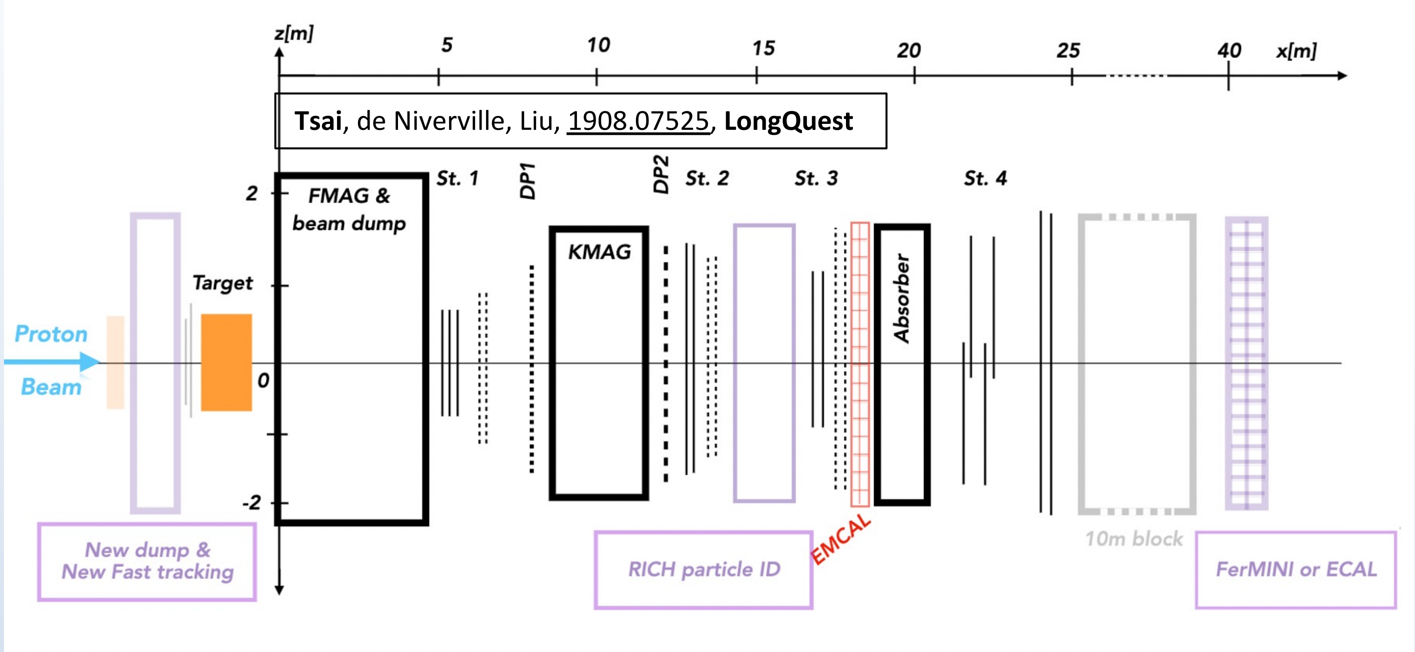


Dark-Sector Searches at Intensity Frontier & Towards New LANL Opportunities

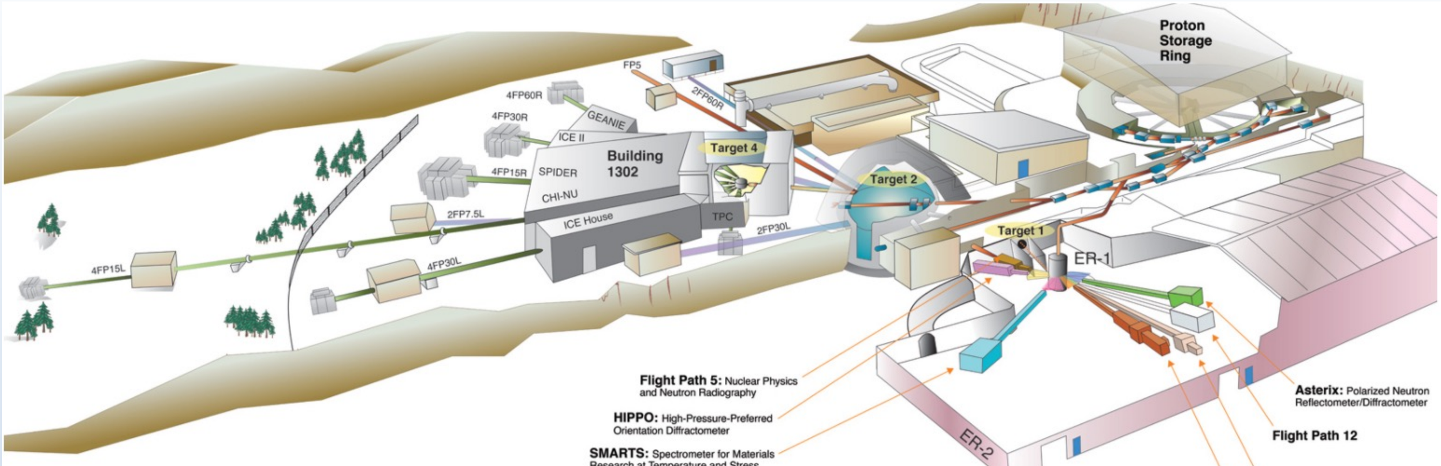
Yu-Dai Tsai, Fermilab/U Chicago

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

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

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

[4] FORMOSA (2010.07941, NEW)



Lujan Center at LANSCE https://lansce.lanl.gov/facilities/index.php

Proton Fixed-Target Experiments
Decay vs Scattering Detectors

[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

Many relevant references listed in the end; Please let me know if there are missing refs.

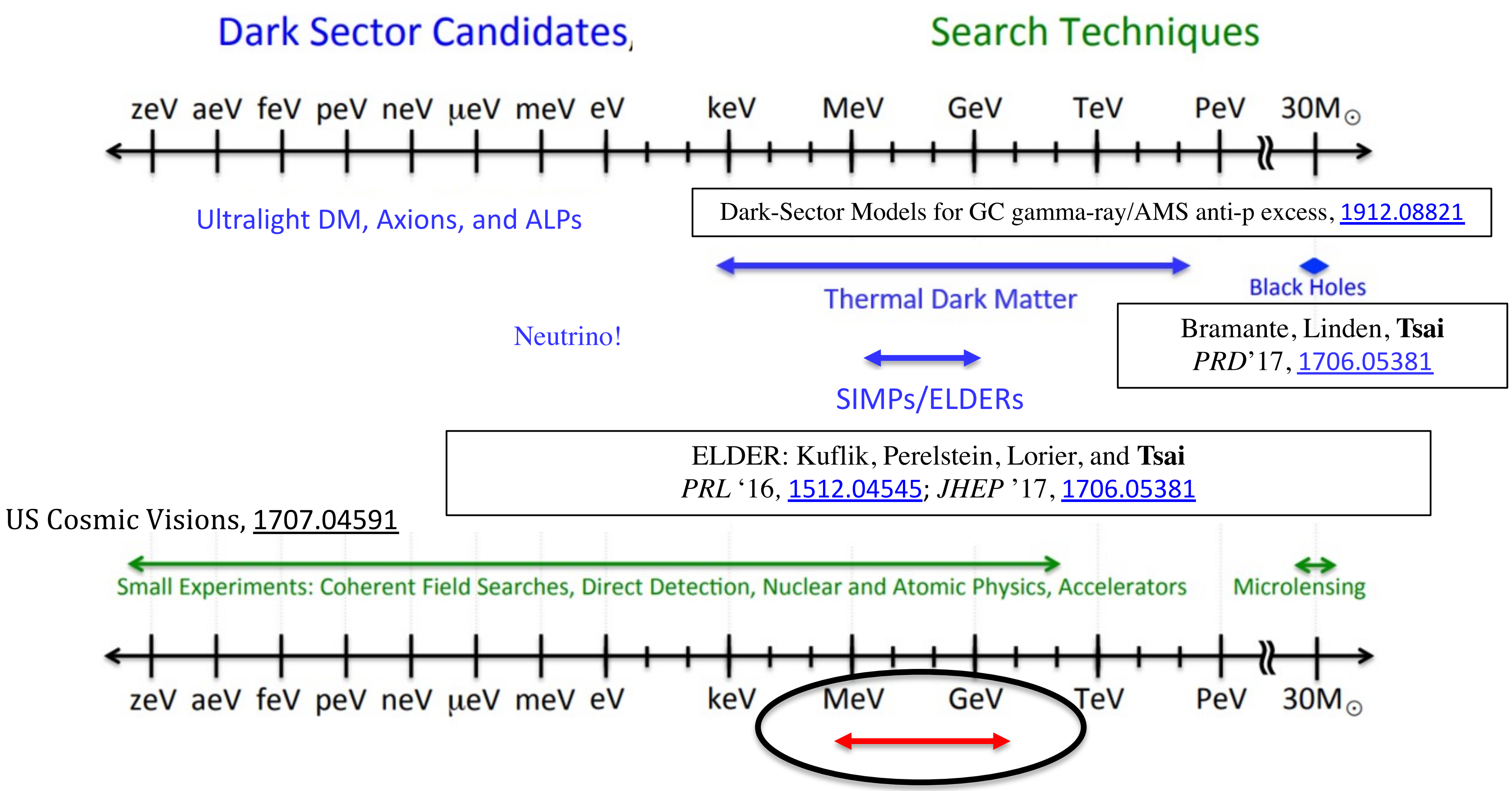
Email: yt444@cornell.edu; arXiv: https://arxiv.org/a/tsai_y_1.html

Outline

- **Motivations:** Why **MeV – 10 GeV New Physics**?
- **Decay vs Scattering** Experimental Probes
- Decay studies (e.g., dark photons) & the **LongQuest** proposal
- Specialized millicharge experiment: **FerMINI** & FORMOSA
- **New LANL Opportunities!**
  in addition to the CCM exp (congrats on the 1st DM result!)

Motivations

Exploration of Dark Sector



- **Astrophysical/cosmological observations:** important to reveal the **actual story of dark matter (DM).**
- **Why fixed-target experiments? And why MeV – GeV+, in addition to the motivation of thermal dark matter**

Why study MeV – GeV+ dark sectors?

Signals of discoveries grow from anomalies

Dark Matter & Standard Model connections

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

⋮

- **Muon g-2 anomaly**
- **EDGES result**
- **LSND & MiniBooNE 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

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

- Millicharged Particles in Neutrino Experiments,
  Magill, Plestid, Pospelov & **Tsai**, PRL '19, 1806.03310
- Cosmic-ray produced MCP in neutrino observatories, 2002.11732, PRD '20

- **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

⋮

Accelerator Probes for New Physics

⋮

- **LSND/MiniBooNE Anomalies**

- Dipole Portal Heavy Neutral Lepton,

  Magill, Plestid, Pospelov, **Tsai**, PRD '18, 1803.03262

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

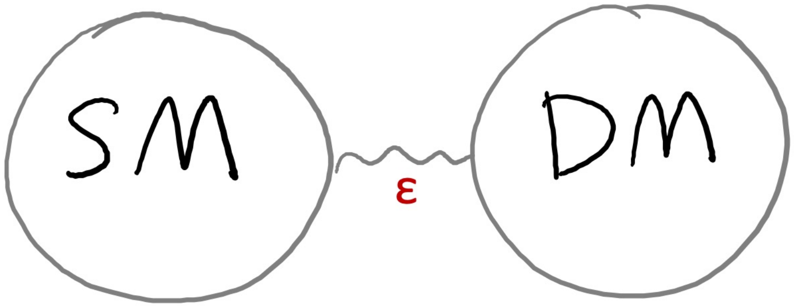
  Argüelles, Hostert, **Tsai**, *PRL '20*, 1812.08768

- **Proton charge radius anomaly:**

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

⋮

The Rise of Dark Sector: Sub-GeV DM



- The **Lee-Weinberg bound** (1977'): **below $\sim 2\ \mathbf{GeV}$**, DM freeze-out through weak-Interaction (e.g. through Z-boson) would overclose the Universe.

- Could consider ways to get around this but generally **sub-GeV DM needs BSM mediators** to freeze-out to proper relic abundance.

- New mediator is needed:
  the rise of **"dark sector" (DM + mediators + stuffs).**
- Another motivation to consider dark sector other than anomalies

Advantages of Accelerator Experiments

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)

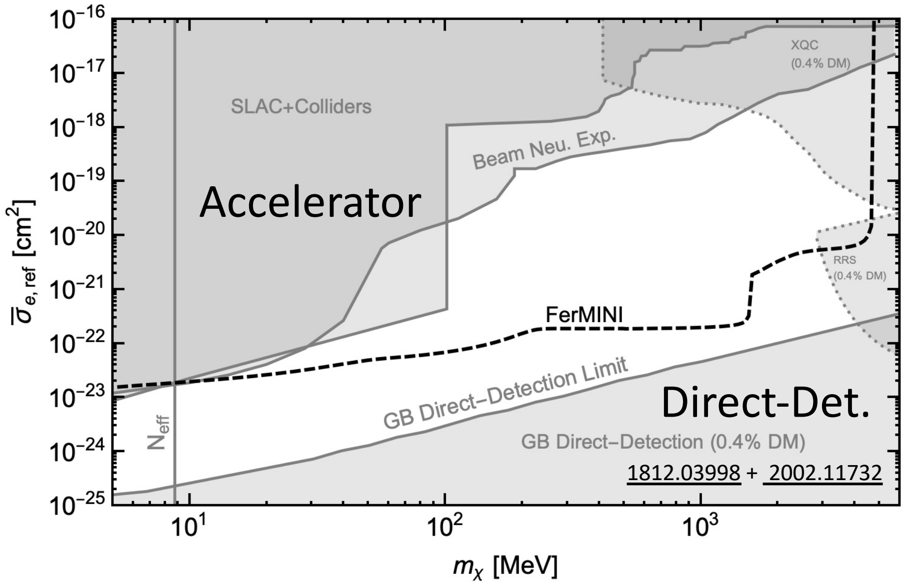
Dark matter direct/indirect detection: abundance, velocity distribution, etc

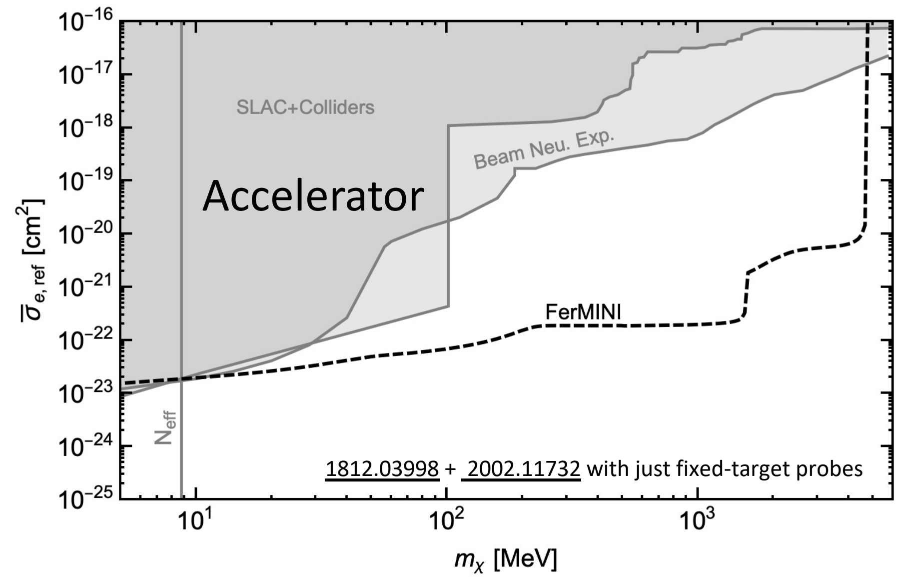
Cosmology: assume cosmological history, species, etc

different

Reveal actual DM story

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





consider **ambient dark matter**

Produce dark particles in collisions

Same mass and interaction strength.

