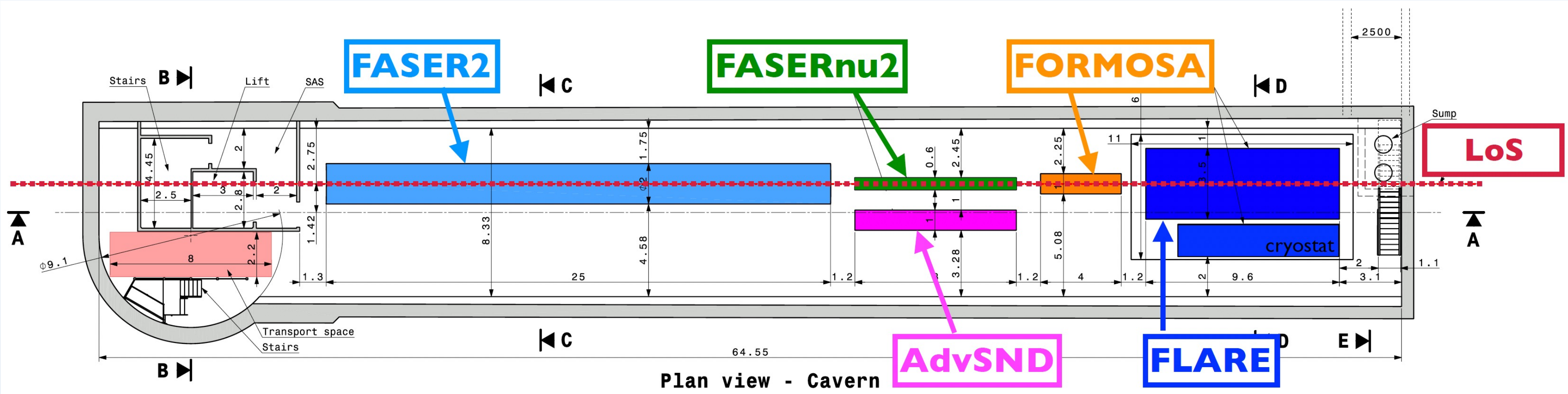


From Felix Kling, See, also, https://arxiv.org/pdf/2109.10905.pdf

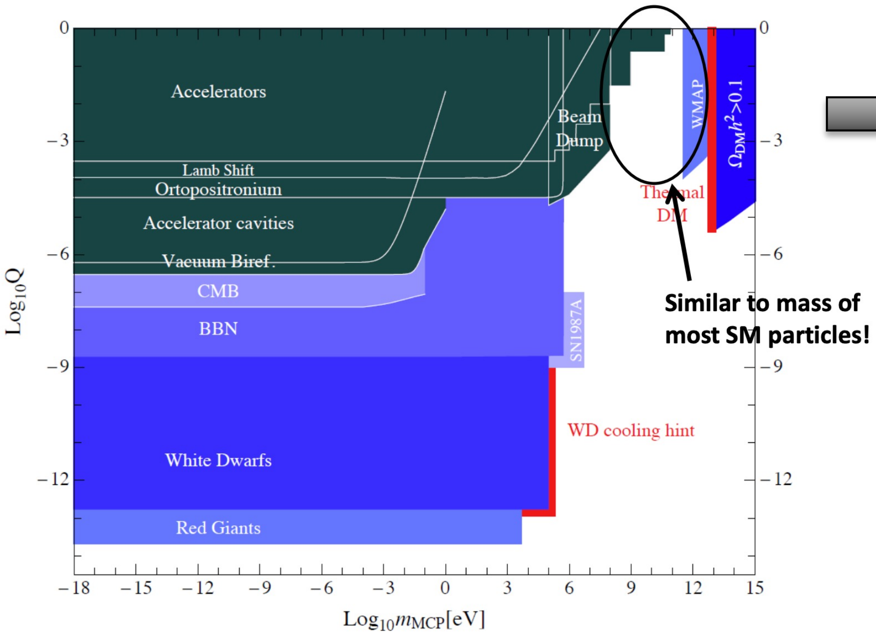
Millicharge Searches at the Forward Physics Facility: Theory Overview, FORMOSA, and FLArE

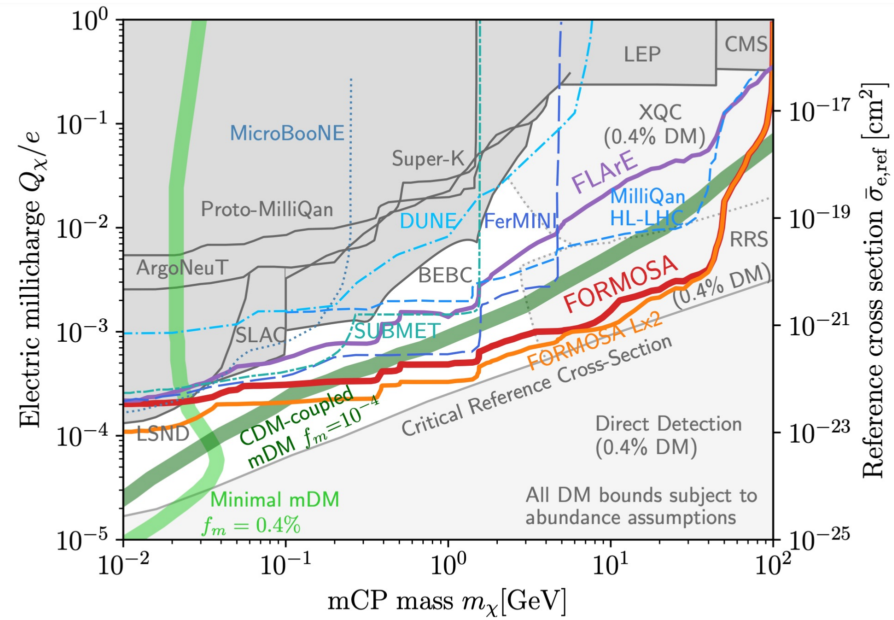
Details of related contributions/talks listed in slides
FORMOSA; FLArE; EM Form Factor; Proton Brem

