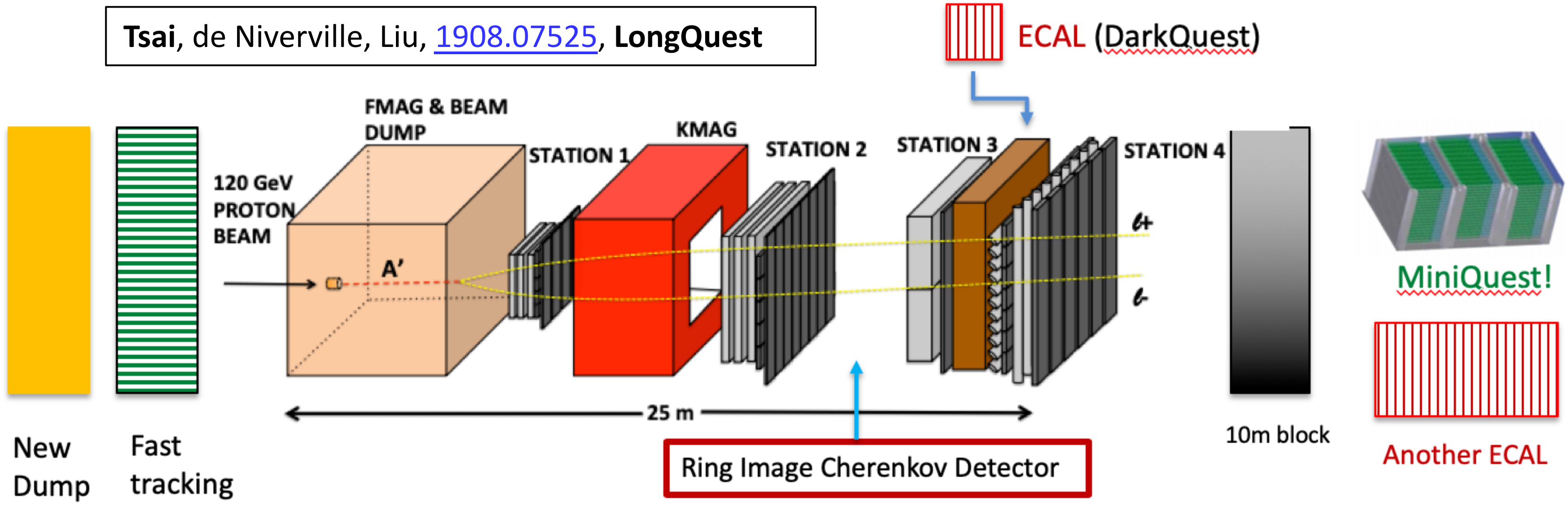
Tsai, de Niverville, Liu, 1908.07525, **LongQuest**



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

Yu-Dai Tsai, 2020

Long-lived Particles at the High-Energy Intensity Frontier

Yu-Dai Tsai, Fermilab/U Chicago

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

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

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

Proton Fixed-Target Experiments: Decay vs Scattering Studies

My other interesting related works:

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

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

(proton-charge radius anomaly) w/ Pospelov

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

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

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

(MiniBooNE Anomaly) w/ Argüelles, Hostert

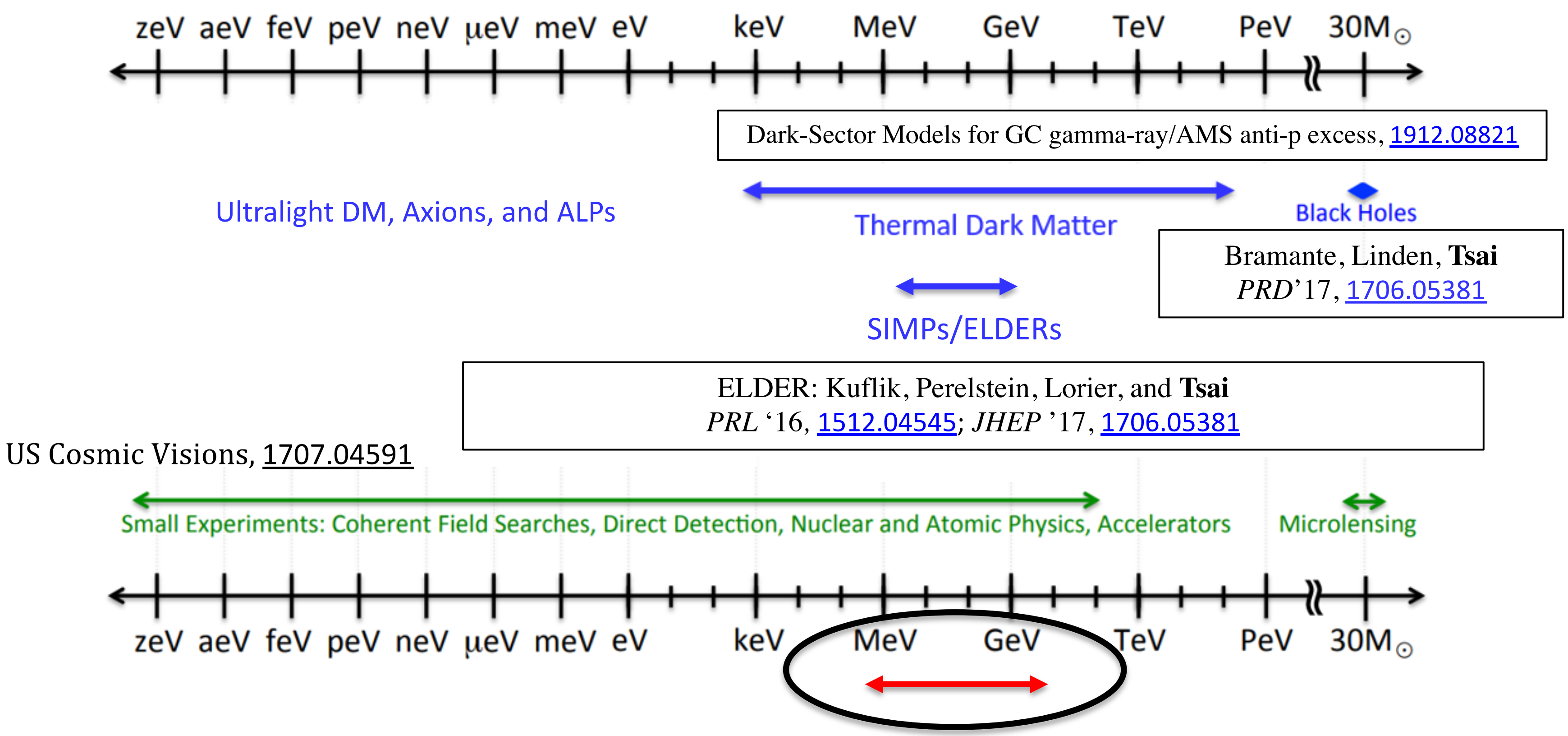
Email: ytsai@fnal.gov; arXiv: https://arxiv.org/a/tsai_y_1.html

Outline

- Why **Long-Lived Particles** in **MeV - few GeV Mass Range**?
  (see Gordan's talk for more)
  Why **proton fixed-target** (FT) experiments?
- **Decay** Experiments (CHARM, NuCal, NA62, DarkQuest, etc)
- **Interesting Decay studies** and the **LongQuest** proposal
- **Scattering** Experiments and the **FerMINI** proposal
- Other new opportunities:
  DUNE ND complex, SHiP, Cosmic-Ray, Neutrino Observatories

Exploration of Dark Matter & Mediator

Dark Sector Candidates, Search Techniques



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

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? (~~or probably systematics~~?)

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

⋮

- **Muon g-2 anomaly** (muon g-2 col., he-pex/0602035)
- **LSND & MiniBooNE anomaly** (LSND PRL ‘95, MiniBooNE PRL ‘07)
- **EDGES result** (EDGES col, nature ‘08)
- **KOTO anomaly** (KOTO, KAON2019)
- **Proton charge radius anomaly** (Pohl, Nature, ‘10)
- **Beryllium anomaly** (Krasznahorkay, PRL ‘15)

⋮

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

Advantages of Proton Fixed-Target Exp.

Proton FT (& Neutrino) Experiments

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

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

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

Not all probes are 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

} different

Cosmological observations:
cosmological history, species, etc

The proton-beam fixed-target facilities

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

Facilities

- **Los Alamos National Lab**
- LANSCE beam (LSND): 10^{23} POT total (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: $\sim 10^{21}$ POT/yr (120 GeV), future
- **CERN SPS beam:**
- NA62: up to 3 x 10^{18} POT/yr (400 GeV), now
- SHiP: up to 10^{19} POT/yr (400 GeV), future
- **CERN LHC:** FASER, 10^{16} POT/yr, much higher energy, future

Proton FT Experiment: Decay vs Scattering

Decay Experiments/Detectors

Including **CHARM decay detector (DD), NuCAL (beam-dump mode), NA62, SeaQuest/DarkQuest**
(see, arXiv:1908.07525, for a detailed comparison)

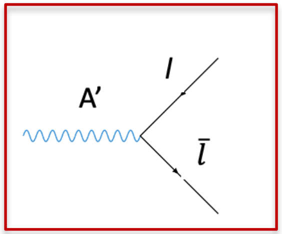
- Experiments optimized to study **decaying particles**, or simply two charged particle final states, e.g. from Drell-Yan (SeaQuest)

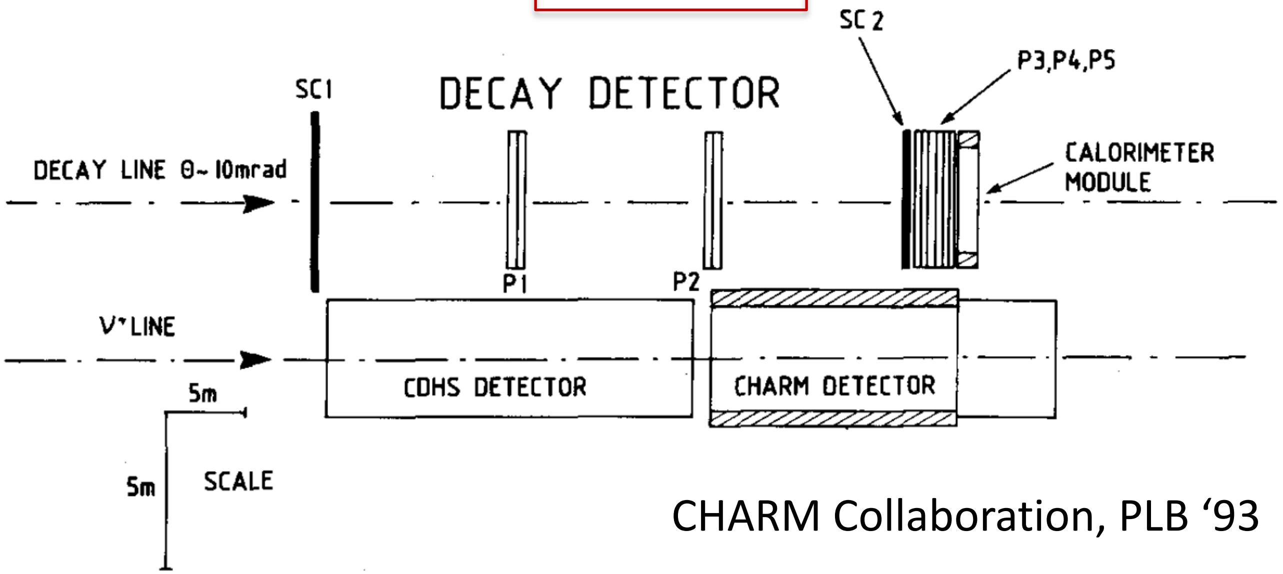
General features:

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

Decay Experiments/Detectors

CHARM Decay Detector





CHARM Collaboration, PLB '93

Layout of the decay beam-dump experiment. SC1 and SC2 are scintillator planes. SC1 is used as a veto counter (sets the start of the decay region).

