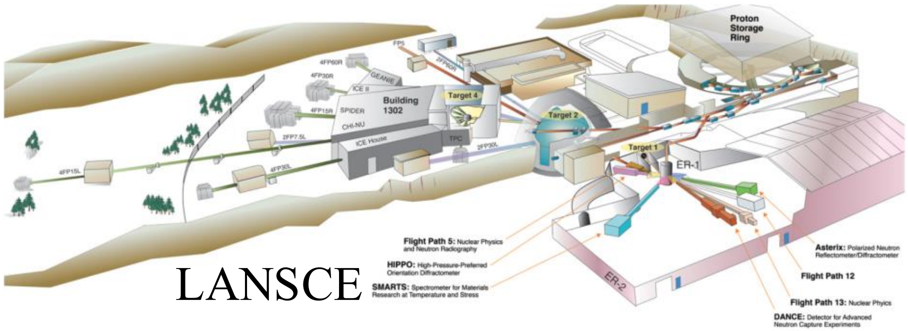
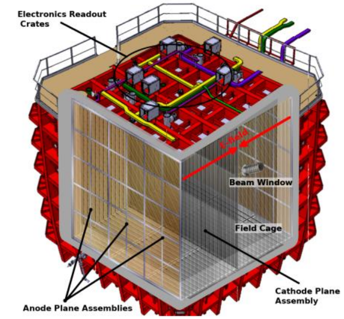


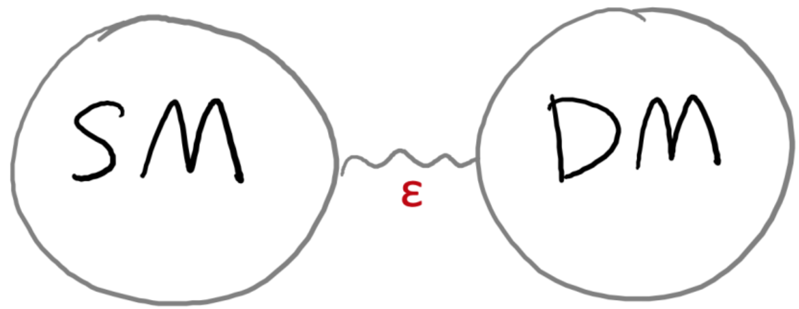




ProtoDUNE-SP
Hennessy, EPJ, 2019

# Millicharged Particles

Yu-Dai Tsai
University of California, Irvine/Los Alamos
Light Dark World (LDW) 2025

# Millicharged Particles




- **Renormalizable "portal" interactions:**

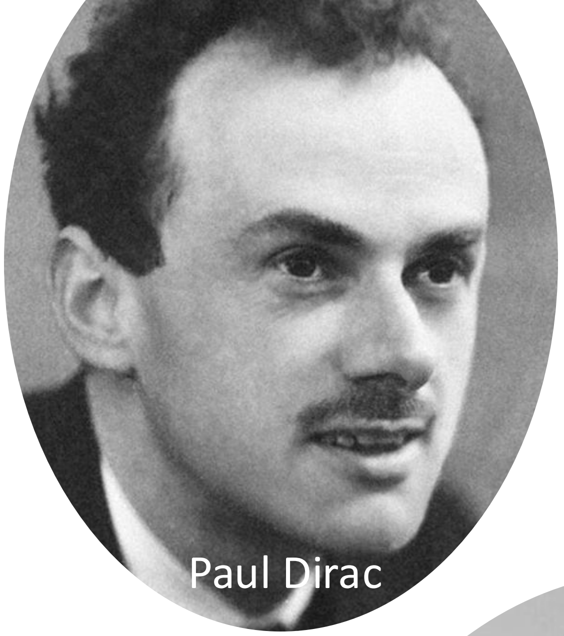
$$\mathcal{L} \supset \begin{cases} -\dfrac{\epsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}\,, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H\,, & \text{Higgs portal} \\ y_n L H N\,, & \text{neutrino portal} \end{cases}$$

- **Millicharge particle (mCP): $U(1)_Y$ hypercharge portal**

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

- **Benchmark Models for Experiments: e.g., CERN SPS & ProtoDUNE+**
- **Growing Theoretical Interest & Developments**

# Outline




- **Theory Motivations &**

  **Probes of Cosmology**

- Experimental Searches

# Theoretical Motivations of Millicharged Particles

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

$Q_\chi$ is the mCP electric charge, $\epsilon = Q_\chi / e$

1. Long-standing questions: *Is electric charge quantized? To what unit? Why?* ***Novel connections to monopoles?***

2. **A generic prediction of string theory**, Wen, Witten, *NPB* 1985

3. **A product of Grand Unification Theories (GUTs)**, Holdom, *PLB* 1986

4. **Finding mCP can be a strong probe of early-universe reheating cosmology** Gan, **Tsai**, 2308.07951

- "Theory Review of Millicharged & Fractionally Charged Particles"
  Planned review for Progress in Particle and Nuclear Physics (PPNP)

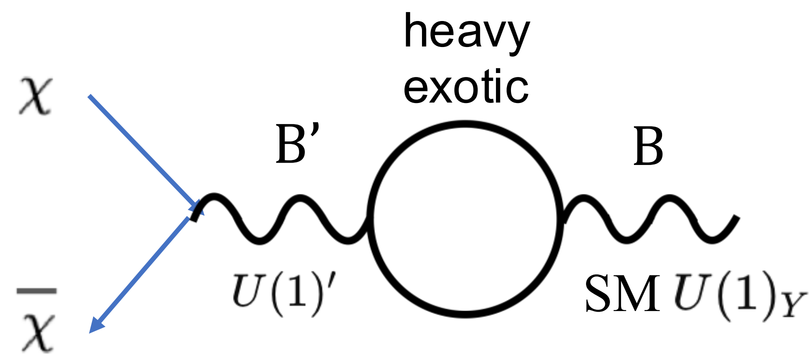
# Two Kinds of Millicharged Particles (mCP)

**“Pure” mCP**

- Theoretical implication of mCP with a **small rational or irrational charge**, NO dark photon needed
- **Prediction of string theories**
- **Indirect test of GUTs models**

**Effective “Kinetic-Mixing” mCP**

- **Predicted by GUTs.**

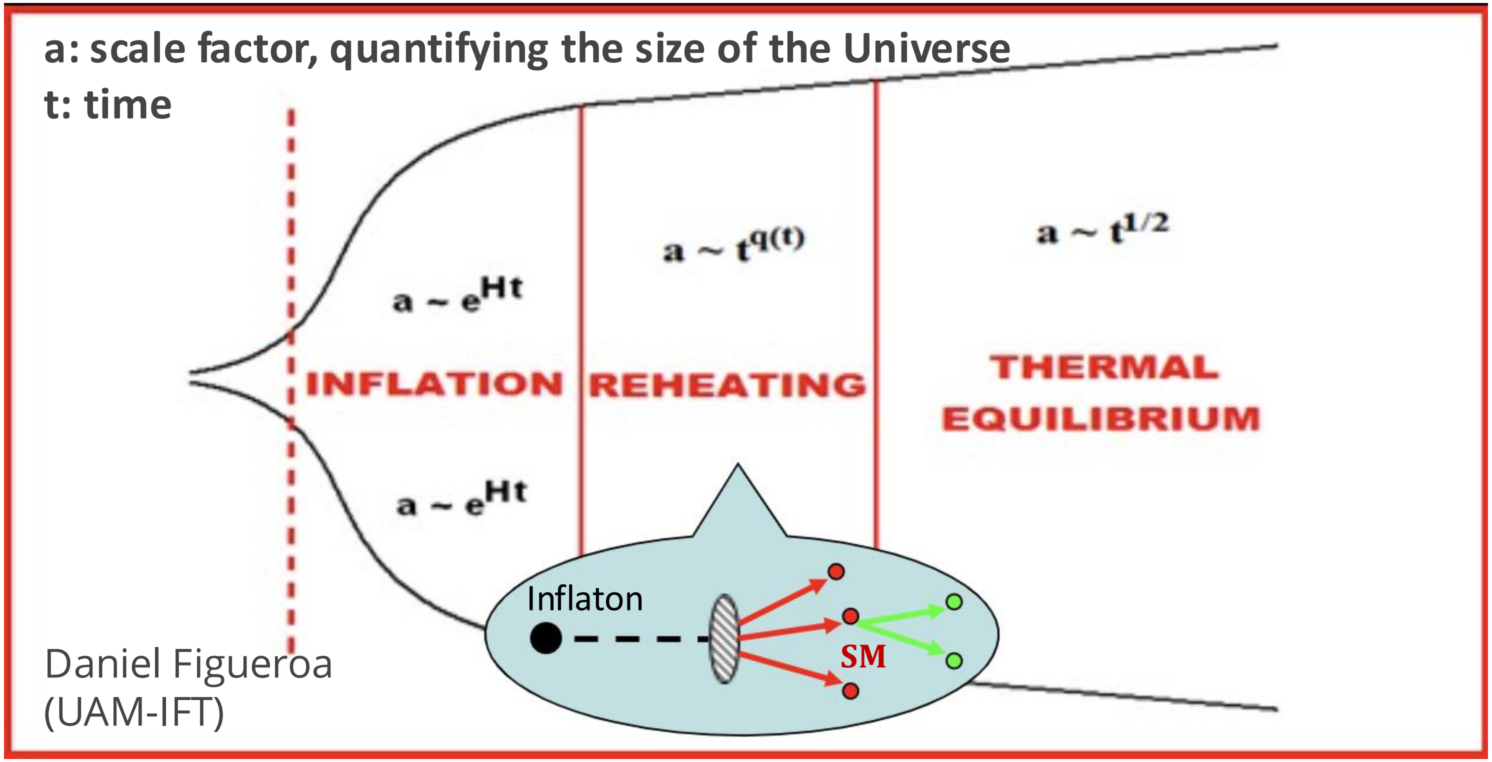



Choose a proper basis:
**massless dark photon B’**
**decouple from SM**

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

**My goal: find and differentiate these mCPs!**

# Probing Inflation & Reheating Cosmology




**We know very little about the reheating phase; washed out in later stage**

$T_{\rm rh}$ is the reheating temperature; BBN is the big bang nucleosynthesis

$$T_{\rm GUT}(\sim 10^{16}\,{\rm GeV}) \gtrsim T_{\rm rh} \gtrsim T_{\rm BBN}(\sim {\rm MeV})$$

