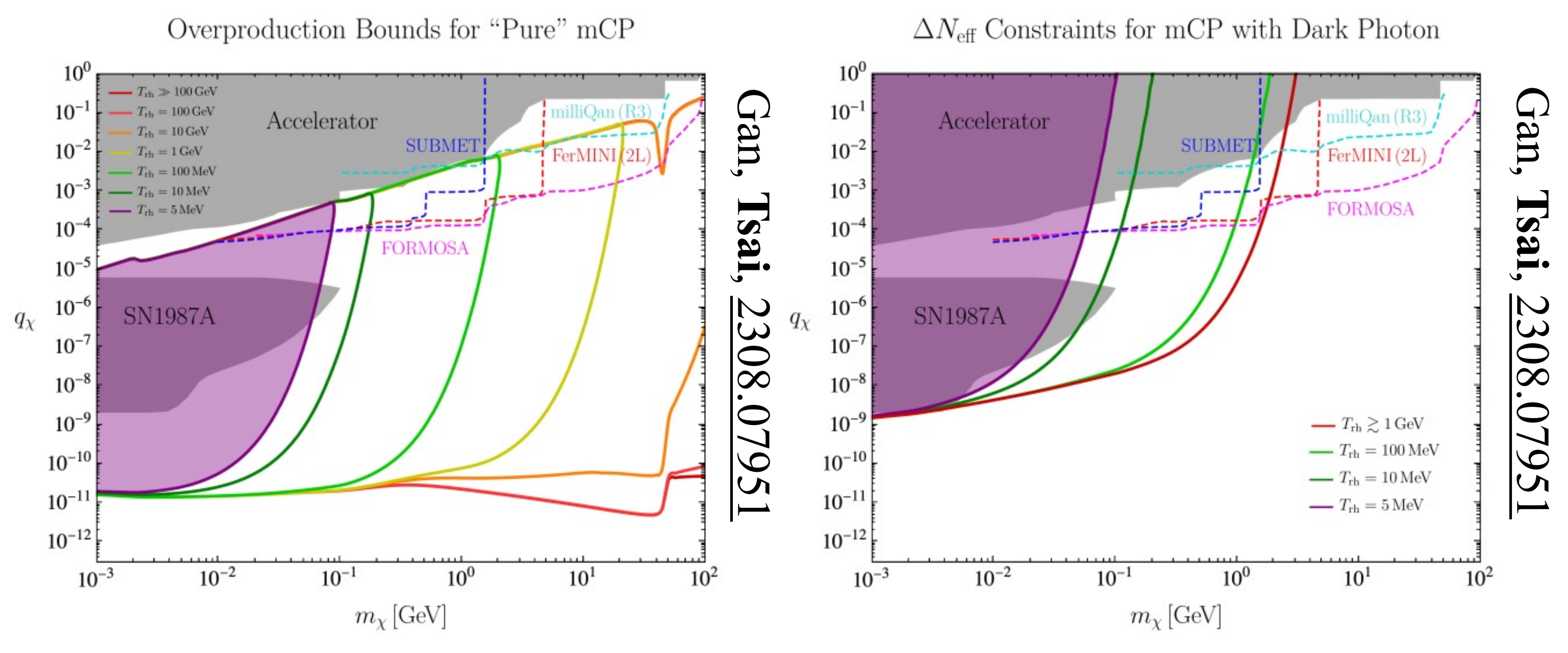
Cosmic Millicharged Background: Testing Reheating Cosmology at FPF



Gan, **Tsai**, 2308.07951

Gan, **Tsai**, 2308.07951

Yu-Dai Tsai

w/ Xucheng Gan, NYU

University of California, Irvine (yudait1@uci.edu)

→ Director's Fellow at LANL (2024)

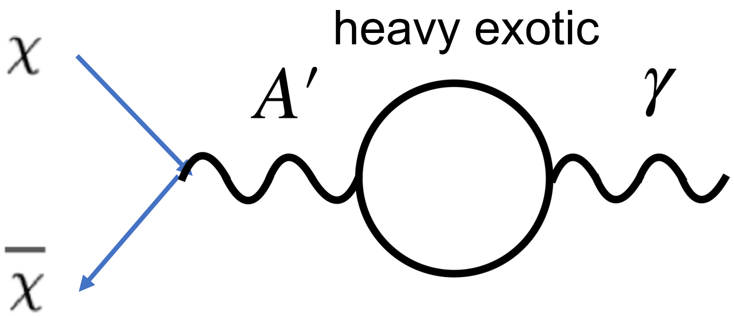
Two Kinds of mCPs

"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

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

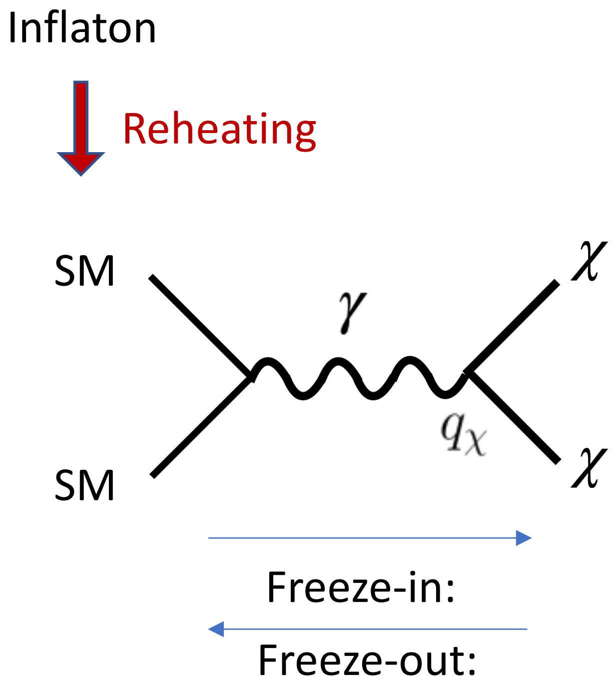
“Pure” Cosmic Millicharge Background (CmB)

“Pure” mCP

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

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

Irreducible Production during Reheating


Inflaton

Reheating

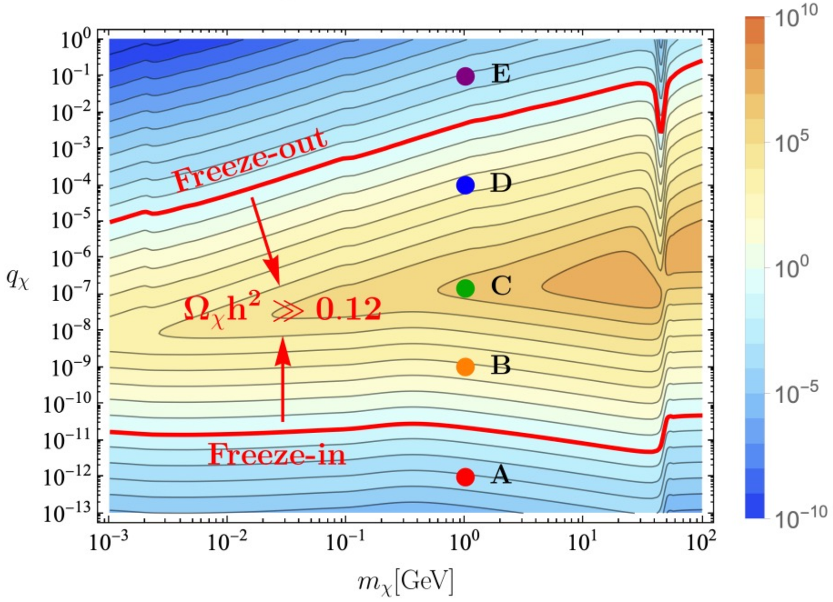
Freeze-in:

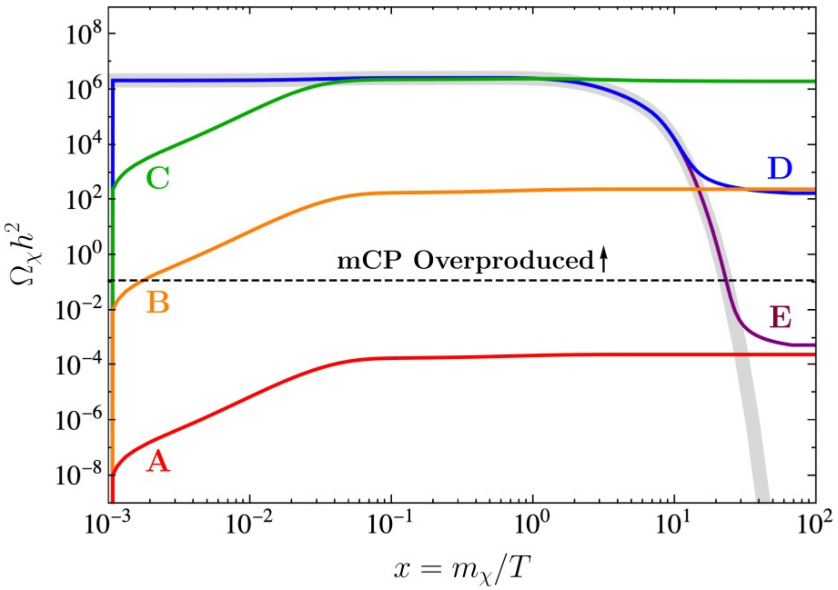
Freeze-out:

The discussions of T_{rh} and other relevant temperatures can be found in, e.g., Giudice+, *PRD* 2021, Co+, *JCAP* 2020

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

$\Omega_\chi h^2 : T_{\rm rh} \gg 100\,{\rm GeV}$ (T_{rh} = 1 TeV)





