Title: Bounding Milli-magnetic charged particles

Date: Mar 14, 2017 01:00 PM

URL: http://pirsa.org/17030083

Abstract: <p>Just like how milli-electric charged particles can exist, so can milli-magnetic charged particles. We review simple ways of evading the standard quantization arguments and why there are no model independent constraints on magnetically charged particles, milli-charged or not. We then provide the first ever model independent bounds coming from magnetar cooling arguments.</p>

Bounding milli-magnetic charged particles

Anson Hook
Stanford

Work in Progress with
Junwu Huang
170X.XXXX

New Particles

- Particle physics has been all about finding new particles
- Particles that make us up (leptons/quarks/Higgs)
- Particles that carry forces (photon/gluon/W/Z/graviton)

Where are they?

- Heavy
  - They have large masses so we haven't been able to produce them yet
- Light but weakly coupled
  - We can produce them, but they are weakly coupled so hard to produce and hard to see

How to find them

- Heavy
    - Collide things at higher and higher energies
- Light but weakly coupled
    - High intensity/luminosity (Do experiment many many many times)

Heavy particles

- At high energies everything interconverts
- Just collide stuff, doesn't matter what it is

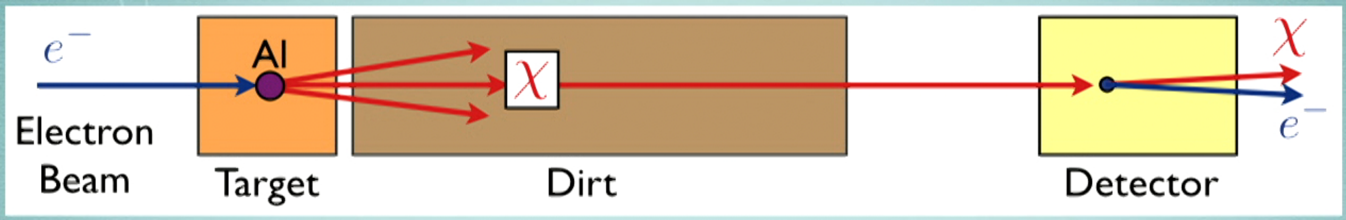
Light particles

- Need high intensity (of what?)
- Converting between particles rarer so what it couples to and how it couples matters
    - Electrons/muons/protons/dark matter/…
    - Gauge charge/dipole moments/Yukawa interactions/…
- Many options = many different experiments

High intensity colliders

- Standard collider but just run at very high luminosity
- Explores new particles weakly coupled to protons/electrons

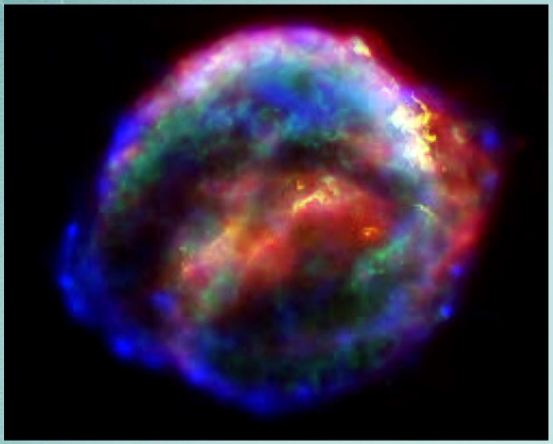
Beam Dump



1406.2698v2

- Collide a large number of protons or electrons or atoms with atoms
- Explores new particles weakly coupled to protons/electrons/atoms/…

