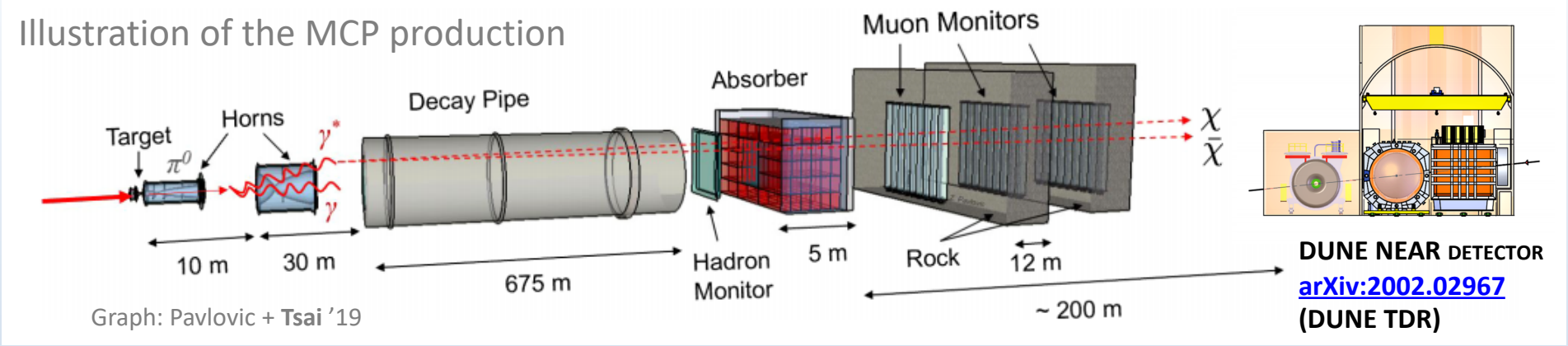

Accelerator Probes for Millicharged Particles & Millicharged Dark Matter

Yu-Dai Tsai, **Fermilab/U Chicago**

On behalf of other LOI authors, Jonathan Assadi, Matthew Citron, Albert De Roeck, Saeid Foroughi-Abari, Gianluca Petrillo, Yun-Tse Tsai, and Jaehoon Yu

LOI Update: link

Contact: ytsai@fnal.gov

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Volodymyr Takhistov (UCLA)
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Jaehyeok Yoo (Korea University)
Jilberto Zamora-Saa (Universidad Andres Bello)

LOI Update: link

LOI Endorsers or White Paper Authors Sign-Up Link: link2

Outline of the LOI

- Not about a specific probe, but a **general overview** of all the experimental programs below:
- - Colliders

  - Proton fixed-target & neutrino experiments

  - Lepton fixed-target experiments

  - MilliQan/FerMINI: dedicated detectors

  - Cosmic-Ray Production and Neutrino Observatories
- Millicharged Strongly Interacting Dark Matter

Outline of the Talk

- Intro
- Experimental Programs
  - **Proton fixed-target & neutrino experiments**
  - Cosmic-Ray Production and Neutrino Observatories
- Millicharged Strongly Interacting Dark Matter

Millicharged Particle & Dark Matter

Finding Minicharge

- **Is electric charge quantized and why?** A long-standing question!

- SM U(1) allows arbitrarily small (any real number) charges.
  Why don't we see them? Motivates **Dirac quantization, Grand Unified Theory (GUT)**, to explain such quantization (anomaly cancellations fix some SM $U(1)_Y$ charge assignments)

- MCP (not confined) is predicted by Superstring theories:
  Wen, Witten, Nucl. Phys. B 261 (1985) 651-677, link

- Link to string compactification and quantum gravity (Shiu, Soler, Ye, PRL '13)

- Conservatively, testing if e/3 is the minimal charge

- MCP could have natural link to dark sector (through dark photon, etc)

- Could account for (sometimes fractional) dark matter (DM) abundance;
  Used for the cooling of gas temperature to explain the EDGES anomaly [EDGES collab., Nature, (2018); Barkana, Nature, (2018)]. See backup slides for more refs

MCP Model

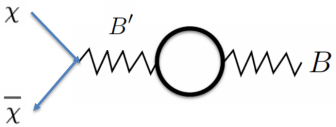
- A particle fractionally (or irrationally) charged under SM U(1) hypercharge, $\mathcal{L}_{\rm MCP} = i\bar{\chi}(\not{\partial} - i\epsilon' e \not{B} + M_{\rm MCP})\chi$

- ϵ' can in principle be arbitrarily small.

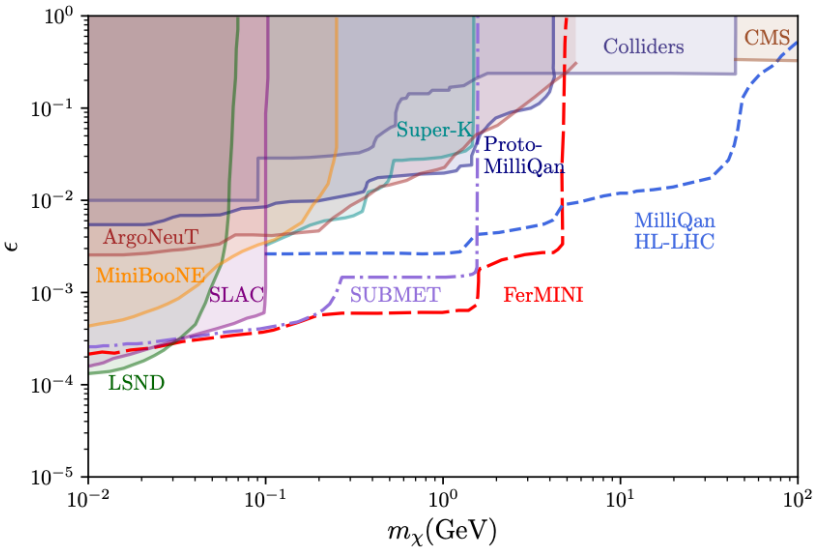
- Can just consider these Lagrangian terms by themselves (no extra mediator, i.e., dark photon). **Completely legal**! Naively **violating the empirical charge quantization**.

- We are simply search for MCP!
  Minimal assumptions = most robust constraints/probes.

