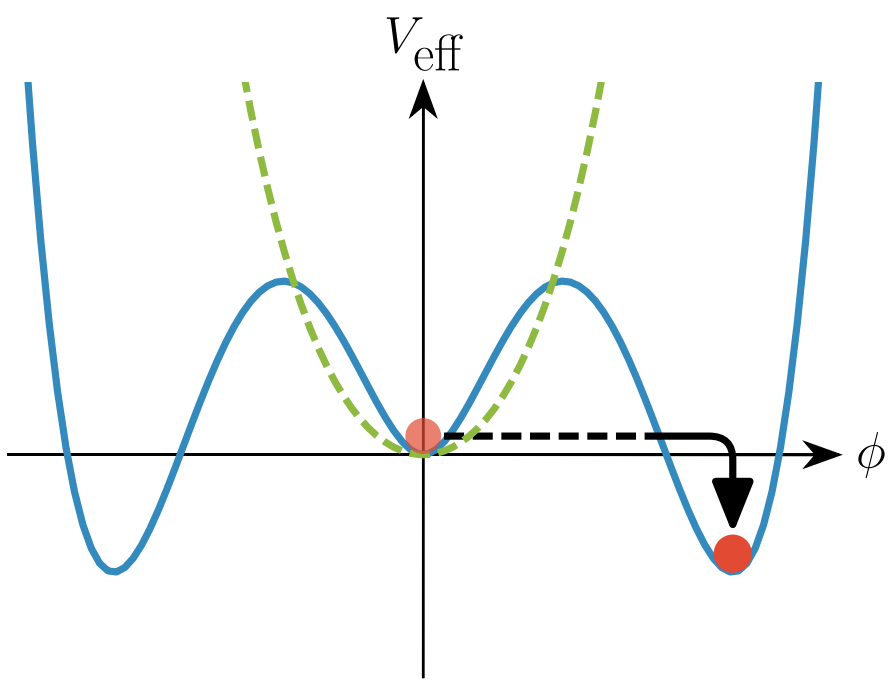
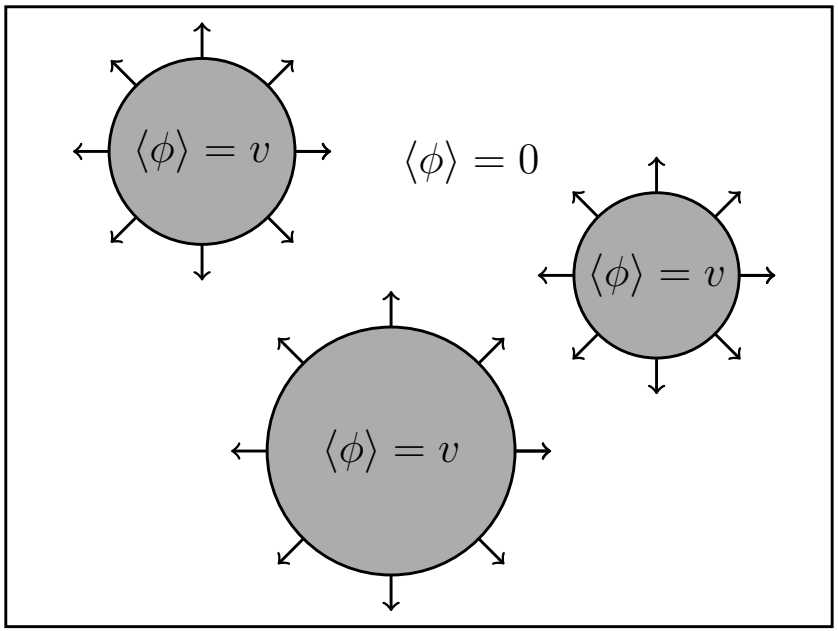


1st-order:



1st-Order Phase Transition

- high- and low-T minima separated by barrier
  $\Longrightarrow$ 1st-order PT via tunneling
  $\Longrightarrow$ bubble nucleation



