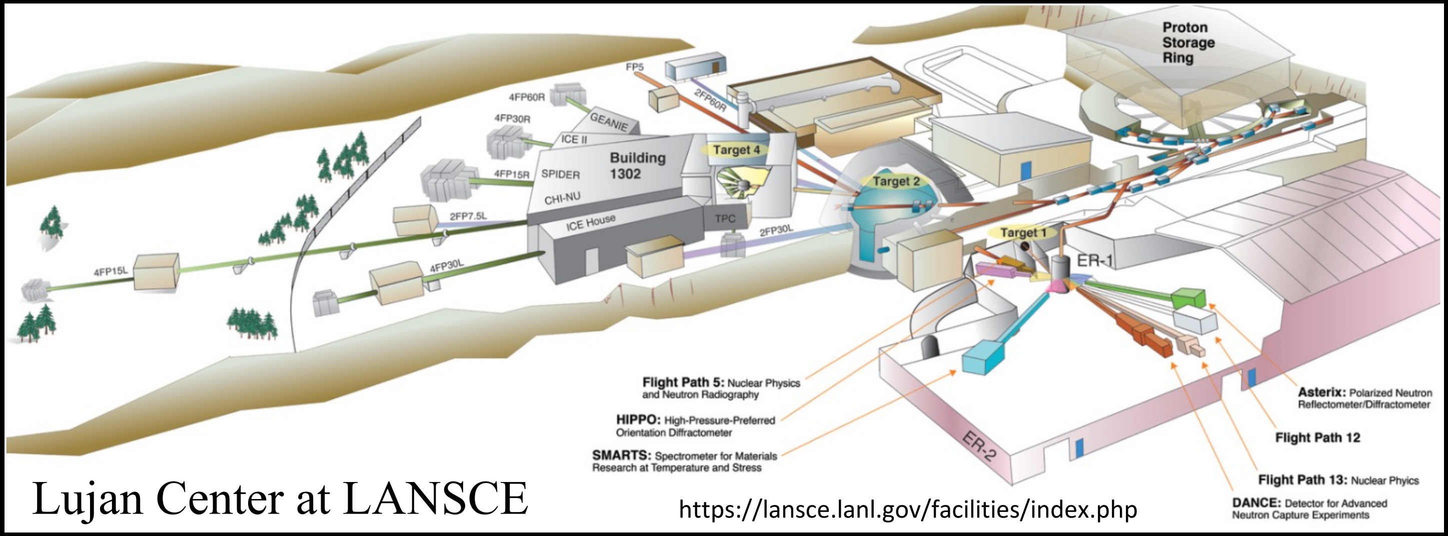
Unveiling Deep Mysteries with Milli Charges: New Physics & Cosmology Probes at LANL

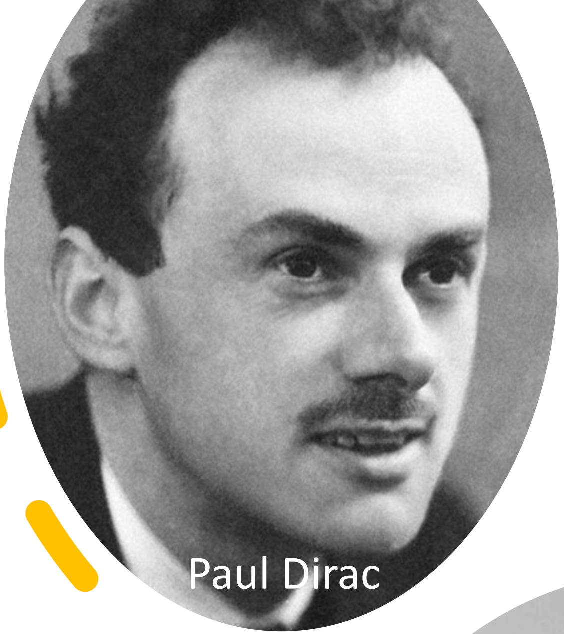


w/Liu & Kranti (LANL), Citron (UC Davis), Hwang & Yoo (Korea U.)

Yu-Dai Tsai
University of California, Irvine (yudait1@uci.edu)
→ Director's Fellow at LANL (2024)

Outline

- **Intro & Motivations**
- Probing "Reheating" Cosmology
- Experimental Searches: LANL, DUNE, and more


Paul Dirac


Frederick Reines

Theoretical Motivations

Millicharged particle (mCP) is a particle χ with {mass, electric charge} = $\{m_\chi, \epsilon e\}$

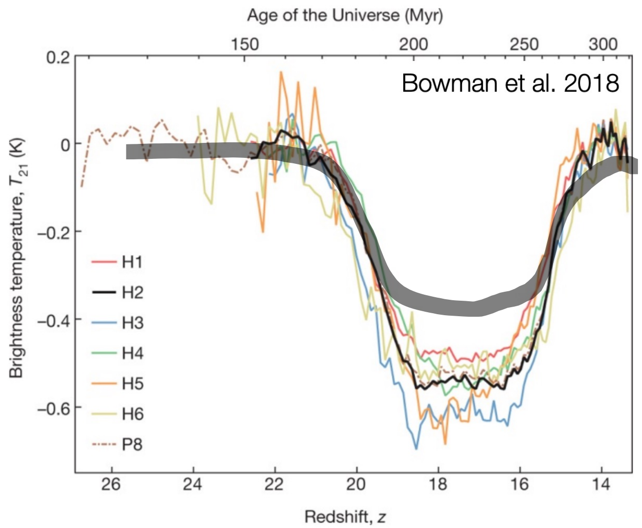
$\epsilon = Q_x/e$

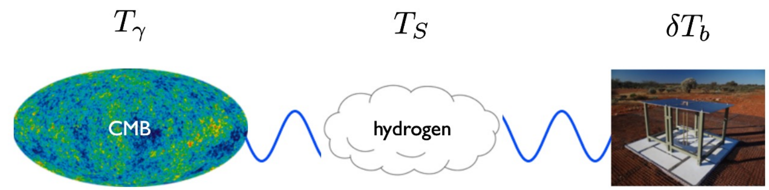
1. **Is electric charge quantized? To what unit? And why?**
   Long-standing questions:

- Inspired **Dirac quantization, Grand Unified Theories (GUTs)**
- **String theory predicts un-confined fractionally charged particles**
  Wen, Witten, Nucl. Phys. B 261 (1985) 651-677
- Link to **string compactification** & **quantum gravity** (Shiu, Soler, Ye, PRL '13)

2. **Millicharged dark matter Implications & explain CMB absorption spectrum**

Motivations: Millicharged Dark Matter (mDM)





Adapted from J. Pritchard

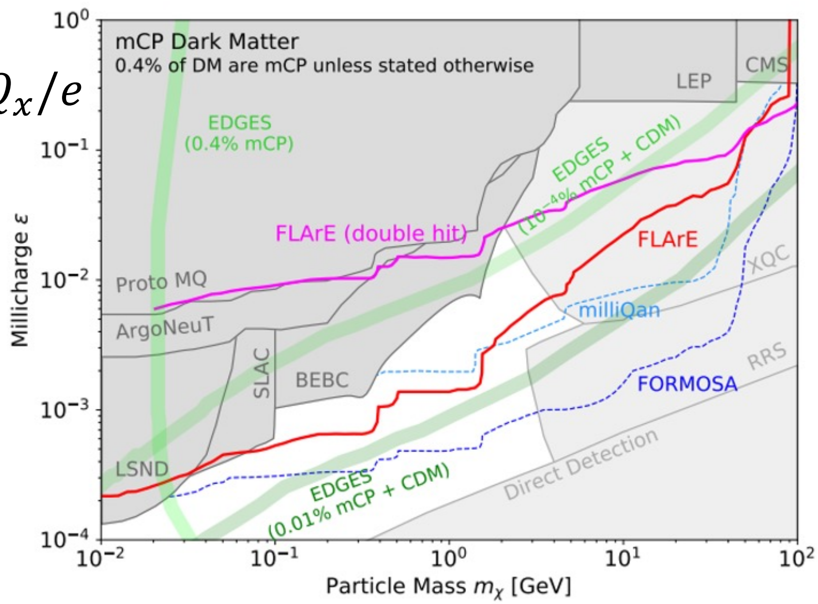
From Jordan Mirocha (UCLA)

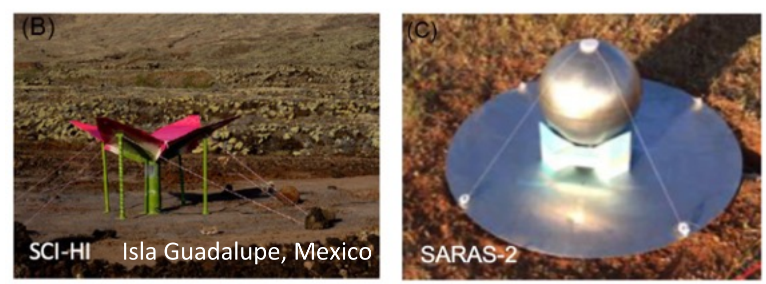
e.g., EDGES

EDGES @ Murchison Radioastronomy Observatory, Western Australia

- 21 cm CMB absorption spectrum
- EDGES anomaly gives a hint of dark matter property
- Many (upcoming) measurements!
  Voytek et al, APJL (2014),
  Singh et al, arXiv: 1710.01101

$$\epsilon = Q_x / e$$

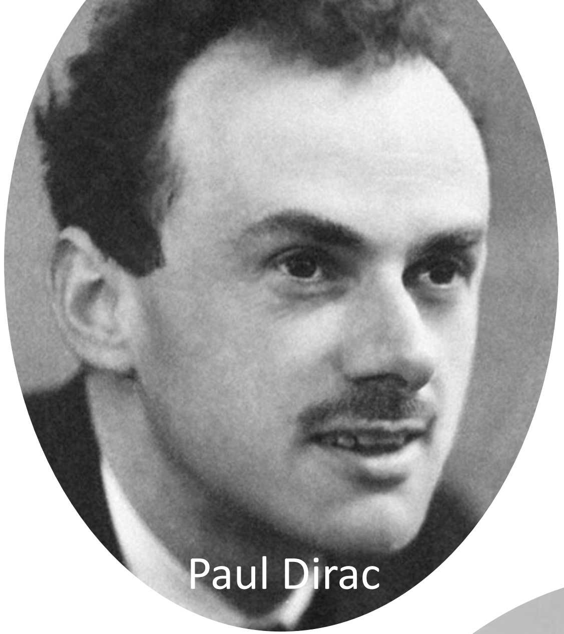




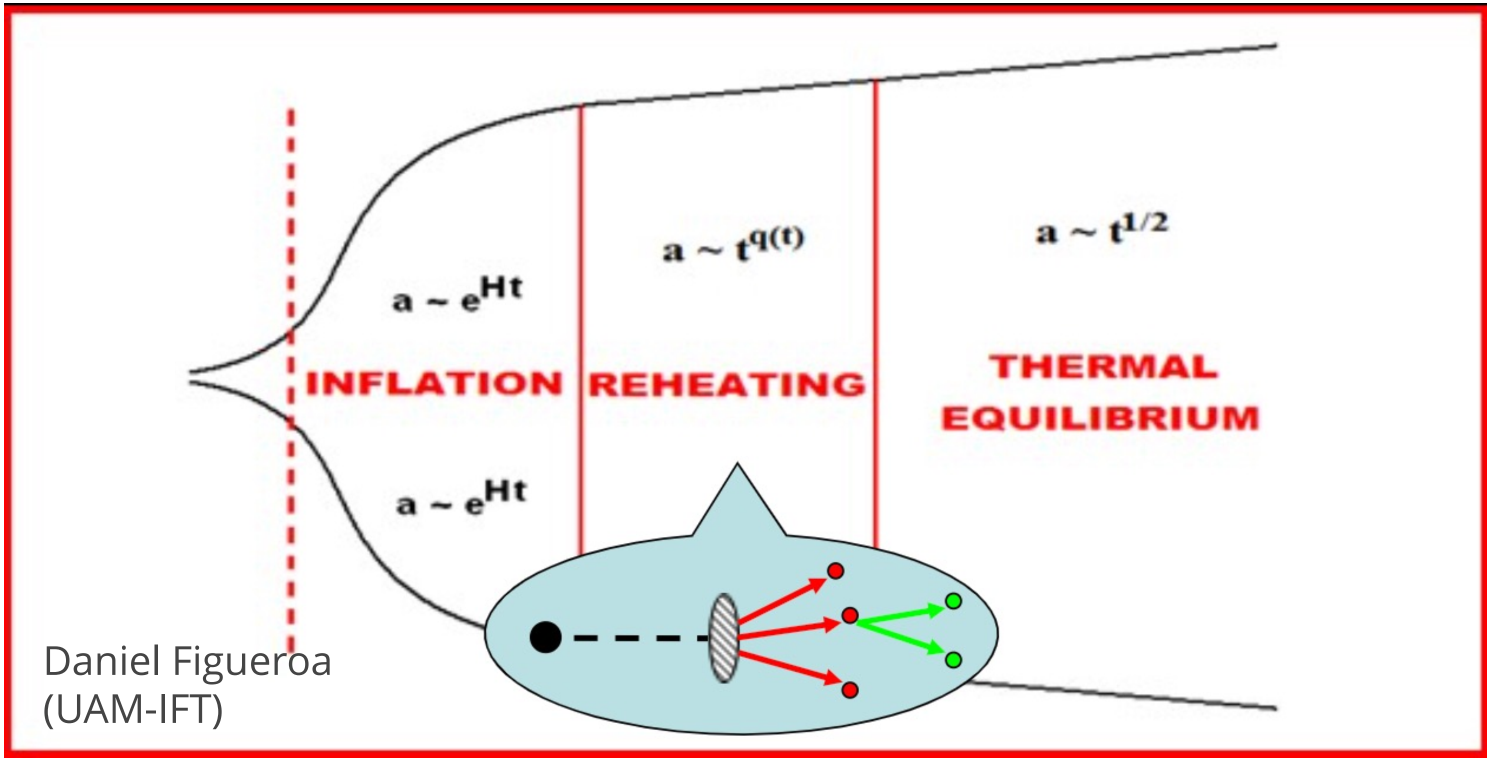
SARAS-3 in North Karnataka, India

Outline

- Intro & Motivations
- **Probing "Reheating" Cosmology**
- Experimental Searches



Inflation and Reheating



a: scale factor, basically quantifying the size of the Universe

t: time

We know very little about reheating. We don't even know what temperature does it reheat to!

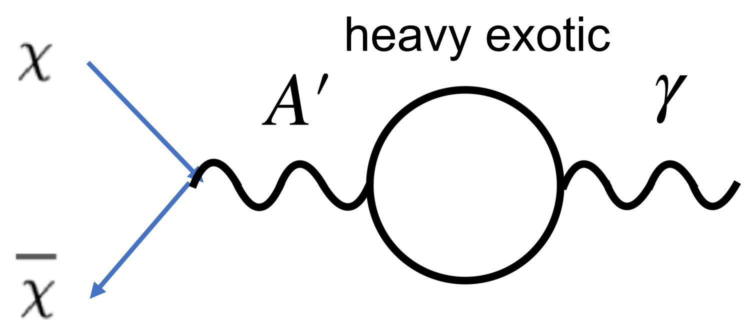
Two Kinds of mCP

“Pure” mCP

- Theoretical implication of mCP with a small (irrational) charge without a dark photon
- Implications on GUTs models
- Implications on string compactifications
  Shiu, Soler, Ye, *PRL* (2013)

Kinetic-mixing mCP

- Compatible with GUTS.



