Fractionally charged particles (millicharged particles)

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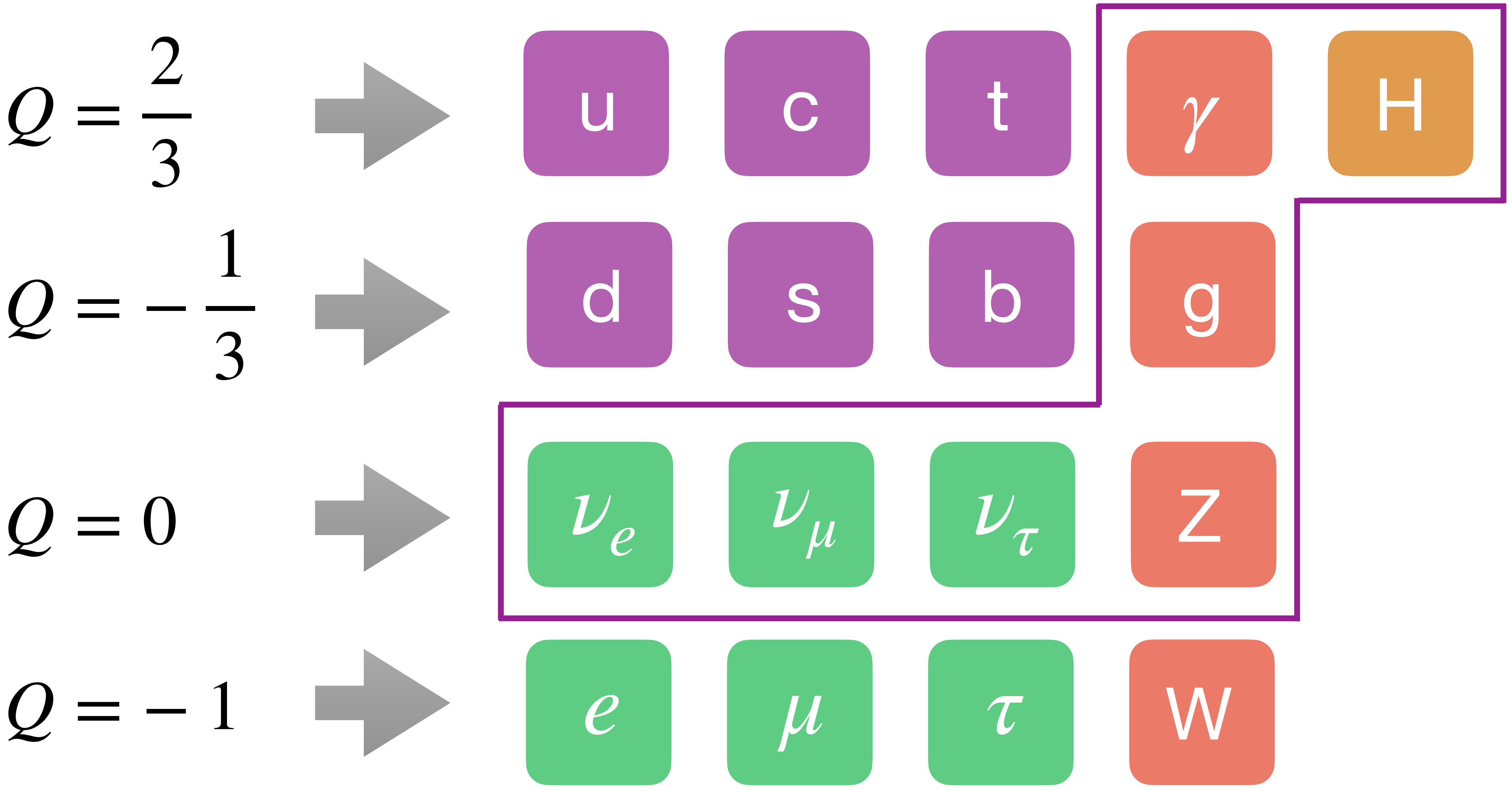
The 2021 Shanghai Particle Physics and Cosmology Symposium (SPCS2021)
Nov 19, 2021

Outline

1. Millicharge
2. Theoretical models
3. Astro/cosmo probes
4. Terrestrial searches

1 Millicharge

Millicharge is a very small electric charge



photon

$$e\, Q_f\, A_\mu^\gamma\, \bar{f} \gamma^\mu f$$

$Q_f = \frac{n}{3}$ is quantized in SM

non-quantized $Q_f \equiv \epsilon \ll 1$ → millicharge

Magnetic monopole leads to charge quantization

Dirac's paper on magnetic monopole & charge quantization in 1931

[from https://inspirehep.net/]

Quantised singularities in the electromagnetic field,

Paul Adrien Maurice Dirac (St John's Coll., Cambridge) (Sep 1, 1931)

Published in: *Proc.Roy.Soc.Lond.A* 133 (1931) 821, 60-72

DOI   cite   2,263 citations

magnetic monopole

↓

charge quantization

$$e = \frac{2\pi\hbar n}{\mu}$$

n is integer

μ is magnetic strength

e is electric strength

Standard model & grand unified theories

Anomaly cancellations in SM lead to charge relations $\sum_i Y_i = 0$

But $U(1)_Y$ in SM in general allows non-quantized charge

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

Embedded into a bigger gauge group? e.g. SU(5) **[Georgi & Glashow, PRL.32.438, 1974]**

→ charge quantization

Stringent constraints on millicharge in SM

$$Q_p - Q_e < (0.8 \pm 0.8) \times 10^{-21} e$$ [Marinelli et al. 1984]

$$Q_n < (-0.1 \pm 1.1) \times 10^{-21} e$$ [Bressi et al. 2011]

$$Q_n < (-0.4 \pm 1.1) \times 10^{-21} e$$ [Baumann et al. 1988]

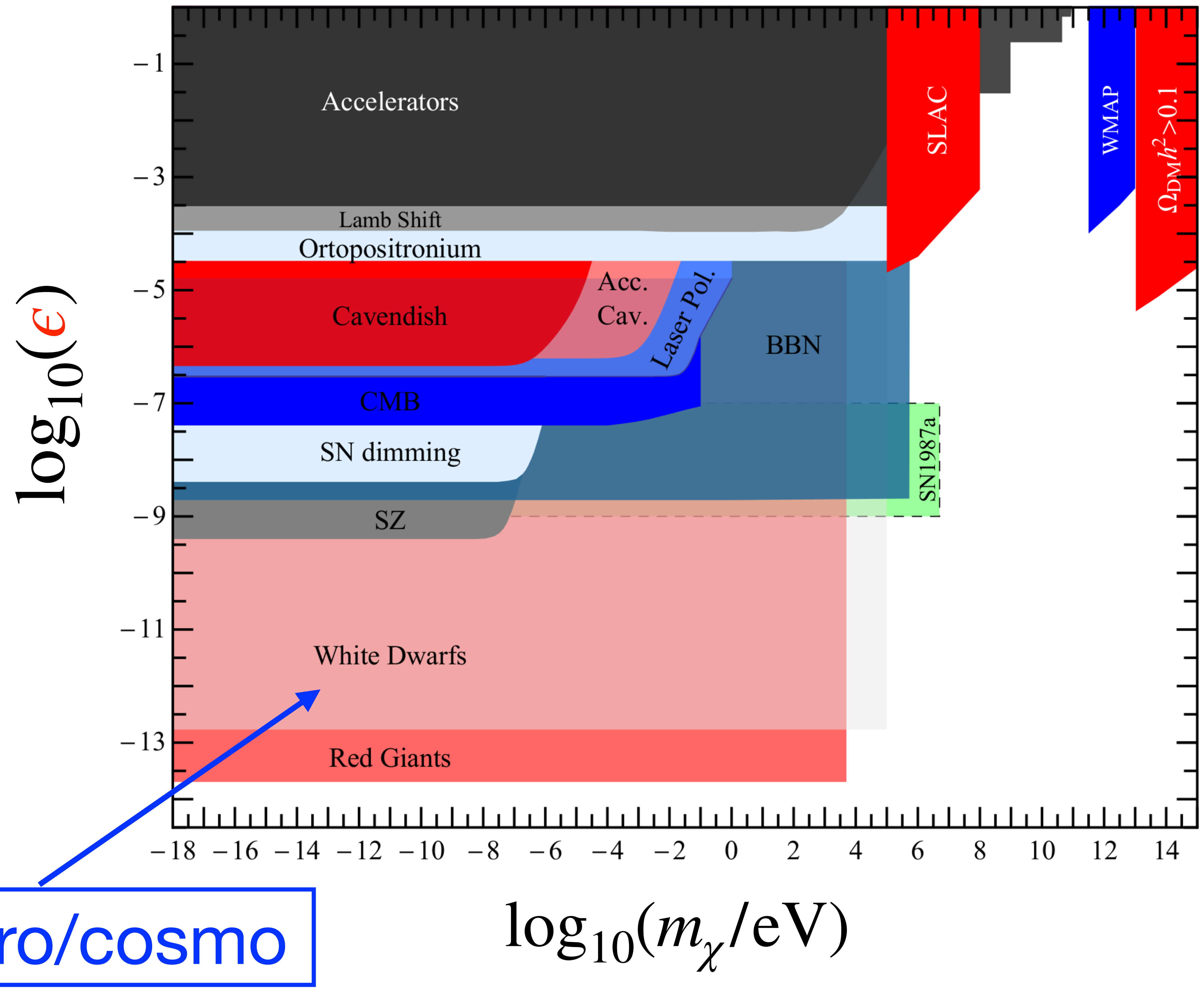
$$Q_\nu < 10^{-17} e$$ [Barbiellini et al. 1987]

[Siemensen et al., PRD 97, 052004 (2018)]

Millicharge in BSM can be quite “large”

