Self-Consistent Parker Bound on Magnetic Monopoles

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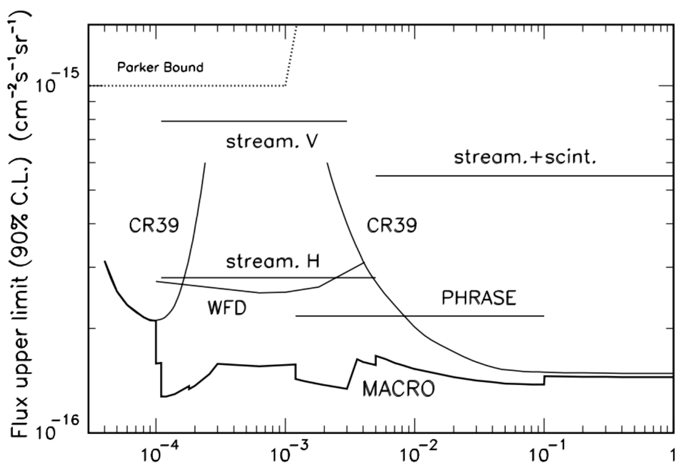
Based on arXiv: 2605.21281 in collaboration with Chun-Yan Jiang（姜春燕）, Nayun Jia（贾拿云）and Xin Zhang（张鑫）

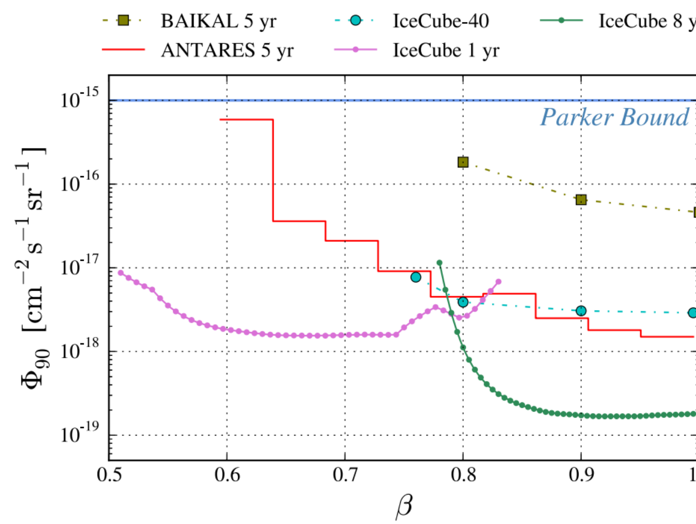
Magnetic monopole: motivation and searches

1. Magnetic monopole as a **striking tracer of fundamental symmetries of nature**:
   - Explanation of **electric charge quantization**: $Q_E Q_M = \hbar c \dfrac{n}{2}$

     P. A. M. Dirac, Proc. Roy. Soc. Lond. A 133 (1931) 60-72
   - **Topological defect** in grand/partially unified gauge theories, necessary for **energy spectra completeness** G. 't Hooft, NPB, 79 (1974) 276; A. M. Polyakov, JETP Lett. 20 (1974) 194
2. Direct searches in cosmic rays



MACRO, EPJC 25, 511-522 (2002)



IceCube, PRL 128, 051101 (2022)

Nonrelativistic monopoles flux upper limit $\sim 10^{-16}\ \mathrm{cm^{-2}s^{-1}sr^{-1}}$ (MACRO)

