Bounding milli-magnetic charged particles

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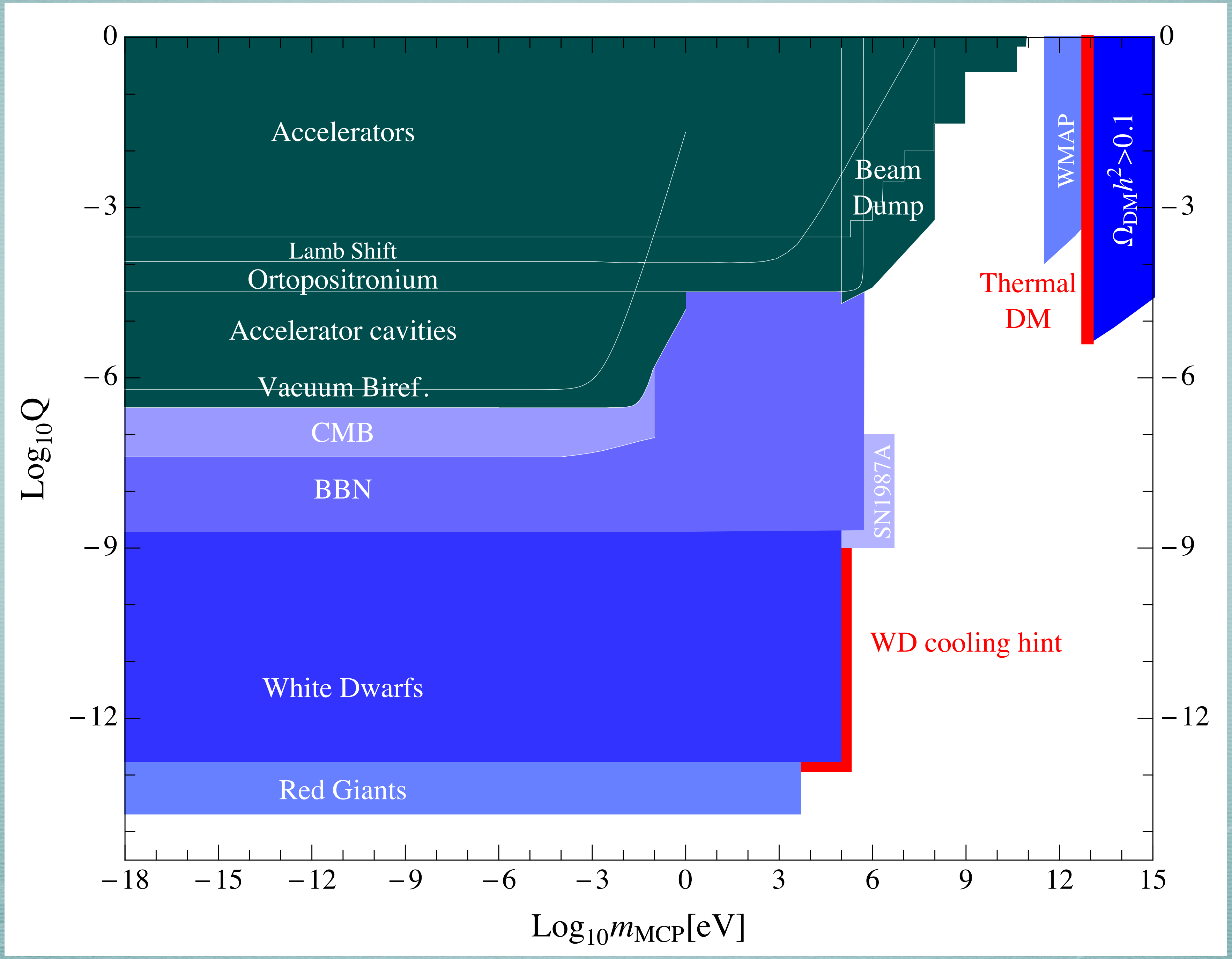
New light particles

- Old particle / new interactions
  - Fifth force
- New particle / old interactions
  - Gravity
  - Electricity and magnetism
- So what about new particles that carry charge and mass?

