Monopoles and Cosmological Magnetic Fields

Takeshi Kobayashi

collaborators:
Michele Doro, Mariia Khelashvili, Andrew J. Long, Daniele Perri

Next Frontiers in Magnetic Monopole Searches, IHEP

WHY COSMIC $\boldsymbol{B}$?

- $\boldsymbol{B}$ fields are ubiquitously observed in our universe
- Monopoles arriving from outer space are unavoidably accelerated in the cosmic $\boldsymbol{B}$
- This talk focuses on large-scale & space-filling $\boldsymbol{B}$ ($\leftrightarrow$ magnetars)

※ I will consider monopoles with a single Dirac charge unless otherwise stated

OUTLINE

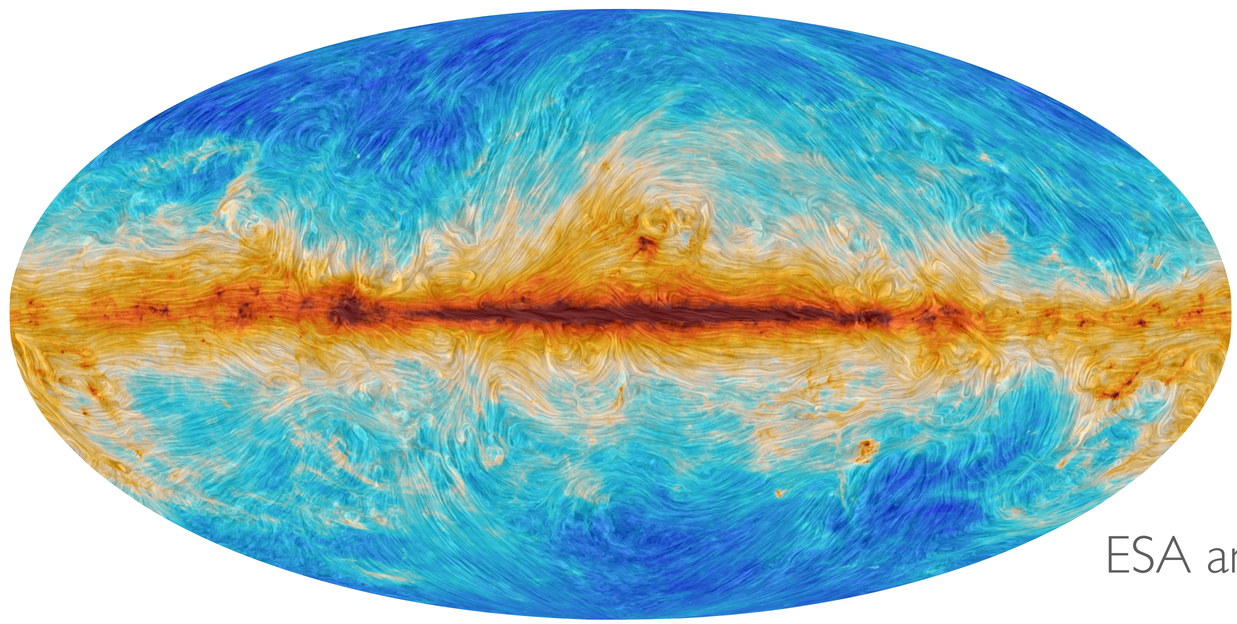
1. Acceleration in cosmic $\boldsymbol{B}$
2. Backreaction on cosmic $\boldsymbol{B}$
3. Pair production in cosmic $\boldsymbol{B}$

OUTLINE

1. Acceleration in cosmic $\boldsymbol{B}$
2. Backreaction on cosmic $\boldsymbol{B}$
3. Pair production in cosmic $\boldsymbol{B}$

GALACTIC (MILKY WAY) B

- The Milky Way hosts fields of $B \sim 10^{-6}\,\mathrm{G}$, $\lambda \sim 1\,\mathrm{kpc}$



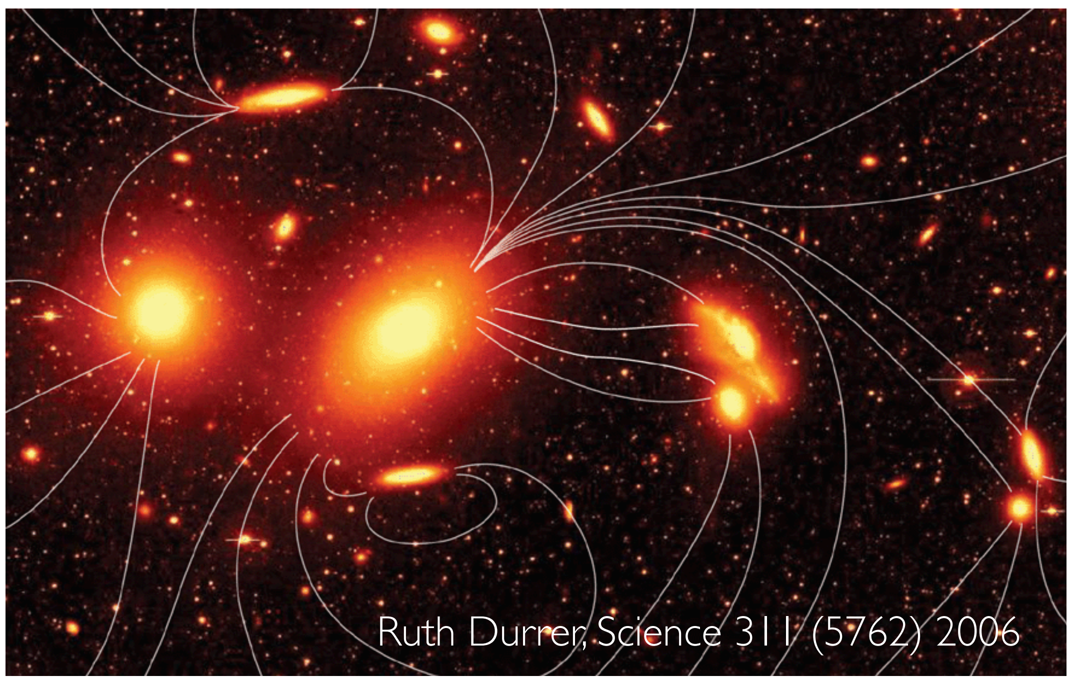
ESA and the Planck Collaboration

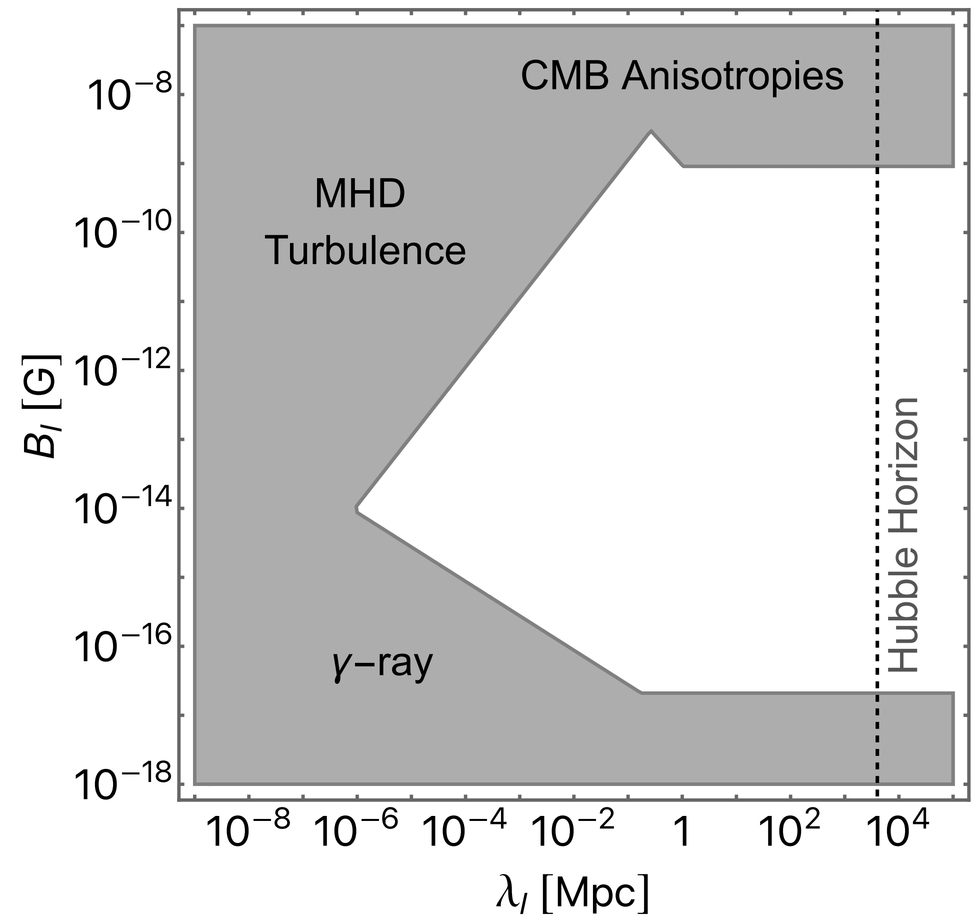
- Generally assumed to arise from a dynamo amplification of seed fields within $10^{-30}\,\mathrm{G} \lesssim B \lesssim 10^{-10}\,\mathrm{G}$

- Origin of seed fields could be purely astrophysical, but could also be primordial

INTERGALACTIC B

- Gamma-ray experiments in the past decade have suggested fields in intergalactic voids with $10^{-15}\,\mathrm{G} \lesssim B \lesssim 10^{-9}\,\mathrm{G}$ and large λ (e.g. Mpc)

