Self-Consistent Parker Bound on Magnetic Monopoles

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@ Next Frontiers in Magnetic Monopole Searches

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Key messages of this talk

1. For magnetic monopoles in the intermediate mass range (10^{12} GeV $\lesssim m \lesssim 10^{18}$ GeV), the conventional extended Parker bound is significantly affected (mostly relaxed) by orders of magnitude, once the unavoidable pre-acceleration by small-scale turbulent magnetic fields are taken into account.

   Note 1: This intermediate mass range (10^{12} GeV $\lesssim m \lesssim 10^{18}$ GeV) is very well motivated from a particle physics point of view (e.g. Pati-Salam model).

   Note 2: lighter monopoles ($m \lesssim 10^{12}$ GeV) are expected to be accelerated to relativistic velocities. They are not considered in this talk.

2. Absent substantial improvement in the astrophysical treatment, future large-area nuclear track detector searches, such as MANDATE could therefore set the most stringent flux limits in this region of parameter space.

Astrophysical constraints on monopole abundance (I)

1. **The Parker bound**:

- Spirits: neutralization bound; whole galaxy as a detector.
- Based on energy extraction from the **Galactic magnetic fields (GMF)** due to monopole acceleration
- The observation of a large-scale GMF constrain the monopole flux.

Slight deviation: $F \lesssim \frac{1}{6\pi^2}\frac{m(\gamma_i - 1)}{g^2 l_c}\tau_{\rm gen}^{-1}$

Significant deviation: $F \lesssim \frac{\sqrt{2}}{24\pi^2}|g|^{-1}\left(\frac{R}{l_c}\right)^{1/2} B\tau_{\rm gen}^{-1}$

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

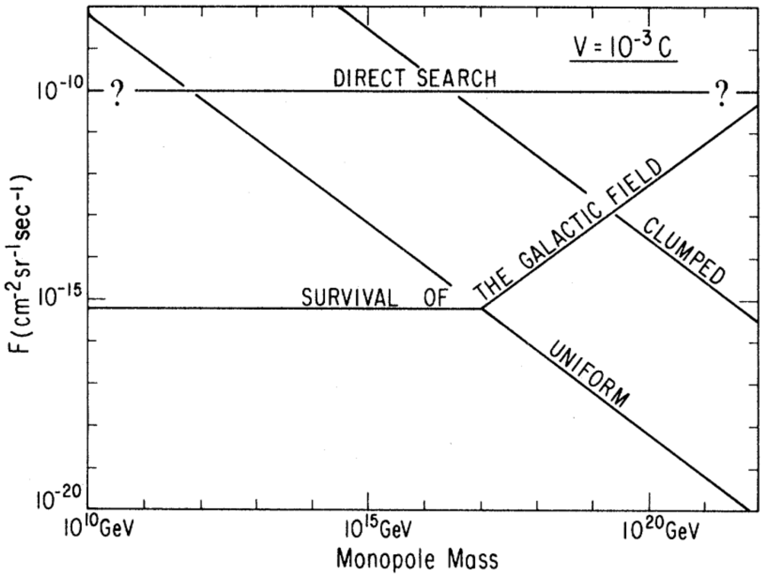
m: monopole mass

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)

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



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

Astrophysical constraints on monopole abundance (II)

2. The extended Parker bound: A simple model for the magnetic field strength

$$\frac{dB}{dt} = \gamma B - \alpha B^2 - \frac{Fg}{1+\mu/B}, \qquad \mu \equiv \frac{m_{17} v^2}{lg}$$

(All quantities are dimensionless by appropriate rescaling.) Analytic analysis of the equation gives the following (approximate) survival condition for B: $F < (\mu + B_0)\gamma$, with B_0 being the seed field strength. **This is the same as the original Parker bound derived using seed field parameters.**

