No room for monopole dark matter

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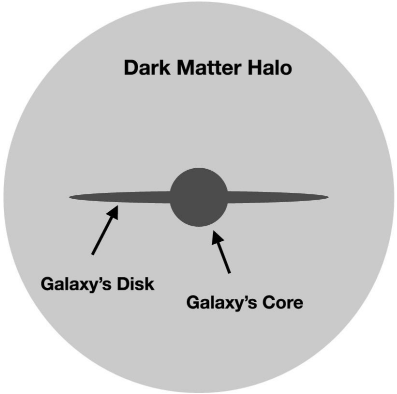
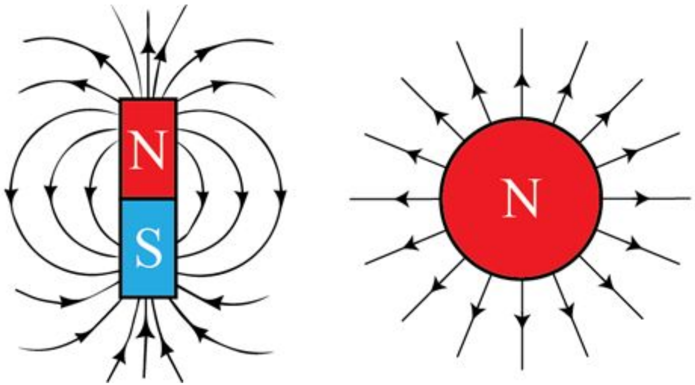


Dark matter - quick recap

- Matter interacting gravitationally, but invisible to light
- Cosmological density: $\Omega_{\mathrm{DM}} h^2 = 0.12$
- Must be stable
- Dark sector: secluded from SM, with hidden particles and forces. Interacts very weakly with SM.

I. Context and motivation



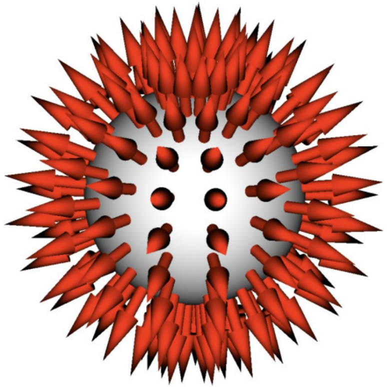
Monopoles

First introduced by Dirac (1931), as sources for the magnetic field, to solve the charge quantization problem:

$$q_e q_m = 2\pi n, \quad n \in \mathbb{Z}$$

Point-like, no prediction for their mass and abundances.

I. Context and motivation



Monopoles

Later (1974), 't Hooft and Polyakov $\longrightarrow$ monopoles naturally appear as topological solitons:

Topologically stable field configurations that behave like particles: mass and momentum (but extended objects).

Appear in theories where $\pi_2(G/H) \neq 0$

I. Context and motivation

Why monopole dark matter ?

- Stable (topology)
- Predicted mass
- Their cosmology is not well studied

II. 't Hooft Polyakov Dark Sector

The model: $G = \mathrm{SO}(3)_D \to H = \mathrm{SO}(2)_D, \quad \phi_a \sim \mathbf{3}_{\mathrm{SO}(3)_D}$

$$\mathcal{L} = -\frac{1}{4} F_a^{\mu\nu} F_{\mu\nu a} + \frac{1}{2} D_\mu \phi_a D^\mu \phi_a + V(\phi)$$

$$V(\phi) = \frac{\lambda}{4} (\phi_a \phi_a - \eta^2)^2$$

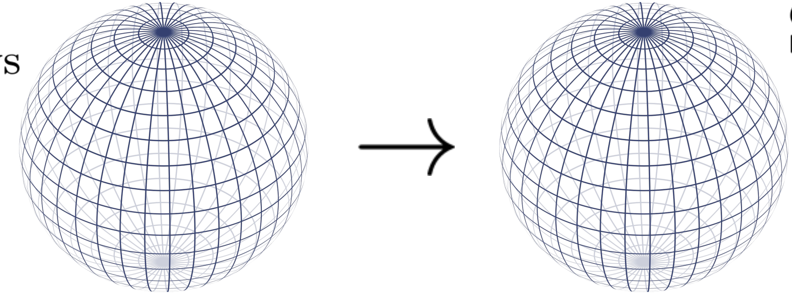
Only 3 parameters: (λ, g, η)

