Towards Constraining Dark Sectors with 21-cm Cosmology

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

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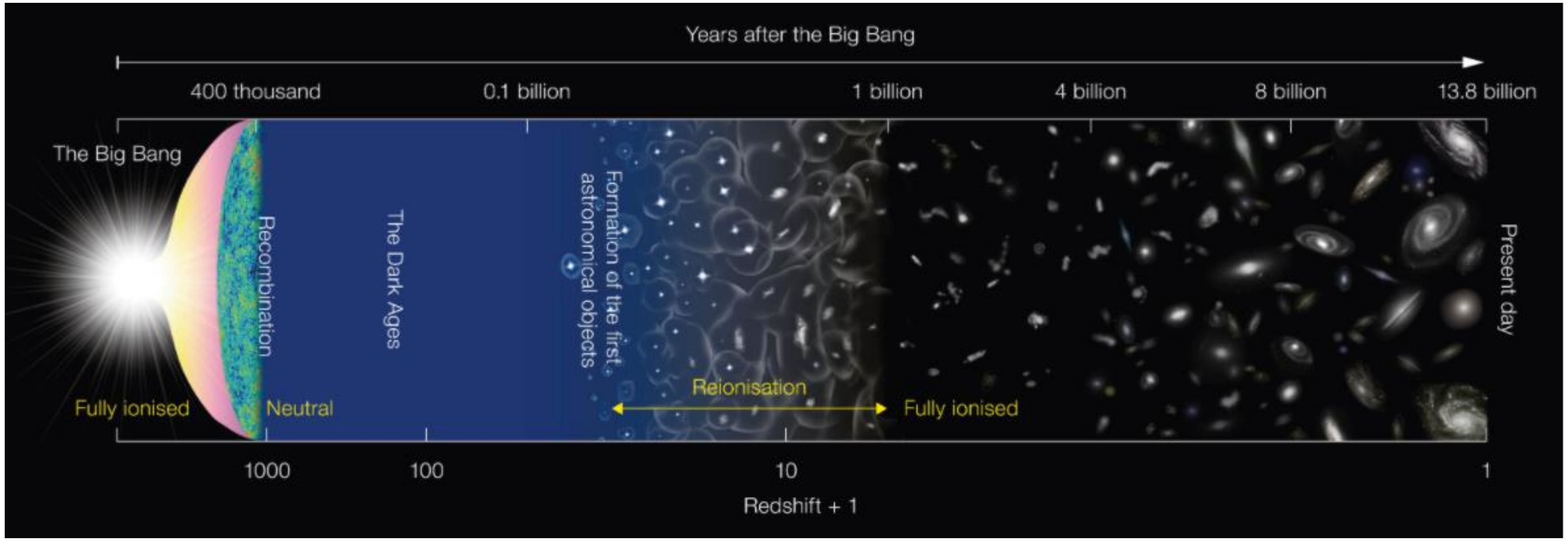
Plan

- Basics of 21-cm Cosmology
- Dark Cooling - Valid Models
- Predictions

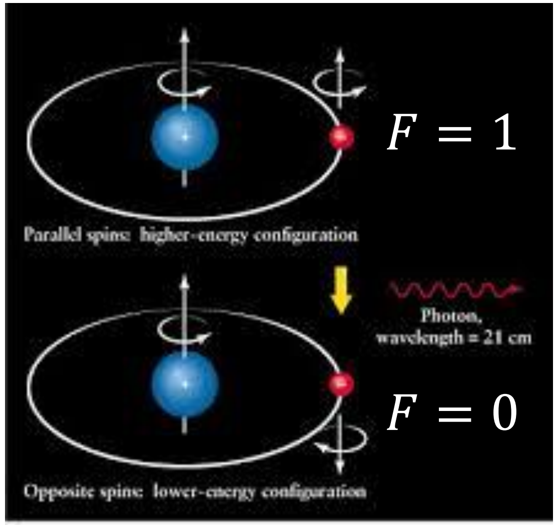
Introduction to 21-cm Cosmology



- After ($z \sim 1100$) neutral Hydrogen is the most abundant component of the baryonic matter.

- Most hydrogen is at its 1s ground state

- The hyperfine splitting of the ground state corresponds to 21-cm ($6 \times 10^{-6} eV$)



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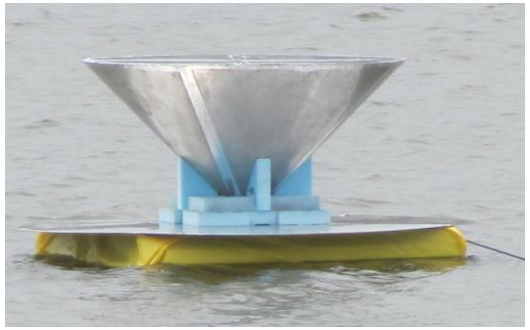
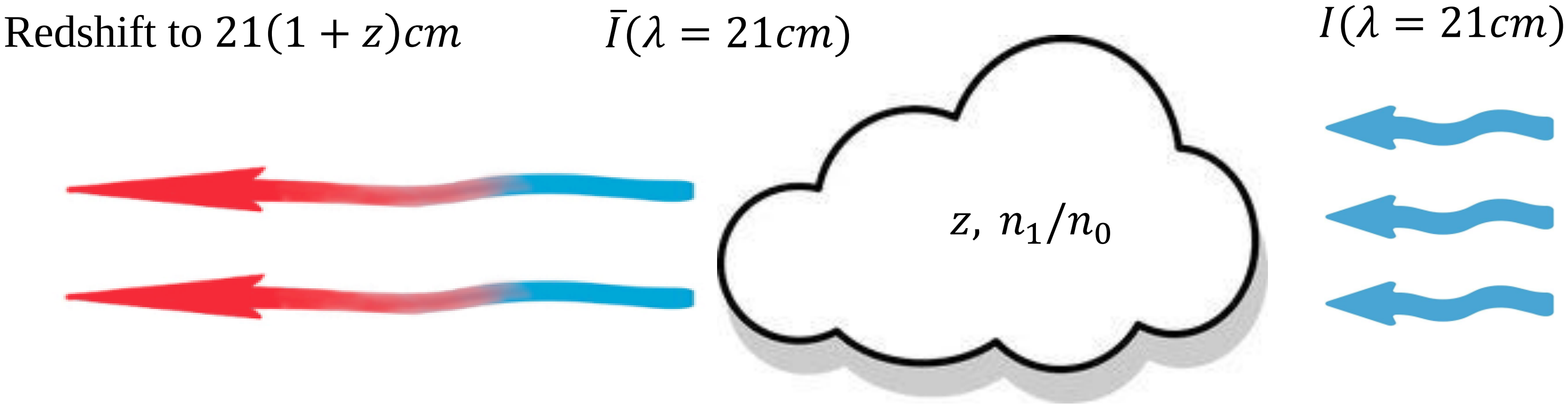
- CMB photons transverse through dense Hydrogen clouds before reaching us



SARAS 3 Antenna



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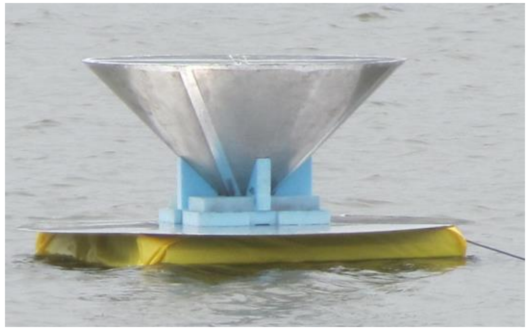

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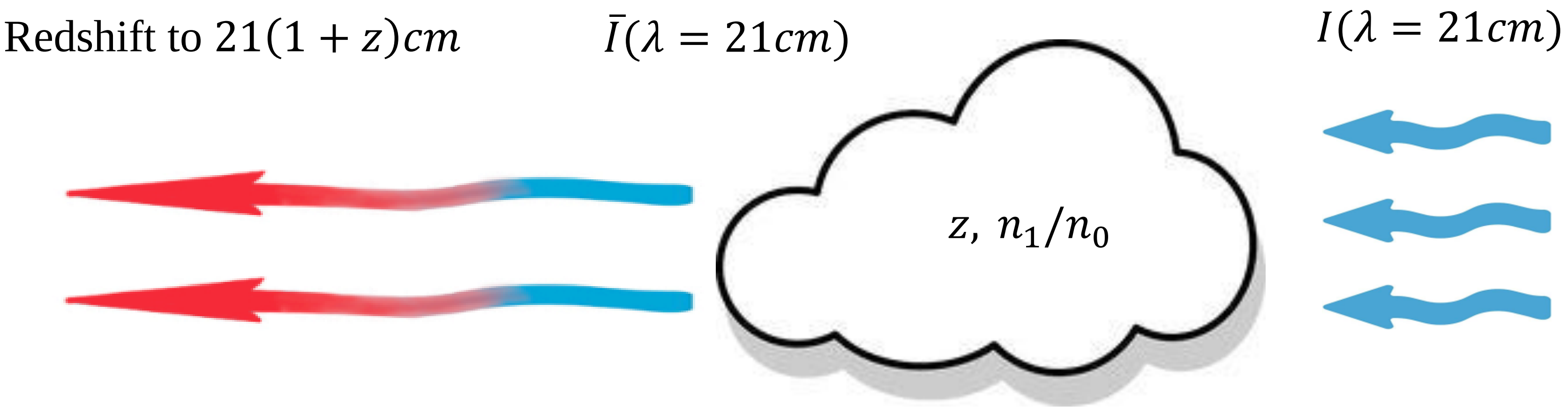

