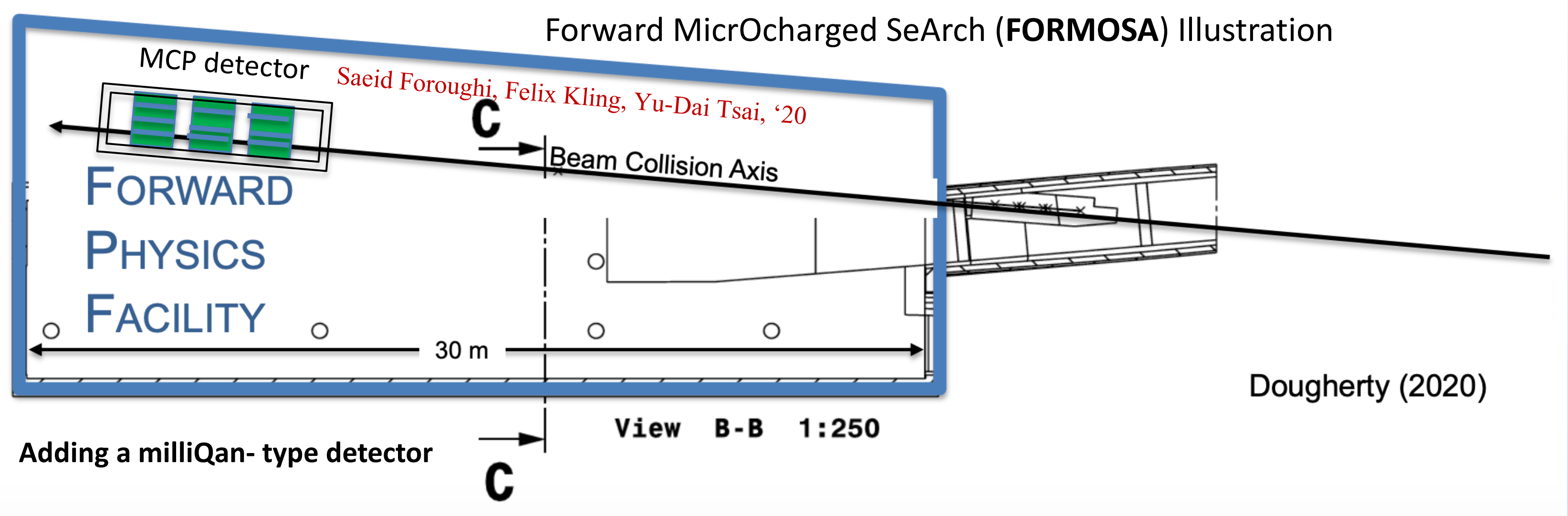


Motivation, status, and prospects for millicharged particles

Yu-Dai Tsai, Fermilab / U Chicago

LOI: Accelerator Probes of MCP: link, Sign-Up Link: link2

LOI: scintillation-based detectors for millicharged particles: link3

HEP/Astro Results Forum on Nov. 11, 2020 (link4)

Email: ytsai@fnal.gov ; arXiv: https://arxiv.org/a/tsai_y_1.html

Outline of the Talk

- Intro & Motivation
- **RF6-focused** Programs

  - Lepton fixed-target experiments

  - Proton fixed-target & neutrino experiments

  - MCP Specific Experiments

    (When **high energy** meets **high intensity**)

  - Cosmic-Ray Production and Neutrino Observatories

Millicharged Strongly Interacting Dark Matter

Snowmass LOI/White Paper: Accelerator Probes for MCP & MDM

Yu-Dai Tsai, Jonathan Assadi, Matthew Citron, Albert De Roeck,
Saeid Foroughi-Abari, Gianluca Petrillo, Yun-Tse Tsai, Jaehoon Yu (+ Zuowei Liu)

Endorsers:

Joshua Barrow (University of Tennessee, Knoxville)
Joshua Berger (Colorado State University)
Joseph Bramante (Queen's University)
Paolo Crivelli (ETH Zurich)
Mohamed Darwish (U Antwerpen, Belgium)
Patrick deNiverville (LANL)
Jonathan Lee Feng (UC Irvine)
William Foreman (Illinois Institute of Technology)
Maria Vittoria Garzelli (University of Hamburg)
Spencer Gessner (SLAC)
Carlo Giunti (INFN Torino)
Sergei Gninenko
(Institute for Nuclear Research, Moscow)
Frank Golf (University of Nebraska-Lincoln)
Jan Hajer (Université catholique de Louvain)
Roni Harnik (Fermilab)
Anthony Hartin (UCL)
Christopher S. Hill (Ohio State University)
Matheus Hostert (University of Minnesota)
Gianluca Inguglia (Austrian Academy of Sciences)
Catherine James (Fermilab)
Sudip Jana (Max-Planck-Institut für Kernphysik)
Jay Hyun Jo (Yale University)
Kevin Kelly (Fermilab)
Doojin Kim (Texas A&M University)
Dmitry Kirpichnikov (INR RAS)
Felix Kling (SLAC)
Simon Knapen (CERN)
Willem G.J. Langeveld (Verified Logic)
Ivan Lepetic (Rutgers University)
Bryce Littlejohn (Illinois Institute of Technology)
Ming X. Liu (LANL)
Zhen Liu (University of Maryland, College Park)
Christopher Lundberg-Palacios (UC Berkeley)
Valery Lyubovitskij (Institut für Theoretische Physik, Universität Tübingen)
David W. Miller (University of Chicago)
Kevin McFarland (University of Rochester)
Rukmani Mohanta (University of Hyderabad)
Julian B. Munoz (CfA-SAO)
Ornella Palamara (Fermilab)
Vishvas Pandey (University of Florida)
Zarko Pavlovic (Fermilab)
Alexey Petrov (Wayne State University)
James Pinfold (CERN)
Ryan Plestid (University of Kentucky)
Thomas Rizzo (SLAC)
Ryan Schmitz (UC Santa Barbara)
Philip Schuster (SLAC)
Dipan Sengupta (UC San Diego)
Ian Shoemaker (Virginia Tech)
Yotam Soreq (Technion - Israel Institute of Technology, Haifa, Israel)
Alex Sousa (University of Cincinnati)
Shufang Su (University of Arizona)
Maximilian Swiatlowski (TRIUMF)
Volodymyr Takhistov (UCLA)
Douglas Tuckler (Carleton University)
Jaehyeok Yoo (Korea University)
Jilberto Zamora-Saa (Universidad Andres Bello)

LOI: link;

LOI Endorsers or White Paper Authors Sign-Up Link: link2 (**welcome to sign up!**)

Intro & Motivations

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 some Superstring theories:
  Wen, Witten, Nucl. Phys. B 261 (1985) 651-677, Youtube: [link]
- Link to **string compactification** and **quantum gravity** (Shiu, Soler, Ye, PRL '13)
- Conservatively, testing if e/3 is the minimal charge
- 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)].

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.

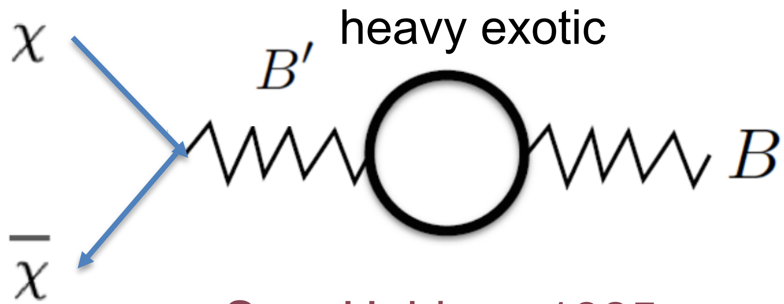
- Can just consider these Lagrangian terms by themselves (no extra mediator, i.e., dark photon). **Completely legal**! Naively **violating the empirical charge quantization** (cool).

- 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**

Kinetic Mixing and MCP Phase

- **Coupled to new dark fermion χ**



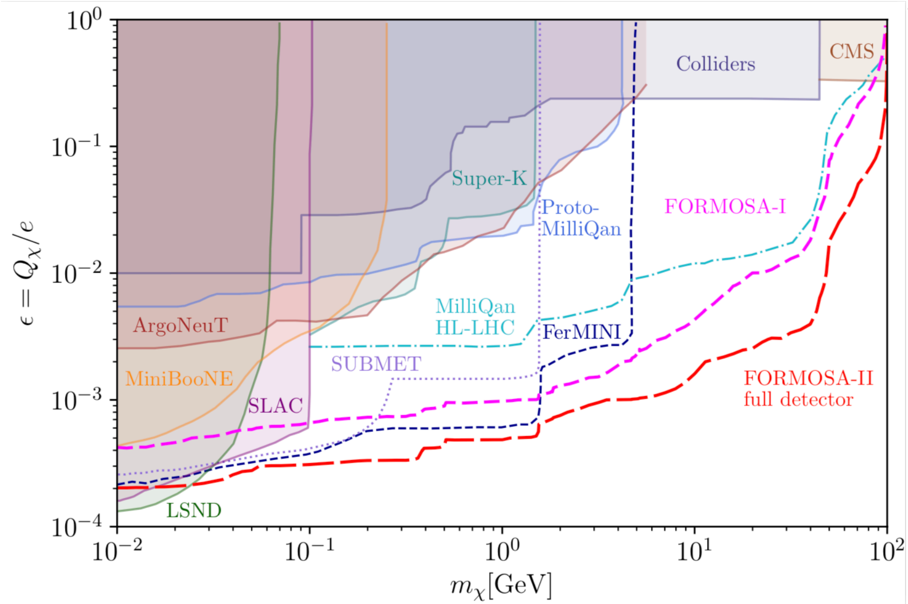
(SM: Standard Model)

See, Holdom, 1985

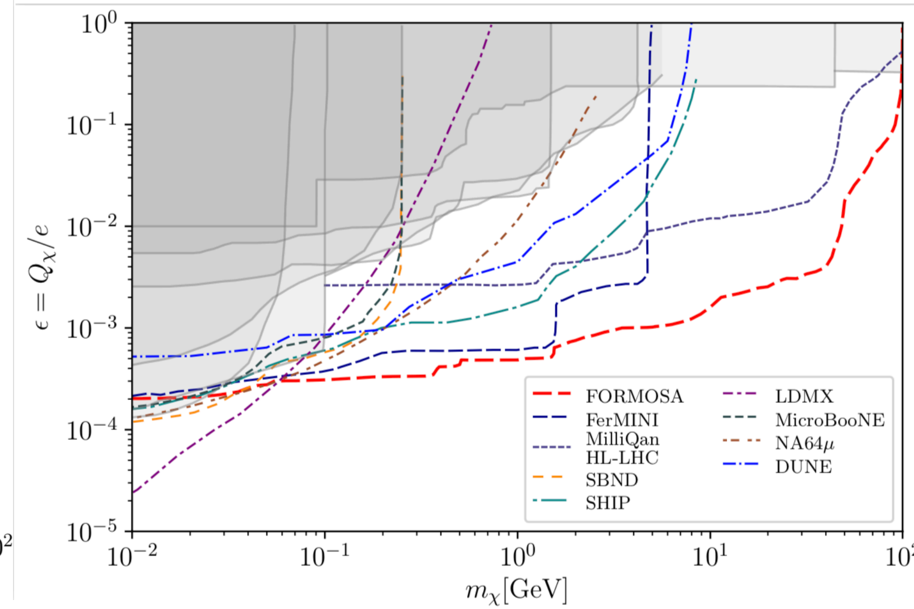
$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ + ie'B\!\!\!/' + iM_{\text{MCP}})\chi$$

- 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.)
- **Dark photon is not necessary for MCP!**
  Focus on MCP low-energy phenomenology today, not affected by dark photon