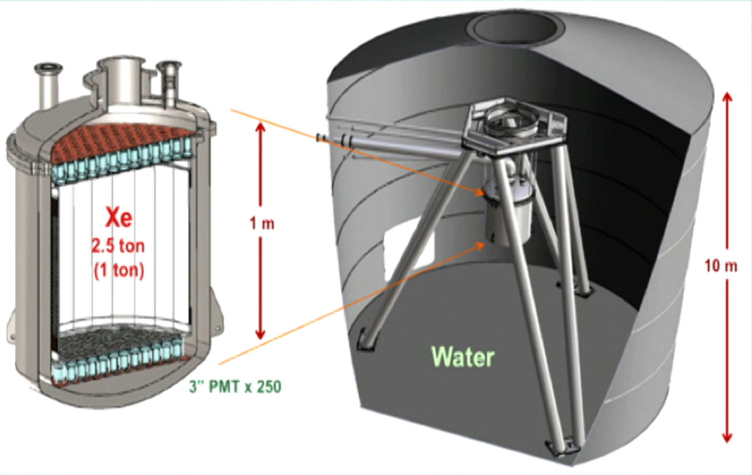
High density



- Neutron stars
- Red Giants
- Supernova

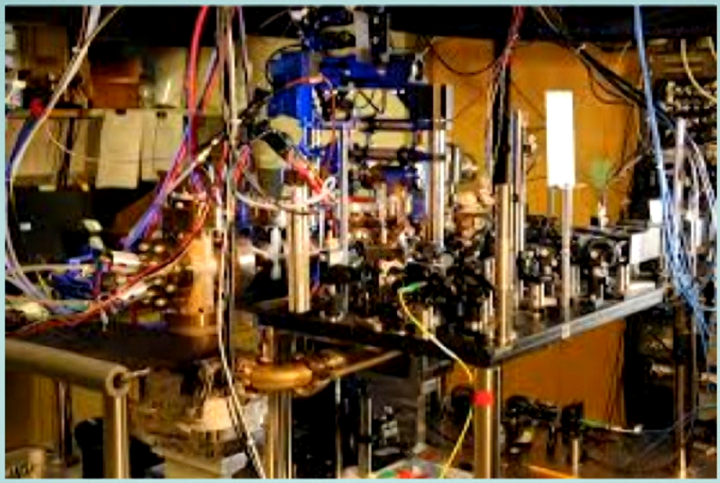
- New particles as new sources of
  - Cooling
  - Energy transport
  - Production mechanism combined with direct detection

Direct detection : Dark matter



- Large energy flux of dark matter
- Collision of dark matter with nuclei
    - Nuclear recoils
    - Electron recoils in the future

Dark Matter

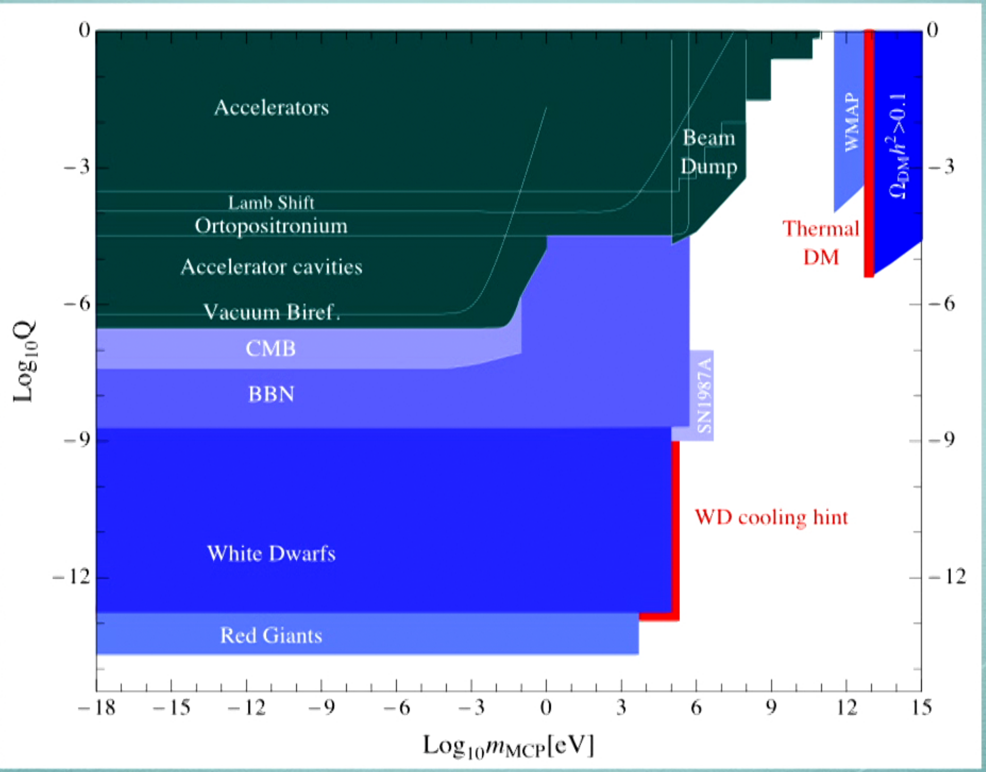


- If dark matter has macroscopic size look for time dependent processes
    - Time dependent dipole moments, charge, mass…

New light particles

- Many different scenarios
- New particle / old interactions
  - Gravity
  - Electricity and magnetism
- So what about new particles that carry charge and mass?

Milli-charged particles



1311.0029

Milli-charged particles

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

Outline

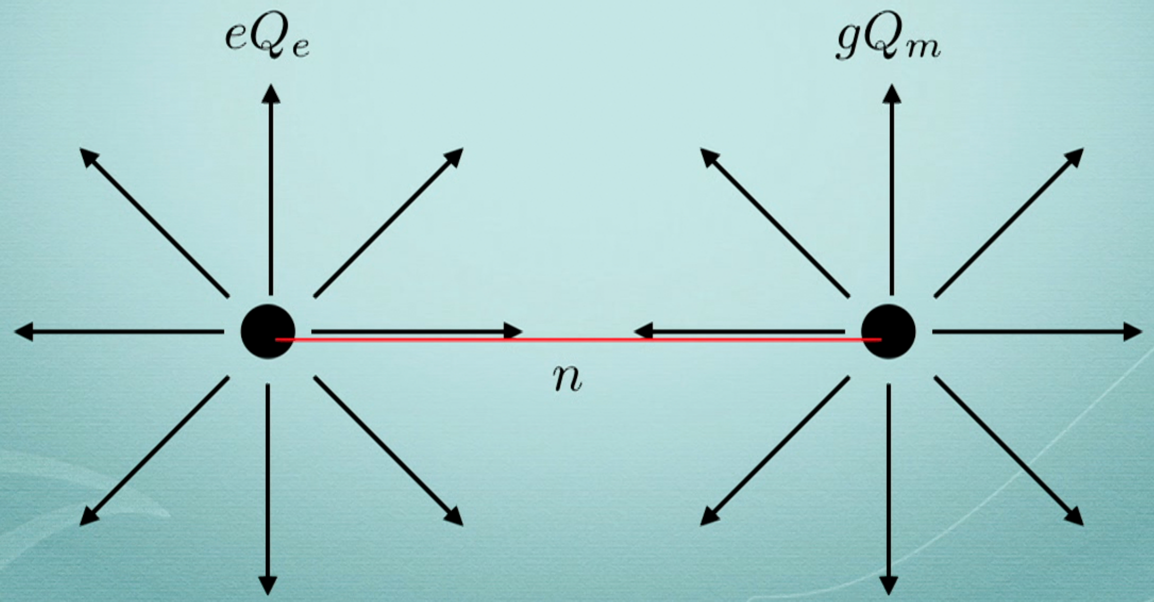
- Milli-magnetic charged particles
- Constraints
- Conclusion