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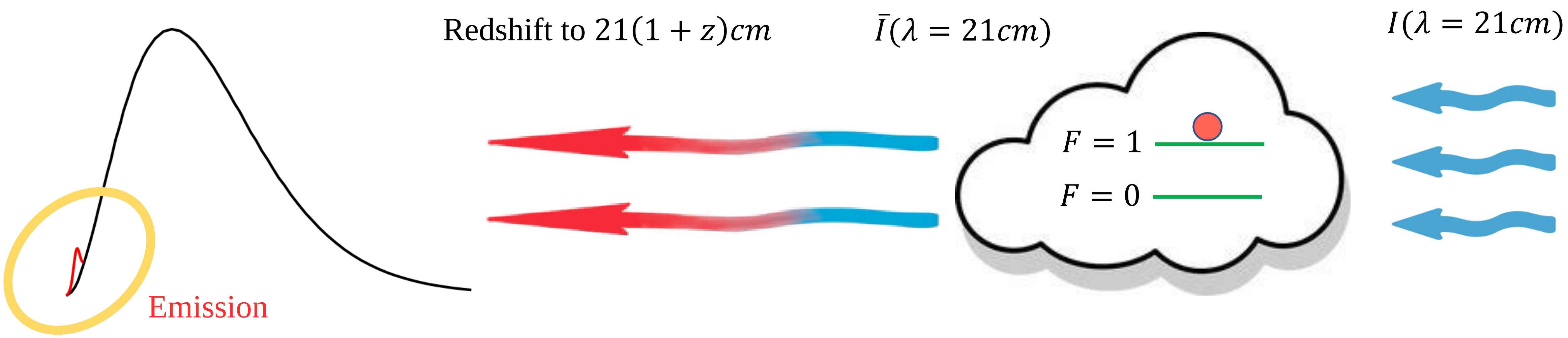
- The measured intensity at $21(1+z)cm$ depends on the relative occupancy of the Hyperfine levels at redshift z



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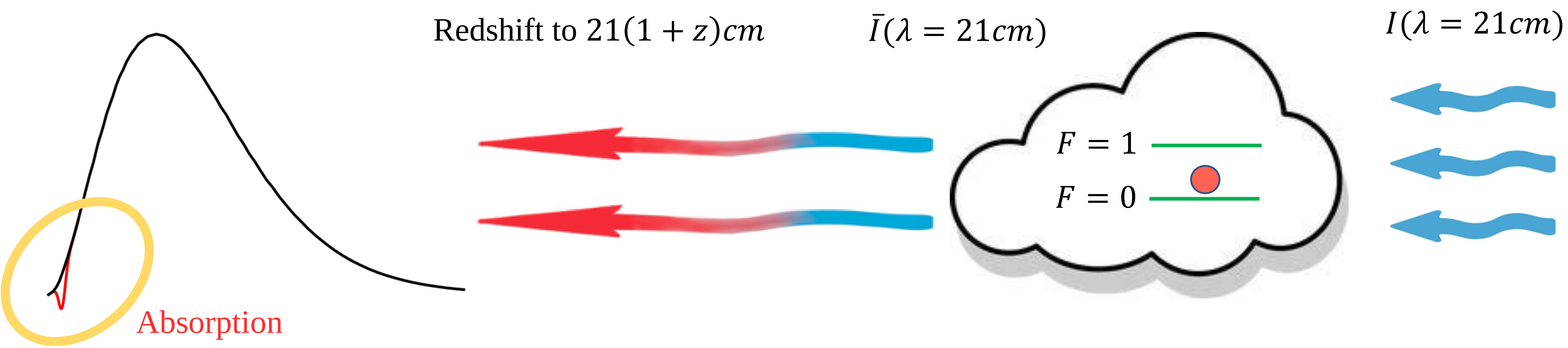

Introduction to 21-cm Cosmology

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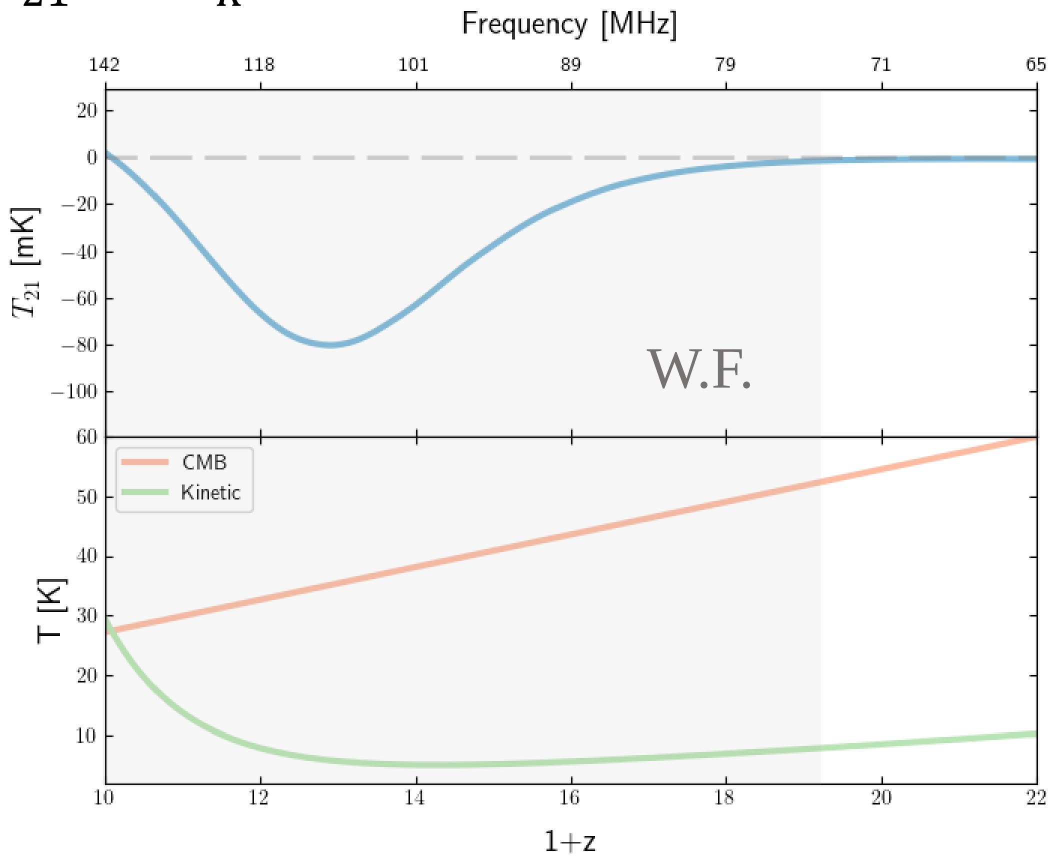