Different assumptions

Proton FT (& Neutrino) Experiments

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

  O(1 – 400) GeV (I will compare Fermilab/CERN facilities)
- **Shielded/underground**: lower background
- Many of them existing and many to come:

  strength in numbers

Proton Facilities of Interest

Fermilab / CERN current & future facilities

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	near-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 – HL LHC	10^{16} POT/yr	$\sqrt{s}$ = 13 TeV	near-future

Lujan Neutron Target (800 MeV protons, $\sim 10^{22}$ POT/yr), now

Proton FT Experiment: Decay vs Scattering

Decay Experiments/Detectors

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

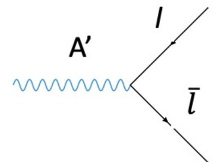
- Experiments optimized to study **decaying particles**, or simply two charged particle final states, e.g. from Drell-Yan (SeaQuest)

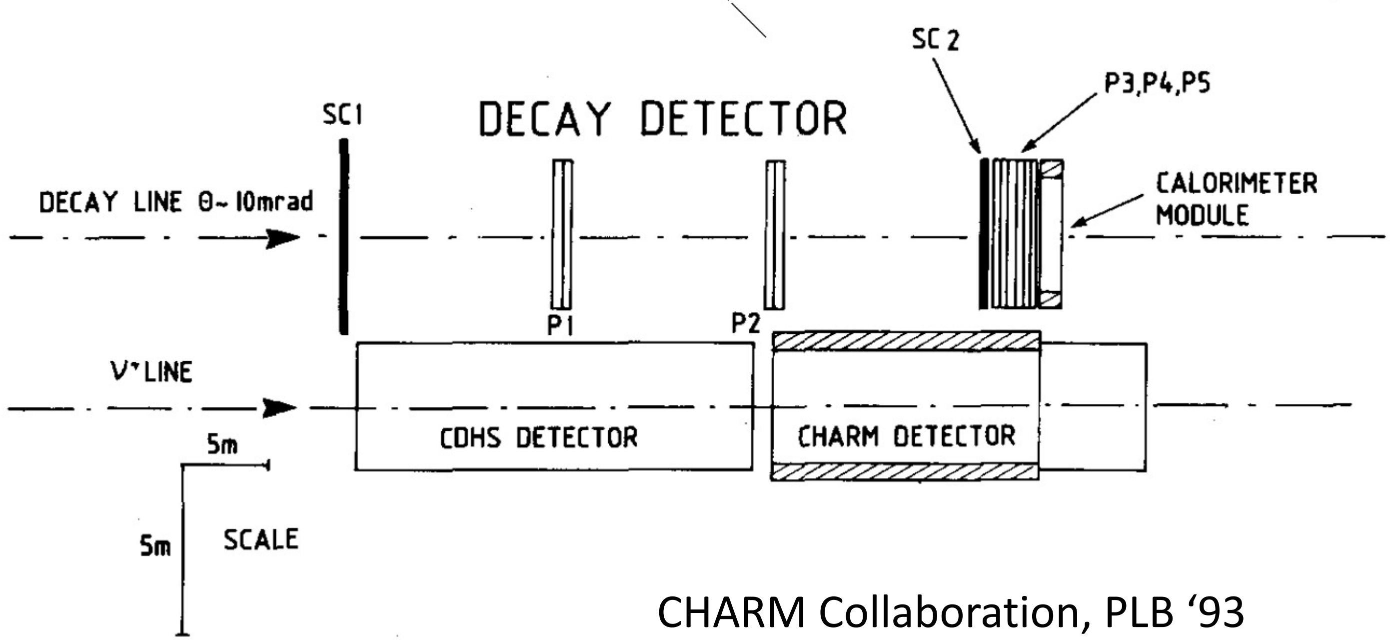
General features:

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**
   (kaon rare decays, dark mediators, e.g., dark photons)

Decay Experiments/Detectors

CHARM Decay Detector





CHARM Collaboration, PLB ‘93

CHARM: CERN HAmburg Rome Moscow

Legion of Decay Experiments

Existing Probes

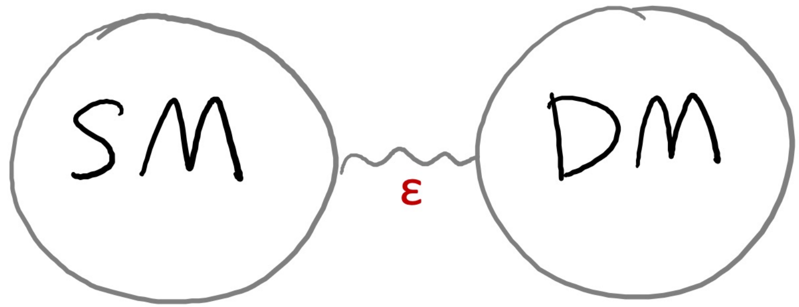
Future Probes

Experiment	Beam Energy	POT	$L_{\mathrm{dist.}}$	L_{dec}
CHARM	400 GeV	2.4e18	480 m	35 m
NuCal	70 GeV	1.7e18	64 m	23 m
NA62	400 GeV	*1.3e16/1e18	82 m	75 m
SeaQuest	120 GeV	*1.4e18/1e20	5 m	*7 m
LongQuest	120 GeV	*1e20	5 m	*7/13 m
DUNE ND	120 GeV	1e21	500 m	*1m
LANL - CCM	800 MeV	2.25e22 (3yr)	20 m	1.2 m

- $L_{dist.}$ = from target to detector (longer will lose short-lived particles)
- L_{dec} = length of the decay region (the longer the better)
- *means still to be determined
- See, e.g., 1908.07525 for a systematic comparison
- Conducting a comprehensive study for general & Snowmass purposes

Interesting Long-Lived Particles for Decay Studies

The Rise of Dark Sector: Sub-GeV DM



- The **Lee-Weinberg bound** (1977'): **below $\sim \mathbf{2\ GeV}$**, DM freeze-out through weak-Interaction (e.g. through **Z-boson**) would **overclose the Universe**.

- Could consider ways to get around this but generally **sub-GeV DM needs BSM mediators** to freeze-out to proper relic abundance.

- Mediator is needed for a proper freeze-out: the rise of "dark sector" (DM + mediators + stuffs).
- Another motivation to consider dark sector other than anomalies

Renormalizable "Portals"

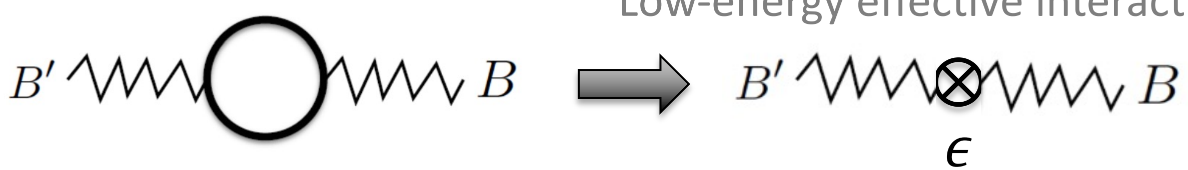
- Dark sectors can include mediator particles coupled to the SM via the following **renormalizable interactions.**
- **High-Dim. axion portal is also popular**

$$
\mathcal{L} \supset \begin{cases} \boxed{-\dfrac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu} \,, \quad \text{vector portal}} \\ (\mu\phi + \lambda\phi^2) H^\dagger H \,, \quad \text{Higgs portal} \\ y_n L H N \,, \quad \text{neutrino portal} \end{cases}
$$

(Holdom, '85)

(See Dark-Sector 2016 report 1608.08632)

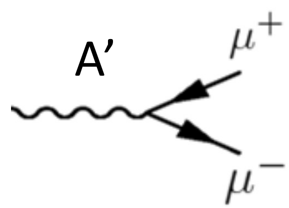
Low-energy effective interaction



Mass from Dark Higgs or Stueckelberg

mass basis

Dark photon A':

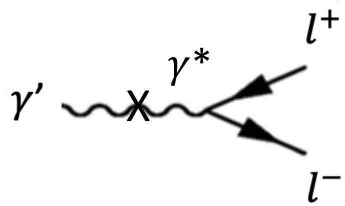


Dark-Sector Phenomenology
Studying “dark photon” portal

- **“Dark Sector”:** DM + “mediators” to SM

$$\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu} + \epsilon e A'^{\mu}J^{EM}_{\mu}$$

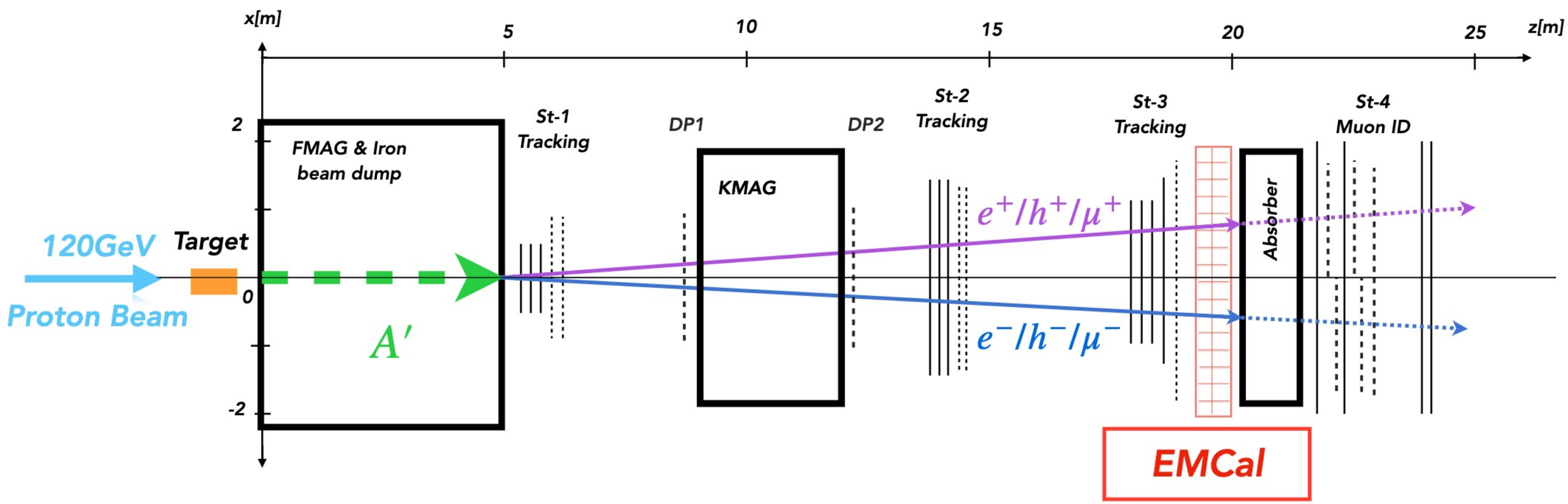
kinetic mixing



- **One of the three 4-dimentional “portals” to dark sectors**
- **These “portals” help connect dark matter to SM and is essential for GeV or sub-GeV thermal dark matter**
(see, **Lee-Weinberg Theorem**, Lee, Weinberg, PRL 77)

Details of LongQuest: A Multi-Purposed Detector

SpinQuest -> DarkQuest @ Fermilab



Yongbin Feng (Fermilab), for DarkQuest collaboration, PPC21

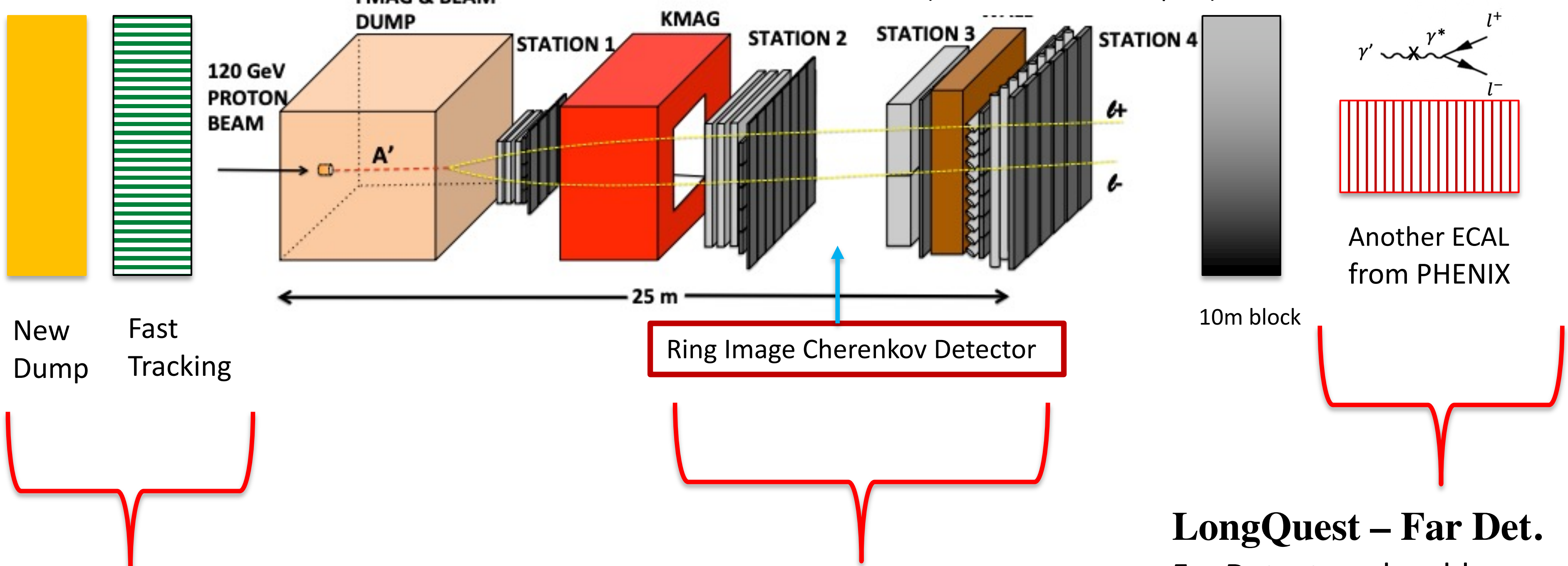
arXiv:1509.00050 (Gardner, Holt, Tadepalli); arXiv:1804.00661 (Berlin, Gori, Schuster, Toro) + …
DarkQuest is a proposal for **EMCal installation** after current **SpinQuest run** (Fall 2023)

Nhan Tran (Fermilab) was rewarded Fermilab LDRD funding
and is leading detailed SeaQuest/DarkQuest study + Snowmass white paper.