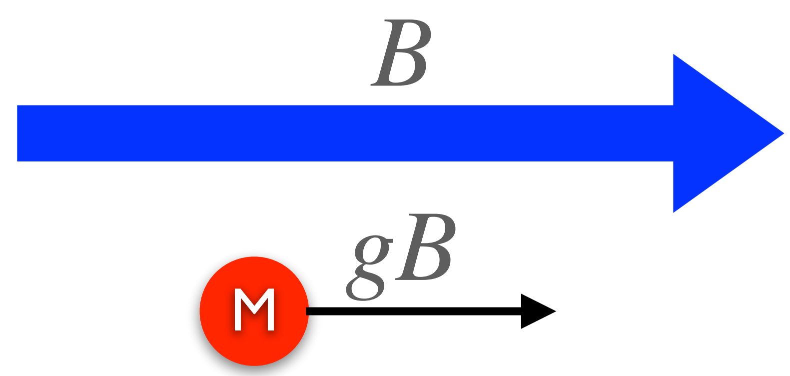




- Alternative interpretations (e.g. plasma beam instability) exist, but are becoming less plausible

- Very likely to be remnants of primordial B

MONOPOLE ACCELERATION



- Galactic B

$B \sim 10^{-6}\,\mathrm{G},\ \lambda \sim 1\,\mathrm{kpc} \ \rightarrow \ gB\lambda \sim 10^{11}\,\mathrm{GeV}$

- Intergalactic B

e.g. $B \sim 10^{-15}\,\mathrm{G},\ \lambda \sim 1\,\mathrm{Mpc} \ \rightarrow \ gB\lambda \sim 10^{5}\,\mathrm{GeV}$

e.g. $B \sim 10^{-9}\,\mathrm{G},\ \lambda \sim 1/H \ \rightarrow \ gB\lambda \sim 10^{14}\,\mathrm{GeV}$

- cf. Earth B

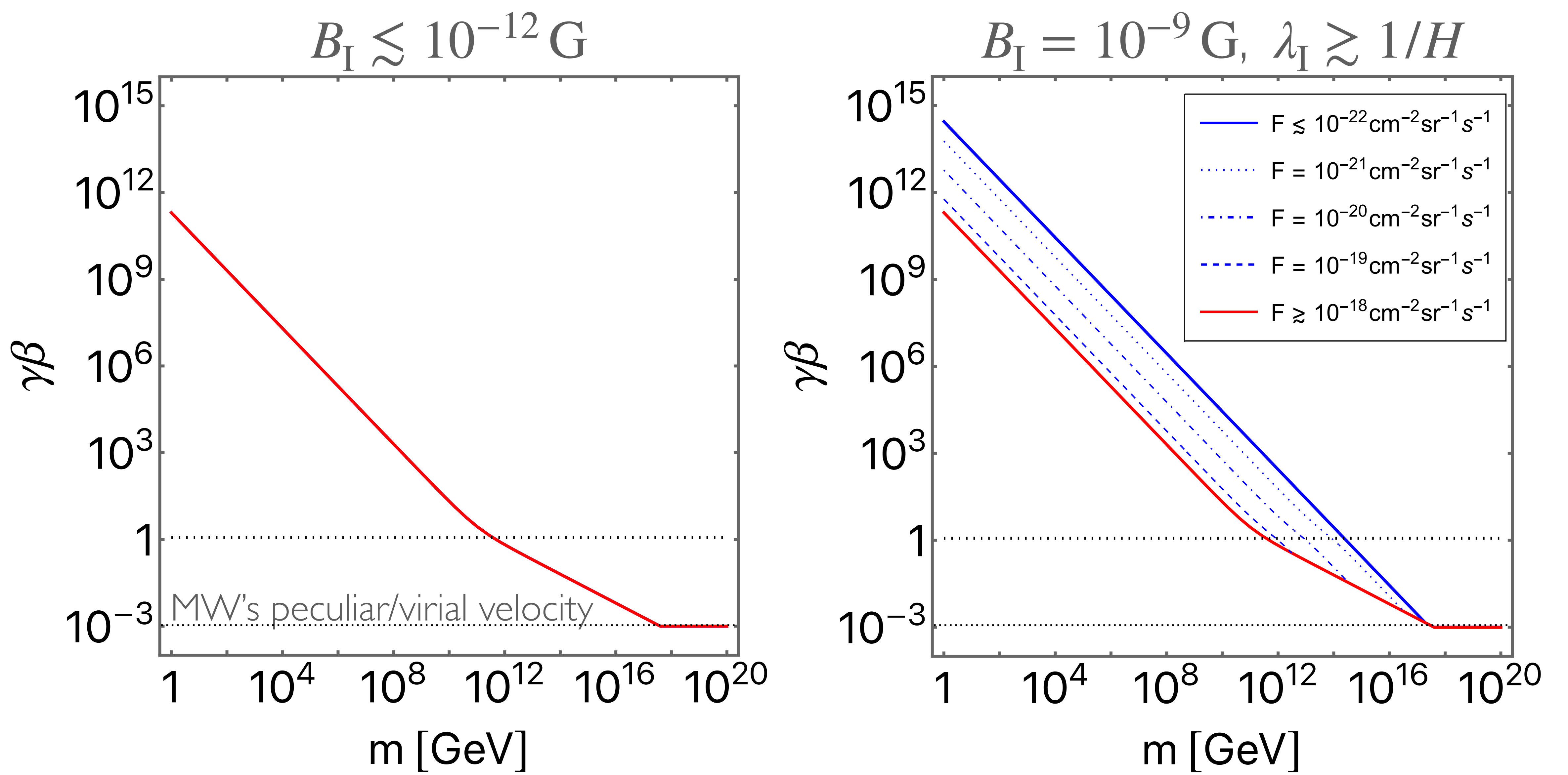
$B \sim 1\,\mathrm{G},\ \lambda \sim 10^{4}\,\mathrm{km} \ \rightarrow \ gB\lambda \sim 10^{4}\,\mathrm{GeV}$

GALACTIC OR EXTRAGALACTIC MONOPOLES

- Monopoles can stay clustered with the Milky Way until today only if $m \gtrsim 10^{18}\,\mathrm{GeV}$

- Lighter monopoles come from outside the Milky Way, and hence are accelerated by intergalactic and galactic $\boldsymbol{B}$ before arriving at Earth

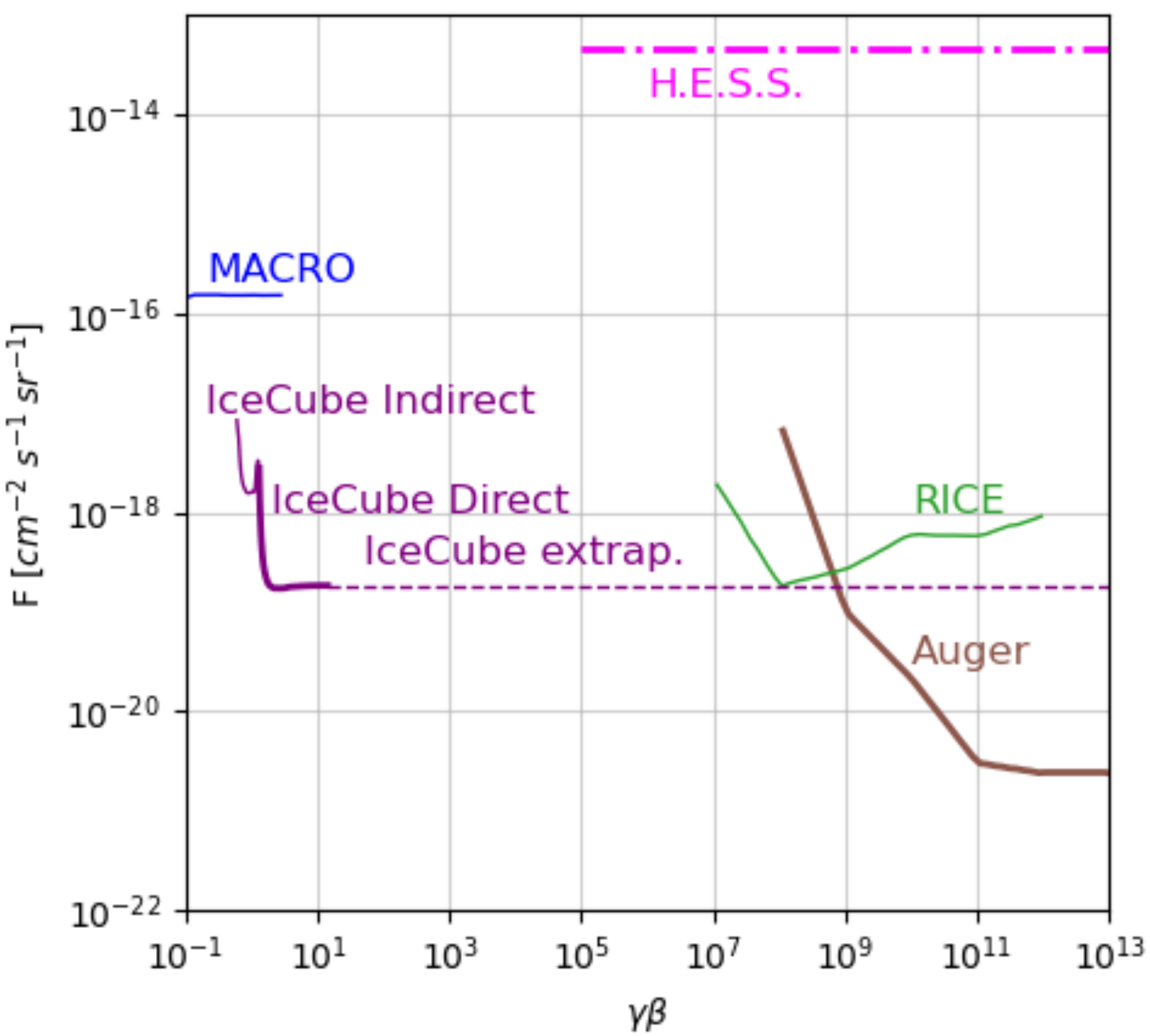
MONOPOLE VELOCITY AT EARTH



- Monopoles with masses up to $10^{12} - 10^{14}$ GeV are accelerated to relativistic velocities
- Prescription for calculating monopole velocity given in Perri, Bondarenko, Doro, TK '24

