Magnetic Monopole Dark Matter

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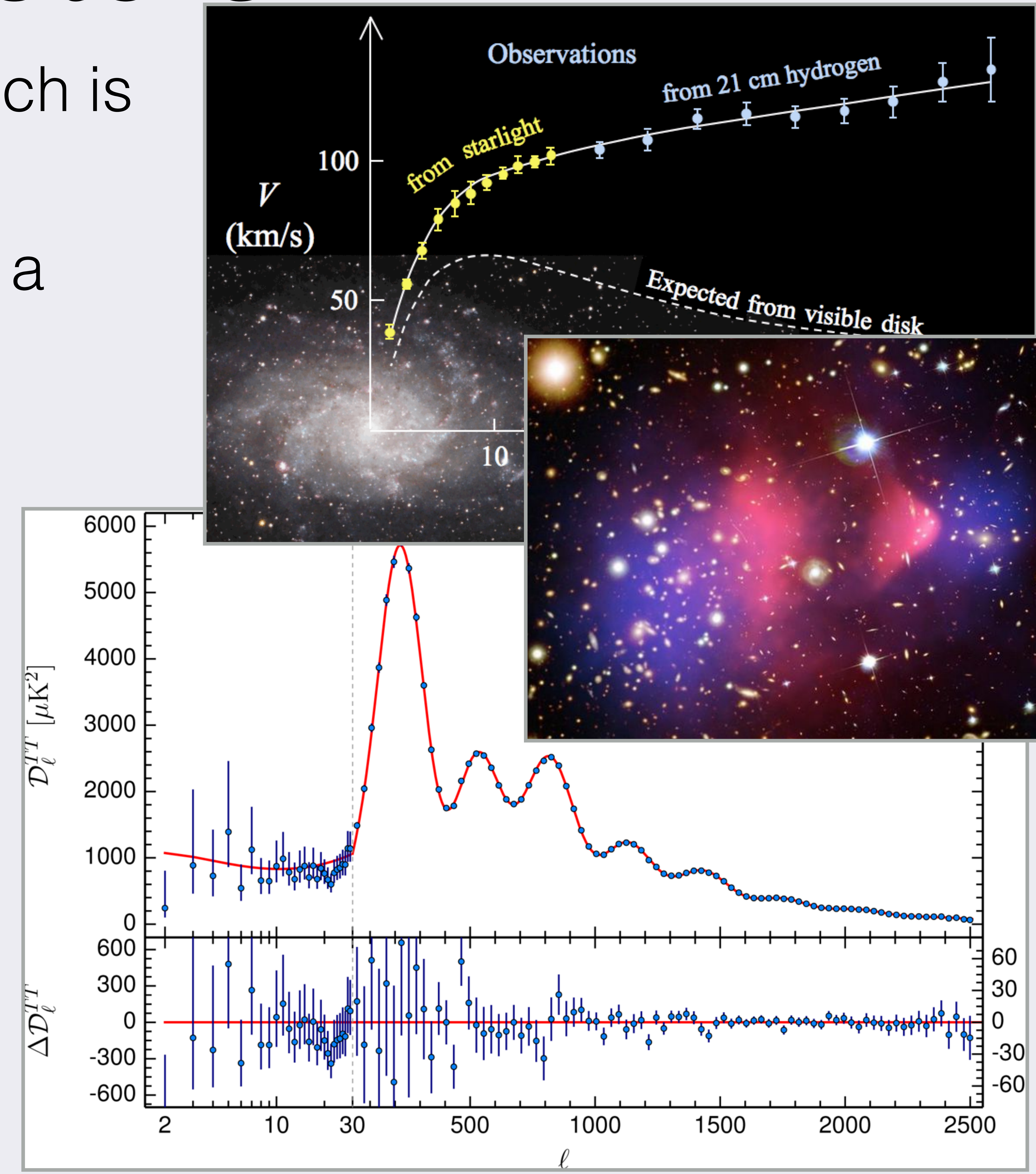
Dark Sectors