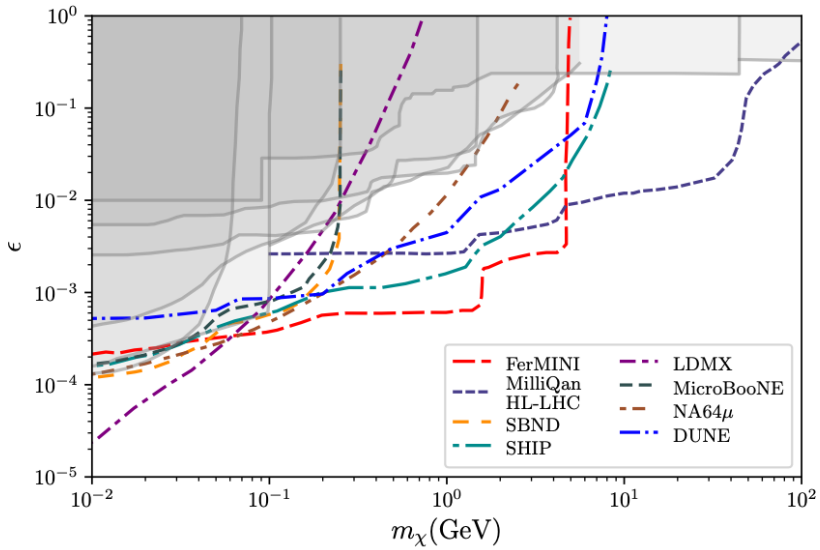
- This could come from vector portal **Kinetic Mixing** (Holdom, '85)
  - a nice origin to the above terms
  - help give rise to **dark sectors**
  - easily compatible with **Grand Unification Theory**
  - see backup slides



Compilation



(a) Existing bounds and MCP dedicated experiments



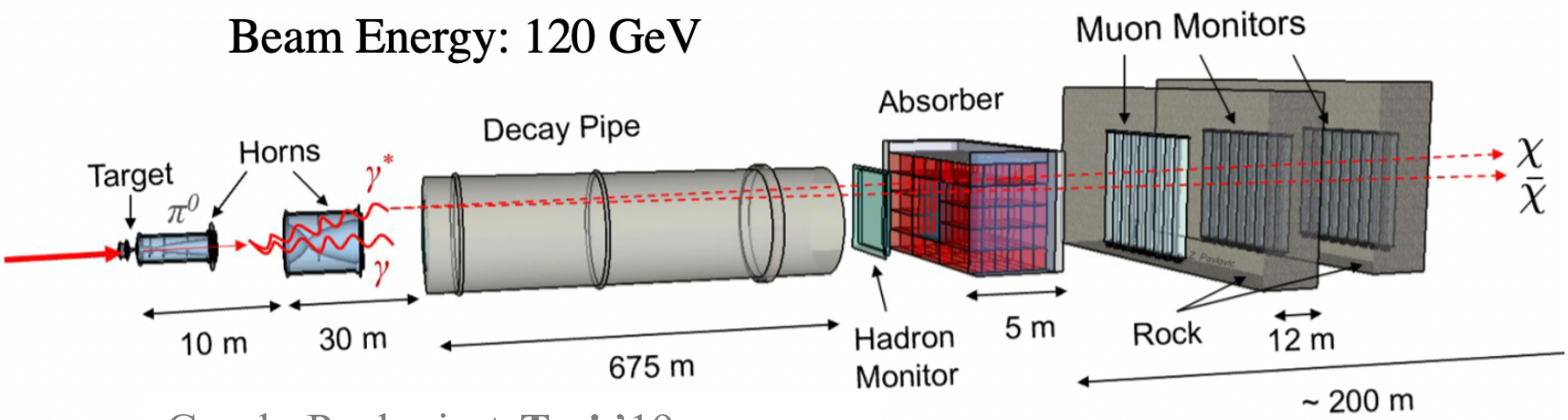
(b) Comparison of future projections

- Our search is simply a search for particles (fermion χ) with **{mass, electric charge}** =
- **The result for scalar MCP is simi** $\{m_\chi, \epsilon e\}$
- $\epsilon \equiv Q_\chi / e.$

MCP in Proton Fixed-Target & Neutrino Experiments

MCP Produced in Fixed-Target Experiments

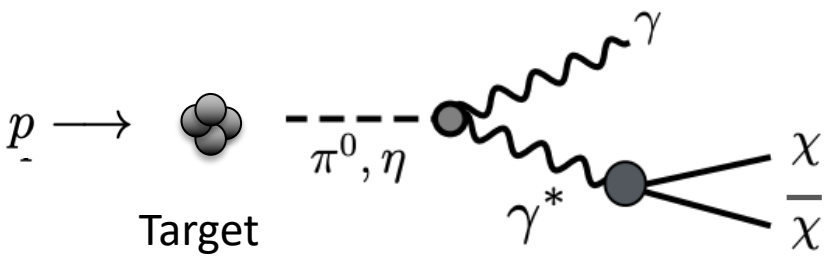
Example: Neutrinos at the Main Injector (NuMI) beamline
See arXiv:1507.06690 (NuMI collaboration)



Graph: Pavlovic + **Tsai** '19
Also, see arXiv:1812.03998

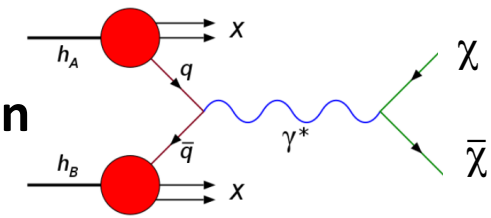
Important Production Channels of MCP

- ❑ **Production: Meson Decays**

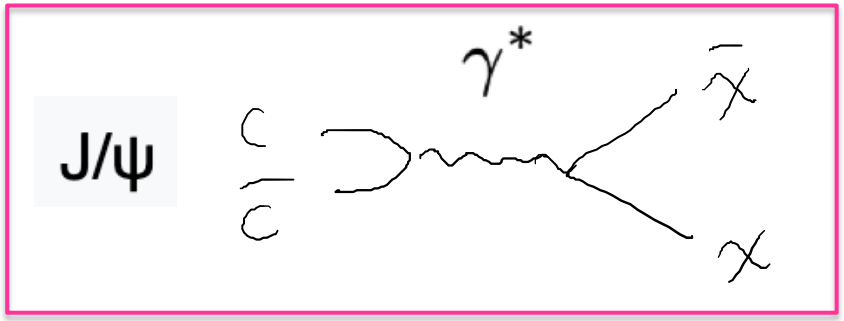


Modified from 1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

- ❑ **Production: Drell-Yan**



- ❑ **Heavy (vector) mesons are important for high-mass mCP's in high-energy beams**