Choose a proper basis: massless dark photon A’ decouple from SM

$$\mathcal{L}_{\rm MCP} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\rm MCP})\chi$$

Cosmic Millicharge Background (CmB)

Gan, **Tsai**, 2308.07951

"Pure" mCP

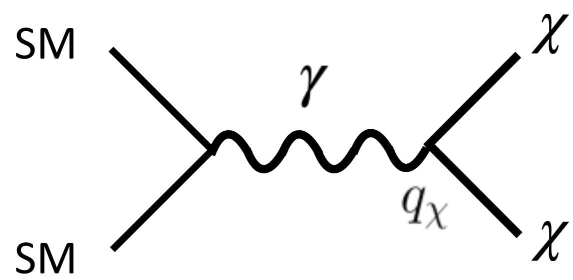
- mCP with a **small (irrational) charge & no dark photon**
- **Indirect test of GUTs models**
- **Indirect test of string compactifications**
  Gan, Shiu, **Tsai**, in progress

$$\mathcal{L}_{\rm MCP} = i\bar{\chi}(\partial\!\!\!/ - i\epsilon' e B\!\!\!/ + M_{\rm MCP})\chi$$

Irreducible Production during Reheating

Inflaton

Reheating at temperature T_{rh}



"Freeze-in"

"Freeze-out" when it stops

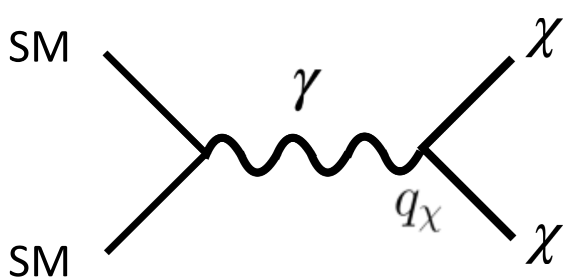
Cosmic Millicharge: Overproduction During Reheating

Gan, **Tsai**, 2308.07951

Irreducible Production during Reheating

Inflaton

Reheating at temperature T_{rh}



"Freeze-in"

"Freeze-out"
when it stops

mCP can be easily "overproduced", to more than that of the observed amount of dark matter (DM)

$$\Omega_{\rm DM} h^2 \sim 0.12$$

Currently measured DM abundance

$$\Omega \equiv \frac{\rho}{\rho_c}$$

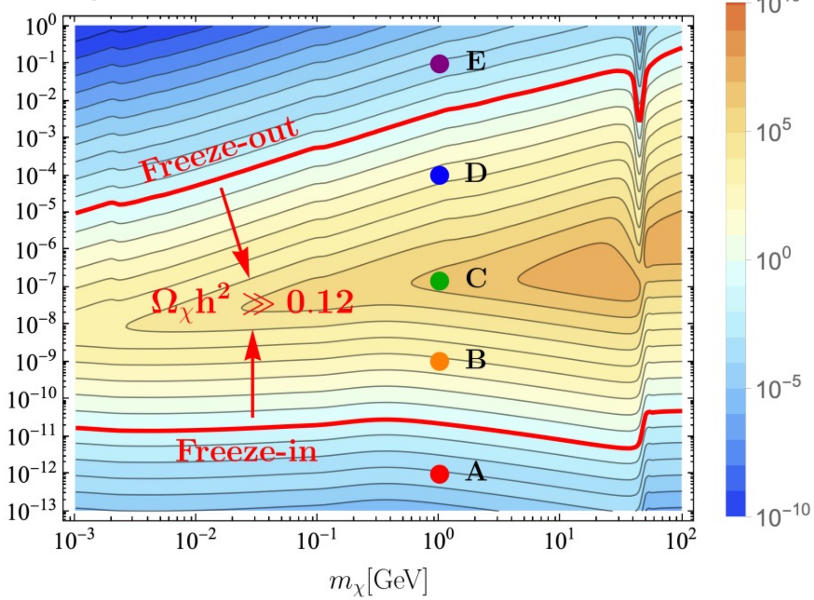
Density is normalized by ρ_c, the critical density for a flat Universe; h = 0.674

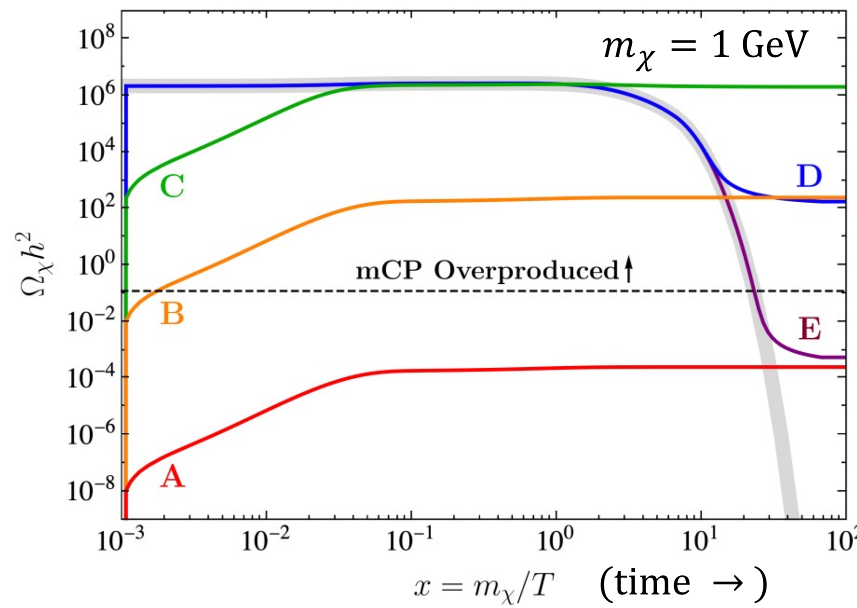
$$\rho_c = \frac{3H^2}{8\pi G}$$

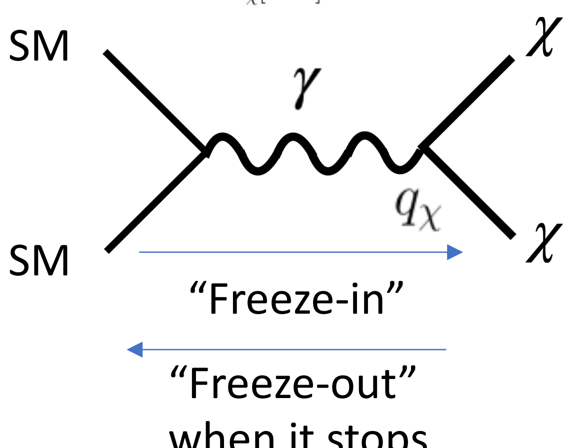
“Pure” CmB Cosmology: Freeze-in and Freeze-out

T_{rh} = 1 TeV (or above)

$\epsilon = Q_x/e$





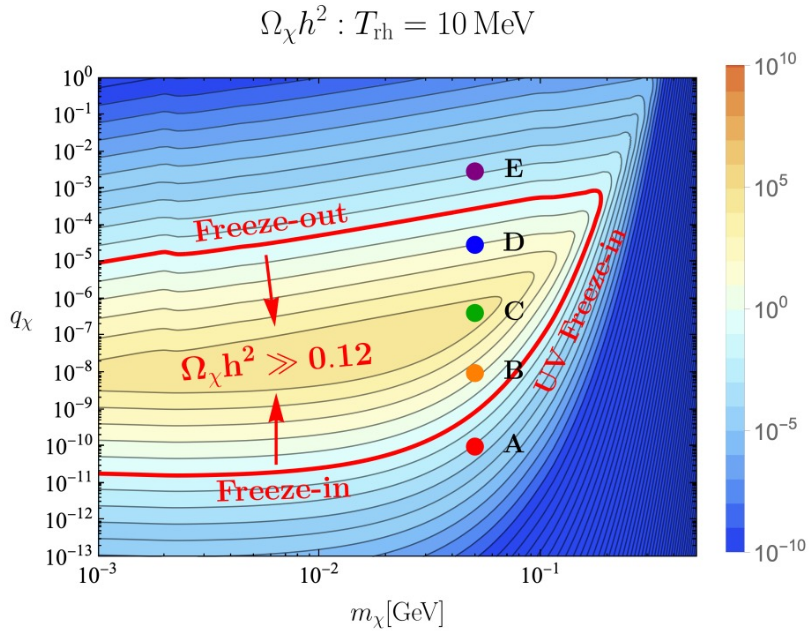


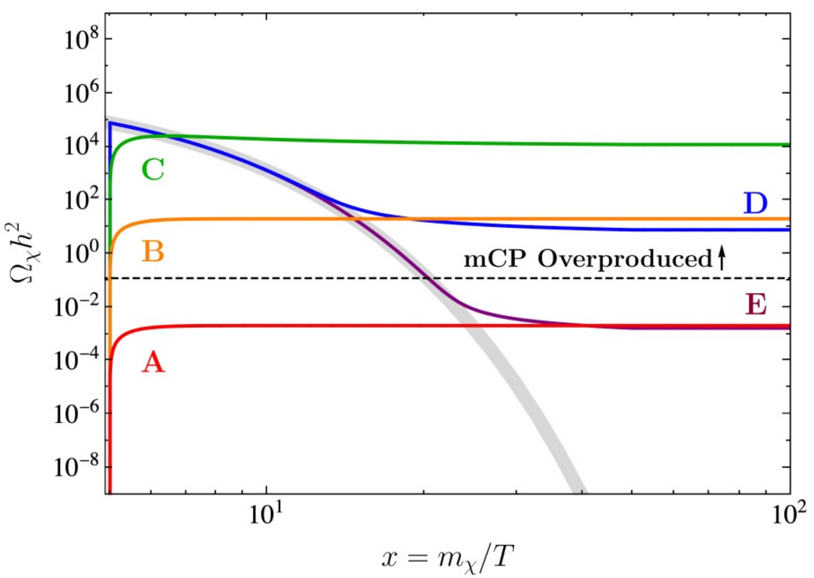
$$\dot{n}_\chi + 3Hn_\chi \simeq \mathcal{C}_n(T)\left(1 - \frac{n_\chi^2}{n_{\chi,\rm eq}^2}\right),$$

$$\mathcal{C}_n(T) = 2n_Z\langle\Gamma\rangle_{Z\to\chi\bar{\chi}} + 2n_f n_{\bar{f}}\langle\sigma v\rangle_{f\bar{f}\to\chi\bar{\chi}}$$

"Pure" CmB Cosmology: Low-Reheat Temperature

T_{rh} = 10 MeV

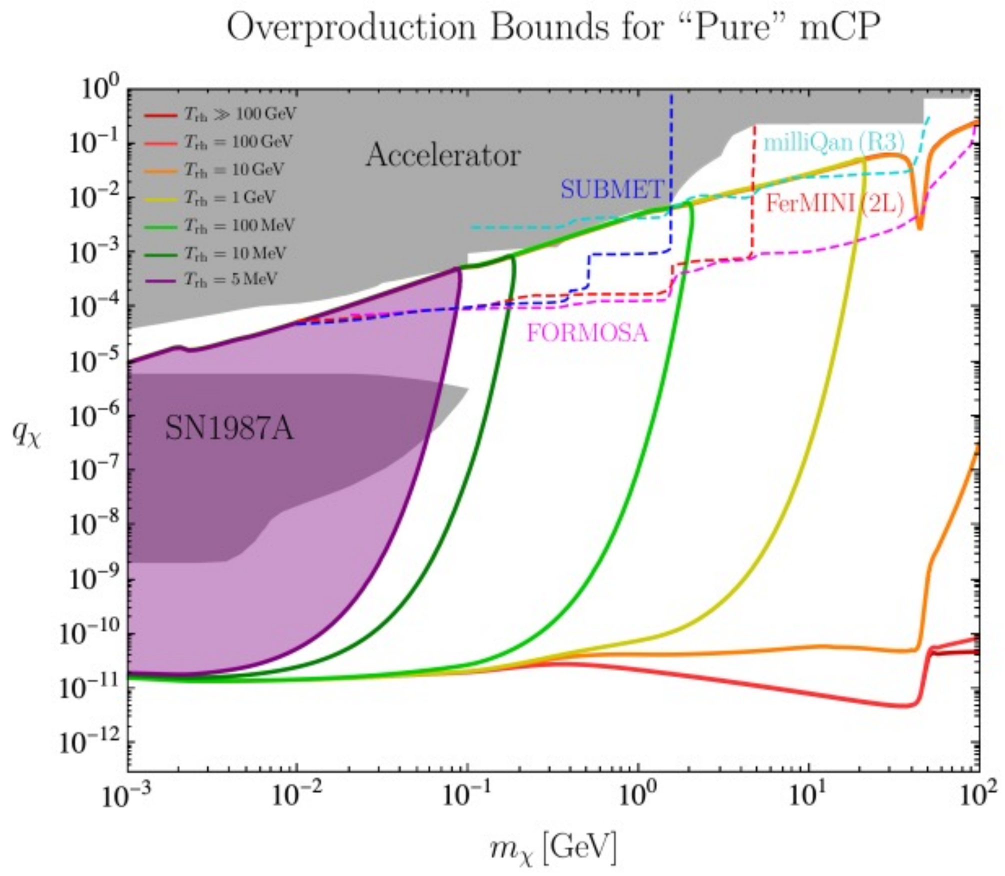




For the freeze-in at low $\mathrm{T_{rh}}$, mCP-SM interaction is suppressed exponentially: the coupling has to increase exponentially to compensate it

The freeze-in curve holds the approximate relation: $q_\chi \propto \exp\left(\frac{m_\chi}{T_{\rm rh}}\right)$

“Pure” CmB from Irreducible Production



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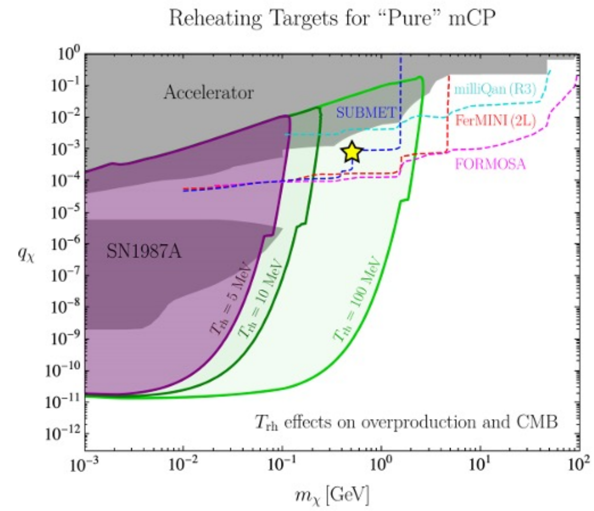
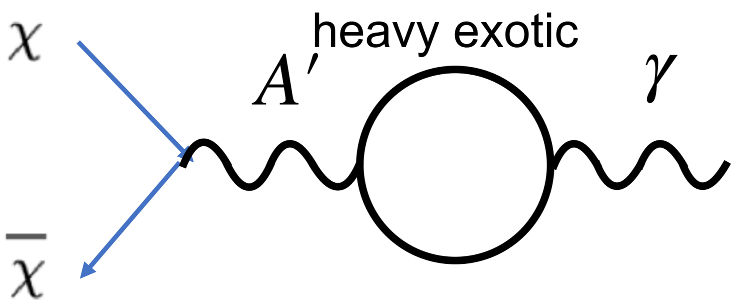