Absorption signal at cosmic dawn

Dark Cooling – Enhanced Absorption

Elastic DM-SM interactions cool the baryonic gas

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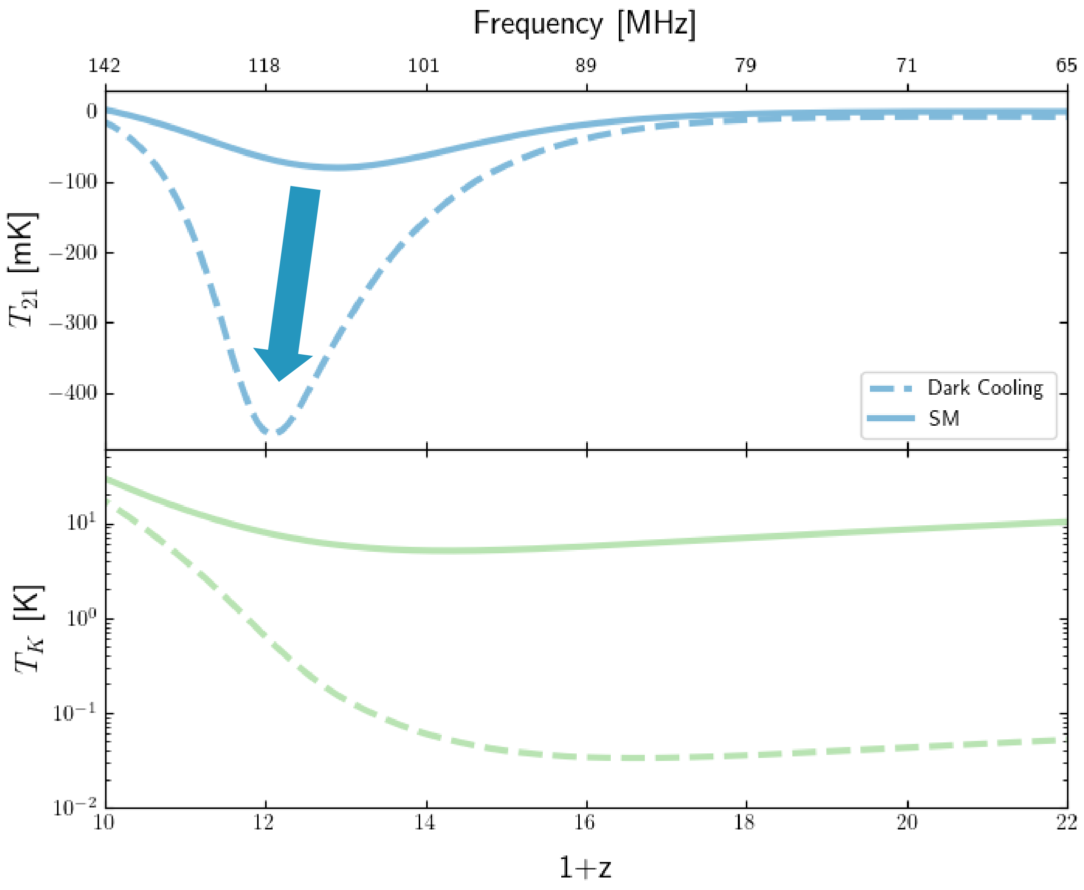
Impact on 21-cm

Enhanced absorption
at cosmic dawn



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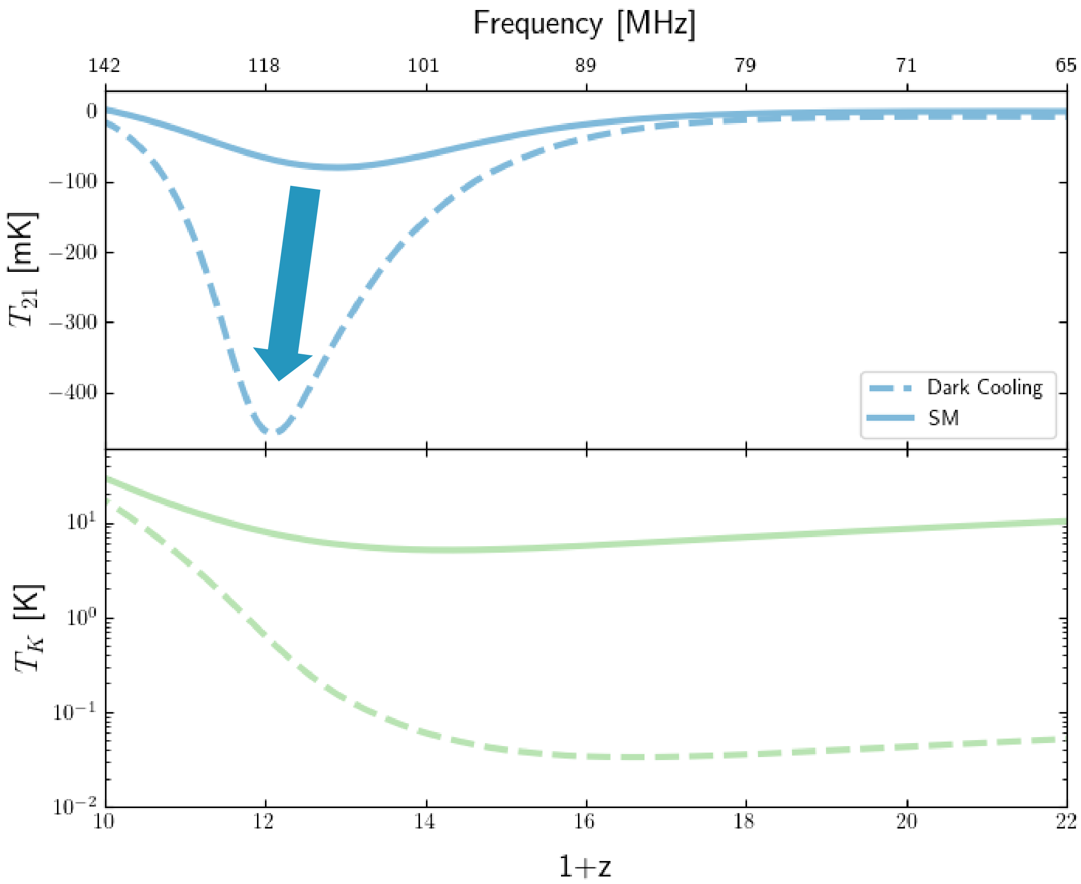

Anomalous absorption signal

Constrain over cooling?

Dark Cooling – Viable Models

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

- CMB constraints imply $f_m < 0.4\%$

[K. K. Boddy et al, 2018]

[Barkana, Outmezguine, Redigolo, Volansky, 2018]

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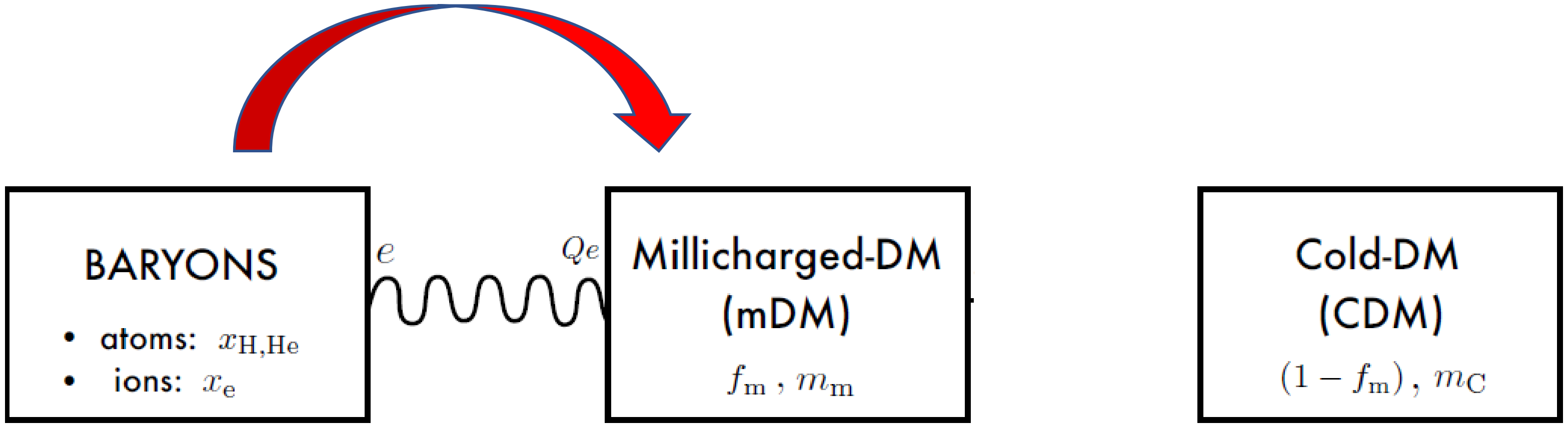