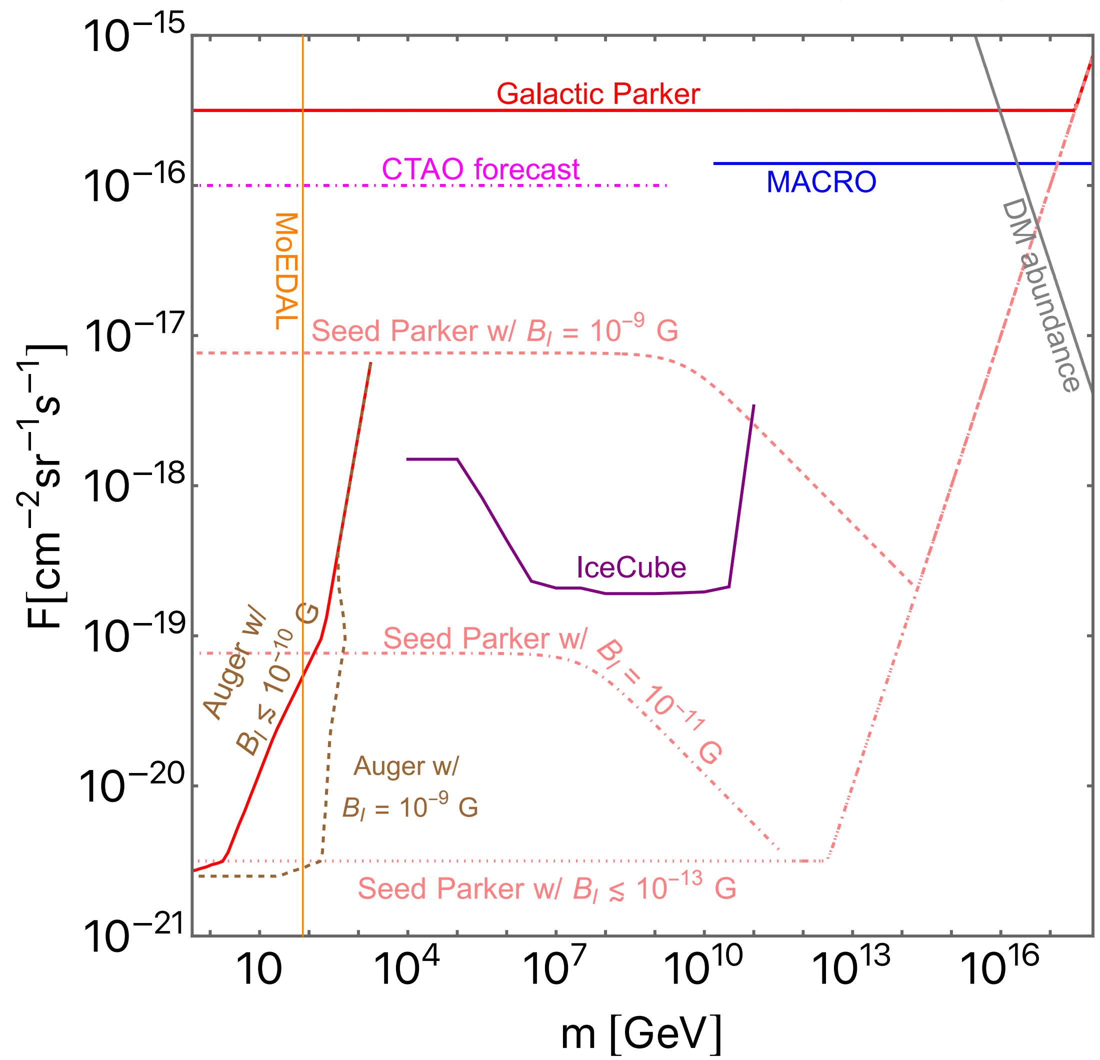
FLUX BOUNDS VS. MASS

We can now map experimental bounds in velocity space onto mass space (after also taking into account deceleration at Earth)



cf. talks this morning

Perri, Doro, TK '25



cf. talk by Toshihiro Fujii

MONOPOLE = AMATERASU ?

The Telescope Array recently detected an ultra-high-energy particle with $E_k \approx 2 \times 10^{11}\,\mathrm{GeV}$ from the direction of the Local Void

Telescope Array Collaboration, Science 382, 903–907 (2023)

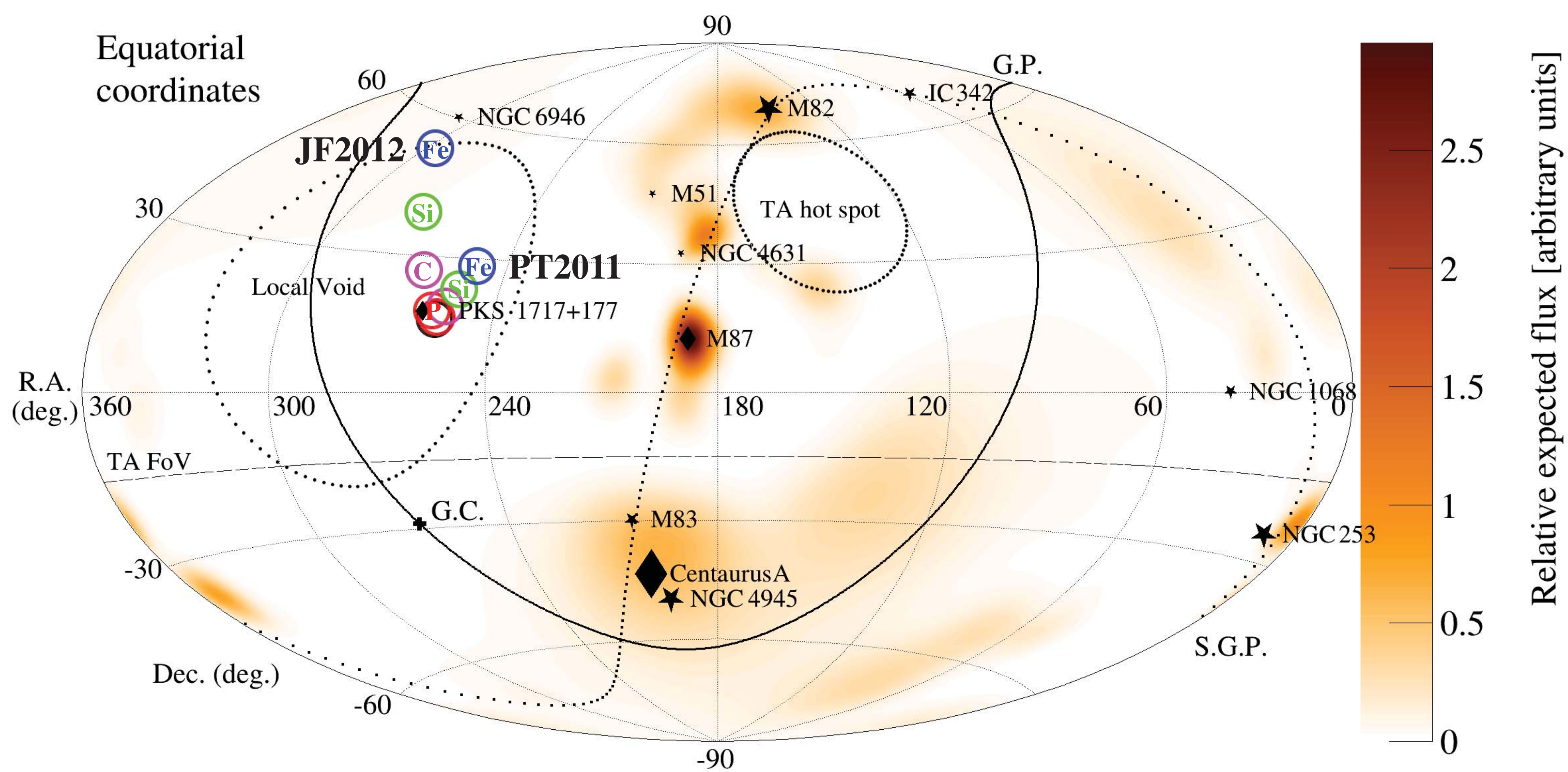


Fig. 2. Arrival direction of the high-energy event compared with potential sources. The arrival direction of the 27 May 2021 high-energy cosmic-ray particle (black circle) on a sky map in equatorial coordinates. Colored circles indicate calculated back-tracked directions assuming two models of the Milky Way regular magnetic field, labeled JF2012 (*31*) and PT2011 (*32*). For each model, different symbols indicate the directions calculated for four possible primary species: proton (P; red), carbon (C; purple), silicon (Si; green), and iron (Fe; blue). The color bar indicates the relative flux expected from the inhomogeneous source-density distribution in the local LSS, smeared with a random Milky Way magnetic field. For comparison, nearby gamma ray–emitting active galactic nuclei are shown with filled diamonds and nearby starburst galaxies galaxy PKS 1717+177. The dotted large circle centered around (R.A., Dec.) = (146.7°, 43.2°) indicates the previously reported TA hot spot (*21*). The dashed horizontal line indicates the limit of the TA field of view (FoV). The dotted circle centered around (R.A., Dec.) = (279.5°, 18.0°) is the location of the Local Void (*40*). The galactic plane

cf. talk by Toshihiro Fujii

MONOPOLE = AMATERASU ?

The Telescope Array recently detected an ultra-high-energy particle with $E_k \approx 2 \times 10^{11}\,\mathbf{GeV}$ from the direction of the Local Void

Consistent with a monopole accelerated in galactic $\boldsymbol{B}$.

If this interpretation is correct, improved limits on intergalactic $\boldsymbol{B}$ can be obtained.