Parameter choices:

magnetic charge: unit Dirac charge

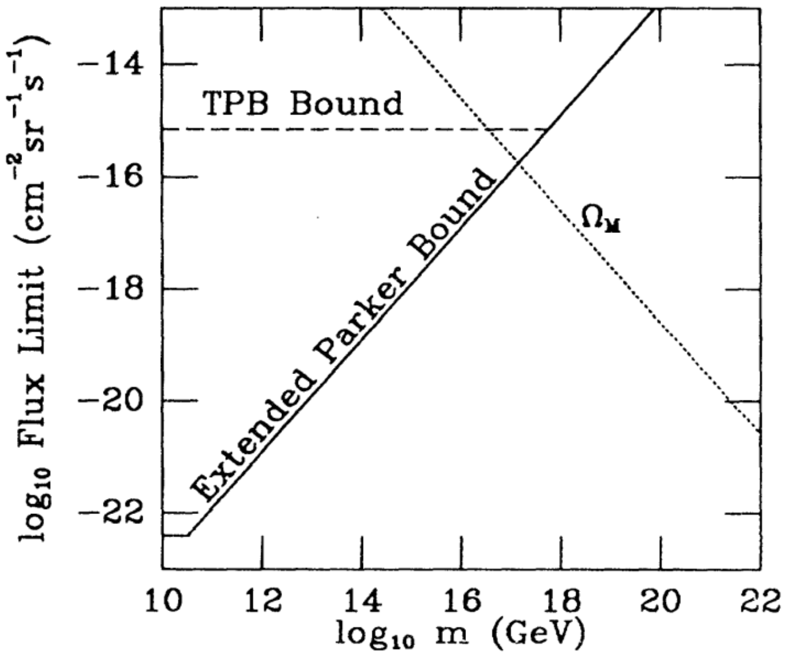
monopole incident velocity: $10^{-3} c$

coherence length of GMF: 1 kpc

seed field strength: 10^{-12} G

regeneration time of GMF: 10^{8} yr

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



Issues with the conventional Parker bound

1. Issues with two key parameters:

   Coherence length: dynamo eigenmode localization vs. front propagation (interaction among multiple eigenmodes)

   Regeneration time: inverse growth rate of a certain dynamo eigenmode vs. the ordering timescale of the GMF as a whole

2. Issues with the initial conditions:

   Monopole initial velocity: usually fixed as $10^{-3}c$, which ignores acceleration by pre-existing magnetic fields (such as turbulent magnetic fields).

   Seed field strength: fixed as 10^{-12} G, which is somewhat hand-waving.

3. Issues with flux conversion (for the extended Parker bound)

   Monopole flux: $F = \frac{nv}{4\pi}$ may change between the seed-field stage and the current epoch.

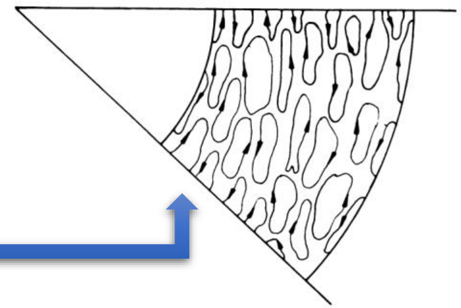
D. Moss, A. Shukurov, D. Sokoloff, Geophys. Astrophys. Fluid Dyn. 89, 285 (1998)

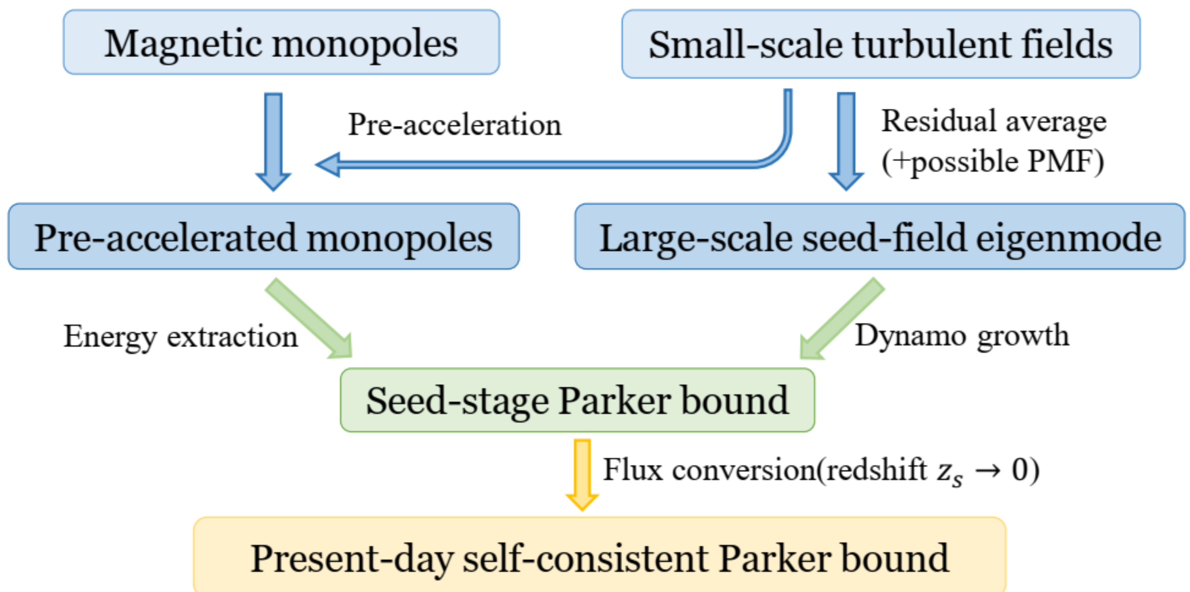
T. Arsharkian, R. Beck, M. Krause, D. Sokoloff, A&A 494, 21–32 (2009)

