Dark Sectors with 21-cm Cosmology: Imprints

A detailed analysis of the global 21-cm signal in dark cooling scenarios

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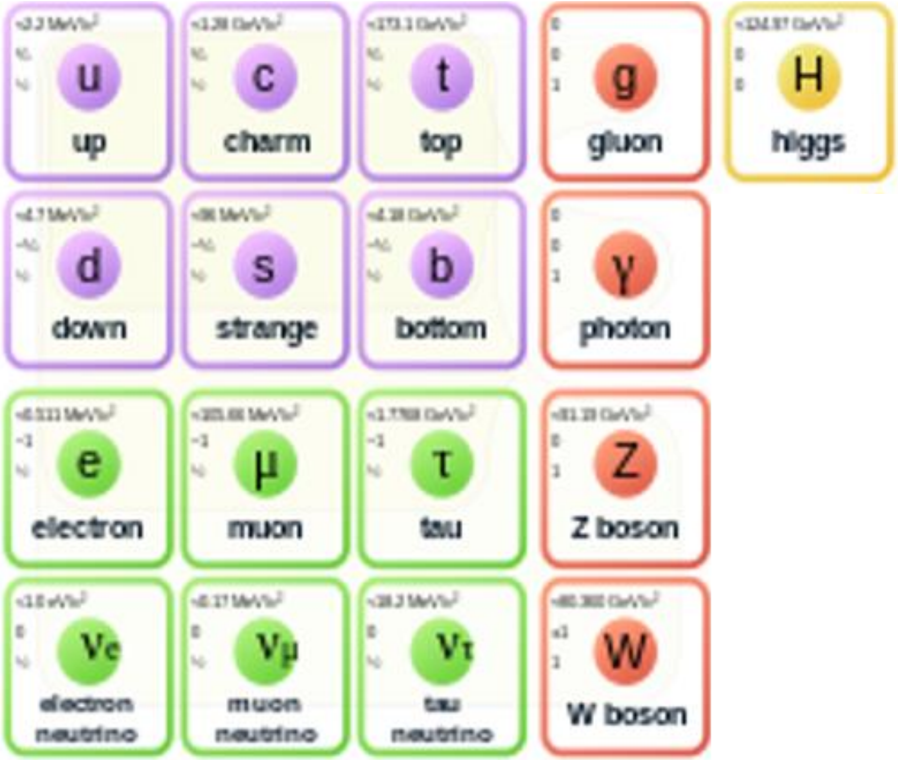
DM Intro: Standard CDM

Standard Model (15%)



Dark Matter (85%)

?

DM Intro: Standard CDM

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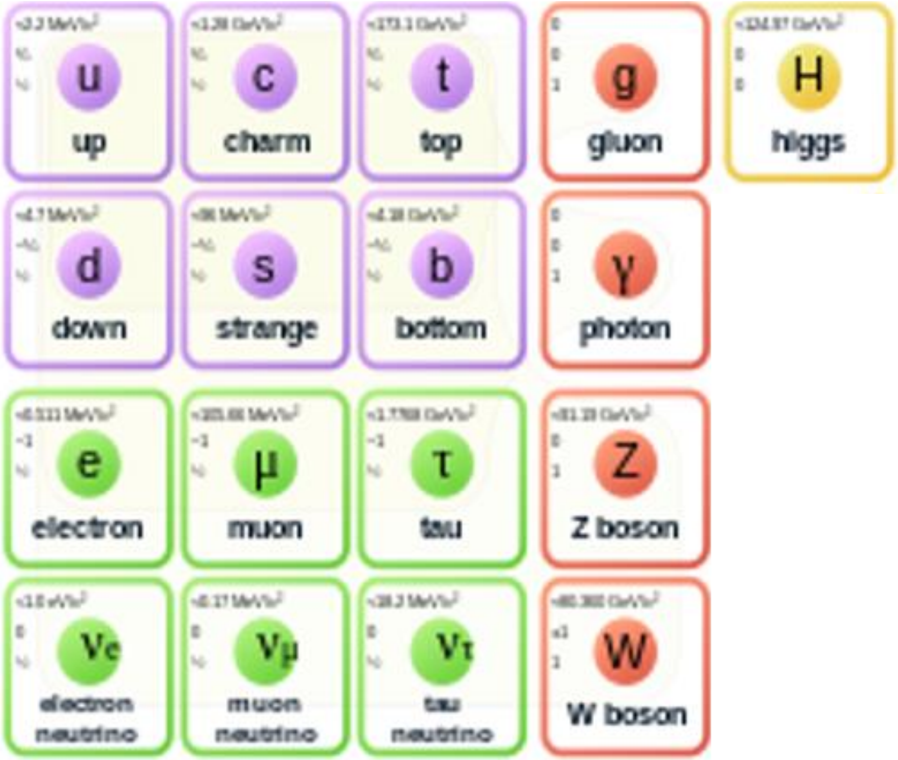

Dark Matter (85%)

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How do we produce DM?

DM Intro: Dark Sectors

Production mechanisms assume:

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Production mechanisms assume:

- Different mass and interactions for DM

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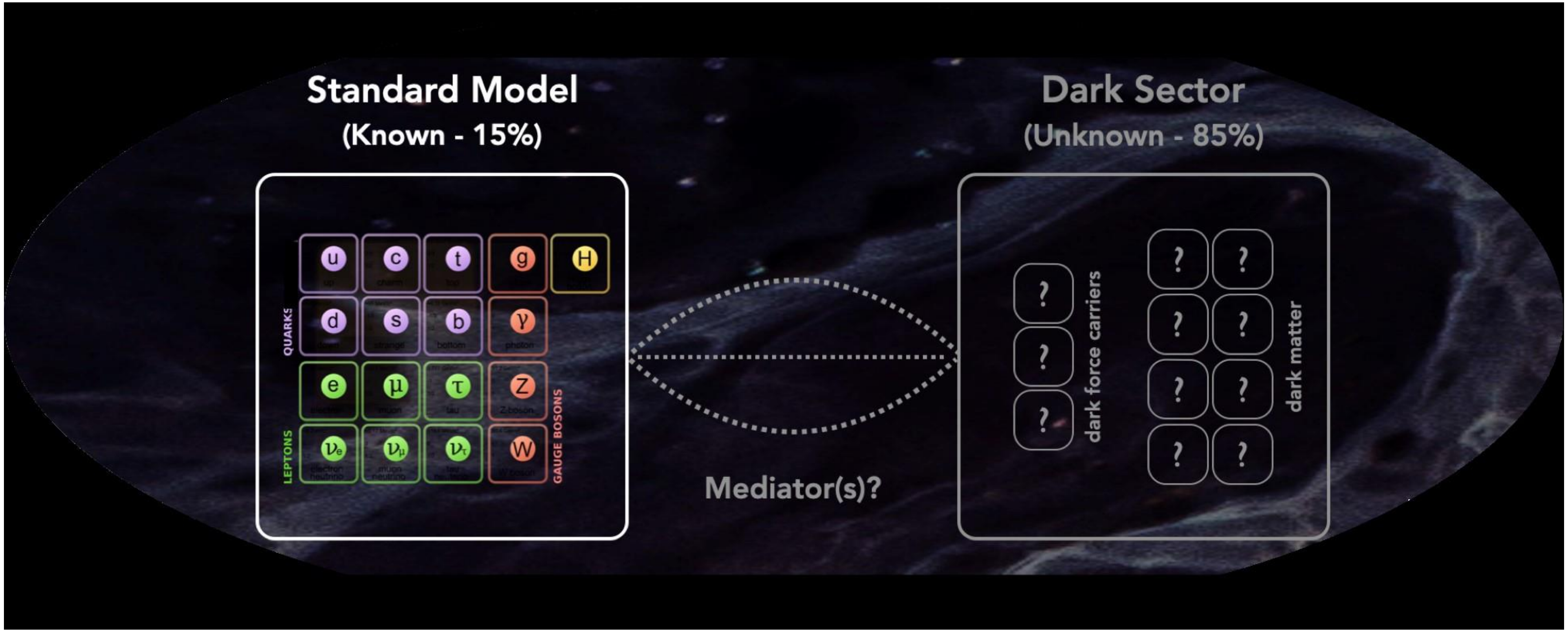
Production mechanisms assume:

- Different mass and interactions for DM
- Dark sectors?



Why 21-cm?

Why 21-cm?

Probing strongly interacting
small dark fractions

Direct detection

Colliders

Too strong → atmosphere overburden
Small fraction → small rates

Not strong enough → Small rates
Too massive → Insufficient E_{CM}

21-cm can close the gap between colliders and
direct detection

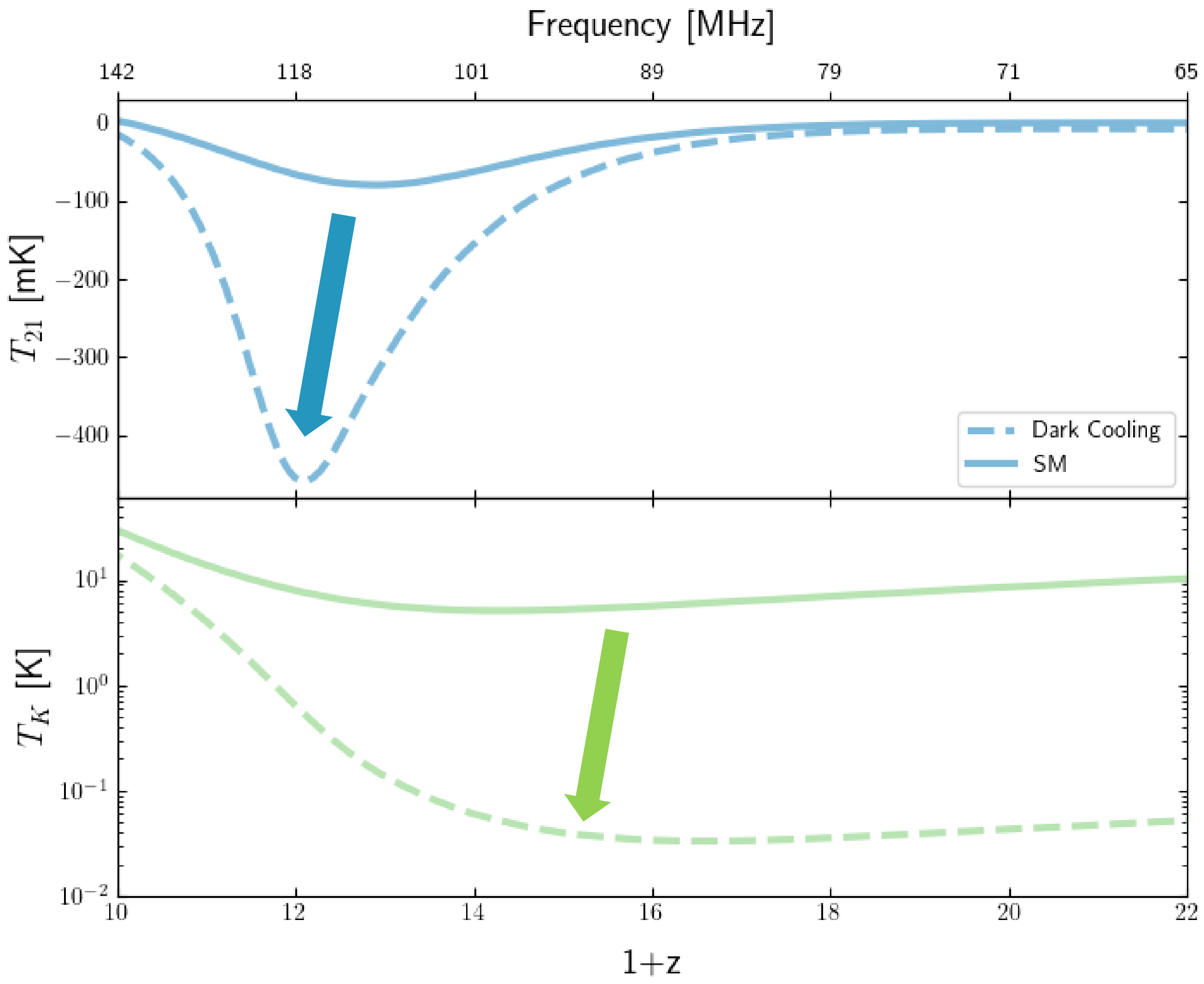
How 21-cm?

Dark Cooling in 21-cm Cosmology

Elastic DM-SM interactions cool the baryonic gas

Enhanced absorption at cosmic dawn
(and dark ages)

[Tashiro et al. 2014, Munoz et al. 2015]



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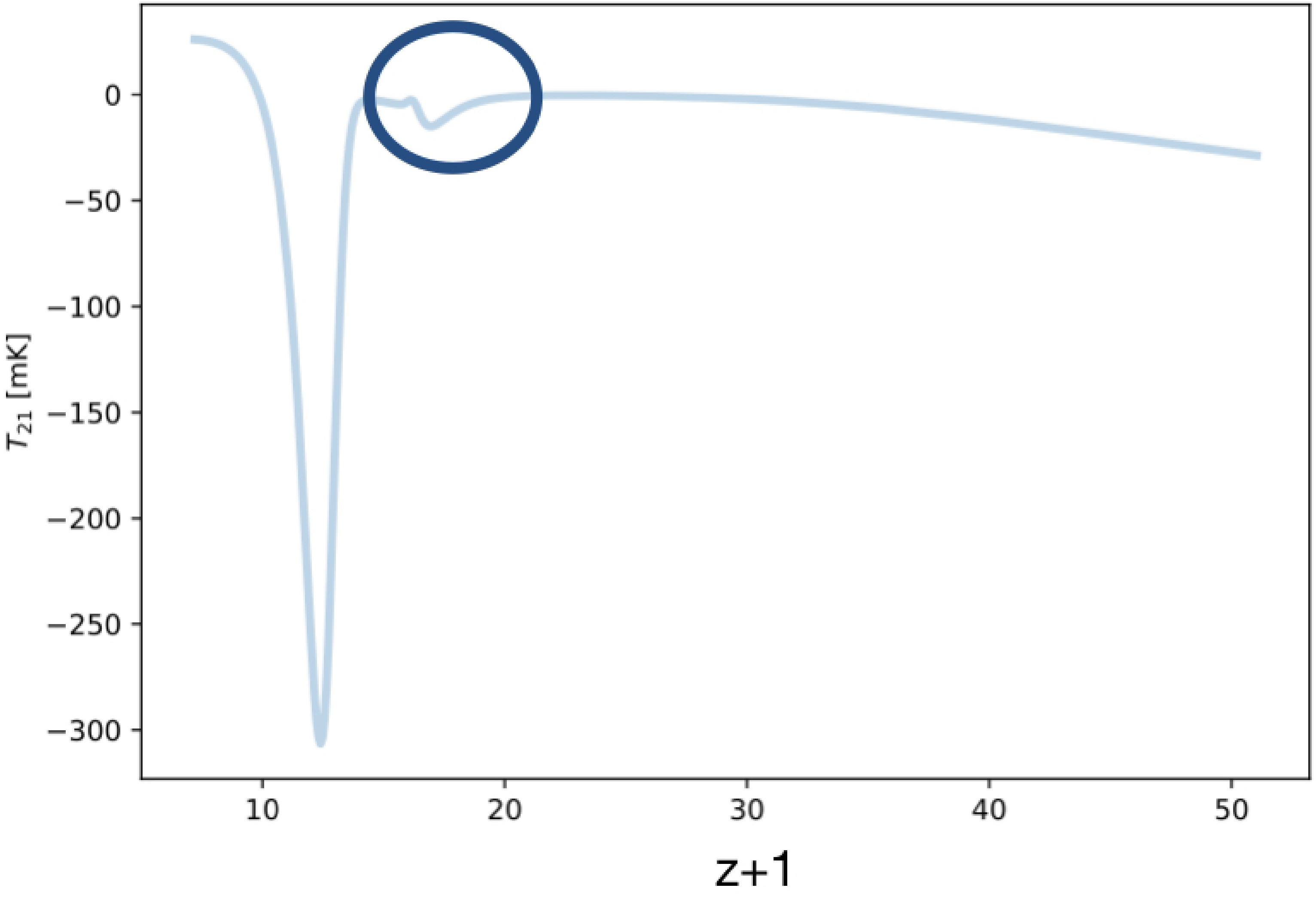

Unique features
due to Lyα inefficiency

Which DM scenarios?

