A Particle Physicist's Perspective on EDGES

Sam McDermott

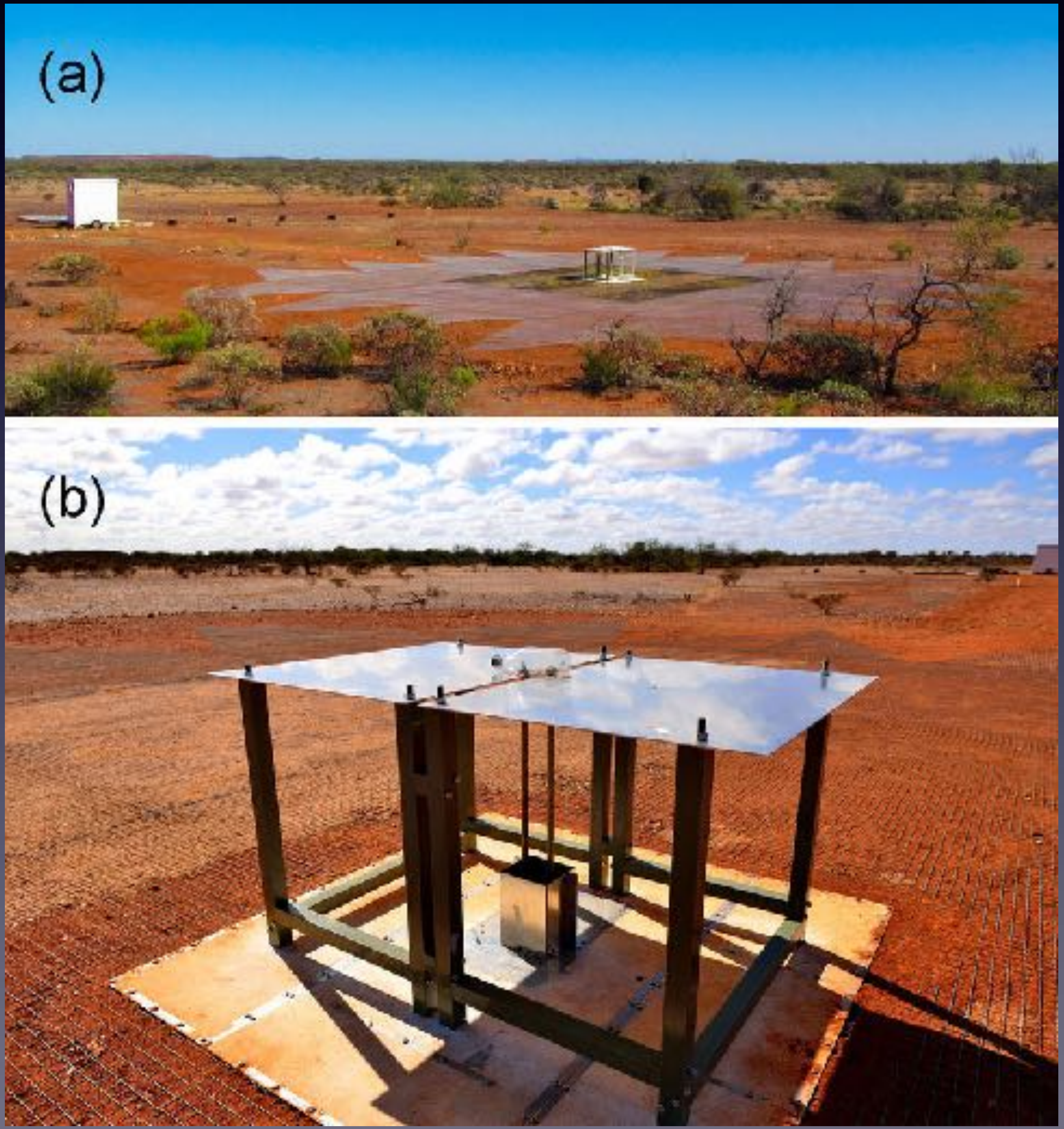
with Asher Berlin, Dan Hooper, & Gordan Krnjaic
1803.02804, PRL

Fermilab

EDGES

Bowman et al, Nature 555 (2018)

Experiment to Detect the Global Epoch of reionization Signature

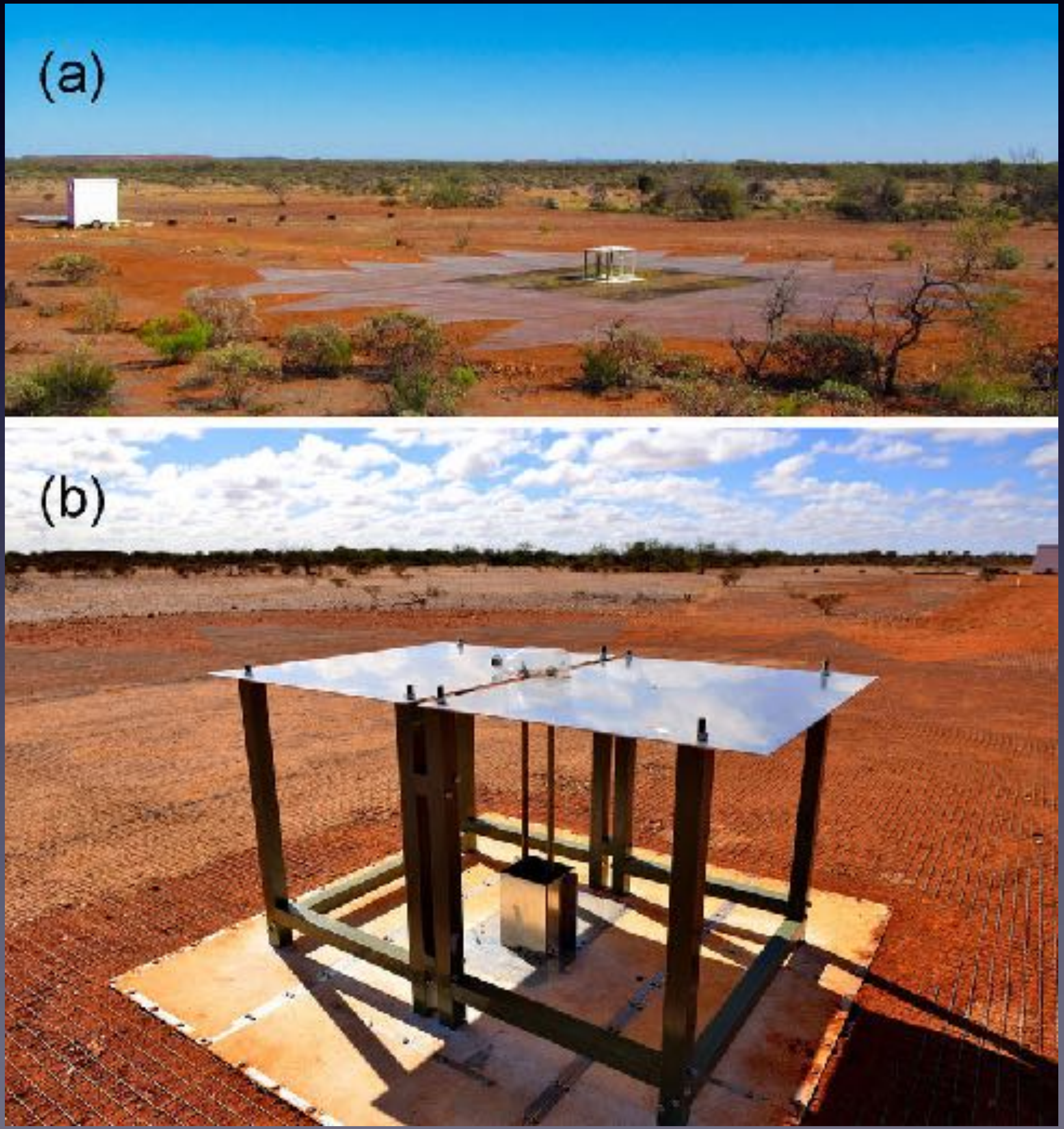


EDGES

Bowman et al, Nature 555 (2018)

Experiment to Detect the Global Epoch of reionization Signature

Detects the absorption strength of the spin flip transition of neutral H in the 1s state



EDGES

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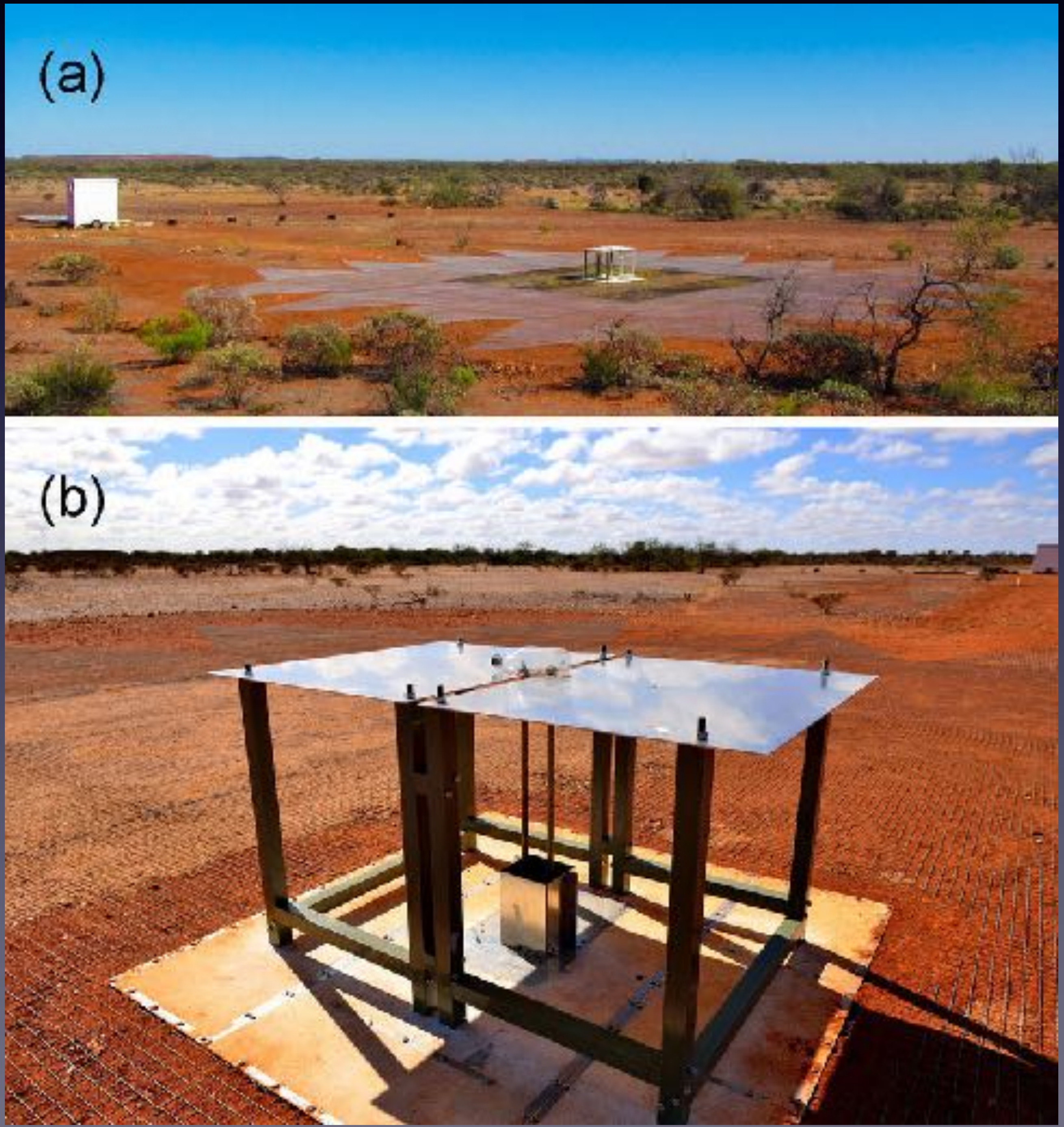
$T_{21} \sim (T_S - T_{CMB,0})/(1+z)$



EDGES

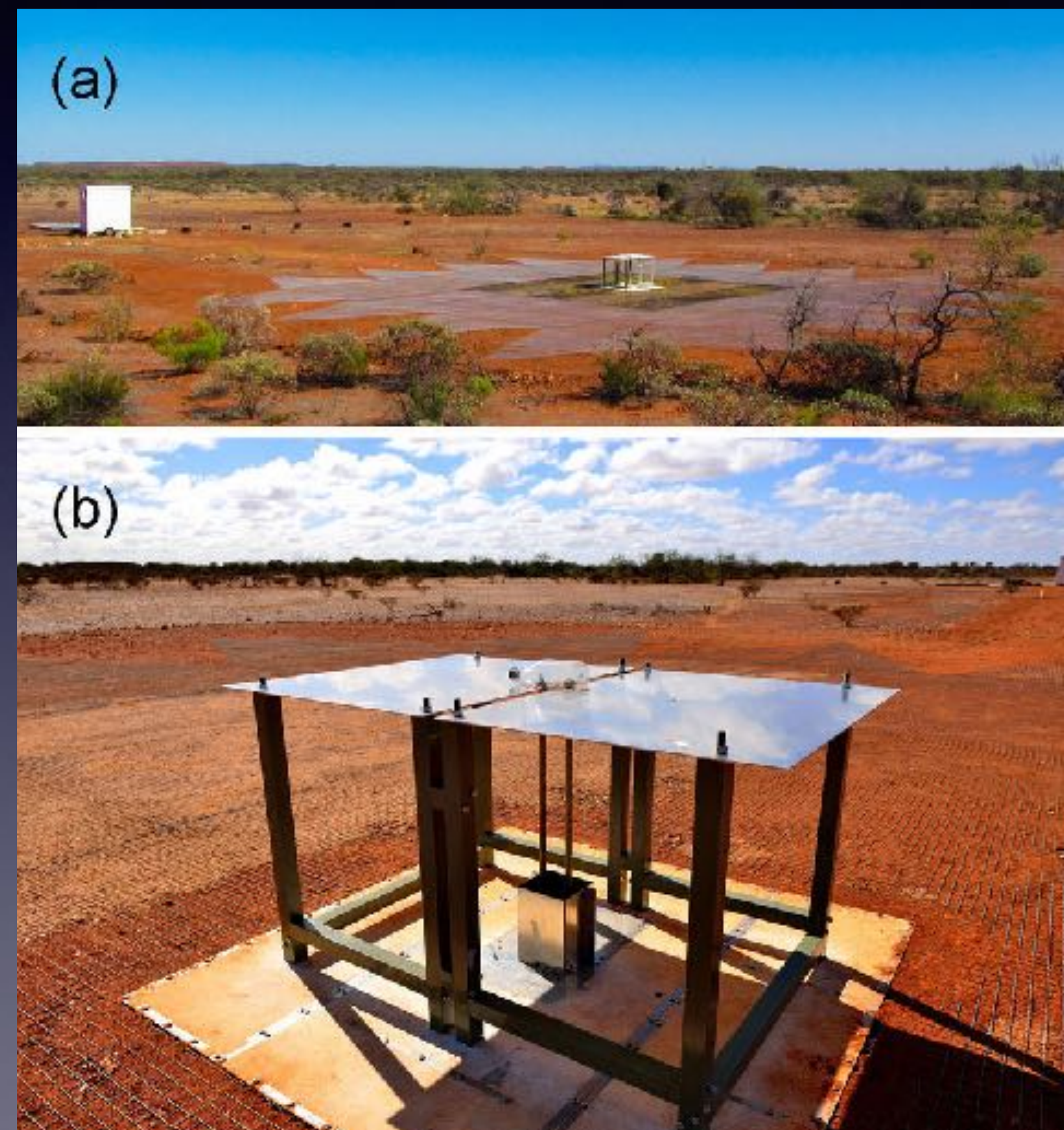
Bowman et al, Nature 555 (2018)

Experiment to Detect the Global Epoch of reionization Signature

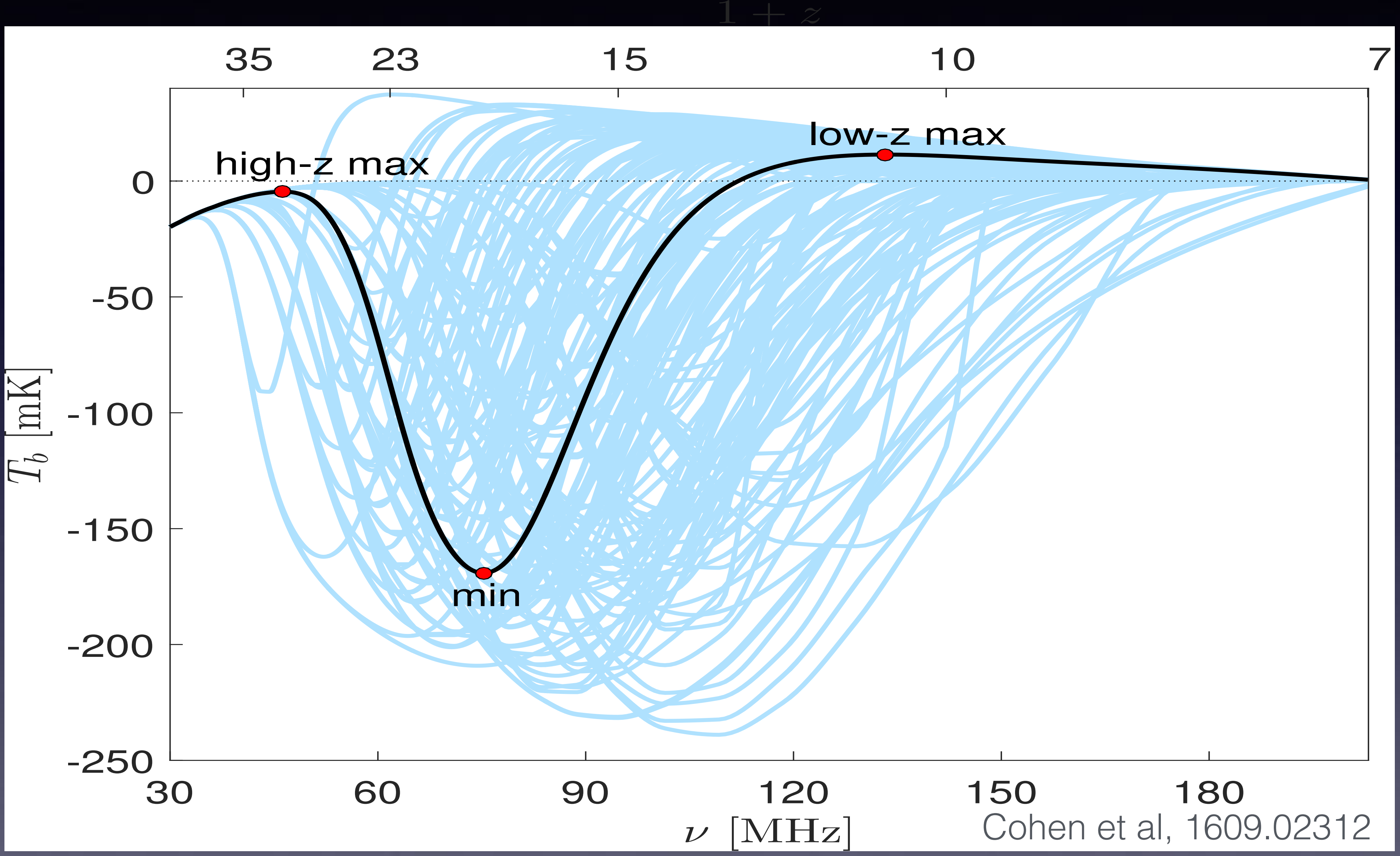
Detects the absorption strength of the spin flip transition of neutral H in the 1s state

$T_{21} \sim (T_S - T_{CMB,0})/(1+z)$

$T_{21,SM} > -200$ mK

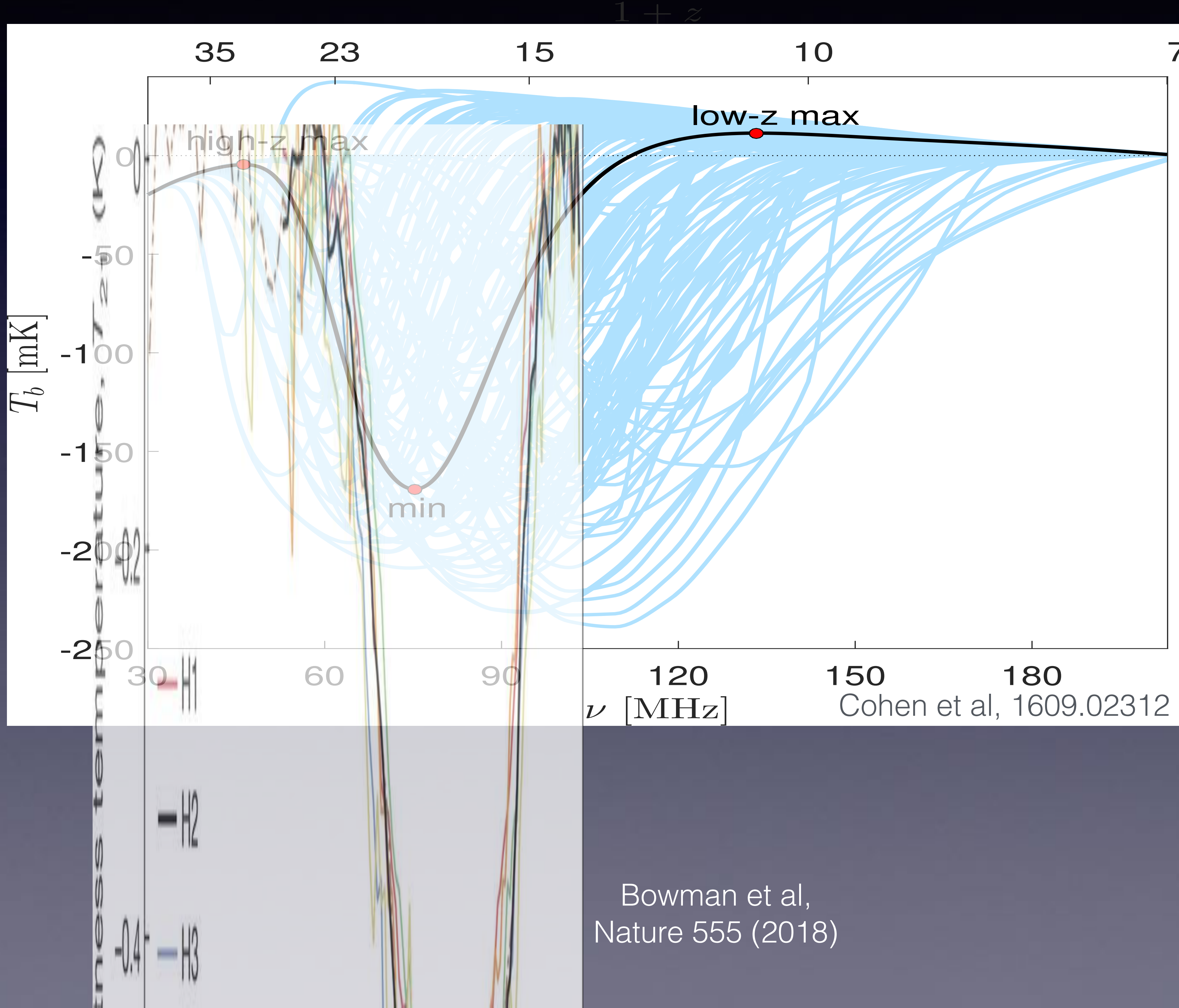


EDGES



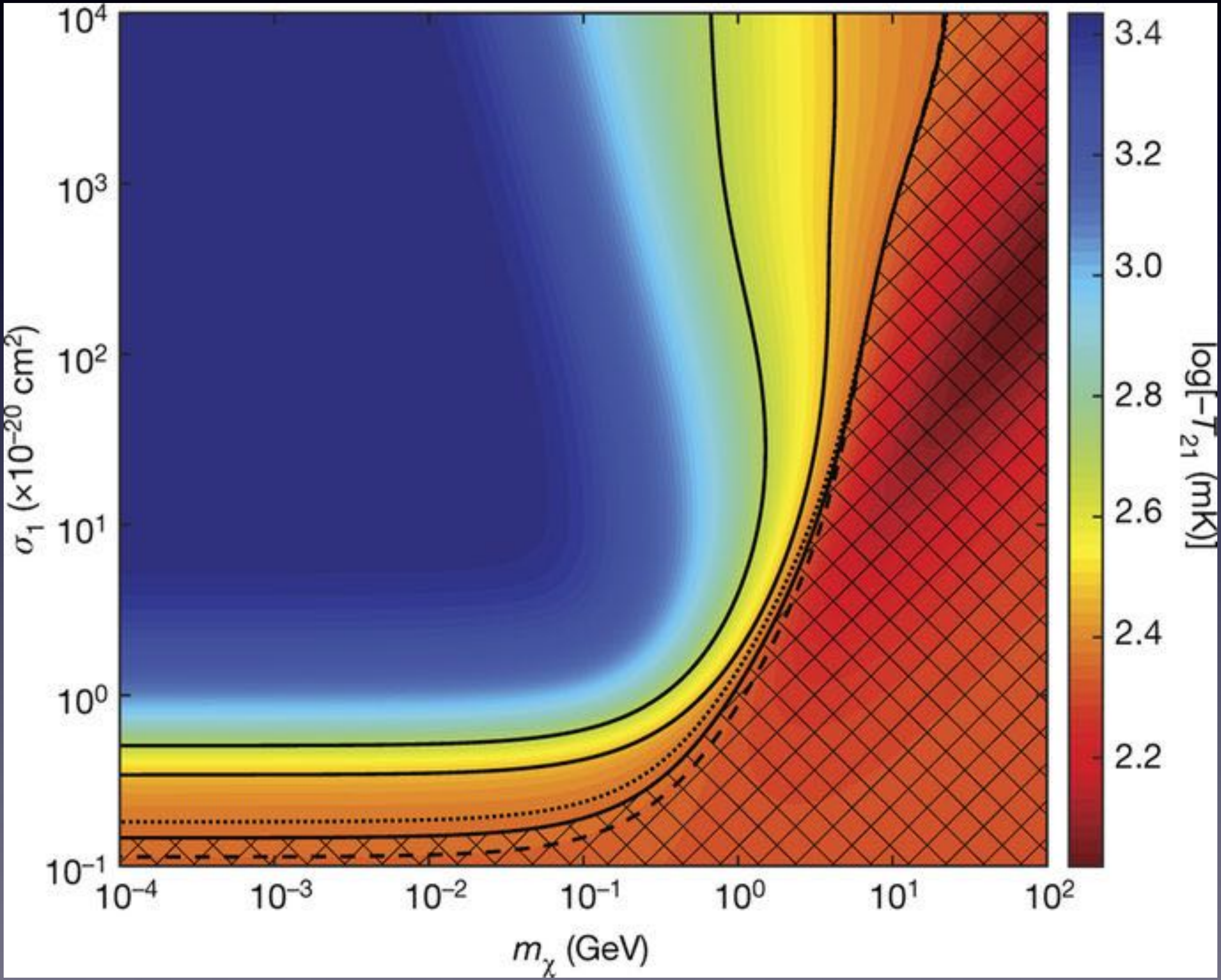
1 + z
35
23
15
10
7
high-z max
low-z max
min
0
-50
-100
-150
-200
-250
T_b [mK]
30
60
90
120
150
180
ν [MHz]
Cohen et al, 1609.02312

EDGES



Bowman et al,
Nature 555 (2018)

(Putative) EDGES Signal



Barkana
Nature 555
(2018)