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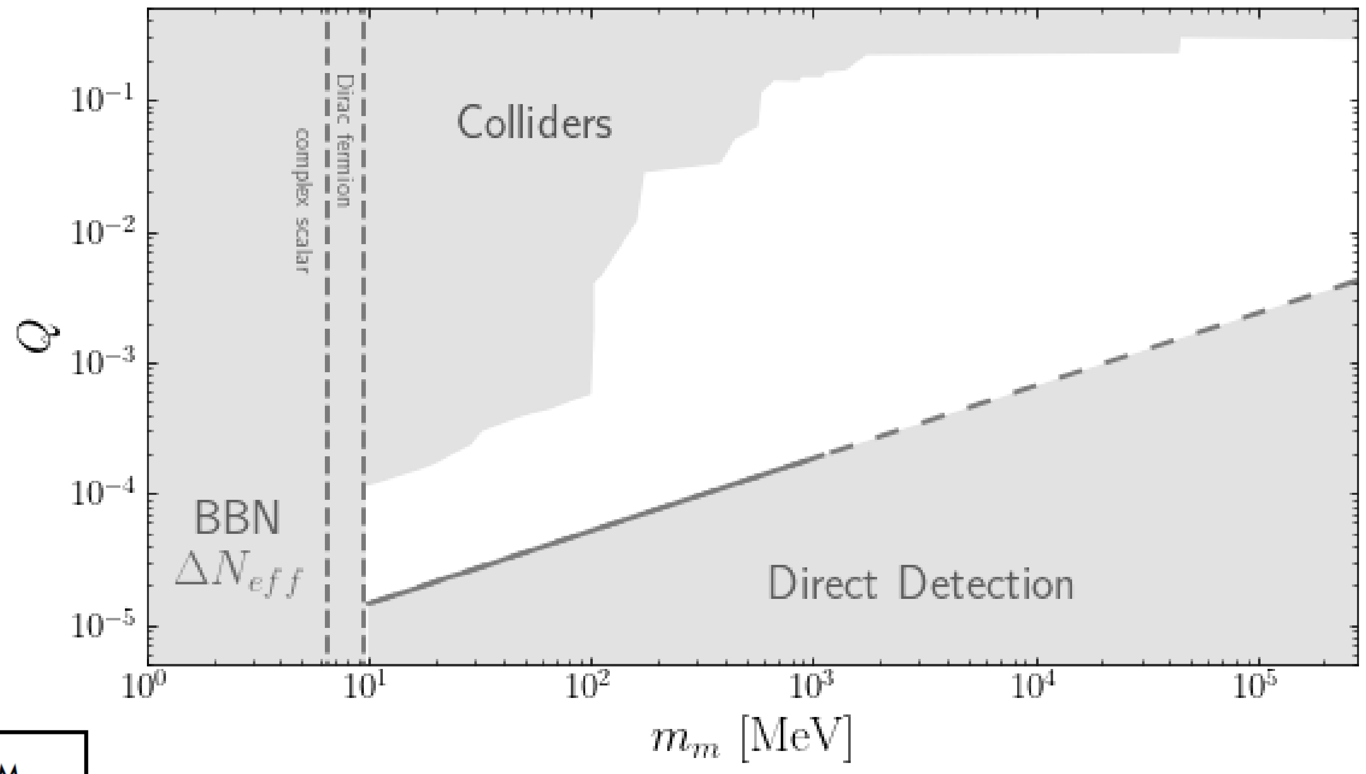

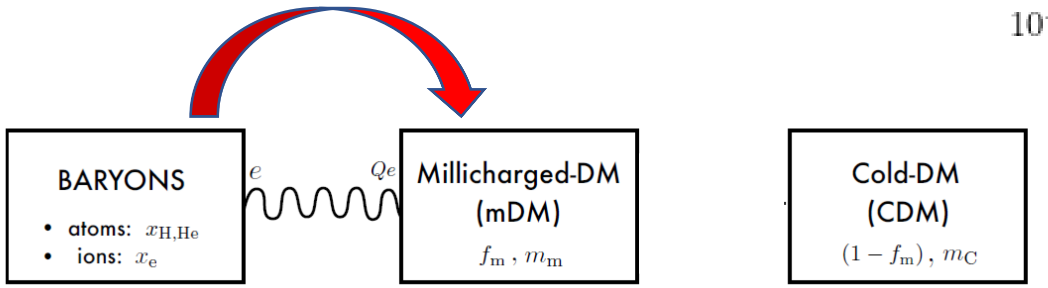

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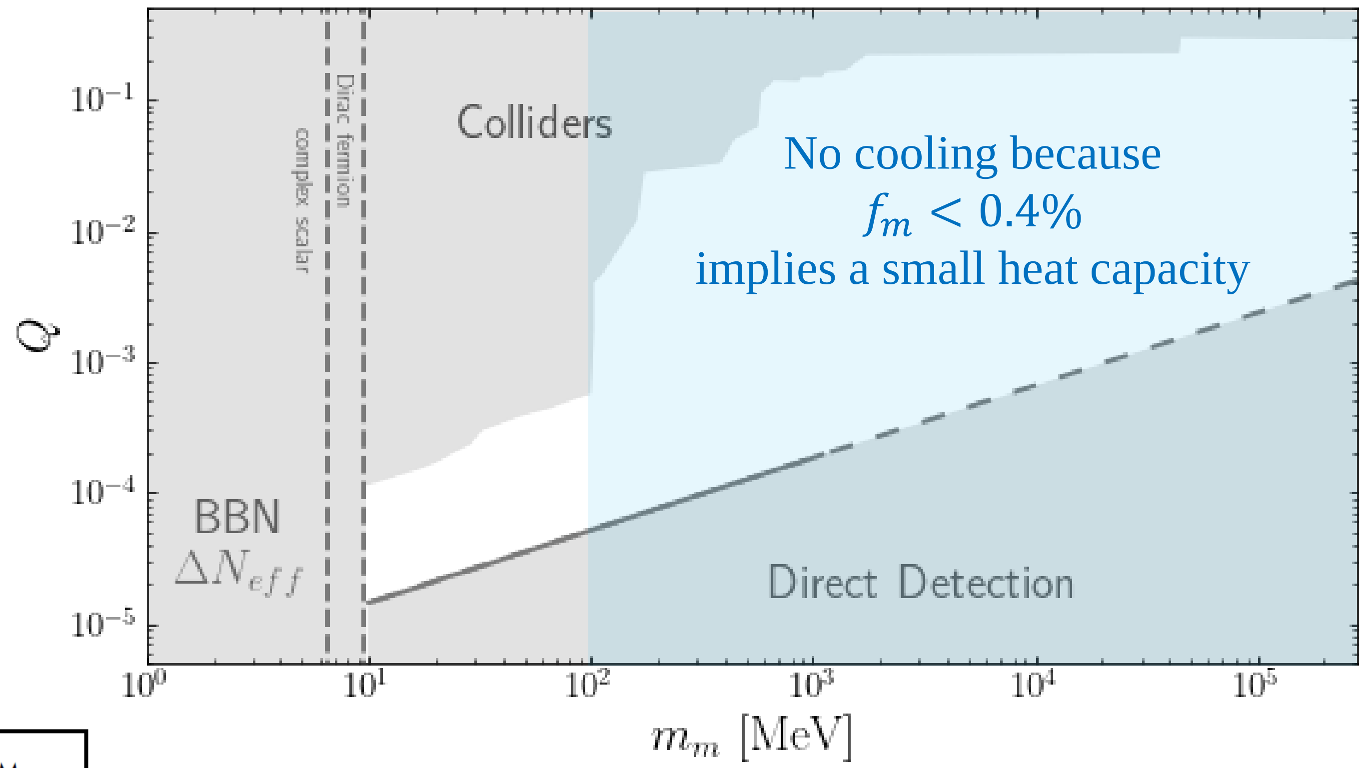

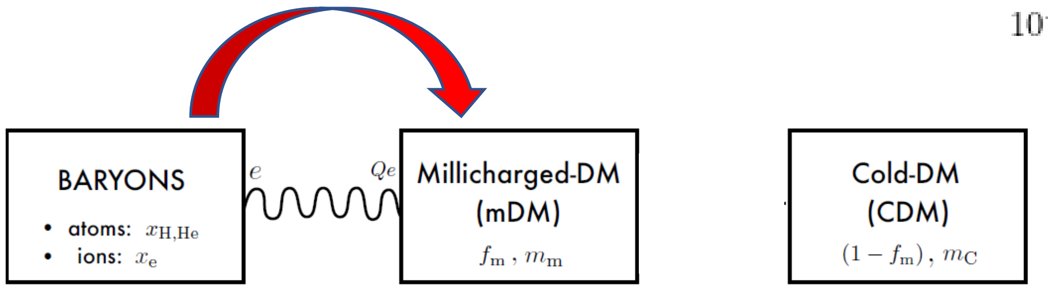

Dark Cooling – Viable Models

- $g_m g_C = 0$ is arbitrary
- General scenario allows $g_m g_C \neq 0$

[Liu, Outmezguine, Redigolo, Volansky, 2019]

