DPF-Pheno 2024

Cosmic Millicharge Background and Reheating Probes

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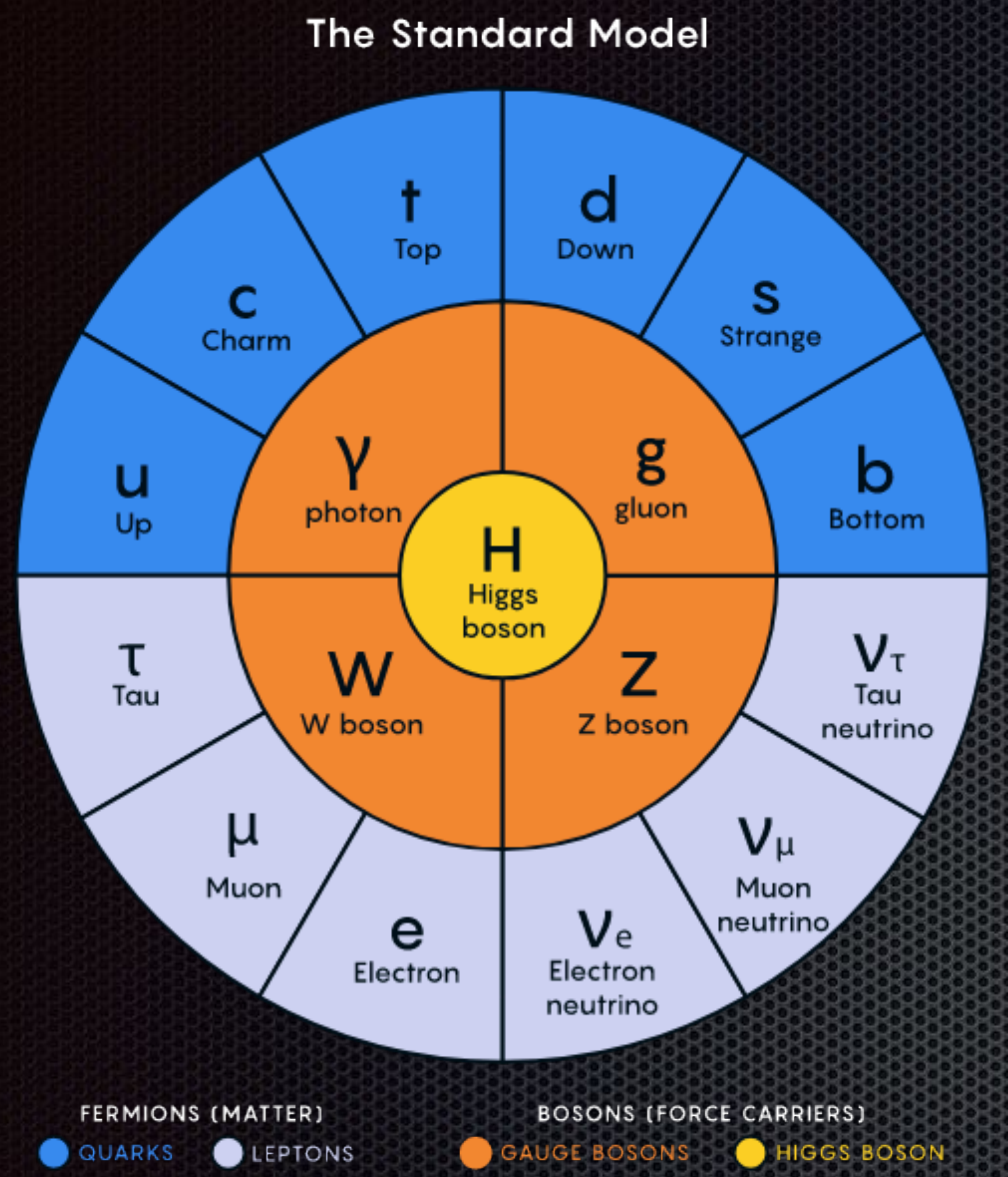
2308.07951

with **Yu-Dai Tsai** (UC Irvine)

Movitations



Do particles $q \ll 1$ exist ?

Dark Matter Candidate

Kinetic Mixing

Test of GUT

21cm Cosmology

Interesting Phenomena

Quark: $q = 2/3, 1/3$

Two Kinds of Millicharged Particles

Pure mCP

$$\mathscr{L} \supset q_\chi A \cdot j_\chi$$

Kinetic Mixing mCP

$$\mathscr{L} \supset g_d A' \cdot j_\chi - \frac{\epsilon}{2} F F'$$

Kinetic Mixing Millicharged Particle

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Bob Holdom 1985

Kinetic Mixing Millicharged Particle

$$\mathscr{L} \supset g_d A' \cdot j_\chi - \frac{\epsilon}{2} F F'$$

Massless Dark Photon

$$A' \to A' + \epsilon A$$

$$\mathscr{L} \supset q_\chi A \cdot j_\chi$$

$$q_\chi = \epsilon g_d / e$$

Kinetic Mixing Millicharged Particle

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$$A' \to A' + \epsilon A$$

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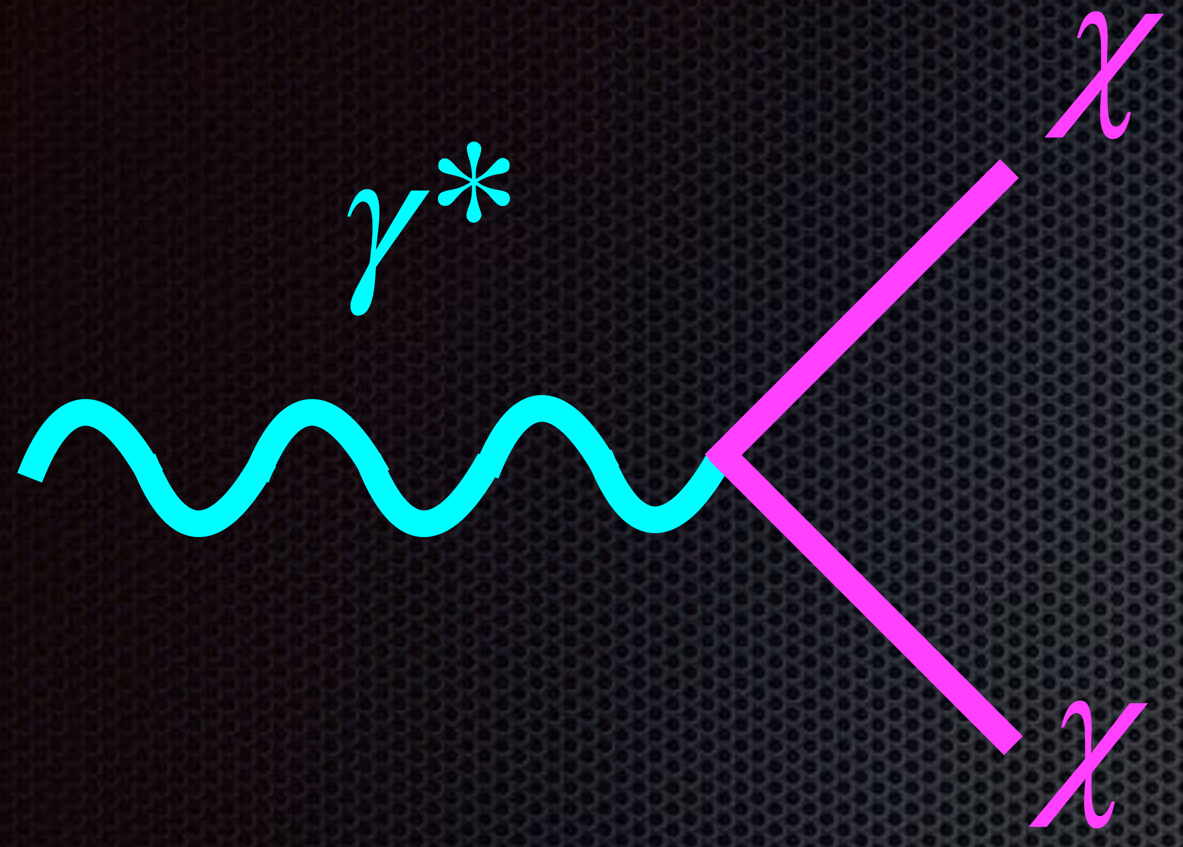
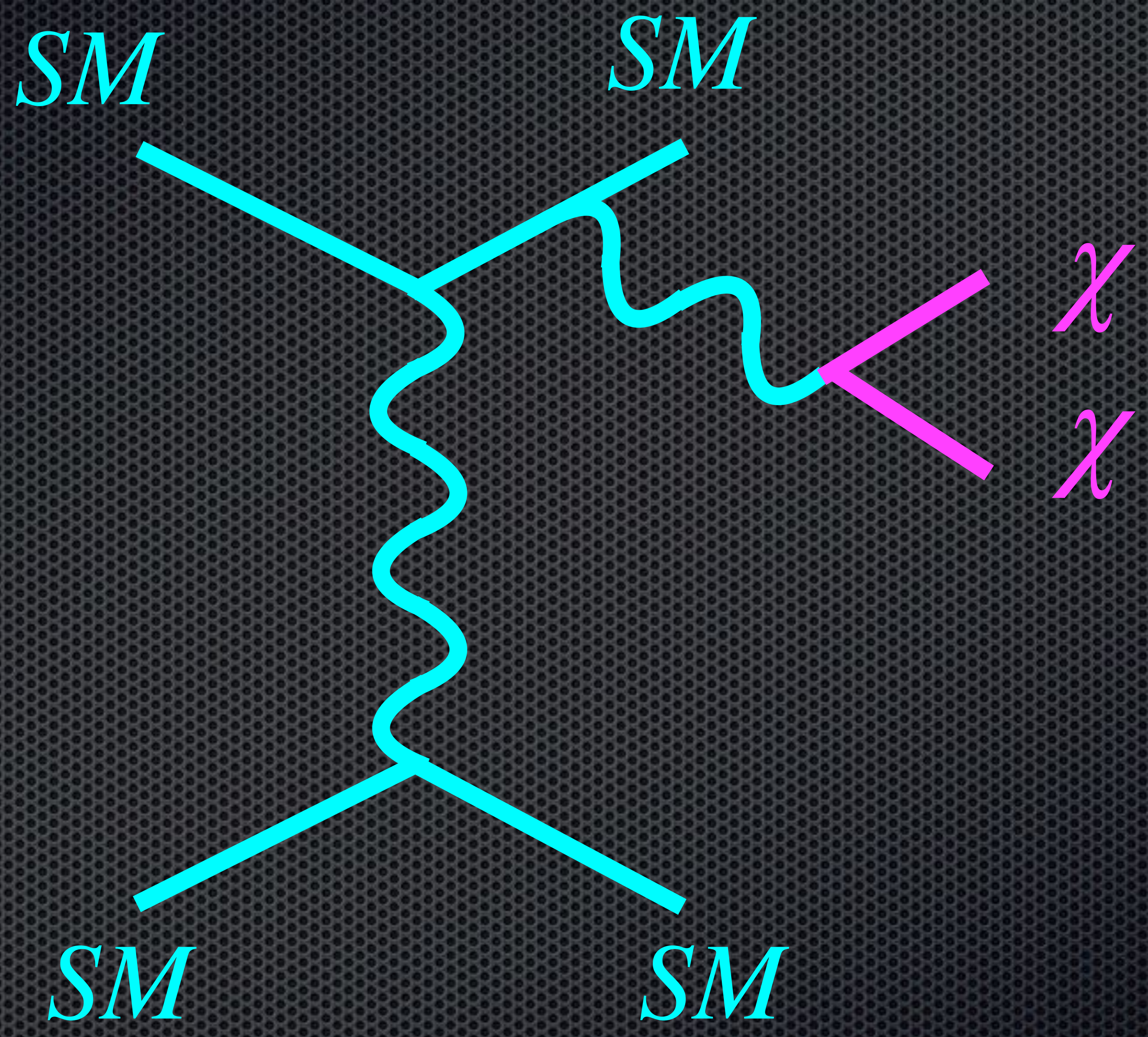
$$q_\chi = \epsilon g_d / e$$

