Parker Bounds and Monopole Production from Primordial Magnetic Fields

DarkCosmoGrav

Speaker:
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DP, Takeshi Kobayashi
Phys.Rev.D 106 (2022) 6, 063016

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arXiv:2302.xxxxx

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Contents of the Talk

- ✓ Magnetic monopoles and topological defects.
- ✓ Bounds on the monopole abundance.
- ✓ Minicharged monopoles and their bounds.
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Can a Monopole Really Exist?

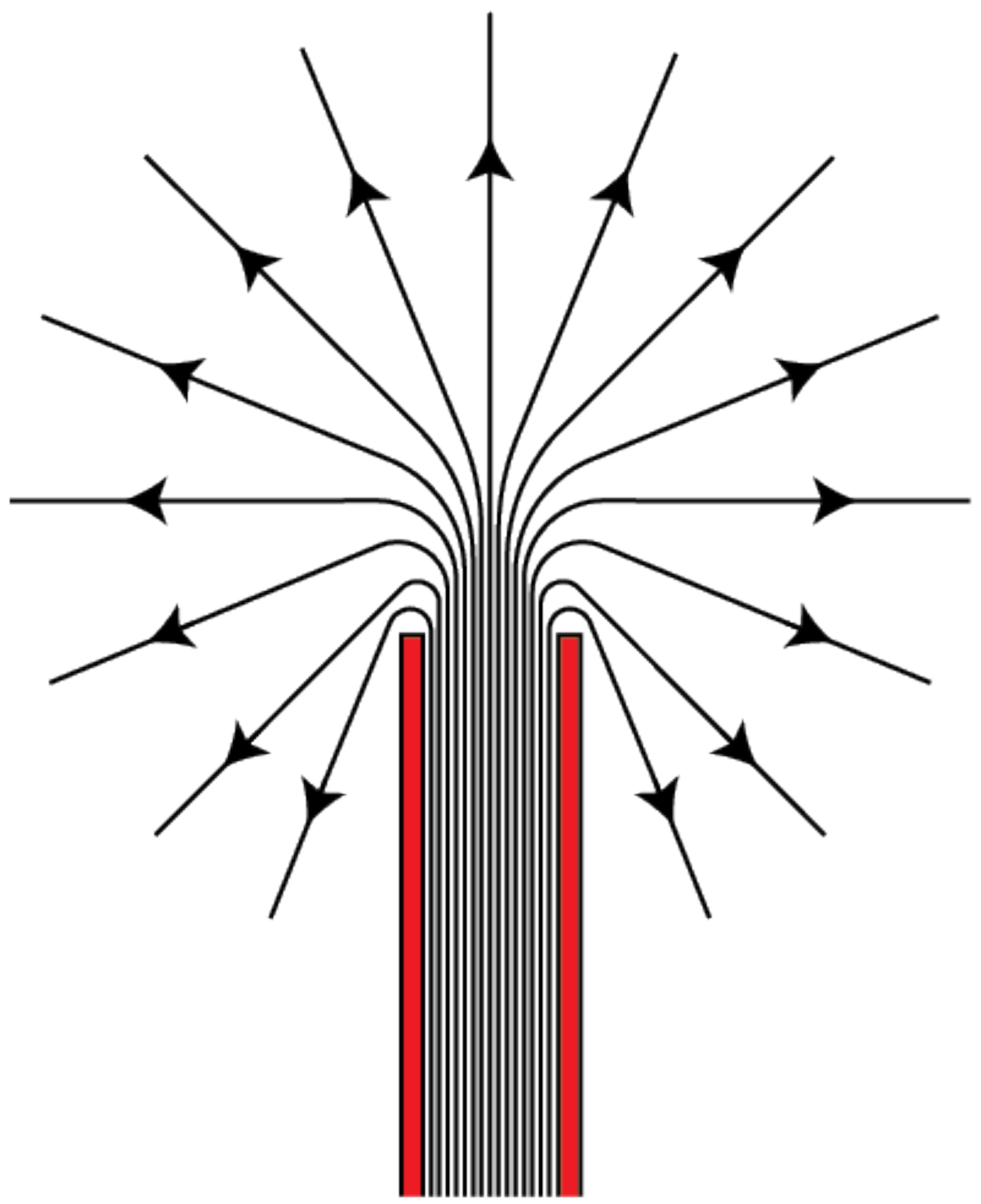
Dirac Monopoles and the Quantization of the Electric Charge

$$\vec{B}_{\text{mono}} = g\frac{\vec{r}}{r^3}$$

- Dirac was the first to suppose the existence of magnetic monopoles.
- In 1948 he proposed a model for a monopole made of *one semi-infinite string solenoid*.
- The existence of magnetic monopoles is consistent with quantum theory once imposed the *charge quantization condition*:

$$g = 2\pi n/e = n g_{\text{D}}$$

- Monopoles provides a strong theoretical explanation for the quantization of the electric charge.



Can a Monopole Really Exist?

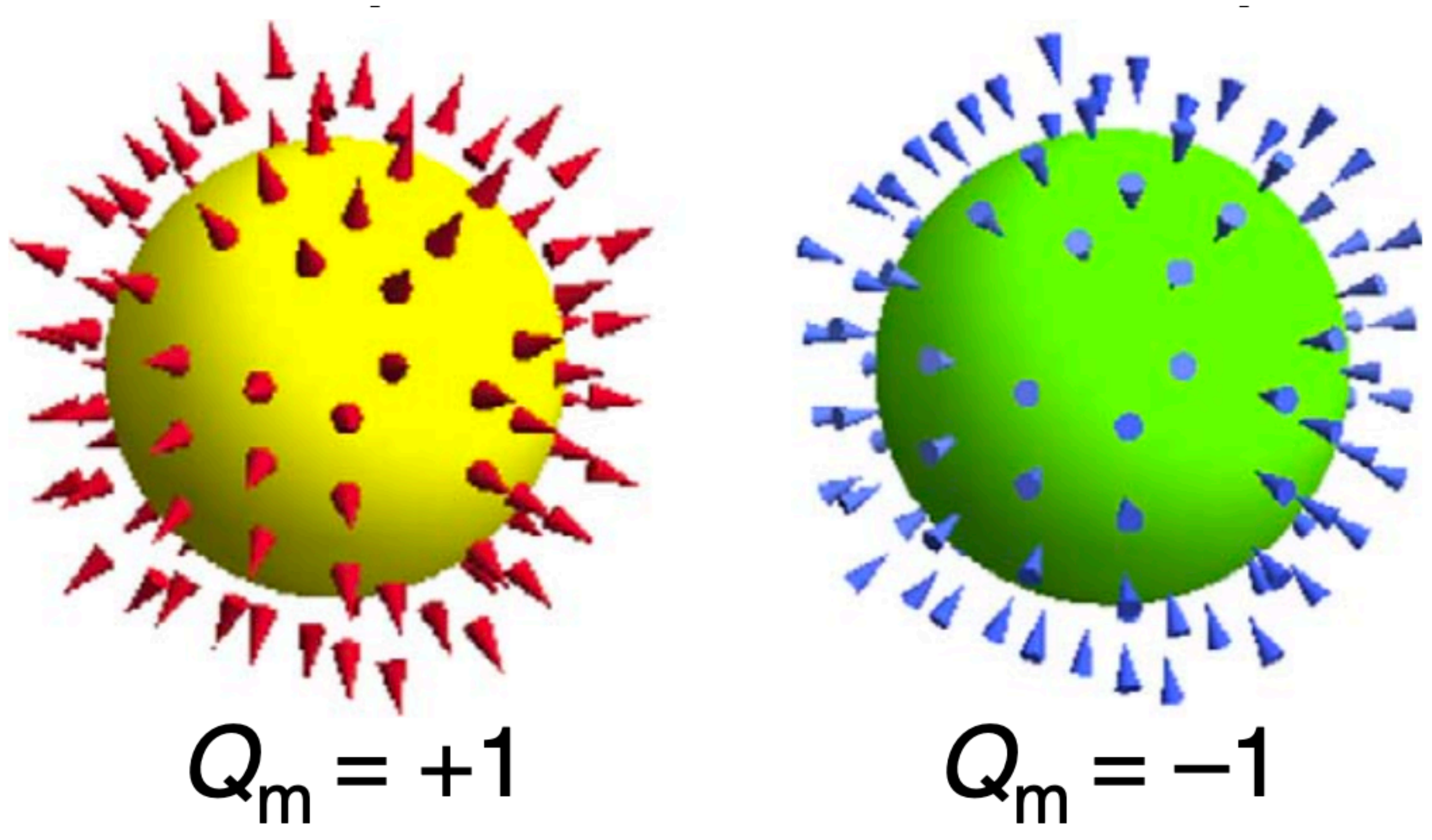
’T Hooft-Polyakov Monopoles and Topological Defects

- In 1974 ’T Hooft and Poliakov presented a model of monopoles as zero-dimensional solitonic solutions of the vacuum manifold.
- The simplest example is the Georgi-Glashow model: $SU(2) \to U(1)$

$$\mathscr{L}(t,\vec{x}) = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \frac{1}{2}(D_\mu\phi^a)(D^\mu\phi^a) - \frac{1}{4}\lambda(\phi^a\phi^a - \eta^2)^2$$

- The monopole configuration is described by the *hedgehog solution* for the scalar field after the symmetry breaking:

$$\phi^a(\vec{x}) = \delta_{ia}\left(\frac{x^i}{r}\right)F(r)$$



Can a Monopole Really Exist?

’T Hooft-Polyakov Monopoles and Topological Defects

- ’T Hooft-Poliakov monopoles can be interpreted as *topological defects* linked to non-trivial second homotopy groups of the vacuum manifold:

$$\pi_2(G/H) \neq \mathrm{I}$$

Each time a simply connected group is broken into a smaller group that contains U(1) *there is production of monopoles.*

↓

Monopoles are *inevitable predictions* of Grand Unified Theories:

$$SU(5) \rightarrow SU(3) \times SU(2) \times U(1) \rightarrow SU(3) \times U(1)$$

Could Monopoles be Dark Matter?