Compilation



(a) Existing bounds and MCP dedicated experiments



(b) Comparison of future projections

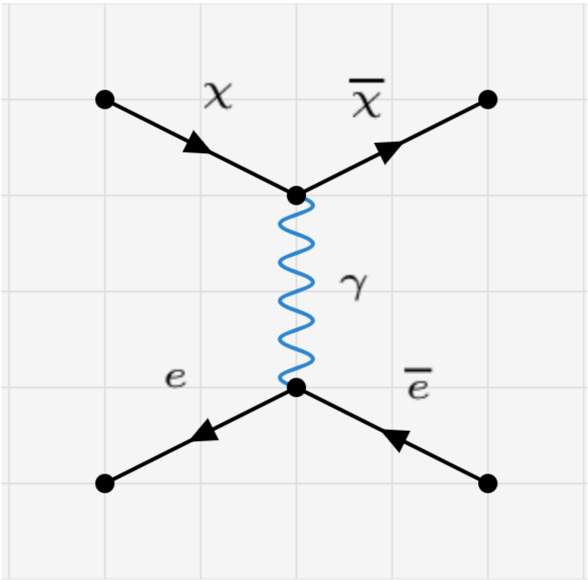
$\epsilon \equiv Q_\chi/e.$

- Our search is simply a search for particles (fermion χ) with **{mass, electric charge}** = $\{m_\chi, \epsilon e\}$
- **The result for scalar MCP is similar**
- LOI Update: link
- LOI Endorsers or White Paper Authors Sign-Up Link: link2

MCP is interesting itself, and is one of the simplest dark-sector test models for accelerator experiments

Millicharged Particle: Signature

Three Signatures: **Scattering, Ionization, Missing**



- **“Hard” (MeV-level) electron elastic scattering:**

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

- **Ionization (eV-level):** ~ very low-energy scattering**:**

  MilliQan: arXiv:1410.6816, Haas, Hill, Izaguirre, Yavin

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

- **Missing energy/momentum/monophoton/Z decay** (something missing)

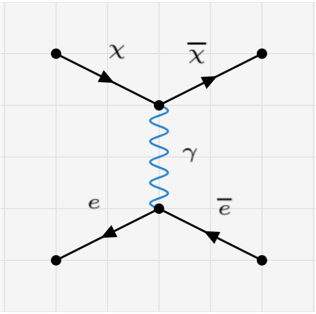
MCP Detection: **Electron Scattering**

- $\boldsymbol{Q^2}$ 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

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

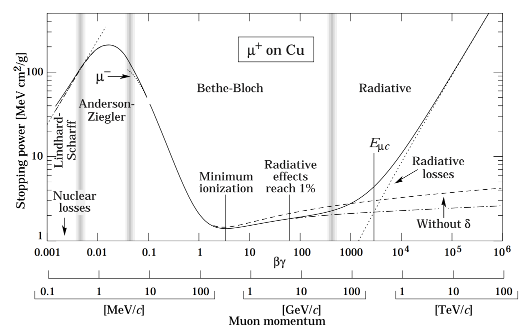
- Sensitivity greatly enhanced by accurately **measuring low energy electron recoils** **for MCP's & light-mediator scattering**



MCP Detection: **Ionization**

- Want very low momentum transfer**: ionization and scintillation signature**
- Signature proportional to **- dE/dx of the MCP, referred to as energy loss/stopping power**
- Can be approximated with the Bethe-Bloch Formula (various modified versions and detailed considerations.)

$$\left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2.$$



intentionally make the plot small so we don’t get into too much details of this.
http://pdg.lbl.gov/2020/reviews

Lepton Fixed-Target Machines

SLAC mQ

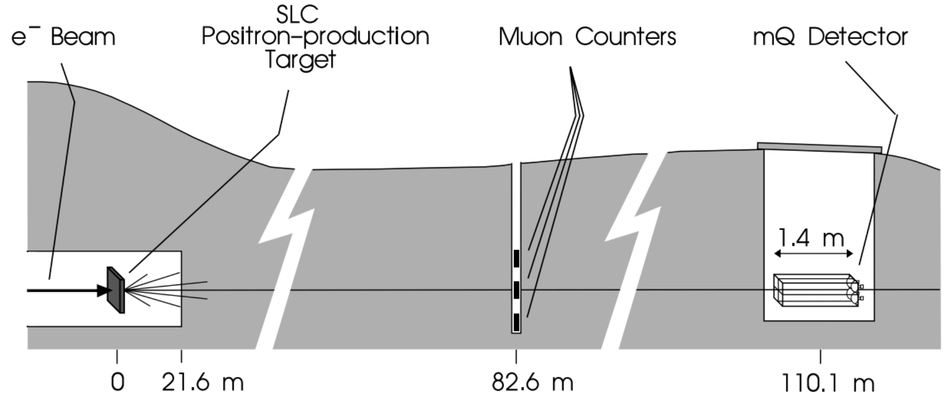
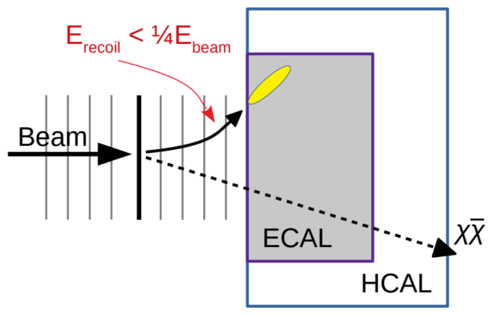


FIG. 1. Layout of the experiment. Shown is a vertical cross section.

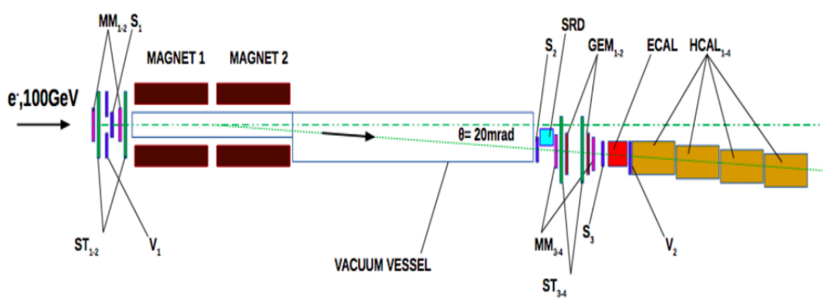
- 29.5 GeV Electron Beam
- Prinz et al, PRL 98, [9804008]
- The detector consists of a 2 x 2 array of blocks of plastic scintillator, each having dimensions 21 cm x 21 cm x 130 cm, and each coupled to an 8-in. hemispherical photomultiplier tube.
- The longitudinal axis of the array lies along the beam direction.
- Motivated milliQan
(**much better sensitivity to do this in Hadron machines if background is controlled**)

Fixed-Target Machines
LDMX & NA64

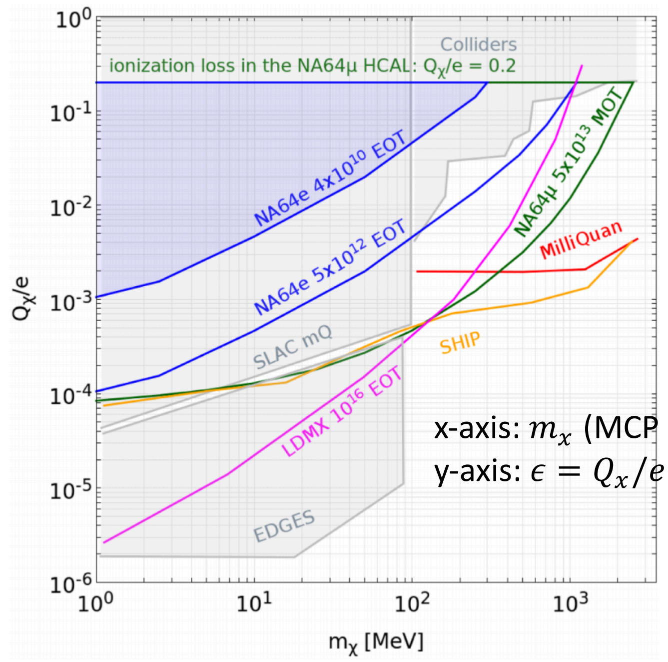
1808.05219 (LDMX collaboration)



1710.00971 (NA64 collaboration)



- Won't get into details for these



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

Berlin, Blinov, Krnjaic, Schuster, Toro, 1807.01730
Gninenko, Kirpichnikov, Krasnikov, 1810.06856
(can consider both electron and muon modes)

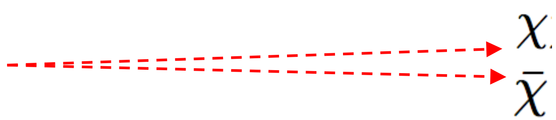
Proton Fixed-Target & Neutrino Experiments

“High-Energy Intensity Machines”

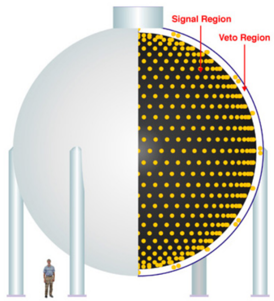
Proton Fixed-Target

Fermilab Beams:

- **Booster Neutrino Beam (BNB)**
  10^{20} POT/yr (8 GeV)

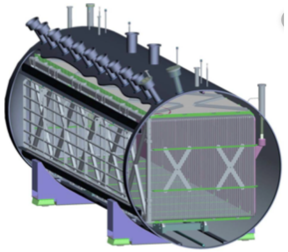


MiniBooNE Detector



arXiv:0806.4201
MiniBooNE collaboration

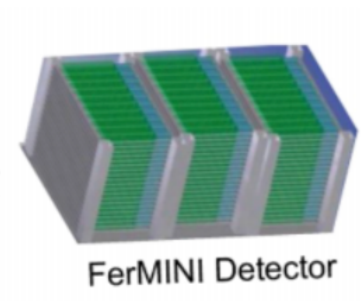
MicroBooNE Detector



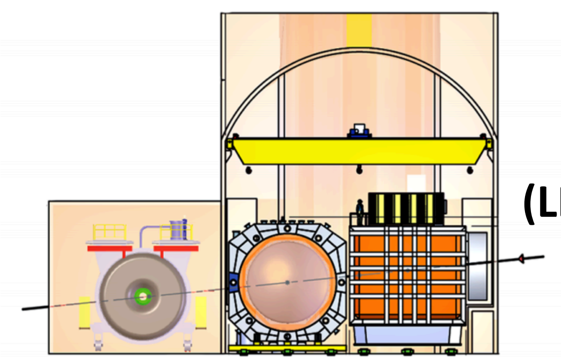
arXiv:1612.05824
MicroBooNE collaboration

- **Nutrino Main Injector (NuMI)**
  4 x 10^{20} POT/yr (120 GeV)

- **Long Baseline Neutrino Facility (LBNF),** 10^{21} POT/yr (120 GeV)



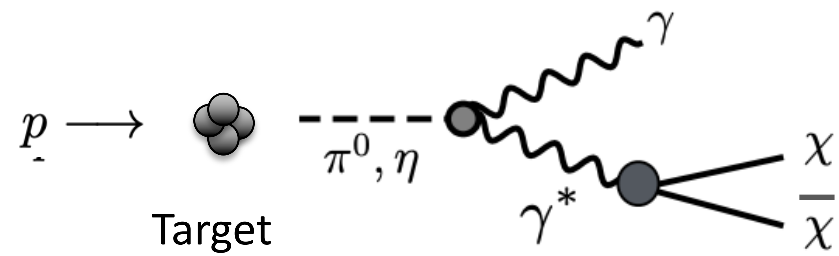
DUNE Near Detector



(LBNF)

