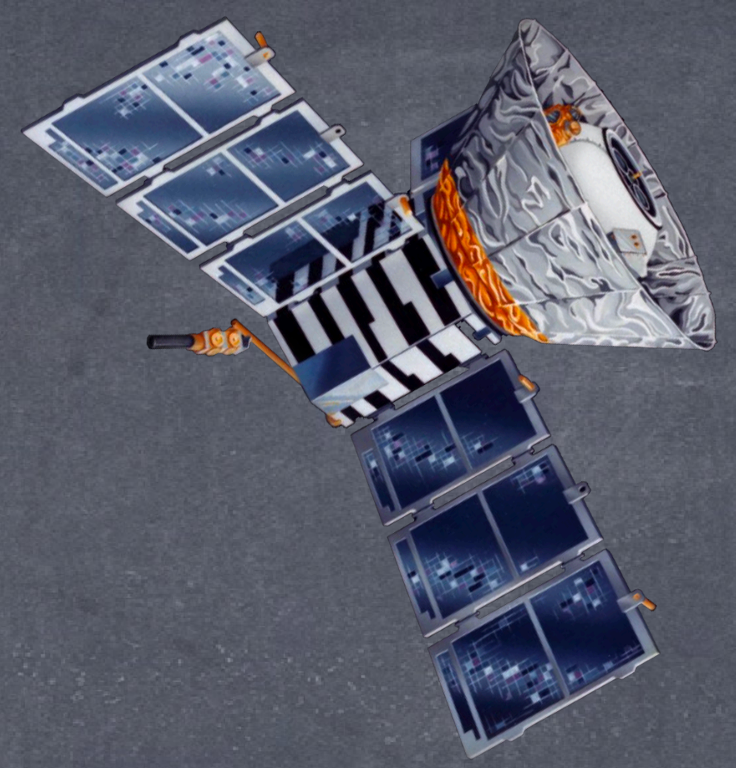
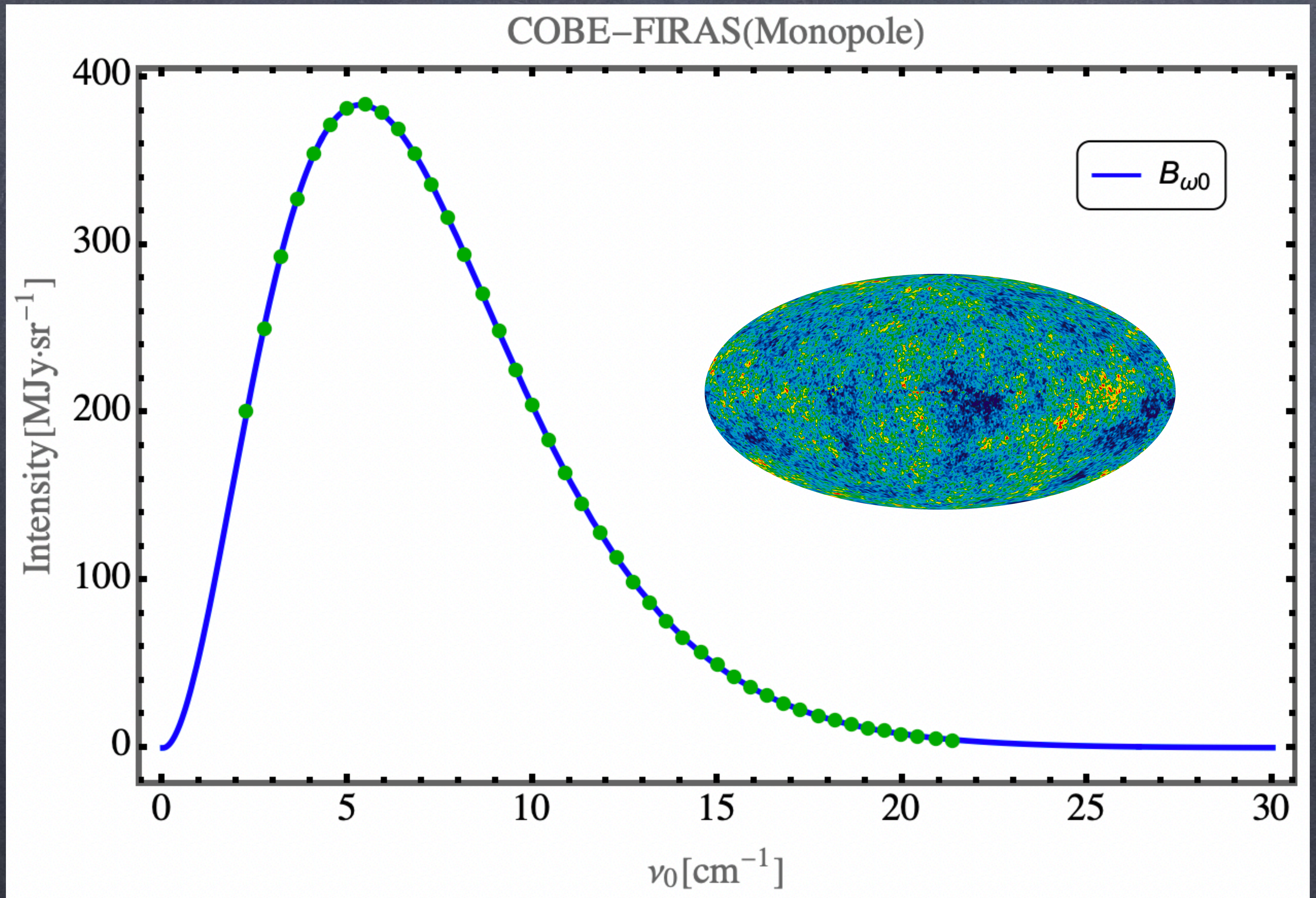
Dark Photon Oscillation in Non-Minimal Dark Sector

Asher Berlin, Jeff A. Dror, **XG**, Joshua T. Ruderman

(In preparation: arXiv. 2206.XXXXX)

COBE-FIRAS





The Far Infrared Absolute Spectrophotometer

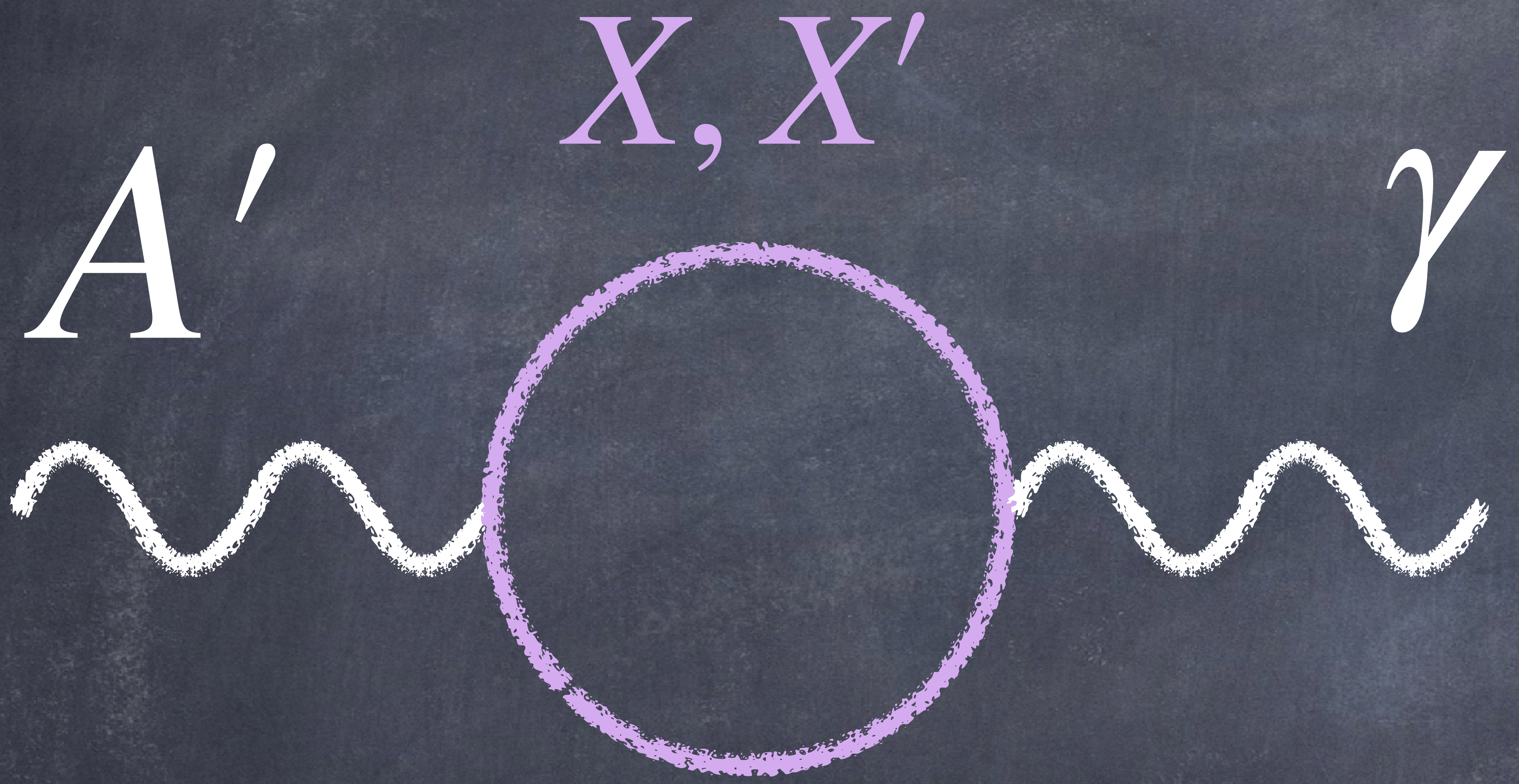
CMB is "perfect" blackbody(1994)

The existence of new physics may distort the CMB spectrum

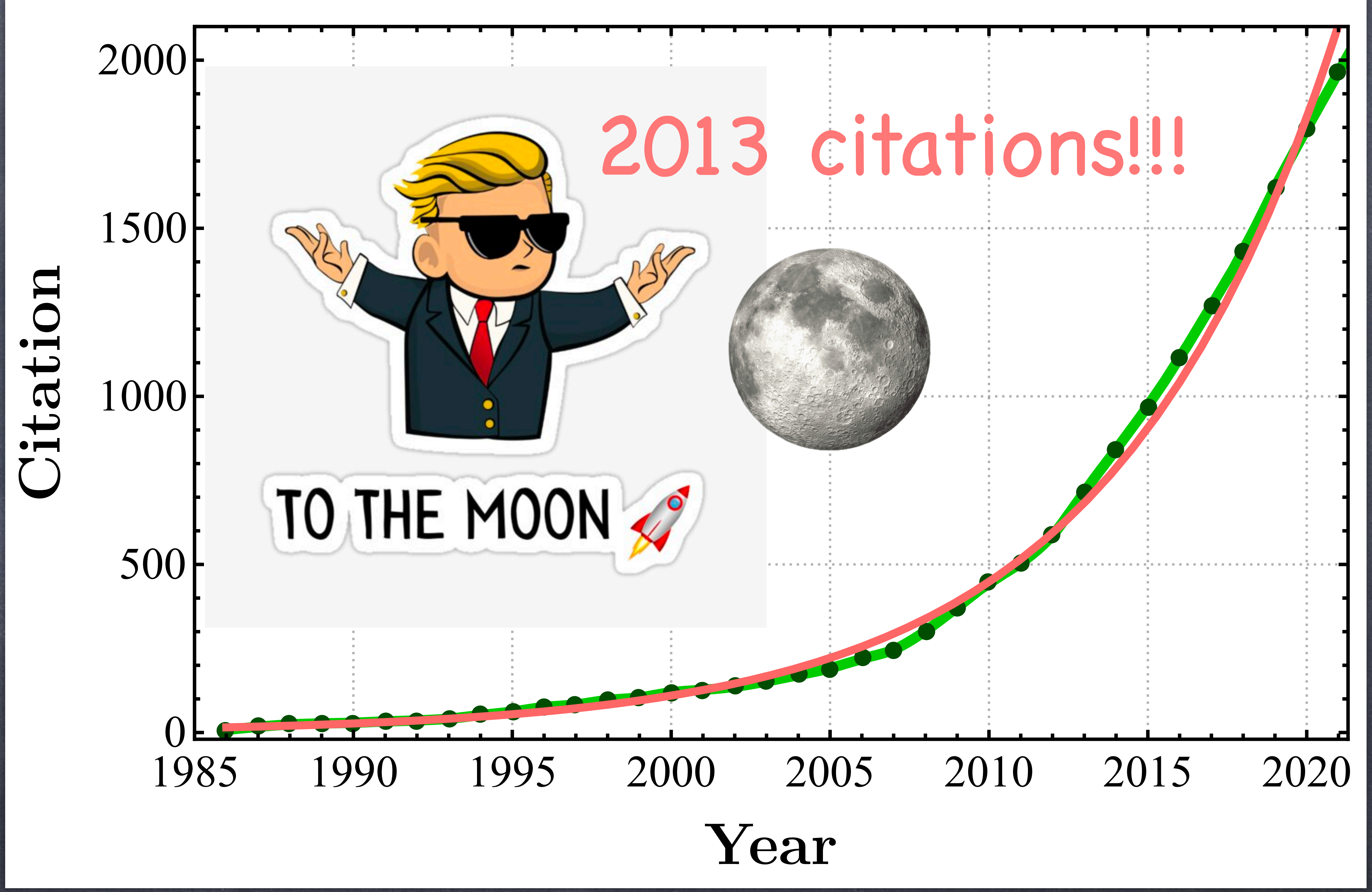
Energy injection or loss:

DM Decay/Anni into SM, PBH, $\gamma \leftrightarrow A', a, \ldots$

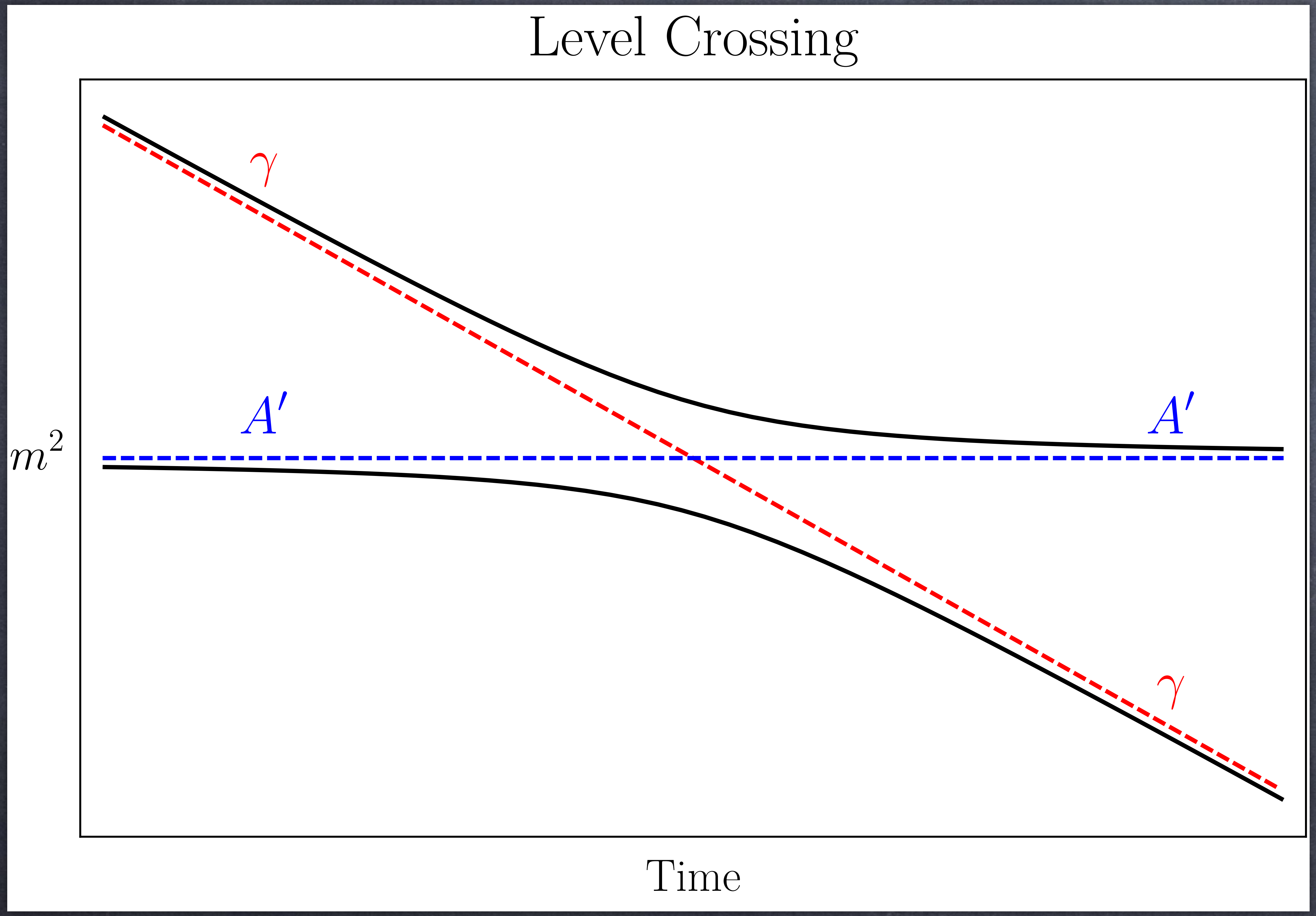
KineticMixing

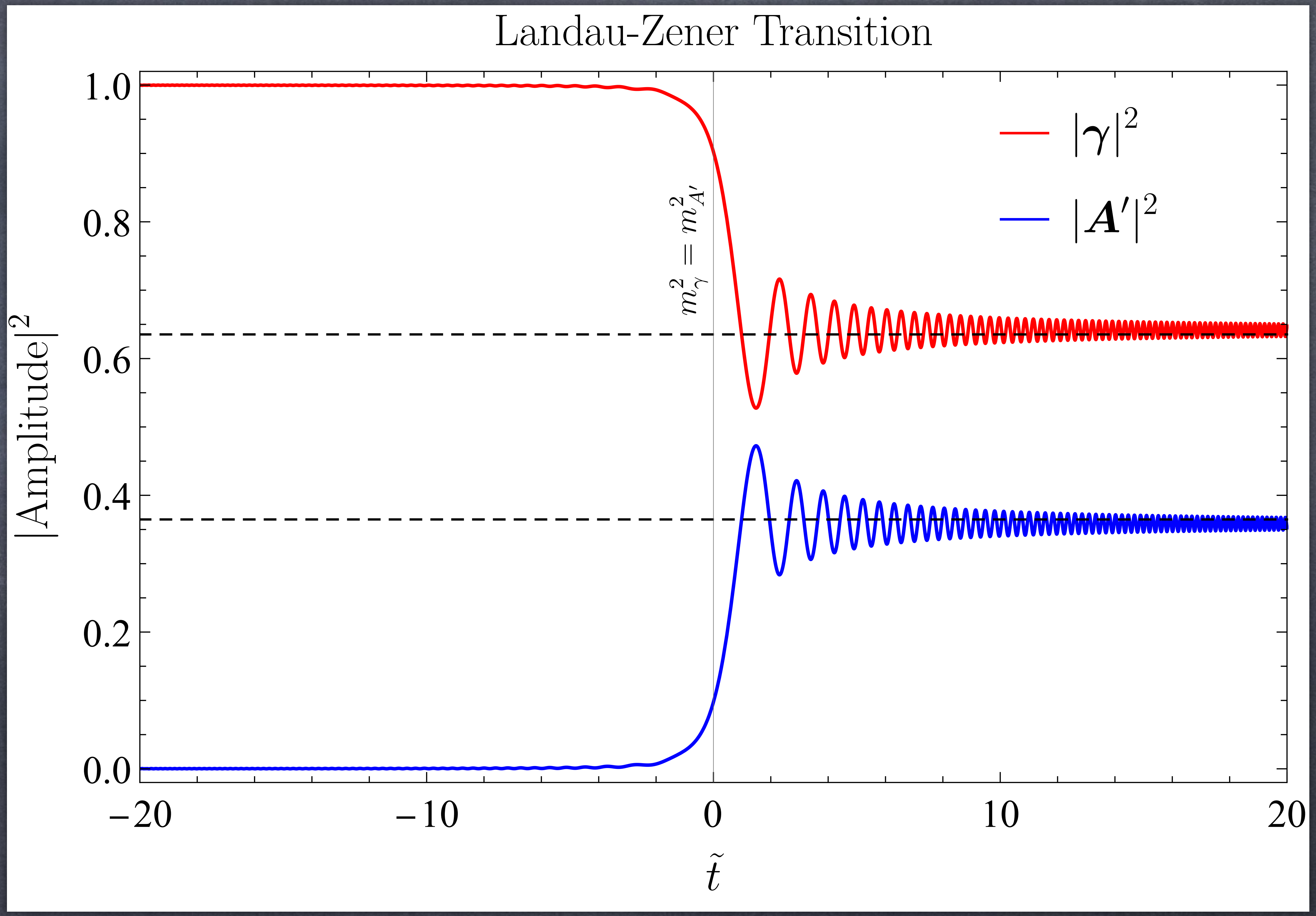


Bob Holdom 1985



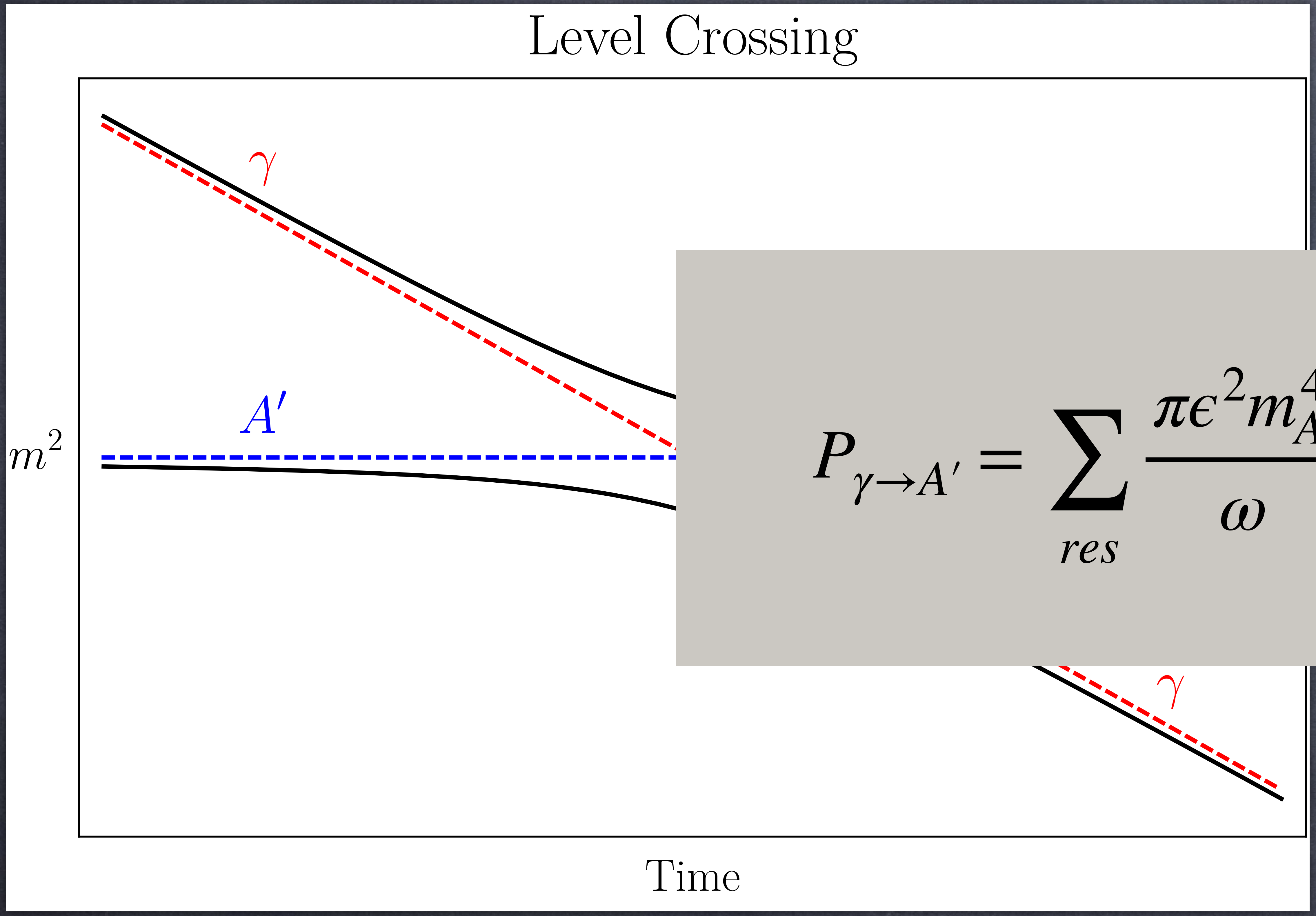
Landau-Zener Transition

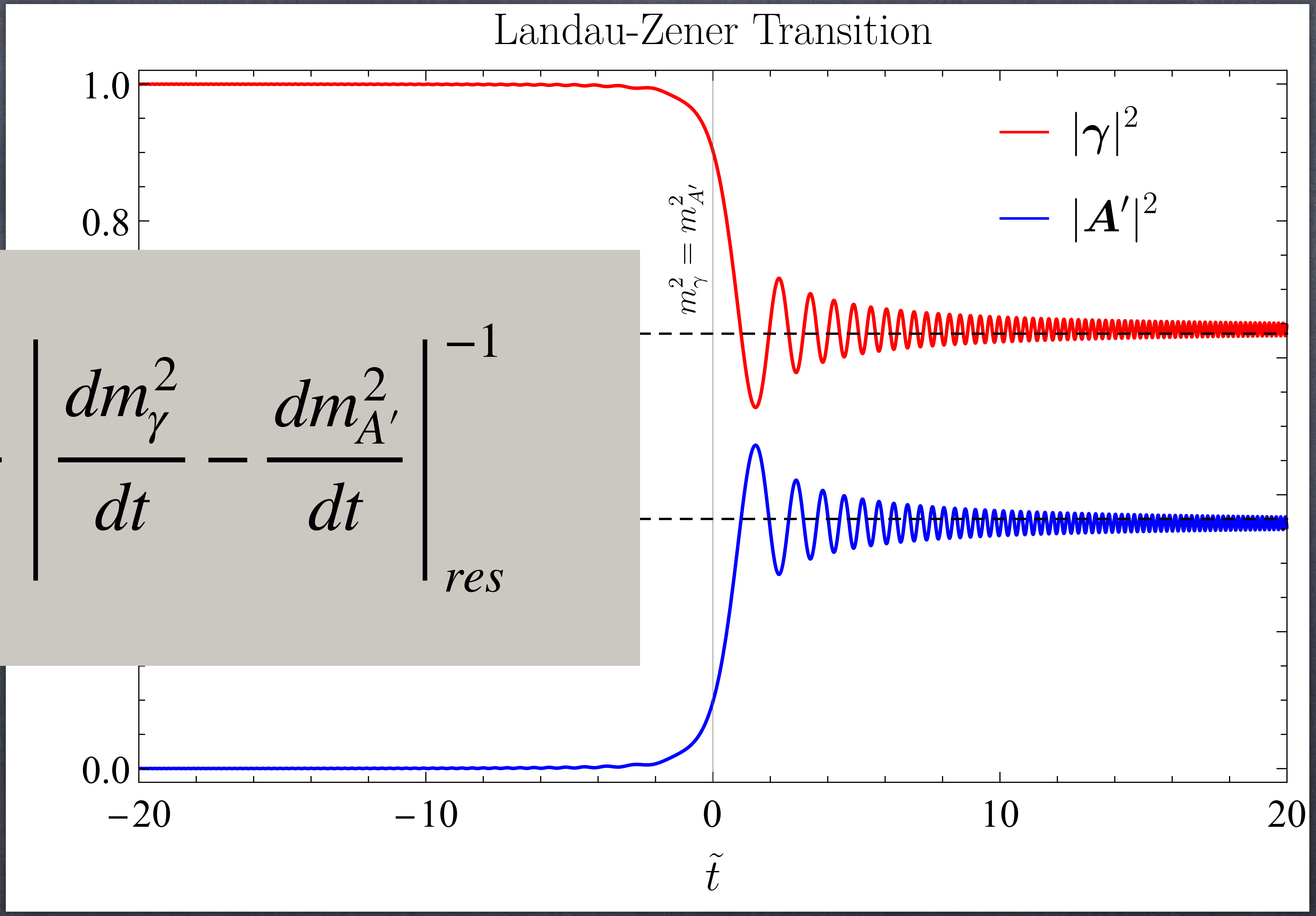




Landau, Zener 1932

Landau-Zener Transition

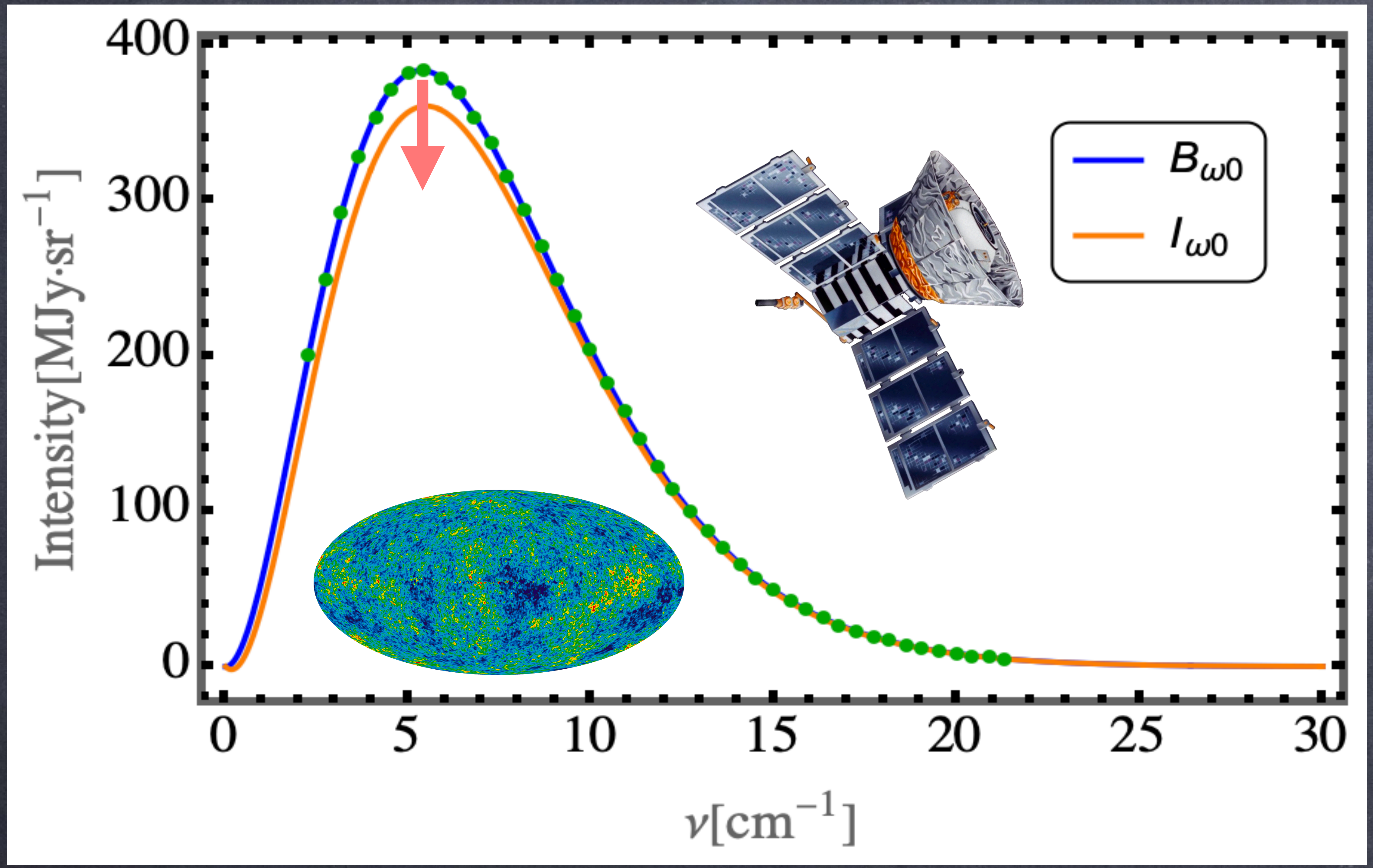




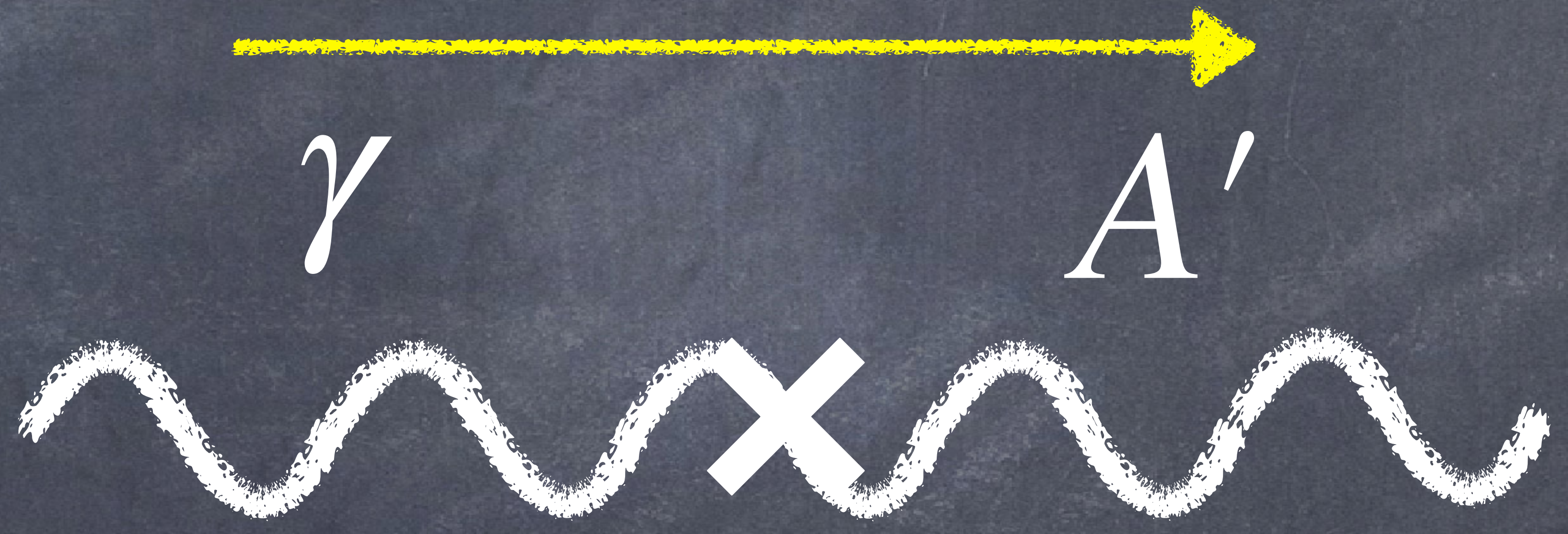