[Jaeckel & Ringwald, 1002.0329]

$$e\,\epsilon\,A_\mu^\gamma\,\bar{\chi}\,\gamma^\mu\,\chi$$

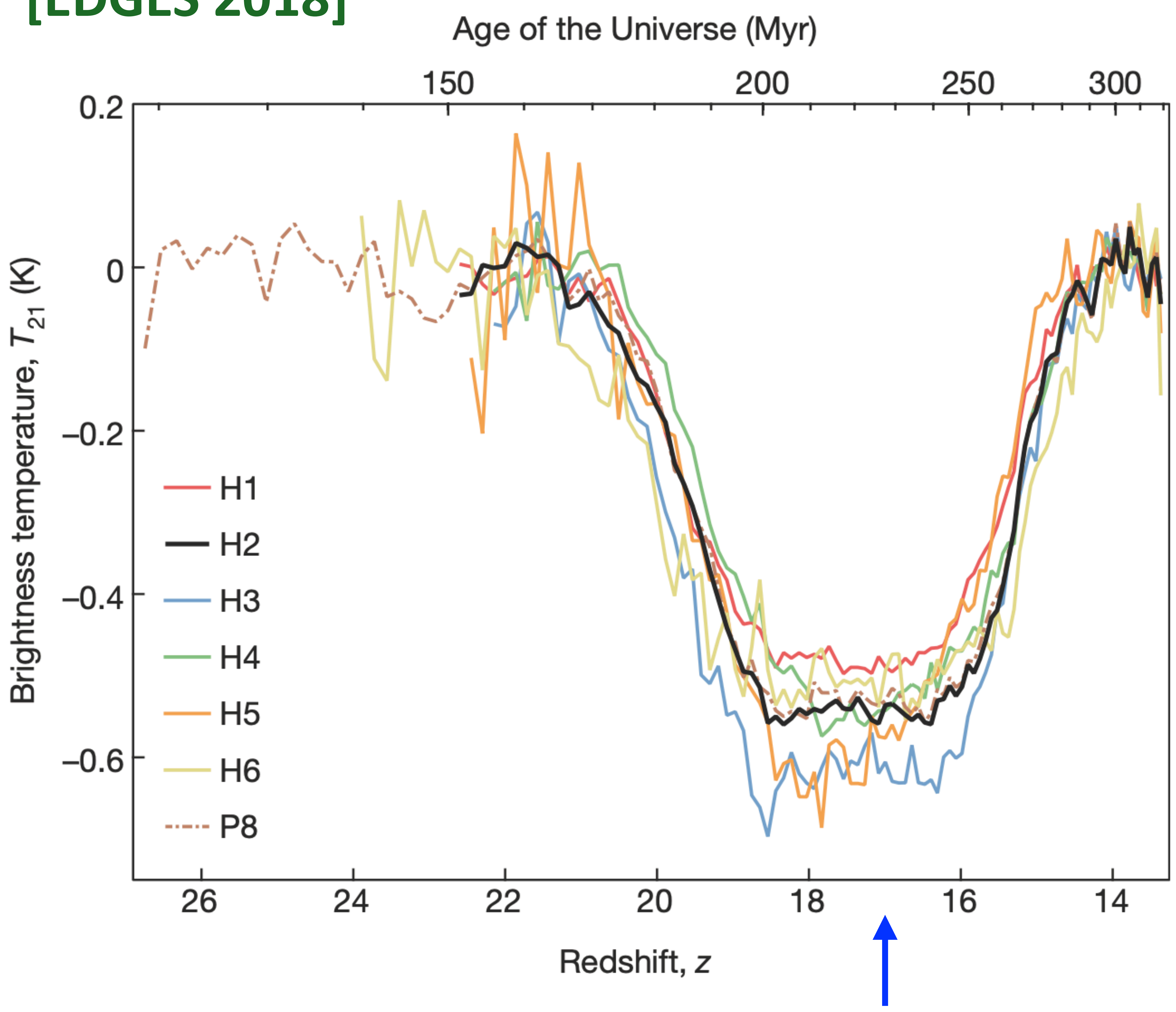


terrestrial

astro/cosmo

Millicharged DM can explain EDGES 21 cm anomaly

[EDGES 2018]



DM can cool gas

Millicharged DM xsec

$$\sigma \propto v^{-4}$$

easier to evade early universe constraints

colder gas or hotter CMB than expected

2 theoretical models

Models to generate millicharged particles (MCPs)

$e\,\epsilon\,A_\mu^\gamma\,\bar{\chi}\,\gamma^\mu\,\chi$ → χ is MCP

Kinetic mixing ←

Mass mixing

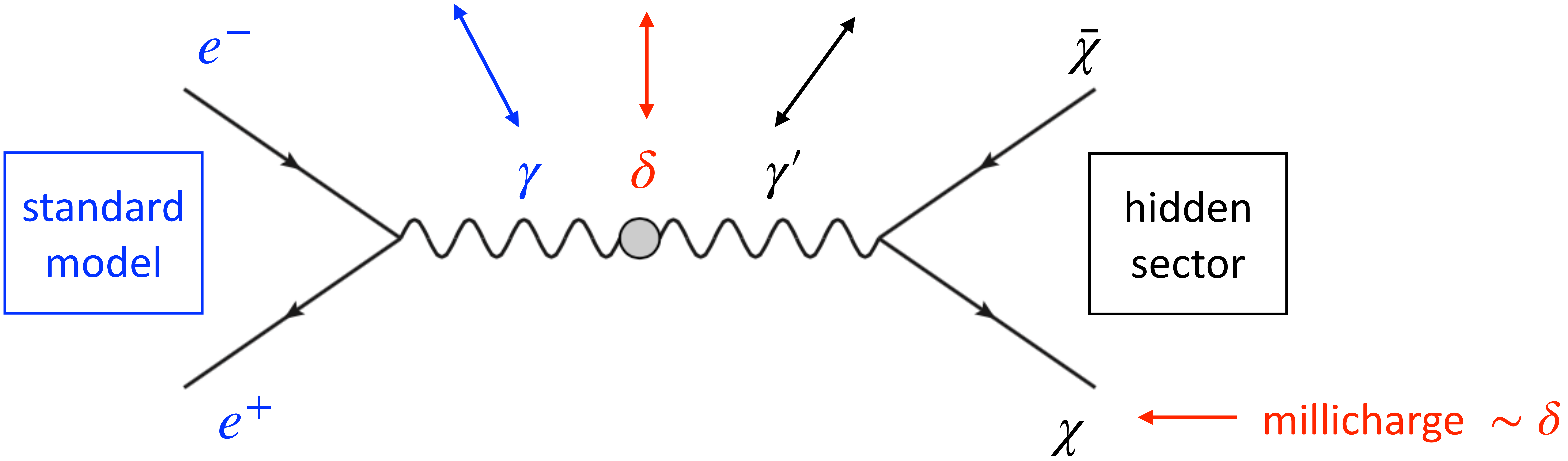
Kinetic mixing between two U(1) fields

Kinetic mixing between two U(1) fields: A_1 & A_2

$$\mathscr{L} = -\frac{1}{4}F_{2\mu\nu}F_2^{\mu\nu} - \frac{\delta}{2}F_{2\mu\nu}F_1^{\mu\nu} - \frac{1}{4}F_{1\mu\nu}F_1^{\mu\nu}$$

[Holdom, Phys.Lett. 166B, 196 (1986)]

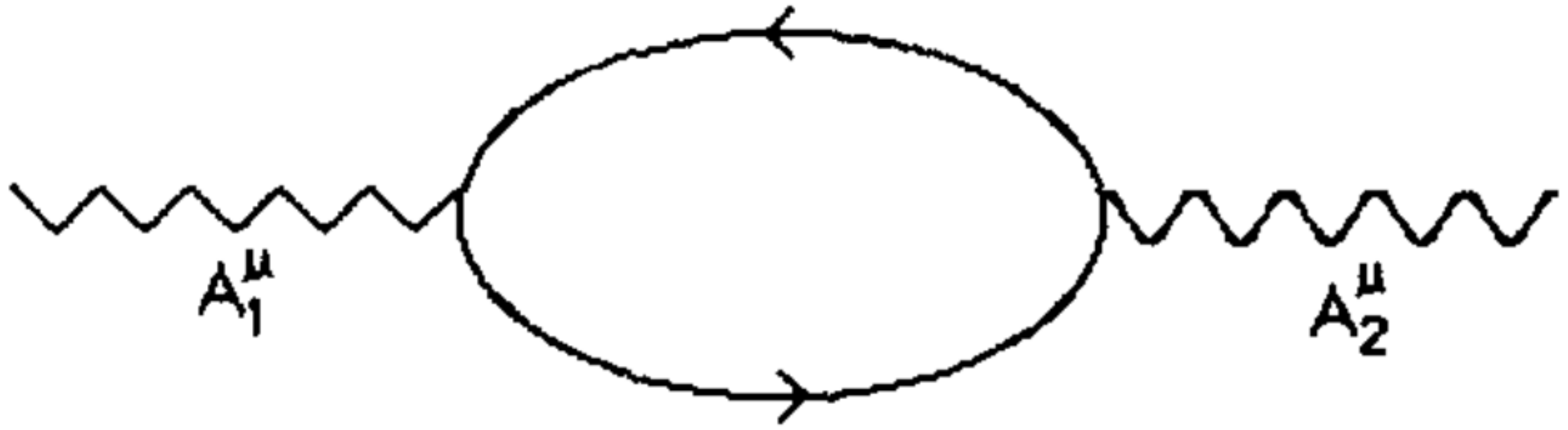
[Foot & He, Phys. Lett. 267B, 509 (1991)]



One example to generate kinetic mixing

[Holdom, Phys.Lett. 166B (1986) 196-198]

