# New Bounds on Monopole from Intergalactic Magnetic Fields


**Speaker:**
**Daniele Perri**



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

**DP**, Takeshi Kobayashi
arXiv:2307.07553


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# Contents of the Talk

- ✓ Models of magnetic monopoles.
- ✓ New bounds on the monopole abundance.
- ✓ Minicharged monopoles and magnetic black holes.
- ✓ Schwinger effect and monopole pair production.
- ✓ Conclusion.

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# Can a Monopole Really Exist?

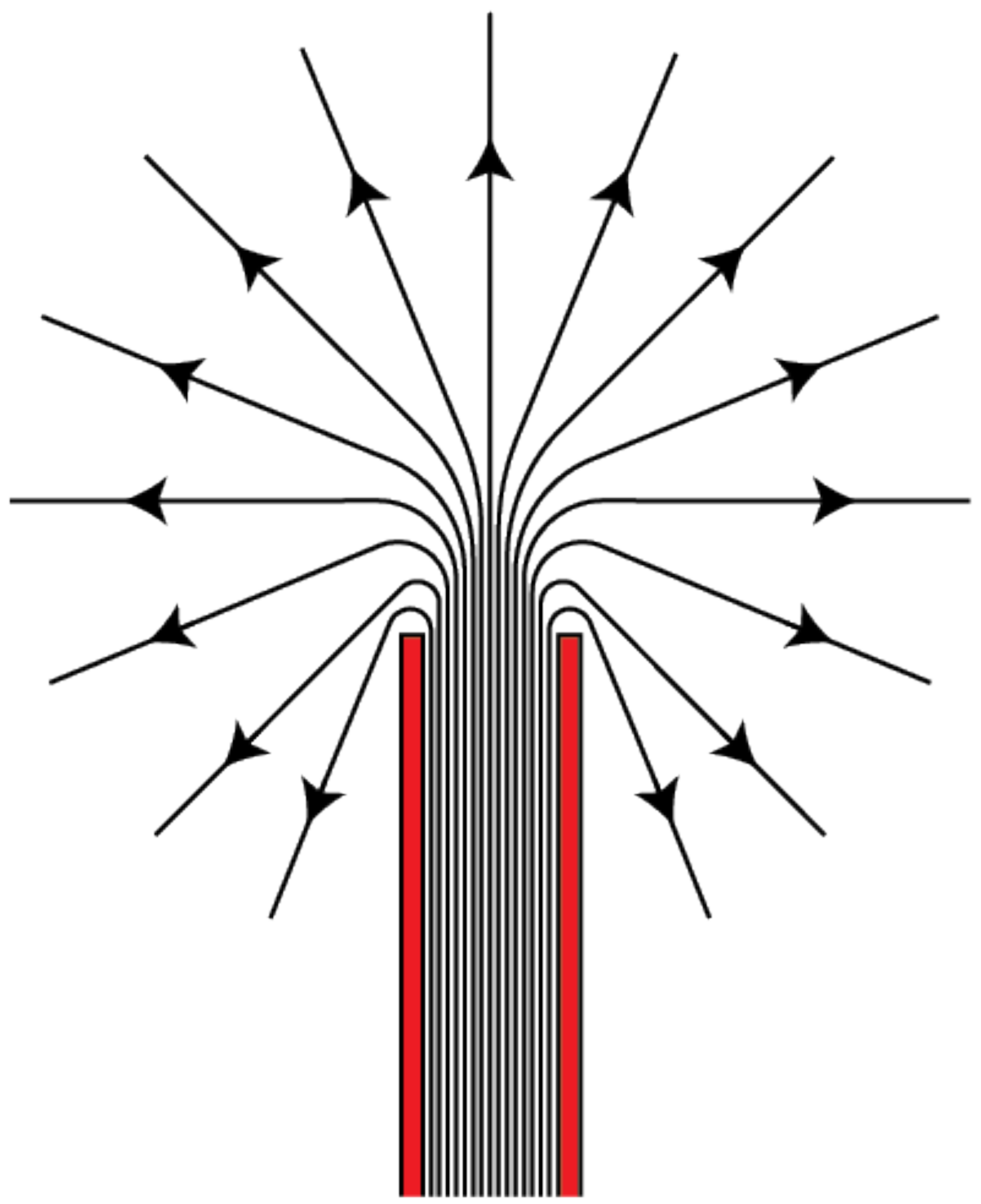
## Dirac Monopoles and the Quantization of the Electric Charge

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

- 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*:

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

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



# Can a Monopole Really Exist?

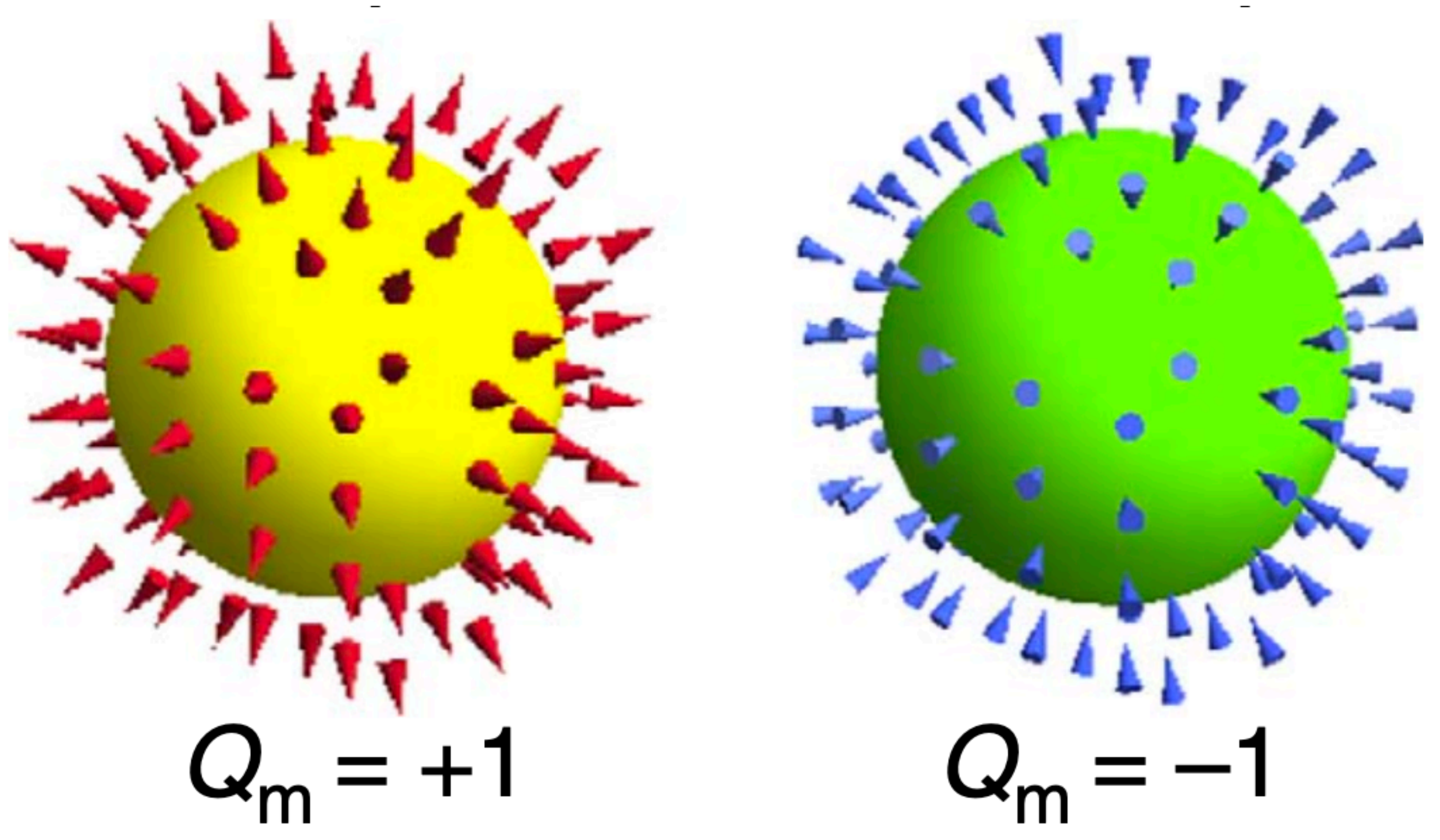
## 'T Hooft-Polyakov Monopoles and Topological Defects

- 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:

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

*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:

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

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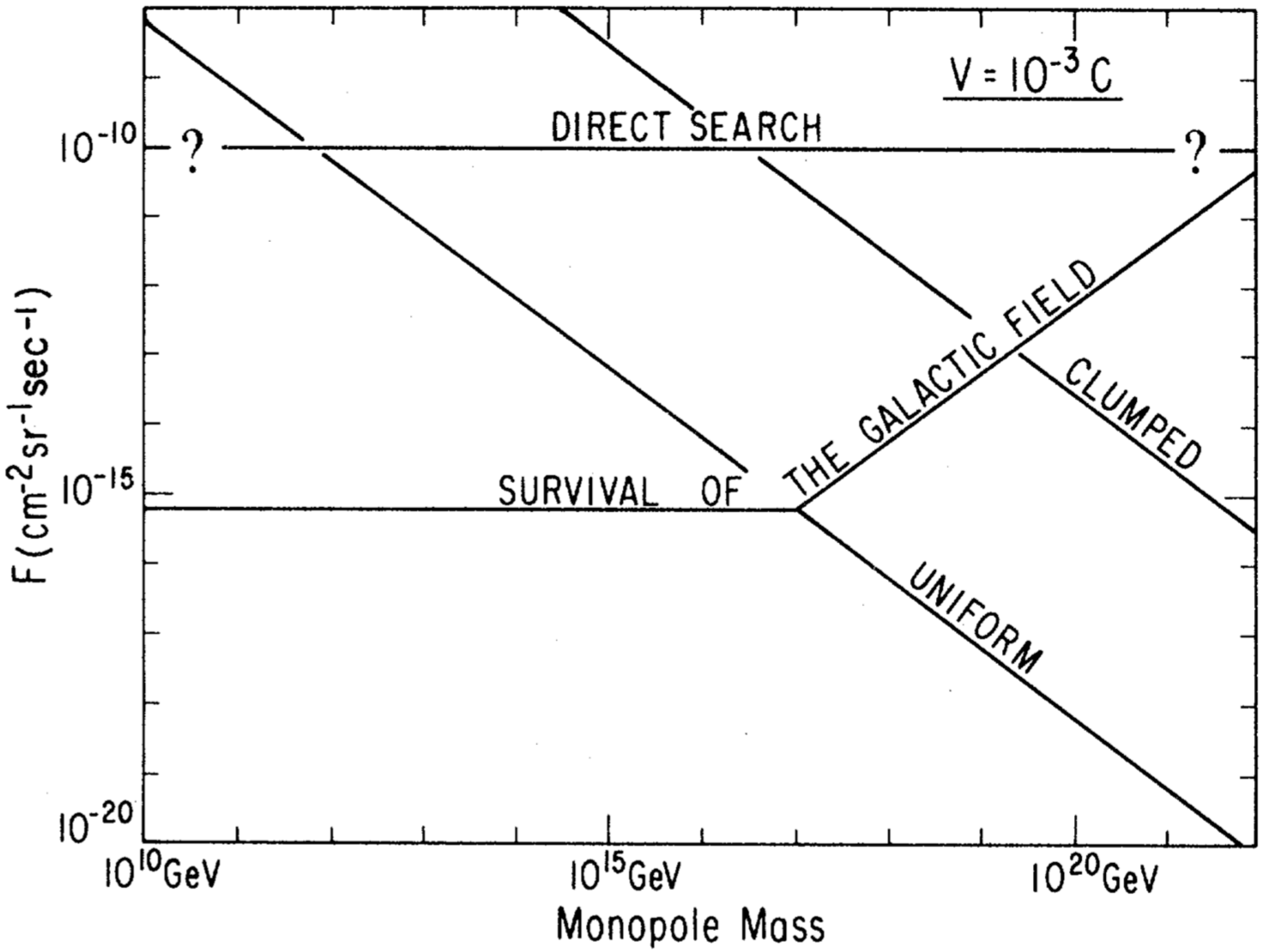
# Parker Bound on the Monopole Flux

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 Bounds from Primordial Magnetic Fields

*An analogous of the Parker bound can be derived from primordial magnetic fields.*

Long, Vachaspati (2015)
arXiv:1504.03319

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

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

$$\frac{\dot{\rho}_{\rm B}}{\rho_{\rm B}} = -\,\Pi_{\rm red} - \Pi_{\rm acc}$$

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

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

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

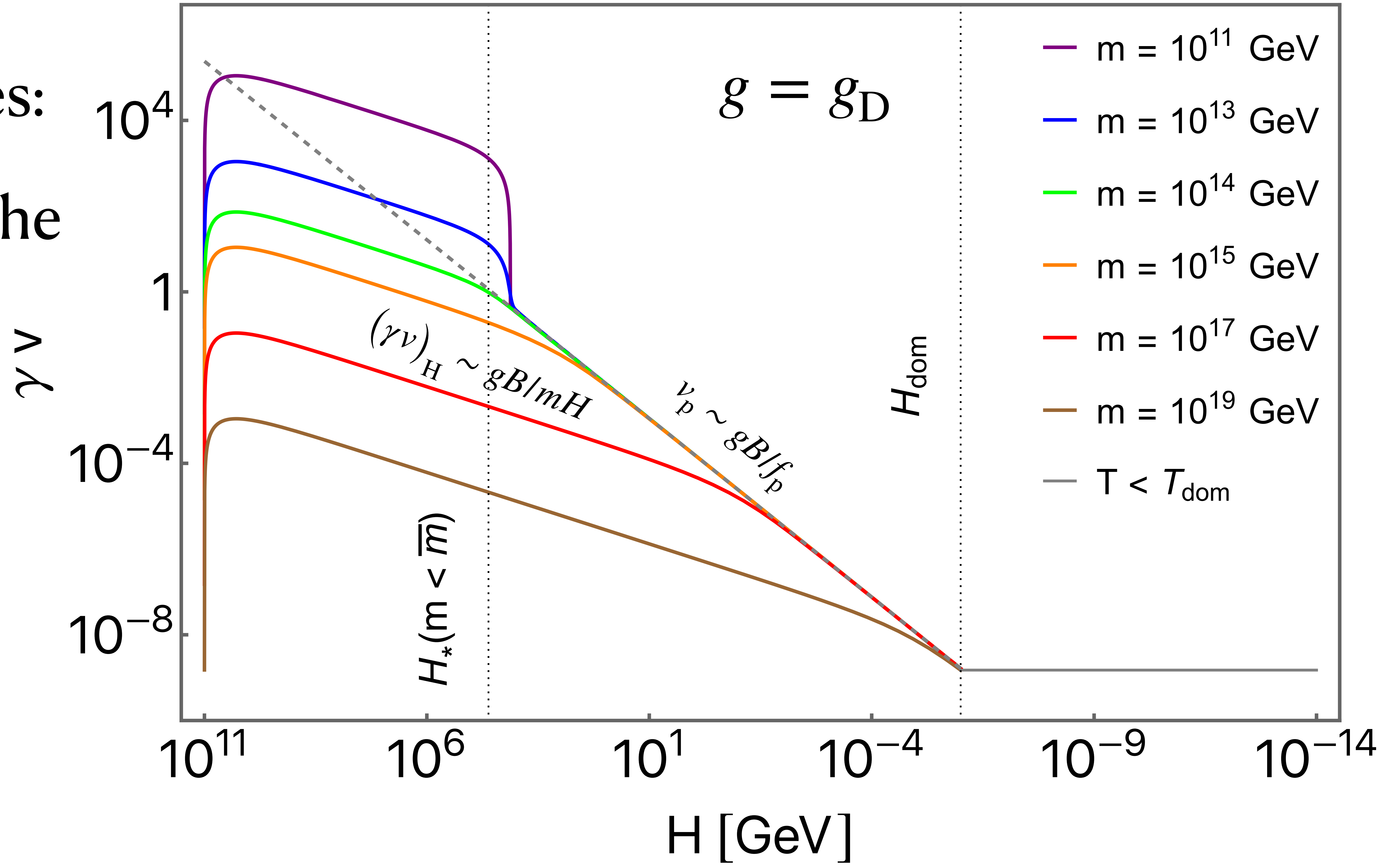
# The Equation of Motion of the Monopoles

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

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:

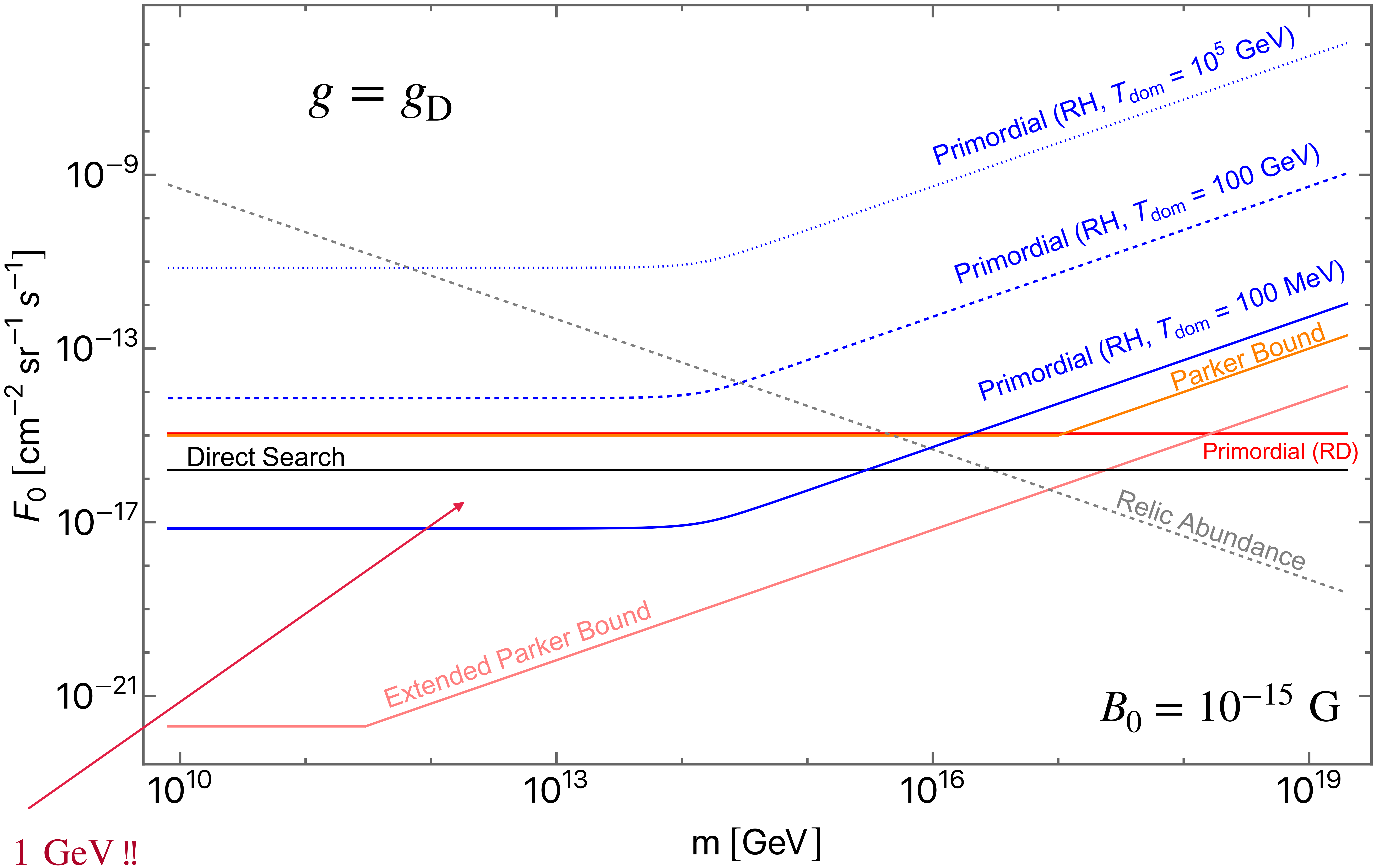
$$n_0 \lesssim \max\left\{ 10^{-21}\ \text{cm}^{-3},\ 10^{-21}\ \text{cm}^{-3} \left(\frac{m}{10^{19}\ \text{GeV}}\right)\left(\frac{g_{\rm D}}{g}\right)^2 \right\}$$

