The sorrows of old Monopole

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with **Felix BRUMMER, Giacomo FERRANTE, Théodore FISCHER**

*** No room for monopole dark matter,** arXiv:2509.21924

*** The price for monopole dark matter,** in preparation

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Outline

* Why no observable magnetic monopoles ?

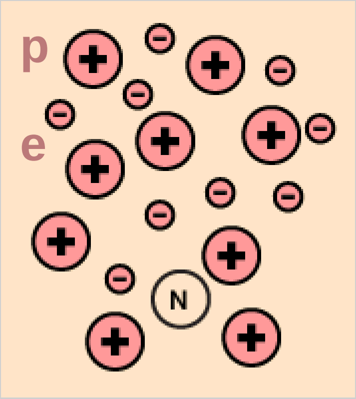
* Dark magnetic monopoles: can they be dark matter ?

* Monopole relic abundance from phase transitions

* Comparing abundances of electric & magnetic relics

Why no magnetic monopoles?

Electric monopoles (charges) :



Magnetic monopoles : never observed

$$F_M = n_M v \lesssim 10^{-16} cm^{-2} s^{-1}$$

(variety of cosmo / astro / direct bounds)

e.g. Mavromatos, Mitsou, 2020

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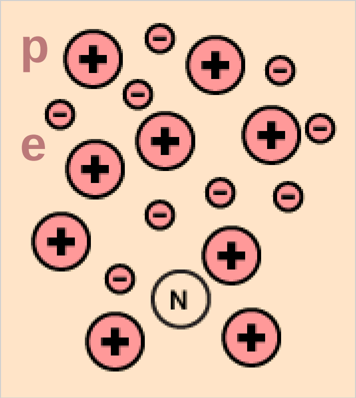

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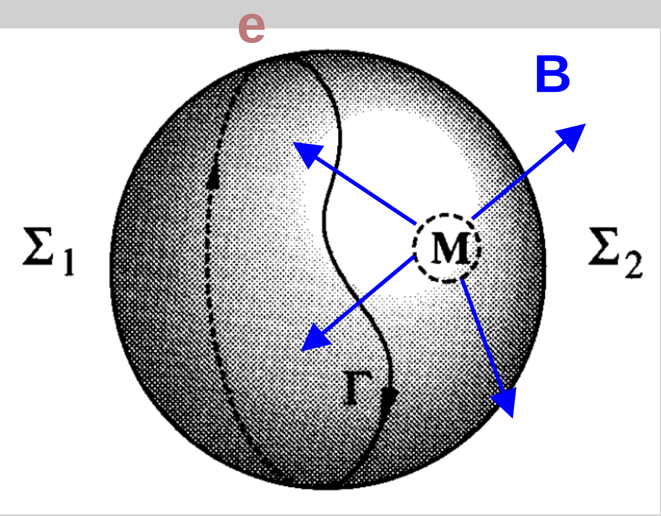
However, electric charges ARE quantised.

Dirac (1931): if a magnetic monopole exists, then charges MUST BE quantised.

$$q_E q_M = 2\pi n$$



Vilenkin Shellard 1994

Why no magnetic monopoles?

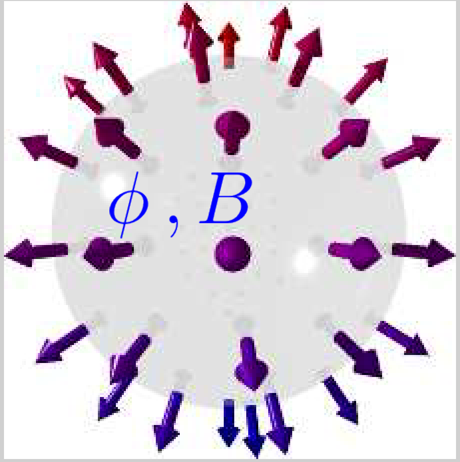
Magnetic monopoles DO exist
IF electromagnetism descends
from **simple non-abelian symmetry**

$$SO(3) \xrightarrow{\langle \phi_3 \rangle} U(1)_{em} \simeq SO(2)$$

't Hooft 1974
Polyakov 1974

Vacuum manifold
(minima of scalar-field potential)

$$\frac{G}{H} = \frac{SO(3)}{SO(2)} \simeq S^2$$



Maps from **dim-2 closed surfaces**
into vacuum manifold

$$\pi_2(S^2) = \mathbb{Z}$$

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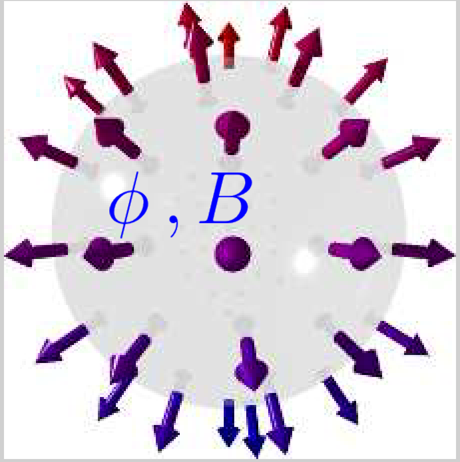

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$$\pi_2(S^2) = \mathbb{Z}$$

But, in **Standard Model** …

$$SU(2)_w \times U(1)_Y \xrightarrow{\langle \phi_2 \rangle} U(1)_{em}$$

… no monopoles !

$$\pi_2(S^3) = 1$$

Why no magnetic monopoles?

Grand Unification

$$SU(5) \xrightarrow{\langle \phi_{\mathbf{24}} \rangle} SU(3)_c \times SU(2)_w \times U(1)_Y$$

… far too many monopoles !

$$F_M = n_M v \sim 10^{-2} cm^{-2} s^{-1}$$

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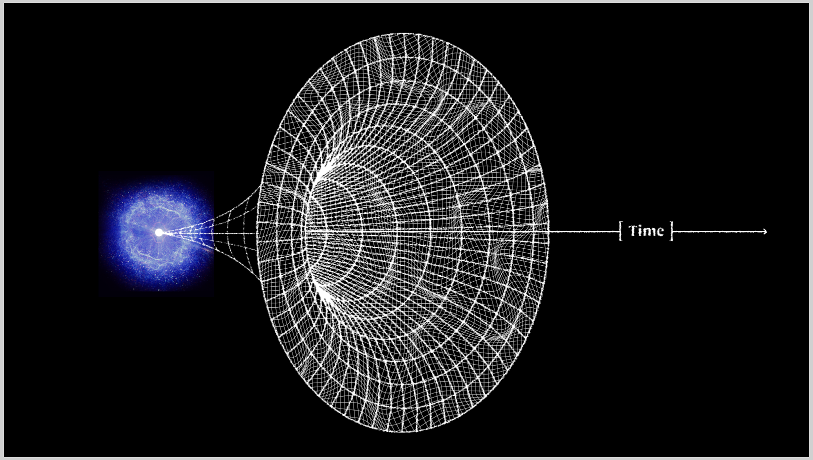
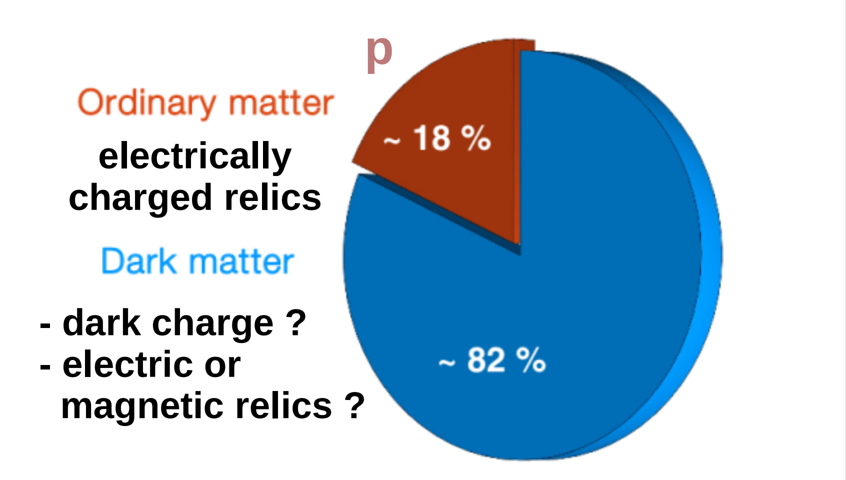