2 high scale fermions charged under two U(1)s



$$\mathscr{L} = -\frac{1}{4} F_{2\mu\nu} F_2^{\mu\nu} - \frac{1}{4} F_{1\mu\nu} F_1^{\mu\nu} - \frac{\delta}{2} F_{2\mu\nu} F_1^{\mu\nu}$$

$$\delta = \frac{e_1 e_2}{6\pi^2} \ln \frac{m'_{12}}{m_{12}}$$

Models to generate millicharged particles (MCPs)

Kinetic mixing

Mass mixing

Stueckelberg mass mixing between two U(1) fields

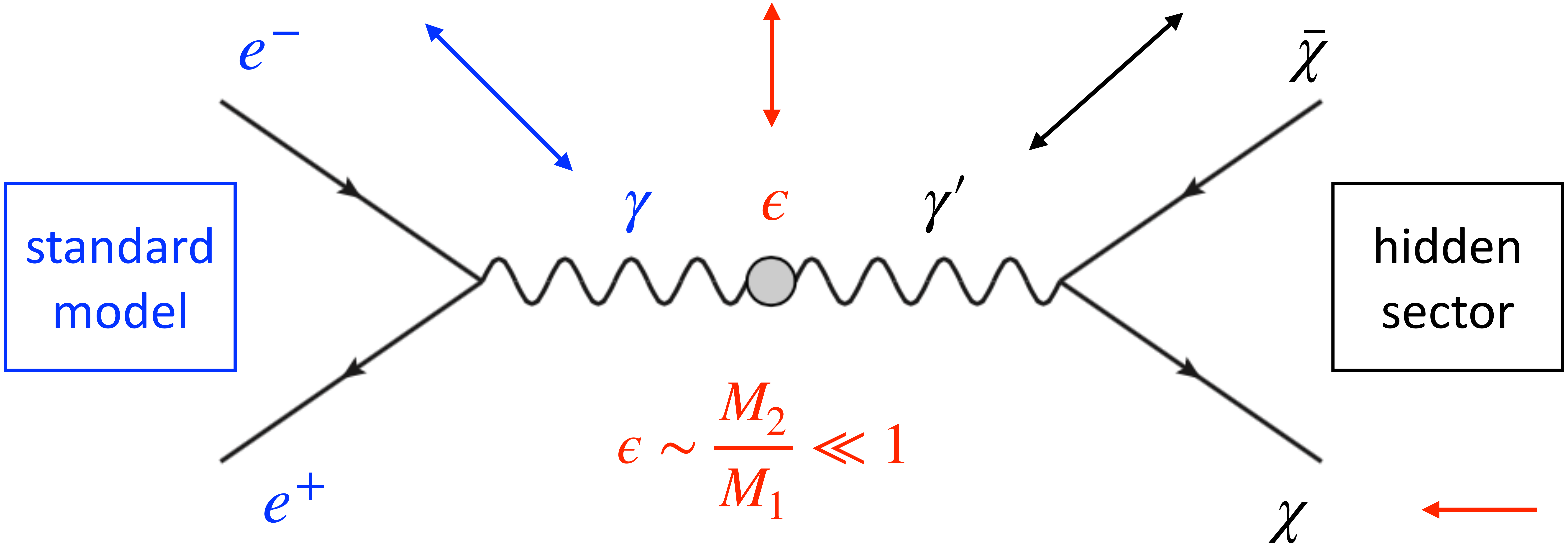
Stueckelberg mass mixing between two U(1) fields: A_1 & A_2

[Kors & Nath hep-ph/0402047]

[Feldman, ZL, Nath, hep-ph/0603039]

[Cheung & Yuan hep-ph/0701107]

$$\mathscr{L} = -\frac{1}{4}F_{2\mu\nu}F_2^{\mu\nu} - \frac{1}{2}(\partial_\mu\sigma + M_1 A_{1\mu} + M_2 A_{2\mu})^2 - \frac{1}{4}F_{1\mu\nu}F_1^{\mu\nu}$$



$$\epsilon \sim \frac{M_2}{M_1} \ll 1$$

millicharge $\sim \epsilon$

“Toy” model w/ both kinetic & mass mixings

$$-\frac{1}{4}F_{1\mu\nu}F_1^{\mu\nu} - \frac{1}{4}F_{2\mu\nu}F_2^{\mu\nu} - \frac{\delta}{2}F_{1\mu\nu}F_2^{\mu\nu} + J'_\mu A_1^\mu + J_\mu A_2^\mu - \frac{1}{2}M_1^2 A_{1\mu}A_1^\mu - \frac{1}{2}M_1^2\epsilon^2 A_{2\mu}A_2^\mu - M_1^2\epsilon A_{1\mu}A_2^\mu$$

after field redefinition & rotation ⟶ canonical $(-F^2/4)$ & diagonal mass matrix

degeneracy | dark photon | SM photon

$$\frac{1}{\sqrt{1-2\delta\epsilon+\epsilon^2}}\left(\frac{\epsilon-\delta}{\sqrt{1-\delta^2}}J_\mu + \frac{1-\delta\epsilon}{\sqrt{1-\delta^2}}J'_\mu\right)A_M^\mu + \frac{1}{\sqrt{1-2\delta\epsilon+\epsilon^2}}\left(J_\mu - \epsilon J'_\mu\right)A_\gamma^\mu$$

mass mixing → millicharge

[Feldman, ZL, Nath, hep-ph/0702123, 309 cites]

[see also, Fabbrichesi et al., 2005.01515, The Dark Photon [review], p 7-9]

Kinetic versus mass mixings (in “realistic” model)

common features

hidden boson mix w/ hypercharge (instead of photon) $\Longrightarrow$ 3 by 3 mass matrix

hidden boson → photon-like (dark photon) $m_{A'} \ll m_Z$

hidden boson → hypercharge-like $m_{A'} \gg m_Z$

difference

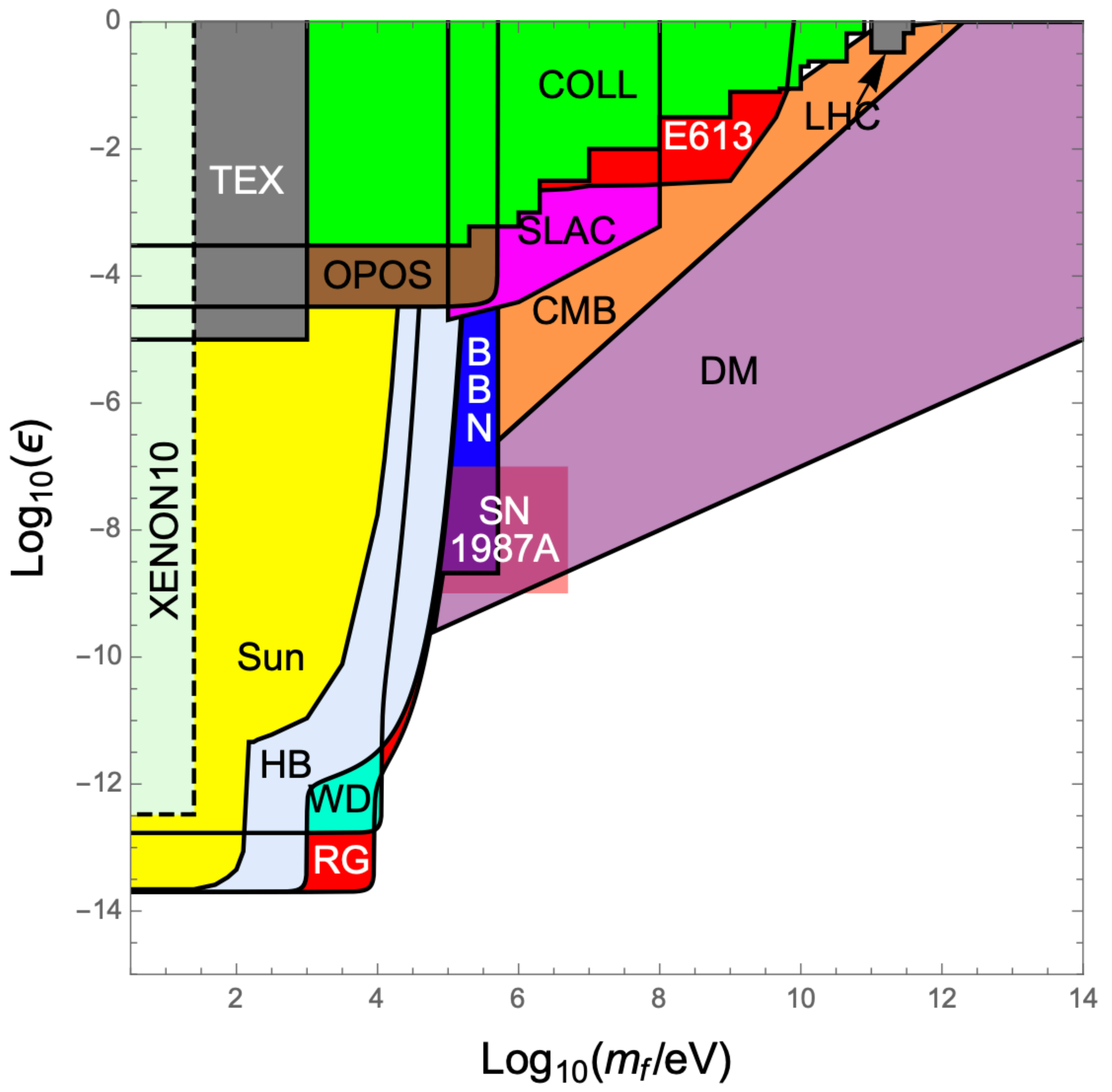
mass mixing $\Longrightarrow$ millicharge & massive dark photon

kinetic mixing $\Longrightarrow$ millicharge & massless dark photon

[Feldman, ZL, Nath, hep-ph/0702123, 309 cites]

