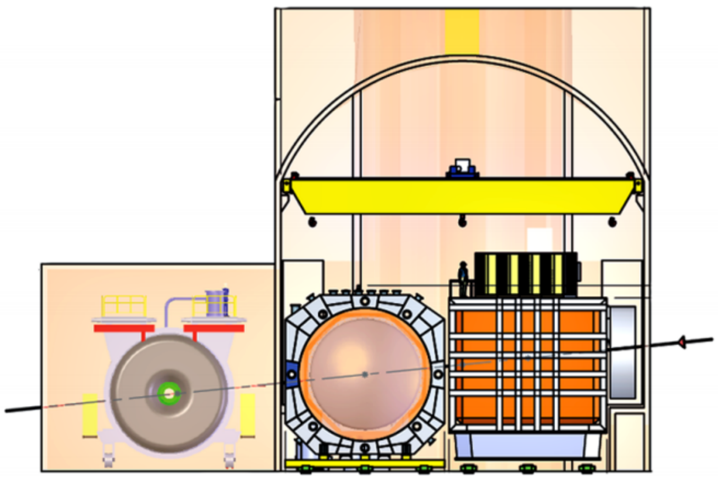
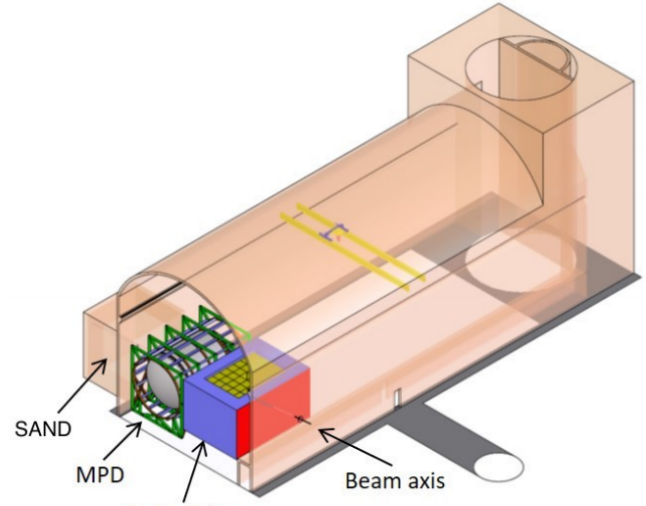


[arXiv:2002.02967](#), DUNE TDR V - I



[arXiv:2002.02967](#), DUNE TDR V-I

Dark-Sector Searches at the DUNE Near Detector Complex: Decay vs Scattering

Yu-Dai Tsai, **Fermilab / UChicago (KICP)**

[1] MCP in Neutrino Experiments (1806.03310, ***PRL '19***)

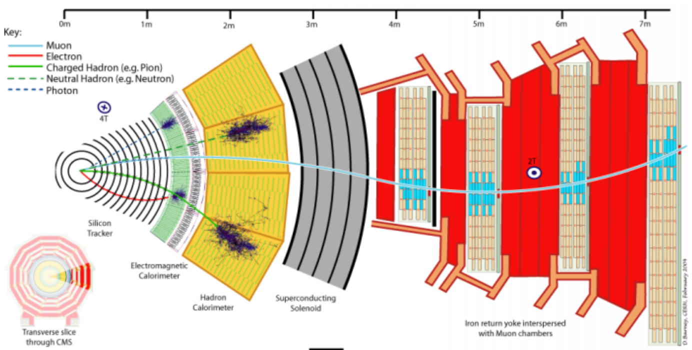
[2] Dark photon, inelastic dark matter, muon g-2 window (1908.07525)

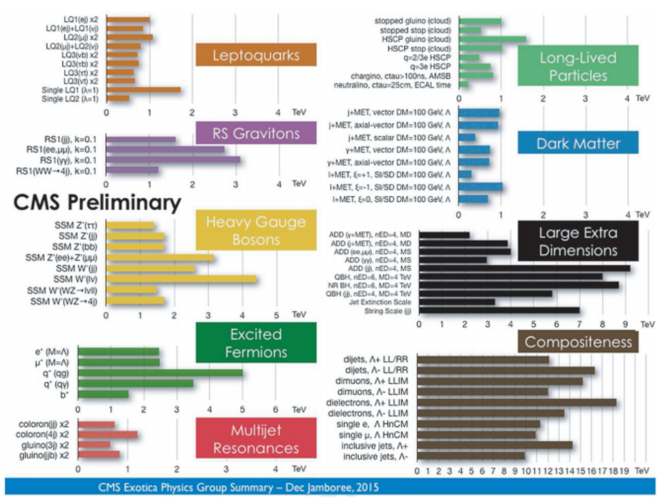
[3] The FerMINI Experiment (1812.03998, ***PRD '19***)

[4] (Up) scattering + decay studies, **in preparation**

LHC vs DUNE

High energy frontier

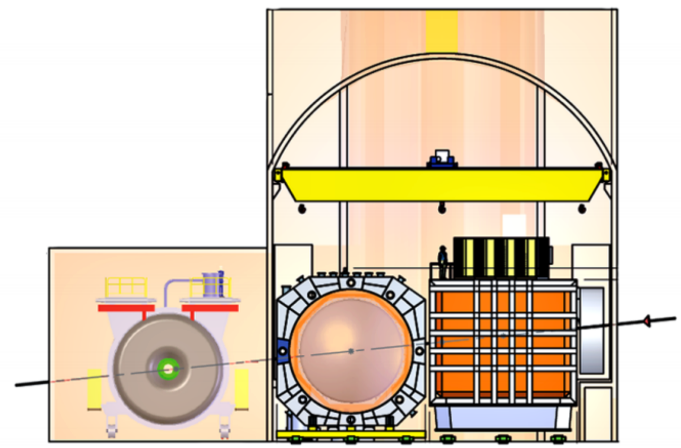




https://indico.fnal.gov/event/18430/session/8/contribution/17

redesigned from Roni Harnik's

High-energy Intensity frontier



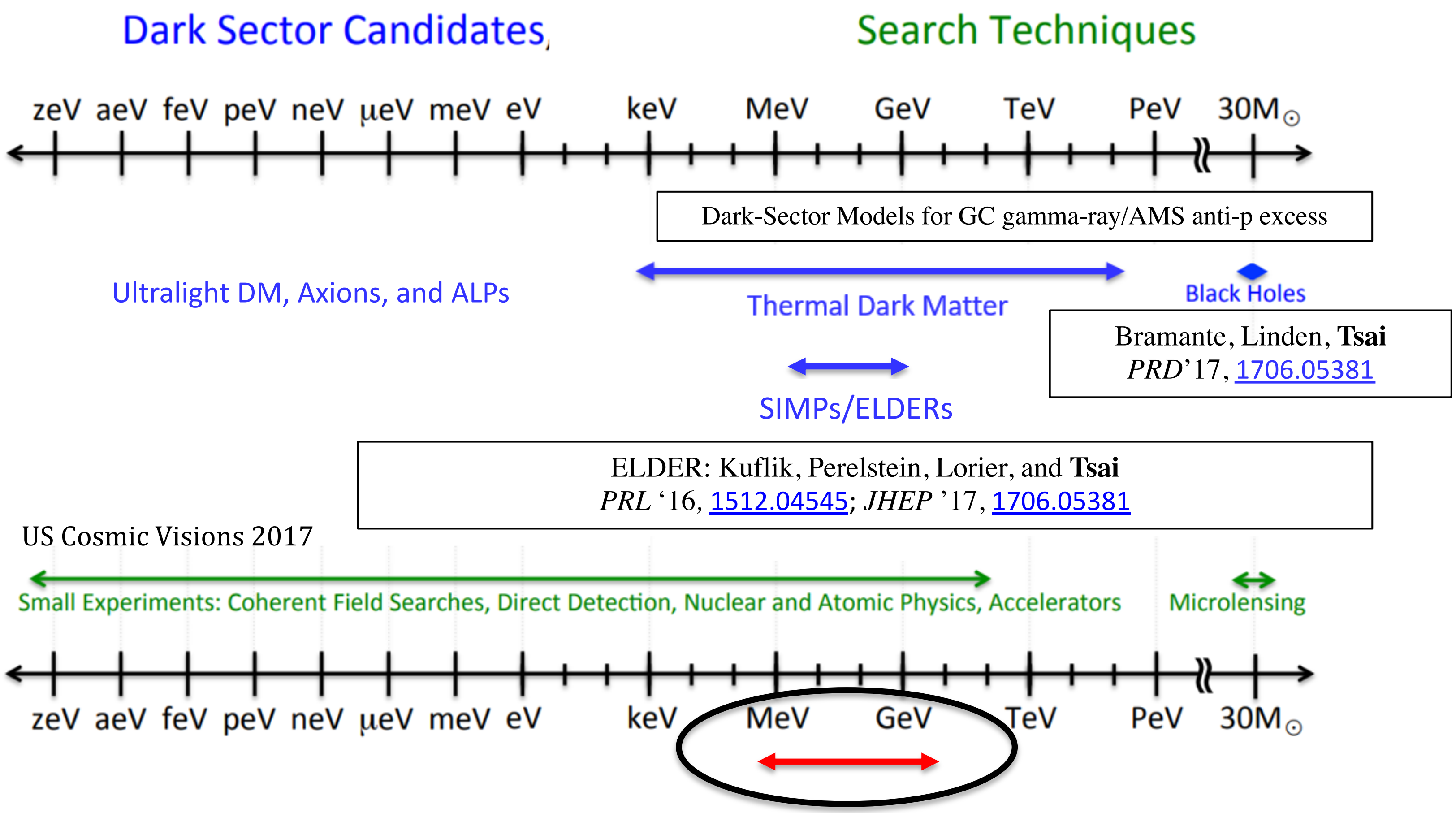
arXiv:2002.02967, **DUNE TDR V I**

Yu-Dai Tsai, Fermilab, 2020

Outline

- Intro: Why **DUNE**? Why **MeV - GeV** New Physics?
- **Decay** vs **Scattering** Experimental Probes
- Decay studies: renormalizable portals and **Inelastic Dark Matter (new results!)**
- Scattering study: **millicharged particles (MCP)** & **Strongly Interacting Dark Matter (new plots!)**
- Scattering + Decay & FerMINI proposal

Exploration of Dark Matter & Mediator



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

Fixed-Target Neutrino Experiments

- **High statistics**, LBNF/DUNE will have $\sim \mathbf{10^{22}}$ **Protons on Target** (POT)
- Neutrinos are **dark-sector particles**.
- Relatively high-energy proton beams on targets: **O(100 – 400) GeV** (I will compare Fermilab/CERN facilities)
- Shielded/underground: lower background
- Many of them existing and many to come: **strength in numbers**
- **Produce these particles with less assumptions**

