(Minicharged) magnetic monopole with mineral detectors

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Based on
AK and Daniele Perri in progress

Apr. 16, 2026 @ MDvDM 2026

Paleo detector

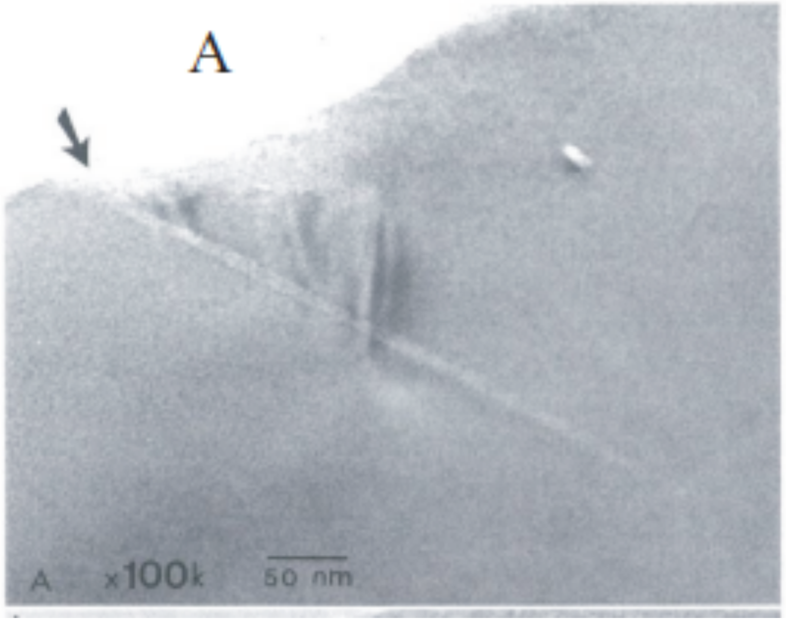
Ancient mineral as a detector

Baum, Drukier, Freese, Górski, and Stengel, PLB, 2020

- long exposure $T_{\rm exp} = \mathcal{O}(10) - \mathcal{O}(10^3)\,{\rm Myr}$

- may detect even very rare (low flux) relics of the Universe

$$N = 4 \times \left(\frac{F}{10^{-17}\,/{\rm cm}^2/{\rm s}/{\rm sr}}\right)\left(\frac{A}{{\rm cm}^2}\right)\left(\frac{T_{\rm exp}}{\rm Gyr}\right)$$



- fission track in apatite

- not necessarily account for the whole dark matter

PALEOCCENE collaboration, Phys. Dark Univ., 2023

$$F = 6 \times 10^{-11}\,/{\rm cm}^2/{\rm s}/{\rm sr} \times \left(\frac{\rho}{\rho_{\rm dm,\,loc} = 0.3\,{\rm GeV}/c^2/{\rm cm}^3}\right) \times \left(\frac{v}{233\,{\rm km/s}}\right)\left(\frac{10^{16}\,{\rm GeV}/c^2}{m}\right)$$

- including (minicharged) monopoles (this talk), topological defects, Q-balls…

Yin, PRD, 2026

AK, Kuwahara and Watanabe, JHEP, 2026

Contents

Monopoles

- electromagnetic duality
- interaction with matter
- existing bounds and sensitivity

Minicharged monopoles

- dark monopole and kinetic mixing
- dark monopole-string network

Electromagnetic duality

Maxwell equations

- in vacuum (Heaviside-Lorentz units)

$$\vec{\nabla} \cdot \vec{E} = 0 \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{1}{c}\frac{\partial}{\partial t}\vec{B} \qquad \vec{\nabla} \times \vec{B} = \frac{1}{c}\frac{\partial}{\partial t}\vec{E}$$

- if you prefer SI/Gaussian units, please see backup slides

- symmetric under $\vec{E} \rightarrow \vec{B}$ $\quad \vec{B} \rightarrow -\vec{E}$

$$1\,\mathrm{G}\,[\mathrm{G}] = \frac{1}{\sqrt{4\pi}}\sqrt{\mathrm{dyn}}/\mathrm{cm}\,[\mathrm{HL}]$$

- to keep them symmetric even in the presence of electric charge/current, one needs magnetic charge/current, too.

$$\vec{\nabla} \cdot \vec{E} = \rho_e \qquad \vec{\nabla} \cdot \vec{B} = \rho_m$$

$$\vec{\nabla} \times \vec{E} = -\vec{J}_m - \frac{1}{c}\frac{\partial}{\partial t}\vec{B} \qquad \vec{\nabla} \times \vec{B} = \vec{J}_e + \frac{1}{c}\frac{\partial}{\partial t}\vec{E}$$

- symmetric under

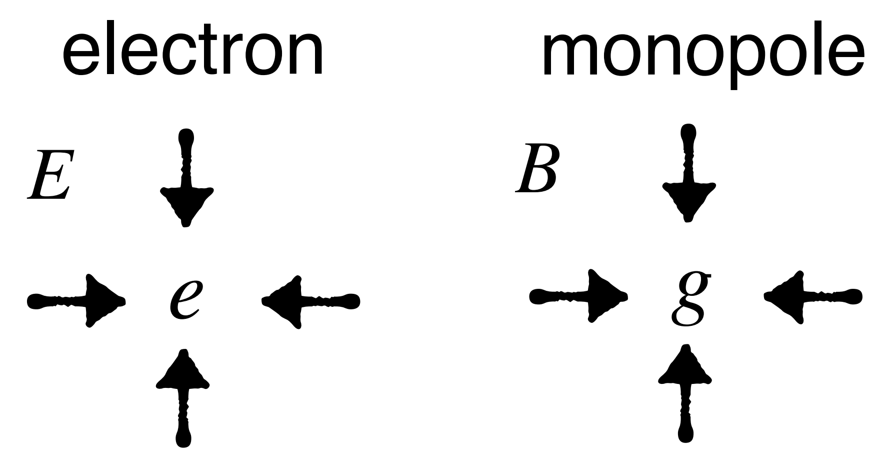
$$\vec{E} \rightarrow \vec{B} \qquad \rho_e \rightarrow \rho_m \qquad \vec{J}_e \rightarrow \vec{J}_m$$

$$\vec{B} \rightarrow -\vec{E} \qquad \rho_m \rightarrow -\rho_e \qquad \vec{J}_m \rightarrow -\vec{J}_e$$

Monopoles

Stable

- lightest magnetically charged particle (monopole) is stable as the lightest electrically charged particle (electron)



- cosmological relics may account for (a tiny fraction of) dark matter

Classical interaction

- monopole generates classical electromagnetic field according to Maxwell equations

$$\vec{\nabla} \cdot \vec{B} = \rho_m$$

$$\vec{\nabla} \times \vec{E} = -\vec{J}_m - \frac{1}{c}\frac{\partial}{\partial t}\vec{B}$$

- generated electromagnetic fields exert electromagnetic force on matter (and vice versa)

$$\vec{F} = e\left(\vec{E} + \frac{\vec{v}}{c} \times \vec{B}\right) + g\left(\vec{B} - \frac{\vec{v}}{c} \times \vec{E}\right)$$

Monopoles

Quantum interaction

- to make electron wave function single valued in the presence of a monopole, it should follow Dirac quantization

$$\frac{g}{g_D} = \frac{eg}{2\pi\hbar c} = \mathbb{Z}$$

$$g_D = 68.5 \times e$$

- perturbative electric charge ↔ non-perturbative magnetic charge

- challenging to compute a cross section of direct pair-annihilation into photons (quantum) in a reliable way, but not challenging to compute a bound-state formation (classical) cross section

As a topological defect ('t Hooft-Polyakov)

- when simple G (say, grand unification of standard-model gauge couplings) is broken into H including U(1), monopole appears as extended object (condensation of Higgs and gauge boson)

