BARKANA, NJO, REDIGOLO, VOLANSKY. [ARXIV:1803.03091]
LIU, NJO, REDIGOLO, VOLANSKY. [ARXIV:1908.06986]

NADAV JOSEPH OUTMEZGUINE

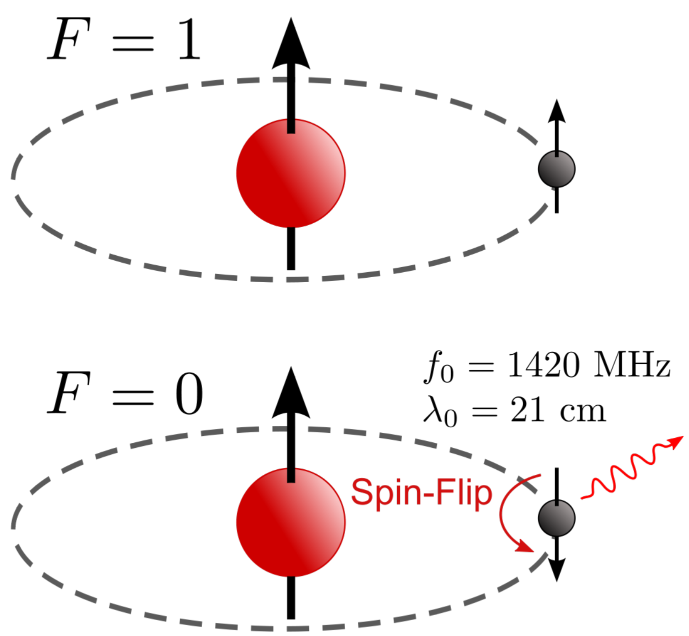
TEL AVIV UNIVERSITY

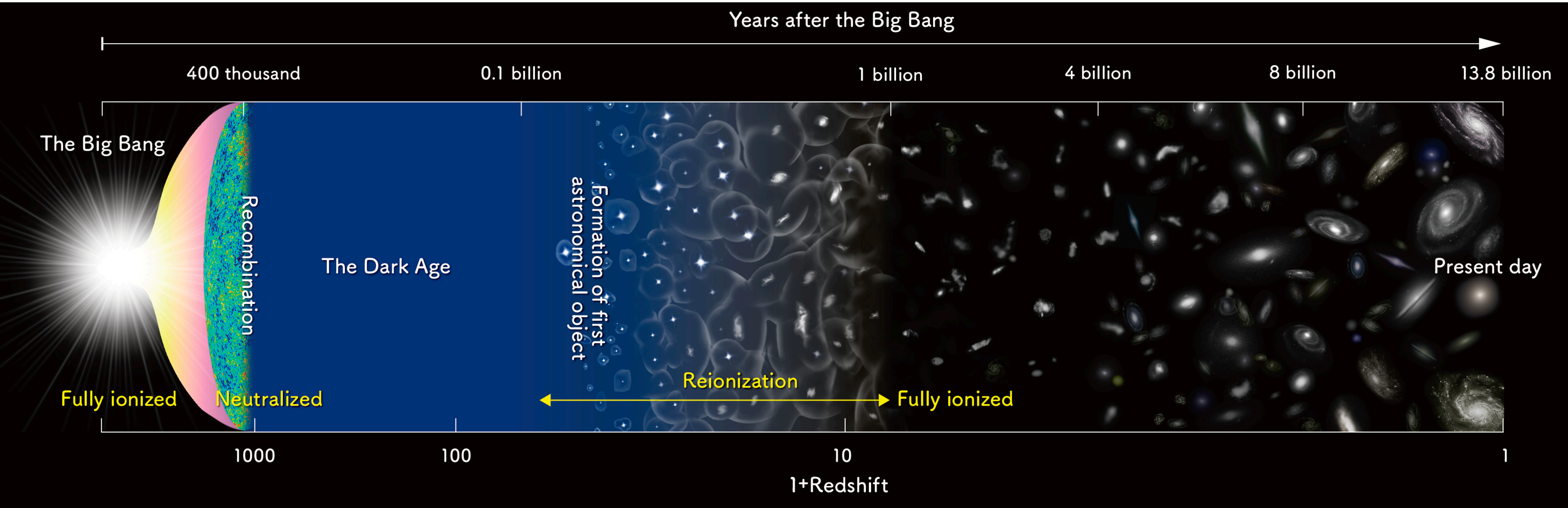
GGI - SEP 2019

21-CM COSMOLOGY WITH CHARGED DARK MATTER

WHY SHOULD I CARE –1. (PHYSICS)

When H atoms are abundant, hyperfine transitions can be used to track the temperature of baryons

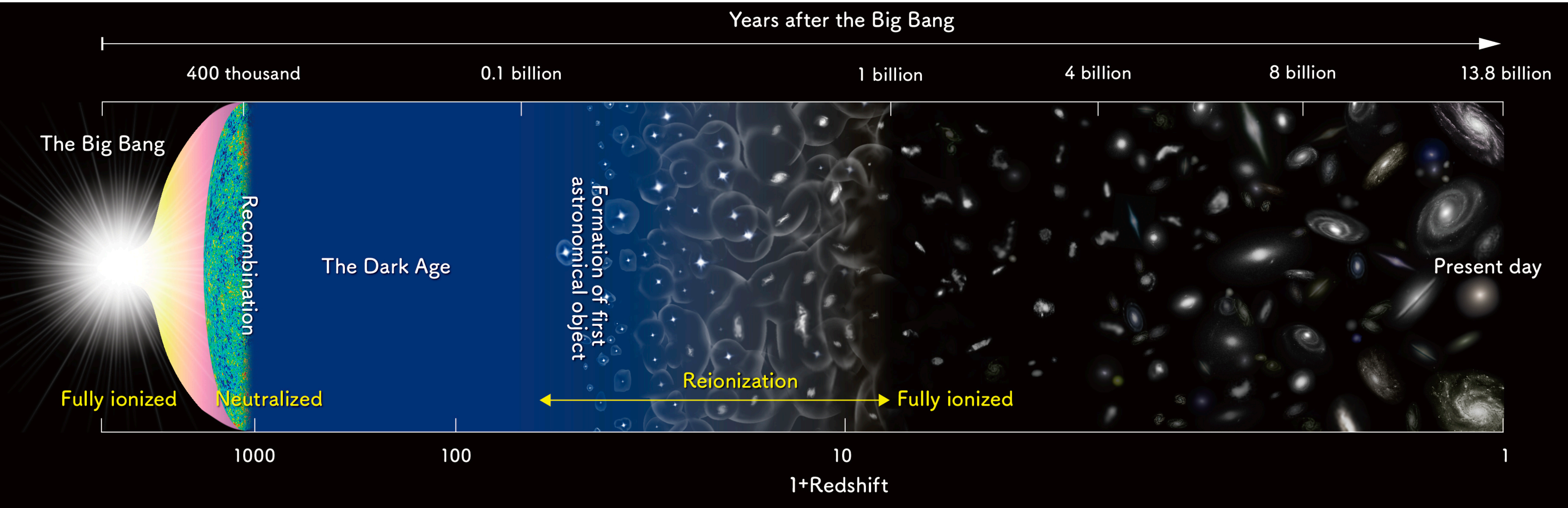




WHY SHOULD I CARE -1. (PHYSICS)

A glance into an epoch yet to be explored: $(1100 \lesssim z+1 \lesssim 15)$

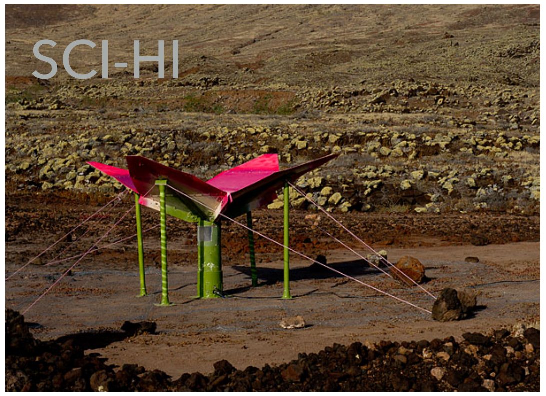
- Coldest Epoch, post recombination but before reionization
- Lots of H atoms → Lots of hyperfine transitions
- Another test of ΛCDM

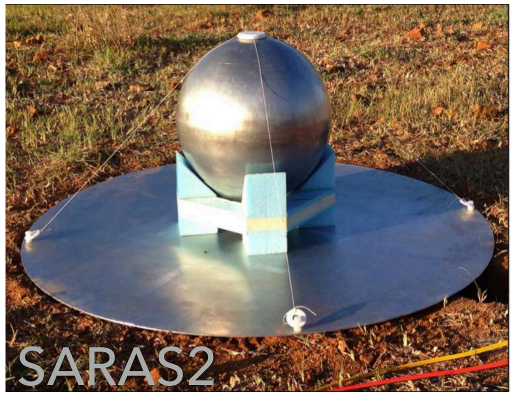


WHY SHOULD I CARE –2. (EXPERIMENTS)

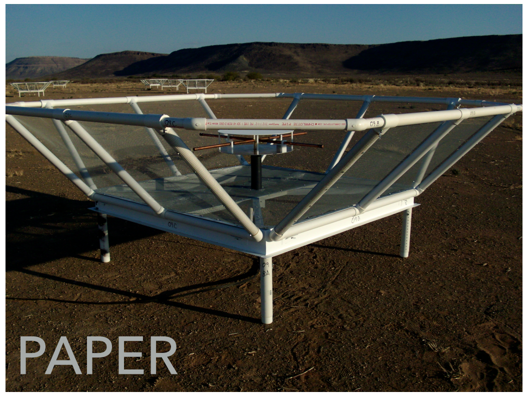
Many(!) experiments

Global signal





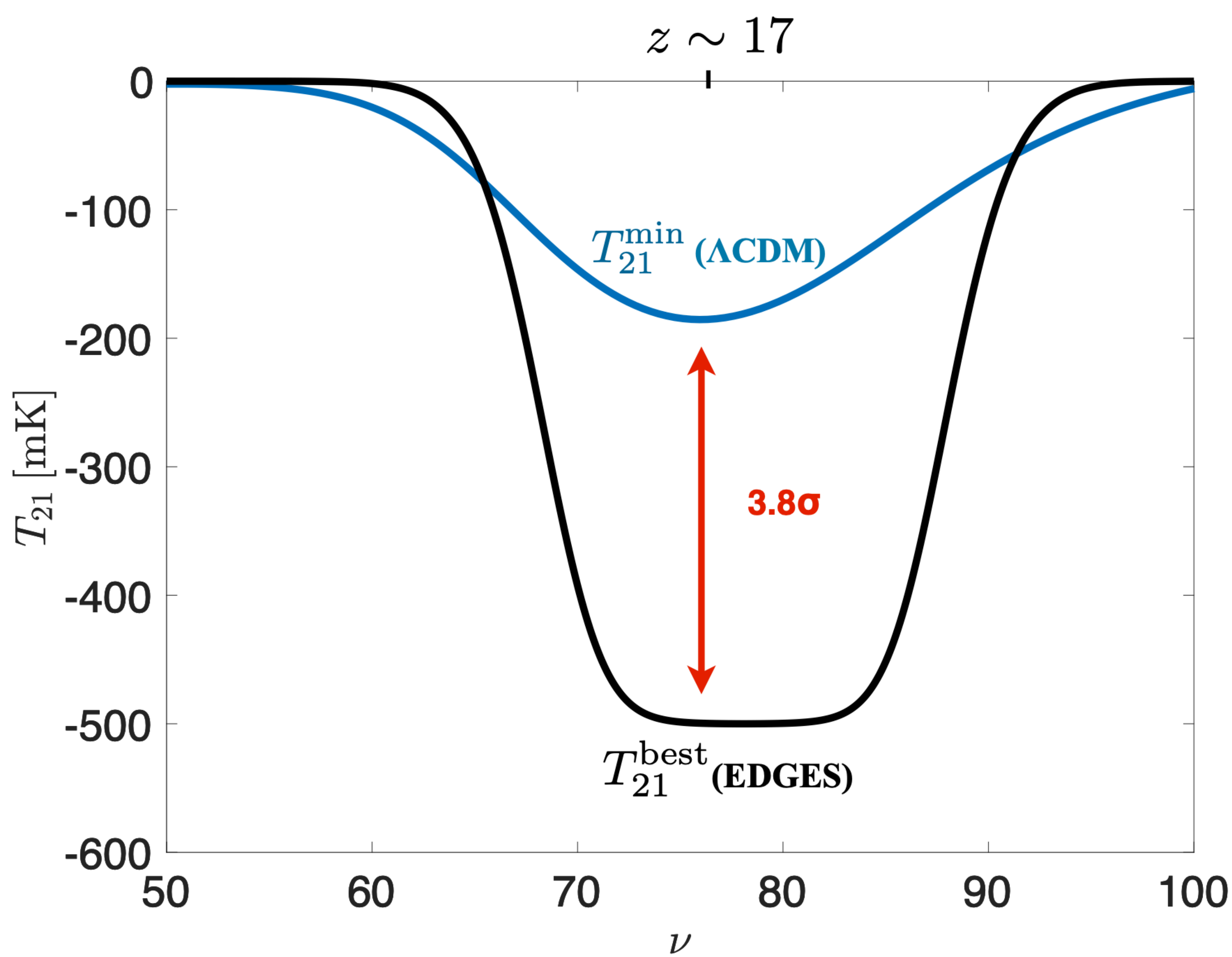
Fluctuations



And more…

WHY SHOULD I CARE –3. (SOCIOLOGY)

Possibly an anomalous signal - Bowman et al., 2018



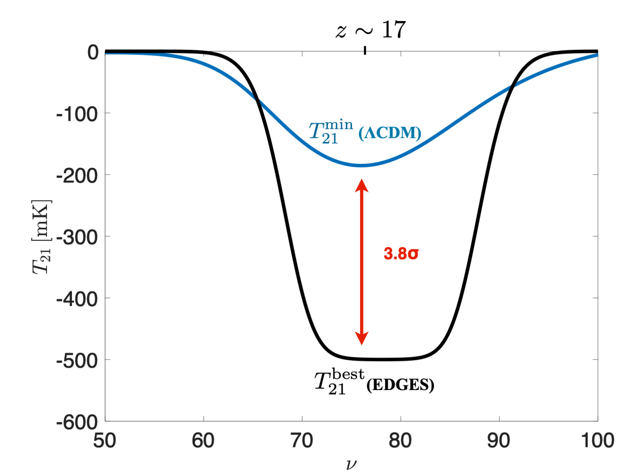
From E.D.Kovetz talk at GGI last year

BASICS

Spin Temperature: $$\frac{n_1}{n_0} \equiv \frac{g_1}{g_0} e^{-E_{21}/T_s} \simeq 3\left(1 - \frac{E_{21}}{T_s}\right)$$

Standard Model Evolution:

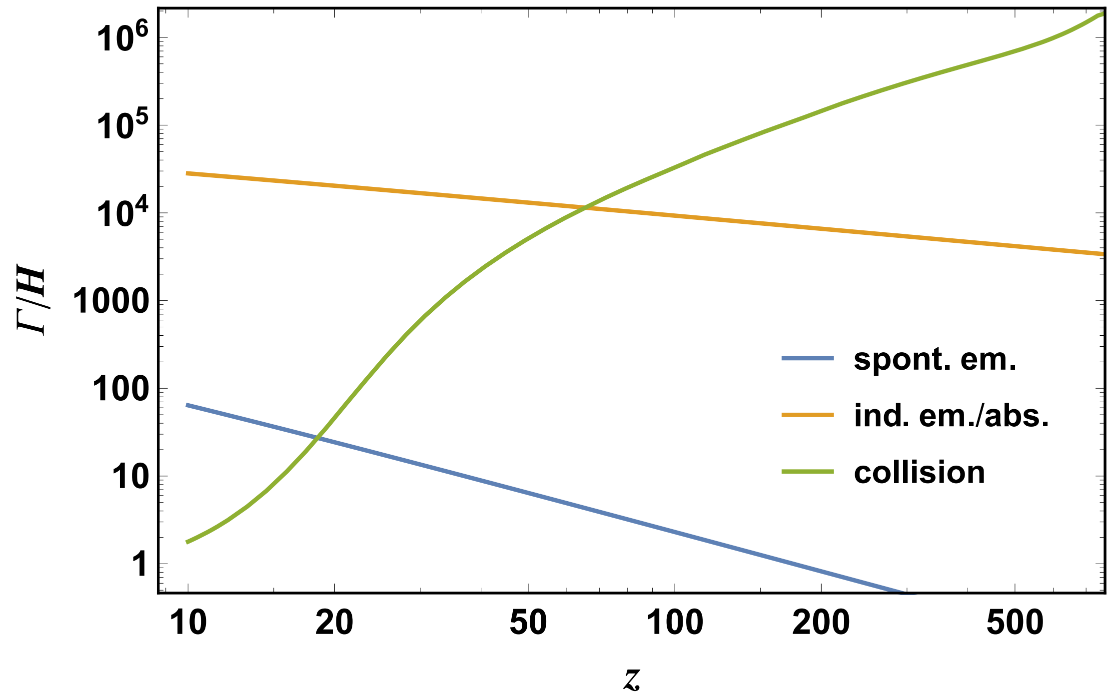
- H-H and H-e collisions
- Spontaneous emission and induced emission/absorption
- Coupling to Lya radiation