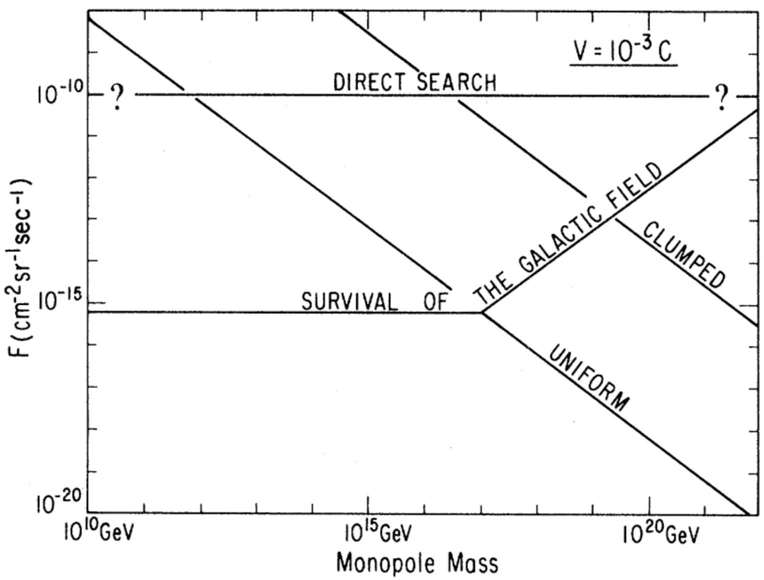
Relativistic monopoles flux upper limit $\sim 10^{-18} - 10^{-19}\ \mathrm{cm^{-2}s^{-1}sr^{-1}}$ (IceCube)

Parker bound: two regimes

- **The Parker bound:** Based on energy extraction from the Galactic magnetic fields (GMF) due to monopole acceleration. **Two regimes**

  a) **Slight deviation:** $m(\gamma_i - 1) \gg |g|Bl_c$, upper limit $F^{\rm up} = \frac{1}{6\pi^2}\frac{m(\gamma_i - 1)}{g^2 l_c}\tau_{\rm E}^{-1}$

  b) **Significant deviation:** $m(\gamma_i - 1) \ll |g|Bl_c$, upper limit $F^{\rm up} = \frac{1}{24\pi^2|g|}\left(\frac{2R}{l_c}\right)^{1/2} B\tau_{\rm E}^{-1}$



g: magnetic charge (unit Dirac charge $g \simeq 69e$)

m: monopole mass

γ_i: monopole Lorentz boost factor ($v_i = 10^{-3}c$)

l_c: coherence length of GMF (10^{21} cm)

B: magnetic field strength (3 μG)

$\tau_{\rm E}$: energy regeneration time of GMF (10^{15} s)

R: radius of the magnetized region of the Galaxy (10^{23} cm)

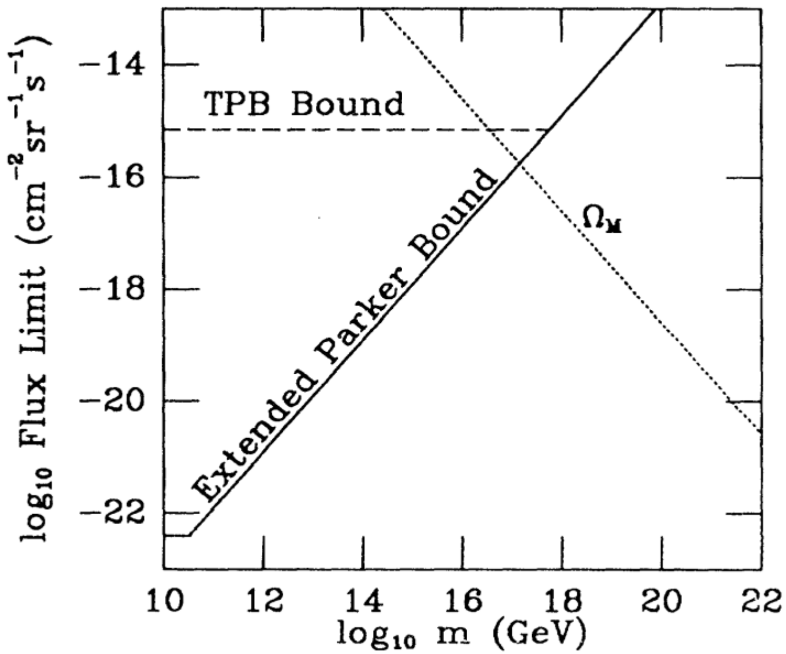
M. Turner, E. Parker, T. Bogdan, PRD 26 (1982) 1296

T. Kobayashi, D. Perri, PRD 108, 083005 (2023)

C. Zhang, S.-H. Zhang, B. Fu, J.-F. Zhang and X. Zhang, JHEP 08 (2024) 220

Parker bound: key issues

- **The Parker bound:** A well-defined and self-consistent formulation is lacking due to a number of **key issues**
  - ① **Extended (seed-field) Parker bound:** seed field strength and flux conversion?
  - ② **Regeneration time and coherence length:** field amplification vs. field ordering?
  - ③ **Treatment of the monopole initial velocity:** pre-acceleration by turbulent fields?