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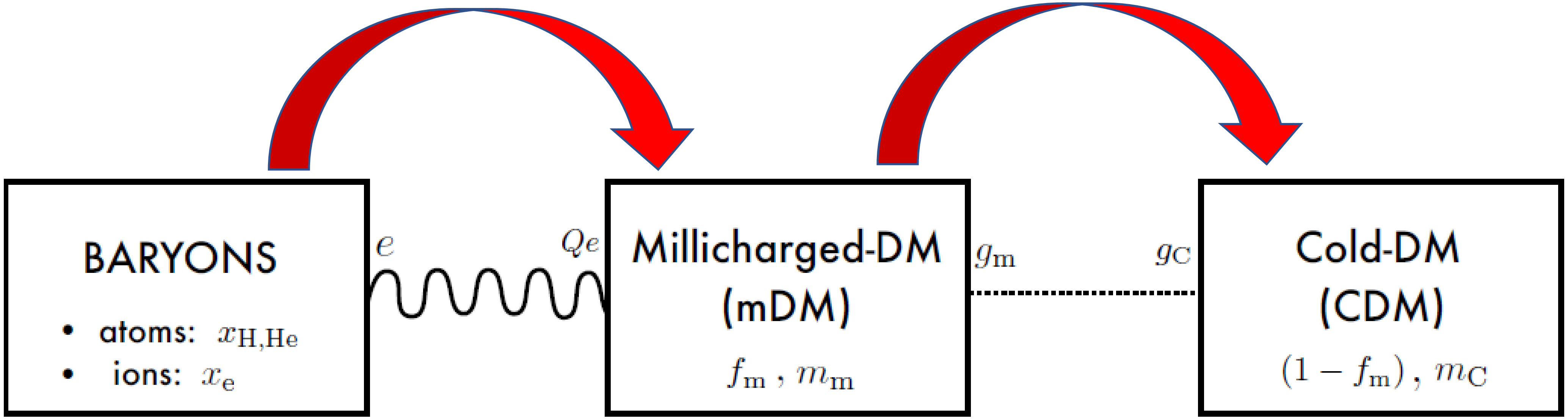
- $g_m g_C = 0$ is arbitrary
- General scenario allows $g_m g_C \neq 0$
- mDM-CDM interactions effectively increase the heat capacity of mDM



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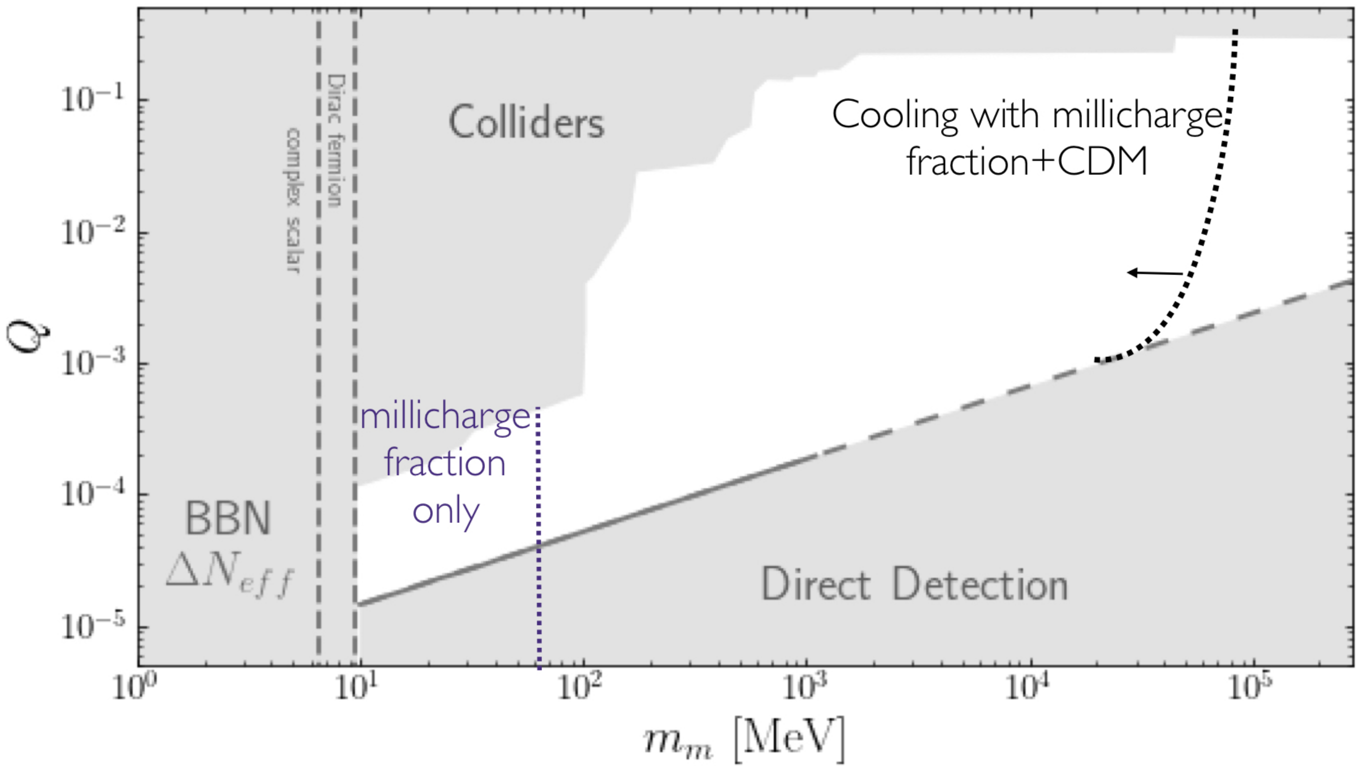

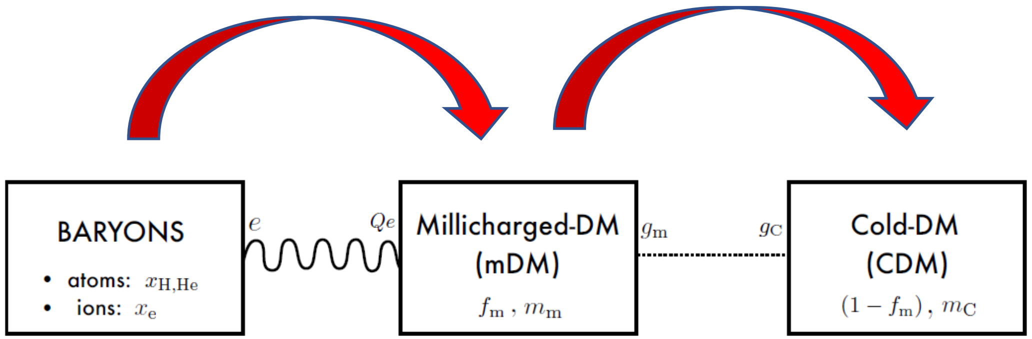

How Much Can we Cool?

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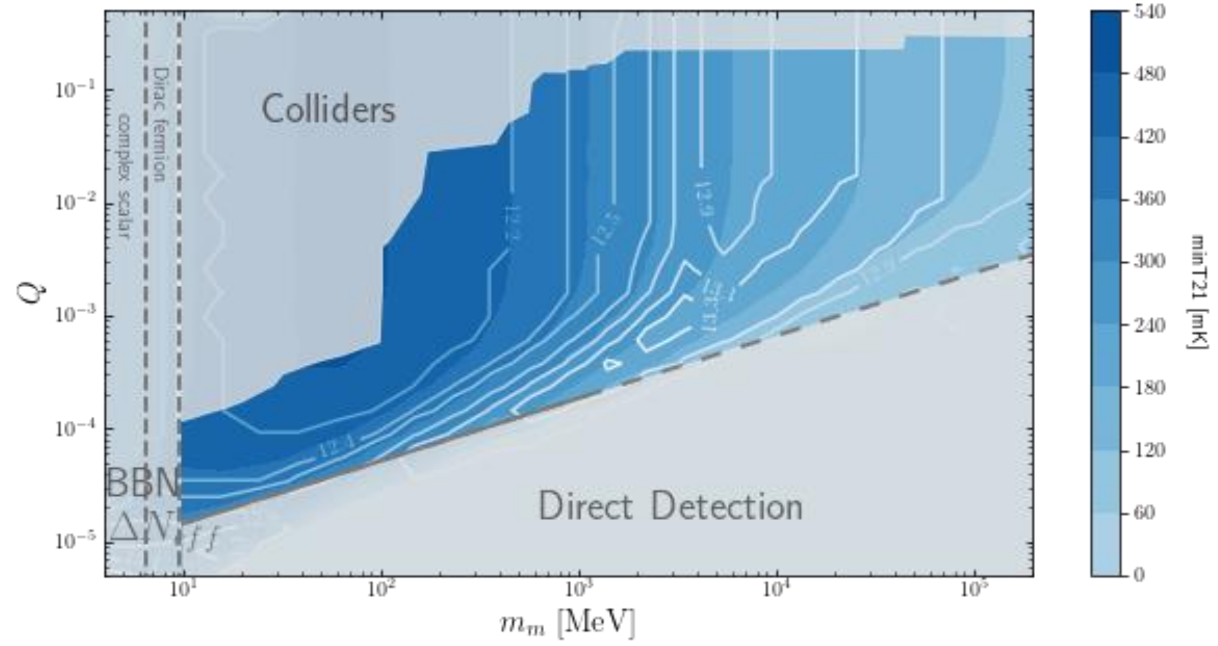
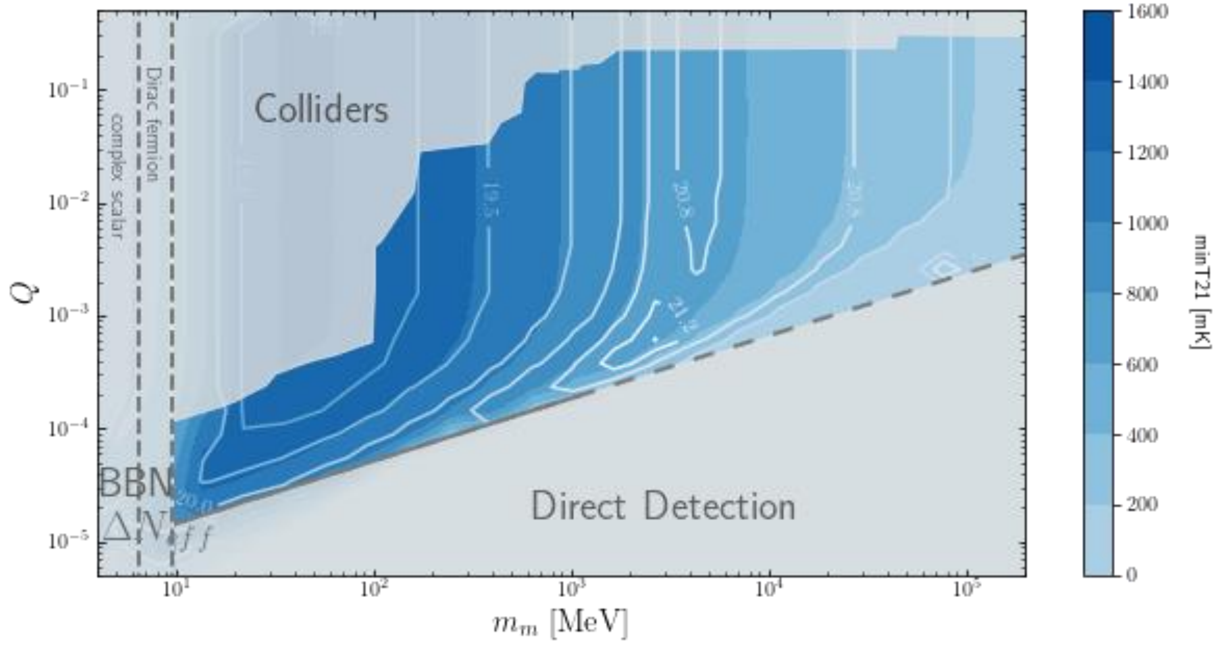


