Karlsruhe Institute of Technology

Institute for Theoretical Particle Physics

Predicting dark matter and gravitational waves signals from a dark Higgs mechanism

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Based on work in preparation with: Torsten Bringmann, Tomás Gonzalo, Felix Kahlhöfer, Carlo Tasillo

27. September 2023

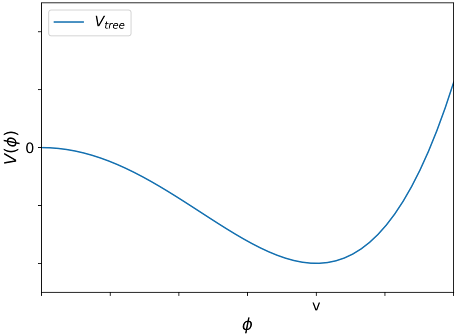
Motivation
Decoupled dark sector

- Consider a dark sector which does not (or only very feebly) interact with the SM
- *Dark matter nightmare scenario*
  $\rightarrow$ no testable laboratory predictions
- However, a first-order phase transition could give an observable GW background
- What kind of signal could this give?

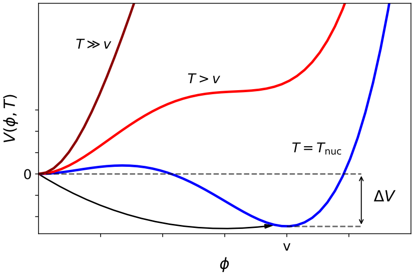
Dark matter model

$$\mathcal{L} = |D_\mu \Phi|^2 - \frac{1}{4} A'^2_{\mu\nu} + \mu^2 |\Phi|^2 - \frac{\lambda}{4} |\Phi|^4 + i\chi_L \not{D} \chi_L + i\chi_R \not{D} \chi_R - y\Phi \chi_L^\dagger \chi_R + \mathrm{h.c.}$$

- Minimal dark sector with:
  - Scalar field Φ: Dark Higgs
  - U(1) symmetry with gauge boson A'_μ
  - Fermionic DM candidate χ
- Model requirements:
  1. create a strong GW signal
  2. obtain correct relic abundance of DM



First-order phase transition



- Radiative corrections to $\langle\phi\rangle$ summarised in V_{eff}
- Symmetry restoration at high T
- Tunneling of background field through pot. barrier

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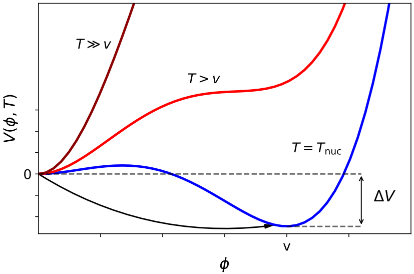
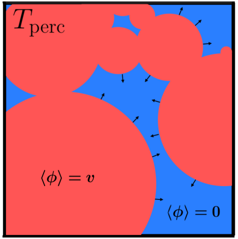


- Radiative corrections to $\langle\phi\rangle$ summarised in $V_{\rm eff}$
- Symmetry restoration at high T
- Tunneling of background field through pot. barrier

- Bubble nucleation, expansion and collision
- Production of gravitational waves



Dark Higgs mechanism

- Field expansion around vev: $\Phi = (\phi + v)e^{i\varphi/F}/\sqrt{2}$

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)(\partial^\mu \phi) - \frac{1}{2}m_\phi^2(v)\phi^2 - \frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{1}{2}m_A^2(v)A'_\mu A'^\mu + g^2 v A'_\mu A'^\mu \phi + \frac{g^2}{2}\phi^2 A'_\mu A'^\mu$$
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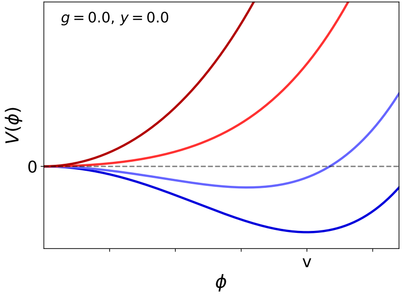

