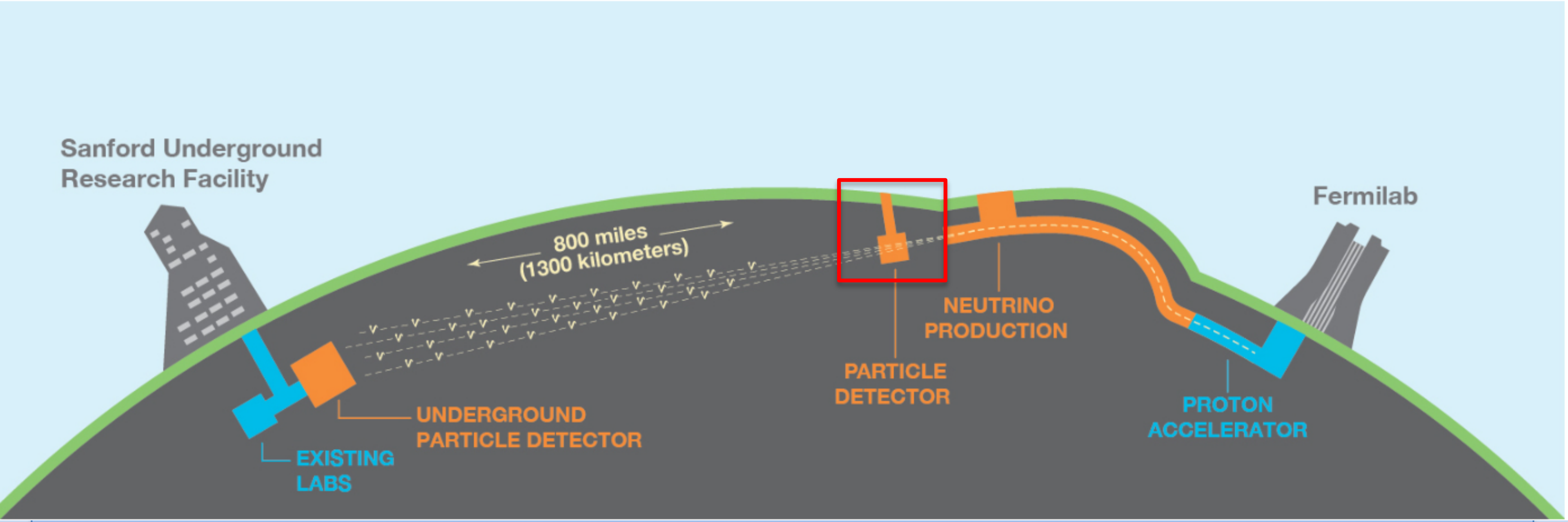


FerMINI - Fermilab Search for Millicharged Particles & Strongly Interacting Dark Matter

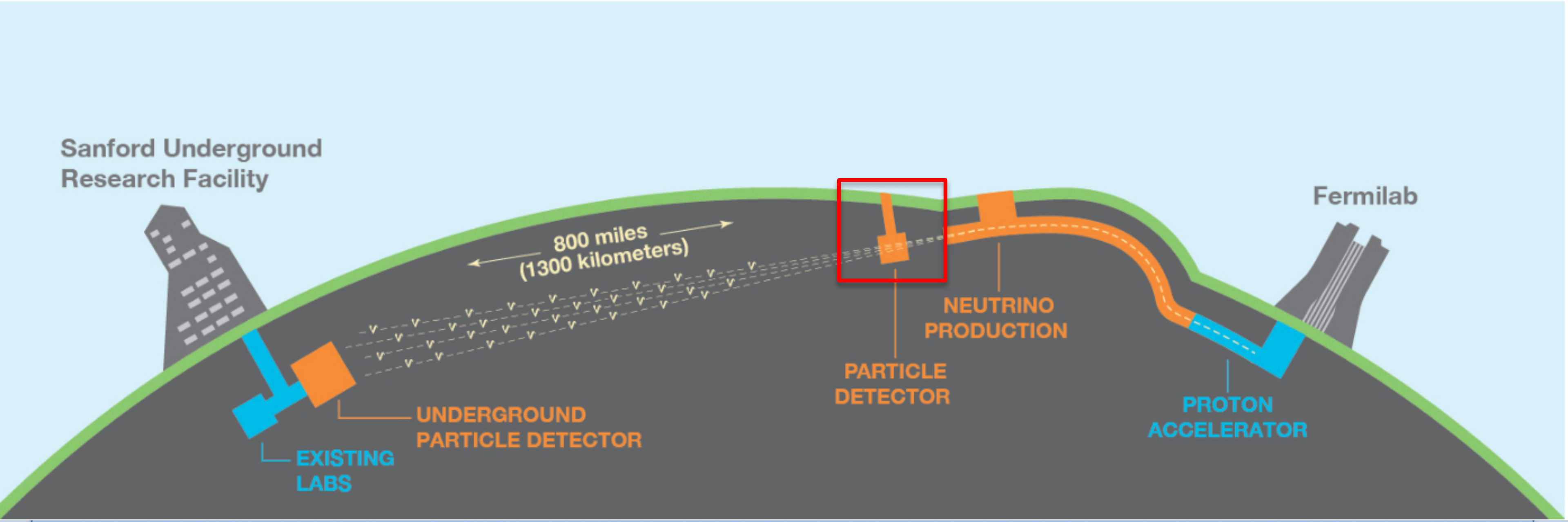
Yu-Dai Tsai, Fermilab/U.Chicago (WH674)

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

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

New paper out: 1908.07525 (to submit to PRL)

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



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! Coming out now: 1908.07525

FerMINI Proposal May '19

Chris Hill
OSU

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Jim Hirschauer
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David Miller
U Chicago

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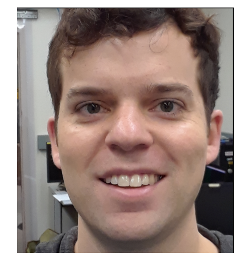

Ryan Heller
Fermilab

Maxim Pospelov
Minnesota / Perimeter

Ryan Plestid
McMaster

Albert de Roeck
CERN

Joe Bramante
Queen's U

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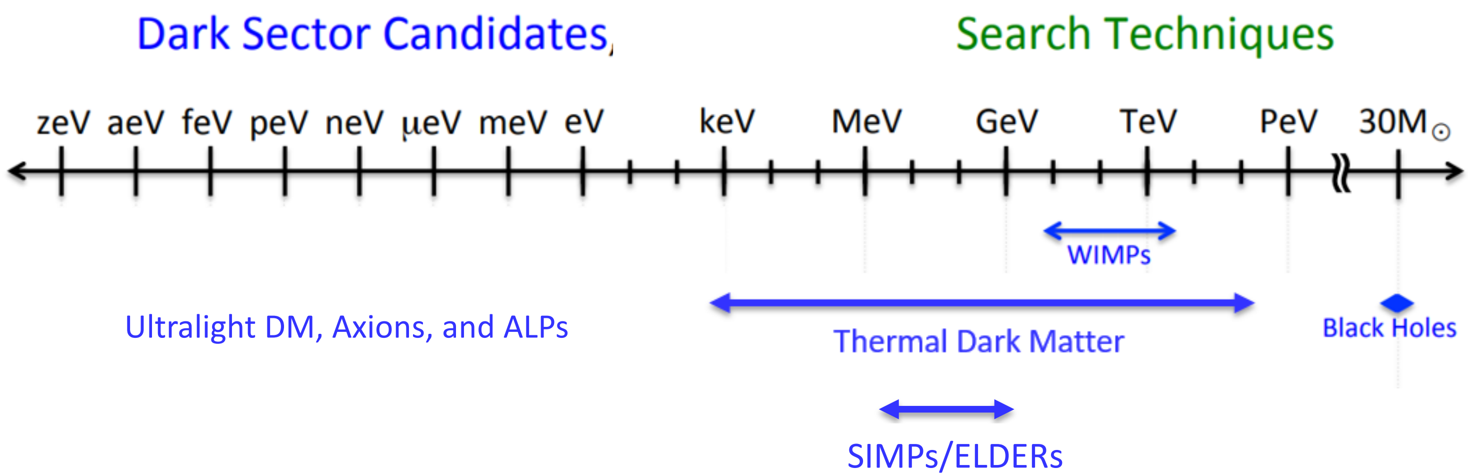
Outline

- Motivations
- Dark Sectors @ Fixed-Target & Neutrino Experiments
- Millicharged Particle (mCP)
- Bounds & Projections @ Neutrino Detectors
- **The FerMINI Experiment**
- Connect to Strongly Interacting Dark Matter

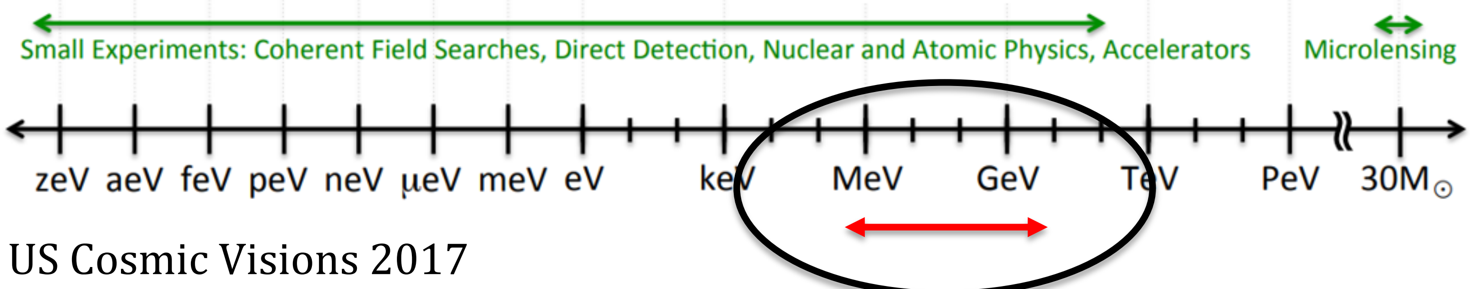
Neutrino & Proton Fixed-Target (FT) Experiments:

Some natural habitats for signals of
weakly interacting / long-lived / hidden particles

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 Neutrino/FT experiments? And why MeV – GeV+?**

Neutrino & Proton FT Experiments

- Neutrinos are **weakly interacting particles**.
- 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

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

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?)~~

Yu-Dai Tsai, Fermilab, 2019

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**

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, submitted to *PRL*

  (**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

⋮

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 in e charges? 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) (WIMP or Freeze-in scenarios)

- 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 to explain the EDGES anomaly (severely constrained, see **more reference later**)

Millicharged Particle: Models

mCP Model

- Small charged particles under U(1) hypercharge

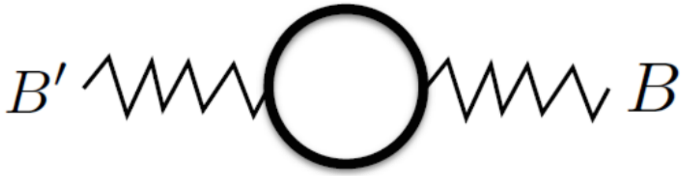
$$\mathcal{L}_{\mathrm{MCP}} = i\bar{\chi}(\not{\partial} - i\epsilon' e \not{B} + M_{\mathrm{MCP}})\chi$$

