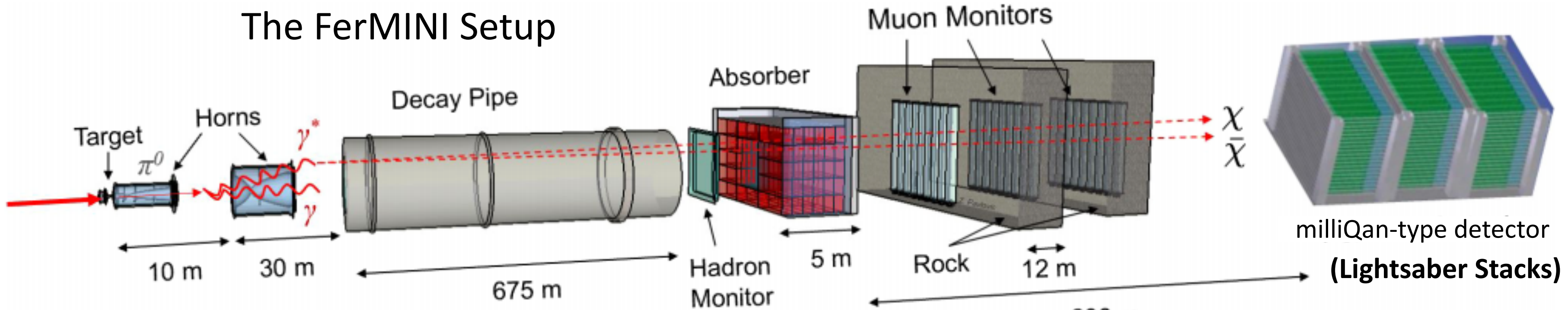
The FerMINI Setup



Kelly, **Tsai**, 1812.03998; Graph: Pavlovic + **Tsai** '19

Accelerator Probes for Millicharged Particles

Yu-Dai Tsai, Fermilab/U.Chicago (WH674)

An overview (see a lot of refs in the following slides), plus

[1] The FerMINI Experiment (1812.03998, ***PRD '19***)

[2] Millicharged Particles (MCPs) in Neutrino Experiments (1806.03310, ***PRL '19***)

[3] Cosmic-ray Produced MCPs in Neutrino Observatories (2002.11732, **NEW**) + ongoing works!

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

Outline

- **Intro (theory & models) of millicharged particles (MCP)**
- **Experimental Program Overview**

  - Colliders

  - Electron Fixed-Target

  - Proton Fixed-Target: NuMI facilities, BNB Facilities, DUNE
- **Details on Proton Fixed-Target / Neutrino Experiments**
- **Specialized Experiments: MilliQan & FerMINI**
- Millicharged Strongly Interacting Dark Matter (EDGES related)
- Cosmic-Ray Production and Neutrino Observatories

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 some Superstring theories:
  Wen, Witten, Nucl. Phys. B 261 (1985) 651-677
  https://www.youtube.com/watch?v=AmUI2qf9uyo (watch 15:50 to 17:28)
- Link to **string compactification** and **quantum gravity** (Shiu, Soler, Ye, PRL '13)
- Conservatively, testing if e/3 is the minimal charge

Minicharge Dark Sector

- MCP could have natural link to **dark sector** (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)].
  A small fraction of the DM as MCP can potentially explain EDGES observation of anomalous absorption of 21 cm spectrum

- See more reference and discussions about this in later pages

MCP Model

- A particle fractionally (or irrationally) charged under SM U(1) hypercharge $\mathcal{L}_{\mathrm{MCP}} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\mathrm{MCP}})\chi$

- ϵ' can in principle be arbitrarily small.

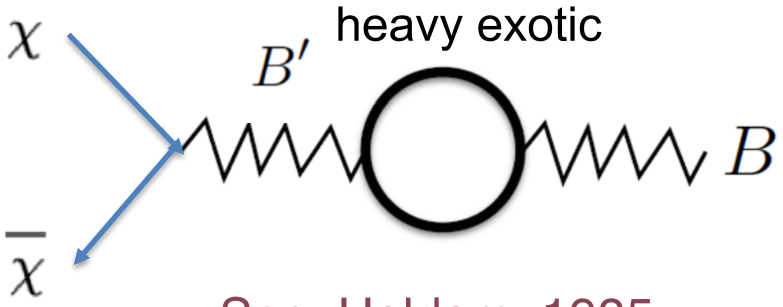
- Can just consider these Lagrangian terms by themselves (no extra mediator, i.e., dark photon). **Completely legal**! Naively **violating the empirical charge quantization** (cool).

- 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

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

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

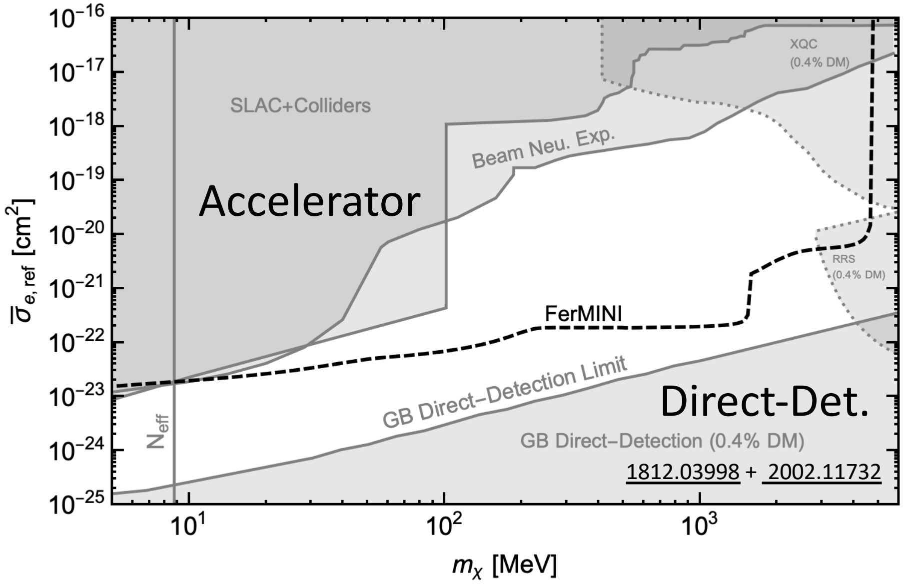
- Millicharged particle (MCP) can be a **low-energy consequence** of **massless dark photon** (a new U(1) gauge boson) coupled to **a new fermion (become MCP** in a convenient basis.)

Important Notes!

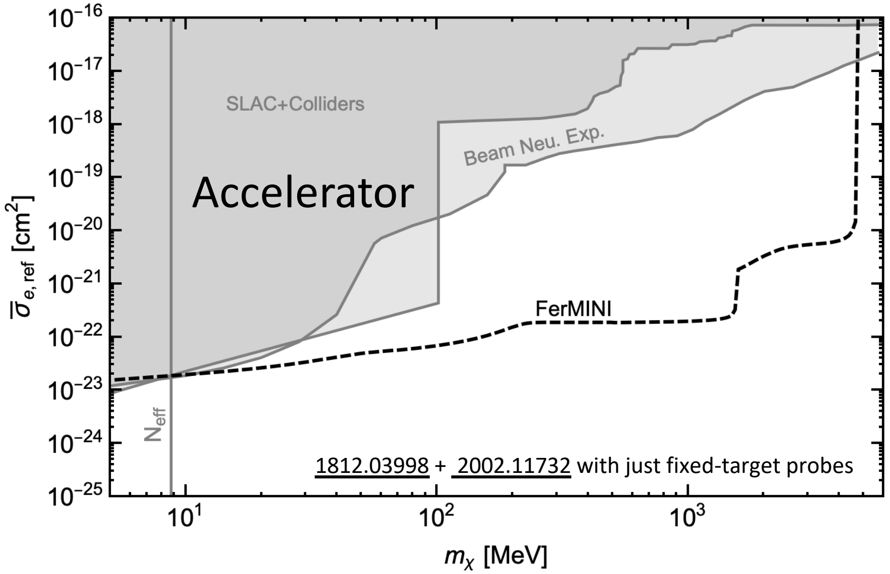
- Our search is simply a search for particles (**fermion χ**) with **{mass, electric charge}** = $\{m_\chi, \epsilon e\}$
- **Minimal theoretical inputs/parameters**

  (need **high-energy/intensity machines** to probe in MeV – GeV+ mass regime)
- **Dark photon not necessary for MCP particles** (Neff, Self-Int. could provide extra constraints)
- Similar bound/sensitivity applies to scalar MCPs

Not all bounds are created with equal assumptions Example: Constraints on Millicharged Dark Matter



1812.03998 + 2002.11732



1812.03998 + 2002.11732 with just fixed-target probes

Also consider **ambient dark matter**

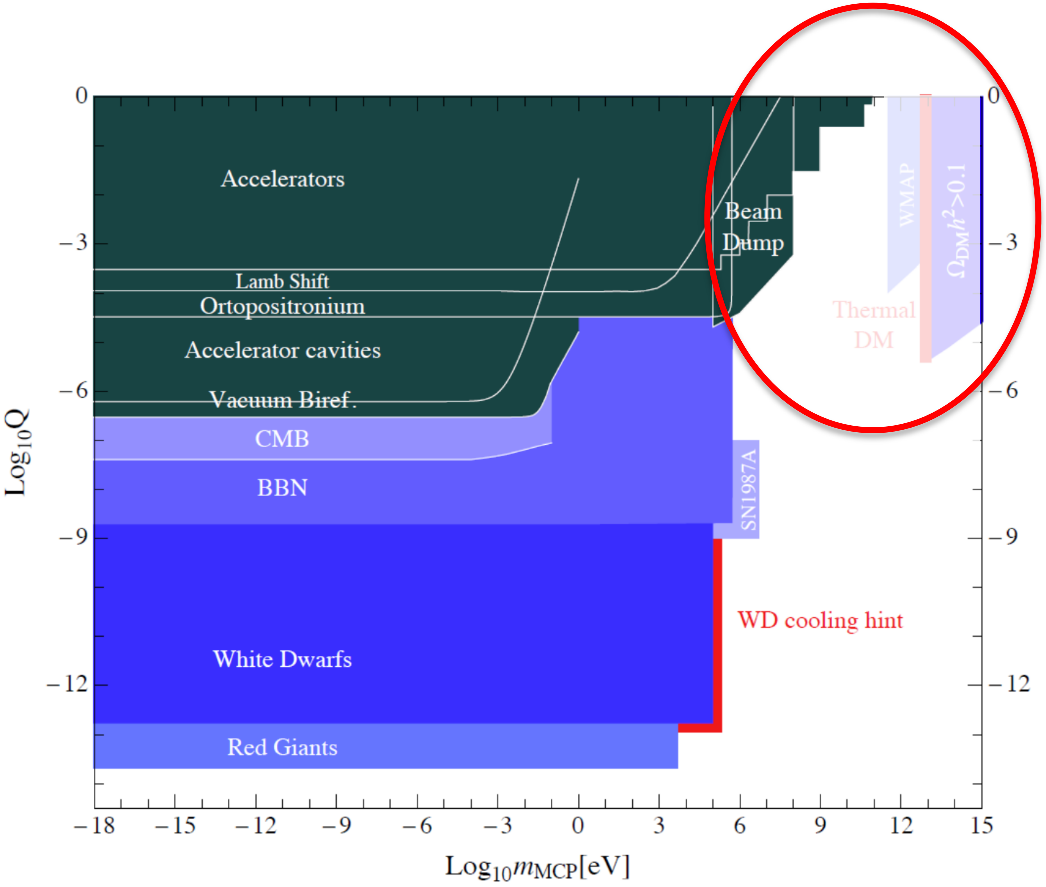
Produce dark particles in collisions

Same mass and interaction strength.

Different assumptions

Details of these figures will be explained later

A few years ago …

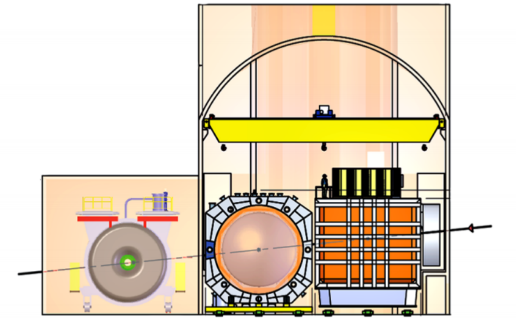


Haas, 2017, Fermilab Wine & Cheese

Our Three Ways to Produce/Study MCPs

More reference shown in following slides!

