Monopole dark matter ?

Michele Frigerio

*Laboratoire Charles Coulomb, CNRS & Université de **Montpellier***

*Laboratoire Physique Théorique Hautes Énergies, CNRS & Sorbonne Université, **Paris***

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

*** No room for minimal monopole dark matter,** PRD 113 (2026) L091701 - 2509.21924

*** The price for monopole dark matter,** 260x.xxxxx

Horizons Beyond the Standard Model

ICTP-SAIFR, São Paulo, June 1-12, 2026

LUPM
Montpellier

SPhT
Bruxelles

LUPM
Montpellier

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Outline

* Reminder: why no observable magnetic monopoles

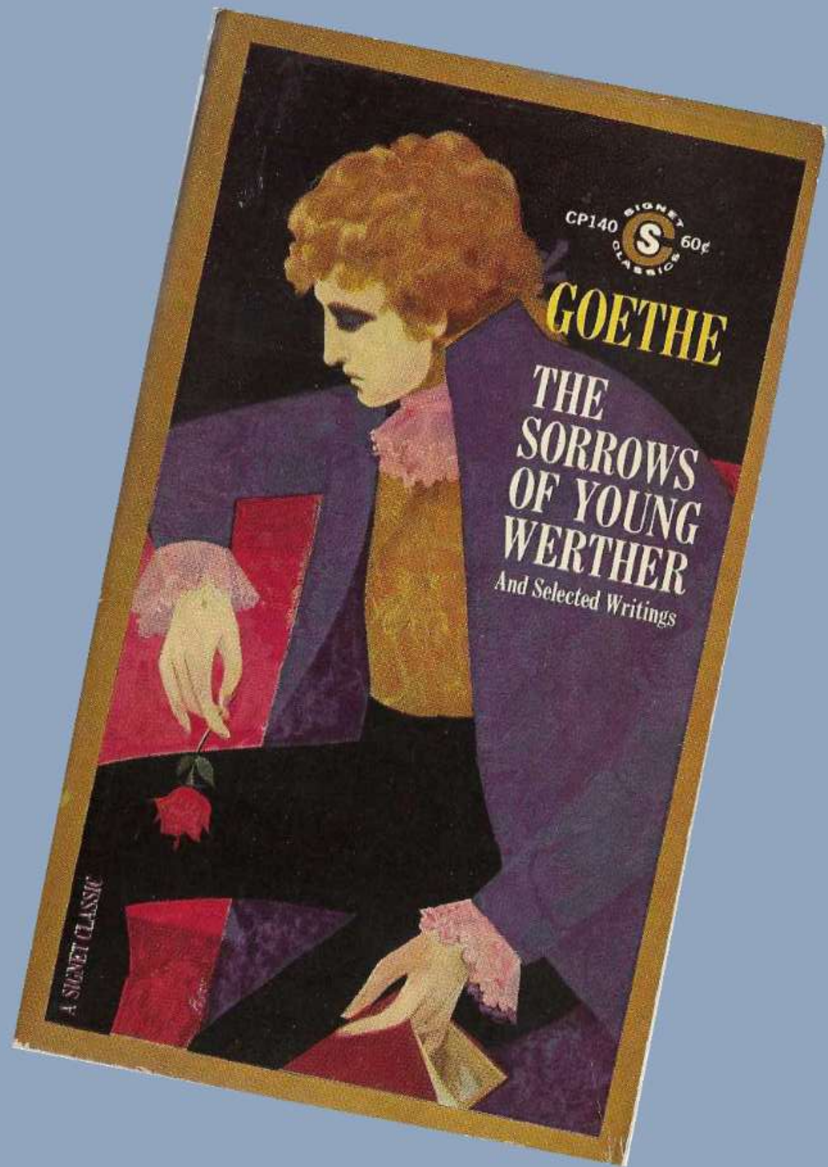
* Dark-sector magnetic monopoles: can they be dark matter ?

* Monopole relic abundance from phase transitions

* Comparing abundances of electric & magnetic relics

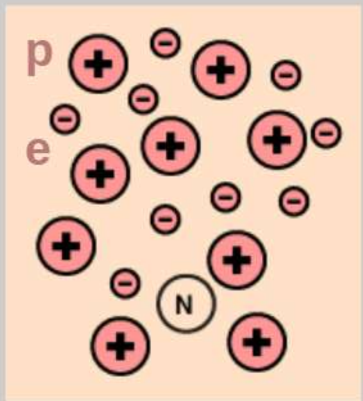
* Minimal model in details, possible extensions...

The sorrows of old Monopole



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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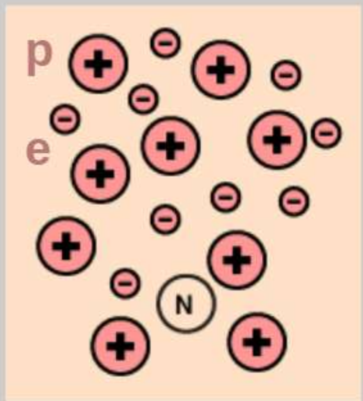

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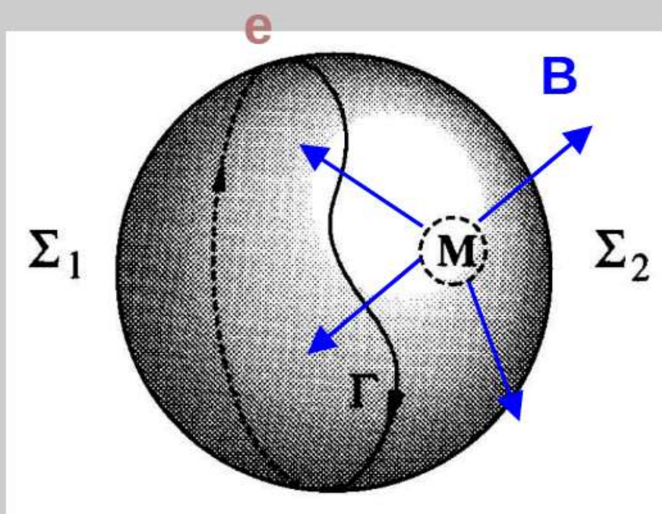
However, electric charges ARE quantised.

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
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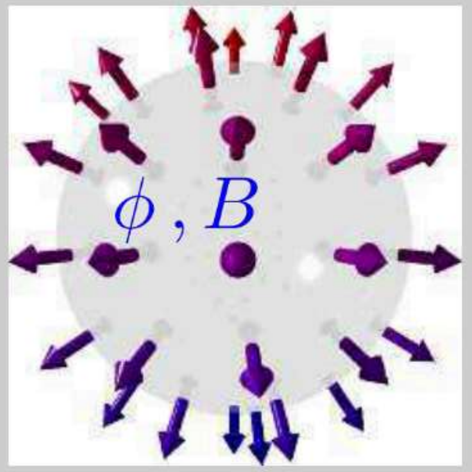

Vacuum manifold
(minima of scalar-field potential)

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

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

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

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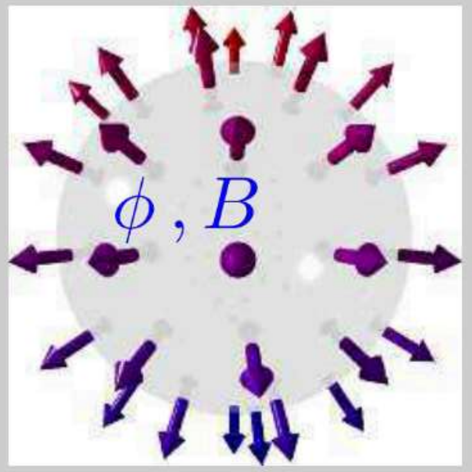

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But, in **Standard Model** …

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

$$SO(4) \xrightarrow{\langle \phi_2 \rangle} SO(3)_{custodial}$$

… no monopoles !

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

Why no magnetic monopoles?

Still, charge quantisation can be realised by **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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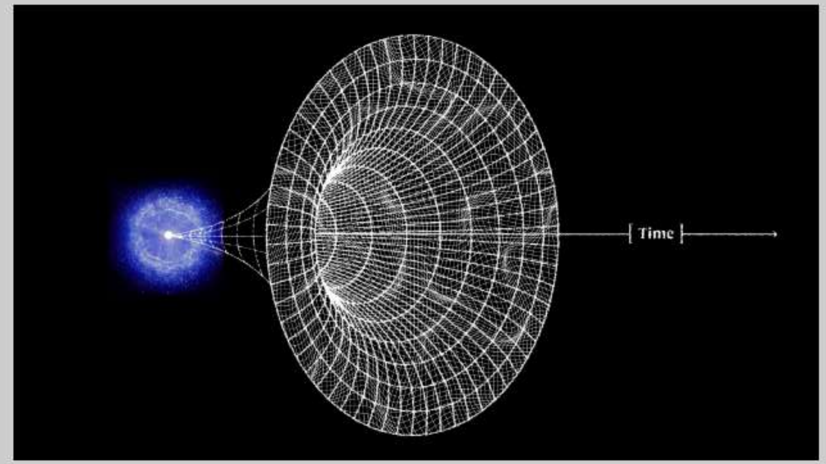
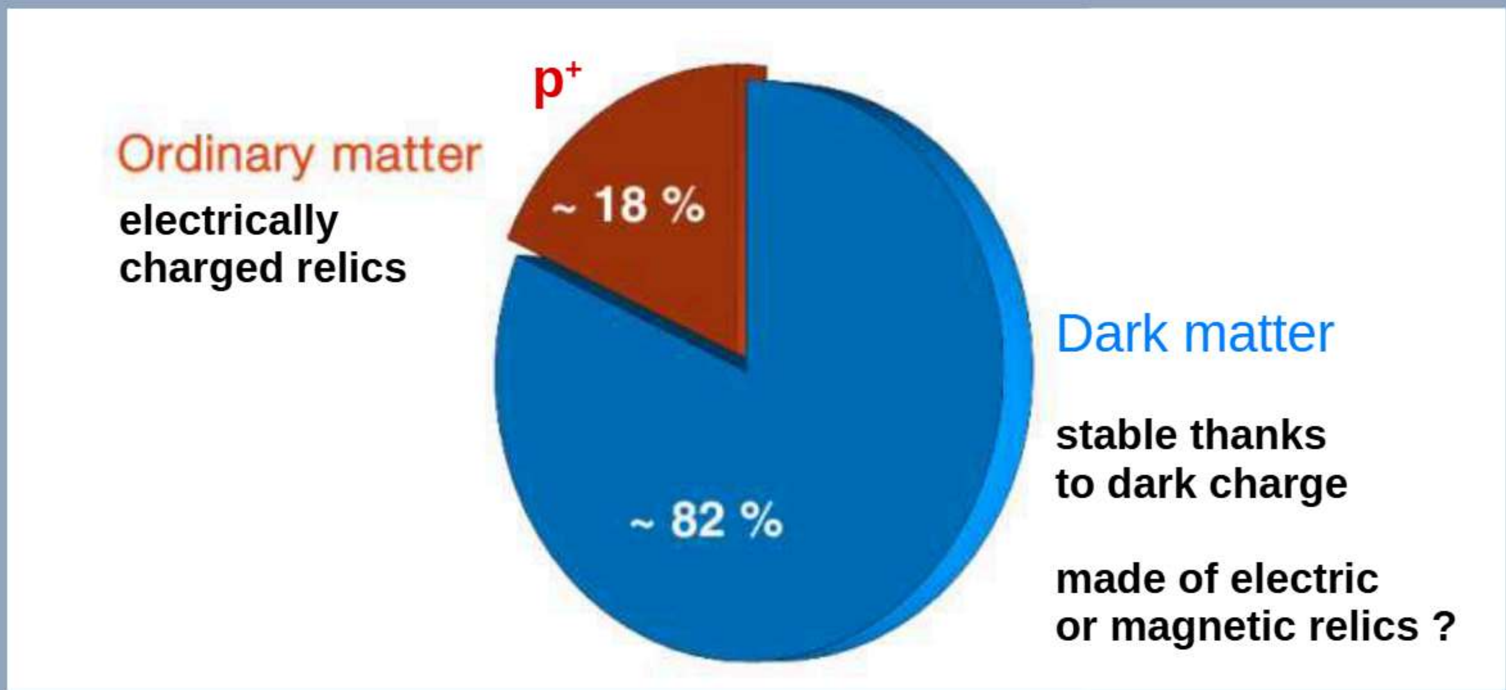


Inflation exponentially dilutes relic abundances, solving monopole problem as long as

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

¨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**

Monopoles in the dark sector ?



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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Dark electrically-charged particles widely studied.

