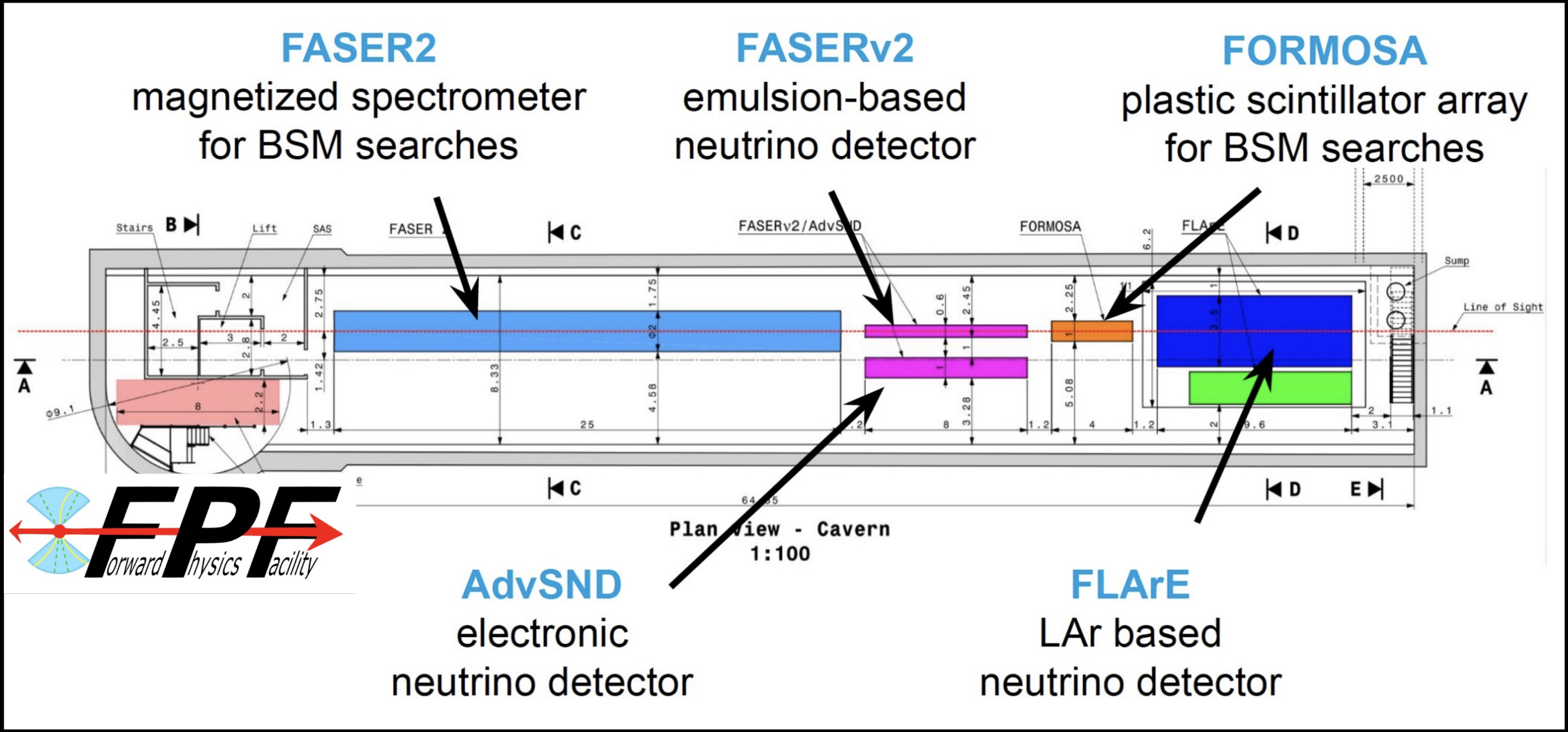
Dark Sector & Neutrino Properties at FLArE @ LHC Forward Physics Facility: Bridging the High-Low Energy Studies



FASER2
magnetized spectrometer
for BSM searches

FASERν2
emulsion-based
neutrino detector

FORMOSA
plastic scintillator array
for BSM searches

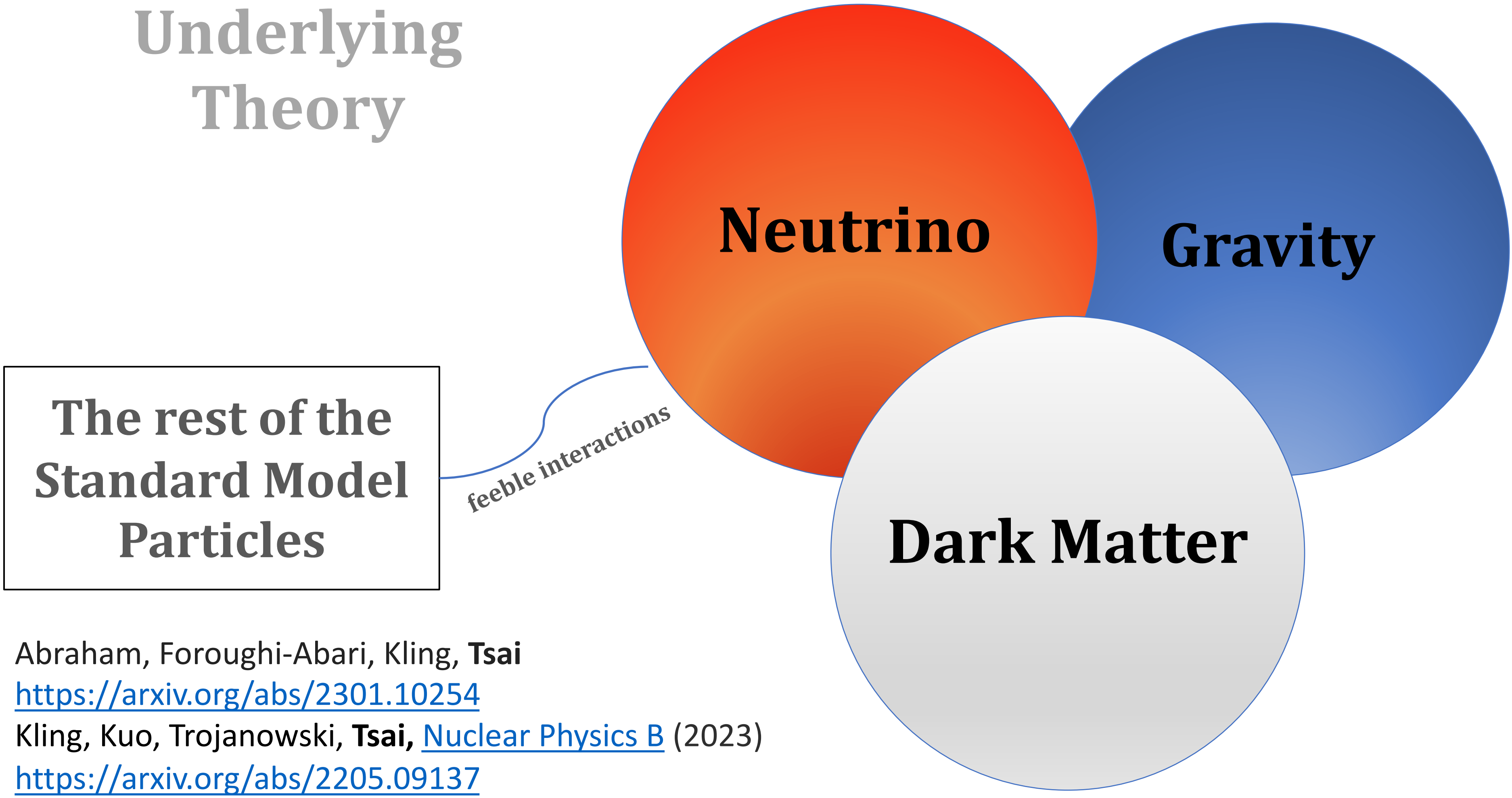
AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

Yu-Dai Tsai
University of California, Irvine (yudait1@uci.edu)

The Elusive Universe

Underlying Theory



Neutrino

Gravity

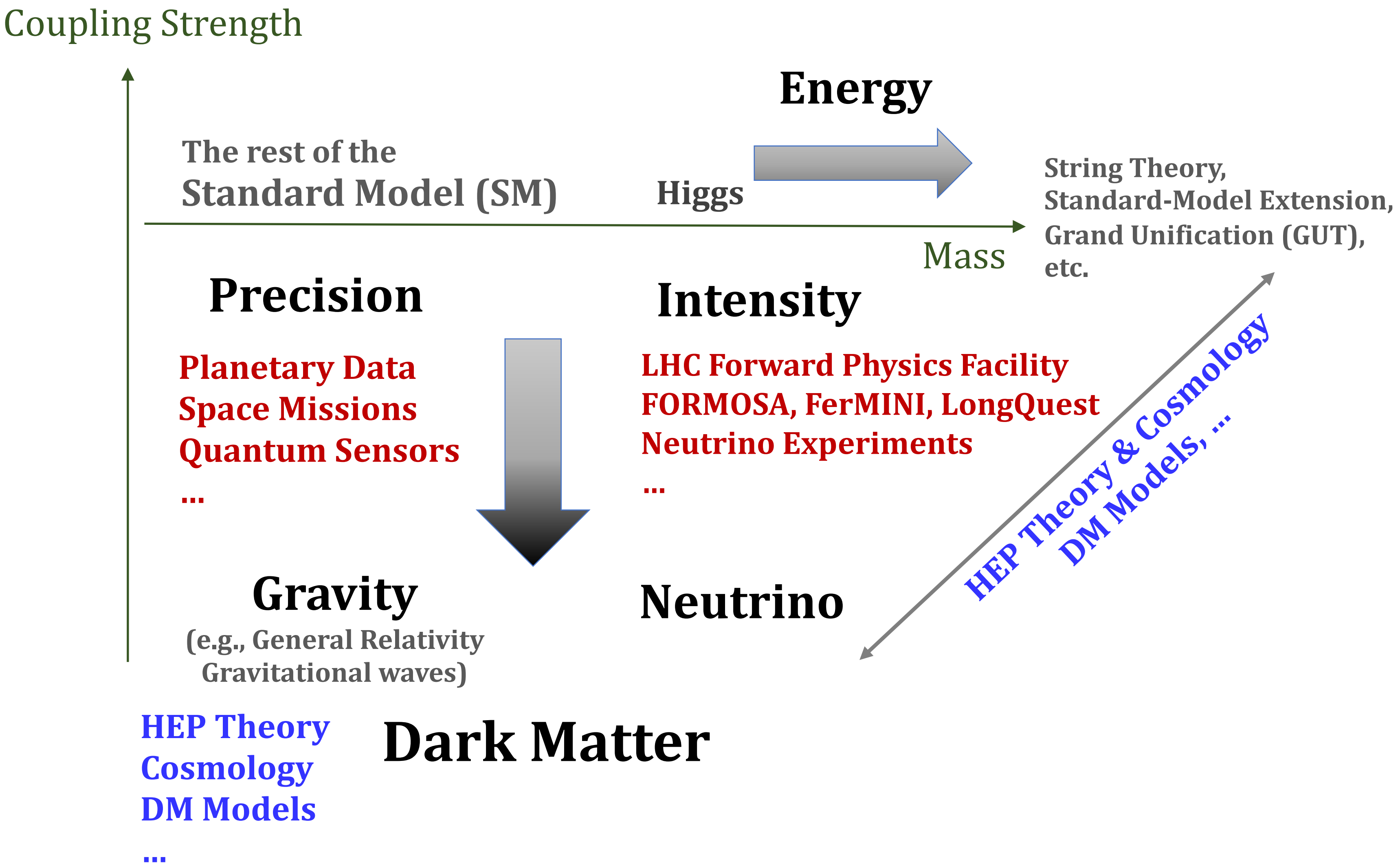
Dark Matter

The rest of the Standard Model Particles

feeble interactions

Abraham, Foroughi-Abari, Kling, **Tsai**
https://arxiv.org/abs/2301.10254
Kling, Kuo, Trojanowski, **Tsai,** Nuclear Physics B (2023)
https://arxiv.org/abs/2205.09137
+ ongoing studies & discussions
Apologies if the talk is not as polished as other talks ☺

Strong Probes of the Elusive Universe



Coupling Strength

Energy

The rest of the
Standard Model (SM)

Higgs

String Theory,
Standard-Model Extension,
Grand Unification (GUT),
etc.