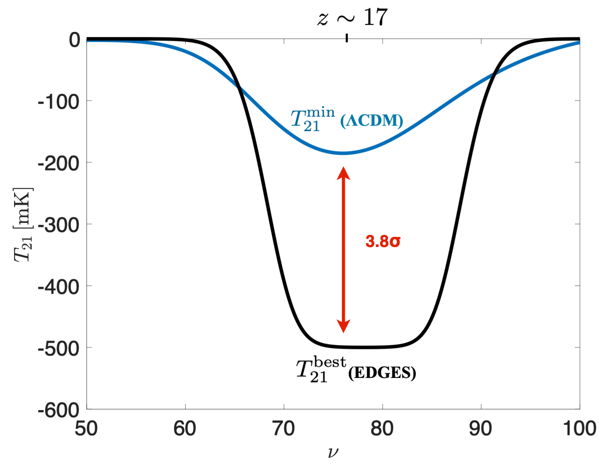


BASICS

Evolution - Boltzmann

- Dominant rate always larger the Hubble $\rightarrow$ detailed balance





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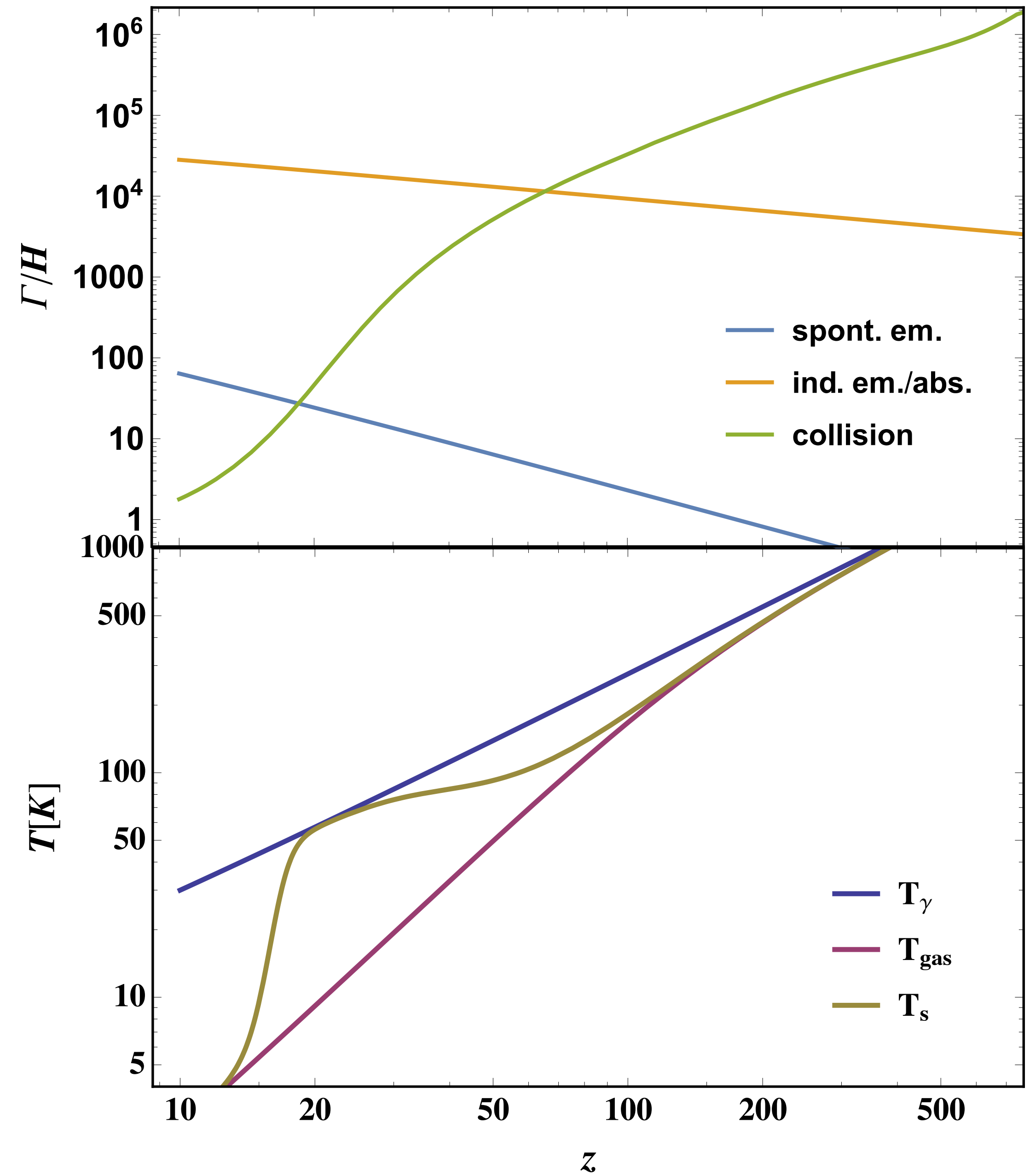
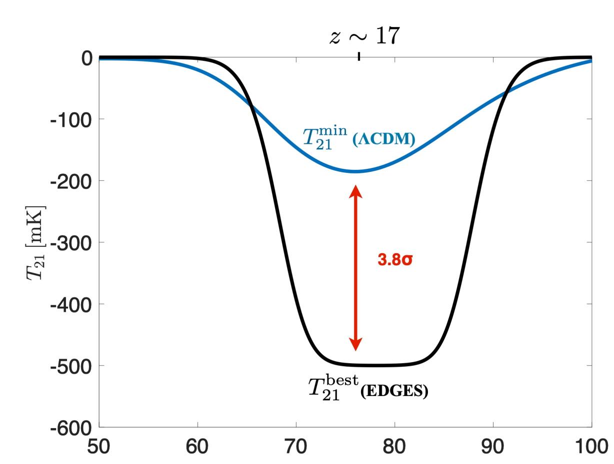
- Dominant rate always larger the Hubble $\rightarrow$ detailed balance
- Spin temperature follows the dominant process:

$$\Delta T_s = \frac{c_{\rm col}\Delta T_{\rm gas} + c_{{\rm Ly}\alpha}\Delta T_{{\rm Ly}\alpha}}{c_{\rm ind} + c_{\rm col} + c_{{\rm Ly}\alpha}}$$

$$\Delta T = T - T_{\rm CMB}$$





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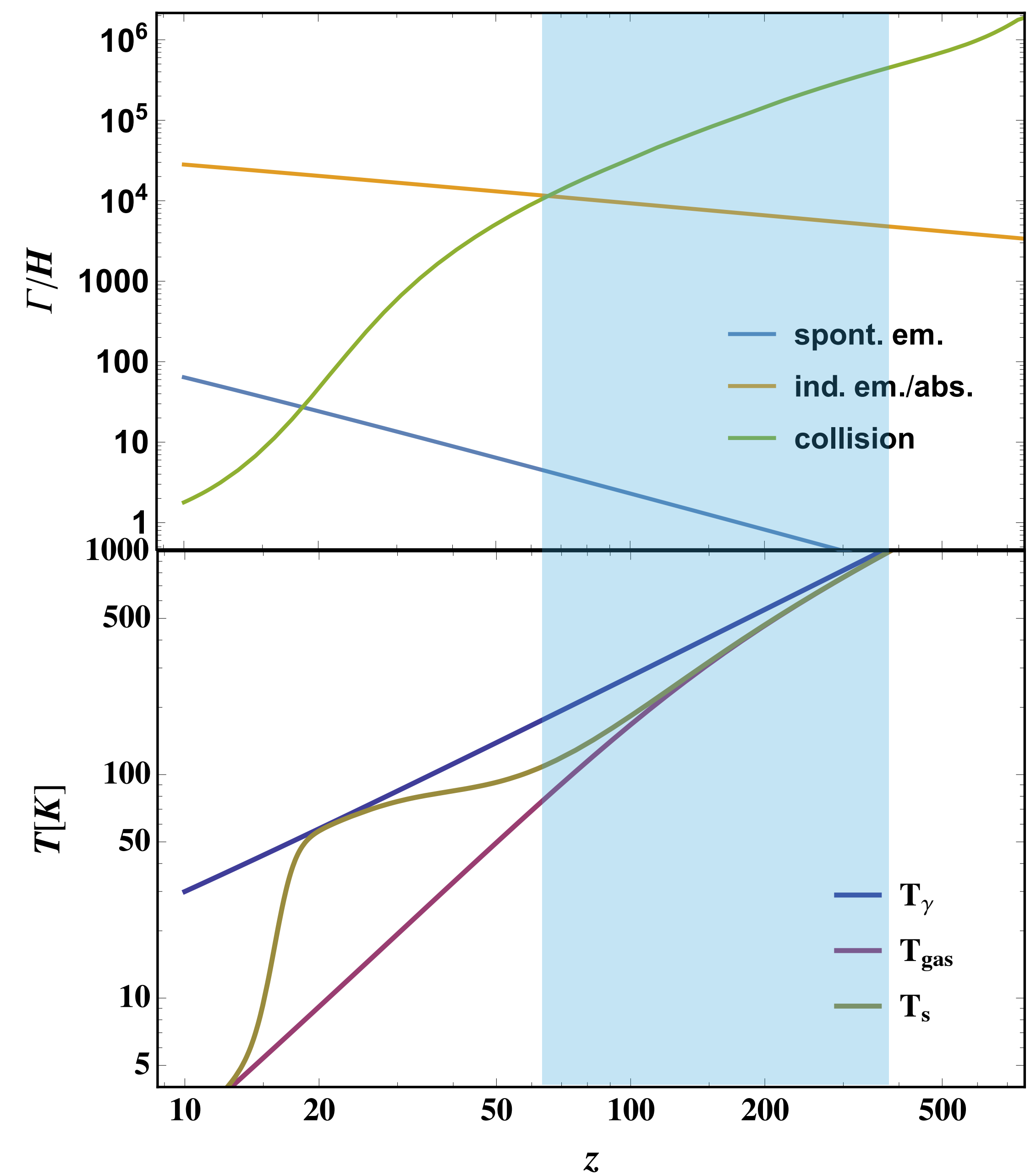

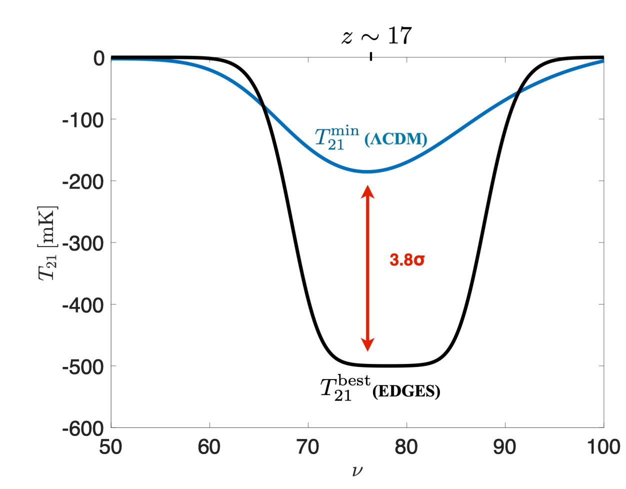

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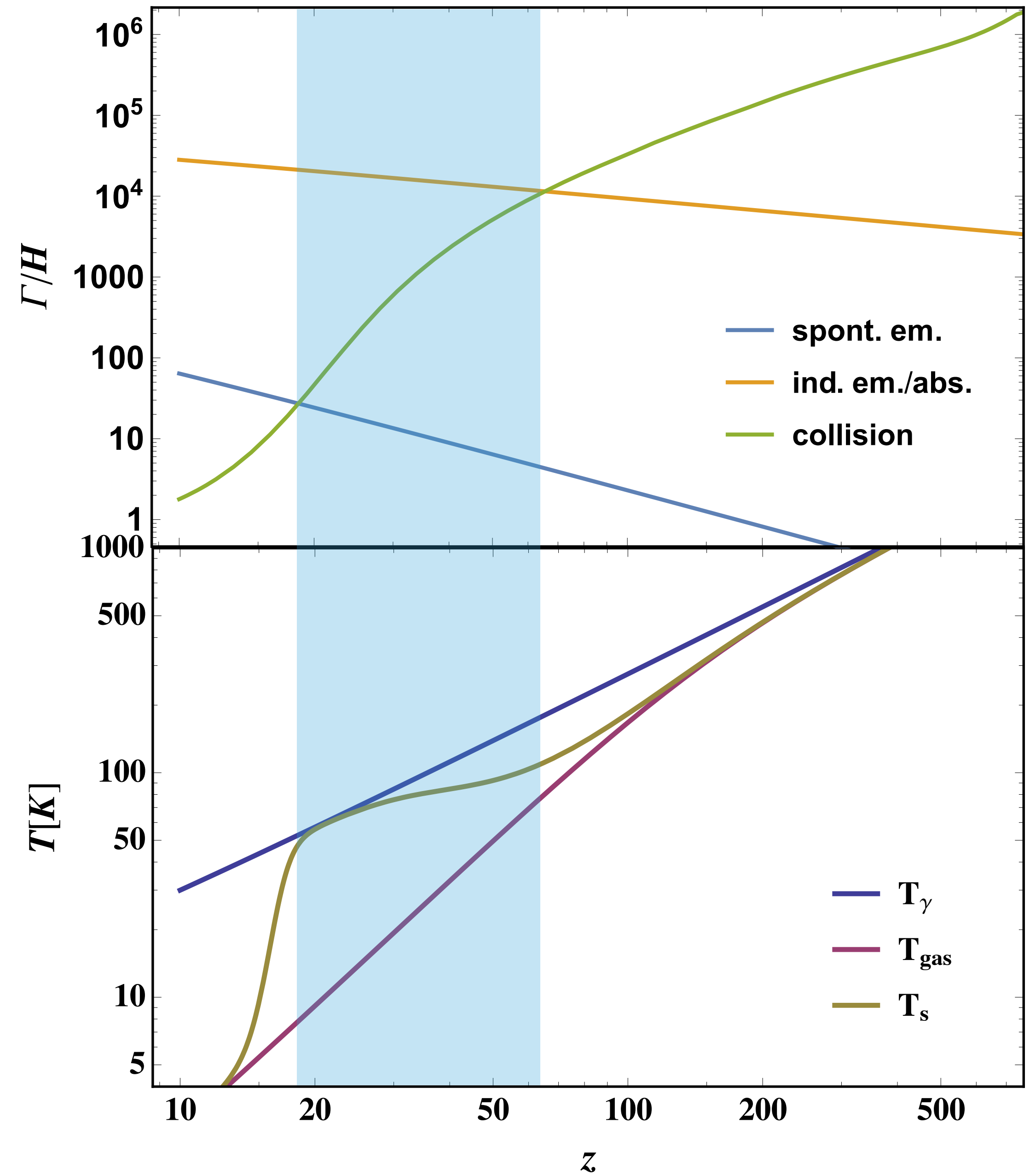

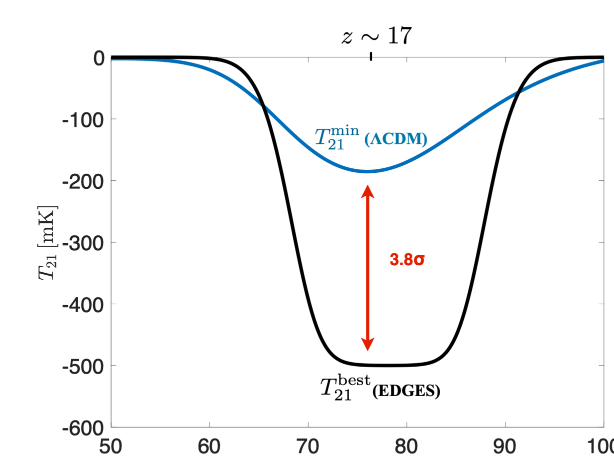

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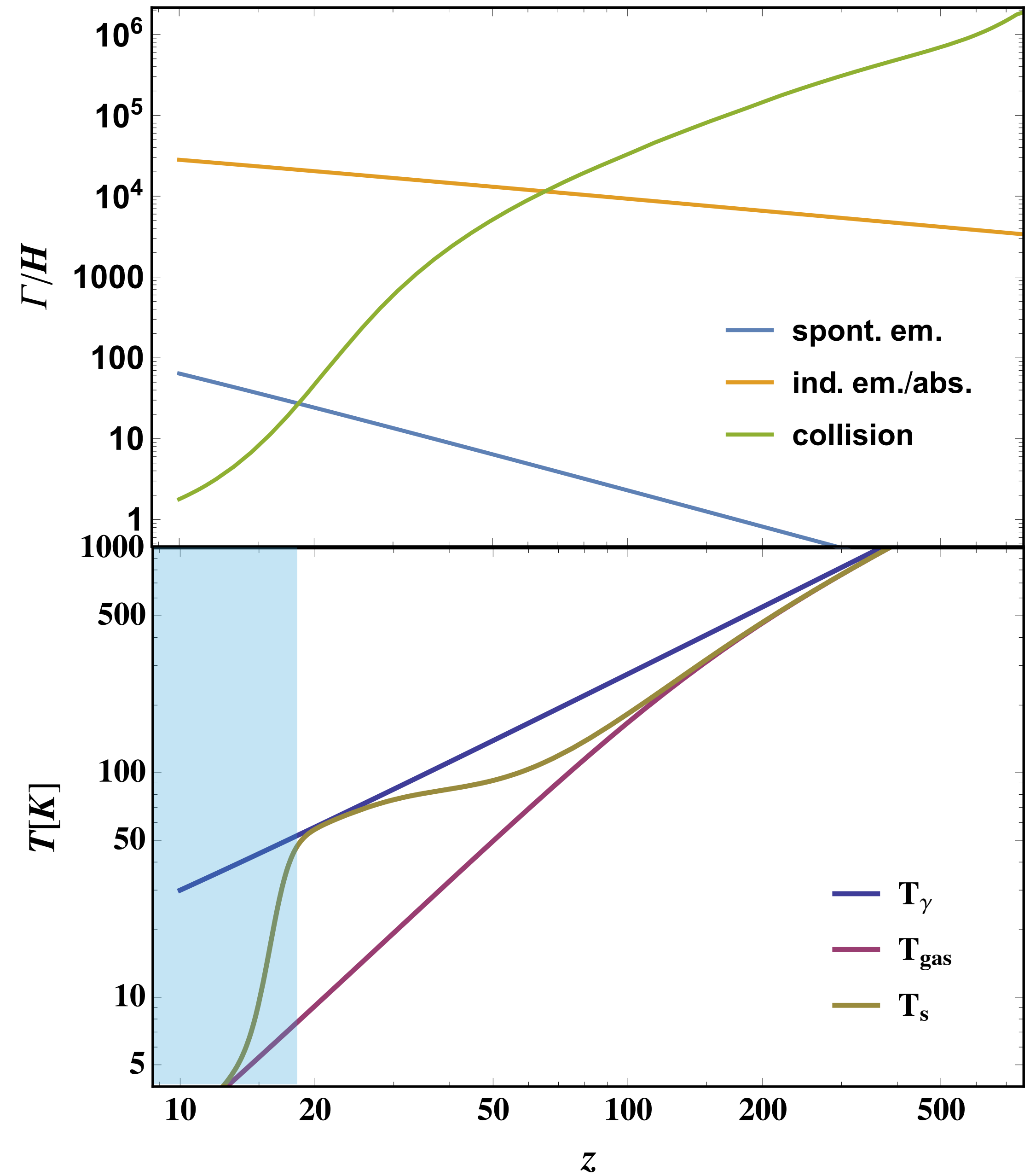

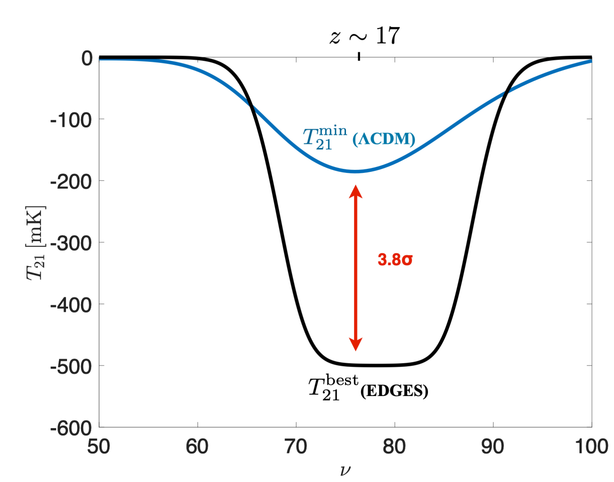

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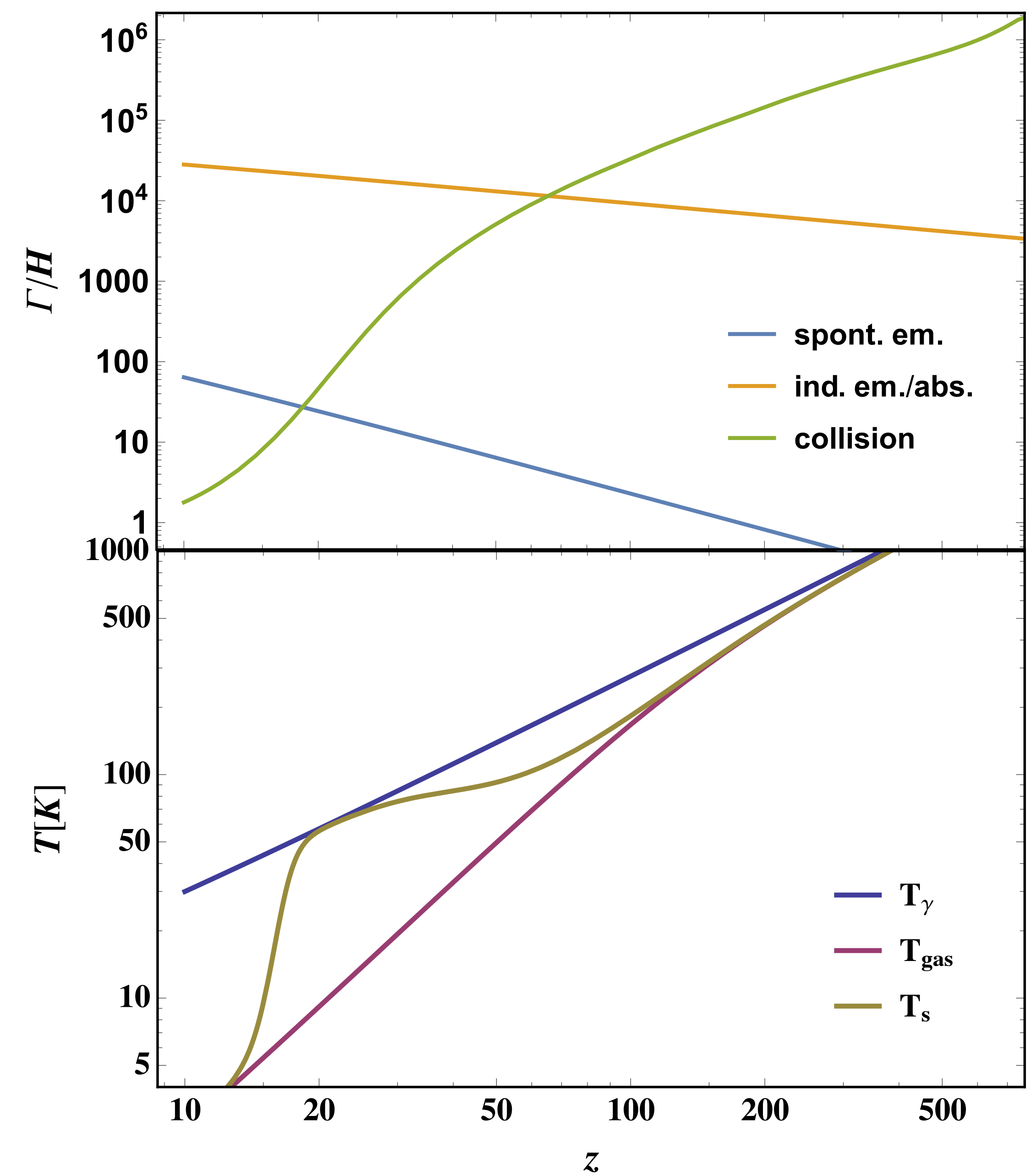
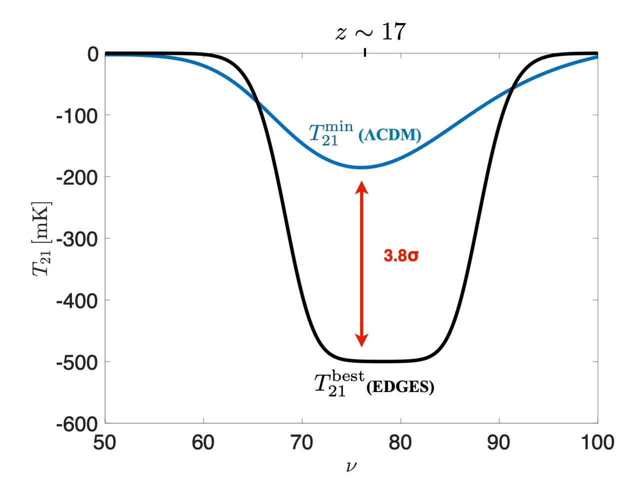