Milli-charged particles



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Milli-charged particles

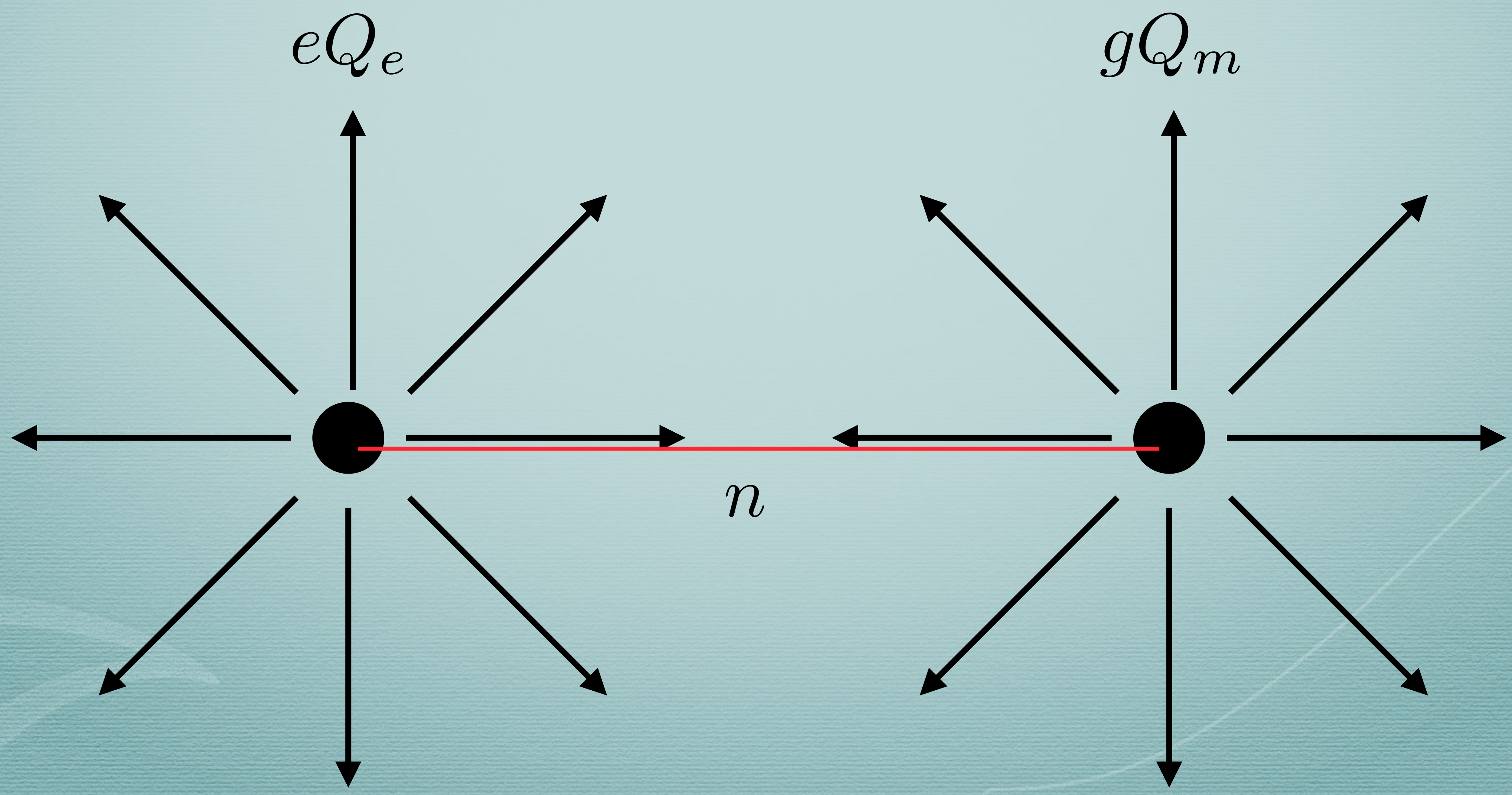
- Two types of charges under the photon
- Electric and magnetic (hence E+M)
- What about milli-magnetic charged particles?
    - Quantization of angular momentum

Angular momentum

- Electric charge can be quantized in units of electron charge but quarks have fractional charge
- Will evade constraints in a similar manner
  - Physical string
  - All finite energy objects have quantized charges

Angular momentum

$$L = \int d^3x\, x \times (E \times B) = \frac{eg}{4\pi} Q_e Q_m \hat{n}$$



Angular momentum

$$L = \int d^3x \, x \times (E \times B) = \frac{eg}{4\pi} Q_e Q_m \hat{n}$$

$$g = \frac{2\pi}{e} \qquad L = \frac{\mathbb{Z}}{2} \qquad Q_e Q_m = \mathbb{Z}$$

- Given that electrons exist, there exists a minimum magnetic charge
- Most work directed towards this mimimim charge

Angular momentum

$$L = \sum_i \int d^3x \, x \times (E_i \times B_i) = \sum_i \frac{e_i g_i}{4\pi} Q_e^i Q_m^i \hat{n}$$

$$\sum_i Q_e^i Q_m^i = \mathbb{Z}$$

- Generalization to multiple U(1)
- Can have charges which are subminimal!
- Rest of angular momentum carried by other U(1) field

Example

	E	B	E'	B'
e	1	0	ϵ	0
m	0	$-\epsilon$	0	1

- Angular momentum in U(1) canceled by angular momentum in U(1)’

Plausible?

