Milli-Magnetic Monopole Dark Matter and the Survival of Galactic Magnetic Fields

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based on MG, Ian Shoemaker, Natalia Tapia Arellano, arXiv:2105:05769, to appear in JHEP

Dark Sectors and Dark Monopoles

- Broad theory space for models of dark matter
  - Focus on broad paradigms, with novel physical properties, that have perhaps been overlooked
  - Dark sectors kinetically mixed with Standard Model particles have a rich phenomenology and deserved focused attention
  - + dark monopoles -> novel features

- Monopoles very interesting objects since the time of Dirac

Natural to investigate magnetic monopoles of a dark sector, and whether they can comprise all or some fraction of the dark matter

[Hook, Huang, 2018]

[Terning, Verhaaren, 2018, 2019]

Dark Sectors and Dark Monopoles

Model

- Assume magnetic monopoles in spectrum
- U(1) symmetry breaking giving mass to dark photon, as well as:
  - Confinement of magnetic charge
  - physical flux tube (Nielsen-Olesen string), thickness set by inverse dark photon mass
  - String tension
- Electric-electric kinetic mixing

$$\boxed{\mathcal{L} \supset \varepsilon F'_{\mu\nu} F^{\mu\nu}}$$

Holdom 1985

- Dirac charge quantization condition violated in either sector [Terning, Verhaaren, 2018, 2019]

Monopole Interactions: Zwanziger's two-potential formalism [Csaki, Shirman, Terning], [Terning, Verhaaren, 2018]

- Questions of how (dark) monopoles interact with electric charges are subtle, because of the impossibility of constructing a local, Lorentz invariant action for electric and magnetic charges
- Introduce two gauge potentials A, B for each sector: (A,B) and (A_D ,B_D)
- B potential couples locally to magnetic charges, and A potential couples locally to electric charges

In the gauge basis, the ordinary and dark magnetic currents couple to magnetic potentials

$$\mathcal{L} = gK \cdot B + g_D K_D \cdot B_D$$

Monopole Interactions: Zwanziger's two-potential formalism [Csaki, Shirman, Terning], [Terning, Verhaaren, 2018, see also Hook, Huang '17]

Undo the kinetic mixing with $A \to A + \varepsilon A_D$

But to maintain the Zwanziger form of the action in the diagonal mass basis, one must shift the magnetic potentials: $B_D \to B_D - \varepsilon B$, $B \to B$

$$\begin{aligned}\mathcal{L} \to \mathcal{L} \quad &= \boxed{(gK - \varepsilon g_D K_D)} \cdot B + g_D K_D \cdot B_D \\ &= gK \cdot B + g_D K_D \cdot \boxed{(B_D - \varepsilon B)}\end{aligned}$$

Effective magnetic potential experienced by a dark magnetic monopole

Source for ordinary magnetic potential

Effective magnetic field felt by dark magnetic monopole

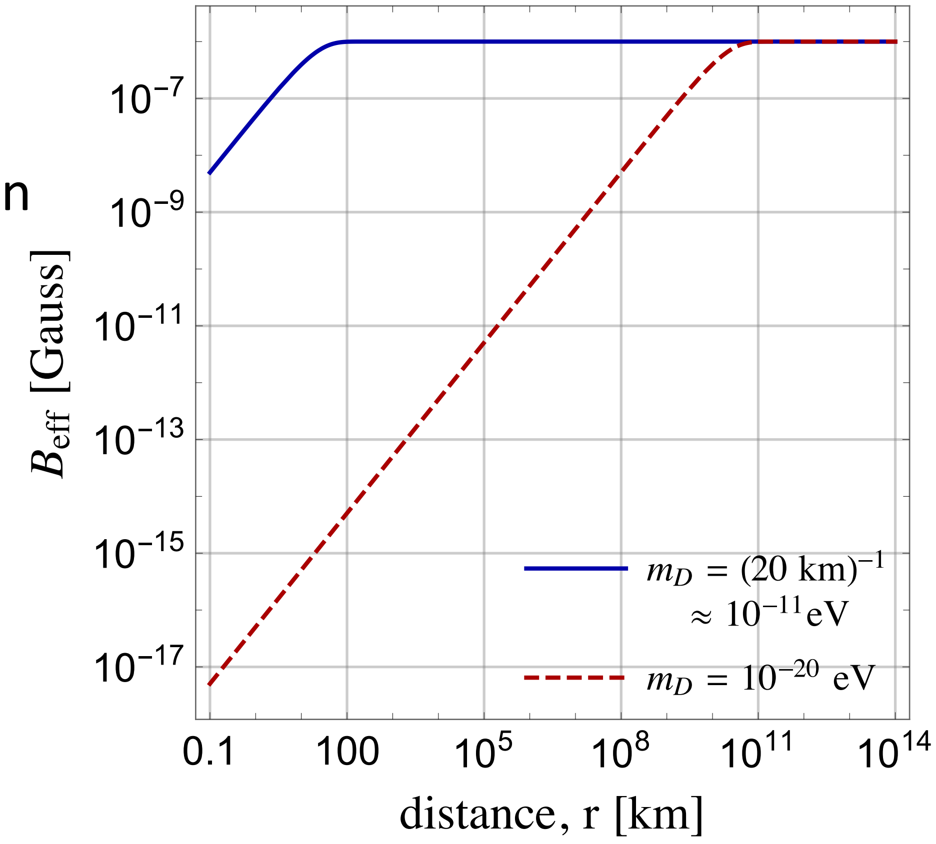
At long distances (compared to inverse dark photon mass) :