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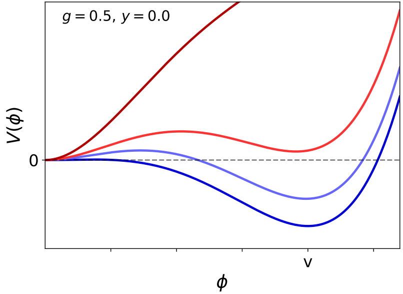

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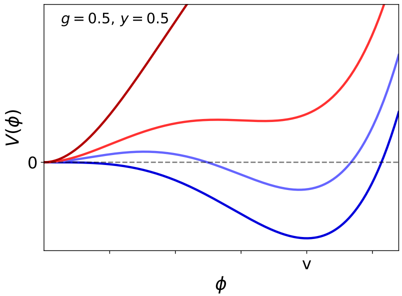

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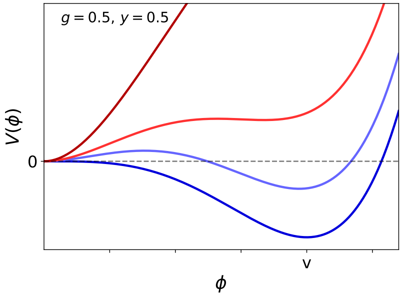
- Model parameters: Couplings λ, g, y, energy scale determined by v
- Large potential barrier: strong PT
  $\Rightarrow$ Require sizable couplings: $\lambda^2, g \sim 0.1$



GW Spectrum

- Fit signal to numerical simulations

$$\Omega_{\mathrm{signal}}(f) = \Omega_{\mathrm{tot}}(\alpha, \beta/H, T_{\mathrm{perc}}, v_{\mathrm{w}}) S(f/f_{\mathrm{peak}})$$

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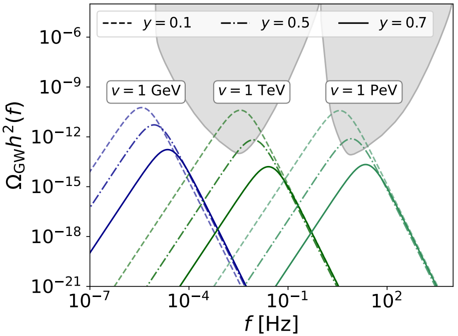
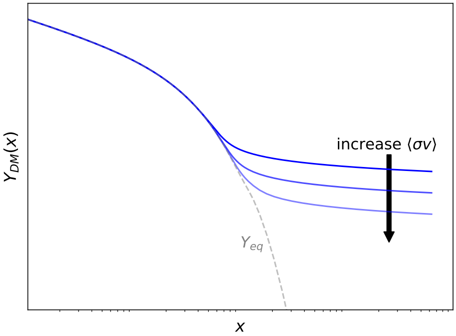


Freeze-out production of DM

- Produce relic abundance via freeze-out mechanism



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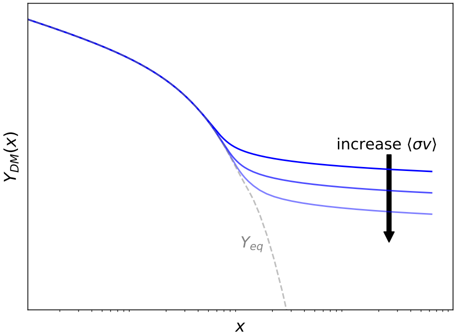

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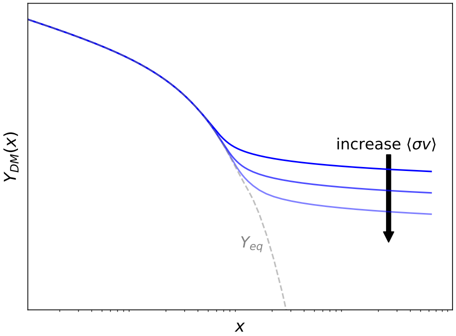