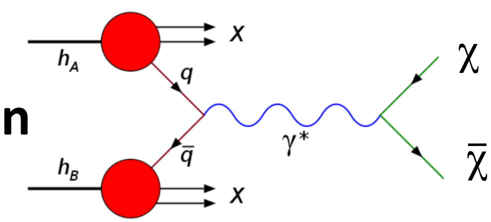
Some Production Channels of MCP

- ❑ **Production: Meson Decays**

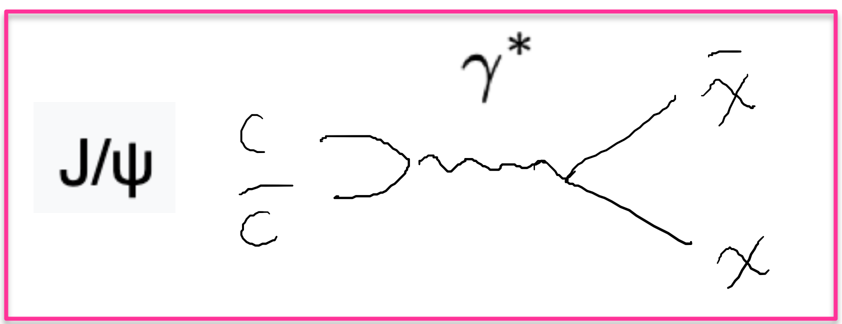


Modified from 1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

- ❑ **Production: Drell-Yan**



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



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

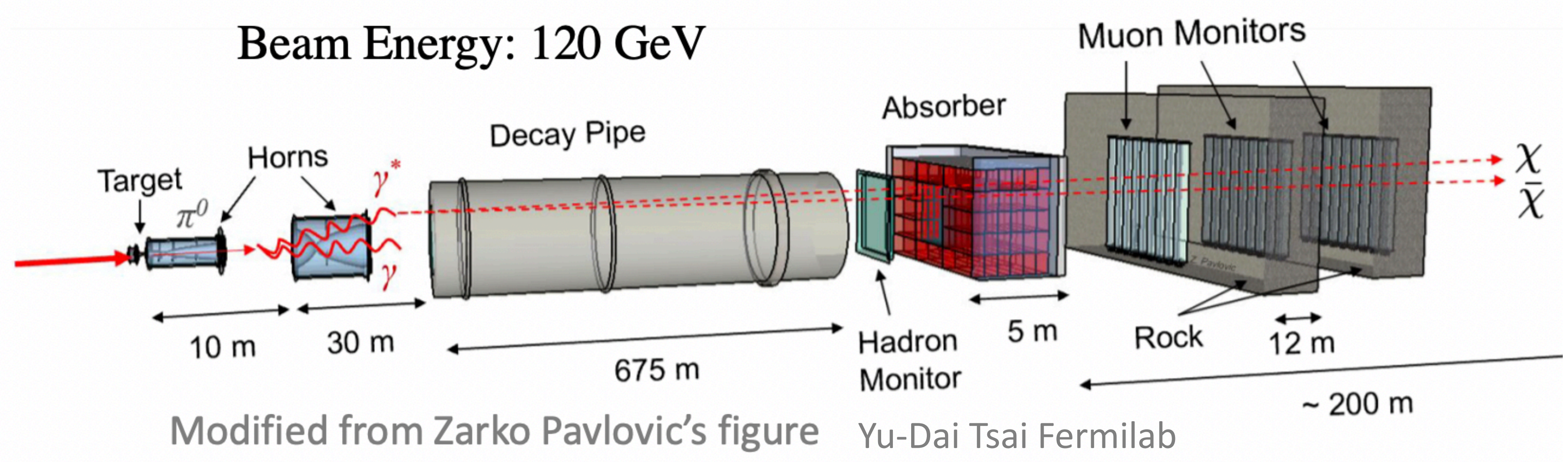
$BR(\pi^0 \to \gamma e^- e^+) = 0.01$

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

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

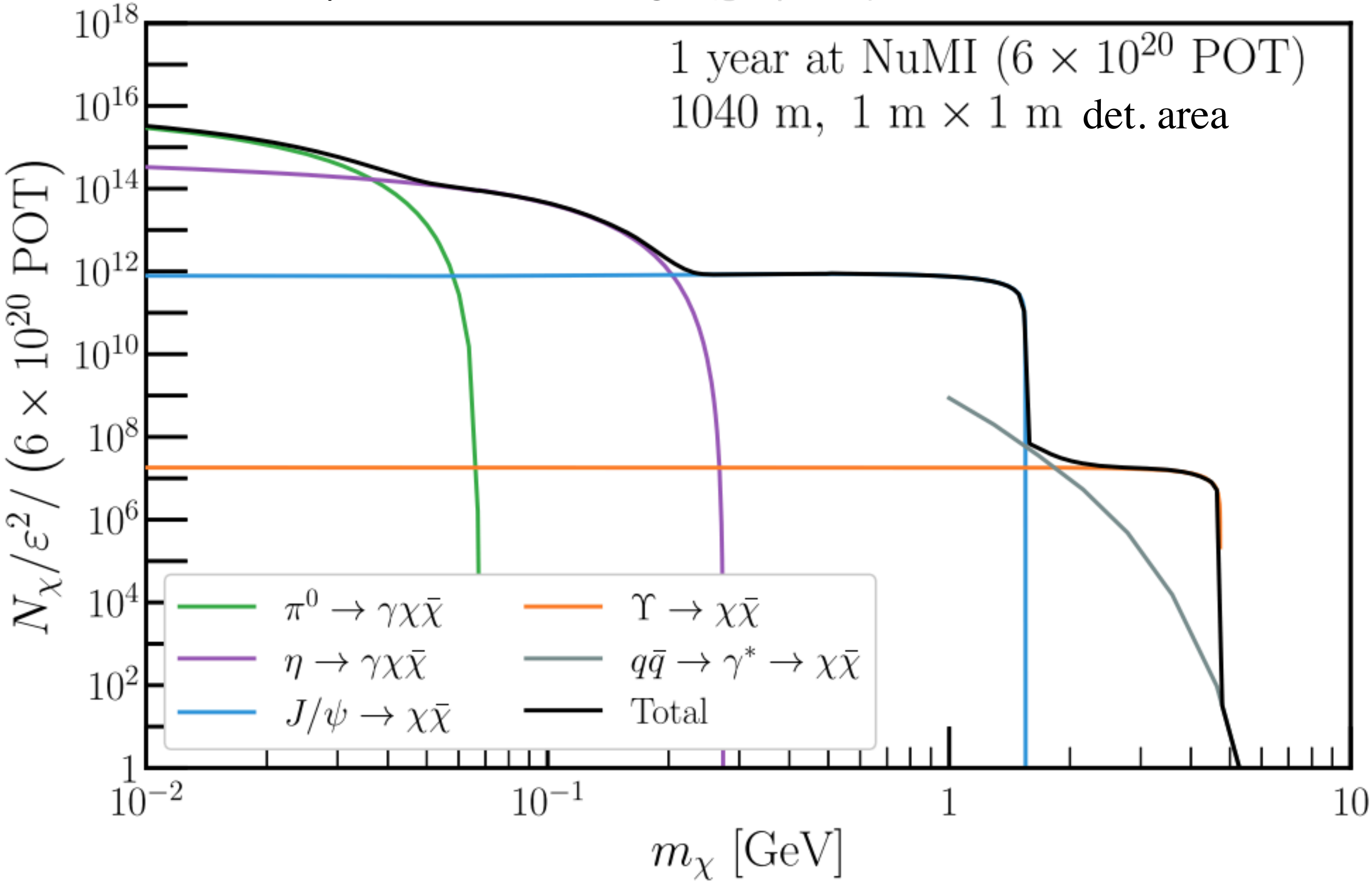
MCP Produced in Fixed-Target Experiments

Example: Neutrinos at the Main Injector (NuMI) beamline
See https://arxiv.org/abs/1507.06690 (NuMI collaboration)

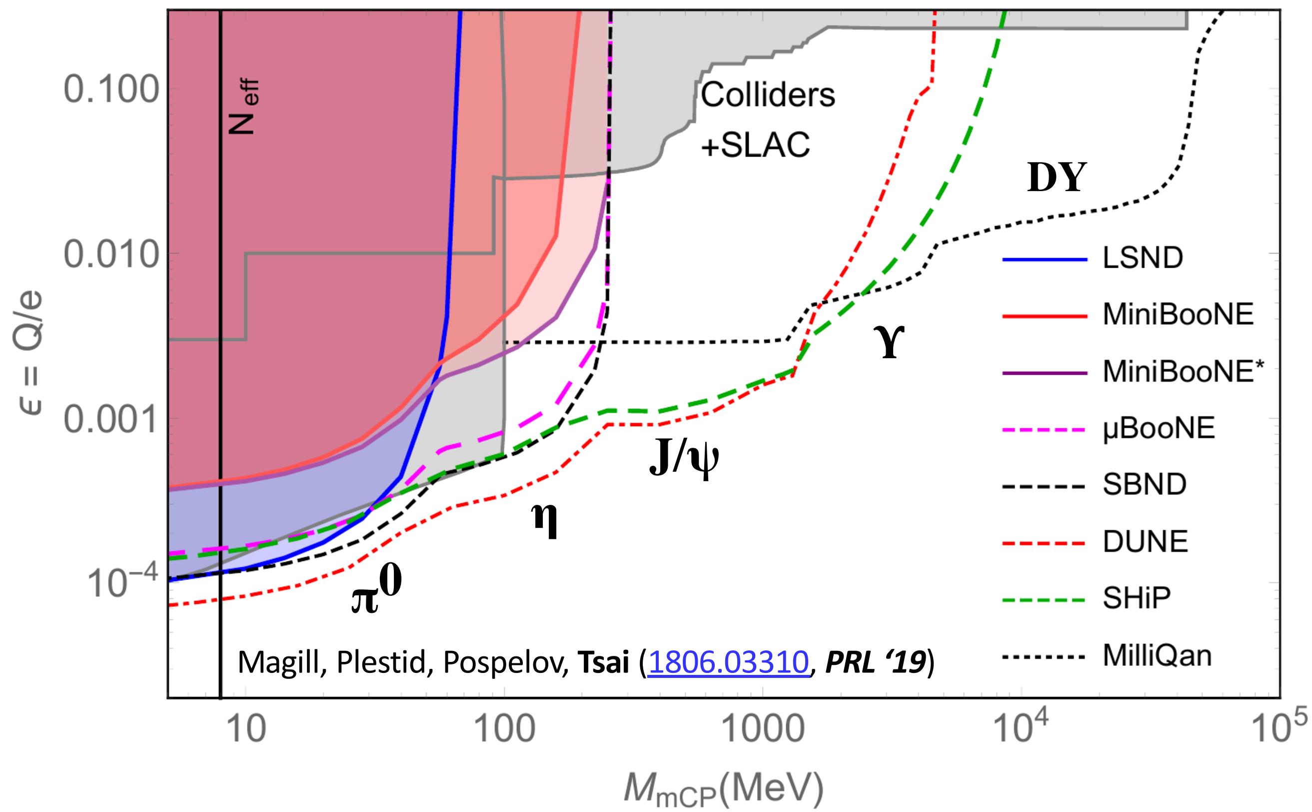


MCP Production/Flux

120 GeV proton beam on target (graphite)



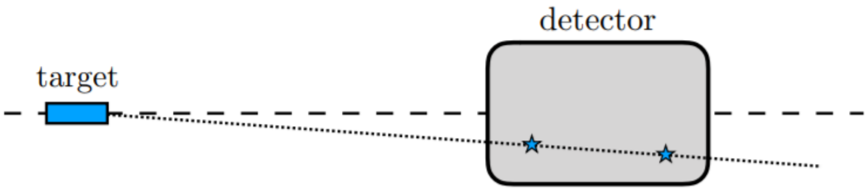
Sensitivity at Neutrino Detectors



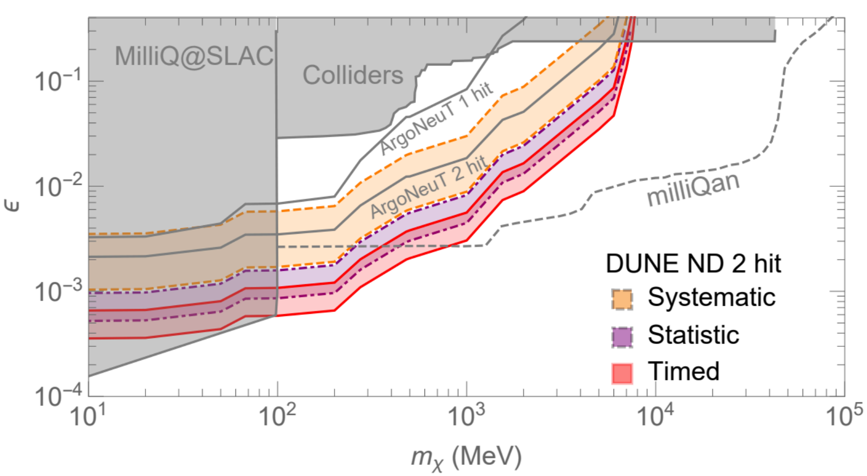
- Magill, Plestid, Pospelov, **Tsai** (1806.03310, ***PRL '19***)
- Can use **timing information** to improve sensitivity
- Double-hit to reduce & control background (see next page)