- Ordinary electrically charged particles couple to dark photon
- Dark magnetic monopoles couple to ordinary photon, and experience an effective magnetic field

$$B_{\rm eff} = B_D - \varepsilon B \to \varepsilon B \left(1 - e^{-m_D r}\right)$$

- Turnover scale set by dark photon mass, the thickness of the magnetic flux tube/Nielsen-Olesen string
- ``unsuppressed'' far from ordinary source
- suppressed close to ordinary source

[Terning, Verhaaren, '18, see also Hook, Huang '17]



In general for detection, need the dark magnetic flux tube to fit inside the experiment

Non-relativistic Dark Magnetic Monopoles

$$H = \frac{p^2}{2\mu} - \frac{\alpha_D}{r} e^{-m_D r} + C\pi v_D^2 r + gQ_m Bz$$

$$\boxed{Q_m = \varepsilon g_D/g}$$

- Properties of ground state:
  - Hydrogen-like if $\boxed{m_D \ll \alpha_D M}$ otherwise "Airy-like"
  - Absolutely stable (if dark monopoles have opposite flavors)
  - long-range van der Waals interactions, short distance Coulomb interactions
- Magnetic fine structure constant assumed to be perturbative

SIDM bounds on dark magnetic monopoles

- SIDM bounds on long-range Coulomb interactions explored by a number of authors

[Feng, Kaplinghat, Tu, Yu, ‘09],
[Cyr-Racine, Sigurdson ’13],
[Cline, Liu, Moore, Xue, ‘13],
[Agrawal, Cyr-Racine, Randall, Scholtz, ’16]

- Bound state dark magnetic monopoles have long- and short- range interactions with other bound states

- ``Free “ mmCPs have long range Coulomb interactions, regulated by interparticle spacing or dark Debye length

Strength of interactions constrained by Bullet cluster and, independently, by the existence of elliptical galaxies (“halo ellipticity”)

Cross-section

- Hard scattering: change in kinetic energy comparable to change in potential energy. This has an impact parameter less than the Bohr radius, provided we're in the ``fast limit" where

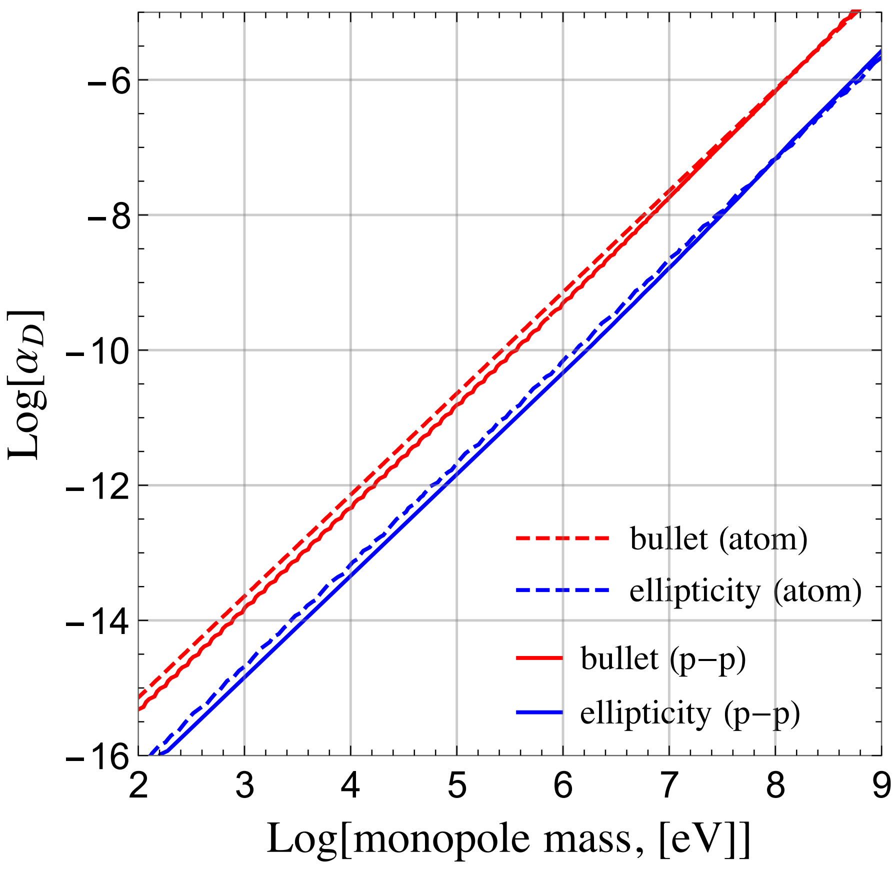
$$\boxed{v \gg \alpha_D}$$

  - Elastic hard scattering dominated by Rutherford scattering
  - forward singularity cut off by appropriate length scale (Bohr radius or interparticle length)

- Soft scattering doesn't see the charge: large impact parameter
  - approximately solve classical equation of motion and integrate over impact parameters
  - Parametrically the same as the hard scattering cross-section since we're a posteriori in the fast limit

Halo Ellipticity and Bullet Cluster bounds

$$\sigma_T \lesssim 0.7\ \mathrm{cm}^2/\mathrm{g} \qquad \text{(bullet)}$$
$$\Gamma \lesssim 10 H_0 \qquad \text{(halo ellipticity)}$$



