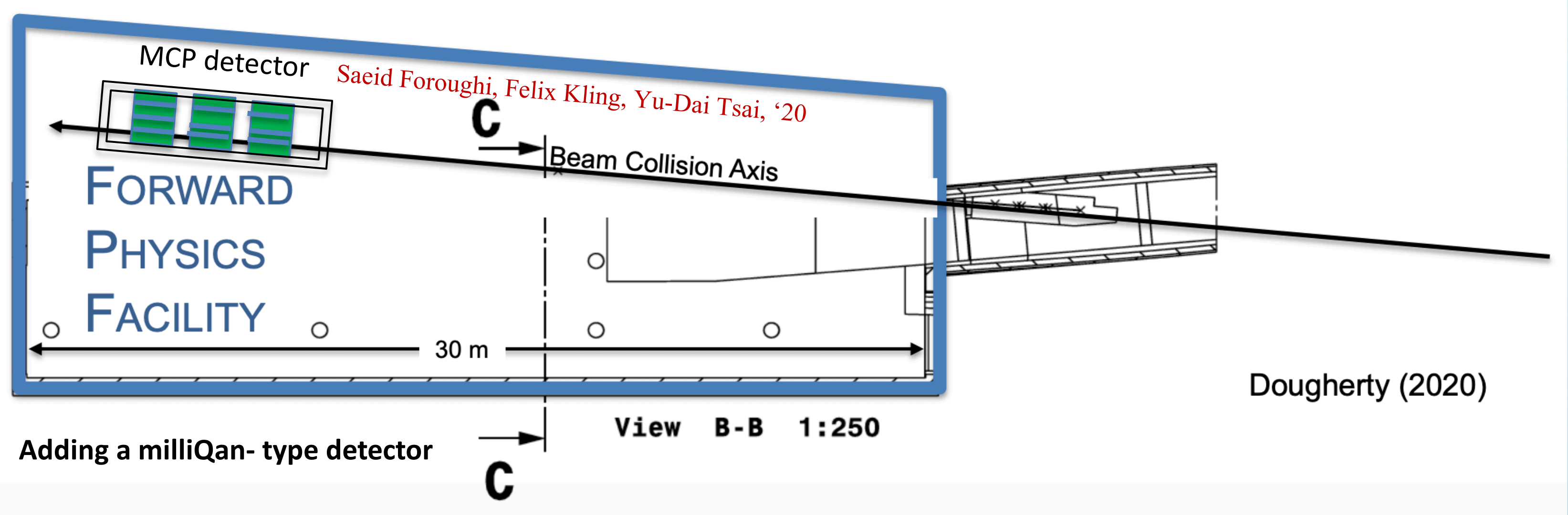


When High Energy Meets High Intensity

Yu-Dai Tsai, Fermilab/U Chicago

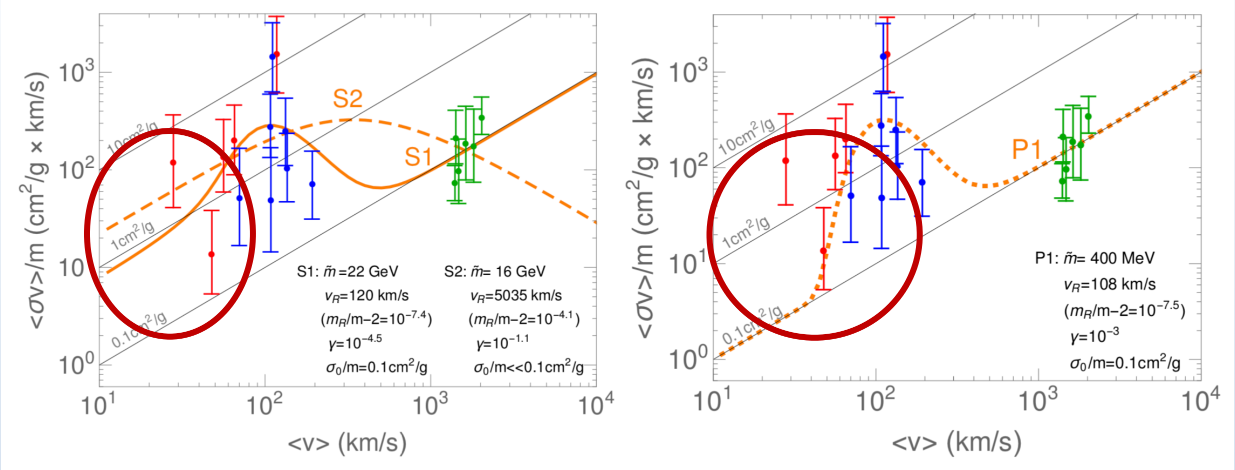
[1] FORMOSA: Looking Forward to Millicharged Dark Sectors (2010.07941)

[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 data** (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
- High-Energy Intensity Experiments & Interesting Models
- Resonant Dark Meson
- Vision & Future Outlook

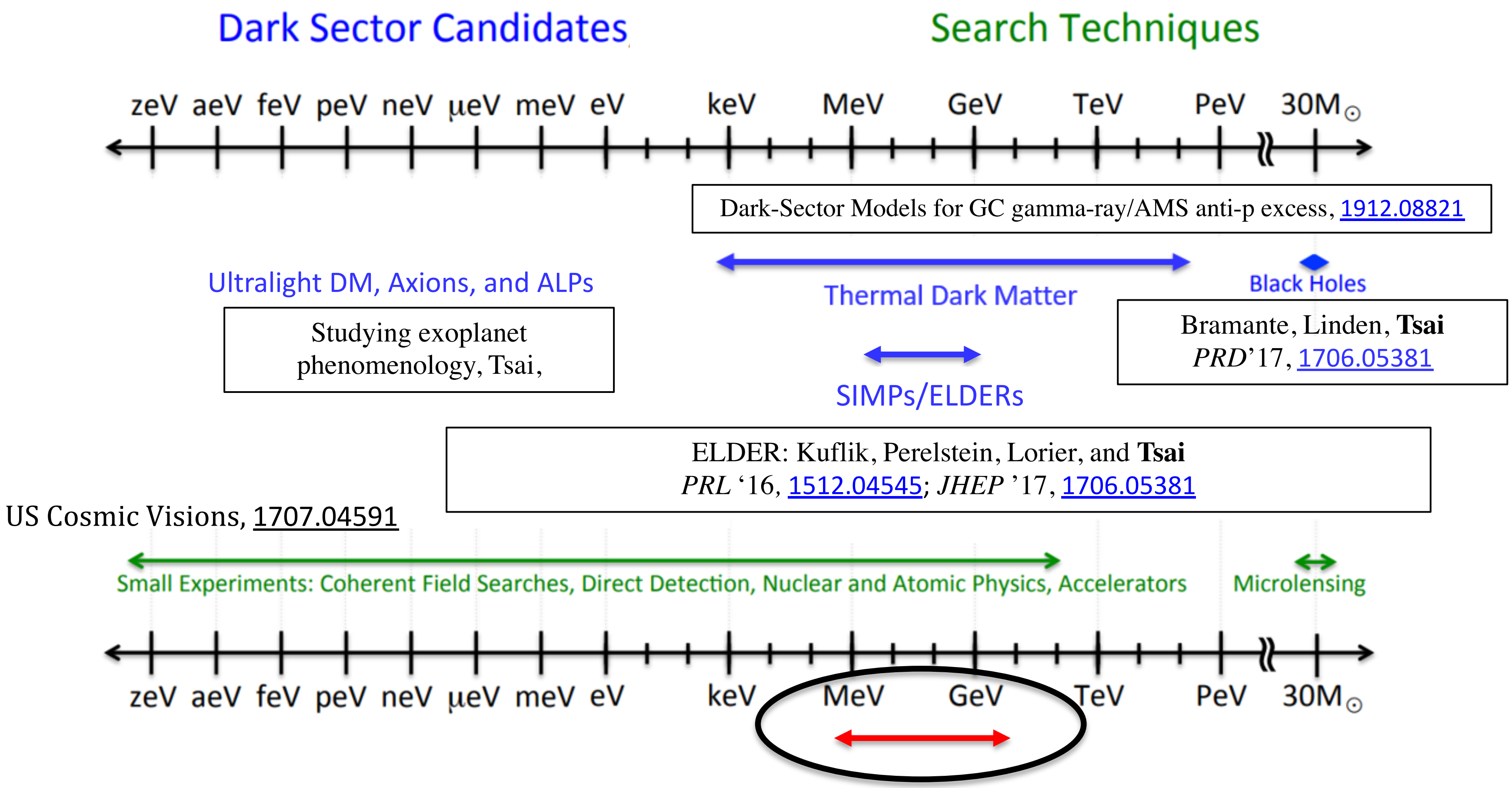
Dark Matter Complementarity:

Why accelerator / astro probe?

Why MeV – GeV range?