- We measure the brightness temperature:

$$T_{21} \simeq \left(T_s - T_{\rm CMB}\right)\frac{1-e^{-\tau}}{1+z} \geq \left(T_{\rm gas} - T_{\rm CMB}\right)\frac{1-e^{-\tau}}{1+z} \equiv T_{21}^{\rm min}$$



THE EDGES ANOMALY

Evolution - Boltzmann

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- Spin te
  domin

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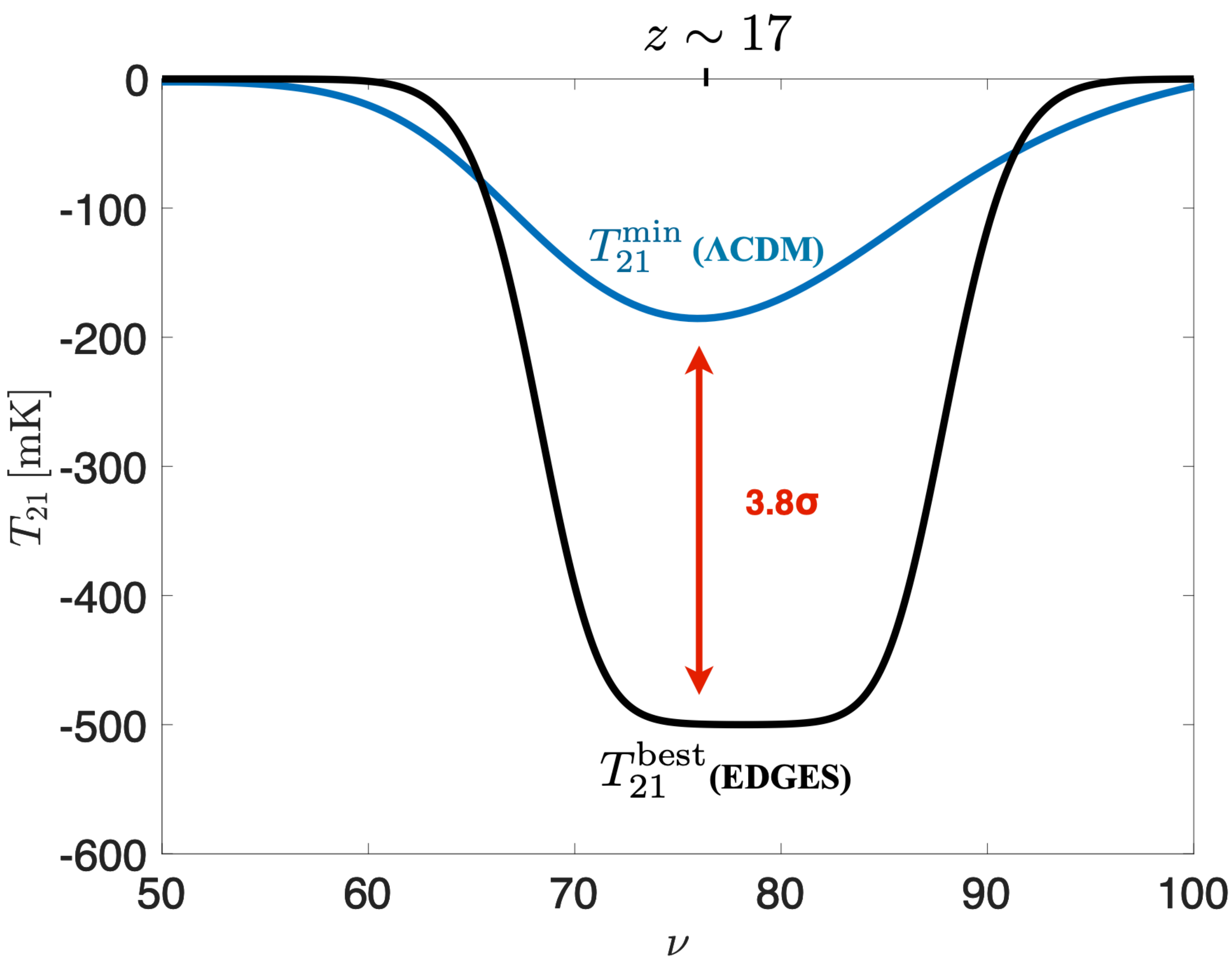

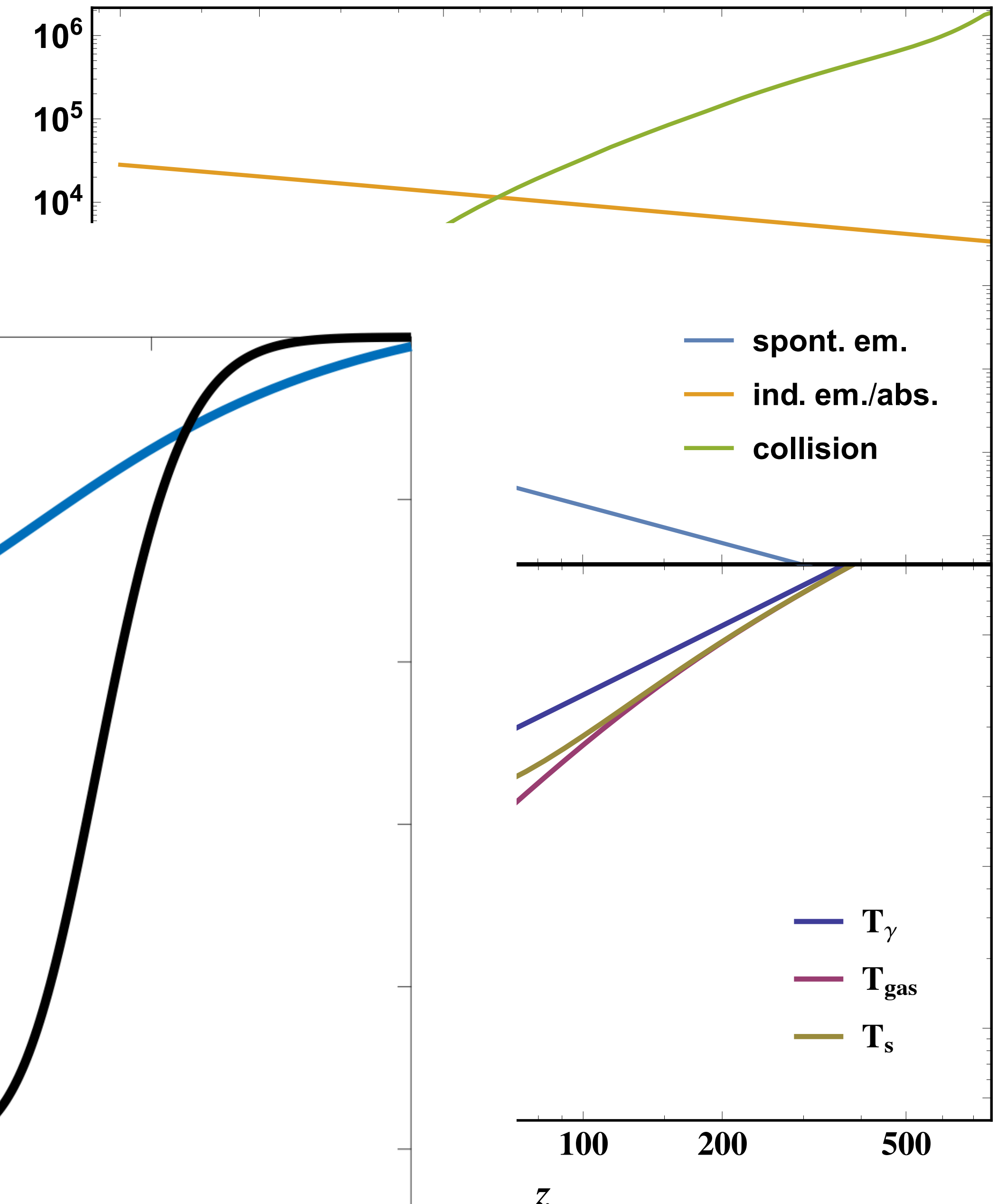

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THE EDGES ANOMALY

Translated to baryons temperature

$$T_{\rm b}^{\rm EDGES}\Big|_{z=17} = 3.2^{+1.9}_{-1.55}{\rm K} \qquad \Delta T_{\rm b}^{\rm EDGES} \equiv \left(T_{\rm b}^{\rm EDGES} - T_{\rm b}^{\Lambda{\rm CDM}}\right)\Big|_{z=17} = -\,3.6^{+1.9}_{-1.55}{\rm K}$$

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- Cool the gas
  - Earlier photon - baryon decoupling (Falkowski, Petraki)
  - DM - baryon scattering (Kadota,Silk,Tashiro, 2014; Ali-Haimoud,Kovetz,Munoz,2015; Barkana, 2018; Loeb,Munoz,2018; Berlin,Hooper,Krnjaic,McDermott, 2018; Barkana,**NJO**,Redigolo,Volansky, 2018; Liu,Slatyer 2018; Kovetz, Poulin, Gluscevic, Boddy, Barkana, Kamionkowski, 2018;…)
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  - ...
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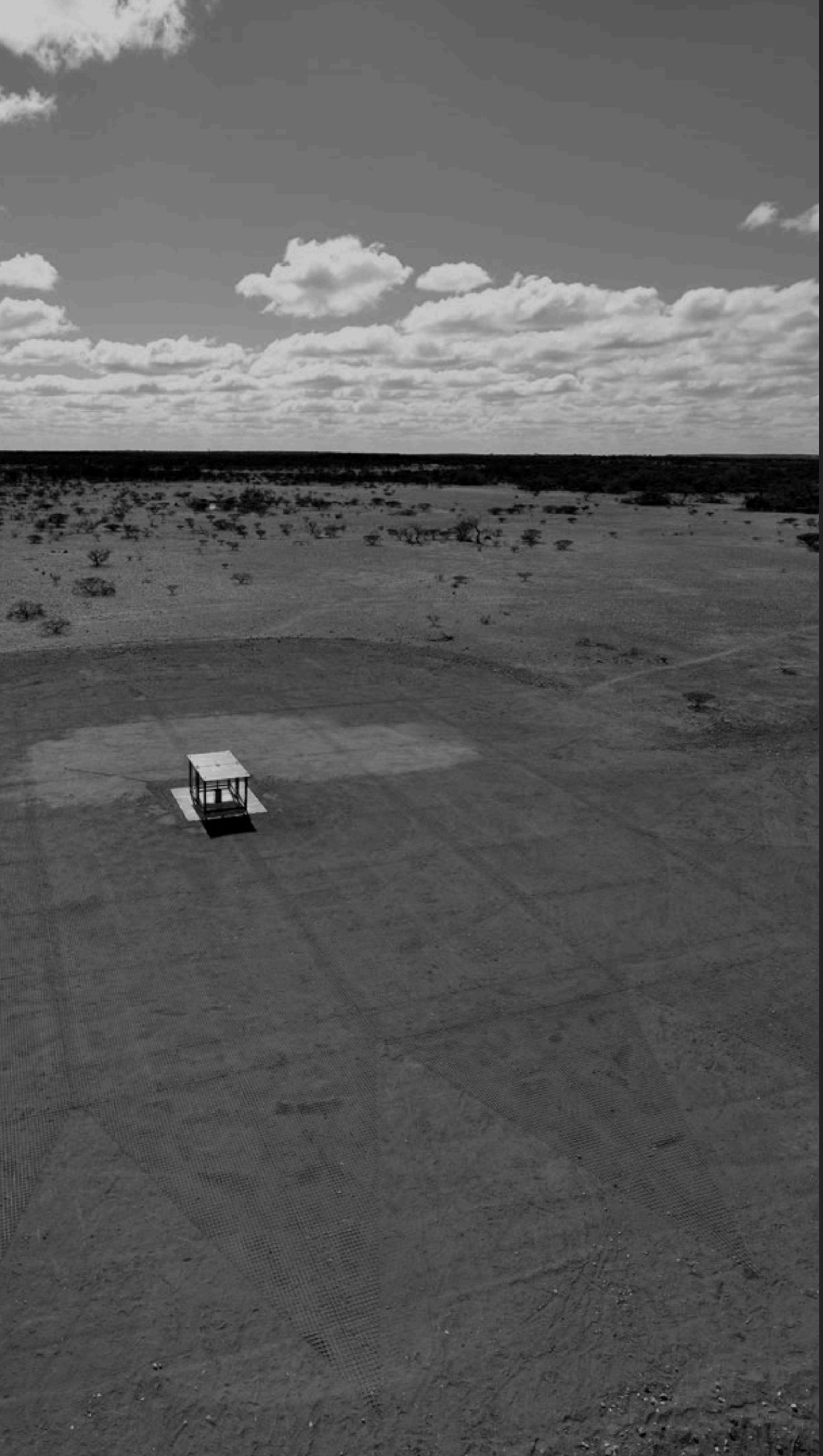
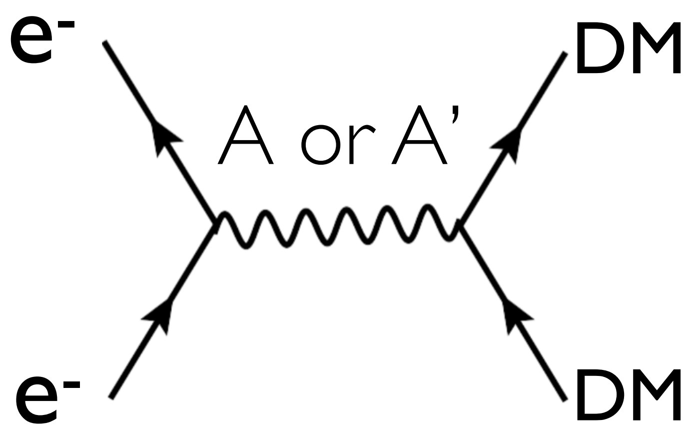


BARKANA, <u>NJO</u>, REDIGOLO, VOLANSKY.
[ARXIV:1803.03091]

MILLICHARGED DARK MATTER @ 21-CM

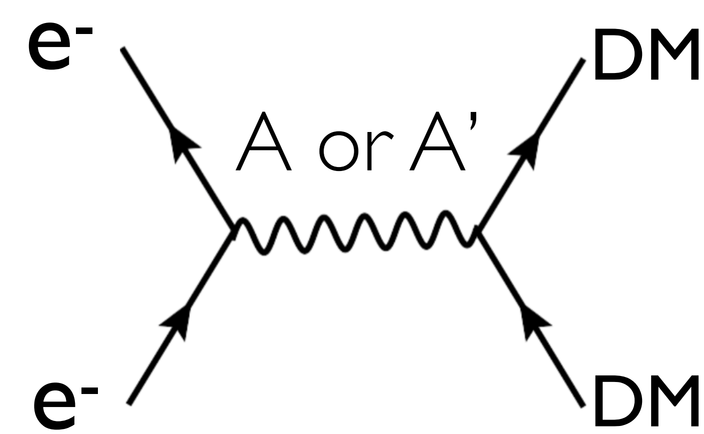
MILLICHARGED DARK MATTER

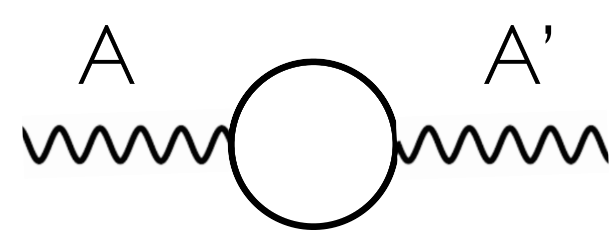
- DM carries as small electric charge
- Two classes
  - "Pure" millicharge



MILLICHARGED DARK MATTER

- DM carries as small electric charge
- Two classes
  - "Pure" millicharge
  - Hidden photon portal





Holdom (1985)

$$\mathscr{L} = -\frac{1}{4}F^2 - \frac{1}{4}F'^2 - \frac{\epsilon}{2}FF' + m_{A'}^2 A'^2 + J_{\rm SM}A + J_{\rm DM}A'$$

$$\to -\frac{1}{4}F_1^2 - \frac{1}{4}F_2^2 + m_{A'}^2 A_2^2 + J_{\rm SM}A_1 + \left(J_{\rm DM} - \epsilon J_{\rm SM}\right) A_2$$

DM – BARYON SCATTERING

Gas temperature evolution is modified

$$\frac{dT_{\rm gas}}{d\log a} = -2T_{\rm gas} + 2\frac{\Gamma_C}{H}\left(T_{\rm CMB} - T_{\rm gas}\right) + \frac{3}{2}\sum_{I=\{{\rm H},{\rm He},p,e\}} \frac{\dot{Q}^I_{\rm gas}}{H}$$

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Gas temperature evolution is modified

SM

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Adiabatic

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SM | DM

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$\dot{Q}^I_{\rm gas} \sim$ Energy (temperature) transfer + momentum transfer (drag)

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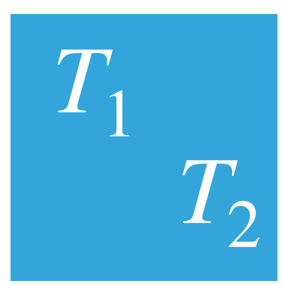