P1 to P5 are sets of instrumented planes (4 planes of proportional drift tubes)

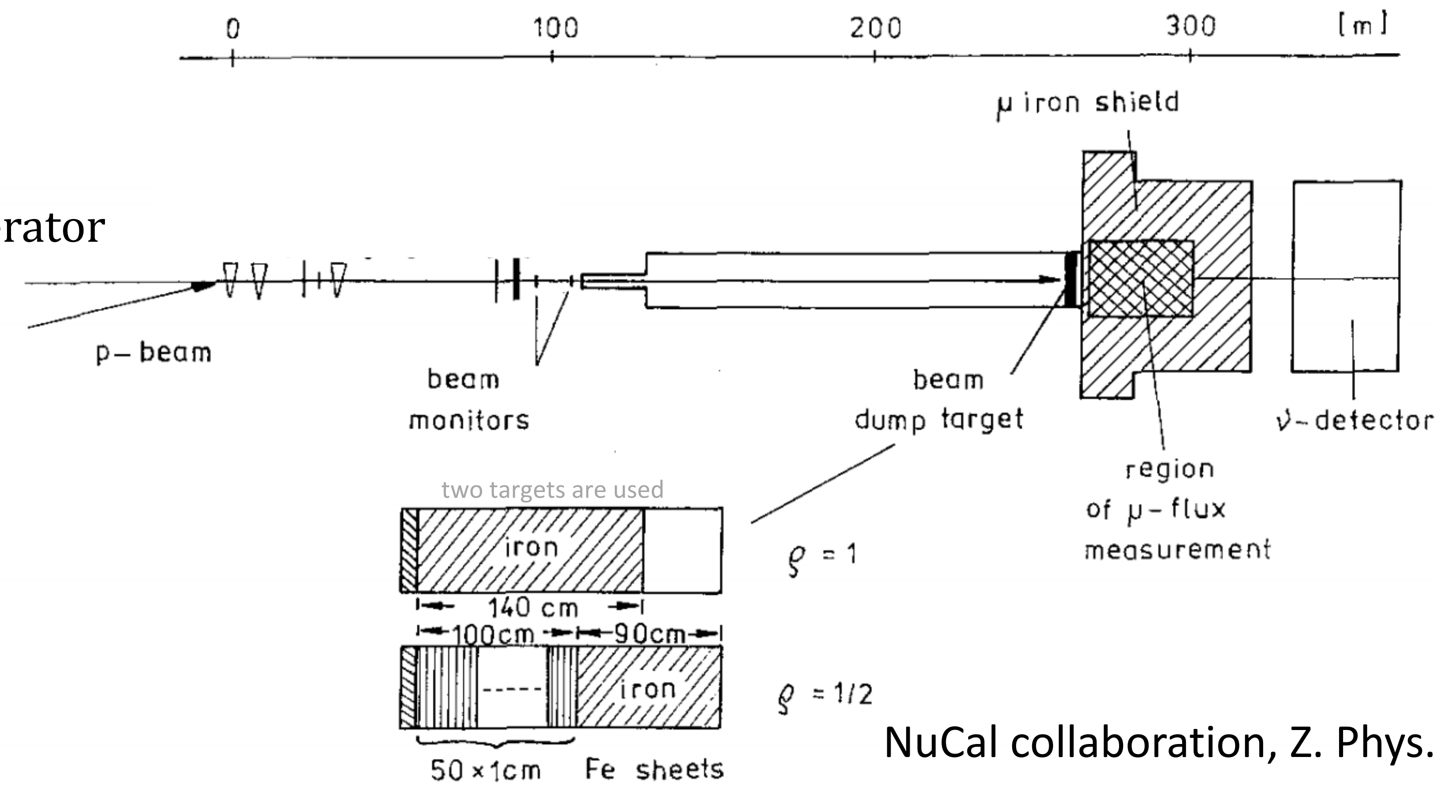
The estimated angular resolution for an electromagnetic shower is a few milliradians.

https://www.sciencedirect.com/science/article/abs/pii/037026938390275?via%3Dihub

CHARM: CERN HAmburg Rome Moscow

ν-calorimeter (NuCal) beam-dump experiment

U70 accelerator
(70 GeV)

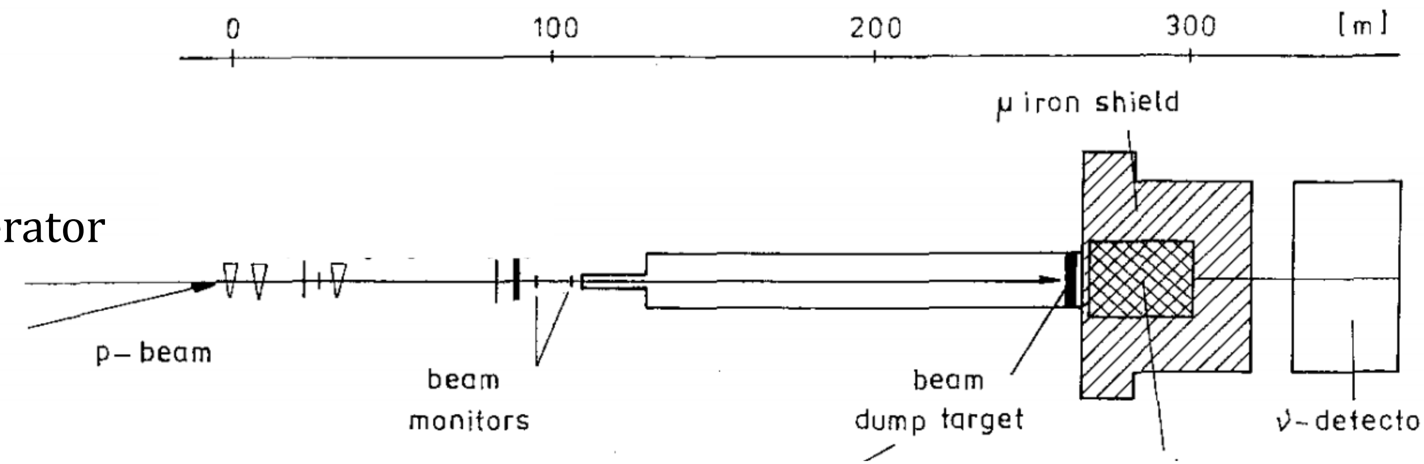


NuCal collaboration, Z. Phys. '91

To **minimize the distance between target and detector**,
the iron beam dump is located directly in front of the muon shield.

ν-calorimeter (NuCal) detector details

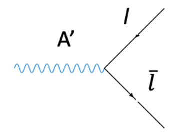
U70 accelerator
(70 GeV)



- The neutrino detector is located at a distance of 64 m down-stream of the beam dump. The target part of the detector consists of 36 modules with the following structure per module
- a magnetized iron frame for the muon momentum measurement - an aluminium plate (5 cm) as neutrino target and shower absorber which fills the inner free space of 3 x 3 m^2 of the frame
- x-y drift chamber planes of 4.5 x 4.5 m^2 for the track measurements in the target part and in the iron frame
- a CH2-1iquid scintillator target calorimeter of 10 counters, each with the transversal dimension of 5 x 0.3 m^2 and a thickness of 0.20 m, giving a sensitive plane of 5 x 3 m^2.

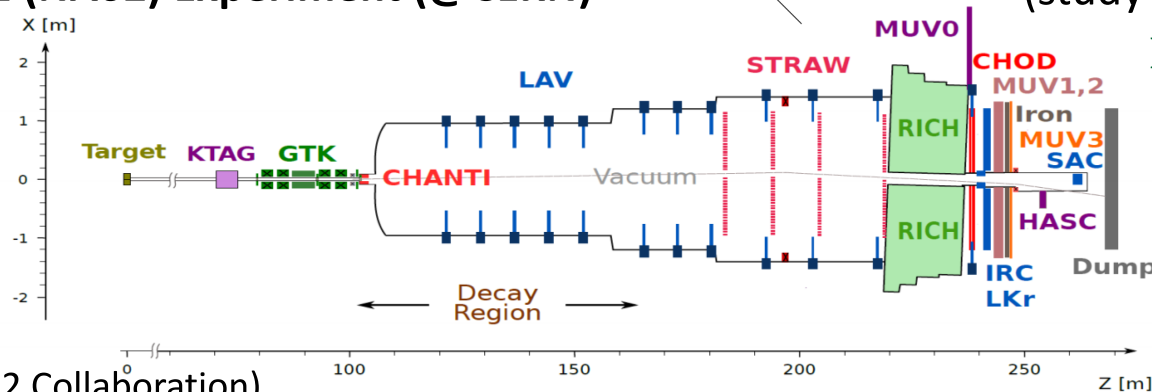
Decay Experiments/Detectors

North Area 62 (NA62) Experiment (@CERN)



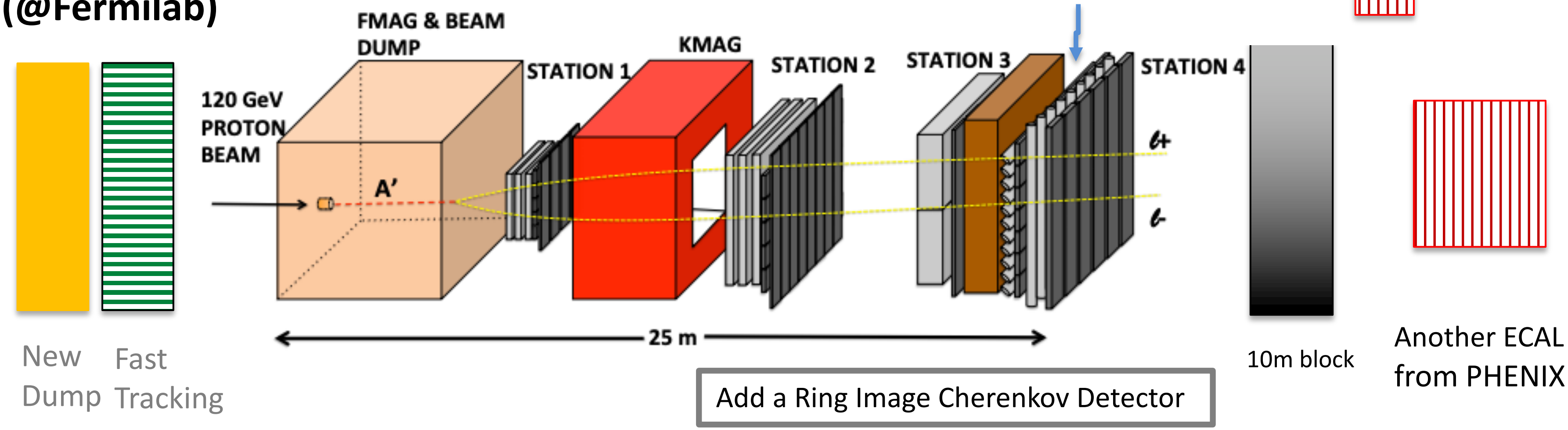
(study rare kaon decays)

$K^+ \to \pi^+ \nu\bar{\nu}$



1703.08501 (NA62 Collaboration)

SeaQuest/LongQuest-Proposal, **Tsai**, deNiverville, Liu, '19 **(@Fermilab)**



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

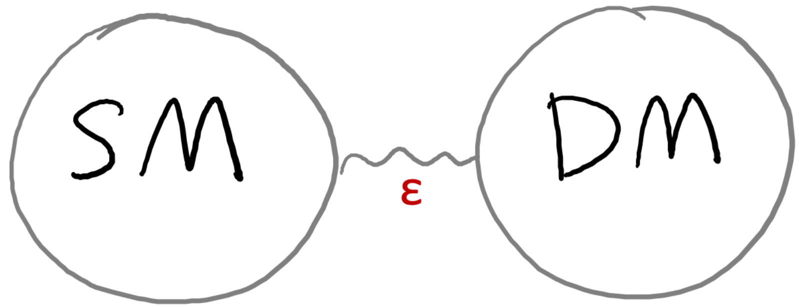
Legion of probes

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

- *indicates not yet decided
- see, arXiv/1908.07525 (**Tsai**, deNiverville, Liu)
- $\boldsymbol{L_{dist}}$ is the **distance between target & detector**
- $\boldsymbol{L_{dec}}$ is the **length of the decay regime**
- Can add DUNE and SHiP once the designs are settled

Interesting LLPs for Decay Studies
Applying the legion of probes!

The Rise of Dark Sector



- The **Lee-Weinberg bound** (77’): **below ~ 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 light 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).