II. ‘t Hooft Polyakov Dark Sector

Monopoles in the model

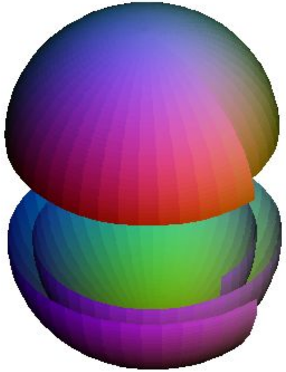
$$G/H \simeq \mathbb{S}^2 \qquad \Longrightarrow \qquad \pi_2(G/H) = \mathbb{Z} \; : \; g_m = \frac{4\pi n}{g}$$

$\mathbb{S}^2_{\text{phys}}$



$\mathbb{S}^2_{\text{field}}$

E.g.



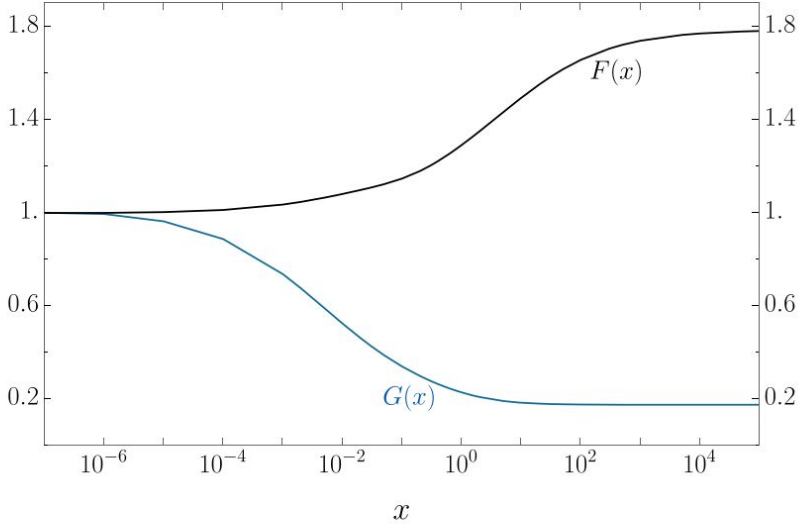
II. ‘t Hooft Polyakov Dark Sector

Monopoles in the model

The mass and radius can be numerically computed:

$$m_M = \frac{4\pi}{g}\eta F(\lambda/g^2) \sim \frac{4\pi}{g}\eta$$

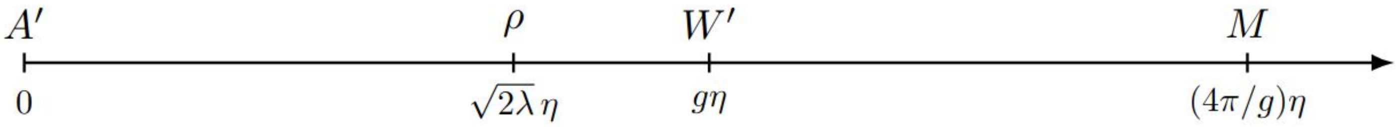
$$r_M = \frac{10}{g\eta}G(\lambda/g^2) \sim \frac{10}{g\eta}$$



II. ‘t Hooft Polyakov Dark Sector

Two dark matter candidates

Mass spectrum:



There are two DM candidates: $W'^{\pm_e}$ and $M^{\pm_m}$

Goal: understand if there is a region in parameter space where,

Fixed by phase transition

$$\Omega_M h^2 \sim 0.12 \gg \Omega_{W'} h^2$$

Fixed by freeze-out

III. Cosmological history and phase transition

Higgs portal

The dark sector is in thermal contact with the SM through a higgs portal,

$$\mathcal{L}_{DS+SM} \supset \frac{\lambda_{\phi H}}{2}\phi^2|H|^2$$

We assume that the two sectors share the same temperature T.