- 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 χ**



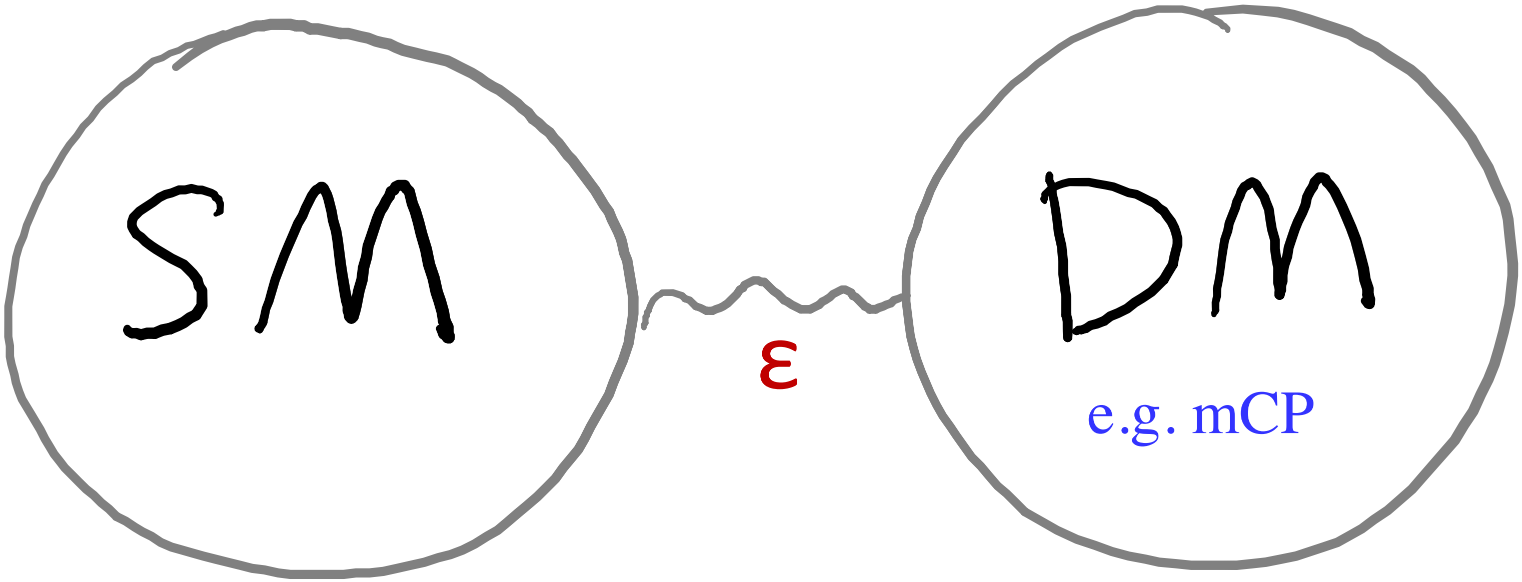
(SM: Standard Model)

See, Holdom, 1985

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

- New Fermion χ charged under 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): $Q = \kappa e' \cos\theta_W$ $\epsilon \equiv \kappa e' \cos\theta_W / e.$

The Rise of Dark Sector



Yu-Dai Tsai, Fermilab, 2019

Important Notes!

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

  (finding MCP in the regime massless or light A’ is strongly

  constrained by cosmology!)

- More **violent violation of the charge quantization**

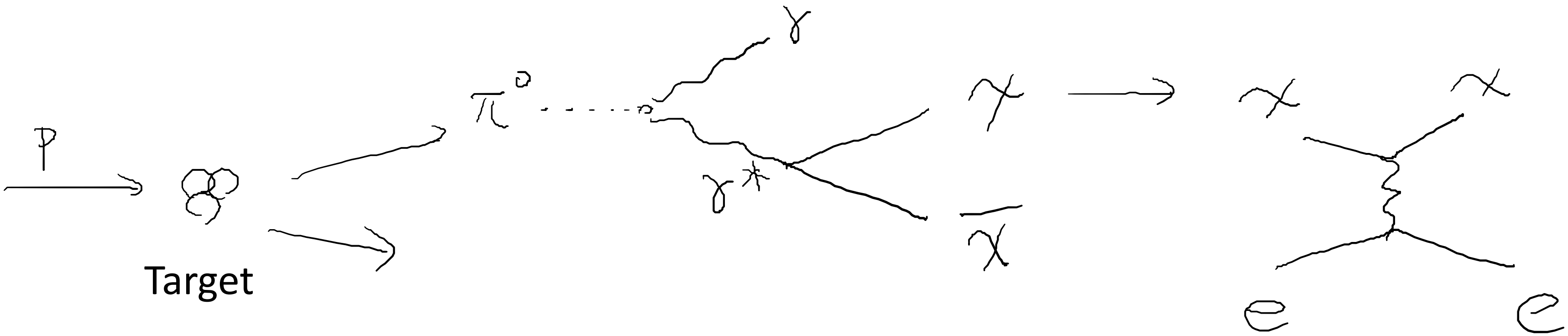
  (if not generating millicharge through kinetic mixing)

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

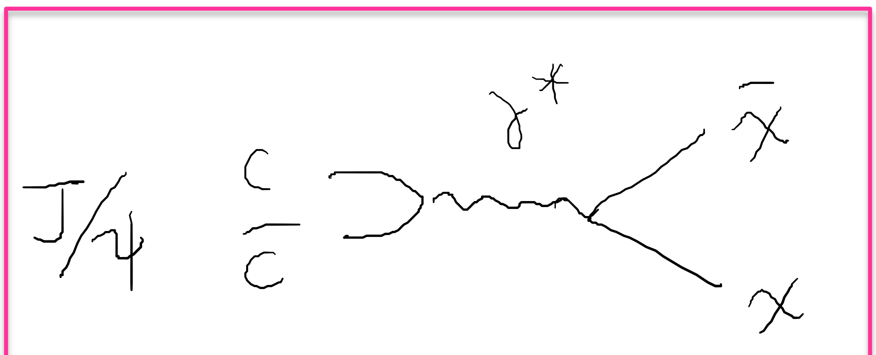
  see Shiu, Soler, Ye, arXiv:1302.5471, PRL ’13 for more detail.

Millicharged Particle: Signature

MCP (or light DM with light mediator): production & detection



- ❑ production:
  meson decays
- ❑ detection:
  scattering electron



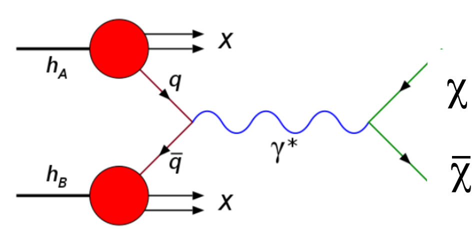
BR($\pi^0 \rightarrow 2\gamma$) = 0.99

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

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

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

- ❑ **Heavy mesons are important for higher mass mCP's in high enough beam energy**
- ❑ **Important and often neglected!**

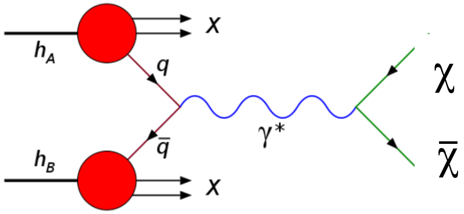


MCP productions

- For **η** & **π^0**, Dalitz decays: $\pi^0/\eta \rightarrow \gamma\,\chi\,\bar{\chi}$ dominate
- For **J/ψ** & **Υ**, direct decays: J/ψ, $\Upsilon \rightarrow \chi\,\bar{\chi}$ dominate.
  Important for high-mass mCP productions!
- The branching ratio for a meson, *M*, to mCPs is given roughly by

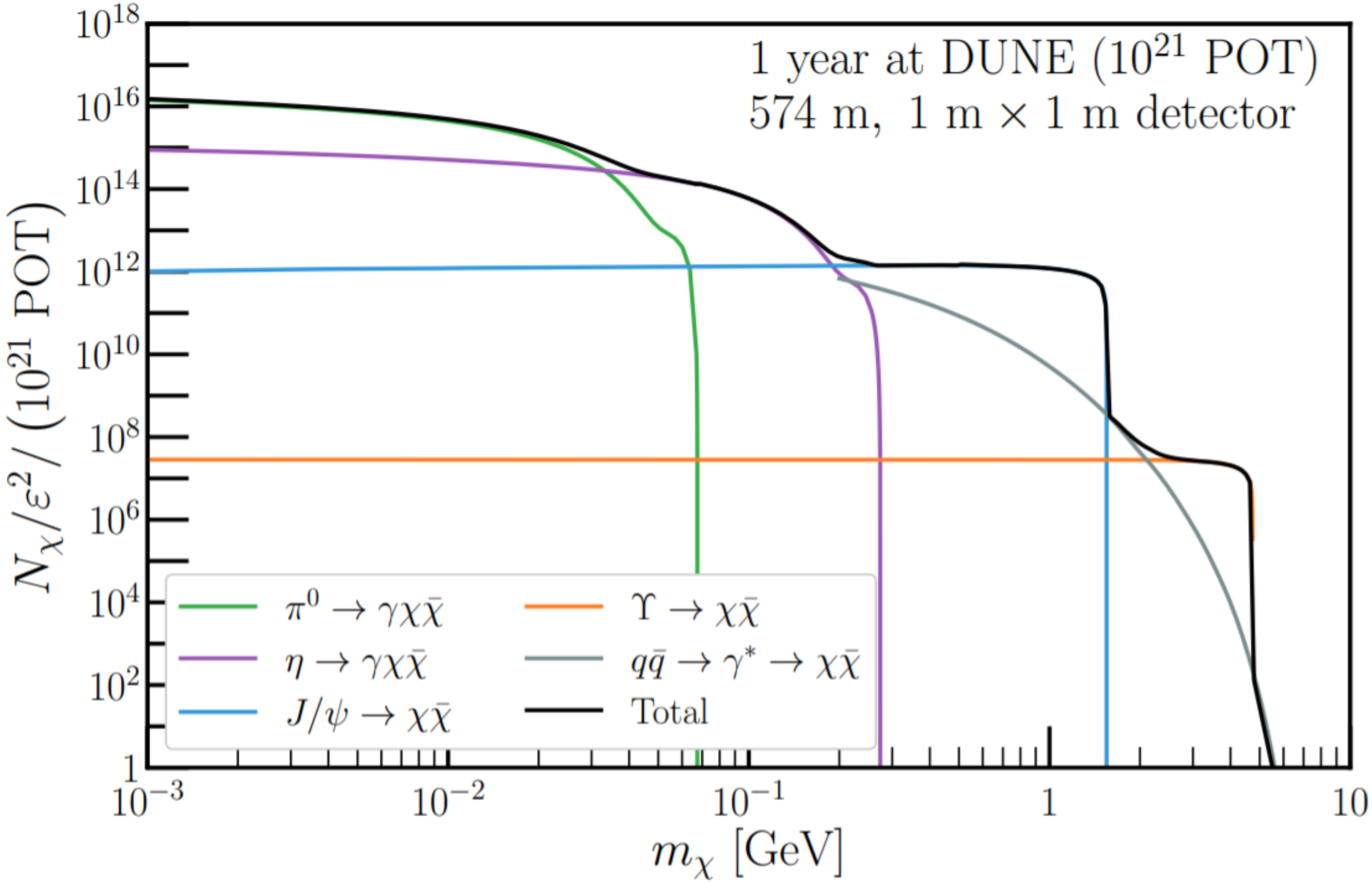
$$\mathrm{BR}(\mathcal{M} \to \chi\bar{\chi}) \approx \epsilon^2 \times \mathrm{BR}(\mathcal{M} \to X e^+ e^-) \times f\left(\frac{m_\chi}{M}\right),$$

- M: the mass of the parent meson, X:any additional particles, $f(m_\chi/M)$: phase space factor as a function of m_χ/M.
- Also consider **Drell-Yan production of mCP** from **q q-bar annihilation**.



https://en.wikipedia.org/wiki/Drell%E2%80%93Yan_process

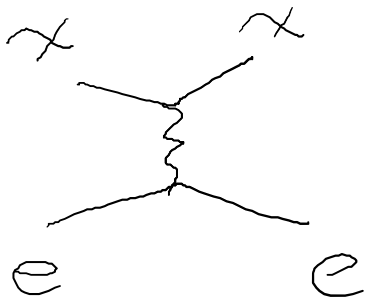
MCP Production/Flux



- We 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, $f(m_\chi/M)$: phase space factor
- We also include Drell-Yan production for the high mass MCPs (see arXiv:1812.03998)

Detection: MCP Elastic Scattering with Electrons

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



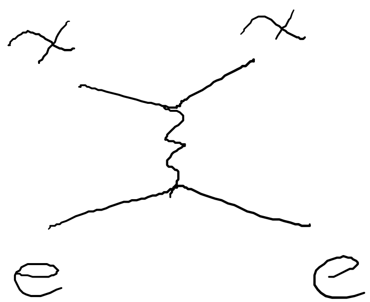
- $\boldsymbol{Q^2}$ is the squared 4-momentum transfer.
- Integrate over Q^2, total cross section dominated by the small Q^2 contribution, we have $\sigma_{e\chi} = 4\pi\,\alpha^2\varepsilon^2/Q_{min}{}^2$.
- **Light mediator:** the total cross section is dominated by the small Q^2 contribution