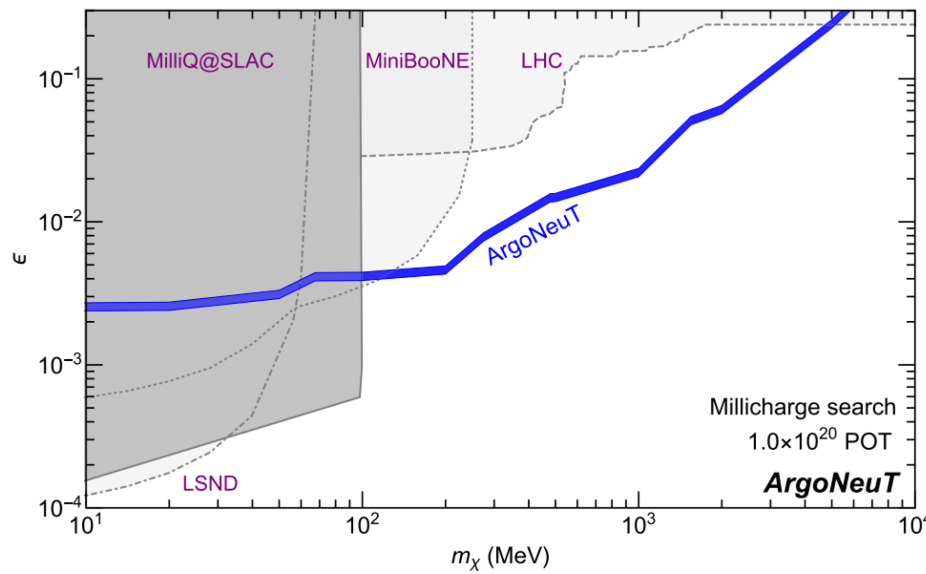
x-axis: m_x (MCP mass),
y-axis: $\epsilon = Q_x/e$ (charge ratio).

Double-Hit Technique & ArgoNeuT Result



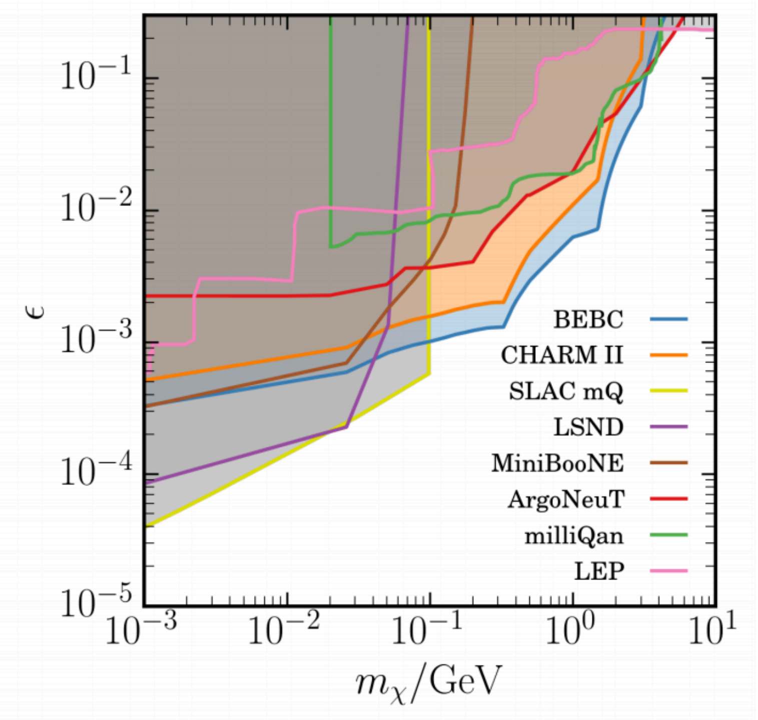
Harnik, Liu, Ornella: double-scattering, point back to target to reduce the background (ArgoNeuT & DUNE), arXiv:1902.03246 / ArgoNeuT collab: arXiv:1911.07996





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

Double-Hit Technique & ArgoNeuT Result



Marocco & Sarkar, 2011.08153

BEBC WA66 beam dump experiment & CHARM II Experiment

High-Energy Intensity Machines!

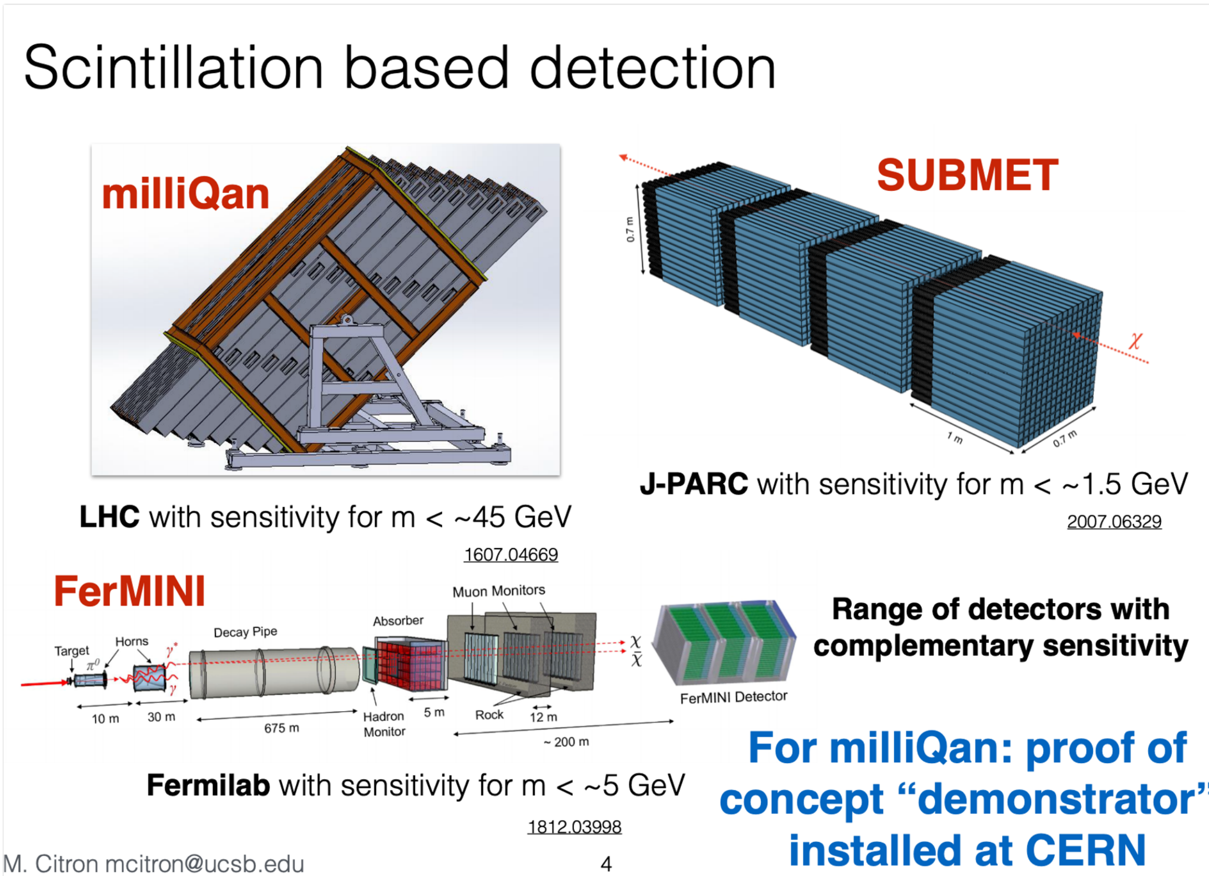
Systematic re-analysis of all experiments

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

MCP Specific Searches:
Scintillator-based Experiments

Snowmass LOI (link):
Sensitivity reach of scintillator-based detectors for millicharged particles

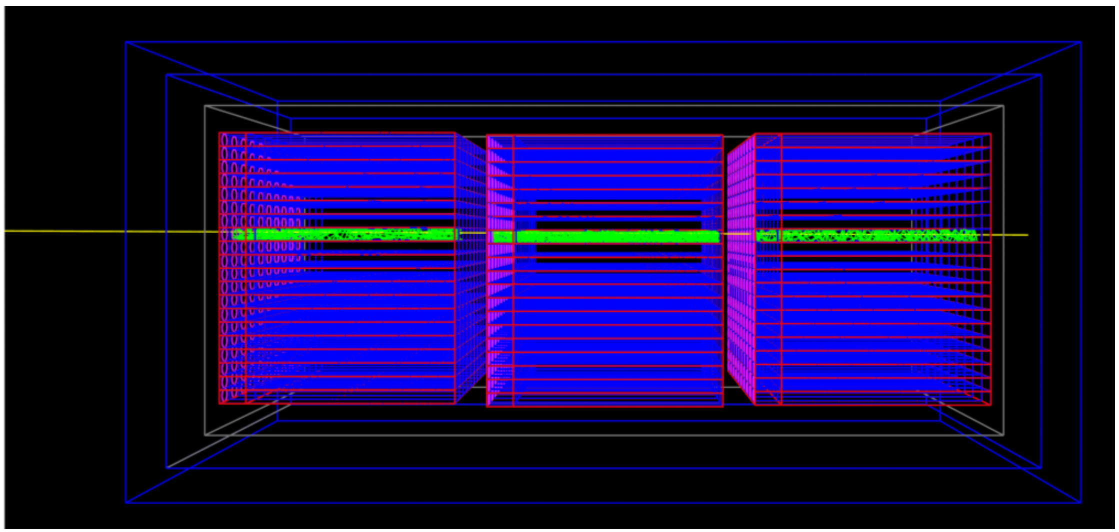
Matthew Citron, Chris Hill, David Miller, Albert De Roeck, David Stuart, Yu-Dai Tsai, Jae Hyeok Yoo