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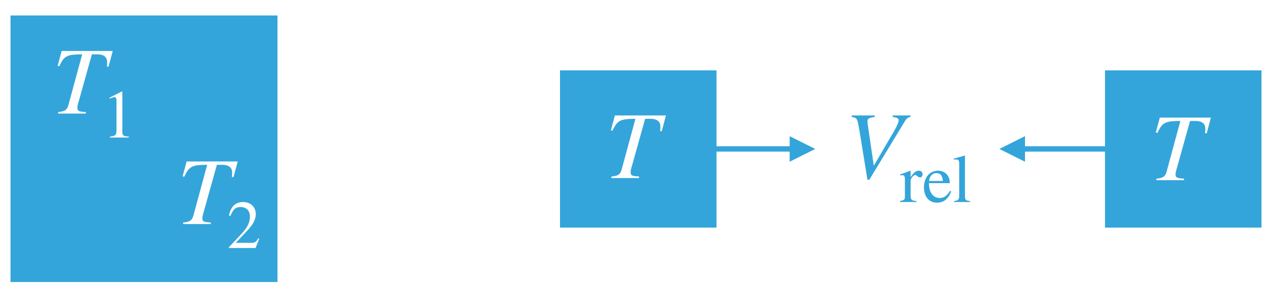

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Requirements:

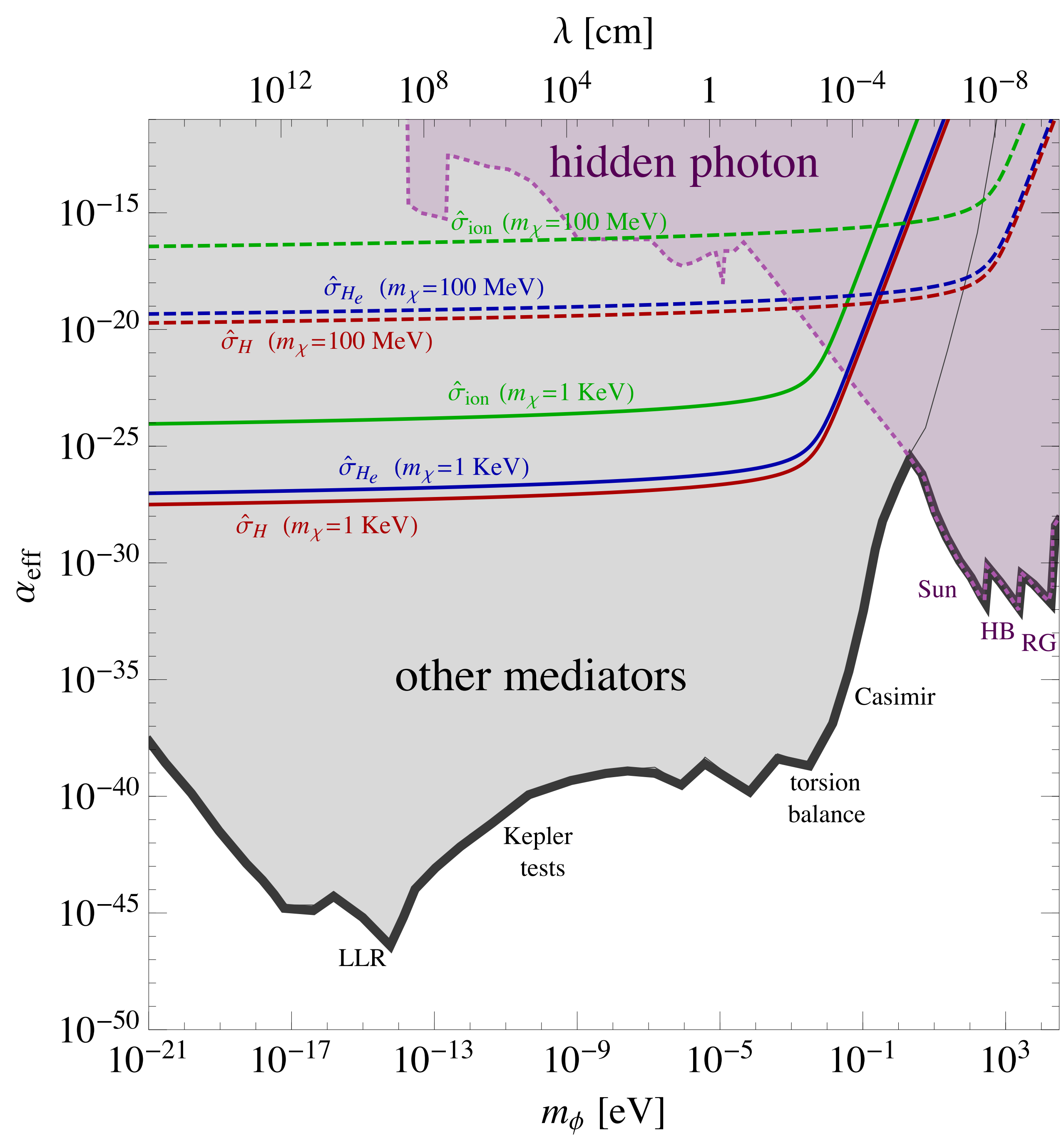
- CMB anisotropies constraints - **small cross section at early times**
- Faster then Hubble - **large cross section at later times**
- IR dominated process - **velocity dependence, light mediator** ($\sim v_{\rm rel}^{-4}$)

DM – BARYON SCATTERING

Velocity dependence → long range force (light mediator)

SCREENED OR UNSCREENED?

- 5th force experiments rules out unscreened force.
- DM is (effectively?) millicharged
- Atoms are neutral
- Cooling only by interacting with electors and protons



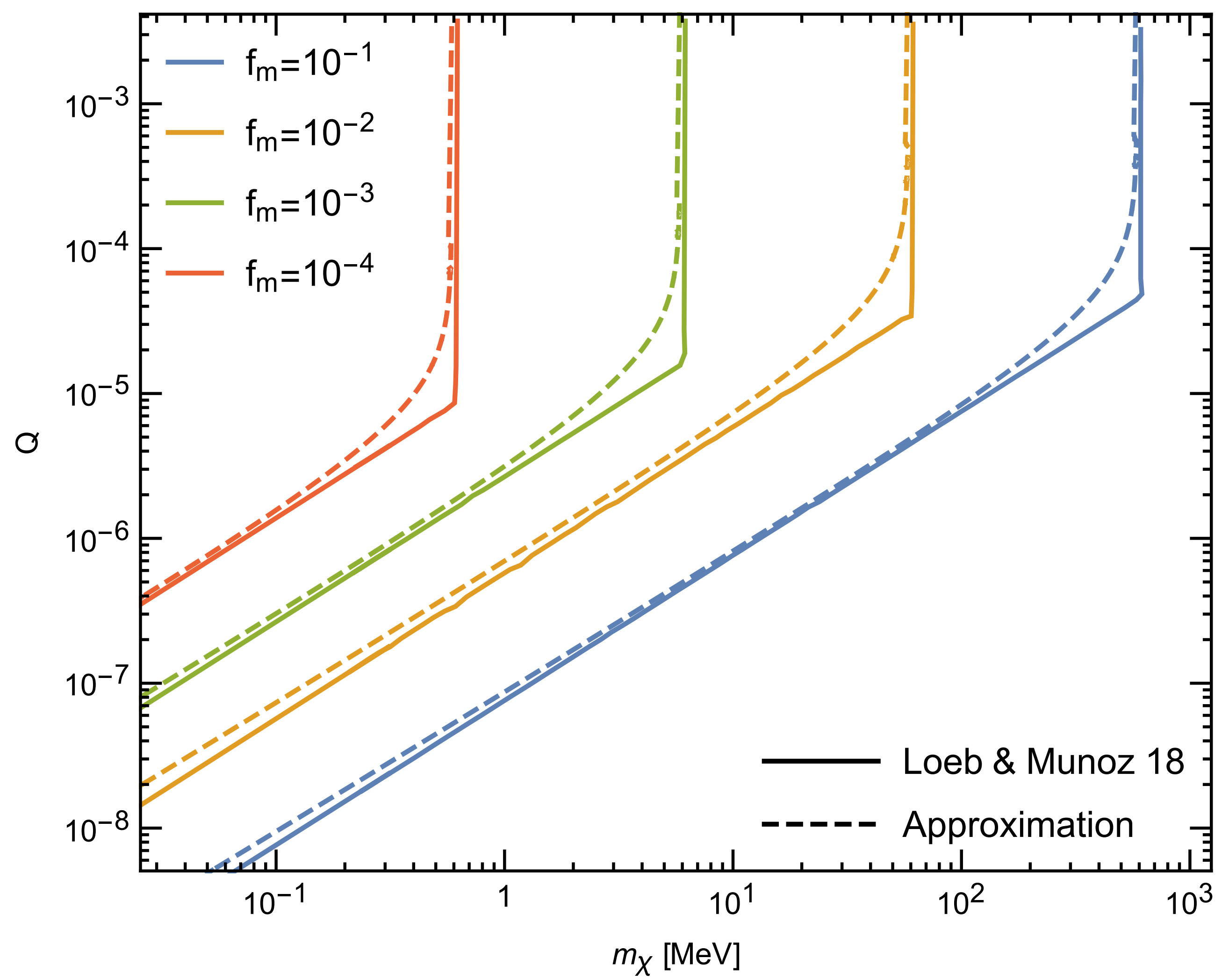
(Barkana,**NJO**,Redigolo,Volansky, 2018)

ANALYTICS

Very cool estimates (ignoring bulk motion):

$$m_{\rm mDM} \lesssim f_{\rm m} \times 6\ {\rm GeV}$$

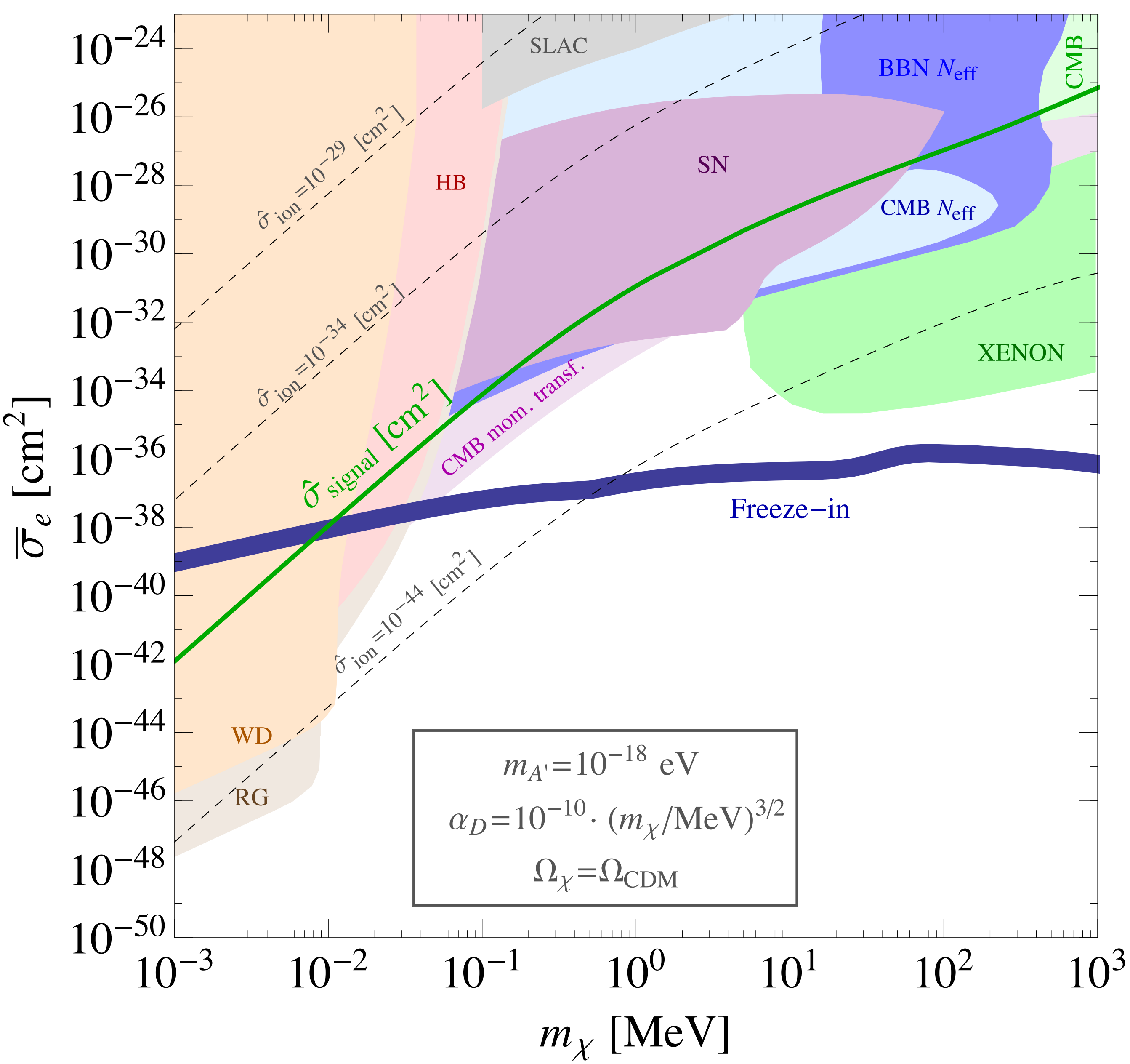
$$\frac{f_{\rm m}\rho_{\rm DM}}{m_{\rm m}} \frac{x_e \mu_{p{\rm m}}}{m_p + m_{\rm m}} \frac{\langle \sigma_T^{p{\rm m}} v_{\rm rel}^2 \rangle}{\frac{T_{\rm m}}{m_{\rm m}} + \frac{T_{\rm b}}{m_p}} (T_{\rm b} - T_{\rm m}) \simeq H T_{\rm b}$$



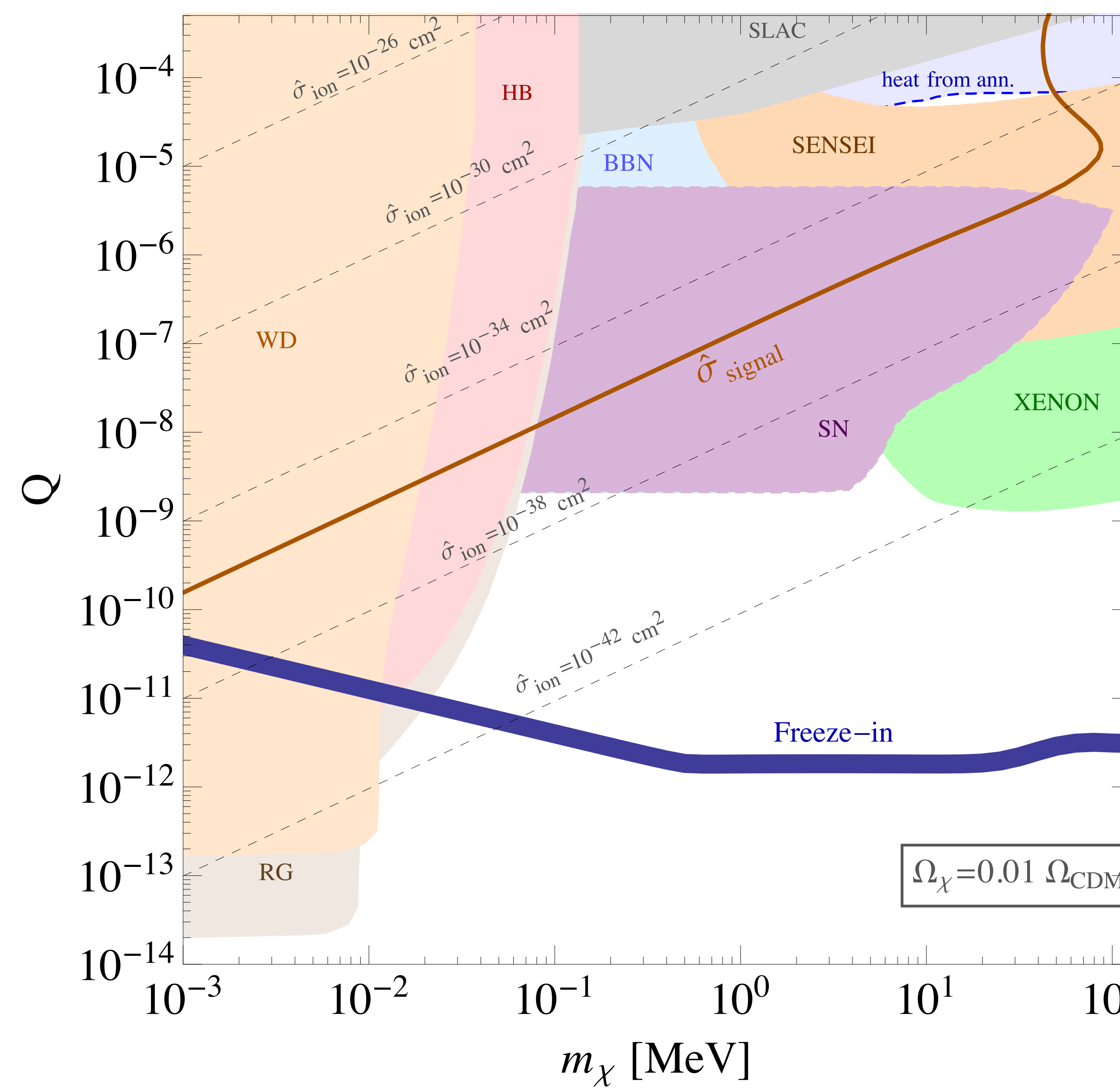
PARAMETER SPACE

Screened force → millicharged DM (mDM)

Hidden Photon



"Pure" mDM

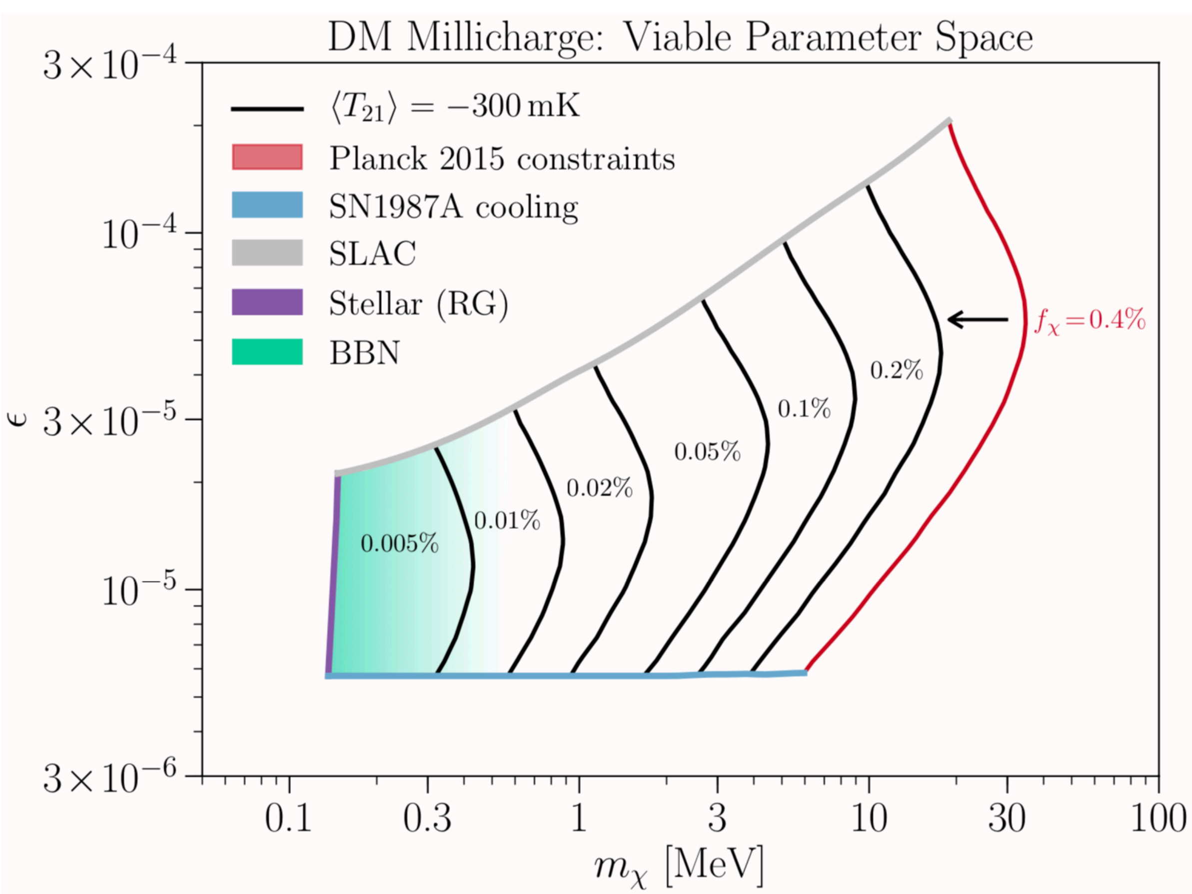


(Barkana,**NJO**,Redigolo,Volasky, 2018)

