Magnetic Monopoles in Cosmic Magnetic Fields: Acceleration and Constraints

Speaker:

Daniele Perri

DP, T. Kobayashi
Phys.Rev.D 108 (2023) 8, 083005

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

DP, K. Bondarenko, M. Doro,
T. Kobayashi
Phys. Dark Univ. 46 (2024), 101704

UNIWERSYTET
WARSZAWSKI

DP, M. Doro, T. Kobayashi
arXiv:2502.xxxxx

Warsaw Seminar - 16/01/25

Contents of the Talk

- ✓ <u>Monopoles: theory, interaction, production.</u>
- ✓ Monopole dynamics and bounds: late universe.
- ✓ Monopole dynamics and bounds: early universe.
- ✓ Schwinger effect and monopole pair production.
- ✓ Conclusion.

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

DP, T. Kobayashi
Phys.Rev.D 108 (2023) 8, 083005

DP, K. Bondarenko, M. Doro, T. Kobayashi
Phys. Dark Univ. 46 (2024), 101704

DP, M. Doro, T. Kobayashi
arXiv:2502.xxxxx

UNIWERSYTET WARSZAWSKI

Symmetrization of the Maxwell equations

Since the end of the 19th Century the idea of symmetrizing the Maxwell's equations of Electromagnetism has always fascinated physicists

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 J + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$

- Null divergence of the magnetic field corresponds to the absence of point-like sources for the magnetic field.
- Introducing point-like sources would symmetrize the equations.

Can a Monopole Really Exist?

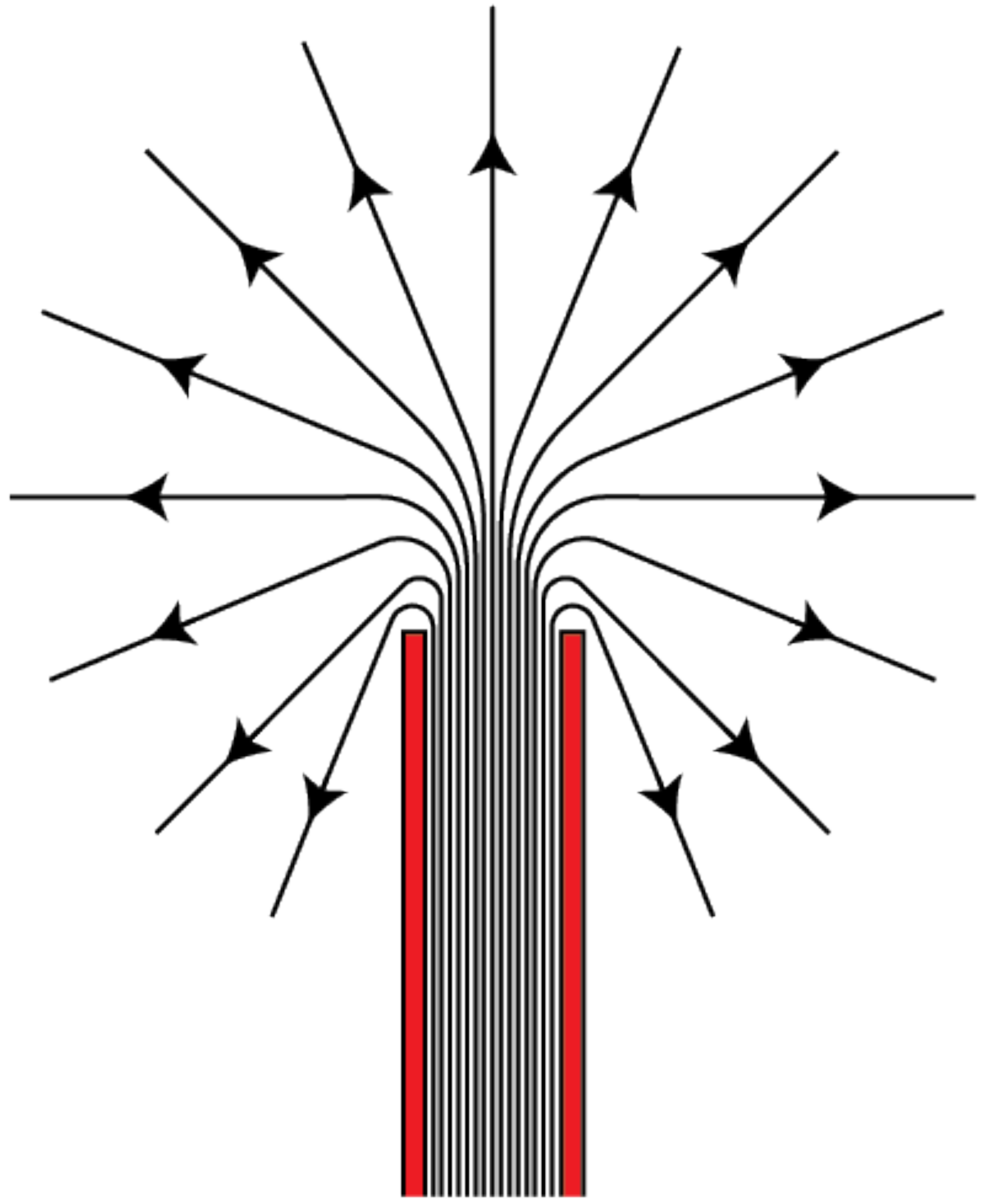
Dirac Monopoles and the Quantization of the Electric Charge

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

- Dirac was the first to suppose the existence of magnetic monopoles.
- In 1948 he proposed the model of 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 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 proposed a model of monopoles 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 a production of monopoles.*

↓

Monopoles are *inevitable predictions* of Grand Unified Theories:

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

Can a Monopole Really Exist?

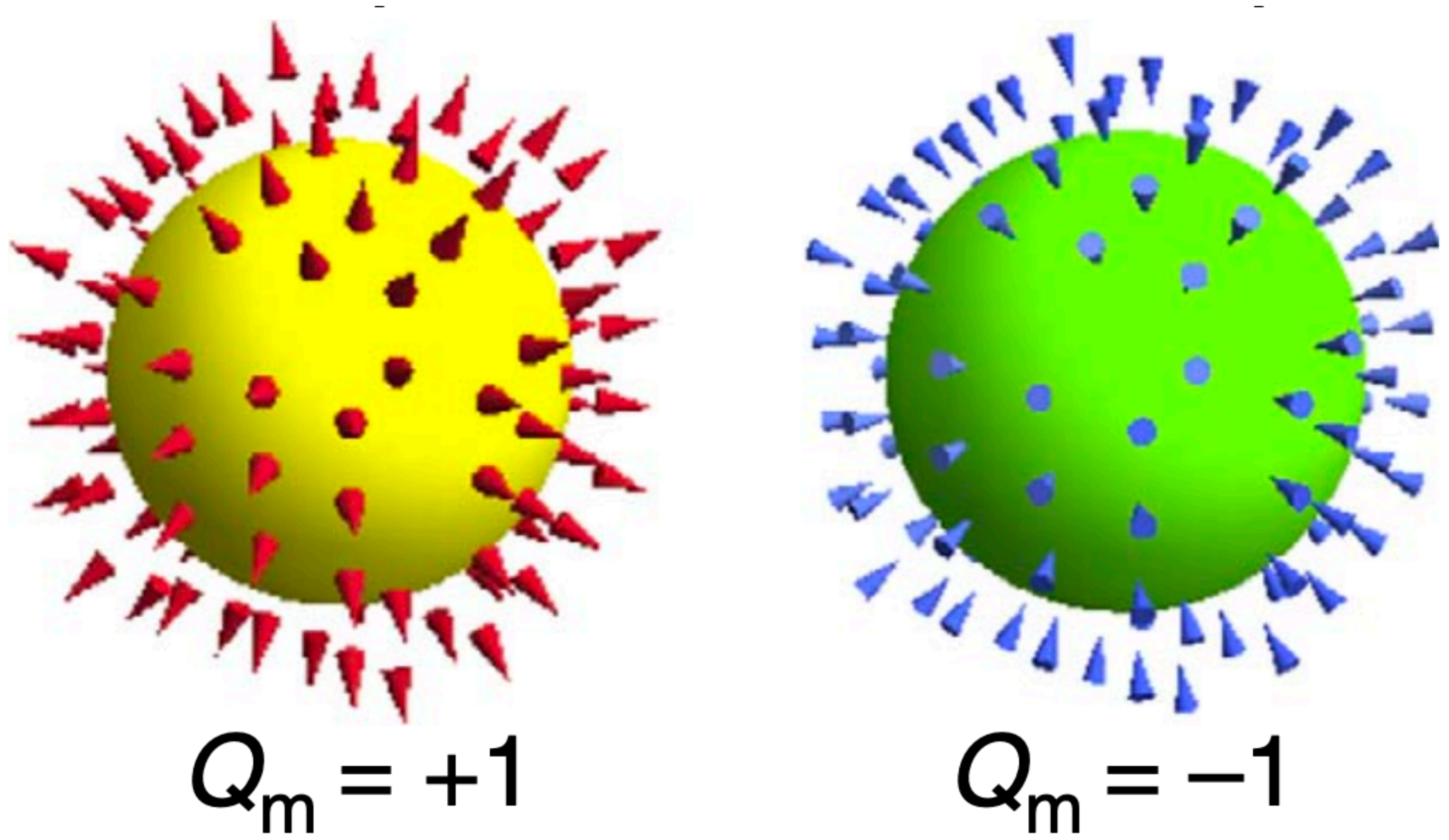
’T Hooft-Polyakov Monopoles and Topological Defects

- The ’T Hooft - Poliakov monopole is a zero-dimensional solitonic solution of the vacuum manifold.
- The simplest example is the Georgi-Glashow model: $SU(2) \rightarrow U(1)$

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

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

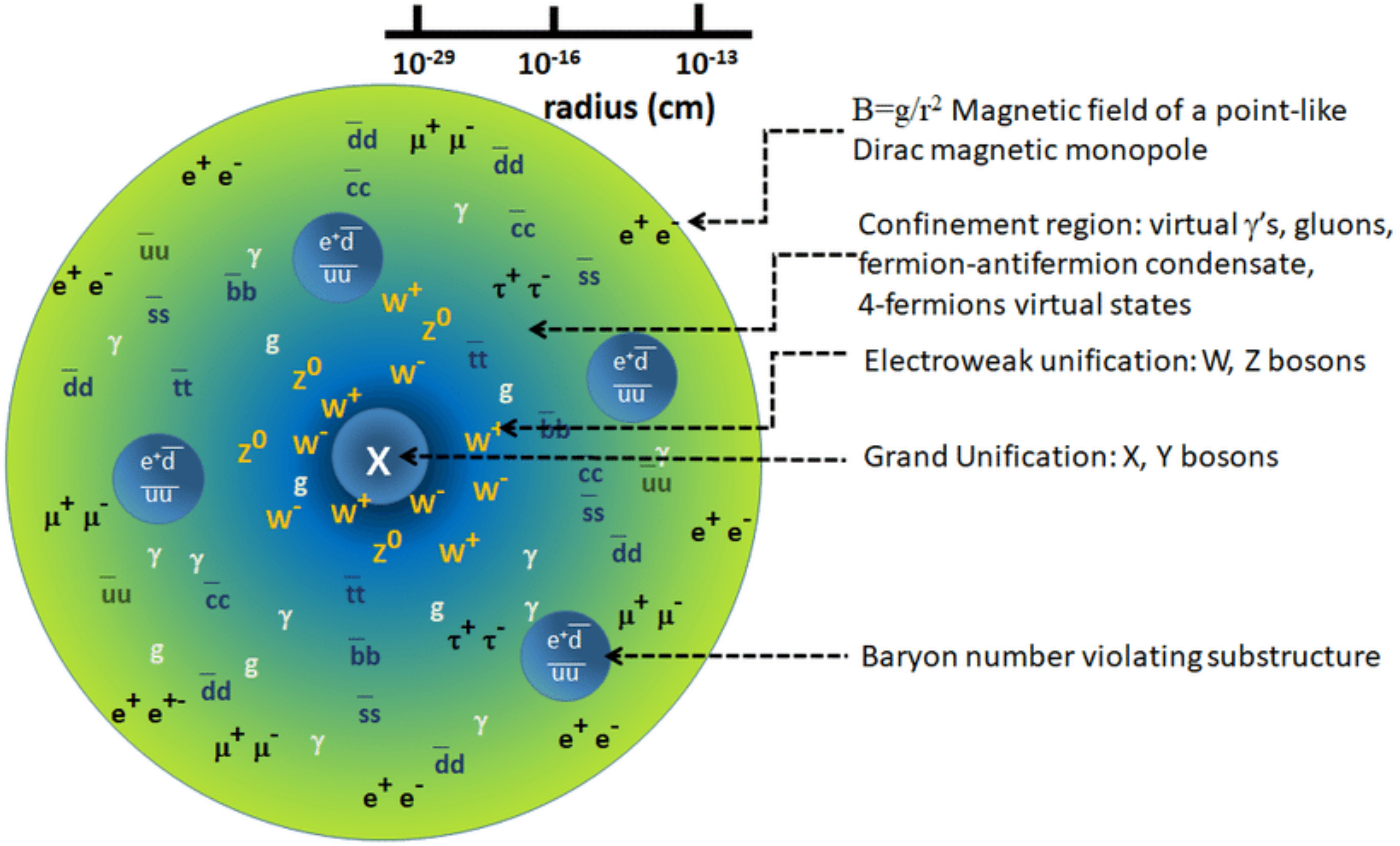
$$\phi^{a}(\vec{x}) = \delta_{ia}\left(\frac{x^{i}}{r}\right)F(r)$$



Monopoles in Grand Unified Theories

Monopoles are *inevitable predictions* of Grand Unified Theories:

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



Inside the core, *the symmetry is restored* and *all the states of the GUT are excited.*

$$m \sim \frac{4\pi}{g}\eta, \quad r \sim \frac{1}{m}$$

Production mechanisms

There are three main production mechanisms of magnetic monopoles in the early universe.