Only few interesting papers on **dark magnetic monopoles.**

idea by
Murayama, Shu 2009,

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Limitations of available analyses:

- *second-order phase transition only*
- *electric counterpart: initially ignored, later studied in restricted range of parameters*
- *monopole abundance overestimated in some cases*

Minimal dark sector

't Hooft 1974
Polyakov 1974

SO(3) spontaneous breaking to SO(2)

scalar self-coupling

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

symmetry breaking scale

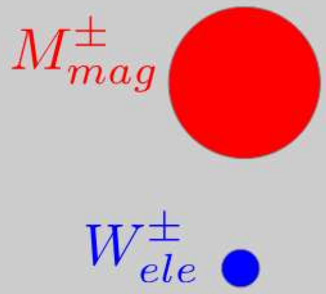
$$0 < g \ll 4\pi$$

dark SO(3) gauge coupling

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

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

Monopole is large, classical
field configuration



[CP conservation assumed for simplicity : no θ term, no dyons]

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

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

[CP conservation assumed for simplicity : no θ term, no dyons]

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

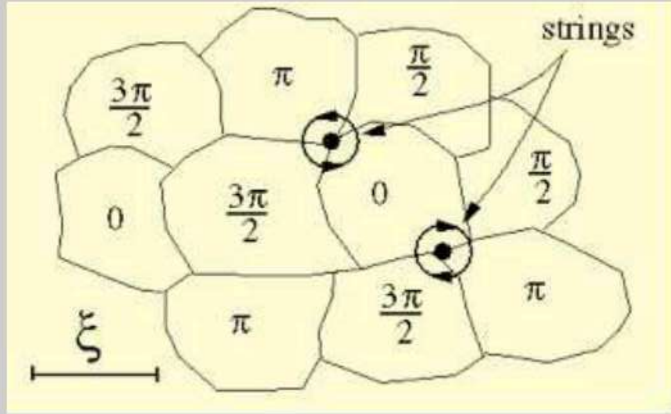
Kibble mechanism to form topological defects:

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

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

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

Kibble 1976



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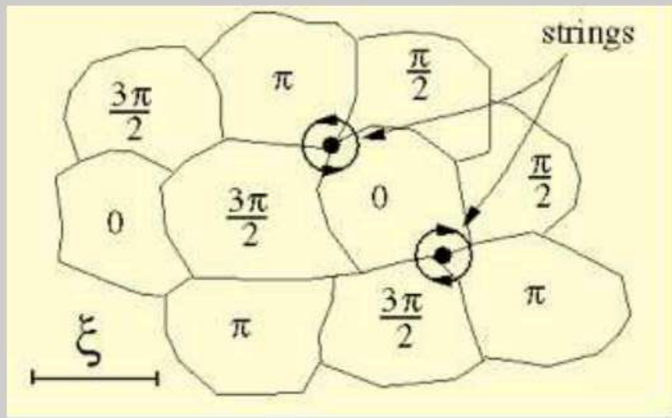

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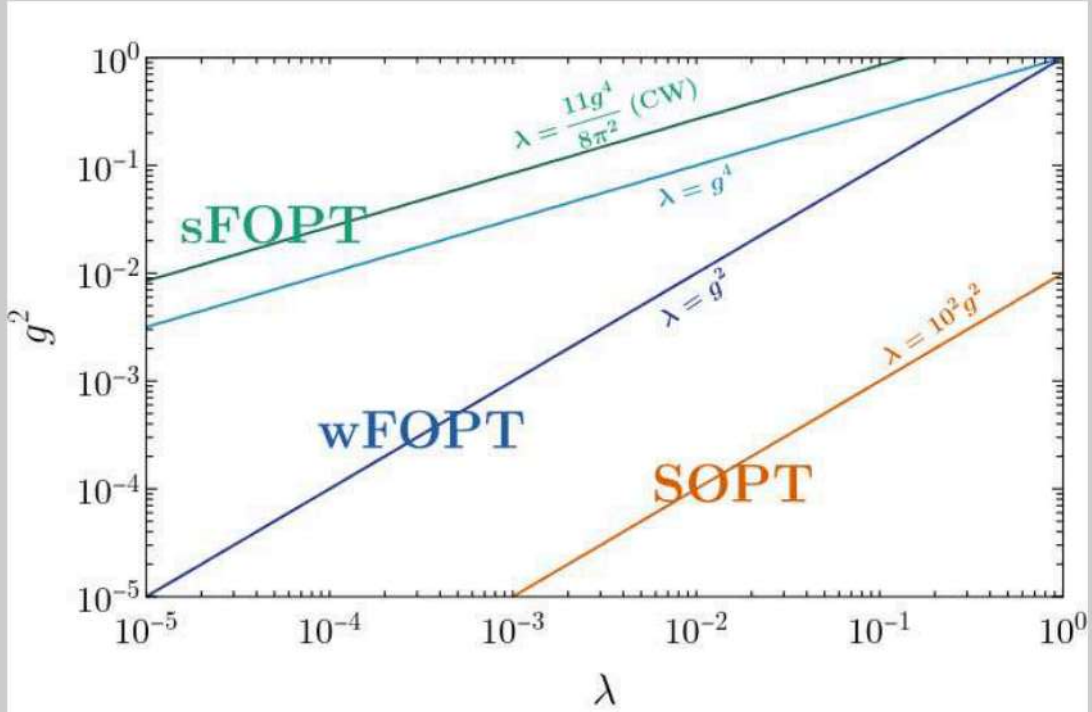
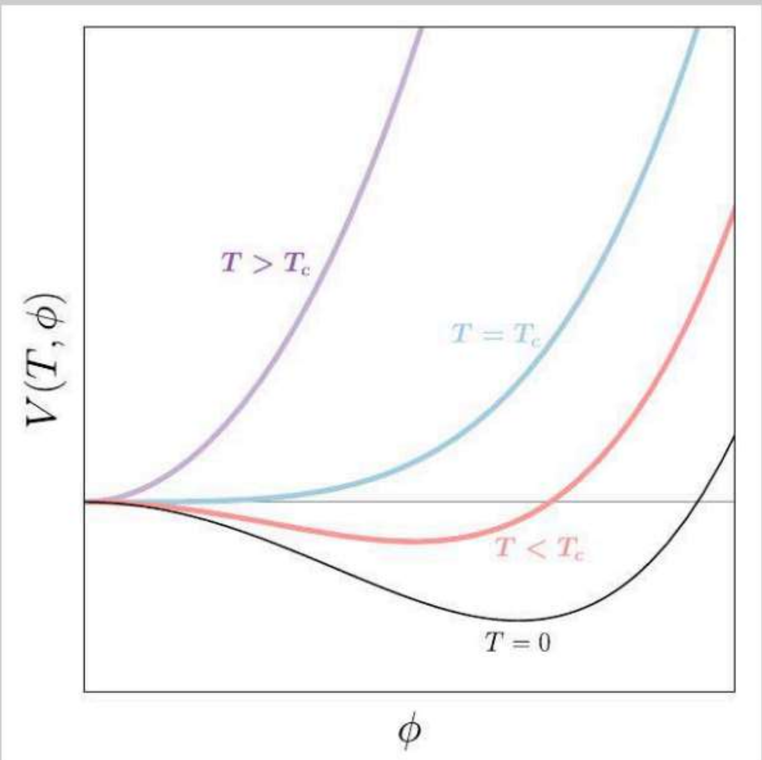


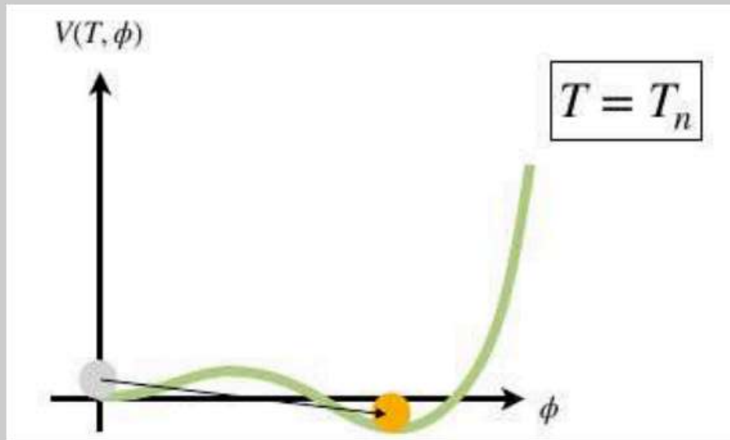
Correlation length ξ strongly depends on **Order of Phase Transition:**
Second, weakly First, strongly First

