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

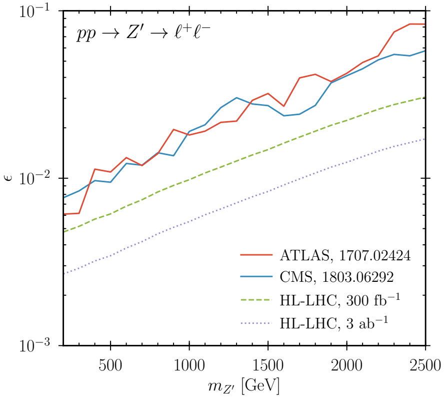
$$\mathcal{L} \supset -\frac{1}{4} Z_{\ell\,\mu\nu} Z_\ell^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{\epsilon}{2} B_{\mu\nu} Z_\ell^{\mu\nu}$$

$\epsilon \longrightarrow$ kinetic mixing

after SSB:
$Z - Z'$ mass mixing

LEP-2:
$m_{Z'} \gtrsim 200$ GeV

LHC:
$\epsilon \neq 0 \;\Rightarrow \ell^+\ell^-$ resonance

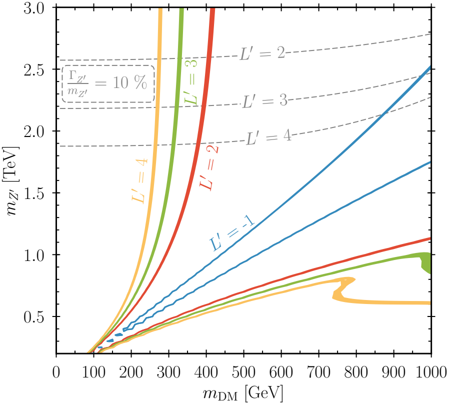


Dark Matter

Anomaly Cancellation

$\longrightarrow$ two generations of SM vector-like leptons (+ RH ν)

$\longrightarrow$ after SSB: 4 additional fermions: e_4^-, e_5^-, ν_4, ν_{DM}



Spontaneous Symmetry Breaking

ℓ spontaneously broken by $\Phi = \frac{1}{\sqrt{2}}(\phi + i\eta)$ with $L_\Phi = 3$

- $\phi \to \phi + v_\Phi \implies m_{Z'} \simeq 3 g_\ell v_\Phi$
- $h - \phi$ mixing $\implies$ signal strength reduced by $\cos^2\theta_H$
- dark leptons $\implies h \to \gamma\gamma$ modified

LEP-2: four-fermion contact interactions $\implies v_\Phi > 1.88$ TeV
choose $v_\Phi = 2$ TeV

For the rest of this talk:
neglect Higgs portal coupling and kinetic mixing
$\implies$ only Z', Φ, and dark leptons

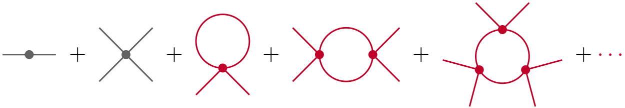
$$\mathcal{L} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + D_\mu \Phi^\dagger D^\mu \Phi + \mu_\Phi^2 \Phi^\dagger \Phi - \lambda_\Phi \left(\Phi^\dagger \Phi\right)^2 + \text{Yukawa terms}$$

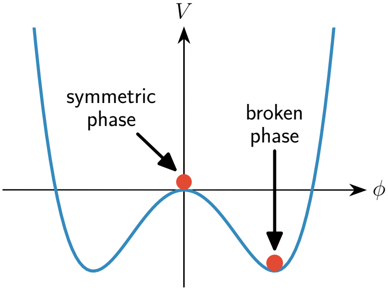
Symmetry Restoration

effective Potential

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

e.g. $\lambda\phi^4$ at 1-loop:





Symmetry Restoration

effective Potential

$$V_{\text{eff}}(\phi, T) = V_{\text{tree}}(\phi) + V_{\text{loop}}^{T=0}(\phi) + V_{\text{loop}}^{\text{thermal}}(\phi, T)$$