Use bounds as input to energy loss from Parker effect

Parker Effect for Dark Magnetic Monopoles

1. Dark magnetic monopoles essentially “free”: magnetic charges accelerated by background field and energy-loss argument applies
2. Magnetic monopoles in atomic-like ground state:
   - In background magnetic field of Milky Way, ground state is unstable to decay

$$\Gamma = K S_0 e^{-2S_0} = \left(\frac{4\alpha_D^5 \mu^3}{g Q_m B(d)}\right) e^{-\frac{2\alpha_D^3 \mu^2}{3 g Q_m B(d)}} \qquad \text{(WKB)}$$

(This is a problem in Landau and Liftshitz, that happily enough comes with a solution)

   - After tunneling, essentially ``free’’ magnetic charges accelerated by background field and energy-loss argument applies

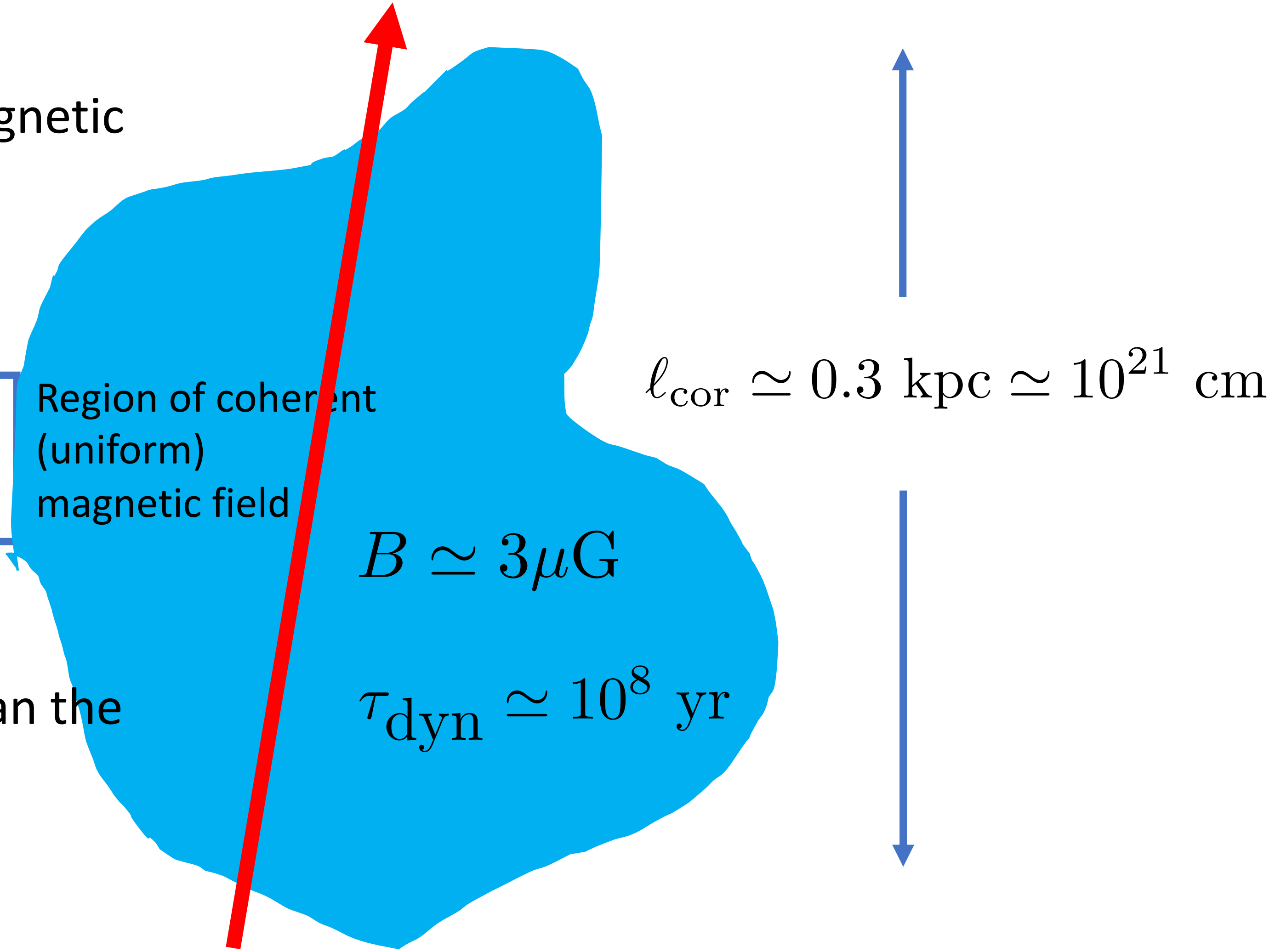
Parker effect in the Milky Way [Parker ’70; Turner, Parker, Bogdan, ’82; Parker ’83; Parker ’97; Adams et al ‘93]

- Magnetic monopoles accelerated by magnetic fields, dissipating magnetic field energy
- Leads to stringent bounds on number density of ordinary monopoles

$$\boxed{\tau_{\rm diss} \simeq \frac{B^2}{j \cdot B}} \qquad \boxed{\Omega_M \lesssim 10^{-9}}$$

$(M \sim 10^{16}\,\mathrm{GeV})$

- Require dissipation of magnetic field energy occurs on timescales greater than the dynamo timescale.



