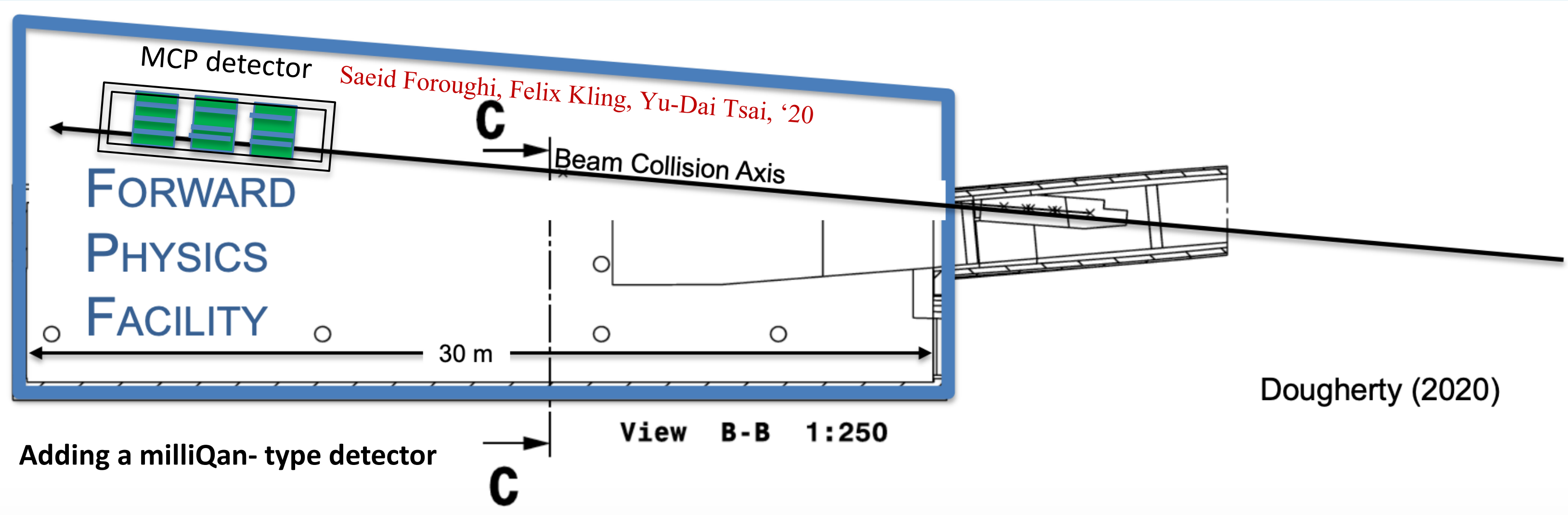


When High Energy Meets High Intensity

Yu-Dai Tsai, Fermilab/U Chicago

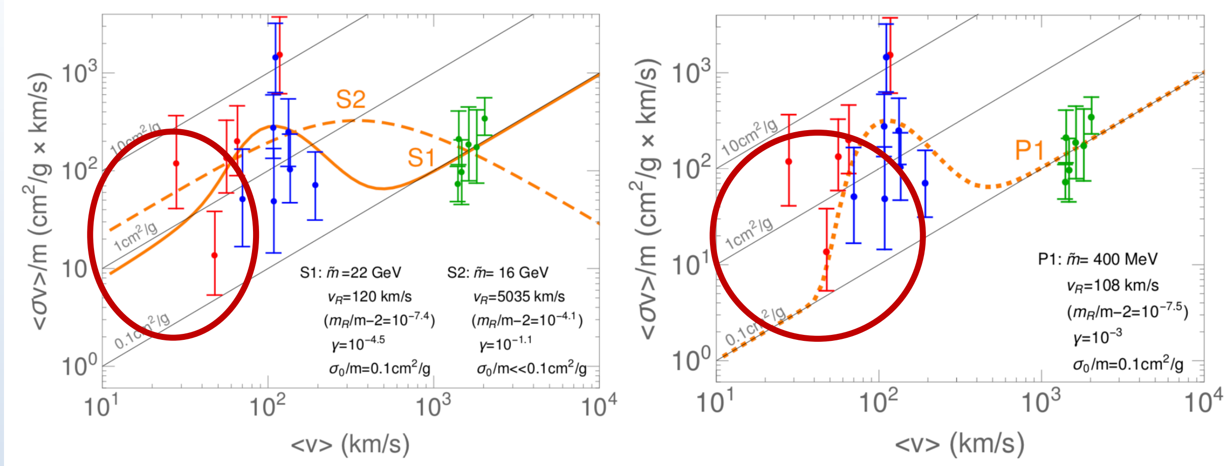
[1] FORMOSA: Looking Forward to Millicharged Dark Sectors (2010.07941)

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

[3] Cosmic-ray Produced MCPs in Neutrino Observatories (2002.11732)

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

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



New Experiments, New Models & Complementarity with Astro-Cosmo Searches

Yu-Dai Tsai, Fermilab/U Chicago

[6] Resonant Self Interacting Dark Mesons (2008.08608)

[7] New Pathways to to the Relic Abundance of Vector-Portal Dark Matter (2011.01240)

[8] Elastically Decoupling Dark Mater (1512.04545)

arXiv: https://arxiv.org/a/tsai_y_1.html

Contact: ytsai@fnal.gov

What do I do?

- New Dark Matter Models

- Accelerator Probes (New Experimental Proposals)

- Novel Astrophysical/Cosmological Searches

  - **Light axion effects on Trans-Neptunian object (TNO) & exoplanet precessions** (w/ Vagnozzi, Visinelli, Wu)

  - Is GW170817 a primordial black hole event?

  - Dark Matter in neutron stars

  - **Small-scale test of v-dep. SIDM** (w/ Kaplinghat, Valli, Yu)

Outline

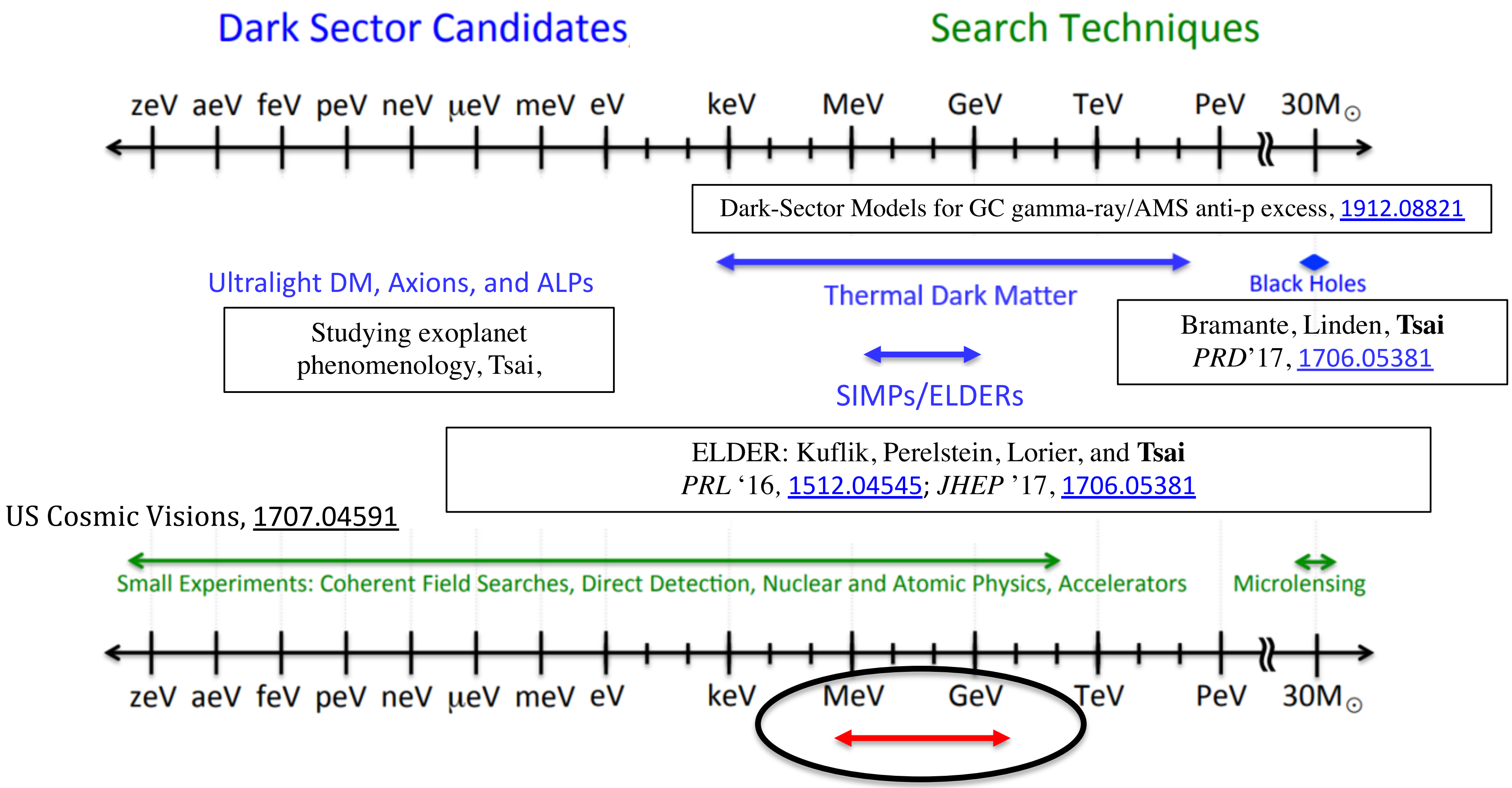
- Dark Matter Complementarity
- Proton Fixed-Target: Scattering
- LHC Forward Experiment
- Proton Fixed-Target: Decay
- Resonant Dark Meson

Dark Matter Complementarity:

Why accelerator / astro probe?
Why MeV – GeV range?

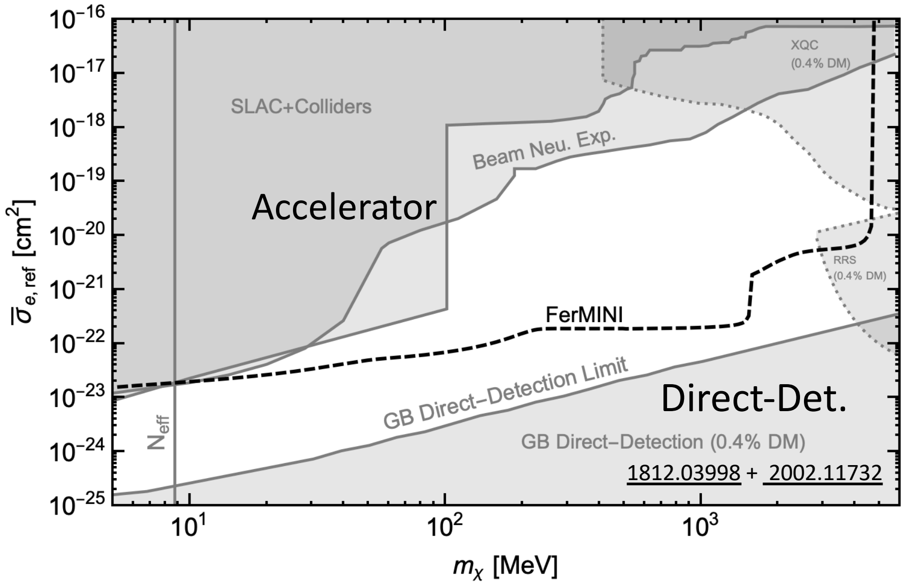
Yu-Dai Tsai, Fermilab, ‘20

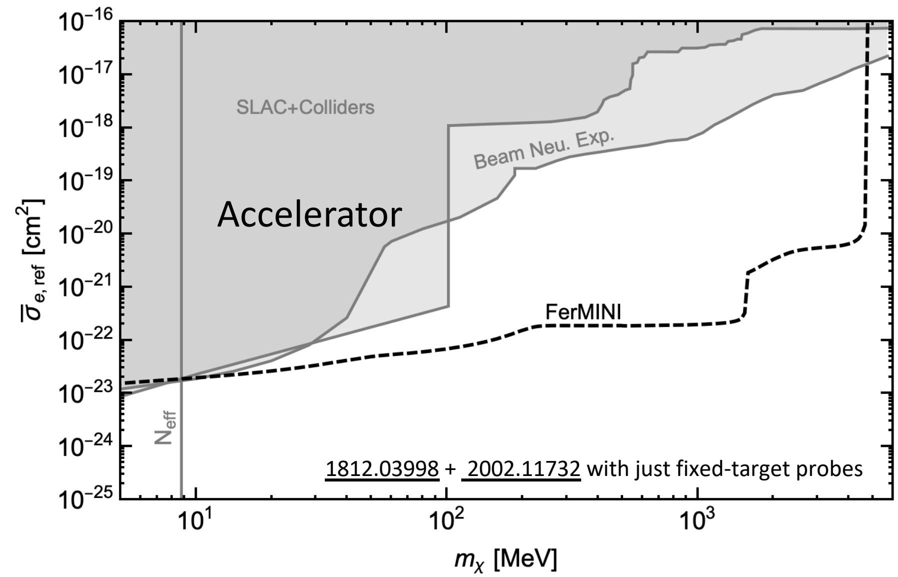
Exploration of Dark Matter & Mediator



- Resonant SIDM w/ Hitoshi+; Kinetic Decoupling DM w/. Tracy+
- Two Major Probes: **Accelerator** & **Astro-Cosmo Searches**, and why?
- **MeV to GeV** mass region?

Example: Constraints on Millicharged Dark Matter





Also consider **ambient dark matter**

Produce dark particles in collisions

Same mass and interaction strength.

Different assumptions

Some details of these figures will be explained later

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 & Cosmic ray, etc)

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

Cosmology: assume cosmological history, species, etc

} different

Accelerator Experiments:

Focusing on Proton Fixed-Target & LHC Forward Experiments

Accelerator Experiments

- **Produce these particles**
- **“Robust” Bounds**

  - Independent of DM abundance / velocity dist.
- Many of them existing and many to come:

  complement each other
- **Dark matter attenuation** in atmosphere and crust

  is not an issue usually
- Are these really the astro / cosmo dark matter?

Proton Fixed-Target & Neutrino Experiments

- **High-Energy Intensity Frontier**
- **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

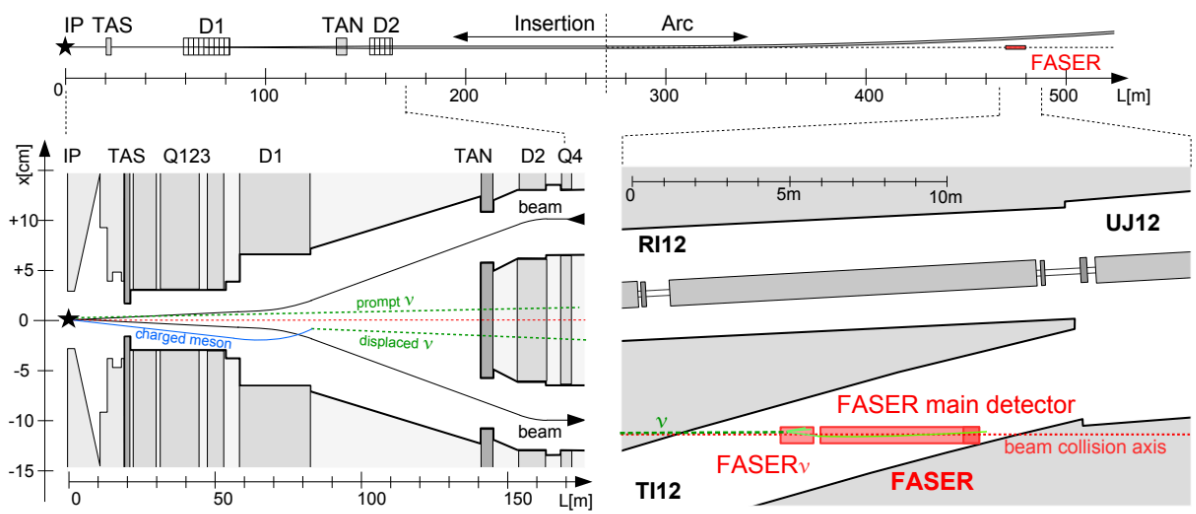
LHC Forward Physics Region

- **LHC collision** + **fixed-targe-like intensity**:

  High-Intensity Energy Frontier

- Benefits from both worlds! No need to build a new beamline

- The **FASER** & **FASER-nu** collaboration
- **Forward Physics Facility** Proposal
- New proposal: **FORMOSA** & **Forward Proto-DUNE**,
- **New Neutrino Campus**



Astro-Cosmo Dark Matter Searches

Why is it so important?
Hints on DM Properties

Searching for “Actual” Dark Matter

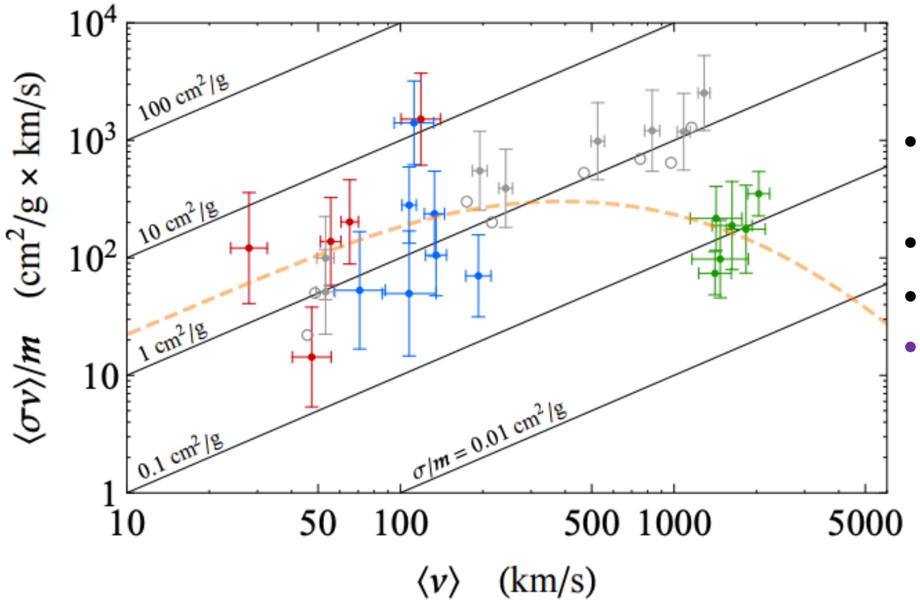
- **Direct Detection**: Searching for local ambient dark matter

- **Small-scale structure study**: Searching for the effects of dark matter in galaxies and clusters

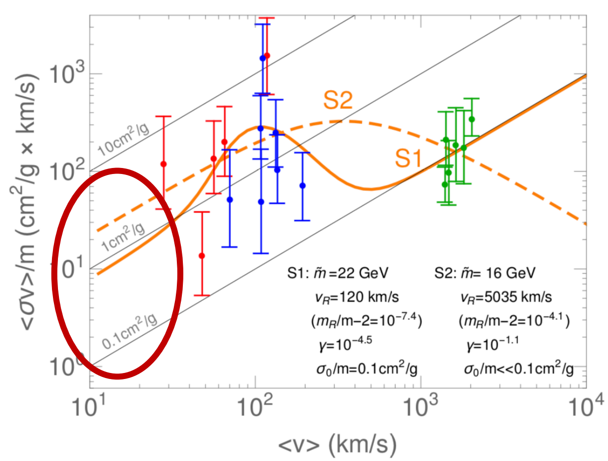
- **Cosmological measurement**: searching for the dark matter effects on the cosmic evolution

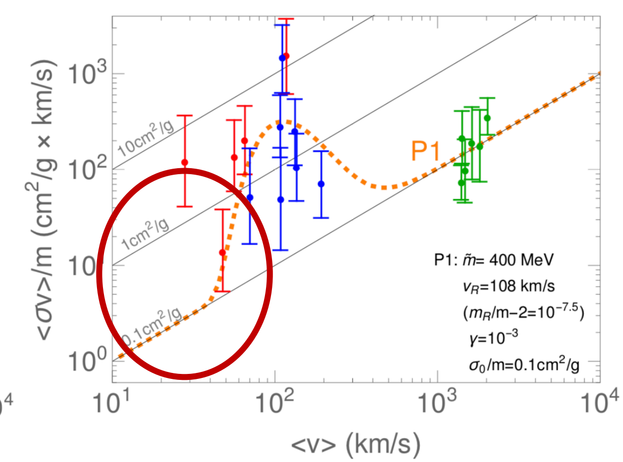
- **Reveal the actual story of dark matter!**

Small-Scale Structure Study



- Plot includes dwarfs (red), low surface brightness (LSBs) spiral galaxies (blue) and clusters (green)
- Diagonal lines are contours of constant σ/m .
- **Velocity-Dependent Self-Interacting Dark Matter**
- Kaplinghat, Tulin, Yu, arXiv:1508.03339





Why study MeV – GeV+ dark sectors?