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

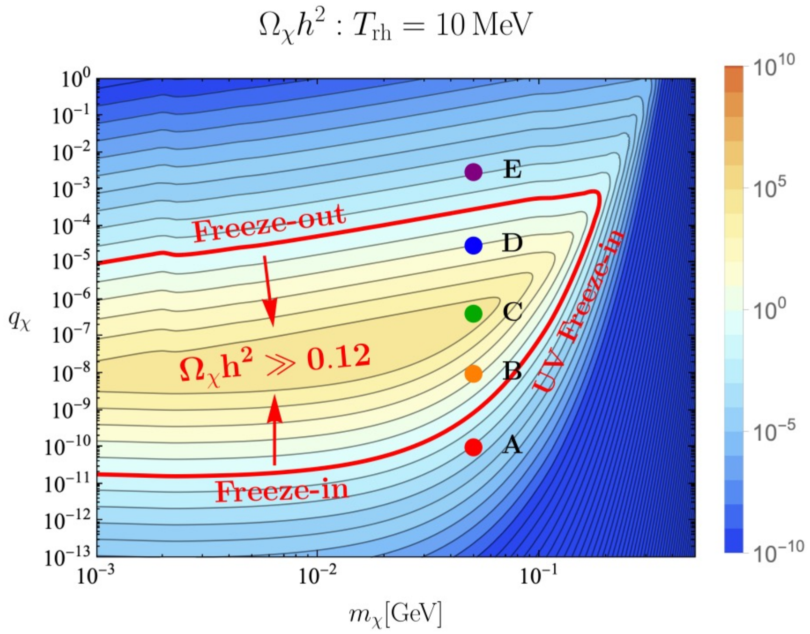
$$\dot{n}_\chi + 3H n_\chi \simeq \mathcal{C}_n(T)\left(1 - \frac{n_\chi^2}{n_{\chi,{\rm eq}}^2}\right),$$

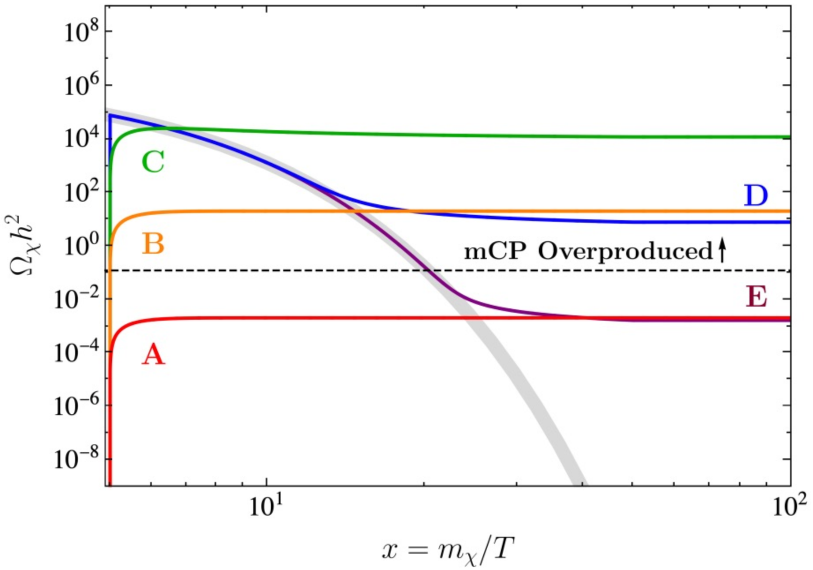
Freeze-out: $Y_\chi^{\rm FO} \sim \frac{1}{q_\chi^2 \alpha_{\rm em}^2}\frac{m_\chi}{m_{\rm pl}},$

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

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

"Pure" CmB Cosmology: Low Reheat Temperature





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

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

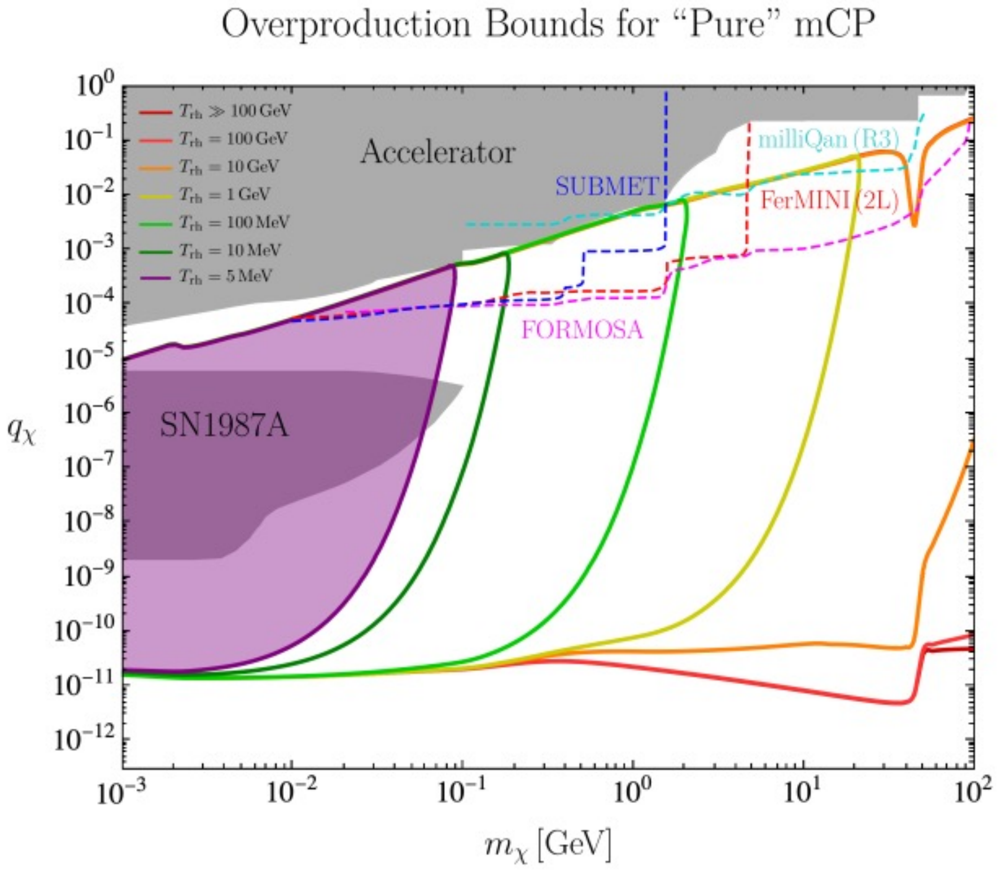
Objectives

I. New Constraints

II. Probing Reheat Temperatures

III. Differentiate Two Types of MCPs

“Pure” CmB from Irreducible Production

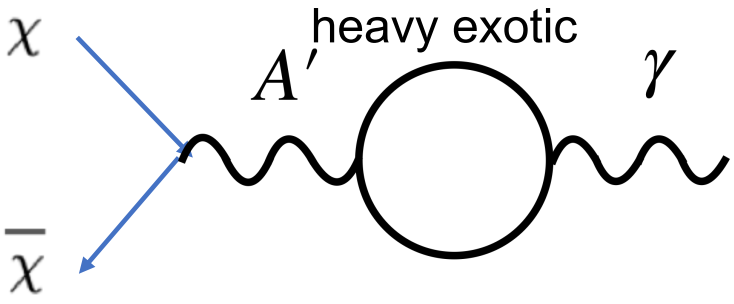


Gan, **Tsai**, 2308.07951

- Minimal reheating temperature larger than T_{BBN}
- Our purple bound is covering the SN1987A constraint (gray region from Chang, JHEP 2018)

Kinetic-Mixing Cosmic Millicharge Background (CmB)

Kinetic-mixing mCP



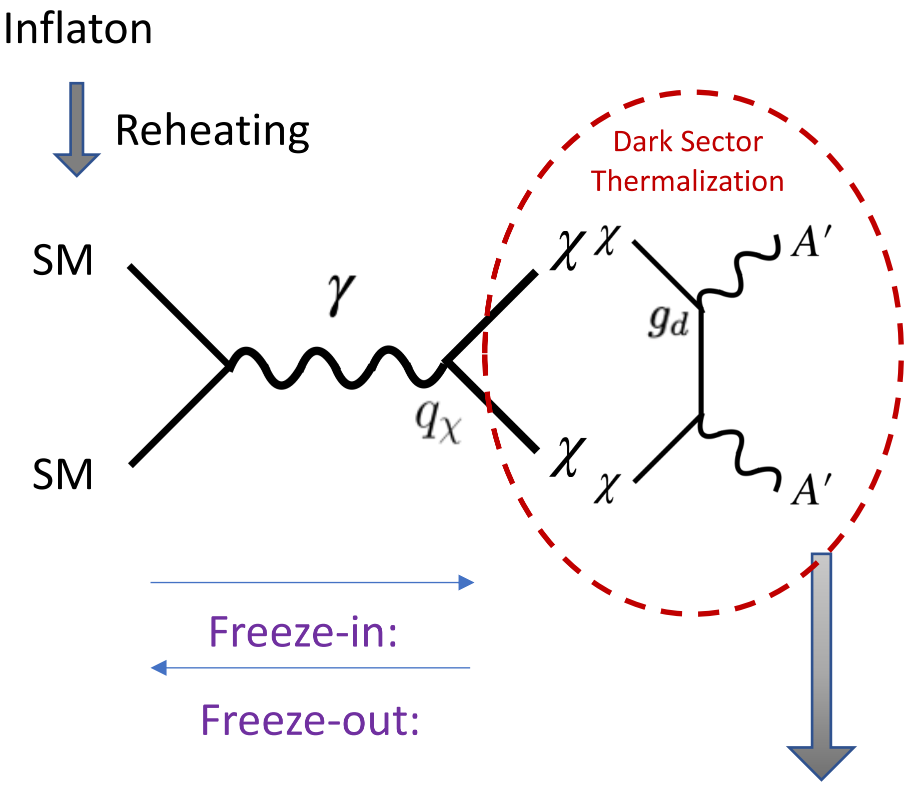
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} + i\bar{\chi}(\not{\partial} + ie'\not{B}' + iM_{\rm MCP})\chi$$