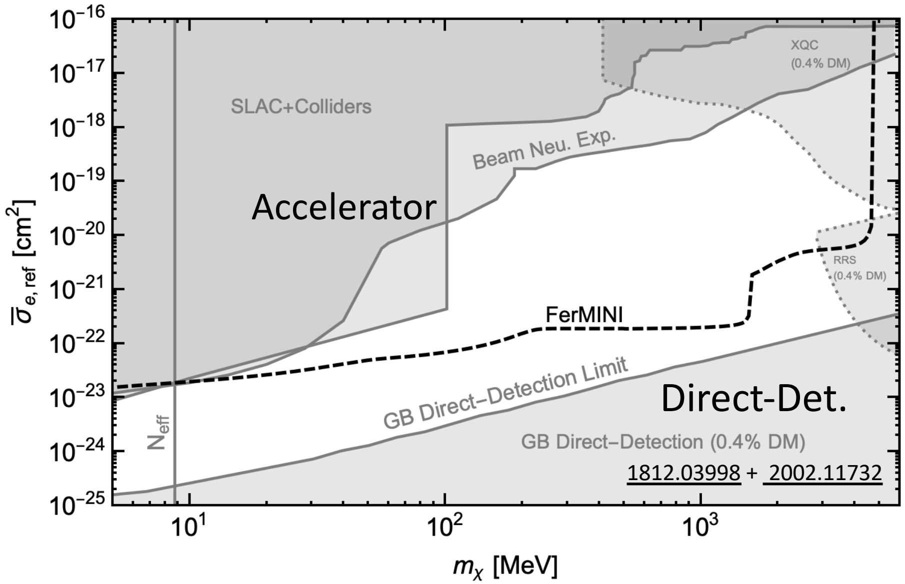
Yu-Dai Tsai, Fermilab, '20

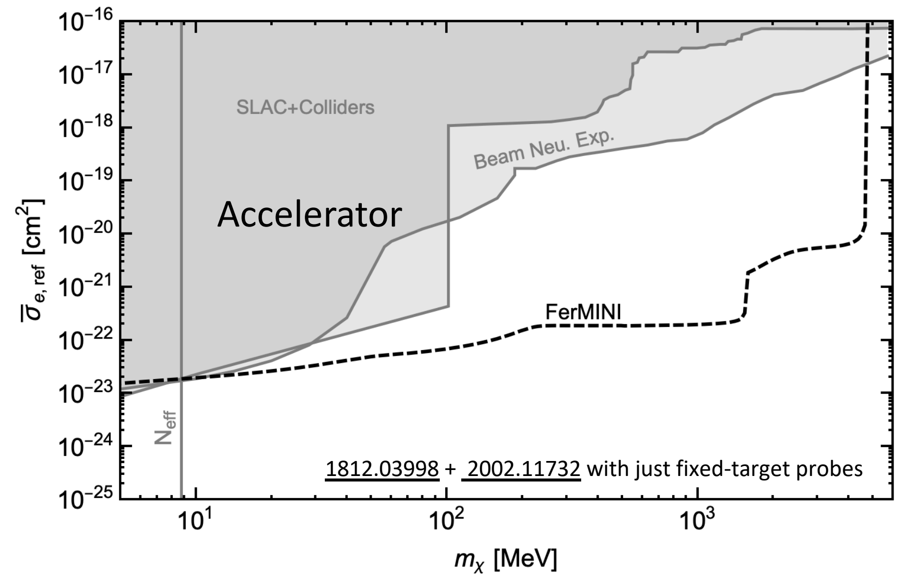
Exploration of Dark Matter & Mediator



- 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

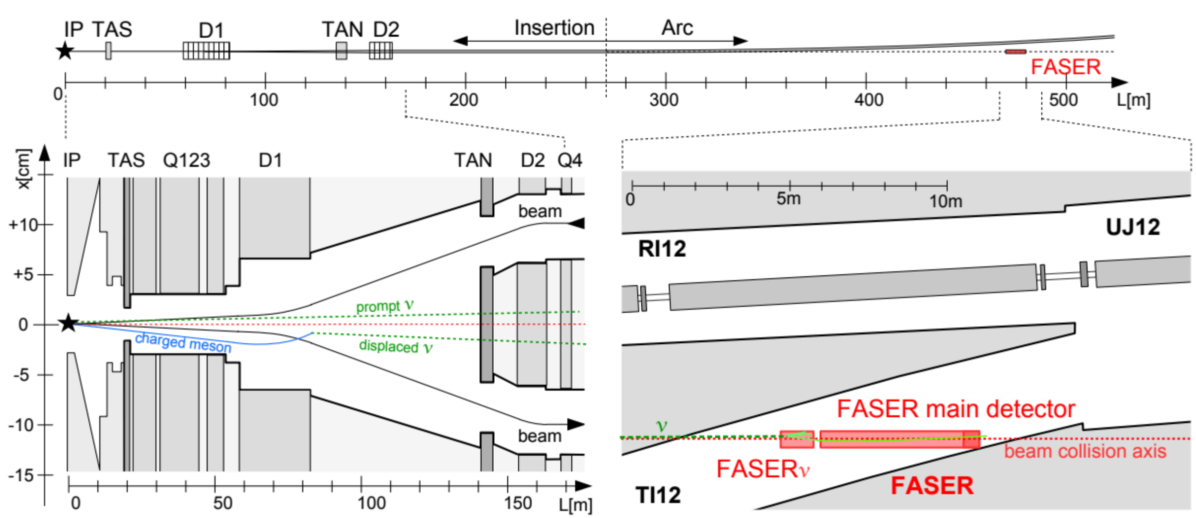
LHC Forward Physics Region

- **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**



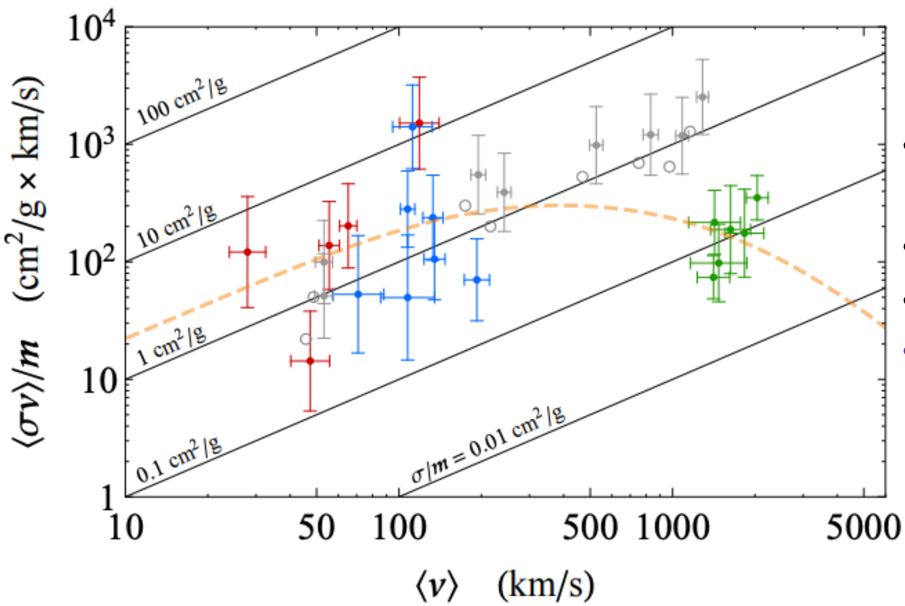
Astro-Cosmo Dark Matter Searches

Why is it so important?
Hints on DM Properties

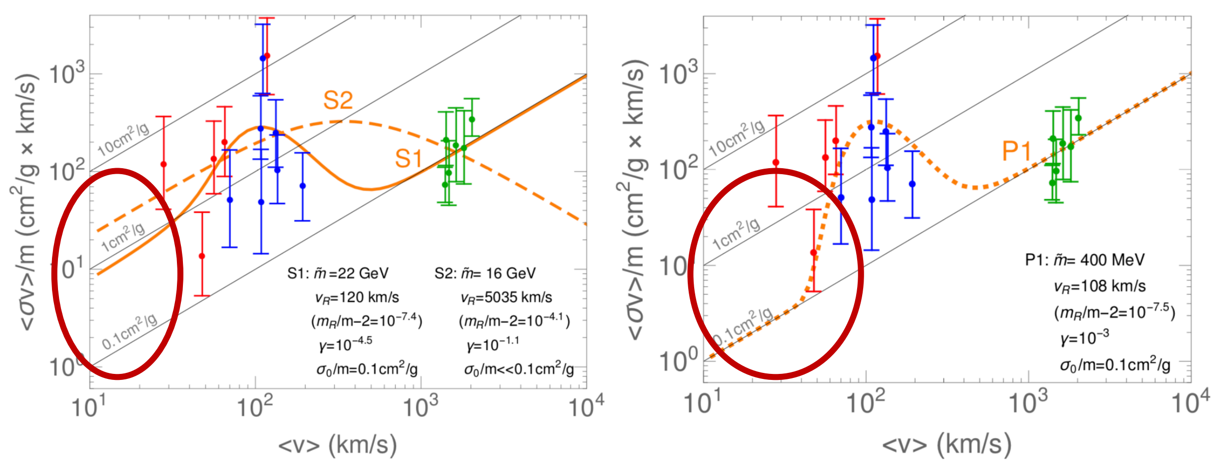
Searching for "Actual" Dark Matter

- **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 & 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

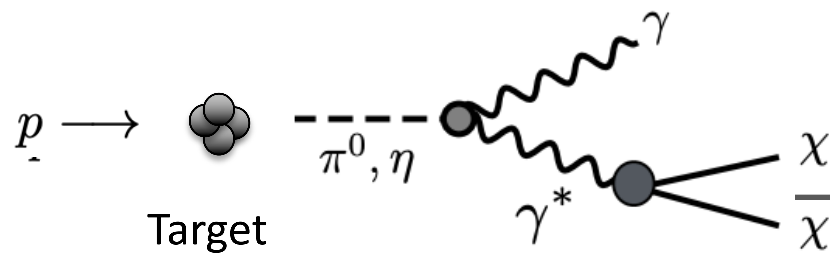
- **MiniBooNE, SBND, MicroBooNE, MINERvA, DUNE, etc**
- Many have primary goals to study **neutrino scattering** and/or **neutrino oscillation**

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)**

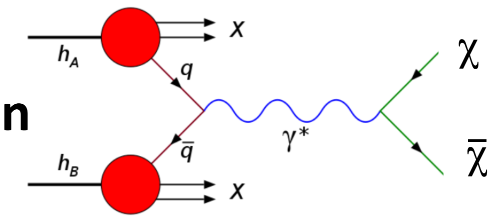
Some Production Channels

- ❑ **Production: Meson Decays**

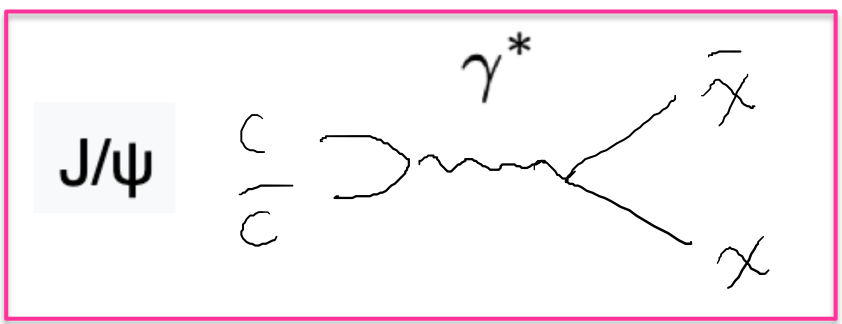


Modified from 1703.06881 (Izaguirre, Kahn, Krnjaic, Moschella)

- ❑ **Production: Drell-Yan**



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



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

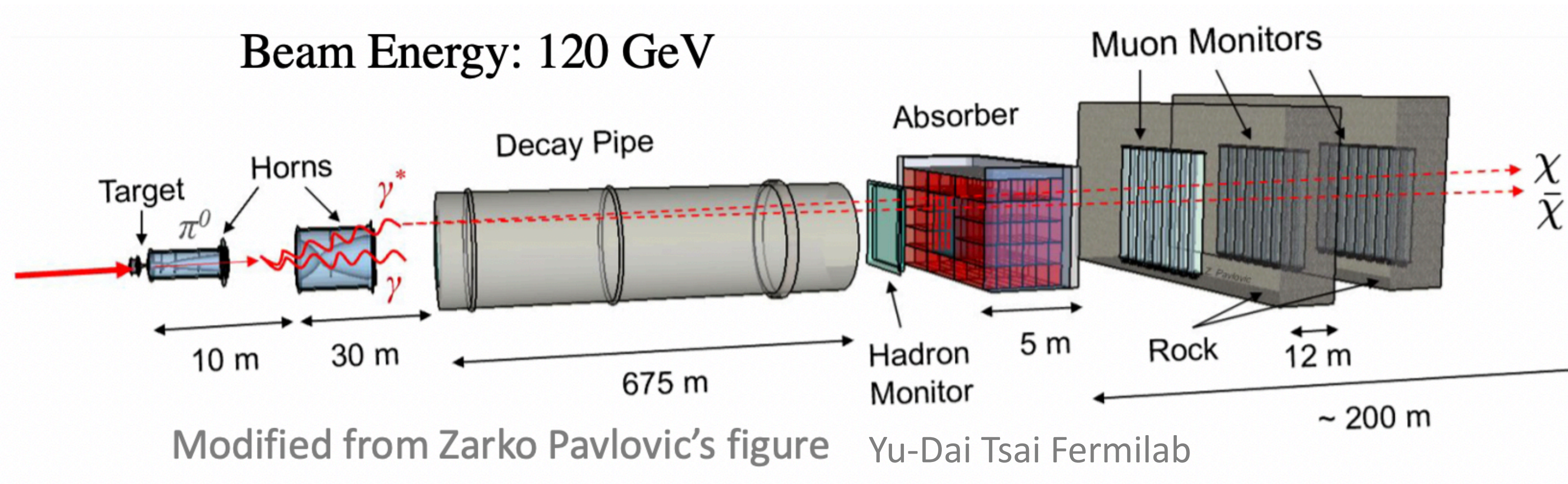
$BR(\pi^0 \to \gamma e^- e^+) = 0.01$

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

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

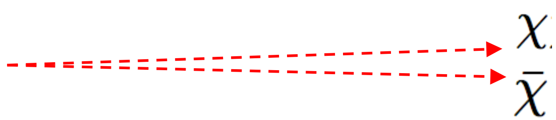
MCP Produced in Fixed-Target Experiments

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



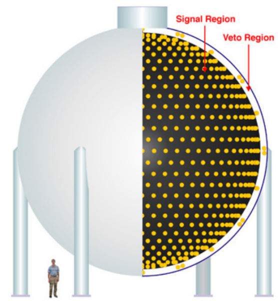
Yu-Dai Tsai, Fermilab, 2020

Scattering Detectors



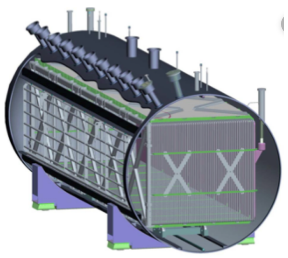
- NuMI Beam
- BNB
- LBNF (future)

MiniBooNE Detector



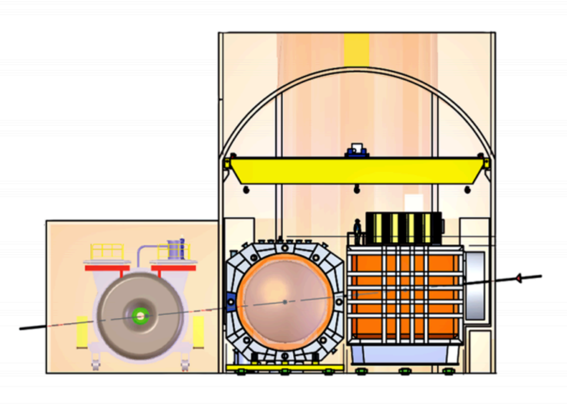
arXiv:0806.4201
MiniBooNE collaboration

MicroBooNE Detector



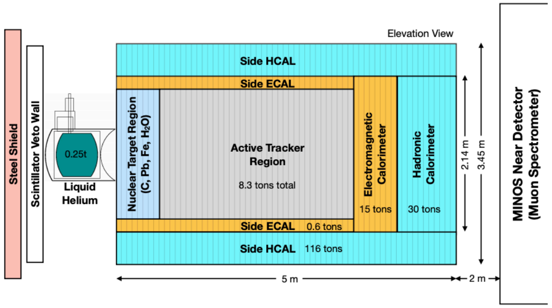
arXiv:1612.05824
MicroBooNE collaboration

DUNE Near Detector



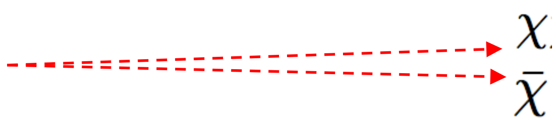
arXiv:2002.02967, DUNE TDR V - I

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

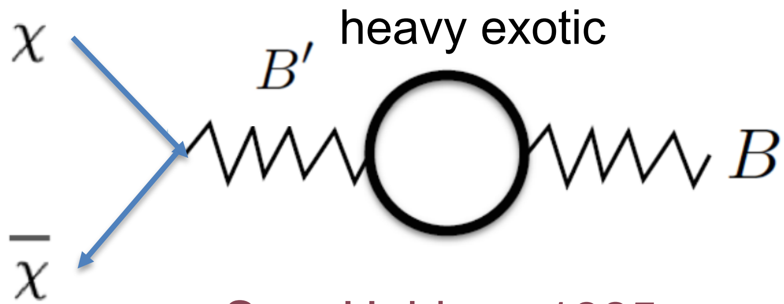
Millicharged Particle: Model & Signature

Model: Millicharged Particles

- Particles with **arbitrary mass** and **small charge**
- No need for dark photon, but can be a consequence of massless dark photon theory
- Test of **charge quantization**, and thus **grand unification theory, superstring theory, string compactifications** (Wen, Witten, Nucl. Phys. B 261 (1985) 651-677, Youtube: [link])
- 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)

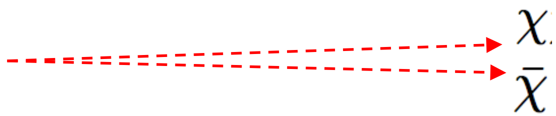
See, Holdom, 1985

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

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

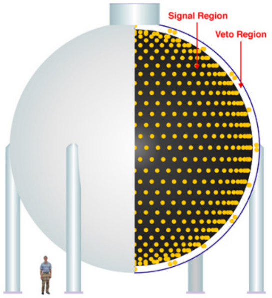
- Millicharged particle (MCP) can be a **low-energy consequence** of **massless dark photon** (a new U(1) gauge boson) coupled to **a new fermion (become MCP** in a convenient basis.)