Revealing the dark secrets of the Universe

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**
- **LSND & MiniBooNE anomaly**
- **EDGES result**
- **Beryllium anomaly**
- **Small-Scale Structure Problems**

⋮

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

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

⋮

- **Muon g-2 anomaly**
- **LSND & MiniBooNE anomaly**
- **EDGES result**
- Beryllium anomaly
- **Small-Scale Structure Problems**

⋮

Below ~ MeV there are also **strong bounds**

Boldface: I studied / **Red**: I have studied and require dark matter property

My studies on these anomalies

- **Proton charge radius anomaly:**
- Light Scalar & Dark Photon at Borexino & LSND, Pospelov, **Tsai**, PLB ‘18, 1706.00424
- **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
- **EDGES 21-cm absorption spectrum anomaly**
- Millicharged Particles in Neutrino Experiments, Magill, Plestid, Pospelov & **Tsai**, PRL ‘19, 1806.03310
- FerMINI Experiment, Kelly & **Tsai**, PRD ’19, 1812.03998
- Cosmic-ray produced MCP in neutrino observatories, 2002.11732
- **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

When High Energy Meets High Intensity

Proton Fixed-Target &
Collider-Forward Experiments

When Energy meets Intensity

Vision of this part of my research program:

- Filling low-mass / high-mass gap

  (dark sector, e.g. portals, MCP, etc)

- low-energy / high-energy gap

  (neutrino, nuclear physics)

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), 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**: 10^{16} POT/yr, $\sqrt{s}$ = 13 TeV

Scattering Experiments
vs
Decay Experiments

Scattering Experiments:

Studying Neutrinos and Dark Matter Scattering

FORMOSA & Forward-DUNE

Scattering Detectors

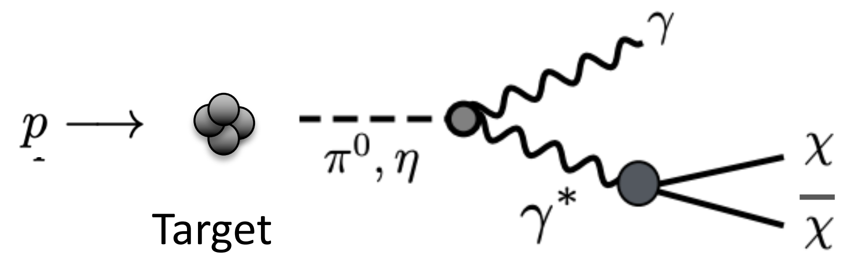
- **MiniBooNE, SBND, MicroBooNE, MINERvA, DUNE, etc**
- Many have primary goals to study **neutrino scattering** and/or **neutrino oscillation**

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)**

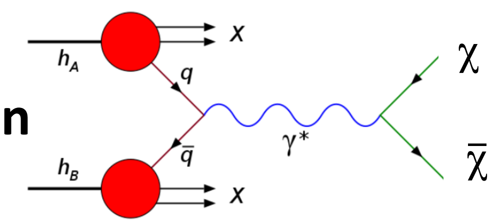
Some Production Channels

- ❑ **Production: Meson Decays**

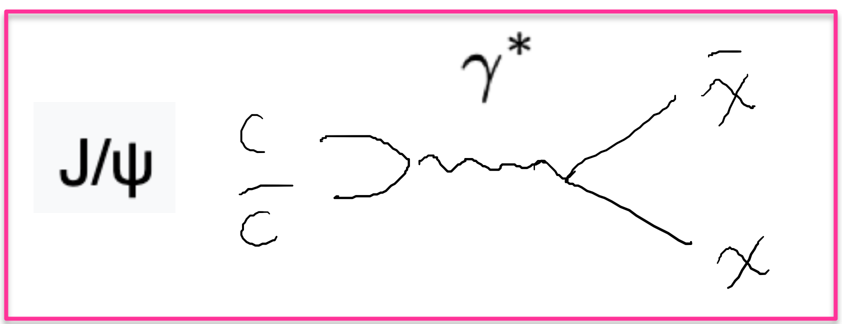


Modified from 1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

- ❑ **Production: Drell-Yan**



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



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

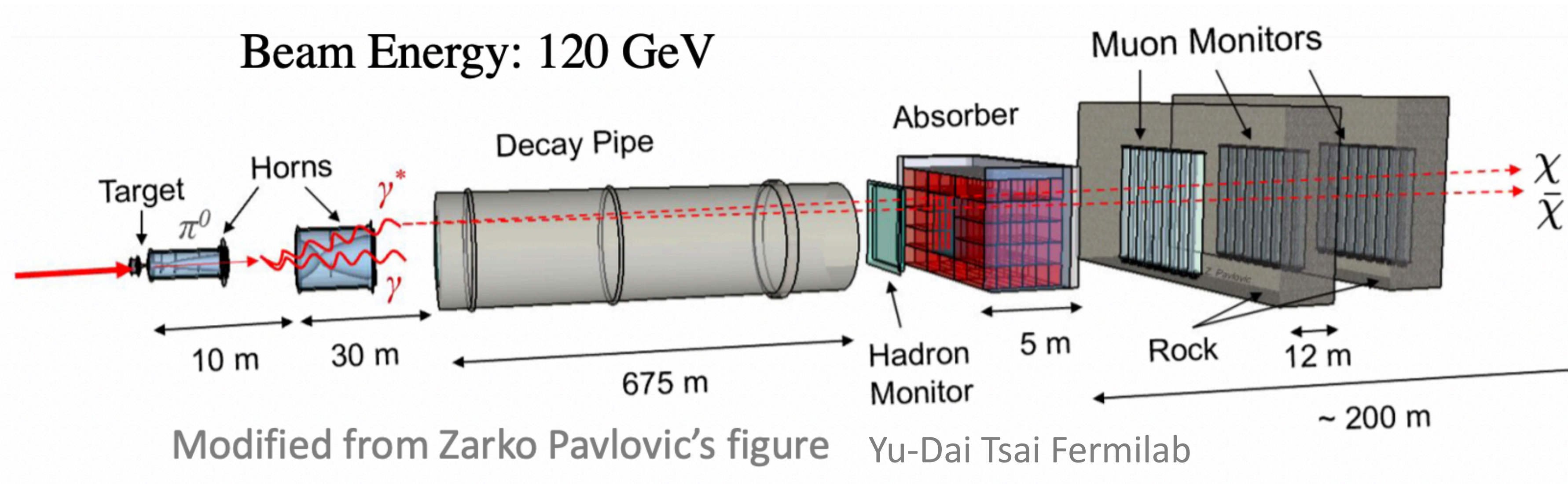
$BR(\pi^0 \rightarrow \gamma e^- e^+) = 0.01$

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

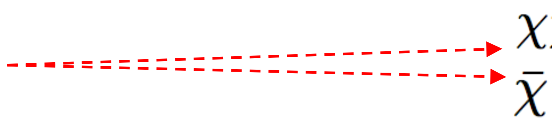
$BR(J/\psi \rightarrow e^- e^+) = 0.06$

MCP Produced in Fixed-Target Experiments

Example: Neutrinos at the Main Injector (NuMI) beamline
See https://arxiv.org/abs/1507.06690 (NuMI collaboration)

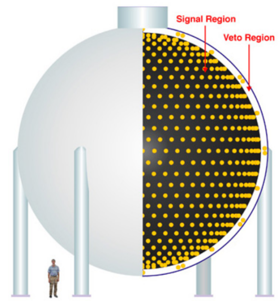


Scattering Detectors



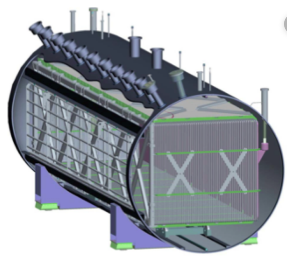
- NuMI Beam
- BNB
- LBNF (future)

MiniBooNE Detector



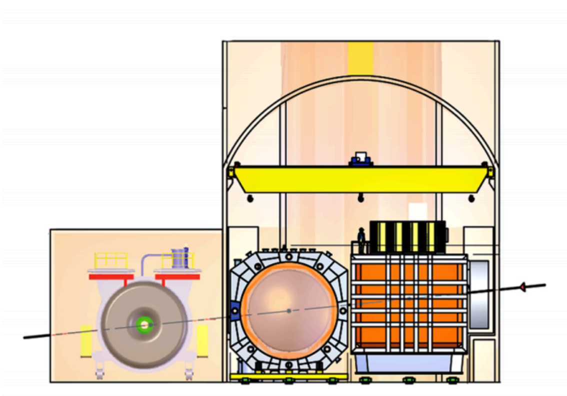
arXiv:0806.4201
MiniBooNE collaboration

MicroBooNE Detector



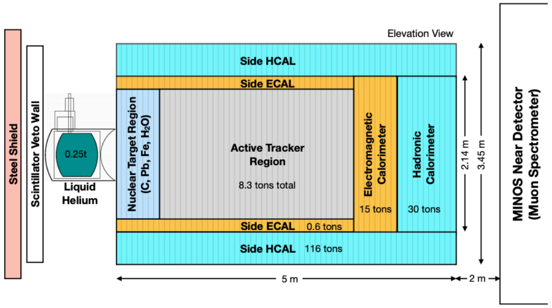
arXiv:1612.05824
MicroBooNE collaboration

DUNE Near Detector



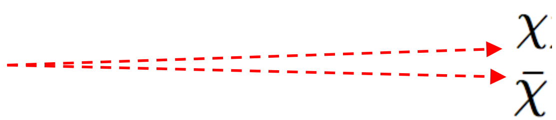
arXiv:2002.02967, DUNE TDR V - I

MINERvA Detector



arXiv:1109.2855
MINERvA collaboration

Specialized “Scattering” Detectors



- NuMI beam
- BNB
- LBNF (future)

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

Facilities

- **Fermilab NuMI** beam: $\sim$ 10^20 POT/yr (120 GeV), now

  Neutrinos at the Main Injector (NuMI) , for NIMOs +

- **Fermilab LBNF** beam (future): $\sim 10^{21}$ POT/yr (120 GeV),

  Long Baseline Neutrino Facility (LBNF), for DUNE

- **CERN HL-LHC**: 10^{16} POT/yr equivalent, $\sqrt{s}$ = 13, 14 TeV

Millicharged Particle: Model & Signature

Model: Millicharged Particles

- Test of **charge quantization**, and thus **grand unification theory, superstring theory, string compactifications** (Wen, Witten, Nucl. Phys. B 261 (1985) 651-677, Youtube: [link])

- No need for dark photon, but can be a consequence of massless dark photon theory

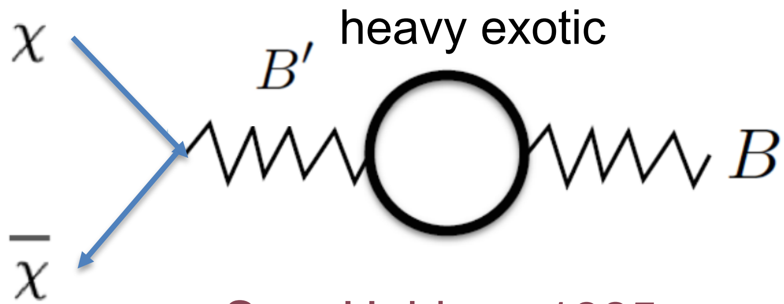
- Our search is simply a search for particles (**fermion χ**) with **{mass, electric charge}** = $\{m_\chi, \epsilon e\}$

- A particle fractionally (or irrationally) charged under SM U(1) hypercharge $\mathcal{L}_{\mathrm{MCP}} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\mathrm{MCP}})\chi$

- **EDGES result** is another hint on **DM Properties**

Kinetic Mixing and MCP Phase (skip)

- **Coupled to new dark fermion χ**



(SM: Standard Model)

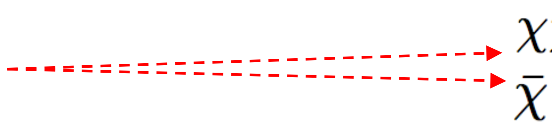
See, Holdom, 1985

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

- New fermion χ charged under new gauge boson B'.

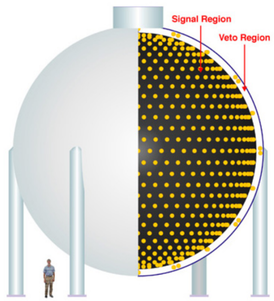
- Millicharged particle (MCP) can be a **low-energy consequence** of **massless dark photon** (a new U(1) gauge boson) coupled to **a new fermion (become MCP** in a convenient basis.)

Scattering Detectors



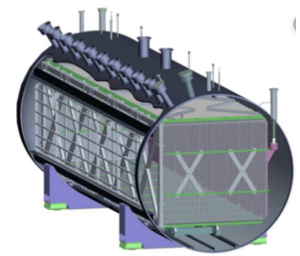
- NuMI Beam
- BNB
- LBNF (future)

MiniBooNE Detector



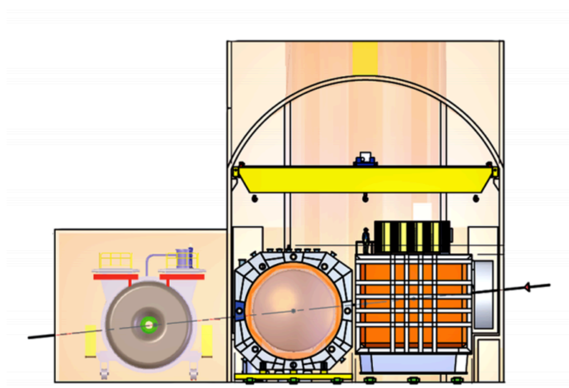
arXiv:0806.4201
MiniBooNE collaboration

MicroBooNE Detector



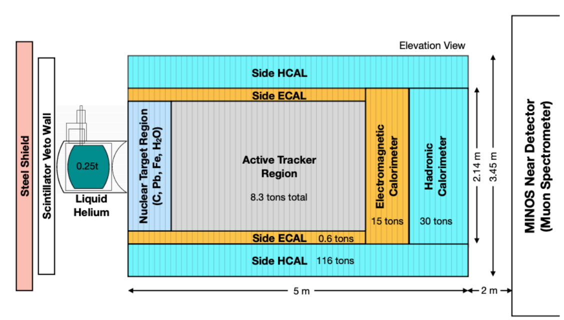
arXiv:1612.05824
MicroBooNE collaboration

DUNE Near Detector



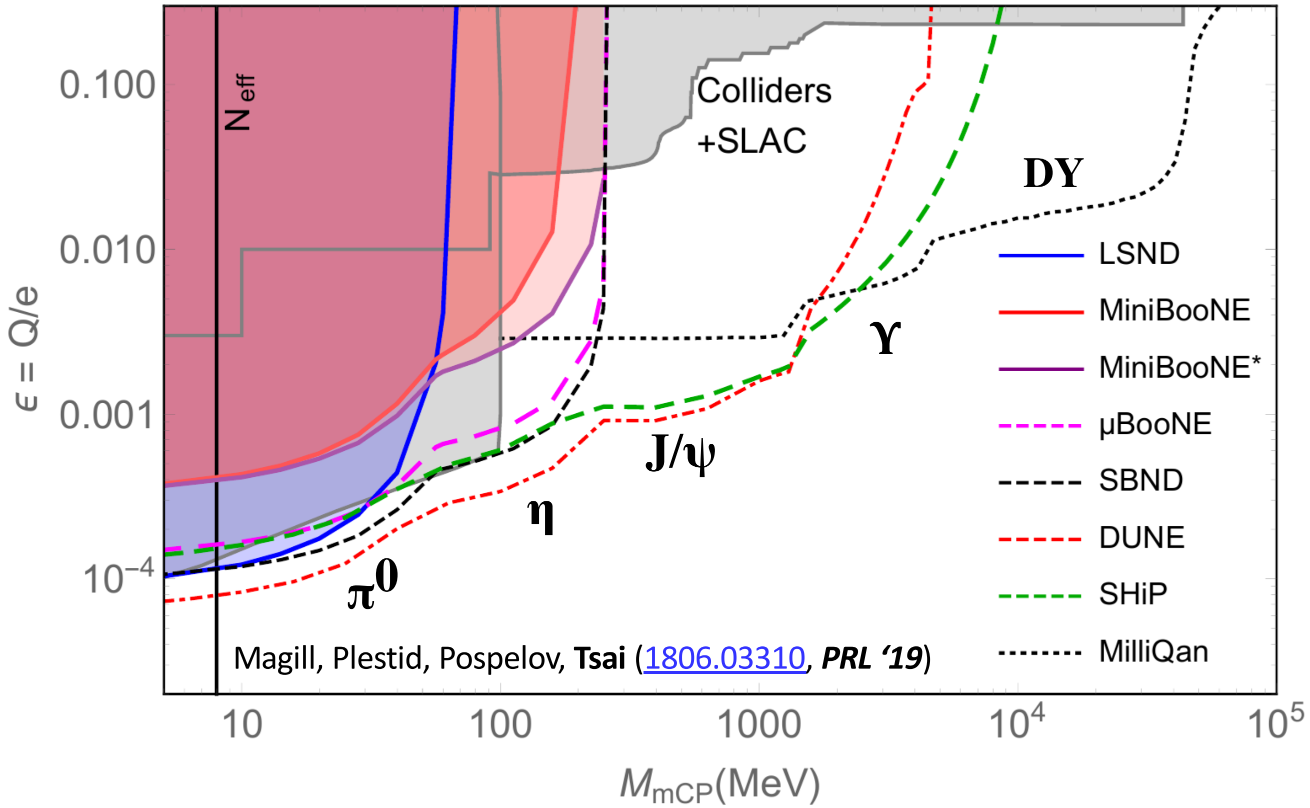
arXiv:2002.02967, DUNE TDR V - I

MINERvA Detector



arXiv:1109.2855
MINERvA collaboration

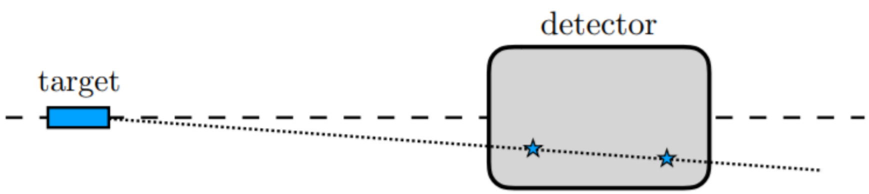
Sensitivity at Neutrino Detectors

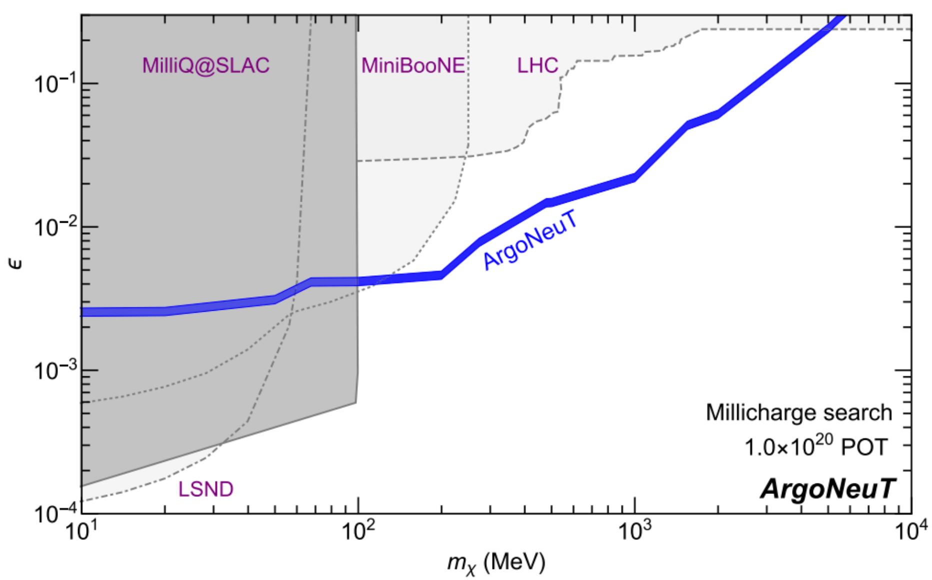


- **Electron recoil-energy threshold: MeV to 100 MeV**
- Can use **timing information** to improve sensitivity
- Double-hit to reduce background (**see next page**)
- Will include more updates later!

x-axis: m_x (MCP mass),
y-axis: $\epsilon = Q_x/e$ (charge ratio).

Double-Hit Consideration: ArgoNeuT Study & Constraint





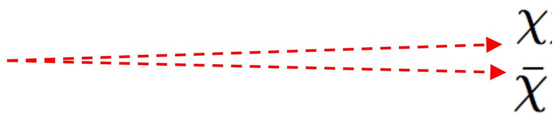
x-axis: m_x (MCP mass),
y-axis: $\epsilon = Q_x/e$ (charge ratio).