Magnetic monopole (accelerated, with little deflection since for mmCPs $\Delta v \ll v_0$)

Revisited Parker Bound

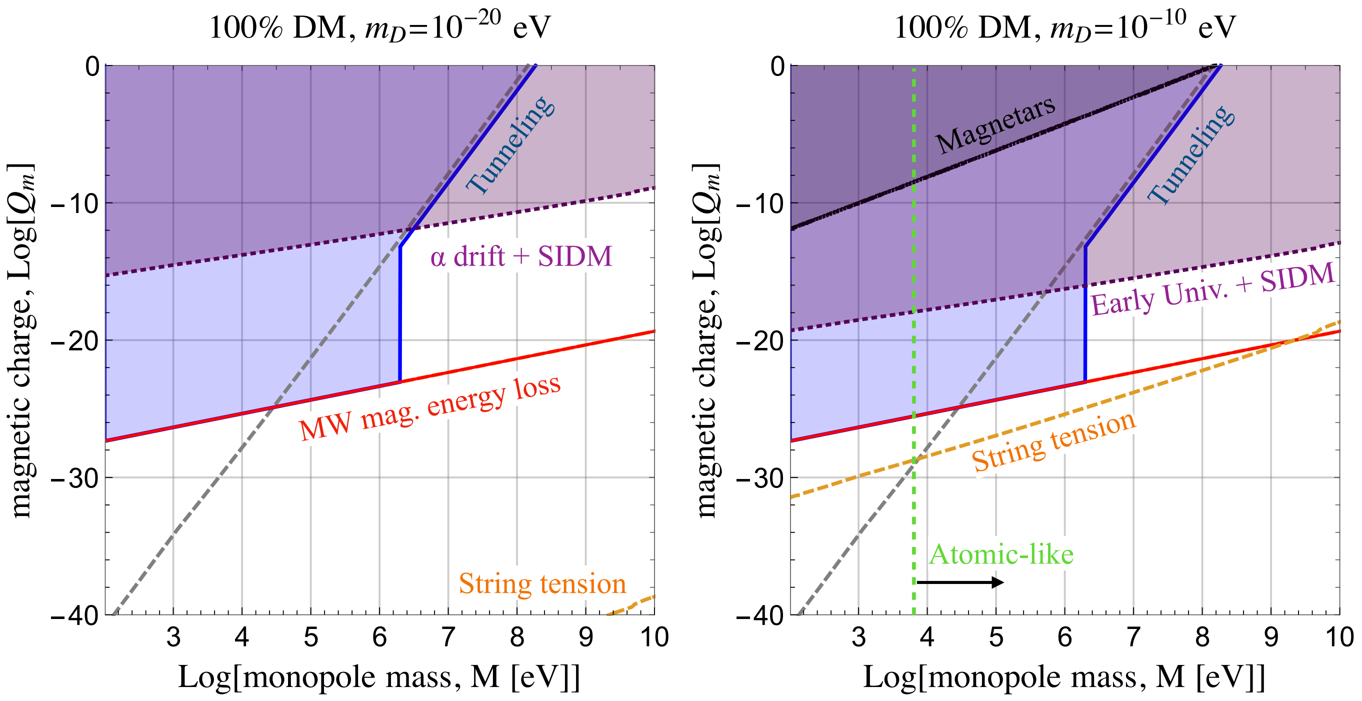
- Repeated energy-loss analysis of Turner, Parker, and Bogdan (1982), updated for modified coupling

- Stringent bound driven by large size of coherent magnetic domain ~ 0.3 kpc and galactic dynamo timescale ~ 10^5 years, and the large number density of dark monopole dark matter

$$\boxed{\begin{aligned} Q_m \quad &< \quad \sqrt{\frac{1}{12\pi}\frac{1}{\tau_{\rm dyn}}\frac{v\,M^2}{g^2\rho_{DM}\,\ell}\left(\frac{\rho_{DM}}{\rho_M}\right)} \\ &\simeq \quad 4.5\times 10^{-26}\,\left(\frac{M}{10^4\ {\rm eV}}\right)\,\left(\frac{\rho_{DM}}{\rho_M}\right)^{1/2} \end{aligned}}$$

$$\boxed{Q_m = \varepsilon g_D/g}$$

Parker bound on dark magnetic monopoles



Light purple exclusion: cone of Milky Way magnetic energy loss (red) and requirement that tunneling occurs on timescales less than the galactic dynamo timescale

Dark purple exclusion (dotted): SIDM bounds on g_D combined with other independent bounds on ε

Magnetar bounds weaker than Parker bounds, especially at small dark photon masses

Summary

- Dark sectors + kinetic mixing can be a rich area of phenomenology
- Milli-magnetic monopole interactions with ordinary photon strongly constrained by
  - magnetars [Hook, Huang, '18]
  - Galactic Parker effect (presented here)
- Heavier dark magnetic monopole masses more weakly constrained