7 (2023)

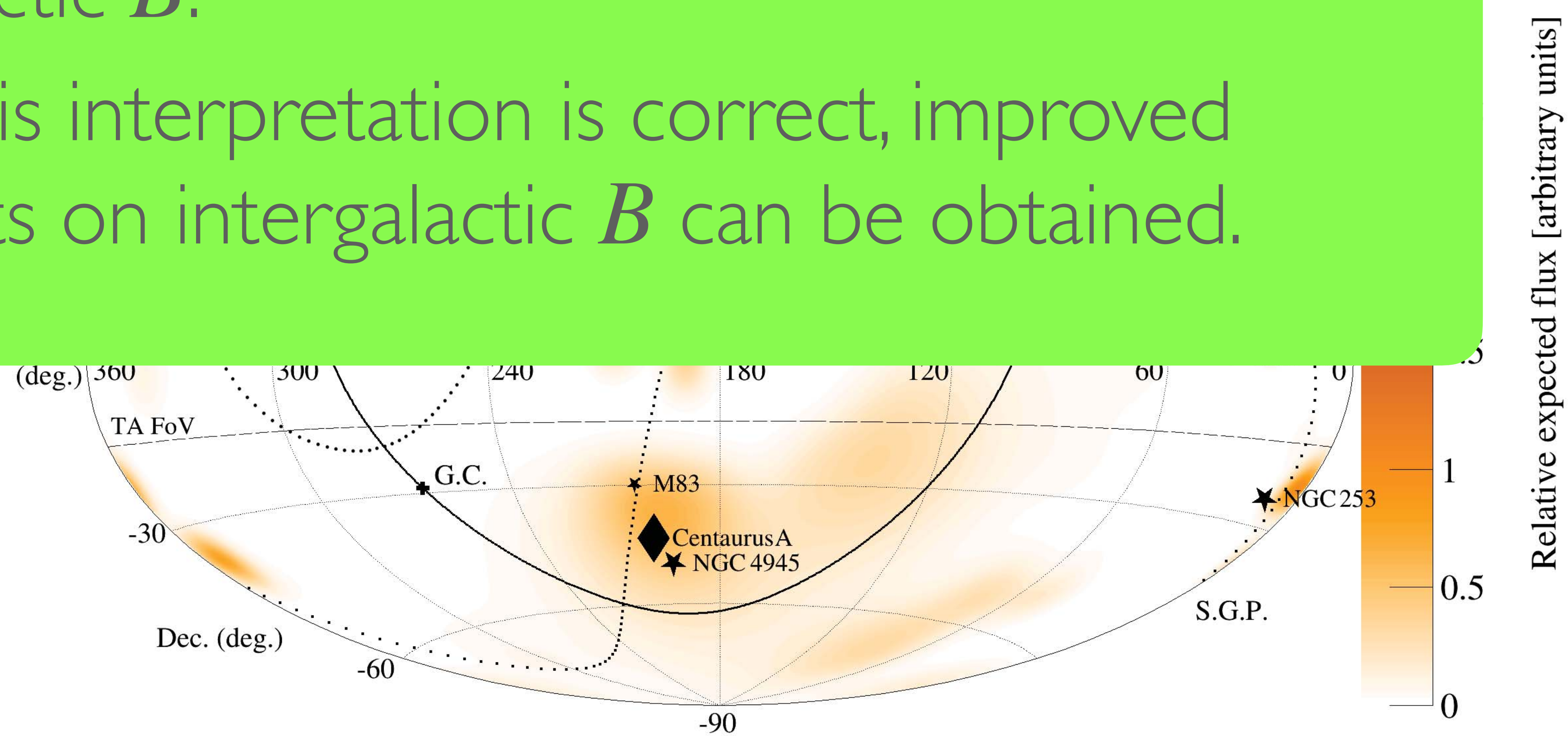
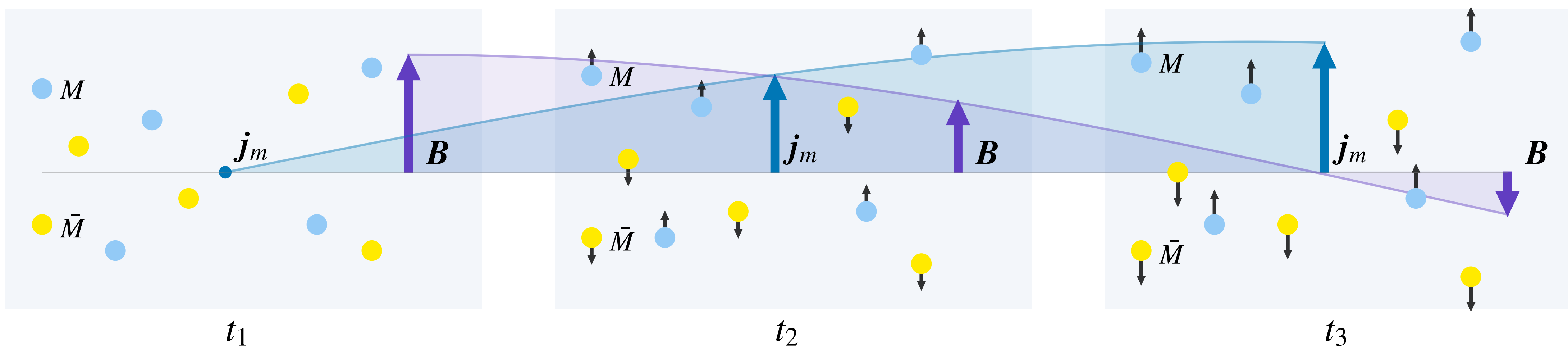


Fig. 2. ... **of the** ... **compa** ... **source** ... tion of ... high-er ... particle ... sky ma ... coordir ... indicate ... tracked directions assuming two models of the Milky Way regular magnetic field, labeled JF2012 (*31*) and PT2011 (*32*). For each model, different symbols indicate the directions calculated for four possible primary species: proton (P; red), carbon (C; purple), silicon (Si; green), and iron (Fe; blue). The color bar indicates the relative flux expected from the inhomogeneous source-density distribution in the local LSS, smeared with a random Milky Way magnetic field. For comparison, nearby gamma ray–emitting active galactic nuclei are shown with filled diamonds and nearby starburst galaxies ... galaxy PKS 1717+177. The dotted large circle centered around (R.A., Dec.) = (146.7°, 43.2°) indicates the previously reported TA hot spot (*21*). The dashed horizontal line indicates the limit of the TA field of view (FoV). The dotted circle centered around (R.A., Dec.) = (279.5°, 18.0°) is the location of the Local Void (*40*). The galactic plane ...

OUTLINE

1. Acceleration in cosmic $\boldsymbol{B}$
2. Backreaction on cosmic $\boldsymbol{B}$
3. Pair production in cosmic $\boldsymbol{B}$

BACKREACTION ON COSMIC $\boldsymbol{B}$



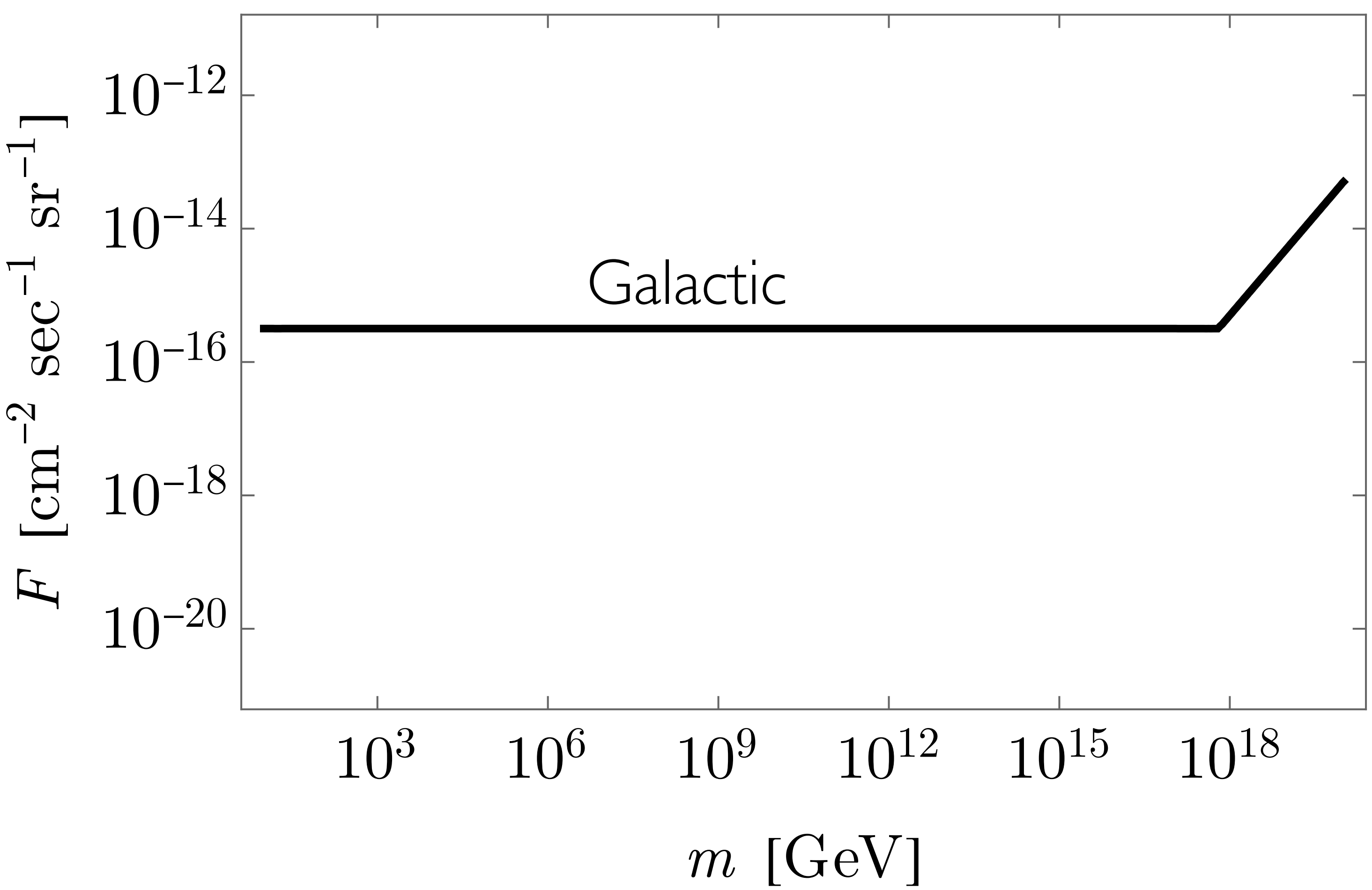
- Monopoles drain energy from cosmic $\boldsymbol{B}$ and induce plasma oscillations