2) During reheating:

$$n_0 \lesssim \max\left\{ 10^{-16}\ \text{cm}^{-3} \left(\frac{B_0}{10^{-15}\ \text{G}}\right)^{3/5} \left(\frac{T_{\rm dom}}{10^{6}\ \text{GeV}}\right)\left(\frac{g_{\rm D}}{g}\right)^{3/5}, \right.$$
$$\left. 10^{-13}\ \text{cm}^{-3} \left(\frac{m}{10^{17}\ \text{GeV}}\right)\left(\frac{T_{\rm dom}}{10^{6}\ \text{GeV}}\right)\left(\frac{g_{\rm D}}{g}\right)^2 \right\}$$

# Bounds on the Monopole Flux

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




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

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# Could Monopoles be Dark Matter?

Monopoles are often suggested as possible candidates for Dark Matter.

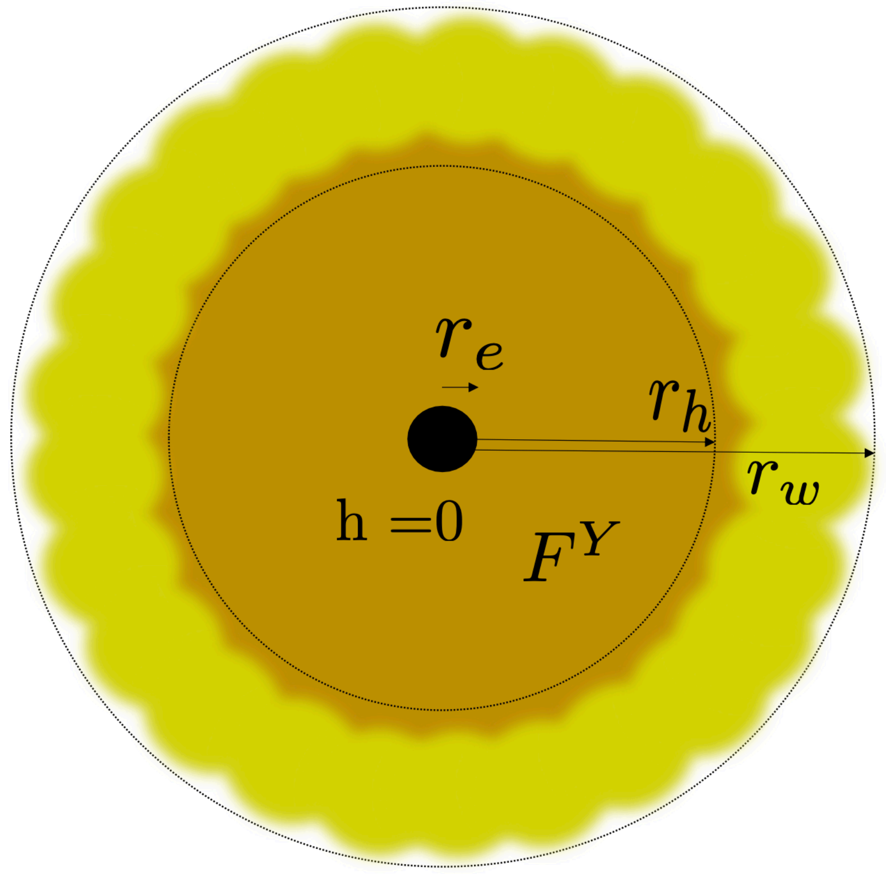
Standard magnetic monopoles must be very heavy to cover all the Dark Matter of the universe ($m \gtrsim 10^{17}$ GeV).

$\downarrow$

- *Minicharged monopoles* relax the bounds opening the possibility of lighter monopoles as Dark Matter.

- *Magnetically charged black holes* act as very heavy magnetic monopoles.

Maldacena (2020)
arXiv:2004.06084



# A Model for Minicharged Monopoles

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

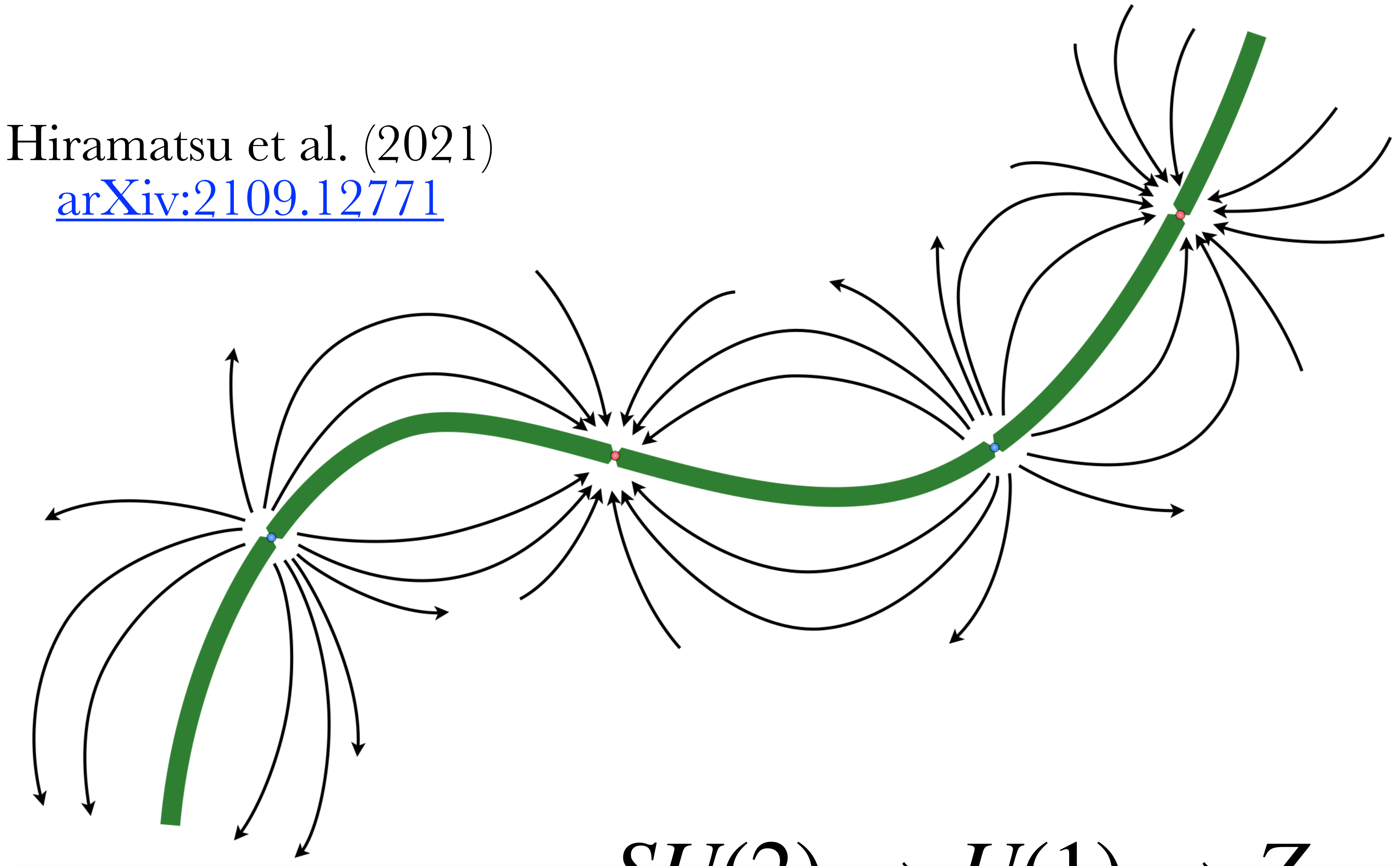
$$\mathscr{L}_{\text{gauge}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'^{a}_{\mu\nu}F'^{a\mu\nu} + \frac{\phi^a}{2\Lambda}F'^{a}_{\mu\nu}F^{\mu\nu} \qquad V = \frac{\lambda_1}{4}(\phi_1\cdot\phi_1 - v_1^2) + \frac{\lambda_2}{4}(\phi_2\cdot\phi_2 - v_2^2) + \frac{k}{2}(\phi_1\cdot\phi_2)^2$$