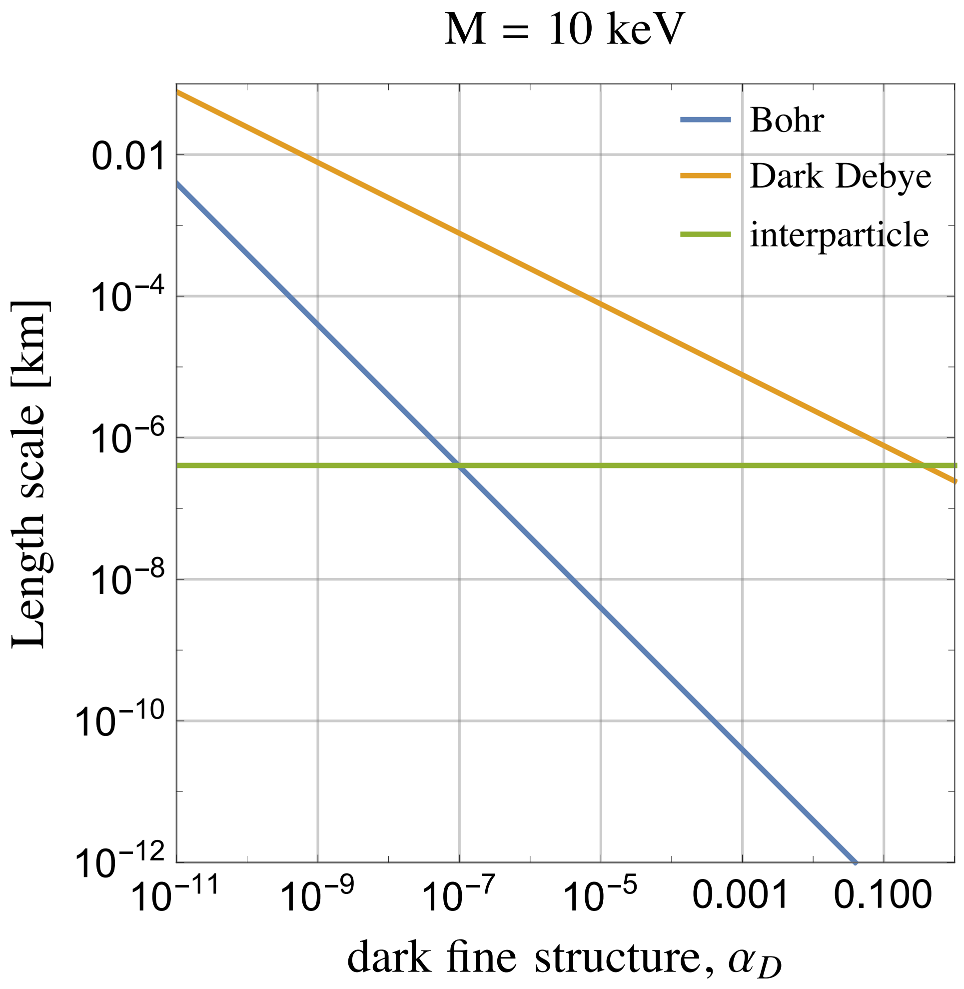
- Currently investigating cosmological ``freeze-in'' targets, as well as signatures and bounds from laboratory experiments

Backups

Length scales

- Bohr radius less than interparticle spacing :
- Ground state has no magnetic properties and is stable, but in a background magnetic field it becomes **unstable**, provided effective magnetic field larger than internal tension
- Need to wait for bound monopoles to tunnel before Parker effect can initiate

- Bohr radius bigger than interparticle spacing :
- Galactic population is a dark plasma, more complicated story, but don't have to wait for tunneling to occur, and each dark monopole is accelerated by the effective magnetic field



Transition depends on dark monopole mass and magnetic fine structure constant

Cross-section

- Usually quoted in terms of a "momentum transfer" or "transport" cross-section which cuts out forward scattering, effectively capturing only hard scattering

$$\boxed{\sigma_T = \int \frac{d\sigma}{d\cos\theta}(1-\cos\theta)d\cos\theta}$$

- Numerous soft scattering vs. few hard scatterings: both could be important
  - soft scattering needs a different treatment than computing the transfer cross-section
- Bound-state-bound-state monopole scattering is a 4-body problem
  - Resort to several approximations

Soft Scattering [following Ackerman, Buckley, Carroll, Kamionowski, 2006]

- Each soft scatter contributes a small momentum-transfer q, but over many scatterings these can add up to a sizable change in kinetic energy.
- To estimate this effect we approximately solved the classical equations of motion of a single monopole bound state moving in the van der Waals potential of another bound state.
- This will give an estimate of the number of soft scatterings, and therefore timescale, needed to cause a change in kinetic energy comparable to the initial kinetic energy

Soft Scattering [adapted from Ackerman, Buckley, Carroll, Kamionowski, 2006]

Approximate inter-bound state potential as

$$\boxed{V_{\mathrm{vdW}} \sim -\frac{\alpha_D}{L_0}\frac{L_0^6}{r^6}}$$

$$\boxed{\delta q \simeq \pm V'_{\mathrm{vdW}}(b)\left(\frac{b}{v}\right)}$$

to first order in transit time $T \simeq b/v$

Bound state undergoes a random walk as it orbits the halo, with $\boxed{\langle \delta v^2 \rangle = (\delta v)^2 \delta n}$ non-vanishing

Estimate the timescale for $\boxed{\langle \delta v^2 \rangle \simeq v^2}$ after a certain number of orbits, and require that timescale τ_{soft} to be on the age of the galaxy or longer