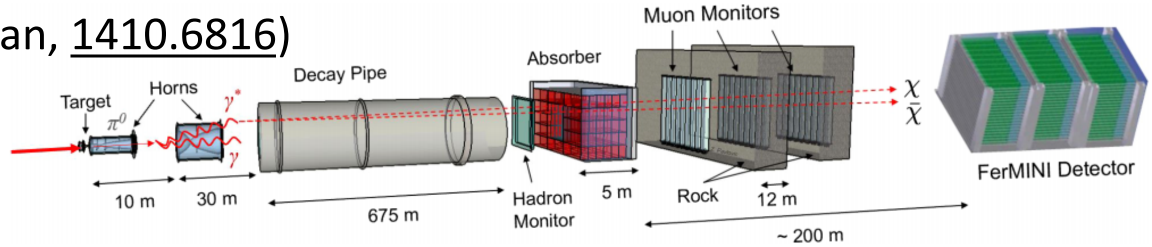
(I) MCPs in fixed-target neutrino experiments, 1812.03998



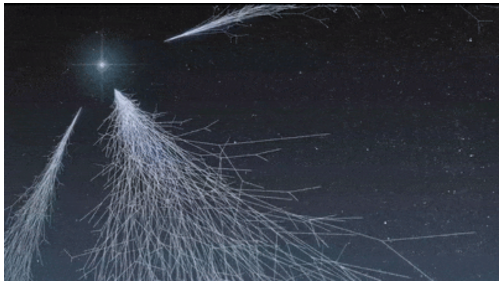
arXiv:2002.02967, **DUNE TDR V - I**

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

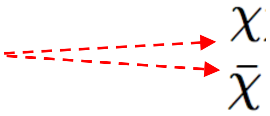
(directly motivated by milliQan, 1410.6816)



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



by Chantelauze, Staffi, and Bret

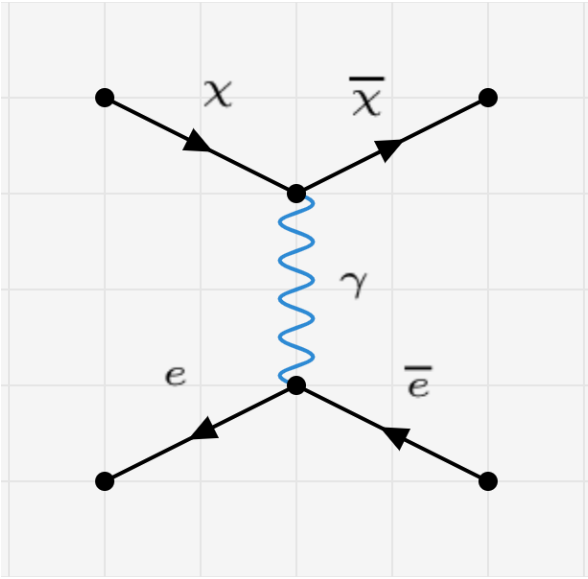


Super-K, http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

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

Millicharged Particle: Signature

MCP Detection: Hard Scattering or Ionization



- **"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

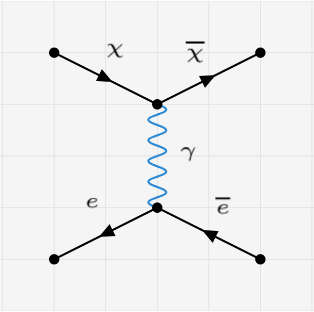
  FerMINI: arXiv:1812.03998, Kelly, **Tsai**

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

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

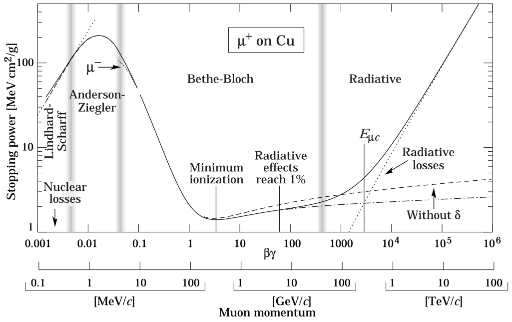
- Sensitivity greatly enhanced by accurately **measuring low energy electron recoils** for MCP's & light-mediator scattering



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

Accelerator Probes: Overview

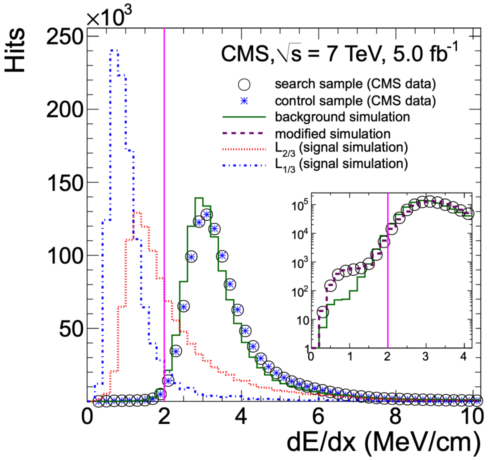
Note: MeV – GeV+ Dark Sector are motivated by
thermal freeze-out dark matter (DM) & **anomalies**
We don't need to search in the dark!

Yu-Dai Tsai, Fermilab, 2020

Collider: LEP & LHC

- LEP: **Z decay** (though The coupling to Z is suppressed by $\sin^2\theta_W$.)
- See, H. Goldberg, L.J. Hall, Phys. Lett. B174 (1986) 151.
- S. Davidson, B.A. Campbell, D. Bailey, Phys. Rev. D43 (1991) 2314.

- LHC: **A dE/dx study** of the particle, focus on ±2e/3 and ±e/3
- selecting tracks with low charge measurements in silicon tracking detector.
- arXiv:1210.2311 (CMS)
- Should redo this analysis with the current data.

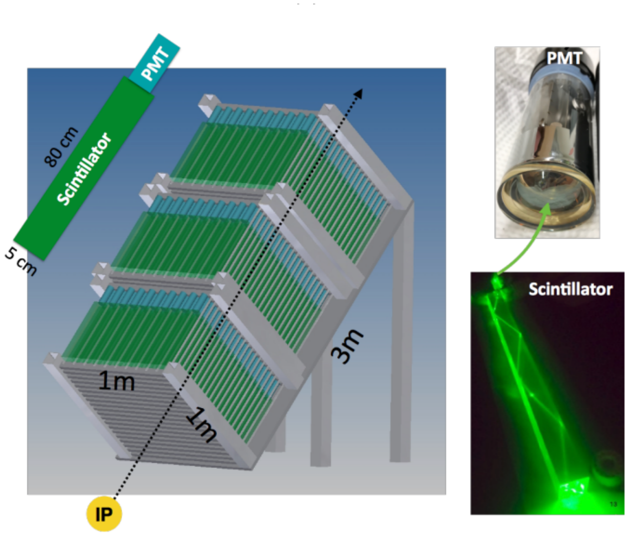


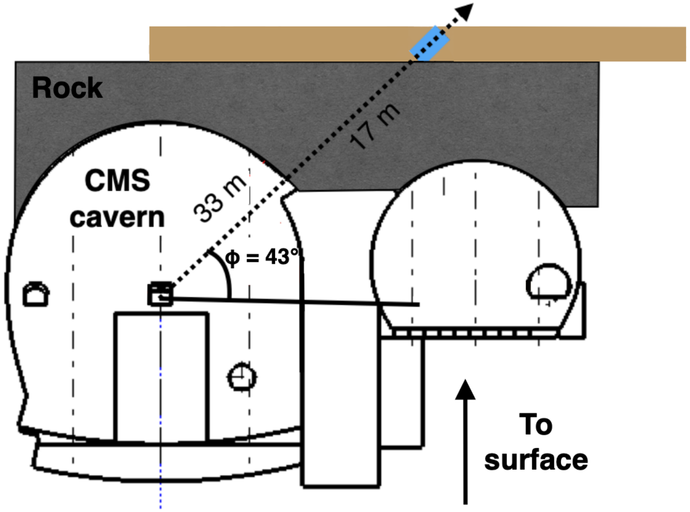
More Proton Experiments

milliQan

- MilliQan: arXiv:1410.6816, Haas, Hill, Izaguirre, Yavin
- Also will show an update from the milliQan-prototype!
- From milliQan Collaboration:

- LOI: 1607.04669
- First result update: 2005.06518 (will get into this more)

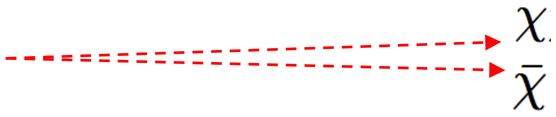




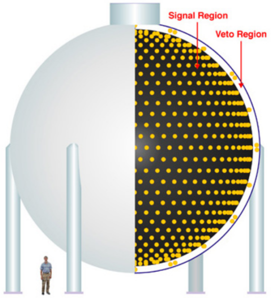
Proton Fixed-Target

Example Beams:

- **Booster Neutrino Beam (BNB)**

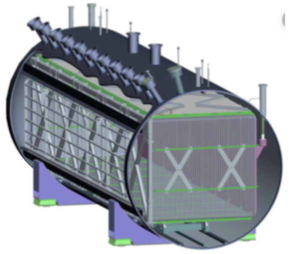


MiniBooNE Detector



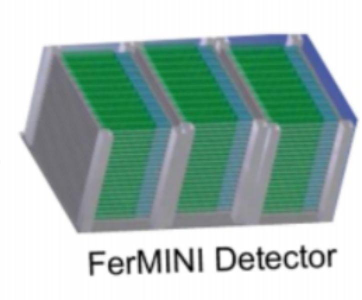
arXiv:0806.4201
MiniBooNE collaboration

MicroBooNE Detector

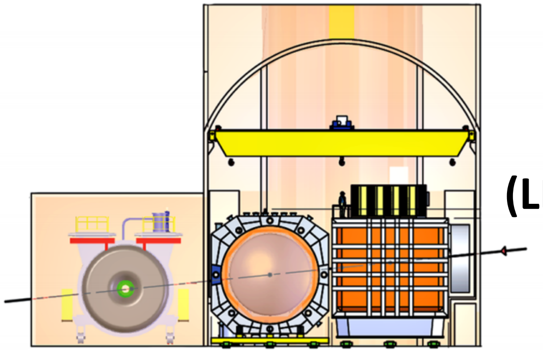


arXiv:1612.05824
MicroBooNE collaboration

- **Nutrino Main Injector (NuMI)**
- **Long Baseline Neutrino Facility (LBNF)**



DUNE Near Detector

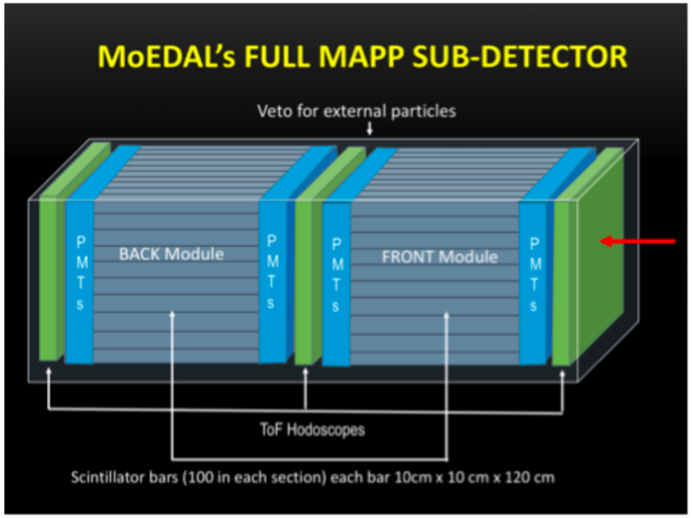


(LBNF)

Discuss details later

Other Probes

- MOEDAL@LHC: https://www.mdpi.com/2218-1997/5/2/47 (MoEDAL Collaboration Progress Report), see MAPP sub-detector



Lepton Fixed-Target Machines

SLAC mQ

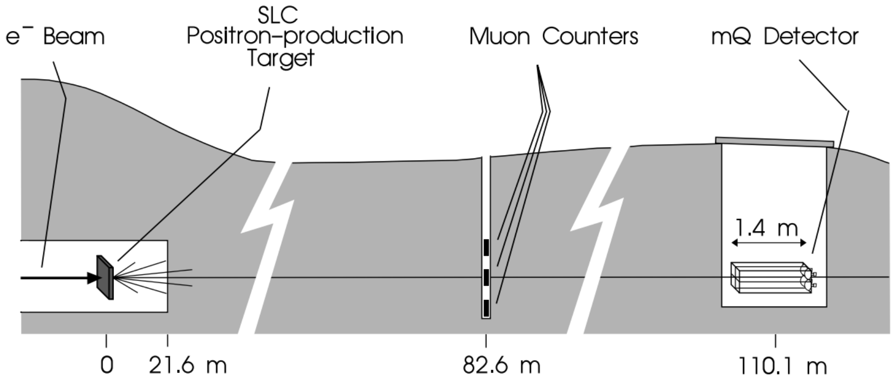
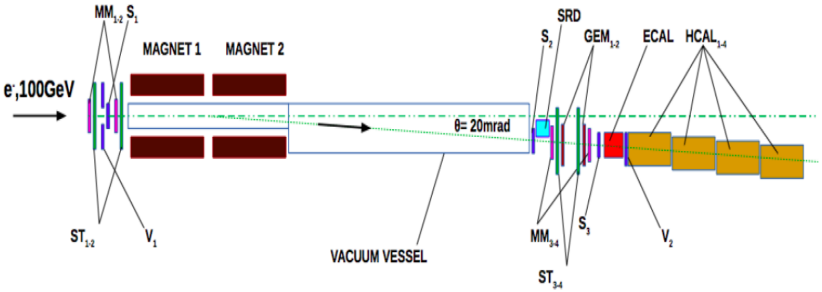


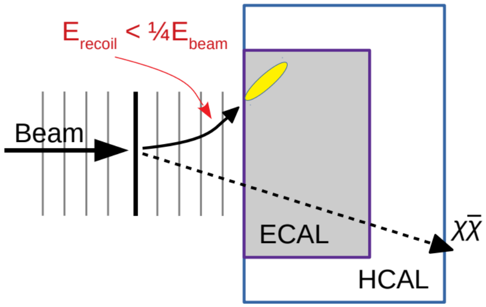
FIG. 1. Layout of the experiment. Shown is a vertical cross section.