1st-Order Phase Transition

- high- and low-T minima separated by barrier
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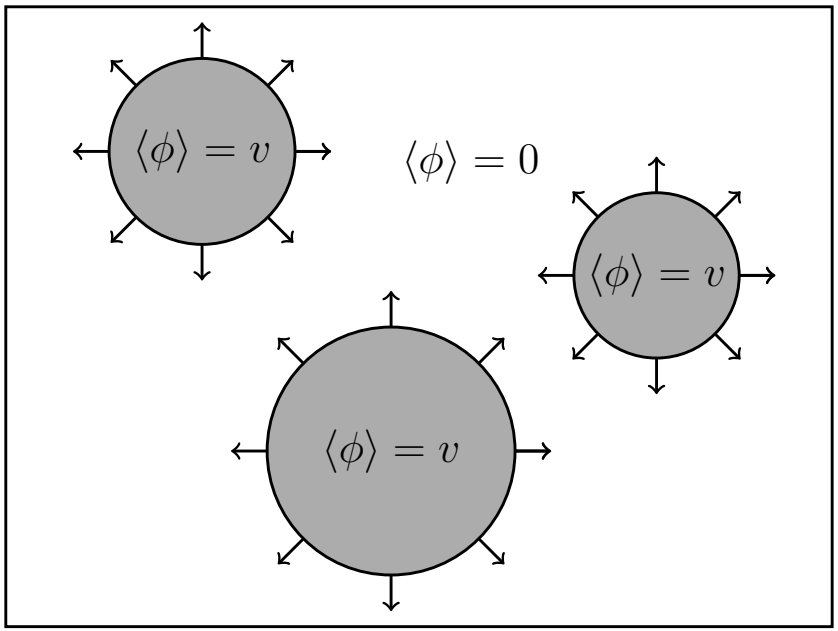
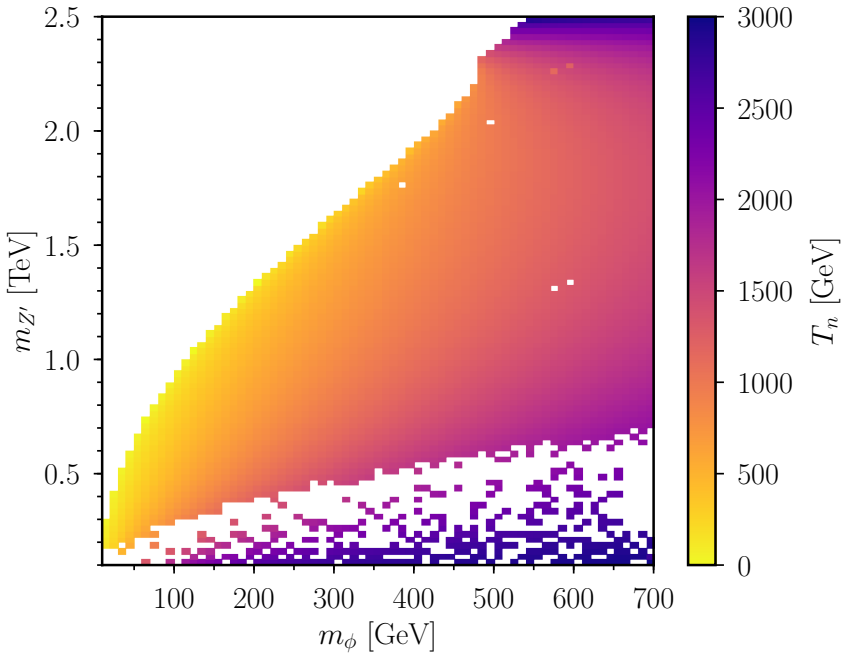
- nucleation rate:
  $\Gamma(T) \propto e^{-S_E(T)}$ $\qquad S_E(T) = \dfrac{1}{T}\int d^3x \left[\dfrac{1}{2}(\nabla\phi)^2 + V_{\text{eff}}(\phi, T)\right]$
- nucleation temperature (T_n): $\Gamma \sim H$

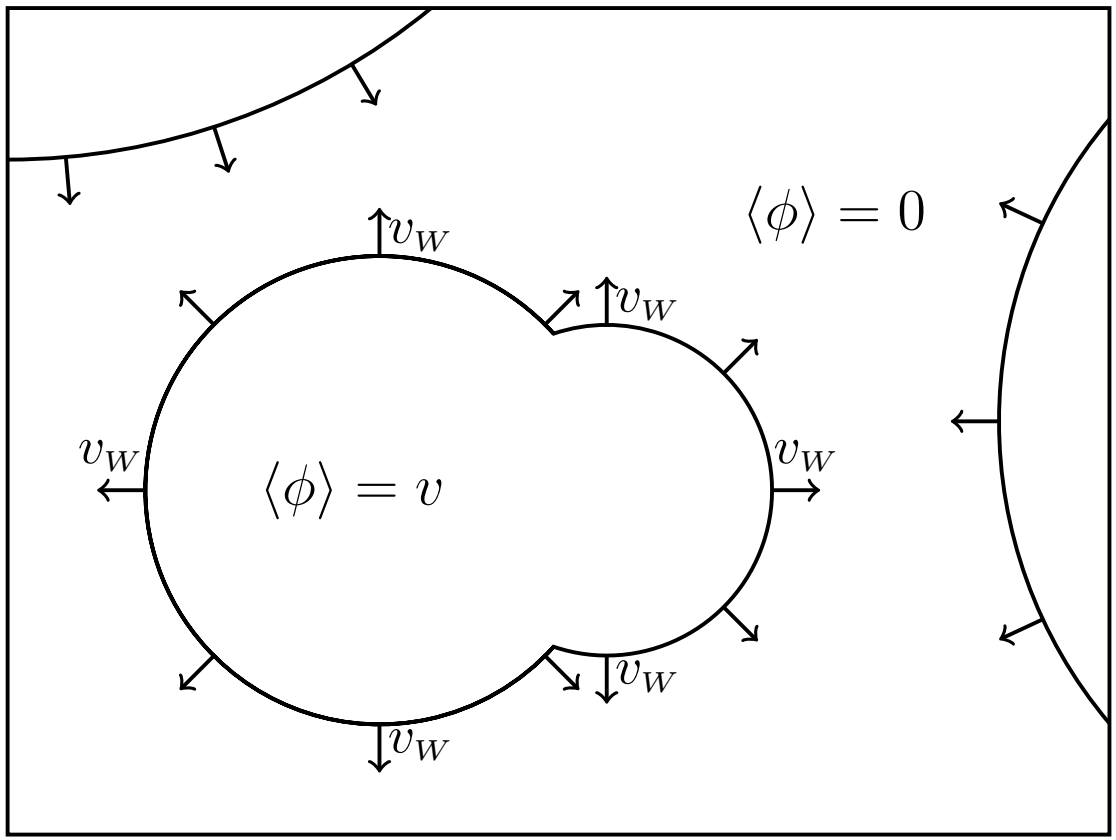




Gravitational Waves

GW spectrum: $h^2\Omega_{\mathsf{GW}} \simeq h^2\Omega_\phi + h^2\Omega_{\mathsf{sw}} + h^2\Omega_{\mathsf{turb}}$