Milli-magnetic charge

- Monopoles : Yes
- Milli-magnetic charges : ???
- Why don't people look for this?
- Quantization of angular momentum

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

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
  - Fractional charges?
  - Monopoles at low energy?

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
- Electron has milli charge under dark U(1)

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

Kinetic Mixing

$$\mathcal{L} \supset \epsilon F F_D$$

$$E \leftrightarrow E_D$$
$$B \leftrightarrow B_D$$

- Dark Monopoles pick up milli-magnetic charge
  - Result required by consistency
  - Can be seen explicitly for 't Hooft Polyakov monopoles

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

Magnetic transformation

$$\mathcal{L} \supset F^2 + F\tilde{G}$$

- Integrate out G
  - Theory of the photon
- Integrate out F
  - Theory of the dual photon

Magnetic transformation

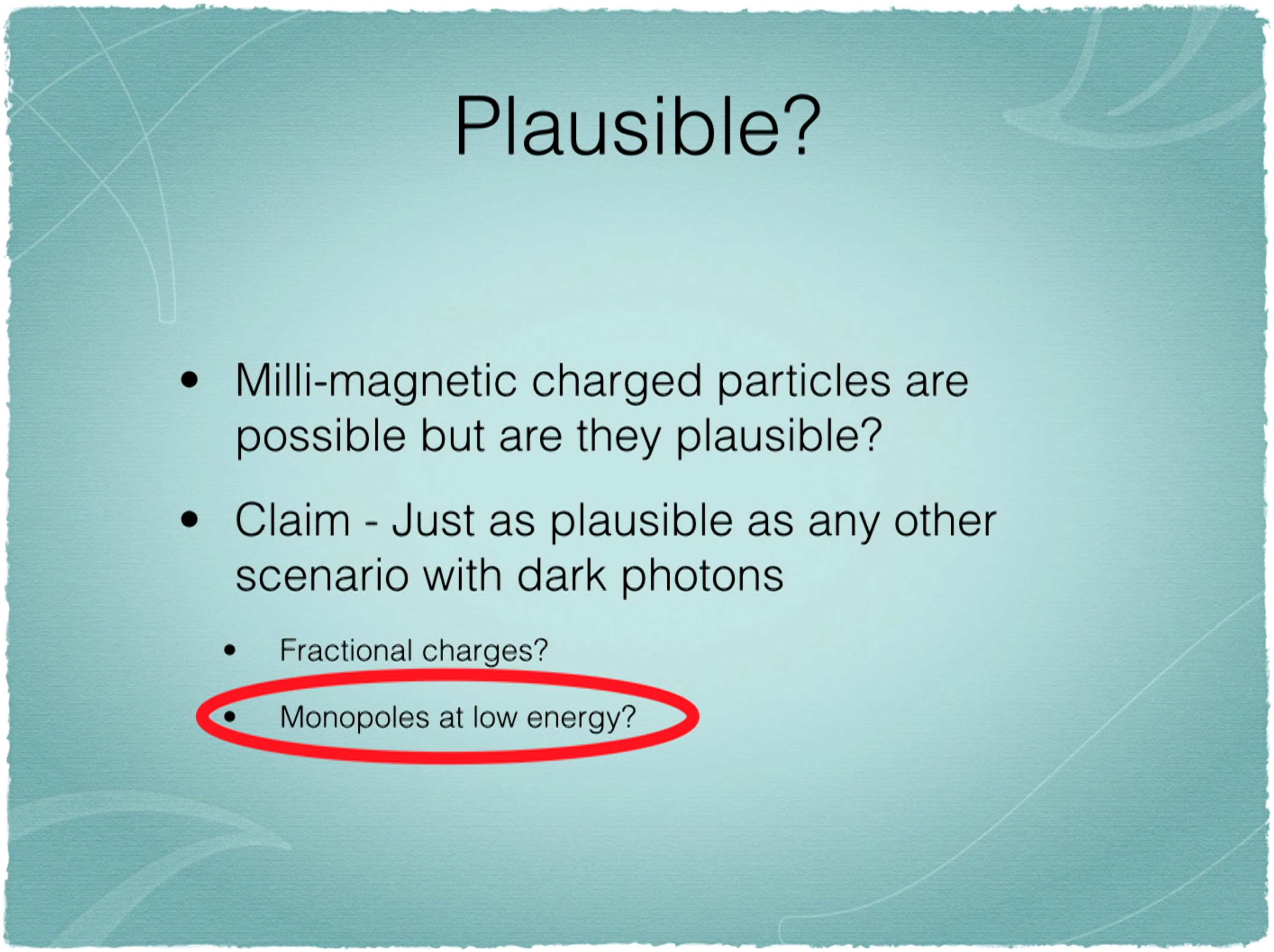
$$\mathcal{L} \supset F^2 + F_D^2 + \epsilon F_D F + F\tilde{G} + F_D \tilde{G}_D$$