MCP Detection: electron scattering

- 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

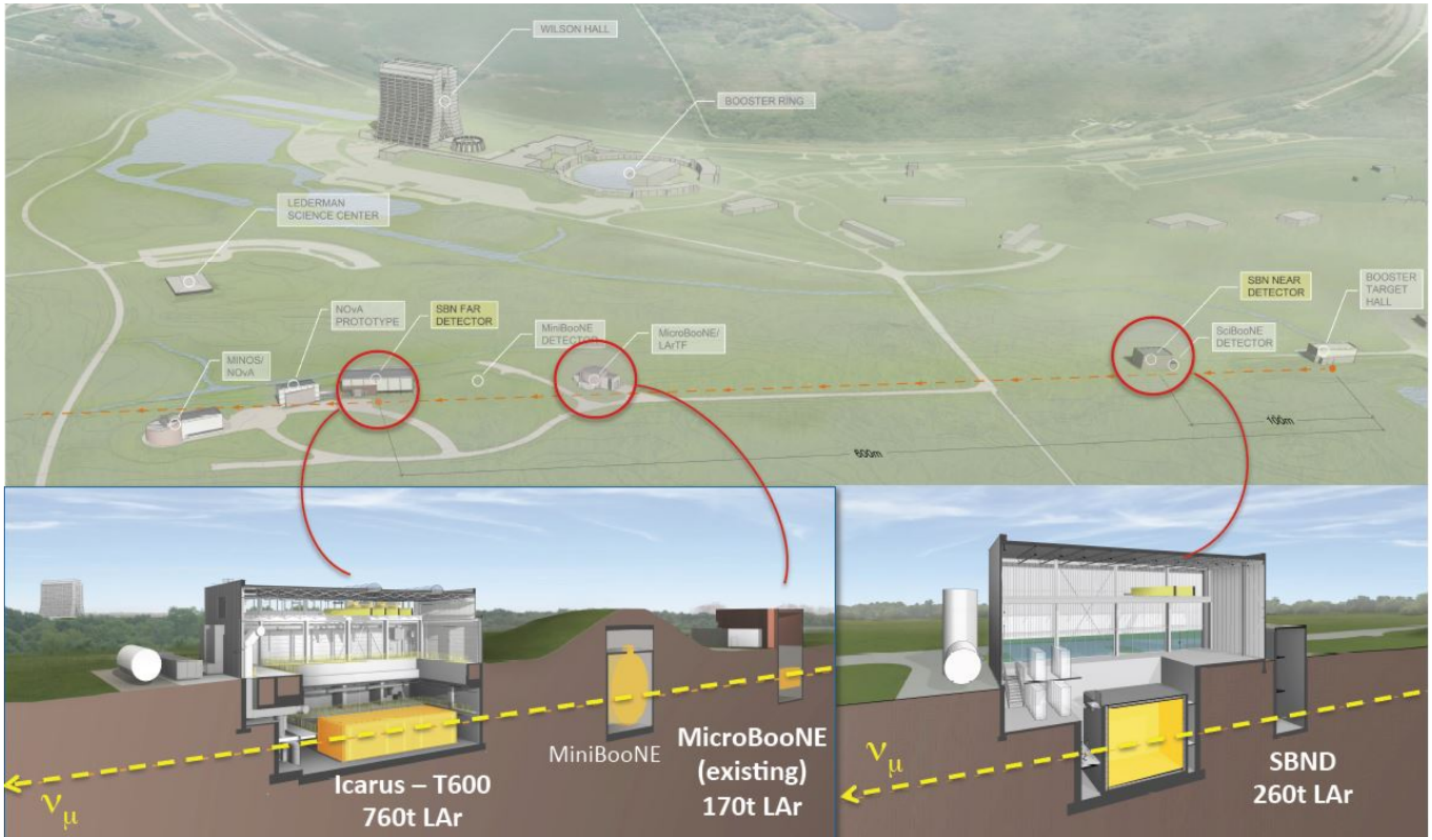
$$\sigma_{e\chi} = 2.6 \times 10^{-25}\mathrm{cm}^2 \times \epsilon^2 \times \frac{1\ \mathrm{MeV}}{E_e^{(\mathrm{min})} - m_e}.$$

- Sensitivity greatly enhanced by accurately **measuring low energy electron recoils for mCP's & light dark matter - electron scattering,**
- See e.g., Magill, Plestid, Pospelov, **YT**, 1806.03310 & deNiverville, Frugiuele, 1807.06501 (for sub-GeV DM)



MCP @ Neutrino Detectors

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, $\varepsilon_{sensitivity} \propto E_{e,\,R,min}^{1/4}\ Bg^{1/8}$

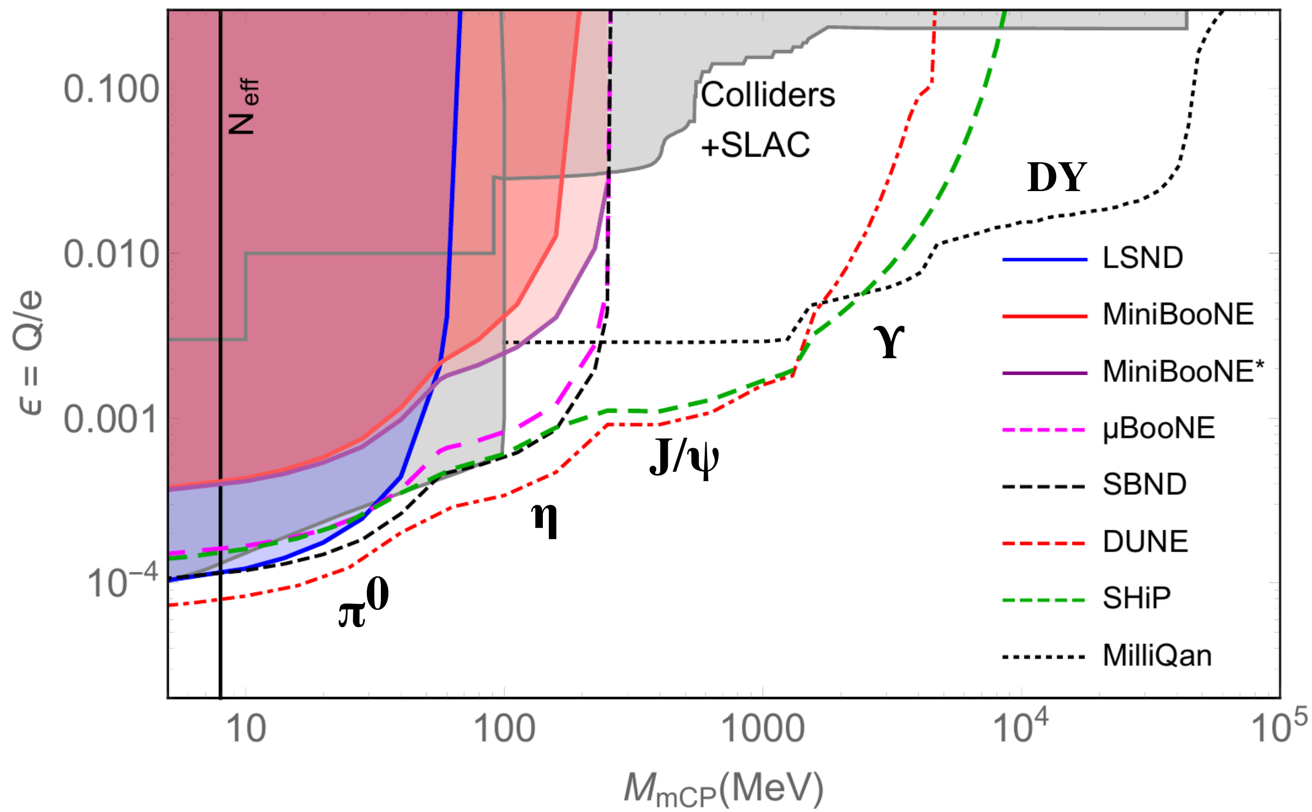
MCP Bound/Sensitivity

- **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)

Sensitivity and Contributions



- MilliQan: Haas, Hill, Izaguirre, Yavin, (2015), + (LOT arXiv:1607.04669)
- N_{eff}: Bœhm, Dolan, and McCabe (2013)
- Colliders/Accelerator: Davidson, Hannestad, Raffelt (2000)
- SLAC mQ: Prinz el al, PRL (1998);

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 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.

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)]).

Background for Future Measurements

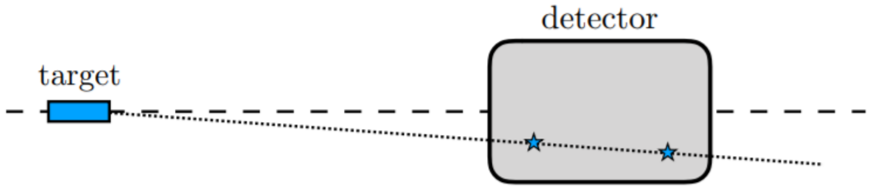
- Single-electron background for ongoing/future experiments for **MicroBooNE, SBND, DUNE, and SHiP?**
- Background discussions:

  1) From neutrino fluxes (calculable),

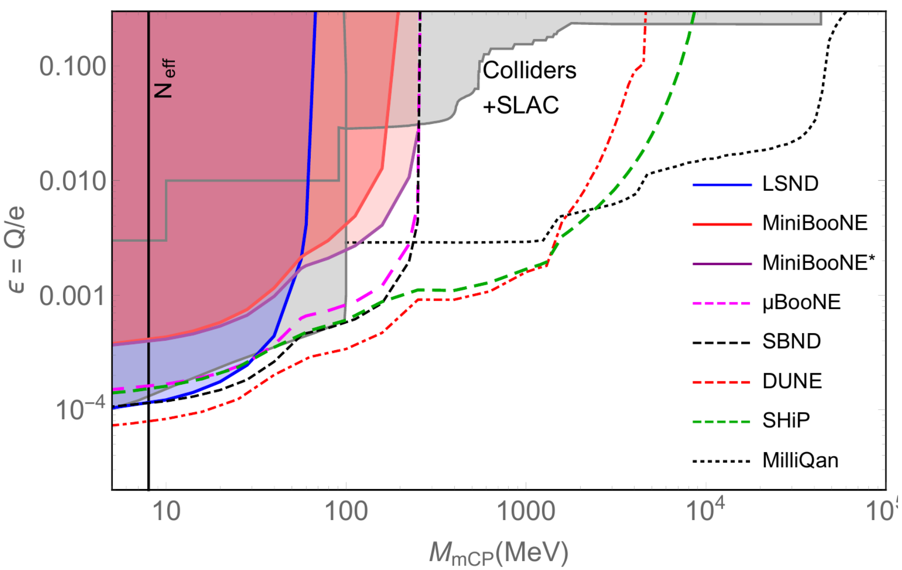
     [i.e. **ve** → **ve** and **vn** → **ep**], greatly reduced by **maximum electron recoil energy cuts E_e(max)**

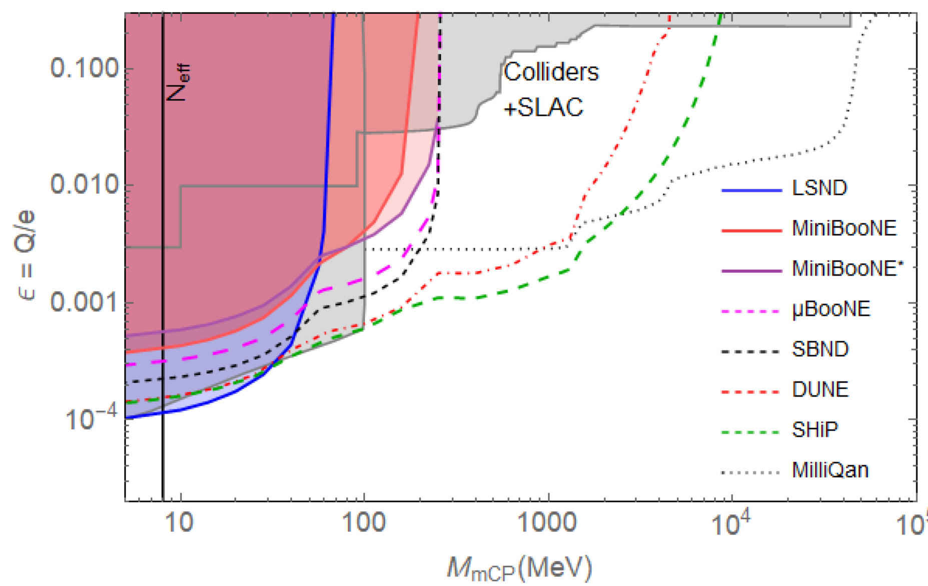
  2) other: times a factor (10-20) to account for these

  3) Harnik, Liu, Ornella: multi-scattering, point back to target to reduce the background (ArgoNeuT), arXiv:1902.03246!