Inflation exponentially dilutes relic abundances, solving monopole problem as long as

$$T_{inf} < T_{GUT}$$

¨Monopoles are a sharp prediction of Grand Unification, but possibly the only monopole in the Universe passed by the Earth just before we built the detector¨ ***G. Senjanovic***

Dark monopoles as dark matter ?



Dark gauge symmetry. Motivations:

- analogy with visible sector

- lightest charged particles are absolutely stable

- calculable relic abundances

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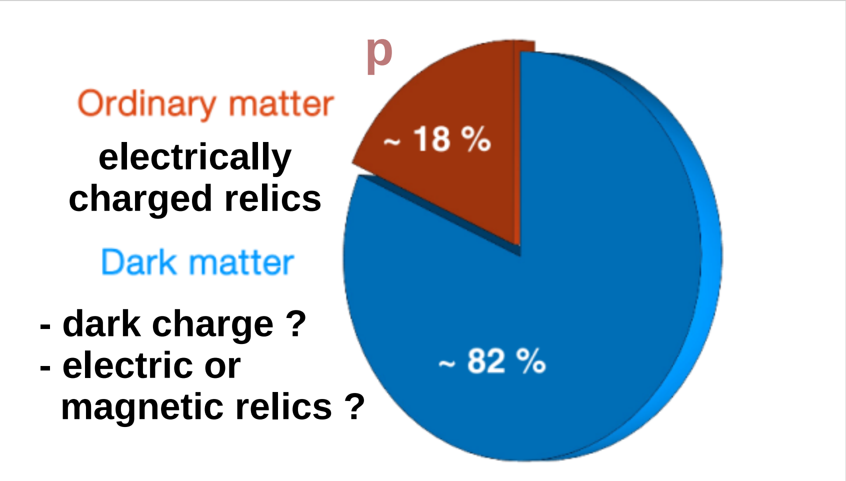

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While dark electrically-charged particles are widely studied, only few interesting papers on **dark magnetic monopoles**

Murayama, Shu, 2009
Baek, Ko, Park, 2013
Khoze, Ro, 2014
...

Limitations of available analyses:

- *only second-order phase transition*
- *either electric counterpart ignored, or restrictive range for parameters*
- *overestimate of monopole abundance, in some cases*

Minimal dark sector

‘t Hooft 1974
Polyakov 1974

SO(3) spontaneous breaking to SO(2)

$$0 < g \ll 4\pi$$

dark SO(3) gauge coupling

scalar self-coupling

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

symmetry breaking scale

$$m_W = g\eta \ll m_M \simeq \frac{4\pi}{g}\eta$$

$$r_M \simeq \frac{1}{m_W} \gg \frac{1}{m_M}$$

Monopole is large, classical field configuration

$M^{\pm}_{mag}$

$W^{\pm}_{ele}$

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Portal between **dark sector** & **visible sector**

$$V_{portal} = \frac{\lambda_{\phi H}}{2}\,\phi^a\phi^a\,H^\dagger H$$

(i) thermalisation at phase-transition time

(ii) small perturbation to dark thermal potential

$$\left(\frac{T_c}{10^{14}\mathrm{GeV}}\right)^{1/2} \lesssim \lambda_{\phi H} \ll \lambda, g^2$$

Monopoles from phase transition

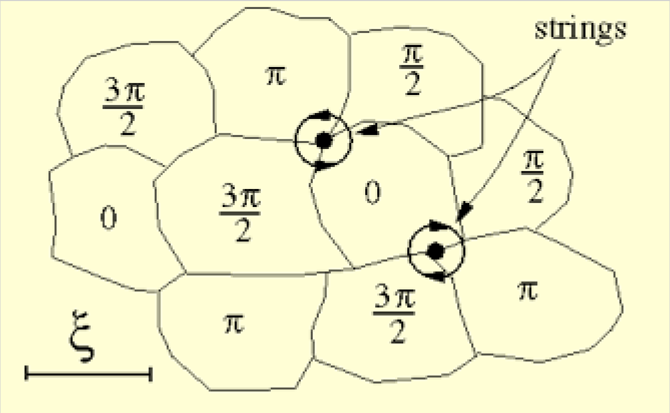
Kibble mechanism to form topological defects:

symmetry restoration at large T $\quad \langle \phi_a \rangle = 0$

phase transition below T_c $\quad \langle \phi_a(\mathbf{x}) \rangle = \eta \, \hat{\mathbf{n}}(\mathbf{x})$

scalar-field correlation length is finite $\quad n_M \simeq \dfrac{1}{8\xi^3}$

Kibble 1976



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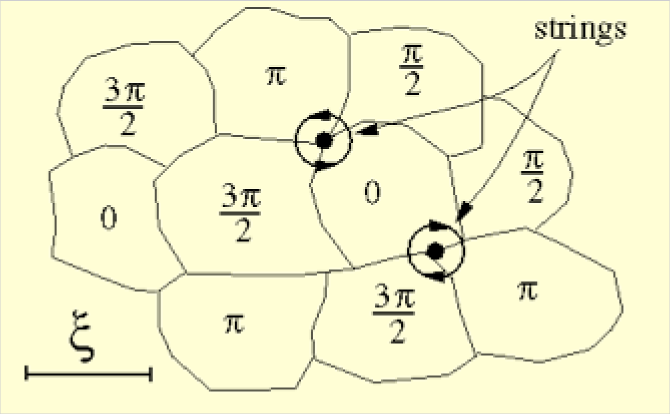