Yu-Dai Tsai, **University of California, Irvine**

Contact: yt444@cornell.edu or yudait1@uci.edu

Tremendous Progress in Millicharge Studies





Andy Haas, Fermilab, 2017

- Both **experimental** & **theoretical** advances
- Led by **milliQan**, followed by neutrino experiments, **FerMINI, SUBMET, FORMOSA, FLArE**
- **EDGES** rejuvenated millicharged & strongly interacting dark matter
- **Quantum devises** to search for millicharged dark matter (mDM), from Quantised & Stanford

Millicharged Particles (mCP) is an important benchmark model

RF06 Classification; **PBC** Benchmark

Benchmarks in Final State x Portal Organization

	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	*m_χ vs. y [m_A/m_χ=3,α_D=.5]* **$m_{A'}$ vs. y** [α_D=0.5, 3 m_χ values] <u>m_χ vs. α_D [m_A/m_χ=3, y=y_{fo}]</u> m_χ vs. m_A [α_D=0.5, y=y_{fo}] *Millicharge m vs. q*	<u>$m_{A'}$ vs. ϵ [decay-mode agnostic]</u> ***$m_{A'}$ vs. ϵ [decays]***	**iDM m_χ vs. y [$m_{A'}/m_\chi$=3,α_D=.5] (anom connection)** **SIMP-motivated cascades [slices TBD]** $U(1)_{B-L / \mu-\tau / B-3\tau}$ (DM or SM decays)
Scalar	m_χ vs. sinθ [λ=0, fix m_S/m_χ, g_D] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	*m_S vs. sinθ* [λ=0] *m_S vs. sinθ* [λ=s.t. Br(H→ss ~10^{-2})]?	Dark Higgsstrahlung (w/vector) scalar SIMP models Leptophilic/leptophobic dark Higgs
Neutrino	e/μ/τ a la1709.07001	*m_N vs. U_e* *m_N vs. U_μ* *m_N vs. U_τ* Think more about reasonable flavor structures	Sterile neutrinos with new forces
ALP	m_χ vs. fq/l [λ=0, fix m_a/m_χ, g_D] (thermal target excluded) What about f_γ, f_G?	*m_a vs. f_γ* *m_a vs. f_G* *m_a vs. f_q=f_l* *m_a vs. f_w*	FV axion couplings

Bold = BRN benchmark, *italic=PBC benchmark.* others are new suggestions. <u>Underline=CV benchmarks that were not used in BRN</u>

PBC: The Physics Beyond Colliders initiative at CERN

Millicharged Particles @ Snowmass

Accelerator Probes of Millicharged Particles and Dark Matter

Authors: (the endorsers are now listed in the second page)
Yu-Dai Tsai (Fermilab), Jonathan Assadi (UT Arlington), Matthew Citron (UC, Santa Barbara), Albert De Roeck (CERN), Saeid Foroughi-Abari (U Victoria), Gianluca Petrillo (SLAC), Yun-Tse Tsai (SLAC), Jaehoon Yu (UT Arlington)

Endorsers:

Joshua Barrow (University of Tennessee, Knoxville)
Joshua Berger (Colorado State University)
Joseph Bramante (Queen's University)
Paolo Crivelli (ETH Zurich)
Mohamed Darwish (U Antwerpen, Belgium)
Patrick deNiverville (LANL)
Jonathan Lee Feng (UC Irvine)
William Foreman (Illinois Institute of Technology)
Maria Vittoria Garzelli (University of Hamburg)
Spencer Gessner (SLAC)
Carlo Giunti (INFN Torino)
Sergei Gninenko (Institute for Nuclear Research, Moscow)
Frank Golf (University of Nebraska-Lincoln)
Jan Hajer (Université catholique de Louvain)
Roni Harnik (Fermilab)
Anthony Hartin (UCL)
Christopher S. Hill (Ohio State University)
Matheus Hostert (University of Minnesota)
Gianluca Inguglia (Austrian Academy of Sciences)
Catherine James (Fermilab)
Sudip Jana (Max-Planck-Institut für Kernphysik)
Jay Hyun Jo (Yale University)
Kevin Kelly (Fermilab)
Doojin Kim (Texas A&M University)
Dmitry Kirpichnikov (INR RAS)
Felix Kling (SLAC)
Simon Knapen (CERN)
Willem G.J. Langeveld (Verified Logic)
Ivan Lepetic (Rutgers University)
Bryce Littlejohn (Illinois Institute of Technology)
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Julian B. Munoz (CfA-SAO)
Ornella Palamara (Fermilab)
Vishvas Pandey (University of Florida)
Zarko Pavlovic (Fermilab)
Alexey Petrov (Wayne State University)
James Pinfold (CERN)
Ryan Plestid (University of Kentucky)
Thomas Rizzo (SLAC)
Ryan Schmitz (UC Santa Barbara)
Philip Schuster (SLAC)
Dipan Sengupta (UC San Diego)
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Alex Sousa (University of Cincinnati)
Shufang Su (University of Arizona)
Maximilian Swiatlowski (TRIUMF)
Volodymyr Takhistov (UCLA)
Douglas Tuckler (Carleton University)
Jaehyeok Yoo (Korea University)
Jilberto Zamora-Saa (Universidad Andres Bello)

Snowmass LOI: link

Sensitivity reach of scintillation-based detectors for millicharged particles

Matthew Citron,[1] Christopher S. Hill,[2] David W. Miller,[3] David Stuart,[1] A. De Roeck,[4] Yu-Dai Tsai,[5,3] and Jae Hyeok Yoo[6]