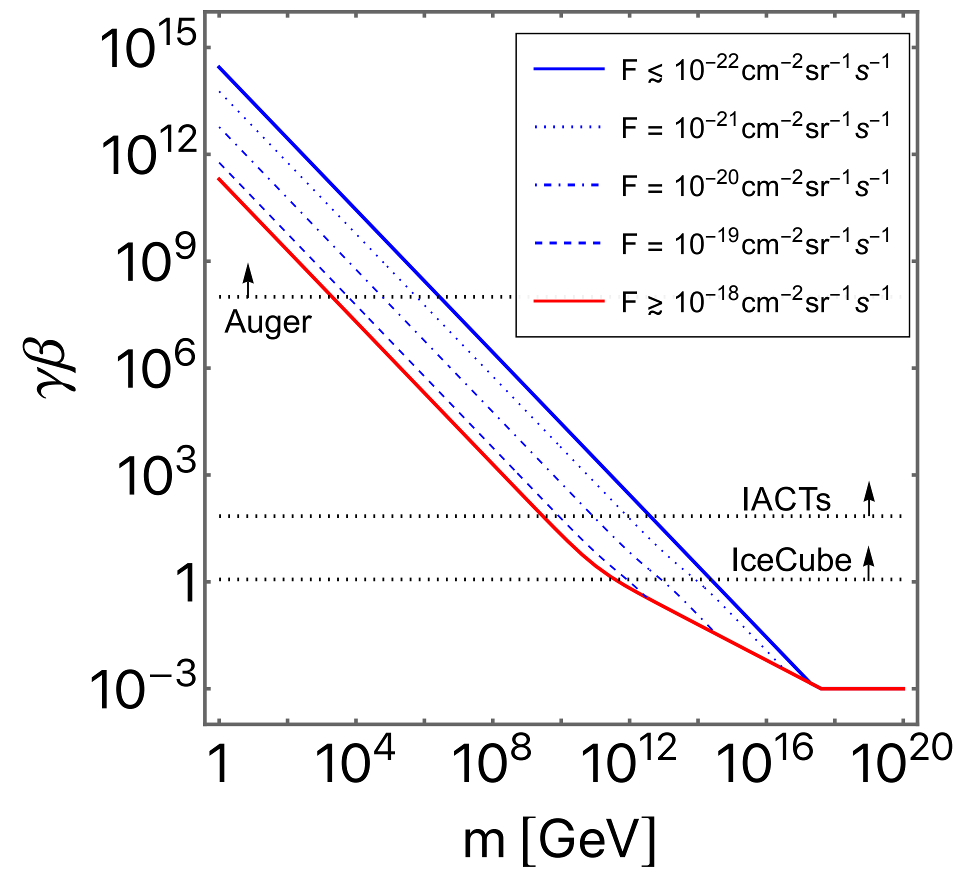
- abundance is determined by Kibble-Zurek mechanism (and possible subsequent annihilation; though we do not go in details)

Relic monopoles

Evolution in the late Universe

- acceleration through intergalactic and Galactic magnetic fields

- weakens Galactic magnetic fields (Parker bounds)



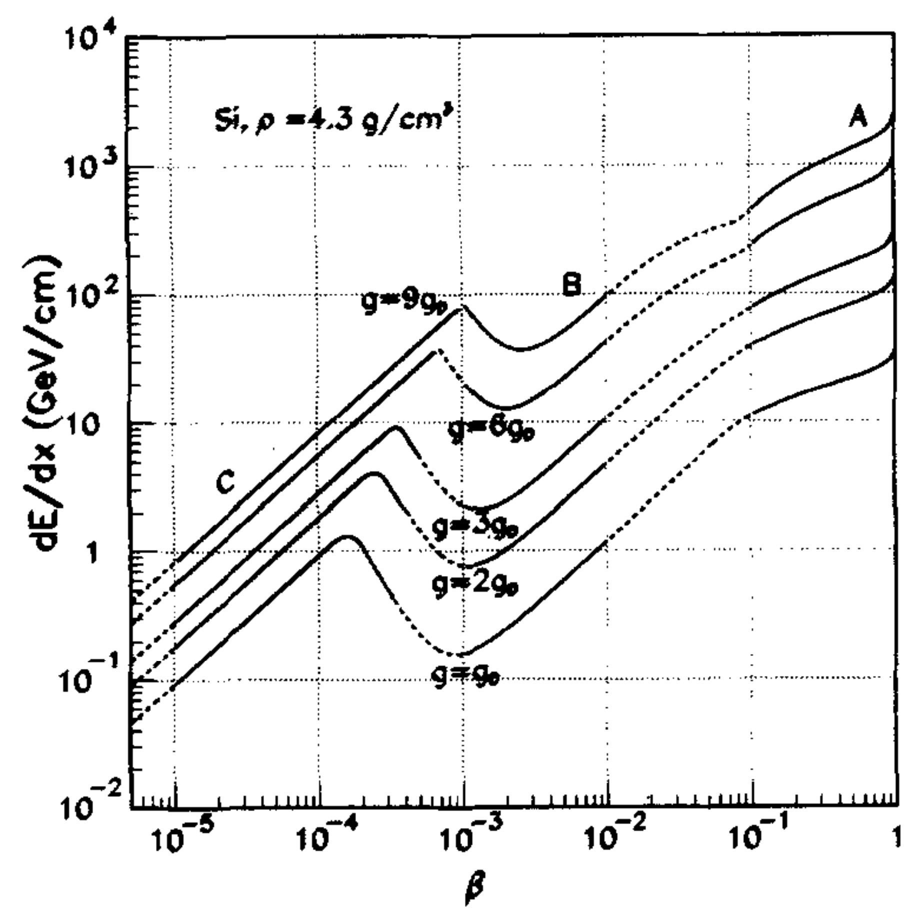
Stopping power for a monopole

- slow: elastic collision with atoms (via magnetic dipole)

- intermediate: collective excitation of atoms; Lindhard (dielectric constant approx.)

