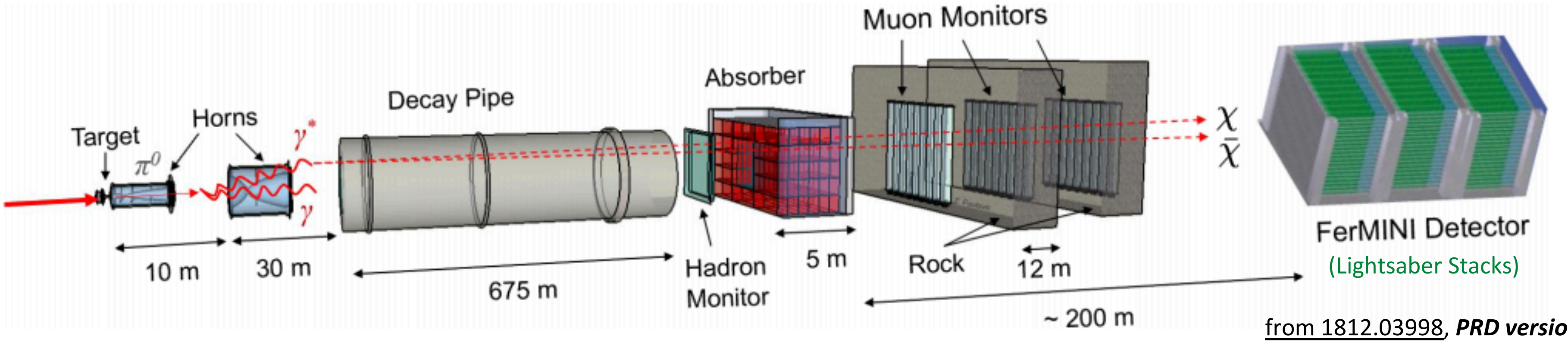


from 1812.03998, ***PRD version***

FerMINI - Fermilab Search for Millicharged Particle & Strongly Interacting Dark Matter

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

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

with Kelly (1812.03998, ***PRD '19***)

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

FerMINI Proposal DOE + LDRD (35 pgs)


Chris Hill
OSU


Andy Haas
NYU


Jim Hirschauer
Fermilab

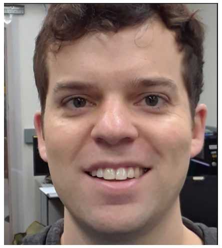

David Miller
U Chicago


David Stuart
UCSB


Zarko Pavlovic
Fermilab


Yu-Dai Tsai
Fermilab/U.Chicago


Cindy Joe
Fermilab


Ryan Heller
Fermilab

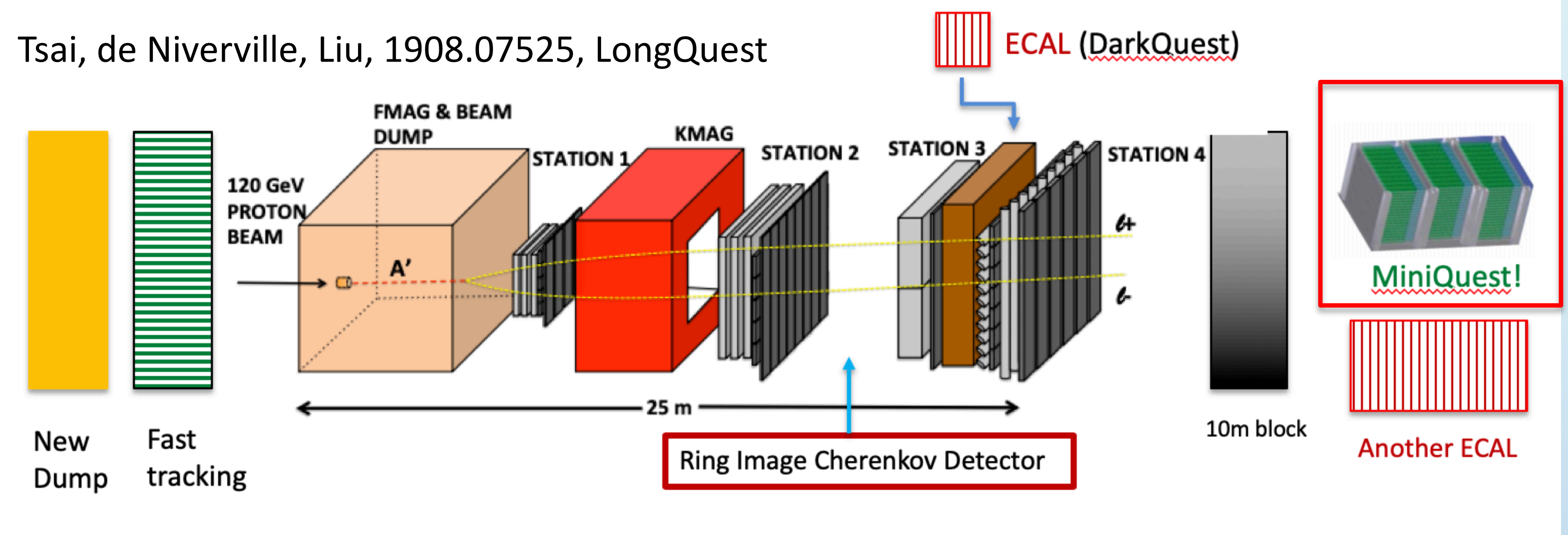

Maxim Pospelov
Minnesota / Perimeter


Ryan Plestid
McMaster


Albert de Roeck
CERN


Joe Bramante
Queen’s U


Bithika Jain
ICTP-SAIFR



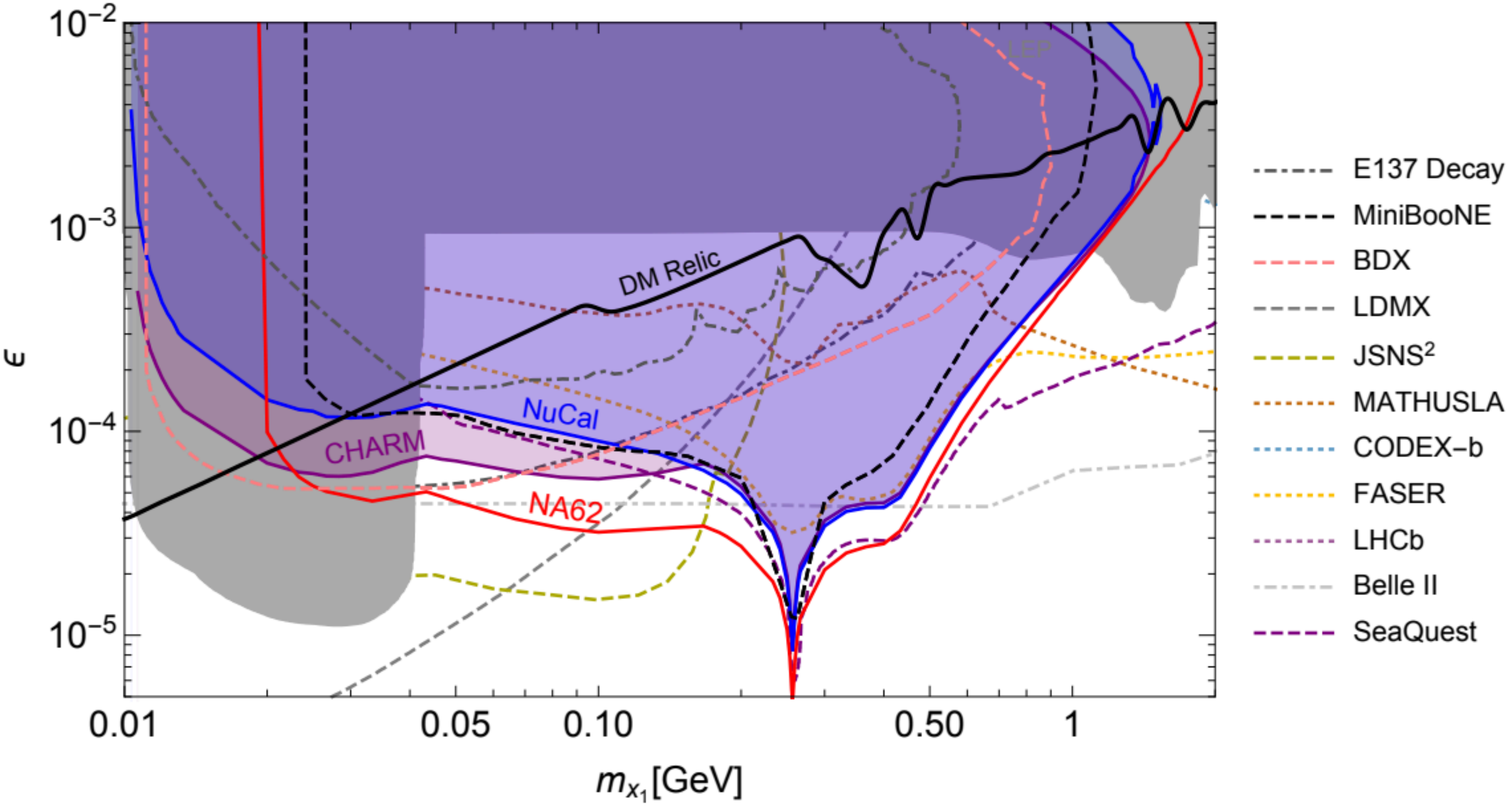
Tsai, de Niverville, Liu, 1908.07525, LongQuest

Long-Lived Particles in the High-Energy Frontier of the Intensity Frontier

- Light Scalar & Dark Photon at BoreXino & LSND, 1706.00424 (proton-charge radius anomaly)
- Dipole Portal Heavy Neutral Lepton, 1803.03262 (LSND/MiniBooNE anomalies)
- Dark Neutrino at Scattering Exp: CHARM-II & MINERvA! 1812.08768 (MiniBooNE Anomaly)
- Closing **dark photon**, **inelastic dark matter**, and **muon g-2 windows**; &

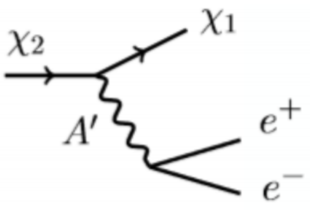
  the LongQuest Proposal! 1908.07525 (muon g-2 Anomaly)

Tsai, de Niverville, Liu, 1908.07525



(e) Compilation of relevant constraints and sensitivity projections for iDM with $\alpha_D = 0.1$ and $\Delta = 0.1$.

Inelastic Dark Matter:



Outline

- Motivations & Intro to **Millicharged Particle (MCP)**
- **The FerMINI Experiment**
- Link to **Strongly Interacting Dark Matter**
- **Broader Perspective:**

  Why proton-fixed target? High energy + Intensity; Not assume abundance

  Why MeV to GeV? Many anomalies and new physics explanations

  (Maybe we don't need to search in the dark)

Some anomalies involving MeV-GeV+ Explanations

⋮

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

⋮

Below ~ MeV there are also **strong astrophysical/cosmological bounds**

Millicharged Particles

Is electric charge quantized?

Other Implications

Finding Minicharge

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

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

- 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 result [EDGES collab., Nature, (2018); Barkana, Nature, (2018)].
A small fraction of the DM as MCP can potentially explain EDGES anomaly (under intense studies, see **more reference later**)

Millicharged Particle: Models

MCP Model

- Small charged particles under U(1) hypercharge

$$\mathcal{L}_{\rm MCP} = i\bar{\chi}(\not{\partial} - i\epsilon' e \not{B} + M_{\rm MCP})\chi$$

- Can just consider these Lagrangian terms by themselves (no extra mediator, i.e., dark photon), one can call this a "pure" MCP

- Or this could be from Kinetic Mixing
  - give a nice origin to this term
  - an example that gives rise to **dark sectors**
  - easily compatible with Grand Unification Theory
  - I will not spend too much time on the model

Kinetic Mixing and MCP Phase

- **Coupled to new dark fermion (scalar) χ**

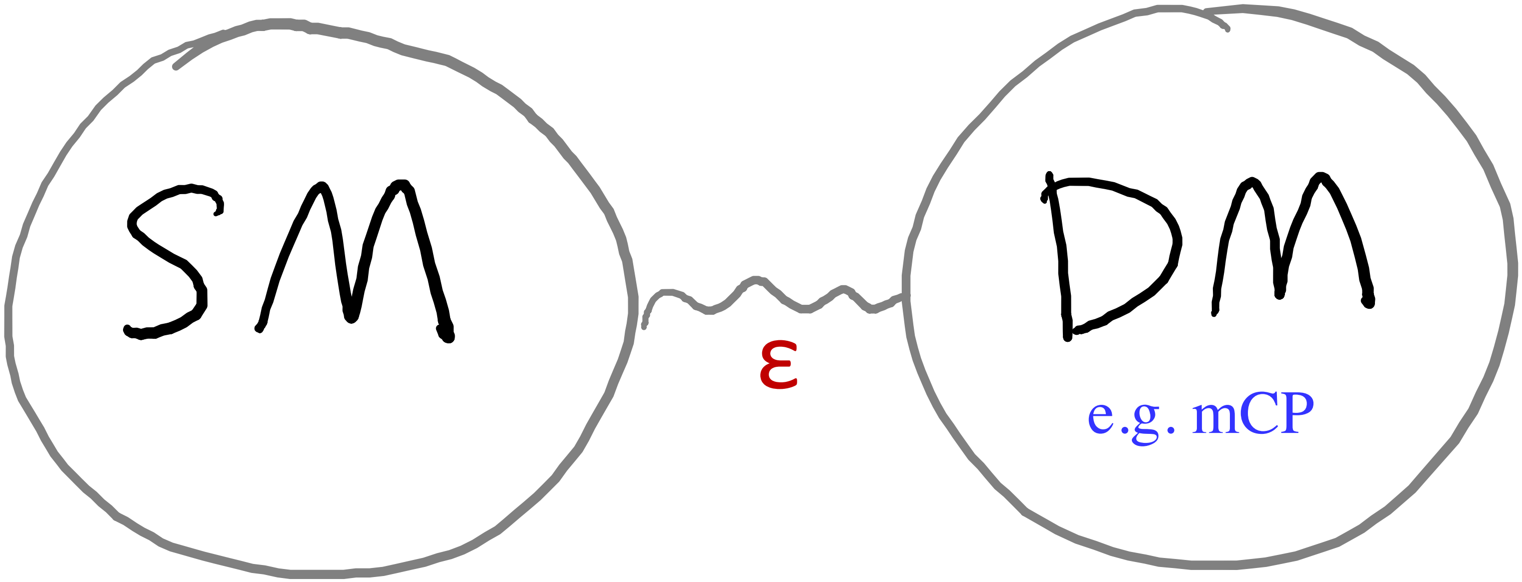
(SM: Standard Model)

See, Holdom, 1985

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

- New Fermion χ charged under dark U(1)’
- Field redefinition into a more convenient basis for massless B', $B' \to B' + \kappa B$
- new fermion acquires an small EM charge Q (the charge of mCP χ): $Q = \kappa e' \cos\theta_W$ $\quad \epsilon \equiv \kappa e' \cos\theta_W / e.$

The Rise of Dark Sector



Important Notes!

- Our search is simply a search for particles (**fermion χ**) with
  {mass, electric charge} = $\{m_\chi, \epsilon e\}$
- **Minimal theoretical inputs/parameters**
  (harder to probe in MeV – GeV+ mass regime)
- **MCPs do not have to be DM in our searches**
- The bounds we derive **still put constraints on DM as well as dark sector scenarios.**
- Not considering bounds on dark photon
  (not necessary for MCP particles)
- Similar bound/sensitivity applies to scalar MCPs

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)

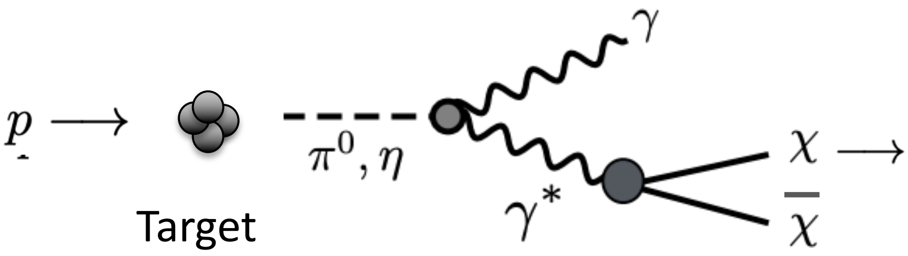
- Test of **GUT models**, and **String Compactifications**

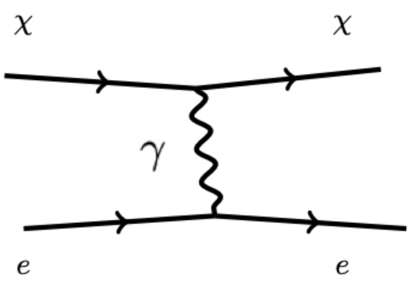
  see Shiu, Soler, Ye, arXiv:1302.5471, PRL ’13 for more detail.