Dark Cooling: Viable Models

- mDM is the only viable model that can lead to an $\mathcal{O}(1)$ cooling at cosmic dawn

[Barkana et al. 2018]

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- Order one cooling requires large cross sections

Astrophysical heating → 0

$$\frac{dT_k}{dt} = -2HT_k + \frac{2}{3}\dot{Q}_{Comp} + \frac{2}{3}\dot{Q}_{DM}$$

Dark Cooling: Viable Models

- mDM is the only viable model that can lead to an $\mathcal{O}(1)$ cooling at cosmic dawn

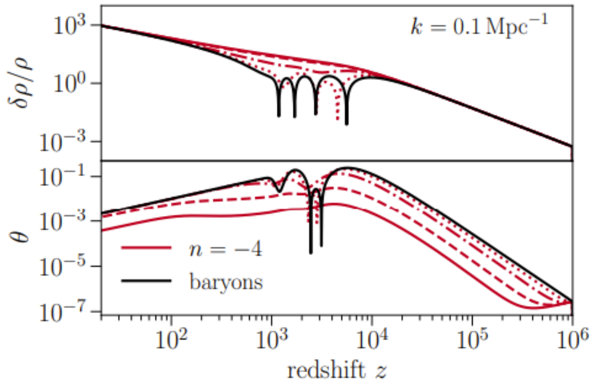
[Barkana et al. 2018]

- Order one cooling requires large cross sections

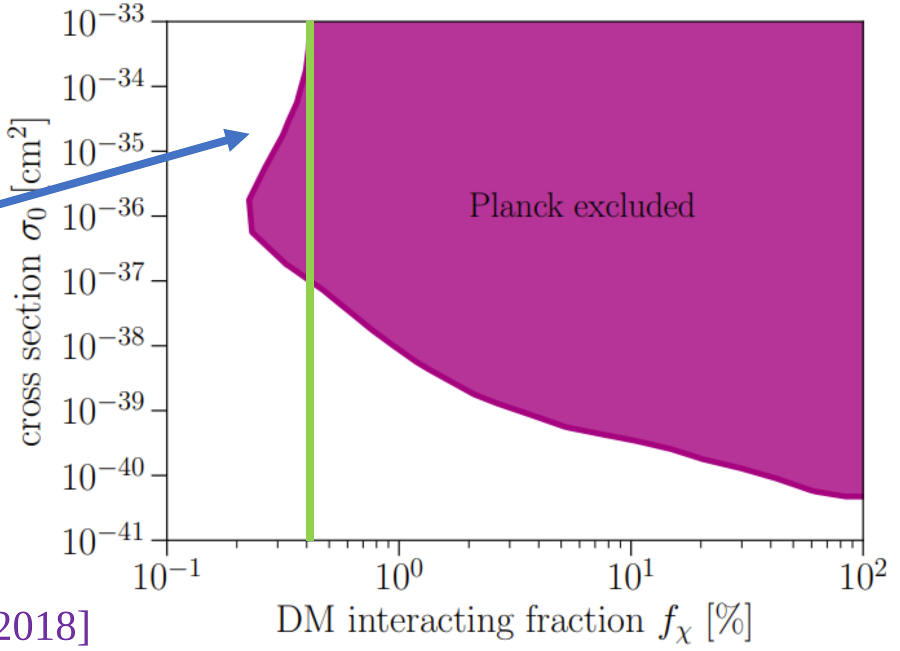
- CMB anisotropy constraints imply $f_m \equiv \frac{\Omega_{mDM}}{\Omega_{DM}} < 0.4\%$

$\Omega_{mDM} < \Omega_b$ uncertainty

Joint oscillations



[K. K. Boddy et al, 2018]



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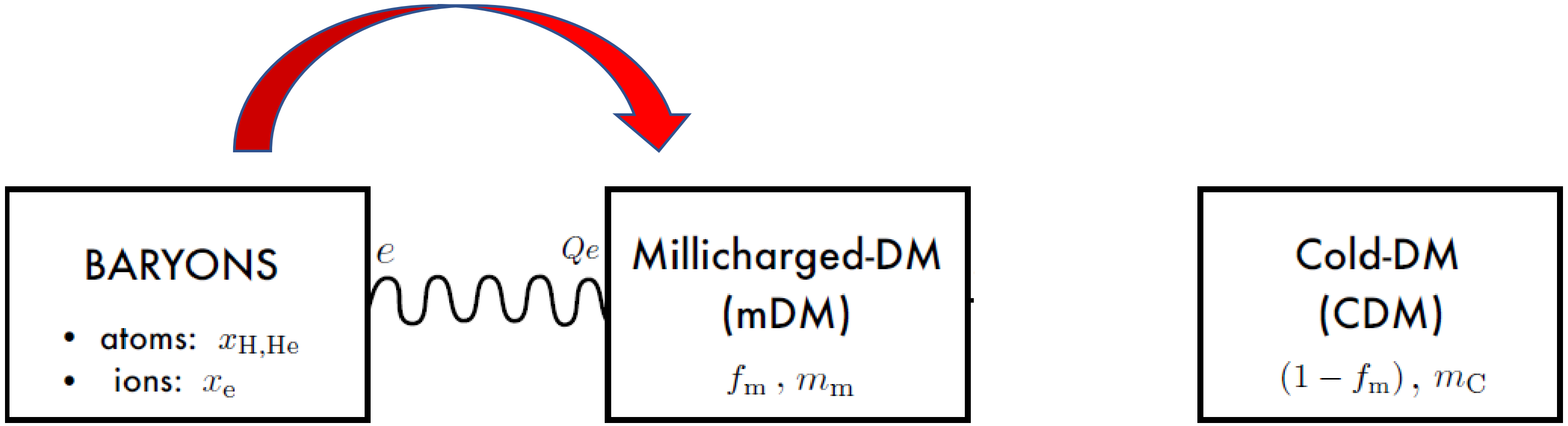

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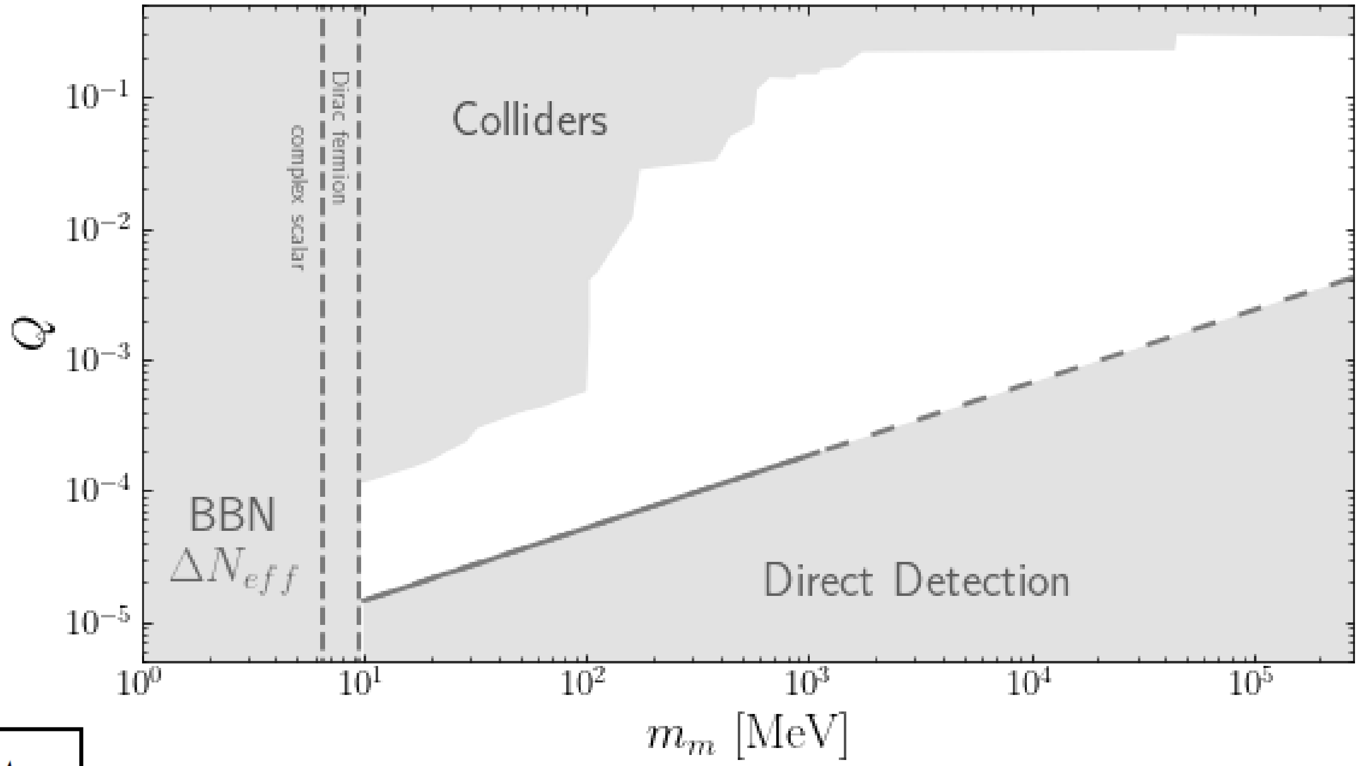

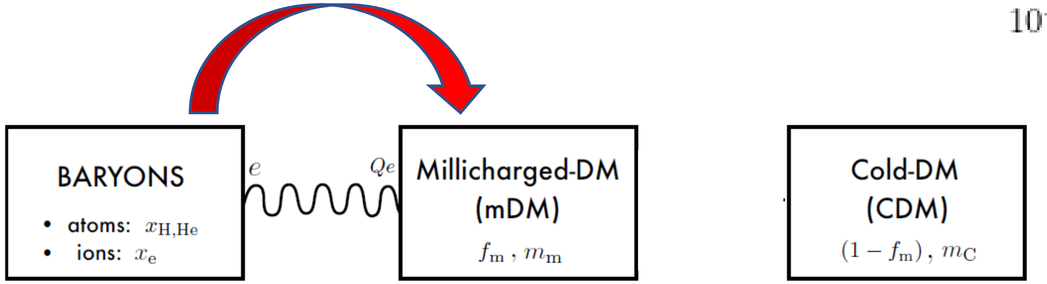

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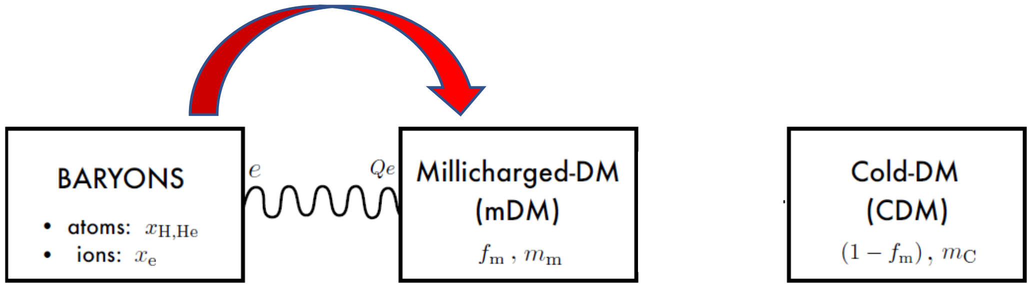
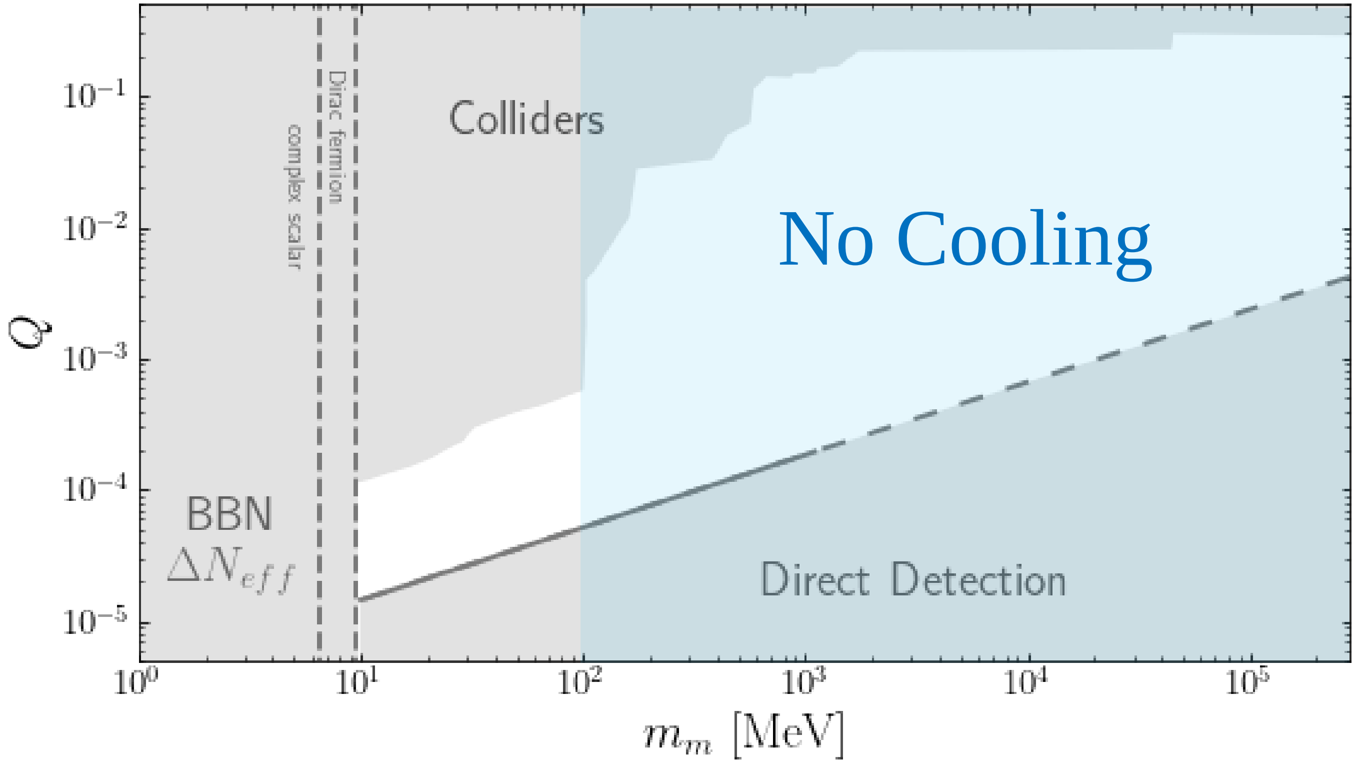
Insufficient heat capacity at large masses





Dark Cooling – Viable Models

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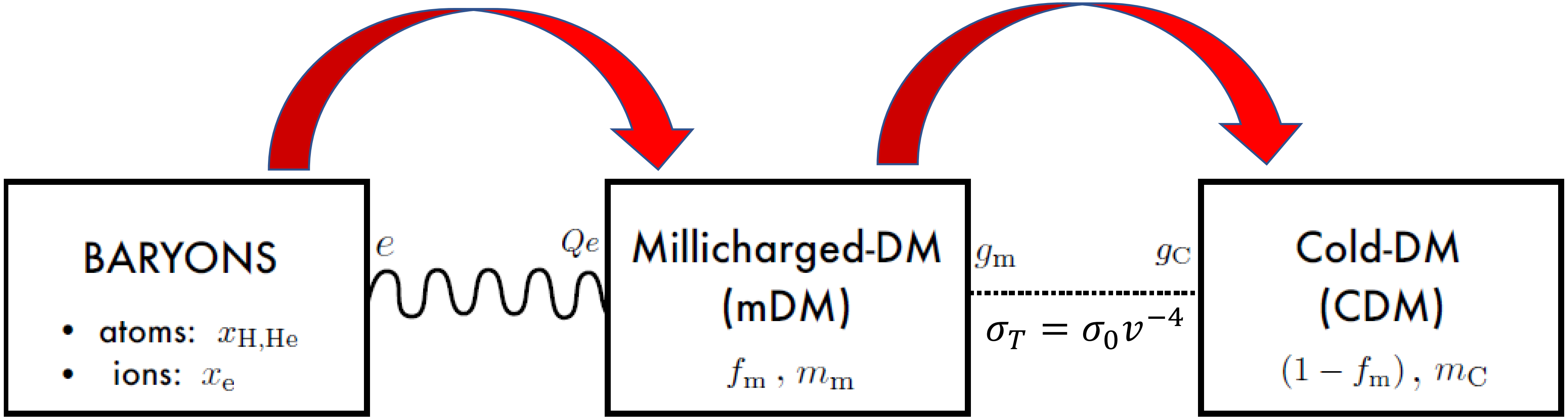
- mDM-CDM interactions effectively increase the heat capacity of mDM

[Liu et al. 2019]



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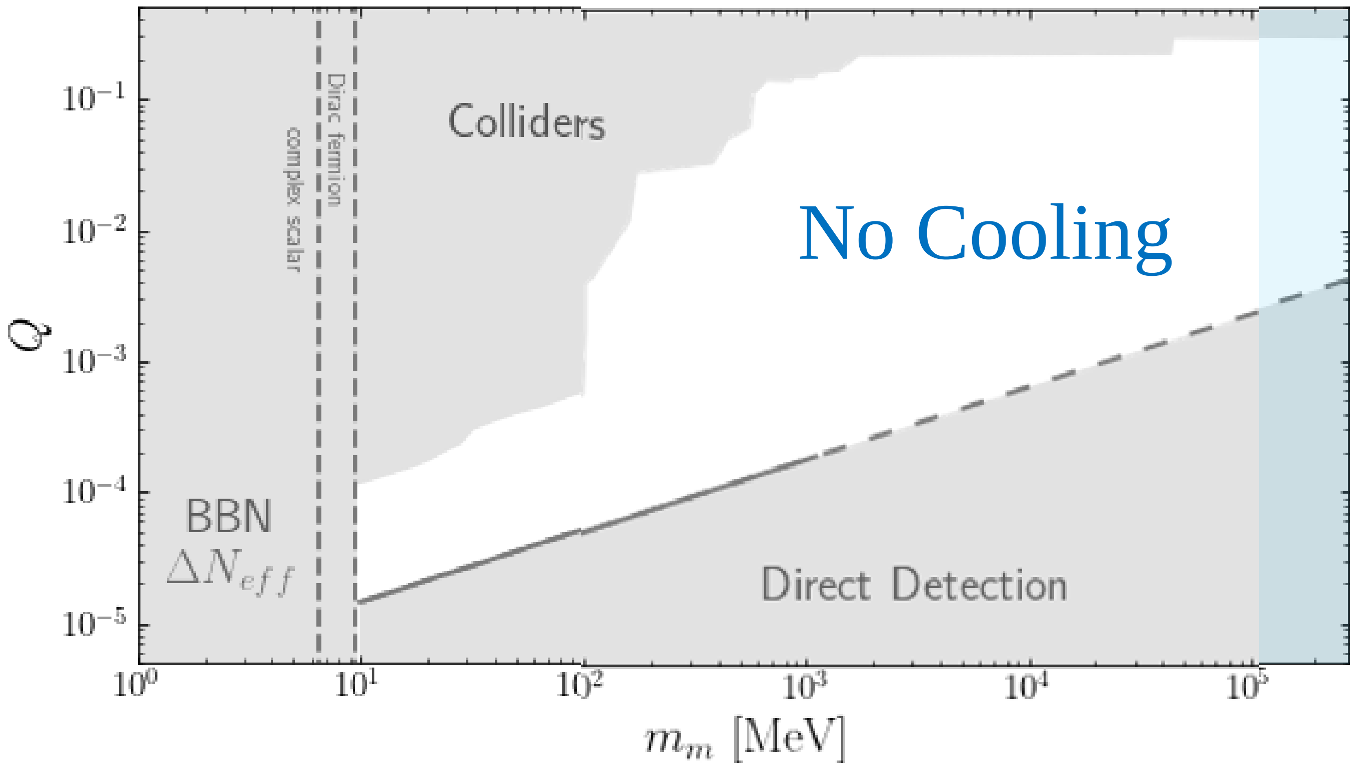