- fast: excitation and ionization of atoms; Bethe-Bloch e→gβ

Derkaoui *et. al.*, Astropart. Phys., 1998

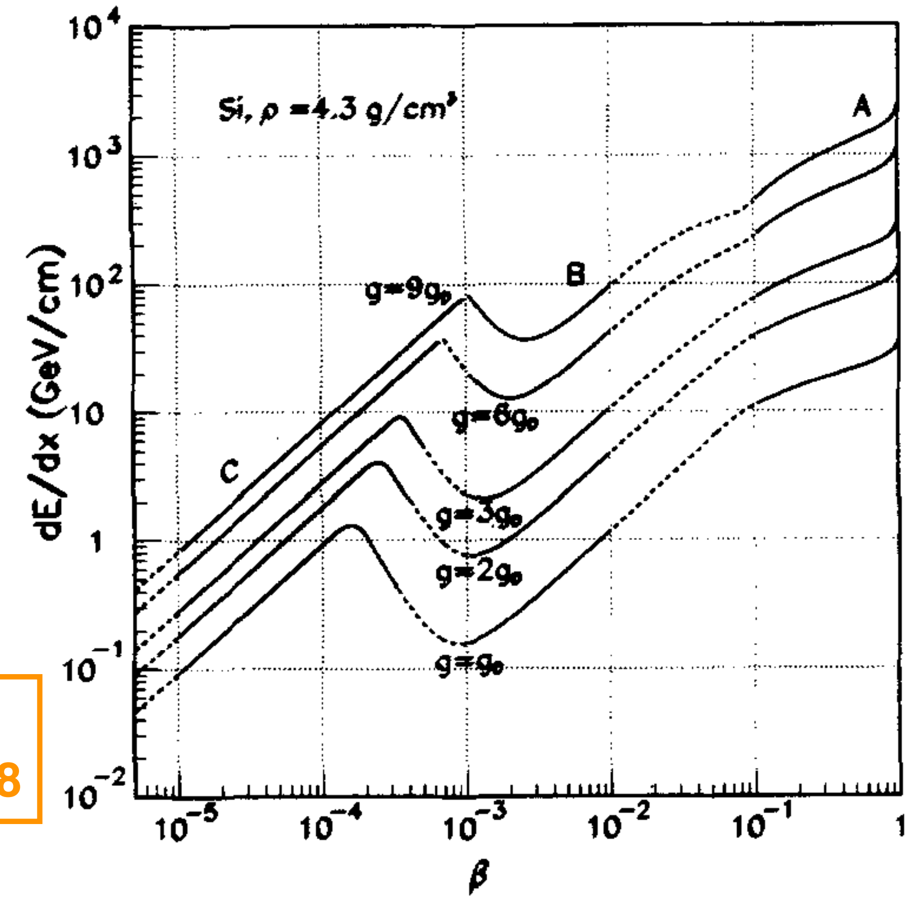


More on stopping power

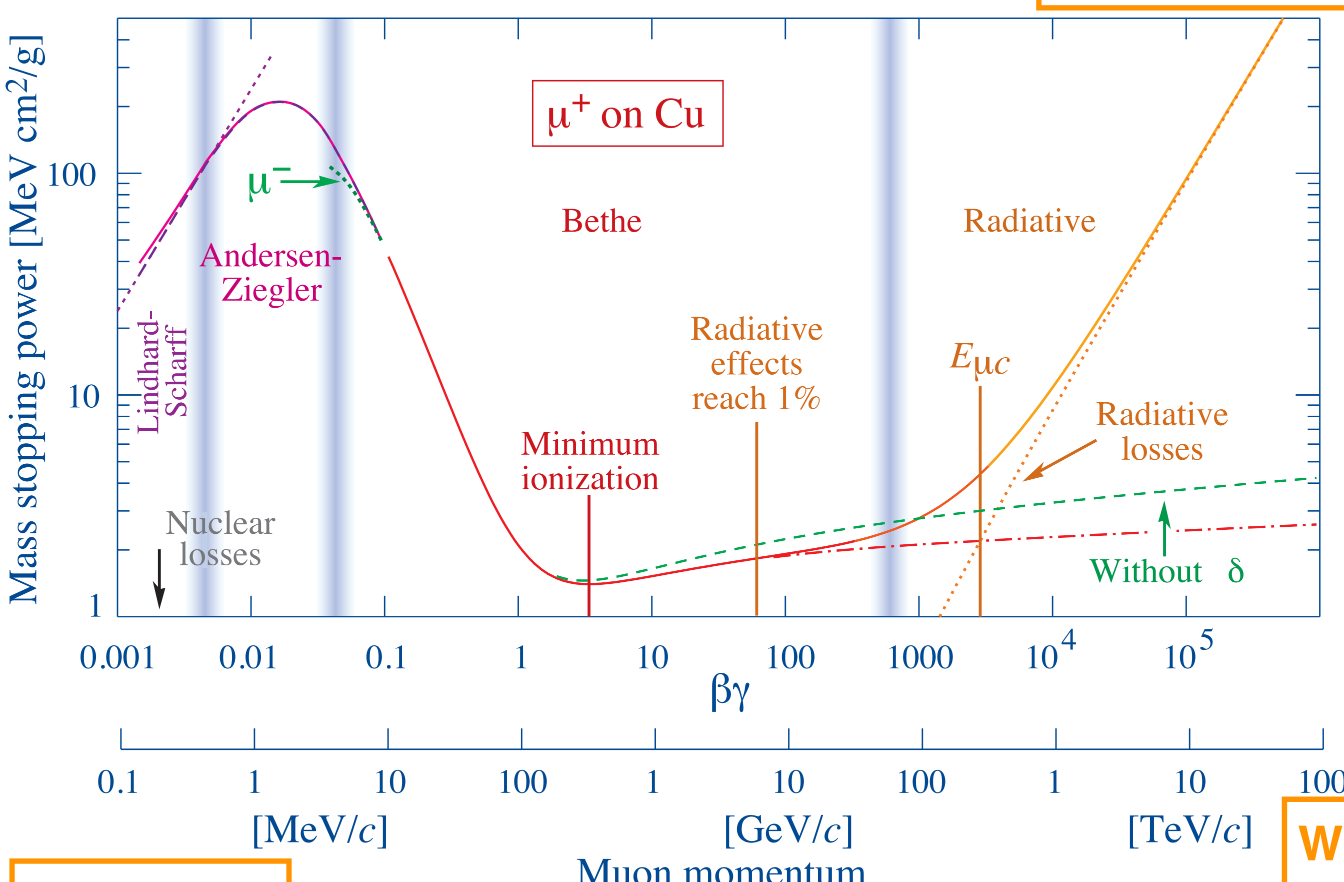
Stopping power for a monopole

- relativistic interaction is similar to a charged particle (electromagnetic induction)

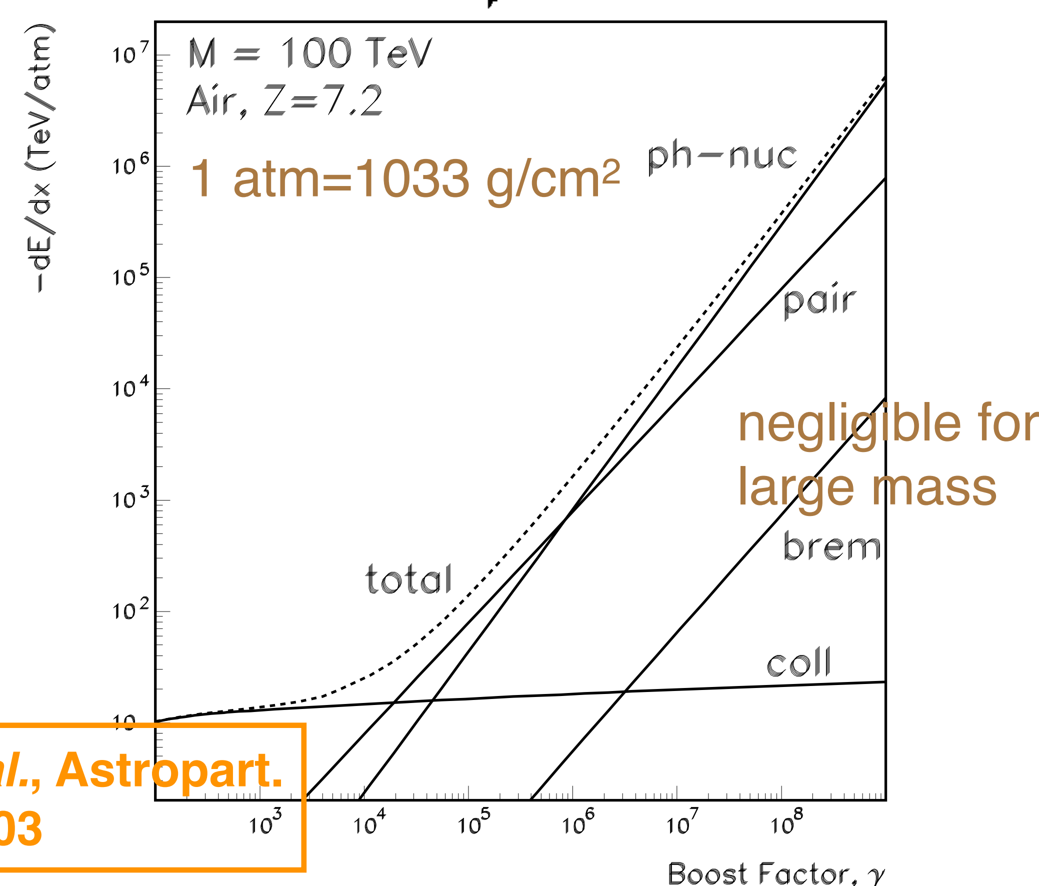
- non-relativistic interaction is different