- During phase transitions in the early universe (Kibble mechanism):

$$\frac{n_M}{s} \sim 10^2 \left(\frac{T_c}{M_{\rm Pl}}\right)^3$$

(Second or slightly first order PT)

$$\frac{n_M}{s} \sim \left[\left(\frac{T_c}{M_{\rm Pl}}\right) \log\left(\frac{M_{\rm Pl}^4}{T_c^4}\right)\right]^3$$

(Strongly first order PT)

- Thermal production:

$$\frac{n_M}{s} \sim 10^2 \left(\frac{m_M}{T_{\rm max}}\right)^3 \exp\left(-\frac{2m_M}{T_{\rm max}}\right)$$

- Production of monopole pairs via the Schwinger effect in strong magnetic fields:

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

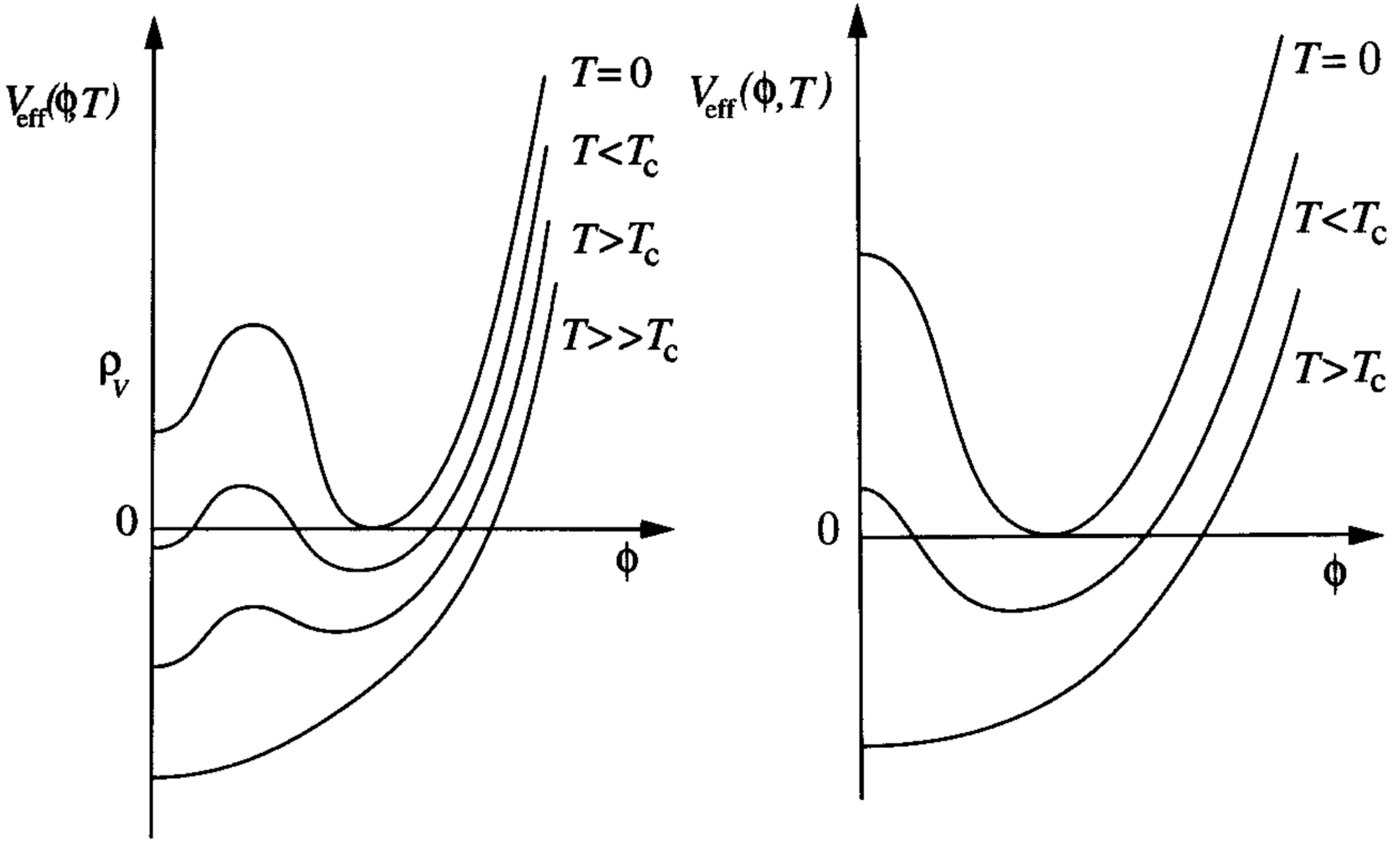
Cosmological Monopole Problem

Around one monopole per Hubble volume is produced during phase transitions in the early universe.

- The abundance of produced monopoles can easily over-dominate the energy density of the universe:

$$\rho_{\mathrm{M,loc}} \sim \rho_{\mathrm{crit}} \left(\frac{v}{10^{11}\ \mathrm{GeV}} \right)^4$$

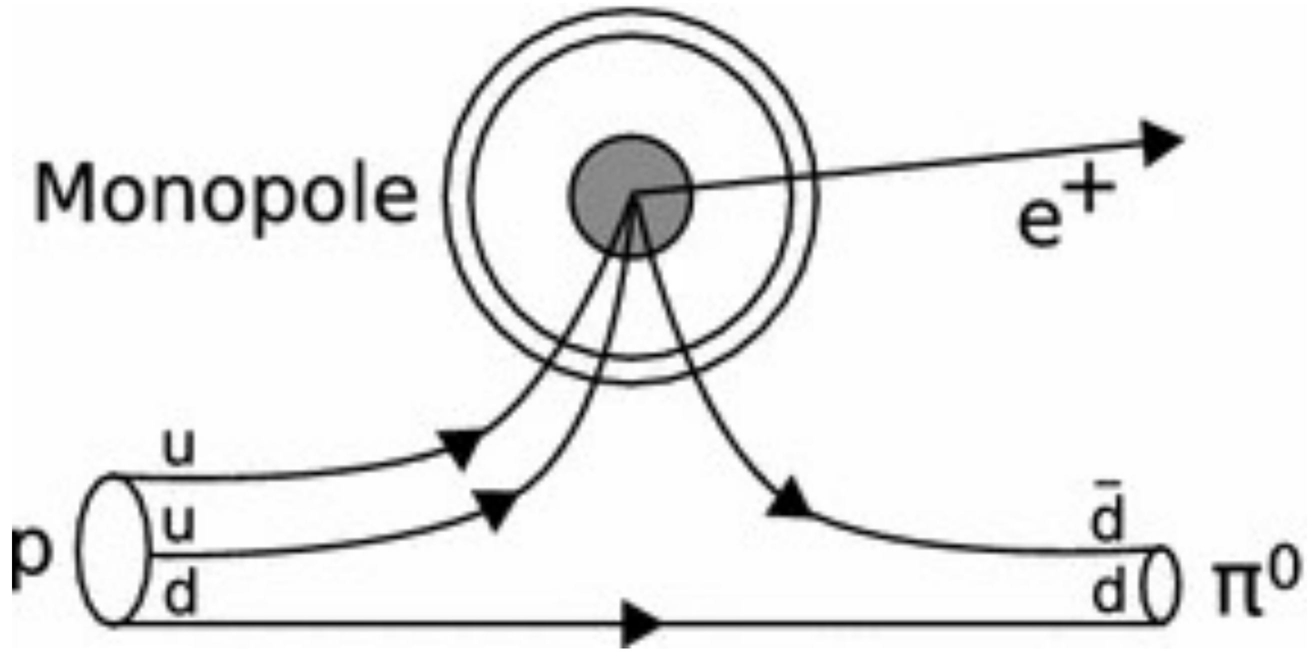
- Inflation provides a good solution to the problem.

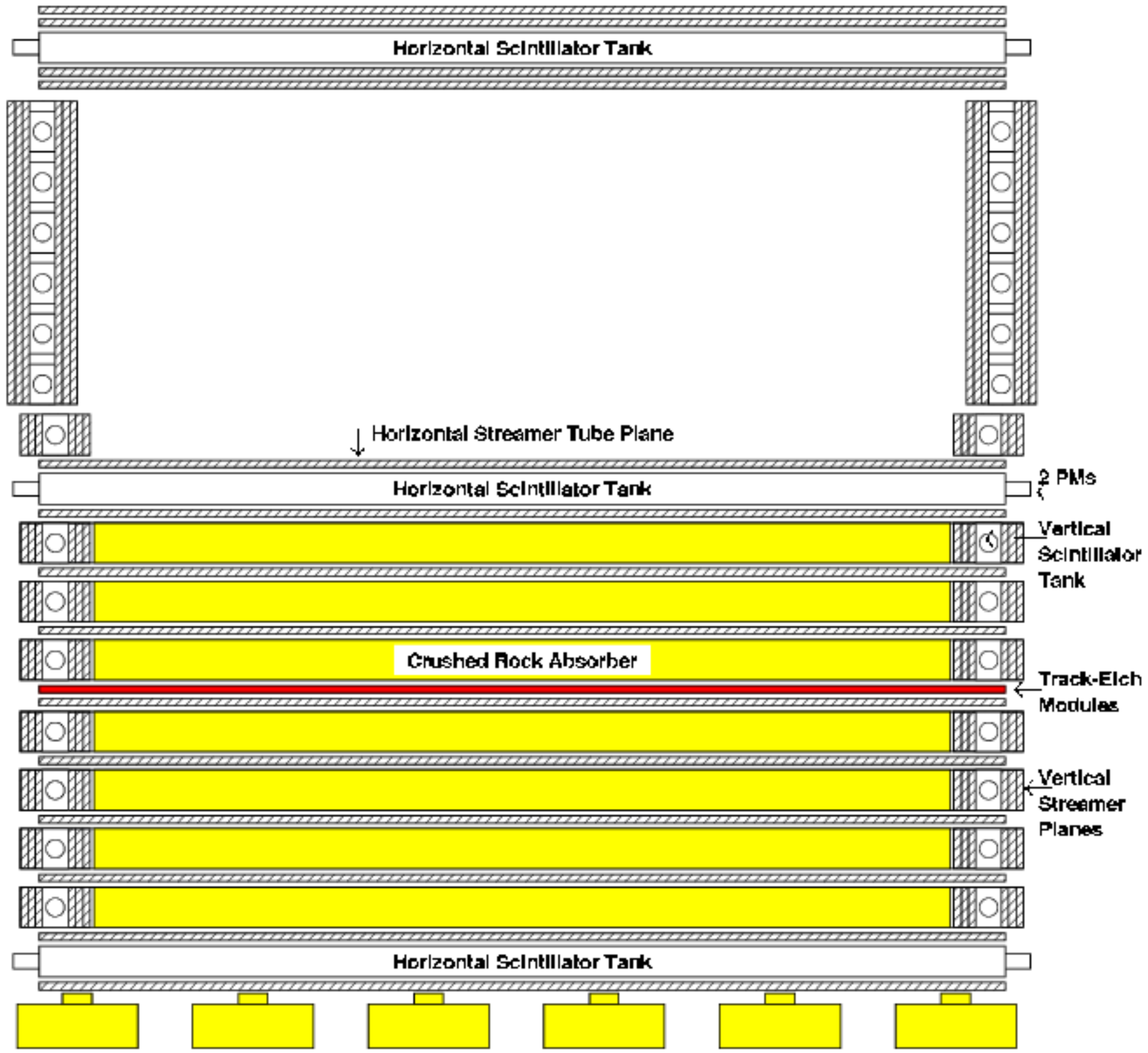


Direct Detection of Monopoles

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, IceCube);
- Catalysis of nucleon decays (only for GUT monopoles).





Magnetic Monopoles and Cosmic Magnetic Fields

The evolutions of magnetic monopoles and cosmic magnetic fields are strictly coupled throughout the universe's history.

Cosmic magnetic fields accelerate the monopoles ⟷ Accelerated monopoles extract energy from cosmic magnetic fields

↓ Monopole bounds are affected by the acceleration

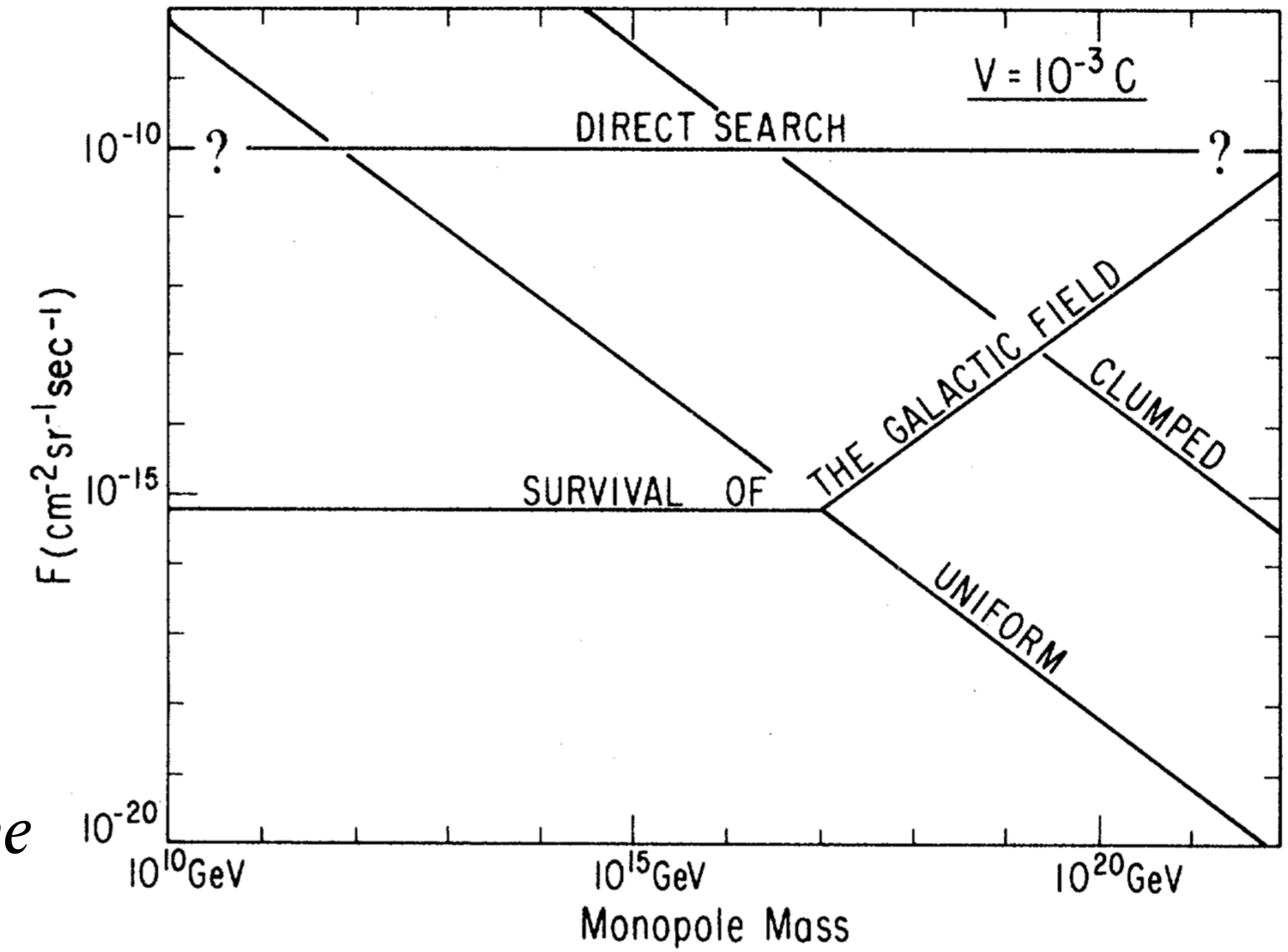
↓ The survival of cosmic magnetic fields might lead to new bounds

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.

The bound can be even extended considering the seed field of the Galaxy.



Contents of the Talk

- ✓ Monopoles: theory, interaction, production.
- ✓ Monopole dynamics and bounds: late universe.
- ✓ Monopole dynamics and bounds: early universe.
- ✓ Schwinger effect and monopole pair production.
- ✓ Conclusion.

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

DP, T. Kobayashi
Phys.Rev.D 108 (2023) 8, 083005

DP, K. Bondarenko, M. Doro, T. Kobayashi
Phys. Dark Univ. 46 (2024), 101704

DP, M. Doro, T. Kobayashi
arXiv:2502.xxxxx

UNIWERSYTET WARSZAWSKI

Magnetic Monopoles and Cosmic Magnetic Fields

The evolutions of magnetic monopoles and cosmic magnetic fields are strictly coupled throughout the universe's history.