Millicharged Particle: Signature

Production & Detection:

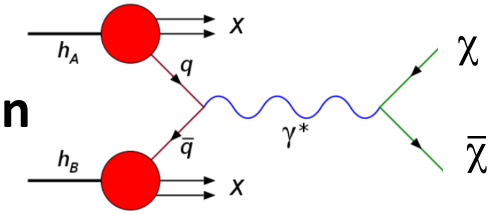
MCP (or light DM with massless mediator):





See, also
1411.1055
1703.06881

- ☐ **Production: Meson Decays**
- ☐ **Production: Drell-Yan**



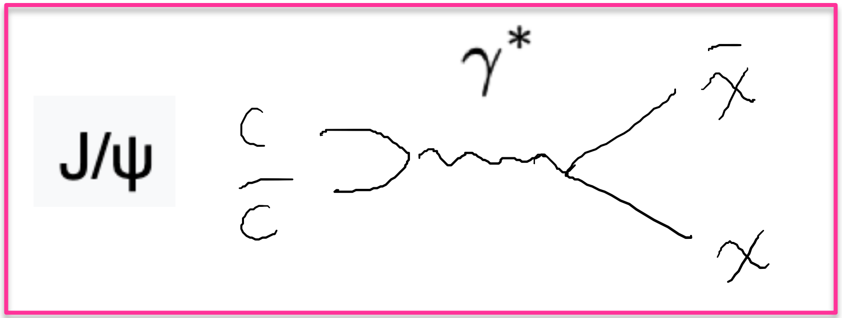
- ☐ Detection: Electron Scattering

Similar topology:

deNiverville, Pospelov, Ritz, ’11,

Batell, deNiverville, McKeen, Pospelov, Ritz, ‘14

Kahn, Krnjaic, Thaler, Toups, ’14 …



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

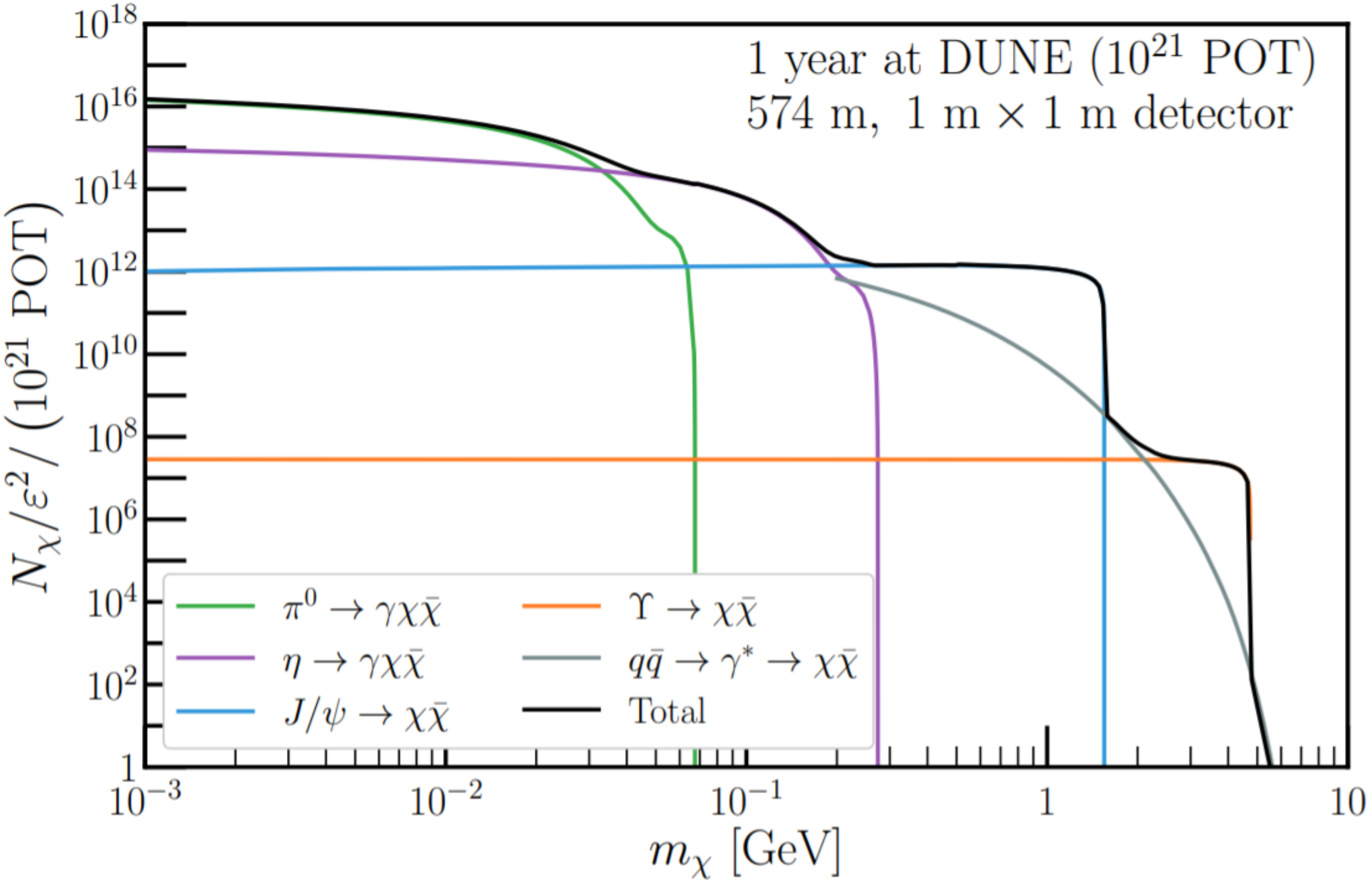
$BR(\pi^0 \to \gamma e^- e^+) = 0.01$

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

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

- ☐ **Heavy mesons are important for high-mass mCP’s in high-energy beams**

MCP Production/Flux

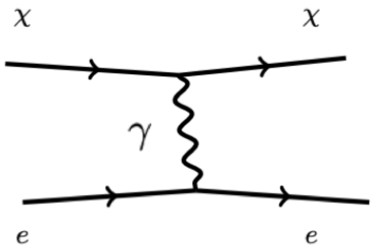


MCP Detection: Electron Scattering & Ionization

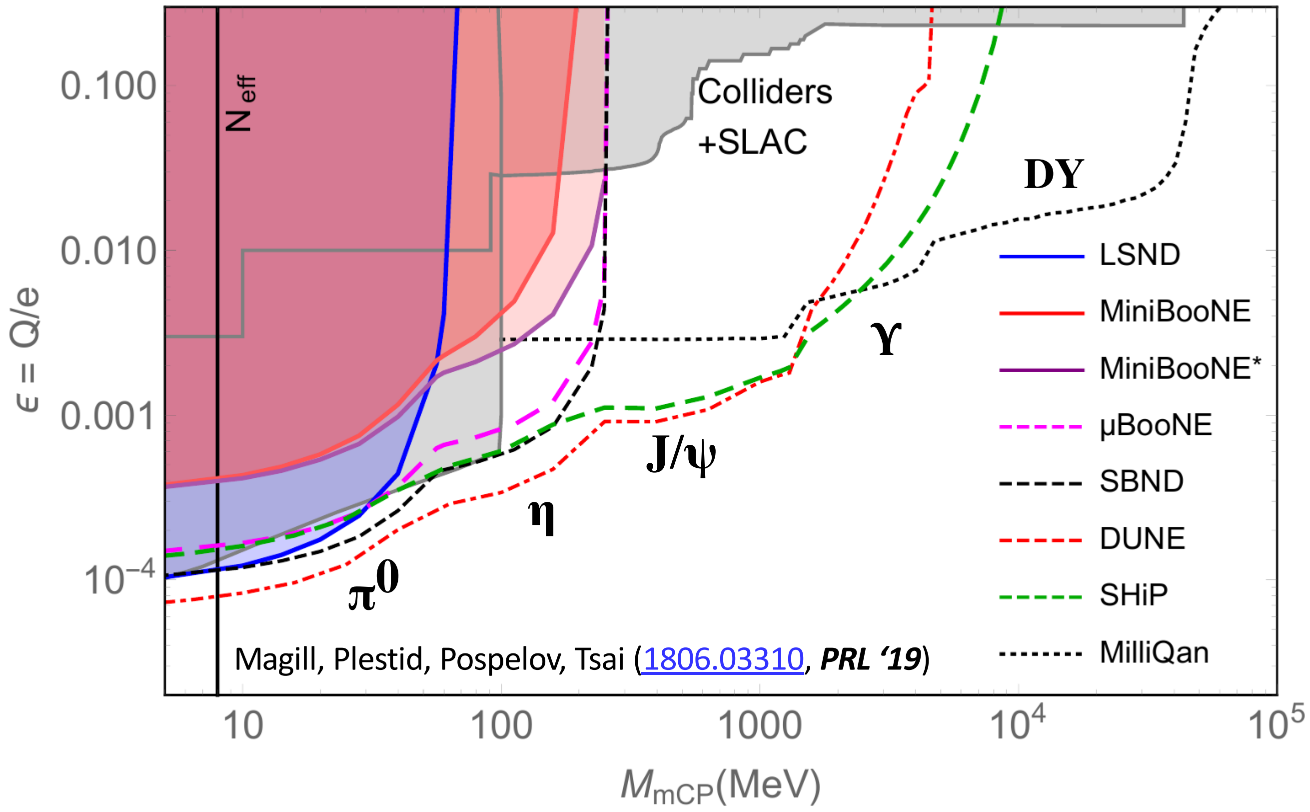
- $\boldsymbol{Q^2}$ is the squared 4-momentum transfer.
- lab frame: $Q^2 = 2m_e\,(E_e - m_e)$, $E_e - m_e$ is the electron recoil energy.
- Expressed in **recoil energy threshold**, ${E_e}^{(min)}$, we have

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

- Sensitivity greatly enhanced by accurately **measuring low energy electron recoils** **for mCP's & light dark matter - electron scattering,**
- See Magill, Plestid, Pospelov, **YT**, 1806.03310 (MCP in neutrino Experiments) & deNiverville, Frugiuele, 1807.06501 (for sub-GeV DM)
- Very low-energy scattering**: Ionization (eV-level)!**



Sensitivity at Neutrino Detectors



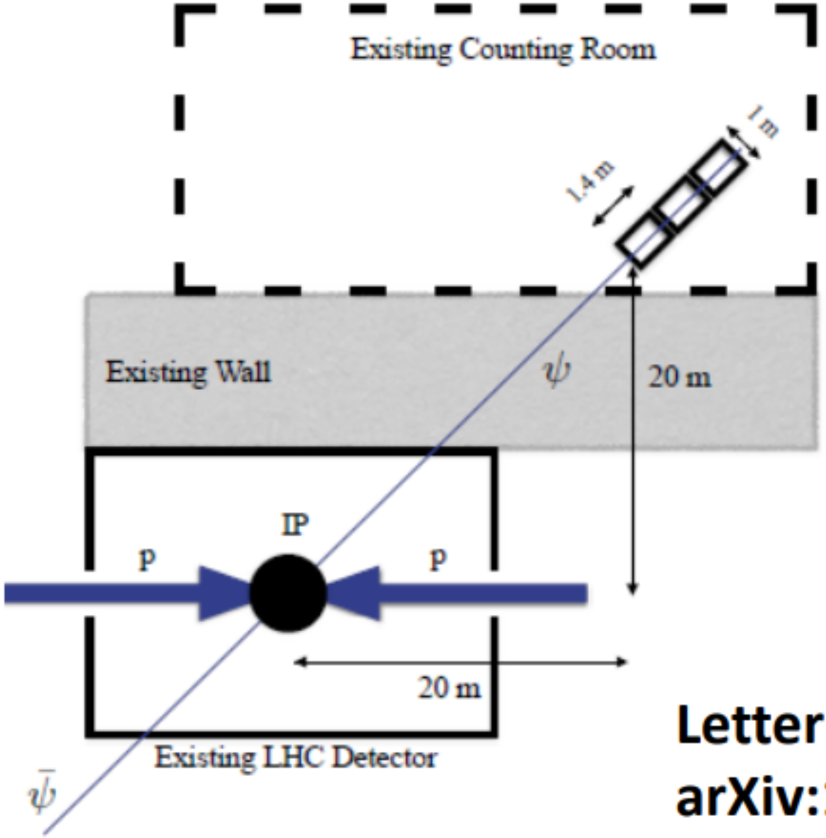
- **Electron recoil-energy threshold: MeV to 100 MeV**
- SLAC mQ: Prinz el al, PRL (1998); Colliders/accelerator: Davidson, Hannestad, Raffelt (2000); N_{eff}: Bœhm, Dolan, and McCabe (2013)
- Harnik, Liu, Palamara: double-hit to reduce background + Ivan Lepetic (ArgoNeuT+DUNE) '19 (Also see Ornella's talk!)

Low-cost fixed-target probes of dark sector/long-lived Particles

FerMINI as an example

MilliQan @ LHC: General Idea

- Require **triple coincidence in small time window (15 nanoseconds)**
- Q down to 10^{-3} e, each MCP produce averagely ~ 1 photo-electron (PE) observed per ~ 1 meter long scintillator
- Long axis points at the **CMS Interaction Point (P5)**.



Letter of intent: arXiv:1607.04669

Andrew Haas, Fermilab (2017)

Andy Haas, Christopher S. Hill, Eder Izaguirre, Itay Yavin, 1410.6816, PRD ’15

FerMINI:

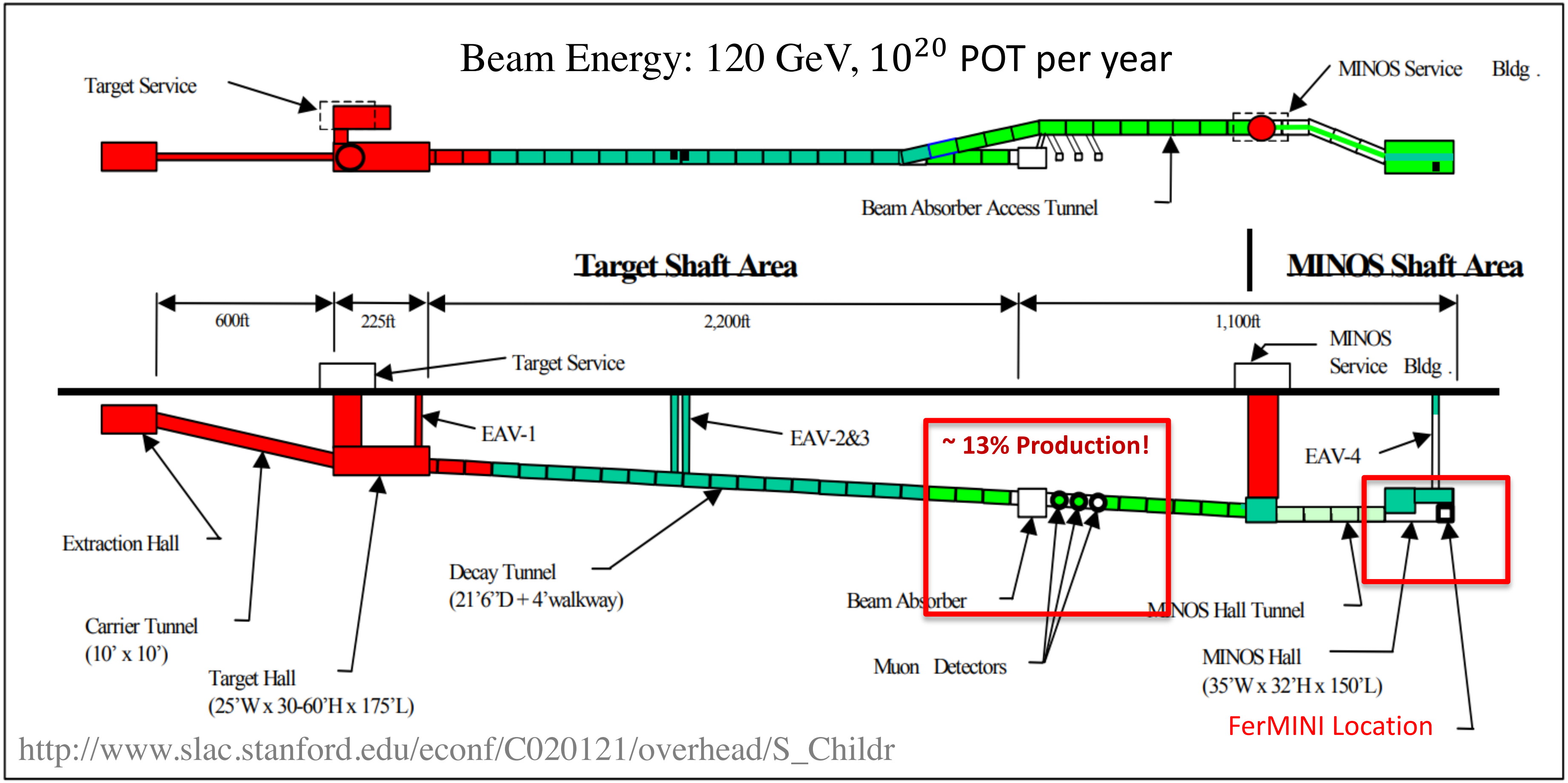
A Fermilab Search for MINI-charged Particle