3 astro/cosmo probes

Energy loss argument in star evolutions



White dwarfs

Supernova

Red giant stars

Horizontal branch stars

Sun

[see e.g. Vinyoles, Vogel, 1511.01122]

A small fraction of millicharged DM is allowed by CMB

[Dubovsky et al, hep-ph/0311189v2]

WMAP data on the CMB anisotropy: $\Omega_\chi h^2 < 0.007$

[de Putter et al, 1805.11616]

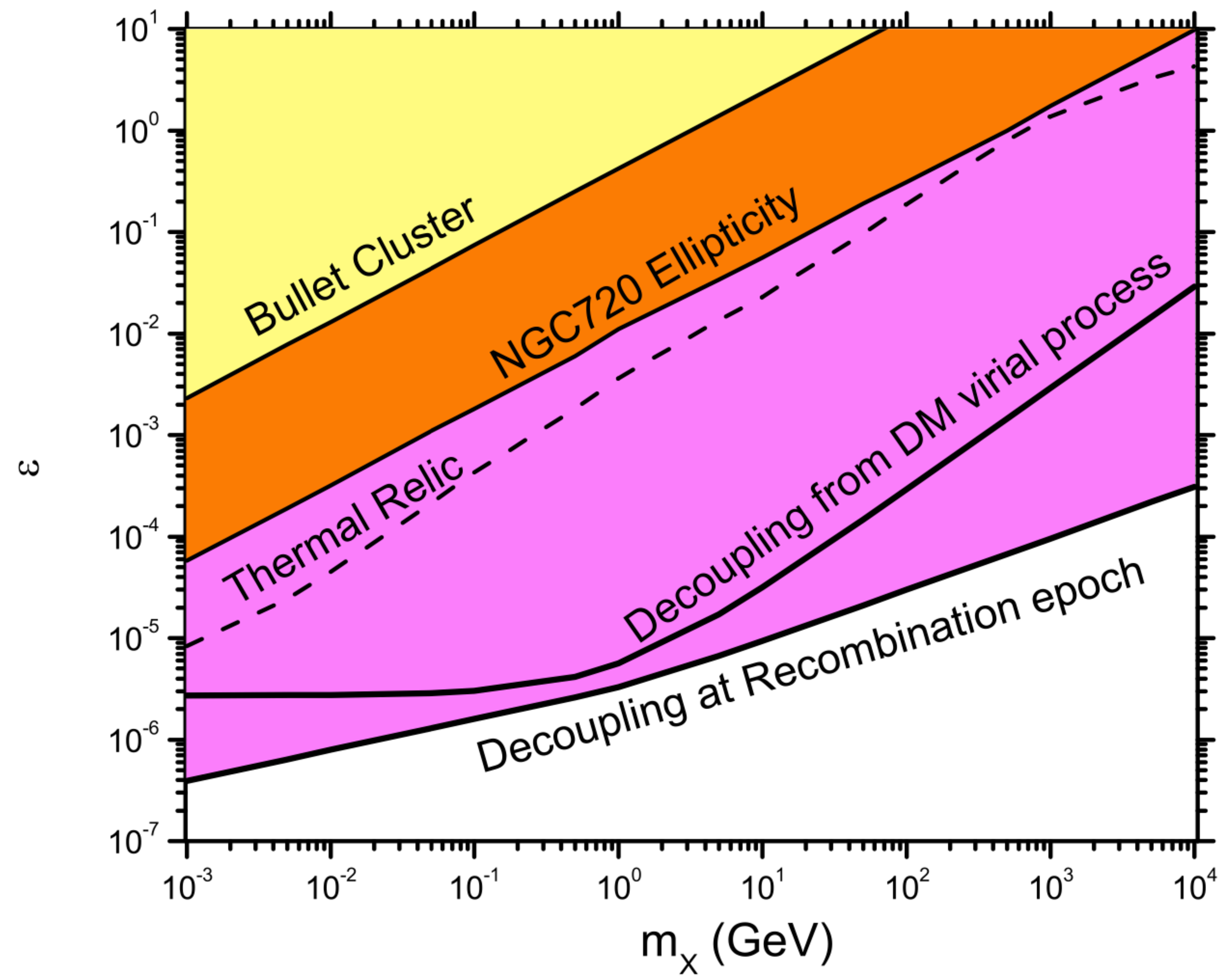
[Kovetz et al, 1807.11482]

[Boddy et al 1808.00001]

The Planck limits vanish if millicharged DM is less than 0.4%; DM essentially becomes cosmologically indistinguishable from a small additional amount of baryons.

Or millicharge has to be very small to not disturb CMB

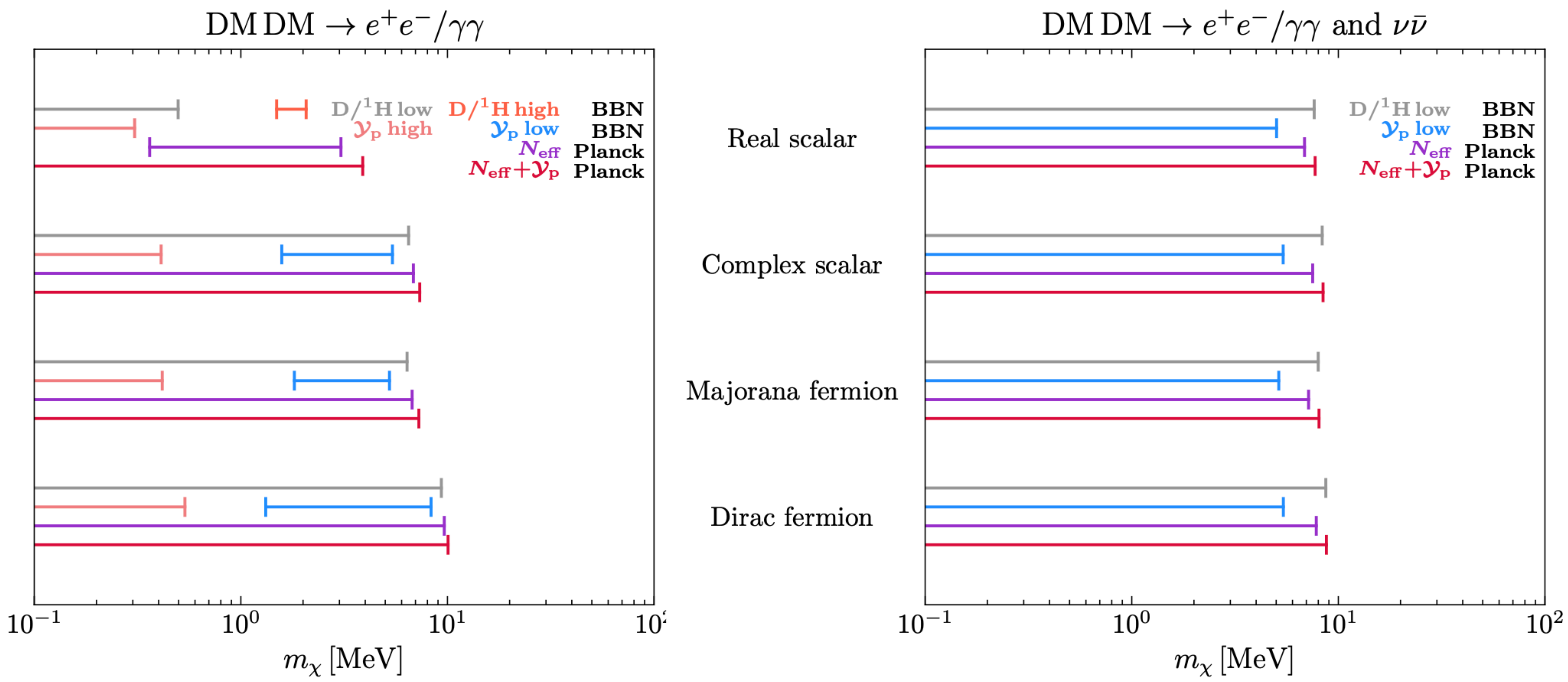
[McDermott, Yu, Zurek, 1011.2907]



completely decouple MCPDM
from baryon at recombination

N_{eff} constraints

light MCP and/or annihilations → N_{eff} neutrinos → constrained by BBN & CMB



[Depta et al, 1901.06944]

4 terrestrial searches

Precision tests of QED

[Dobroliubov, Ignatiev, PRL 1990]

electron/muon g-2 (2-loop)