Scattering Detectors



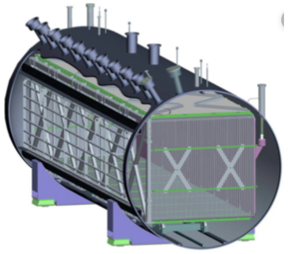
- NuMI Beam
- BNB
- LBNF (future)

MiniBooNE Detector



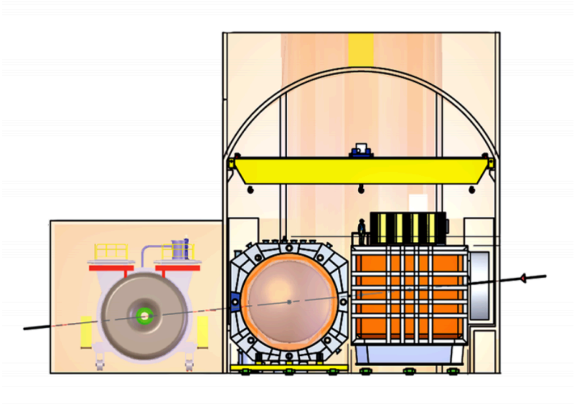
arXiv:0806.4201
MiniBooNE collaboration

MicroBooNE Detector



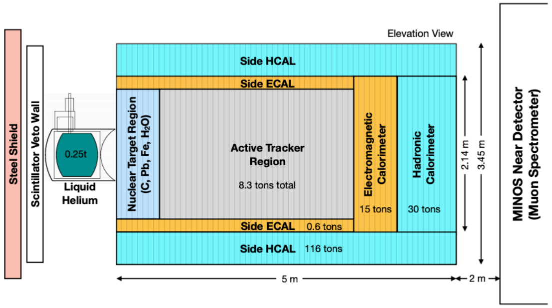
arXiv:1612.05824
MicroBooNE collaboration

DUNE Near Detector



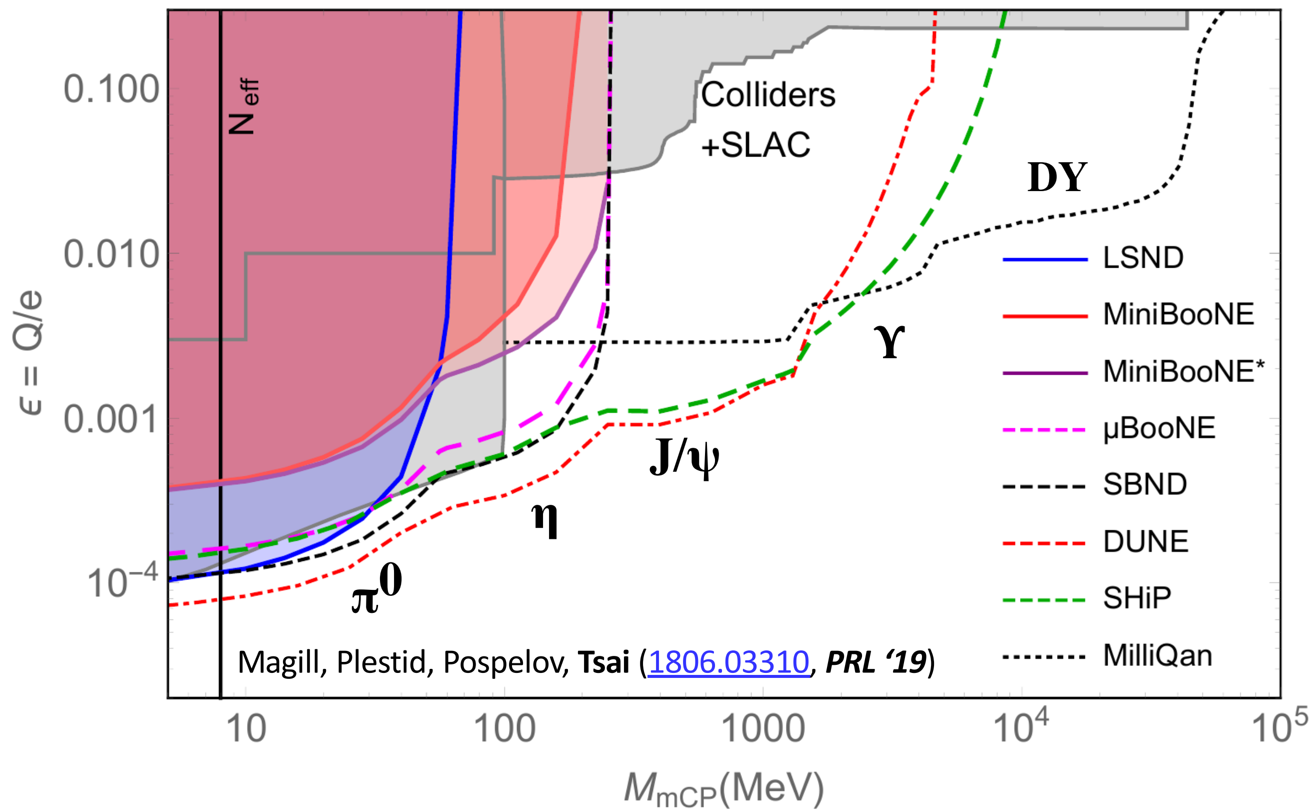
arXiv:2002.02967, DUNE TDR V - I

MINERvA Detector



arXiv:1109.2855
MINERvA collaboration

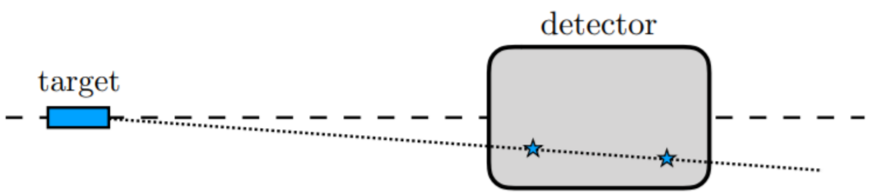
Sensitivity at Neutrino Detectors

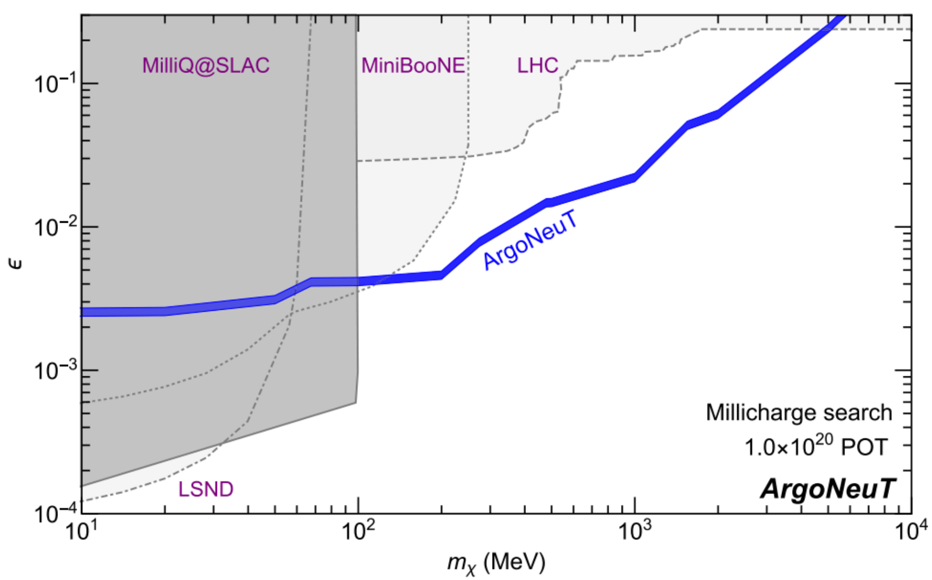


- **Electron recoil-energy threshold: MeV to 100 MeV**
- Can use **timing information** to improve sensitivity
- Double-hit to reduce background (**see next page**)
- Will include more updates later!

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

Double-Hit Consideration: ArgoNeuT Study & Constraint





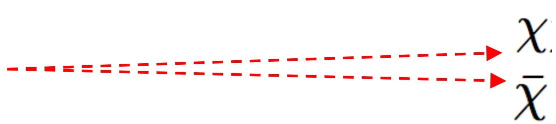
x-axis: m_x (MCP mass),
y-axis: $\epsilon = Q_x/e$ (charge ratio).

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

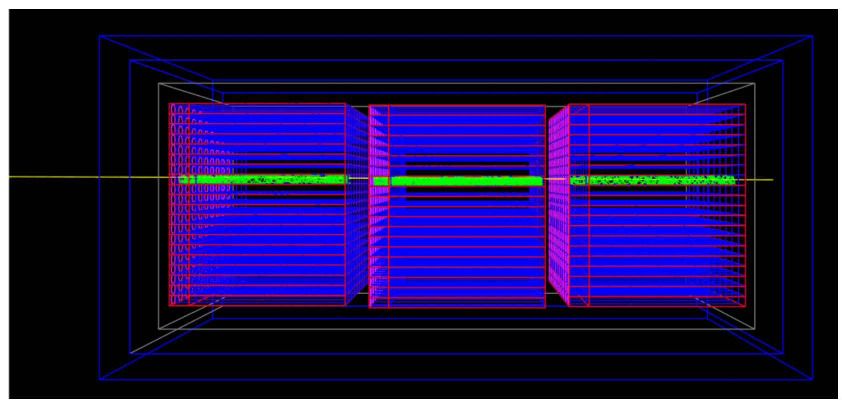
Specialized “Scattering” Detectors



- 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

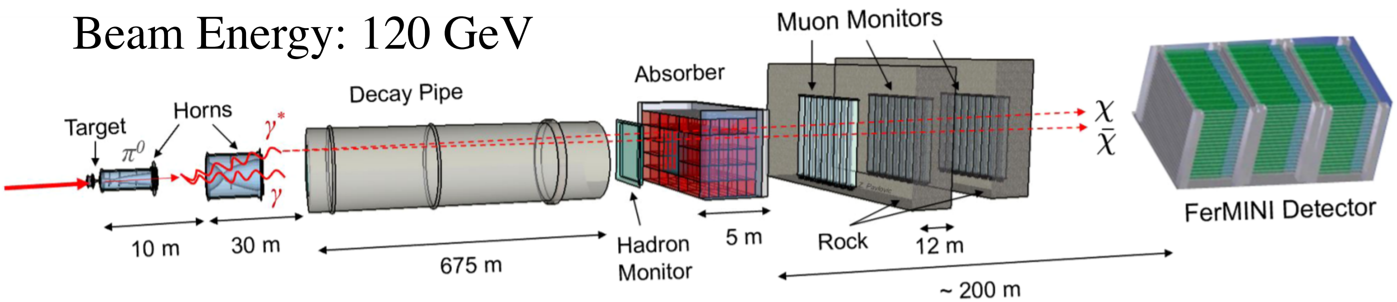
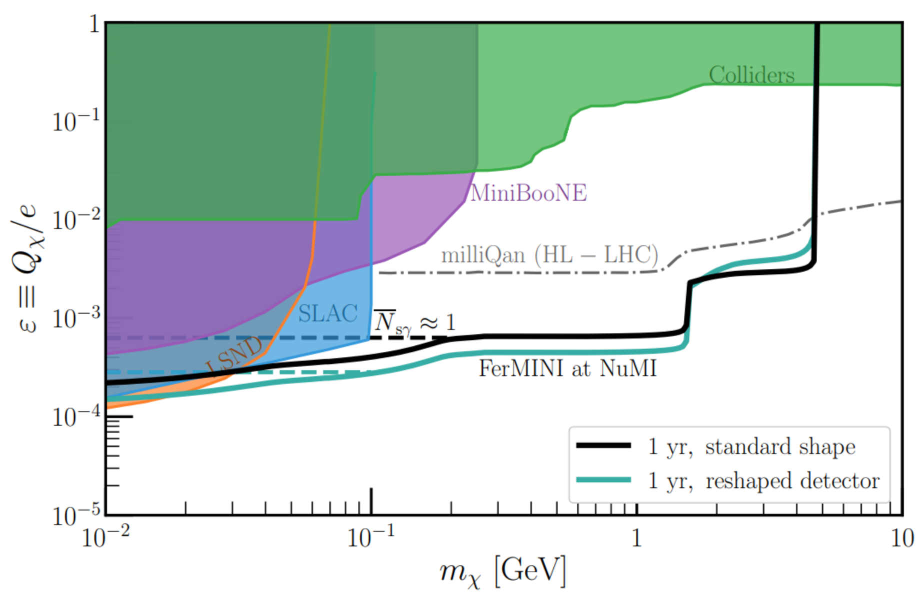


FIG. 3. An illustration of the FerMINI experiments utilizing the NuMI facility.