Kelly, **YT**, arXiv:1812.03998 (PRD`19)

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

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

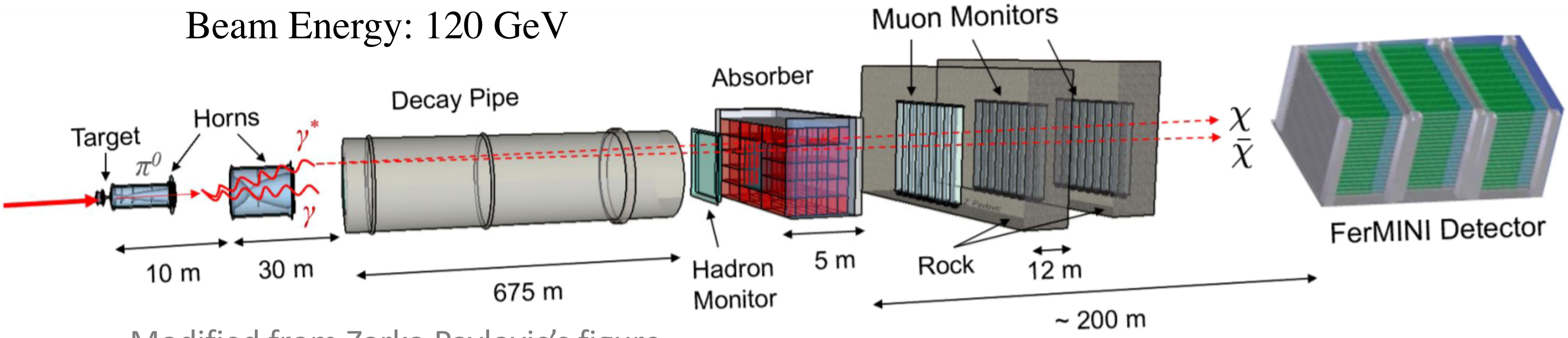
Site 1: NuMI Beam & MINOS ND Hall



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 @ NuMI-MINOS Hall



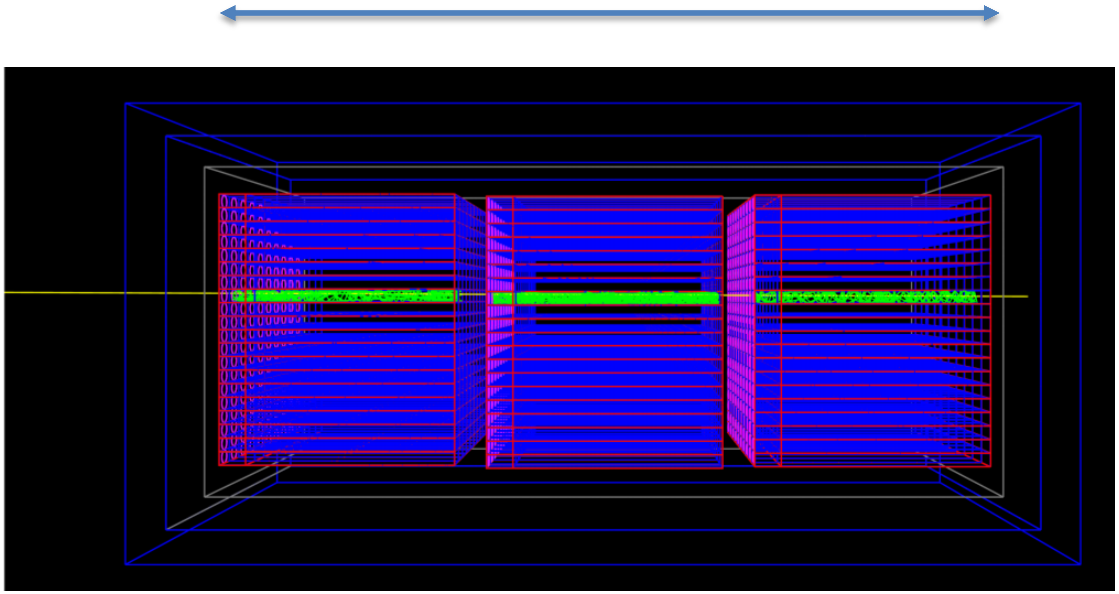
Modified from Zarko Pavlovic's figure

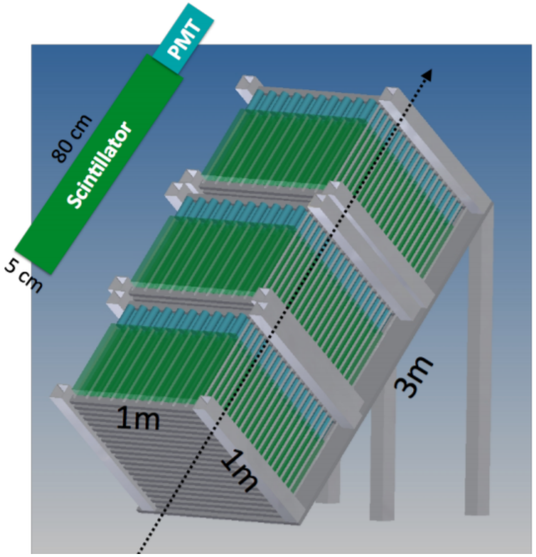
An illustration of the FerMINI experiments utilizing the NuMI facility.

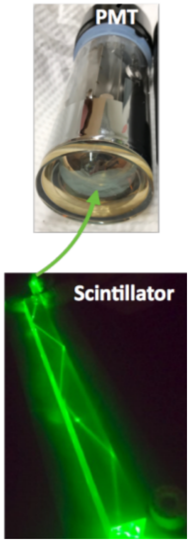
MINOS hall downstream of NuMI beam

Detector Concept

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



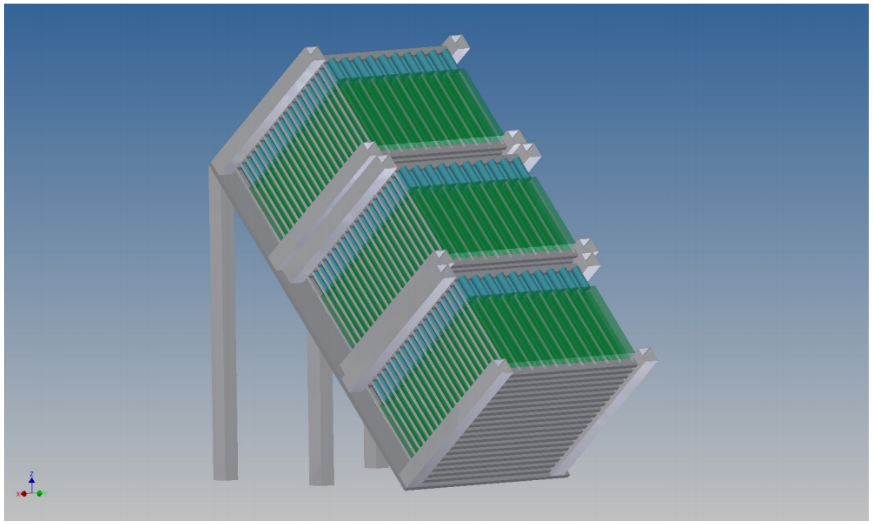




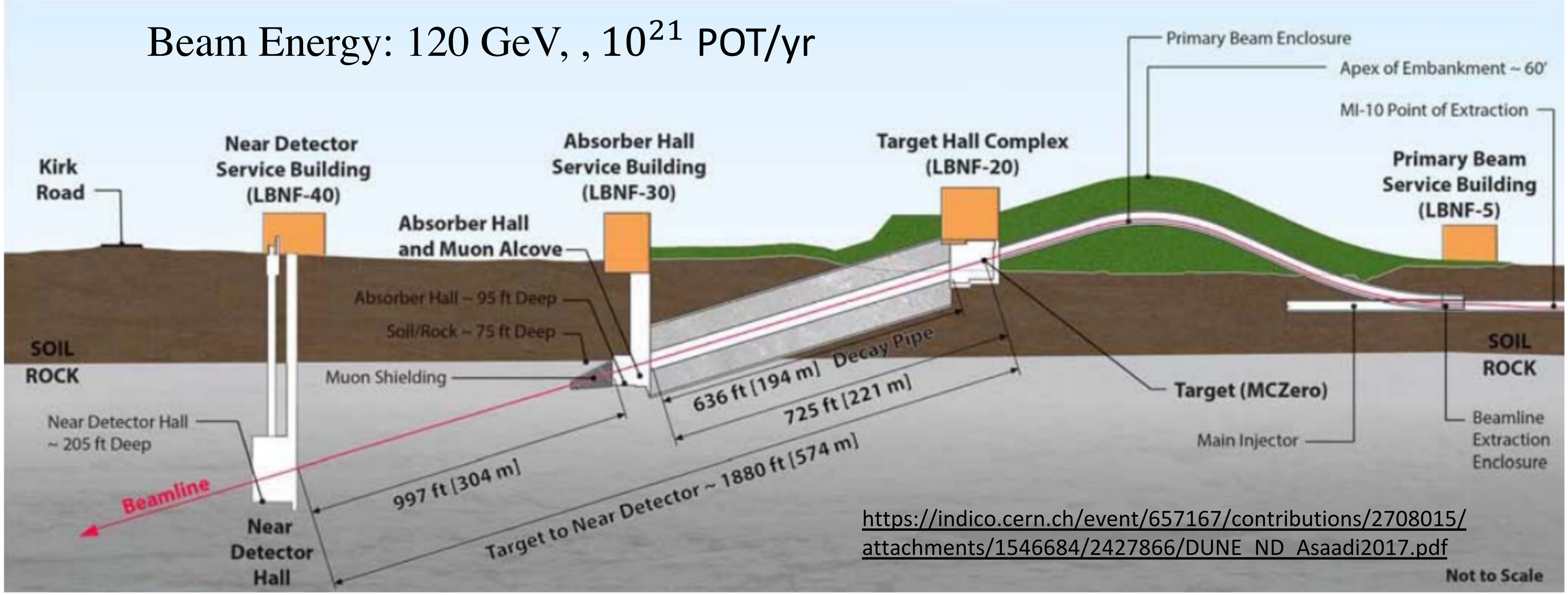
See arXiv:1607.04669; arXiv:1810.06733

Detector: Details of the Nominal Design

- Total: **1 m × 1 m** (transverse plane) × **3 m** (longitudinal) **plastic scintillator array.**
- **3 sections** each containing **400 5 cm × 5 cm × 80 cm scintillator bars** optically coupled to **high-gain photomultiplier (PMT).**
- A **triple-incidence within a 15 ns time window** along longitudinally contiguous bars in each of the 3 sections required to reduce the **dark-current noise (the dominant background)**.



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**!

Photoelectrons (PE) from Scintillation

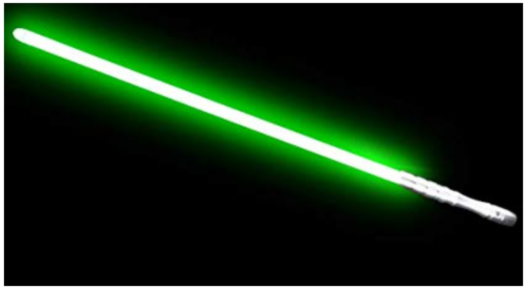
- **The averaged number of photoelectron (PE)** seen by the detector from single MCP is:

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

$\langle dE/dx \rangle$ 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 $\mathbf{10^6}$, $\epsilon \sim \mathbf{10^{-3}}$ roughly gives one PE in **one meter plastic scintillation bar**



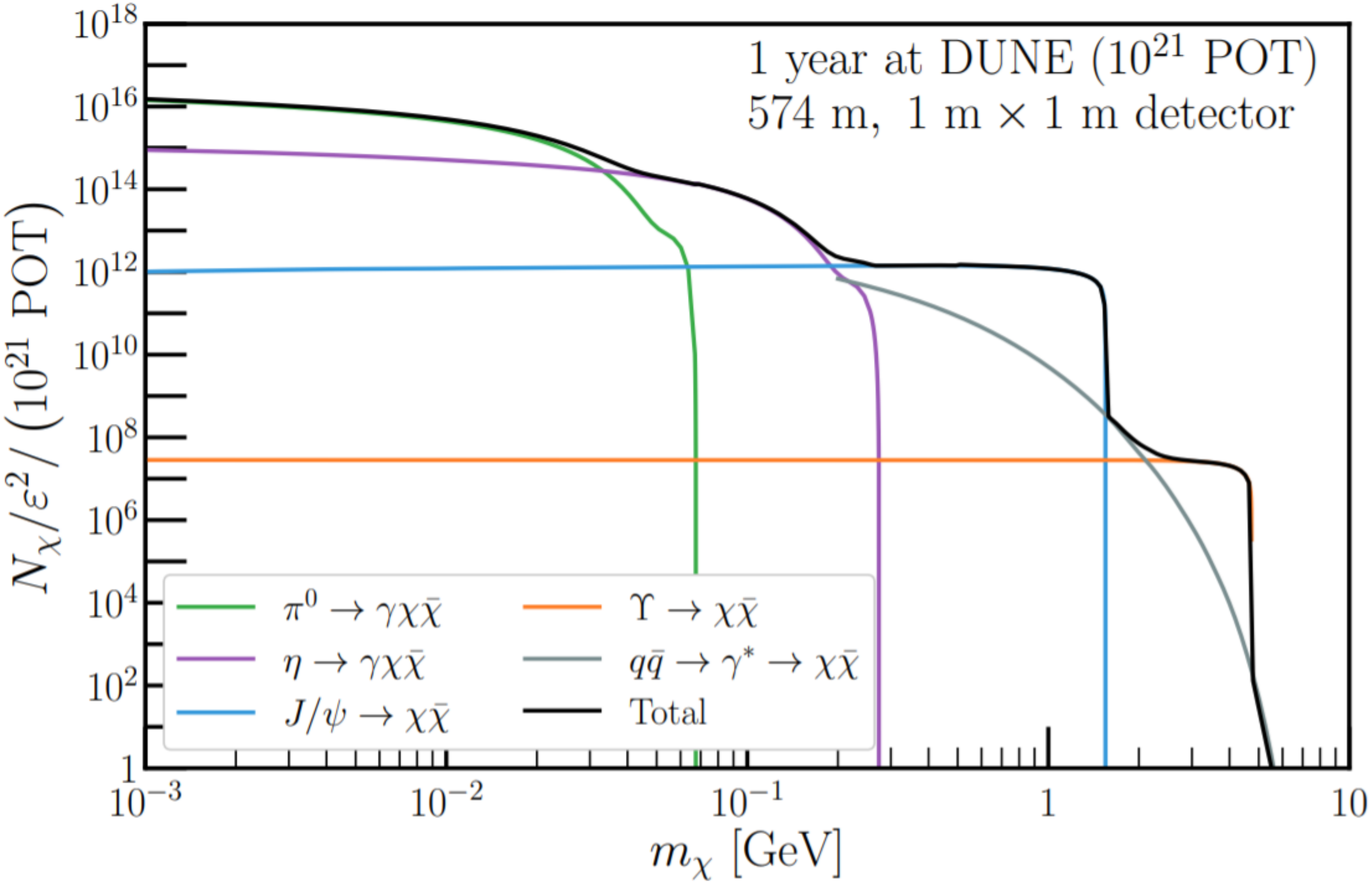
Signature: Triple Coincidence

- 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 photoelectron is:

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

- $\boldsymbol{N_{x,detector}} = \boldsymbol{N_x}$ x **P .**

MCP Production/Flux



Detector Background

- 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

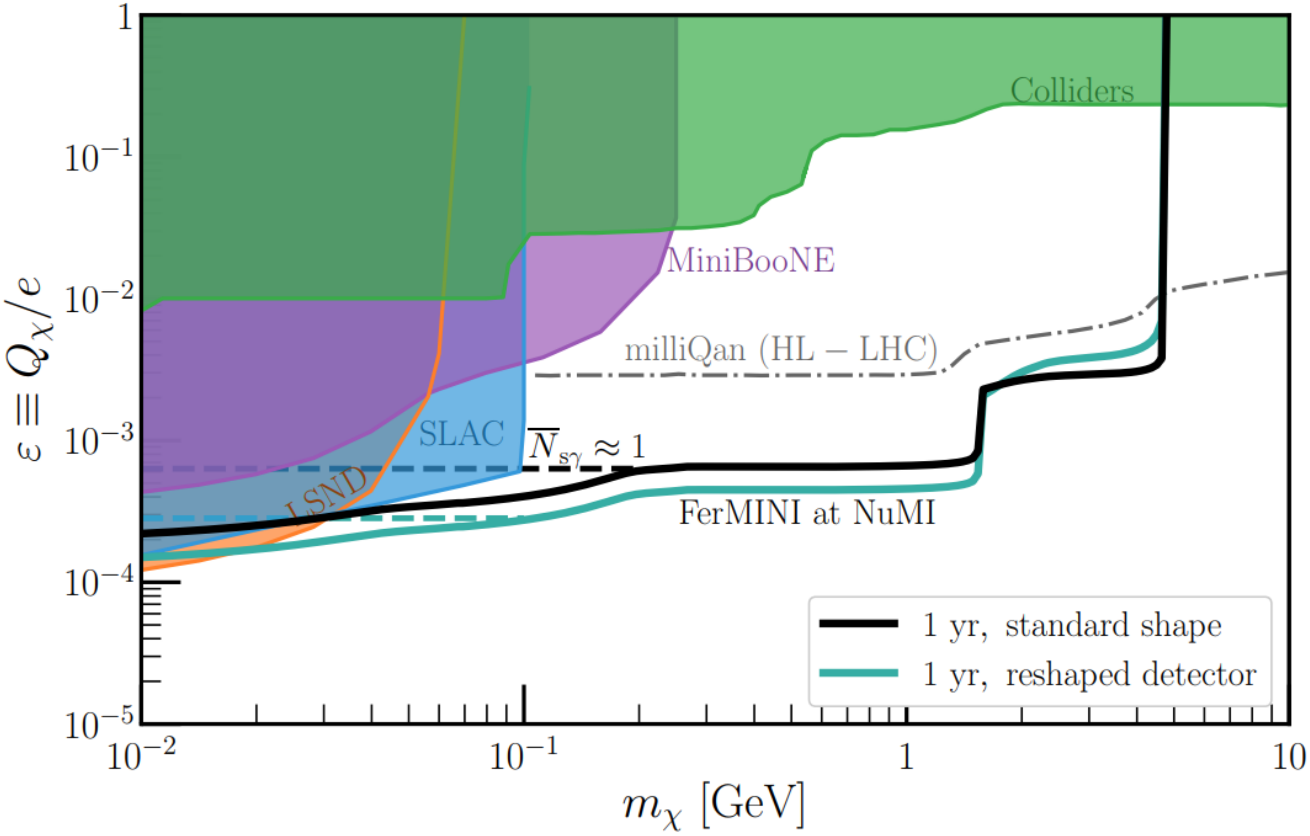
  - Offset middle detector
- **Dark current: triple coincidence**

Dark Current Background @ PMT

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

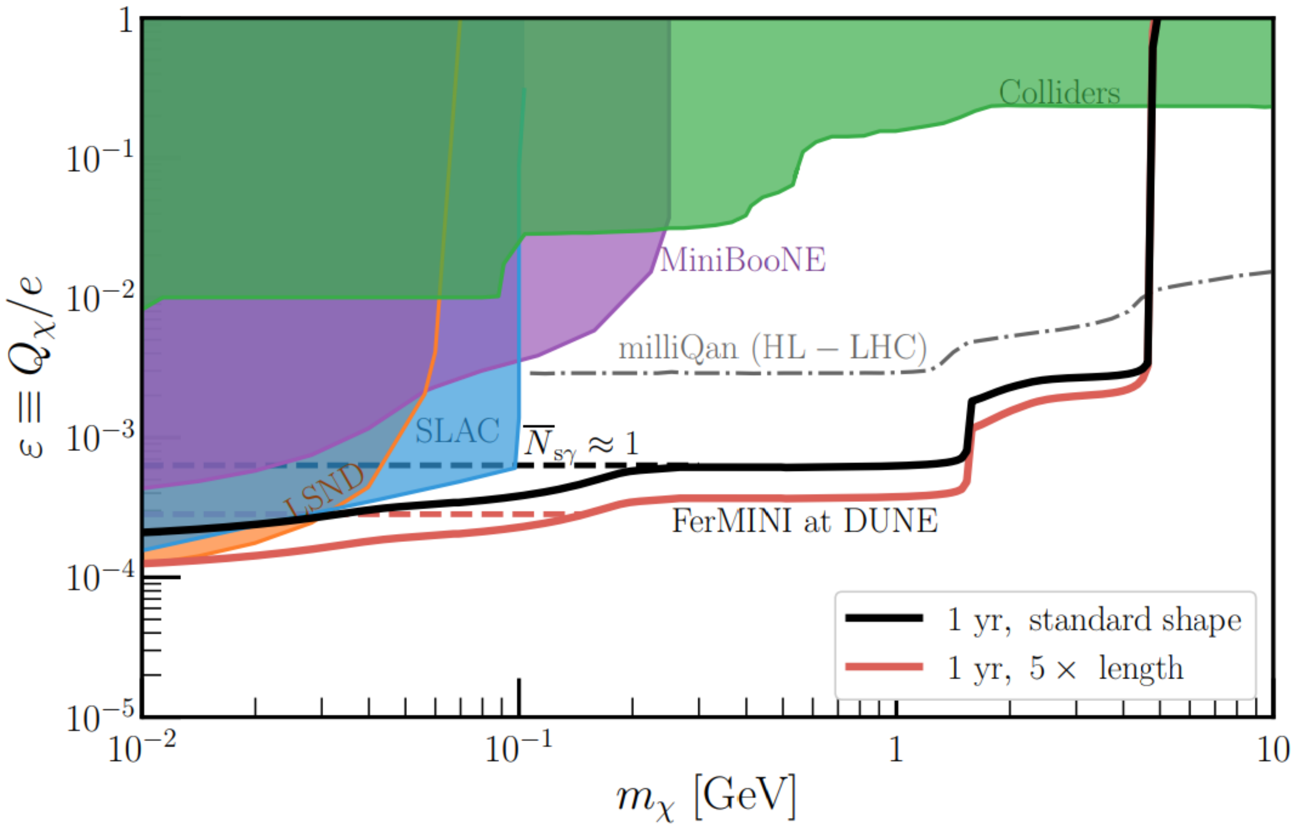
  $\boldsymbol{v_B^3}$ **Δt**$^{\mathbf{2}}$ **= 2.8 x** $\mathbf{10^{-8}}$ **Hz**, for **Δt = 15 ns.**
- There are 400 such set in the nominal design.
- The total background rate is 400 x 2.8 x 10^{-8} ~ 10^{-5} Hz
- ~ **300 events** in one year of trigger-live time
- **Quadruple coincidence can reduce this BG to essentially zero!**

FerMINI @ MINOS



Yu-Dai Tsai,
Fermilab

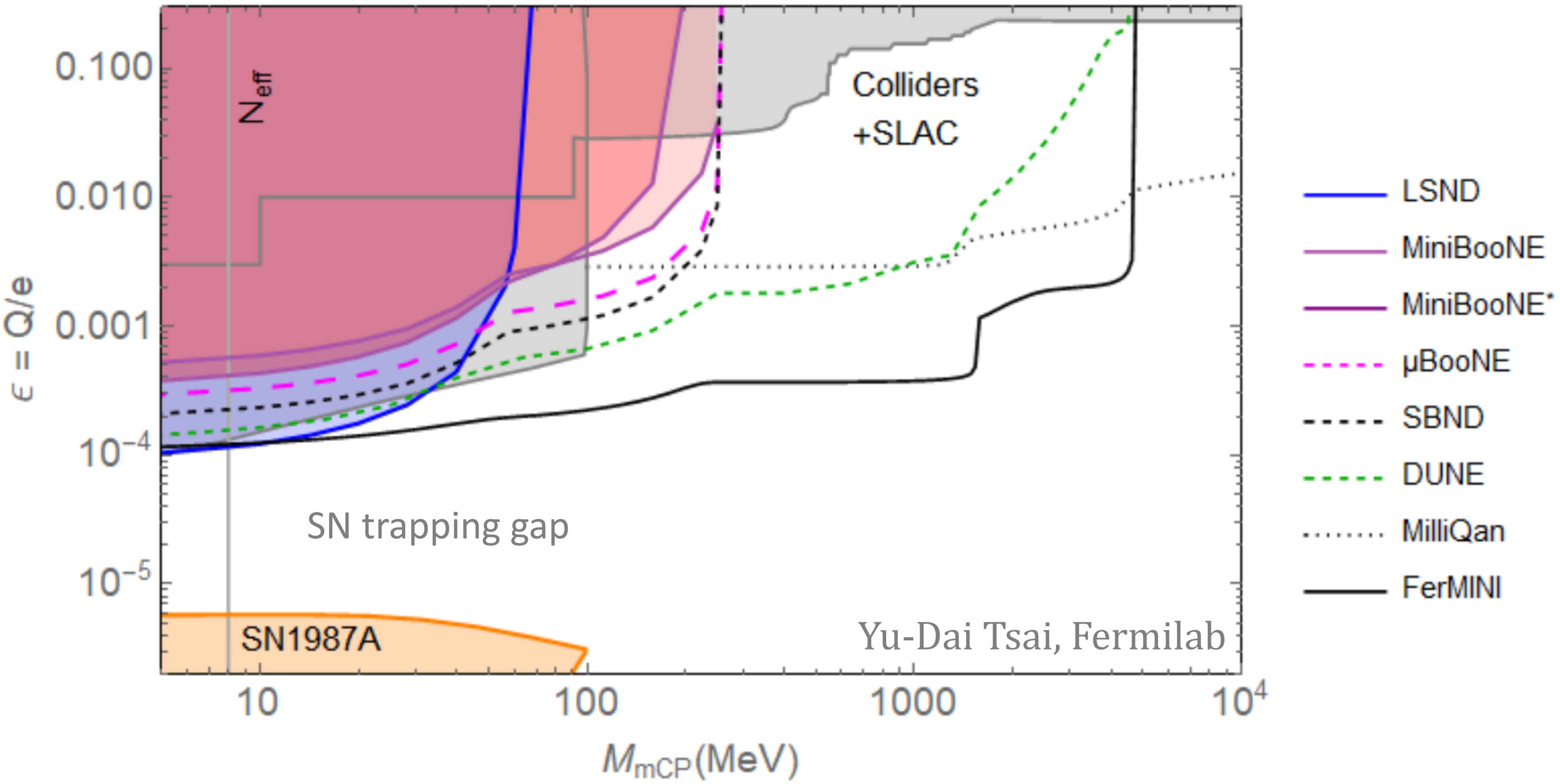
FerMINI @ DUNE



Yu-Dai Tsai, Fermilab

- **Hope to Incorporate it into the near detector proposal.**

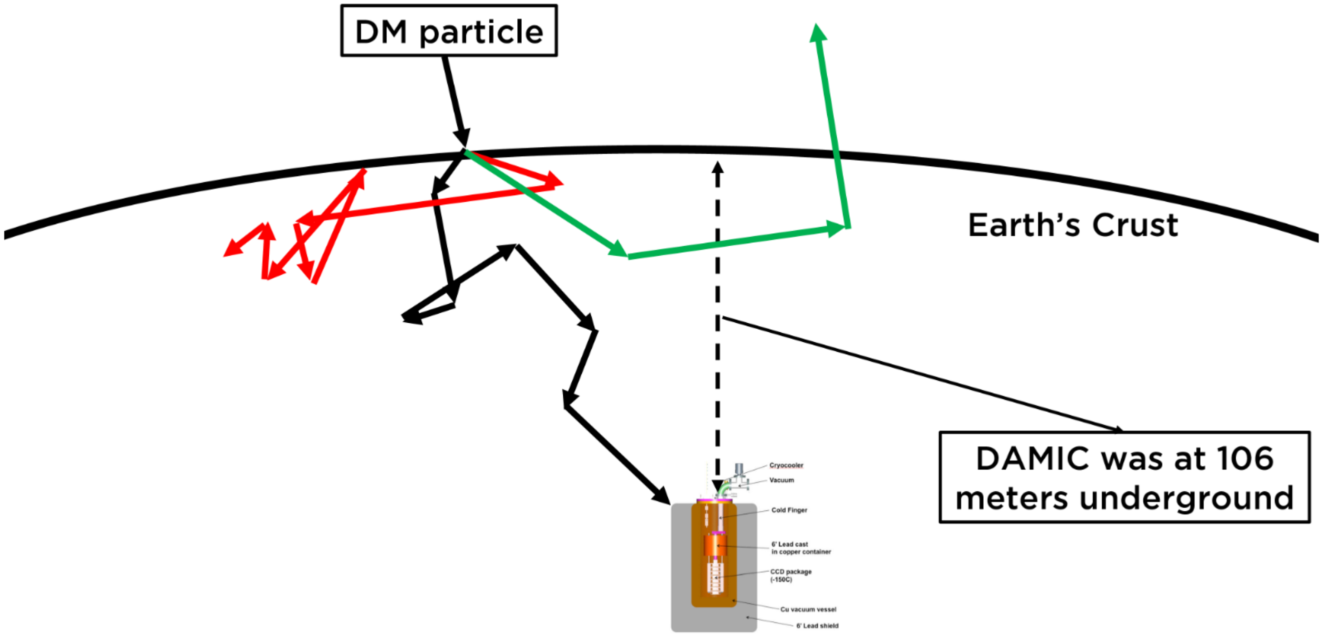
Compilation of MCP Probes



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

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

Strongly Interacting Dark Matter

See, e.g., arXiv:1905.06348 (Emken, Essig, Kouvaris, Sholapurkar '19)

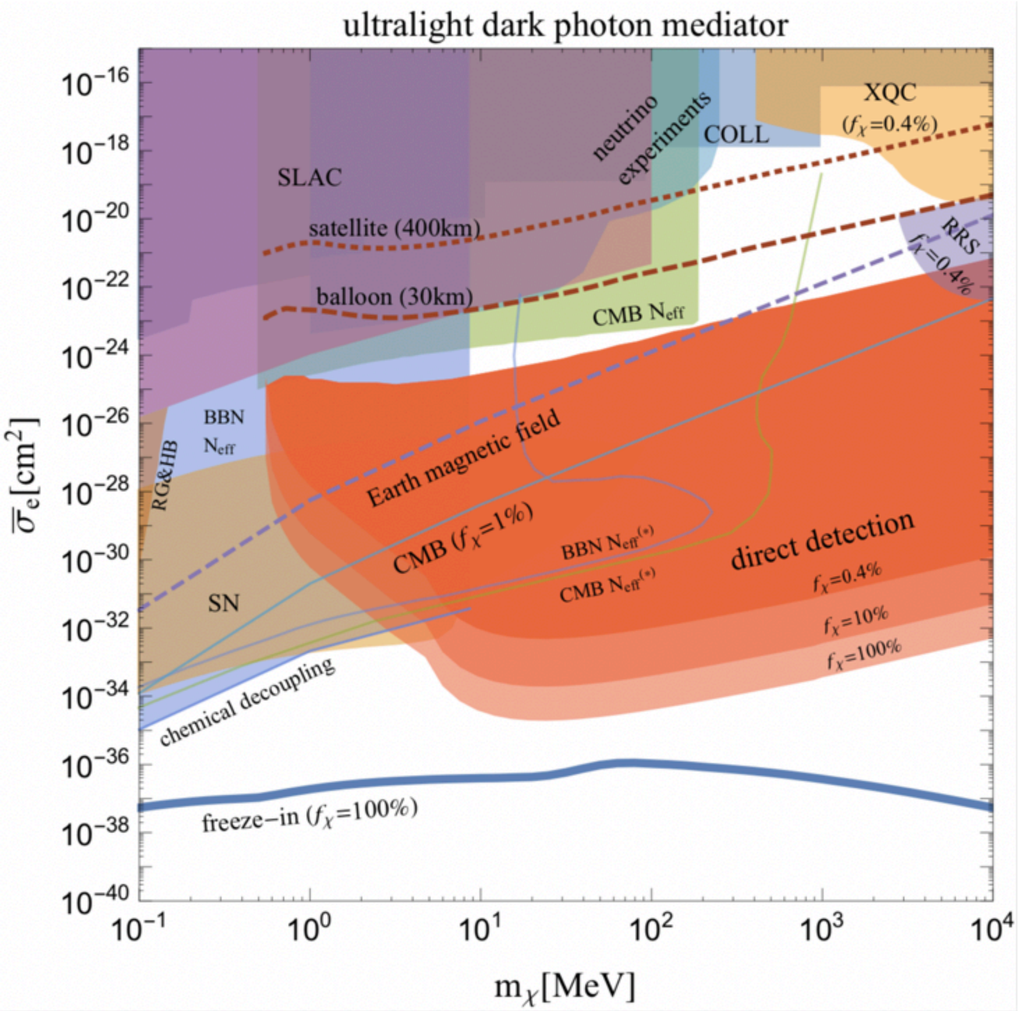
Scatterings both on electrons and nuclei in the **Earth's crust, atmosphere**, and **shielding material** attenuate the expected **local dark matter flux** at a terrestrial detector, so that such experiments lose sensitivity to dark matter above some **critical cross section**.