[1] *University of California, Santa Barbara, California 93106, USA*
[2] *The Ohio State University, Columbus, Ohio 43218, USA*
[3] *University of Chicago, Chicago, Illinois 60637, USA*
[4] *CERN, Geneva 1211 Switzerland*
[5] *Fermi National Accelerator Laboratory (Fermilab), Batavia, Illinois 60510, USA*
[6] *Korea University, Seoul 02841, Republic of Korea*

(Dated: March 30, 2021)

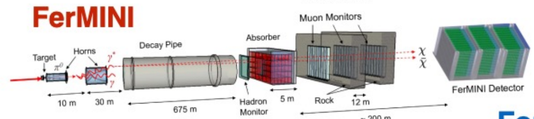
In this project we will evaluate the sensitivity for particles with charge much smaller than the electron charge with dedicated scintillator-based detectors at a range of facilities, including the CERN LHC, Fermilab and J-PARC. The data from the milliQan demonstrator will be used to comprehensively evaluate backgrounds for each detector, as well as provide a robust simulation of the response of the detector to low-charge particles.

Scintillation based detection

More details on SUBMET/FerMINI in Nahn's talk tomorrow!

LHC with sensitivity for m < ~45 GeV
1607.04669

J-PARC with sensitivity for m < ~1.5 GeV
2007.06329



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 6

Matthew's slide

FOROMOSA: https://indico.cern.ch/event/1110746/contributions/4701718/

Theory overview & connections to cosmic frontier (CF)

Theoretical Motivations

- **Is electric charge quantized and why?** A long-standing question!
- SM U(1) allows arbitrarily small (any real number) charges.
  Why don't we see them? Motivates
  Dirac quantization, Grand Unified Theory (GUT), to explain such quantization
  (anomaly cancellations fix some SM $U(1)_Y$ charge assignments)
- MCP (not confined) is predicted by some Superstring theories:
  Wen, Witten, Nucl. Phys. B 261 (1985) 651-677
  https://www.youtube.com/watch?v=AmUI2qf9uyo (watch 15:50 to 17:28)
- Link to **string compactification** and **quantum gravity** (Shiu, Soler, Ye, PRL '13)
- Conservatively, testing if e/3 is the minimal charge
- Simply a search for particles with **{mass, electric charge}** = $\{m_\chi, \epsilon e\}$

$\epsilon = Q_x/e$

mCP Model

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

- ϵ' can in principle be arbitrarily small.

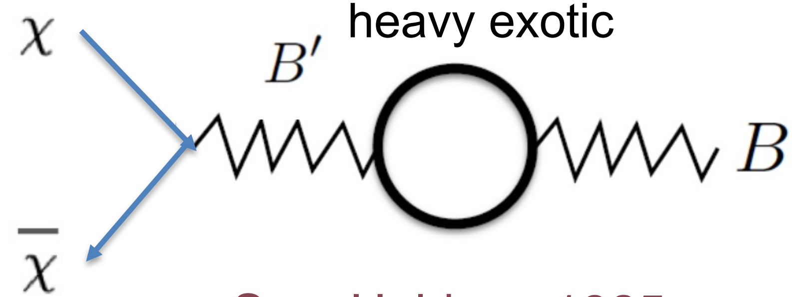
- Can just consider these Lagrangian terms by themselves (no extra mediator, i.e., dark photon).
  Completely legal! Naively **violating the empirical charge quantization** (cool).

- We are simply search for MCP!
  Minimal assumptions = most robust constraints/probes.

- This could come from vector portal **Kinetic Mixing** (Holdom, '85)
  - a nice origin to the above terms
  - help give rise to **dark sectors**
  - easily compatible with **Grand Unification Theory**

Kinetic Mixing and MCP Phase

- **Coupled to new dark fermion χ**



(SM: Standard Model)

See, Holdom, 1985

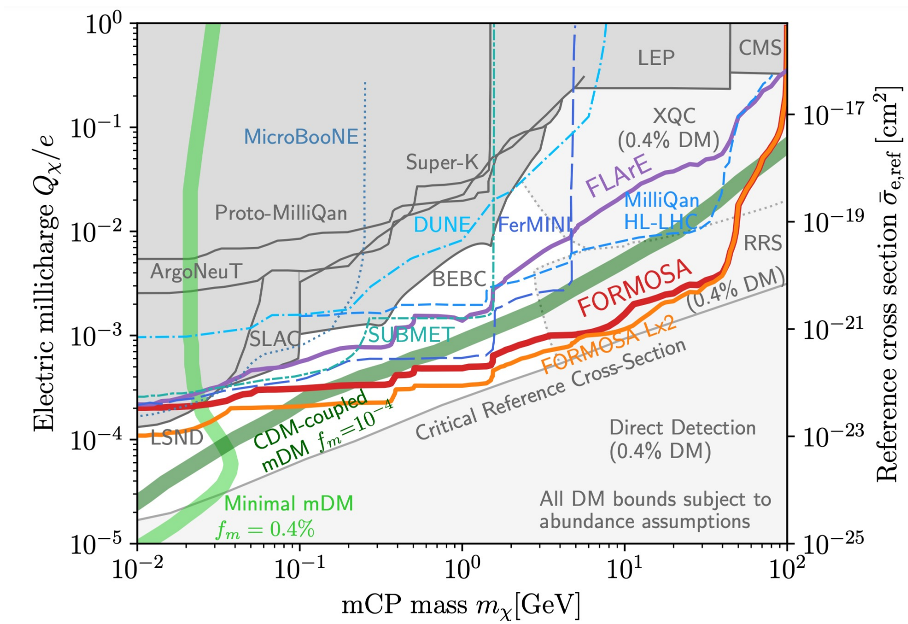
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} B'_{\mu\nu} B'^{\mu\nu} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ + ie' B\!\!\!/' + iM_{\rm MCP})\chi$$

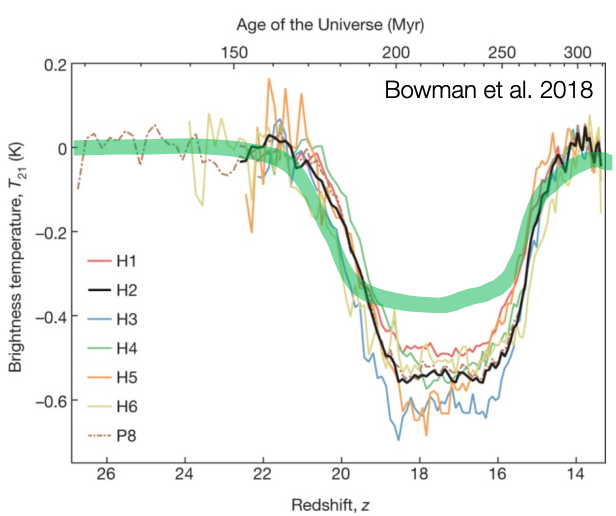
- New fermion χ charged under new gauge boson B'.

