Dark Monopole Dark Matter

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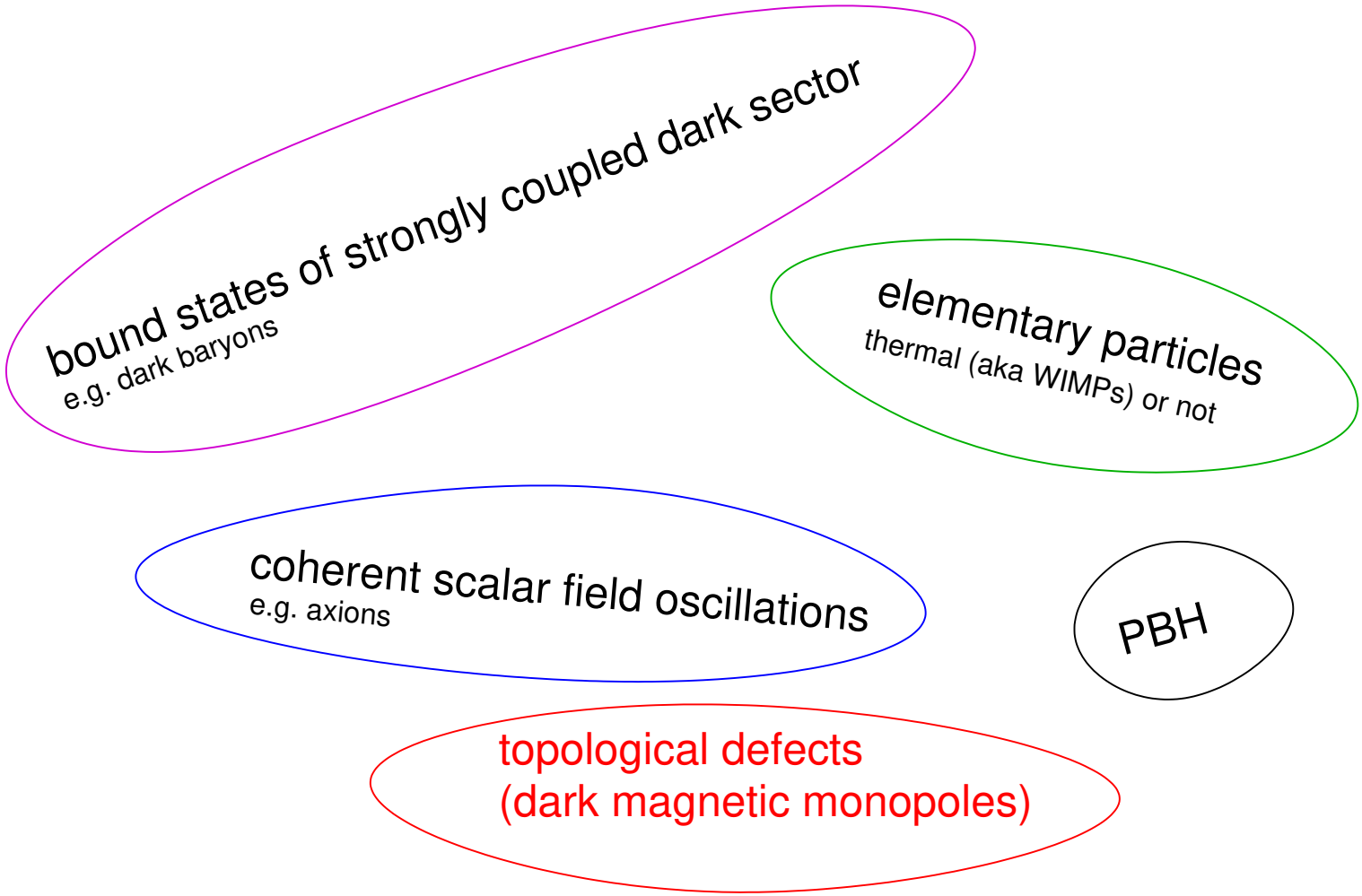
Dark matter wishlists

The Universe: DM must be stable and come with a production mechanism.

The physicist: ideally, DM properties should be calculable and DM models should give rise to testable signatures.

Dark matter candidates, with a broad brush

What could DM be made of? (Not exhaustive. . .)



Features of dark monopole dark matter

Imagine a dark sector with its own gauge interactions giving rise to dark magnetic monopoles.

Dark monopoles can be DM:

- stable due to topological charge
- can be produced in a thermal phase transition
- predictive framework
- phenomenology: dark radiation, gravitational waves (?)

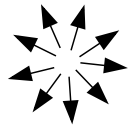
Review: the t'Hooft-Polyakov monopole

$G = \mathrm{SU}(2)$ gauge group with a scalar triplet ϕ^a and potential

$$V = \frac{\lambda}{4}\left(\phi^a\phi^a - \eta^2\right)^2 \qquad \left(+\frac{\lambda_{\phi H}}{2}\phi^a\phi^a|H|^2, \text{ important later}\right)$$

Finite-energy static field configuration → 't Hooft, Polyakov '74

$$\langle\phi^a(\vec{x})\rangle = f(r)\frac{x^a}{r} \qquad \text{"hedgehog"}$$



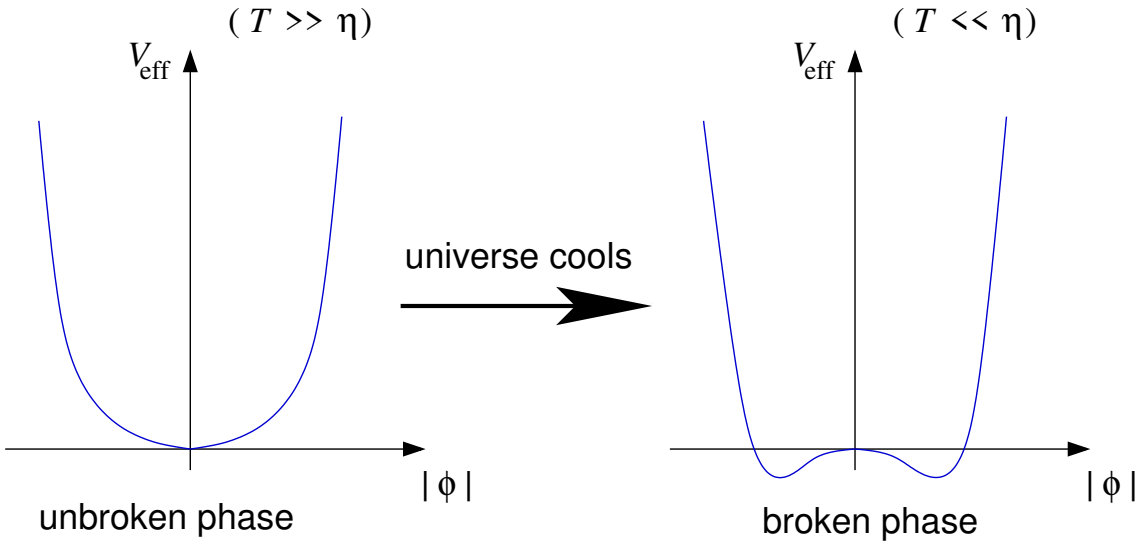
with $f(r) \to \eta$ as $r \to \infty$.