Not all bounds are created equal

→ Assumptions

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

Accelerator-based: Collider, Beam Dump, …
Fixed-Target Neutrino Experiments (DUNE)

techinical ↓

Cosmic-ray productions / Astrophysical production (SN1987A & neutron-star mergers) observation in large detectors / energy loss or cooling,
Rely on modeling/observations of (complicated/ extreme/rare) systems

Dark matter direct/indirect detection: abundance, velocity distribution, etc
Cosmology: assume cosmological history, species, etc

DUNE ND Complex:
Super Exciting Opportunities

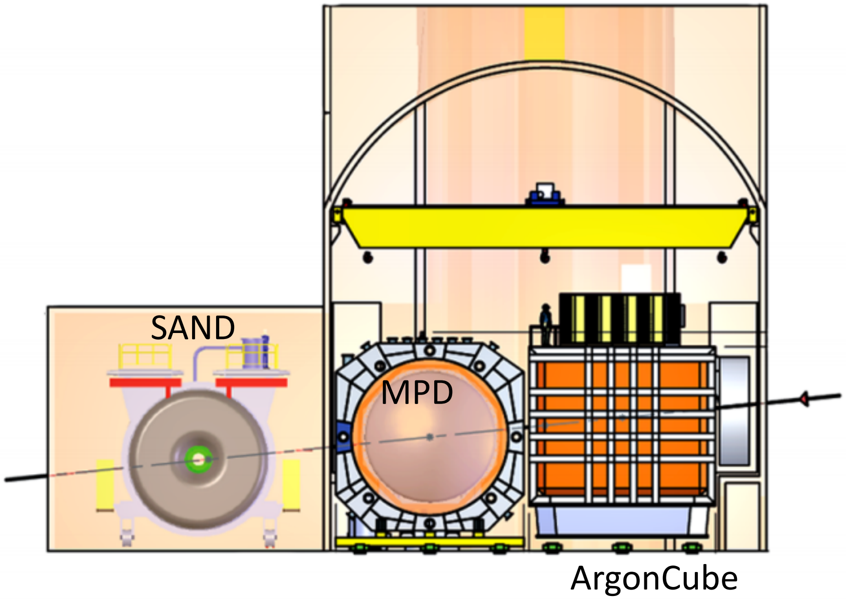
DUNE Near-Detector Complex

- **120 GeV proton beam** on target**,** $\sqrt{s}$ **= 15.4 GeV, 10^22 POT** accumulated in **10 years: High-energy Intensity Frontier!**
- DUNE TDR VI: arXiv:2002.02967, CDR of ND will be released this year

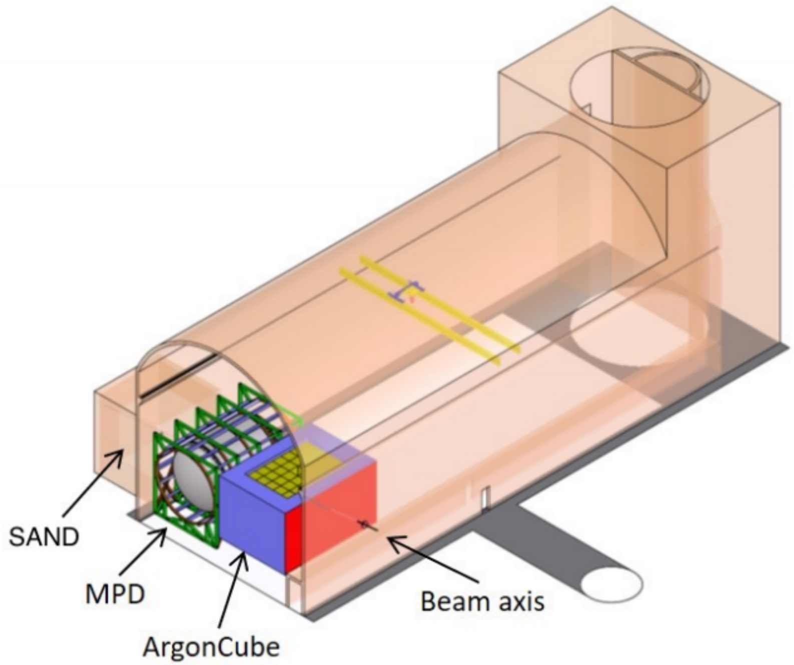
ND complex has 3 detectors:

- **ArgonCube**: Liquid Argon Time Projection Chamber (LArTPC)
- **MPD**: multi-purpose high pressure gas TPC (HPgTPC, ND-GAr) w/ magnetic field + EMCal
- **SAND**: Scintillator Array Near Detector: precision beam monitoring detector. See Steve's talk for updates

DUNE Near Detector (ND) Complex



arXiv:2002.02967, DUNE TDR V - I



arXiv:2002.02967, DUNE TDR V - I

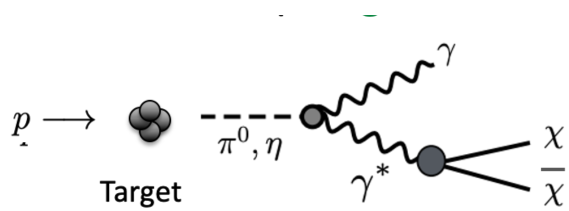
ND Complex Facilities

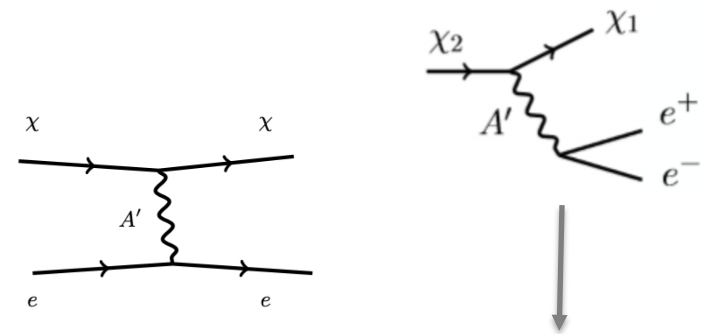
Table 5.1: High-level breakdown of the three major detector components and the capability of movement for the DUNE ND, along with functions and primary physics goals.

Component	Essential Characteristics	Primary function	Select physics aims
LArTPC (ArgonCube)	Mass	Experimental control for the FD.	$\nu_\mu(\overline{\nu}_\mu)$ CC
	Target nucleus Ar	Unoscillated E_ν spectra measurements.	ν-e$^-$ scattering
	Technology FD-like	Flux determination.	ν_e+$\overline{\nu}_e$ CC Interaction model
Multipurpose detector (MPD)	Magnetic field	Experimental control for the LArTPCs.	$\nu_\mu(\overline{\nu}_\mu)$ CC
	Target nucleus Ar	Momentum-analyze μ's produced in LAr.	ν_e CC, $\overline{\nu}_e$
	Low density	Measure exclusive final states with low momentum threshold.	Interaction model
DUNE-PRISM (capability)	ArgonCube+MPD move off-axis	Change flux spectrum	Deconvolve flux $\times$ cross section; Energy response; Provide FD-like energy spectrum at ND; ID mismodeling.
Beam Monitor (SAND)	On-axis	Beam flux monitor	On-axis flux stability
	High-mass polystyrene target	Neutrons	Interaction model;
	KLOE magnet		Atomic number (A) dependence; ν-e$^-$ scattering.

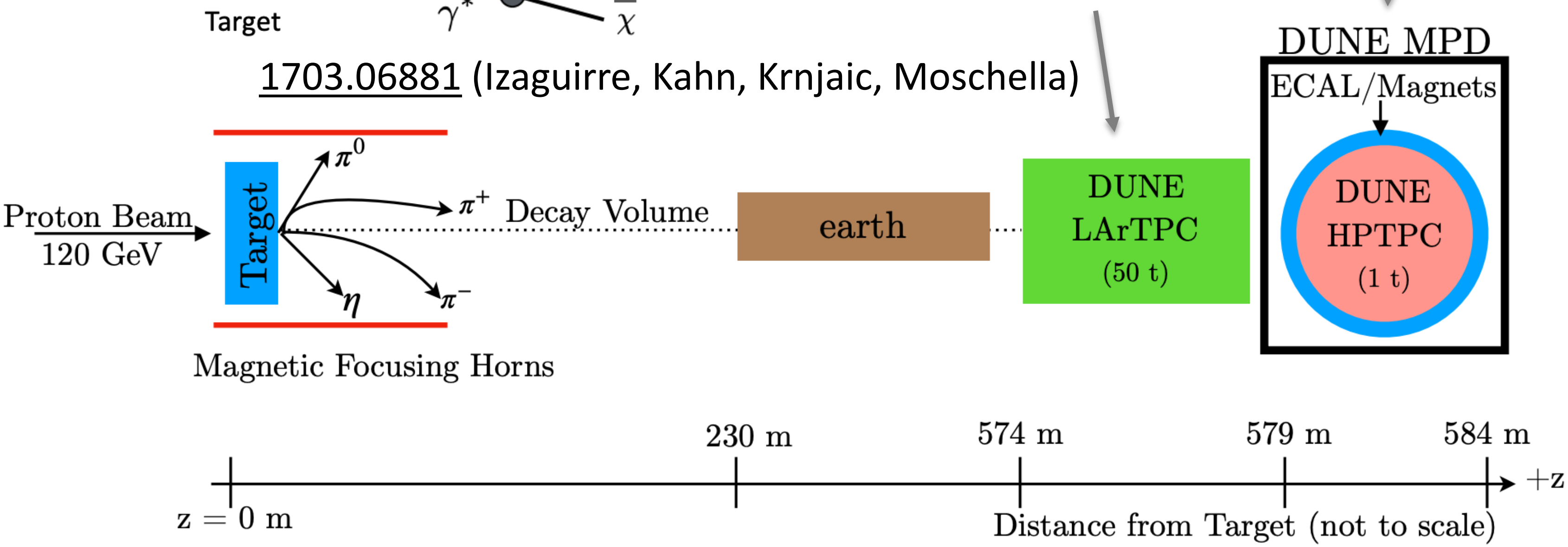
DUNE TDR, V - I, https://arxiv.org/pdf/2002.02967.pdf

Simplified Configuration





1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)



1912.07622 (Berryman, Gouvêa, Fox, Kayser, Kelly, Raaf)

Decay vs **Scattering**

Inelastic Dark Matter & **Millicharged Particles**

Decay Study

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

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

General features:

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

HPgTPC

- Muon spectrometer
- ND is small compared to the Far Detector (FD), charged tracks will exit the LArTPC, and the energy cannot be measured precisely.