- Remove kinetic mixing by field redefinition

$$A \to A + \epsilon A_D$$
$$B_D \to B_D - \epsilon B$$

- Their monopoles become charged under our E+M

$$\mathcal{L} \supset F^2 + F_D^2 + F\tilde{G} + F_D \tilde{G}_D$$


Plausible?
Milli-magnetic charged particles are possible but are they plausible?
Claim - Just as plausible as any other scenario with dark photons
Fractional charges?
Monopoles at low energy?

Light monopoles?

- Strong theory bias against light monopoles
- Due to the original discovery of monopoles in grand unified theories

Light monopoles?

$$\mathcal{L} \supset -\frac{1}{4}F^2 - \frac{1}{4}F_D^2 + 2\epsilon F\tilde{F}_D + \frac{1}{2}m_D^2 B_D^2$$

- Perform E+M duality on the previous example
- Electron now : perfectly reasonable for it to be light!

Light monopoles?

	E	B	E'	B'
e	1	0	0	$-\epsilon$
e_D	0	$-\epsilon$	1	0

- Just a dark electron with magnetic mixing
- Magnetic Stuckleberg mass

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?

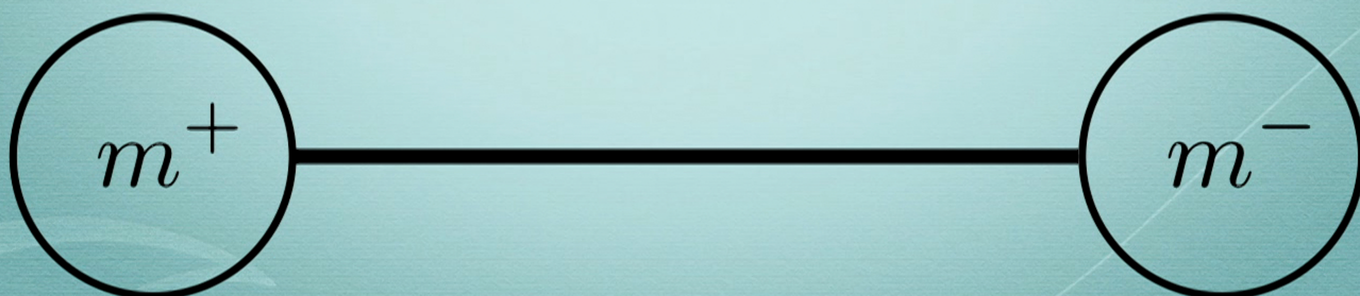
Physical Picture

	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

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

- As long as distance long enough that dark magnetic field is screened, then electron and monopole can interact

Outline

- ~~Milli-magnetic charged particles~~
- Constraints
- Conclusion

Constraints

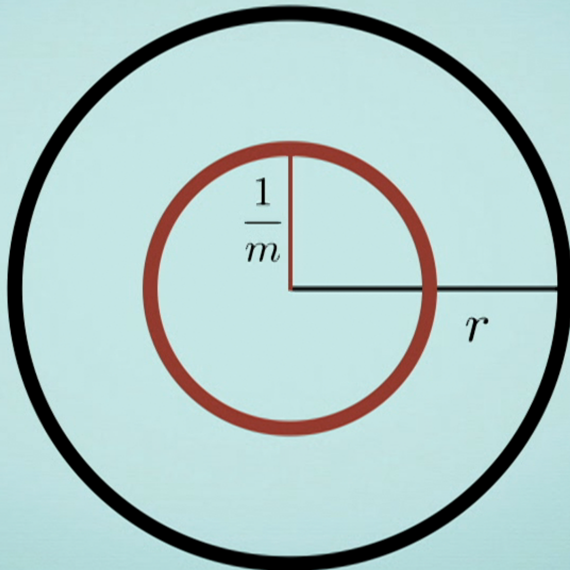
- If magnetic charges already exist around us
  - Astrophysical constraints/experimental constraints/…
- If they are not surrounding us
  1. No constraints if they are non-perturbative ('t Hooft Polyakov monopoles)
  2. Weak constraints if fundamental

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

Non-perturbative monopoles



- ’t Hooft Polyakov monopoles have size larger than Compton wavelength

Non-perturbative monopoles

- Magnetic charge conserved so pair produce monopoles
- De Broglie wavelength of colliding particles much smaller than physical size of monopoles
- Cross section for producing particles is exponentially suppressed due to decoupling