Park et al. 2019

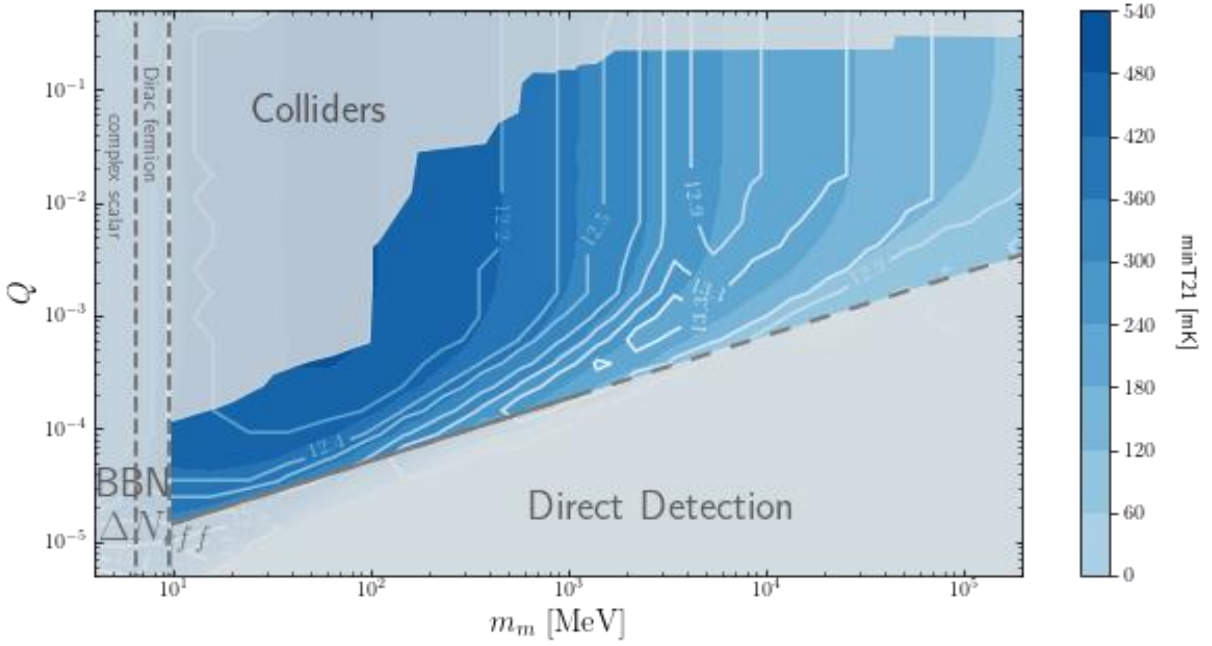
$$\min\{T_{21}^{SM}\} = -80mK$$

How Much Can we Cool?



Cohen et al. 2017

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



Park et al. 2019

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

Summary

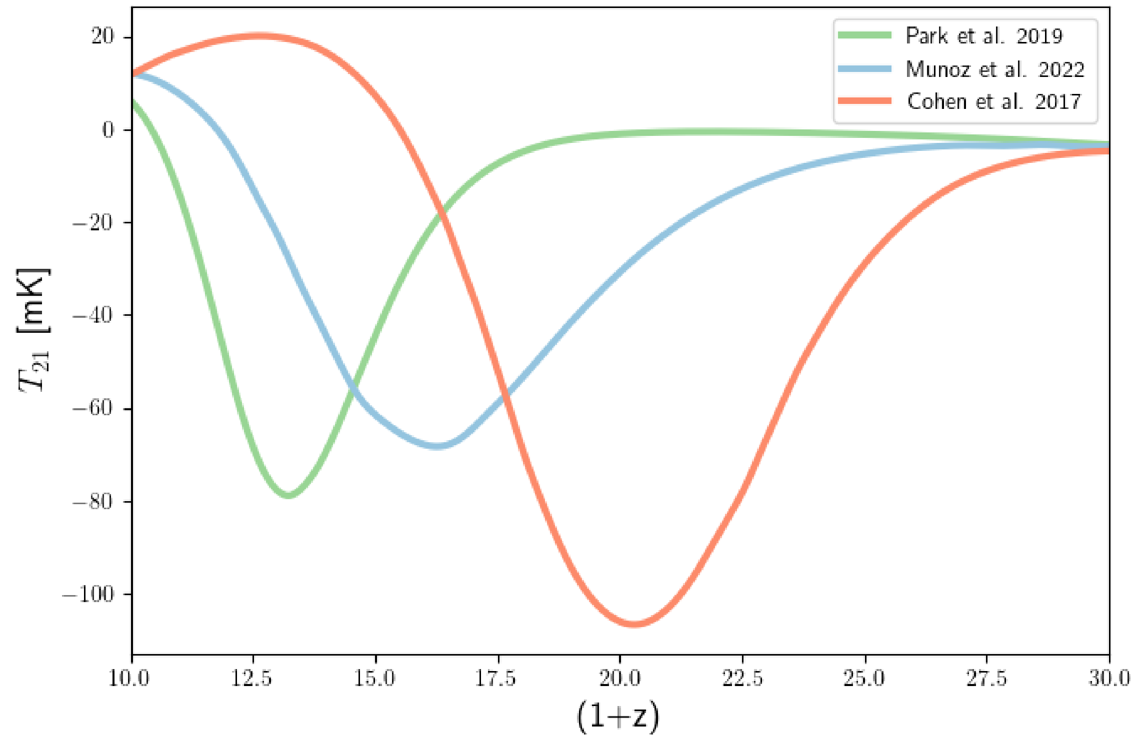
- T_{21} is strongly related to T_K at cosmic dawn
- DM-SM elastic interactions cool the baryons, therefore enhancing the absorption signal
- mDM is the only viable DM model that can generate and $\mathcal{O}(1)$ cooling
- mDM can generally also interact with CDM
- Current measurements can lead to strong constraints from overcooling