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

Scalar thermal potential

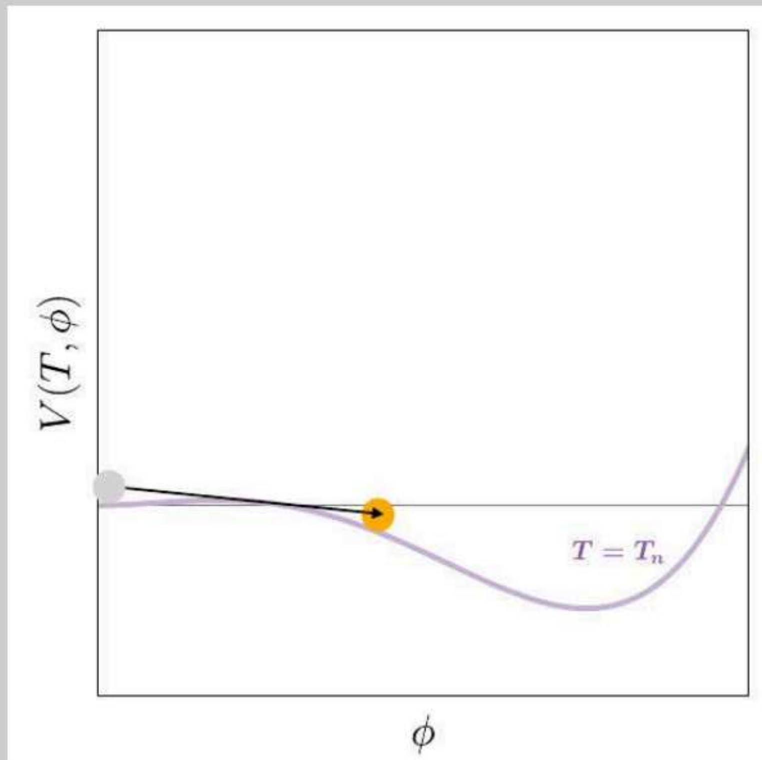
SOPT





wFOPT

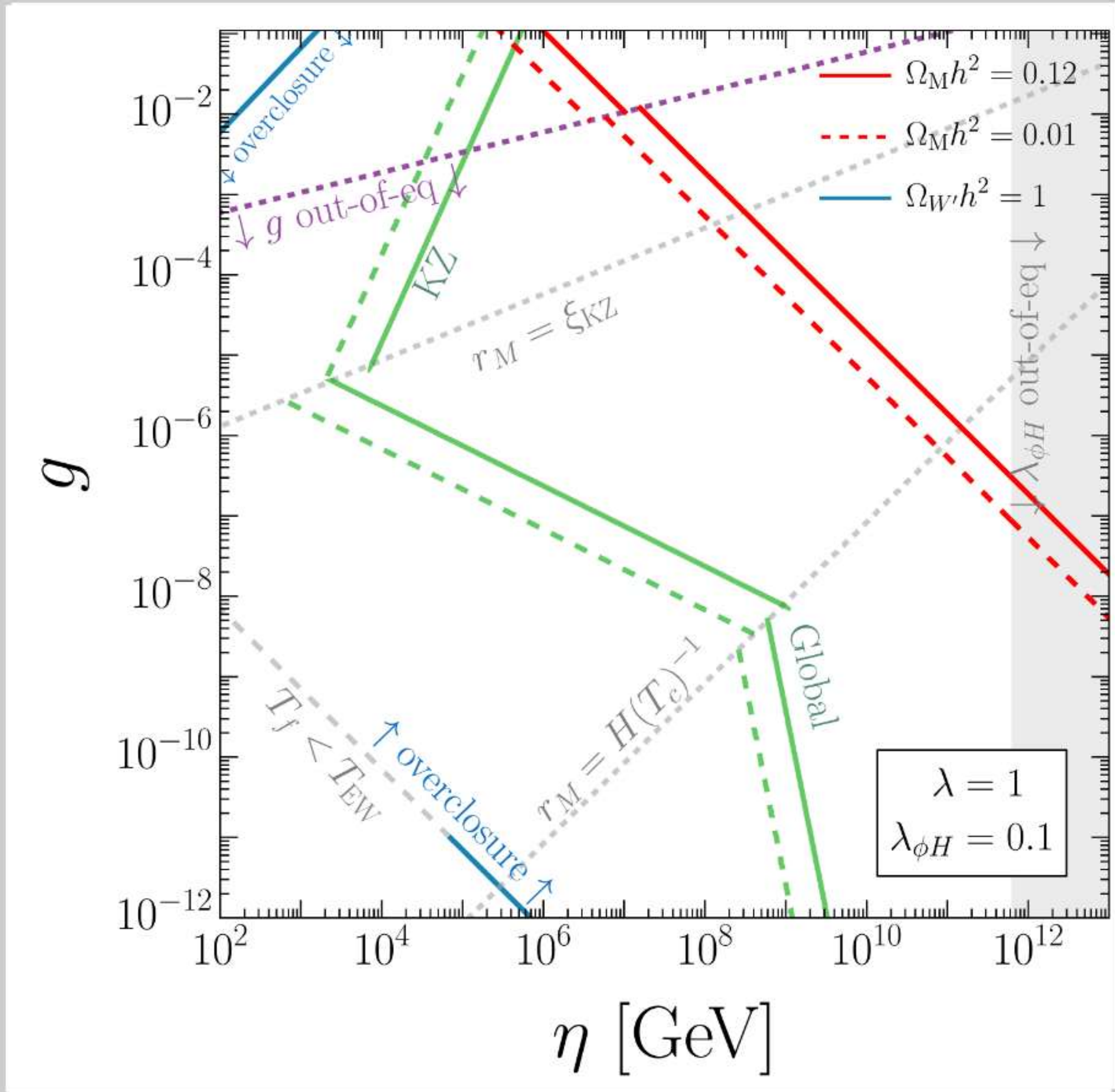
sFOPT



Pics courtesy of Giacomo Ferrante

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

Second order

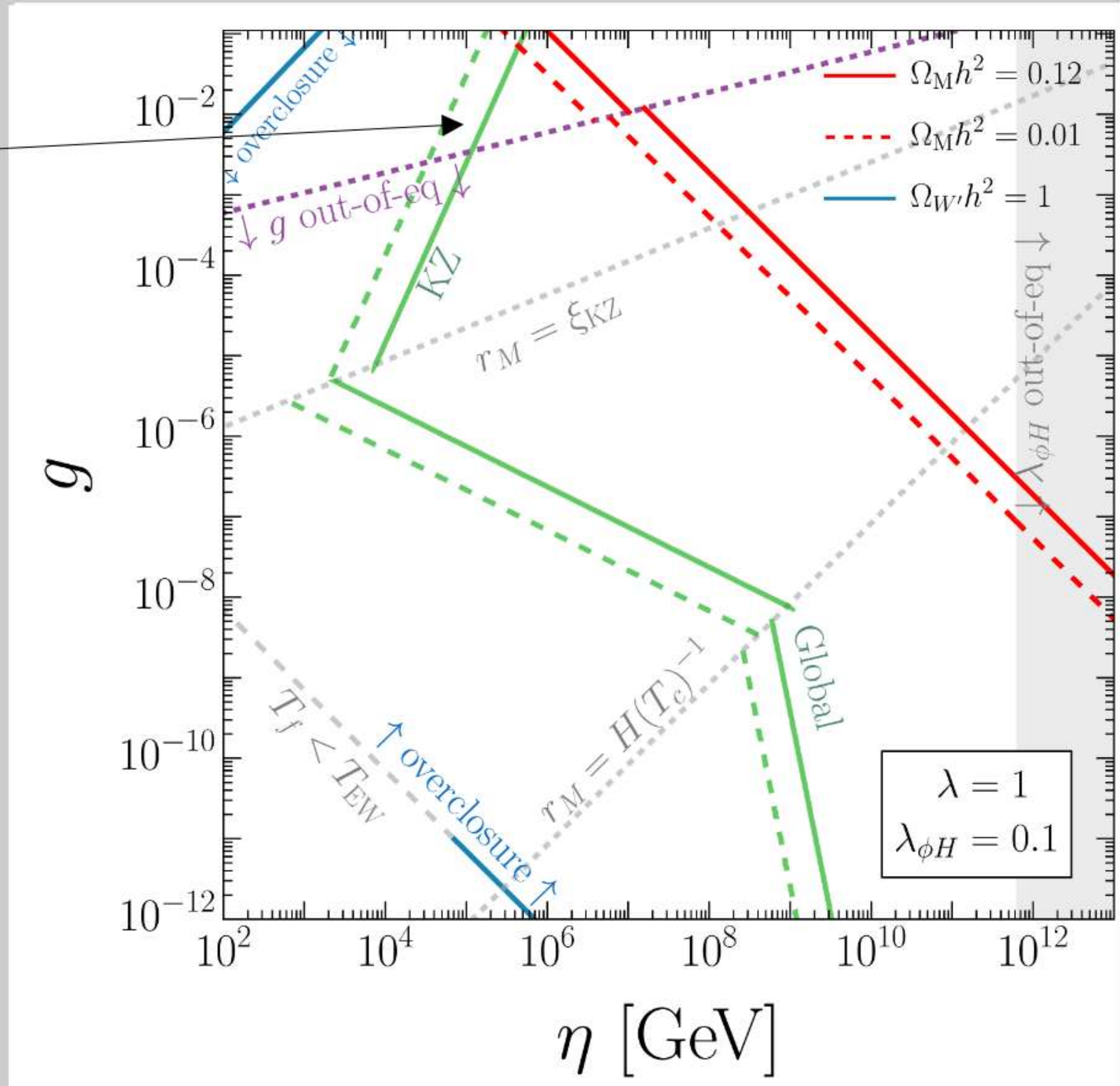


Second order

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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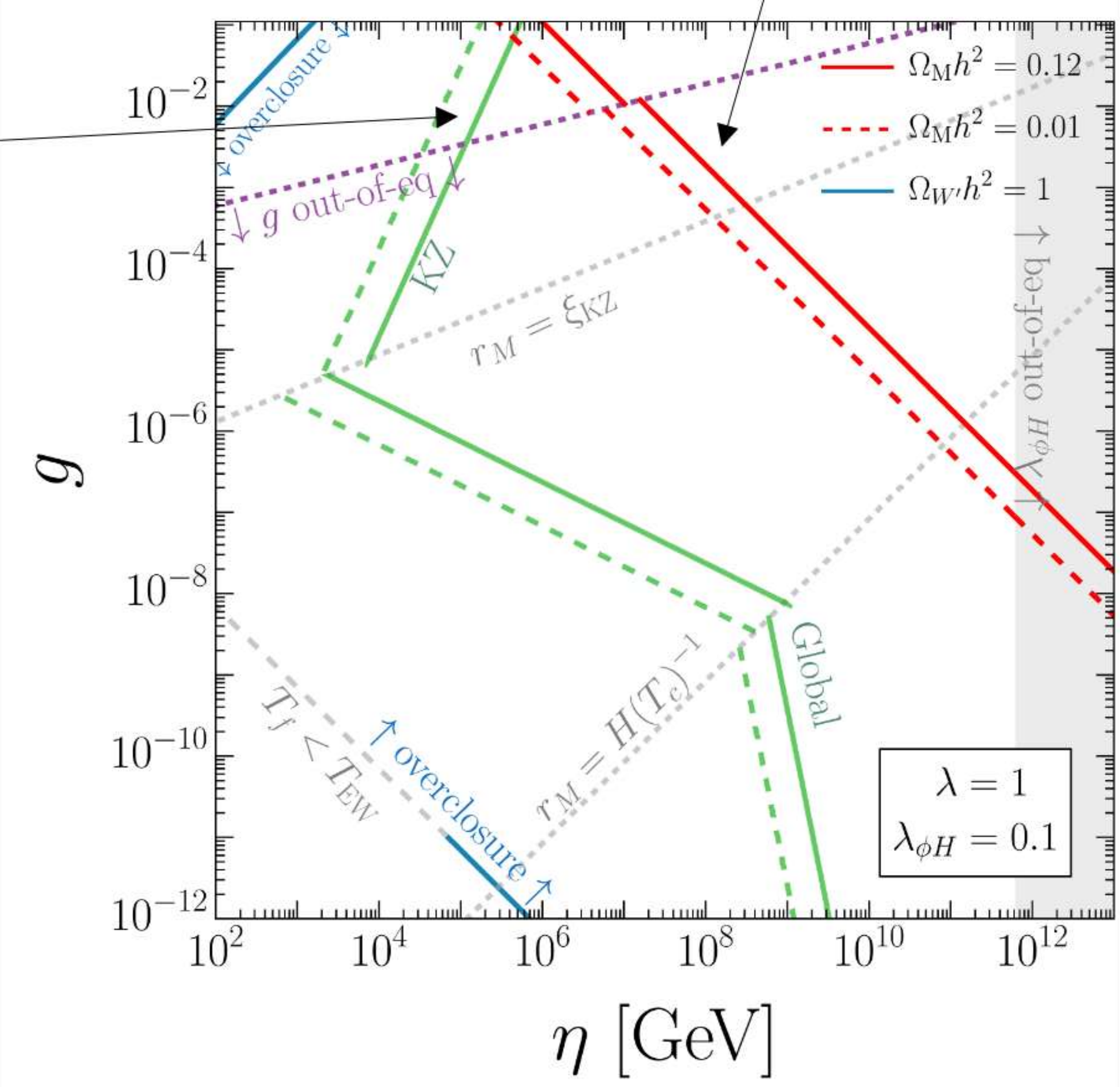

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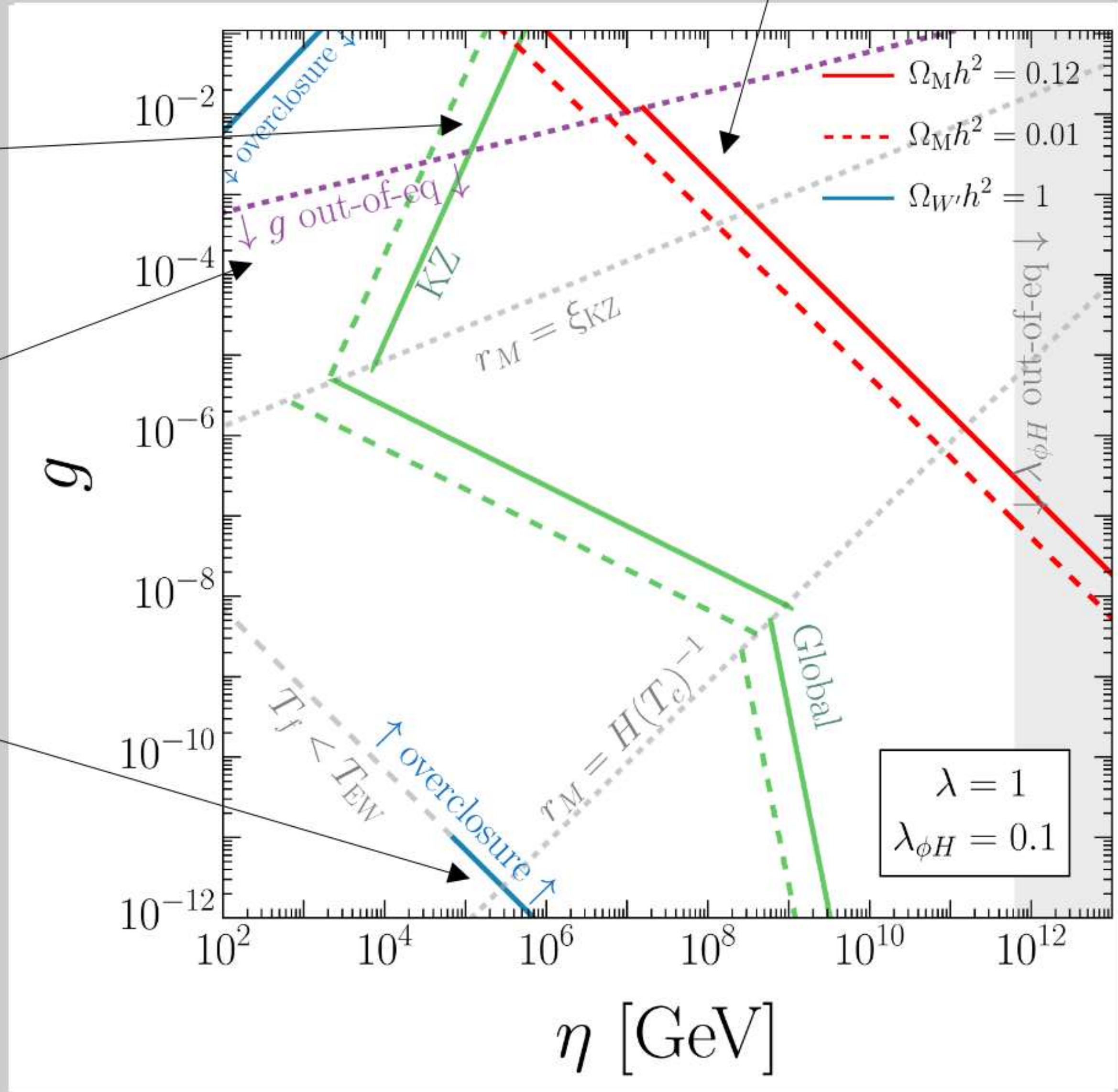
For small g transverse W's are sub-thermal