PARAMETER SPACE

STATUS

- E.D.Kovetz et.al (2018) revisited CMB constraints using Planck 2015 concluding $\Omega_{\rm mDM} \lesssim 4 \times 10^{-3} \Omega_{\rm DM}$



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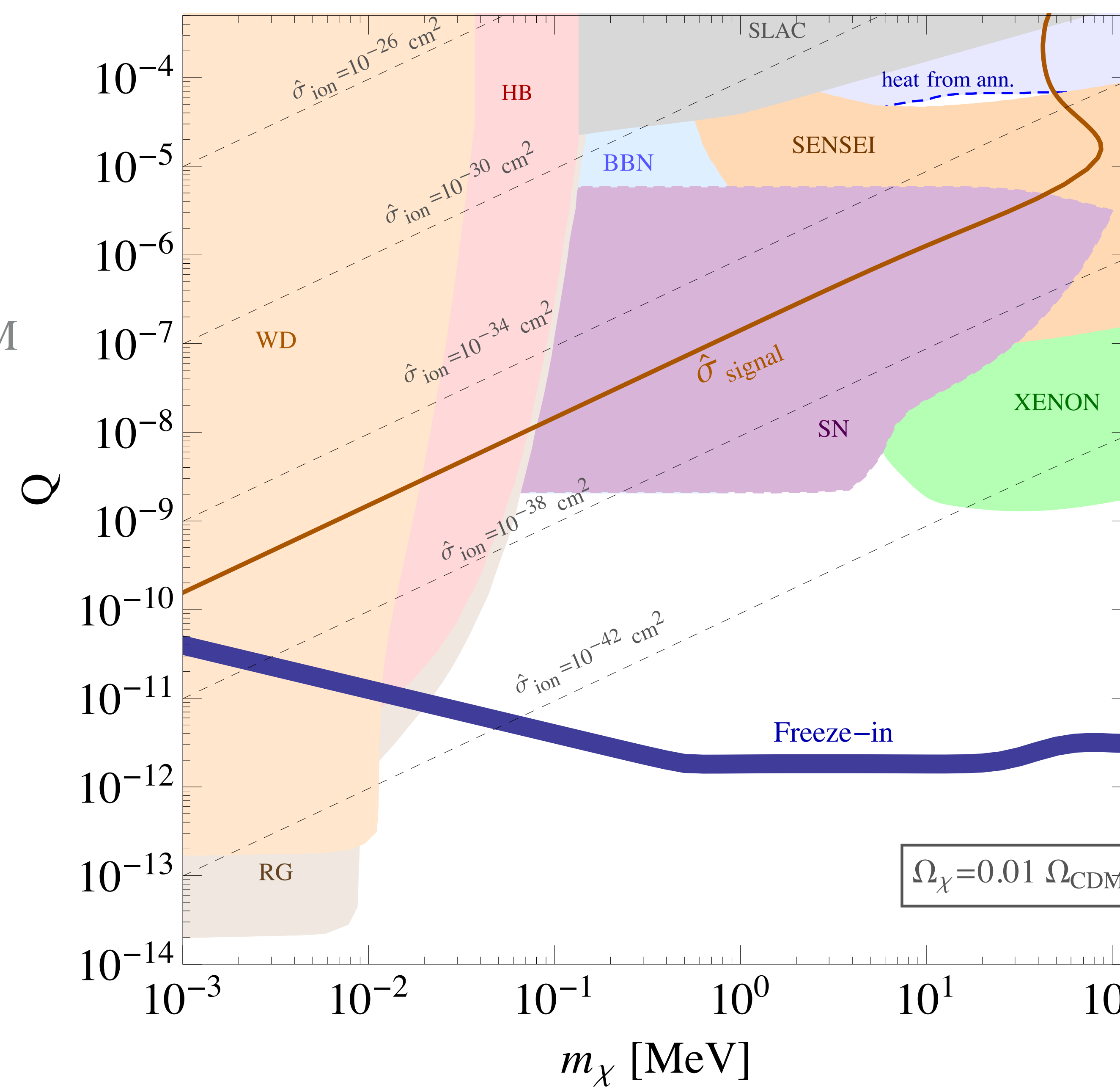
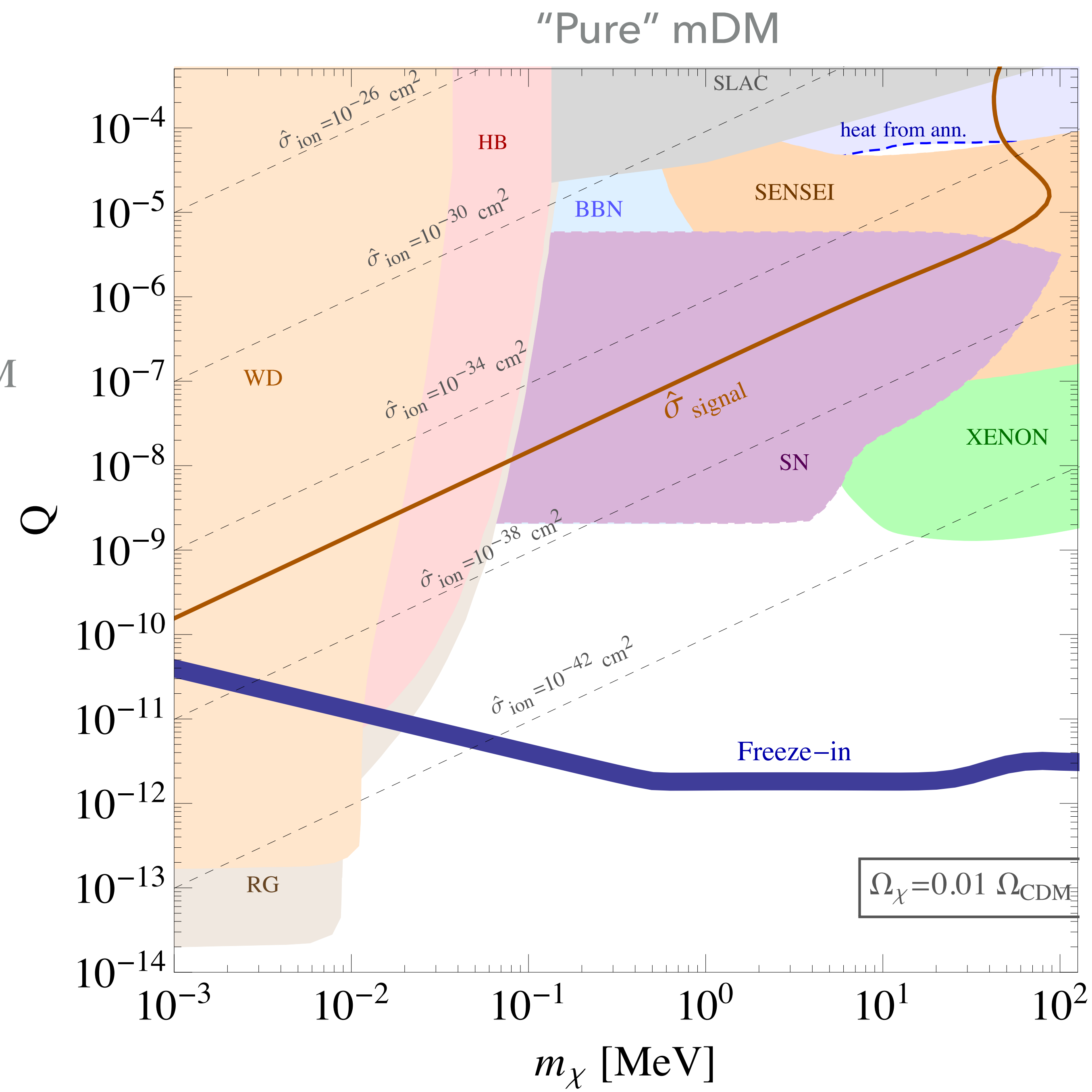


(Barkana,**NJO**,Redigolo,Volasky, 2018)

PARAMETER SPACE

STATUS

- E.D.Kovetz et.al (2018) revisited CMB constraints using Planck 2015 concluding $\Omega_{\rm mDM} \lesssim 4 \times 10^{-3}\Omega_{\rm DM}$
- Together with $N_{\rm eff}$ constraints, hidden photon explanation is excluded.
- Probably also without it.
- The end?



(Barkana,**NJO**,Redigolo,Volasky, 2018)

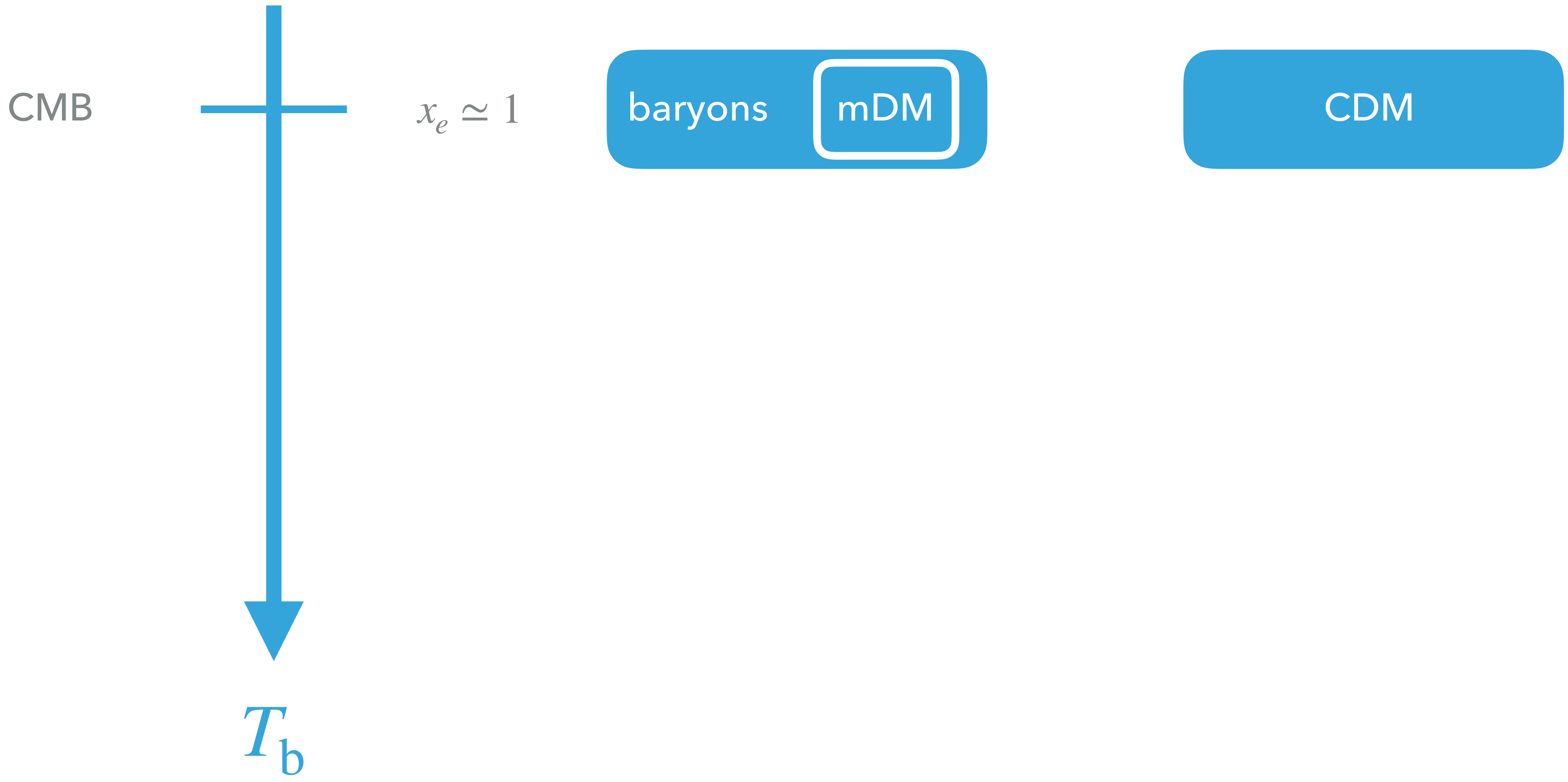
LIU, NJO, REDIGOLO, VOLANSKY,

[ARXIV:1908.06986]

REVIVING MILLICHARGED DARK MATTER

FRAMEWORK

General idea: use the CDM bath as a reservoir.



FRAMEWORK

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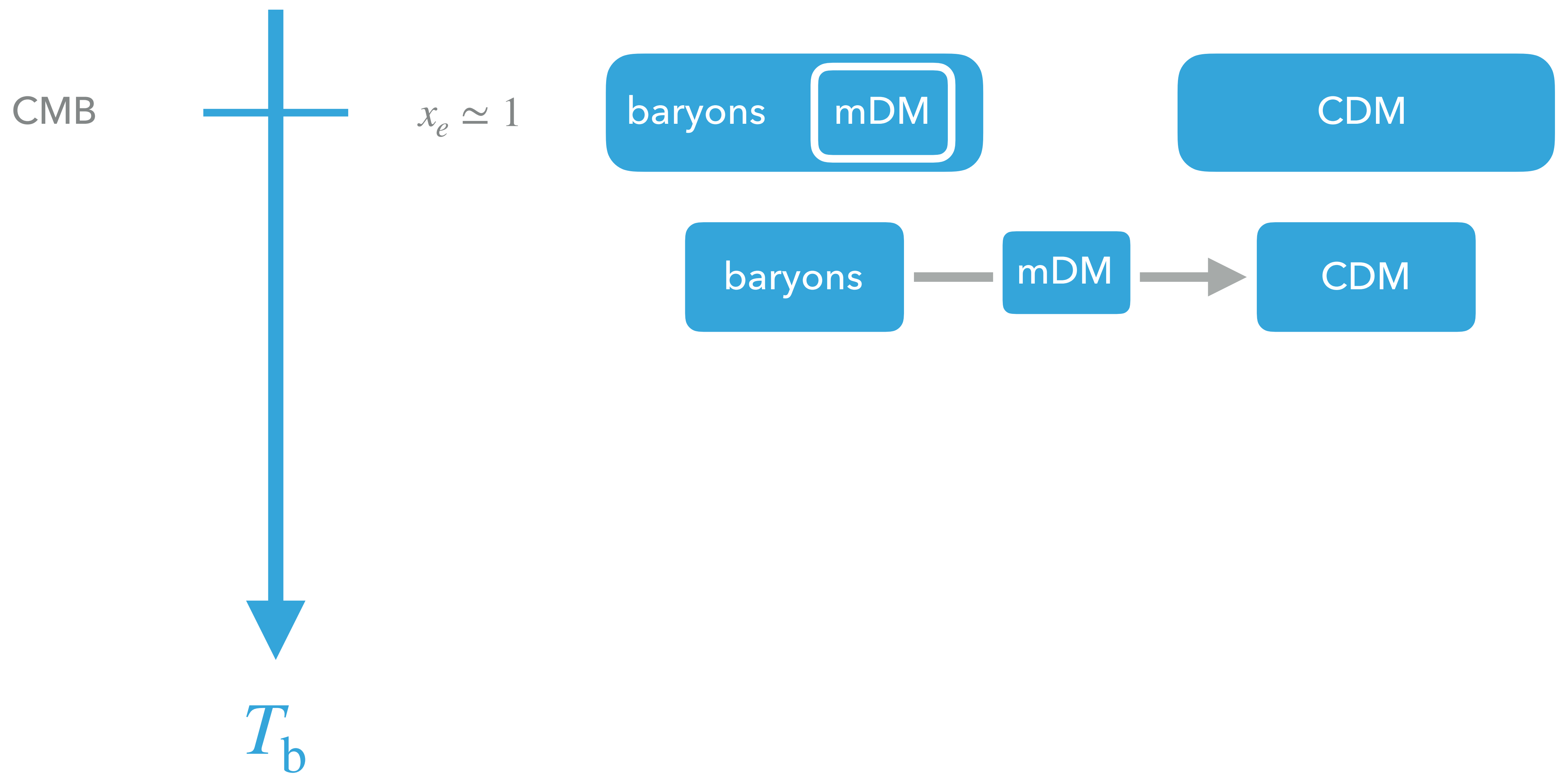

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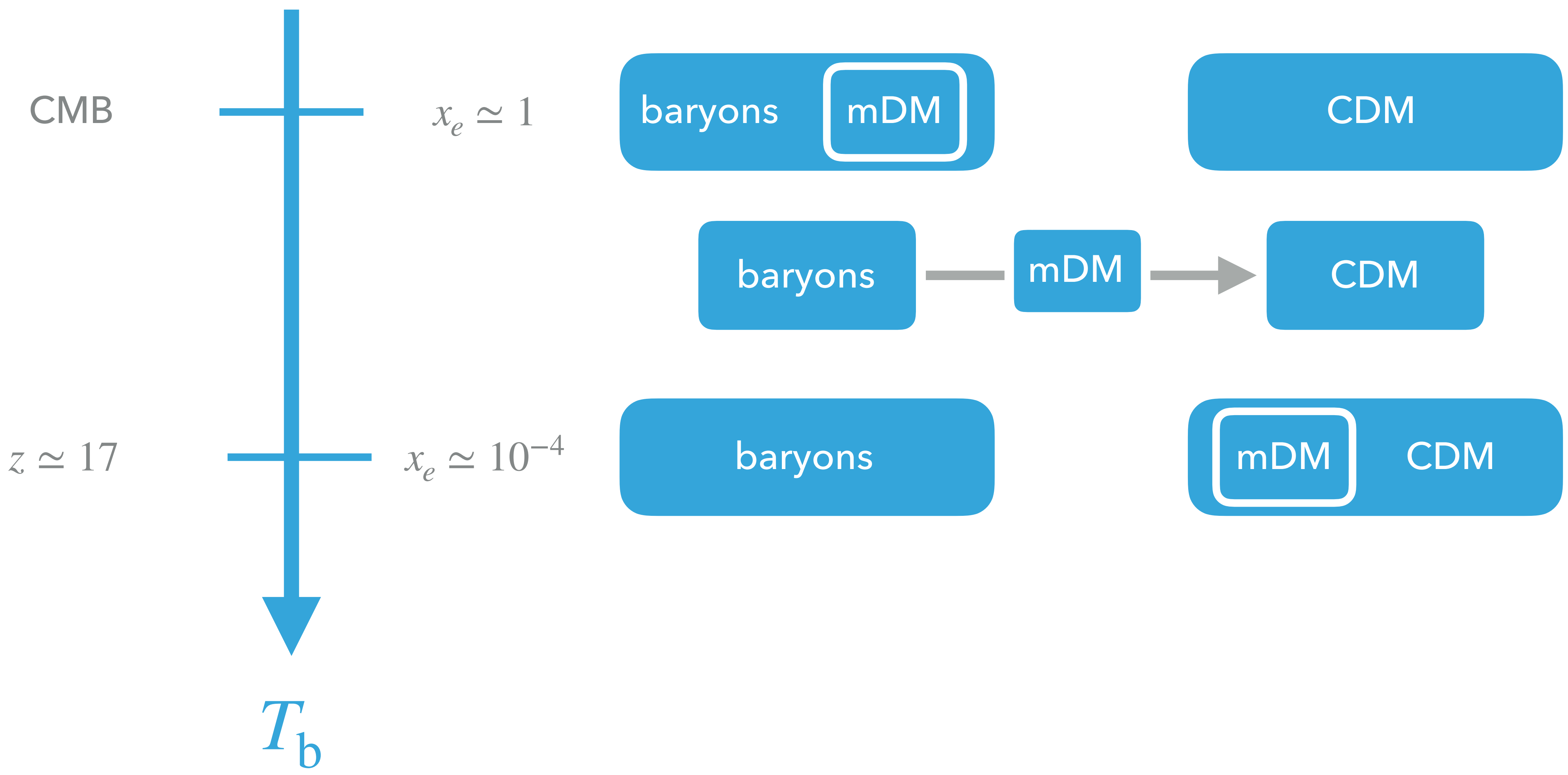