Much evidence dark matter, but not much is known about its particle nature

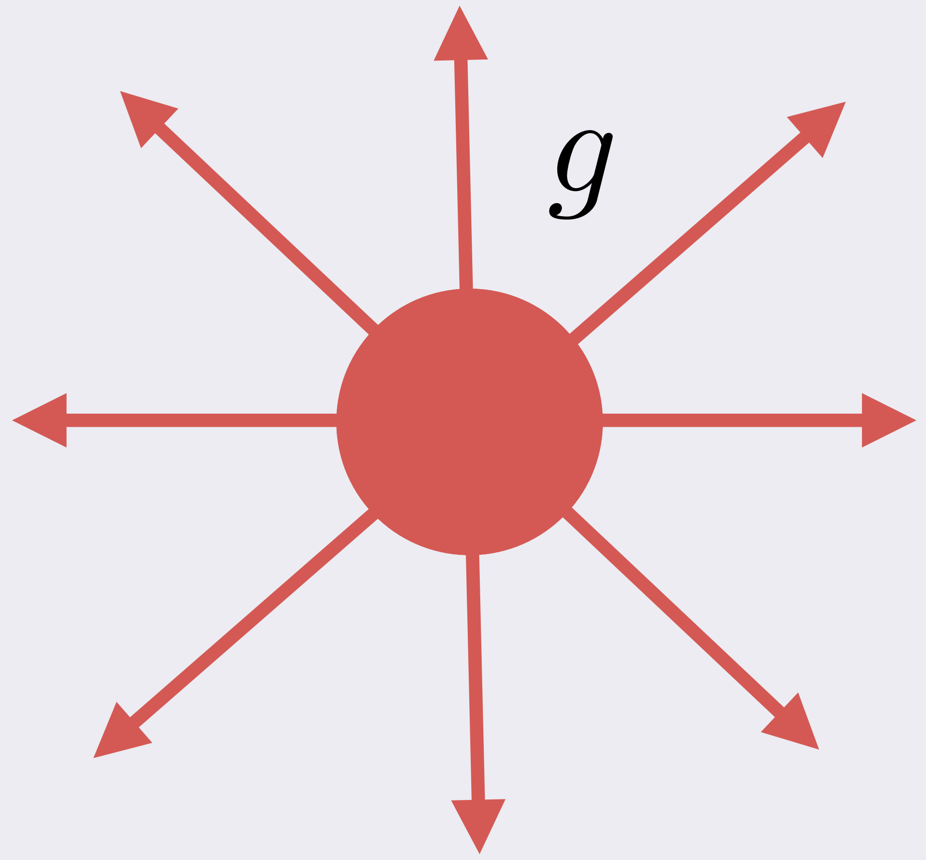
Early models of dark matter envisioned a single particle, or simple sector

Frameworks like Neutral Naturalness and Dynamical Dark Matter motivate richer hidden sectors

The dark sector may not be so different from ours



Dirac Monopoles



We naively consider a monopole as something like

$$\boldsymbol{B} = \frac{g}{r^2}\hat{\boldsymbol{r}}$$

This also implies that $\nabla \cdot \boldsymbol{B} \neq 0$, which is a bit worrying

We usually do all our quantum mechanics in terms of a vector potential that satisfies

$$\boldsymbol{B} = \nabla \times \boldsymbol{A} \;\Rightarrow\; \nabla \cdot \boldsymbol{B} = 0$$

Dirac cleverly determined a way to have our cake and eat it too

Dirac Monopoles

Simple construction, flux string with an endpoint

Change of string location is simply a gauge transformation

$$\vec{A}' = \vec{A} + g\nabla\Omega_C$$

The usual Aharonov-Bohm phase leads to charge quantization

$$qg = \frac{N}{2} \qquad b(\mu) = \frac{4\pi}{e(\mu)}$$

Same result from quantized angular momentum of the field between electric and magnetic charges, even if no string is invoked

$$\vec{L} = qg\hat{r}$$

Cleary Monopoles charged under the SM photon are too strongly charged to be Dark Matter

Magnetic Dark Matter

Consider a dark sector with a $U(1)_D$ gauge group and coupling e_D that has magnetic monopoles with coupling

$$b_D = \frac{4\pi}{e_D}$$

Such monopoles may be part of the dark matter, but how do we detect them?

If there is kinetic mixing between $U(1)_{\mathrm{E\&M}}$ and $U(1)_D$ then the dark monopoles can obtain a small coupling to our photon

To see how this happen, we need a local Lagrangian for electric and magnetic currents

A Local Lagrangian

Describing electric *and* magnetic charges with an action is tricky

Zwanziger developed a local Lagrangian at the cost of using two vector potentials

$$F^X_{\mu\nu} \equiv \partial_\mu X_\nu - \partial_\nu X_\mu$$

$$\mathcal{L} = -\frac{1}{4}\left(F^{\mu\nu}F^A_{\mu\nu} + {}^*F^{\mu\nu}F^B_{\mu\nu}\right) - eA_\mu J^\mu - \frac{4\pi}{e}B_\mu K^\mu$$

Local Magnetic

Local Electric

$$F_{\mu\nu} = \frac{n^\alpha}{n^2}\left(n_\mu F^A_{\alpha\nu} - n_\nu F^A_{\alpha\mu} - \varepsilon_{\mu\nu\alpha}{}^{\beta} n^\gamma F^B_{\gamma\beta}\right)$$

Related to Dirac String

Introduce a second copy in the dark sector and a kinetic mixing term

$$\mathcal{L}_\varepsilon = \varepsilon \frac{n^\alpha n^\mu}{n^2} g^{\beta\nu}\left(F^A_{D\alpha\beta}F^A_{\mu\nu} - F^B_{D\alpha\beta}F^B_{\mu\nu}\right) = \frac{\varepsilon}{2}F_{\mu\nu}F^{\mu\nu}_D$$