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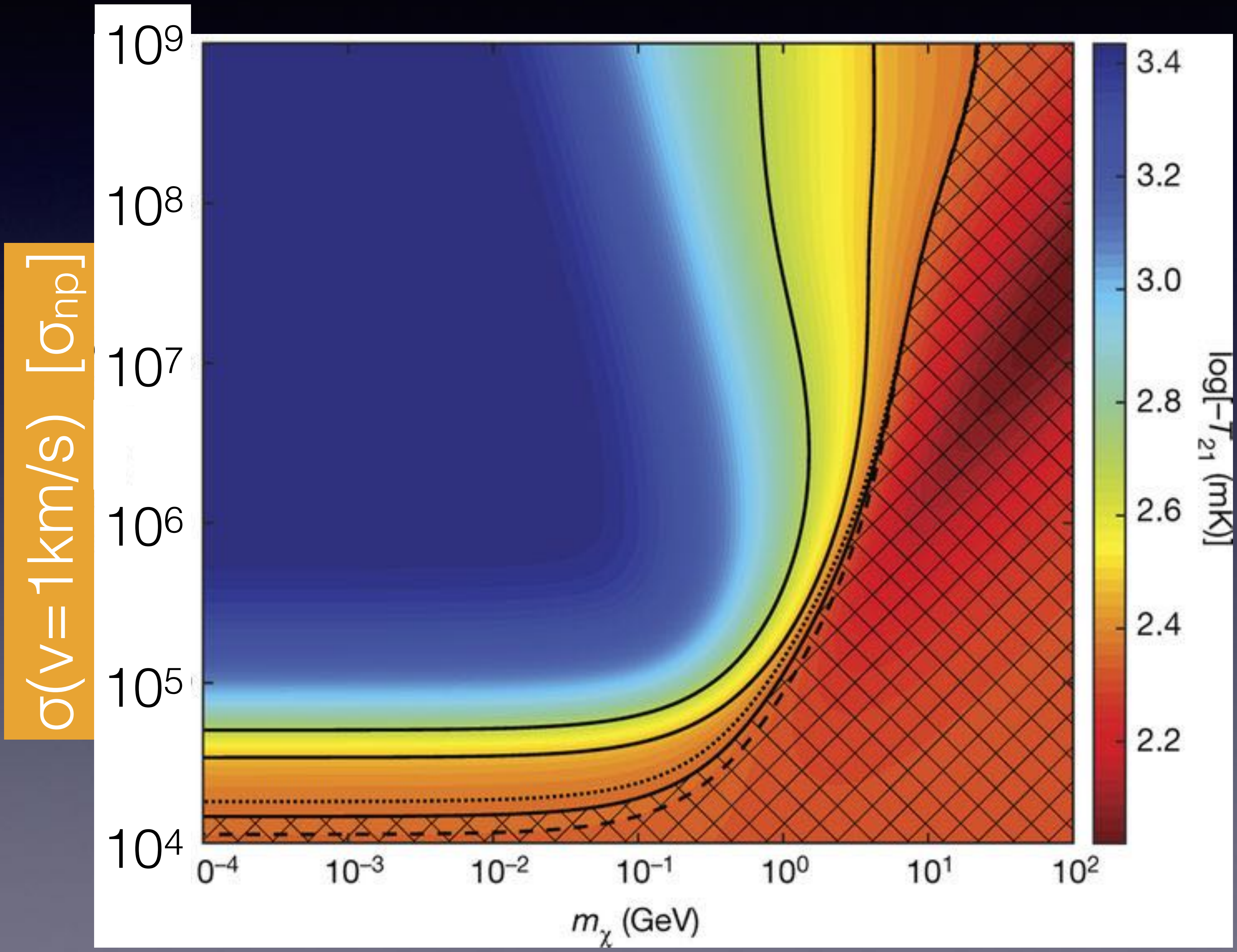
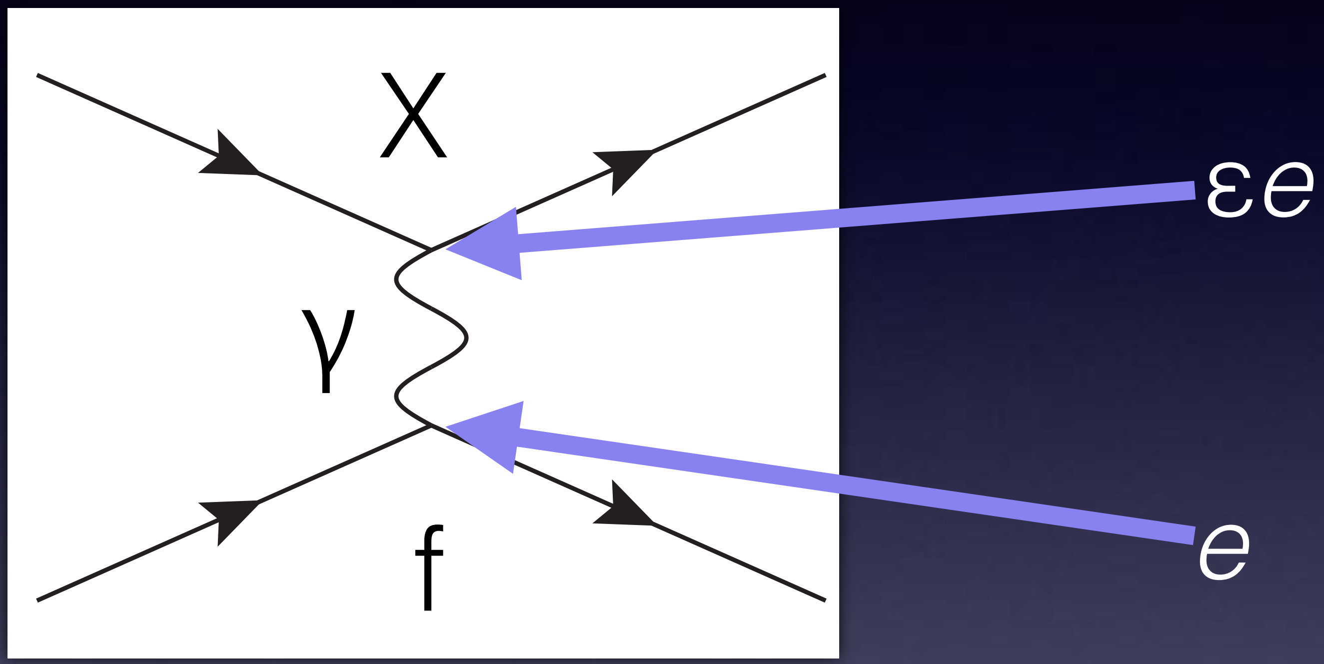


Barkana
Nature 555
(2018)

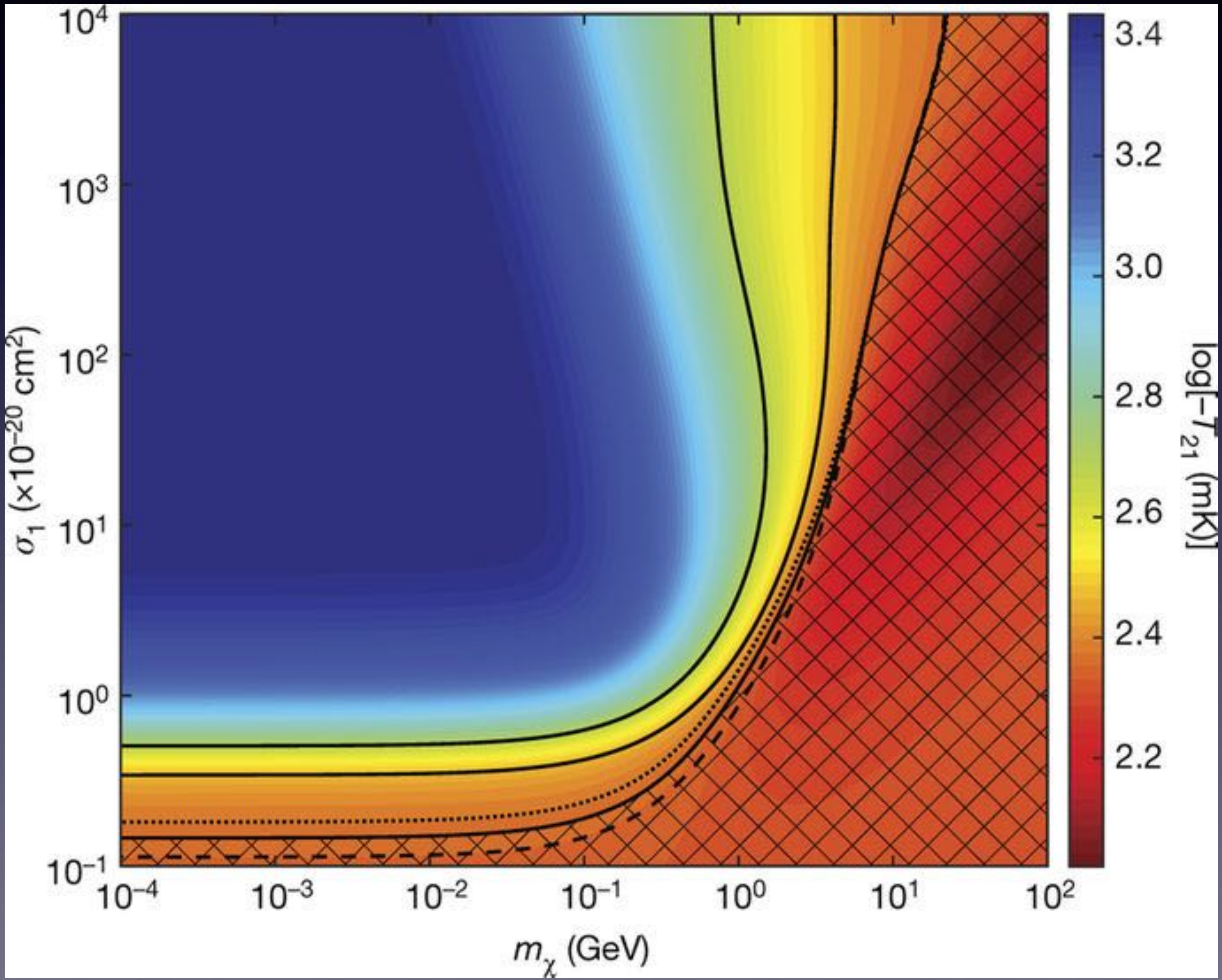
Millicharge Scattering



$$\frac{d\sigma_{Xf}}{d\Omega} = \frac{\alpha_{\rm EM}^2 \epsilon^2}{4\mu_{Xf}^2 v_{\rm rel}^4 \sin^4(\frac{\theta}{2})} \rightarrow$$

$$\rightarrow \sigma_t \simeq \frac{2\pi\alpha_{\rm EM}^2\epsilon^2}{\mu_{Xf}^2 v_{\rm rel}^4}\left[60 + \ln\left(\frac{x_e \epsilon^2}{10^{-12}}\right)\right]$$

(Putative) EDGES Signal



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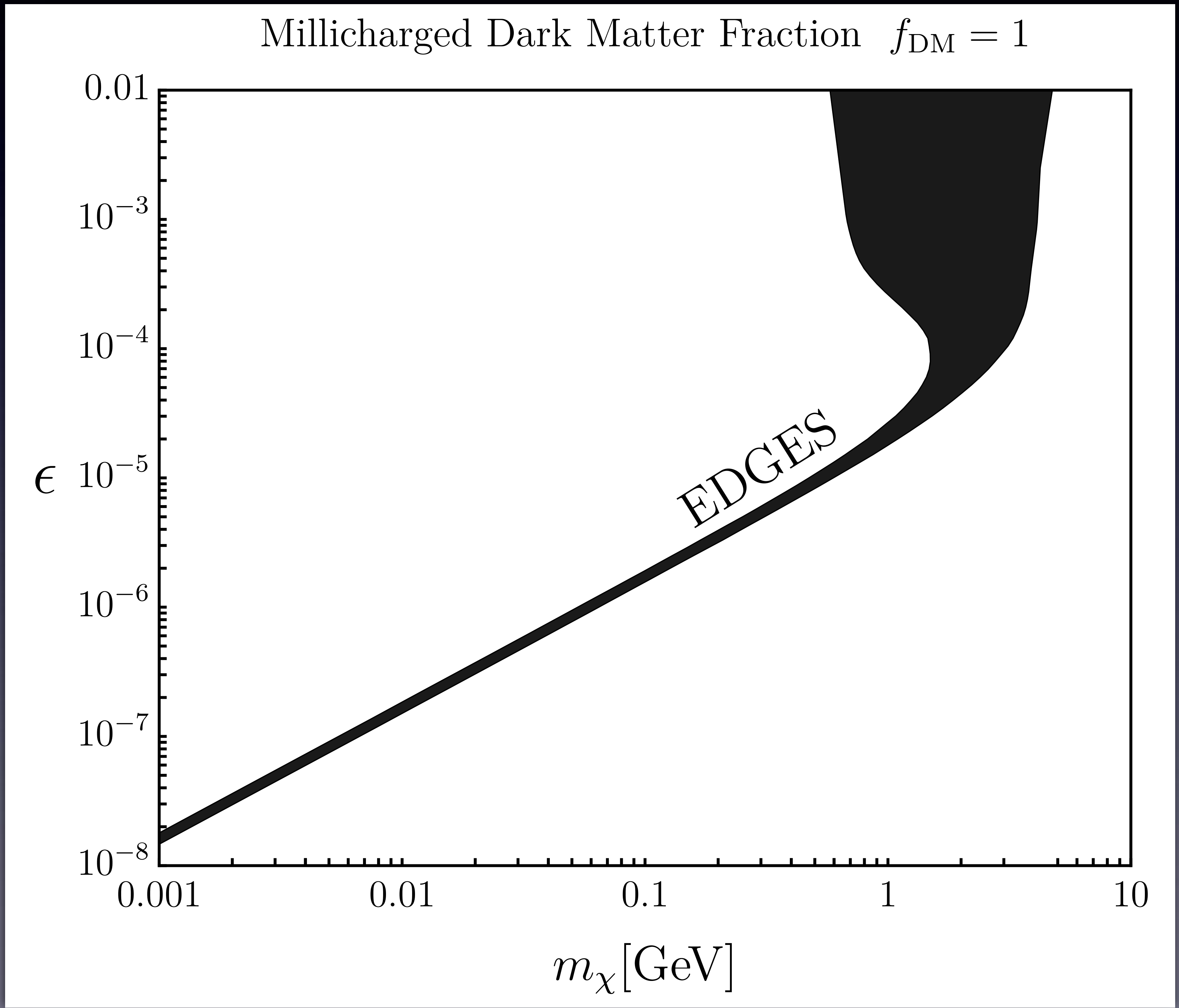
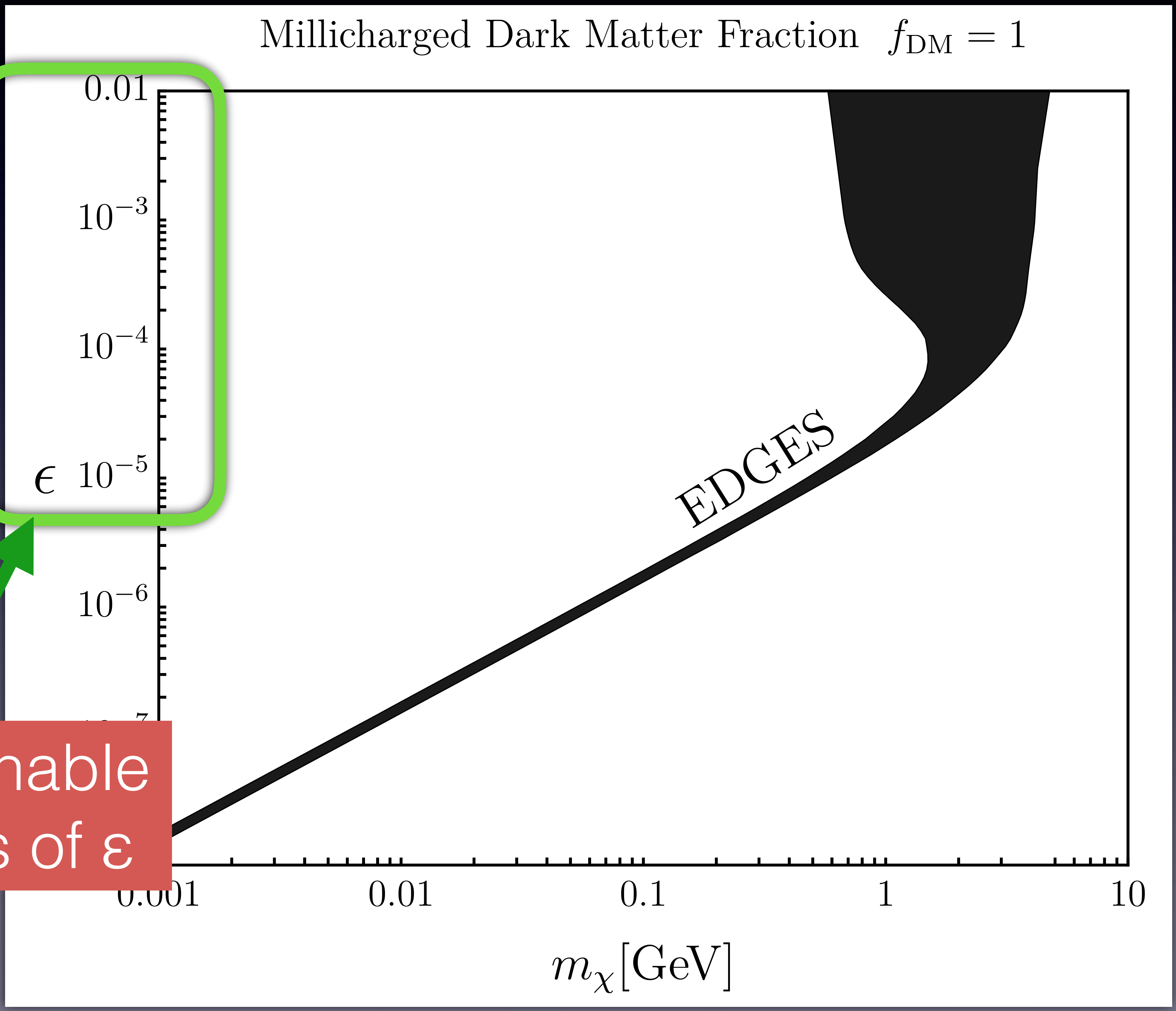


see also:
Muñoz & Loeb 1802.10094 (forth-coming in Nature)

Barkana et al., 1803.03091

Liu & Slatyer, 1803.09739

(Putative) EDGES Signal



Reasonable values of ε

see also:
Muñoz & Loeb 1802.10094 (forth-coming in Nature)

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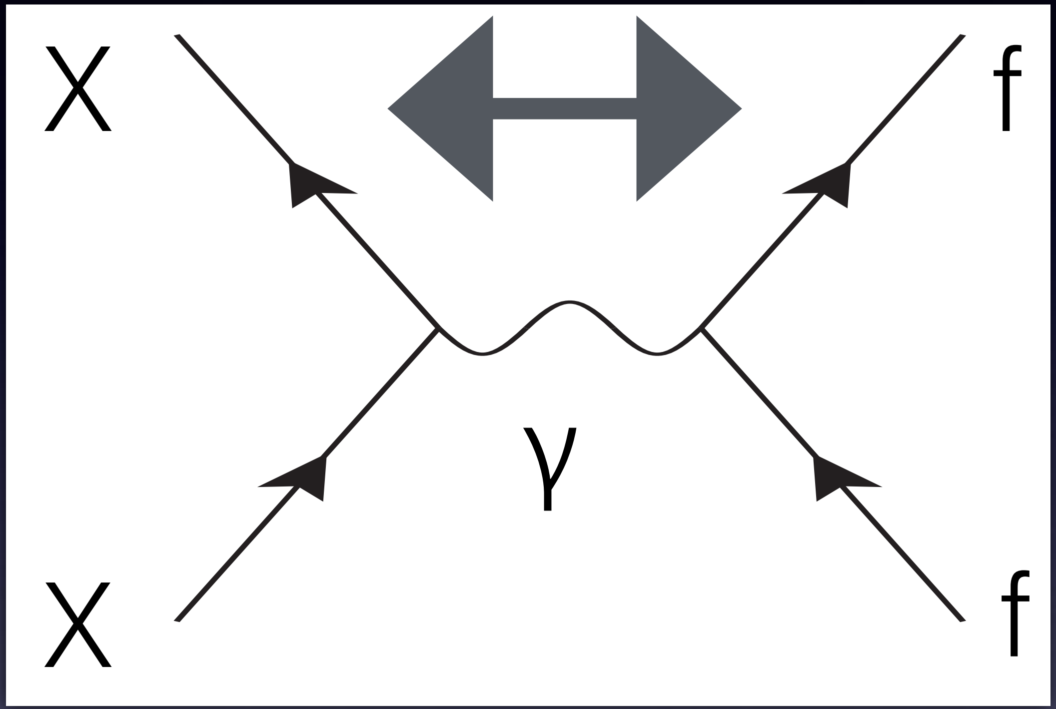
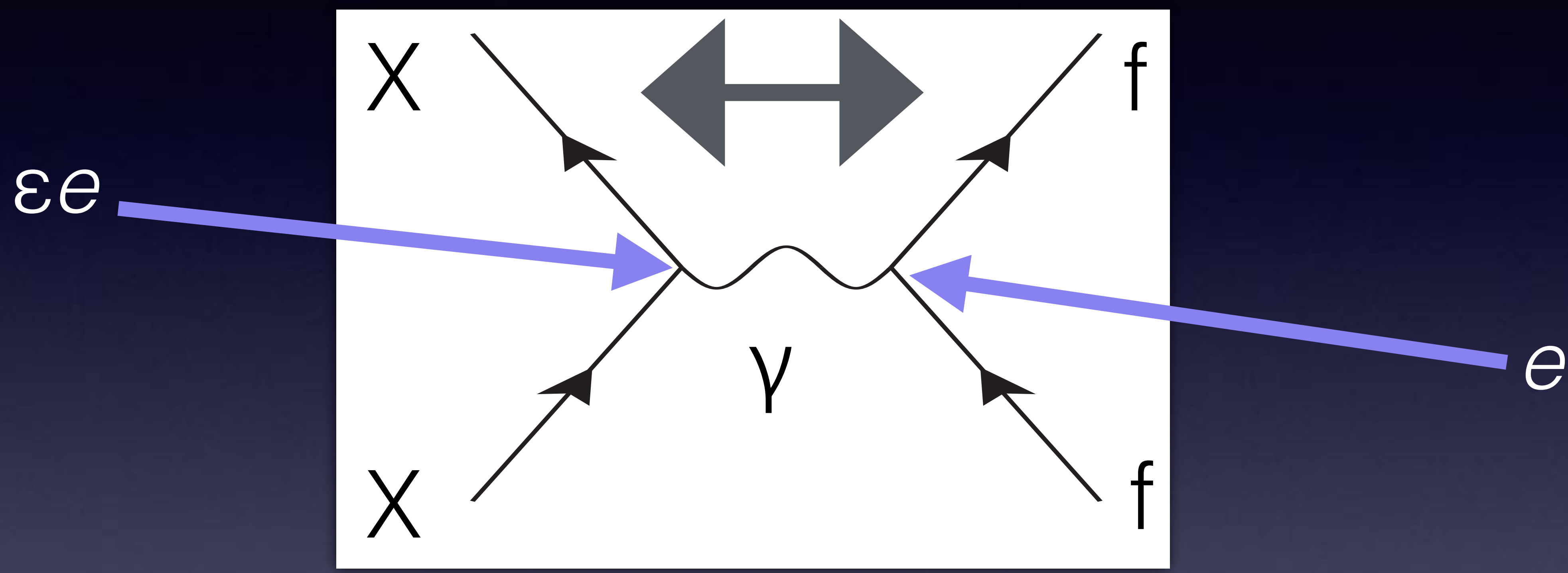
Outline

1. Astrophysical & Cosmological Implications
2. Future Directions

Early Univ. Production

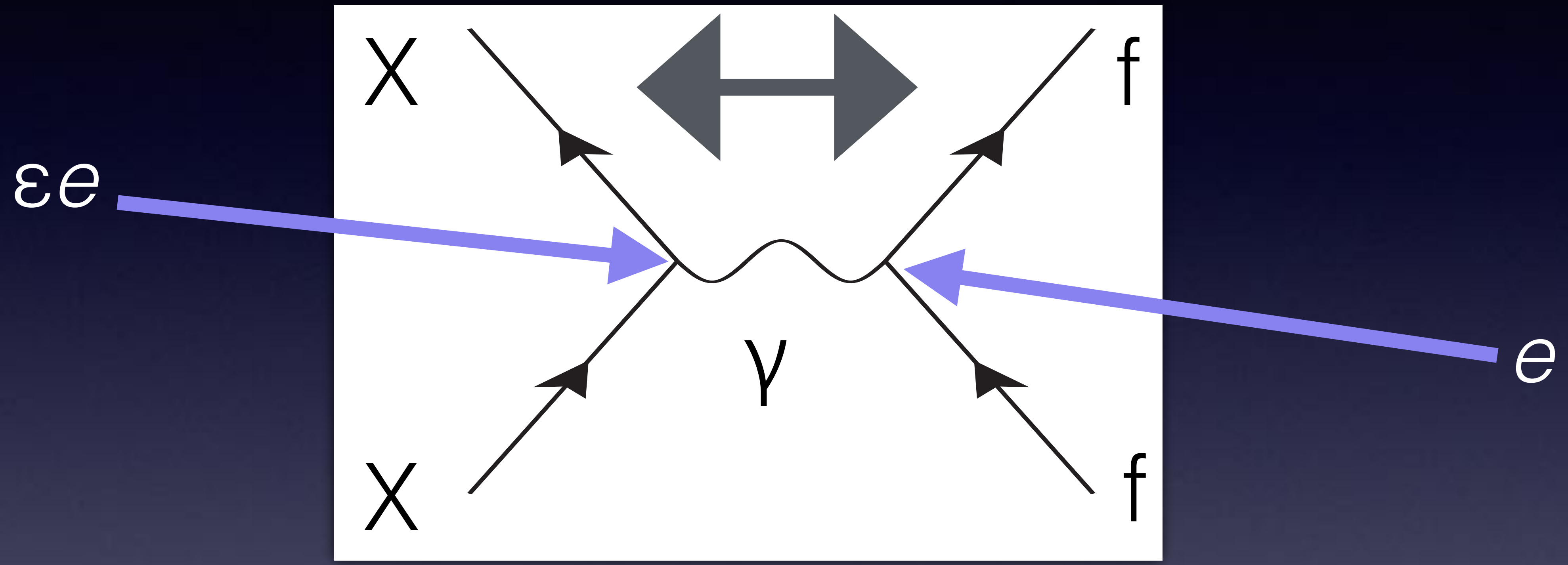


Early Univ. Production



Annihilation: $\sigma v = \pi \alpha^2 \varepsilon^2 / m_X^2$

Early Univ. Production



Annihilation: $\sigma v = \pi\alpha^2\varepsilon^2/m_X^2$

Thermalized: $n_X\sigma v(T=m_X) \sim H(T=m_X) \Rightarrow \varepsilon > 10^{-7}(m_X/\text{GeV})^{1/2}$