III. Cosmological history and phase transition

Effective potential at finite temperature

The quantity that tracks the phase transition in the dark sector is the thermal effective potential for the scalar $V_{\text{eff}}(\phi, T)$. At one loop,

$$V_{\text{eff}}^{(1)}(\phi, T) = V^{(0)}(\phi) + V^{(1)}(\phi, T=0) + V^{(1)}(\phi, T)$$

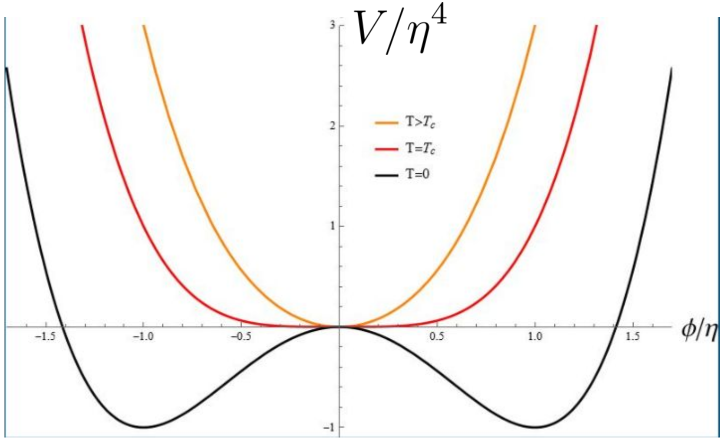
$$V^{(1)}(\phi, 0) = \sum_i \frac{n_i}{64\pi^2} m_i^4(\phi) \log \frac{m_i^2(\phi)}{\Lambda^2}$$

$$V^{(1)}(\phi, T) = \frac{T^4}{2\pi^2} \sum_i (\pm n_i) \int_0^\infty dq\, q^2 \log \left[1 \mp \exp\left(-\sqrt{q^2 + \frac{m_i^2(\phi)}{T^2}} \right) \right]$$

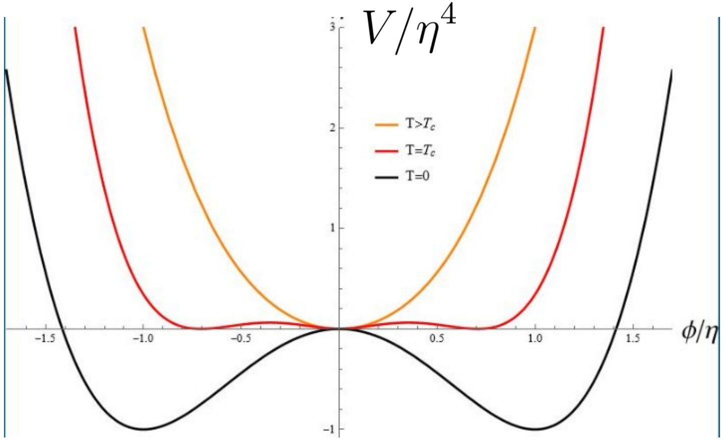
III. Cosmological history and phase transition

Effective potential at finite temperature

We distinguish two types of phase transition: second and first order



second order



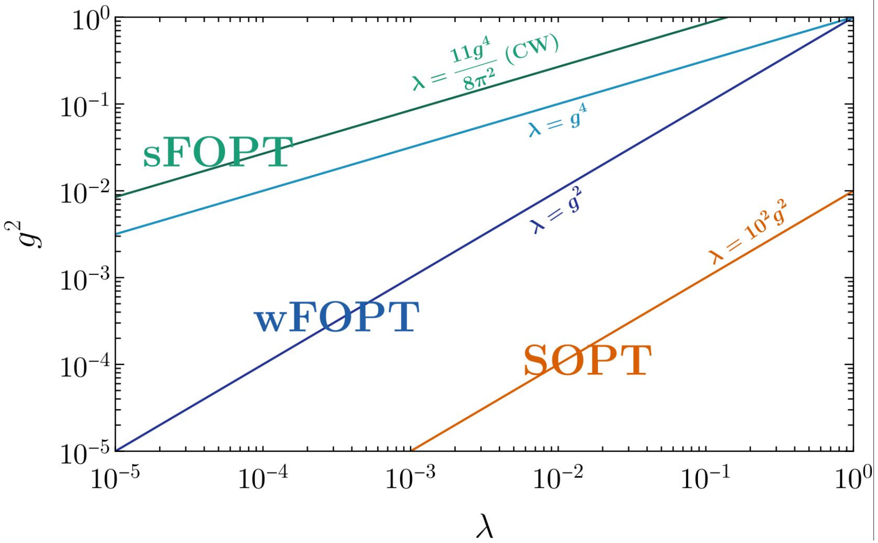
first order

III. Cosmological history and phase transition

Phase space of the model

We consider three possible scenario:

- second order (SOPT)
- weakly first order (wFOPT)
- strongly first order (supercooled)