Goal

- 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

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

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

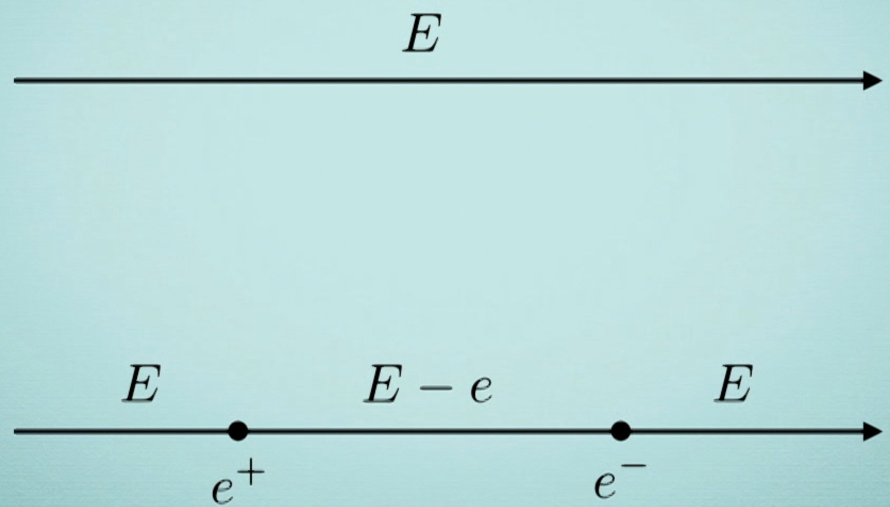
Schwinger pair production

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

- If electric field larger than mass of fermion, then unsuppressed production of fermions
- As mentioned before, everything can always be understood physically

2D example

- Two equal energy configurations



$$eEd = 2m_e$$

2D example

- As mentioned before, things are exponentially suppressed if length scales don't match
- Creating a pair of electrons a distance $d = \frac{2m_e}{eE}$ apart
- Quantum mechanical size associated with an electron is $1/m_e$
- Process is no longer exponentially suppressed if $d < \frac{1}{m_e}$

Schwinger pair production

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

- Intuitive understanding of formula in terms of distance scales
- Milli-magnetic charged particles have strings attached

2D example

- Energetically string energy is

$$E_{\text{string}} = m_A^2 d$$

- Unsuppressed production occurs when

$$d \sim 1/m$$

- String irrelevant to pair production when

$$E_{\text{string}} = m_A^2/m < E_{\text{else}} = 2m$$

$$m_A < m$$

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 ~ $10^{13\text{-}16}$ gauss ~ MeV^2
  - Age ~ $10^{3\text{-}5}$ years
  - Luminosity (persistent x-rays) ~ $10^{33\text{-}36}$ ergs/s ~ B^2 V/t
  - ~ 20 observed, ~ kiloparsec away
  - Not much known about them