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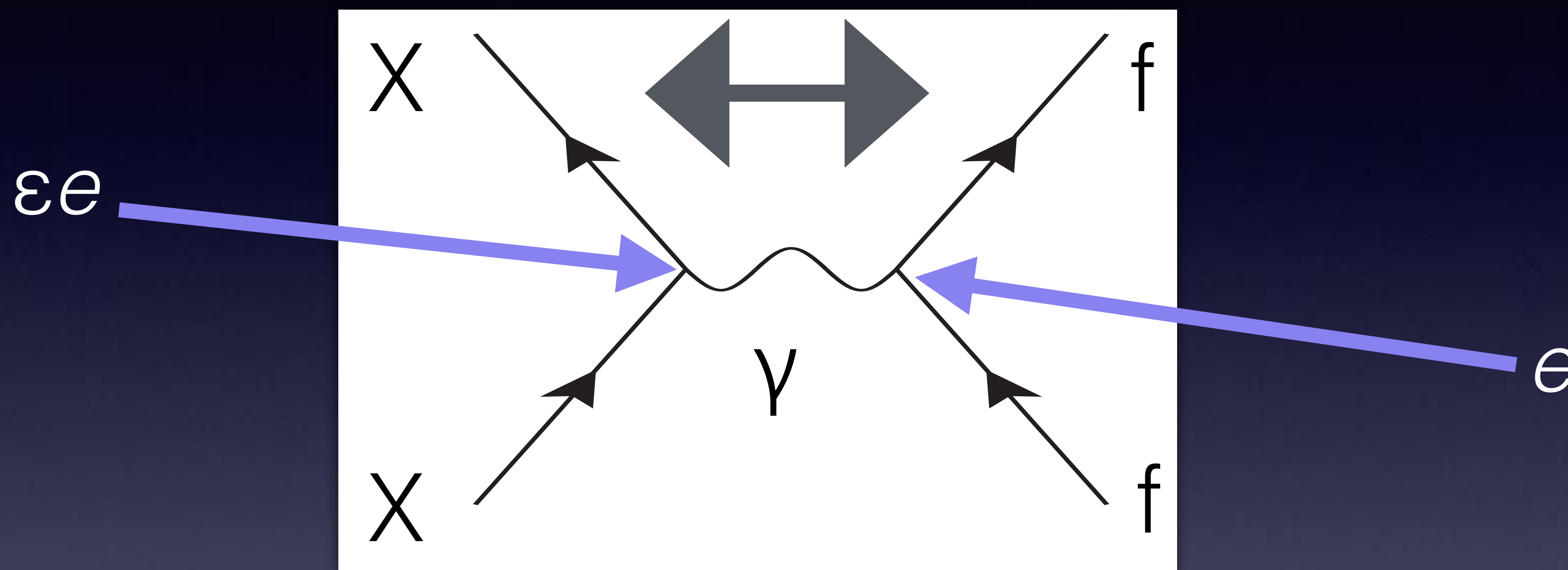

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Thermalized: $n_X\sigma v(T{=}m_X) \sim H(T{=}m_X) \Rightarrow \varepsilon > 10^{-7}(m_X/\mathrm{GeV})^{1/2}$

Relic abundance: $\sigma v \approx \sigma v_{th}\,(\varepsilon/10^{-3})^2\,/\,(m_X/\mathrm{GeV})^2$

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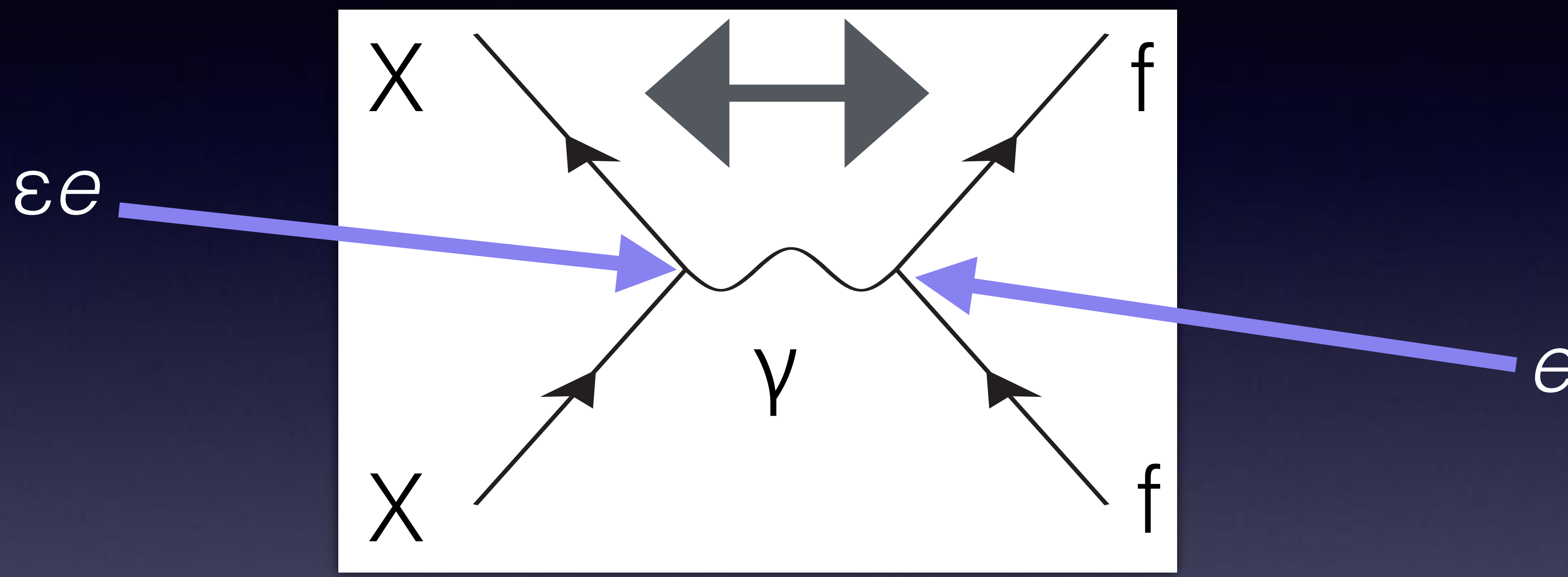

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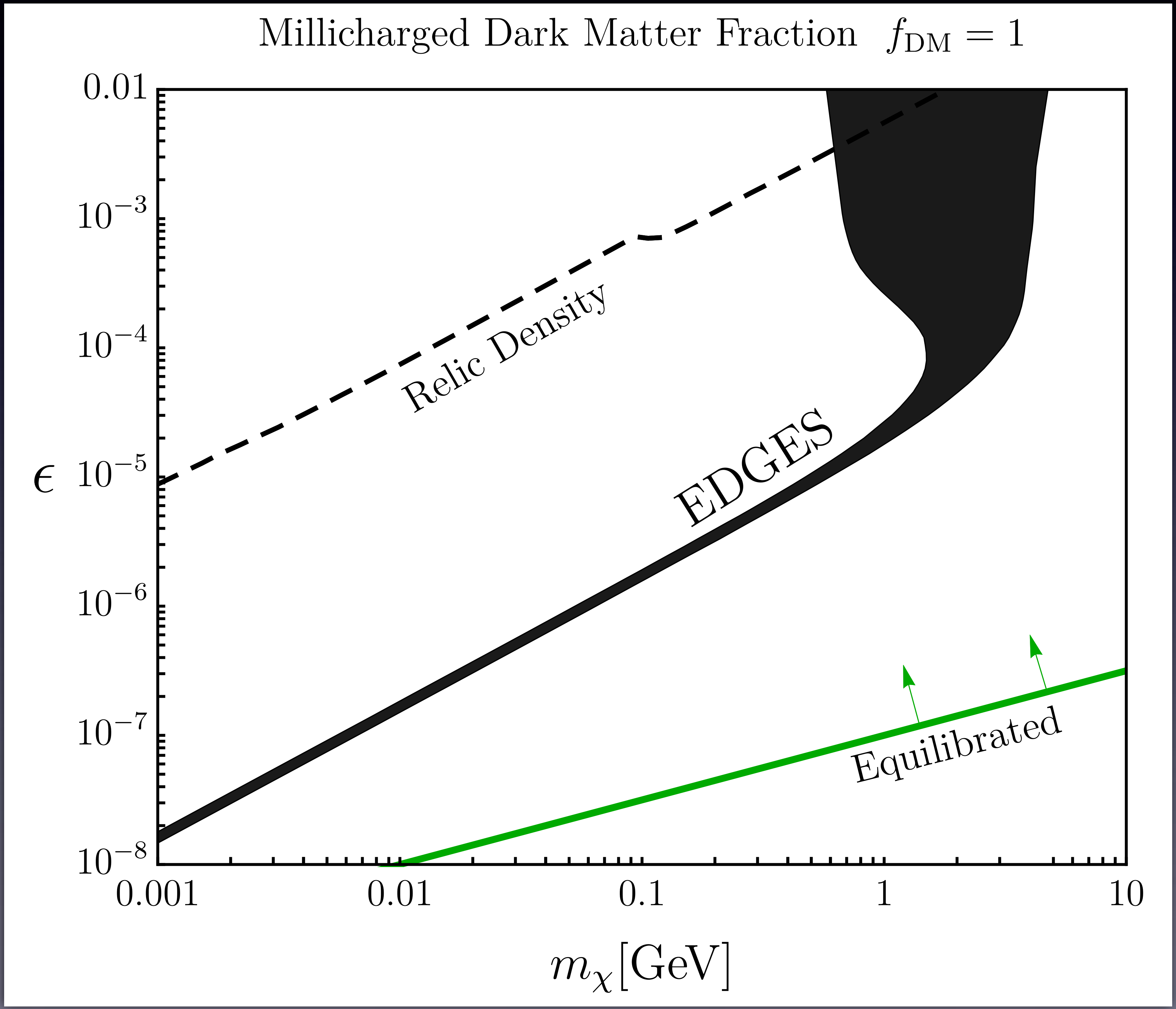
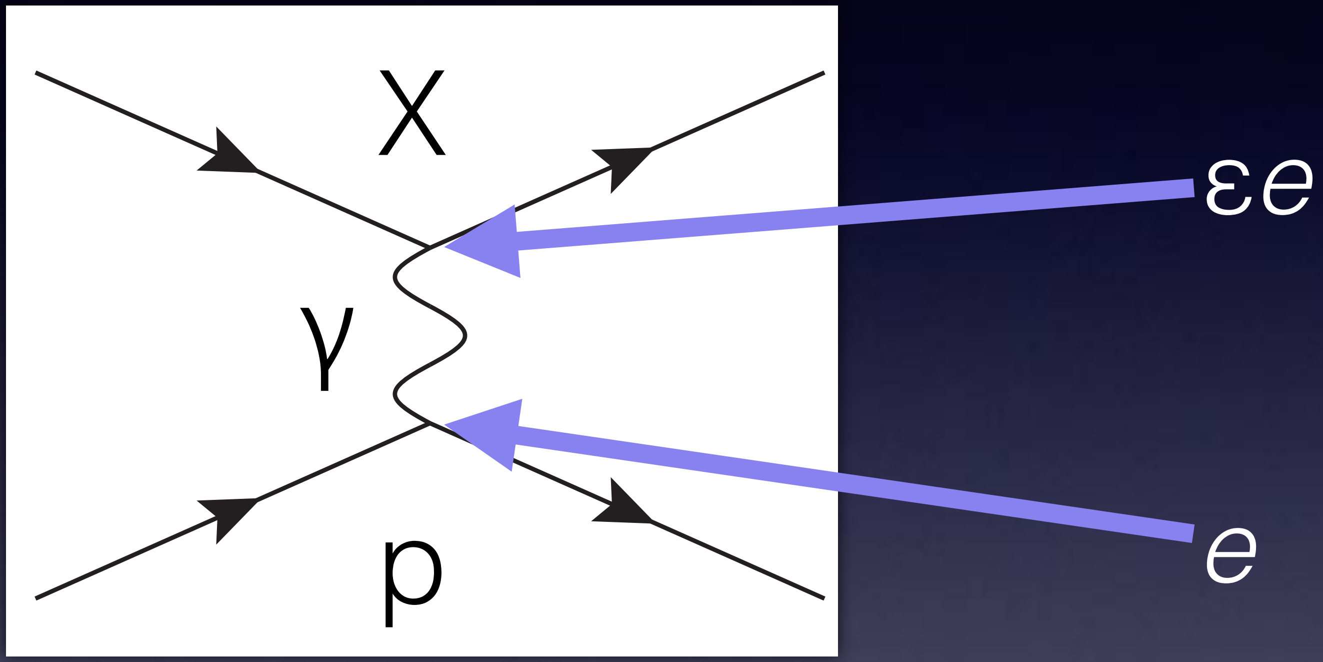
Thermalized: $n_X\sigma v(T=m_X) \sim H(T=m_X) \Rightarrow \varepsilon > 10^{-7}(m_X/\mathrm{GeV})^{1/2}$

Relic abundance: $\Omega_{DM}h^2 \approx 0.1\ (m_X/\mathrm{GeV})^2 / (\varepsilon/10^{-3})^2$

Relic Density

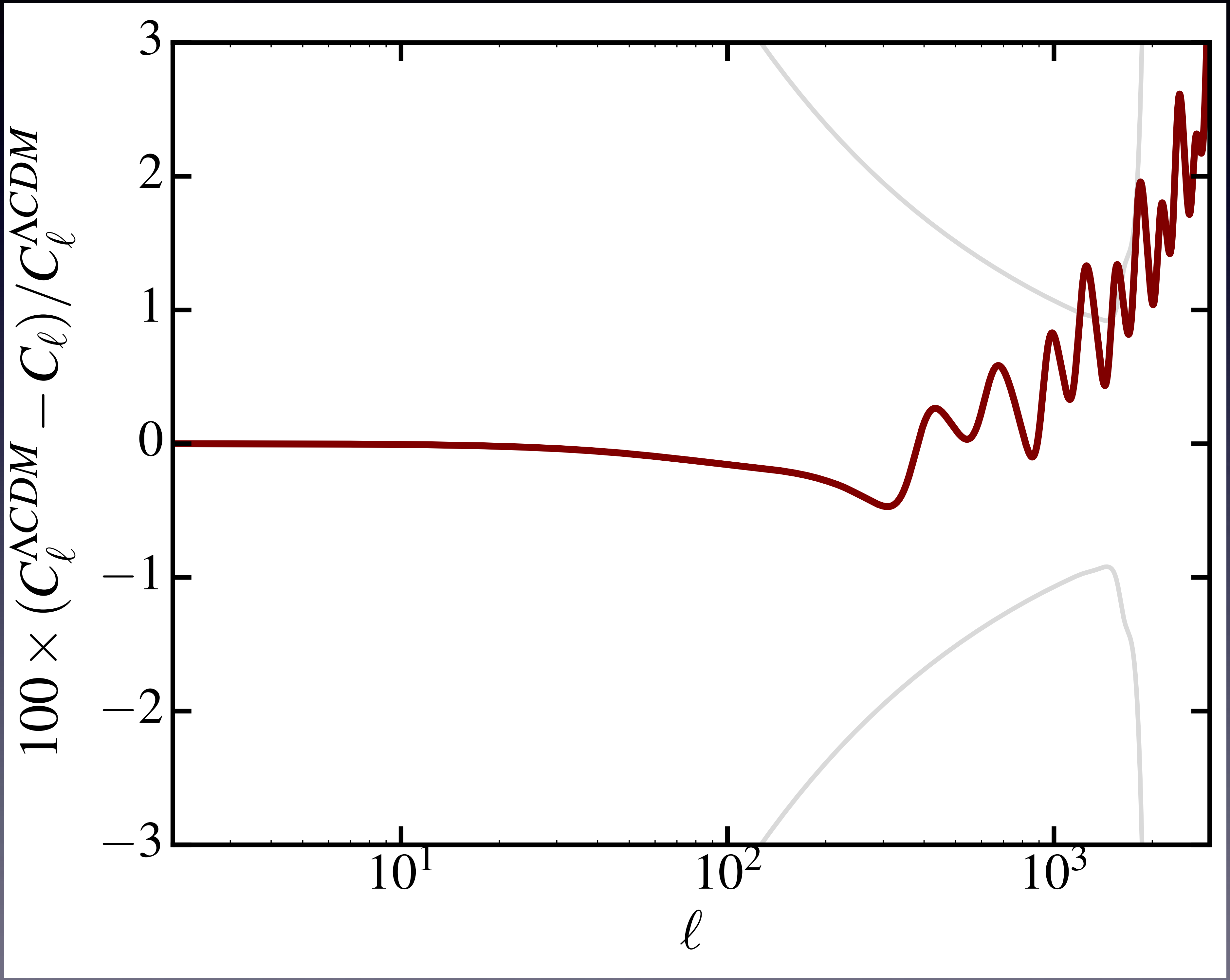


CMB



Baryons should not scatter efficiently with dark matter at the time of CMB: $\Gamma_{Xp} < H_{rec}$

CMB



Gluscevic & Boddy, 1712.07133

CMB

Rate of change of baryon temperature:

Dubovsky et al., hep-ph/0311189
& 1310.2376
McDermott, Yu, & Zurek 1011.2907

$$\frac{\langle \frac{d}{dt}\delta T\rangle}{T} = \frac{4}{\sqrt{2\pi}}\frac{\rho_X \sigma_0 \mu_{Xp}^2}{3 m_X m_b v_{\rm rel}} \cdot \frac{1}{T}$$

$$\simeq \frac{4}{3\sqrt{2\pi}}\frac{\rho_X \sigma_0 \mu_{Xp}}{m_X + m_p}\left(\frac{\mu_{Xp}}{T^3}\right)^{1/2} \sim \frac{\epsilon^2}{(m_X + m_p)\sqrt{\mu_{Xp}}}$$

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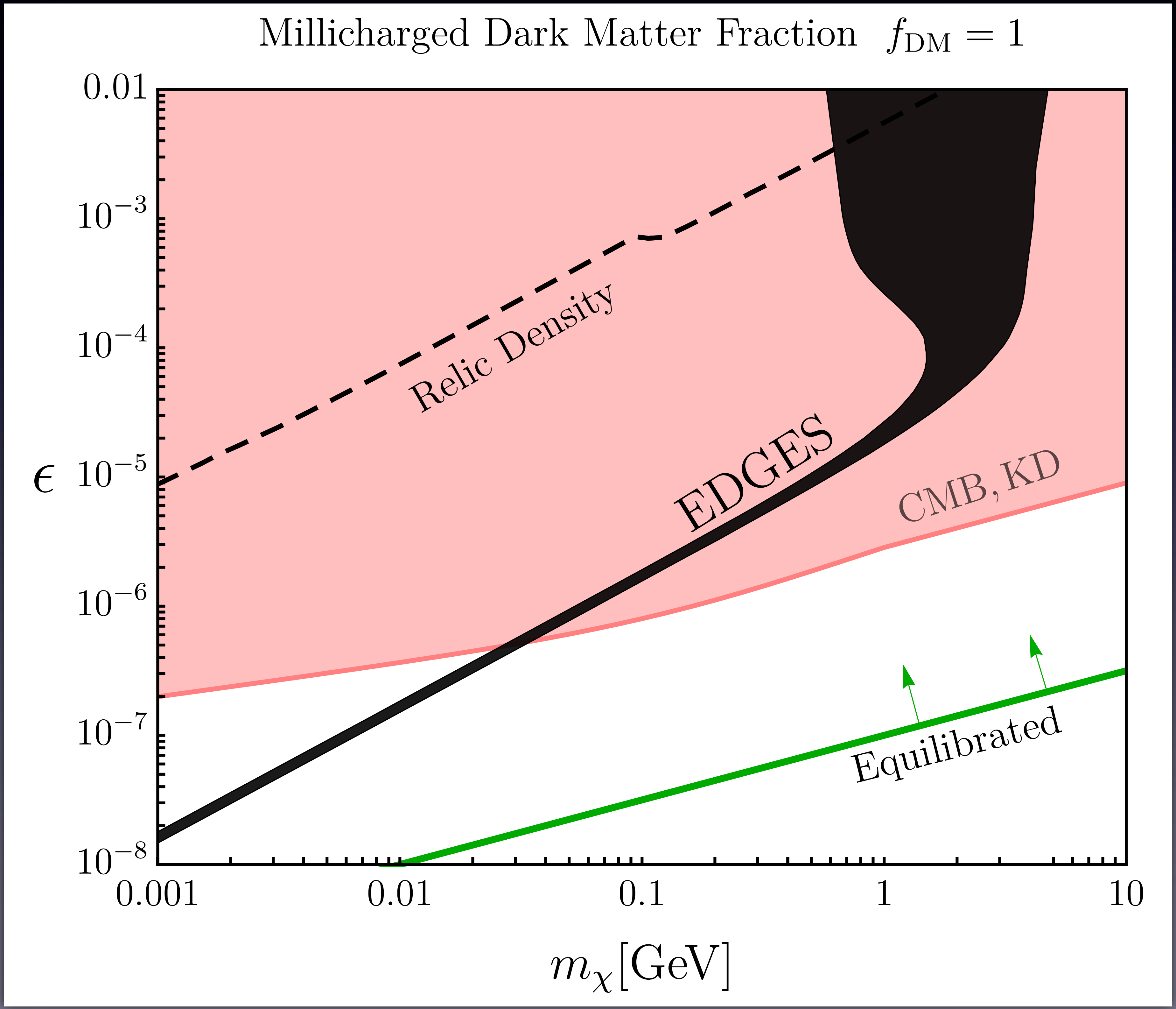
(warning — new work indicates this is too conservative)

Gluscevic & Boddy, 1712.07133
Boddy & Gluscevic, 1801.08609
Xu, Dvorkin, & Chael, 1802.06788
Slatyer & Wu, 1803.09734
de Putter et al., 1805.11616
Gluscevic et al., to appear

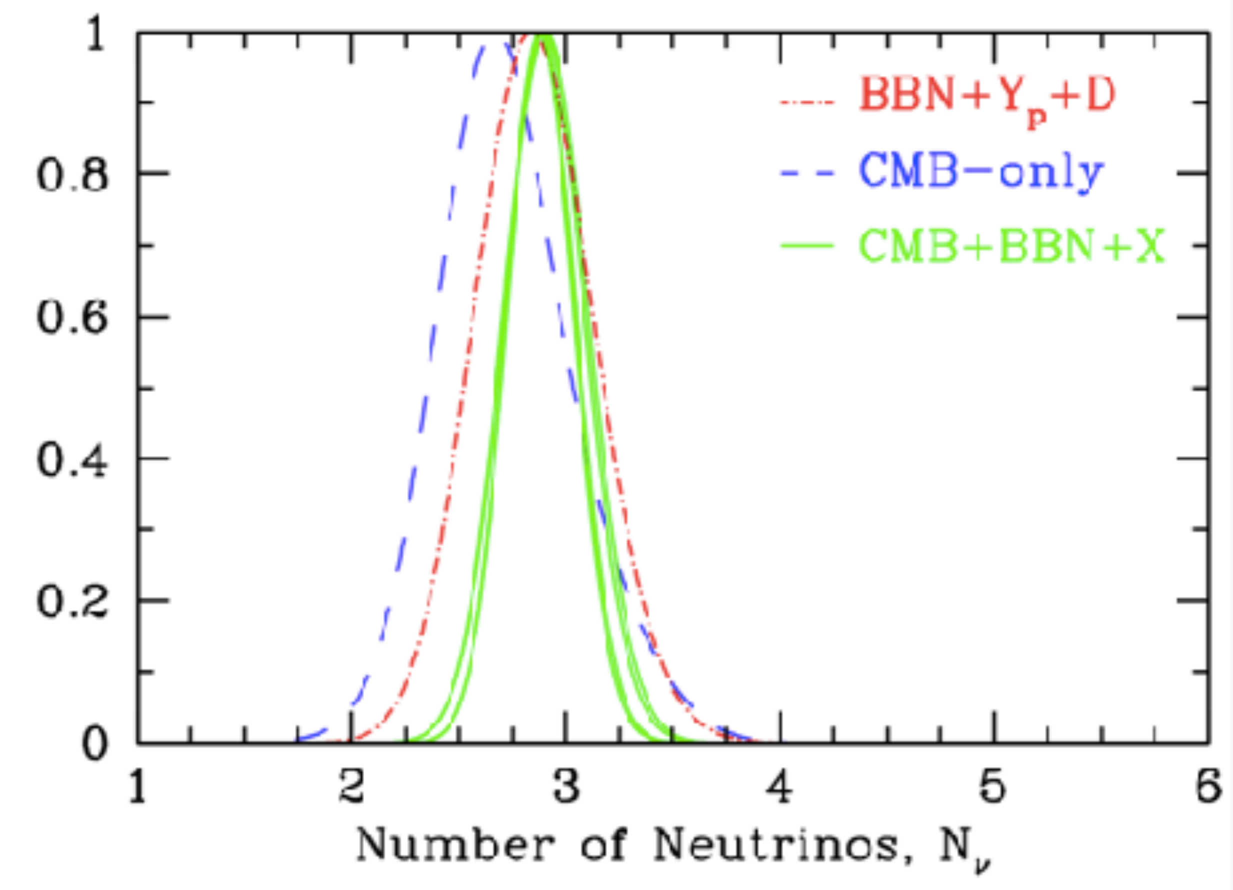
CMB Bound



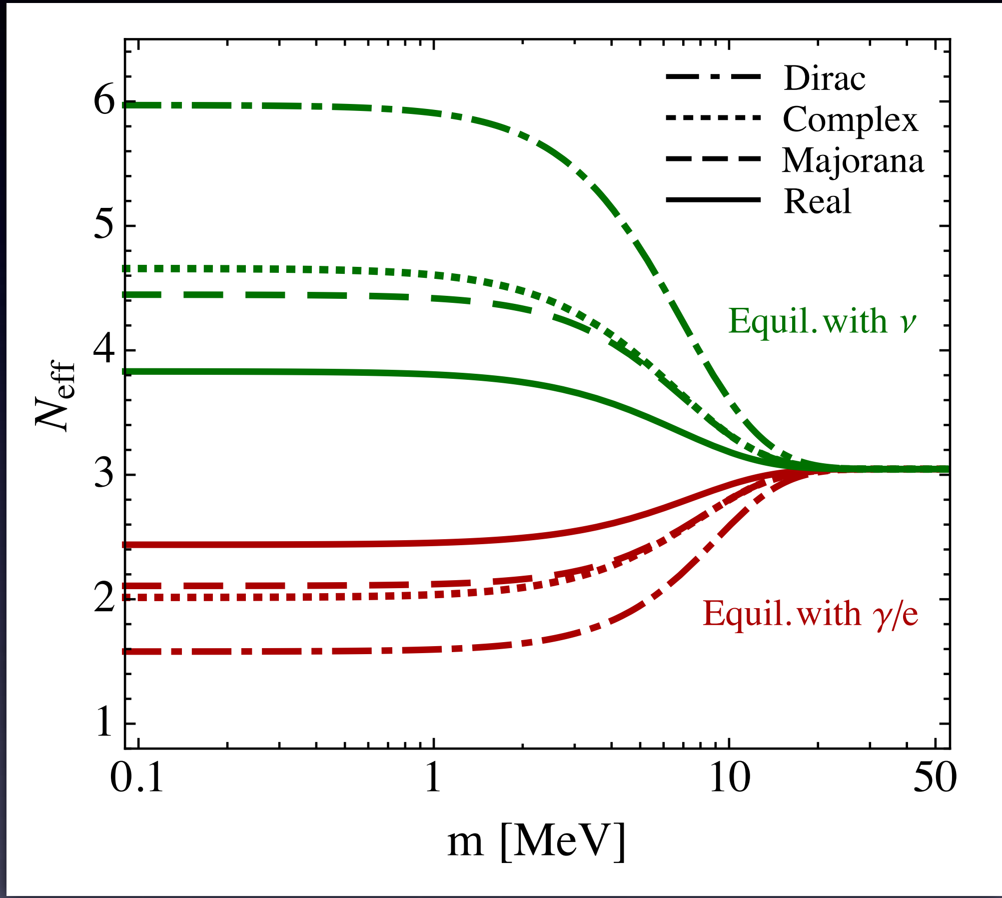
Millicharged Dark Matter Fraction $f_{\rm DM} = 1$
0.01
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
ϵ
0.001
0.01
0.1
1
10
m_χ[GeV]
Relic Density
EDGES
CMB, KD
Equilibrated

