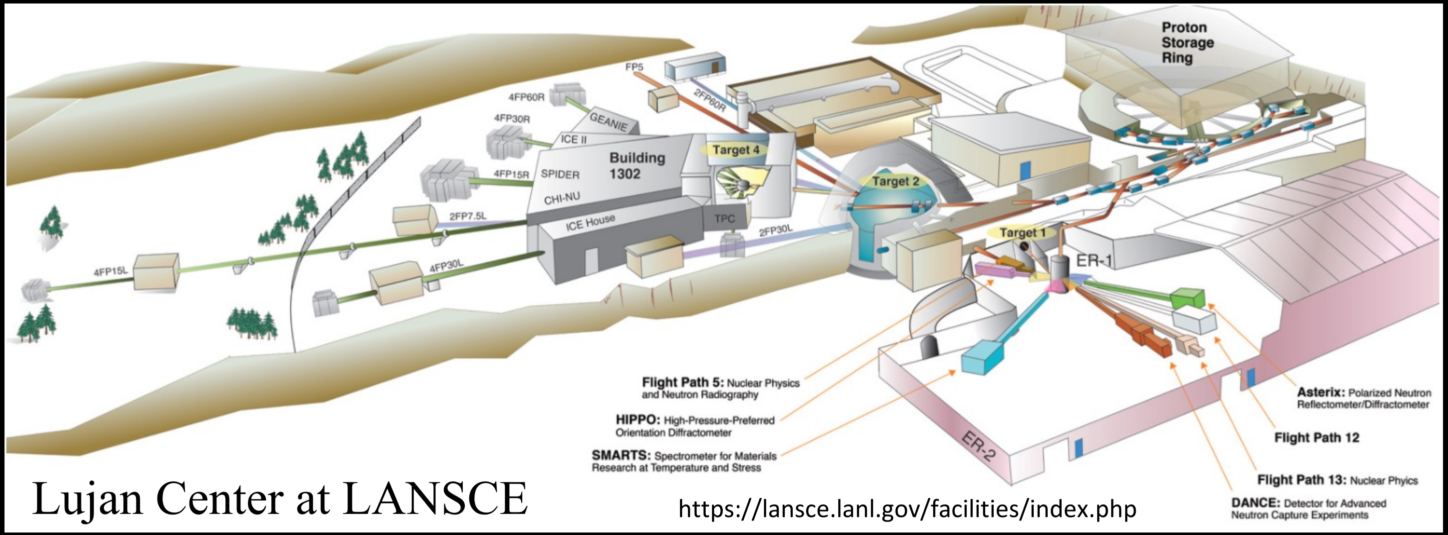
Millicharge Dark Sector & Reheating Cosmology at Fermilab SBN and LANL LANSCE-mQ



Gan, **Tsai**, 2308.07951 + Liu & Gunthoti (LANL), Citron, Hwang, Yoo

Yu-Dai Tsai
University of California, Irvine (yt444@cornell.edu)
→ Los Alamos National Laboratory

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:

a. Inspired Dirac quantization, Grand Unified Theories (GUTs)

b. **String theory** predicts un-confined **fractionally charged particles** (included in this talk), Wen, Witten, Nucl. Phys. B 261 (1985)

c. Link to string compactification & quantum gravity (Shiu, Soler, Ye, PRL '13)

- **Writing a theory review summarizing these developments**

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

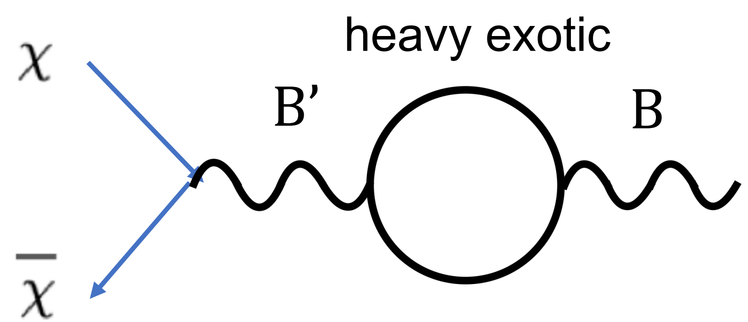
Two Kinds of mCPs

“Pure” mCP

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

Kinetic-mixing mCP

- Compatible with GUTS.



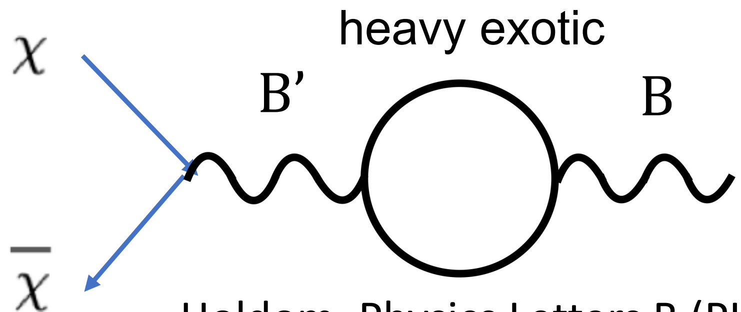
Choose a proper basis: massless dark photon A’ decouple from SM

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

How can we differentiate them?

Kinetic Mixing mCPs

Coupled to new dark fermion χ



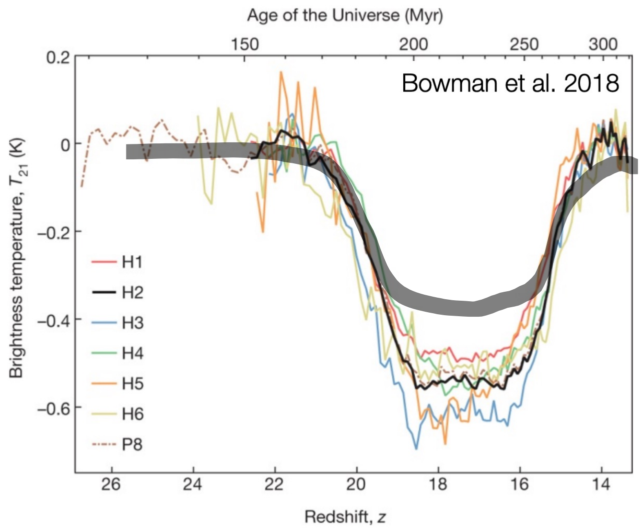
(Standard Model $U(1)_Y$)

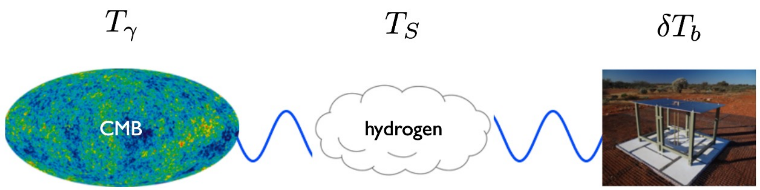
Holdom, Physics Letters B (PLB), 1985

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

- New Fermion χ charged under U(1)'
- Field redefinition into a more convenient basis for massless B', $B' \to B' + \kappa B$
- new fermion acquires a small EM charge Q (the charge of mCP χ): $Q = \kappa e' \cos\theta_W$, $\epsilon \equiv \kappa e' \cos\theta_w / e$.

Motivations: Millicharged Dark Matter (mDM)





Adapted from J. Pritchard

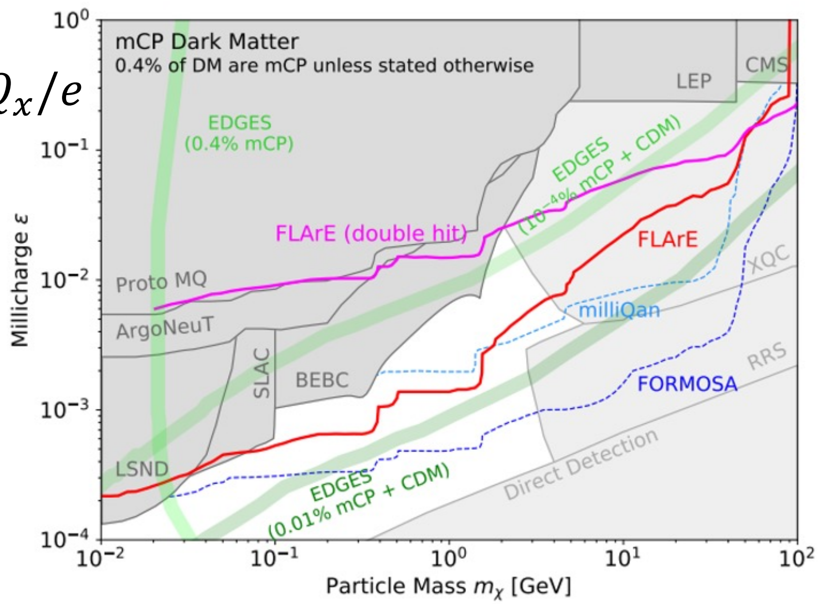
From Jordan Mirocha (UCLA)