Perturbative Magnetic Charge

Kinetic mixing is not enough, we must also break the $U(1)_D$

When we add the electric mass term $-\frac{m_D^2}{2} A_{D\mu} A_D^{\mu}$

We find

$$\overline{J}_\mu = J_\mu \qquad \overline{J}_{D\mu} = J_{D\mu} + \epsilon e^2 J_\mu$$

$$\overline{K}_\mu = K_\mu - \epsilon e^2 K_{D\mu} \qquad \overline{K}_{D\mu} = K_{D\mu}$$

where the barred currents couple to the unmixed potentials

Electrically charged visible particles obtain small dark electric charge

Dark magnetic charges obtain small visible magnetic charge

The charge quantization: $\overline{q}\,\overline{g} + \overline{q}_D \overline{g}_D = q g + q_D g_D = \frac{N}{2}$

Physical Strings

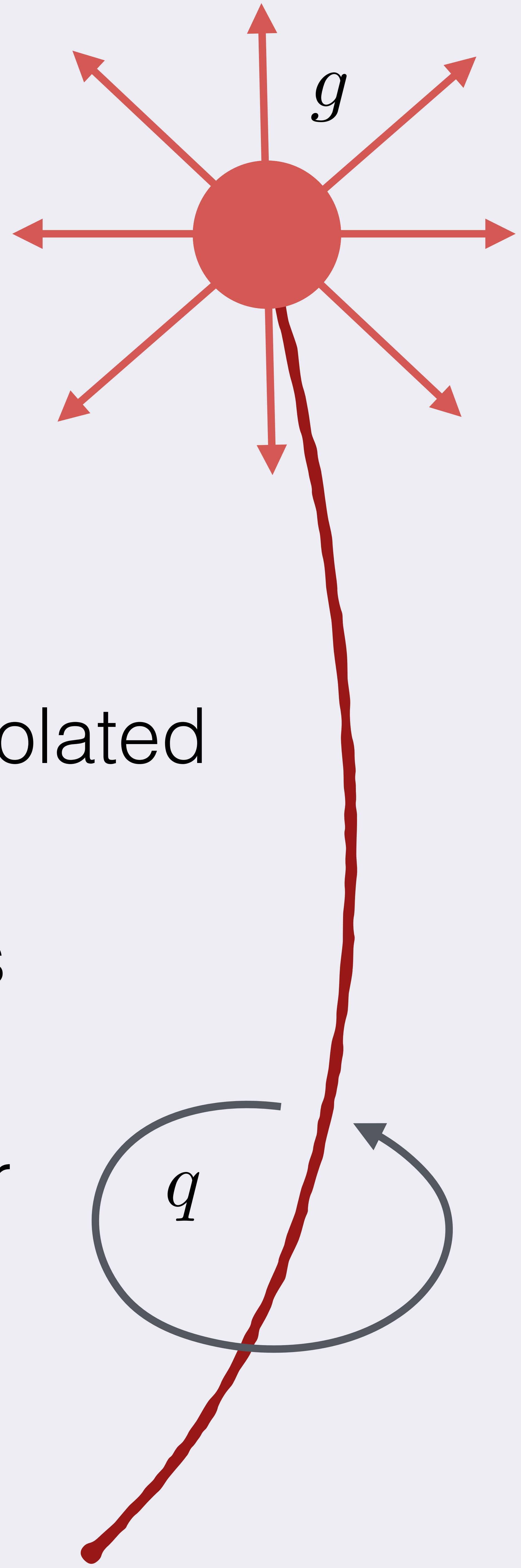
When the dark U(1) is broken by the mass term $-\frac{m_D^2}{2} A_{D\mu} A_D^\mu$

The dark magnetic charges that couple to B_D^μ confine

Monopole-antimonopole pairs are connected by Nielsen-Olesen flux tubes which behave like strings with tension $\sim \mathcal{O}(m_{DA}^2)$

This physical tube can be detected through Aharanov-Bohm (AB) phase shifts

Small Magnetic Charge



Below the dark photon mass, we can integrate it out

In this limit, there is only one contribution to the AB phase of a visible electric charge encircling a dark flux string:

$$\Phi_{\rm AB} = 4\pi\varepsilon q g_D$$

This physical phase indicates there charge quantization is violated at these low scales

In other words the flux string connecting the dark monopoles is physical

If these monopoles make up some fraction of the dark matter this phase shift presents a new search strategy

Magnetic Dipole Dark Matter

Magnetic dipoles like these can be made cosmologically stable if their constituents carry different flavor quantum numbers

We imagine some dynamics that give an asymmetry to particles of one flavor and antiparticles of the other, to preserve charge neutrality

The symmetric component of the populations annihilate quickly because of their large couplings, leaving the stable mixed flavor states