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



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

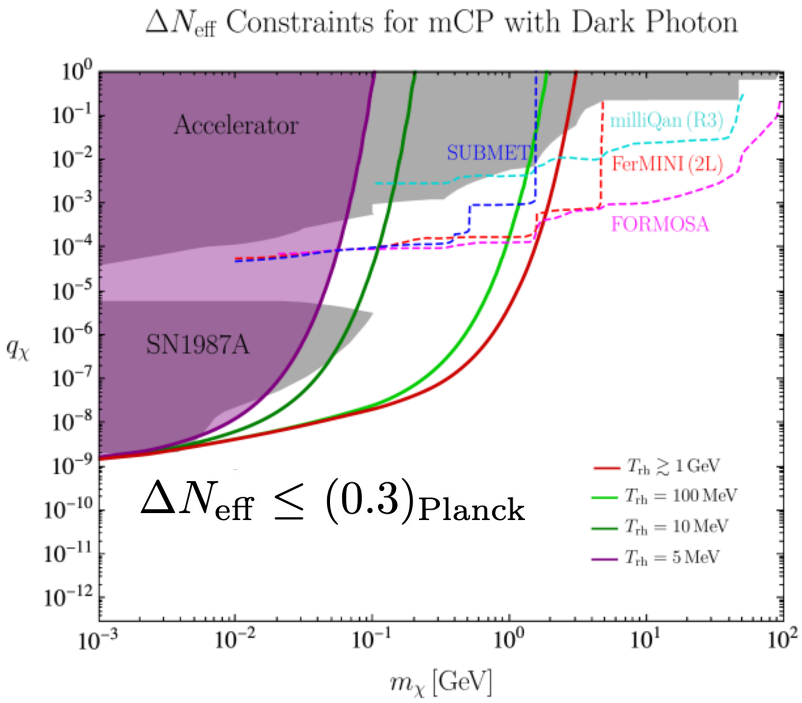
- Freeze-in from the heat bath
- χ thermalizing with dark photon: Require effective transfer of χ entropy to dark radiation A' here

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

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

  - A quick ΔN_{eff} estimation:

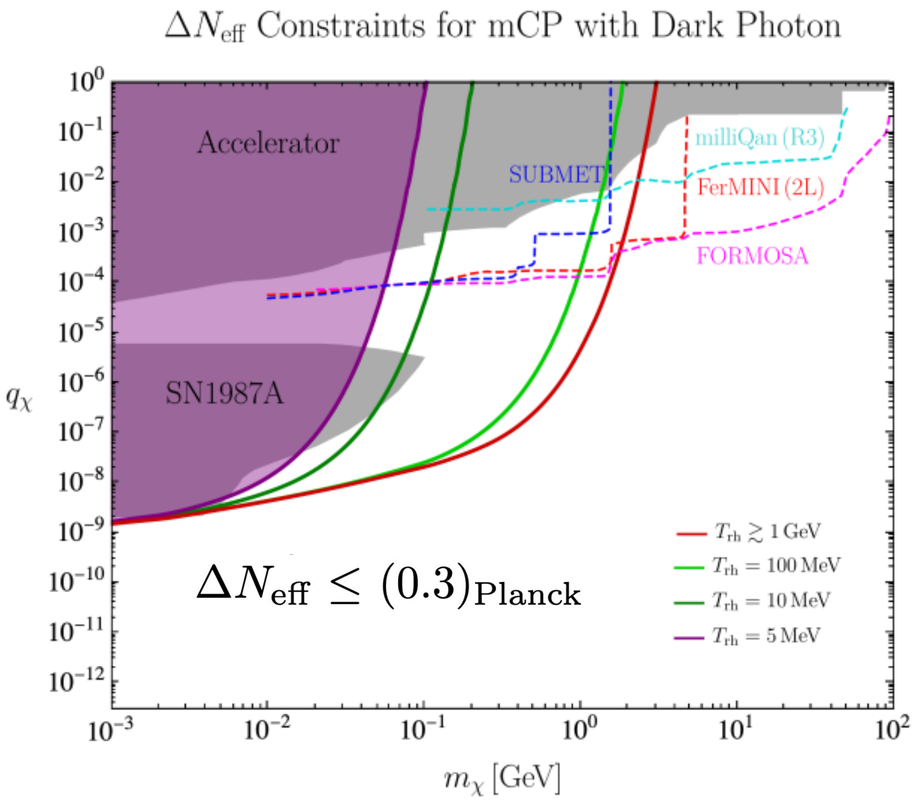
$$\Delta N_{\mathrm{eff}} \sim q_\chi^2 \alpha_{\mathrm{em}}^2 \frac{m_{\mathrm{pl}}}{m_\chi}$$



Gan, **Tsai**, 2308.07951

- Our purple bound is again covering the SN1987A constraint

Kinetic-Mixing CmB Cosmology



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

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

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

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

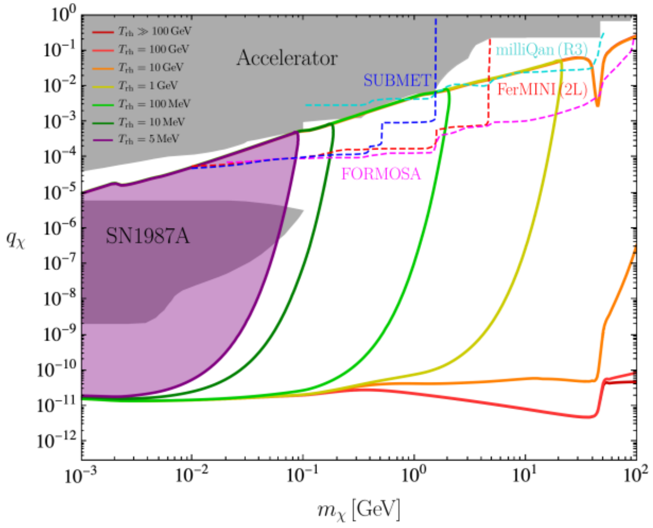
Objectives

I. New Constraints

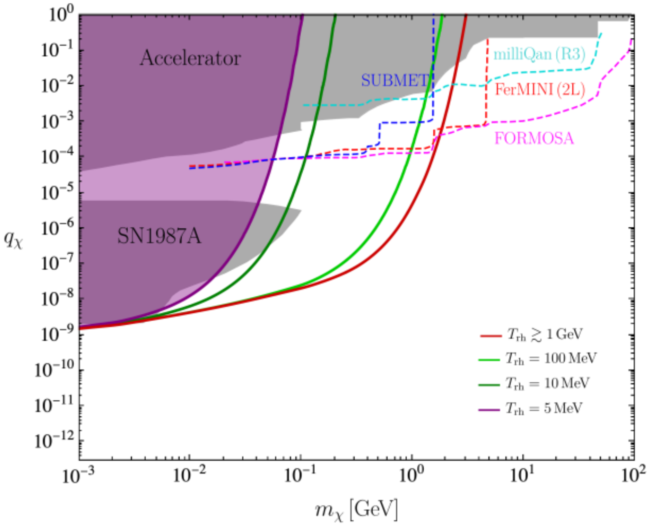
II. Probing Reheat Temperatures

III. Differentiate Two Types of MCPs

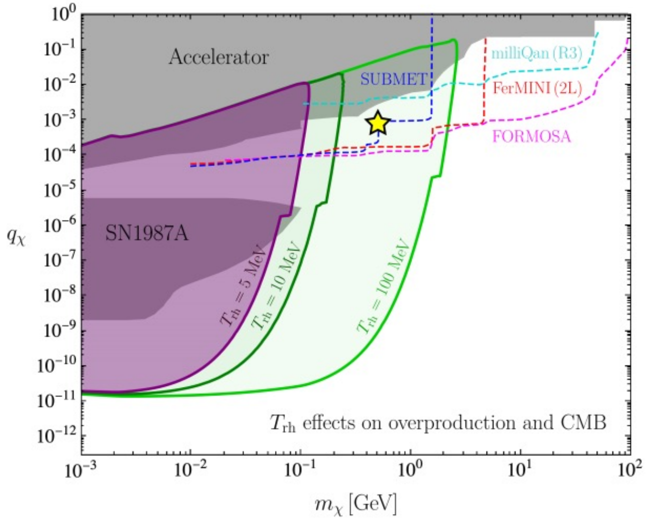
Testing Reheat Temperatures in Both Cases



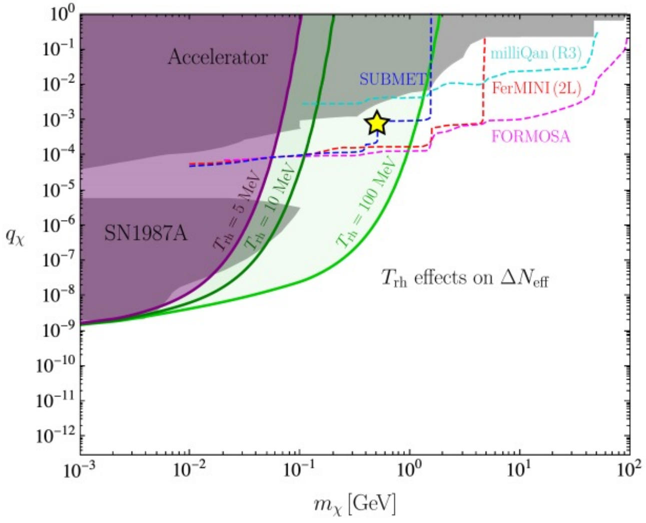
Overproduction Bounds for “Pure” mCP



$\Delta N_{\rm eff}$ Constraints for mCP with Dark Photon



Reheating Targets for “Pure” mCP

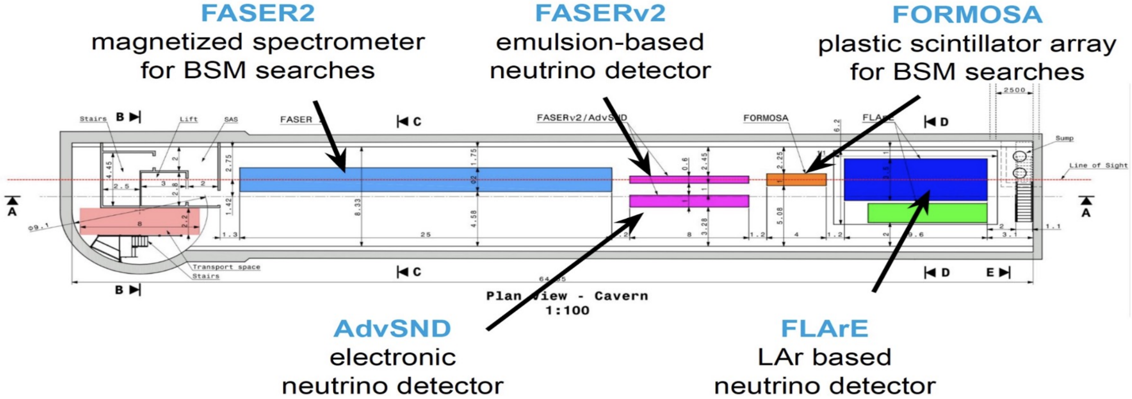


Reheating Targets for mCP with Dark Photon

Compilations of Dedicated mCP Searches (next 3 years)