- Minimal reheating temperature larger than T_{BBN} (e.g., Hasegawa+, JCAP19; Hannestad, PRD04)
- **Our purple bound is covering the SN1987A constraint** (gray region from Chang+, JHEP18)

Kinetic-Mixing Cosmic Millicharge Background (CmB)

Kinetic-mixing mCP



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

Choose a proper basis:
massless dark photon A' decouple from SM

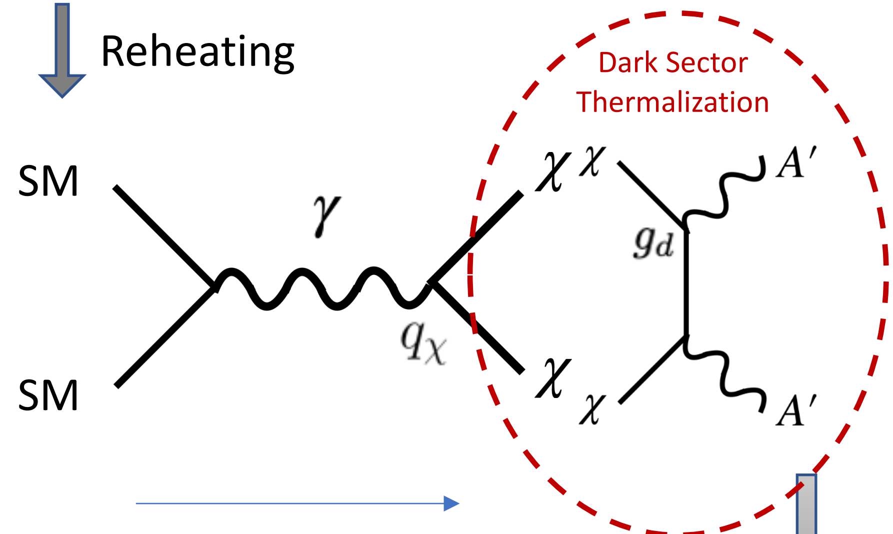
$$q_\chi = \frac{\epsilon g_d}{e}$$

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

Kinetic-mixing mCP

Inflaton

Reheating



Freeze-in:

Freeze-out:

massless dark photon A' will affect N_{eff}
See Vogel, Redondo, JCAP (2014),
Adshead, Ralegankar, Shelton JCAP (2022)

Kinetic-Mixing CmB Cosmology:

N_{eff} Effects from Dark Photon

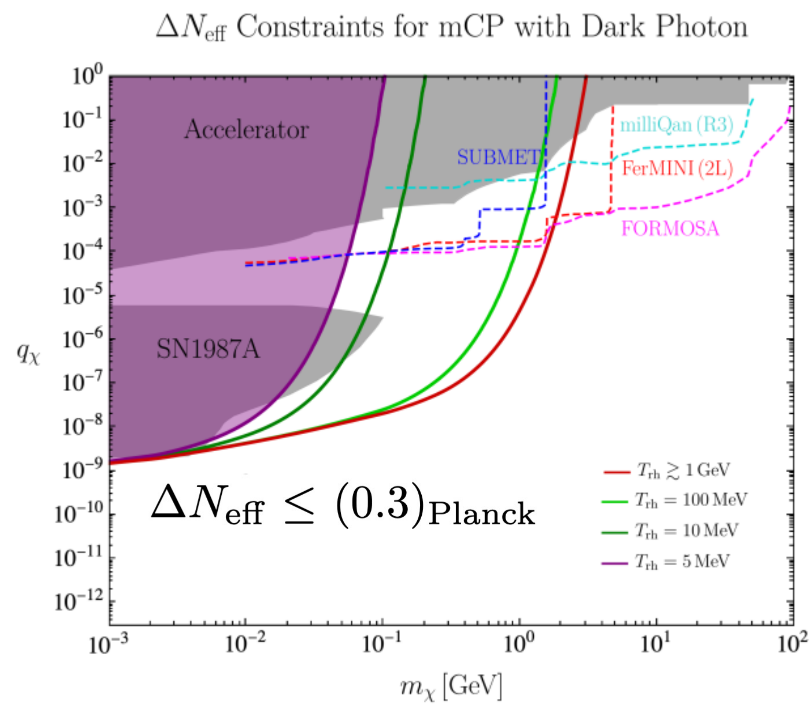
- Freeze-in from the heat bath
- χ thermalizing with dark photon: Require effective transfer of χ entropy to dark radiation A' here

$$\frac{n_\chi^{\rm FI}\langle\sigma v\rangle_{\rm dth}}{H} \sim q_\chi^2\alpha_{\rm em}^2\alpha_d^2\left(\frac{m_{\rm pl}}{T}\right)^2 \gg 1.$$

$$\alpha_d \gg 10^{-4}$$

- A quick ΔN_{eff} estimation:

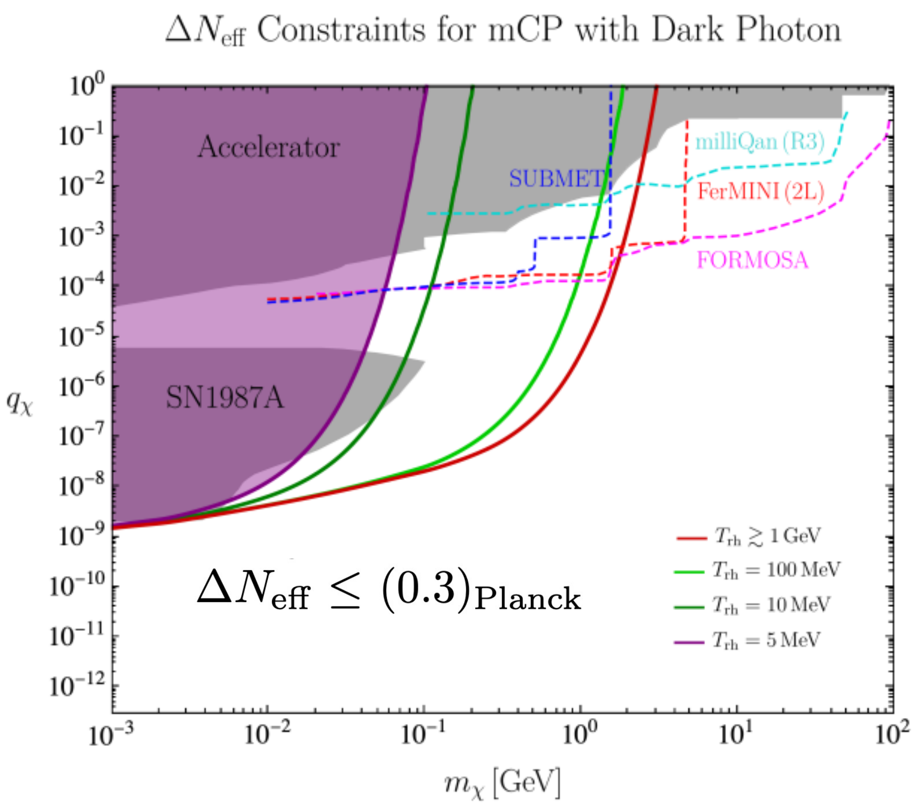
$$\Delta N_{\rm eff} \sim q_\chi^2\alpha_{\rm em}^2\frac{m_{\rm pl}}{m_\chi}$$



Gan, **Tsai**, 2308.07951

- **Our purple bound is again covering the SN1987A constraint**

Kinetic-Mixing CmB Cosmology



$$q_\chi \sim 10^{-7} \left(\frac{m_\chi}{1\,{\rm GeV}}\right)^{1/2} \left(\frac{\Delta N_{\rm eff}}{0.3}\right)^{1/2} . \; m_\chi \leq {\rm T_{rh}}$$

$$q_\chi \propto \exp\left(\frac{m_\chi}{T_{\rm rh}}\right) . \; m_\chi > {\rm T_{rh}}$$

Considering higher reheating temperatures for region to the right of the red curve:

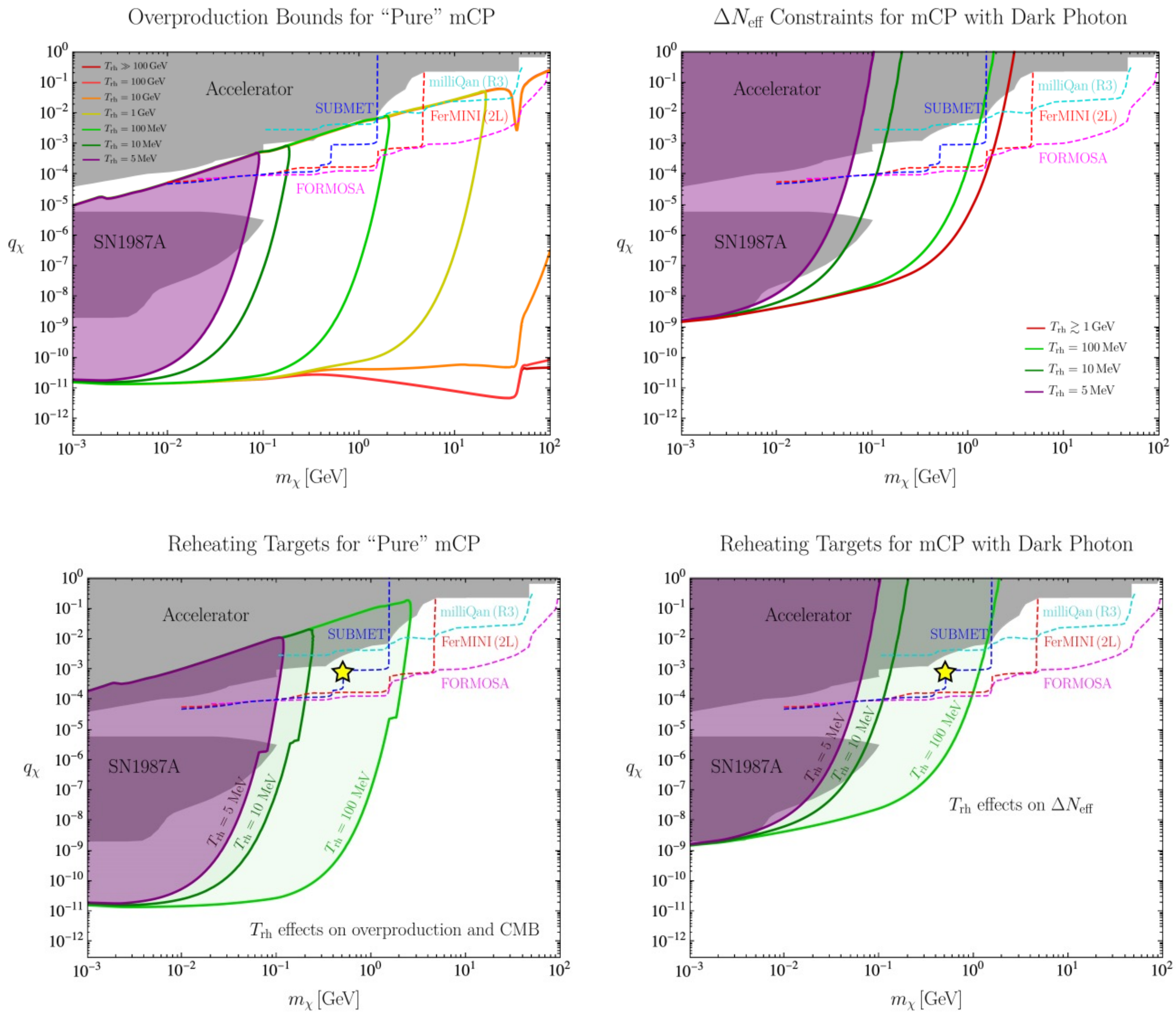
$$\Delta N_{\rm eff} \lesssim g_{A'} \, \frac{4}{7} \left(\frac{g_{*,S}(T \ll T_{\rm QCD})}{g_{*,S}(T \gg T_{\rm QCD})}\right)^{4/3} \simeq 0.1,$$

See Gan, **Tsai**, 2308.07951 for detailed discussions

Current: $\Delta N_{\rm eff} \leq (0.3)_{\rm Planck}$

Future: $\Delta N_{\rm eff} \leq (0.06)_{\rm CMB\text{-}S4}$

Testing Reheat Temperatures in Both Cases



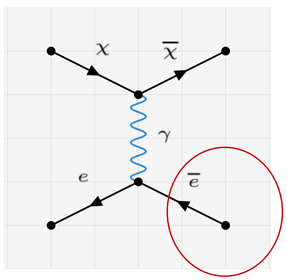
Outline

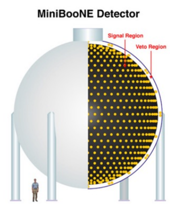
- Intro
- Probing Reheating Cosmology
- **Experimental Searches**

Two Search Methods: Scattering & Scintillation

(A) **Electron Scattering**

~ energy exchange set by detector threshold (> MeV)





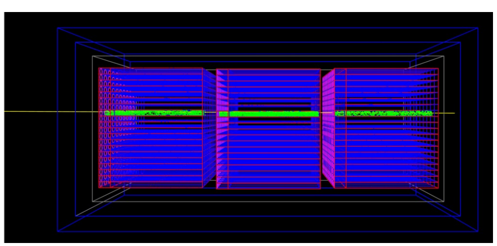
e.g. neutrino detector
MiniBooNE (arXiv:0806.4201)

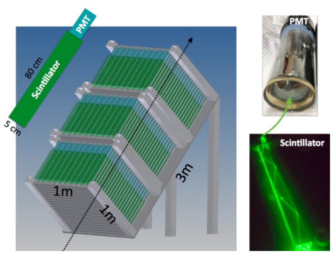
$$\sigma_{e\chi} \simeq 2.6 \times 10^{-25} \mathrm{cm}^2 \times \epsilon^2 \times \frac{1 \ \mathrm{MeV}}{E_e^{(\mathrm{min})} - m_e}.$$