- Milli-magnetic charged particles are possible but are they plausible?
- Claim - Just as plausible as any other scenario with dark photons

Kinetic Mixing

$$\mathcal{L} = -\frac{1}{4}F^2 - \frac{1}{4}F_D^2 + 2\epsilon F_D F + \frac{1}{2}m_D^2 A_D^2$$

- Dark photon with kinetic mixing
- Naturally gives epsilon charged matter

Kinetic Mixing

- Maxwell's equations are more natural when dealing with monopoles

$$\partial_\mu F^{\mu\nu} - \epsilon \partial_\mu F_D^{\mu\nu} = e J^\nu$$

$$\partial_\mu F_D^{\mu\nu} - \epsilon \partial_\mu F^{\mu\nu} = m_D^2 A_D^\nu + e_D J_D^\nu$$

$$\partial_\mu \tilde{F}^{\mu\nu} = 0$$

$$\partial_\mu \tilde{F}_D^{\mu\nu} = g_D K_D^\nu$$

Kinetic Mixing

$$A \to A + \epsilon A_D$$

- Photon is not massive
- Use field redefinition to remove kinetic mixing while keeping photons massless

Kinetic Mixing

$$A \rightarrow A + \epsilon A_D$$

$$\partial_\mu F^{\mu\nu} - \epsilon \partial_\mu F_D^{\mu\nu} = e J^\nu$$

$$\partial_\mu F_D^{\mu\nu} - \epsilon \partial_\mu F^{\mu\nu} = m_D^2 A_D^\nu + e_D J_D^\nu$$

$$\partial_\mu \tilde{F}^{\mu\nu} = 0$$

$$\partial_\mu \tilde{F}_D^{\mu\nu} = g_D K_D^\nu$$

Kinetic Mixing

- Our electron epsilon charged under their U(1)
- Their monopoles epsilon charged under our U(1)!

$$\partial_\mu F^{\mu\nu} = eJ^\nu$$

$$\partial_\mu F_D^{\mu\nu} = m_D A_D^\nu + e_D J_D^\nu + \epsilon e J^\nu$$

$$\partial_\mu \tilde{F}^{\mu\nu} = -\epsilon g_D K_D^\nu$$

$$\partial_\mu \tilde{F}_D^{\mu\nu} = g_D K_D^\nu$$

Kinetic Mixing

	E	B	E'	B'
e	1	0	ϵ	0
m	0	$-\epsilon$	0	1

- Exactly the charge assignments mentioned earlier

Physical Picture

$$\mathcal{L} = -\frac{1}{4}F^2 - \frac{1}{4}F_D^2 + 2\epsilon F_D F + \frac{1}{2}m_D^2 A_D^2$$

- What is the physical picture of this Lagrangian?

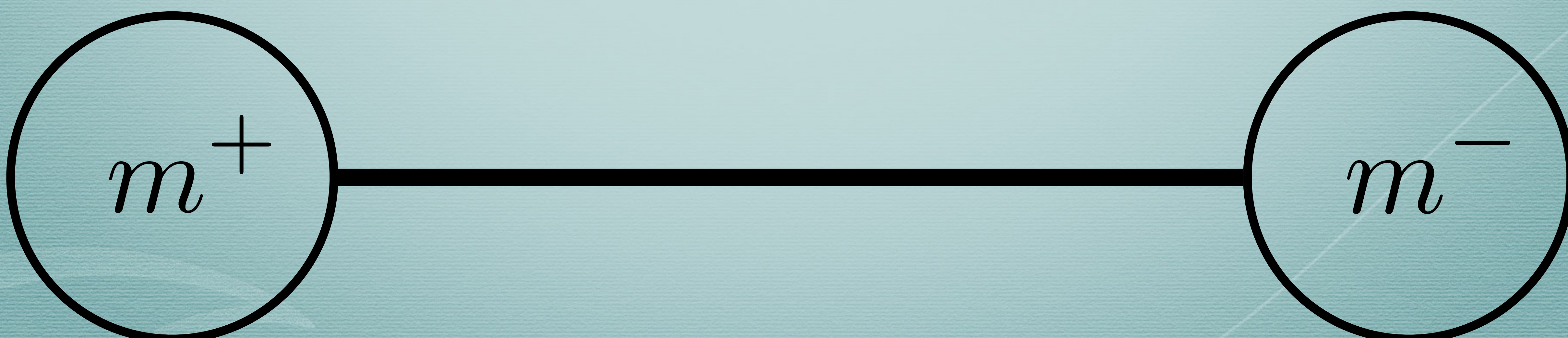
Physical Picture

	E	B	E'	B'
h'	0	0	1	0
e	1	0	ϵ	0
m	0	$-\epsilon$	0	1

- Milli-magnetic charge
- Dark U(1) Higgsed so monopoles are confined
    - Like QCD, strings connecting monopole with anti-monopole

Physical Picture

- Dark U(1) Higgsed so monopoles are confined
    - Like QCD, strings connecting monopole with anti-monopole