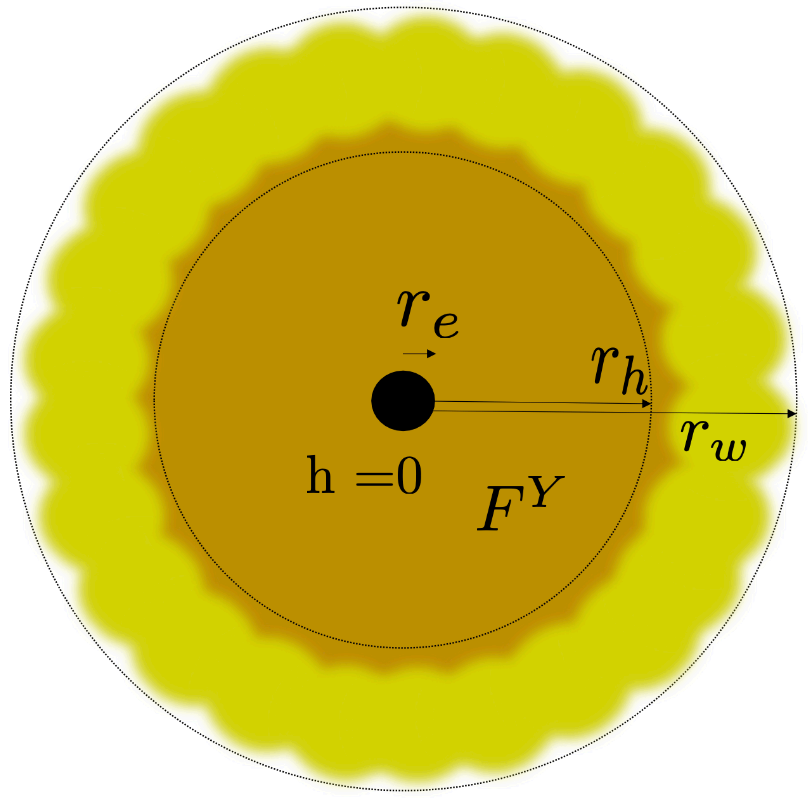
Monopoles are often suggested as possible candidates for Dark Matter.

Standard magnetic monopoles must be very heavy to cover all the Dark Matter of the universe ($m \gtrsim 10^{17}$ GeV).

↓

- *Minicharged monopoles* relax the bounds opening the possibility of lighter monopoles as Dark Matter.
- *Magnetically charged primordial black holes* act as very heavy magnetic monopoles.

Maldacena (2020)
[arXiv:2004.06084](https://arxiv.org/abs/2004.06084)



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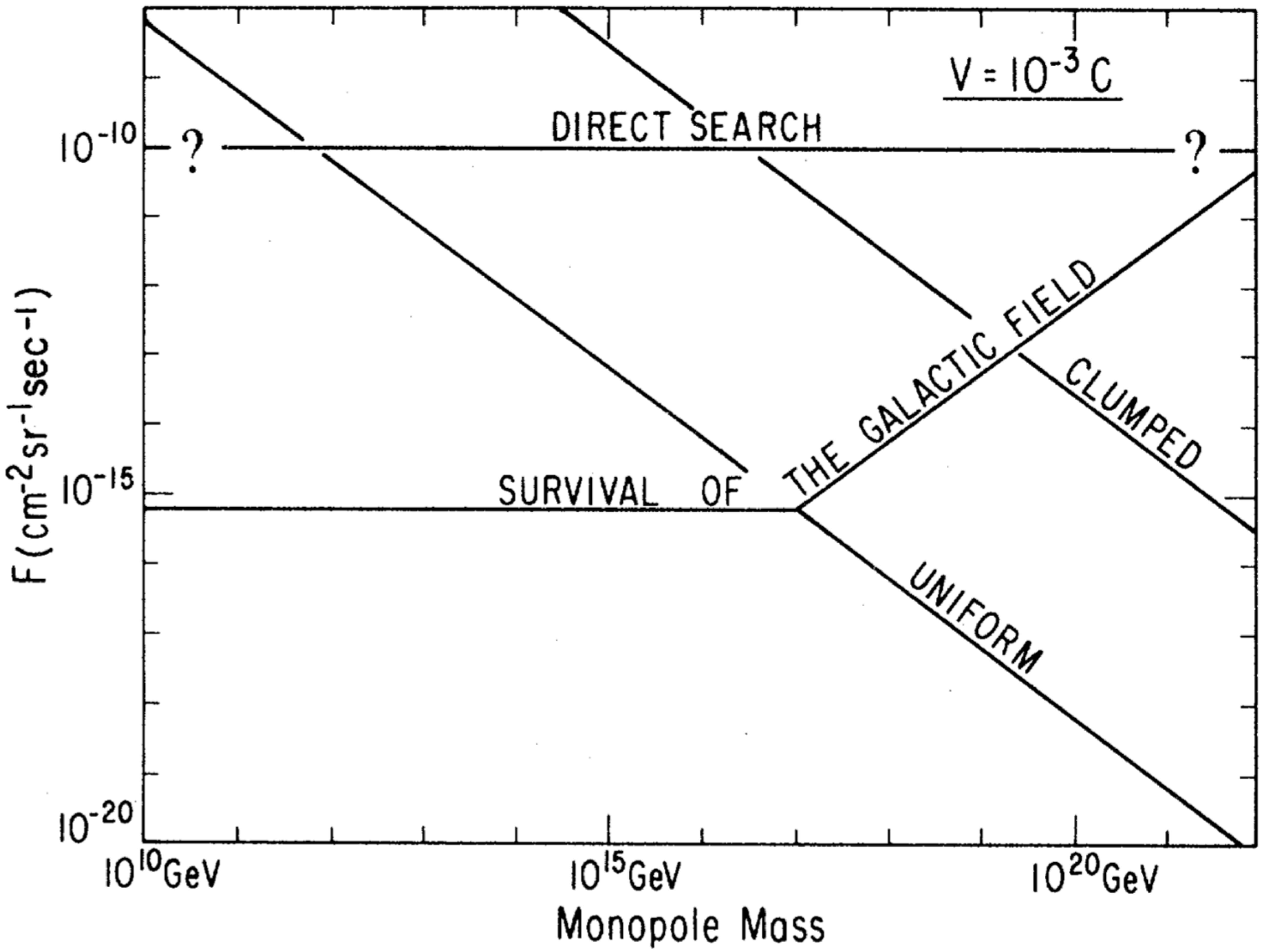
Parker Bound on the Monopole Flux

In 1970 Parker proposed a bound on the monopole flux today inside our Galaxy:

- The Galaxy presents a magnetic field of $\sim 2 \times 10^{-6}$ G;
- The Galactic magnetic field accelerates the monopoles losing its energy;
- The survival of the field provides a bound on the monopole flux today.



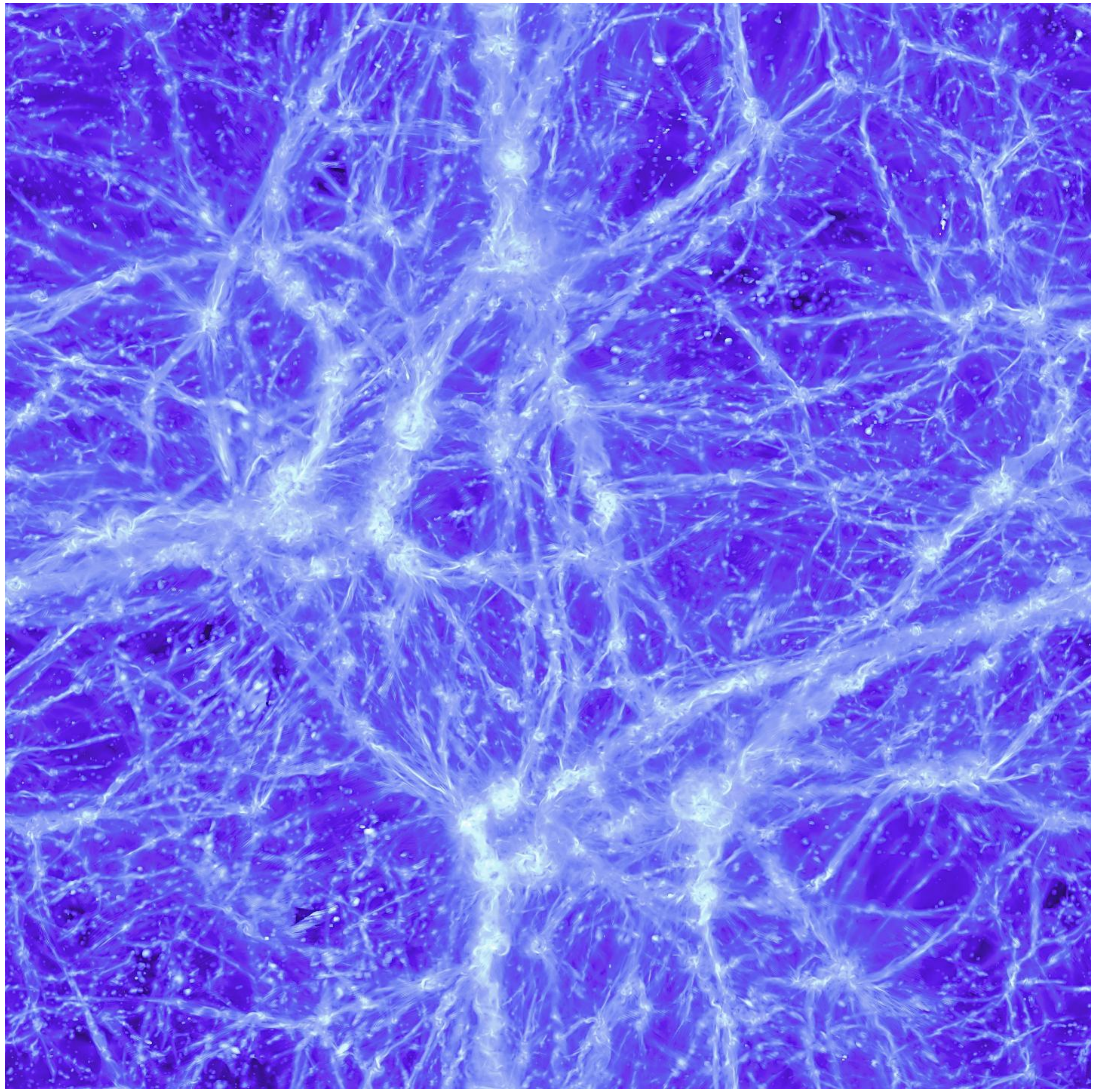
New Parker Bounds from Primordial Magnetic Fields

- Strong evidences for intergalactic magnetic fields $\gtrsim 10^{-15}$ G with a *primordial origin*.