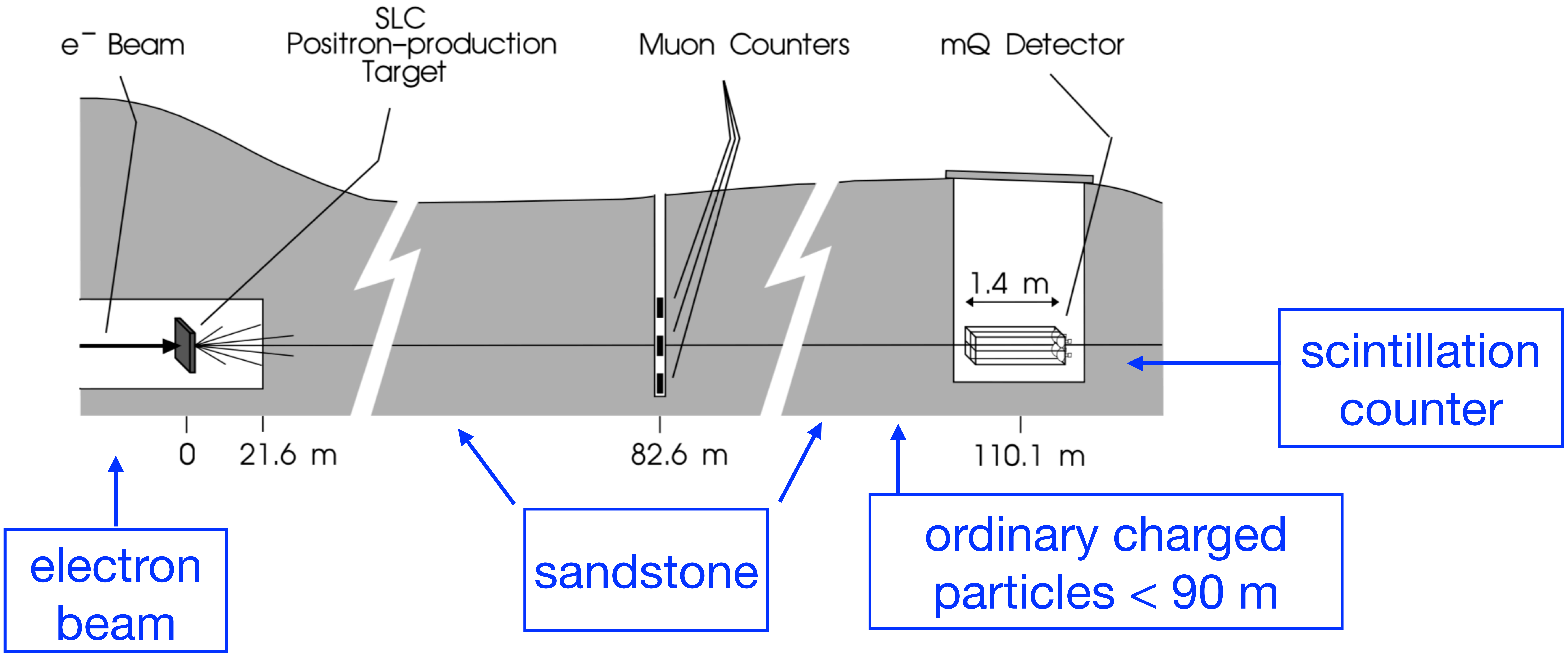
Lamb shift (1-loop)

orthopositronium decay

but QED precision limits are weak compared to others

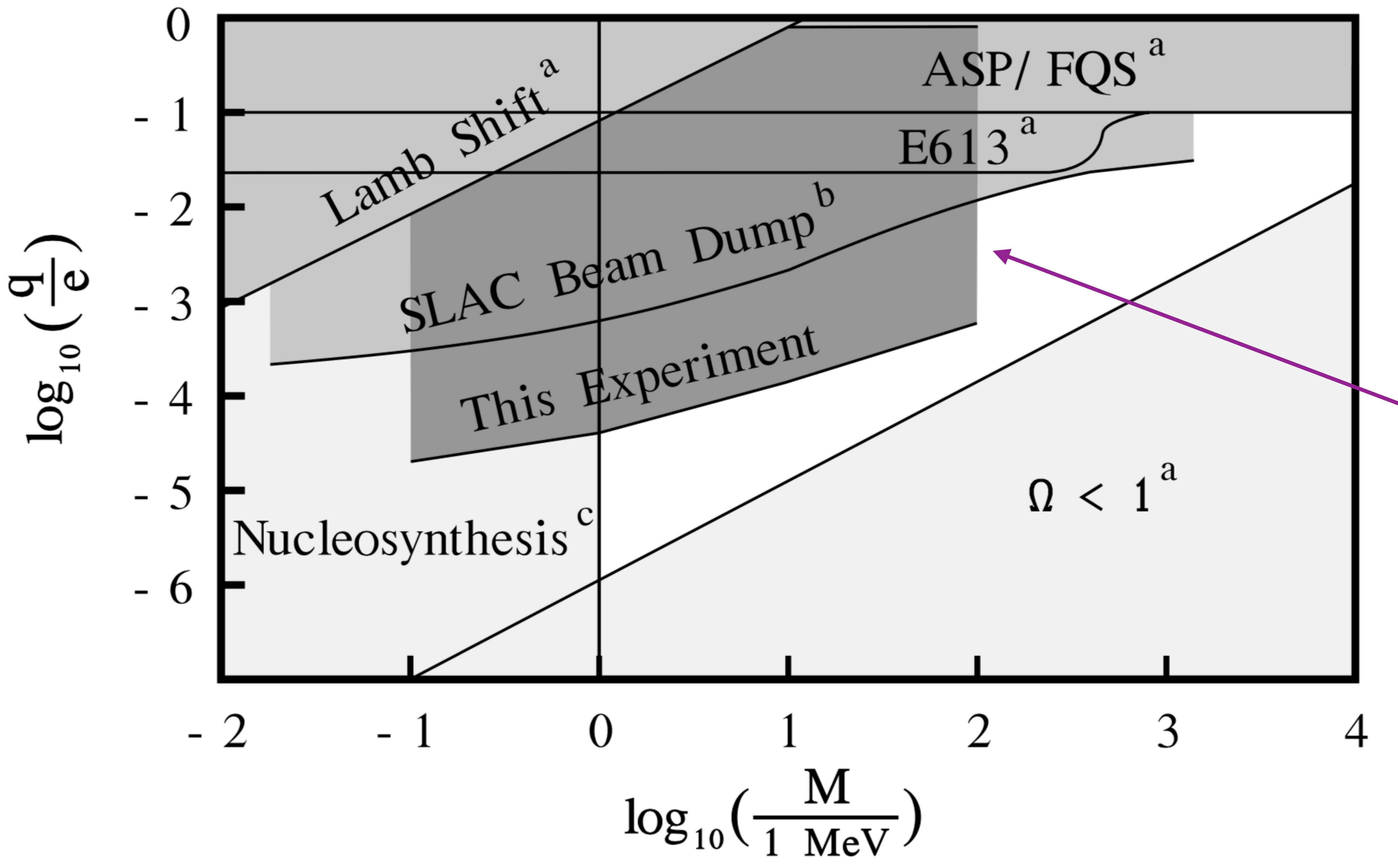
SLAC mQ: electron beam dump experiment

[Prinz et al, PRL 81.1175, 1998]



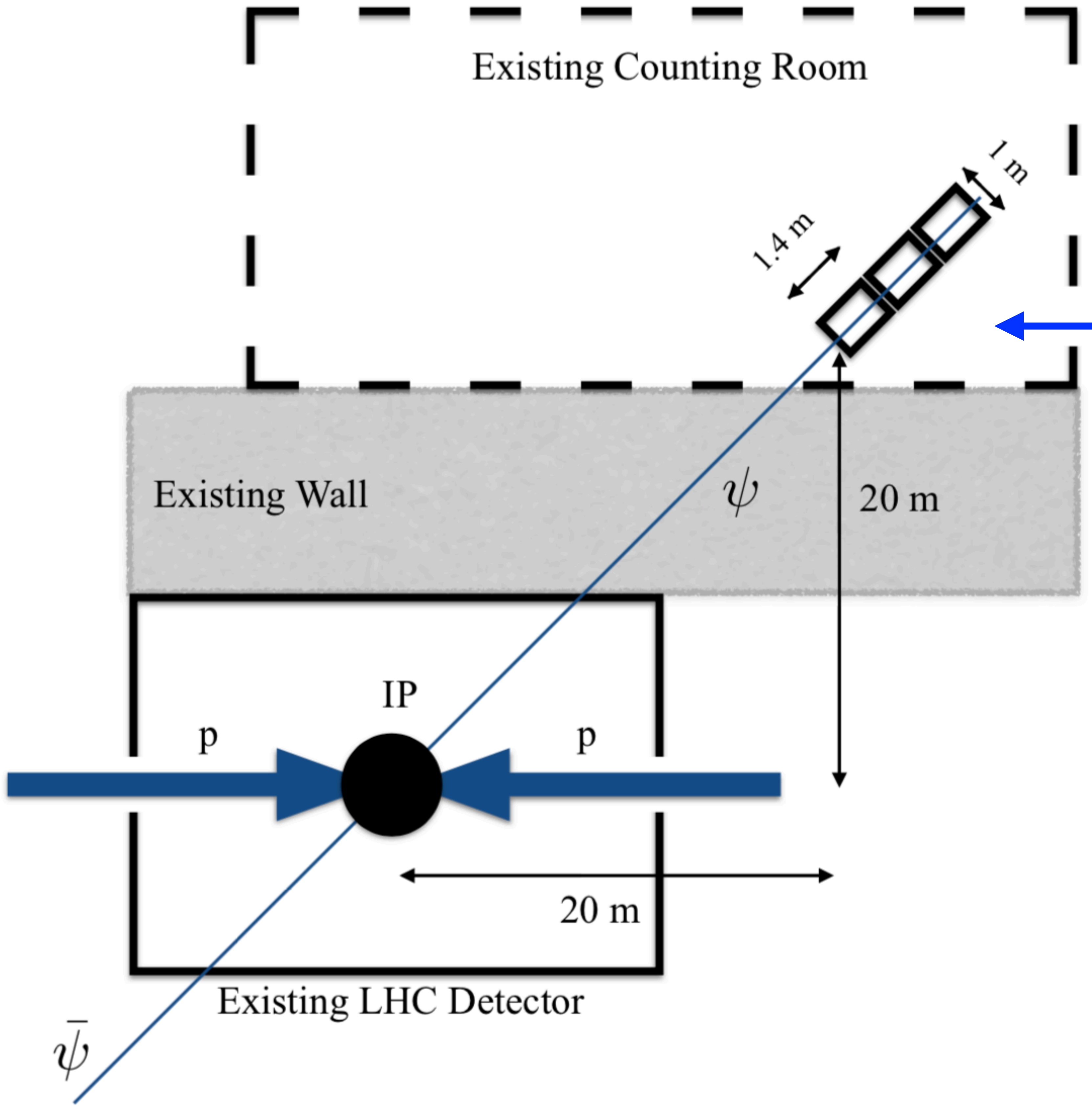
SLAC mQ constraints on millicharge

[Prinz et al, PRL 81.1175, 1998]