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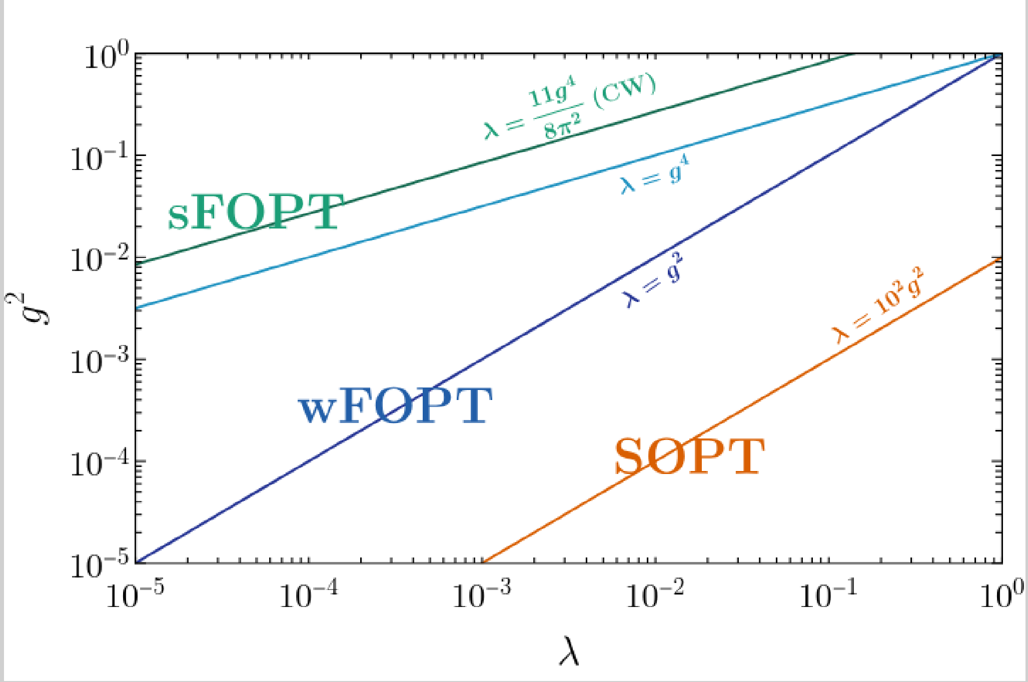


Correlation length strongly depends on **Order of Phase Transition:** Second, weakly First, strongly First.

Order depends on **shape of scalar thermal potential,** determined by field couplings.

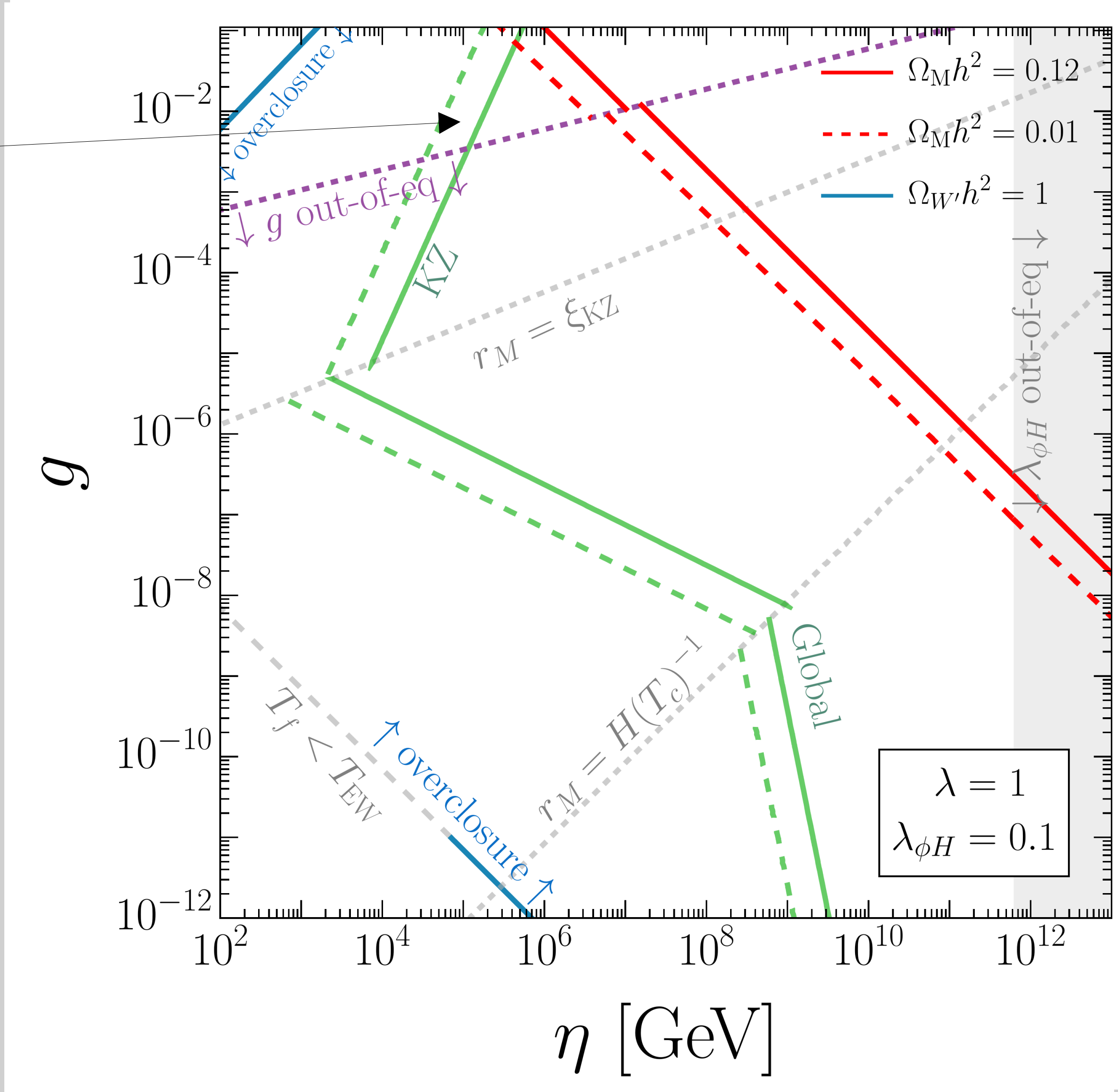
$M^{\pm}_{mag}$ $W^{\pm}_{ele}$

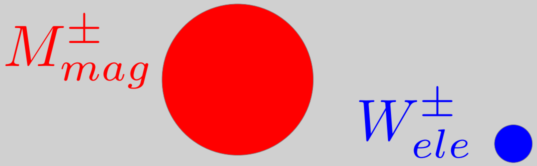
Second order

In principle correlation length diverges at T_c
but **time to relax is finite** due to expansion

$$\xi_{KZ} \simeq \frac{1}{H(T_c)} \left[\frac{H(T_c)^2}{2\lambda\eta^2} \right]^{0.29}$$

Kibble 1976
Zurek 1985





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W thermal bath **dissipates energy of monopoles** which thus can annihilate