# Cosmic Millicharge Background (CmB)

## “Pure” mCP

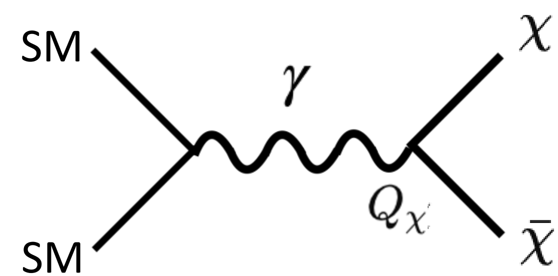
- mCP with a **small (irrational) charge & no dark photon**
- **Generic prediction of string theory**
- **Indirect test of GUTs models**
- **Indirect test of string compactifications**

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

## Irreducible Production during Reheating

Inflaton Decays

Reheating at temperature $T_{rh}$




**Thermal Production & Annihilation**

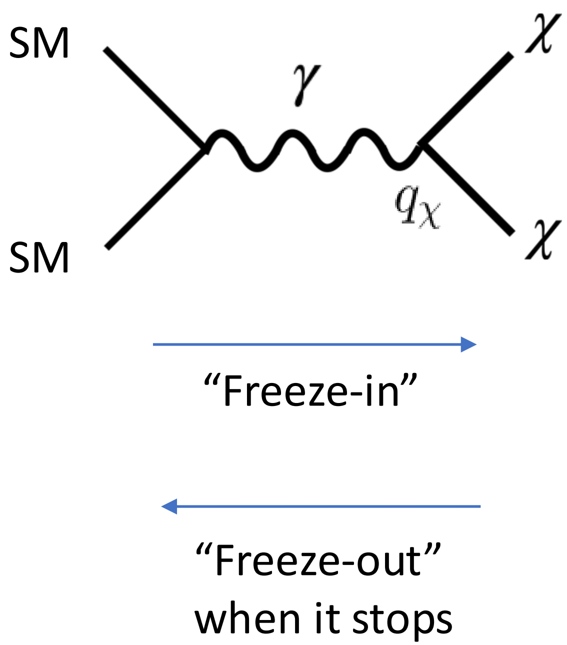
**mCP can be easily “overproduced”, to more than that of the observed amount of dark matter**

# Cosmic Millicharge: Overproduction During Reheating

**Irreducible Production during Reheating**

Inflaton

Reheating at temperature $T_{rh}$




**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

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

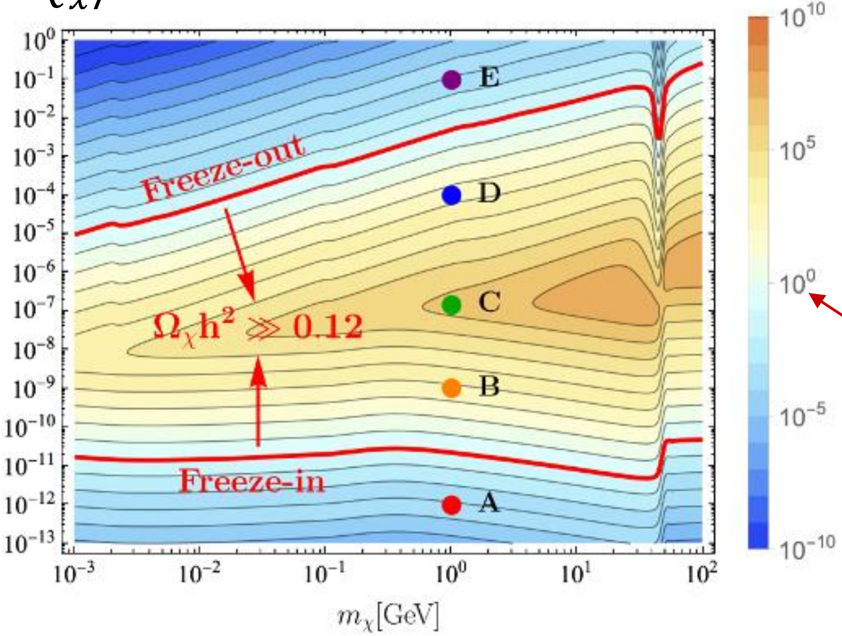
Density is normalized by $\rho_c$, the critical density for a flat Universe; $h$ = 0.674

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

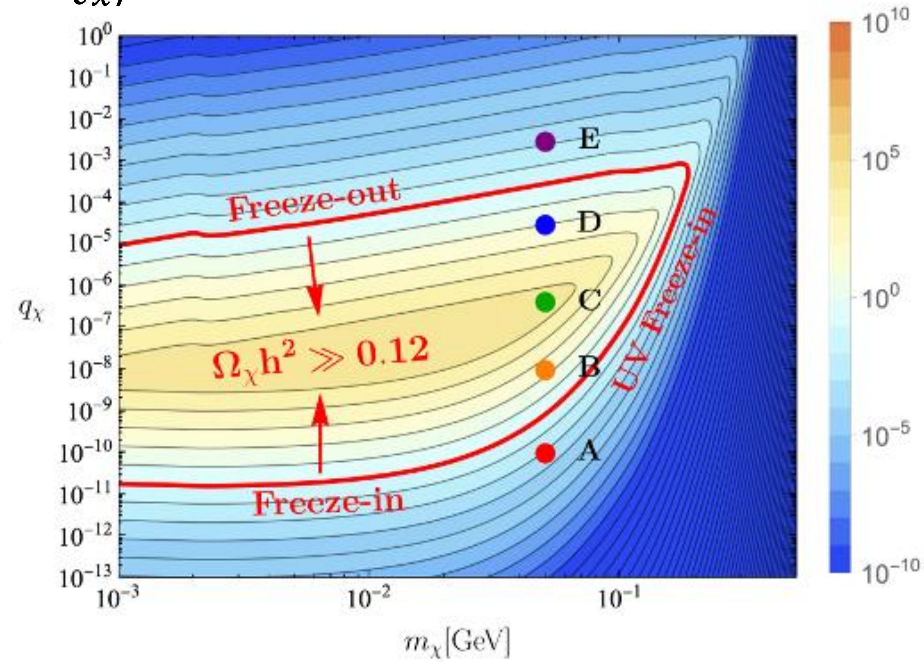
Gan, **Tsai**, JHEP (2025), 2308.07951

# mCP Parameters that Lead to Overproduction

$\epsilon = Q_x/e$ $T_{rh}$ >> 100 GeV



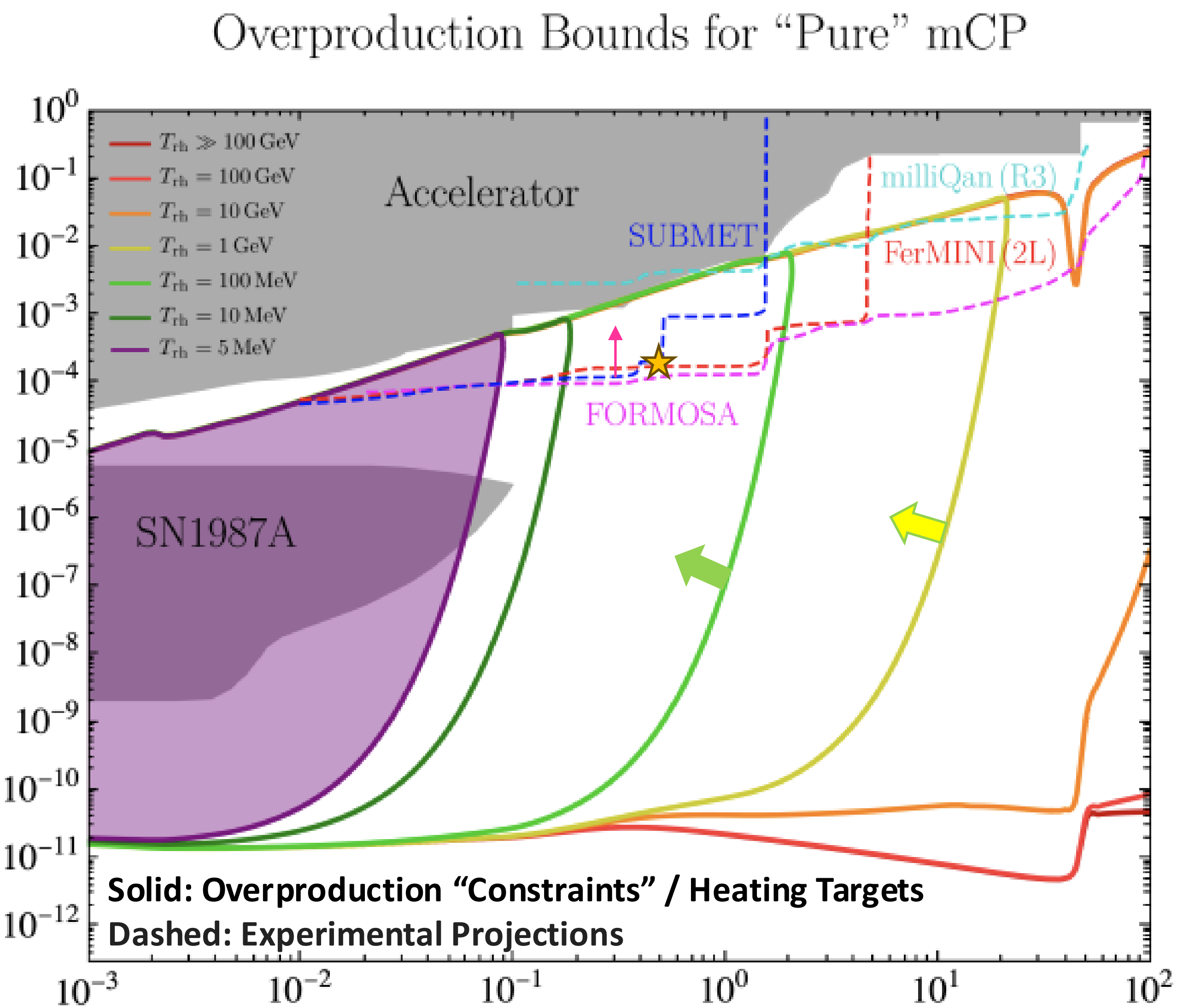

$\epsilon = Q_x/e$ $T_{rh}$ = 10 MeV




$$\dot{n}_\chi + 3Hn_\chi \simeq \mathcal{C}_n(T)\left(1 - \frac{n_\chi^2}{n_{\chi,\mathrm{eq}}^2}\right), \quad \mathcal{C}_n(T) = 2n_Z\langle\Gamma\rangle_{Z\to\chi\bar{\chi}} + 2n_f n_{\bar{f}}\langle\sigma v\rangle_{f\bar{f}\to\chi\bar{\chi}}$$