BR($\pi^0 \to 2\gamma$) = 0.99

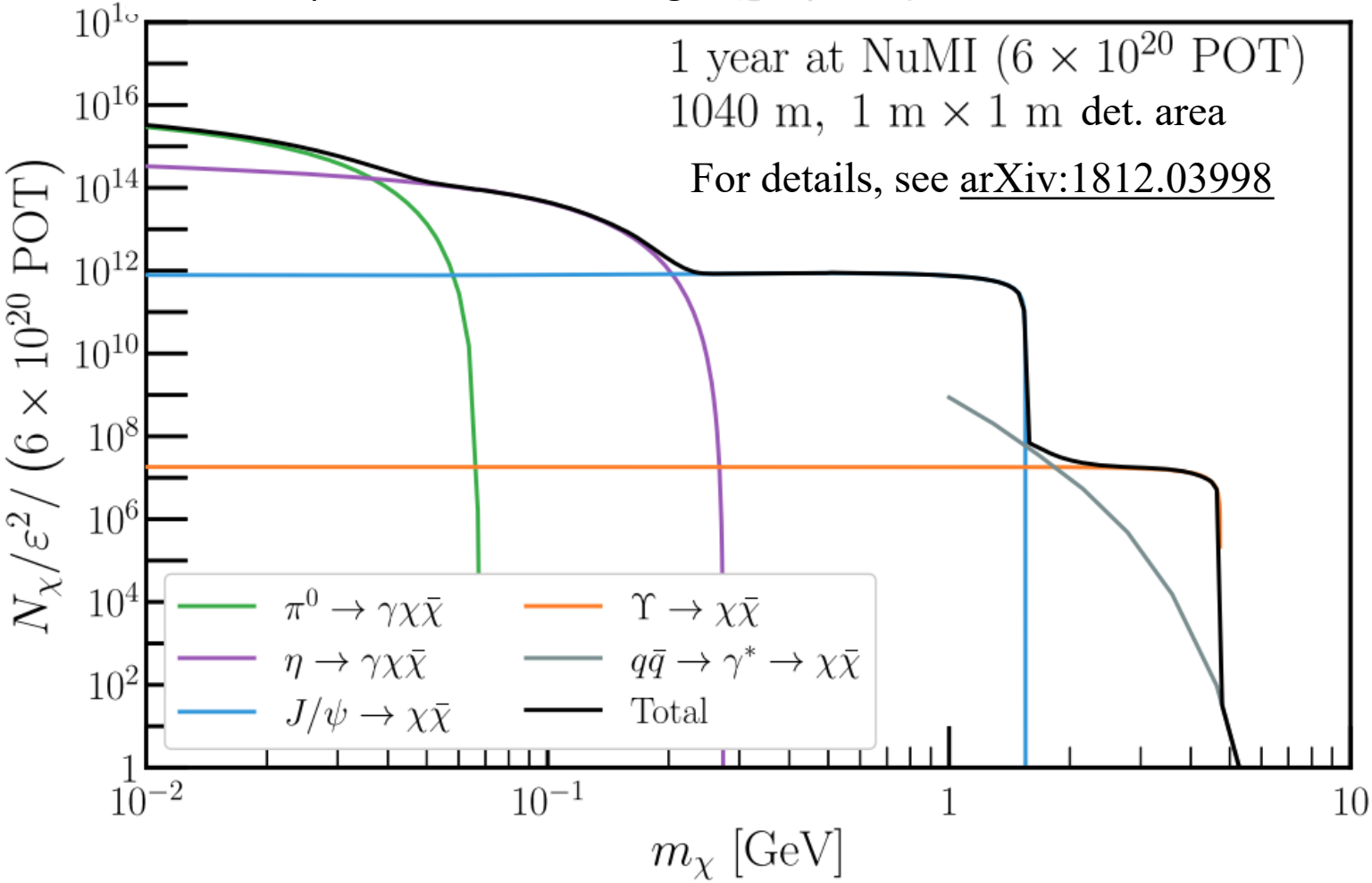
BR($\pi^0 \to \gamma e^- e^+$) = 0.01

BR($\pi^0 \to e^- e^+$) = $6 * 10^{-6}$

BR($J/\psi \to e^- e^+$) = 0.06

MCP Production/Flux

120 GeV proton beam on target (graphite)

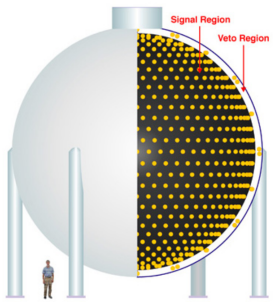


Scattering Detectors

Useful Beamlines:

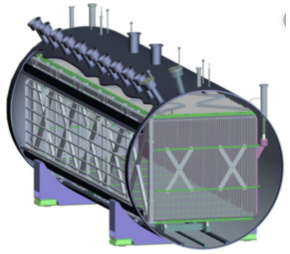
- **BNB**
- **NuMI**
- **CERN SPS**
- **LBNF (future)**

MiniBooNE Detector



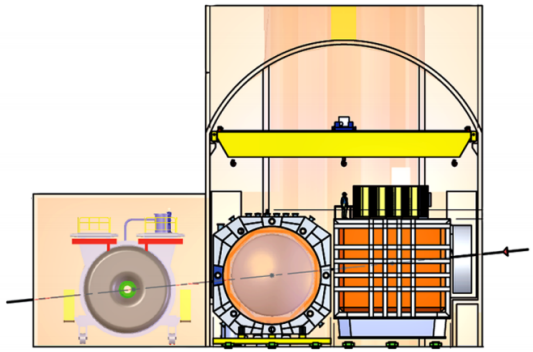
arXiv:0806.4201
MiniBooNE collaboration

MicroBooNE Detector



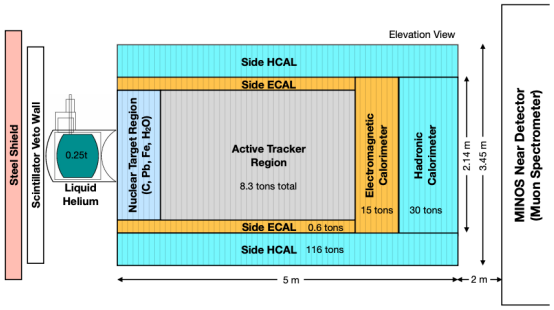
arXiv:1612.05824
MicroBooNE collaboration

DUNE Near Detector



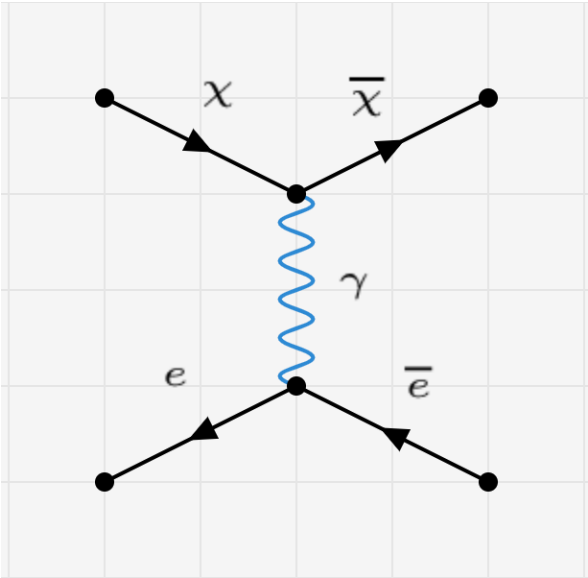
arXiv:2002.02967, DUNE TDR V - I

MINERvA Detector



arXiv:1109.2855
MINERvA collaboration

MCP Detection: Hard Scattering or Ionization



- **"Hard" (MeV-level) electron elastic scattering: (single / double hit)**

  Magill, Plestid, Pospelov, **Tsai**, 1806.03310 (MCP in neutrino Experiments)