Backup

Astrophysical Modeling

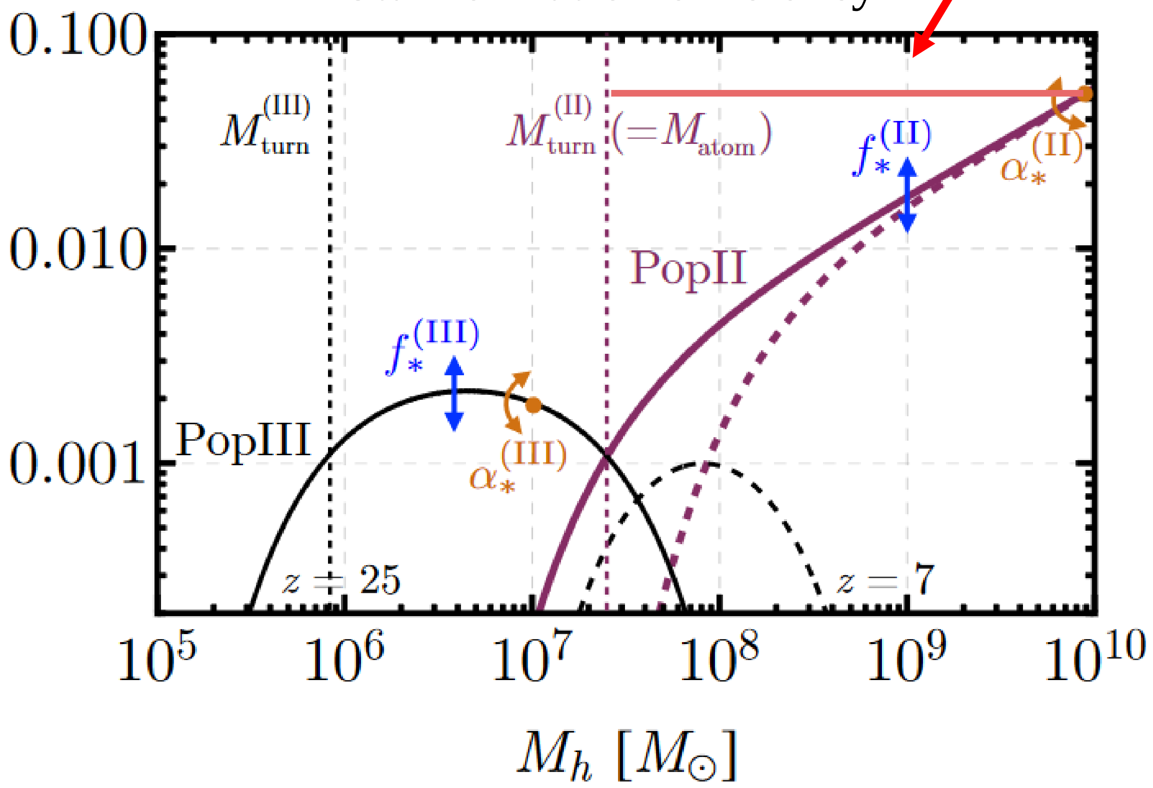
Astrophysical Modeling

Fiducial scenarios of leading models



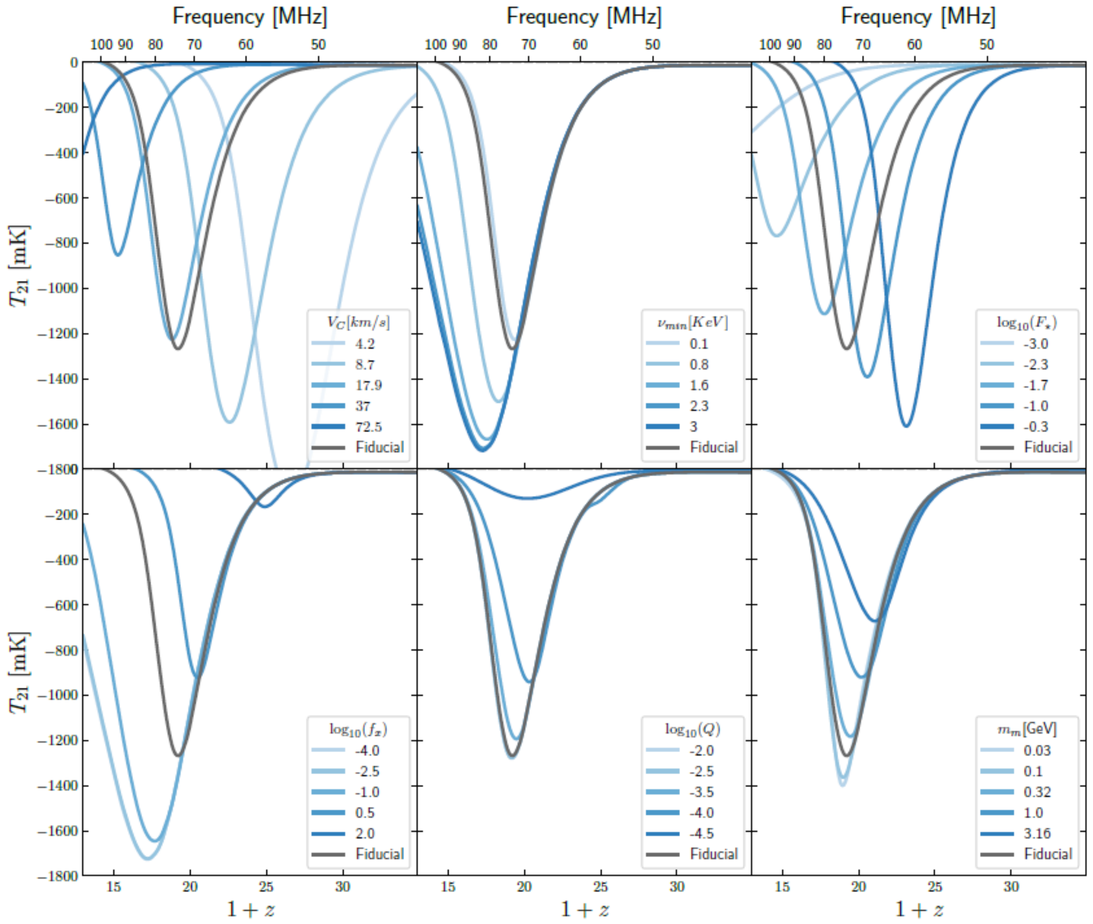
Cohen et al. 2017

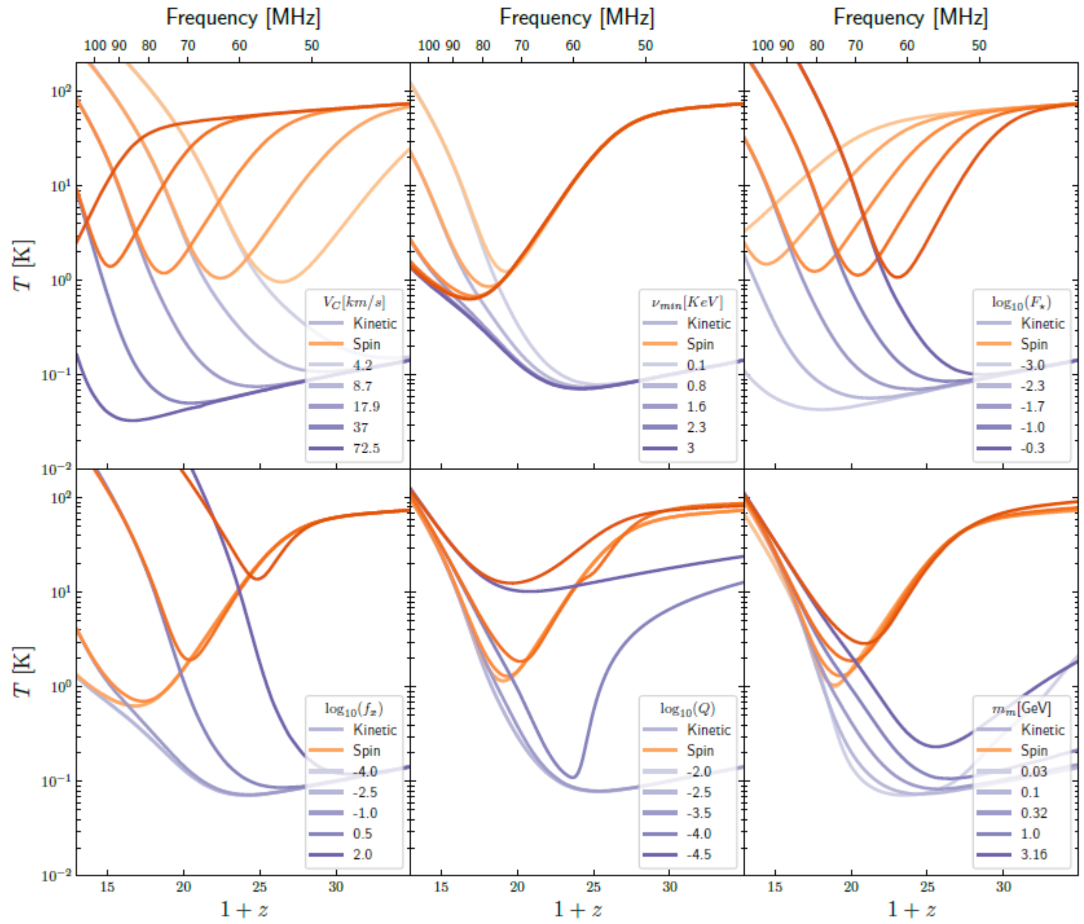
Star formation efficiency



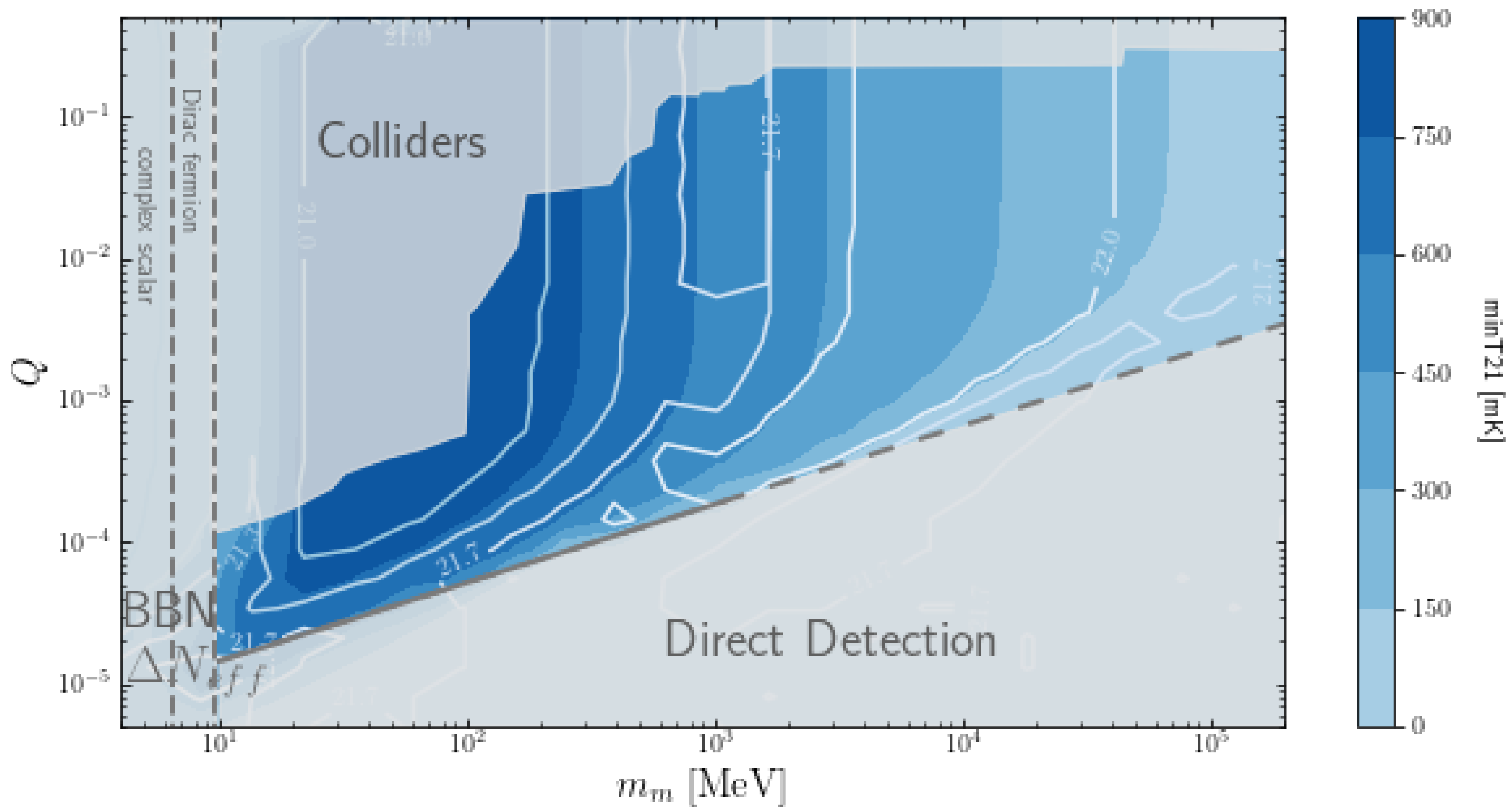
[Munouz et al. 2022]

Astrophysical Parameters