m > 100 MeV
MCP yield die off

MilliQan: proposed scintillation detector @ LHC

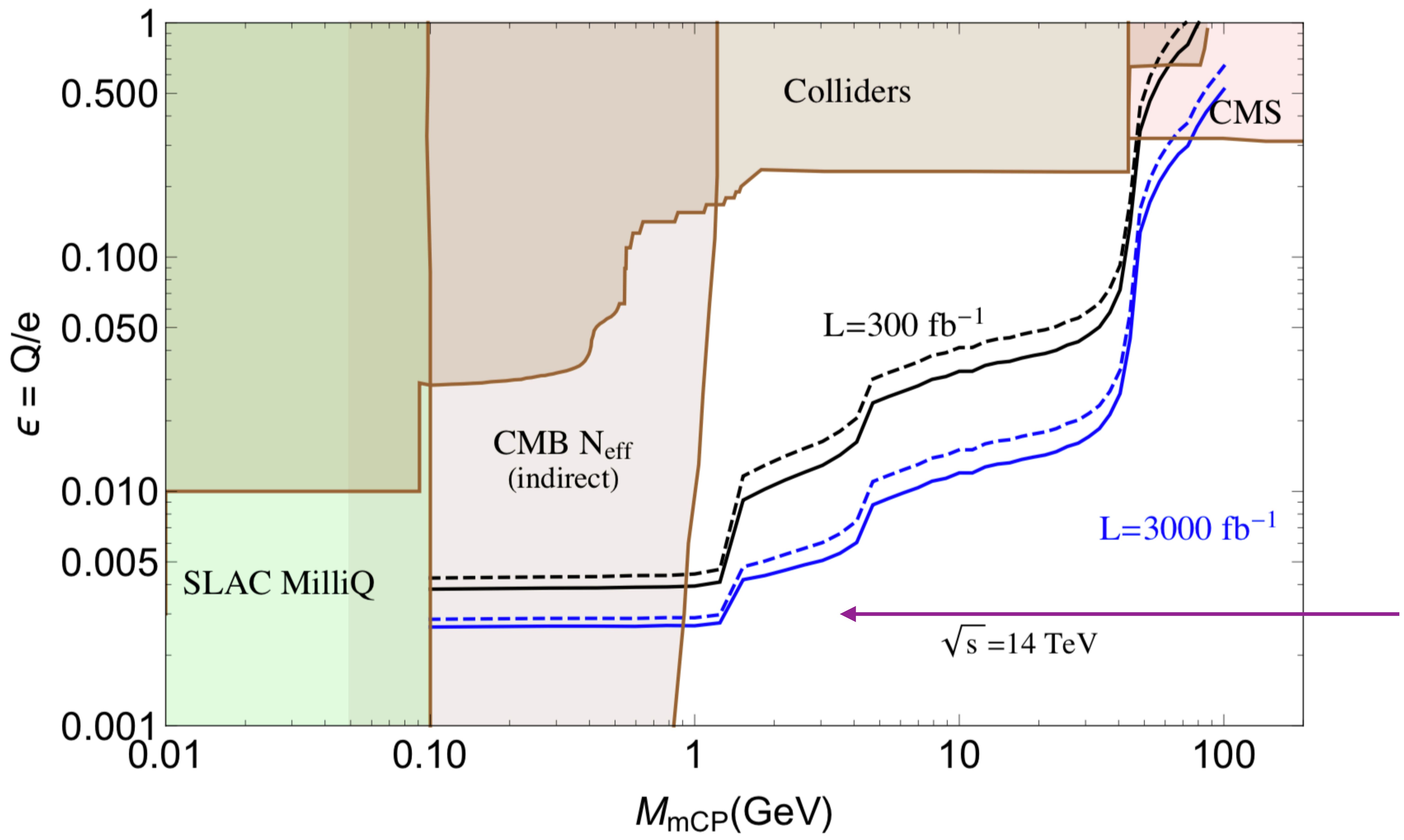


$1\ \text{m} \times 1\ \text{m} \times 3\ \text{m}$ plastic scintillators array with 3 sections (pointing to CMS IP), each containing 400 $5\ \text{cm} \times 5\ \text{cm} \times 80\ \text{cm}$ scintillator bars coupled to PMT. 33 m away from CMS IP.

[Haas et al., 1410.6816]

[Ball et al., 1607.04669]

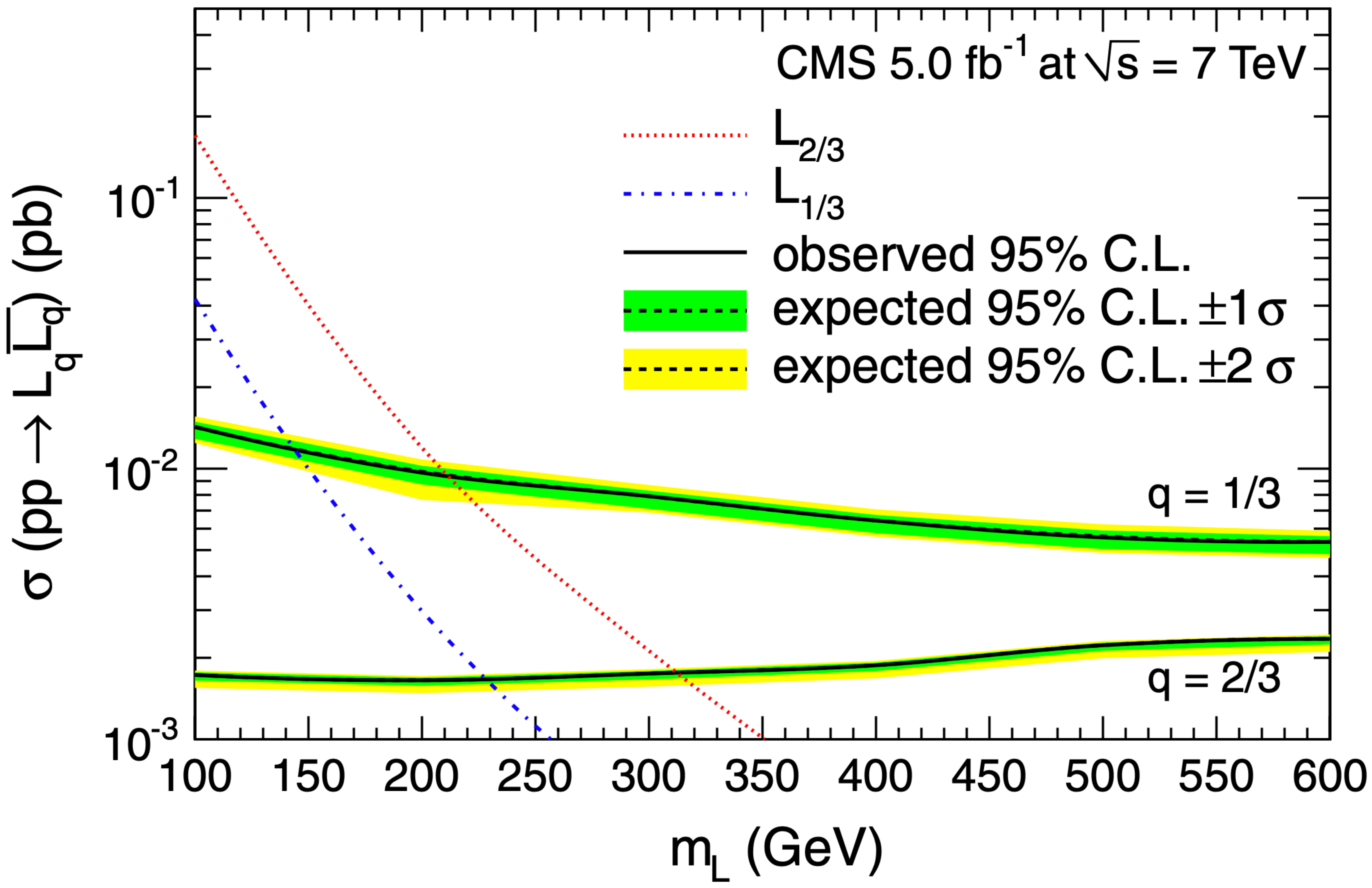
MilliQan sensitivity on millicharged particles



[Ball et al., 1607.04669]