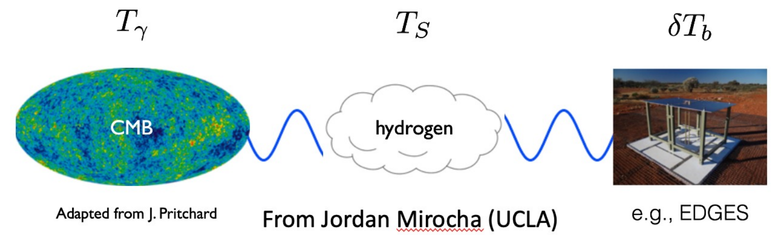
- Millicharged particle (MCP) can be a **low-energy consequence** of **massless dark photon** (a new U(1) gauge boson) coupled to **a new fermion (become MCP** in a convenient basis.)

What if dark matter (DM) is millicharged

CF: EDGES & Millicharged Dark Matter





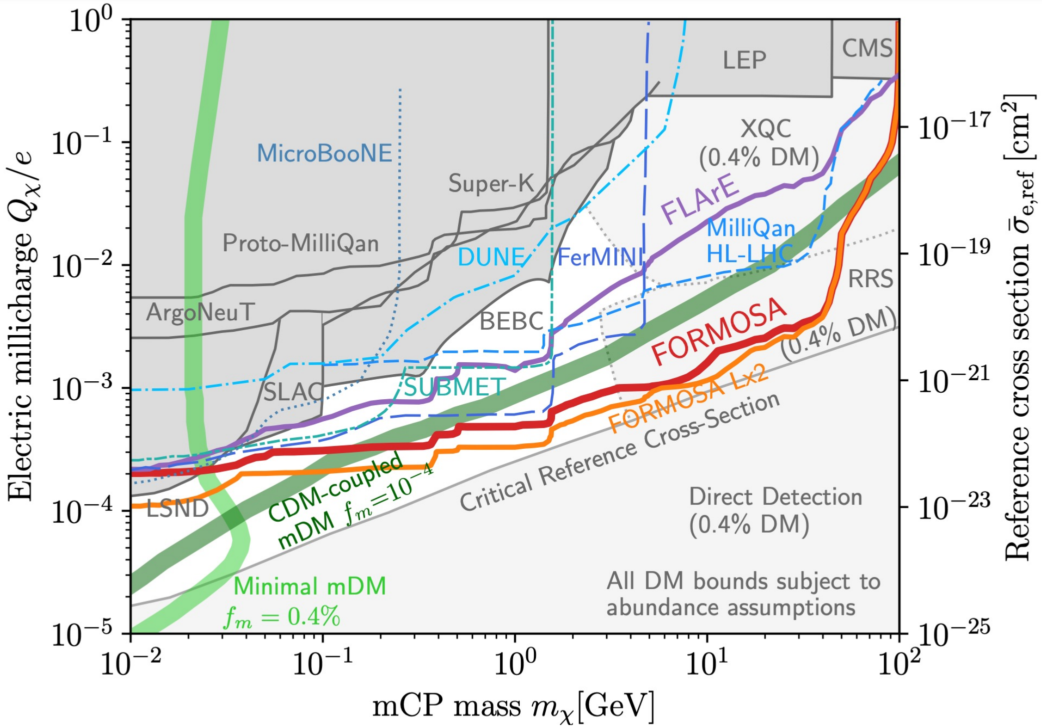


- EDGES gives another hint of dark matter property, just like small-scale structure
- **Can add this to new milliQan papers**
- Connecting to **cosmology** & **dark matter** direct-detection folks
- Demonstrate to **them the power of accelerator probes** & **milliQan-type detectors**
- See Liu, Outmezguine, Redigolo, Volansky, ’19 for the 10^{-4} curve

CF: Strongly Interacting Dark Matter

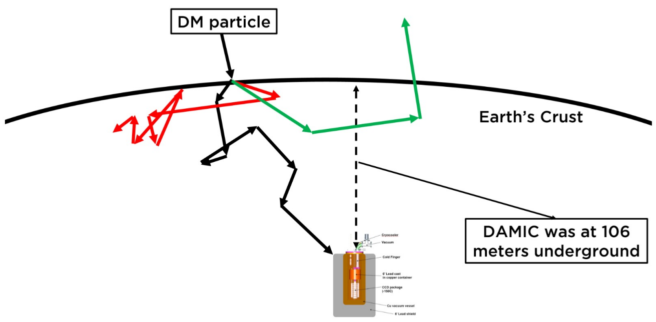
MCP / LDM with ultralight dark photon mediators

