Next Frontiers for Magnetic Monopole Searches

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12 September 2026

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Papers and collaborators for this talk

Next Frontiers for Magnetic Monopole Searches

- Phys. Rev. D 111 (2025) 10, 102004 ← mostly this today
- Phys. Rev. Lett. 133 (2024) 7, 071803 ↓ plus some of these
- Nature 602 (2022) 7895, 63-67
- Phys. Rev. D 100 (2019) 1, 015041
- Phys. Rev. Lett. 119 (2017) 24, 241601

Igor Ostrovskiy

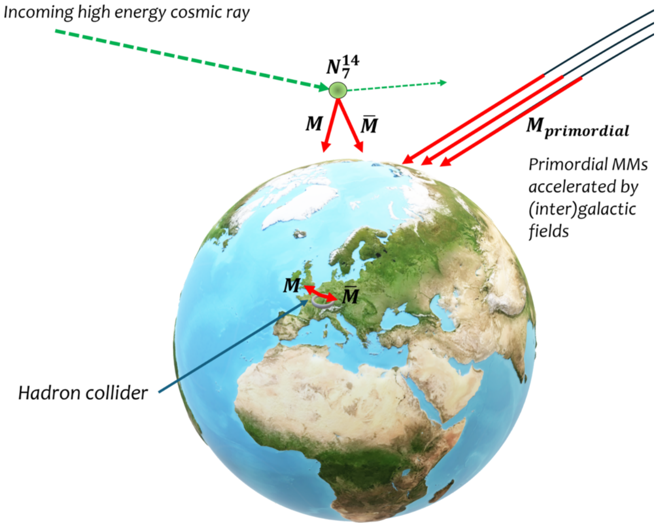
Aditya Upreti

Arttu Rajantie

David Ho

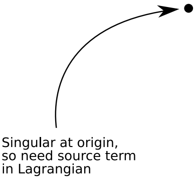
MoEDAL

Next Frontiers for Magnetic Monopole Searches

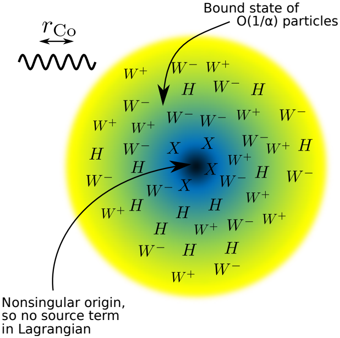


Structure of magnetic monopoles

1. Elementary



2. Composite



't Hooft '74, Polyakov '74

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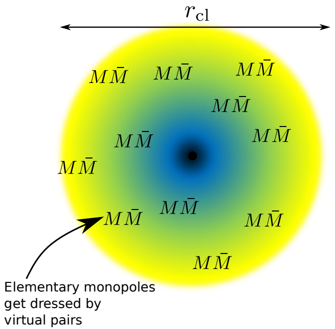

Göbel '70, Goldhaber '81

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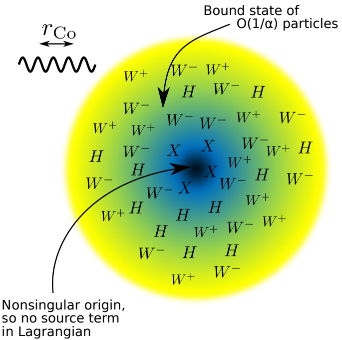

't Hooft '74, Polyakov '74

Magnetic monopoles in the infrared

MMs may have structure, but at large distances one only sees the magnetic charge g, spin s, and mass m.

$$\partial_\nu F^{\nu\mu} = J^\mu_{\text{electric}}$$
$$\implies \partial_\mu \partial_\nu F^{\nu\mu} = 0 = \partial_\mu J^\mu_{\text{electric}}$$

i.e. electric charge is conserved

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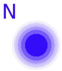

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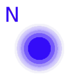

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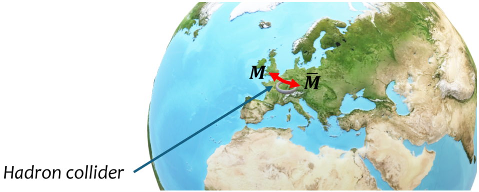
i.e. magnetic charge is conserved

these unique properties $\implies$ observation would be conclusive!