Cosmic magnetic fields accelerate the monopoles ⟷ Accelerated monopoles extract energy from cosmic magnetic fields

↓ Monopole bounds are affected by the acceleration

↓ The survival of cosmic magnetic fields might lead to new bounds

Relativistic monopoles in the universe?

In literature, monopole velocity on Earth is usually assumed to be comparable to the MW peculiar velocity $\sim 10^{-3}$ *c but this is not always the case.*

- Depending on the amplitude and coherence length, intergalactic magnetic fields accelerate monopoles in voids:

$$m\frac{d}{dt}(\gamma v) = gB$$

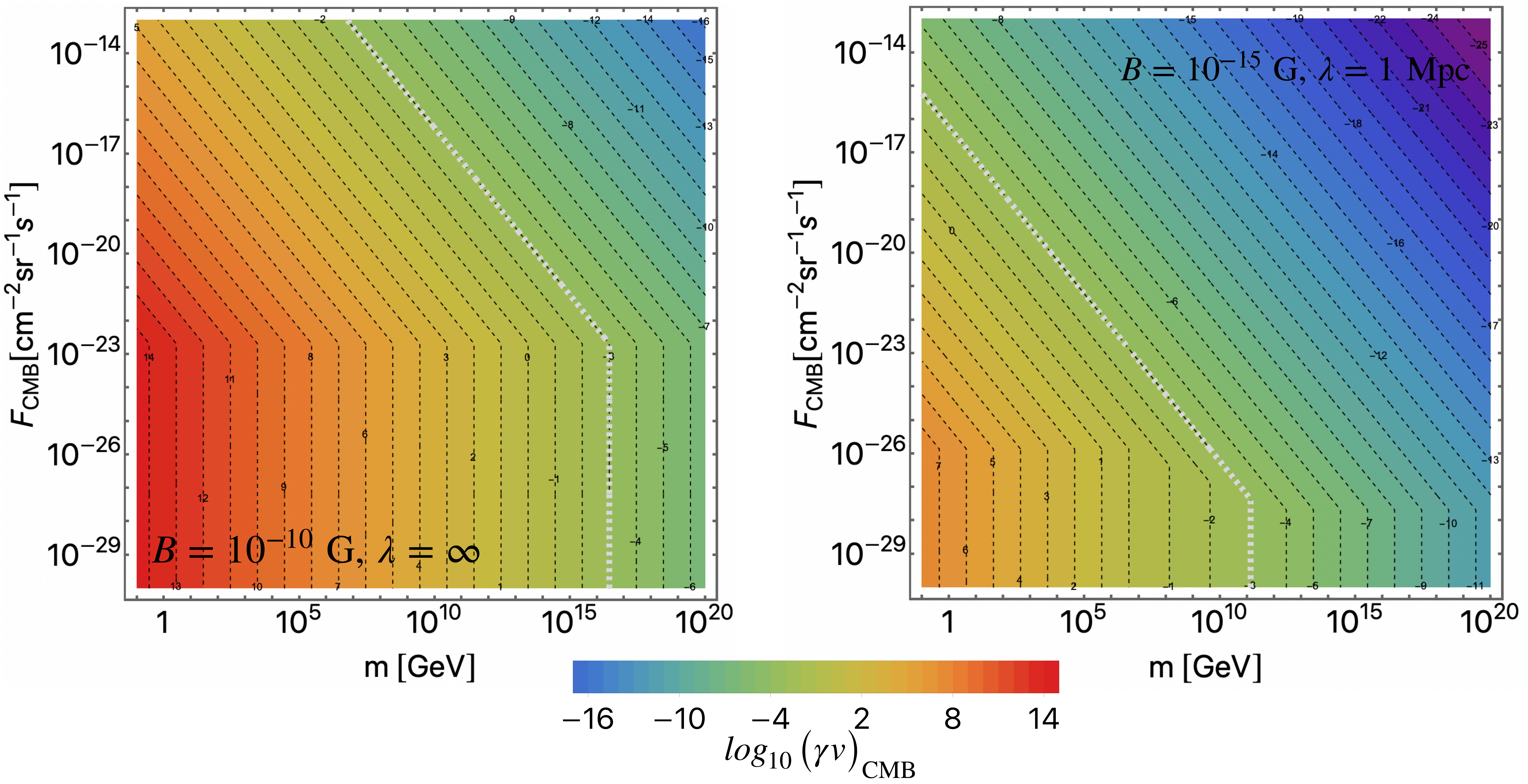
- In the presence of enough monopoles, this causes backreaction on the intergalactic fields that oscillate on cosmological scales.

$$(\gamma v)_{\rm CMB} \sim \min\left(\frac{gB}{mH_0}, \frac{B^2}{4\pi m F_{\rm CMB}}\right)$$

for homogeneous fields

In the presence of backreaction, the velocity shows a flux dependence.

Relativistic monopoles in the universe?



Intergalactic magnetic fields can accelerate the cosmic population of monopoles to relativistic velocities.

Relativistic monopoles in the universe?

Intergalactic magnetic fields can accelerate the cosmic population of monopoles to relativistic velocities.

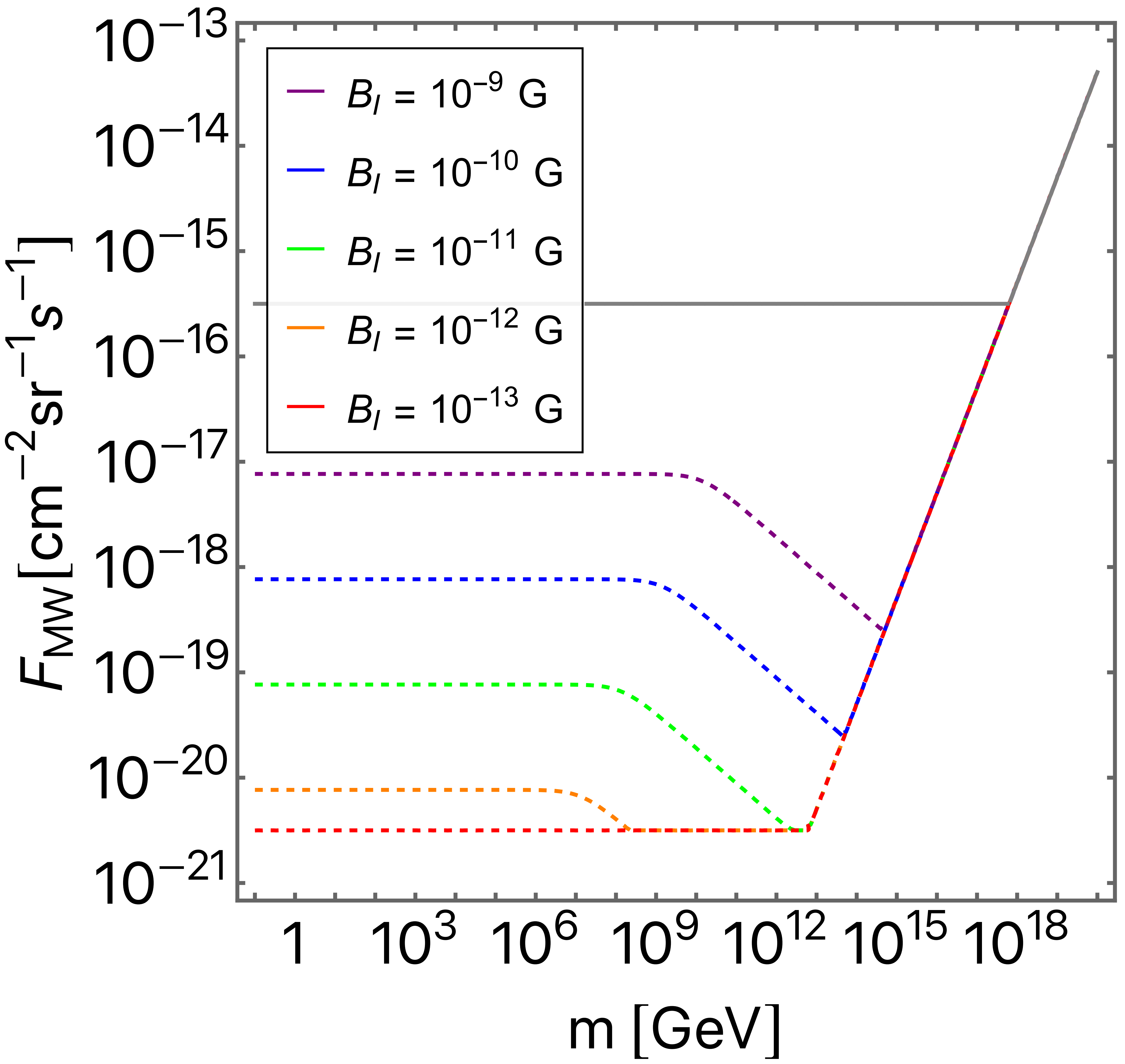
Modification of Galactic Parker bounds

Galactic Parker bounds depend on the monopole incident velocity on the Milky Way (intergalactic acceleration).

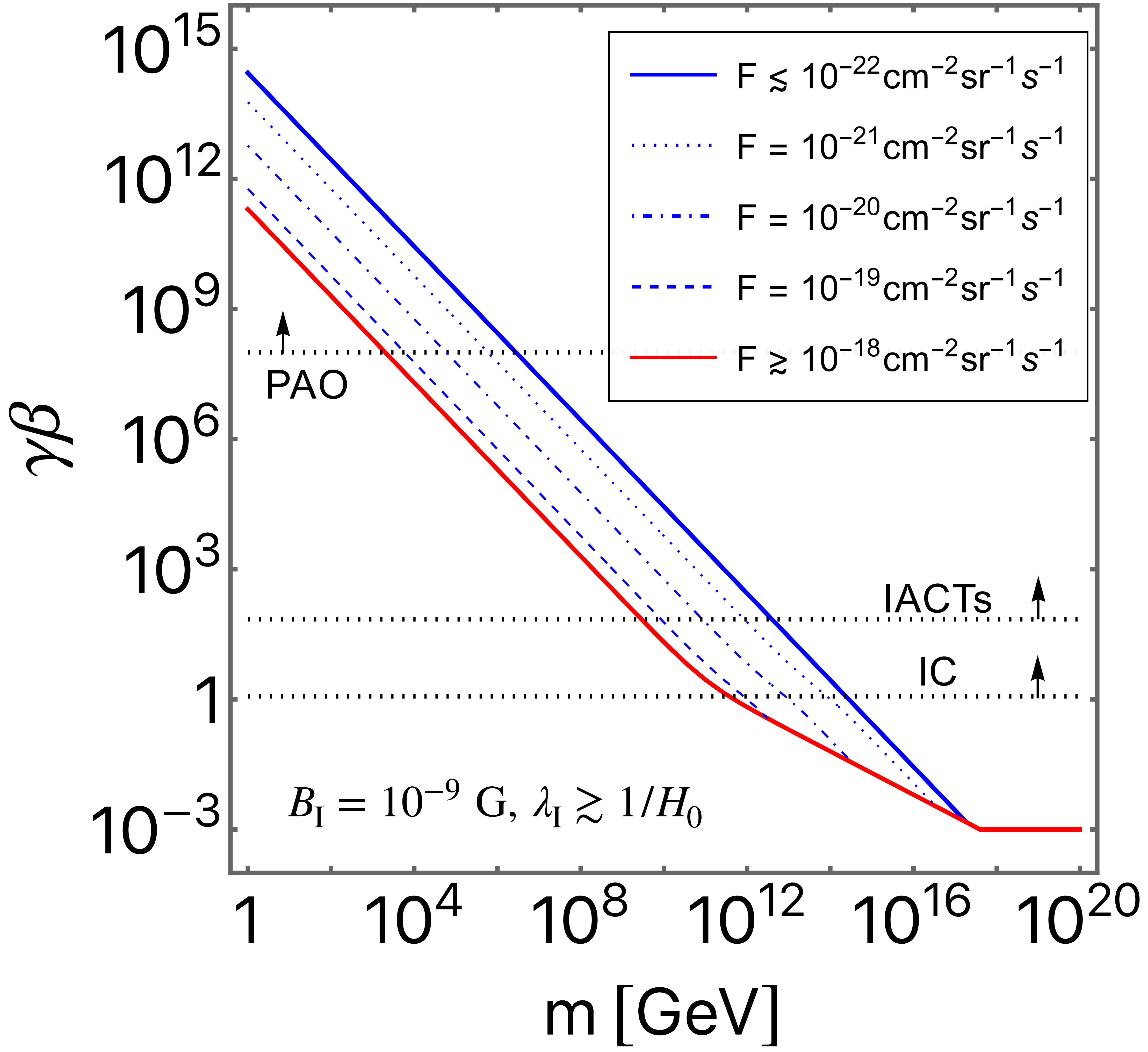
The bounds are weakened for large values of the monopole velocity:

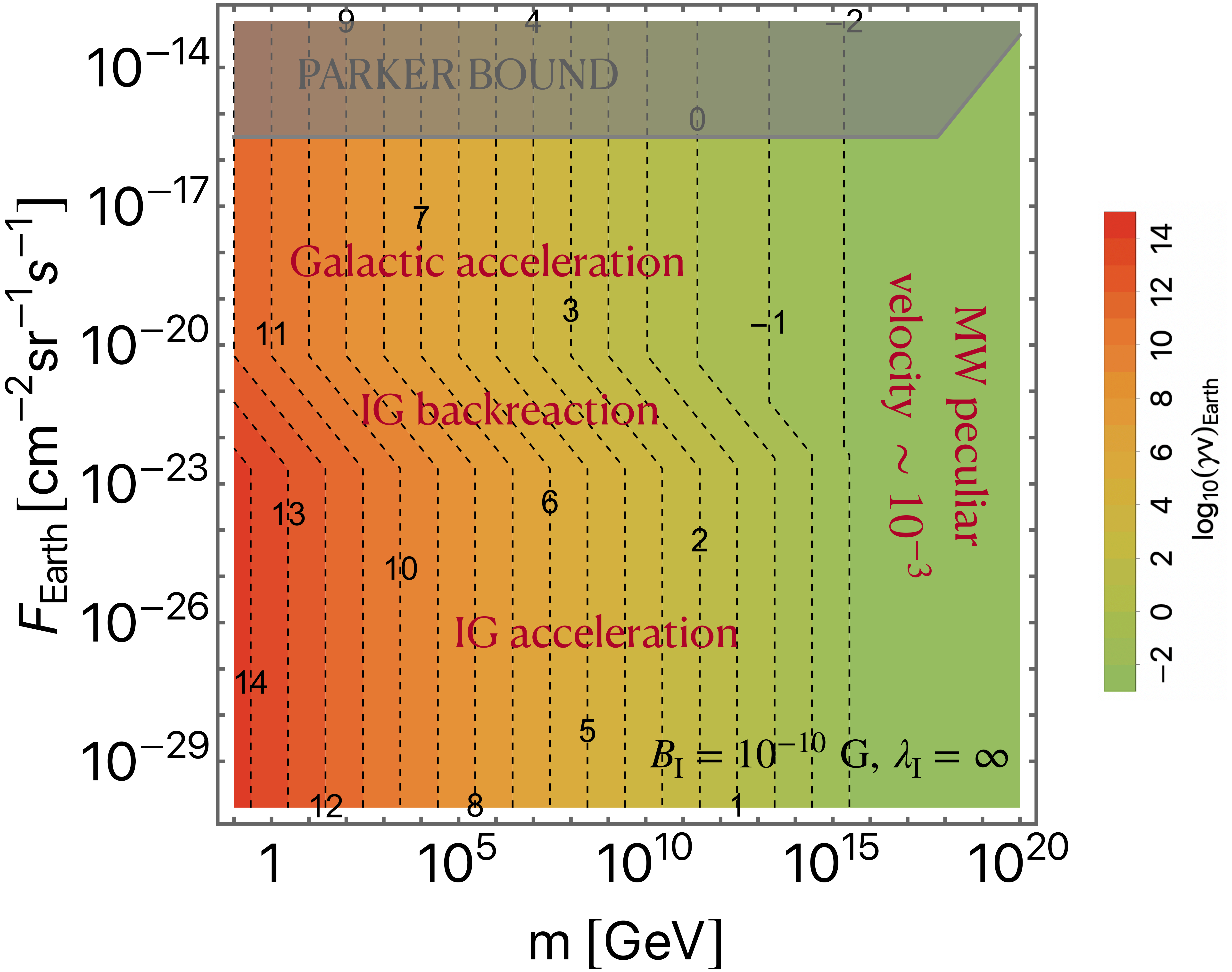
1. *The Galactic bound is not affected by acceleration in intergalactic magnetic fields.*