Derkaoui *et. al.*, Astropart. Phys., 1998



PDG, 2018



Wick *et. al.*, Astropart. Phys., 2003

Relic monopoles

Summary of existing constraints

- not clustering into Galaxy

$$F_{\rm mon} = 4 \times 10^{-13} \beta /{\rm cm}^2/{\rm s}/{\rm sr} \;\times \left(\frac{\rho_{\rm mon}}{\rho_{\rm dm,\,glo} = 2 \times 10^{-6}\,{\rm GeV}/c^2/{\rm cm}^3} \right) \left(\frac{10^{16}\,{\rm GeV}/c^2}{M_{\rm mon}} \right)$$

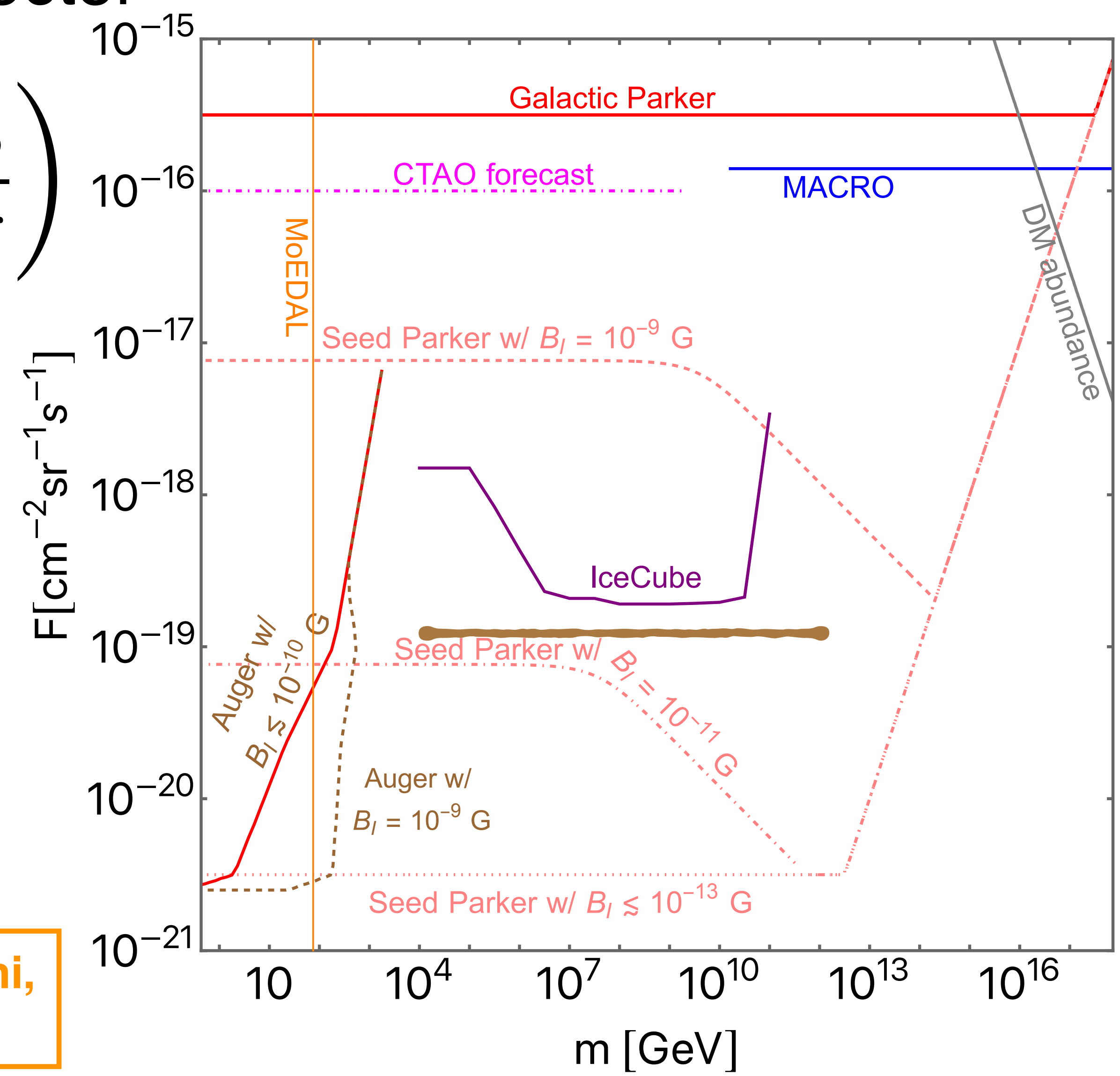
- remember sensitivity of a paleo detector

$$N = 4 \times \left(\frac{F}{10^{-17}\,/{\rm cm}^2/{\rm s}/{\rm sr}} \right) \left(\frac{A}{{\rm cm}^2} \right) \left(\frac{T_{\rm exp}}{\rm Gyr} \right)$$

- old study of mica: $g/g_D > 2$ to leave etchable tracks

$$F_{\rm mon} < 1 \times 10^{-19}\,/{\rm cm}^2/{\rm s}/{\rm sr}$$

Fleischer, Price and Woods, Phys. Rev., 1969



Perri, Doro and Kobayashi, Phys. Dark Univ., 2025

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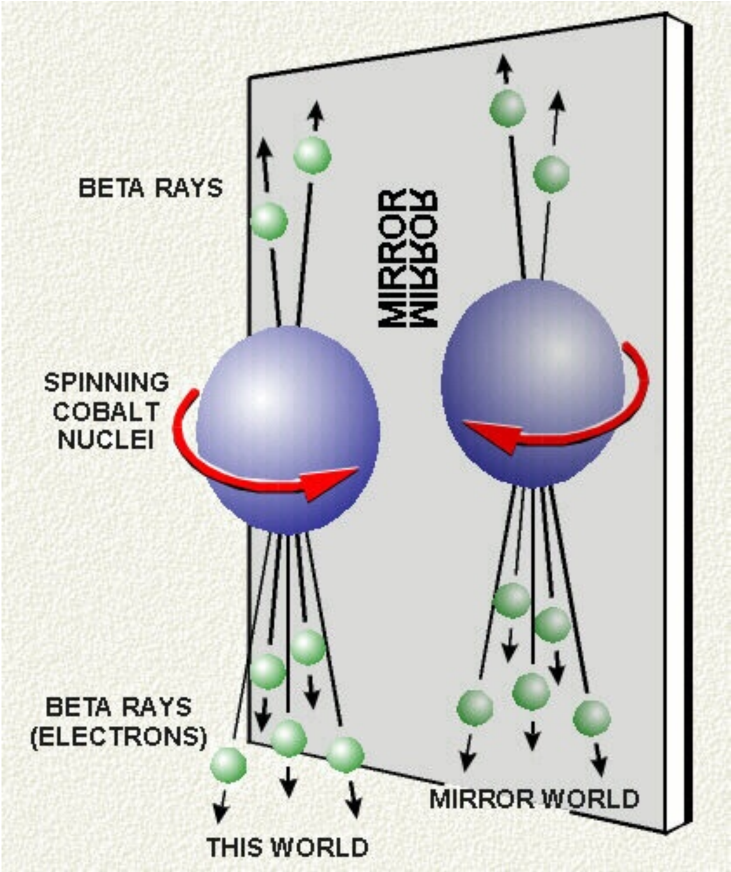
Minicharged monopoles

- dark electrodynamics
- dark monopole-string network

Dark electrodynamics

Dark sector



- example: mirror world (motivated by puzzling P-violation in weak interaction)

- dark photon; dark electron; dark monopole…

$$\vec{\nabla} \cdot \vec{E}' = \rho_e' \qquad \vec{\nabla} \cdot \vec{B}' = \rho_m'$$

$$\vec{\nabla} \times \vec{E}' = -\vec{J}_m' - \frac{1}{c}\frac{\partial}{\partial t}\vec{B}' \qquad \vec{\nabla} \times \vec{B}' = \vec{J}_e' + \frac{1}{c}\frac{\partial}{\partial t}\vec{E}'$$