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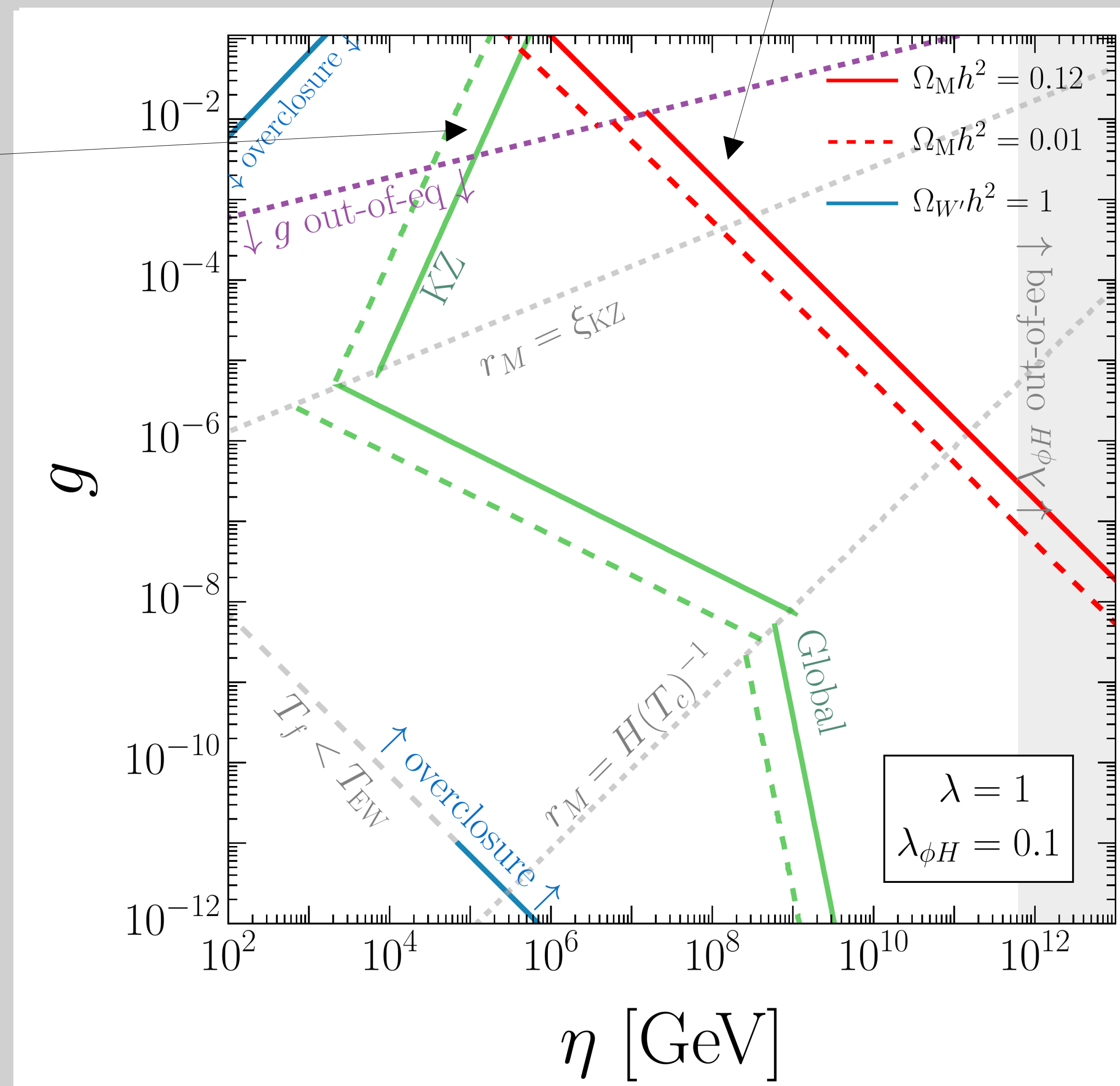

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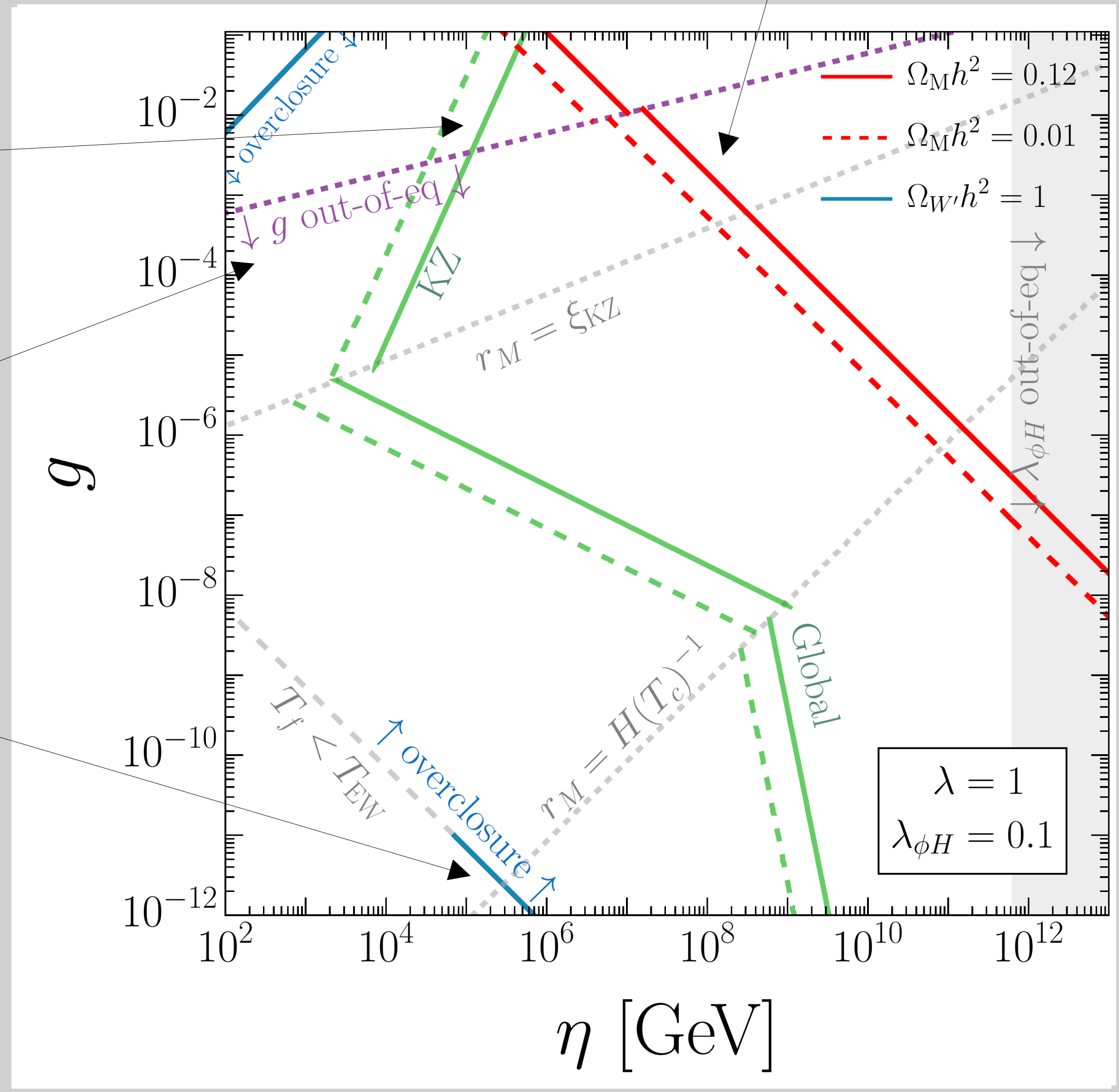
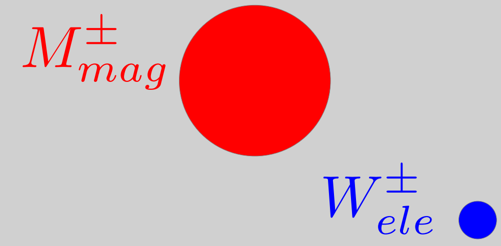
For small g transverse W's are sub-thermal