MMs produced in colliders



Collider cross sections

Composite MM production is expected to be very suppressed for particle collisions,

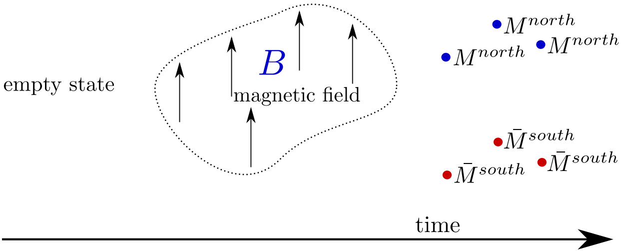
$$\sigma_{pp\to M\bar{M}} \propto |\langle M\bar{M}|\hat{\mathcal{O}}|E\rangle|^2 = \left|\int \mathrm{d}x \psi_{M\bar{M}}(x)\mathcal{O}e^{iEx}\right|^2 \lesssim e^{-2Er_{\mathrm{cl}}} \leq e^{-4/\alpha}$$

due to exponentially small $e^{-4/\alpha} \approx 10^{-238}$ overlap of states.

Witten '79, Drukier & Nussinov '82

Papageorgakis & Royston '14, Demidov & Levkov '15

Schwinger production as the golden channel

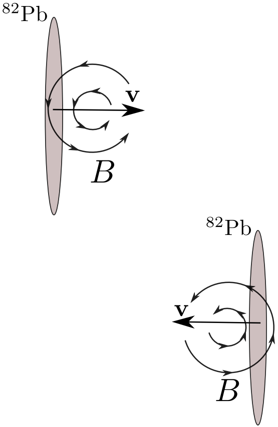


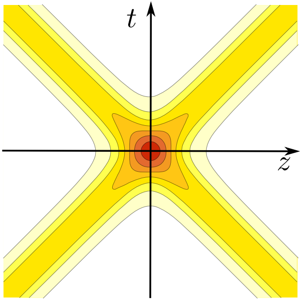
- MMs spontaneously produced in strong B fields
- coherent B field avoids $e^{-4/\alpha}$ suppression

Affleck & Manton '81

Magnetic fields in heavy-ion collisions

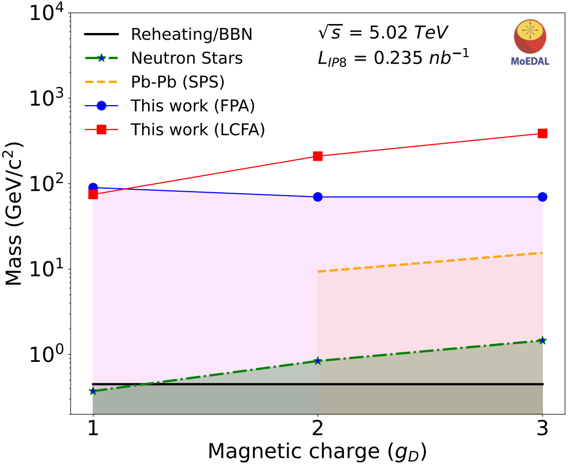
Strongest known magnetic fields are produced in ultraperipheral heavy-ion collisions at LHC, $B \sim 7.6\ \mathrm{GeV}^2$.





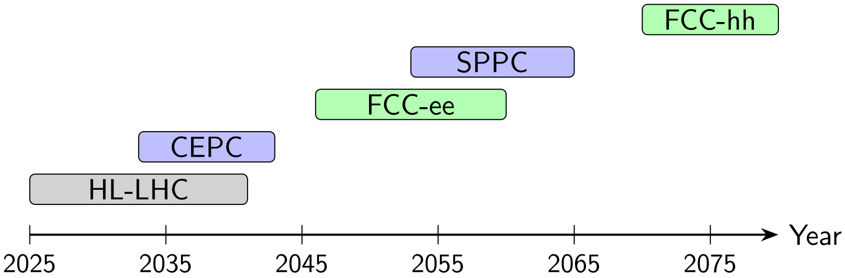
Field varies on inverse timescale $\omega \sim 73$ GeV.