T. Arsharkian, R. Stepanov, R. Beck, M. Krause, D. Sokoloff, Astron. Nachr. 332, No. 5, 524 – 536 (2011)

The Parker bound: self-consistent formulation

- **The Parker bound:** self-consistent formulation
  - ① **Magnetic reservoir:** the lowest eigenmode of the galactic mean-field dynamo at the seed stage, with well-defined regeneration time and localization width.
  - ② **Dual role of small-scale turbulent magnetic fields:**
    - Pre-acceleration of monopoles
    - Contribution to the seed field via residual average





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

Parameters for the computation

- Parameters of magnetic monopoles:

  Monopole initial velocity before pre-acceleration: $v_{i0} = 10^{-3}c$

  Magnetic charge: $g = g_{\mathrm{D}} \approx 69e$

- Parameters related to the galactic disc (Milky Way):

  Half-thickness of the galactic disc: $h_0 = 500$ pc

  Magnetized radius of the galactic disc: $r_0 = 9$ kpc

- Parameters related to the lowest eigenmode of the mean-field dynamo:

  Field regeneration time of the lowest dynamo eigenmode: $\tau_B = 0.5$ Gyr, inferred from simulation study of L. F. S. Rodrigues et al., MNRAS 483, 2424–2440 (2019)

  Localization radius of the lowest dynamo eigenmode: $r_s = 6$ kpc, as a working benchmark

- Parameters related to small-scale turbulent magnetic fields:

  Turbulent magnetic field strength: $b_0 = 5\ \mu$G

  Velocity integral scale/outer scale of turbulence: $L_u = 100$ pc

  Magnetic integral scale $L_{\mathrm{int}} = \kappa L_{\mathrm{u}}, \kappa = 1/3$ from simulation studies of P. Bhat et al., MNRAS 429, 2469–2481 (2013), see also A. Shukurov and K. Subramanian, *Astrophysical Magnetic Fields*, CUP 2022

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Derived parameters and formulas

- The lowest dynamo eigenmode

(Derived) localization width/coherence length: $\Delta r \sim \sqrt{r_0 h_0} \approx 2.1\ \text{kpc}$

Number of turbulent magnetic field cells contained in the localization region: $N_l = \frac{3h_0 r_s \Delta r}{L_{\text{int}}^3}$

Seed field strength estimate via residual average and solenoidality: $\tilde{B} \simeq \frac{1}{3}\frac{b_0}{N^{1/2}}\frac{L_{\text{int}}}{\Delta r} \simeq 3.6 \times 10^{-11}\ \text{G}$

- Monopole pre-acceleration by turbulent magnetic fields:

Effective coherence length: $l_{\text{eff}} = \frac{3}{2} L_{\text{int}} = 50\ \text{pc}$

Kinetic energy gained by monopole: $m(\gamma_i - 1) \simeq \max\{m(\gamma_{i0} - 1), (N_t/2)^{1/2} g b_0 l_{\text{eff}}\},\ N_t = \frac{r_0}{l_{\text{eff}}}$

- Modified evolution equation:

Taking into account the geometrical factor Q related to the shape of the localization region of the lowest dynamo eigenmode, we have (F_s denotes the seed-stage flux) (Gaussian units)

$$\frac{\mathrm{d}B}{\mathrm{d}t} = \gamma B - \alpha B^2 - 12\pi^2 Q^{-1} \frac{F_s g}{1 + 2\mu/B}, \qquad \gamma = \tau_B^{-1}, \qquad Q = \frac{3h_0}{\Delta r + 2h_0}, \qquad \mu \equiv \frac{2m(\gamma_i - 1)}{g\Delta r}$$

The upper limit on F_s can be inferred via an analysis of the solution of the evolution equation, similar to the original EPB paper.