Physical Picture

	E	B	E'	B'
h'	0	0	1	0
e	1	0	ϵ	0
m	0	$-\epsilon$	0	1

If dark photon mass is irrelevant

- Electron generates a field $E, B, E' = \epsilon E, B' = \epsilon B$
- Monopole feels a field $E_{\text{eff}} = -\epsilon E + E' = 0$

$$B_{\text{eff}} = -\epsilon B + B' = 0$$

Physical Picture

	E	B	E'	B'
h'	0	0	1	0
e	1	0	ϵ	0
m	0	$-\epsilon$	0	1

$$B' = \epsilon B e^{-m_{A'} r}$$

- Electron generates a field
- Monopole feels a field
- As long as distance long enough that dark magnetic field is screened, then electron and monopole can interact

$$B_{\text{eff}} = \epsilon B (e^{-m_{A'} r} - 1)$$

Constraints

- If magnetic charges already exist around us
    - Astrophysical constraints/experimental constraints/…
- If they are not surrounding us

1. No constraints if they are non-perturbative (’t Hooft Polyakov monopoles)
2. Weak constraints if fundamental

Parker bound

$$\mathcal{F}_{\text{Parker}} = 10^{-16}\,\text{cm}^{-2}\,\text{s}^{-1}\,sr^{-1}$$

- Magnetic fields accelerate monopoles
  - Energy in monopoles comes from B field
  - If too much energy is taken, then B field of Milky Way neutralized
  - Usually applied to some cosmological abundance

Goal

- Obtain model independent bounds on milli-magnetic charged particles

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- Obtain model independent bounds on milli-magnetic charged particles
- Perturbative production can be exponentially suppressed
- Need non-perturbative production
- Exponentially large number of initial states (photons)
- Extremely large electric and magnetic fields

Schwinger pair production

- Production of electric (magnetic) particles in a strong electric (magnetic) field

$$\frac{P}{Vt} = \frac{e^2E^2}{4\pi^3}e^{\frac{-\pi m^2}{eE}}$$

$$\frac{P}{Vt} = \frac{\epsilon^2 g^2 B^2}{8\pi^3}e^{\frac{-\pi m^2}{\epsilon g B}+\frac{g^2}{4}} \qquad g = \frac{4\pi}{e}$$

Schwinger pair production

- We have monopoles connected by strings
- Easy to modify pair production to account for strings

$$\frac{P}{Vt} \sim e^{-\frac{\pi m^2}{eE - m_A^2}}$$

- As long as string tension smaller than ε Electric/Magnetic field then pair production proceeds as before

Schwinger pair production

- Unsuppressed production of milli-magnetic charged particles if there is a large magnetic field
- Largest magnetic fields in the universe are at magnetars
- Production of magnetic particles neutralizes magnetic field
  - Require that it is not neutralized over the lifetime of magnetar

Magnetars

- Neutron stars with extremely large magnetic fields
  - Size ~ 10 km
  - B ~ 10^{13-16} gauss ~ MeV^2
  - Age ~ 10^{3-5} years
  - Luminosity (persistent x-rays) ~ 10^{33-36} ergs/s ~ B^2 V/t
  - ~ 20 observed, ~ kiloparsec away
  - Not much known about them