Mass

Precision

Planetary Data
Space Missions
Quantum Sensors
...

Intensity

LHC Forward Physics Facility
FORMOSA, FerMINI, LongQuest
Neutrino Experiments
...

HEP Theory & Cosmology
DM Models, ...

Gravity

(e.g., General Relativity
Gravitational waves)

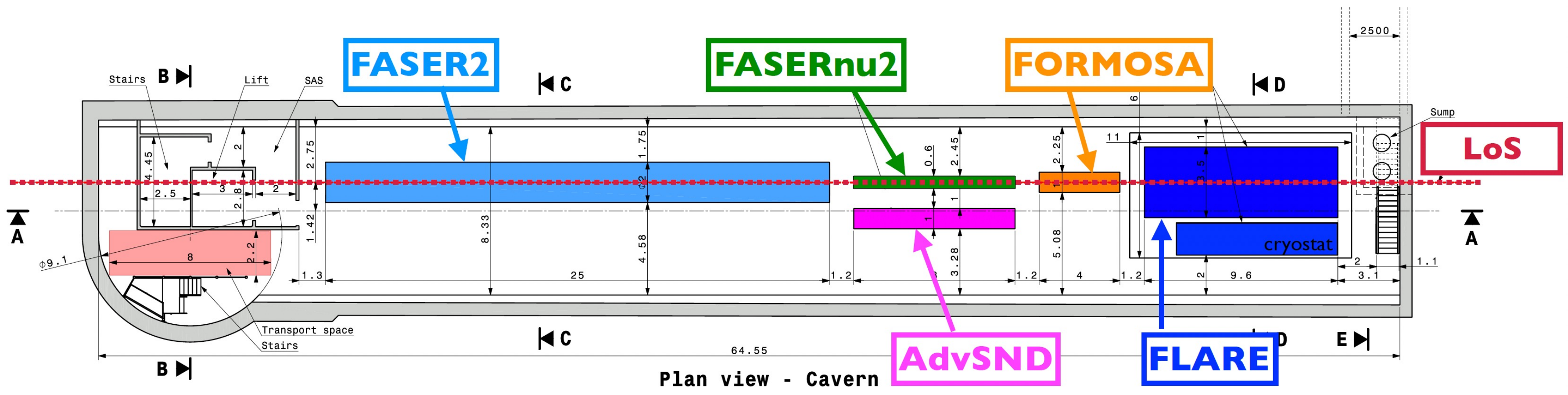
Neutrino

HEP Theory
Cosmology
DM Models
...

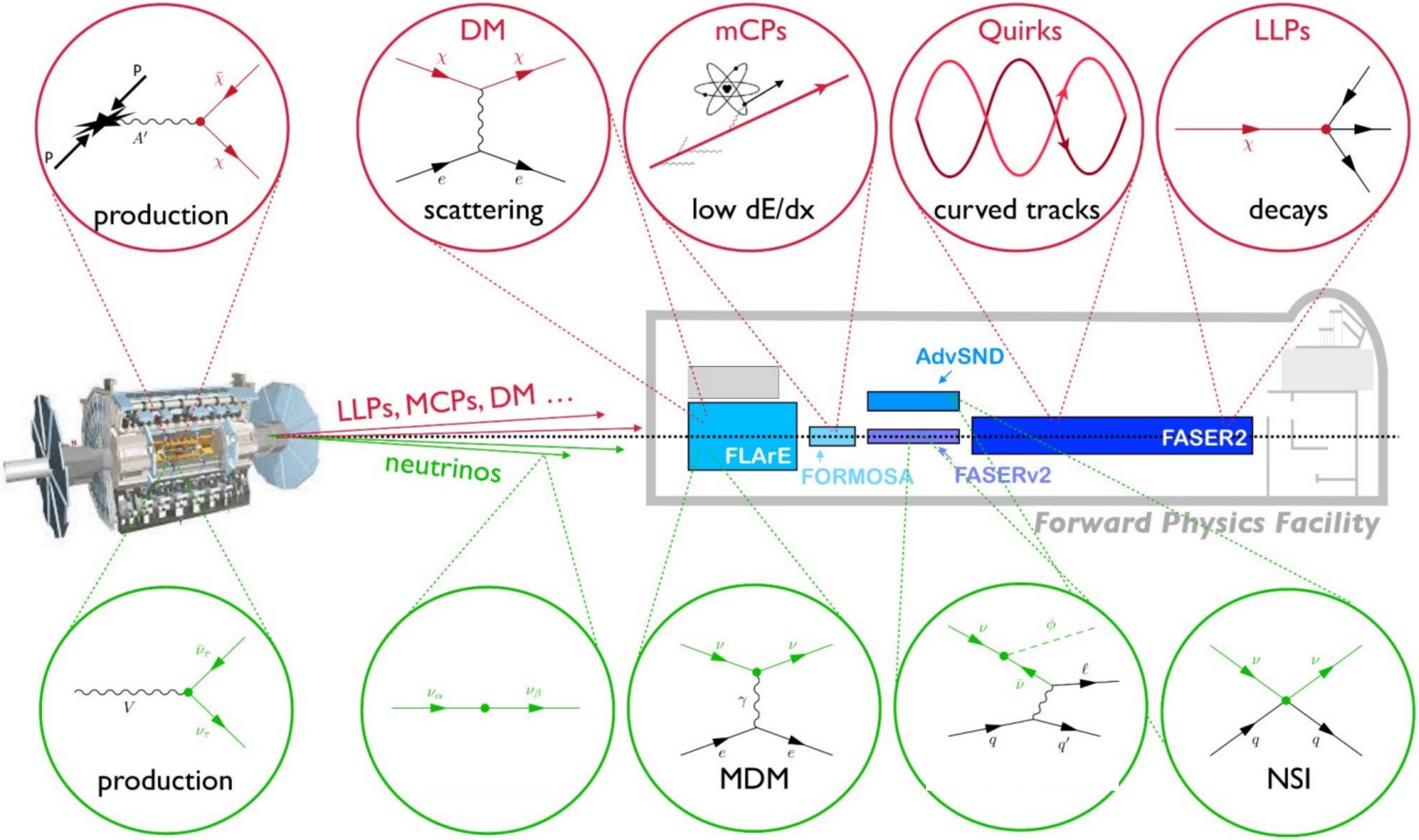
Dark Matter

Outline

1. **Forward Physics Facility & FLArE**
2. **Millicharge Dark Sector**
3. **Neutrino EM Properties**
4. **Cosmic Background Neutrino, Asteroids, and Quantum Sensors**



Forward Physics at the LHC

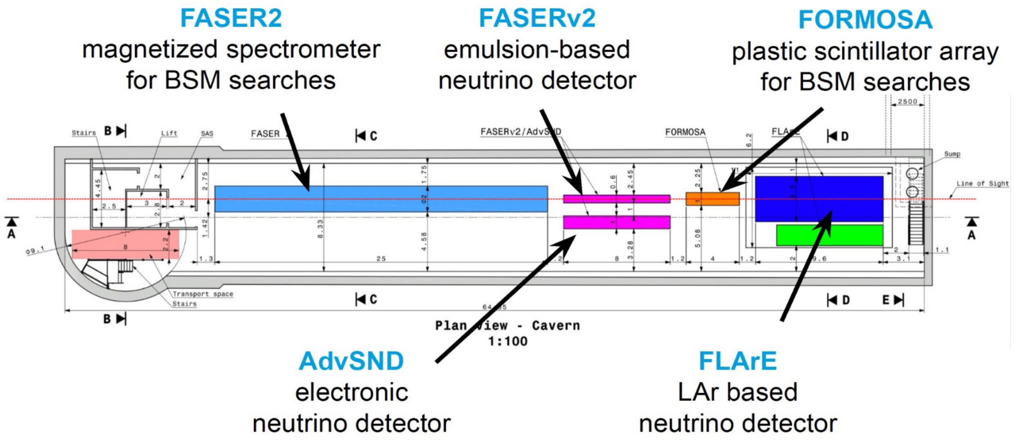


- Feng et al, Journal of Physics G (2023) https://arxiv.org/abs/2203.05090
- The HL-LHC project will deliver proton-proton collisions at 14 TeV with an integrated luminosity of 3 ab^{-1} for both ATLAS & CMS

Opportunities with FPF

- The **F**orward **P**hysics **F**acility (FPF): proposed to host a suite of detectors in the forward region of the ATLAS interaction point
  - Guaranteed SM progress from ~ a million neutrinos at ~ TeV energies
  - Rich program of BSM physics searches

- A proposed timeline
  - Build FPF during long shutdown 3 from 2026-2028
  - Install detectors in 2029
  - Start data taking soon after the beginning of of Run 4
- Great opportunities for junior researchers in a relative short timescale
- With the experience from the pathfinder experiments like FASER