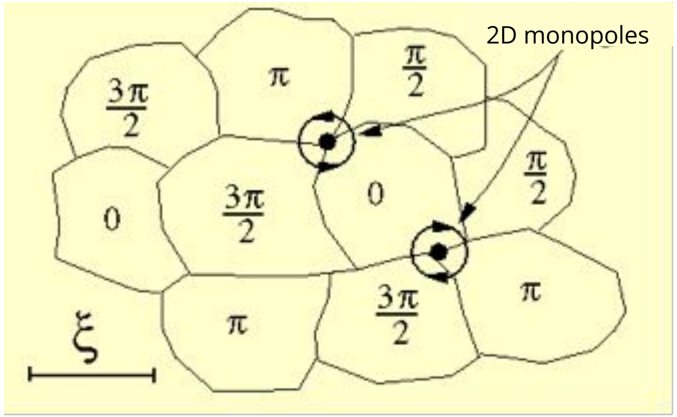
IV. Monopole relic density

Production

The number density of monopoles produced can be linked to the correlation length at that time by

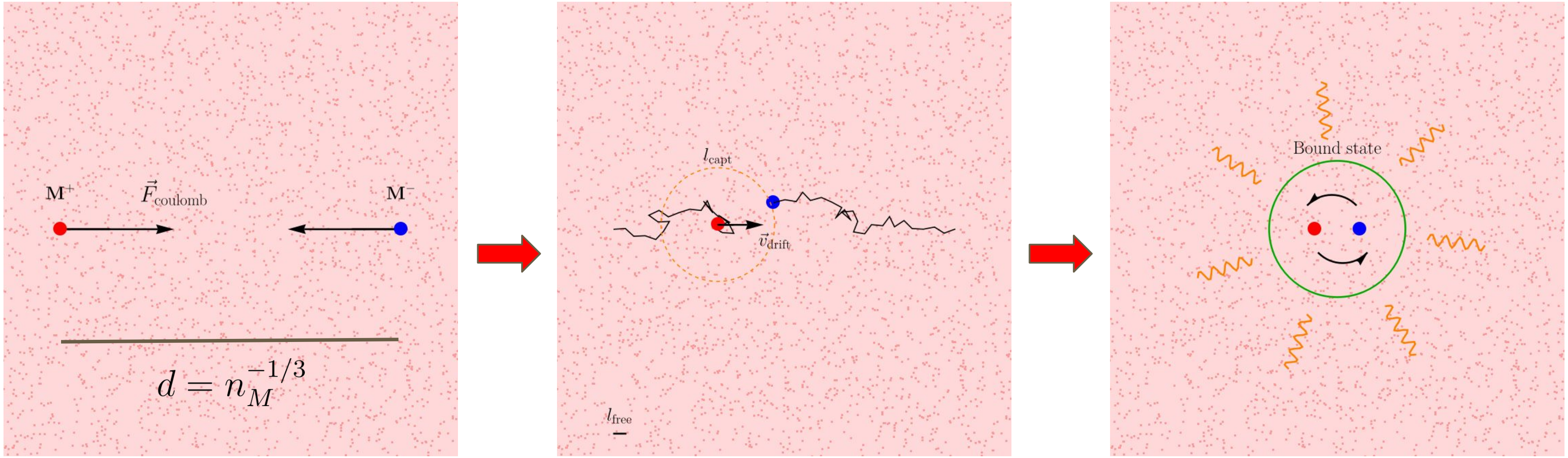
$$n_M \simeq p\xi^{-3}(T_{\rm prod}),$$

with $p = 1/8$ for monopoles



IV. Monopole relic density

Annihilations

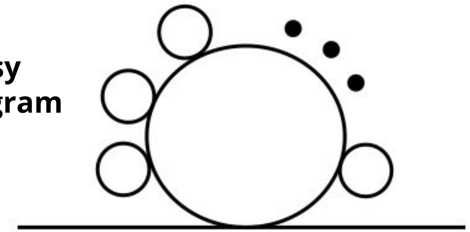


$$\Gamma_a = \frac{v_{\text{drift}}}{d}$$ → Solve Boltzmann Equation

[Preskill 1979, Vilenkin 1994]

IV. Monopole relic density

Daisy diagram



SOPT ($\lambda/\mathbf{g^2} \gg 1$)