MINOS hall downstream of NuMI beam

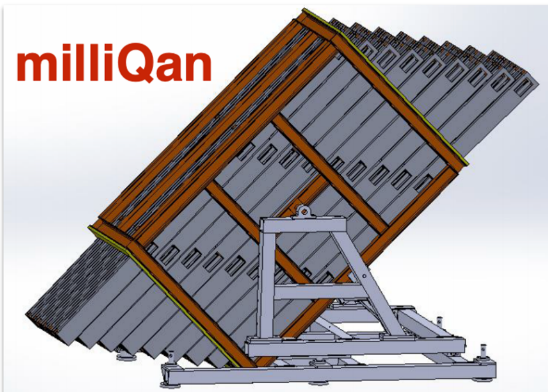
Yu-Dai Tsai
Fermilab

Snowmass LOI (link):
Sensitivity reach of scintillator-based detectors for millicharged particles
Matthew Citron, Chris Hill, David Miller, Albert De Roeck, David Stuart, Yu-Dai Tsai, Jae Hyeok Yoo

Scintillation based detection

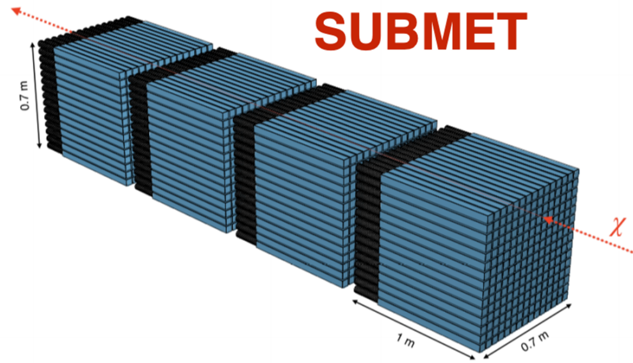
https://arxiv.org/pdf/2007.06329.pdf

30 GeV



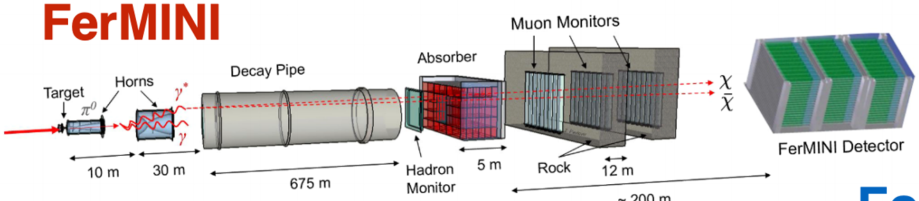
LHC with sensitivity for m < ~45 GeV

1607.04669



J-PARC with sensitivity for m < ~1.5 GeV

2007.06329



Fermilab with sensitivity for m < ~5 GeV

1812.03998

Range of detectors with complementary sensitivity

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

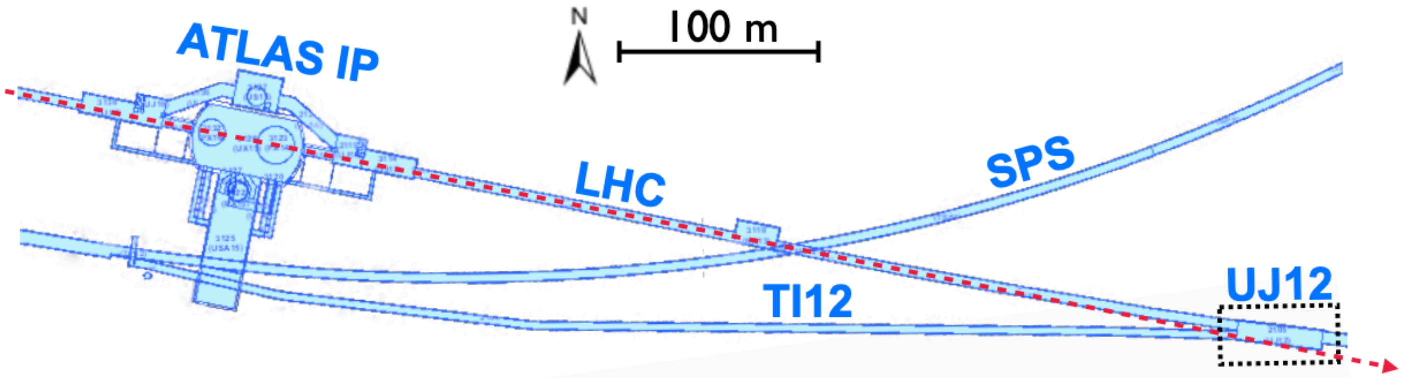
M. Citron mcitron@ucsb.edu 4

Directly from Matthew's talk at Snowmass NF3 meeting: link

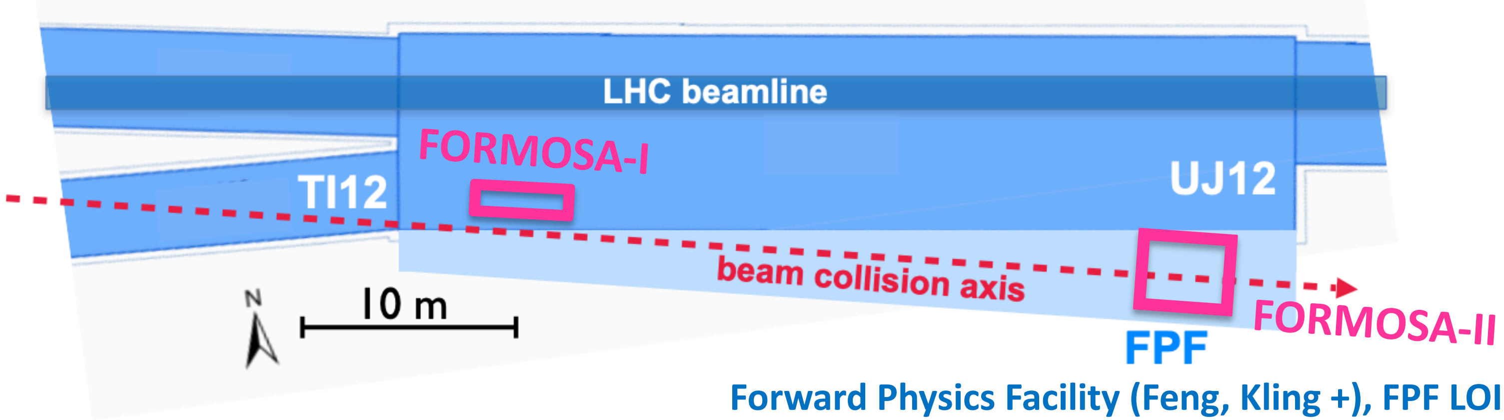
Going Forward:
Best of both worlds

FORMOSA: FORward MicrOcharge SeArch

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



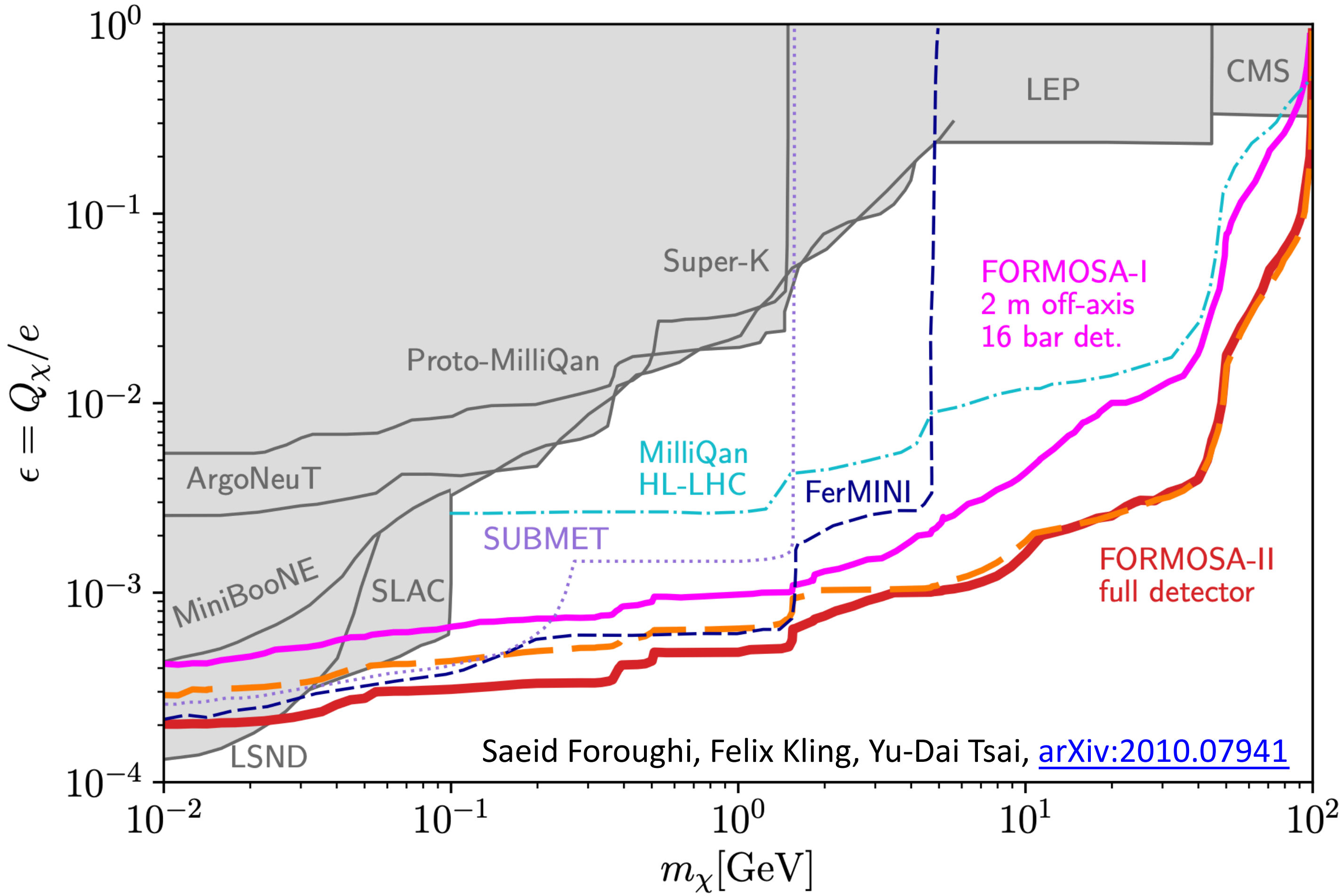
Place milliQan-type detectors at …



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

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

FORMOSA Sensitivity



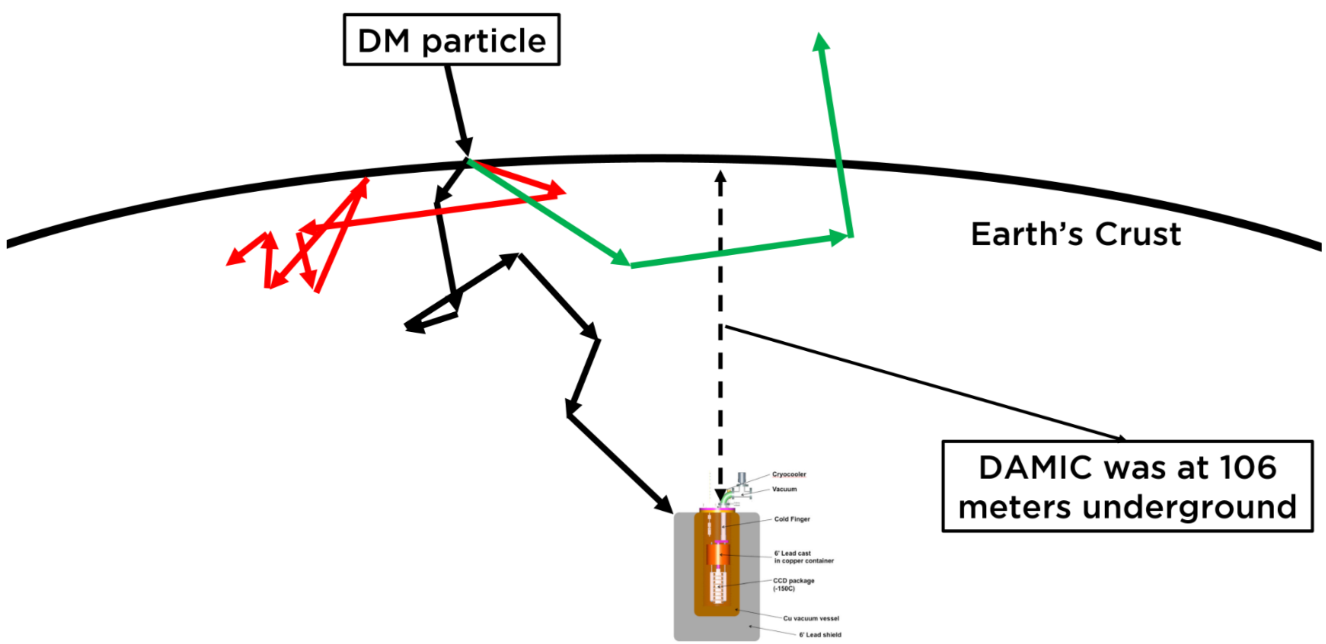
FORMOSA-I: ~ 0.2 m × 0.2 m × 4 m consisting of 4 layers of 16 scintillator bars @UJ12/TI12 tunnel.