Limits of the underground Direct Detection (DD) Experiments, including **SENSEI, CDMS-HVeV, XENON10, XENON100, and DarkSide-50**

One can call the DM that could escape the DD bound this way as **Strongly Interacting Dark Matter (SIDM)**

Not to confuse with Self Interacting Dark Matter (also SIDM)

Millicharged (with ultralight A’) SIDM Window



From arXiv:1905.06348, they defined **reference cross section:**

$$\bar{\sigma}_e \equiv \frac{16\pi\alpha\alpha_D\kappa^2\mu_{\chi e}^2}{(q_{ref}^2+m_{A'}^2)^2},$$

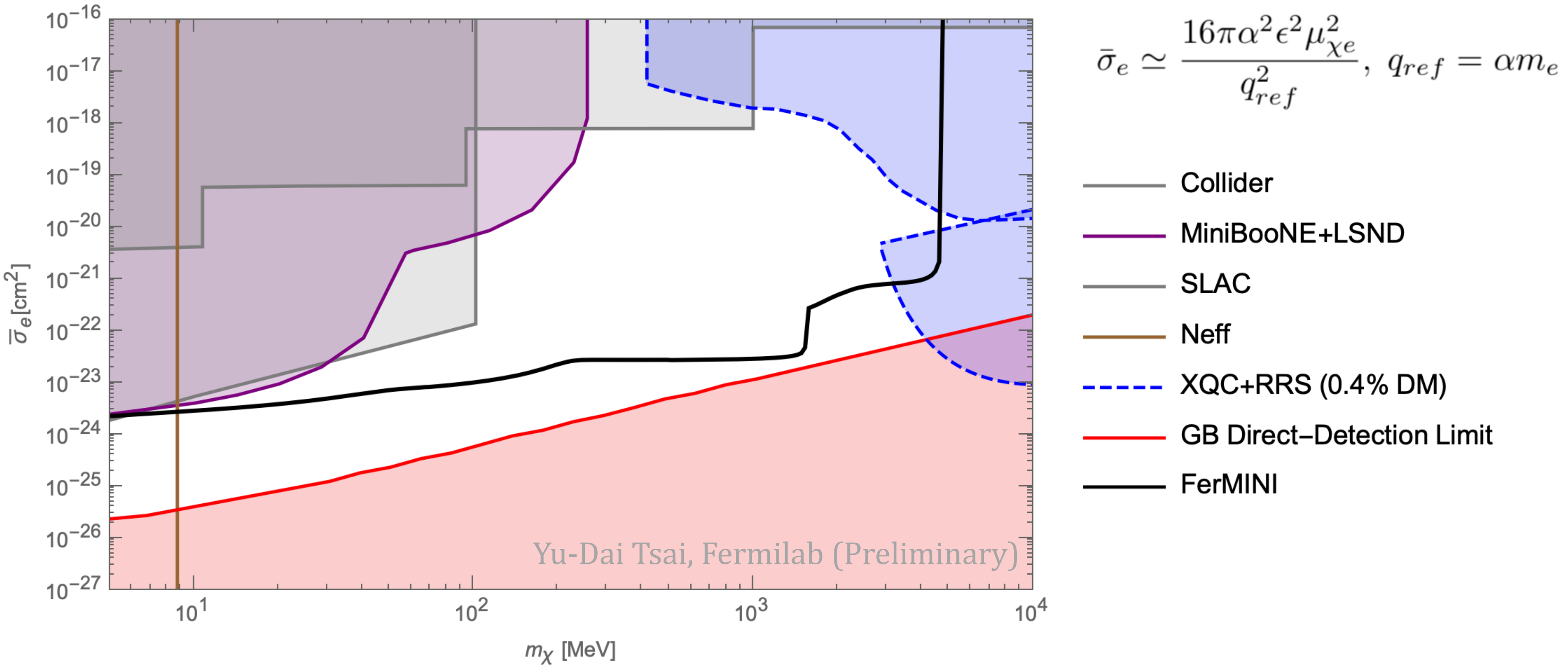
$$m_{A'} \to 0,\ q_{ref} = \alpha m_e$$

q_{ref} is chosen as the typical momentum transfer in DM-electron collisions for noble-liquid / semiconductor targets.

Agonistic to the abundance setting mechanism for the SIDM window.

FerMINI Probe of Millicharged SIDM

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



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

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

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.

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.
   Join us on the proposal! (ytsai@fnal.gov)

FerMINI:
Alternative Designs
& New Ideas

New Ideas …

- **Combine with neutrino detector**: behind, in front, or sandwich them
- Combine with **DUNE PRISM**: moving up and down
- **FerMINI + DUNE 3-D scintillation detector (3DST)**
- Combine with **SPS/SHiP facilities**
- Can potentially probe (electric) **dipole portal dark fermion**, **quirks**, etc.
- **Join the Proposal:** ytsai@fnal.gov

Looking Ahead

- Exploring **Energy Frontier of the Intensity Frontier** (complementary to and **before HL-LHC upgrade**)
- **Cosmology-driven models / more motivated models.**
- Near-future (and almost free) opportunity (**NuMI Facility, SBN program, DUNE Near Detector**, etc.)
- Other new **low-cost alternatives/proposals (~ $1M)** to probe hidden particles and new forces **(FerMINI is just a beginning!)**
- **Dark sectors in neutrino telescopes**

Thank You!

Thanks for the invitation!

Not all bounds are created with equal assumptions

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)

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

Cosmology: assume cosmological history, species, etc

} different

⟶ "Assumptions"

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

- **Astrophysical/cosmological observations** are important to reveal the **actual story of dark matter (DM).**

Backup Slides

Potential Detection Limitation: $N_{photon} \leq 1$

- **Define: ε_{low} as $N_{sintilator\ photon}$ = 1**
- **Roughly around or below this, one really have to worry about scintillator performance**
- **One can elongate the scintillator or consider alternative materials to help.**

Material	Photons/keV	Density (g/cm^3)	* Length needed (cm)	Speed (ns)	Cost for 5x5 cm ($)	Notes
Plastic BC408	10	1.03	145	~2	~200	Current choice
NaI	38	3.67	11	~230	~800	Slow, fragile
LaBr3(Ce)	63	5.08	5	~16	~3000	Radioactive
Liquid Xe	62	2.95	8	~2 / ~34	~1000?	Cryogenic, ultraviolet

- Andy Haas, Fermilab, 2017

* Length needed to get 3 photons for charge 1/1000 e

NuMI (MINOS) / LBNF (DUNE)

Now and the future bests in POTs

- **LSND:** total of 10^{23} POT (beam: 800 MeV)
- **Fermilab (FT):**

- NuMI beam: 1 - 4 x 10^{20} POT/yr (120 GeV)
- LBNF beam: 1 - 2 x 10^{21} POT/yr (120 GeV)

- **CERN SPS (FT):**

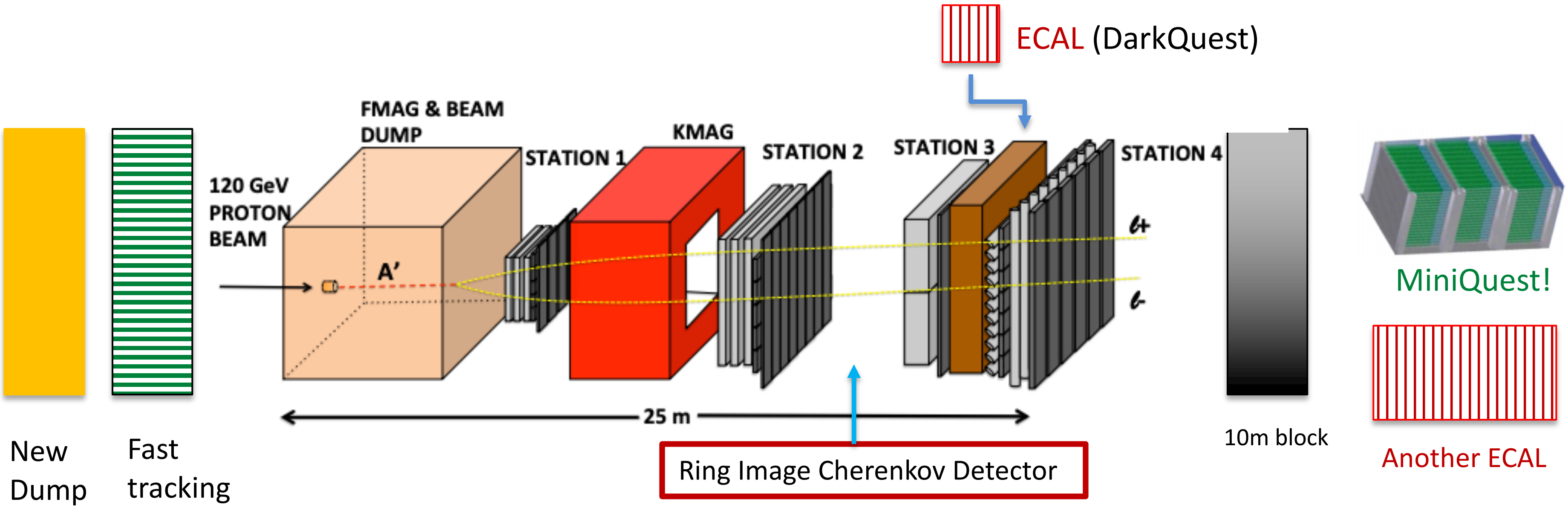
- NA62: up to 3 x 10^{18} POT/yr (400 GeV)
- SHiP: up to 10^{19} POT/yr (400 GeV)

- **FASER (collider, forward)**: 10^{16}-10^{17} POT/yr

  much higher energy

LongQuest: Three Stage Retool of SpinQuest, as Dedicated Long-Lived Particle Experiment

arXiv:1908.07525, Tsai, DeNiverville, Liu '19



ECAL (DarkQuest)

New Dump

Fast tracking

Ring Image Cherenkov Detector

10m block

MiniQuest!

Another ECAL

LongQuest III

Front dump and fast tracking

LongQuest I

Add RICH or HBD for main detector

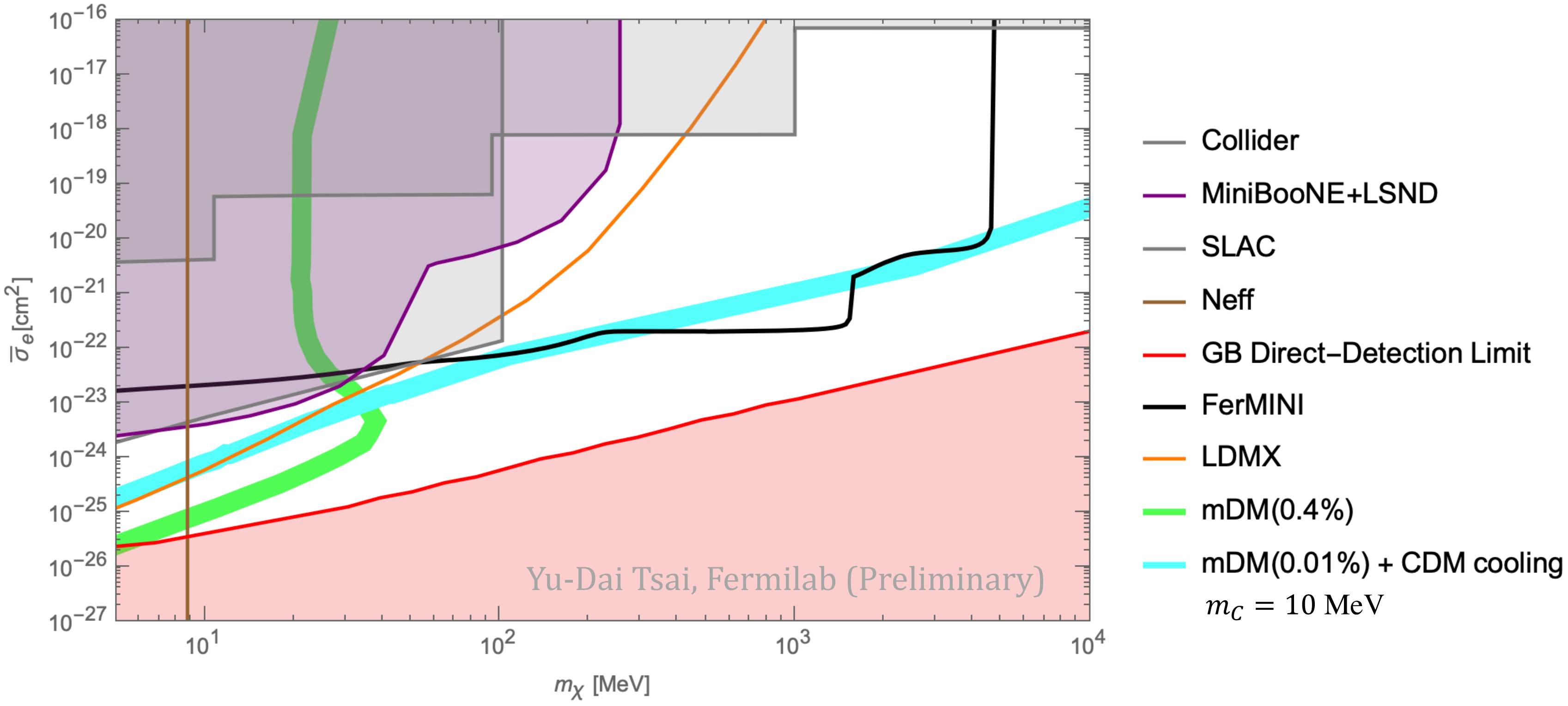
LongQuest II

Add Far Detectors!