- 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.
- employ a scintillation counter designed to be sensitive to signals as small as a single scintillation photon (from a single excitation or ionization).
- Motivated milliQan and lFerMINI
  (**much better sensitivity to do this in Hadron machines if background is controlled**)

Fixed-Target Machines
LDMX & NA64

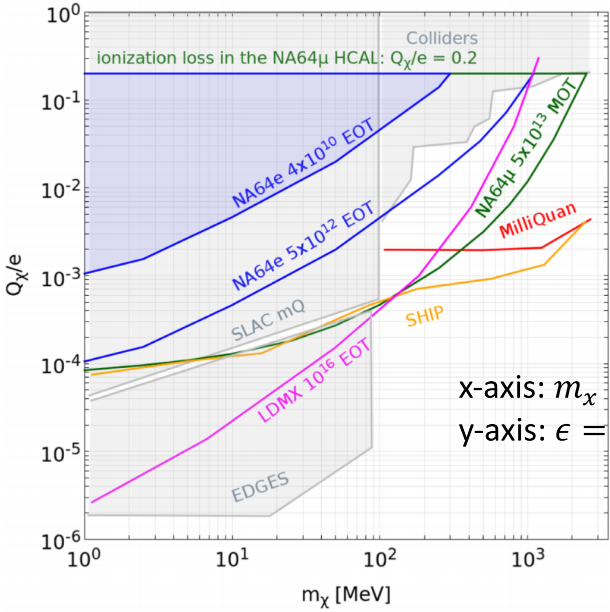


1710.00971 (NA64 collaboration)



1808.05219 (LDMX collaboration)

- Won't get into details for these



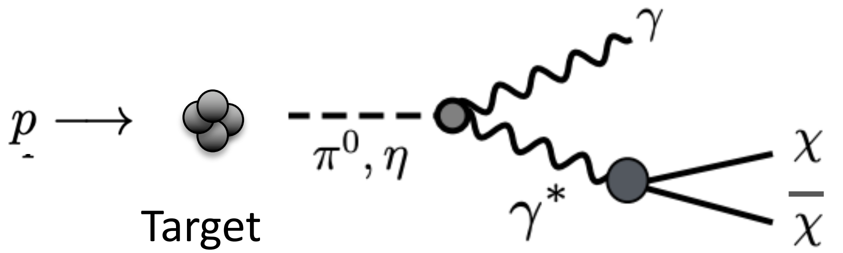
x-axis: m_x (MCP mass),
y-axis: $\epsilon = Q_x/e$ (charge ratio).

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

MCP in Fixed-Target Neutrino Experiment

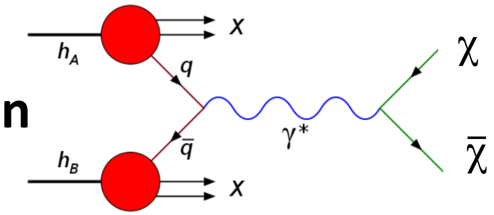
Some Production Channels of MCP

- ☐ **Production: Meson Decays**

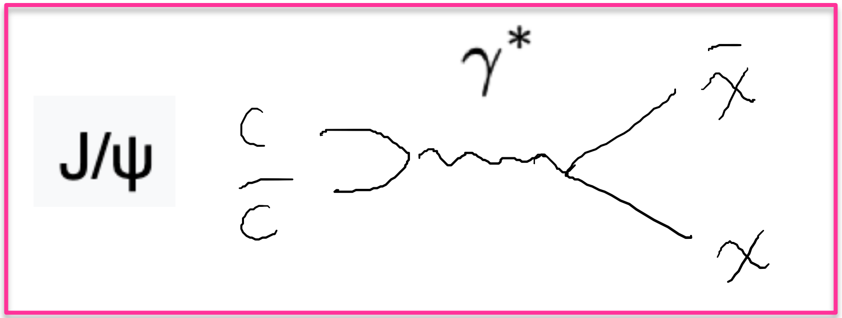


Modified from 1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

- ☐ **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

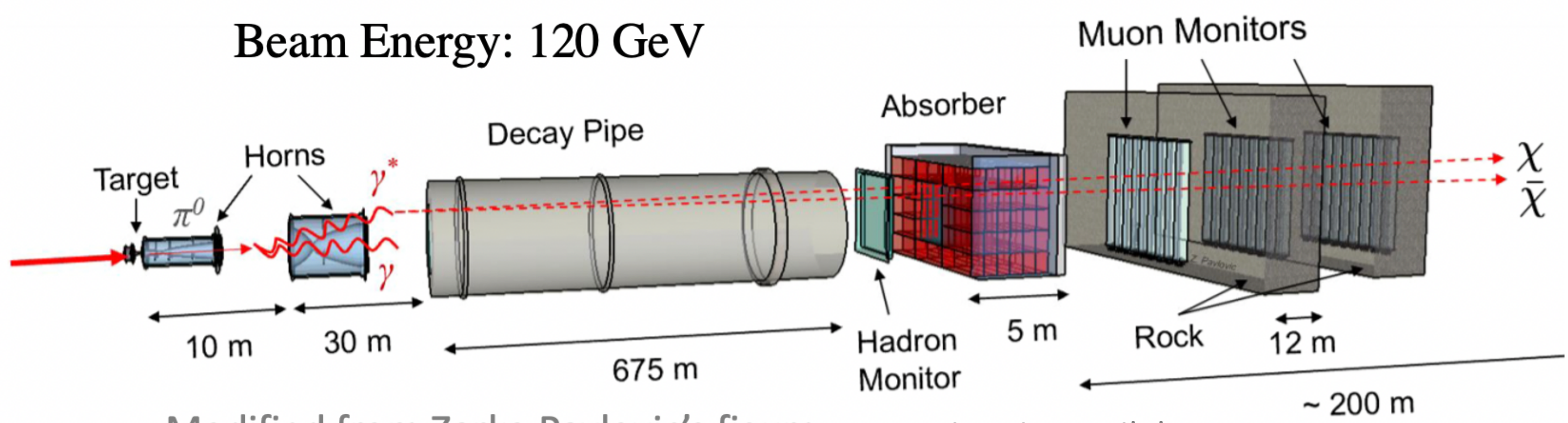
BR($\pi^0 \to \gamma e^- e^+$) = 0.01

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)

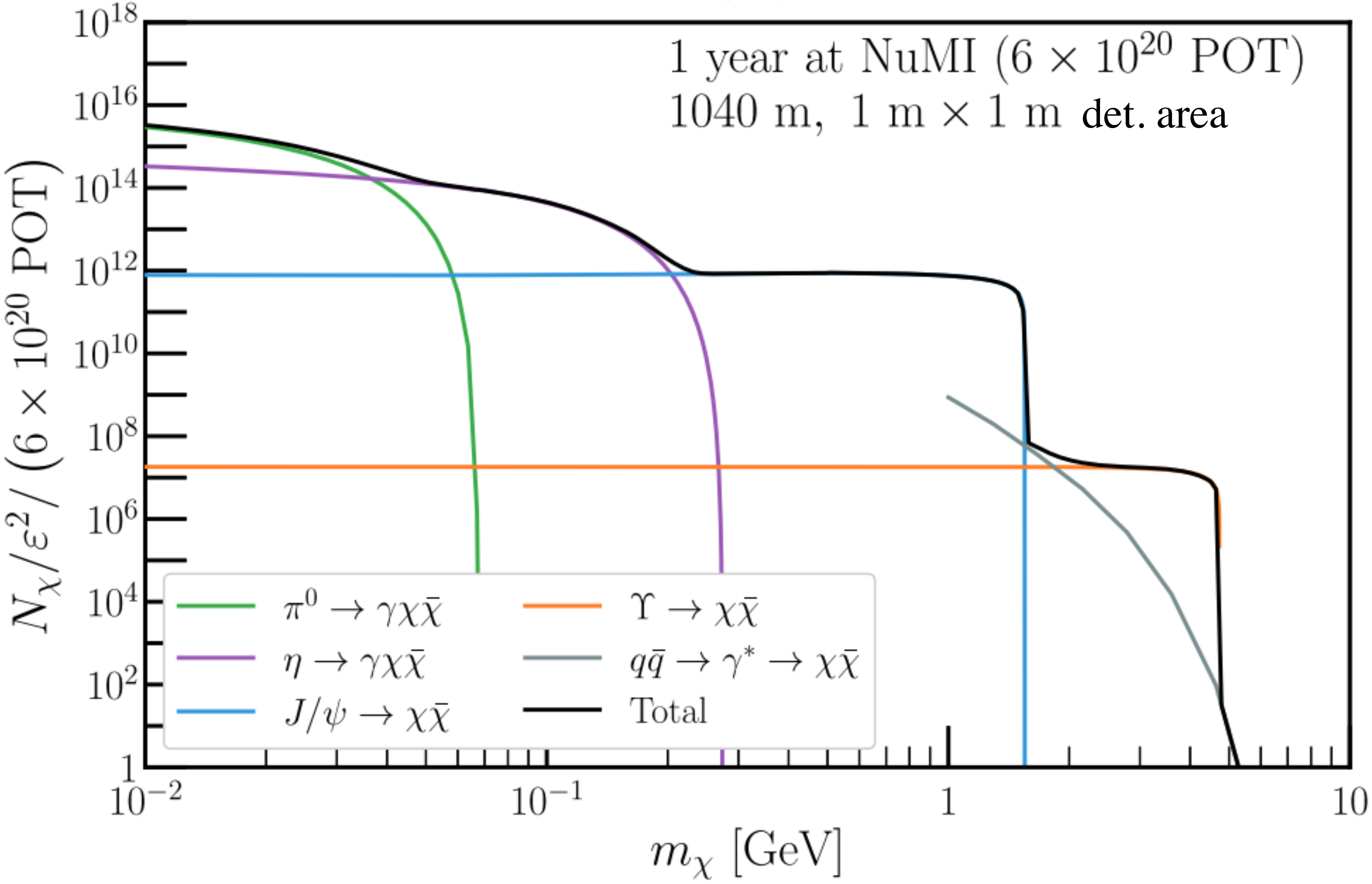


Modified from Zarko Pavlovic's figure

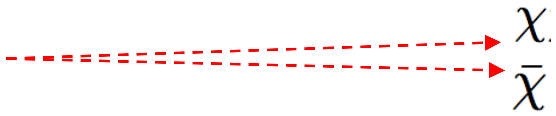
Yu-Dai Tsai Fermilab

MCP Production/Flux

120 GeV proton beam on target (graphite)



Scattering Detectors

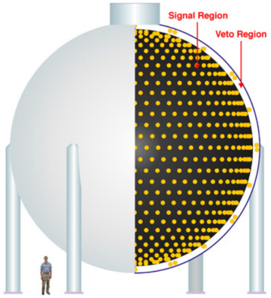


Other beams:

- BNB

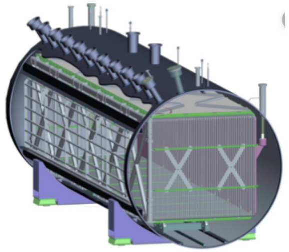
- LBNF (future)

MiniBooNE Detector



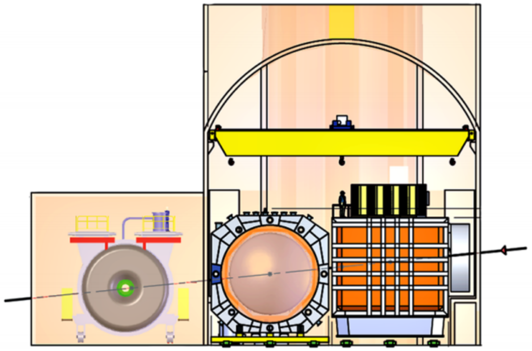
arXiv:0806.4201
MiniBooNE collaboration

MicroBooNE Detector



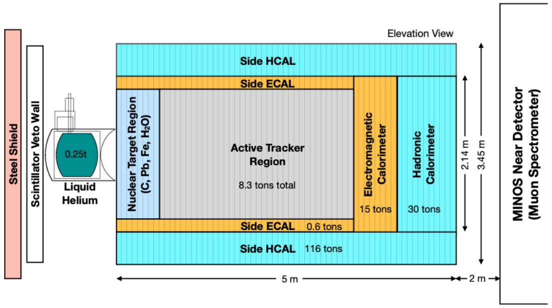
arXiv:1612.05824
MicroBooNE collaboration

DUNE Near Detector



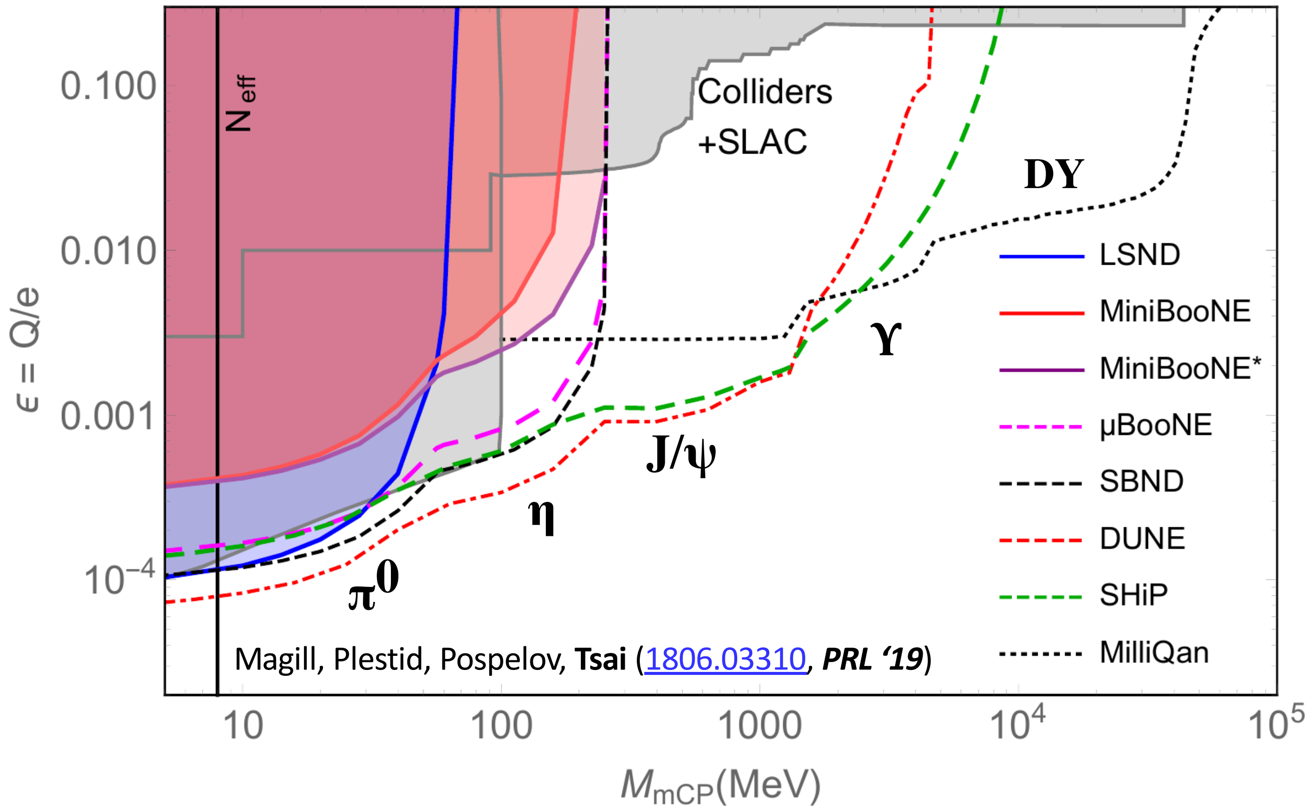
arXiv:2002.02967, DUNE TDR V - I

MINERvA Detector



arXiv:1109.2855
MINERvA collaboration

Sensitivity at Neutrino Detectors

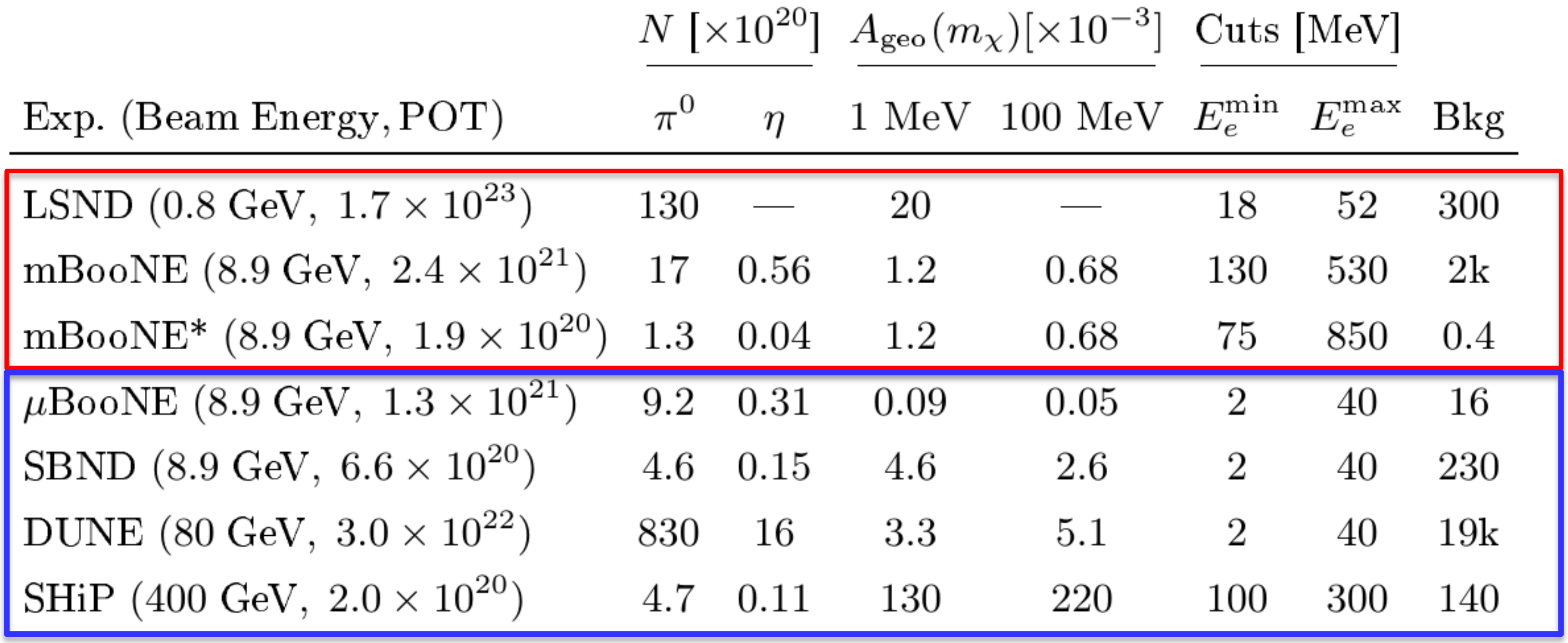


Magill, Plestid, Pospelov, **Tsai** (1806.03310, ***PRL '19***)

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

- **Electron recoil-energy threshold: MeV to 100 MeV**
- Can use **timing information** to improve sensitivity
- Double-hit to reduce background (see next page)
- Will include more updates later!

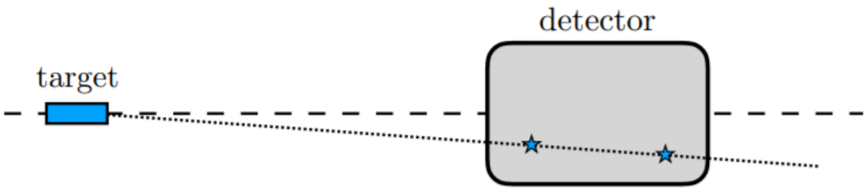
Analysis Summary (skip)

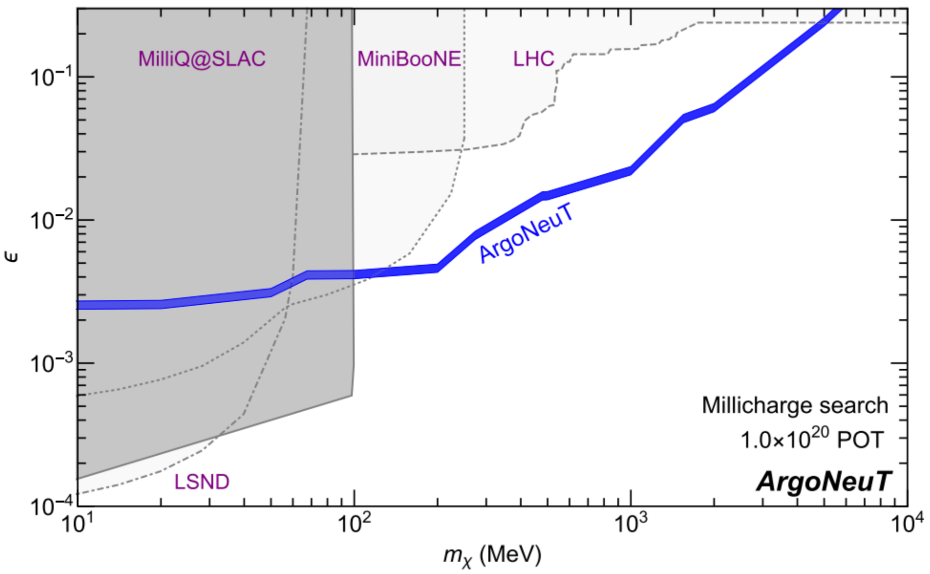


		N [$\times 10^{20}$]		$A_{\text{geo}}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
	Exp. (Beam Energy, POT)	π^0	η	1 MeV	100 MeV	E_e^{min}	E_e^{max}	Bkg
Existing	LSND (0.8 GeV, 1.7×10^{23})	130	—	20	—	18	52	300
	mBooNE (8.9 GeV, 2.4×10^{21})	17	0.56	1.2	0.68	130	530	2k
	mBooNE* (8.9 GeV, 1.9×10^{20})	1.3	0.04	1.2	0.68	75	850	0.4
Future	μBooNE (8.9 GeV, 1.3×10^{21})	9.2	0.31	0.09	0.05	2	40	16
	SBND (8.9 GeV, 6.6×10^{20})	4.6	0.15	4.6	2.6	2	40	230
	DUNE (80 GeV, 3.0×10^{22})	830	16	3.3	5.1	2	40	19k
	SHiP (400 GeV, 2.0×10^{20})	4.7	0.11	130	220	100	300	140

- $\varepsilon \propto E_{e,\,R,min}^{1/4}\; Bg^{1/8}$
- cos θ > 0 is imposed (∗except for at MiniBooNE's DM run where a cut of cos θ > 0.99 effectively reduces backgrounds to zero [Dharmapalan, MiniBooNE, (2012)]).
- Efficiency of 0.2 for Cherenkov detectors, 0.5 for nuclear emulsion detectors, and 0.8 for liquid argon time projection chambers.