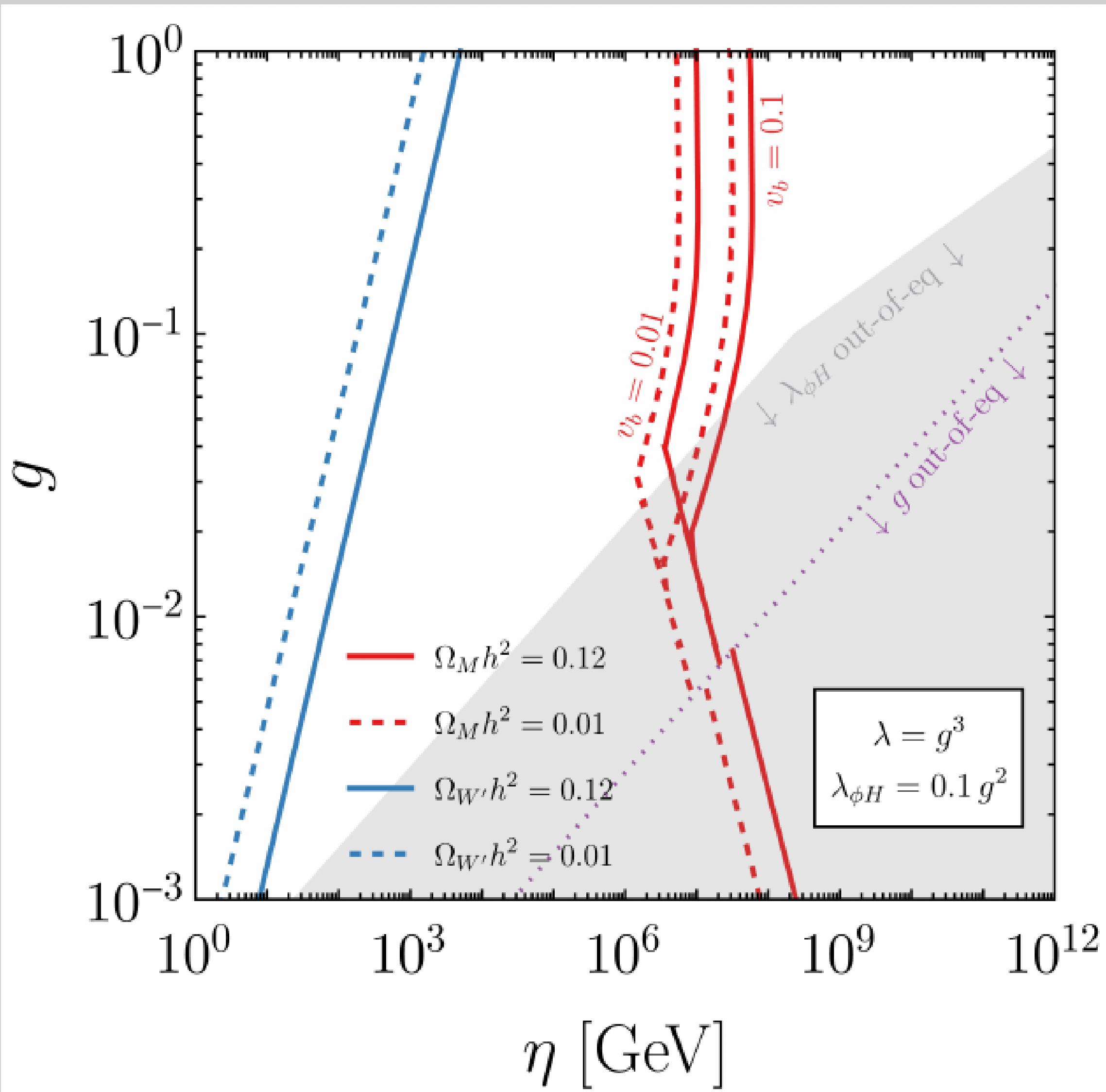
However **longitudinal W's** necessarily thermalised (as they belong to scalar)

Therefore, freeze-out determines W abundance





Weakly first order



Potential barrier present at T_c

Thermal fluctuations allow **nucleation of bubbles of true vacuum**

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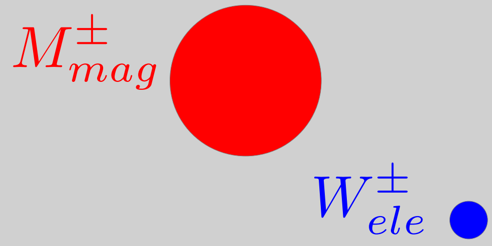