mCP depletion: $\chi\bar{\chi} \to A'A'$

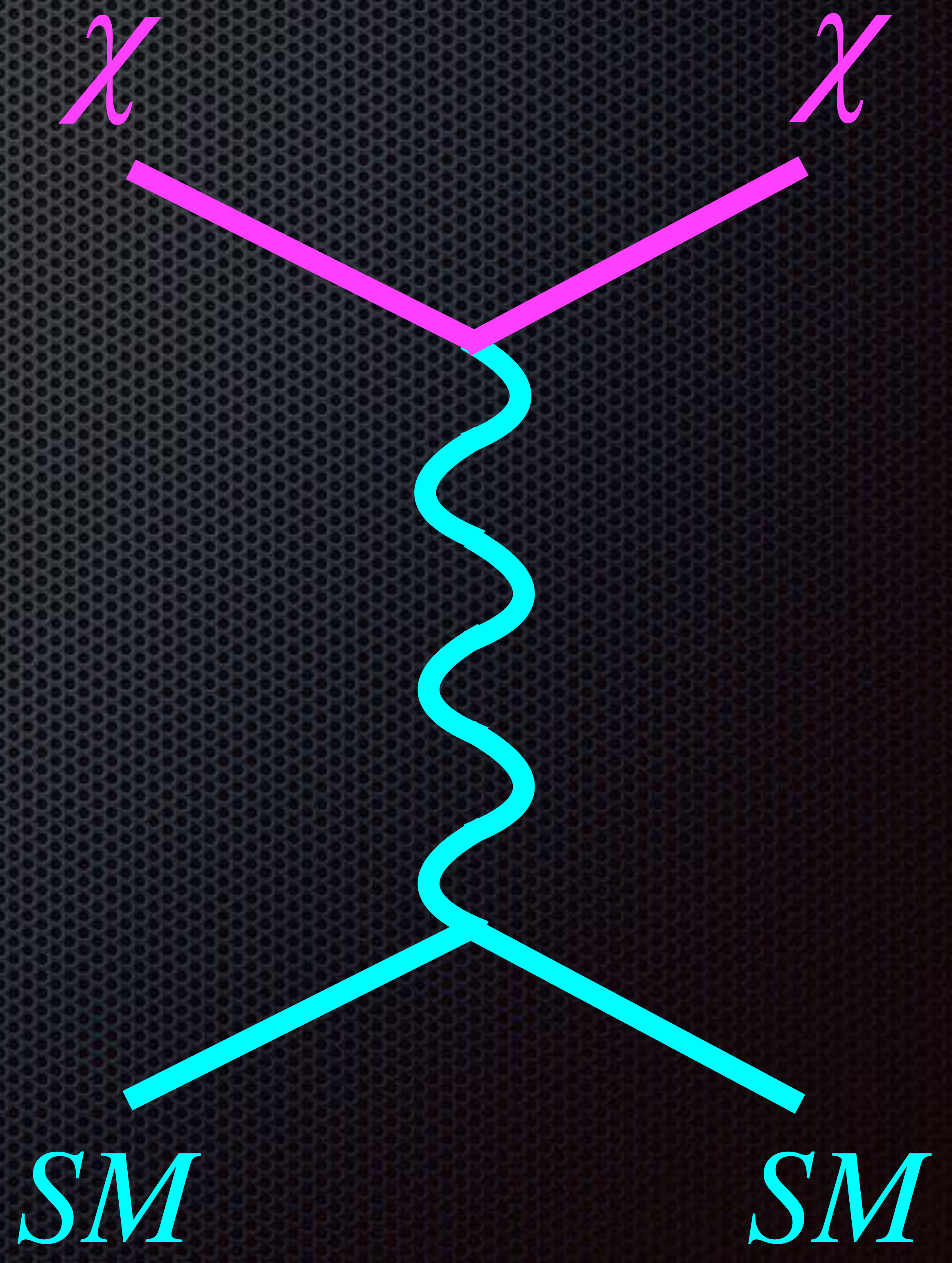
Millicharged Particle Detections



Stellar/Supernova
Energy Loss

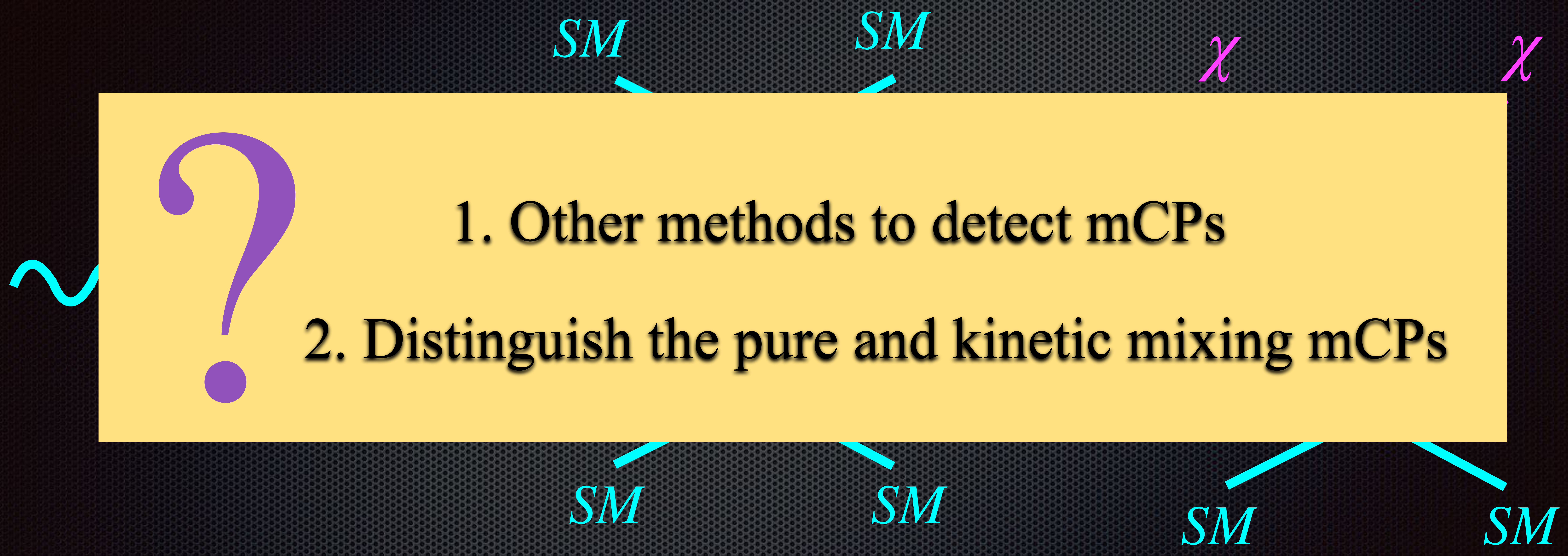


Missing Momentum



Dark Matter Direct Detection,
CMB Anisotropy,
Beam Dump

Millicharged Particle Detections



1. Other methods to detect mCPs
2. Distinguish the pure and kinetic mixing mCPs

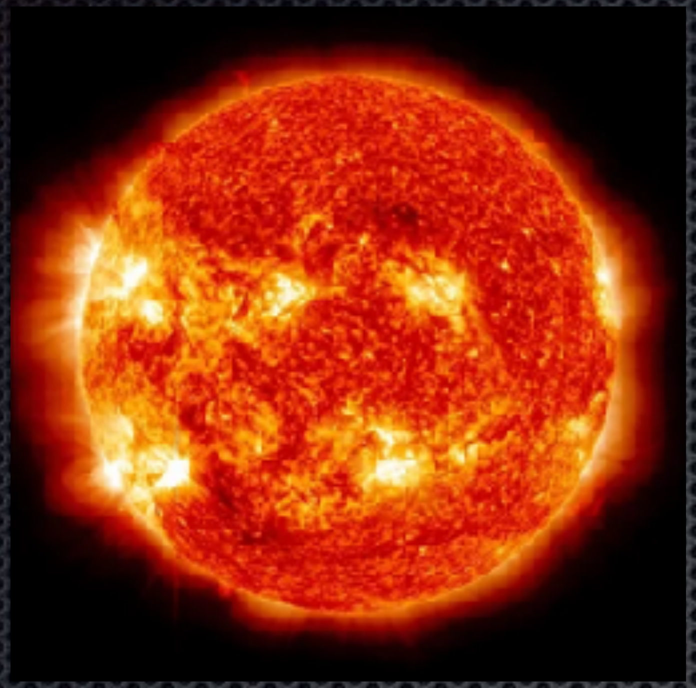
Stellar/Supernova Energy Loss

Missing Momentum

Dark Matter Direct Detection, CMB Anisotropy, Beam Dump

Cosmic Millicharge Background

Star as the Lab



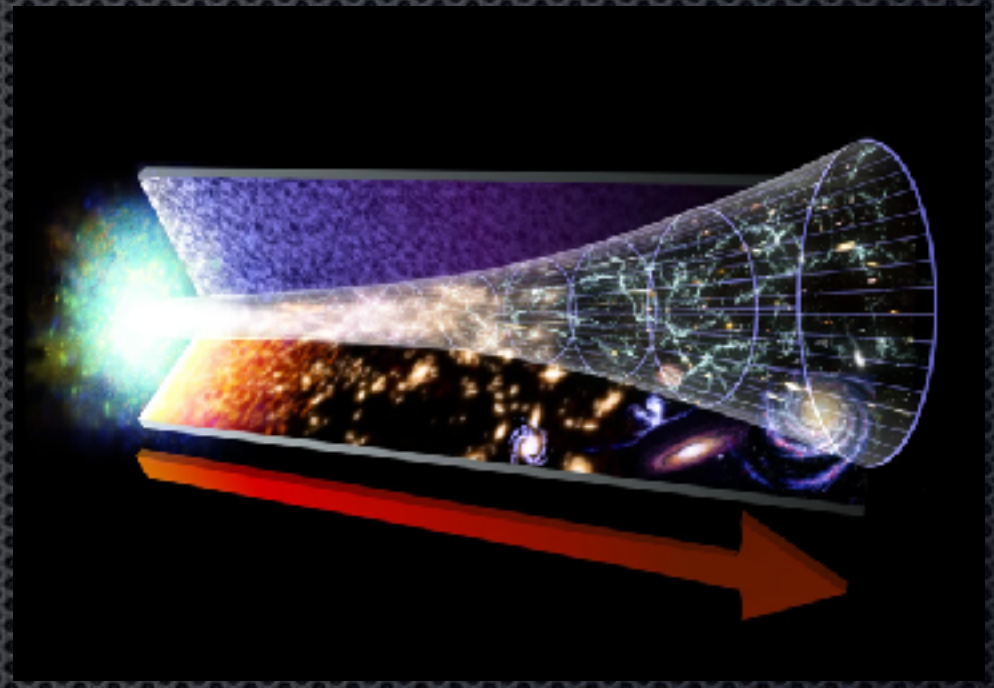
$T_{\rm Sun} \sim 300\,\mathrm{eV}$

$T_{\rm HB} \sim 3\,\mathrm{keV}$

$T_{\rm RG} \sim 200\,\mathrm{keV}$

$T_{\rm SN} \sim \mathrm{MeV}$

Universe as the Lab



$T_{\rm rh} > T_{\rm BBN} \sim 5\,\mathrm{MeV}$

Kawasaki, Kohri, Sugiyama, 2000

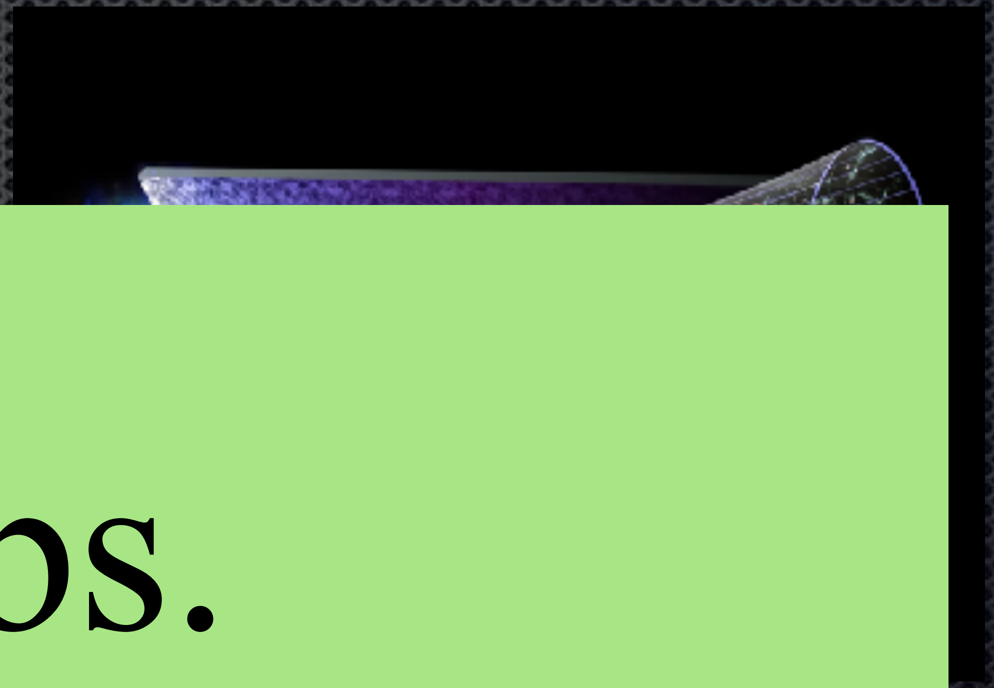
$T_{\rm rh} < \rho_{\rm inf}^{1/4} \sim 10^{16}\,\mathrm{GeV}$

Planck 2018, 1807.06211

Cosmic Millicharge Background

Star as the Lab

Universe as the Lab



Stars are good labs.
The universe is even better.