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

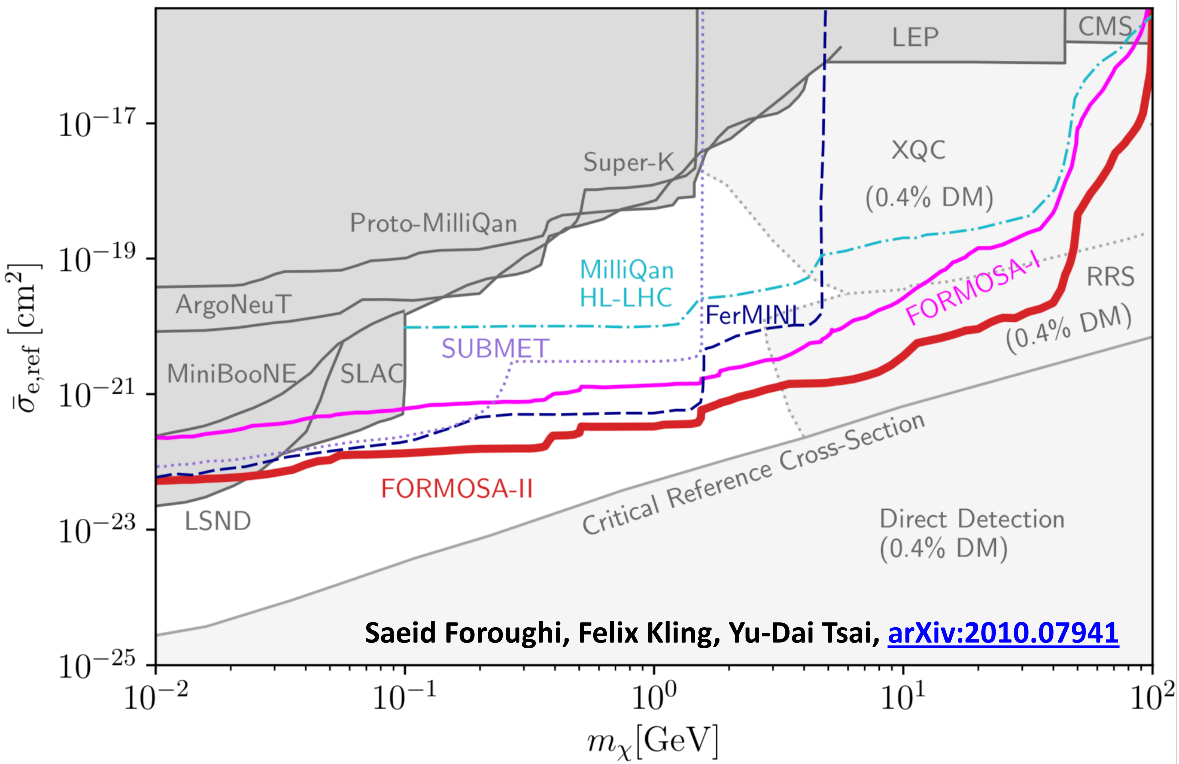
$$\bar{\sigma}_{\mathrm{e,ref}} = \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{\mathrm{d,ref}}^4}\,,\, q_{\mathrm{d,ref}} = \alpha m_e$$

- 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

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

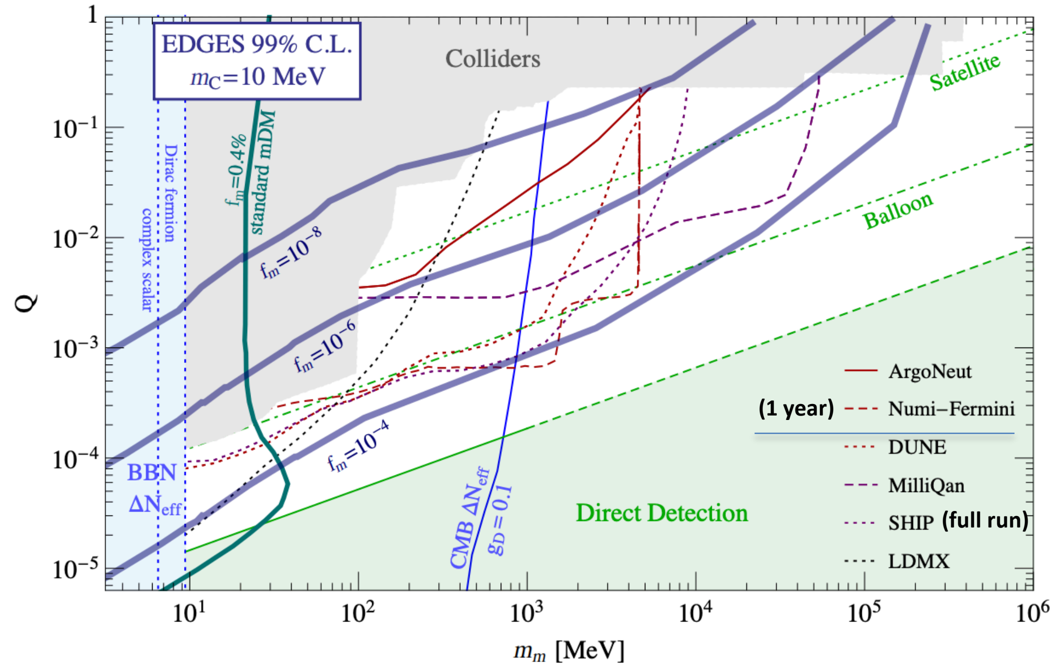


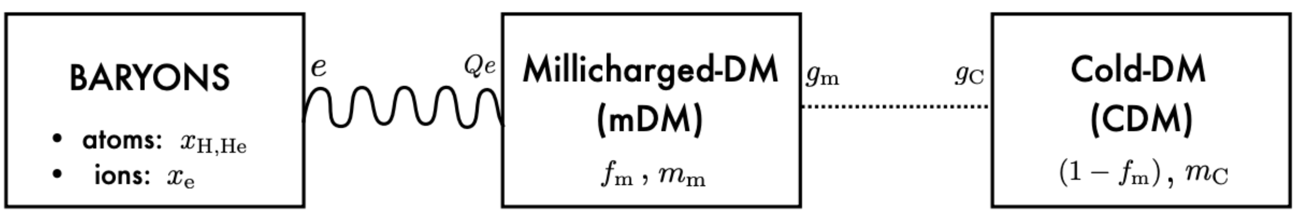
- We will add this figure with all the projections to the appendix of the LOI

- 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

Yu-Dai Tsai, Fermilab

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)

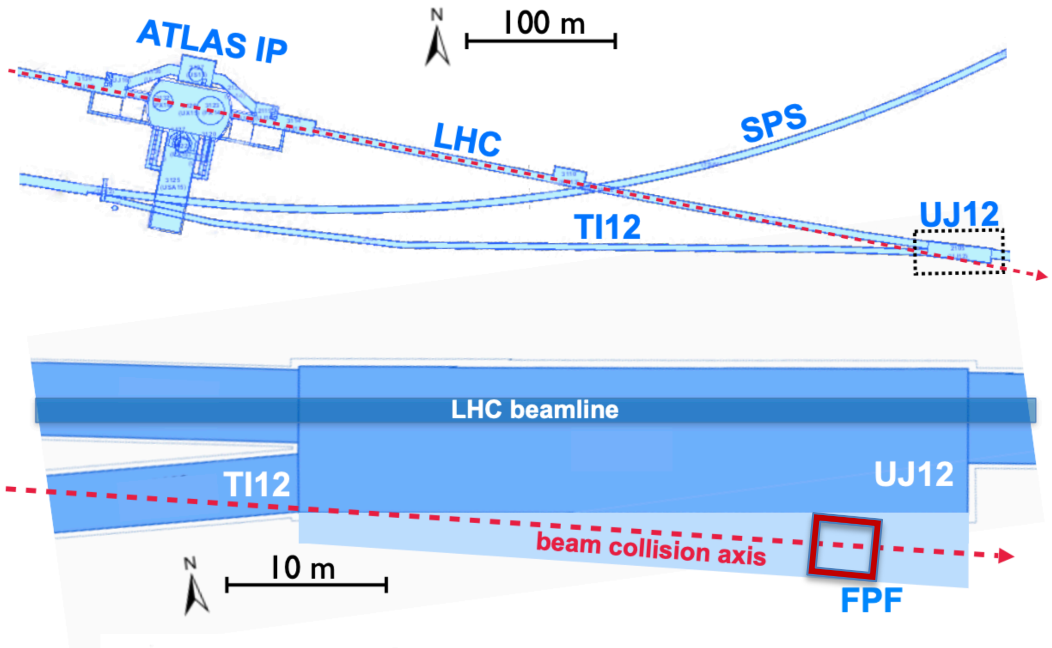
  (Sher, Stevens, 1710.06894, MoEDAL-MAPP, 1909.05216 , Chu +, 2001.06042)

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

  Strong advantage at the FORMOSA site!)

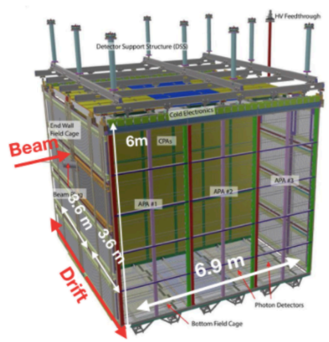
- Other Neutrino Physics Topics (maybe?)
- Saeid Foroughi, Felix Kling, Yu-Dai Tsai, ongoing

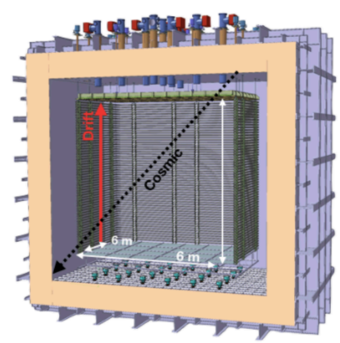
Forward Proto-DUNE & Neutrino Campus!



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

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



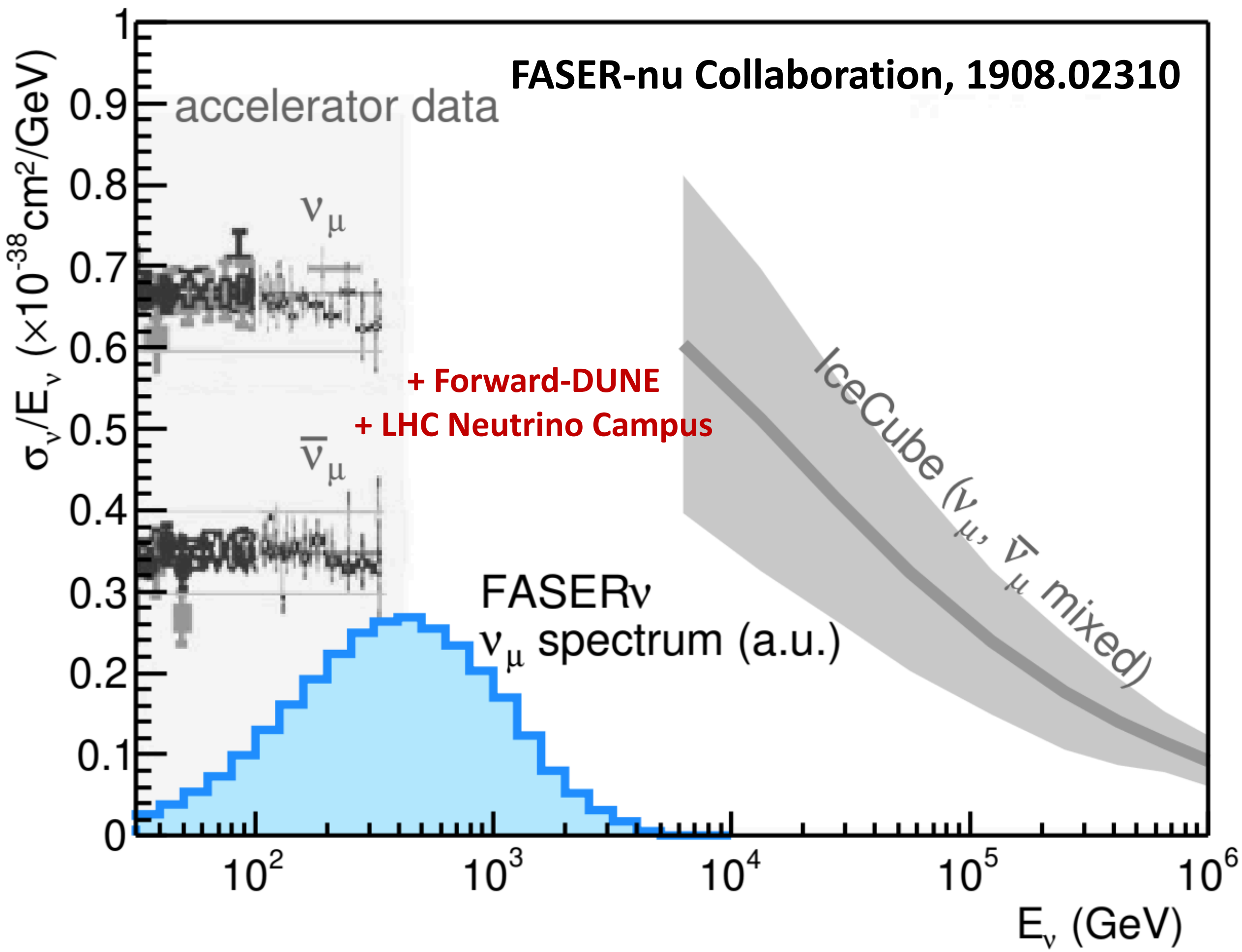


Duel-Phase (DP) Detector
6 x 6 x 6 m^3 LAr TPC

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

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)

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

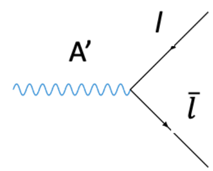
3. Simple design thus relatively low cost (tracking planes + ECal)