LongQuest: Three Part Upgrad of SpinQuest, as Dedicated Long-Lived Particle Experiment

arXiv:1908.07525, Tsai, de Niverville, Liu ‘19

Modified from arXiv:1509.00050 (Gardner, Holt, Tadepalli)



LongQuest – Dump & Track

Front dump and fast tracking

LongQuest – Particle ID

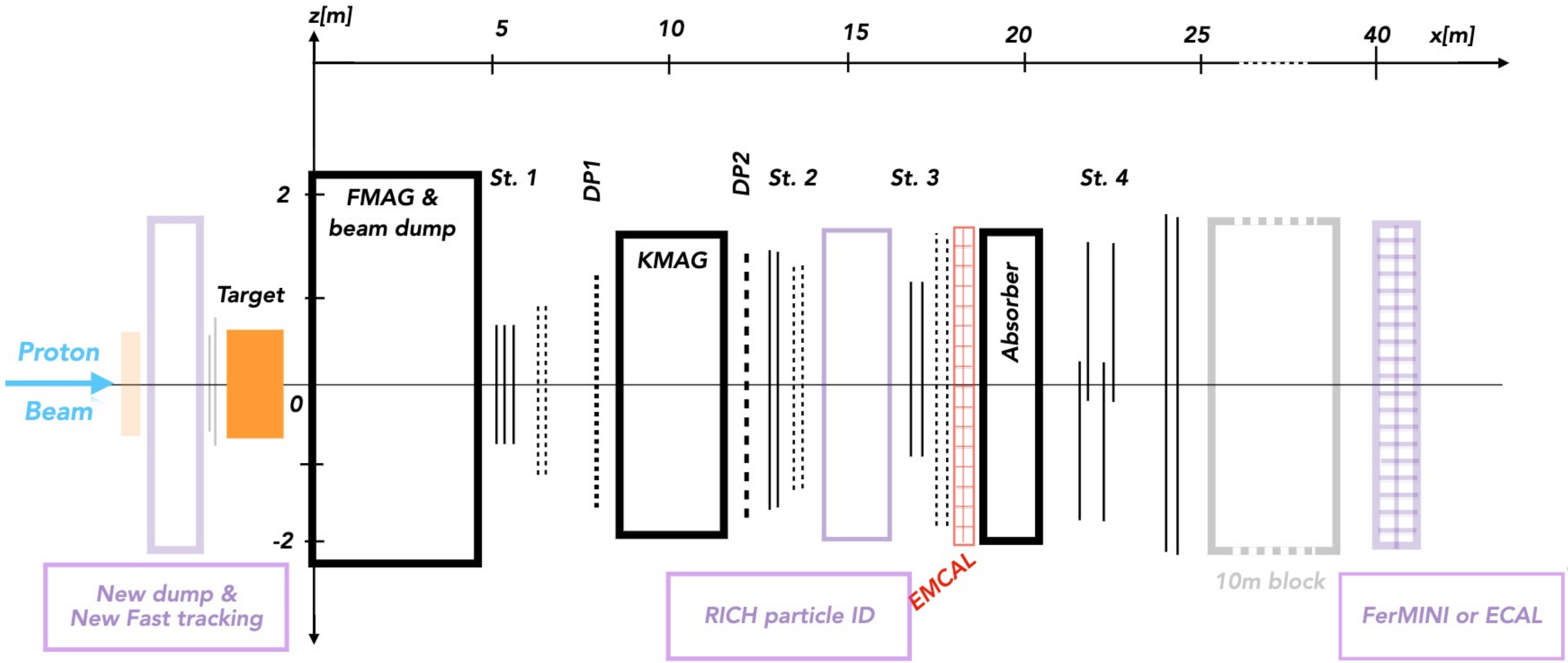
Getting **RICH** (from PHENIX exp.) or HBD for particle id.

LongQuest – Far Det.

Far Detectors: low bkg. another **ECAL**, or Millicharge detector

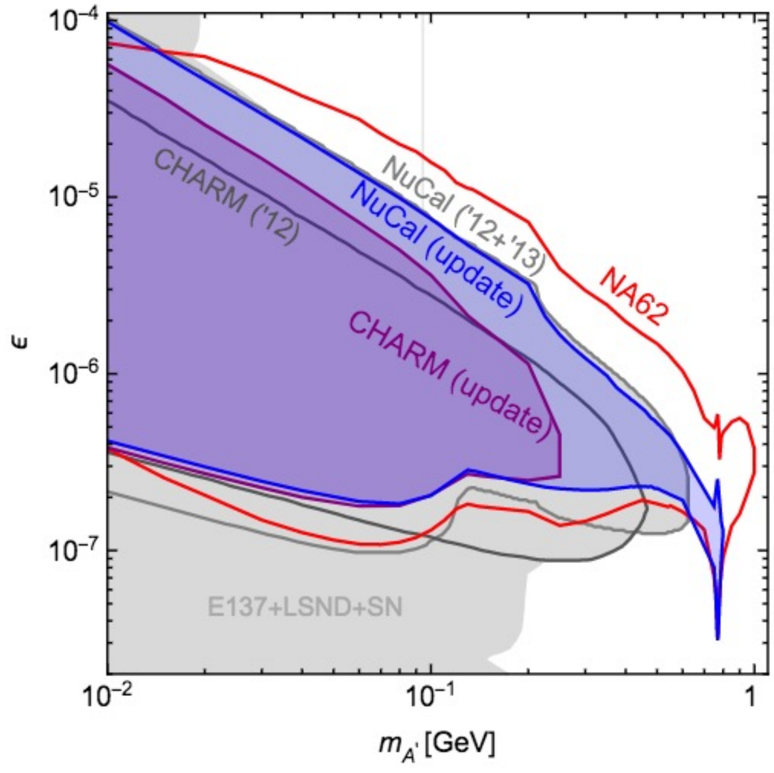
LongQuest Updated Configuration

arXiv:1908.07525, Tsai, de Niverville, Liu ‘19

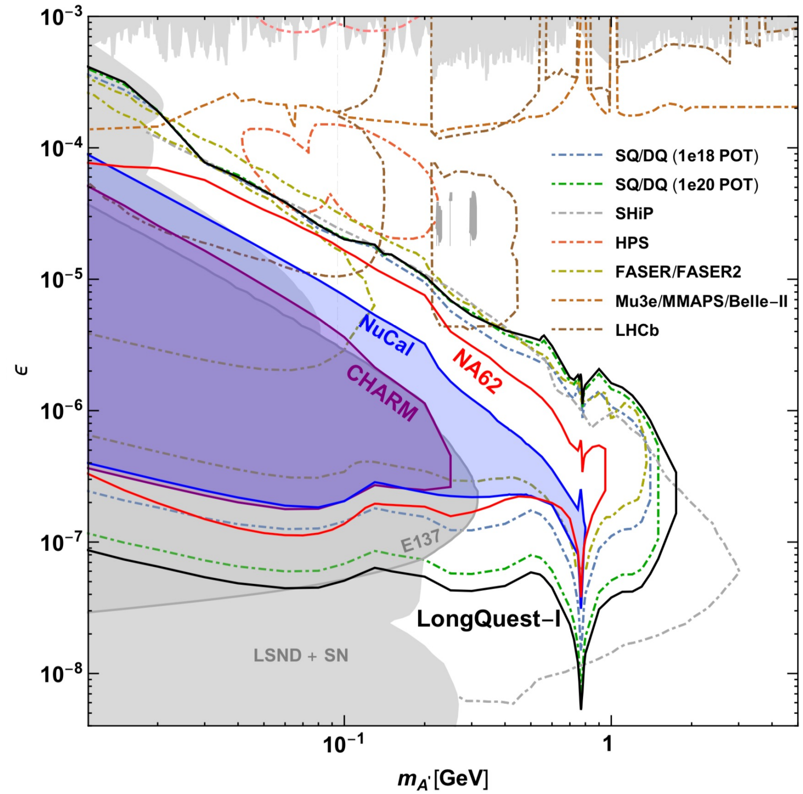


Yongbin Feng (Fermilab), for DarkQuest collaboration, PPC21

Legion of Probes on Dark Photon



(a) Updates on dark photon bounds and NA62 projection.



(b) Compilation of projections and constraints on dark photon.

Ilten, Soreq, Williams, and Xue 1801.04847 compilation of probes

Consider proton bremsstrahlung production properly
resonance from mixing with the ρ and ω mesons

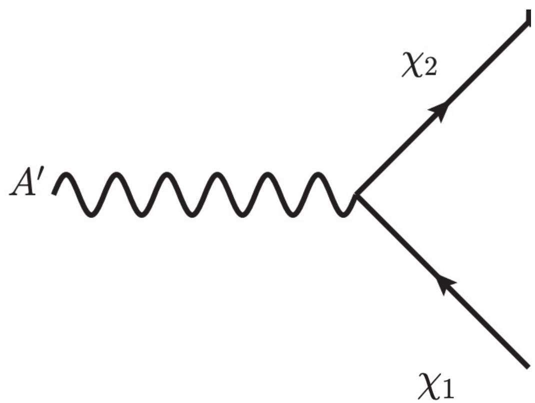
New Projections from NA62 and LongQuest,
Tsai, de Niverville, Liu, 1908.07525,
Many new projections since ‘19

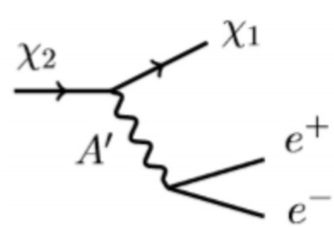
Inelastic Dark Matter

- One of the few viable **MeV – GeV thermal dark matter candidates**
- A "**thermal target**" for DM searches
- Can **explain g-2** and **freeze-out to the right relic DM abundance**
- Smith, Weiner, arXiv:0101138, + many papers

$$\mathcal{L} \supset \sum_{i=1,2} \bar{\chi}_i (i\not{\partial} - m_{\chi_i})\chi_i - (g_D A'_\mu \bar{\chi_1}\gamma^\mu \chi_2 + \text{h.c.}).$$

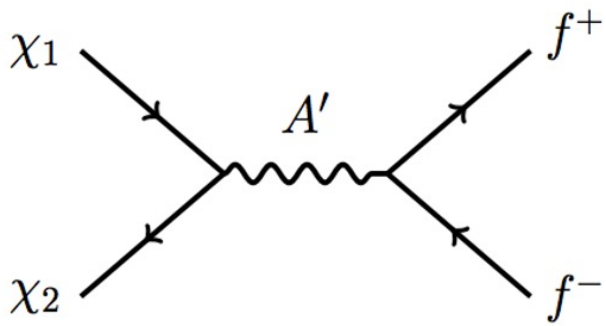
$$\Delta \equiv \frac{m_2 - m_1}{m_1}. \qquad g_D \equiv \sqrt{4\pi\alpha_D}. \qquad m_{A'} > m_{x1} + m_{x2}.$$





1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

Inelastic Dark Matter (iDM)



1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

$$m_1 \sim \frac{\epsilon\,(\alpha_D\,\alpha_{\rm em}\,T_{\rm eq}\,m_{\rm pl})^{1/2}}{(m_{A'}/m_1)^2}\;e^{-x_f\Delta/2}\;,$$

- Co-annihilation
  freeze out to right relic abundance but **avoid CMB constraints**
- Suppressed at the CMB epoch
- Considered **thermal targets** for newly proposed experiments
- Suppressed at the CMB epoch

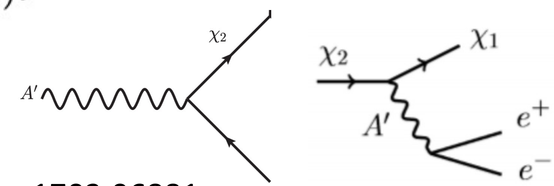
- Collider: 1508.03050 (Izaguirre, Krnjaic, Shuve)
  Fixed target:
- 1703.06881 (FT: Izaguirre, Kahn, Krnjaic, Moschella),
- 1804.00661 (**SeaQuest**: Berlin, Gori, Schuster, Toro)
- 1902.05075 (g-2: Mohlabeng)
- 1908.07525 (Strong bounds: Tsai, de Niverville, Liu)
- 1911.03176 (Belle II update, Duerr, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, Tunney)

⋮

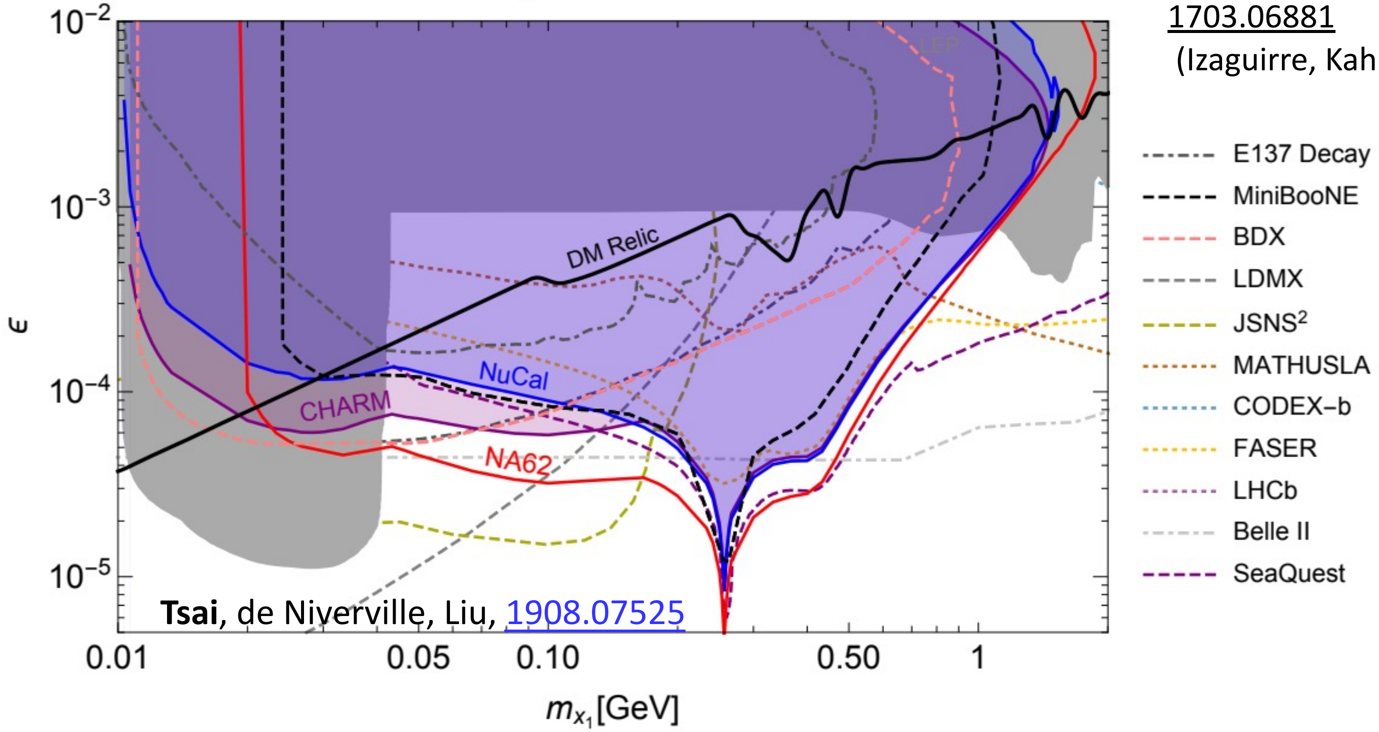
New Bounds on Inelastic Dark Matter

Inelastic Dark Matter: $$\mathcal{L} \supset \sum_{i=1,2} \bar{\chi}_i (i\partial\!\!\!/ - m_{\chi_i})\chi_i - (g_D A'_\mu \bar{\chi_1}\gamma^\mu \chi_2 + \text{h.c.}).$$

$$\Delta \equiv \frac{m_2 - m_1}{m_1}. \qquad g_D \equiv \sqrt{4\pi\alpha_D}.$$



1703.06881
(Izaguirre, Kahn, Krnjaic, Moschella),



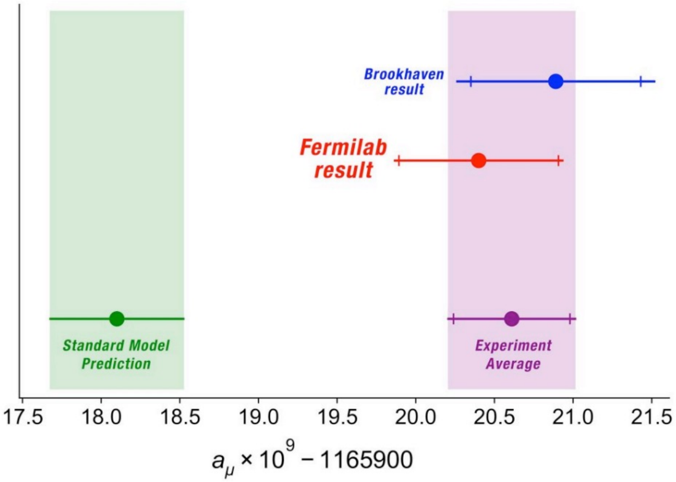
(e) Compilation of relevant constraints and sensitivity projections for iDM with $\alpha_D = 0.1$ and $\Delta = 0.1$. $m_{A'}/m_{\chi 1} = 3.$