photoelectron drops below one when $\epsilon \lesssim O(10^{-3})$

CMS searches on fractional charged particles

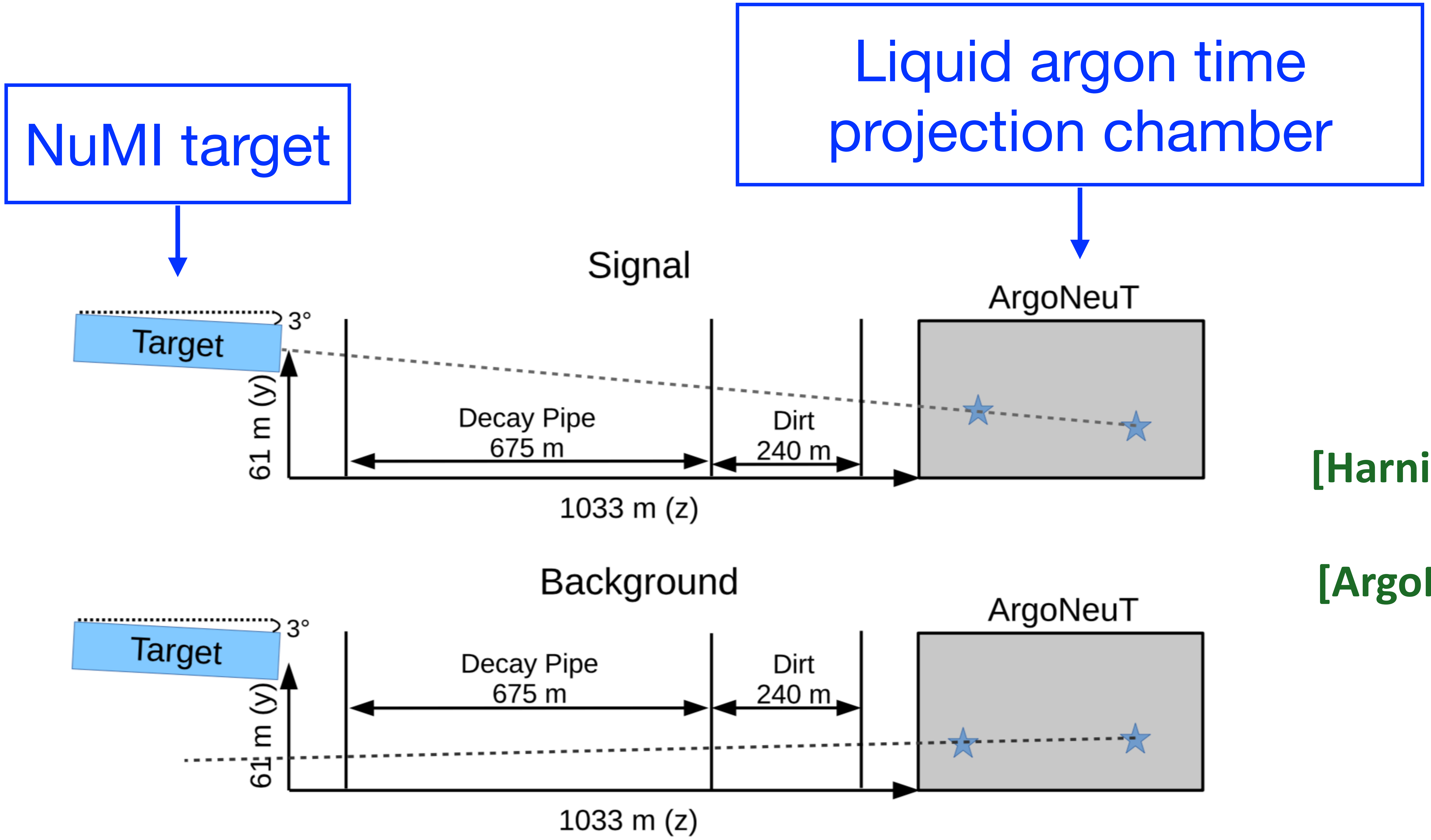


[CMS, 1210.2311]

exclude mass below 310 (140) GeV for $2e/3$ $(e/3)$

low-charge tracks in silicon tracking detector

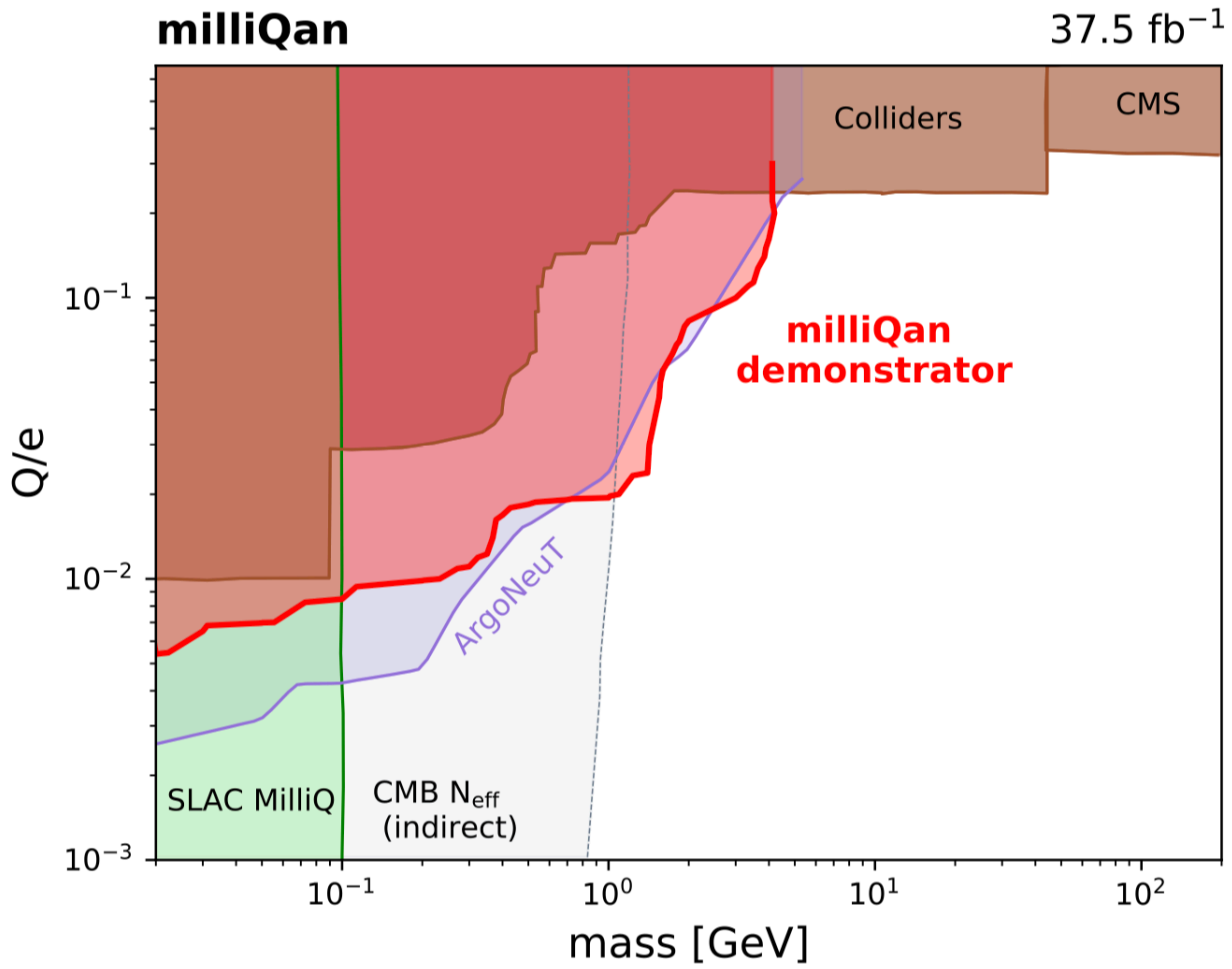
ArgoNeuT @ FermiLab: liquid argo neutrino detector



[Harnik et al., 1902.03246]

[ArgoNeuT, 1911.07996]

Limits from ArgoNeuT & MilliQan demonstrator (1%)



[ArgoNeuT, 1911.07996]

ArgoNeuT 10^{20} POT

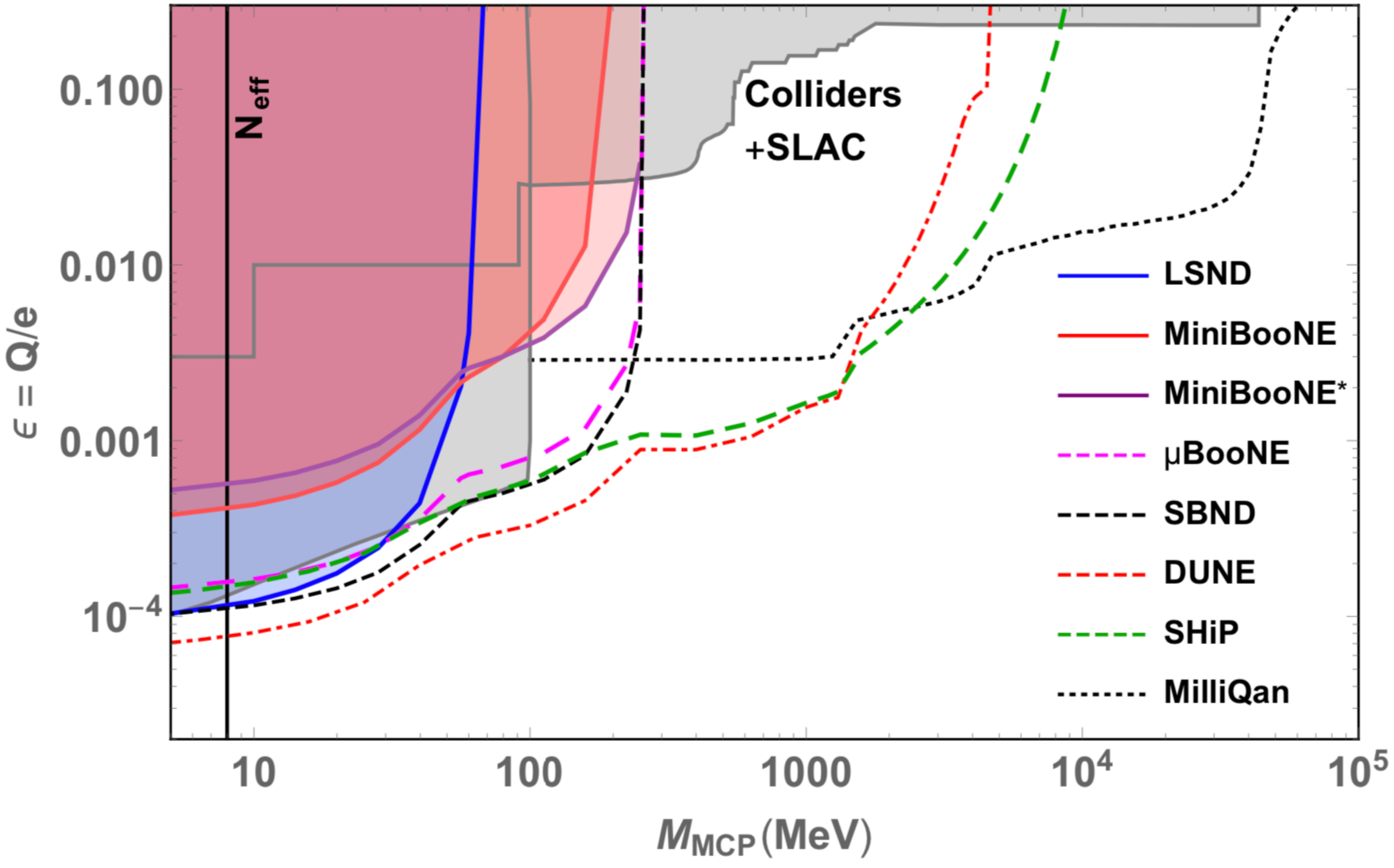
[milliQan demonstrator, 2005.06518]