BBN

Cyburt et al, 1505.01076



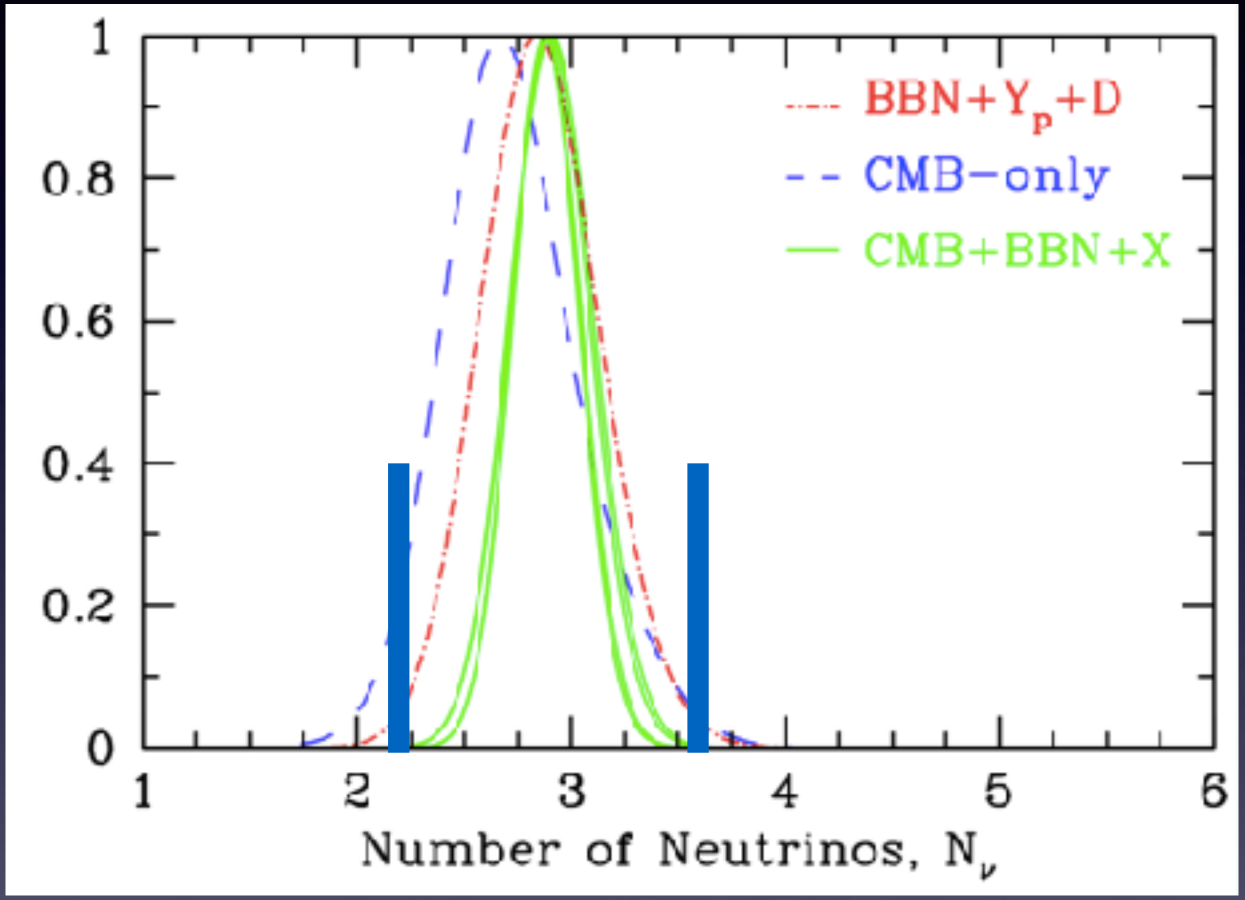
Boehm et al, 1303.6270



$N_\nu > N_{\nu,SM}$ at time of SM nucleosynthesis injects entropy, screws up agreement w/ observation

BBN

Cyburt et al, 1505.01076



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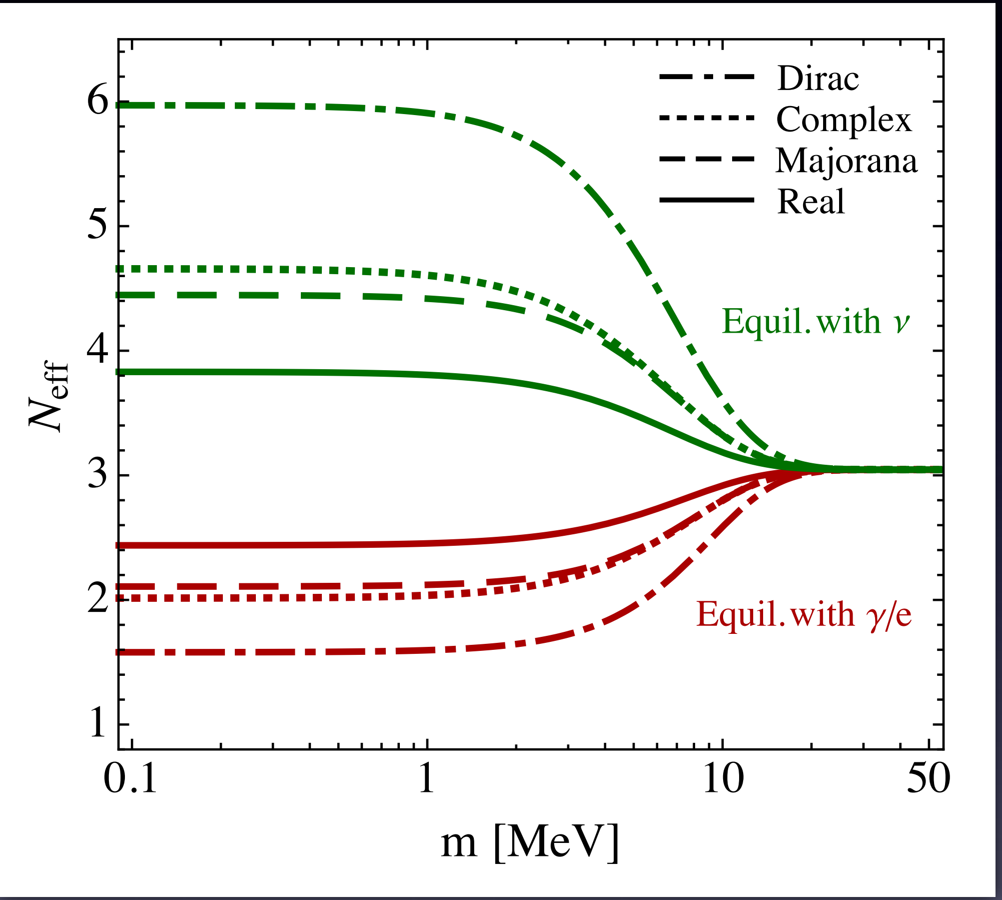

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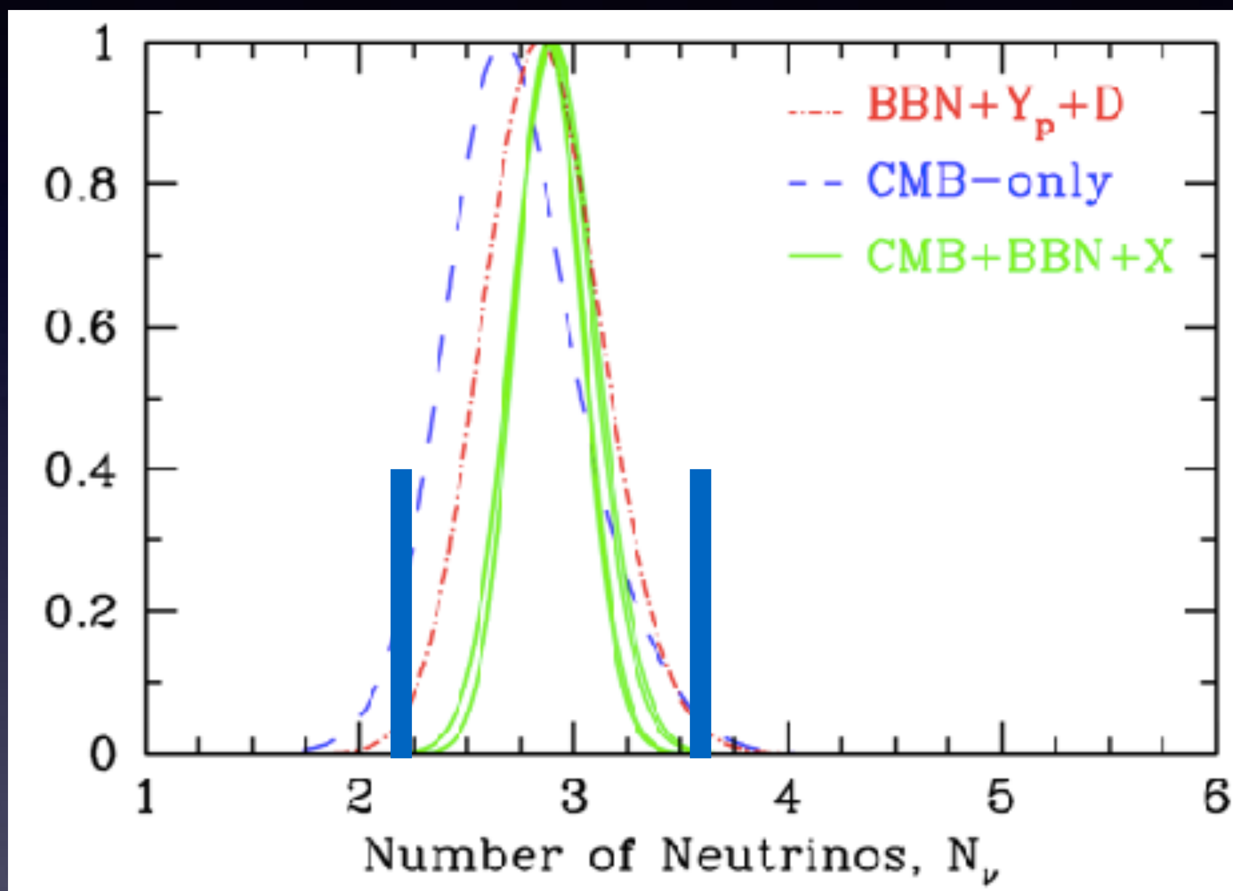

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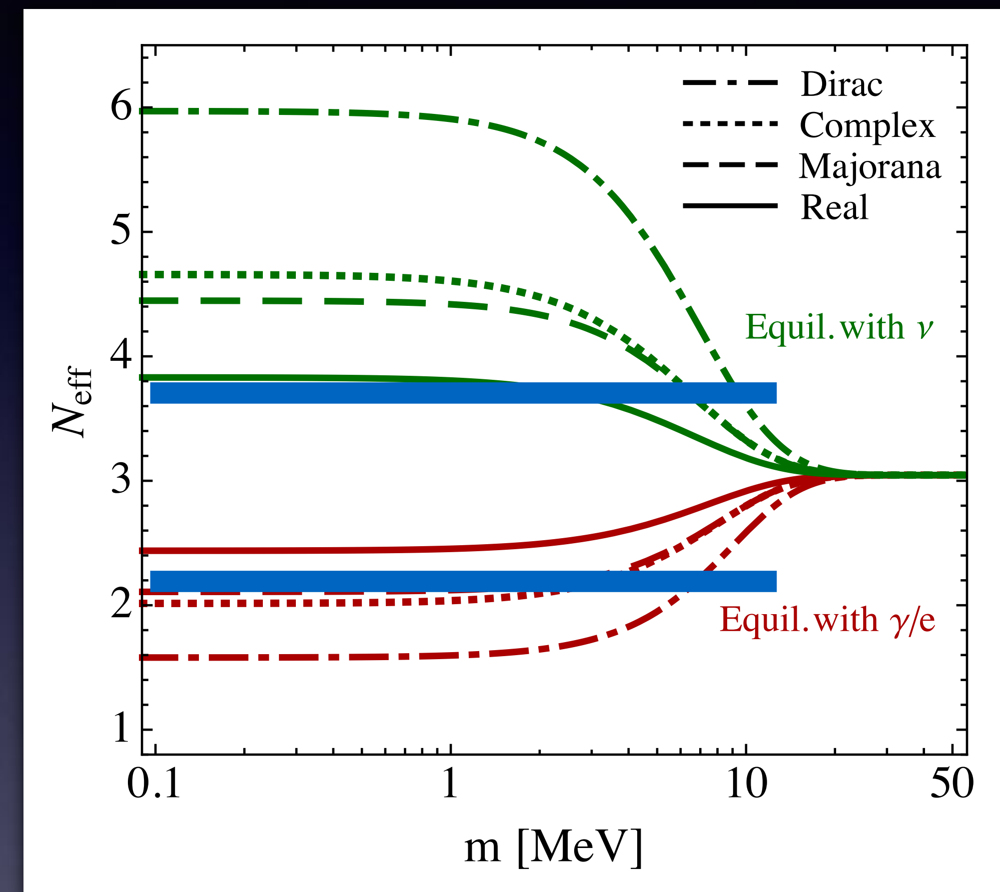
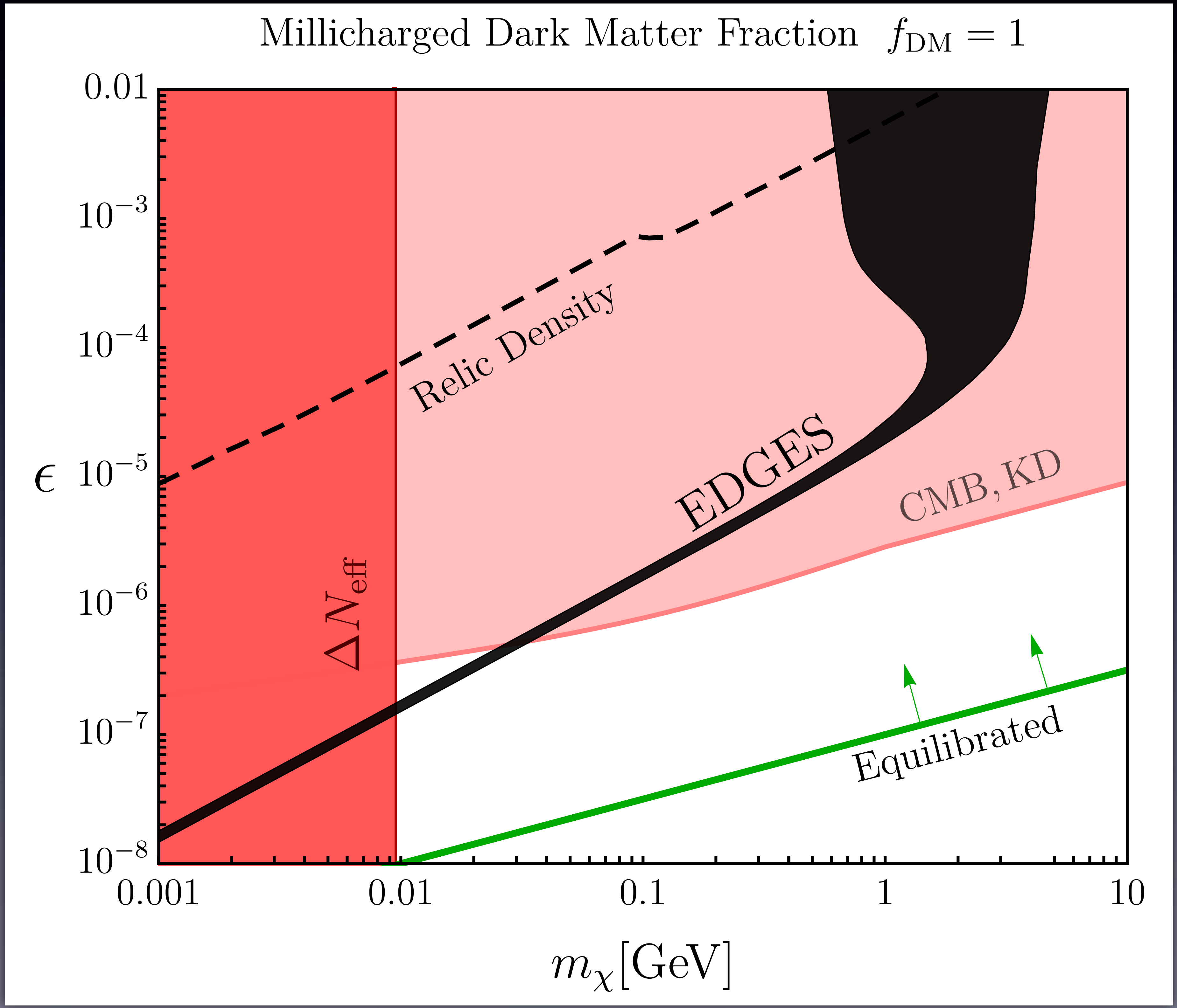


$N_\nu > N_{\nu,SM}$ at time of SM nucleosynthesis injects entropy, screws up agreement w/ observation

Generically rules out $m_X \lesssim$ 10 MeV

BBN



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10^{-8}
ϵ
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0.1
1
10
m_χ[GeV]
Relic Density
EDGES
CMB, KD
ΔN_{eff}
Equilibrated

Crash Course: SN1987A

Credit: Colin Legg

Core collapse supernova in the LMC detected simultaneously in Jan 1987 with three instruments (Baksan, IMB, and Kamiokande II)

~ 99% of the difference in grav. binding energy radiated away in the form of neutrinos over ~ 10 seconds

(see my talk tomorrow for more details!)

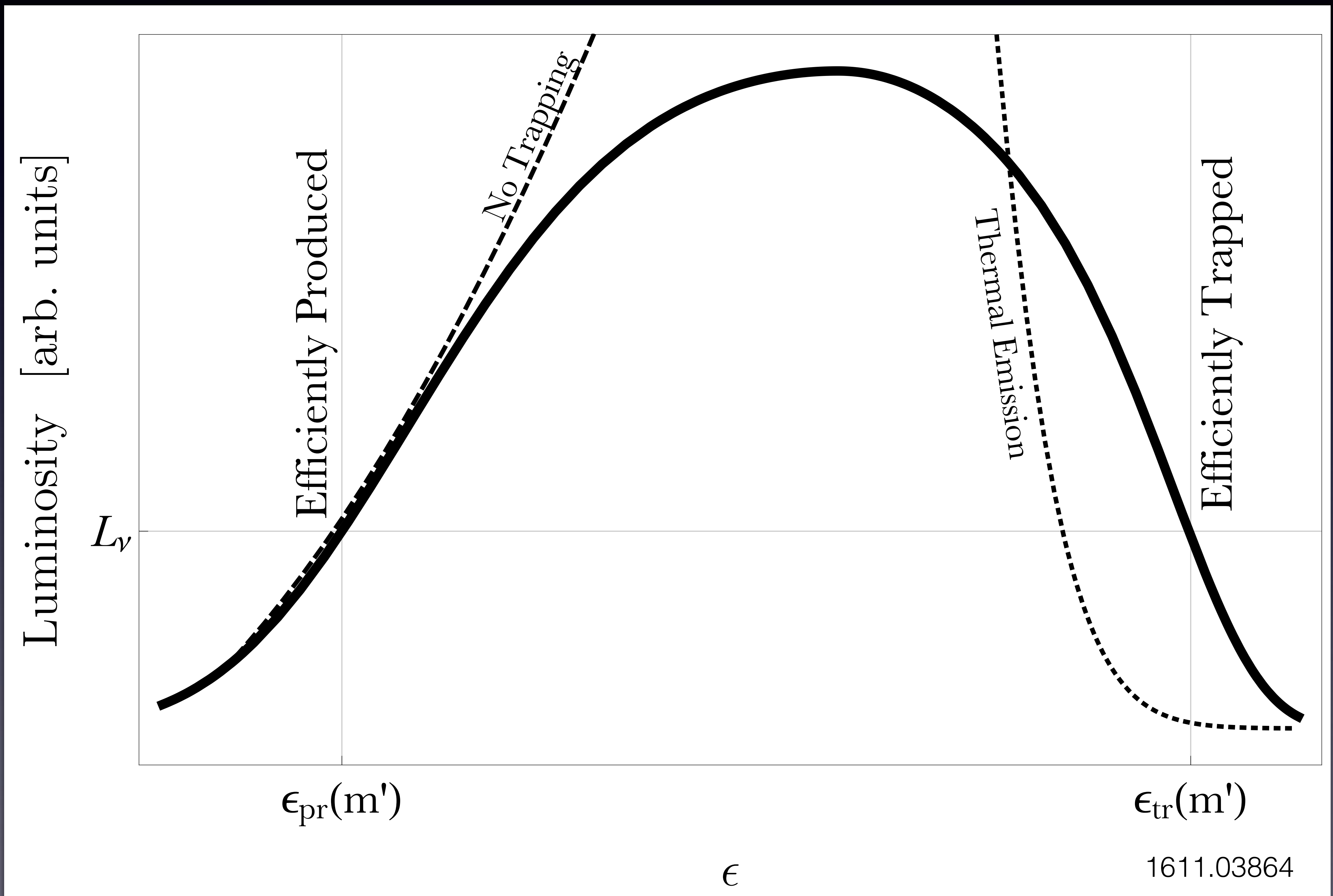
Crash Course: SN1987A

Credit: Colin Legg

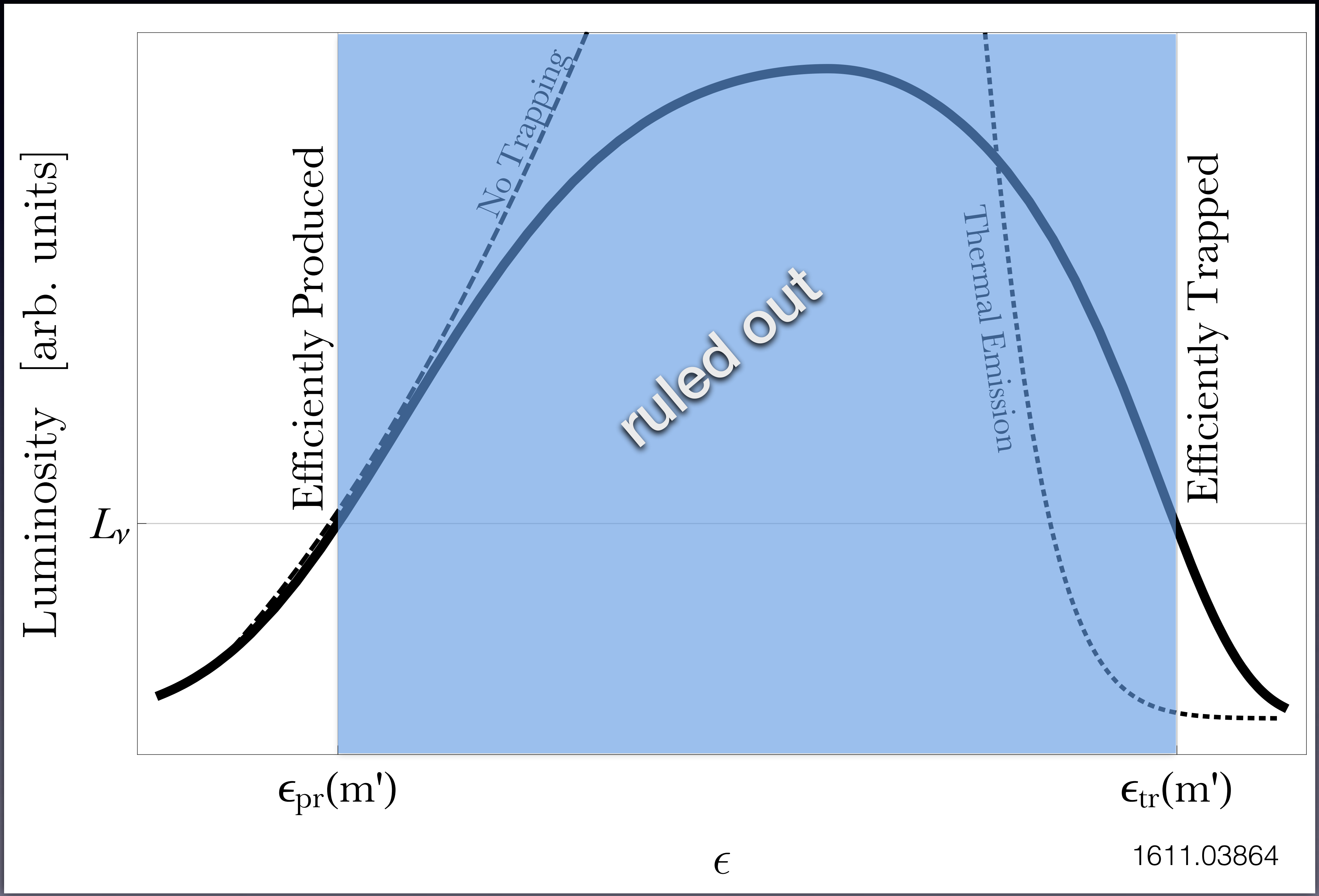
- Cooling phase is consistent with analytic expectation
- …but wouldn't be if a new "energy sink" competed with Standard Model processes
- Limited amount of luminosity may be diverted to novel particles $\Longleftrightarrow$ bounds on new coupling with SM

(see my talk tomorrow for more details!)