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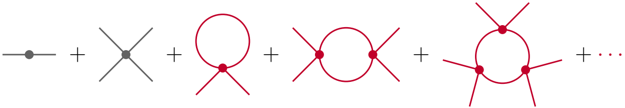
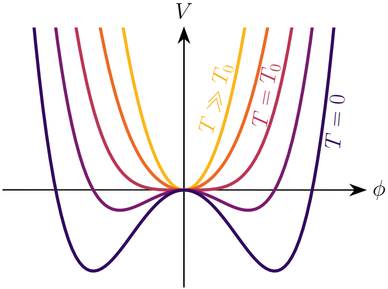


in the early Universe:

thermal corrections typically restore the symmetry

$\Longrightarrow$ symmetry breaking phase transition



Cosmological Phase Transitions

finite-T corrections restore symmetry at high T

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

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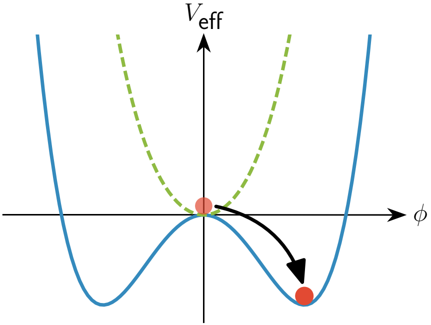
2 types of phase transitions:

cross-over:



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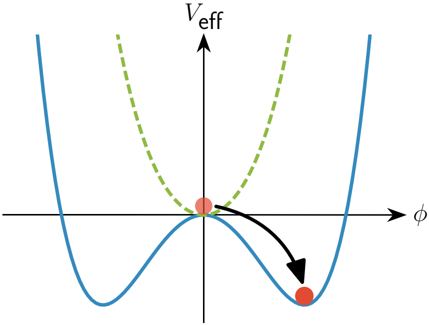
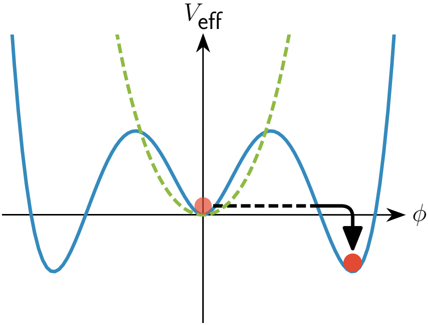


1st-order:



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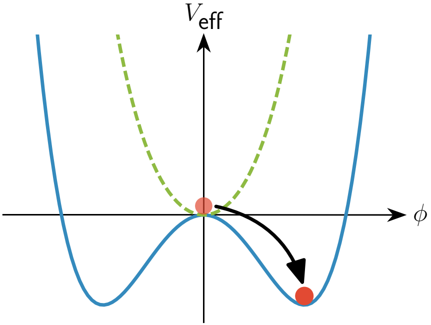

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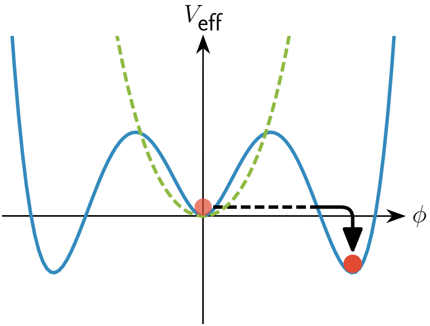


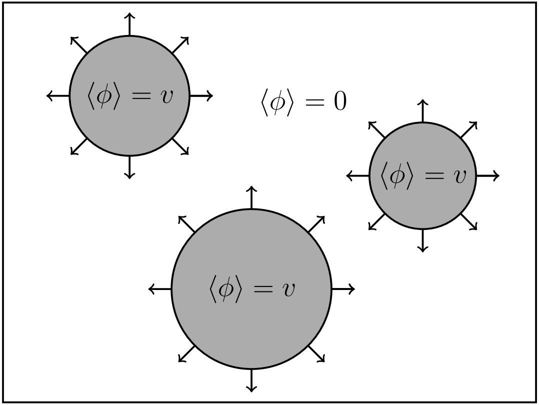
Gravitational Waves only from 1st-order Transition!