Photon-dark photon mixing

- photon and dark photon have the same quantum number and thus can mix with each other (remember, say, photon-rho meson mixing); mixing parameter ε

Visible-dark electrodynamics

Maxwell equations

- electron can generate a dark electric field and dark monopole can generate a visible magnetic field

$$\vec{\nabla}\cdot\vec{E}=\rho_e \qquad \vec{\nabla}\cdot\vec{B}=\rho_m-\epsilon\rho'_m$$

$$\vec{\nabla}\times\vec{E}=-\vec{J}_m+\epsilon\vec{J}'_m-\frac{1}{c}\frac{\partial}{\partial t}\vec{B} \qquad \vec{\nabla}\times\vec{B}=\vec{J}_e+\frac{1}{c}\frac{\partial}{\partial t}\vec{E}$$

$$\vec{\nabla}\cdot\vec{E}'=\rho'_e+\epsilon\rho_e \qquad \vec{\nabla}\cdot\vec{B}'=\rho'_m$$

$$\vec{\nabla}\times\vec{E}'=-\vec{J}'_m-\frac{1}{c}\frac{\partial}{\partial t}\vec{B}' \qquad \vec{\nabla}\times\vec{B}'=\vec{J}'_e+\epsilon\vec{J}_e+\frac{1}{c}\frac{\partial}{\partial t}\vec{E}'$$

$$\vec{F}=e\left(\vec{E}+\frac{\vec{v}}{c}\times\vec{B}\right)+(g-\epsilon g')\left(\vec{B}-\frac{\vec{v}}{c}\times\vec{E}\right)$$

$$+(e'+\epsilon e)\left(\vec{E}'+\frac{\vec{v}}{c}\times\vec{B}'\right)+g'\left(\vec{B}'-\frac{\vec{v}}{c}\times\vec{E}'\right)$$

Minicharged monopoles

Visible-dark electrodynamics

- no interaction between an electron and a dark monopole as it is (no problem in keeping electron wave function single-valued in the presence of a dark monopole)

$$\vec{F}_e = e\frac{\vec{v}}{c} \times \vec{B} + \epsilon e \frac{\vec{v}}{c} \times \vec{B}'$$

$$\vec{\nabla} \cdot \vec{B} = -\epsilon \rho'_m \quad \vec{\nabla} \cdot \vec{B}' = \rho'_m$$ and thus $$\vec{B} = -\epsilon \vec{B}'$$

- because we can always redefine visible-dark photons so that monopole does not generate a visible magnetic field

Dark Meissner effect

- visible-dark photons become distinguishable once a dark photon obtains a mass and a dark magnetic field is confined into a string

$$\vec{F}_e = e\frac{\vec{v}}{c} \times \vec{B} \qquad \vec{\nabla} \cdot \vec{B} = -\epsilon \rho'_m$$

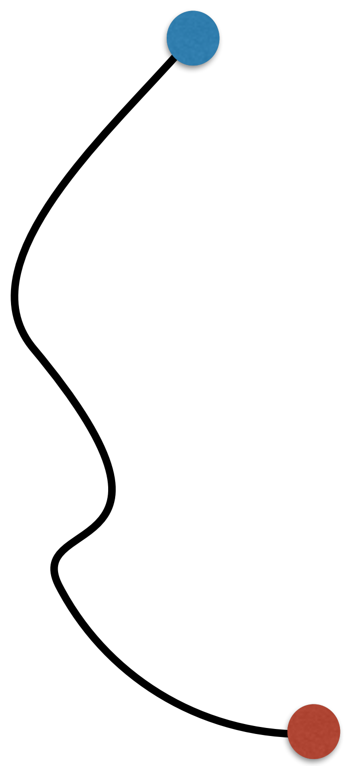
- at a large distance, a dark monopole looks like a minicharged (-εg') visible monopole

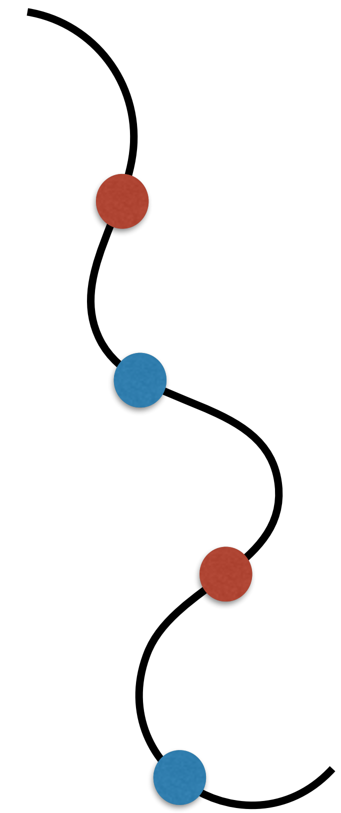
Minicharged monopoles

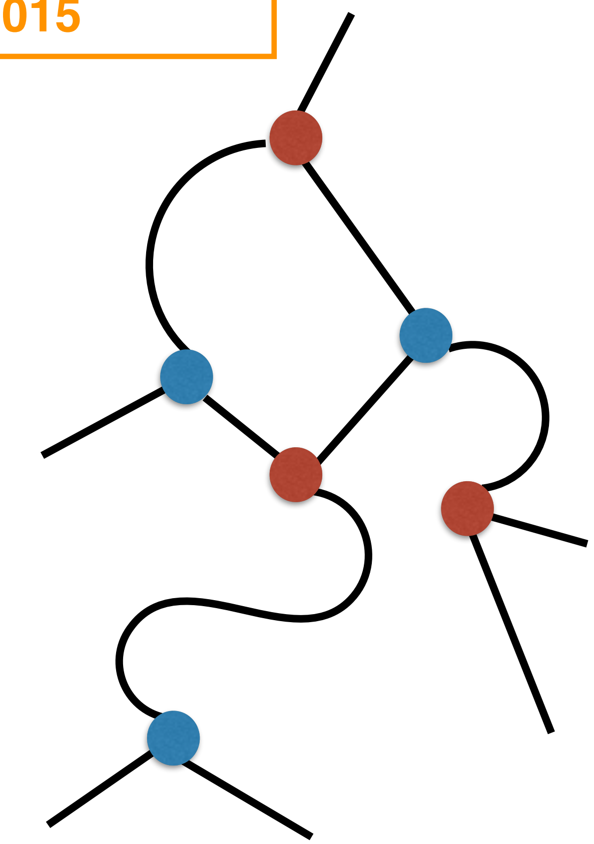
As a topological defect ('t Hooft-Polyakov)

- dark monopole-string network: $U(1) \to Z_N$

Kibble and Vachaspati, J. Phys. G, 2015







- N=1 (“dumbbell”): dark monopole-anti-monopole feel a constant (with distance) attractive force and annihilate quickly; no monopole or string is left

- N=2 (“necklace”): dark monopole is pulled in both ways and thus annihilation is not quick; one string per Hubble volume is left and monopoles are distributed along the string

- N>2 (“network”): monopoles are distributed uniformly and connected by strings (our interest)

Relic minicharged monopoles

Relic network

- inter-string distance is comparable with an inter-monopole distance

$$\rho_{\rm mon} \sim \frac{M_{\rm mon}}{d^3}$$

$$\rho_{\rm str} \sim \frac{\mu}{d^2} \sim 0.1 \rho_{\rm dm,\, glo} \times \left(\frac{\mu}{\rm MeV^2}\right) \left(\frac{\rho_{\rm mon}}{\rho_{\rm dm,\, glo} = 2 \times 10^{-6}\, {\rm GeV}/c^2/{\rm cm}^3}\right)^{2/3} \left(\frac{10^{16}\,{\rm GeV}}{M_{\rm mon}}\right)^{2/3}$$