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



Saeid Foroughi, Felix Kling, Yu-Dai Tsai, arXiv:2010.07941

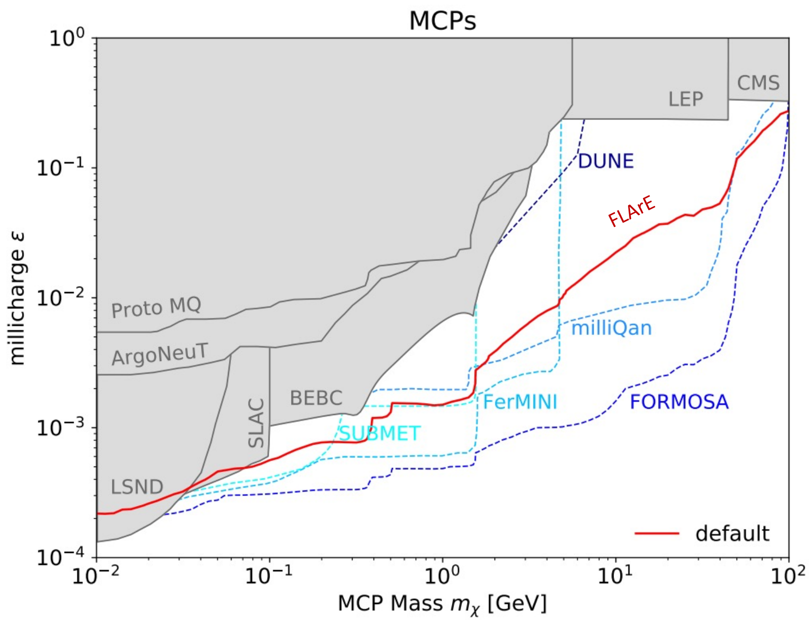
- We will add this figure with all the projections to the Snowmass White Paper
- **Can add this to new milliQan papers**

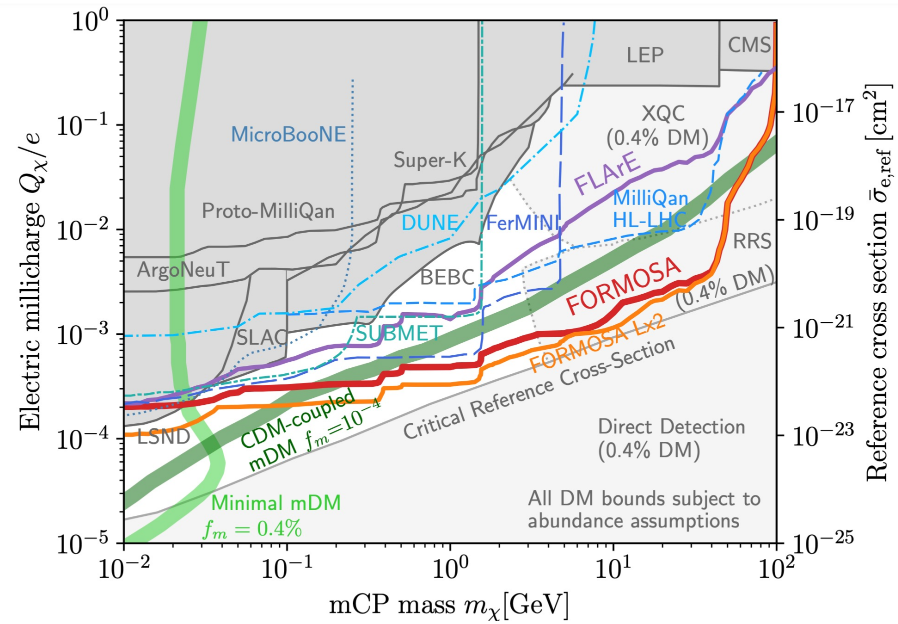


DMATIS (Dark Matter ATtenuation Importance Sampling), Mahdawi & Farrar '17

- 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

Probes for Millicharged Particles & DM



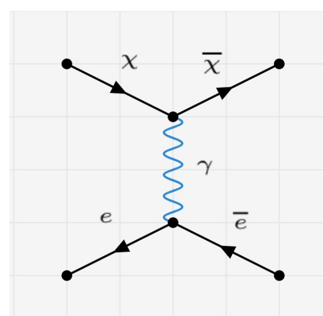


- Colliders
- Proton fixed-target and neutrino experiments
- Lepton fixed-target experiments
- Cosmic-ray accelerator
- LOT: https://www.snowmass21.org/docs/files/summaries/RF/SNOWMASS21-EF9_EF10_NF3_NF5_CF1_CF3_CF7_TF7_TF8_TF9_AF5_UF3_Yu-Dai_Tsai-114.pdf

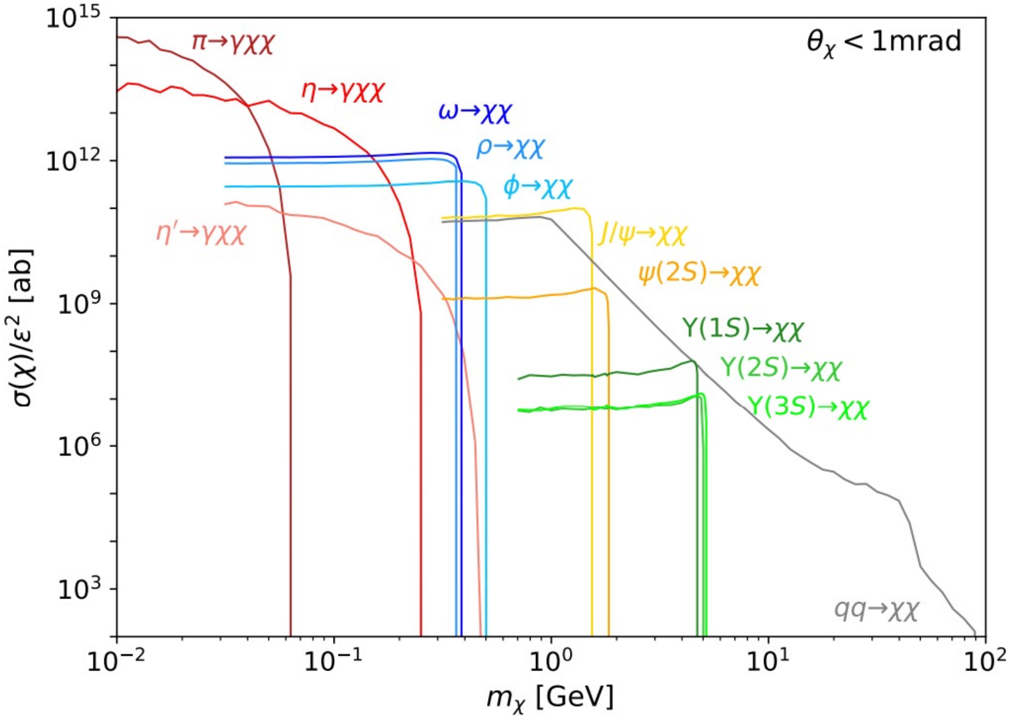
MCP is interesting itself, and is one of the **simplest dark-sector test models** for accelerator experiments