F. C. Adams, M. Fatuzzo, K. Freese, G. Tarlé, R. Watkins, M. Turner, PRL 70 (1993) 2511-2514

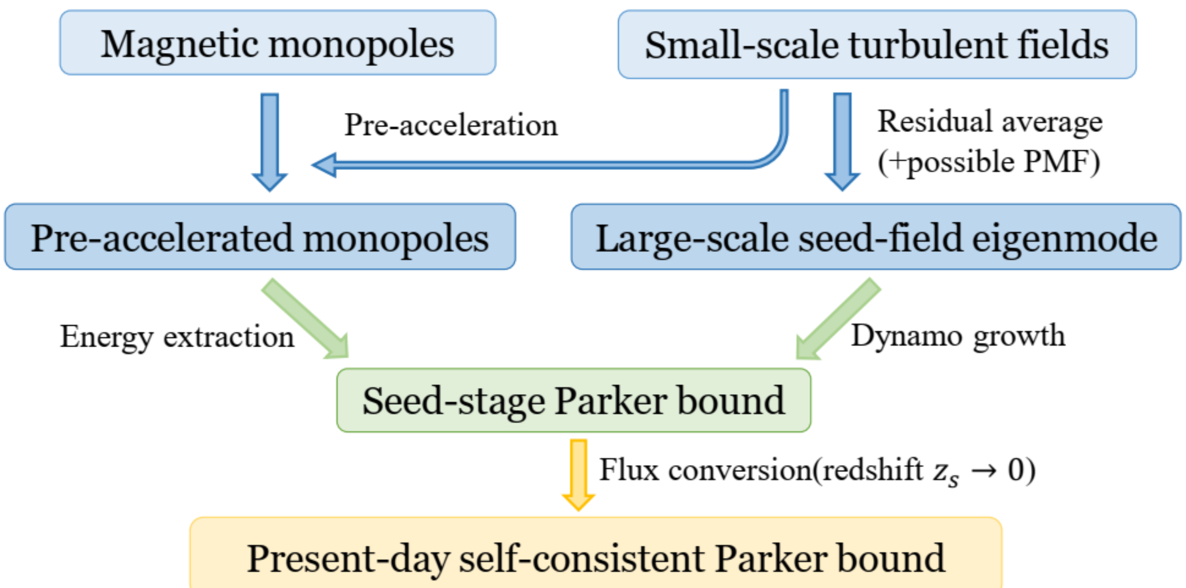
Parker bound: self-consistent formulation

- **The Parker bound:** self-consistent formulation

  ① **Target:** large-scale lowest seed-field eigenmode of the galactic dynamo, with well-defined regeneration time and localization width ($\Delta r \sim \sqrt{r_0 h_0}$).