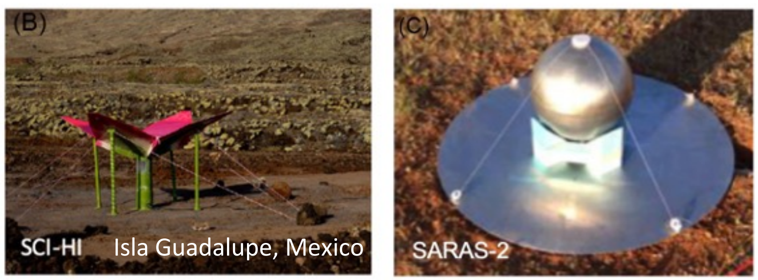
e.g., EDGES

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

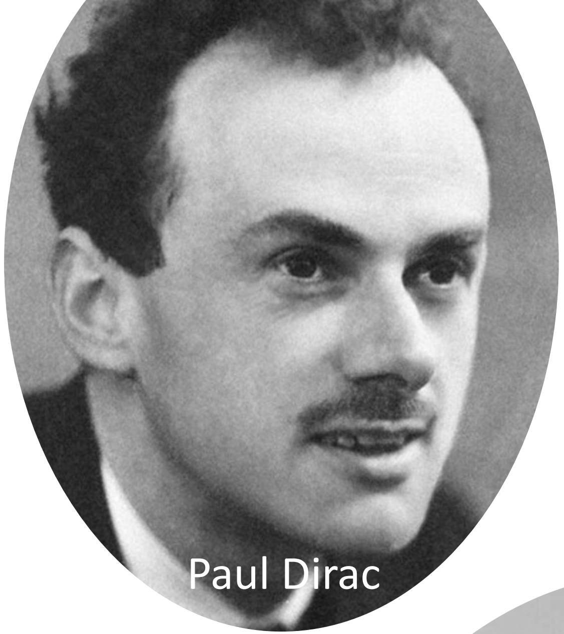
$\epsilon = Q_x/e$





SARAS-3 in North Karnataka, India

Outline

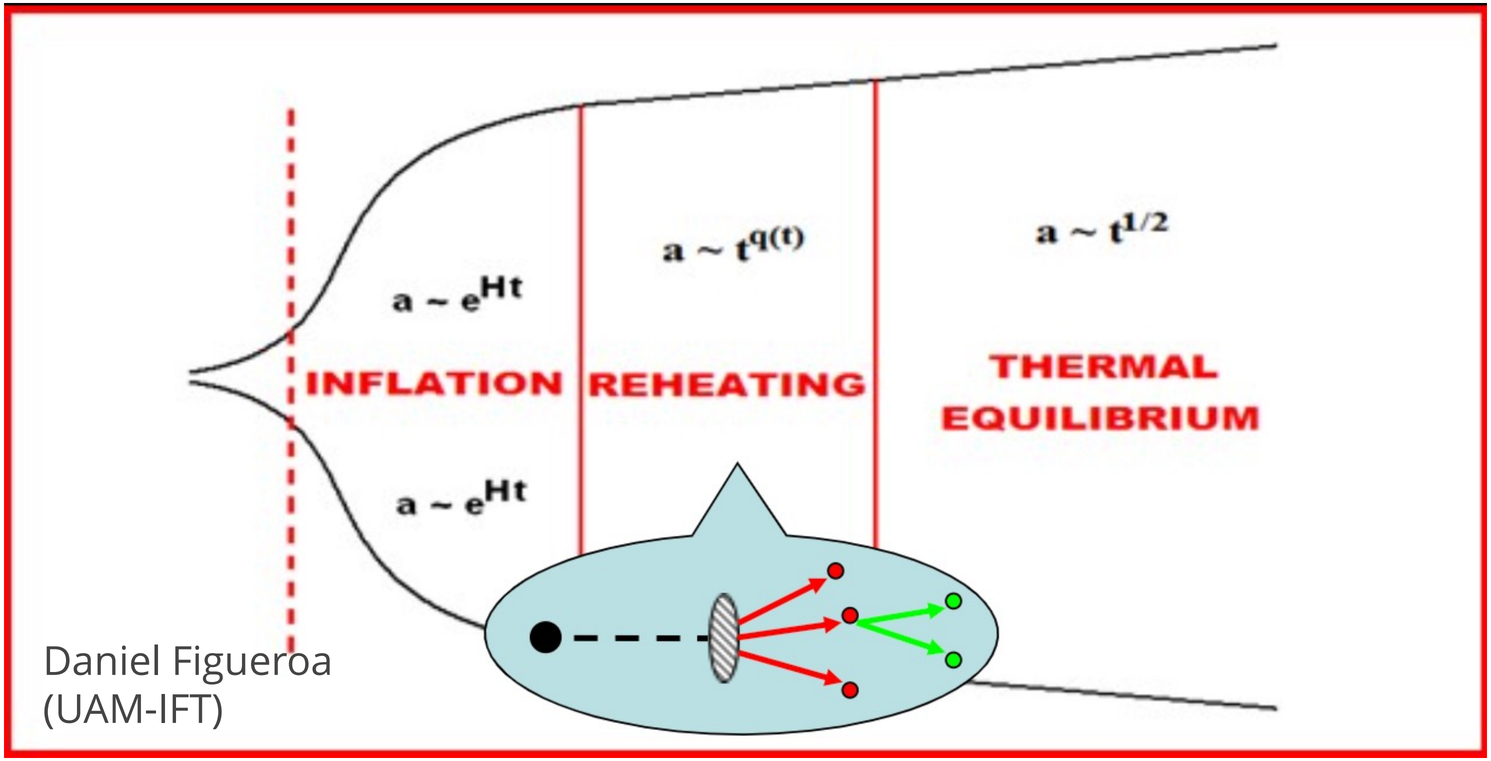


- Intro & Motivations
- **Probing Reheating Cosmology**

  Differentiate 2 types of mCPs

- 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!

Cosmic Millicharge Background (CmB)

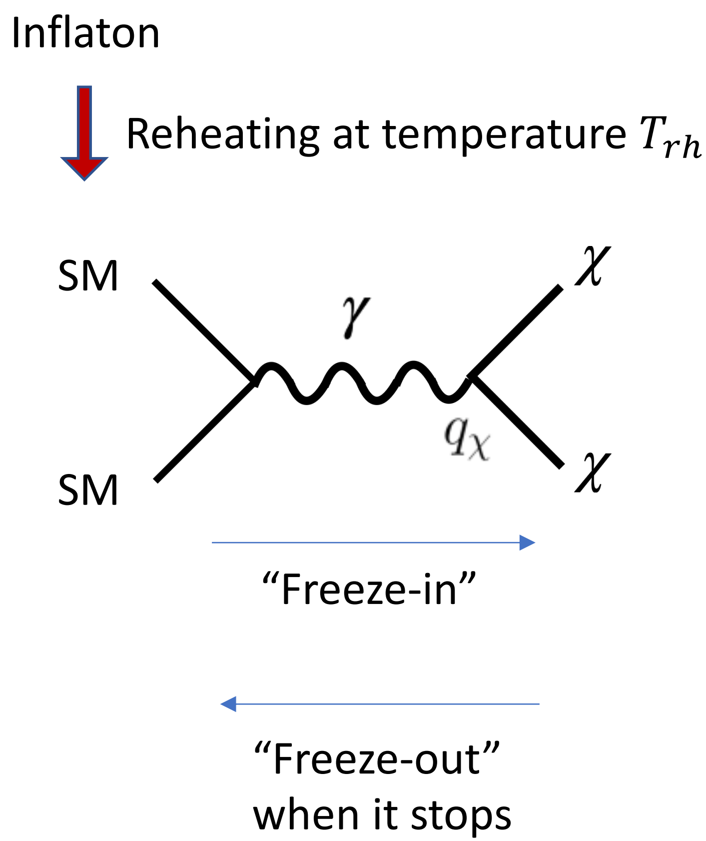
Gan, **Tsai**, 2308.07951

"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

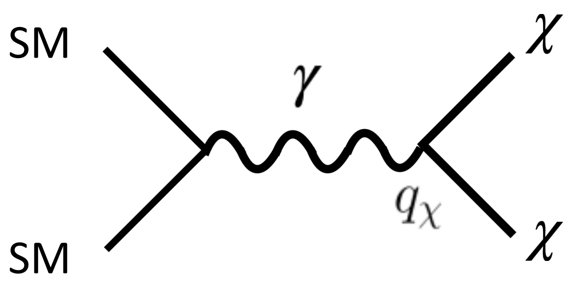


Cosmic Millicharge: Overproduction During Reheating
Gan, **Tsai**, 2308.07951

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

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

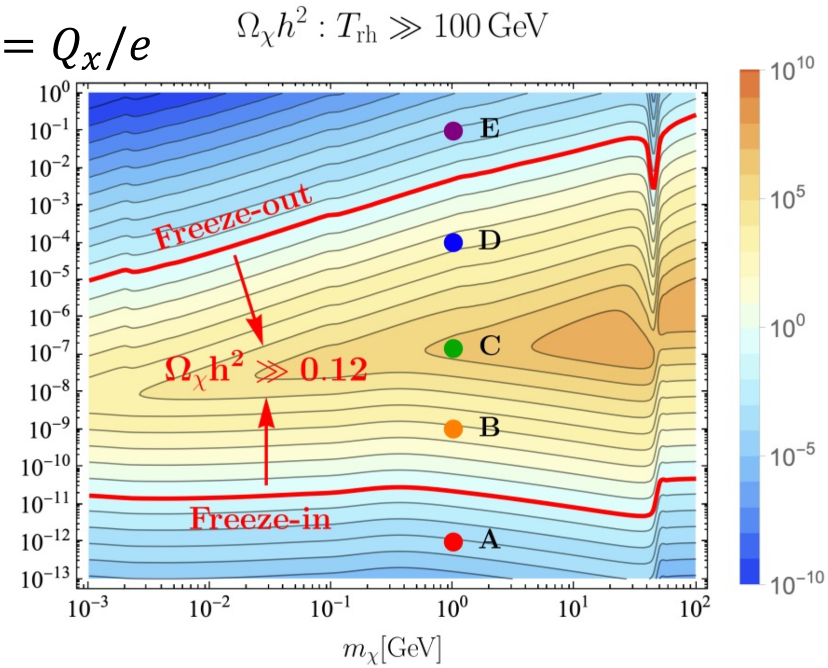
Density is normalized by ρ_c, the critical density for a flat Universe; h = 0.674

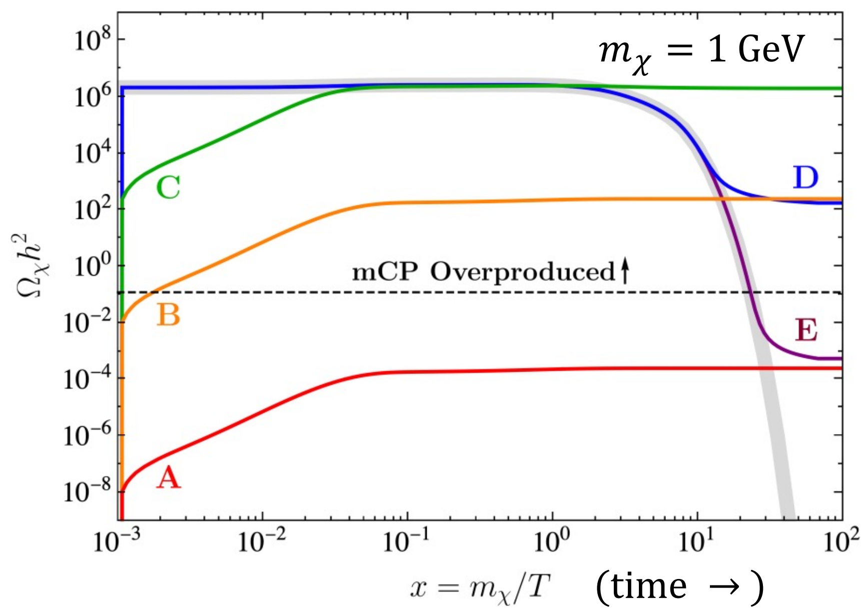
$$\rho_c = \frac{3H^2}{8\pi G}$$

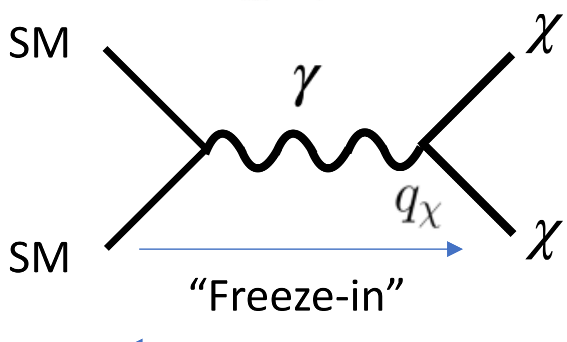
“Pure” CmB Cosmology: Freeze-in and Freeze-out

T_{rh} = 1 TeV (or above)

$\epsilon = Q_x/e$







“Freeze-in”