Renormalizable "Portals"

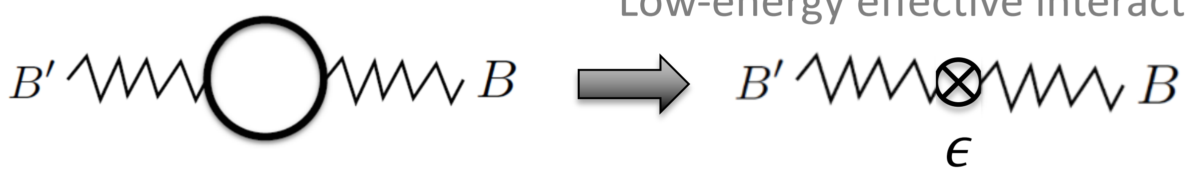
- Dark sectors can include mediator particles coupled to the SM via the following **renormalizable interactions.**
- **High-Dim. axion portal is also popular**

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

(Holdom, '85)

(See Dark-Sector 2016 report 1608.08632)

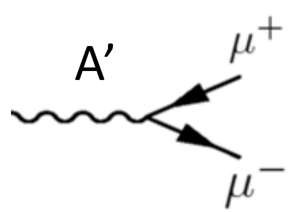
Low-energy effective interaction



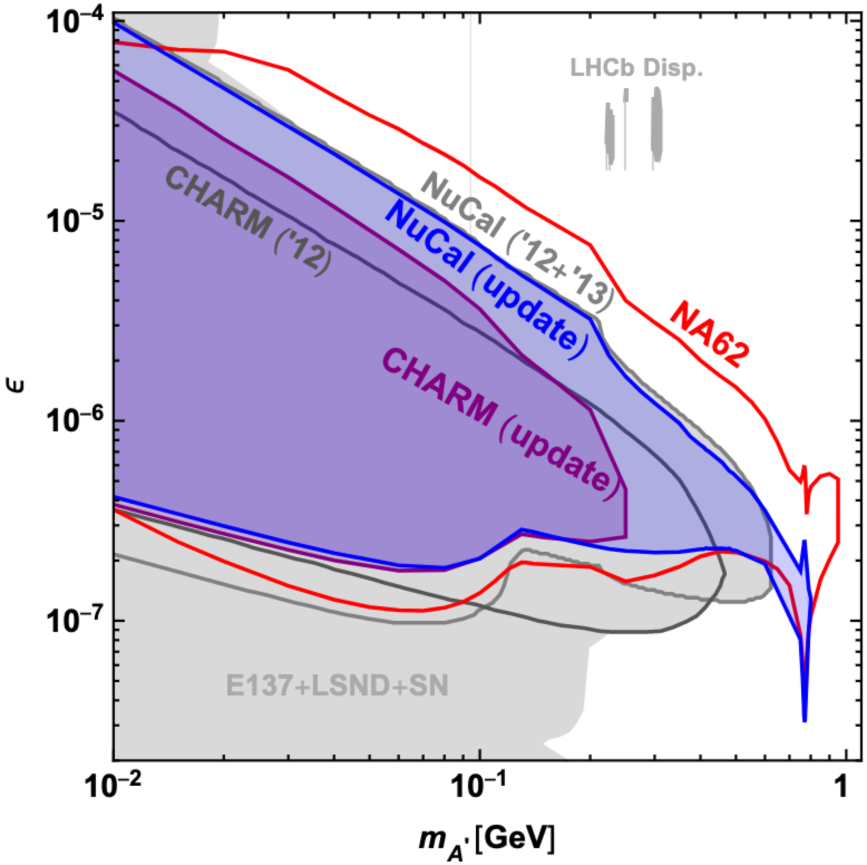
Mass from Dark Higgs or Stueckelberg

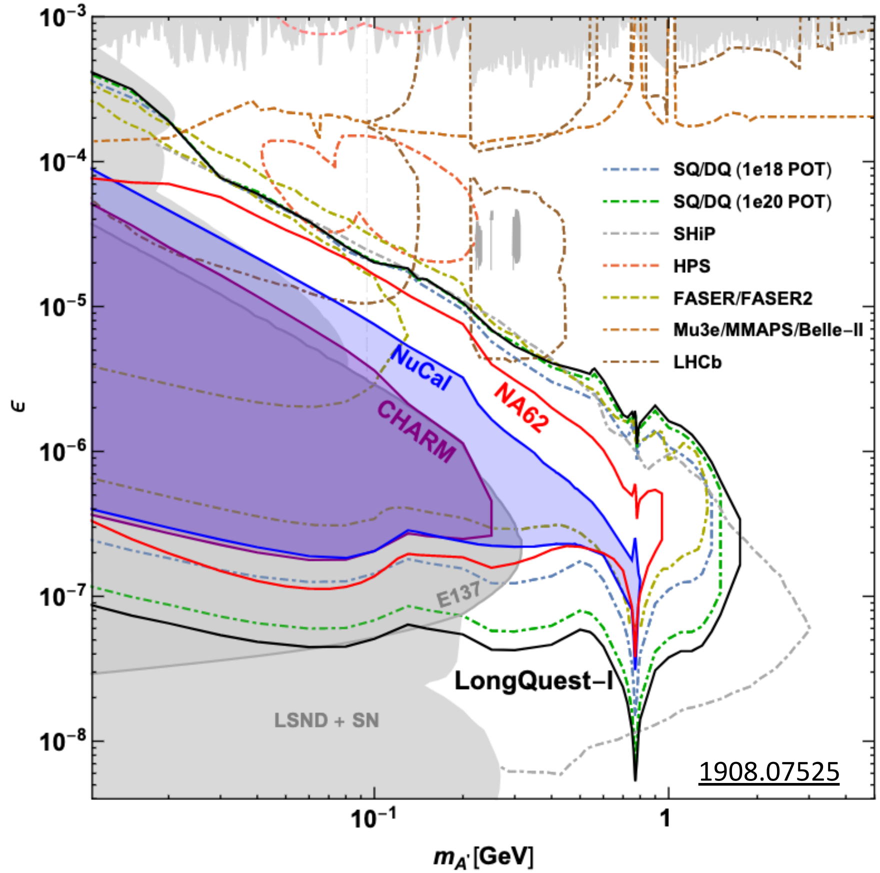
mass basis

Dark photon A':



Legion of Probes on Dark Photon





Tsai, de Niverville, Liu, 1908.07525

- **Adding proton brem. production properly:** resonant enhancement from mixing with ρ and ω mesons

Improved Weizacher-Williams (Mat.-Fys. '39) (IWW) app. (Kim, Tsai '73)

- **New Projections from NA62 & LongQuest**,

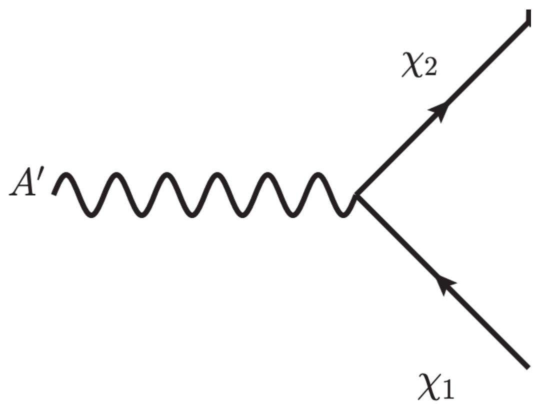
for **compilation of probes / refs,** see, Ilten, Soreq, Williams, and Xue, 1801.04847

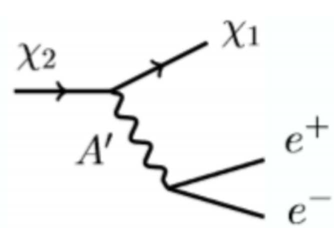
Inelastic Dark Matter

- 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

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

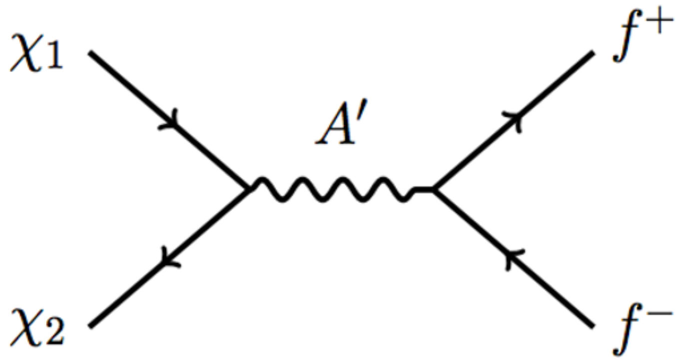
$$\Delta \equiv \frac{m_2 - m_1}{m_1}. \qquad g_D \equiv \sqrt{4\pi\alpha_D}. \qquad m_{A'} > m_{x1} + m_{x2}.$$





1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

Inelastic Dark Matter (iDM)



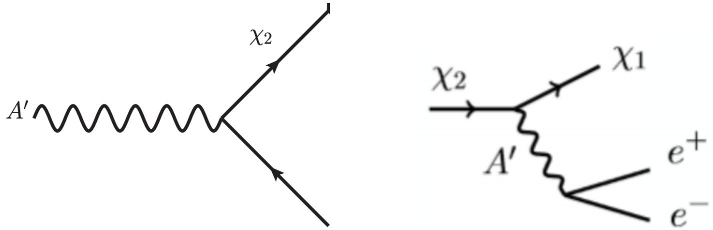
- Co-annihilation
  freeze out to right relic abundance but **avoid CMB constraints**
- Considered **thermal targets** for newly proposed experiments
- 1703.06881 (**Izaguirre, Kahn, Krnjaic, & Moschella**)
- Collider studies: 1508.03050 (Izaguirre, Krnjaic, Shuve)
- LHC lifetime frontier: 1810.01879 (Berlin, Kling)
- Fixed-target probes: next page

iDM in Fixed-Target

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):