Double-Hit Consideration: ArgoNeuT Study & Constraint





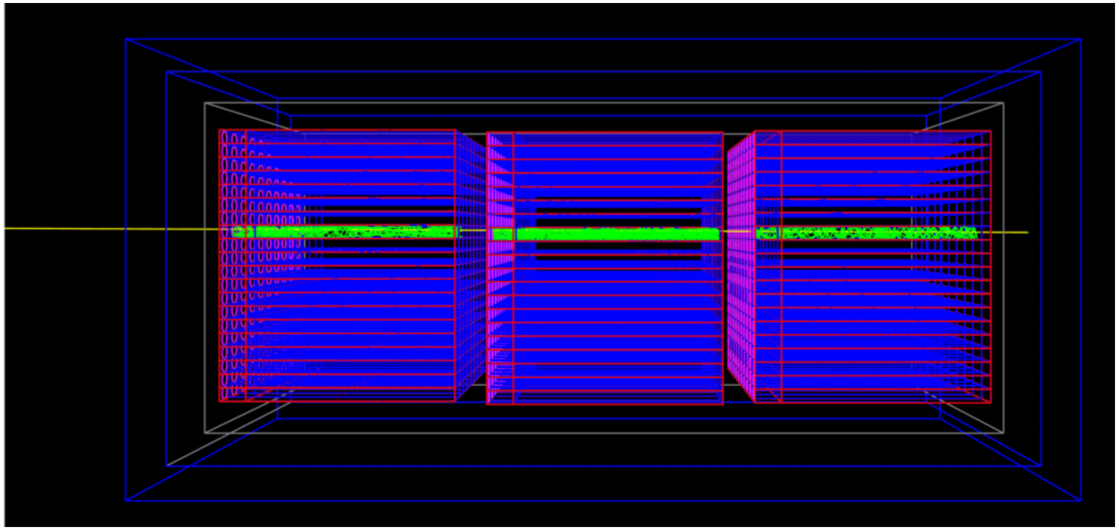
Harnik, Liu, Ornella: multi-scattering, point back to target to reduce the background (ArgoNeuT & DUNE), arXiv:1902.03246 / ArgoNeuT collab: arXiv:1911.07996

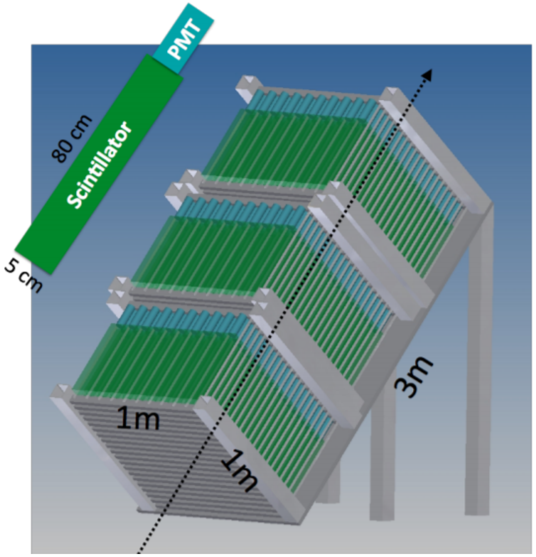
x-axis: m_x (MCP mass),
y-axis: $\epsilon = Q_x/e$ (charge ratio).

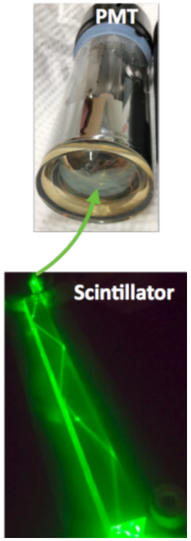
Specialized MCP Detectors

MCP Detector Concept

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







1607.04669, (MilliQan Collaboration)
Ball, Brooke, Campagnari, De Roeck, Francis, Gastal, Golf, Goldstein, Haas, Hill, Izaguirre, Kaplan, Magill, Marsh, Miller, Prins, Shakeshaft, Stuart, Swiatlowski, Yavin

FerMINI

A Fermilab Search for **MINI-charged Particle based on scintillating detectors**
Kelly, **Tsai**, 1812.03998 (PRD19)

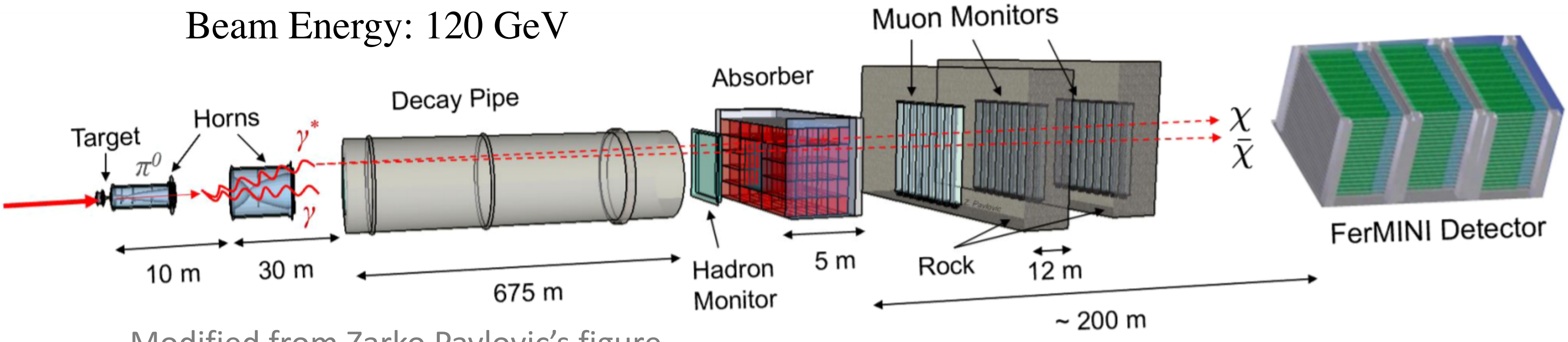
Directly inspired by milliQan concept (Haas, Hill, Izaguirre, Yavin, 1410.6816)

Visually "a detector made of stacks of light sabers,"

can potentially probe other new-physics scenarios like **small-electric-dipole dark fermions**, or **quirks**, etc

FerMINI @ NuMI-MINOS Hall

Beam Energy: 120 GeV



Modified from Zarko Pavlovic’s figure

An illustration of the FerMINI experiments utilizing the NuMI facility.

MINOS hall downstream of NuMI beam

Photoelectrons (PE) from Scintillation

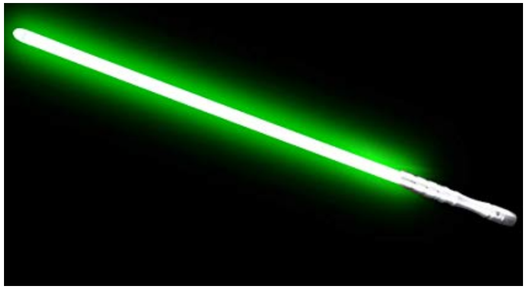
- **The averaged number of photoelectron (PE)** seen by the detector from single MCP is:

$$N_{PE} \propto \left\langle -\frac{dE}{dx} \right\rangle \times l_{scint}, \quad \left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2.$$

$\langle dE/dx \rangle$ is the "mass stopping power" (PDG 2018)

One can use modified **Bethe-Bloch Formula** to get an approximation

- $\boldsymbol{N_{PE}} \sim \epsilon^2 \times \boldsymbol{10^6}$ for **1 - meter plastic scintillation bar**
- $\epsilon \sim \boldsymbol{10^{-3}}$ roughly gives one PE



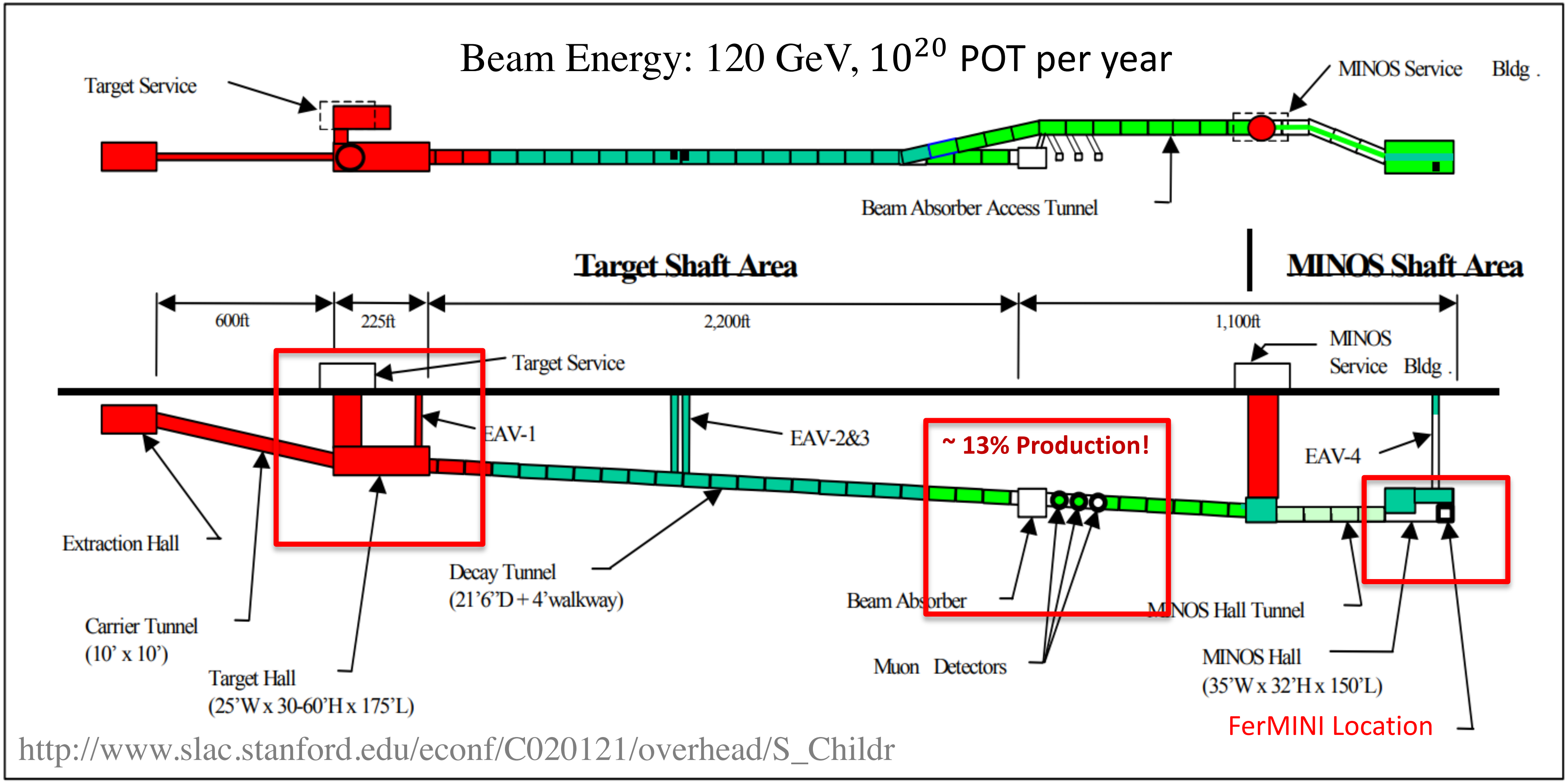
Signature: Triple Coincidence

- Based on Poisson distribution, zero event in each bar correspond to $\boldsymbol{P_0} = \boldsymbol{e^{-N_{PE}}}$, so the probability of seeing triple incident of one or more photoelectrons is:

$$P = \left(1 - e^{-N_{PE}}\right)^3$$

- **$N_{x,detector}$ = N_x (going through detector) x P.**

Site 1: NuMI Beam & MINOS ND Hall



Beam Energy: 120 GeV, 10^{20} POT per year

~ 13% Production!