2. *The seed Galactic bound is strongly affected by the acceleration.*



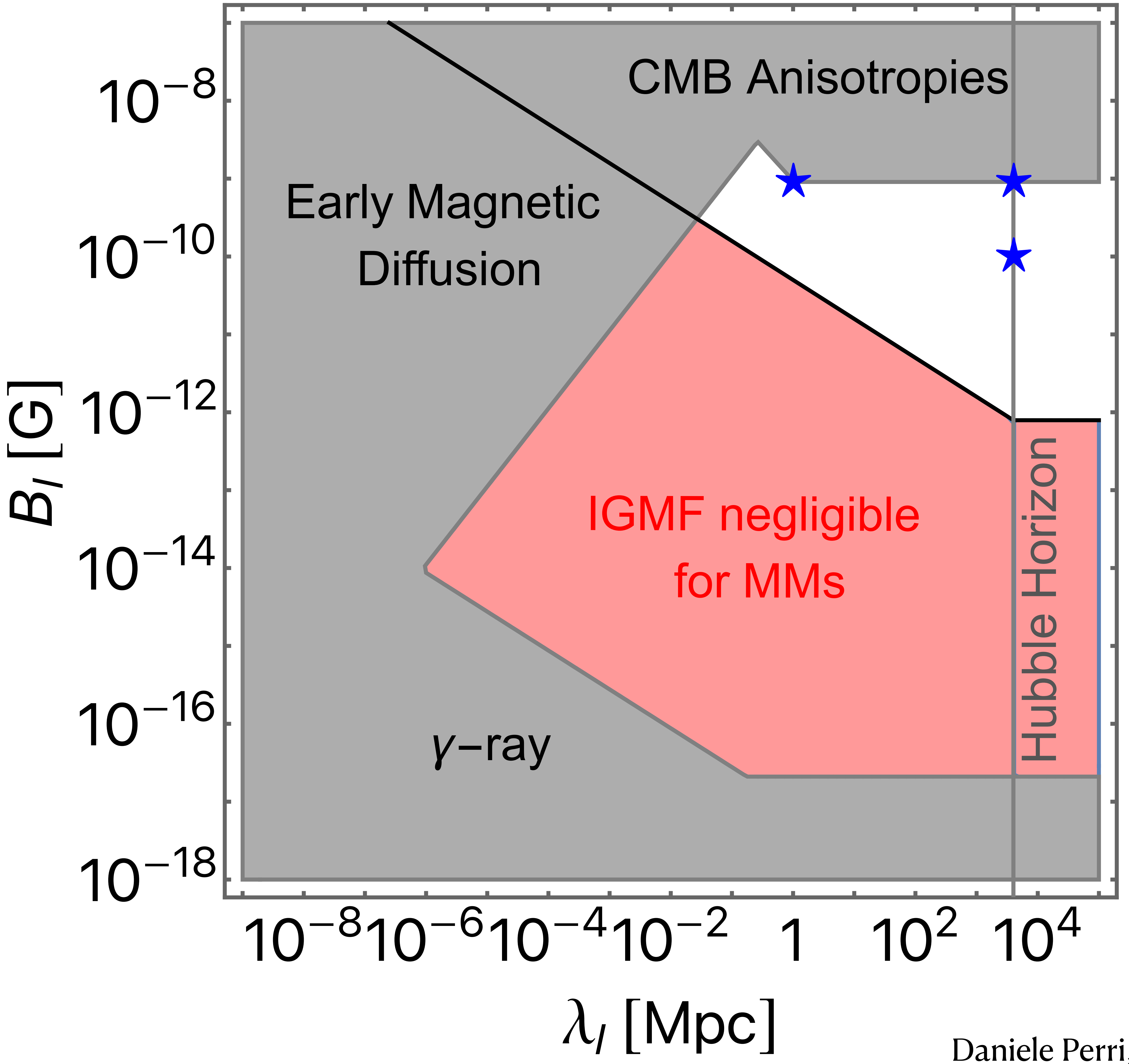
Acceleration in Late Universe Magnetic Fields





Knowing the acceleration, it is possible to relate the monopole velocity to the mass for a fixed flux.

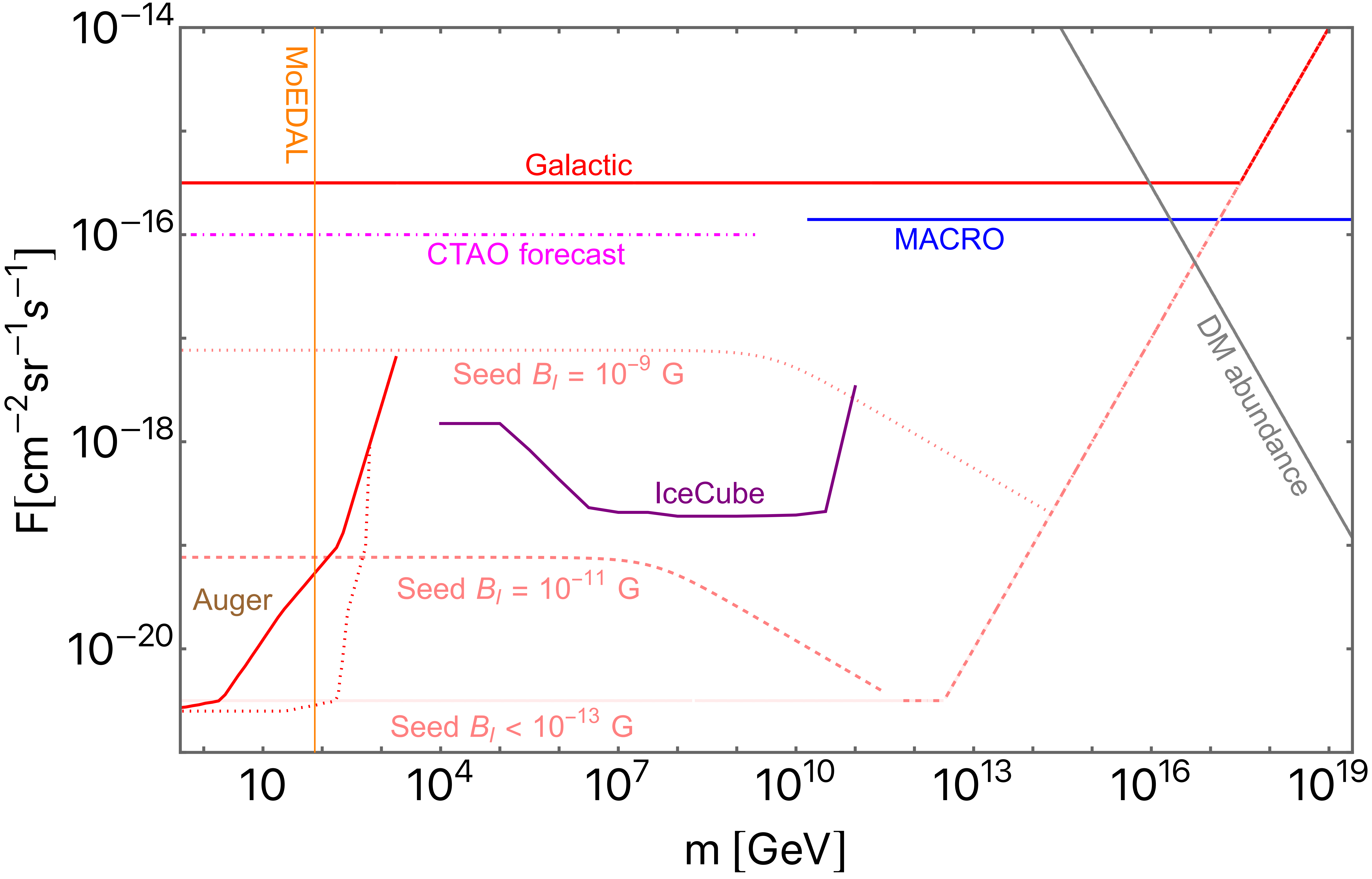
Acceleration in Late Universe Magnetic Fields



- Depending on the characteristics of IGMFs and the monopole flux, the monopole velocity might be fixed by acceleration in IGMFs.

Monopole velocity might be an independent test of IGMFs.

Modification of Direct Search Bounds



- Cosmic-ray experiments (ex. IceCube, Auger) constrain the monopole flux in function of the velocity at the detector.
- The bounds can be recasted in terms of the mass once an acceleration mechanism is fixed.

Monopole acceleration drastically changes the scenario of the bounds (search with cosmic-ray detectors!)

Contents of the Talk

- ✓ Monopoles: theory, interaction, production.
- ✓ Monopole dynamics and bounds: late universe.
- ✓ Monopole dynamics and bounds: early universe.
- ✓ Schwinger effect and monopole pair production.
- ✓ Conclusion.

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

DP, T. Kobayashi
Phys.Rev.D 108 (2023) 8, 083005

DP, K. Bondarenko, M. Doro, T. Kobayashi
Phys. Dark Univ. 46 (2024), 101704

DP, M. Doro, T. Kobayashi
arXiv:2502.xxxxx

UNIWERSYTET WARSZAWSKI

Magnetic Monopoles and Cosmic Magnetic Fields

The evolutions of magnetic monopoles and cosmic magnetic fields are strictly coupled throughout the universe's history.

Cosmic magnetic fields accelerate the monopoles ⟷ Accelerated monopoles extract energy from cosmic magnetic fields

↓ Monopole bounds are affected by the acceleration

↓ The survival of cosmic magnetic fields might lead to new bounds

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:

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

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

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

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

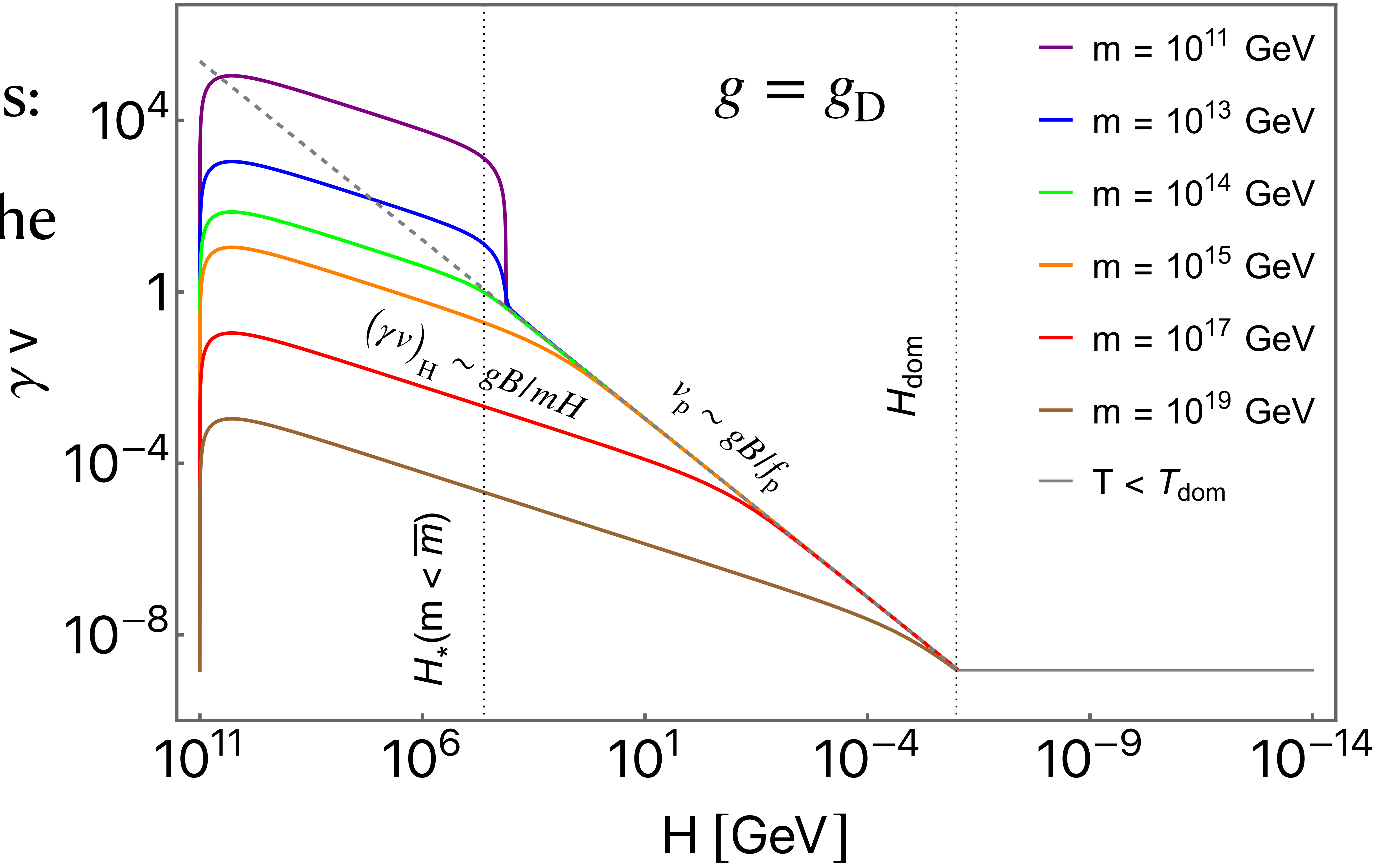
The Equation of Motion of the Monopoles

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

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.