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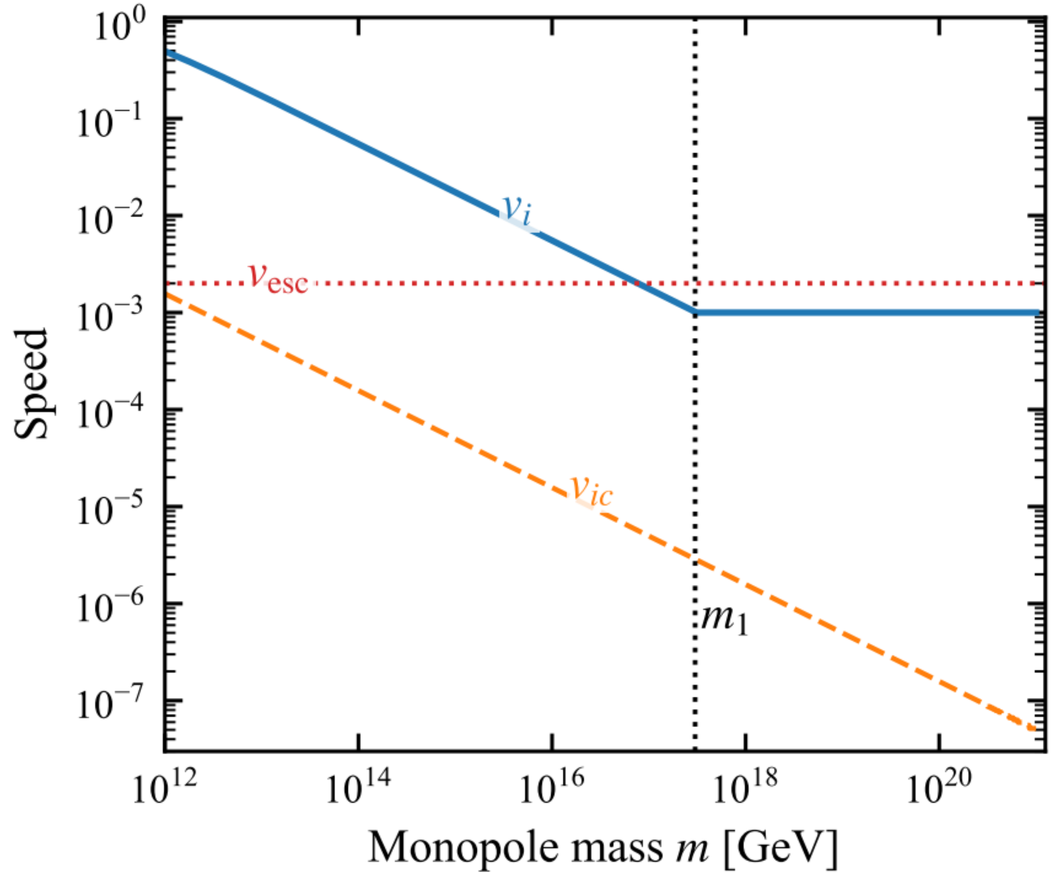
Monopole pre-acceleration by turbulent fields

- **Main message:** Turbulent pre-acceleration pushes MMs into the slight-deviation regime.
  - v_i: monopole velocity after turbulent pre-acceleration
  - v_{ic}: boundary dividing the slight and significant deviation regimes for the seed-field Parker bound