MM mass bounds from Schwinger production

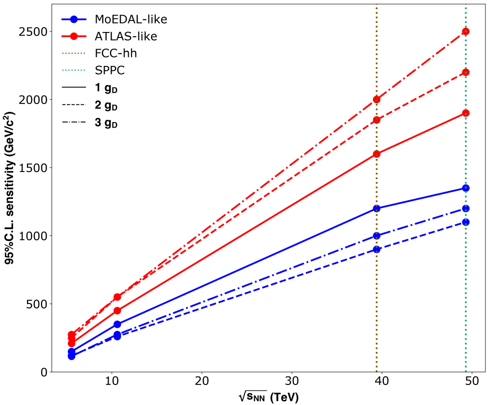


OG & Rajantie '17, MoEDAL '22

Future energy-frontier colliders



Collider reach for Schwinger MM production



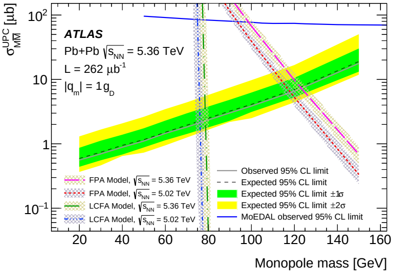
Proposed Pb–Pb collisions at $\sqrt{s_{NN}} \sim$ 40-50 TeV

$\Longrightarrow$ Schwinger MM production up to masses $\sim$ 2 TeV

Analysis as in MoEDAL '22

Status of Schwinger production cross section

- Bounds are conservative due to theoretical uncertainty
- Cross section known for:
  - constant B at $g^2 \gg 1$
  - varying B at $g^2 \ll 1$
- True cross section for varying B at $g^2 \gg 1$



ATLAS '25

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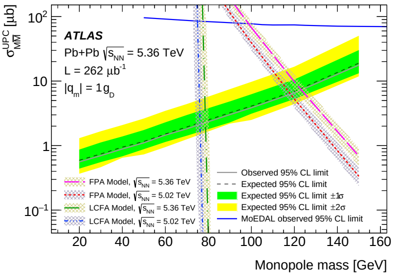
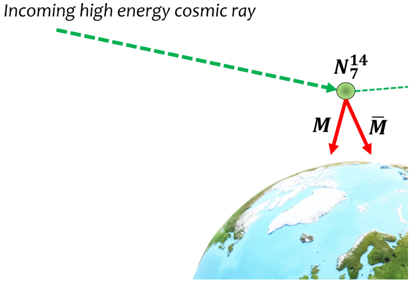


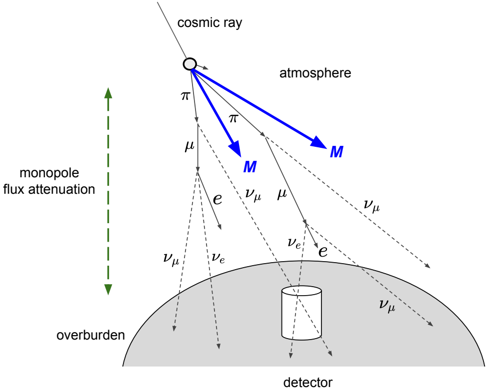
ATLAS '25

more on this from Arttu Rajantie on Monday

MMs produced in cosmic rays



Monopoles From an Atmospheric Fixed Target Experiment



Iguro, Plestid & Takhistov '21

see also Iguro, Mathur, Shoemaker & Takhistov '24

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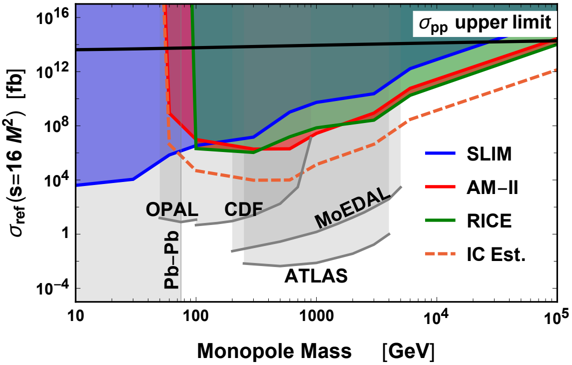