  Harnik, Liu, Ornella, arXiv:1902.03246; ArgoNeuT collab: arXiv:1911.07996

- **Ionization (eV-level):** ~ very low-energy scattering**: (triple / quadruple scintillation)**

  MilliQan: arXiv:1410.6816, Haas, Hill, Izaguirre, Yavin (see Mathew's talk)

  FerMINI: arXiv:1812.03998, Kelly, **Tsai**

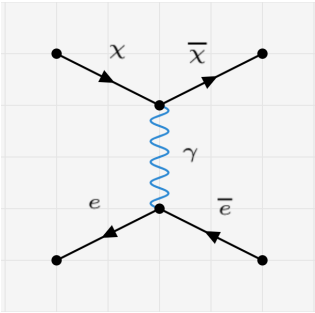
MCP Detection: Electron Scattering

- $\boldsymbol{Q^2}$ is the squared 4-momentum transfer.

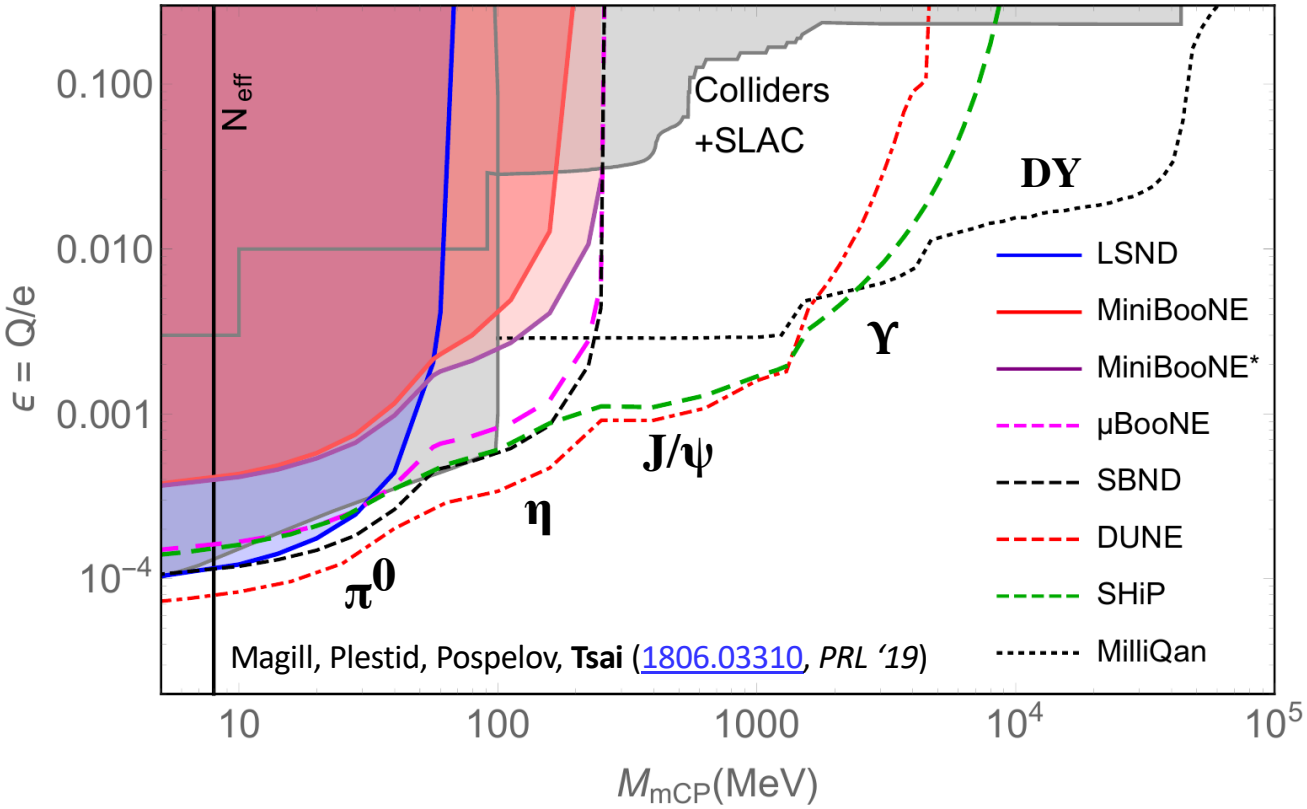
- lab frame: $Q^2 = 2m_e\,(E_e - m_e)$, $E_e - m_e$ is the electron recoil energy.
- Expressed in **recoil energy threshold**, $E_e{}^{(min)}$, we have

$$\sigma_{e\chi} \simeq 2.6 \times 10^{-25}\mathrm{cm}^2 \times \epsilon^2 \times \frac{1\ \mathrm{MeV}}{E_e^{(\mathrm{min})} - m_e}.$$

- Sensitivity greatly enhanced by accurately **measuring low energy electron recoils** **for MCP's & light-mediator scattering**



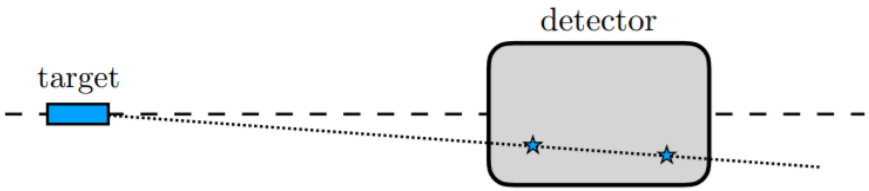
Sensitivity at Neutrino Detectors



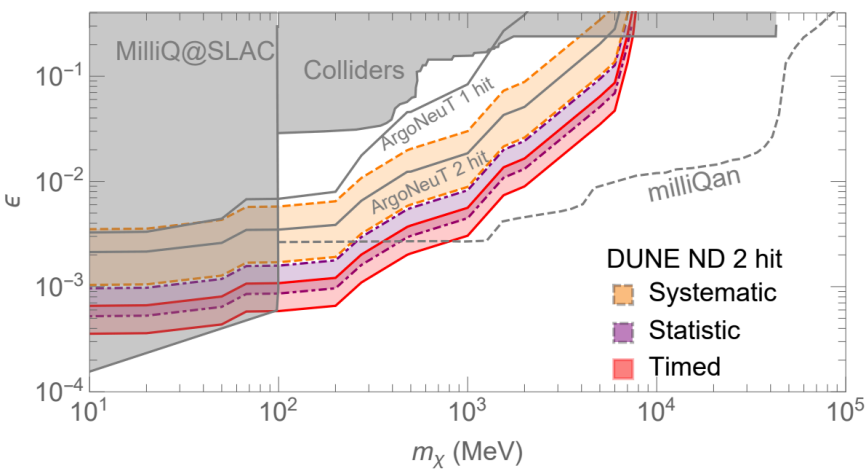
x-axis: m_x (MCP mass),
y-axis: $\epsilon = Q_x/e$ (charge ratio).