- $h^2\Omega_\phi$: collision of bubble walls



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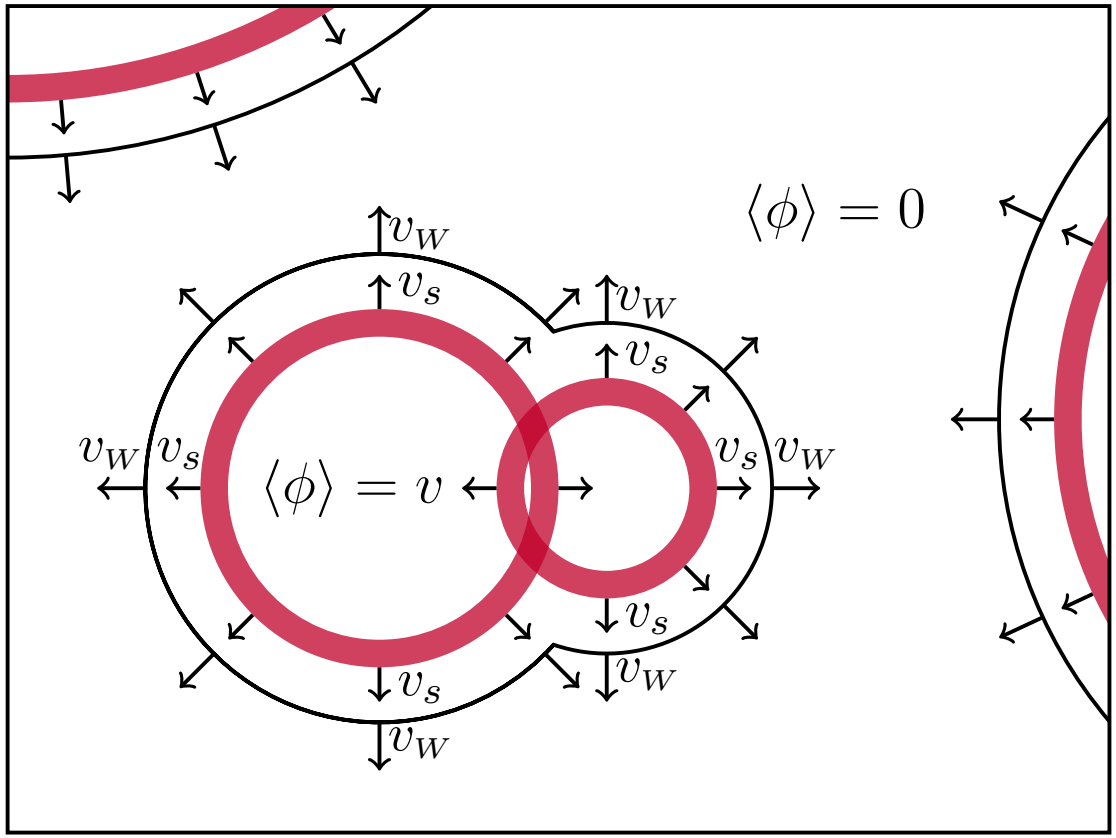

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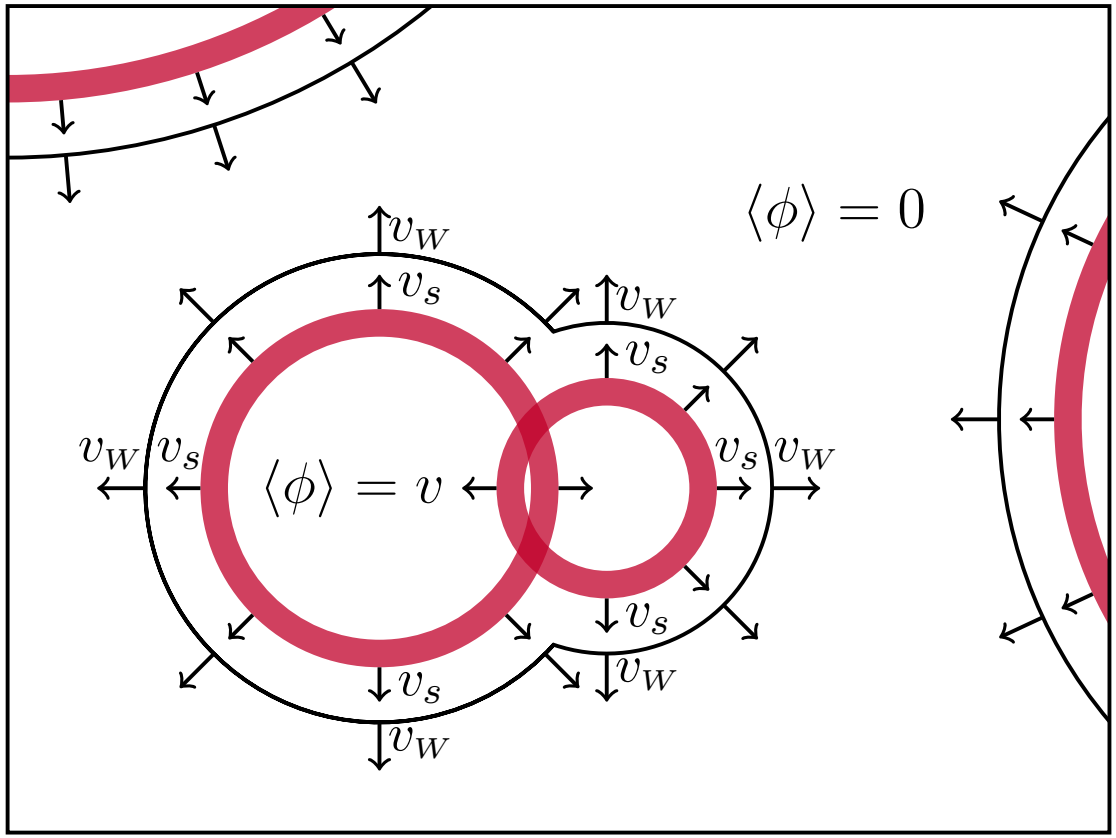
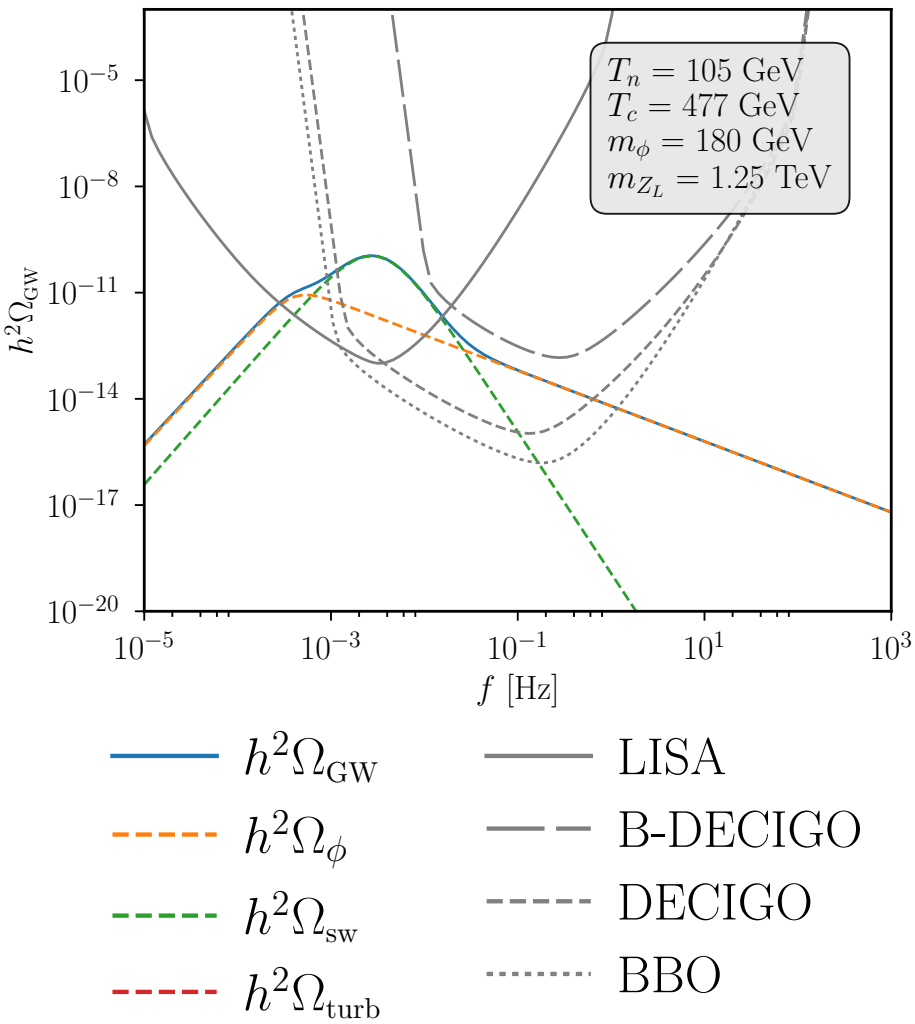
- $h^2\Omega_{\mathsf{sw}}$: sound waves in the plasma
- $h^2\Omega_{\mathsf{turb}}$: turbulence, vortical fluid motion