  -> **CHARM, NuCal, NA62, LongQuest,**

  -> **DUNE (preliminary)**

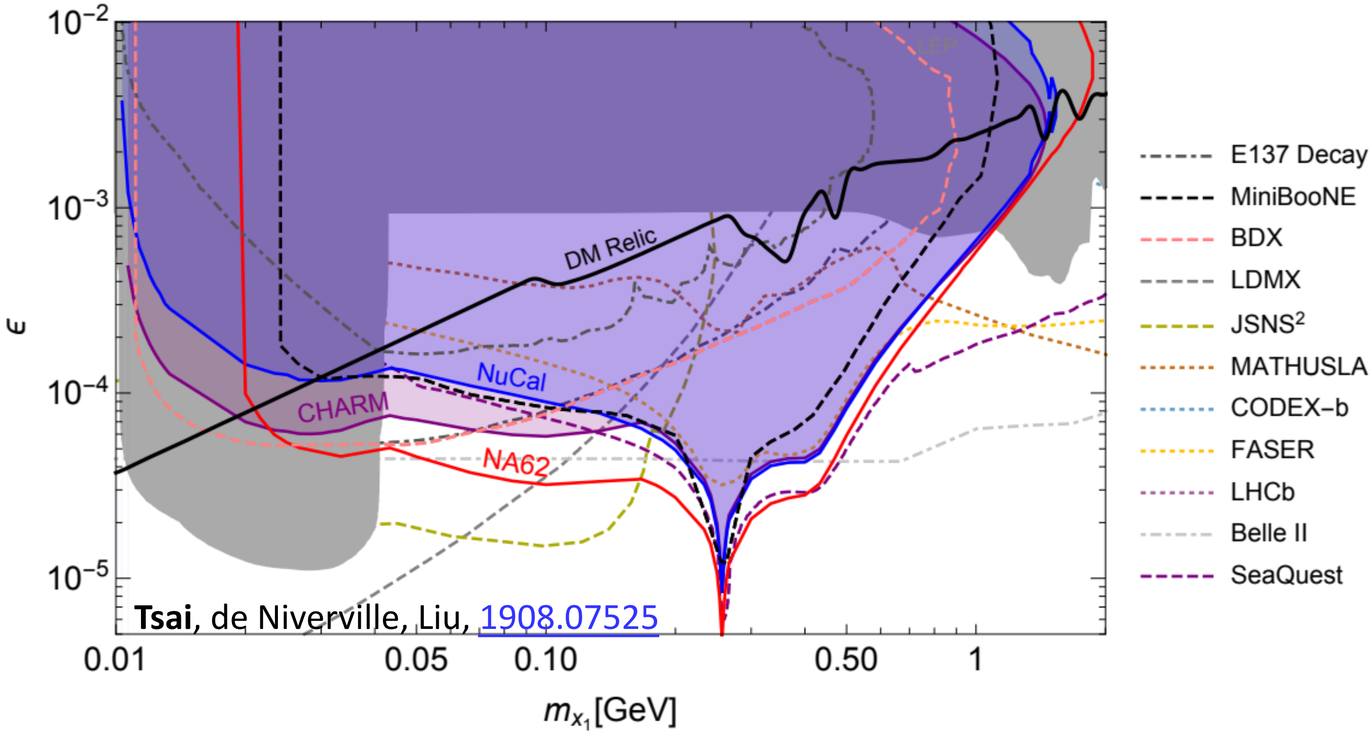


1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella),

New Bounds on Inelastic Dark Matter

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

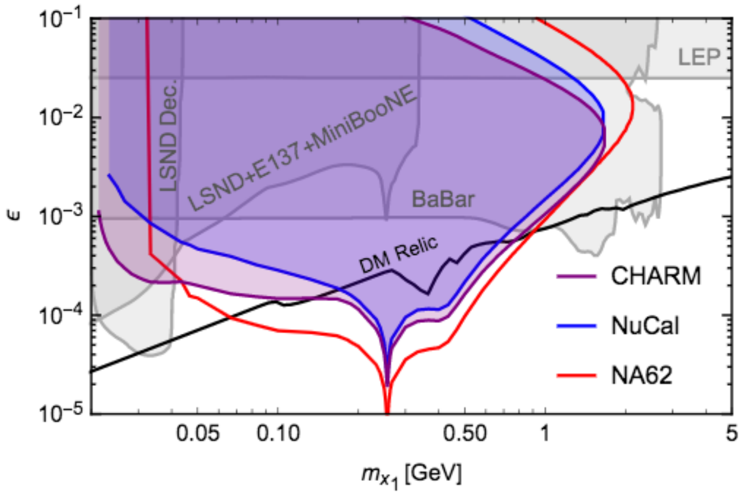
$$\Delta \equiv \frac{m_2 - m_1}{m_1}. \qquad g_D \equiv \sqrt{4\pi\alpha_D}.$$



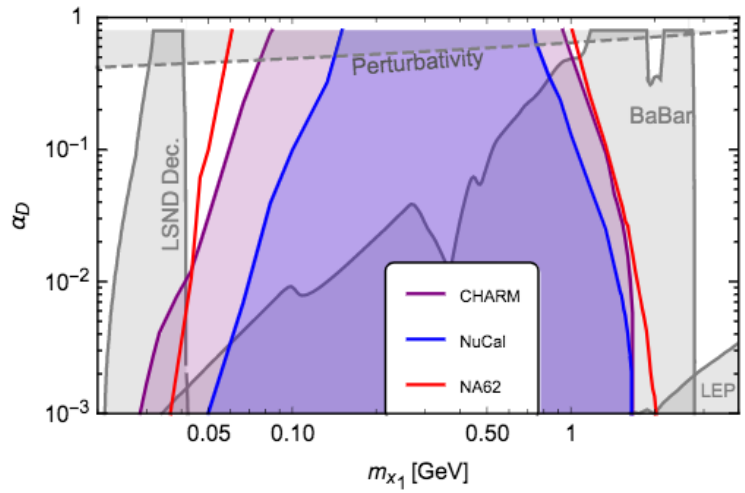
(e) Compilation of relevant constraints and sensitivity projections for iDM with $\alpha_D = 0.1$ and $\Delta = 0.1$. $m_{A'}/m_{x1}$ = 3.

Tsai, de Niverville, Liu, 1908.07525 + reference in previous slides
See, Duerr, Ferber, Hearty, Kahlhoefer, Schmidt-Hoberg, Tunney, 1911.03176, for Belle II update

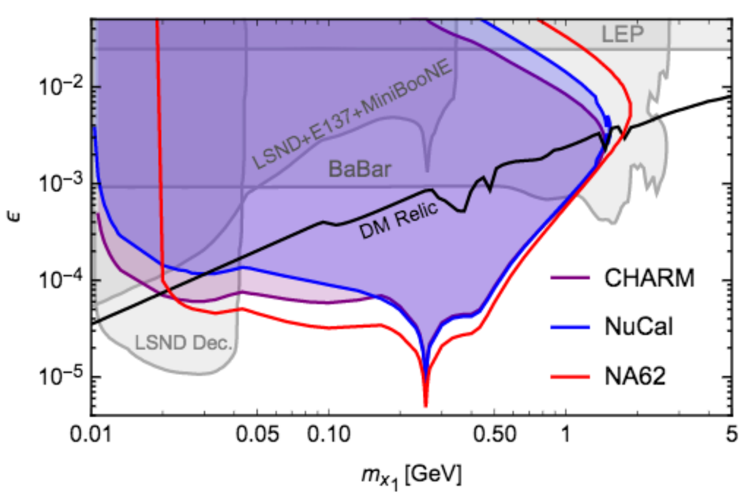
Results: iDM Thermal Target (small mass-splitting)



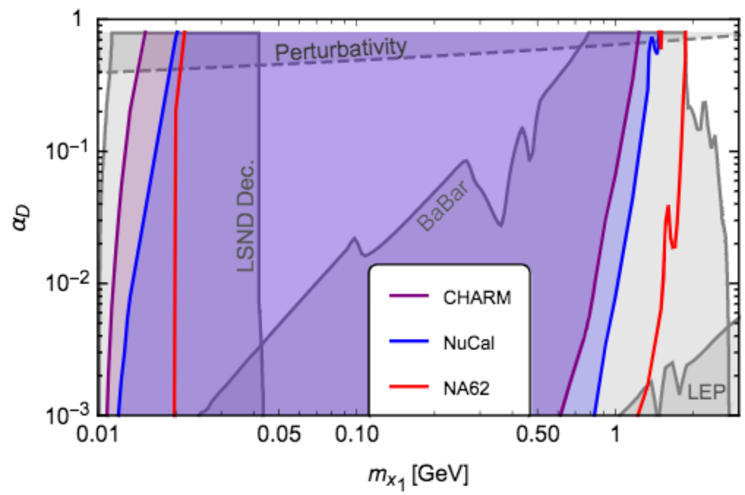
(a) iDM: $\Delta = 0.05$, α_D=0.5.



(b) iDM Thermal Target: $\Delta = 0.05$, $\epsilon = \epsilon_{\rm relic}$.



(c) iDM: $\Delta = 0.1$, α_D=0.1.



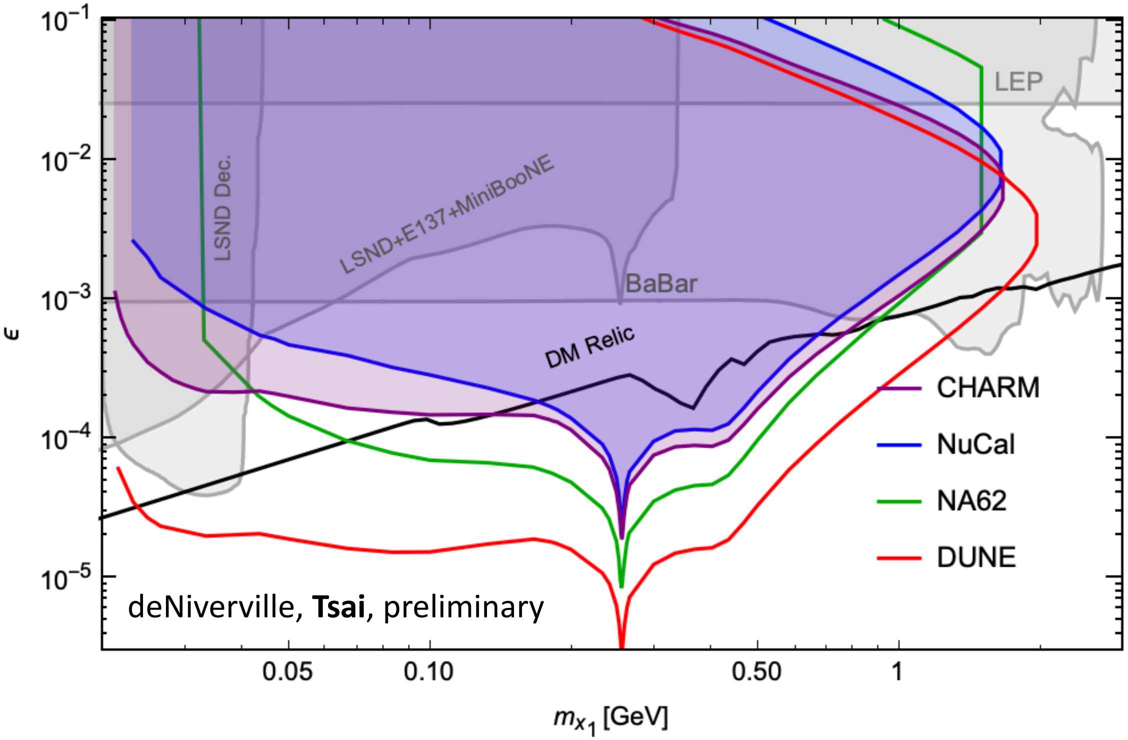
(d) iDM Thermal Target: iDM $\Delta = 0.1$, $\epsilon = \epsilon_{\rm relic}$.

1908.07525 (Tsai, de Niverville, Liu)