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

Therefore, freeze-out determines W abundance



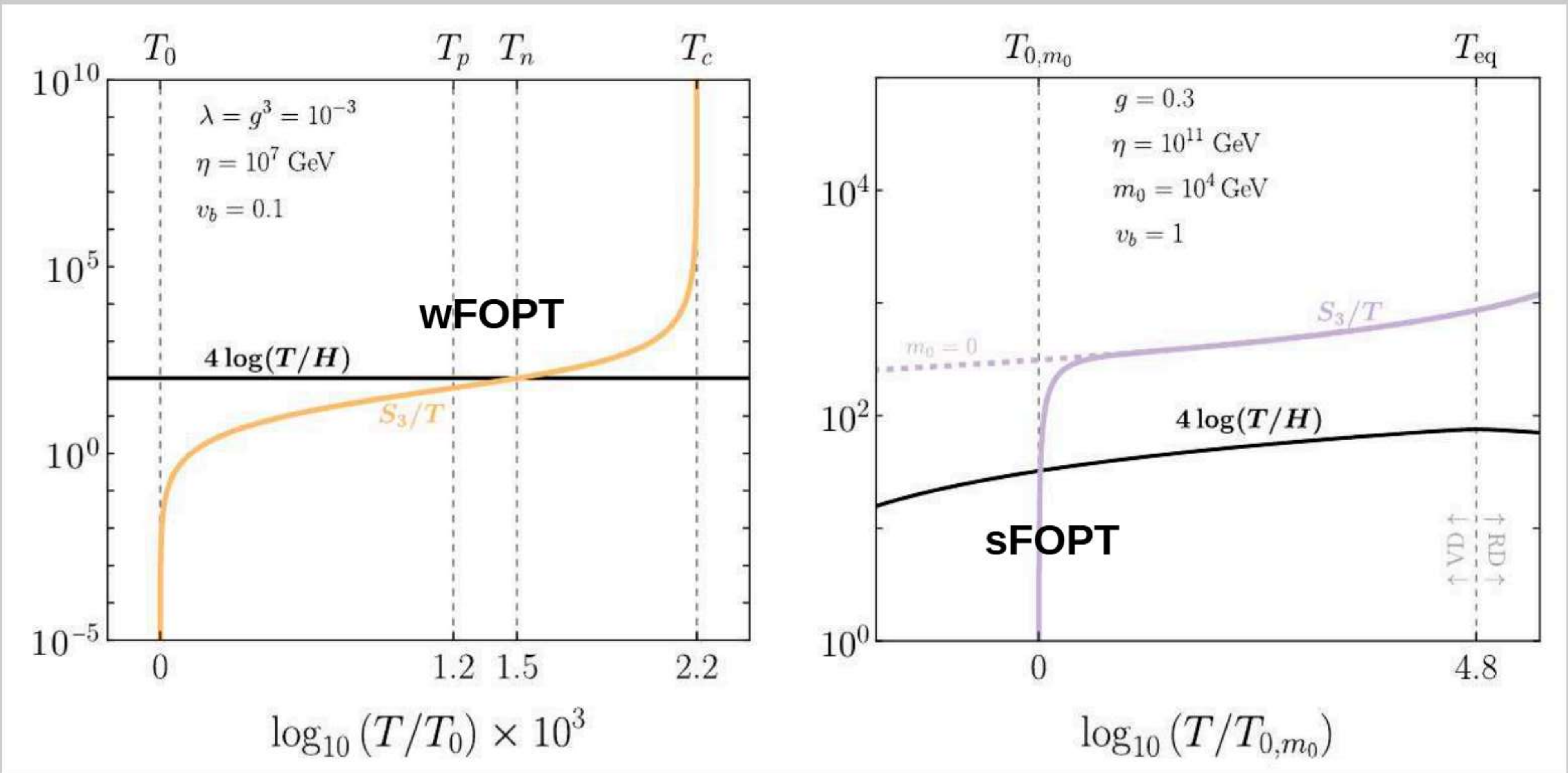
Nucleation rate vs Hubble expansion

Bounce action S_3 controls nucleation rate

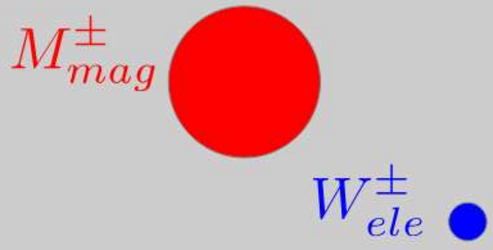
$$\Gamma(T) \simeq T^4 e^{-S_3/T}$$

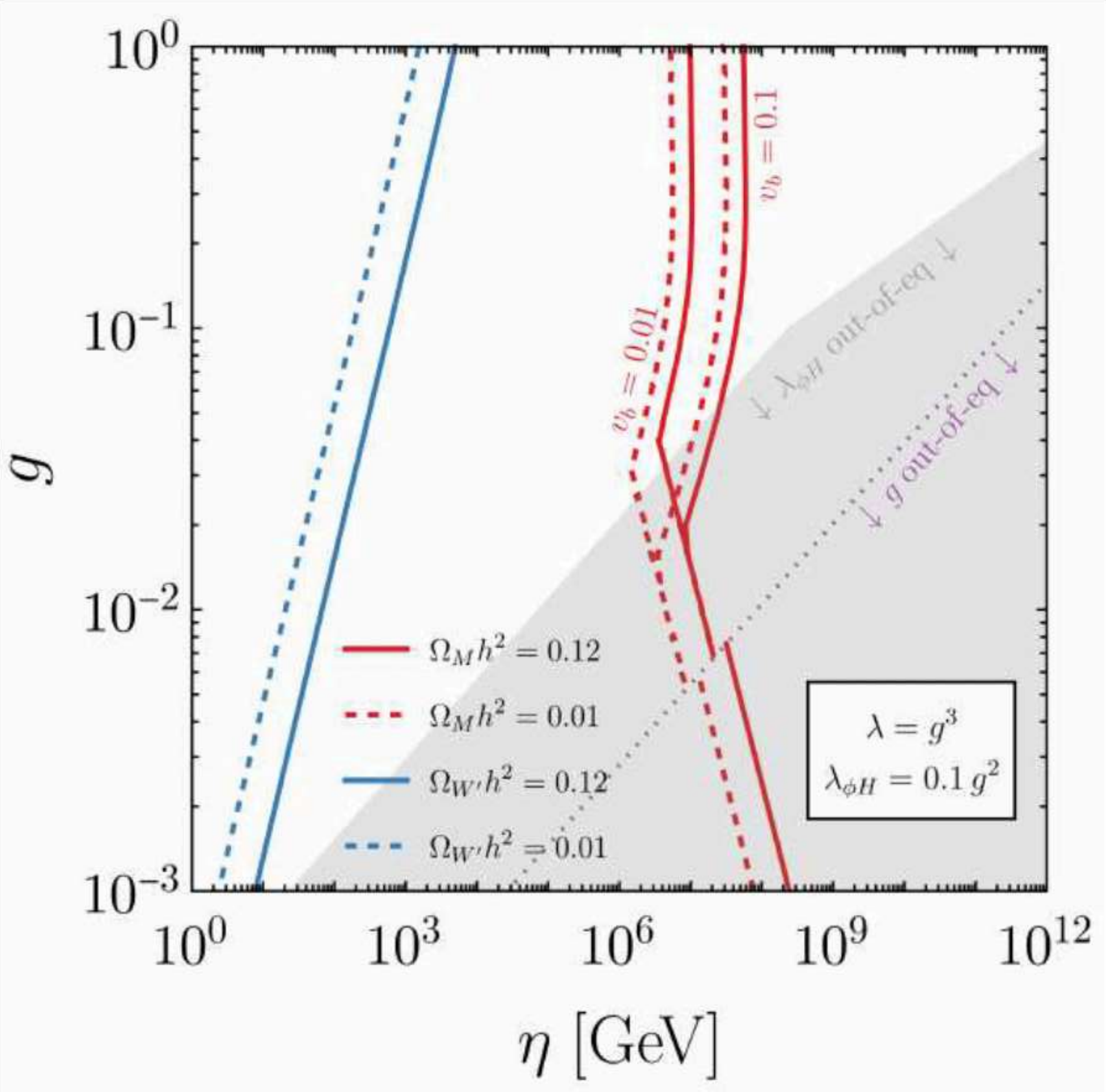
Nucleation temperature defined by

$$\Gamma(T_n) = H(T_n)^4$$



Weakly first order





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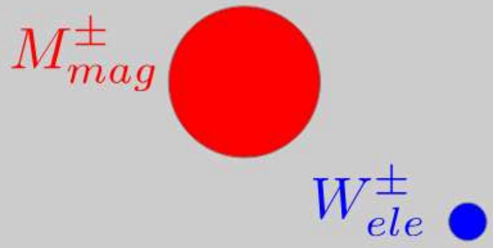

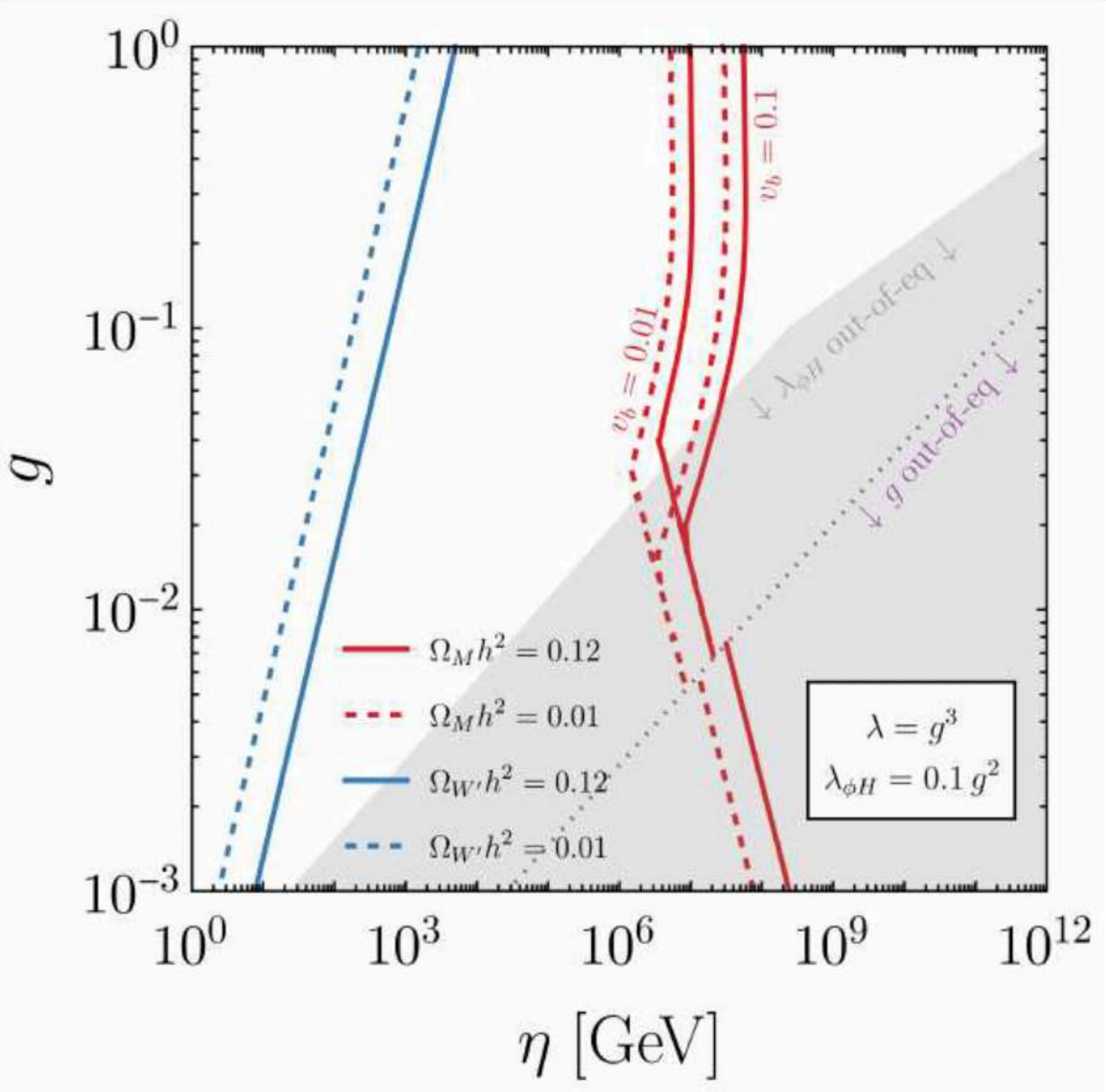

Potential barrier present at T_c

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

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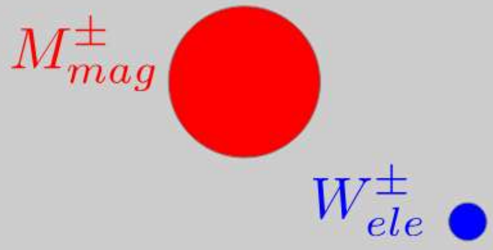

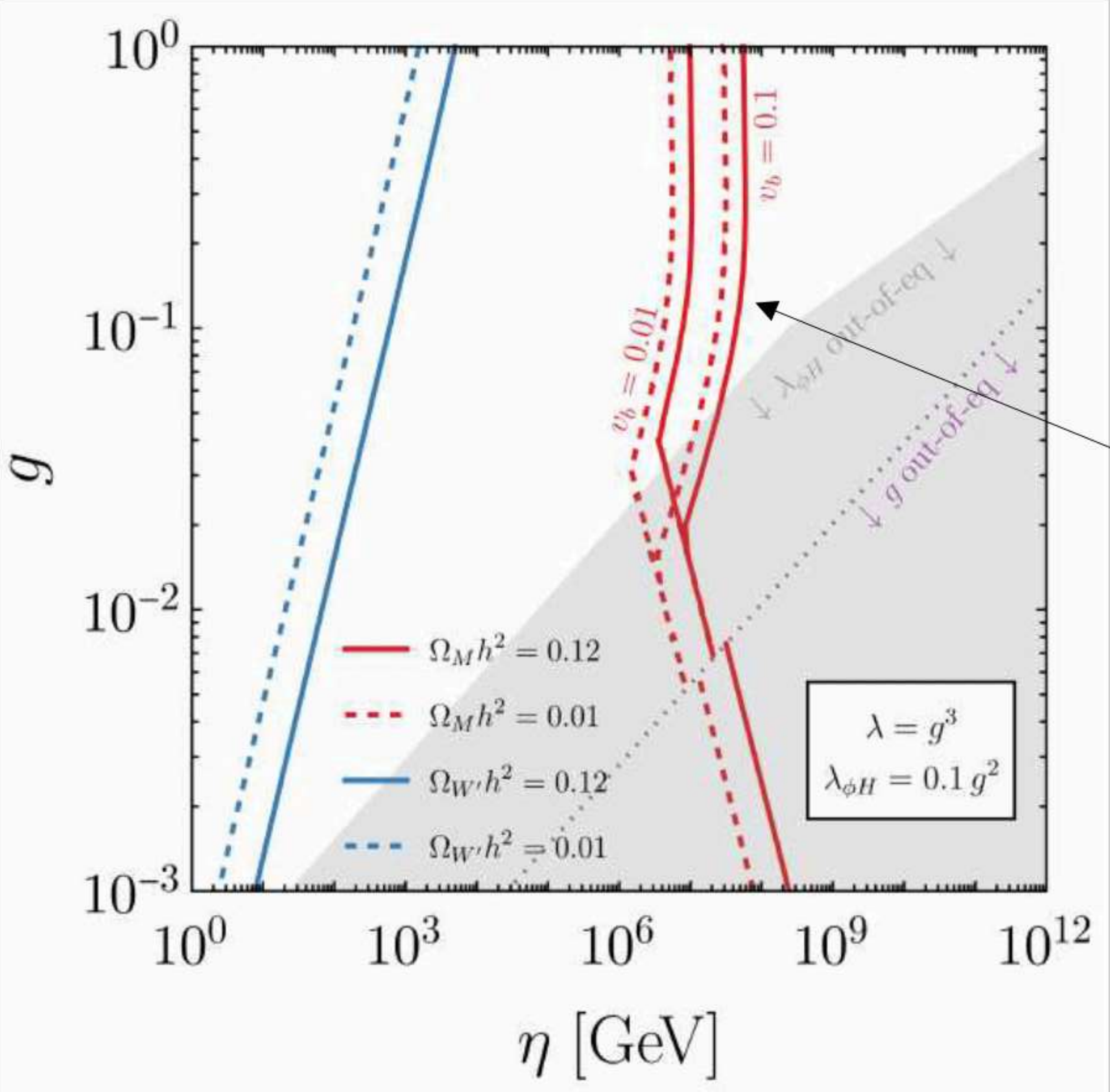

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Thermal fluctuations allow **nucleation of bubbles of true vacuum**

Bubble radius at percolation determines correlation length

$$\xi \simeq R_p \simeq 4.4 \frac{v_b}{\beta}$$

FOPT completion rate:

$$\beta \equiv \left. \frac{d \log \Gamma(t)}{dt} \right|_{t_p}$$

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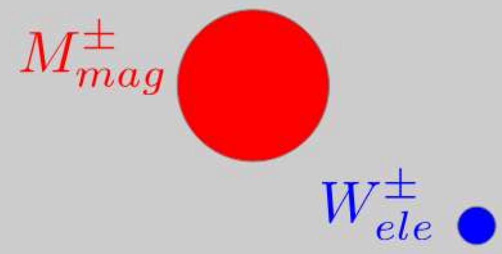