- possibly problematic in cosmology **Cheng, Valentino and Visinelli, JHEAp, 2026**

- remember a (non-clustering) flux and sensitivity of paleo detector

$$F_{\rm mon} = 4 \times 10^{-13} \beta/{\rm cm}^2/{\rm s}/{\rm sr} \times \left(\frac{\rho_{\rm mon}}{\rho_{\rm dm,\, glo} = 2 \times 10^{-6}\, {\rm GeV}/c^2/{\rm cm}^3}\right) \left(\frac{10^{16}\,{\rm GeV}/c^2}{M_{\rm mon}}\right)$$

$$N = 4 \times \left(\frac{F}{10^{-17}/{\rm cm}^2/{\rm s}/{\rm sr}}\right) \left(\frac{A}{\rm cm^2}\right) \left(\frac{T_{\rm exp}}{\rm Gyr}\right)$$

- $\rho_{\rm str}/F_{\rm mon}$ depends only on $\rho_{\rm mon}/M_{\rm mon}$

Relic minicharged monopoles

Dark photon constraints

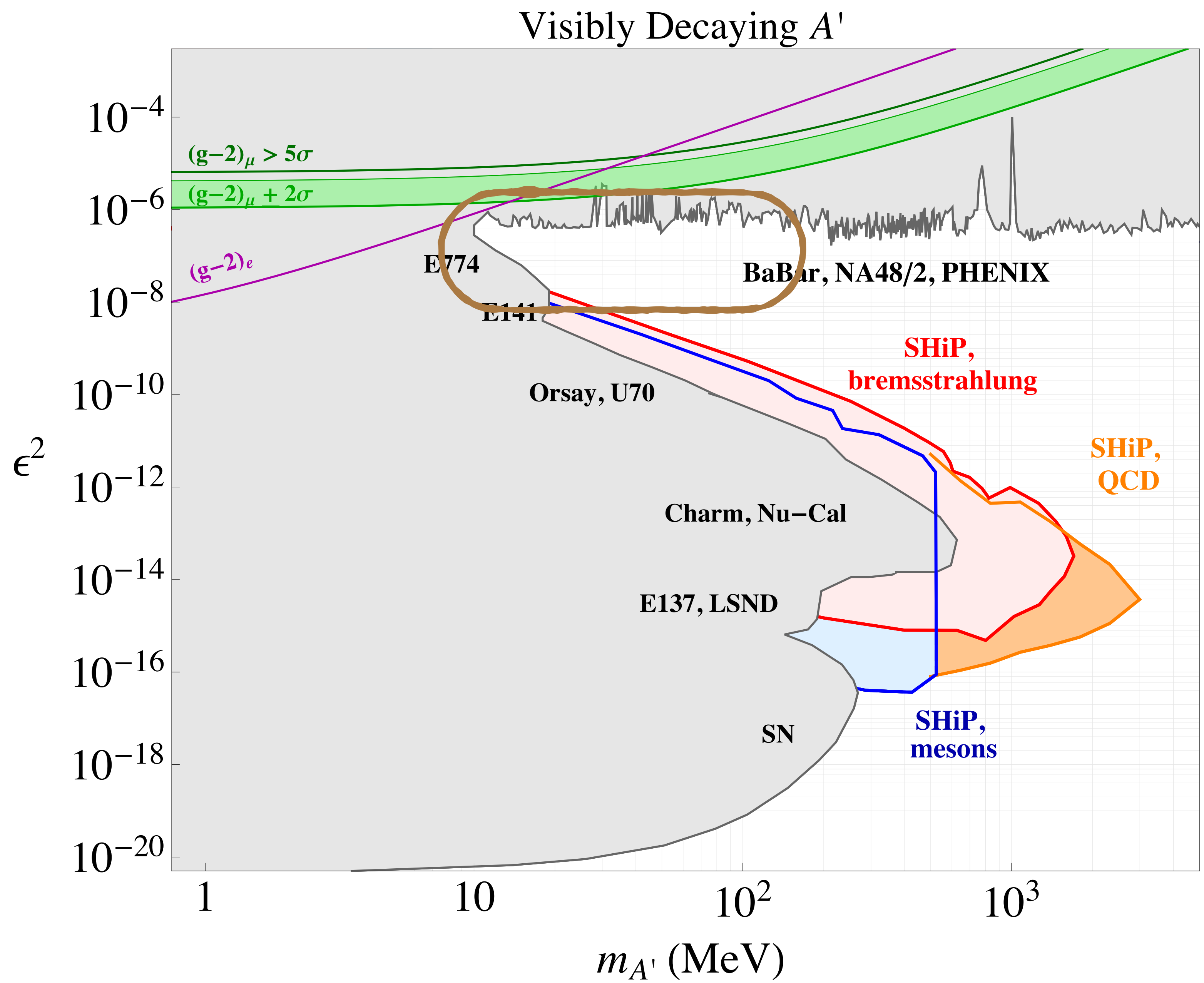
- electromagnetically charged visible particles can produce a dark photon, which decays into a pair of electron and positron

$$\vec{\nabla} \cdot \vec{E}' = \rho_e' + \epsilon \rho_e$$

$$\vec{F} = \epsilon e \left(\vec{E}' + \frac{\vec{v}}{c} \times \vec{B}' \right)$$

- string tension and thus a dark photon mass need to be around or below 100 MeV

- unexplored region around 10-100 MeV dark photon and 10^{-4} mixing



SHiP collaboration, Rep. Prog. Phys., 2016

Summary

Monopole

- motivated by electromagnetic duality
  - also arises in grand unified theory of particle physics
- not clustering into Galaxy
  - semi-relativistic velocity

Mini-charged monopole

- dark monopole looks like mini-charged monopole after dark photon obtains mass
- form monopole-string network
- evolution in the late universe is to be investigated
  - clustering into Galaxy or not would depend on mixing parameter
- synergy with accelerator search for dark photon

Thank you

Monopoles

Electromagnetic duality

- Maxwell equations in vacuum (SI units)

$$\vec{\nabla} \cdot \vec{E} = 0 \qquad \vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial}{\partial t}\vec{B} \qquad \vec{\nabla} \times \vec{B} = \epsilon_0 \mu_0 \frac{\partial}{\partial t}\vec{E}$$

- symmetric under $\vec{E} \to c\vec{B} \qquad \vec{B} \to -\frac{1}{c}\vec{E}$

- to keep Maxwell equations symmetry even in presence of electric charge/current, one needs magnetic charge/current, too.

$$\vec{\nabla} \cdot \vec{E} = \frac{1}{\epsilon_0}\rho_e \qquad \vec{\nabla} \cdot \vec{B} = \mu_0 \rho_m$$

$$\vec{\nabla} \times \vec{E} = -\mu_0 \vec{J}_m - \frac{\partial}{\partial t}\vec{B} \qquad \vec{\nabla} \times \vec{B} = \mu_0 \vec{J}_e + \epsilon_0 \mu_0 \frac{\partial}{\partial t}\vec{E}$$

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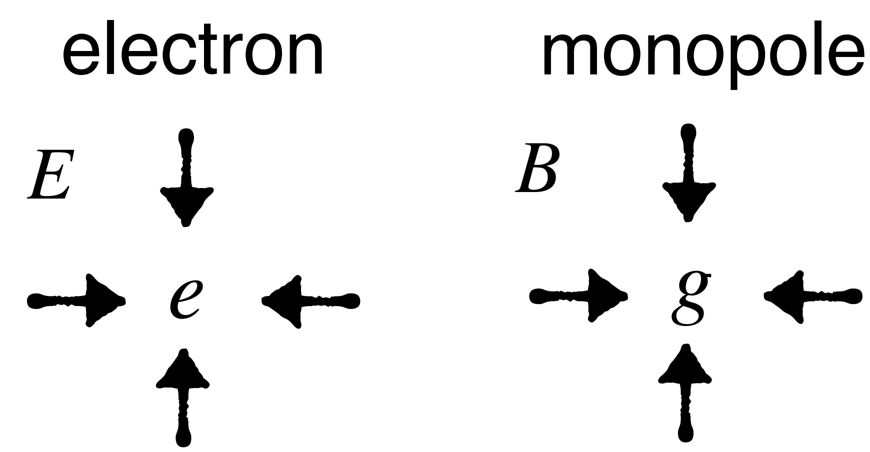
$$\vec{B} \to -\frac{1}{c}\vec{E} \qquad \rho_m \to -c\rho_e \qquad \vec{J}_m \to -c\vec{J}_e$$