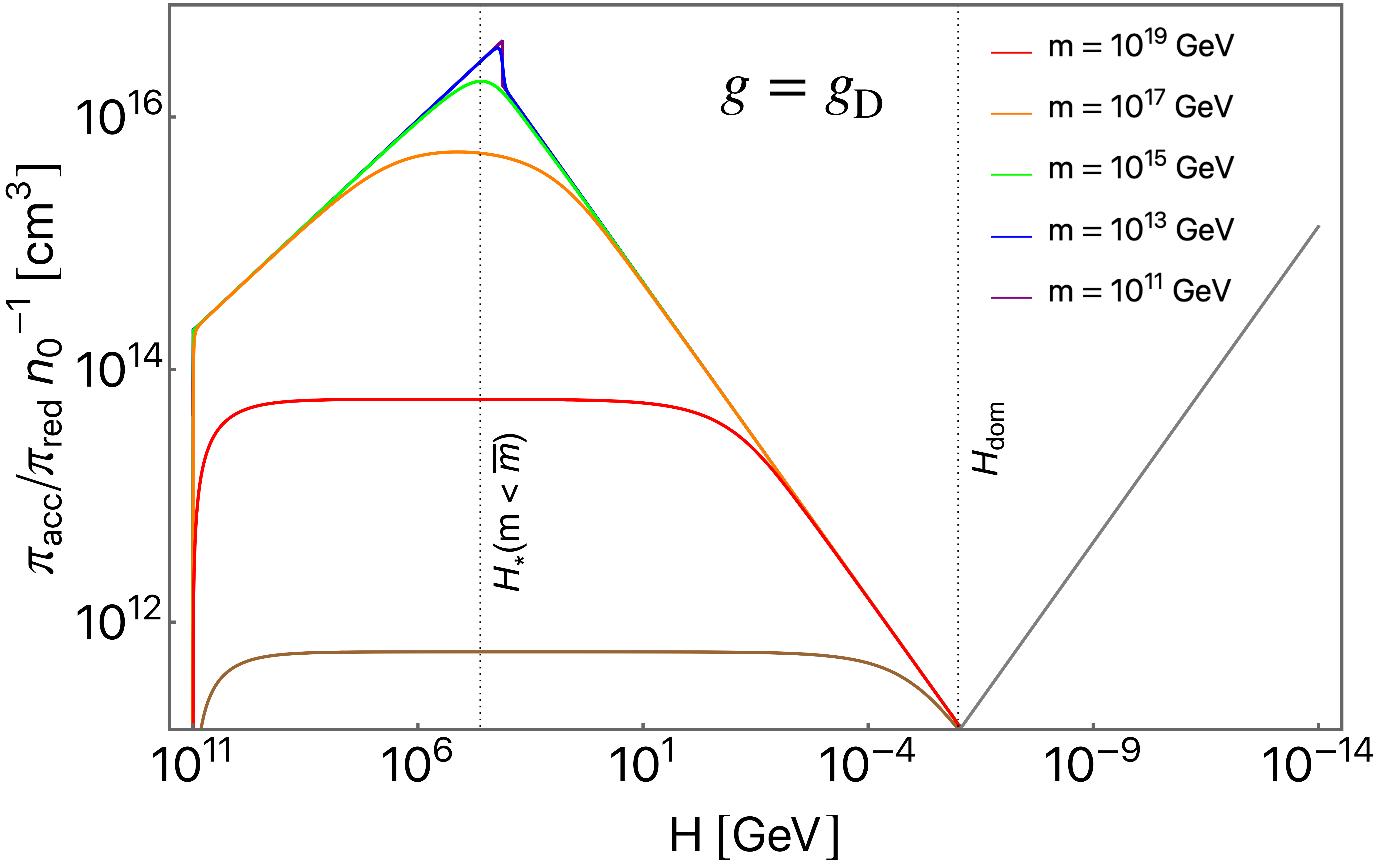
$$f_{\rm p} \sim \frac{e^2 g^2 \mathcal{N}_c}{16\pi^2} T^2$$



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

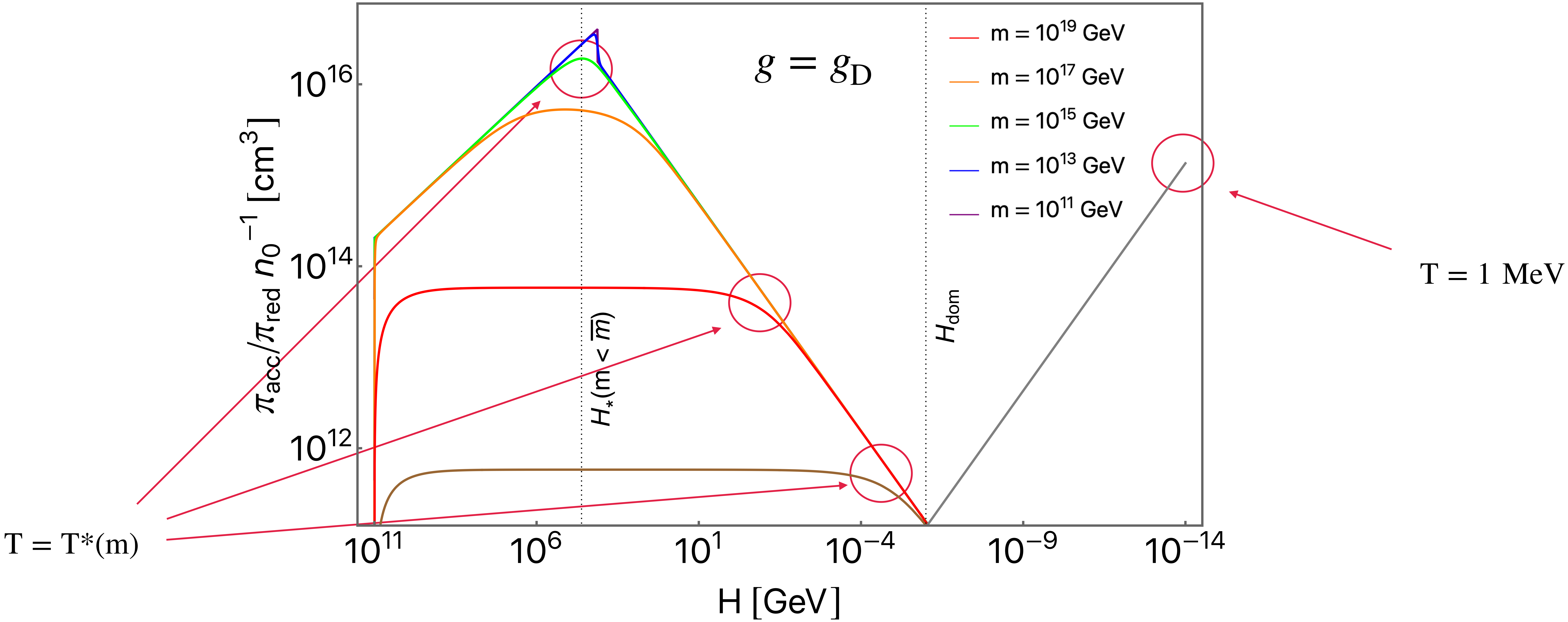
The Evolution of Π_{acc}/Π_{red}

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



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.



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:

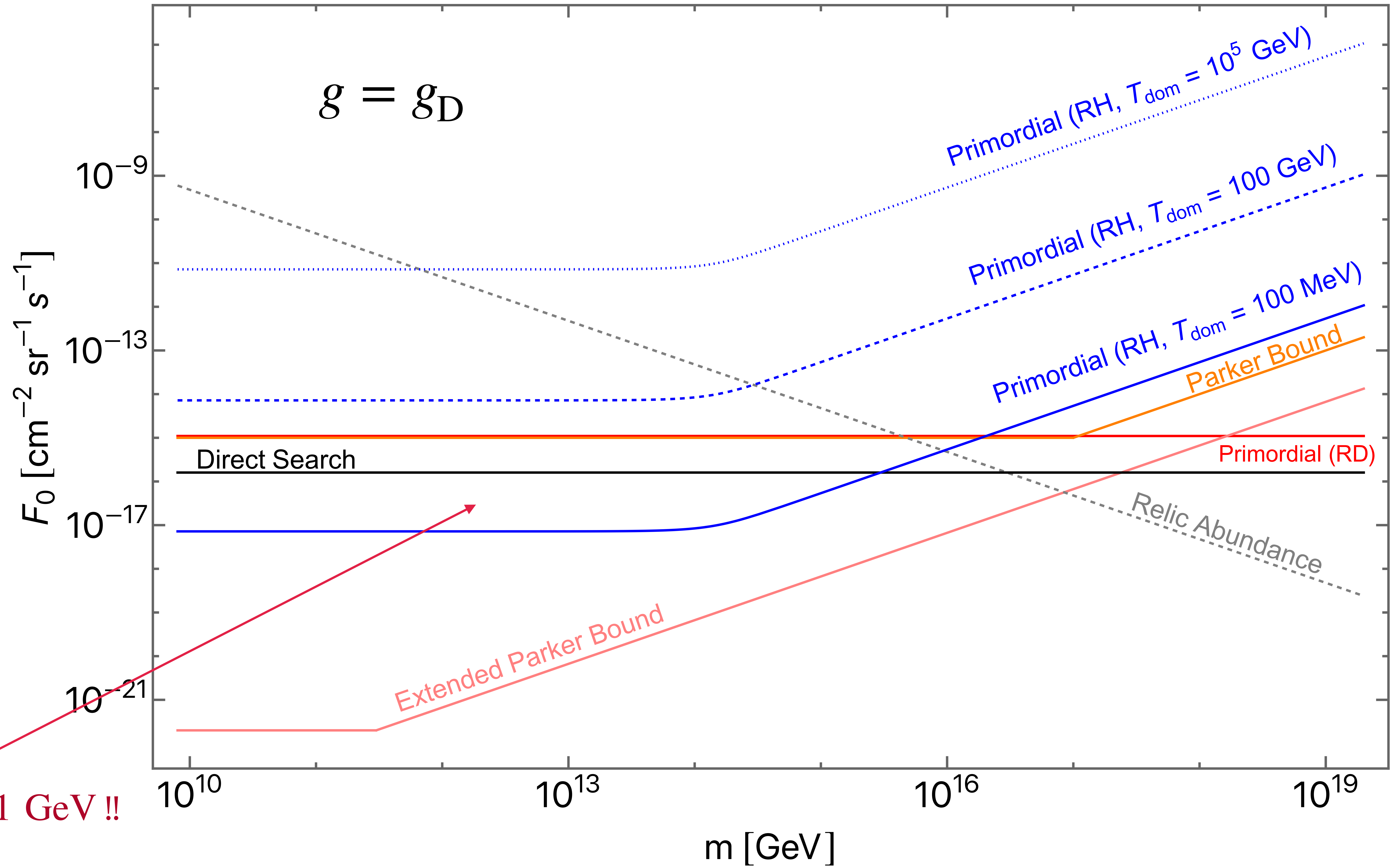
$$n_0 \lesssim \max\left\{ 10^{-21}\ \mathrm{cm}^{-3},\ 10^{-21}\ \mathrm{cm}^{-3} \left(\frac{m}{10^{19}\ \mathrm{GeV}}\right)\left(\frac{g_D}{g}\right)^2 \right\}$$

2) During reheating:

$$n_0 \lesssim \max\left\{ 10^{-16}\ \mathrm{cm}^{-3} \left(\frac{B_0}{10^{-15}\ \mathrm{G}}\right)^{3/5}\left(\frac{T_{\rm dom}}{10^{6}\ \mathrm{GeV}}\right)\left(\frac{g_D}{g}\right)^{3/5},\right.$$
$$\left. 10^{-16}\ \mathrm{cm}^{-3} \left(\frac{m}{10^{14}\ \mathrm{GeV}}\right)\left(\frac{T_{\rm dom}}{10^{6}\ \mathrm{GeV}}\right)\left(\frac{g_D}{g}\right)^2 \right\}$$

Bounds on the Monopole Flux

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



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

Could Monopoles be Dark Matter?

Monopoles are sometimes suggested as possible candidates for Dark Matter.

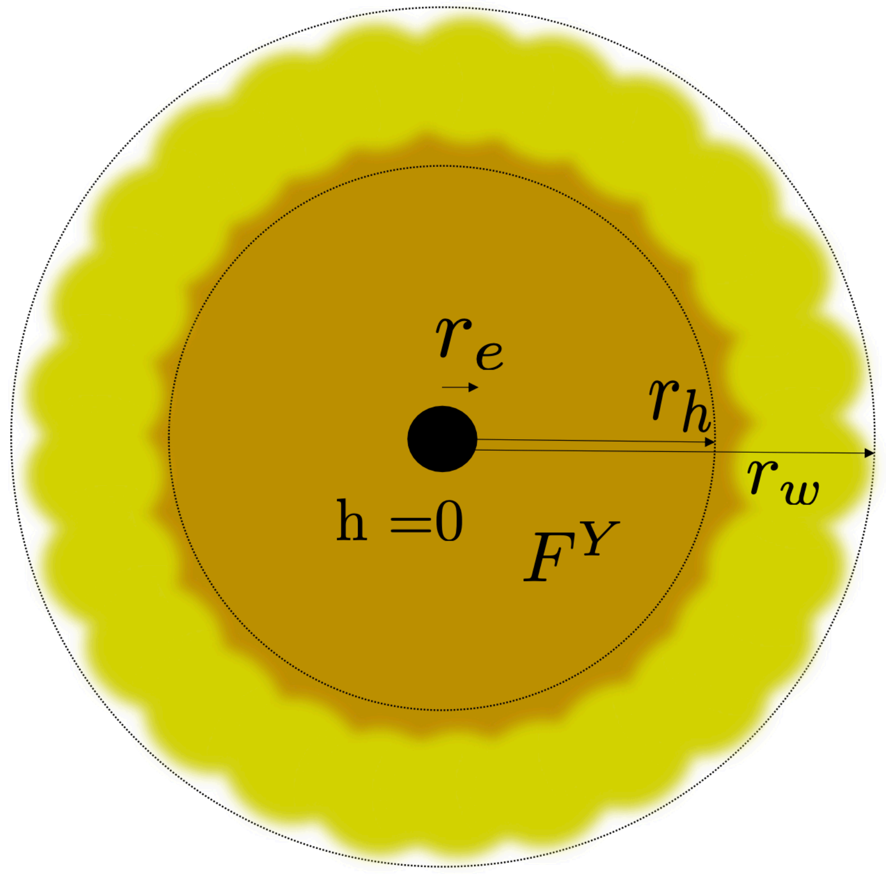
Standard magnetic monopoles must be very heavy to cover all the Dark Matter of the universe ($m \gtrsim 10^{17}$ GeV).