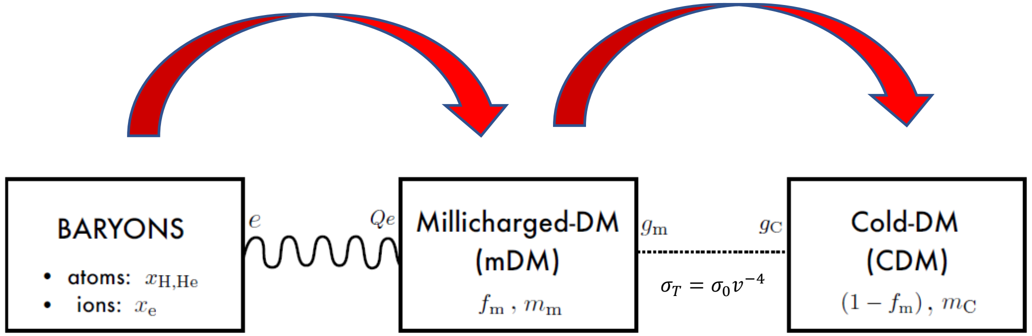

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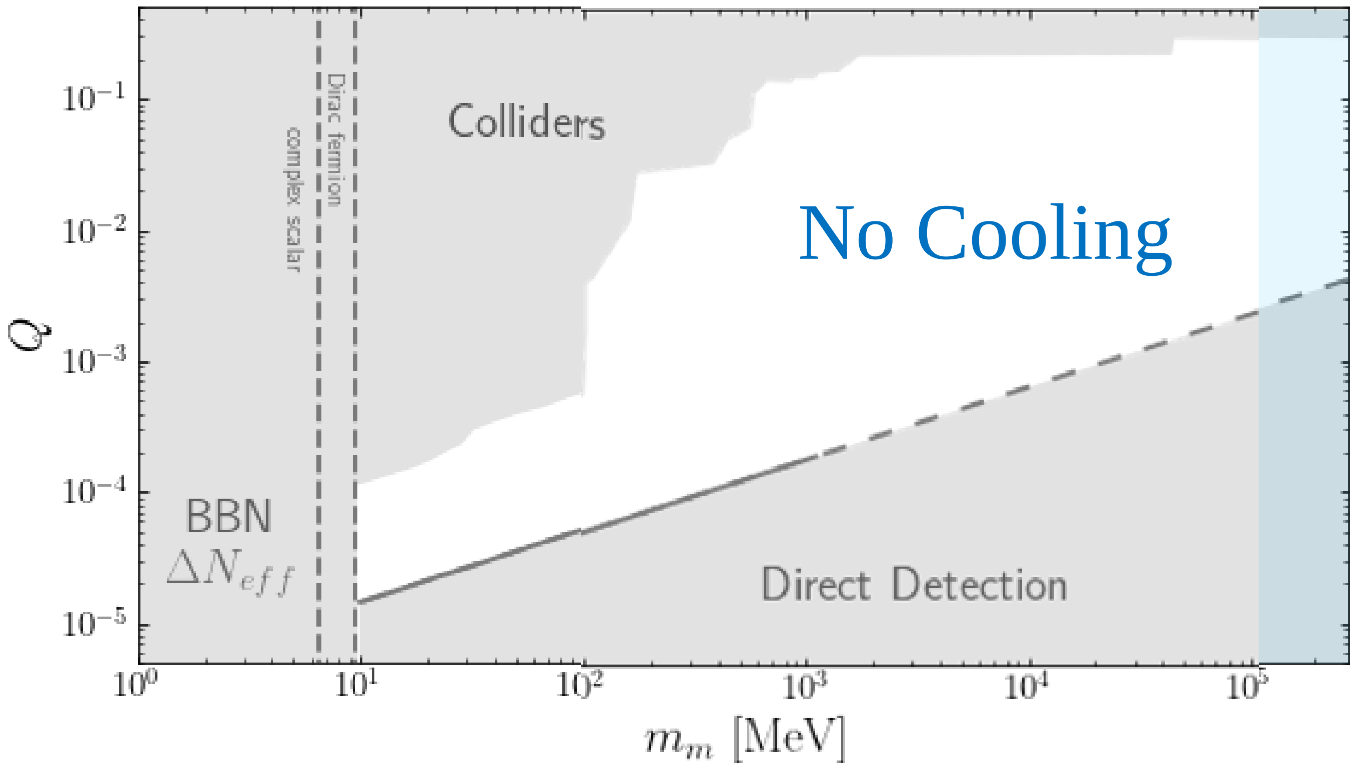
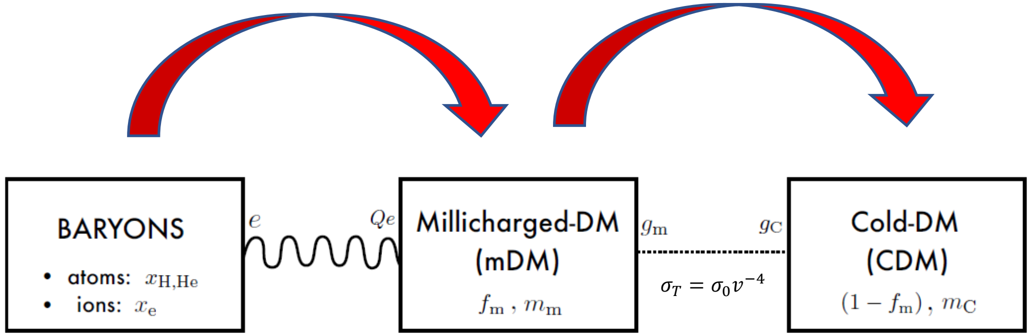


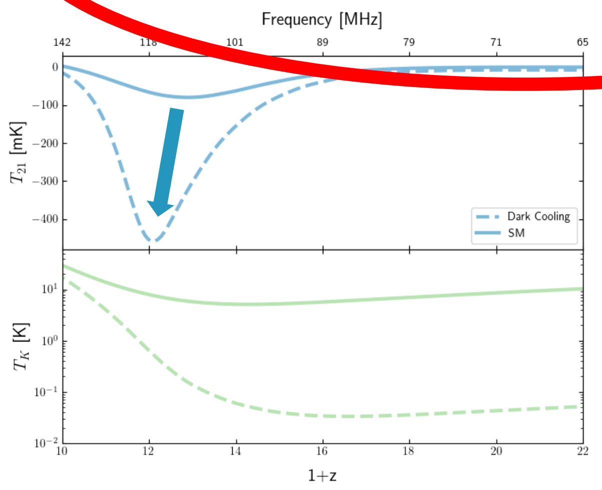


Dark Cooling – Enhanced Absorption

Elastic DM-SM interactions cool the baryonic gas

[Tashiro et al. 2018]

Enhanced absorption at CD
(and dark ages)



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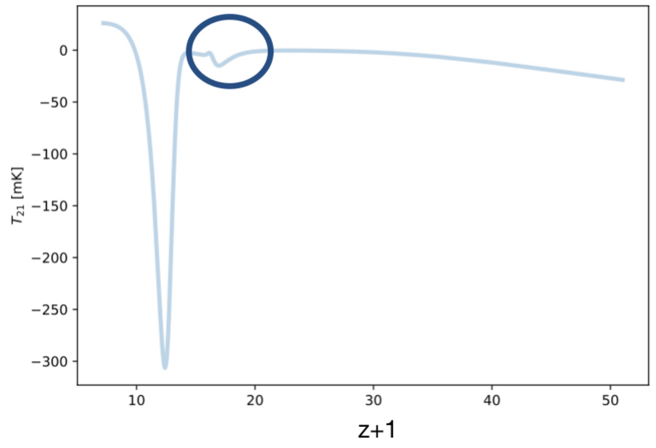


Anomalous absorption signal

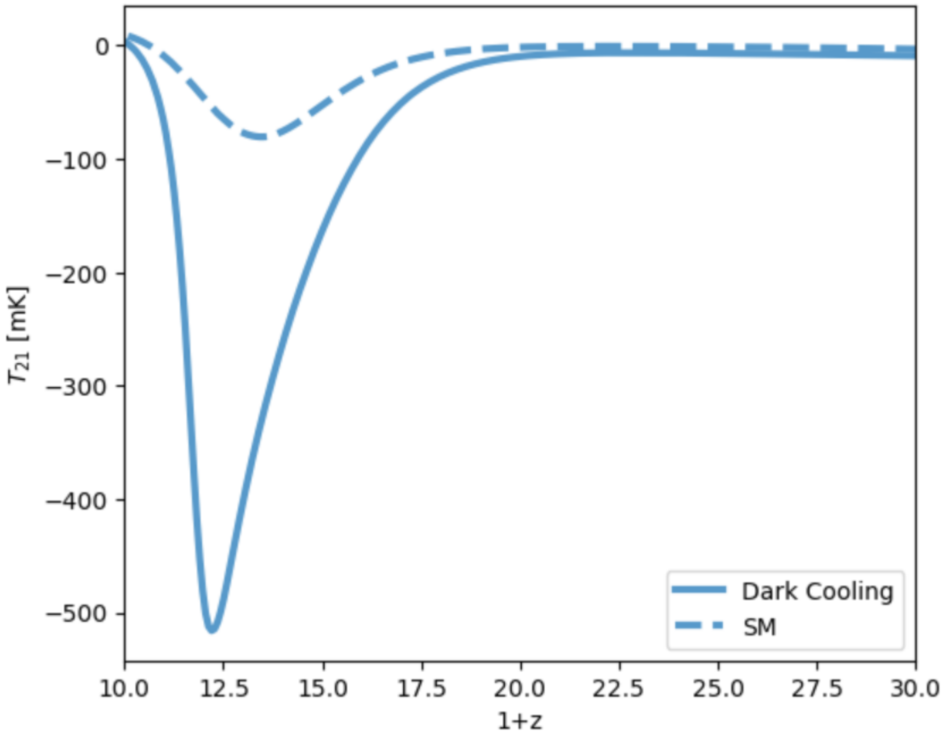
Probe DM-SM interactions

Dark Cooling in 21-cm Cosmology

How deep is the dark cooling signal?

Dark Cooling in 21-cm Cosmology

Assume astrophysical model by
Park et al. 2019



Dark Cooling in 21-cm Cosmology

Assume astrophysical model by
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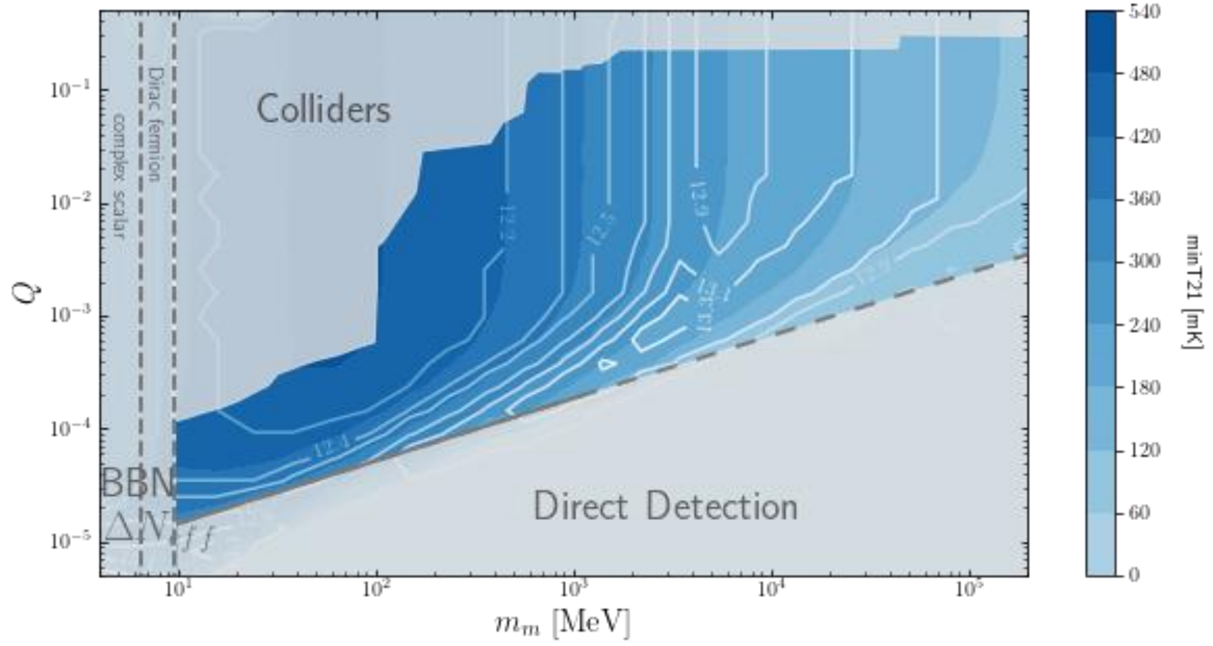
(Maximal mDM-CDM interactions)



$$\min\{T_{21}^{SM}\} = -80mK$$

Dark Cooling in 21-cm Cosmology

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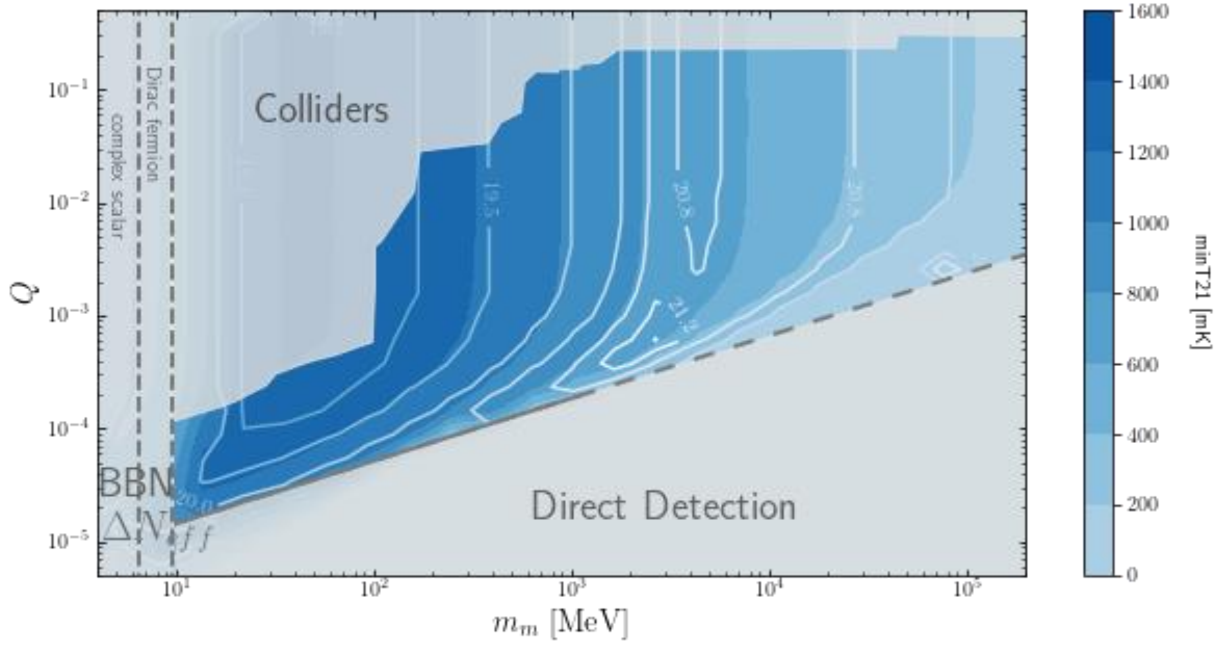

$$\min\{T_{21}^{SM}\} = -120mK$$

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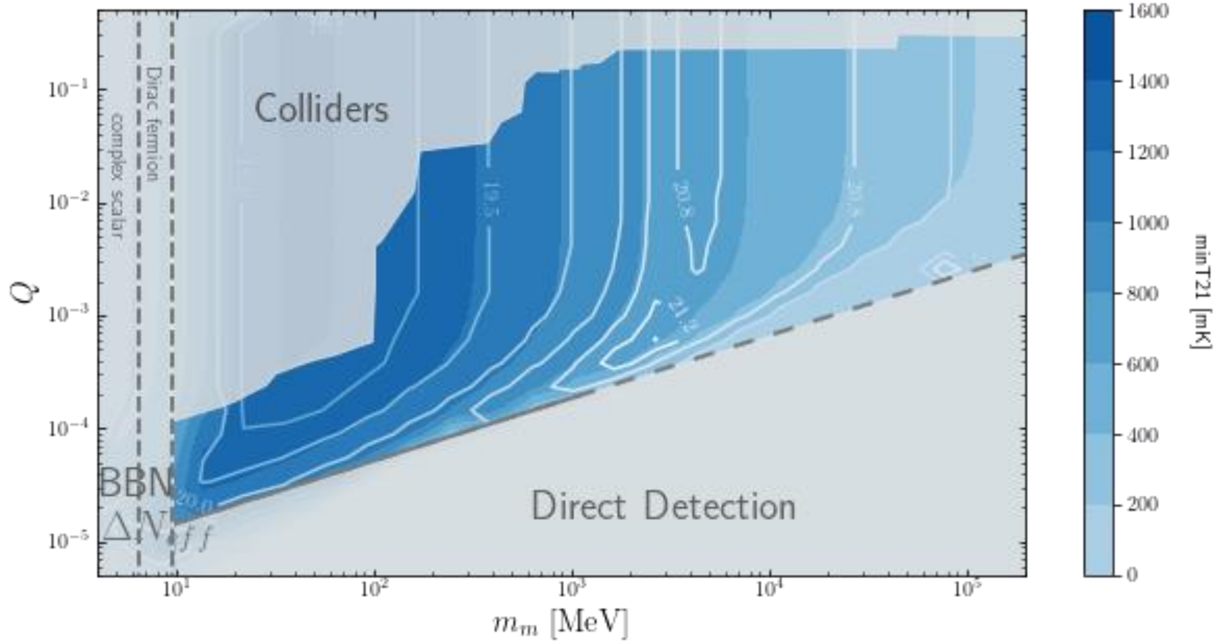