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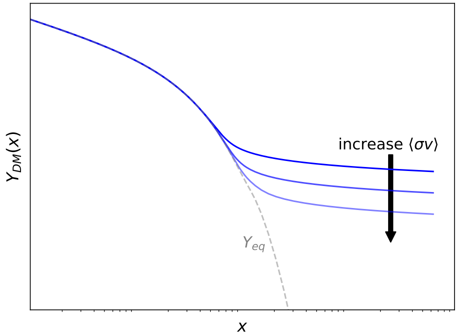

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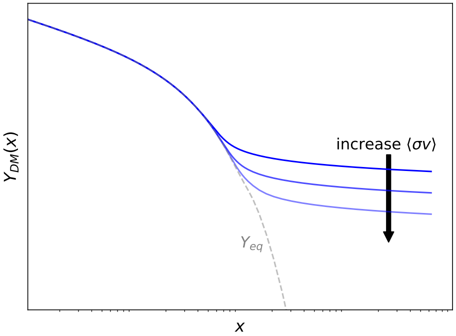

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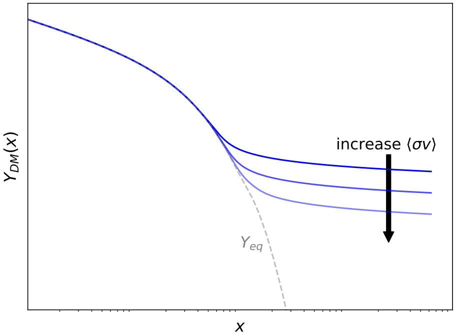

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- Freeze-out puts PT around the EW scale → LISA sensitivity range!

Freeze-out production of DM

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- Allows separate temperature evolution of SM and DS

Thermal evolution of the dark sector

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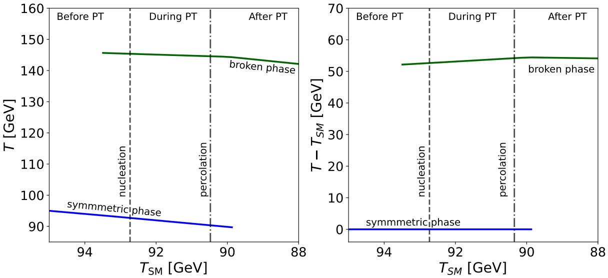

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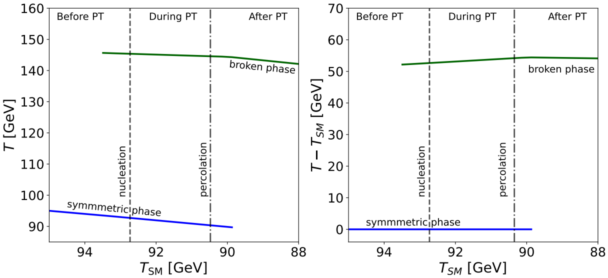

- Separate temperature evolution of SM and DS after PT

Dilution

- During radiation domination:
  $\rho_{\mathrm{tot}} \propto a^{-4}$ and $\rho_{\mathrm{GW}} \propto a^{-4} \Rightarrow \Omega_{\mathrm{GW}} = \text{const.}$
- Reheating of DS: Additional, non-rel. contribution to ρ_{tot}
- Possible period of matter-domination after PT
- Dilution factor

$$D = \frac{a_f^4}{a_{\mathrm{perc}}^4} \frac{H_f^2}{H_{\mathrm{perc}}^2}$$

arxiv:2109.06208

- Dilution of GW signal amplitude:

$$\Omega_{\mathrm{GW}} h^2 \propto \frac{1}{D^{4/3}}$$

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Higgs portal coupling

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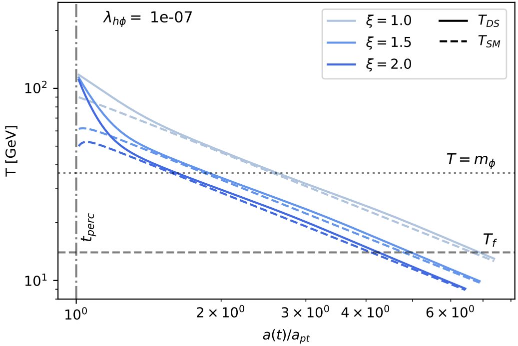
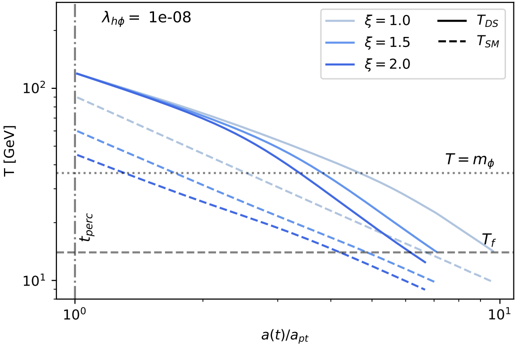
- Thermalisation via decays $\phi \to b\bar{b}$ and $h \to \phi\phi$
- Solve Boltzmann equation after PT

$$\dot{s}_{\mathrm{DS}} = -3Hs_{\mathrm{DS}} - \frac{m_\phi}{T_{\mathrm{DS}}} \Gamma_{\phi \to b\bar{b}} n_\phi^{\mathrm{eq}} \left(\frac{n_\phi}{n_\phi^{\mathrm{eq}}} - 1 \right) - \Gamma_{h \to \phi\phi} n_h^{\mathrm{eq}} \left[\left(\frac{n_\phi}{n_\phi^{\mathrm{eq}}} \right)^2 - 1 \right]$$

Thermalisation between SM and DS

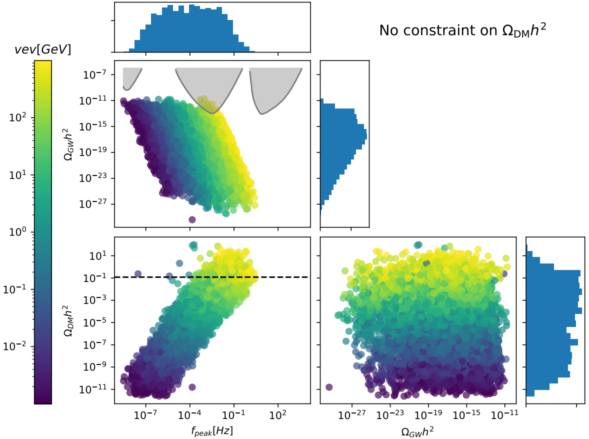




- Significant dilution effect for very small portal couplings $\lambda_{h\phi} \lesssim 10^{-8}$

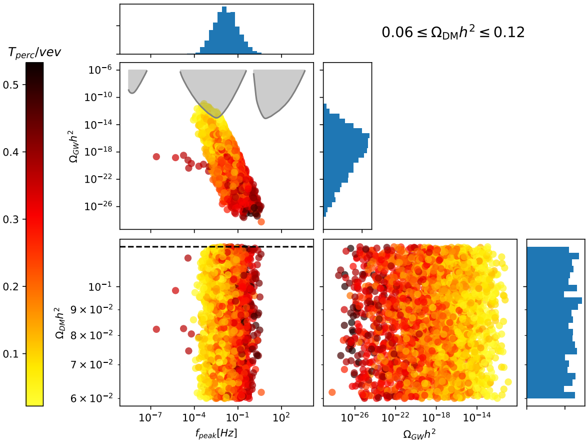
Gravitational wave signal

- Scan over parameter space in λ, g, y, v, $1 \leq \xi_{\rm nuc} \leq 2$ and $10^{-7} \leq \lambda_{h\phi} \leq 10^{-6}$
- Get "typical" prediction of model