- Far from the origin: G broken to $\mathrm{U}(1)$
- 2 massive gauge bosons $W'^{\pm}$ with mass $m_{W'} = g\eta$
- The monopole has a $\mathrm{U}(1)$ magnetic charge, $\frac{1}{2\pi}\int_{S^2} F = 1$
- $\mathrm{U}(1)$ magnetic coupling $\frac{4\pi}{g}$
- Monopole mass $m_M = \frac{4\pi}{g}\eta$
- Monopole radius $\propto 1/(g\eta)$

Dark monopole cosmology

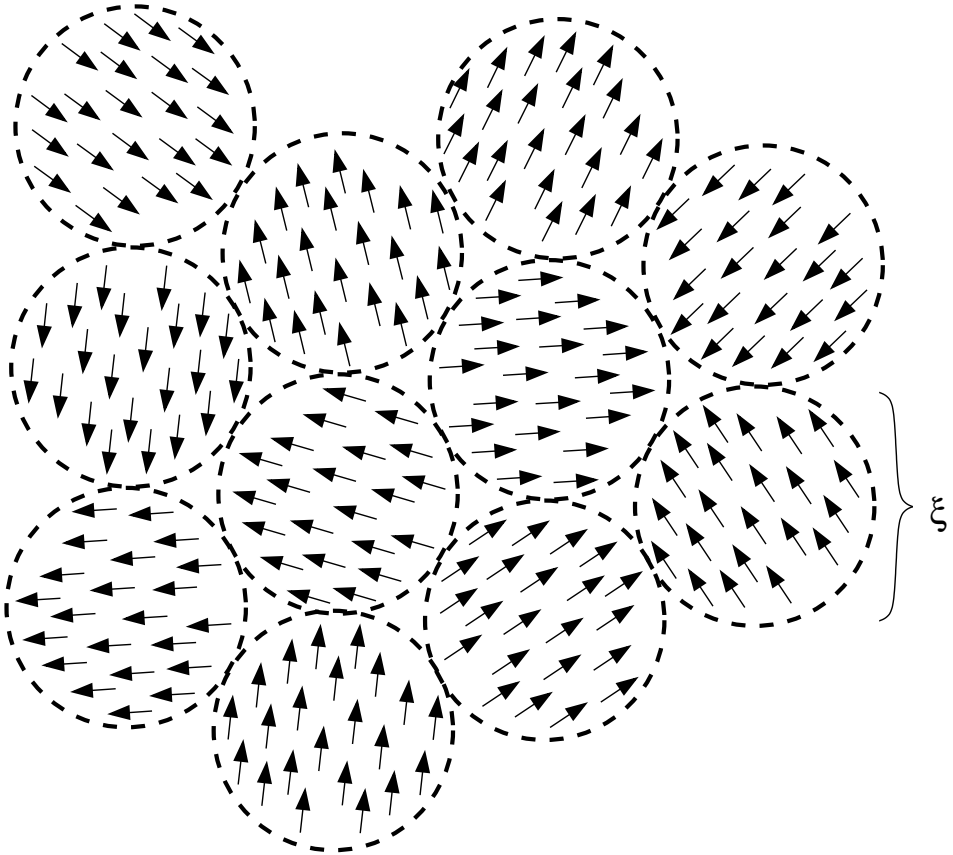
Postulate a dark gauge group G with monopoles in a dark sector.

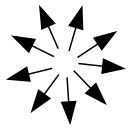
At large temperatures in the early universe, G is restored by thermal effects. As the universe cools, there is a phase transition towards the broken phase.



Dark monopole cosmology

After the phase transition, the scalar field orientation on $S^2 \simeq G/\mathrm{U}(1)$ is random but correlated over domains with correlation length ξ



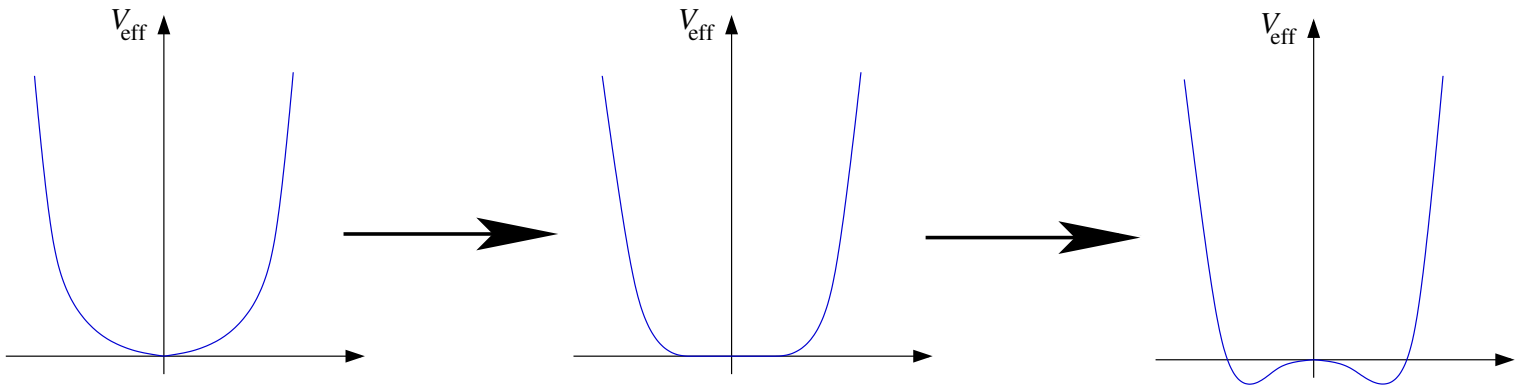
At the intersections, monopoles can form:  → Kibble '76

To know their abundance, need to calculate ξ.