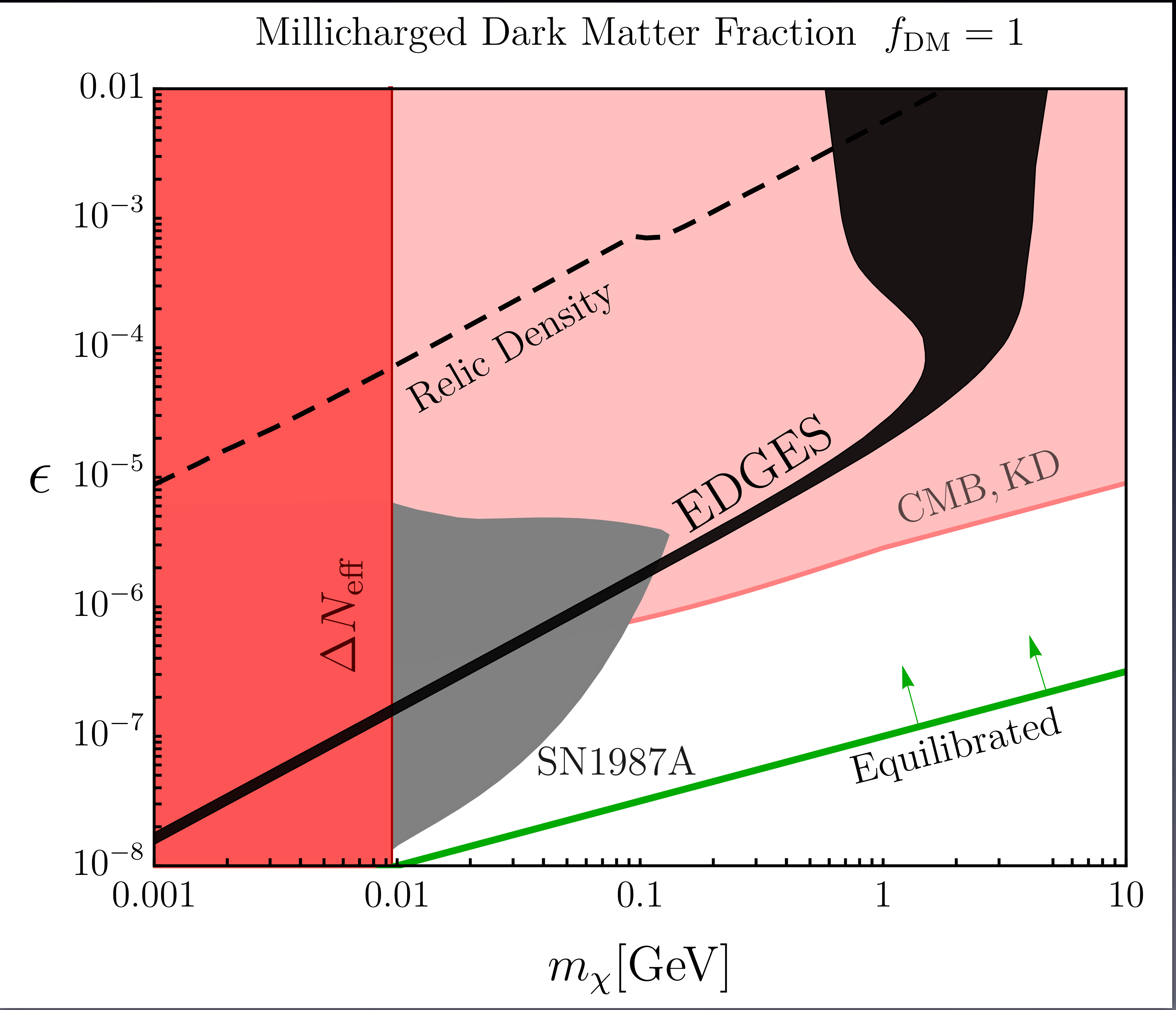
Bounds (schematic)



Bounds (schematic)



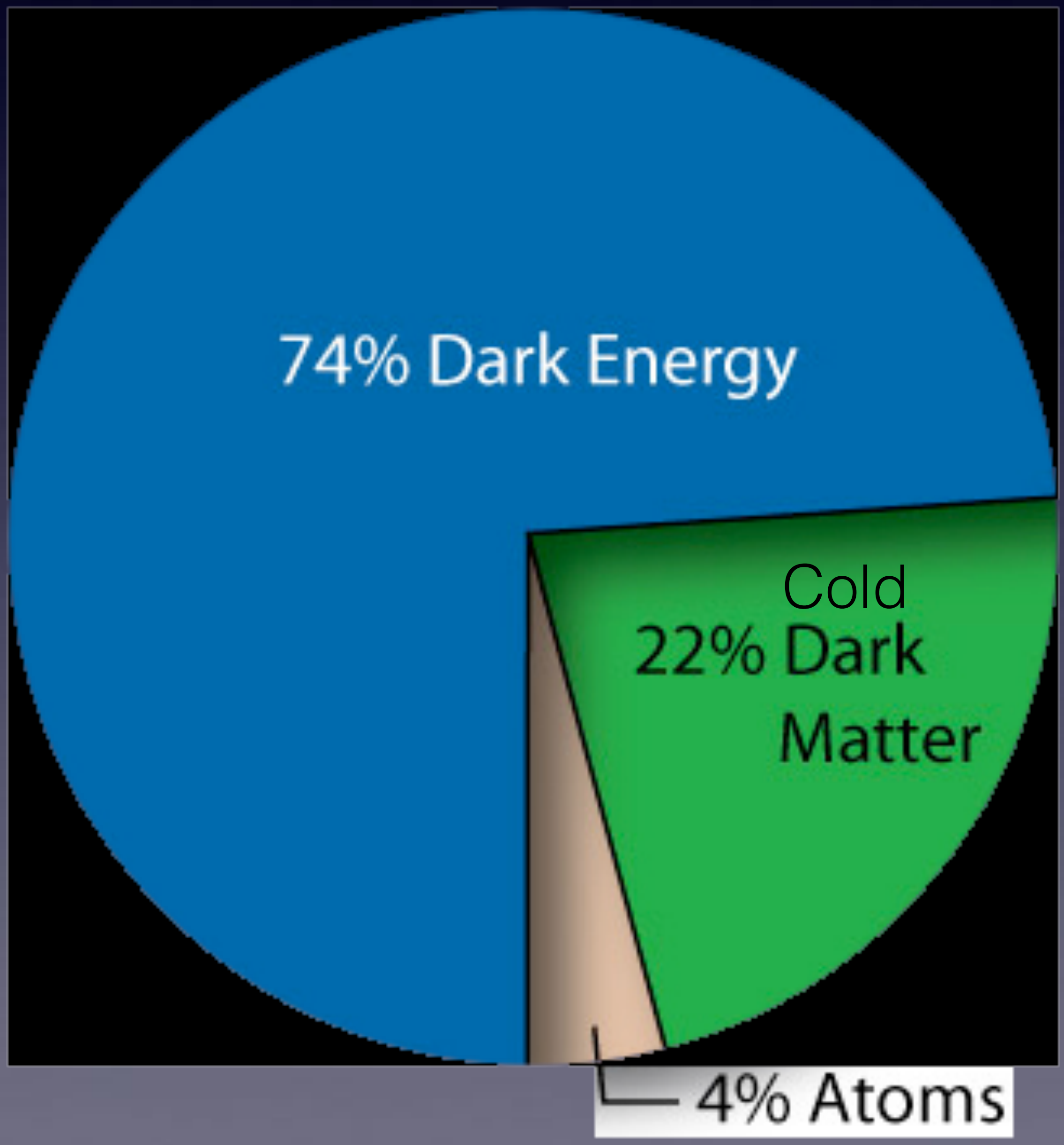
EDGES Constraints



Caveats?

Perhaps only a subdominant component of dark matter has a millicharge (the rest is cold, collisionless, etc)

http://www.solstation.com/x-objects/darkhalo.htm



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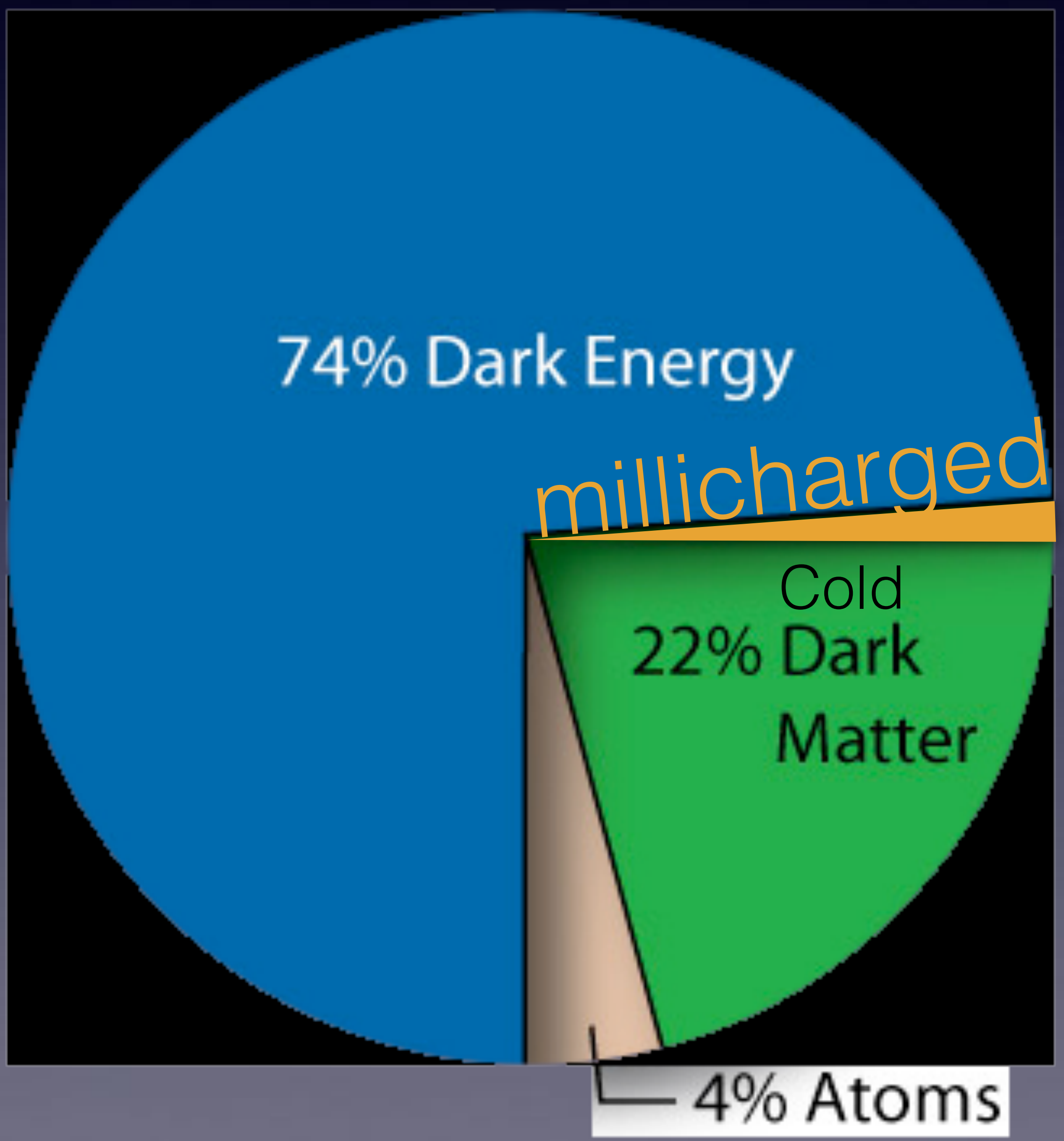

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$f_{DM} = \Omega_{millicharge}/\Omega_{DM}$

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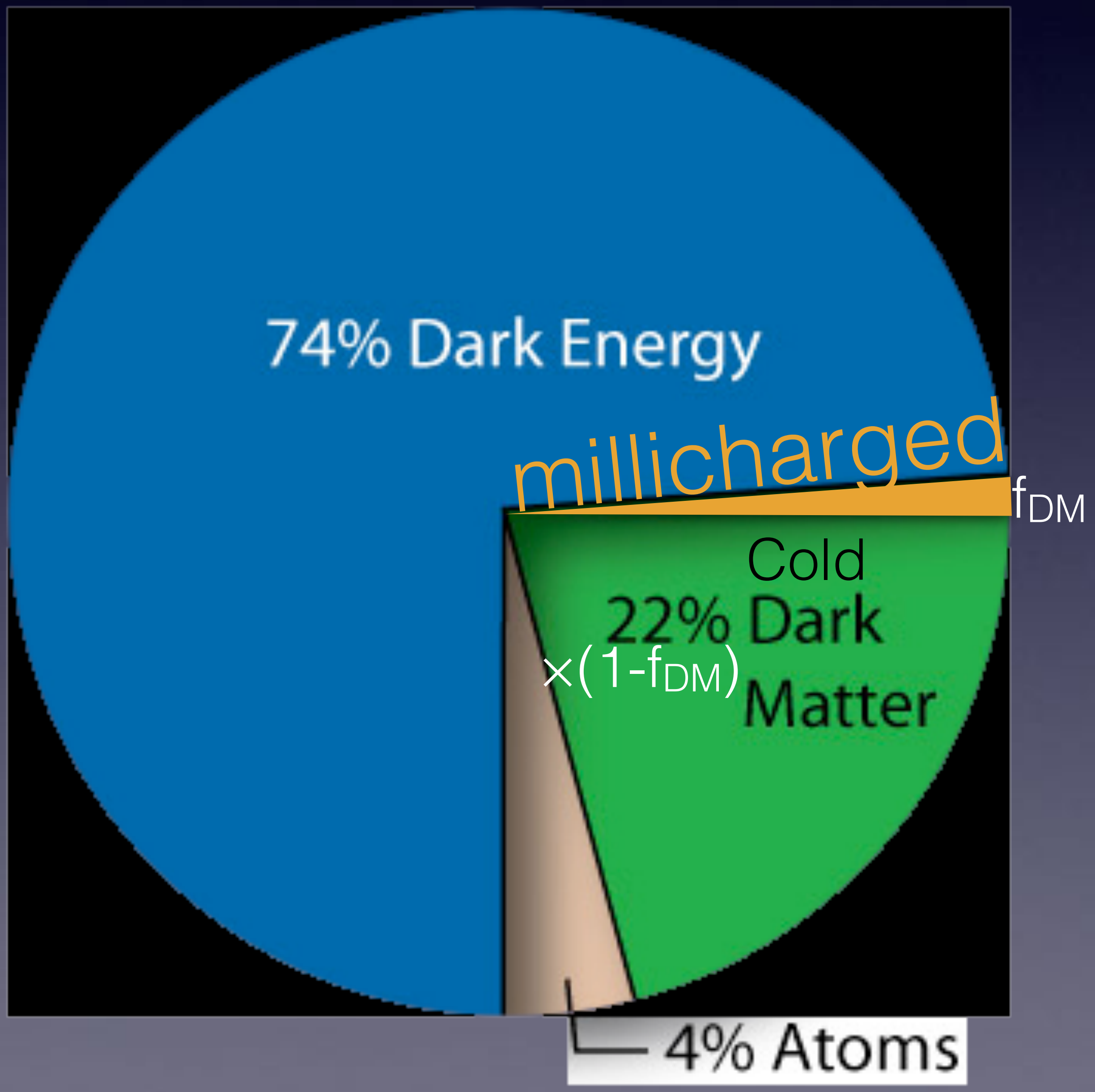

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- Preferred region, relic density curve, CMB bounds change
- BBN and SN don't

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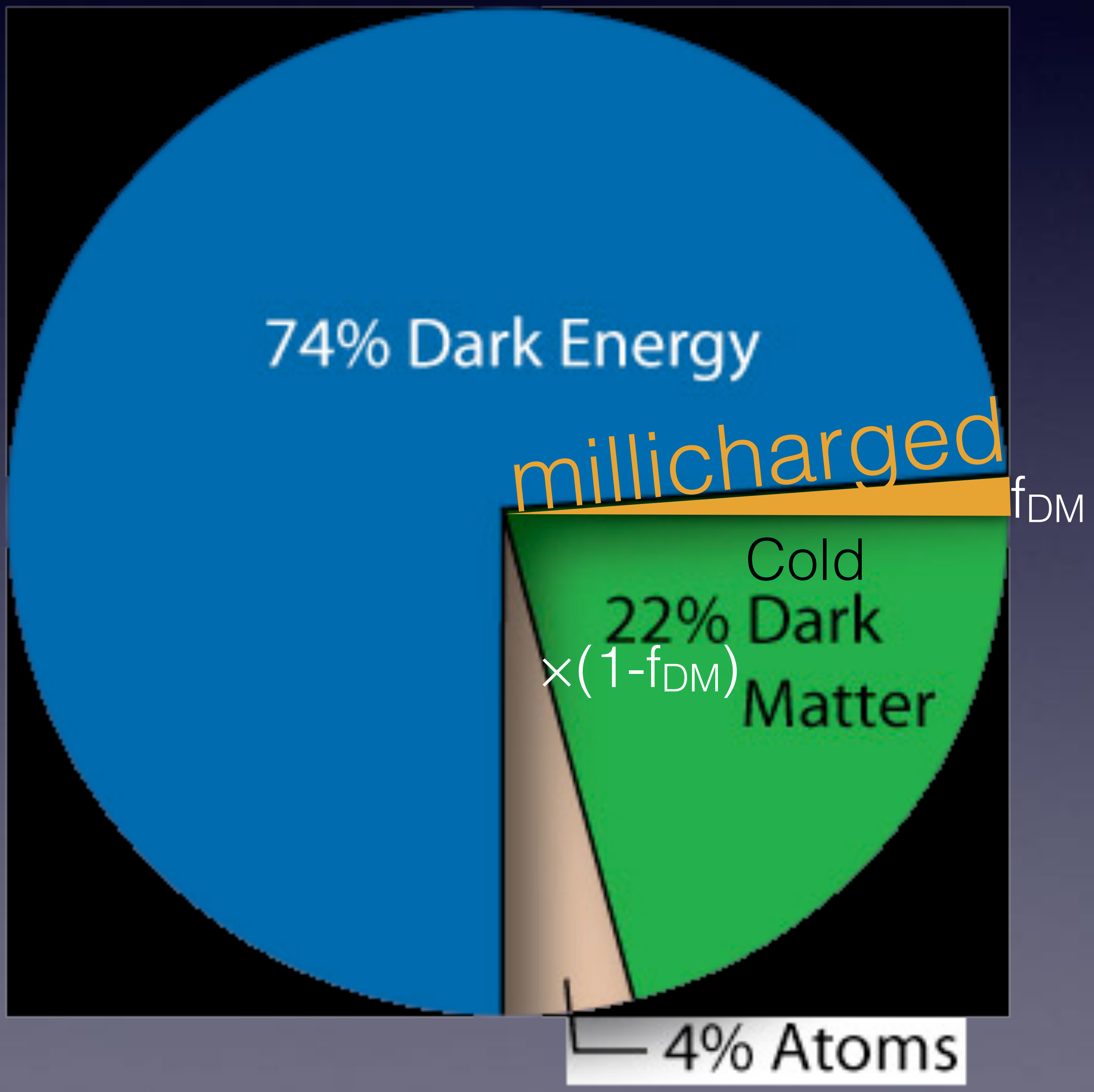

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$\sim f^{3/4}$ (Munoz and Loeb, 1802.10094)

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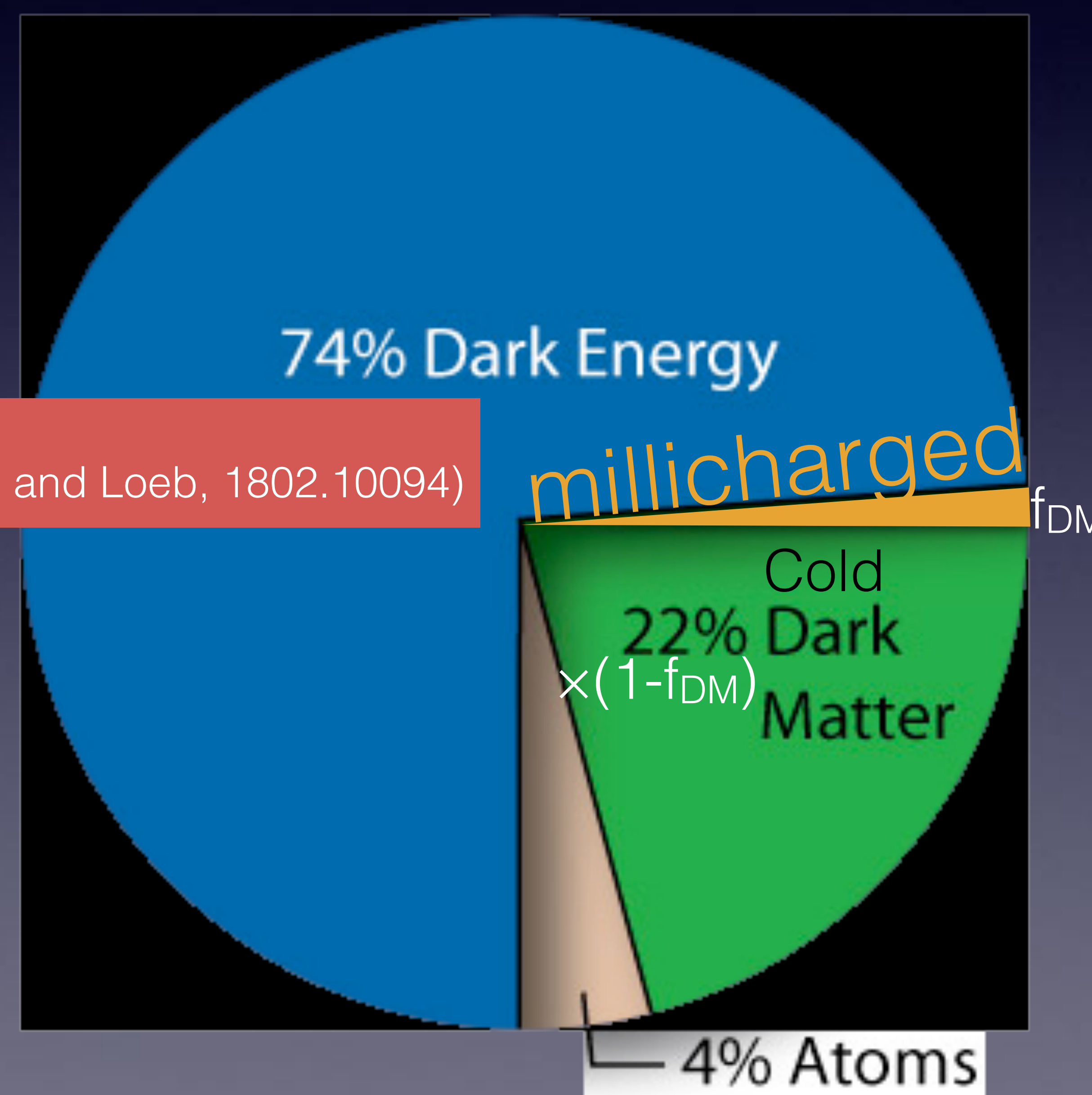

Caveats?

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$\sim f^{1/2}$

$$f_{DM} = \Omega_{millicharge}/\Omega_{DM}$$

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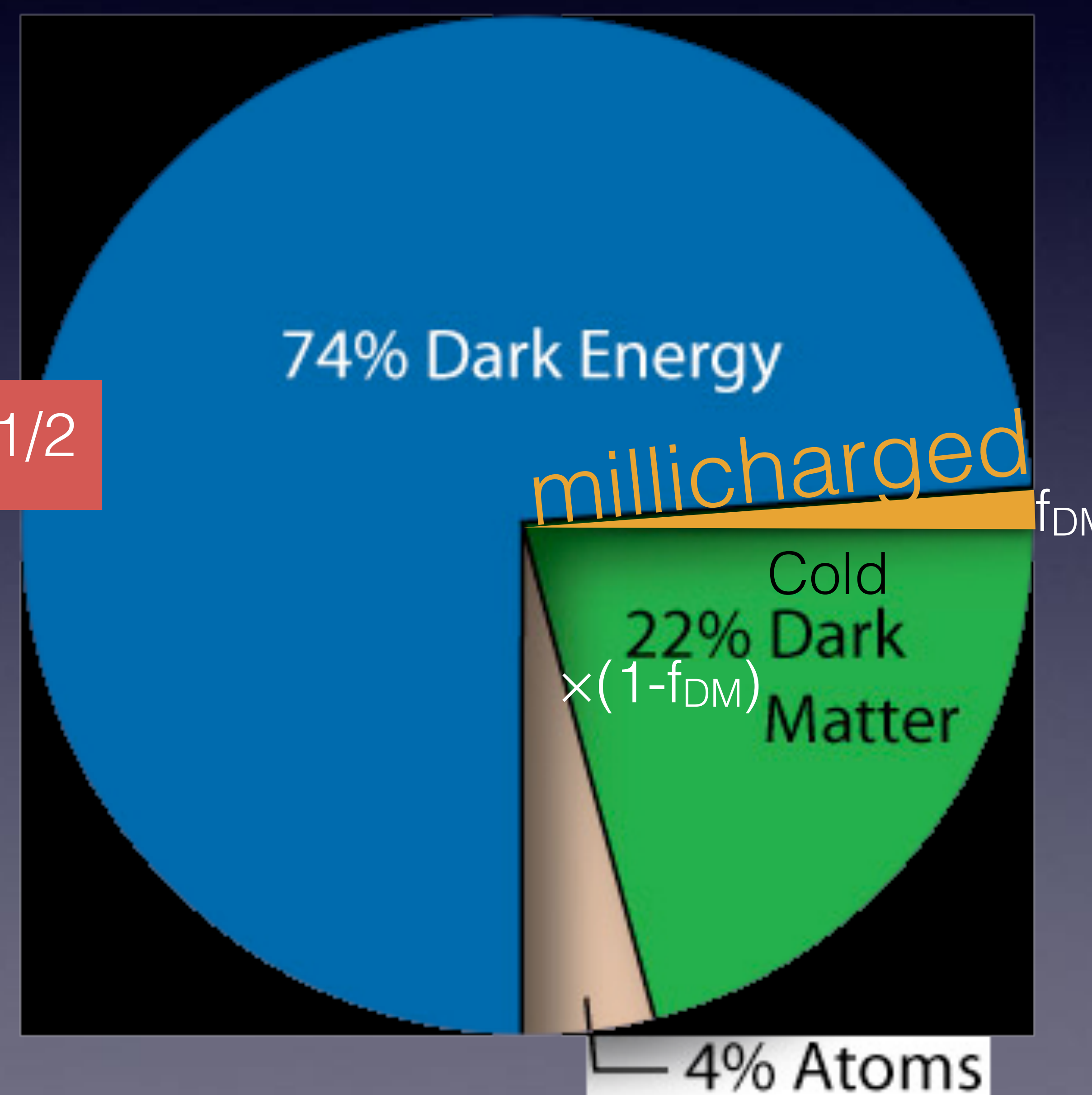