Gan, **Tsai**, JHEP (2025), 2308.07951

# Millicharge Search as a Probe for Reheating Temperature



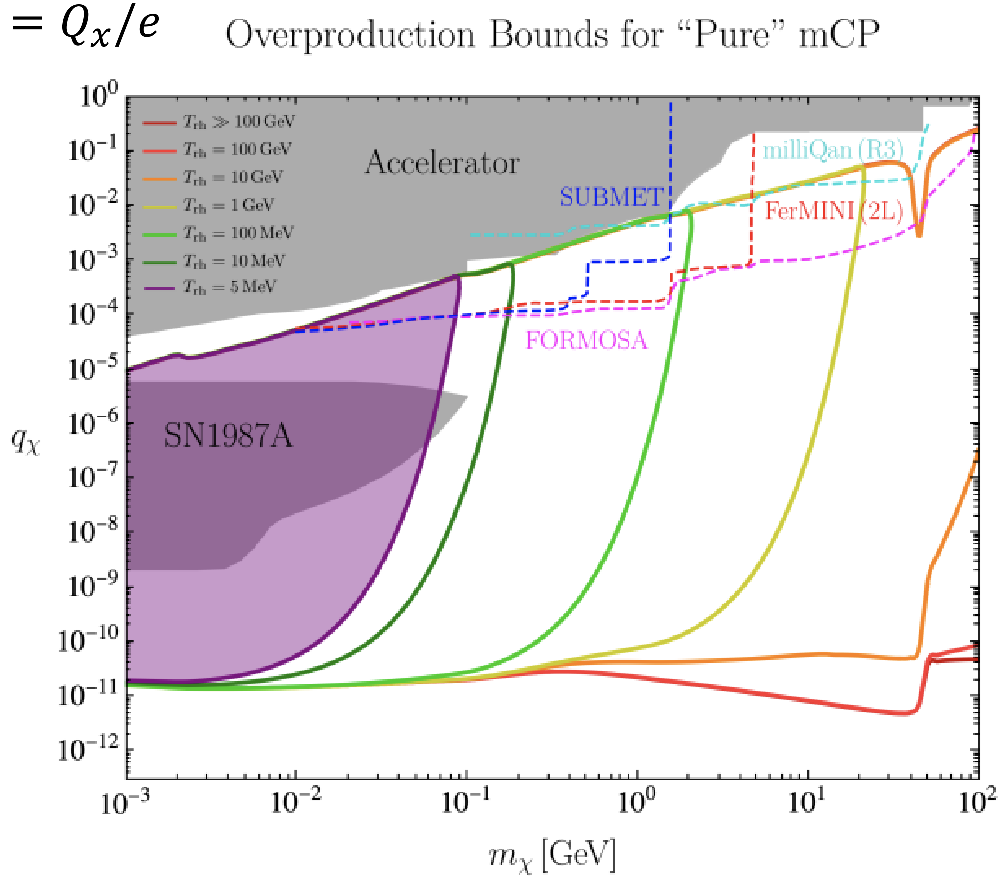

Charge in unit of electron charge

Mass of millicharge particle (GeV)

Gan, **Tsai**, 2308.07951

# “Pure” CmB from Irreducible Production

$\epsilon = Q_x/e$

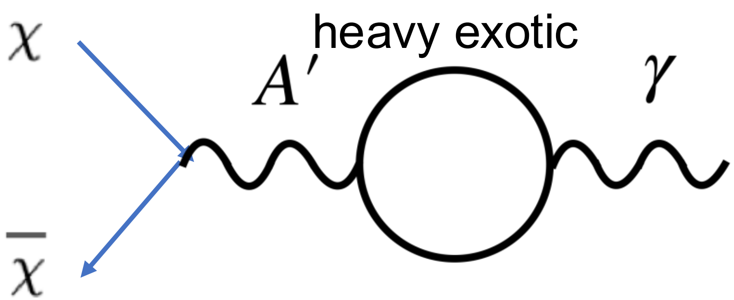



Gan, **Tsai**, 2308.07951

- Minimal reheating temperature larger than $T_{BBN}$ (e.g., Hasegawa+, *JCAP* 19; Hannestad, *PRD* 04)
- **Our purple bound is covering the SN1987A constraint** (gray region from Chang+, *JHEP* 18)

# Kinetic-Mixing Cosmic Millicharge Background (CmB)

## Kinetic-mixing mCP




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

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

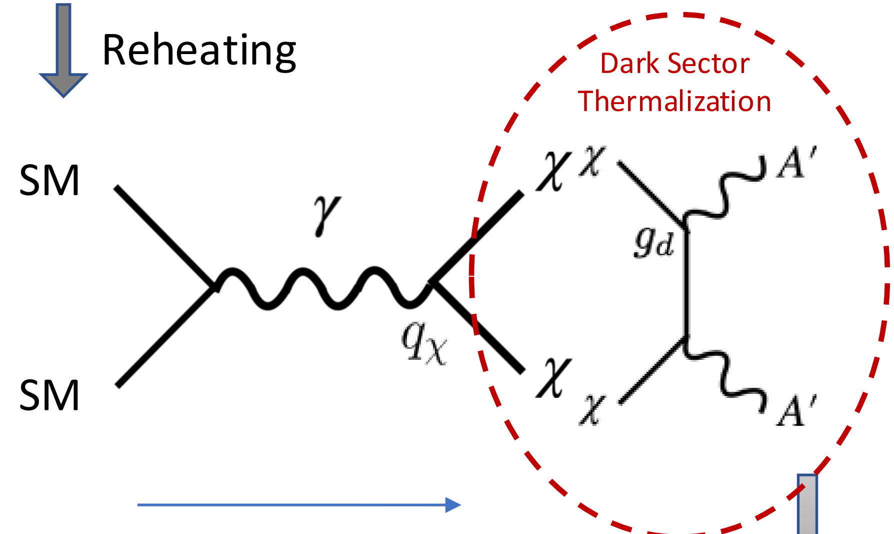
$$q_\chi = \frac{\epsilon g_d}{e}$$

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

## Kinetic-mixing mCP

Inflaton

Reheating



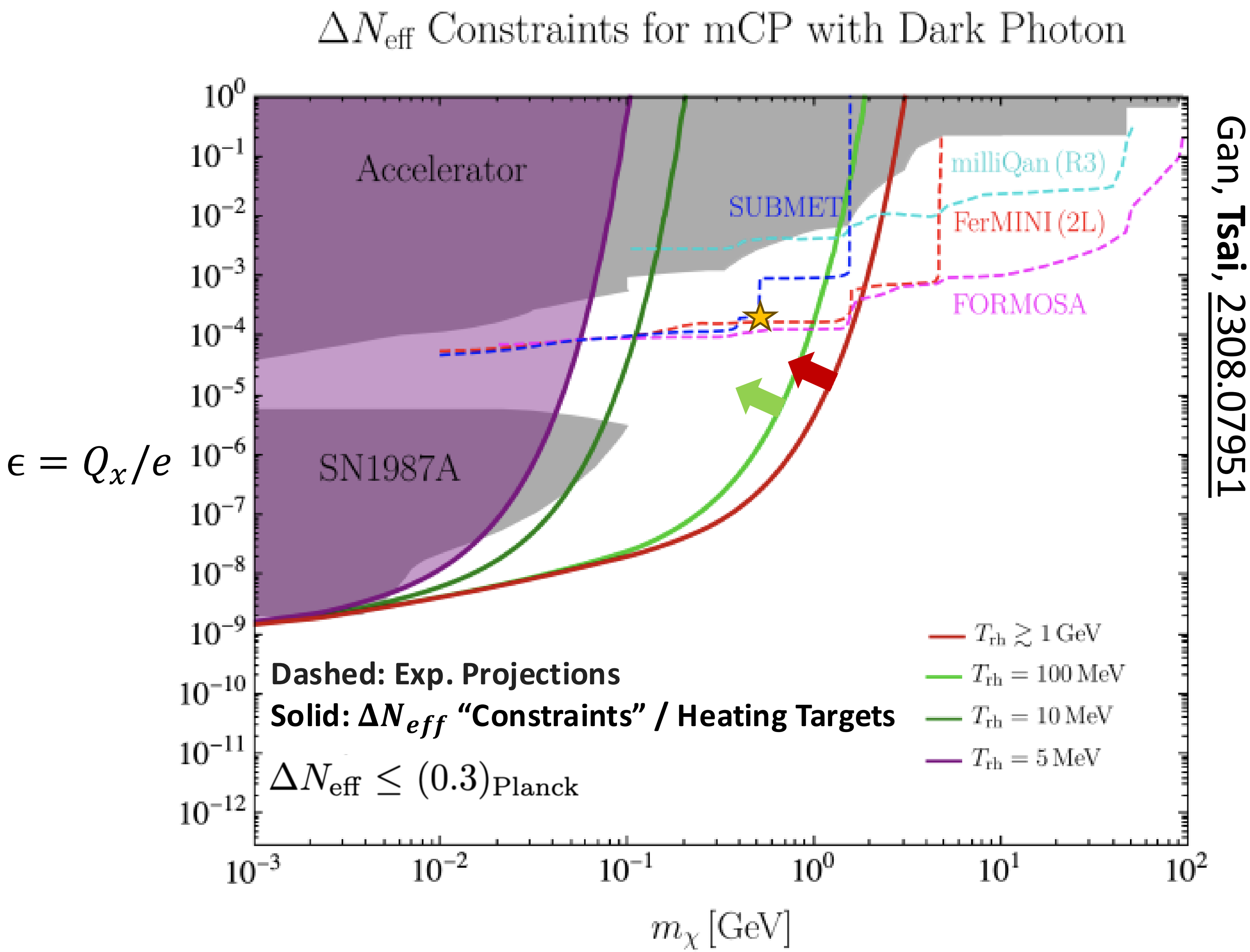

Freeze-in:

Freeze-out:

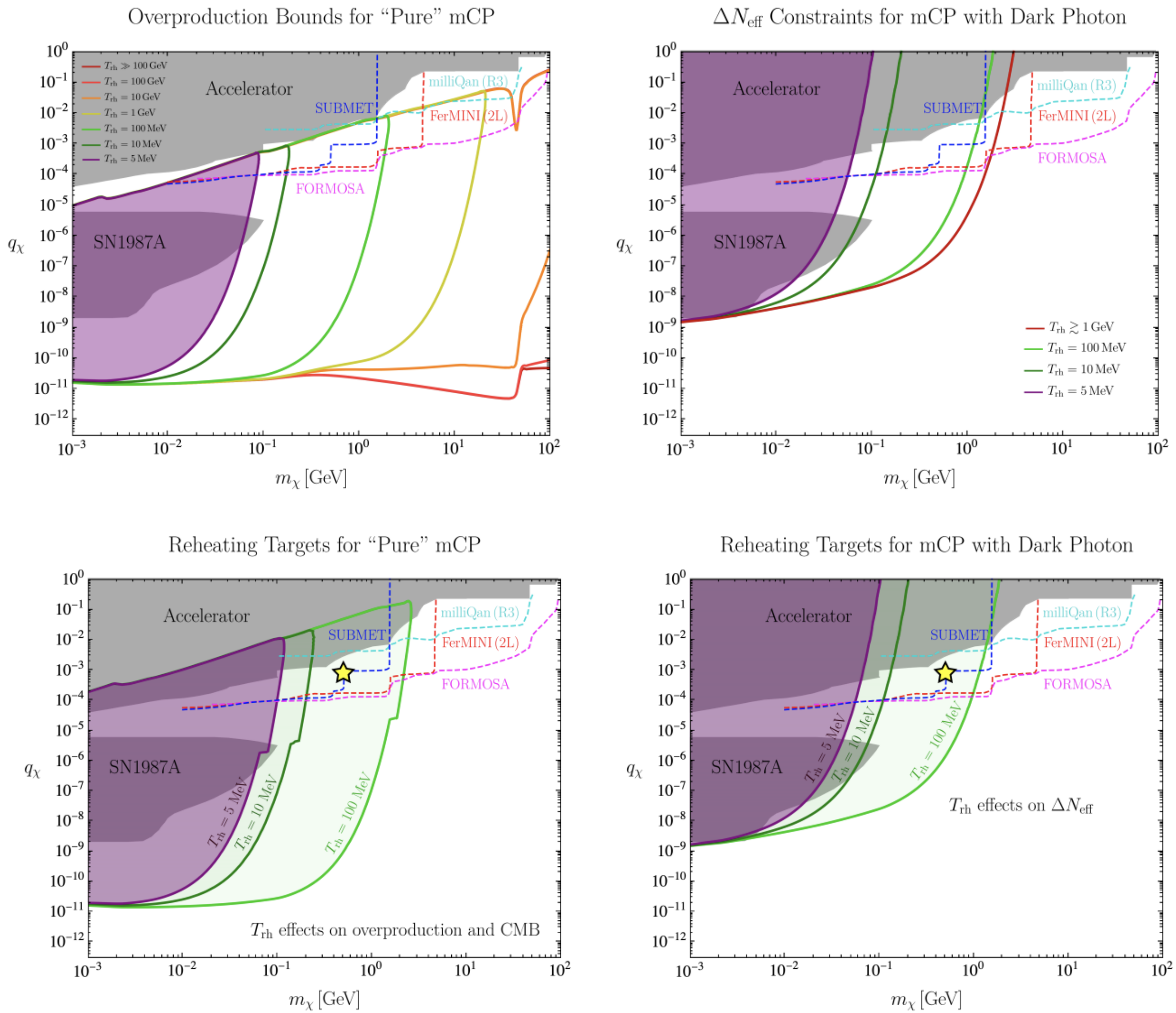
massless dark photon A’ will affect $N_{eff}$

See Vogel, Redondo, *JCAP* 14,
Adshead, Ralegankar, Shelton, *JCAP* 22

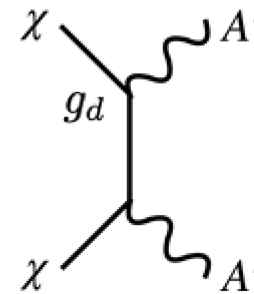
# Millicharge Search as a Probe for Reheating Temperature



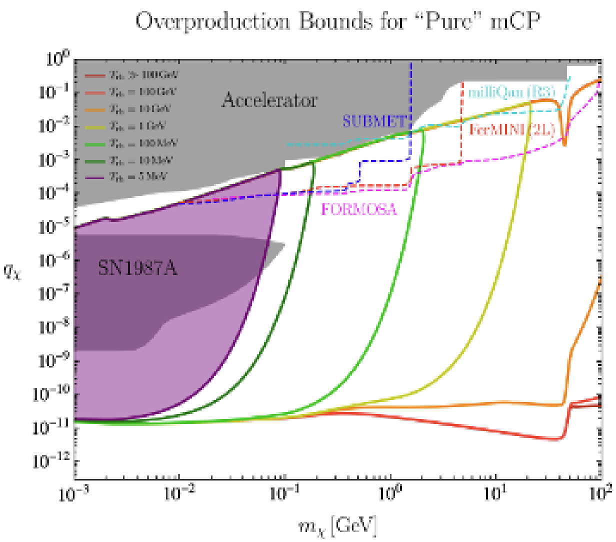
# Testing Reheat Temperatures in Both Cases



# **Another Key Objective:**
# Differentiate Two Types of MCPs




$g_d = 0$

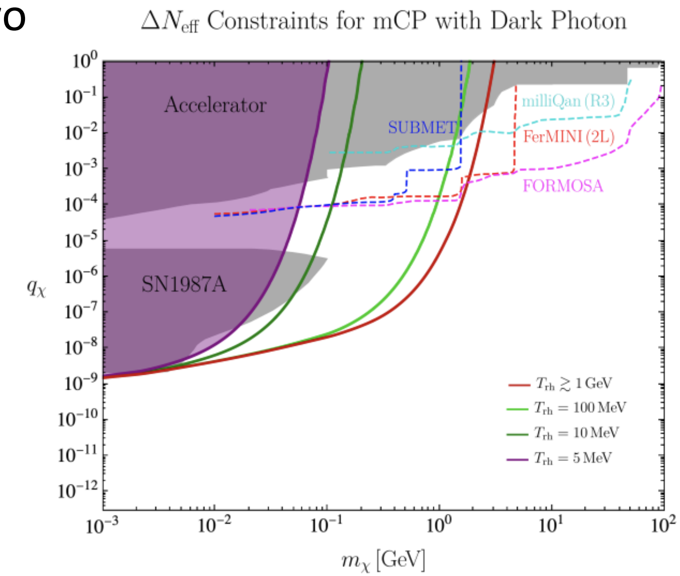



moderate $g_d$

Interpolate between the two

?

Sizable $g_d$




- Theoretically, is there a limit on how small $g_d$ can be, for a given $q_\chi$?
- Combined with cosmology, we may distinguish two mCPs

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

# “Distinguishability” Conditions

Gan, **Tsai**, JHEP (2025), 2308.07951

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

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

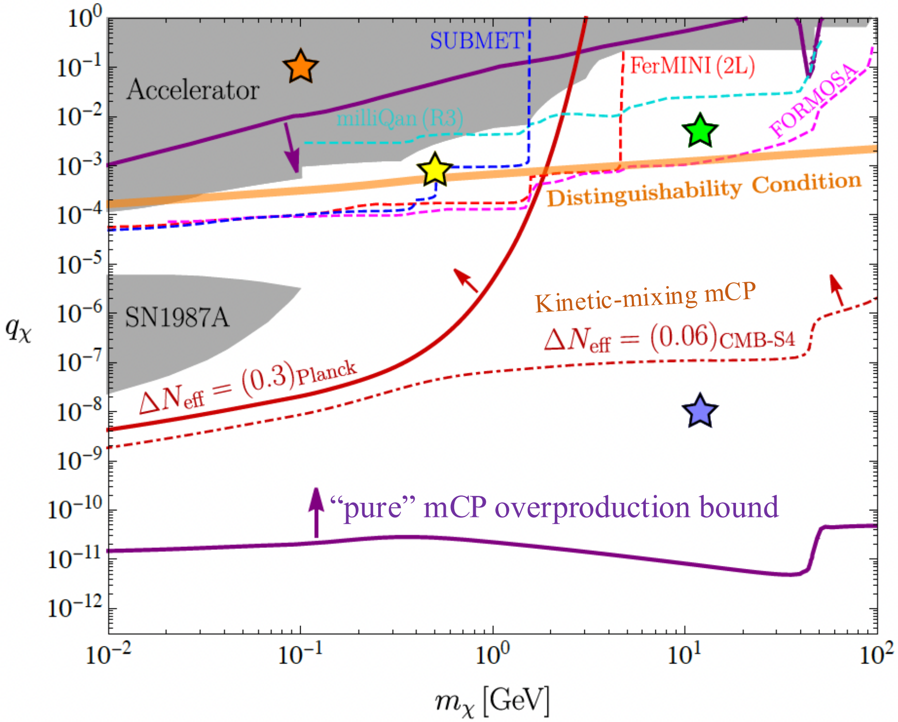
  Burgess *et al*, *JCAP* 08

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

$$q_\chi \gtrsim \frac{1}{\alpha_{\rm em}^{1/2}} \left( \frac{m_\chi}{\mathcal{F} m_{\rm pl}} \right)^{1/4}, \qquad \mathcal{F} \approx \frac{375}{16\pi^3 e^{5/2} g_*^{1/2}}$$