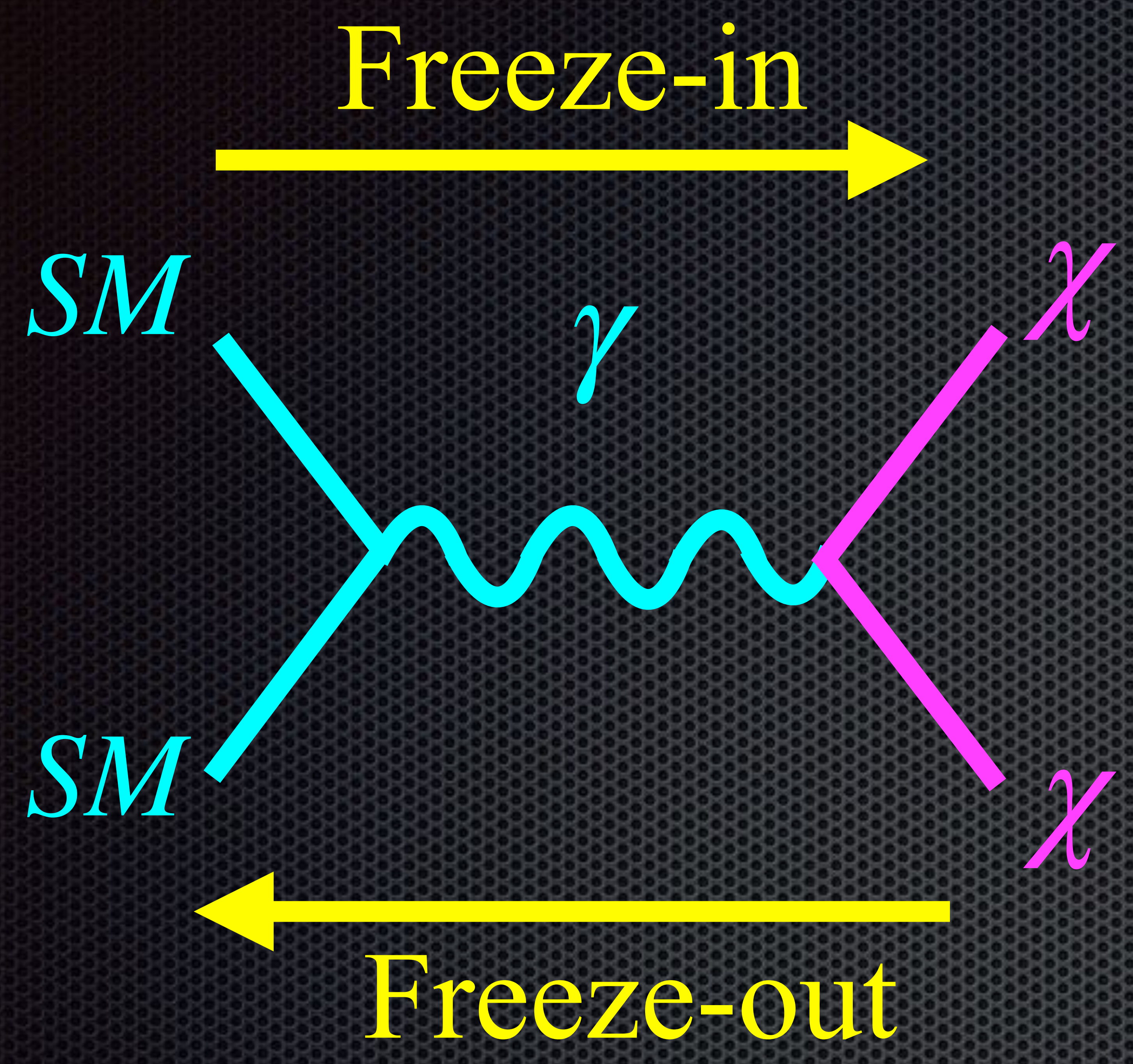
$T_{\rm RG} \sim 200\,\text{keV}$

$T_{\rm SN} \sim \text{MeV}$

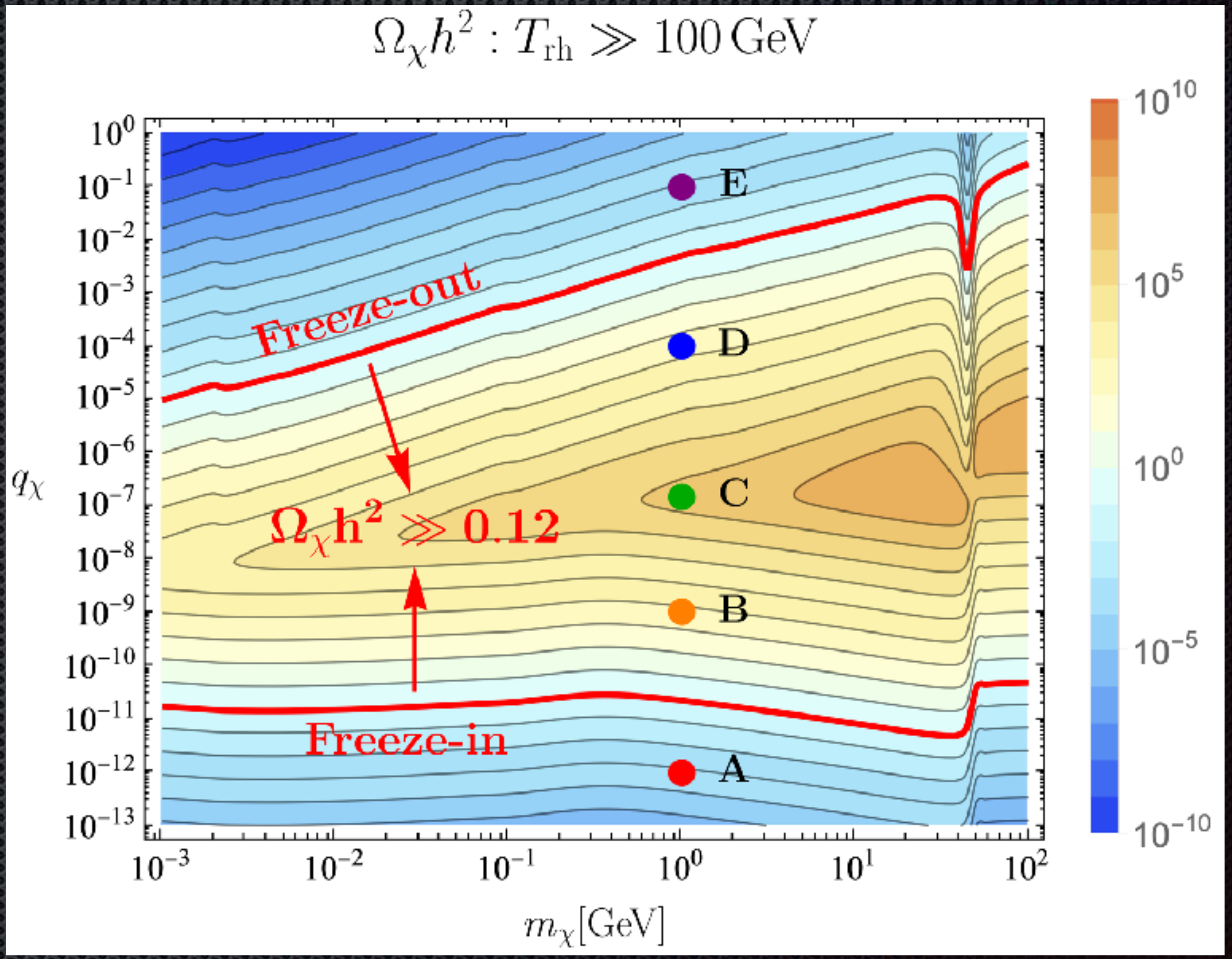
$T_{\rm rh} < \rho_{\rm inf}^{1/4} \sim 10^{16}\,\text{GeV}$

Planck 2018, 1807.06211

Pure Millicharged Background



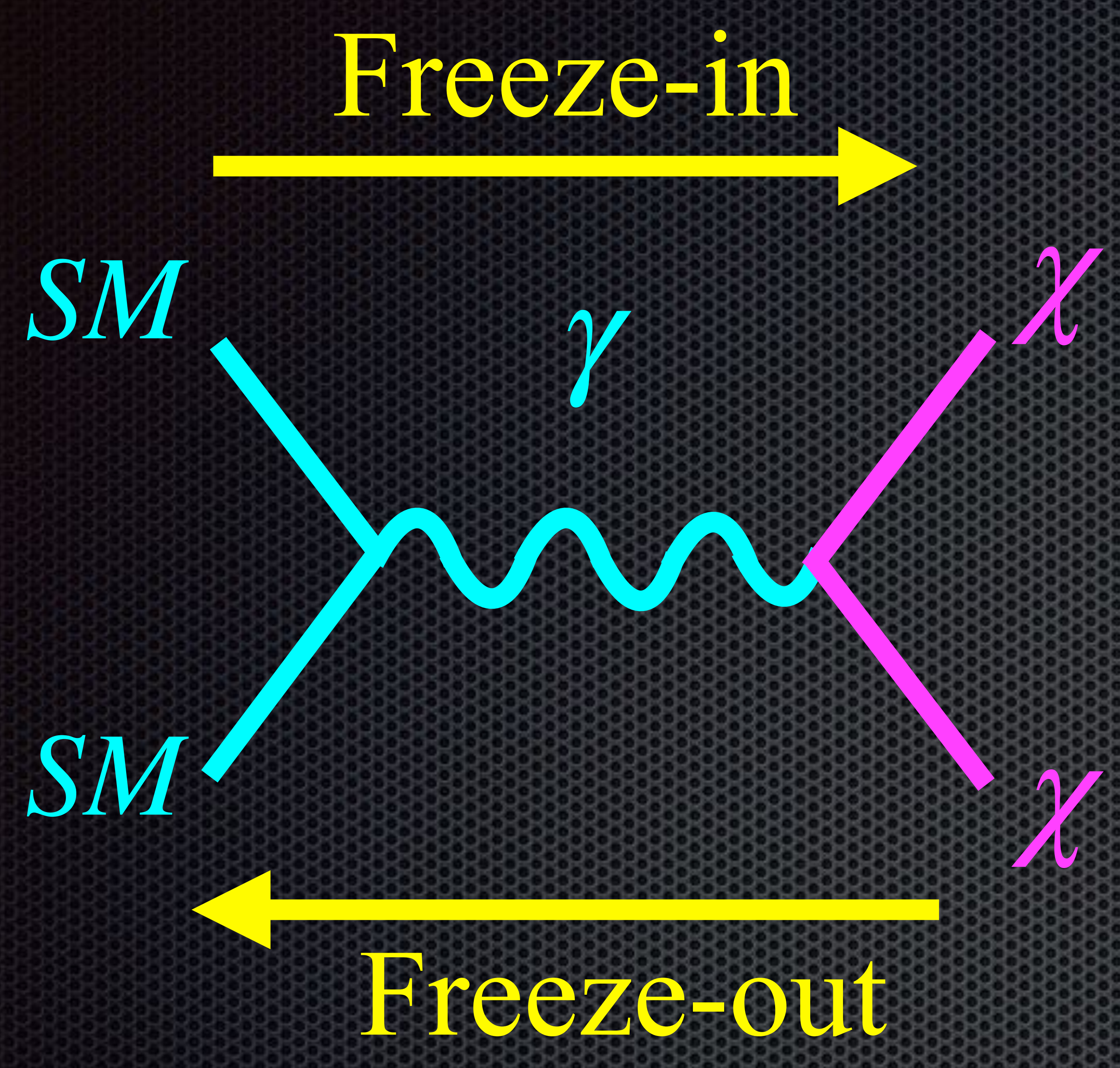
$$\mathrm{SM} + \mathrm{SM} \leftrightarrow \chi + \bar{\chi}$$



X. Gan, Tsai, 2023

Stability: $\mathbb{Z}_2$ Symmetry!

Pure Millicharged Background



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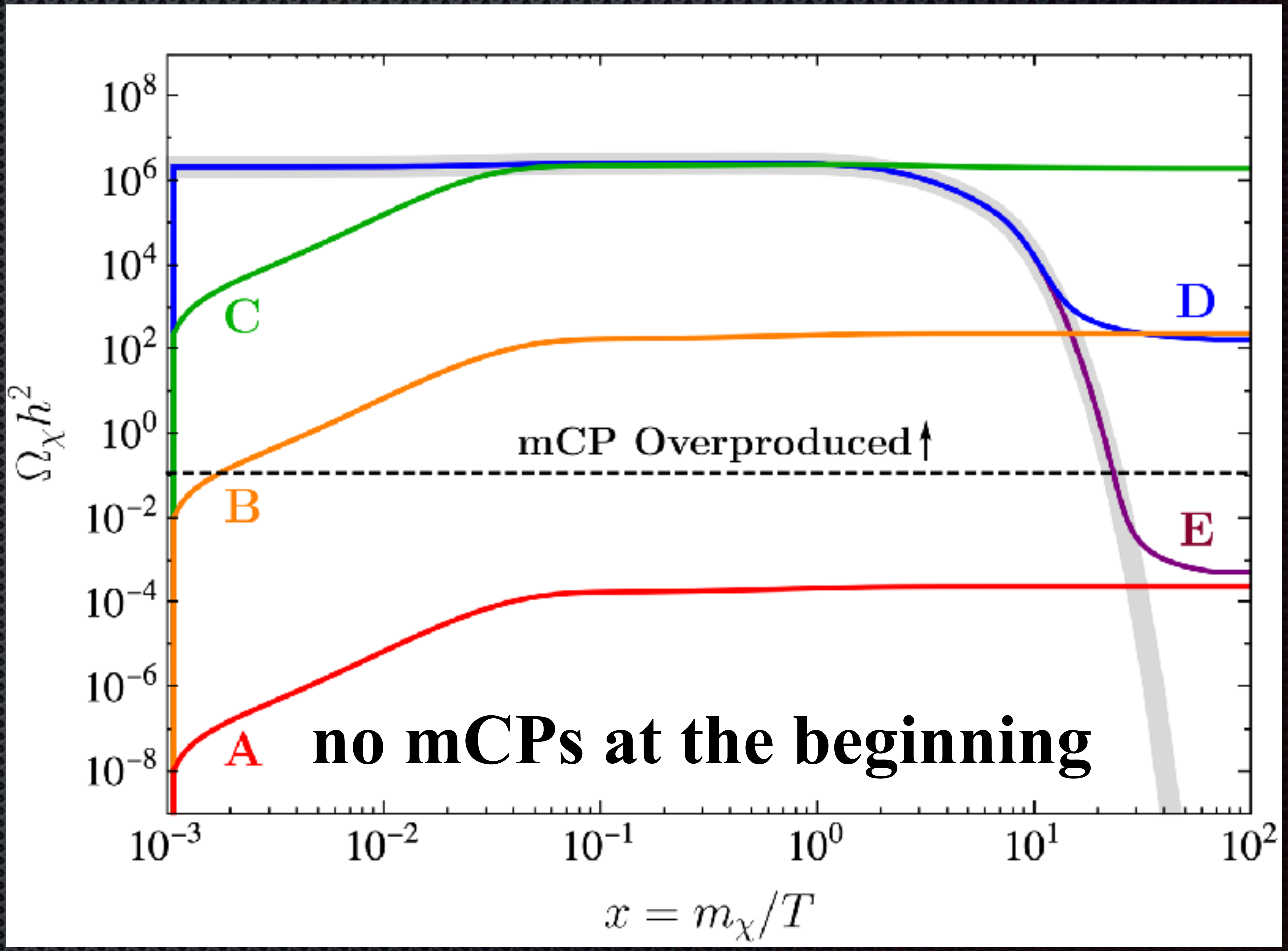
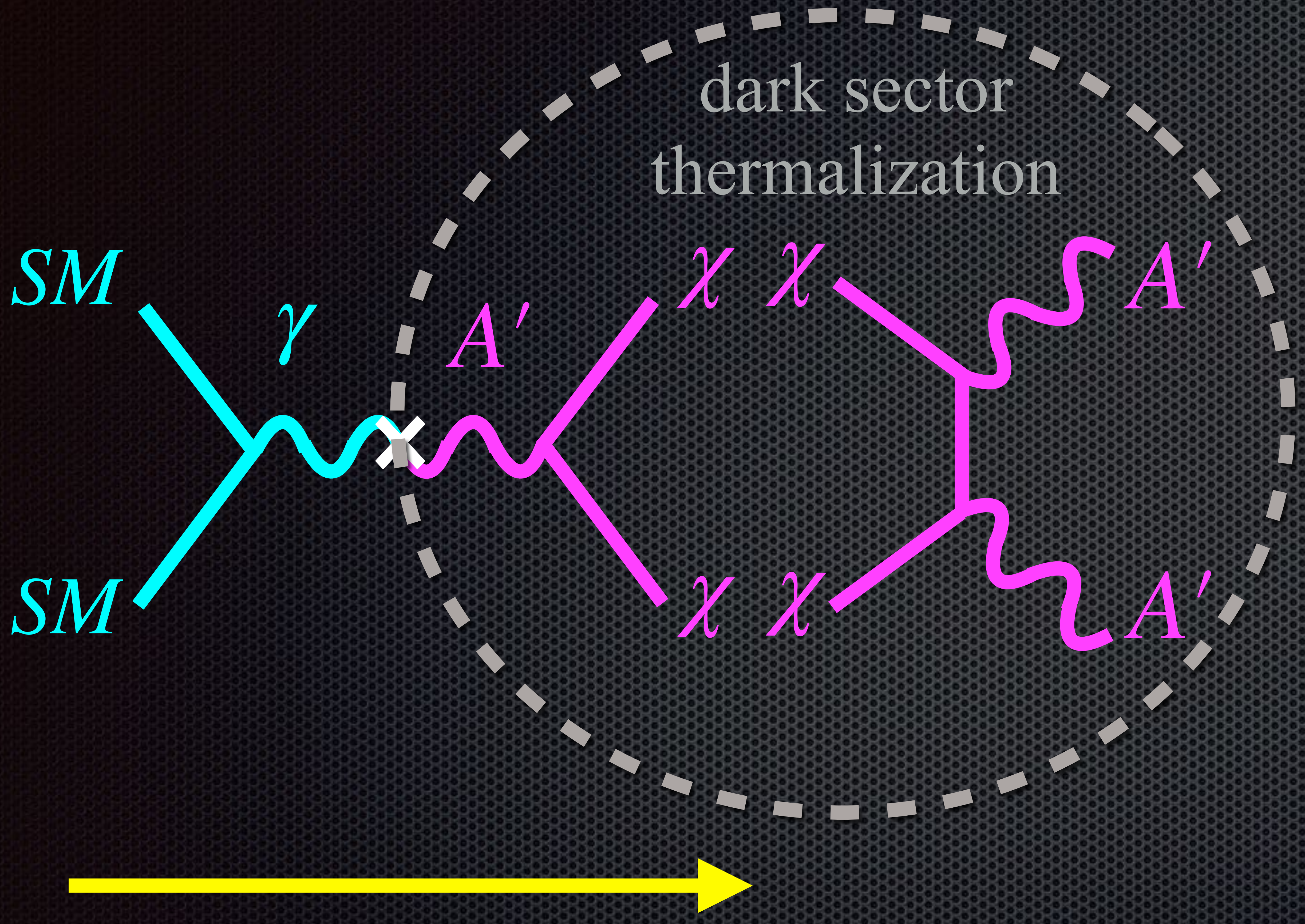