Detectability



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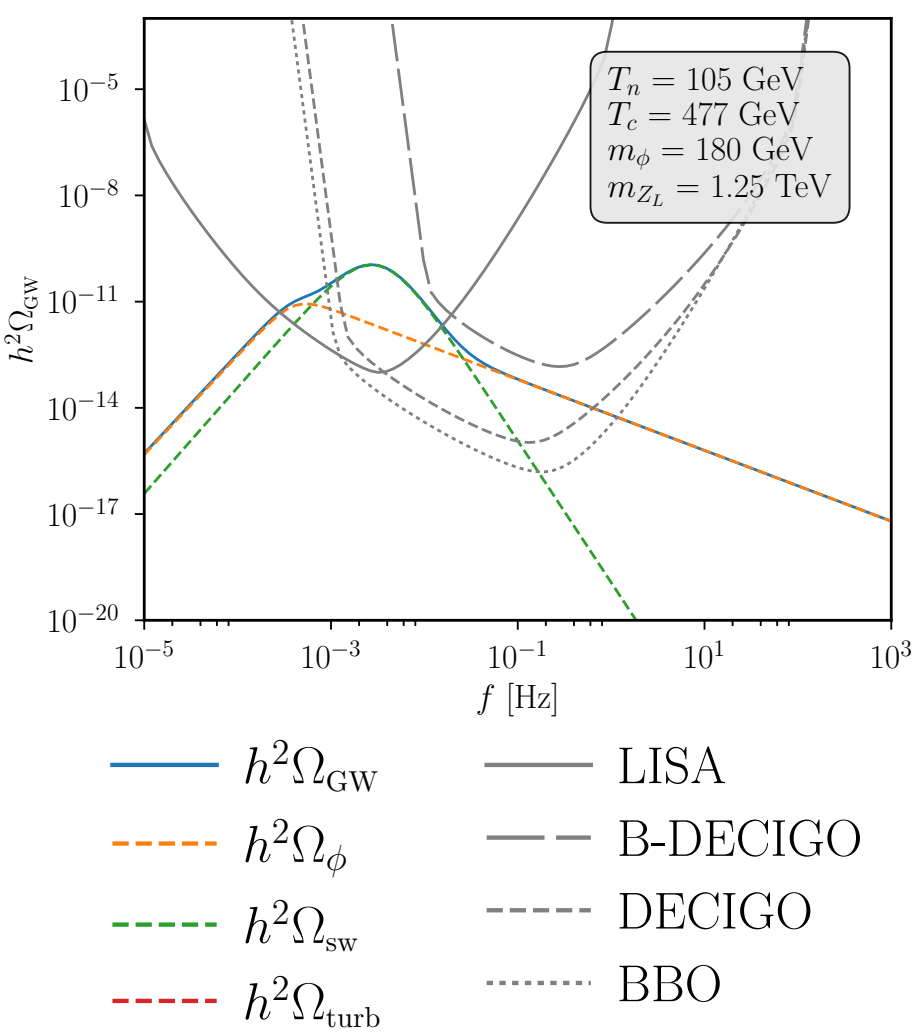