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

# Regions of Interests

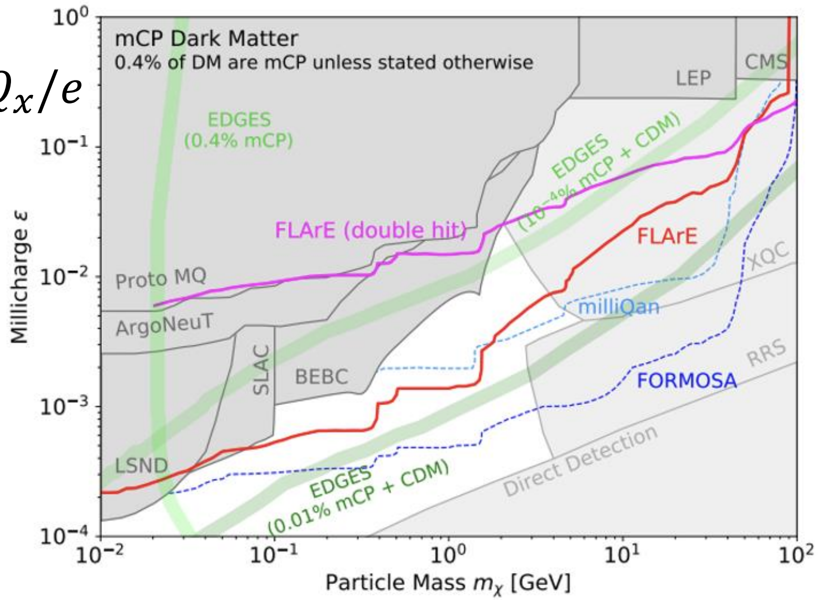



- **Orange Star:** favoring "pure" mCP
- **Yellow Star:** testing reheat temperatures
- **Green Star:** 1) testing reheat temperatures with CMB-S4 2) currently favoring kinetic-mixing mCP
- **Purple Star:** favoring kinetic-mixing mCP can be reached by direct-detection exps.

**Our study can be extended to other BSM searches, mCP is one of the cleanest examples**

# Millicharged Dark Matter (mDM)?

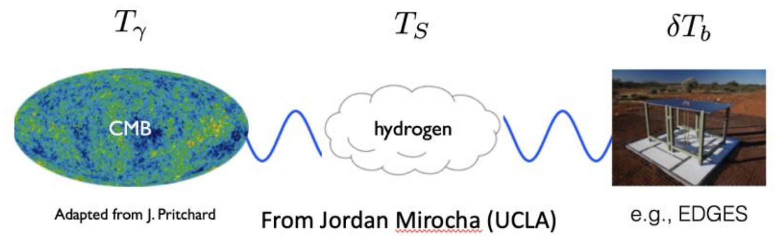
$\epsilon = Q_x / e$




Green: Liu, Outmezguine, Redigolo, Volansky, PRD (2019),
Kling, Kuo, Trojanowski, Tsai *NPB* (2023)

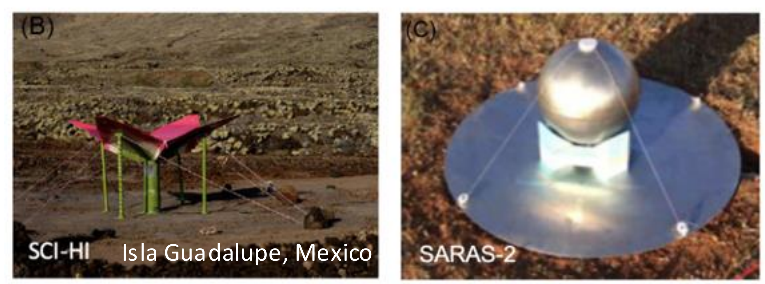
**The depletion of local density:**

- McDermott, Yu & Zurek, *PRD* (2011)
- Supernova shock waves expel the charged constituents from the disk
- Galactic magnetic fields prevent them from re-entering




EDGES @ Murchison Radioastronomy Observatory, Western Australia

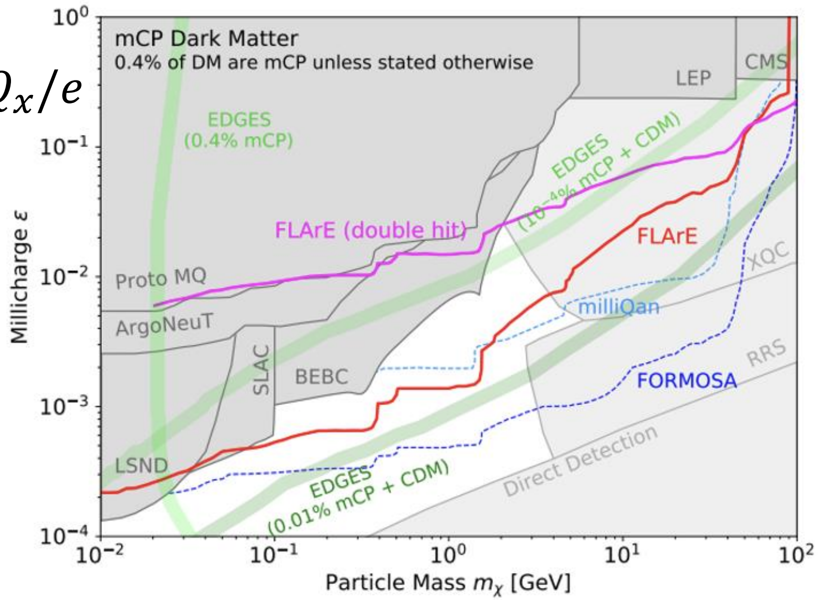
- 21 cm CMB absorption spectrum
- Many (upcoming) measurements!
  Voytek et al, APJL (2014),
  Singh et al, arXiv: 1710.01101

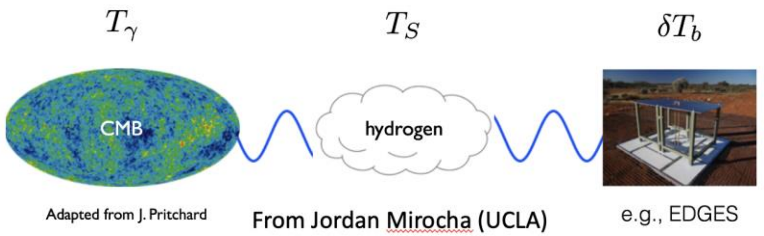



SARAS-3 in North Karnataka, India

# Millicharged Dark Matter (mDM)

$\epsilon = Q_x/e$



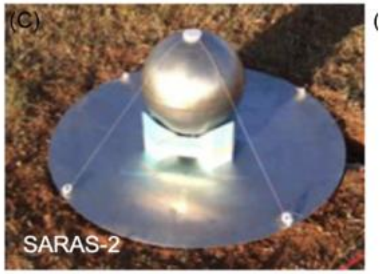




EDGES @ Murchison Radioastronomy Observatory, Western Australia

- 21 cm CMB absorption spectrum
- Many (upcoming) measurements!
  Voytek et al, APJL (2014),
  Singh et al, arXiv: 1710.01101

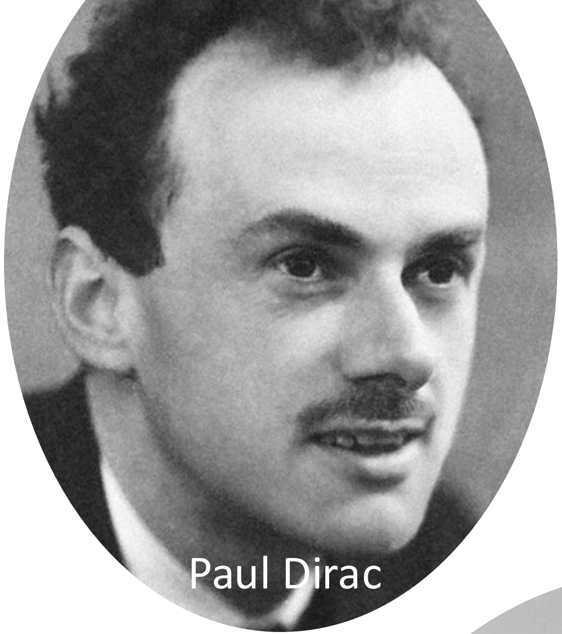
**Also claims & considerations for overdensity**

- Atmospheric & Earth Stopping Accumulates Slow Moving mDM
  Pospelov, Ramani, PRD (2021)
- Quantum sensors (Iron Trap) can be applied to study them
  Budker, Graham, Ramani, Schmidt-Kaler, Smorra, Ulmer et al., PRX (2022)