Second-order phase transitions

Regime: $g^2 \lesssim \lambda$

A second-order phase transition proceeds smoothly:



Monopoles from Kibble-Zurek mechanism → Kibble '76, Zurek '85, correlation length

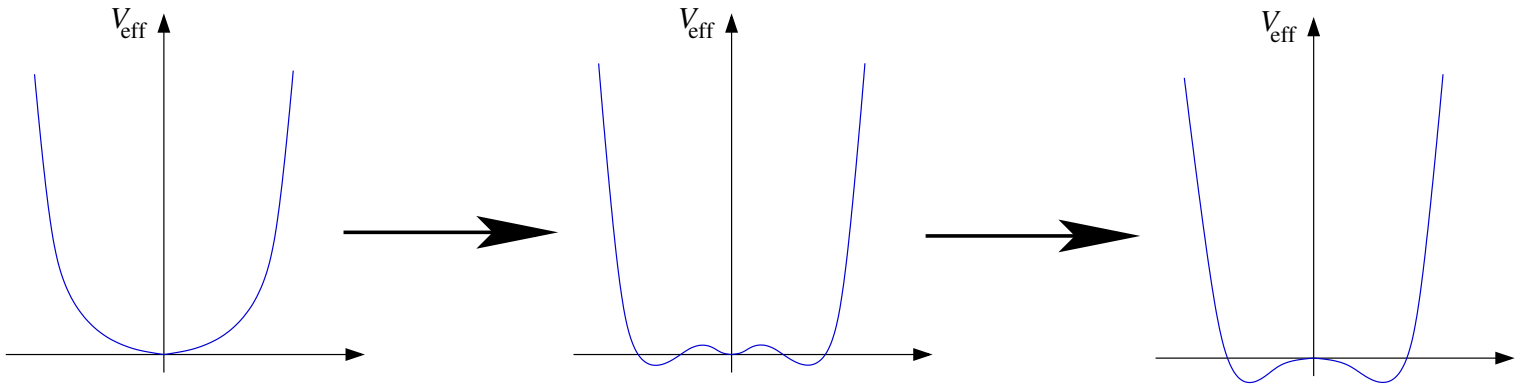
$$\xi = (H(T_c)\,\xi_0)^{1/(1+\nu)}\,/H(T_c)$$

H = Hubble, $T_c \approx \sqrt{\frac{12}{5}}\eta$ = critical temperature, $\nu \approx 0.7$ = critical exponent, $\xi_0^2 = 1/(2\lambda\eta^2)$. → Murayama/Shu '09

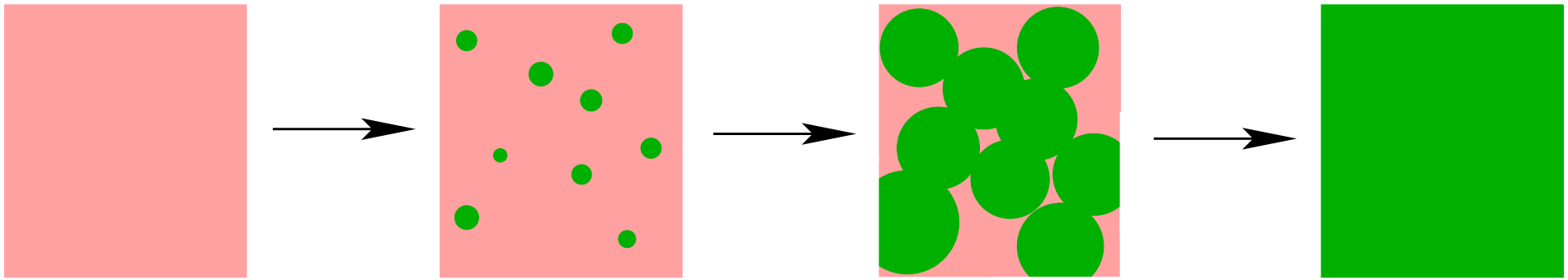
First-order phase transitions

Regime: $g^2 \gtrsim \lambda$

A first-order phase transition proceeds via bubble nucleation:



Correlation length = bubble radius at percolation



unbroken phase

bubbles of true vacuum form

bubbles expand and percolate

broken phase

First-order phase transitions

Bubble nucleation from vacuum tunnelling → Coleman '77, Linde '83...

Nucleation density:

$$\Gamma = T^4 \left(\frac{S_3}{2\pi T}\right)^{3/2} e^{-S_3/T}, \qquad S_3 = \text{3d thermal "bounce" action}$$

Efficient nucleation if

$$\Gamma(T) \gtrsim H(T)^4$$

(bubbles nucleate faster than universe expands).

Inverse duration parameter:

$$\beta \equiv \left.\frac{\mathrm{d}\log\Gamma}{\mathrm{d}\,t}\right|_{\text{percolation}}$$

First-order phase transitions

See e.g. review by → Athron/Balázs/Fowlie/Morris/Wu '23

- **Weak** FOPT have small latent heat and are fast (complete within one Hubble time):

$$\xi = \left(\frac{8\pi v_{\text{wall}}^3}{1-P}\right)^{1/3} \frac{1}{\beta}$$

  $1 - P = 0.29$ = percolation threshold, v_{wall} = bubble wall velocity

- **Strong** FOPT have large latent heat and can be slow and supercooled = universe vacuum-energy dominated at completion (period of thermal inflation):

$$\xi^{-3} = \frac{\Gamma}{\beta}(-\log P)^{-\sigma}\Big(\mathbf{\Gamma}(\sigma, 0) - \mathbf{\Gamma}(\sigma, -\log P)\Big)$$

  $\sigma \equiv 1 + 3H/\beta$, $\mathbf{\Gamma}$ = incomplete Gamma function → Levi/Opferkuch/Redigolo '22
  Here $v_{\text{wall}} = 1$: no friction in vacuum-energy domination
  - This gives ξ if bubble radius at nucleation negligibly small
  - Otherwise: account for initial radius, computed in thick-wall approximation

Technical parenthesis

Computation of the bounce: large hierarchy of scales $T_{\text{nucleation}} \ll T_c \approx m_{W'}$

$\rightarrow$ need to use running parameters in 1-loop thermal potential to avoid large logs (issues of residual scale dependence $\rightarrow$ Gould/Tenkanen '21)

Choose RG scale = πT ("hard" scale of thermal Matsubara modes) for describing vacuum transition

Field redefinitions

$$\Rightarrow \qquad V = \frac{m_T^2}{2}\phi^2 - \frac{\delta_T}{3}\phi^3 + \frac{\lambda_T}{4}\phi^4$$