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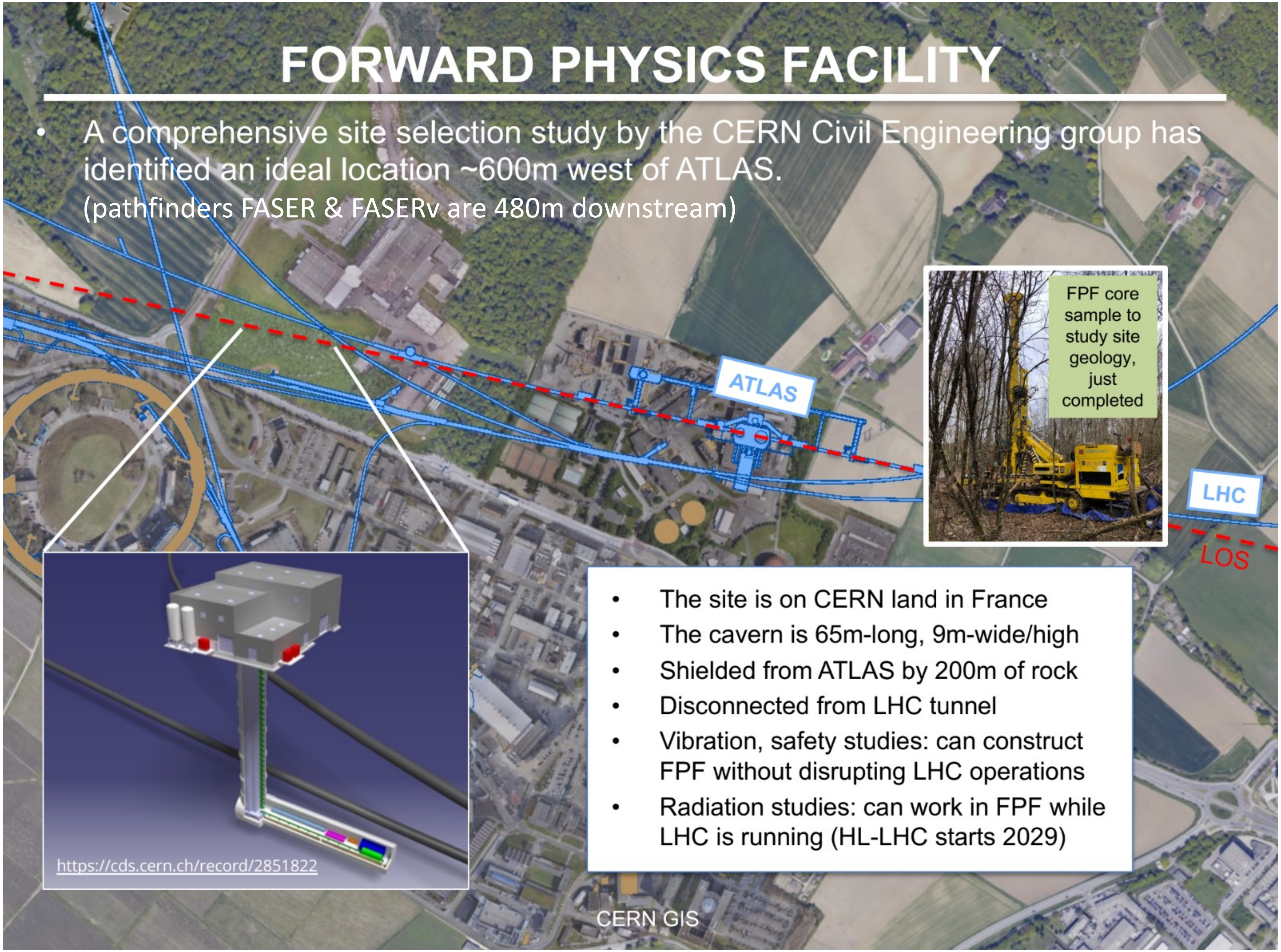
Modified form Bian, Shively, Wu’s Slides from BNL P5 Town Hall

FORWARD PHYSICS FACILITY

- A comprehensive site selection study by the CERN Civil Engineering group has identified an ideal location ~600m west of ATLAS.

(pathfinders FASER & FASERν are 480m downstream)



FPF core sample to study site geology, just completed

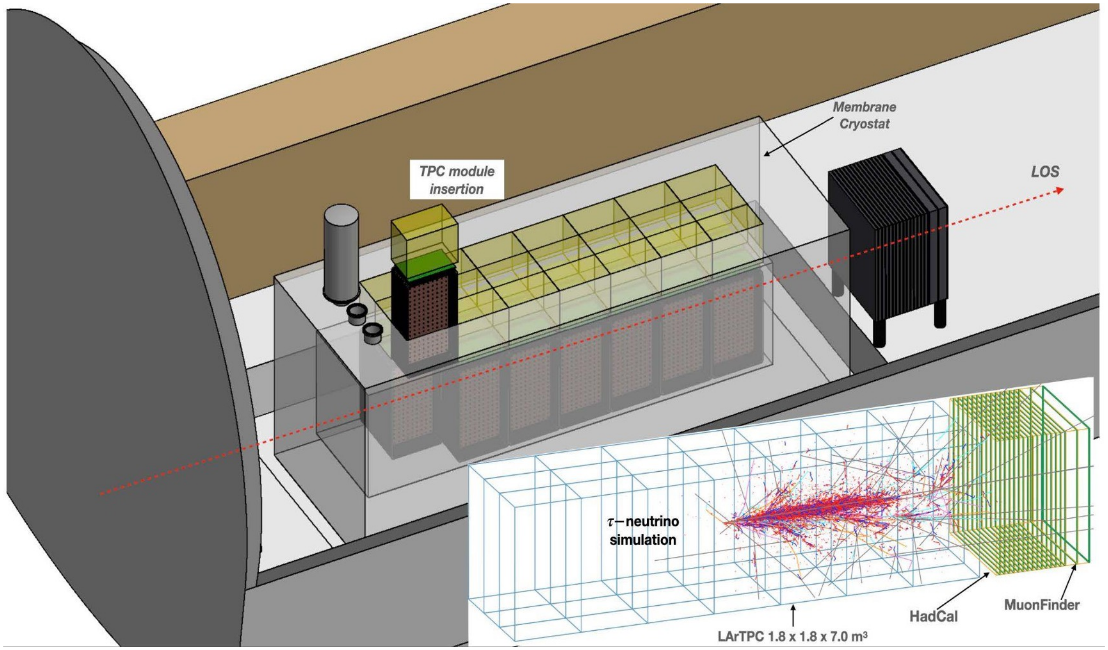
https://cds.cern.ch/record/2851822

- The site is on CERN land in France
- The cavern is 65m-long, 9m-wide/high
- Shielded from ATLAS by 200m of rock
- Disconnected from LHC tunnel
- Vibration, safety studies: can construct FPF without disrupting LHC operations
- Radiation studies: can work in FPF while LHC is running (HL-LHC starts 2029)

CERN GIS

Forward LAr Experiment (FLArE)

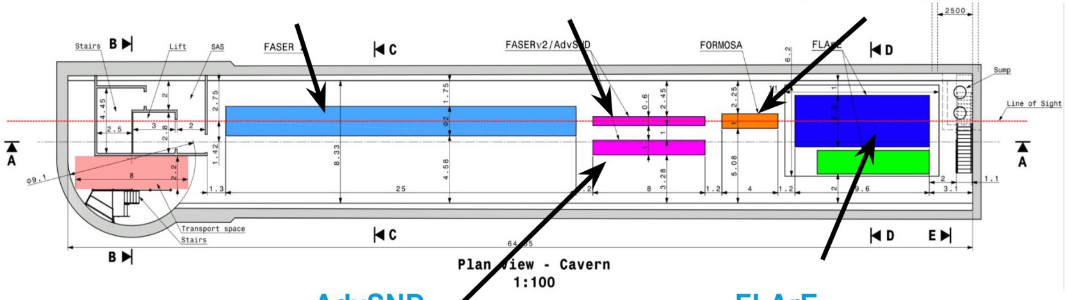
- Segmented liquid argon TPC
    - ○ 10 tons fiducial mass
    - ○ 1m × 1m × 7m
- Neutrino detection, light dark matter searches
- Wide dynamic range: ~10 MeV to hundreds of GeV
- R&D is helped by the considerable investment in the field (ICARUS, MicroBooNE, SBND, DUNE, …)
    - ○ High spatial and kinematic resolution
    - ○ Effective trigger in the presence of large muon backgrounds



Modified form Bian, Shively, Wu’s Slides from BNL P5 Town Hall

$10^5\ \nu_e$, $10^6\ \nu_\mu$, $10^4\ \nu_\tau$ interactions at ~TeV energies.

Implications for Neutrino properties, QCD, and astroparticle physics.



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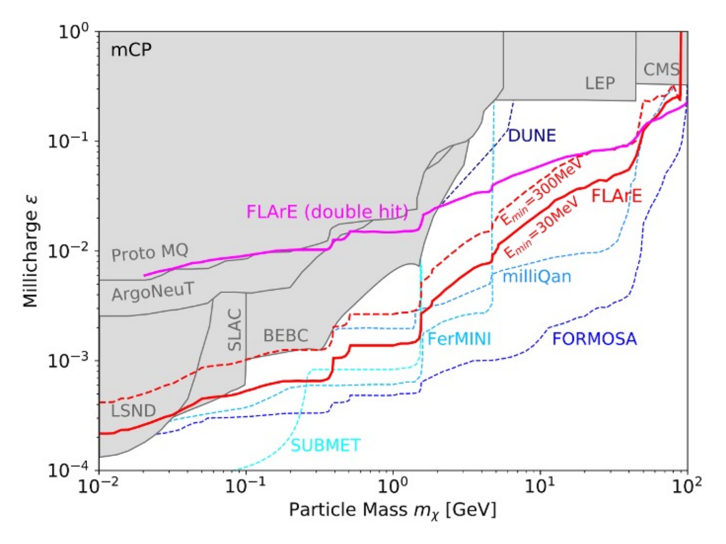
> *Our highest immediate priority accelerator and project is the HL-LHC, …including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.*
> – Snowmass 2021 Energy Frontier Report

> *The full physics potential of the LHC and the HL-LHC...should be exploited.* — 1st recommendation of the 2020 European Strategy Update

Modified form the FPF Presentation from BNL P5 Town Hall

Outline

1. **Forward Physics Facility and FLArE**
2. **Millicharge Dark Sector** (details see my review talk: [link])
3. **Neutrino EM Properties**
4. **Cosmic Background Neutrino, Asteroids, and Quantum Sensors**

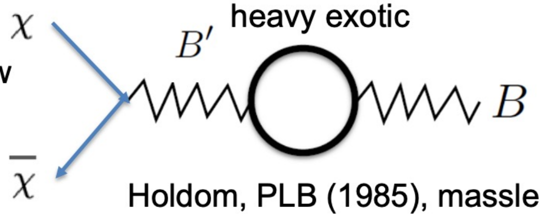


Kling, Kuo, Trojanowski, **Tsai,** NPB (2023)

Theoretical Motivations

Paul Dirac

- **Is electric charge quantized and why?** A long-standing question
- Motivates **Dirac quantization, Grand Unified Theories (GUTs)**
- **Fractionally charged particles (not confined) is predicted by some Superstring theories**: Wen, Witten, NPB (1985)
- Link to **string compactification, quantum gravity, and reheating in Cosmology,** Shiu, Soler, Ye, PRL (2013), Gan, Shiu, **Tsai**, in progress
- **Conservatively, testing if e/3 is the minimal charge**
- Simply a search for particles with **{mass, electric charge}** = $\{m_\chi, \epsilon e\}$, $\epsilon = Q_x/e$
- **Massless dark photon yields millicharged particles; dark matter implication (backup slide)**



heavy exotic

Coupled to new dark fermion χ

(SM: Standard Model)

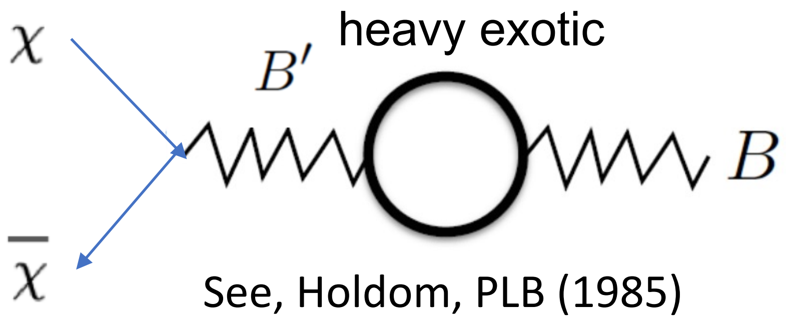
Holdom, PLB (1985), massless dark photon B'

mCP Model

- A particle fractionally (or irrationally) charged under SM U(1) hypercharge $\mathcal{L}_{\mathrm{MCP}} = i\bar{\chi}(\not{\partial} - i\epsilon' e \not{B} + M_{\mathrm{MCP}})\chi$
- 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.**
- We are simply search for MCP!
Minimal assumptions = most robust constraints/probes.
- This could come from vector portal **Kinetic Mixing**
\- 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, PLB (1985)

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

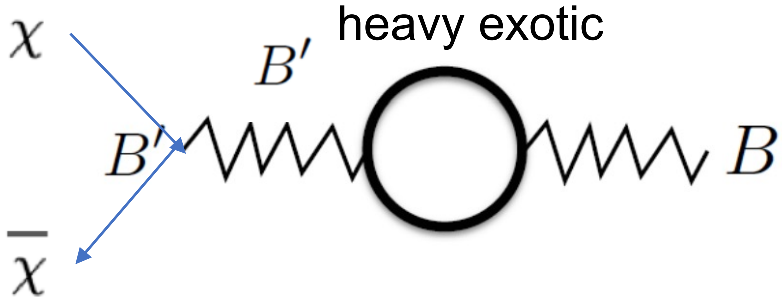
- New fermion χ charged under new gauge boson B’.

