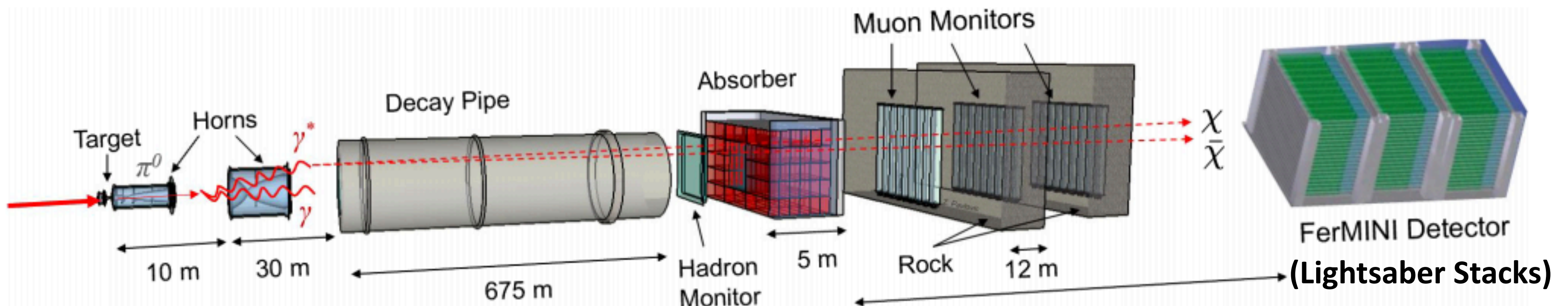


Kelly, Tsai, 1812.03998; Graph: Pavlovic + Tsai '19

Millicharged Dark Sectors from Fixed-Target and Cosmic-Ray Productions

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

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

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

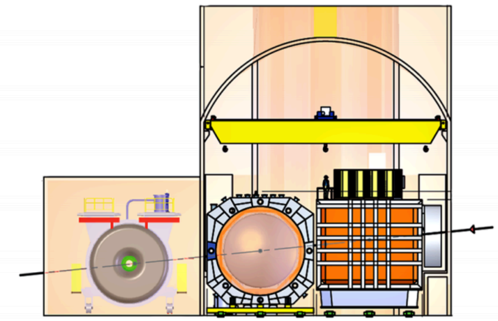
[3] Cosmic-ray Produced MCPs in Neutrino Observatories (2002.11732, **NEW**)

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

Our Three Ways to Produce/Study MCPs

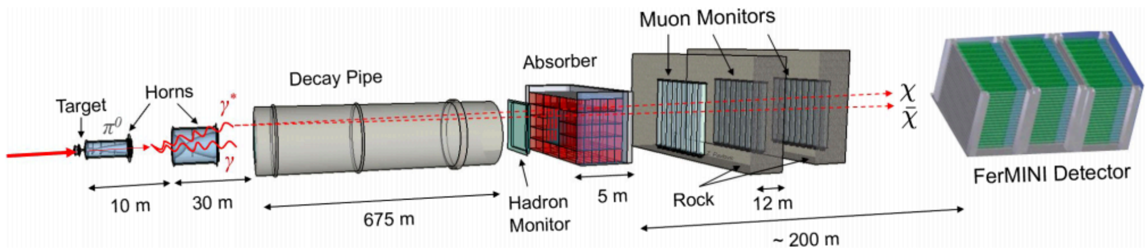
More reference shown in following slides!

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



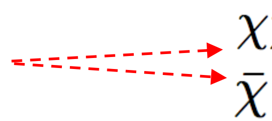
arXiv:2002.02967, **DUNE TDR V - I**

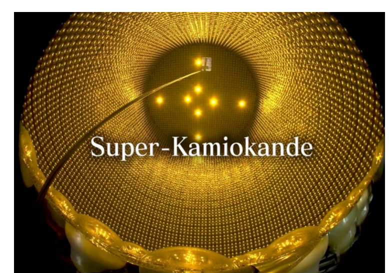
(II) Fixed-target produced MCP detected by specialized detector (FerMINI), 1812.03998



(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

Outline

- **Intro**
- **MCP in Neutrino Experiments**
- Specialized experiment: **FerMINI**
- **Cosmic-Ray** Production and Neutrino Observatories
- **Strongly Interacting Dark Matter**
- Why **study dark-sector direct production?**

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)
- Link to **string compactification** and **quantum gravity** (Shiu, Soler, Ye, PRL '13)
- Testing if **e/3 is the minimal charge**
- MCP could have natural link to **dark sector** (dark photon, etc)
- Could account for **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

MCP Model

- A particle fractionally charged under SM U(1) hypercharge

$$\mathcal{L}_{\rm MCP} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\rm MCP})\chi$$

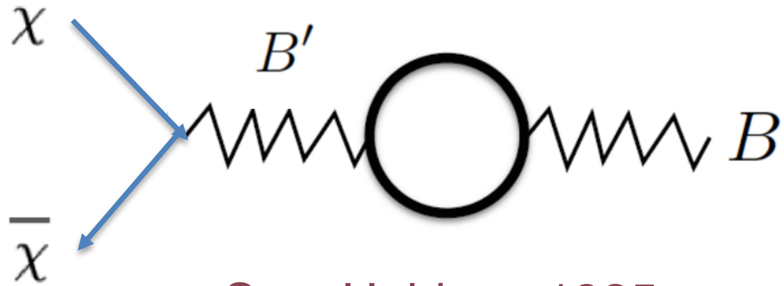
- Can just consider these Lagrangian terms by themselves (no extra mediator, i.e., dark photon). **Completely legal**! Naively violating the empirical charge quantization (cool!).

- We are only probing **MCP** here! **Minimal assumptions. Most robust constraints.**

- This could be from vector portal **Kinetic Mixing** (Holdom, '85)
  - a nice origin to the above term
  - 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

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

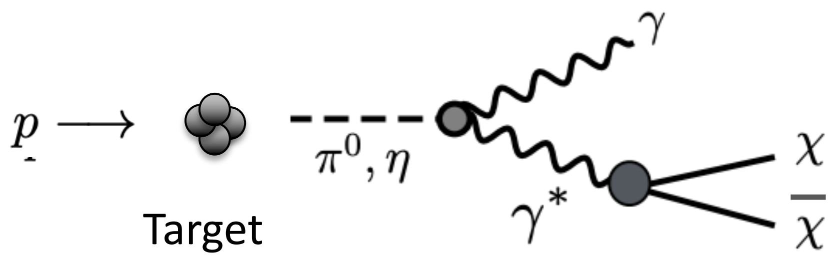
- New fermion χ charged under new gauge boson B'.

- 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.)

Millicharged Particle: Signature

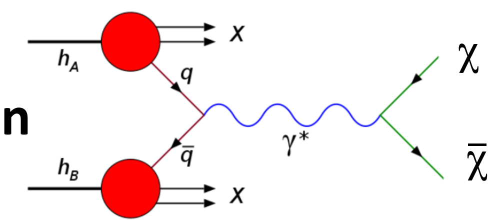
Production of MCP

- ❑ **Production: Meson Decays**

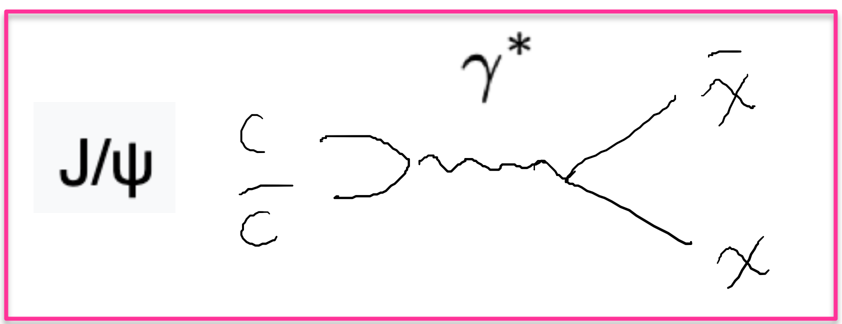


Modified from 1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

- ❑ **Production: Drell-Yan**



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



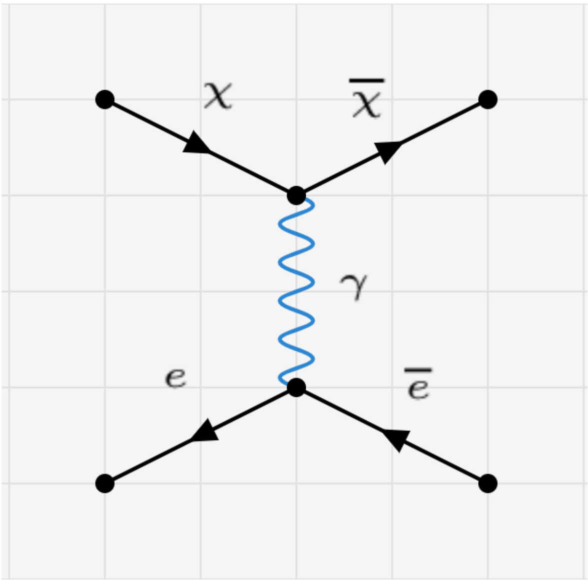
BR($\pi^0 \to 2\gamma$) = 0.99

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 Detection: Ionization or “Hard” Scattering



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

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

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

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

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

MCP Detection: Electron Scattering & Ionization

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

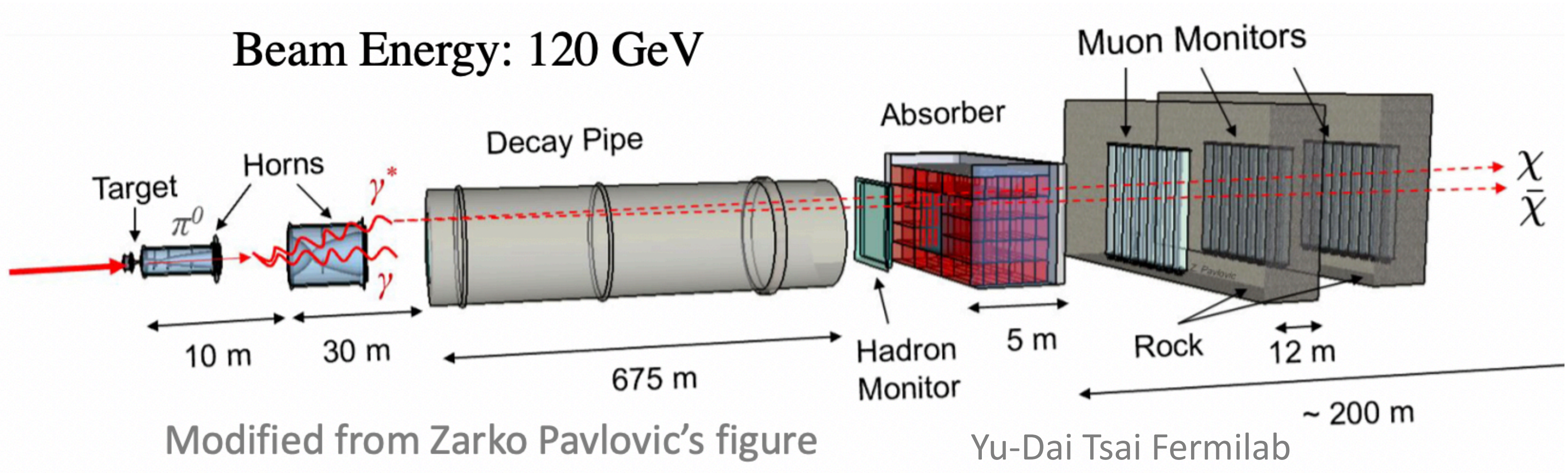
- lab frame: $Q^2 = 2m_e\,(E_e - m_e)$, $E_e - m_e$ is the electron recoil energy.
- Expressed in **recoil energy threshold**, ${E_e}^{(min)}$, we have