$$P_{\gamma\to A'} = \sum_{res} \frac{\pi\epsilon^2 m_{A'}^4}{\omega} \left| \frac{dm_\gamma^2}{dt} - \frac{dm_{A'}^2}{dt} \right|_{res}^{-1}$$

Landau, Zener 1932

$$\gamma \to A'$$

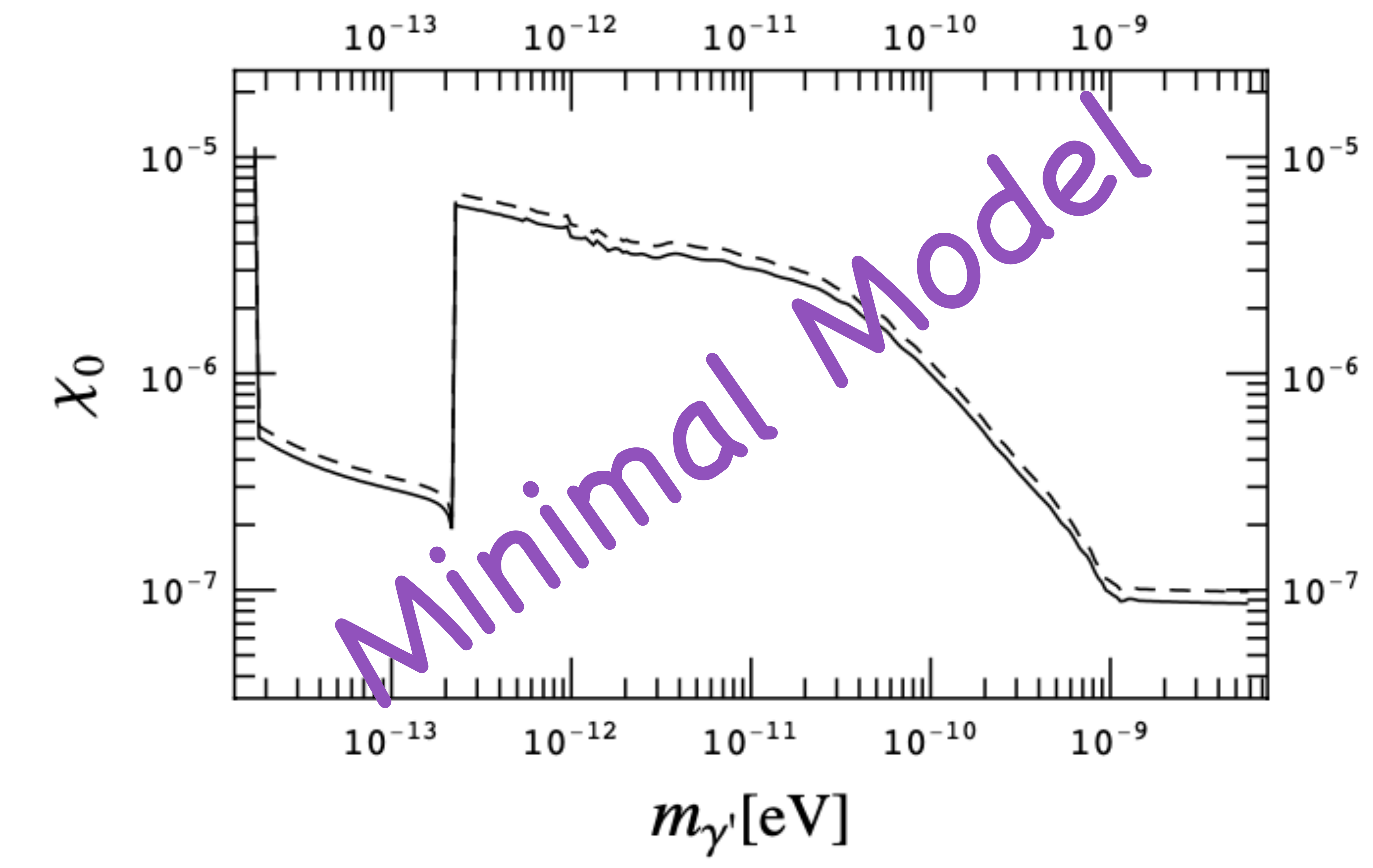


CMB photons get less!



$$I_{\omega_0} = B_{\omega_0}\left(1 - P_{\gamma \to A'}\right)$$

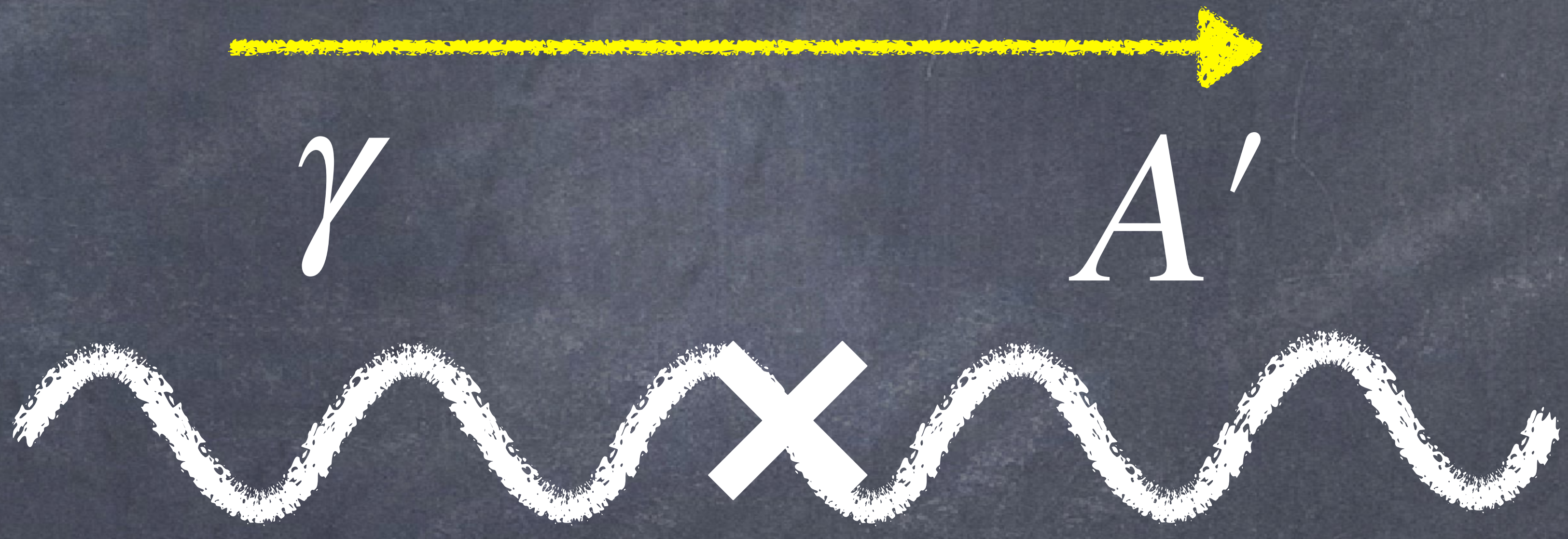
$$\gamma \to A'$$



Mirrizi, Redondo, Sigl 2009 JCAP

FIRAS Bound of Dark Photon

CMB photons get less!