Terning CV 1906.00014

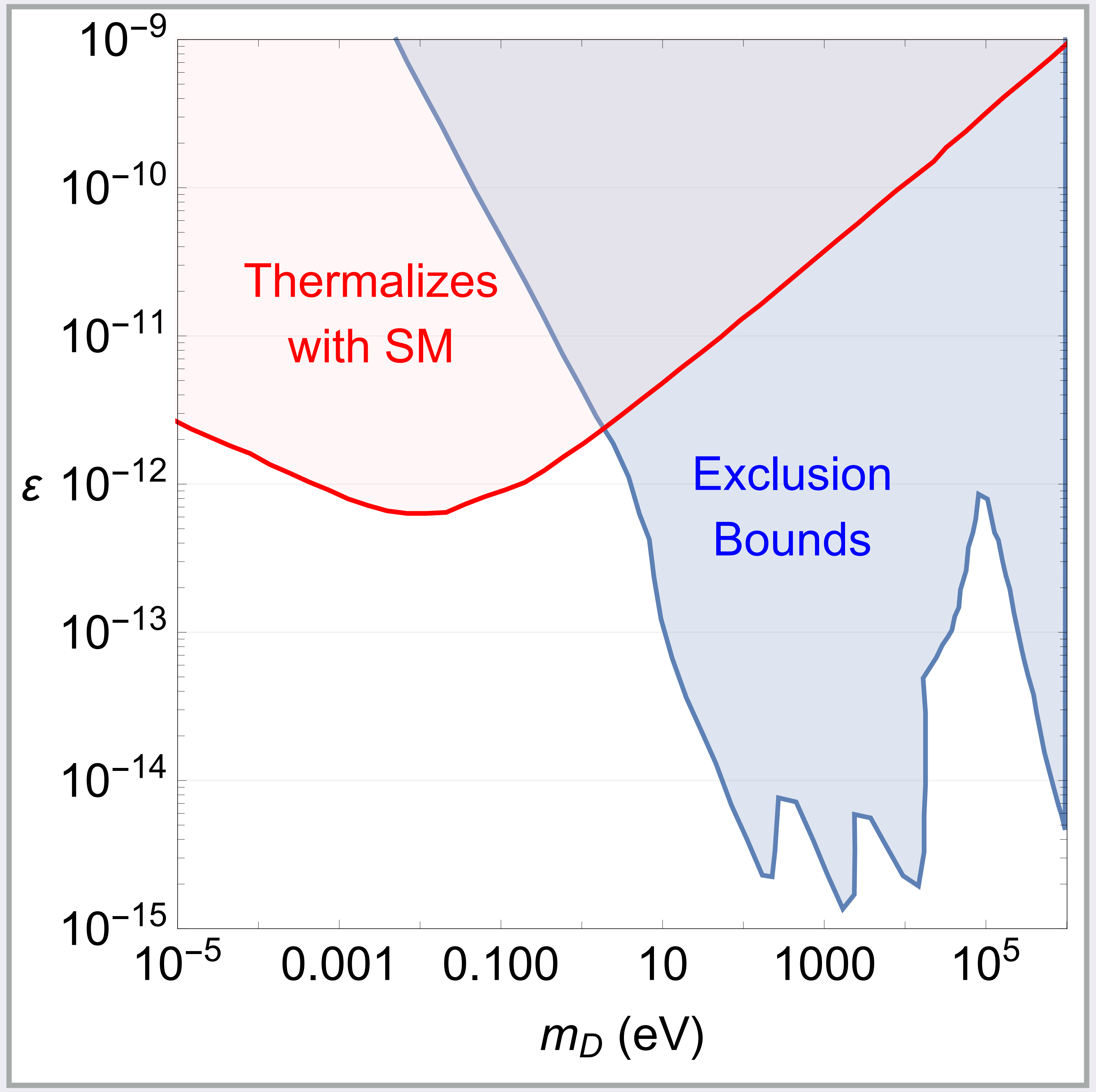
Constraints

The usual bounds on massive dark photons apply

In addition, the strong magnetic fields of magnetars can pair produce magnetic particles, providing a source of energy loss