Tsai, de Niverville, Liu, 1908.07525

See, Duerr, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, Tunney, 1911.03176, for Belle II update

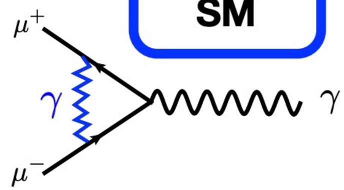
The muon (g-2): an additional motivation to search for dark photons

B. Abi, et al. Phys. Rev. Lett. 126, 141801 (2021)



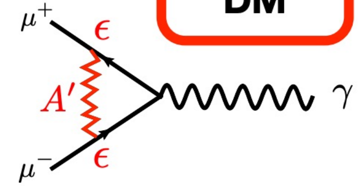
TO NOTE: Lattice QCD calculations S. Borsanyi et al. Nature 593 (2021) reduce discrepancy. Hadronic corrections to be directly measured by MUonE EXP @ CERN G. Abbiendi. PoS ICHEP2020, 223 (2021)

SM



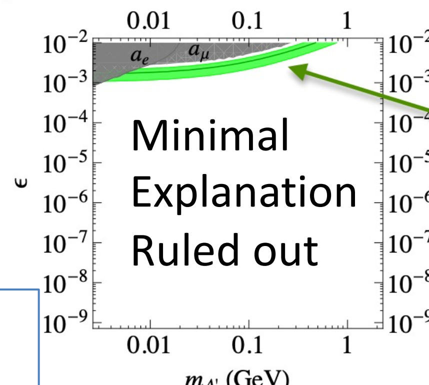
$$(g_s - 2)^{\gamma}_{\mu} \simeq \frac{\alpha}{2\pi}$$
$$\simeq 10^{-3}$$

DM



$$(g_s - 2)^{A'}_{\mu} \simeq \frac{\alpha}{2\pi} \times \epsilon^2 \qquad (m_{A'} \ll m_\mu)$$
$$\simeq 10^{-3} \times \epsilon^2$$

M. Pospelov, A. Ritz and M. B. Voloshin, Phys. Lett. B 662, 53 (2008)



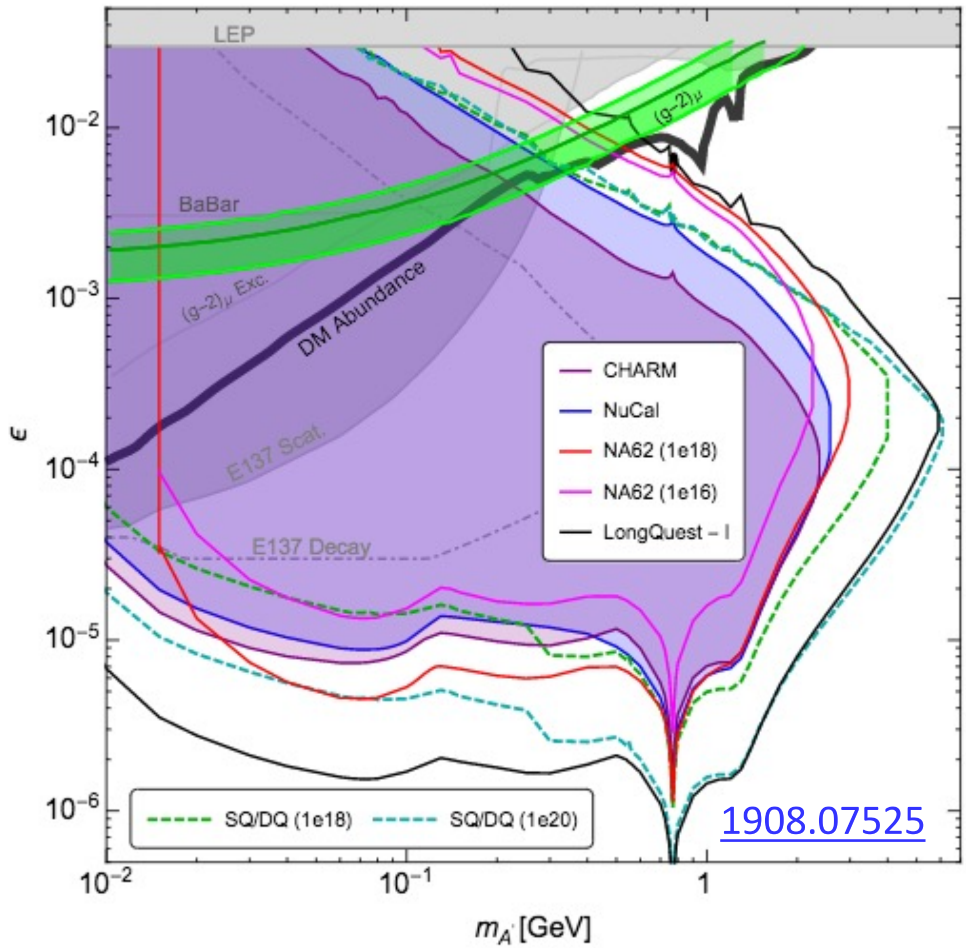
A' may explain observed anomaly

Paolo Crivelli | 25.05.2021 | 10

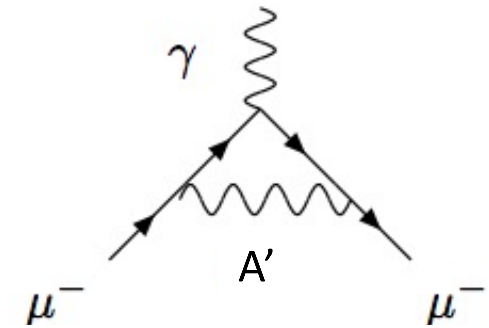
Slides of Dr. Paolo Crivelli (ETH, Zurich)

More complicated models related to Dark Matter & Cosmology?

Inelastic Dark Matter
& Muon g-2 explainer



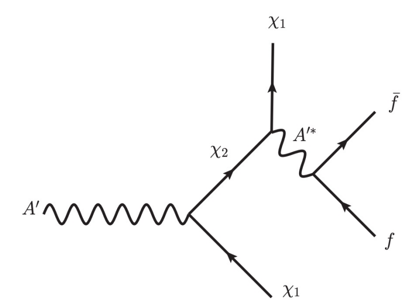
(a) iDM: $\Delta = 0.4$, α_D=0.1. With muon $g-2$ and DM regimes.
$m_{A'}/m_{x1}$ = 3.



$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{th} = (274 \pm 73) \times 10^{-11},$$

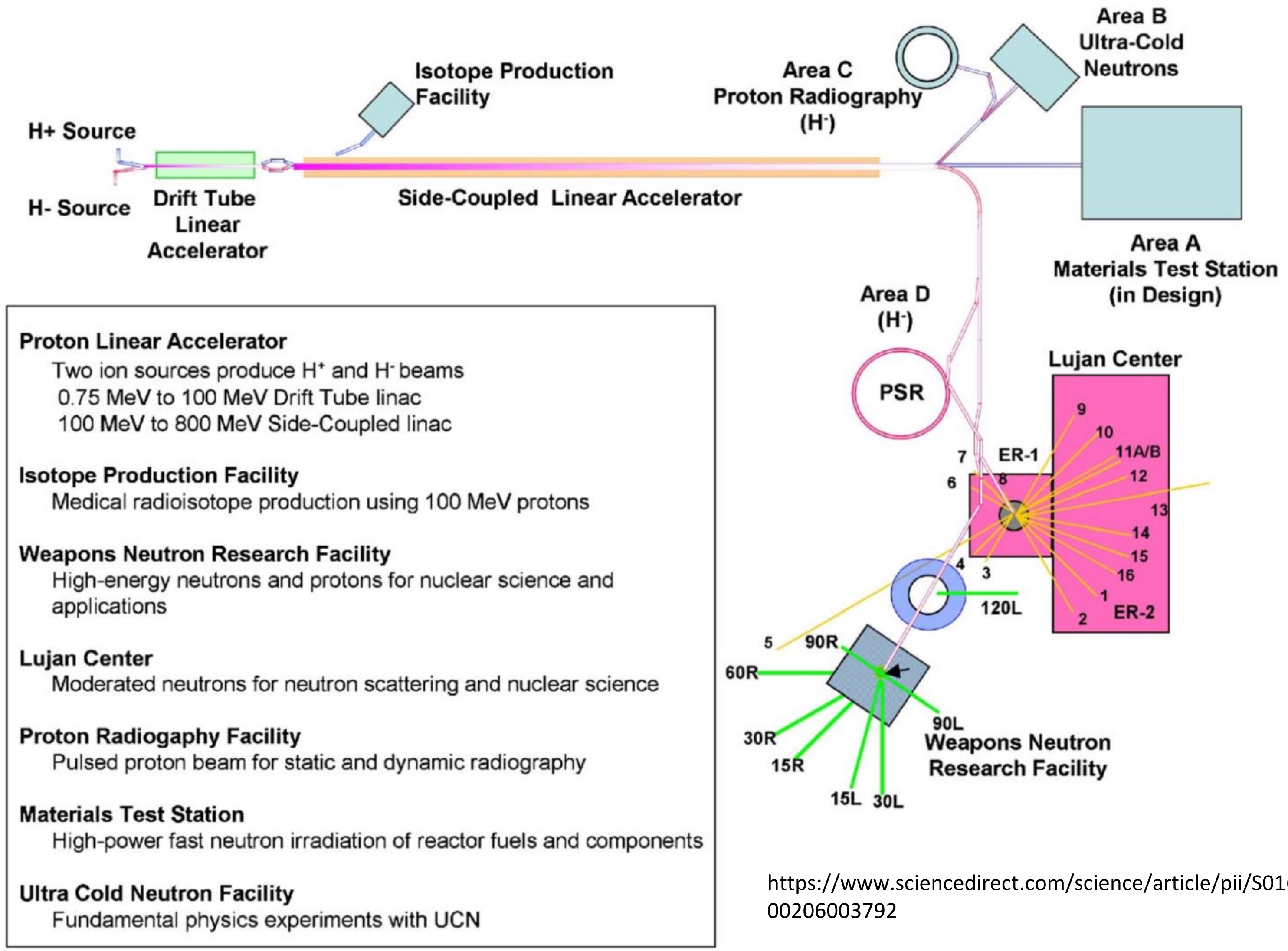
See, e.g., Fayet, 2007 (hep-ph/0702176)

- 1902.05075, Mohlabeng



- 1908.07525, **Tsai**, deNiverville, Liu
- 2012.08595, Duerr et al, detailed BaBar analysis may rule out the g-2 region

LANL-LLP Opportunity!



https://www.sciencedirect.com/science/article/pii/S0168900206003792

Fig. 1. Layout of the LANSCE user facility.

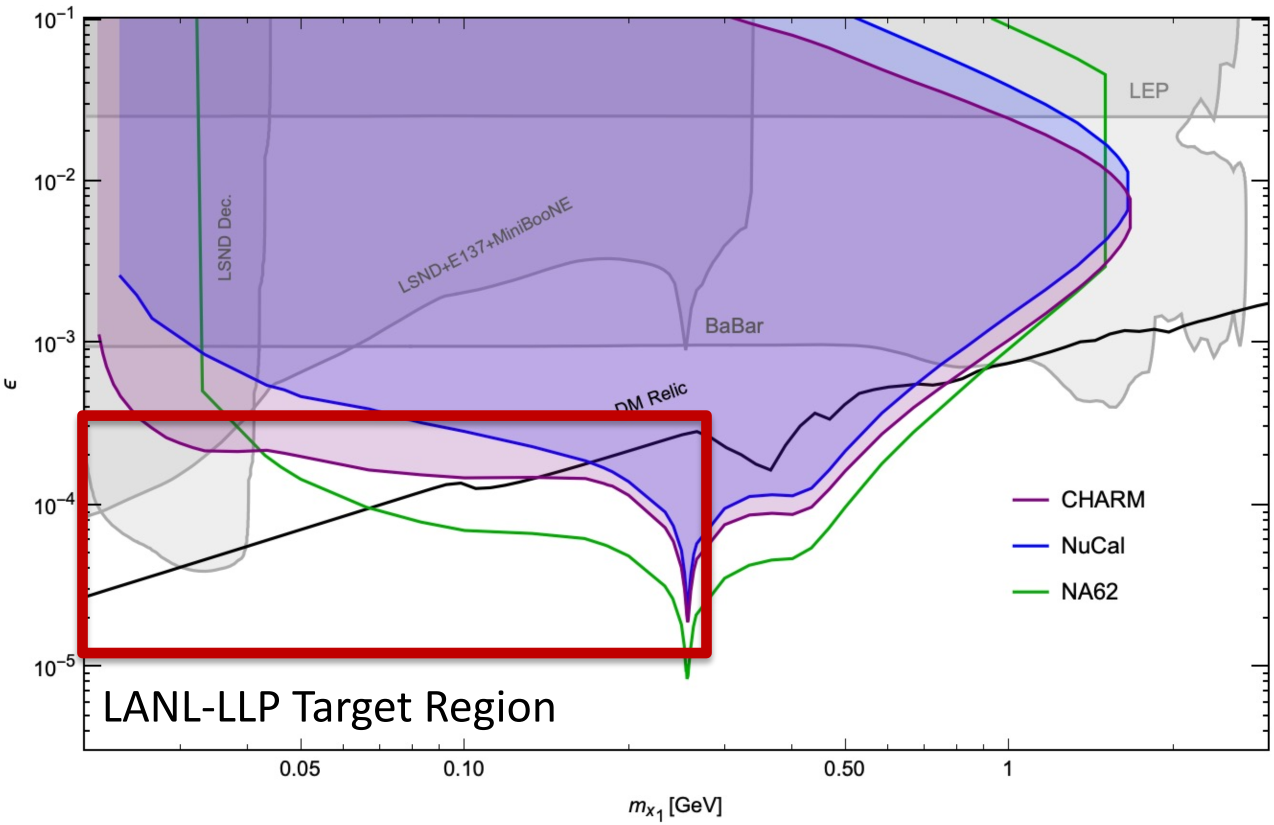
LANL-LLP Target: Inelastic Dark Matter

Inelastic Dark Matter: $\mathcal{L} \supset \sum_{i=1,2} \bar{\chi}_i(i\not{\partial} - m_{\chi_i})\chi_i - (g_D A'_\mu \bar{\chi_1}\gamma^\mu\chi_2 + \text{h.c.}).$