Monopoles

Stable

- lightest magnetically charged particle (monopole) is stable as lightest electrically charged particle (electron)



- cosmological relics may account for (a tiny fraction) of dark matter

Classical interaction

- monopole generates classical electromagnetic field according to the (modified) Maxwell equations

$$\vec{\nabla} \cdot \vec{B} = \mu_0 \rho_m$$

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- generated electromagnetic fields exert electromagnetic force on matter (and vice versa)

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Monopoles

Quantum interaction

- to make electron wavefunction in presence of monopole single-valued, they should follow Dirac quantization

$$\frac{g}{g_D} = \frac{eg}{2\pi\epsilon_0 \hbar c^2} = \mathbb{Z}$$

$$g_D = 68.5 \times ec$$

- perturbative electric charge ↔ non-perturbative magnetic charge

- challenging to compute cross section of direct pair-annihilation into photons (quantum) in a reliable way, but not challenging to compute bound-state formation (classical) cross section

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$$\vec{B} \rightarrow -\vec{E} \quad \rho_m \rightarrow -\rho_e \quad \vec{J}_m \rightarrow -\vec{J}_e$$

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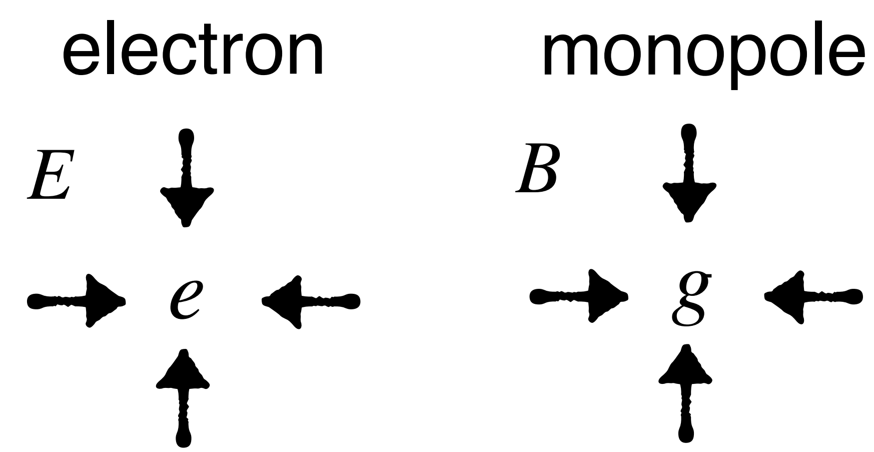

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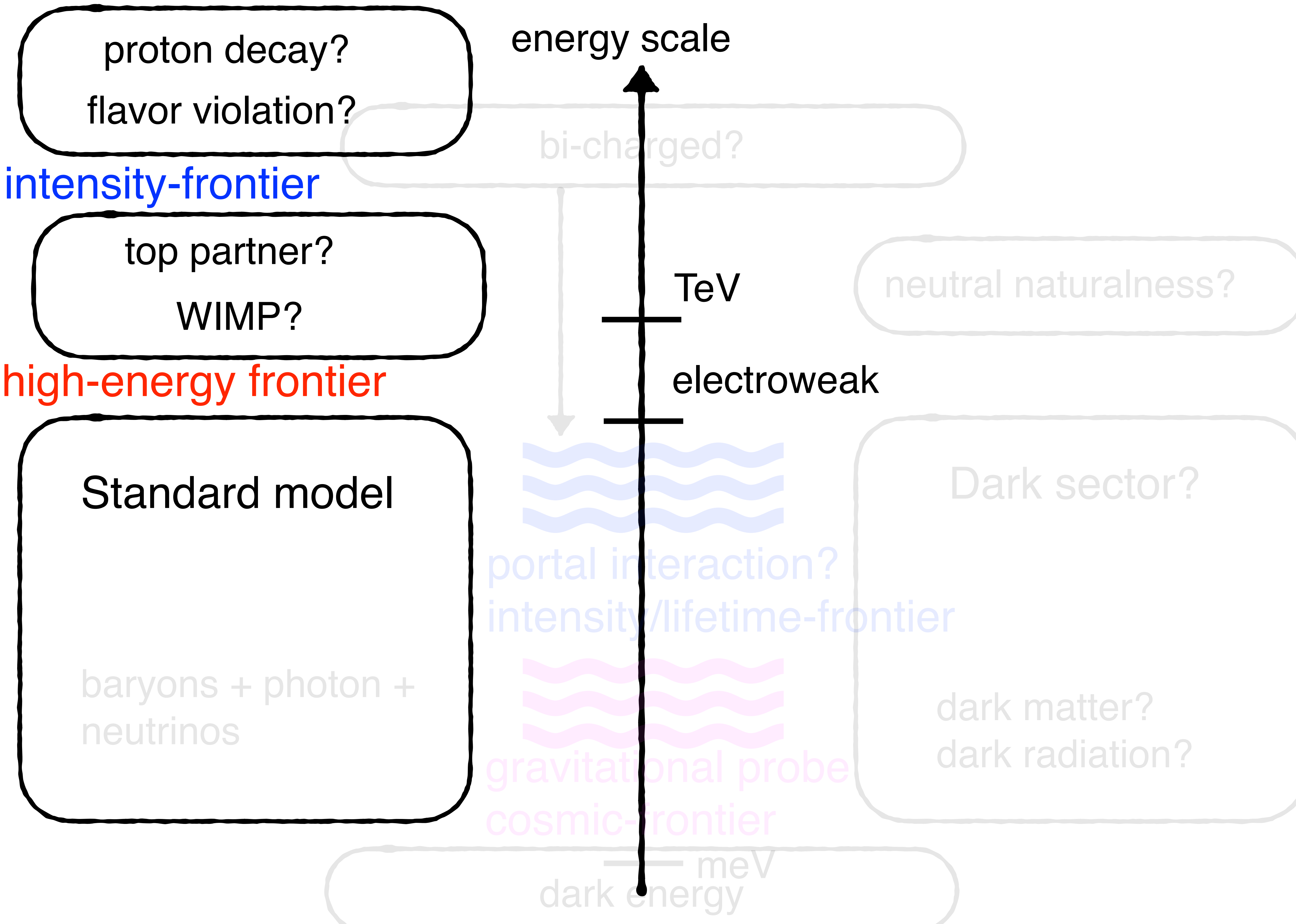
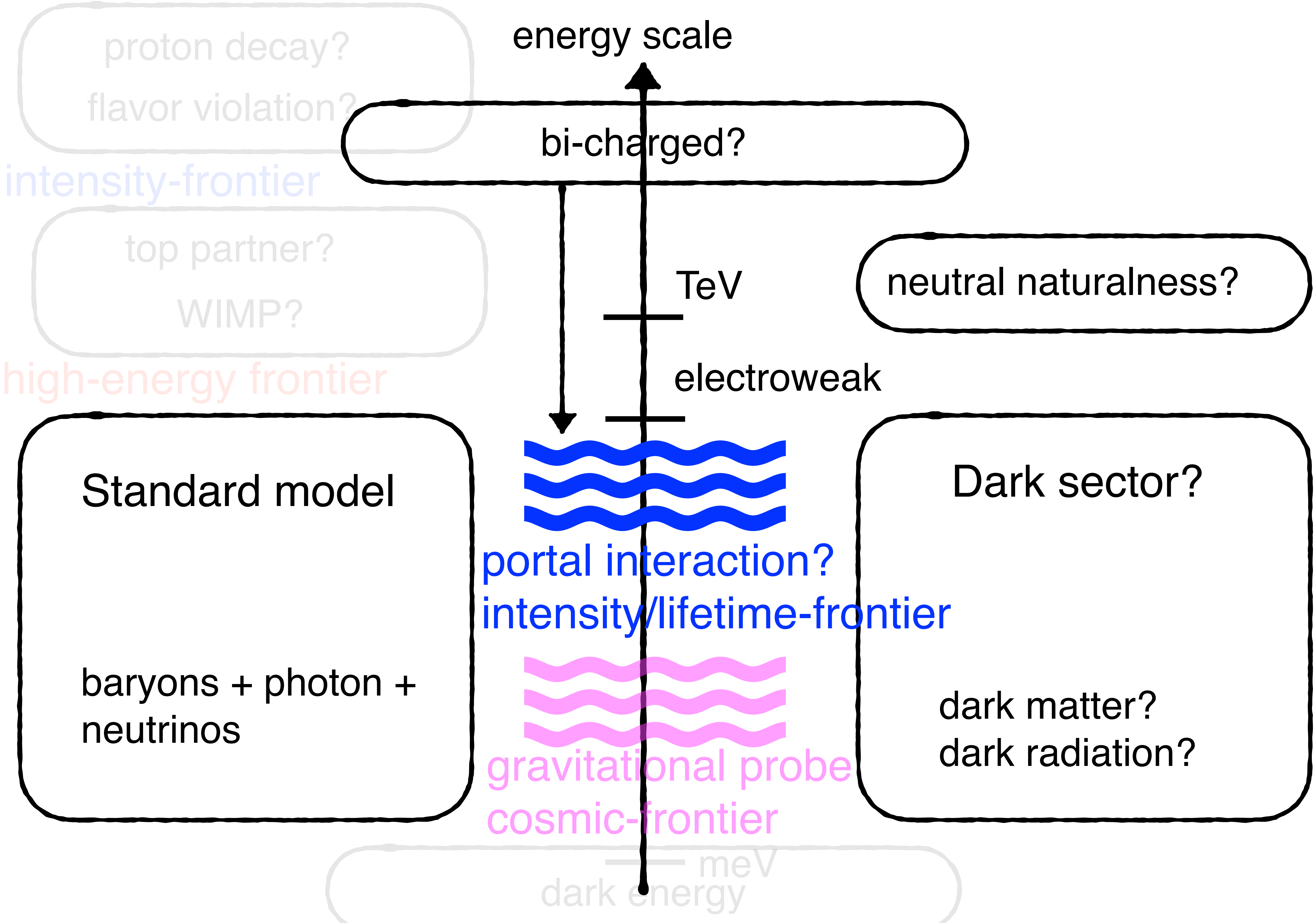
High-energy physics