More Conservative Cuts on Threshold





$$\varepsilon \propto E_{e,R,min}^{1/4}$$

Exp. (Beam Energy, POT)	Cuts [MeV] $E_e^{\min}$	Cuts [MeV] $E_e^{\max}$
μBooNE (8.9 GeV, 1.3×10^{21})	2	40
SBND (8.9 GeV, 6.6×10^{20})	2	40
DUNE (80 GeV, 3.0×10^{22})	2	40

Cuts [MeV] $E_e^{\min}$	Cuts [MeV] $E_e^{\max}$
30	70
30	70
30	70

Summary

- Technique can be easily applied to more generic **light dark matter** and other **hidden particles with light mediators**

  - Production from **heavy neutral mesons** are important (often neglected in literature)

  - Signature favor **low electron-recoil energy threshold**

- For more realistic analysis: include realistic **background,** $E_{e,\,R,min}$ **cut**, etc

Low-cost Fixed-target Probes of Long-Lived Particles

FerMINI as an example:

more to come!

Yu-Dai Tsai, Fermilab, 2019

FerMINI:

Putting dedicated Minicharge Particle Detector (~$2M)
@ Fermilab Beamlines: NuMI or LBNF or @ CERN: SPS
Kelly, **YT**, arXiv:1812.03998 (PRD'19)

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

MilliQan at CERN

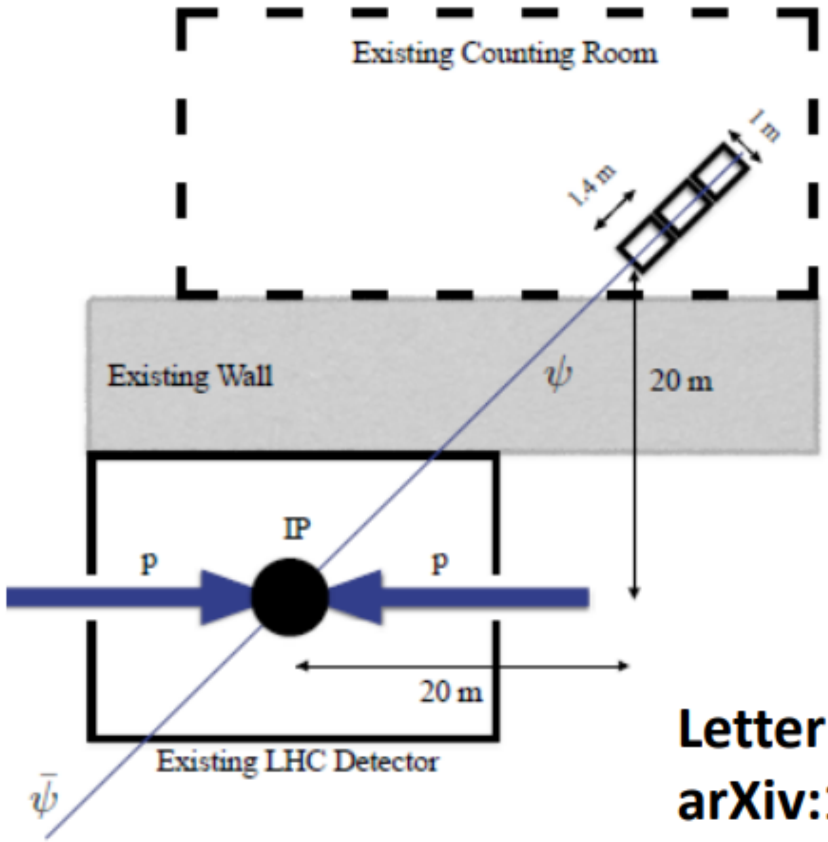
Austin Ball, Jim Brooke, Claudio Campagnari, Albert De Roeck, Brian Francis, Martin Gastal, Frank Golf, Joel Goldstein, **Andy Haas, Christopher S. Hill, Eder Izaguirre**, Benjamin Kaplan, Gabriel Magill, Bennett Marsh, David Miller, Theo Prins, Harry Shakeshaft, David Stuart, Max Swiatlowski, **Itay Yavin**

arXiv:1410.6816, PRD ’15

arXiv:1607.04669, Letter of Intent (LOT)

MilliQan: 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



Letter of intent: arXiv:1607.04669

Andrew Haas, Fermilab (2017)

MilliQan: Design

- Total: **1 m × 1 m** (transverse plane) × **3 m** (longitudinal) **plastic scintillator array.**
- Long axis points at the **CMS Interaction Point (P5)**.
- **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)**.

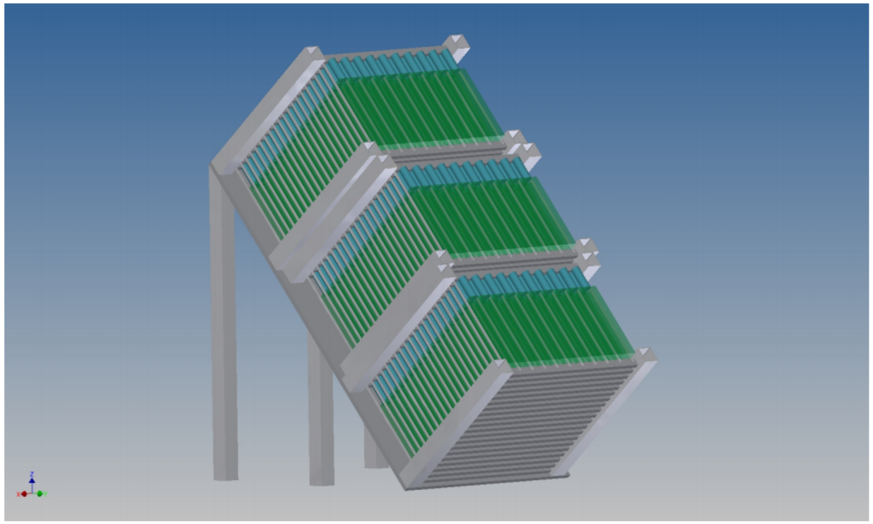


Figure from 1607.04669 (milliQan LOT)

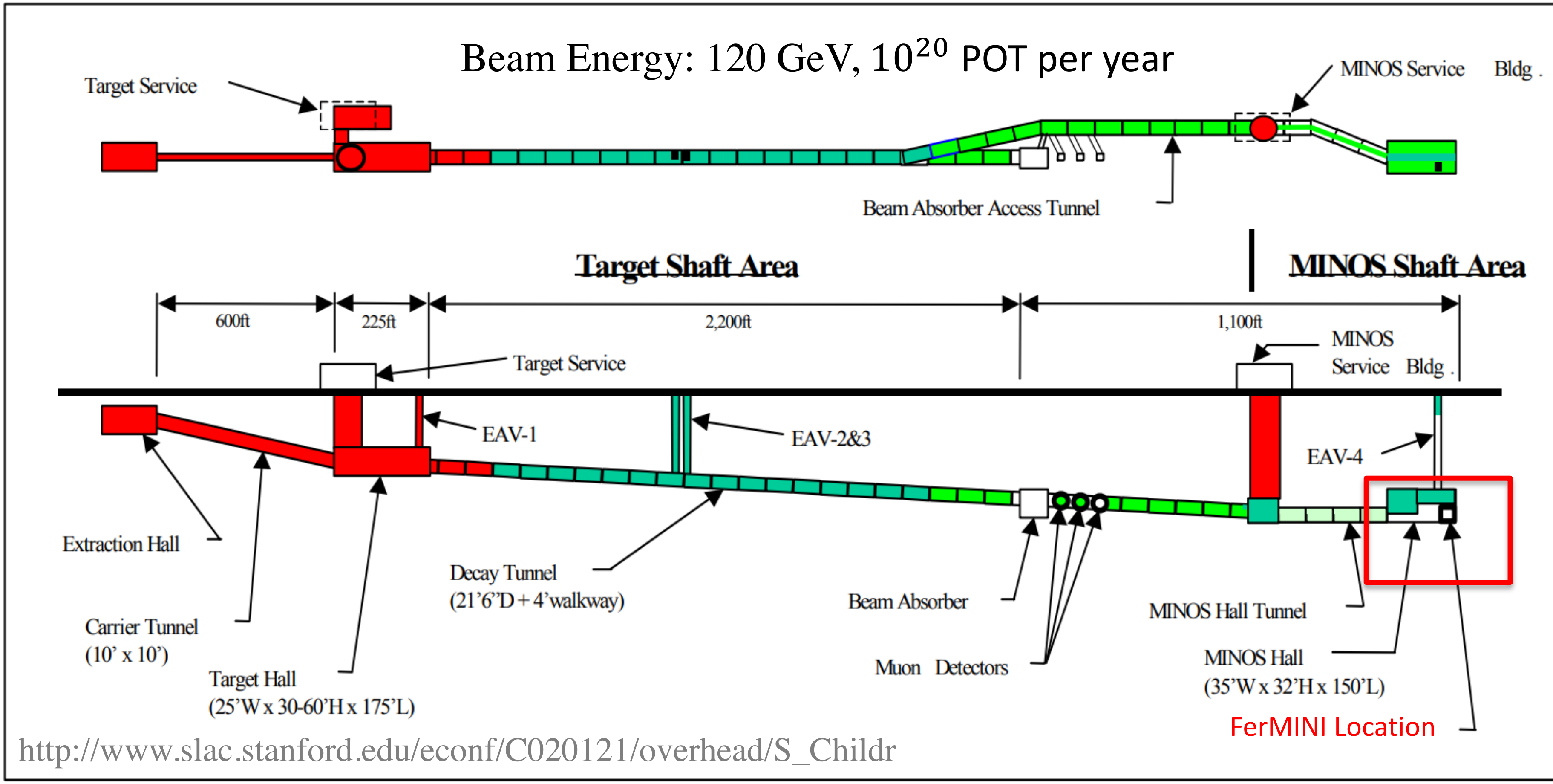
FerMINI:

A Fermilab Search for MINI-charged Particle

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

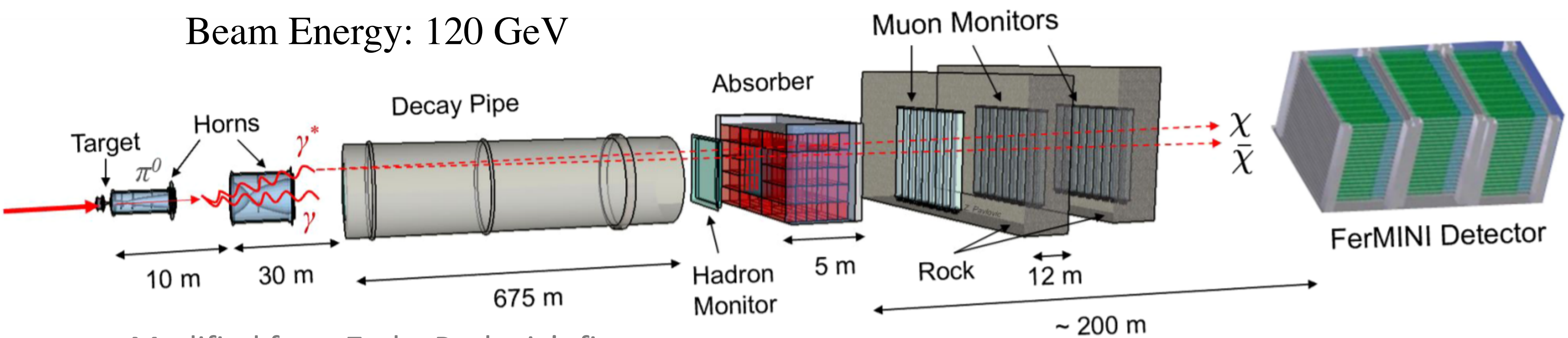
visually "an experiment made of stacks of light sabers"

Site 1: NuMI Beam & MINOS ND Hall



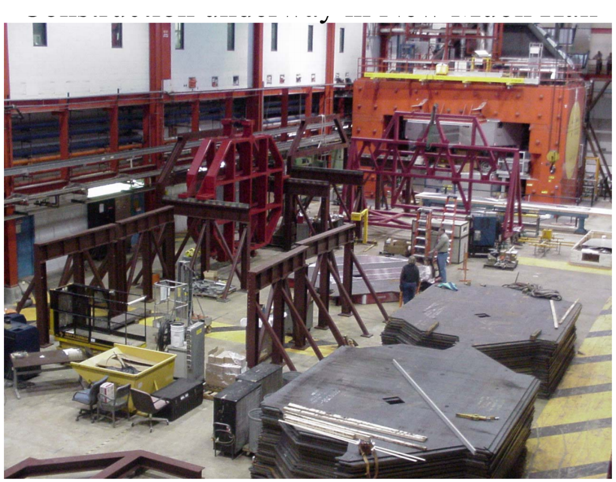
NuMI: Neutrinos at the Main Injector
MINOS: Main Injector Neutrino Oscillation Search, ND: Near Detector
(**MINERvA**: Main Injector Experiment for ν-A is also here)

FerMINI @ NuMI-MINOS Hall



Modified from Zarko Pavlovic's figure

An illustration of the FerMINI experiments utilizing the NuMI facility.