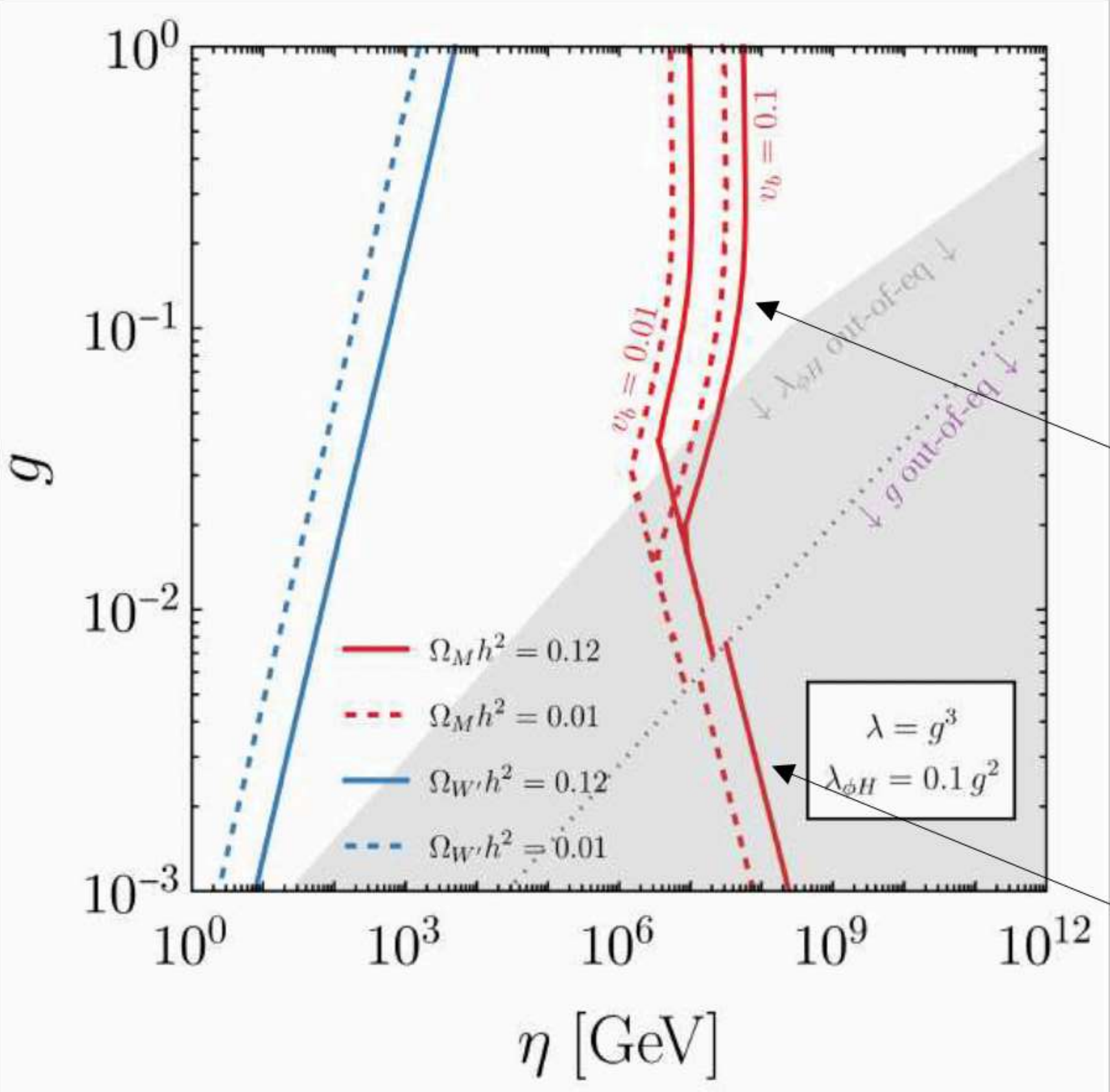

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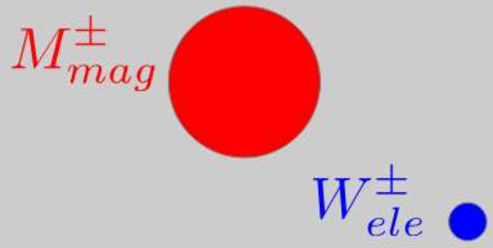
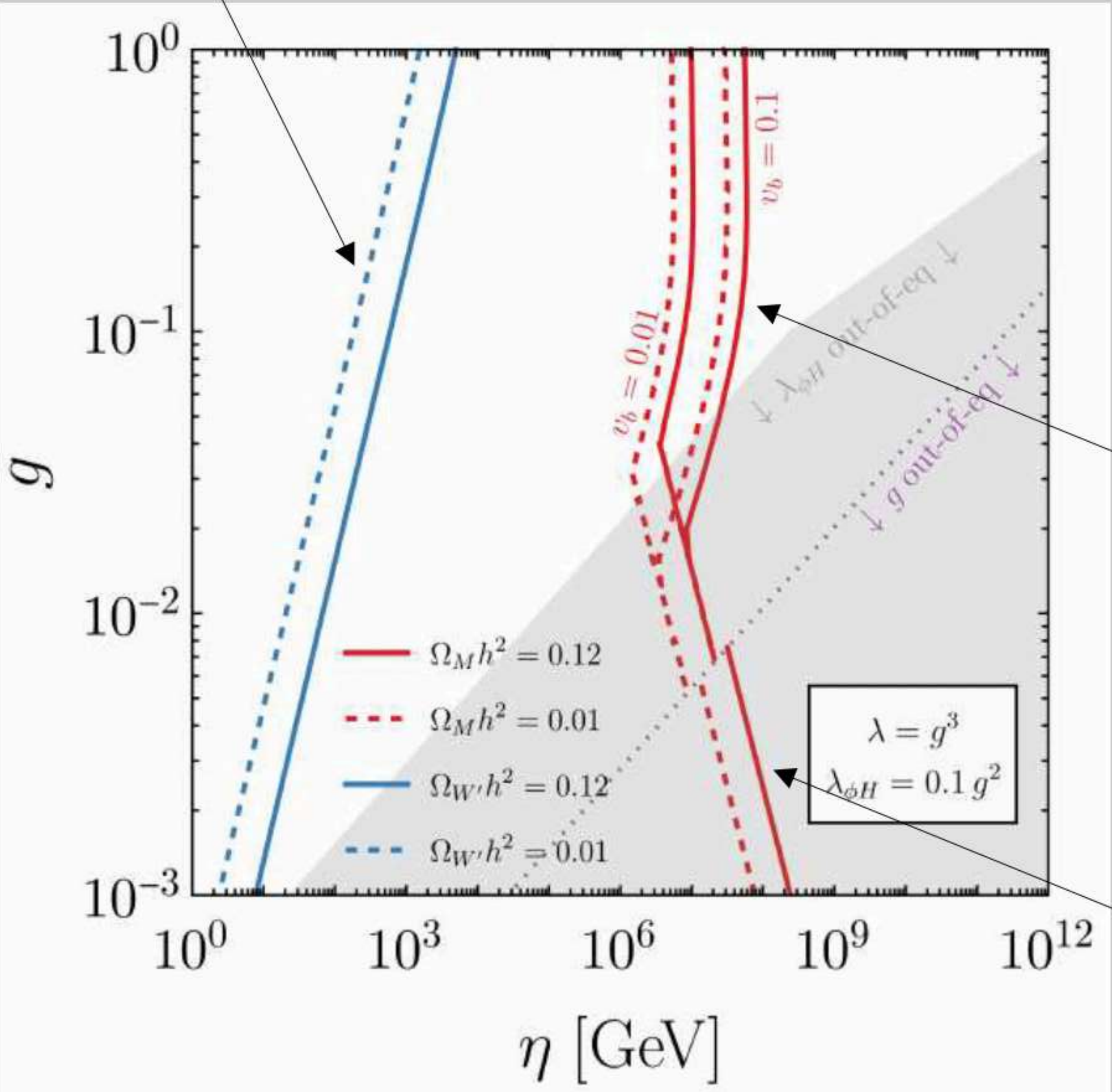


W freeze-out dominate DM abundance



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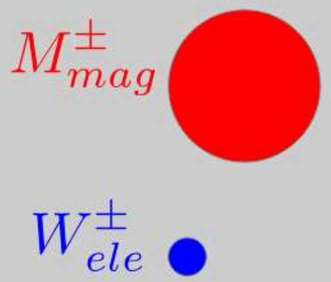
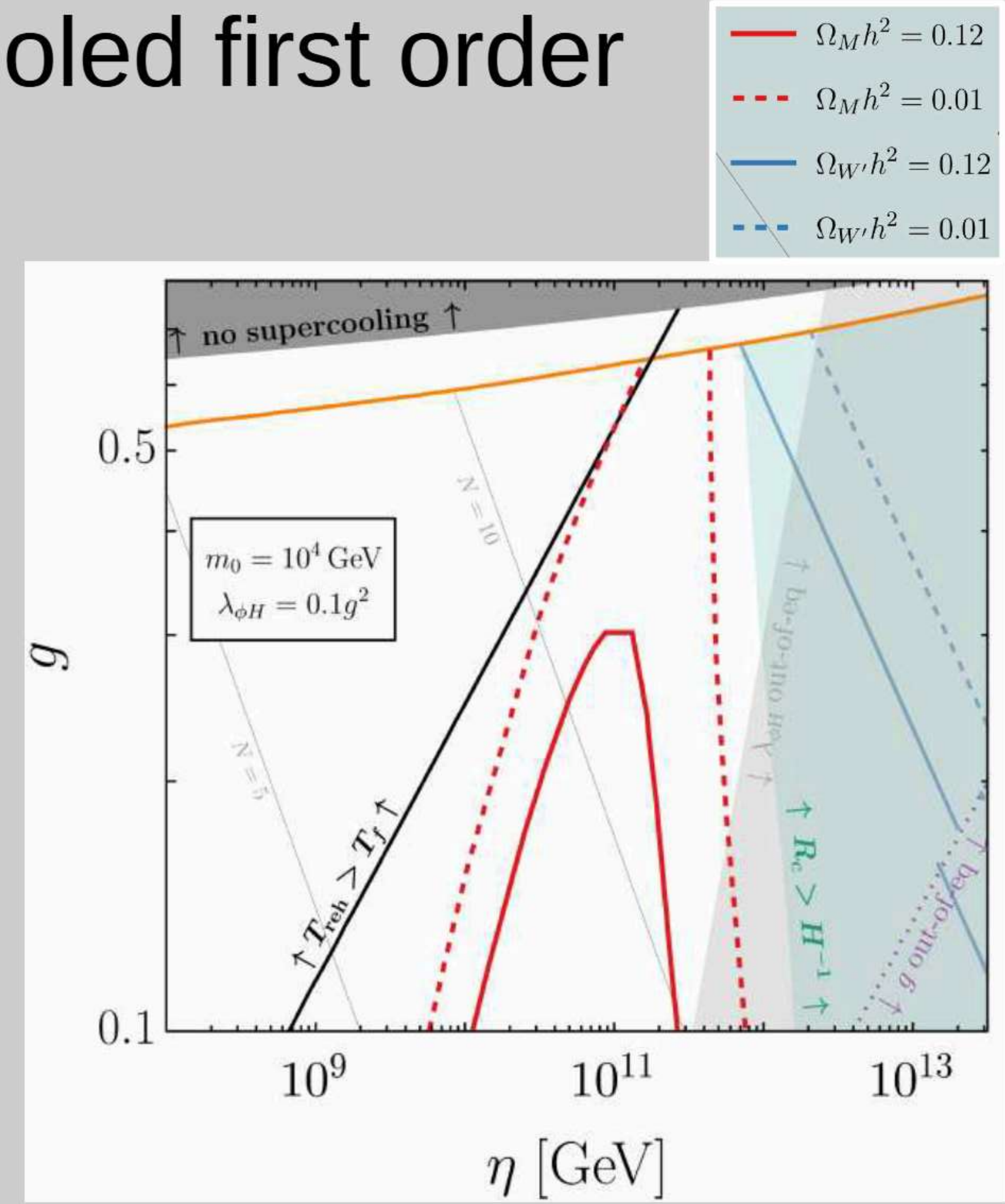
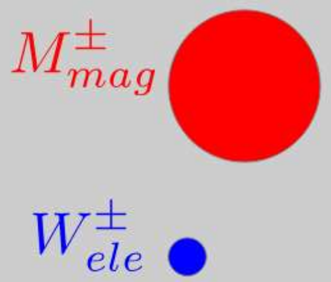