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

3. **FORMOSA**
(installing demonstrator)
+ FLArE



FASER2
magnetized spectrometer
for BSM searches

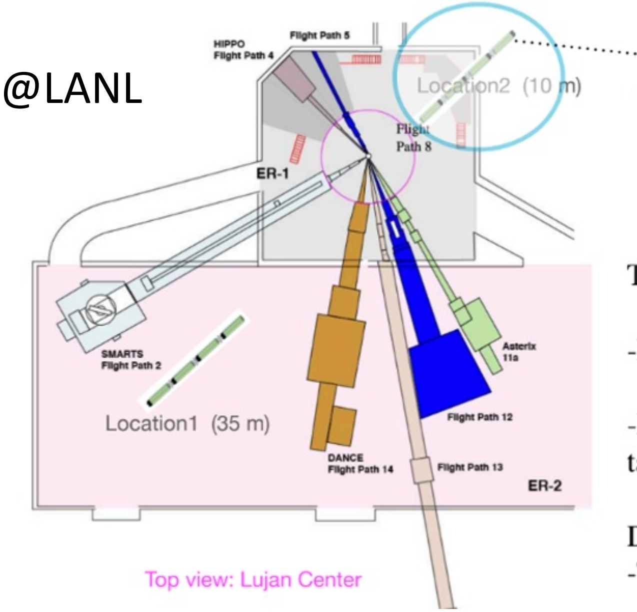
FASERv2
emulsion-based
neutrino detector

FORMOSA
plastic scintillator array
for BSM searches

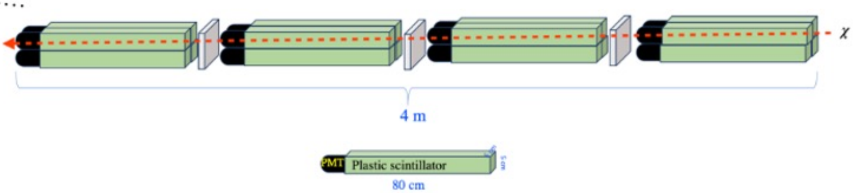
AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

4. **LuMinus**@LANL



Top view: Lujan Center



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

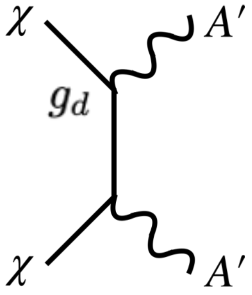
-Location 1: ER-2 area, 35 m from the center of the target

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

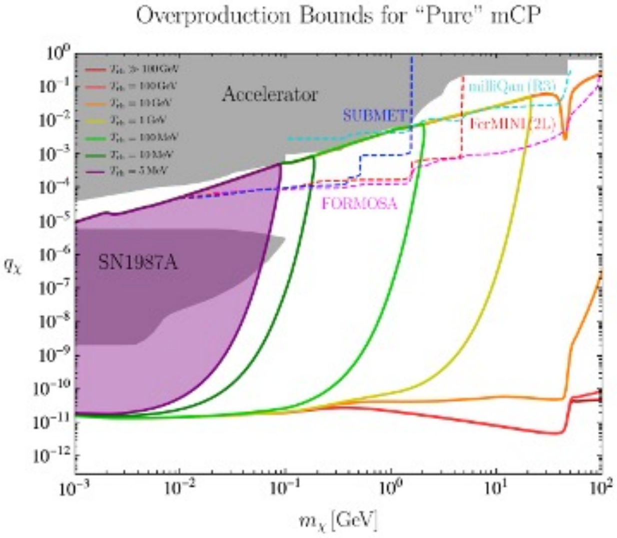
Detector Concept (prototype):
-The scintillator bars (5 cm x 5 cm x 80 cm) are arranged in four layers.

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

Objectives:
III. Differentiate Two Types of MCPs



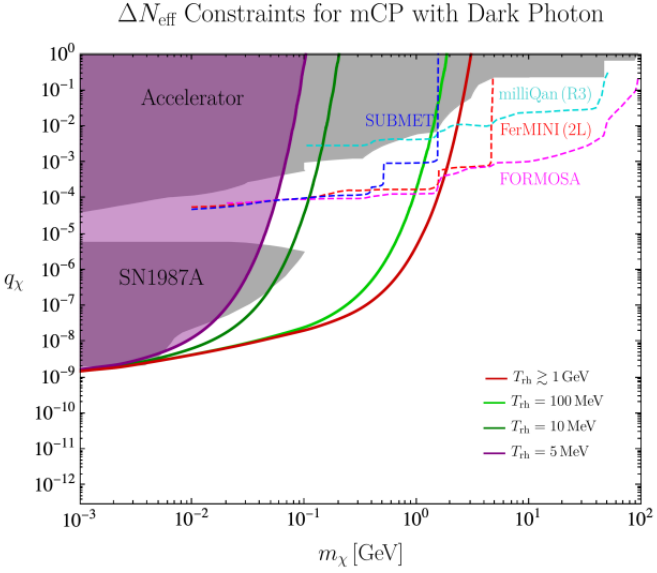
$g_d = 0$


Overproduction Bounds for "Pure" mCP

moderate g_d

Interpolate between the two

Sizable g_d


$\Delta N_{\rm eff}$ Constraints for mCP with Dark Photon

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

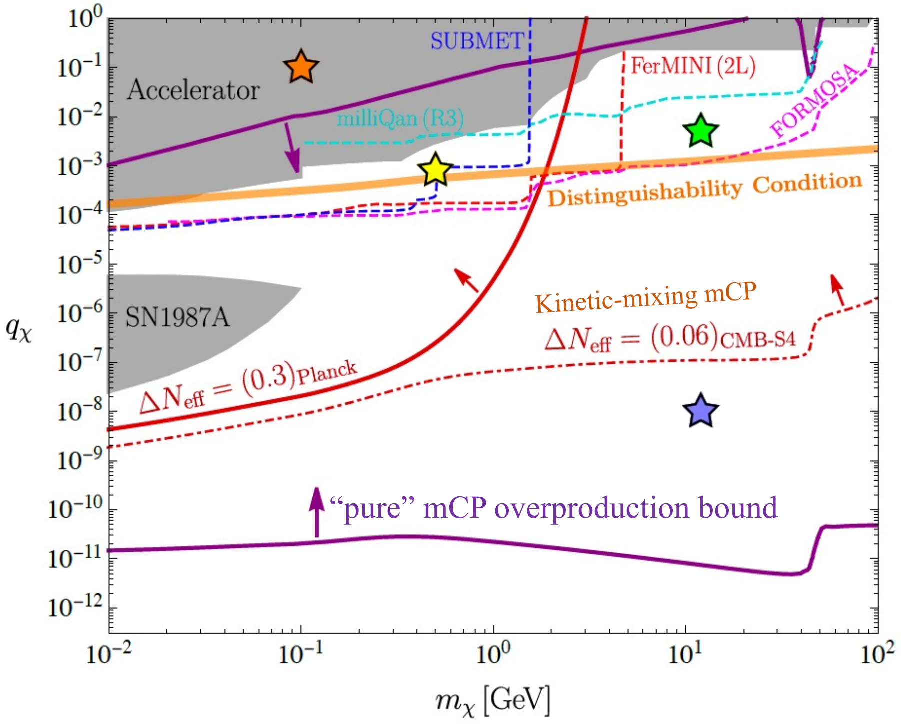
  Burgess *et al*, JCAP (2008)

- 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.)

Outlook

1. Apply to more dark sector particles & searches

   (e.g., axions, dark photons, etc. See Dror+, *PRD* 2021)

2. Further develop the dedicated searches, at **milliQan**, **FORMOSA**, **J-PARC**, **LANL** (+ FLArE, DUNE, SHIP, OSCURA, etc.)

3. More theoretical and cosmological considerations

   (e.g., Giudice+, *PRD* 2021)

   + connecting to dark matter & 21 cm measurements.

4. “**Probing Cosmology**” should be one of the main FPF objectives

Thank you!

Useful References

1. Giudice, Kolb, and Riotto, “Largest temperature of the radiation era and its cosmological implications,” Phys. Rev. D 64 (2001) 023508, arXiv: hep-ph/0005123.
2. Co, Gonzalez, and Harigaya, “Increasing Temperature toward the Completion of Reheating,” JCAP 11 (2020) 038, arXiv:2007.04328 [astro-ph.CO].
3. Vogel, Redondo, JCAP (2014), Dvorkin+, PRD (2019)
4. Davidson+, *PRL* (2000)