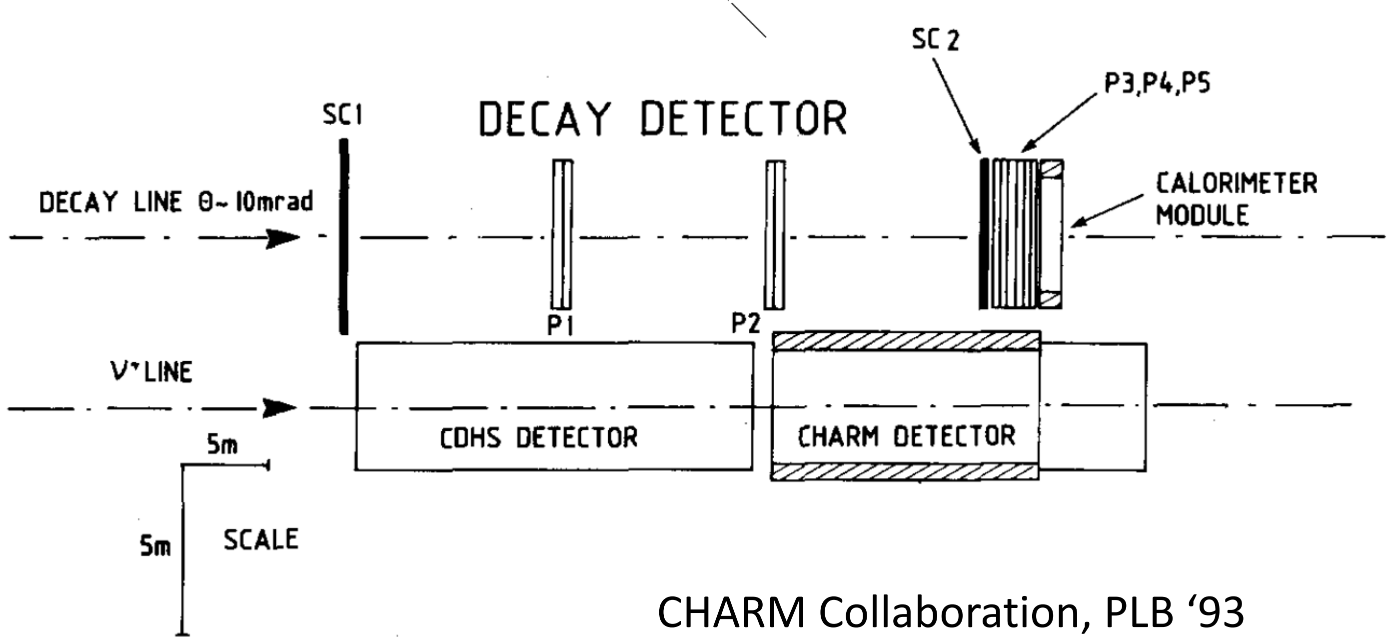
4. Often, there is external magnetic field (track separations/momentum reconstruction/filter-out soft SM radiation)

5. Usually studying **long-lived particles (mediators, e.g., dark photons)**

Decay Experiments/Detectors

CHARM Decay Detector

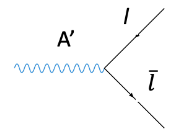




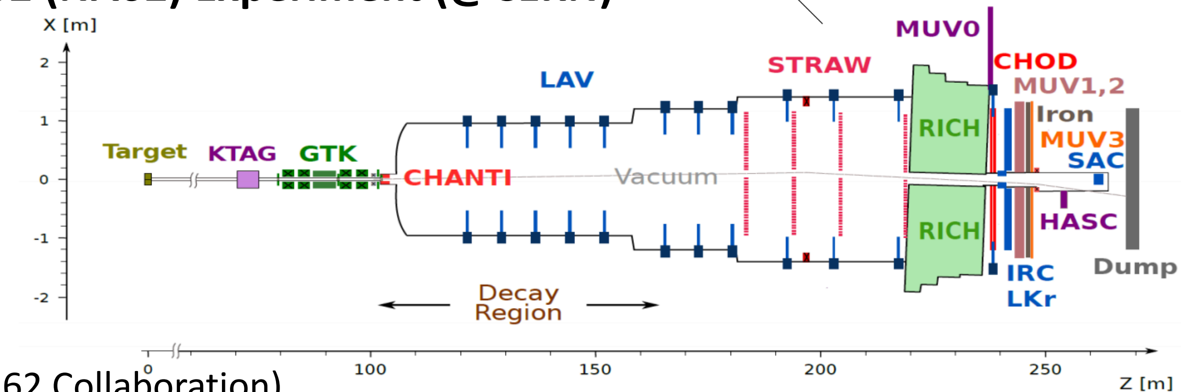
CHARM Collaboration, PLB '93

CHARM: CERN HAmburg Rome Moscow

Decay Experiments/Detectors



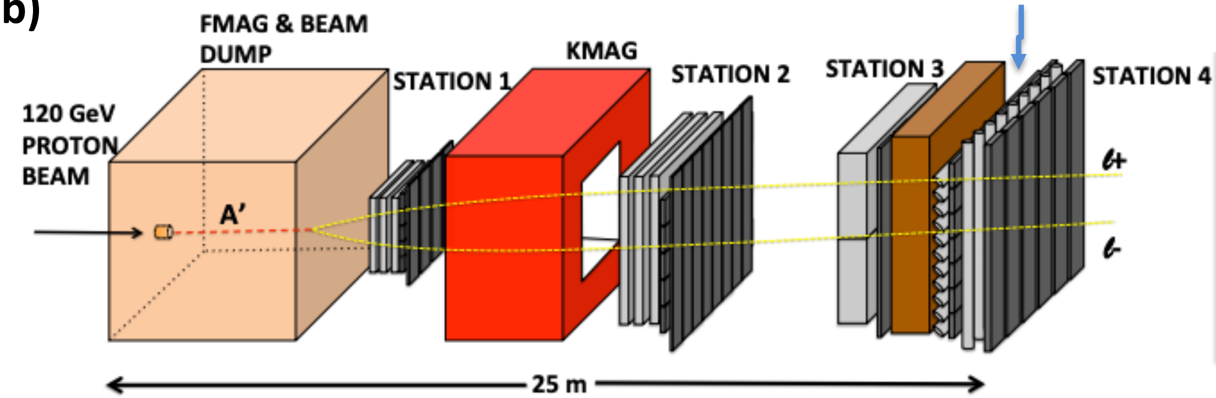
North Area 62 (NA62) Experiment (@CERN)

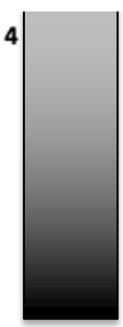


1703.08501 (NA62 Collaboration)

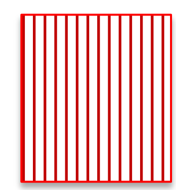
SeaQuest/LongQuest-Proposal, **Tsai**, deNiverville, Liu, '19 (@Fermilab)

Install ECAL from PHENIX





10m block

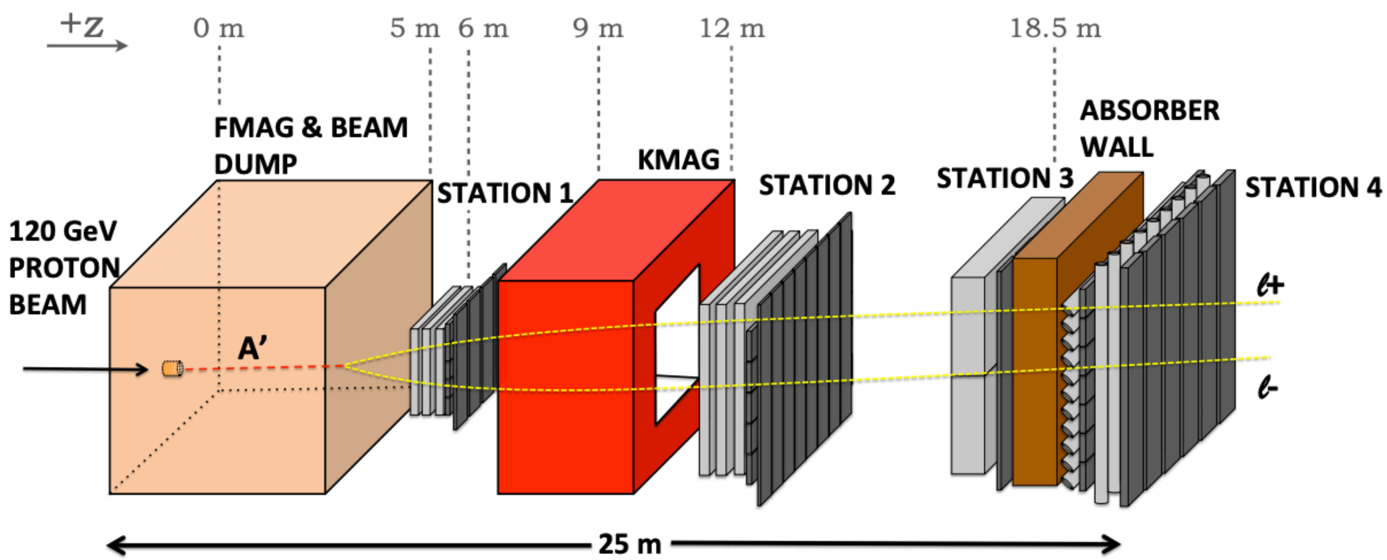


Another ECAL from PHENIX

Add a Ring Image Cherenkov Detector

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

DarkQuest



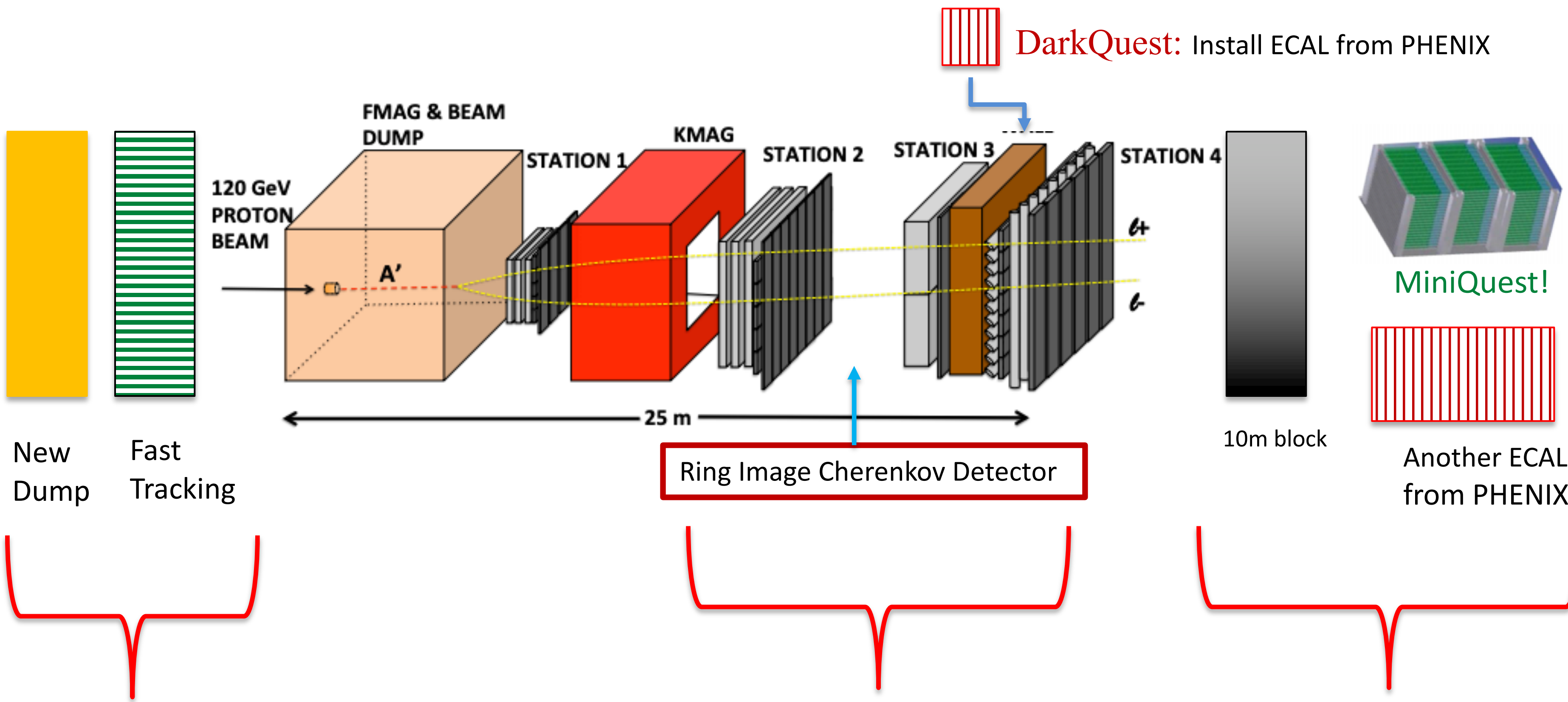
arXiv:1509.00050 (Gardner, Holt, Tadepalli); arXiv:1804.00661 (Berlin, Gori, Schuster, Toro)

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!