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

ArgoNeuT collab: arXiv:1911.07996

New related study:
Marocco & Sarkar, arXiv:2011.08153

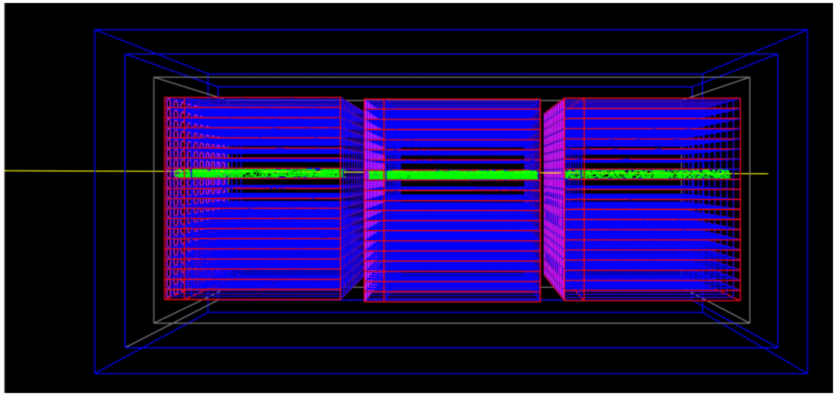
Specialized "Scattering" Detectors



- **NuMI beam**
- **BNB**
- **LBNF (future)**

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

Millicharged Detector



MilliQan, arXiv:1410.6816 (Haas, Hill, Izaguirre, Yavin)
See also arXiv:1607.04669; arXiv:1810.06733; arXiv:2005.06518

FerMINI @ NuMI-MINOS Hall

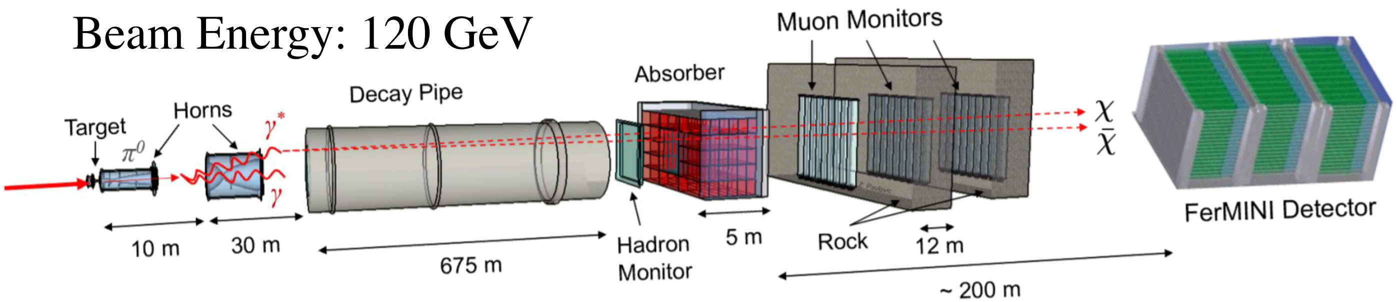
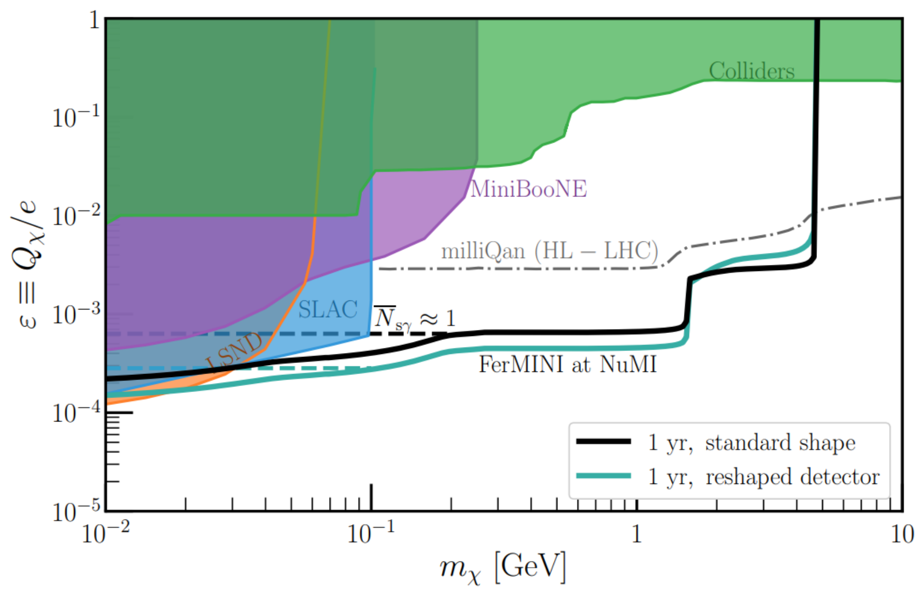


FIG. 3. An illustration of the FerMINI experiments utilizing the NuMI facility.



MINOS hall downstream of NuMI beam

Yu-Dai Tsai
Fermilab

Going Forward:

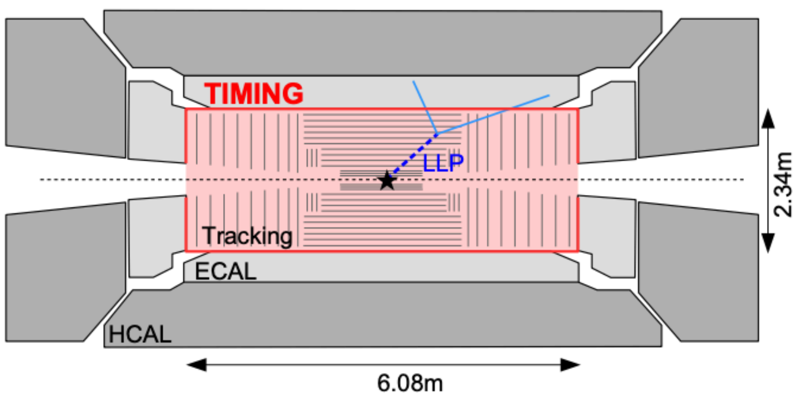
LHC Forward Physics Region!

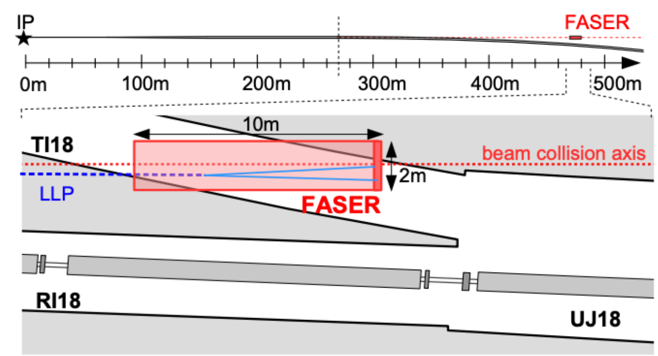
Best of both worlds

Not fixed target, but has fixed-target intensity

Looking **Forward** at LHC!

500 meters

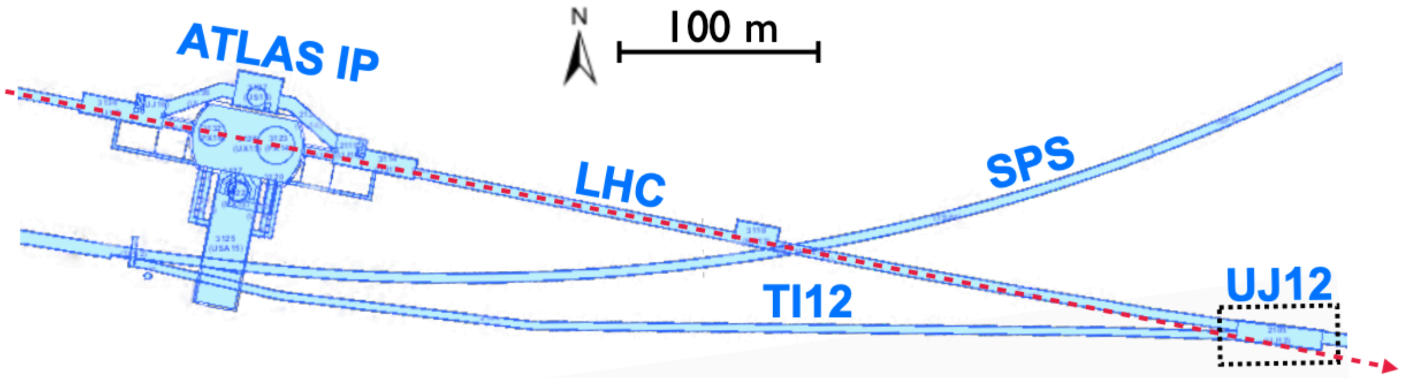




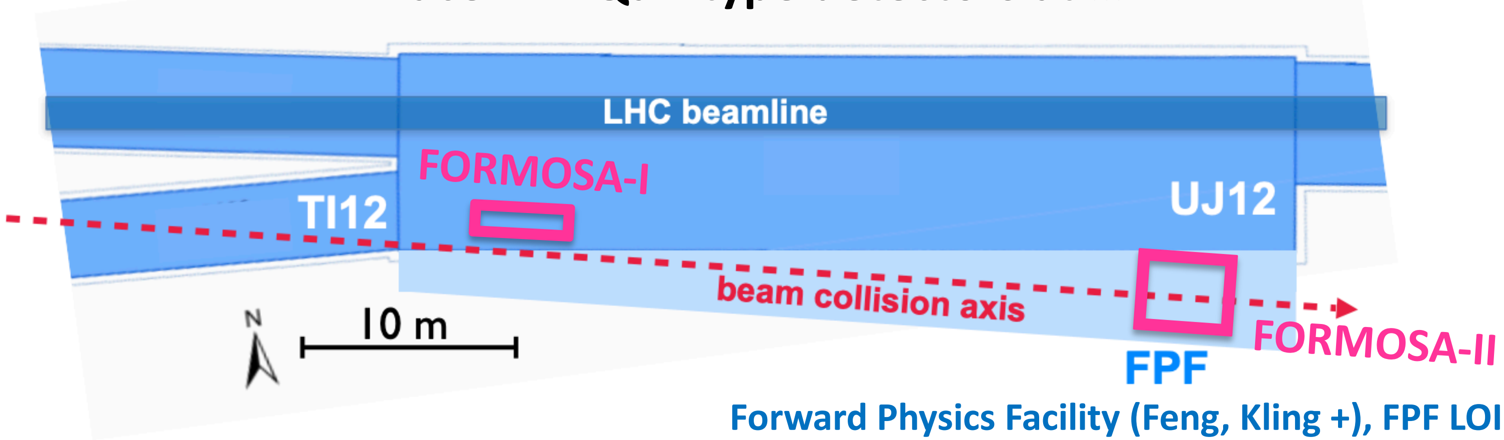
Berlin, Kling, 1810.01879

FORMOSA: FORward MicrOcharge SeArch

Foroughi, Kling, **Tsai**, arXiv:2010.07941



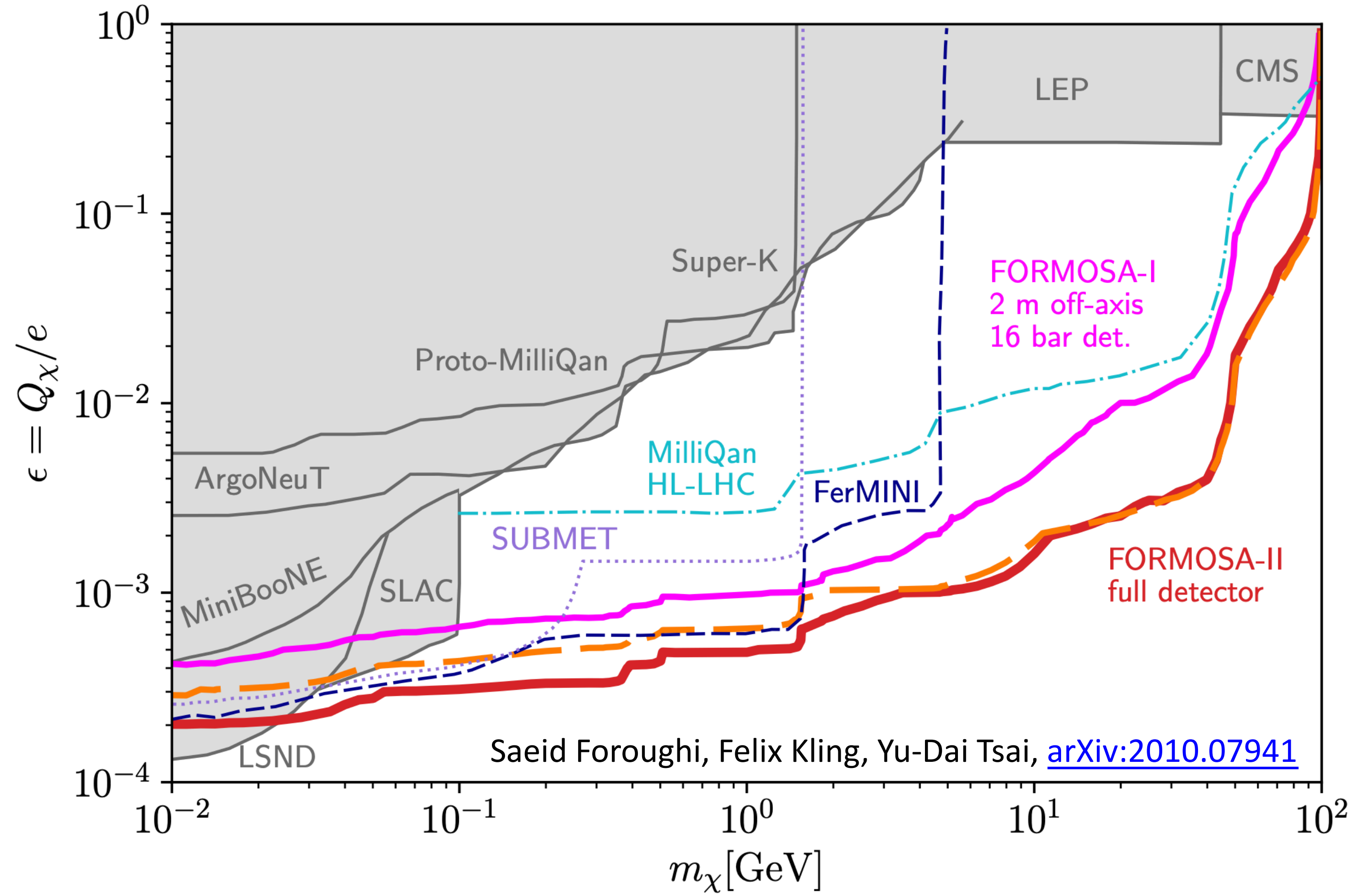
Place milliQan-type detectors at …



Forward Physics Facility (Feng, Kling +), FPF LOI: link

Formosa means "beautiful" in Portuguese and is the ancient name of Taiwan

FORMOSA Sensitivity



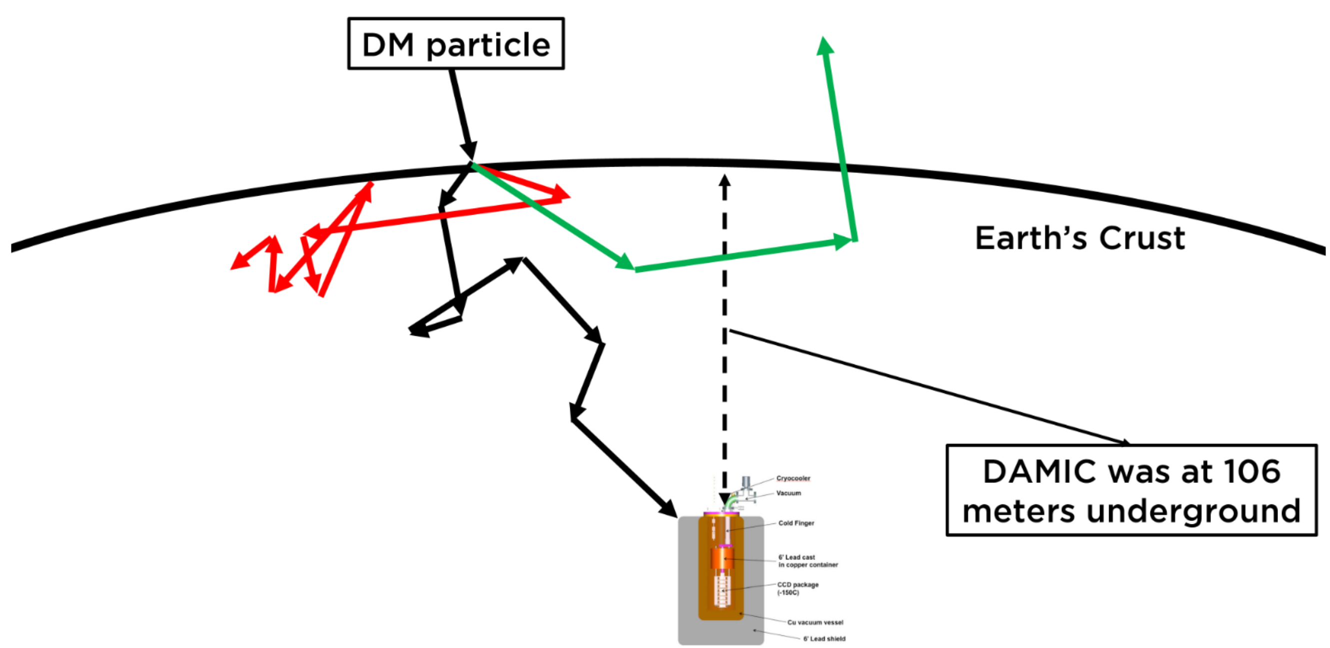
FORMOSA-I: ~ 0.2 m × 0.2 m × 4 m consisting of 4 layers of 16 scintillator bars @UJ12/TI12 tunnel.

FORMOSA-II: ~ 1 m × 1 m × 4 m consisting of 4 layers of 400 scintillator bars @ FPF.

Adding new related study: Marocco & Sarkar, arXiv:2011.08153

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

Reference Cross-Section

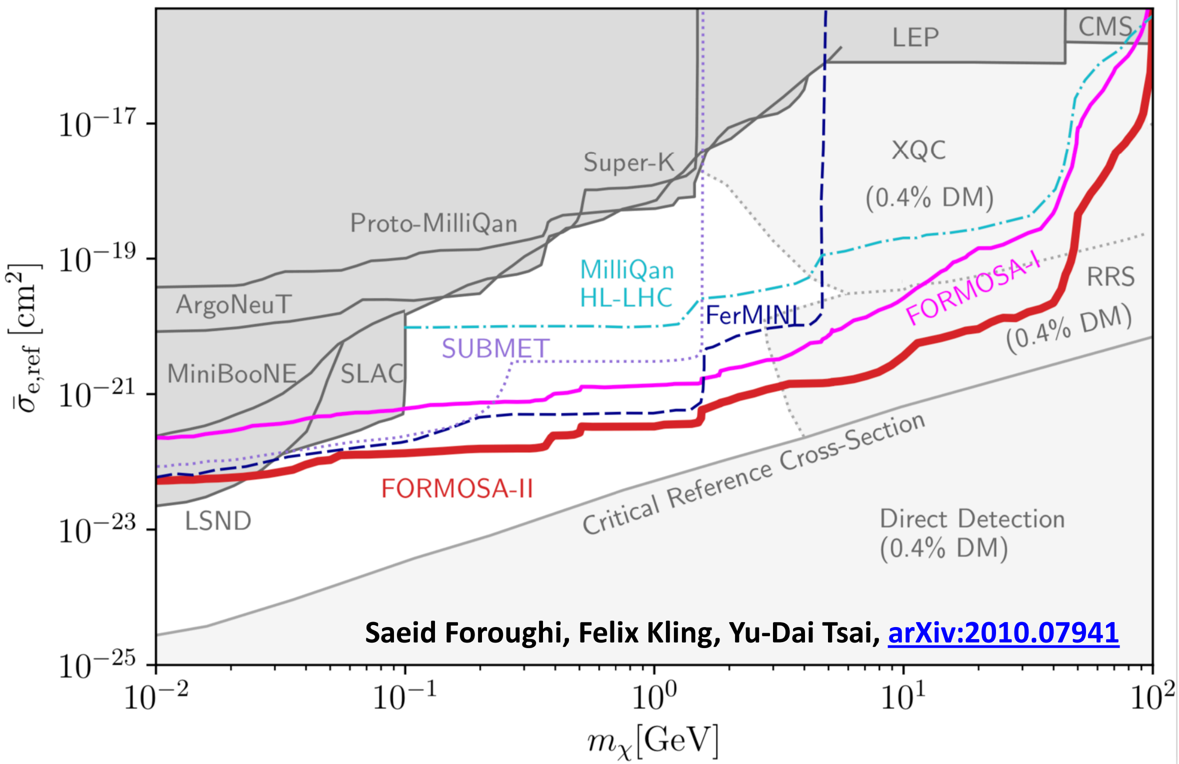
$$\bar{\sigma}_{\mathrm{e,ref}} = \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{\mathrm{d,ref}}^4}\,, q_{\mathrm{d,ref}} = \alpha m_e$$

- Reference Cross-section for MCP-Electron Scattering (Direct Detection)
- $\mu_{\chi e}$ is the reduced mass of the electron and χ , α is the fine structure constant.
- q_{ref} is a reference momentum transfer (for normalization)
- We choose the typical momentum transfer in DM-electron collisions for noble-liquid and semiconductor targets.
- **This just is a normalization**! Can choose the other one for comparison
- Comparing to e.g. **SENSEI, CDMS-HVeV, XENON10, XENON100, and DarkSide-50**