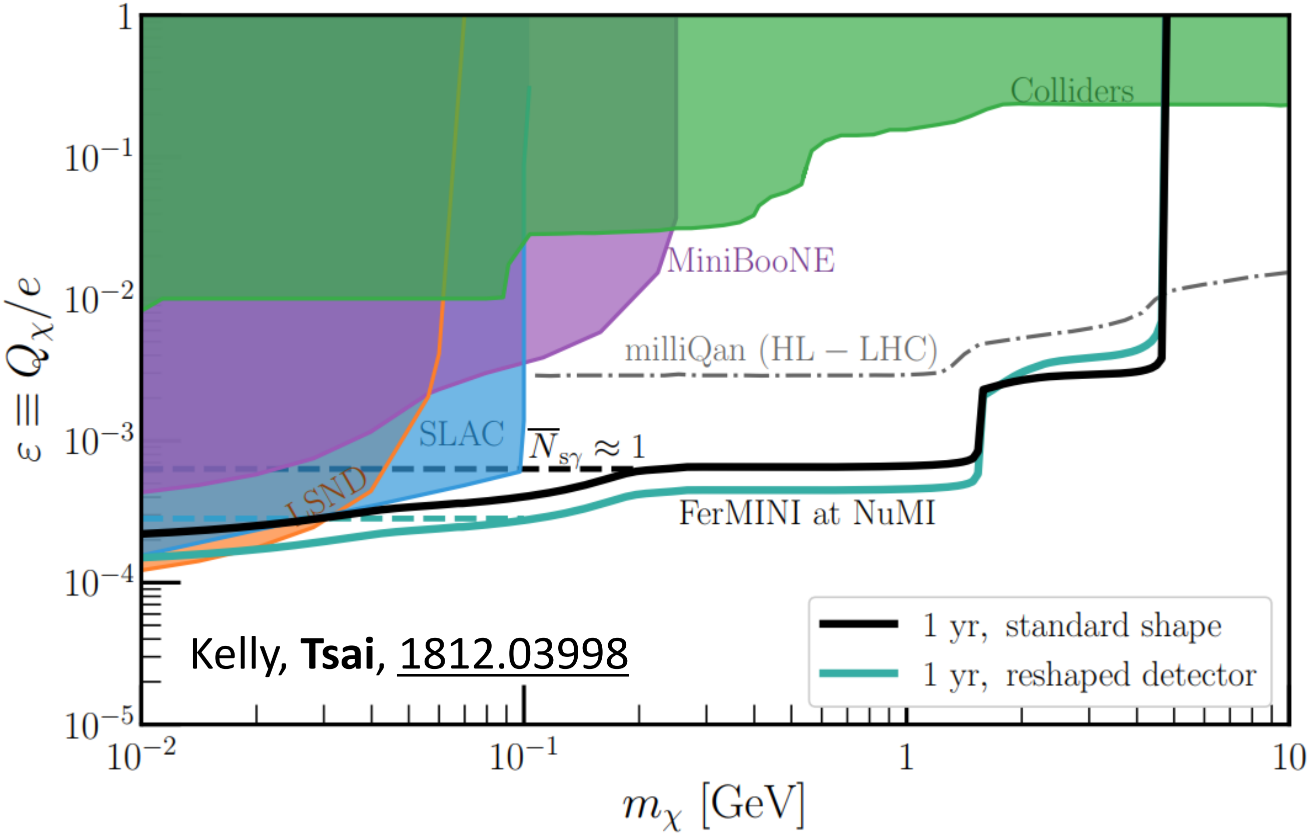
FerMINI Location

http://www.slac.stanford.edu/econf/C020121/overhead/S_Childr

NuMI: Neutrinos at the Main Injector

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

FerMINI @ MINOS



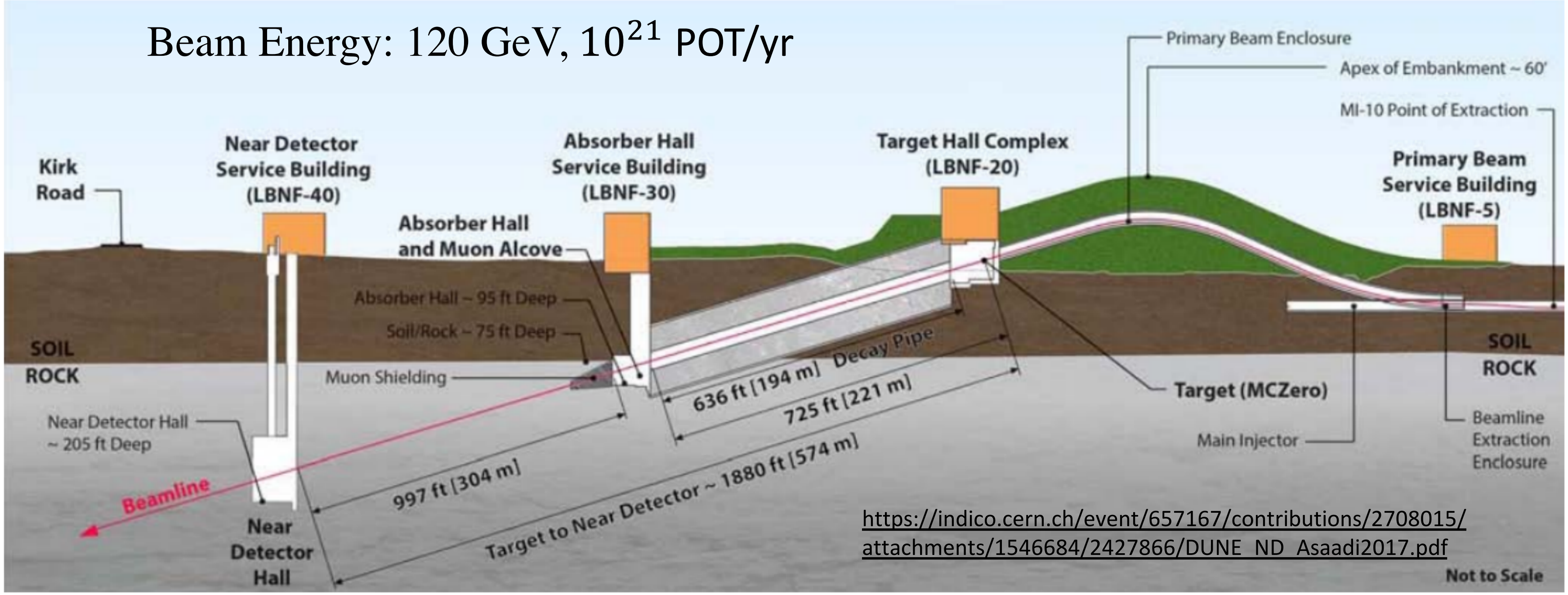
Kelly, **Tsai**, 1812.03998

Yu-Dai Tsai,
Fermilab

Different epsilon now, ε=Q/e

Now it's literally fraction of the charge!

Site 2: LBNF Beam & DUNE ND Hall



Beam Energy: 120 GeV, 10^{21} POT/yr

https://indico.cern.ch/event/657167/contributions/2708015/attachments/1546684/2427866/DUNE_ND_Asaadi2017.pdf

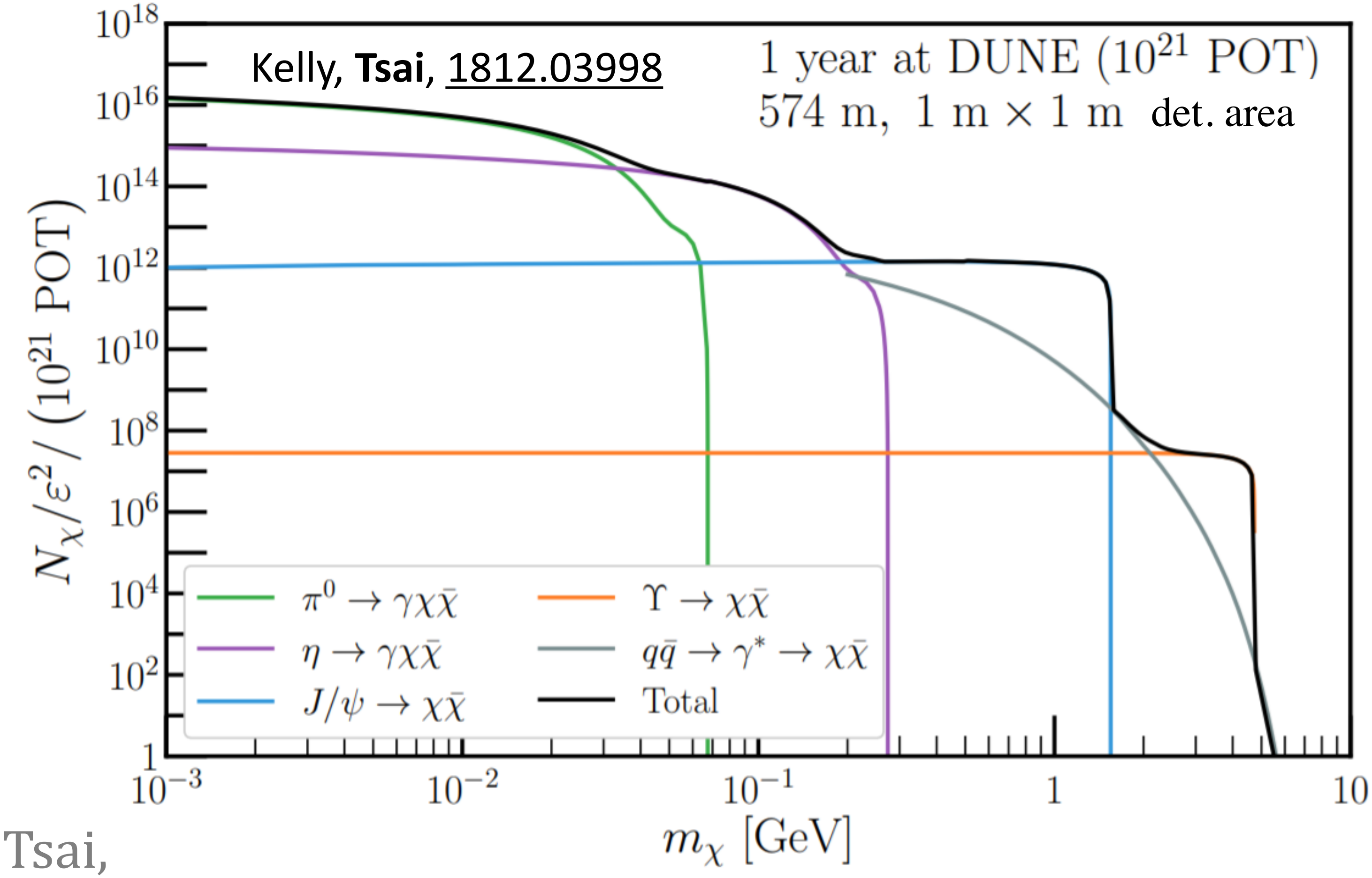
Jonathan Asaadi – University of Texas Arlington

LBNF: Long-Baseline Neutrino Facility

There are many other **new physics opportunities** in the **near detector hall**!
Combine with **DUNE PRISM**?

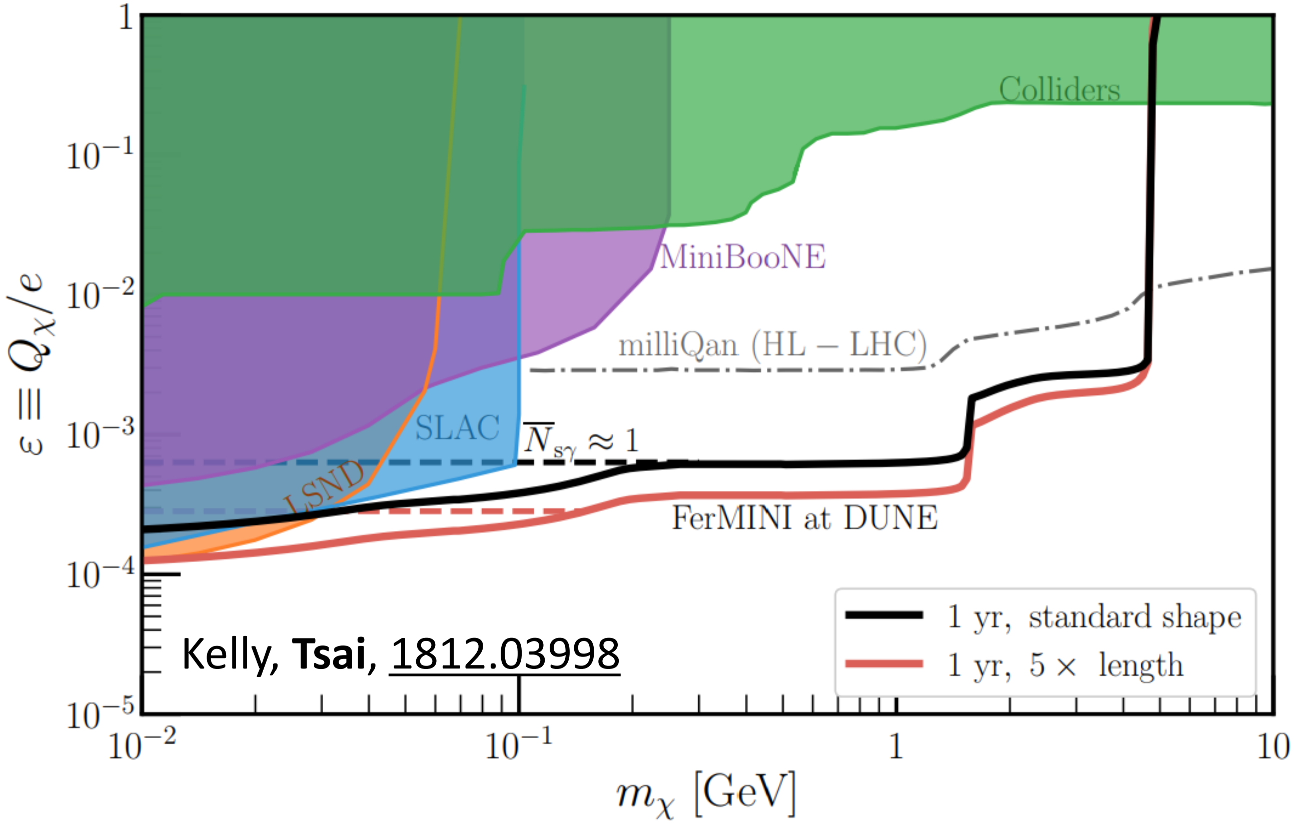
MCP Production/Flux

120 GeV proton beam on target (graphite)



Yu-Dai Tsai,
Fermilab

FerMINI @ DUNE



Kelly, **Tsai**, 1812.03998

Yu-Dai Tsai,
Fermilab

- **Hope to Incorporate it into the near detector proposal.**
- **+ DUNE PRISM? & combine with DUNE to get timing?**