Review of Co+ **JCAP (2020)**

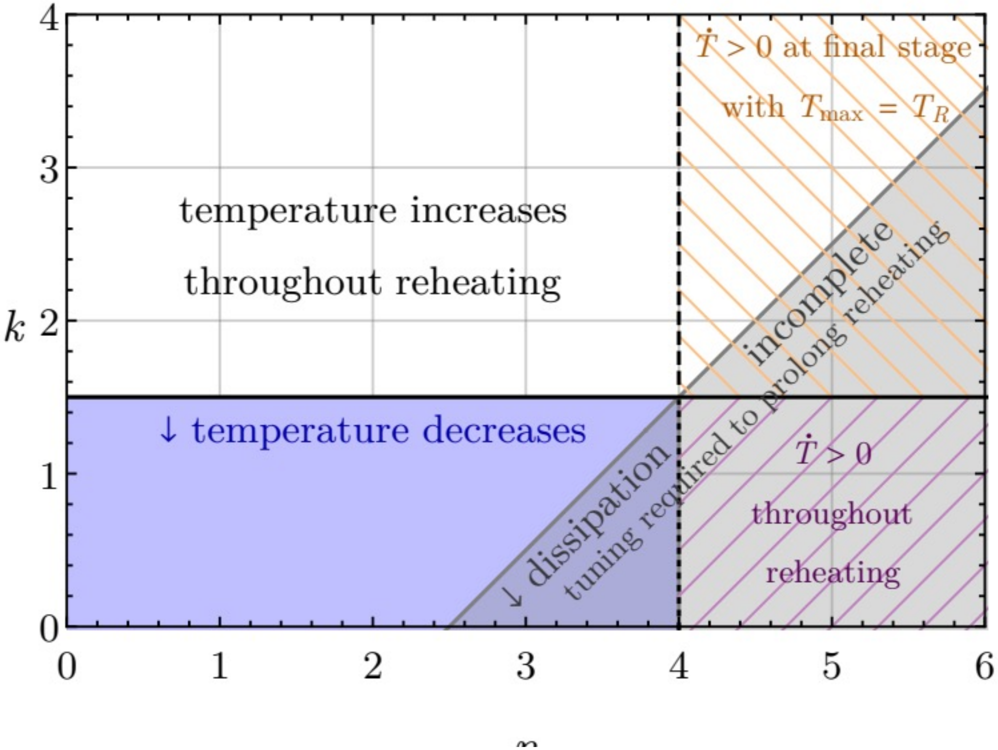
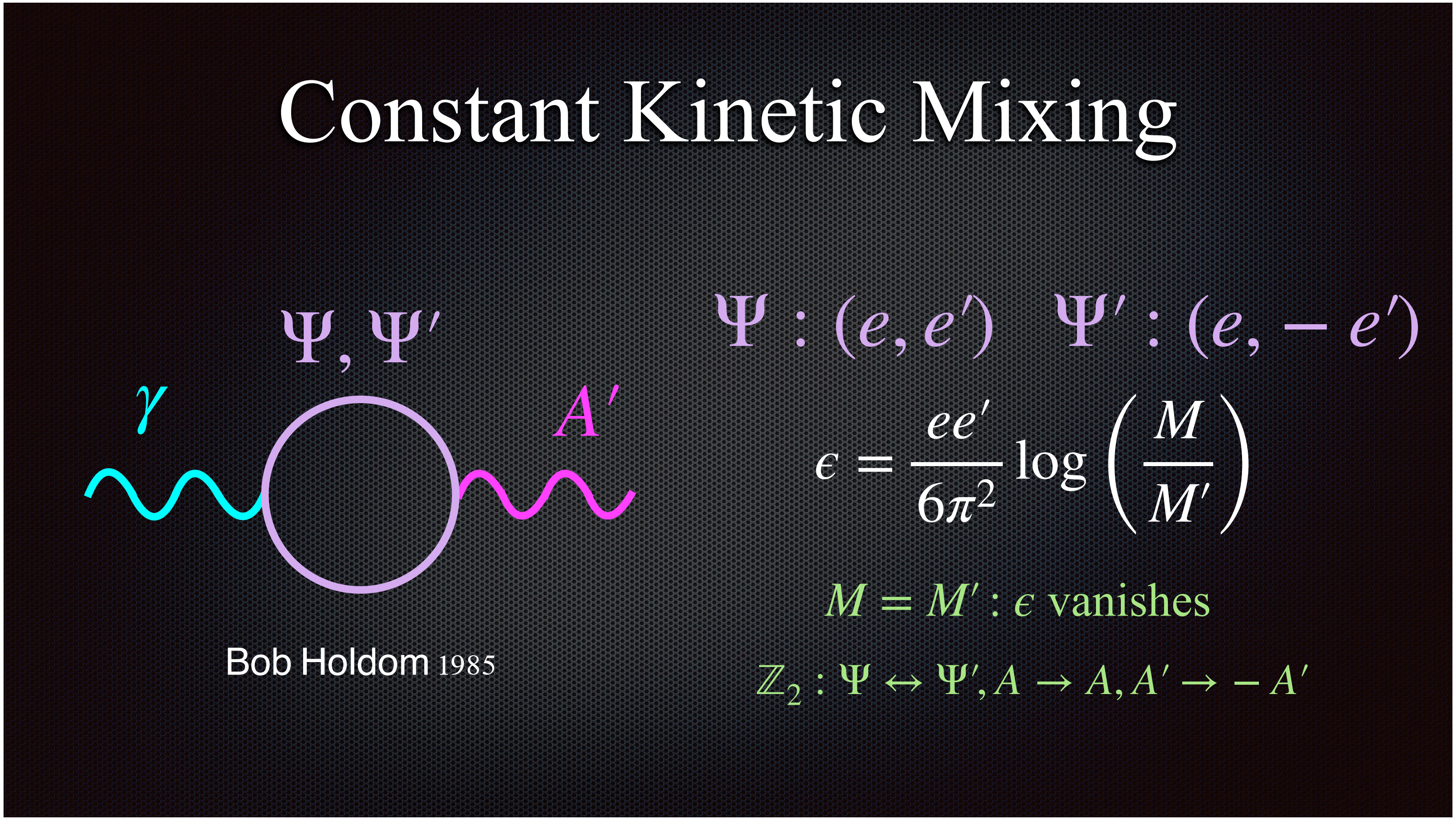


FIG. 2. Different reheating scenarios as a result of different dissipation rates. In our convention described in Sec. 2, the scenarios are distinguished according n and k, which parameterize the dependence of the rate $\Gamma \propto T^n a^k$ on the temperature T and the scale factor a. This diagram excludes instantaneous reheating, which is possible but not of our interest in this paper.



Constant Kinetic Mixing

Bob Holdom 1985

$\Psi : (e, e') \quad \Psi' : (e, -e')$

$$\epsilon = \frac{ee'}{6\pi^2} \log\left(\frac{M}{M'}\right)$$

$M = M'$: ϵ vanishes

$\mathbb{Z}_2 : \Psi \leftrightarrow \Psi', A \rightarrow A, A' \rightarrow -A'$

A slide from Xucheng Gan (NYU)

“Distinguishability” Condition

- Turning down thermalization between χ & A’:

$$g_d \lesssim (16\pi^2 m_\chi / \mathcal{F} m_{\rm pl})^{1/4}$$

$$\mathcal{F} \simeq 375/(16\pi^3 e^{5/2} g_*^{1/2}).$$

- Requirement for kinetic mixing:

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

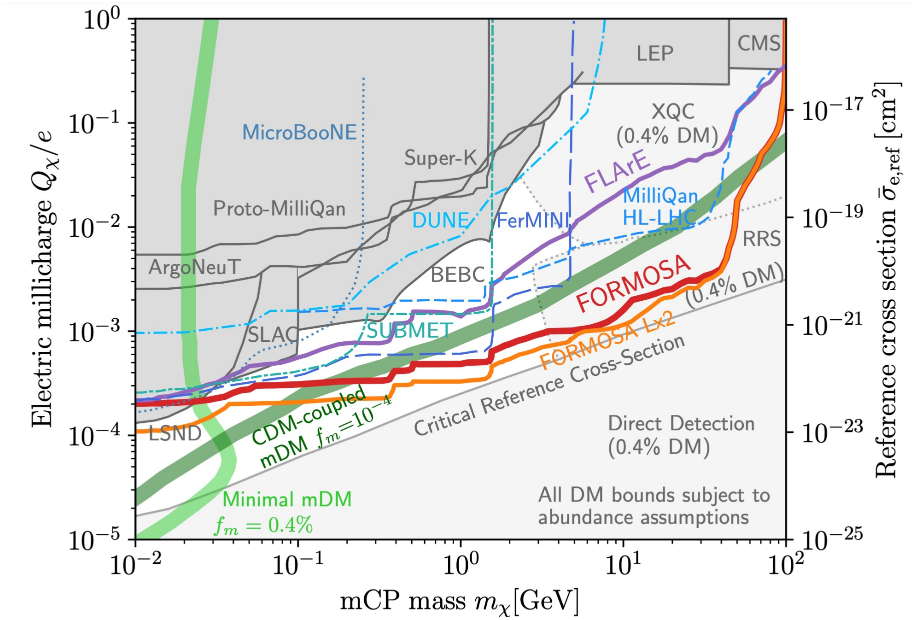
$$\epsilon < 1 \quad \Rightarrow \quad g_d > e q_\chi$$

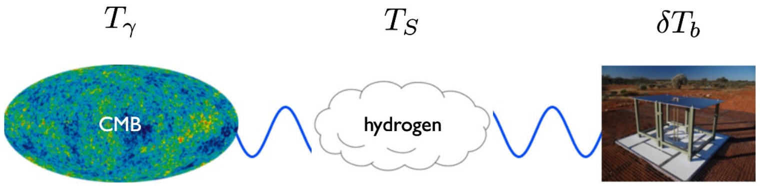
- Considering these two inequalities for gd, we can roughly determine that:

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

One CANNOT de-theramlize χ-A to mimic “pure” mCP!