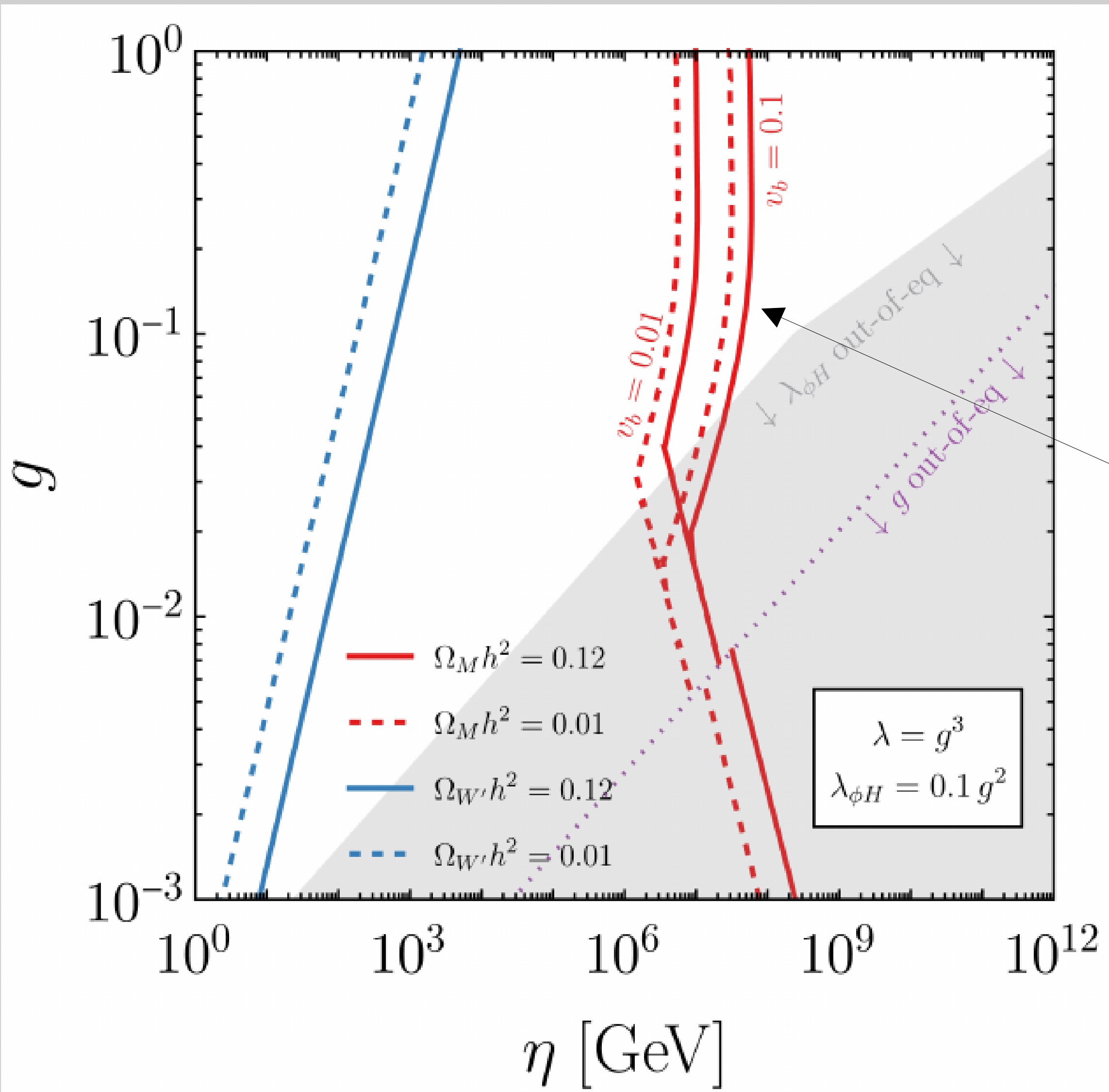

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Thermal fluctuations allow **nucleation of bubbles of true vacuum**

Bubble radius at percolation determines correlation length

$$\xi \simeq R_p \simeq 4.4 v_b \left[\frac{d \log \Gamma(t)}{dt} \right]^{-1}_{t_p}$$

Nucleation rate per unit volume:

$$\Gamma(T) \simeq T^4 e^{-S_3/T}$$

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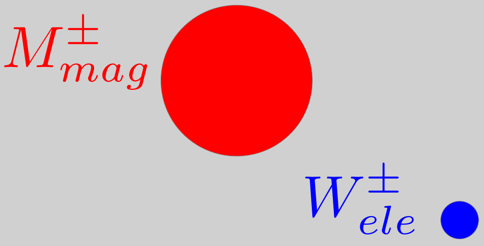

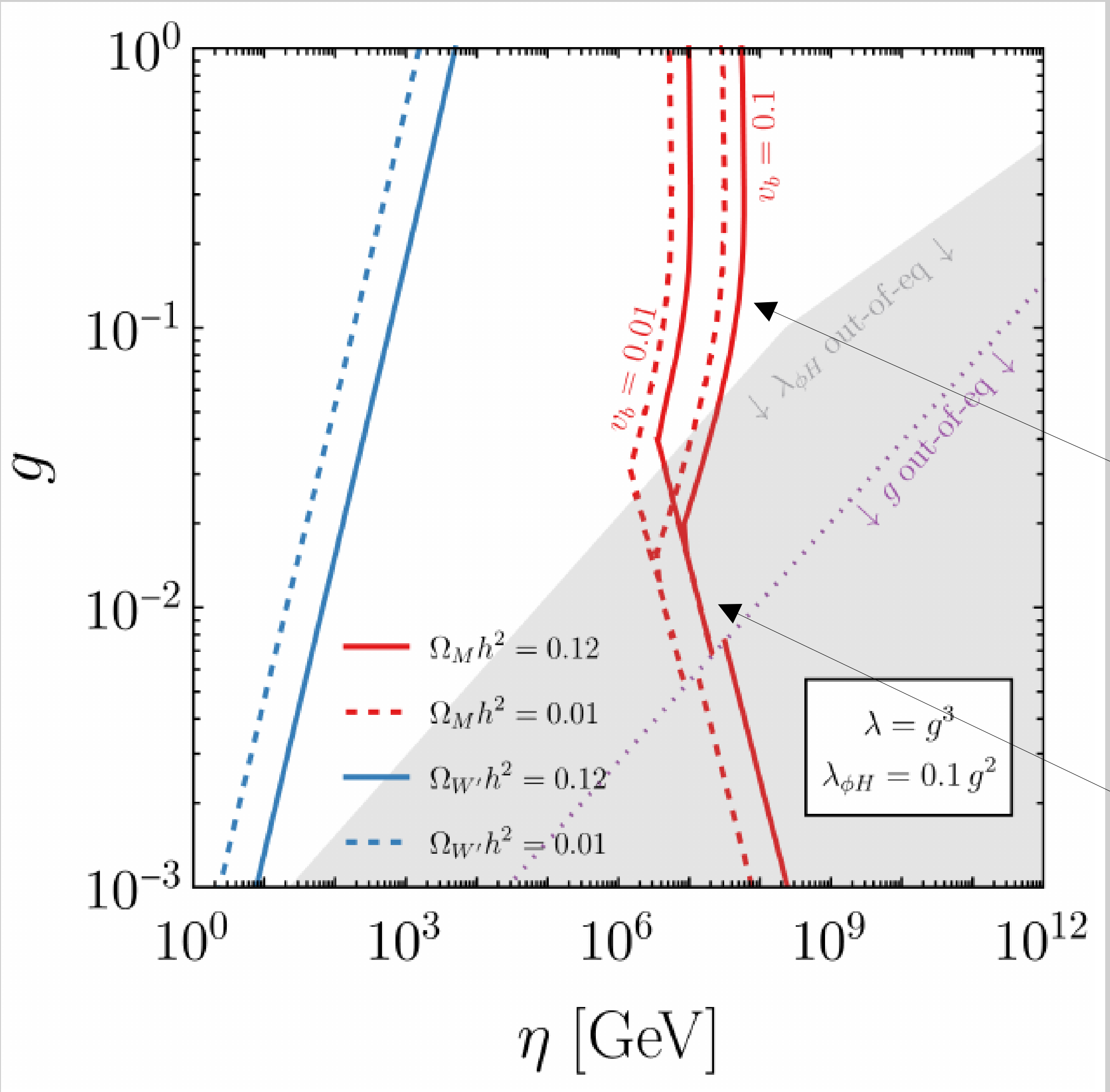

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Later monopole annihilations further reduce abundance