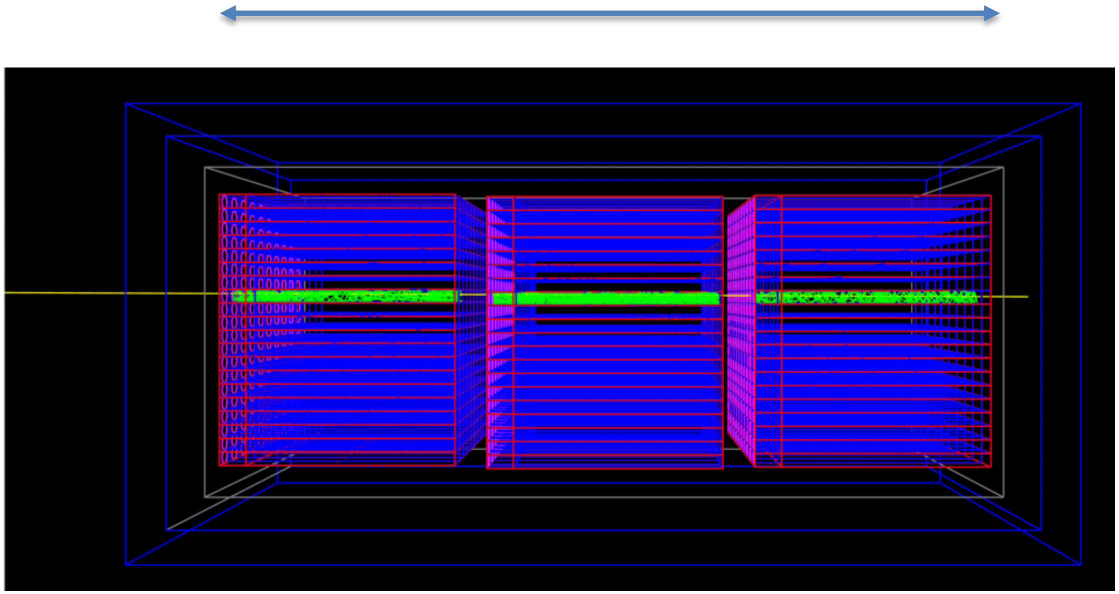


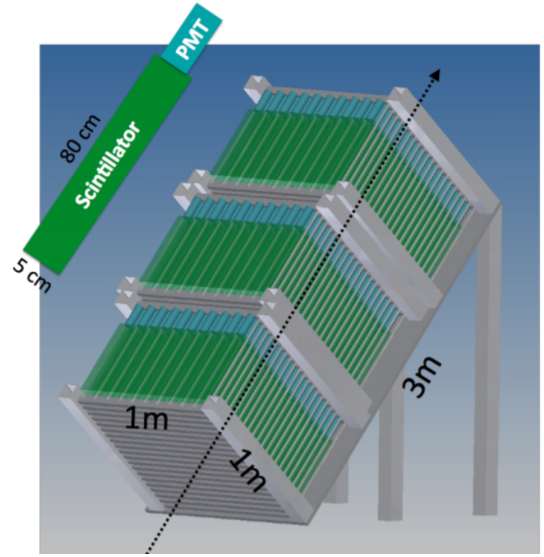
MINOS hall downstream of NuMI beam

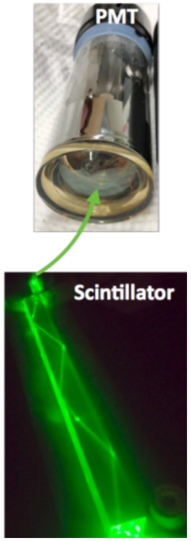
Yu-Dai Tsai
Fermilab

MilliQan Concept

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



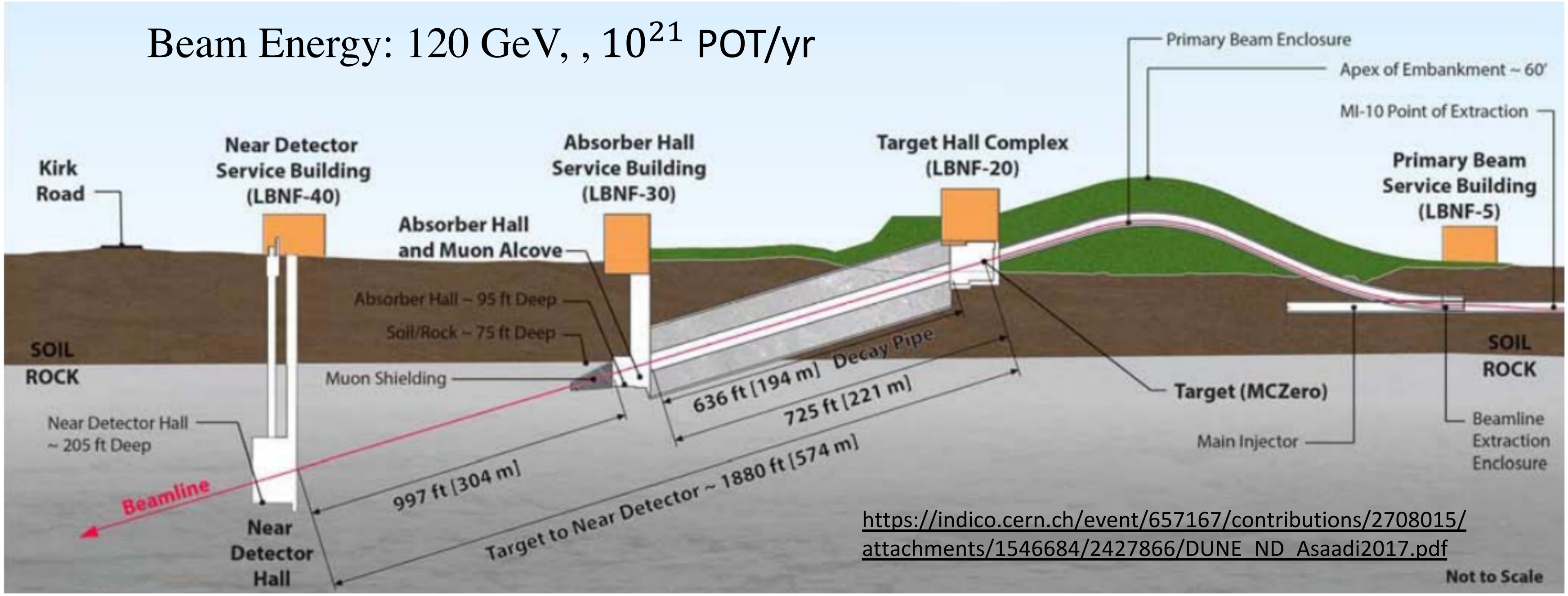




See arXiv:1607.04669; arXiv:1810.06733

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:

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

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

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

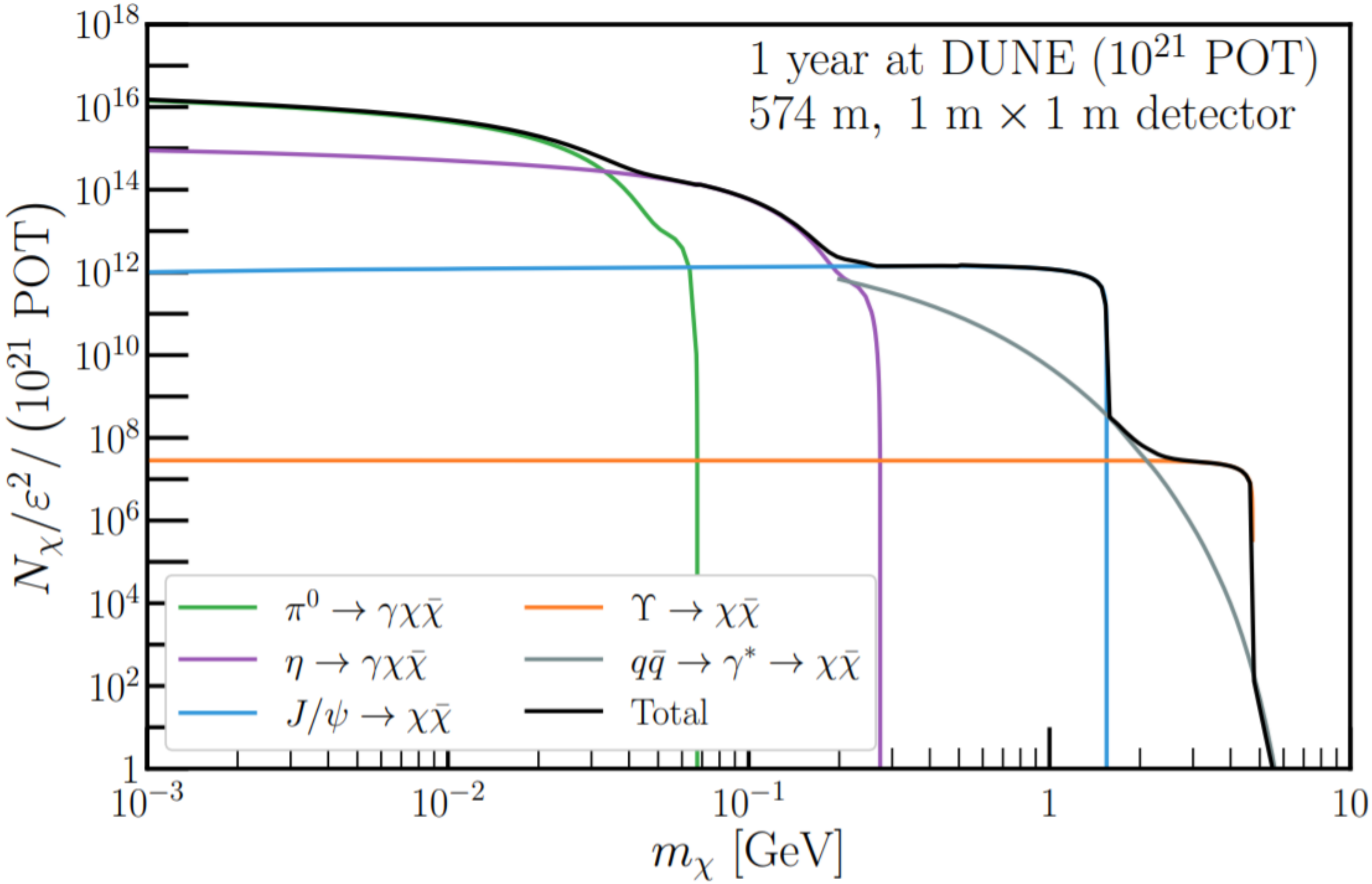
- $\boldsymbol{N_{PE}} \boldsymbol{\sim} \epsilon^{\boldsymbol{2}}$ x $\mathbf{10^6}$, $\epsilon \sim \mathbf{10^{-3}}$ roughly gives one PE in one meter scintillation bar