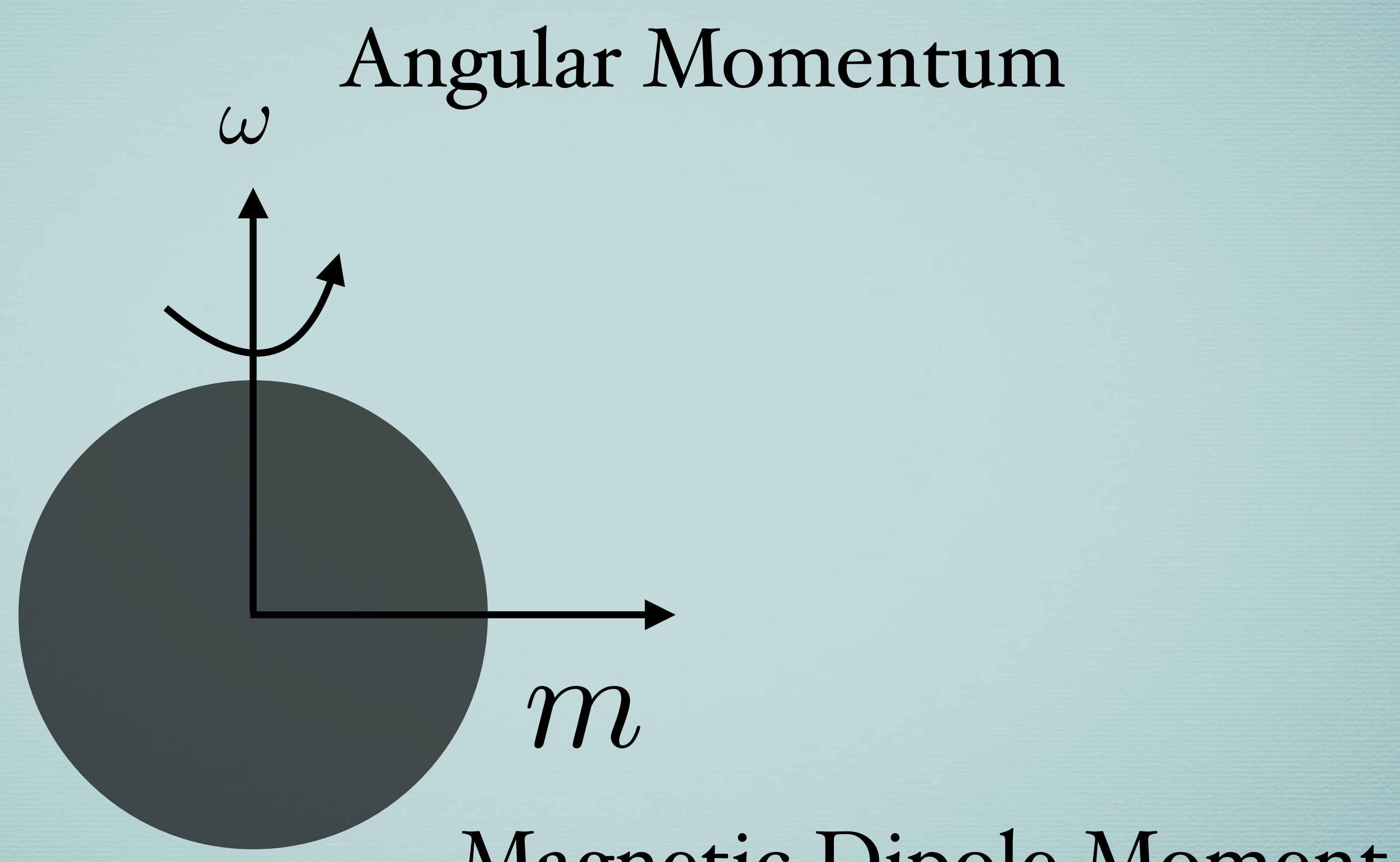
Magnetars

- Anomalous x-ray pulsars
  - Emit soft x rays
  - Anomalous because not powered by standard means
- Soft gamma-ray repeaters
  - Peak luminosity larger than Eddington limit

Magnetic Field

- Evidence for magnetic field is from soft gamma-ray bursts
    - Strong magnetic fields allow for super Eddington luminosity emissions
    - Fall off of burst depends on magnetic instabilities of the magnetar
- Crude estimate of the magnetic field can be made via loss of angular momentum

Magnetic Field



Magnetic Field

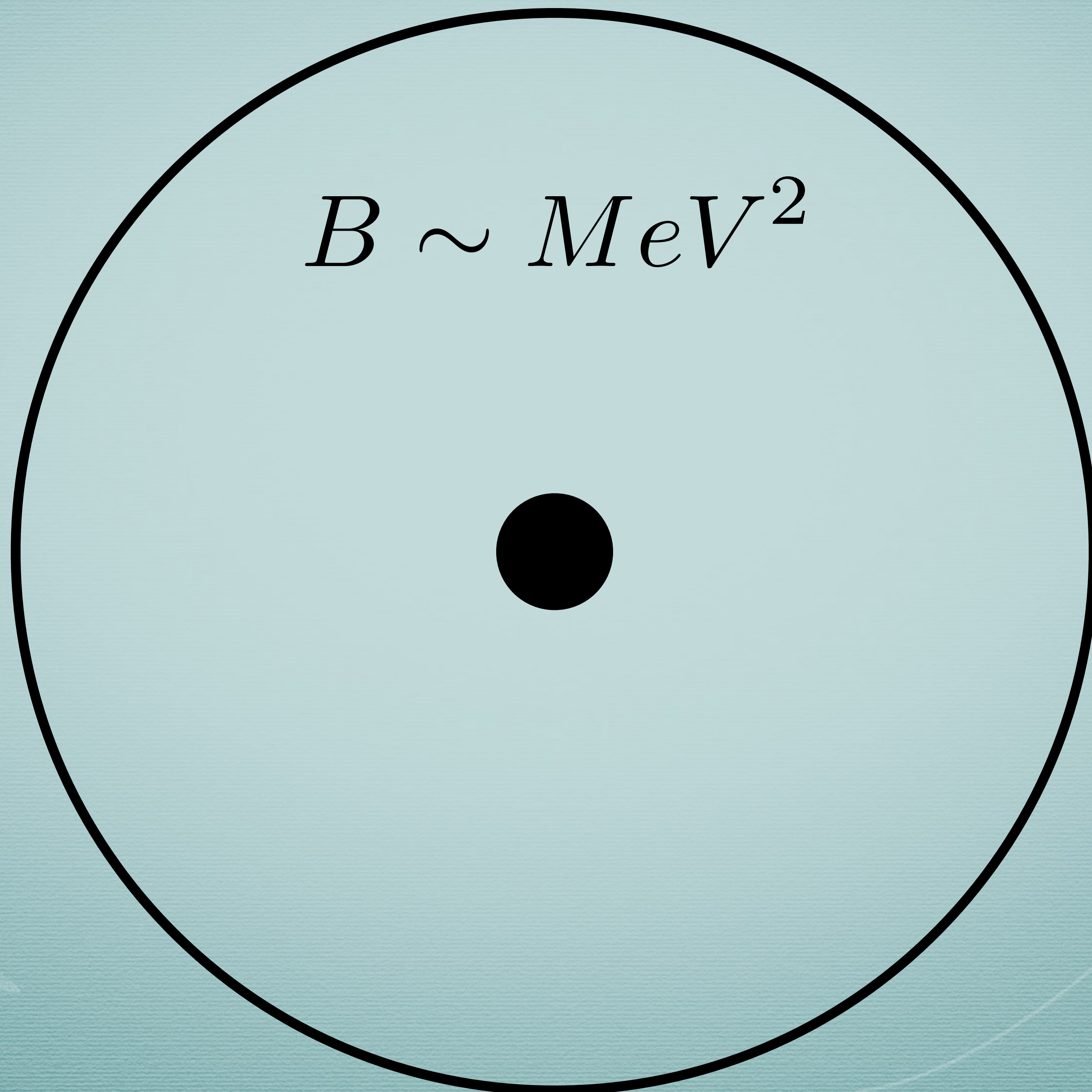
$$B \approx 3 \times 10^{19} \sqrt{\frac{P}{\text{second}} \dot{P}} \,\text{Gauss}$$