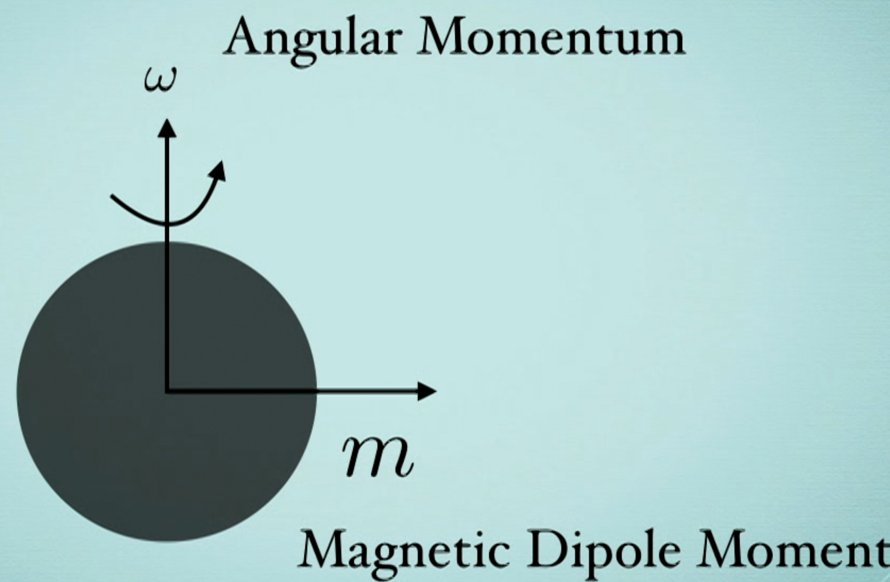
Magnetars

- 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

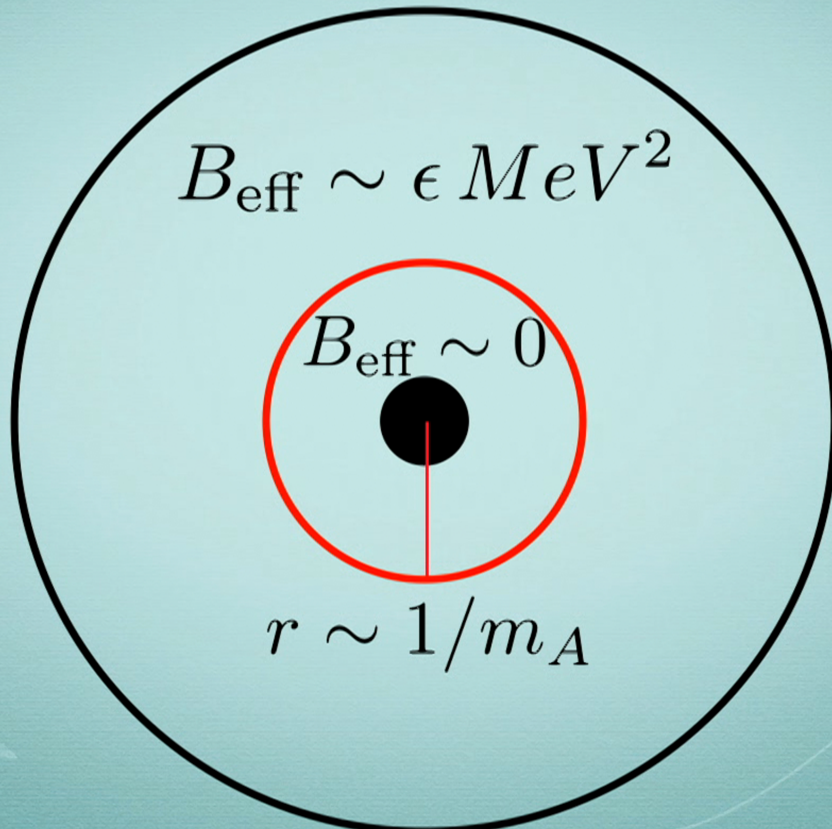
- Given huge uncertainties, we will take the following values
  - Radius = 10 km
  - $B = 10^{15}$ gauss
  - Age = 10^4 years

Magnetars

$$B \sim MeV^2$$

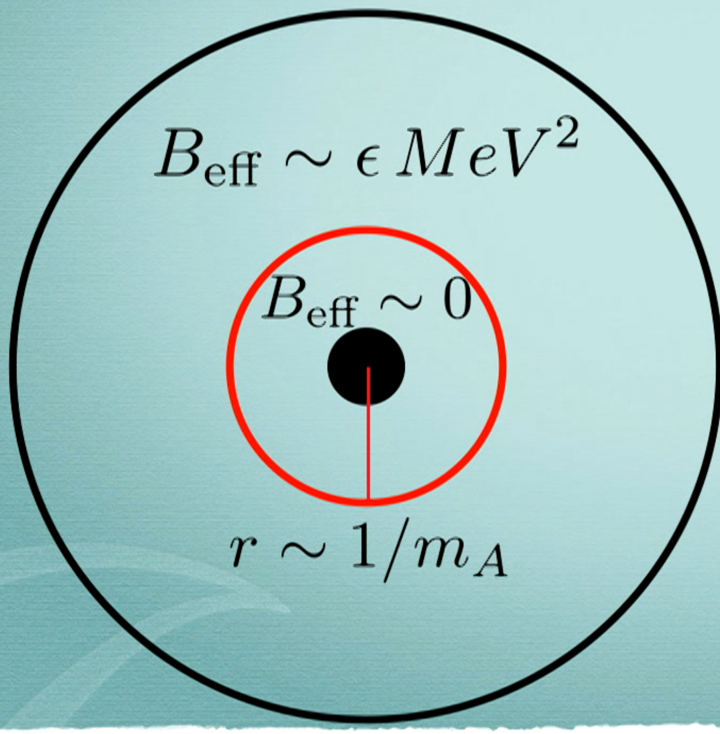
$$B_{\text{eff}} = \epsilon B (e^{-m_{A'} r} - 1)$$

Magnetars



Magnetars

$$10\,\mathrm{km} = r > 1/m_A > 1/m$$



Magnetic field needs to extend more than $1/m_A$ away so that milli-magnetic charged particle feels B field and can screen it