Supercooled first order

Universe stuck in false vacuum
till it becomes vacuum-dominated

Supercooling: several e-folds of inflation before bubble nucleation





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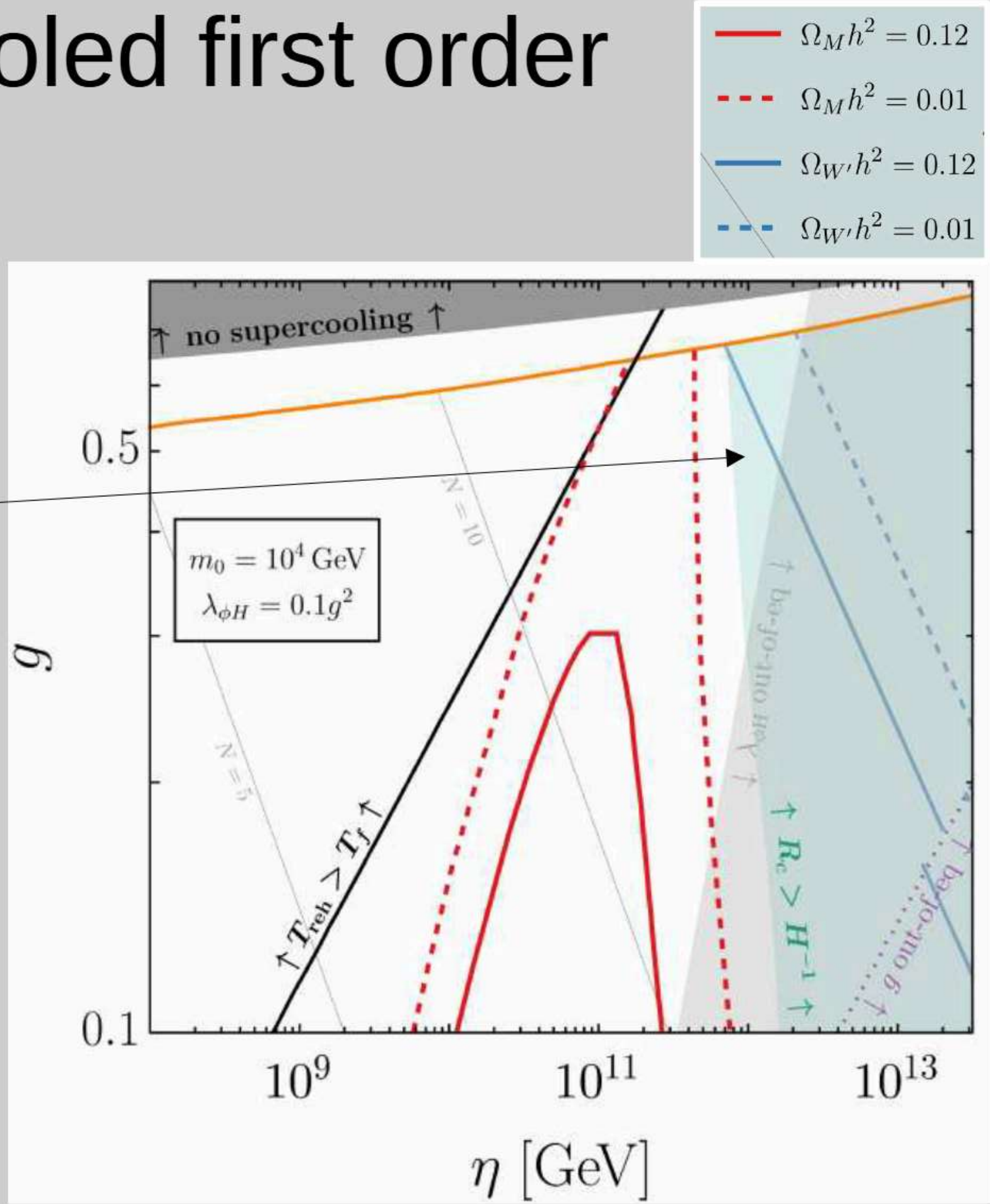

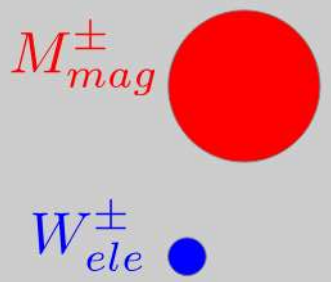

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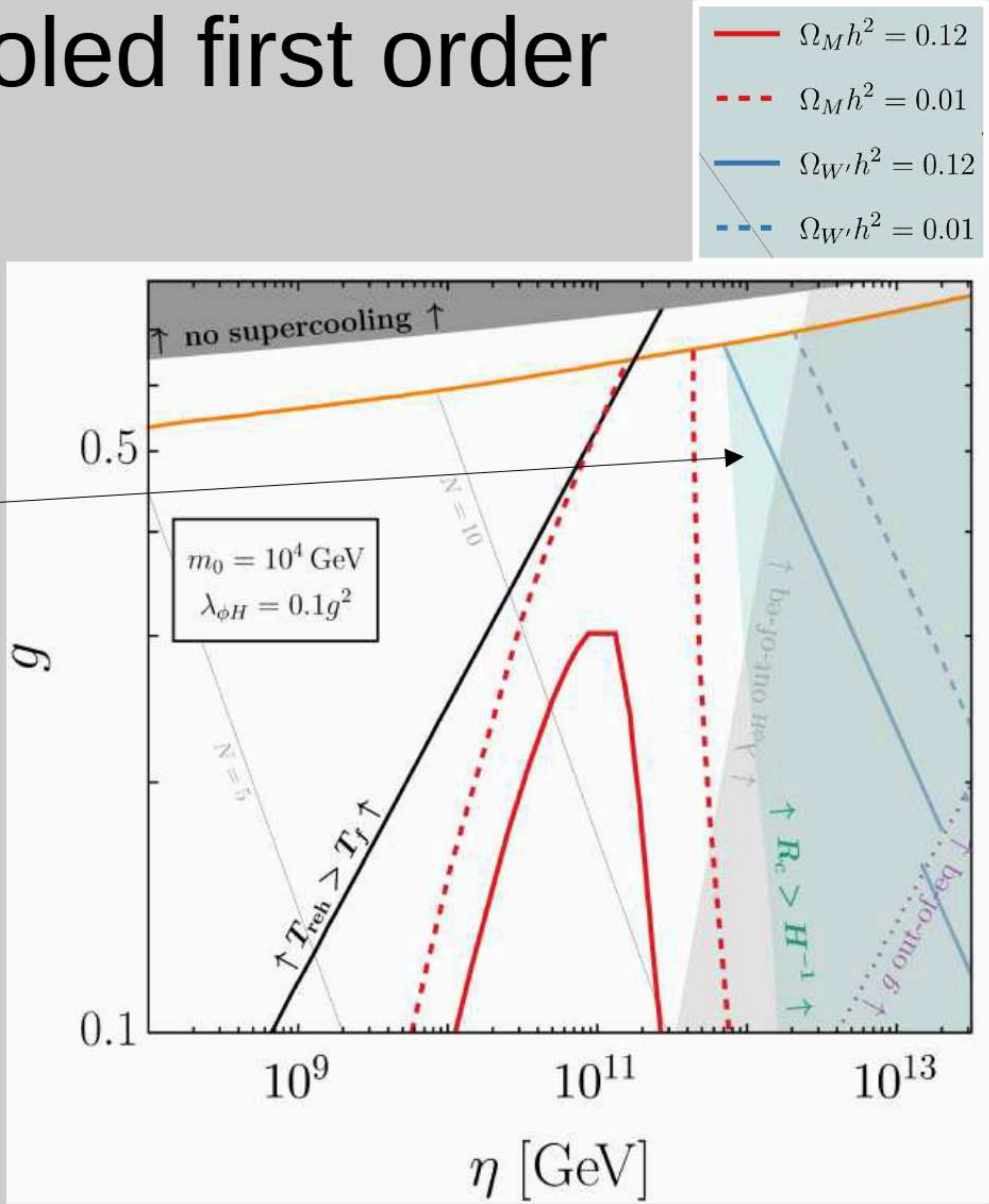

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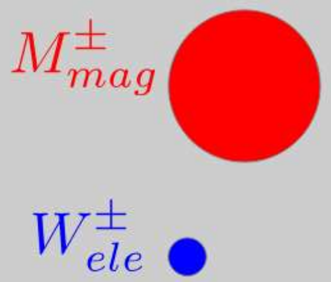

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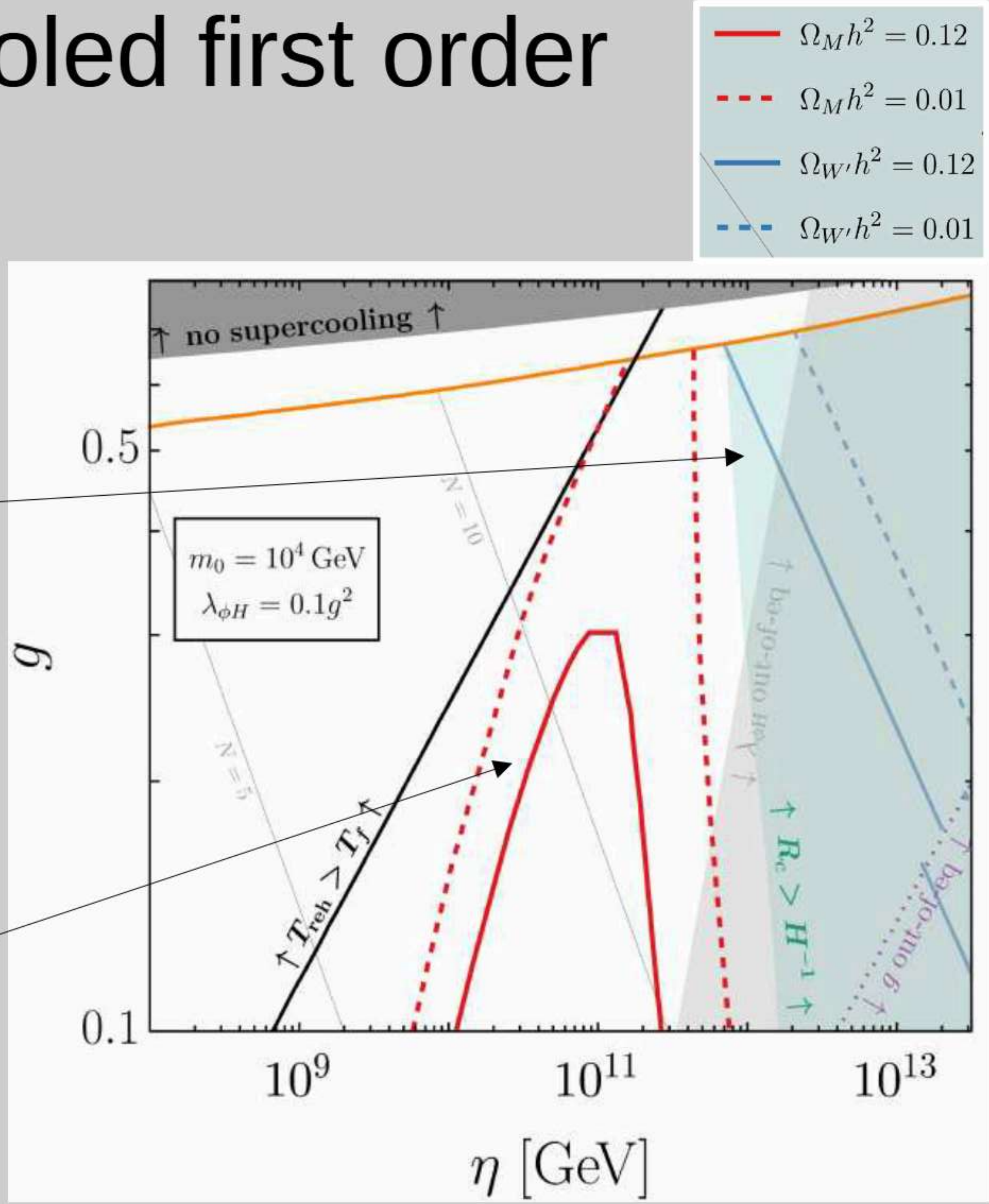
Monopole abundance peaks at some minimal radius, and drops before reaching W ab



Dark matter goes electric !

No room for minimal monopole DM

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

PRD 113 (2026) L091701, arXiv:2509.21924

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

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

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For any symmetry breaking scale η ,
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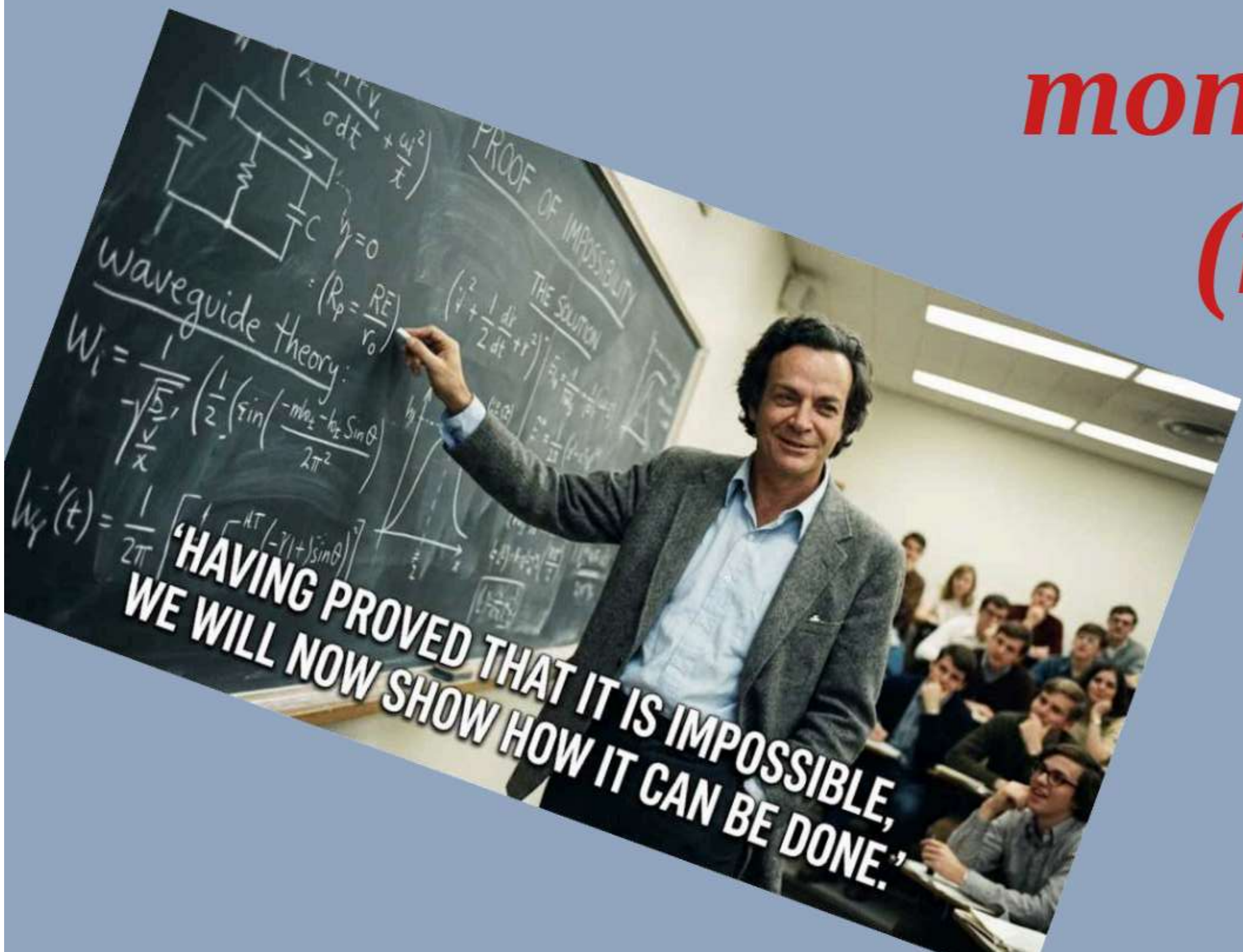
[General remark: dark-matter candidates are very many,
well-motivated & predictive ones are a few,
and it is very hard to fully exclude any]

Less minimal models, to realise monopole DM (maybe)



Ways out for monopole DM

- *Through portals:*

Electric relics annihilate efficiently into Standard Model particles if

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But then scalar thermal potential is strongly deformed:

- modified nature of dark phase transition affects monopole abundance

- necessary interplay with electroweak phase transition: signatures?