SARAS-3 in North Karnataka, India

# Outline



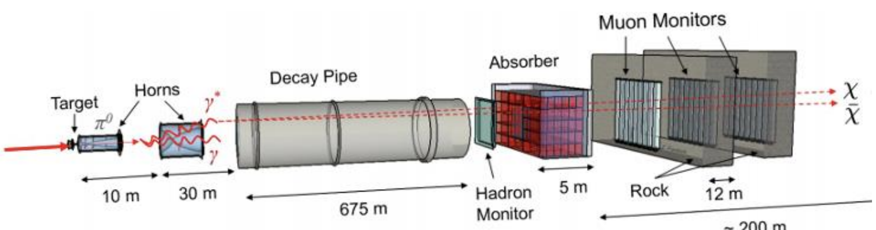

- Theory Motivations &

  Probes of Cosmology

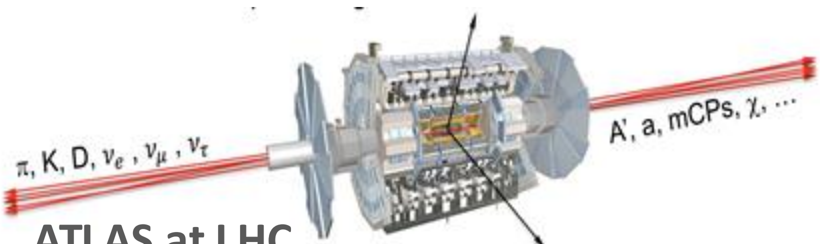
- **Experimental Searches**

# Accelerator: Intensity & Energy Frontiers

### Fixed-Target / Collider Productions

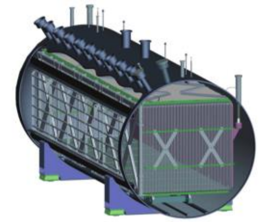



NuMI Proton Beam

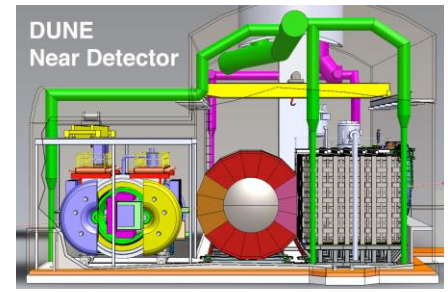



ATLAS at LHC

### 1. Scattering Study

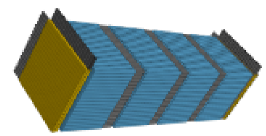


MicroBooNE




DUNE Detectors

### 2. Dedicated Detector



FORMOSA at LHC

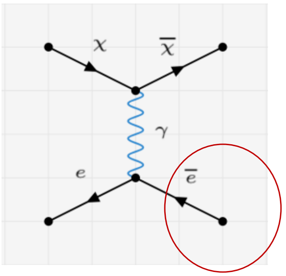
- **We conducted the first millicharge study at neutrino experiments** *(PRL 19)*
- Many experiments (ArgoNeuT, SENSEI) followed up accelerator mCP study.
- Belle and future experiments like FCC: interesting sensitivities & constraints

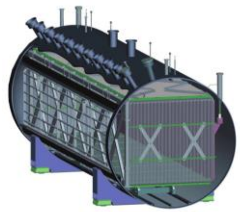
Credits: all pictures are from the named collaborations

# Two Search Methods: Scattering & Scintillation

- **Electron Scattering**

~ energy exchange set by detector threshold (> MeV)



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

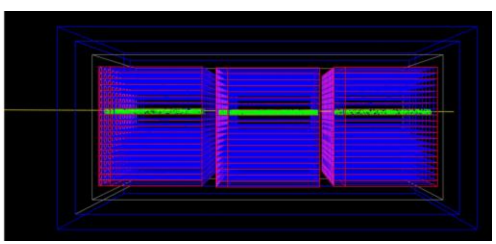
$$\sigma_{e\chi} \simeq 2.6 \times 10^{-25}\text{cm}^2 \times \epsilon^2 \times \frac{1\ \text{MeV}}{E_e^{(\text{min})} - m_e}.$$

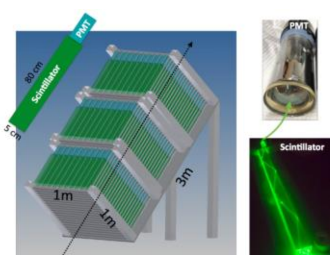
Expressed in **recoil energy threshold**, $E_e^{(min)}$

Magill, Plestid, Pospelov, **Tsai**, *PRL* 19, 1806.03310
Harnik, Liu, Palamara, *JHEP* 19, 1902.03246

- **Dedicated Scintillation Searches** for Millicharge Particles

~ eV-level energy exchange



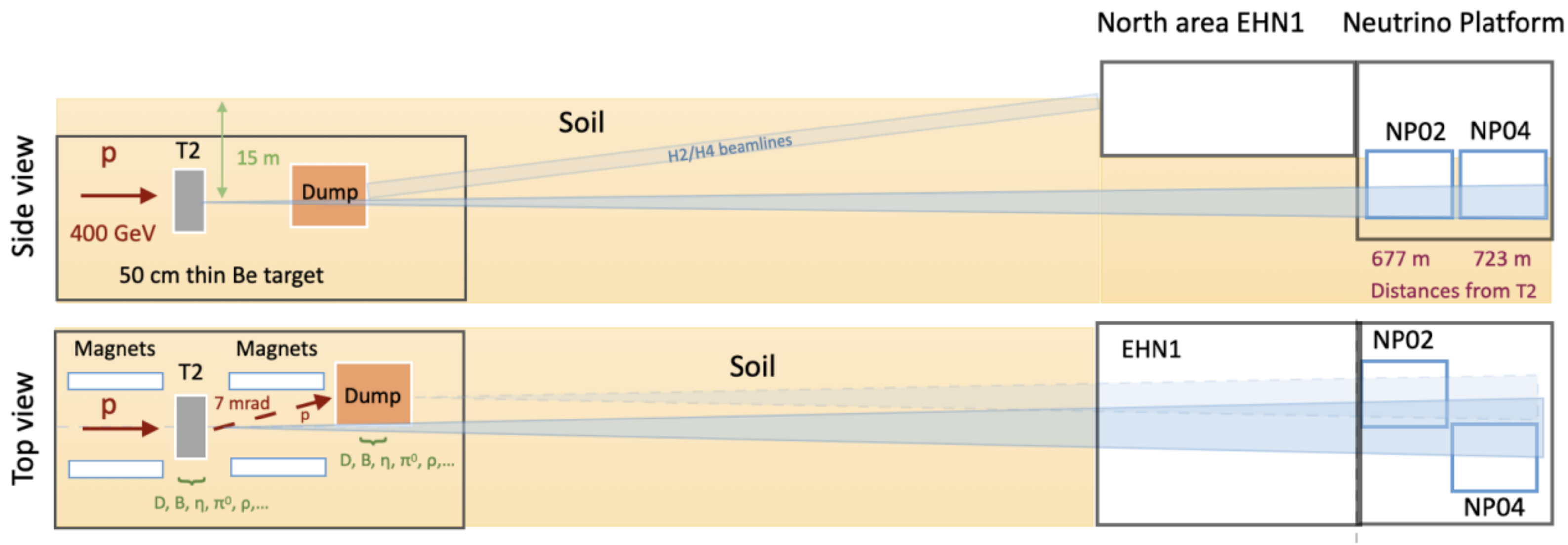



$$\left\langle -\frac{dE}{dx} \right\rangle \propto \epsilon^2.$$

**Energy deposition**

milliQan design, 1607.04669 (MilliQan Collaboration)
FerMINI: Kelly, **Tsai**, *PRD* 19, 1812.03998
FORMOSA: Foroughi-Abari, Kling, **Tsai**, *PRD* 21, 2010.07941
LANSCE-mQ: **Tsai** et al., 2407.07142

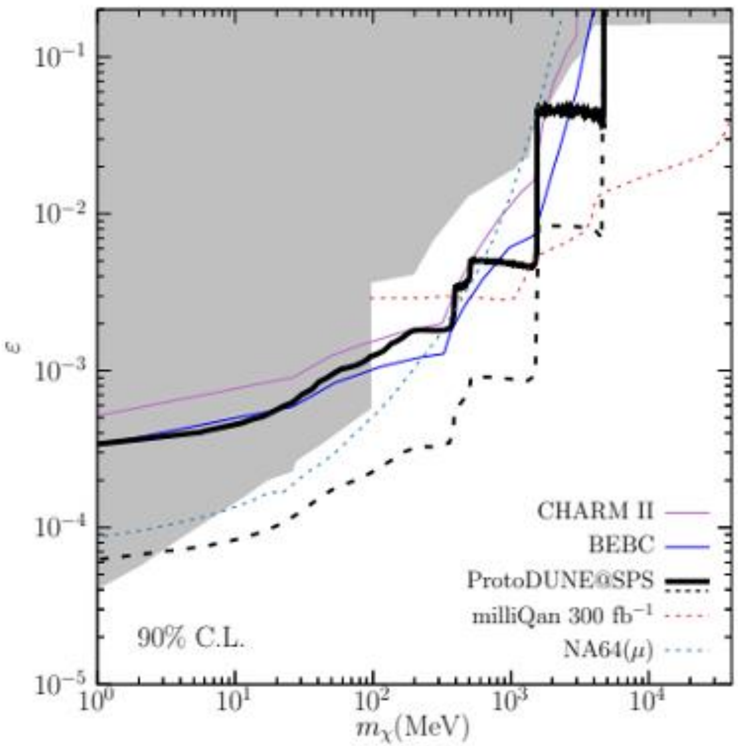
# ProtoDUNE & CERN SPS




- **Energy:** 400 GeV
- **POT:** ∼3.5×1018 POT/year, consider sensitivity for 5 years.
- The target is ∼ 15 m underground, and there are ∼ 500 m of soil between the beam dump and EHN1.