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

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

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

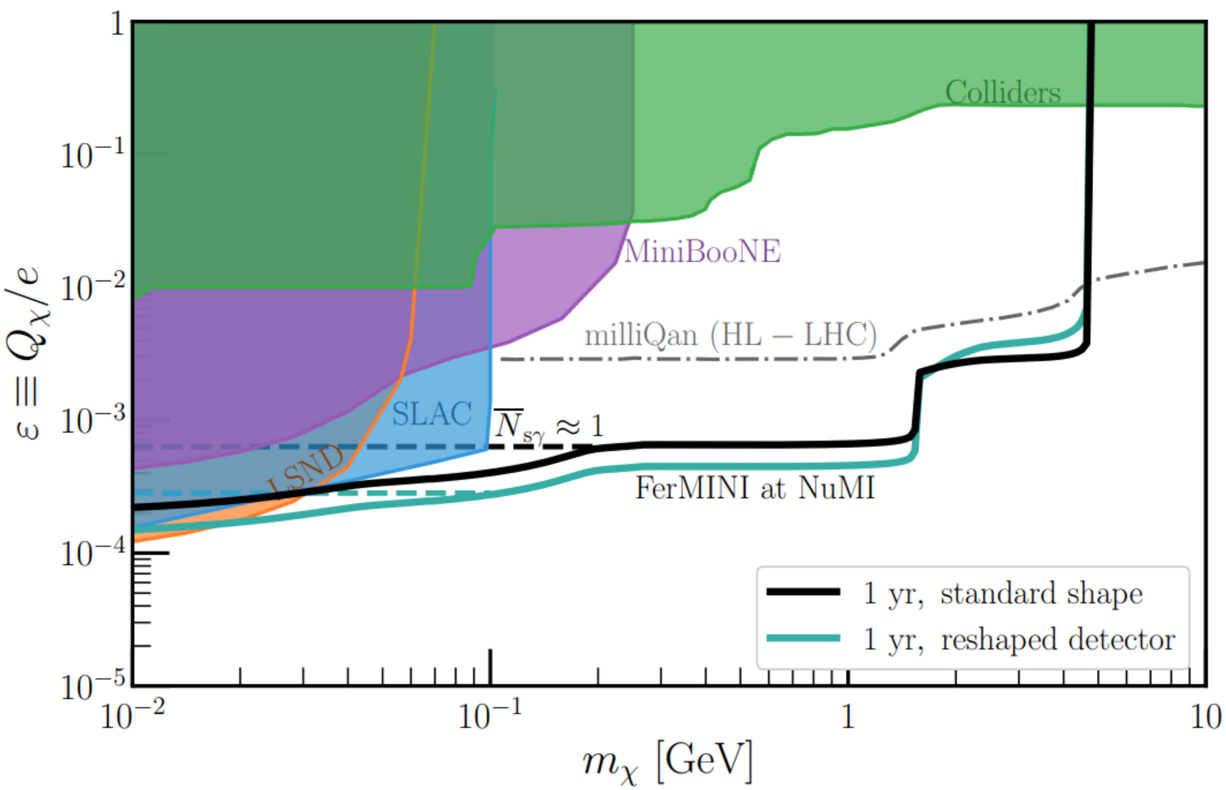
  - Offset middle detector
- **Dark current: triple coincidence**

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^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!**

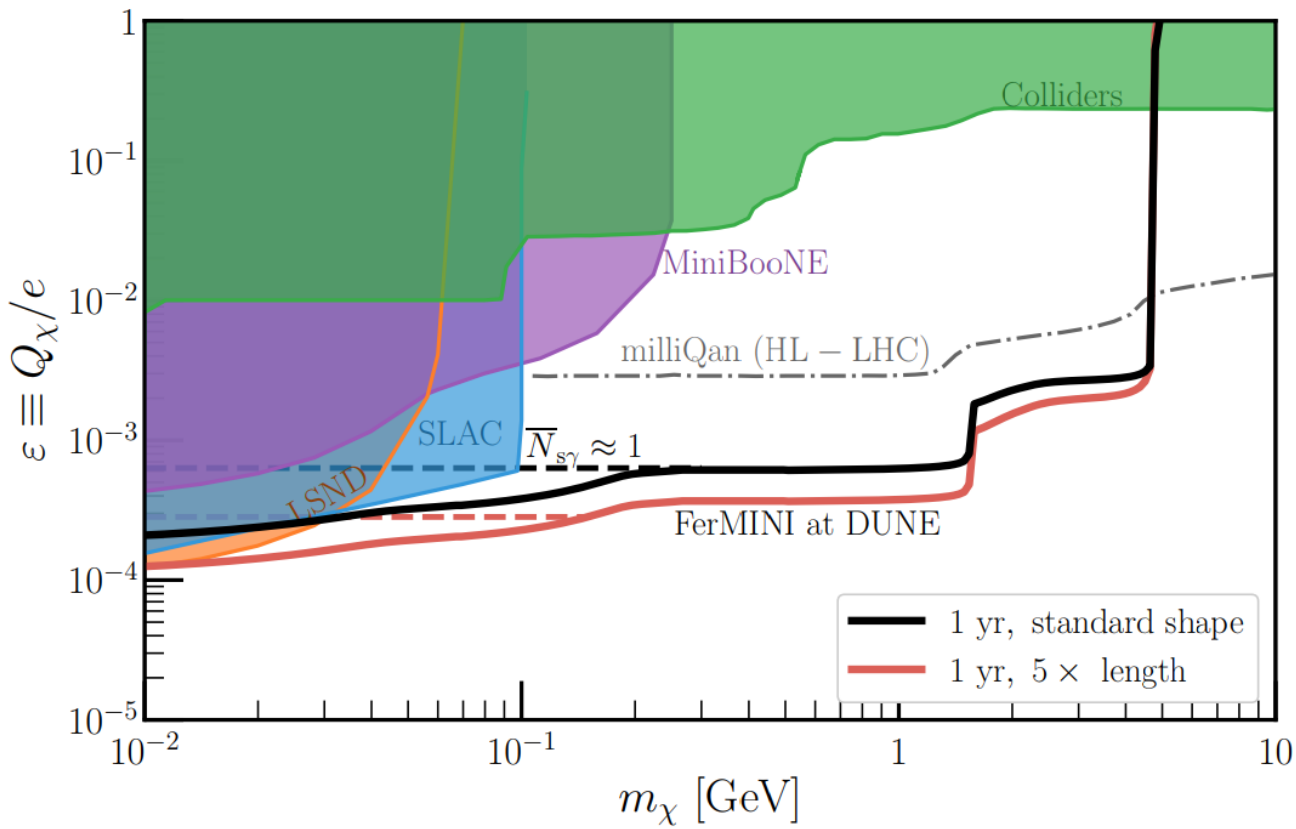
FerMINI @ MINOS



Yu-Dai Tsai,
Fermilab

- Got support from **milliQan members**

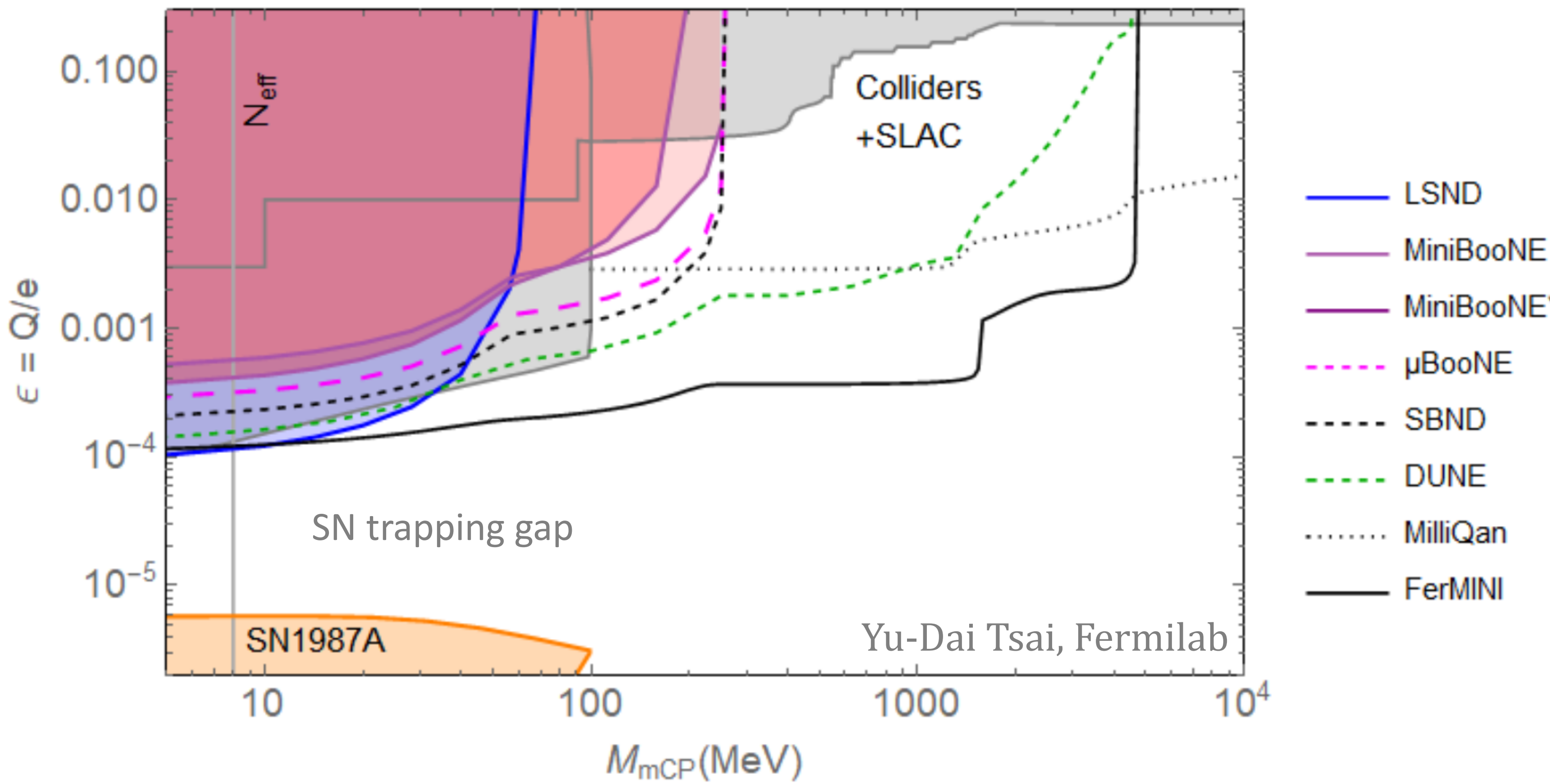
FerMINI @ DUNE



Yu-Dai Tsai, Fermilab

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

Compilation of MCP Probes

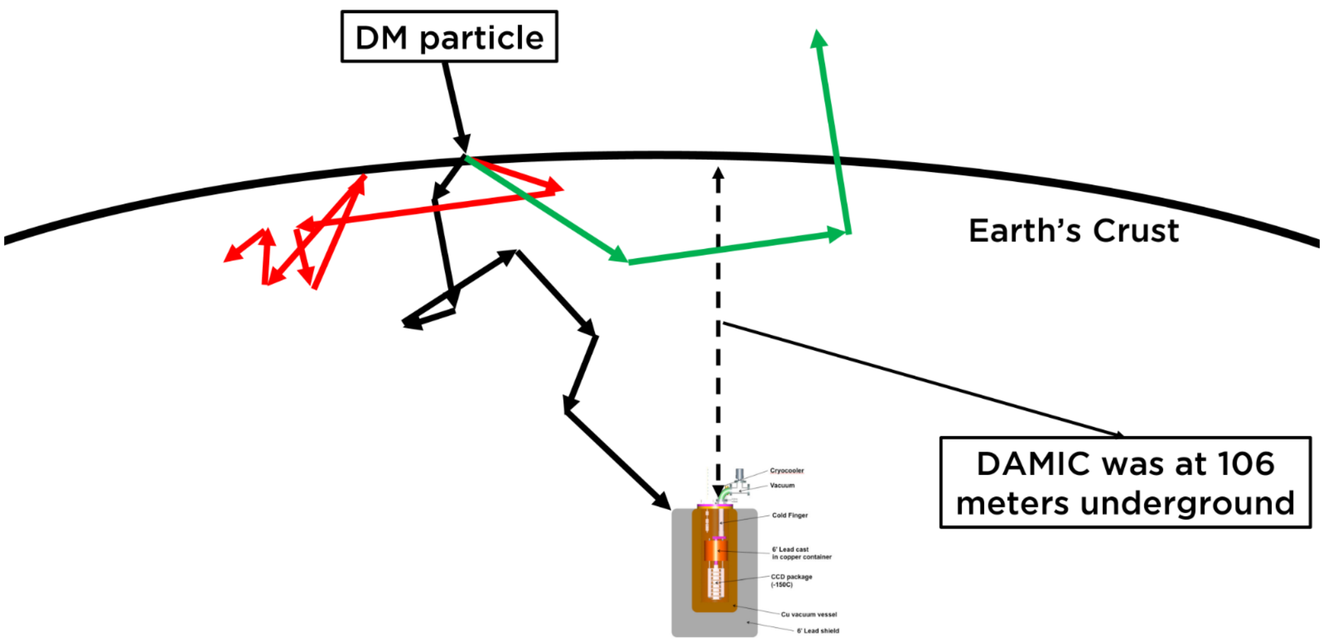


- One can **combine the MCP detector with neutrino detector** to improve sensitivity or reduce background
- Filling up the MCP "cavity"