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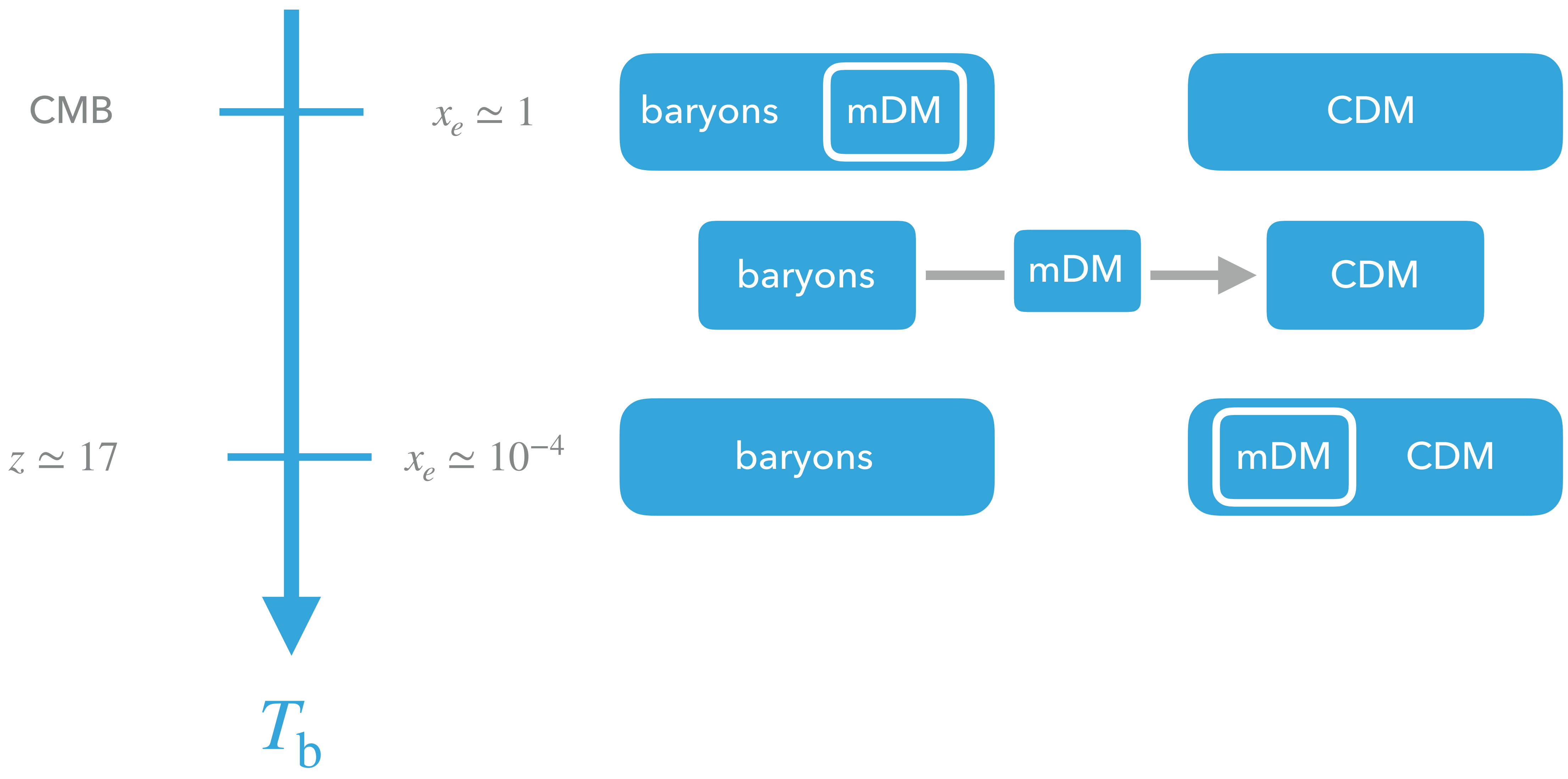

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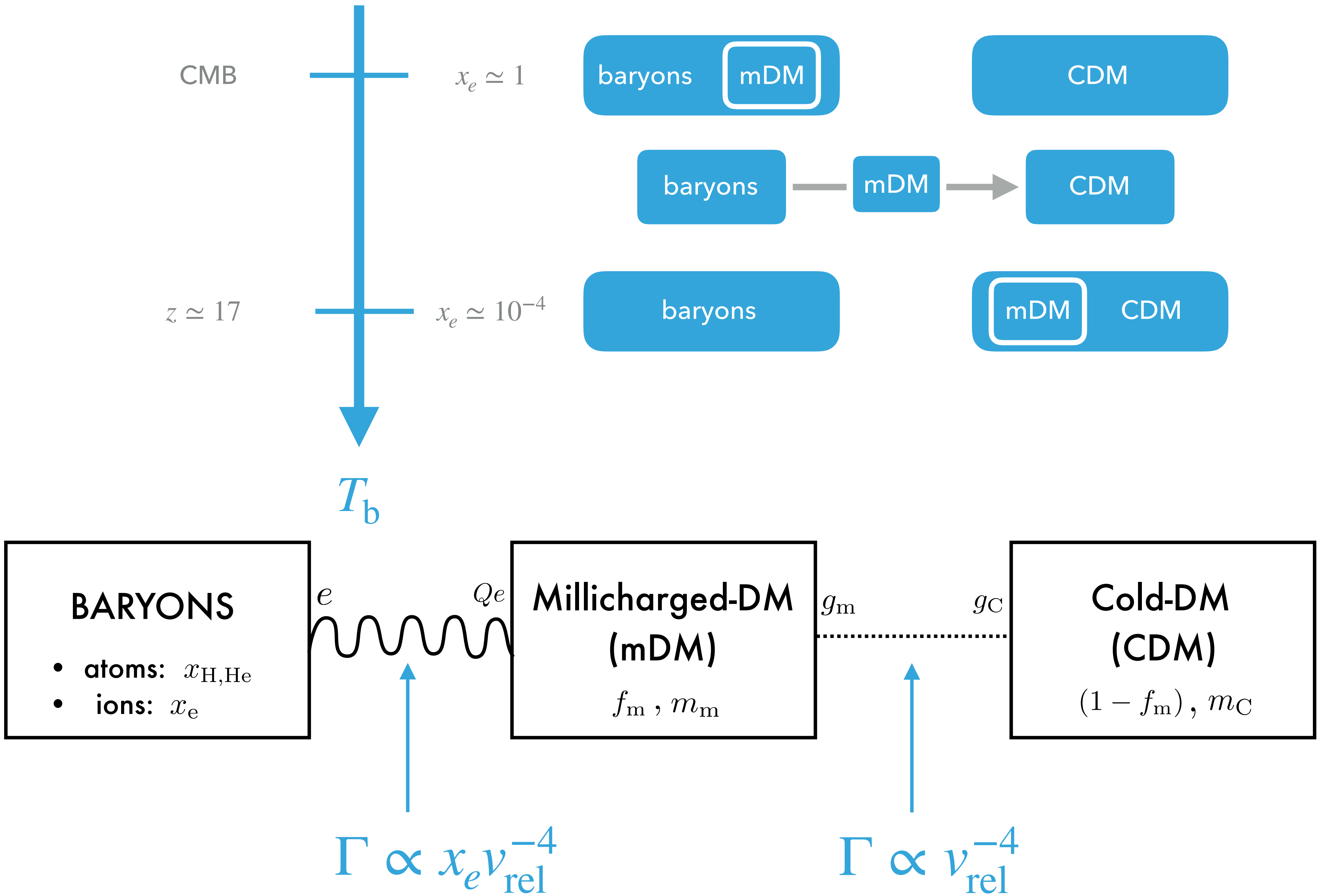

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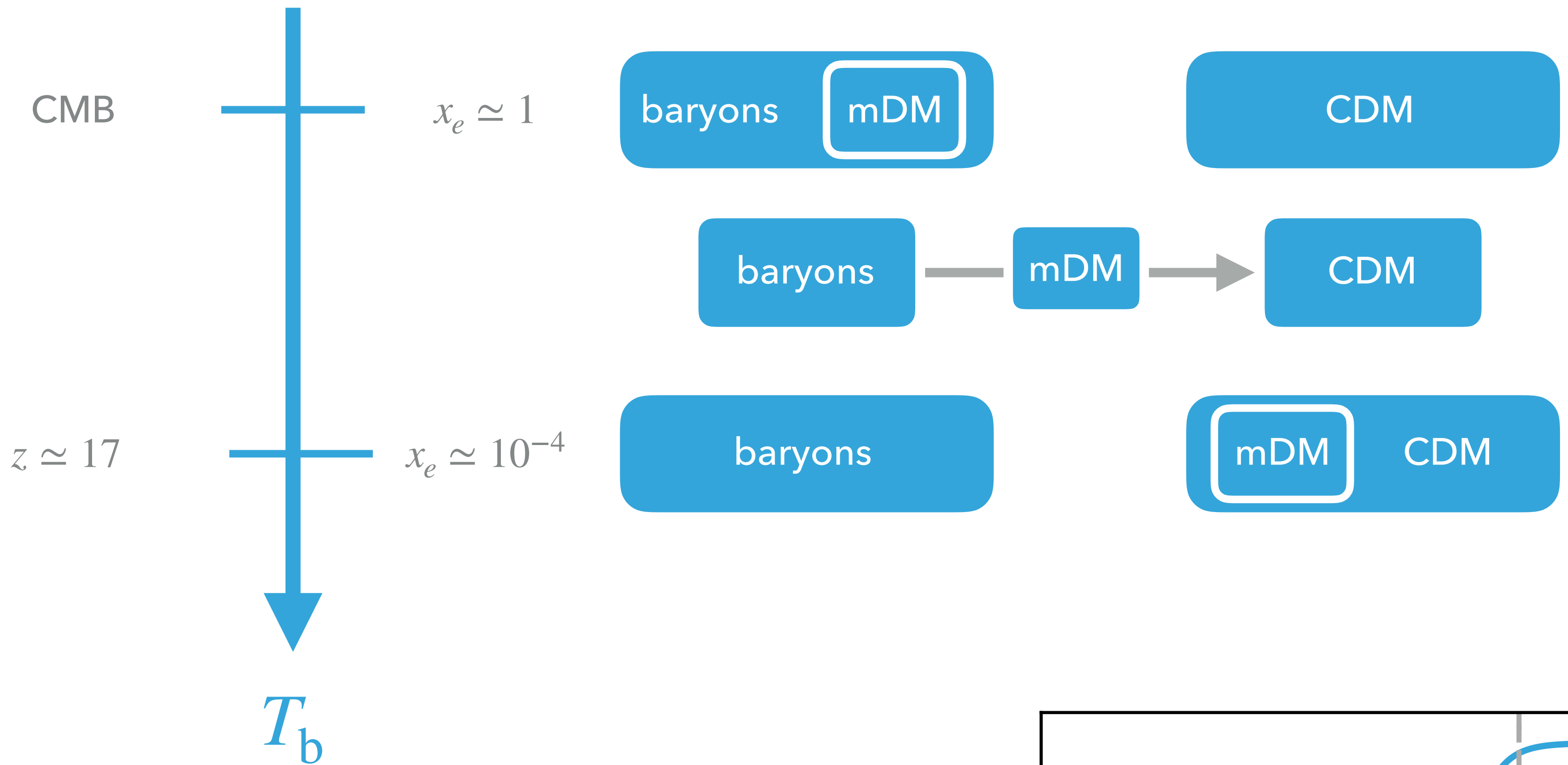
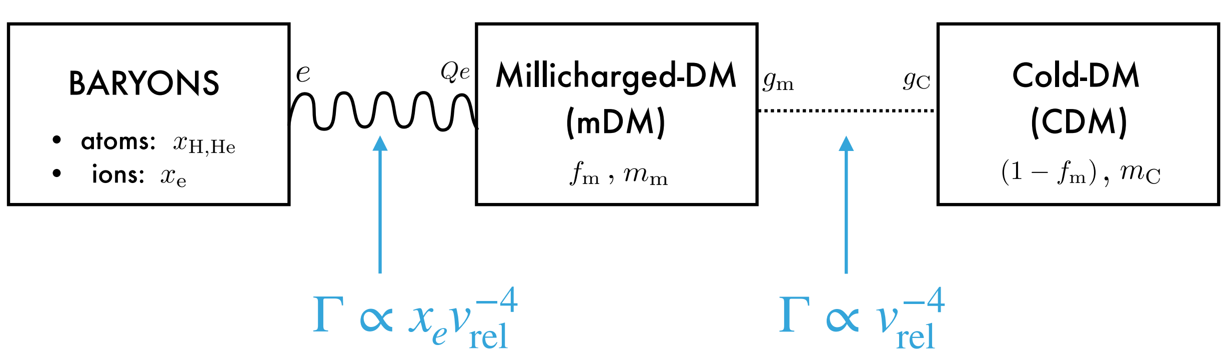
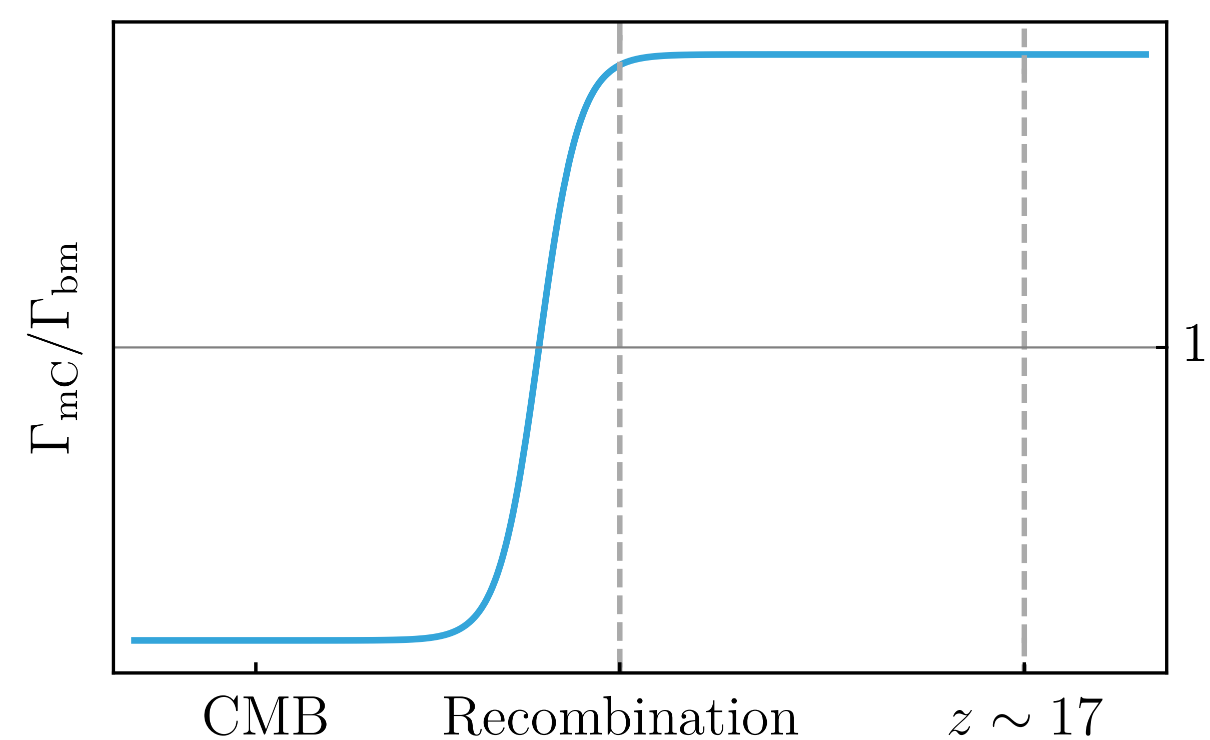






FRAMEWORK

Implications

- CMB anisotropies constraints
  - **hide mDM in the baryonic fluid,** $f_{\rm m} \lesssim 10^{-4}$
  - **large mDM-SM cross section at early times**
  - **small mDM-CDM cross section at early times**
- EDGES at $z \simeq 17$ - **large mDM-CDM cross section at later times**
- IR dominated processes - **velocity dependence, light mediator** $(\sim v_{\rm rel}^{-4})$
- Relative interactions strength is set by x_e

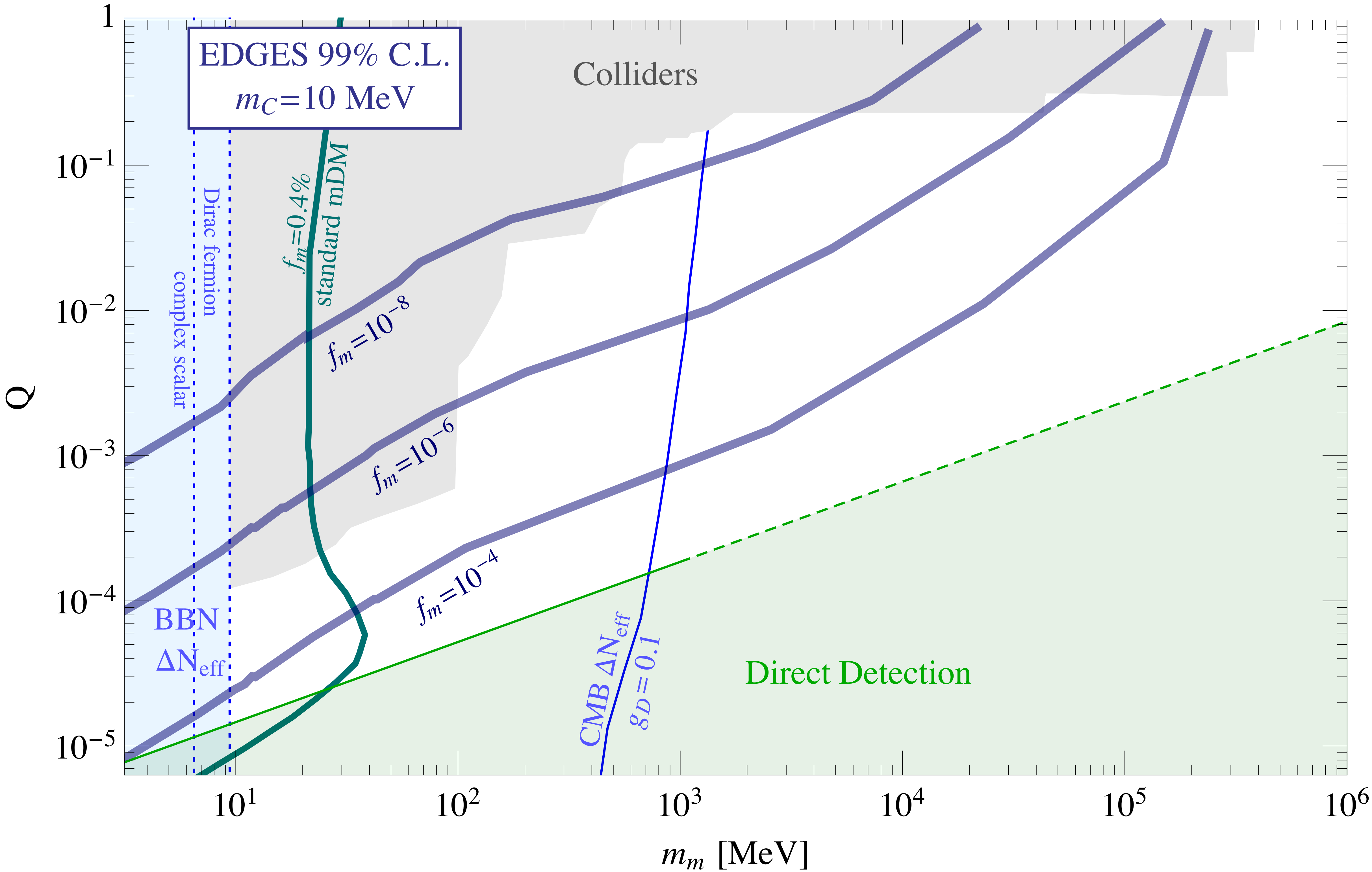
FRAMEWORK

What did we gain?