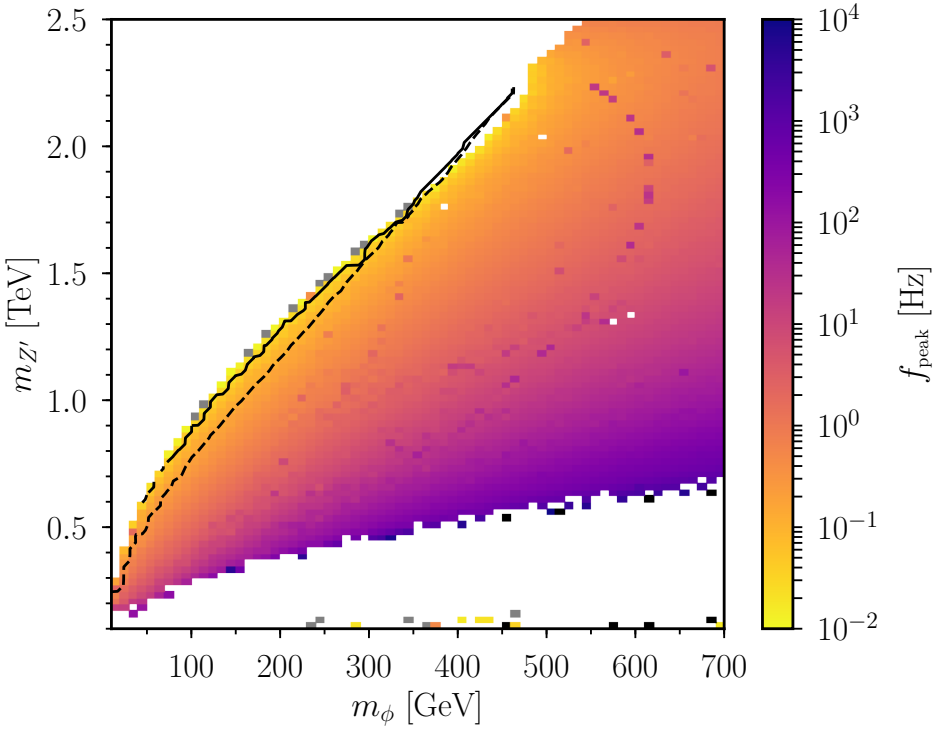

Conclusion

- SM + $U(1)_\ell$ + SM vector-like fermions provide DM candidate
- direct detection constrain Higgs, DM, and $Z - Z'$ mixing angles
- LEP II: $v_\phi > 1700$ GeV, $m_{Z'} > 209$ GeV
- LHC: indirect constraints from Higgs measurements
- L breaking PT can be 1st order
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Future Directions:

- modification of EW phase transition $\longrightarrow$ 1st order
- LHC: Z' searches, search for e_4/e_5 (disappearing tracks?)

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Thank you for your attention!

Heavy Leptons

$$\ell'_L = \begin{pmatrix} N'_L \\ E'_L \end{pmatrix} \sim \left(2, -\frac{1}{2}, L'\right) \qquad \ell''_R = \begin{pmatrix} N''_R \\ E''_R \end{pmatrix} \sim \left(2, -\frac{1}{2}, L''\right)$$