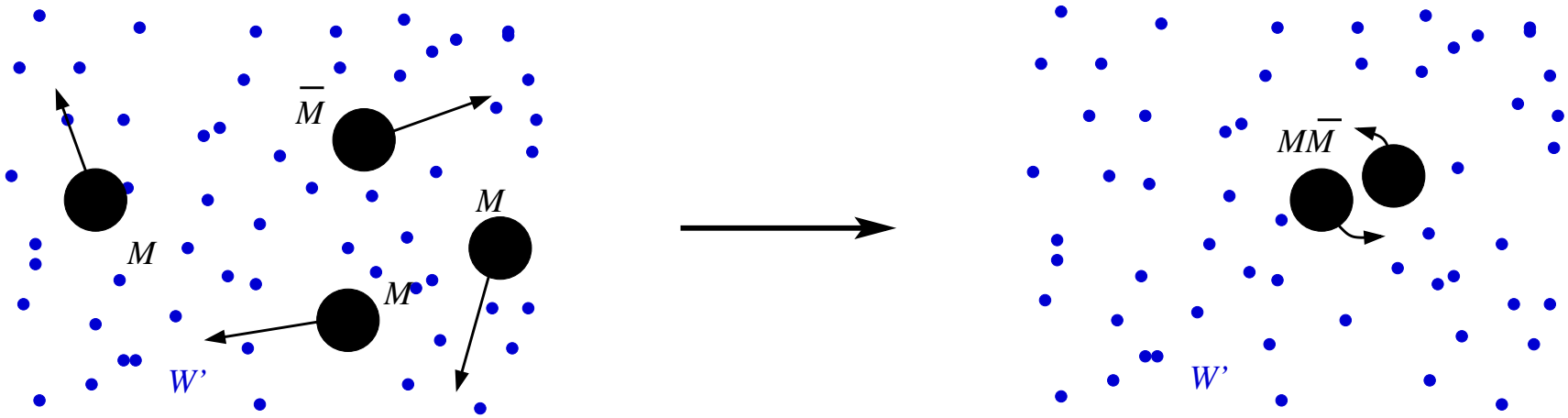
Can now fit S_3 as a function of a single parameter $\kappa_T = \lambda_T \frac{m_T^2}{\delta_T^2}$ $\rightarrow$ Adams '93 which allows for efficient numerical evaluation

See also $\rightarrow$ Salvio '24 "supercool expansion"

Monopole annihilation

After monopole production by any of these phase transitions, they may still annihilate → Zeldovich/Khlopov '78, Preskill '79 if sufficiently dense:

- energy loss in plasma of electrically-charged particles $W'^{\pm}$,
- monopole-antimonopole bound state formation,
- monopolonium decay into dark-sector particles.



Monopole annihilation

Monopolonium annihilation process cannot be computed (easily)

But we only need the bound state formation rate, can be estimated classically.

Yield after annihilation

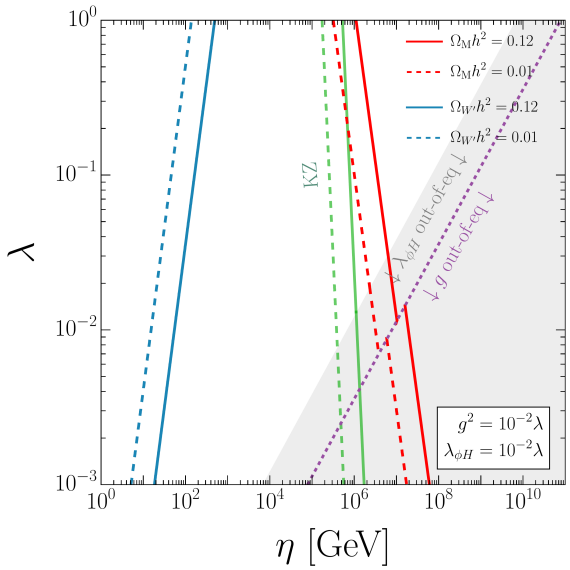
$$\frac{n_M}{s} \propto g^2 \frac{T_a}{M_{\text{Planck}}}$$

where n_M = final monopole number density, s = entropy density,
T_a = temperature where annihilation stops = the larger one of

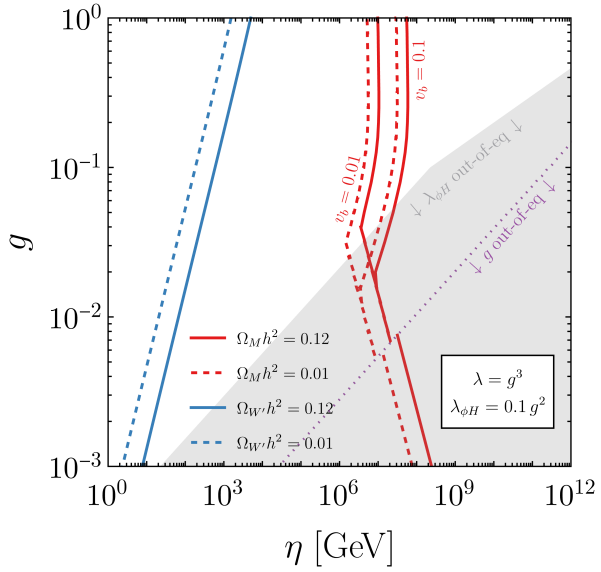
- the freeze-out temperature of the lightest electrically-charged particle
  → Khoze/Ro '14
- or $T_a \sim \eta g^3$, as (capture radius) becomes < (monopole mean free path)
  → Preskill '79

If the initial yield is smaller, this means annihilation is never efficient.

