Parker Bound and Monopole Pair Production from Primordial Magnetic Fields [arXiv:2207.XXXXX]

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1. Abstract

We present new bounds on the cosmic abundance of magnetic monopoles based on the survival of primordial magnetic fields during the reheating ($T > T_{\rm dom}$) and radiation-dominated ($T < T_{\rm dom}$) epochs. The new bounds can be stronger than the conventional Parker bound from galactic magnetic fields, as well as bounds from direct searches. We also apply our bounds to monopoles produced by the primordial magnetic fields themselves through the Schwinger effect, and derive conditions for the survival of the primordial fields.

2. Monopole dynamics

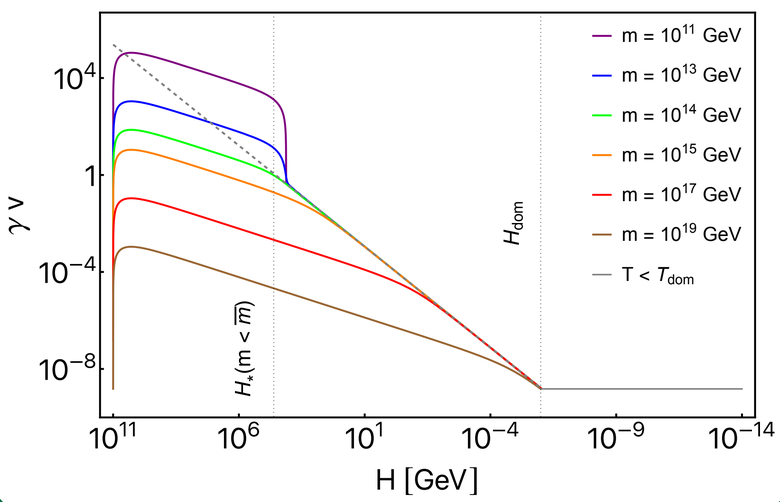
The **equation of motion of a monopole with charge g and mass m** in a FRW metric from the time of the primordial magnetic field generation to the epoch of e^+e^- annihilation is:

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

where $-f_{\rm p}v$ is the **frictional force** due to the interactions of the monopoles with the particles of the primordial plasma and:

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

with $\mathcal{N}_c$ the number the charged relativistic degrees of freedom.



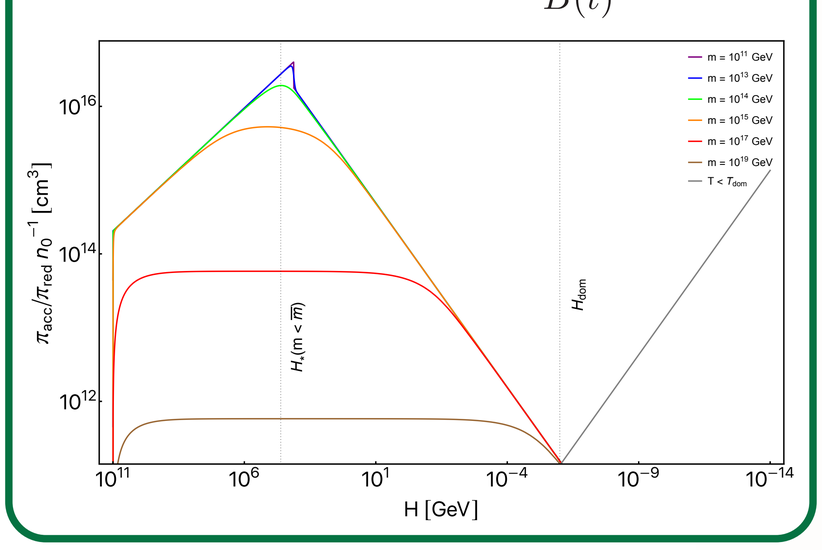
3. Magnetic field energy dissipation

The primordial magnetic fields lose energy accelerating the monopoles. The **evolution of the magnetic field energy density** can be derived by solving the equation:

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

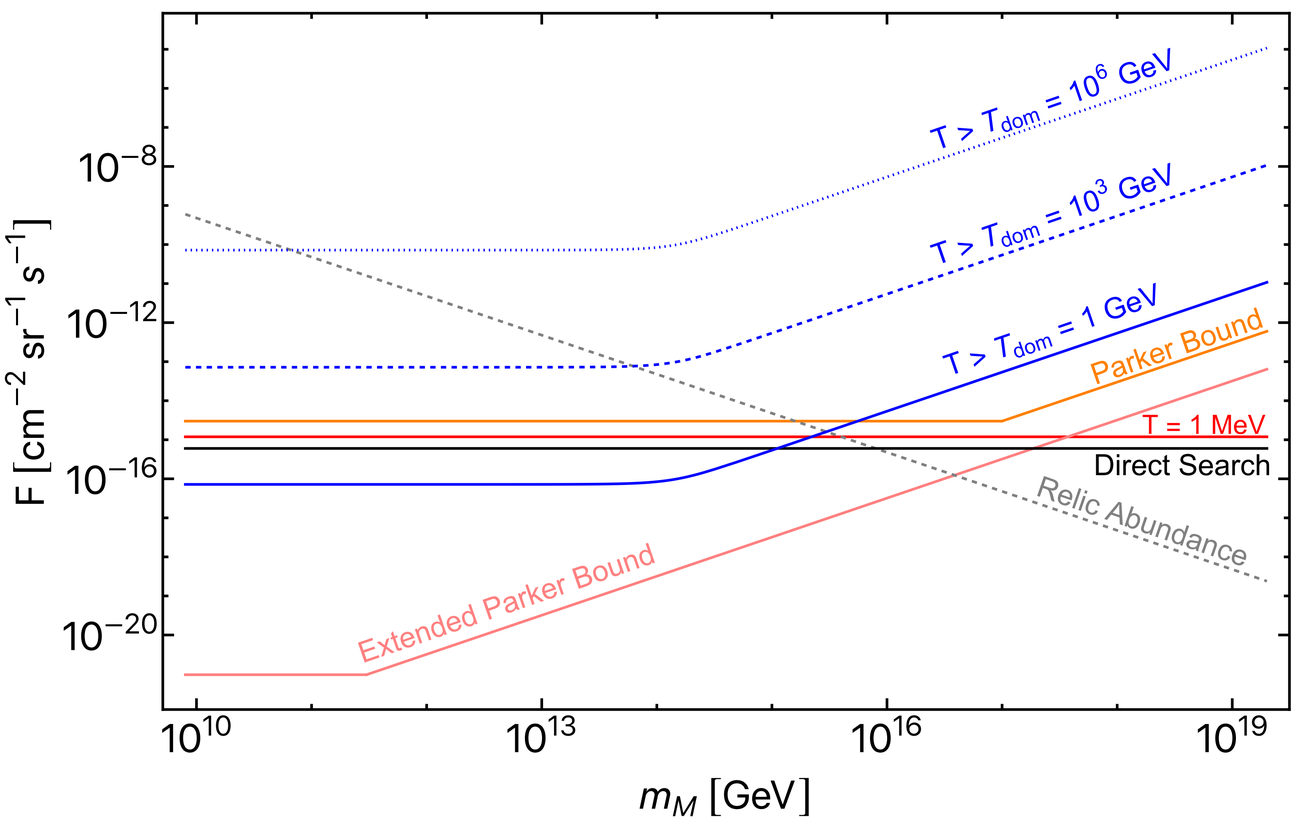
where we define the **dissipation rates** due to redshifting and monopole acceleration as:

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

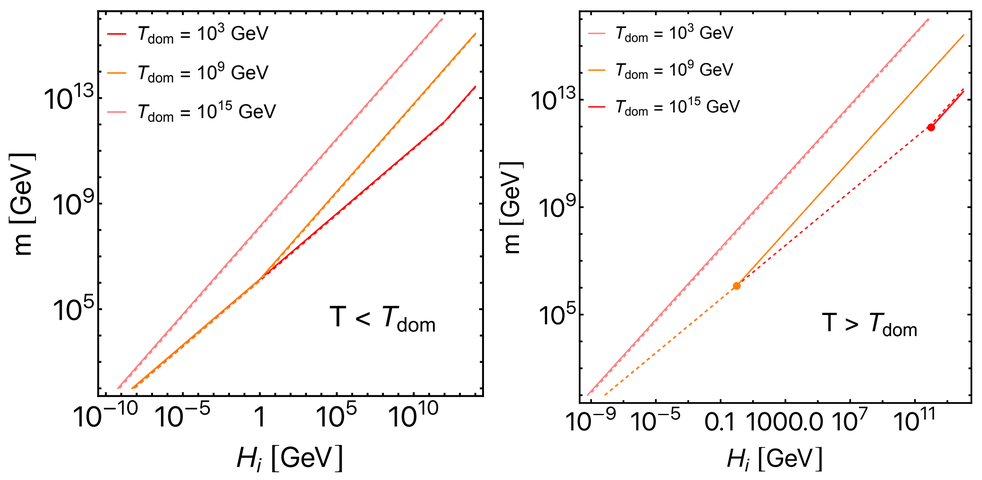


4. Bounds on the monopole flux

We apply the condition $\Pi_{\rm acc}/\Pi_{\rm red} \ll 1$ to the two maxima of the ratio, obtaining upper bounds on the **average monopole number density in the present universe** that we show in the plot. From the maximum during radiation domination at $T \sim 1$ MeV, the result is the same of [1] (red line in the plot). From the maximum during reheating we obtain a new bound that depends on the temperature at the end of reheating, $T_{\rm dom}$ (blue lines in the plot).
We assume **thermal equilibrium for the particles of the plasma** during the reheating epoch, but stronger bounds can be obtained without this assumption.



5. Monopoles produced by the Schwinger effect



We apply our bounds to the monopole pairs produced by primordial magnetic fields via **the Schwinger effect**.
This correspond to the most conservative requirement for the survival of the primordial magnetic fields. The rate of pair production is:

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

We deduce conditions (solid lines in the plots) comparable to the **weak field condition for the instanton calculation of the rate** computed at the time of the primordial magnetic field generation t_i (dashed lines in the plots):

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

It has been shown in [2] that the weak field condition is enough also for the survival of the primordial magnetic fields to the production of Schwinger-produced monopole pairs.

6. Conclusions

We carried out a **comprehensive study of the evolution of the energy density of the primordial magnetic fields** in the early universe. We derived new bounds on the cosmological averaged abundance of magnetic monopoles by generalizing the Parker bound to the survival of the primordial magnetic fields:

1. For a sufficiently small temperature at the end of reheating our bounds become stronger than the original Parker bound and the limits from direct search, even for the mass of a GUT scale monopole.

2. We can neglect all the effects of the monopoles Schwinger-produced by the primordial magnetic fields on the fields themselves once the weak field condition is satisfied.

7. References

[1] A. J. Long and T. Vachaspati. Implications of a primordial magnetic field for magnetic monopoles, axions and dirac neutrinos. *Phys. Rev. Lett. D*, 91:103522, 2015.

[2] T. Kobayashi. Monopole-antimonopole pair production in primordial magnetic fields. *Phys. Rev. D*, 104, 2021.