In this limit (purely scalar theory) the effective potential can be approximated by

$$V^{(1)}_{eff}(\phi,T)=\frac{D}{2}\left(T^2-T_0^2\right)\phi^2-ET\left[2(\phi^2-\eta^2)^{3/2}+(3\phi^2-\eta^2)^{3/2}\right]+\frac{\lambda}{4}\phi^4+\mathcal{O}\left(\frac{m^4}{T^4}\right)$$

with $D=5\lambda/12, \quad E=\lambda^{3/2}/12\pi \quad \text{and } T_0^2=12\eta^2/5.$

It turns out that the loop expansion is non-perturbative close to the critical temperature and one has to resum daisy diagrams to all orders, which effectively amounts to replacing the tree-level masses

$m_i^2(\phi)$ by the effective thermal masses $m^2_{i,\mathrm{eff}}=m_i^2+DT^2$, allowing us to the bound

$$\left(\frac{5}{12}-9\lambda\right)^{-1/2}\lesssim\frac{T_c}{\eta}\lesssim\left(\frac{5}{12}+9\lambda\right)^{-1/2}$$

IV. Monopole relic density

Kibble-Zurek mechanism (SOPT)

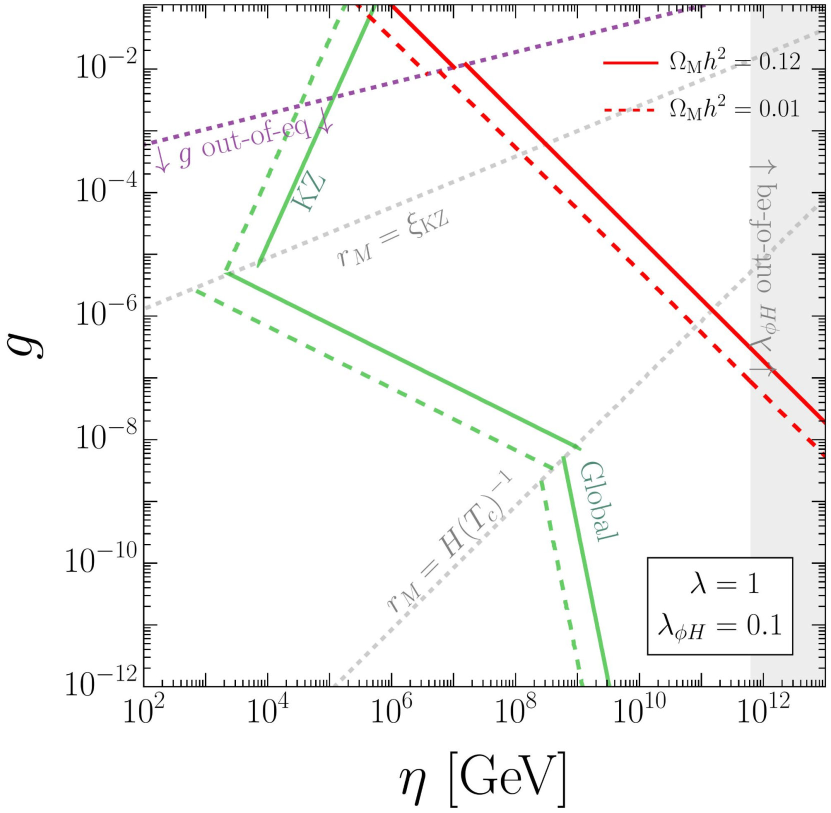
For second order phase transitions, it is well-known that both the correlation length and the relaxation time diverge at the critical temperature.

Fluctuations freeze at a spatial scale $\xi_{\rm KZ} \simeq H^{-1}(T_c)\ [H(T_c)\xi_0]^{0.6}$

where $\xi_0^2 = 1/m_\rho^2$ and H is the Hubble rate.

[Kibble 1976, Zurek 1985]

IV. Monopole relic density



IV. Monopole relic density

FOPT ($\lambda/\mathbf{g}^2 \ll \mathbf{1}$)

In this limit, scalar loops are now negligible and the effective potential is under perturbative control for the range of temperatures of interest.