Dark Current Background @ PMT (may skip)

- **Major Background Source!**
- dark-current frequency to be ν_B= **500 Hz** for estimation (1607.04669)
- For each tri-PMT set, the background rate for triple incidence is

ν_B^3 Δt^2 = 2.8 x 10^{-8} Hz, for **Δt = 15 ns. (for a set of triple PMT)**

- Consider 400 such PMT sets:

the total background rate is 400 x 2.8 x 10^{-8} ~ 10^{-5} Hz

- ~ **300 events** per year of trigger-live time
- **Quadruple coincidence can reduce this BG to essentially zero!**

Detector Background (may skip)

- We will discuss two major **detector backgrounds** and the **reduction technique**
- **SM charged particles from background radiation (e.g., cosmic muons):**

  - Offline veto of events with > 10 PEs

  - Offset middle detector
- **Dark current: triple coincidence**

FerMINI Collaboration (BRN proposal)

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OSU

Andy Haas
NYU

Jim Hirschauer
Fermilab

David Miller
U Chicago

David Stuart
UCSB

Zarko Pavlovic
Fermilab

Yu-Dai Tsai
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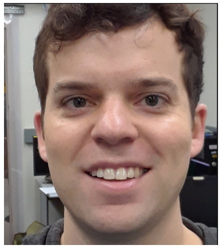
Cindy Joe
Fermilab



Ryan Heller
Fermilab

Maxim Pospelov
Minnesota / Perimeter

Ryan Plestid
McMaster

Albert de Roeck
CERN

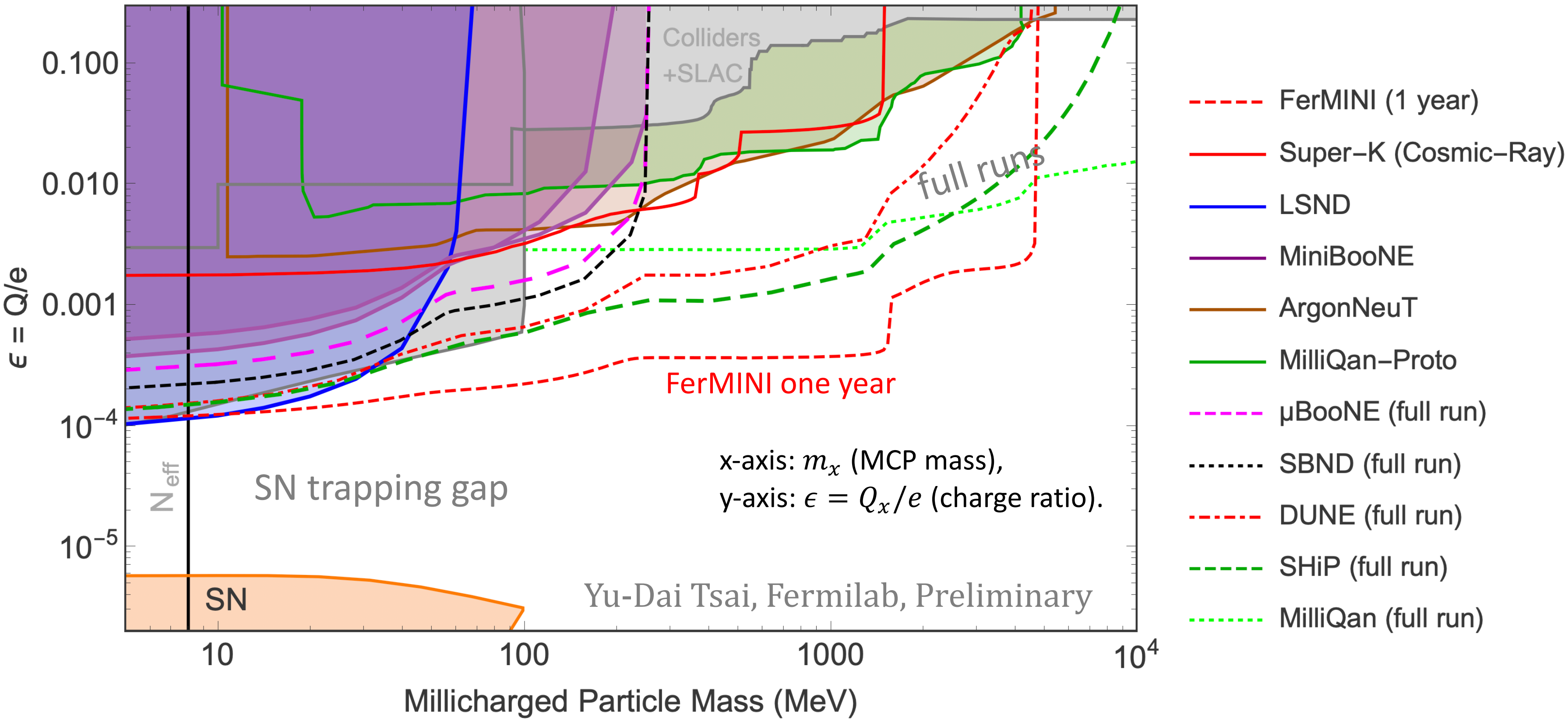
Joe Bramante
Queen’s U

Bithika Jain
ICTP-SAIFR

Broader Message

1. **LHC** entering **long shutdown**
2. **NuMI (and other beams) operating**, shutting down in 5 years
3. **Broadening the physics case for fixed-target facilities**
4. **DUNE near detector design** underway
5. Can develop at NuMI/MINOS and then move to DUNE
6. don't have to wait for HL-LHC
7. **New low-cost detectors? Fermilab + CERN collaboration?**
8. Synergy between **dark matter**, **neutrino**, and **collider** community.
   (contact ytsai@fnal.gov)

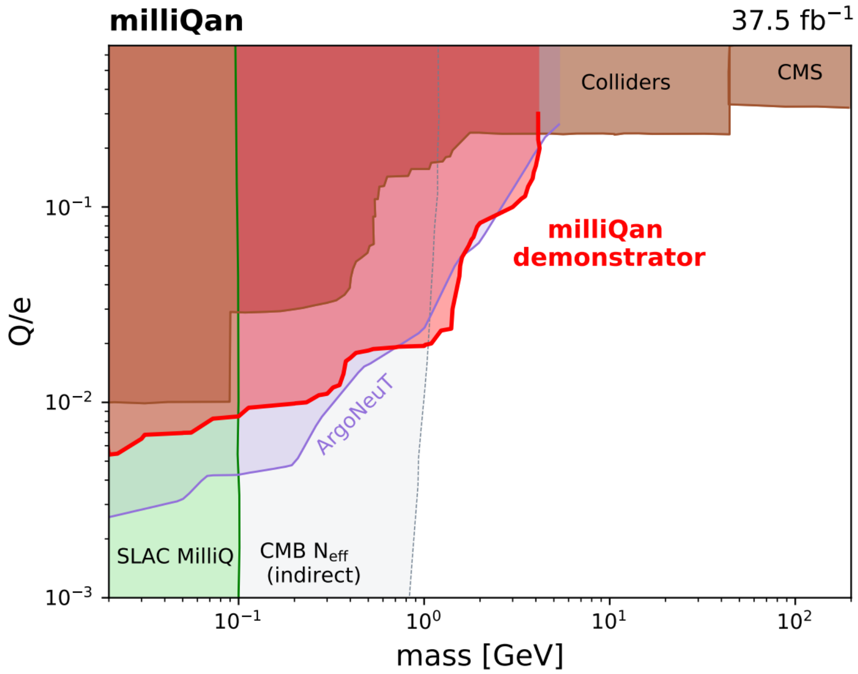
Compilation of MCP Probes

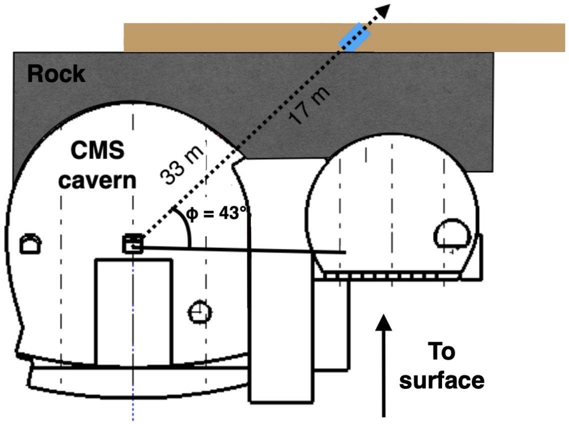


x-axis: m_x (MCP mass),
y-axis: $\epsilon = Q_x/e$ (charge ratio).

- One can **combine the FerMINI with neutrino detector** to improve sensitivity or reduce background
- Filling up the MCP "cavity". **One new probe soon on arXiv!**

Proto-milliQan Update!



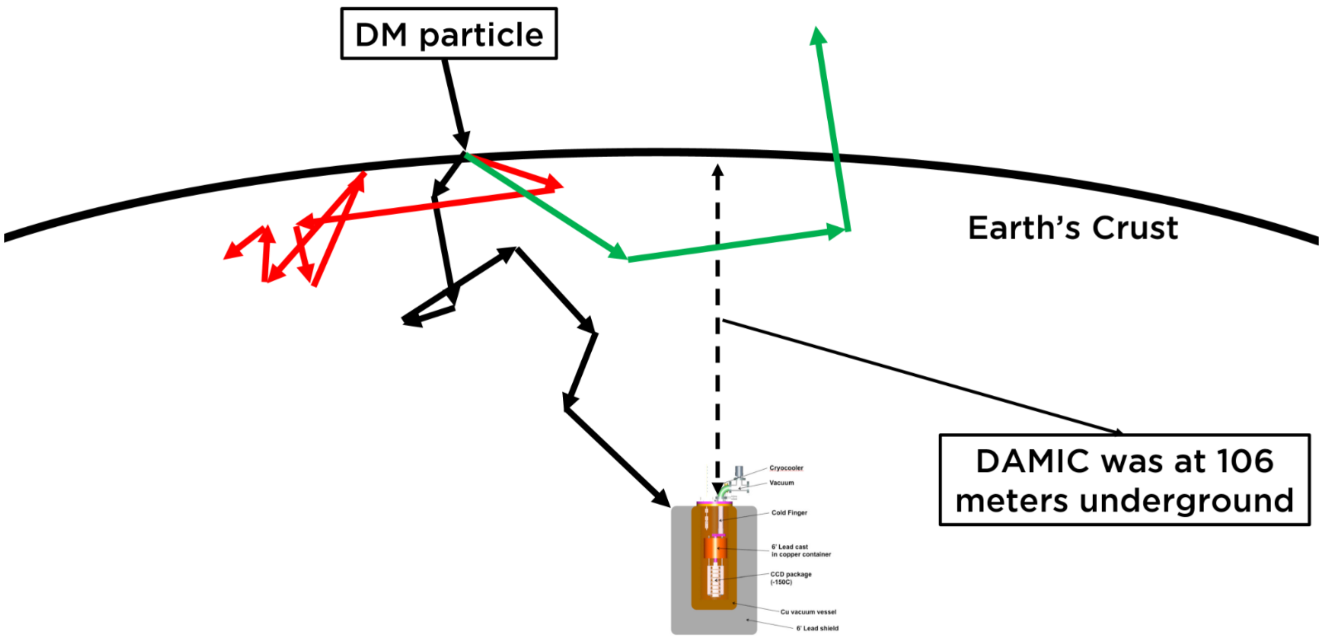


MilliQan prototype: updates on the results
https://arxiv.org/pdf/2005.06518.pdf
(milliQan Collaboration)

- ~1% of the full milliQan (total of 18 bars)
- LHC ’18 of 37.5 fb−1 at a center-of-mass energy of 13 TeV.
- A prototype scintillator-based detector is deployed to conduct the first search at a hadron collider
- 20 and 4700 MeV is excluded at 95% confidence level for charges between 0.006e and 0.3e

Strongly Interacting Dark Matter

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



DM particle

Earth’s Crust

DAMIC was at 106 meters underground

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.