↓

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

- *Magnetically charged 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:

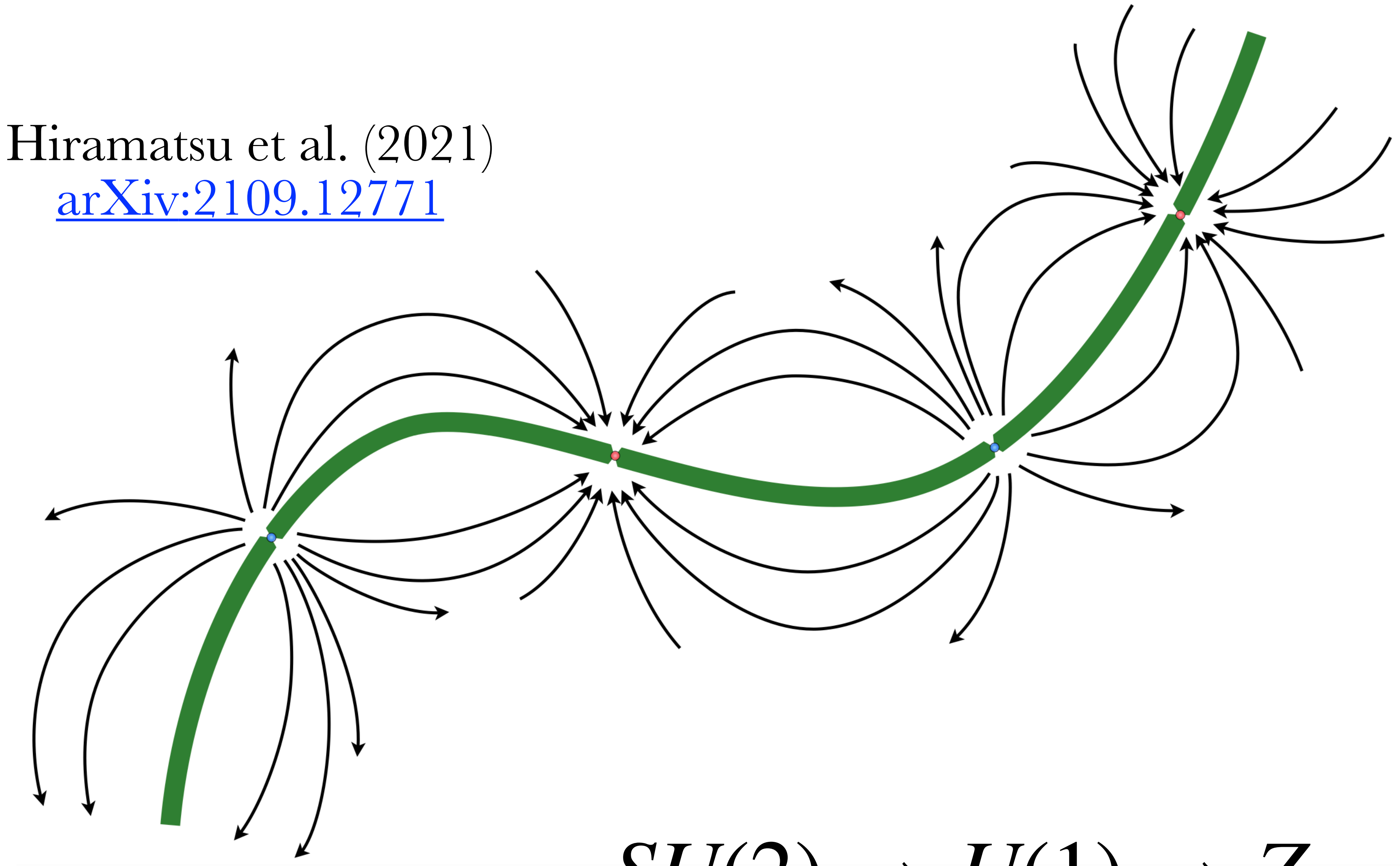
$$\mathscr{L}_{\text{gauge}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'^{a}_{\mu\nu}F'^{a\mu\nu} + \frac{\phi^a}{2\Lambda}F'^{a}_{\mu\nu}F^{\mu\nu} \qquad V = \frac{\lambda_1}{4}(\phi_1 \cdot \phi_1 - v_1^2) + \frac{\lambda_2}{4}(\phi_2 \cdot \phi_2 - v_2^2) + \frac{k}{2}(\phi_1 \cdot \phi_2)^2$$

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.

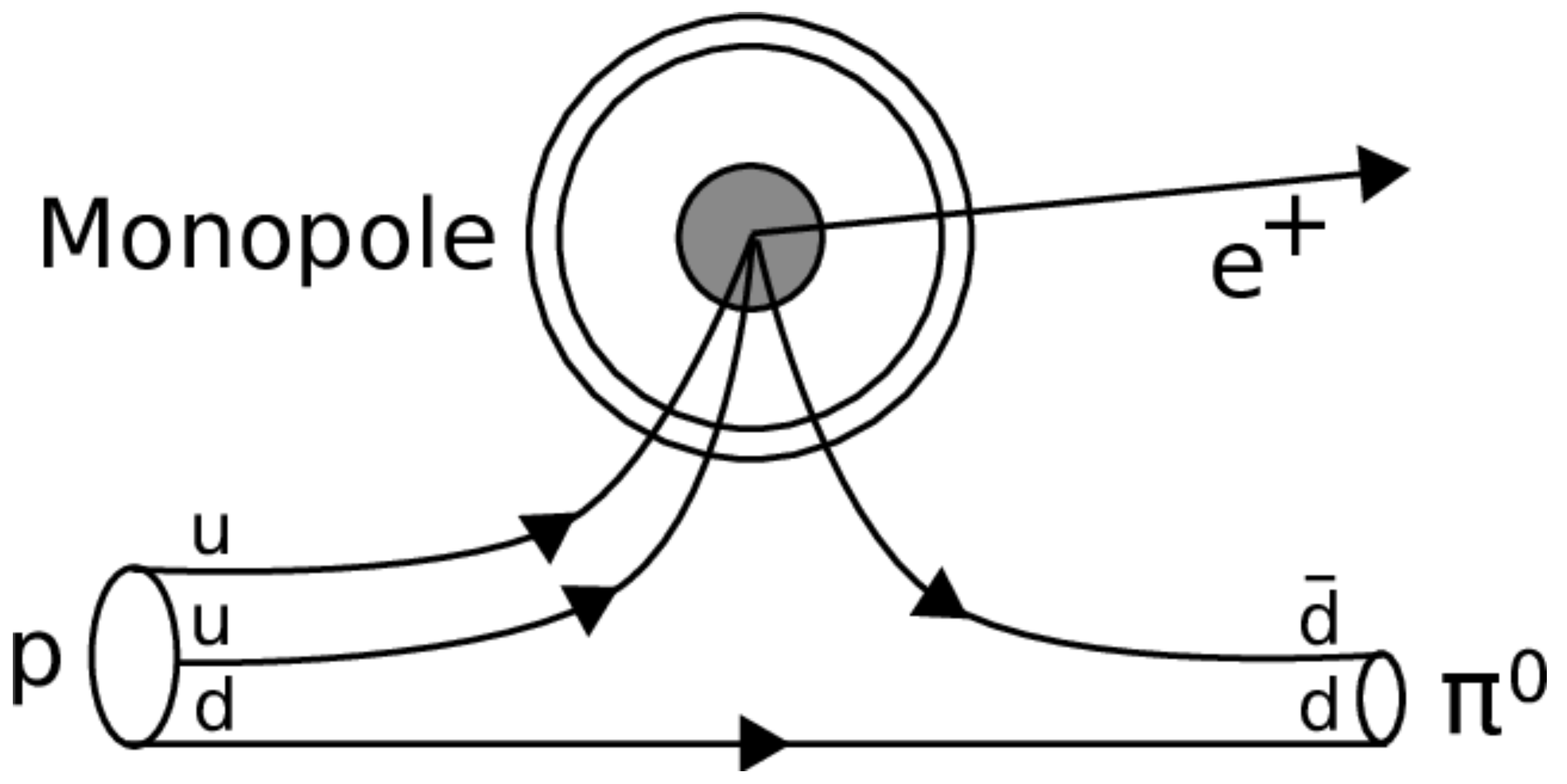
Hiramatsu et al. (2021)
arXiv:2109.12771



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

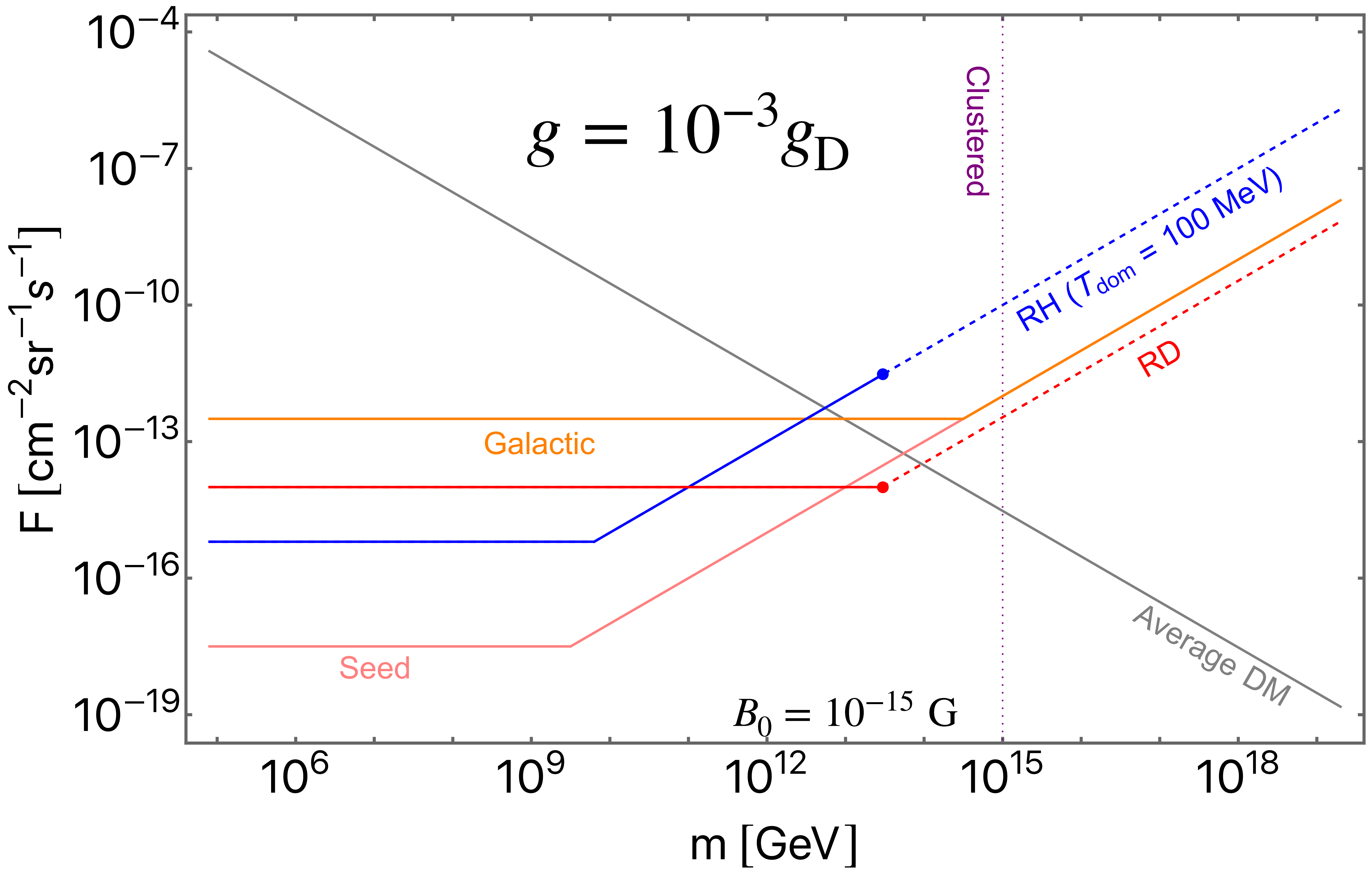
Direct Search of Dark Monopoles?

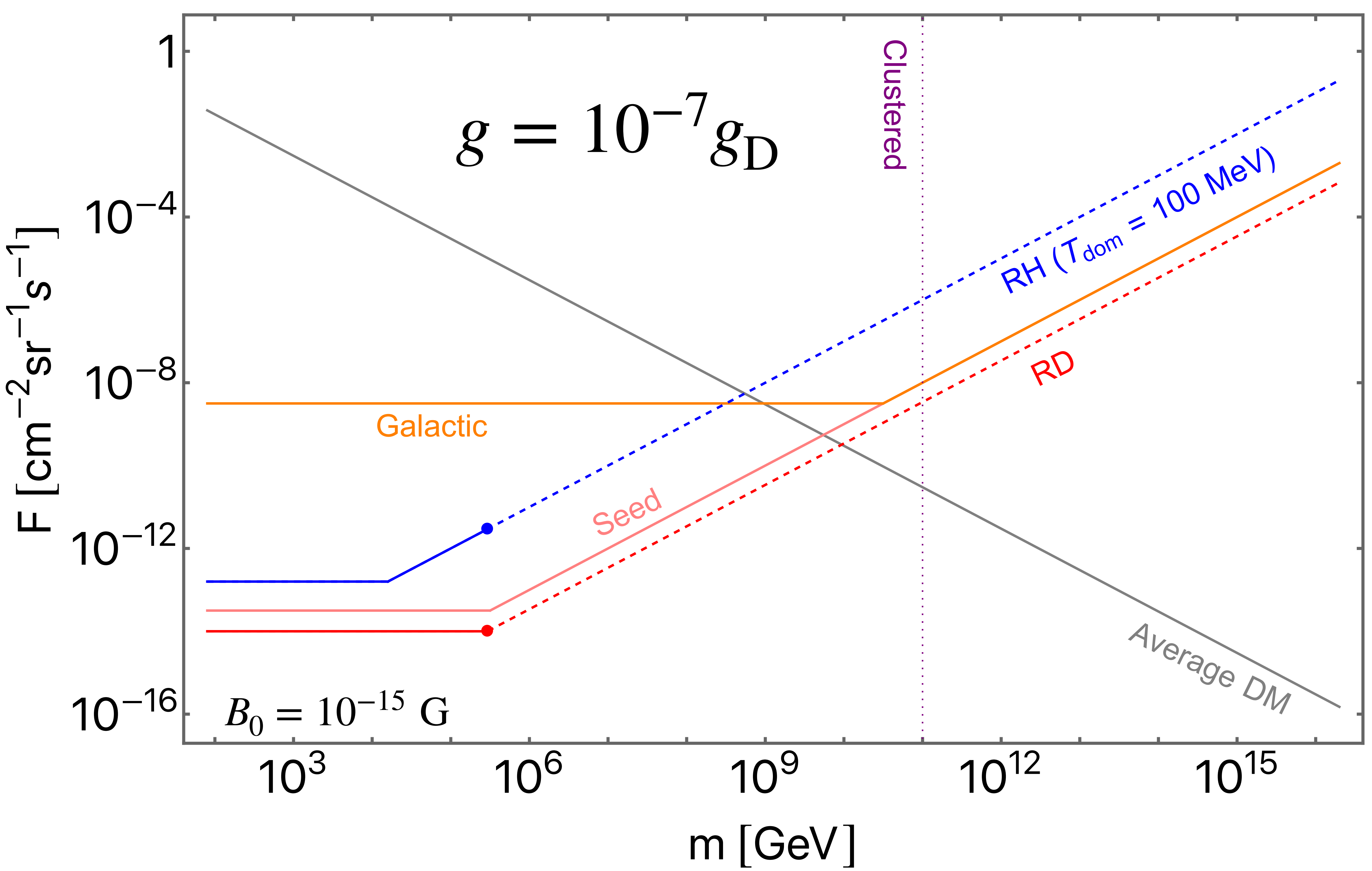
- Minicharged monopoles cannot be direct searched with the standard methods (ex. induction of a current in a coil, energy loss in a calorimeter).
- Even completely dark monopoles can still be detected through the *catalysis of nucleon decays:*