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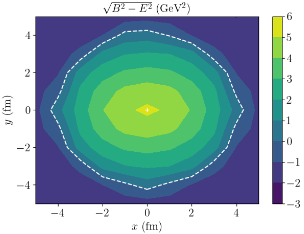
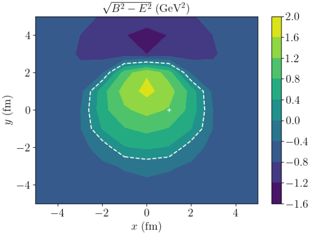
B fields for different ion species

^{56}Fe–^{56}Fe

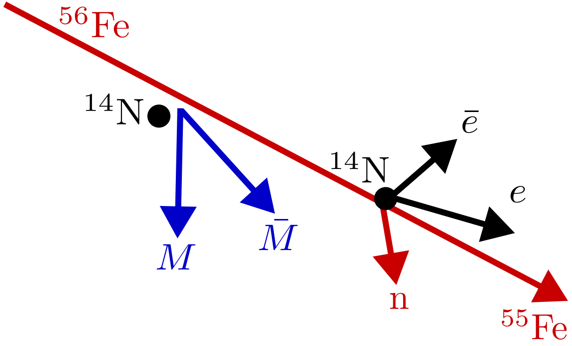


^{56}Fe–^{1}H

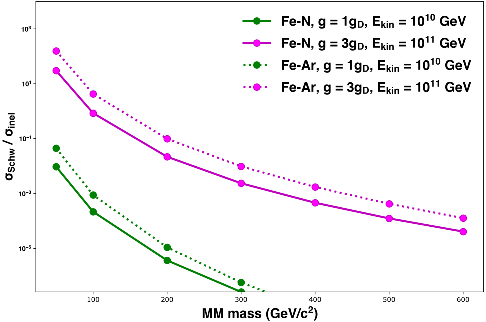


$$B\text{-field energy} = \int_x \frac{1}{2} B^2 = \left(\frac{\sqrt{s}_{NN}}{5.02\text{TeV}} \right) \times \begin{cases} 0.46 \text{ GeV}, & \text{H-H} \\ 230 \text{ GeV}, & \text{Fe-N} \\ 3500 \text{ GeV}, & \text{Pb-Pb} \end{cases}$$

Cosmic ray inelastic collisions



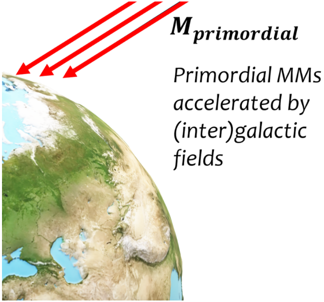
Schwinger MM production from cosmic rays



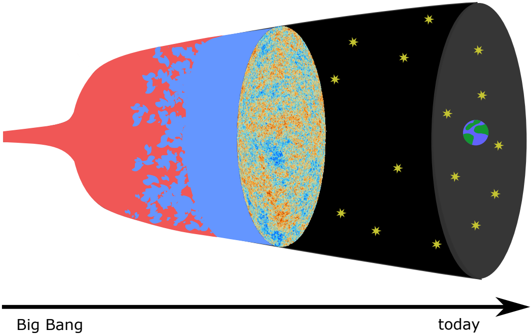
- Despite high energies, low luminosity limits to $m \lesssim 80$ GeV
- No clear improvement on colliders
- Caveat: we stopped after the first inelastic collision, yet $A \to (A-1)$ dominantly

OG, Ostrovskiy & Upreti '24

Primordial MMs



Big Bang cosmology



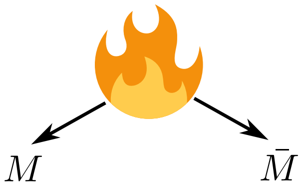
After inflation, the universe reheated to a temperature

$$T_{\text{reheating}} \in [10^{-2}, 10^{16}] \text{ GeV}$$

bounded by nucleosynthesis and limits on gravitational waves.