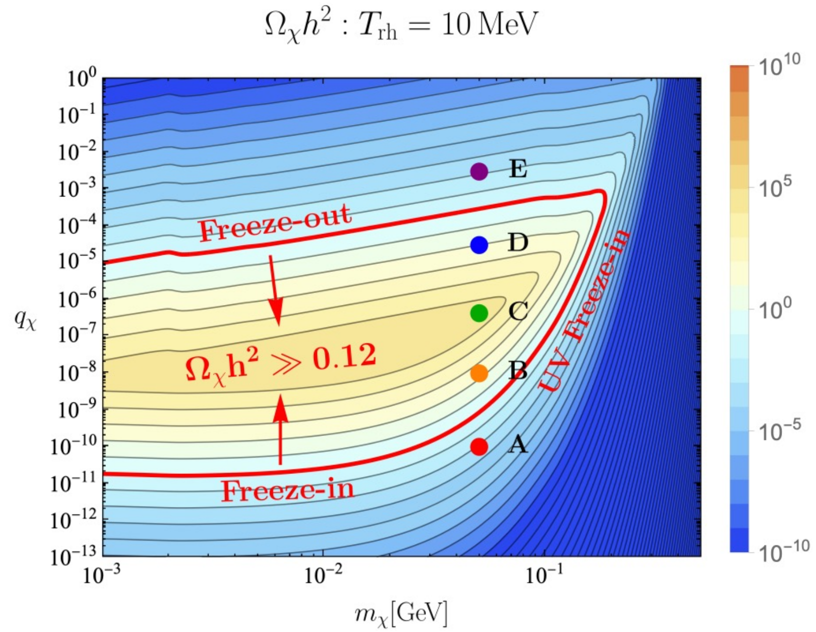
“Freeze-out” when it stops

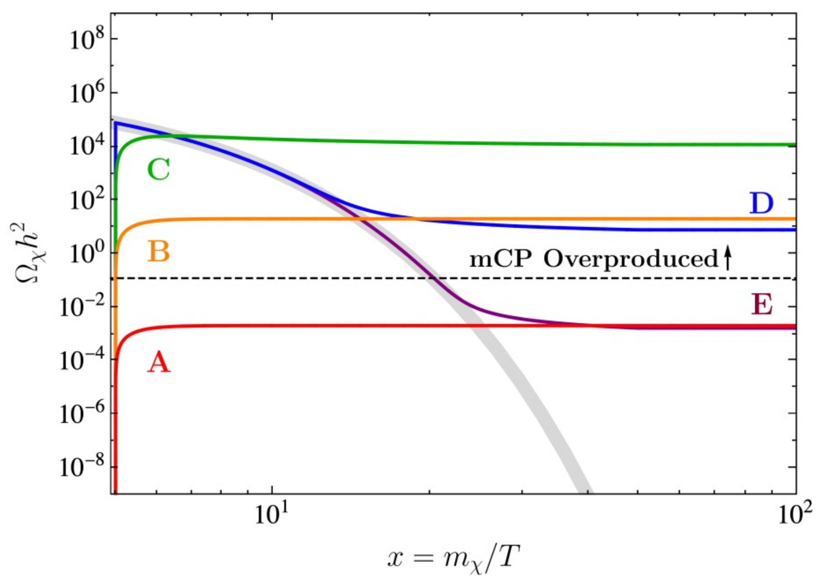
$$\dot{n}_\chi + 3Hn_\chi \simeq \mathcal{C}_n(T)\left(1 - \frac{n_\chi^2}{n_{\chi,\rm eq}^2}\right),$$

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

“Pure” CmB Cosmology: Low-Reheat Temperature

T_{rh} = 10 MeV



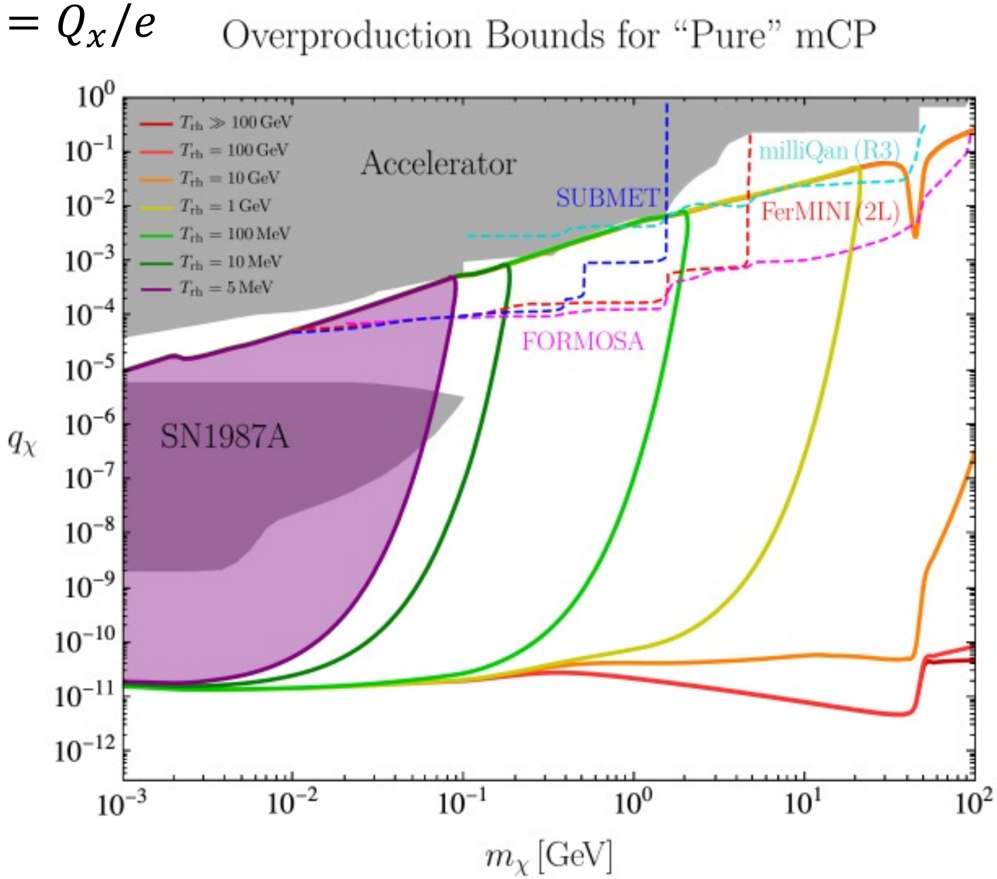


For the freeze-in at low $\mathrm{T_{rh}}$, mCP-SM interaction is suppressed exponentially: the coupling has to increase exponentially to compensate it

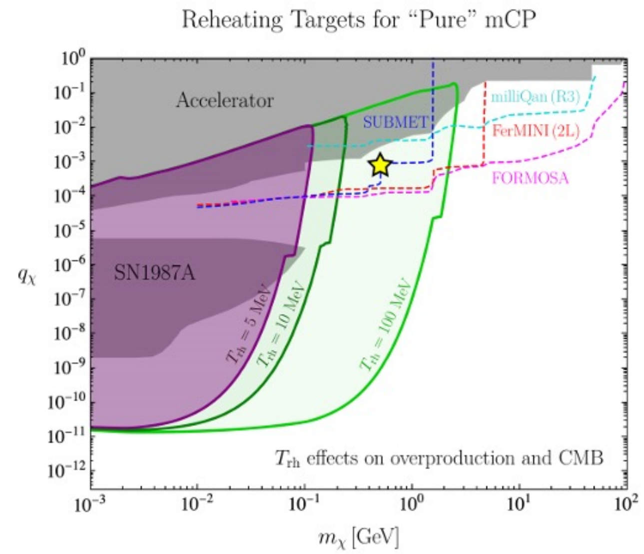
The freeze-in curve holds the approximate relation: $q_\chi \propto \exp\left(\frac{m_\chi}{T_{\rm rh}}\right)$

"Pure" CmB from Irreducible Production

$\epsilon = Q_x/e$



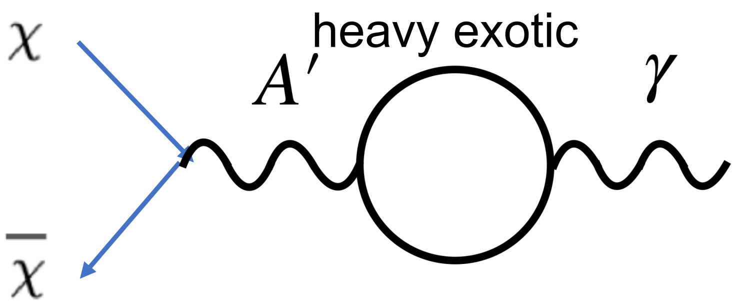
Gan, **Tsai**, 2308.07951



- 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

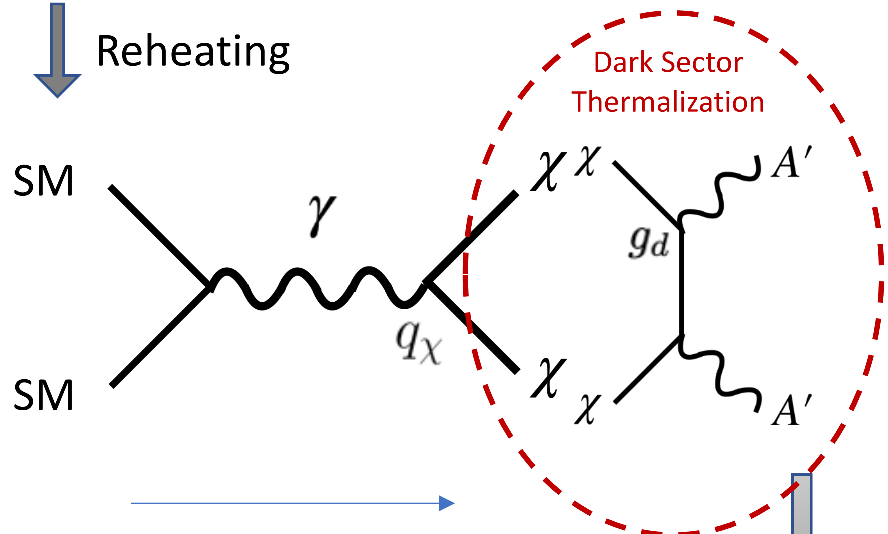
$$q_\chi = \frac{\epsilon g_d}{e}$$

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

Kinetic-mixing mCP

Inflaton

Reheating



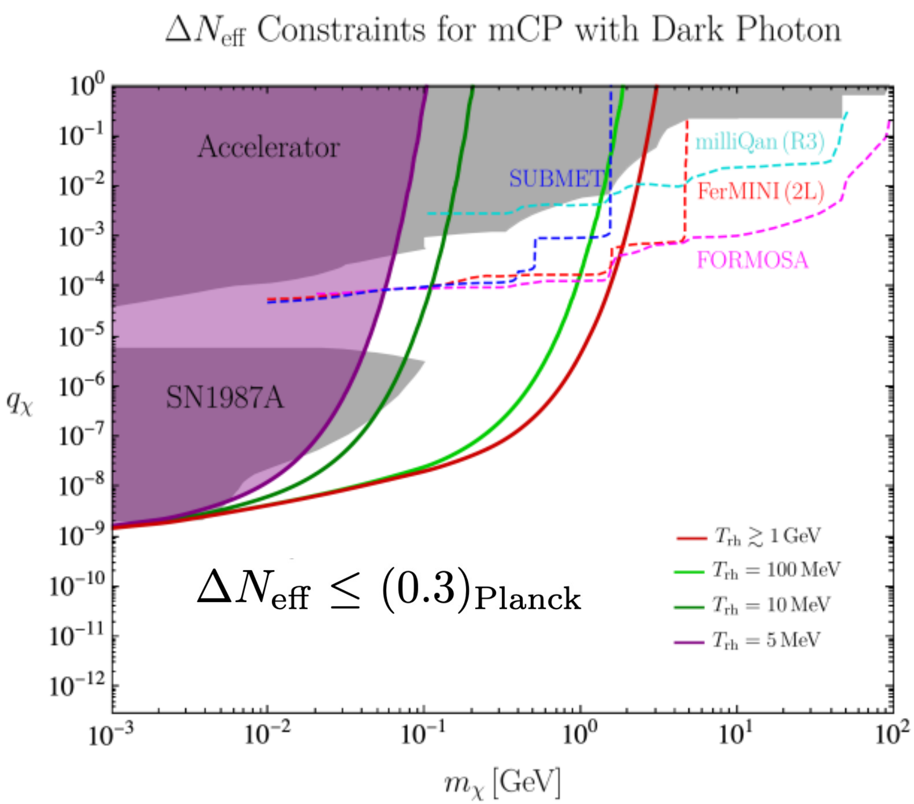
Freeze-in:

Freeze-out:

massless dark photon A' will affect N_{eff}

See Vogel, Redondo, JCAP (2014),
Adshead, Ralegankar, Shelton JCAP (2022)

Kinetic-Mixing CmB Cosmology



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

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

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

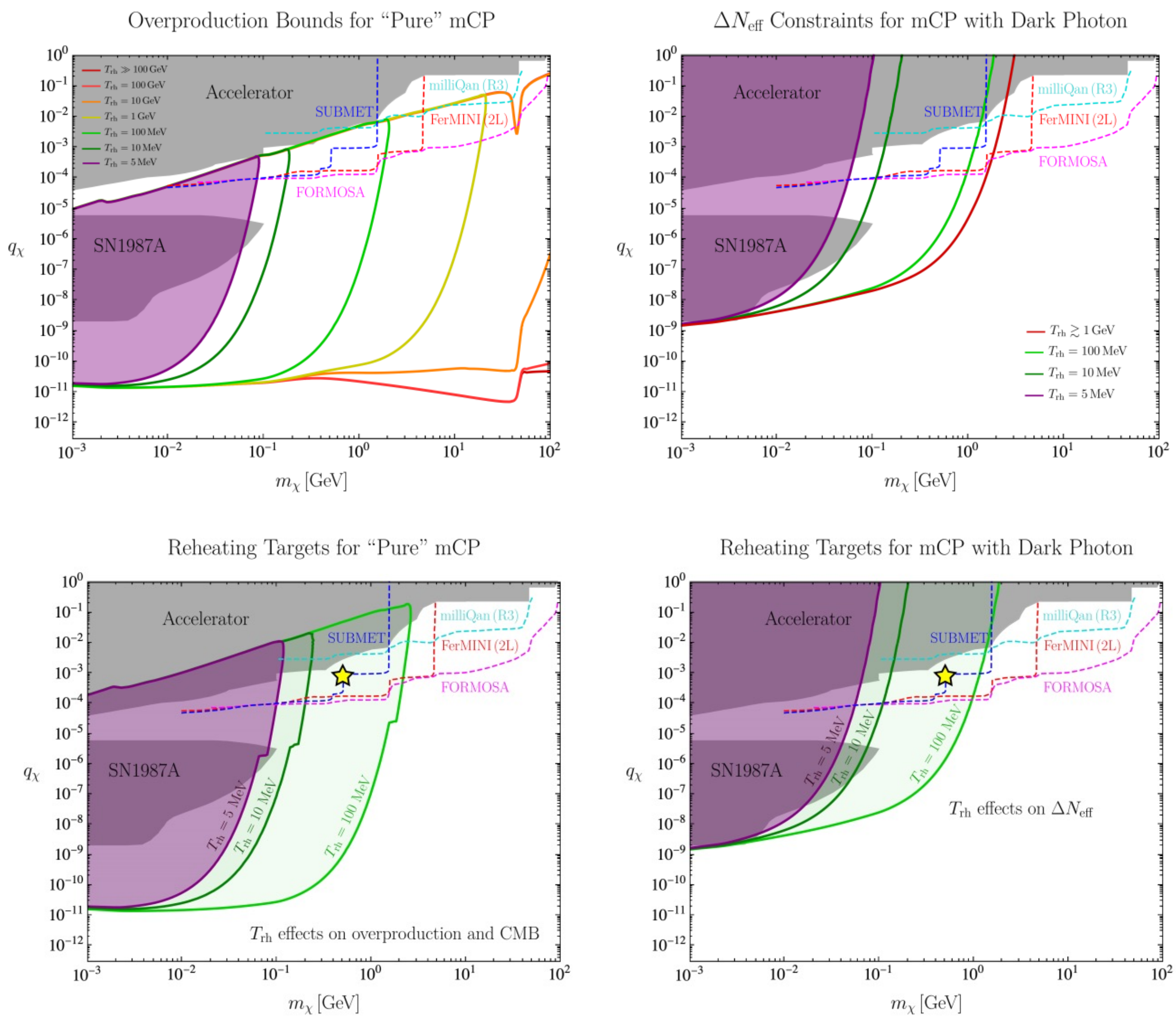
$$\Delta N_{\rm eff} \lesssim g_{A'}\,\frac{4}{7}\left(\frac{g_{*,S}(T \ll T_{\rm QCD})}{g_{*,S}(T \gg T_{\rm QCD})}\right)^{4/3} \simeq 0.1,$$

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

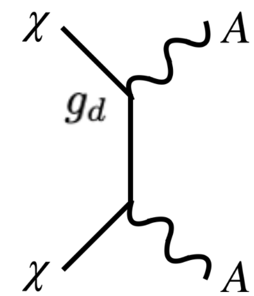
Current: $\Delta N_{\rm eff} \leq (0.3)_{\rm Planck}$

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

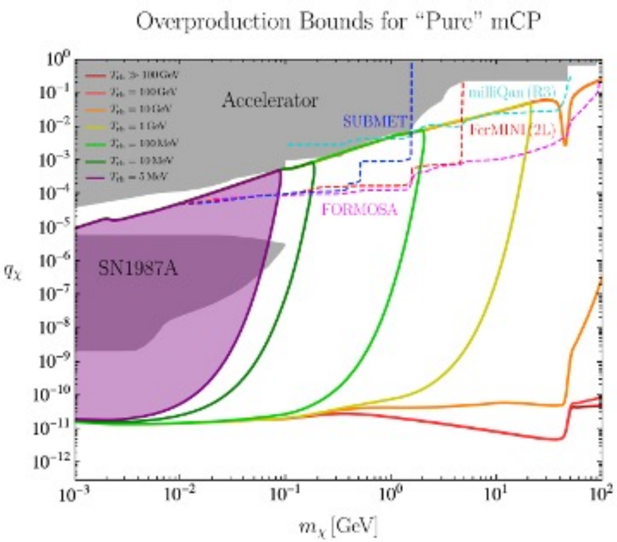
Testing Reheat Temperatures in Both Cases



Another Key Objective:
Differentiate Two Types of MCPs



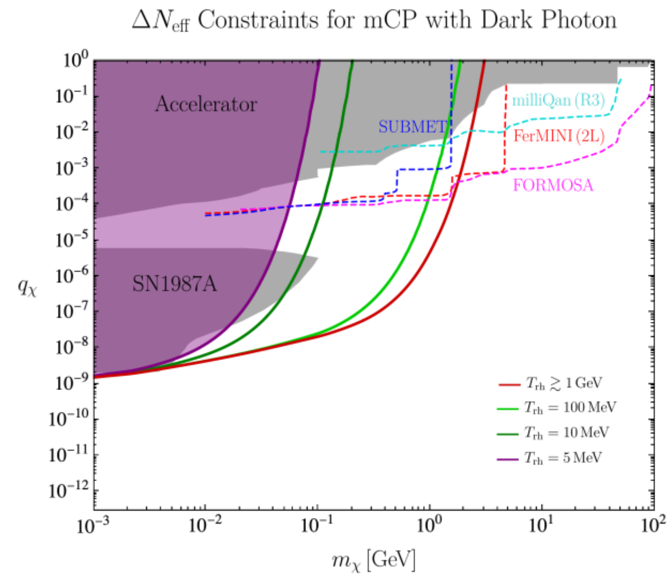
$g_d = 0$



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” Conditions

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: $\epsilon < 1 \quad \Rightarrow \quad g_d > e q_\chi, \quad q_\chi = \frac{\epsilon g_d}{e}$

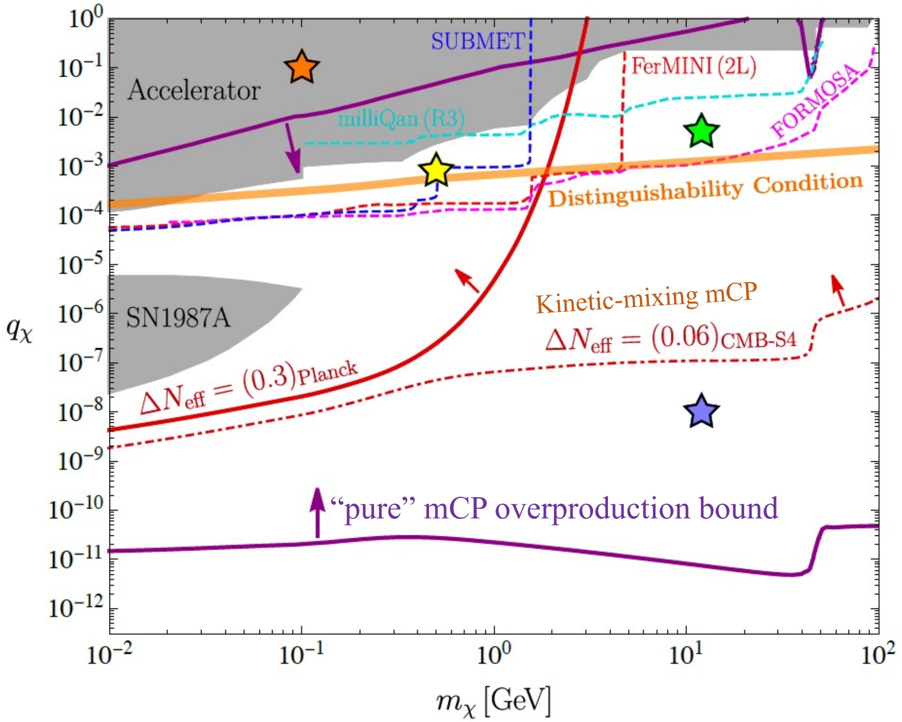
  Burgess *et al*, JCAP (2008)

- 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!

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.)

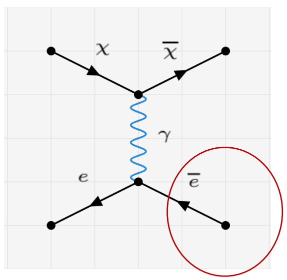
Outline

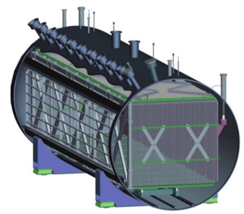
- Intro
- Probing Reheating Cosmology
- **Experimental Searches**

Two Search Methods: Scattering & Scintillation

(A) **Electron Scattering**

~ energy exchange set by detector threshold (> MeV)





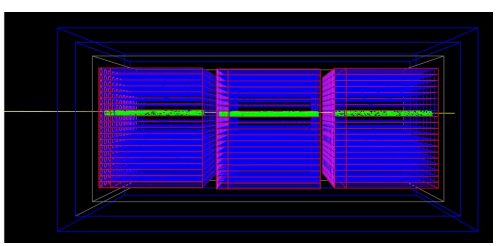
e.g., neutrino detector
Credit: MicroBooNE Col.