- 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.)

Theory: Two Kinds of mCPs

mCP with a massless dark photon

- Compatible with GUTS.



$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} + i\bar{\chi}(\not{\partial} + ie'\not{B}' + iM_{\rm MCP})\chi$$

mCP without a massless dark photon

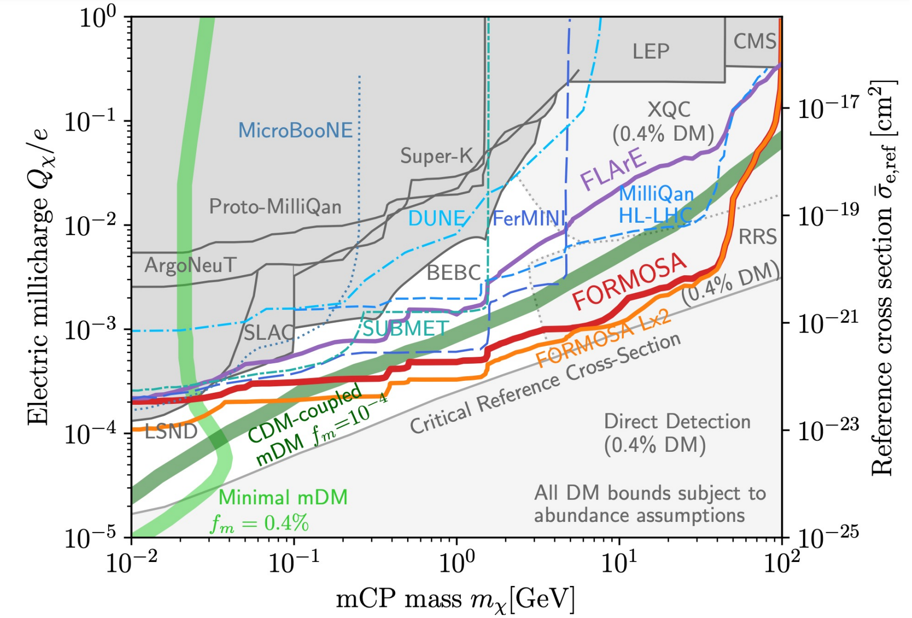
- Interesting to think about the theory implication of mCP with a small irrational charge & no dark photon
- Find ways to distinguish the two and consider the potential implications on GUTs & string compactification Gan, Shiu, **Tsai**, in progress

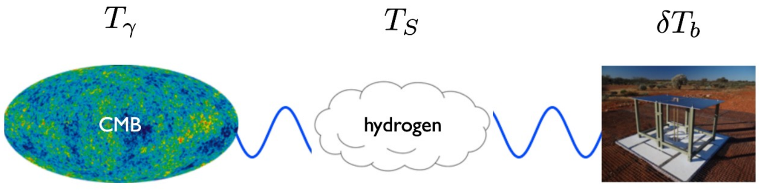
Choose a proper basis: massless B' decouple from SM

$$\mathcal{L}_{\rm MCP} = i\bar{\chi}(\not{\partial} - i\epsilon' e\not{B} + M_{\rm MCP})\chi$$

Effective Lagrangian

EDGES & Millicharged Dark Matter



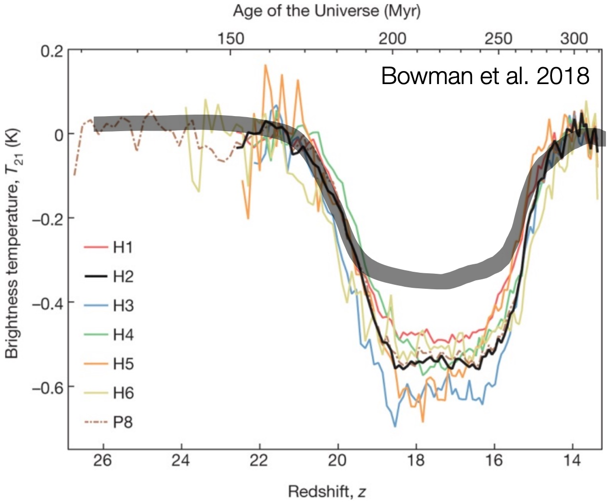


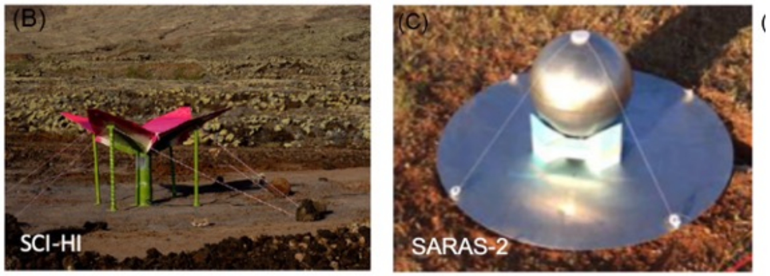
Adapted from J. Pritchard

From Jordan Mirocha (UCLA)

e.g., EDGES

- EDGES gives another hint of dark matter property, just like small-scale structure
- Connecting to **cosmology** & **dark matter** direct-detection folks



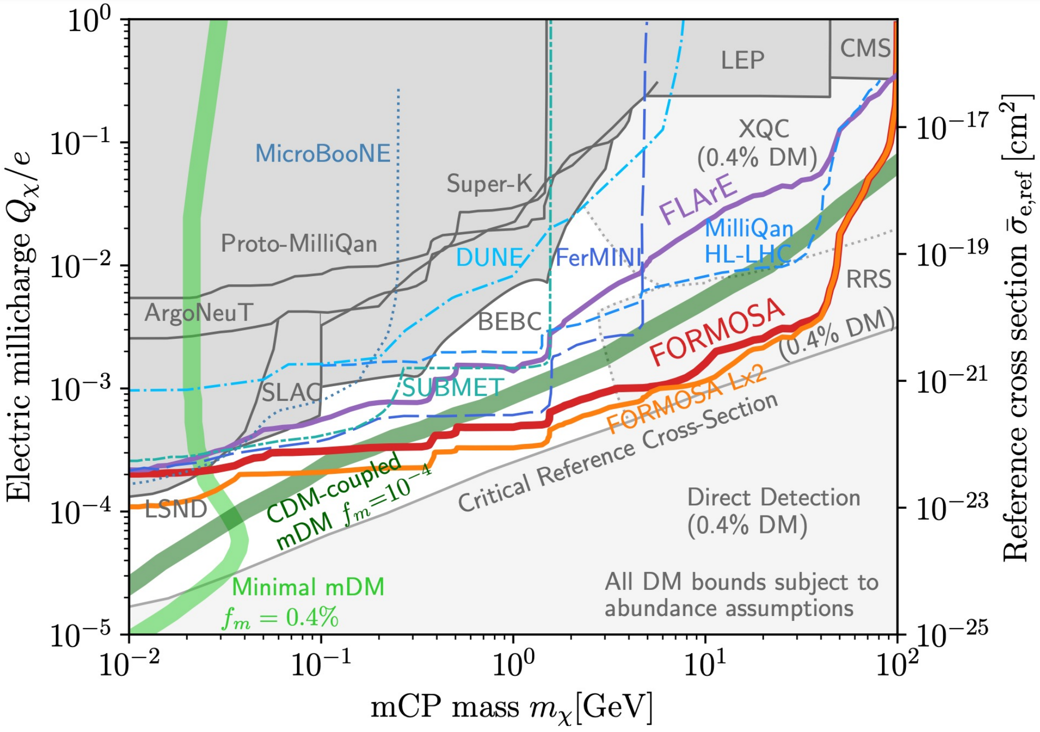


- Voytek et al, APJL (2014)
- Singh et al, 1710.01101

Strongly Interacting Dark Matter

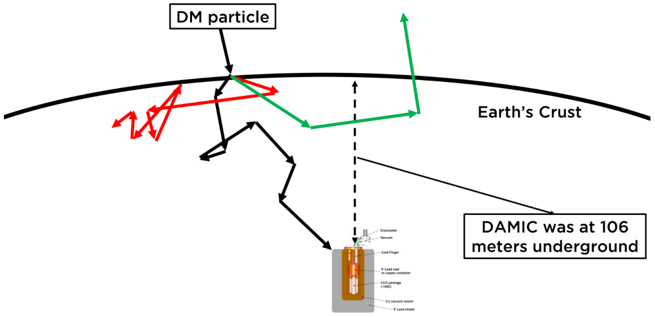
MCP / LDM with ultralight dark photon mediators

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



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

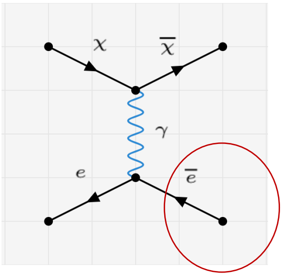
Two Search Methods: Scattering & Scintillation

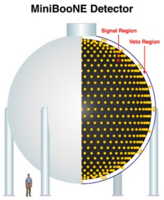
$$\sigma_{e\chi} \simeq 2.6 \times 10^{-25}\text{cm}^2 \times \epsilon^2 \times \frac{1 \text{ MeV}}{E_e^{(\text{min})} - m_e}.$$

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

(A) **Electron Scattering**

~ energy exchange set by detector threshold (~MeV)





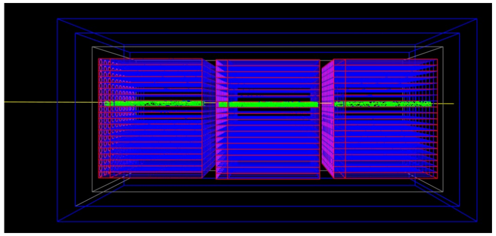
e.g.neutrino Detector
MiniBooNE (arXiv:0806.4201)

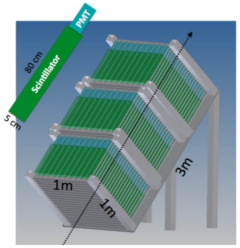
$$\left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2.$$