<u>*First Symmetry Breaking*</u>:
Dark monopoles production;

<u>*Second Symmetry breaking*</u>:
The dark field confined into dark strings connecting the monopoles;

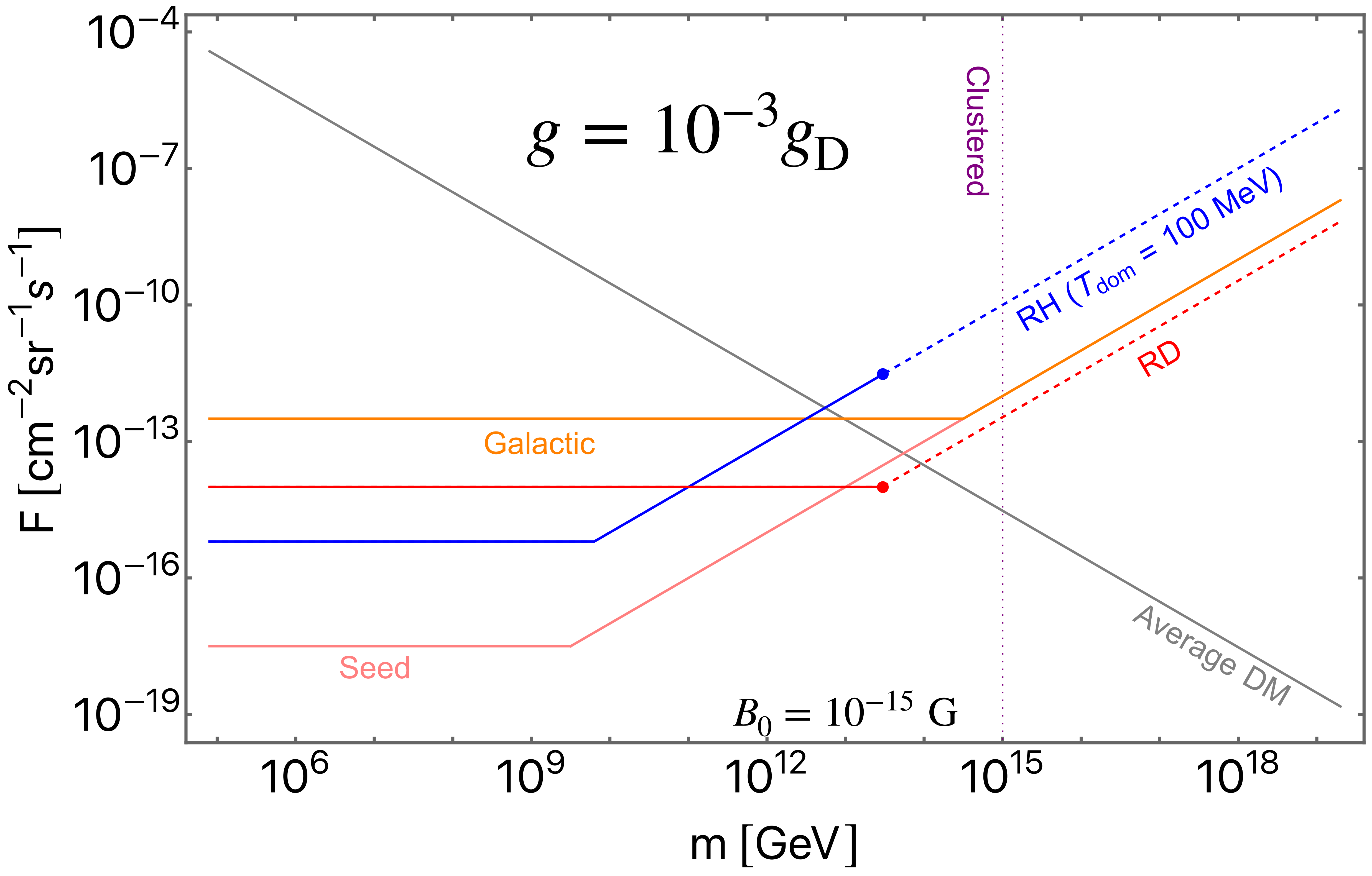
*The mixing term would provide a tiny visible charge to the dark monopoles.*

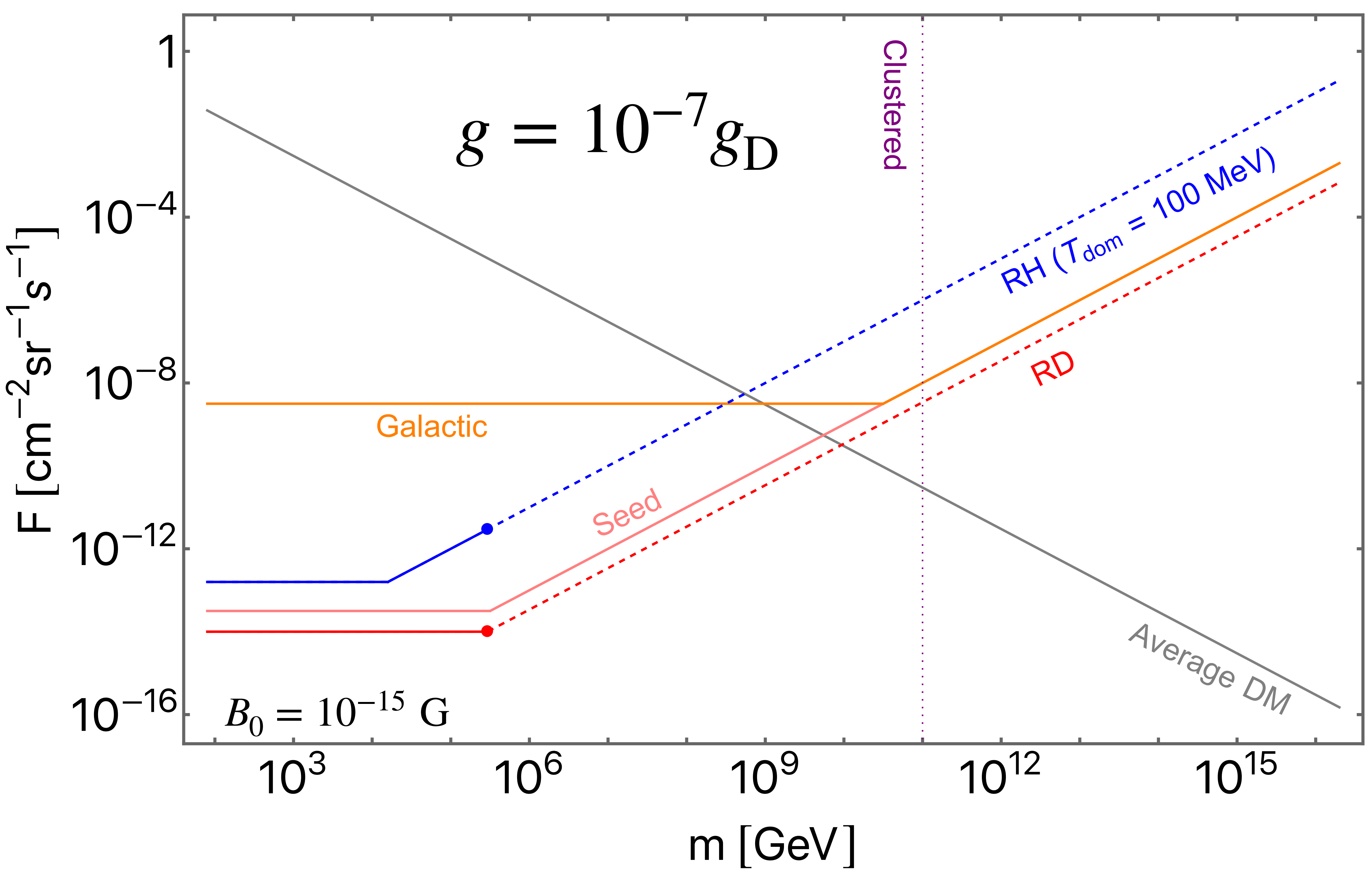
Hiramatsu et al. (2021)
[arXiv:2109.12771](https://arxiv.org/abs/2109.12771)