$$g_D \equiv \sqrt{4\pi\alpha_D}.$$

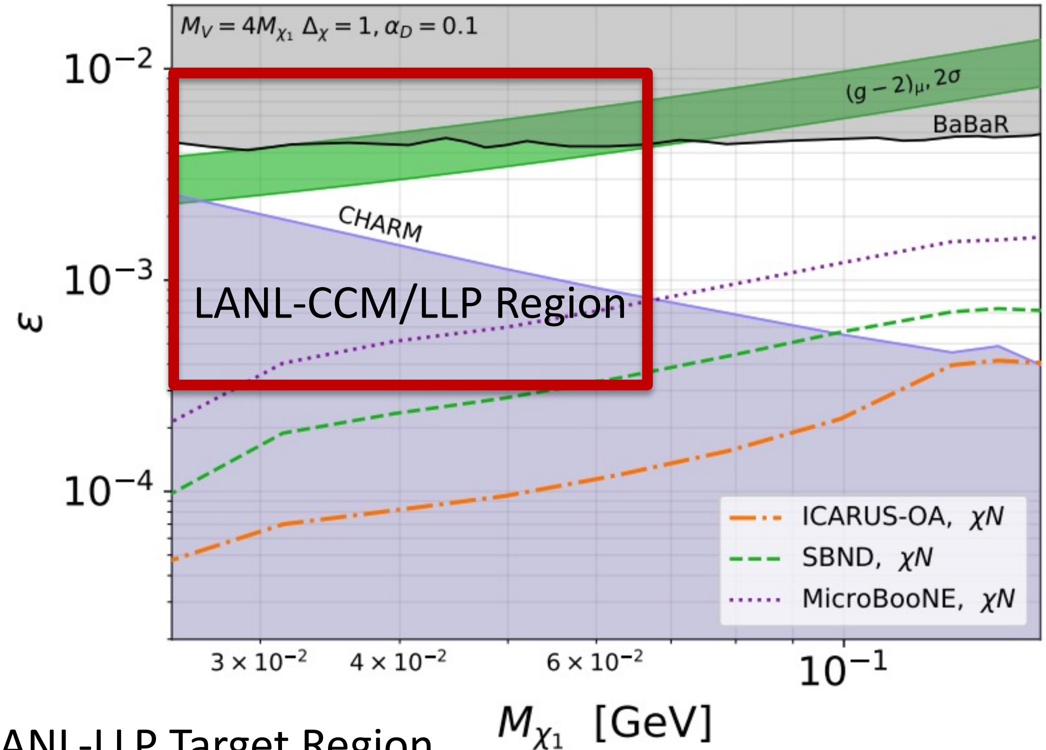
$$\Delta \equiv \frac{m_2 - m_1}{m_1}.$$

- $m_{A'}/m_{x1} = 3$,
- $\Delta = 0.05$,
- $\alpha_D = 0.5$



LANL-LLP Study: deNiverville, Liu, **Tsai,** in preparation

LANL-LLP Target: g-2 Motivated Models



LANL-LLP Target Region

- Batell et al, arXiv:2106.04584
- LANL-**CCM/LLP** Study: deNiverville, **Tsai,** in preparation

Beyond Simple Dark-Sector Models

Can also look into

- Strongly Self-Interaction DM (motivated by dark QCD)
- Cosmology motivated models

New results in preparation!

Scattering Experiments

Scattering Detectors

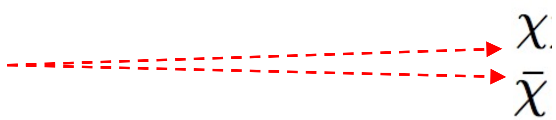
MiniBooNE, SBND, MicroBooNE, MINERvA, DUNE LArTPC, Coherent Captain-Mills (CCM)

- Primary goals to study neutrino scattering and/or neutrino oscillation

Features (comparing to decay detector):

1. higher density
2. complicated design compared to the decaying detector.
3. Smaller fiducial volume (for near-beam detectors); **cost more**.
4. Usually studying **stable particles (**neutrino, dark matter**, millicharged particles)**

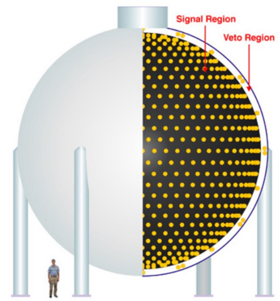
Scattering Detectors



- NuMI Beam
- BNB
- LBNF (future)

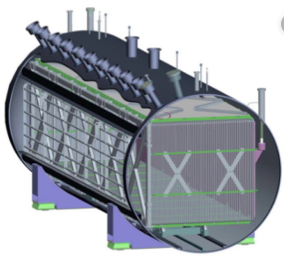
One can do a lot of interesting new physics analyses based on scattering detectors

MiniBooNE Detector



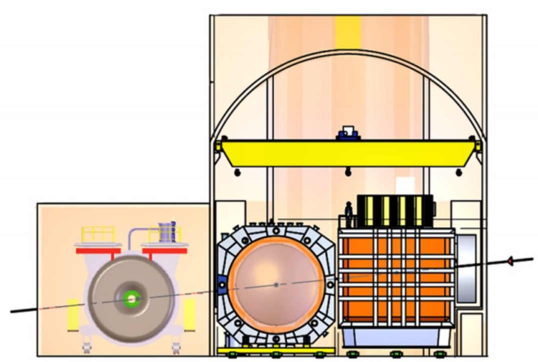
arXiv:0806.4201
MiniBooNE collaboration

MicroBooNE Detector



arXiv:1612.05824
MicroBooNE collaboration

DUNE Near Detector

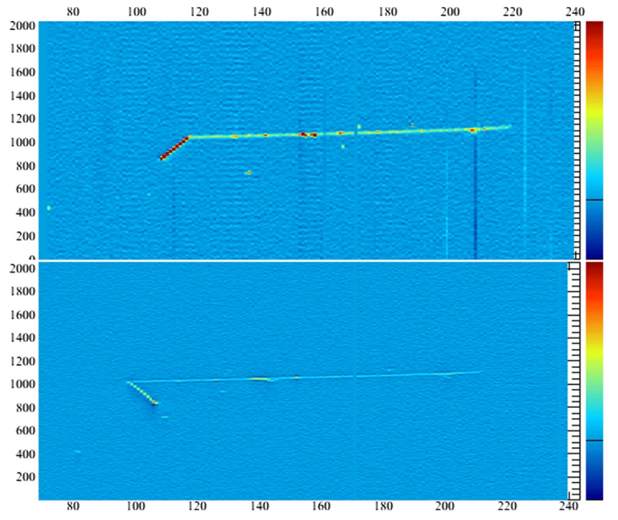


arXiv:2002.02967, DUNE TDR V - I

CCM

https://p25ext.lanl.gov/~lee/CaptainMills/
https://arxiv.org/abs/2105.14020

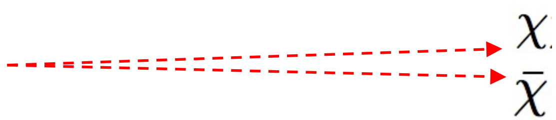
AI & Machine Learning
at the Intensity Frontier



Low energy neutrino event in **ArgoNeuT**, from ArgoNeuT collaboration, PRD '19
https://lss.fnal.gov/archive/2018/pub/fermilab-pub-18-559-nd.pdf

Studying **very faint signals (tracks)** in DUNE, Proto-DUNE, CCM, and other Argonne Detectors, for **MCP, DM**, and other **dark-sector** signatures. New applications for well-developed techniques

Specialized “Scattering” Detectors



- NuMI beam
- BNB
- LBNF (future)

Low-cost / specialized detectors to add to the beam facilities?

Broaden the physics cases

FerMINI - Proton Fixed-Target Search for Millicharged Particle (MCP) & Millicharged Dark Matter (mDM)

Kelly, **Tsai**, arXiv:1812.03998, PRD19

Finding Millicharge (Minicharge)

- **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)** (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**

MCP Model

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

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

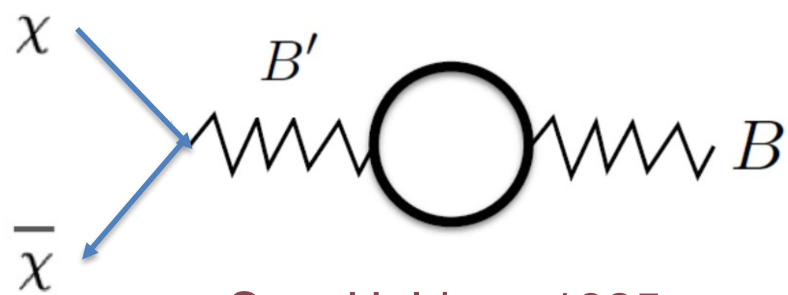
- Can just consider these Lagrangian terms by themselves (no extra mediator, i.e., dark photon). **Completely legal**! Naively violating the empirical charge quantization (cool!).

- 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

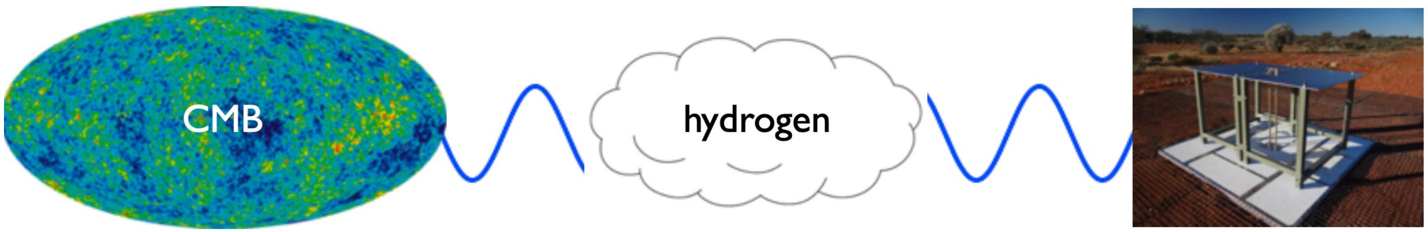
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ + ie'B\!\!\!/' + iM_{\rm MCP})\chi$$

- 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.)

EDGES Measurement

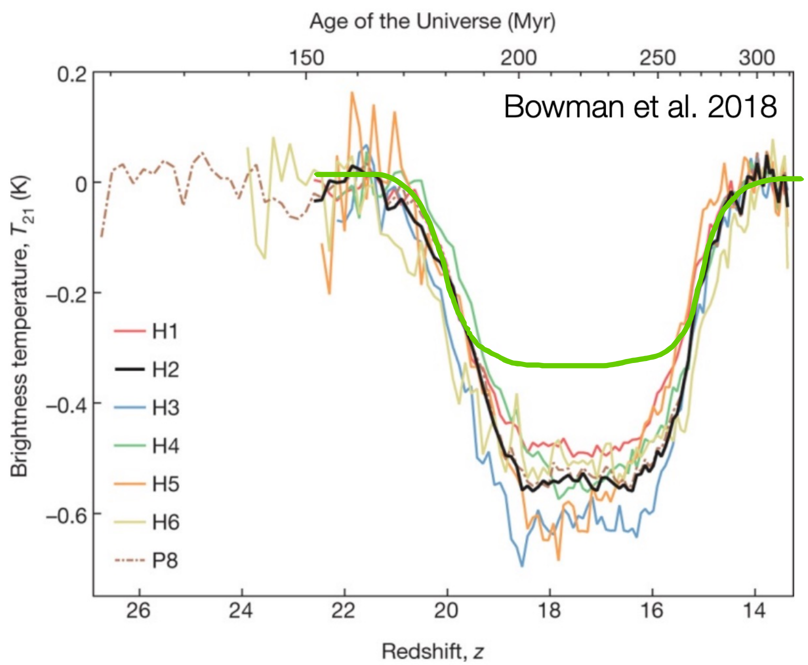
T_γ T_S δT_b



Adapted from J. Pritchard

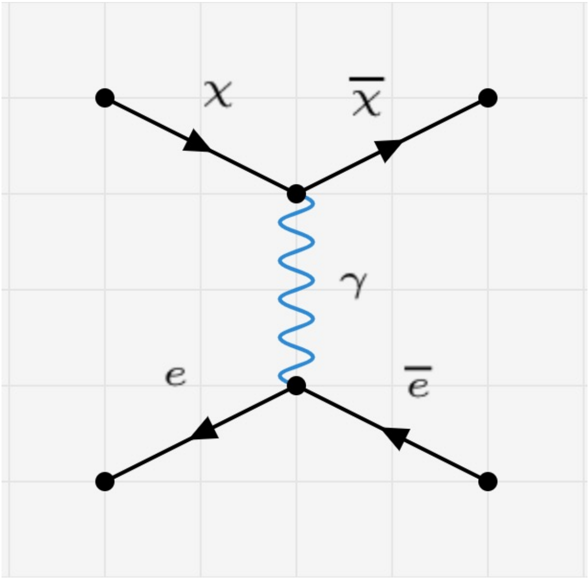
Jordan Mirocha (UCLA)

e.g., EDGES



- EDGES collab., Nature, (2018); Barkana, Nature, (2018), more refs listed in the end

MCP Detection: "Hard" Scattering or Ionization



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

  e.g., MilliQan: arXiv:1410.6816, Haas, Hill, Izaguirre, Yavin

- **"Hard" (MeV-level) electron elastic scattering:**

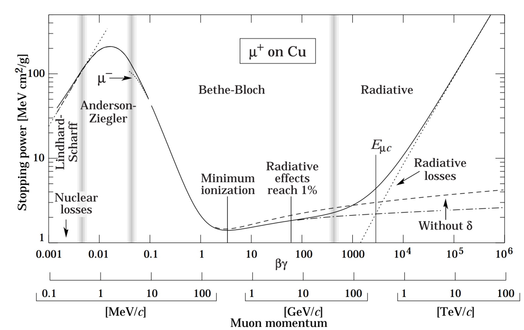
  e.g., Magill, Plestid, Pospelov, **Tsai**, 1806.03310

  (MCP in neutrino Experiments, MiniBooNE, MicroBooNE, SBND, DUNE, SHiP)

MCP Detection: Ionization

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

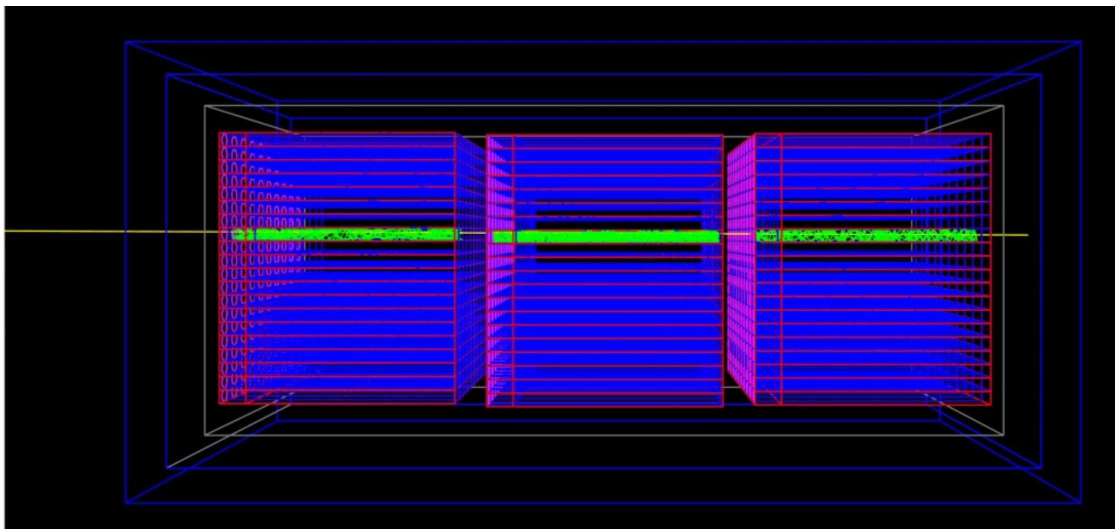
$$\left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2.$$