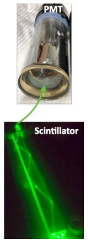
energy deposition

(B) **Scintillation** Study for **Millicharge Particles**

~ eV-level energy exchange

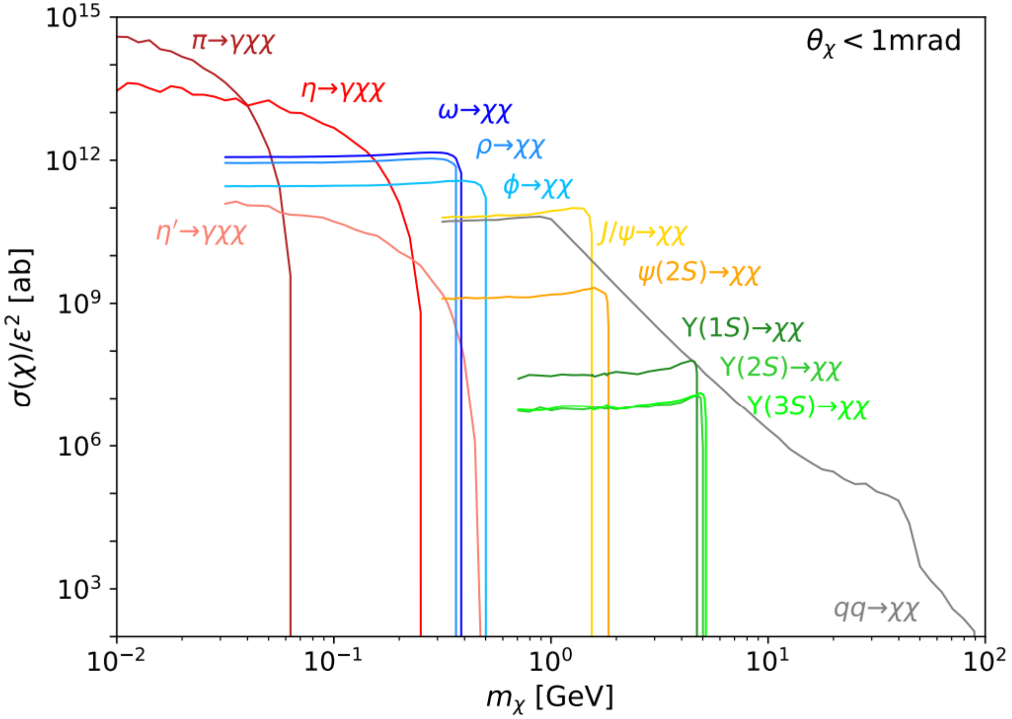






e.g., Haas, Hill, Izaguirre, Yavin, 1410.6816
milliQan design, 1607.04669 (MilliQan Collaboration)

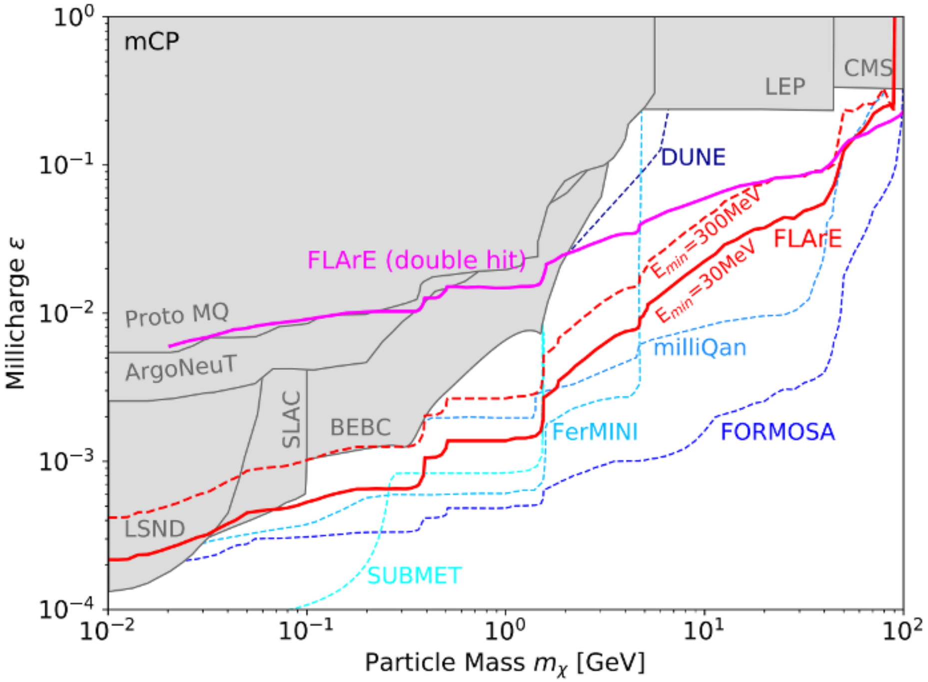
mCP Productions @ FPF



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

MCP production was added to FORESEE by Felix Kling

mCP @ FLArE



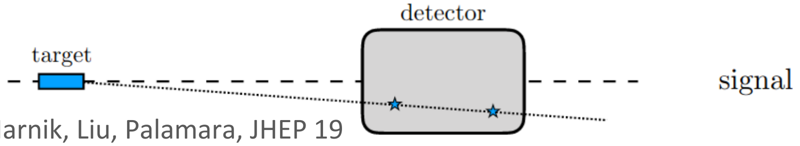
- **FLArE experiment by Jianming Bian:** https://indico.cern.ch/event/1110746/contributions/4701719/
- Nev = 3 expected new physics events in the detector

A. Scattering a-la DM signal: consider χe → χe,

and set electron recoil energy Er within 30 MeV ≲ Er ≲ 1 GeV in FLArE

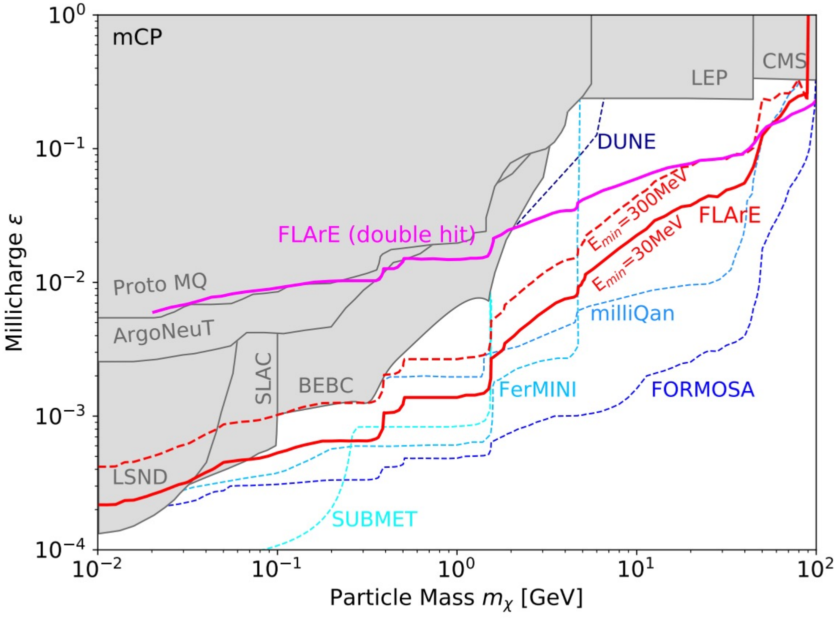
B. Double-hit with softer recoils:

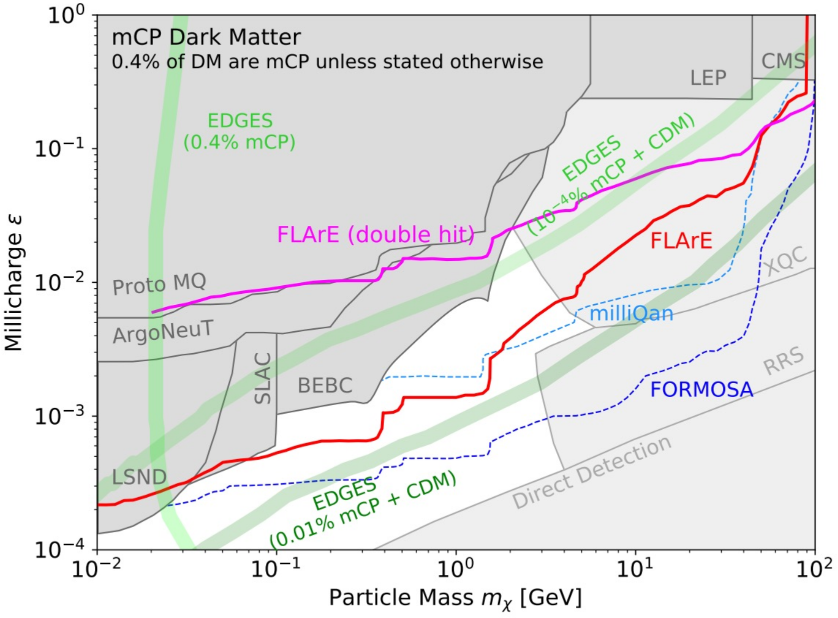
setting Er,min ≃ 2 MeV but with double-hit point back to the target



Harnik, Liu, Palamara, JHEP 19

Millicharge Particles (mCP) & Dark Matter





Most likely, your experiments also have interesting sensitivity on this region,

theoretically and phenomenologically motivated.

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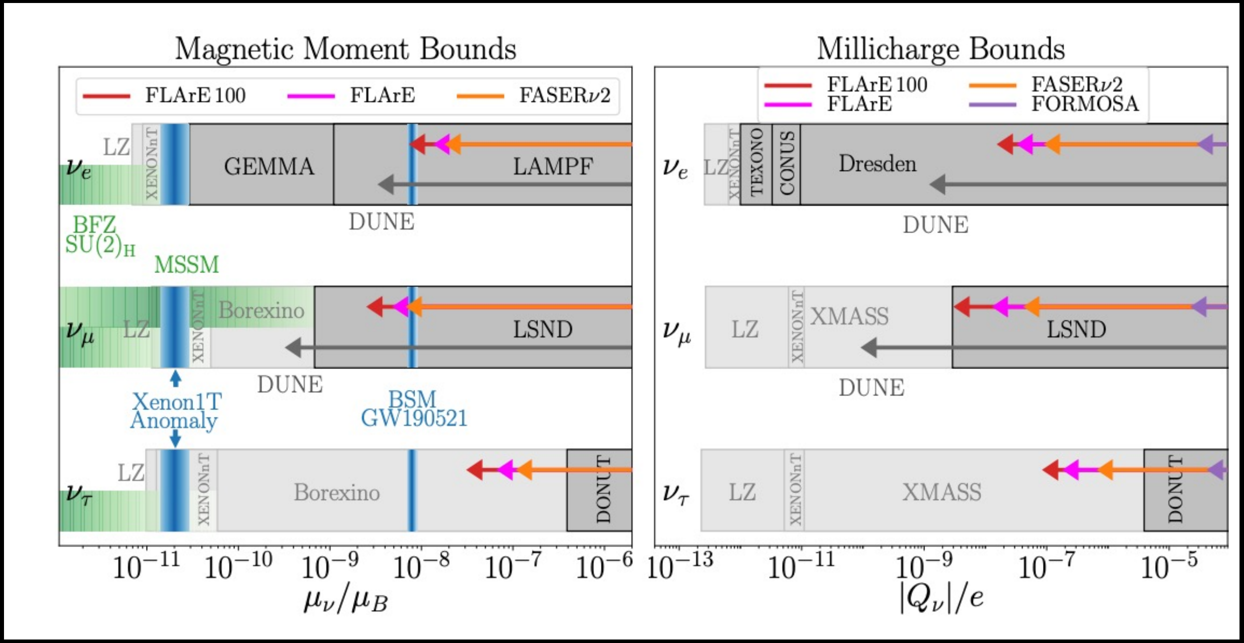


Neutrino Effective Electromagnetic Current

$$\langle \nu_f(p_f)|j^{\mu}_{\nu,\mathrm{EM}}|\nu_i(p_i)\rangle = \overline{u}_f(p_f)\Lambda^{\mu}_{fi}(q)u_i(p_i), \qquad (1)$$

- $\Lambda^{\mu}_{fi}(q)$ is a 3 × 3 matrix in the neutrino mass eigenstates space that encodes the electromagnetic properties of neutrinos.
- In low-q^2 , it simplifies to,

$$\Lambda^{\mu}_{fi}(q) = \gamma^{\mu}(Q_{fi} - \frac{q^2}{6}\left\langle r^2\right\rangle_{fi}) - i\sigma^{\mu\nu}q_{\nu}\mu_{fi} \qquad (2)$$

- with f = i for diagonal and otherwise for transition electromagnetic properties

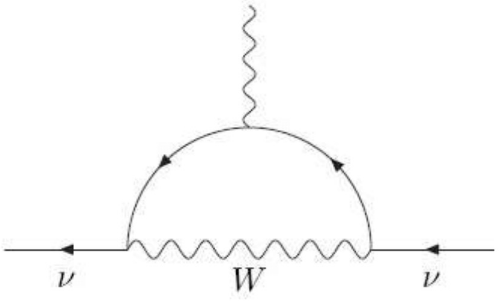
- With right-handed neutrinos & Dirac mass terms for the neutrinos, electric charge is de-quantized and neutrinos can be electrically charged. The charge de-quantization in this case is related to the existence of the non-anomalous symmetry (B − L), Babu et al, PRD (1990).