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

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

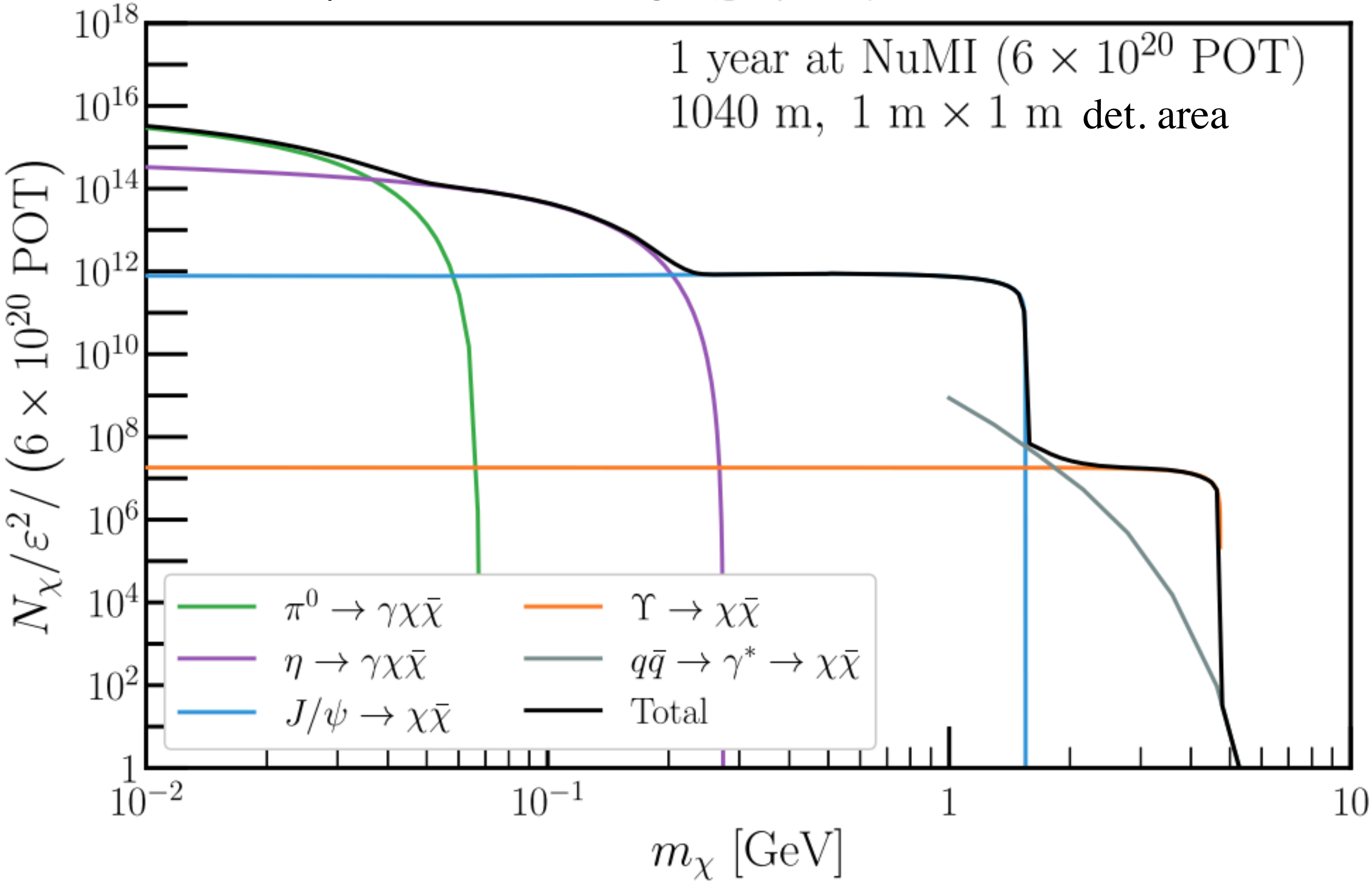
MCP in Fix-Target Neutrino Experiment

MCP Produced in Fixed-Target Experiments

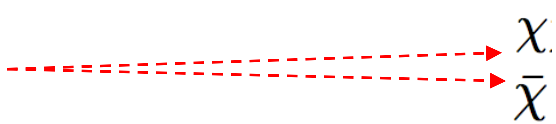


MCP Production/Flux

120 GeV proton beam on target (graphite)

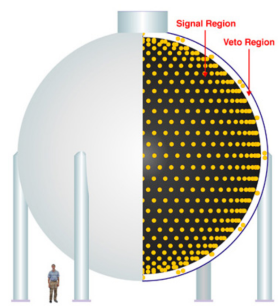


Scattering Detectors



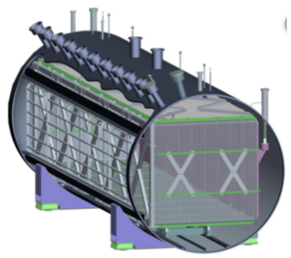
Other beams:
- BNB
- LBNF (future)

MiniBooNE Detector



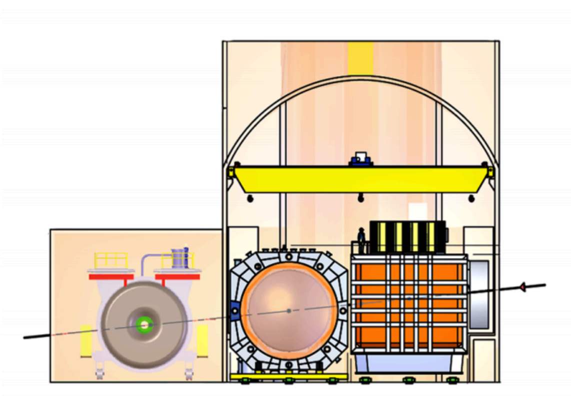
arXiv:0806.4201
MiniBooNE collaboration

MicroBooNE Detector



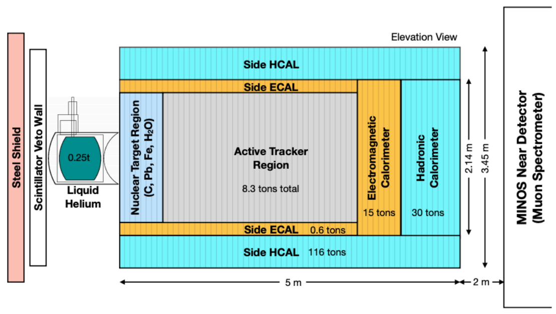
arXiv:1612.05824
MicroBooNE collaboration

DUNE Near Detector



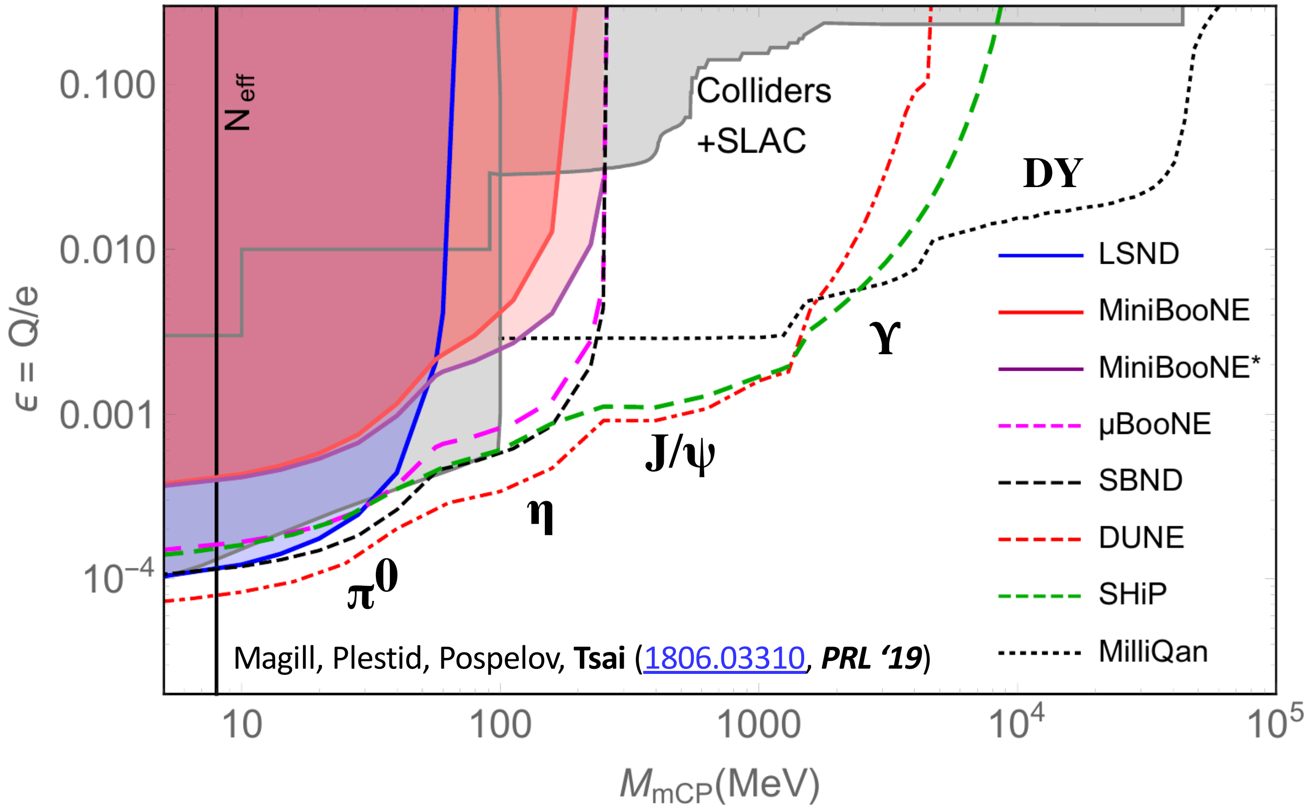
arXiv:2002.02967, DUNE TDR V - I

MINERvA Detector



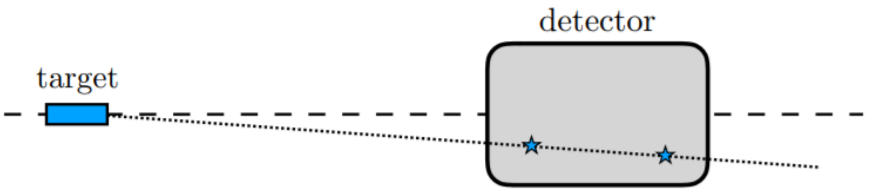
arXiv:1109.2855
MINERvA collaboration

Sensitivity at Neutrino Detectors



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

Double-Hit Consideration: ArgoNeuT Study



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

FerMINI:
A specialized scattering detector

FerMINI Collaboration (BRN proposal)