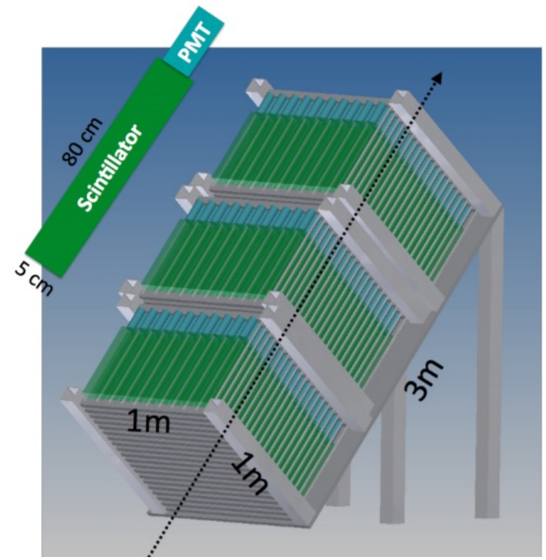


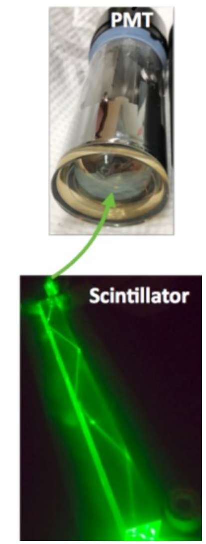
intentionally make the plot small so we don't get into too much details of this.
http://pdg.lbl.gov/2020/reviews

MilliQan: Detector Concept

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



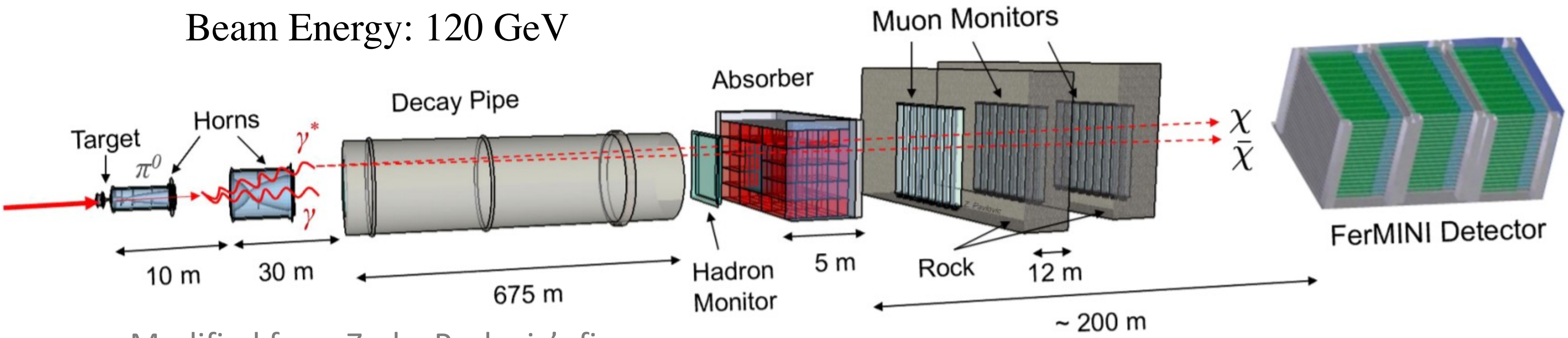




1607.04669, Ball, Brooke, Campagnari, De Roeck, Francis, Gastal, Golf, Goldstein, Haas, Hill, Izaguirre, Kaplan, Magill, Marsh, Miller, Prins, Shakeshaft, Stuart, Swiatlowski, Yavin

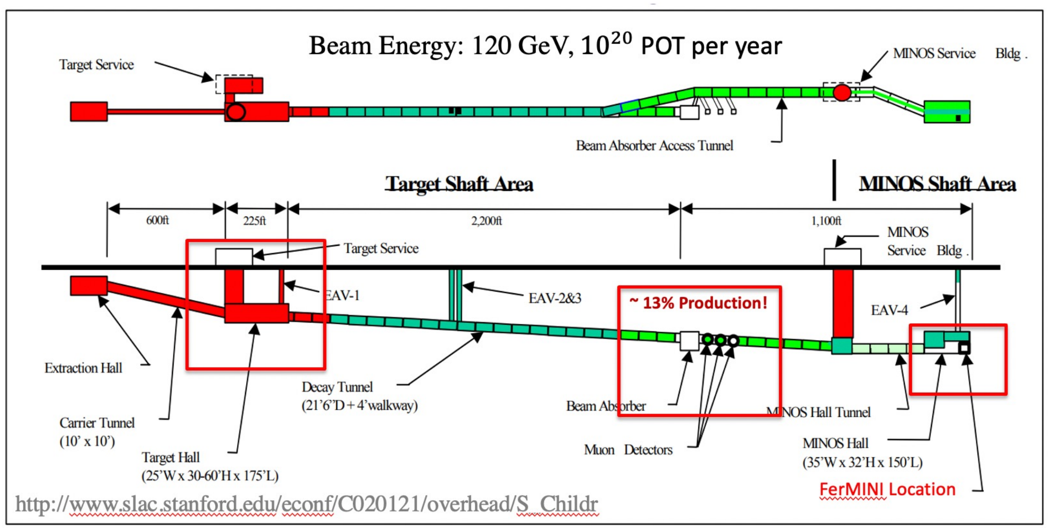
FerMINI:
Fermilab Millicharge Search

FerMINI Site 1: NuMI-MINOS Hall



Modified from Zarko Pavlovic's figure

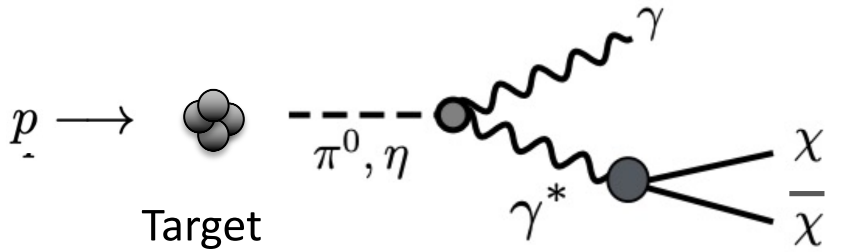
An illustration of the FerMINI experiments utilizing the NuMI facility.



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

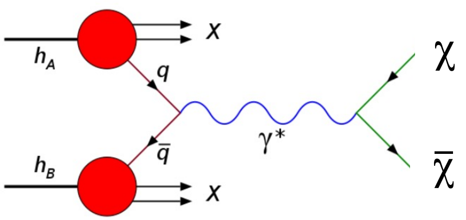
Production of MCP

- Production: Meson Decays



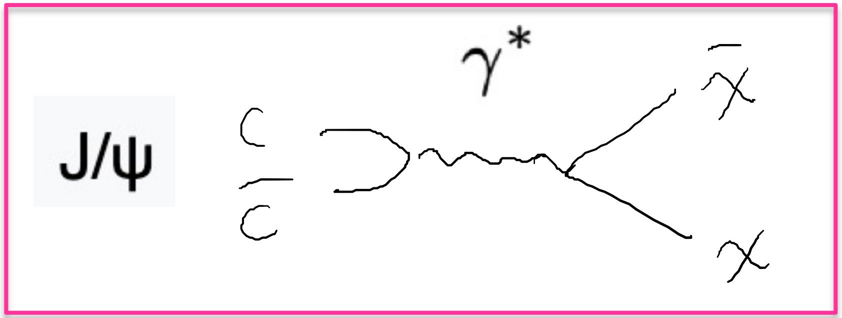
Figures **replaced A’ with photon** from 1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

- Production: Drell-Yan



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

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



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

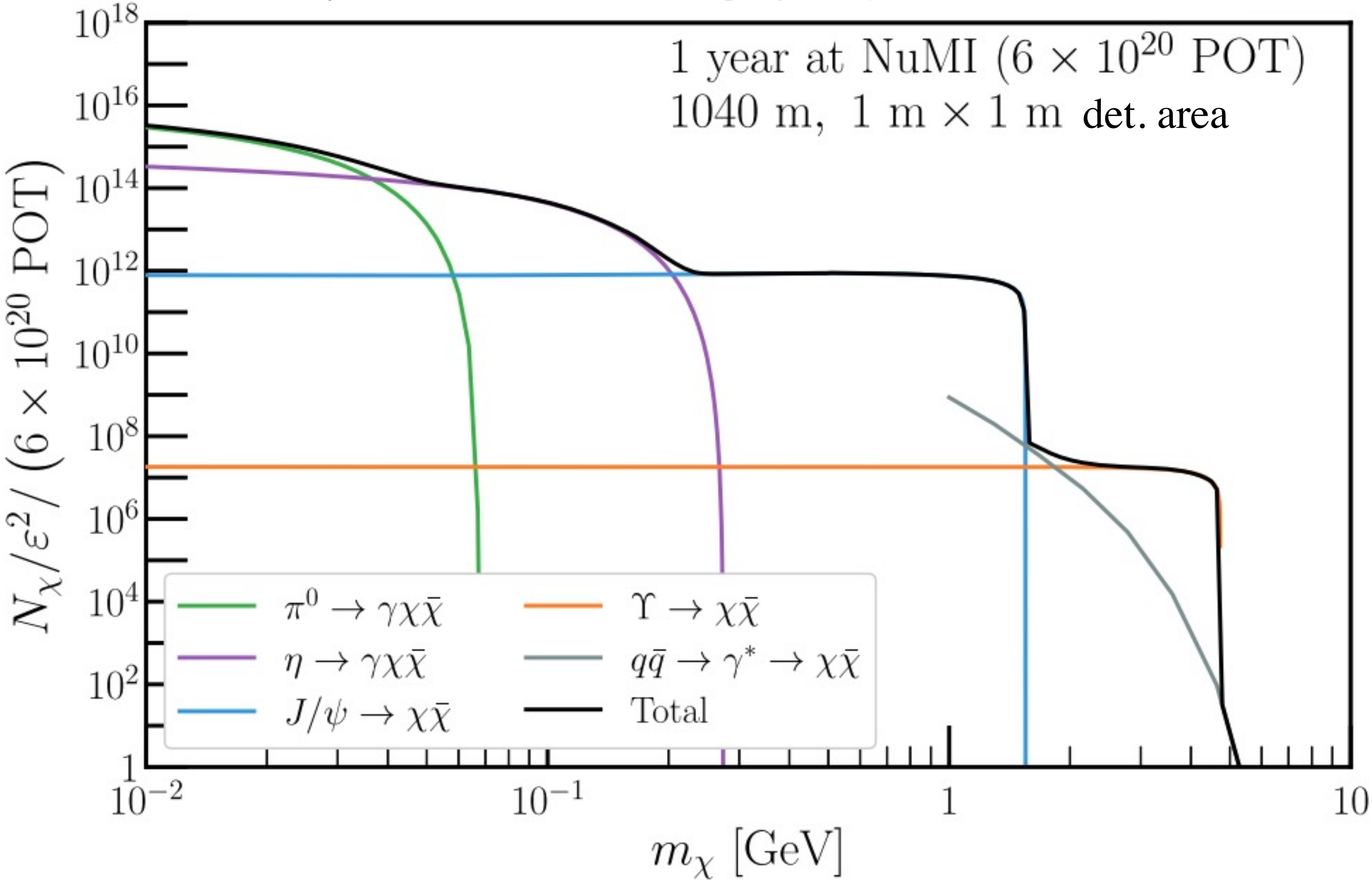
BR($\pi^0 \to \gamma e^- e^+$) = 0.01

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

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

MCP Production/Flux

120 GeV proton beam on target (graphite)



Photoelectrons (PE) from Scintillation

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

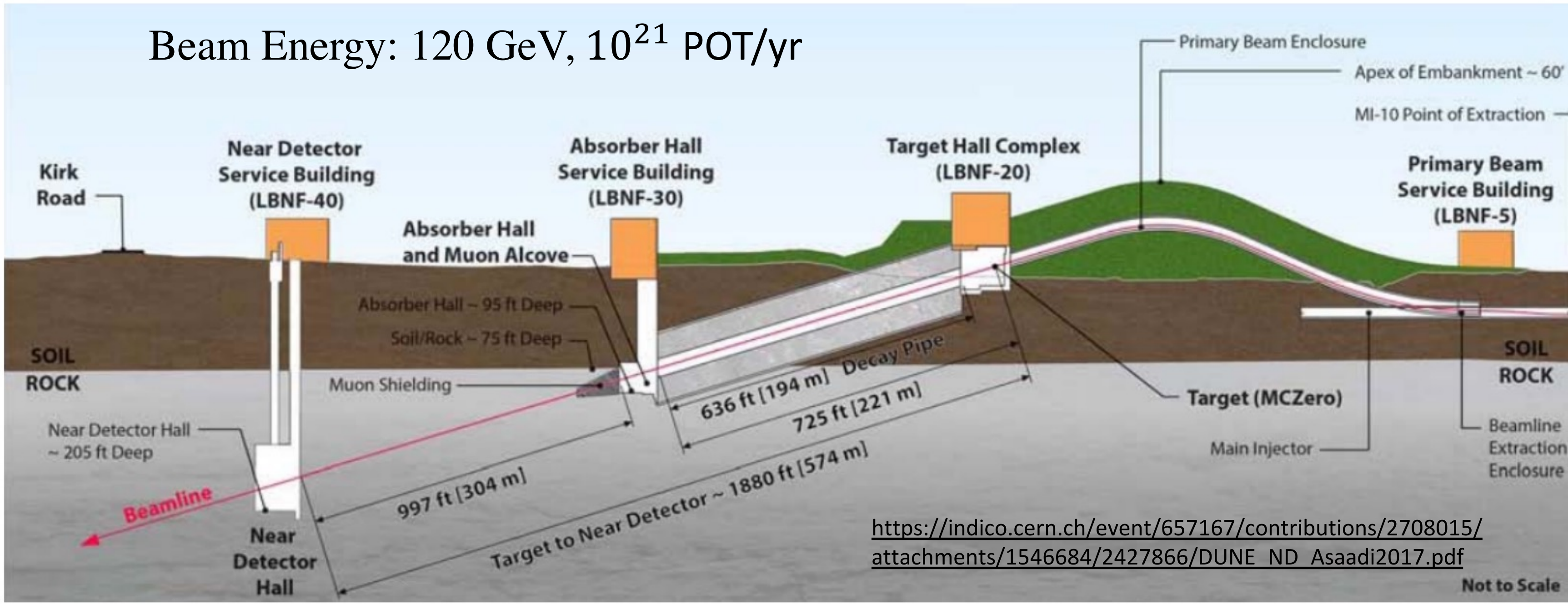
$$N_{PE} \propto \left\langle -\frac{dE}{dx} \right\rangle \times l_{scint}, \quad \left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2.$$