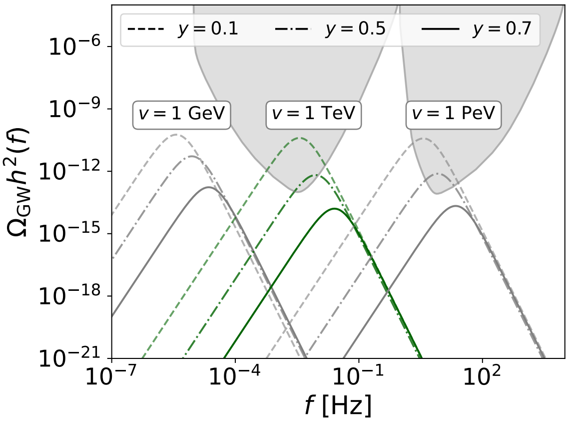
Gravitational wave signal

- Scan over parameter space in λ, g, y, v,
  $1 \leq \xi_{\text{nuc}} \leq 2$ and $10^{-7} \leq \lambda_{h\phi} \leq 10^{-6}$
- Get "typical" prediction of model
- Imposing $0.06 \leq \Omega_{\text{DM}} h^2 \leq 0.12$
  $\Rightarrow$ frequency restricted to LISA sensitivity range



Conclusion

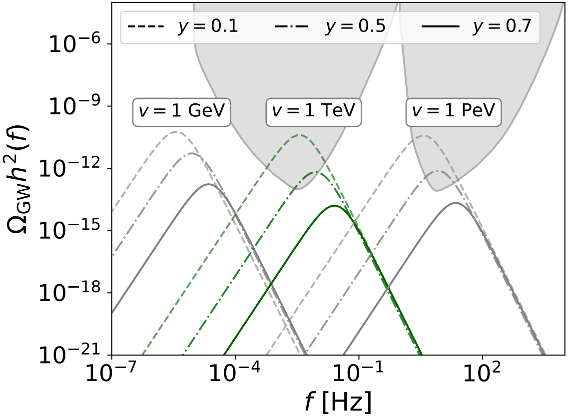
The LISA Miracle



Conclusion

The LISA Miracle

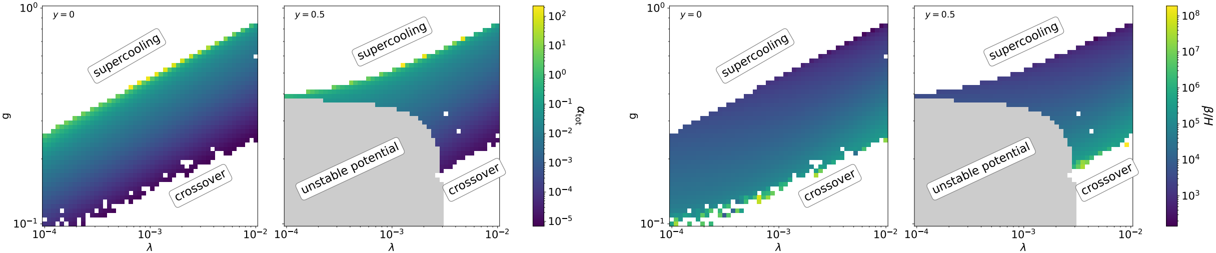
- Freeze-out within the DS implies a PT around the EW scale
- Frequency of the GW signal falls into the LISA sensitivity range
- Feeble coupling to the SM, avoiding laboratory constraints
- *Revival of the WIMP* through GW