- Place a gas argon TPC downstream of the LArTPC to conduct precision measurements of any tracks that exit the LArTPC.

DUNE Multi-Purpose Detector: Gas TPC, ECAL surrounding it, and potentially a muon tagger
(to separate muons and pions that exit the Gas TPC).

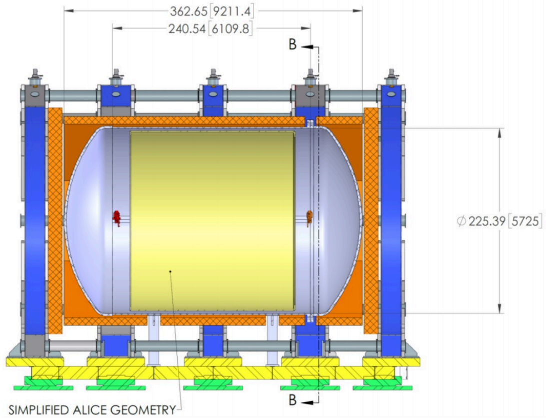


Figure 5.2: The conceptual design of the MPD system for the ND. The TPC is shown in yellow inside the pressure vessel. Outside the pressure vessel, the ECAL is shown in orange, and outside that are the magnet coils and cryostats. The drawing illustrates the five-coil superconducting design.

The HPgTPC has a

- **diameter of 5 m and a length of 5 m.**
- **~ 580 meters away from the target**

arXiv:2002.02967, DUNE TDR V - I

Comparison to Legion of 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
SQ/DQ	120 GeV	*1.4e18/1e20	5 m	*7 m
LongQuest	120 GeV	*1e20	5 m	*7/13 m
DUNE-ND	120 GeV	*1e22	580 m	*5 m

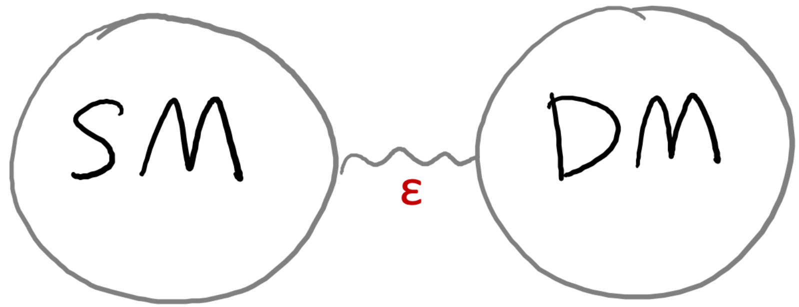
see arXiv:1908.07525 for details

See arXiv:2002.02967 (**DUNE TDR**) for details

*indicates not yet fully decided

Interesting Long-Lived Particles for Decay Studies

The Rise of Dark Sector



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

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

- Mediator is needed for a proper freeze-out: the rise of "dark sector" (DM + mediators + stuffs).

Renormalizable "Portals"

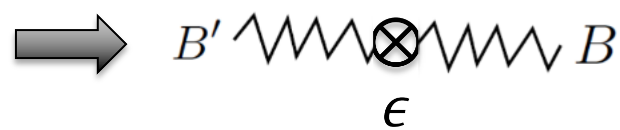
- Dark sectors can include mediator particles coupled to the SM via the following **renormalizable interactions.**
- **High-Dim. axion portal is also popular**

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

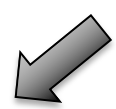
(Holdom, '85)

See Dark Sector 2016 report 1608.08632

Low-energy effective interaction

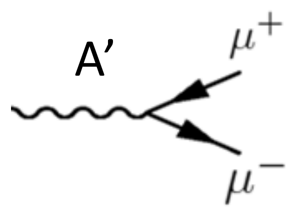


Mass from Dark Higgs or Stueckelberg

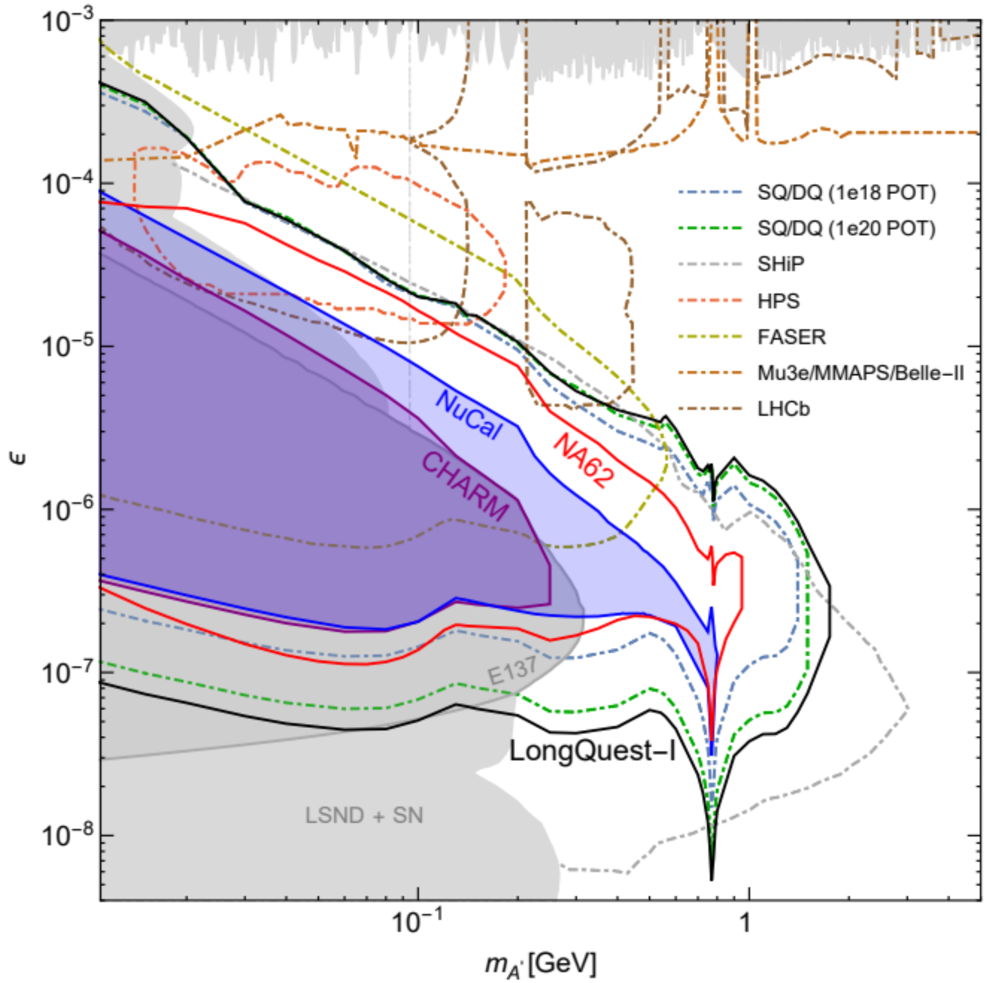


mass basis

Dark photon A':



Legion of Probes on Dark Photon

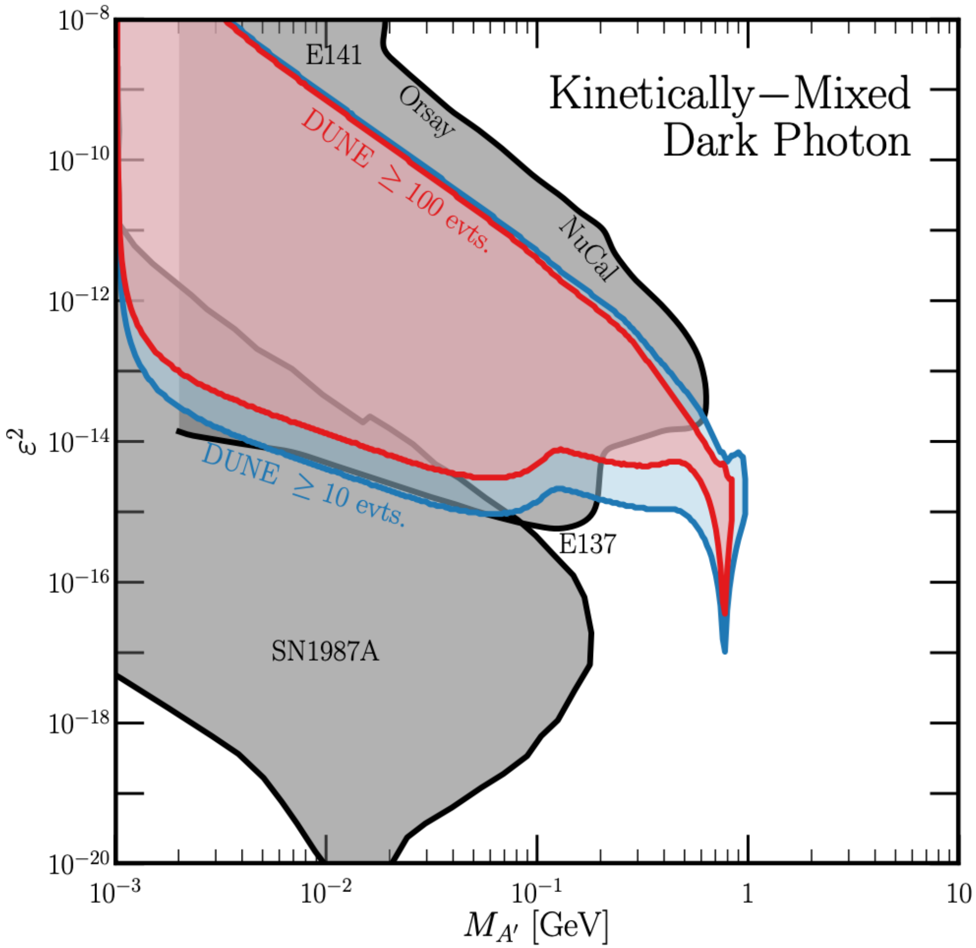


Ilten, Soreq, Williams, and Xue, 1801.04847, for **compilation of probes**, updated in https://gitlab.com/philten/darkcast

1804.00661 (SeaQuest: Berlin, Gori, Schuster, Toro)