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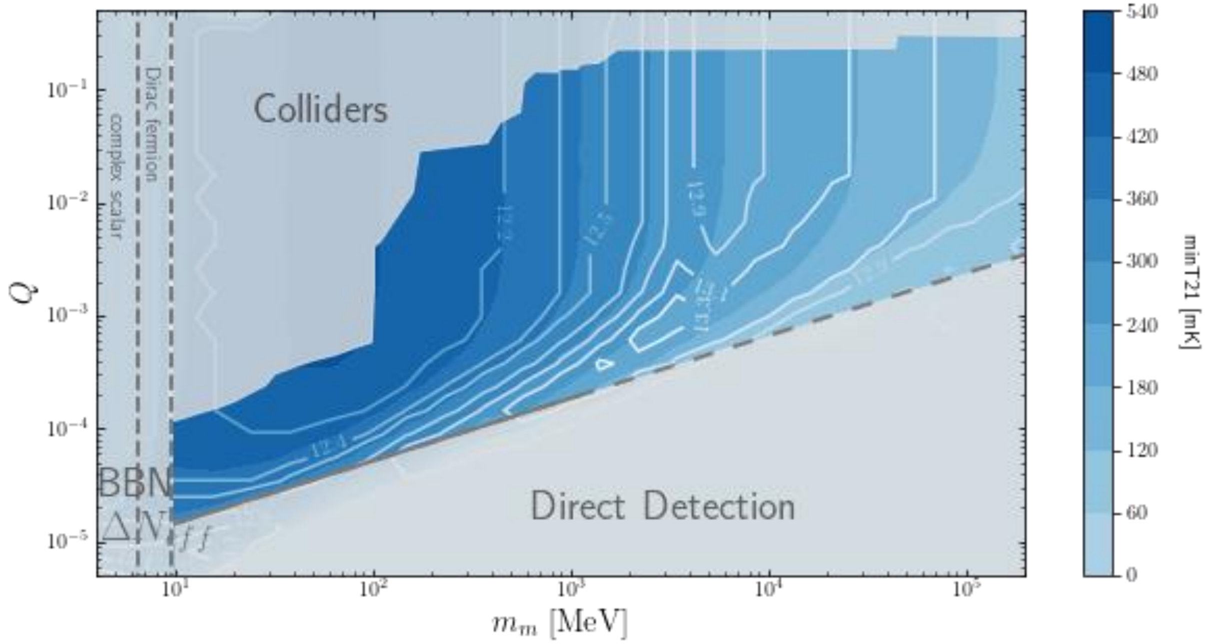

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Cooling vs Astrophysics

Astrophysical heating sources counter cooling

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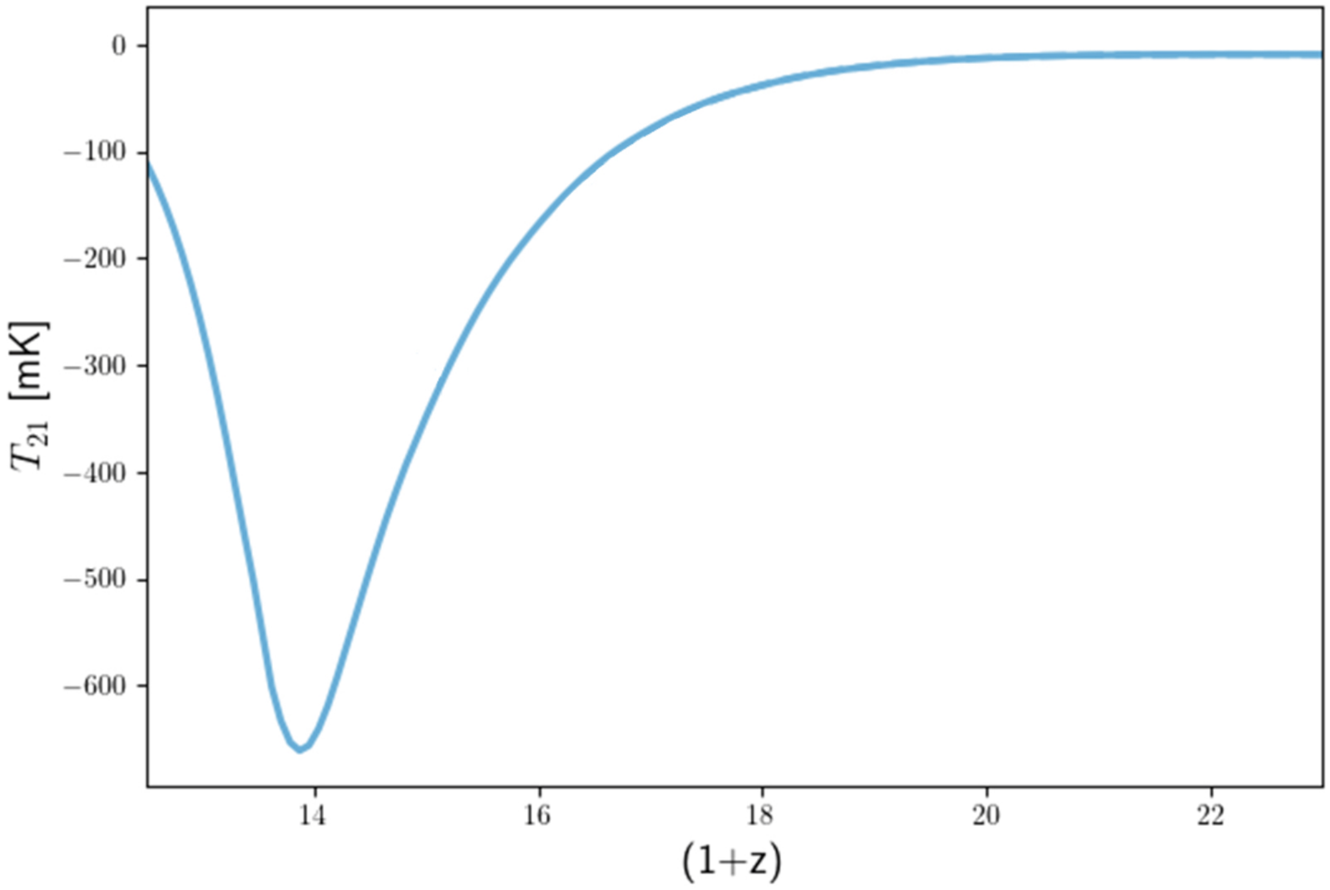

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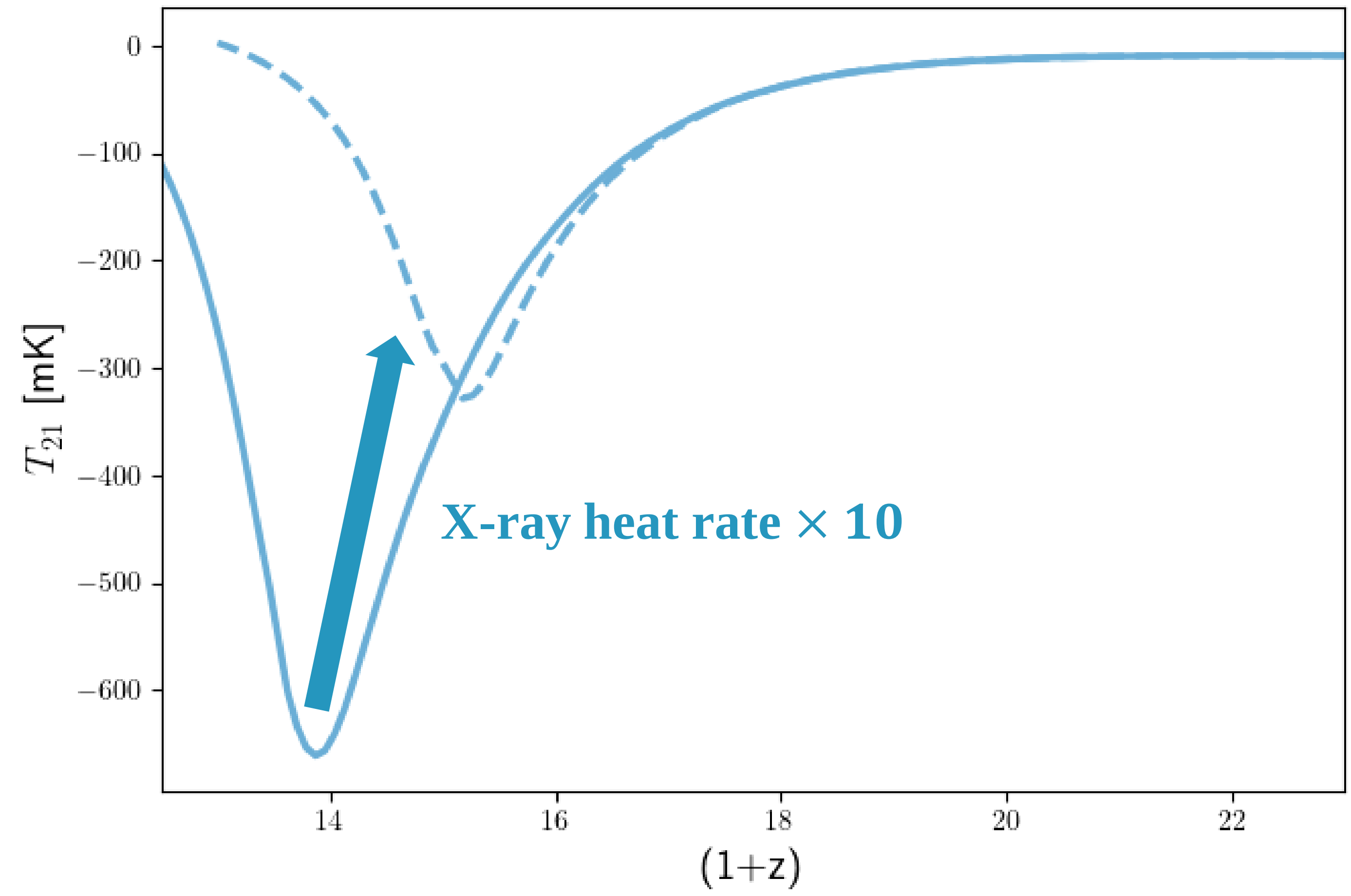
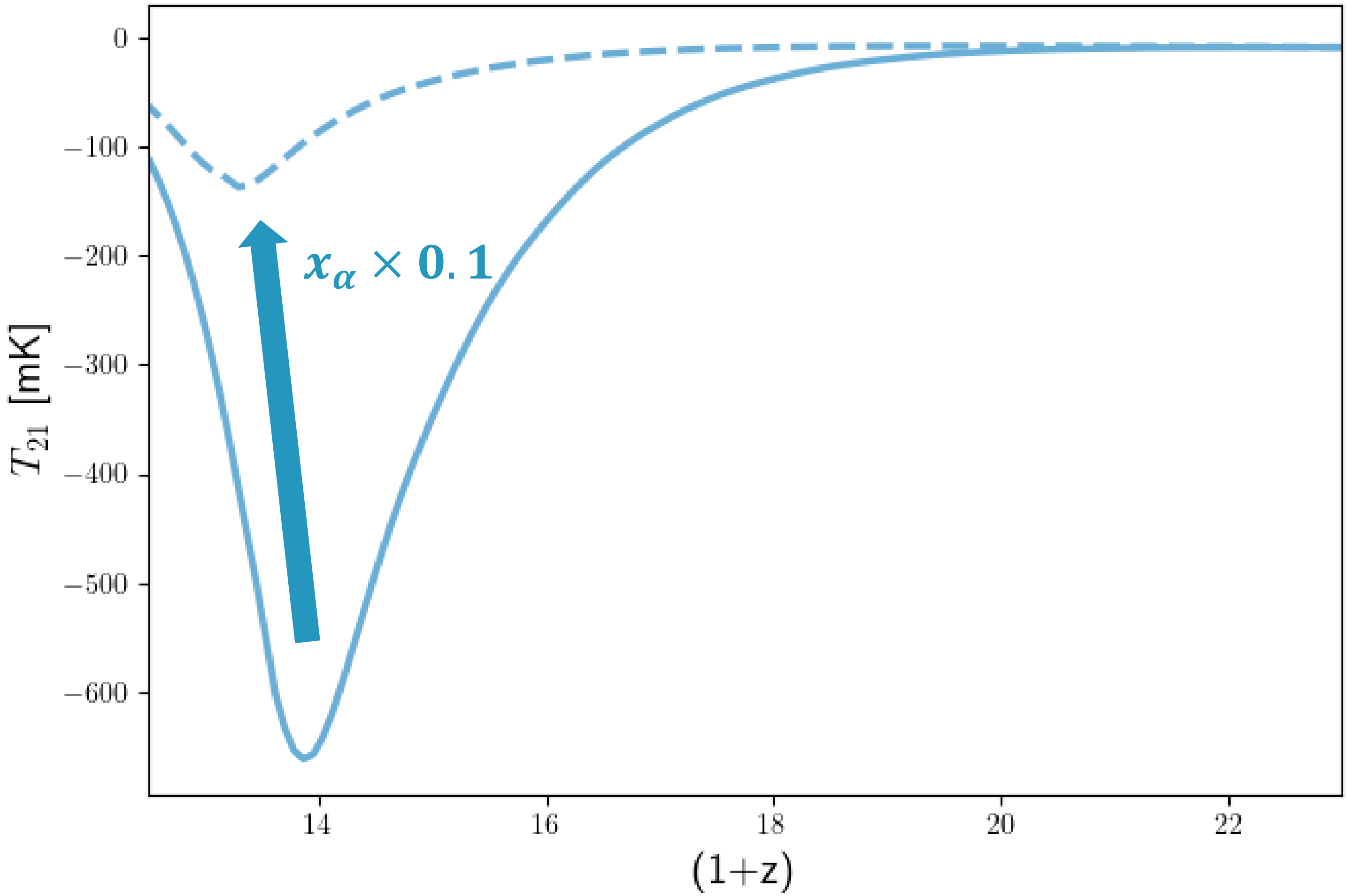