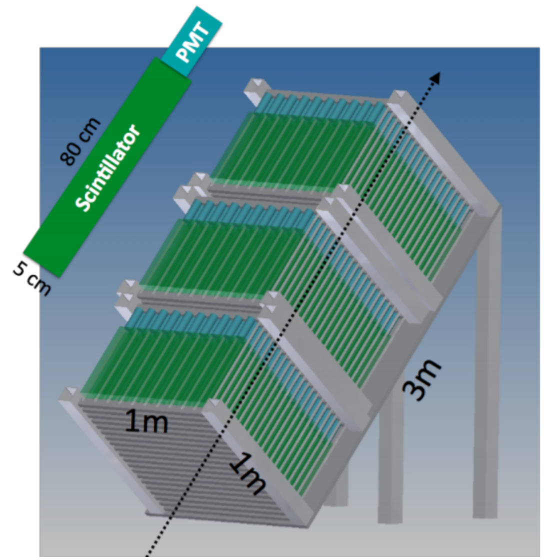


Directly from Matthew's talk at NF3 kickoff meeting: link

Detector Concept: MilliQan

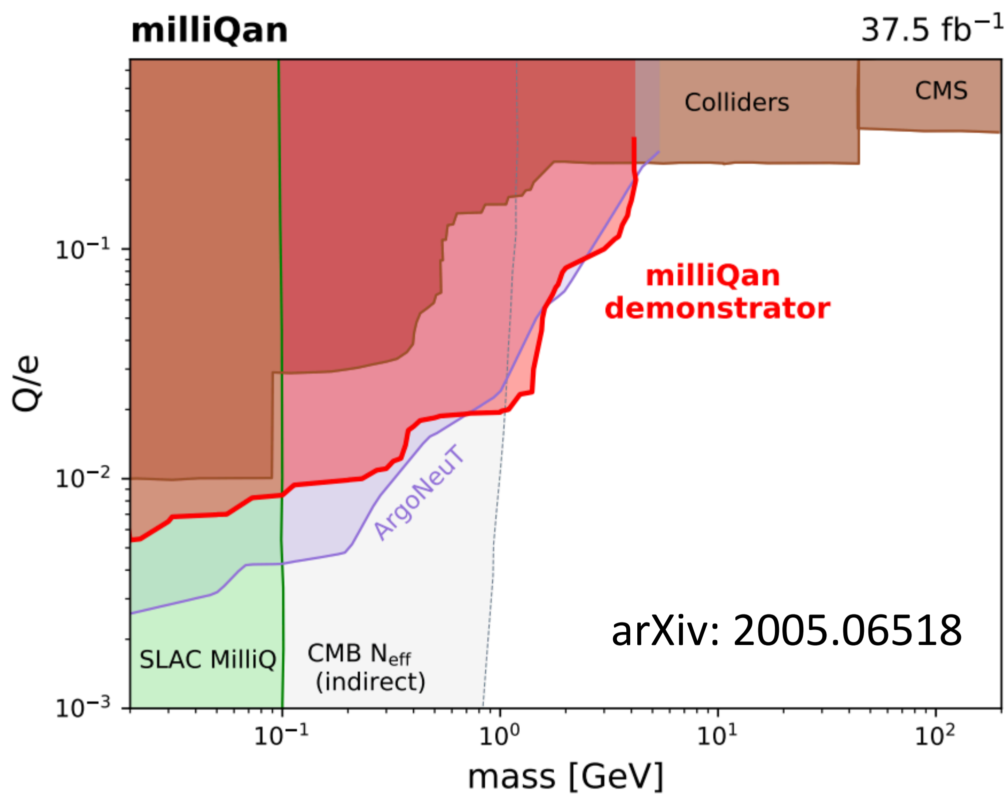
$$(\Delta t)_{\text{offline}} = 15$$

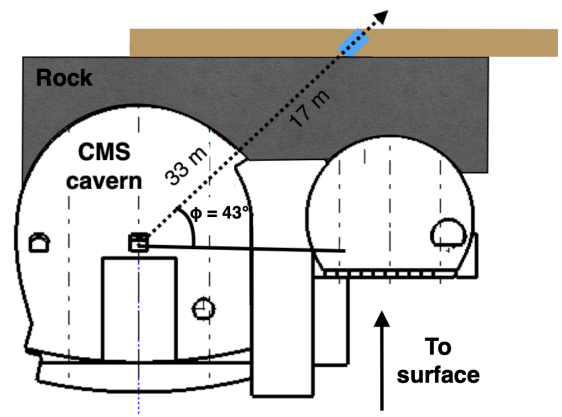




arXiv:1410.6816 (Haas, Hill, Izaguirre, Yavin)
See also arXiv:1607.04669; arXiv:1810.06733; arXiv:2005.06518
It was found that **4-layer quadruple coincidence** is optimal

MilliQan Prototype Result





Ball, Beauregard, Brooke, Campagnari, Carrigan, Citron, De La Haye, De Roeck, Elskens, Escobar Franco, Ezeldine, Francis, Gastal, Ghimire, Goldstein, Golf, Guiang, Haas, Heller, Hill, Lavezzo, Loos, Lowette, Magill, Manley, Marsh, Miller, Odegard, Saab, Sahili, Schmitz, Setti, Shakeshaft, Stuart, Swiatlowski, Yoo, Zaraket, and Zheng

When **Energy** meets **Intensity**

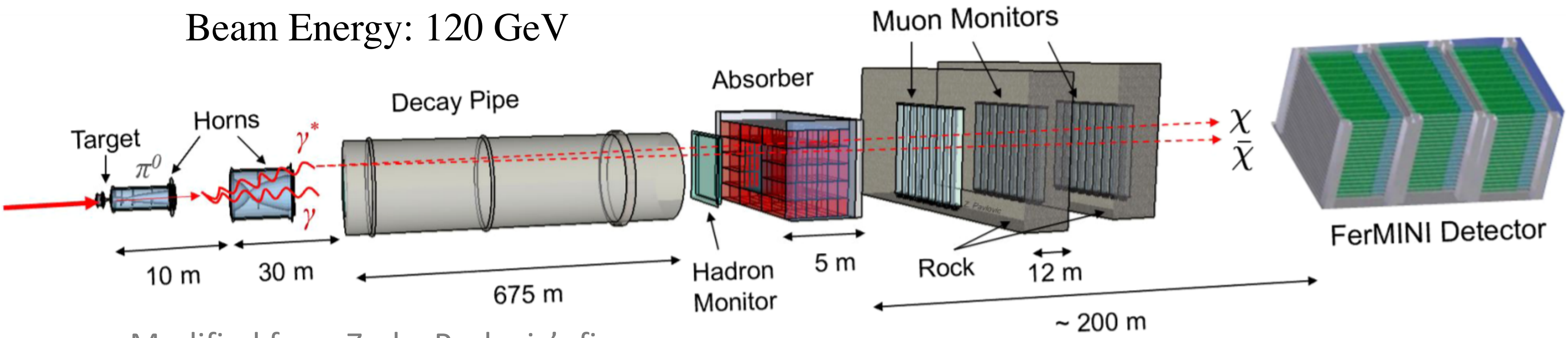
High-Energy Intensity Frontier

- **Proton FT & Neutrino Exps**
- General LLP:
  DarkQuest/LongQuest
- Specified (MCP)
  FerMINI
- **Systematic re-analysis!**

- **High-Intensity Energy Frontier**
- **The LHC Forward Physics Facility**
- General LLP:
  FASER
- Specified (MCP):
  FORMOSA
- **New exciting opportunities**

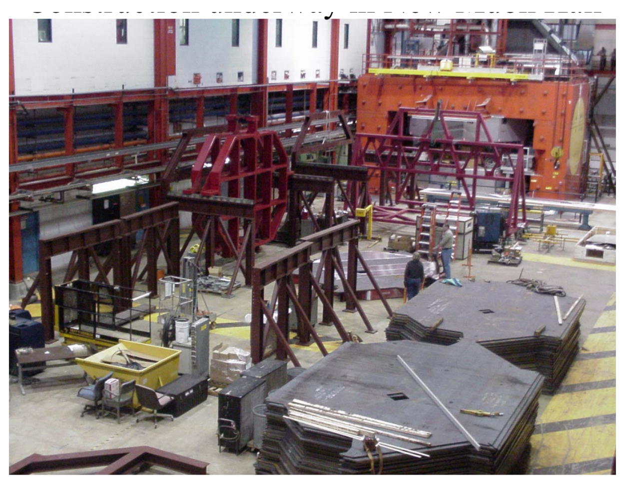
  - **Filling low-mass / high-mass gap for dark matter and MCP**
  - **Filling low-energy / high-energy neutrino scattering gap!**

FerMINI @ NuMI-MINOS Hall



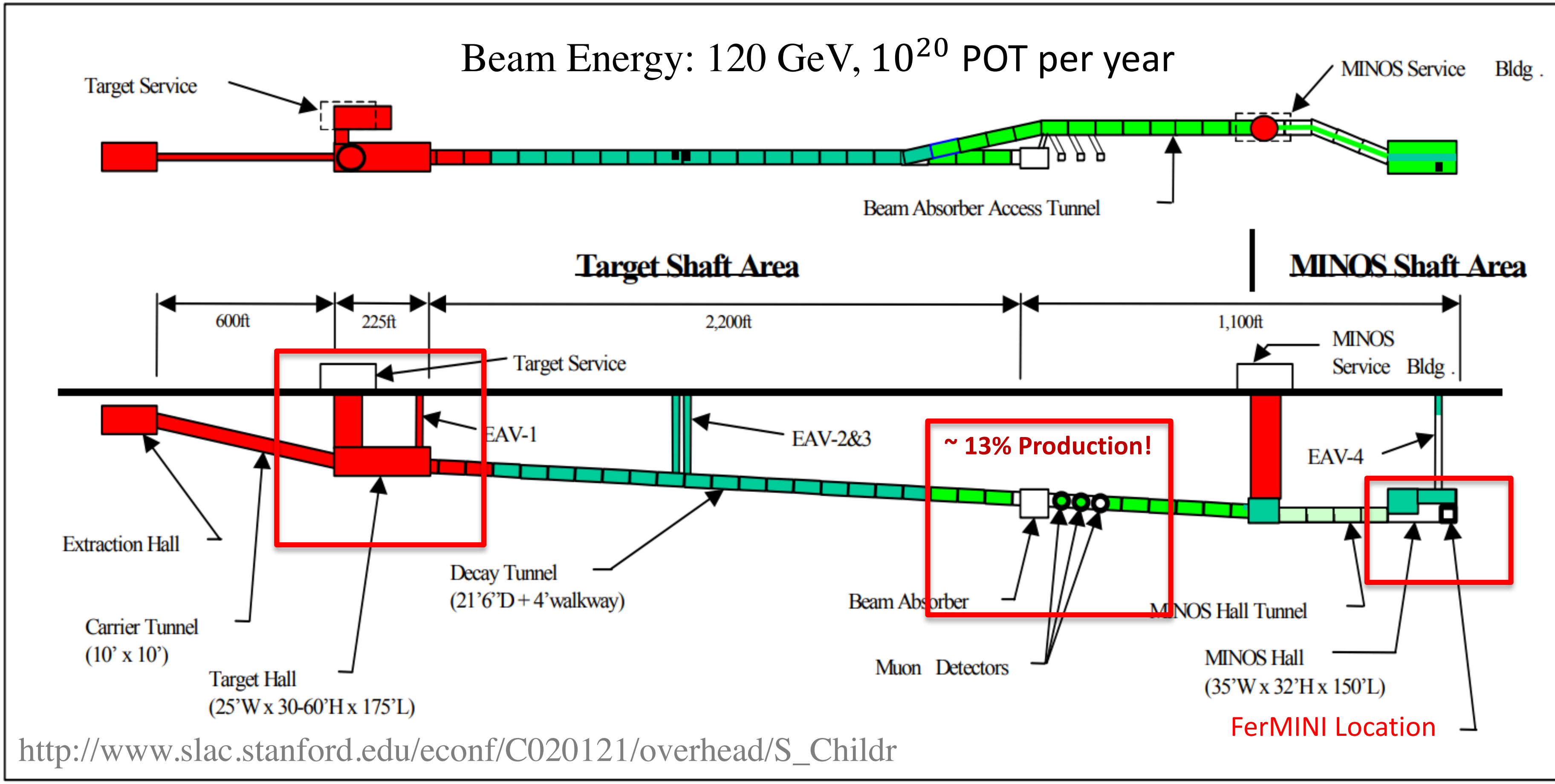
Modified from Zarko Pavlovic's figure

An illustration of the FerMINI experiments utilizing the NuMI facility.