1% of total detector

37/fb in 2018

MCP scatters w/ neutrino experiment target

MCP produced in proton fixed-target experiments → MCP scatters w/ target (electron) in the neutrino detector



[Magill et al., 1806.03310]

solid: data

dashed: projection

Future experiments to probe millicharge

LDMX: electron fixed target

Dark Shine: fixed target

NA64: muon fixed target

FerMINI: scintillators @ proton fixed target

SUBMET: scintillators @ JPARC

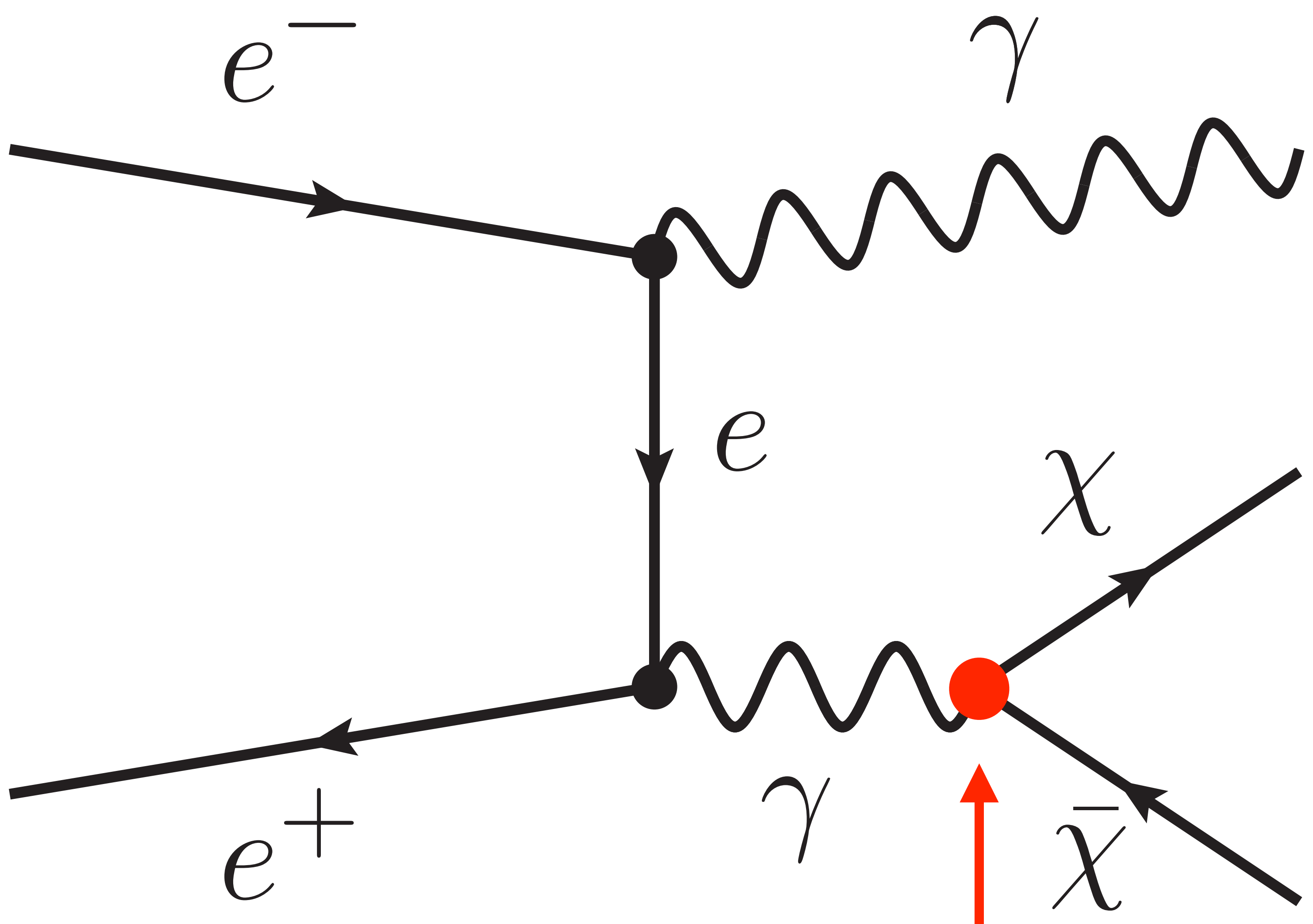
neutrino experiments

DM experiments

Search for millicharged particles at electron colliders

very small ionization signal from millicharge → mono-photon @ electron colliders

[ZL, Zhang, 1808.00983]

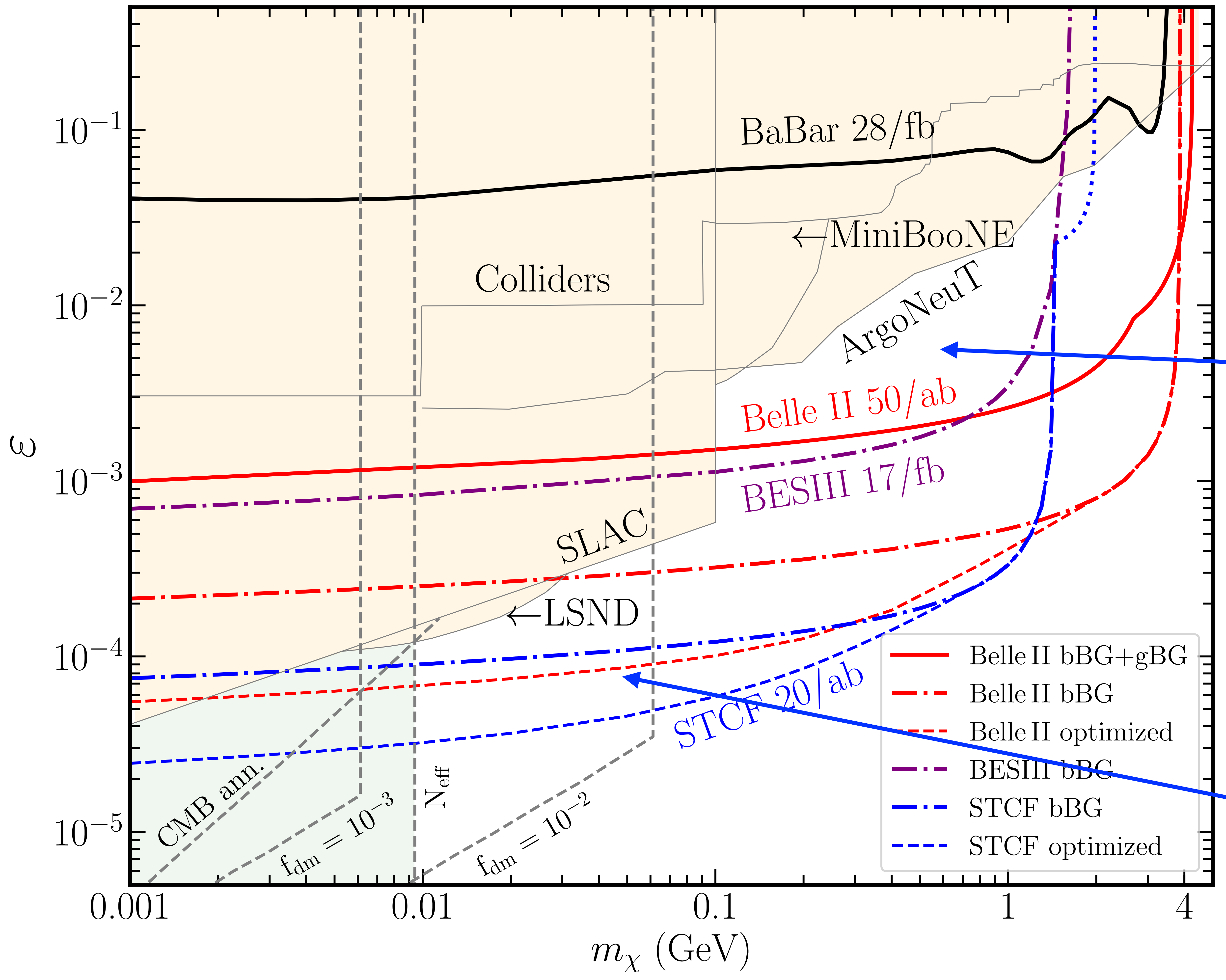


monophoton

"invisible" at electron colliders

millicharge vertex: $e\,\epsilon\,A_\mu^\gamma\,\bar{\chi}\,\gamma^\mu\,\chi$

Electron colliders can probe new parameter regions



diff BG considerations

BaBar

BESIII

new regions: 0.1-4 GeV

Belle II

STCF

$\epsilon \lesssim O(10^{-4})$?

[Liang, ZL, Ma, Zhang, 1909.06847]

Summary

Millicharged particles can naturally appear in kinetic mixing or Stueckelberg mass mixing models

Millicharged particles can be searched for in astrophysics/cosmology processes, precision tests of QED, and accelerator experiments

A number of terrestrial experimental methods have been carried out and recently proposed to search for millicharged particles