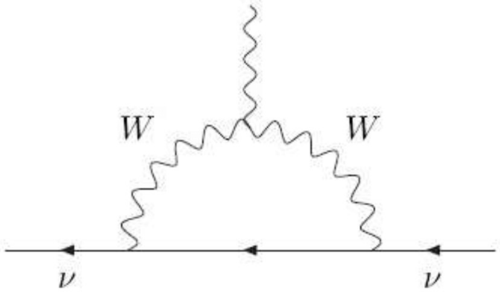
Neutrino Magnetic Moment

The diagonal magnetic moment for a massive Dirac neutrino is given by

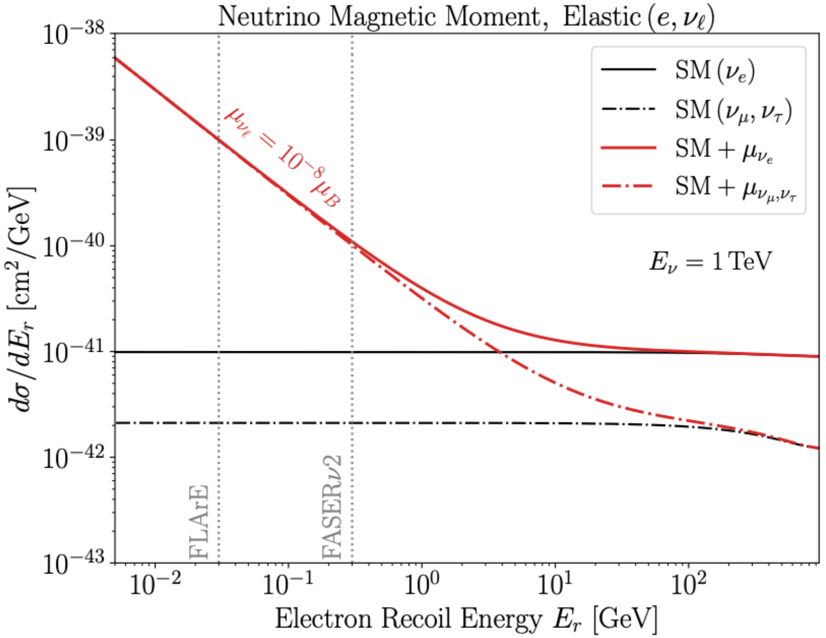
$$\mu_\nu \approx \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \approx 3 \cdot 10^{-19} \mu_B \left(\frac{m_\nu}{1 \text{ eV}} \right) .$$

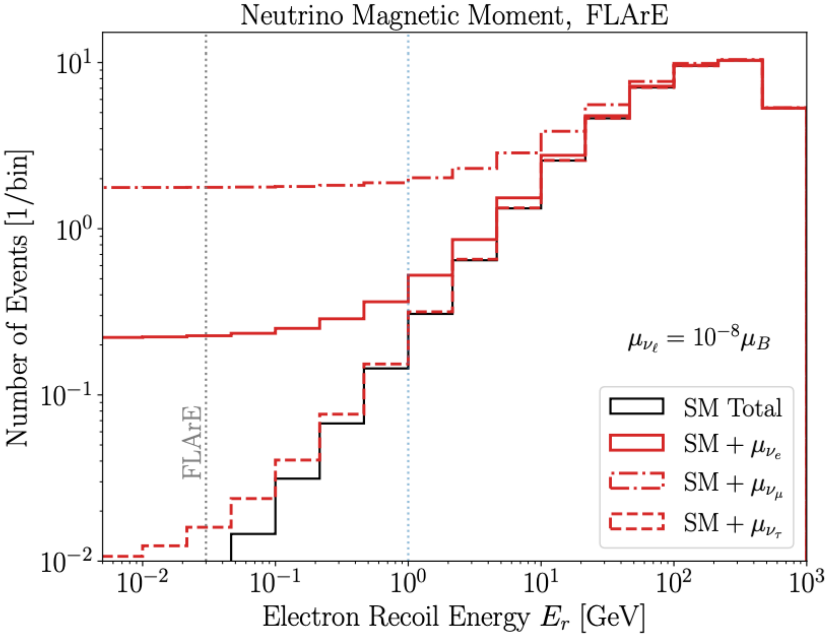
- Where mν is the neutrino mass, e is the electric charge, GF is the Fermi constant and μB = e/(2me) is the Bohr magneton.
- For Majorana neutrinos, and only transition moments are allowed





Neutrino Magnetic Moment





$$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\mathrm{NMM}} = \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\mathrm{SM}} + \frac{\pi^2}{m_e^2}\left(\frac{1}{E_r} - \frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_\ell}}{\mu_{\mathrm{B}}}\right)^2,$$

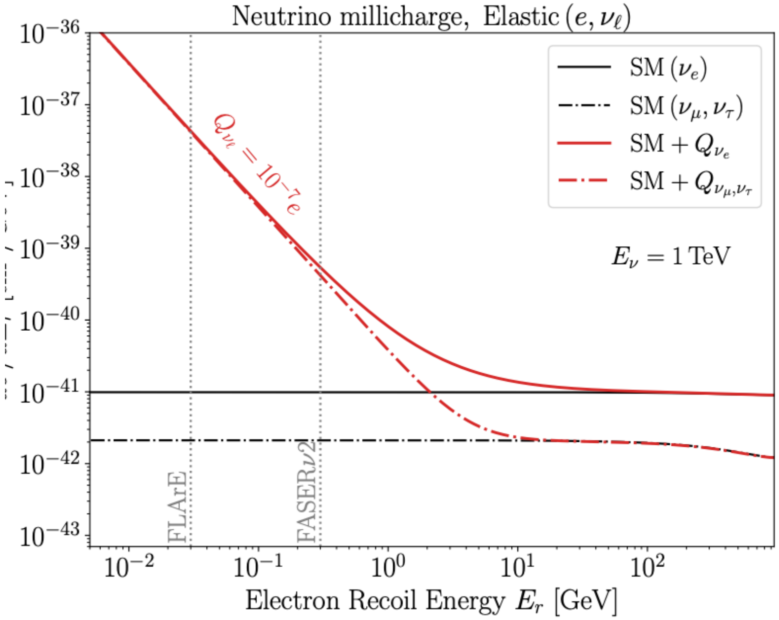
Neutrino Millicharge

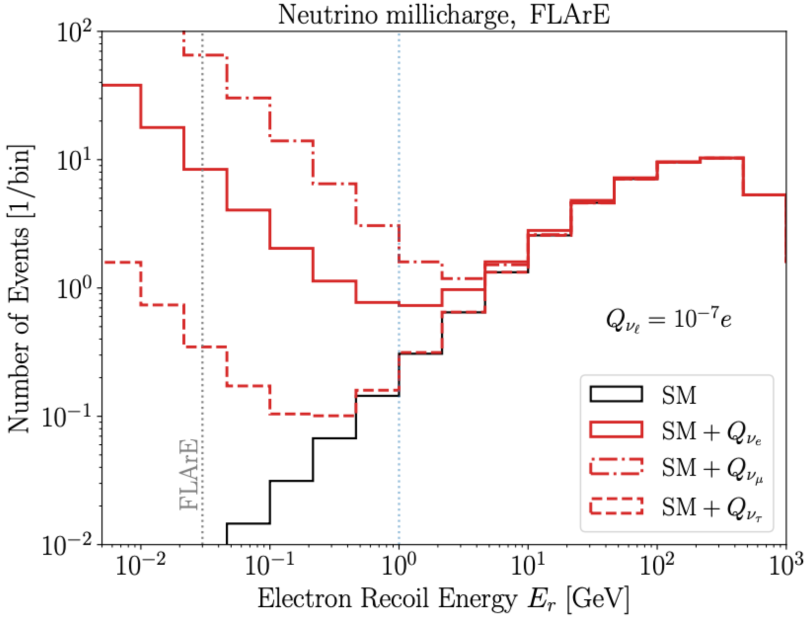
$$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\mathrm{NMC}} = \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\mathrm{SM}} + \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\mathrm{Int}} + \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\mathrm{Quad}}.$$

$$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\mathrm{Int}} = \frac{\sqrt{8\pi}G_F\alpha}{E_\nu^2 E_r}\left(\frac{Q_{\nu_\ell}}{e}\right)\Big[g_V^\ell\big(2E_\nu^2 + E_r^2 - E_r(2E_\nu + E_r)\big) + g_A^\ell\big(E_r(2E_\nu - E_r)\big)\Big]$$

$$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\mathrm{Quad}} = 4(\pi\alpha)^2\left(\frac{Q_{\nu_\ell}}{e}\right)^2\left[\frac{2E_\nu^2+E_r^2-2E_\nu E_r}{m_e E_r^2 E_\nu^2}\right],$$