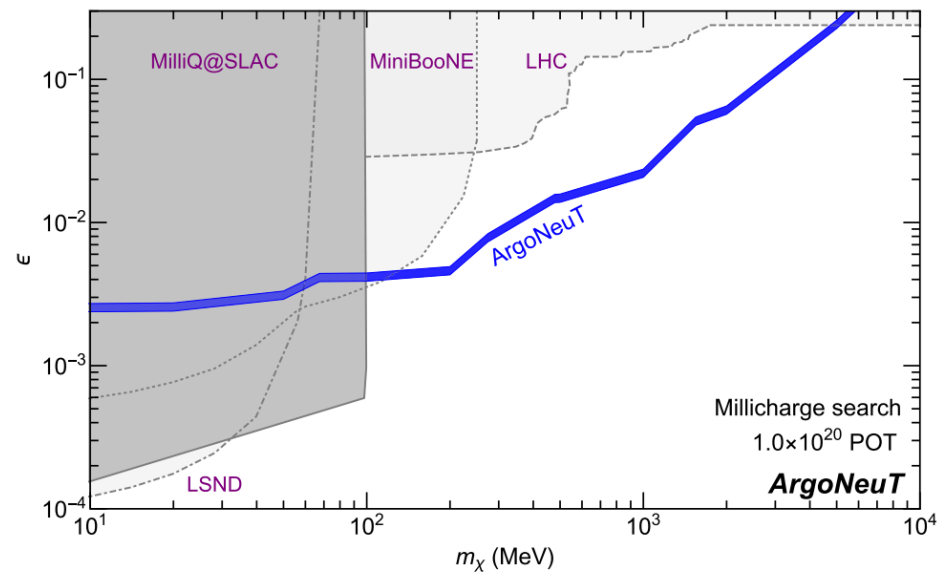
- **Electron recoil-energy threshold: MeV to 100 MeV**
- For more details, see arXiv:1806.03310
- Can use **timing information** to improve sensitivity
- **An improved DUNE analysis updated in the next page**

Double-Hit Technique



Harnik, Liu, Ornella: double-scattering, point back to target to reduce the background (ArgoNeuT & DUNE), arXiv:1902.03246 / ArgoNeuT collab: arXiv:1911.07996



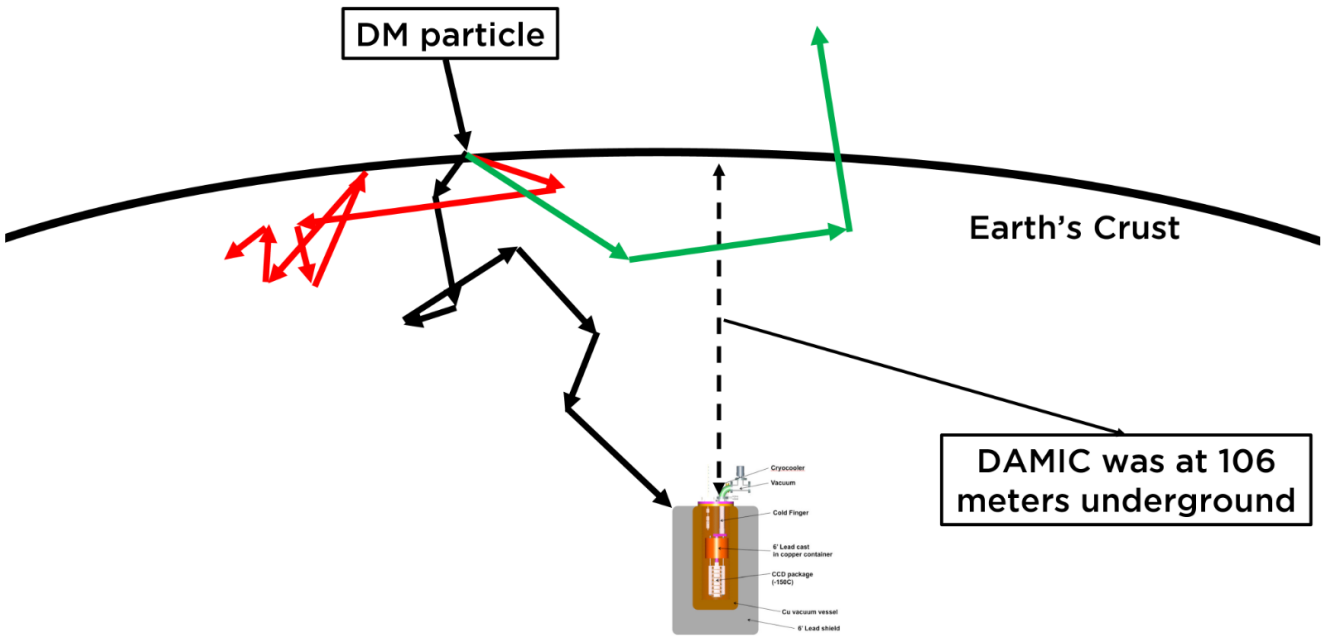


x-axis: m_x (MCP mass),y-axis: $\epsilon = Q_x/e$ (charge ratio).