- Oscillations with galactic $\boldsymbol{B}$ quickly decay (due to escaping monopoles or Landau damping), resulting in $\boldsymbol{B}$ dissipation

- Survival of galactic $\boldsymbol{B}$ sets upper limit on monopole flux
  → Parker bound

PARKER BOUND

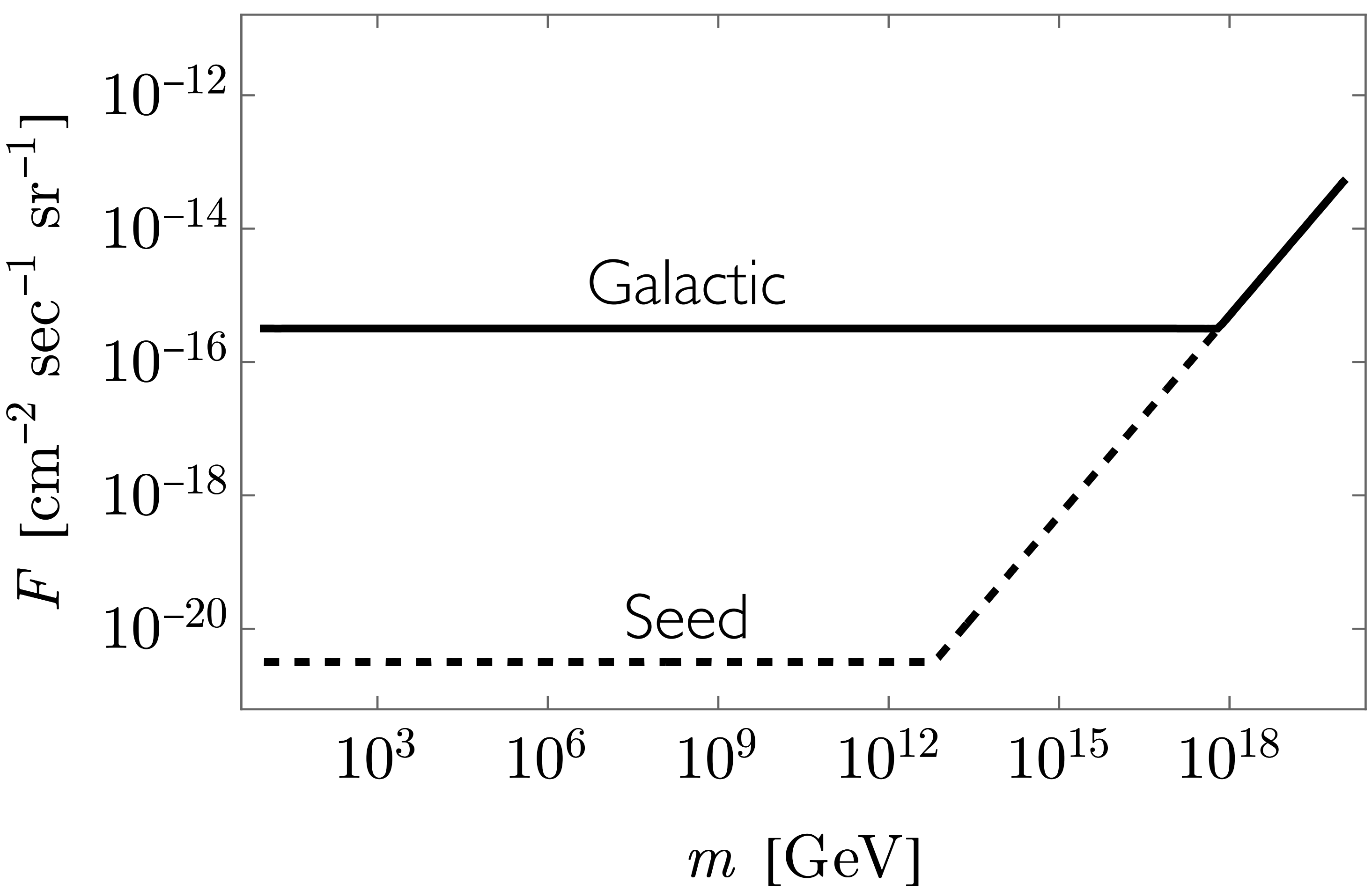
Parker '70 Turner, Parker, Bogdan '82



$$B_{\text{gal}} = 10^{-6}\,\text{G}$$

PARKER BOUND

Parker '70 Turner, Parker, Bogdan '82



$B_{\mathrm{gal}} = 10^{-6}\,\mathrm{G}$

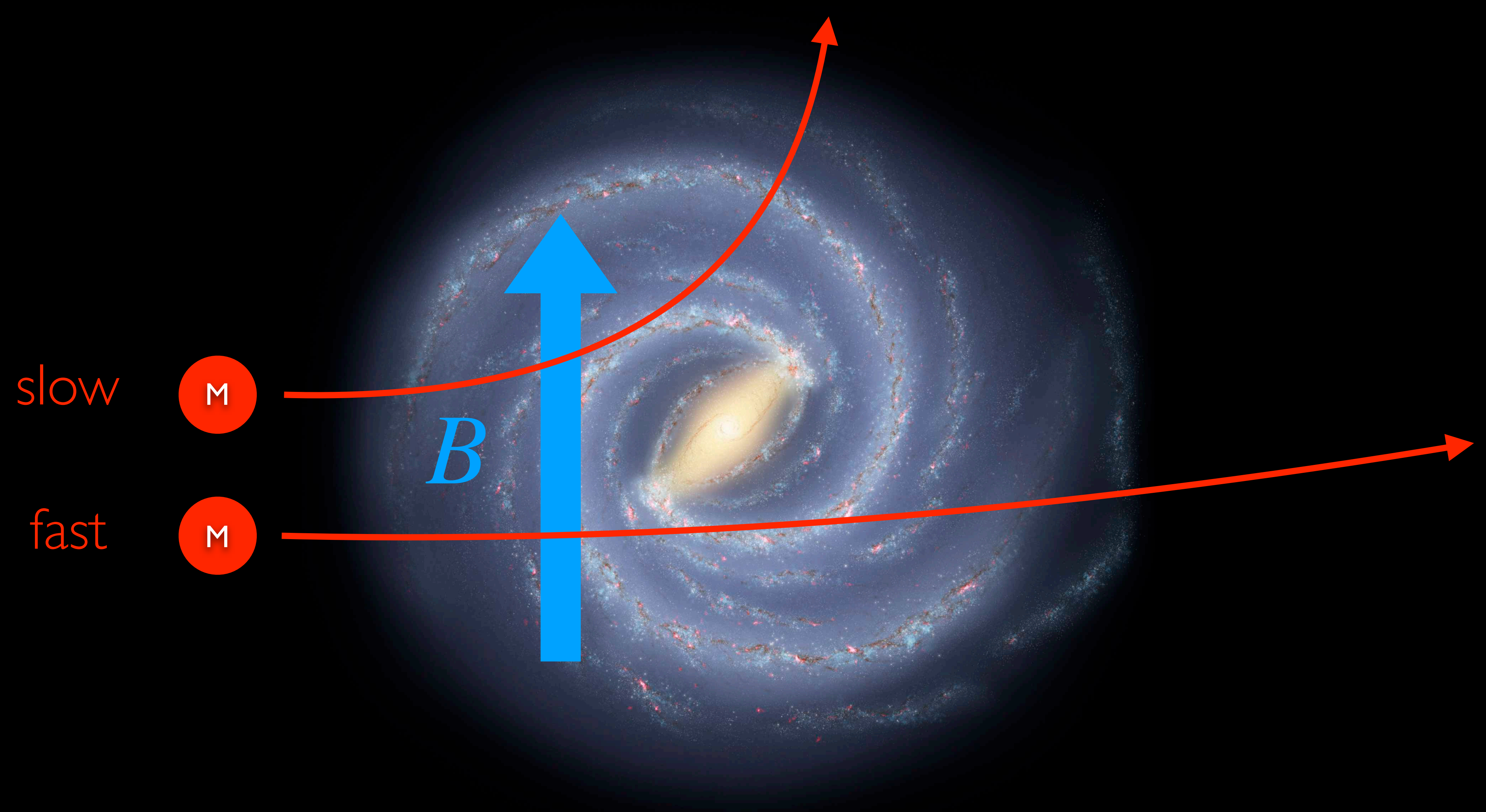
$B_{\mathrm{seed}} = 10^{-11}\,\mathrm{G}$

Further improvement by considering initial seed B

$(10^{-30}\,\mathrm{G} \lesssim B_{\mathrm{seed}} \lesssim 10^{-10}\,\mathrm{G})$ Adams et al.'93

PARKER BOUND: HOW SOLID?