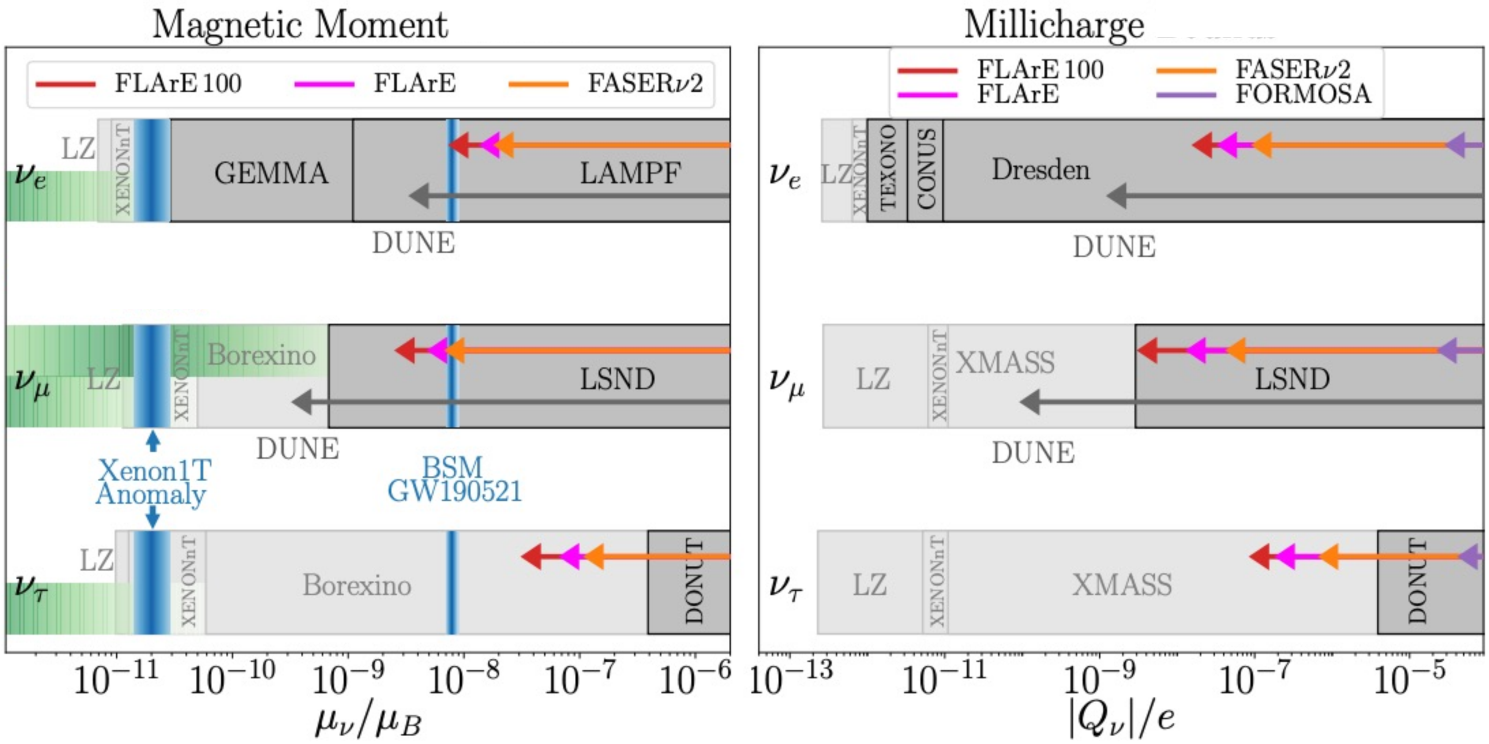
Neutrino Millicharge





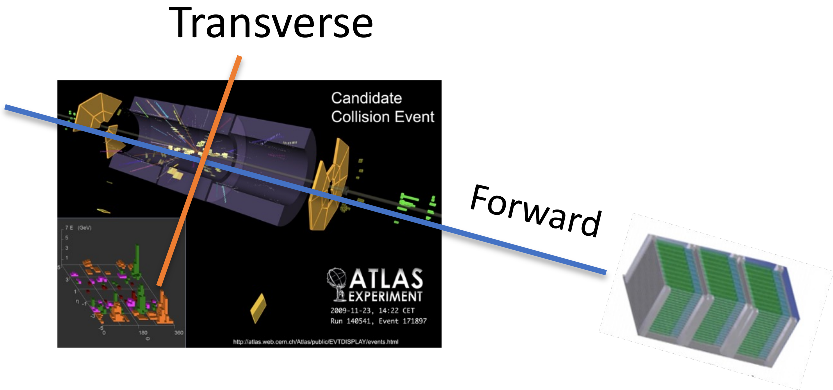
$$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\text{NMC}} = \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\text{SM}} + \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\text{Int}} + \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\text{Quad}}.$$

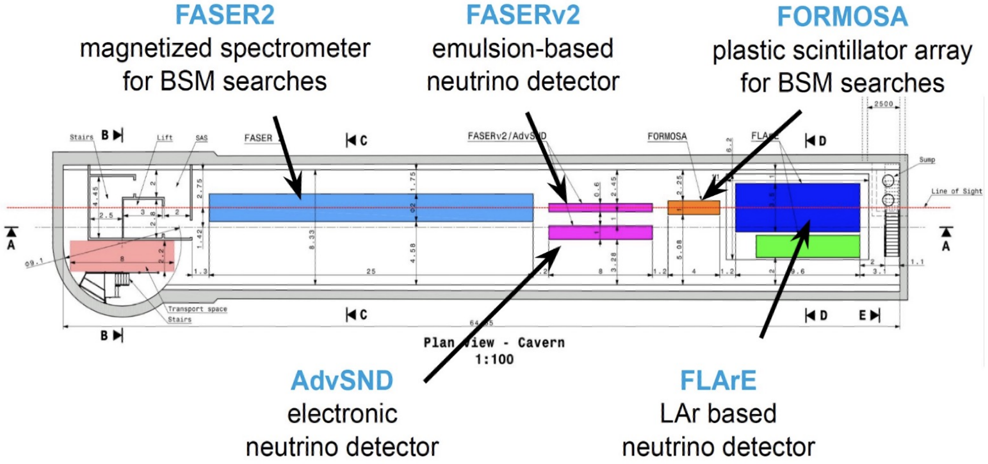
Summary of Results



- Exploring extrapolate the **neutrino charge radius** at both **FLArE & DUNE**
- **Close to measure neutrino charge radii and radiative correction predicted by Standard Model; Interesting experimental challenges**
- **Green: BSM Targets discussed briefly in our paper**

Neutrino Millicharge at FORMOSA, FerMINI, and Other Similar Experiments



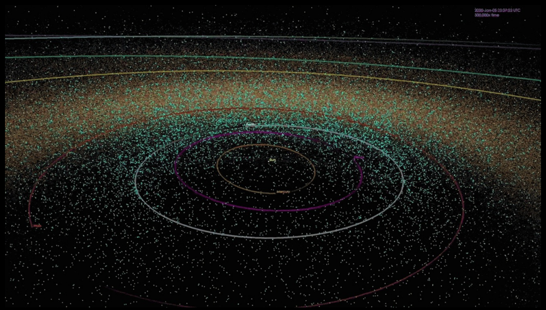


- milliQan Col., PRD (2021), Haas at al, PLB (2015)
- milliQan detector: **long scintillator bars to detector small ionization from mCP**
- milliQan run with great success in the transverse region of CMS
- **FORward MicrOcharge SeArch (FORMOSA),** Foroughi-Abari, Kling, **Tsai**, *PRD (2021),* 2010.07941
- **FerMINI**, Kelly, **Tsai**, PRD (2019), 1812.03998

Outline

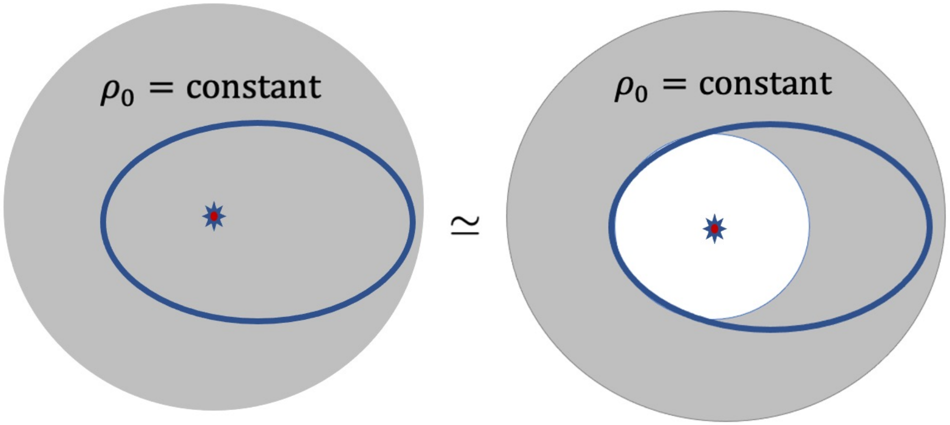
1. Forward Physics Facility & FLArE
2. Millicharge Dark Sector
3. Neutrino EM Properties
4. **Cosmic Background Neutrino, Asteroids, and Quantum Sensors (3)**

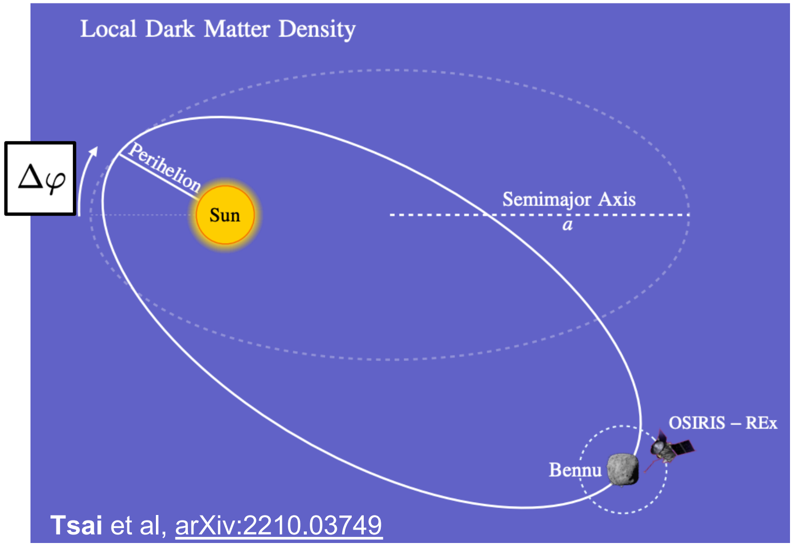
Vera Rubin
Carnegie Institution for Science



Albert Einstein
Mount Wilson Observatory, California

Our Project:
Local DM or Cosmic Neutrinos Induce Precessions





Tsai et al, arXiv:2210.03749

Dark Matter Gravity:
$$\mathbf{F}(\mathbf{r}) = \frac{2\pi}{3} G m \rho_0 \left(\frac{2 r_0^3}{r^2} - 2r \right) \hat{\mathbf{r}}$$
$$\simeq -\frac{4\pi}{3} G m \rho_0 r \hat{\mathbf{r}} + \cancel{\frac{4\pi}{3} G m \rho_0 \frac{r_0^3}{r^2}} \hat{\mathbf{r}}.$$