  ② **Dual role of small-scale turbulent fields:**

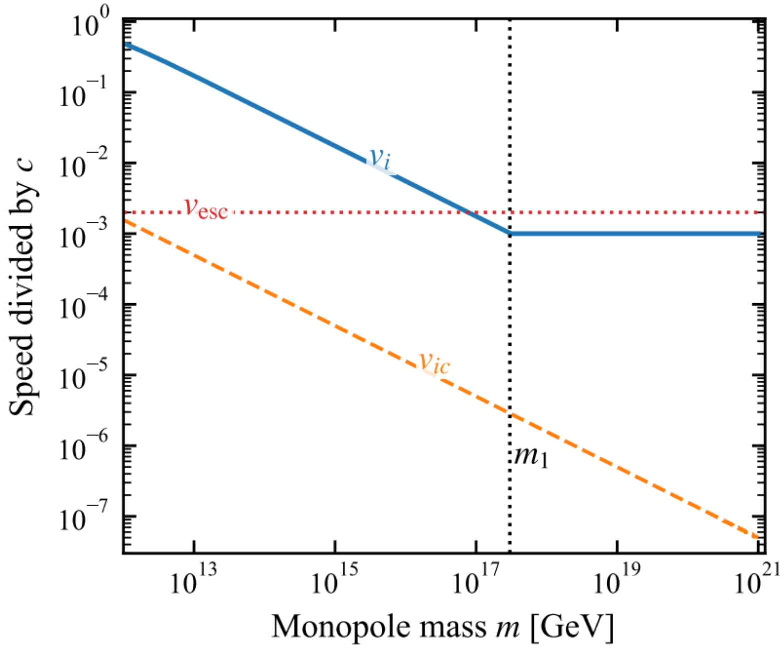
- Pre-acceleration of monopoles: $m(\gamma_i - 1) \simeq \max\{m(\gamma_{i0} - 1), (N_t/2)^{1/2} g b_0 l_{\rm eff}\}$
- Contribution to the seed field via residual average: $\tilde{B} \simeq \frac{1}{3}\frac{b_0}{N^{1/2}}\frac{L_{\rm int}}{\Delta r}$, $N = \frac{3 h_0 r_s \Delta r}{L_{\rm int}^3}$



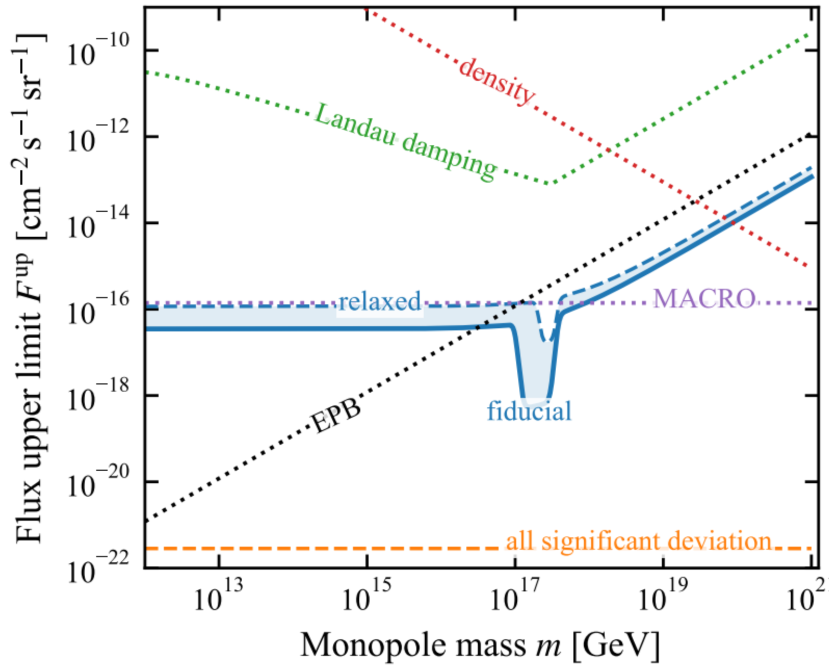
C. Zhang, C.-Y. Jiang, N. Jia and X. Zhang, 2605.21281

Self-consistent Parker bound: results

Monopole pre-acceleration



Self-consistent Parker bound



$$\tau_B = 0.5\,\mathrm{Gyr}, b_0 = 5\mu\mathrm{G}, h_0 = 500\,\mathrm{pc}, L_u = 100\,\mathrm{pc},$$
$$r_0 = 9\,\mathrm{kpc}, \kappa = 1/3, r_s = 6\,\mathrm{kpc}, v_{i0} = 10^{-3}, g = g_D,$$

$$F_{\rm s}^{\rm up} = \frac{1}{12\pi^2}\frac{3h_0}{\Delta r + 2h_0} g^{-1}\left[\frac{4m(\gamma_{i0}-1)}{g\Delta r} + 2\sqrt{3}\left(\frac{\kappa L_u}{h_0}\right)^{1/2} b_0 + \tilde{B}\right]\tau_{\rm B}^{-1}$$

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Self-consistent Parker bound: robustness to PMFs

Primordial magnetic fields (PMFs)

- Inflationary magnetogenesis: nearly scale-invariant spectrum $P_B(k) \propto k^{n_B}$, $n_B = -3 + \epsilon$ with a small positive ϵ.
- Causal PMFs (from phase transitions): typical Batchelor's spectrum $P_B(k) \propto k^2$.