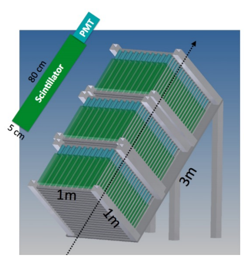
$$\sigma_{e\chi} \simeq 2.6 \times 10^{-25}\text{cm}^2 \times \epsilon^2 \times \frac{1\ \text{MeV}}{E_e^{(\text{min})} - m_e}.$$

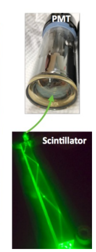
Expressed in **recoil energy threshold**, $E_e^{(min)}$

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

~ eV-level energy exchange







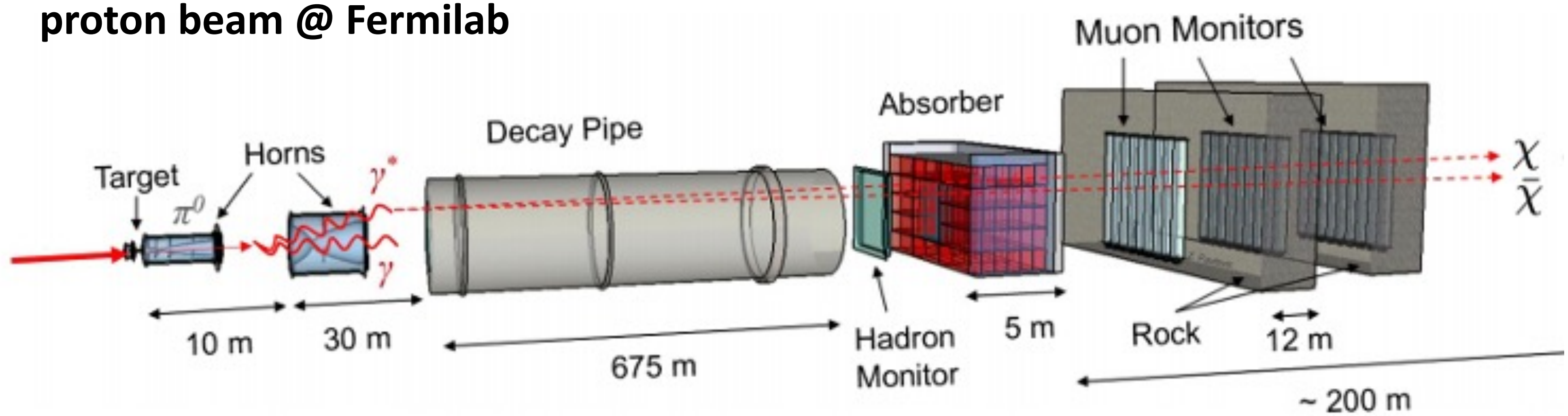
$$\left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2.$$

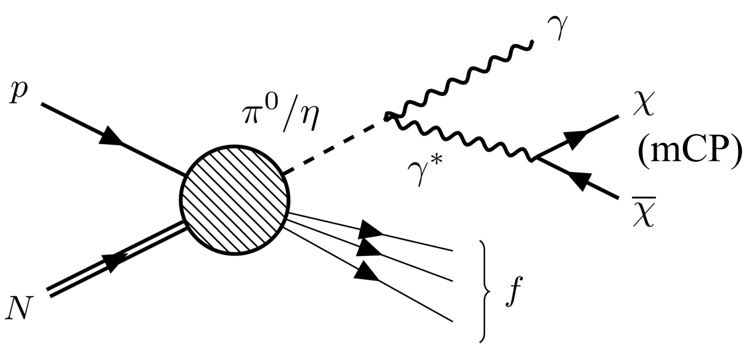
Energy deposition

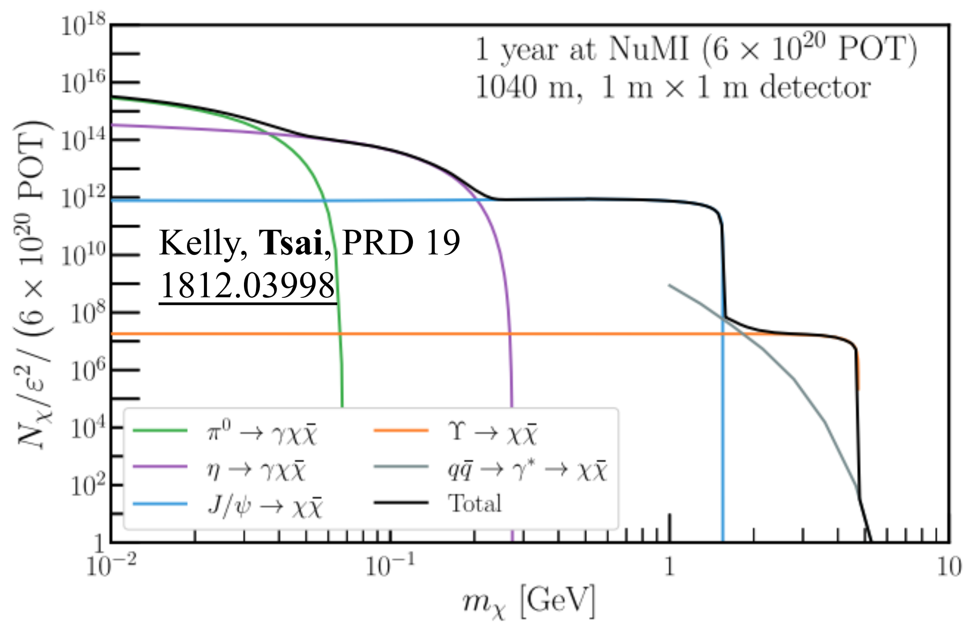
e.g., Haas, Hill, Izaguirre, Yavin, 1410.6816
milliQan design, 1607.04669 (MilliQan Collaboration)

Accelerator Productions

120 GeV NuMI
proton beam @ Fermilab



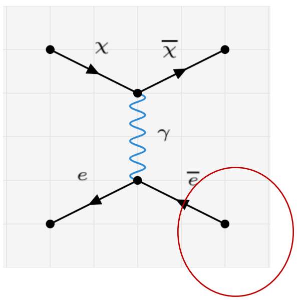


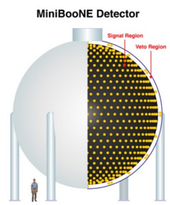


Two Search Methods: Scattering & Scintillation

(A) **Electron Scattering**

~ energy exchange set by detector threshold (~ MeV)





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

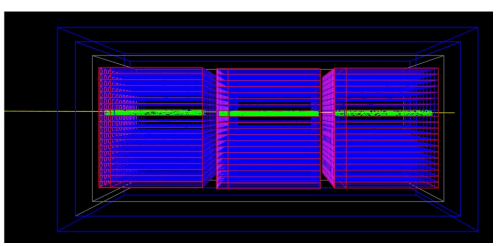
$$\sigma_{e\chi} \simeq 2.6 \times 10^{-25}\mathrm{cm}^2 \times \epsilon^2 \times \frac{1\ \mathrm{MeV}}{E_e^{(\mathrm{min})} - m_e}.$$

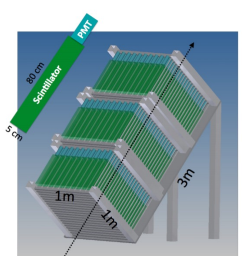
Expressed in **recoil energy threshold**, $E_e{}^{(min)}$

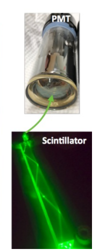
Magill, Plestid, Pospelov, **Tsai,** PRL 19, 1806.03310

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

~ eV-level energy exchange







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

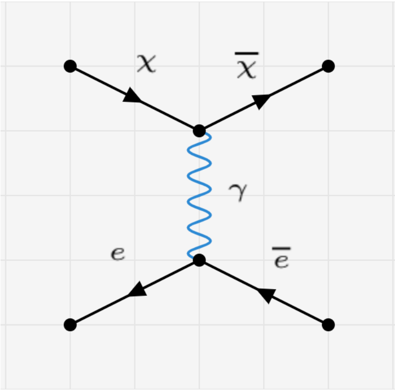
Energy deposition

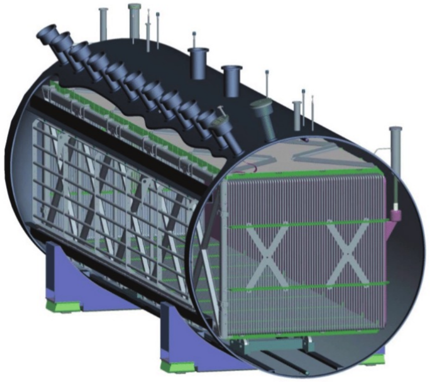
e.g., Haas, Hill, Izaguirre, Yavin, 1410.6816
milliQan design, 1607.04669 (MilliQan Collaboration)

Electron Scattering Searches

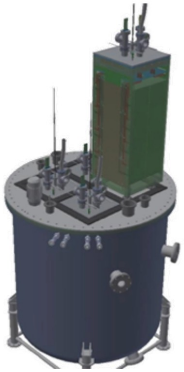
Electron Scattering ~ energy exchange set by detector threshold (~ MeV)

High-Intensity NuMI/LBNF proton beam@ Fermilab





MicroBooNE Detector



ArgonCube 2x2 (4 modules)

Image credits: MicroBooNE & ArgonCube Cols.