Bound

$$E_{\text{loss}} = 2Q_m g B r$$

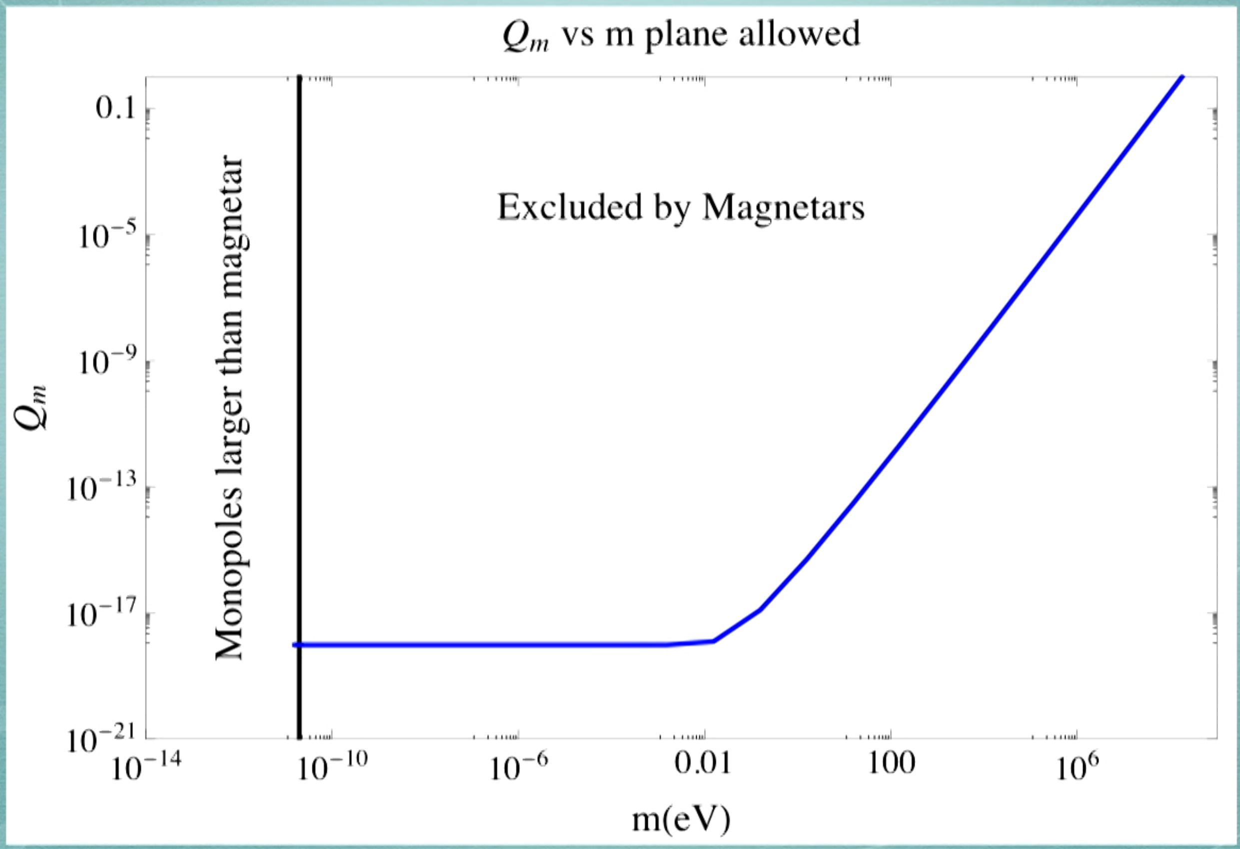
- Energy loss due to production of monopoles
- After pair production, monopoles carry away energy

Bound

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

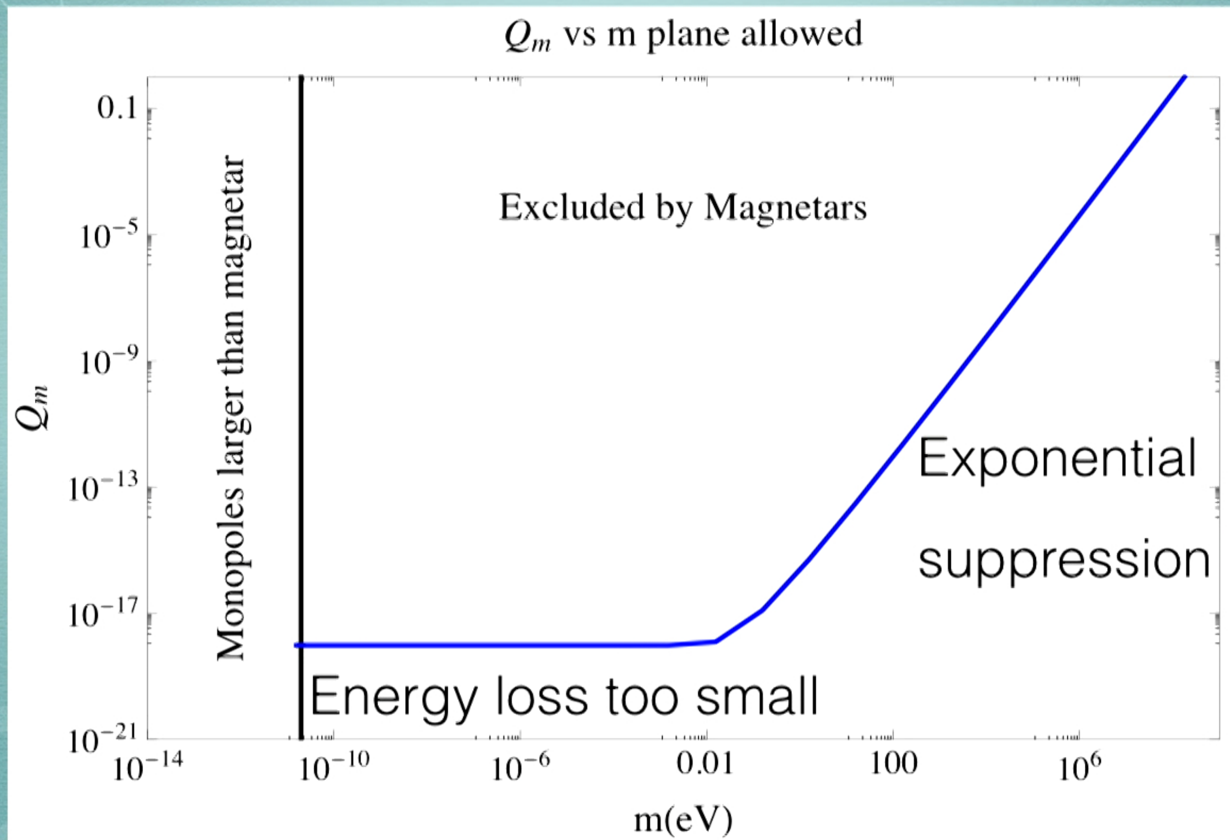
- Magnetic field is not neutralized by pair production during the lifetime of magnetar
- Equivalent to saying that total energy loss must be smaller than observed energy loss