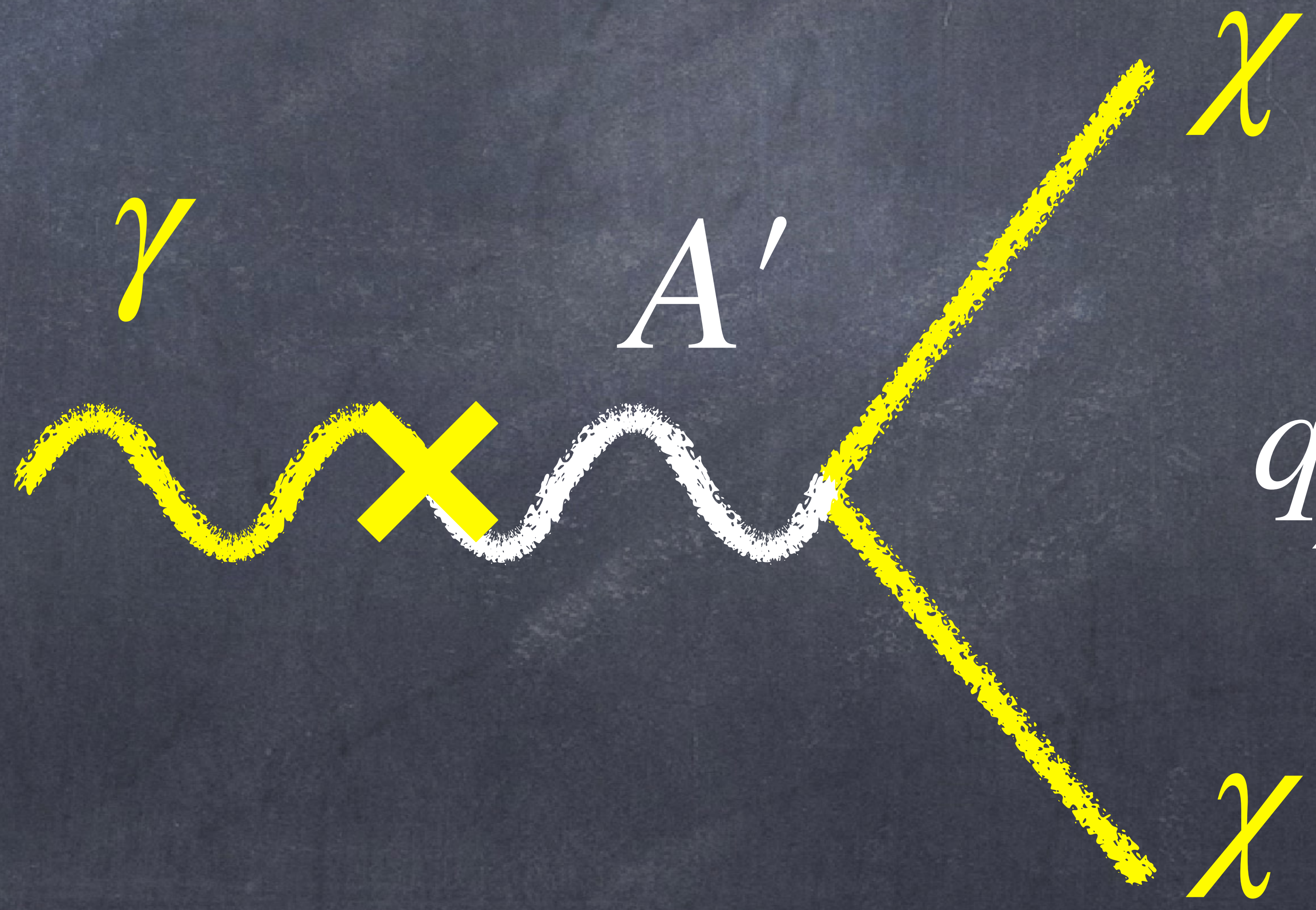
$$I_{\omega_0} = B_{\omega_0}\left(1 - P_{\gamma \to A'}\right)$$

Next-to-Minimal Model

Similar as the electron in SM, we introduce a particle χ charged under $U(1)_d$

$$m_{A'} \ll E$$

$$A' \rightarrow A' + \epsilon A$$



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

Millicharged Particle(mCP)

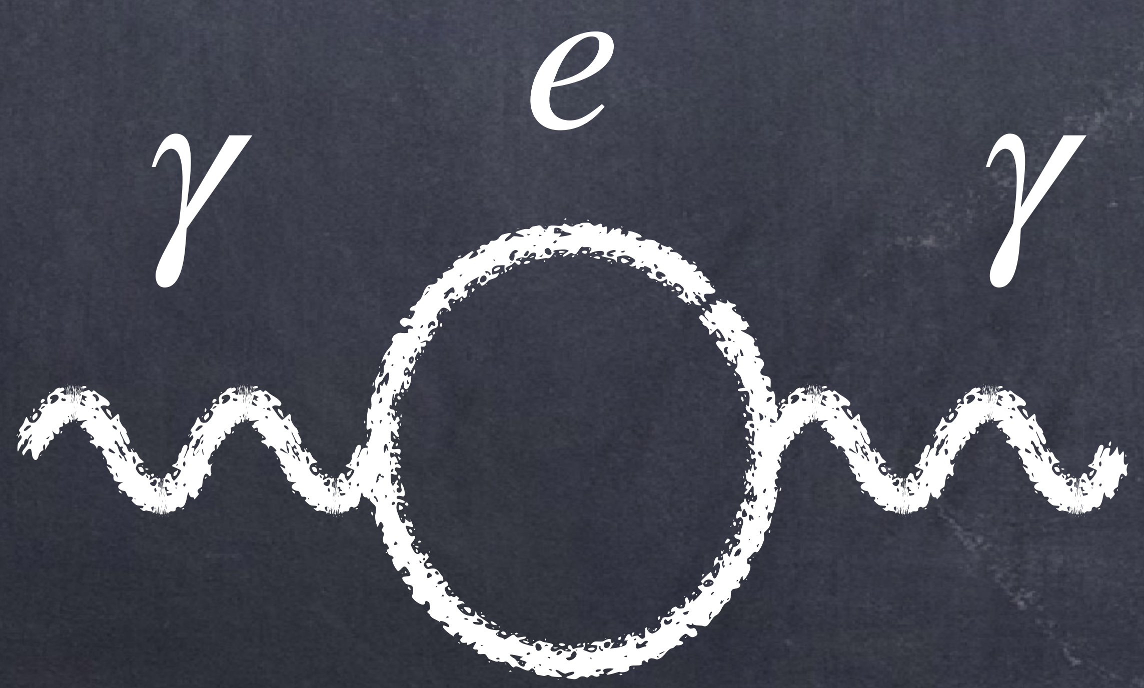
χ gives dark photon effective mass

Standard Model Sector

Plasmon Mass

$$m_\gamma^2 = \frac{4\pi\alpha_{em} n_e}{m_e}$$

Free Electron

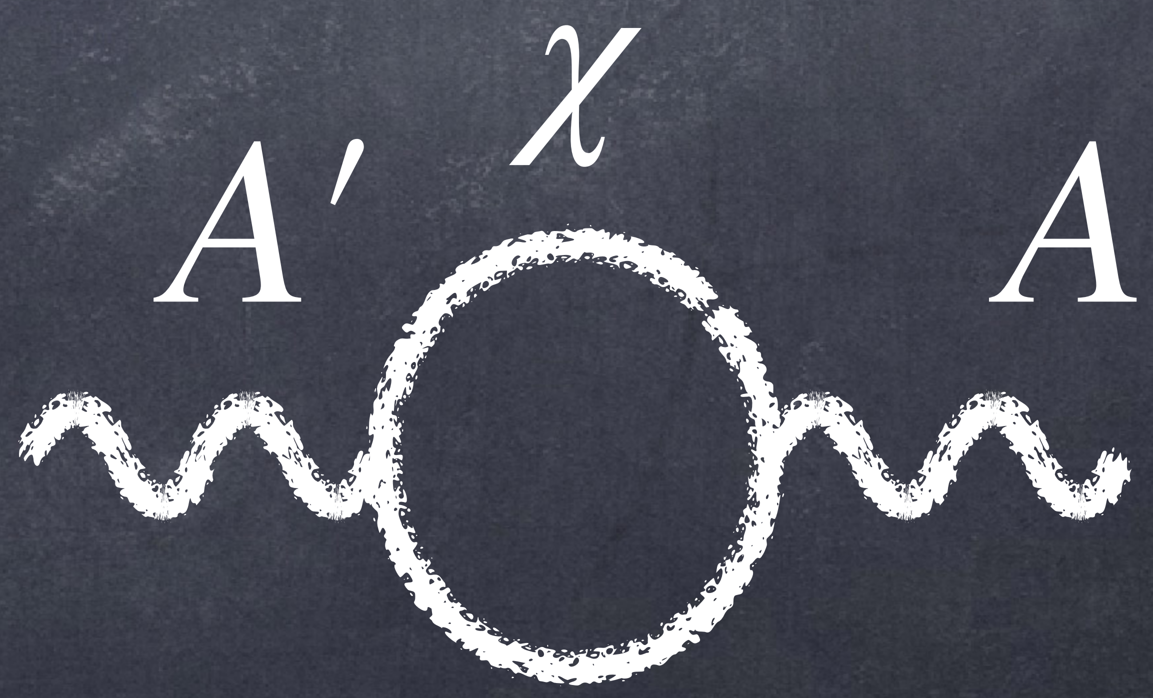


Dark Sector

Dark Plasmon Mass

$$m_{A'}^2 = \frac{4\pi\alpha_d n_\chi}{m_\chi}$$

Free χ



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Plasmon Mass

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Free Electron

Dark Sector

Dark Plasmon Mass

$$m_{A'}^2 = \frac{4\pi\alpha_d n_\chi}{m_\chi}$$

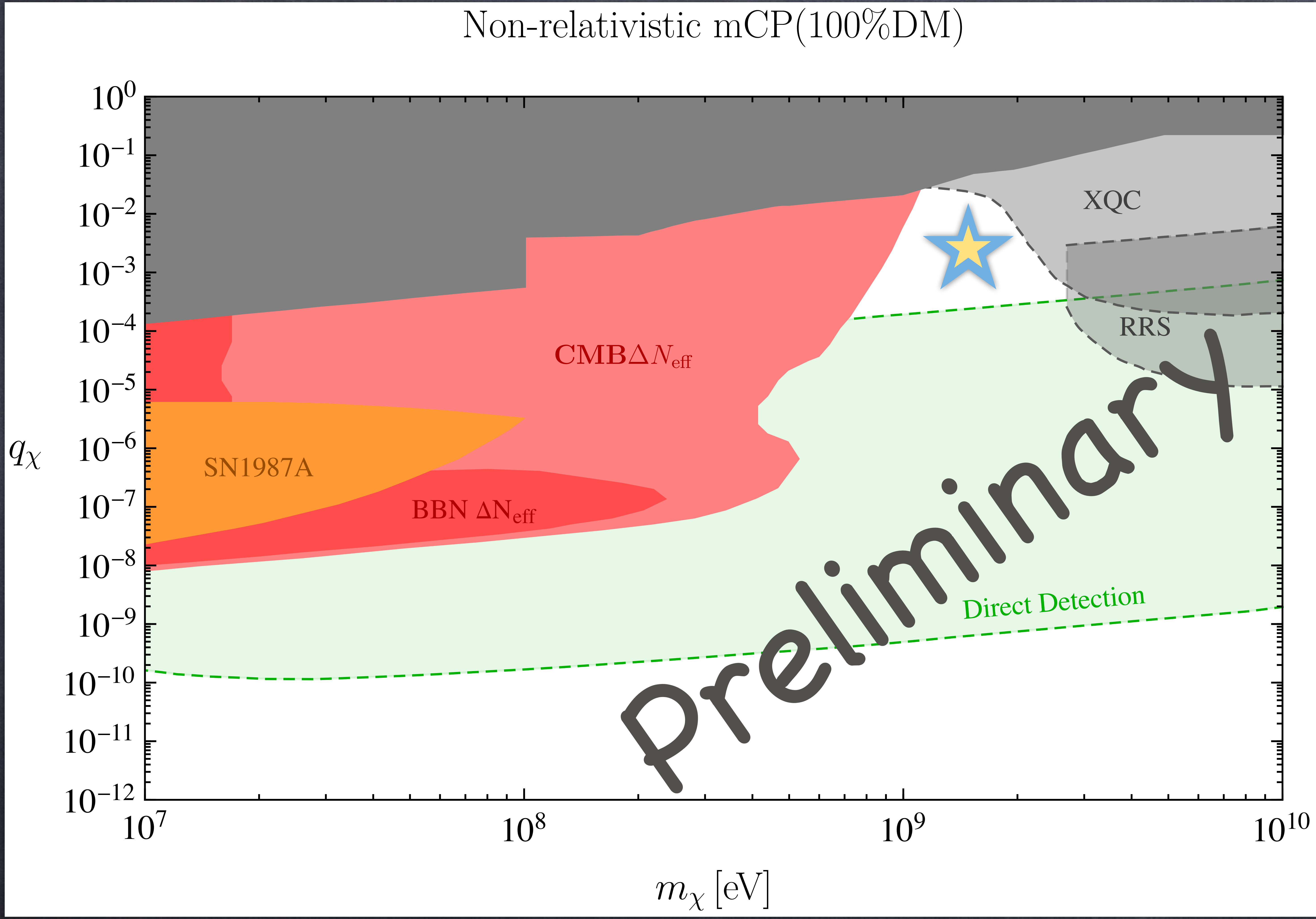
Free χ

Even though A' bare mass is zero,
because of the matter effect of χ
we still have $P_{\gamma\to A'} > 0$.