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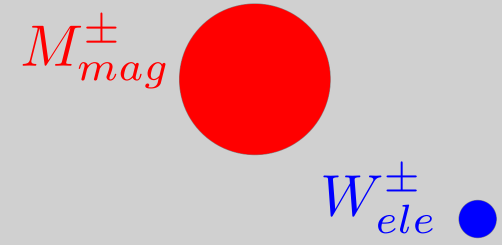
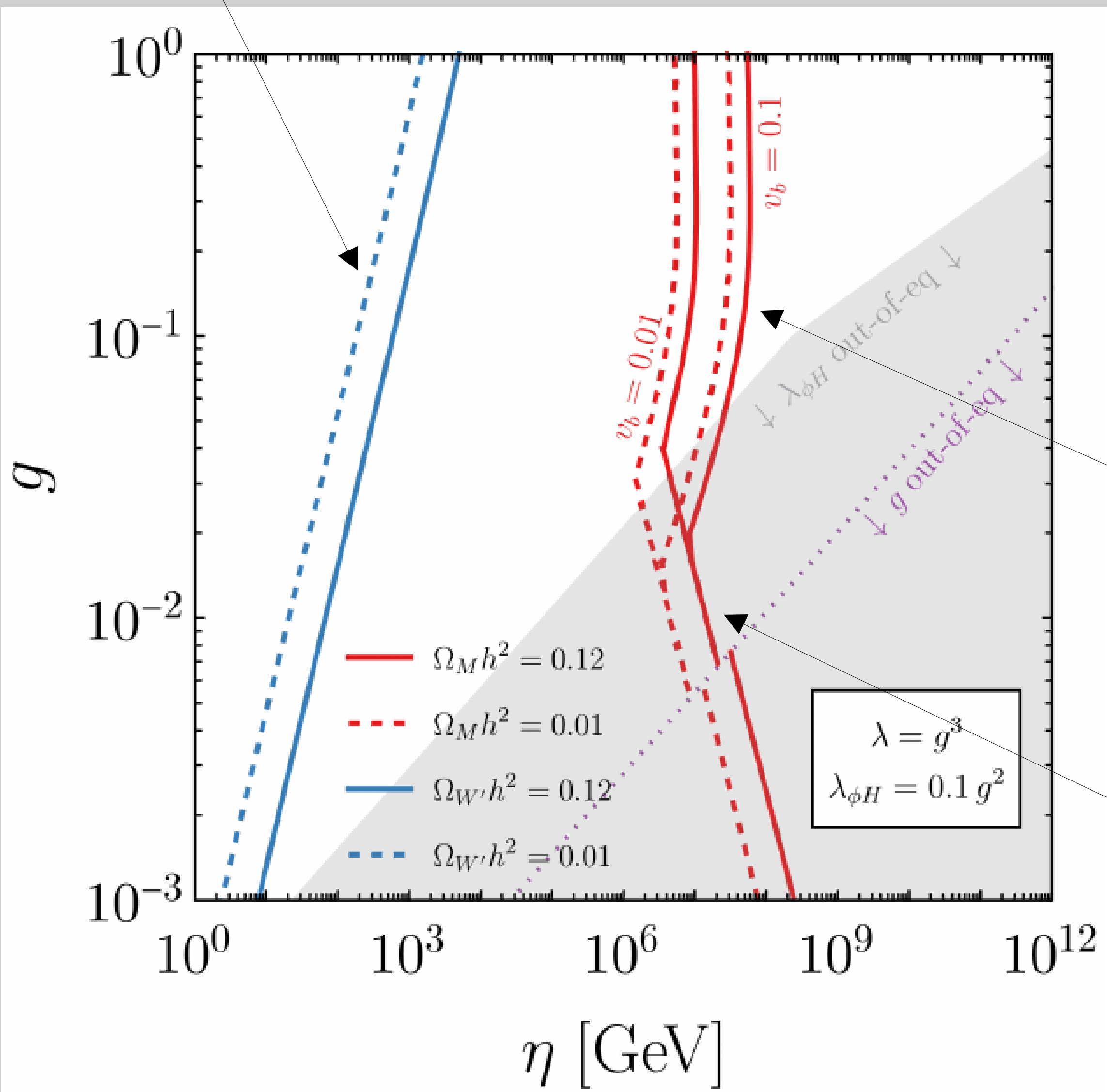


W freeze-out
dominate dark-matter abundance



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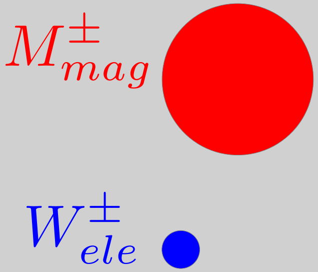
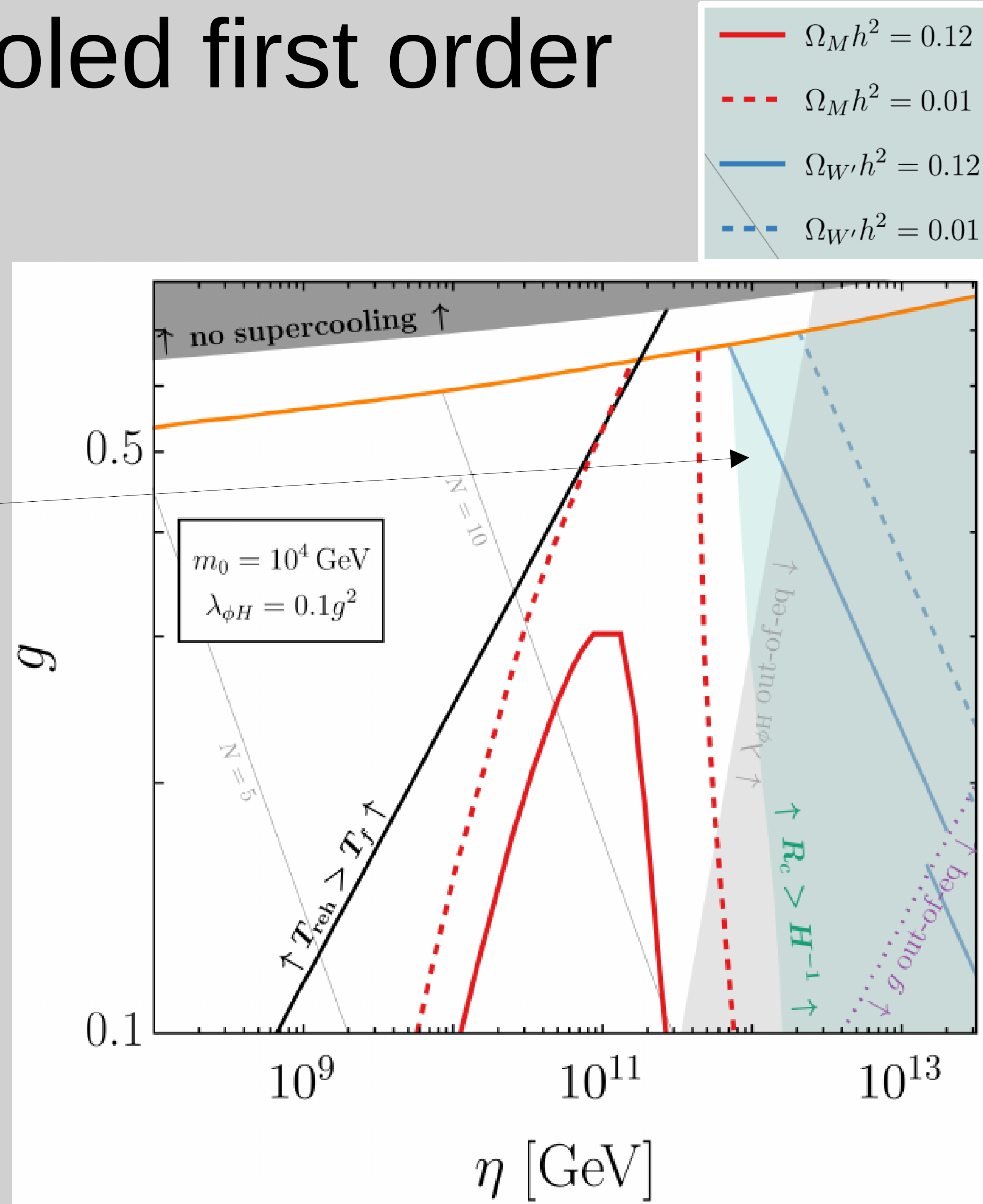