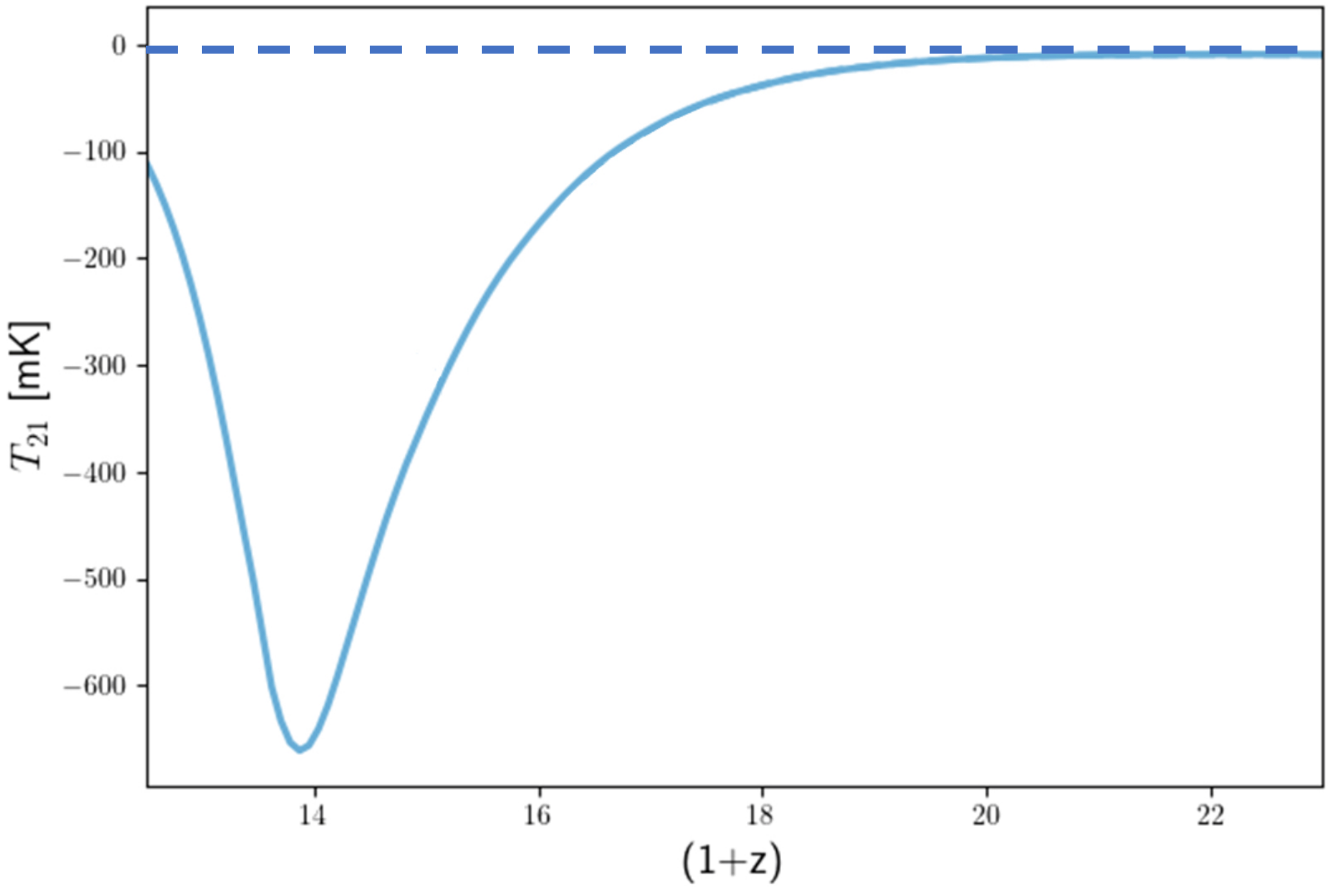
Cooling vs Astrophysics

$Ly\alpha$ photons couple $T_s \rightarrow T_C^{eff} \rightarrow T_K$



Cooling vs Astrophysics

Reionization - Without HI there is no 21-cm signal



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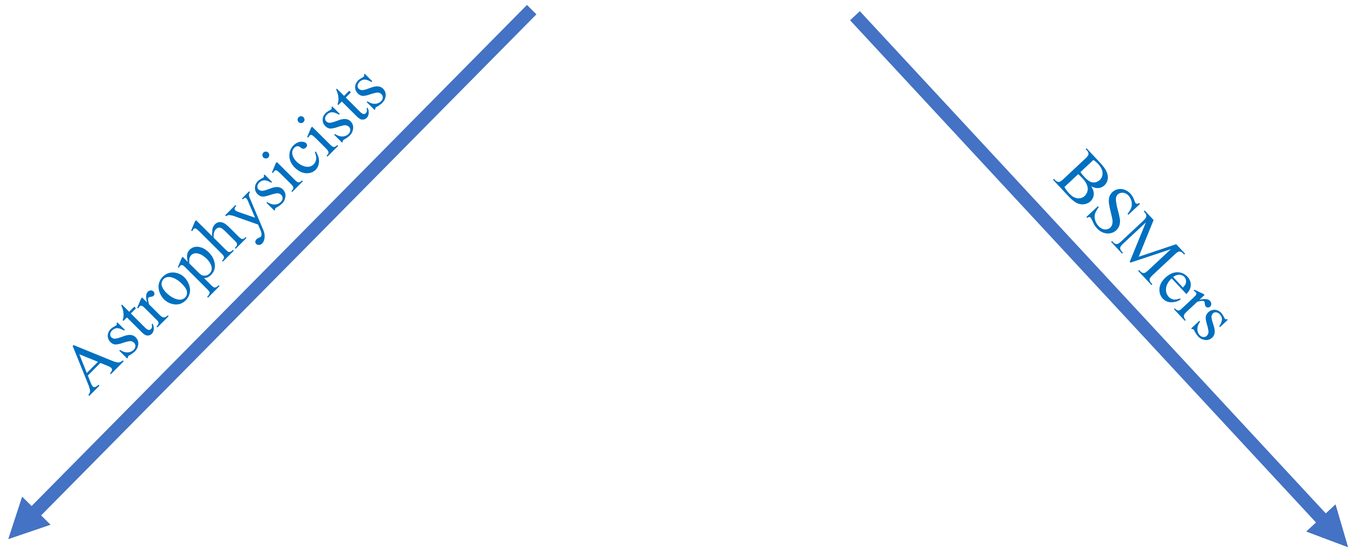

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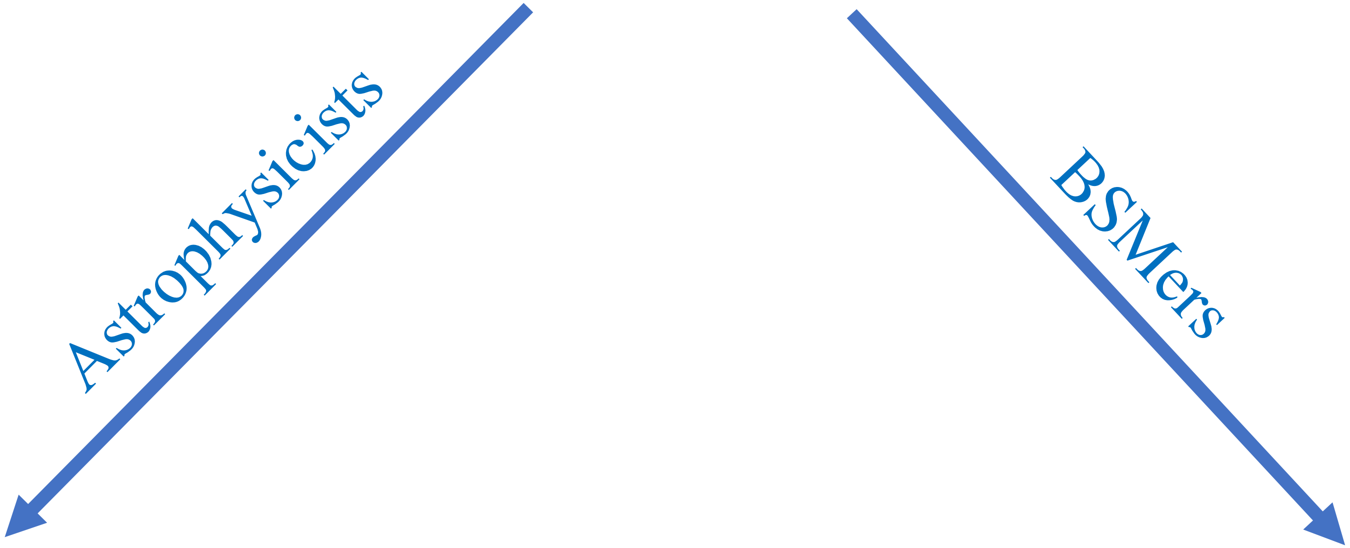

Use the signal to study astrophysics

Cooling vs Astrophysics

21-cm signal

Astrophysicists

BSMers

Use the signal to study astrophysics

Limit astrophysics with other probes and study DM with 21-cm

Cooling vs Astrophysics

The countering effects are subject to constraints

- Reionization

Electron scattering optical depth of CMB $\tau_e = 0.054 \pm 0.0070$ at 68% C.L.

[Planck 2018]

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The dark fraction of pixels in QSO spectra $x_{HI} \leq 0.06 + 0.05(1\sigma)$ by z=5.9

[McGreeer et al. 2015]

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- X-rays

Unresolved cosmic X-ray background $I_X \leq 2.51 \times 10^{-13} erg cm^{-2} s^{-1} \deg^{-2}$

[Fialkov et al. 2016, Cappelluti 2012, Lehmer et al. 2012]

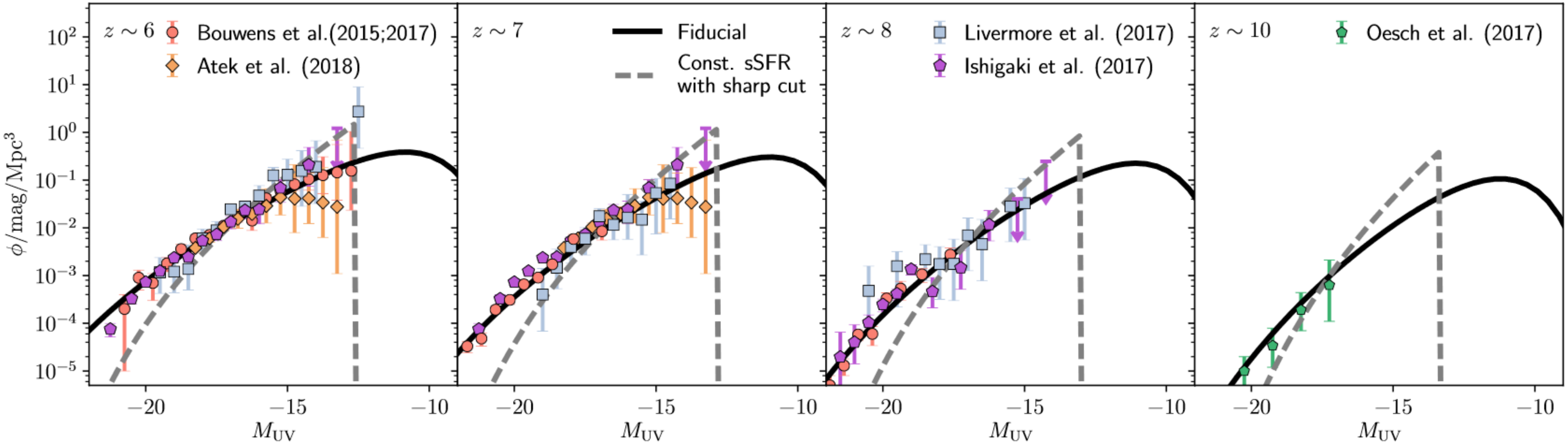
Cooling vs Astrophysics

The countering effects are subject to constraints

- Star formation

UV luminosity functions

[Park et al. 2018]



Astrophysics Modeling

Counter Cooling: Inefficient Lyα

Lyman band emission from astrophysical sources

Counter Cooling: Inefficient Lyα

Lyman band emission from astrophysical sources

- Assume Lyman band emission is dominated by popII (popIII) stars [Wyithe & Loeb 2004]

$$\epsilon = \frac{\dot{\rho}_\star}{\bar{m}_b} \left\langle \frac{dN_\star}{dE} \right\rangle$$

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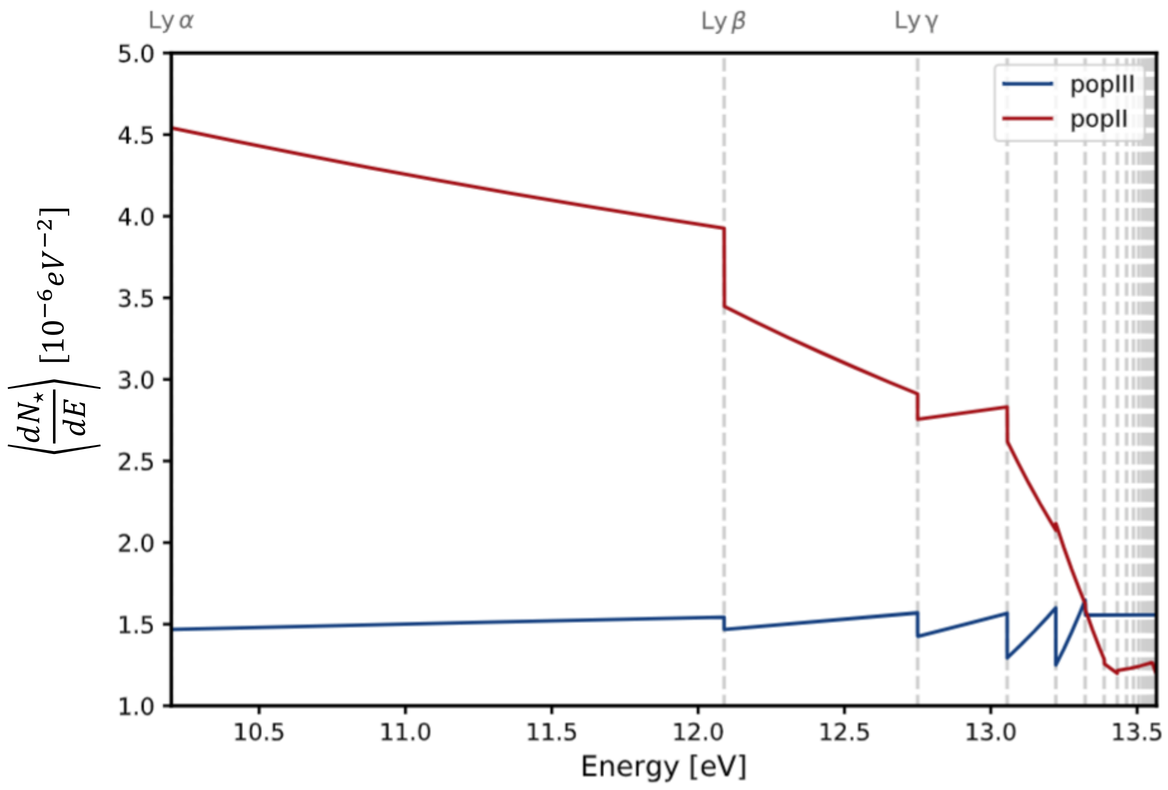
[Barkana & Loeb 2004, Leitherer et al. 1999, Bromm & Larson 2004]



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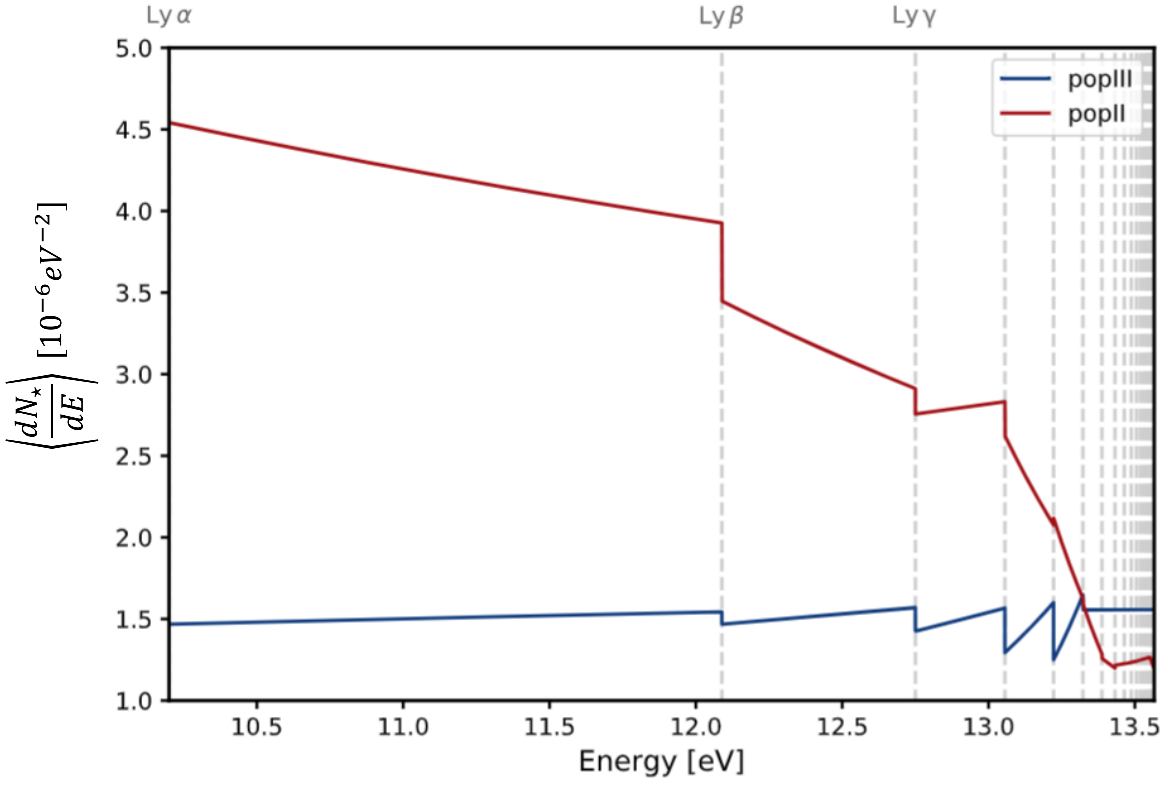
- Lyman band photons are emitted by the same source as ionizing photons