Chris Hill
OSU

Andy Haas
NYU

Jim Hirschauer
Fermilab

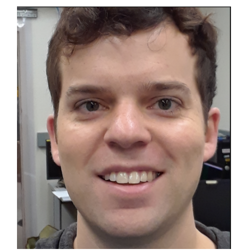
David Miller
U Chicago

David Stuart
UCSB

Zarko Pavlovic
Fermilab

Yu-Dai Tsai
Fermilab/U.Chicago

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

Subsection Outline

- Motivations of Millicharged Particle (MCP)
- **The FerMINI Experiment:**

  Proton Fixed-Target Scintillation Experiment to

  Search for Minicharged Particles
- FerMINI as a probe of **Strongly Interacting Dark Matter**

FerMINI

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

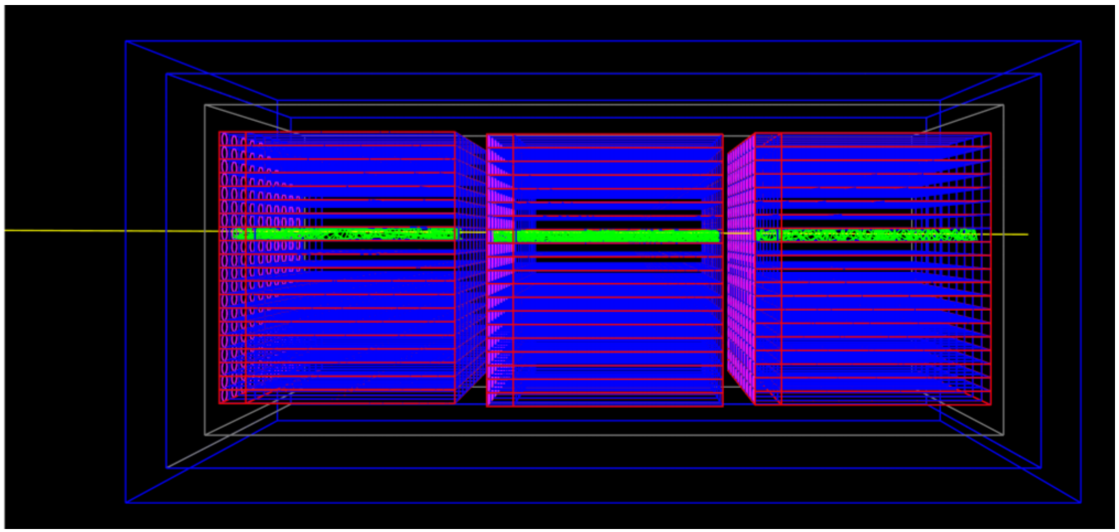
Directly inspired by milliQan concept (Haas, Hill, Izaguirre, Yavin, 1410.6816)

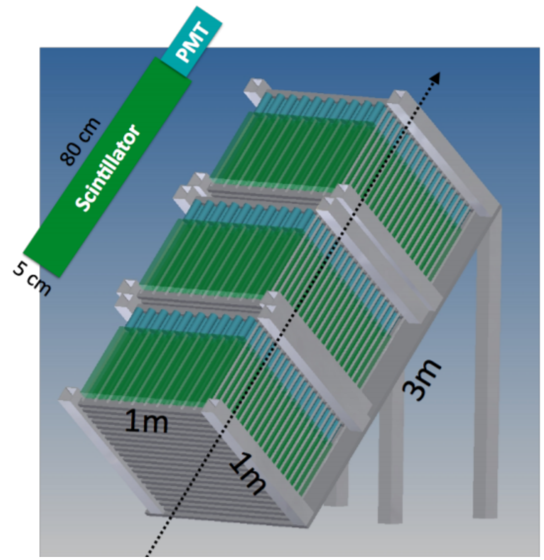
Visually "a detector made of stacks of light sabers,"

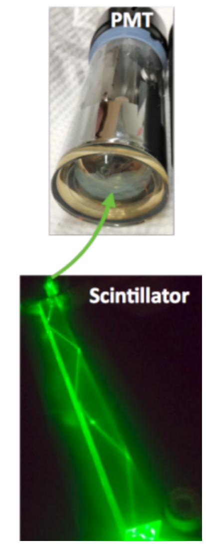
can potentially probe other new-physics scenarios like **small-electric-dipole dark fermions**, or **quirks**, etc

Detector Concept

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







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

Photoelectrons (PE) from Scintillation

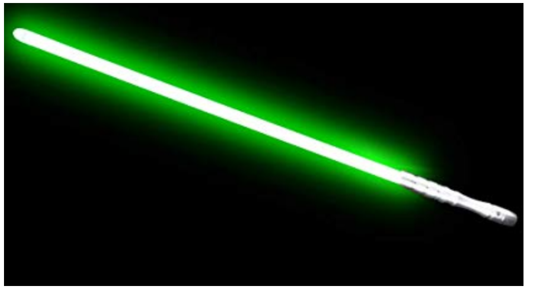
- **The averaged number of photoelectron (PE)** seen by the detector from single MCP is:

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

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

One can use **Bethe-Bloch Formula** to get a good approximation

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



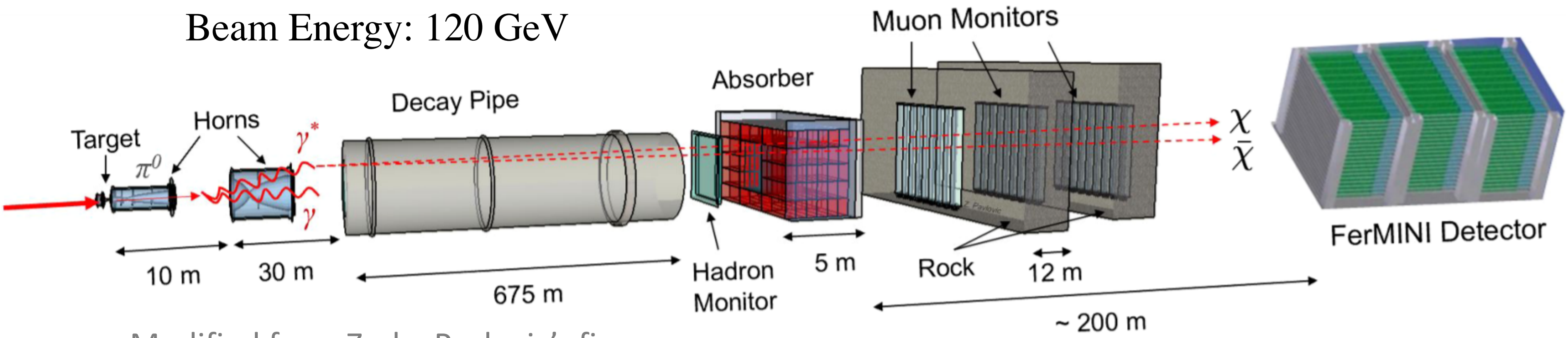
Signature: Triple Coincidence

- 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.**

FerMINI @ NuMI-MINOS Hall



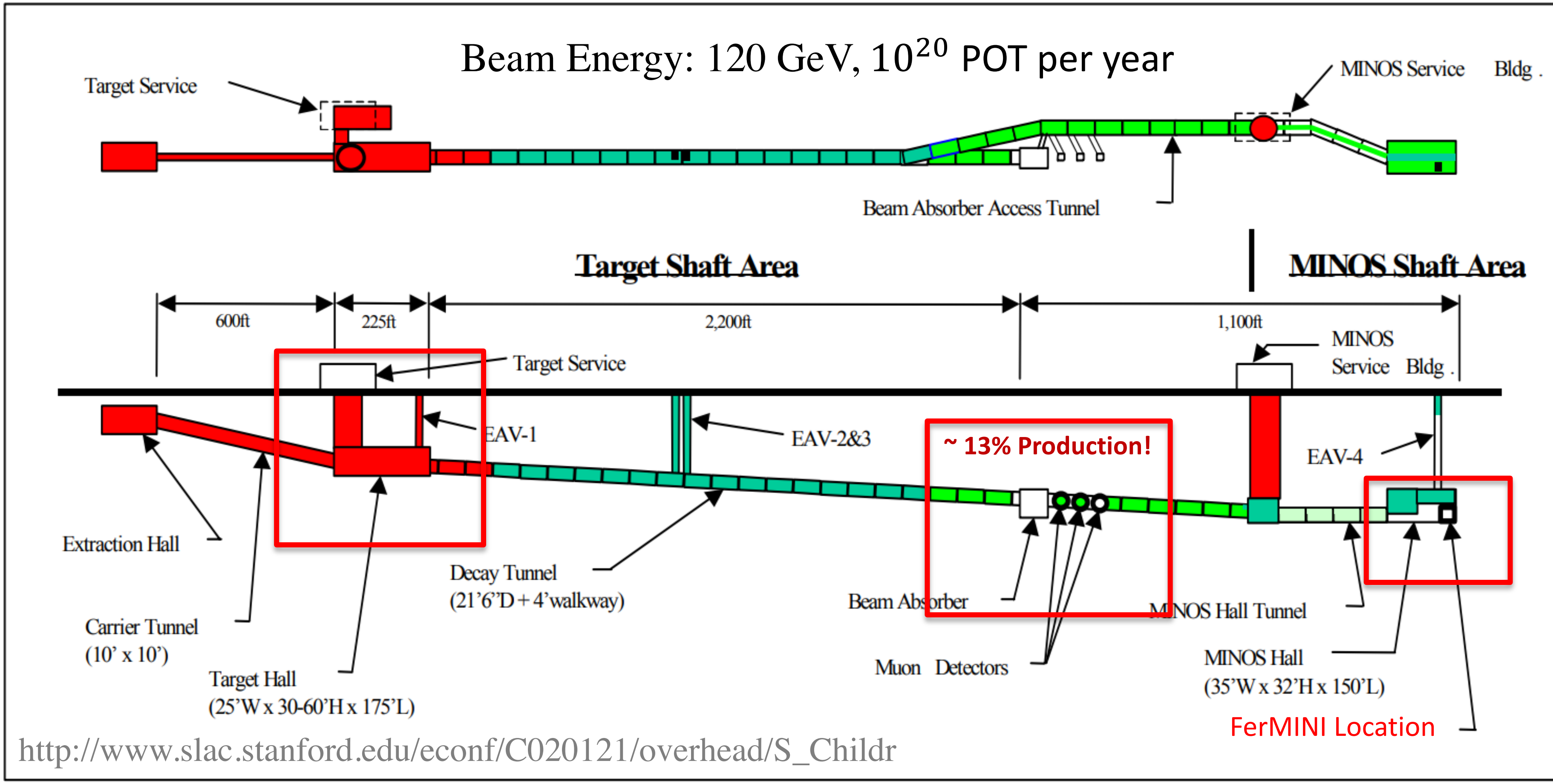
Modified from Zarko Pavlovic's figure

An illustration of the FerMINI experiments utilizing the NuMI facility.

MINOS hall downstream of NuMI beam

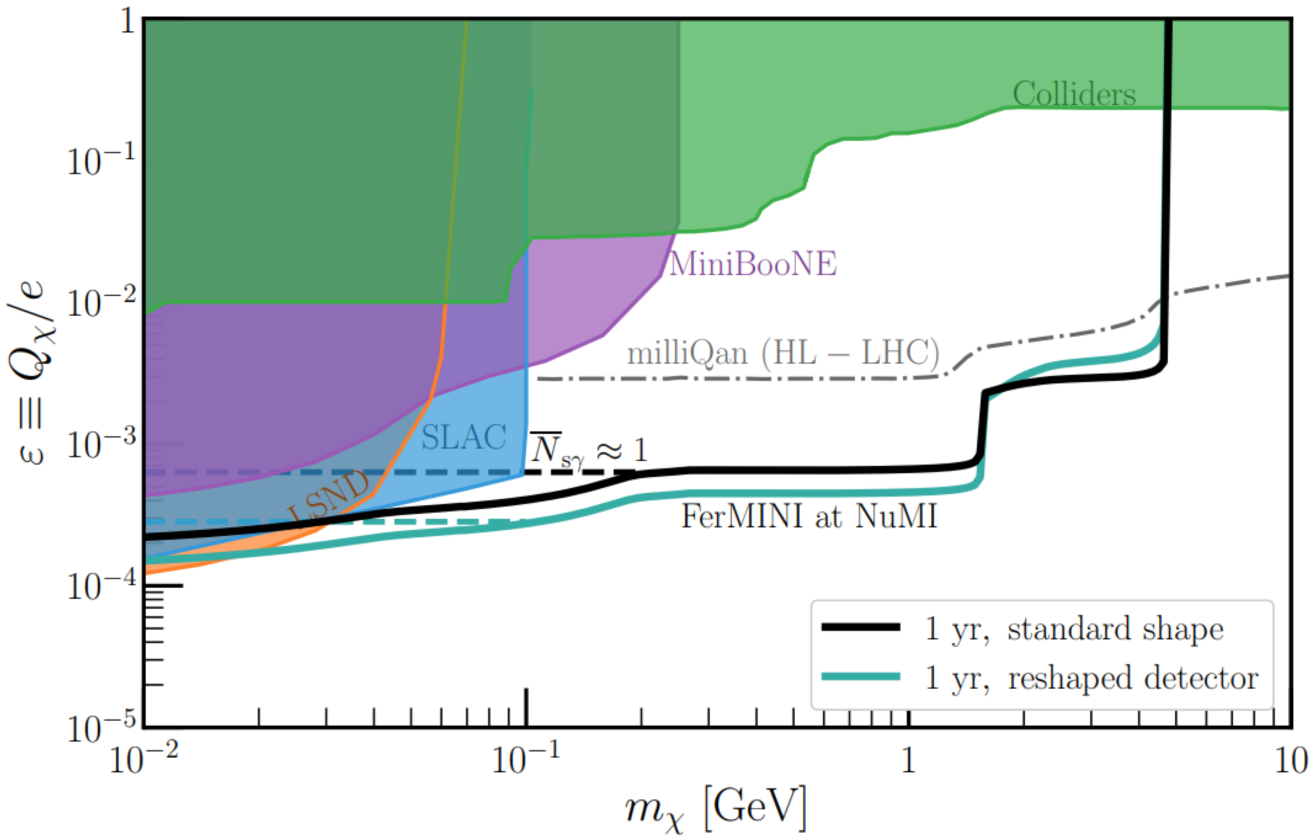
Yu-Dai Tsai
Fermilab

Site 1: NuMI Beam & MINOS ND Hall



NuMI: Neutrinos at the Main Injector
MINOS: Main Injector Neutrino Oscillation Search, ND: Near Detector

FerMINI @ MINOS

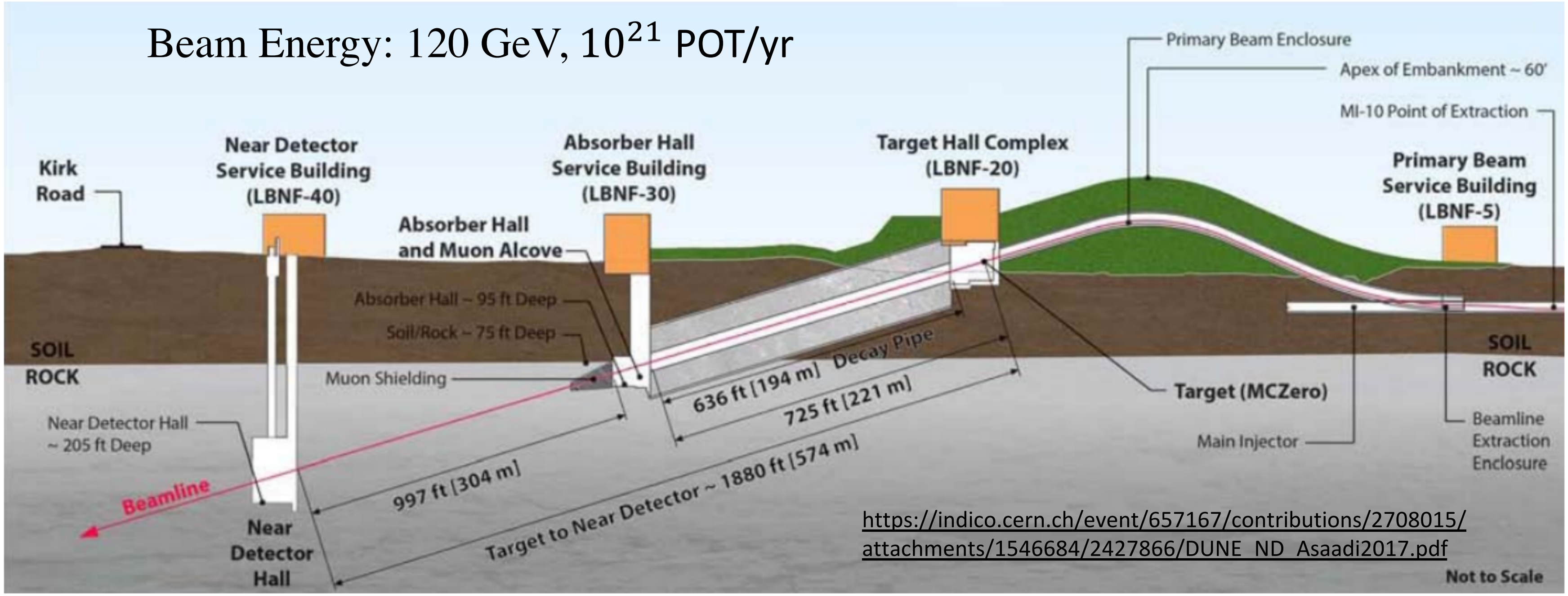


Yu-Dai Tsai, Fermilab

Different epsilon now, *ε*=Q/e

Now it's literally fraction of the charge!