MINOS hall downstream of NuMI beam

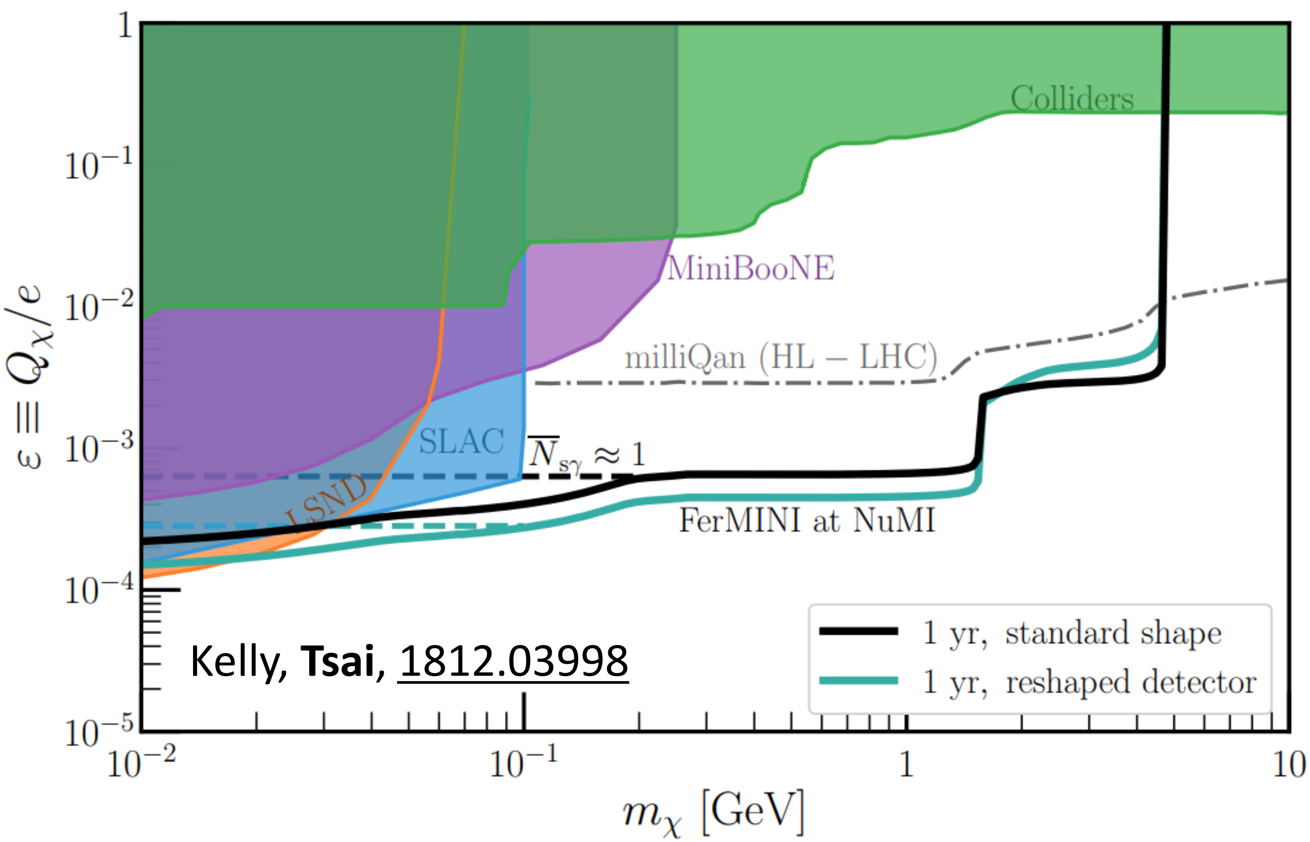
Site 1: NuMI Beam & MINOS ND Hall



NuMI: Neutrinos at the Main Injector

MINOS: Main Injector Neutrino Oscillation Search, ND: Near Detector

FerMINI @ MINOS



Yu-Dai Tsai, Fermilab

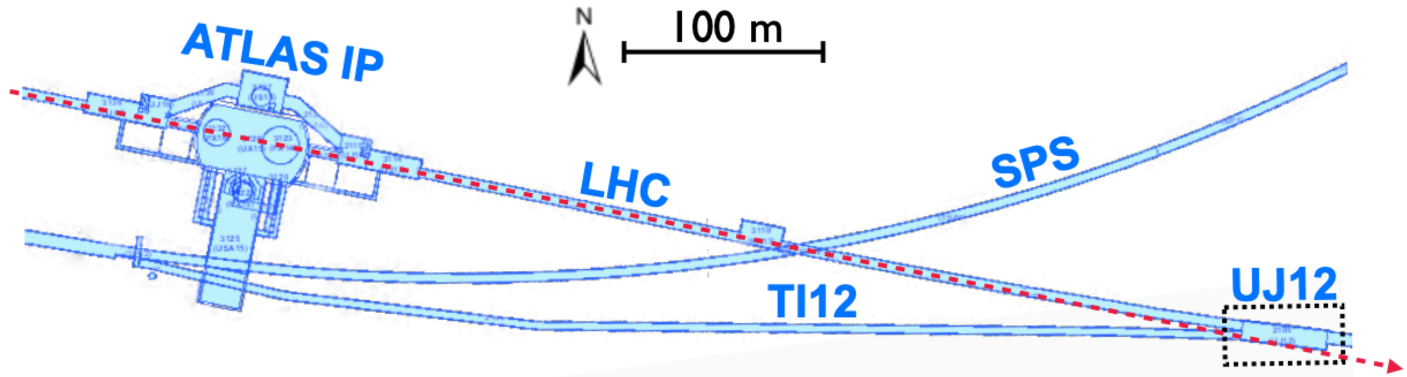
Different epsilon now, ε=Q/e

Similar Sensitivity @ DUNE Site

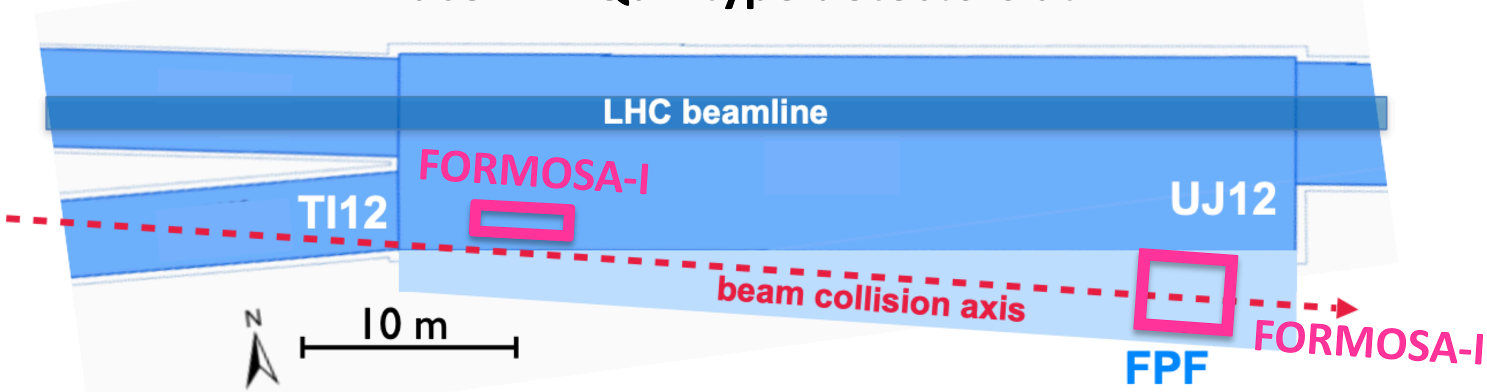
New Opportunity at the Forward Physics Facility:
The High-Intensity Energy Frontier