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

# Bounds on Minicharged Monopoles



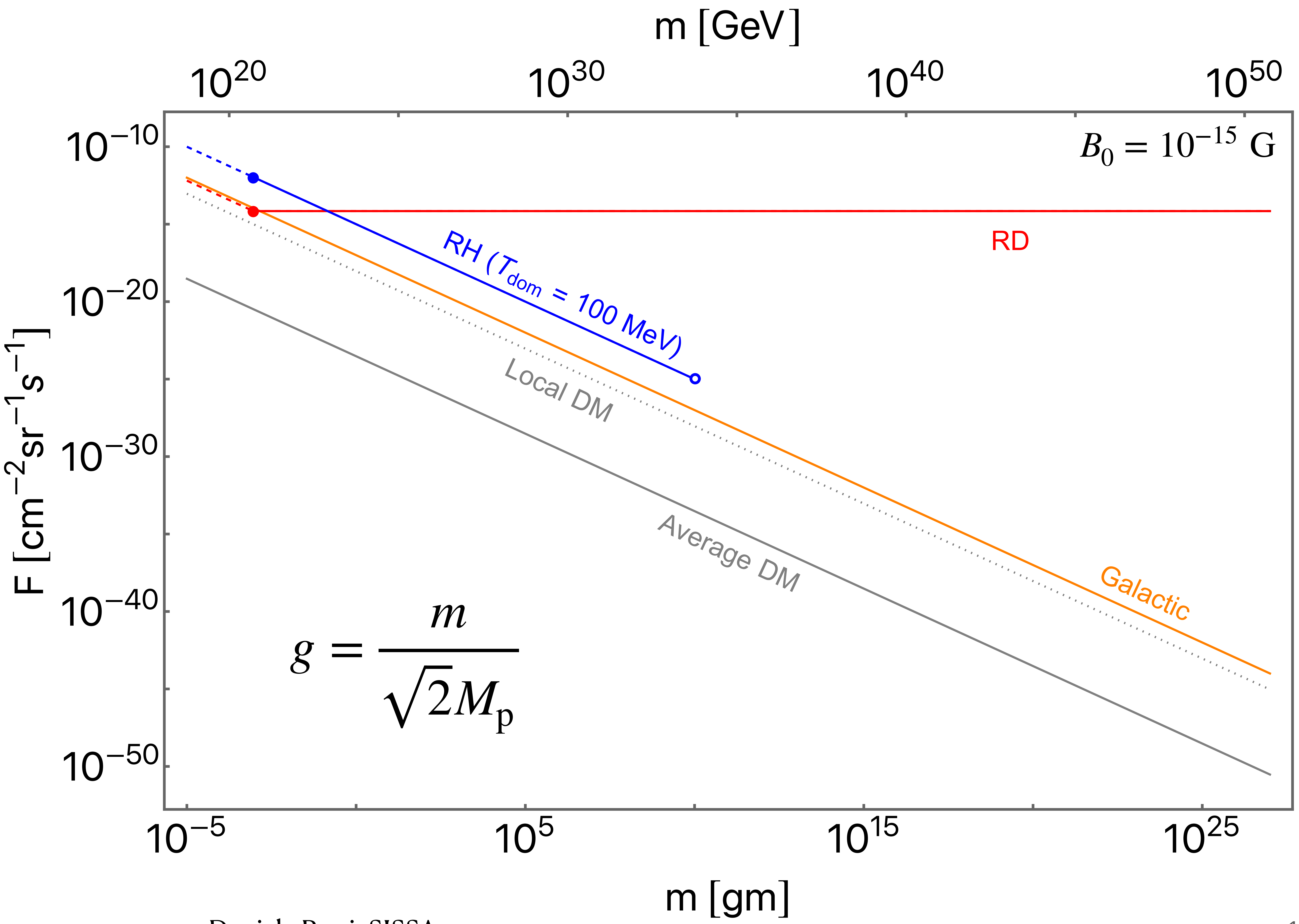

- The primordial bounds are less dependent on the monopole charge and they are the **strongest** for small charges.
- Minicharged monopoles cluster with the Galaxy and be DM for masses **much smaller than $M_{\rm Pl}$**.

# Bounds on Magnetic Black Holes

- Extremal magnetic BHs have a *fixed mass-to-charge ratio.*

- Cosmological bounds are the strongest (caveat: **Parker bound from M31** seems **stronger**)

- Extremal magnetic BH cluster with Milky Way, **but not all galaxies.**



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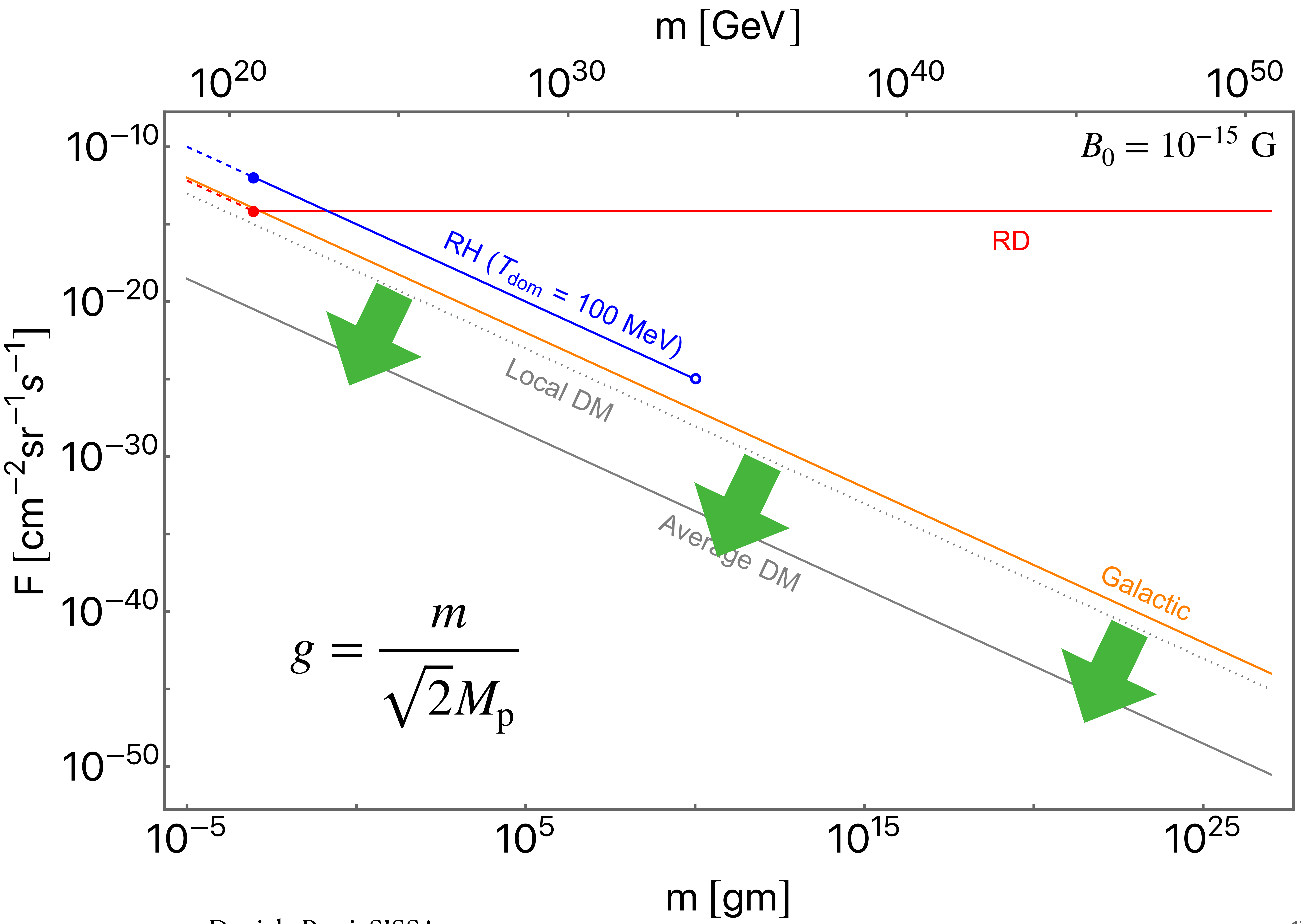

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# Schwinger Effects and Monopole Pair Production

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

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

The instanton computation is valid under the ***weak field condition***:

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

*The survival of the fields after pair production and the acceleration of the produced monopoles provides the most conservative bound on the primordial magnetic field amplitude.*

# Schwinger Effects and Monopole Pair Production

1. The producing pairs extract energy from the magnetic fields $\sim 2m$.

Takeshi Kobayashi (2021)
arXiv:2105.12776

2. The produced pairs are accelerated by the magnetic fields → apply the primordial bounds on the monopole abundance produced by the fields themselves.

⬇

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

*The survival of the fields after production and acceleration of the monopoles is insured by the* ***weak field condition,*** *with only a negligible log contribution.*

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# Conclusion

- We derived *new competitive bounds on the abundance of magnetic monopoles* by generalizing the Parker bound to the survival of primordial magnetic fields.

- We studied under which condition magnetic monopoles are *possible Dark Matter candidates*.

  1. For $g = g_{\rm D}$ they can be DM only for masses comparable to or larger than $M_{\rm Pl}$.
  2. Minicharged monopoles can be DM for much smaller masses.
  3. Extremal magnetic BH are excluded as DM candidates.

- We obtained the *most conservative bound on the primordial magnetic field amplitude* from the Schwinger pair production of monopoles.