- Upper bound on CDM mass $m_{\mathrm{C}} \lesssim 6\,\mathrm{GeV}$
- Upper bound on mDM mass* $m_{\mathrm{m}} \lesssim 200\,\mathrm{GeV}$
- Lower bound on the mDM fraction is significantly smaller $f_{\mathrm{m}} \gtrsim 10^{-8}$
- Model lives below colliders reach, but above direct detection reach
- Many prediction for near future experiments

* a complicated combination of CMB constraints + the required rate for EDGES

RESULTS – MDM PARAMETERS



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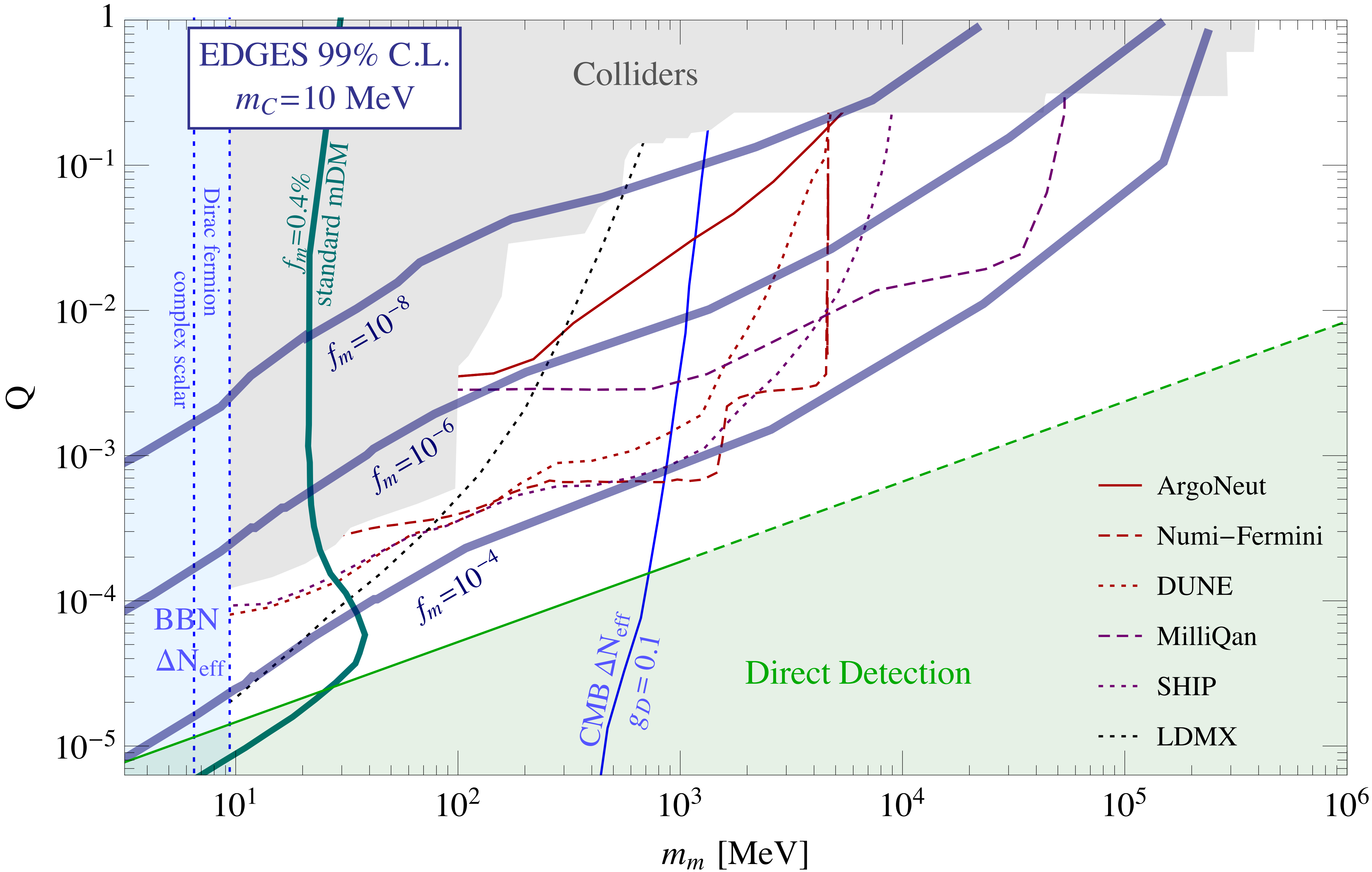

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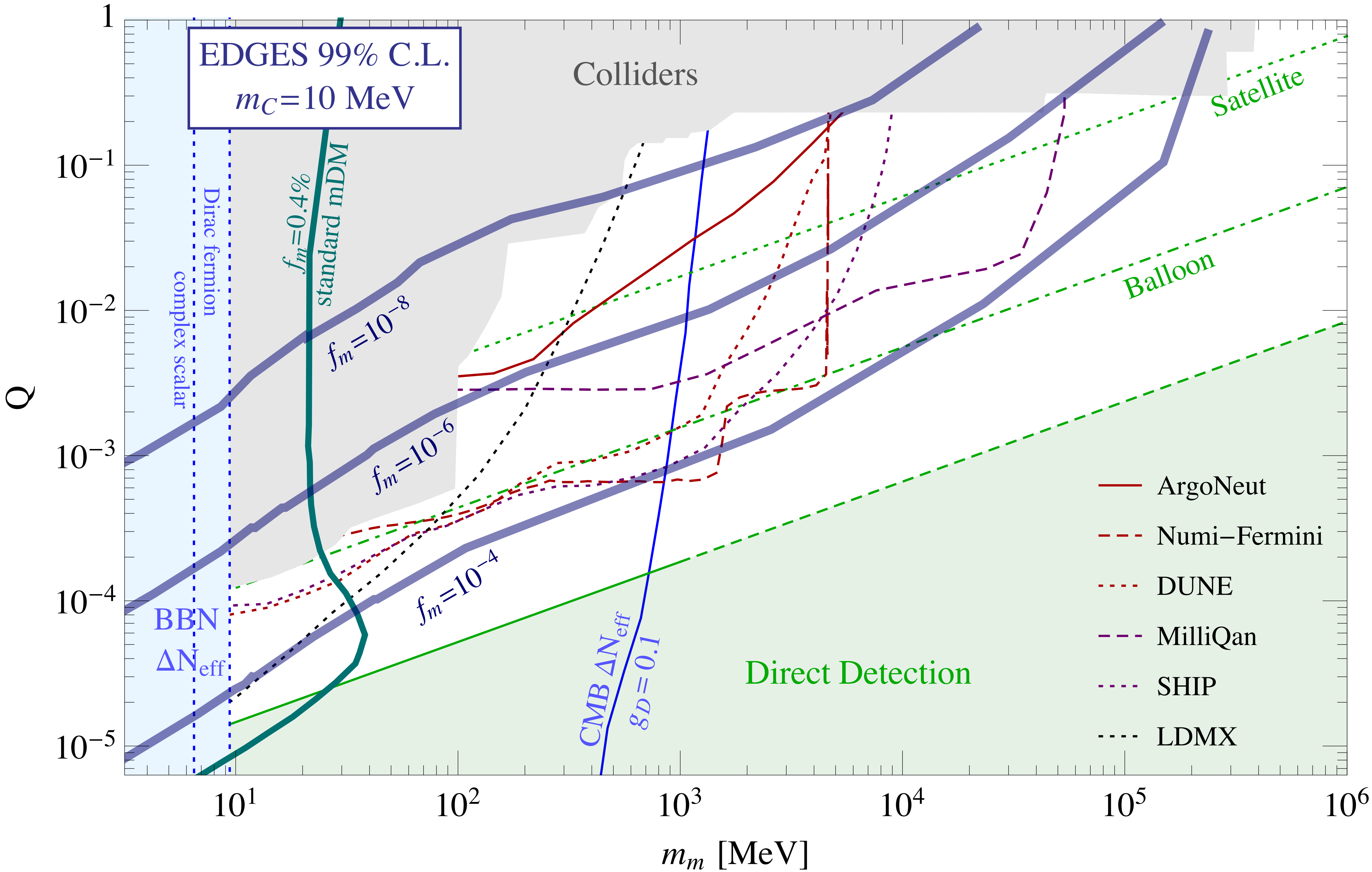


RESULTS

Other general statements

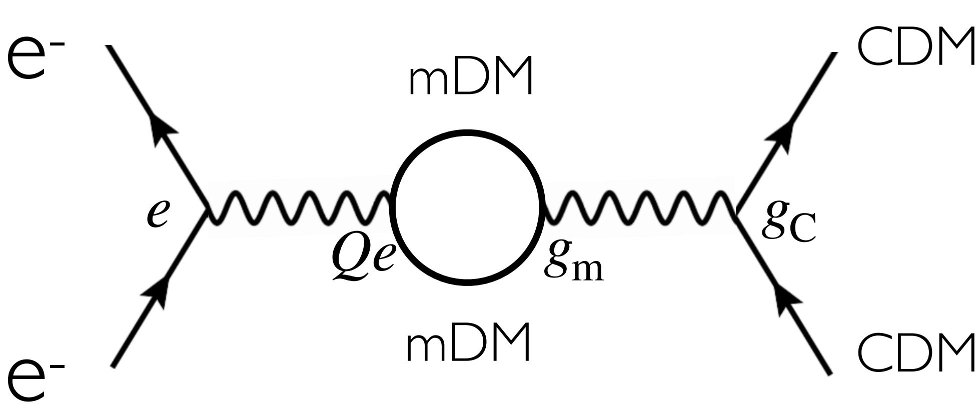
- Lower bound on CDM and mDM mass from $N_{\rm eff}$: $m_{\rm C,m} \gtrsim 10\,{\rm MeV}$
- Mass ordering*: $m_{\rm m} \gtrsim m_{\rm C}/10$
- For $m_{\rm m} \gtrsim 100\,{\rm MeV}$ the inner structure of H and He atoms is sufficiently resolved, cooling is dominated by mDM-atoms interactions

* a complicated combination of CMB constraints + the required rate for EDGES

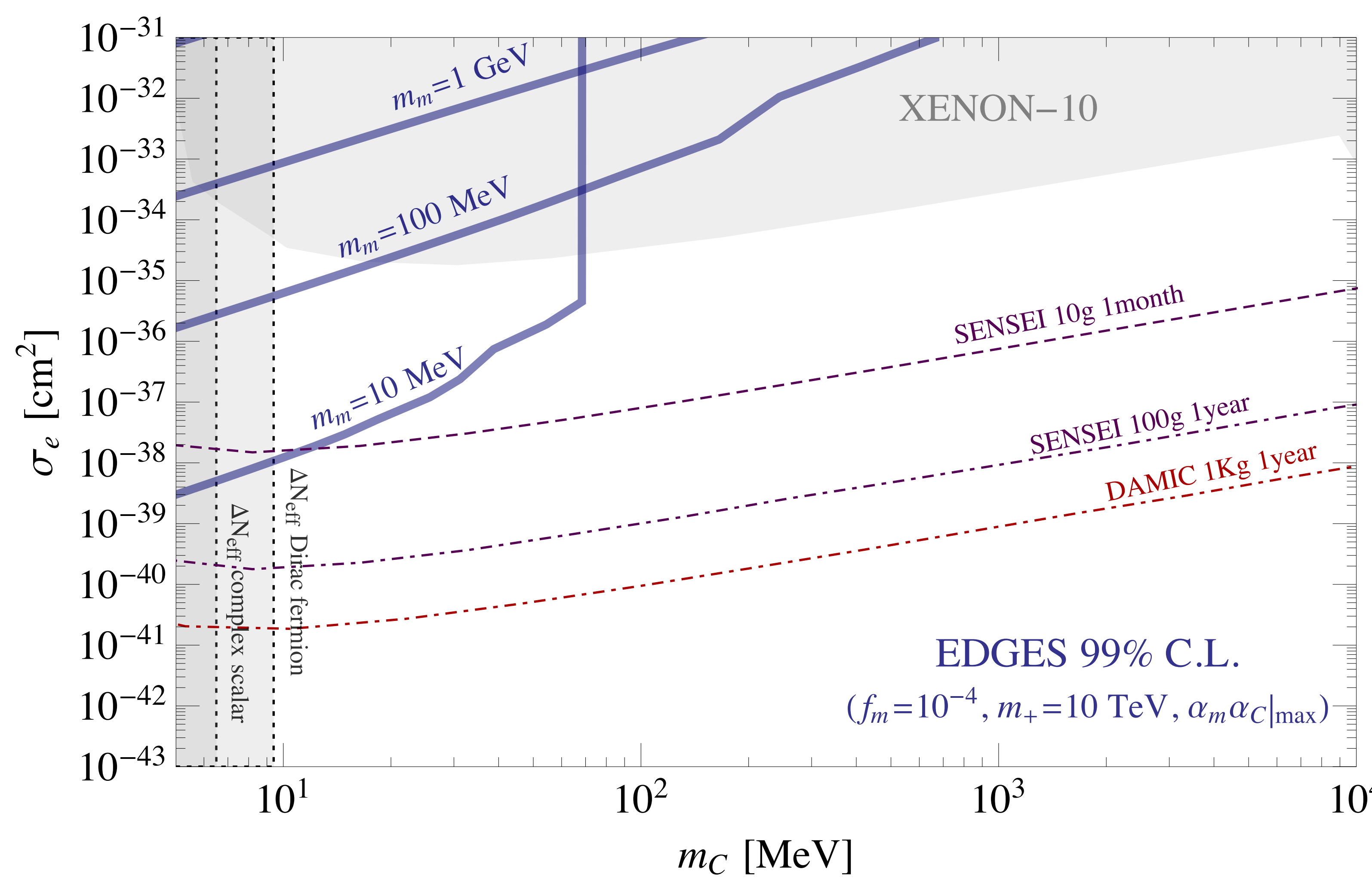
RESULTS – CDM PARAMETERS

Constraints

- Conservative self interactions constraints: $\frac{\alpha_C^2}{m_C^3} \lesssim 10^{-11}\mathrm{GeV}^{-3}$
- Loop induced CDM-SM coupling



$$\Rightarrow \quad \bar{\sigma}_e \simeq \frac{8Q^2\alpha_C\alpha_m}{\alpha_{EM}^2\mu_{em}^2}\left(\log\frac{\Lambda}{m_m}\right)^2$$



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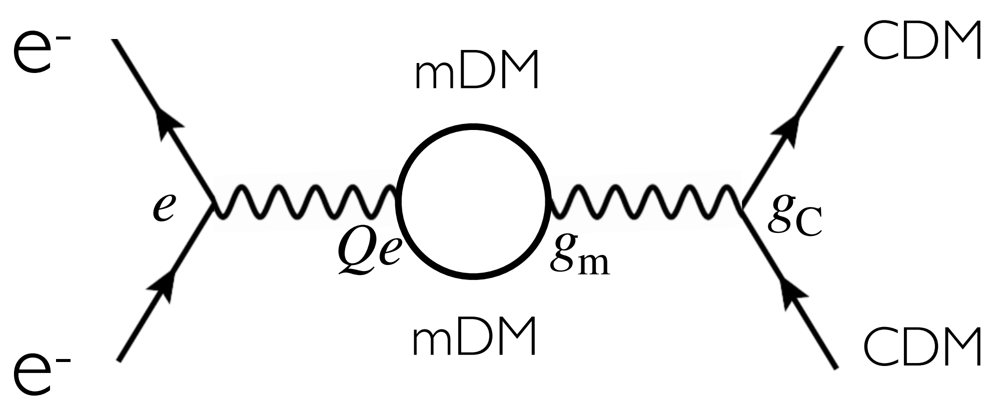

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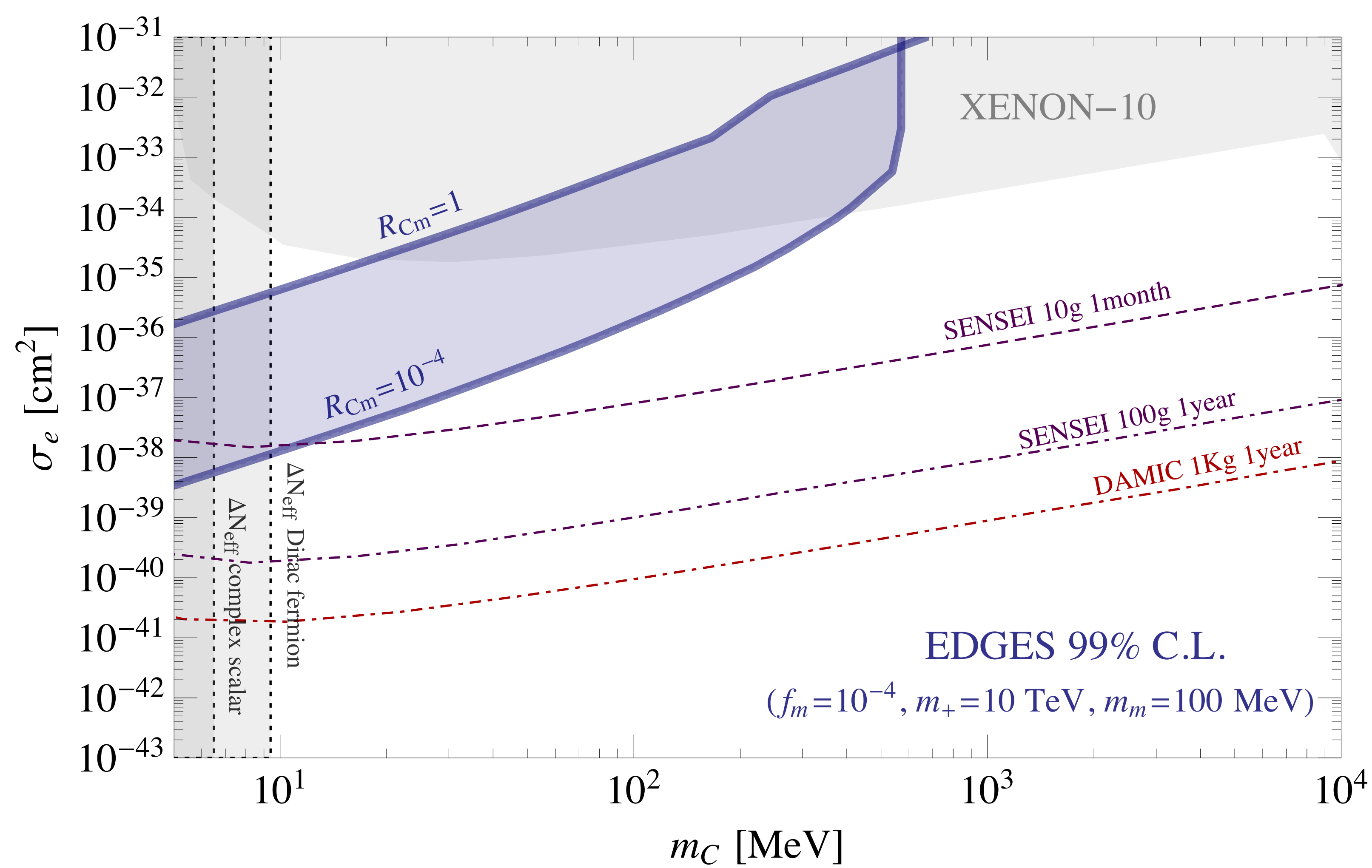