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

Bounds on Minicharged Monopoles

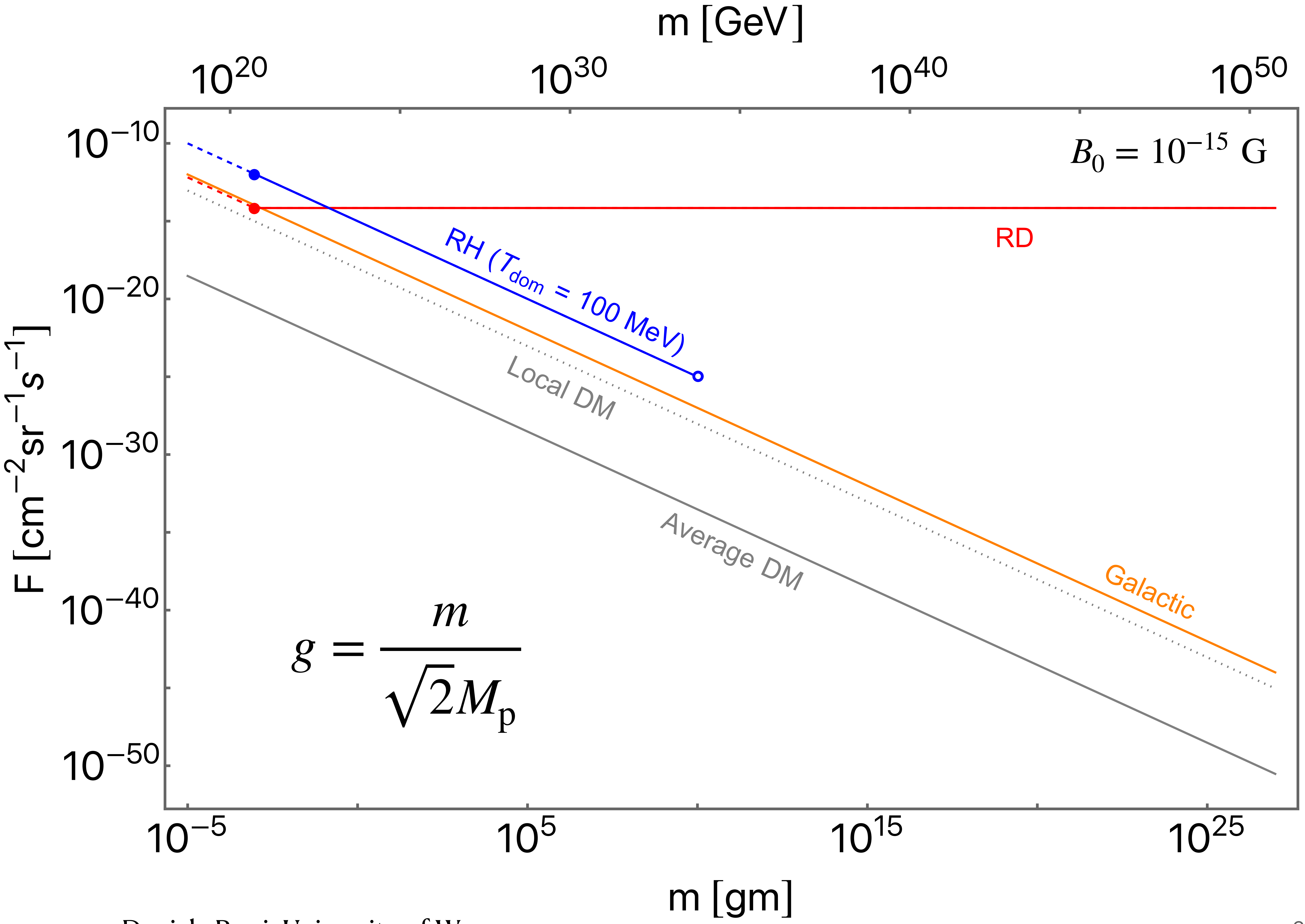




- The primordial bounds are less dependent on the monopole charge and they are the **strongest** for small charges.
- Minicharged monopoles can cluster with the Galaxy and be DM for masses **much smaller than** $M_{\rm Pl}$.

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.**

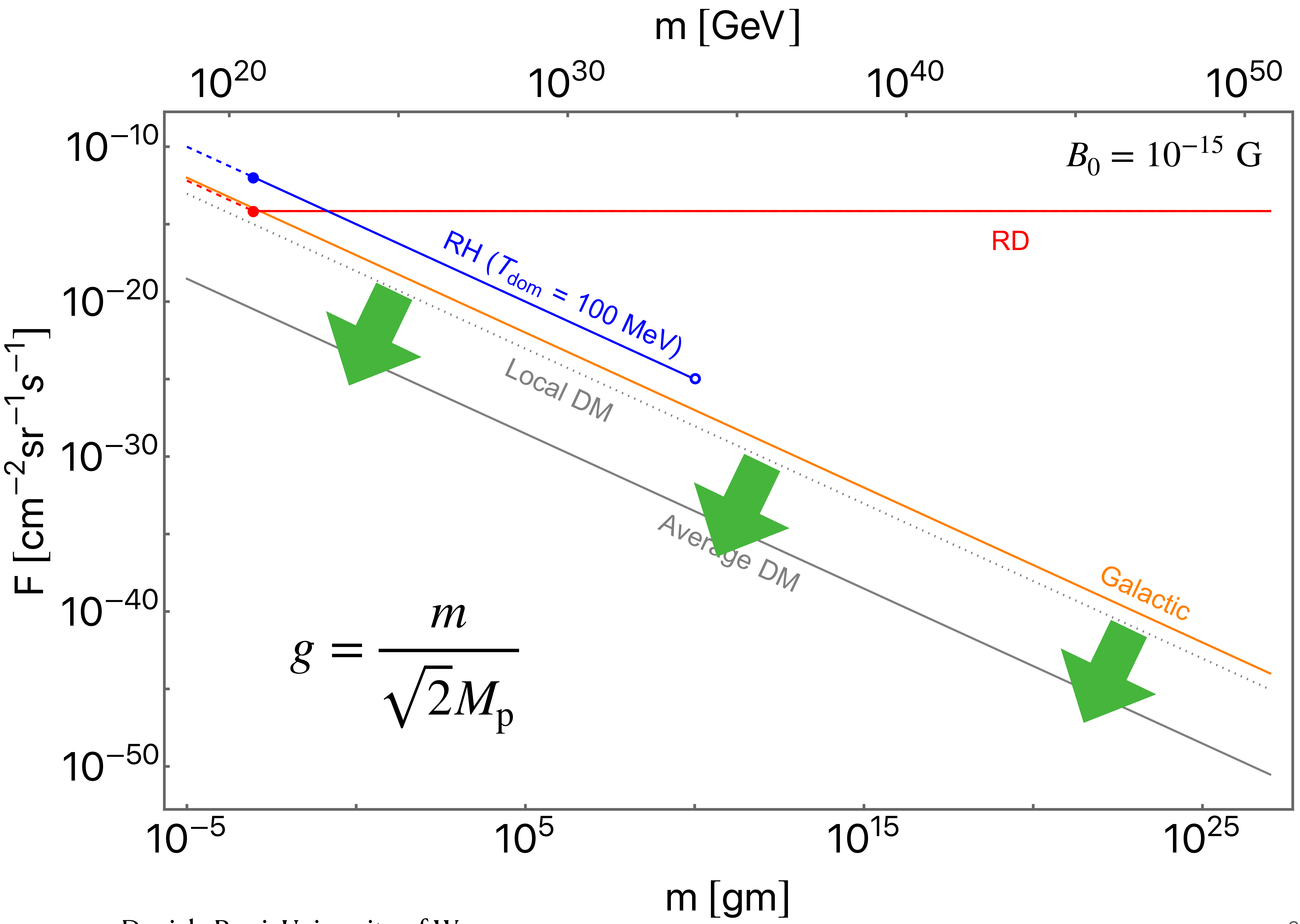


Bounds on Magnetic Black Holes

- 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.**



Contents of the Talk

- ✓ Monopoles: theory, interaction, production.
- ✓ Monopole dynamics and bounds: late universe.
- ✓ Monopole dynamics and bounds: early universe.
- ✓ Schwinger effect and monopole pair production.
- ✓ Conclusion.

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

DP, T. Kobayashi
Phys.Rev.D 108 (2023) 8, 083005

DP, K. Bondarenko, M. Doro, T. Kobayashi
Phys. Dark Univ. 46 (2024), 101704

DP, M. Doro, T. Kobayashi
arXiv:2502.xxxxx

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

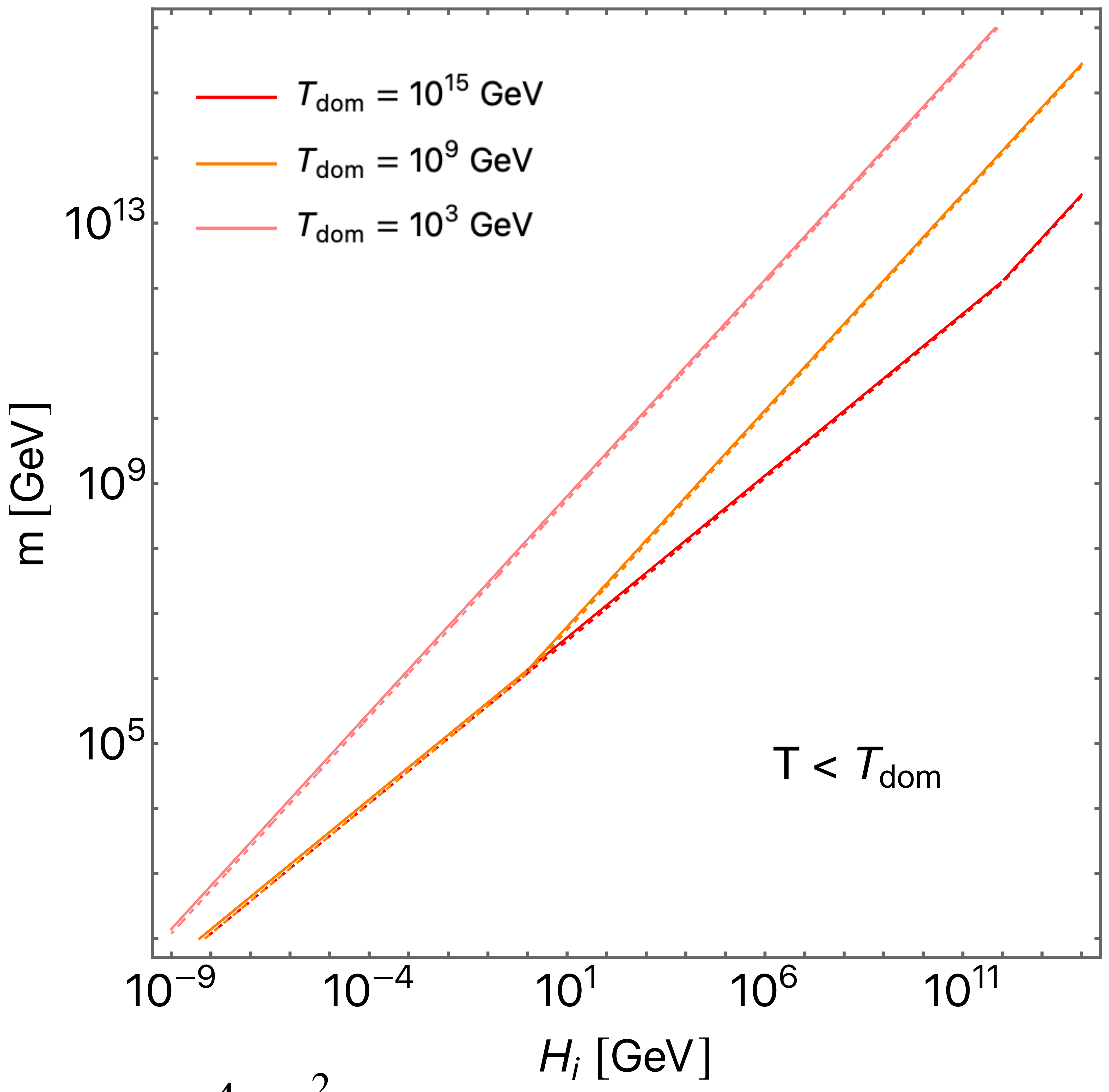
2. The produced pairs are accelerated by the magnetic fields → apply the primordial bounds on the monopole abundance produced by the fields themselves.

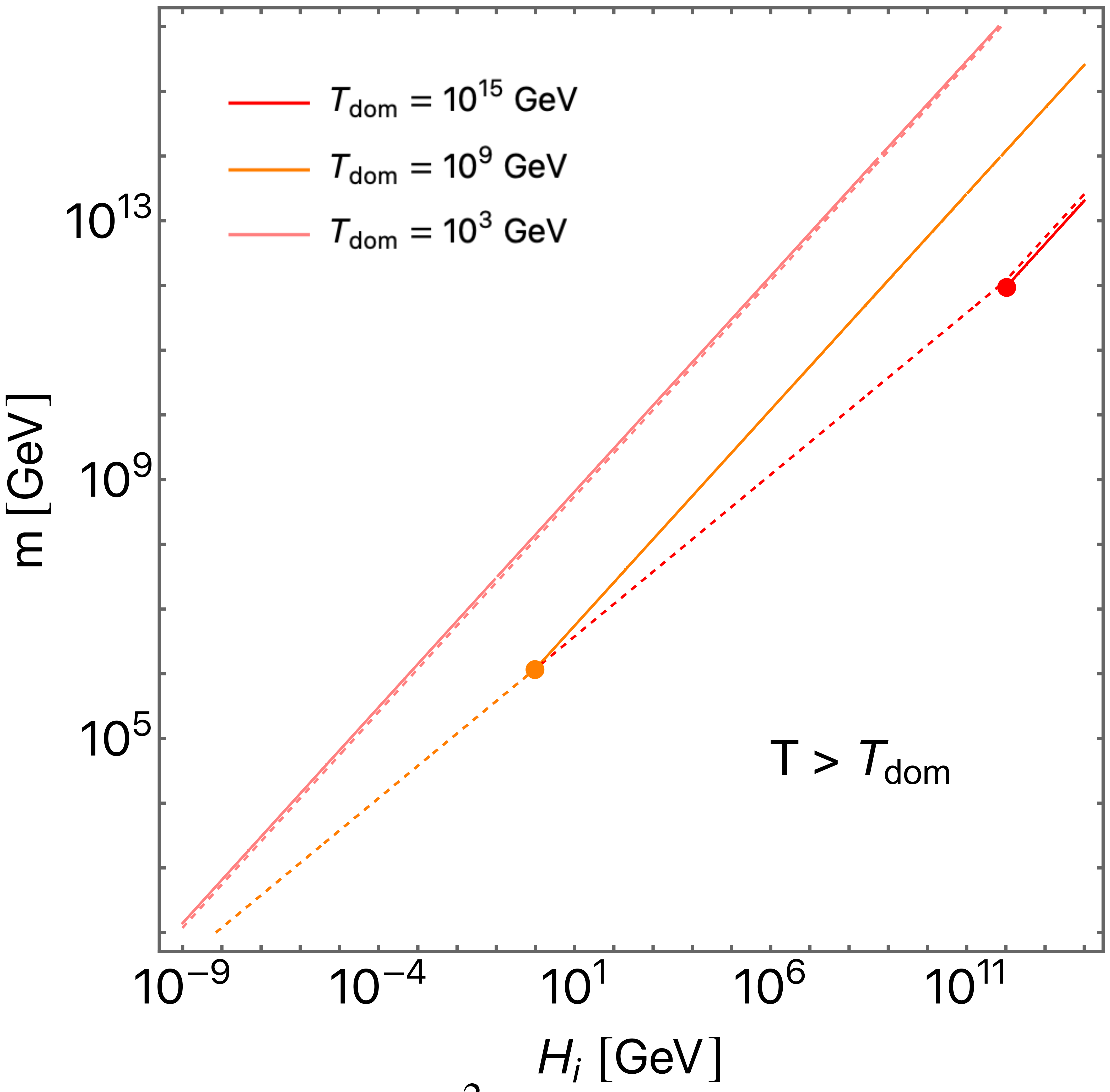
↓

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

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.*

Schwinger Effects and Monopole Pair Production





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

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

Contents of the Talk

- ✓ Monopoles: theory, interaction, production.
- ✓ Monopole dynamics and bounds: late universe.
- ✓ Monopole dynamics and bounds: early universe.
- ✓ Schwinger effect and monopole pair production.
- ✓ Conclusion.