To be studied

Ways out for monopole DM

- *Through portals:*

Electric relics annihilate efficiently into Standard Model particles if

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

But then scalar thermal potential is strongly deformed:

- modified nature of dark phase transition affects monopole abundance

- necessary interplay with electroweak phase transition: signatures?

To be studied

Portals to other sectors: e.g. coupling φ to an inflaton, to produce monopoles non-thermally at preheating

Bai, Korwar, Orlofsky 2020

Ways out for monopole DM

- *Through different topologies:*

Different symmetry breaking leads to different topological defects

$$SO(3) \xrightarrow{\langle \phi_{\mathbf{5}} \rangle} O(2) \qquad \frac{SO(3)}{O(2)} \simeq RP^2 \qquad \pi_2(RP^2) = \mathbb{Z} \quad \pi_1(RP^2) = \mathbb{Z}_2$$

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one Alice defect observed
at Bourse du Commerce
Paris, March 2025

Ways out for monopole DM

- *À la Grand Unification:*

Heavy dark, electric relics ($m_W = g\,\eta$) decay into
(much) lighter dark, electric relics

(as GUT scale particles decay into SM particles)

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(as GUT scale particles decay into SM particles)

However, no much space to hide light dark particles:

- if they behave like matter, they still contribute to dark matter

- if they behave like radiation, they contribute to N_{eff}
[recall that monopoles already imply a dark U(1) photon]

F. Brummer, G. Ferrante, T. Fischer, M.Frigerio
***The price for monopole dark matter*, 260x.xxxxx**

Suppressing electric relics

Add (anomaly-free) dark fermions to ‘t Hooft-Polyakov model :

$\chi^i, \psi^i \sim \mathbf{2}_{SU(2)}$

$$\mathcal{L} \supset -m_f\, \chi^i \epsilon_{ij} \psi^j - y\, \chi^i \epsilon_{ij} \phi^a \, (\sigma^a)^j_k \, \psi^k$$

After SSB, two Dirac fermions with dark electric charge $q = -\frac{1}{2}$:

$$m_{e'} = m_f - y\eta$$
$$m_{\mu'} = m_f + y\eta$$

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Thermal population of *e’* freezes-out annihilating into dark radiation :

$$\langle \sigma v \rangle_{\bar{e}' e' \to \gamma' \gamma'} \approx \frac{g^4}{256 \pi m_{e'}^2} \qquad \Omega_{e'} h^2 \sim 0.1 \left(\frac{0.4}{g}\right)^4 \left(\frac{m_{e'}}{100\,\mathrm{GeV}}\right)^2$$

Electric relics are **sub-dominant DM component**

IF *e’* is sufficiently light: **well below the electroweak scale**

Irreducible dark radiation

$$\Delta N_{\rm eff} = \frac{4}{7}\left(\frac{11}{4}\right)^{4/3}\left(\frac{T_D^0}{T_{\rm SM}^0}\right)^4 \times \left\{ \begin{array}{cc} 2 & (\gamma') \\ 7/2 & (e') \end{array} \right.$$

If very light, dark fermions would directly contribute to radiation: already excluded.

If heavier, they may increase T^0_D by injecting entropy into dark sector after decoupling.

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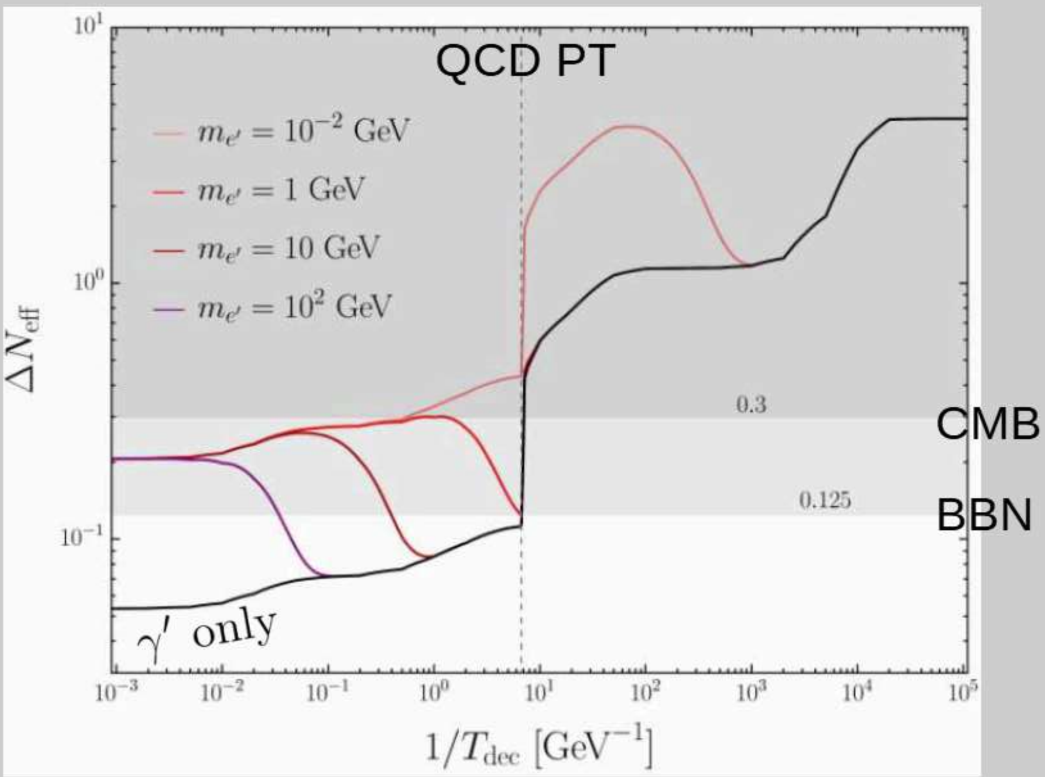

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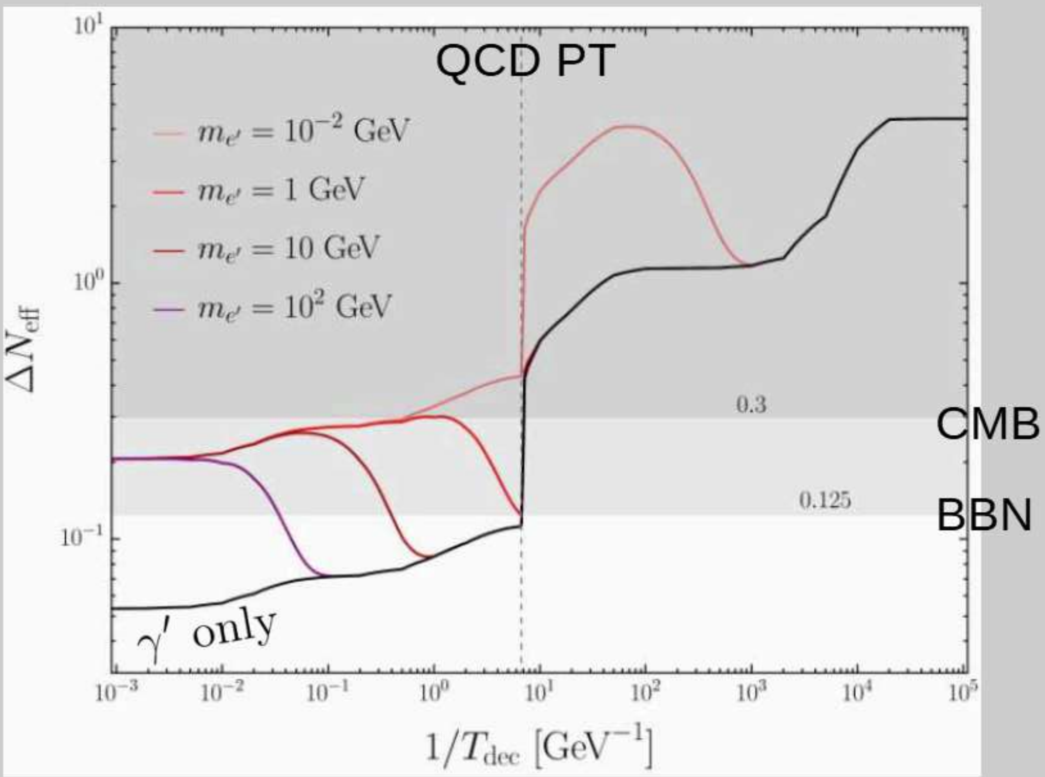

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Rate suppressed by small mixing between Higgs and dark scalar
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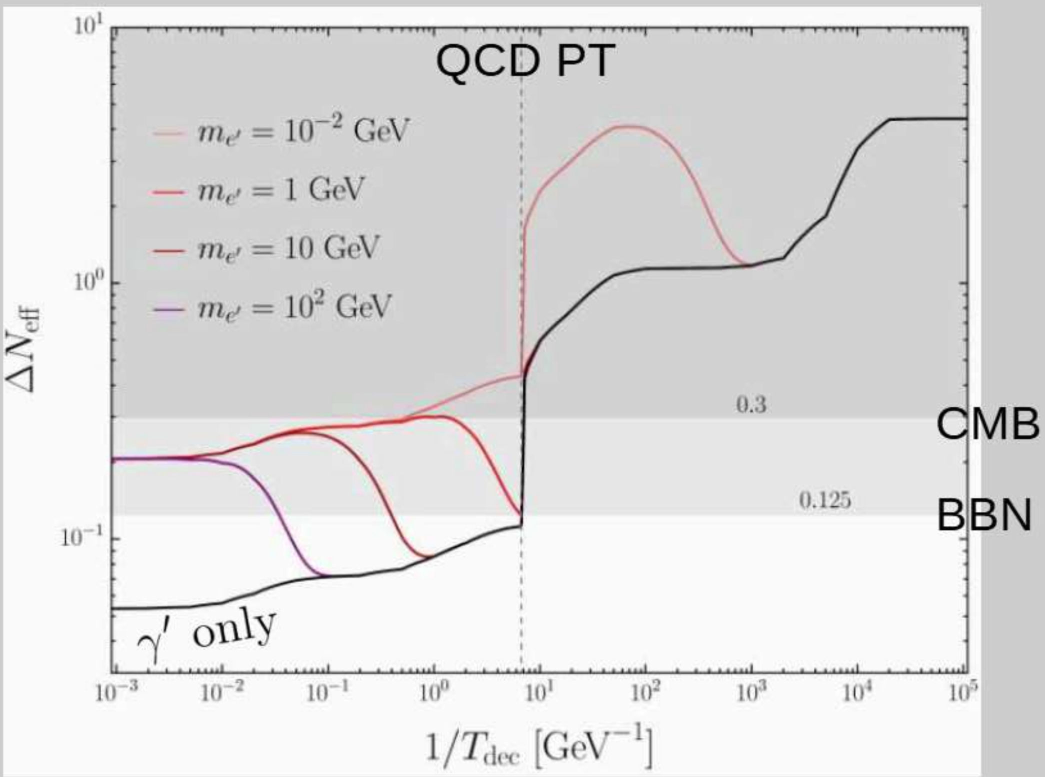

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Dark photon + Electric relics necessarily imply
N_{eff} close to present bounds

Monopole abundance revisited (I)

- Initially light electric relics contribute to monopole annihilations, eventually their final abundance becomes negligible

- Monopole DM requires large hierarchy of scales, $\eta \gg v$, thus the two sectors decouple early $\Rightarrow$ irreducible N_{eff}

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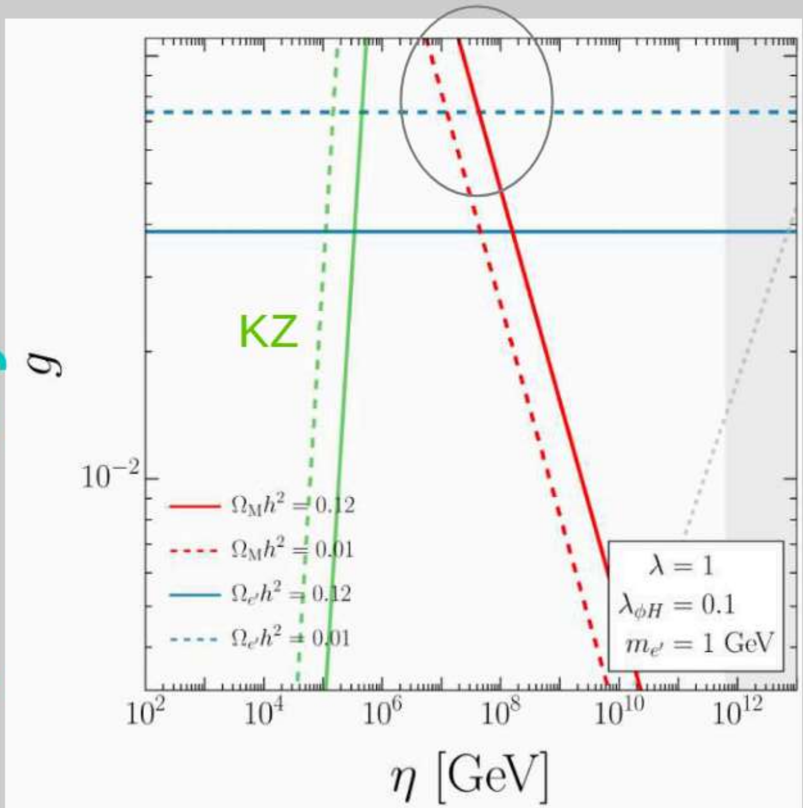
Second Order PT