MM production in cosmology

Thermal fluctuations can directly produce MMs, or by freezing in after phase transitions, Rajantie '02



expected can produce MMs thermally up to $m_{\text{max}} \sim 45\,T_{\text{reheating}}$

Turner '82, Collins & Turner '84, Lindblom & Steinhardt '85

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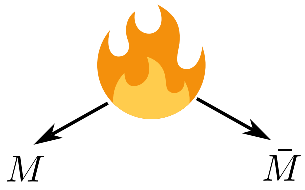

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$$\implies m_{\text{max}} \in [0.5, 5 \times 10^{17}] \text{ GeV}$$

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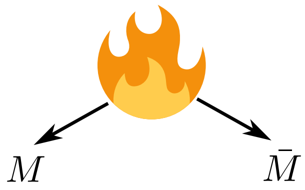

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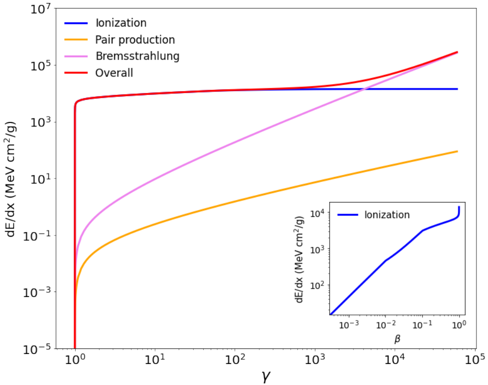
Primordial magnetic fields can also produce MMs Kobayashi '21

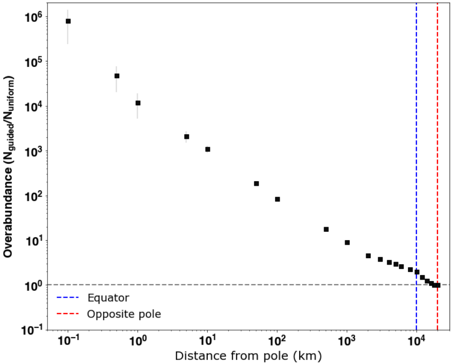
MMs travel the Universe and eventually meet the Earth

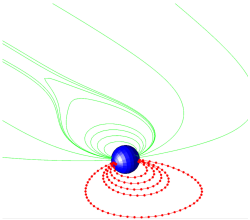


MMs then interact with the atmosphere and slow down

OG, Ostrovskiy & Upreti '24

Touchdown overabundance at Earth's poles





light/slowish MMs follow Earth's B-field lines

$$\gamma m v^2 \ll g B r$$

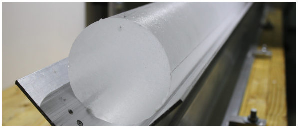
OG, Ostrovskiy & Upreti '24

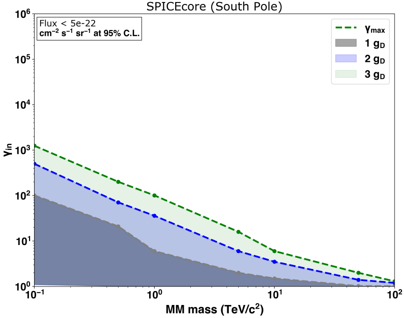
Search strategies for primordial MMs

OG, Ostrovskiy & Upreti '24

Strategy 1: Polar ice search

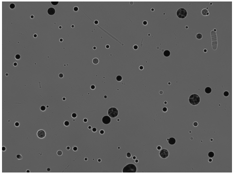
- few m^3 ice cores $\rightarrow$ SQUID scan
- enhanced flux in polar ice
- *very* sensitive to small m, γ

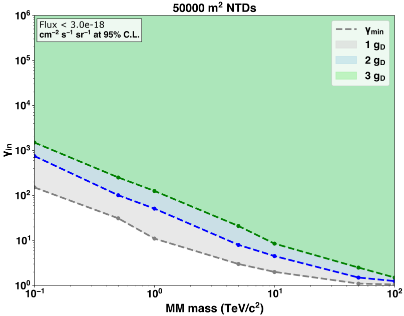




Strategy 2: Next-generation Nuclear Track Detector

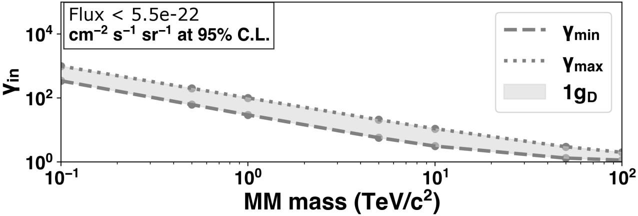
- 50,000 m^2 array $\gg$ SLIM, MACRO
- not necessarily near pole
- larger m, γ, complements ice cores