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

(B) **Dedicated Scintillation Searches** for Millicharge Particles

~ eV-level energy exchange





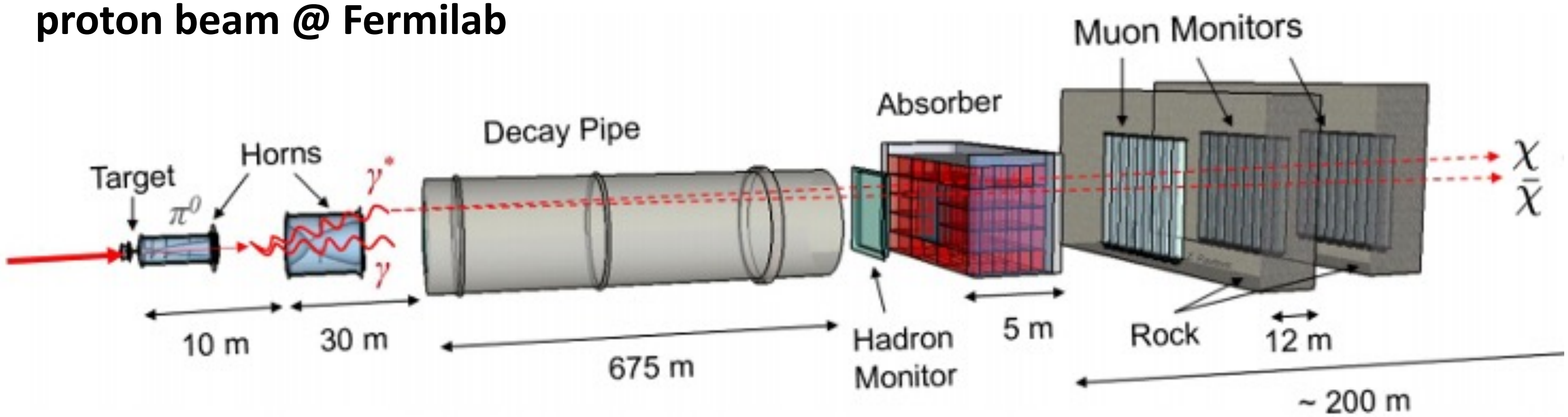
$$\left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2.$$

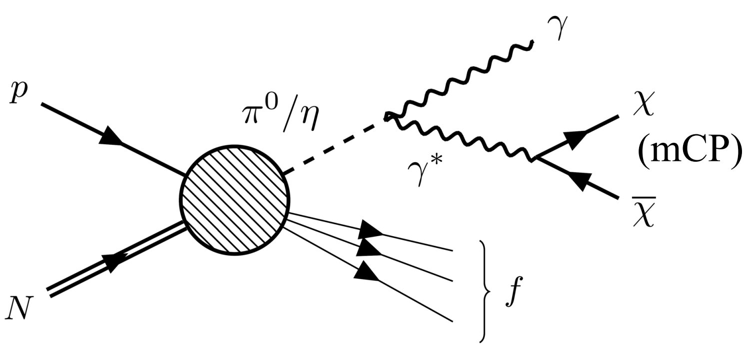
Energy deposition

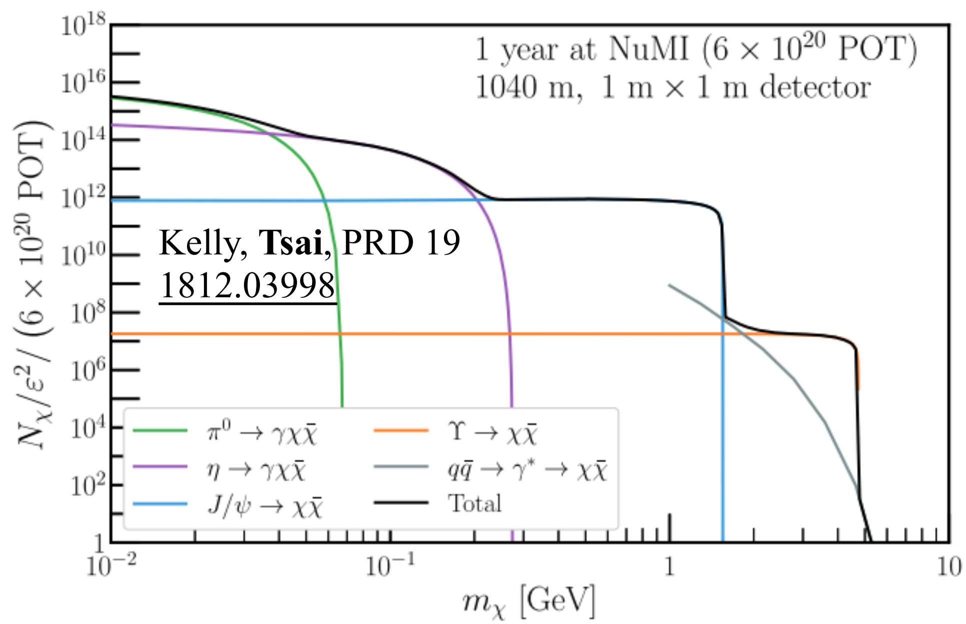
e.g., Haas, Hill, Izaguirre, Yavin, 1410.6816
milliQan design, 1607.04669 (MilliQan Collaboration)

Accelerator Productions

120 GeV NuMI
proton beam @ Fermilab





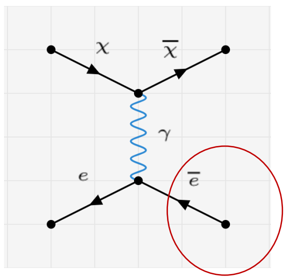


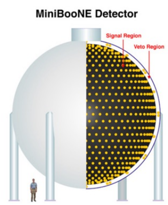
Kelly, **Tsai**, PRD 19
1812.03998

Two Search Methods: Scattering & Scintillation

(A) **Electron Scattering**

~ energy exchange set by detector threshold (~ MeV)





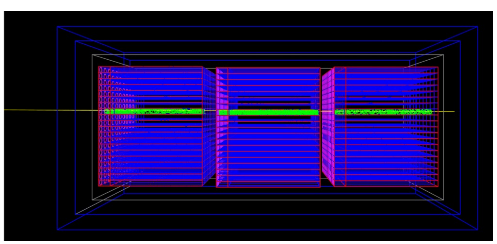
e.g.neutrino Detector
MiniBooNE (arXiv:0806.4201)

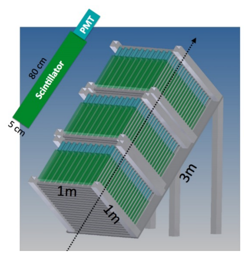
$$\sigma_{e\chi} \simeq 2.6 \times 10^{-25} \text{cm}^2 \times \epsilon^2 \times \frac{1 \ \text{MeV}}{E_e^{(\text{min})} - m_e}.$$

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

(B) **Dedicated Scintillation Searches** for Millicharge Particles

~ eV-level energy exchange





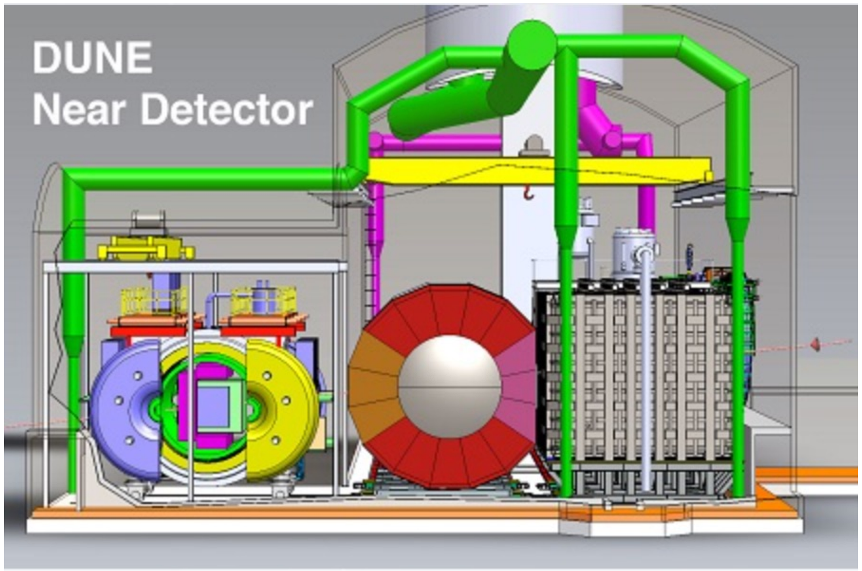
$$\left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2.$$

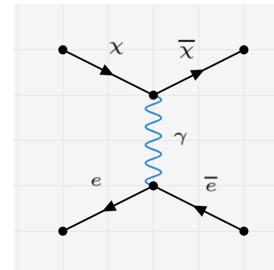
Energy deposition

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

Electron Scattering Searches

Electron Scattering ~ energy exchange set by detector threshold (~ MeV)





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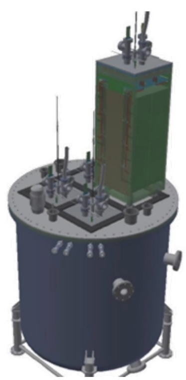
Expressed in **recoil energy threshold**, $E_e{}^{(min)}$

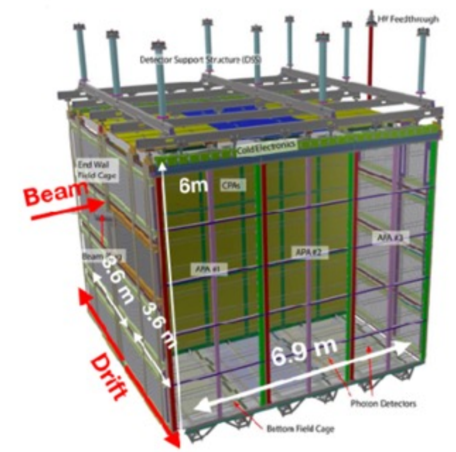
120 GeV NuMI proton beam @ Fermilab



ArgonCube 2x2 (4 modules)

Weber (U of BERN), PAC-2x2-June-2021

400 GeV SPS proton beam @ CERN



ProtonDune-SP

DUNE col., JINST 15 (2020)

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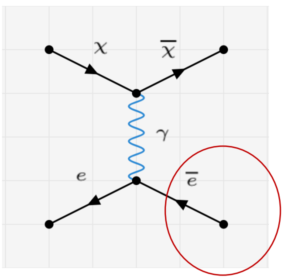

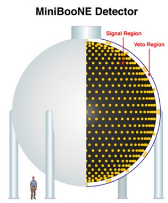

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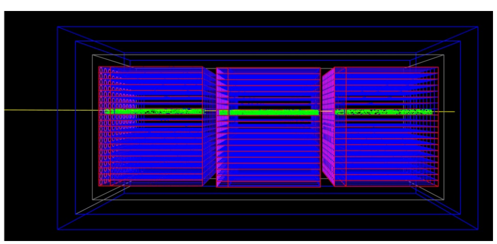
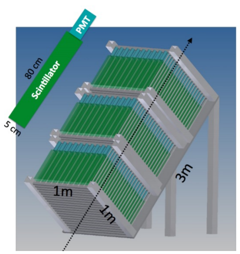
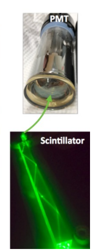
Expressed in **recoil energy threshold**, $E_e{}^{(min)}$

(B) **Dedicated Scintillation** Searches for **Millicharge Particles**

~ eV-level energy exchange







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milliQan design, 1607.04669 (MilliQan Collaboration)

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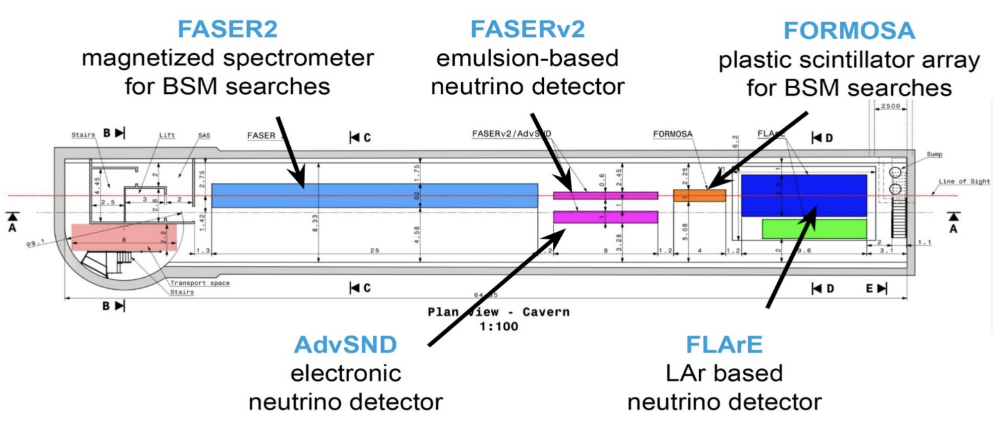
Energy deposition

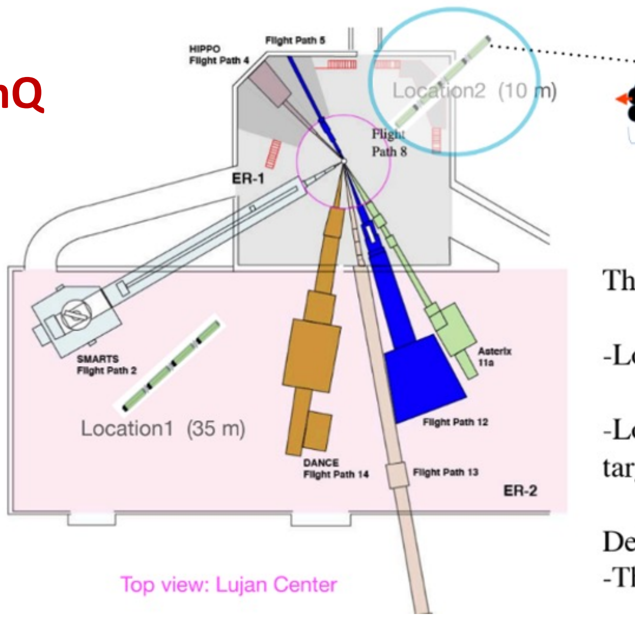
Dedicated mCP Searches (next 3 years)

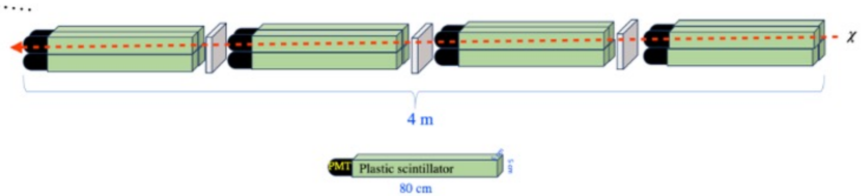
1. **milliQan** (taking data); 2. **SUBMET**: mCP search at J-PARC; **fully approved**

3. **FORMOSA**
   (installing demonstrator)



4. **LANSCE-mQ**
   @LANL





There are two possible locations for MCPx at the Lujan Center.

-Location 1: ER-2 area, 35 m from the center of the target

-Location 2: In the flight path 8 area at ER-1, 10 m from the center of the target.

Detector Concept (prototype):
-The scintillator bars (5 cm x 5 cm x 80 cm) are arranged in four layers.