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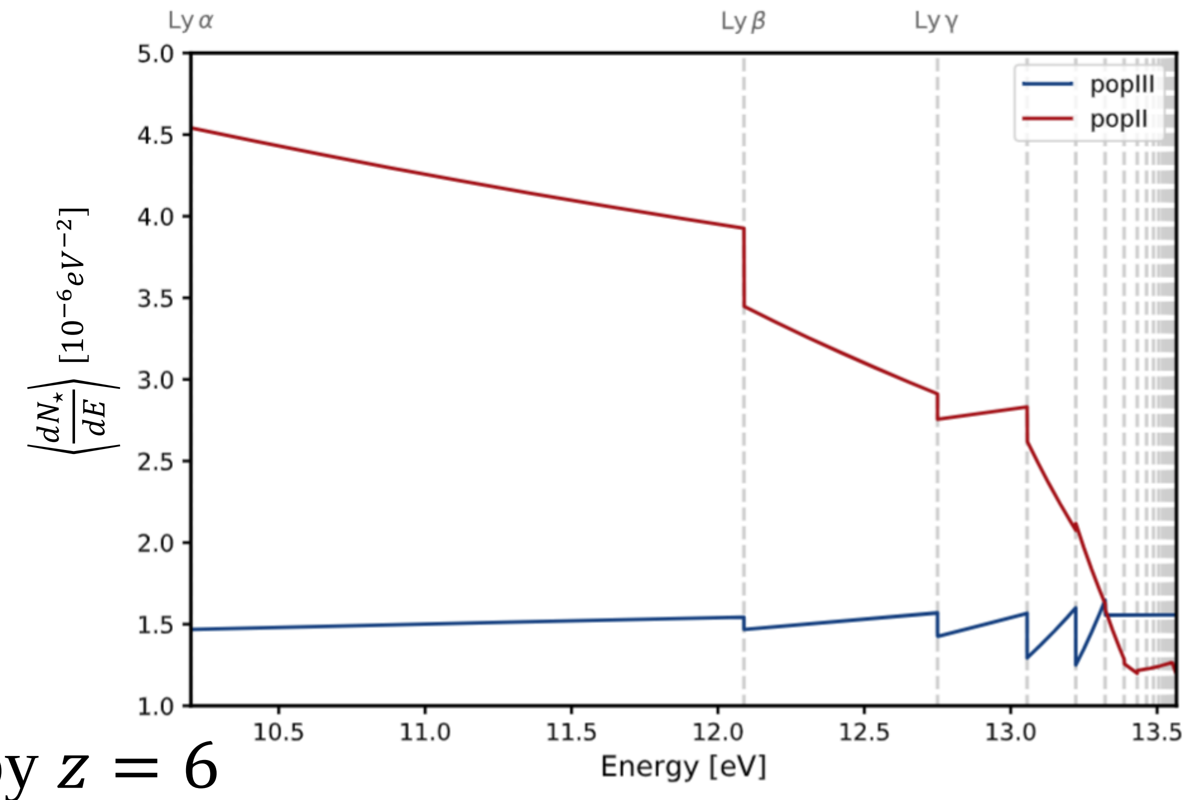


- Lyman band photons are emitted by the same source as ionizing photons

- Weak Lyman band emission due to small $\left\langle\frac{dN_\star}{dE}\right\rangle$ is inconsistent with reionization by $z = 6$

Counter Cooling: Inefficient Lyα

$$\epsilon = \frac{\dot{\rho}_\star}{\overline{m}_b}\left\langle\frac{dN_\star}{dE}\right\rangle$$

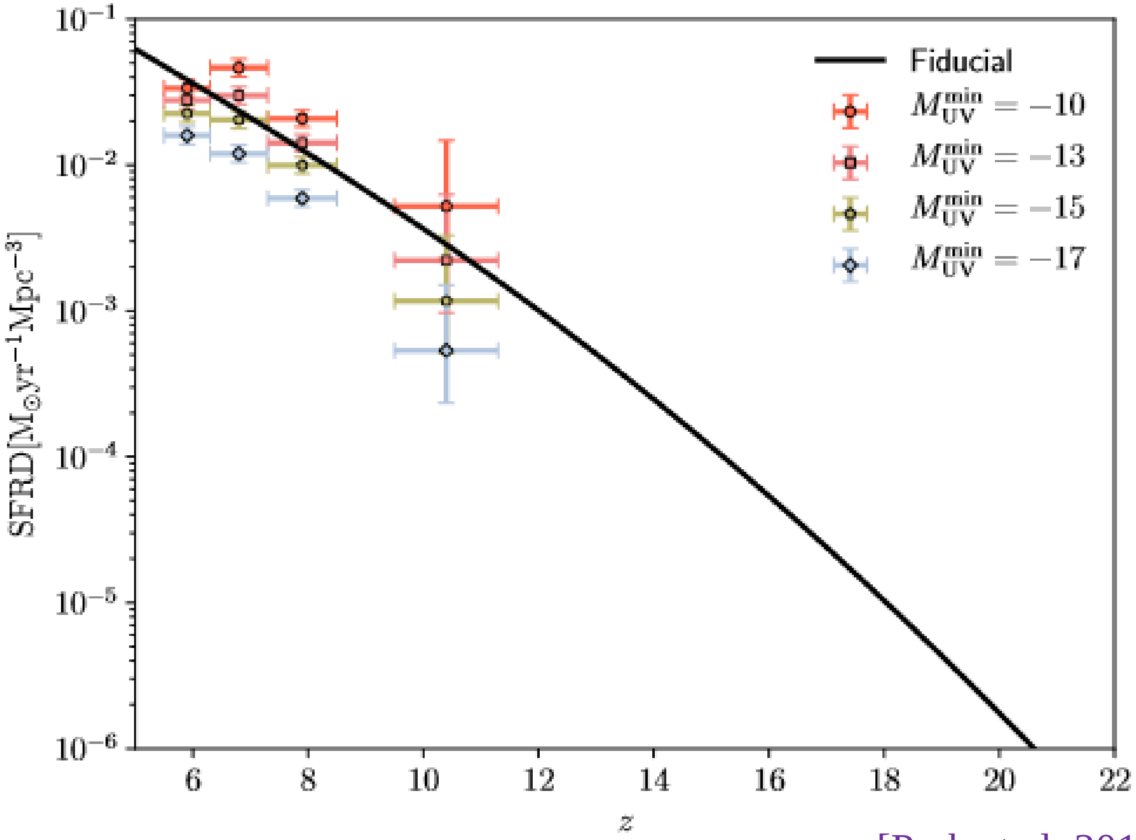
- Weak Lyman band emission due to suppressed star formation is inconsistent with measurements of UVLFs

- Model star formation efficiency

$$f_\star = F_\star\left(\frac{M_h}{M_\odot}\right)^{\alpha_\star} e^{-M_{cut}/M_h}$$

[Sun et al. 2016]

$$SFR \propto L_{UV,1500}$$



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Counter Cooling: Inefficient Lyα

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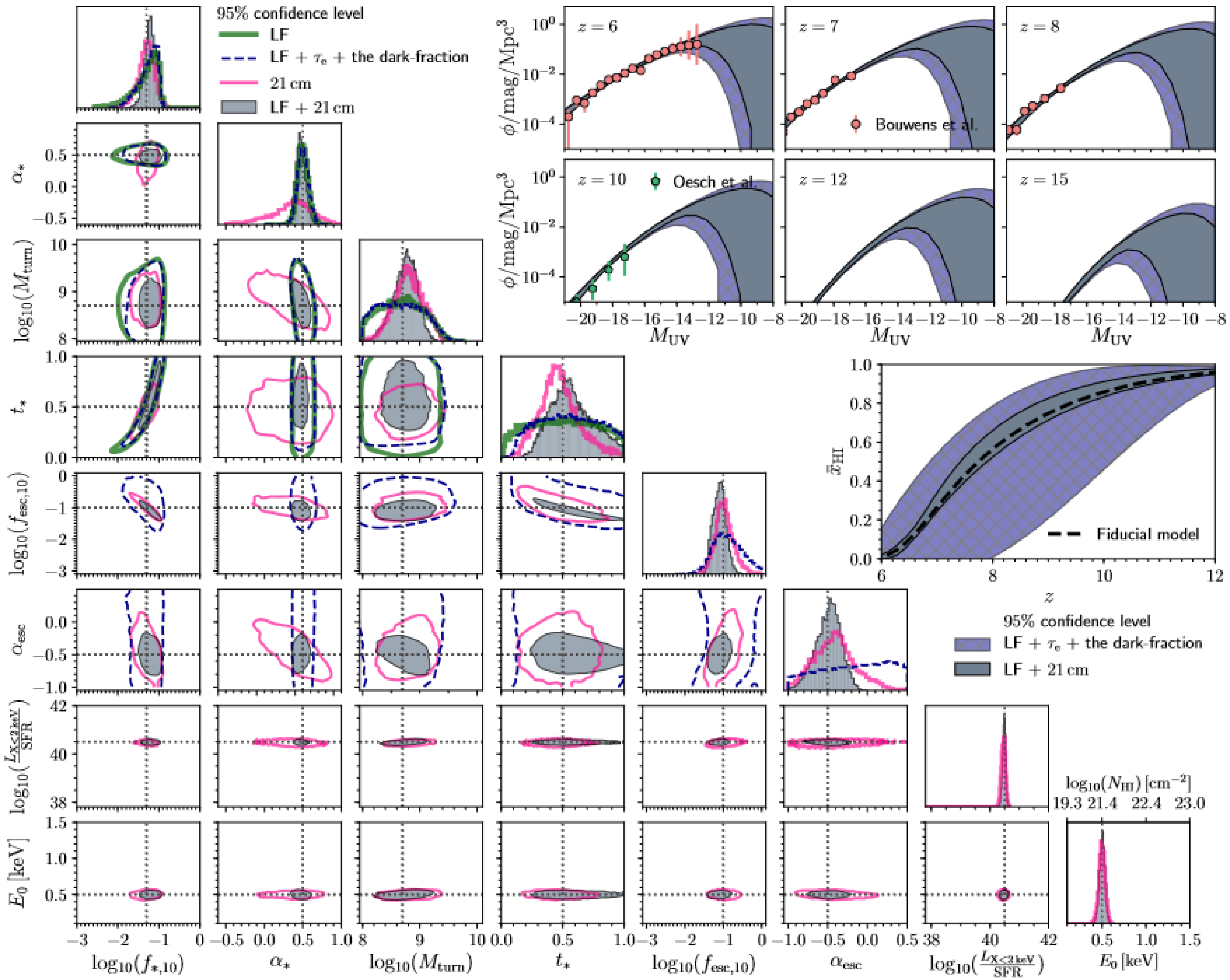
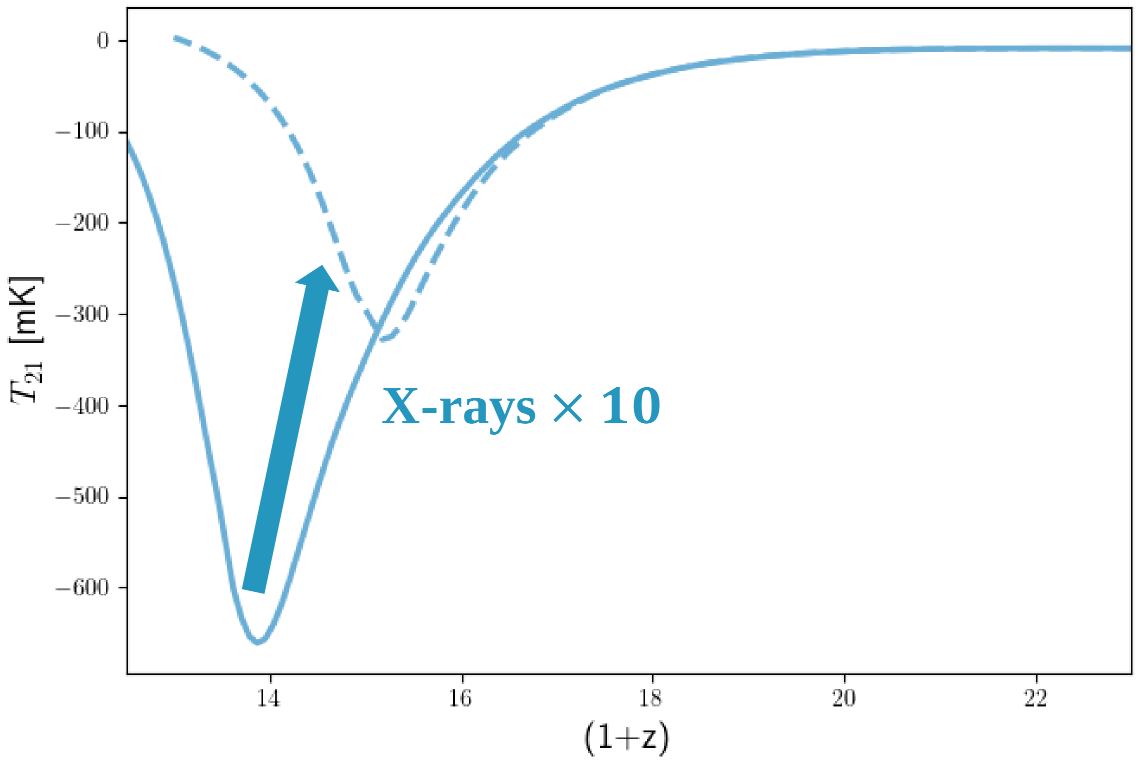


Counter Cooling : Heating

$$\frac{dT_K}{dlog(a)} = -2T_K + \frac{1}{H}\left(\dot{Q}_{Dark\ Cooling} + \dot{Q}_{Comp} + \dot{Q}_{Xrays} + \dot{Q}_{CMB} + \dot{Q}_{Ly\alpha}\right)$$



Typically subdominant to X-rays

[Meiksin 2021, Venumadhav et al. 2018, Chen & Miralda 2003]

Counter Cooling : Heating

- Soft band (<2KeV) X-ray emissivity (HMXBs + attenuation in neutral ISM)

[Fragos et al. 2013, Das et al. 2017]

$$\epsilon_X = \frac{\dot{\rho}_\star}{\overline{m}_b}\left(\frac{E}{E_0}\right)^{-\alpha_X} \Theta(E - E_{min})$$

$$\alpha_X = 1$$

Counter Cooling : Heating

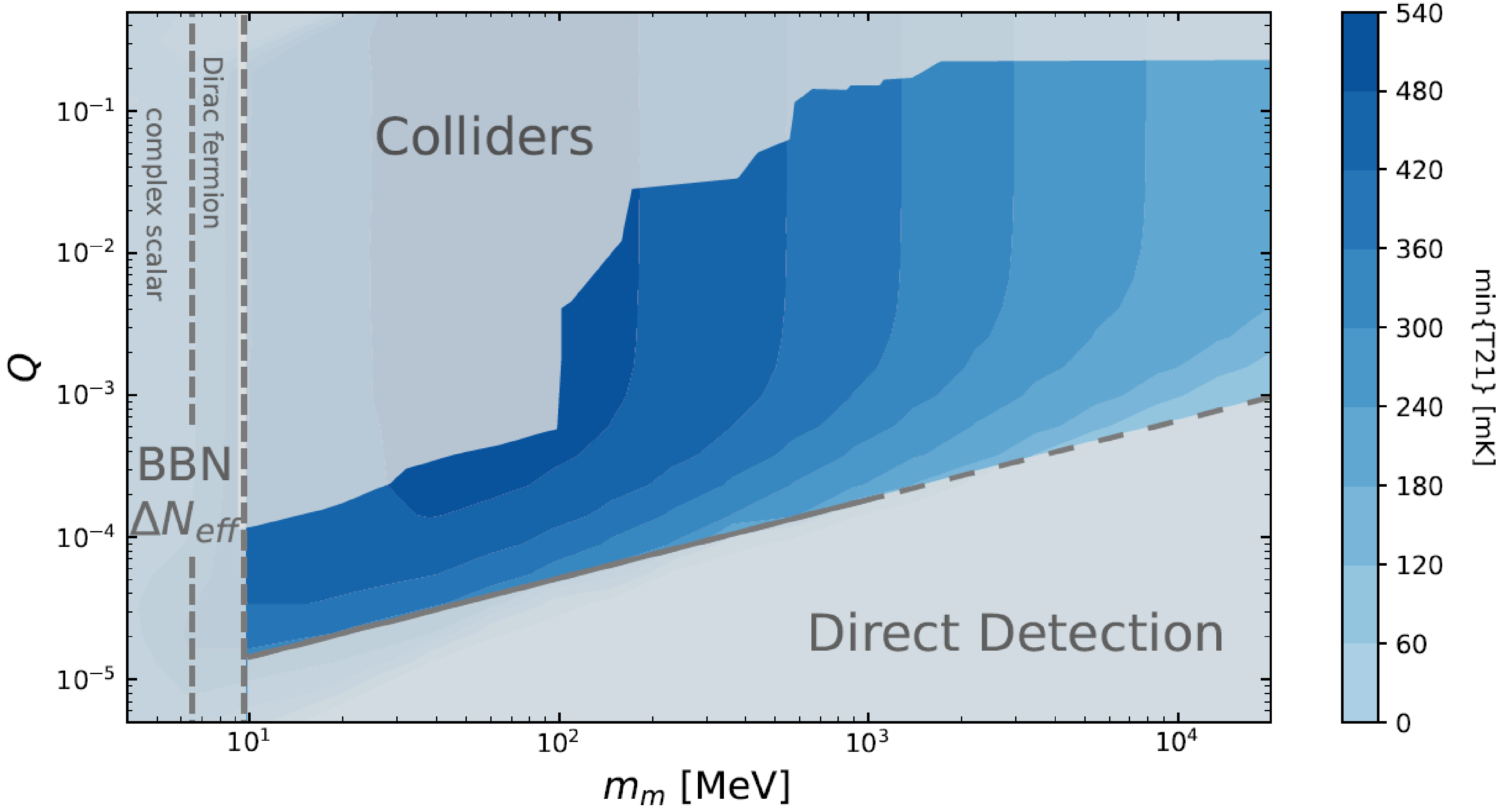
- Soft band (<2KeV) X-ray emissivity is dominated by HMXBs

$$\epsilon_X = \frac{\dot{\rho}_\star}{\overline{m}_b}\left(\frac{E}{E_0}\right)^{-\alpha_X} \Theta(E - E_{min}) \qquad \alpha_X = 1$$