Parker bounds are sensitive to the monopoles' incident velocity

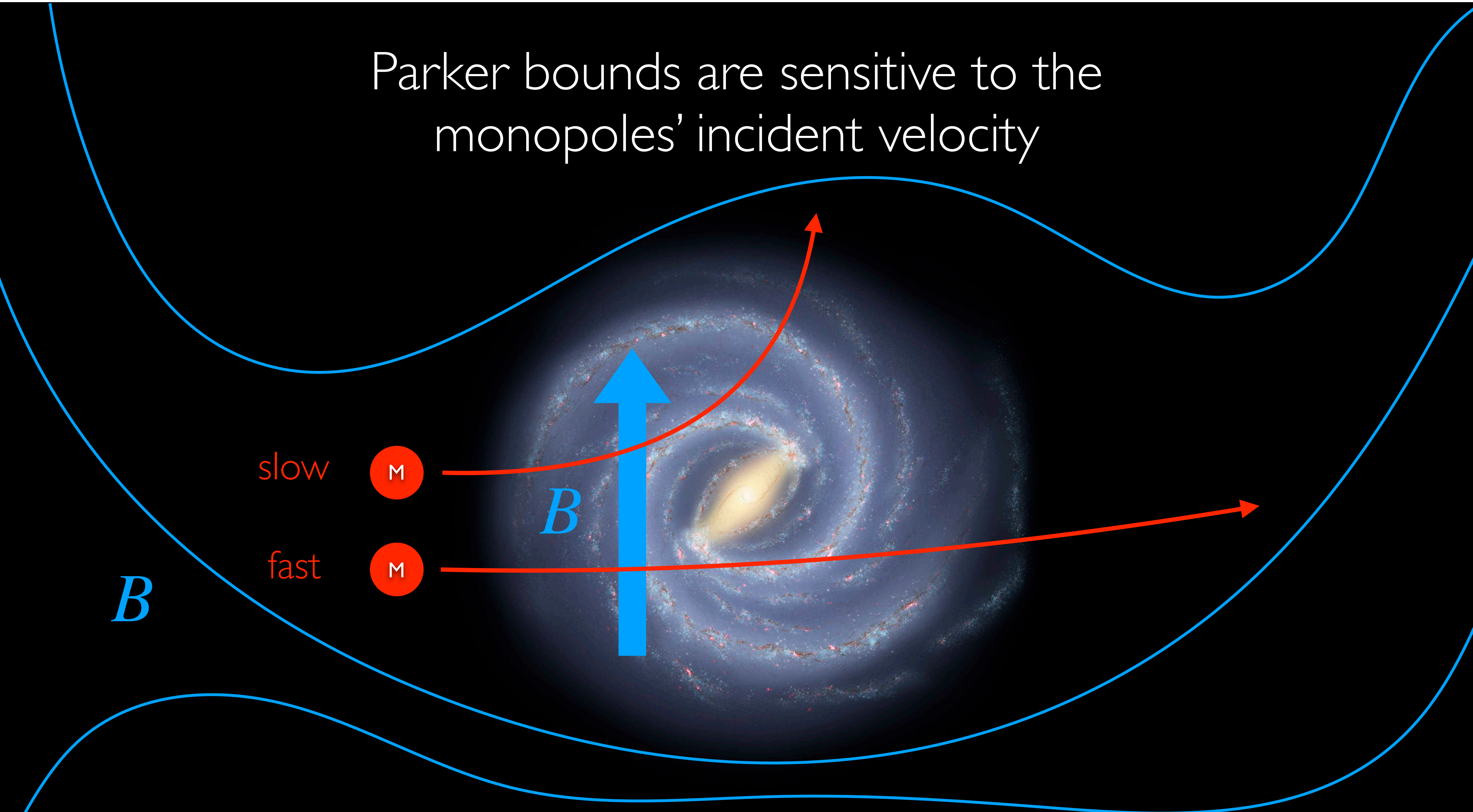


usual assumption: $v \sim 10^{-3} \sim$ (MW's peculiar velocity)

MW image: NASA/JPL-Caltech/R.Hurt

PARKER BOUND: HOW SOLID?

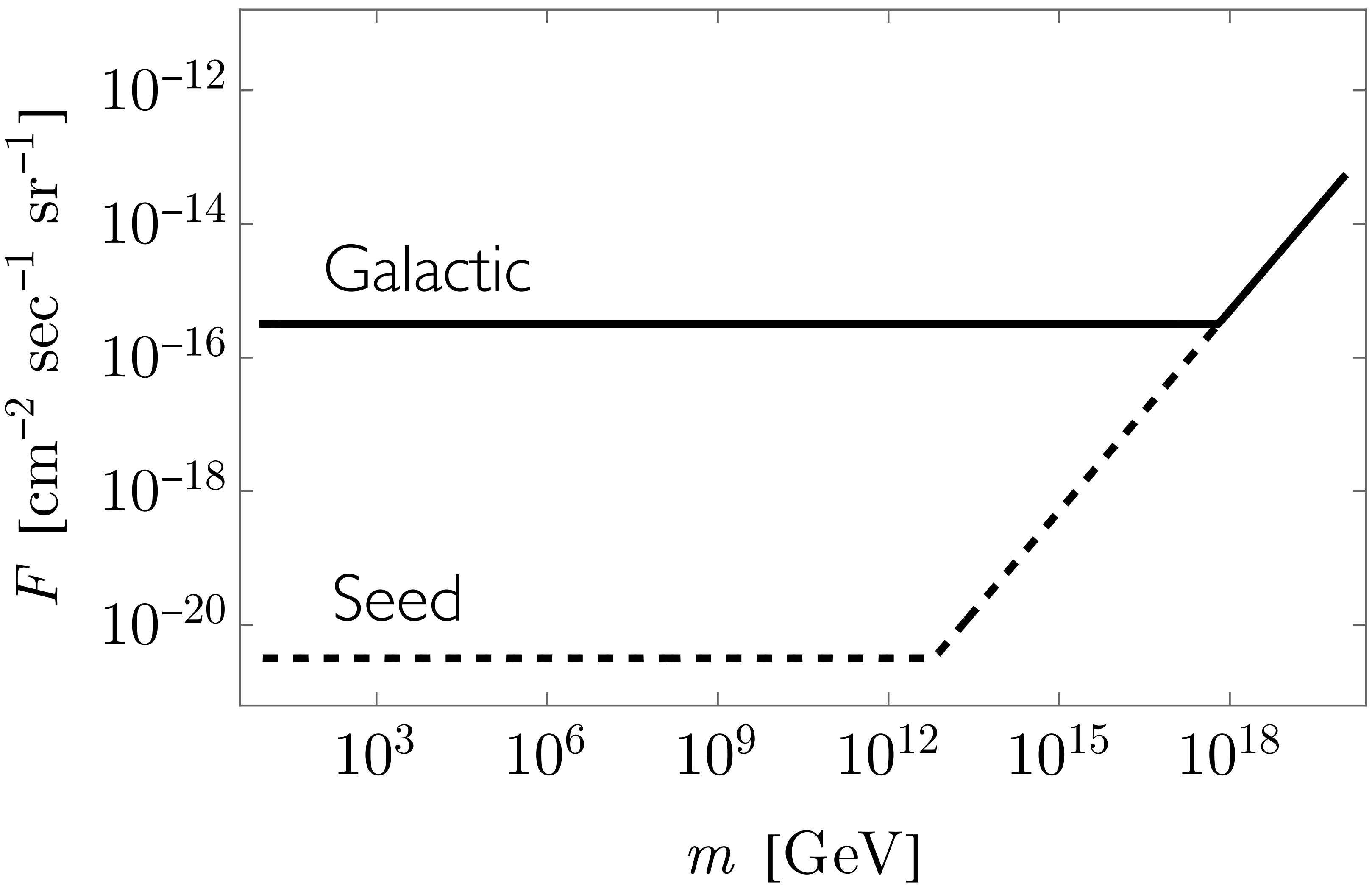
Parker bounds are sensitive to the monopoles' incident velocity



usual assumption: $v \sim 10^{-3}$ ~ (MW's peculiar velocity)

MW image: NASA/JPL-Caltech/R.Hurt

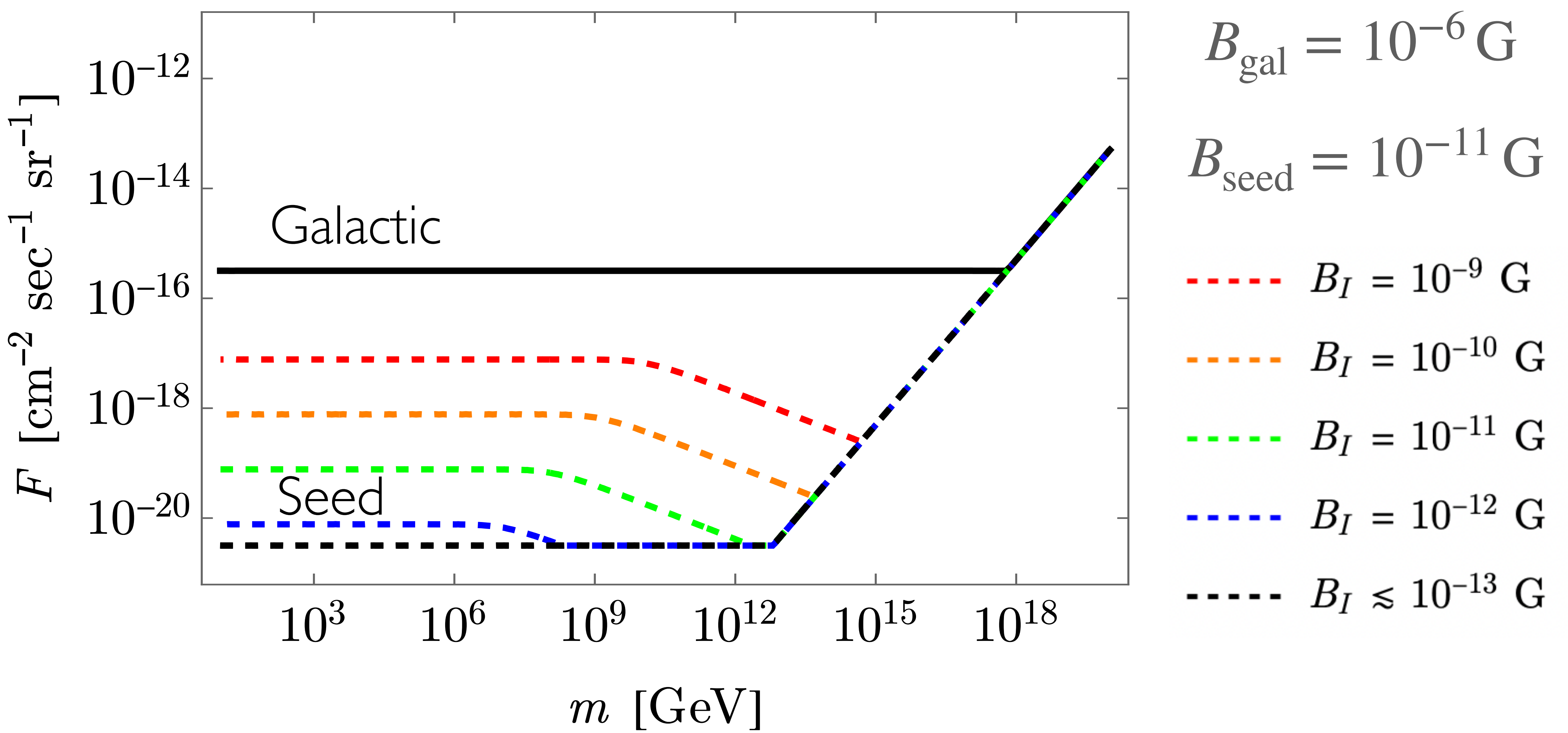
PARKER BOUND: HOW SOLID?