Probe of Millicharged Dark Matter

MCP / LDM with ultralight dark photon mediators

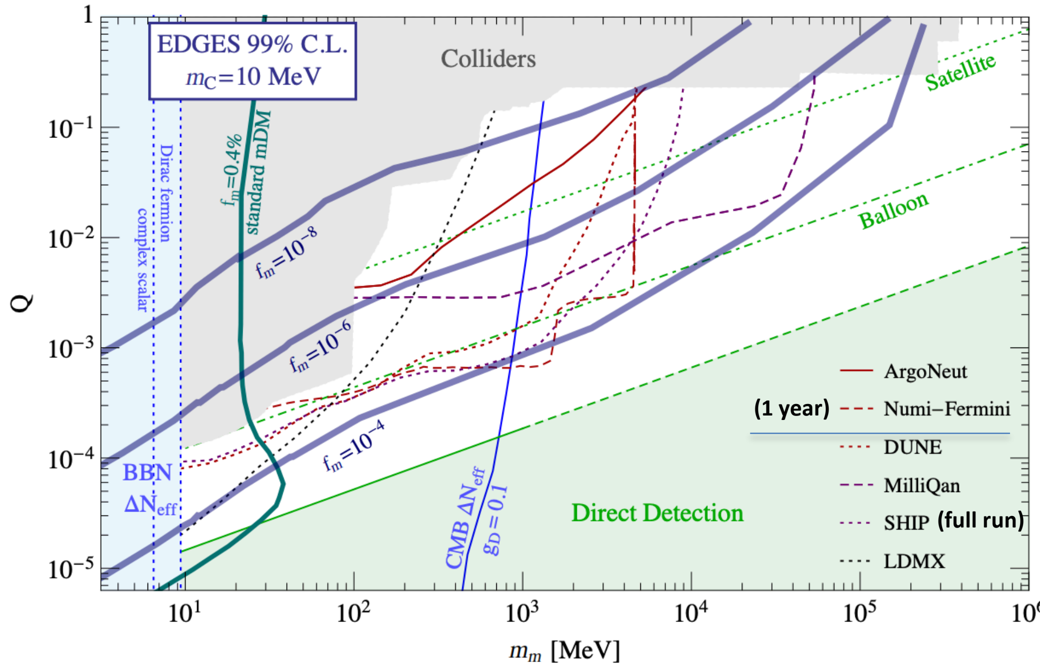
$$\bar{\sigma}_e \simeq \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{ref}^2}, \; q_{ref} = \alpha m_e$$

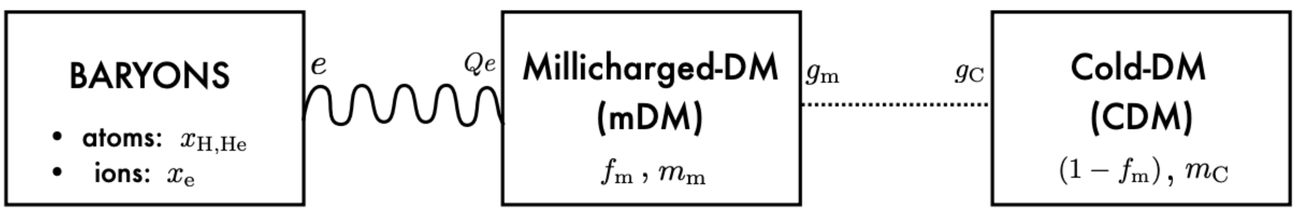


- We will add this figure with all the projections to the appendix of the LOI

- 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

Reviving MDM for EDGES





Liu, Outmezguine, Redigolo, Volansky, ’19

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

FORMOSA: Neutrino & EDM

FORMOSA can study

- Heavy Neutrino Electric Dipole Moment (ongoing)

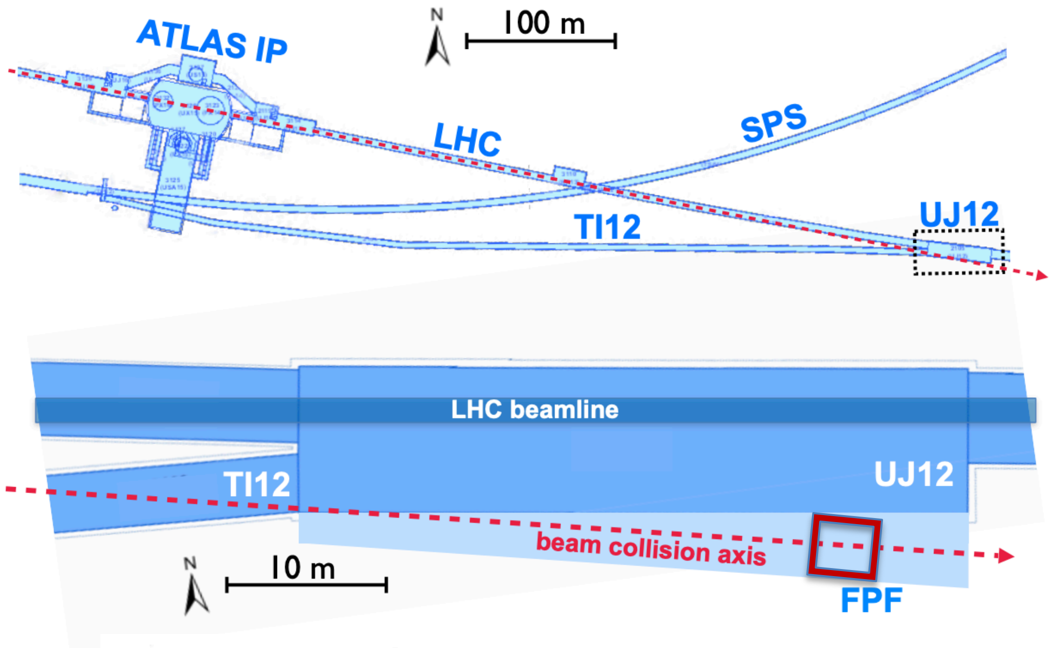
  (Sher, Stevens, 1710.06894, MoEDAL-MAPP, 1909.05216 , Chu +, 2001.06042)

- **Tau Neutrino Electric Dipole Moment** (exciting!)

  Strong advantage at the FORMOSA site!)

- Other Neutrino Physics Topics (maybe?)
- Saeid Foroughi, Felix Kling, Yu-Dai Tsai, ongoing

Forward Proto-DUNE & Neutrino Campus!



New idea!
Kling, **Tsai** (+ Feng, Foroughi, Cavanna)

Single-Phase (SP) liquid argon time projection chamber (LArTPC)
7.2×6.0×6.9 m^3

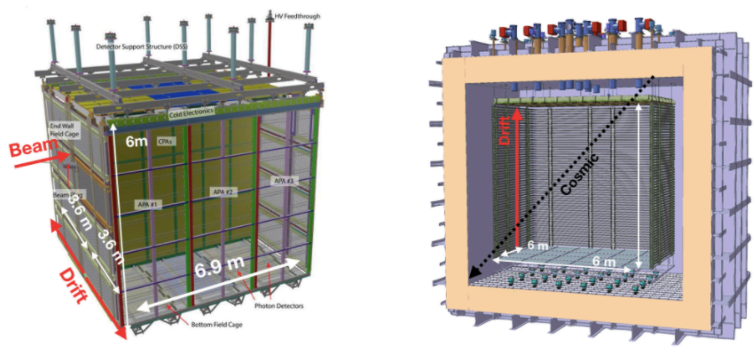
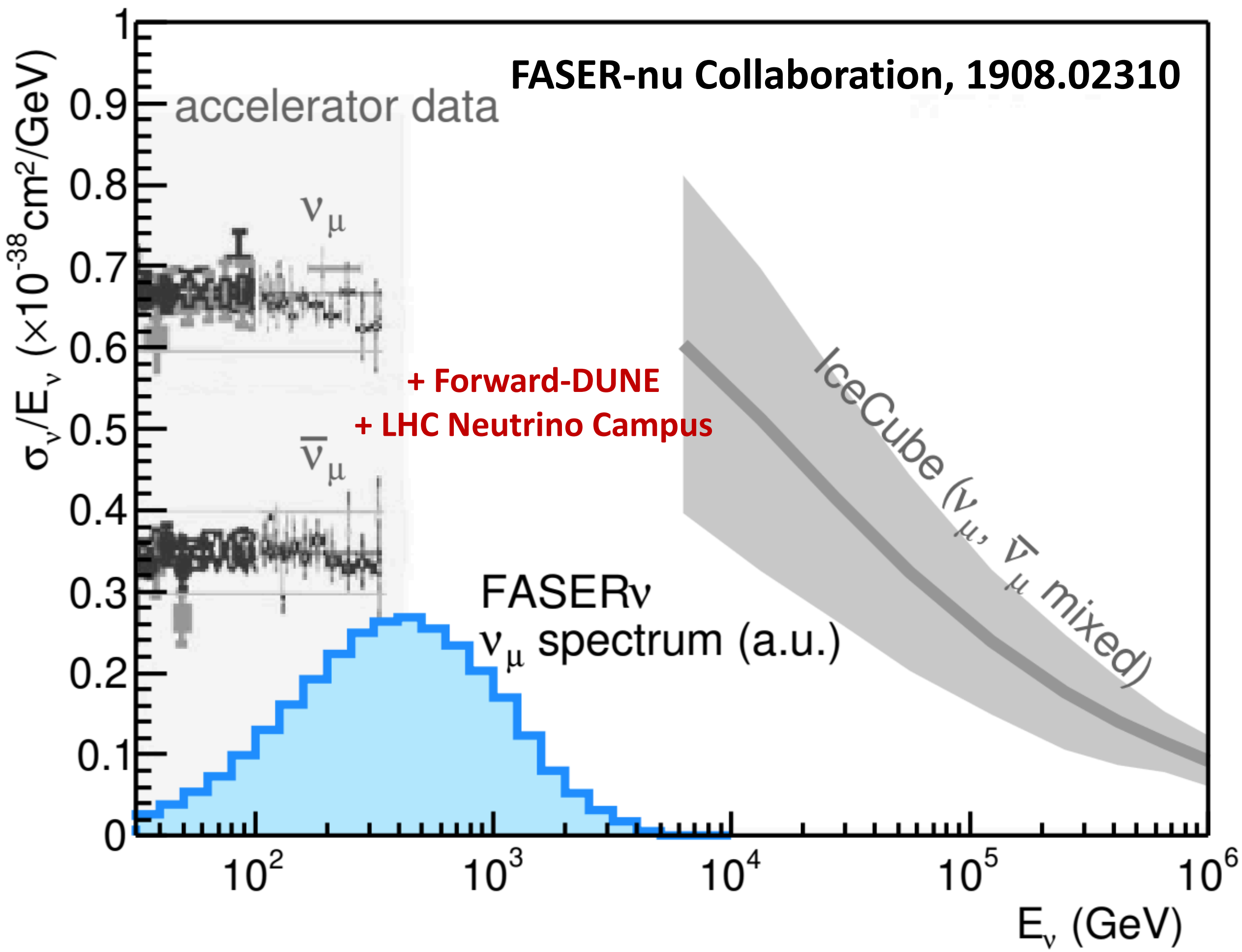


Figure 3: Left: draft of ProtoDUNE-SP [2]. Right: draft of ProtoDUNE-DP [3]

Duel-Phase (DP) Detector
6 x 6 x 6 m^3 LAr TPC

DUNE Collaboration (arXiv:1706.07081 + arXiv:1409.4405)
Updates, see, e.g. arXiv:1910.10115 & arXiv:2007.06722

Forward Proto-DUNE & New Neutrino Campus!



New Idea: FORWARD-DUNE & New Neutrino Campus

Kling, **Tsai** (+ Feng, Cavanna)

Summary

- **Proton Fixed-Target** Experiments
- **LHC Forward** Experiments

can study

- **Millicharged Particles**
- **Other Dark Matter Models**
- **Neutrinos & New Neutrino Physics**

Decay Experiments

LongQuest Experiment

Decay Experiments/Detectors

Including **CHARM decay detector (DD), NuCAL, NA62, SeaQuest, DUNE Near Detector (ND)** (see, e.g. arXiv:1908.07525),

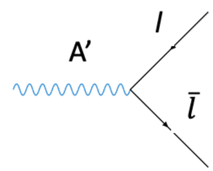
- Experiments optimized to study **decaying particles**, or simply two charged particle final states, e.g. from Drell-Yan (SeaQuest)

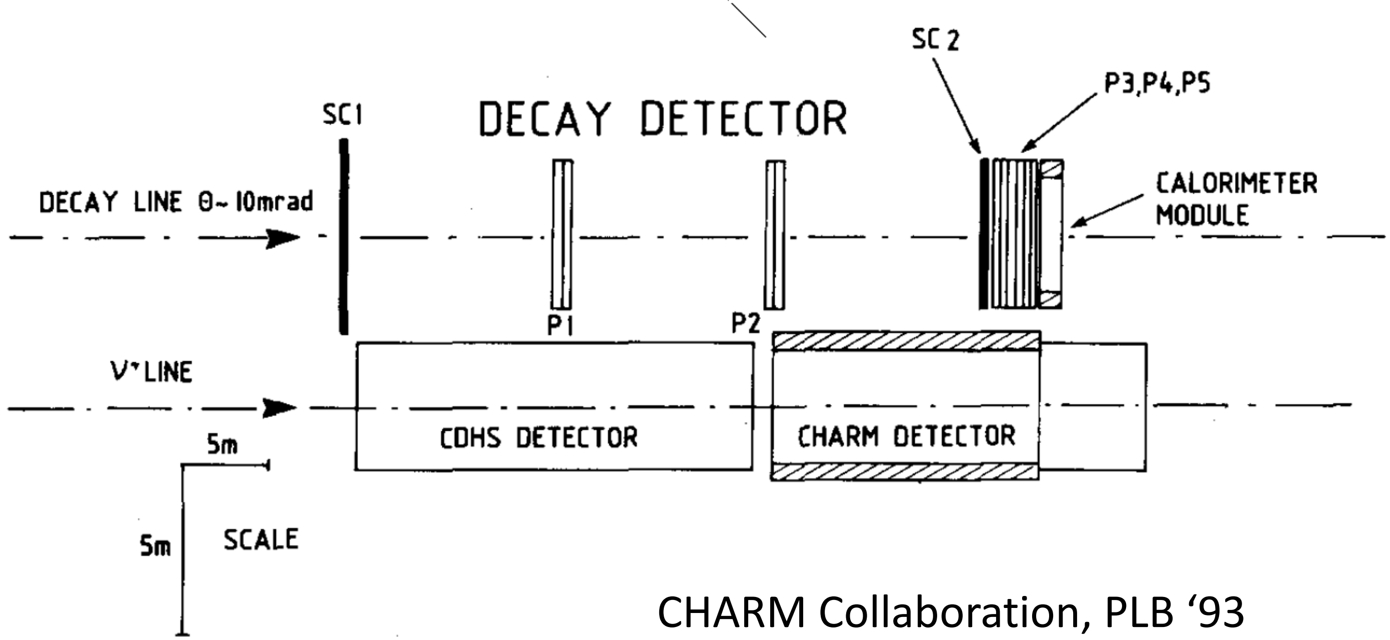
General features:

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 (mediators, e.g., dark photons)**

Decay Experiments/Detectors

CHARM Decay Detector



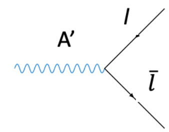


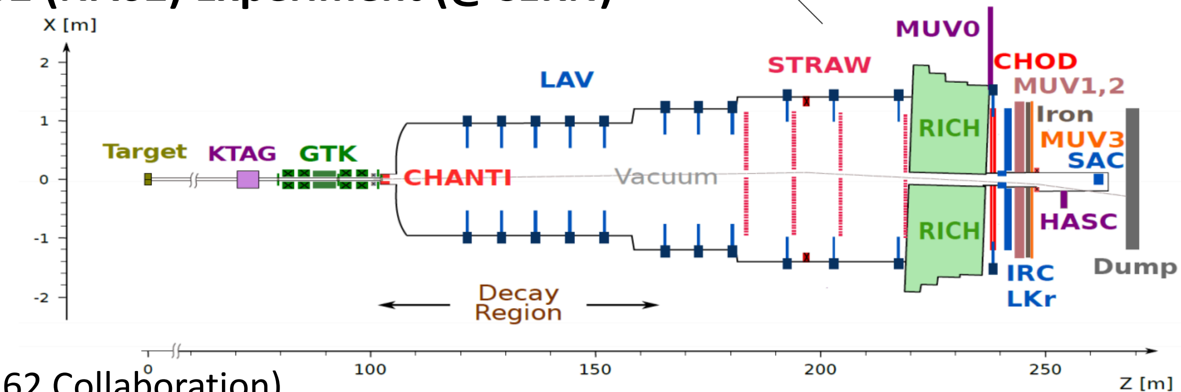
CHARM Collaboration, PLB '93

CHARM: CERN HAmburg Rome Moscow

Decay Experiments/Detectors

North Area 62 (NA62) Experiment (@CERN)

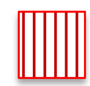


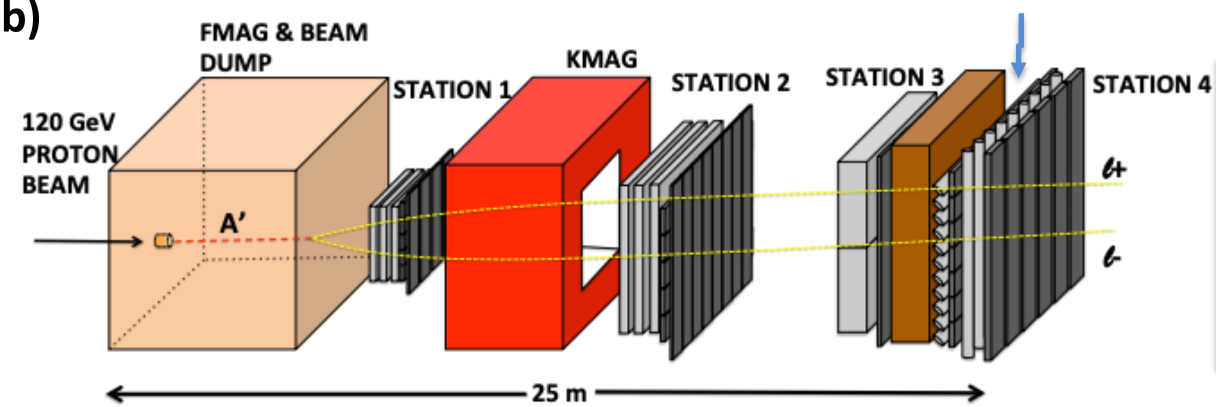


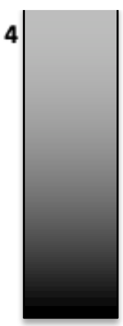
1703.08501 (NA62 Collaboration)

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

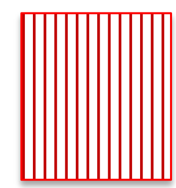
Install ECAL from PHENIX







10m block

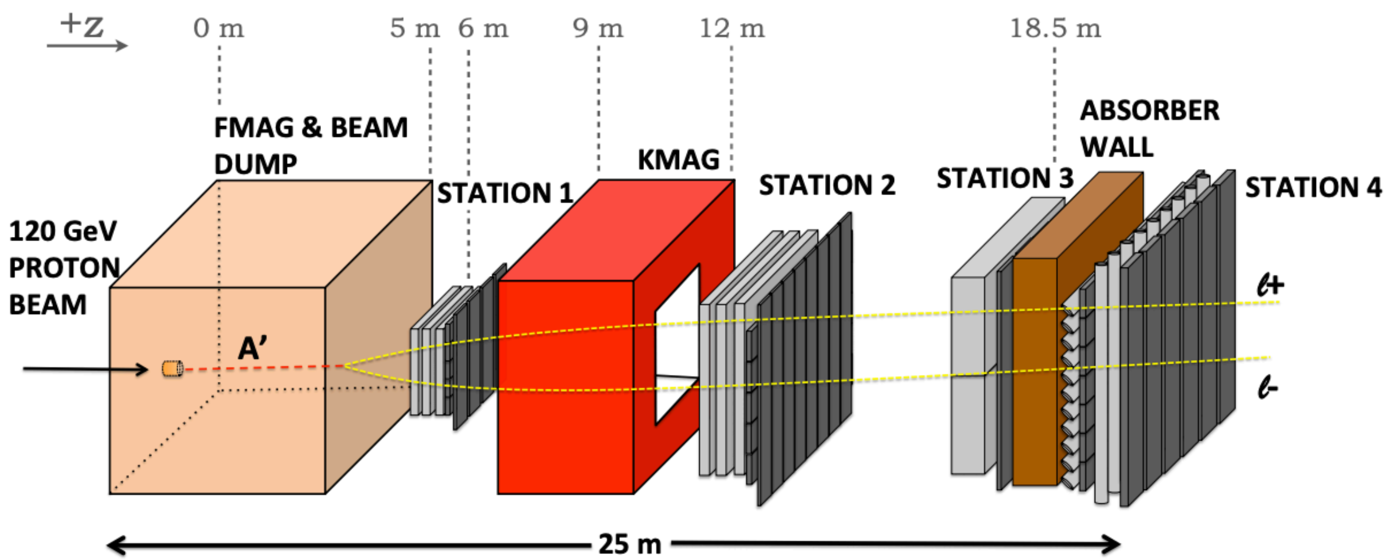


Another ECAL from PHENIX

Add a Ring Image Cherenkov Detector

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

DarkQuest



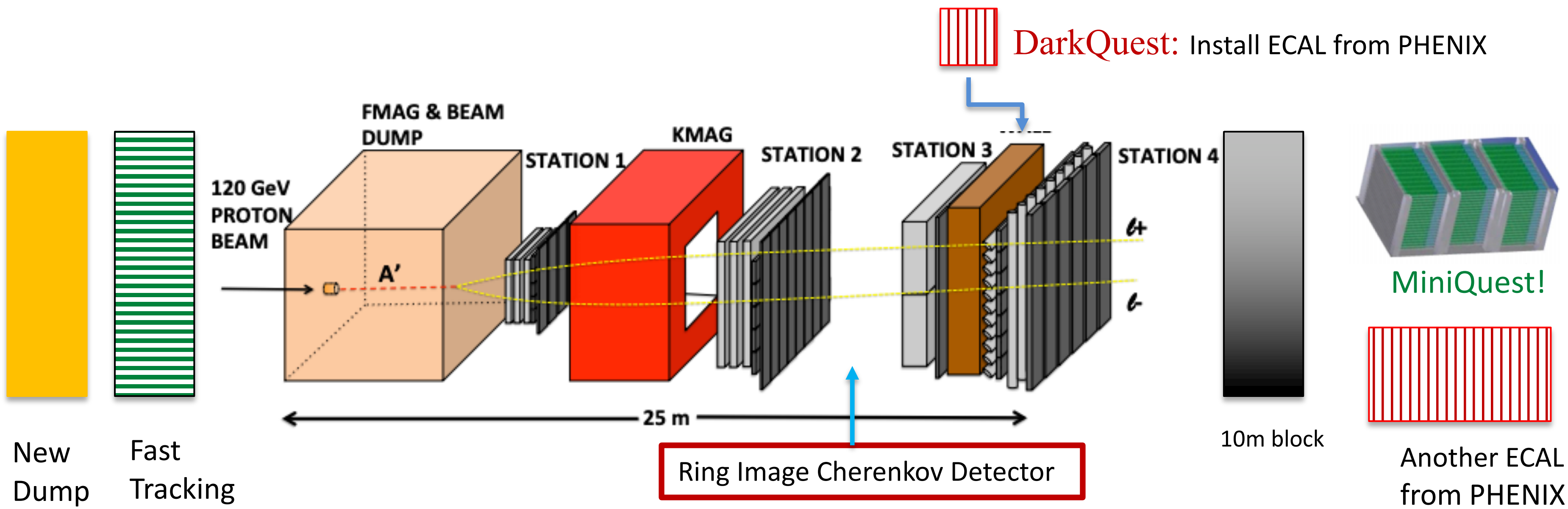
arXiv:1509.00050 (Gardner, Holt, Tadepalli); arXiv:1804.00661 (Berlin, Gori, Schuster, Toro)

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: 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

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

LongQuest II

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

Yu-Dai Tsai, Fermilab, 2020

LongQuest (I-III)

- A search for long-lived particles **with extended decay length**, **improved decay detectors**, and **additional long based-line detectors** using SeaQuest (SpinQuest) facility.
- Working on a pheno paper with Ming Liu, Kun Liu, and Patrick de Niverville.