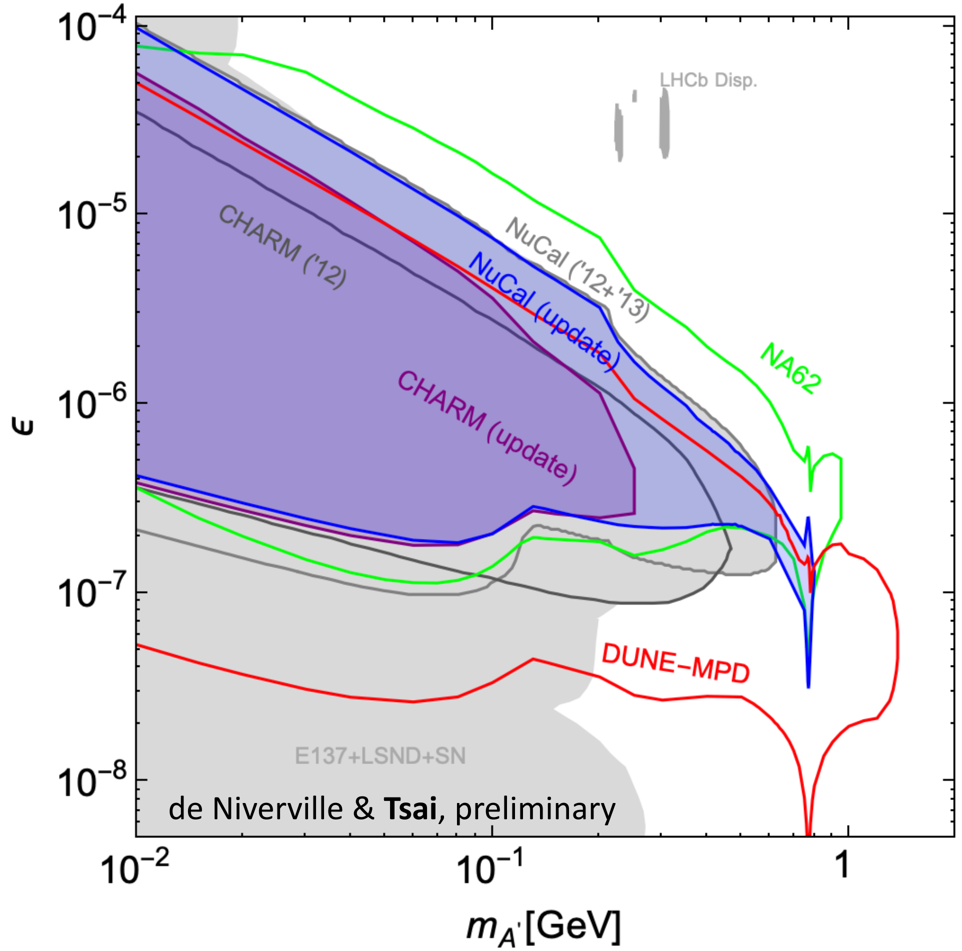
1908.07525 (NA62 + LongQuest, Tsai, de Niverville, Liu)

Dark Photon in DUNE



Berryman, deGouvêa, Fox, Kayser, Kelly, Raaf, 1912.07622 (PRD’19)

Legion of Probes on Dark Photon



New Projections from NA62 and DUNE-MPD, Preliminary update

Take into account Proton Bremsstrahlung production properly

Tsai, de Niverville, Liu, [1908.07525]

+

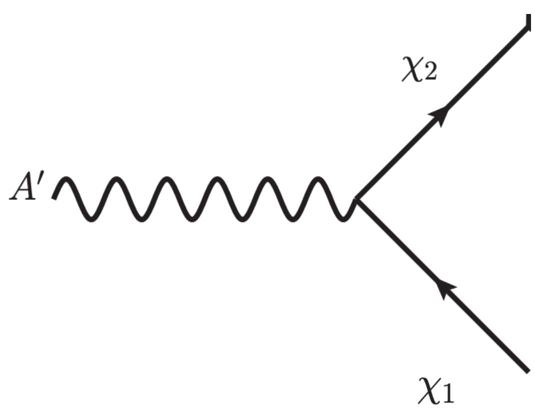
We (deNiverville & Tsai) also did a new simplified detector simulation here

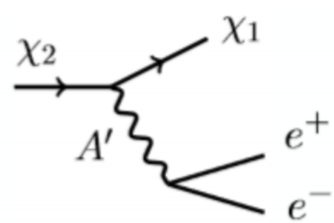
Inelastic Dark Matter

- 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

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

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





1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

iDM in Fixed-Target and Collider

- 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)

Inelastic Dark Matter (iDM)

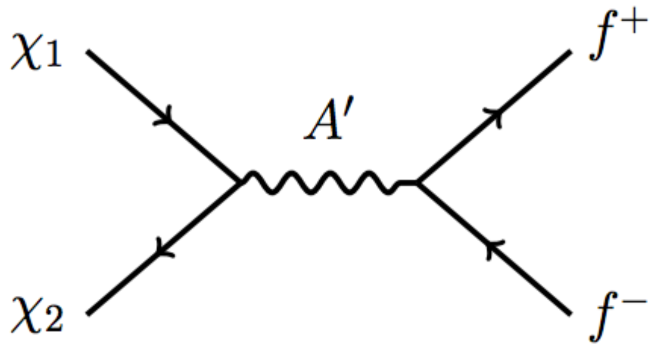


FIG. 1. Leading order diagram for $\chi_1\chi_2 \to f^+f^-$ coannihilation, which sets the DM relic abundance in the $m_{A'} > m_{1,2}$ regime.

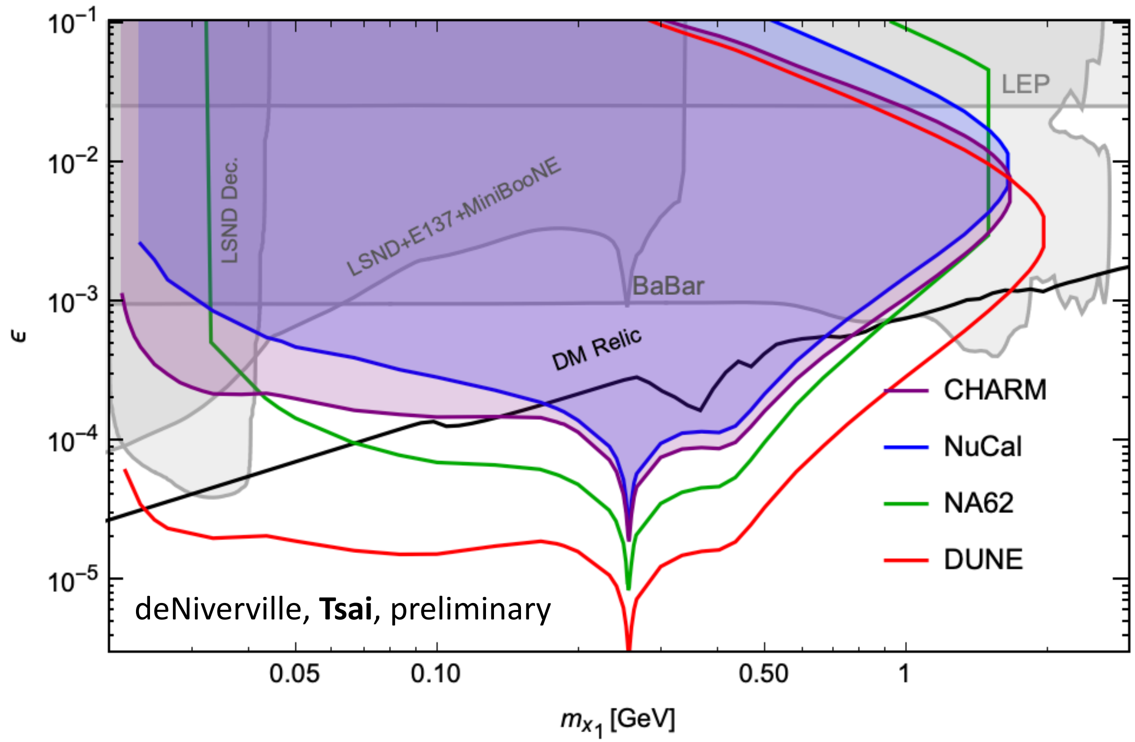
1703.06881 (Izaguirre, Kahn, Krnjaic, and Moschella)

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

New Bounds on Inelastic Dark Matter

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

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



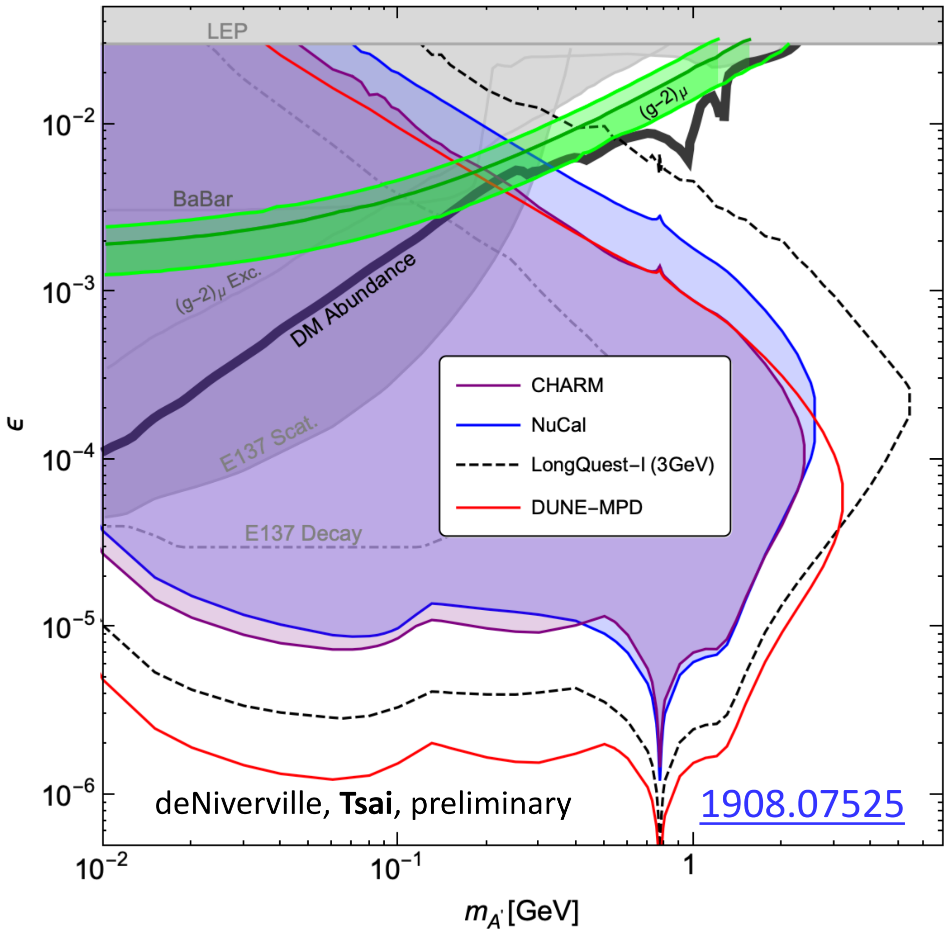
- $m_{A'}/m_{\chi 1} = 3,$
- $\Delta = 0.05,$
- $\alpha_D = 0.5$