Coloma, L´opez-Pav´on, Molina-Bueno, Urrea, *JHEP* (2024)
2304.06765

# ProtoDUNE & CERN SPS



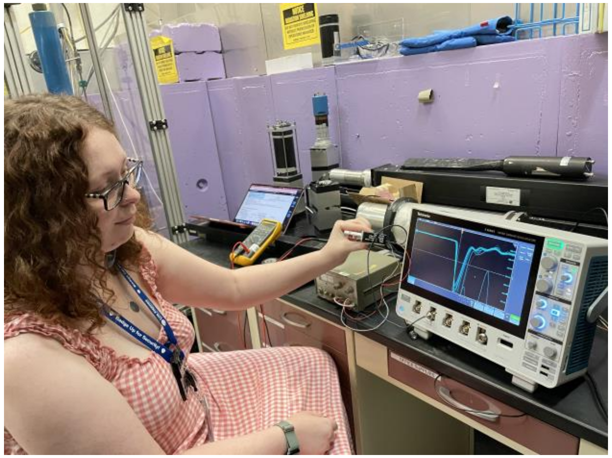

- Since the setup is background-limited, the dashed black line indicates the ultimate sensitivity achievable if backgrounds can be reduced

Coloma, L´opez-Pav´on, Molina-Bueno, Urrea, *JHEP* (2024)
2304.06765

# Dedicated Scintillation-Based Millicharged Experiments

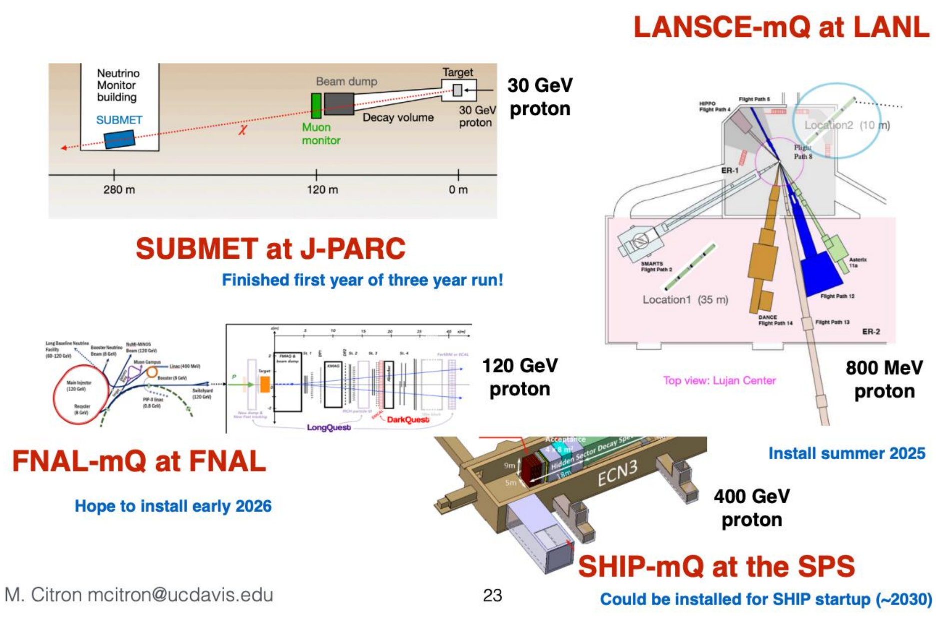
1. **FORMOSA @CERN**
- **Proposed it & conducted flux calculations with PhD Student**
  Abari, Kling, **Tsai**, *PRD 21*
- Demonstrator installed & taking data
- **Featured on P5 Report**

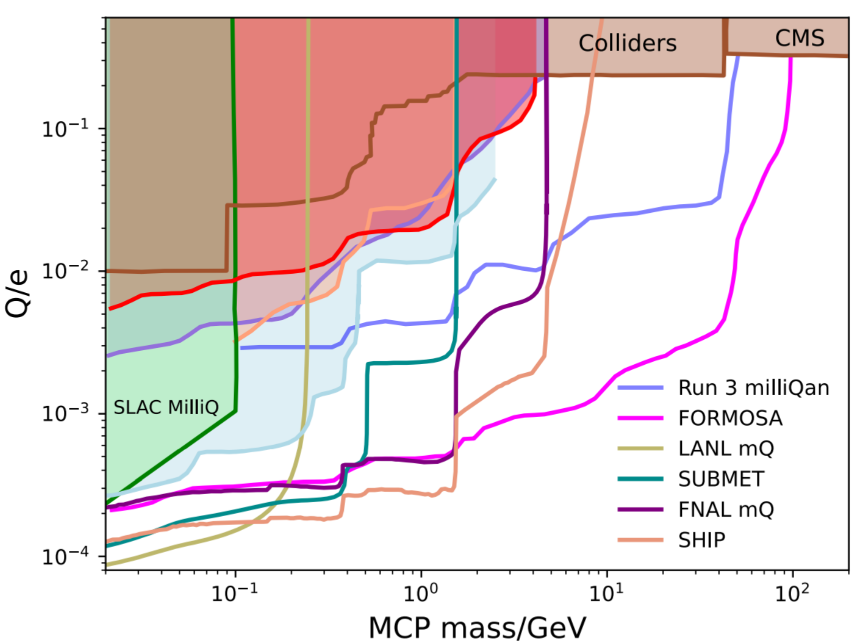

2. **LANSCE-mQ @LANL**
- **A tiny "pathfinder" has taken data**
- **Tsai** et al., 2407.07142
- **Received $165k funding for 2025**



Samantha Kelly (PhD Student) at LANSCE@LANL

3. **LongQuest-mQ @Fermilab**
- **Study mCP & Long-Lived Particles**
- **Tsai**, et al., *PRL* 21




# Updates:

- **MicroBooNE completing dedicated millicharge analysis** (Arellano, Evans, …)
- **For dedicated searches:**

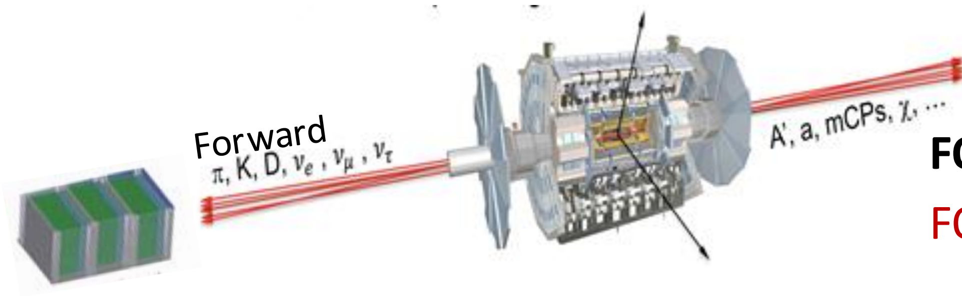
1. **LANL LDRD $165k funding for '25**
2. Featured on P5 report
3. Demonstrators are built and full detectors under way

**Students:**

**Undergrads:** Domingo (UCI), Bailloeul (UCD), Hwang (BU)

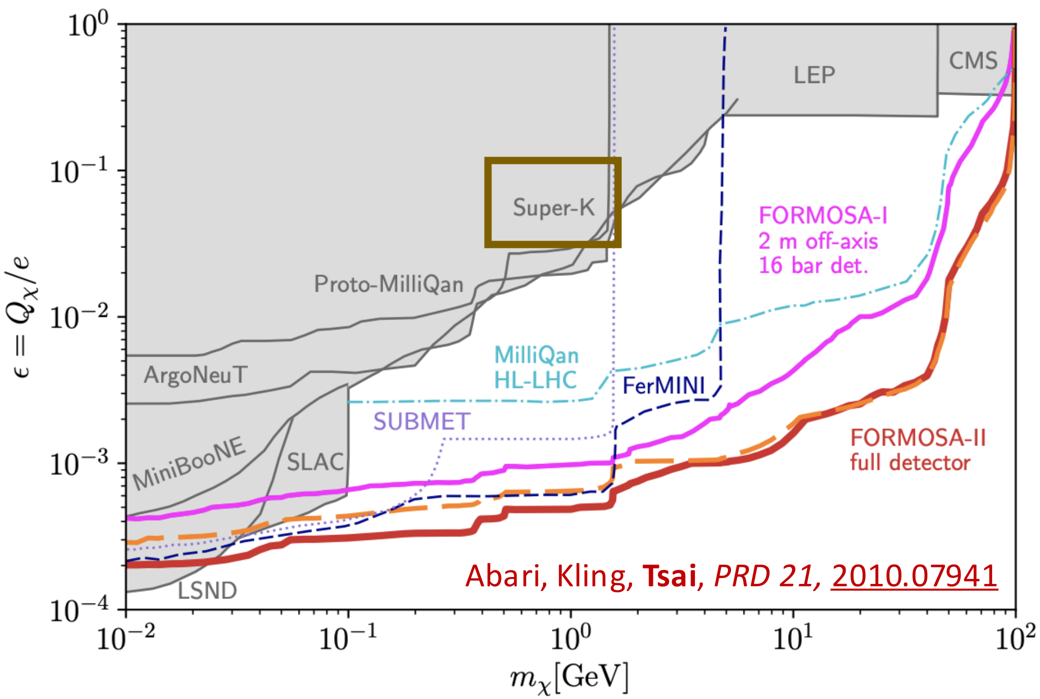
**PhDs:** Li (UCR), Kelly (UCD)