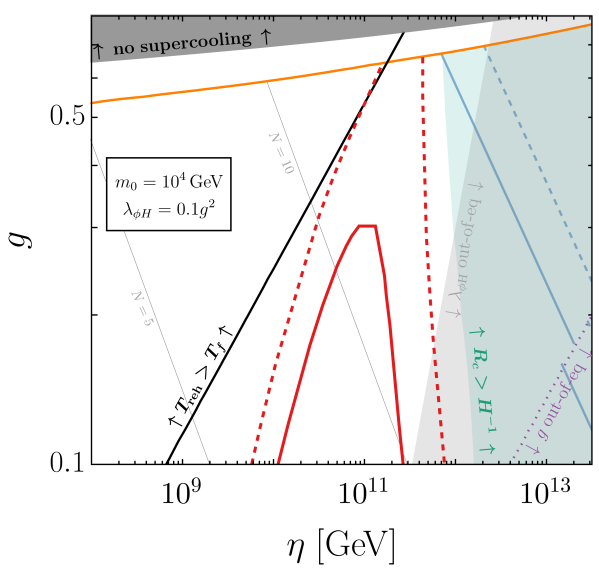
No room for minimal monopole dark matter



second order



weakly first order



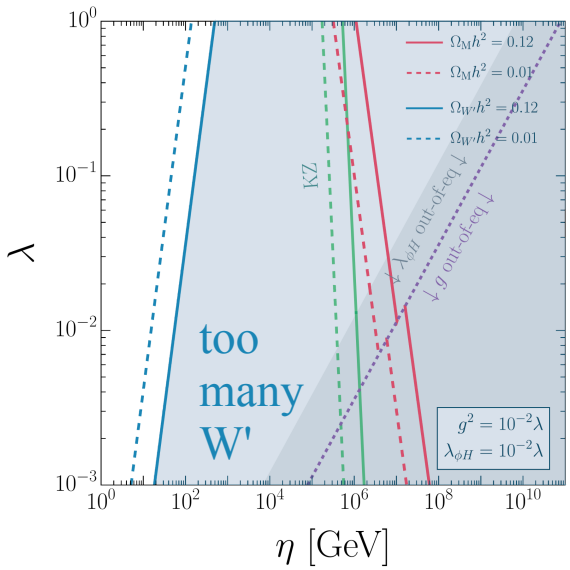
supercooled

The model predicts $\Omega_M h^2 = 0.1$ on the solid red line.

But it also predicts $\Omega_{W'} h^2 \gg \Omega_M h^2$: the massive $W'^{\pm}$ gauge bosons are stable and will dominate the DM abundance.

(W' dark matter is interesting, see e.g. → Baek/Ko/Park '13, Xie/Zhan '26, but not for this talk...)

No room for minimal monopole dark matter



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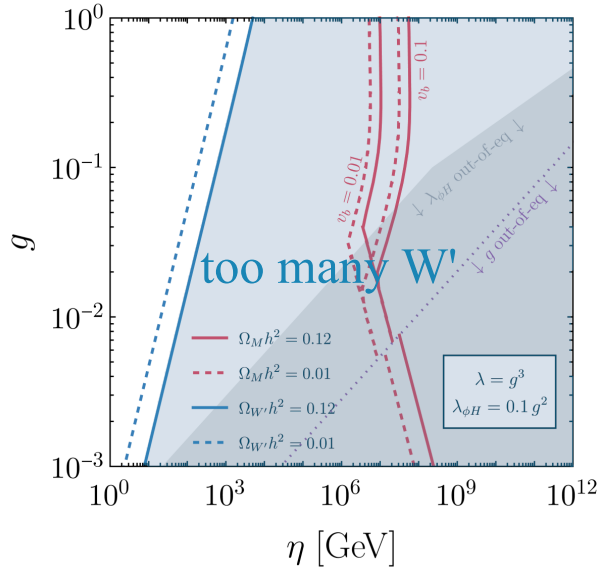

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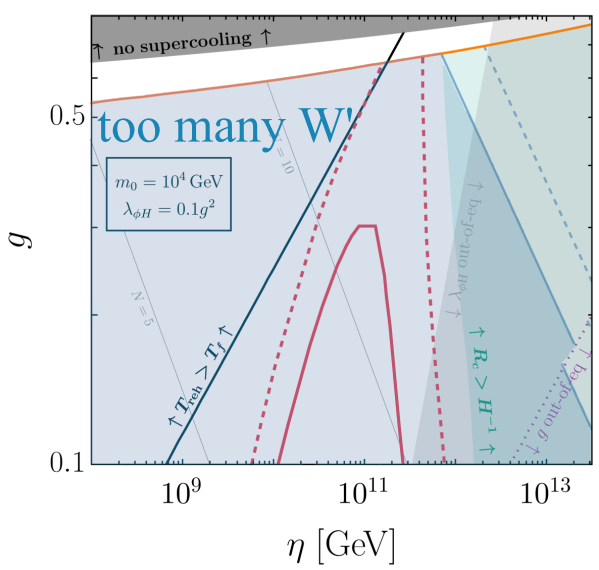

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No room for minimal monopole dark matter

Conclusion 1

In the minimal model, the DM abundance is never dominated by monopoles (always by $W'^{\pm}$ gauge bosons).

Potential ways out

- We have assumed that the temperature of the dark sector is that of the SM (thermal contact via a Higgs portal coupling). If the two sectors are thermally decoupled, the ratio $\Omega_M/\Omega_{W'}$ might be different.
- We have assumed that monopoles are created by a thermal phase transition. Other production mechanisms may lead to other conclusions. E.g. parametric resonance → Bai/Korwar/Orlofsky '20
- In the minimal model, $W'^{\pm}$ is stable.
  Next: study a non-minimal model where $W'^{\pm}$ decays.

Dark monopoles with dark fermions

Add two left-handed Weyl fermion doublets χ and ψ with $\mathrm{U}(1)_{\mathrm{global}}$-symmetric Lagrangian

$$\mathcal{L}_{\mathrm{U}(1)_F} = i\chi^\dagger \bar{\sigma}^\mu D_\mu \chi + i\psi^\dagger \bar{\sigma}^\mu D_\mu \psi - \left[y\, \chi^i \epsilon_{ij} \phi^a \, (\sigma^a)^j_k \, \psi^k + m_f \, \chi^i \epsilon_{ij} \psi^j + \mathrm{h.c.} \right]$$