Productions & Signatures @ FPF

Sensitivity greatly enhanced by **measuring low-energy electron recoils or scintillations & ionizations, for both mCP and light-mediator DM scattering**



mCP Productions @ FPF



Foroughi-Abari, Kling, and **Tsai**, arXiv:2010.07941, PRD 20

MCP production was added to FORESEE by Felix

Ongoing works to add to production channels, see Foroughi-Abari, Ritz, arXiv:2108.05900

mCP Signatures in FPF

- 1. **mCP** scintillation/ionization
  FORMOSA

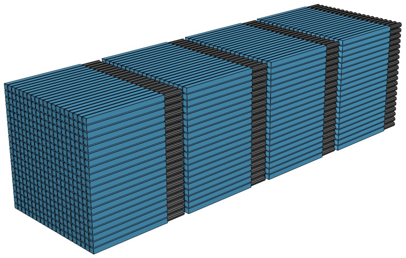
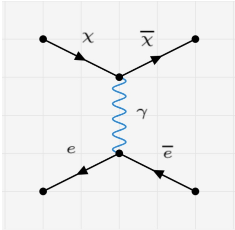
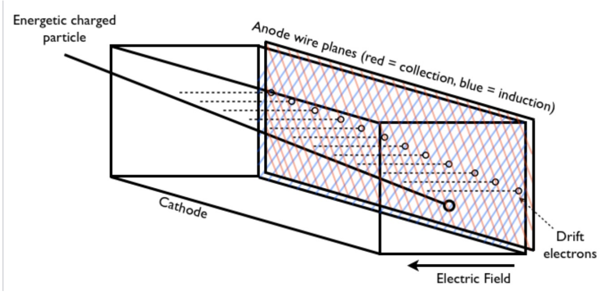


FIG. 13. A diagram of the FORMOSA detector components. The scintillator bars are shown in blue connected to PMTs in black.

- 2. Electron scattering:
  FLArE:





https://en.wikipedia.org/wiki/Time_projection_chamber

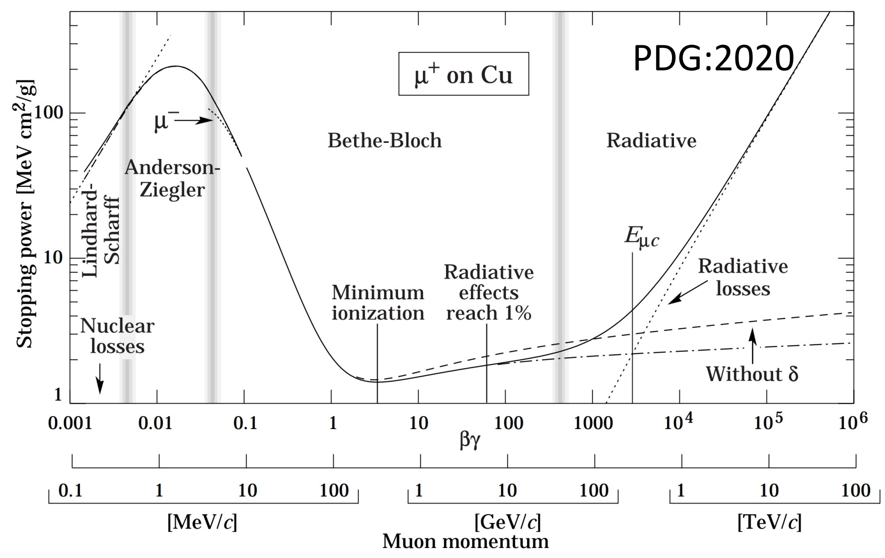
$$\sigma_{e\chi} \simeq 2.6 \times 10^{-25}\text{cm}^2 \times \epsilon^2 \times \frac{1\ \text{MeV}}{E_e^{(\text{min})} - m_e}.$$

Expressed in **recoil energy threshold**, $E_e^{(min)}$

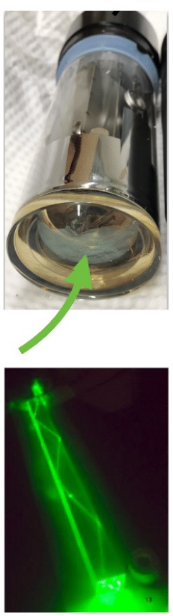
mCP @ FORMOSA

- Want very low momentum transfer**: ionization and scintillation signature**
- Signature proportional to **- dE/dx of the MCP, referred to as energy loss/stopping power**

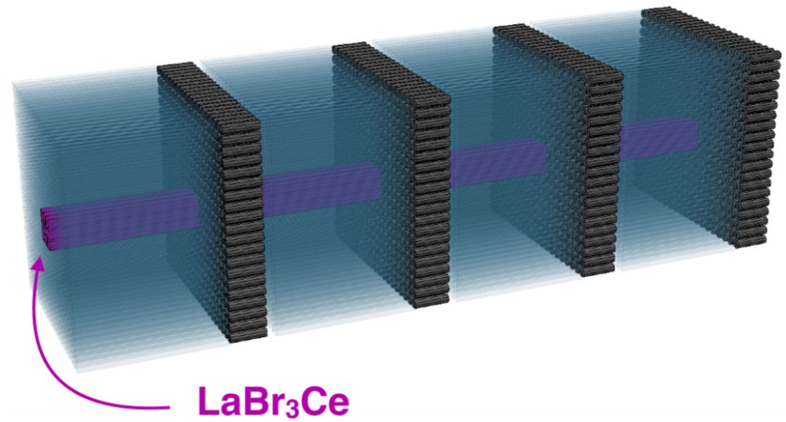
$$\left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2.$$