Plan

- How does FIRAS data constrain non-relativistic millicharged particle (Dark Matter)?
- How does FIRAS data constrain relativistic millicharged particle (Dark Radiation)?
- How do millicharged particles modify the dark photon FIRAS bound?

Non-relativistic mCP: $f_\chi = 100\,\%$



Direct Detection/XQC/RRS

Emken, Essig, Kouvaris, Sholapurkar 1905.06348,
Mahdawi, Farrar 1804.03073

CMB/BBN $\Delta N_{\rm eff}$

Vogel, Redondo 1311.2600

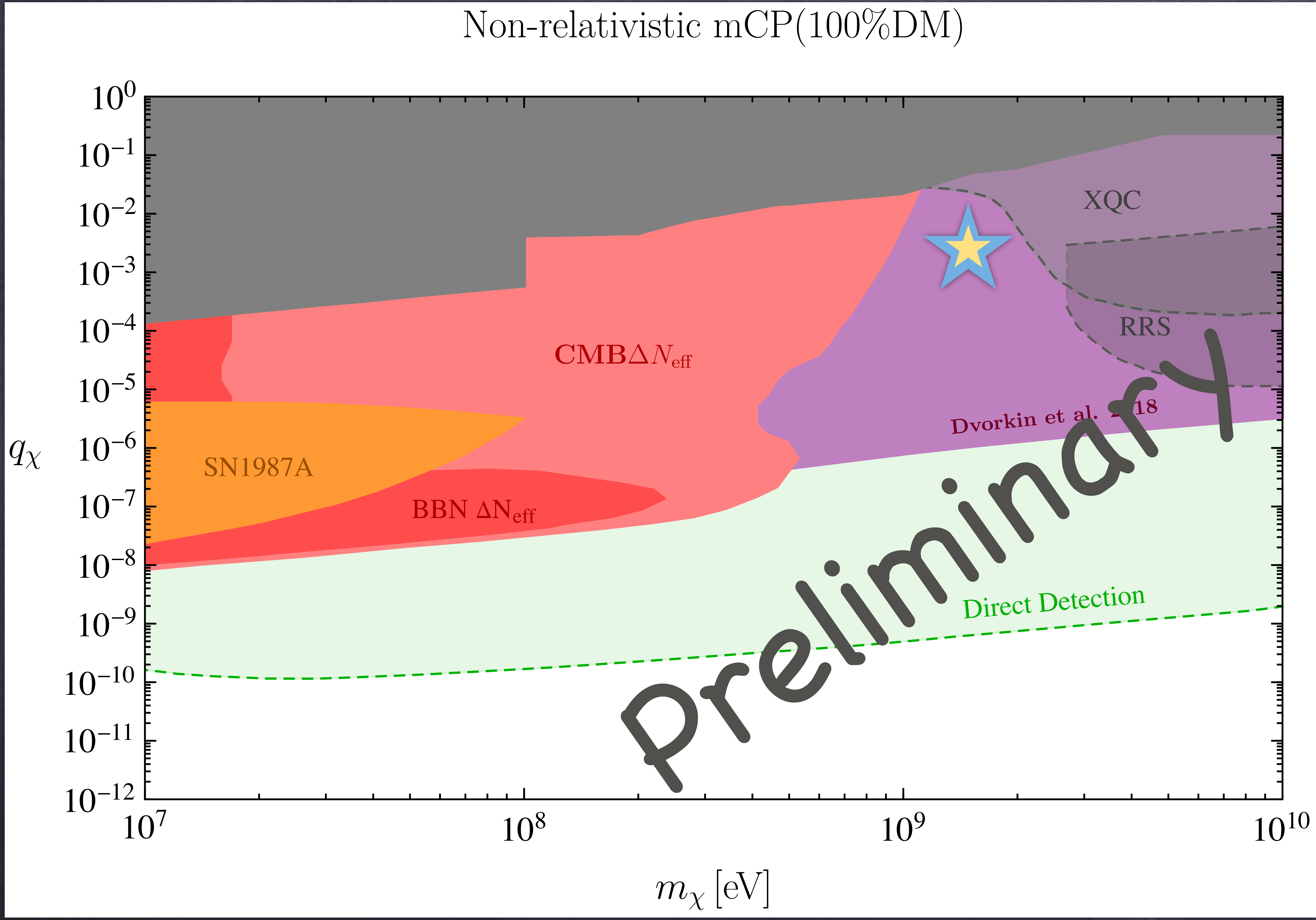
Ground Based Experiments

SLAC-mQ, ArgoNet, Collider etc

Unclosed Gap:

$m_\chi \sim 1 GeV, \quad q_\chi \sim 10^{-3}$

Non-relativistic mCP: $f_\chi = 100\,\%$



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CMB: DM-Baryon Scattering

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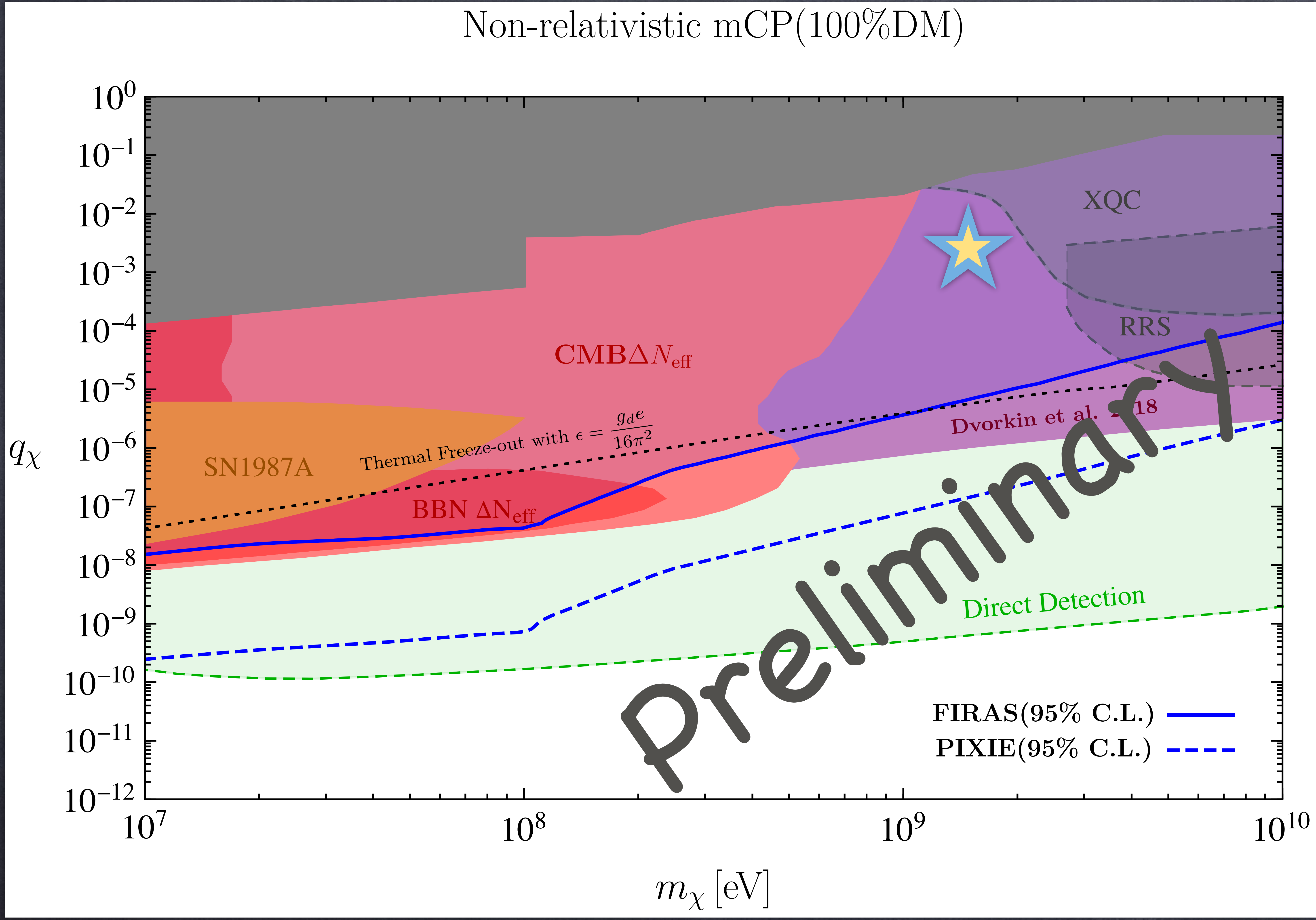

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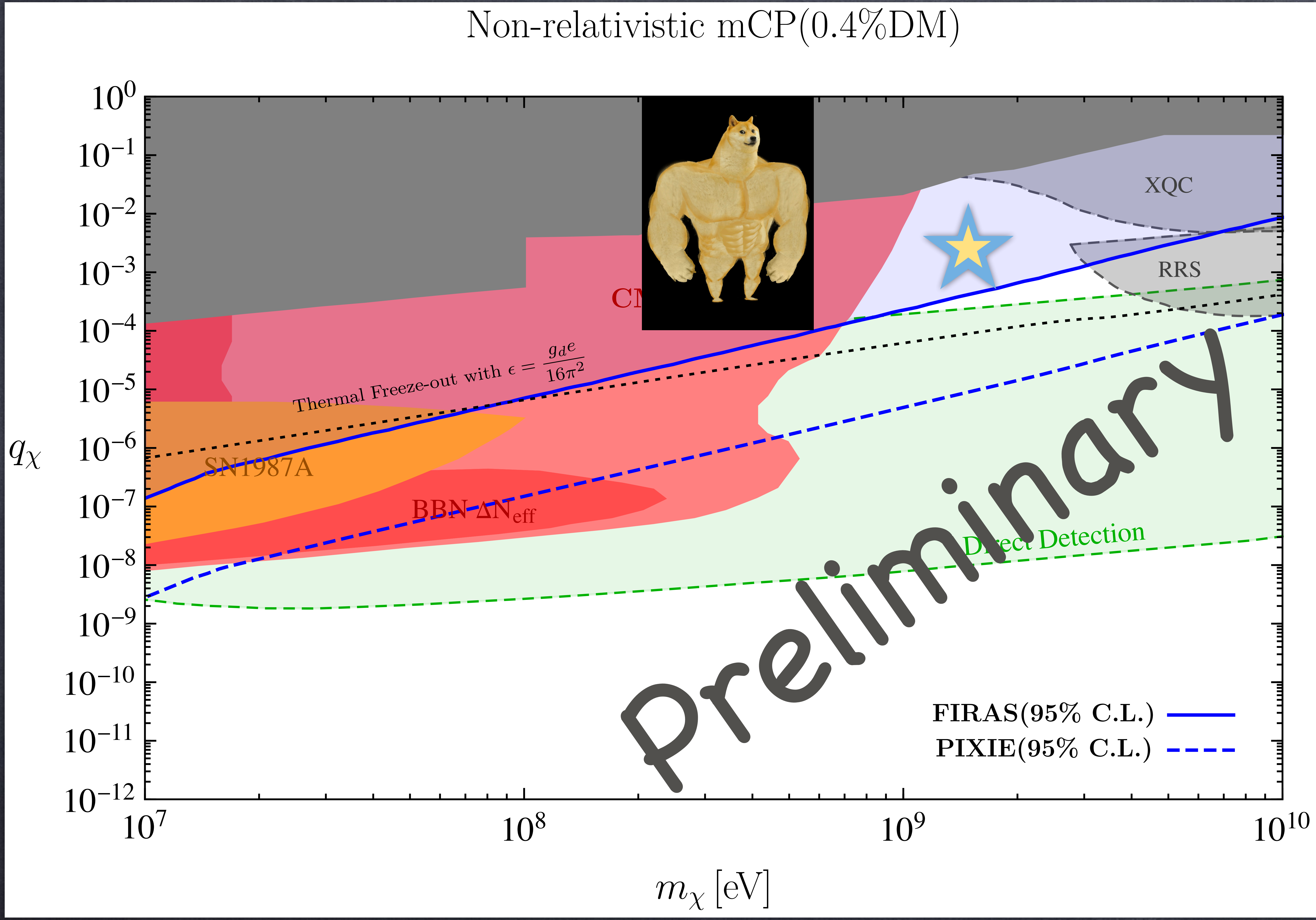
FIRAS(PIXIE): Our work

Non-relativistic mCP: $f_\chi = 0.4\,\%$



If mCPs are just %-leval of DM, CMB bound of DM-baryon scattering doesn't apply any more because mCPs can mimic the behavior of baryons.