X. Gan, Tsai, 2023

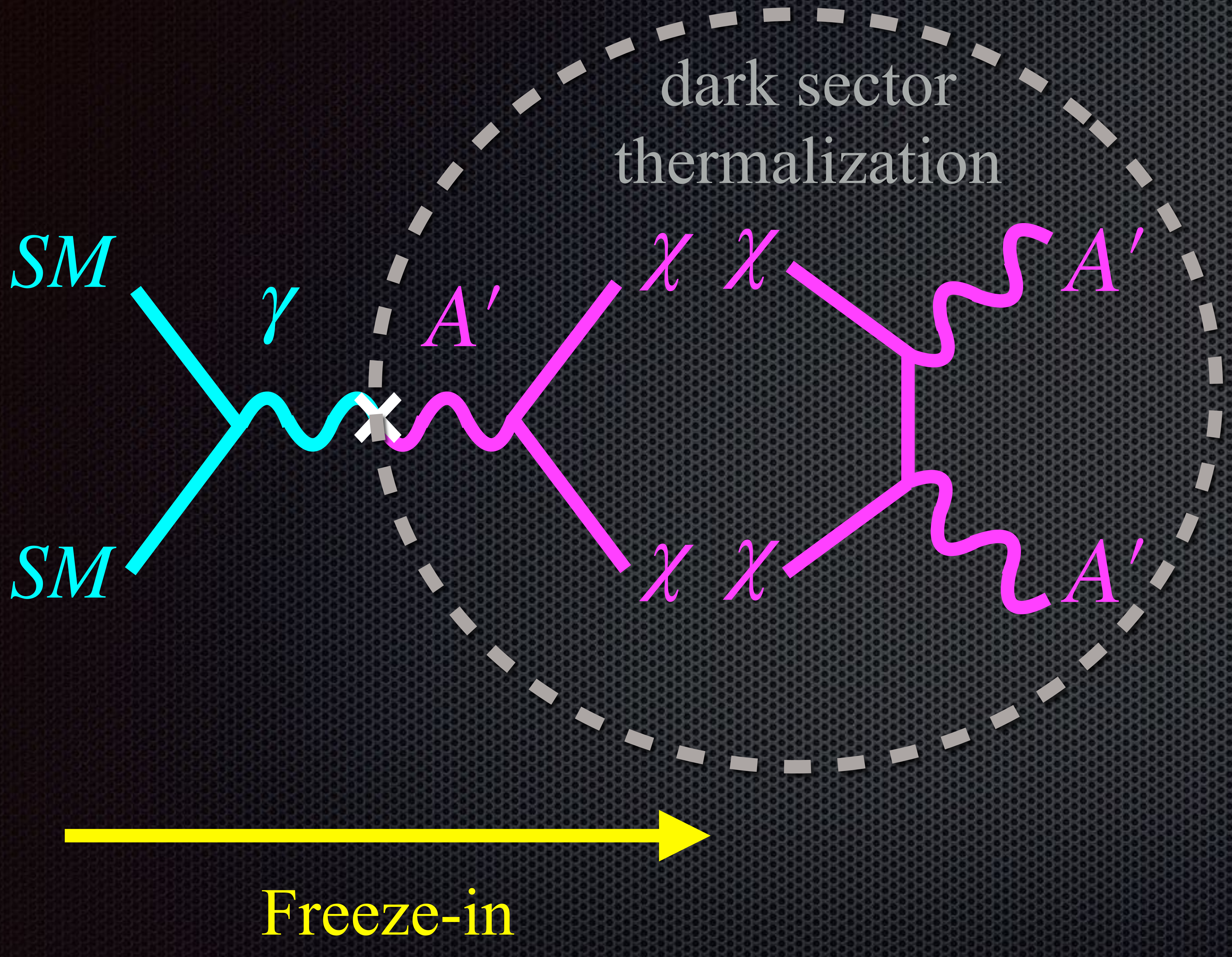
Stability: $\mathbb{Z}_2$ Symmetry!