- Observed periods of a few seconds
- dP/dt ~ 10^{-11}
- B ~ 10^{15} gauss ~ MeV^2
- More refined estimates change results by only O(1) factors

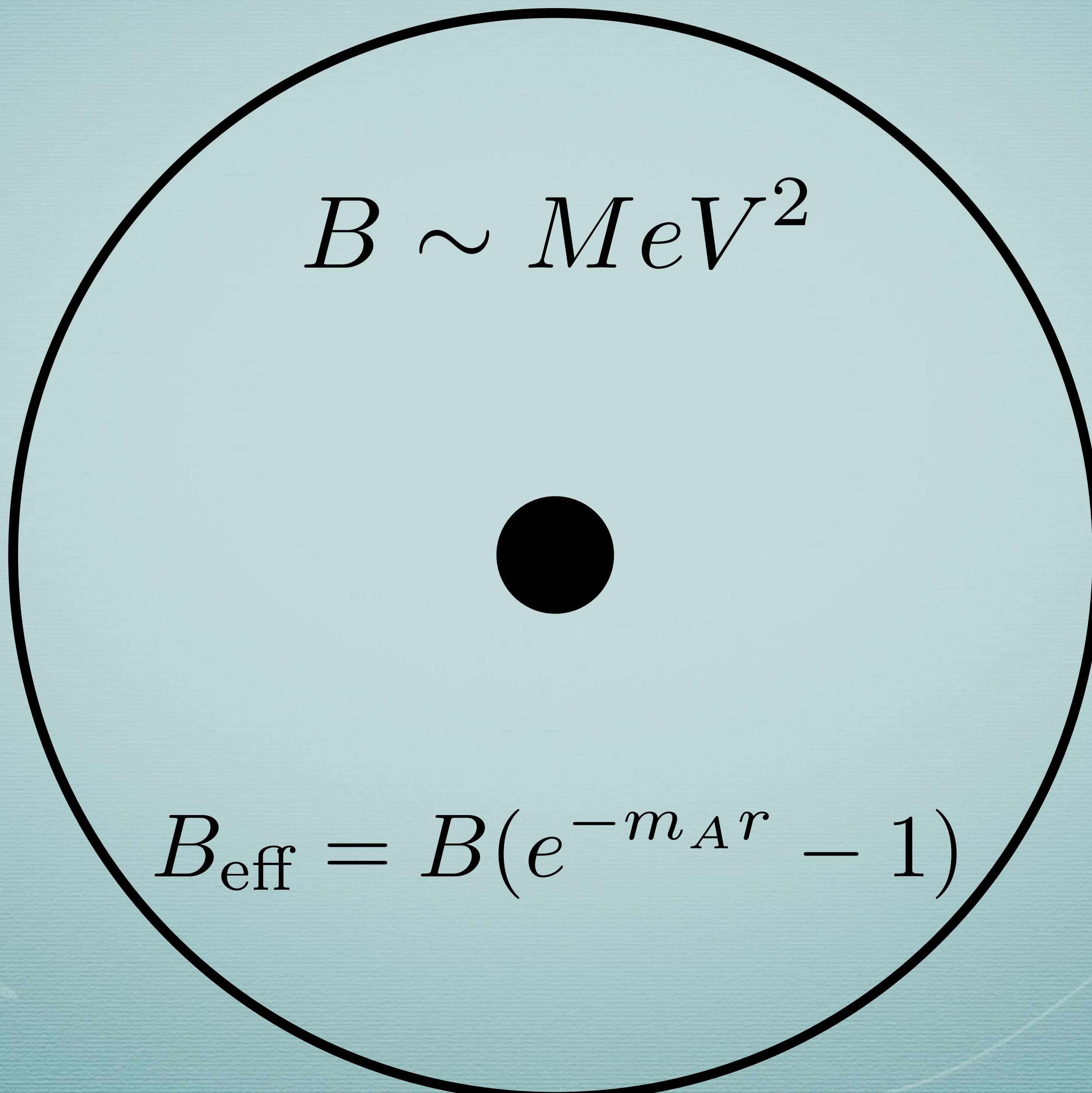
Magnetars

- Given huge uncertainties, we will take the following values
  - Radius = 10 km
  - $B = 10^{15}$ gauss
  - Age = 10^4 years