Millicharged Dark Matter

Strongly Interacting Dark Matter

DM-SM Interaction too strong that attenuation stop the particles from reach the direct detection detector



DMATIS (Dark Matter ATtenuation Importance Sampling), Mahdawi & Farrar '17

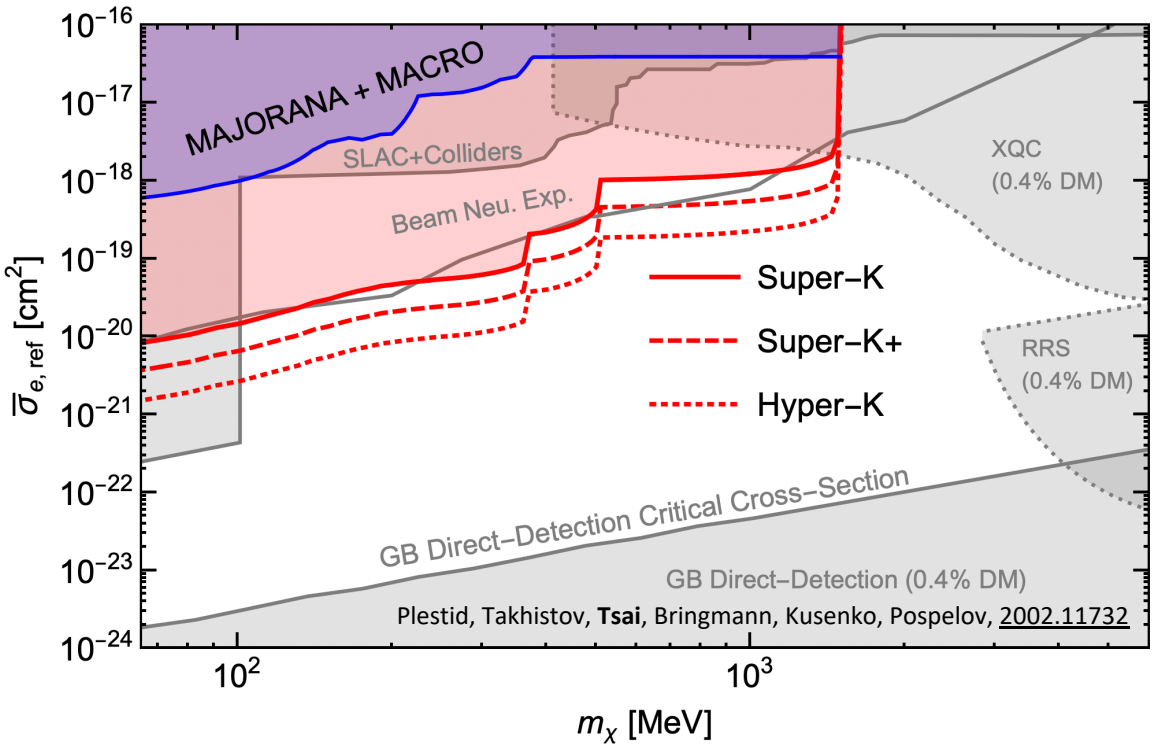
Reference Cross-Section

$$\bar{\sigma}_{\mathrm{e,ref}} = \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{\mathrm{d,ref}}^4}\,, q_{\mathrm{d,ref}} = \alpha m_e$$

- Reference Cross-section for MCP-Electron Scattering (Direct Detection)
- $\mu_{\chi e}$ is the reduced mass of the electron and χ , α is the fine structure constant.
- q_{ref} is a reference momentum transfer (for normalization)
- We choose the typical momentum transfer in DM-electron collisions for noble-liquid and semiconductor targets.
- **This just is a normalization**! Can choose the other one for comparison
- Comparing to e.g. **SENSEI, CDMS-HVeV, XENON10, XENON100, and DarkSide-50**

Probe of Millicharged SIDM

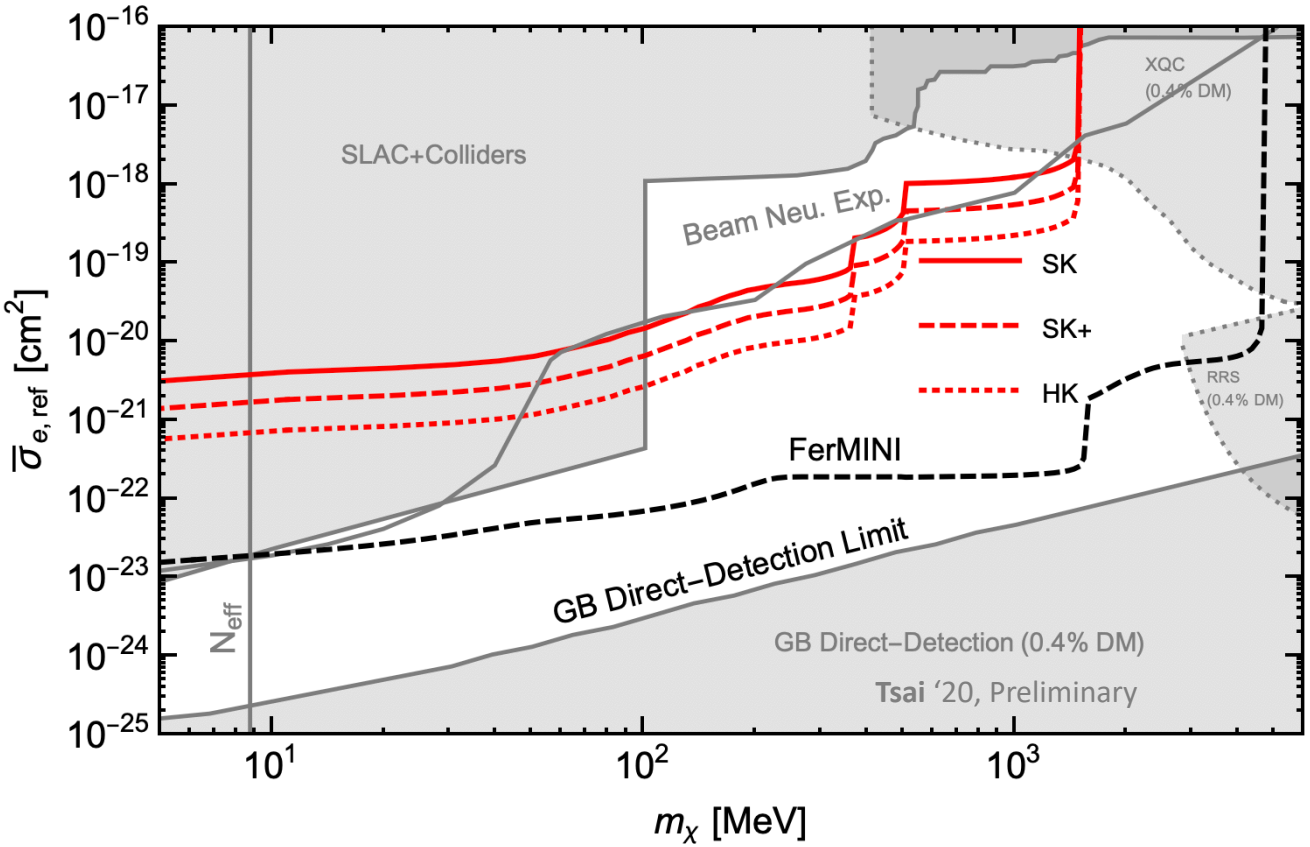
$$\bar{\sigma}_e \simeq \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{ref}^2}, \; q_{ref} = \alpha m_e$$