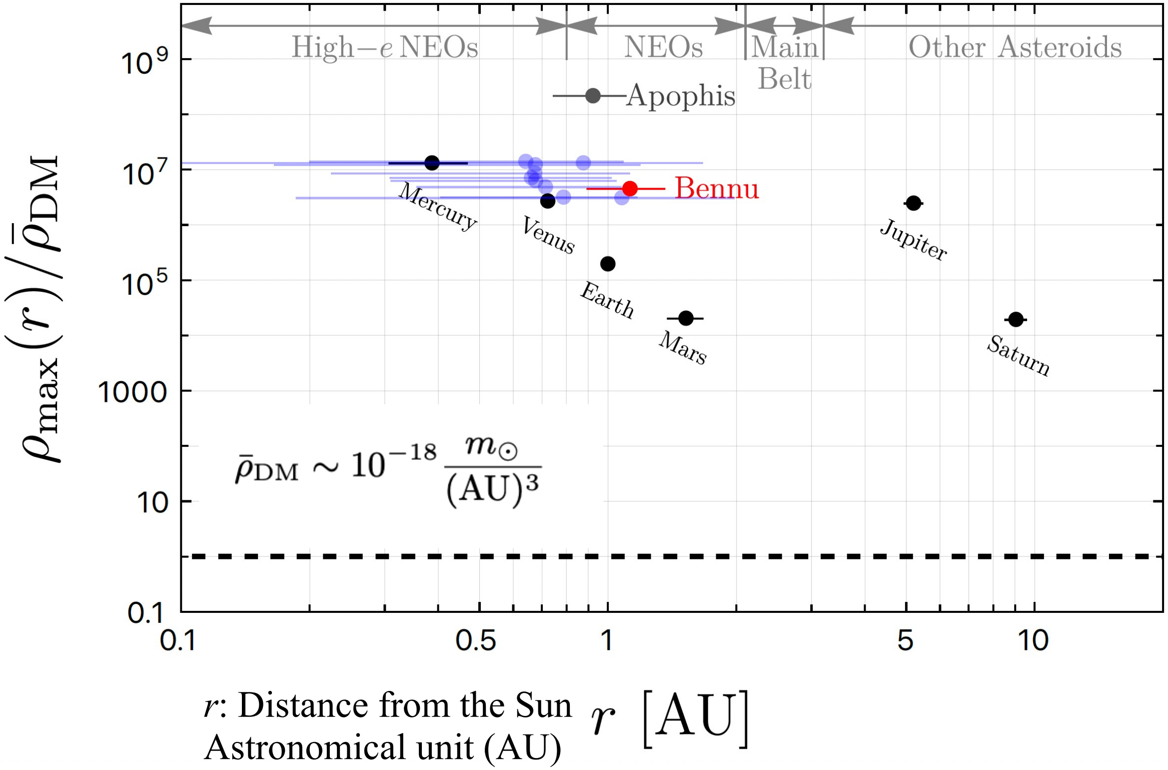
m is the mass of the object

Induced Precession: $\Delta\varphi \simeq -4\pi^2 \rho_0 a^3 (1 - e^2)^{1/2} / M_\odot$

1) New Model-Independent Constraints on DM Profile

Tsai, Eby, Arakawa, Farnocchia, Safronova, arXiv:2210.03749

- $\boldsymbol{\rho_{max}}$**(r)** is the derived **upper bound on DM though only gravitational interaction**
- $\bar{\rho}_{DM}$ = 0.3 GeV/cm^3
- NEO: Near-Earth Objects



$\bar{\rho}_{\mathrm{DM}} \sim 10^{-18}\,\frac{m_\odot}{(\mathrm{AU})^3}$

r: Distance from the Sun
Astronomical unit (AU)

- The **horizontal lines** are NOT error bars, but the **coverage of the constraints.**
- 2) Can set strong constraints on **DM-SM long-range forces**

3) Implications of the Constraints: CvB

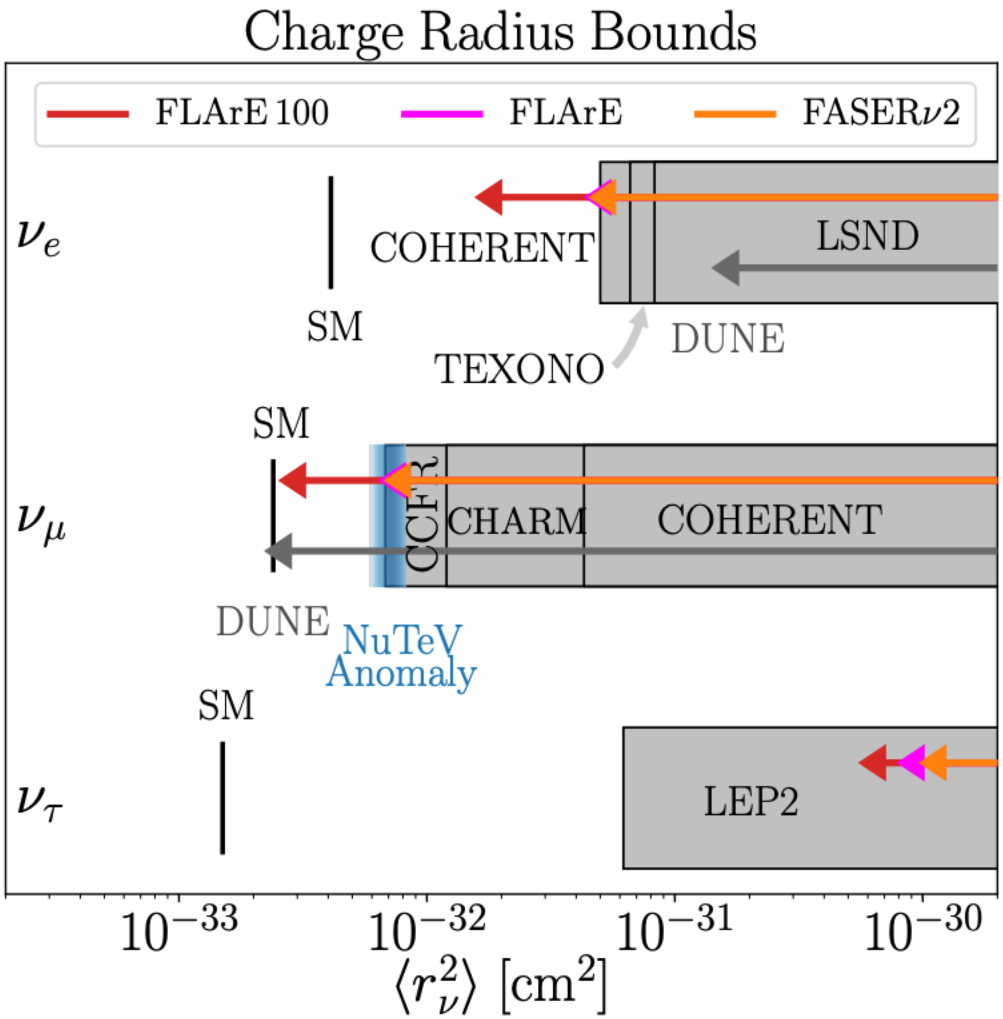
- Close-to-leading constraints on **cosmic neutrino background (CvB)** over-density profile.

$$\boxed{\eta \equiv n_\nu/\bar{n}_\nu \lesssim 3.4\times 10^{11}(0.1\ \mathrm{eV}/m_\nu),\ 95\%\ \mathrm{CL}\quad [\mathrm{Planets}]}$$

$\eta \leq 1.1\times 10^{11}$ (95% CL), from $\nu_e + {}^3H \to {}^3H_e^+ + e^-$
KATRIN Col., *PRL* (2022), the leading lab constraint.

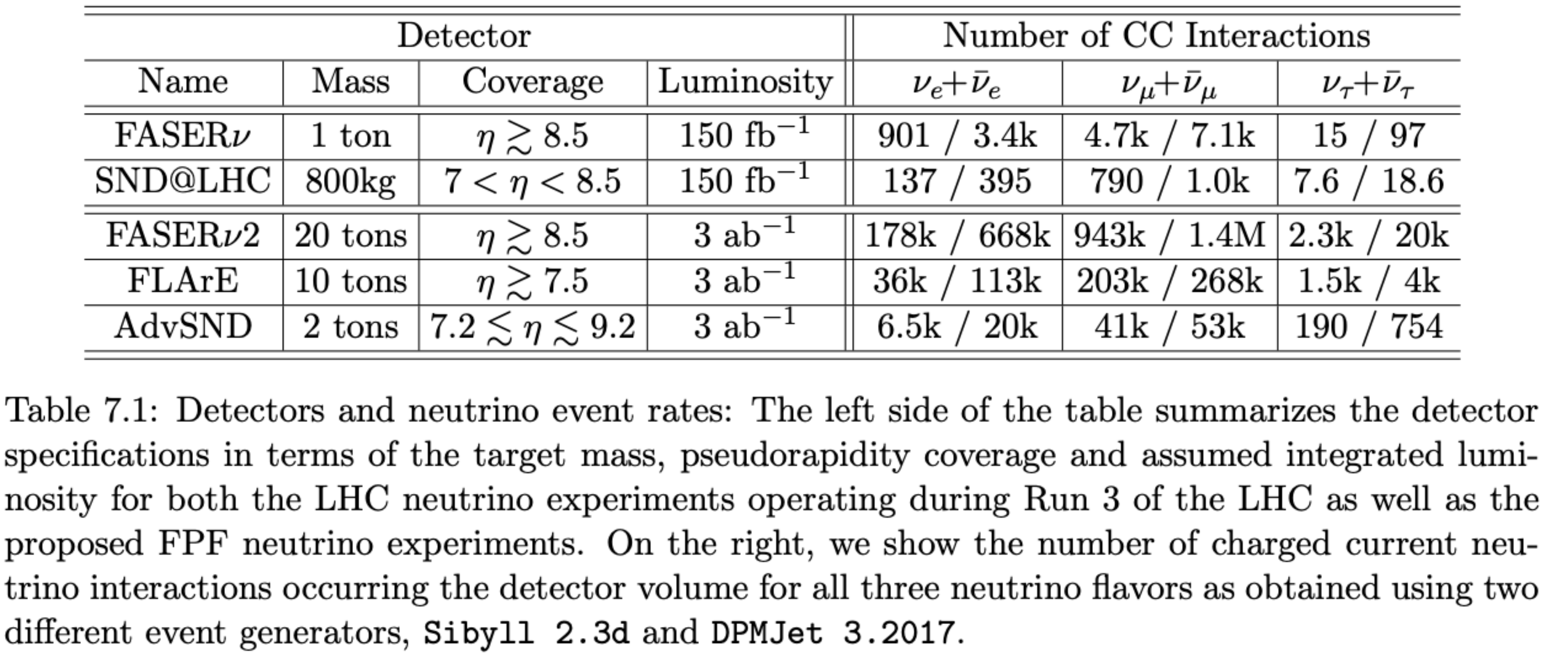
Dedicated search for CvB see, e.g., the PTOLEMY proposal,
PTOLEMY collaboration, arXiv:1808.01892 (2022)

Other CvB phenomenology, see, e.g., Brdar et al, *PLB* (2022)



Abraham, Foroughi-Abari, Kling, **Tsai**
https://arxiv.org/abs/2301.10254

Summary Table



Detector				Number of CC Interactions		
Name	Mass	Coverage	Luminosity	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
FASERν	1 ton	$\eta \gtrsim 8.5$	150 fb^{-1}	901 / 3.4k	4.7k / 7.1k	15 / 97
SND@LHC	800kg	$7 < \eta < 8.5$	150 fb^{-1}	137 / 395	790 / 1.0k	7.6 / 18.6
FASERν2	20 tons	$\eta \gtrsim 8.5$	3 ab^{-1}	178k / 668k	943k / 1.4M	2.3k / 20k
FLArE	10 tons	$\eta \gtrsim 7.5$	3 ab^{-1}	36k / 113k	203k / 268k	1.5k / 4k
AdvSND	2 tons	$7.2 \lesssim \eta \lesssim 9.2$	3 ab^{-1}	6.5k / 20k	41k / 53k	190 / 754

Table 7.1: Detectors and neutrino event rates: The left side of the table summarizes the detector specifications in terms of the target mass, pseudorapidity coverage and assumed integrated luminosity for both the LHC neutrino experiments operating during Run 3 of the LHC as well as the proposed FPF neutrino experiments. On the right, we show the number of charged current neutrino interactions occurring the detector volume for all three neutrino flavors as obtained using two different event generators, `Sibyll 2.3d` and `DPMJet 3.2017`.

- Feng et al, Journal of Physics G (2023), https://arxiv.org/abs/2203.05090

Thank you!