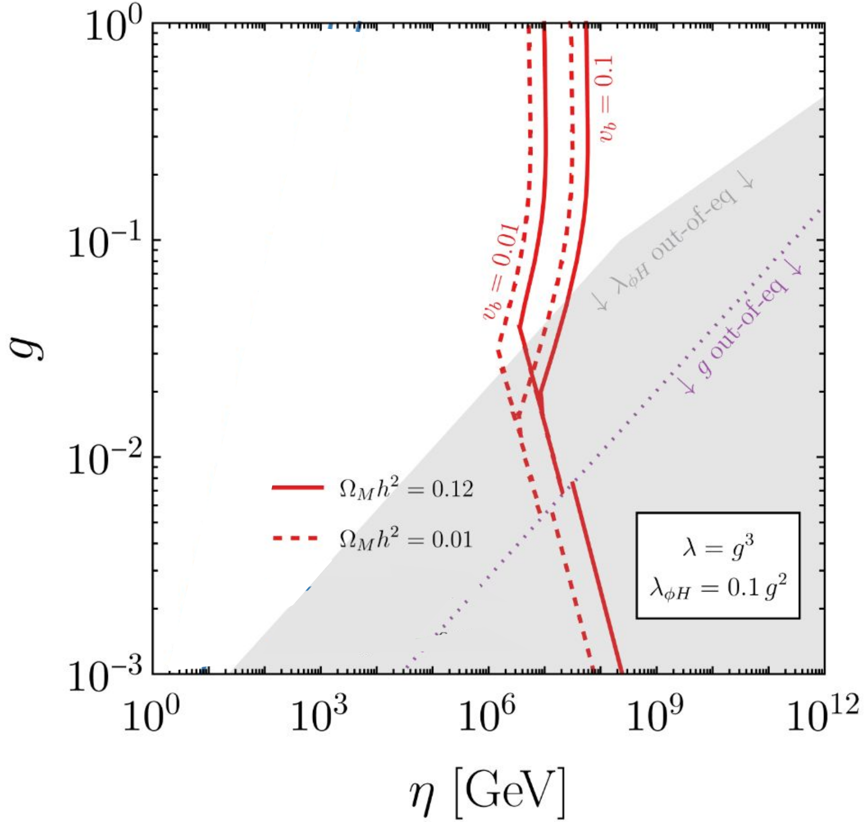
The potential develops a barrier between the false vacuum and the true one and the PT proceeds via bubble nucleation.

The correlation length is given by the bubble radius at the time of percolation:

$$\xi(T_{\rm prod}) = R_{\rm bubble}(T_{\rm perc}),$$

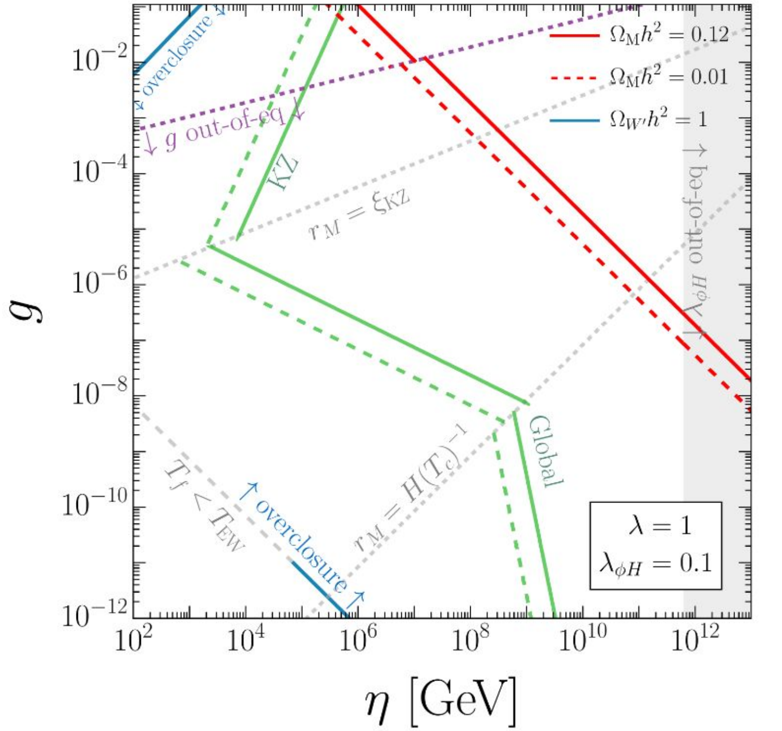
which is evaluated numerically.