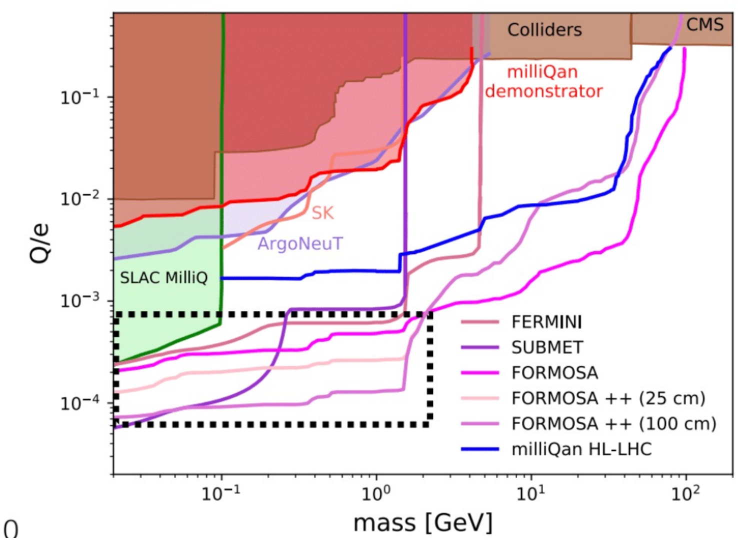


mCP @ FORMOSA



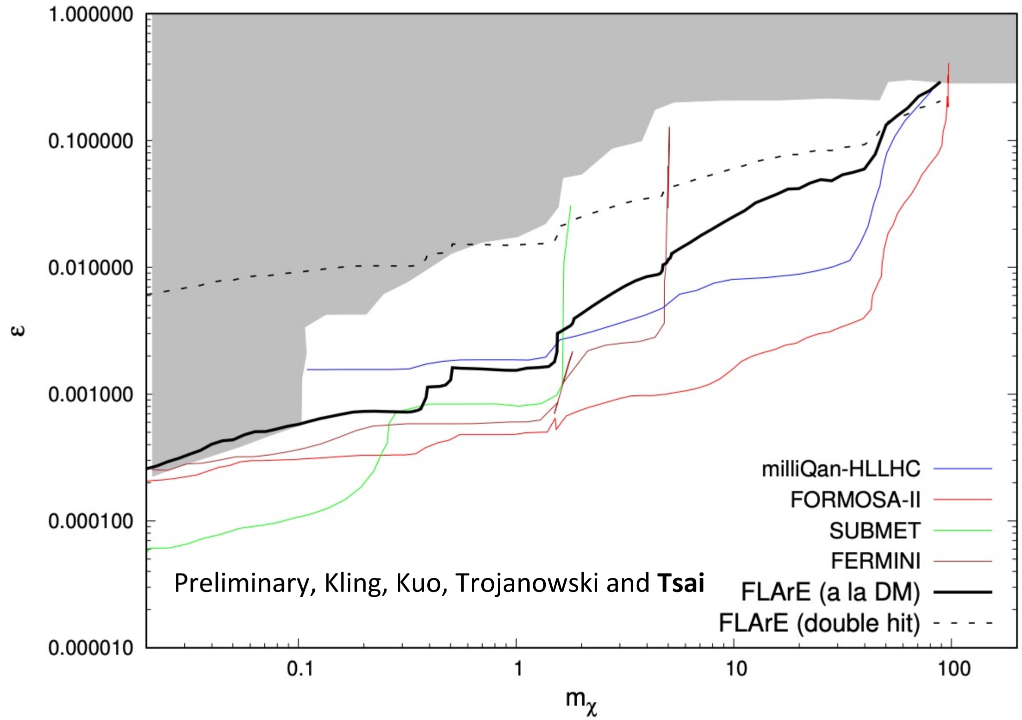
- **Key idea**: use scintillator bar array to detect (very) small ionisation from low charged particles
- Expected signal: few scintillation photons in multiple layers
- Each bar + PMT must be capable of detecting a single scintillation photon
- Control backgrounds: signal in each layer within small (~15 ns) time window and that points towards the IP
- Modular design is easy to scale and adapt!





M. Citron mcitron@ucsb.edu

mCP @ FLArE



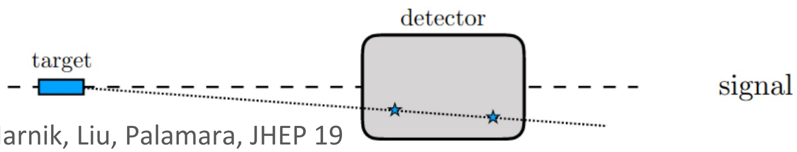
FLArE experiment by Jianming Bian: https://indico.cern.ch/event/1110746/contributions/4701719/

A. Scattering a-la DM signal: consider $\chi e \rightarrow \chi e$,

   and set electron recoil energy Er within 30 MeV $\lesssim$ Er $\lesssim$ 3 GeV in FLArE