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

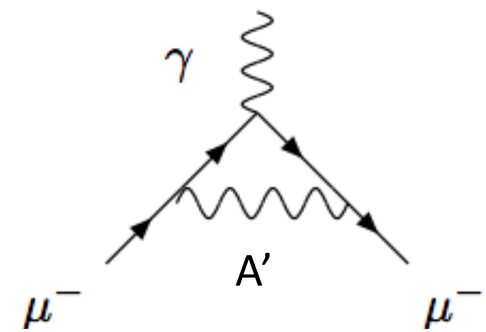
$$g_D \equiv \sqrt{4\pi\alpha_D}.$$

1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella),
1908.07525 (Tsai, de Niverville, Liu)

Inelastic Dark Matter
& Muon g-2 explainer

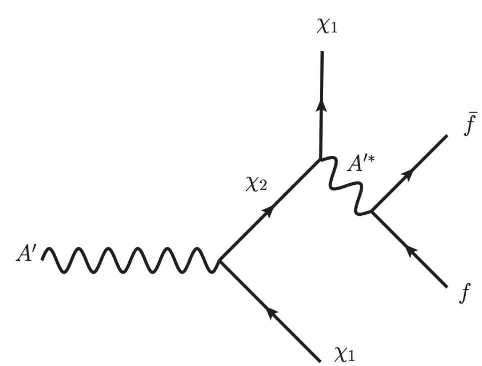


(a) iDM: $\Delta = 0.4$, α_D=0.1. With muon $g-2$ and DM regimes. $m_{A'}/m_{x1}$ = 3.



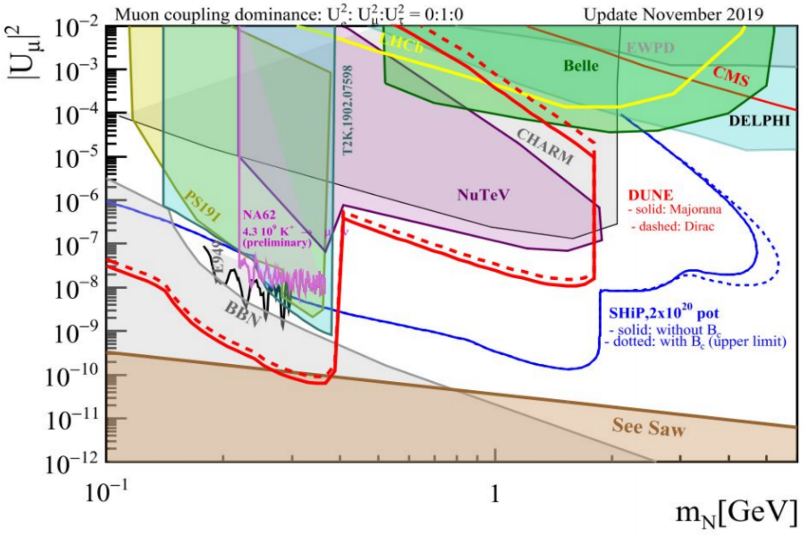
$$\Delta a_\mu \equiv a_\mu^{exp} - a_\mu^{th} = (274 \pm 73) \times 10^{-11},$$

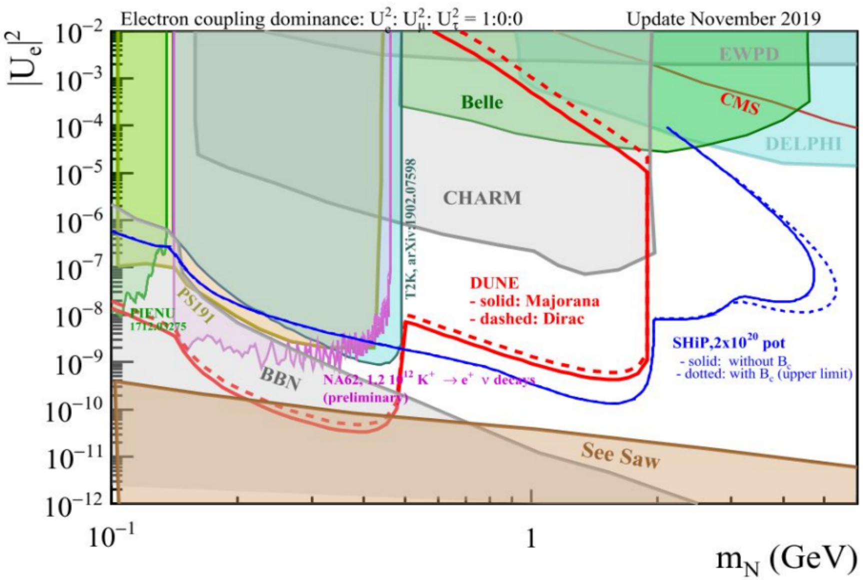
See, e.g., Fayet, 2007 (hep-ph/0702176)



- arXiv:1902.05075 by Mohlabeng arXiv:1908.07525 (our paper)

HNL Searches





Included channels : $N \to \nu e^+ e^-, \ \nu e^\pm \mu^\mp, \ \nu \mu^+ \mu^-, \ \nu \pi^0, \ e^\mp \pi^\pm$

Very similar to the iDM search

Albert De Roeck, Georgios Christodoulou, **Haifa Sfar**.

Beyond Simple Dark-Sector Models

Currently looking into

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

New results in preparation!

Scattering Study

Scattering Detectors

MiniBooNE, SBND, MicroBooNE, MINERvA, DUNE LArTPC, etc

- Study neutrino scattering and/or neutrino oscillation

Features (comparing to decay detectors):
These features are correlated

1. Higher density

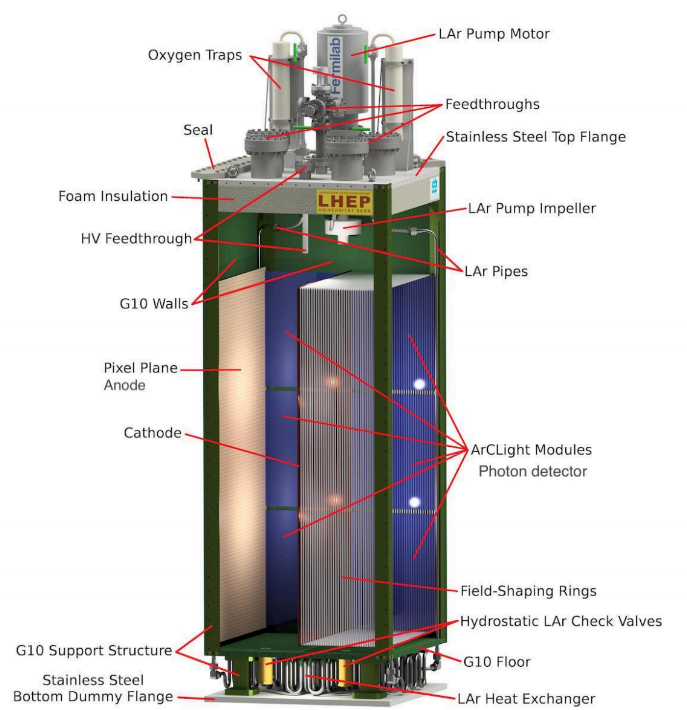
2. Complicated design compared to the decaying detector.

3. Cost more with the same volume

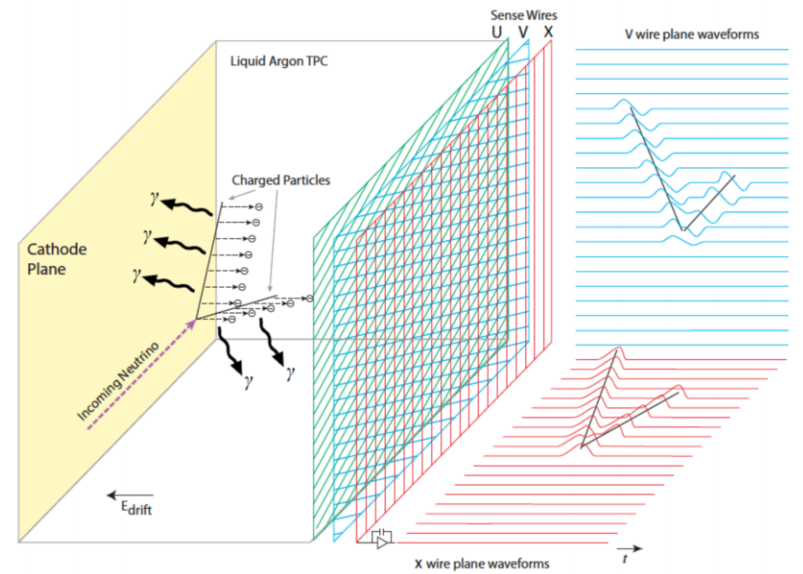
4. Usually studying **stable particles**
(neutrino, **dark matter**, **millicharged particles**)

Scattering Study with DUNE LArTPC

- LArTPC (ArgonCube) consists of an array of **35** modular time projection chambers (TPCs) sharing a cryostat. (~ 50 tons.)
- Study ArgonCube 2 x 2 demonstrator would be beneficial for our study
- Neutrino beams parallel to the cathode



Just one module



recorded by digitizing the waveforms of current induced on the anode as the distribution of ionization charge passes by or collected on the electrode.