# Thank You!!

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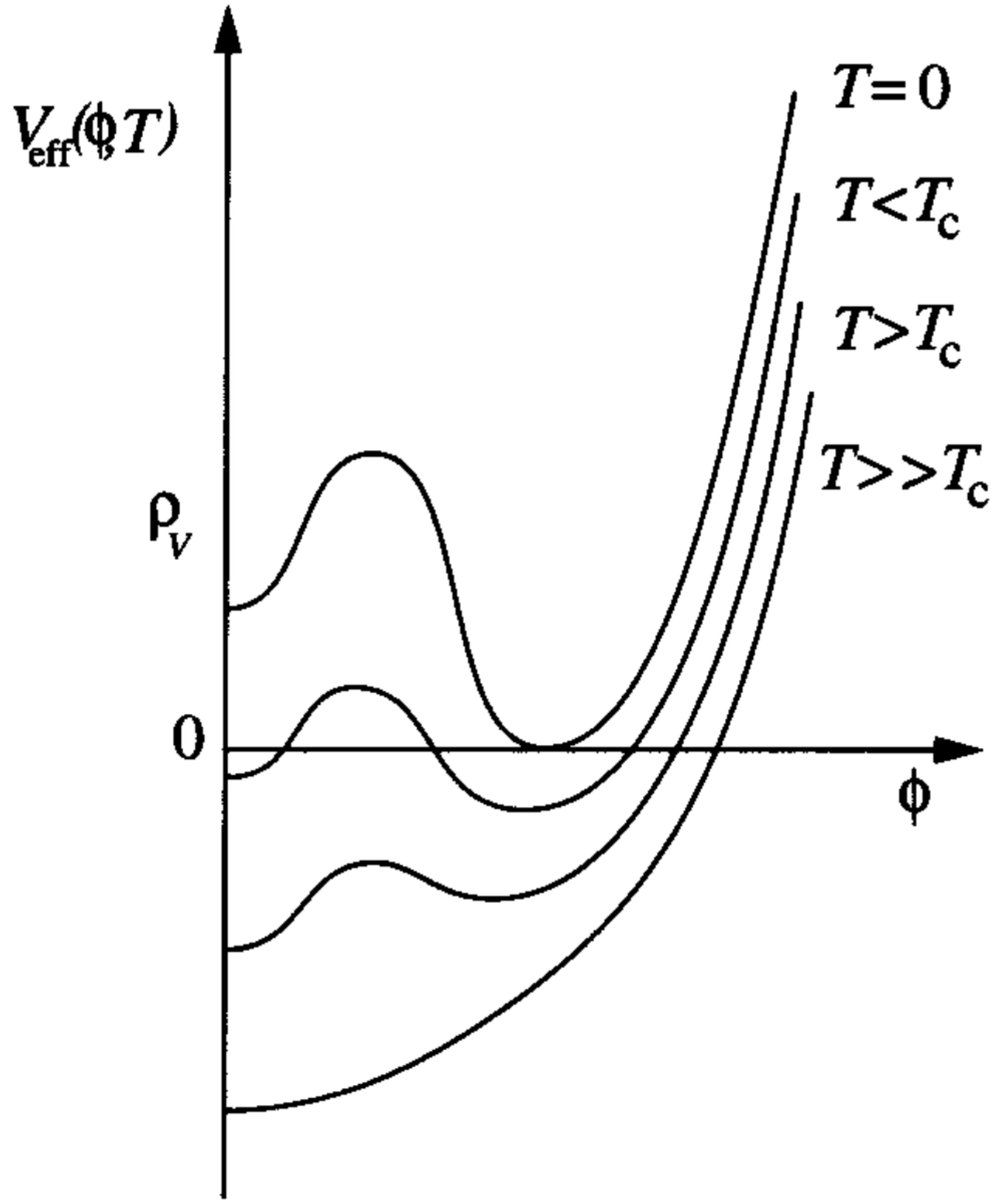
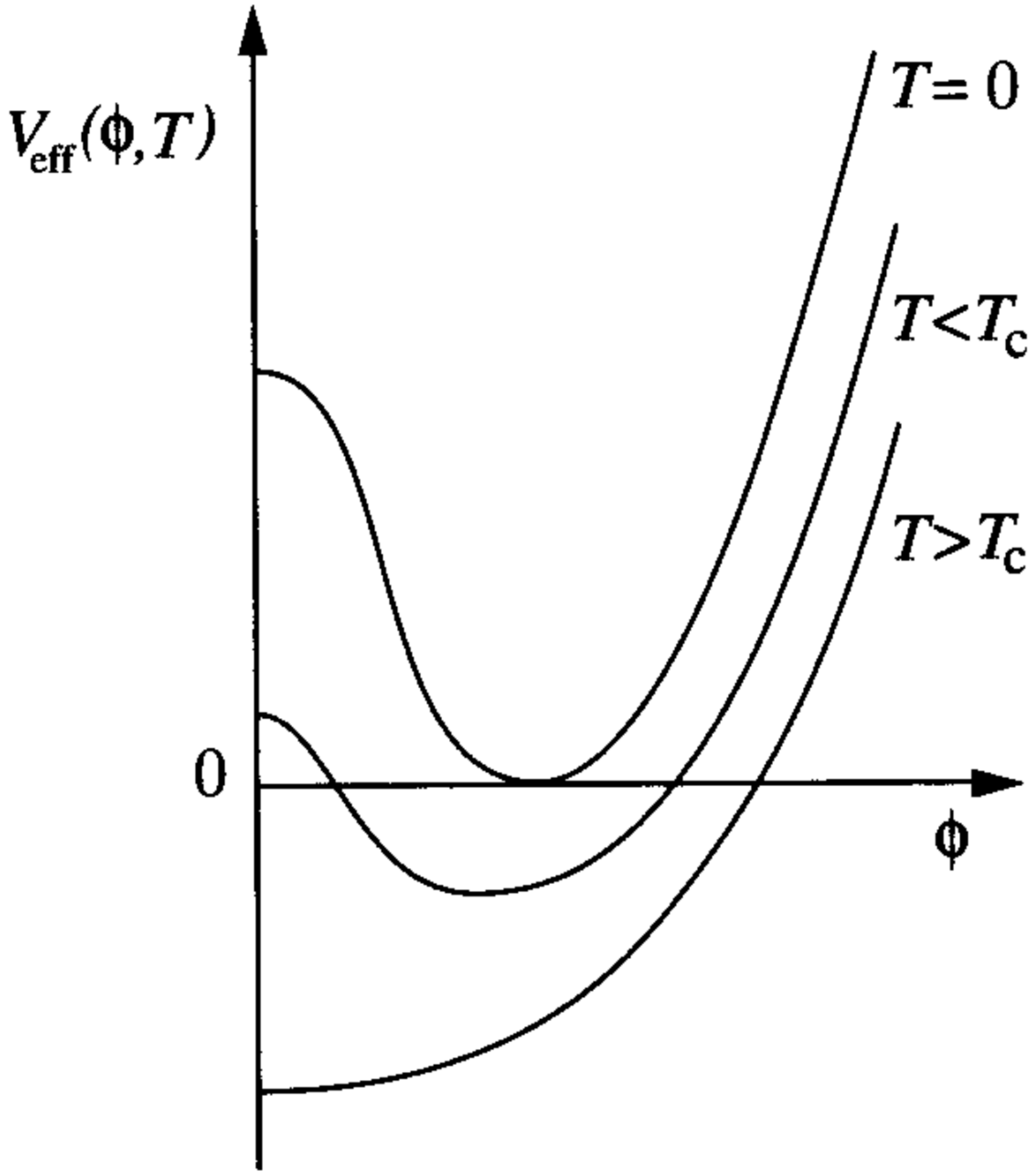
# Monopole Production in Phase Transitions

- 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.