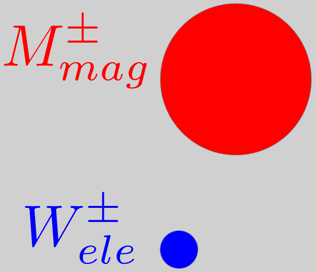
Supercooled first order

Universe stuck in false vacuum till it becomes vacuum-dominated

Supercooling: several e-folds of inflation before bubble nucleation

W's diluted exponentially





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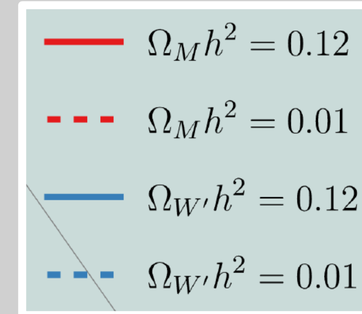

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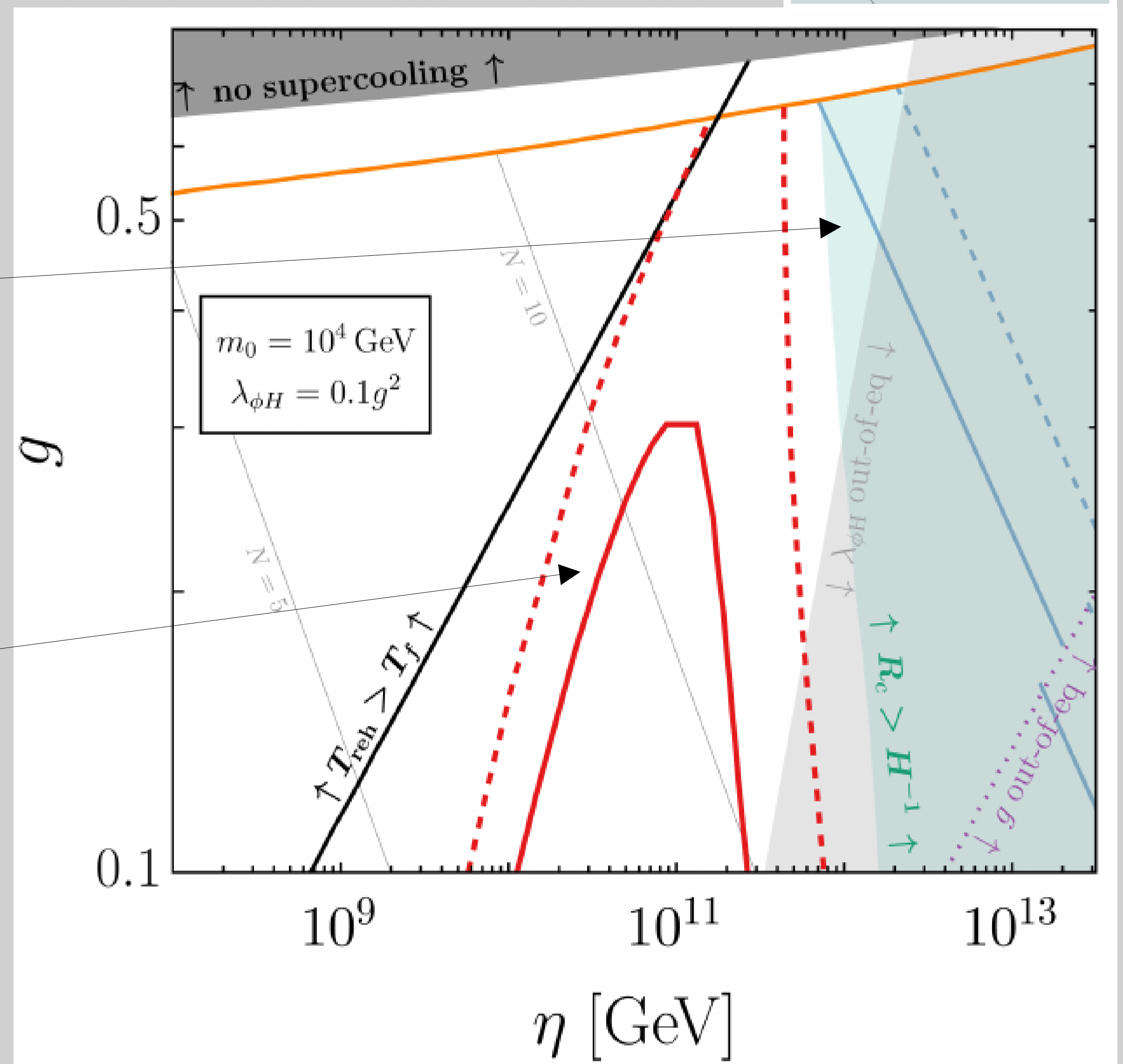

Longer the supercooling, larger the initial **critical bubble radius**

$$\xi \simeq R_p = R_{critical} + R_{expansion}$$

Monopole abundance peaks at minimal radius, and drops before reaching W abundance

Dark matter goes electric !

F. Brummer, G. Ferrante, T. Fischer, M.Frigerio

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In all cases, a small fraction of dark matter is made by monopoles

***Electric relics** abundance >> **Magnetic relics** abundance*

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Phenomenological 'theorem' for the minimal dark sector :

For any symmetry breaking scale η ,
for any perturbative values of the couplings g & λ ,
one has $\Omega_W \gg \Omega_M$

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[Note: dark-matter candidates are very many,
well-motivated ones are a few,
and it is very hard to fully exclude any]

Ways out for monopole DM

F. Brummer, G. Ferrante, T. Fischer, M.Frigerio
***The price for monopole dark matter*, in preparation**

- *The Grand-Unification way:*

Electric relics from phase transition decay into lighter particles

$$\text{Fermions } \psi \sim \mathbf{2}_{SO(3)} \quad : \qquad W^{\pm} \to \psi^{\pm 1/2} \psi^{\pm 1/2}$$

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However, no much space to hide a light dark sector:

- dark-fermion relic abundance must be suppressed

- only dark photon must contribute to dark radiation, for viable N_{eff}

Ways out for monopole DM

- *The portal way:*

Electric relics annihilate efficiently into Standard Model particles:

$$\text{large Higgs portal } \lambda_{\phi H} > \lambda, g^2$$

Ways out for monopole DM

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Scalar thermal potential strongly deformed

- modified nature of dark phase transition affects monopole abundance

- necessary interplay with electroweak phase transition: signatures?

Ways out for monopole DM

- *The topological way:*

Different symmetry breaking leads to different topological defects

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“ Alice’s ” electromagnetism is non-abelian !

- both monopoles & cosmic strings,

with non-trivial cosmological evolution

- electric relics also have different history

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one Alice’s defect observed at Bourse du Commerce in March 2025

Supplemental material