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

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

Future Probes

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

arXiv/1908.07525

Interesting Long-Lived Particles for Decay Studies

Yu-Dai Tsai, Fermilab, 2020

Renormalizable "Portals"

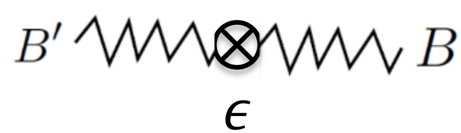
- Dark sectors can include mediator particles coupled to the SM via the following **renormalizable interactions.**
- **High-Dim. axion portal is also popular**

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

(Holdom, '85)

(See Dark-Sector 2016 report 1608.08632)

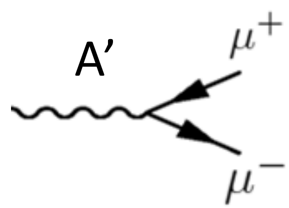
Low-energy effective interaction



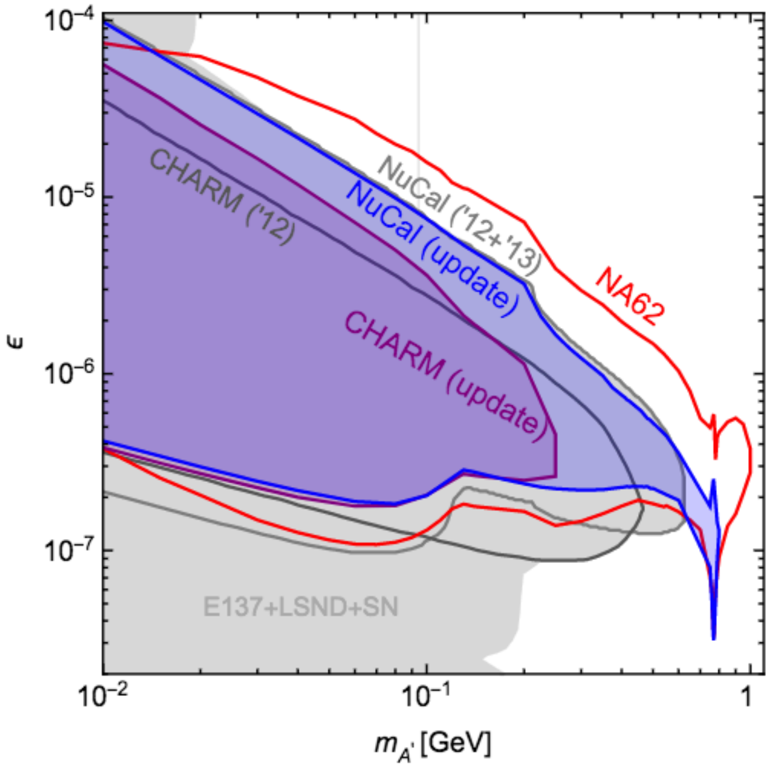
Mass from Dark Higgs or Stueckelberg

mass basis

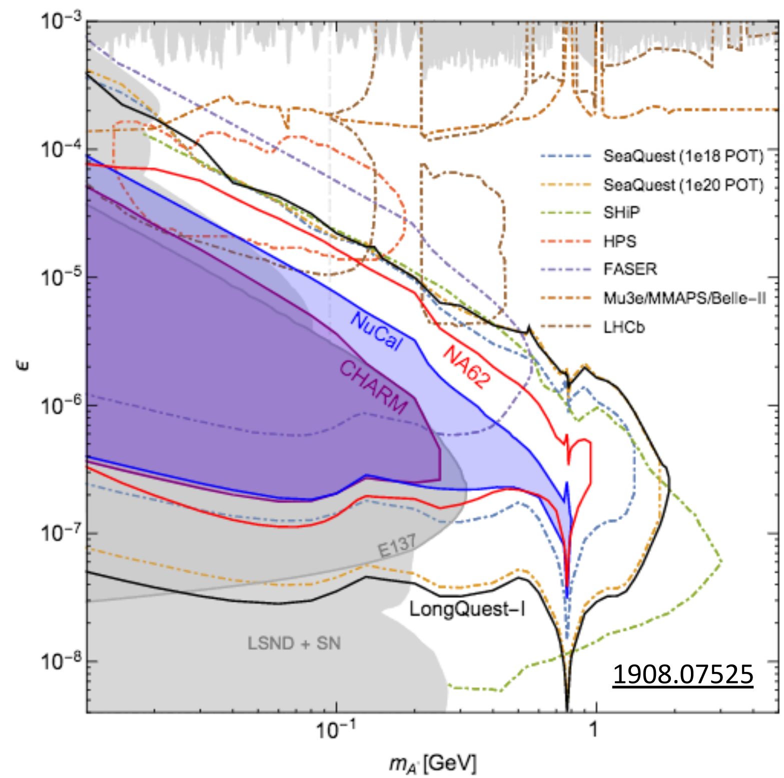
Dark photon A':



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)

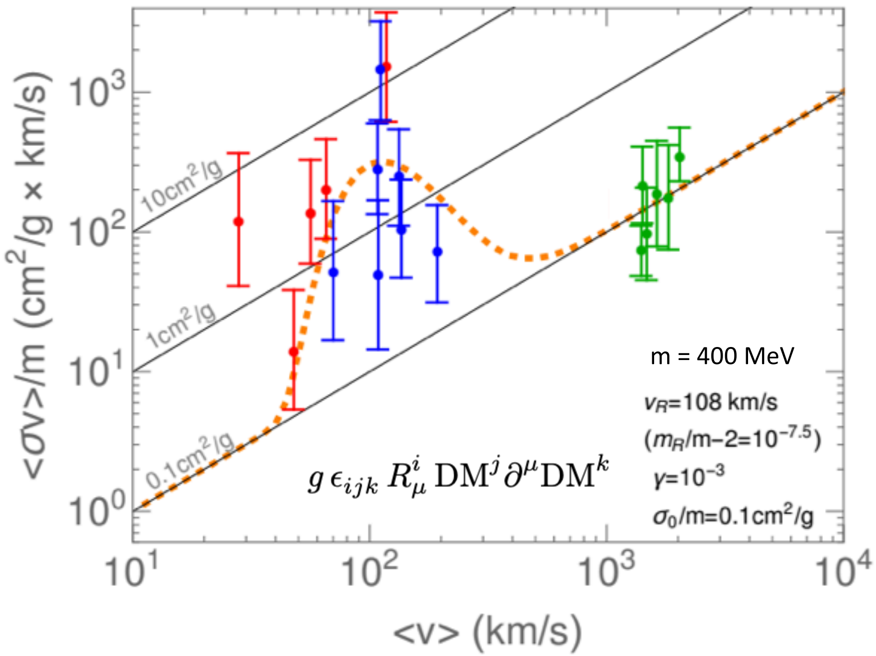
  Motivated by small-scale problems

Resonant Dark Mesons

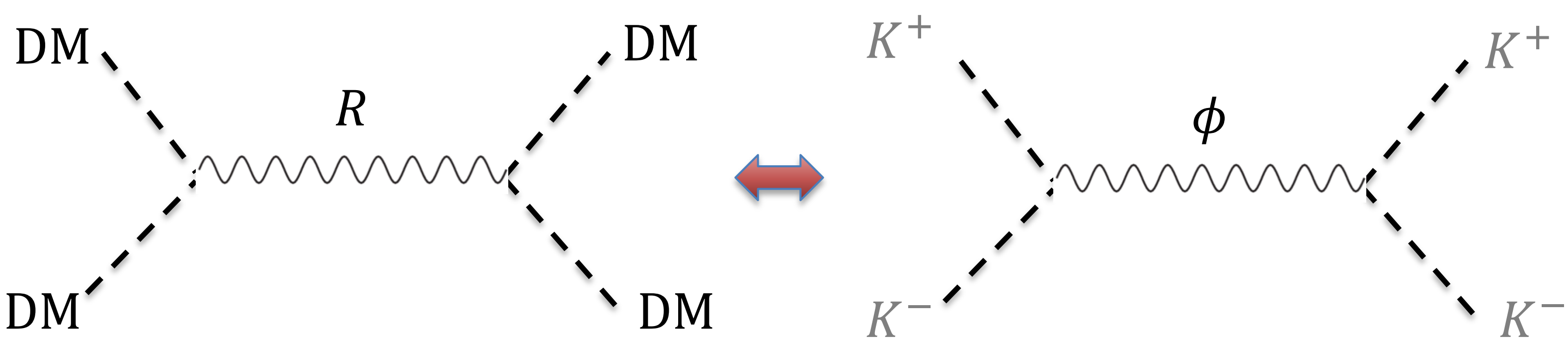
Yu-Dai Tsai, Fermilab, 2020

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

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

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

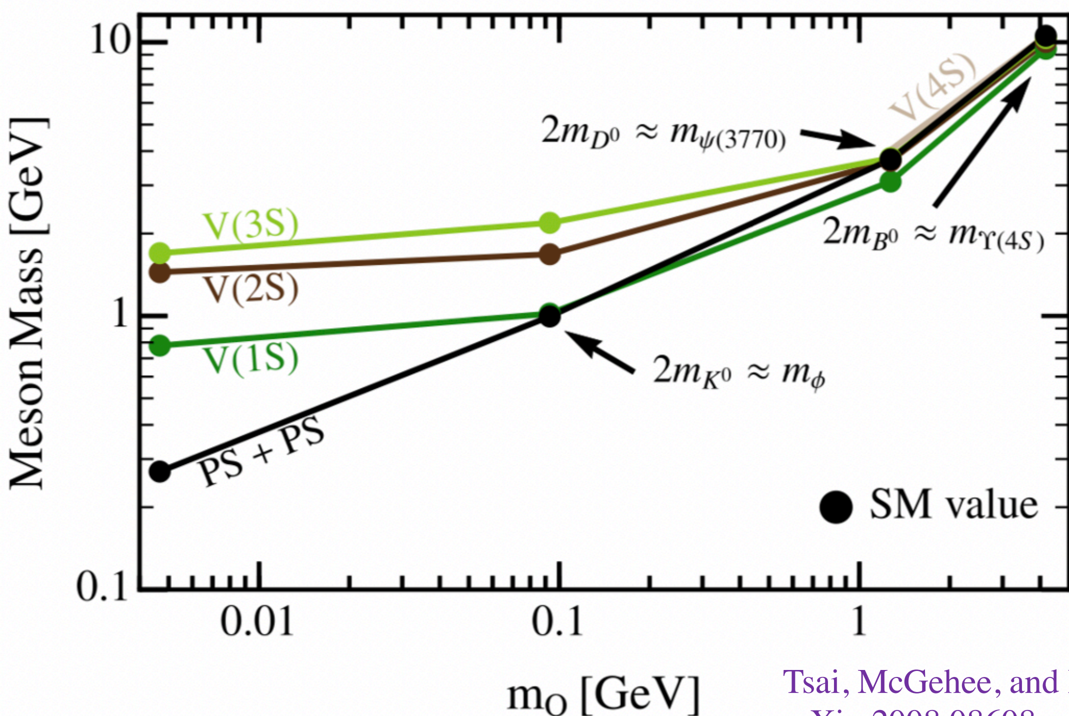
$$\frac{m(B_{s1}) - m(B^*) - m(K^0)}{m(B_{s1})} = 0.0011,$$

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

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

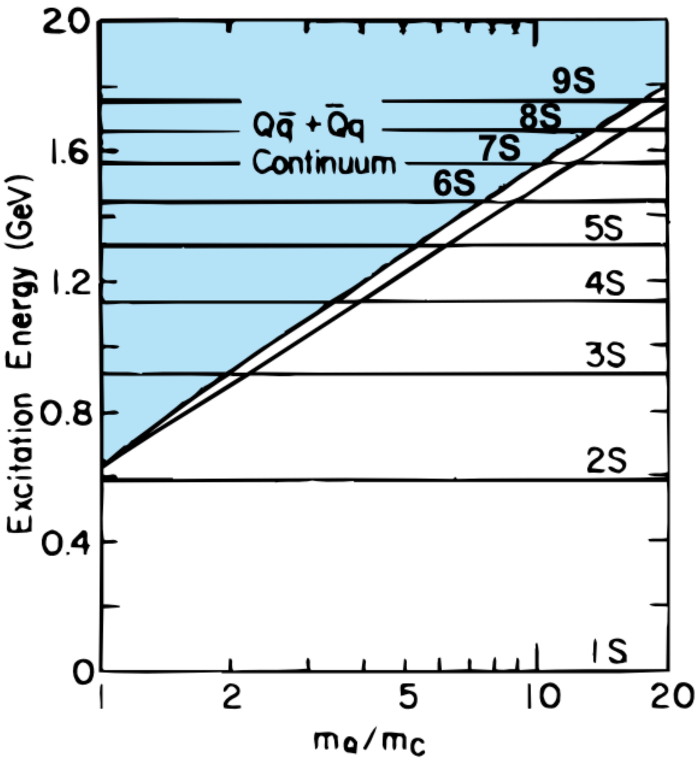


Tsai, McGehee, and Murayama, arXiv:2008.08608

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



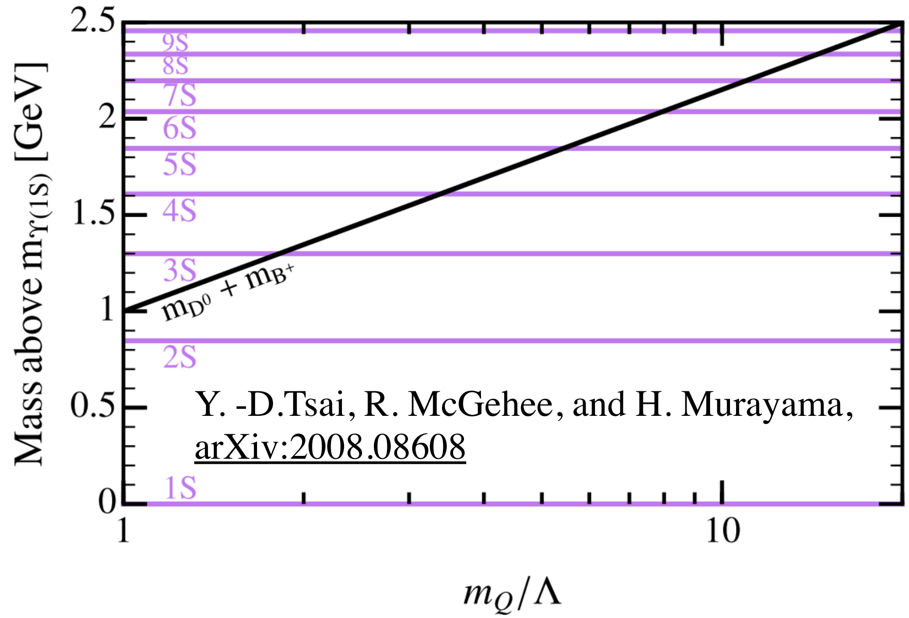


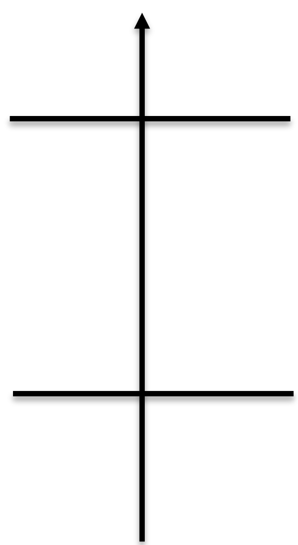
Figure 3: The crossings of the sum of heavy quark pseudoscalar meson masses and heavy quarkonium excited states for different heavy quark masses, m_Q.