EDGES & Millicharged Dark Matter



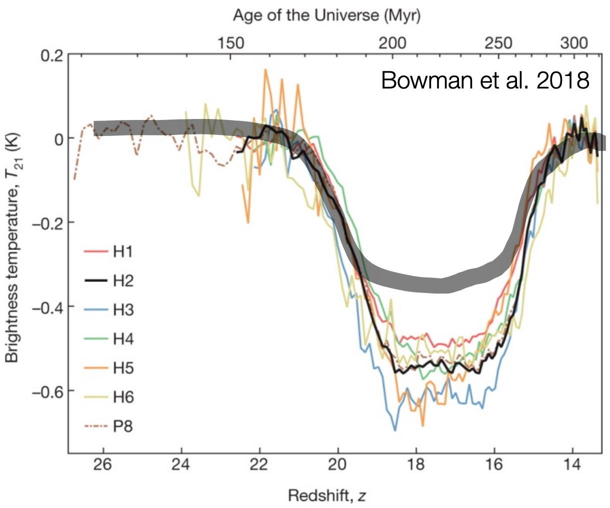


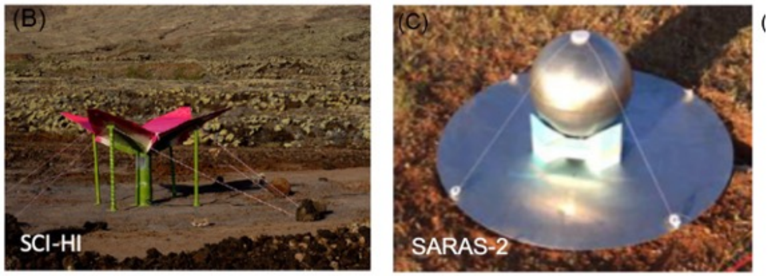
Adapted from J. Pritchard

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



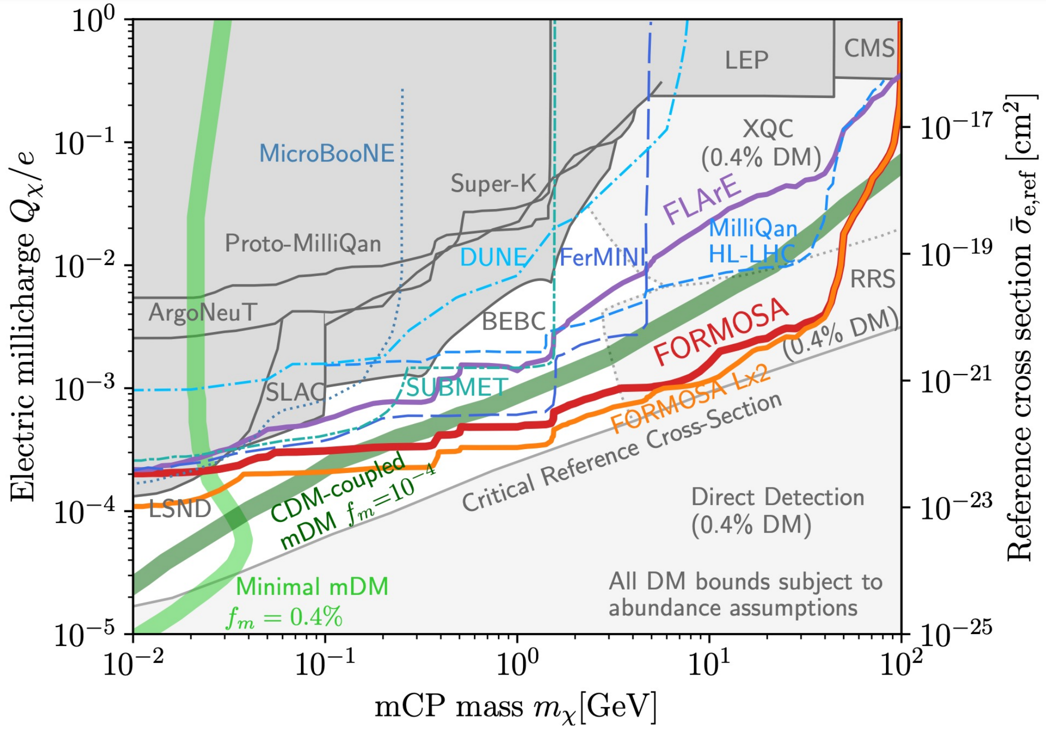


- Voytek et al, APJL (2014)
- Singh et al, 1710.01101

Strongly Interacting Dark Matter

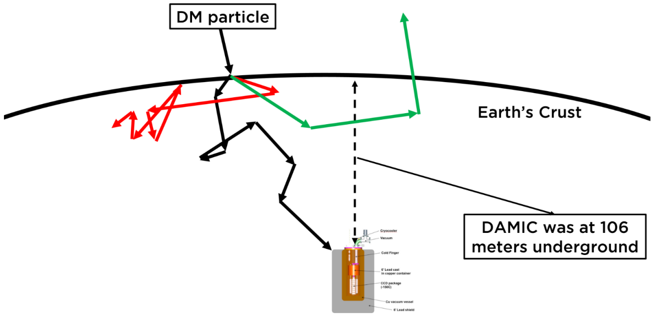
MCP / LDM with ultralight dark photon mediators

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



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

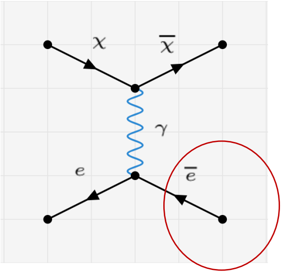
Two Search Methods: Scattering & Scintillation

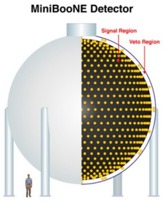
(A) **Electron Scattering**

~ energy exchange set by detector threshold (~MeV)

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

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





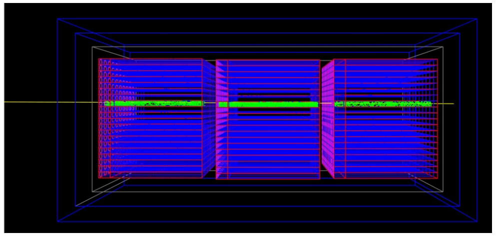
e.g.neutrino Detector
MiniBooNE (arXiv:0806.4201)

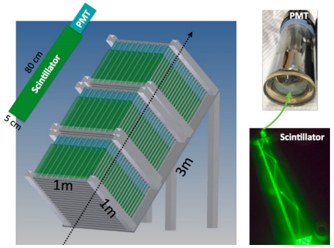
(B) **Scintillation** Study for **Millicharge Particles**

~ eV-level energy exchange

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

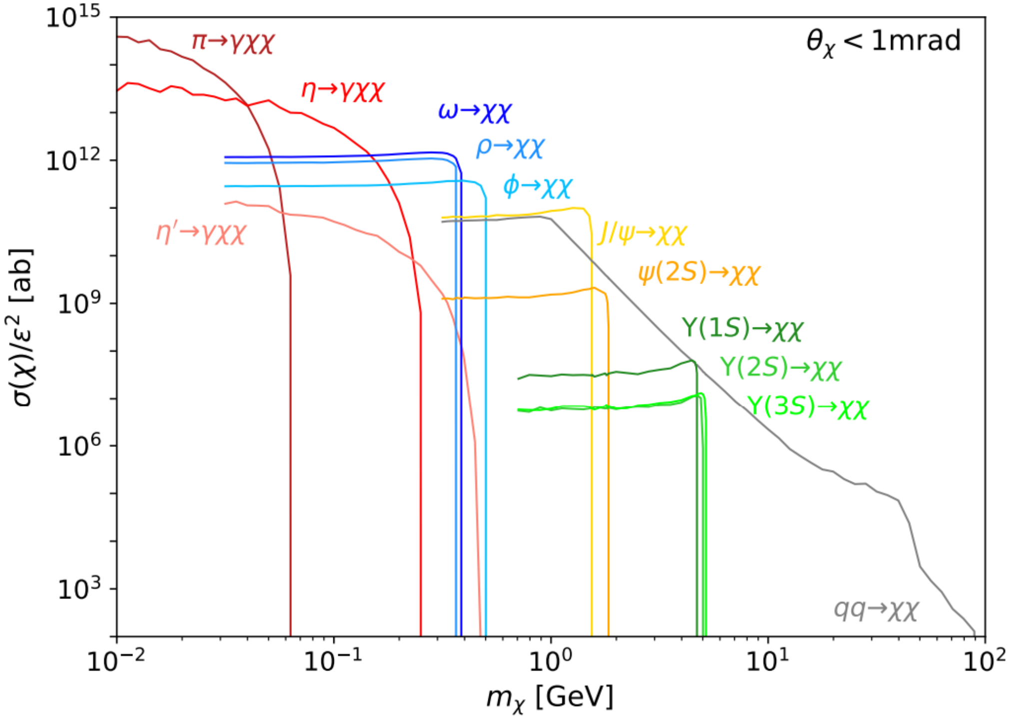
energy deposition





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

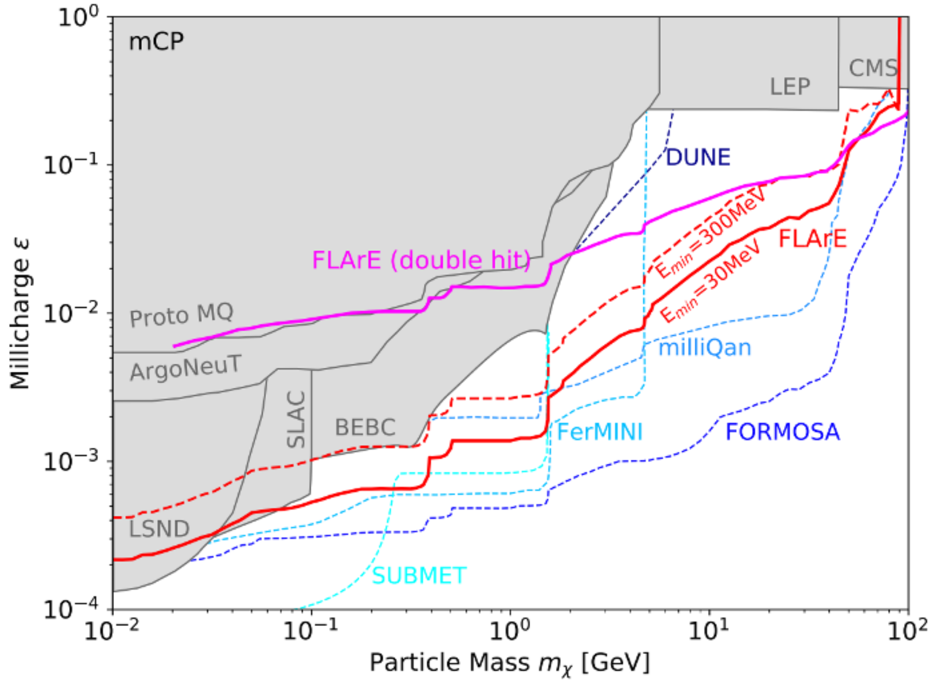
mCP Productions @ FPF



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

MCP production was added to FORESEE by Felix Kling

mCP @ FLArE



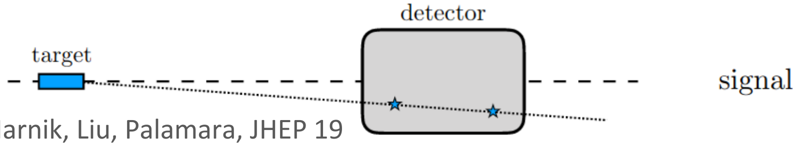
- **FLArE experiment by Jianming Bian:** https://indico.cern.ch/event/1110746/contributions/4701719/
- Nev = 3 expected new physics events in the detector