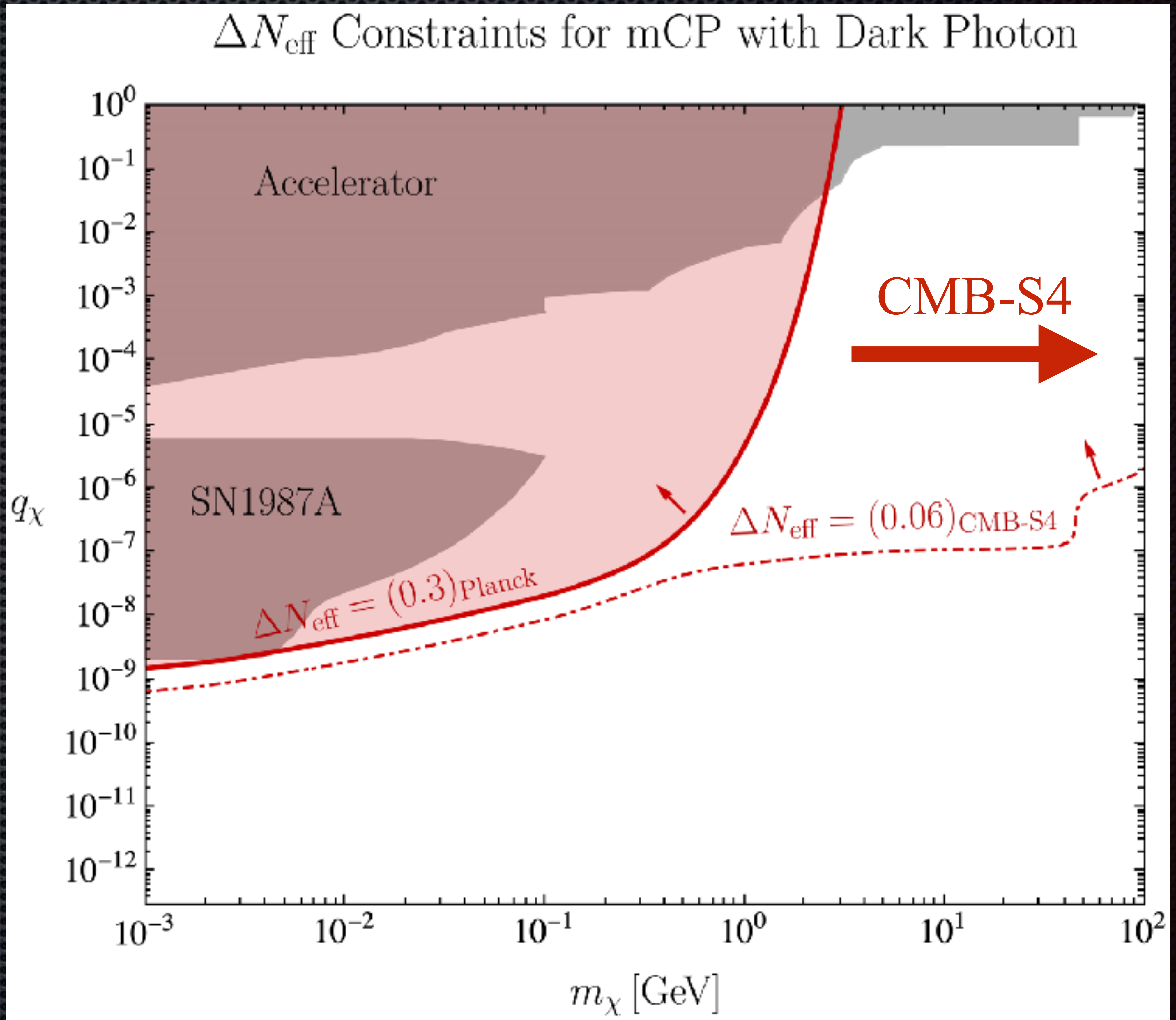
Kinetic Mixing Millicharged Background



Freeze-in

Kinetic Mixing Millicharged Background



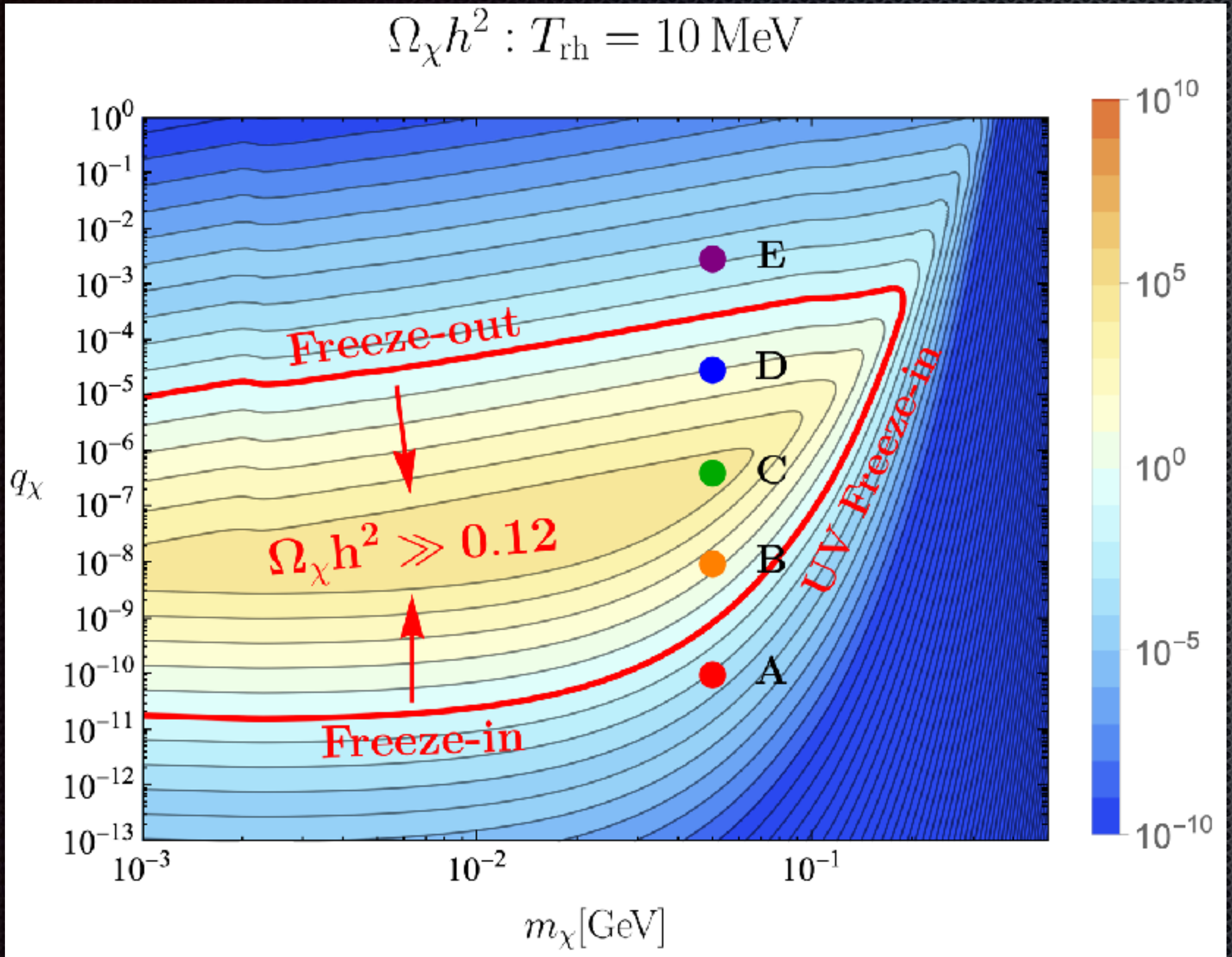


Vogel, Redondo 2013

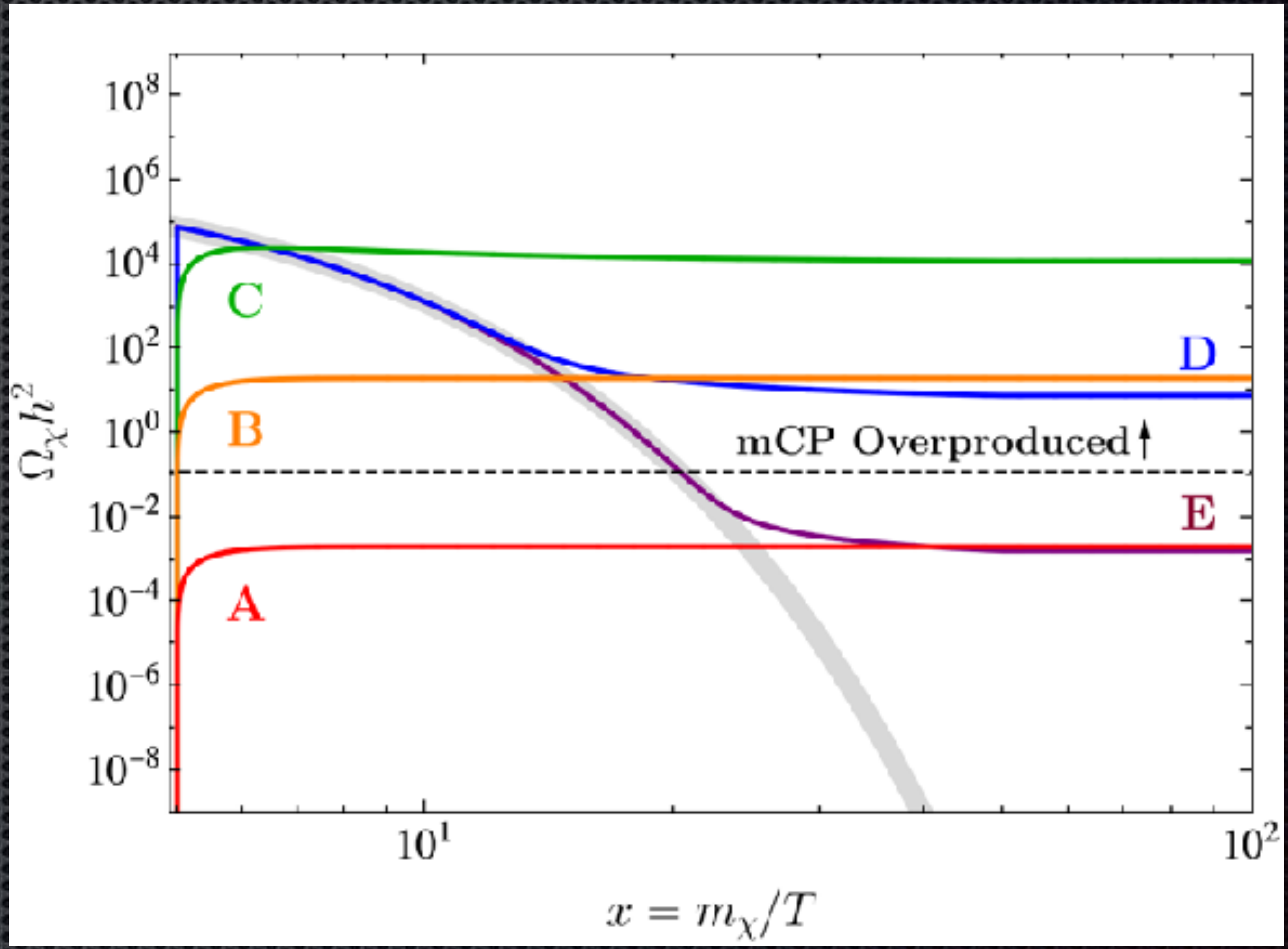
Adshead, Ralegankar, Shelton 2022

X. Gan, Tsai 2023

Test Low Reheating Temperature



X. Gan, Tsai, 2023

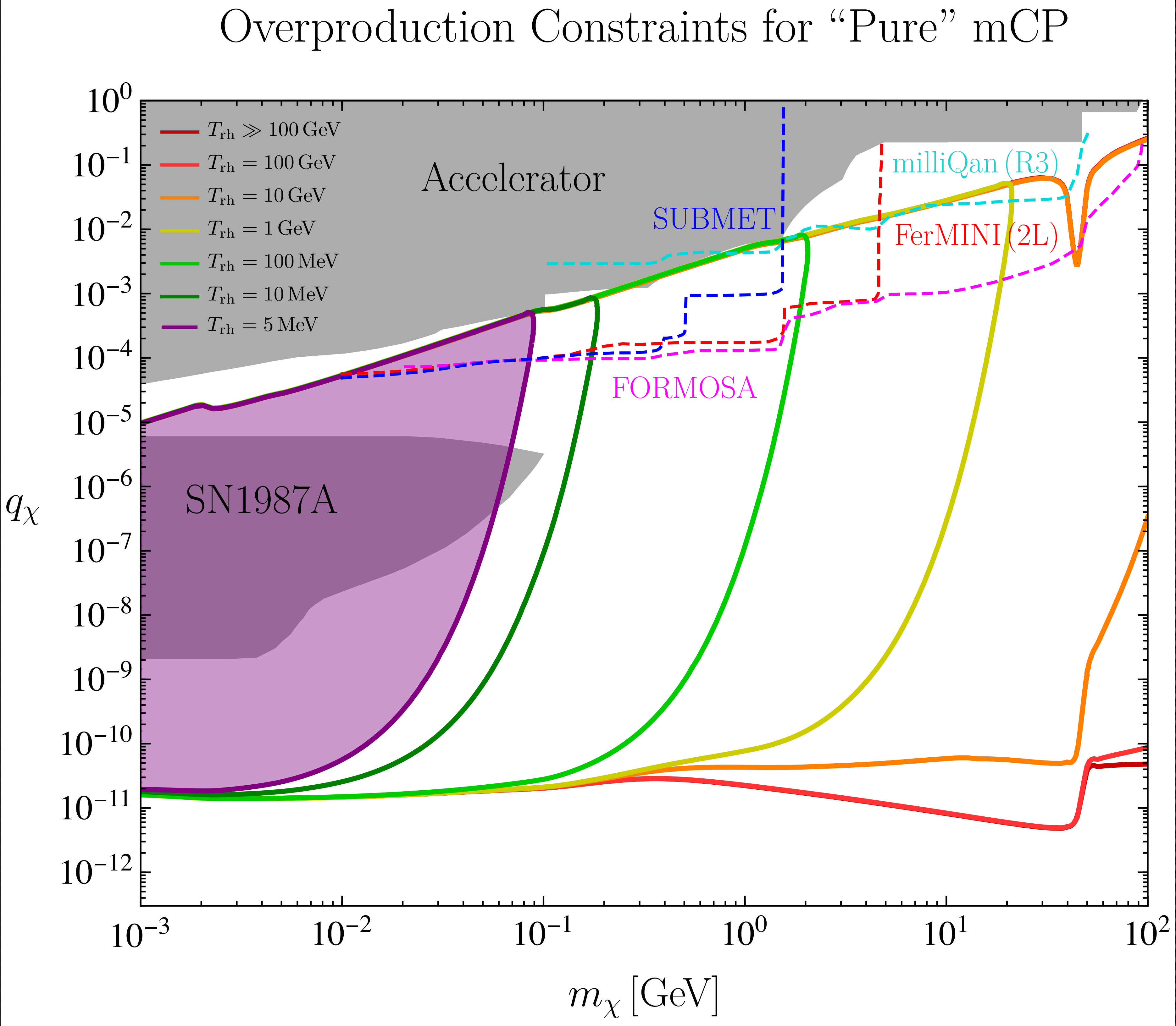


$$T_{\rm rh} \ll m_\chi$$

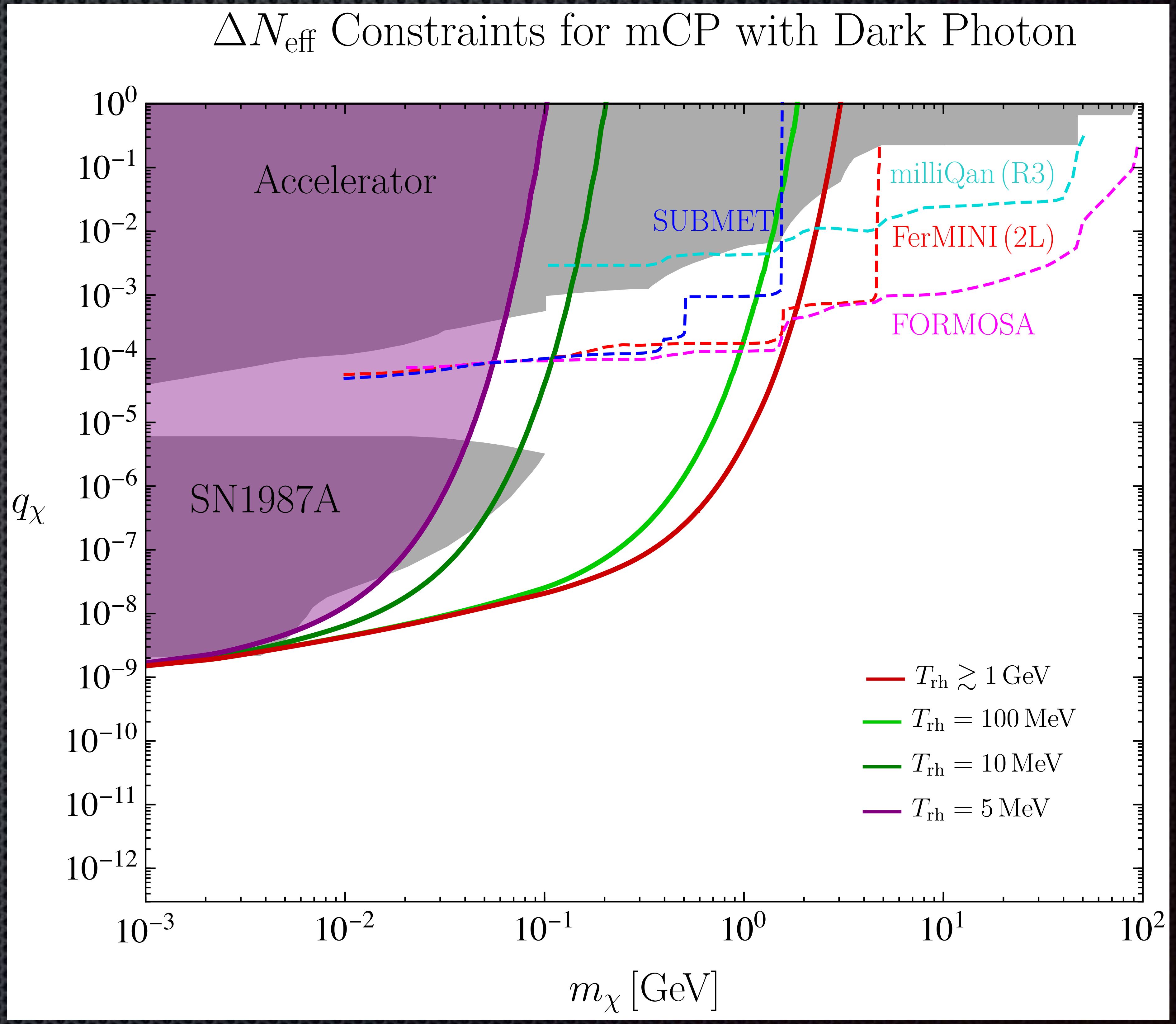
$$Y_\chi^{\rm FI} \sim q_\chi^2 \alpha_{\rm em}^2 \frac{m_{\rm pl}}{T} \times \frac{m_\chi}{T_{\rm rh}} \exp\left(-\frac{2m_\chi}{T}\right)$$

Exponential Suppression!

Test Low Reheating Temperature



Pure mCPs



Kinetic Mixing mCPs

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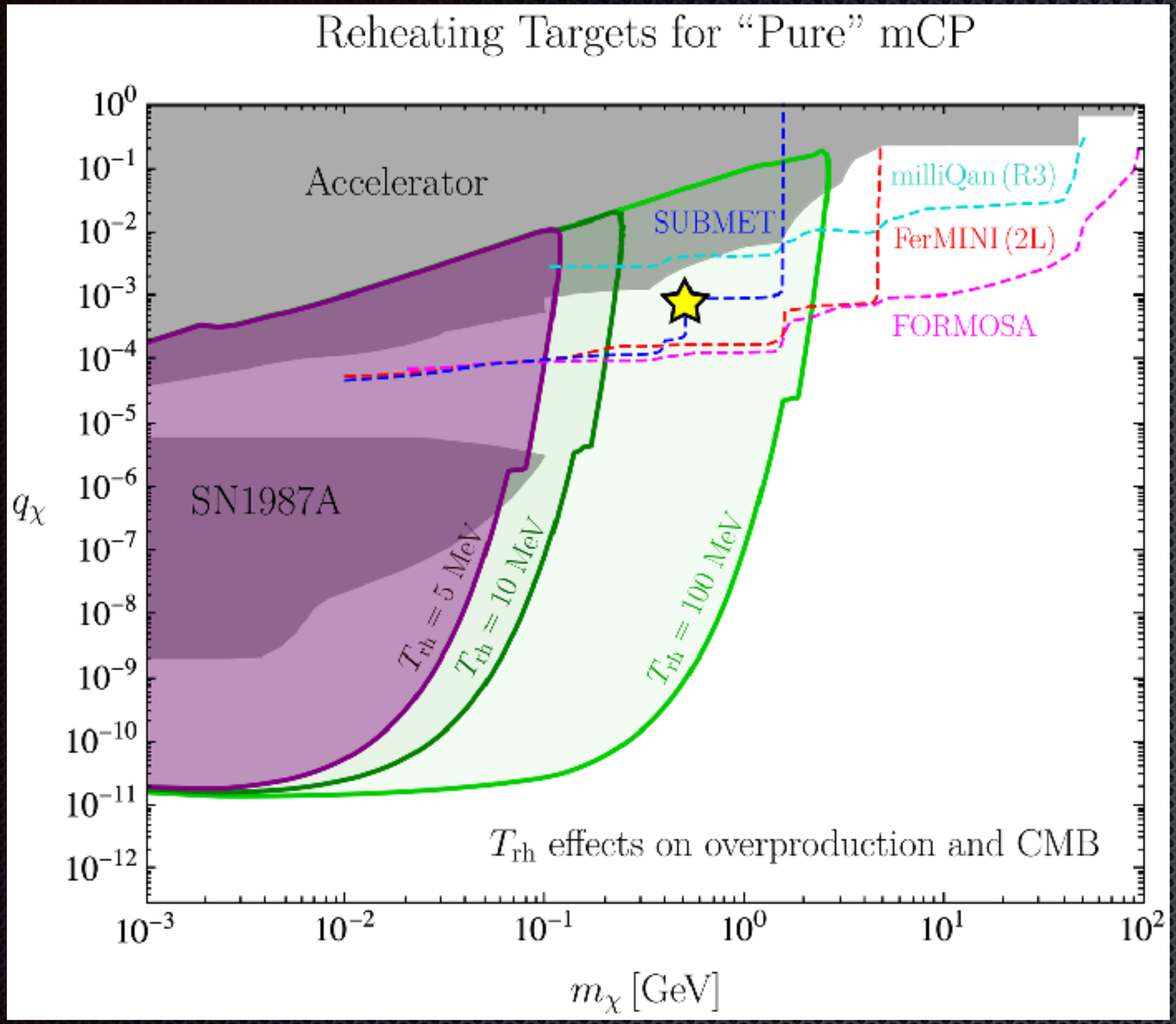
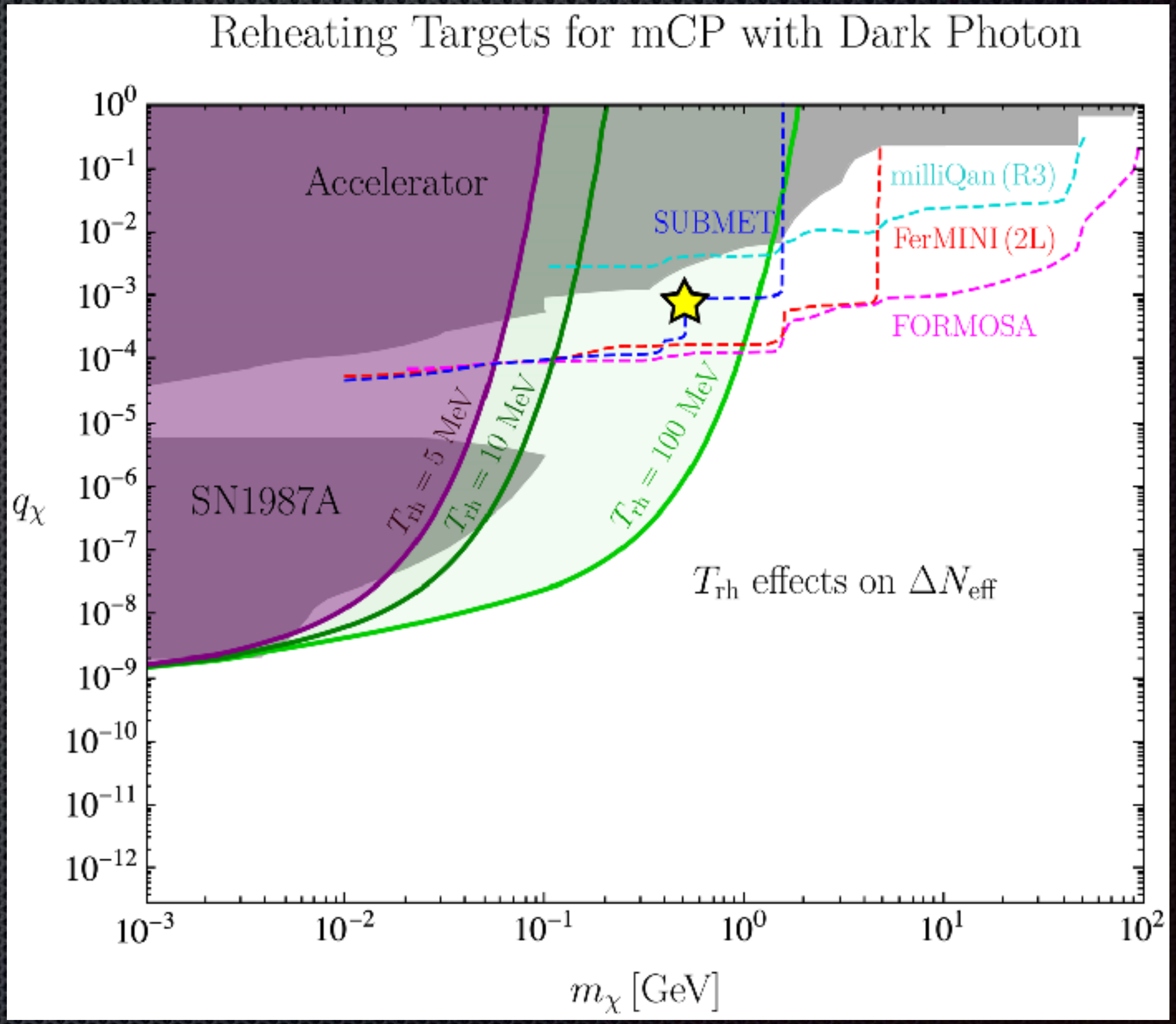
Test Low Reheating Temperature