- (Most of the) models provide that magnetogenesis happens during inflation or soon after the end.

An analogous of the Parker bound can be derived from the persistence of the primordial fields until today.

Long, Vachaspati (2015)
arXiv:1504.03319



New Parker Bounds from Primordial Magnetic Fields

- The process of monopole acceleration extracts energy also from the primordial magnetic fields.

- The evolution of the *magnetic field energy density* in the presence of monopoles is described by the equation:

$$\frac{\dot{\rho}_B}{\rho_B} = -\Pi_{red} - \Pi_{acc}$$

$$\Pi_{red}(t) = 4H(t) \qquad\qquad \Pi_{acc}(t) = \frac{4g}{B(t)} v(t) n(t)$$

- The magnetic fields survive under the condition $\Pi_{acc}/\Pi_{red} \lesssim 1$.

Necessary to study the equation of motion of the monopoles!!

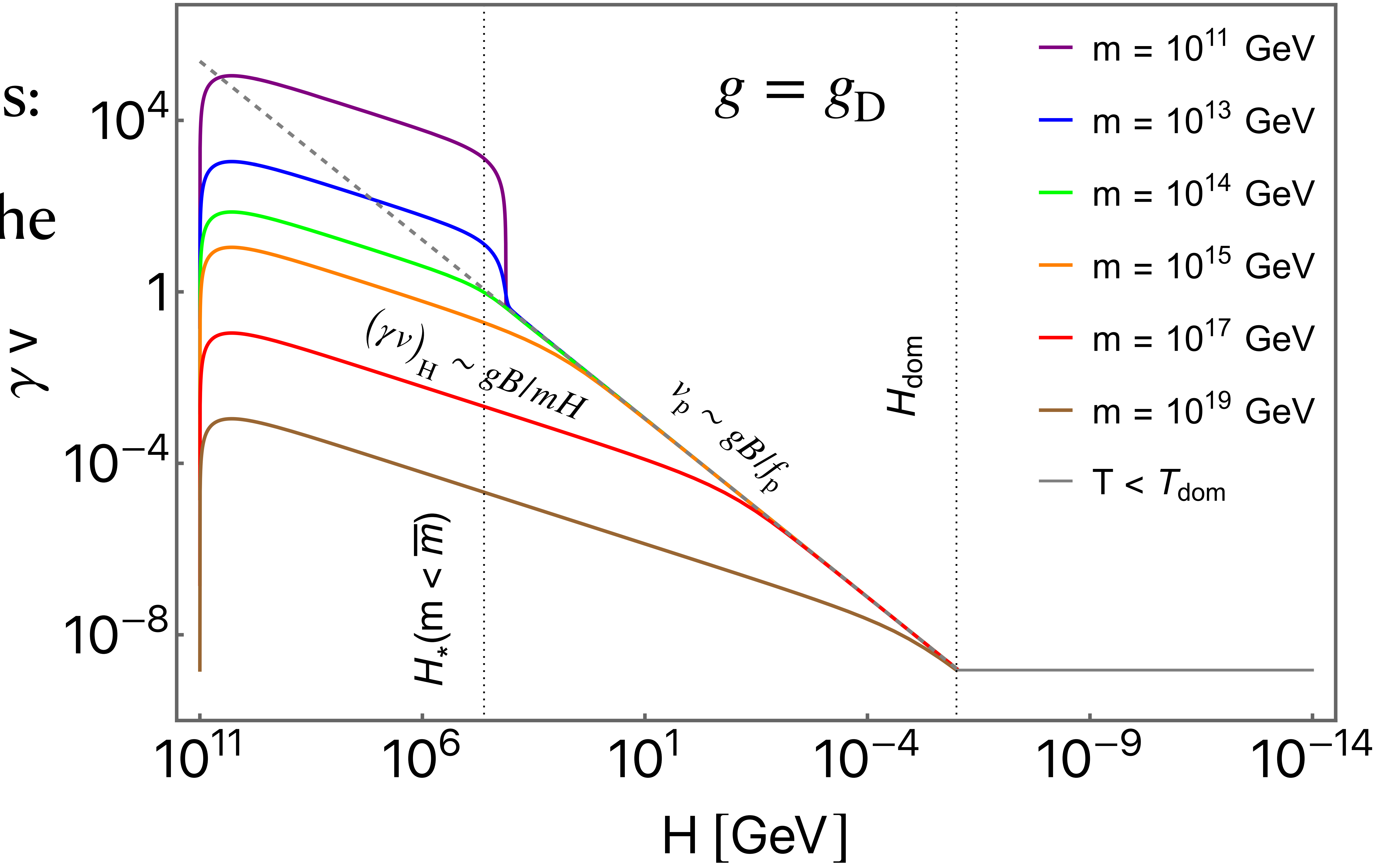
The Equation of Motion of the Monopoles

$$m\frac{d}{dt}(\gamma v) = gB - \left(f_{\rm p} + mH\gamma\right) v$$

Two external forces act on the monopoles:

- gB, the *magnetic force* that accelerates the monopoles;
- $-f_{\rm p}v$, the *frictional force* due to the interaction with the particles of the primordial plasma.

$$f_{\rm p} \sim \frac{e^2 g^2 \mathcal{N}_c}{16\pi^2} T^2$$



The *expansion of the universe* acts as an effective additional frictional force.

Bounds on the Monopole Flux

- From each of the two maxima through the condition $\Pi_{\rm acc}/\Pi_{\rm red} \lesssim 1$ we obtain bounds on the monopole abundance today:

1) During radiation domination:

$$n_0 \lesssim \max\left\{ 10^{-20}\ \mathrm{cm}^{-3},\ 10^{-20}\ \mathrm{cm}^{-3} \left(\frac{m}{10^{19}\ \mathrm{GeV}}\right)\left(\frac{g_{\rm D}}{g}\right)^2 \right\}$$

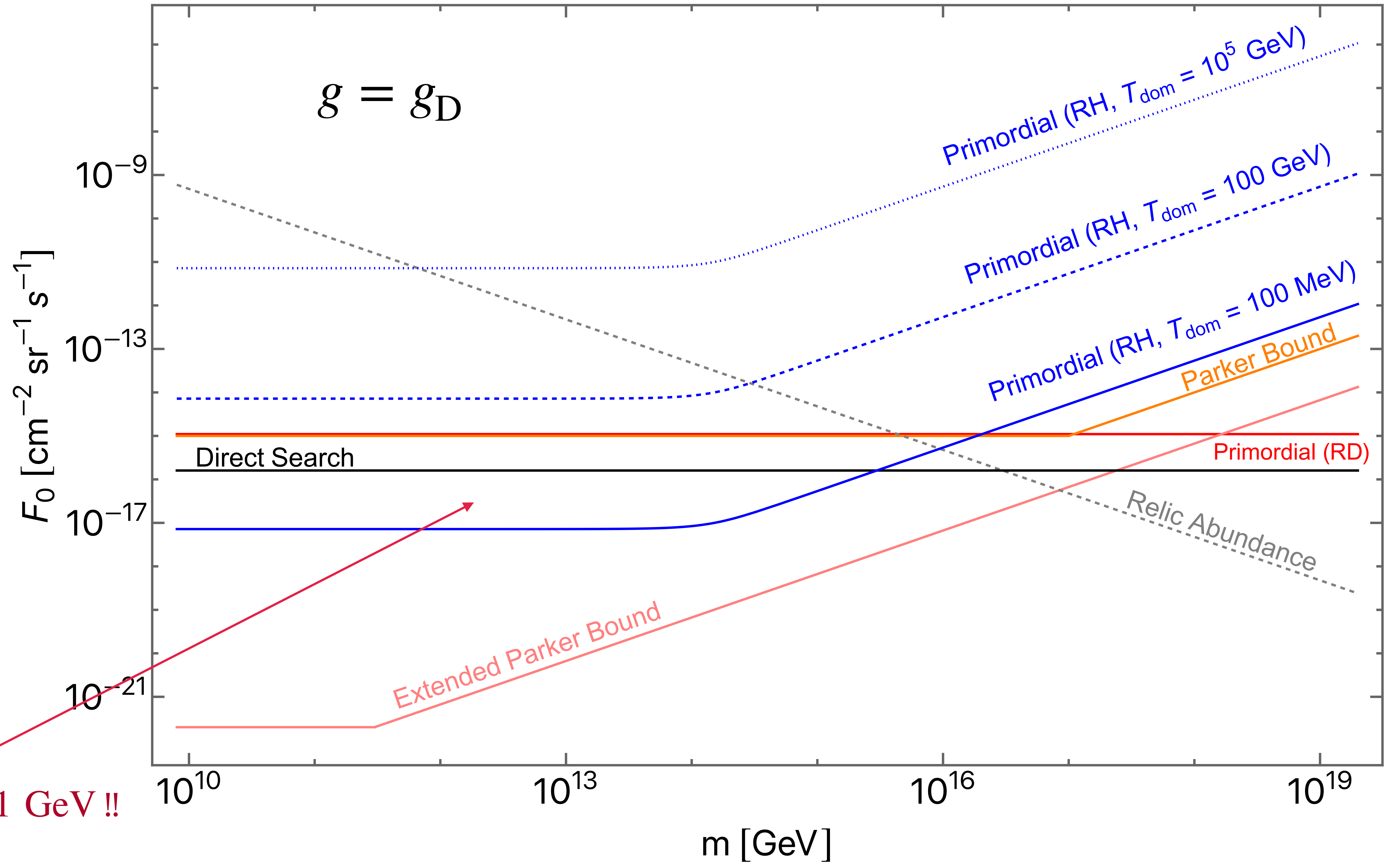
2) During reheating:

$$n_0 \lesssim \max\left\{ 10^{-15}\ \mathrm{cm}^{-3} \left(\frac{B_0}{10^{-15}\ \mathrm{G}}\right)^{3/5}\left(\frac{T_{\rm dom}}{10^{6}\ \mathrm{GeV}}\right)\left(\frac{g_{\rm D}}{g}\right)^{3/5}, \right.$$

$$\left. 10^{-15}\ \mathrm{cm}^{-3} \left(\frac{m}{10^{14}\ \mathrm{GeV}}\right)\left(\frac{T_{\rm dom}}{10^{6}\ \mathrm{GeV}}\right)\left(\frac{g_{\rm D}}{g}\right)^2 \right\}$$

Bounds on the Monopole Flux

- We compare the new bounds with previous bounds on the monopole abundance:



Stronger for $T_{dom} \lesssim 1$ GeV !!