Interpreting τ_{soft} in terms of a scattering rate, $\boxed{\tau_{\mathrm{soft}} \simeq \left(\langle n \sigma_{\mathrm{soft}} v \rangle\right)^{-1}}$

$$\boxed{\sigma_{\mathrm{soft}} \sim \frac{\alpha_D^2}{M^2 v^4}}$$

Cross Section

- In summary, in the fast limit

$$\boxed{v \gg \alpha_D}$$

we see the cross-section for both hard and soft scattering is parametrically the same as Coulomb scattering

- In the opposite limit $\boxed{v \ll \alpha_D}$ the cross-section is too large as it is set by the Bohr radius; then milli-magnetic monopoles can't be all of the dark matter

[Terning, Verhaaren, 2019]

Tunneling of bound monopole ground state in background magnetic field

While the lowest level magnetic bound state is quantum mechanically stable in vacuum, it isn't in a background magnetic field

$$\Gamma = K S_0 e^{-2S_0} = \left(\frac{4\alpha_D^5\mu^3}{gQ_m B(d)}\right) e^{-\frac{2\alpha_D^3\mu^2}{3gQ_m B(d)}} \qquad \text{(WKB)}$$

$$S_0 = 1/(3B)$$

(natural atomic units)

(This is a problem in Landau and Liftshitz, that happily enough comes with a solution)

For a mixed monopole mass, SIDM constraints bound α_D from above, so using this as input, we obtain the largest upper bound on Q_m by requiring the decay happens on time scales longer than the dynamo timescale.

$$Q_m \lesssim \frac{-Q_m^*}{W_{-1}\left(-\frac{1}{3\alpha_D^2 M\tau_{\rm dyn}}\right)}, \qquad Q_m^* \equiv \frac{\alpha_D^3 M^2}{6gB(d)},$$

If α_D is smaller than the SIDM bound, then the upper bound on Q_m decreases

Parker Effect (Turner, Parker, Bogdan, 1982)

$$\langle \Delta E \rangle \times 2\mathcal{F} \times 4\pi\ell^2 < \frac{B^2}{8\pi}\frac{4\pi}{3}\ell^3\frac{1}{\tau_{\rm dyn}},$$

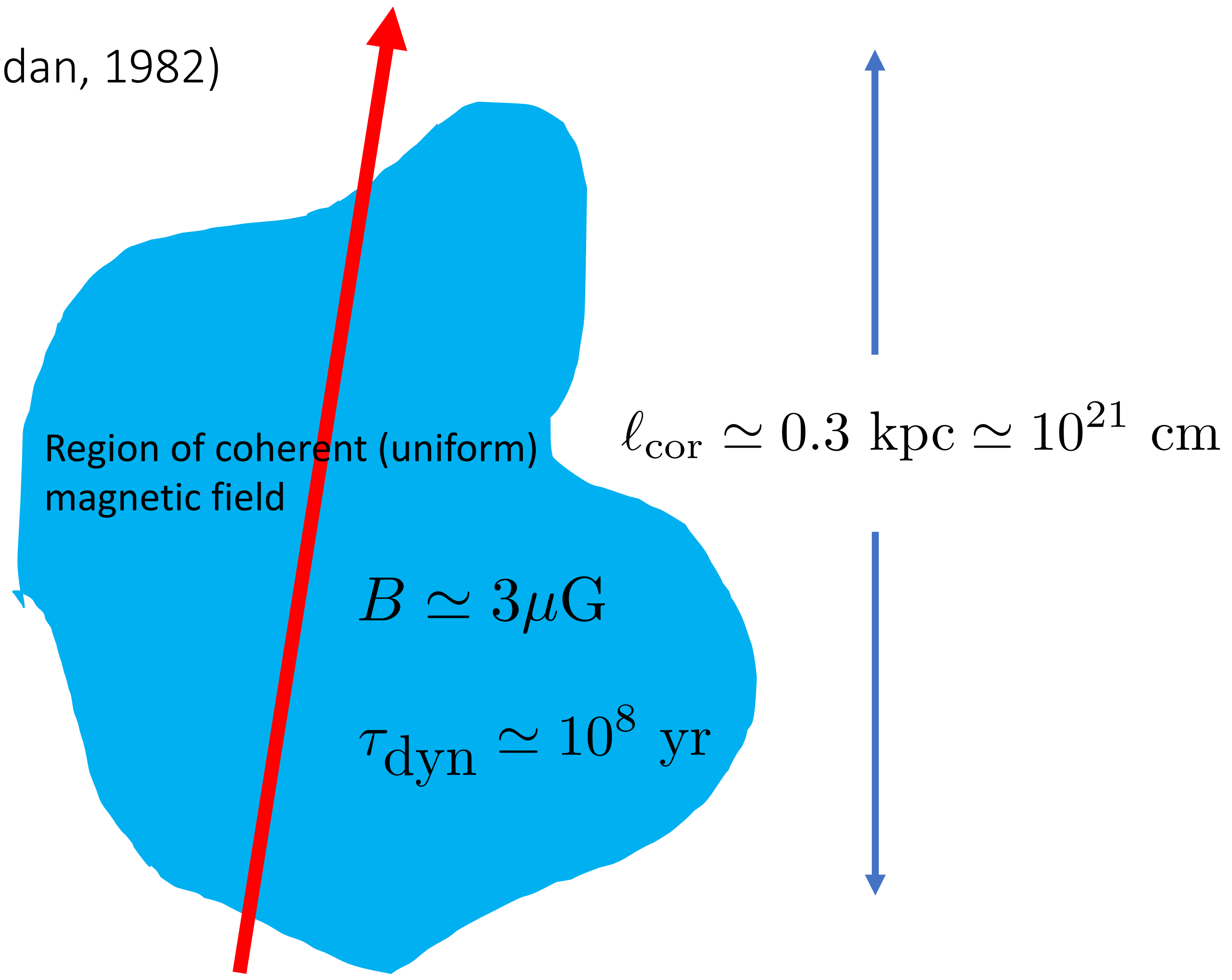
$$\langle \Delta E \rangle \equiv T_{\rm f} - T_{\rm i} \simeq \frac{1}{2}(\Delta t)^2\frac{d^2T}{dt^2}$$