T0: time when the interaction occurs

arXiv:2002.02967, DUNE TDR V - I

Simplest Target Model: Millicharged Particles

Signature Similar to nu-e scattering

Finding Minicharge

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

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

- Link to **string compactification** and **quantum gravity** (Shiu, Soler, Ye, PRL '13)

- Testing if **e/3 is the minimal charge**

- MCP could have natural link to **dark sector** (dark photon, etc)

- Could account for **dark matter (DM) abundance**

\- Used for the cooling of gas temperature to explain the **EDGES anomaly** [EDGES collab., Nature, (2018); Barkana, Nature, (2018)].
  A small fraction of the DM as MCP can potentially explain EDGES observation

MCP Model

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

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

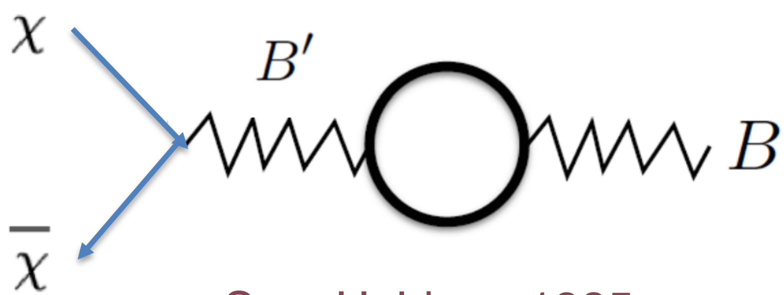
- Can just consider these Lagrangian terms by themselves (no extra mediator, i.e., dark photon). **Completely legal**! Naively violating the empirical charge quantization (cool!).

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

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

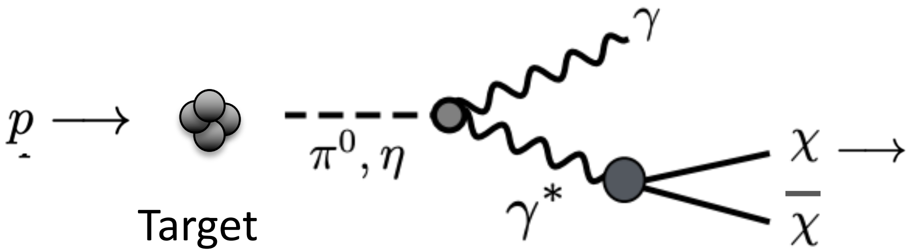
See, Holdom, 1985

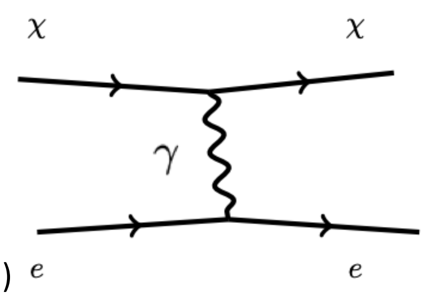
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ + ie'B\!\!\!/' + iM_{\rm MCP})\chi$$

- 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**.)**
- See Holdom, 1985; or arXiv:1806.03310

Production & Detection:

MCP (or light DM with massless mediator):



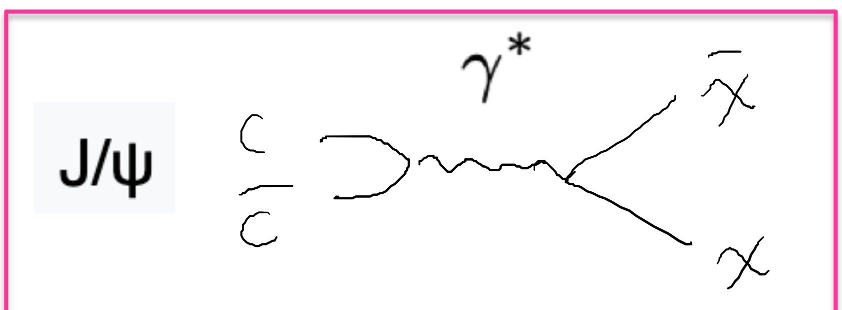


Figures **replaced A' with photon** from 1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

See, also 1411.1055

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

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



❑ Detection: Electron Scattering

χ

$\bar{\chi}$

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

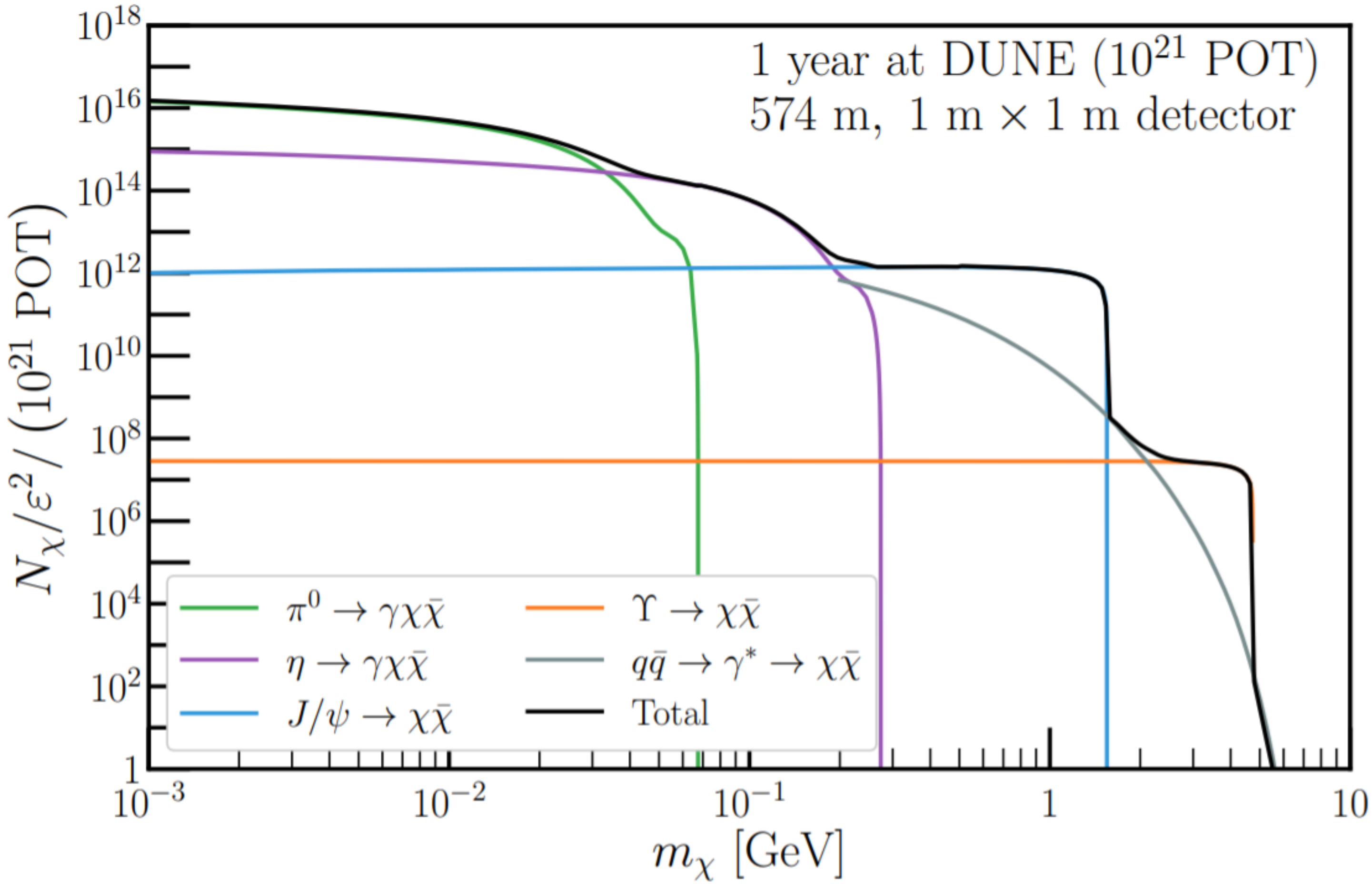
BR($\pi^0 \to \gamma e^- e^+$) = 0.01

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

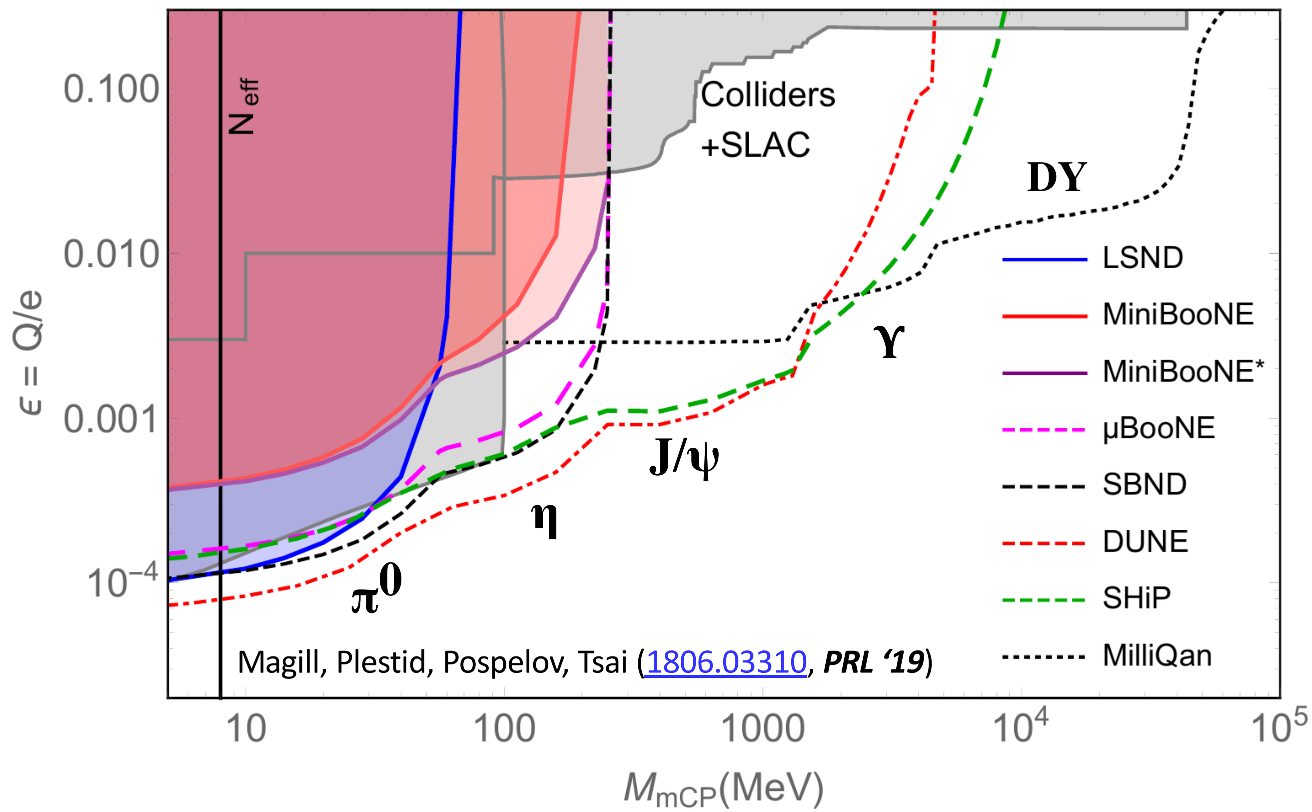
$$\sigma_{e\chi} \simeq 2.6 \times 10^{-25}\text{cm}^2 \times \epsilon^2 \times \frac{1\ \text{MeV}}{E_e^{(\text{min})} - m_e}.$$