Schwinger Effects and Monopole Pair Production

Primordial magnetic fields are strong enough to produce significant amount of monopole-antimonopole pairs through the Schwinger Effect:

$$\Gamma = \frac{(gB)^2}{(2\pi)^3} \exp\left[-\frac{\pi m^2}{gB} + \frac{g^2}{4}\right]$$

We apply the primordial bounds on the monopole abundance produced by the fields themselves obtaining the *most conservative bound on the primordial magnetic field amplitude*:

$$B \lesssim \frac{4\pi m^2}{g^3}$$

*The survival of the fields after production (T. Kobayashi (2021) arXiv:2105.12776) and acceleration of the monopoles is insured by the **weak field condition**.*

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A Model for Minicharged Monopoles

A simple example of how the dark sector can produce minicharged monopoles without breaking the Dirac quantization condition:

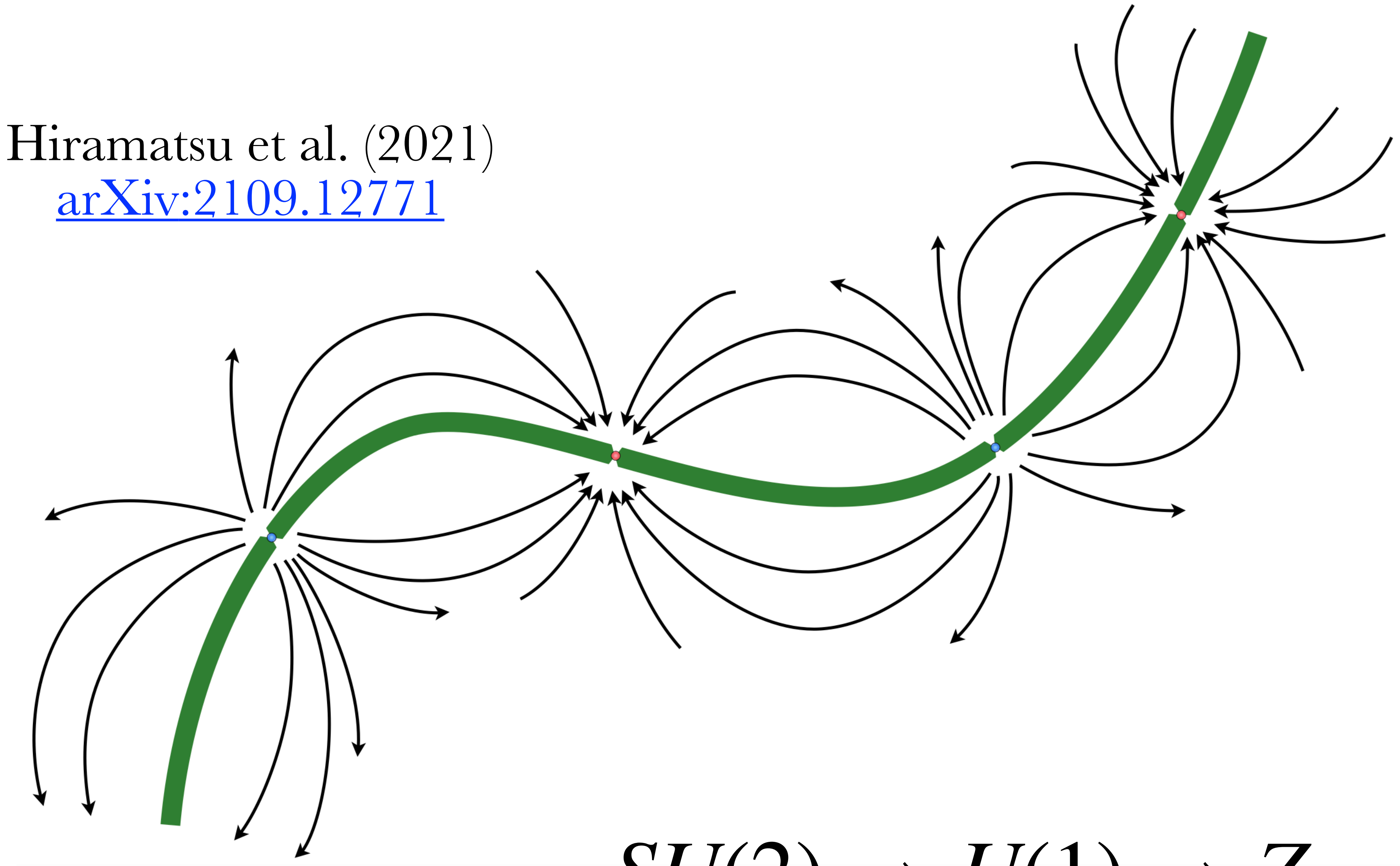
$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'^{a}_{\mu\nu}F'^{a\mu\nu} + \frac{\phi^a}{2\Lambda}F'^{a}_{\mu\nu}F^{\mu\nu} \qquad V = \frac{\lambda_1}{4}(\phi_1 \cdot \phi_1 - v_1^2) + \frac{\lambda_2}{4}(\phi_2 \cdot \phi_2 - v_2^2) + \frac{k}{2}(\phi_1 \cdot \phi_2)^2$$

First Symmetry Breaking:
Dark monopoles production;

Second Symmetry breaking:
The dark field confined into dark strings connecting the monopoles;

The mixing term would provide a tiny visible charge to the dark monopoles.

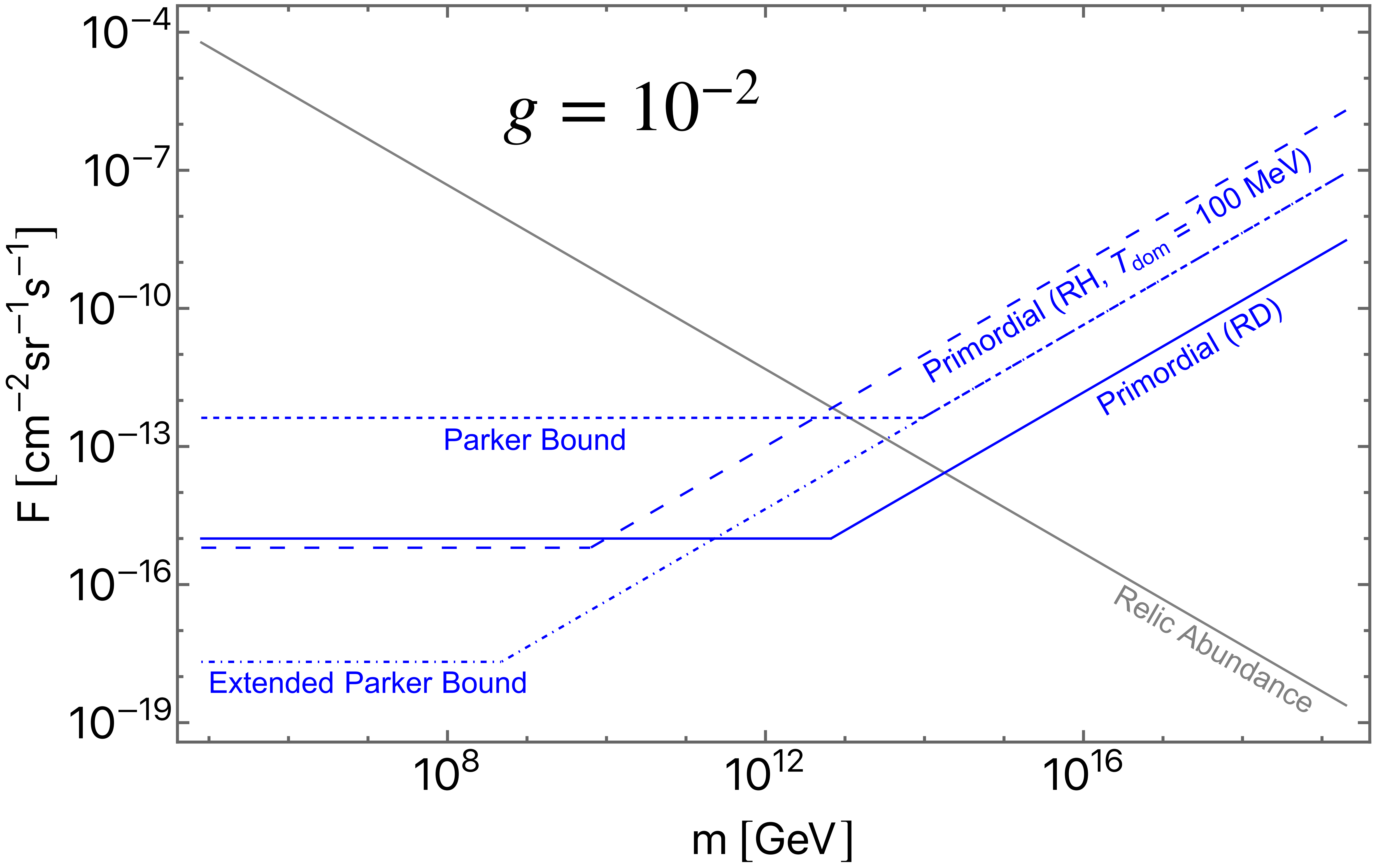
Hiramatsu et al. (2021)
arXiv:2109.12771