5. **FerMINI**@Fermilab: updating sensitivity projection

Dedicated mCP Searches (next 3 years)

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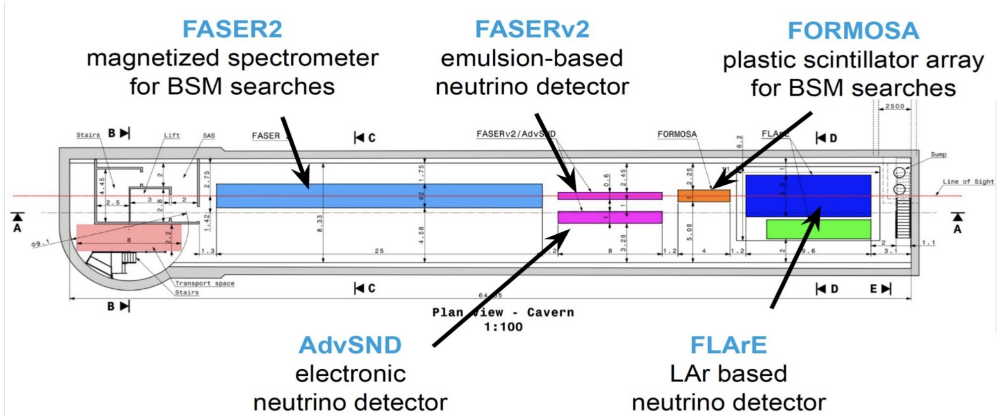
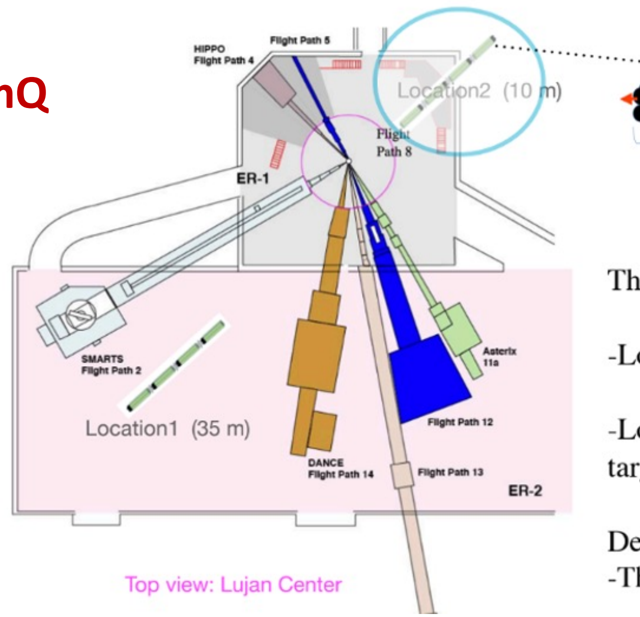
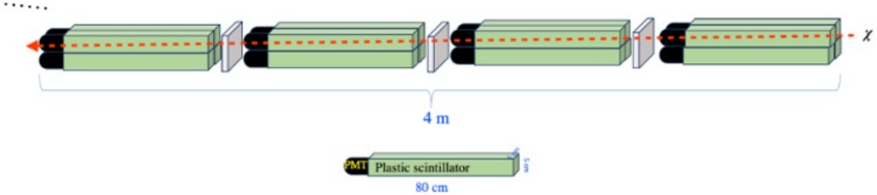
3. **FORMOSA**
   (installing demonstrator)



4. **LANSCE-mQ**
   @LANL





There are two possible locations for MCPx at the Lujan Center.

-Location 1: ER-2 area, 35 m from the center of the target

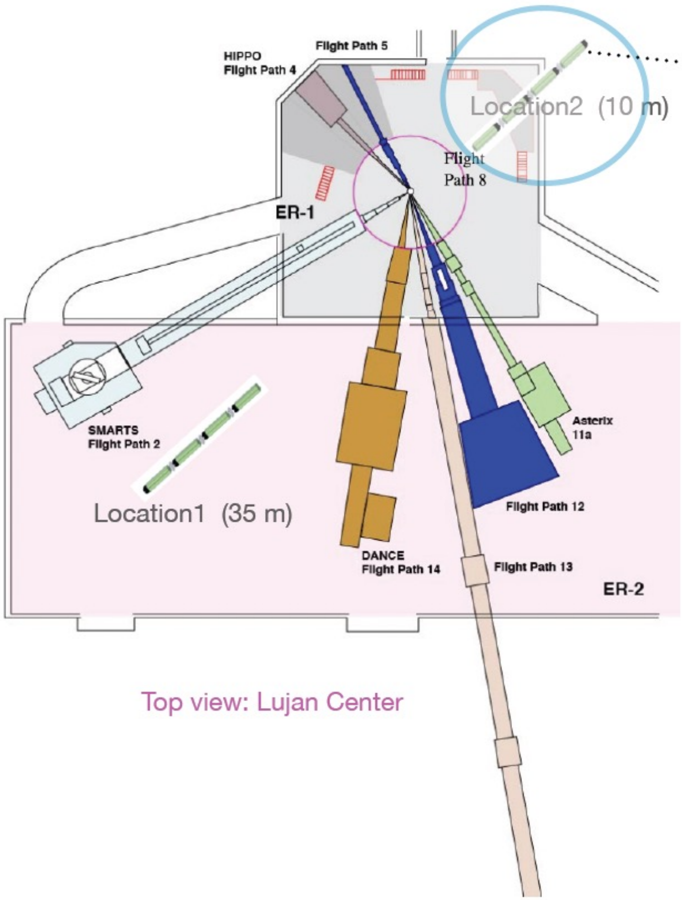
-Location 2: In the flight path 8 area at ER-1, 10 m from the center of the target.

Detector Concept (prototype):
-The scintillator bars (5 cm x 5 cm x 80 cm) are arranged in four layers.

5. **FerMINI**@Fermilab: updating sensitivity projection

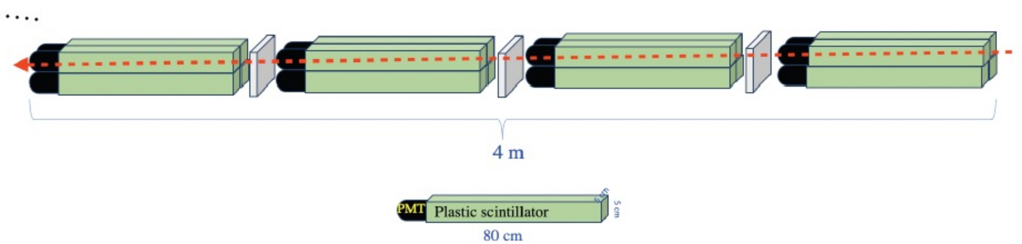
Detector Placement

800 MeV Proton Beam



Kranti Gunthoti (LANL)

- Numbers of layers to be determined
- May only need one or two.



There are two possible locations for MCPx at the Lujan Center.

-Location 1: ER-2 area, 35 m from the center of the target

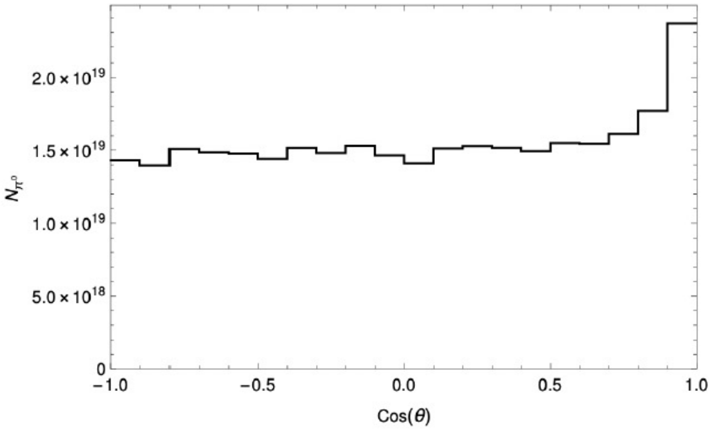
-Location 2: In the flight path 8 area at ER-1, 10 m from the center of the target.

Detector Concept (prototype):
-The scintillator bars (5 cm x 5 cm x 80 cm) are arranged in four layers.

-A photomultiplier tube (PMT) is attached to one end of each bar.

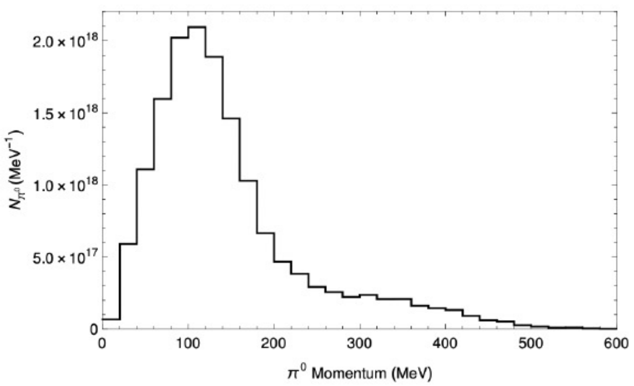
-This detector will be 90 degrees w.r.t. the proton beam.

Lujan Center: Meson Productions



-The π^0 angular distributions produced at the Lujan target, assuming POT=2.71×10^{21}.

-The total number of π^0s, $N\pi^0$, scales linearly with Protons on Target (POT), based on the simulations $N\pi^0 = 0.115 \times POT$.



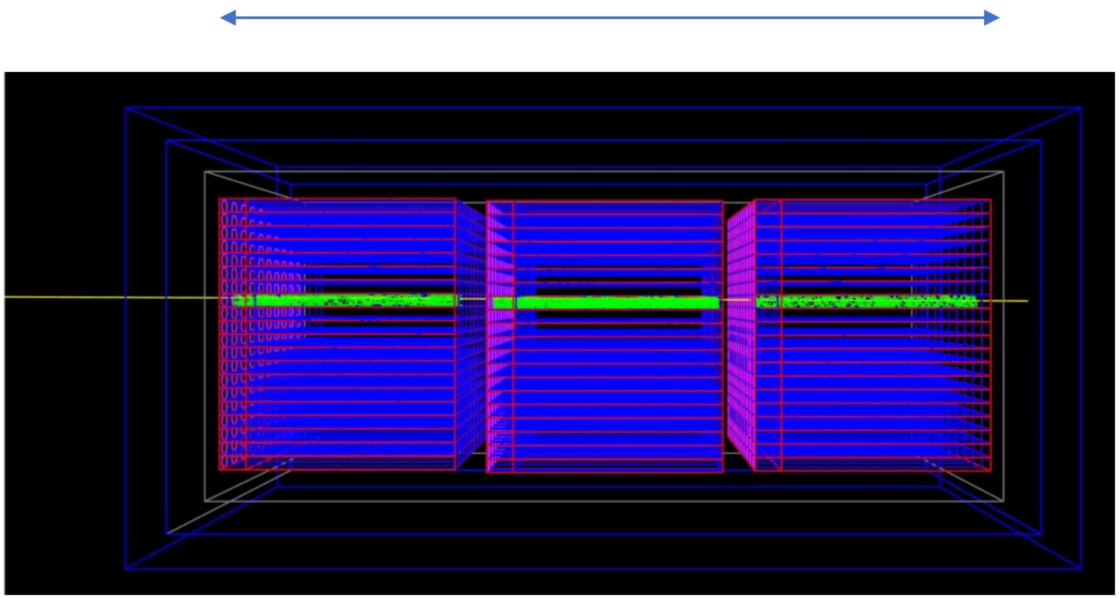
-The momentum distribution peaks between 100 and 120MeV, with a mean momentum of 146MeV.

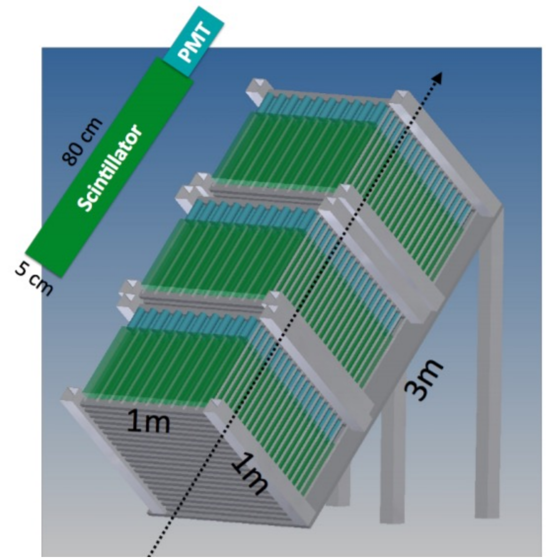
Phys. Rev. D **106**, 012001

CCM Collaboration, PRD, Vol. 106, No. 1 (2022)
https://arxiv.org/abs/2105.14020

Detector Concept

$\Delta t \sim 20$ nanoseconds (ns)

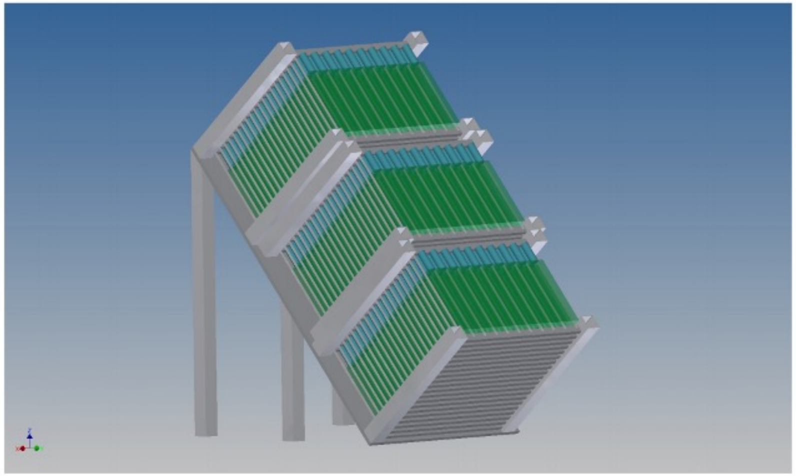




See arXiv:1607.04669; arXiv:1810.06733

Detector: Some Details of the Nominal Design

- Nominal: **1 m × 1 m** (transverse plane) × **n (3) m** (longitudinal) **plastic scintillator array.**
- **n layers** each containing ~ 100 scintillator bars optically coupled to **high-gain photomultiplier (PMT)**.
- A **n-coincidence within a 20 ns time window** along longitudinally contiguous bars in each of the layers required to reduce the **dark-current noise (the dominant background)**.