FORMOSA: FORward MicrOcharge SeArch

Foroughi, Kling, **Tsai**, arXiv:2010.07941



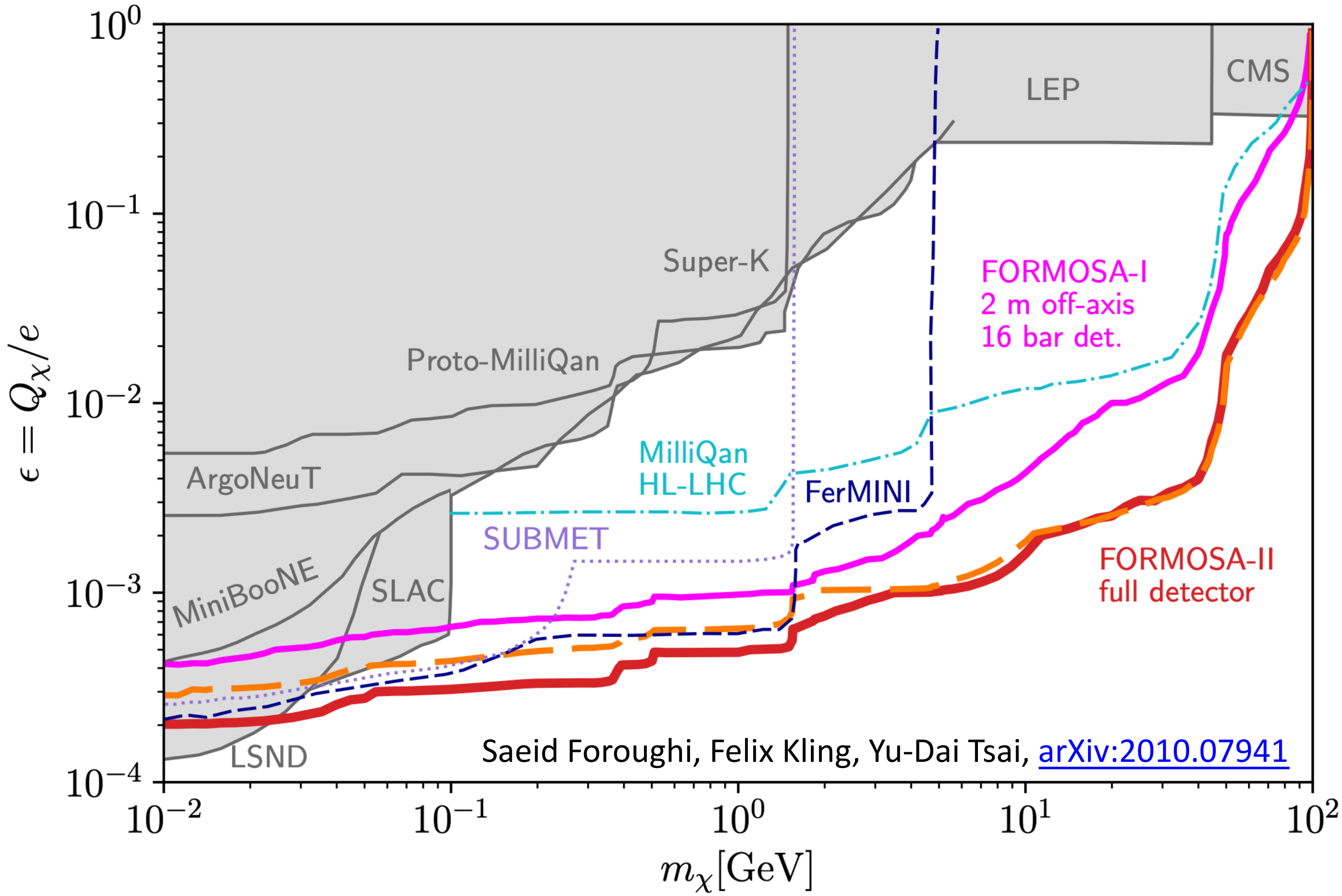
Place milliQan-type detectors at …



Forward Physics Facility (Feng, Kling +), FPF LOI: link

Formosa means "beautiful" in Portuguese and is the ancient name of Taiwan

FORMOSA Sensitivity

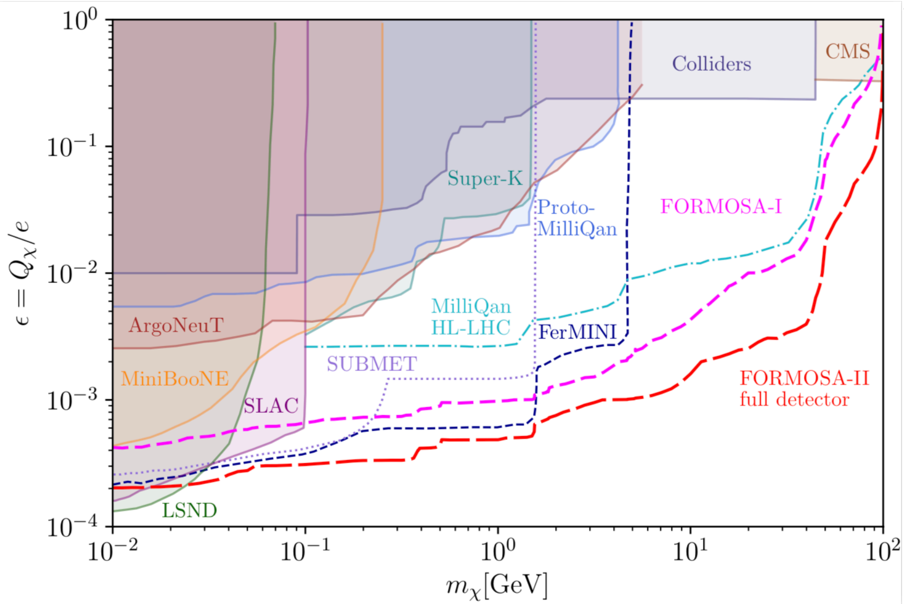


FORMOSA-I: ~ 0.2 m × 0.2 m × 4 m consisting of 4 layers of 16 scintillator bars @UJ12/TI12 tunnel.

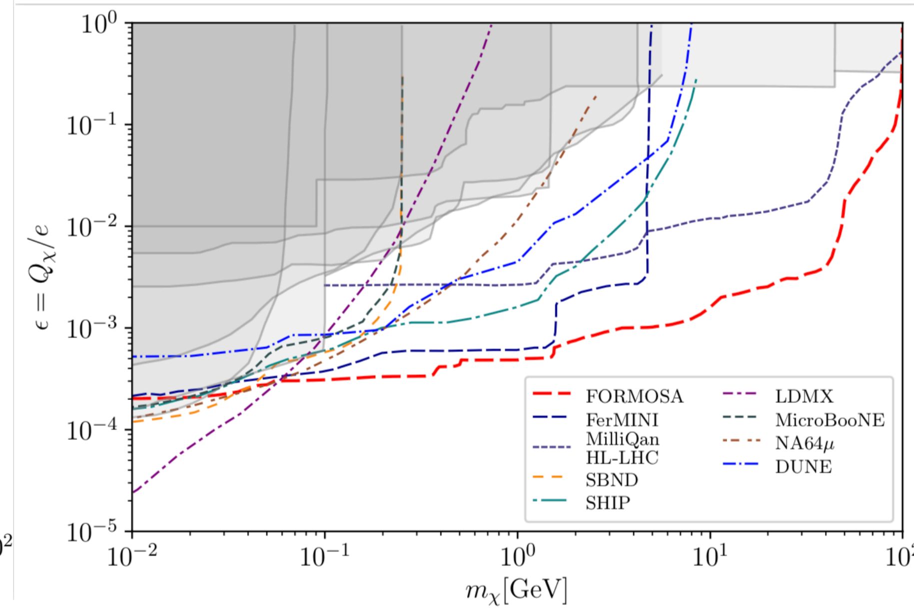
FORMOSA-II: ~ 1 m × 1 m × 4 m consisting of 4 layers of 400 scintillator bars @ FPF.

FORMOSA can also probe **Tau & Heavy Neutrino Electric Dipole Moment**!

Compilation of MCP Probes



(a) Existing bounds and MCP dedicated experiments



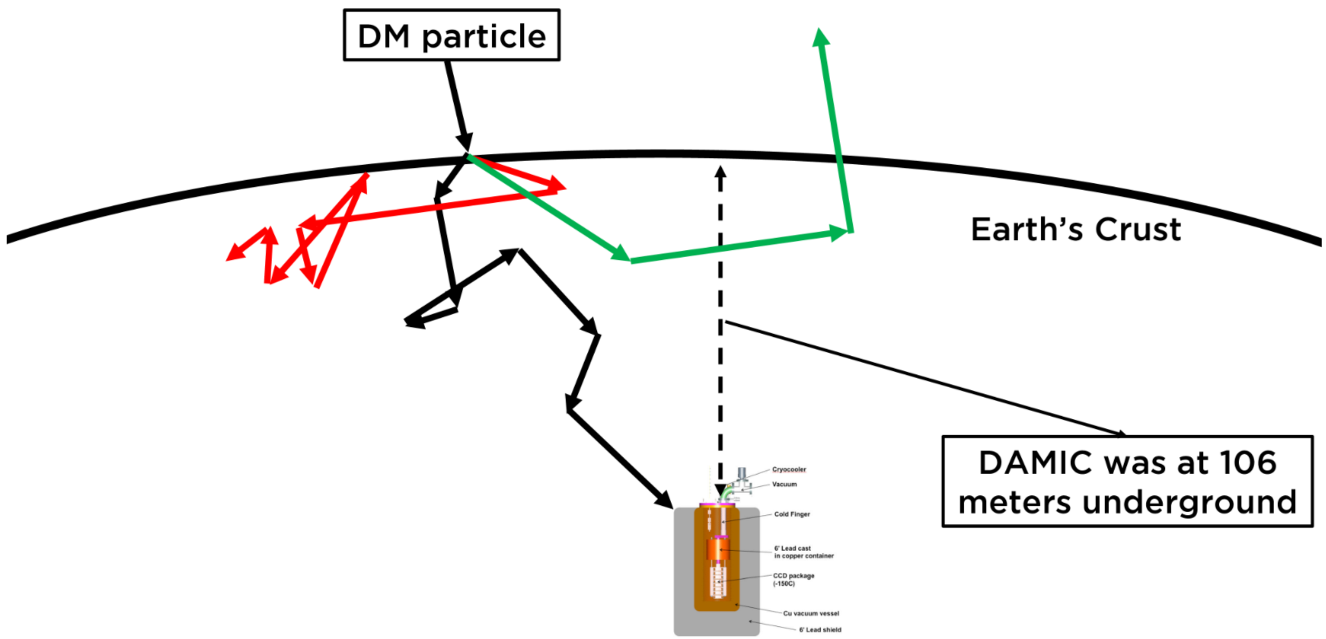
(b) Comparison of future projections

LOI Update: link

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

Strongly Interacting Dark Matter

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

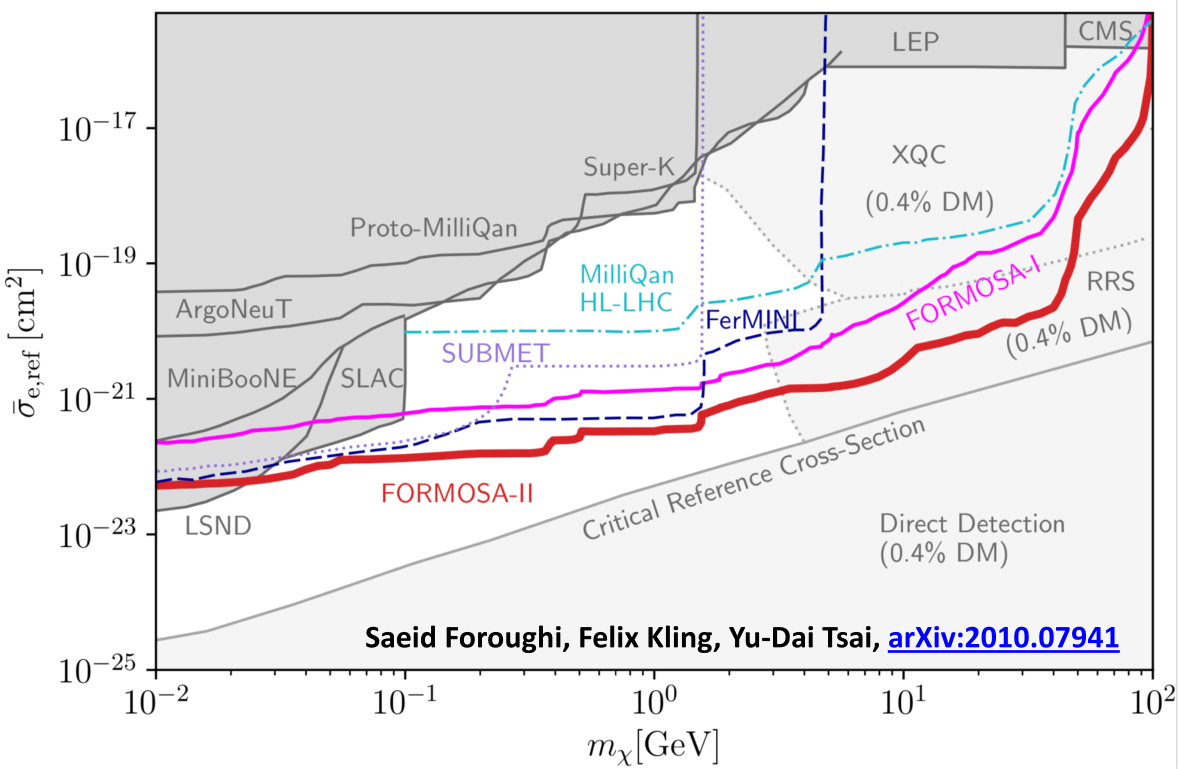


DMATIS (Dark Matter ATtenuation Importance Sampling), Mahdawi & Farrar '17

Probe of Millicharged Dark Matter

MCP / LDM with ultralight dark photon mediators

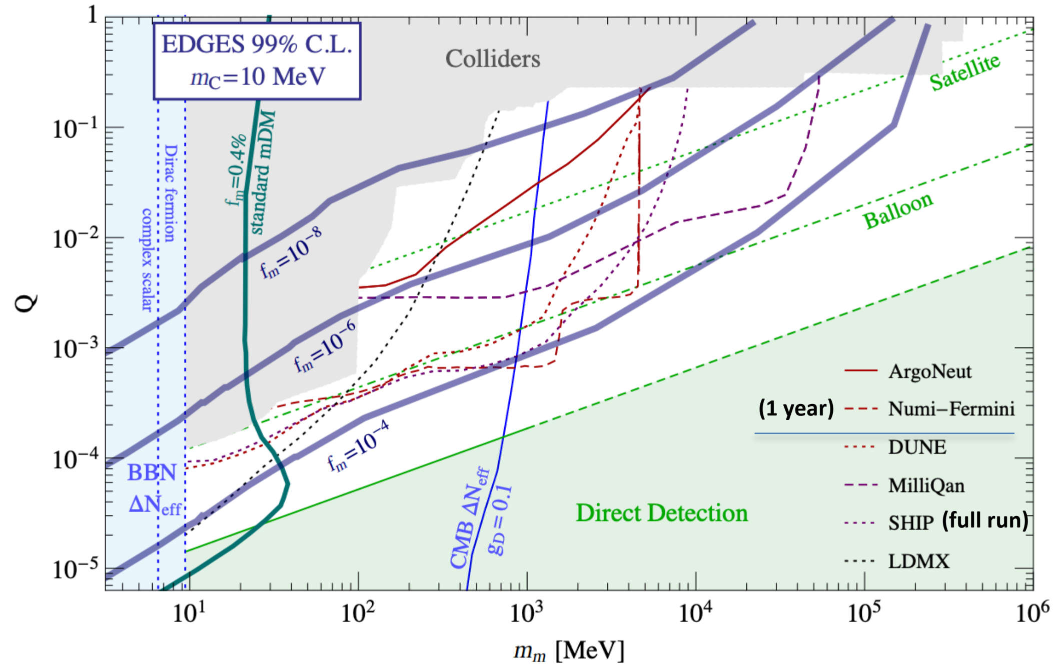
$$\bar{\sigma}_e \simeq \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{ref}^2},\ q_{ref} = \alpha m_e$$