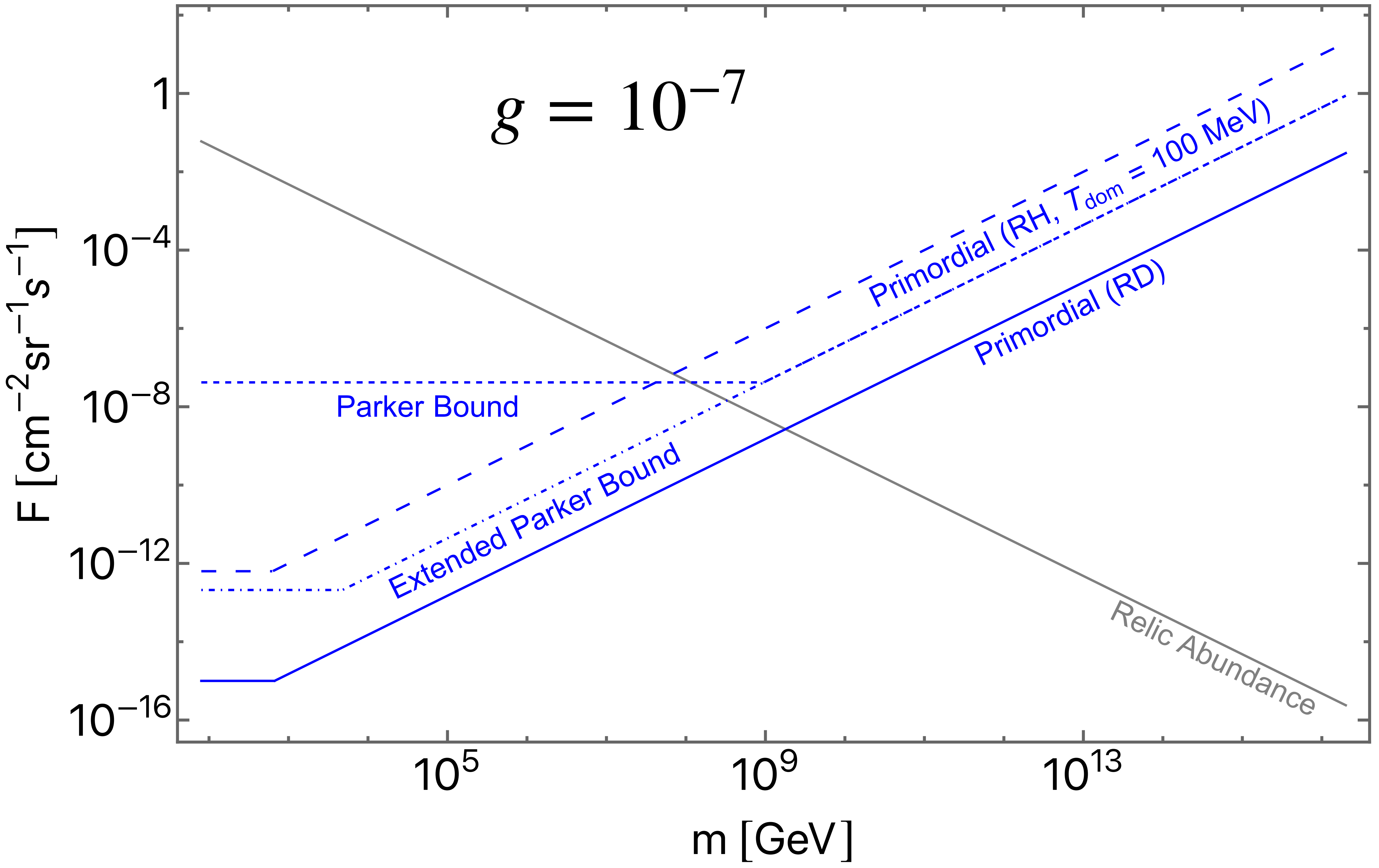


$SU(2) \to U(1) \to Z_2$

Bounds on Minicharged Monopoles

The bounds do not change all in the same way with the magnetic charge of the monopoles:

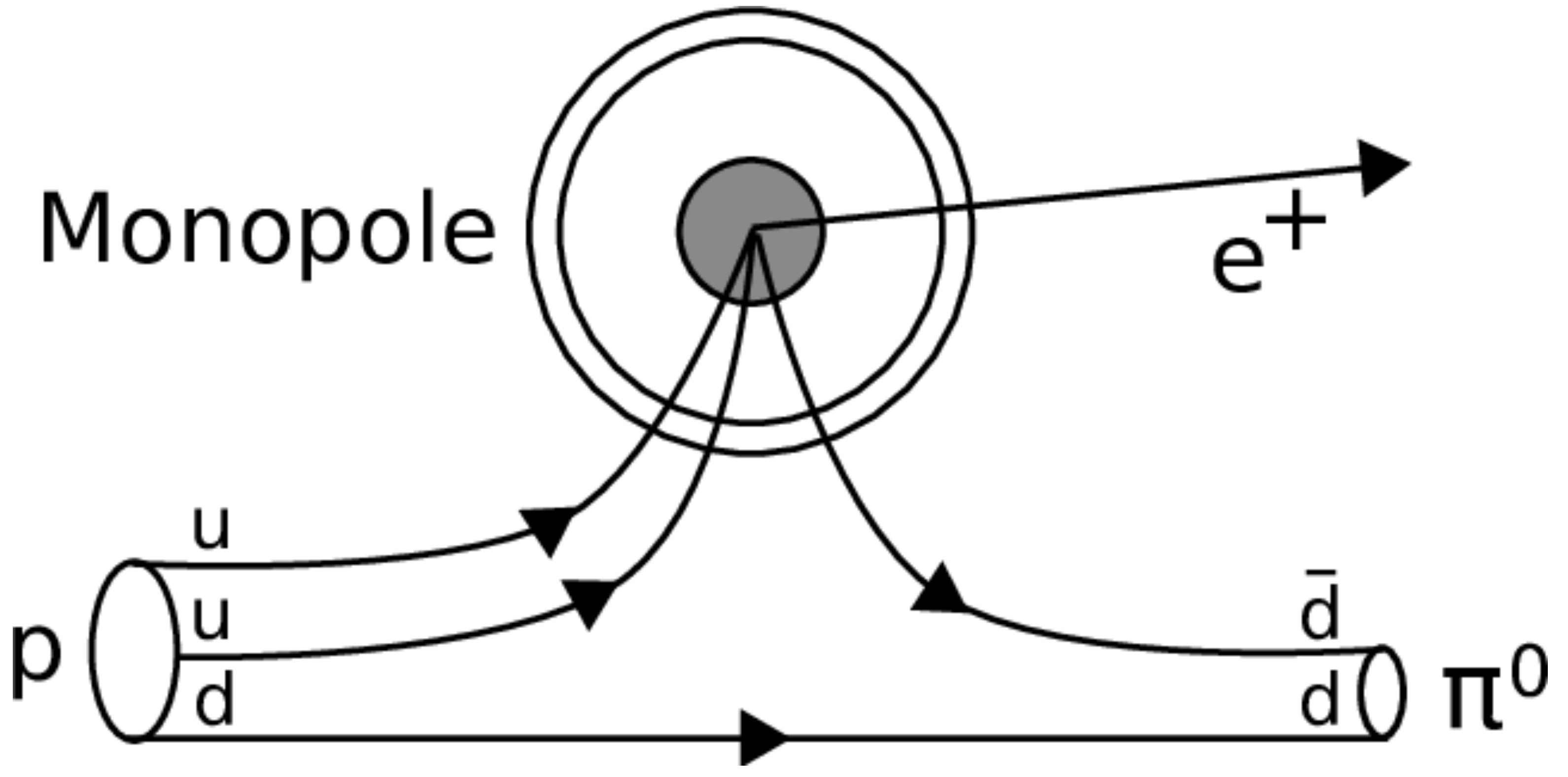




The primordial Parker bounds are less dependent of the monopole charge and they are the **strongest** for small charges.

Direct Search of Dark Monopoles?

- Minicharged monopoles cannot be direct searched with the standard methods (ex. induction of a current in a coil, energy loss in a calorimeter).
- Even completely dark monopoles can still be detected through the *catalysis of nucleon decays:*



Such bounds are almost *independent of the charge* but depends strongly on the UV completion of the theory (not possible for Dirac monopoles).

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Conclusion

- Magnetic monopoles are *inevitable predictions* of GUT and are a possible Dark Matter candidate.
- We carried out a *comprehensive study of the monopole dynamics* in the early universe and their back-reaction to the *primordial magnetic fields*.
- We derived *new bounds on the abundance of magnetic monopoles* by generalizing the Parker bound to the survival of the primordial magnetic fields:

  1. For $g = g_D$ with a sufficiently small reheating temperature our bound becomes *stronger than the original Parker bound and the limits from direct search*.
  2. For minicharged monopoles the *primordial bounds can become the strongest* and the only possibility for direct search (up to now!) is through the *catalysis of nucleon decays*.

Thank You!!

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Monopoles as topological defects

't Hooft - Polyakov Monopoles

- Topological defects comes from non trivial configurations of the vacuum manifold;
- They are classified in terms of the homotopy groups of the manifold;
- Examples are domain walls, cosmic strings, monopoles and textures;
- Monopoles are linked to non-trivial configuration of the second homotopy group of the vacuum manifold structure.