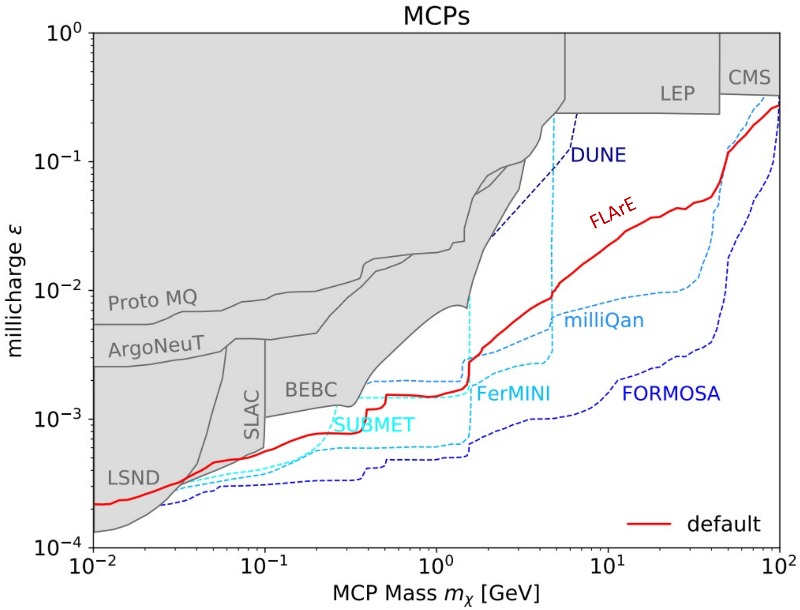
B. Double-hit with softer recoils:

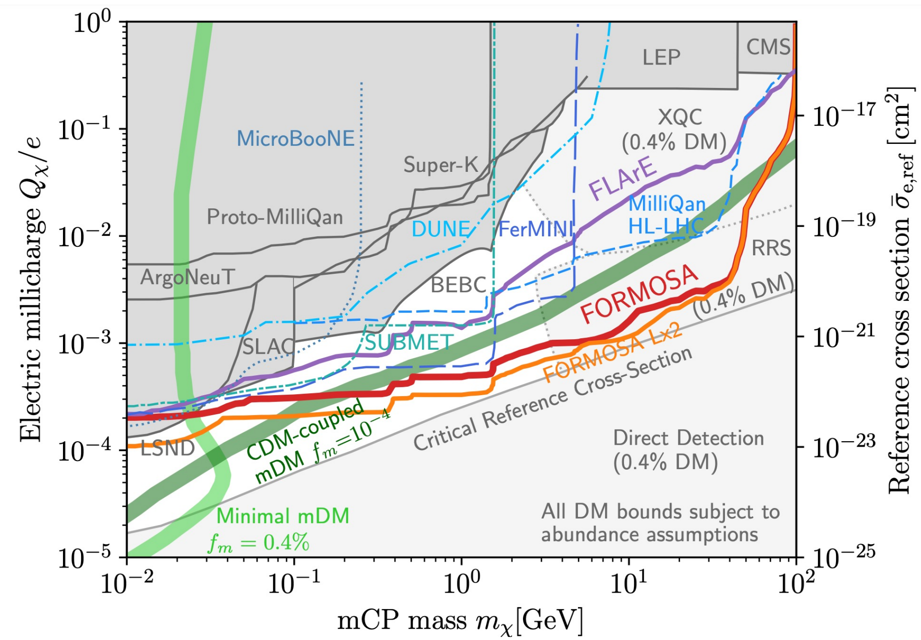
   setting Er,min $\simeq$ 2 MeV but with double-hit point back to the target



Harnik, Liu, Palamara, JHEP 19

mCP and mDM Compliation Plot

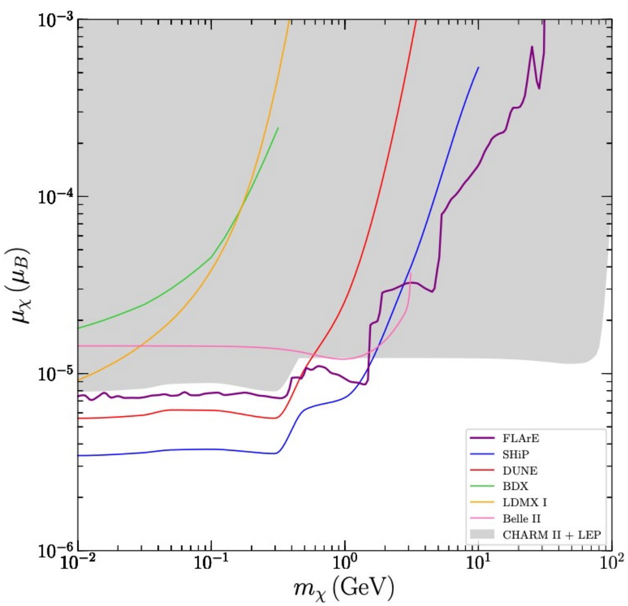




Dark states with electromagnetic form factors

millicharge (ϵQ):	$\epsilon e\, \bar{\chi}\gamma^{\mu}\chi A_{\mu}$,	**Dimension-4**
magnetic dipole (MDM):	$\frac{1}{2}\mu_{\chi}\, \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$,	**Dimension-5**
electric dipole (EDM):	$\frac{i}{2}d_{\chi}\, \bar{\chi}\sigma^{\mu\nu}\gamma^{5}\chi F_{\mu\nu}$,	
anapole moment (AM):	$a_{\chi}\, \bar{\chi}\gamma^{\mu}\gamma^{5}\chi\partial^{\nu}F_{\mu\nu}$,	**Dimension-6**
charge radius (CR):	$b_{\chi}\, \bar{\chi}\gamma^{\mu}\chi\partial^{\nu}F_{\mu\nu}$.	

dim-5: MDM/EDM



- Jui-Lin Kuo, Dark States with EM form factors at FLArE
- https://indico.cern.ch/event/1110746/contributions/4706475/attachments/2382127/4070342/FPF_Kuo.pdf

- Preliminary result by Kling, Kuo, Trojanowski and **Tsai**

Discussions

- Comments for millicharge & EM form factor sections of the FPF long paper?
- Quirk signatures in FORMOSA/FLArE?
- Can we design FLArE as an mCP tracker?

Thank you!