Magnetars



Magnetars



Bound

$$E_{\rm loss} = 2Q_m g B_{\rm eff} r$$

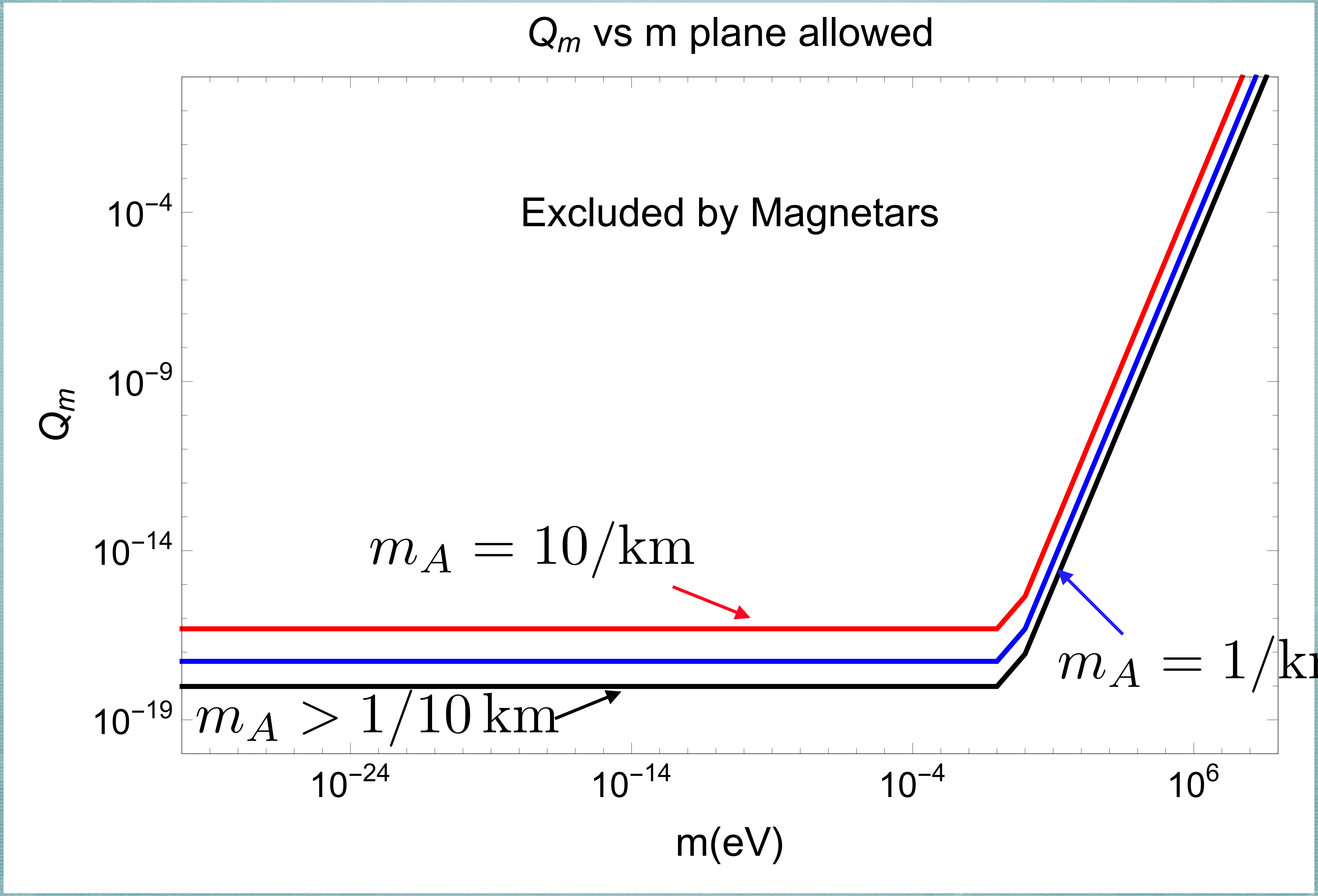
- Energy loss due to production of monopoles
- After pair production, monopoles carry away energy

Bound

$$\frac{dE}{dt\, dV} = \frac{Q_m^2 g^2 B_{\rm eff}^2}{4\pi^3} e^{\frac{-\pi m^2}{Q_m g B_{\rm eff}}} E_{\rm loss} \lesssim \frac{B^2}{2t_{\rm lifetime}}$$