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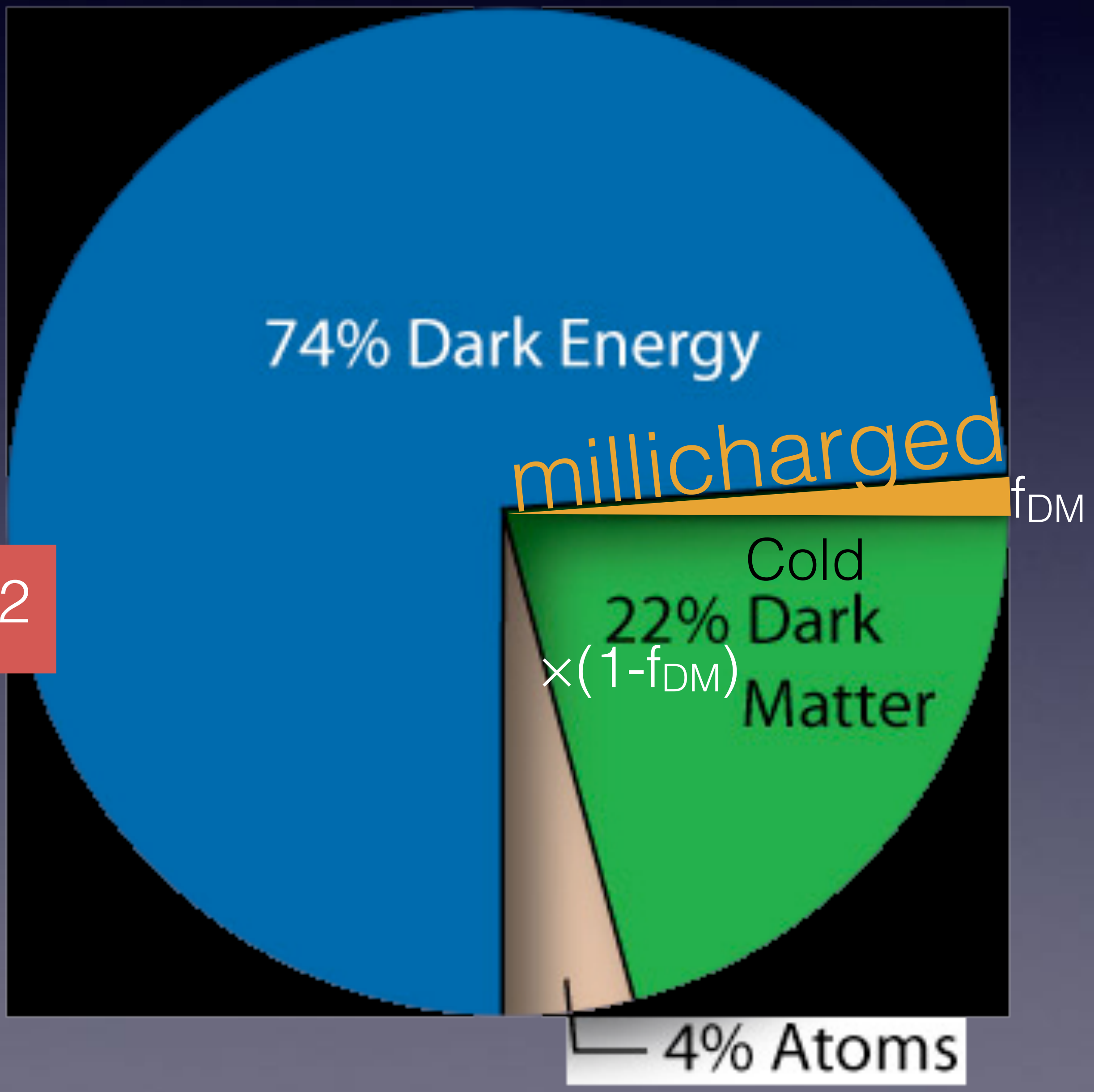
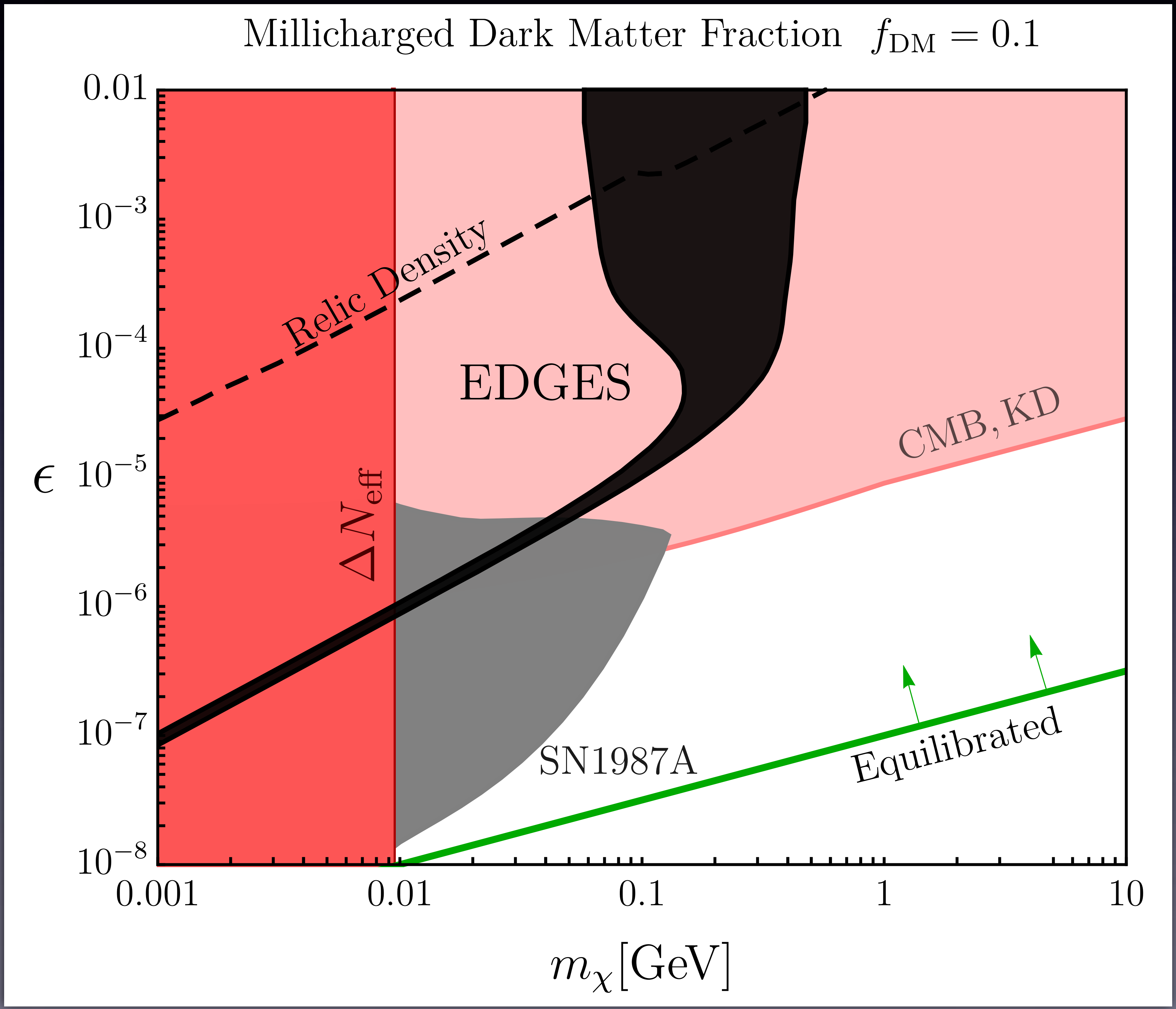


EDGES Constraints



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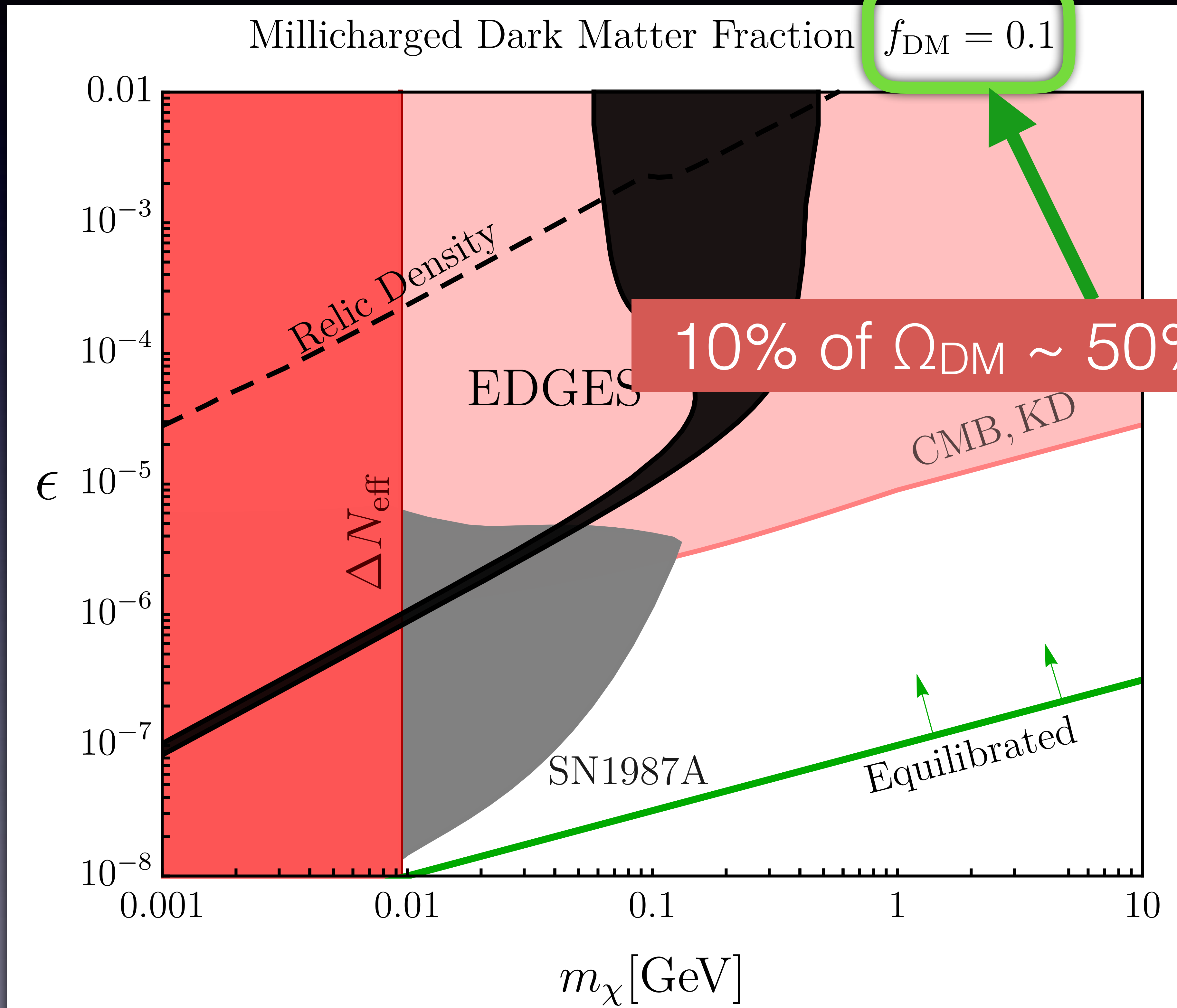
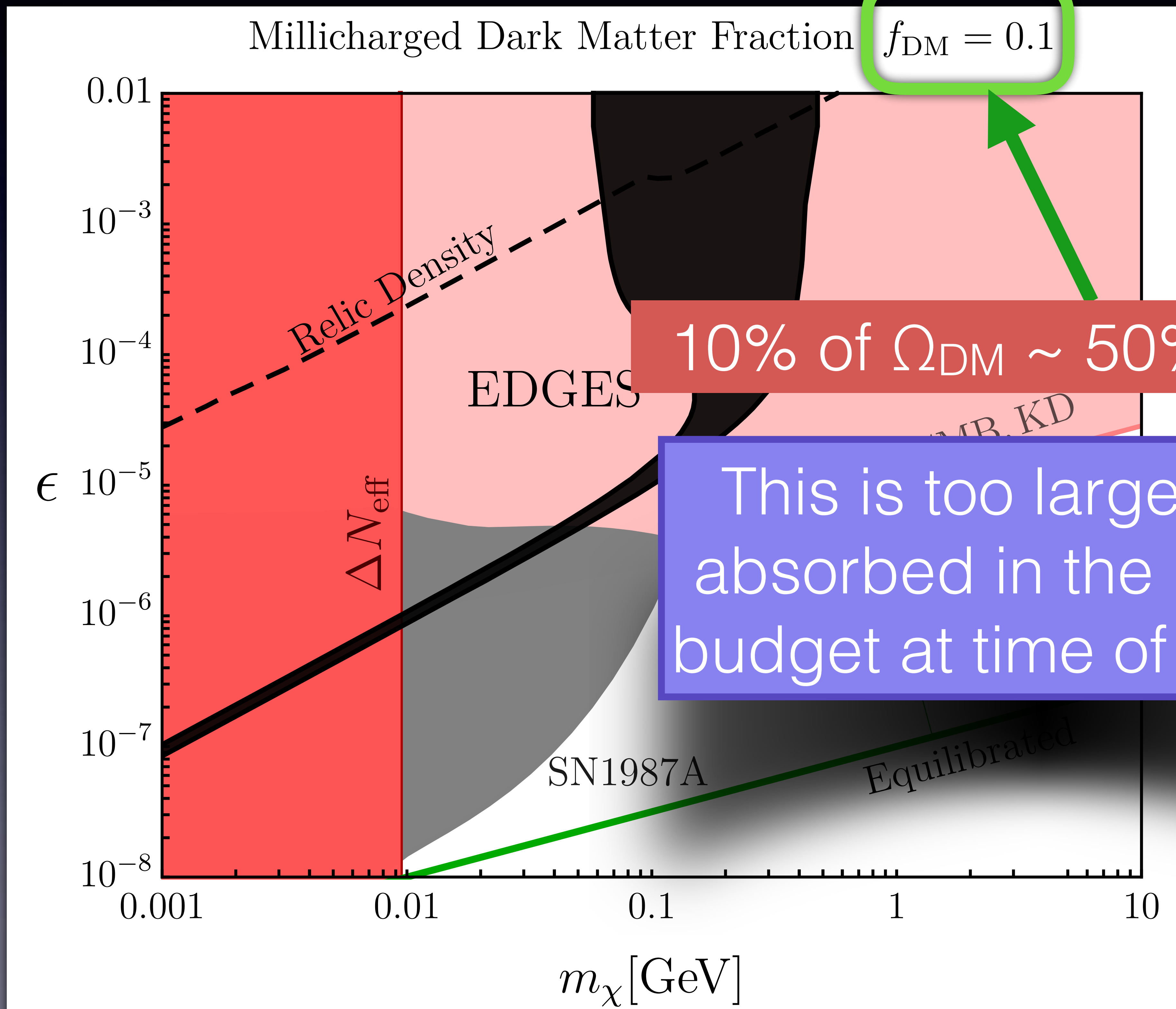


10% of Ω_{DM} ~ 50% of Ω_b

EDGES Constraints



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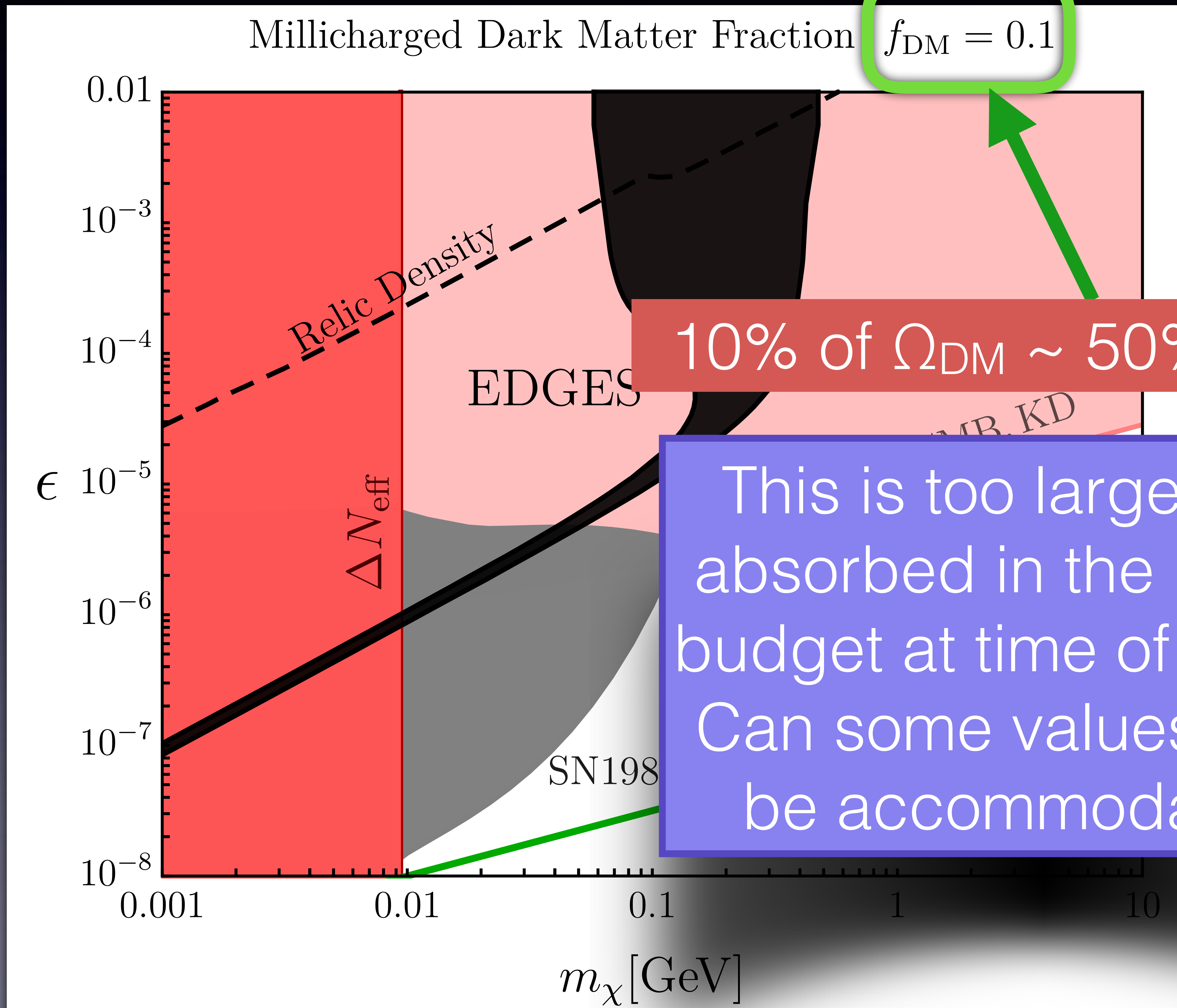
This is too large to be absorbed in the baryon budget at time of CMB…

EDGES Constraints

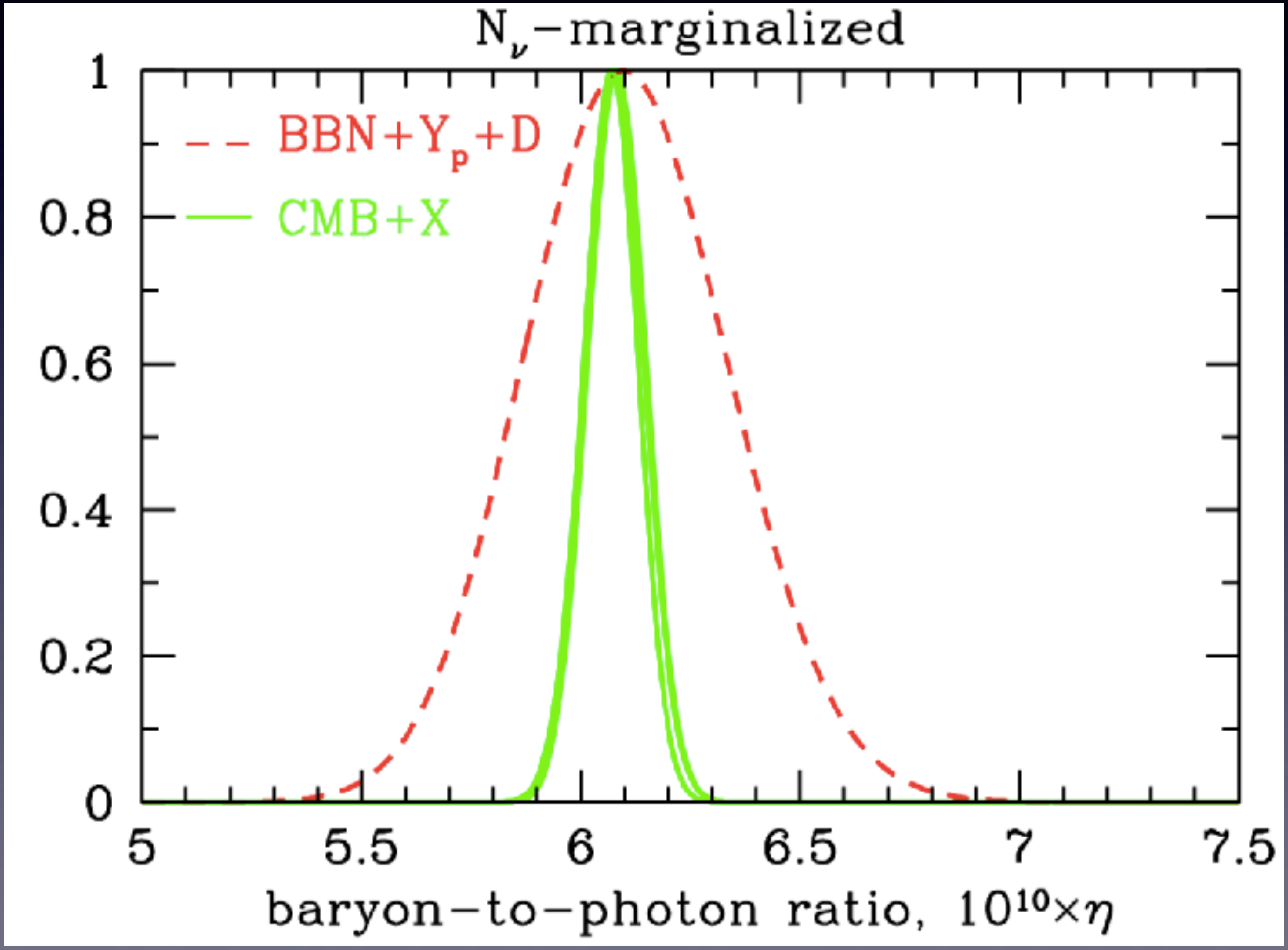


10% of Ω_{DM} ~ 50% of Ω_b

This is too large to be absorbed in the baryon budget at time of CMB… Can some values of f_{DM} be accommodated?

Ω_b: BBN vs. CMB

Cyburt et al, 1505.01076



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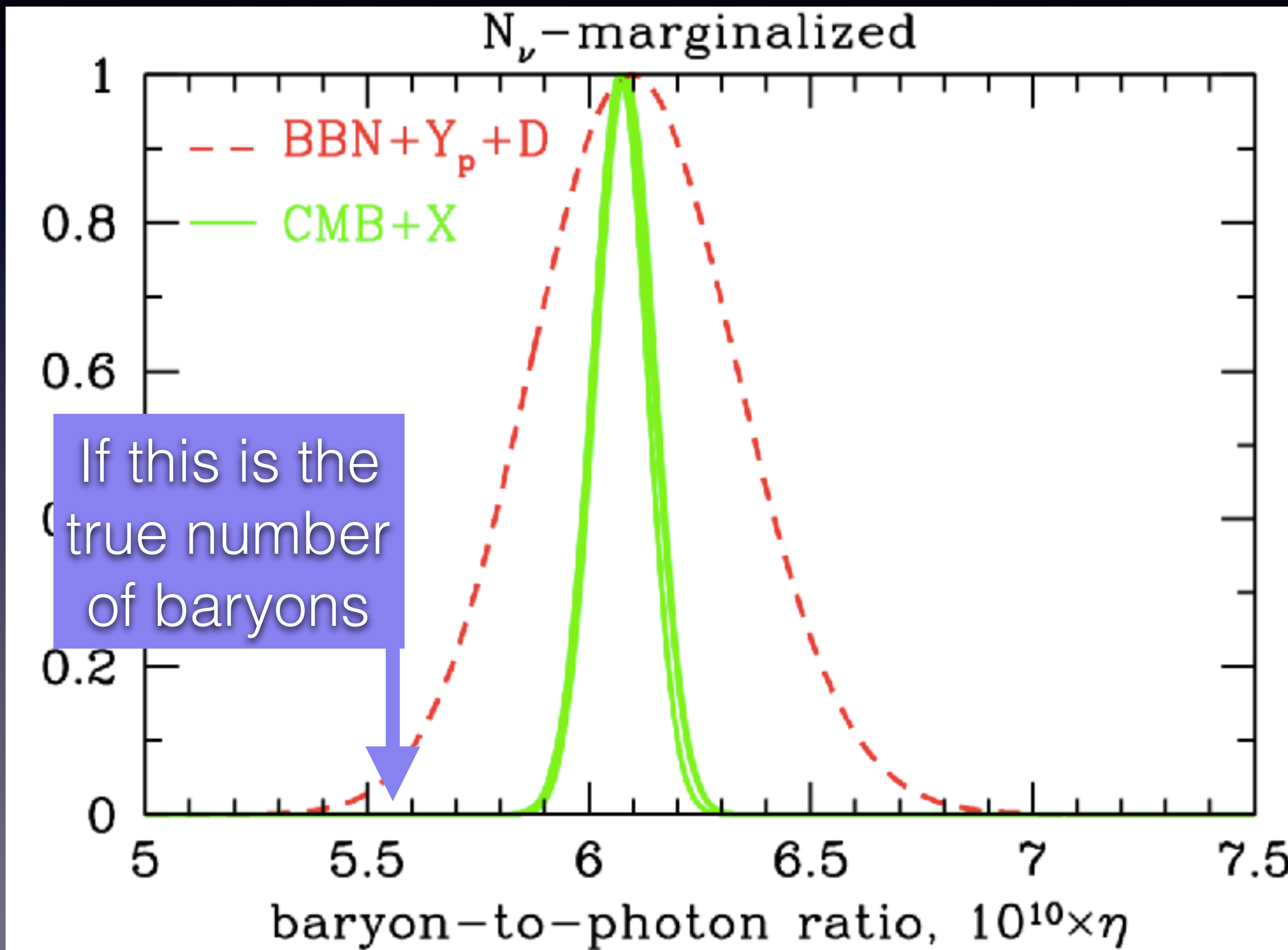

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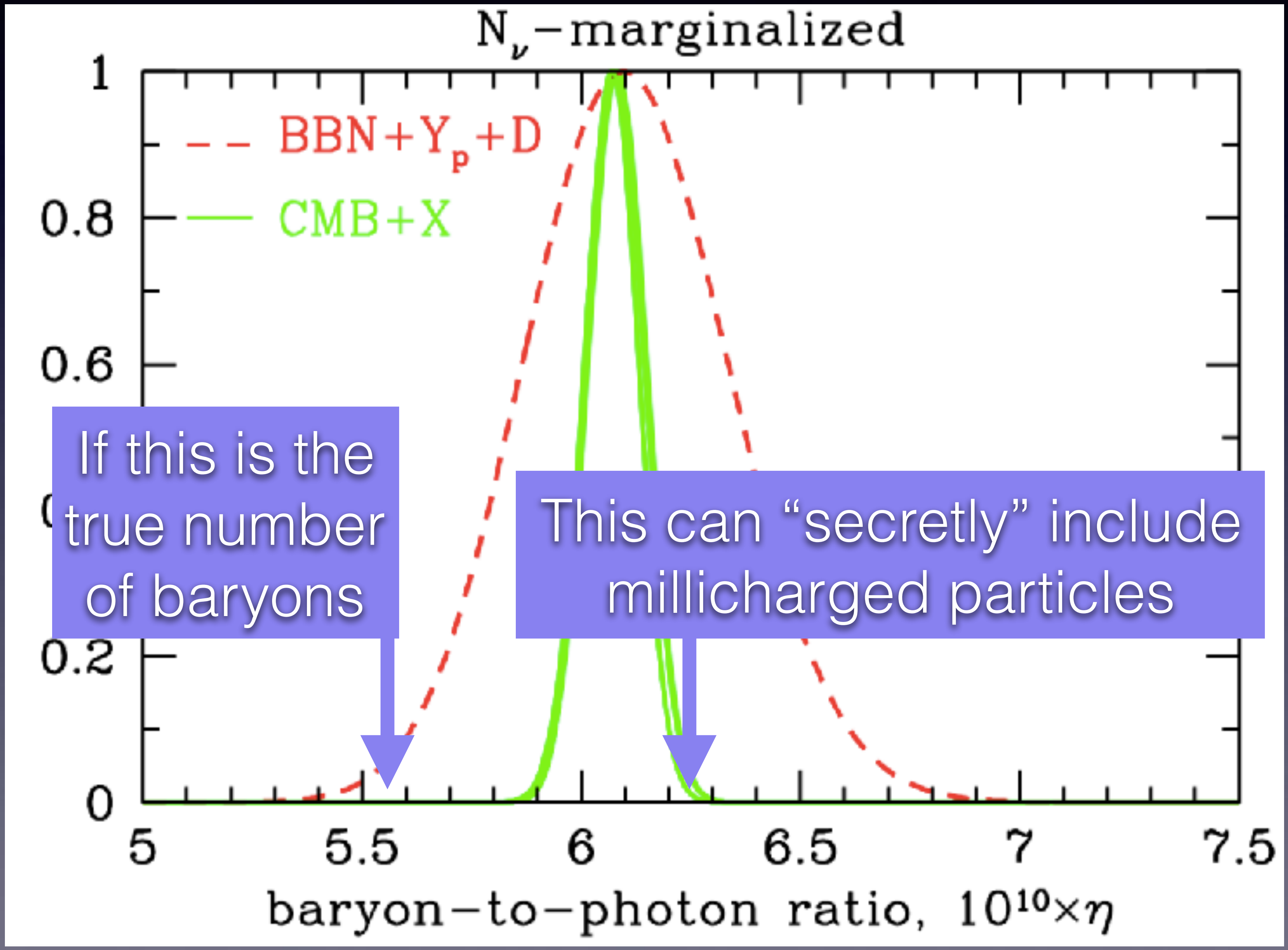