Bound



Q_m vs m plane allowed
Excluded by Magnetars
Monopoles larger than magnetar
Q_m
0.1
10^{-5}
10^{-9}
10^{-13}
10^{-17}
10^{-21}
10^{-14}
10^{-10}
10^{-6}
0.01
100
10^{6}
m(eV)

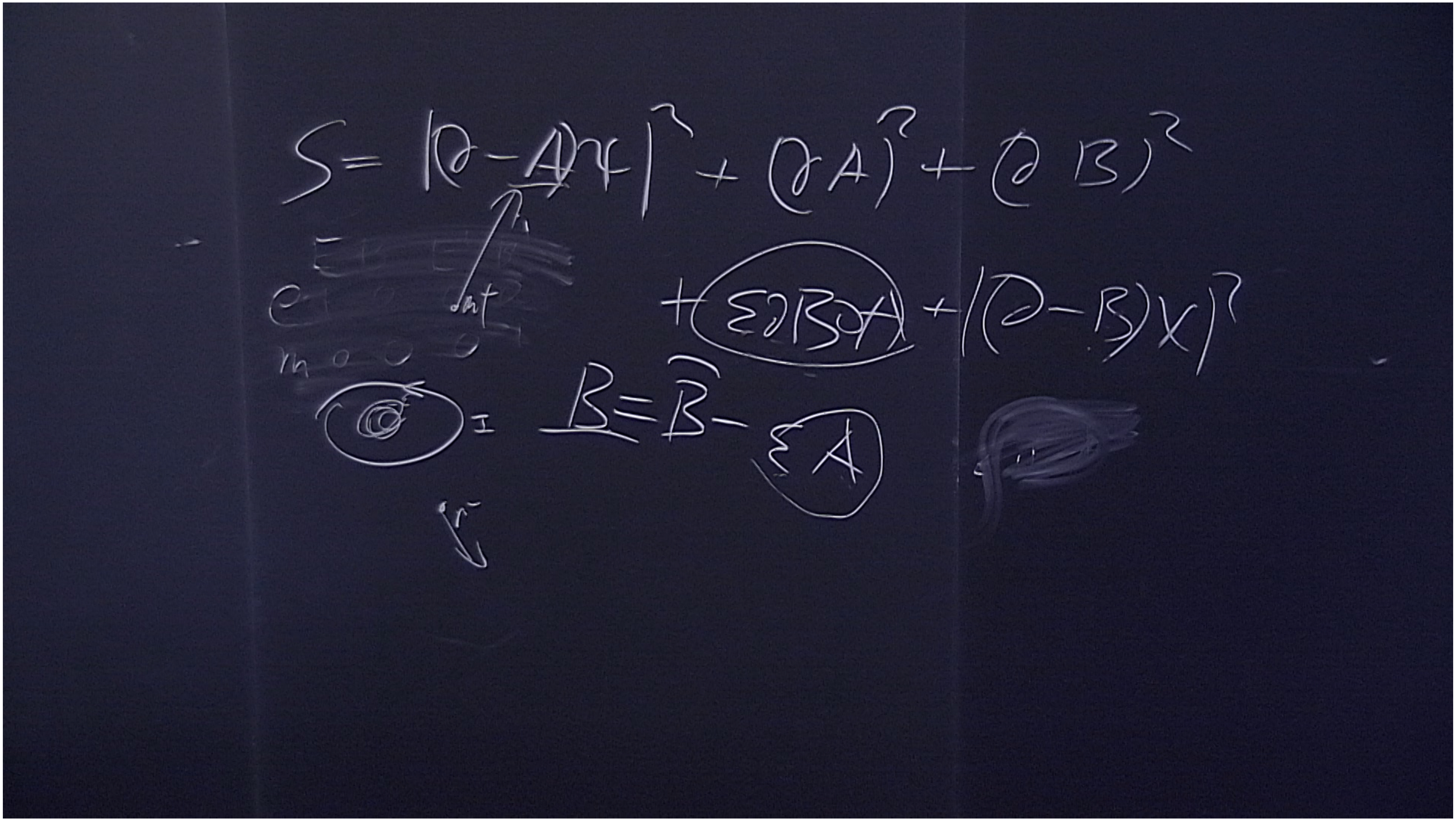
Bound



Q_m vs m plane allowed
0.1
10^{-5}
10^{-9}
10^{-13}
10^{-17}
10^{-21}
Q_m
Monopoles larger than magnetar
Excluded by Magnetars
Exponential
suppression
Energy loss too small
10^{-14}
10^{-10}
10^{-6}
0.01
100
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


S = |(∂ − A)ψ|^2 + (∂A)^2 + (∂B)^2
+ ε∂B∂A + |(∂ − B)χ|^2
B = B̃ − εA