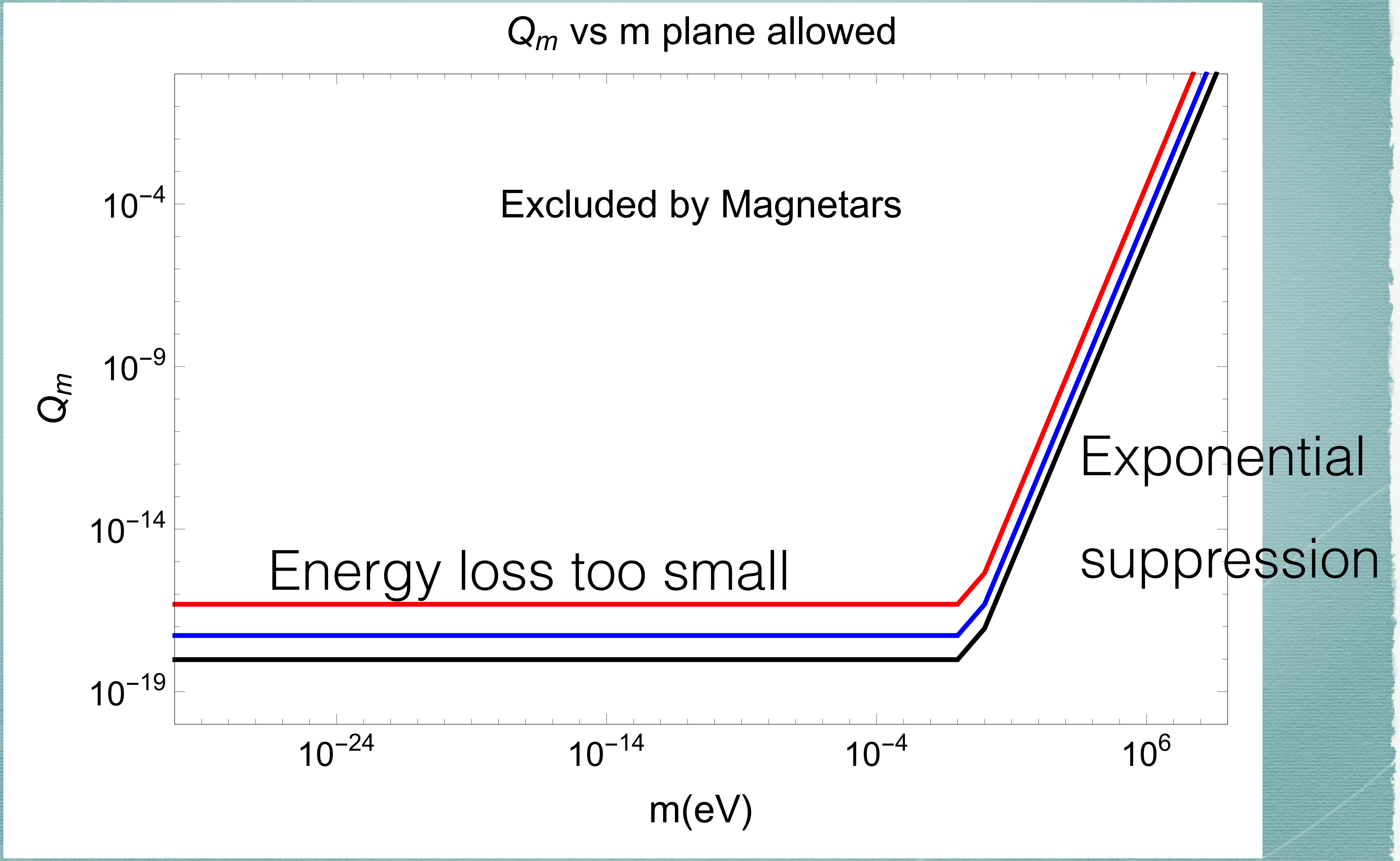
- Magnetic field is not neutralized by pair production during the lifetime of magnetar
- Equivalent to saying that total energy loss must be smaller than observed energy loss

Bound



Q_m vs m plane allowed
Excluded by Magnetars
Q_m
10^{-4}
10^{-9}
10^{-14}
10^{-19}
10^{-24}
10^{-14}
10^{-4}
10^{6}
m(eV)
$m_A = 10/\mathrm{km}$
$m_A = 1/\mathrm{km}$
$m_A > 1/10\,\mathrm{km}$

Bound


Q_m vs m plane allowed
Excluded by Magnetars
Energy loss too small
Exponential
suppression
Q_m
10^{-4}
10^{-9}
10^{-14}
10^{-19}
10^{-24}
10^{-14}
10^{-4}
10^{6}
m(eV)

Conclusion

- Just like there can be milli-electric charged particles, there can be milli-magnetic charged particles
- Currently NO model independent bounds
    - Model dependent bounds are weak and often come from cosmology
- Magnetars have large magnetic fields that let one place new very strong model independent bounds