New Bounds on Inelastic Dark Matter

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

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

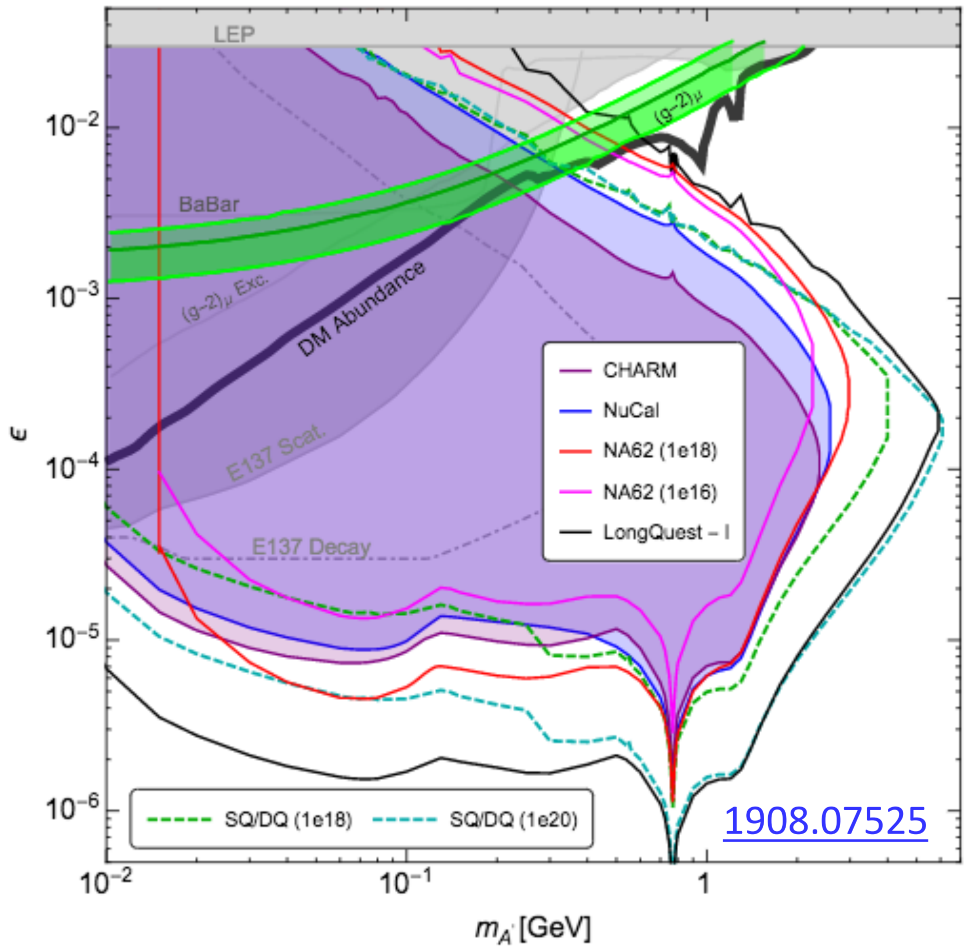


- $m_{A'}/m_{\chi 1}$ = 3,
- $\Delta = 0.05$,
- $\alpha_D = 0.5$

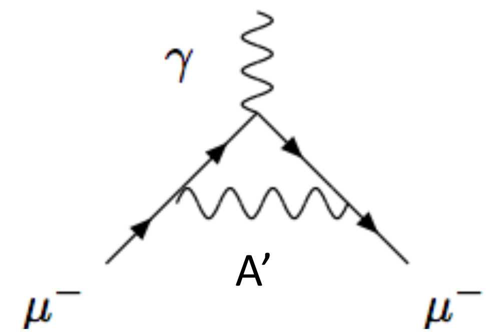
DUNE TDR V - I
arXiv:2002.02967,

DUNE preliminary results by deNiverville & **Tsai**,

Inelastic Dark Matter & Muon g-2 explainer



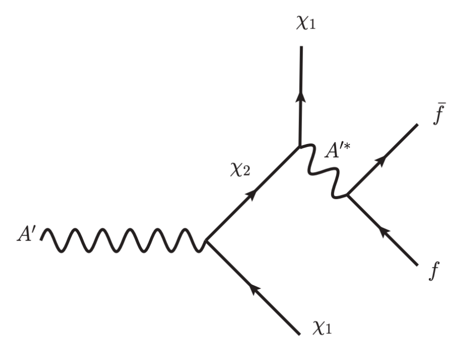
(a) iDM: $\Delta = 0.4$, α_D=0.1. With muon $g-2$ and DM regimes. $m_{A'}/m_{x1}$ = 3.



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

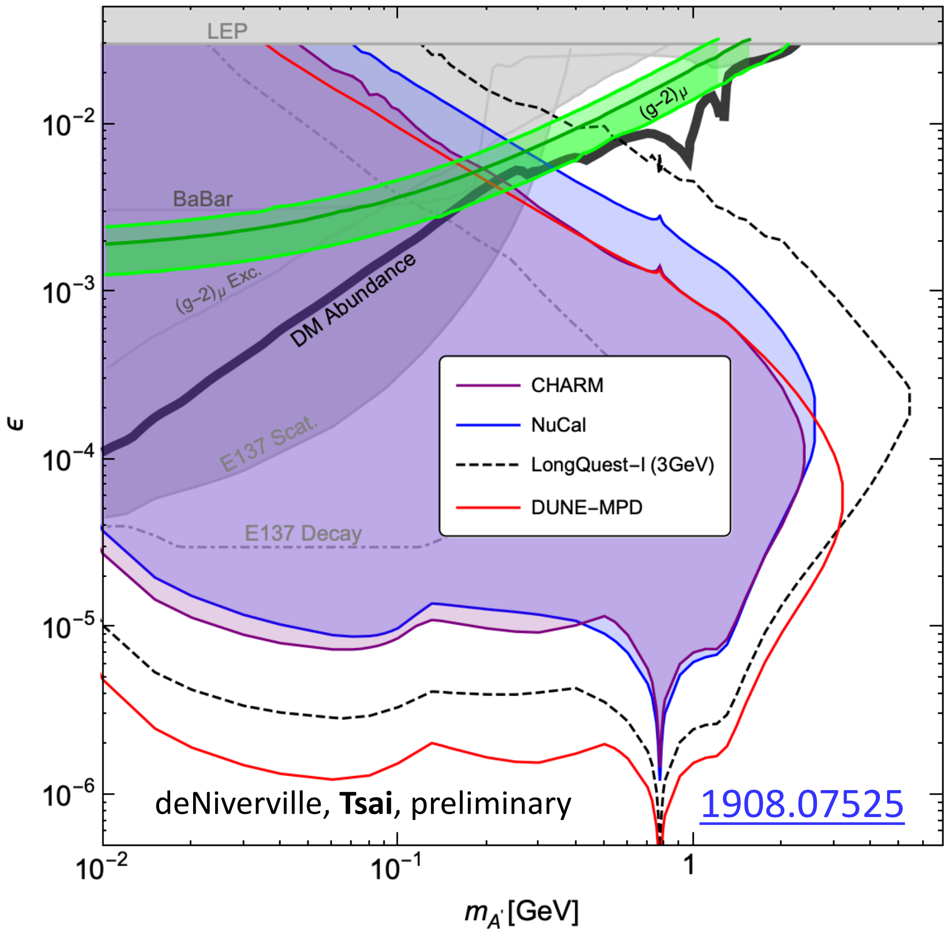
See, e.g., Fayet, 2007 (hep-ph/0702176)

- 1902.05075, Mohlabeng



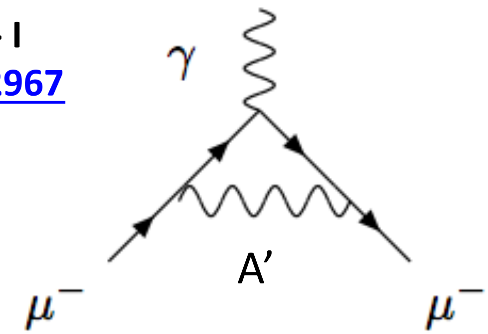
- 1908.07525,**Tsai**, deNiverville, Liuz

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.

DUNE TDR V - I
arXiv:2002.02967



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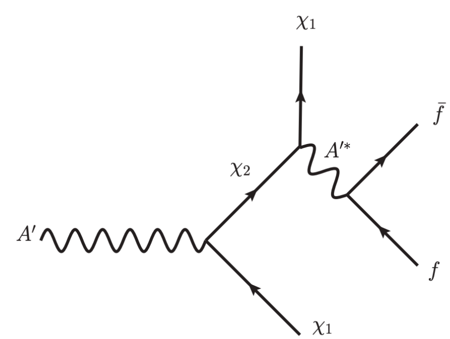


- 1908.07525,**Tsai**, deNiverville, Liuz

Beyond Simple Dark-Sector Models

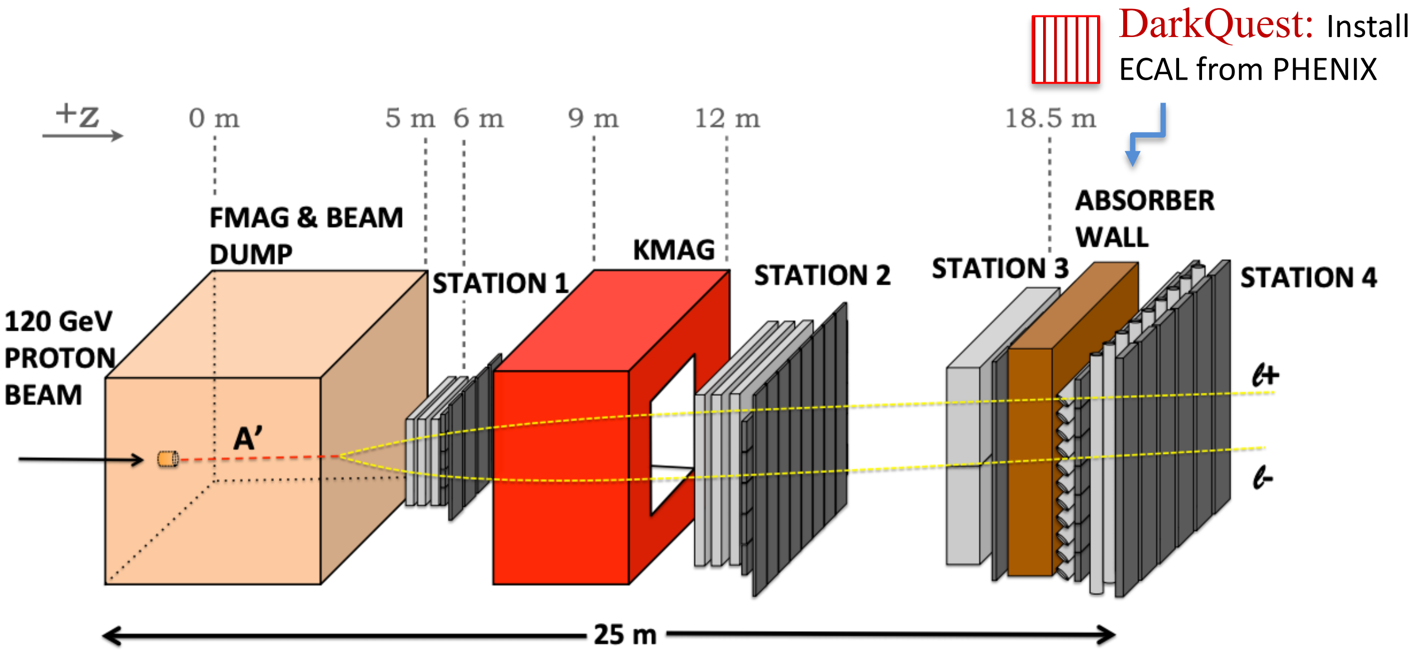
I am currently looking into

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

New results in preparation!

Details of LongQuest: A Multi-Purpose Detector

SeaQuest/DarkQuest



arXiv:1509.00050 (Gardner, Holt, Tadepalli); arXiv:1804.00661 (Berlin, Gori, Schuster, Toro)

Nhan Tran (Fermilab) was rewarded Fermilab LDRD funding (w/ Krnjaic & Toups) and is leading detailed SeaQuest/DarkQuest study + snowmass white paper.

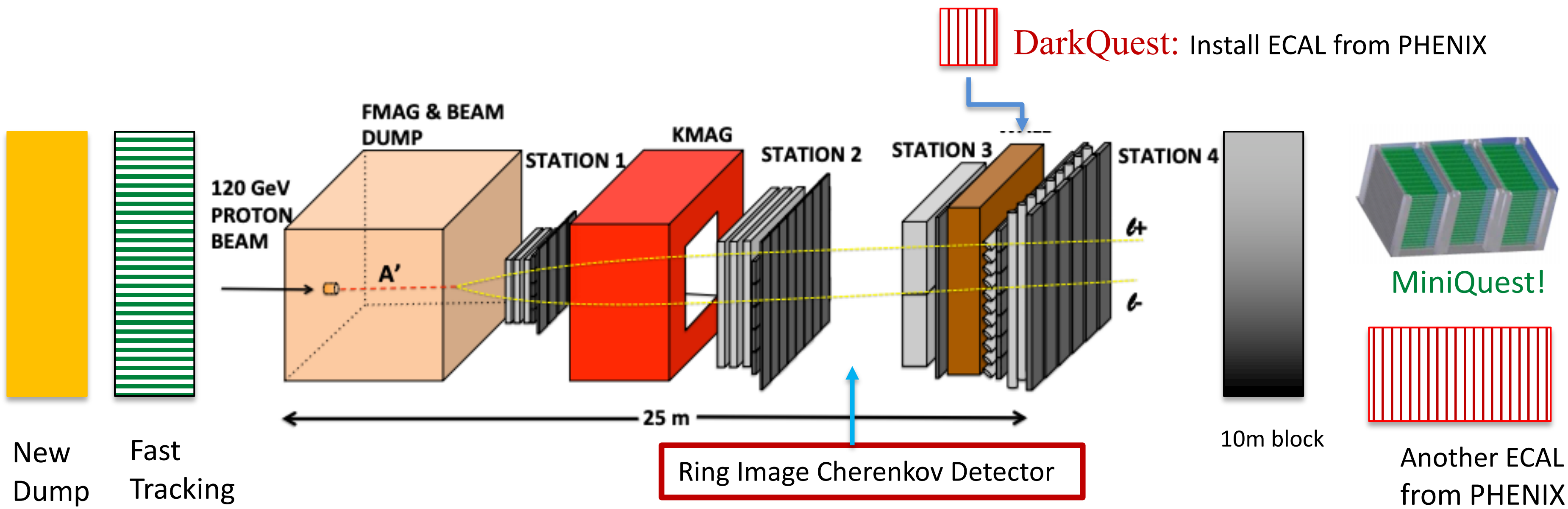
We are looking into long-term plan: arXiv:1908.07525 (**Tsai**, de Niverville, Liu)

LongQuest (I-III)

- A search for long-lived particles **with an improved decay detector (I)**, **additional long based-line detectors (II), and possibly new dump + tracking (III)** using SeaQuest facility.
- Working on a pheno paper with Ming Liu, Kun Liu, and Patrick de Niverville.