1st-Order Phase Transition

high- and low-T minima separated by barrier

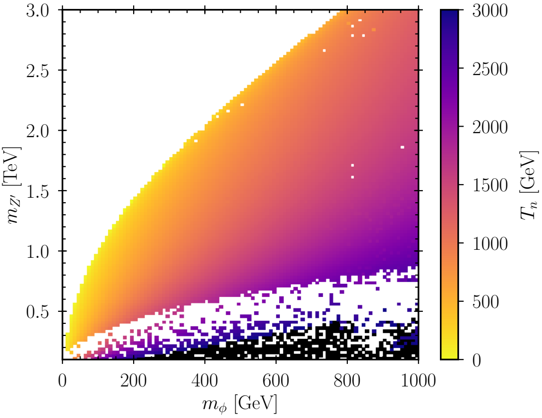
$\Longrightarrow$ 1st-order PT via tunneling

$\Longrightarrow$ bubble nucleation



Nucleation Temperature

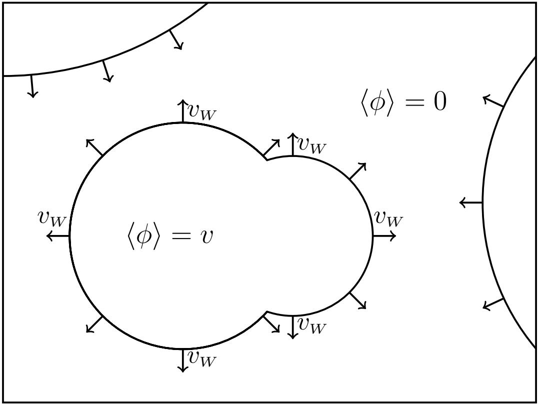
- nucleation rate $\longleftrightarrow$ Hubble expansion
  $\Gamma(T) \longleftrightarrow H(T)$
- nucleation temperature (T_n): $\Gamma/H^4 \sim 1$



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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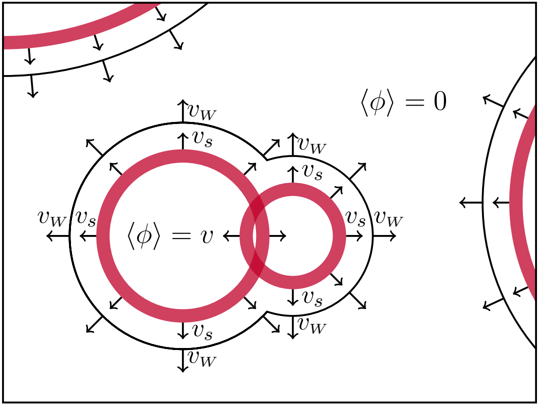

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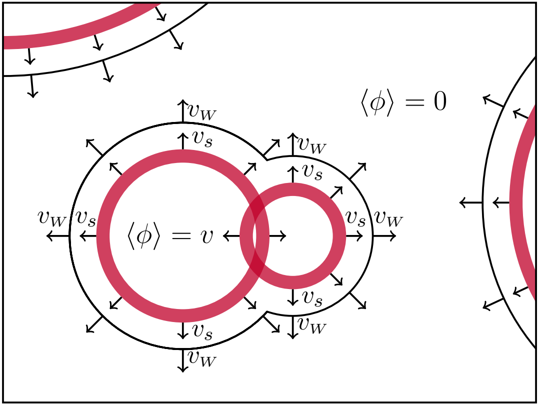
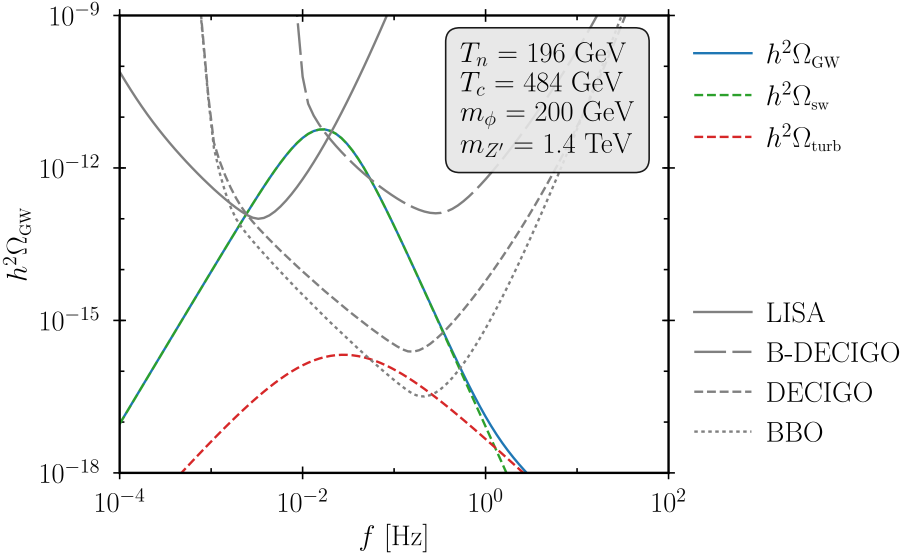
- $h^2\Omega_{\mathsf{sw}}$: sound waves in the plasma
- $h^2\Omega_{\mathsf{turb}}$: turbulence, vortical fluid motion