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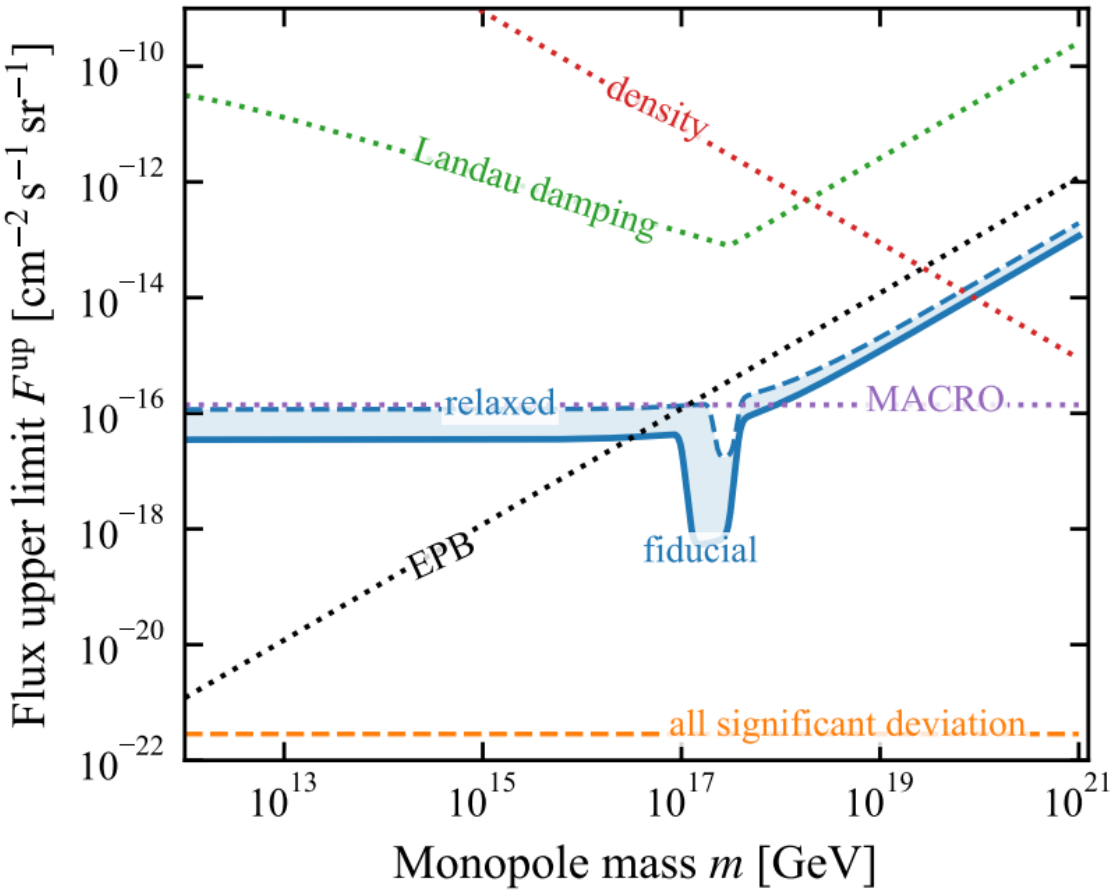
Self-consistent Parker bound: results



- Flux conversion

$$F^{\mathrm{up}} = \mathcal{C} F_s^{\mathrm{up}}$$

- Three cases
  - Case I: $v_L < v_{\mathrm{esc}}$
  - Case II: $v_i > v_{\mathrm{esc}}$
  - Case III: $v_i < v_{\mathrm{esc}} < v_L$
- Flux conversion factor in Case III:

$$\mathcal{C} \approx \frac{\Delta_{\mathrm{LG}}}{\Delta_{\mathrm{Galaxy}}} = \begin{cases} 10^{-1}, \text{conservative} \\ 10^{-2}, \text{reference} \\ 10^{-3}, \text{aggressive} \end{cases}$$

- Relaxed parameters: (blue dashed)

$\tau_B = 0.3$ Gyr, $b_0 = 10\ \mu$G, conservative $\mathcal{C}$

Contribution from pre-acceleration, numerically $\sim 4.5\ \mu$G

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

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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 $P_B(k) \propto k^2$.