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

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

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

Site 2: LBNF Beam & DUNE ND Hall

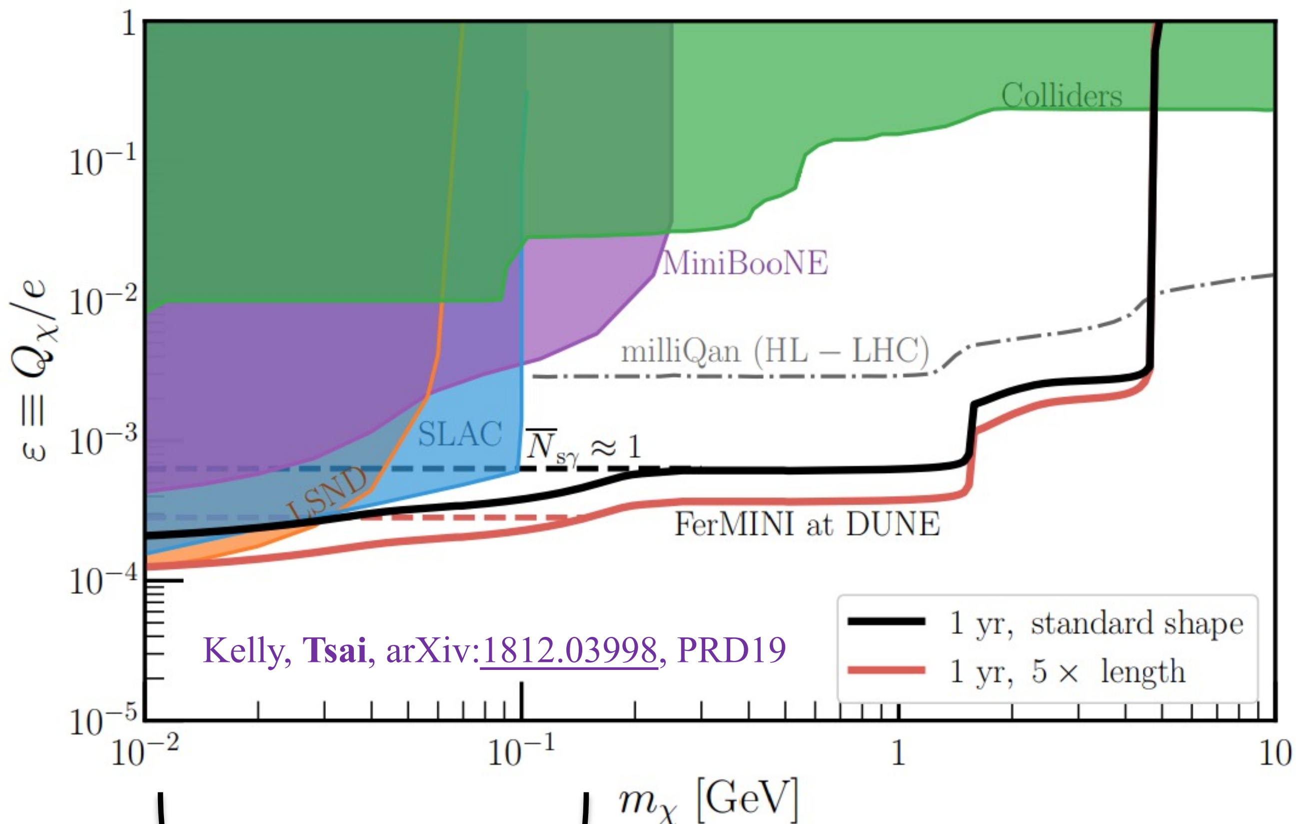


Jonathan Asaadi – University of Texas Arlington

LBNF: Long-Baseline Neutrino Facility

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

FerMINI @ DUNE

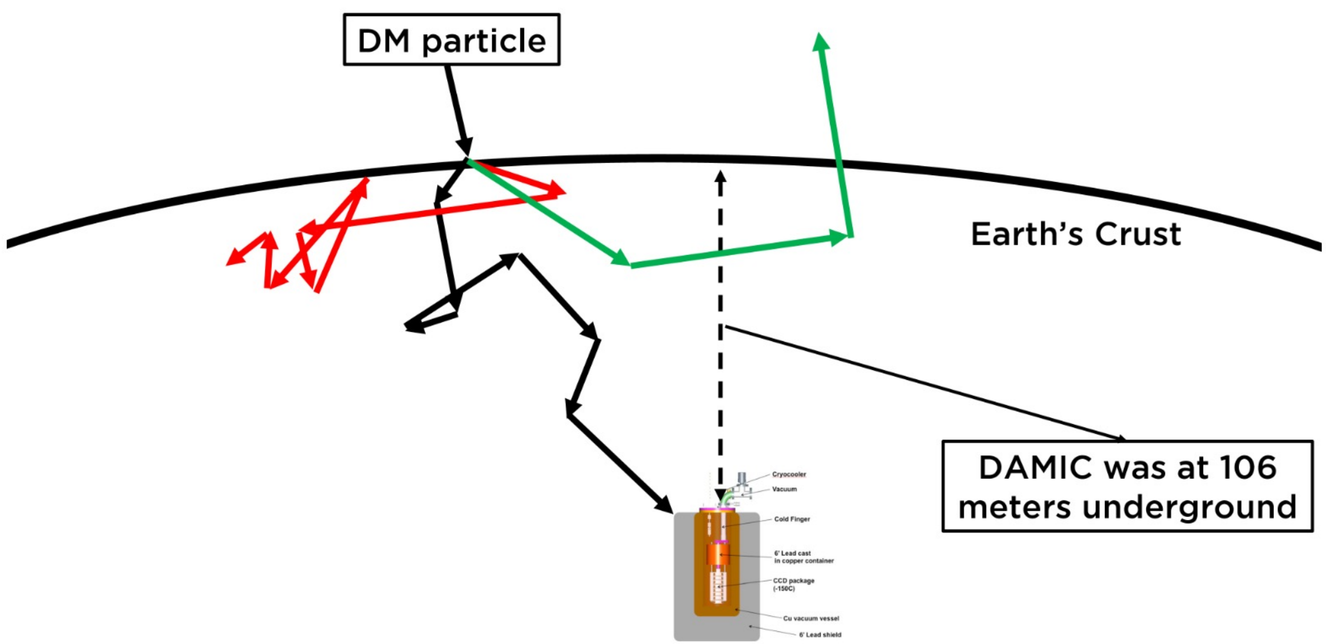


Yu-Dai Tsai,
Fermilab

- Can be improved by considering **timing** & just **double-coincidence**, instead of triple or quadruple coincidence, see SUBMET, Kim, Hwang, Yoo, arXiv:2102.11493, JHEP21

Strongly Interacting Dark Matter

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

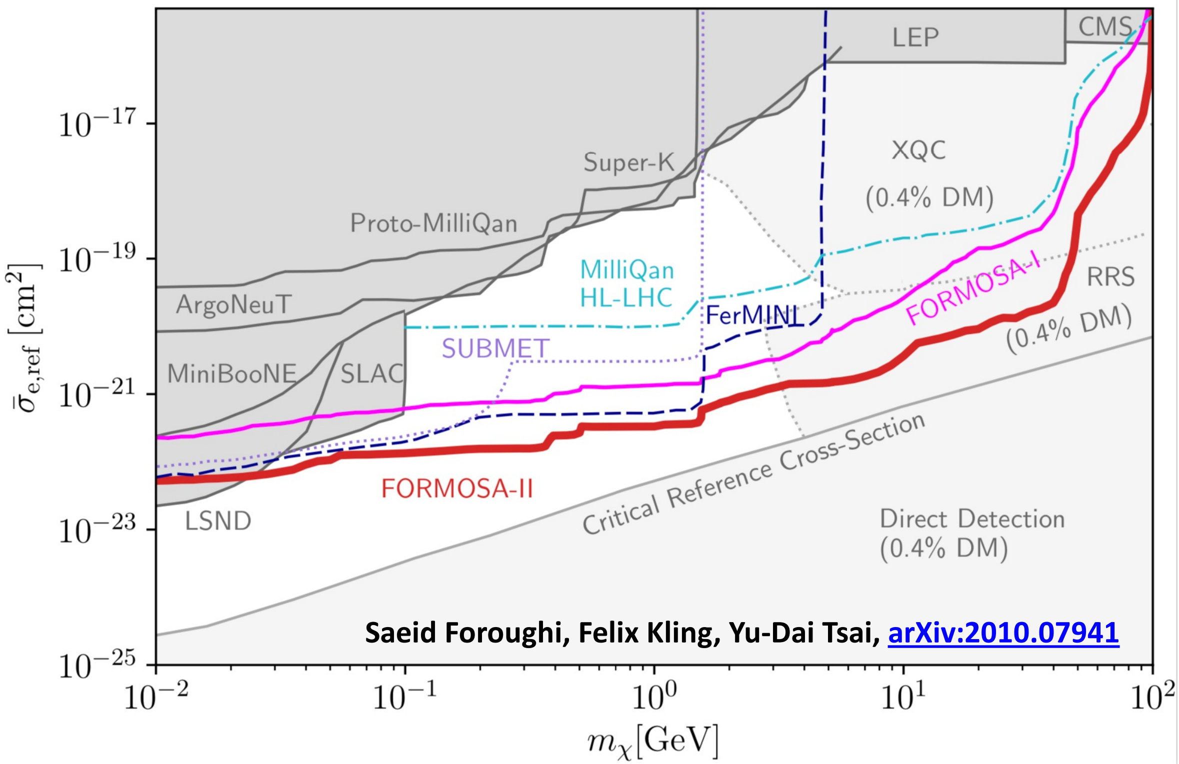


DMATIS (Dark Matter ATtenuation Importance Sampling), Mahdawi & Farrar '17

Probe of Millicharged Dark Matter

MCP / LDM with ultralight dark photon mediators

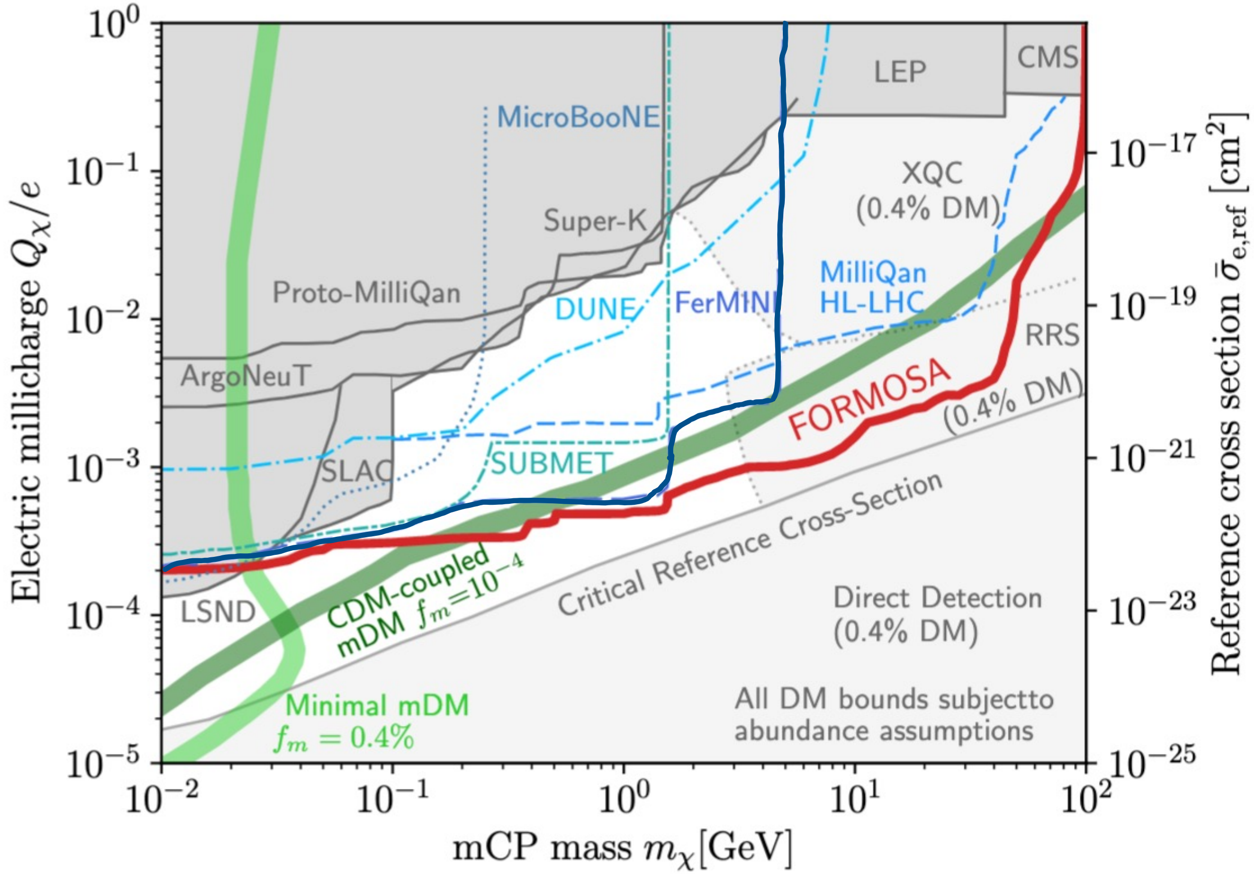
$$\bar{\sigma}_e \simeq \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{ref}^2}, \; q_{ref} = \alpha m_e$$



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

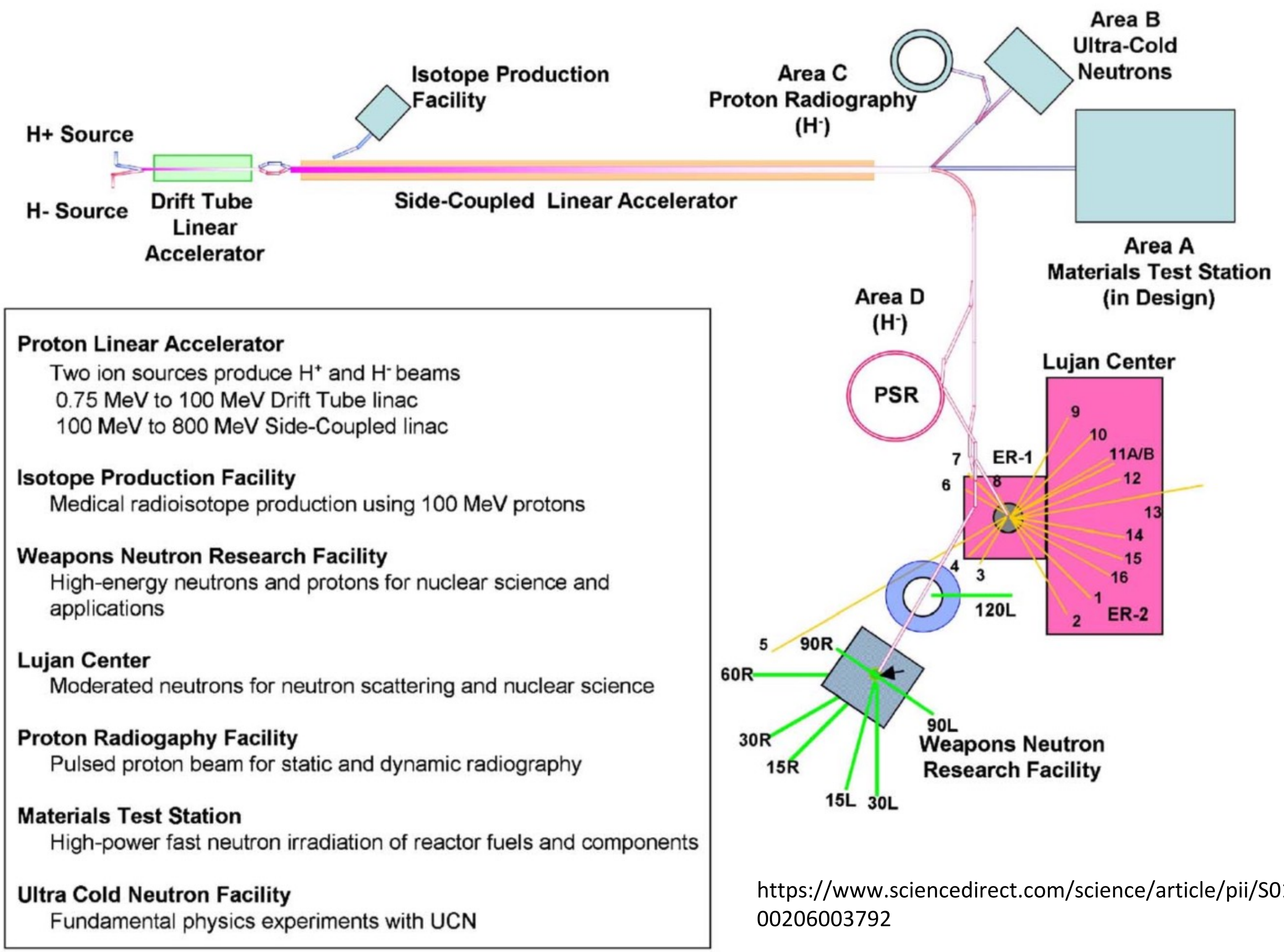
- Here we plot the **critical reference cross-section** see 1905.06348 (Emken, Essig, Kouvaris, Sholapurkar)
- **Accelerator probes can help close the Millicharged SIDM window!**
- Cosmic-ray production & Super-K detection 2002.11732