High-energy? physics



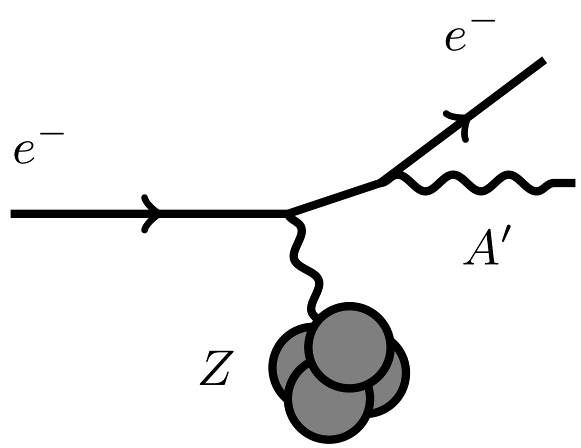
Intensity frontier

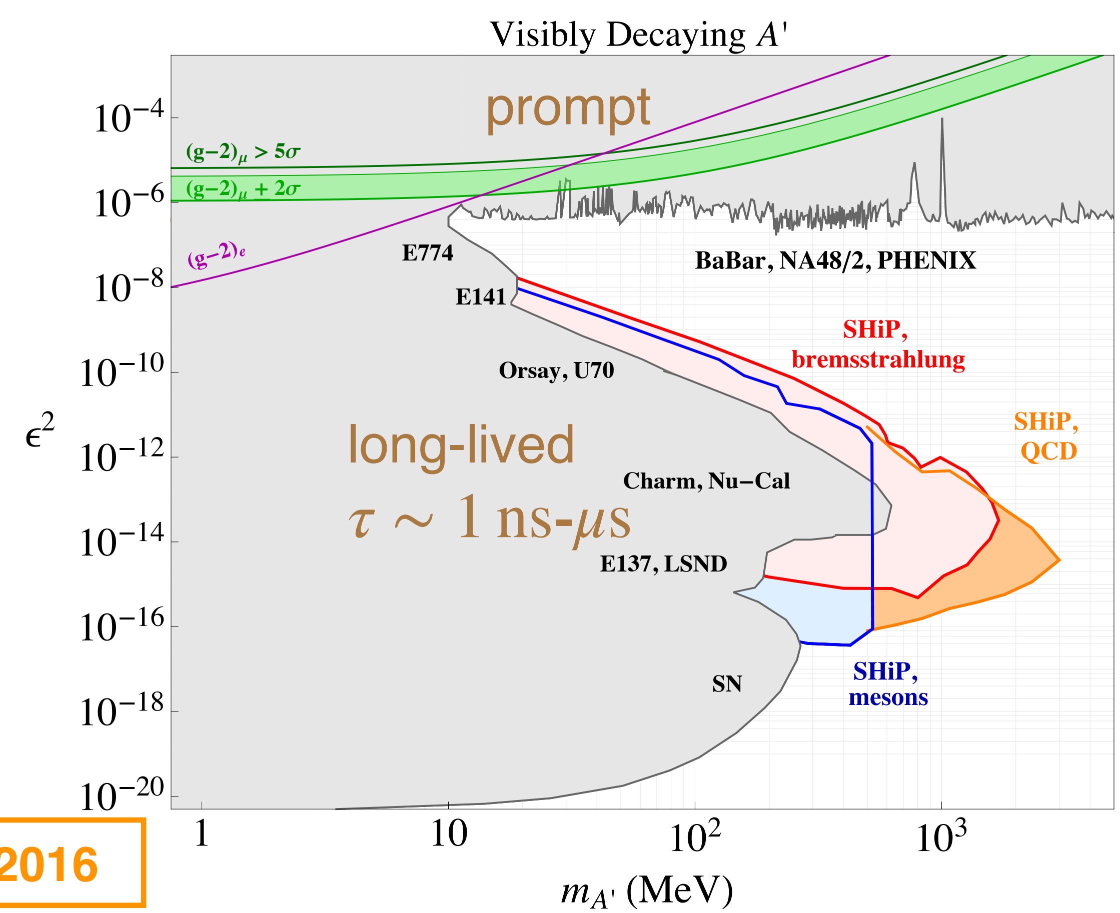
Dark photon portal $\frac{\epsilon_Y}{2} Y^{\mu\nu} F'_{\mu\nu}$

- kinetic mixing between the hyper-charge gauge boson and dark photon
- SM particles feebly couple to dark photon $\epsilon e j_e^\mu A'_\mu$ - integration by parts $\epsilon_Y \cos\theta_W = \epsilon$
- mass from dark Higgs (or Stueckelberg)

Beam-dump experiment e.g., CHARM, E137, SHiP…

target shield detector





$A' \to$ SM

e^+e^-

SHiP collaboration, Rep. Prog. Phys., 2016