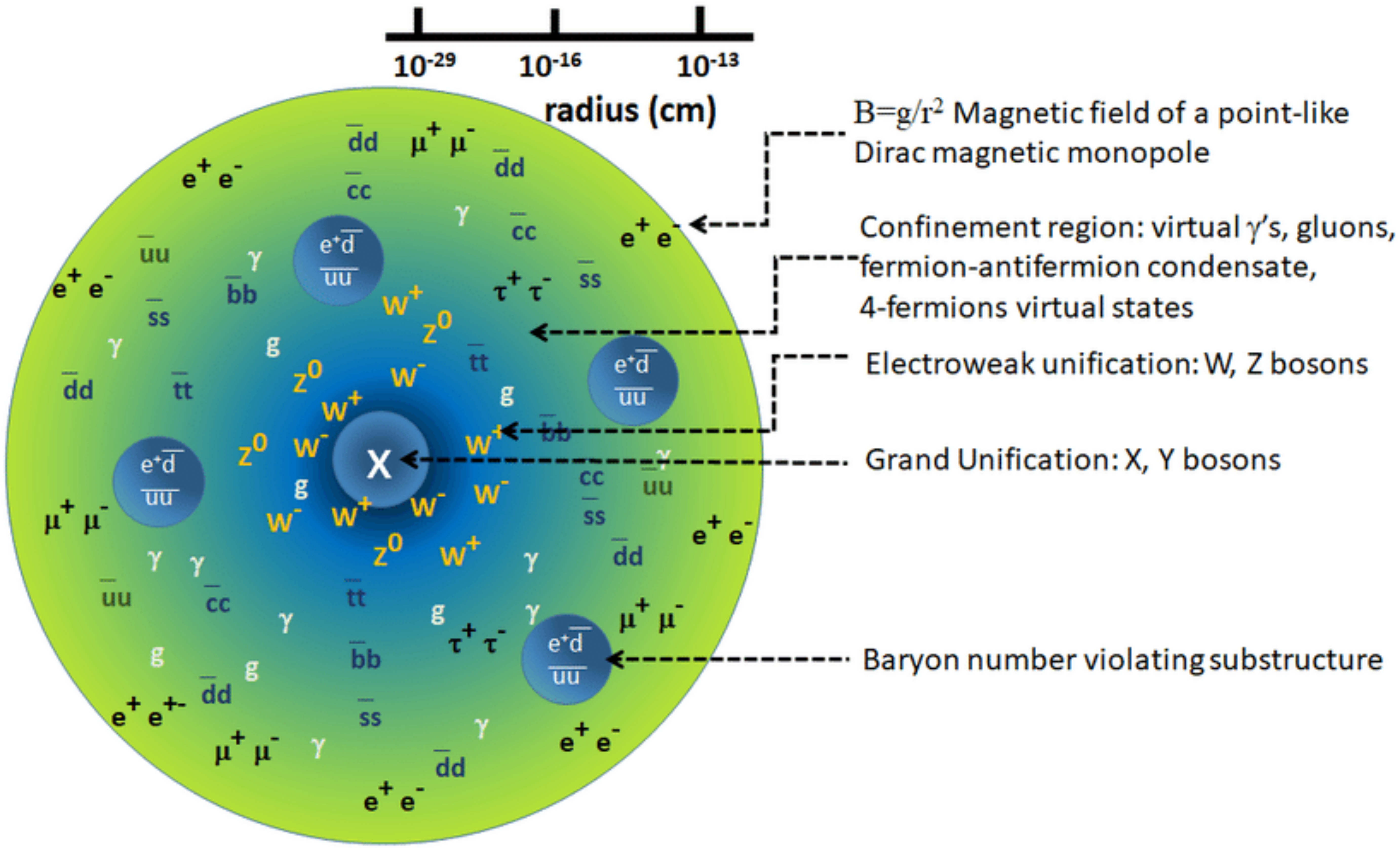
X	$\pi_1(X)$	$\pi_2(X)$	$\pi_3(X)$	$\pi_4(X)$	$\pi_5(X)$	$\pi_6(X)$	$\pi_7(X)$
$Sp(1)$	0	0	$\mathbb{Z}$	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}_{12}$	$\mathbb{Z}_2$
$Sp(n), n \geq 2$	0	0	$\mathbb{Z}$	$\mathbb{Z}_2$	$\mathbb{Z}_2$	0	$\mathbb{Z}$
$SU(3)$	0	0	$\mathbb{Z}$	0	$\mathbb{Z}$	$\mathbb{Z}_6$	0
$SU(n), n \geq 4$	0	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
$Spin(7)$	0	0	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$
$Spin(8)$	0	0	$\mathbb{Z}$	0	0	0	$\mathbb{Z} \oplus \mathbb{Z}$
$Spin(n), n \geq 9$	0	0	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$
$SO(3)$	$\mathbb{Z}_2$	0	$\mathbb{Z}$	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}_{12}$	$\mathbb{Z}_2$
$SO(5)$	$\mathbb{Z}_2$	0	$\mathbb{Z}$	$\mathbb{Z}_2$	$\mathbb{Z}_2$	0	$\mathbb{Z}$
$SO(6)$	$\mathbb{Z}_2$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
$SO(7)$	$\mathbb{Z}_2$	0	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$
$SO(8)$	$\mathbb{Z}_2$	0	$\mathbb{Z}$	0	0	0	$\mathbb{Z} \oplus \mathbb{Z}$
$SO(n), n \geq 9$	$\mathbb{Z}_2$	0	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$
G_2	0	0	$\mathbb{Z}$	0	0	$\mathbb{Z}_3$	0
F_4, E_6, E_7, E_8	0	0	$\mathbb{Z}$	0	0	0	0
S^2	0	$\mathbb{Z}$	$\mathbb{Z}$	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}_{12}$	$\mathbb{Z}_2$
S^3	0	0	$\mathbb{Z}$	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}_{12}$	$\mathbb{Z}_2$
S^4	0	0	0	$\mathbb{Z}$	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z} \oplus \mathbb{Z}_{12}$
S^5	0	0	0	0	$\mathbb{Z}$	$\mathbb{Z}_2$	$\mathbb{Z}_2$

TABLE A.1: Homotopy groups of connected compact simple Lie groups [Jam95] and spheres S^n for $2 \leq n \leq 5$ [Tod63]. Notice that there are isomorphisms $Sp(1) \cong SU(2) \cong Spin(3)$, $Sp(2) \cong Spin(5)$ and $SU(4) \cong Spin(6)$

Monopoles in Grand Unified Theories

Monopoles are *inevitable predictions* of Grand Unified Theories:

$$SU(5) \to SU(3) \times SU(2) \times U(1) \to SU(3) \times U(1)$$

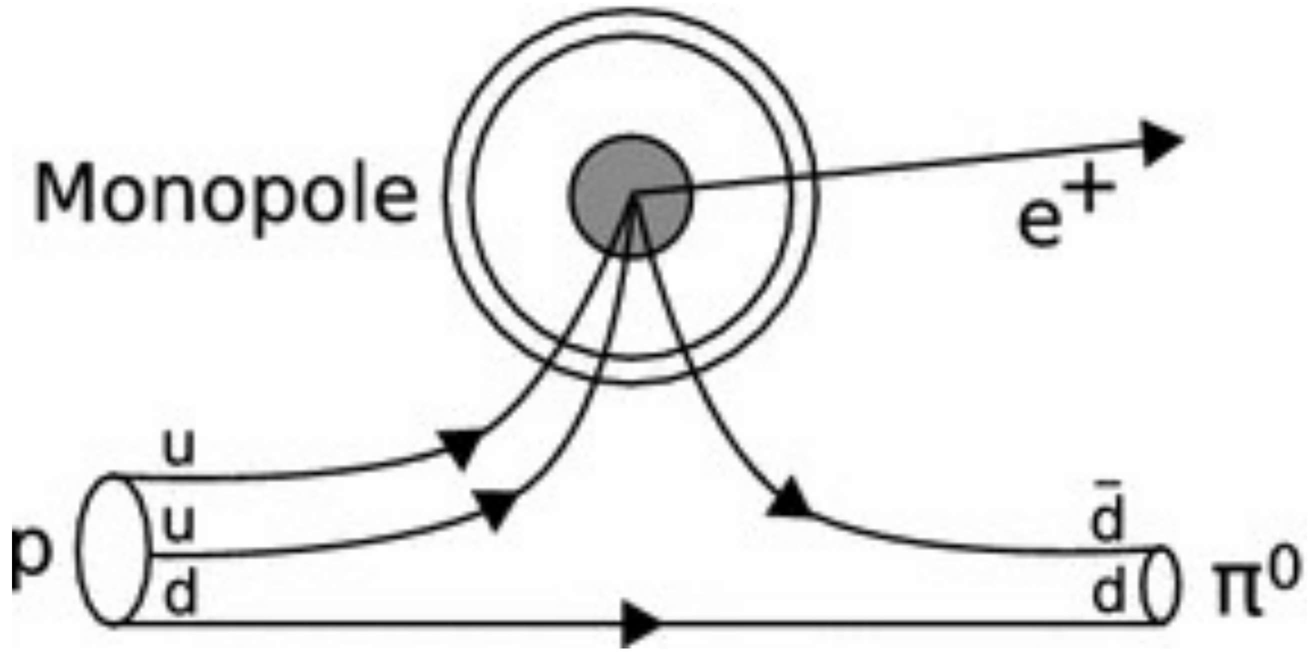


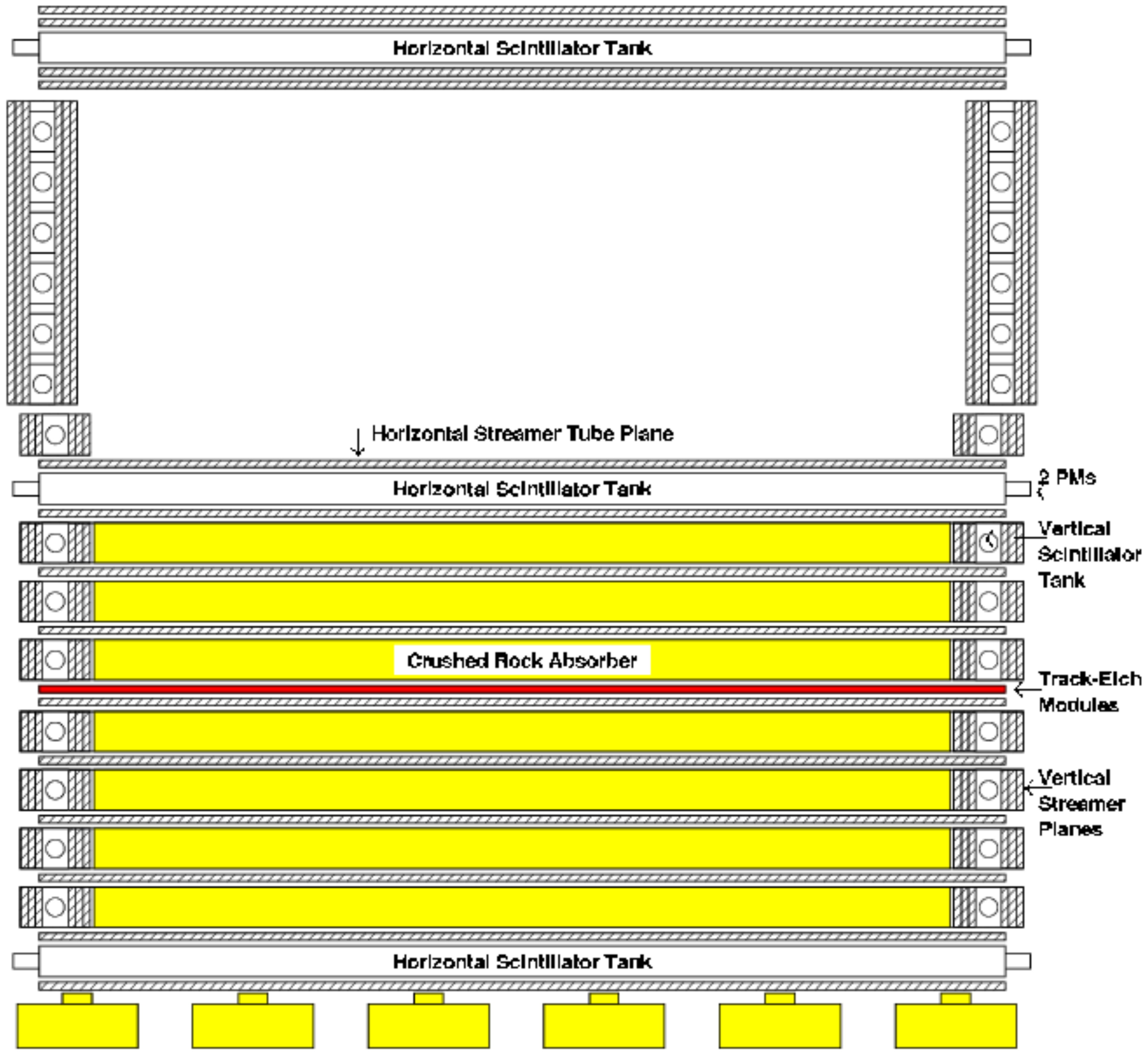
They present a complex structure inside the core where *all the states of the GUT are excited.*