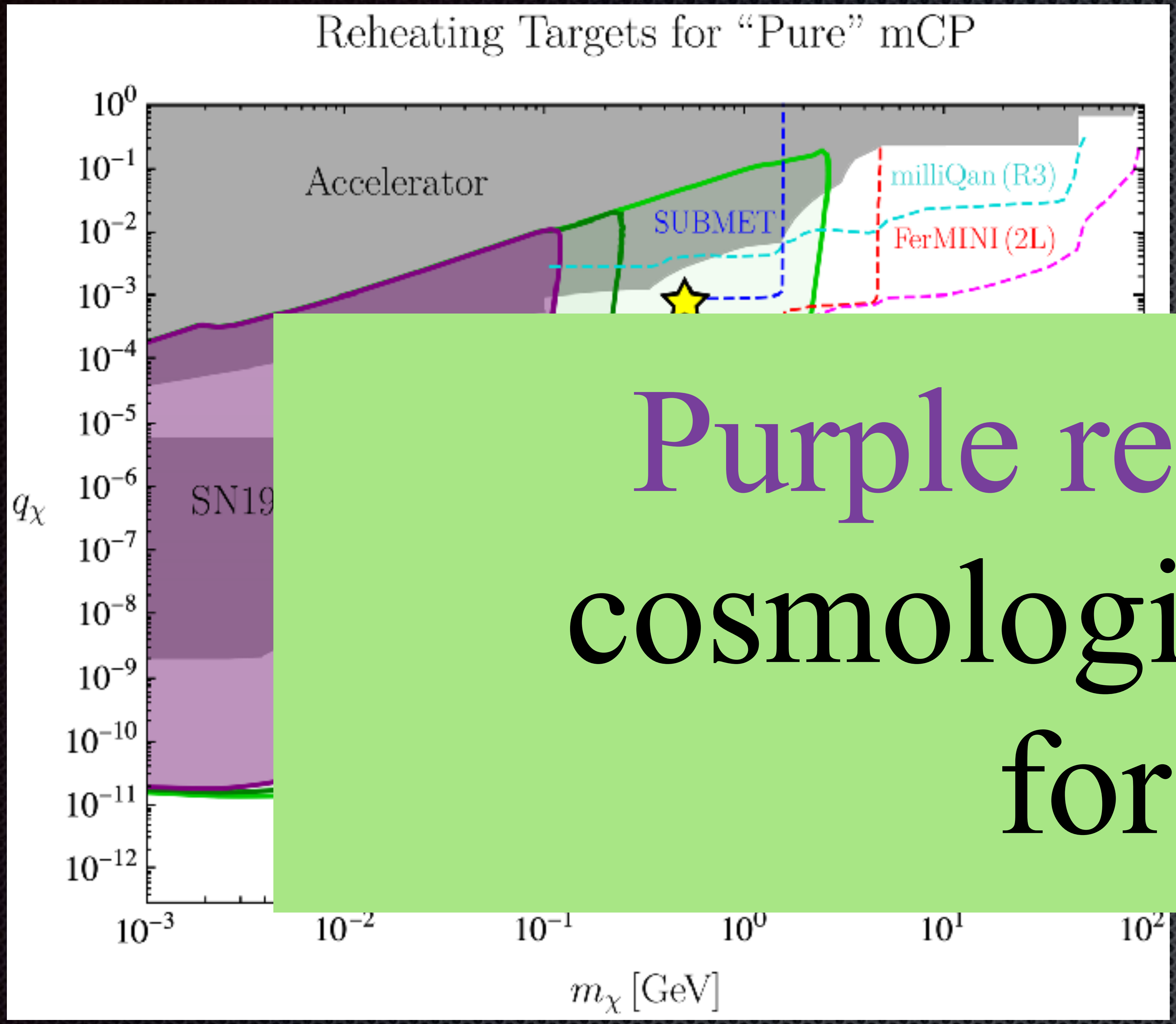
Pure mCPs

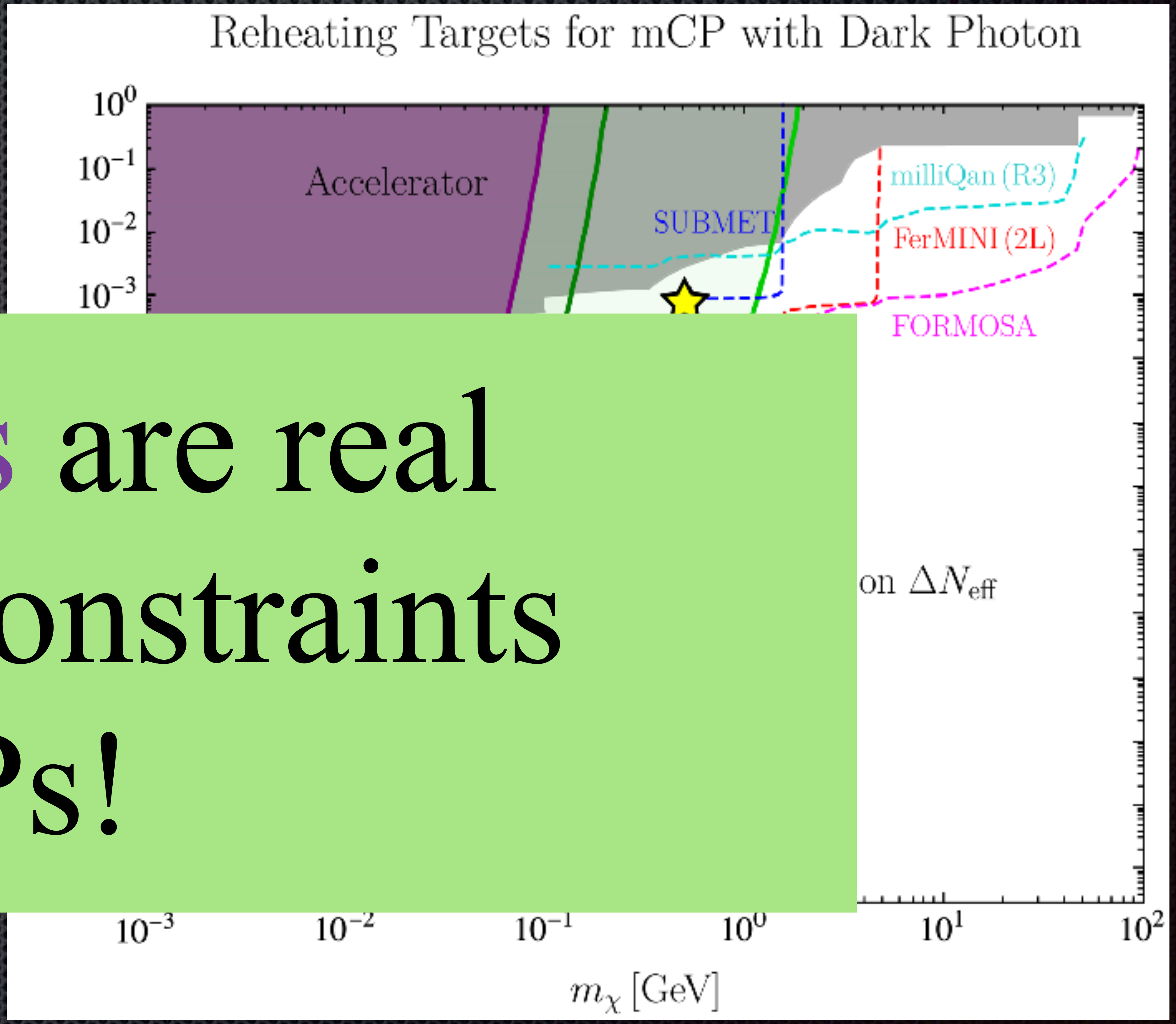


Kinetic Mixing mCPs

X. Gan, Tsai, 2023

Test Low Reheating Temperature





Purple regions are real cosmological constraints for mCPs!