Estimate $\frac{d^2T}{dt^2}$ from the Lorentz force law,

assuming static magnetic field.

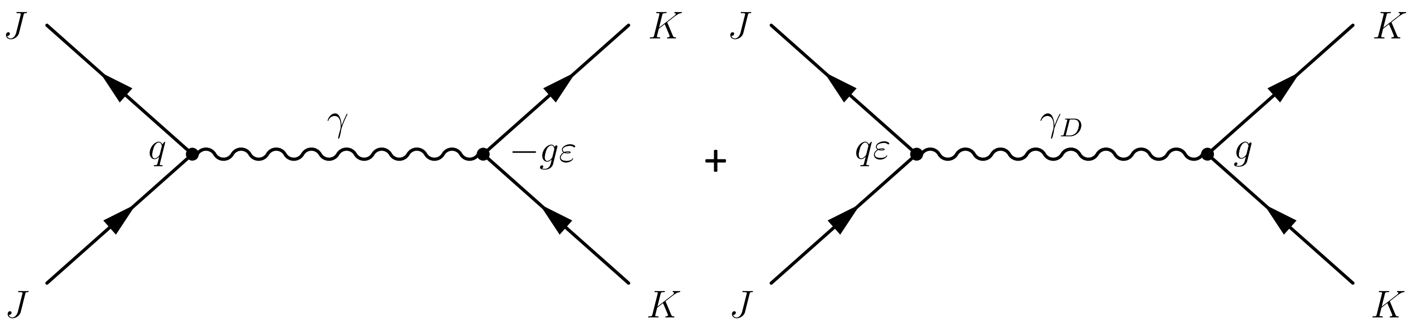
Require dissipation of magnetic field energy occurs on timescales greater than the dynamo timescale.

Bound flux or, given a density, the magnetic coupling (mmCP)



Magnetic monopole (accelerated, with little deflection since for mmCPs $\Delta v \ll v_0$)

mmCP production



Terning, Verhaaren, 2020

- If CP is a good symmetry, then s-channel pair production of dark magnetic monopoles from (Standard Model) fermions and single (dark/ordinary) photon exchange vanishes at leading order in ε

$$\mathcal{A} = 0$$

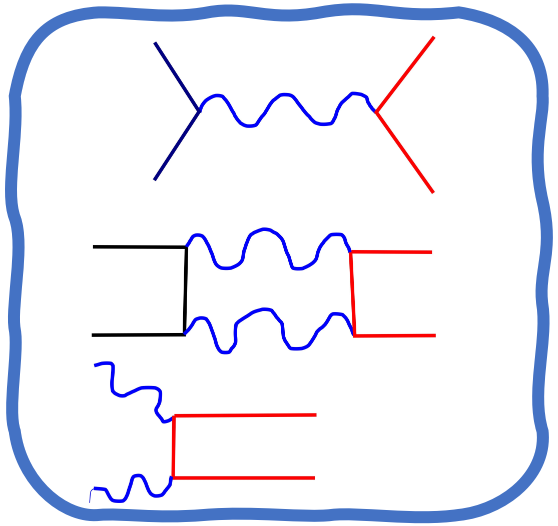
- Originates from different CP properties of electric field ($J^{PC} = 1^{--}$) and magnetic field ($J^{PC} = 1^{-+}$)

mmCP production in early Universe: freeze-in

Dark electrically charged particles X can be dark matter candidates, produced through the non-thermal freeze-in mechanism
X produced through single photon/dark-photon exchange, or X can be the dark photon itself

Dark magnetic monopoles are weakly coupled to the SM, and have unusual production mechanisms:

- Dark photon-dark photon fusion induced production non-zero
  (Terning, Verhaaren, 2020)
- Expect dark photon-photon fusion induced production to be non-vanishing
- Expect box diagrams to be non-vanishing



Investigating whether this leads to qualitatively different preferred regions: stay tuned!