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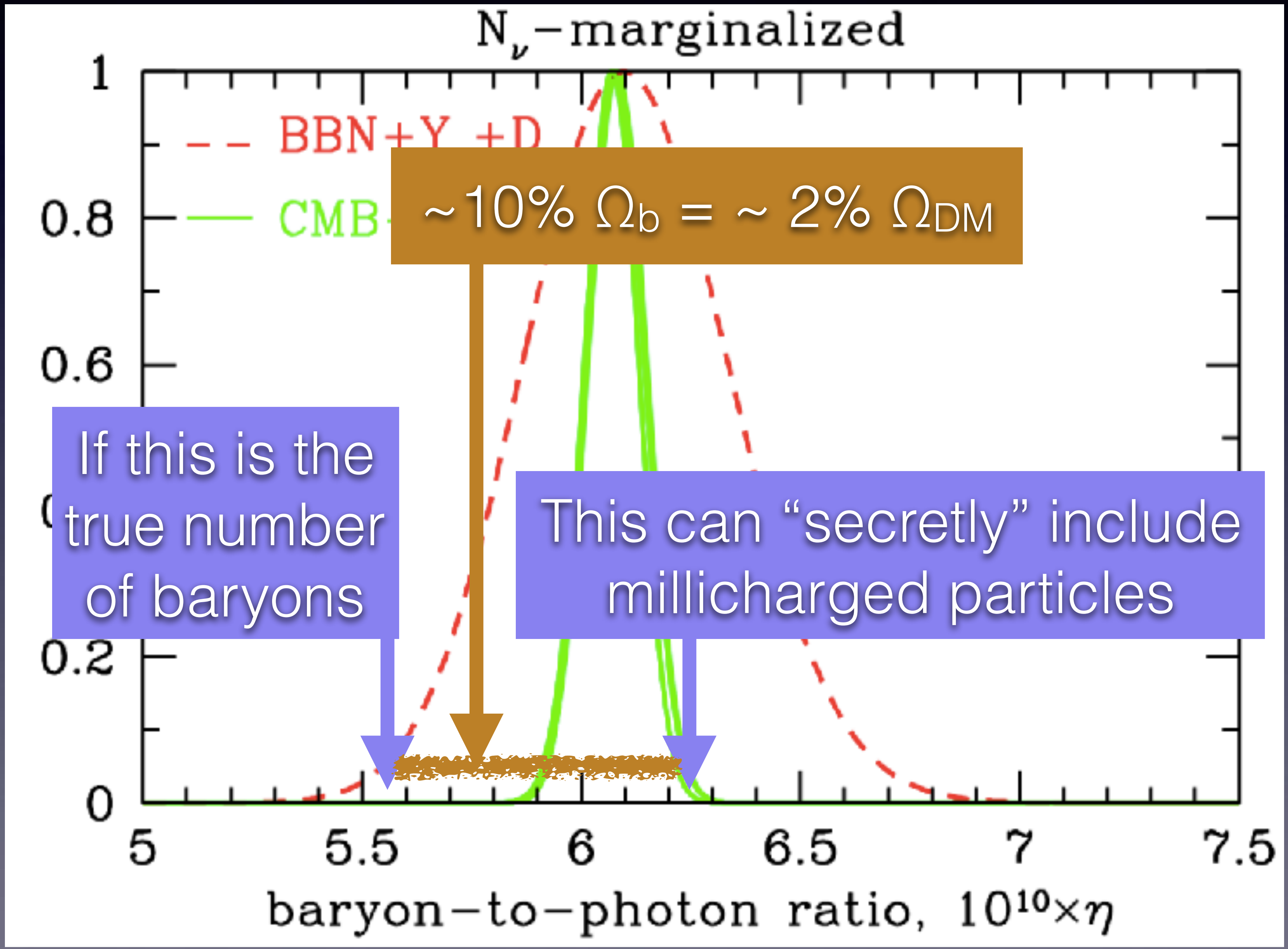

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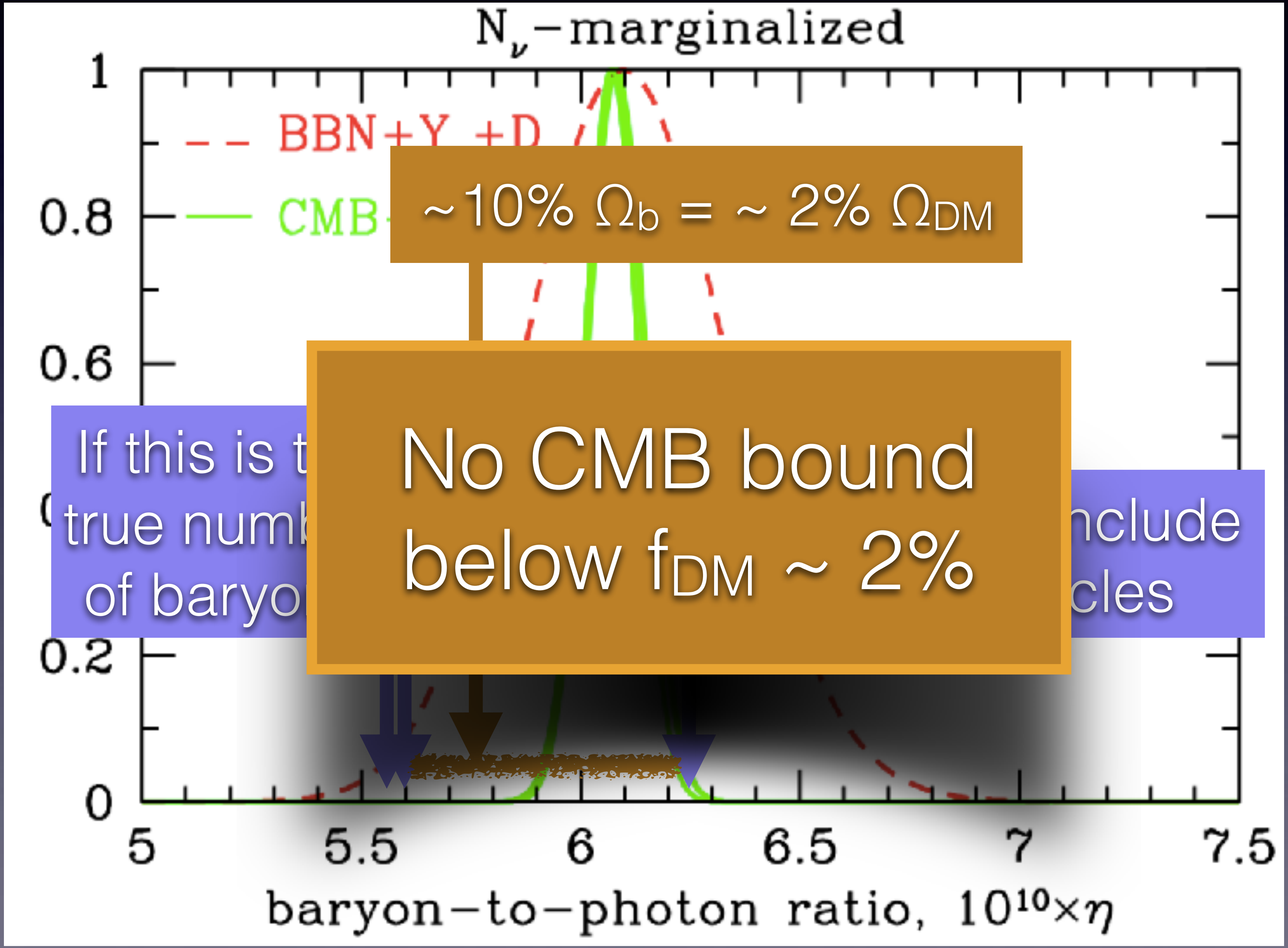


~10% Ω_b = ~ 2% Ω_{DM}

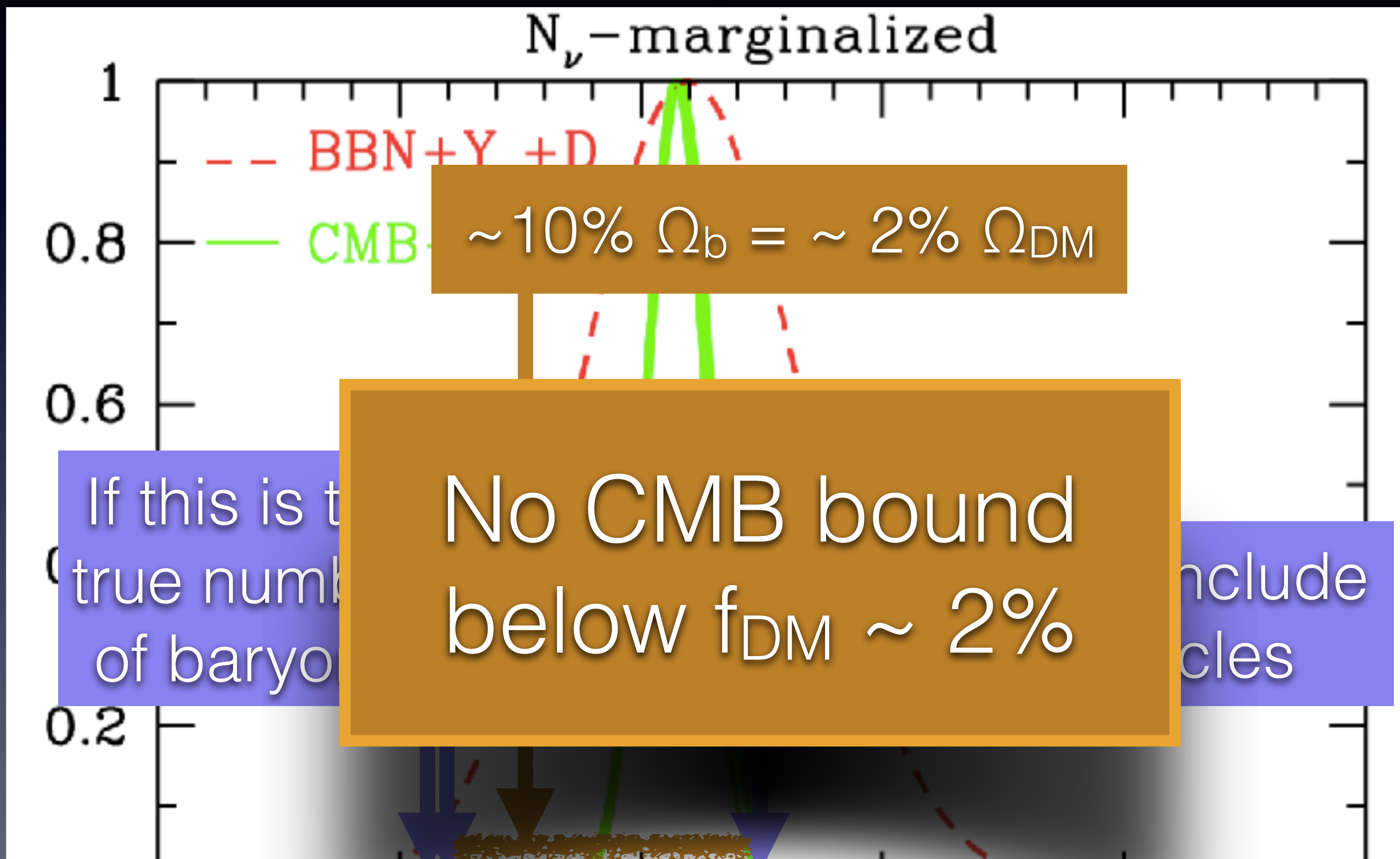
If this is t
true numb
of baryo

nclude
cles

No CMB bound below f_{DM} ~ 2%

Ω_b: BBN vs. CMB

Cyburt et al, 1505.01076



~10% Ω_b = ~ 2% Ω_{DM}

If this is t
true numb
of baryo

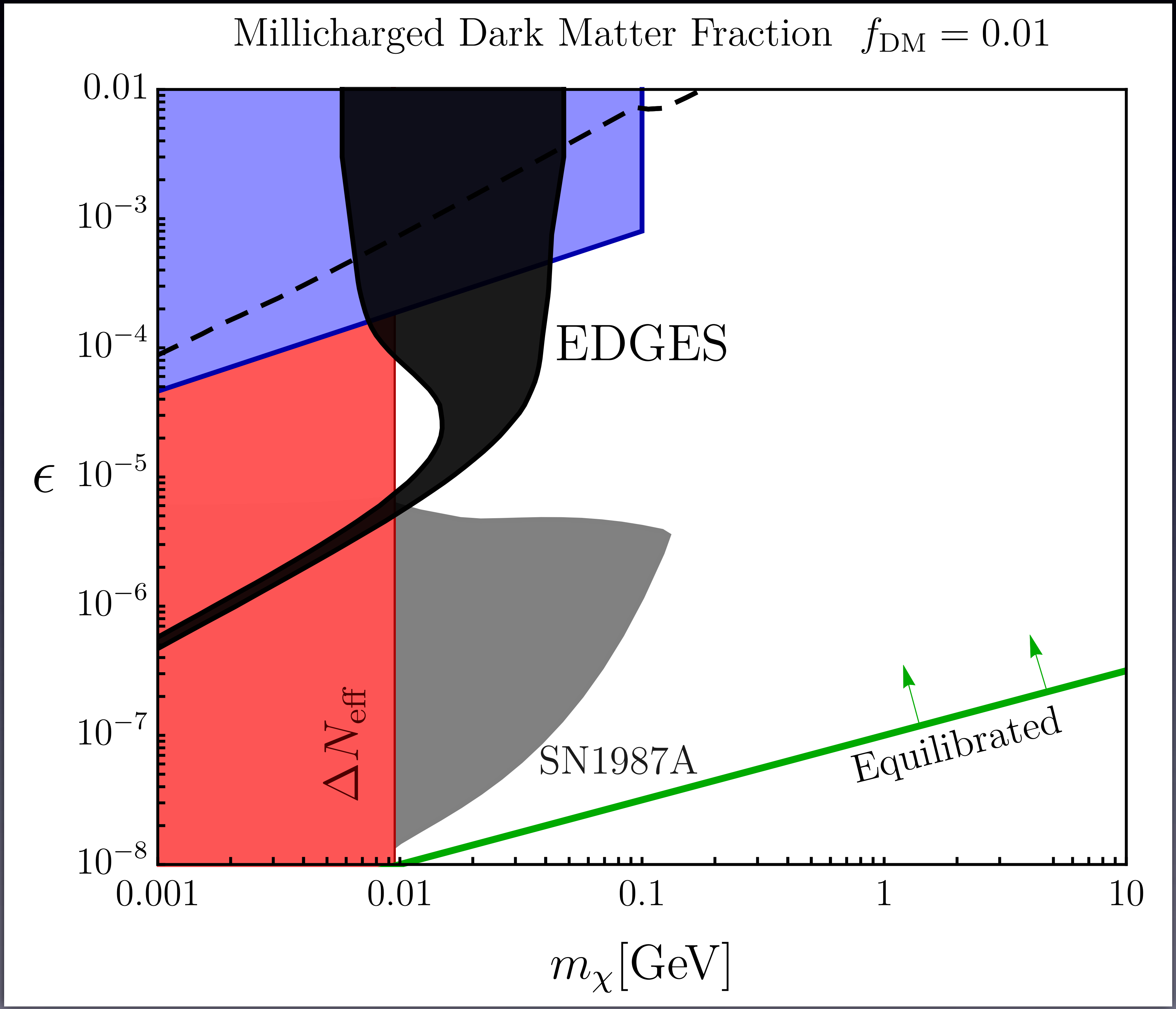
nclude
cles

No CMB bound below f_{DM} ~ 2%

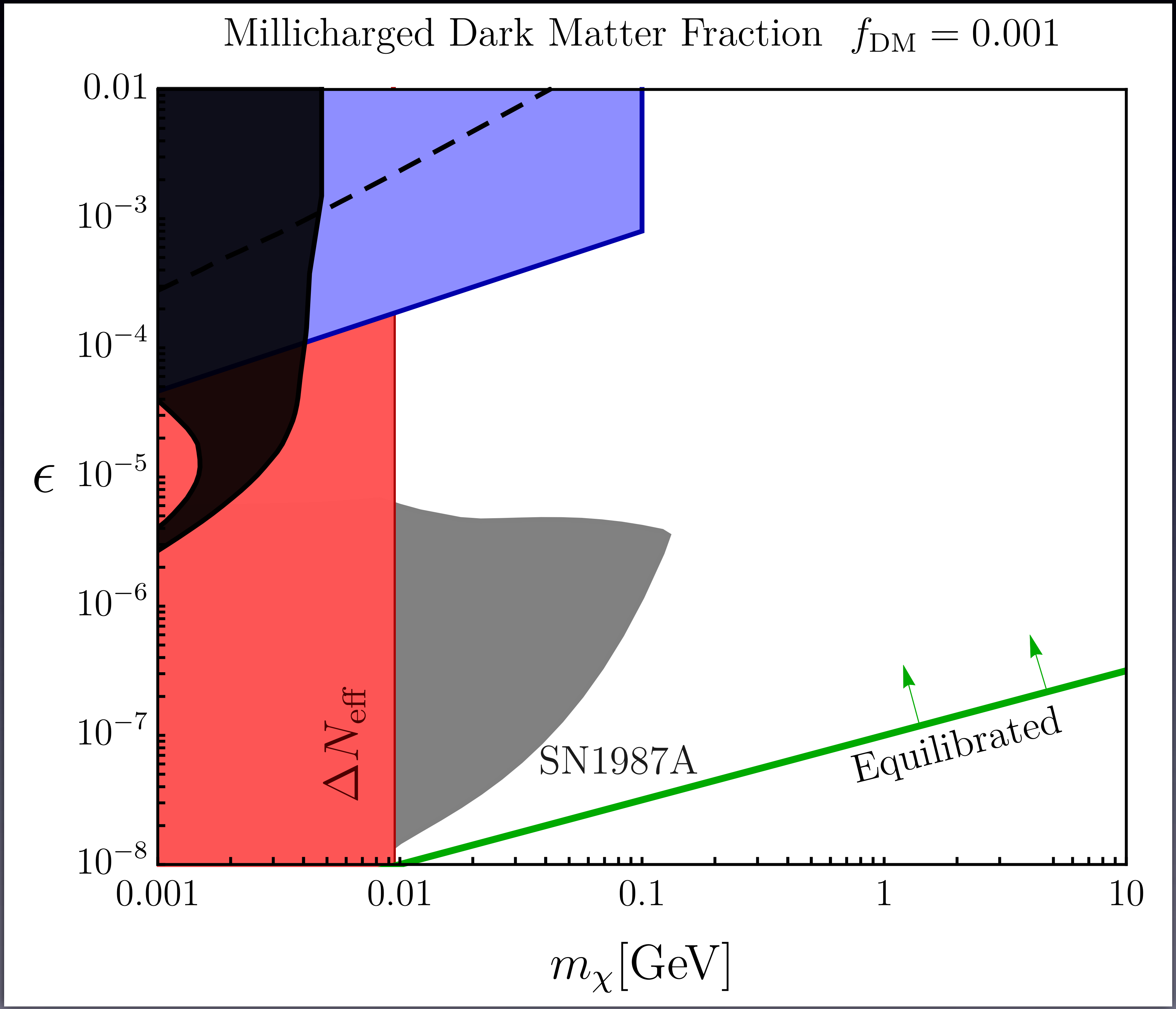
!

1805.11616, de Putter et al.: “we derive a new upper limit on the fraction of tightly coupled dark matter…<0.6% ”

EDGES Constraints



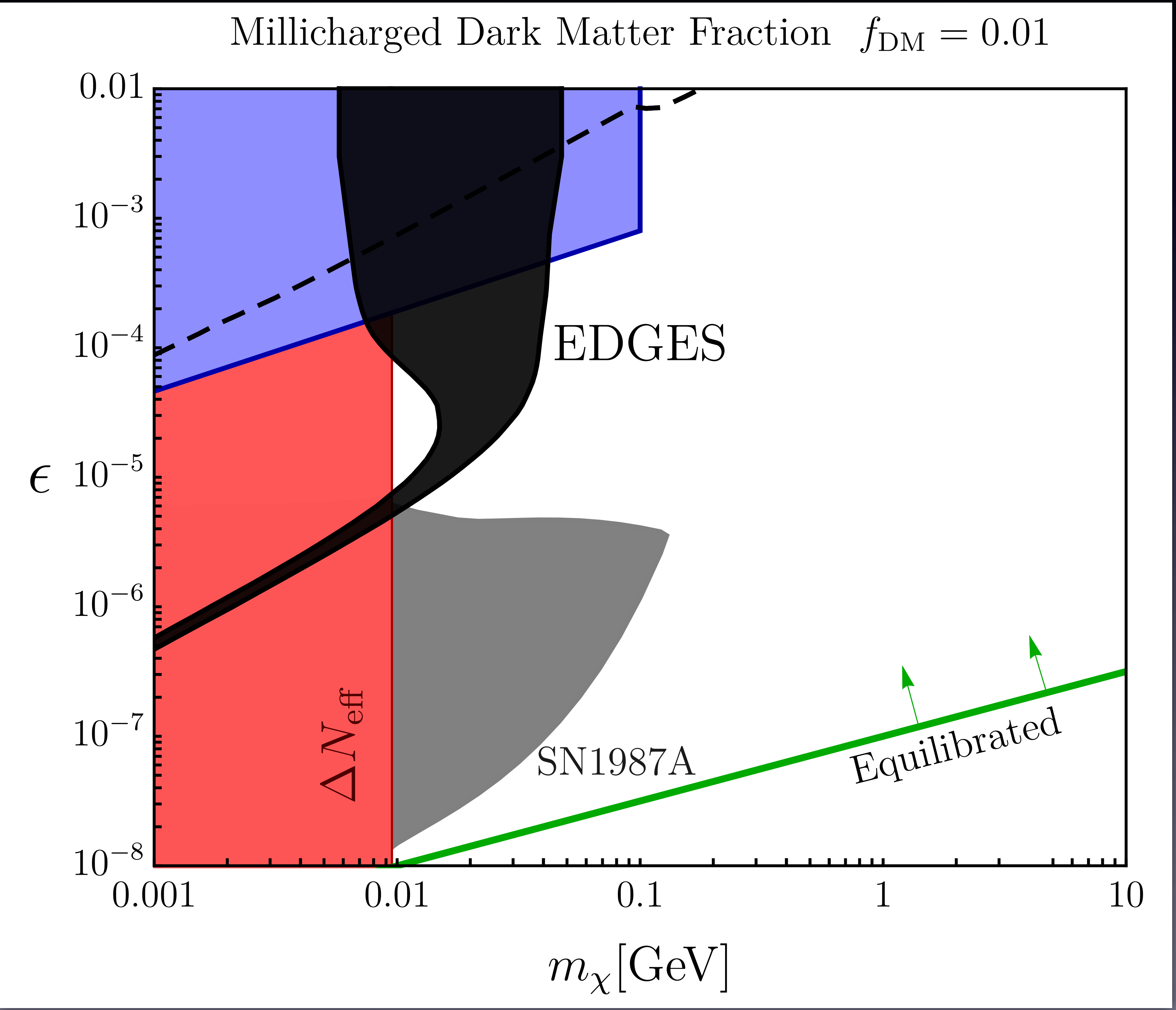
EDGES Constraints



Outline

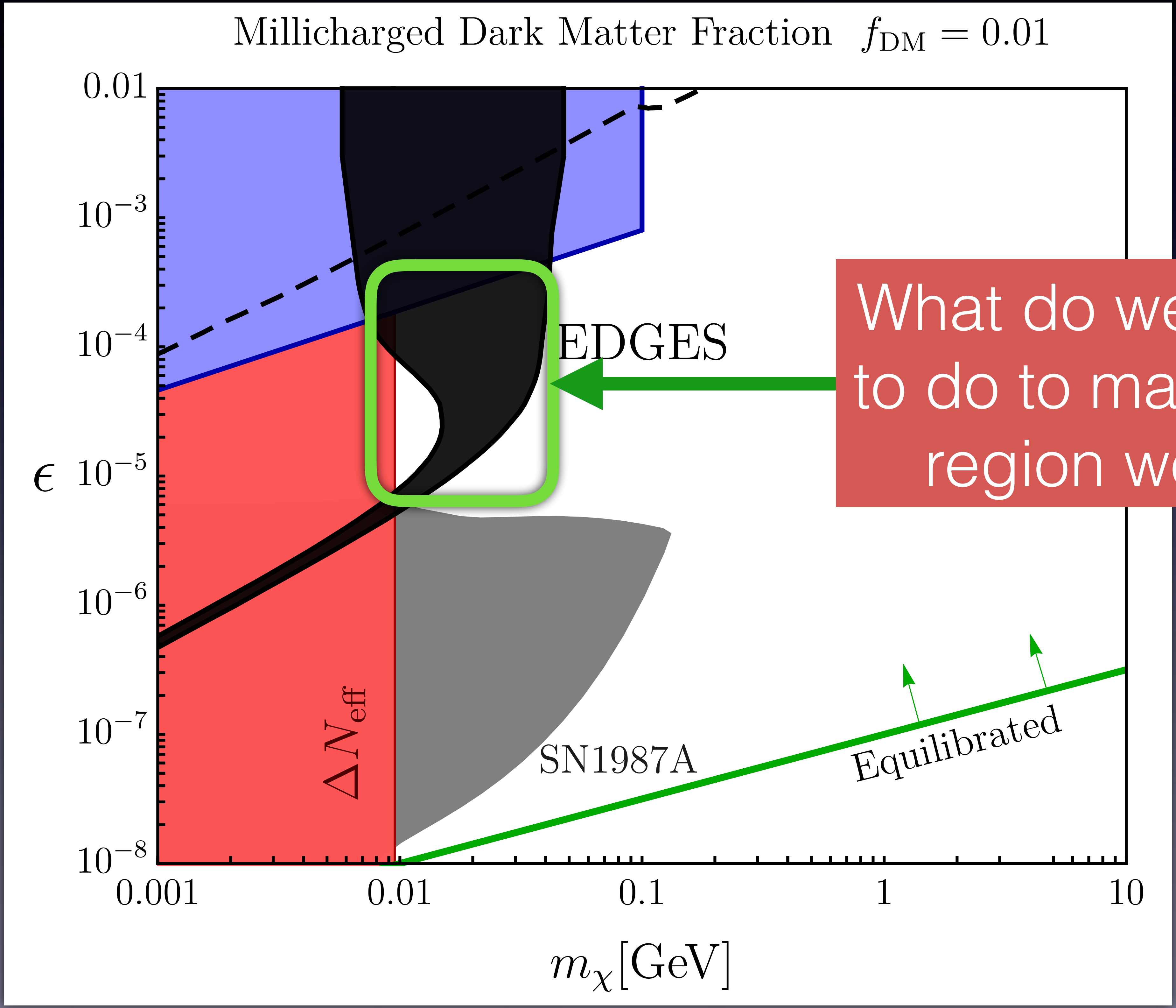
1. Astrophysical & Cosmological Signatures
2. Future Directions

EDGES, f_{DM}=1%



Millicharged Dark Matter Fraction $f_{\rm DM} = 0.01$
0.01
10^{-3}
10^{-4}
ϵ
10^{-5}
10^{-6}
10^{-7}
10^{-8}
EDGES
$\Delta N_{\rm eff}$
SN1987A
Equilibrated
0.001
0.01
0.1
1
10
m_χ[GeV]

EDGES, f_{DM}=1%



What do we need to do to make this region work?