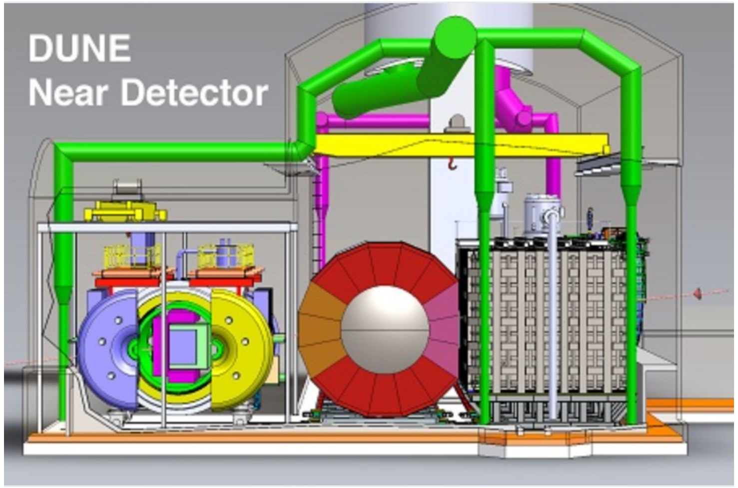
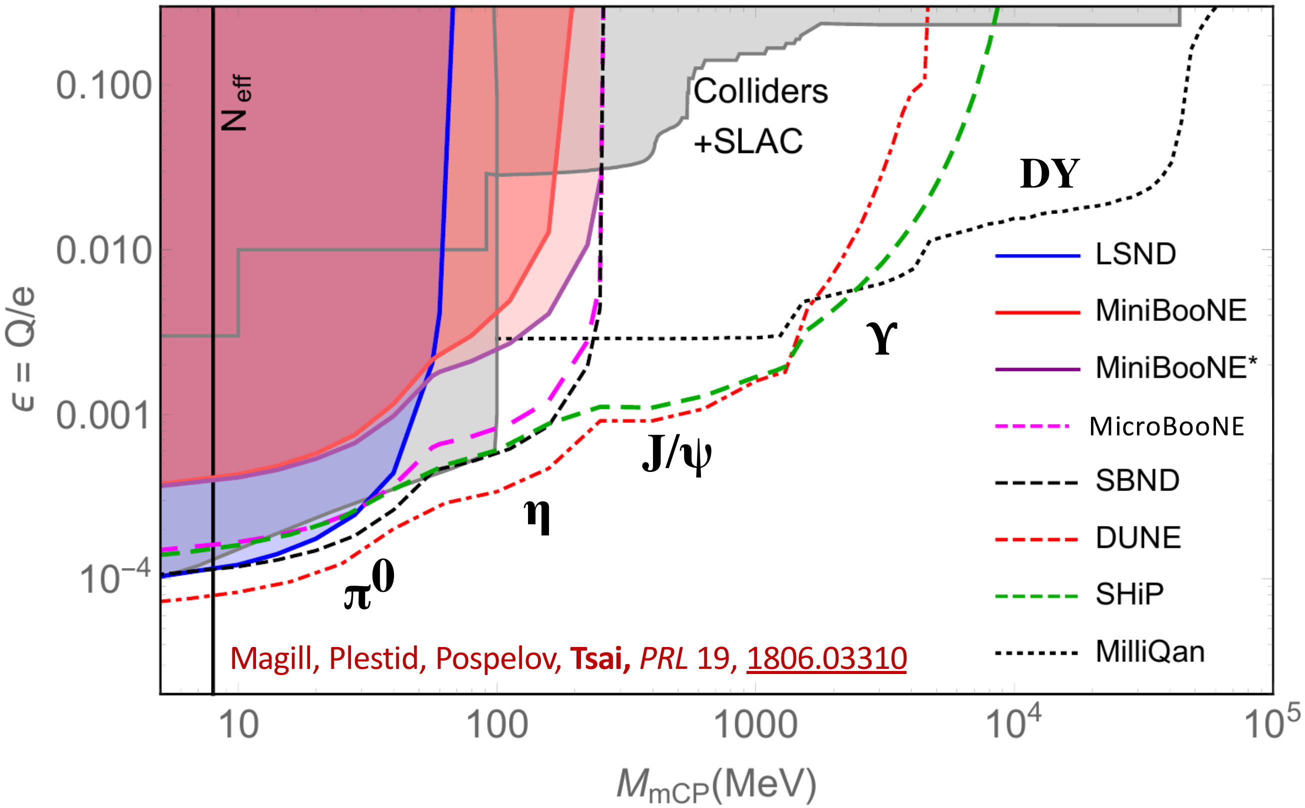


Image from DUNE col.

1. **Proper millicharge analysis** at **MicroBooNE**

2. Develop coalescent plan to study neutrino electromagnetic properties at **MicroBooNE, Icarus, ArgonCube 2x2**, **SBND** and LHC neutrino experiments, e.g., **Forward Liquid Argon Experiment (FLArE)** Kling, Kuo, Trojanowski, **Tsai**, 2205.09137

Sensitivity and Contributions



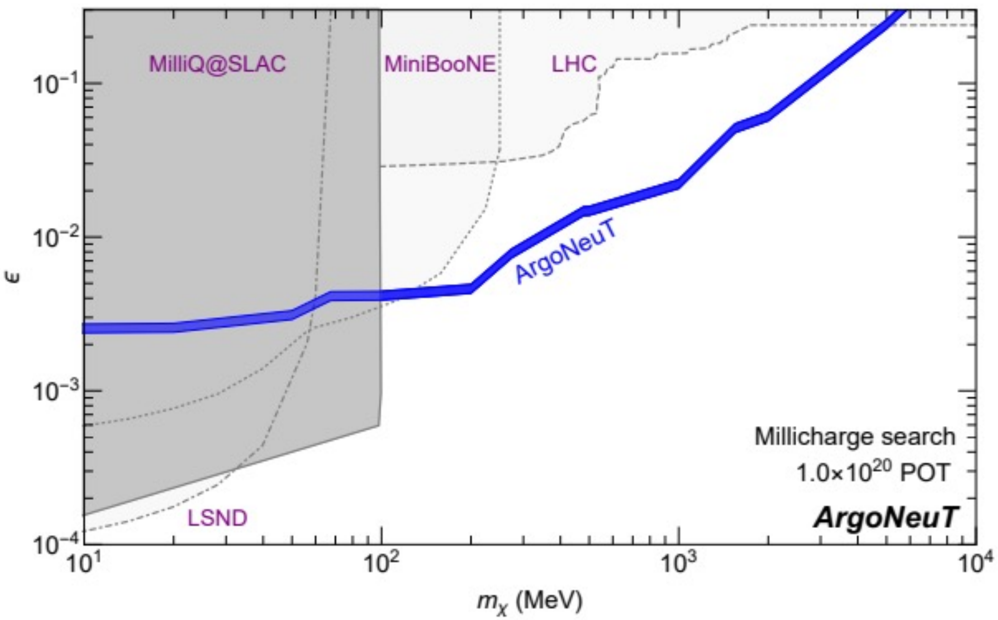
χe → χe scattering:

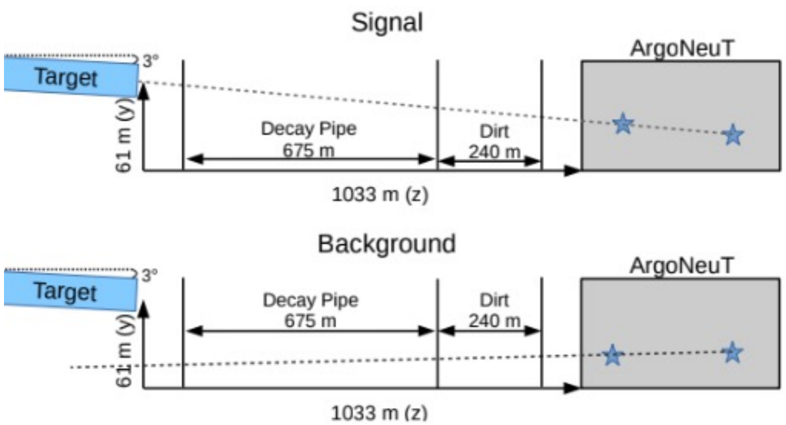
$$\frac{d\sigma}{dE_r} \propto \frac{1}{E_r^2}$$

- E_r is the kinetic energy of the recoiled electron
- **Energy threshold** is important

- MiniBooNE* is the **MiniBooNE dark-matter run**: thick target and no horn focusing
- **One can can set set recoil energy within ~ 30 MeV $\lesssim E_r \lesssim$ 1 GeV** to reduce background for liquid argon detectors
- Alternative: double-hit with softer recoils, setting $E_{r,\text{min}} \simeq$ 2 MeV
- **Preliminary discussions and studies of MicroBooNE(-like) experiments**

ArgoNeuT Millicharge Analysis





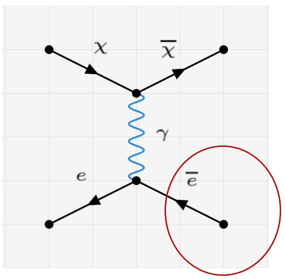
$E_{r,\min} \simeq 2$ MeV

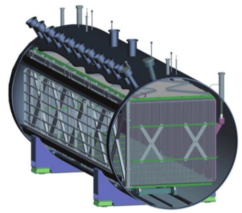
ArgoNeuT collaboration, PRL (2020), 1911.07996

Two Search Methods: Scattering & Scintillation

(A) **Electron Scattering**

~ energy exchange set by detector threshold (~ MeV)





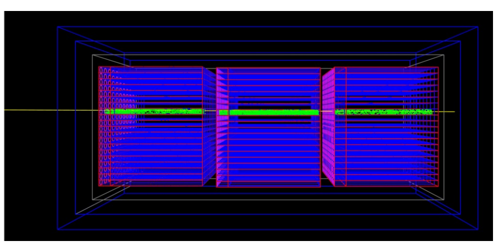
e.g. neutrino detector
Credit: MicroBooNE Col.

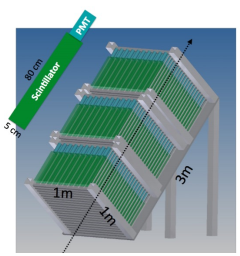
$$\sigma_{e\chi} \simeq 2.6 \times 10^{-25}\mathrm{cm}^2 \times \epsilon^2 \times \frac{1\ \mathrm{MeV}}{E_e^{(\mathrm{min})} - m_e}.$$

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

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

~ eV-level energy exchange





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

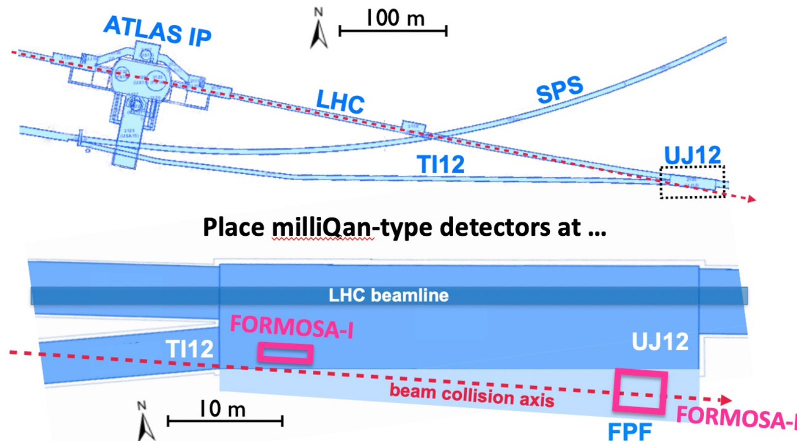
Energy deposition

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

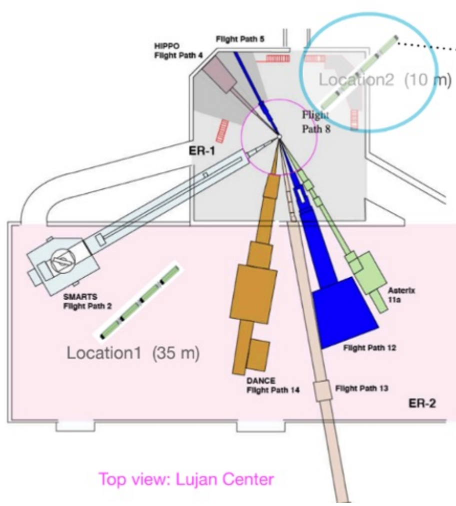
Dedicated mCP Searches in Next 3 Years

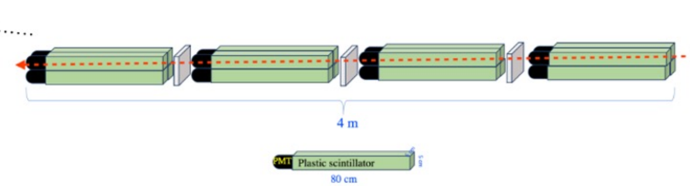
1. **milliQan** (taking data); 2. **SUBMET**: mCP search at J-PARC; **fully approved**