$$\nu'_R \sim (1, 0, L') \qquad \nu''_L \sim (1, 0, L'')$$

$$e'_R \sim (1, -1, L') \qquad e''_L \sim (1, -1, L'')$$

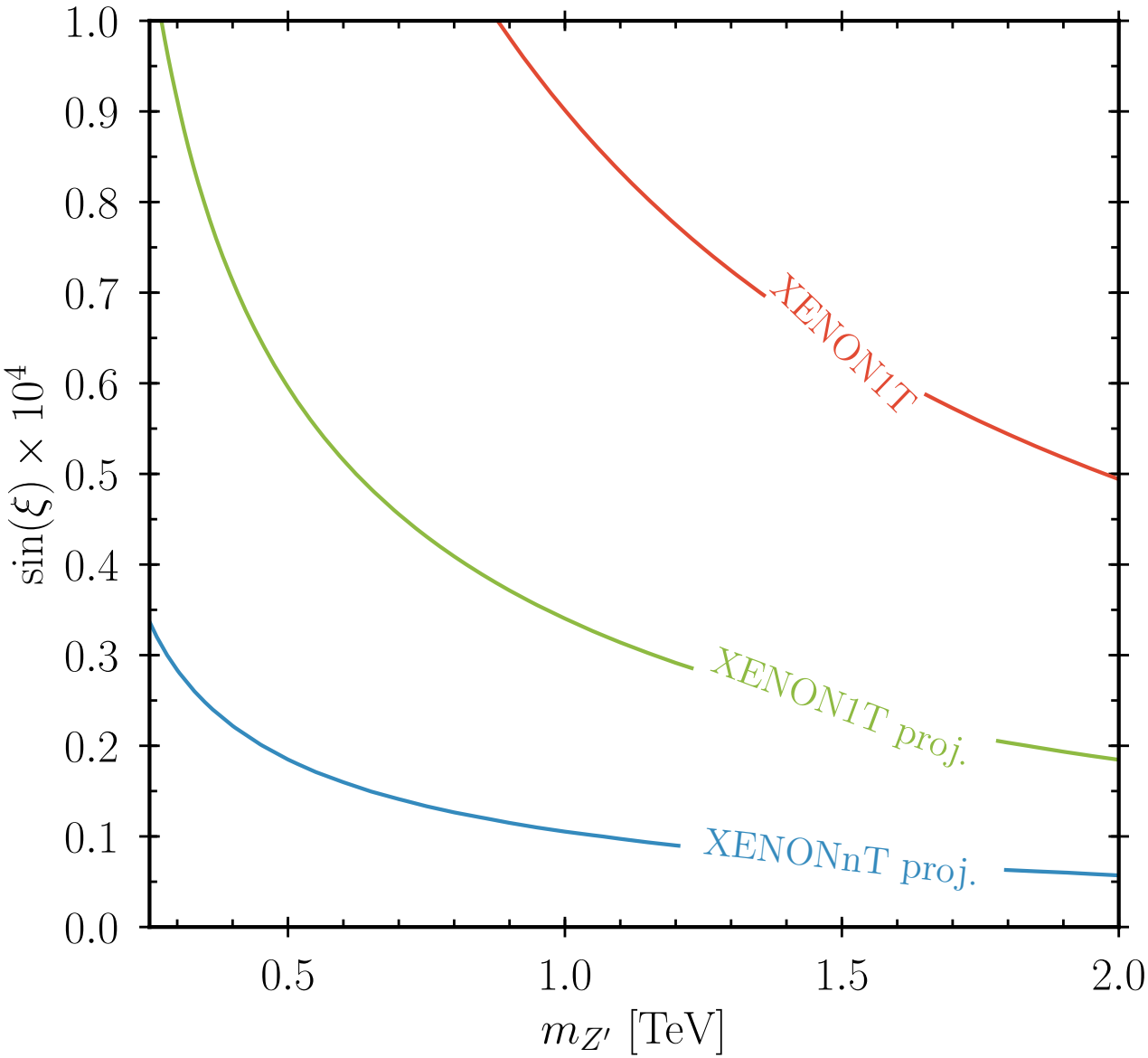
$$\begin{aligned} \mathcal{L} \supset & - c_\ell\, \bar{\ell}''_R \Phi \ell'_L - c_\ell\, \bar{e}''_L \Phi e'_R - c_\nu\, \bar{\nu}''_L \Phi \nu'_L \\ & - y_e \left(\bar{\ell}'_L H e'_R + \bar{\ell}''_R H e''_L\right) - y_\nu \left(\bar{\ell}'_L \tilde{H} \nu'_R + \bar{\ell}''_R \tilde{H} \nu''_L\right) + \text{h.c.} \end{aligned}$$

mass eigenstates:

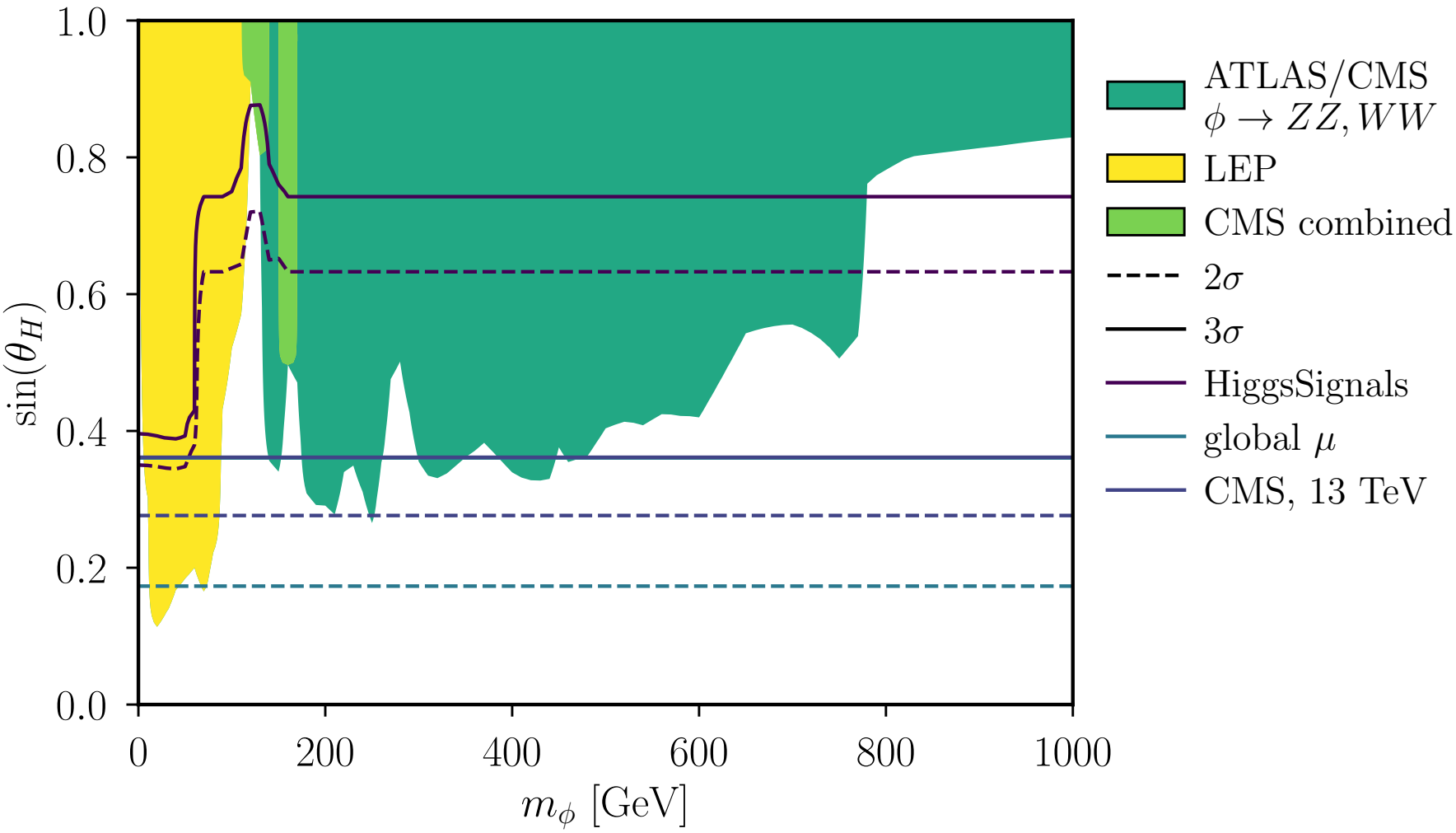
$$\begin{pmatrix} \nu_4 \\ \nu_{\text{DM}} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\text{DM}} & \sin\theta_{\text{DM}} \\ -\sin\theta_{\text{DM}} & \cos\theta_{\text{DM}} \end{pmatrix} \begin{pmatrix} N'_L + N''_R \\ \nu''_L + \nu'_R \end{pmatrix}$$