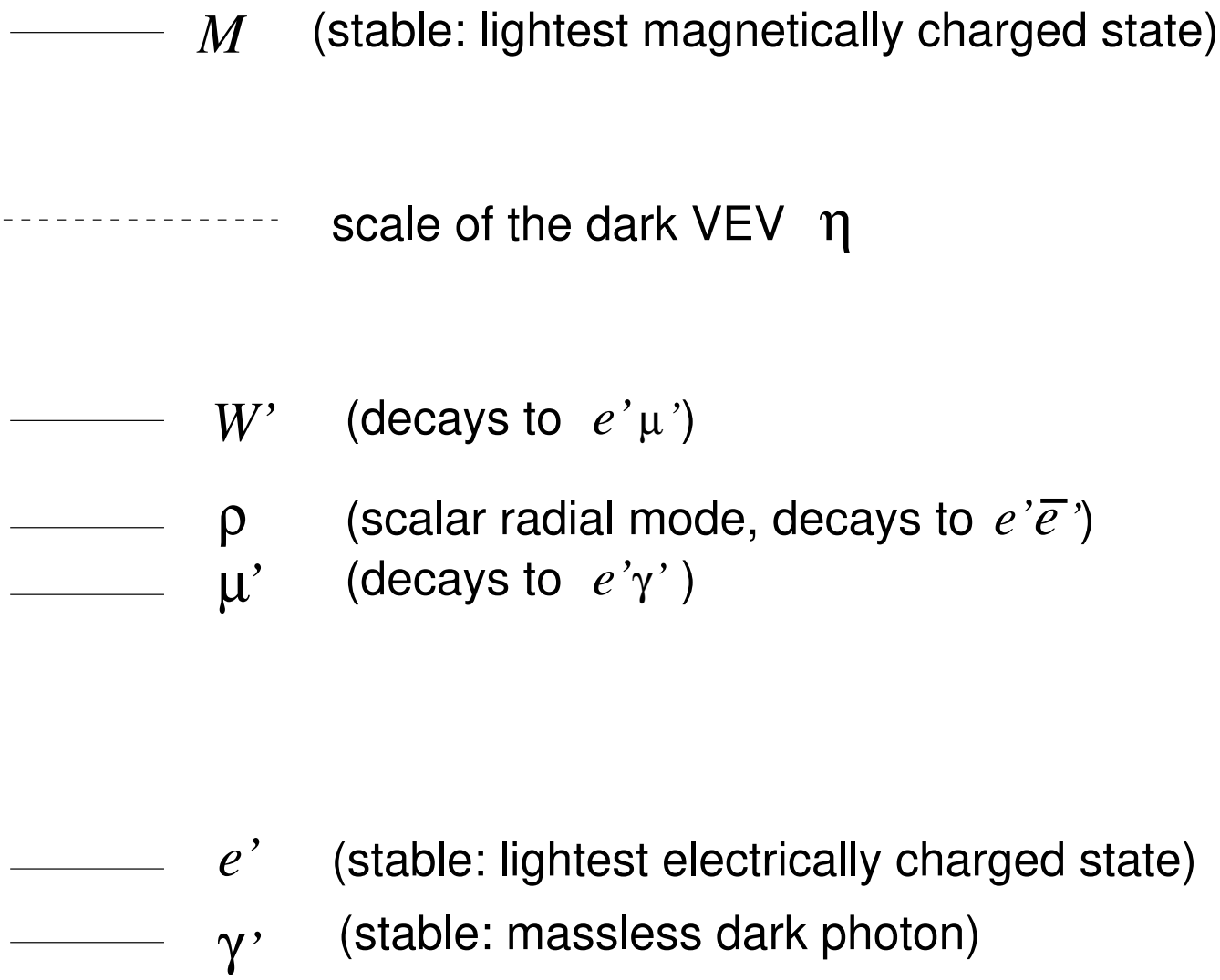
	χ	ψ	ϕ
$\mathrm{SU}(2)$	**2**	**2**	**3**
$\mathrm{U}(1)_{\mathrm{global}}$	1	-1	0

After spontaneous breaking $G \to \mathrm{U}(1)$: two Dirac fermions μ' and e' with $\mathrm{U}(1)$ charge $1/2$, masses $y\eta \pm m_f$, opposite $\mathrm{U}(1)_{\mathrm{global}}$ charges.

Explicit $\mathrm{U}(1)_{\mathrm{global}}$ breaking by (small) extra Yukawa couplings
$\Rightarrow \mu' \to e'\gamma'$ decays allowed.