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

TABLE I. This table provides a comparison of experiments considered in this paper. *Indicates not yet decided; $L_{\text{dist.}}$ is the distance from the target to the decay region; $L_{\text{dec.}}$ is the fiducial particle decay length. The detector areas $A_{\text{dec.}}$ are more complicated and not listed in the table. Our information regarding the NA62 experimental configuration was updated directly through contact with the NA62 collaboration

Yu-Dai Tsai, Fermilab, 2020

arXiv/1908.07525

Interesting Long-Lived Particles for Decay Studies

Yu-Dai Tsai, Fermilab, 2020

Renormalizable "Portals"

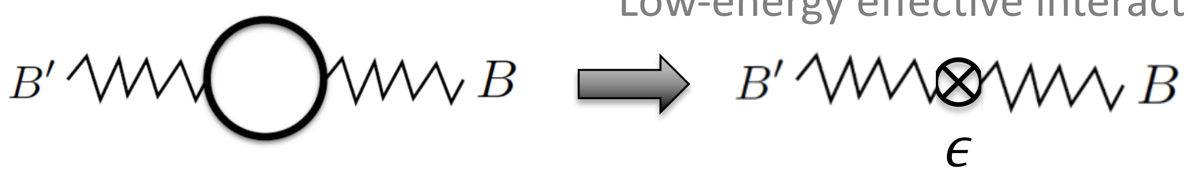
- Dark sectors can include mediator particles coupled to the SM via the following **renormalizable interactions.**
- **High-Dim. axion portal is also popular**

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

(Holdom, '85)

(See Dark-Sector 2016 report 1608.08632)

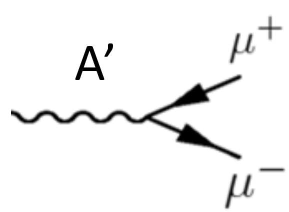
Low-energy effective interaction



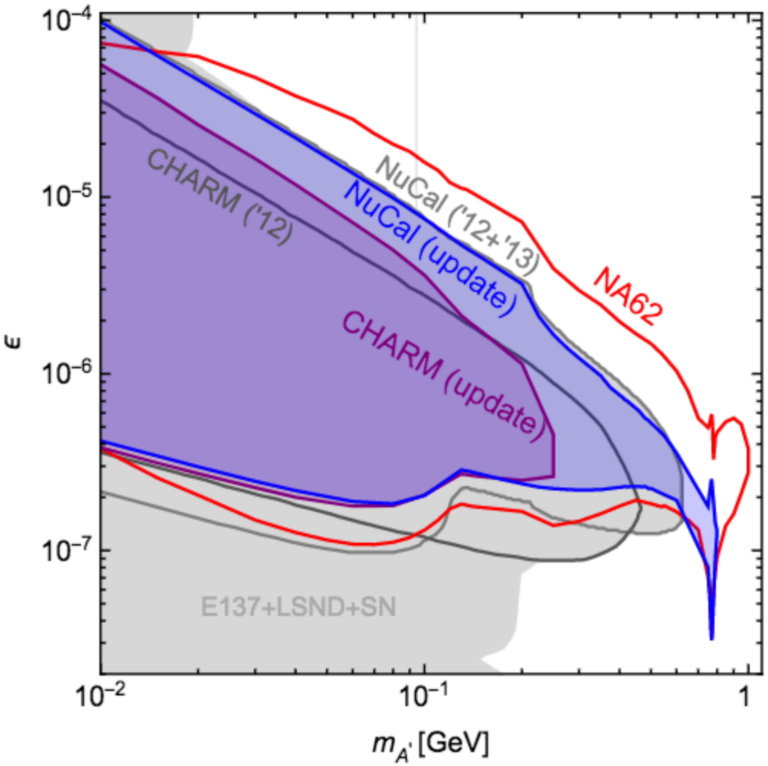
Mass from Dark Higgs or Stueckelberg

mass basis

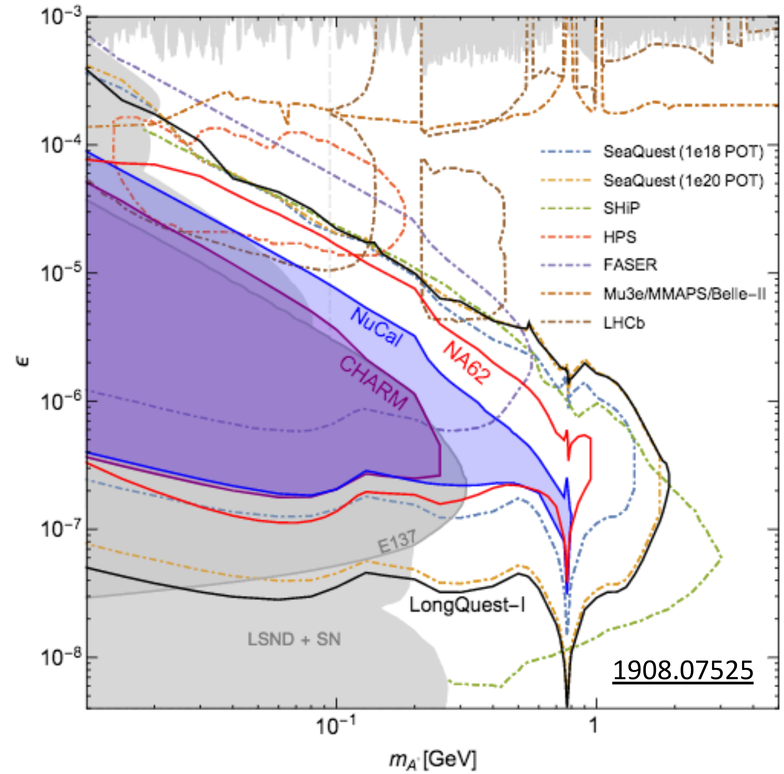
Dark photon A':



Legion of Probes on Dark Photon



(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

Beyond Simple Dark-Sector Models

- Cosmology motivated models:

  Inelastic Dark Matter, etc

- Strongly Self-Interaction DM

  (motivated by dark QCD)

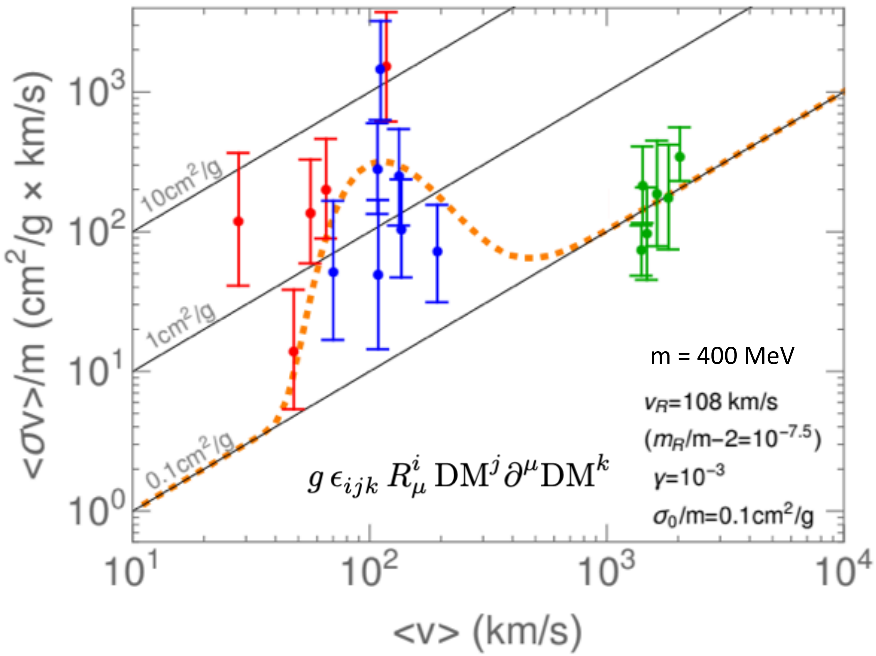
  Motivated by small-scale problems

Resonant Dark Mesons

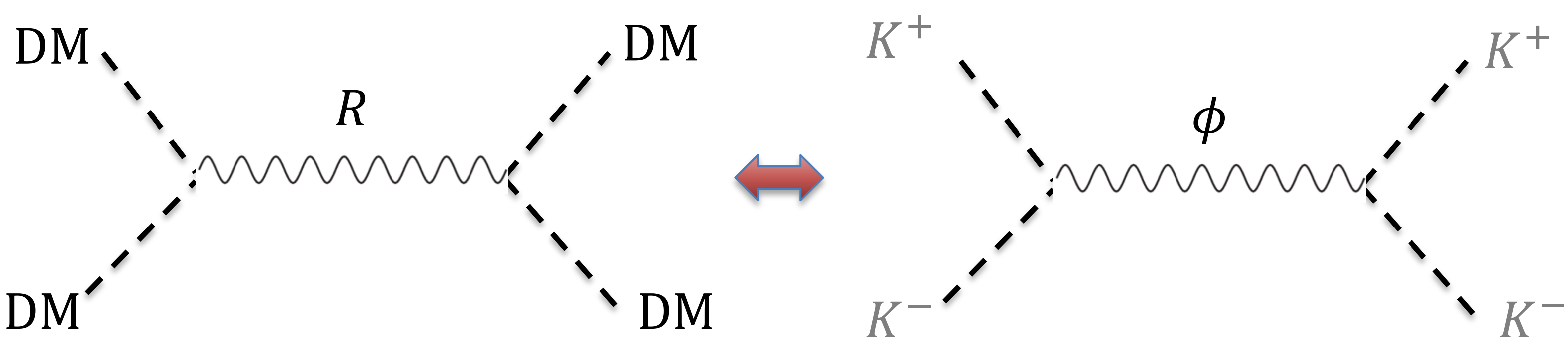
Yu-Dai Tsai, Fermilab, 2020

Resonant SIDM: Vector Resonance

Interaction Lagrangian	L	$J_{\rm DM}$	J_R^P	S	γ
$g\, R\, \overline{\rm DM}\gamma^5{\rm DM}$	0	$\frac{1}{2}$	0^-	$\frac{1}{4}$	$\frac{g^2}{32\pi}$
$g R\, {\rm DM}^i {\rm DM}^i$	0	0	0^+	$\frac{1}{3}$	$\frac{g^2}{16\pi\, m_R^2}$
$g\, \epsilon_{ijk}\, R^i_\mu\, {\rm DM}^j \partial^\mu {\rm DM}^k$	1	0	1^-	1	$\frac{g^2}{384\pi}$
$\frac{1}{\Lambda} R_{\mu\nu}\, \mathcal{T}^{\mu\nu}_{\rm DM}$	2	0	2^+	5	$\frac{m_R^2}{30720\pi\Lambda^2}$



$$m_R = 2\, m_{\rm DM}(1+\Delta),$$



QCD & Meson Spectrum

Lessons from QCD. $K^+K^- \to \phi$, $B^0\overline{B}^0 \to \Upsilon(4S)$.

- $m_{K^\pm(u\bar{s}/\bar{u}s)} \approx 493$ MeV; $m_{\phi(s\bar{s})} \approx 1019$ MeV.
- $m_{B^0} \approx 5279$ MeV; $m_{\Upsilon(4S)} \approx 10580$ MeV.
- Inspired by these, we will build a 2-flavor light quarks with hidden-QCD and an asymmetric dark matter model later
- Can use the **ϕ-K-K system** to build a light dark matter model with proper freeze-out
- Link to **ELDER/SIMP** models with **existing lattice results**
- See Tsai, McGehee, and Murayama, arXiv:2008.08608 for details

SM resonances

$$\frac{m(^8\mathrm{Be}) - 2m(\alpha)}{m(^8\mathrm{Be})} = 0.000012,$$

$$\frac{m(^{12}\mathrm{C}^*) - m(^8\mathrm{Be}) - m(\alpha)}{m(^{12}\mathrm{C}^*)} = 0.000026.$$

Triple-alpha process

$$\frac{m(\phi) - 2m(K^0)}{m(\phi)} = 0.024,$$

$$\frac{m(D^{0*}) - m(D^0) - m(\pi^0)}{m(D^{0*})} = 0.0035,$$

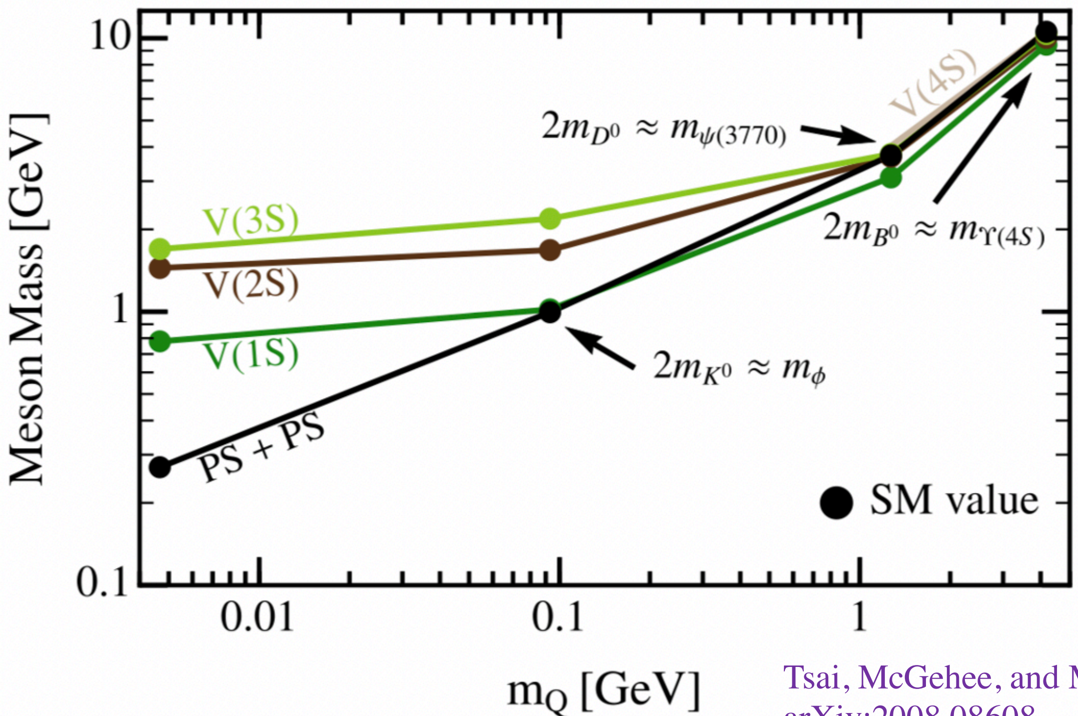
$$\frac{m(B_{s1}) - m(B^*) - m(K^0)}{m(B_{s1})} = 0.0011,$$

$$\frac{m(\Upsilon(4S)) - 2m(B^0)}{m(\Upsilon(4S))} = 0.0019.$$

Summarized in Tsai, McGehee, and Murayama, arXiv:2008.08608

- The beryllium-8 ground state has almost exactly the energy of two alpha particles., ^{8}Be + 4He has almost exactly the energy of an excited state of 12C. (7.66 MeV 0+ excited state of 12 C),
- The resonance greatly increases the probability that an incoming alpha particle will combine with beryllium-8 to form carbon.
- This resonance was predicted by Fred Hoyle before its actual observation, based on the physical necessity for it to exist, in order for carbon to be formed in stars.
- This energy resonance and process gave very significant support to Hoyle's hypothesis of stellar nucleosynthesis, which posited that all chemical elements had originally been formed from hydrogen, the true primordial substance.
- The anthropic principle has been cited to explain the fact that nuclear resonances are sensitively arranged to create large amounts of carbon and oxygen in the universe.
- Wiki/Triple-alpha_process
- J. D. Barrow and F. J. Tipler, The Anthropic Cosmological Principle. 1988.

Meson resonances

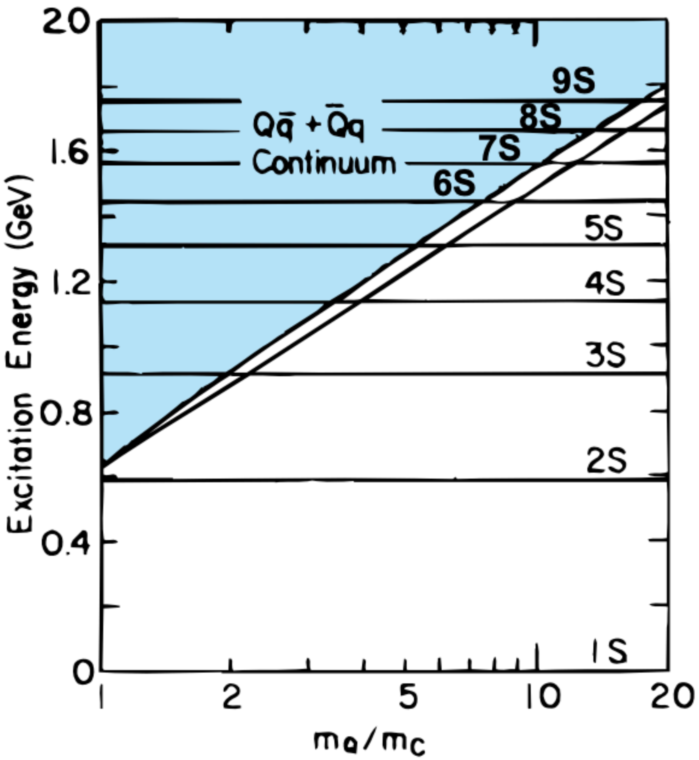


Tsai, McGehee, and Murayama, arXiv:2008.08608

For $m_Q = m_d$,

we show π^0 as well as the average masses of the first three ρ and ω states. For $m_Q = m_s$, we show K^0 and the first three ϕ's. For $m_Q = \{m_c, m_b\}$, we show D^0 and B^0 as well as the first four ψ and Υ states, respectively.

Heavy Quark Dark Meson Model



- C. Quigg and J. L. Rosner, "Quarkonium Level Spacings," Phys. Lett. B 71 (1977) 153–157.