Dubovsky et. al. 0311189, 1310.2376

Putter, Dore, Gleyzes, Green, Meyers 1805.11616

FIRAS bound from CMB spectral distortion gets a bit weaker, but **still exists.**

Relativistic mCP

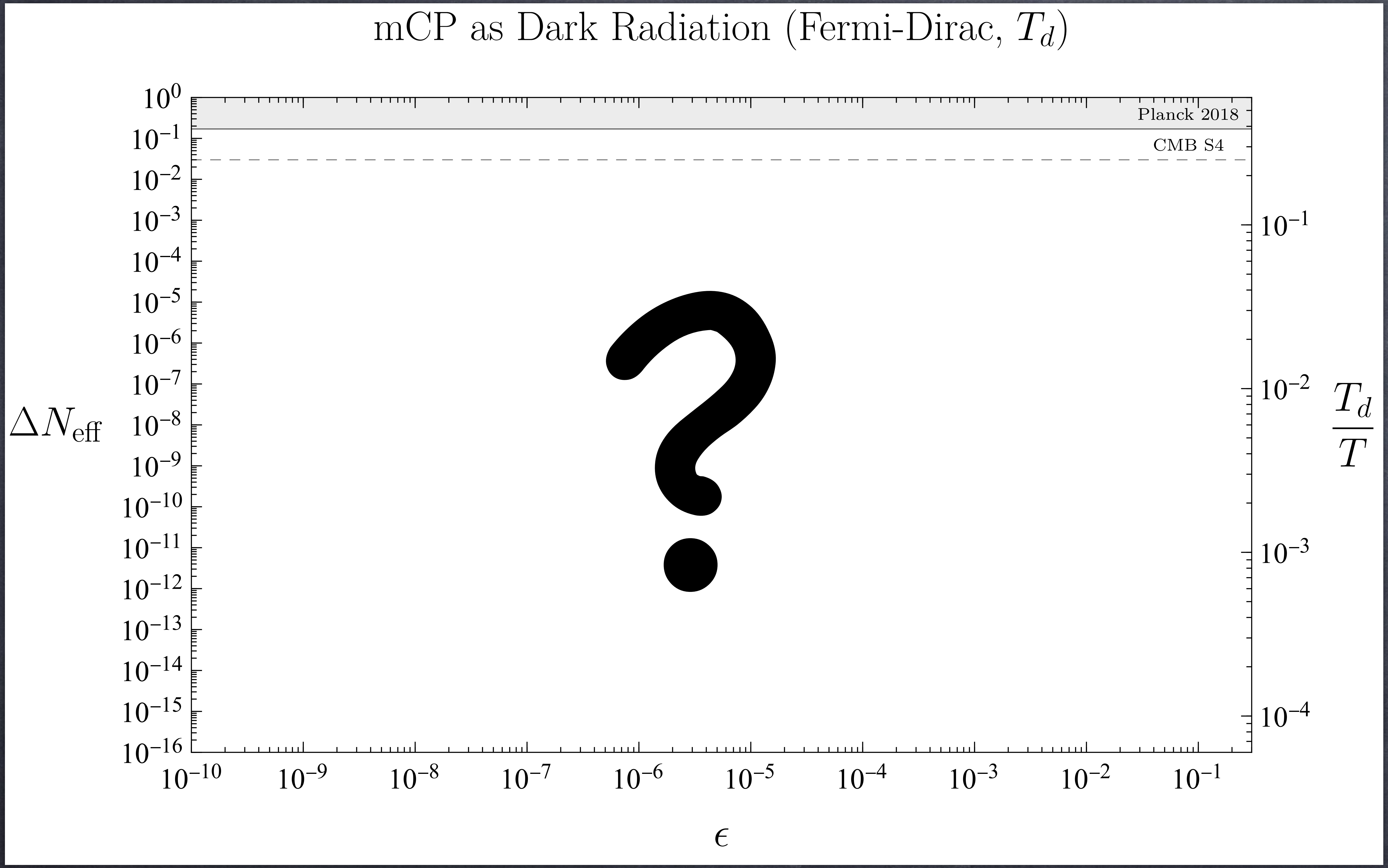
Relativistic mCPs are the dark radiation and contribute to the ΔN_{eff}

$$\begin{cases} \text{Planck 2018: } N_{eff} = 2.99^{+0.34}_{-0.33} \\ \text{BBN: } N_{eff} = 2.85 \pm 0.28 \\ \text{CMB S4 (Future): } \Delta N_{eff} \sim 0.03 \end{cases}$$

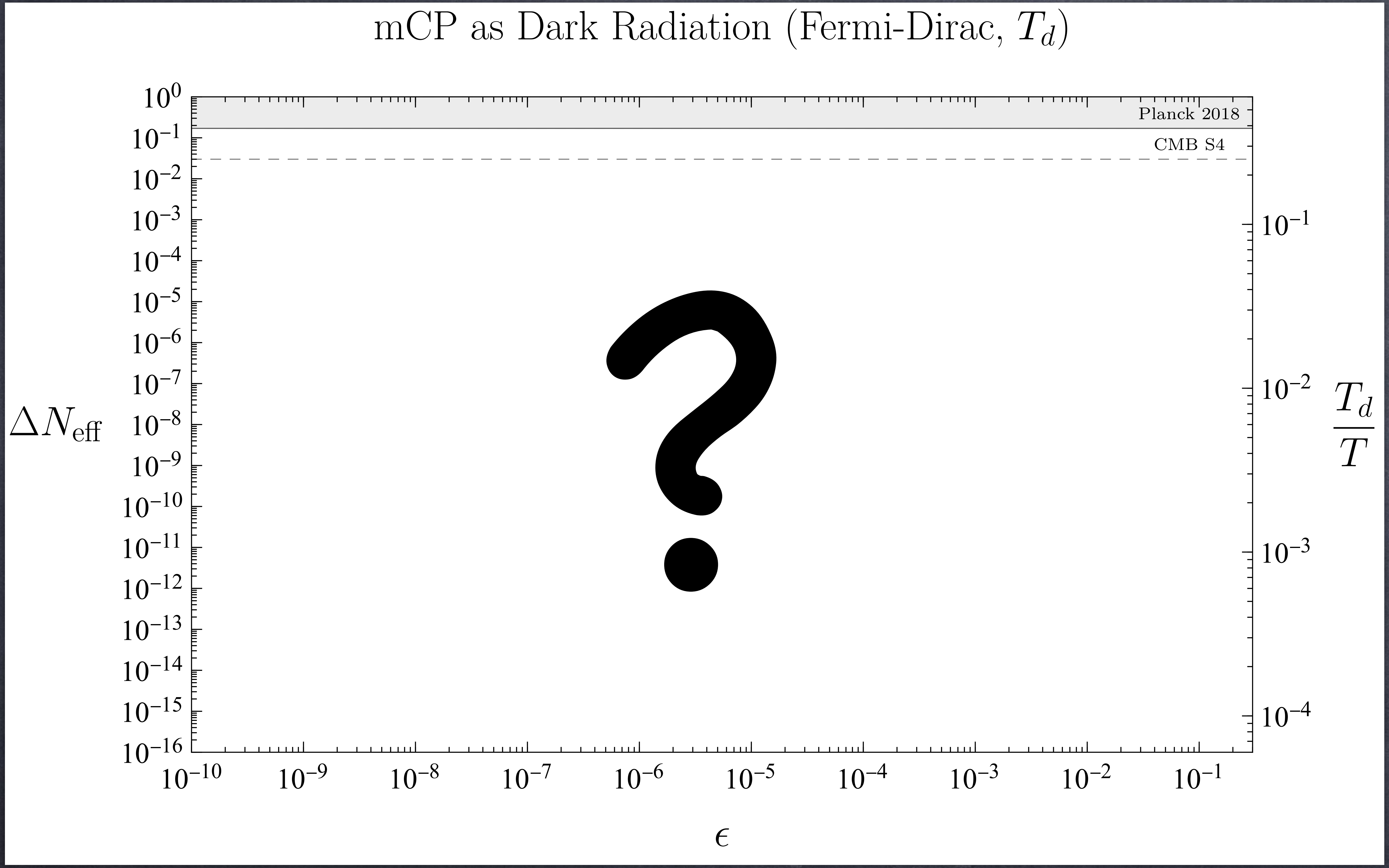
For mCPs carrying little amount of charge

$q_\chi \sim 10^{-14}$, FIRAS can give much stronger bound.

Relativistic mCP



Relativistic mCP



Assume mCPs is produced with thermal phase space.

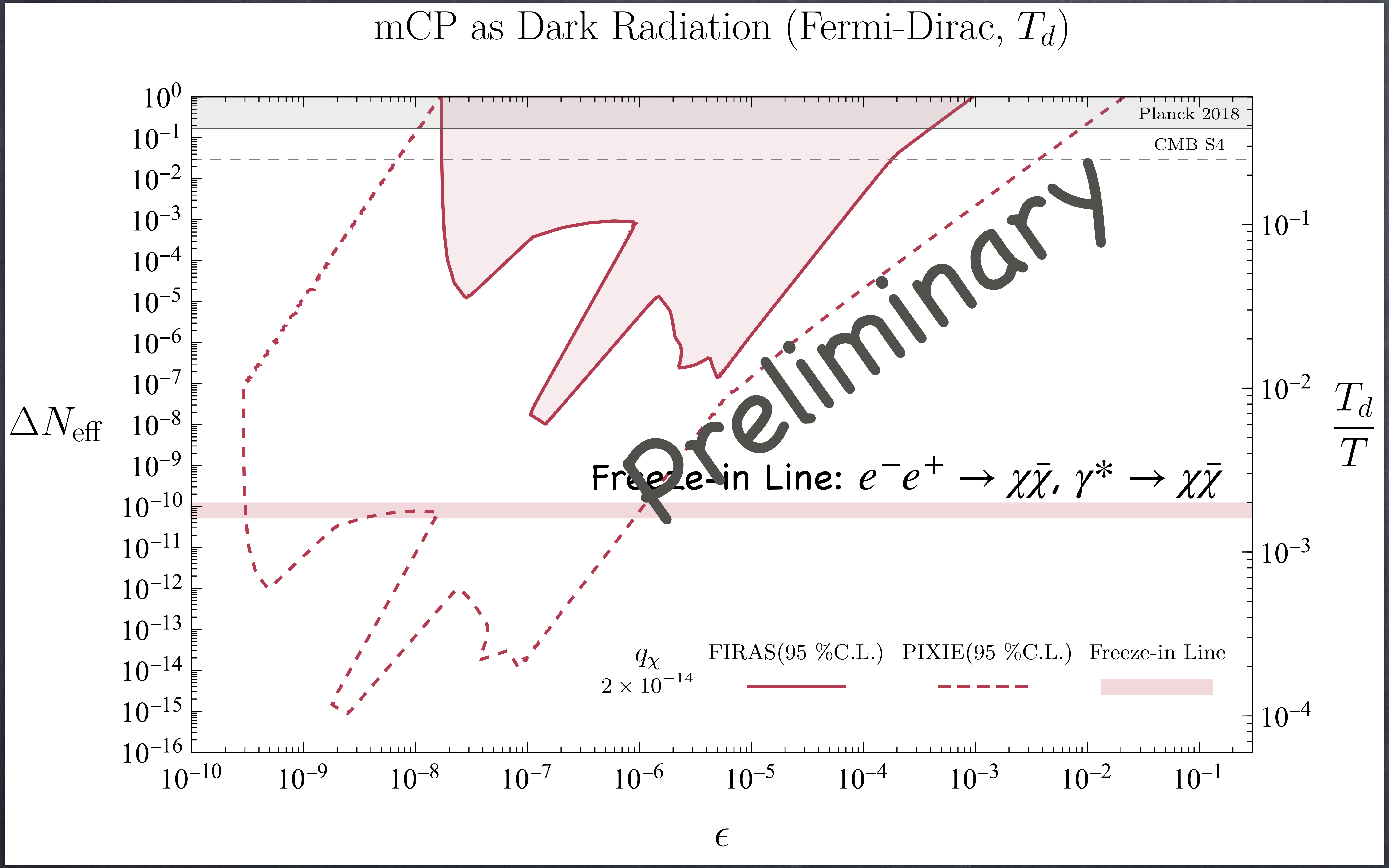
$$m_{A'} \sim g_d T_d$$

$$\Delta N_{eff} \sim \left(T_d / T_{SM}\right)^4$$

$$m_{A'} \propto \frac{q_\chi}{\epsilon} \times \left(\Delta N_{eff}\right)^{1/4}$$

Can reach very small ΔN_{eff} !!!