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

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



LongQuest III

Front dump and fast tracking

LongQuest I

Add RICH (from PHENIX exp.) or HBD for particle id, to help bkg of, e.g., $(K_L^0 \to \pi^\pm e^\mp \nu)$

LongQuest II

Far Detectors: low bkg.
Millicharge detector
Or another ECAL!

Scattering Experiments

Scattering Experiments/Detectors

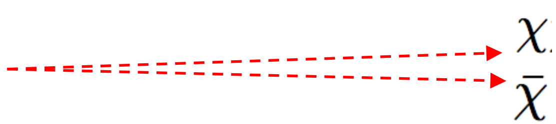
MiniBooNE, SBND, MicroBooNE, MINERvA, DUNE, etc

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

Features (comparing to decay detector):

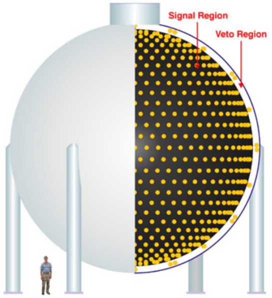
1. higher density
2. complicated design compared to the decaying detector.
3. Smaller fiducial volume (for near-beam detectors); **cost more**.
4. Usually studying **stable particles (**neutrino, **dark matter, etc)**

Scattering Detectors



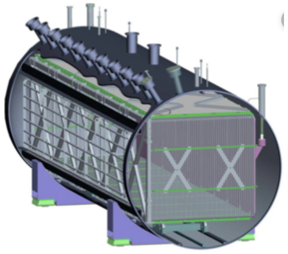
Other beams:
- BNB
- LBNF (future)

MiniBooNE Detector



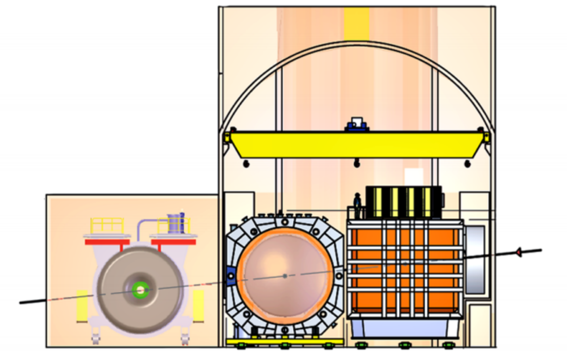
arXiv:0806.4201
MiniBooNE collaboration

MicroBooNE Detector



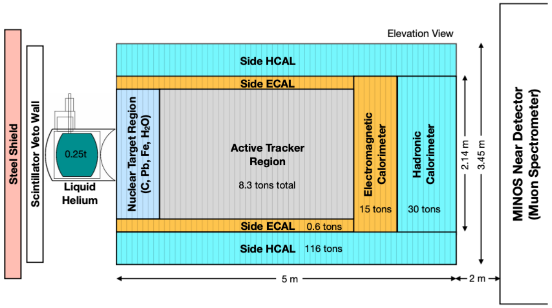
arXiv:1612.05824
MicroBooNE collaboration

DUNE Near Detector



arXiv:2002.02967, DUNE TDR V - I

MINERvA Detector

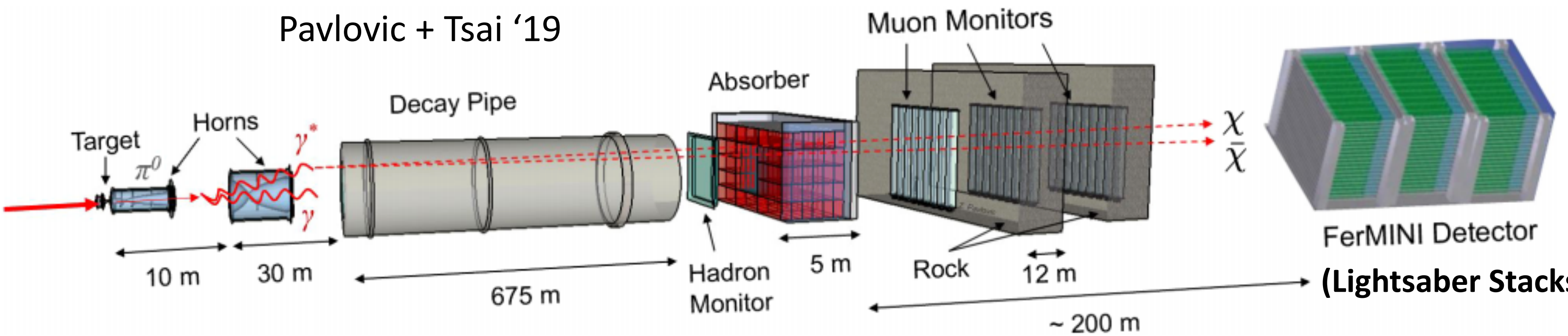


arXiv:1109.2855
MINERvA collaboration

FerMINI: Fixed-Target Millicharged Particle Search

- specialized “scattering experiment” to search for millicharged particles using stacks of scintillators studying triple/quadruple coincident signature

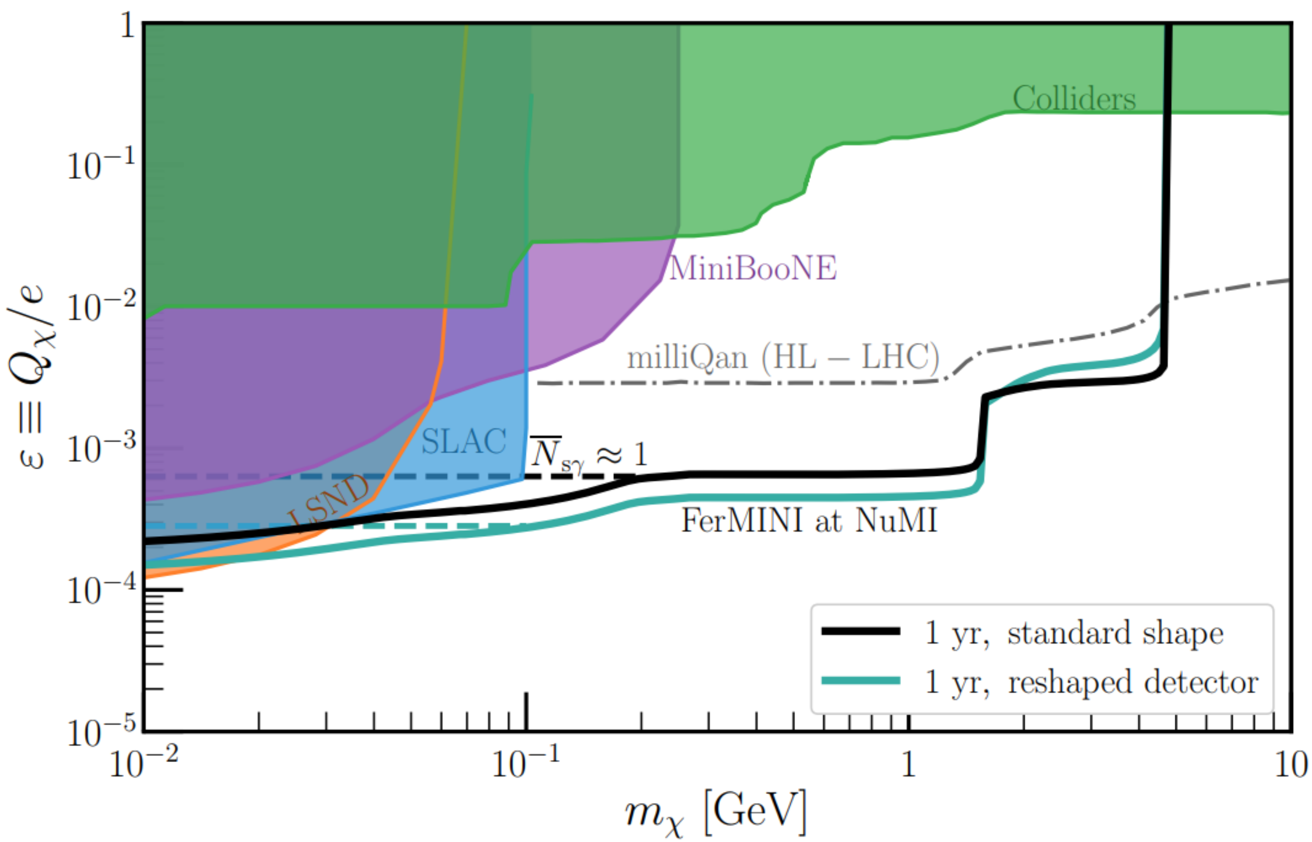
Pavlovic + Tsai ‘19



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

arXiv: 1410.6816, milliQan (Haas, Hill, Izaguirre, Yavin)

FerMINI @ MINOS



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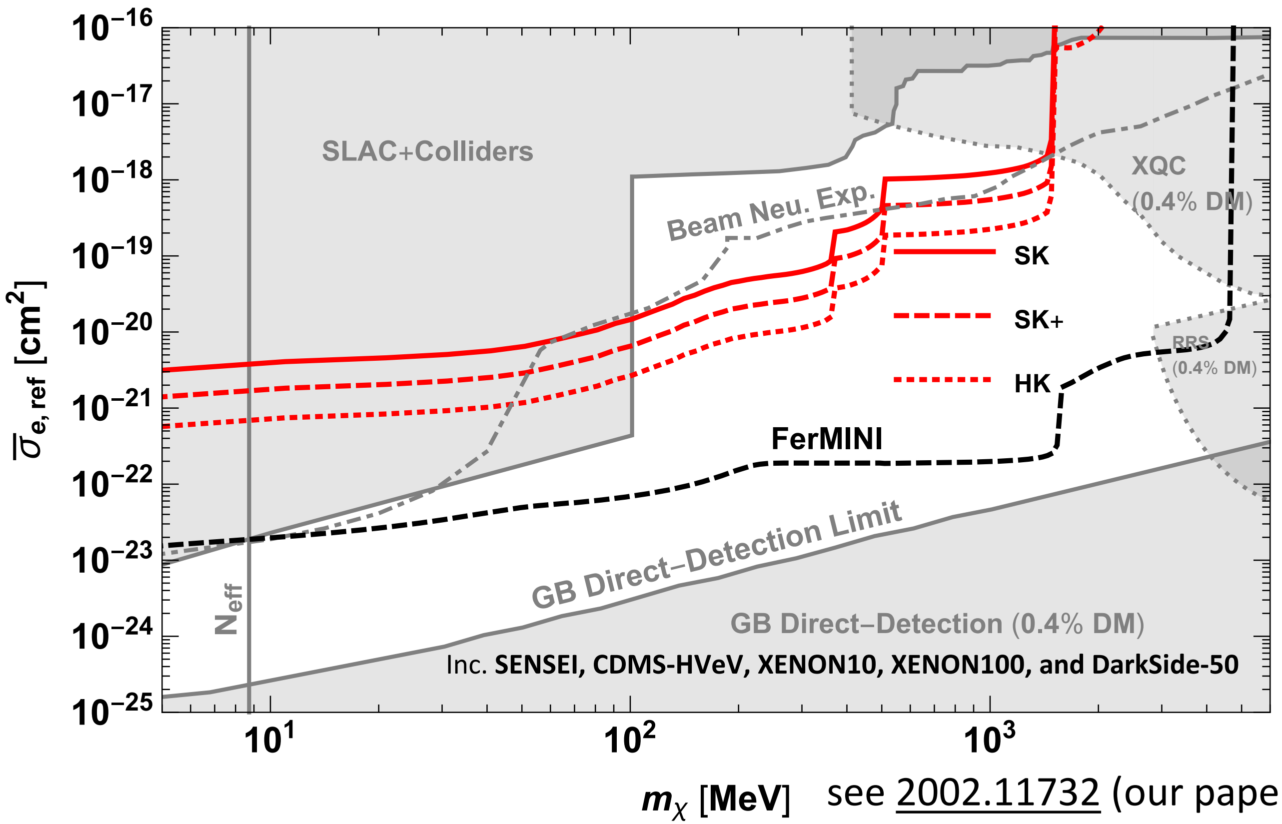
Different epsilon now, ε=Q/e

Now it's literally fraction of the charge!