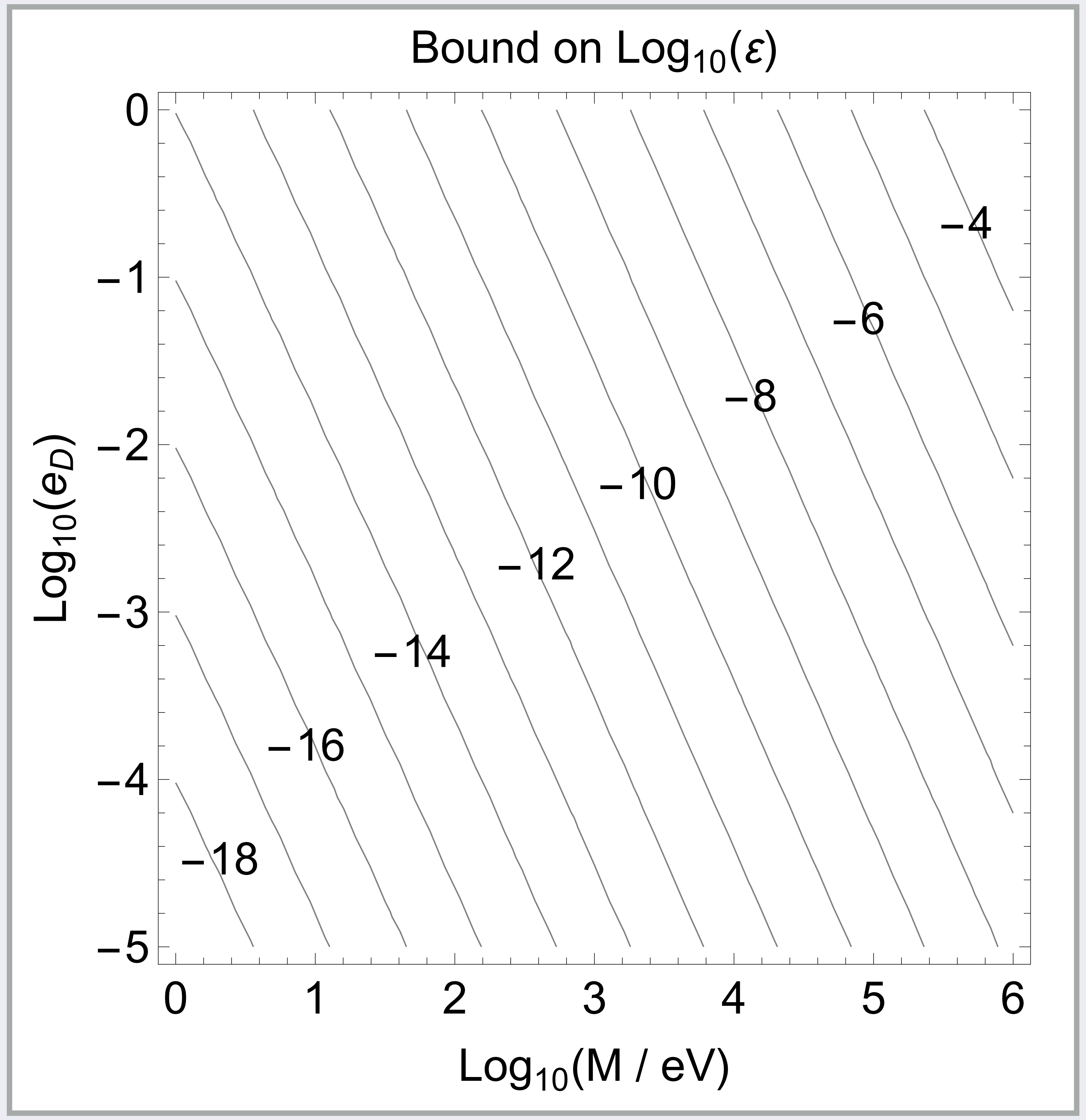
The final de-excitation of the bound states proceeds slowly by visible photon emission

Late photon decays are constrained, requiring that the monopoles never thermalize with the SM and initially confine in their ground state