Site 2: LBNF Beam & DUNE ND Hall



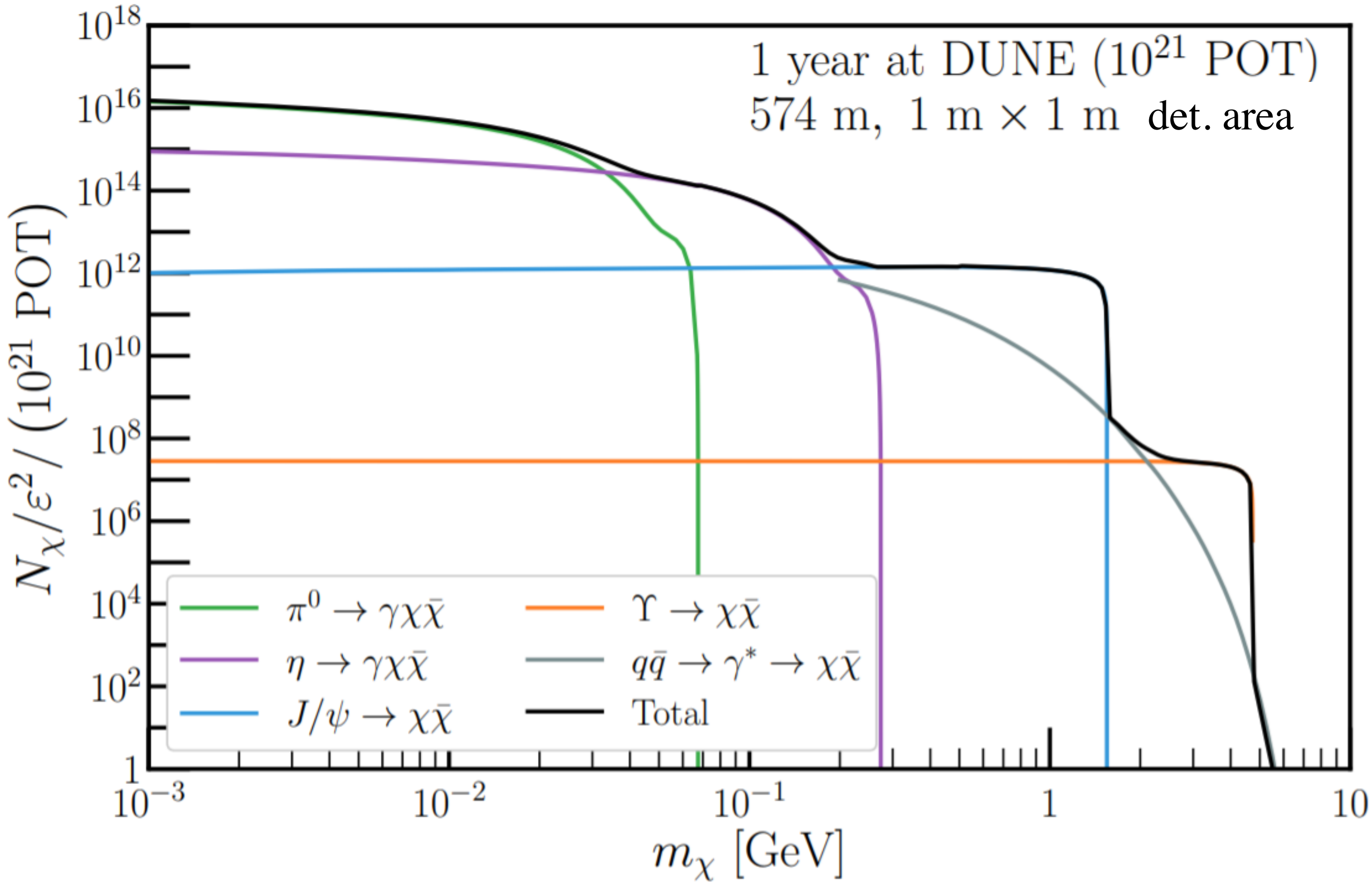
Jonathan Asaadi – University of Texas Arlington

LBNF: Long-Baseline Neutrino Facility

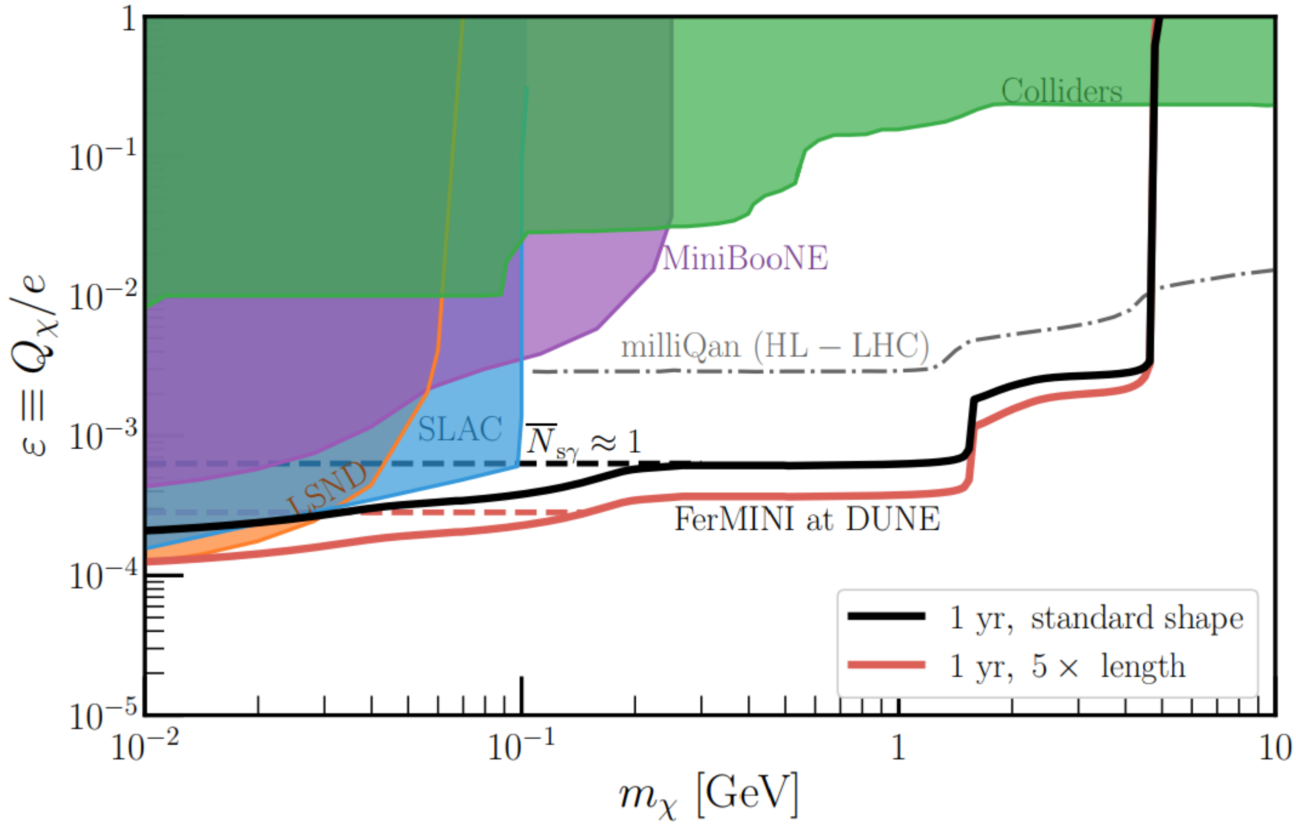
There are many other **new physics opportunities** in the **near detector hall**! Combine with **DUNE PRISM**?

MCP Production/Flux

120 GeV proton beam on target (graphite)



FerMINI @ DUNE



Yu-Dai Tsai,
Fermilab

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

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**

Dark Current Background @ PMT (may skip)

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

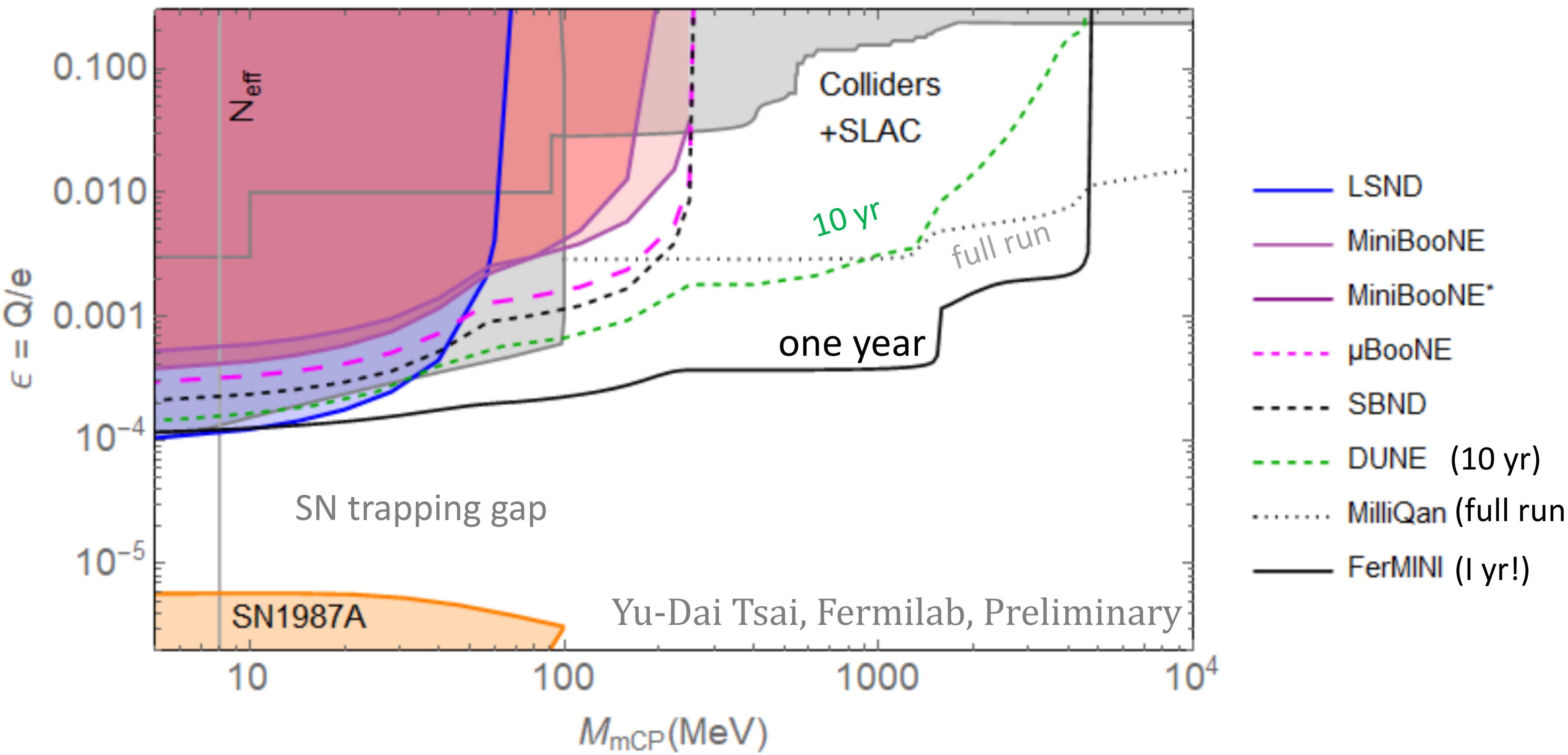
  v_B^3 **Δt^2 = 2.8 x 10^{-8} Hz**, for **Δt = 15 ns.**
- Consider 400 such PMT sets:

  the total background rate is 400 x 2.8 x 10^{-8} ~ 10^{-5} Hz
- **~ 300 events** in one year of trigger-live time
- **Quadruple coincidence can reduce this BG to essentially zero!**

Advantages of FerMINI: Timeliness, Low-cost, Movable, Tested, Easy to Implement, …

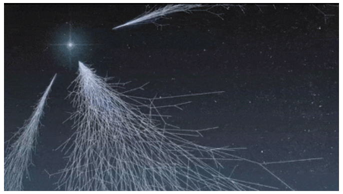
1. **LHC** entering **long shutdown**
2. **NuMI operating**, shutting down in 5 years
   (DO IT NOW! Fermilab! USA!)
3. Broadening the physics case for fixed-target facilities
4. **DUNE near detector design** still underway
5. Can develop at NuMI/MINOS and then move to DUNE
6. **Sensitivity better than milliQan for MCP up to 5 GeV** and don't have to wait for HL-LHC
7. Synergy between **dark matter**, **neutrino**, and **collider** community.
   (contact ytsai@fnal.gov)