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

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

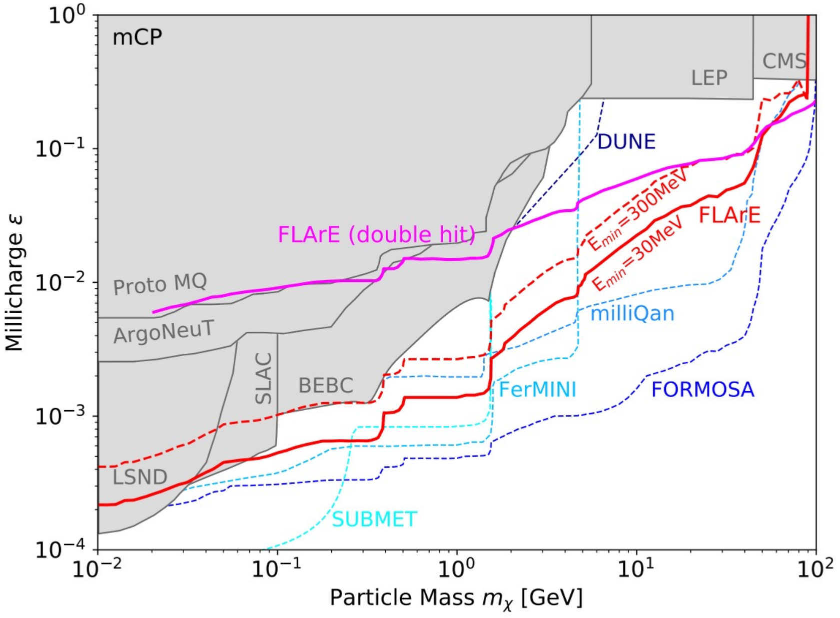
B. Double-hit with softer recoils:

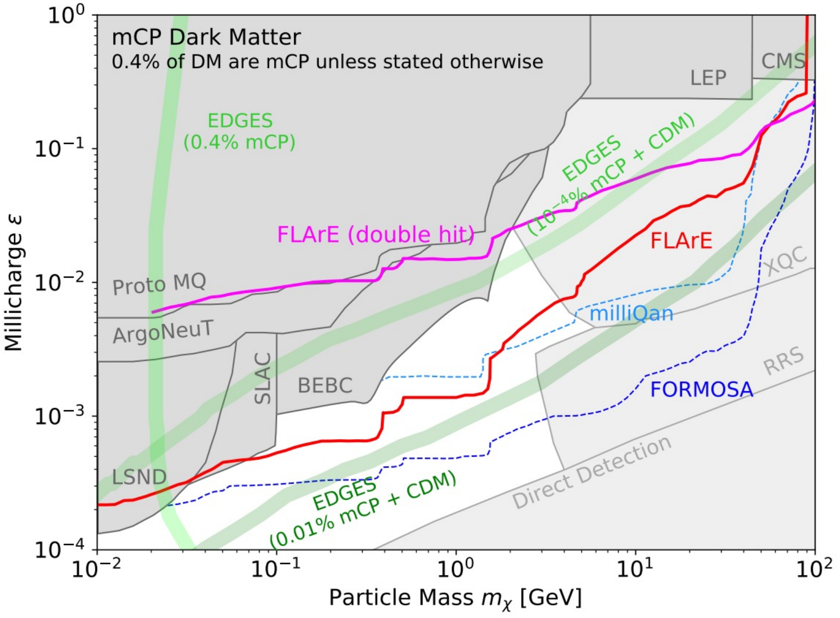
setting Er,min ≃ 2 MeV but with double-hit point back to the target



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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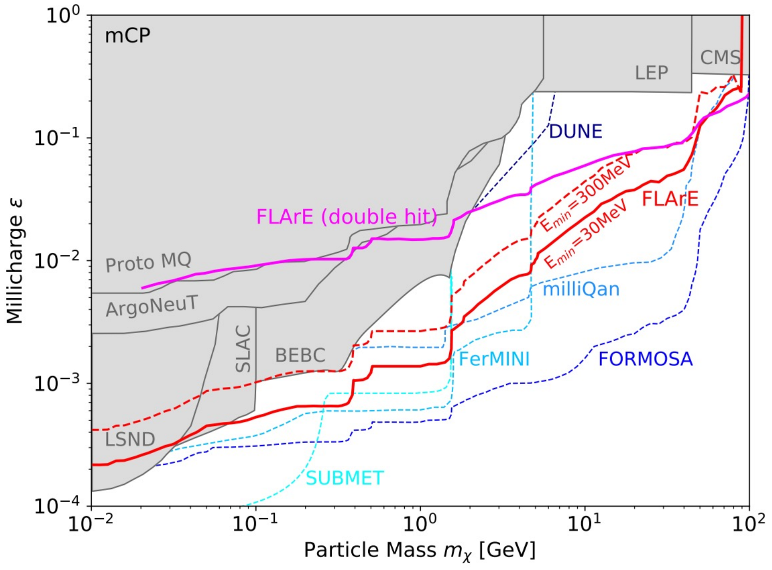

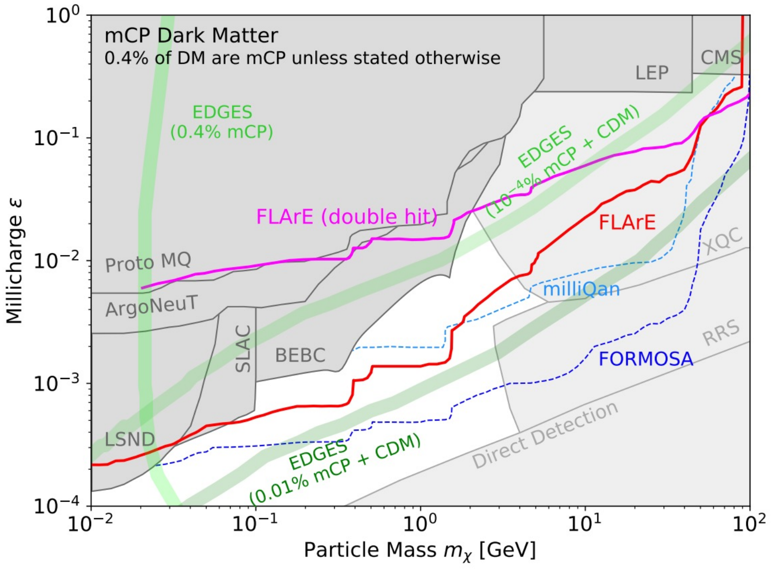

- With 30 MeV to 20 GeV energy-range and additional angular cuts, the expected neutrino-induced background rate can be as low as O(20) events during the HL-LHC era in the 10-tonne, from neutrino-electron scatterings, while quasielastic and resonant nuclear scatterings of ve also contribute non-negligibly.
- We assume the neutrino-induced DIS events can be rejected due to the presence of additional visible tracks in the detector.

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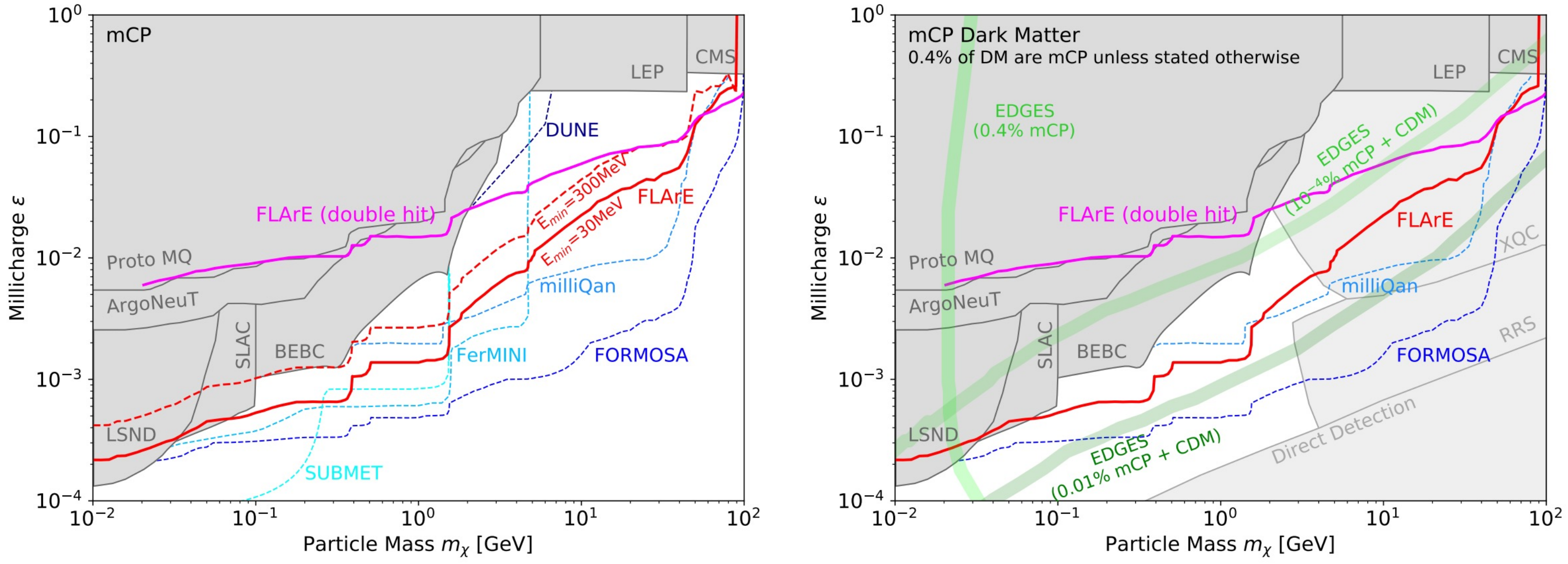


- In our estimates, we use far-forward neutrino fluxes and spectra in Batell et al, PRD (2021), obtained using the fast neutrino flux simulation introduced in Kling et al, PRD (2021) and we use GENIE, Andreopoulos et al (2010), to study neutrino interactions.
- Extra background due to ambient gamma-ray activity, intrinsic radioactivity, or electronic noise, ArgoNeuT, PRD (2019), discussed for the ArgoNeuT detector, can be reduced with high threshold or double coincidence

Neutrino Effective Electromagnetic Current

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

- $\Lambda^{\mu}_{\mathrm{fi}}$(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).