- Upper limit on ϵ_X from unresolved X-ray background

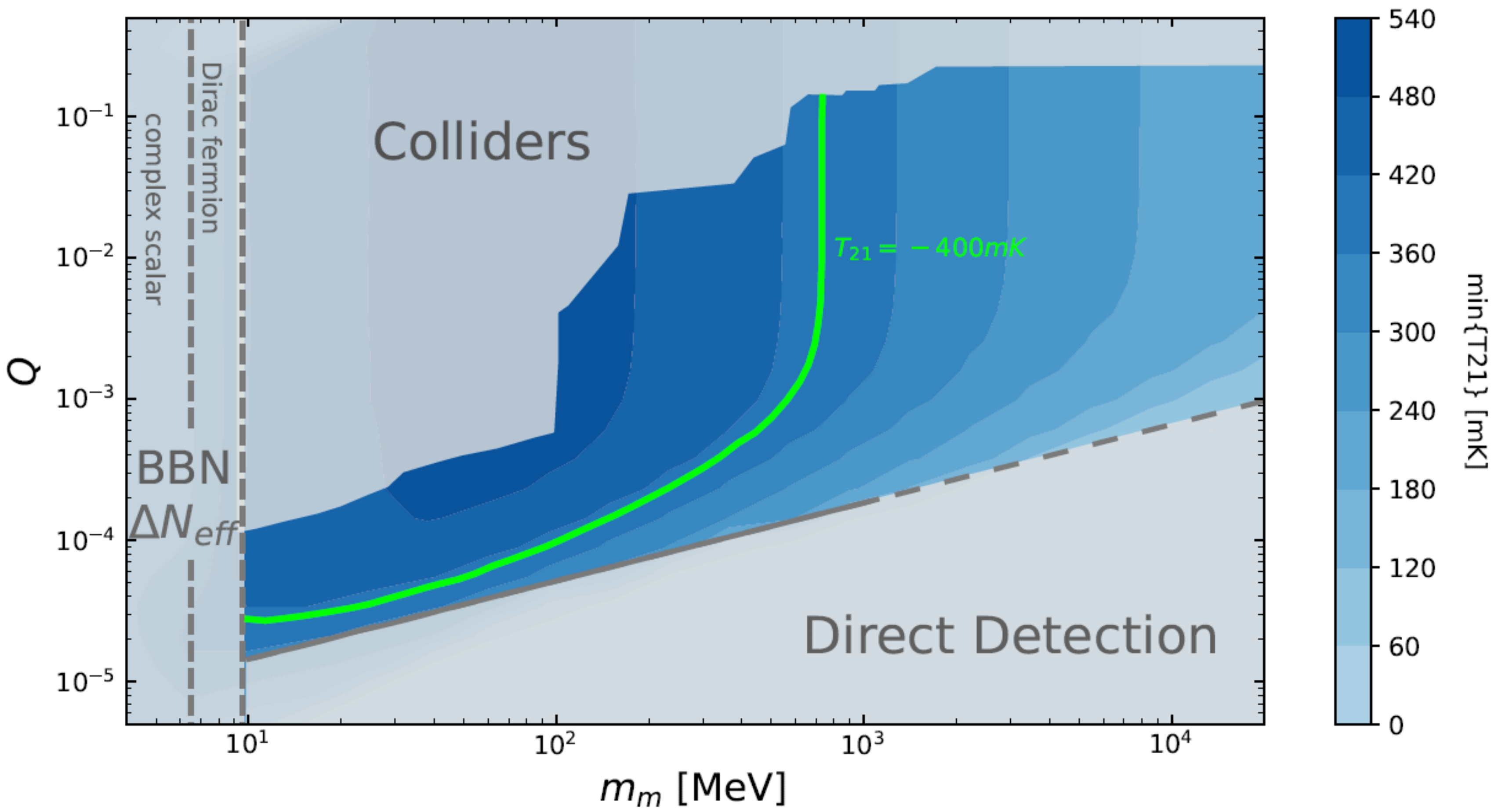
(Does not account for softer additional populations)

Dark Cooling: Enhanced Absorption



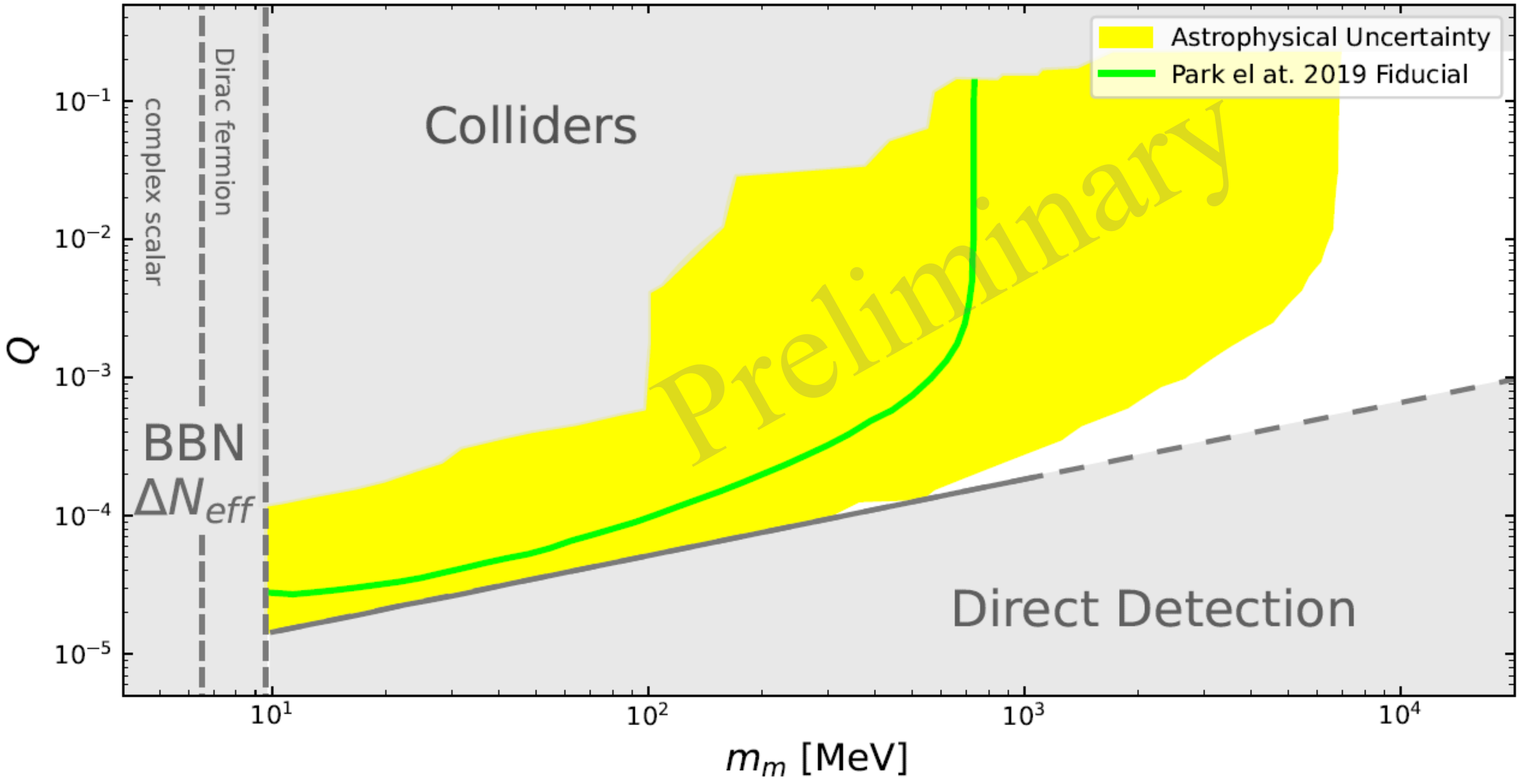
Dark Cooling: Enhanced Absorption

- Assume $-400mK$ sensitivity (~twice the SARAS3 RMS)



Dark Cooling: Enhanced Absorption

- Assume $-400mK$ sensitivity (~twice the SARAS3 RMS) [Singh et al. 2021]
- Scan over the astrophysical parameter space



Dark Cooling: Enhanced Absorption

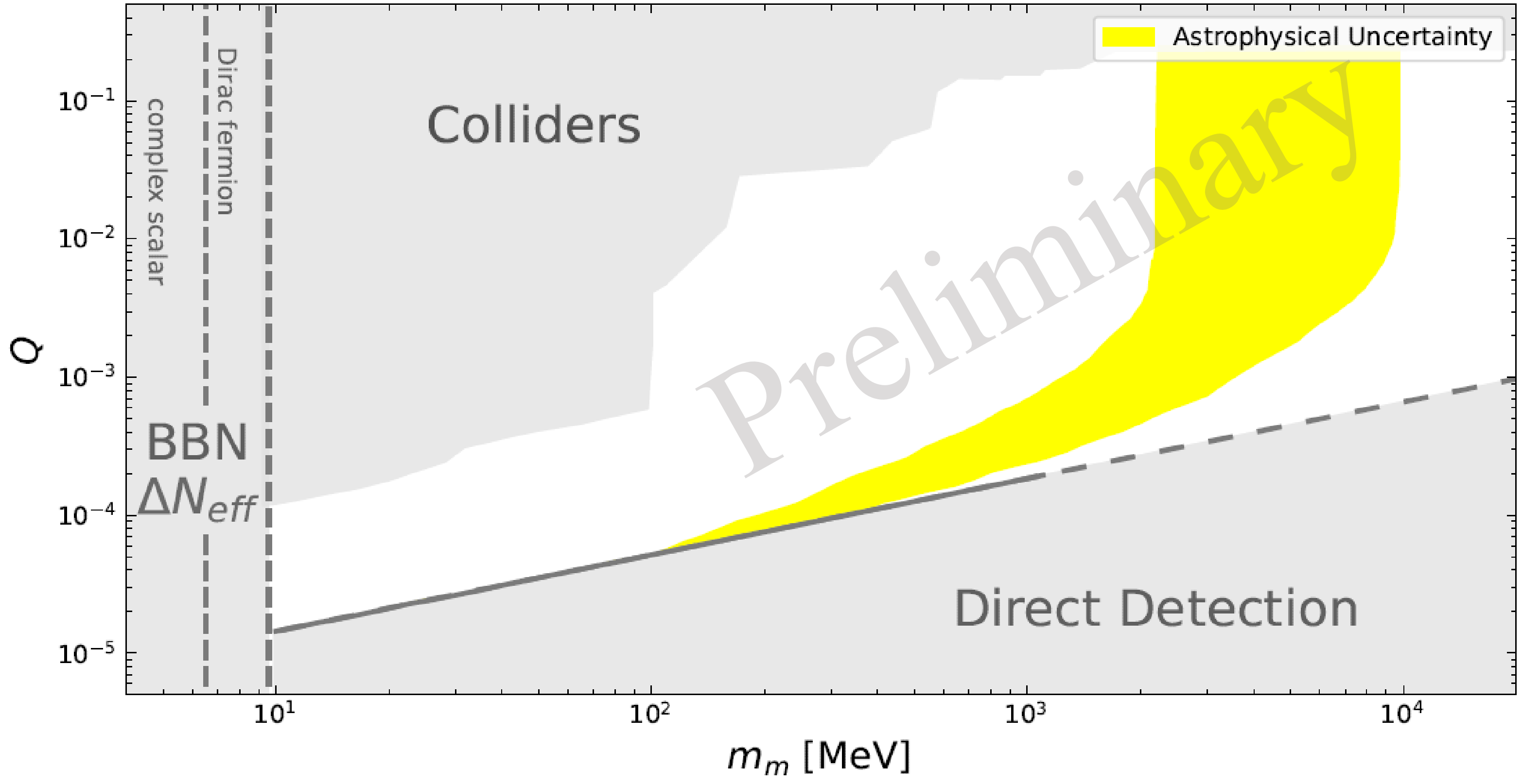
Current astrophysical knowledge is insufficient to robustly probe mDM with the global signal

What about the future?

Dark Cooling: Enhanced Absorption

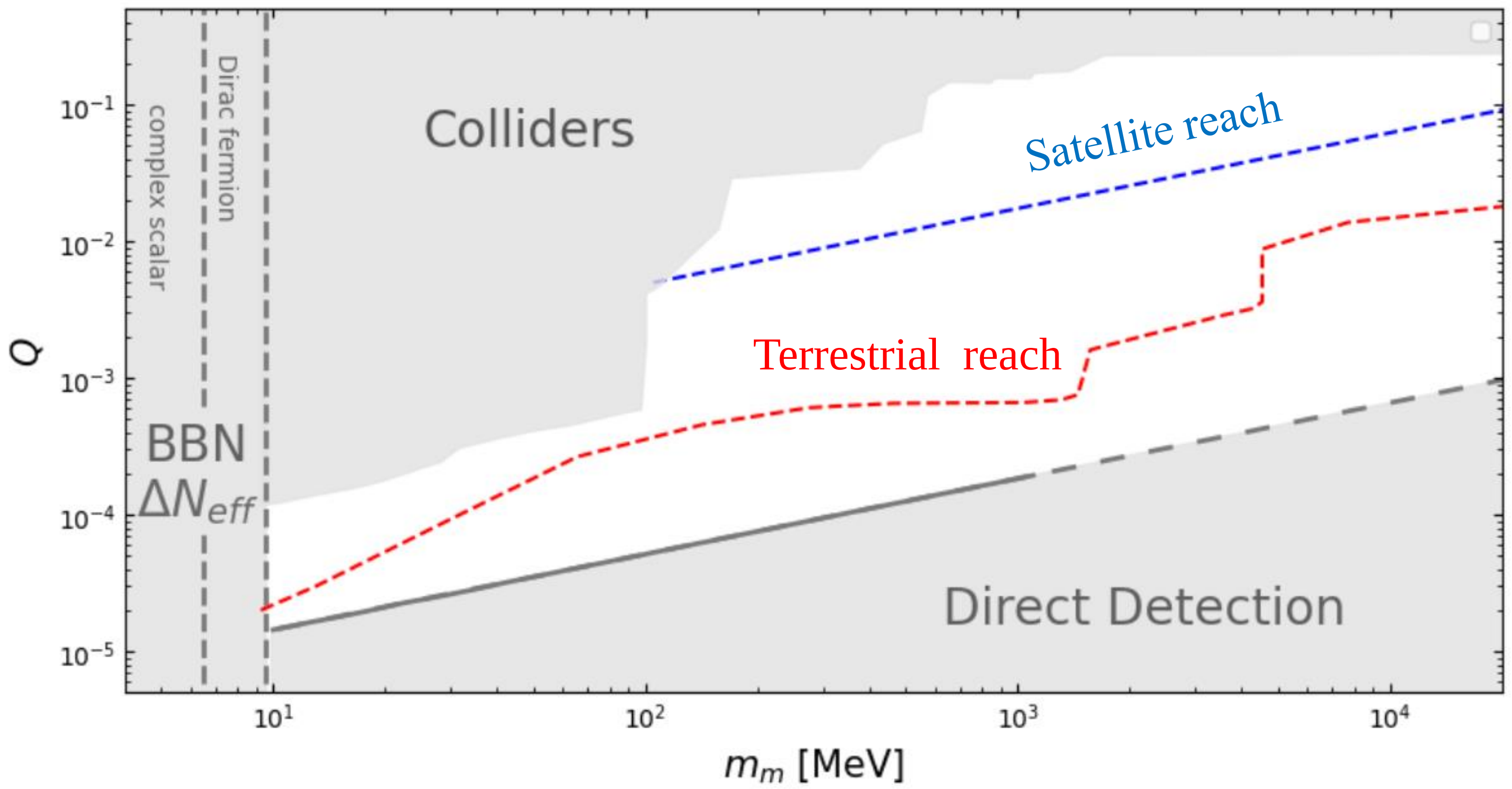
- Assume $-400mK$ sensitivity (~twice the SARAS3 RMS)
- Scan over the astrophysical parameter space

Prospects including Athena



Dark Cooling: Enhanced Absorption

- Some of the experiments are not yet approved
- Time scale is unclear



Counter Cooling: Inefficient Lyα

Unique Feature of Dark Cooling

Counter Cooling: Inefficient Lyα

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_c^{-1}}{1 + x_\alpha + x_c}$$

$$x_\alpha = \frac{8\pi\lambda_\alpha^2 \gamma_\alpha E_{21}}{9 A_{10} T_\gamma} \sum_{I=cont,inj} S_\alpha^I \bar{J}_\alpha^I$$

[Chen & Miralda 2004, Hirata 2005]

Line shape and Lyα-H interactions

$$S_\alpha^I \sim \int dE\, [\phi_{10}(E) + \phi_{01}(E)] \frac{J^I(E)}{\bar{J}_\alpha^I}$$

Unaltered flux
(astrophysics)