Compilation of MCP Probes



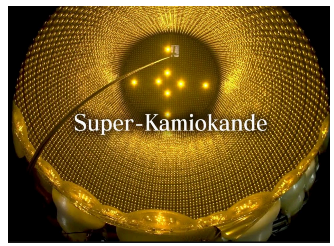
- One can **combine the MCP detector with neutrino detector** to improve sensitivity or reduce background
- Filling up the MCP "cavity"

MCP in Neutrino Observatories

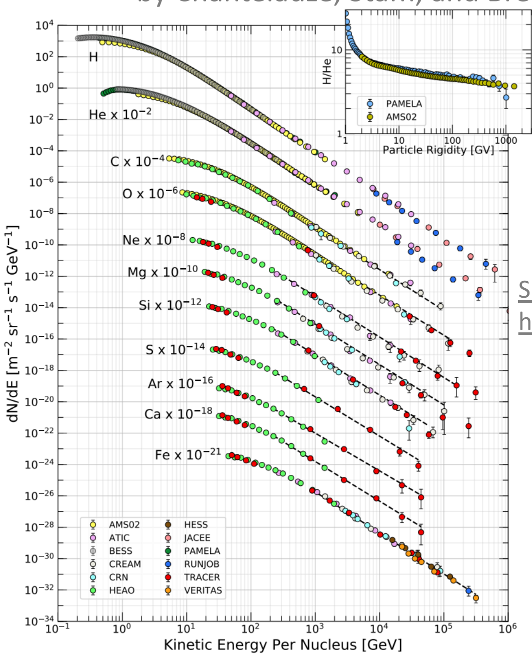


by Chantelauze, Staffi, and Bret

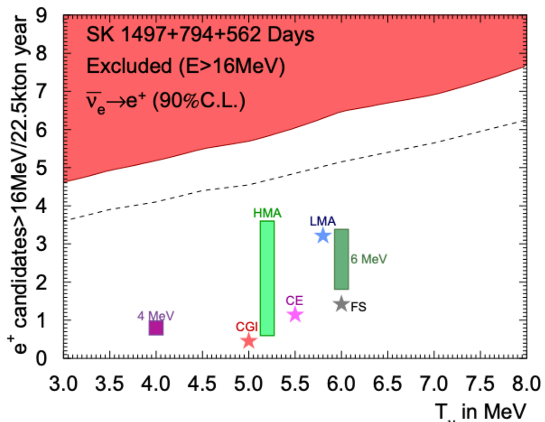
χ $\bar{\chi}$



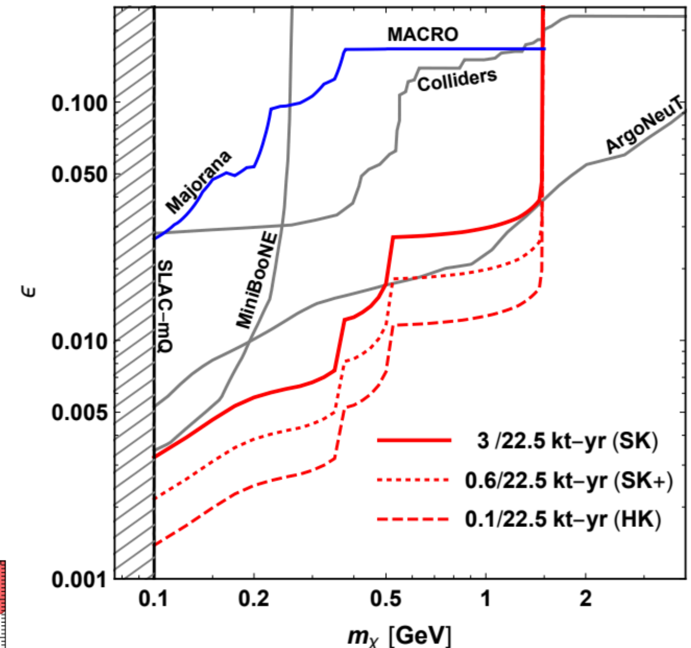
Super-K, http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html



PDG, RPP, 2019



1111.5031 (Super-K Collaboration)

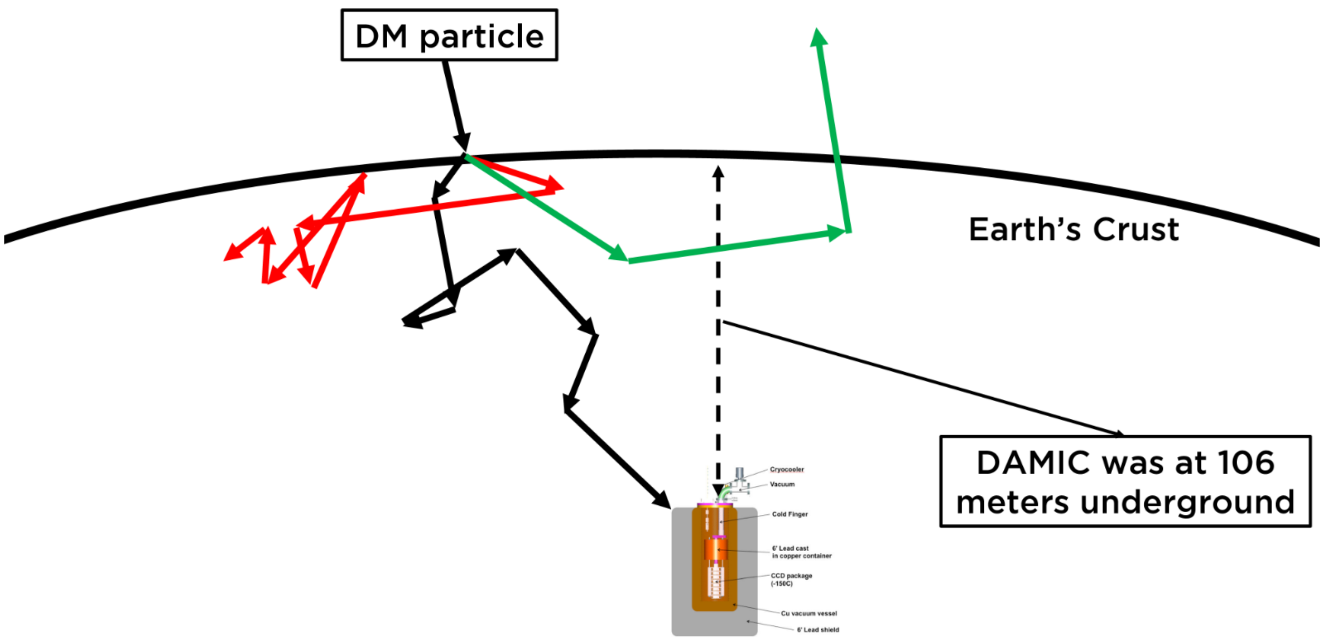


2002.11732 (our paper)
+ FerMINI projection

Yu-Dai Tsai
Fermilab

Strongly Interacting Dark Matter

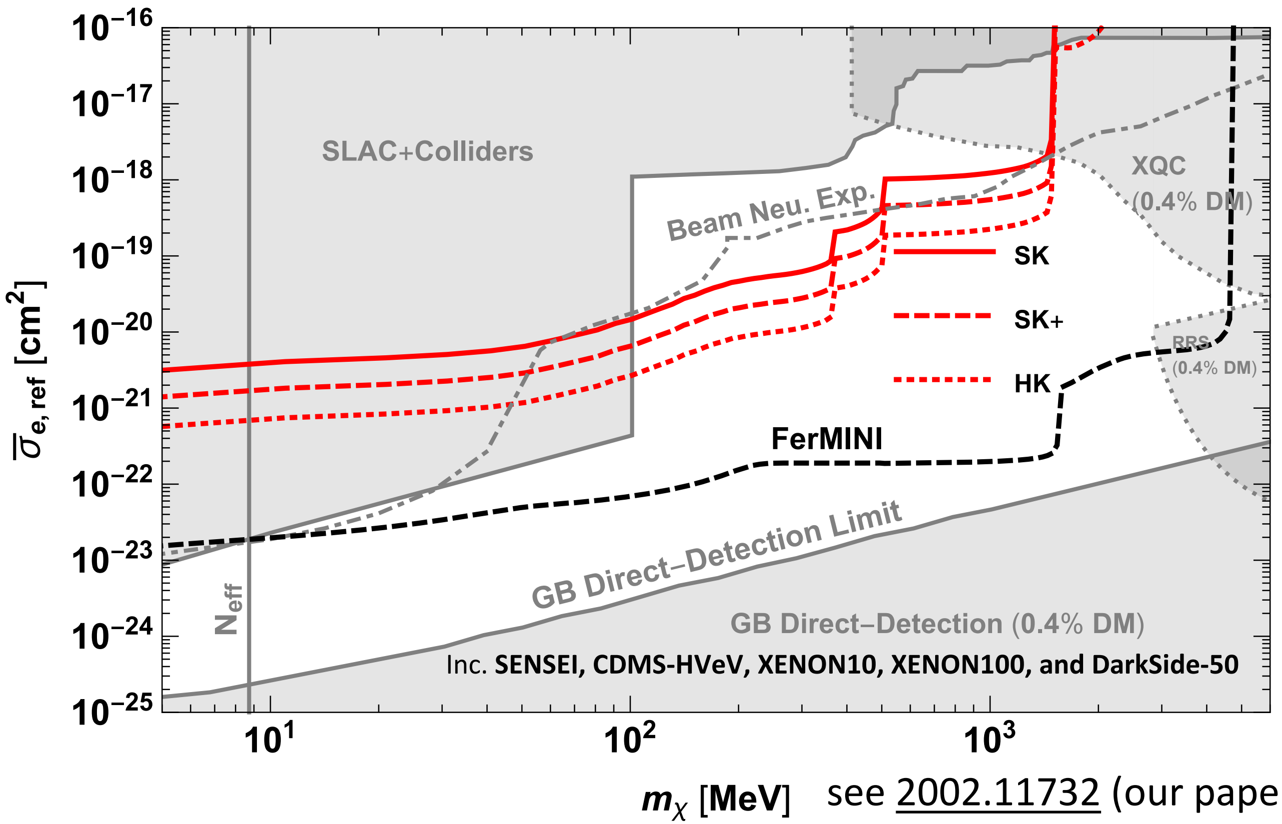
DM-SM Interaction too strong that attenuation stop the particles from reach the direct detection detector