$$\begin{pmatrix} e_4 \\ e_5 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix} \begin{pmatrix} E'_L + E''_R \\ e''_L + e'_R \end{pmatrix}$$

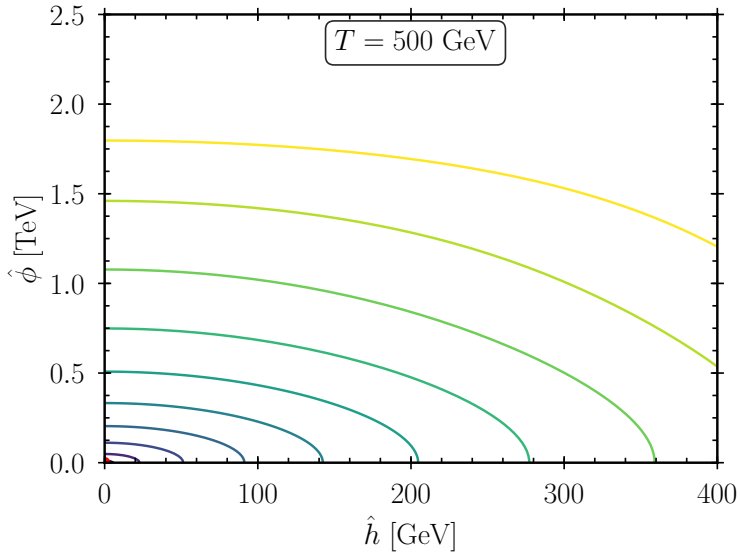
Direct Detection Limits on $Z - Z'$ Mixing