See arXiv:1607.04669; arXiv:1810.06733

Photoelectrons (PE) from Scintillation

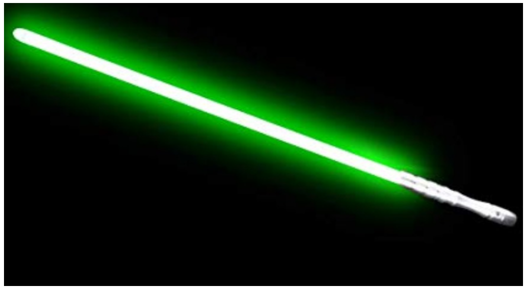
- **The averaged number of photoelectron (PE)** seen by the detector from single MCP is:

$$N_{PE} \propto \left\langle -\frac{dE}{dx} \right\rangle \times l_{scint}, \ \left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2.$$

$\langle dE/dx \rangle$ is the "mass stopping power" (PDG 2018)

One can use Bethe-Bloch Formula to get a good approximation

- $\boldsymbol{N_{PE} \sim} \epsilon^{\mathbf{2}}$ x $\mathbf{10^6}$, $\epsilon \sim \mathbf{10^{-3}}$ roughly gives one PE in one meter plastic scintillation bar



Signature: N-Layers Coincidence

- Based on Poisson distribution, zero event in each bar correspond to $\boldsymbol{P_0 = e^{-N_{PE}}}$, so the probability of seeing triple incident of one or more photoelectron is:

$$P = (1 - \exp[-N_{\mathrm{PE}}])^{n_{\mathrm{layers}}}$$

- $\boldsymbol{N_{\mathbf{x,detection}} = N_{\mathbf{x,passing\ detector}}}$ x $\mathbf{P}$

Dark Current Background @ PMT

- dark-current frequency to be $\boldsymbol{v_B}$**~ 50 - 500 Hz** for estimation (2005.06518)

  (Hamamatsu R7725 can reach 50 Hz during recent testing)

- For each tri-PMT set (using 500 Hz as a conservative estimation),

  the background rate for triple incidence is

  $\boldsymbol{v_B^3\ \Delta t^2 = 5 \times 10^{-8}}$ **Hz**, for **Δt = 20 ns.**

- Consider 100 sets as a nominal design.
- The total background rate is 100 x 5 x 10^{-8} ~ 5 x10^{-6} Hz
- ~ **160 background events** in one year of trigger-live time
- **Fixed-target experiment trigger-live time can be way shorter!**
- FerMINI: Kelly, **Tsai**, PRD (2019), 1812.03998

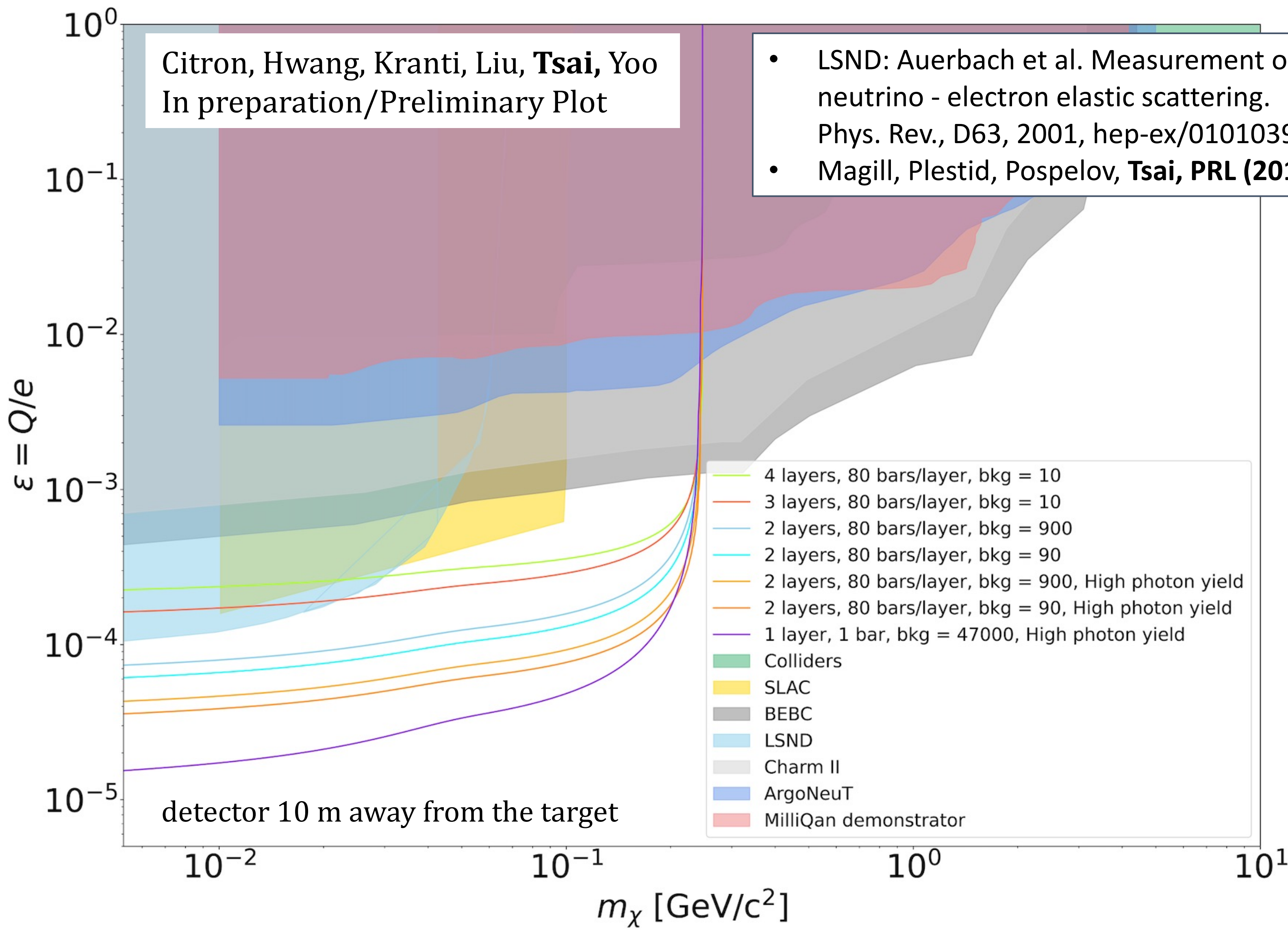
  SUBMET: Kim, Hwang, Yoo, JHEP (2021), 2102.11493

Fixed Target Live Time (LANSCE Beam)

- Width of a single proton bunch: triangular pulse ~ 270 ns wide
- Set acquisition time window = 500 ns
- **Live time/year =**
  500*ns* x 20*Hz* x 86400*s* x 365d ~ 315 seconds
- **Dark current background per year ~ 0.002 for 3 layers**
- We can afford **N = 1 or 2 layers** for fixed-target searches: larger signal rate

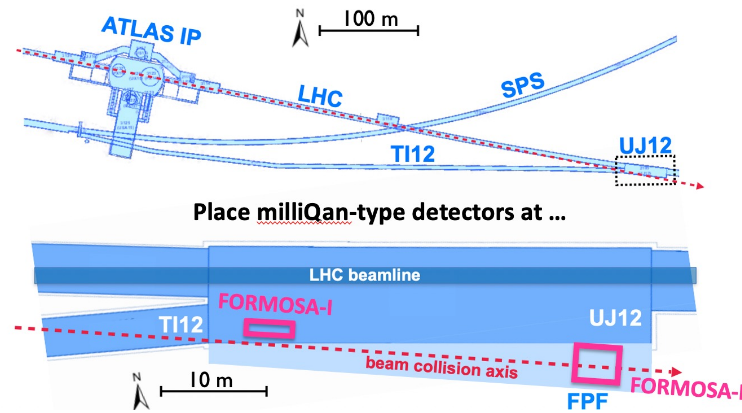
$$P = (1 - \exp[-N_{\mathrm{PE}}])^{n_{\mathrm{layers}}}$$

mCP Sensitivity Reach



- LSND: Auerbach et al. Measurement of electron - neutrino - electron elastic scattering. Phys. Rev., D63, 2001, hep-ex/0101039
- Magill, Plestid, Pospelov, **Tsai, PRL (2019)**

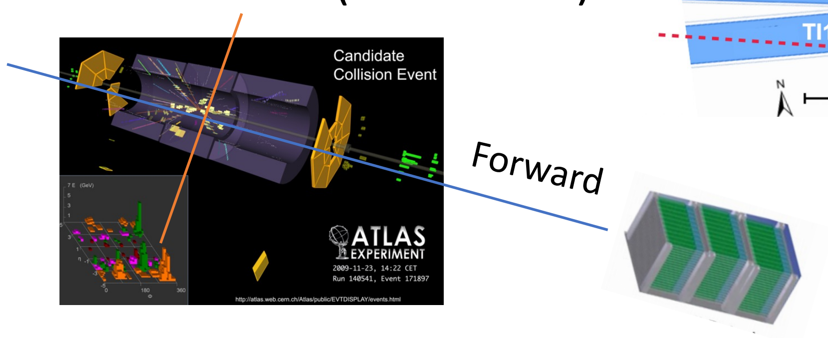
Some Other Ways to Study mCPs



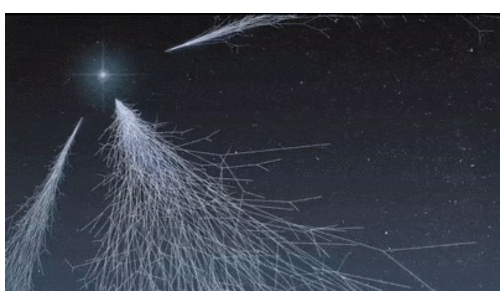
(I) **FORward MicrOcharge SeArch, FORMOSA!**

Foroughi-Abari, Kling, **Tsai**, 2010.07941, *PRD (2021)*

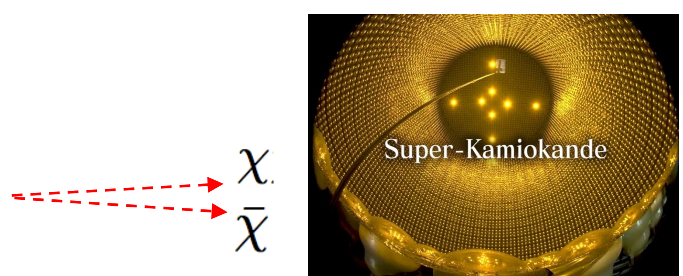
Transverse (traditional)



(II) **Cosmic-ray production** and detection in **large neutrino observatories (Super-K)**, Plestid, Takhistov, **Tsai** et al, 2002.11732, *PRD* 20.

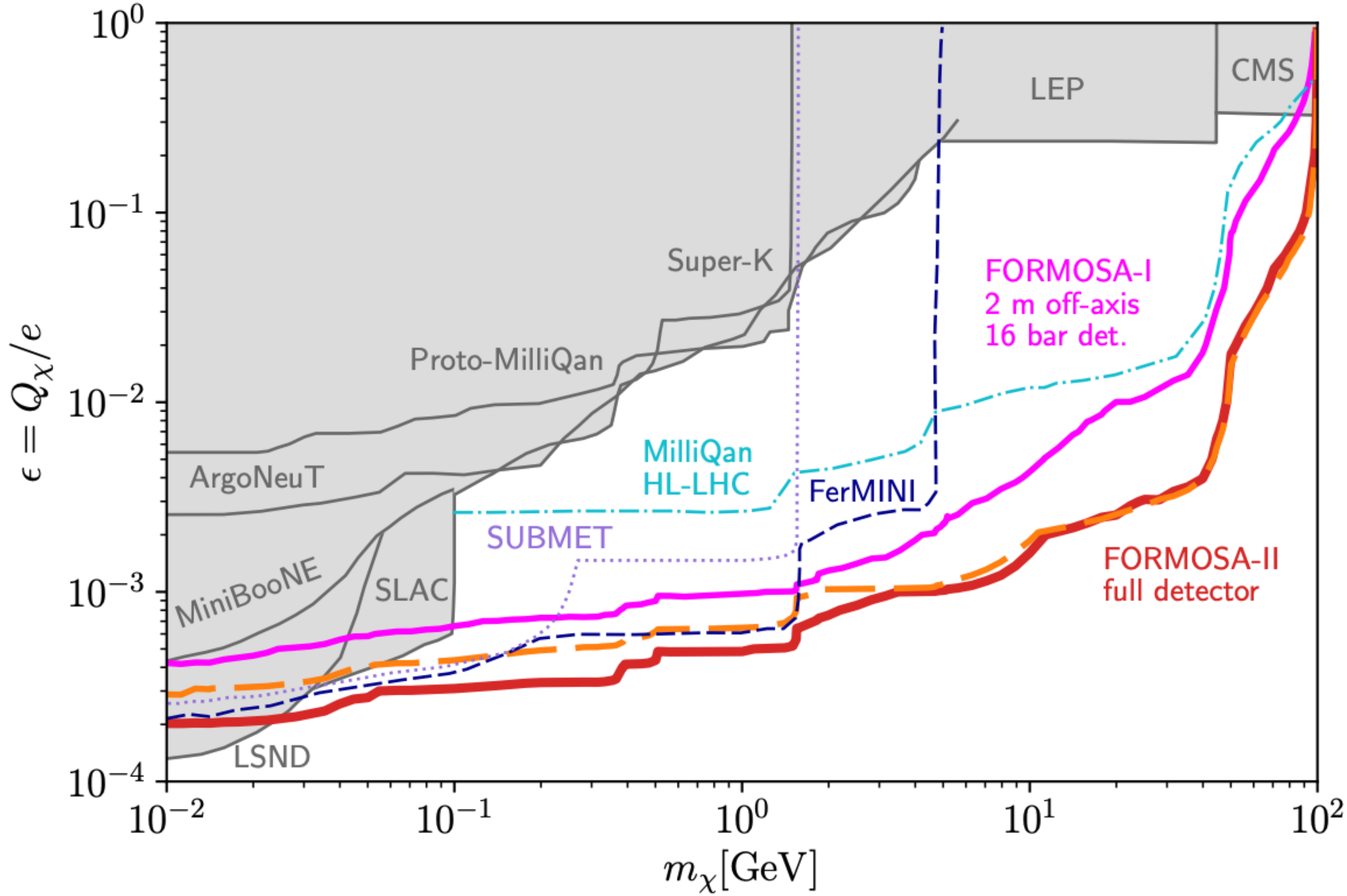


by Chantelauze, Staffi, and Bret



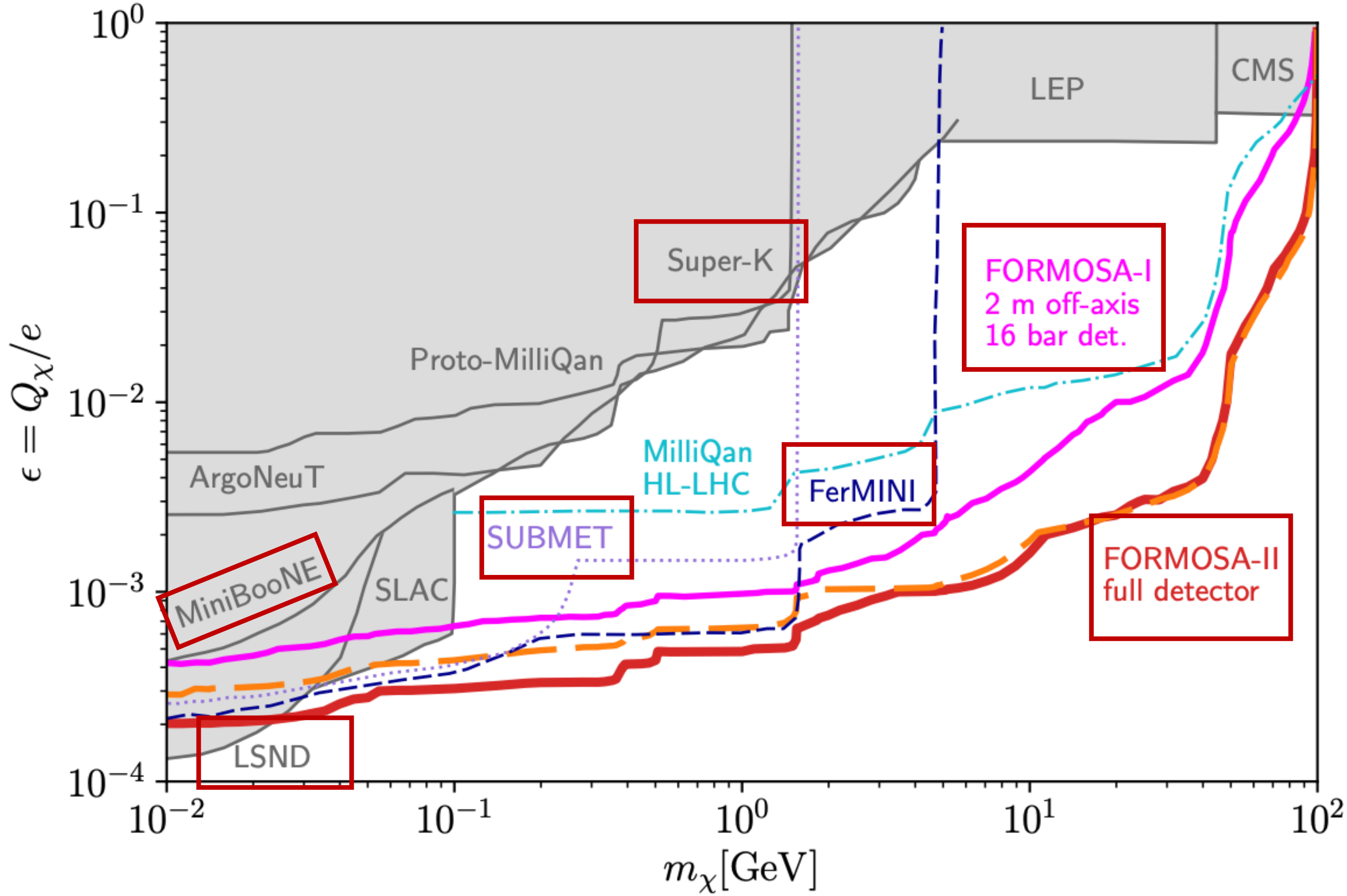
Super-K, http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html