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

FerMINI Probe of Millicharged SIDM

MCP / LDM with ultralight dark photon mediators, all curves except FerMINI are from arXiv:1905.06348



see 2002.11732 (our paper)

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

- Here we plot the **electron-scattering Millicharged SIDM** see 1905.06348 (Emken, Essig, Kouvaris, Sholapurkar)
- **FerMINI can help close the Millicharged SIDM window!**

Yu-Dai Tsai, Fermilab

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;

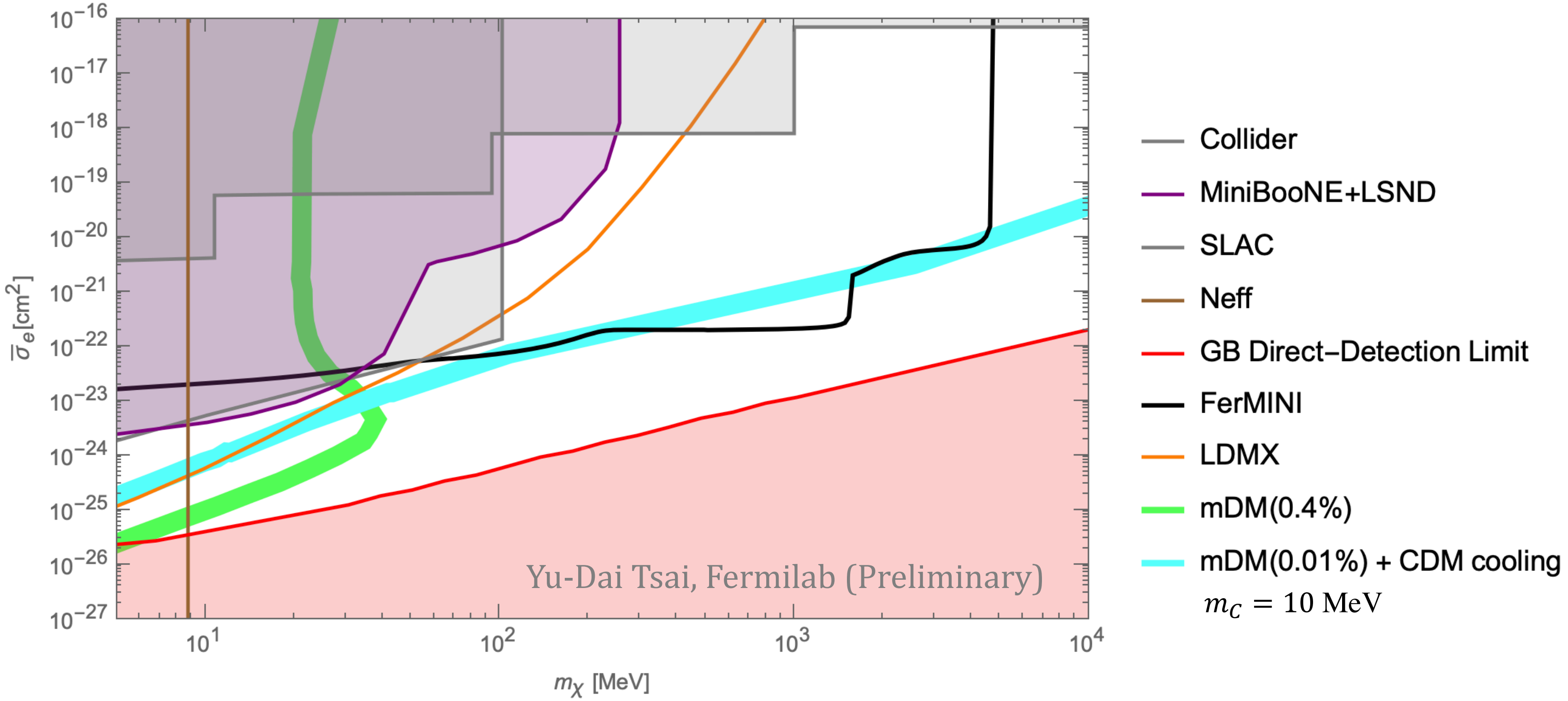
Kovetz, Poulin, Gluscevic, Boddy, Barkana, Kamionkowski, 1807.11482;

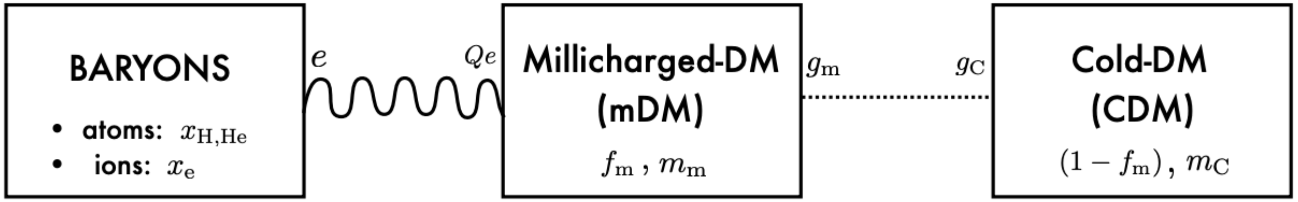
Liu, Outmezguine, Redigolo, Volansky, 1908.06986:

"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.

Reviving MDM for EDGES





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Liu, Outmezguine, Redigolo, Volansky, '19

Not all bounds are created with equal assumptions

→ Assumptions

Or, how likely is it that theorists would be able to argue our ways around them

Accelerator-based: Collider, **Fixed-Target Experiments**
Some other ground-based experiments

techinical ↓

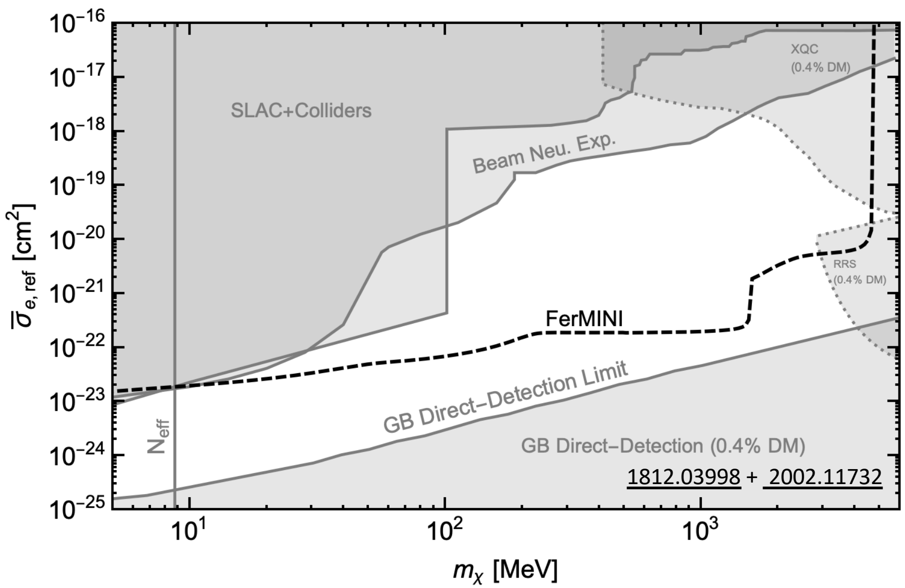
Astrophysical productions (not from ambient DM): energy loss/cooling, etc:
Rely on modeling/observations of (extreme/complicated/rare) systems (SN1987A & neutron-star mergers)

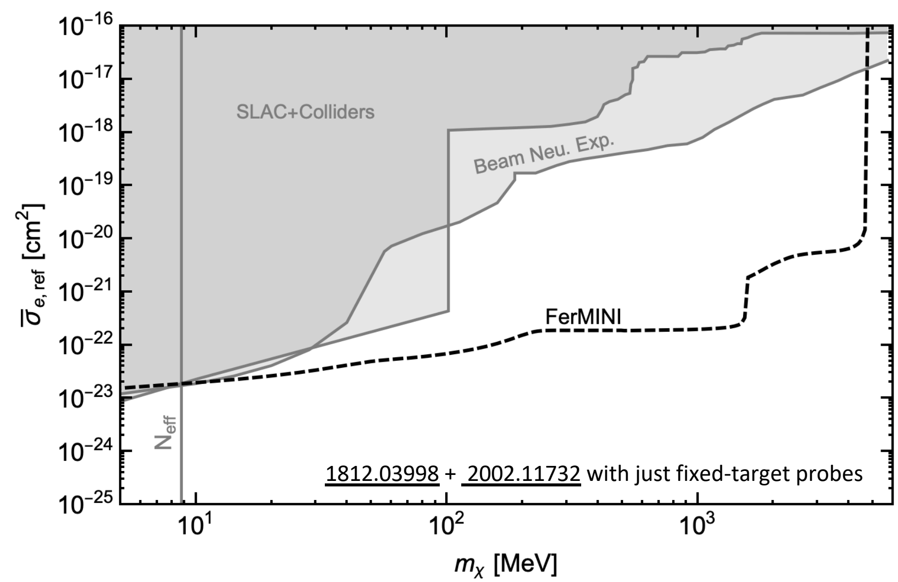
Dark matter direct/indirect detection: abundance, velocity distribution, etc

Cosmology: assume cosmological history, species, etc

} different

Example: Constraints on Millicharged Dark Matter





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

Looking Ahead

- Exploring **Energy Frontier of the Intensity Frontier** (complementary to and **before HL-LHC upgrade**)
- **Cosmology-driven models: relaxions, baryogenesis models**
- **other motivated models: quirks, KOTO-related models**
- Near-future (and almost free) opportunity (**NuMI Facility, SBN program, DUNE Near Detector**, etc.)
- Other new **low-cost alternatives/proposals (~ $1M)** to probe exotic stable particles **(FerMINI)** and new forces **(LongQuest)**
- **Dark sectors in neutrino observatories**

Thank You!

Backup Slides

Additional Motivations

- Won’t get into details, but it’s interesting to find **“pure” MCP, that is WITHOUT a massless or ultralight dark photon** (finding MCP in the regime where ultralight/massless A’ is strongly constrained by cosmology!)
- More **violent violation of the charge quantization** (if not generating millicharge through kinetic mixing)
- Test of **GUT models**, and **String Compactifications** see Shiu, Soler, Ye, arXiv:1302.5471, PRL ’13 for more detail.