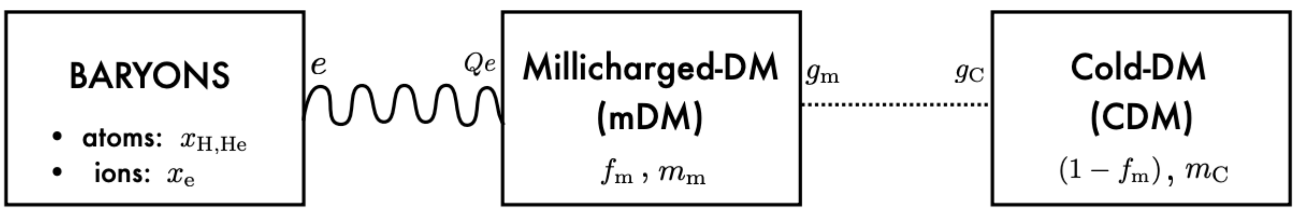


- We will add this figure with all the projections to the appendix of the LOI

- Here we plot the **critical reference cross-section** see 1905.06348 (Emken, Essig, Kouvaris, Sholapurkar)
- **Accelerator probes can help close the Millicharged SIDM window!**
- Cosmic-ray production & Super-K detection 2002.11732

Reviving MDM for EDGES

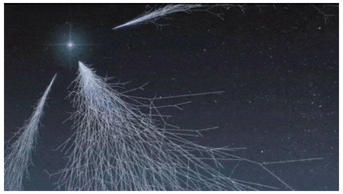




Liu, Outmezguine, Redigolo, Volansky, '19

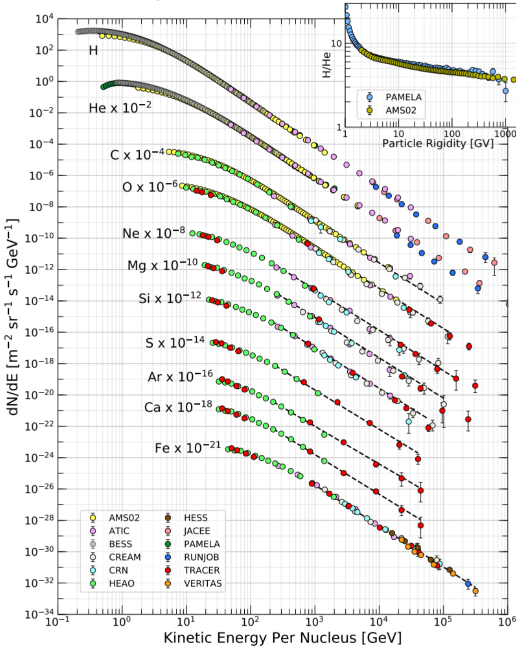
Cosmic-Ray Production & Neutrino Observatories

MCP in Neutrino Observatories

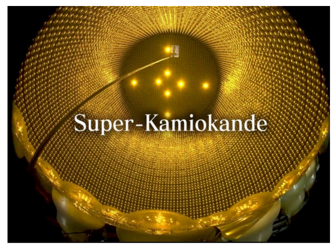


by Chantelauze, Staffi, and Bret

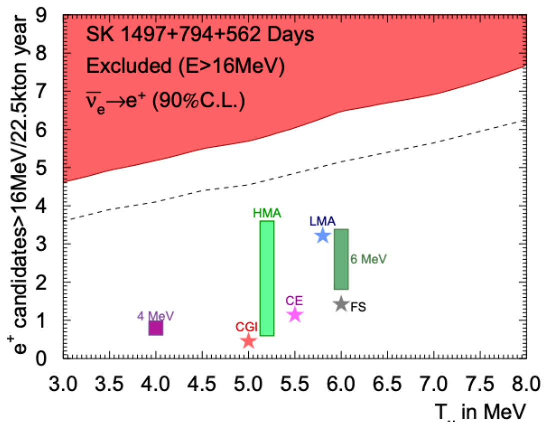
χ $\bar{\chi}$



PDG, RPP, 2019

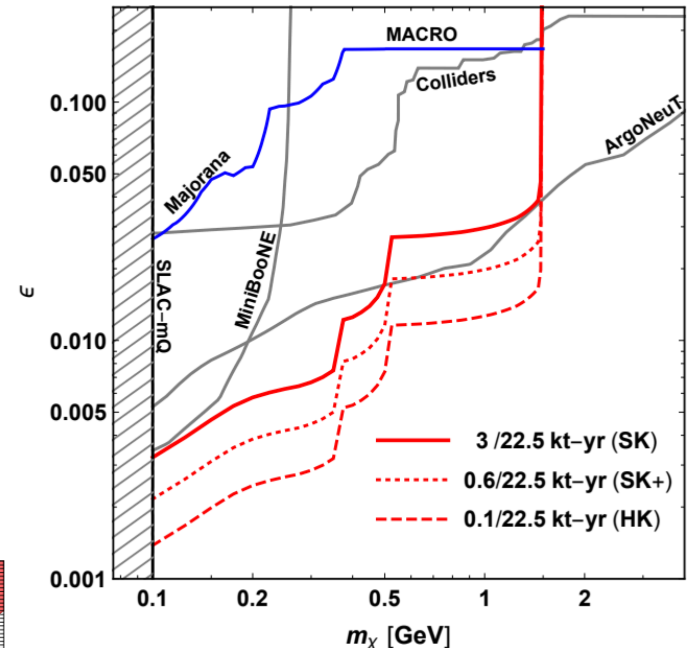


Super-K, http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html



1111.5031 (Super-K Collaboration)

Supernova Relic Neutrino Search at Super–K



2002.11732 (Plestid, Takhistov, **Tsai**, Bringmann, Kusenko, Pospelov, '20)

Conclusion

- MCP is motivated and a minimal test model for accelerator experiments
- We see the power and complementarity of accelerator probes in studying MeV to GeV+ dark sector
- We plan to write a white paper detailing the experimental probes
- New idea has already come out of this practice,
  e.g., FORMOSA, Forward (proto-)DUNE, etc
  (The high-energy / high-intensity frontier is exciting!)

Thank you!
Special thanks to the organizers

Energy & Intensity Facilities

- **LSND:** Total of 10^{23} POT (beam: 800 MeV), King of POT
- **Fermilab** (undergoing a Proton Improvement Plan, PIP):
- Booster Beam (BNB): $\sim 10^{20}$ POT/yr (8 GeV), now
- NuMI beam: 1 - 4 x 10^{20} POT/yr (120 GeV), now
- LBNF beam (future): $\sim 10^{21}$ POT/yr (120 GeV), future
- **CERN SPS beam:**
- NA62: up to 3 x 10^{18} POT/yr (400 GeV), now
- SHiP: up to 10^{19} POT/yr (400 GeV), future
- **CERN LHC**: 10^{16} POT/yr, $\sqrt{s}$ = 13 TeV

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.

Outline of the LOI

- Not about a specific experiment/search, but a **general overview** of all the experimental programs (please see all the reference in the LOI: link):

  - Colliders (LHC, Belle II, BESIII, BaBar, STCF, …)

  - Proton fixed-target & neutrino experiments (LSND, ArgoNeuT, DUNE+)

  - Lepton fixed-target experiments (LDMX, NA64, …)

  - Dedicated experiments (MilliQan, FerMINI, SUBMET, ForMINI, …)

  - Cosmic-Ray Production and Neutrino Observatories (Super-K, …)

- Millicharged Strongly Interacting Dark Matter

- A more detailed/general review talk:

  HEP/Astro Results Forum on Nov. 11, 2020 (link2)

Reference Cross-Section

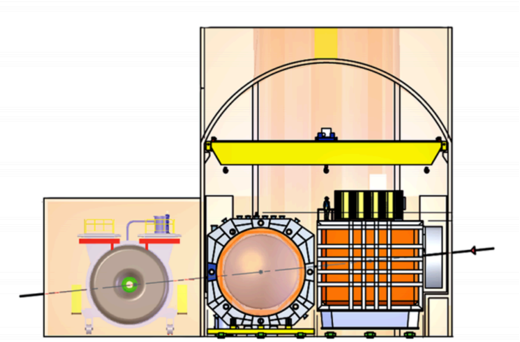
$$\bar{\sigma}_{\mathrm{e,ref}} = \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{\mathrm{d,ref}}^4}\,, q_{\mathrm{d,ref}} = \alpha m_e$$

- 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**

Recap: Three Ways to Produce/Study MCPs

More reference shown in following slides!

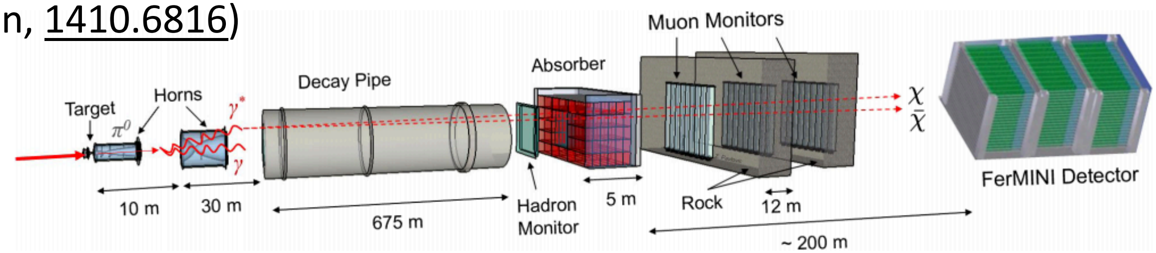
(I) MCPs in fixed-target neutrino experiments, 1812.03998



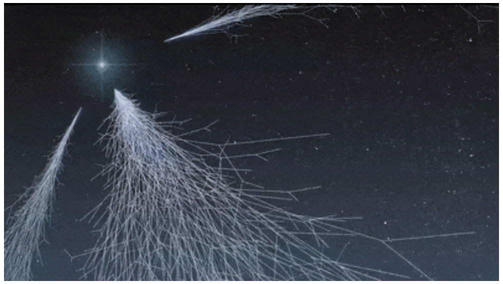
arXiv:2002.02967, DUNE TDR V - I

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

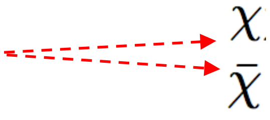
(directly motivated by milliQan, 1410.6816)



(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)