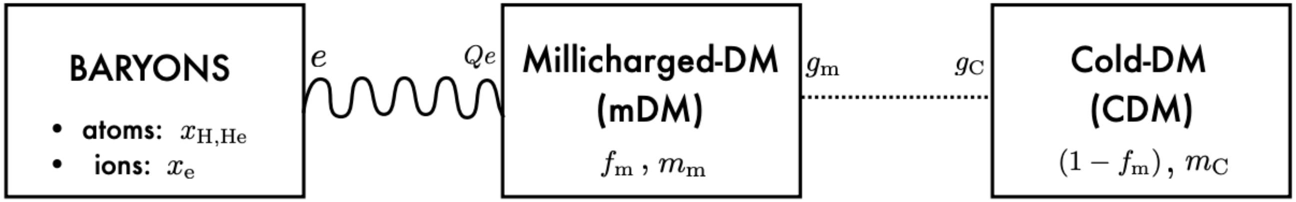
XQC & RRS

1. X-ray Quantum Calorimeter: X-ray detector aboard a sounding rocket
2. RRS (RICH, ROCCHIA,SPIRO), Ahlen et al., Harvard-Smithsonian Observatory pre- print 2292 (1986).
3. RRS is on balloon

Reviving mDM for EDGES



Yu-Dai Tsai, Fermilab (Preliminary)



BARYONS

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

Millicharged-DM (mDM)

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

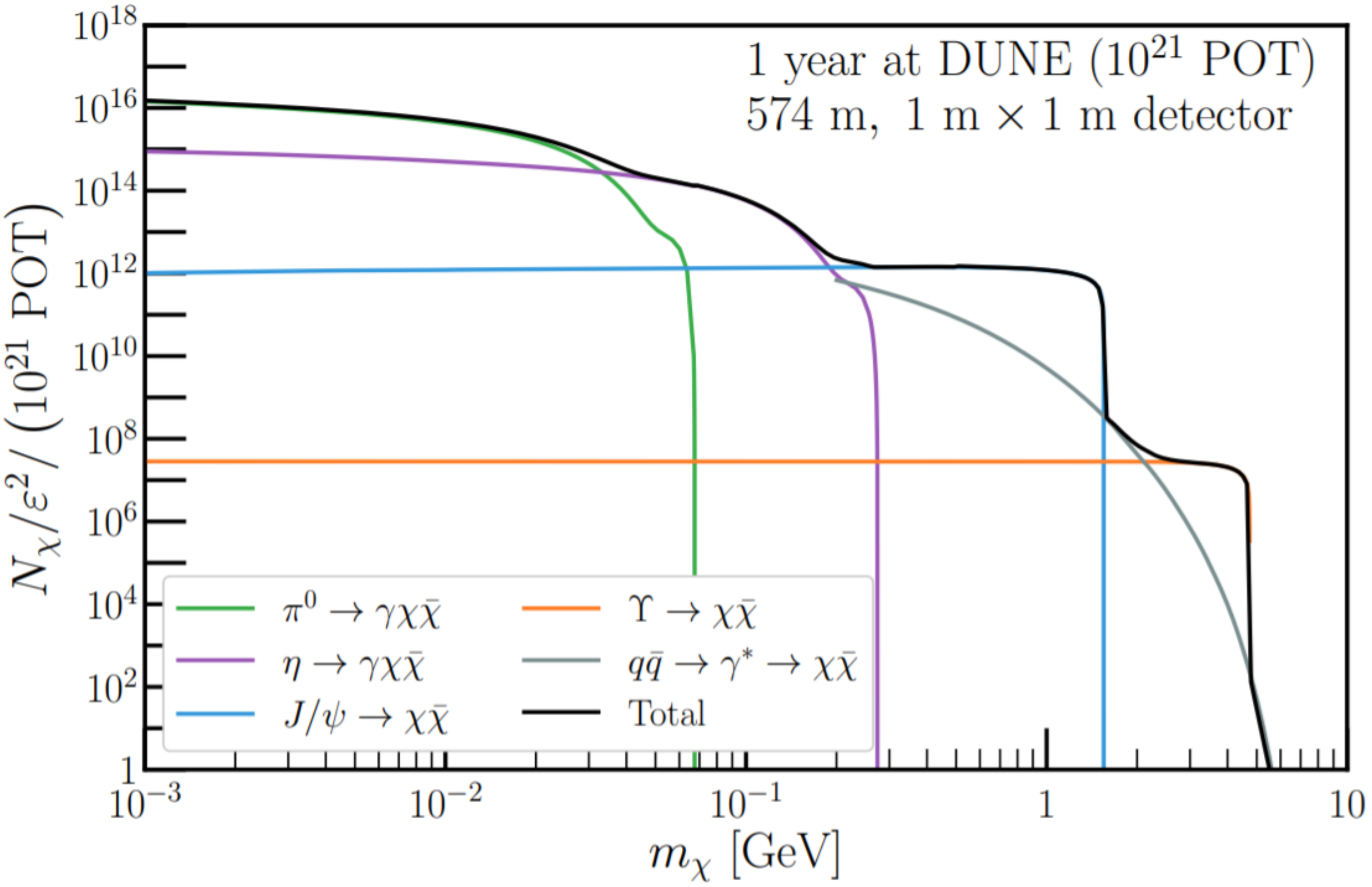
Cold-DM (CDM)

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

Backup Slides

Liu, Outmezguine, Redigolo, Volansky, ‘19

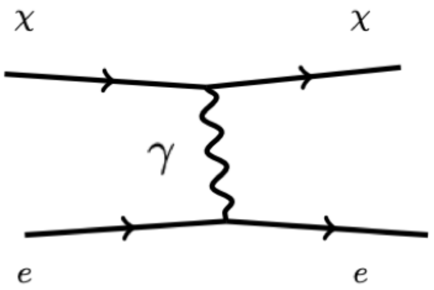
MCP Production/Flux



- Use PYTHIA to generate neutral meson Dalitz or direct decays from the pp collisions and rescale by considering, $\mathrm{BR}(\mathcal{M} \to \chi\bar{\chi}) \approx \epsilon^2 \times \mathrm{BR}(\mathcal{M} \to X e^+ e^-) \times f\left(\frac{m_\chi}{M}\right)$,
- M: mass of the parent meson, X:additional particles, f(m_χ/M): phase space factor
- We also include Drell-Yan production for the high mass MCPs (see arXiv:1812.03998)

Detection: MCP Elastic Scattering with Electrons

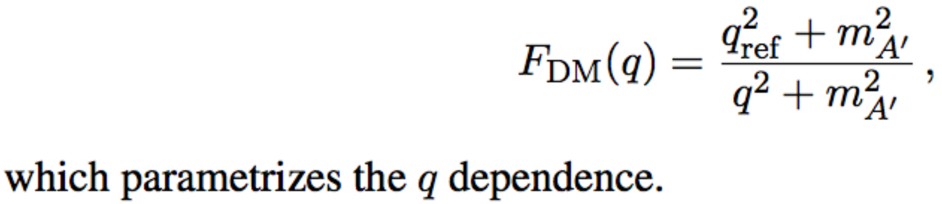
$$\frac{\mathrm{d}\sigma_{e\chi}}{\mathrm{d}Q^2} = 2\pi\alpha^2\epsilon^2 \times \frac{2(s-m_\chi^2)^2 - 2sQ^2 + Q^4}{(s-m_\chi^2)^2 Q^4}.$$



- Q^2 is the squared 4-momentum transfer.
- Integrate over Q^2, total cross section dominated by the small Q^2 contribution, we have $\sigma_{e\chi} = 4\pi\,\alpha^2\varepsilon^2/{Q_{min}}^2$.
- **Light mediator:** the total cross section is dominated by the small Q^2 contribution

Backup Slides

DM Form Factor Defined in 1905.06348



$$F_{\text{DM}}(q) = \frac{q_{\text{ref}}^2 + m_{A'}^2}{q^2 + m_{A'}^2}\,,$$

which parametrizes the q dependence.

Alternatives (Straightforward)

1. **Quadruple incidence:** further background reduction, sacrifice event rate but potentially gain better control of background, reduce the background naively by **10^{-5}**
   Basically zero dark-current background experiment?

2. Different lengths for each detectors

3. Different materials:

Material	Photons/keV	Density (g/cm^3)	* Length needed (cm)	Speed (ns)	Cost for 5x5 cm ($)	Notes
Plastic BC408	10	1.03	145	~2	~200	Current choice
NaI	38	3.67	11	~230	~800	Slow, fragile
LaBr3(Ce)	63	5.08	5	~16	~3000	Radioactive
Liquid Xe	62	2.95	8	~2 / ~34	~1000?	Cryogenic, ultraviolet

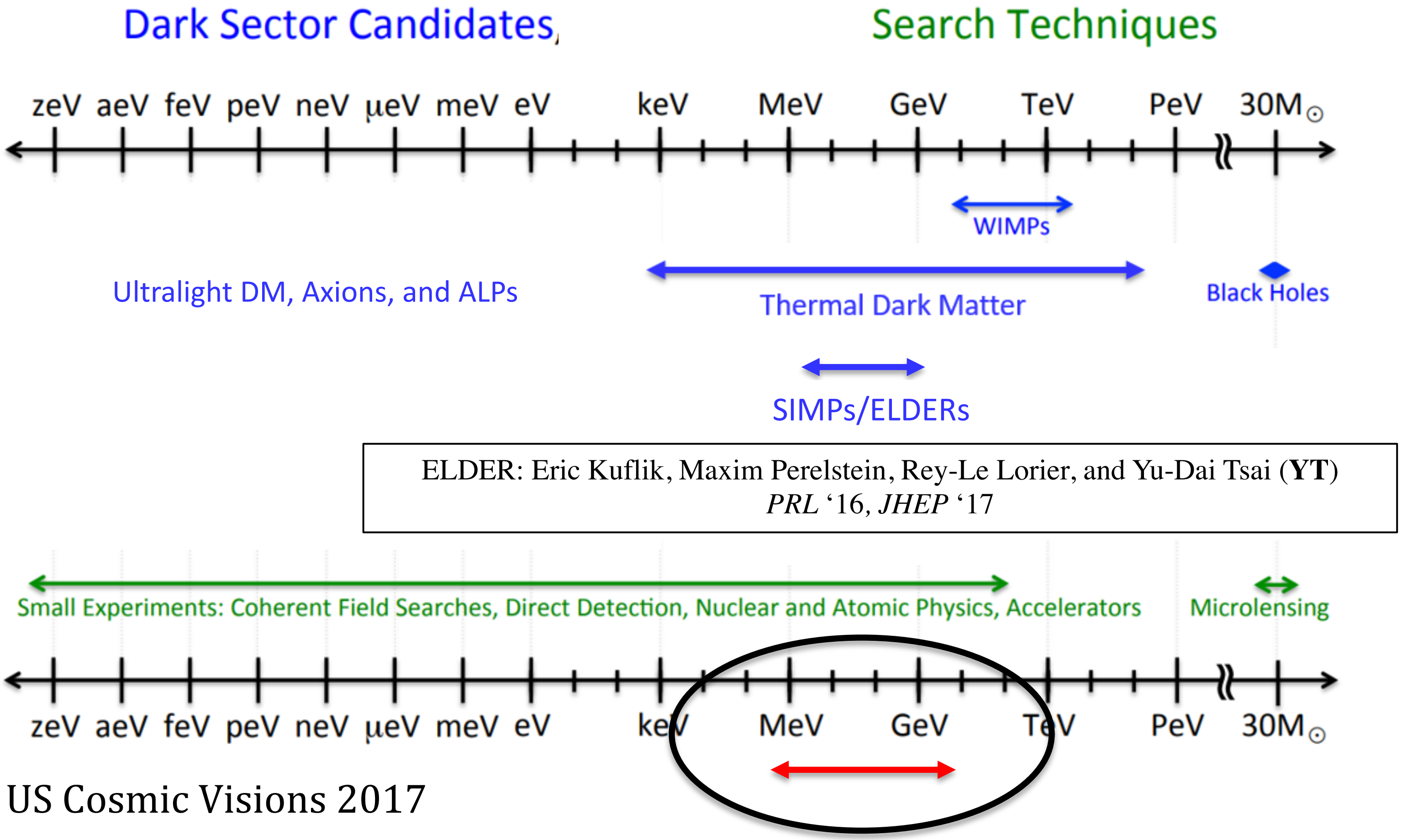
- Andy Haas, Fermilab, 2017

* Length needed to get 3 photons for charge 1/1000 e

Backup Slides

Even More Backup Slides
(Deleted Intro)

Exploration of Dark Matter & Dark Sector



ELDER: Eric Kuflik, Maxim Perelstein, Rey-Le Lorier, and Yu-Dai Tsai (**YT**)
PRL '16, *JHEP* '17

US Cosmic Visions 2017

- **Astrophysical/cosmological observations** are important to reveal the **actual story of dark matter (DM).**
- **Why FT experiments? And why MeV – GeV+?**

Proton FT Experiments

- High statistics, e.g. LSND has 10^{23} Protons on Target (POT)
- Shielded/underground: lower background
- Many of them existing and many to come:

  strength in numbers
- Relatively high energy proton beams on targets exist

  O(100 – 400) GeV (I will compare Fermilab/CERN facilities)
- Produce hidden particles / involve less assumptions

Backup
Slides

Why study MeV – GeV+ dark sectors?

Signals of discoveries grow from anomalies

Maybe nature is telling us something so we don’t have to search in the dark? ~~(most likely systematics?)~~

Backup
Slides

Some anomalies involving MeV-GeV+ Explanations

$\vdots$

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

$\vdots$

Below ~ MeV there are also **strong astrophysical/cosmological bounds**

ν Hopes for New Physics: Personal Trilogy

⋮

- **Light Scalar** & **Dark Photon** at Borexino & LSND

  Pospelov & **YT**, PLB '18, 1706.00424 (**proton charge radius anomaly**)

- **Dipole Portal Heavy Neutral Lepton**

  Magill, Plestid, Pospelov & **YT** , PRD '18, 1803.03262

  see also Coloma, Machado, Martinez-Soler, **Shoemaker**, 1707.08573

  (**LSND/MiniBooNE anomalies**)

- **Millicharged Particles** in Neutrino Experiments

  Magill, Plestid, Pospelov & **YT**, PRL '19, 1806.03310

  (**EDGES 21-cm measurement anomaly**)

deNiverville, Pospelov, Ritz, '11,

Batell, deNiverville, McKeen, Pospelov, Ritz, '14

Kahn, Krnjaic, Thaler, Toups, '14 …

⋮

New Physics in Proton FT Experiments

- **Millicharged Particles** in **FerMINI Experiments**

  Kelly & **YT,** 1812.03998

  (**EDGES Anomaly**)

- **Dark Neutrino** at Scattering Experiments: CHARM-II & **MINERvA!**

  Argüelles, Hostert, **YT**, 1812.08768, under *PRL* review

  (**MiniBooNE Anomaly**)

- **Probing Dark Photon, Inelastic Dark Matter**, and **Muon g-2 Windows** with **LongQuest Proposal!** (Comin out Monday night!)

Happy to talk about these during the coffee break; WH674

⋮

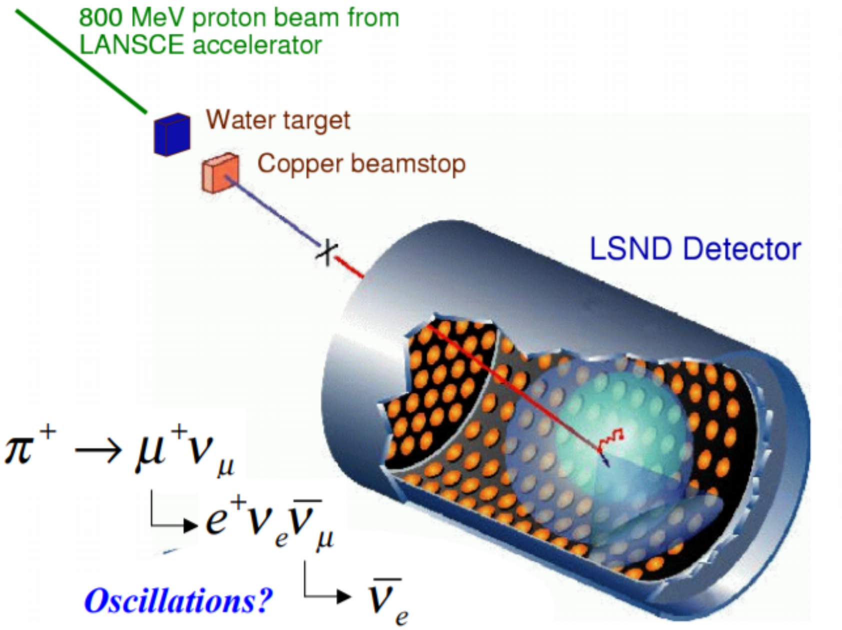
Other New Physics Probes

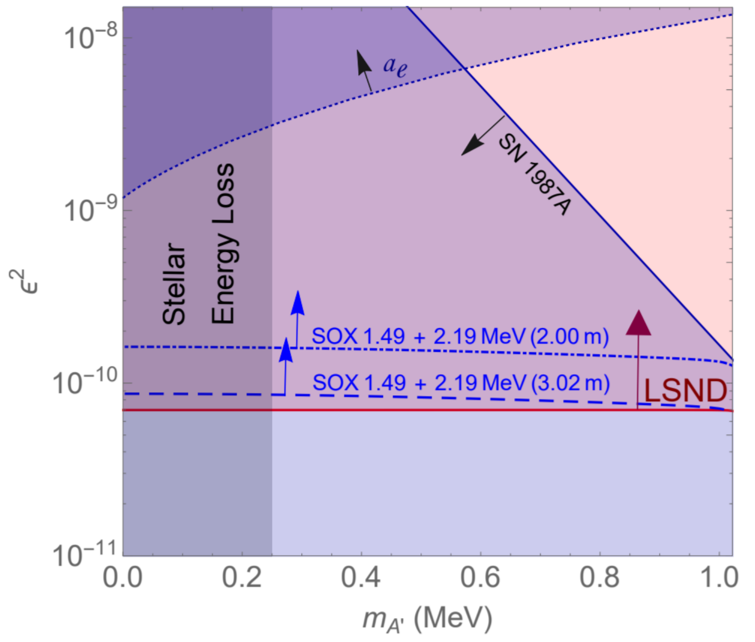
Backup
Slides

Dark Photon @ LSND

Pospelov & **YT**, PLB ‘18, 1706.00424

$$\mathcal{L}_{\rm d.ph.} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2(A'_\mu)^2 + \epsilon A'^\mu J_\mu^{EM}.$$