IV. Monopole relic density

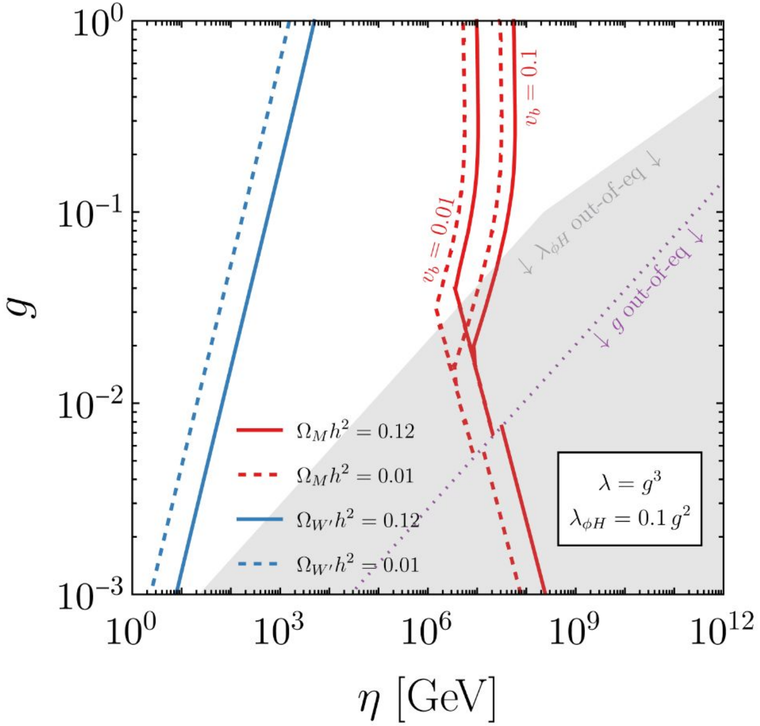


V. Comparing relic densities

SOPT

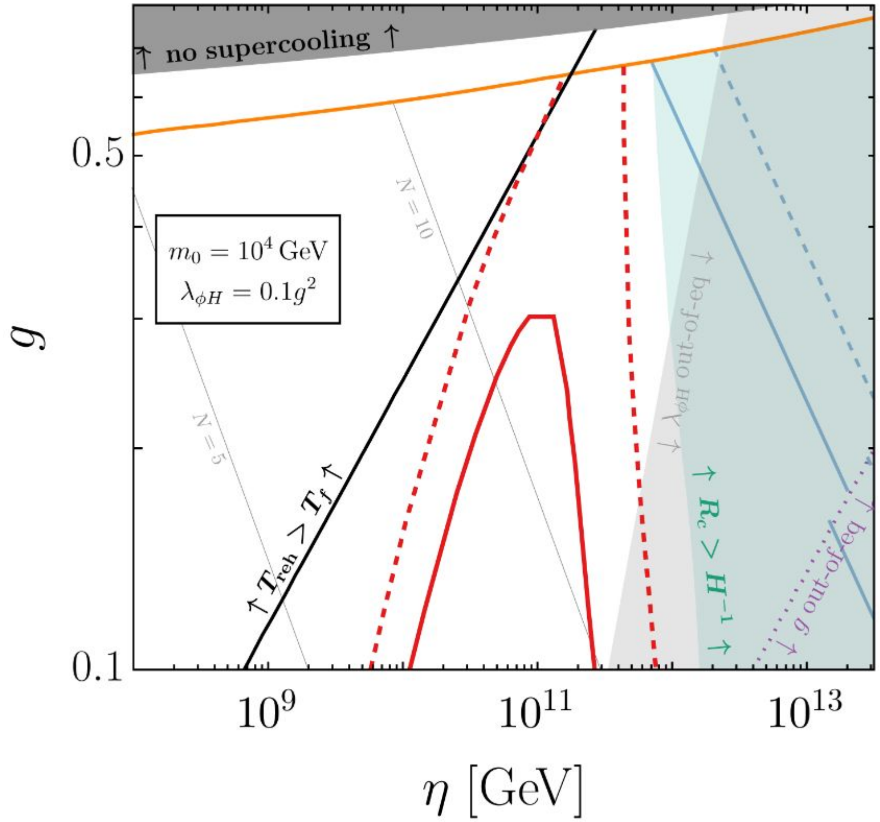


wFOPT



V. Comparing relic densities

Supercooled scenario



Conclusion and outlooks

- Our analysis shows that $\Omega_M \ll \Omega_{W'}$, for all possible (perturbative) ranges for g, λ and η: dark monopoles cannot constitute a sizeable fraction of dark matter
- We are currently working on less minimal models where the dark sector is extended with extra light charged particles, allowing W' to decay and monopoles to dominate in some regions.