Direct Observations of Monopoles

There are different strategies used for the direct observation of magnetic monopoles:

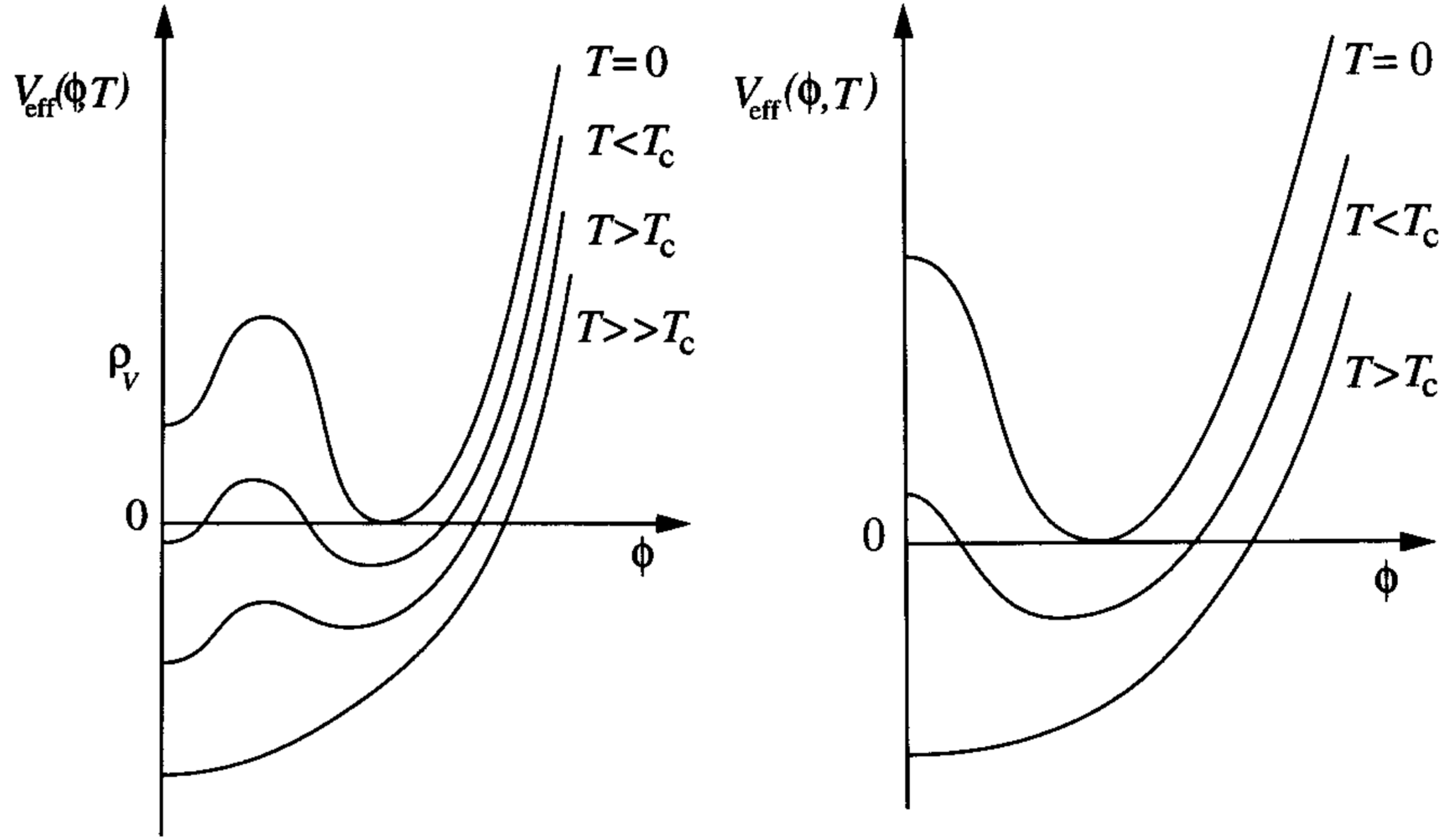
- Induction of electric currents into a coil;
- Energy loss by ionization (Ex. MACRO experiment);
- Catalysis of nucleon decays (only for GUT monopoles).





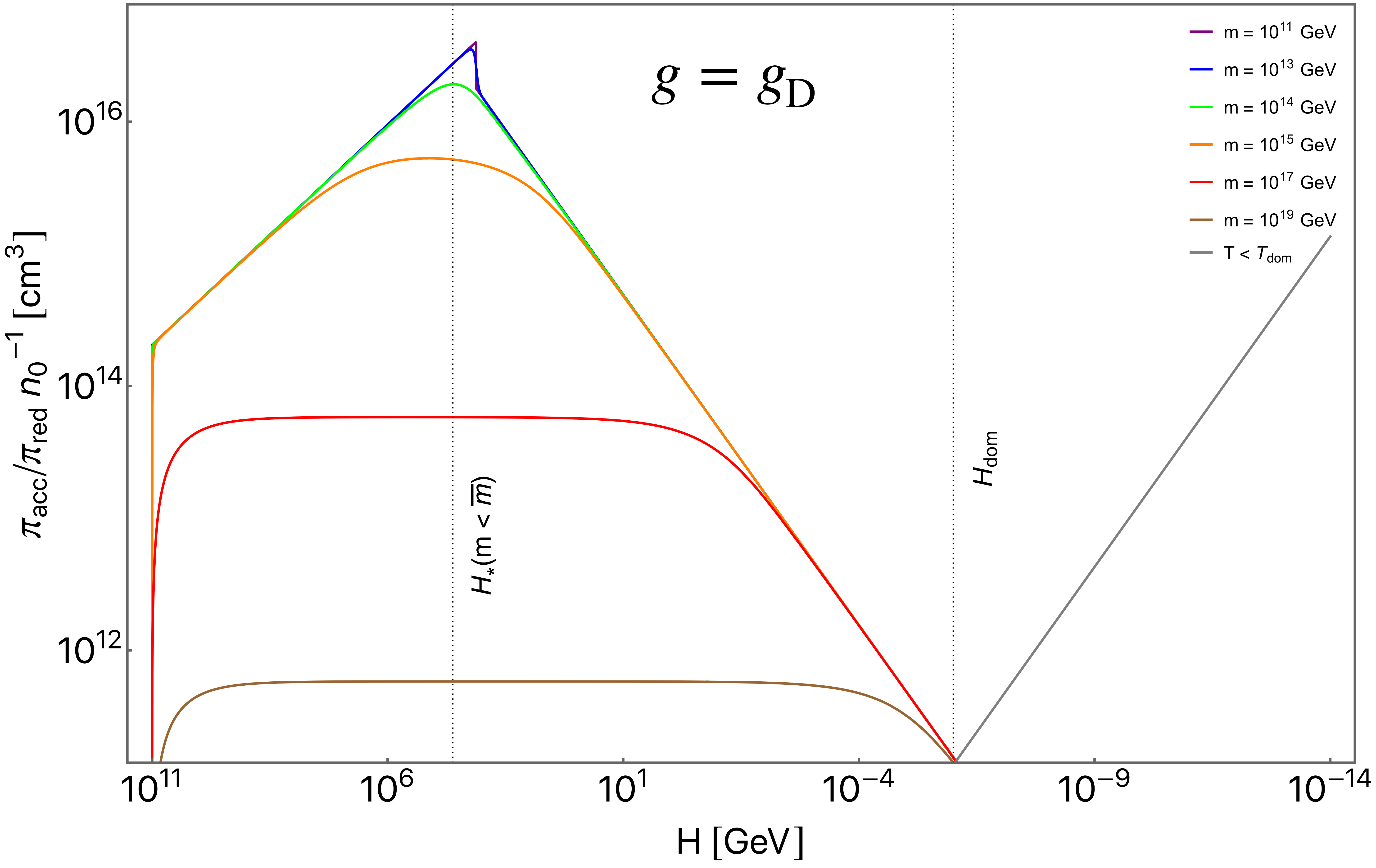
Monopole Production in Phase Transitions

- Monopoles are produced in the early universe during phase transition.
- The abundance of produced monopoles can easily over-dominate the energy density of the universe.
- Inflation provides a good solution to the problem.



The Evolution of Π_{acc}/Π_{red}

- The expression for Π_{acc}/Π_{red} presents two local maxima: one during reheating and one during the following era of radiation domination.