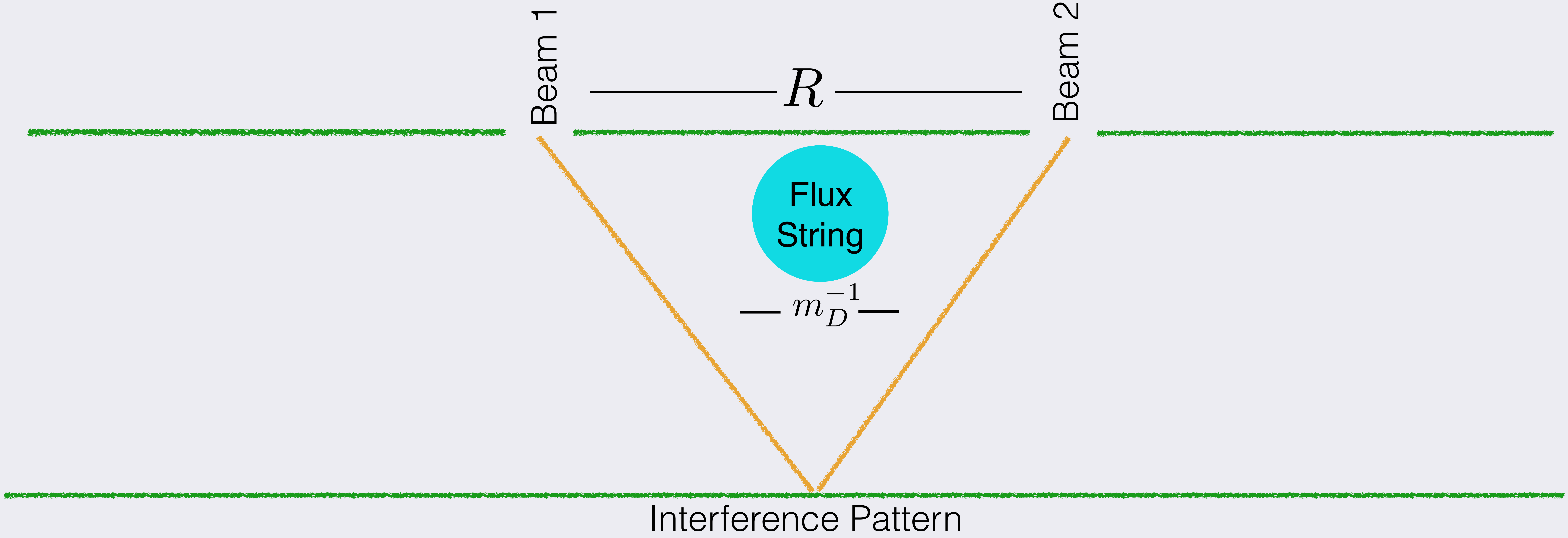
Magnetar Lifetimes

Hook, Huang 1705.01107



Aharonov-Bohm

Schematic of two-slit type experimental set up



The phase shift is $$\Phi_{AB} \sim 2\pi q g_D \frac{Le\varepsilon}{Re_D}$$

Results

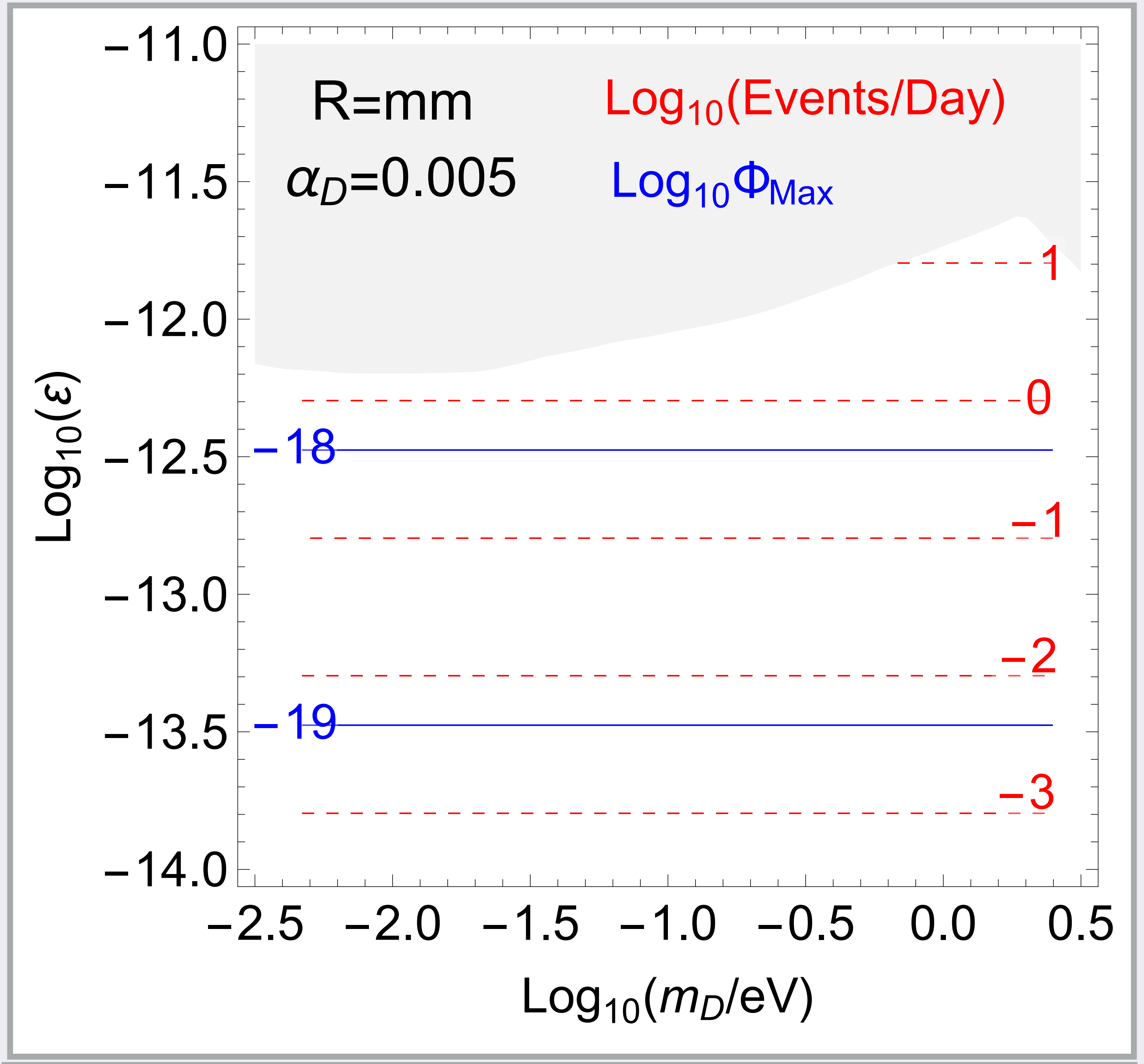
Latest AB phase precision was about (1986)