Strongly Interacting Dark Matter

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)

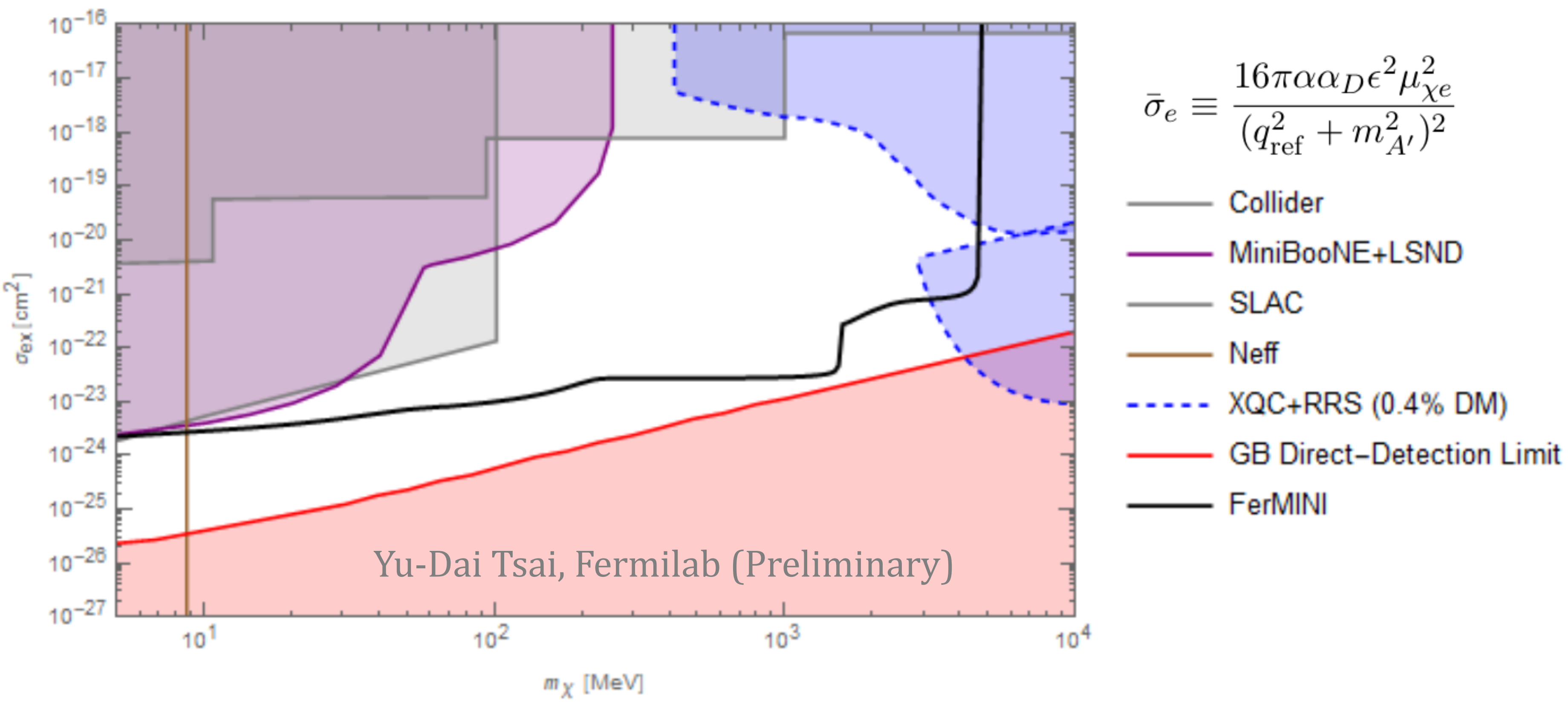
Scatterings both on electrons and nuclei in the **Earth's crust, atmosphere**, and **shielding material** attenuate the expected **local dark matter flux** at a terrestrial detector, so that such experiments lose sensitivity to dark matter above some **critical cross section**.

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)

FerMINI Probe of Millicharged SIDM



- Here we plot the **electron-scattering Millicharged SIDM**
- **FerMINI can help close the Millicharged SIDM window!**

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

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

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.
- **Detail Proposal:** Kelly, Plestid, Pospelov, **YT** + milliQan people (ytsai@fnal.gov)

Other New Physics Probes

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)

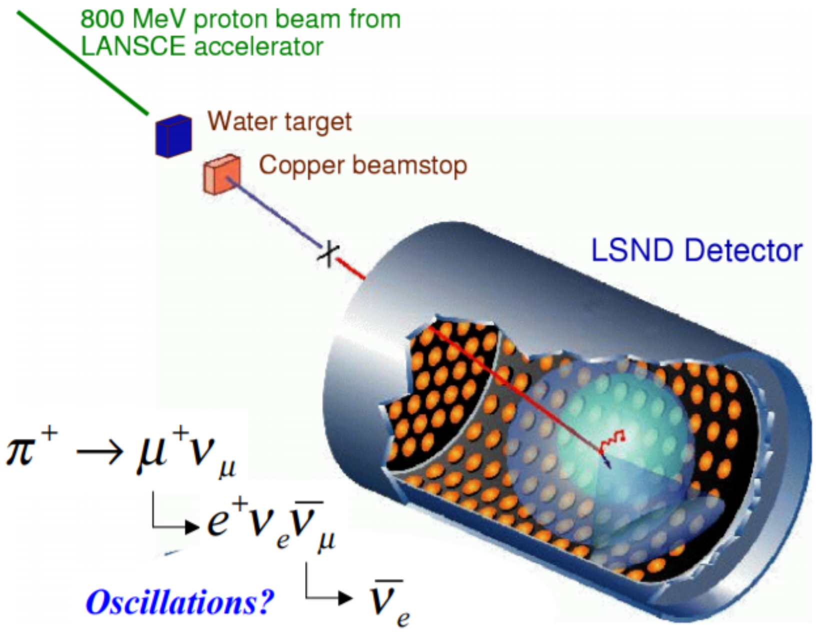
- **FASER (collider, forward)**: 10^{16}-10^{17} POT/yr

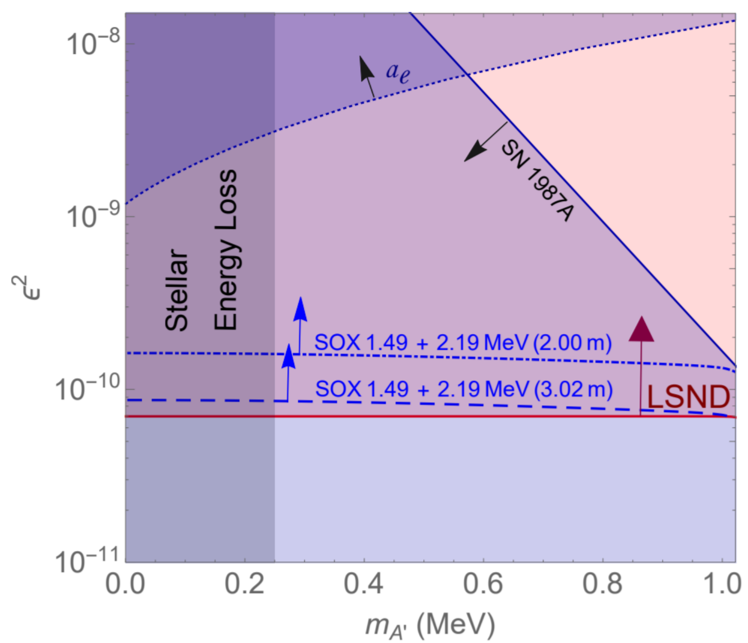
  much higher energy

Yu-Dai Tsai
Fermilab

Dark Photon @ LSND

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

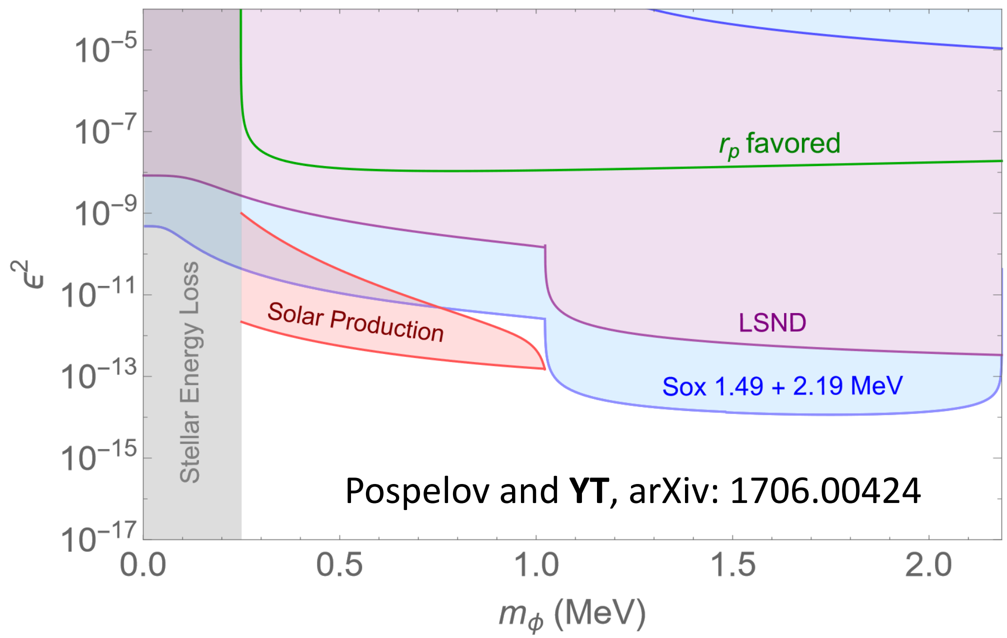


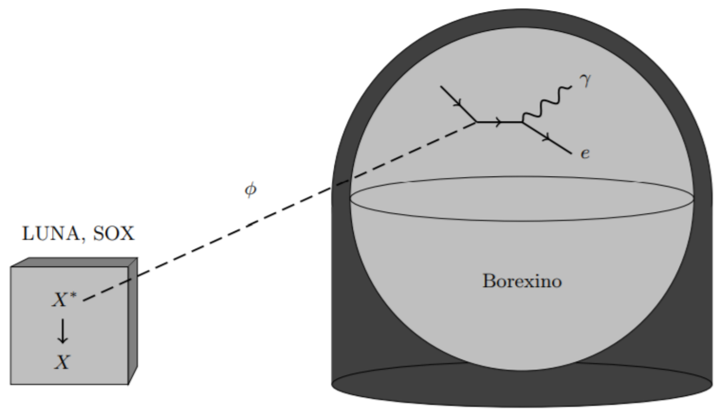


- Major energy depositions: $e + A' \to e + \gamma$

Light Scalar @ LSND & Borexino

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

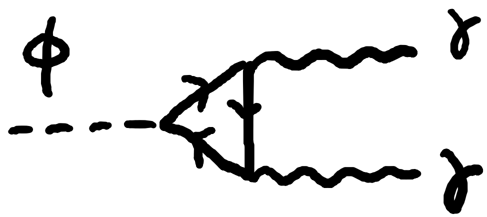




- β^- decay chain:
  $^{144}Ce \to ^{144}Pr + e^- + \bar{\nu}_e$
  $\searrow$ $^{144}Nd + e^- + \bar{\nu}_e$