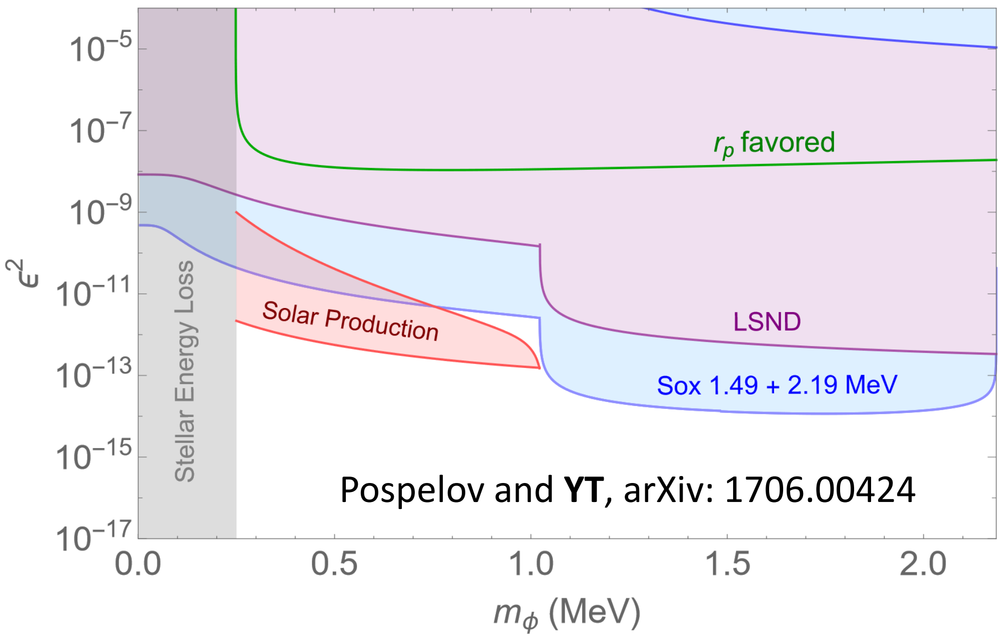
Backup
Slides

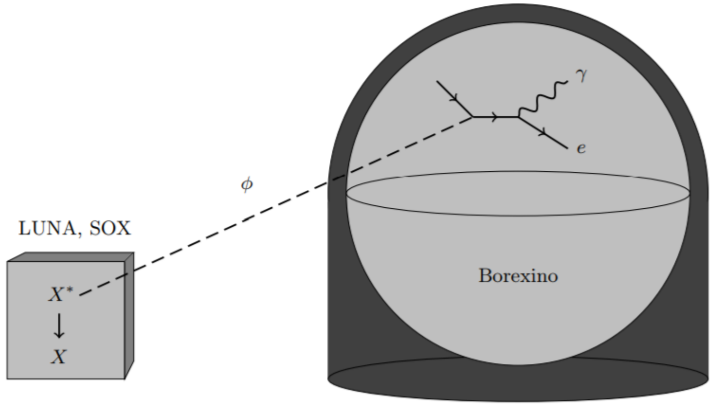
- Major energy depositions: $e + A' \to e + \gamma$.

Light Scalar @ LSND & Borexino

Pospelov & **YT**, PLB '18, 1706.00424

$$\mathcal{L}_\phi = \frac{1}{2}(\partial_\mu\phi)^2 - \frac{1}{2}m_\phi^2\phi^2 + (g_p\bar{p}p + g_n\bar{n}n + g_e\bar{e}e + g_\mu\bar{\mu}\mu + g_\tau\bar{\tau}\tau)\phi.$$





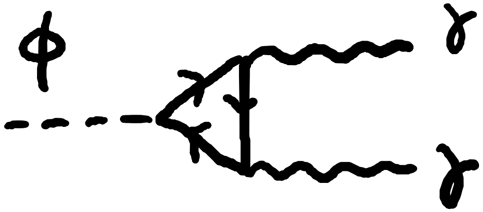
- β^- decay chain:

$$^{144}\text{Ce} \to {}^{144}\text{Pr} + e^- + \bar{\nu}_e$$
$$\searrow {}^{144}\text{Nd} + e^- + \bar{\nu}_e$$

$e\phi \to e\gamma$ $\qquad$ $\phi \to \gamma\gamma$ $\qquad$ $\phi \to e^+e^-$

$$\boxed{\epsilon^2 \equiv g_e g_p/e^2}$$

$$g_e = (m_e/m_\mu)g_\mu,\ g_\tau = (m_\tau/m_\mu)g_\mu,\ g_p = (m_p/m_\mu)g_\mu,$$



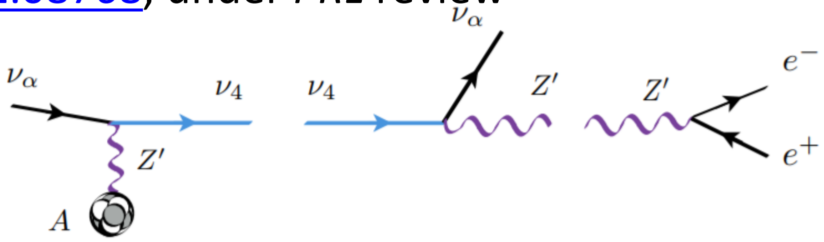
diphoton decay

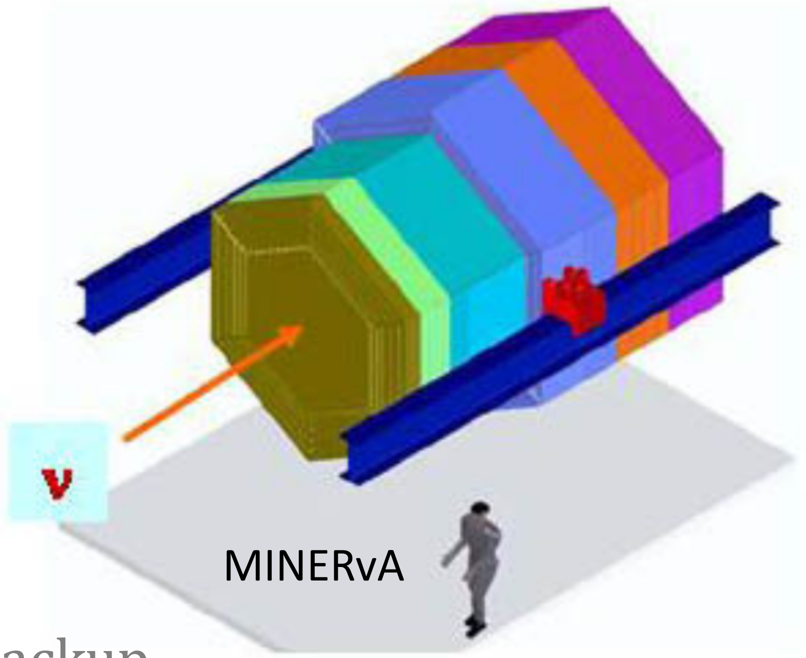
Dark Neutrino at CHARM & MINERvA

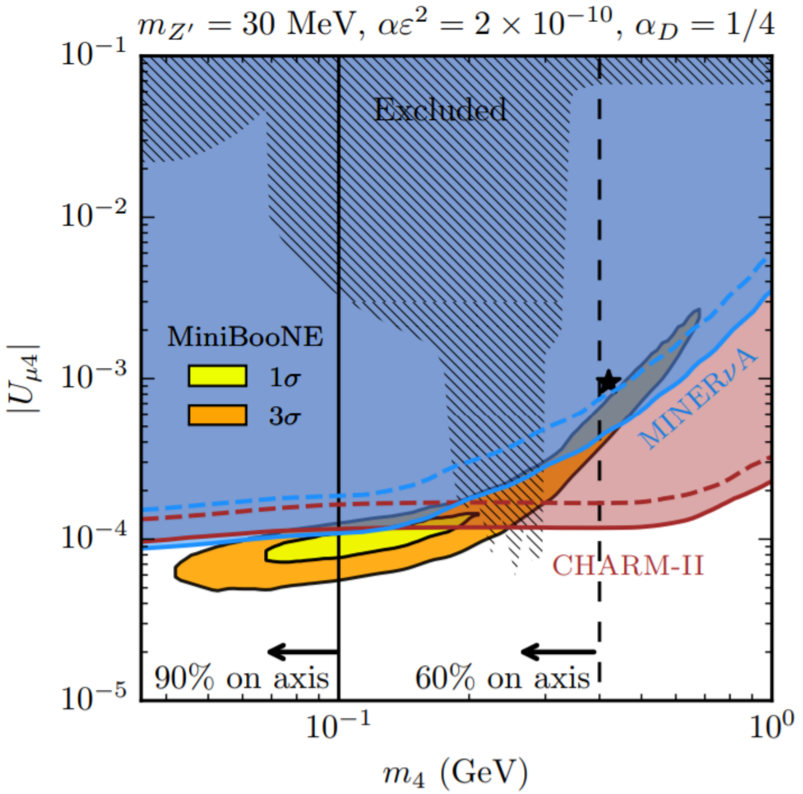
Argüelles, Hostert, **YT**, 1812.08768, under *PRL* review

$$\mathscr{L}_{\rm int} \supset \quad g_D \bar{\nu}_D \gamma_\mu \nu_D Z'^\mu + e\varepsilon Z'^\mu J^{\rm EM}_\mu,$$

$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i}\nu_i, \quad (\alpha = e, \mu, \tau, D).$$



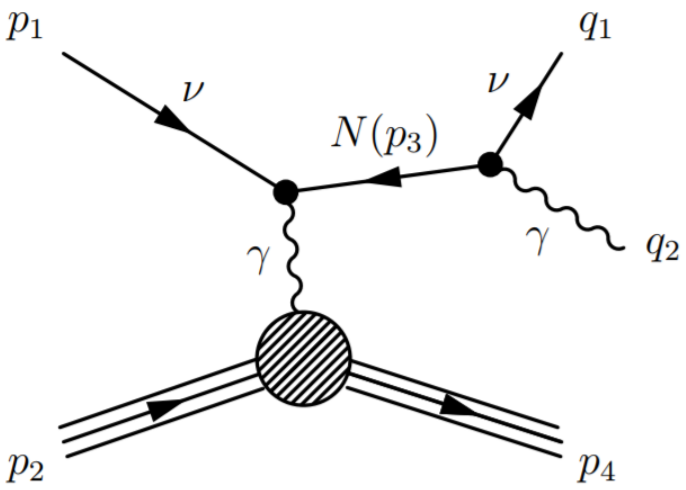




Backup Slides

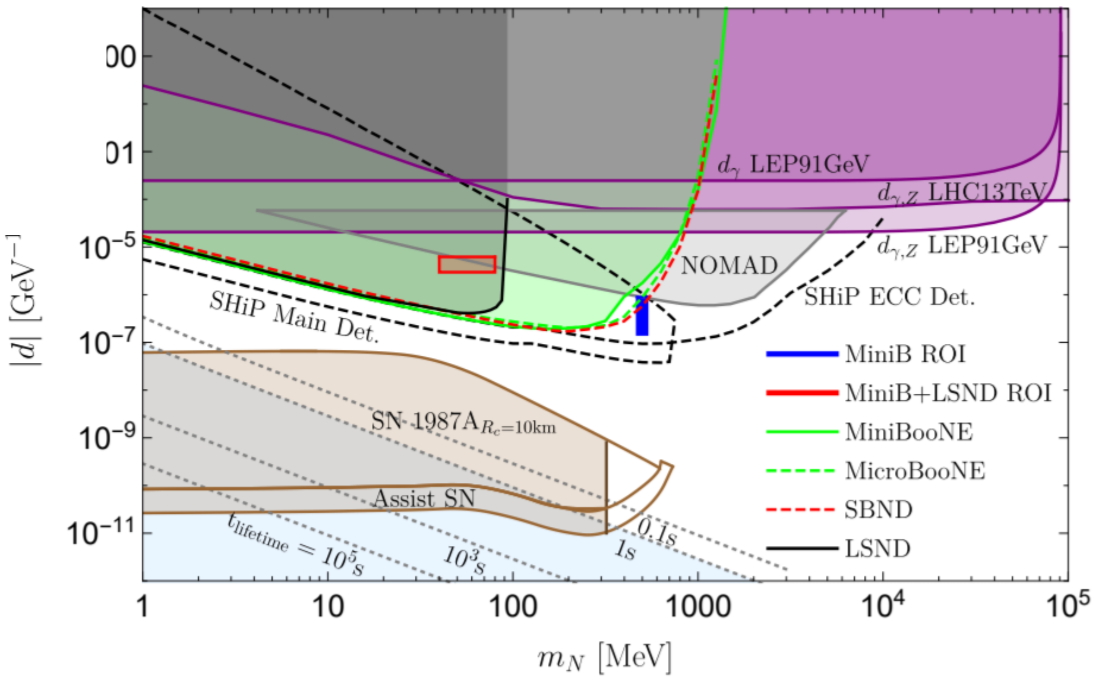
Dipole-Portal Heavy Neutral Lepton

Magill, Plestid, Pospelov & **YT** , PRD ’18, 1803.03262



$$\mathcal{L} \supset \bar{L}\left(d_{\mathcal{W}} \mathcal{W}^a_{\mu\nu}\tau^a + d_B B_{\mu\nu}\right)\tilde{H}\sigma_{\mu\nu}N_D + h.c.$$

$$\mathcal{L} \supset \bar{N}(i\not{\partial} - m_N)N + (d\bar{\nu}_L\sigma_{\mu\nu}F^{\mu\nu}N + h.c).$$



Backup Slides

(detail) Meson Production Details

- At LSND, the π0 (135 MeV) spectrum is modeled using a Burman-Smith distribution
- Fermilab's Booster Neutrino Beam (BNB): π0 and η (548 MeV) mesons. π0's angular and energy spectra are modeled by the **Sanford-Wang distribution**. η mesons by the Feynman Scaling hypothesis.
- SHiP/DUNE: pseudoscalar meson production using the **BMPT distribution**, as before, but use a beam energy of 80 GeV
- J/ψ (3.1 GeV), we assume that their energy production spectra are described by the distribution from **Gale, Jeon, Kapusta, PLB '99**, nucl-th/9812056.
- Upsilon, Y (9.4 GeV): Same dist. , normalized by data from HERA-B, I. Abt et al., PLB (2006), hep-ex/0603015.
- Calibrated with existing data [e.g. NA50, EPJ '06, nucl-ex/0612012, Herb et al., PRL '77]. and simulations from other groups [e.g. deNiverville, Chen, Pospelov, and Ritz, Phys. Rev. D95, 035006 (2017), arXiv:1609.01770 [hepph].]