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

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.



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

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 $n_c = n_{\bar{b}}$.

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

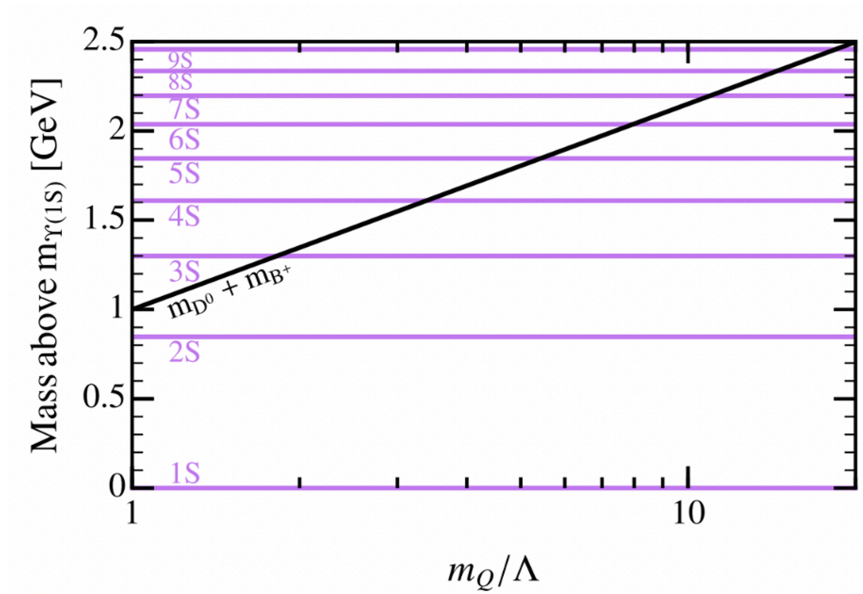
$$V(r) = C\ln(r/r_0)\,,$$

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

in the large n limit. The mass splitting is

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

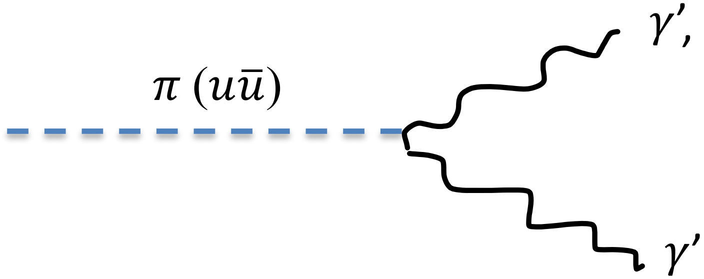
$$m_Q \approx n^2\left(\frac{4}{3e}\right)^2\Lambda.$$

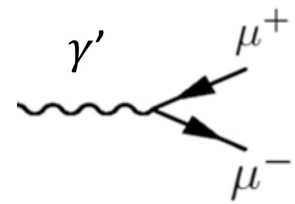


$$\Delta_n/m_Q \sim n^{-3}$$

Decays to Dark Photon

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



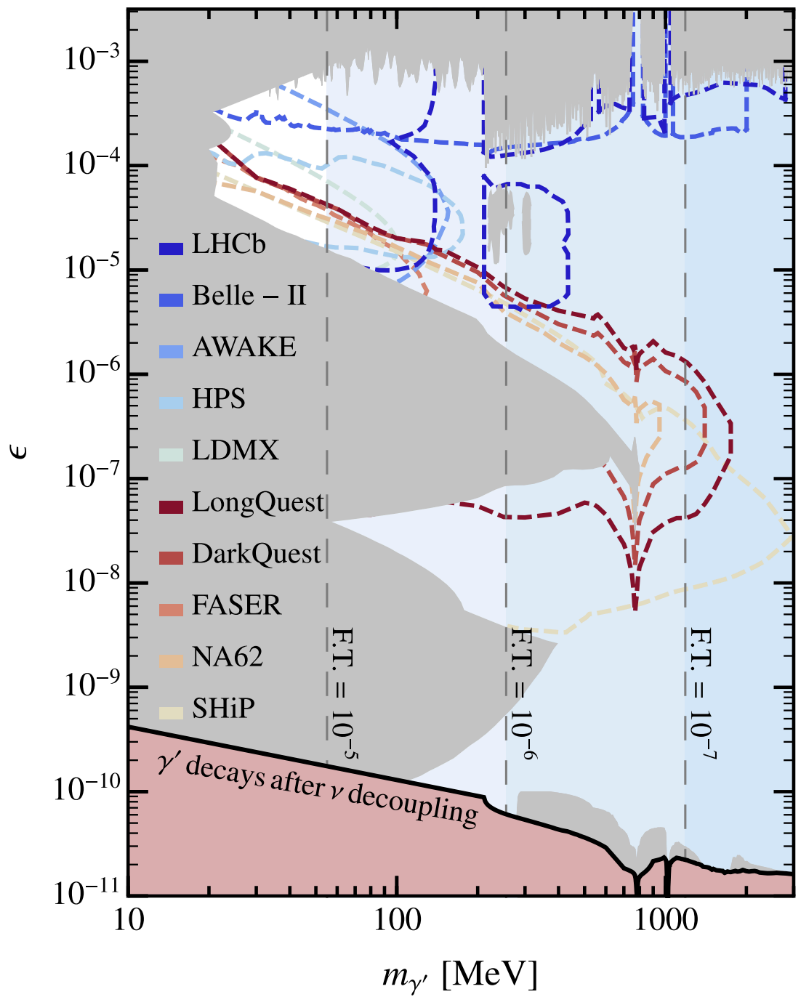


- $m_{ADM} = m_B \sim m_Q \sim 5\ m_P \sim 5$ GeV

- $\Lambda \sim m_\pi > 2\ m_{\gamma\prime}$
  (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

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

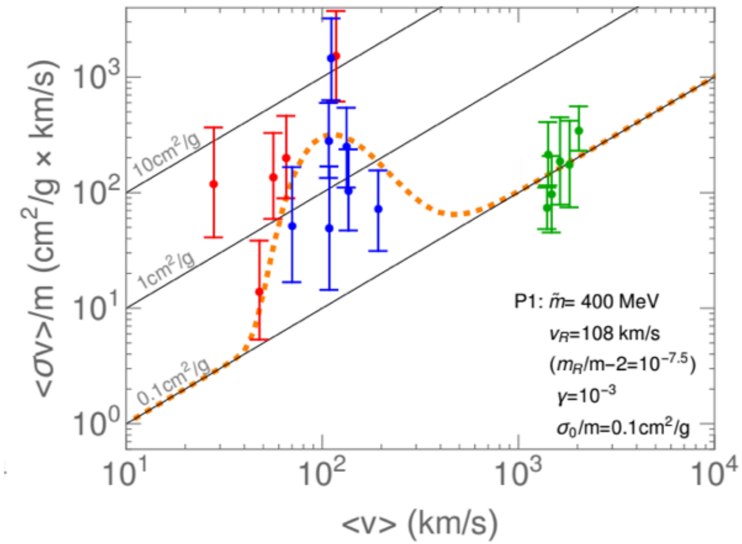
$m_Q \sim 5$ GeV

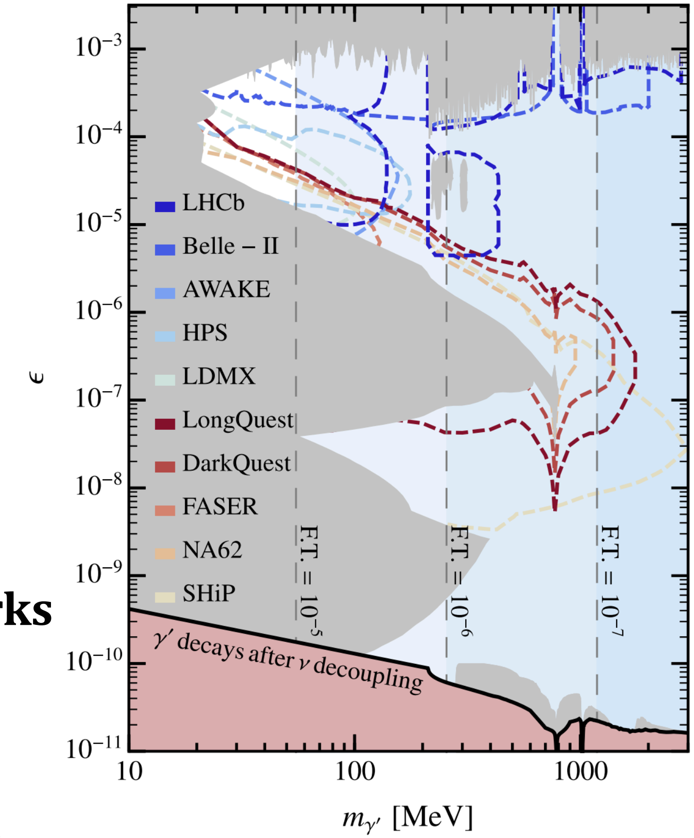
$m_Q/\Lambda \sim 10$ is desired

$\Lambda \sim m_{\pi'} > 2\, m_{\gamma'}$

(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 $\epsilon = 10^{-9} - 10^{-3}$

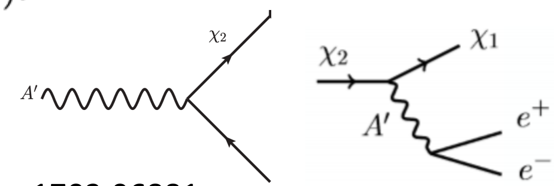
Inelastic Dark Matter

Yu-Dai Tsai, Fermilab, 2020

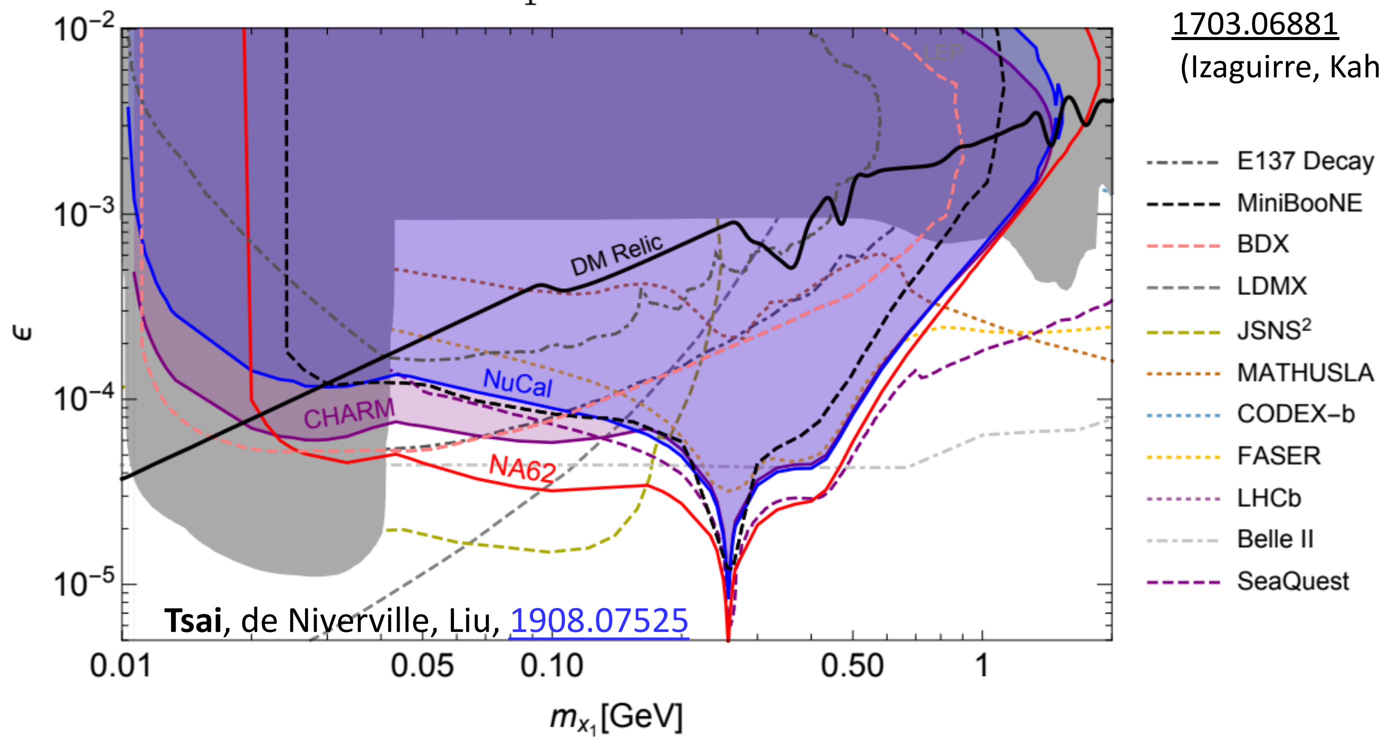
New Bounds on Inelastic Dark Matter

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**

Thank You!

Thanks for the Invitation!