Strategy 3: Iron ore conveyor

- iron ore on conveyor → SQUID scan
- 1,000 tons *very* sensitive to MM flux
- but narrow range of m, γ depends on ore depth and location



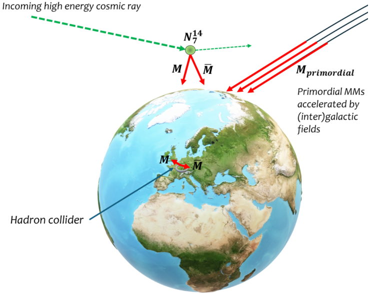
Next Frontiers for Magnetic Monopole Searches

MM observations verifiable

- unique magnetic properties
- MMs are stable

Schwinger effect golden channel

- FCC and SPCC can each produce ~ 2 TeV MMs
- cosmic rays luminosity limited to ~ 80 GeV MMs



Searches for primordial MMs

1. ice cores at Earth's poles
2. wide area NTDs
3. iron ore conveyor

Thanks for listening!

Backup slides

Dirac quantisation condition

- For a consistent quantum theory, electric e and magnetic g couplings must satisfy:

$$\frac{eg}{2\pi} \in \mathbb{Z}$$

Dirac '31

- This implies that magnetic charges are strongly coupled,

$$\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}, \qquad \alpha_M = \frac{g^2}{4\pi} \approx 34$$

- It also implies that for MMs the classical radius is larger than the Compton wavelength

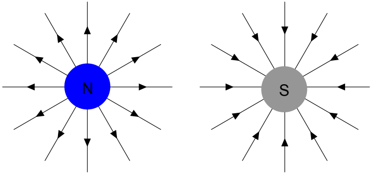
$$r_{cl} = \frac{g^2}{4\pi m} > r_{Co} = \frac{1}{m}$$

Magnetic monopole broadening

- The energy of a $M\bar{M}$ pair

$$E(r) = 2m - \frac{\alpha_m}{r},$$

becomes negative if $r < r_{cl}/2$.

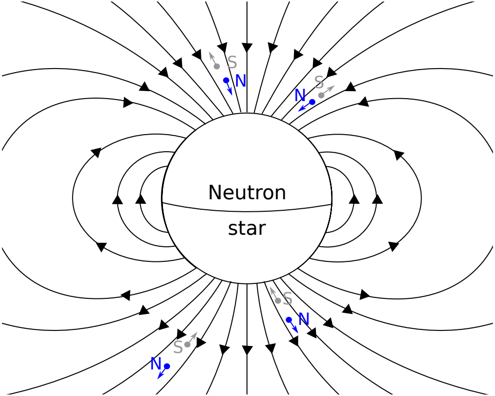


- Thus, for stability, MMs should have structure on $r \lesssim r_{cl}$.

Göbel '70, Goldhaber '81

- Screening by monopole loops?

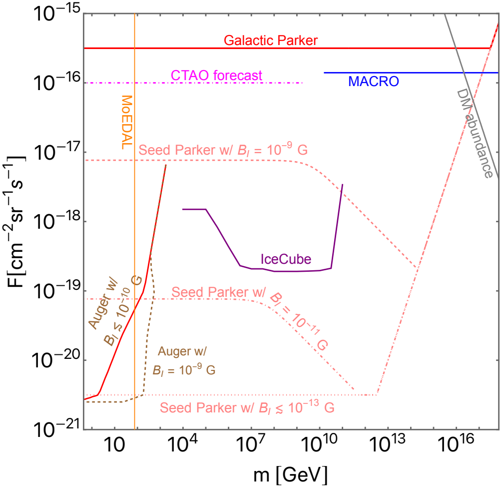
Astrophysical Schwinger production of MMs



MMs created by the dipole B fields around neutron stars, or by other cosmic B fields.

OG & Rajantie '17, Kobayashi '21

Recasting Experimental Constraints on Relativistic Magnetic Monopoles



Perri, Doro & Kobayashi