Compilation of Sensitivity Reaches



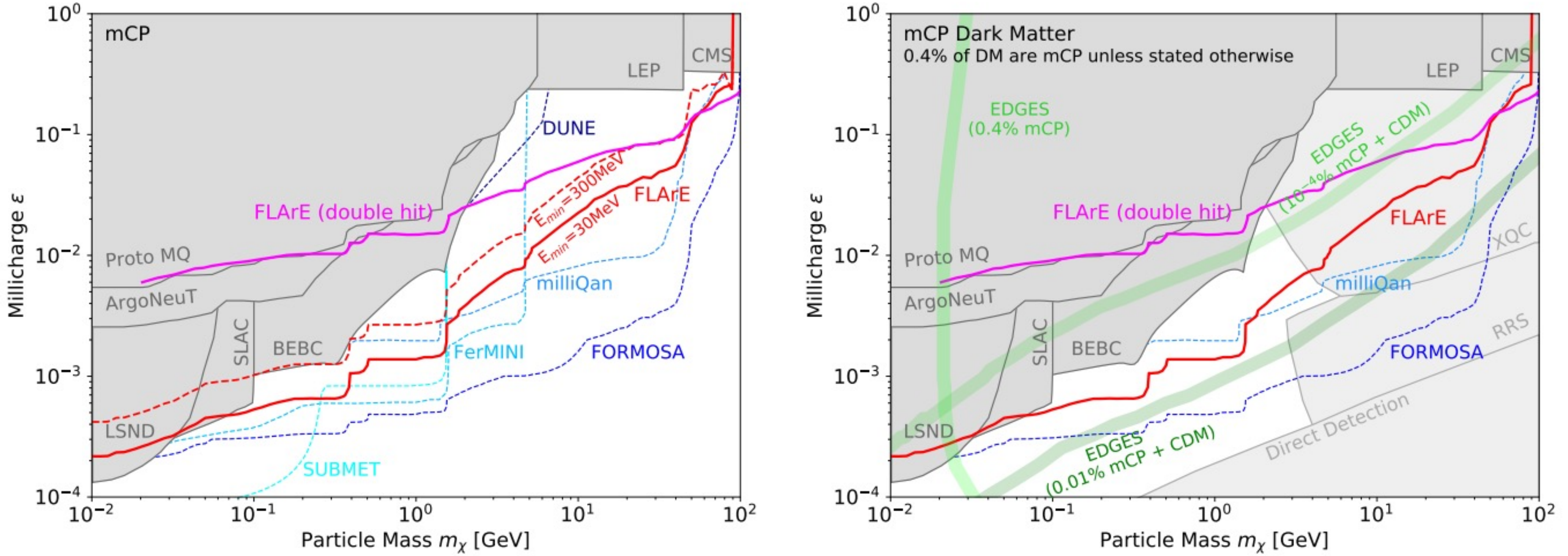
Foroughi-Abari, Kling, **Tsai**,
Phys. Rev. D 104, 035014 (2021), 2010.07941

Compilation of Sensitivity Reaches



Foroughi-Abari, Kling, **Tsai**,
Phys. Rev. D 104, 035014 (2021), 2010.07941

mCP Searches vs mDM Searches



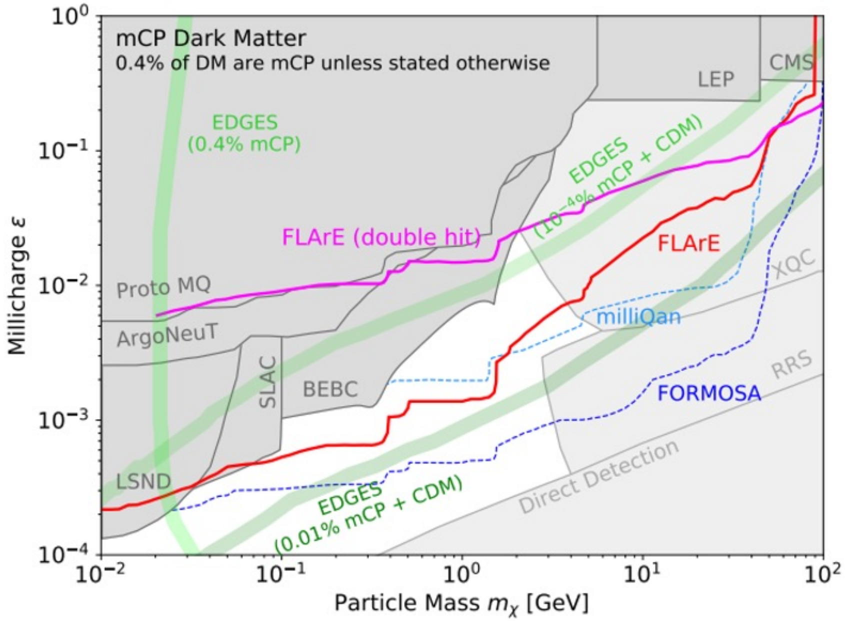
Kling, Kuo, Trojanowski, **Tsai,** NPB (2023), 2205.09137

Shows two advantages of accelerator searches

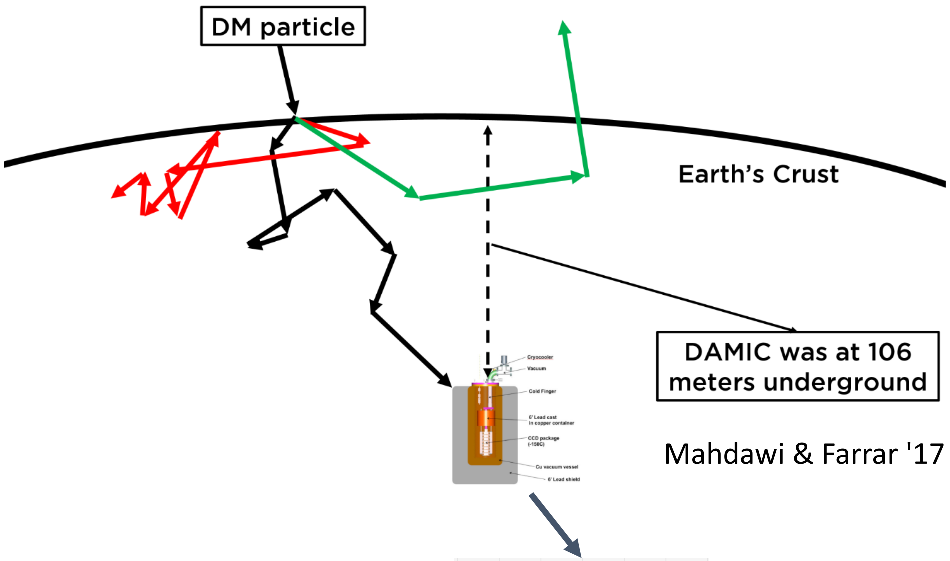
Motivation: Accelerator Searches for mDM

MCP / LDM with ultralight dark photon mediators

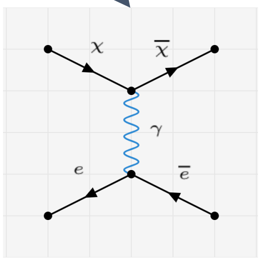
$$\bar{\sigma}_e \simeq \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{ref}^2}, \quad q_{ref} = \alpha m_e$$



Foroughi, Kling, **Tsai**, PRD (2021), 2010.07941



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

Outlook

1. **mCPs are excellent targets to fundamental theories, cosmology, & dark matter physics**
2. Excellent experimental target at

   LANL, milliQan, **FORMOSA**, **J-PARC** +DUNE, SHIP, CCM.
3. Study **dark photons** (**Tsai**, deNiverville, Liu, *PRL* 21, 1908.07525)

   other **dark matter candidates** (CCM, *PRD* 22, 2105.14020)

   and **milli-magnetic monopoles** (Graesser et al., *JHEP* 22, 2105.05769)

   for further cosmology & accelerator searches at LANL

Frederick Reines

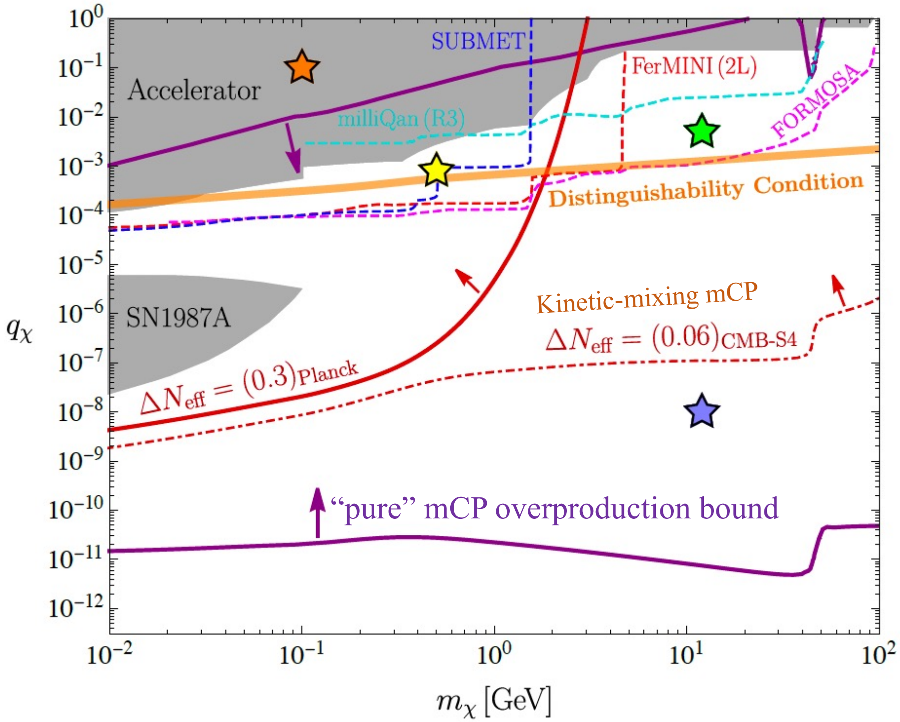
Nobel Prize Laureate @ LANL; Professor at UC Irvine

Utilized a **nuclear reactor to study free neutrinos**

We have an opportunity to explore the millicharge dark sector and unveil deep mysteries of the Universe at LANL

Thank you!

Other Regions of Interests



- **Orange Star:** favoring "pure" mCP
- **Yellow Star:**

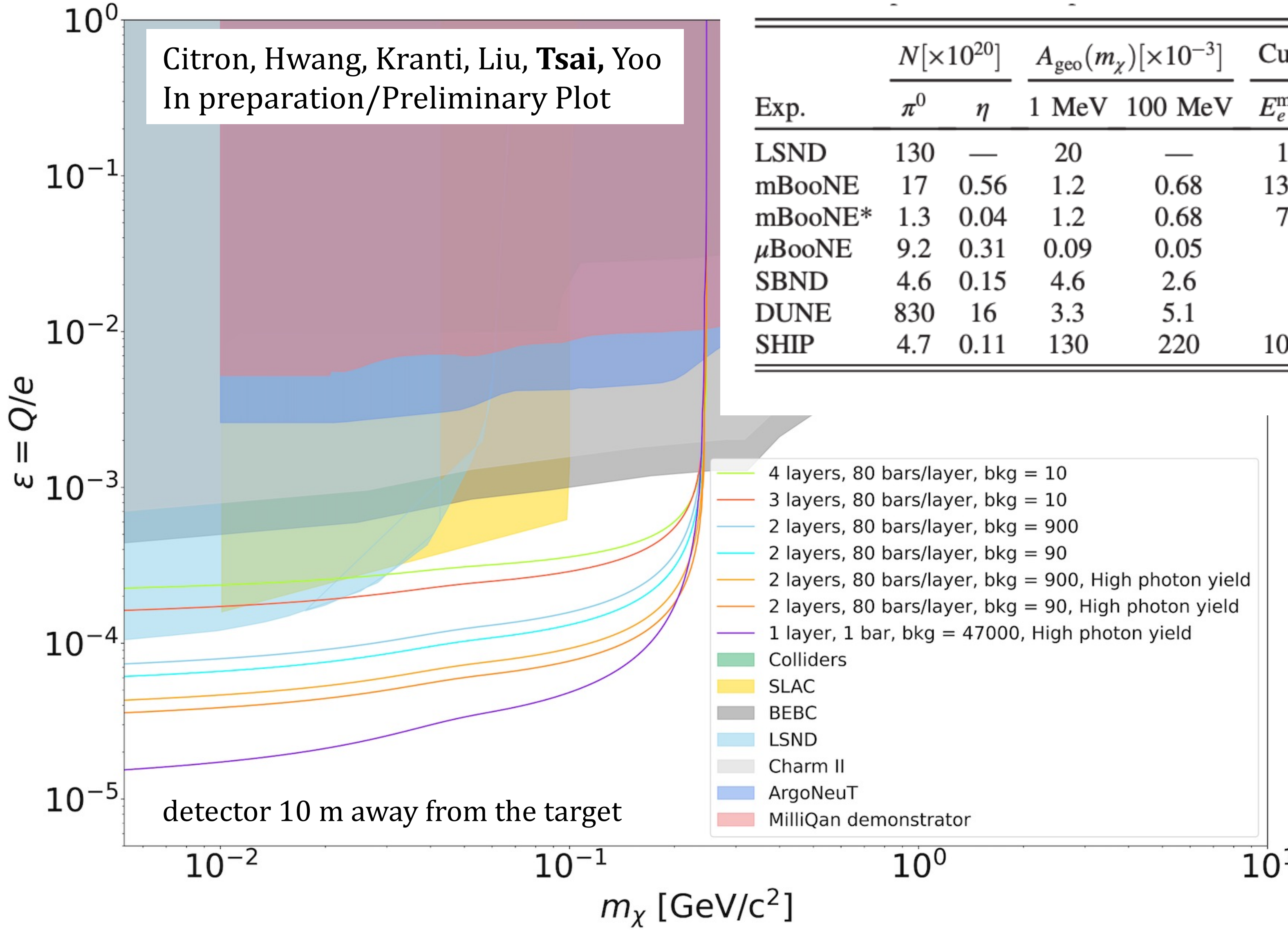
  testing reheat temperatures
- **Green Star:**