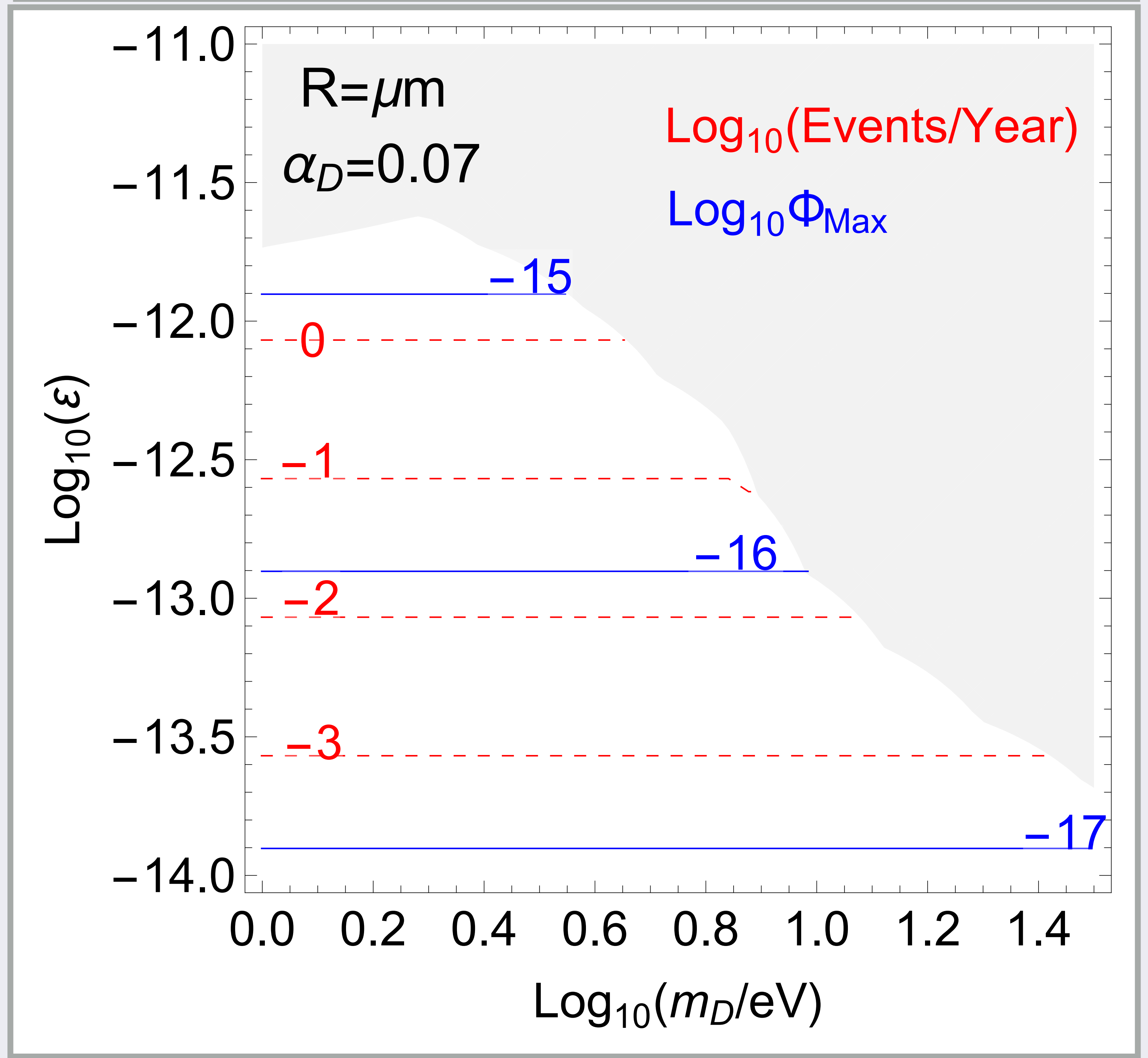
$$\Phi \sim 10^{-3}$$

But there was no need to go further

Since then electron beam technology, for electron microscopes as an example, has improved by orders of magnitude

Remember that many WIMP direct detection cross sections seemed impossibly low until there was a good reason to measure them





Conclusions

Dark Matter, or some fraction of it, can be made of the magnetic monopoles of a hidden sector

These monopoles can have have small, perturbative, couplings to the visible photon through photon kinetic mixing

This requires the hidden U(1) be broken, making the monopoles confine into dipoles

These dipoles give rise to phase shifts in Aharonov-Bohm experiments, providing a novel dark matter search strategy

Parameter Estimates

We can model the "quirky" dipole system by a confining linear potential

$$H = \frac{p^2}{M} + C\pi v_D^2 |r| = E$$

where v_D is the VEV that gives mass to the dark photon $m_D = e_D v_D$

This leads to the ground state estimates

$$E \sim M^{-1/3} \left(C\pi v_D^2\right)^{2/3} \qquad L \sim \left(C\pi M v_D^2\right)^{-1/3}$$

So, the smaller the dark photon mass, the longer the string, which enhances the AB signal, and the smaller the energy splitting between excited states

The bound state ground state is s-wave, it has no dipole moment, and hence no AB signal!

Milli Magnetic Constraints

In addition to the magnetar bound one should worry about stellar cooling

Within the plasma of a star the photon has an effective mass and decay into monopole pairs leading to additional cooling of the star