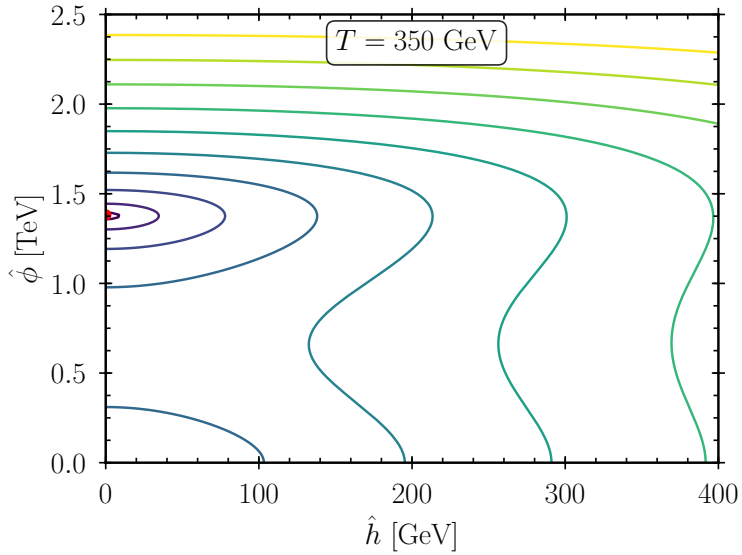


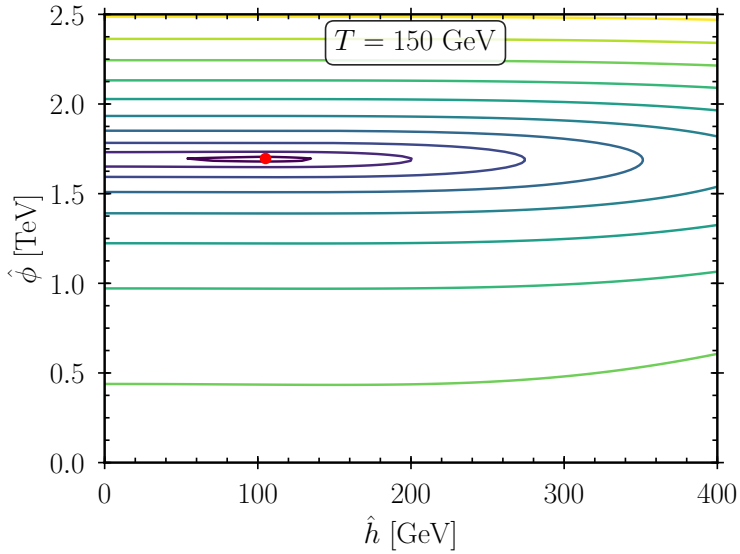
Collider Constraints on Scalar Sector

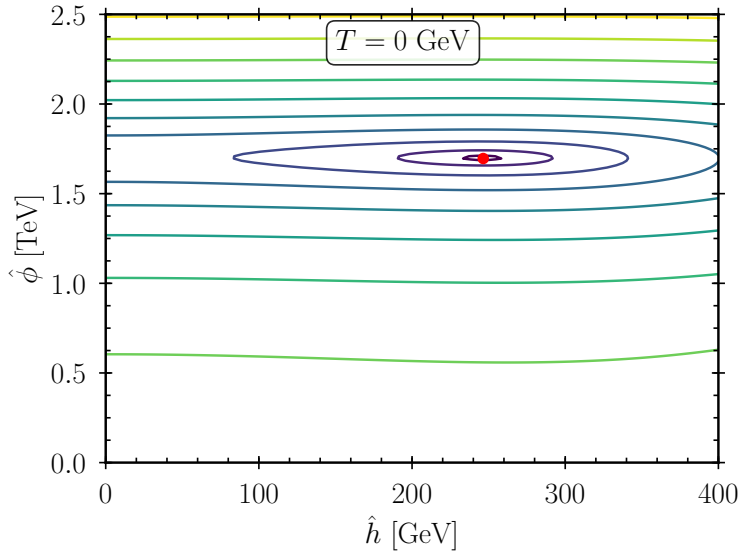


Effective Potential









$$v_\phi = 1.7\,\text{TeV},\ m_\phi = 150\,\text{GeV},\ m_{Z'} = 1\,\text{TeV},\ \sin\theta_H = 0.05$$
$$m_{\text{DM}} = 240\,\text{GeV},\ m_{e_4} = 400\,\text{GeV},\ m_{e_5} = 380\,\text{GeV},\ \sin\theta_{\text{DM}} = 10^{-3}$$

Gravitational Wave Sensitivity

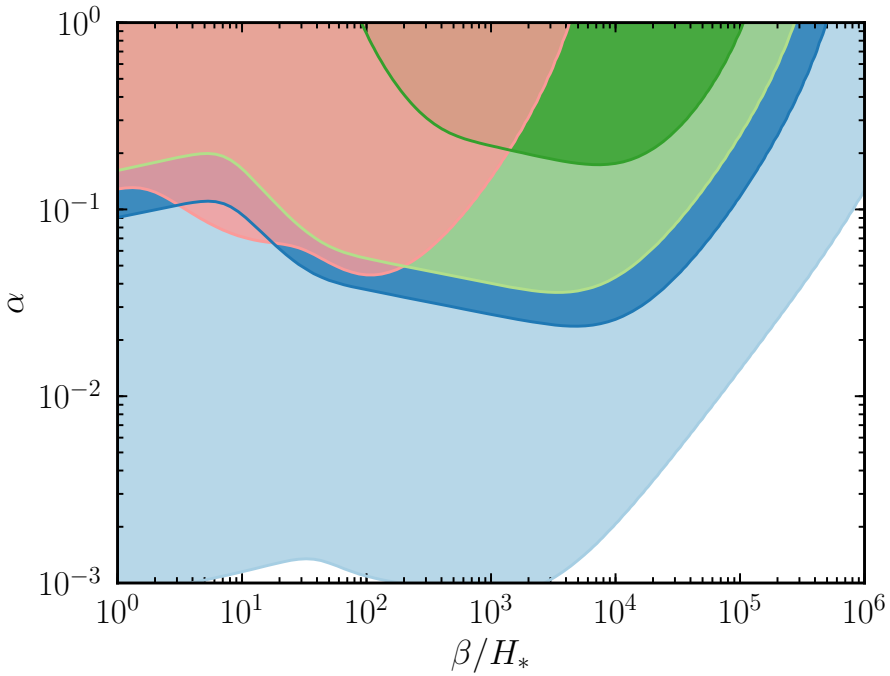
PT strength:

$$\alpha = \frac{\epsilon}{\rho_{\text{rad}}} \simeq \frac{\epsilon}{\pi^2/30\ g(T_*)\,T_*^4}$$

inverse PT duration:

$$\frac{\beta}{H_*} = T_* \left.\frac{d\,S_E(T)}{dT}\right|_{T_*}$$

$T_* = 100$ GeV



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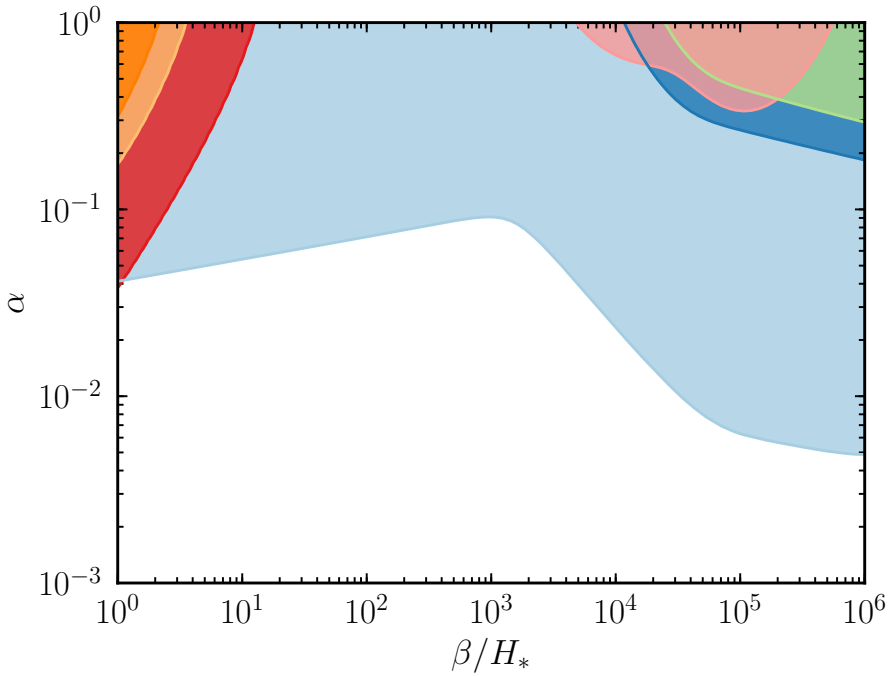

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