- Cosmic-Ray Production/Super-K Detection 2002.11732 (Plestid, Takhistov, **Tsai**, Bringmann, Kusenko, Pospelov)
- Details of electron-scattering Millicharged SIDM, see 1905.06348 (Emken, Essig, Kouvaris, Sholapurkar)

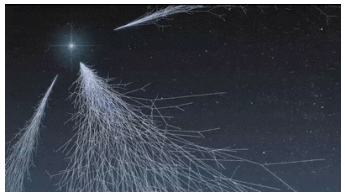
Probe of Millicharged SIDM

$$\bar{\sigma}_e \simeq \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{ref}^2}, \; q_{ref} = \alpha m_e$$



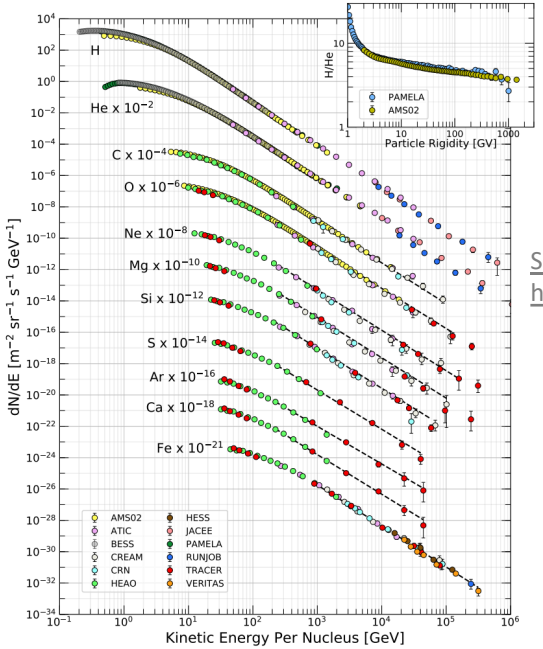
- **More projections soon to be added to the LOI appendix**: link

MCP in Neutrino Observatories



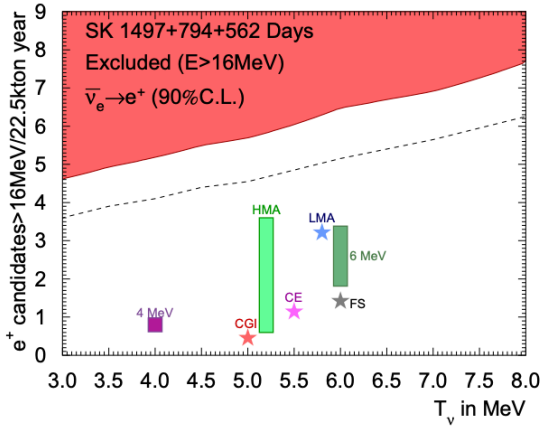
by Chantelauze, Staffi, and Bret

$\chi \quad \bar{\chi}$

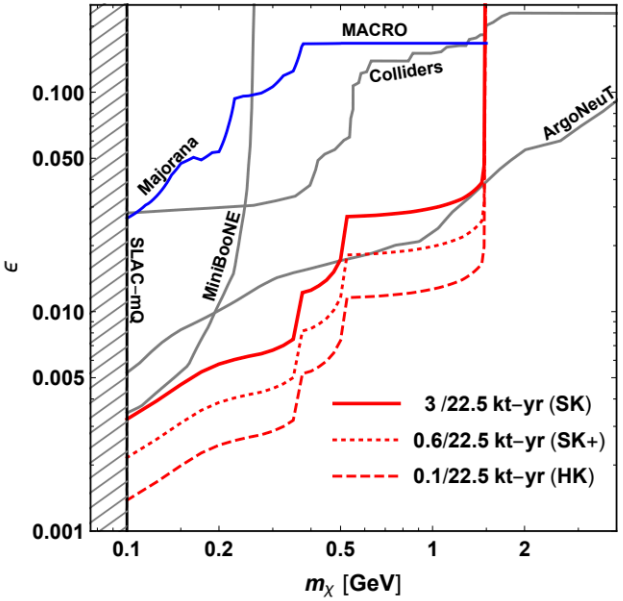


PDG, RPP, 2019

Super-K, http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

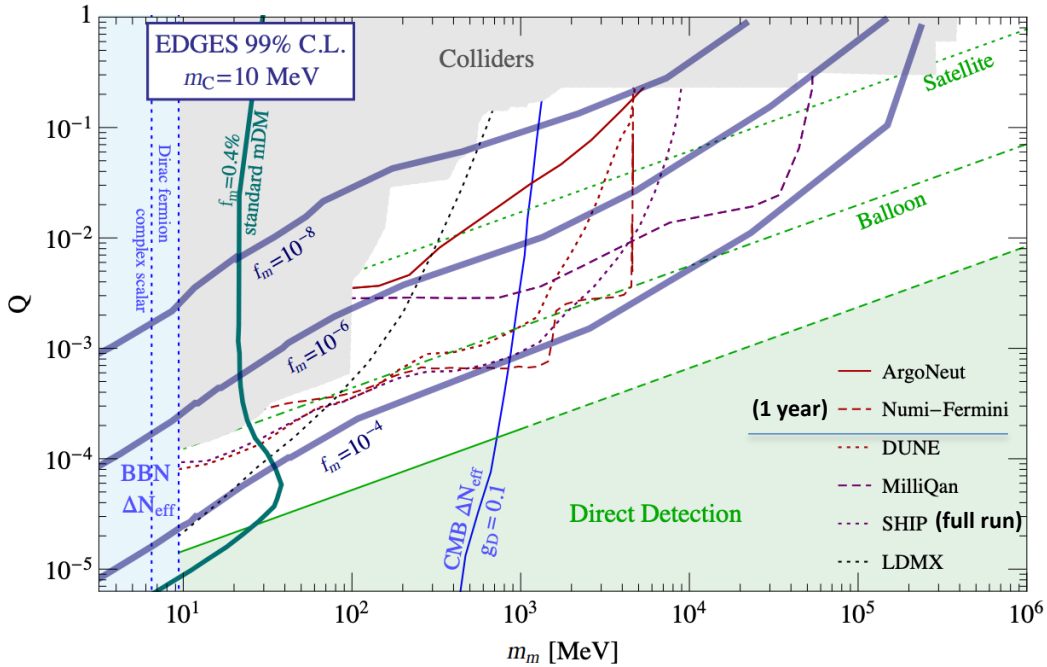


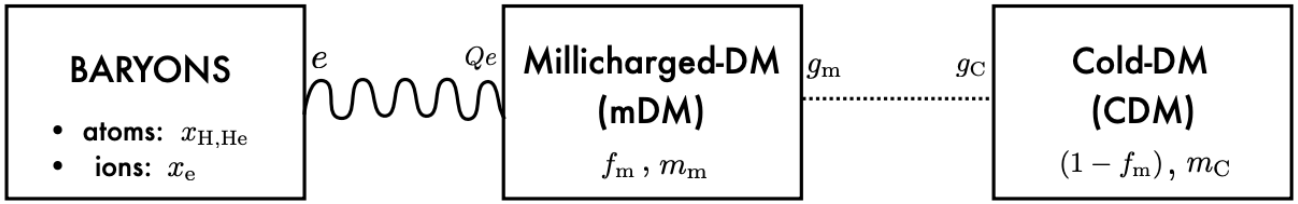
1111.5031 (Super-K Collaboration)