FerMINI Probe of Millicharged SIDM

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



see 2002.11732 (our paper)

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

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

Yu-Dai Tsai, Fermilab

FerMINI Collaboration (BRN proposal)

Chris Hill
OSU

Andy Haas
NYU

Jim Hirschauer
Fermilab

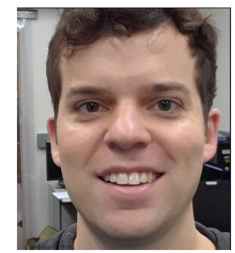
David Miller
U Chicago

David Stuart
UCSB

Zarko Pavlovic
Fermilab

Yu-Dai Tsai
Fermilab/U.Chicago

Cindy Joe
Fermilab



Ryan Heller
Fermilab

Maxim Pospelov
Minnesota / Perimeter

Ryan Plestid
McMaster

Albert de Roeck
CERN

Joe Bramante
Queen's U

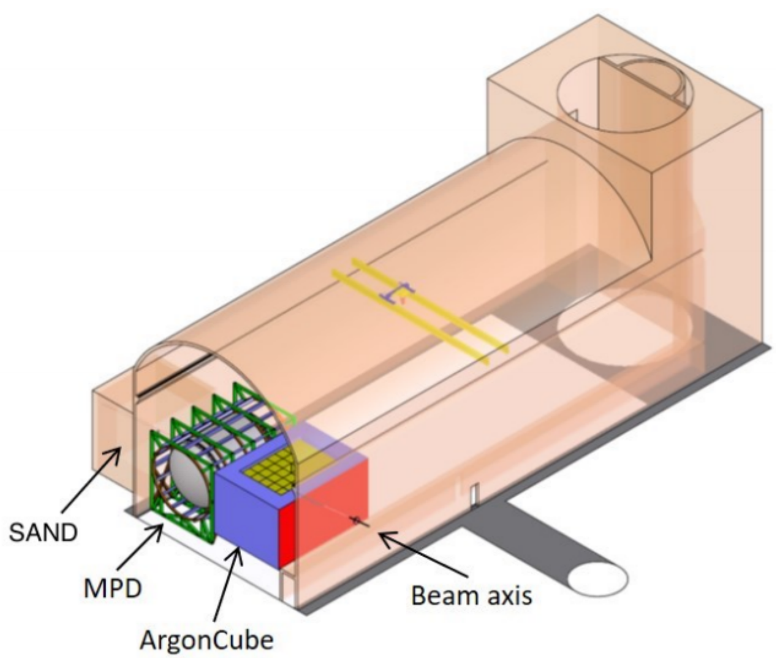
Bithika Jain
ICTP-SAIFR

Looking Ahead

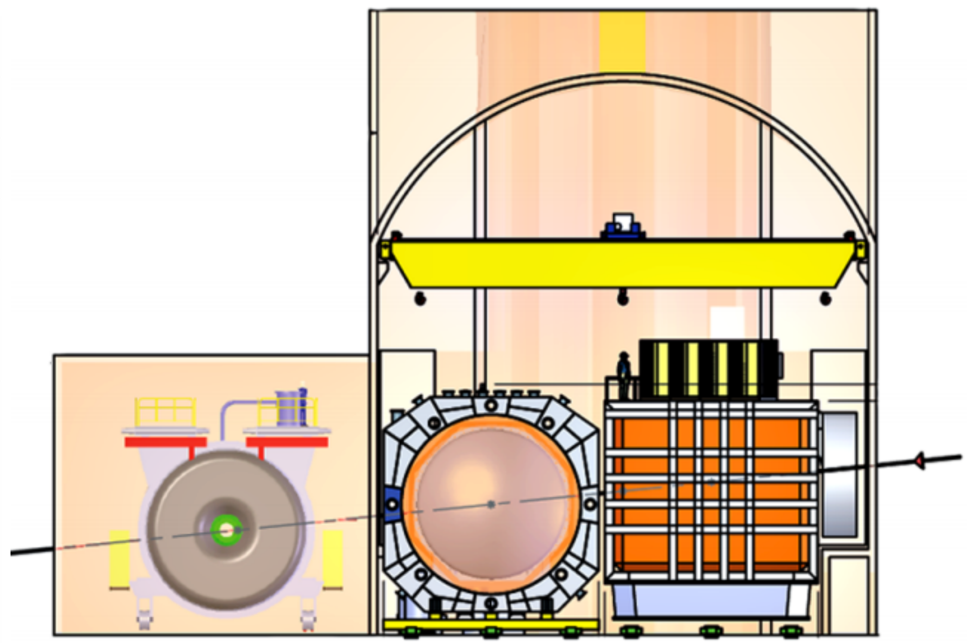
- Exploring **Energy Frontier of the Intensity Frontier** (complementary to and before HL-LHC upgrade)
- **Cosmology-driven models:** **relaxions, baryogenesis models**
- **other motivated models:** **quirks, KOTO-related models**
- Near-future (and almost free) opportunity (**NuMI Facility, SBN program,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

Thank You!

DUNE Near Detector Complex



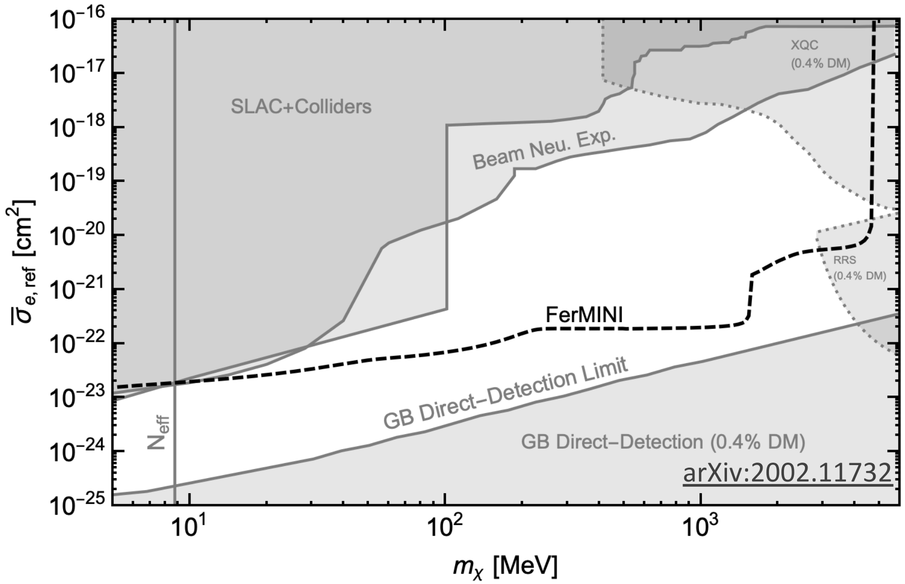
arXiv:2002.02967, DUNE TDR V - I

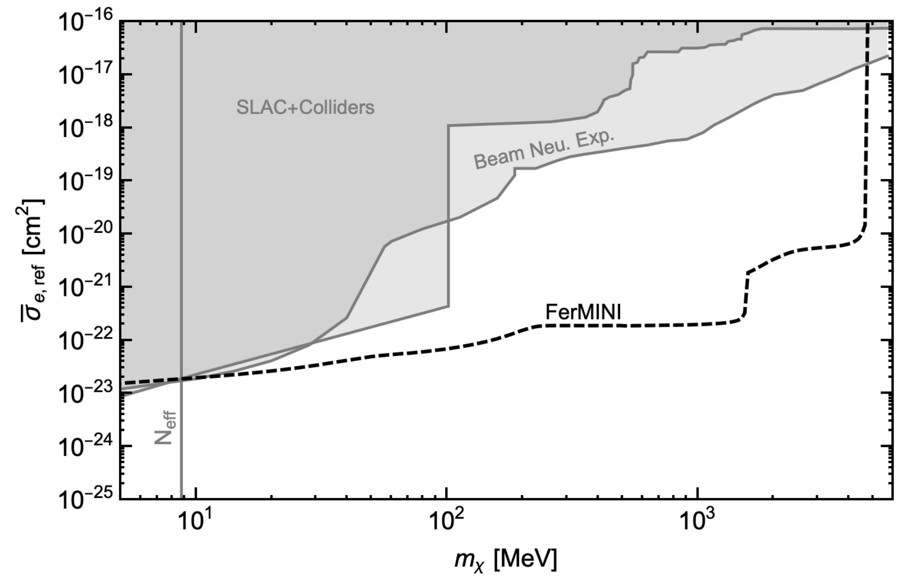


arXiv:2002.02967, DUNE TDR V - I

- **arXiv:2002.02967, DUNE TDR V - I**
- 1912.07622 (Berryman, Gouvêa, Fox, Kayser, Kelly, Raaf)
- New scattering + decay studies
  (De Niverville, De Roeck, Petrillo, **Tsai**, Tsai, in preparation)

Example: Constraints on Millicharged Dark Matter





Also Consider **ambient dark matter**

Produce dark particles in collisions

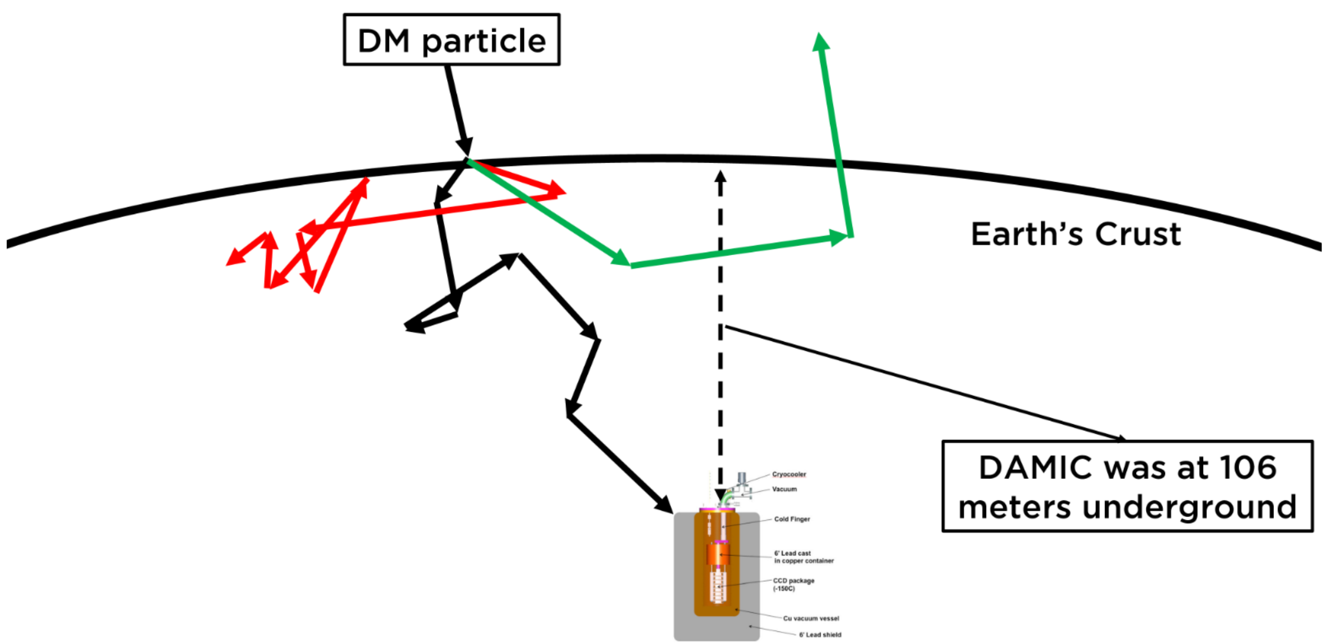
Same mass and interaction strength.