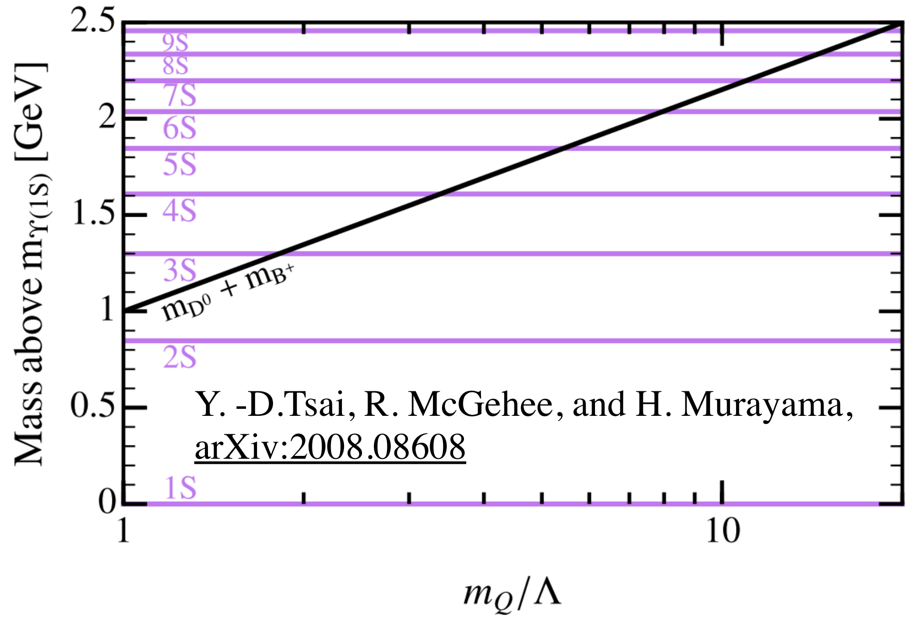


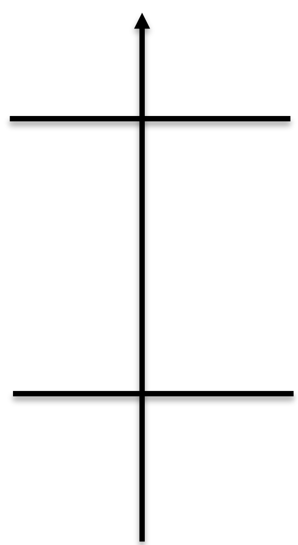
Figure 3: The crossings of the sum of heavy quark pseudoscalar meson masses and heavy quarkonium excited states for different heavy quark masses, m_Q.

Heavy Quark Meson ADM

- Dark matter are not the lightest meson (because of the heavy quark) in the theory, thus cannot be symmetric

- We consider one light quark u and two heavy quarks c' and b' and assume the c' and b' abundances are fixed by their asymmetry $n_c = n_{\bar{b}}$. we will drop the ' since everything is dark state from now on.

Dark meson mass



$$D^0(c\bar{u})B^+(u\bar{b}) \to \Upsilon(c\bar{b})(nS)$$

Heavy Quark Meson ADM

- We consider one light quark u and two heavy quarks c and b and assume the c and b abundances are fixed by their asymmetry $n_c = n_{\bar{b}}.$

$$D^0(c\bar{u})B^+(u\bar{b}) \to \Upsilon(c\bar{b})(nS)$$

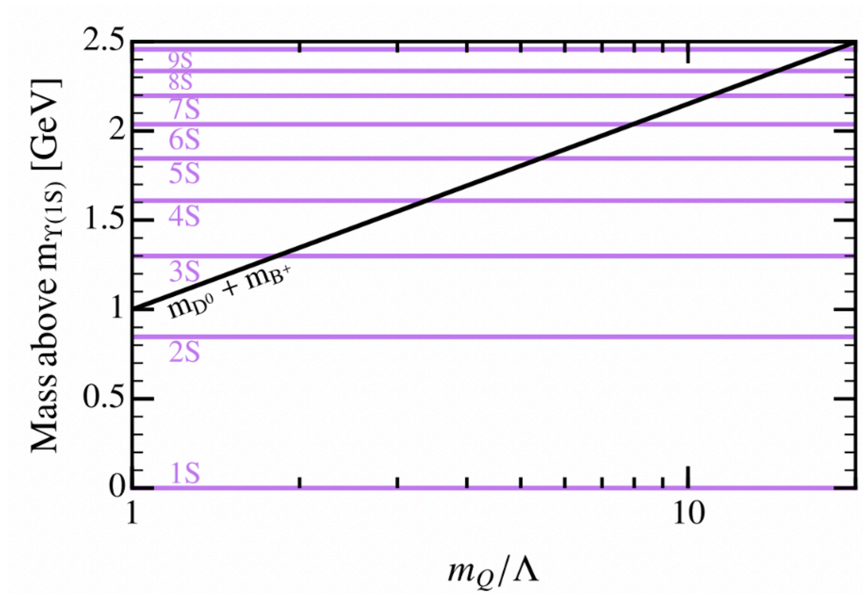
$$V(r) = C\ln(r/r_0)\,,$$

$$m_{\Upsilon(nS)} - m_{\Upsilon(1S)} \approx C\ln\left(\frac{4n}{3}\right)$$

in the large n limit. The mass splitting is

$$\Delta_n \equiv m_{\Upsilon(nS)} - m_{\Upsilon((n-1)S)} = C\left[\frac{1}{n} + \mathcal{O}\left(\frac{1}{n^2}\right)\right].$$

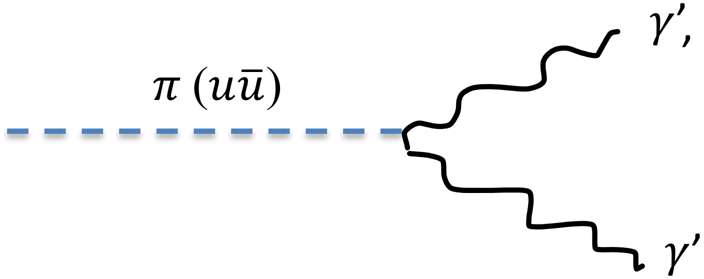
$$m_Q \approx n^2\left(\frac{4}{3e}\right)^2\Lambda.$$

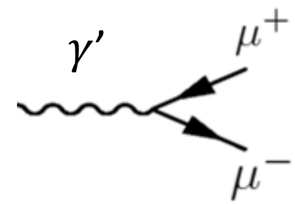


$$\Delta_n/m_Q \sim n^{-3}$$

Decays to Dark Photon

- Dropped the ′ now except for γ, but these are all dark states



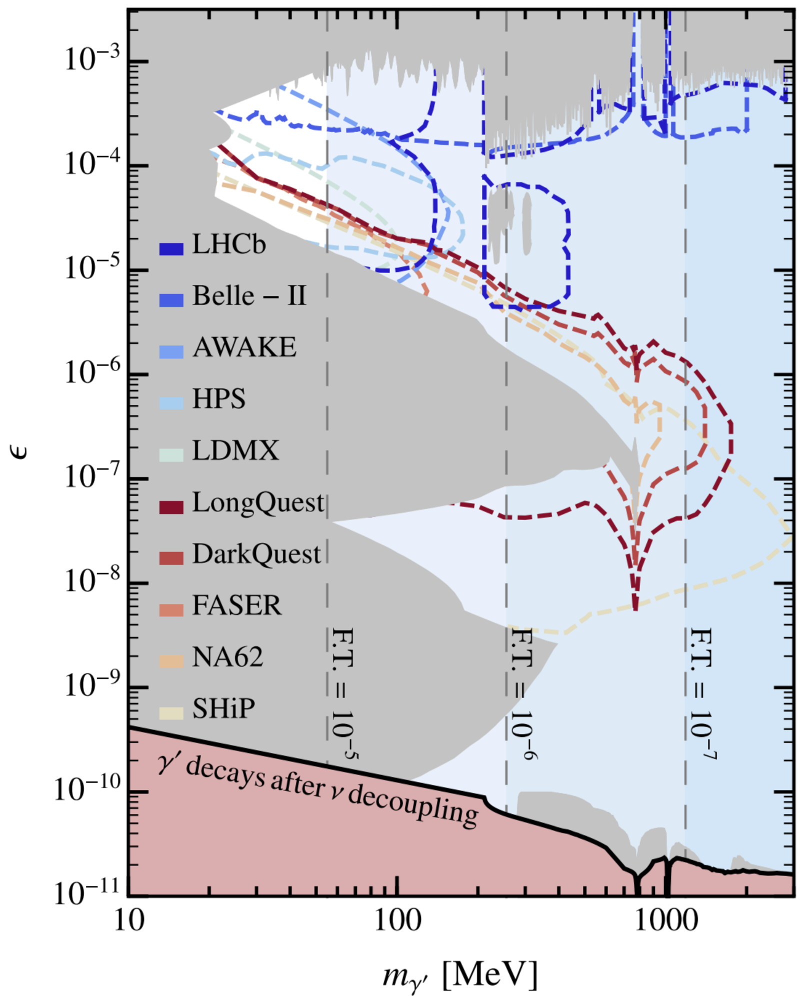


- $m_{ADM} = m_B \sim m_Q \sim 5\, m_P \sim 5$ GeV

- $\Lambda \sim m_\pi > 2\, m_{\gamma'}$
  (assuming the dark neutral pion $\pi\ (u\bar{u})$ decays to two dark photons γ')

- **The lower the mass of the dark photon is, the more likely one hits the resonance**, since the mass of the dark matter is fixed to around 5 GeV

Dark photon for neutral pion decay



π' $(u\bar{u})$ decays to two massive dark photons

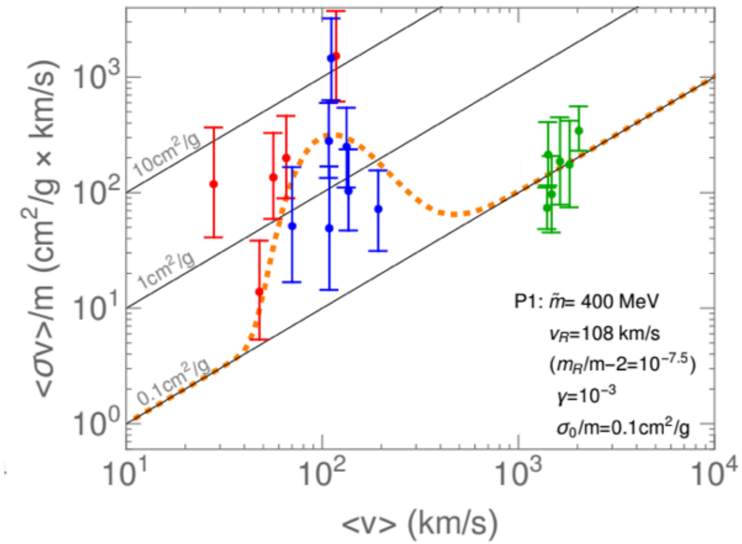
$m_{ADM} = m_B \sim m_Q \sim 5\, m_P$

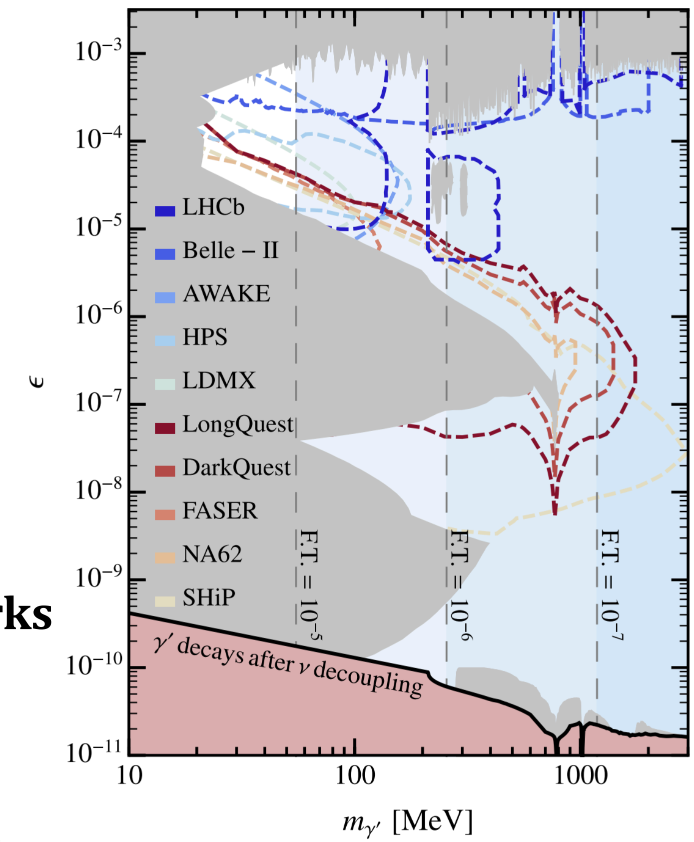
$m_Q \sim 5$ GeV

$m_Q/\Lambda \sim 10$ is desired

$\Lambda \sim m_{\pi'} > 2\, m_{\gamma'}$
(assuming the dark neutral pion π' $(u\bar{u})$ decays to two dark photons γ')

Asymmetric Dark Matter Parameter





Interesting Parameter that everything works

$m_{ADM} = m_B \sim m_Q \sim 5\, m_P$

$g_{BD\gamma(nS)} \sim 27$, (SM value, $g_{BB\gamma(4S)} \sim 25$)

$m_{\gamma'} \sim 100$ MeV, so $m_Q/\Lambda > 50$

Kinetic mixing $\epsilon = 10^{-9} - 10^{-3}$

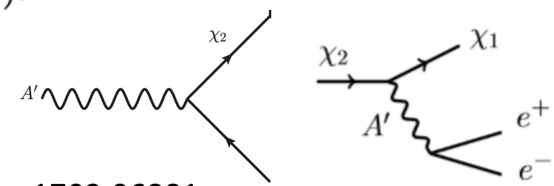
Inelastic Dark Matter

Yu-Dai Tsai, Fermilab, 2020

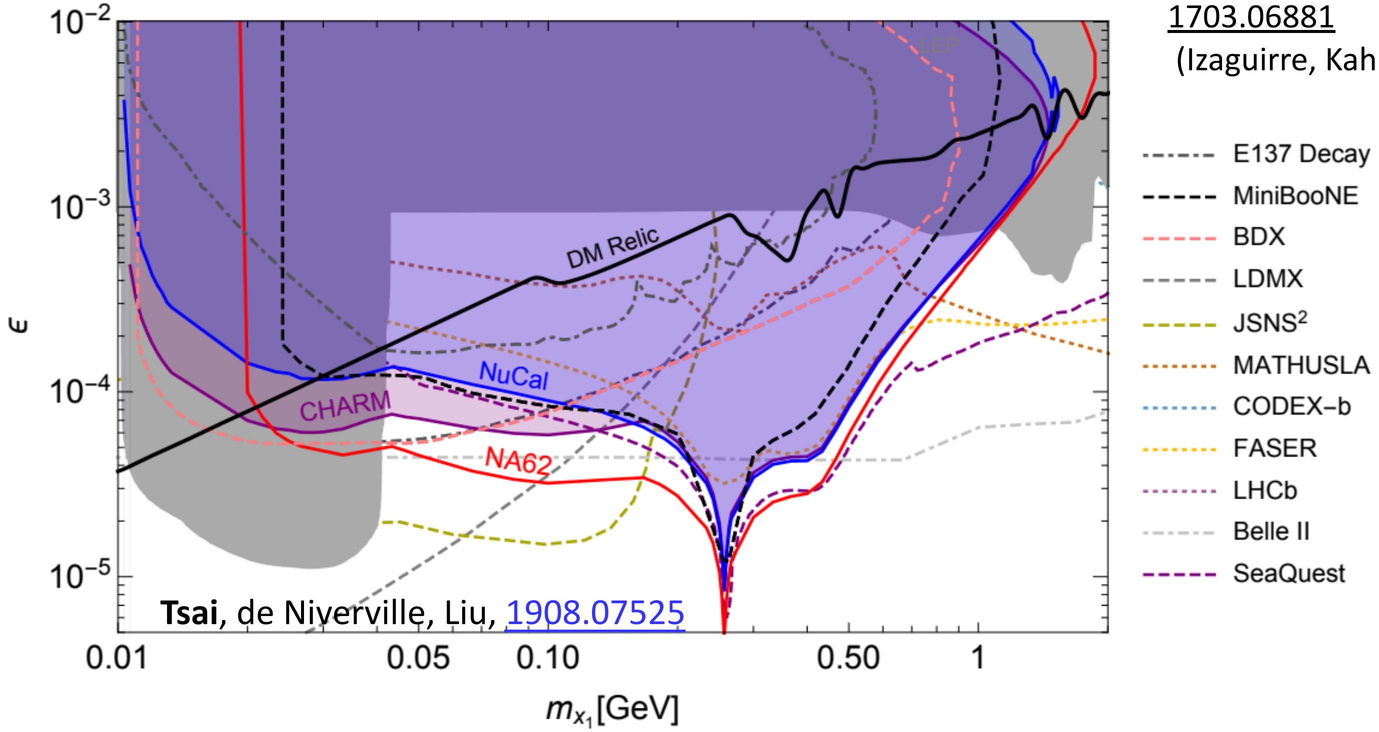
New Bounds on Inelastic Dark Matter

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

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



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

Looking Ahead

- Exploring **New Physics where High Energy meets High Intensity**
- **Cosmology-driven models: relaxions, baryogenesis models**
- **Naturalness-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, FORMOSA)** and new forces **(LongQuest)**
- **Dark sectors in neutrino observatories**
- **New exciting searches for dark matter**

- General Collider Beam-dumps
- ILC Beam-Dump / Forward Exp

Thank You!

Thank for the Invitation!

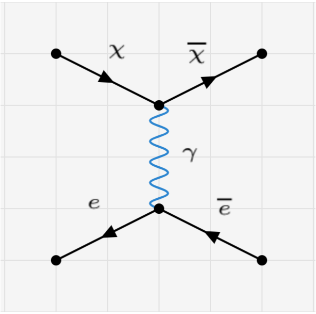
MCP Detection: Electron Scattering

- $\boldsymbol{Q^2}$ is the squared 4-momentum transfer.

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

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

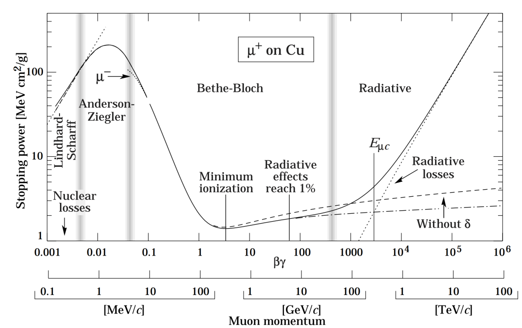
- Sensitivity greatly enhanced by accurately **measuring low energy electron recoils** for MCP's & light-mediator scattering



MCP Detection: Ionization

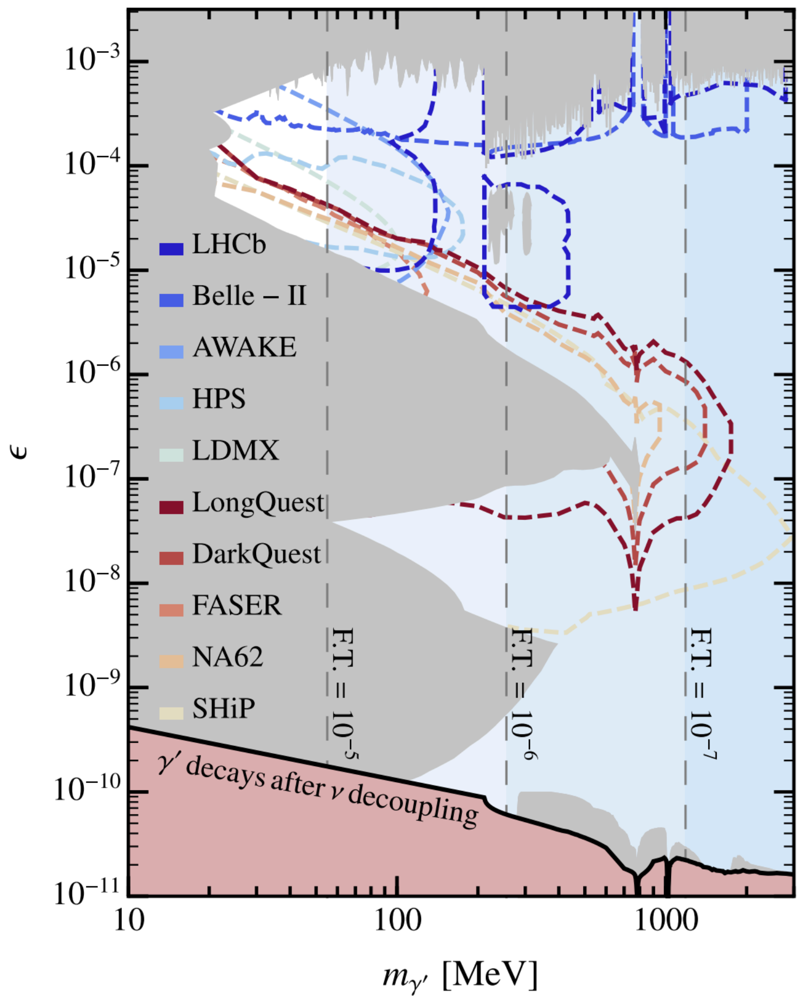
- Want very low momentum transfer**: ionization and scintillation signature**
- Signature proportional to **- dE/dx of the MCP, referred to as energy loss/stopping power**
- Can be approximated with the Bethe-Bloch Formula (various modified versions and detailed considerations.)