Dark monopoles with dark fermions

Dark sector spectrum

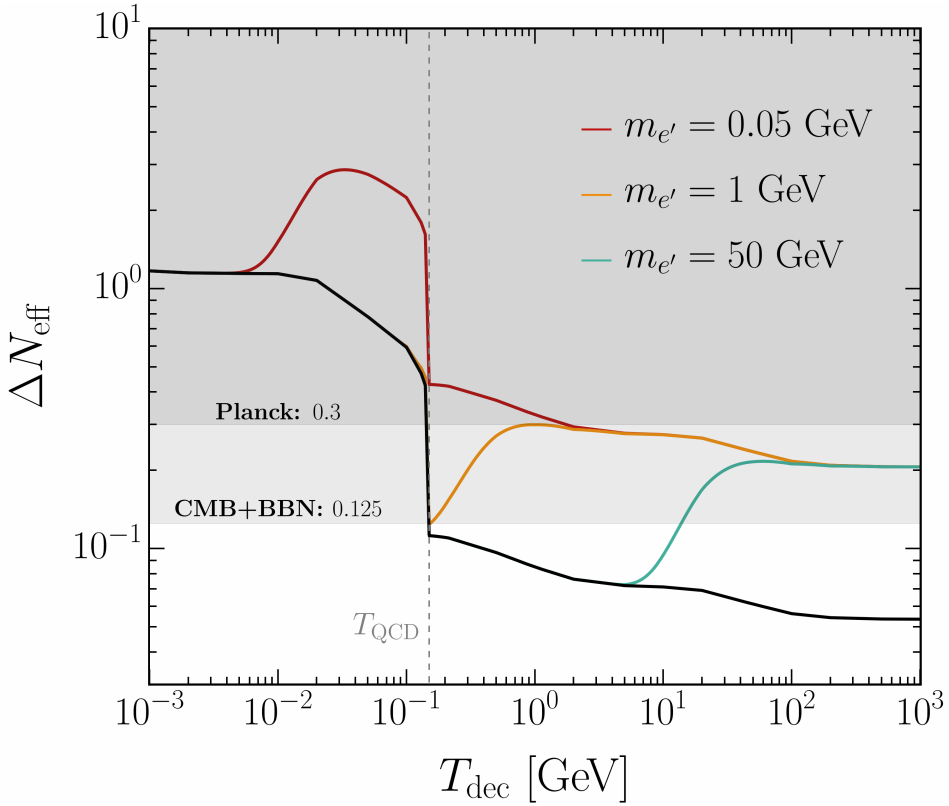


Dark monopoles with dark fermions

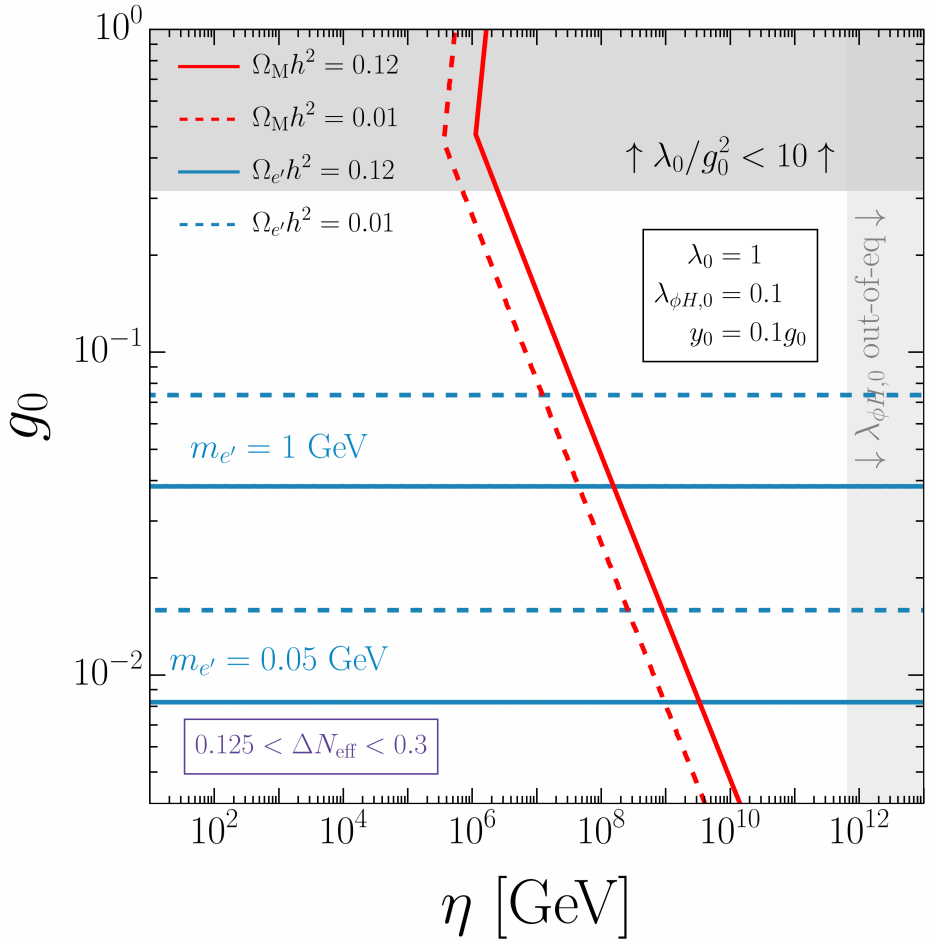
Dark matter now consists of monopoles and of e'. Dark electrons can be light and their relic density arbitrarily small.

However, they contribute to ΔN_{eff} by heating up the dark sector, if freezing out after the dark sector has thermally decoupled from the SM: severely constrained

Thermal contact mediated by $h \leftrightarrow e'\bar{e}'$ where h = SM Higgs.