Impact of PMFs on the self-consistent Parker bound

- Impact of PMF pre-acceleration is negligible

  D. Perri et al., Physics of the Dark Universe 46 (2024) 101704

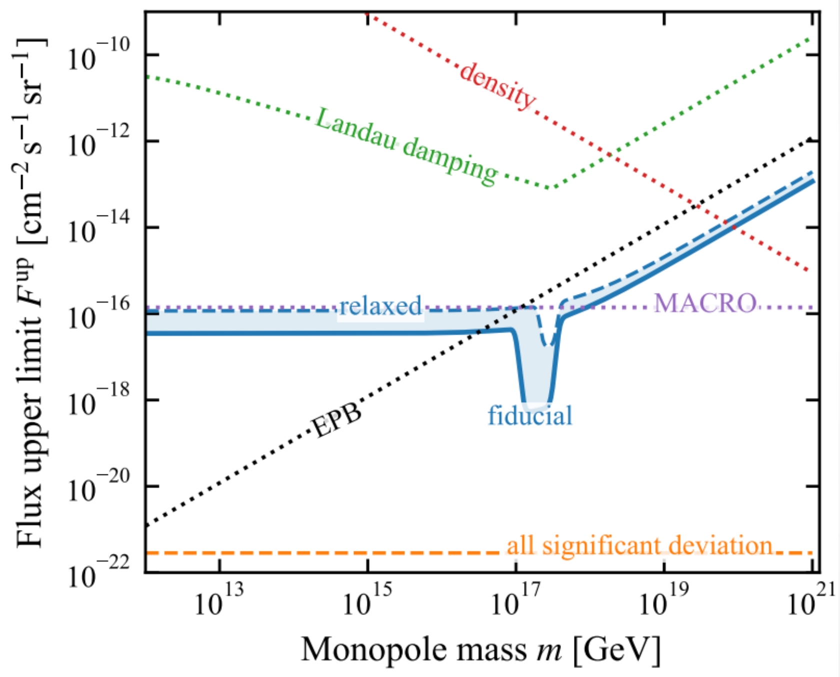
- Impact of PMF on large-scale seed-field amplitude: robustness of the self-consistent Parker bound can be maintained as long as $\tilde{B}_\star \lesssim 2\sqrt{3}\left(\frac{\kappa L_u}{h_0}\right)^{1/2} b_0 \approx 4.47\ \mu\mathrm{G}$. For a nearly-scale invariant spectrum, this translates into ($\chi < 1$ is a projection factor)

$$B_{1\mathrm{Mpc}} < \frac{4.47\times 10^{-6}\,\mathrm{G}}{\chi C_{\mathrm{coll}}}\left(\frac{\lambda_P}{1\,\mathrm{Mpc}}\right)^{\epsilon/2}, \quad C_{\mathrm{coll}} = \left(\frac{n_g}{\bar{n}_{b0}}\right)^{2/3}, \quad \lambda_P = \left(\frac{n_g}{\bar{n}_{b0}}\right)^{1/3}\Delta r.$$

⇨ $\mathcal{O}(0.1\ \mathrm{nG})$ PMF (covoming strength) testable by cosmological probes (Lyα, 21-cm, CMB)

Summary & Outlook

- We present a well-defined and self-consistent formulation of the Parker bound within modern theories of galactic magnetism. Key points:
  - Seed-field eigenmode
  - Dual role of small-scale turbulent fields
  - Flux conversion
  - Robustness to primordial magnetic fields



- Some recent novel proposals of magnetic monopole search:
  - SCEP: PRD 111 (2025) 023020 (USTC group)
  - MANDATE: PRD 111 (2025) 102004 (O. Gould, I. Ostrovskiy, A. Upreti)
  - TRIDENT: https://indico-tdli.sjtu.edu.cn/event/2312/contributions/12590/ (H. Mei)

Thank you for attention