- Sensitivity greatly enhanced by accurately **measuring low energy electron recoils** **for mCP's & light dark matter - electron scattering,**
- Very low-energy scattering**: Ionization (eV-level)!**

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

- See Magill, Plestid, Pospelov, **YT**, 1806.03310 (MCP in neutrino Experiments) & deNiverville, Frugiuele, 1807.06501 (for sub-GeV DM)

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)
- **Patrick, Yun-Tse, Gianluca, Albert, Tsai**, + : ICARUS + ArgonCube demo. + DUNE detailed study

Background for Future Measurements

- Two classes of backgrounds:

  1) From neutrino fluxes (calculable),

  [i.e. **ve → ve** and **vn → ep**], **greatly reduced by maximum electron recoil energy cuts E_e(max),** **because no low Q^2 enhancement (through W/Z)**

  2) Other sources such as

  beam related: **dirt related events**, **mis-id particles**

  external: **cosmics**,

  Multiply a factor of the neutrino-caused background to account for these background

- New studies on **ICARUS, ArgonCube demo, DUNE ND**

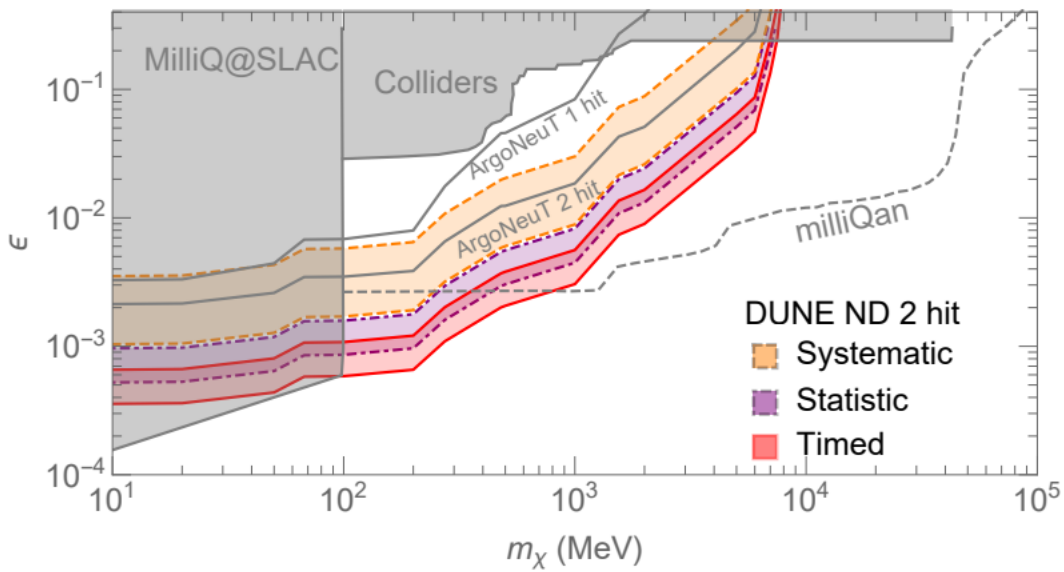
Summary Table

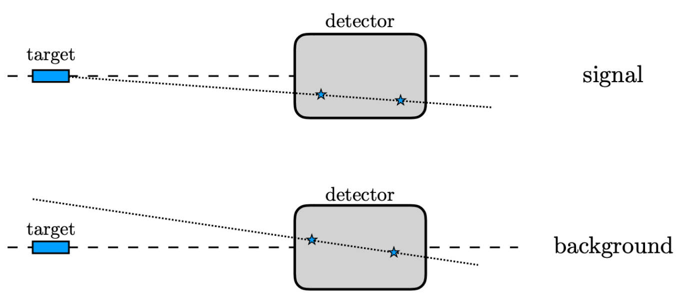
Exp. (Beam Energy, POT)	N [$\times 10^{20}$]		$A_{\rm geo}(m_\chi)$[$\times 10^{-3}$]		Cuts [MeV]		
	π^0	η	1 MeV	100 MeV	$E_e^{\rm min}$	$E_e^{\rm max}$	Bkg
LSND (0.8 GeV, 1.7×10^{23})	130	—	20	—	18	52	300
mBooNE (8.9 GeV, 2.4×10^{21})	17	0.56	1.2	0.68	130	530	2k
mBooNE* (8.9 GeV, 1.9×10^{20})	1.3	0.04	1.2	0.68	75	850	0
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

- $\varepsilon \propto E_{e,\,R,min}^{1/4}\, Bg^{1/8}$
- At **LArTPC**, the **wire/pixel spacing** is assumed to be around **3 mm**, the ionization stopping power is approximately **2.5 MeV/cm**: electrons with total energy larger than at least **2 MeV** produce tracks long enough to be reconstructed across two wires/pixels.

  Efficiency of 0.8 for liquid argon time projection chambers.
- **DUNE LArTPC ND, Using CDR configuration**

Double-Hit + ArgoNeuT Scale-up



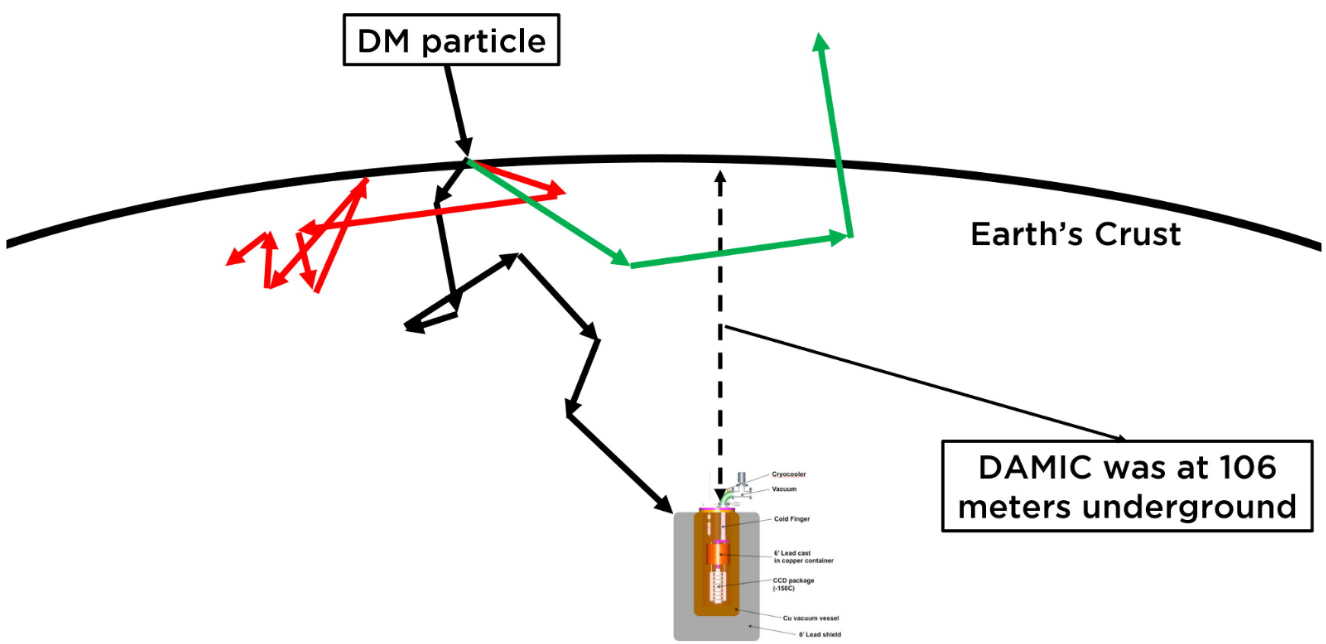


Harnik, Liu, Palamara: double-hit to reduce background

Ivan Lepetic + (ArgoNeuT) ’19

Strongly Interacting Dark Matter

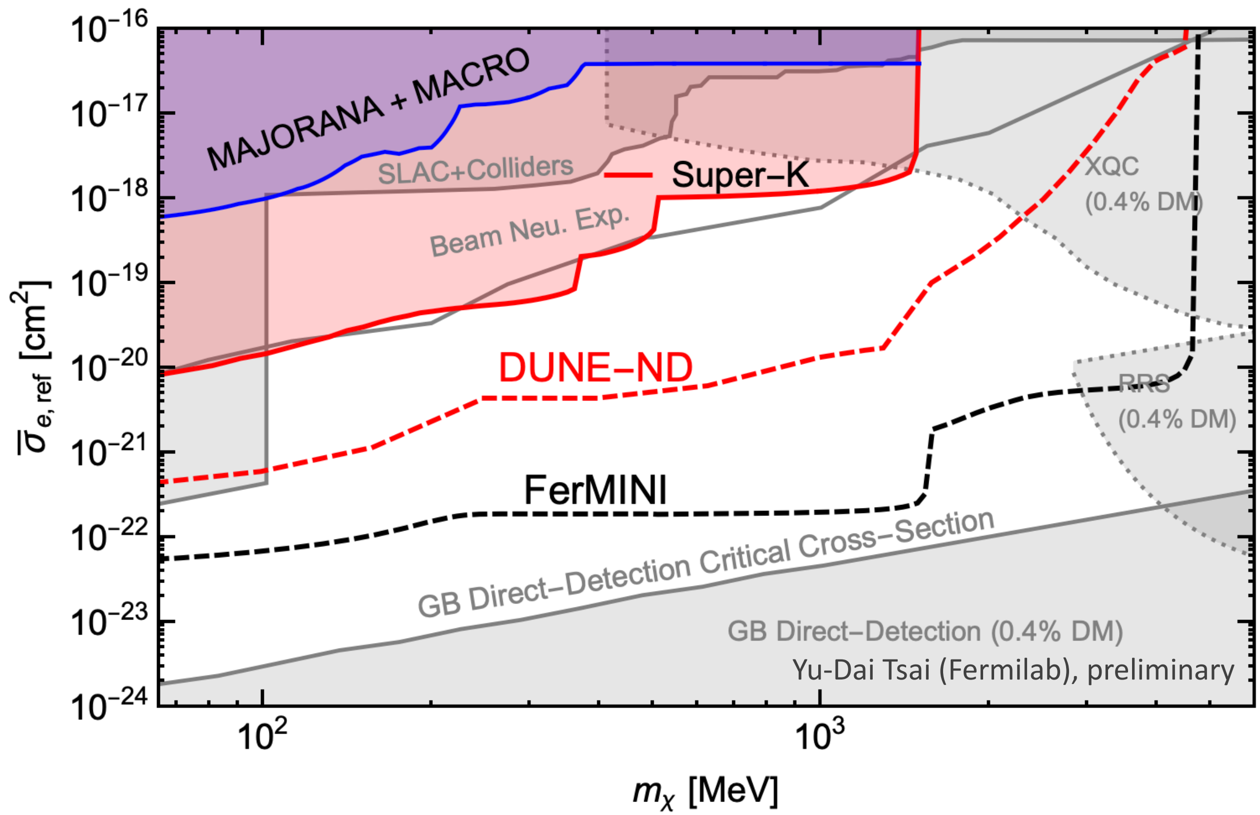
DM-SM Interaction too strong that attenuation stop the particles from reach the direct detection detector