3. **FORMOSA (demonstrator taking data!)**



4. **LANSCE-mQ @LANL**





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

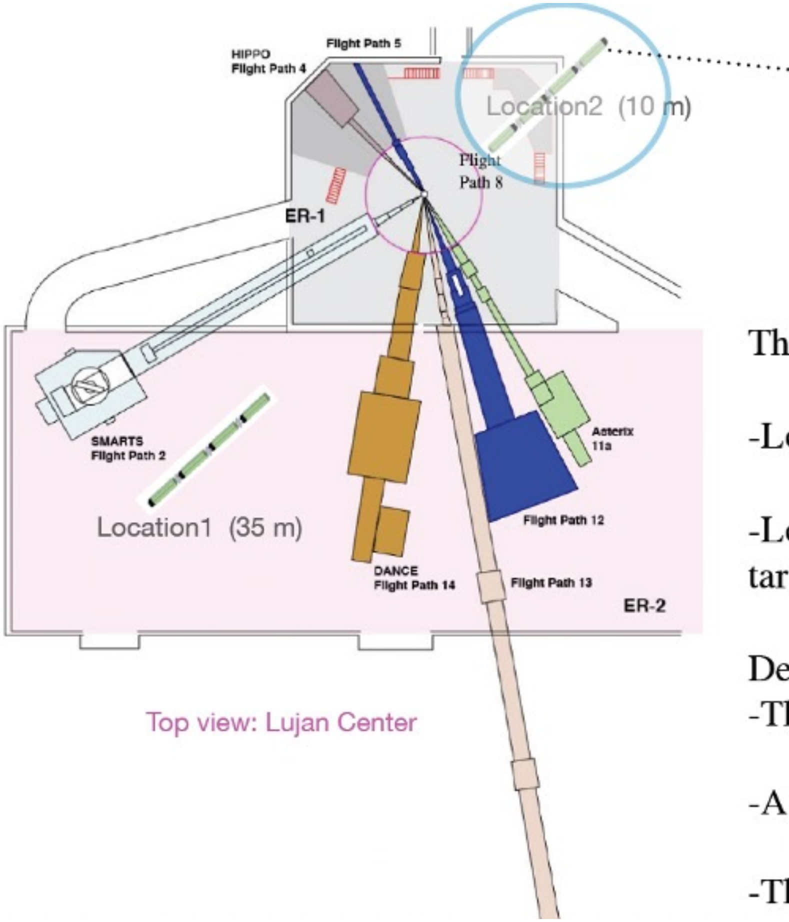
-Location 1: ER-2 area, 35 m from the center of the target

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

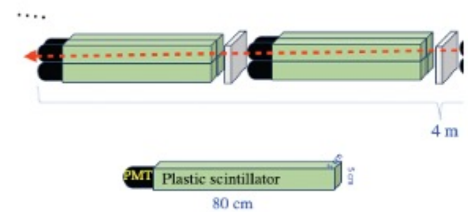
Detector Concept (prototype):
-The scintillator bars (5 cm x 5 cm x 80 cm) are arranged in four layers.

Detector Placement

- 800 MeV Proton Beam



- Numbers of layers to be determined
- **New nominal design: double coincidence.**



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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.

- Meson Productions: CCM, PRD (2022), 2105.14020

- New scintillator like CeBr3, to reduce beam-produced backgrounds

Kranti Gunthoti (LANL)

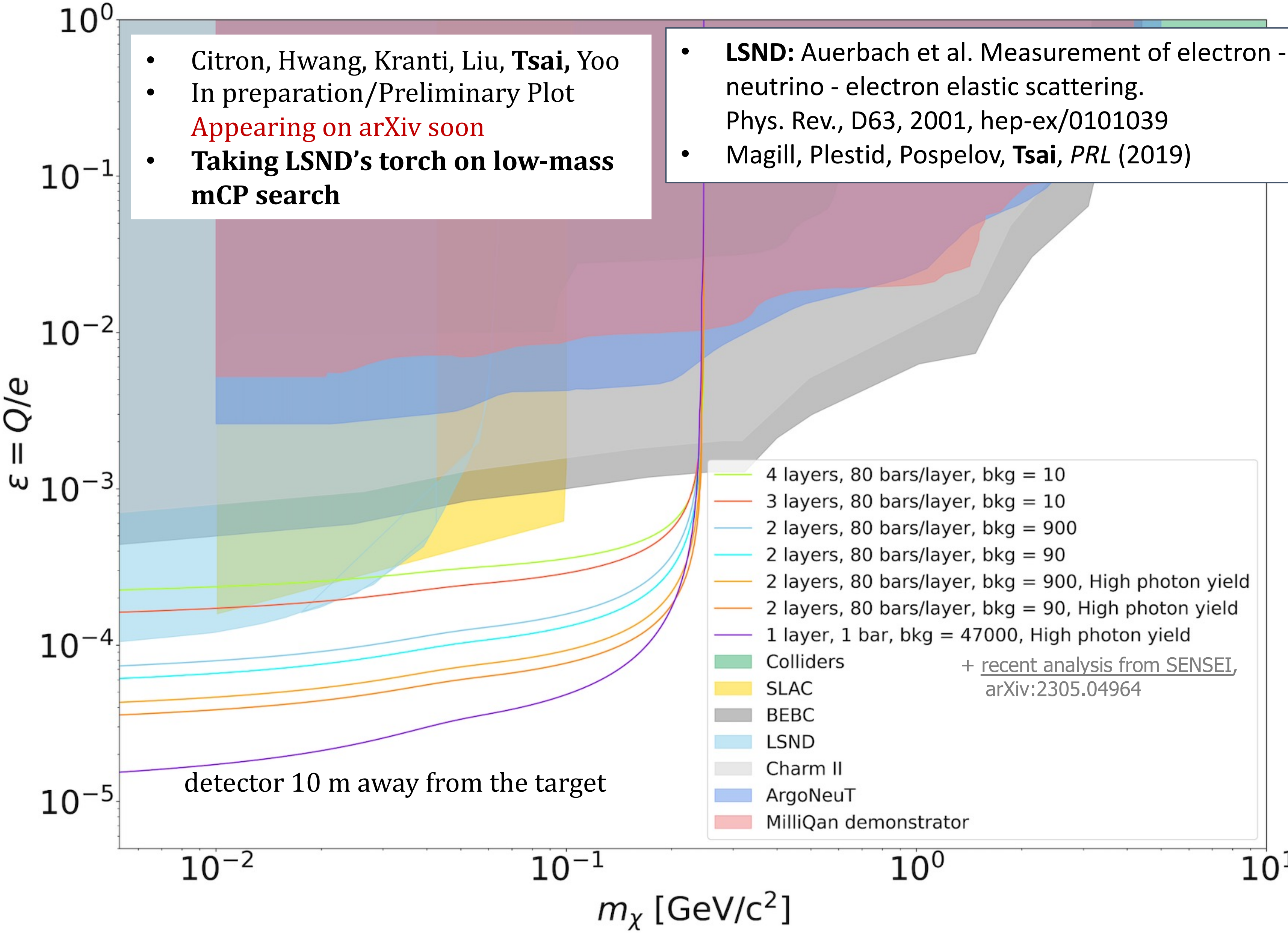
Fixed-Target Live Time (LANSCE Beam)

- 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 ~ 0.15 events per year for 2 layer-coincidence**
- We can afford **N = 1 or 2 layers** for fixed-target searches: larger signal rate: $P = (1 - \exp[-N_{\rm PE}])^{n_{\rm layers}}$

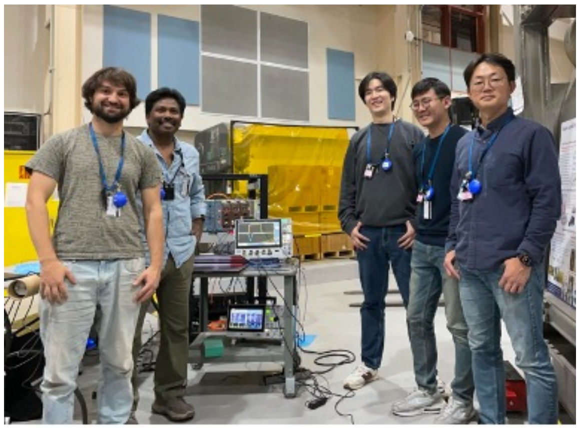
mCP Sensitivity Reach

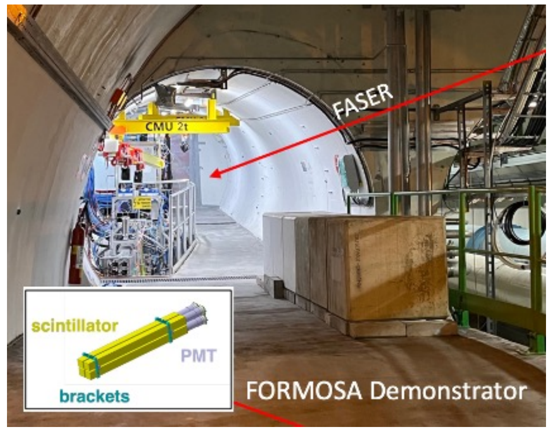
- Citron, Hwang, Kranti, Liu, **Tsai,** Yoo
- In preparation/Preliminary Plot
  Appearing on arXiv soon
- **Taking LSND's torch on low-mass mCP search**

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



Testing & Installation





Experimental team led by **Gunthoti (LANL)** to test/install the detector

A similar detector now installed at CERN to take data.
FORMOSA, Foroughi-Abari, Kling, **Tsai**, PRD (2021), 2010.07941, lead by **Citron (UC Davis)**

Outlook

1. **mCPs are excellent targets to string theories, Grand Unification Theories, cosmology, and dark matte theories & phenomenology**
2. Excellent experimental target at **LANSCE-mQ, FORMOSA**, **J-PARC, DUNE, + MicroBooNE, ICARUS, SBND, MINERvA, CCM, almost any accelerator experiments**
3. LANCSE-mQ can also be an excellent beam monitor
4. **Theory, Pheno/Experiment, and Cosmology Reviews under way.**

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
(With a little bit help from LDRDs ☺)

Thank you!