Relativistic mCP



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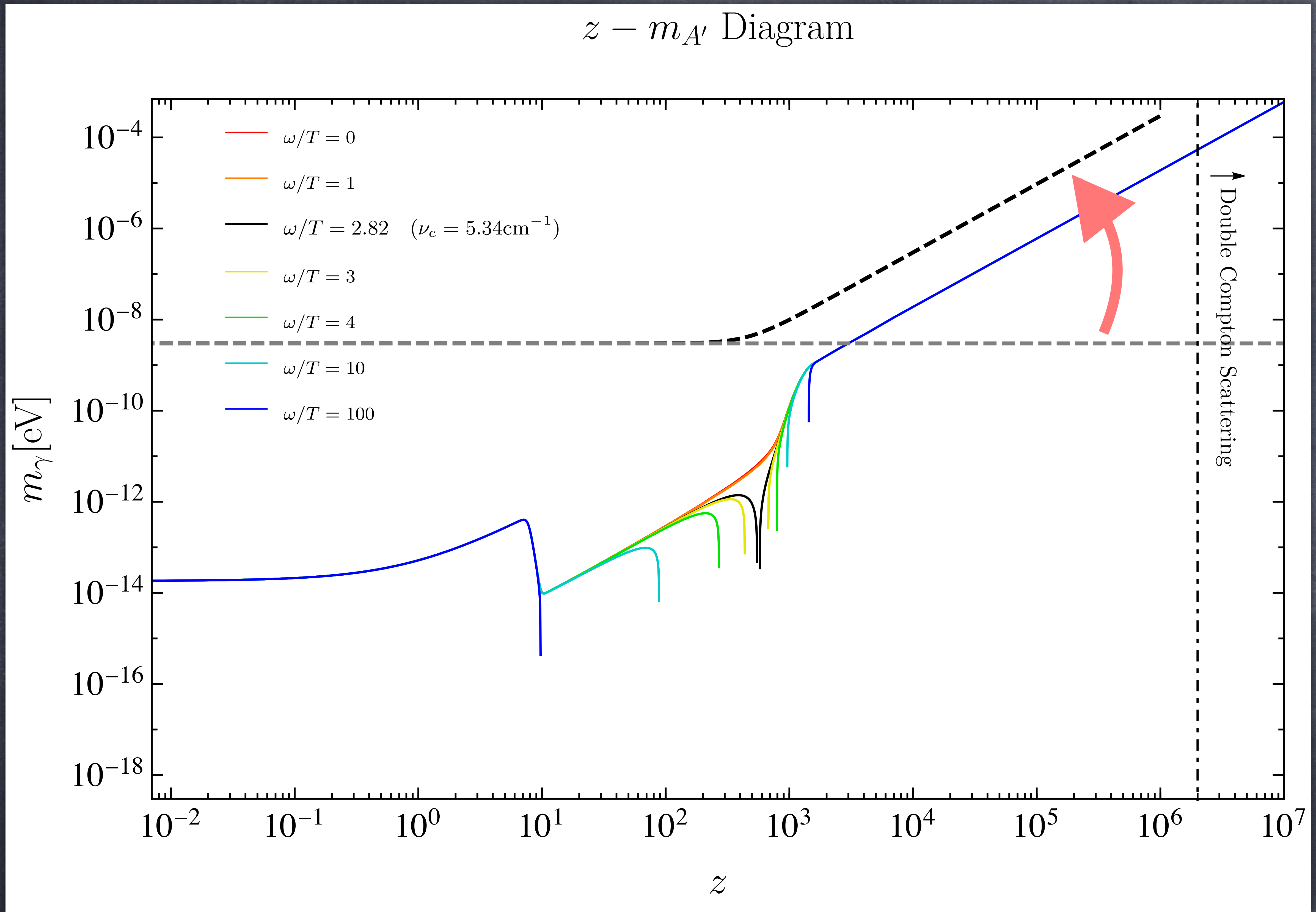
Can reach very small ΔN_{eff} !!!

Can touch Freeze-in line in future PIXIE satellite!!!

How mCPs change the DP bound?

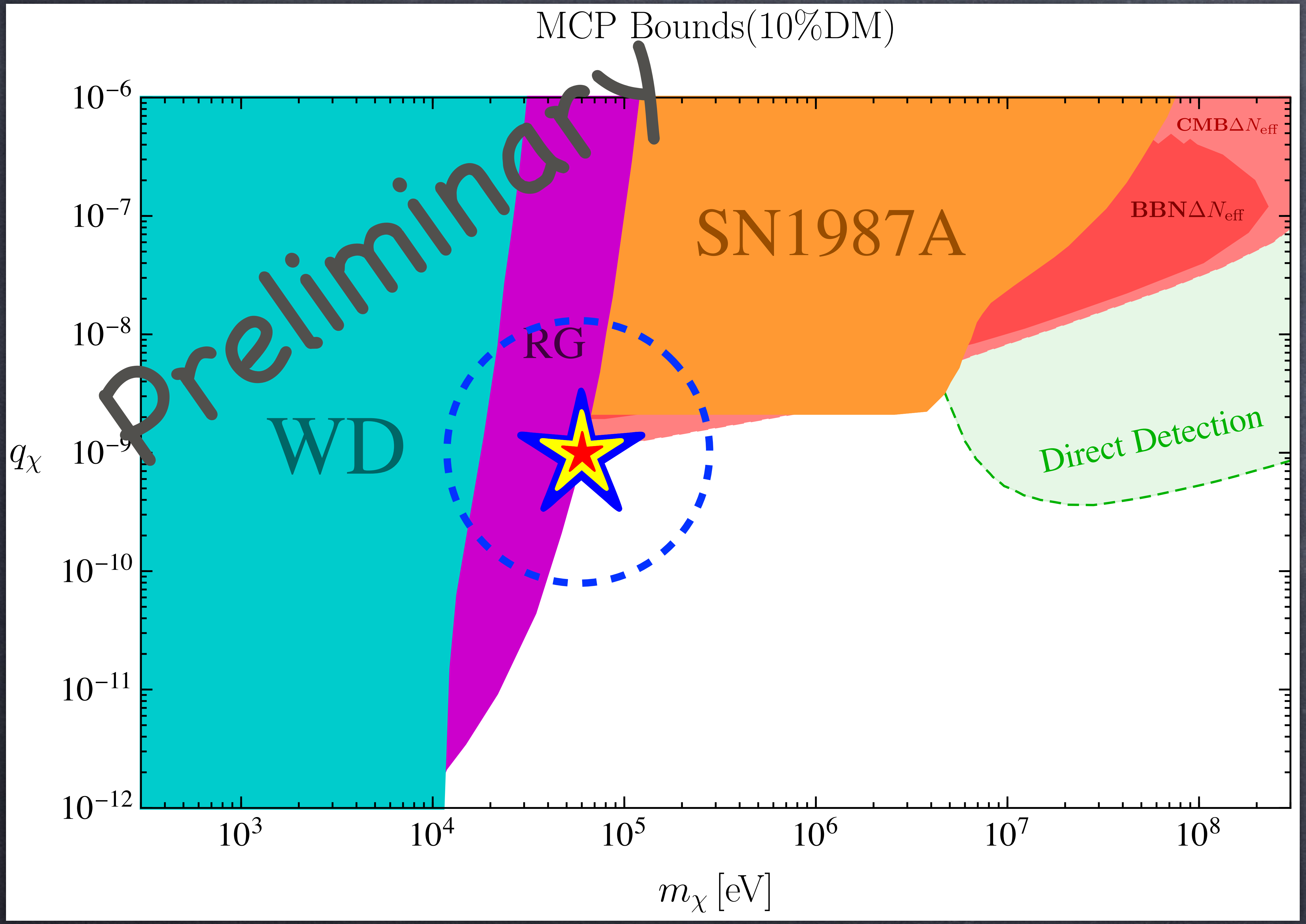


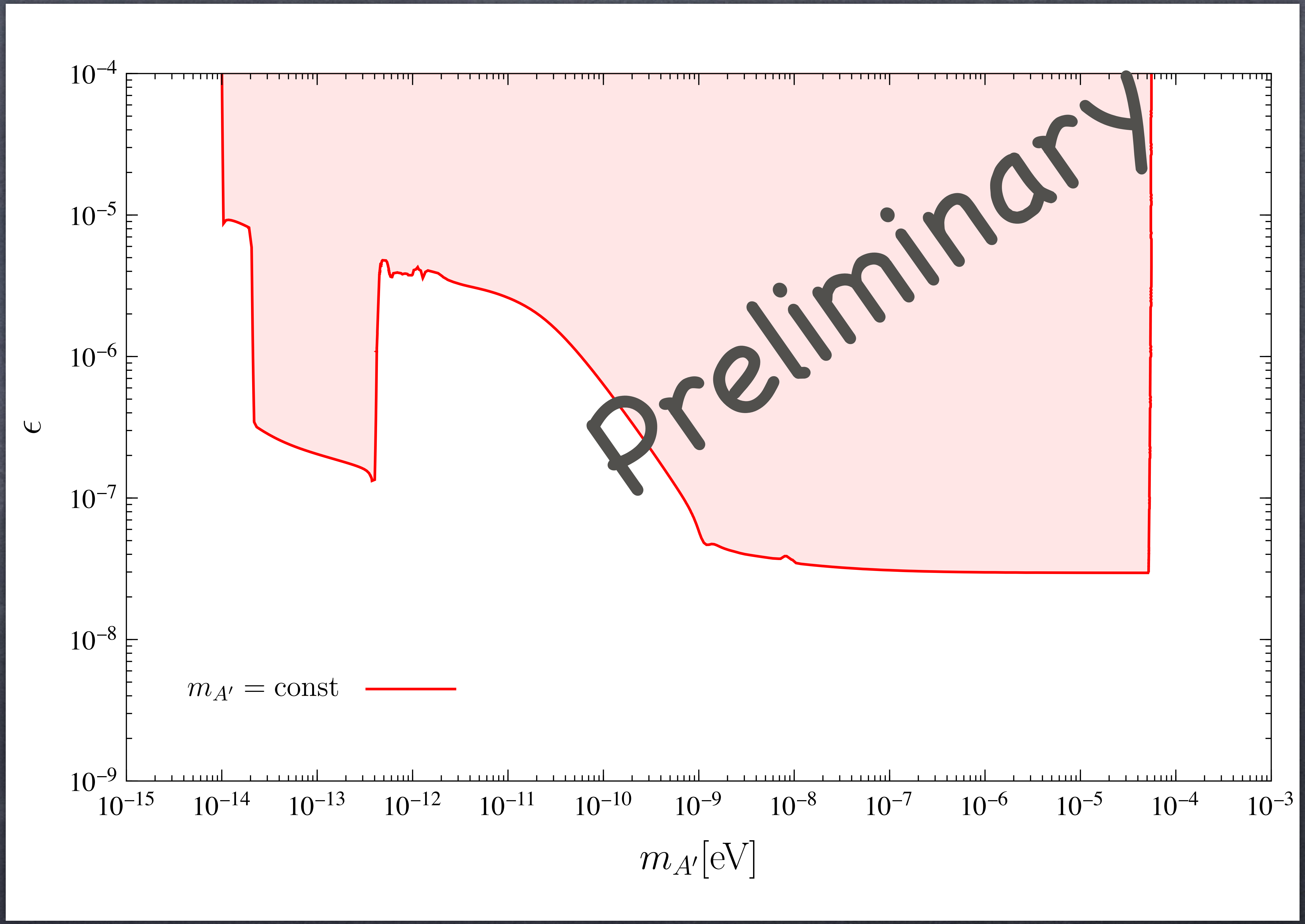
Non-Relativistic

$$m^2_{A'} = m^2_{A',Bare} + m^2_{A',Th}$$

$$m_{A',Th} \simeq \sqrt{\frac{4\pi\alpha_d n_\chi}{m_\chi}} \propto (1+z)^{3/2}$$

How mCPs change the DP bound?





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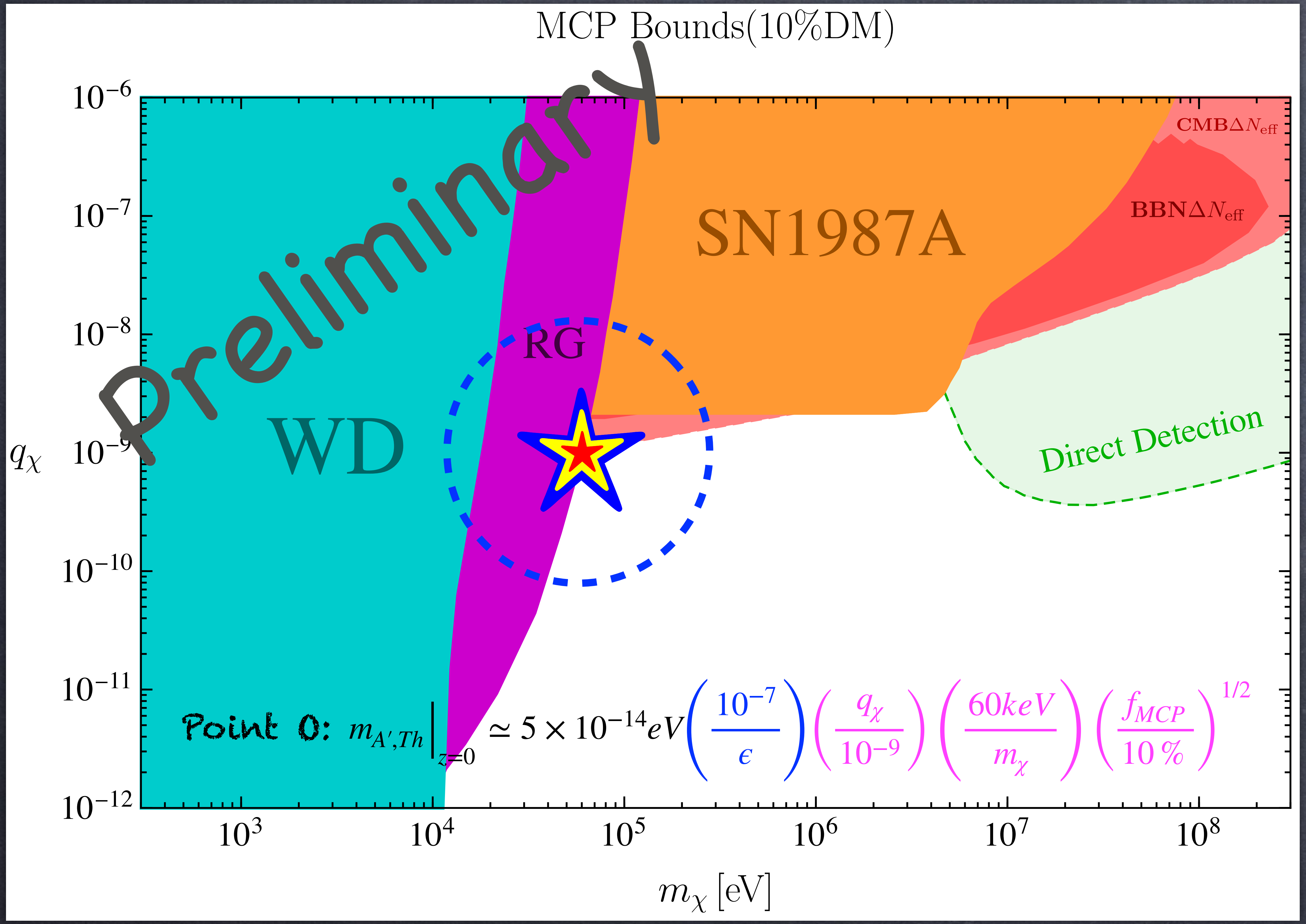