# New Dedicated Millicharged Particle Search at Energy Frontier



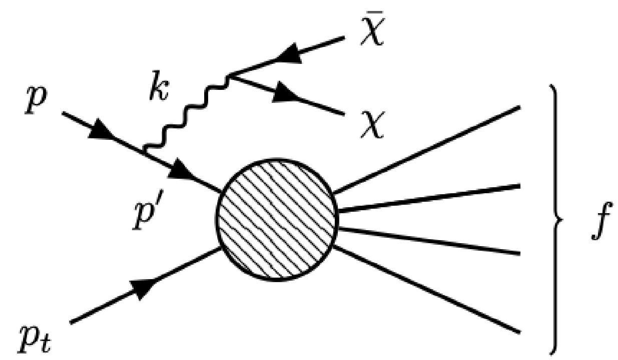

**FORward MicrOcharge SeArch (FORMOSA)**

FORMOSA: ancient name of Taiwan

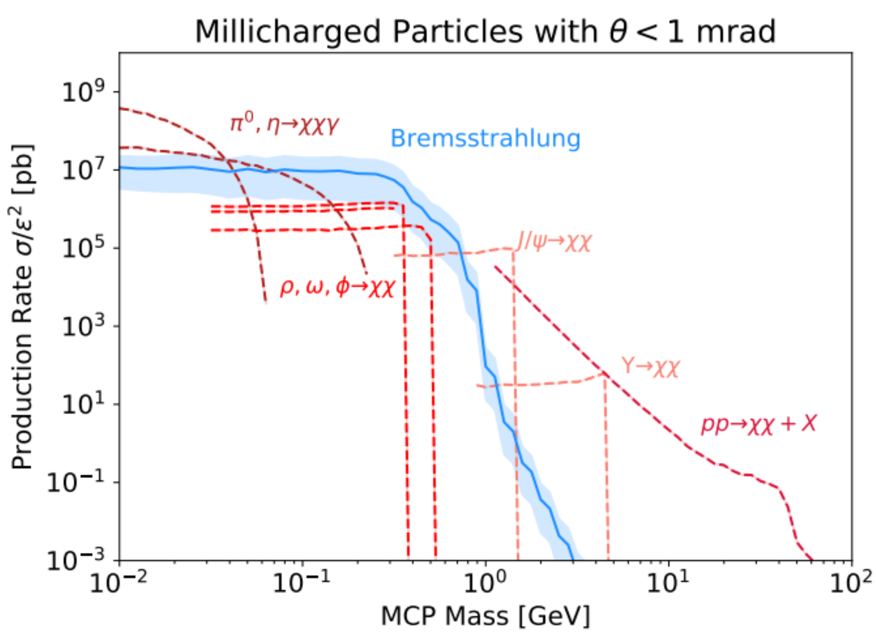


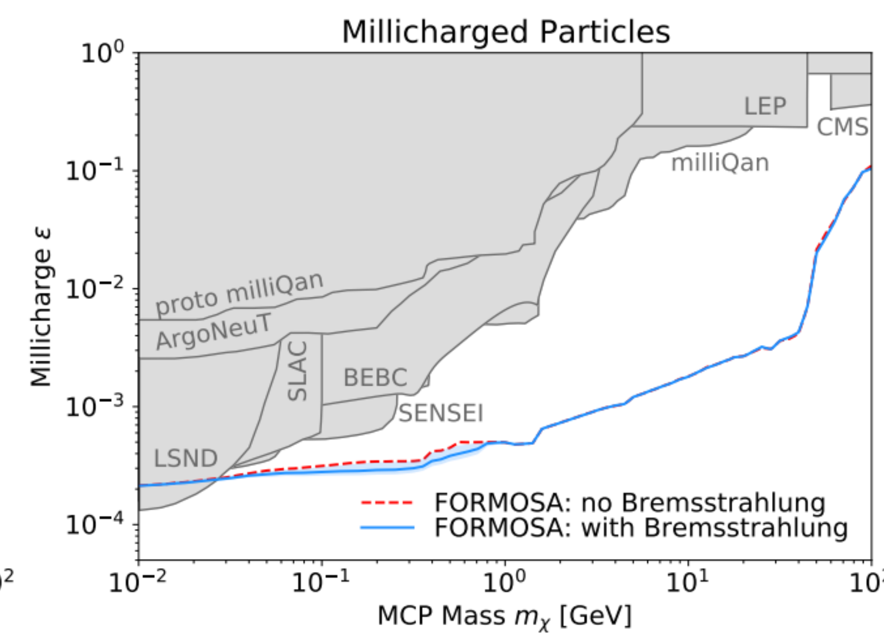

- Long scintillator bars to detector **small ionization** from mCP
- **FORMOSA:** the mCP flux increases by ~ $10^3$ to $10^4$ from the **transverse** to the **forward** region
- CMS has fractionally-charged particle analysis at 7 TeV & 13 TeV
- Cosmic-ray production & Super-K detection (*PRD* 20)

# Proton Bremsstrahlung Production




Foroughi-Abari (2023)




Kling, Reimitz, Ritz, 2509.09437

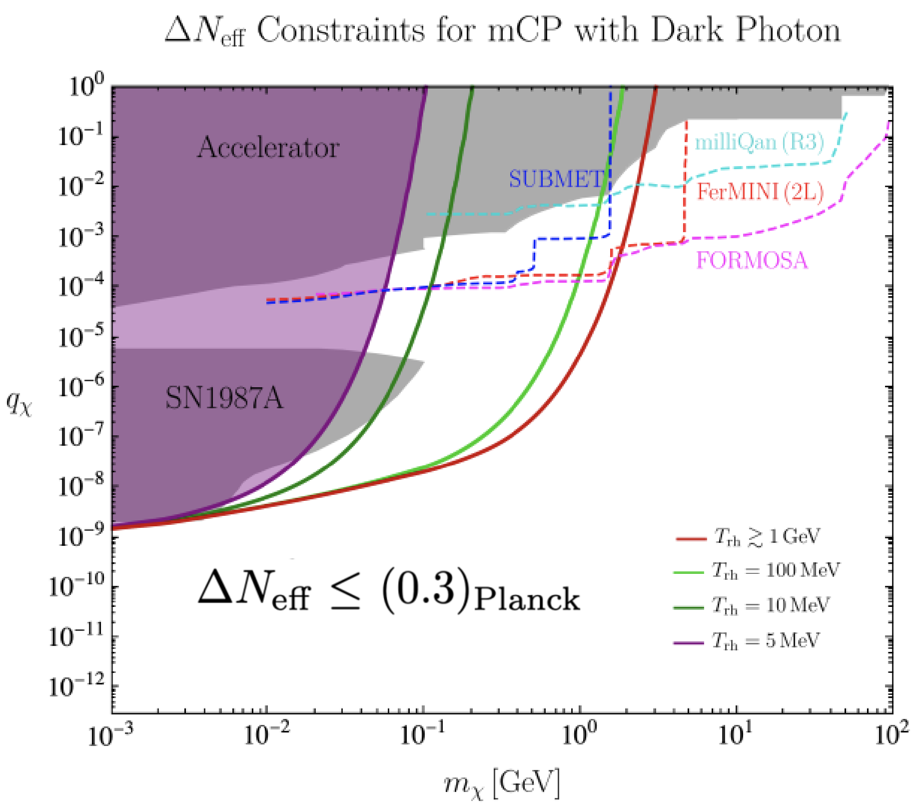
# Summary

**Theory & Cosmology:** Motivations of millicharged particles (mCPs) from string theory, GUTs, and reheating cosmology

**Experimental Searches:** Multiple approaches—scattering, scintillation, and dedicated detectors (FORMOSA, LANSCE-mQ, LongQuest-mQ)—are presented, with updates on current projects and sensitivities at CERN, Fermilab, and LANL.

**Outlook:** More dedicated production studies, more upcoming experimental searches, and extend the cosmology considerations to other dark-sector particles

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

# Outline

- Probing Reheating Cosmology
- Experimental Searches
- **Related Studies**

# Neutrino-Photon (Quantum) Interactions

**Neutrino Electromagnetic Properties:**

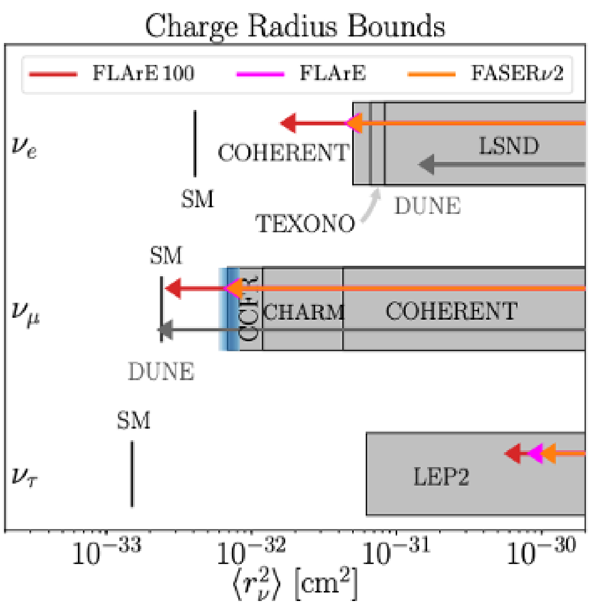
$$\langle \nu_f(p_f)|j^{\mu}_{\nu,\mathrm{EM}}|\nu_i(p_i)\rangle = \overline{u}_f(p_f)\Lambda^{\mu}_{fi}(q)u_i(p_i)$$

low $q^2$ →

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

*charge* *charge radius* *dipole moment*

Giunti et al., *Rev. Mod. Phys* 14, Abraham, Foroughi-Abari, Kling, **Tsai**, *PRD* 25




**Cam also Study Weak Mixing Angle near NuTeV Energy,** Tabrizi, Machado+, *JHEP* 22, *PRL* 20

# **Summary:** Important Explorations in Particle Physics

Coupling Strength

**Energy**

**The rest of the Standard Model (SM), non elusive**

**High-Energy Theories**
**String Theory**
**Grand Unification Theory**

**Precision**

**Intensity**

**Space Mission**
**Quantum Sensors**
**Tsai** et al., *Nature Astronomy* 23
**Tsai** et al., 2309.13106 (CommPhys)
**Tsai** et al., 2210.03749 (JCAP)
**Tsai** et al., 2107.04038 (JCAP)

**Neutrinos**

**Gravity**
(Gravitational Waves)

**Dark Matter (DM)**

Mass

A comprehensive effort is crucial in studying the "Elusive Universe"

**What particle physics can do for cosmology?**