Not all bounds are created with equal assumptions

→ Assumptions

Or, how likely is it that theorists would be able to argue our ways around them

Accelerator-based: Collider, **Fixed-Target Experiments**
Some other ground-based experiments

techinical ↓

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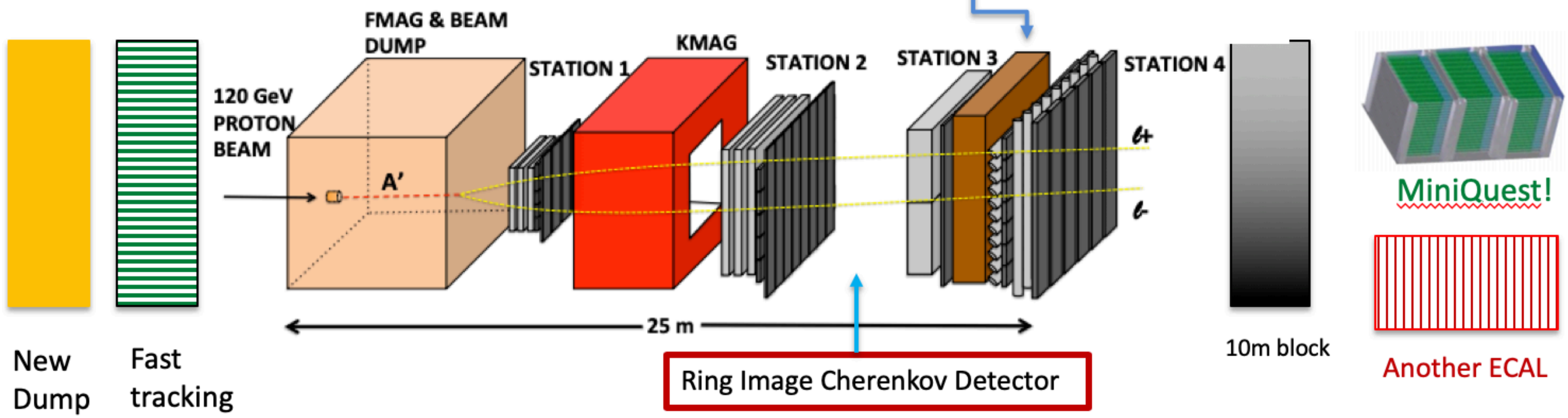
Tsai, de Niverville, Liu, 1908.07525, **LongQuest**



Gardner, Holt, Tadepalli, 1509.00050; Berlin, Gori, Schuster, Toro, 1804.00661, **DarkQuest**

Dark-Sector Searches at the High-Energy Intensity Frontier

Yu-Dai Tsai, Fermilab/U Chicago

[1] Dark photon, inelastic dark matter, muon g-2, and LongQuest (1908.07525)

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

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

[4] Cosmic-ray Produced MCPs in Neutrino Observatories (2002.11732, **NEW**)

Proton Fixed-Target: Decay vs Scattering Experiments

[5] **Light Scalar & Dark Photon** at BoreXino & LSND, 1706.00424, ***PLB '18***

(proton-charge radius anomaly) w/ Pospelov

[6] **Dipole Portal Heavy Neutral Lepton**, 1803.03262, ***PRD '18***

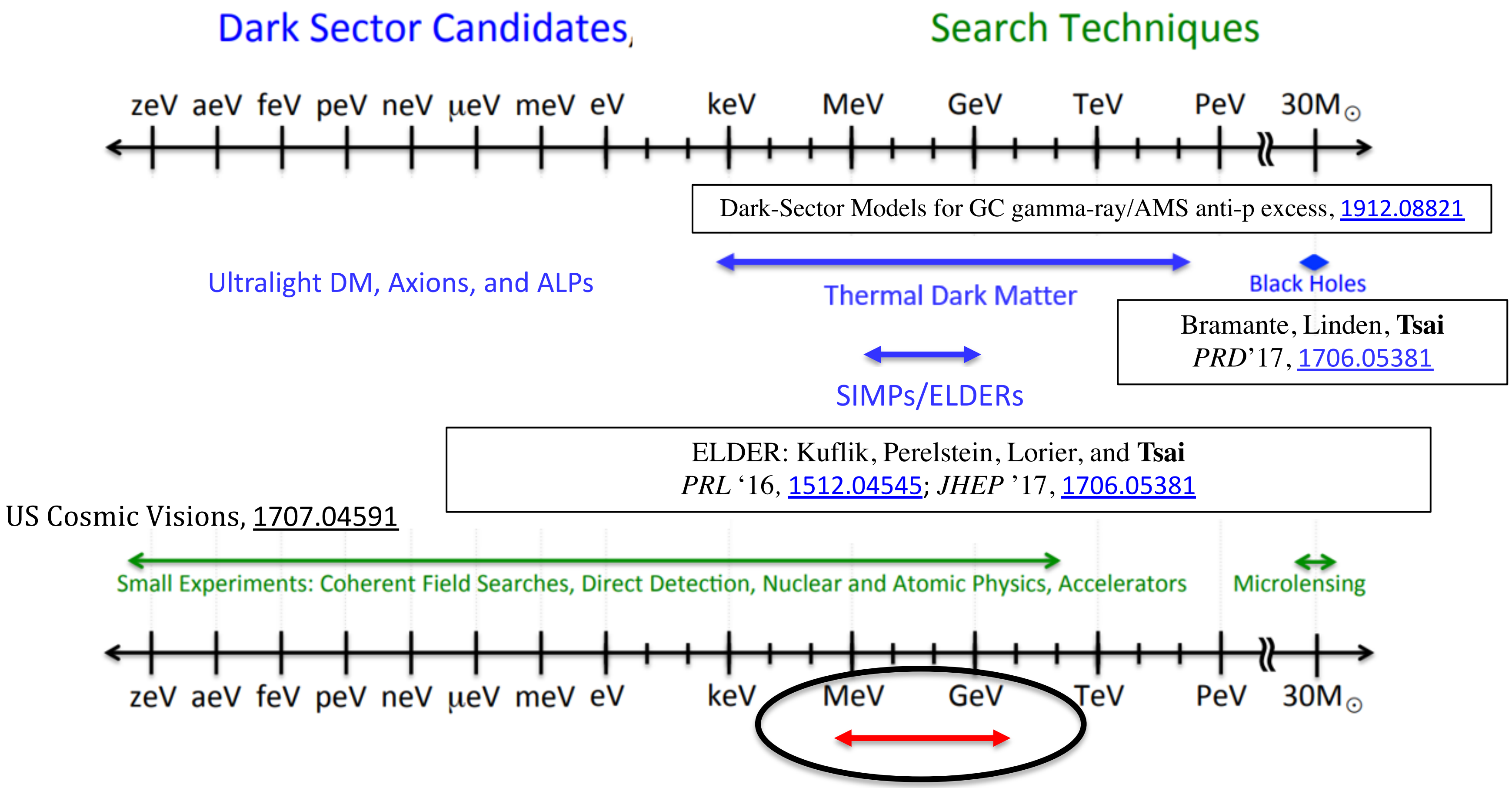
(LSND/MiniBooNE anomalies) w/ Magill, Plestid, Pospelov

[7] **Dark Neutrino** at Scattering Exps: CHARM-II & MINERvA, 1812.08768, ***PRL '19***

(MiniBooNE Anomaly) w/ Argüelles, Hostert

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

Exploration of Dark Matter & Mediator



- Resonant SIDM w/ Hitoshi+; Kinetic Decoupling DM w/. Tracy+ (in prep.)
- **Astrophysical/cosmological observations:** important to reveal the **actual story of dark matter (DM).**
- **Why fixed-target experiments? And why MeV – GeV+?**

Advantages of Proton Fixed-Target Exp.

Proton FT (& Neutrino) Experiments

- **High statistics**, e.g. LSND has $\mathbf{10^{23}}$ **Protons on Target** (POT)
- Neutrinos are **dark-sector particles**.
- Relatively high-energy proton beams on targets:

  O(100 – 400) GeV (I will compare Fermilab/CERN facilities)
- Shielded/underground: lower background
- Many of them existing and many to come:

  strength in numbers
- **Produce these particles with less assumptions**

Why study MeV – GeV+ dark sectors?

Revealing the dark secrets of the Universe

Signals of discoveries grow from anomalies

Maybe nature is telling us something so we don't have to search in the dark? (~~or probably systematics~~?)

Some anomalies involving **MeV - GeV+** Explanations

⋮

- **Muon g-2 anomaly**
- **LSND & MiniBooNE anomaly**
- **EDGES result**
- **KOTO anomaly**
- **Proton charge radius anomaly**
- **Beryllium anomaly**

⋮

Below ~ MeV there are also **strong astrophysical/cosmological bounds** that are hard to avoid even with very relaxed assumptions

ν Hopes for New Physics

⋮

Personal journey to study these scenarios

- **Proton charge radius anomaly:**

- Light Scalar & Dark Photon at Borexino & LSND, Pospelov, **Tsai**, PLB '18, 1706.00424

- **LSND/MiniBooNE Anomalies**

- Dipole Portal Heavy Neutral Lepton, Magill, Plestid, Pospelov, **Tsai**, PRD '18, 1803.03262
- Dark Neutrino at Scattering Experiments: CHARM-II & MINERvA Argüelles, Hostert, **Tsai**, *PRL '20*, 1812.08768

⋮

Fixed-Target for New Physics

- **EDGES 21-cm absorption spectrum anomaly**

- Millicharged Particles in Neutrino Experiments, Magill, Plestid, Pospelov & **Tsai**, PRL ‘19, 1806.03310
- FerMINI Experiment, Kelly & **Tsai**, PRD ’19, 1812.03998
- Cosmic-ray produced MCP in neutrino observatories, 2002.11732

- **Muon g-2 Anomaly**

Dark Photon, Inelastic Dark Matter, and Muon g-2 Windows in CHARM, NuCal, NA62, SeaQuest, and LongQuest, **Tsai**, de Niverville, Liu, 1908.07525

Happy to talk about these offline

⋮

The proton beam fixed-target facilities

that provide natural habitats for signals of
weakly interacting / long-lived / dark-sector particles

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: **FASER (forward)**: 10^{16} POT/yr, future much higher energy, very small detector

Decay Experiments/Detectors

Including **CHARM decay detector (DD), NuCAL, NA62, SeaQuest** (see, arXiv:1908.07525)

- Experiments optimized to study **decaying particles**, or simply two charged particle final states, e.g. from Drell-Yan (SeaQuest)

General features:

1. Large decay volume
2. Low density (likely vacuumed), low background
3. Simple design thus relatively low cost (tracking planes + ECal)
4. Often, there is external magnetic field
   (track separations/momentum reconstruction/filter-out soft SM radiation)
5. Usually studying **long-lived particles (mediators, e.g., dark photons)**