2002.11732 New MCP Constraint from cosmic-ray productions

Reviving MDM for EDGES



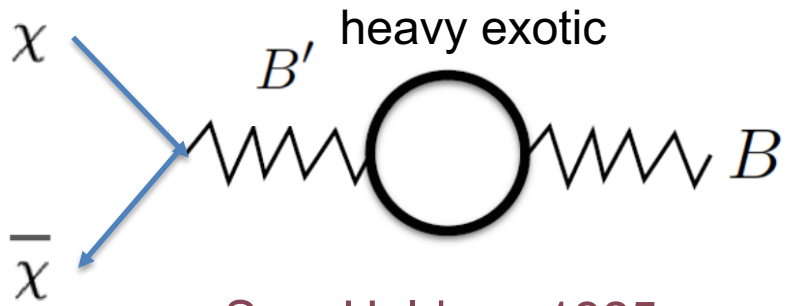


Liu, Outmezguine, Redigolo, Volansky, ’19
For more refs, see backup slides

Thank you!
Special thanks to the organizers

Kinetic Mixing and MCP Phase

- **Coupled to new dark fermion χ**



(SM: Standard Model)

See, Holdom, 1985

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu} + i\bar{\chi}(\not{\partial} + ie'\not{B}' + iM_{\rm MCP})\chi$$

- New fermion χ charged under new gauge boson B'.

- Millicharged particle (MCP) can be a **low-energy consequence** of **massless dark photon** (a new U(1) gauge boson) coupled to **a new fermion (become MCP** in a convenient basis.)
- Important Notes: Our search is simply a search for particles (**fermion χ**) with **{mass, electric charge}** = $\{m_\chi, \epsilon e\}$

More on MCP/DM & 21-cm Cosmology

Some more reference of **Millicharged DM (mDM) and constraints**.

See, e.g.,

McDermott, Yu, Zurek, 1011.2907;

Muñoz, Dvorkin, Loeb, 1802.10094, 1804.01092;

Berlin, Hooper, Krnjaic, McDermott, 1803.02804;

Kovetz, Poulin, Gluscevic, Boddy, Barkana, Kamionkowski, 1807.11482;

Liu, Outmezguine, Redigolo, Volansky, 1908.06986:

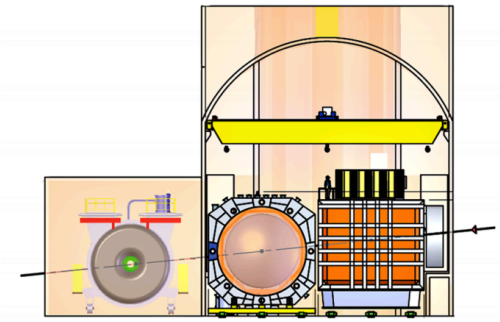
"Reviving Millicharged Dark Matter for 21-cm Cosmology,"

Introduces a long-range force between a subdominant mDM and the dominant cold dark matter (CDM) components. Leads to efficient cooling of baryons in the early universe. Extend the range of viable mDM masses for EDGES explanation to ~ 100 GeV.

Recap: Three Ways to Produce/Study MCPs

More reference shown in following slides!

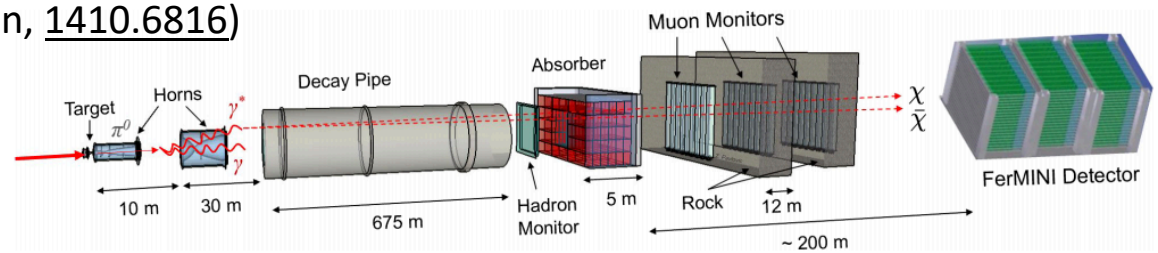
(I) MCPs in fixed-target neutrino experiments, 1812.03998



arXiv:2002.02967, DUNE TDR V - I

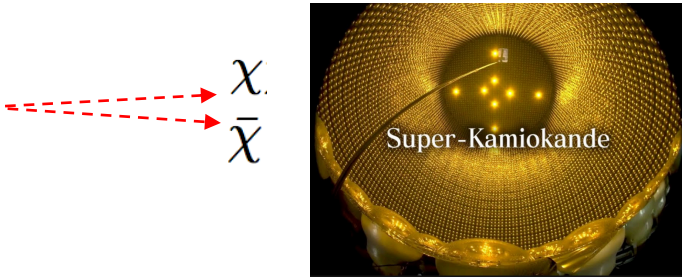
(II) Fixed-target produced MCP detected by specialized detector (FerMINI), 1812.03998

(directly motivated by milliQan, 1410.6816)



(II) Cosmic-ray production and detection in large neutrino observatories, 2002.11732

by Chantelauze, Staffi, and Bret



Super-K, http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

Looking Ahead

- Exploring **Energy Frontier of the Intensity Frontier: Fixed-Target Exp.**
- **Also consider HL-LHC opportunities**
- **Other models: renormalizable portals, axions, inelastic dark matter, SIMP/ELDER, cosmology-driven models**
- **Decay Detector**: CHARM, NuCal, NA62, SeaQuest (e.g. 1908.07525), DUNE Near Detector, SHiP
- Other **low-cost alternatives/proposals (~ $1M)** to probe exotic stable particles **(MilliQan & FerMINI)** and new forces **(Dark/LongQuest)**
- **Dark sectors in neutrino observatories** (e.g. 2002.11732)