Different assumptions

Details of these figures & references will be explained and discussed later

Strongly Interacting Dark Matter

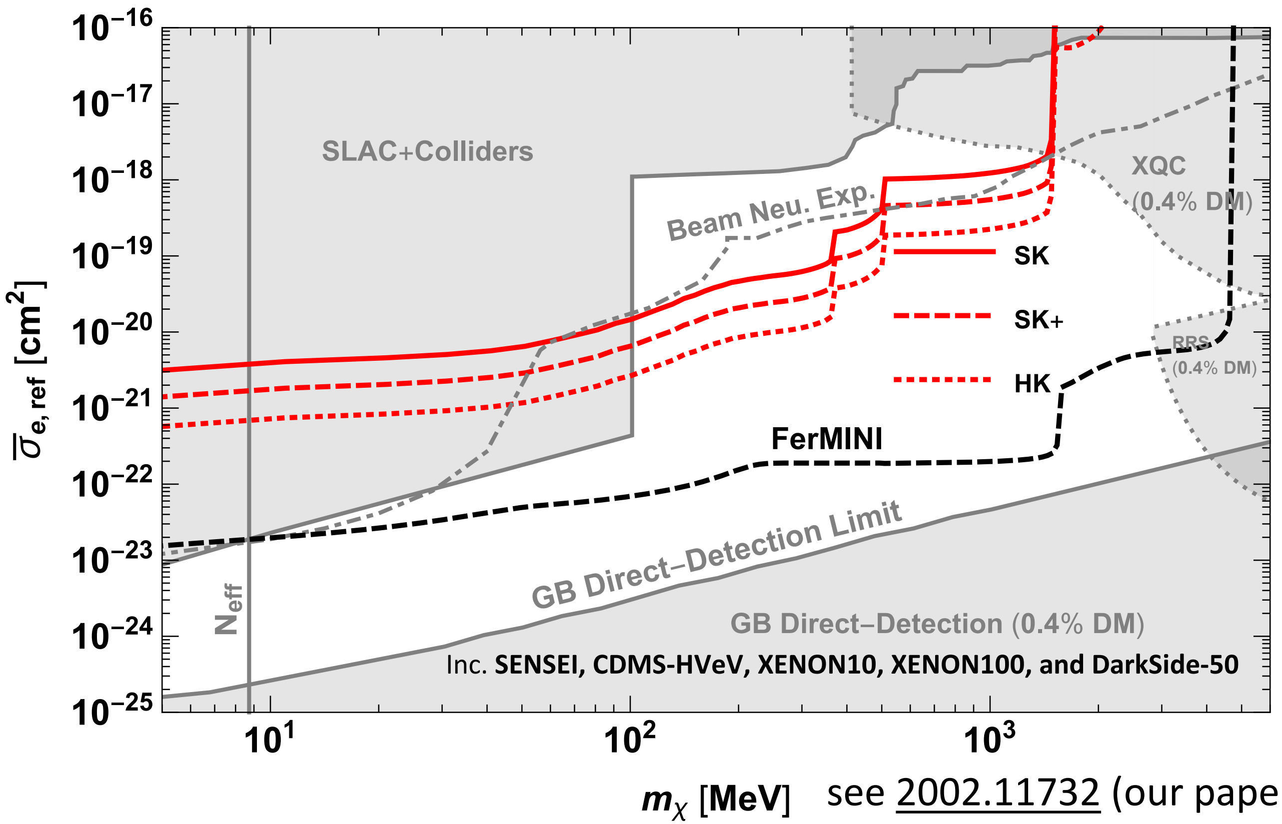
DM-SM Interaction too strong that attenuation stop the particles from reach the direct detection detector



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

FerMINI Probe of Millicharged SIDM

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



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see 2002.11732 (our paper)

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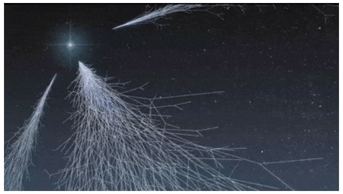
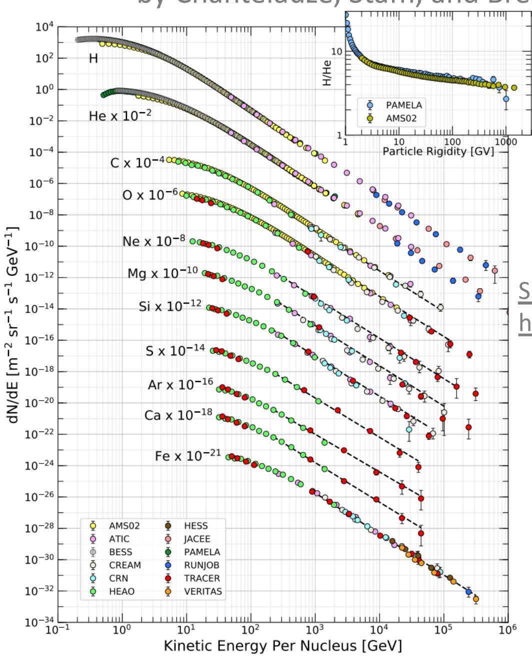
Yu-Dai Tsai, Fermilab

MCP in Neutrino Observatories

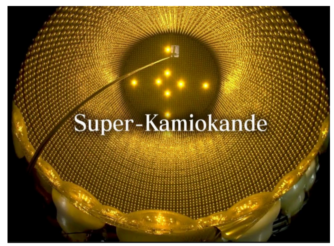


by Chantelauze, Staffi, and Bret

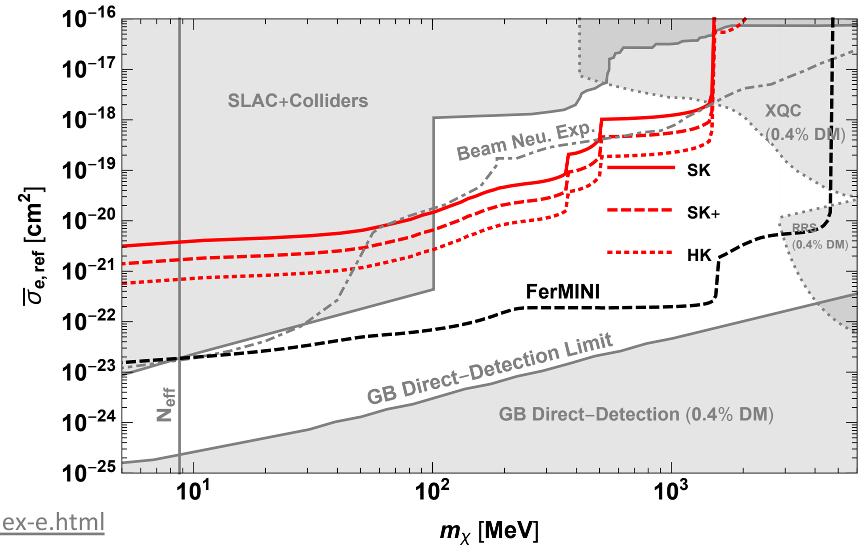
$\chi \;\; \bar{\chi}$



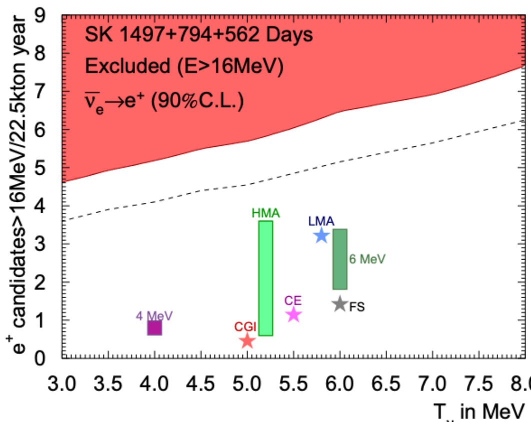
PDG, RPP, 2019



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



2002.11732 (our paper)
+ FerMINI projection



1111.5031 (Super-K Collaboration)

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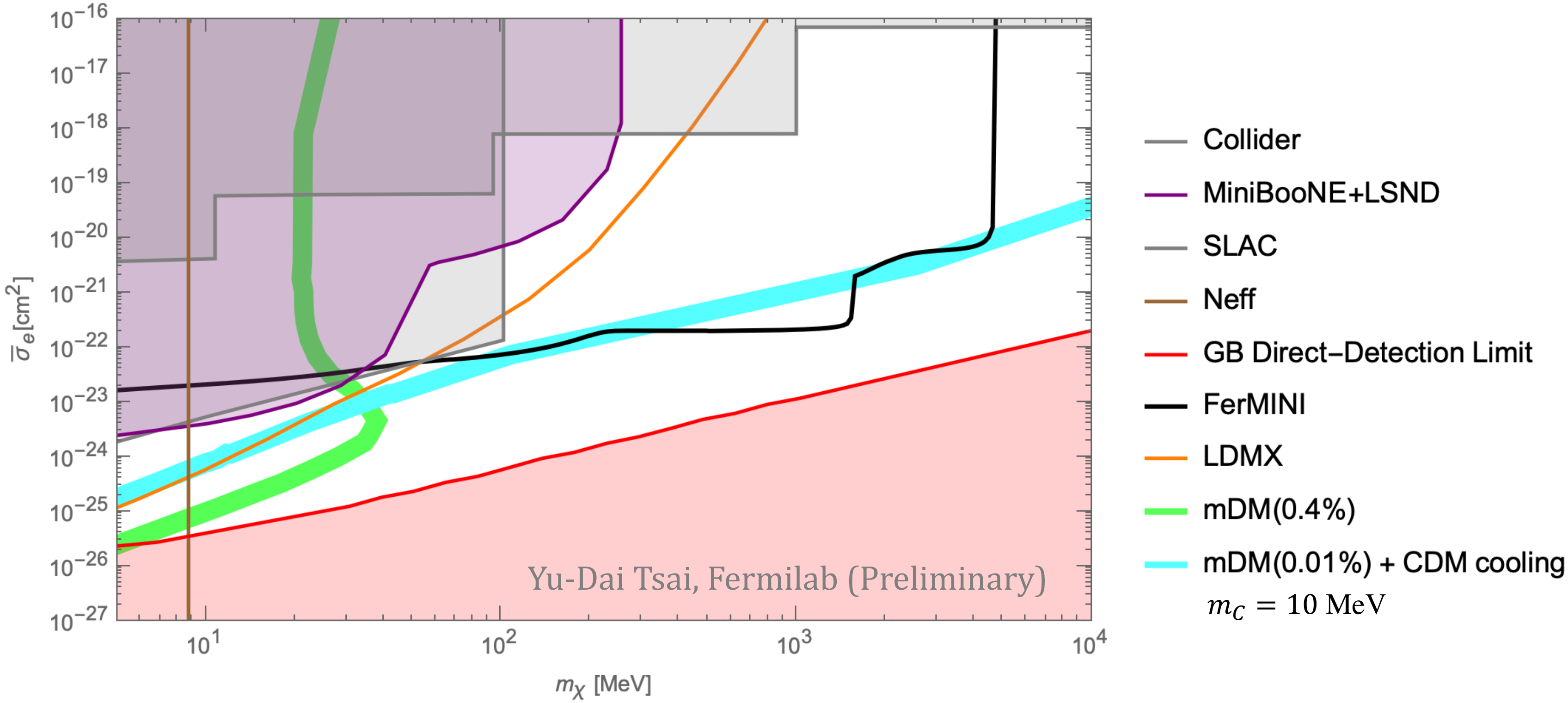
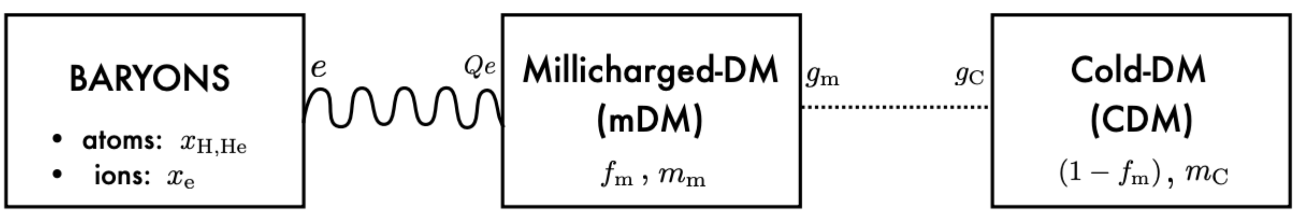
Fermilab

Reviving MDM for EDGES





Yu-Dai Tsai,
Fermilab

Liu, Outmezguine, Redigolo, Volansky, ‘19

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

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