  1) testing reheat temperatures with CMB-S4

  2) currently favoring kinetic-mixing mCP
- **Purple Star:** favoring kinetic-mixing mCP

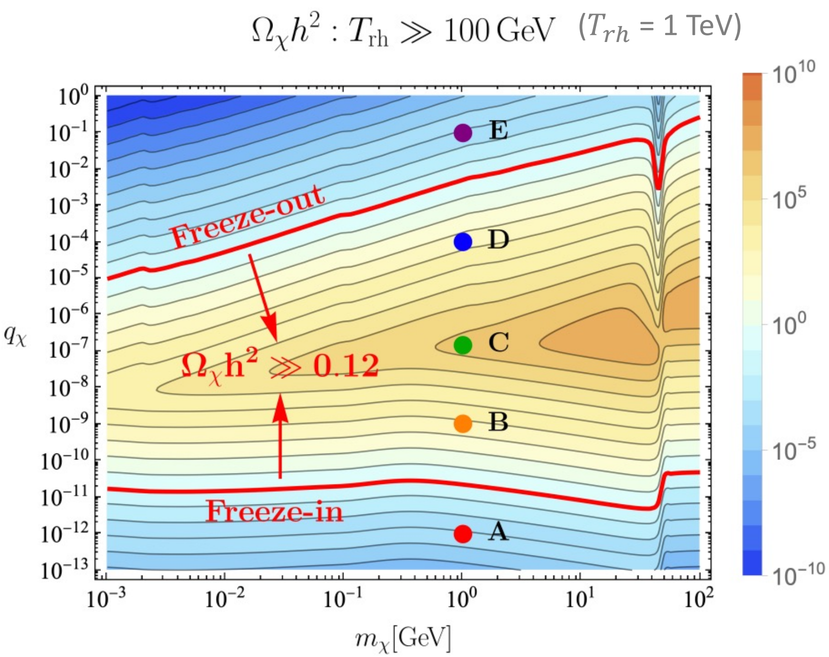
  (can be reached by direct-detection exps.)

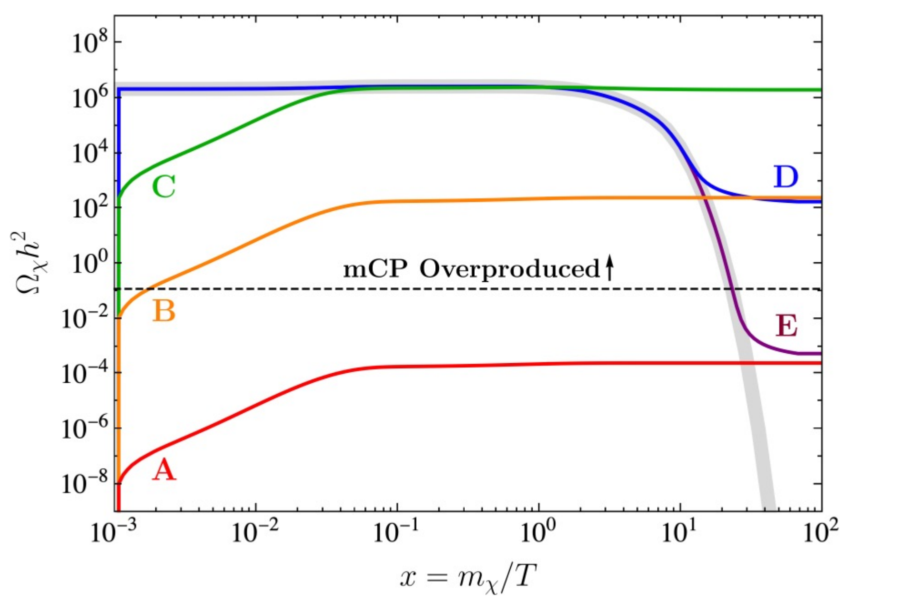
mCP Sensitivity Reach



	$N[\times 10^{20}]$		$A_{\rm geo}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
Exp.	π^0	η	1 MeV	100 MeV	$E_e^{\rm min}$	$E_e^{\rm max}$	Bkg
LSND	130	—	20	—	18	52	300
mBooNE	17	0.56	1.2	0.68	130	530	2k
mBooNE*	1.3	0.04	1.2	0.68	75	850	0.4*
μBooNE	9.2	0.31	0.09	0.05	2	40	16
SBND	4.6	0.15	4.6	2.6	2	40	230
DUNE	830	16	3.3	5.1	2	40	19k
SHIP	4.7	0.11	130	220	100	300	140

“Pure” CmB Cosmology: Freeze-in and Freeze-out





Freeze-in: $Y_\chi^{\rm FI} \sim q_\chi^2 \alpha_{\rm em}^2 \frac{m_{\rm pl}}{T}, \;\; T \gtrsim m_\chi.$

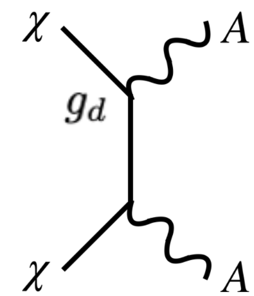
$$\dot{n}_\chi + 3Hn_\chi \simeq \mathcal{C}_n(T)\left(1 - \frac{n_\chi^2}{n_{\chi,\rm eq}^2}\right),$$

Freeze-out: $Y_\chi^{\rm FO} \sim \frac{1}{q_\chi^2 \alpha_{\rm em}^2} \frac{m_\chi}{m_{\rm pl}},$

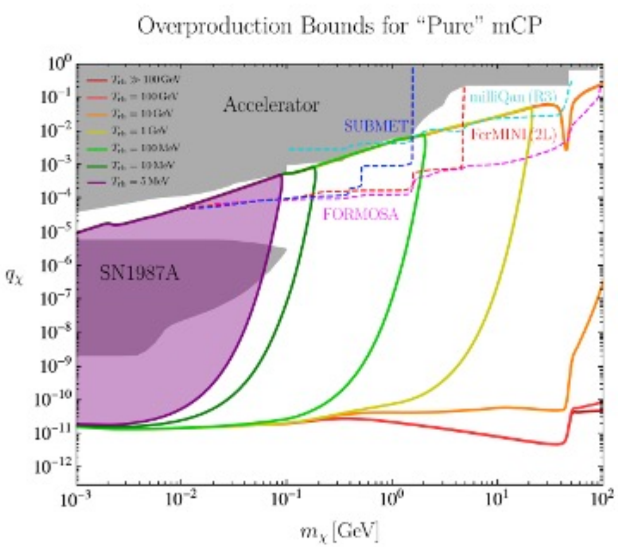
$$\mathcal{C}_n(T) = 2n_Z\langle\Gamma\rangle_{Z\to\chi\bar{\chi}} + 2n_f n_{\bar{f}}\langle\sigma v\rangle_{f\bar{f}\to\chi\bar{\chi}}$$

See, e.g., Vogel, Redondo, JCAP (2014), Dvorkin+, PRD (2019)

Objectives:
Differentiate Two Types of MCPs



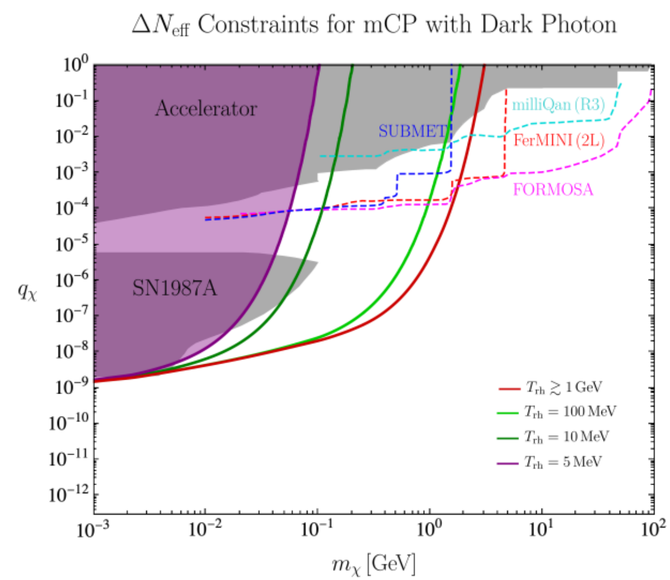
$g_d = 0$



moderate g_d

Interpolate between the two

Sizable g_d



Theoretically, there is a limit on
how small g_d can be, for a given q_χ

“Distinguishability” Condition

Gan, **Tsai**, 2308.07951

- Turning down thermalization between χ – A’: $g_d \lesssim (16\pi^2 m_\chi / \mathcal{F} m_{\rm pl})^{1/4}$

- Requirement for kinetic mixing: $\epsilon < 1 \quad \Rightarrow \quad g_d > e q_\chi, \quad q_\chi = \frac{\epsilon g_d}{e}$

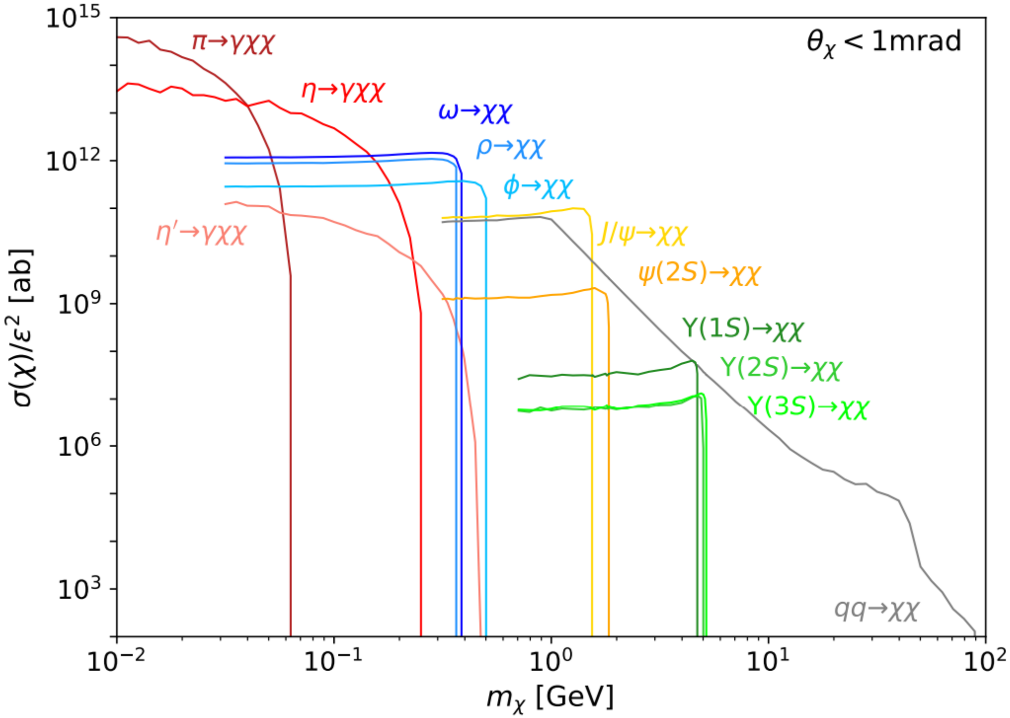
  Burgess *et al*, JCAP (2008)

- Considering these two inequalities for gd, we can roughly determine that:

$$q_\chi \gtrsim \frac{1}{\alpha_{\rm em}^{1/2}} \left(\frac{m_\chi}{\mathcal{F} m_{\rm pl}} \right)^{1/4}$$

One CANNOT de-theramlize χ – A’ interaction rate to mimic “pure” mCP!

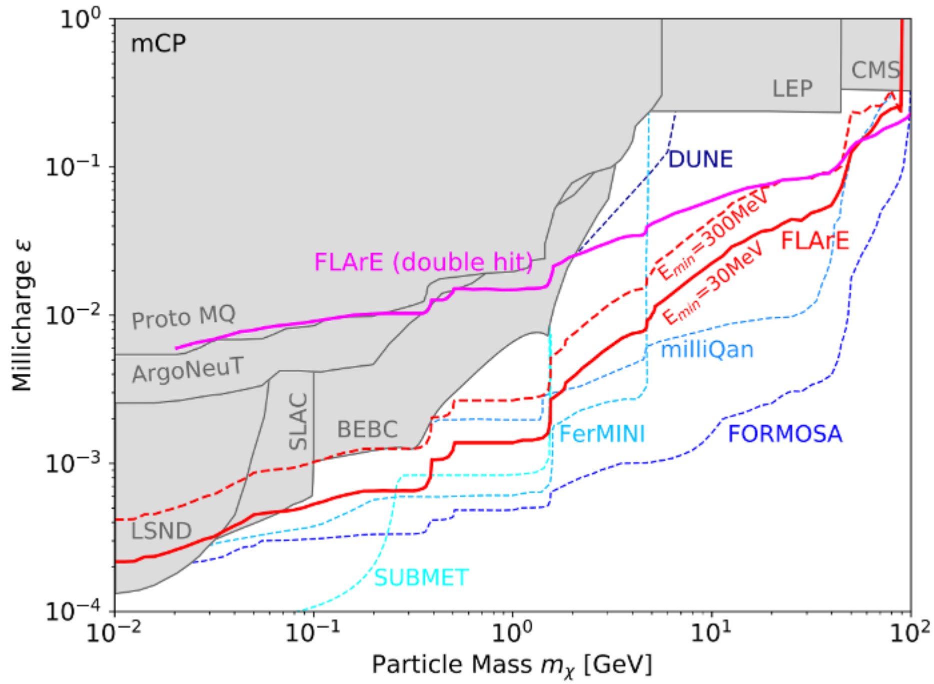
mCP Productions @ Forward Physics Facility



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

MCP production was added to FORESEE by Felix Kling

mCP @ FLArE



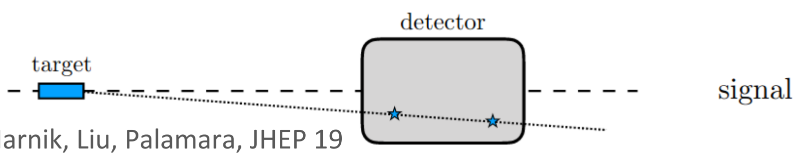
- **FLArE experiment by Jianming Bian: https://indico.cern.ch/event/1110746/contributions/4701719/**
- Nev = 3 expected new physics events in the detector

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