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

DP, T. Kobayashi
Phys.Rev.D 108 (2023) 8, 083005

DP, K. Bondarenko, M. Doro, T. Kobayashi
Phys. Dark Univ. 46 (2024), 101704

DP, M. Doro, T. Kobayashi
arXiv:2502.xxxxx

UNIWERSYTET WARSZAWSKI

Conclusion

The evolutions of magnetic monopoles and cosmic magnetic fields are strictly coupled throughout the universe's history.

- Cosmic magnetic fields can accelerate the cosmic population of monopoles to *relativistic velocities.*

- Considering monopole acceleration in cosmic magnetic fields drastically affects the bounds on the monopole flux:
  - The *extended Galactic Parker Bound* is significantly relaxed in the case of strong intergalactic magnetic fields.
  - Direct searches with cosmic ray detectors can provide the strongest direct bounds.

Conclusion

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

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

  1. For $g = g_\mathrm{D}$ they can be DM only for masses comparable to or larger than M_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.

UNIWERSYTET
WARSZAWSKI

Thank You!!

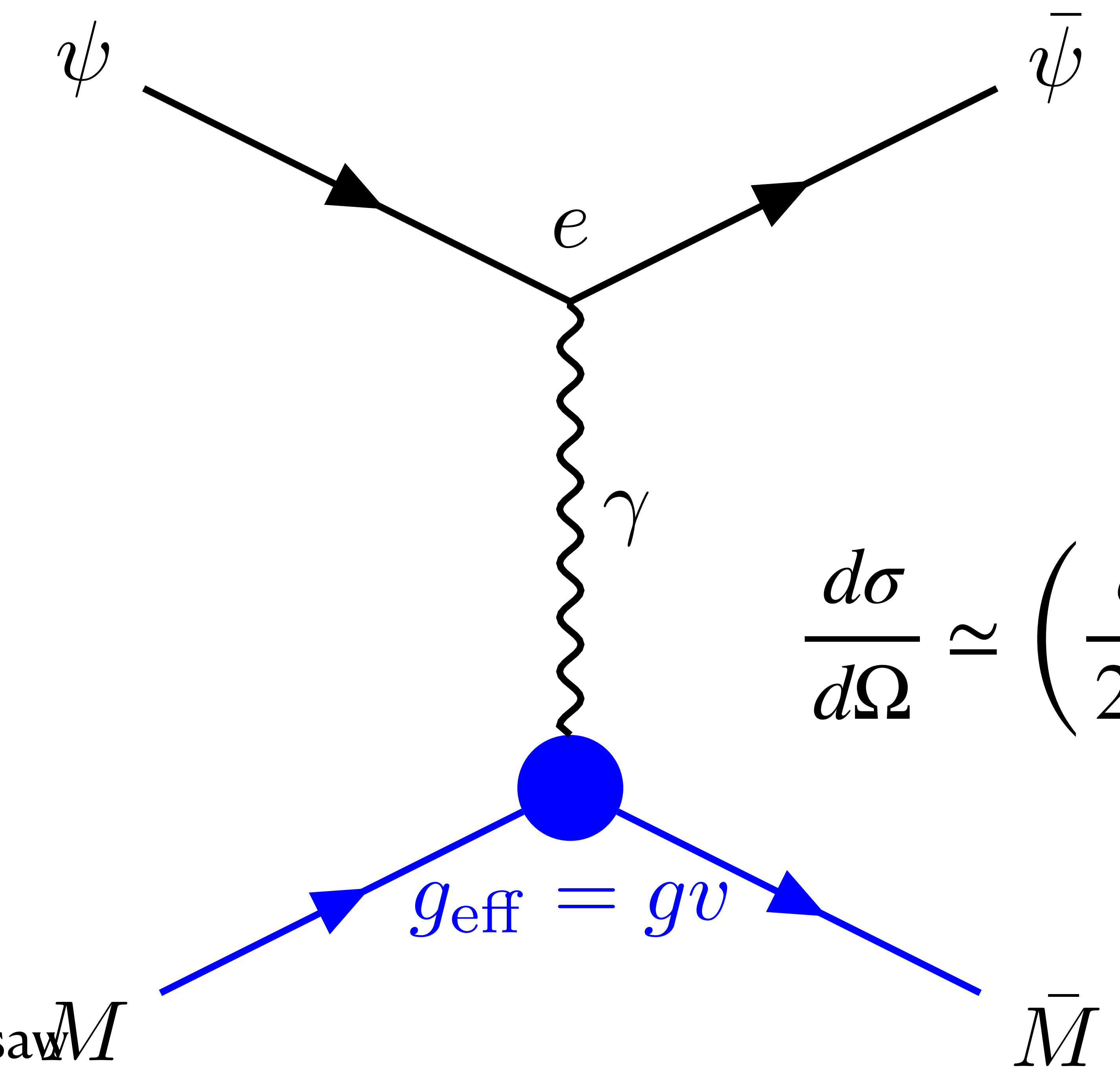
Interaction with matter

Effective field theory approach

- A comprehensive quantum field theory of monopoles has yet to be fully developed, though several attempts have been made.

- Models of monopole-SM interaction have been proposed with velocity-dependent magnetic charges.

The non-perturbativity of the magnetic charge invalidates any attempt to use an effective perturbative approach for relativistic monopoles!!



$$\frac{d\sigma}{d\Omega} \simeq \left(\frac{eg}{2\mu v}\right)^2 \frac{1}{(\theta/2)^4}$$

Cosmological Monopole Problem

Breaking the conformal symmetry of the kinetic term of the gauge field can solve the monopole problem without inflation:

$$\frac{\mathscr{L}}{\sqrt{-g}} \supset -\frac{I^2}{4} F_{\mu\nu} F^{\mu\nu} \qquad \tilde{A}^a_\mu = I A^a_\mu, \quad \tilde{e} = e/I, \quad \tilde{g} = gI$$

- The monopoles might be first produced as global (i.e. at the breaking of the global part of the symmetry).
- Global monopoles show very strong attractive forces and therefore the annihilation process is much more effective:

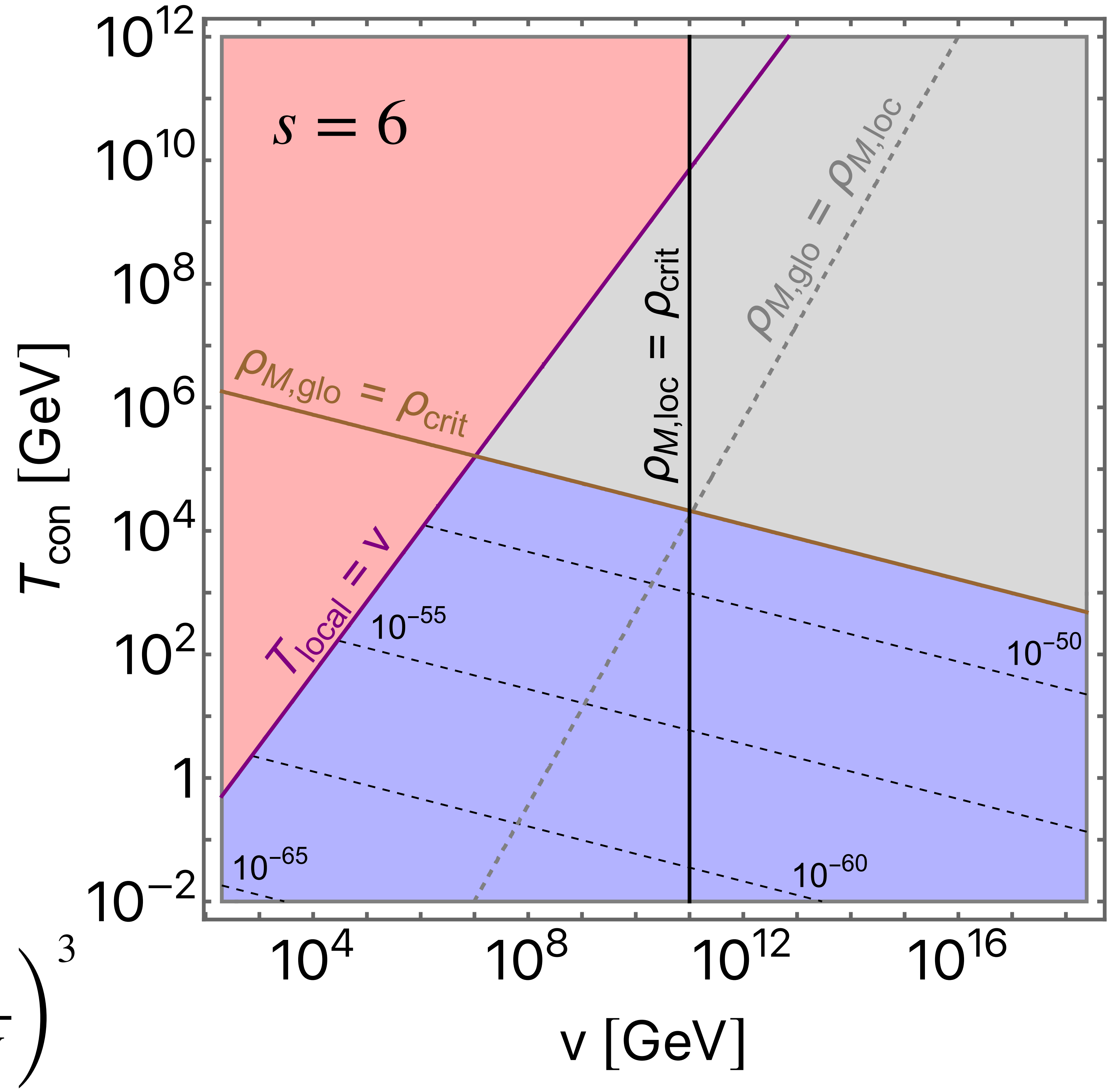
$$\rho_{\mathrm{M,glo}} \sim \rho_{\mathrm{crit}} \left(\frac{v}{10^{14}\ \mathrm{GeV}} \right) \left(\frac{T_{\mathrm{local}}}{10^{3}\ \mathrm{GeV}} \right)^3$$

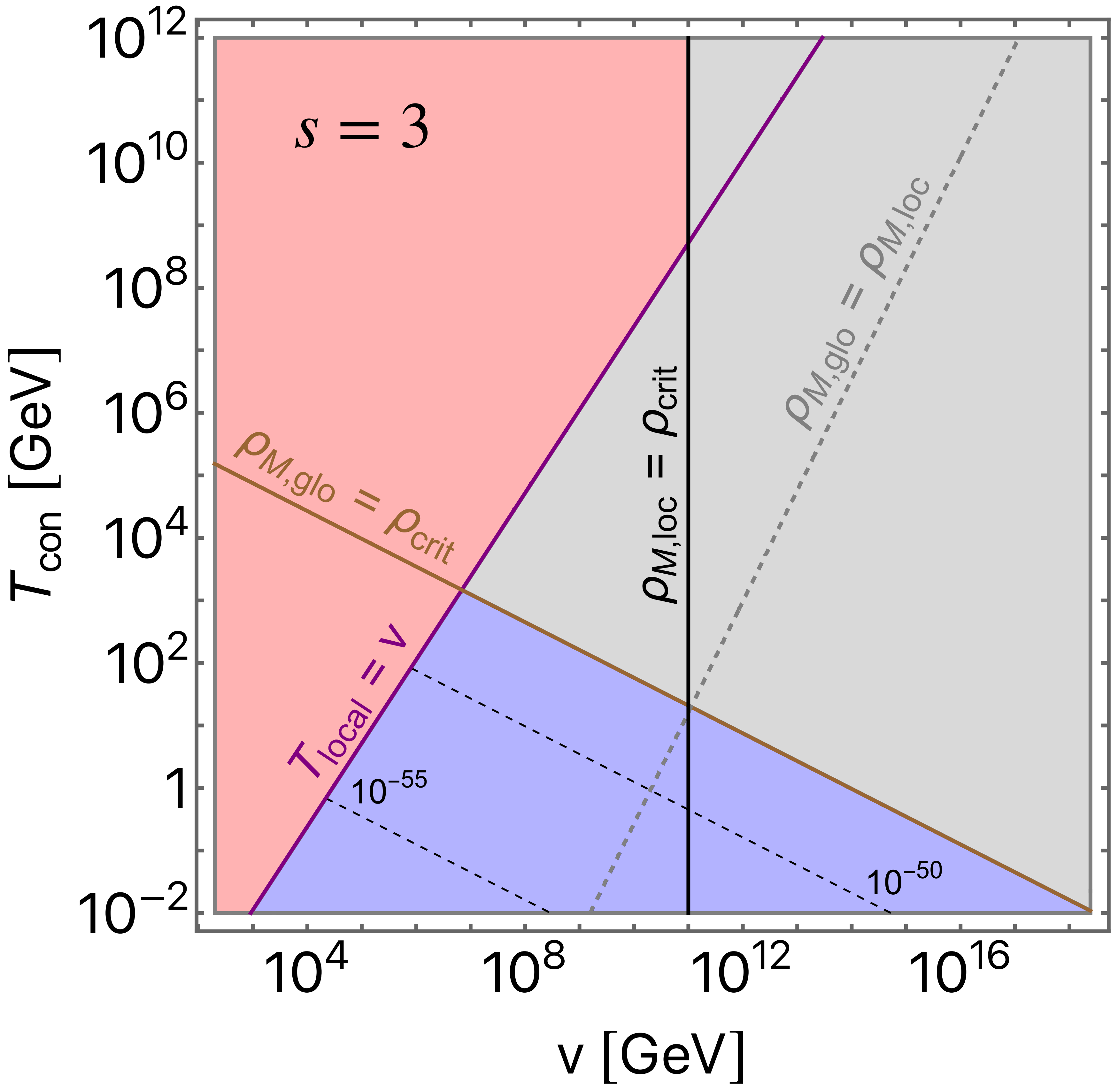
Cosmological Monopole Problem

$$I = \max\left\{\left(\frac{a_{\rm con}}{a}\right)^s, 1\right\}$$

$$\rho_{\rm M,loc} \sim \rho_{\rm crit}\left(\frac{v}{10^{11}\ \rm GeV}\right)^4$$

$$\rho_{\rm M,glo} \sim \rho_{\rm crit}\left(\frac{v}{10^{14}\ \rm GeV}\right)\left(\frac{T_{\rm local}}{10^3\ \rm GeV}\right)^3$$





With the conformal-breaking term, we have access to parameters compatible with the GUT scale even without inflation!