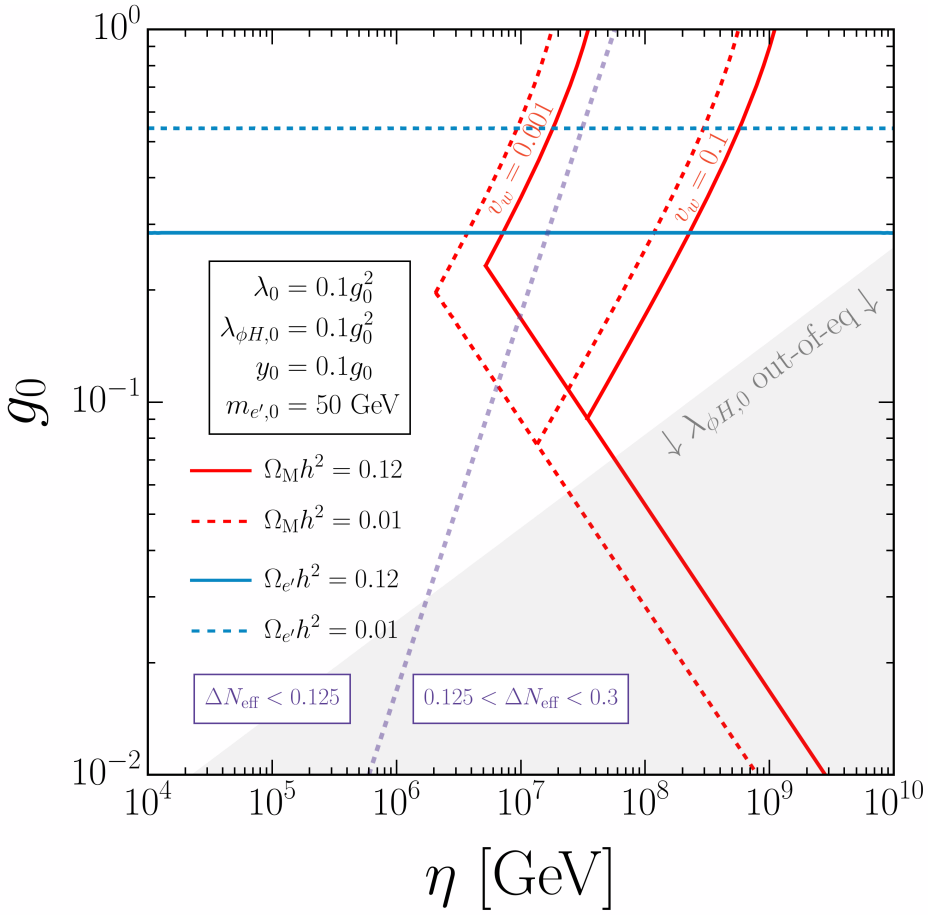


Dark monopoles with dark fermions: Second-order PT



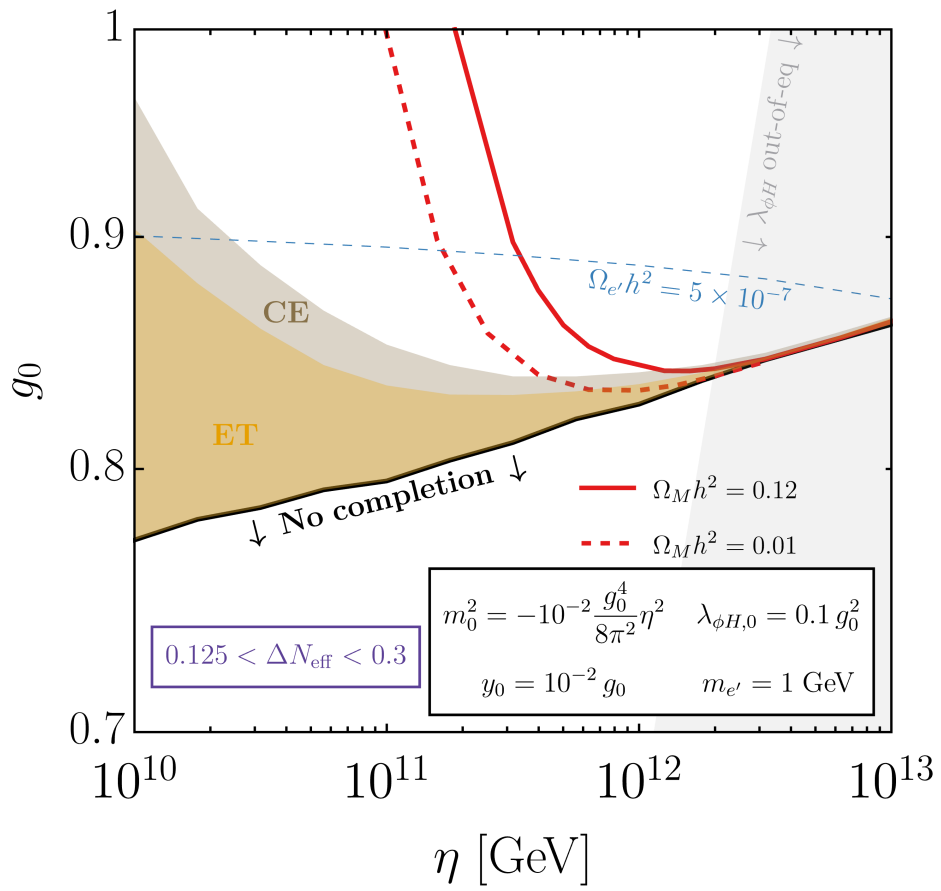
Abundance given by annihilation. Compatibility with $\Delta N_{\rm eff}$ constraints is marginal.

Dark monopoles with dark fermions: weakly FOPT



Abundance from production/annihilation for large/small g. If $v_{\rm wall}$ is small enough, monopole dark matter can be dominant while all $\Delta N_{\rm eff}$ constraints are evaded. Possible? Simulations must decide.

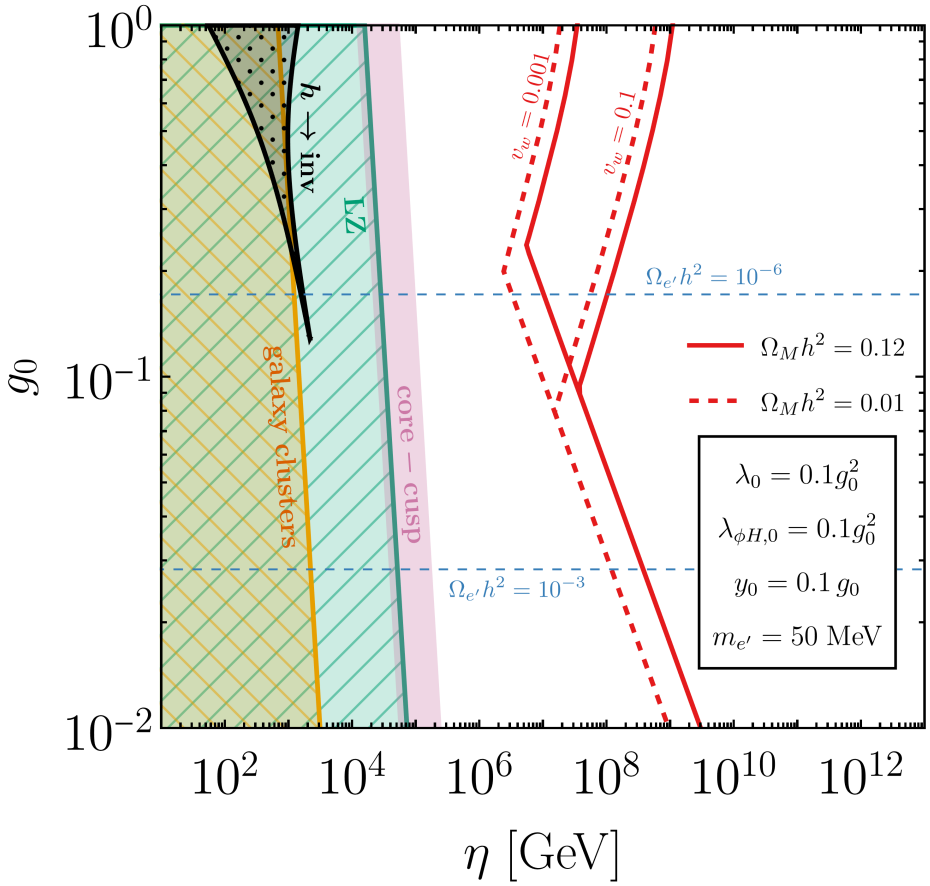
Dark monopoles with dark fermions: strongly FOPT



Compatibility with $\Delta N_{\rm eff}$ constraints is marginal. Future gravitational wave detectors (Cosmic Explorer, Einstein Telescope) might see the phase transition if we're very lucky.

Phenomenology

The model is largely unconstrained except for $\Delta N_{\rm eff}$. Monopoles are very heavy and therefore very rare if they make up the dark matter. E.g. for weak first-order phase transition:



The price for monopole dark matter

Conclusion 2

Monopoles can be the dominant part of dark matter, if the lightest electrically charged particle has mass $\ll m_{W'}$.

This model is on the brink of being ruled out by ΔN_{eff}.

- Future measurements (Simons observatory...) will exclude it, unless they see hints for $N_{\text{eff}} > N_{\text{eff,SM}}$
- Less minimal models with more light d.o.f. will be even more constrained

Moreover, the model requires some fine-tuning to have $m_{e'} \ll m_{\mu'}$.

The price for monopole dark matter

While our numerical results are model-dependent,
the **lessons learned** are general:

- Field-theoretic dark monopoles come with dark massive gauge bosons
- For these to be subdominant in the dark matter abundance, they must decay (or otherwise be diluted)
- The decay products will likely contribute to ΔN_{eff}

Ways out? (Some wildly speculative)

Relax some of our assumptions, e.g.

- No thermal contact between SM and dark sector
- More complicated phase transition dynamics, e.g. nontrivial interference with the electroweak PT
- Other monopole production mechanisms: parametric resonance, BH decay (?), . . .
- Monopoles with different microscopic structure (from extra dimensions? string theory?)