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



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

Dark photon for neutral pion decay



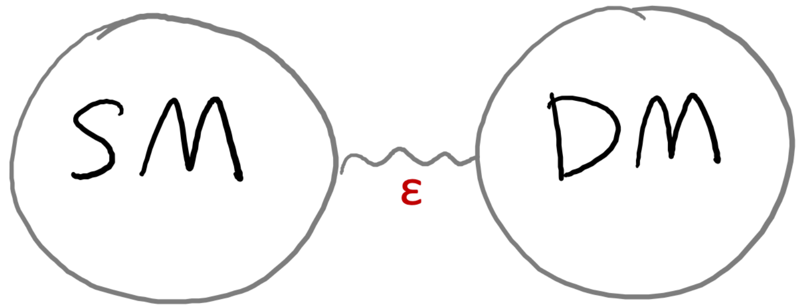
$m_{ADM} = m_B \sim m_Q \sim 5$ GeV

$\Lambda \sim m_{\pi'} > 2\, m_{\gamma'}$
(assuming the dark neutral pion π' (u u-bar) decays to two dark photons γ')

$$\Lambda \approx m_Q \left(\frac{3e\Delta}{4\,\mathrm{F.T.}}\right)^{2/3} \sim m_p \frac{\Omega_{\rm DM}}{\Omega_{B,\rm SM}} \left(\frac{3e\Delta}{4\,\mathrm{F.T.}}\right)^{2/3}.$$

π' ($u\bar{u}$) decays to two massive dark photons

The Rise of Dark Sector: Sub-GeV DM



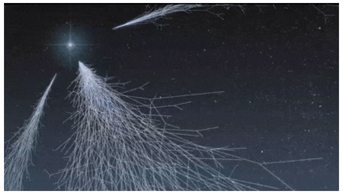
- The **Lee-Weinberg bound** (1977'): **below ~ 2 GeV**, DM freeze-out through weak-Interaction (e.g. through Z-boson) would overclose the Universe.

- Could consider ways to get around this but generally **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

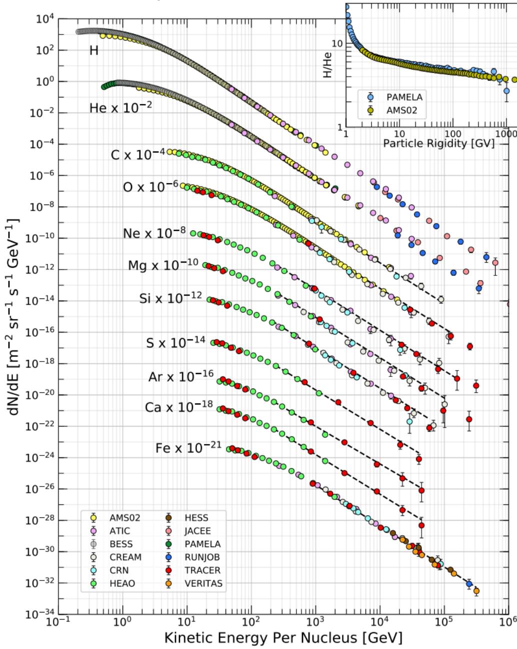
Cosmic-Ray Production & Neutrino Observatories

MCP in Neutrino Observatories

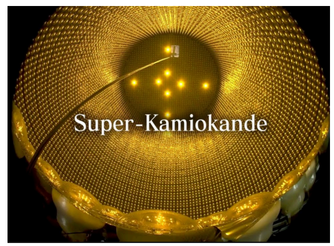


by Chantelauze, Staffi, and Bret

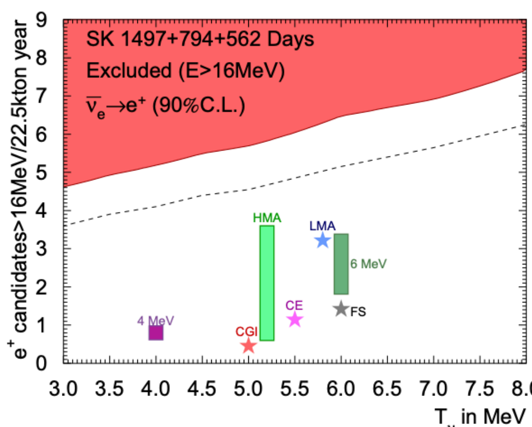
$\chi \quad \bar{\chi}$



PDG, RPP, 2019

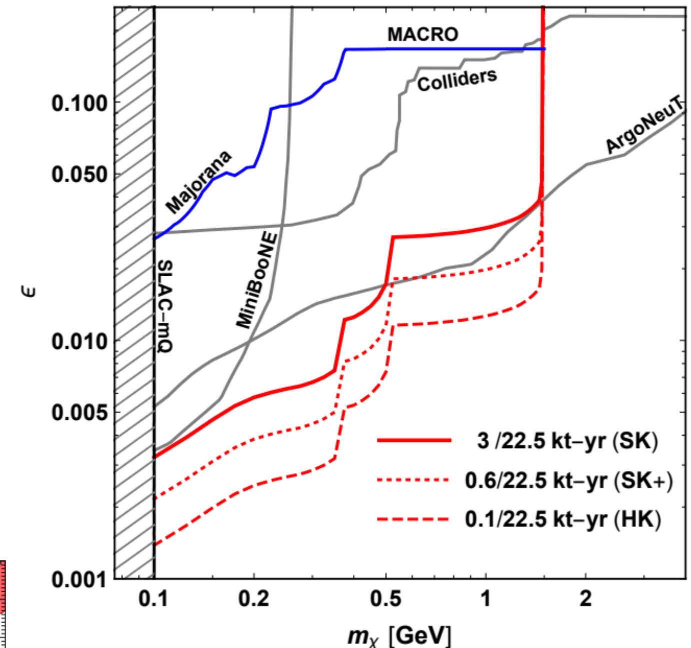


Super-K, http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html



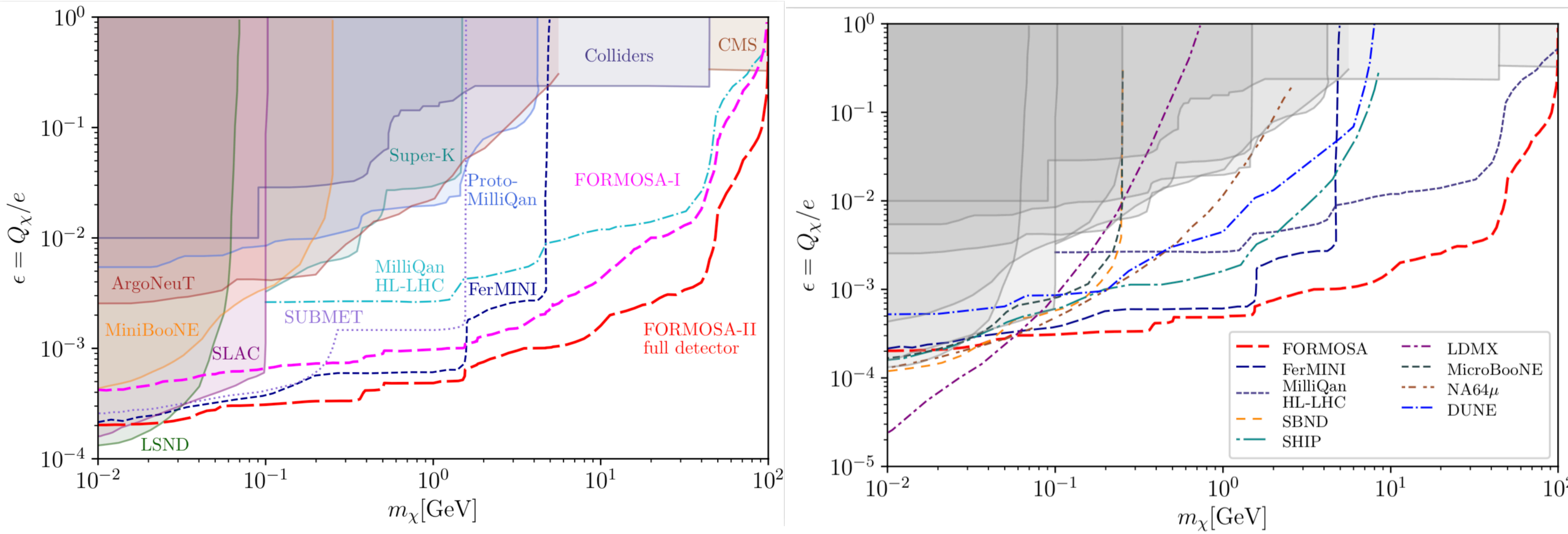
1111.5031 (Super-K Collaboration)

Supernova Relic Neutrino Search at Super−K



2002.11732 (Plestid, Takhistov, **Tsai**, Bringmann, Kusenko, Pospelov, ‘20)

Compilation of MCP Probes



(a) Existing bounds and MCP dedicated experiments

(b) Comparison of future projections

LOI Update: link

LOI Endorsers or White Paper Authors Sign-Up Link: link2

Advantages of FerMINI-type experiments

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. **Timeliness, Low-cost, Movable, Tested, Easy to Implement,**

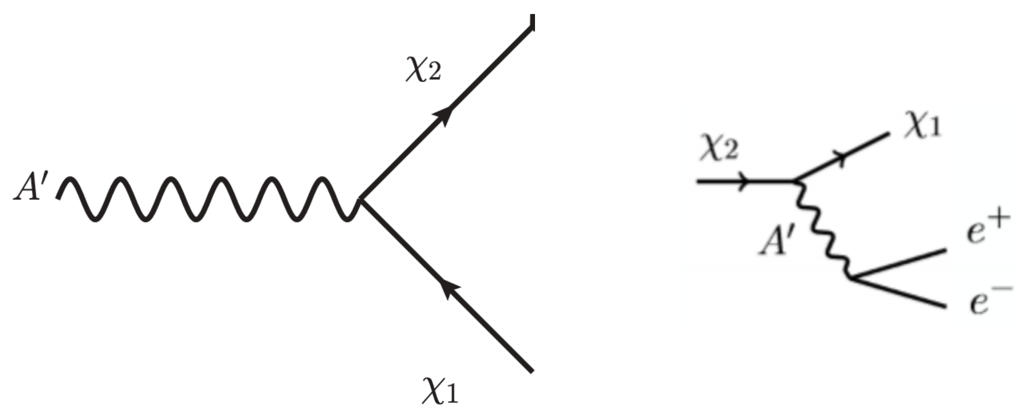
8. Synergy between **dark matter**, **neutrino**, and **collider** community.
   (contact ytsai@fnal.gov)

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

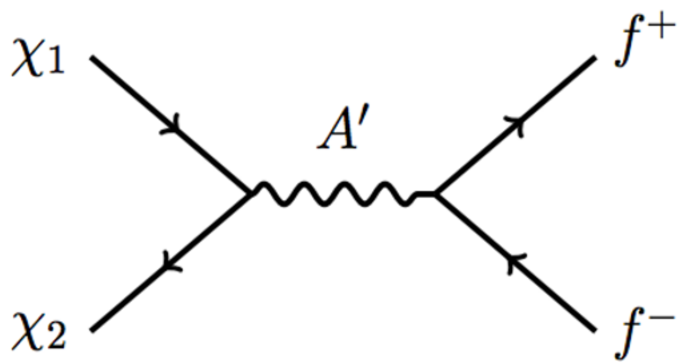
$$\mathcal{L} \supset \sum_{i=1,2} \bar{\chi}_i (i\partial\!\!\!/ - m_{\chi_i})\chi_i - (g_D A'_\mu \bar{\chi_1} \gamma^\mu \chi_2 + \text{h.c.}).$$

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



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

- Suppressed at the CMB epoch
- 1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

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

iDM in Fixed-Target and Collider

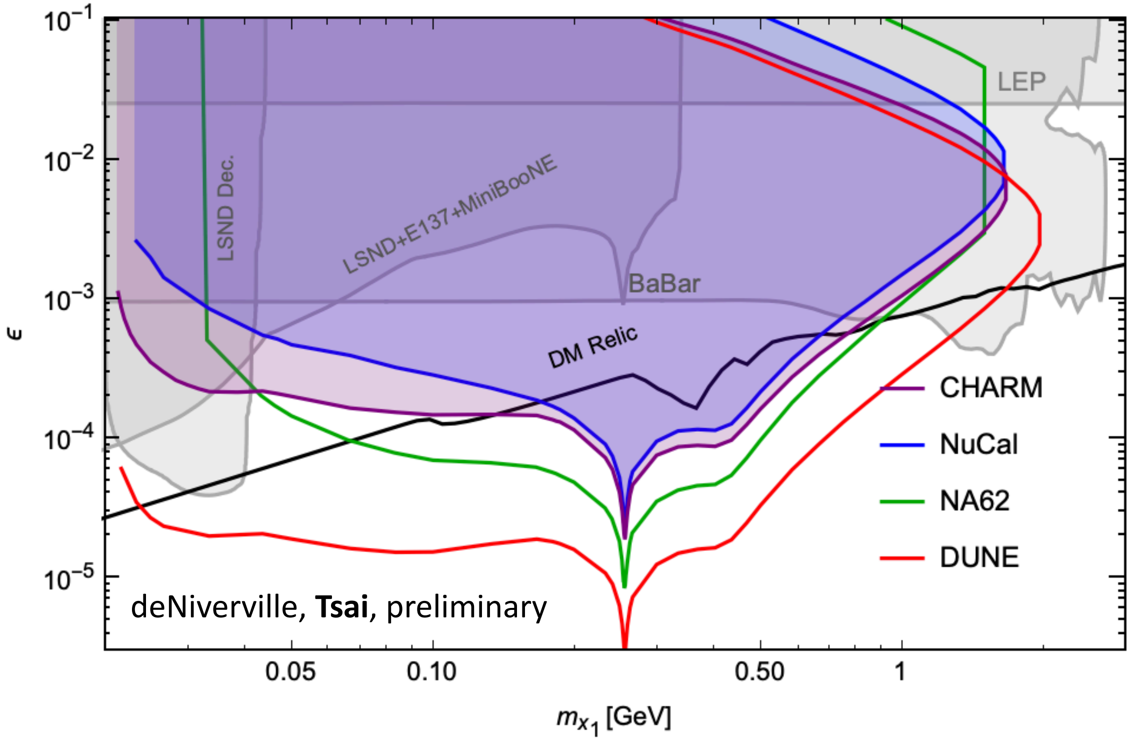
- Collider: 1508.03050 (Izaguirre, Krnjaic, Shuve)

- 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)

New Bounds on Inelastic Dark Matter

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

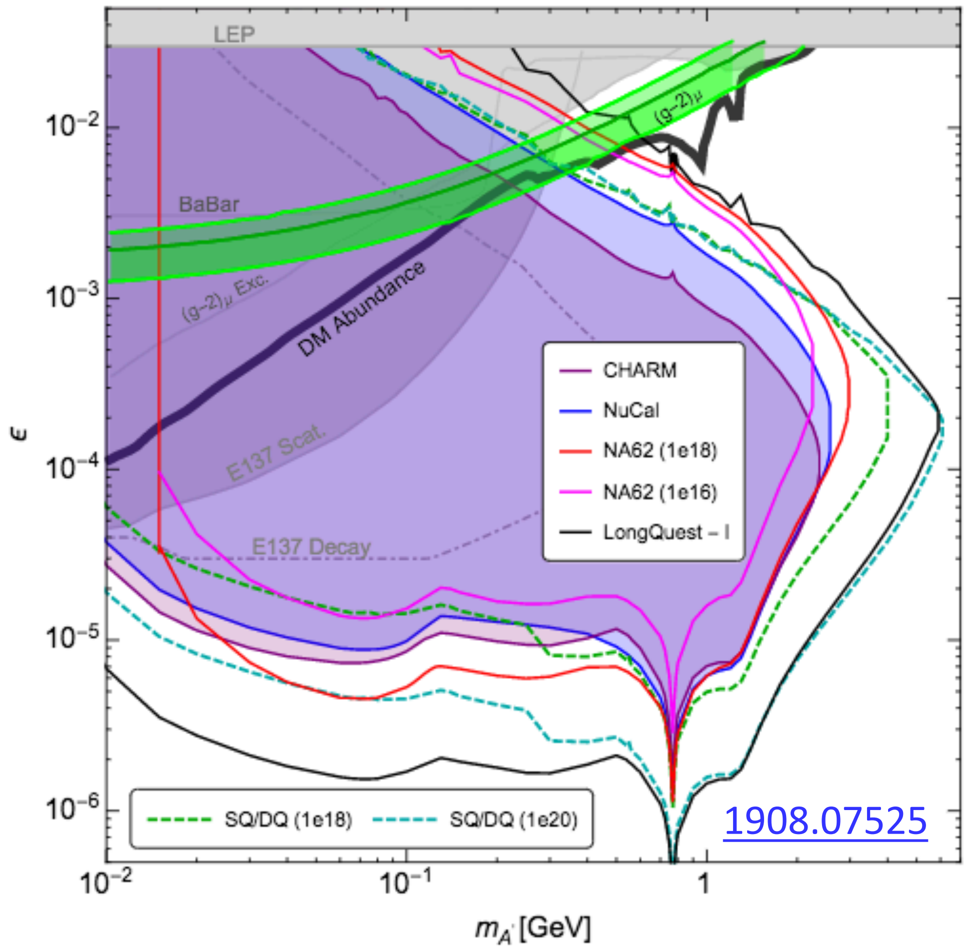
$$\Delta \equiv \frac{m_2 - m_1}{m_1}. \qquad g_D \equiv \sqrt{4\pi\alpha_D}.$$



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

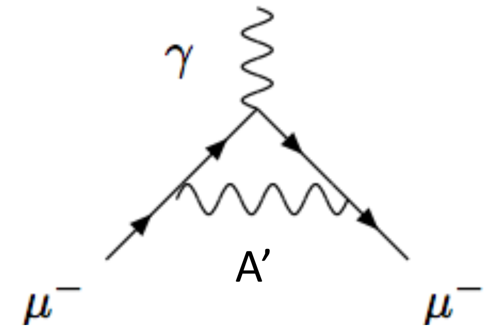
DUNE preliminary results by deNiverville & **Tsai**,

Inelastic Dark Matter & Muon g-2 explainer



(a) iDM: $\Delta = 0.4$, α_D=0.1. With muon $g-2$ and DM regimes.

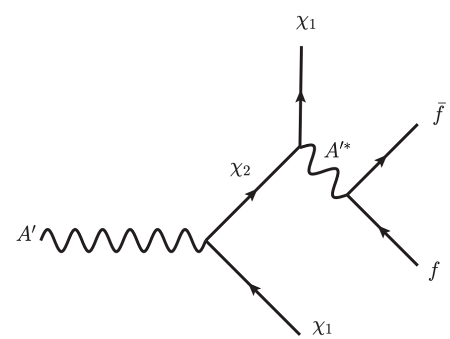
$m_{A'}/m_{x1}$ = 3.



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

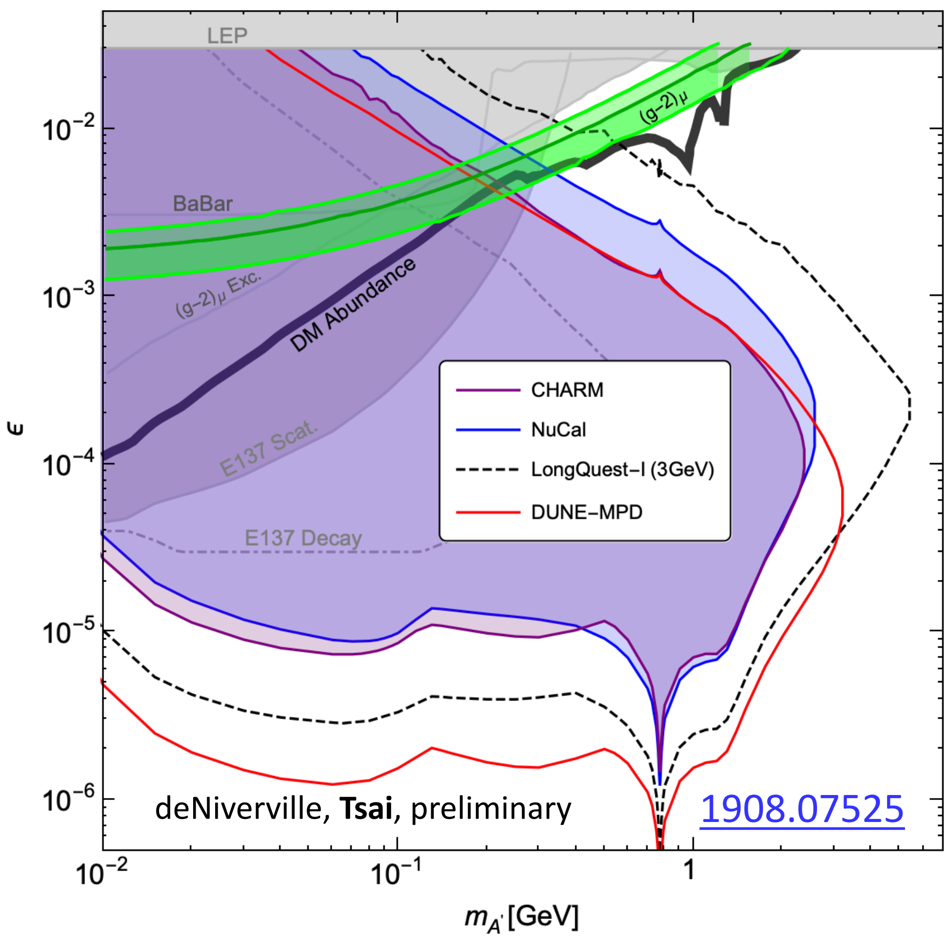
See, e.g., Fayet, 2007 (hep-ph/0702176)

- 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.