However, when both the visible and hidden photon have an electric mass the mixing angle that diagonalizes the masses is

$$\tan 2\phi = \frac{2\varepsilon m_P^2}{m_P^2 - m_D^2}$$

Away from mass degeneracy this makes the effective kinetic mixing

$$\varepsilon \to \varepsilon \frac{m_D^2}{m_D^2 - m_P^2}$$

For $m_D \ll m_P$ this weakens the bounds, making them subleading

Typical plasma masses are a few to tens of keV

A Local Lagrangian

$$\mathcal{L} = -\frac{n^\alpha}{2n^2}\left[n^\mu g^{\beta\nu}\left(F^A_{\alpha\beta}F^A_{\mu\nu} + F^B_{\alpha\beta}F^B_{\mu\nu}\right) - \frac{n_\mu}{2}\varepsilon^{\mu\nu\gamma\delta}\left(F^B_{\alpha\nu}F^A_{\gamma\delta} - F^A_{\alpha\nu}F^B_{\gamma\delta}\right)\right]$$

$$- eJ_\mu A^\mu - \frac{4\pi}{e}K_\mu B^\mu$$

Leads to the equations of motion $\partial_\mu F^{\mu\nu} = e\,J^\nu\ ,\quad \partial_\mu {}^*F^{\mu\nu} = \frac{4\pi}{e}\,K^\nu$

Where

$$F_{\mu\nu} = \frac{n^\alpha}{n^2}\left(n_\mu F^A_{\alpha\nu} - n_\nu F^A_{\alpha\mu} - \varepsilon_{\mu\nu\alpha}{}^\beta n^\gamma F^B_{\gamma\beta}\right)$$

$${}^*F_{\mu\nu} = \frac{n^\alpha}{n^2}\left(n_\mu F^B_{\alpha\nu} - n_\nu F^B_{\alpha\mu} + \varepsilon_{\mu\nu\alpha}{}^\beta n^\gamma F^A_{\gamma\beta}\right)$$

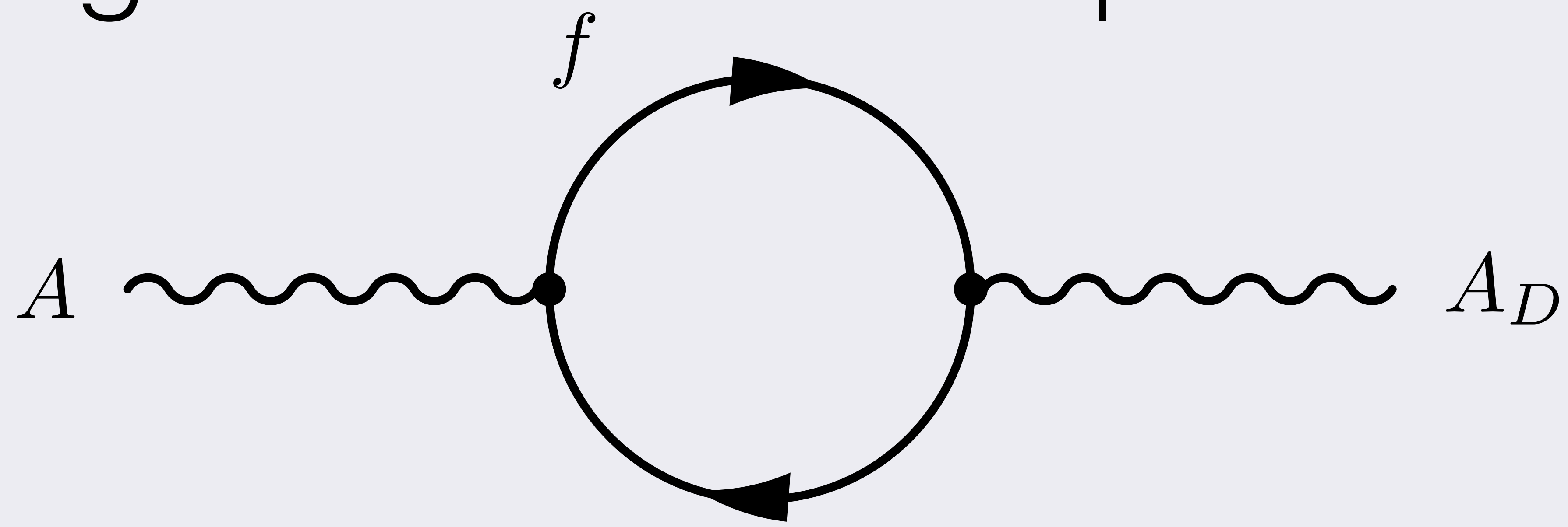
Note that both A_μ and B_μ source $F_{\mu\nu}$ and ${}^*F_{\mu\nu}$

n^μ can be associated with the direction of the Dirac string

Kinetic Mixing with Both Charges

Assume electric and magnetic charges in both the visible and dark sectors

Suppose at some high scale there are particles with electric charges under both U(1)s



The using Laperashvili and Nielsen hep-th/991010 1-loop kinetic mixing is

$$\mathcal{L}_\varepsilon = \varepsilon \frac{n^\alpha n^\mu}{n^2} g^{\beta\nu} \left(F^A_{D\alpha\beta} F^A_{\mu\nu} - F^B_{D\alpha\beta} F^B_{\mu\nu} \right) = \frac{\varepsilon}{2} F_{\mu\nu} F_D^{\mu\nu}$$

The relative sign comes from the non-perturbative charge quantization

$$b(\mu) = \frac{4\pi}{e(\mu)} \qquad Z_e = 1 + \Pi(\mu) \quad Z_b = \frac{1}{1+\Pi(\mu)} \approx 1 - \Pi(\mu)$$