FerMINI: Beam Related Background

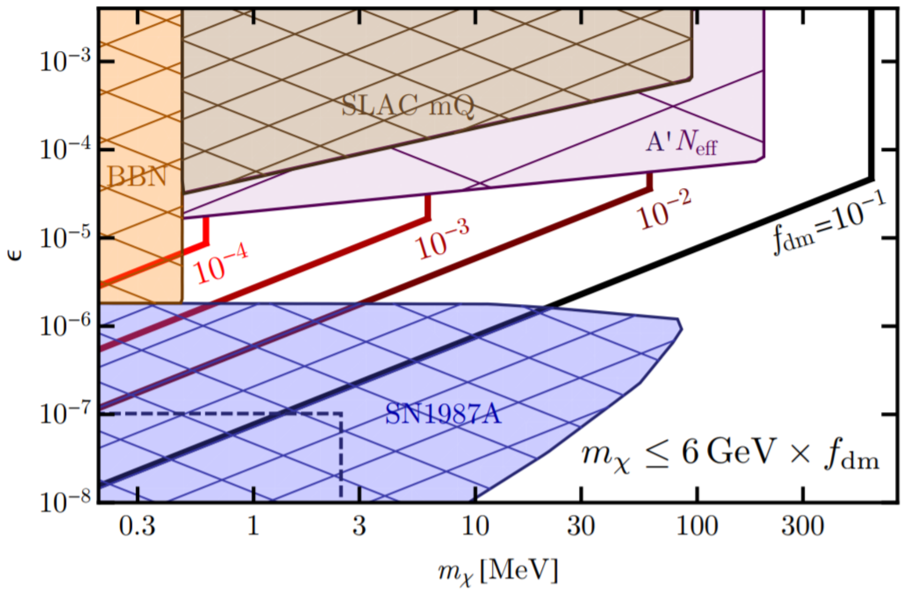
- Shielding: including **absorber and rocks.**
- Controlled: **muon monitors.**
- **Can determine the SM charged particle rate on site**
- **Vetoed similar to the previous veto of cosmic muons.**
- Neutrino produced hard-scattering background: **O($\mathbf{10^{-19}}$)**, negligible.
- To be conservative, we assume the **beam related background** ≈ **dark current background** for our sensitivity determination.
- Based on **SENSEI experience**, beam produced charge background is weaker than cosmic, but of course energy dependence
- Assumed to be at the same level of detector background

Backup
Slides

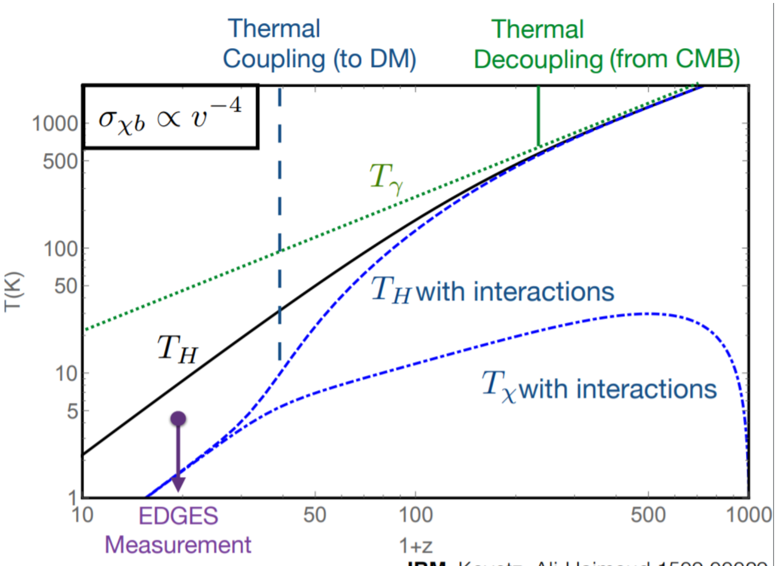
FerMINI: Increasing scintillation photons

- Elongating the scintillator bar does not affect the background from dark current (basically determined by the number of PMTs)
- So we estimate the sensitivity of FerMINI at DUNE for **five times larger scintillation capability**
- And estimate the sensitivity of FerMINI at NuMI for **five time more scintillation capability** but **five times less scintillator bar-PMT sets** (actually reduce dark current background!)

EDGES ANOMALY and MCP Solution



JBM and Loeb 1802.10094

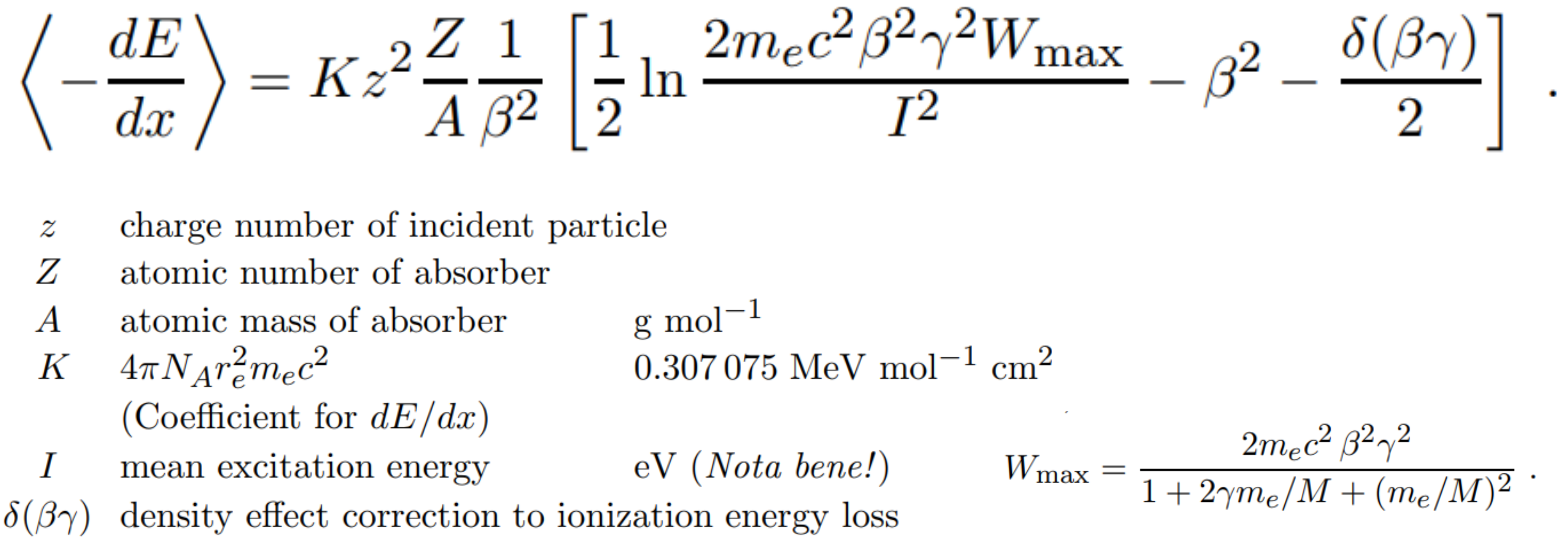


JBM, Kovetz, Ali-Haimoud 1509.00029

Backup
Slides

(Detail) dE/dx formula

- For moderately small epsilon and heavy enough MCP (>> electron mass), one can use Bethe equation to estimate average energy loss.



$$\left\langle -\frac{dE}{dx}\right\rangle = K z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right].$$

z	charge number of incident particle	
Z	atomic number of absorber	
A	atomic mass of absorber	g mol^{-1}
K	$4\pi N_A r_e^2 m_e c^2$ (Coefficient for dE/dx)	0.307 075 MeV mol^{-1} cm^2
I	mean excitation energy	eV (*Nota bene!*)
$\delta(\beta\gamma)$	density effect correction to ionization energy loss	

$$W_{\max} = \frac{2m_ec^2\,\beta^2\gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}.$$

- M: charged particle mass
- For **very small epsilon** (related to the finite length effect), one have to consider **most probable energy deposition & consider landau distribution** for the energy transfer, see arXiv:1812.03998

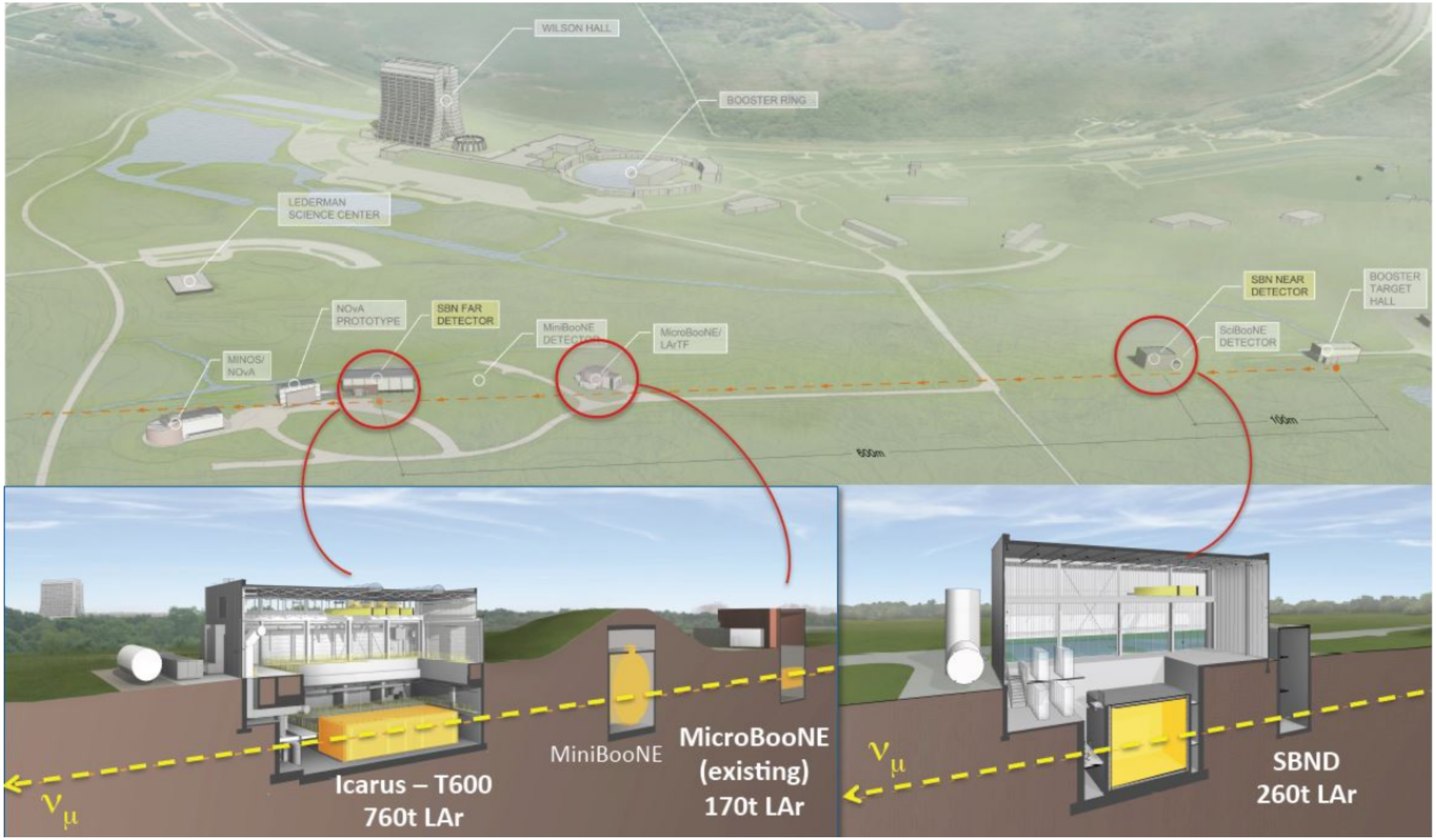
Backup Slides

MCP @ Neutrino Detectors

Backup
Slides

Yu-Dai Tsai, Fermilab, 2019

Neutrino Experiments



https://web.fnal.gov/collaboration/sbn_sharepoint/SitePages/Civil_Construction.aspx

SBND: Short Baseline Near Detector of Booster Beam
MiniBooNE: Mini-Booster Neutrino Experiment
ICARUS (Imaging Cosmic And Rare Underground Signals):
Now a Far Detector of Booster Beam

MCP Signals

- **signal events** s_{event}

$$s_{event} \simeq \sum_{\text{Energies}} N_\chi(E_i) \times \frac{N_e}{\text{Area}} \times \sigma_{e\chi}(E_i;\ m_\chi) \times \mathcal{E}.$$

detection efficiency

- $N_\chi(E_i)$: number of mCPs with energy E_i arriving **at the detector**.
- N_e: **total number of electrons** inside the active volume of the detector
- Area: active volume divided by the average length traversed by particles inside the detector.
- $\sigma_{e\chi}(E_i)$: **detection cross section consistent** with the angular and recoil cuts in the experiment
- Here, $s_{event} \propto \varepsilon^4$. ε^2 from N_x and ε^2 from $\boldsymbol{\sigma}_{ex}$
- Throughout this paper, we choose a credibility interval of $1 - \alpha = 95\%$ (~ 2 sigma)
- Roughly, $\varepsilon_{sensitivity} \propto E_{e,\,R,min}^{1/4}\ Bg^{1/8}$

MCP Bound/Sensitivity

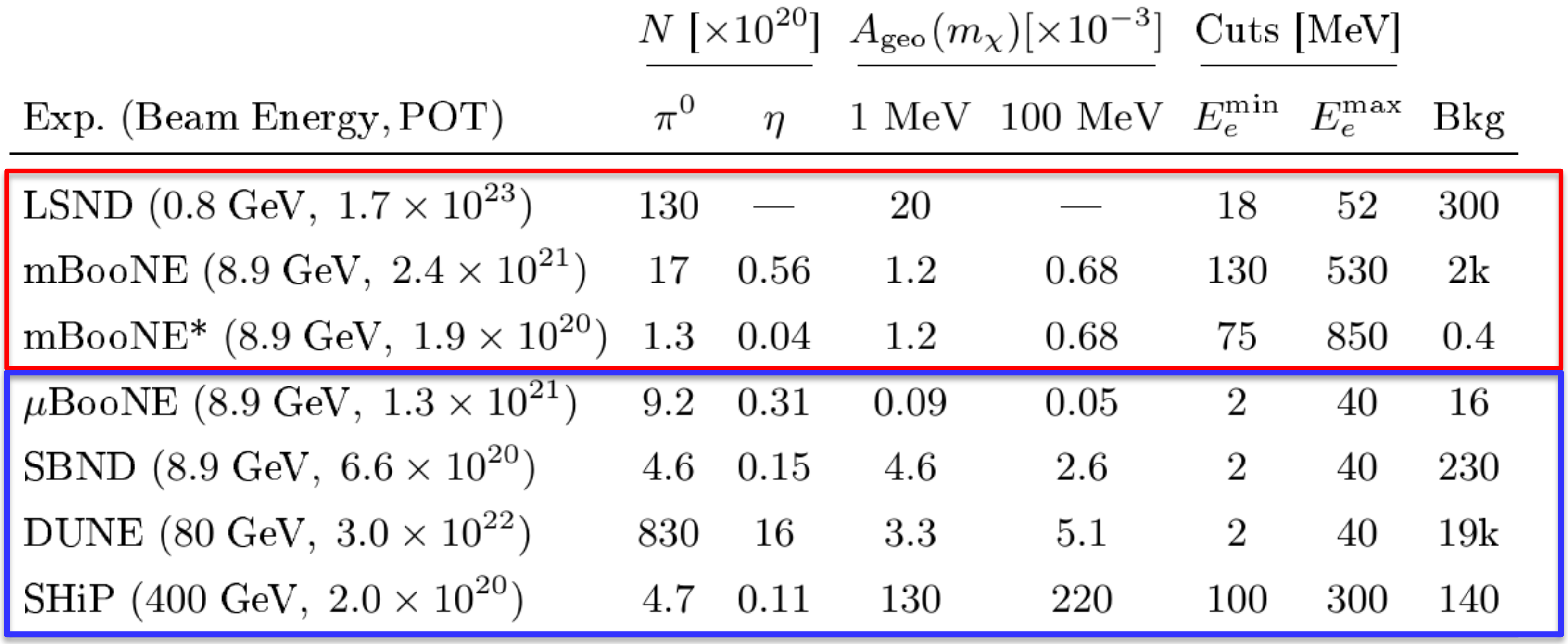
- **signal events s_{event}**

$$s_{event} \simeq \sum_{\text{Energies}} N_\chi(E_i) \times \frac{N_e}{\text{Area}} \times \sigma_{e\chi}(E_i;\; m_\chi) \times \mathcal{E}.$$

- Our sensitivity curves are obtained by performing a standard sensitivity analysis [PDG, PLB 2010]:
- Given a number of background events b and data n, the number of signal events s_{event} . The $(1 - \alpha)$ credibility level is found by solving the equation $\alpha = \Gamma(1 + n, b + s_{event})/\Gamma(1 + n, b)$, where $\Gamma(x, y)$ is the upper incomplete gamma function.
- Throughout this paper, we choose a credibility interval of $1 - \alpha = 95\%$ (~ 2 sigma)

Backup Slides

Summary Table



		N [$\times 10^{20}$]		$A_{\rm geo}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
	Exp. (Beam Energy, POT)	π^0	η	1 MeV	100 MeV	$E_e^{\rm min}$	$E_e^{\rm max}$	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

- $\varepsilon \propto E_{e,\,R,min}^{1/4}\ Bg^{1/8}$
- $\cos\theta > 0$ is imposed (∗except for at MiniBooNE's DM run where a cut of $\cos\theta > 0.99$ 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.

Backup Slides

Recasting Existing Analysis: LSND, MiniBooNE, and MiniBooNE* (DM Run)

- **LSND**: hep-ex/0101039. Measurement of **electron-neutrino electron elastic scattering**
- **MiniBooNE**: arXiv:1805.12028.
  Electron-Like Events in the MiniBooNE Short-Baseline Neutrino Experiment, combines data from both **neutrino and anti-neutrino runs** and consider a sample of **2.4×10^{21}POT** for which we take the **single electron background to be 2.0×10^{3}** events and the **measured rate to be 2.4×10^{3}**
- **MiniBooNE* (DM run)**: arXiv:1807.06137 (came out after our v1)**.**
  Electron recoil analysis.
  Thick target + no horn focusing +
  A cut of cos $\theta > 0.99$ effectively reduces backgrounds to basically zero [Dharmapalan, MiniBooNE, (2012)]).

Backup
Slides