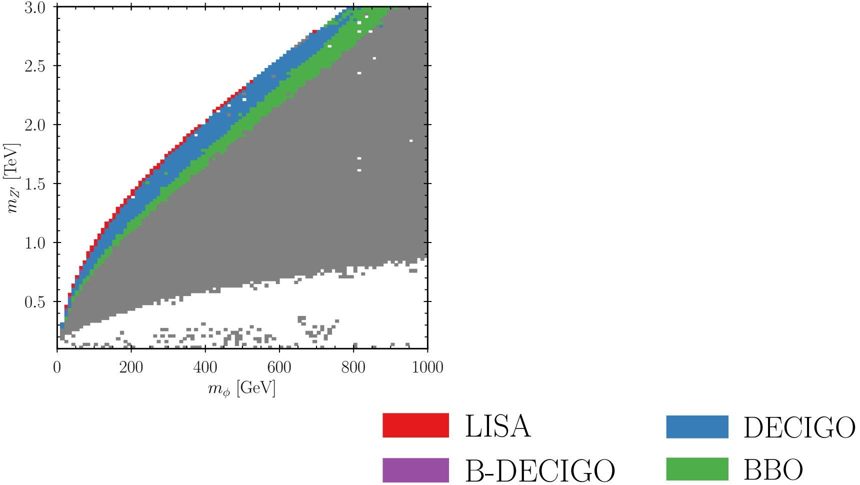


Gravitational Wave Spectrum



Detectability

neglecting heavy leptons



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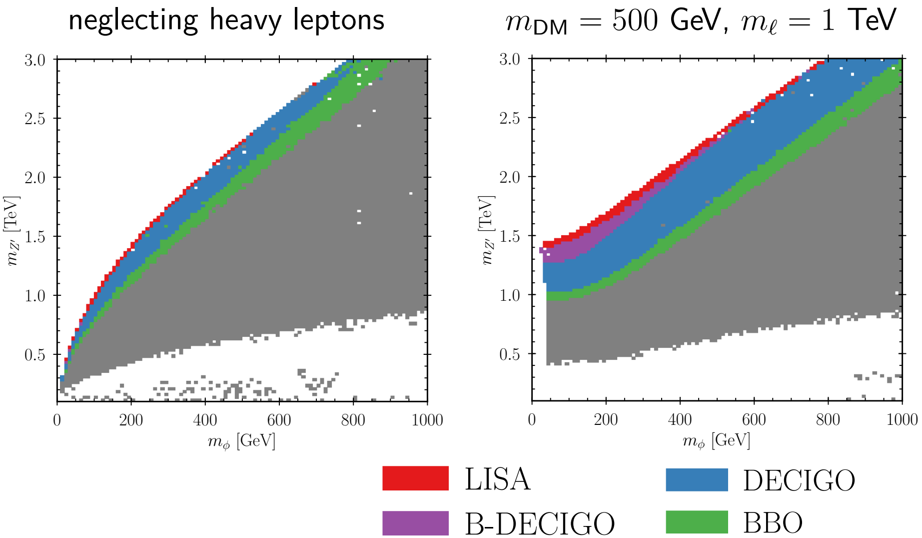

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- SM + $U(1)_\ell$ + SM vector-like fermions provide DM candidate
- LEP-2: $v_\Phi > 1880$ GeV
- LHC: Higgs measurements, Z' searches
  Direct Detection: mixing angles
- ℓ breaking PT can be 1st order
- generated stochastic GW background can be probed by future experiments (LISA, B-DECIGO, DECIGO, BBO)

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Thank you for your attention!