Preliminary

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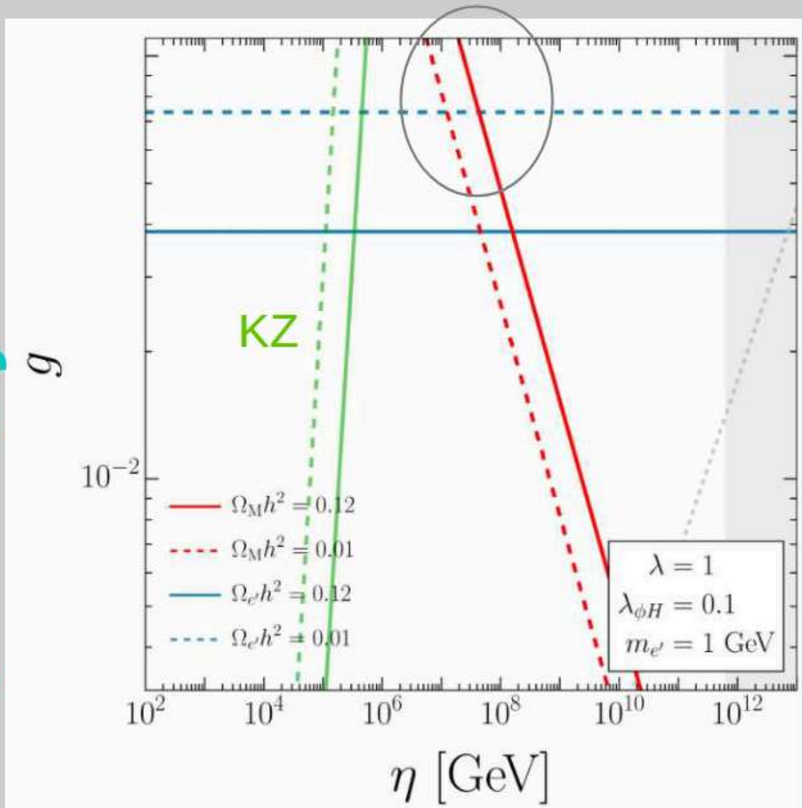
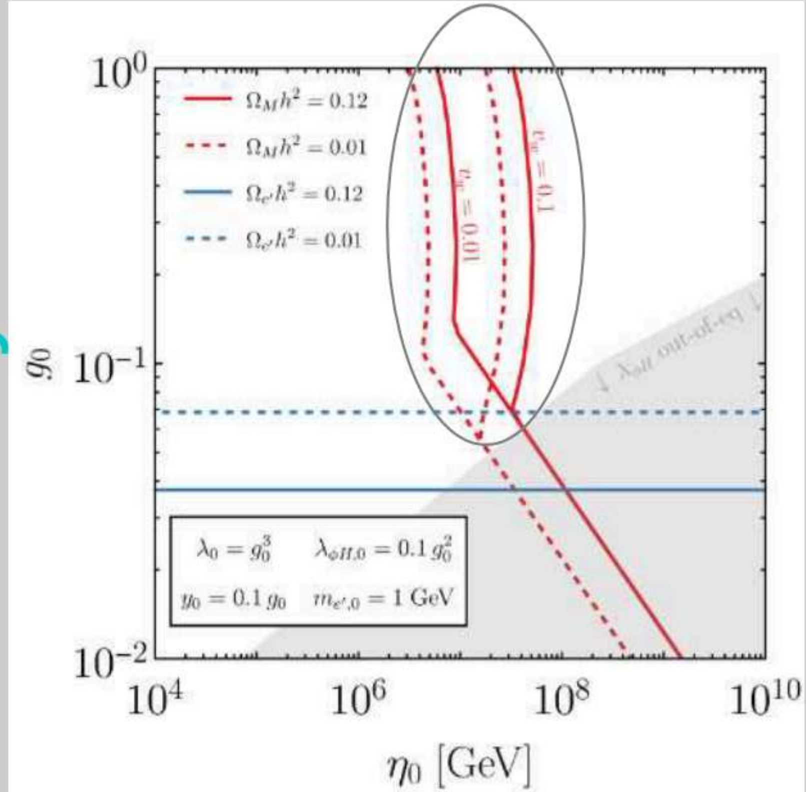


Preliminary

Weakly First Order PT

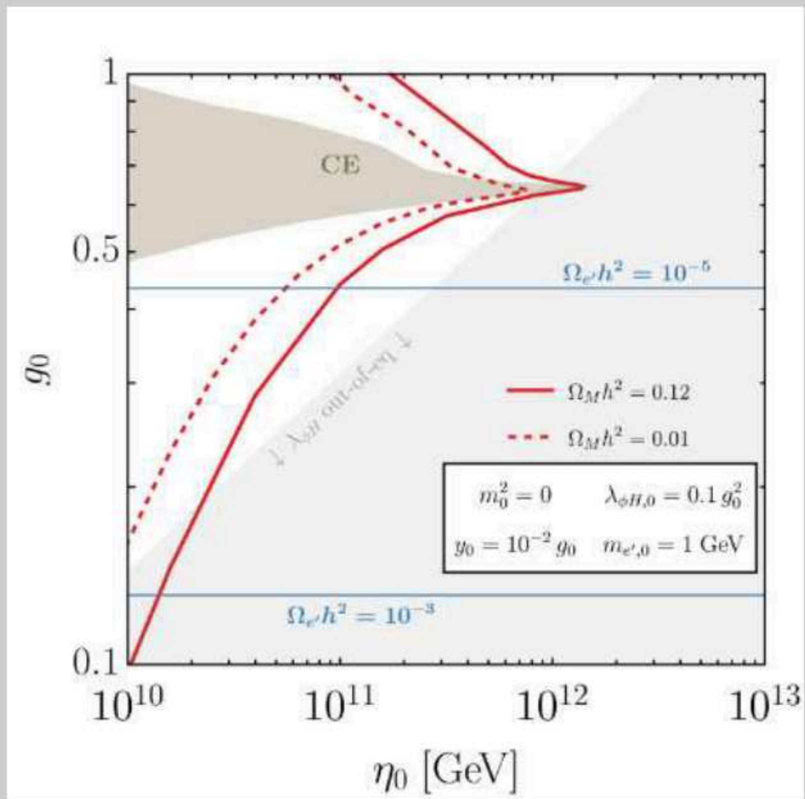


Preliminary

Monopole abundance revisited (II)

Strong (CW) First Order PT

Preliminary



Monopole abundance revisited (II)

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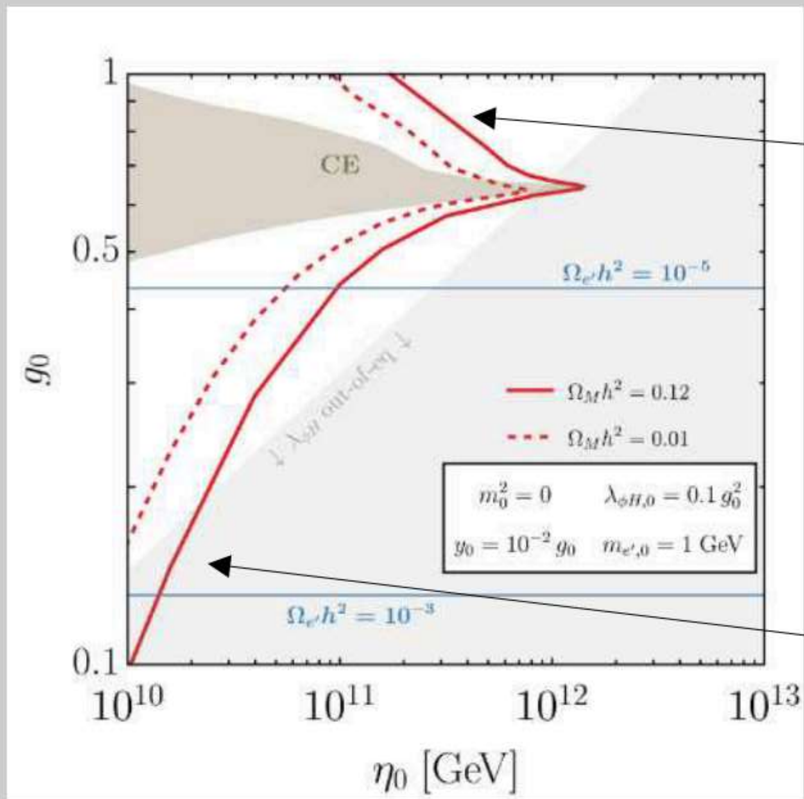

Preliminary

Tunnelling occurs for V''(φ=0) << T²

Tunnelling occurs for small, negative V''(φ=0) ~ T²

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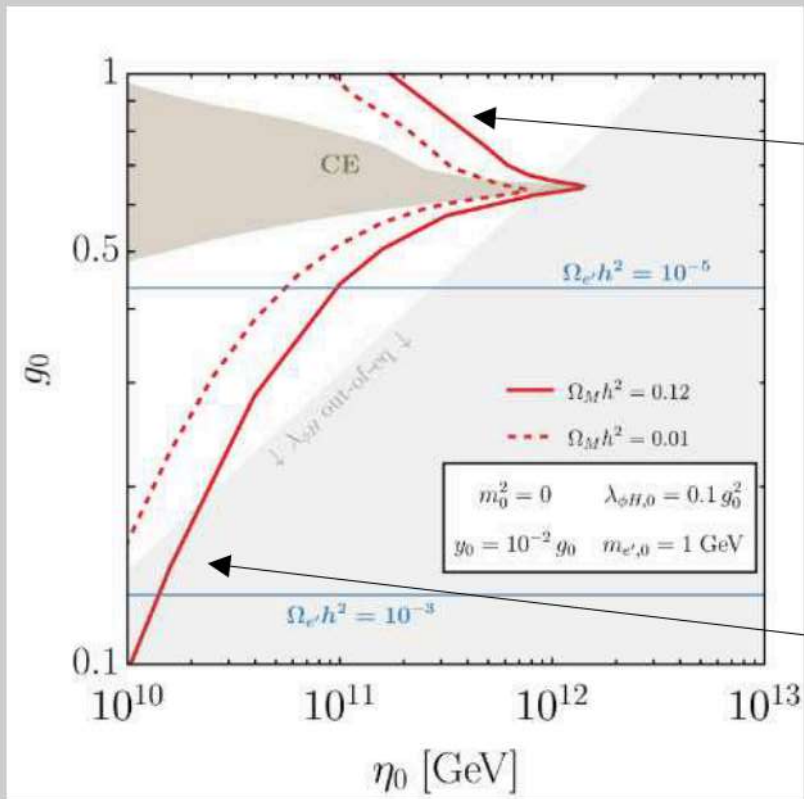

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⇒ need for RGE improved thermal potential: running couplings at $\mu \sim T$

Christiansen
Madge
Puchades-Ibanez
Ramirez-Quezada
Schwaller
2025

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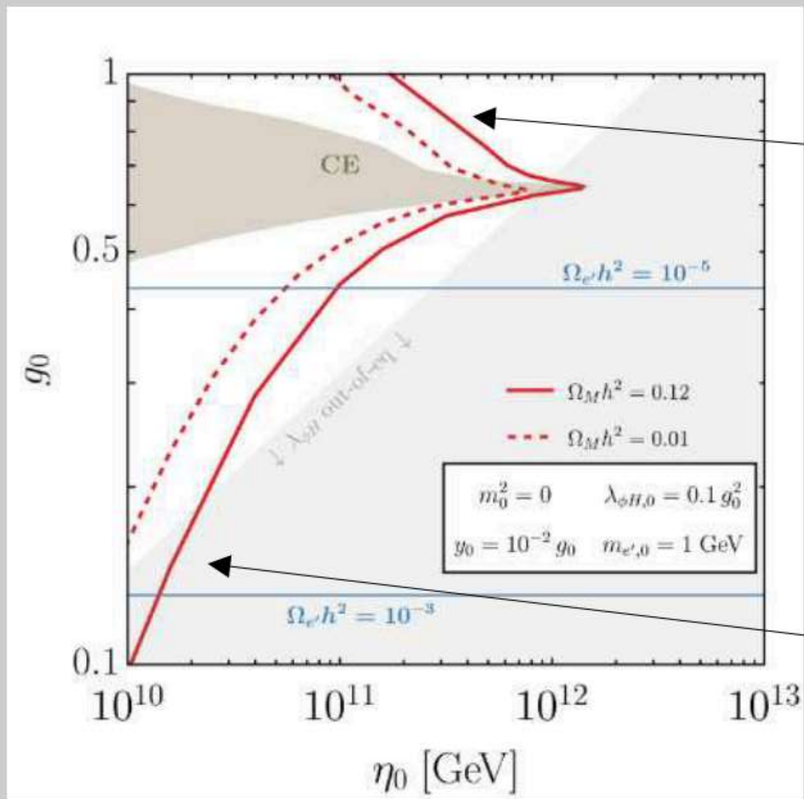

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- In supercooled PT, there is large scale separation: $T_n \ll T_c$
  ⇒ need for RGE improved thermal potential: running couplings at $\mu \sim T$
- The smaller is bubble radius, the larger is gravitational-wave frequency
  ⇒ monopole DM beyond reach of Einstein telescope & Cosmic Explorer

Christiansen Madge Puchades-Ibanez Ramirez-Quezada Schwaller 2025

Summary

- **In visible sector,** magnetic monopoles very rare

- **In dark sector,** monopoles generically subdominant

- Dark monopoles always **negligibly few in minimal model**

- In specific models with **light dark particles,** dark matter can be dominated by **heavy thermally-produced monopoles**

- Indirect signatures include **extra radiation** (unavoidably) and **gravitational waves** (if lucky)