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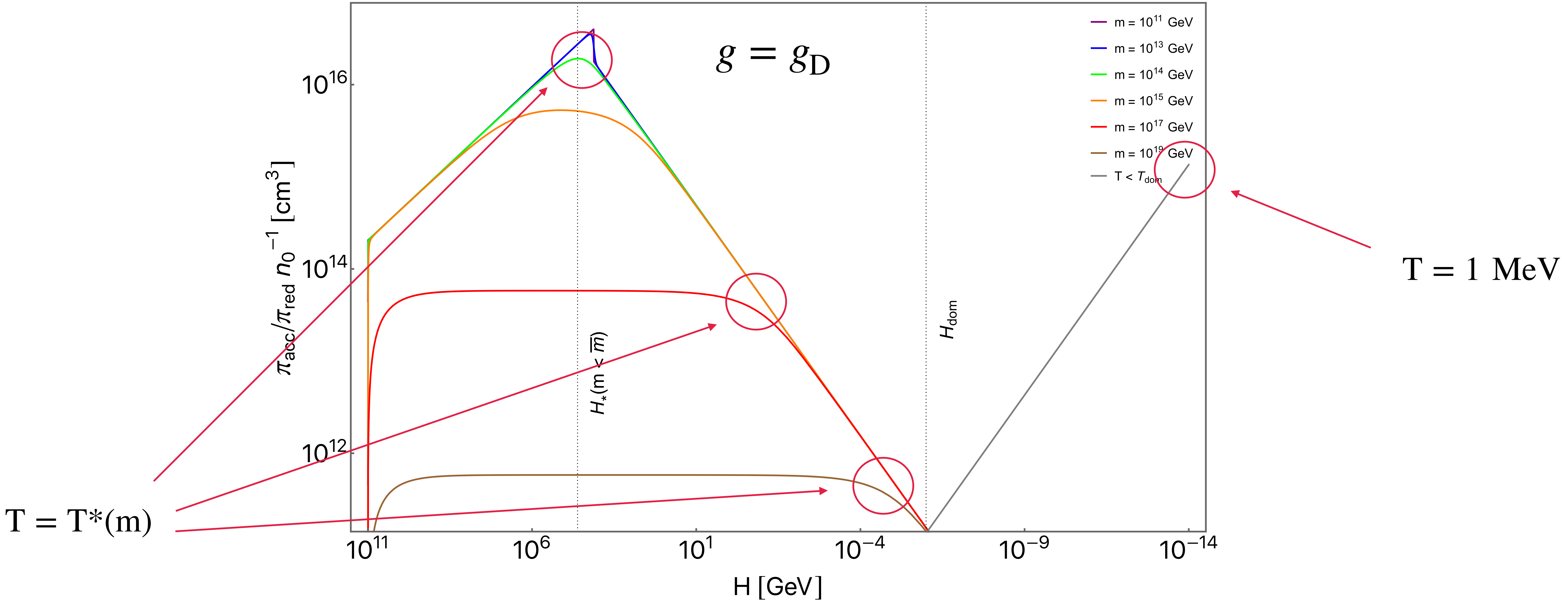


Schwinger Effects and Monopole Pair Production

- The producing pairs extract energy from the magnetic fields that can eventually disappear.

- The bound for the survival of the field reduces to the weak field condition a part for a negligible logarithmic factor:

$$B \lesssim \frac{4\pi m^2}{g^3}\left[1+\log\left(\frac{g^2}{8\pi^3}\frac{m}{H}\right)\right]^{-1}$$

Takeshi Kobayashi (2021)
arXiv:2105.12776

Under the weak field condition the magnetic fields survive pair production.

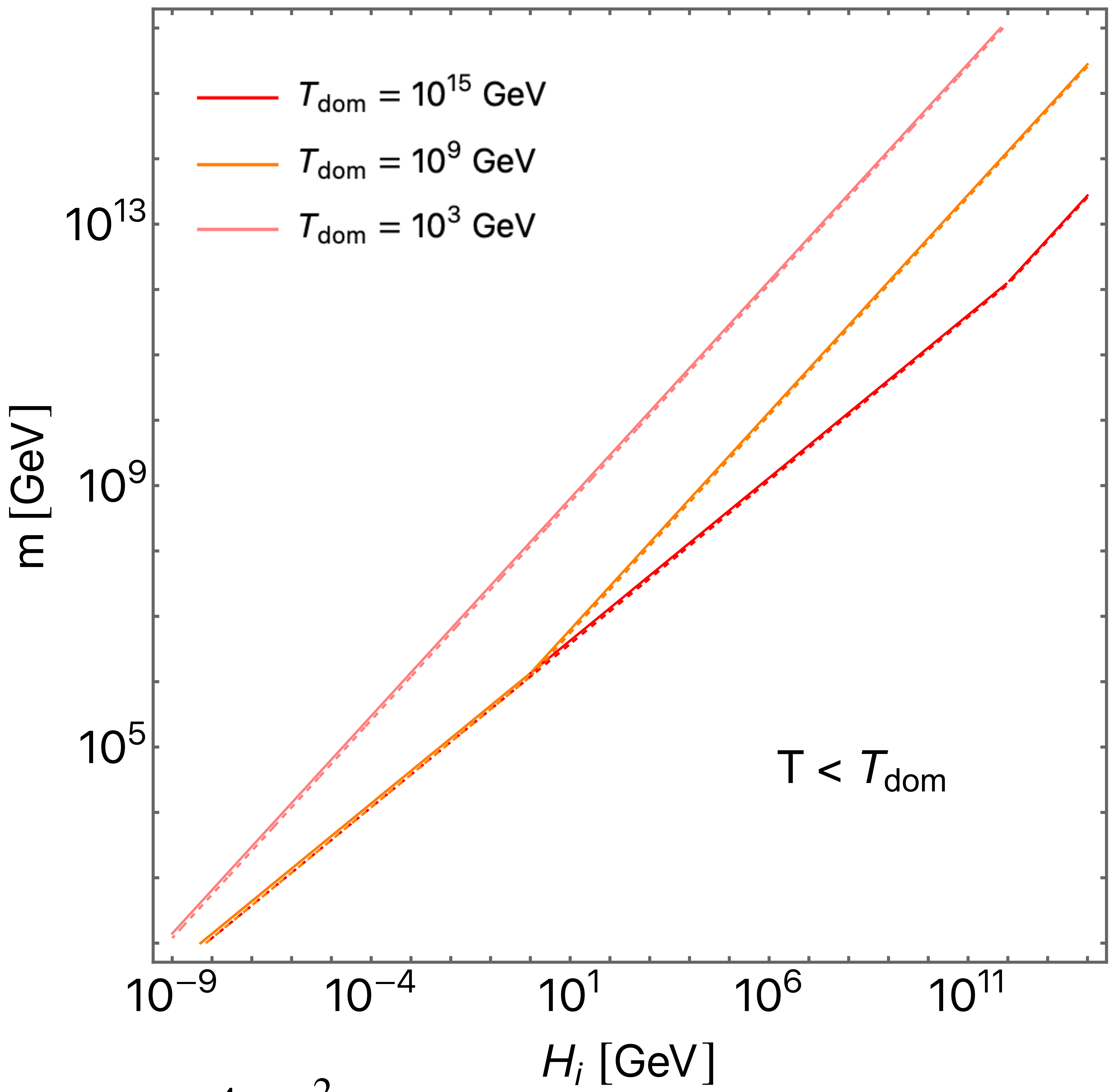
Schwinger Effects and Monopole Pair Production

- The produced pairs are accelerated by the magnetic fields that continues to lose their energy.
- Bounds can be obtained from considering the condition $\Pi_{\rm acc}/\Pi_{\rm red} \lesssim 1$ for the two maxima applied only to pair produced monopoles.
- Also in this case the bounds reduce to the weak field condition a part for a negligible logarithmic factor:

$$B \lesssim \frac{4\pi m^2}{g^3}\left[1 + \log \tilde{x}_{\rm D,B}(m, H_i, T_{\rm dom}, B_0)\right]^{-1}$$

Under the weak field condition the magnetic fields survive pair acceleration.

Schwinger Effects and Monopole Pair Production



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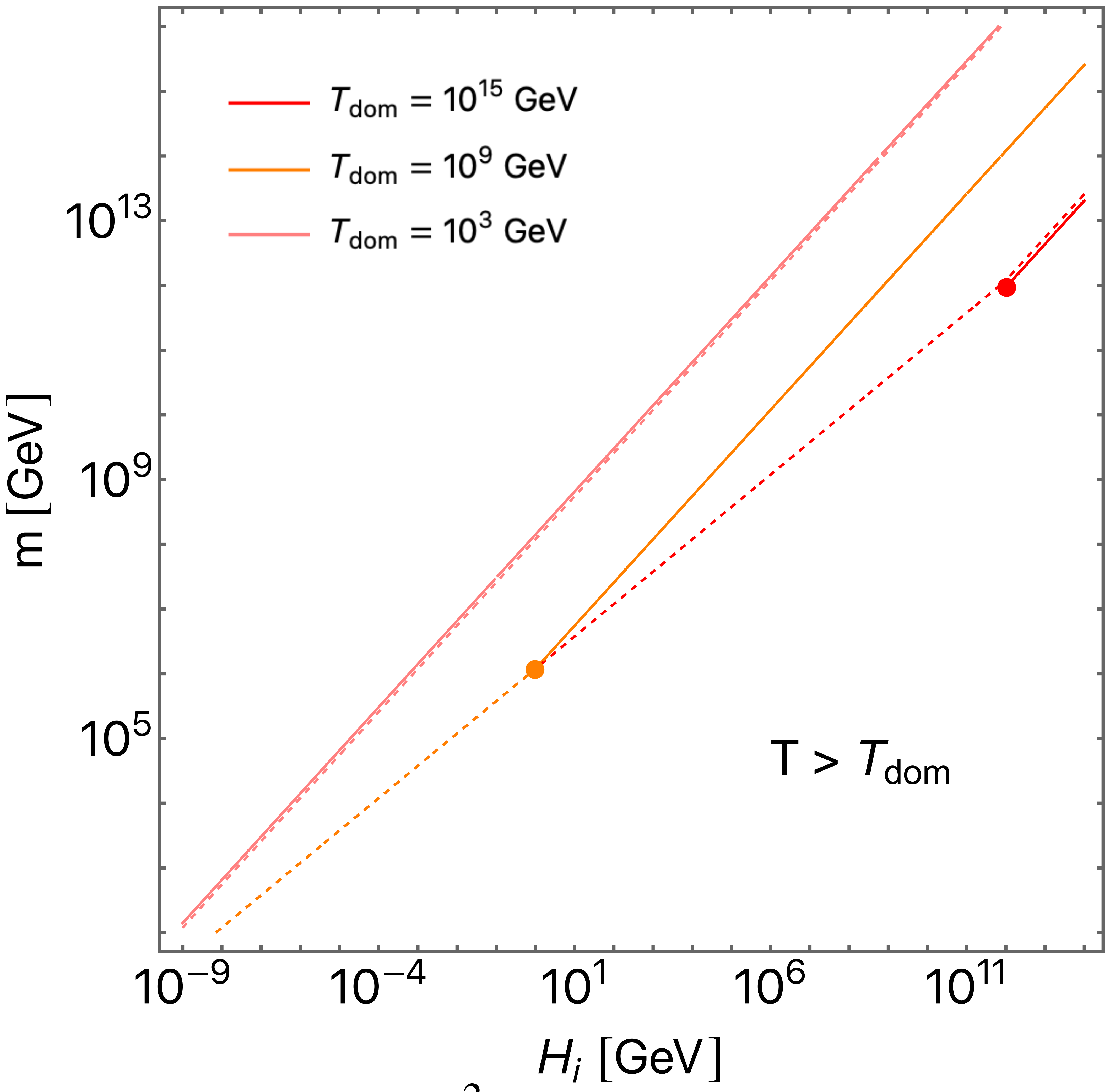

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