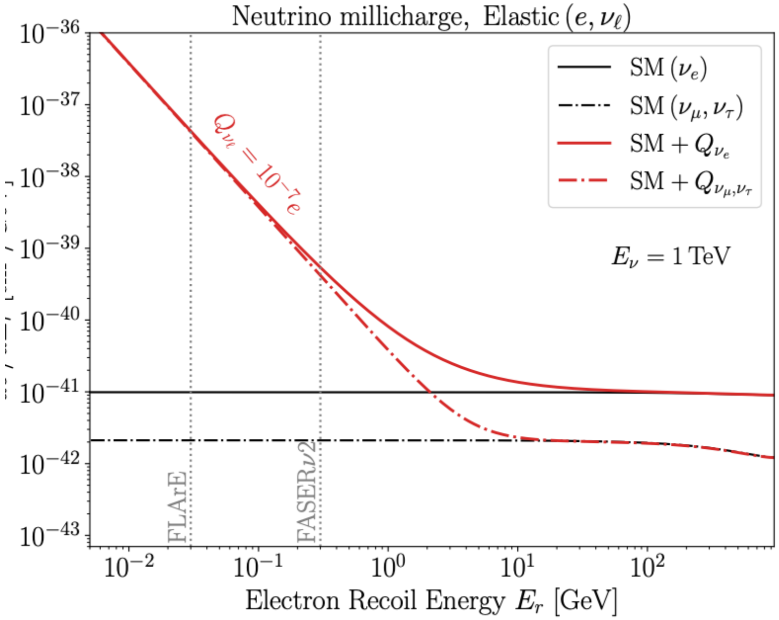
Neutrino Millicharge

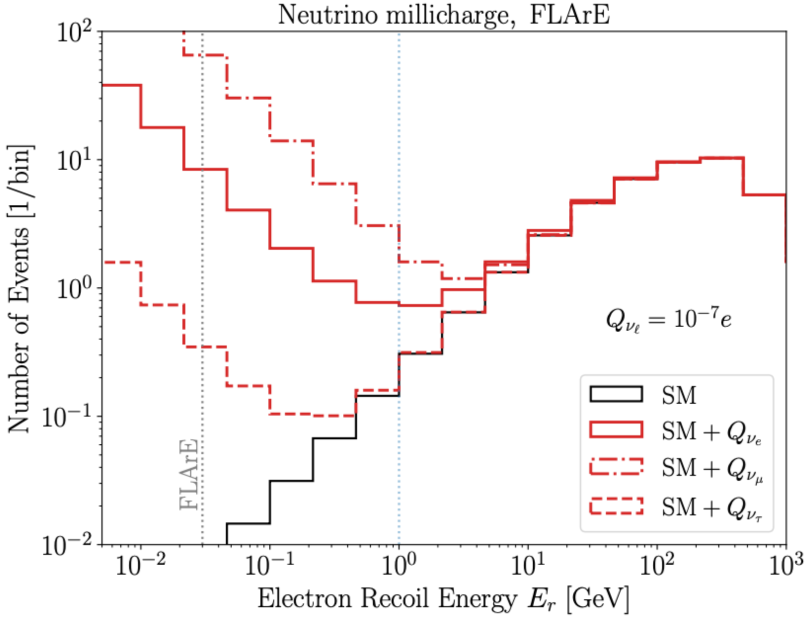
$$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\text{NMC}} = \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\text{SM}} + \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\text{Int}} + \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\text{Quad}}.$$

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

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

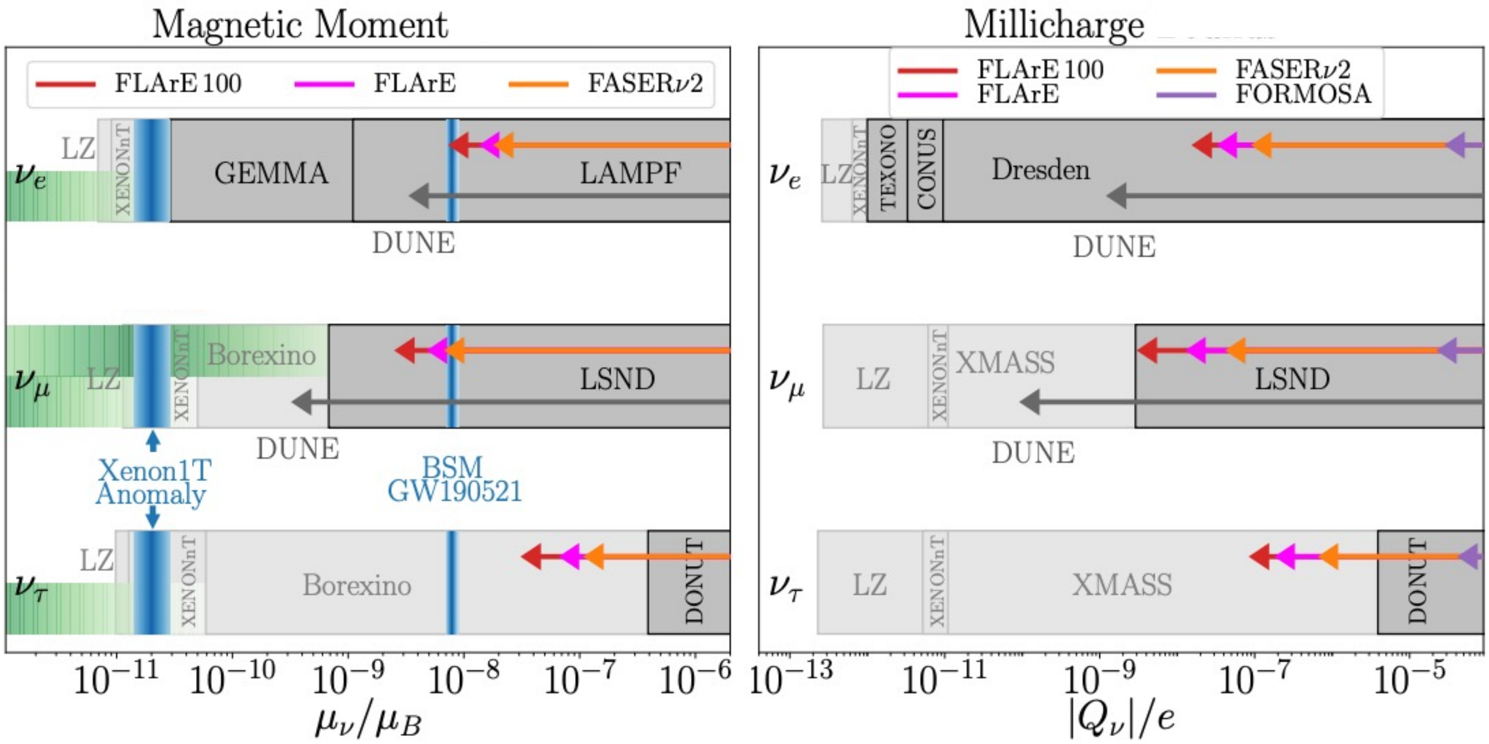
Neutrino Millicharge





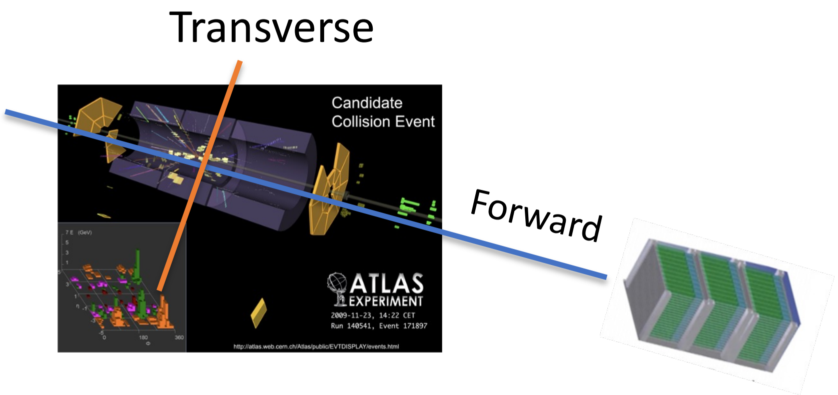
$$\left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm NMC} = \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm SM} + \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm Int} + \left(\frac{d\sigma_{\nu_\ell e}}{dE_r}\right)_{\rm Quad}.$$

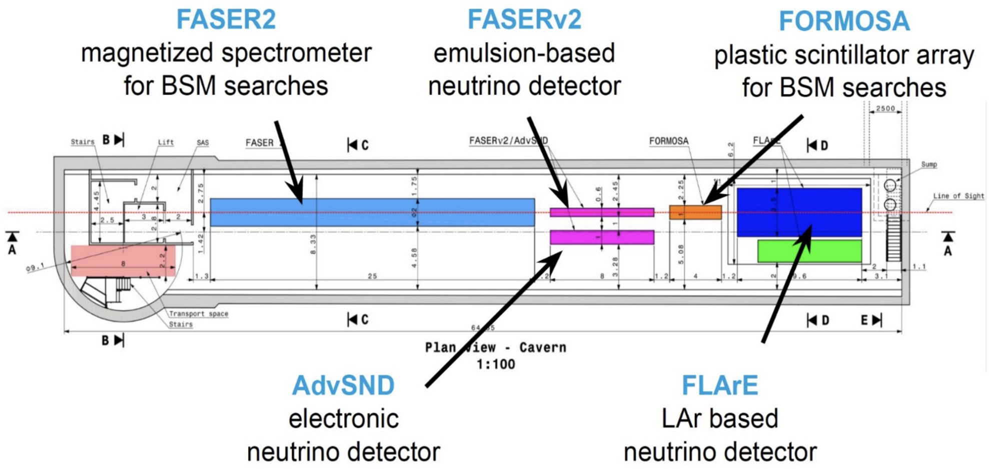
Summary of Results



- 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





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

- 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