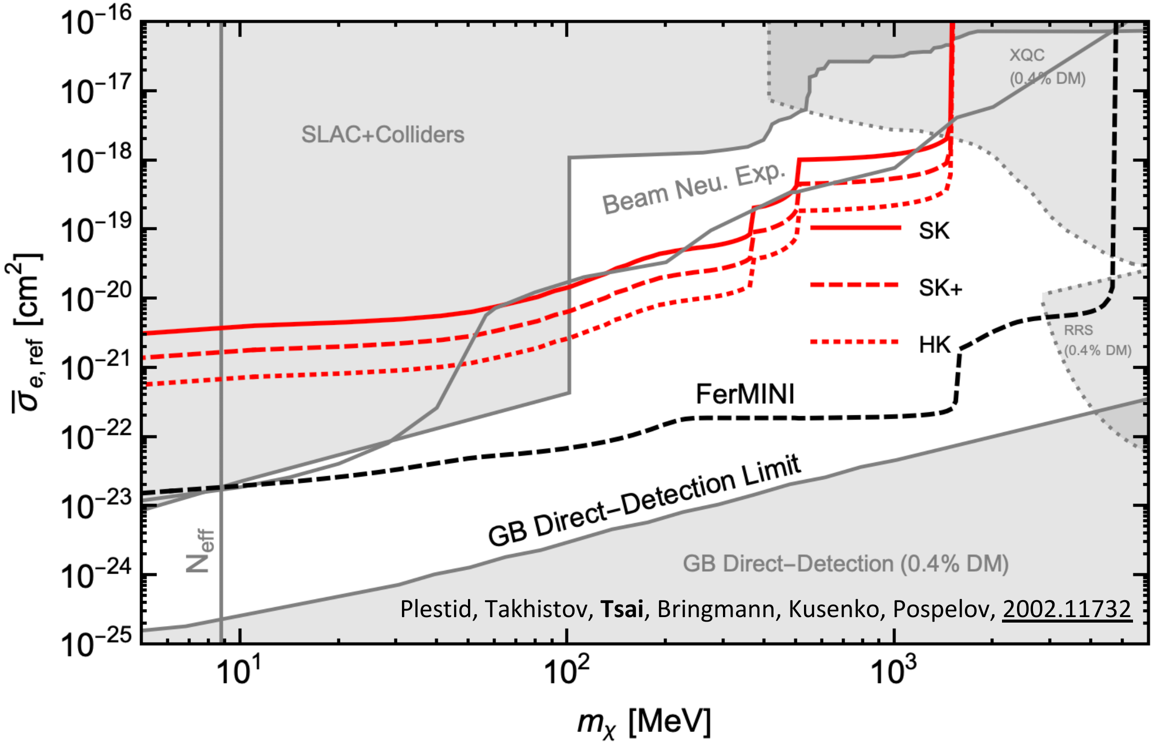
- **This just is a normalization**! Can choose the other one for comparison

- Comparing to e.g. **SENSEI, CDMS-HVeV, XENON10, XENON100, and DarkSide-50**

FerMINI Probe of Millicharged SIDM

MCP / LDM with ultralight dark photon mediators

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

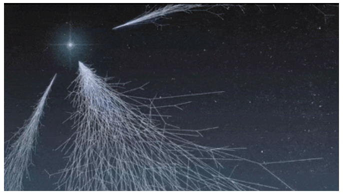


Plestid, Takhistov, **Tsai**, Bringmann, Kusenko, Pospelov, 2002.11732

- Here we plot the **electron-scattering Millicharged SIDM** see 1905.06348 (Emken, Essig, Kouvaris, Sholapurkar)
- Cosmic-Ray Production/Super-K Detection 2002.11732 (our paper)
- **FerMINI can help close the Millicharged SIDM window!**

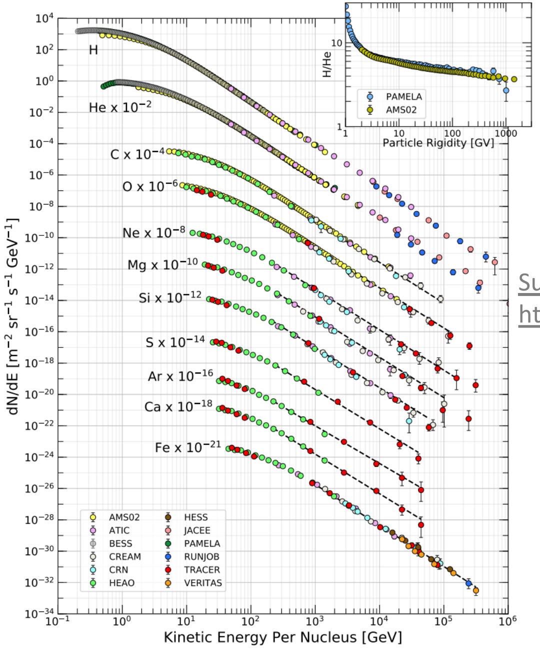
Yu-Dai Tsai,
Fermilab

MCP in Neutrino Observatories



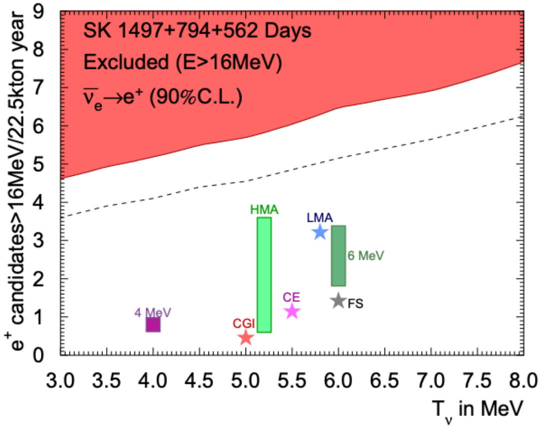
by Chantelauze, Staffi, and Bret

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

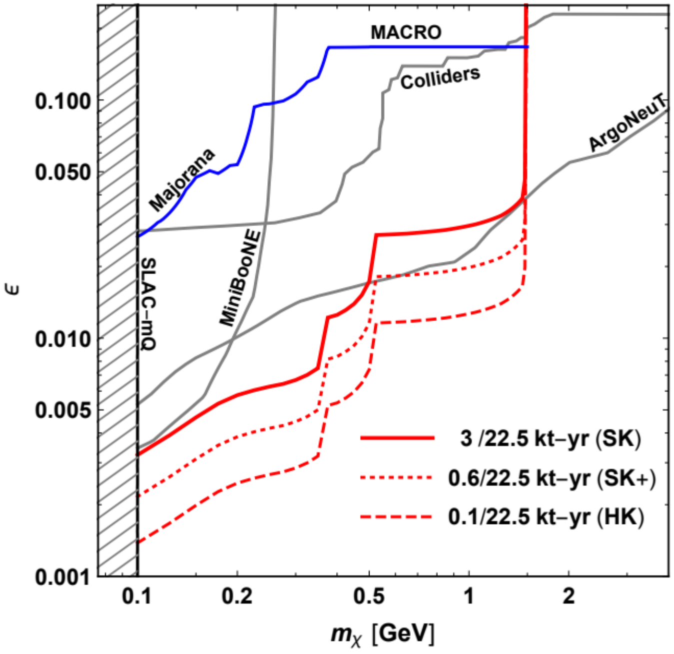


PDG, RPP, 2019

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

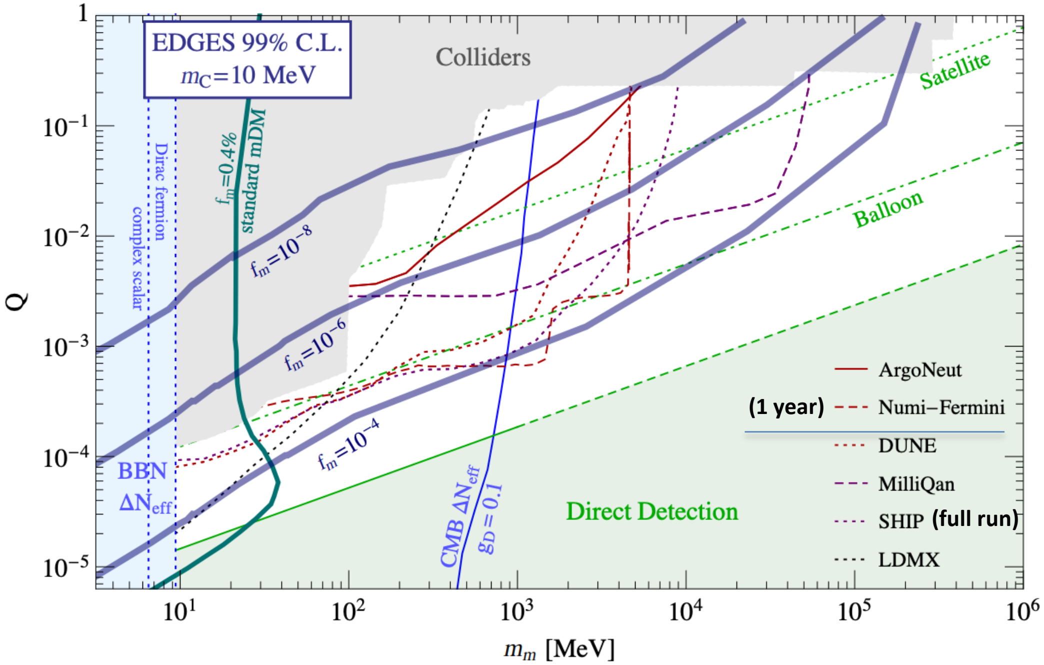


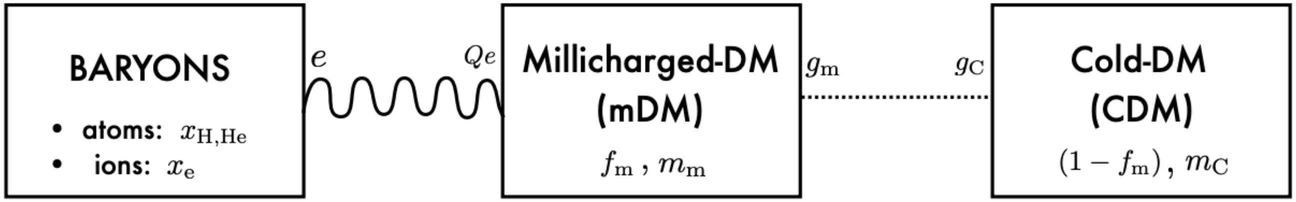
1111.5031 (Super-K Collaboration)



2002.11732 (our paper)
+ FerMINI projection

Reviving MDM for EDGES





BARYONS

- atoms: $x_{\rm H,He}$
- ions: $x_{\rm e}$

e Qe

Millicharged-DM (mDM)

$f_{\rm m}$, $m_{\rm m}$

$g_{\rm m}$ $g_{\rm C}$

Cold-DM (CDM)

$(1 - f_{\rm m})$, $m_{\rm C}$

Liu, Outmezguine, Redigolo, Volansky, ‘19

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.

Looking Ahead

- Exploring **Energy Frontier of the Intensity Frontier: Fixed-Target Exp.** (complementary to and **before HL-LHC upgrade**)
- **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)

Thank you!
Special thanks to the organizers
Gaia, Diego, and Simon