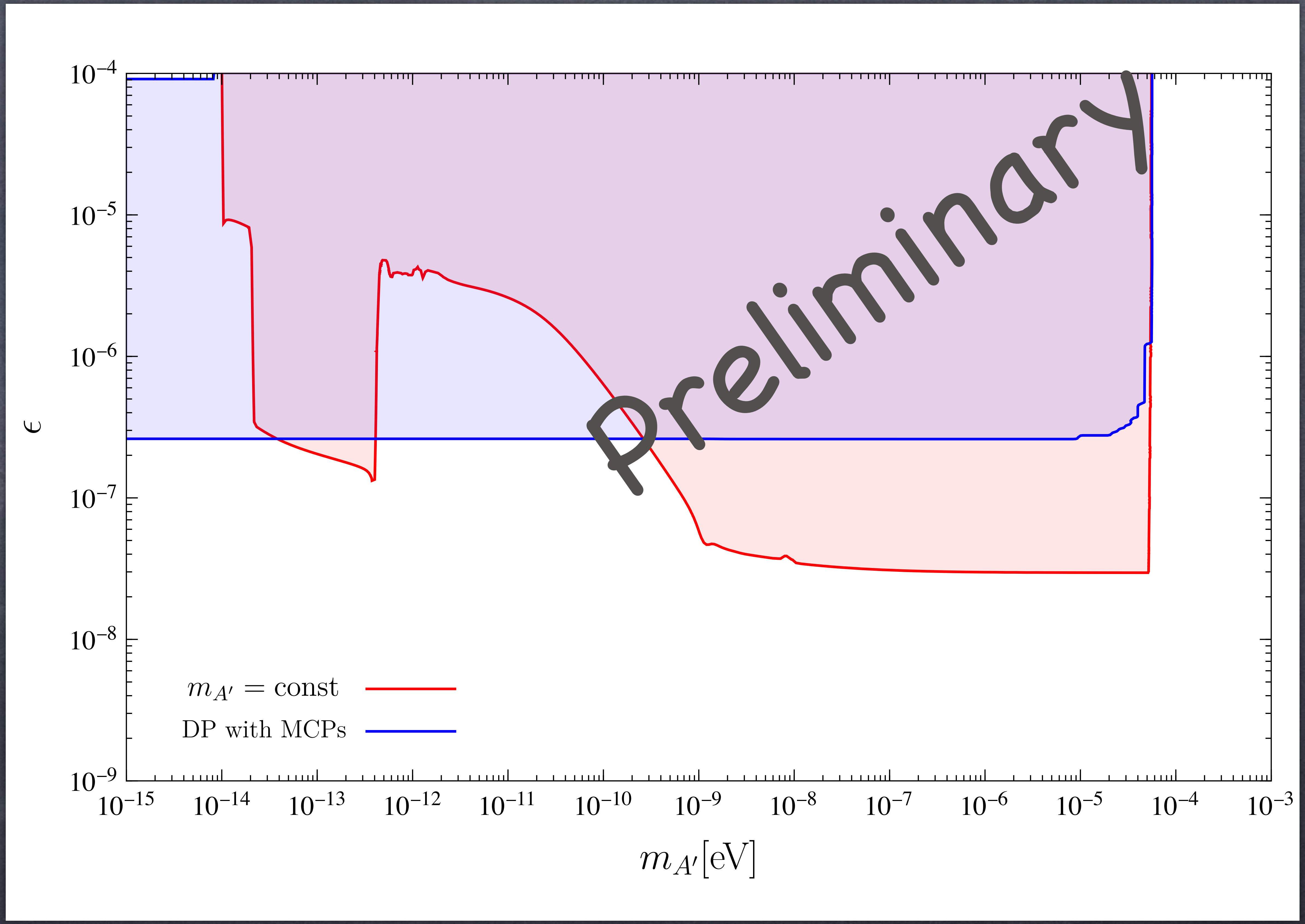

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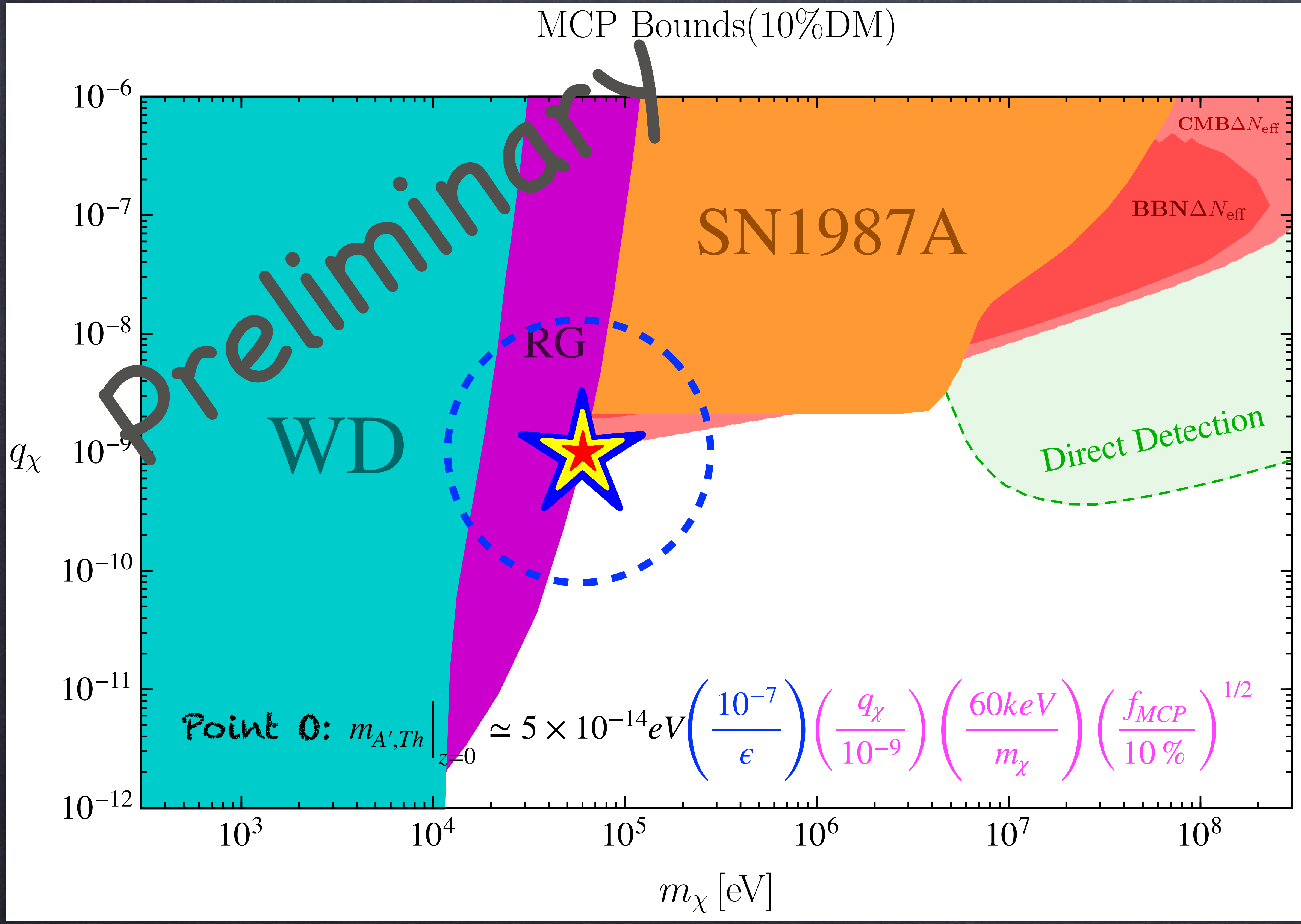
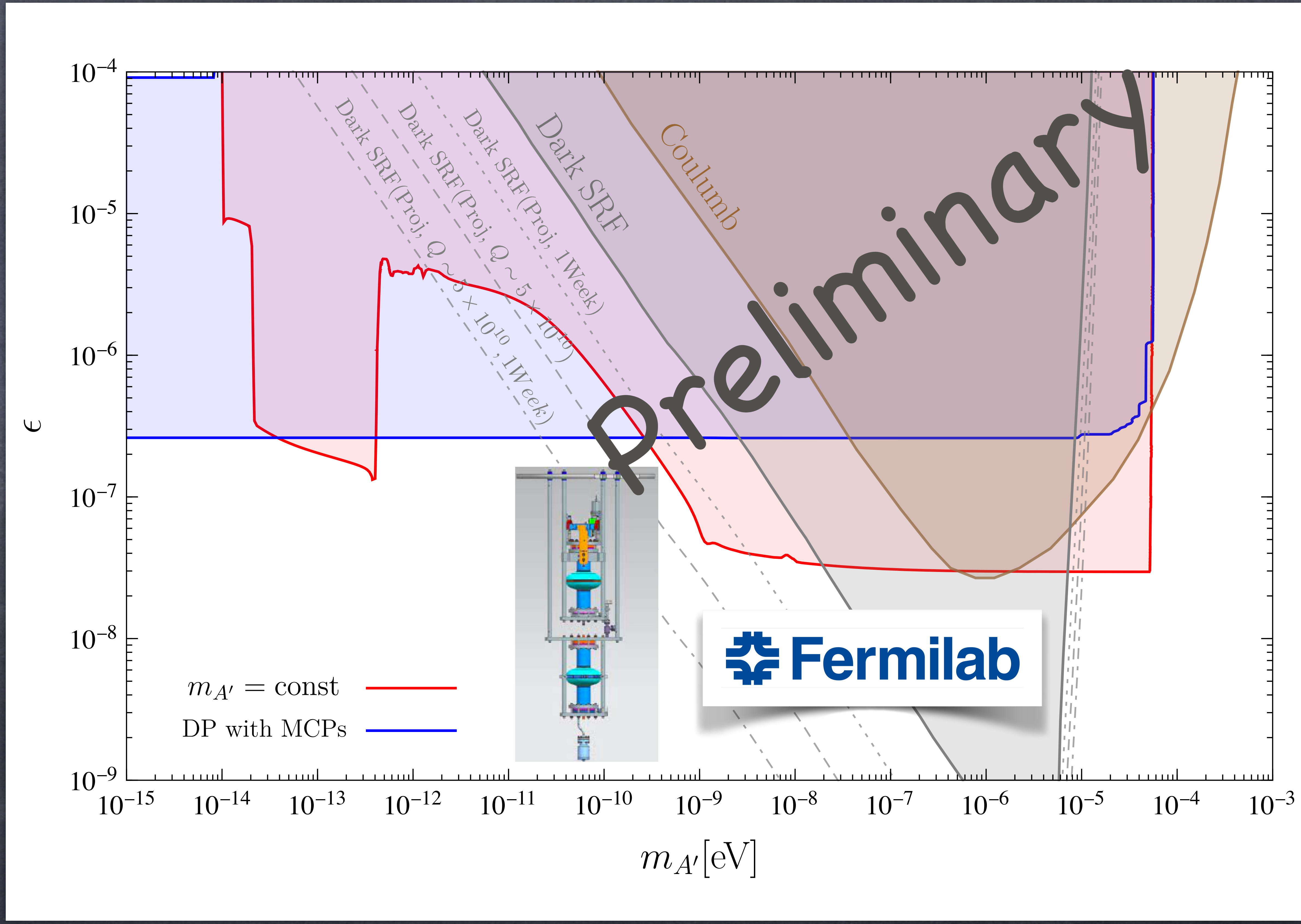
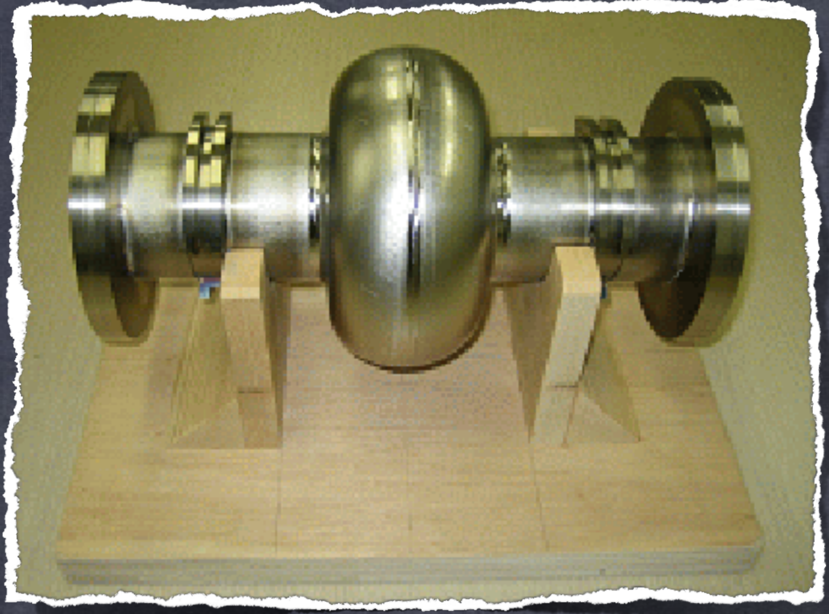




Summary

- From the measurement of COBE-FIRAS, CMB photons have a black body spectrum within the error bar of the observation. The spectral distortion of the CMB spectrum is a powerful tool for detecting new physics.
- The mixing between γ and A' is a good example, and the constraint on A' parameter space is only given in the minimum model assumption (Redondo et al. 2008).
- In non-minimal cases, the matter effect of the MCPs contributes to the dark photon's effective mass.
- We can give strong constraints on MCP parameter space. The existence of MCP can also change the FIRAS bound in A' parameter space, which can be constrained again by ground-based experiments such as Coulumb and Dark SRF.

Appendix



Dark SRF Experiment

Light Shinning Through The Wall

Emitter Cavity
($\gtrsim 10^{25}$ Photons)

Receiver Cavity
(Empty)