Backup Slides

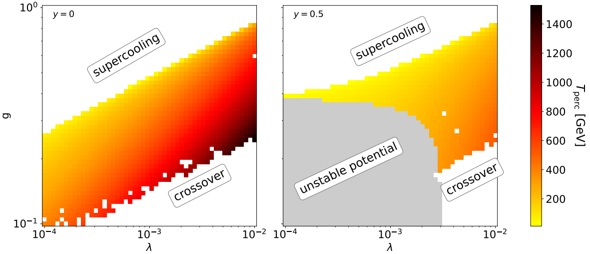
Parameter Space for $v = 1\,$TeV

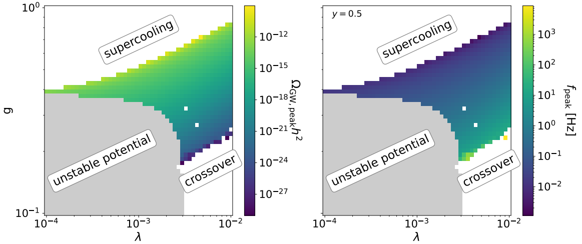
α and β/H



Parameter Space for $v = 1$ TeV

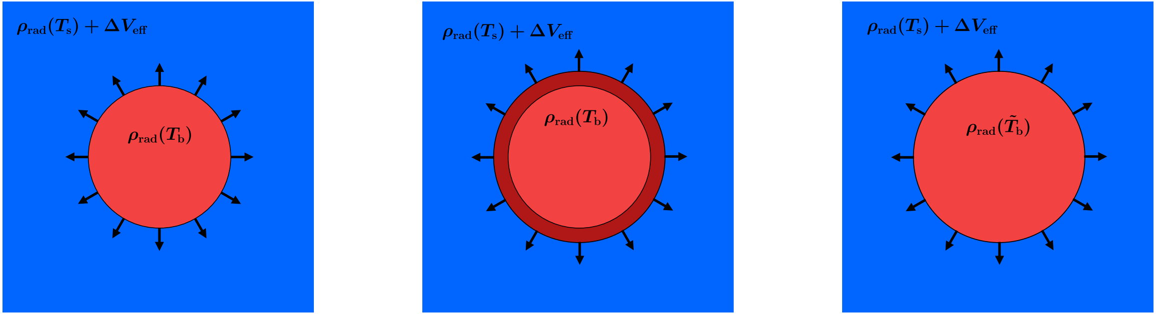
T_{perc} and peak GW signal





Thermalization of the DS

Temperature evolution around the PT

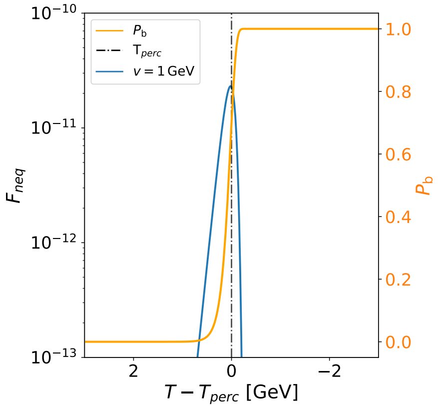


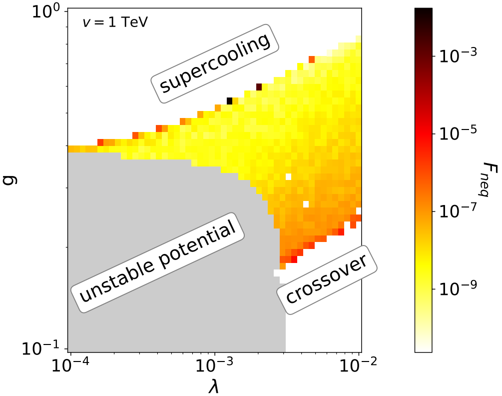
- Energy in broken phase: $E_b(T_s) = P_b(T_s)\rho_b(T_s)$

$$\frac{\mathrm{d}E_b}{\mathrm{d}T_s} = P_b\rho_b' + P_b'\rho_b = -3\frac{\rho_b + p_b}{T_s}P_b + P_b'\rho_s \;\Rightarrow \rho_b' \quad = -3\frac{\rho_b + p_b}{T_s} + \frac{P_b'}{P_b}\left(\rho_{\mathrm{rad},s} + \Delta V_{\mathrm{eff}} - \rho_b\right)$$

- Solve for $T_b(T_s)$

Thermal equilibrium after PT





Excluded parameter points

- Require that DS and SM have thermalised before freeze out, i.e. $\xi_{\mathrm{freezeout}} \leq 1.1$
- First order phase transition: $\lambda \in [10^{-4}, 10^{-2}], g \in [10^{-1}, 10^{0}]$
- Require dark matter candidate χ not to be the lightest particle $\rightarrow m_\phi < m_\chi$ for freeze out
- Vacuum stability: $y < 0.7$
  $\rightarrow y \in [0.1, 0.7]$