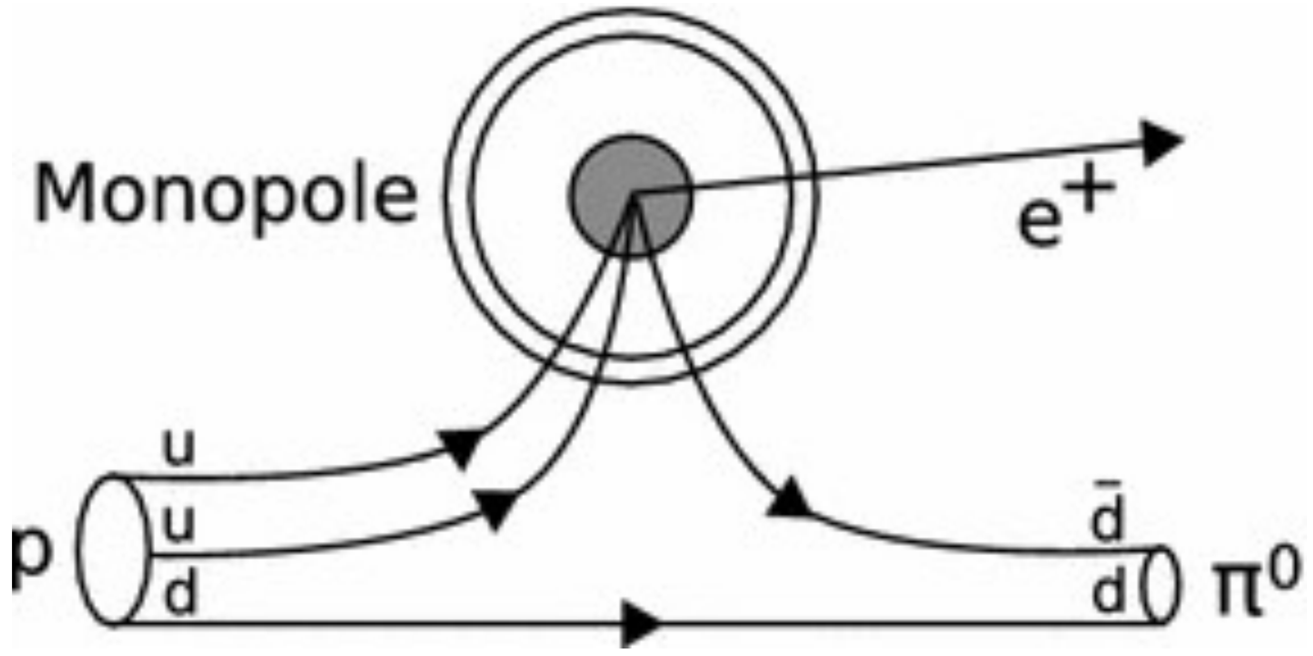


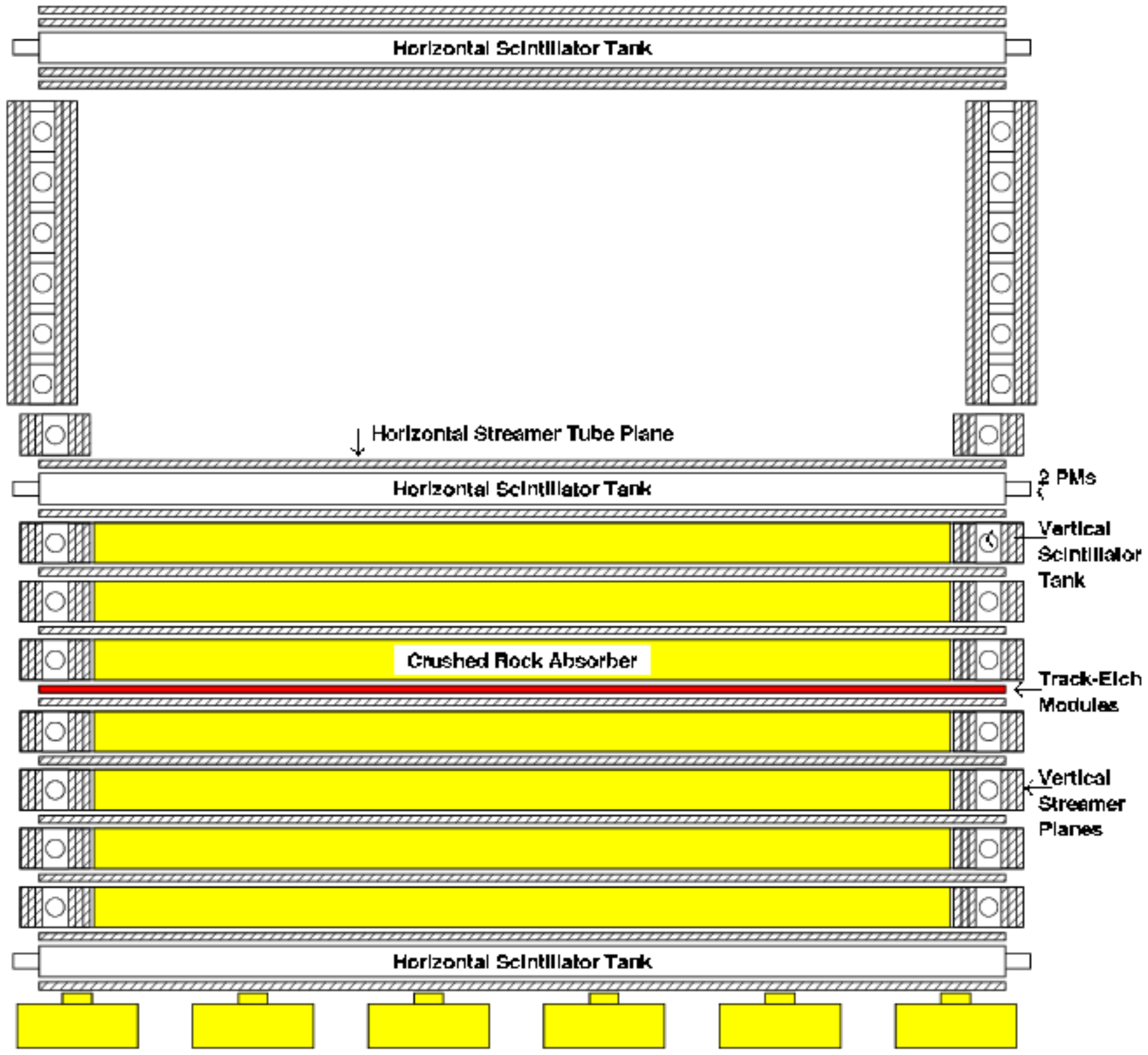



# Direct Observations of Monopoles

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

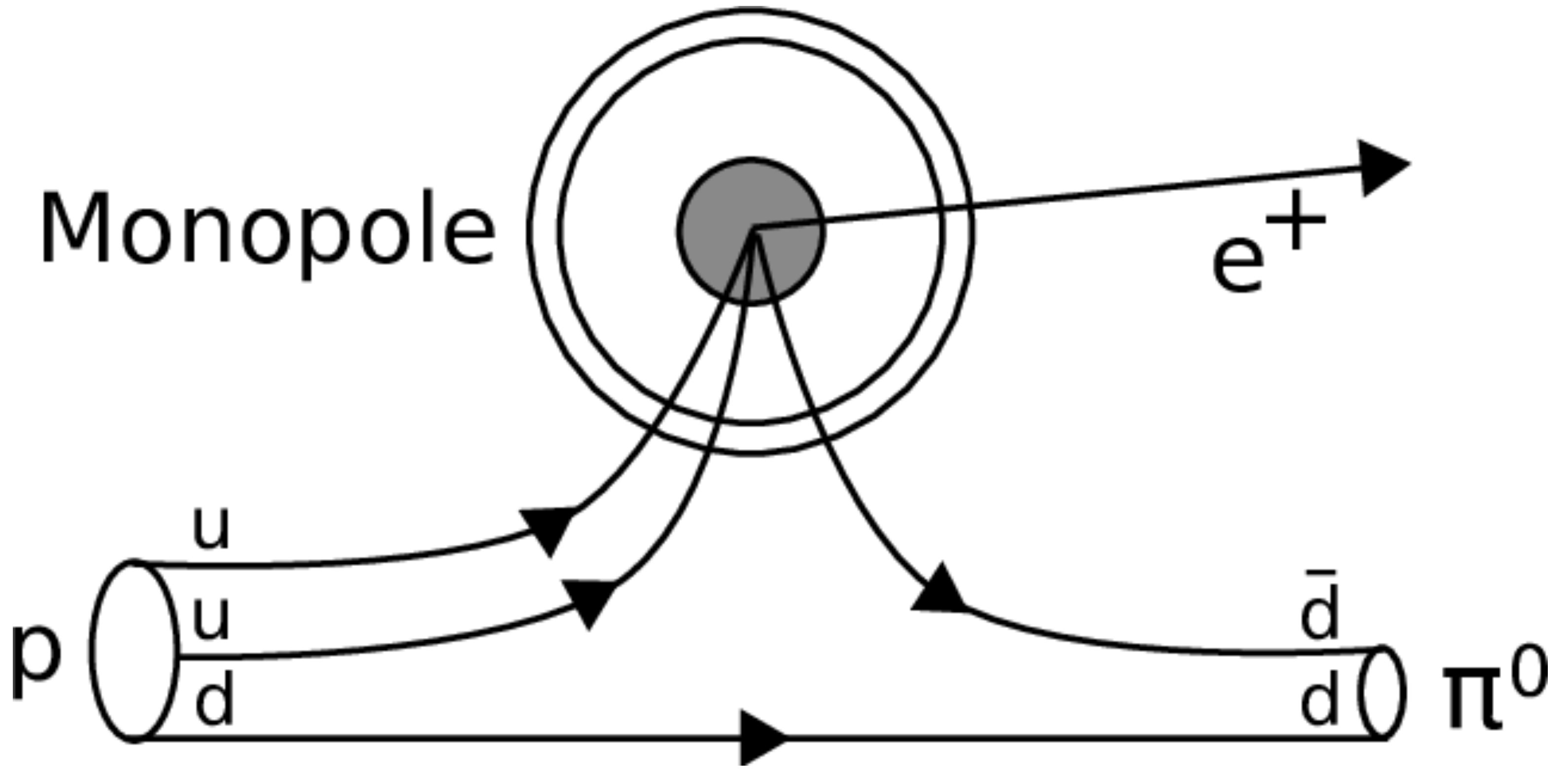
- Induction of electric currents into a coil;
- Energy loss by ionization (Ex. MACRO experiment);
- Catalysis of nucleon decays (only for GUT monopoles).



# Direct Search of Dark Monopoles?

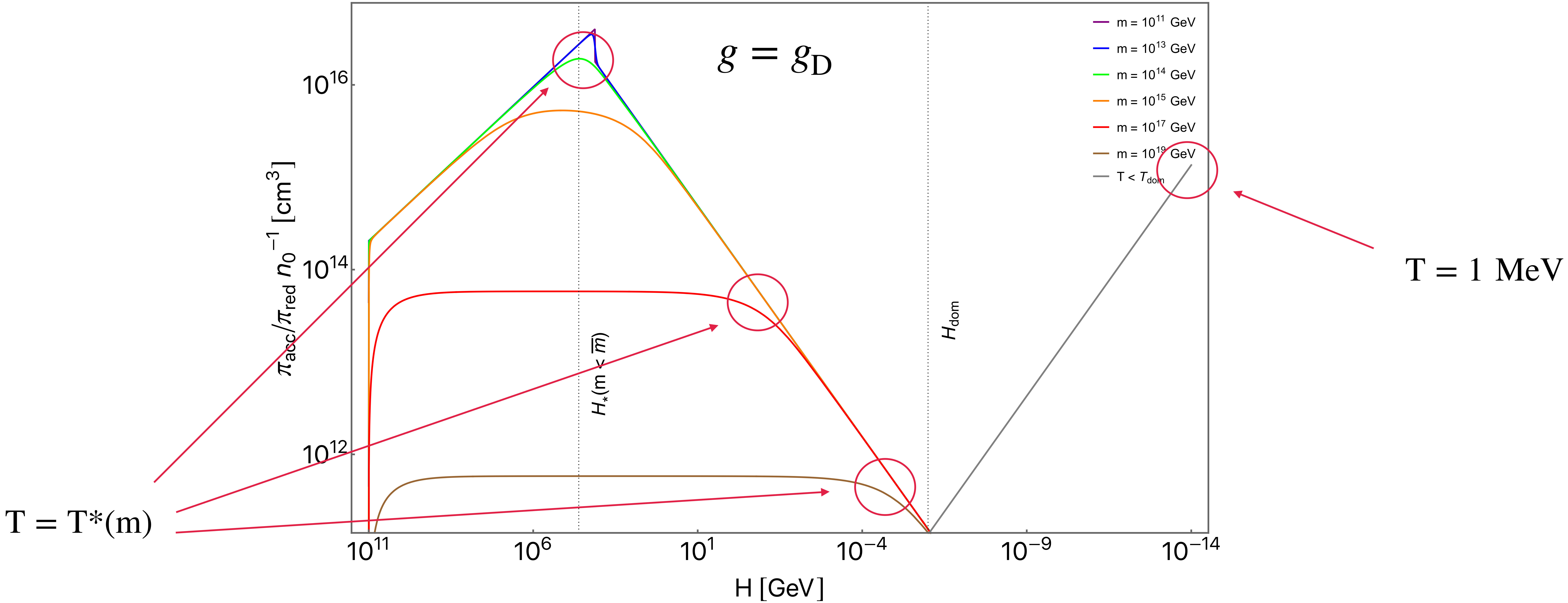
- Minicharged monopoles cannot be direct searched with the standard methods (ex. induction of a current in a coil, energy loss in a calorimeter).
- Even completely dark monopoles can still be detected through the *catalysis of nucleon decays:*