Implications of f_{DM}=1%

1. Relic density via QED alone is problematic — how else to deplete thermal abundance?

Couple to New Force

Many possibilities, but some guidelines:

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- Shouldn’t couple to electrons

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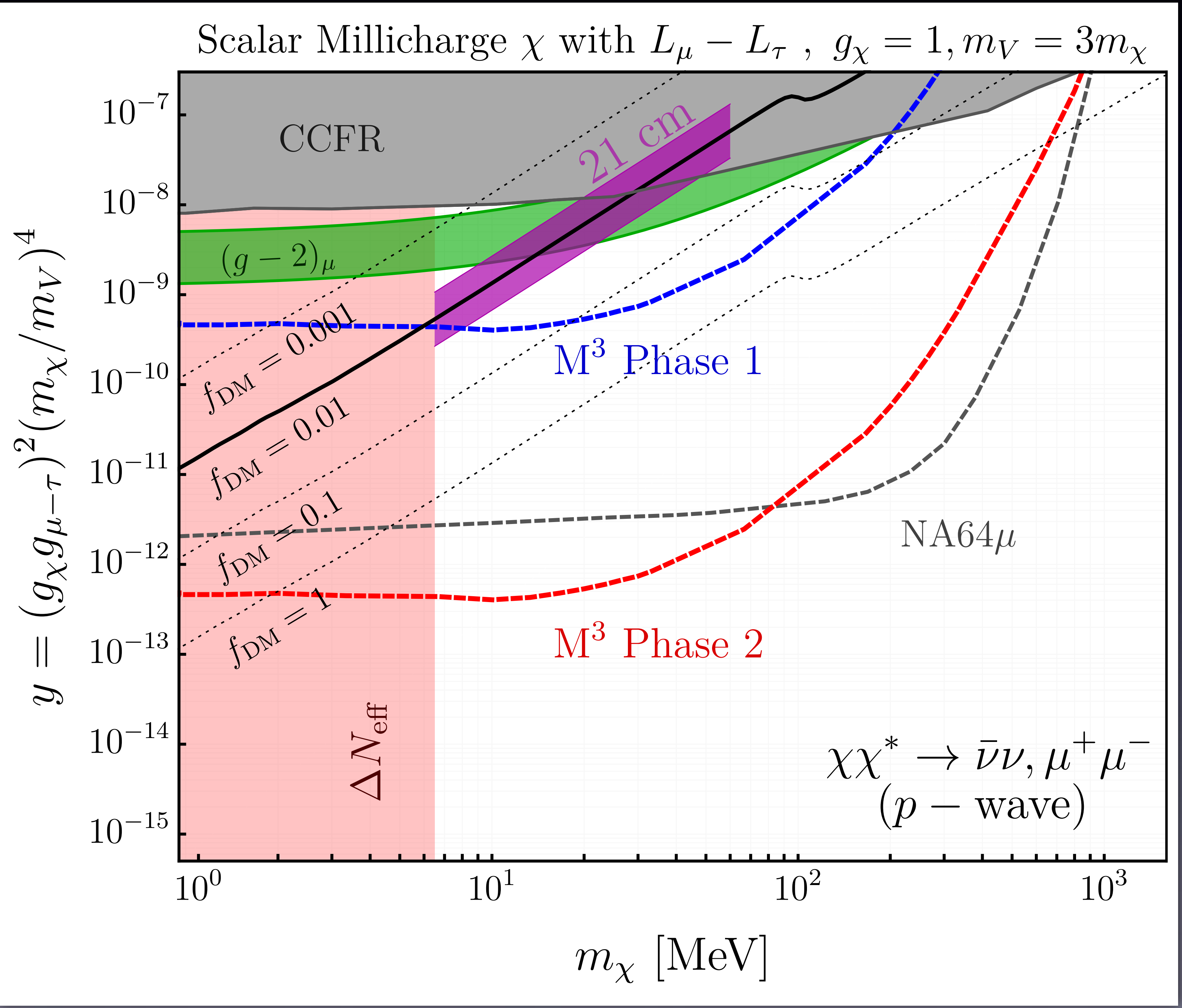
- Shouldn’t inject too much energy during cosmic dark ages

Couple to New Force

Many possibilities, but some guidelines:

- Shouldn't couple to electrons
- Shouldn't inject too much energy during cosmic dark ages
    - neutrinos
    - *p*-wave suppression

Couple to Lμ-Lτ



Implications of f_{DM}=1%

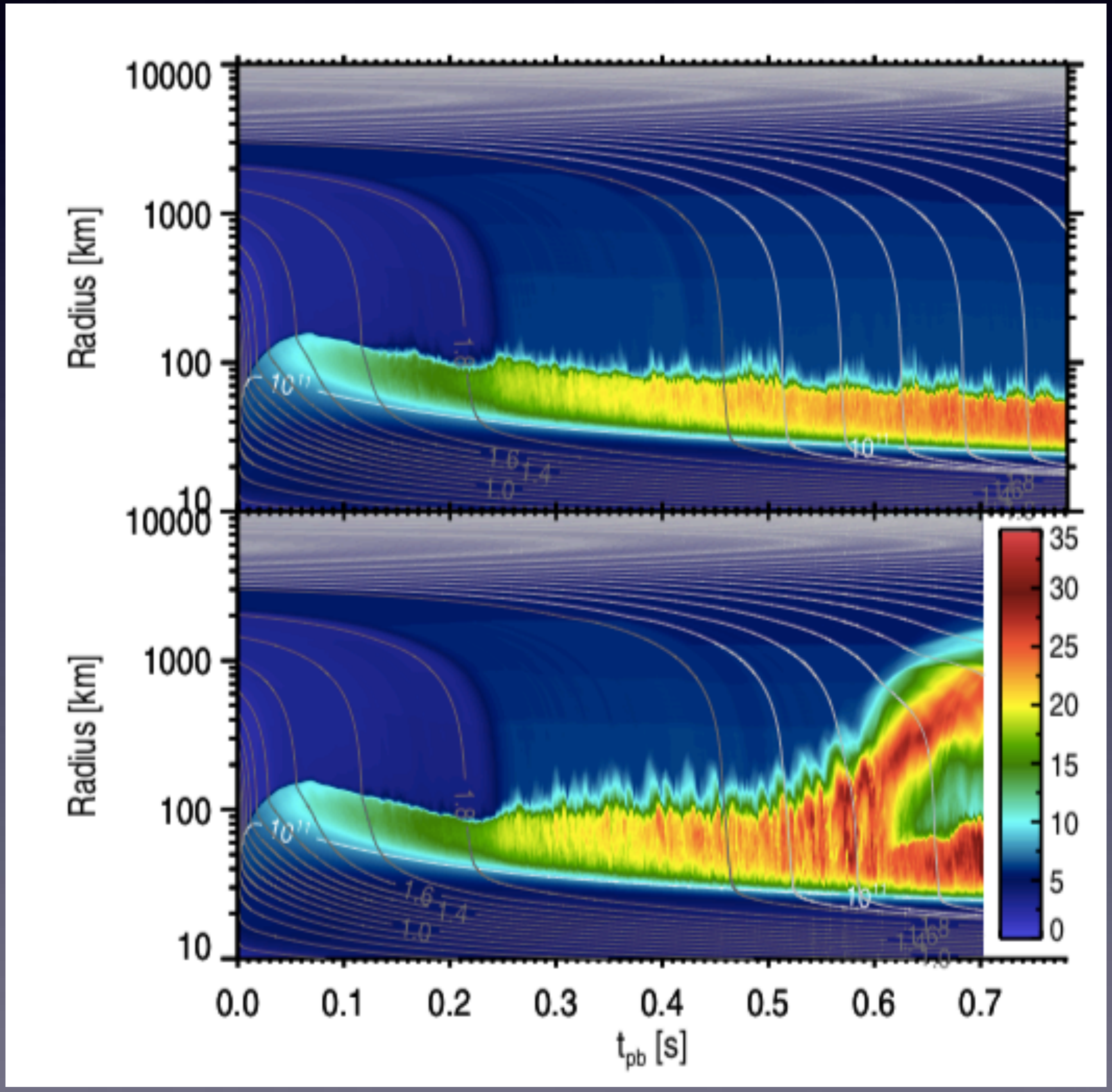
1. Relic density via QED alone is problematic — how else to deplete thermal abundance?

2. Thermal population introduced to SN1987A — how does this affect the eqn of state?

Muon creation in supernova matter facilitates neutrino-driven explosions

R. Bollig,[1,2] H.-T. Janka,[1] A. Lohs,[3] G. Martínez-Pinedo,[3,4] C.J. Horowitz,[5] and T. Melson[1]

Bollig et al 1706.04630



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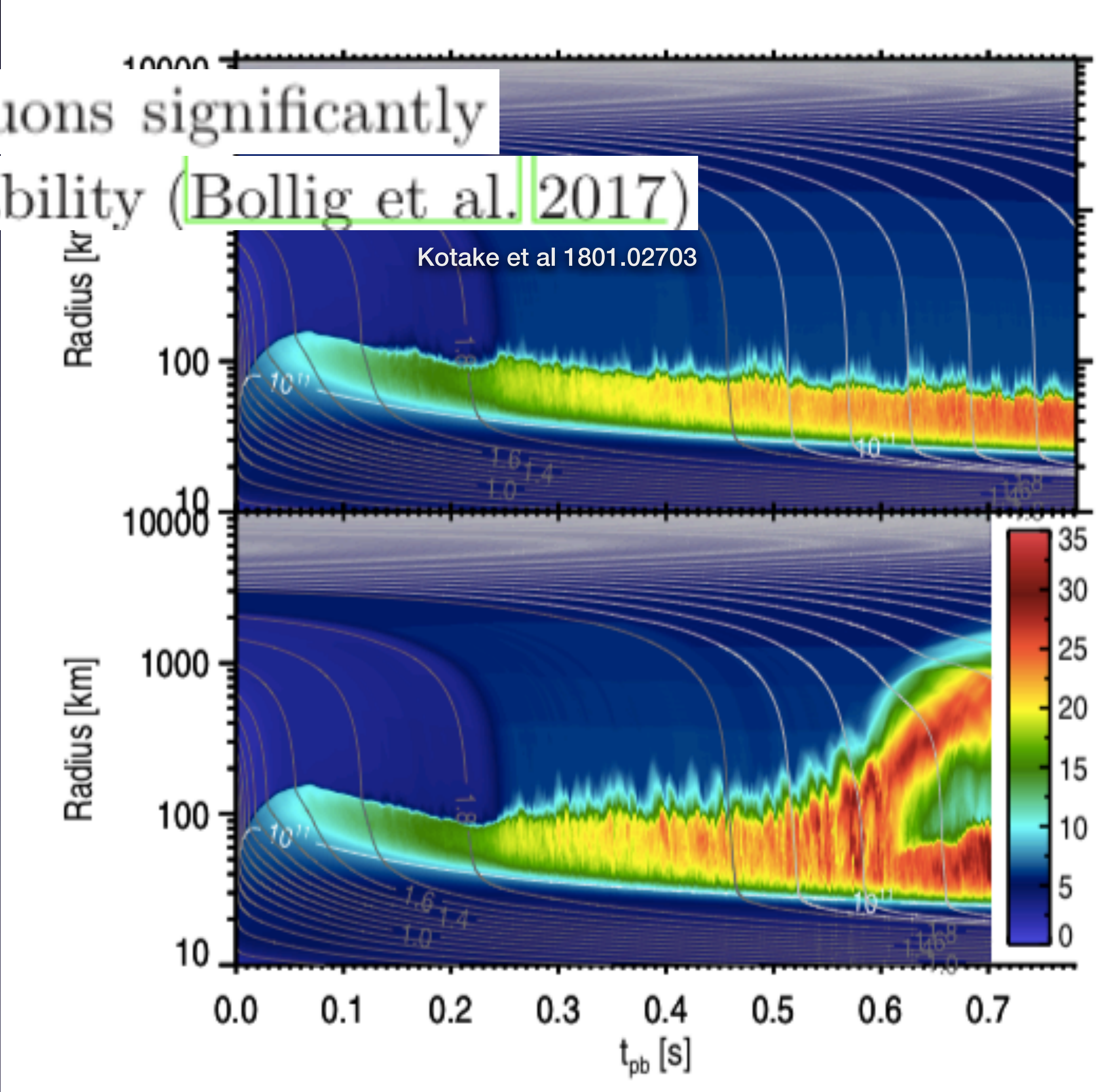
Bollig et al 1706.04630

Inclusion of muons significantly effects explodability (Bollig et al. 2017)

Kotake et al 1801.02703



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1. Relic density via QED alone is problematic — how else to deplete thermal abundance?

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3. Primordial millicharged particles are evacuated from the disk — is any DD possible?

Direct Detection

Reopening the window on charged dark matter

0809.0436

Leonid Chuzhoy

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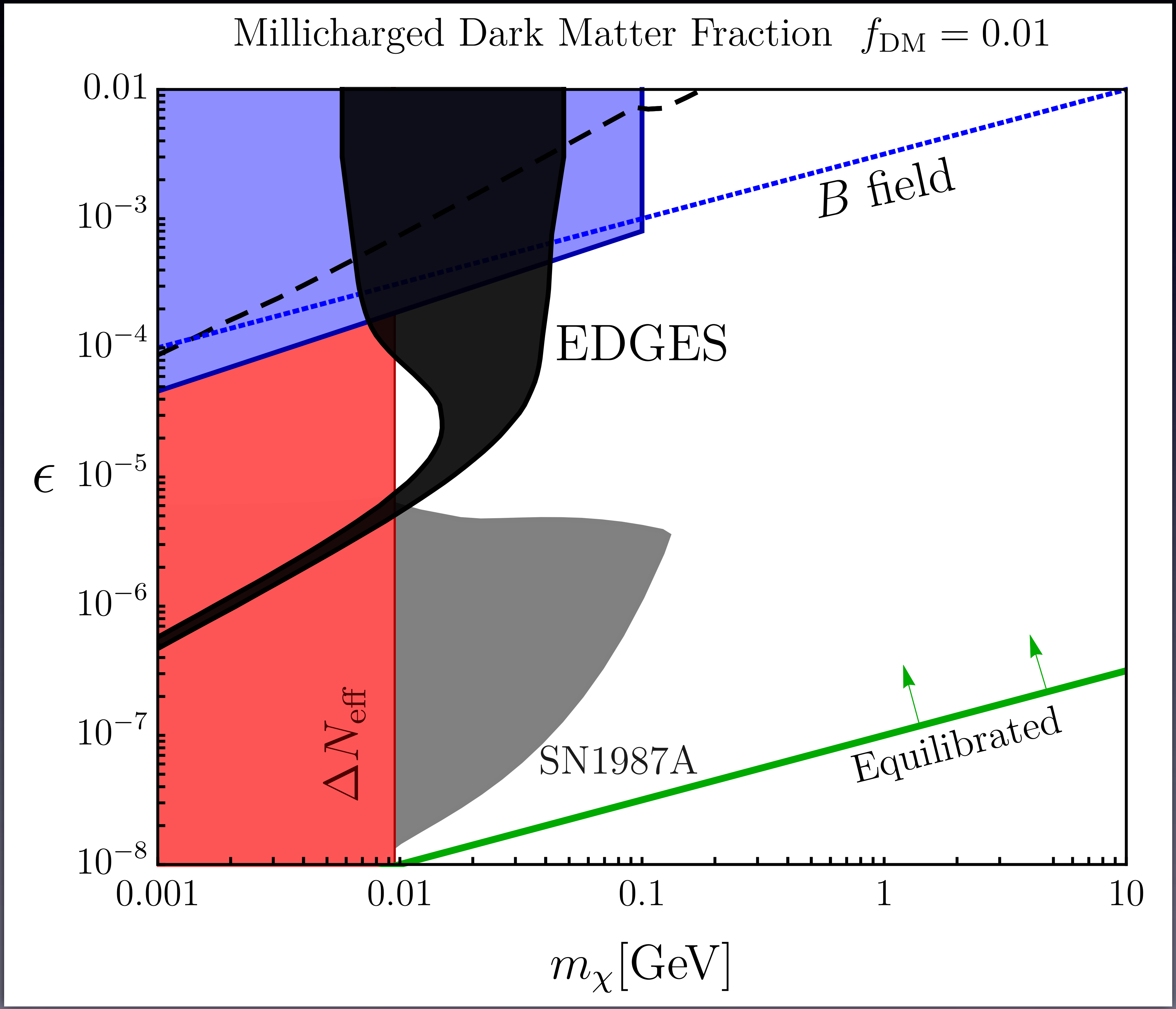
Edward W. Kolb

Department of Astronomy and Astrophysics, Enrico Fermi Institute, and Kavli Institute for Cosmological Physics, The University of Chicago, 5640 S. Ellis, Chicago, IL 60637, USA

ABSTRACT: We reexamine the limits on charged dark matter particles. We show that if their mass and charge fall in the range $100(q_X/e)^2 \lesssim m_X \lesssim 10^8(q_X/e)$ TeV, then magnetic fields prevent particles in the halo from entering the galactic disk, while those initially trapped inside are accelerated through the Fermi mechanism and ejected within about $0.1 - 1$ Gyrs. Consequently, previous constraints on charged dark matter based on terrestrial non-observation are invalid within that range. …

EDGES Constraints



DD for 1% of Ω_{DM}

- Such particles are evacuated from the disk…

DD for 1% of Ω_{DM}

- Such particles are evacuated from the disk…
- …but supernovae are hot!

DD for 1% of Ω_{DM}

- Such particles are evacuated from the disk…
- …but supernovae are hot!
- Do more appear? What is their phase space? What do they look like at DD experiments?
    - Boosted DM (Agashe et al., 1405.7370)
    - Marques-Tavares et al., in prep

Implications of $f_{DM}=1\%$

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2. Thermal population introduced to SN1987A — how does this affect the eqn of state?

3. Primordial millicharged particles are evacuated from the disk — is any DD possible?

4. We've "already seen" DM in the CMB power spectrum — CMB S4 or BBN improvement?

CMB

Different rates, different moments of the Boltzmann equation:

$$\Gamma \simeq n\langle \sigma v \rangle,$$

$$\langle \delta |\dot{\vec{p}}| \rangle \simeq \mu n \langle \sigma v^2 \rangle,$$

$$m\langle \delta \dot{T} \rangle \simeq \mu^2 n \langle \sigma v^3 \rangle$$

CMB

Dubovsky et al., hep-ph/0311189 & 1310.2376
McDermott, Yu, & Zurek 1011.2907

Changing T (2nd moment of Boltzmann eq):

$$\frac{\langle \frac{d}{dt}\delta T\rangle}{T} = \frac{4}{\sqrt{2\pi}}\frac{\rho_X \sigma_0 \mu_{Xp}^2}{3 m_X m_b v_{\rm rel}} \cdot \frac{1}{T_b}$$

$$\simeq \frac{4}{3\sqrt{2\pi}}\frac{\rho_X \sigma_0 \mu_{Xp}}{m_X + m_p}\left(\frac{m_p}{T_p^3}\right)^{1/2}$$

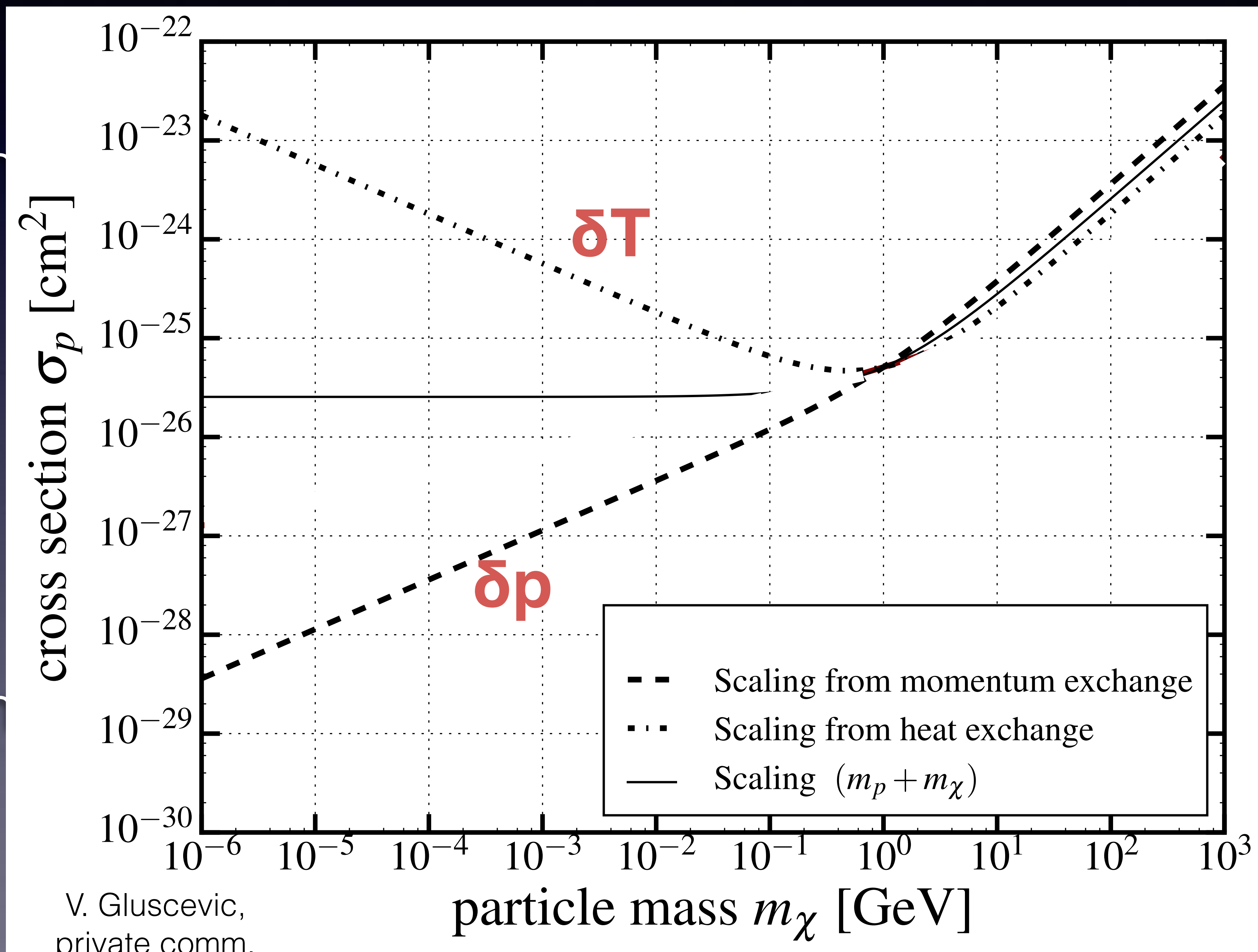
Changing p (1st moment of Boltzmann eq):

$$\frac{\langle \frac{d}{dt}|\delta \vec{p}|\rangle}{\langle|\vec{p}|\rangle} = \frac{2}{3\sqrt{2\pi}}\frac{\rho_X \sigma_0}{m_X + m_p}\left(\frac{m_p}{T_p}\right)^{3/2}$$

Dvorkin, Blum, Kamionkowski 1311.2937
Gluscevic & Boddy, 1712.07133
Boddy & Gluscevic, 1801.08609
Xu, Dvorkin, & Chael, 1802.06788
Slatyer & Wu, 1803.09734
Gluscevic et al., to appear

CMB

Char

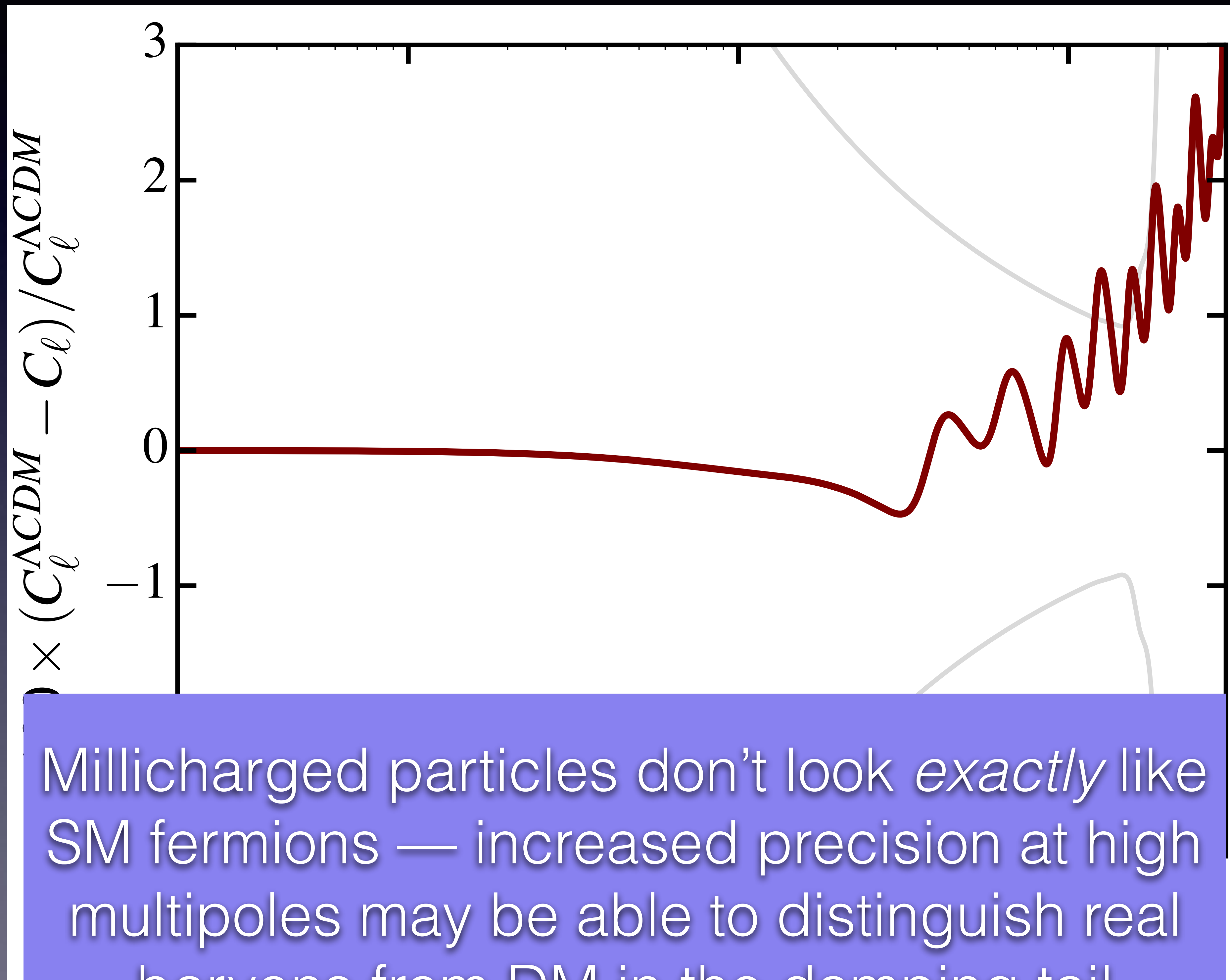


9 & 1310.2376
07

Char

kowski 1311.2937
712.07133
301.08609
1802.06788
734
Gluscevic et al., to appear

CMB



Gluscevic & Boddy, 1712.07133

Millicharged particles don't look *exactly* like SM fermions — increased precision at high multipoles may be able to distinguish real baryons from DM in the damping tail

Gluscevic et al., to appear

Conclusions

- EDGES has possibly detected evidence of dark matter scattering off baryons during the epoch of structure formation
- If it did, it's not “minimal” — a rich structure of auxiliary interactions and signals awaits
- We'll learn (a lot) more (fairly) soon

Conclusions

- EDGES has possibly detected evidence of dark matter scattering off baryons during the epoch of structure formation
- If it did, it's not "minimal" — a rich structure of auxiliary interactions and signals awaits
- We'll learn (a lot) more (fairly) soon

What we find could surprise us!