$B_{\rm gal} = 10^{-6}\,\rm G$

$B_{\rm seed} = 10^{-11}\,\rm G$

PARKER BOUND: HOW SOLID?

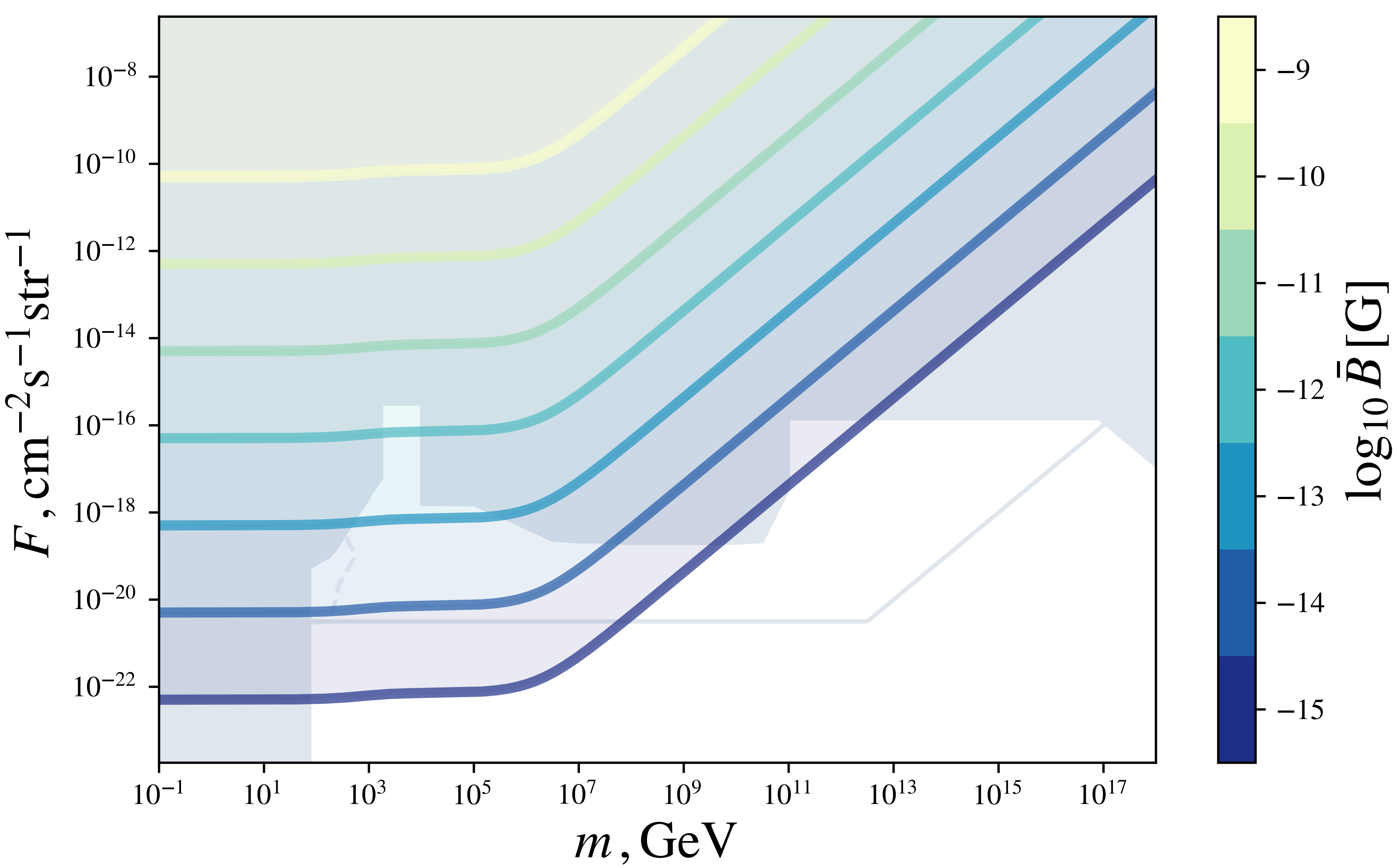


Intergalactic $\boldsymbol{B}$ weakens seed Parker bound

NEW BOUNDS FROM OSCILLATING INTERGALACTIC $\boldsymbol{B}$

Khelashvili, TK, Long '26

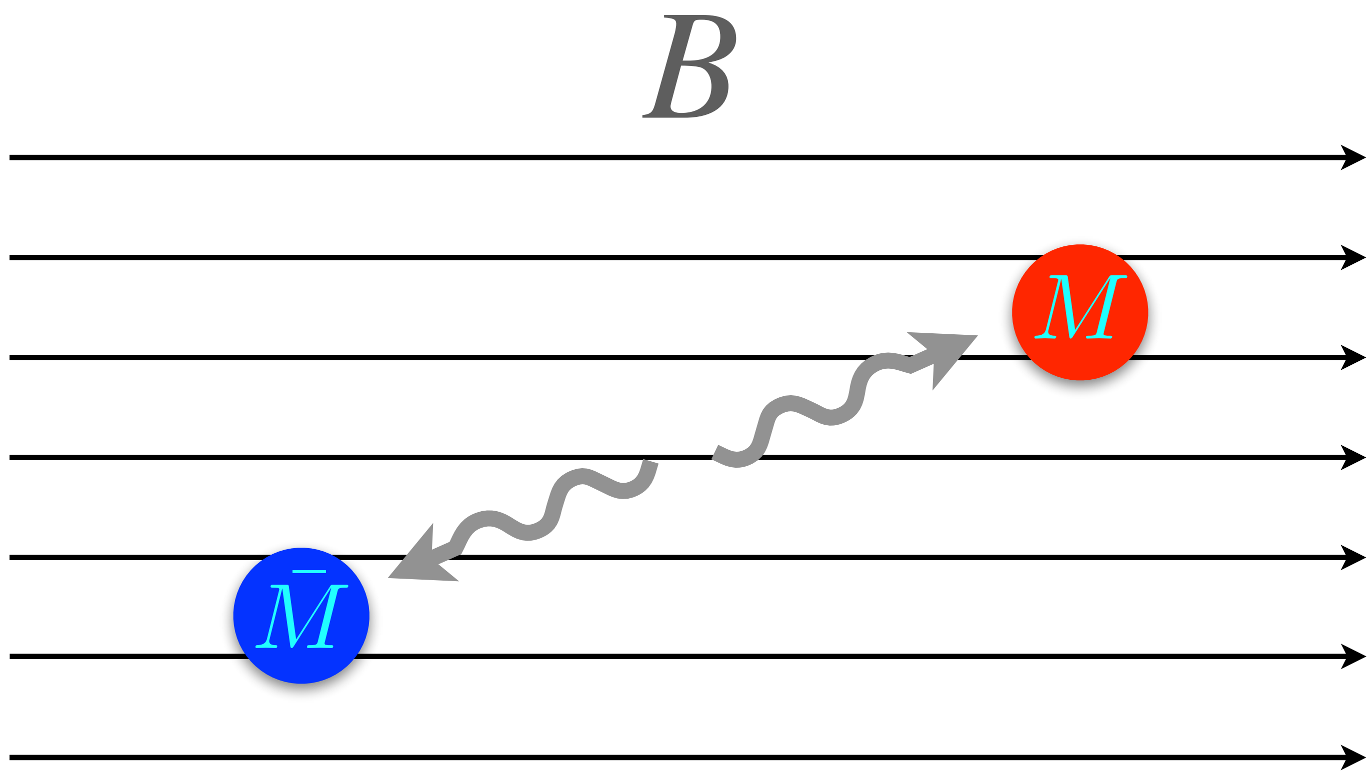
Plasma oscillations with intergalactic $\boldsymbol{B}$ survive over a cosmological timescale, which can be constrained by blazar observations



OUTLINE

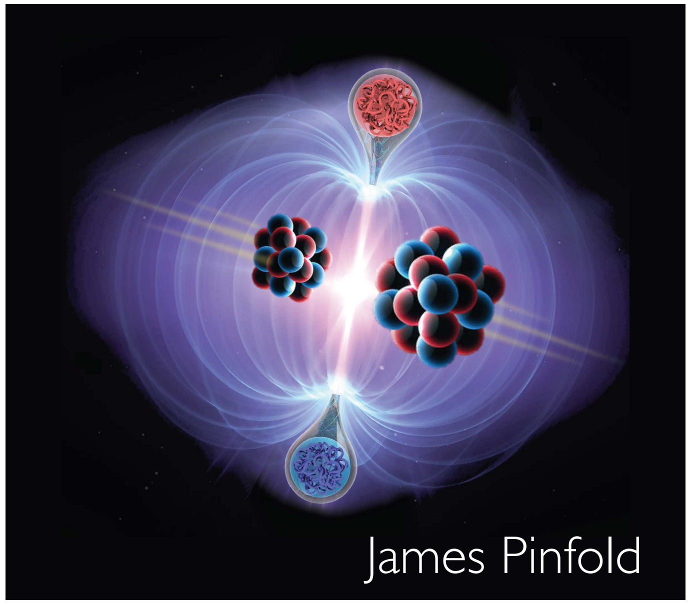
1. Acceleration in cosmic $\boldsymbol{B}$
2. Backreaction on cosmic $\boldsymbol{B}$
3. Pair production in cosmic $\boldsymbol{B}$

SCHWINGER PAIR PRODUCTION OF MONOPOLES IN STRONG B



cf. talks by Oliver Gould & Arttu Rajantie

SCHWINGER MASS BOUNDS



LHC $B \sim 10^{20}\,\mathrm{G} \sim (1\,\mathrm{GeV})^2 \rightarrow m > 75\,\mathrm{GeV}$ MoEDAL '22