Backup Slides

Dark Current Background @ PMT (for Qs)

- 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
  $\boldsymbol{v_B^2}$ **Δt = 5 x** $\mathbf{10^{-4}}$ **Hz**, for **Δt = 20 ns.**
- **~ Background 0.15 events per year** in one year of trigger-live time
- FerMINI: Kelly, **Tsai**, PRD (2019), 1812.03998
  SUBMET: Kim, Hwang, Yoo, JHEP (2021), 2102.11493

Kinetic-Mixing CmB Cosmology:

N_{eff} Effects from Dark Photon

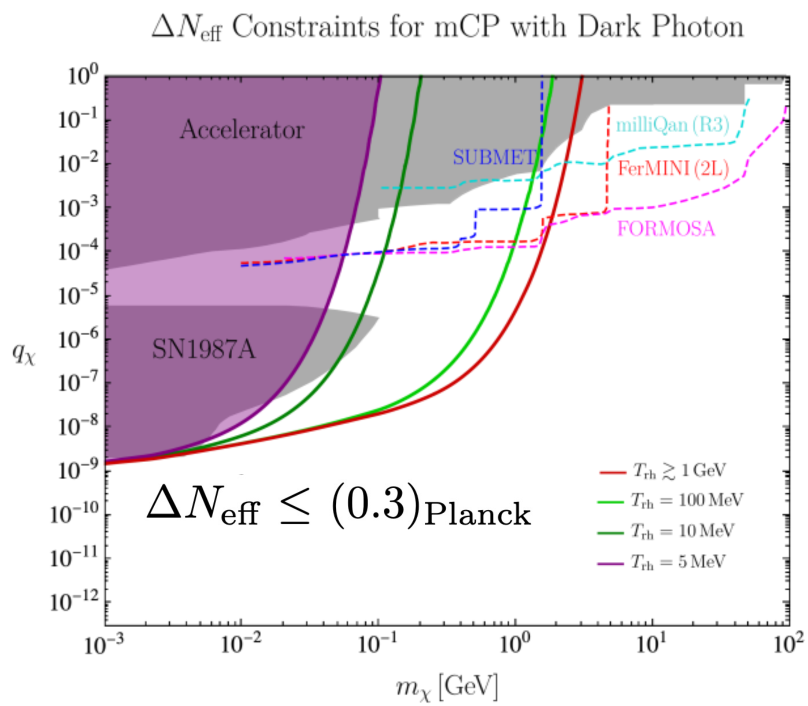
- Freeze-in from the heat bath
- χ thermalizing with dark photon: Require effective transfer of χ entropy to dark radiation A' here

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

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

- A quick ΔN_{eff} estimation:

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

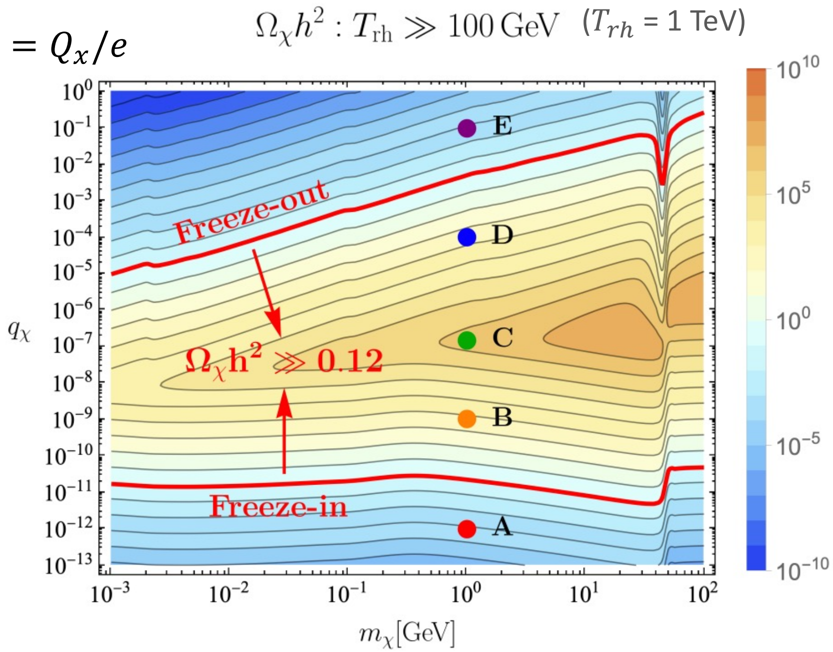


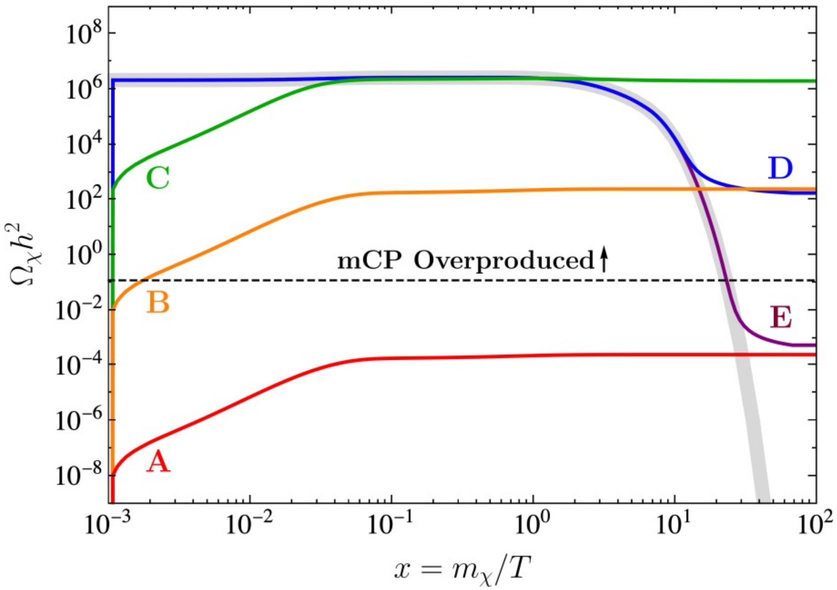
Gan, **Tsai**, 2308.07951

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

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

$\epsilon = Q_x/e$





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

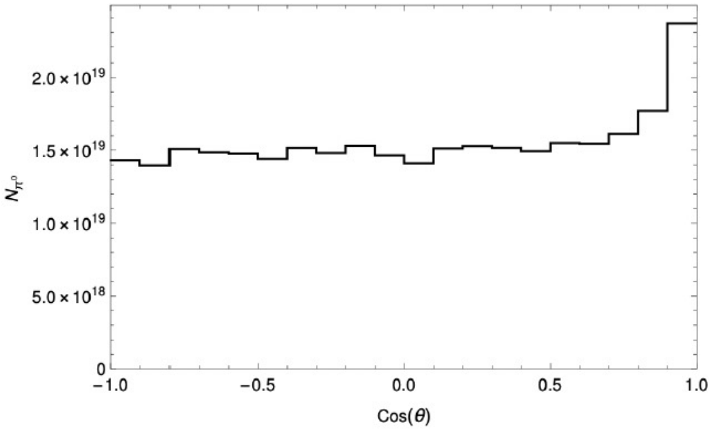
Freeze-out: $Y_\chi^{\rm FO} \sim \frac{1}{q_\chi^2 \alpha_{\rm em}^2} \frac{m_\chi}{m_{\rm pl}},$

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

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

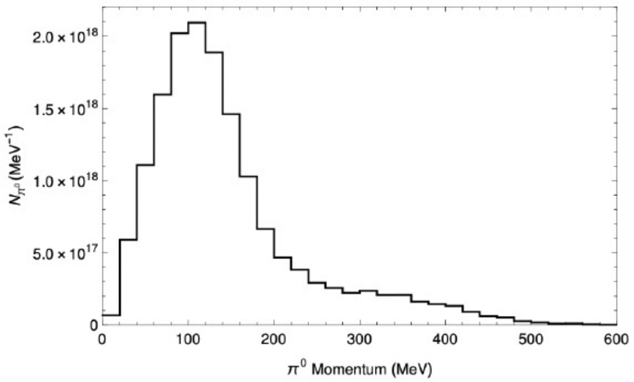
See, e.g., Vogel, Redondo, JCAP (2014), Dvorkin+, PRD (2019)

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 $N\pi^0 = 0.115 \times POT$.



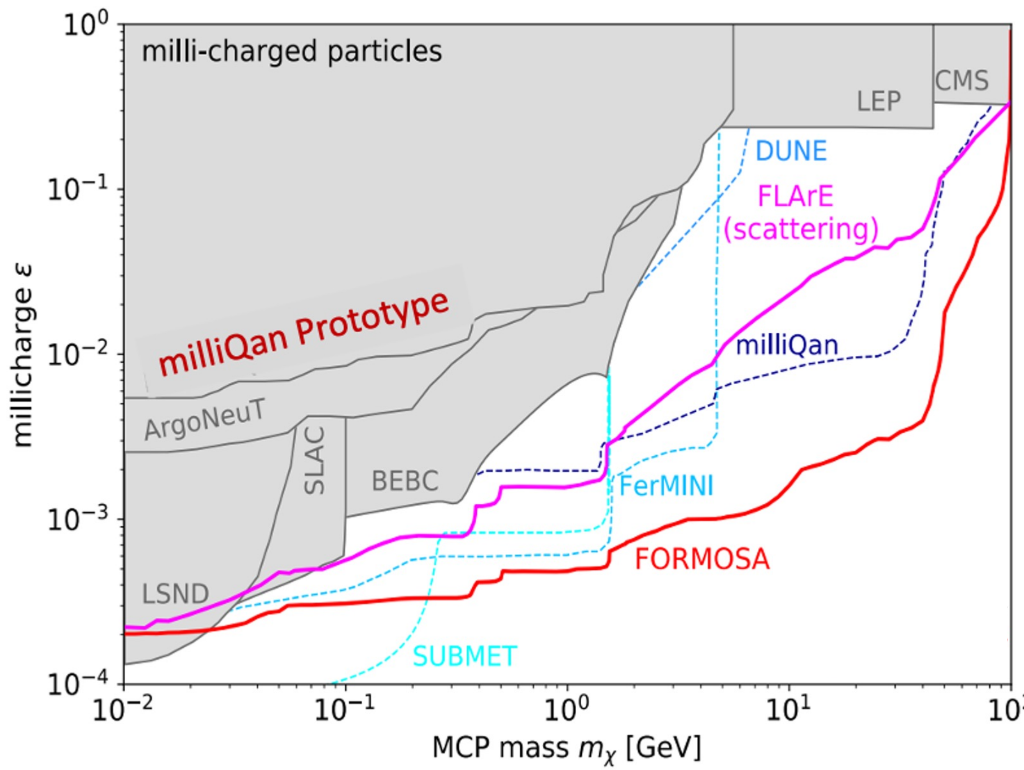
-The momentum distribution peaks between 100 and 120MeV, with a mean momentum of 146MeV.

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

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

Projection and Timelines

- **milliQan prototype** ran successfully and **has set new limits**
- **Full milliQan operating now ('22-'26)**
- **FORMOSA Phase I installation** (end of 2023, Beginning of 2024)
- New scintillator study & R&D ongoing;
- Collaborating with **Matthew Citron (UC Davis)** to design and install prototype to reach even better sensitivity

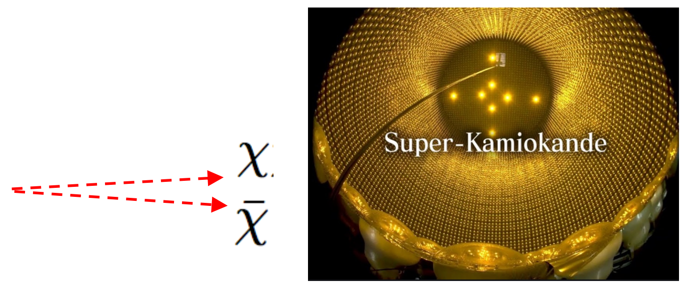


Foroughi-Abari, Kling, **Tsai**, PRD (2021)

Other Ways to Study mCPs

- **Cosmic-ray productions** and detections 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