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

# The Evolution of $\Pi_{acc}/\Pi_{red}$

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



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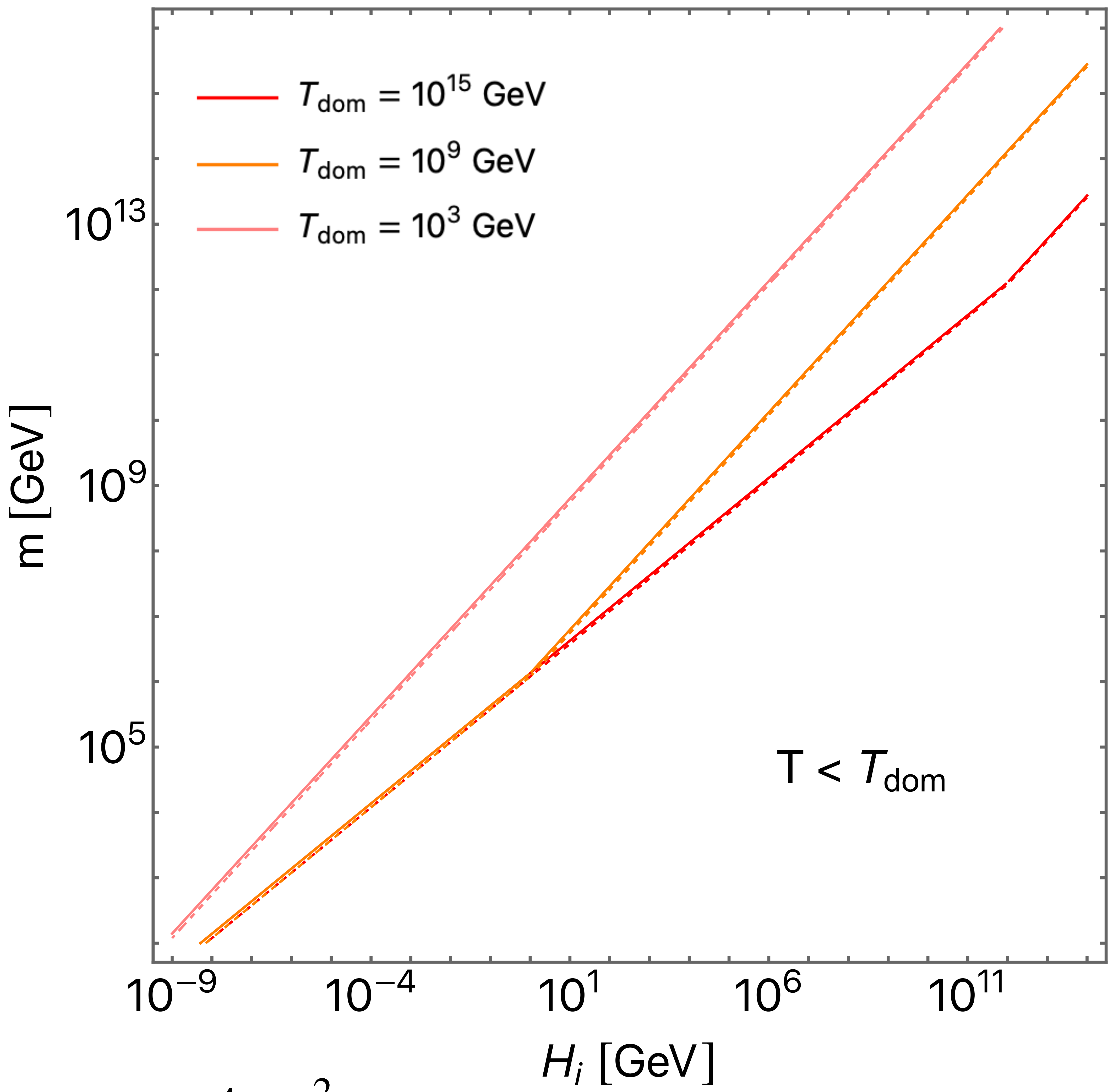


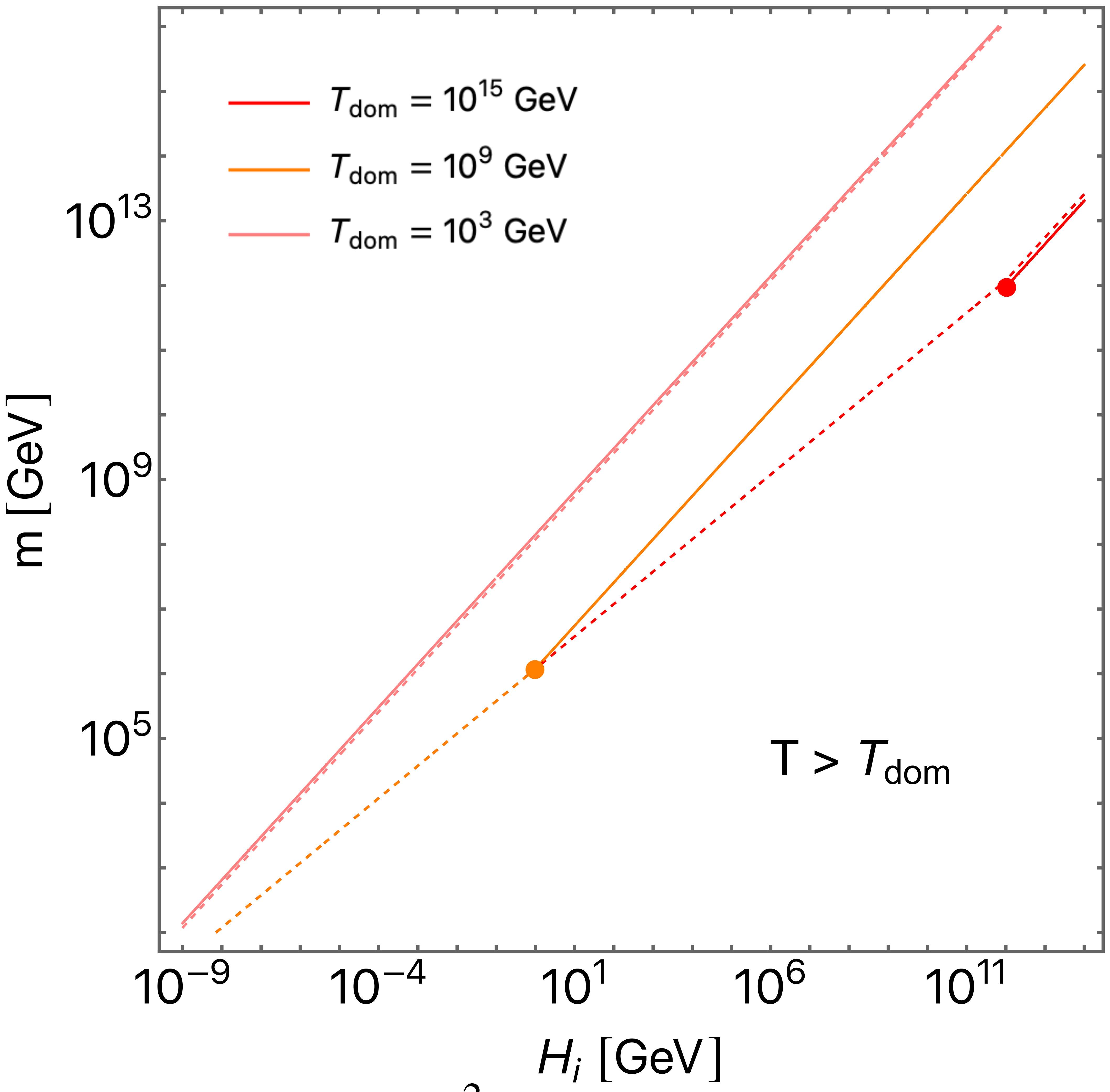


$$B \lesssim \frac{4\pi m^2}{g^3}\left[1+\log \tilde{x}_{\rm D}(m, H_i, T_{\rm dom}, B_0)\right]^{-1}$$

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