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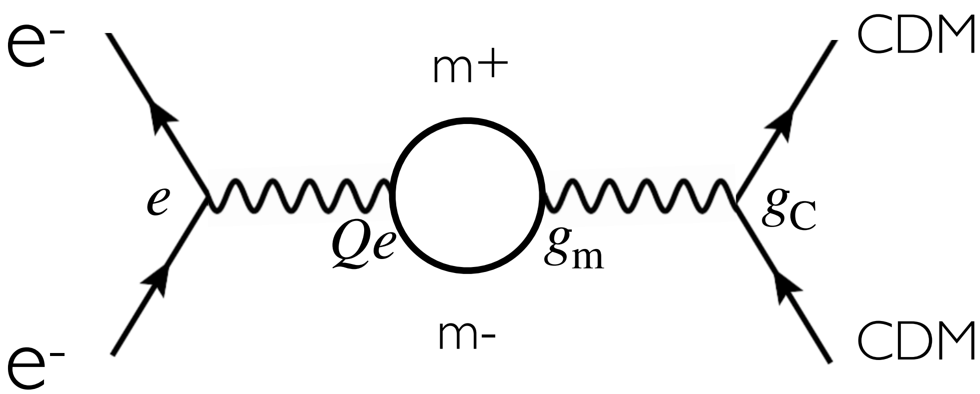
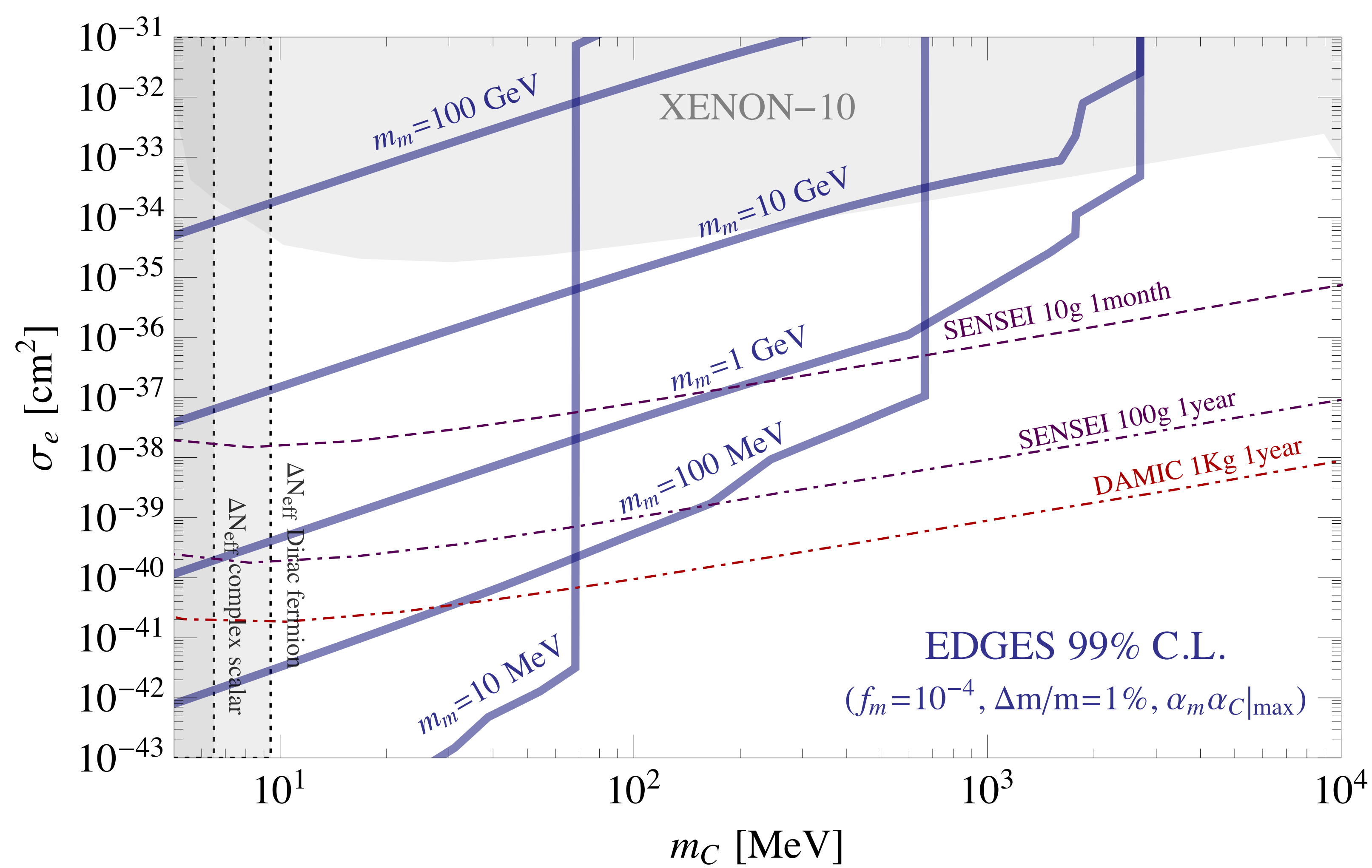


$$\Rightarrow \quad \bar{\sigma}_e \simeq \frac{8Q^2\alpha_C\alpha_m}{\alpha_{EM}^2\mu_{em}^2}\left(\log\frac{m_+}{m_-}\right)^2$$



SUMMARY AND OUTLOOK

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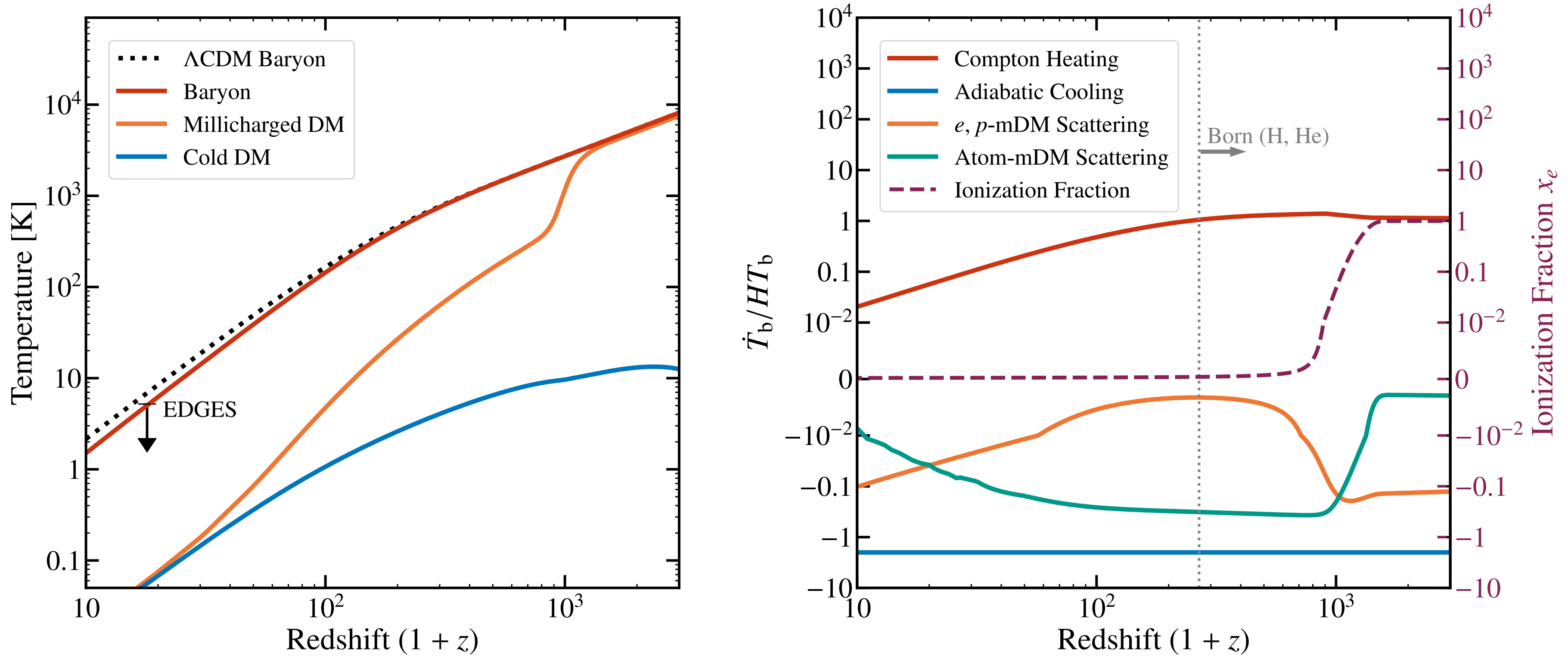
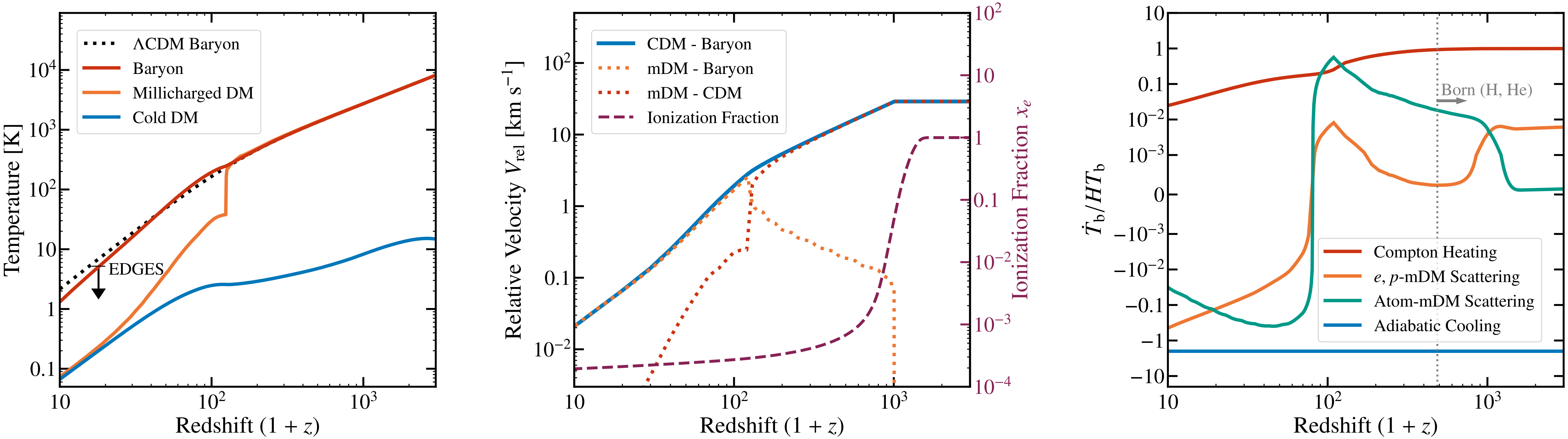
- 21cm spectrum and fluctuations?

THANKS.

EXTRAS?



ΛCDM Baryon
Baryon
Millicharged DM
Cold DM
EDGES
Temperature [K]
Redshift (1 + z)
Compton Heating
Adiabatic Cooling
e, p-mDM Scattering
Atom-mDM Scattering
Ionization Fraction
Born (H, He)
Ionization Fraction x_e



ΛCDM Baryon
Baryon
Millicharged DM
Cold DM
EDGES
Temperature [K]
Redshift (1 + z)
CDM - Baryon
mDM - Baryon
mDM - CDM
Ionization Fraction
Relative Velocity V_rel [km s^−1]
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Born (H, He)
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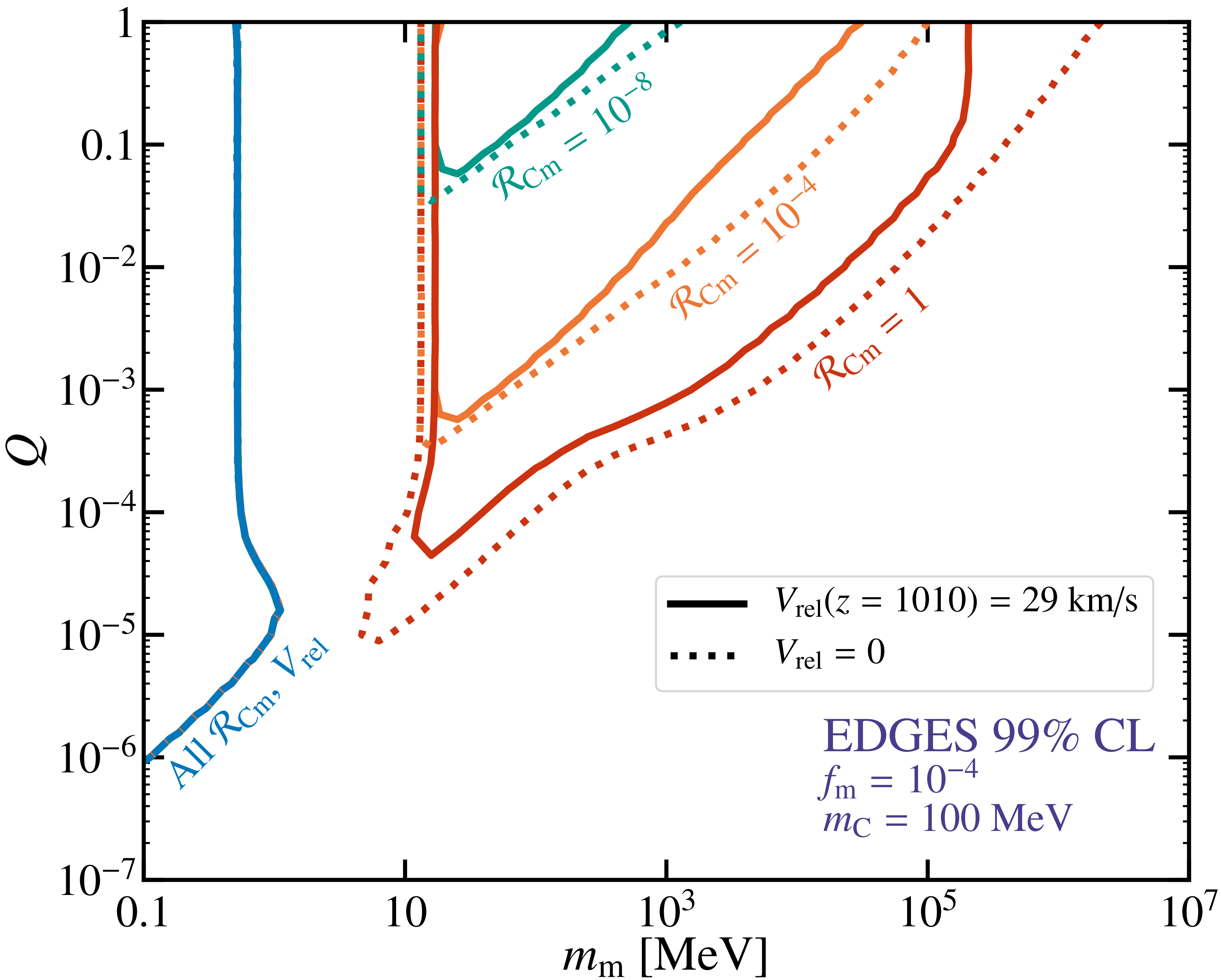
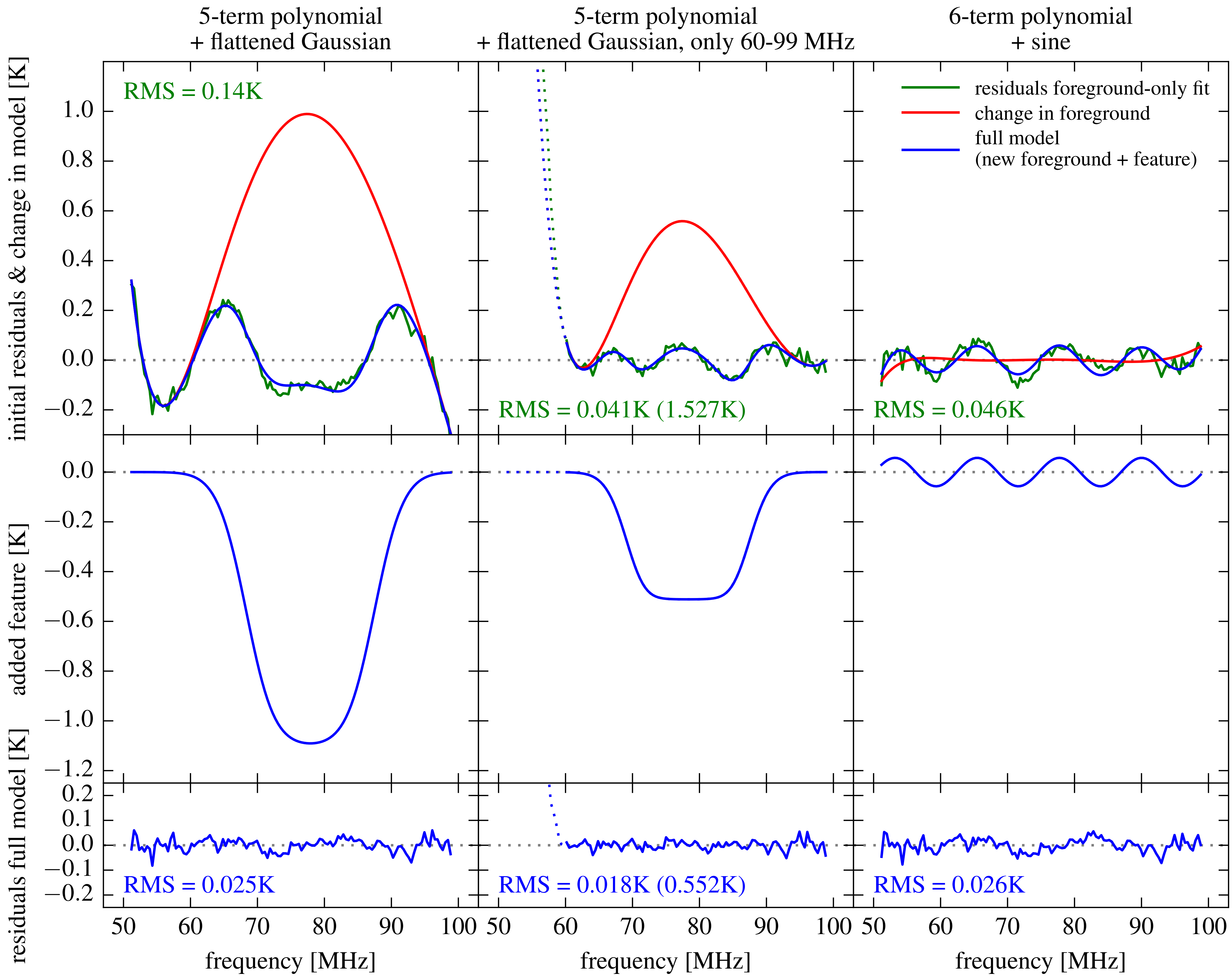


$\mathcal{R}_{\mathrm{Cm}} = 10^{-8}$
$\mathcal{R}_{\mathrm{Cm}} = 10^{-4}$
$\mathcal{R}_{\mathrm{Cm}} = 1$
All $\mathcal{R}_{\mathrm{Cm}}$, V_{rel}
$V_{\mathrm{rel}}(z = 1010) = 29$ km/s
$V_{\mathrm{rel}} = 0$
EDGES 99% CL
$f_{\mathrm{m}} = 10^{-4}$
$m_{\mathrm{C}} = 100$ MeV
Q
m_{m} [MeV]
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
0.1
10
10^{3}
10^{5}
10^{7}



5-term polynomial
+ flattened Gaussian
5-term polynomial
+ flattened Gaussian, only 60-99 MHz
6-term polynomial
+ sine
RMS = 0.14K
RMS = 0.041K (1.527K)
RMS = 0.046K
residuals foreground-only fit
change in foreground
full model
(new foreground + feature)
initial residuals & change in model [K]
added feature [K]
residuals full model [K]
RMS = 0.025K
RMS = 0.018K (0.552K)
RMS = 0.026K
frequency [MHz]
frequency [MHz]
frequency [MHz]