Pure mCPs

Kinetic Mixing mCPs

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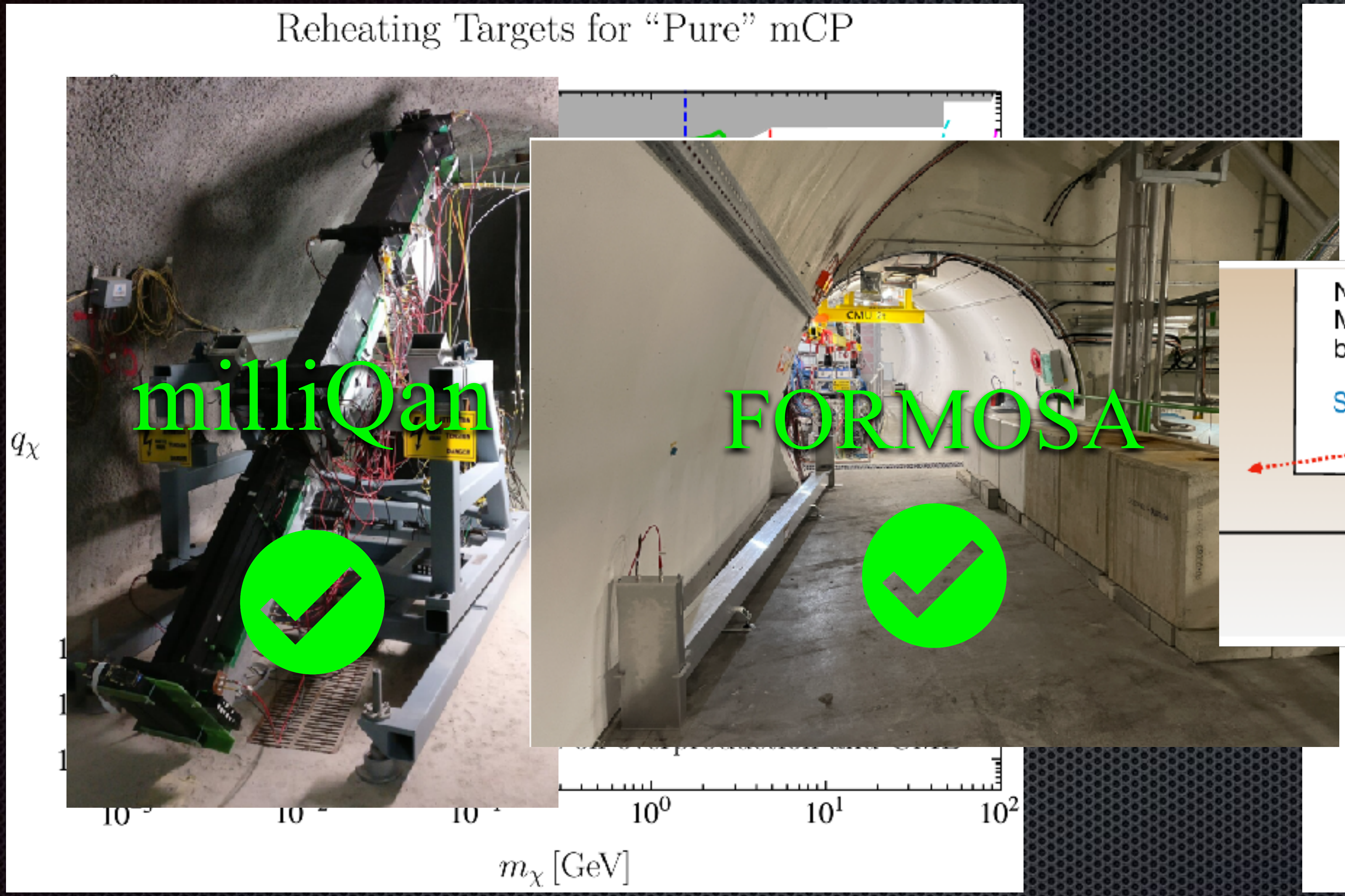
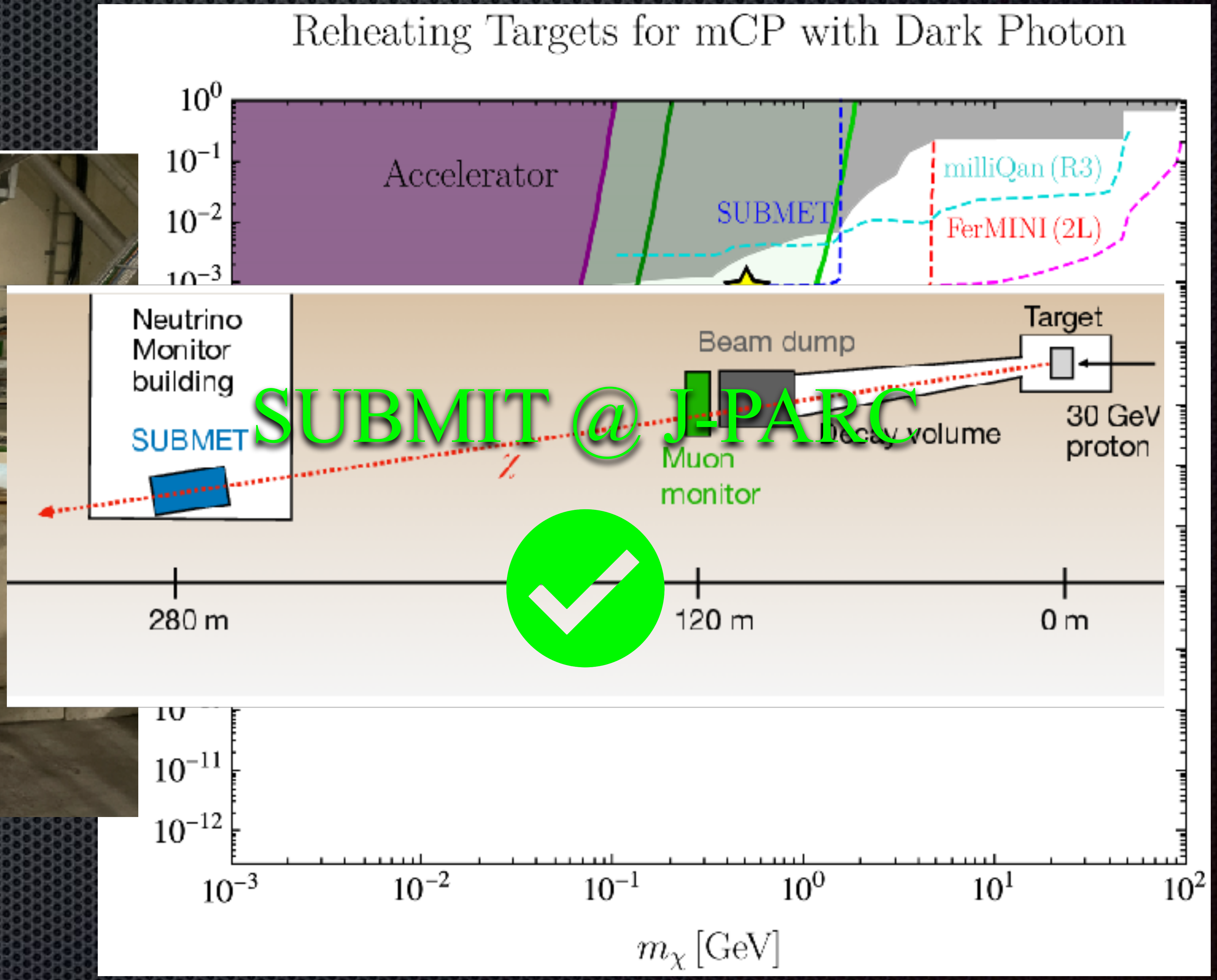
Test Low Reheating Temperature





Pure mCPs

Kinetic Mixing mCPs

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Cosmological Distinguish of Two mCPs

(1) Positive Definiteness $\epsilon < 1$ ⟺ Lower Bound of g_d: $g_d > eq_\chi$

(2) No Dark Thermalization

$$n_\chi^{eq} \langle \sigma v \rangle_{\chi\bar{\chi} \to A'A'} < H$$

X. Gan, Tsai, 2023

Cosmological Distinguish of Two mCPs

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(2) No Dark Thermalization $n_\chi^{eq} \langle \sigma v \rangle_{\chi\bar{\chi} \to A'A'} < H$

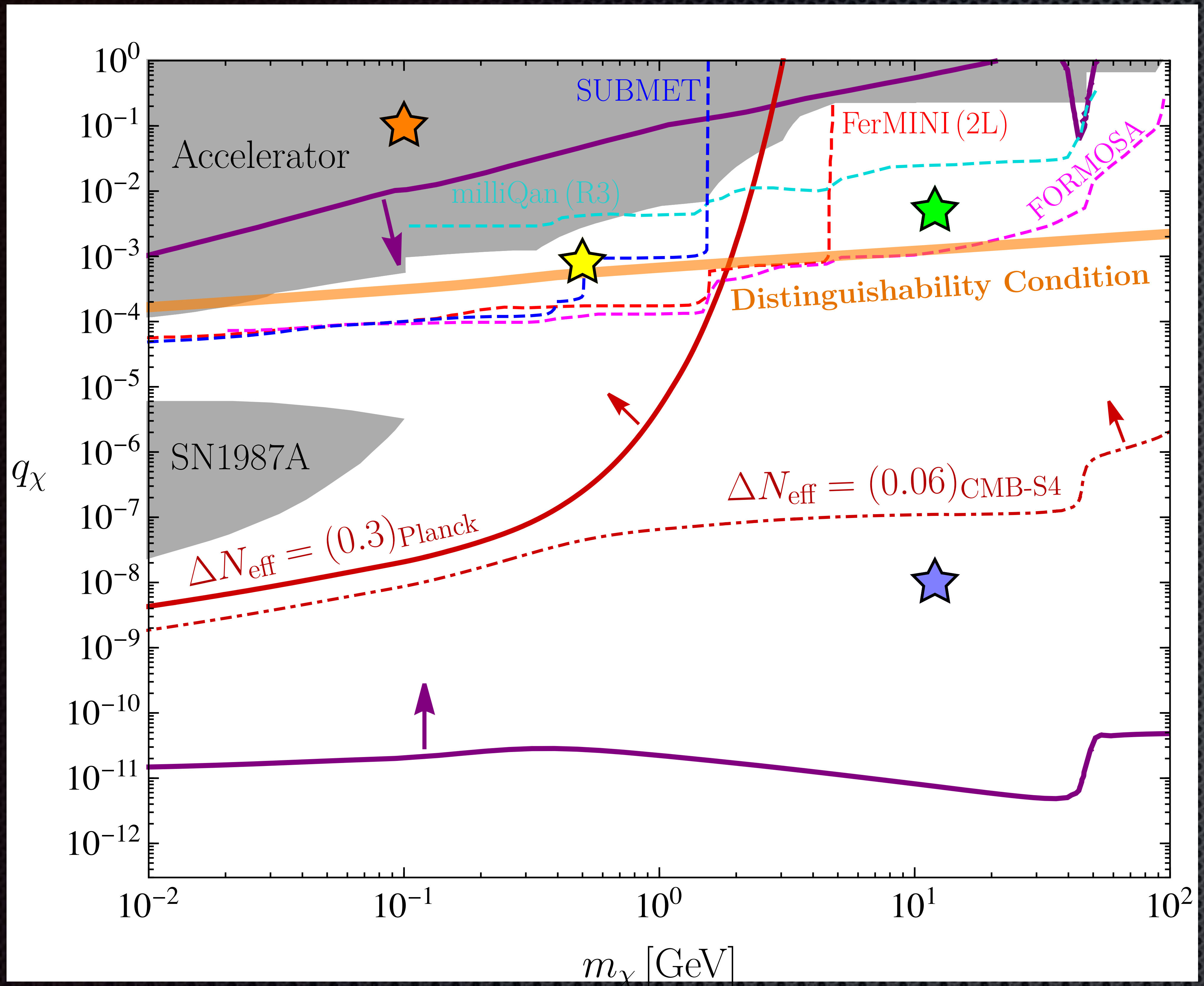
→

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

Two conditions cannot be satisfied at the same time

X. Gan, Tsai, 2023

Target Regions



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- Pure mCPs
- Low T_{rh}
- Kinetic Mixing mCPs (Planck 2018)
  Low T_{rh} (CMB-S4)
- Kinetic Mixing mCPs (DD)

Summary

Motivation

Millicharged particles can easily emerge from kinetic mixing, become the dark matter candidate, serve as a test of GUT, and have many interesting phenomena. They also strongly affect the 21cm signal, which provides convincing explanations for the 21cm anomalies.

Two Kinds of Millicharged Particle

Pure and kinetic mixing millicharged particles.

Millicharged Particle Detections

Star as lab versus Universe as lab

Test Low Reheating Temperature

When $T_{rh} < m_\chi$, mCP production is exponentially suppressed. Given this, the discovery of low-mass mCPs determines the low reheating temperature. This fact motivates the collider and fixed-target searches of mCPs, such as milliQan, FORMOSA, SUBMET.

Cosmological Distinguishment of Two Millicharged Particles

We specify the regions in the mCP parameter space where kinetic mixing mCPs can never mimic pure mCPs given the dark thermalizations. Then, we specify the target regions to detect pure and kinetic mixing mCPs and detect low Trh.

Appendix

Dirac Quantization

Dirac-Schwinger-Zwanziger Quantization Condition:

For arbitrary two particles (e_i, g_i) and (e_j, g_j),

$$e_i g_j - e_j g_i = N/2, \quad N \in \mathbb{N}.$$

If magnetic monopole $(0, g_M)$ exits:

$(e_{SM}, 0)$

$(0, g_M)$

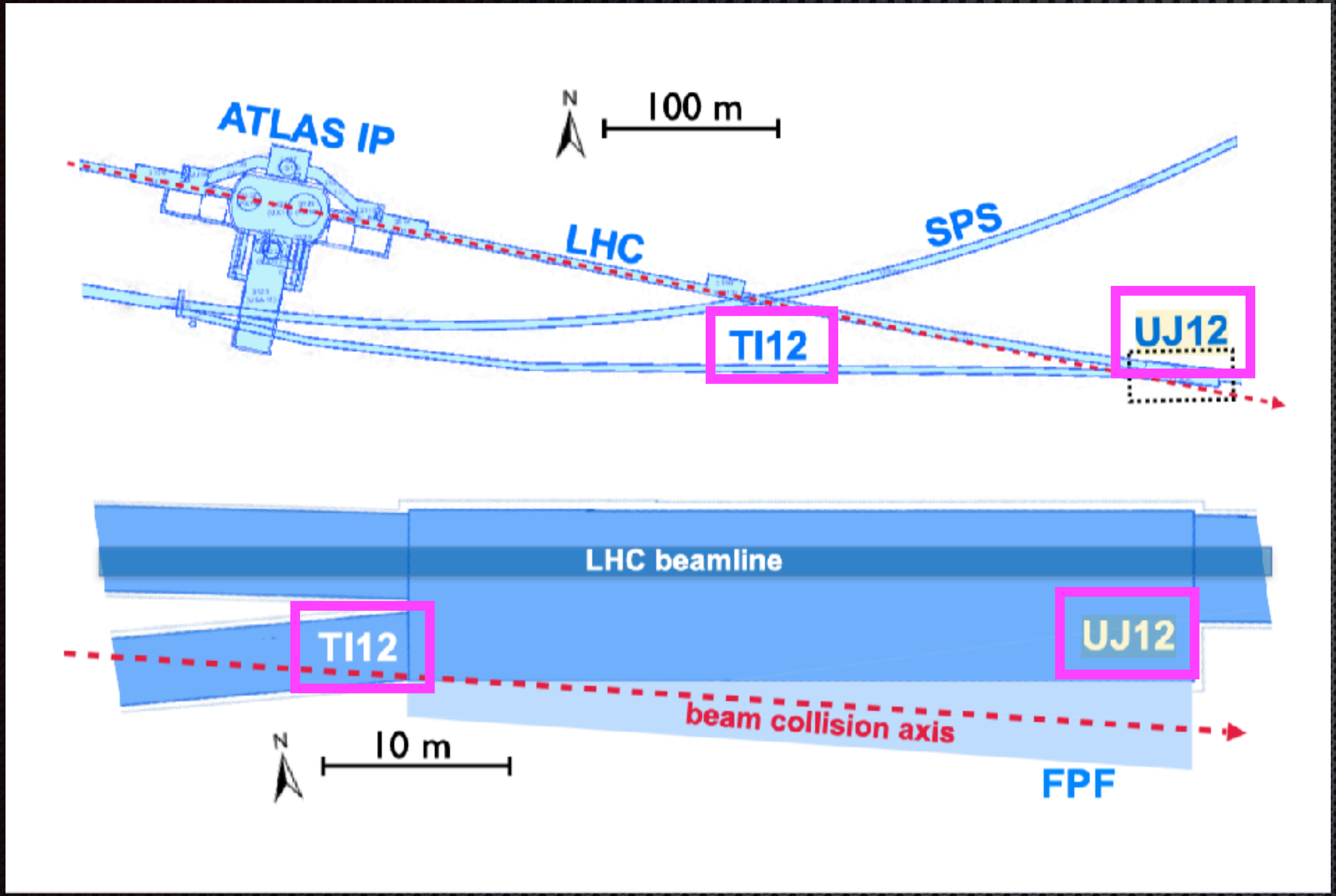
$(q_\chi, 0)$

$$e_{SM} \cdot g_M = m/2$$

$$g_M \cdot q_\chi = n/2$$

$$q_\chi = \frac{n}{m} e_{SM} \in \mathbb{Q}$$

Forward Physics Facility: FORMOSA



FORMOSA-I:

0.2m × 0.2m × 4m Detector

at UJ-12/TJ-12

FORMOSA-II:

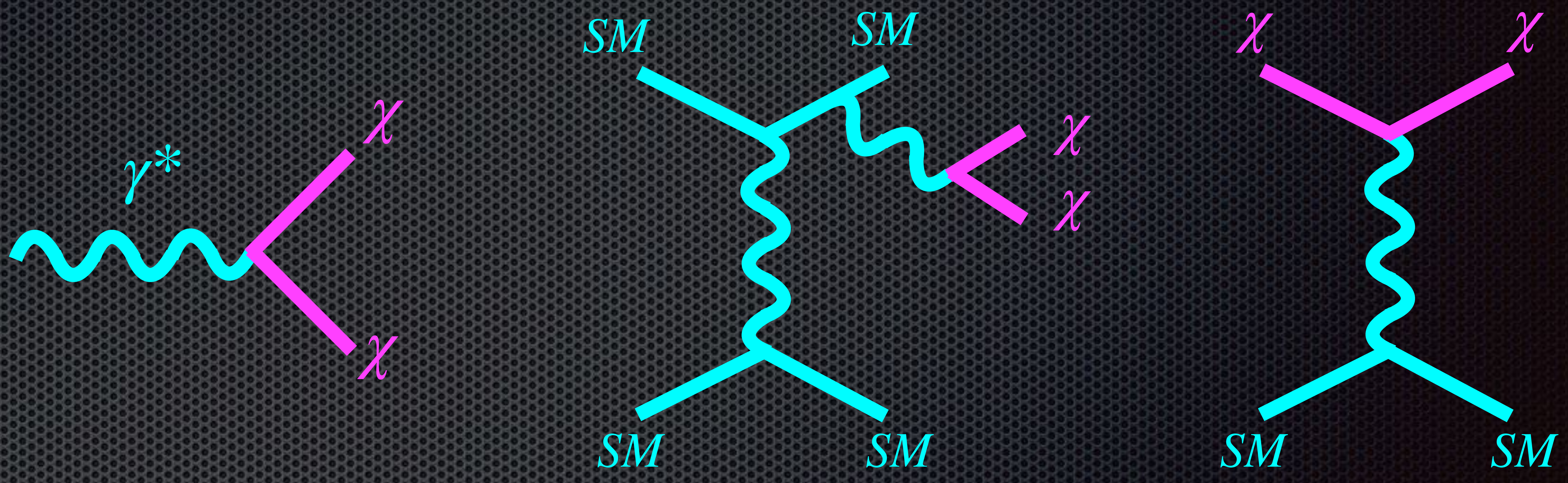
1m × 1m × 4m Detector

at UJ-12/TJ-12

Foroughi-Abari, Kling, Tsai 2020

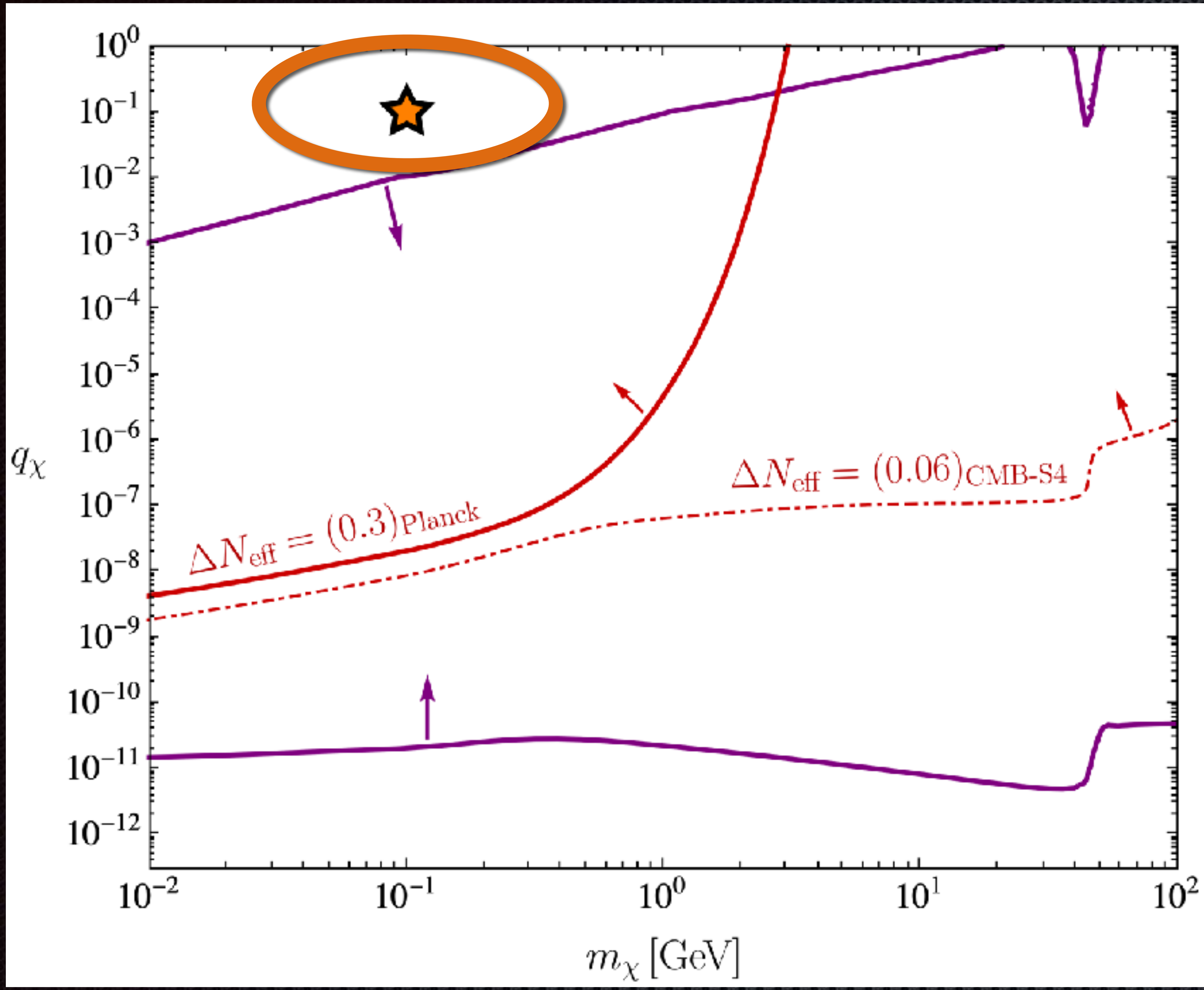
Summary of the mCP Detections

Both Pure and
Kinetic Mixing mCPs



Only
Kinetic Mixing mCPs

Detect the Pure mCP



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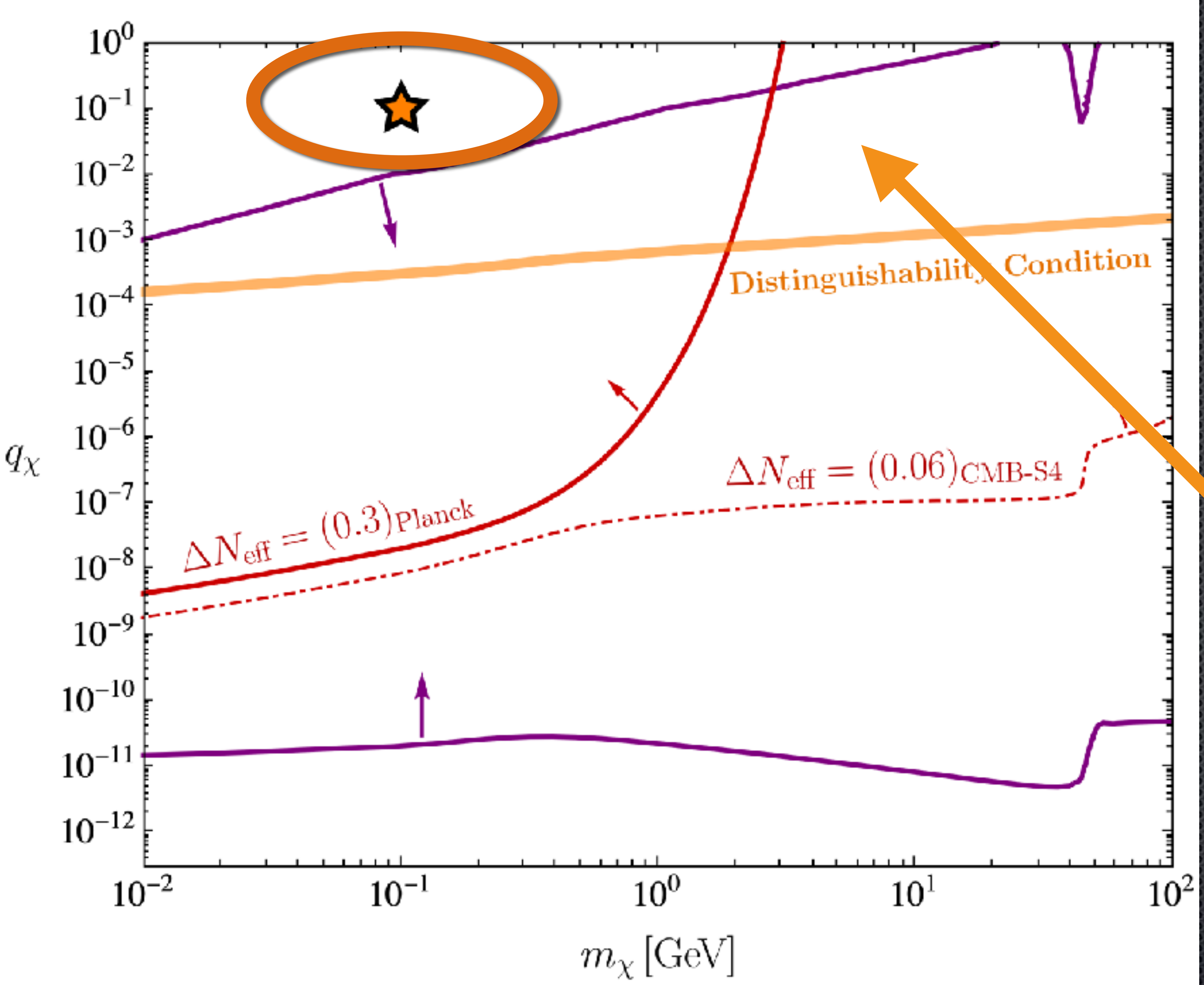
★ Target Region

Excluded by kinetic mixing mCP's $\Delta N_{\rm eff}$ bound, but unexcluded by pure mCP's overproducgion bound

Detect the Pure mCP



X. Gan, Tsai, 2023

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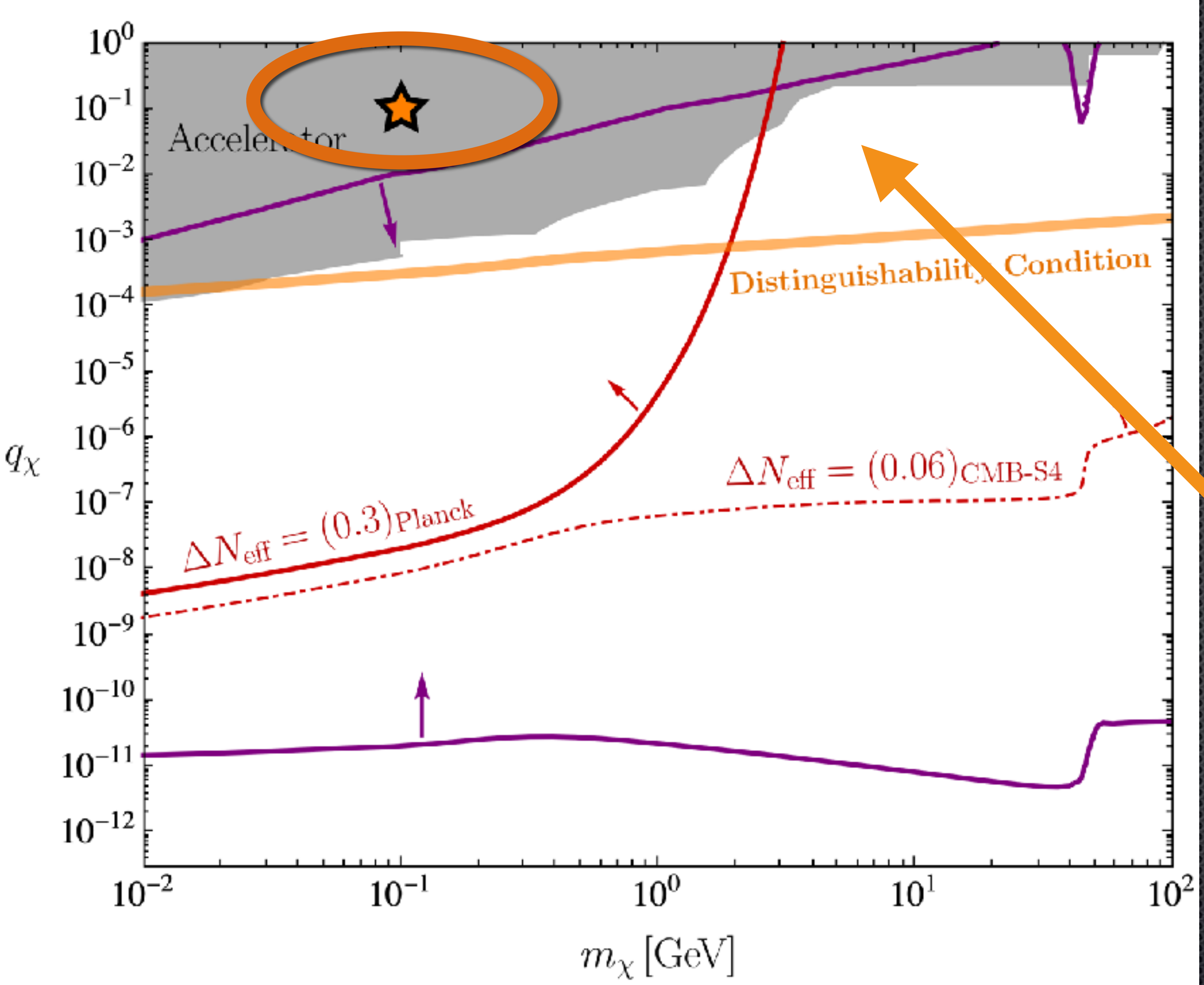
Dark Thermalization

$$\epsilon < 1 \Longleftrightarrow g_d > e q_\chi$$

$$n_\chi \langle \sigma v \rangle_{\chi\bar{\chi} \to A'A'} > H$$

Detect the Pure mCP



X. Gan, Tsai, 2023

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