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

$\epsilon^2 \equiv g_e g_p / e^2$



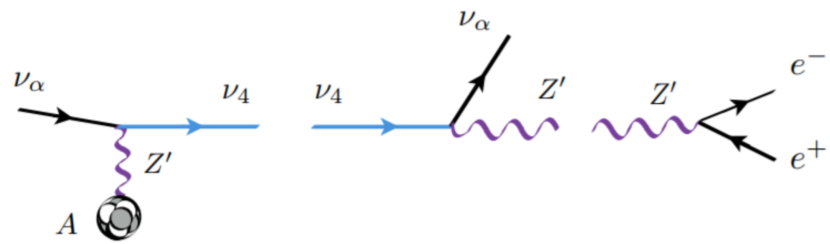
diphoton decay

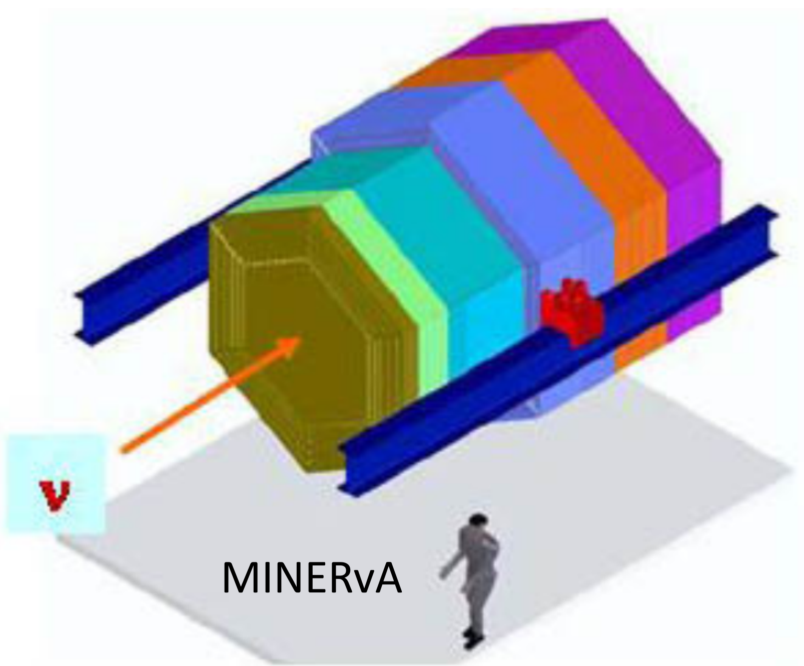
$$g_e = (m_e/m_\mu)g_\mu, \; g_\tau = (m_\tau/m_\mu)g_\mu, \; g_p = (m_p/m_\mu)g_\mu,$$

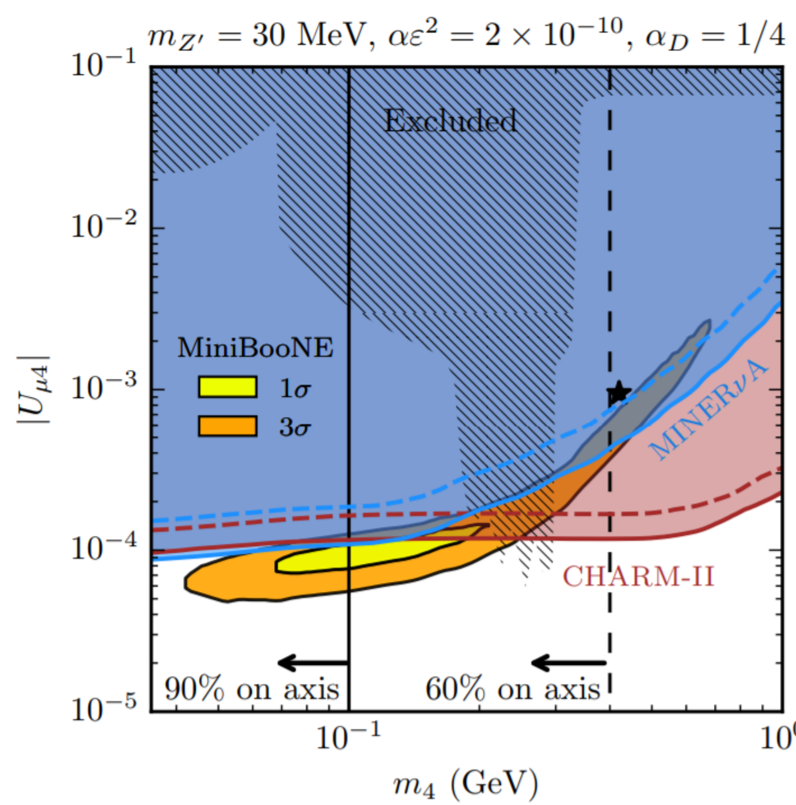
Dark Neutrino at CHARM & MINERvA

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

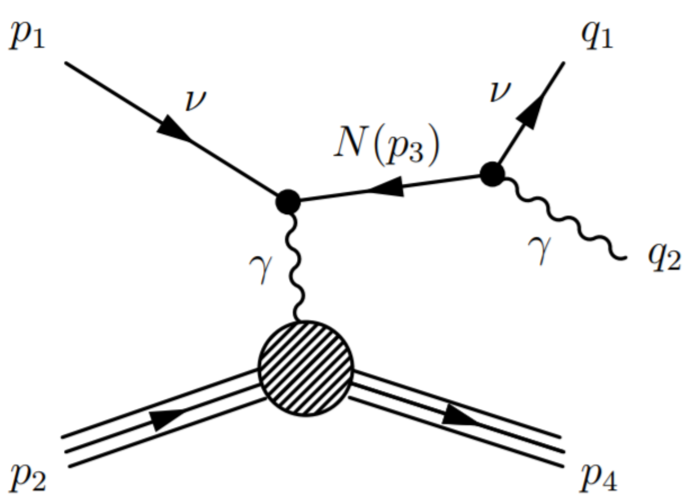
$$\nu_\alpha = \sum_{i=1}^{4} U_{\alpha i} \nu_i, \quad (\alpha = e, \mu, \tau, D).$$





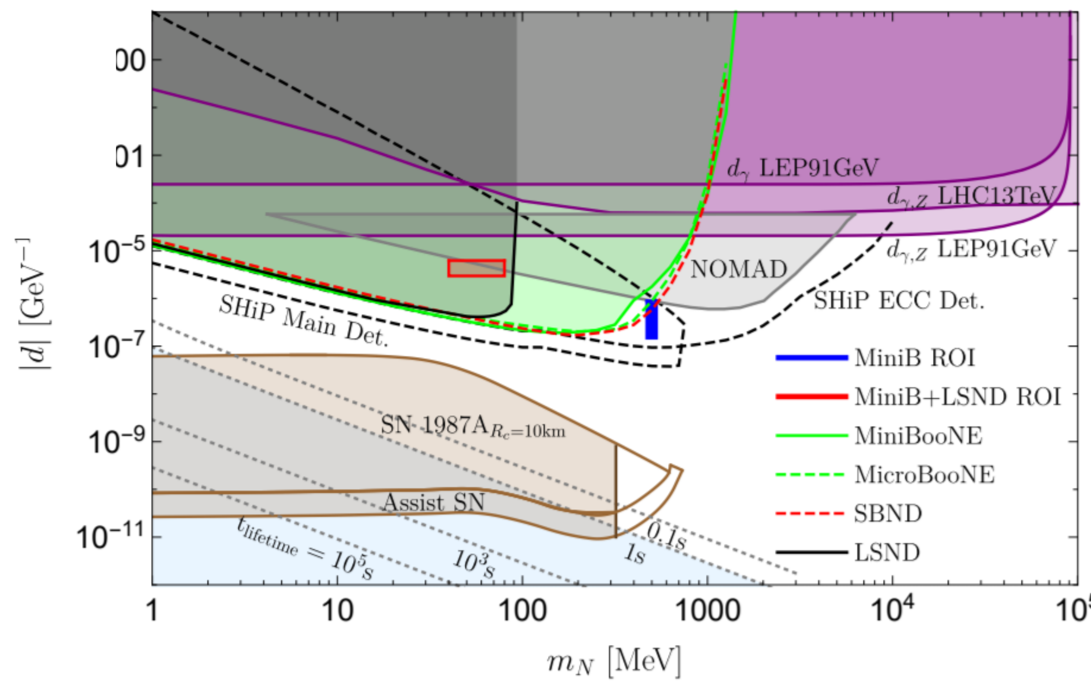


Dipole-Portal Heavy Neutral Lepton



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

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



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!

(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].]

(Detail) dE/dx formula

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

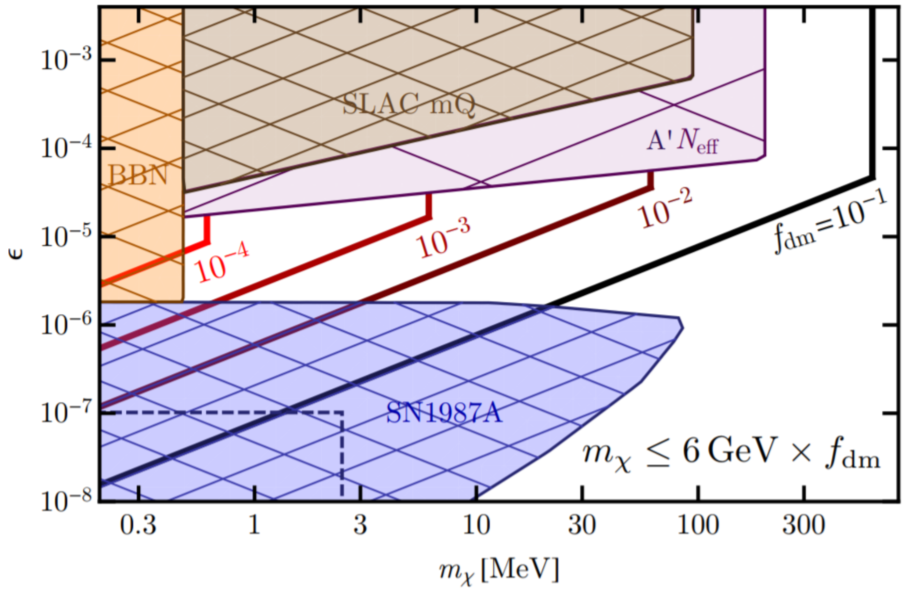
$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] .$$

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	

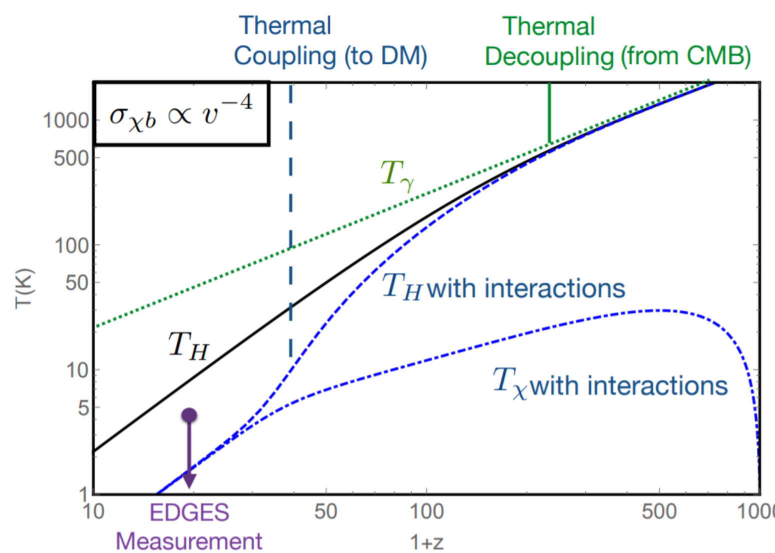
$$W_{\max} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2} .$$

- 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

EDGES ANOMALY and MCP Solution



JBM and Loeb 1802.10094



JBM, Kovetz, Ali-Haimoud 1509.00029