Counter Cooling: Inefficient Lyα

Photons around line center lose energy due to redistribution and recoil with H

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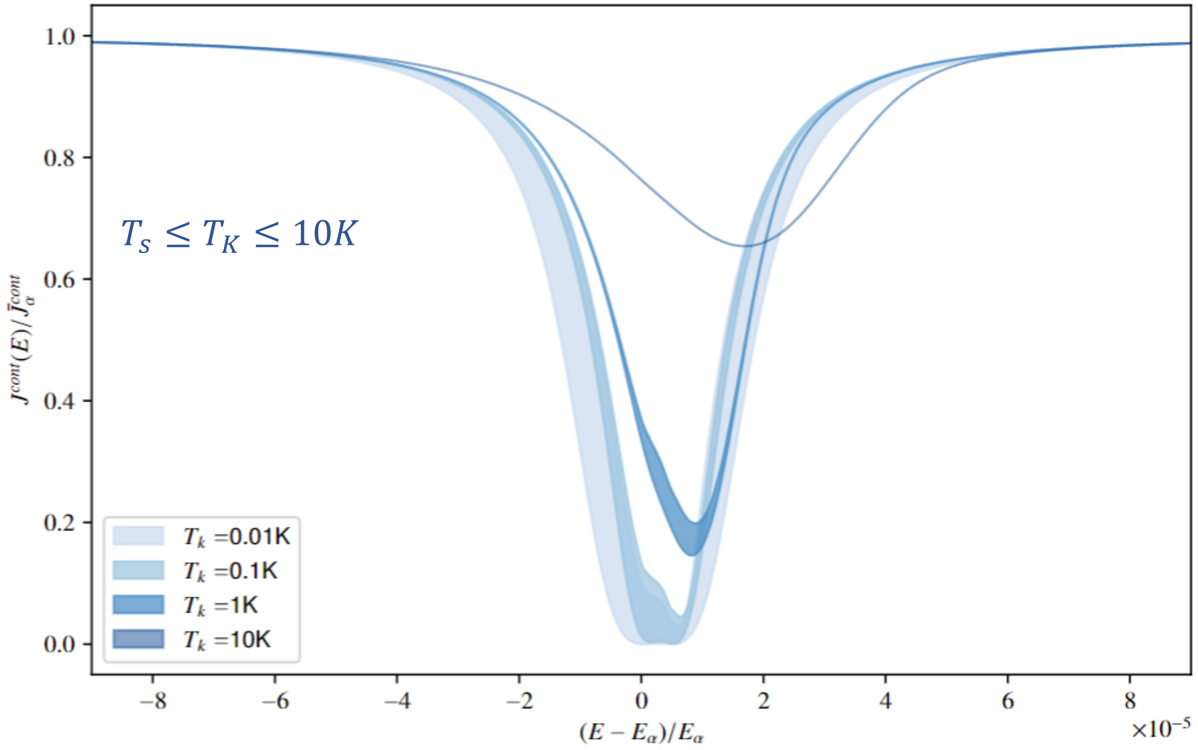
Intensity drops around line center



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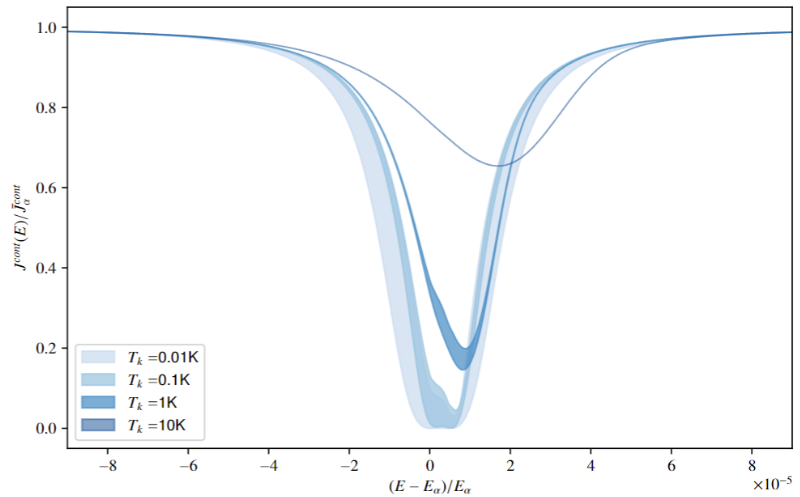

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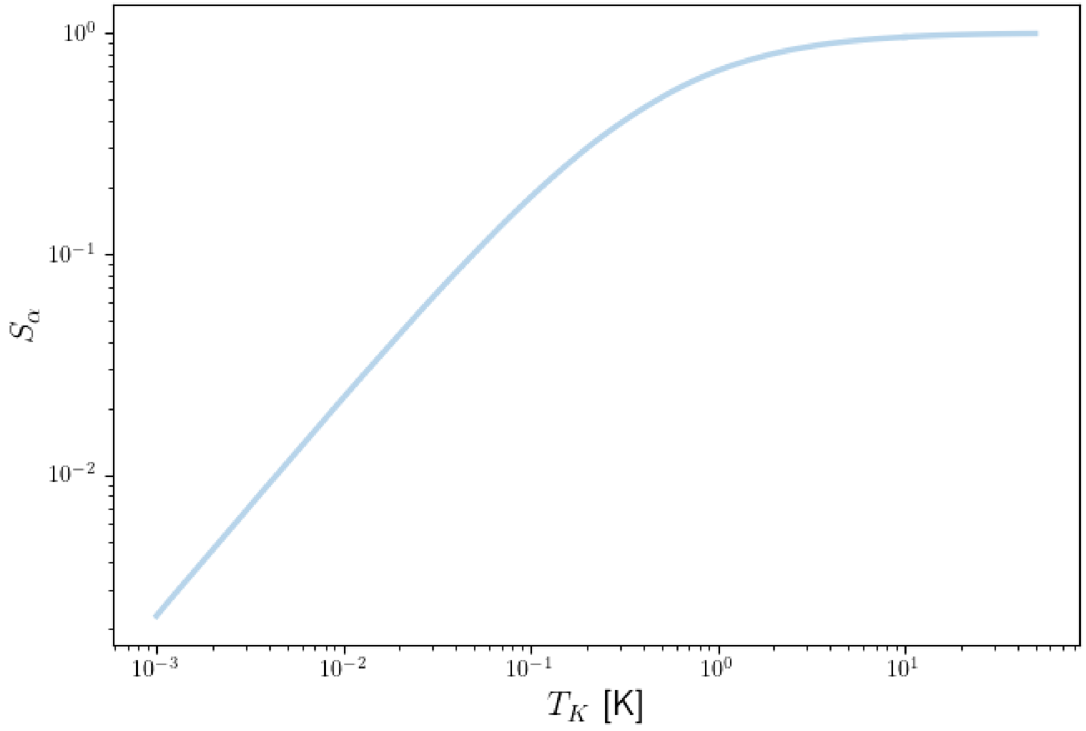


Inefficient Lyα coupling

$$x_\alpha = \frac{8\pi\lambda_\alpha^2\gamma_\alpha E_{21}}{9A_{10}T_\gamma}\sum_{I=cont,inj} S_\alpha^I \bar{J}_\alpha^I$$

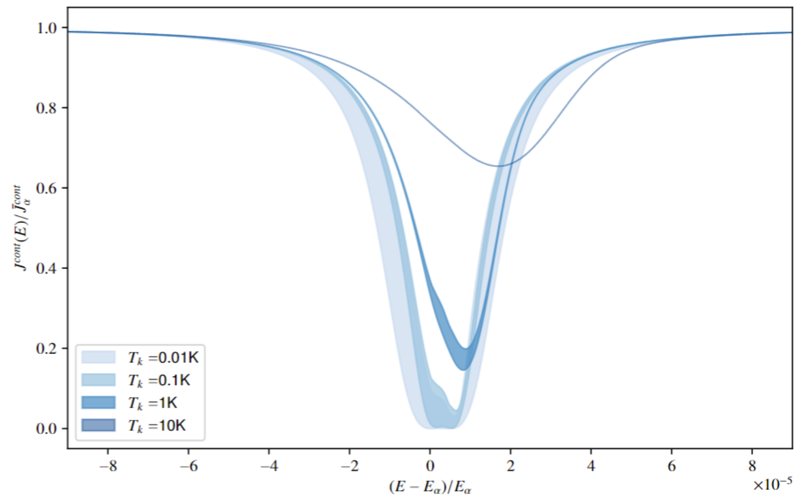
Counter Cooling: Inefficient Lyα

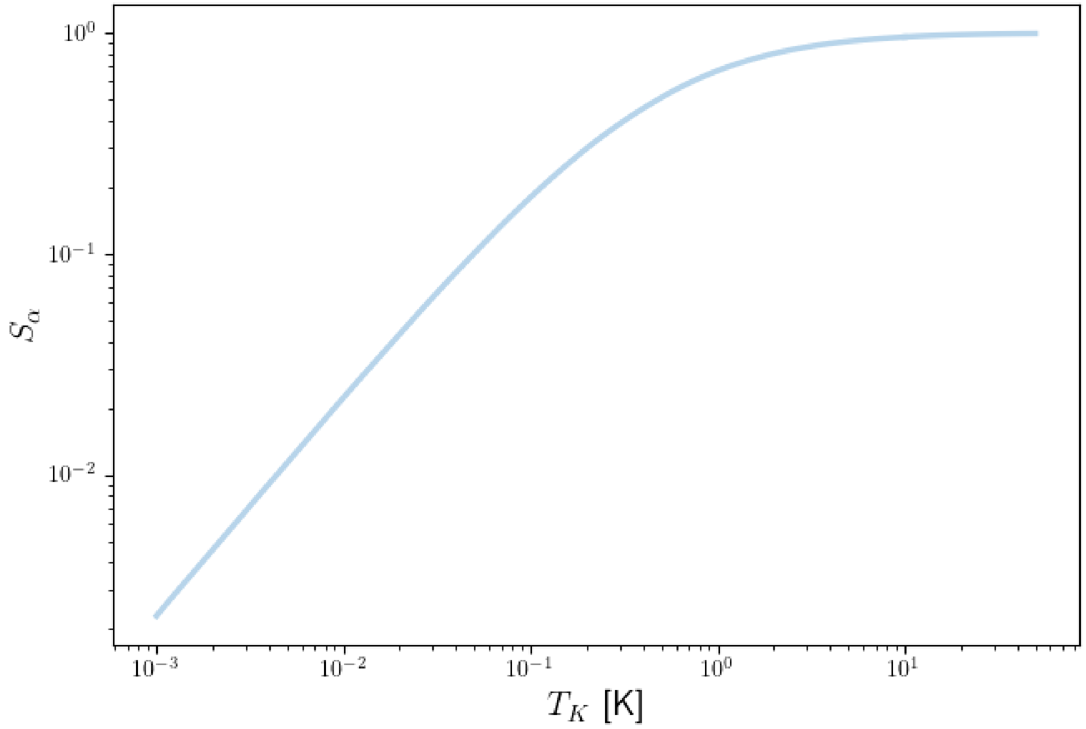
Photons around line center lose energy due to redistribution and recoil with H

Intensity drops around line center

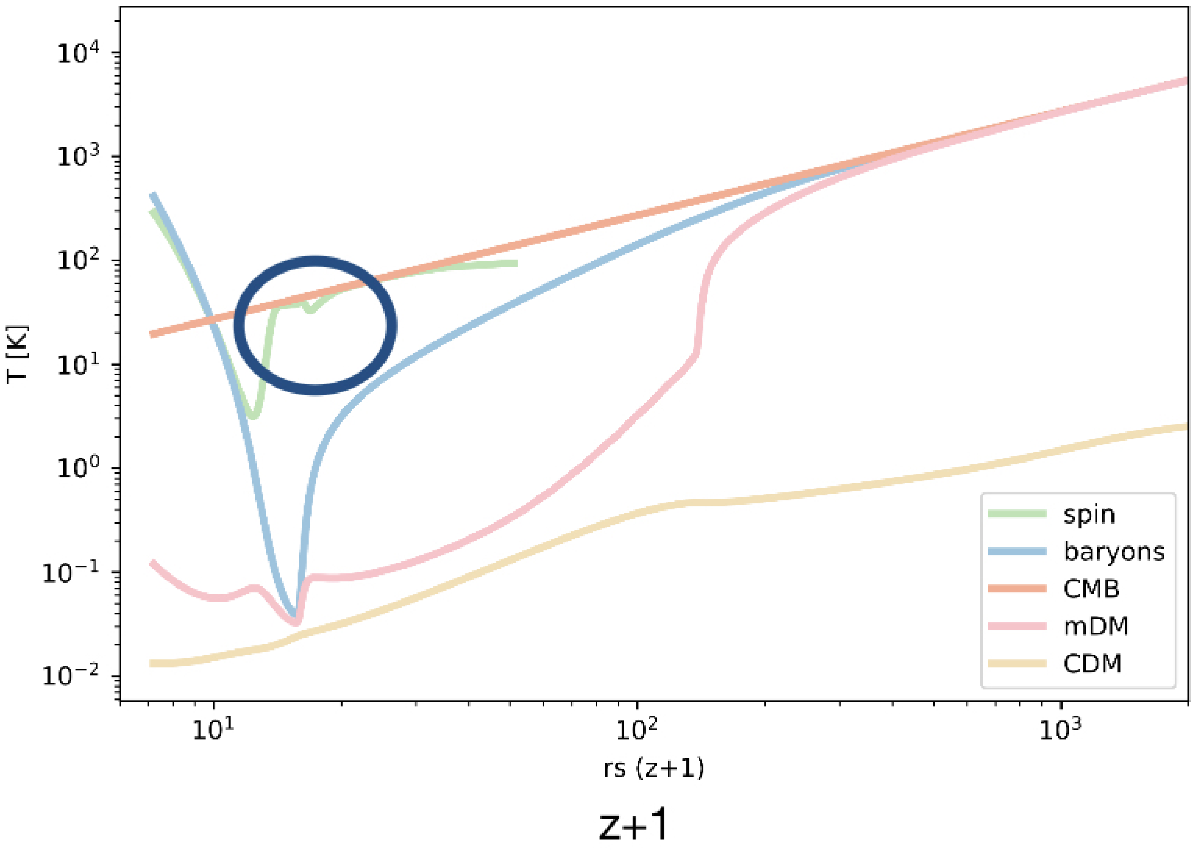
Inefficient Lyα coupling

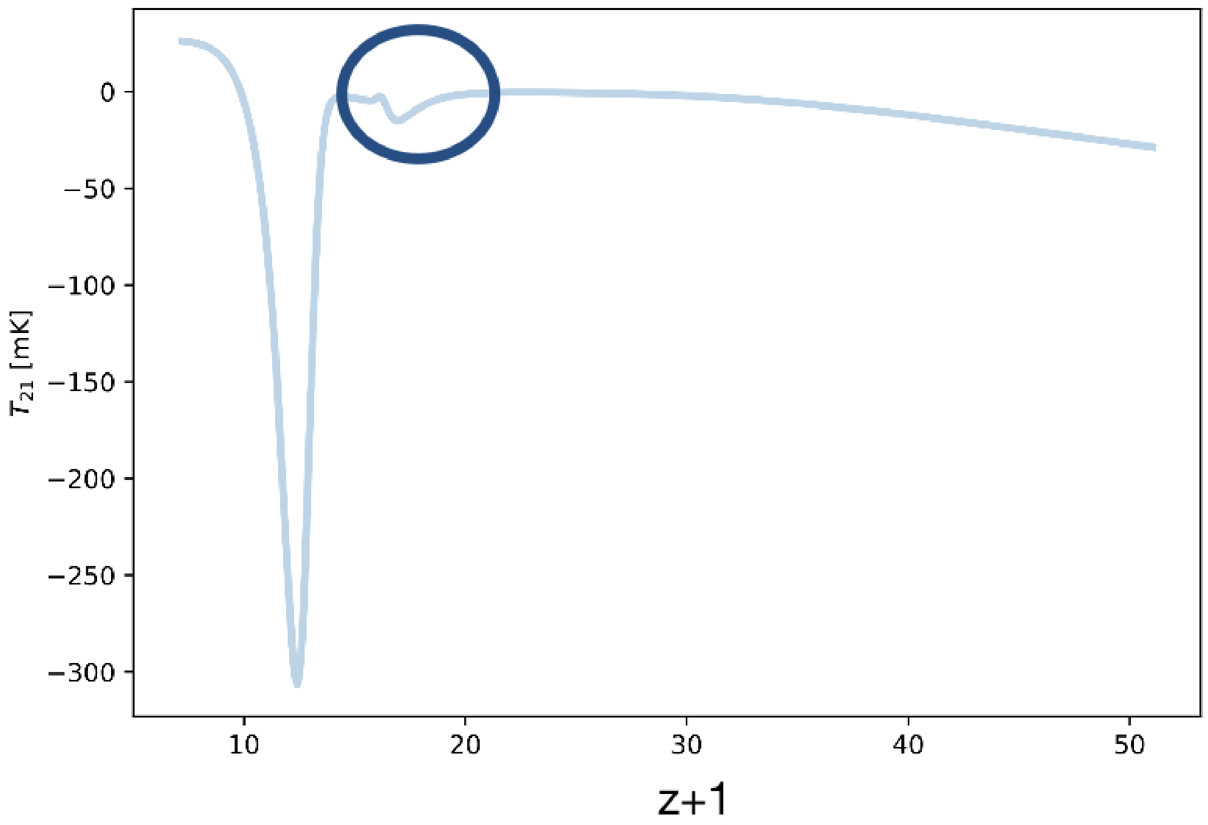
$$x_\alpha = \frac{8\pi\lambda_\alpha^2\gamma_\alpha E_{21}}{9A_{10}T_\gamma} \sum_{I=cont,inj} S_\alpha^I \bar{J}_\alpha^I$$





Counter Cooling: Inefficient Lyα





Thanks for listening

- DM production mechanisms may lead to dark sectors
- A fractional mDM can leave a significant signature on the 21-cm global signal
- Currently, astrophysical uncertainties are too large to probe DM assuming a $-400mK$ sensitivity
- This will change with better X-ray probes such as Athena
- Three fluid mDM in 21-cm power spectrum 2212.08082
- How does the three fluid mDM affect the HMF?

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