Two ways that PMFs may affect the Parker bound

- PMF pre-acceleration: can be neglected due to backreaction effect

  D. Perri, K. Bonderenko, M. Doro and T. Kobayashi, Physics of the Dark Universe 46 (2024) 101704

- Impact of PMF on large-scale seed-field amplitude

  PMF generation and evolution (redshift)

  Protogalaxy stage (before collapse)

  Protogalaxy collapse (flux-freezing approximation)

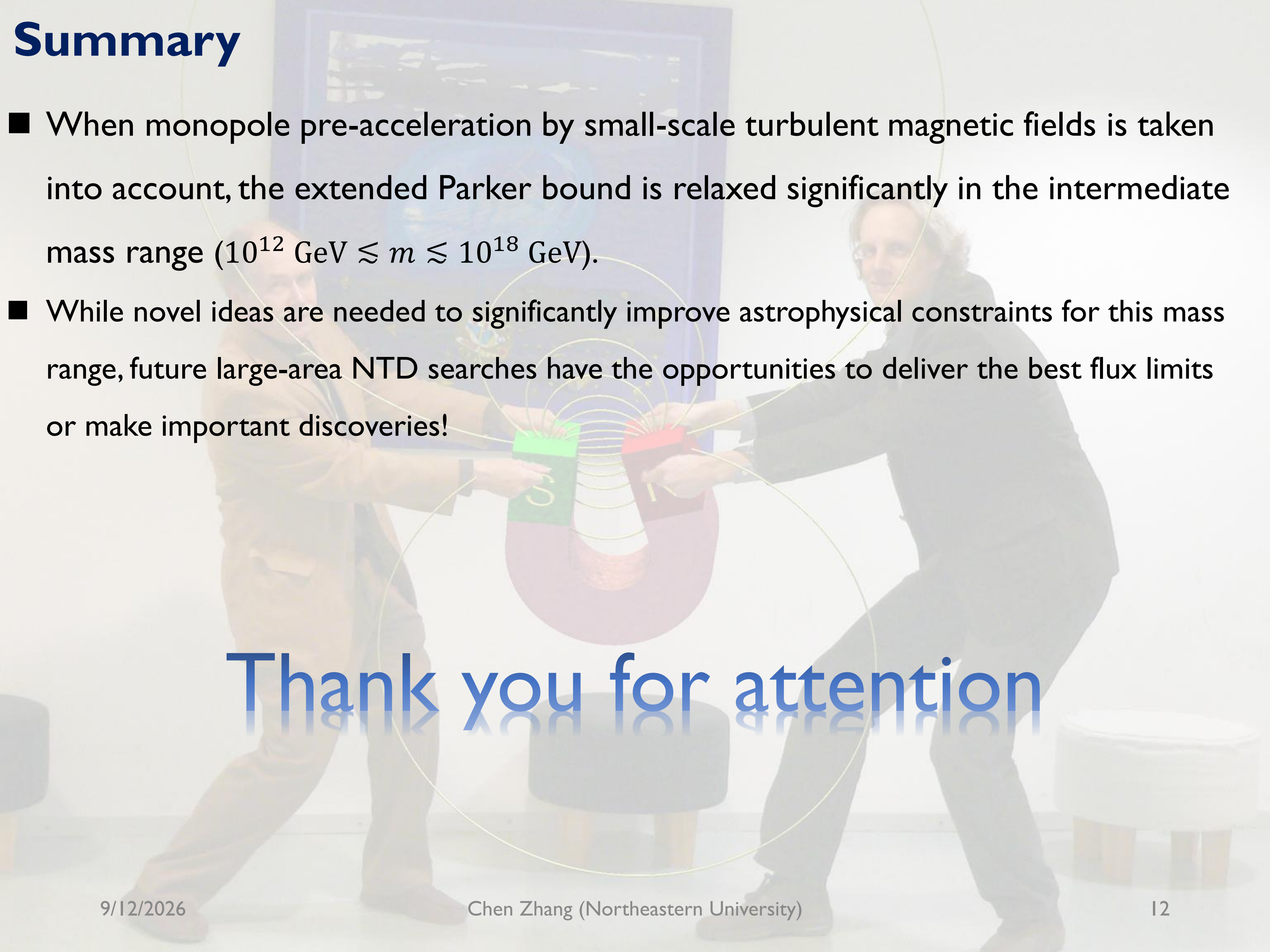
  Projection onto the lowest dynamo eigenmode

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

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

Summary

- When monopole pre-acceleration by small-scale turbulent magnetic fields is taken into account, the extended Parker bound is relaxed significantly in the intermediate mass range (10^{12} GeV $\lesssim m \lesssim 10^{18}$ GeV).
- While novel ideas are needed to significantly improve astrophysical constraints for this mass range, future large-area NTD searches have the opportunities to deliver the best flux limits or make important discoveries!



Thank you for attention