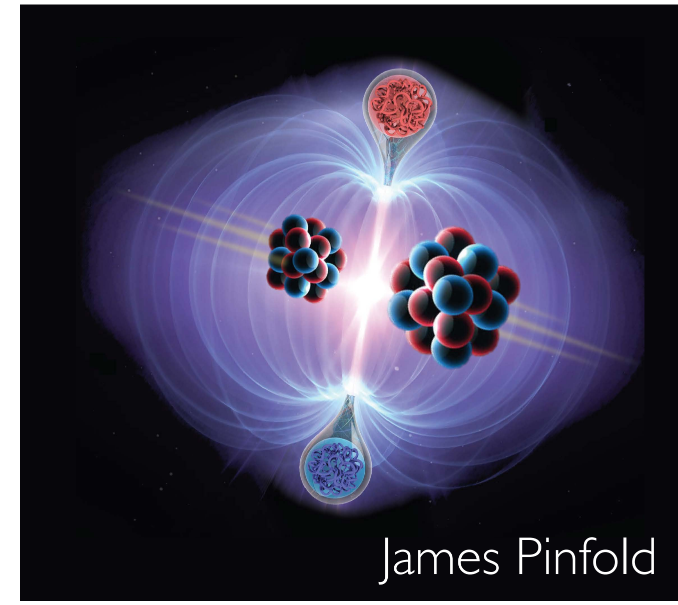
magnetars $B \sim 10^{15}\,\mathrm{G} \sim (10^{-2}\,\mathrm{GeV})^2 \rightarrow m \gtrsim 0.3\,\mathrm{GeV}$

Gould, Rajantie '17 Hook, Huang '17

galactic $B \sim 10^{-6}\,\mathrm{G}$

intergalactic $B \gtrsim 10^{-15}\,\mathrm{G}$

SCHWINGER MASS BOUNDS



LHC $B \sim 10^{20}\,\mathrm{G} \sim (1\,\mathrm{GeV})^2 \;\rightarrow\; m > 75\,\mathrm{GeV}$ MoEDAL '22

magnetars $B \sim 10^{15}\,\mathrm{G} \sim (10^{-2}\,\mathrm{GeV})^2 \;\rightarrow\; m \gtrsim 0.3\,\mathrm{GeV}$

Gould, Rajantie '17 Hook, Huang '17

galactic $B \sim 10^{-6}\,\mathrm{G}$

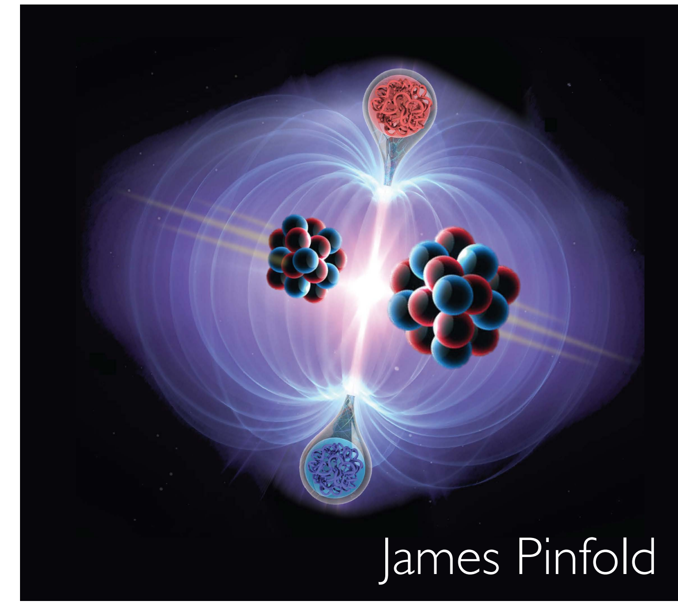
intergalactic $B \gtrsim 10^{-15}\,\mathrm{G}$

Intergalactic B most likely have a primordial origin

SCHWINGER MASS BOUNDS

primordial $B \lesssim 10^{52}\,\mathrm{G} \sim (10^{16}\,\mathrm{GeV})^2$

$B \propto a^{-2}$

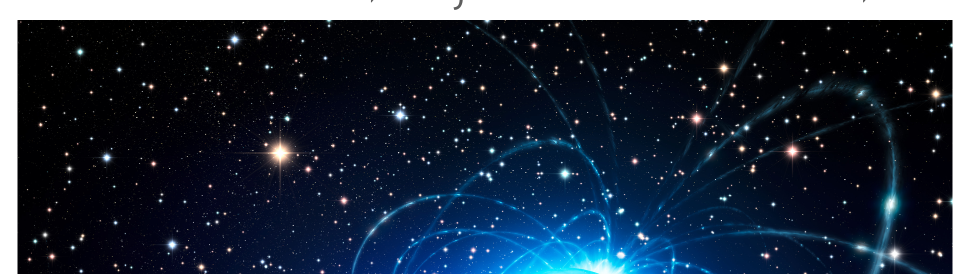


LHC $B \sim 10^{20}\,\mathrm{G} \sim (1\,\mathrm{GeV})^2 \;\rightarrow\; m > 75\,\mathrm{GeV}$ MoEDAL '22

magnetars $B \sim 10^{15}\,\mathrm{G} \sim (10^{-2}\,\mathrm{GeV})^2 \;\rightarrow\; m \gtrsim 0.3\,\mathrm{GeV}$

Gould, Rajantie '17 Hook, Huang '17

galactic $B \sim 10^{-6}\,\mathrm{G}$

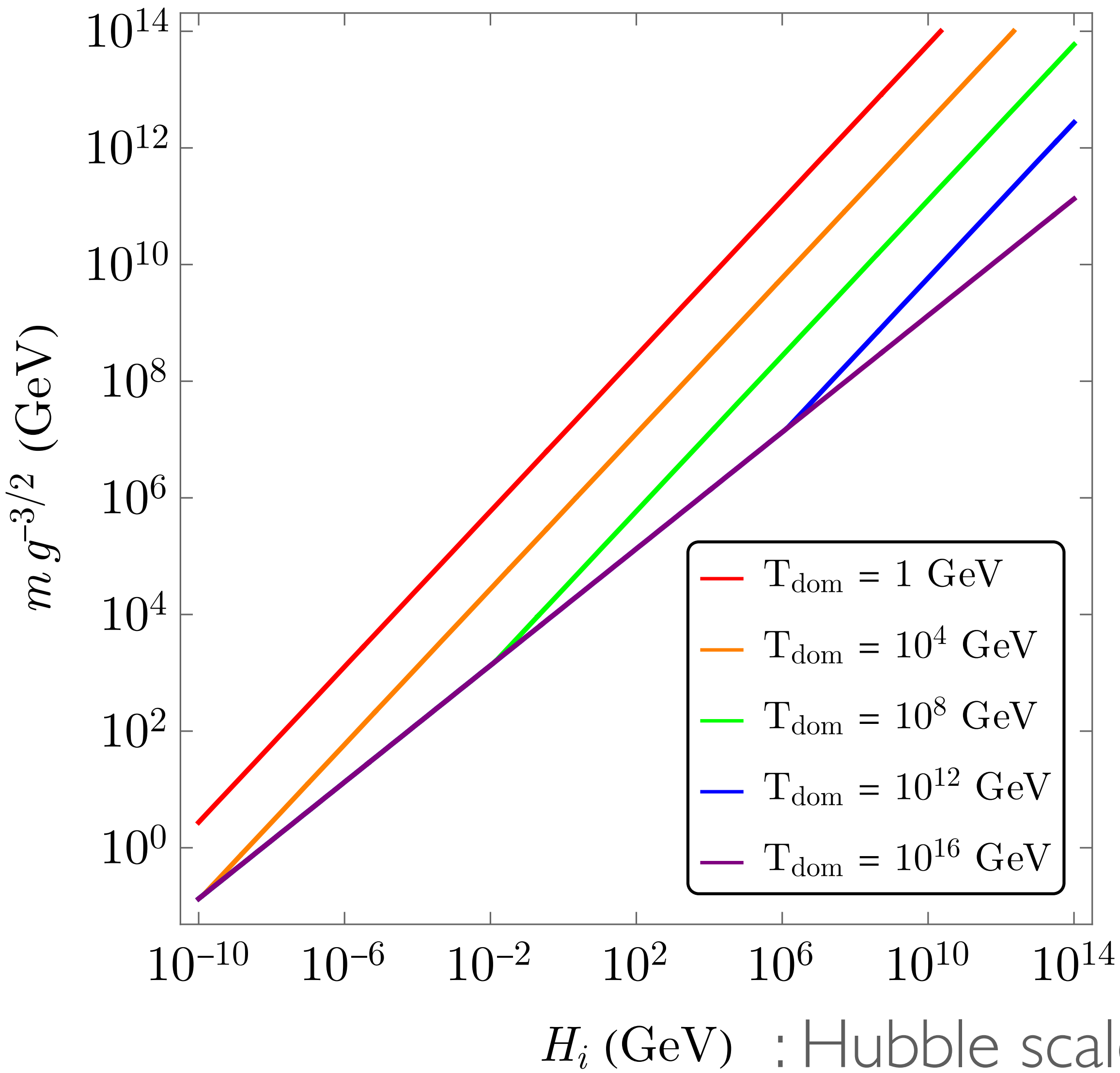


intergalactic $B \gtrsim 10^{-15}\,\mathrm{G}$

Intergalactic B most likely have a primordial origin

MASS LOWER LIMIT FROM PRIMORDIAL $\boldsymbol{B}$

TK '21 TK, Perri '22



: Hubble scale at $\boldsymbol{B}$ generation

$$B_{\mathrm{I},0} = 10^{-15}\,\mathrm{G}$$

Cosmology-dependent bound

→ can also be used to constrain magnetogenesis scenarios

SUMMARY

- Cosmic $\boldsymbol{B}$ fields accelerate, produce, and constrain monopoles

- Recent improvements in the understanding of cosmic $\boldsymbol{B}$ not only provide new opportunities to study monopoles, but also impact existing searches

- Monopoles = Messengers of cosmic $\boldsymbol{B}$
(Don't stop searching for monopoles with $\{m, v\}$ in "forbidden regions" !)