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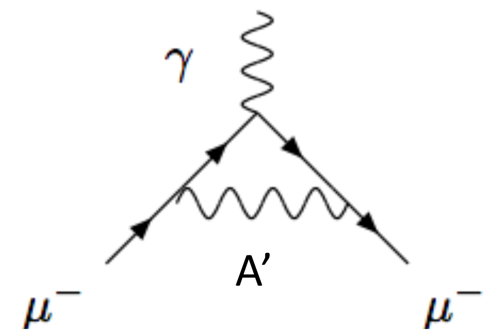

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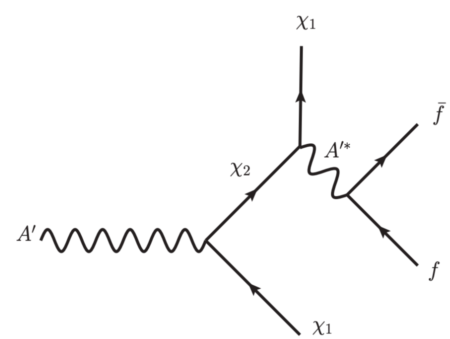
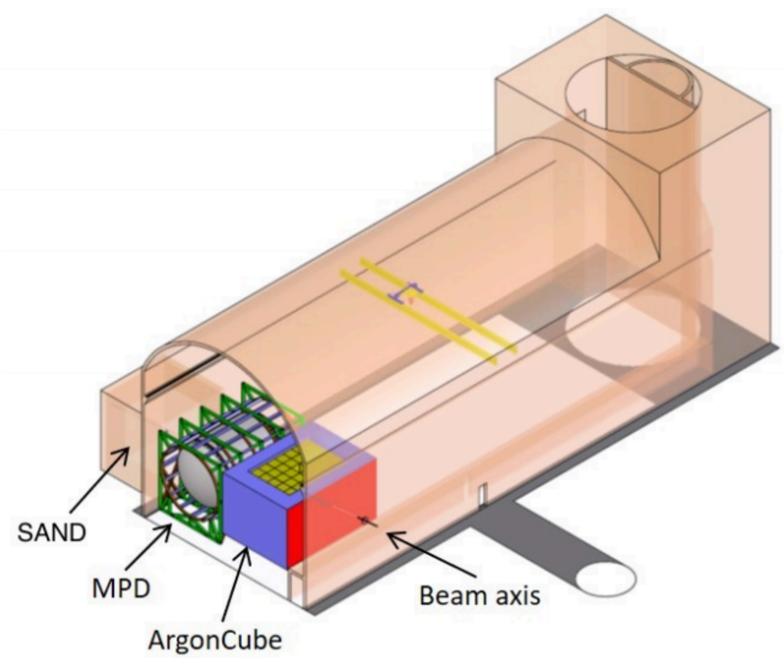
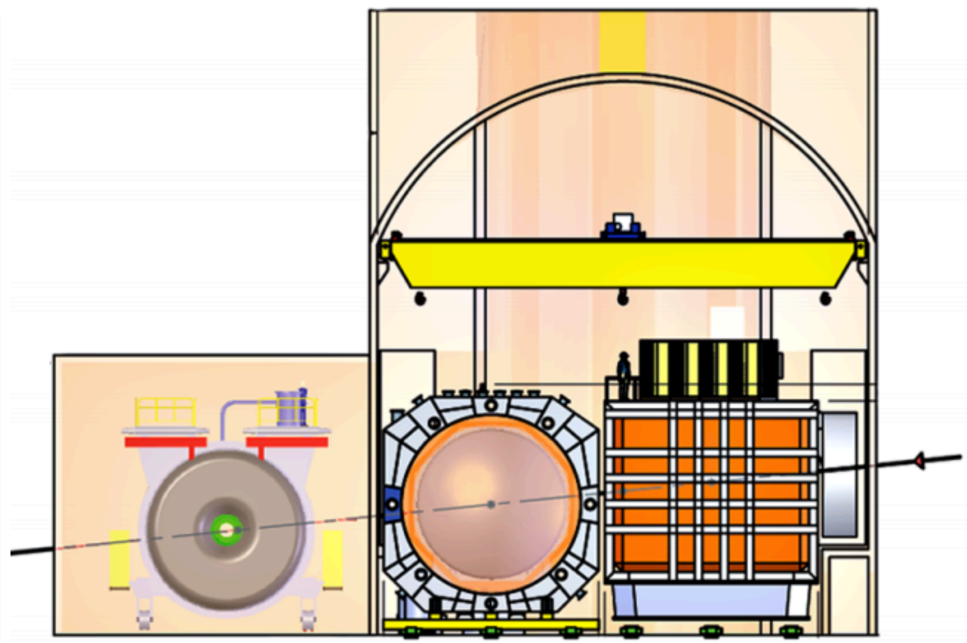


- 1908.07525,**Tsai**, deNiverville, Liuz

DUNE Near Detector Complex



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)

FerMINI Collaboration (BRN proposal)

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OSU

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NYU

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Fermilab

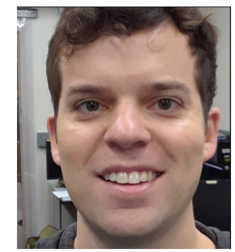
David Miller
U Chicago

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

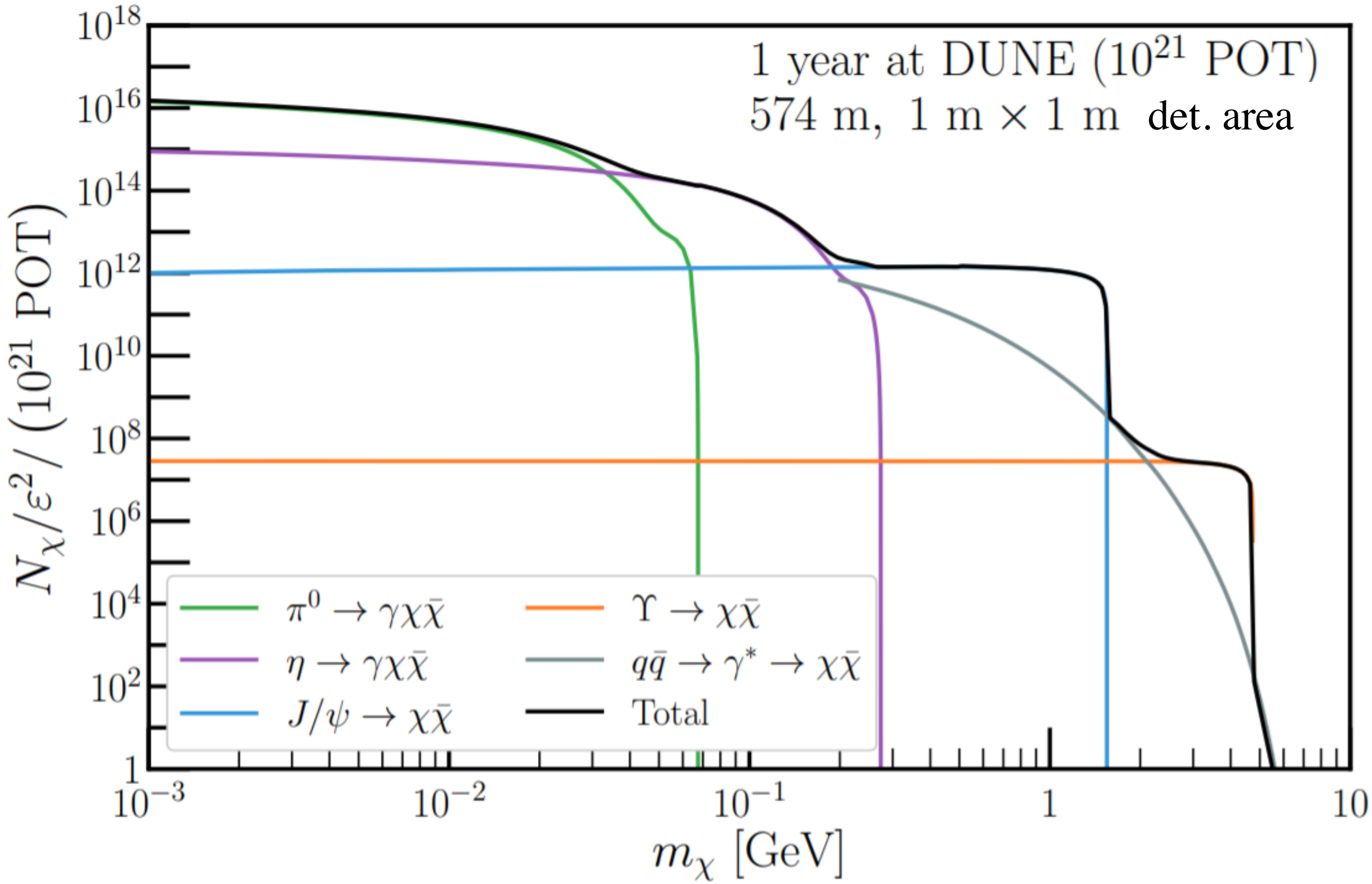
Albert de Roeck
CERN

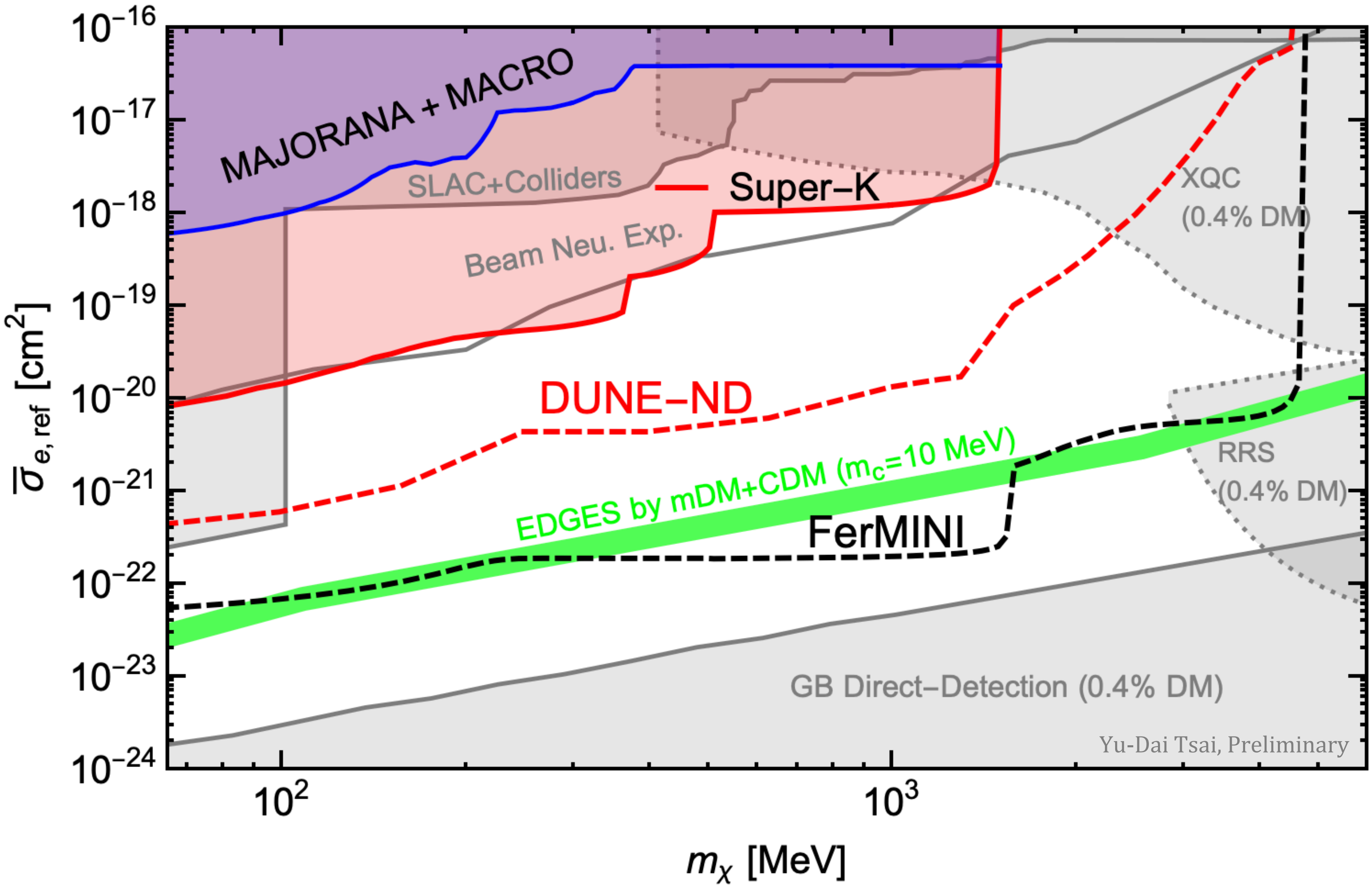
Joe Bramante
Queen’s U

Bithika Jain
ICTP-SAIFR

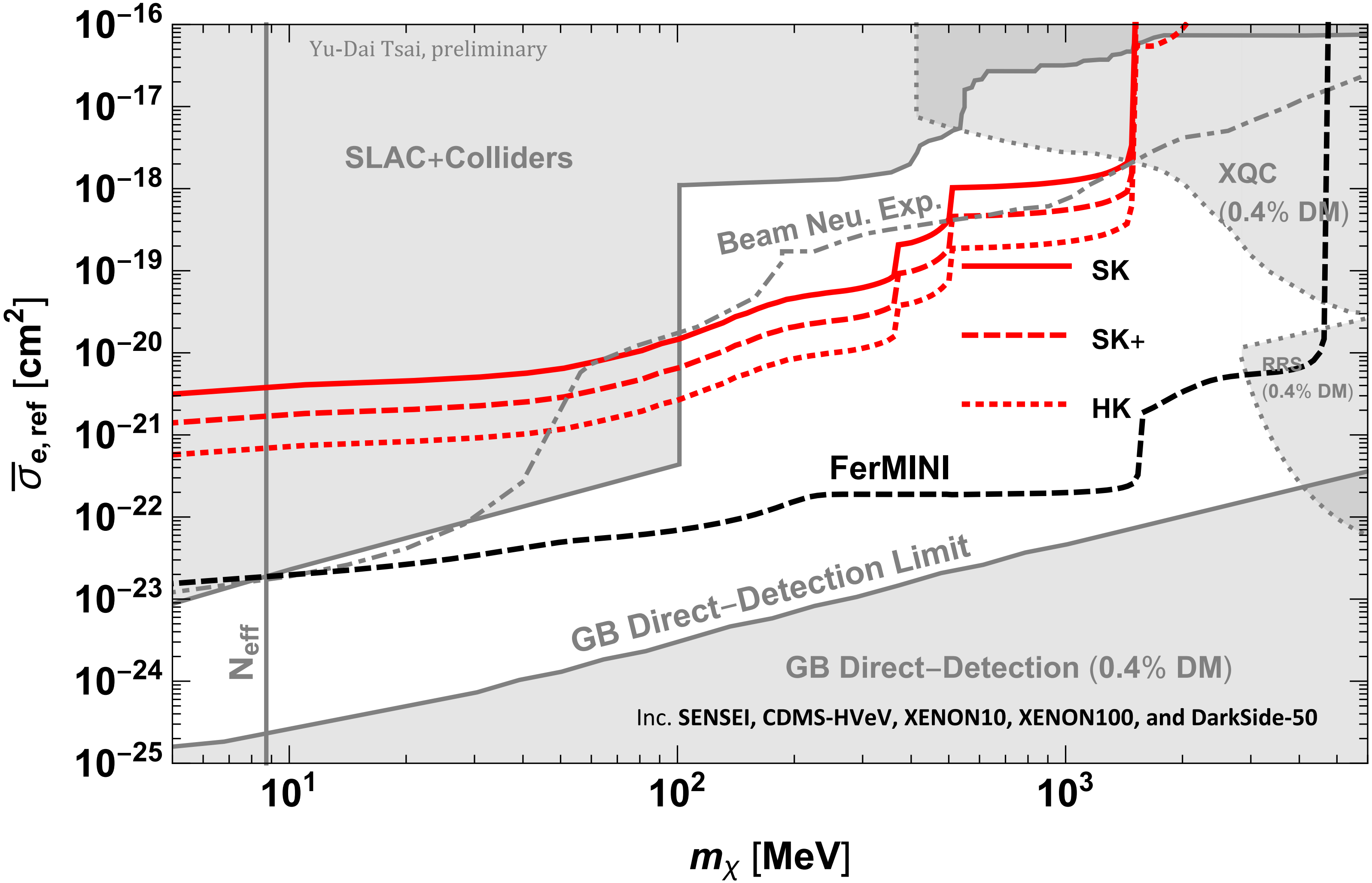
MCP Production/Flux

120 GeV proton beam on target (graphite)





MAJORANA + MACRO
SLAC+Colliders
Super−K
Beam Neu. Exp.
XQC
(0.4% DM)
DUNE−ND
EDGES by mDM+CDM (m_c=10 MeV)
FerMINI
RRS
(0.4% DM)
GB Direct−Detection (0.4% DM)
Yu-Dai Tsai, Preliminary
$\bar{\sigma}_{e,\mathrm{ref}}$ [cm^2]
m_χ [MeV]
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^2
10^3


Yu-Dai Tsai, preliminary
SLAC+Colliders
Beam Neu. Exp.
XQC
(0.4% DM)
SK
SK+
HK
RRS
(0.4% DM)
FerMINI
GB Direct−Detection Limit
GB Direct−Detection (0.4% DM)
Inc. SENSEI, CDMS-HVeV, XENON10, XENON100, and DarkSide-50
N_eff
$\overline{\sigma}_{e,\mathrm{ref}}$ [cm^2]
m_χ [MeV]
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{1}
10^{2}
10^{3}

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 modified **Bethe-Bloch Formula** to get an 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

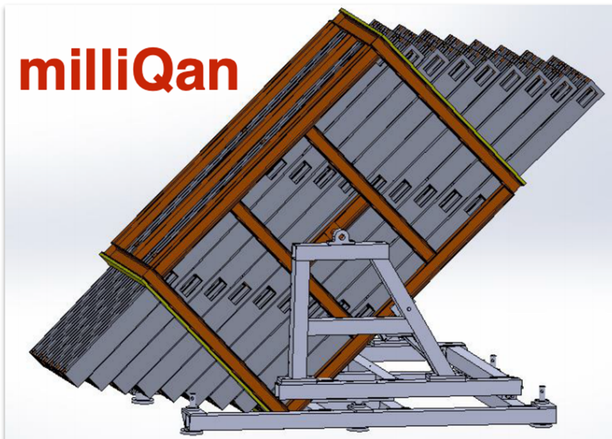
Signature: Triple Coincidence

- 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:

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

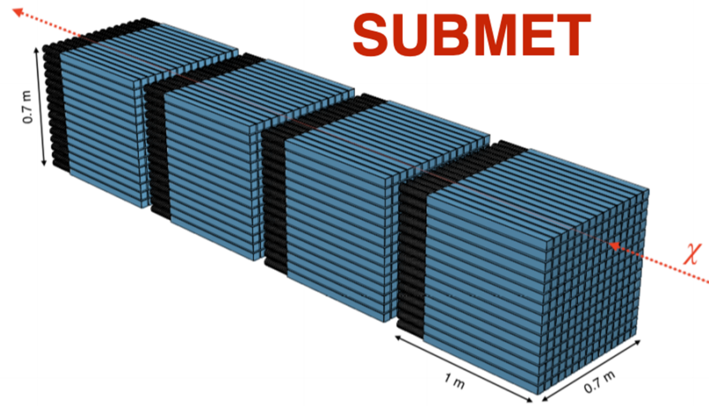
- **$\mathbf{N_{x,detector}}$ = $\mathbf{N_x}$ (going through detector)** x **P.**

Scintillation based detection



LHC with sensitivity for m < ~45 GeV

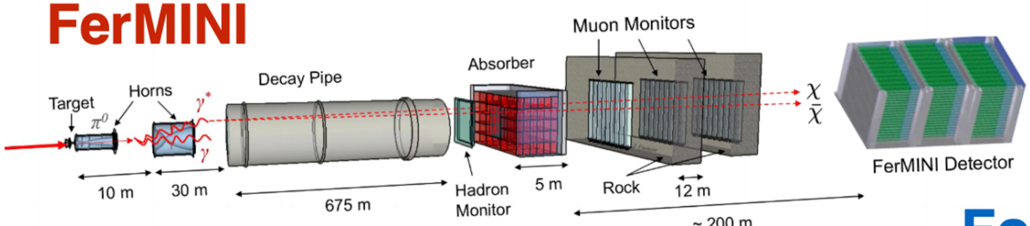
1607.04669



J-PARC with sensitivity for m < ~1.5 GeV

2007.06329

FerMINI



Range of detectors with complementary sensitivity

Fermilab with sensitivity for m < ~5 GeV

1812.03998

For milliQan: proof of concept "demonstrator" installed at CERN

M. Citron mcitron@ucsb.edu 4

Directly from **Matthew Citron**'s talk at NF3 kickoff meeting: link

See Snowmass LOI "Sensitivity reach of scintillator-based detectors for millicharged particles" (link)