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

DUNE Probe of Millicharged SIDM

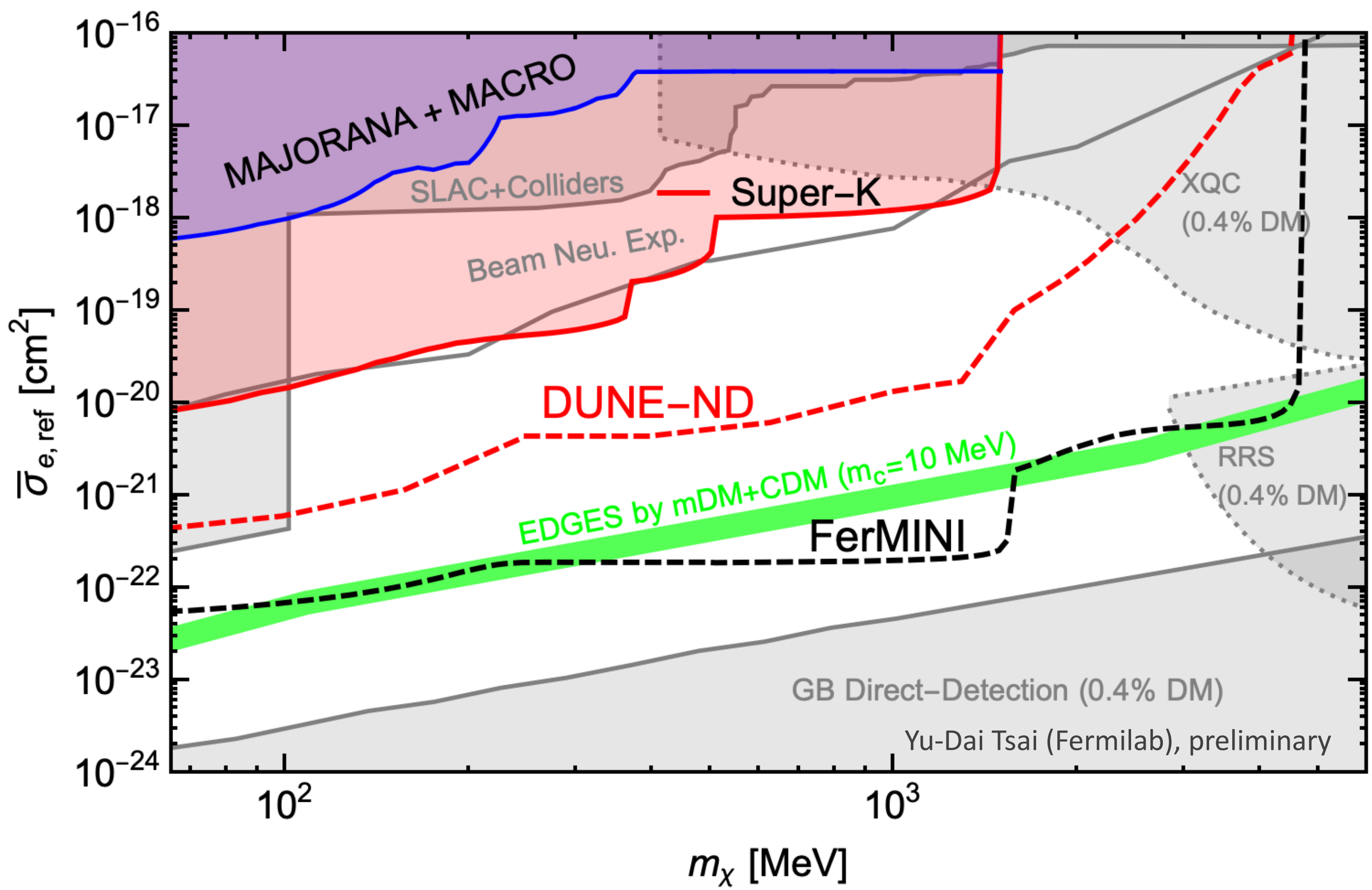
MCP / LDM with ultralight dark photon mediators, all curves except FerMINI are from arXiv:1905.06348

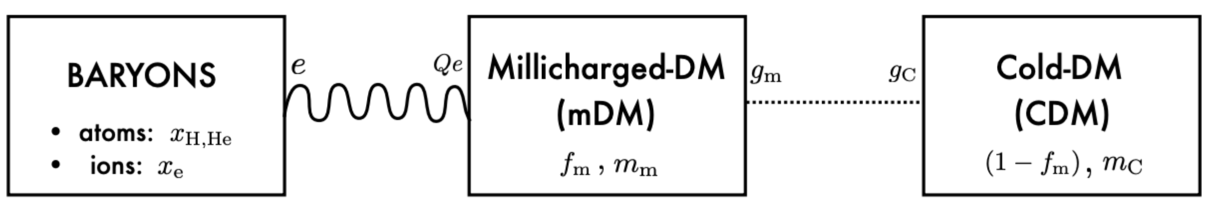


$$\frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{ref}^2},\ q_{ref} = \alpha m_e$$

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

Reviving mDM for EDGES



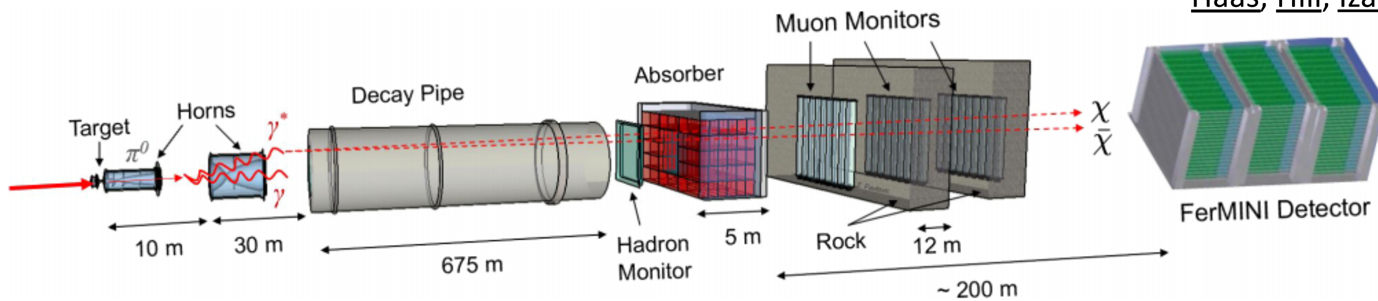


1908.06986 (Liu, Outmezguine, Redigolo, Volansky)

FerMINI: Add-on Detector

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

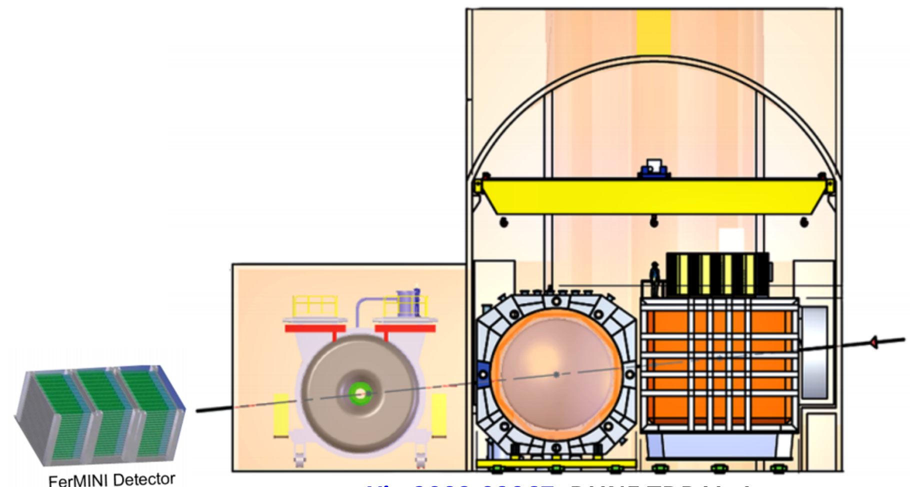
NUMI:



see, e.g., arXiv:1507.06690 (NuMI beam). plot made by Zarko Pavlovic and modified by Yu-Dai Tsai

LBNF/DUNE:

SAND + FerMINI?



arXiv:2002.02967, DUNE TDR V - I

FerMINI Proposal, Kelly, Tsai, 1812.03998

DUNE: The High-Energy Intensity Frontier

Our other analyses that can be applied to DUNE ND Study

[5] **Light Scalar & Dark Photon** at BoreXino & LSND, 1706.00424, ***PLB '18***
(proton-charge radius anomaly) Pospelov, **Tsai**

[6] **Dipole Portal Heavy Neutral Lepton**, 1803.03262, ***PRD '18***
(LSND/MiniBooNE anomalies) Magill, Plestid, Pospelov, **Tsai**

[7] **Dark Neutrino** at Scattering Exps: CHARM-II & MINERvA, 1812.08768, ***PRL '19***
(MiniBooNE Anomaly, see also Pedro's papers) Argüelles, Hostert, **Tsai**

[9] Cosmic-ray produced MCP in **Neutrino Observatories** (2002.11732, **NEW**)

Yu-Dai Tsai @ Fermilab, Email: ytsai@fnal.gov; arXiv: https://arxiv.org/a/tsai_y_1.html.

Thank You!