FerMINI Probes of EDGES DM



FORMOSA is similar to milliQan and FerMINI, but study MCP at LHC forward region

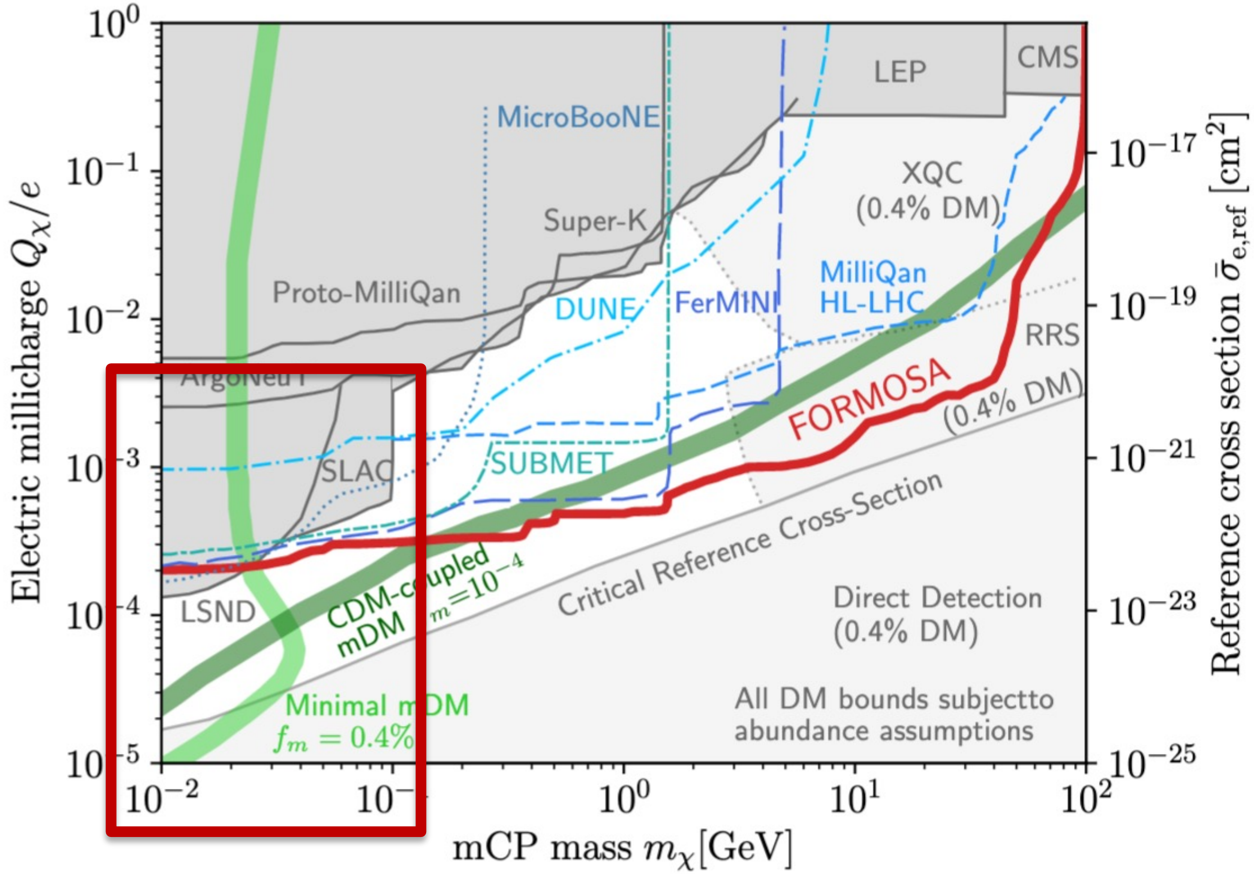
LANL Millicharge Opportunity!



https://www.sciencedirect.com/science/article/pii/S0168900206003792

Fig. 1. Layout of the LANSCE user facility.

LANL-MCP Experiment



LANL-MCP Target Region

Foroughi, Liu, **Tsai**, in preparation

Legion of Decay Experiments

Existing Probes

Future Probes

Experiment	Beam Energy	POT	$L_{\text{dist.}}$	L_{dec}
CHARM	400 GeV	2.4e18	480 m	35 m
NuCal	70 GeV	1.7e18	64 m	23 m
NA62	400 GeV	*1.3e16/1e18	82 m	75 m
SeaQuest	120 GeV	*1.4e18/1e20	5 m	*7 m
LongQuest	120 GeV	*1e20	5 m	*7/13 m
DUNE ND	120 GeV	1e21	500 m	*1m
LANL - CCM	800 MeV	2.25e22	20 m	1.2 m
LANL - MCP	800 MeV	~ 1e22	TBD	TBD
LANL - Decay	800 MeV	~ 1e22	TBD	TBD

- $L_{dist.}$ = from target to detector (longer will lose short-lived particles)
- L_{dec} = length of the decay region (the longer the better)
- *means still to be determined
- See, e.g., 1908.07525 for a systematic comparison
- Conducting a comprehensive study for general & Snowmass purposes

Summary and Big Picture

- **Proton fixed-target/beam-dump** experiments:

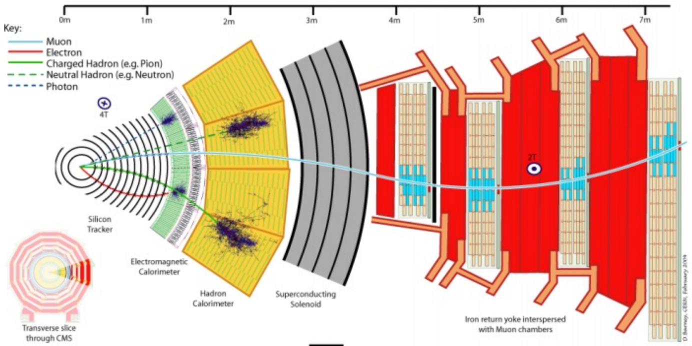
  very powerful searching for MeV-GeV DM and LLP, anomaly motivated

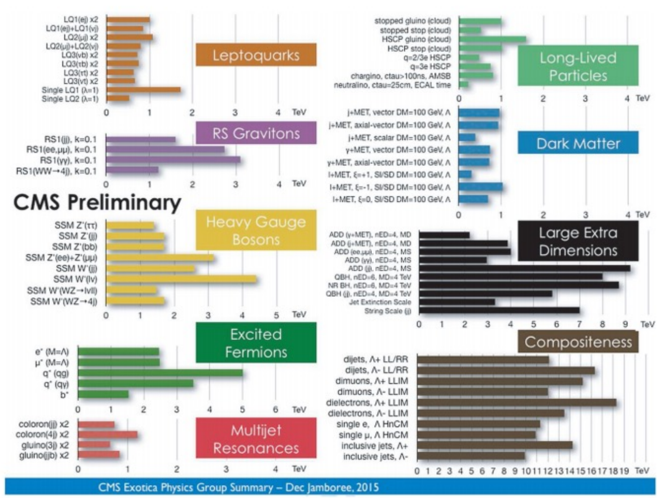
- LANL can be the next center for dark sector search, building a research complex at the **Lujan Center** or **Proton Radiography Facility (pRad)**

- Conduct LLP search like LongQuest (**LANL-LLP**), can do MCP search like FerMINI (**LANL-MCP**): low-cost new experiments!

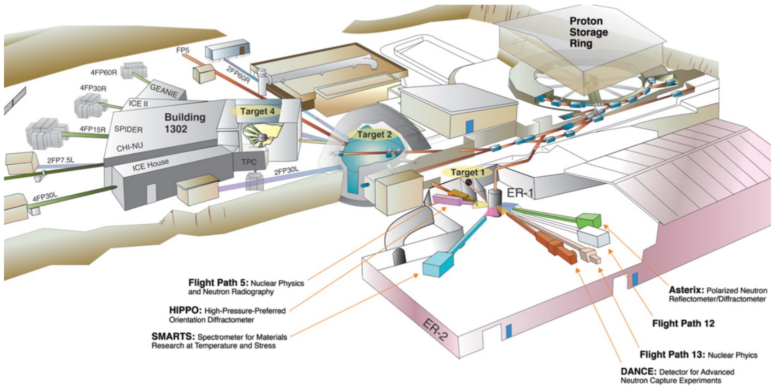
LHC vs LANL New-Physics Complex

High energy frontier





High intensity frontier



https://lansce.lanl.gov/facilities/index.php

New Physics Opportunities!

https://indico.fnal.gov/event/18430/session/8/contribution/17
From Roni Harnik

Yu-Dai Tsai, Fermilab, 2021

Thank you!

There are many other exciting ideas to explore!

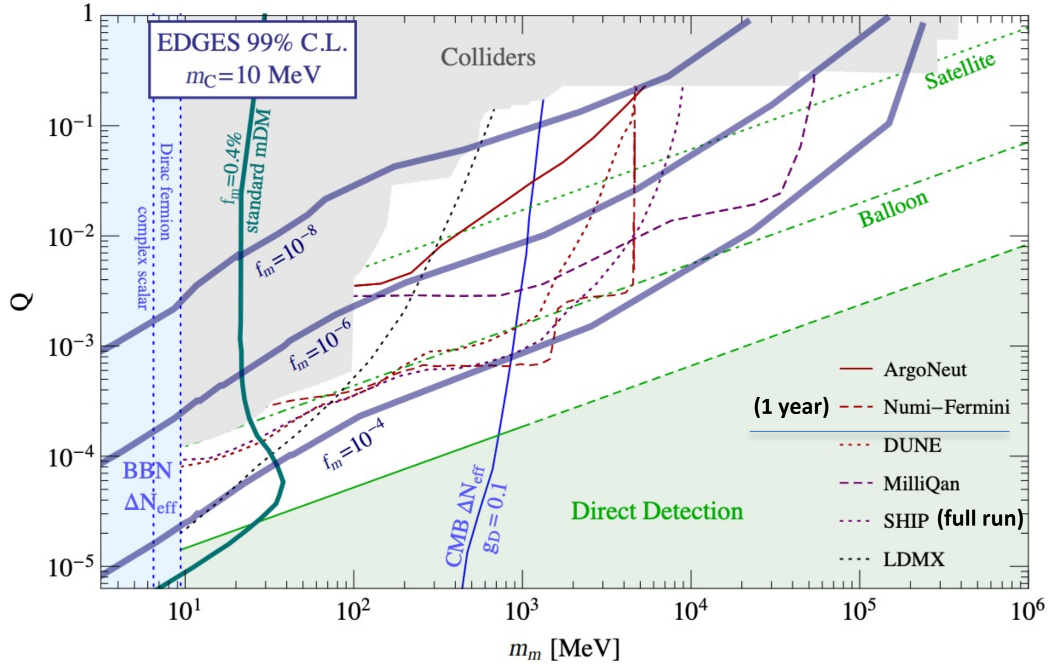
Signature: Triple Coincidence

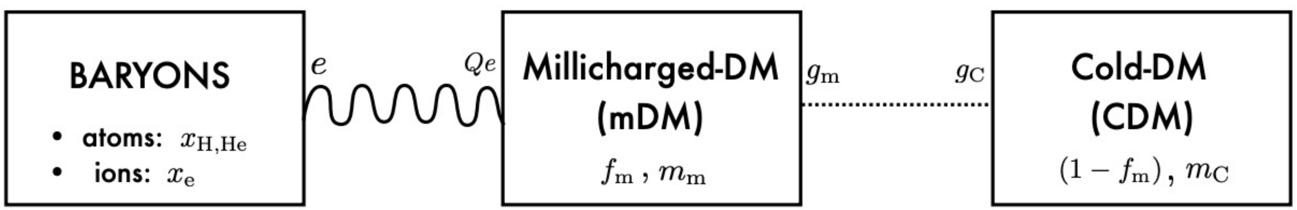
- Based on Poisson distribution, zero event in each bar correspond to $\boldsymbol{P_0} = \boldsymbol{e^{-N_{PE}}}$, so the probability of seeing triple incident of one or more photoelectrons is:

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

- **$N_{x,\mathrm{detection}} = N_{X,\text{going through detector}} \times P.$**

Millicharged DM for EDGES





Liu, Outmezguine, Redigolo, Volansky, '19

EDGES gives another hint of dark matter property, just like small-scale structure

Proton Facilities of Interest

Comparison of Various 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	near-future

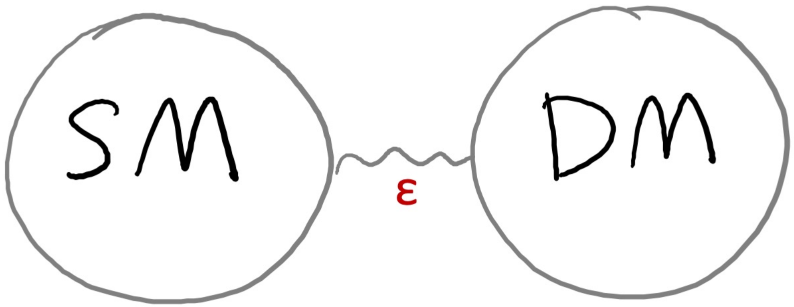
CERN - SPS beam			
NA62	up to 3 x 10^{18} POT/yr	400 GeV	now
SHiP	up to 10^{19} POT/yr	400 GeV	future

CERN – HL LHC	10^{16} POT/yr	$\sqrt{s}$ = 13 TeV	near-future

Lujan & CCM Information!

https://indico.fnal.gov/event/46020/contributions/202757/attachments/137980/172466/LANSCE-PSR-LOITalk-NF-09.pdf

Lee-Weinberg



- The **Lee-Weinberg bound** (1977’): **below $\sim \mathbf{2\ GeV}$**, DM freeze-out through weak-Interaction (e.g., through Z-boson) would overclose the Universe. Freeze-out too early m^2/M^4

- Could consider ways to get around this but generally **sub-GeV DM needs BSM mediators** to freeze-out to proper relic abundance.

- New mediator is needed:
  the rise of **“dark sector” (DM + mediators + stuffs).**
- Another motivation to consider dark sector other than anomalies