Caveats about astrophysical populations

- We assumed that all of bound monopole systems are in their ground state, at least when it is self-consistent to do so.
- This leads to a conservative upper bound on the dark magnetic monopole coupling, arising from bounds on self-interacting dark matter.
- The above assumption is not self-consistent when the interparticle spacing becomes smaller than the Bohr radius, and here we resorted to approximating the galactic population as a non-degenerate, collisionless plasma.
- Characterizing the different occupation numbers requires following the coupled Boltzmann equations, including dissipative processes, over the history of the Milky Way galaxy
- Inelastic collisions between bound monopoles can produce long-lived excited states, dissipating initial kinetic energy, since we're in the limit

$$\boxed{\alpha_D \ll v}$$

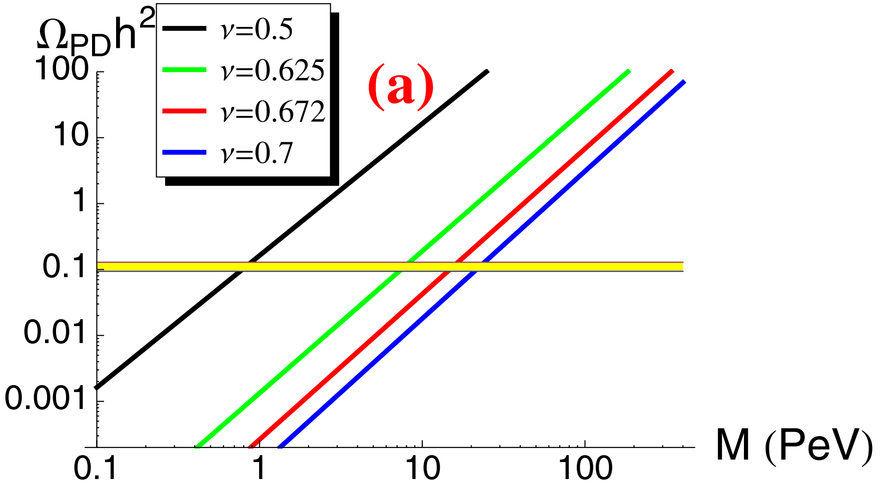
Magnetic plasma oscillations

- Could the decay of galactic magnetic field in the presence of magnetic monopoles be the first half of an oscillation in the galactic magnetic field?
- In other words, could magnetic monopoles support the galactic magnetic field?
- Turner, Bogdan, Parker (1982) and Parker (1987) reach a negative conclusion: Monopoles could induce plasma oscillations in the Galactic magnetic field, given by the plasma frequency w.
- But need the oscillation timescale of B to occur on timescales longer than the Galactic dynamo timescale
- Moreover, to avoid Landau damping on kpc scales, the phase velocity w/k of oscillations needs to be greater than the monopole virial velocity

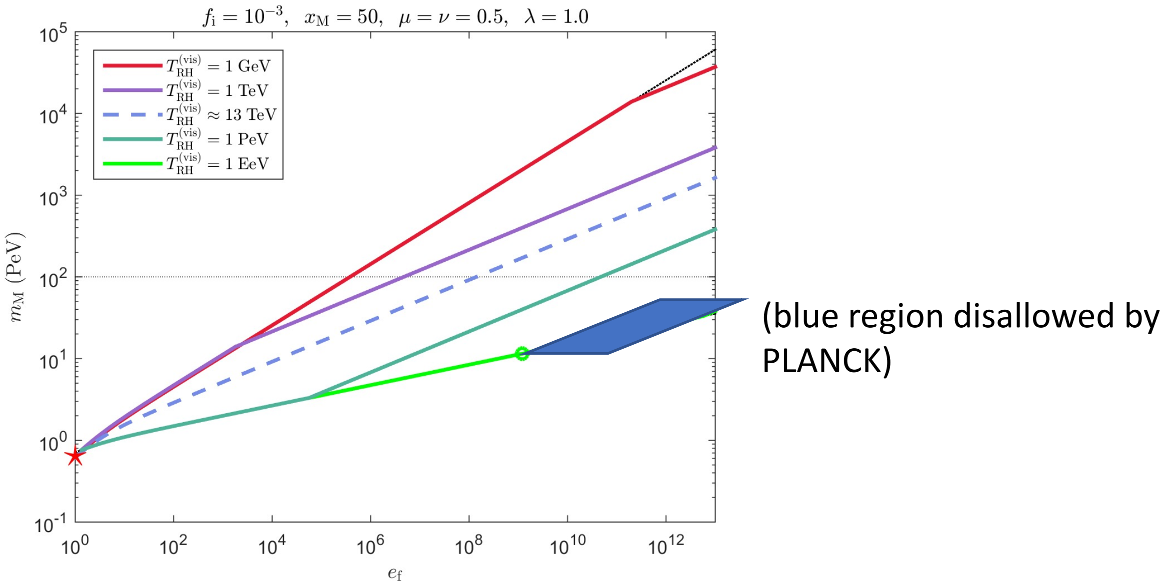
- For mmCP: we repeated same analysis and no region of effective magnetic coupling is possible, so for mmCPs magnetic plasma oscillations are irrelevant

Dark Sectors

- Symmetry breaking in dark sectors can naturally give dark monopoles
- Can be dark matter, produced non-thermally by the Kibble-Zurek mechanism as the Universe cools (phase transition is 2nd order)



Pure radiation-domination in early Universe
(Murayama and Shu, 2010)



With intervening matter-dominated era in early Universe
Lines give relic dark matter (MG, Osinski 2020)

Dark magnetic monopoles + kinetic mixing

At long distances (compared to inverse dark photon mass) :

- Ordinary electrically charged particles couple to dark photon
- Dark magnetic monopoles couple to ordinary photon
- Dark magnetic monopoles experience an effective magnetic field

$$B_{\text{eff}} = B_D - \varepsilon B$$

At short distances:

- Dark electrically charged particles couple to ordinary photon only suppressed by ε
  - Landau levels!
- Dark magnetically charged particles -> ε * additional (distance) suppressed interactions to ordinary photon