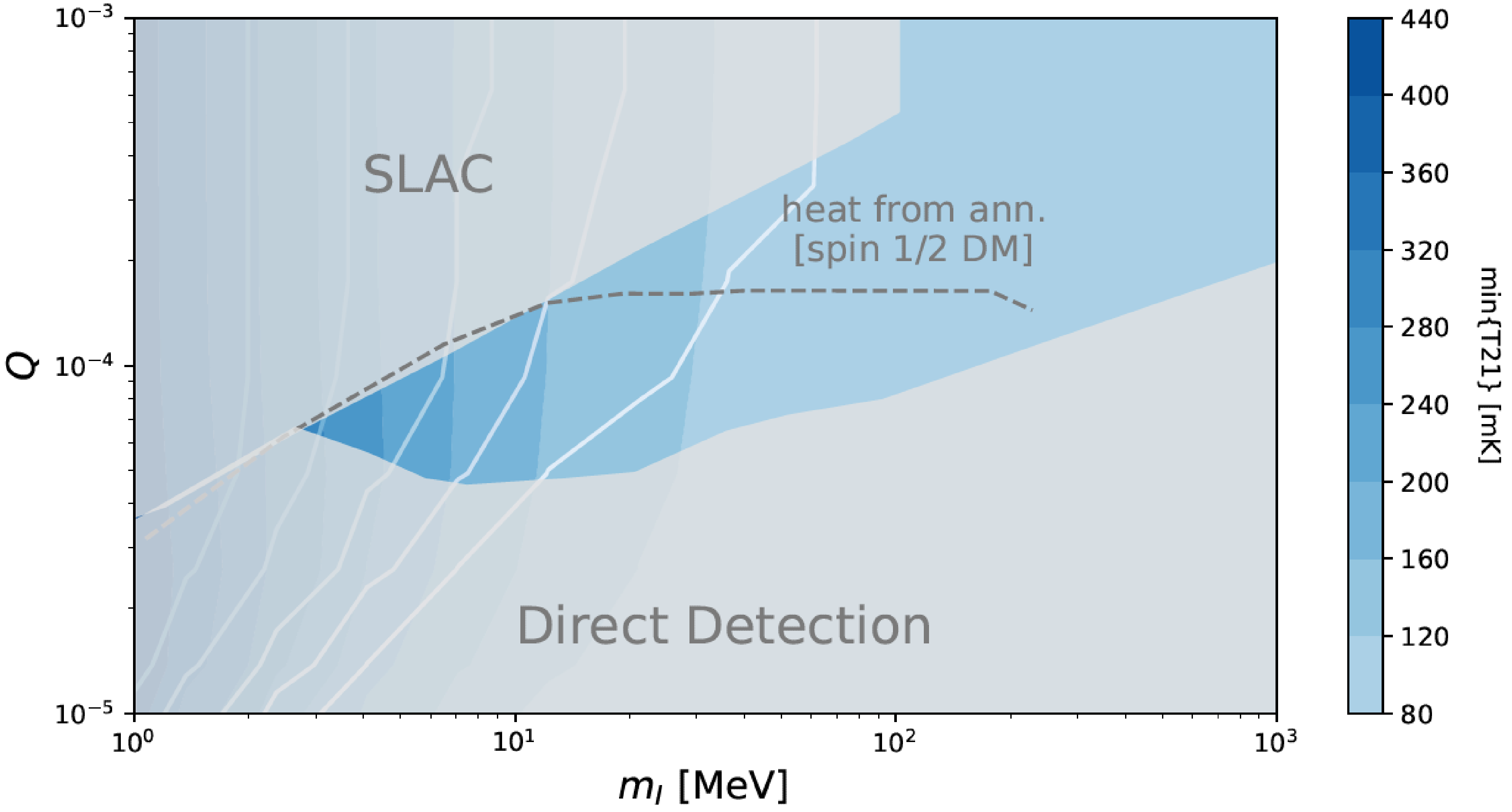


Pumped X-rays



Worst Case Scenario

no mDM - CDM Interactions



21-cm Basics

Introduction to 21-cm Cosmology

- Define the spin temperature

$$\frac{n_1}{n_0} = 3e^{-\frac{E_{21}}{T_s}}$$

- Differential brightness temperature

$$T_{21} \propto T_s(z) - T_\gamma(z)$$

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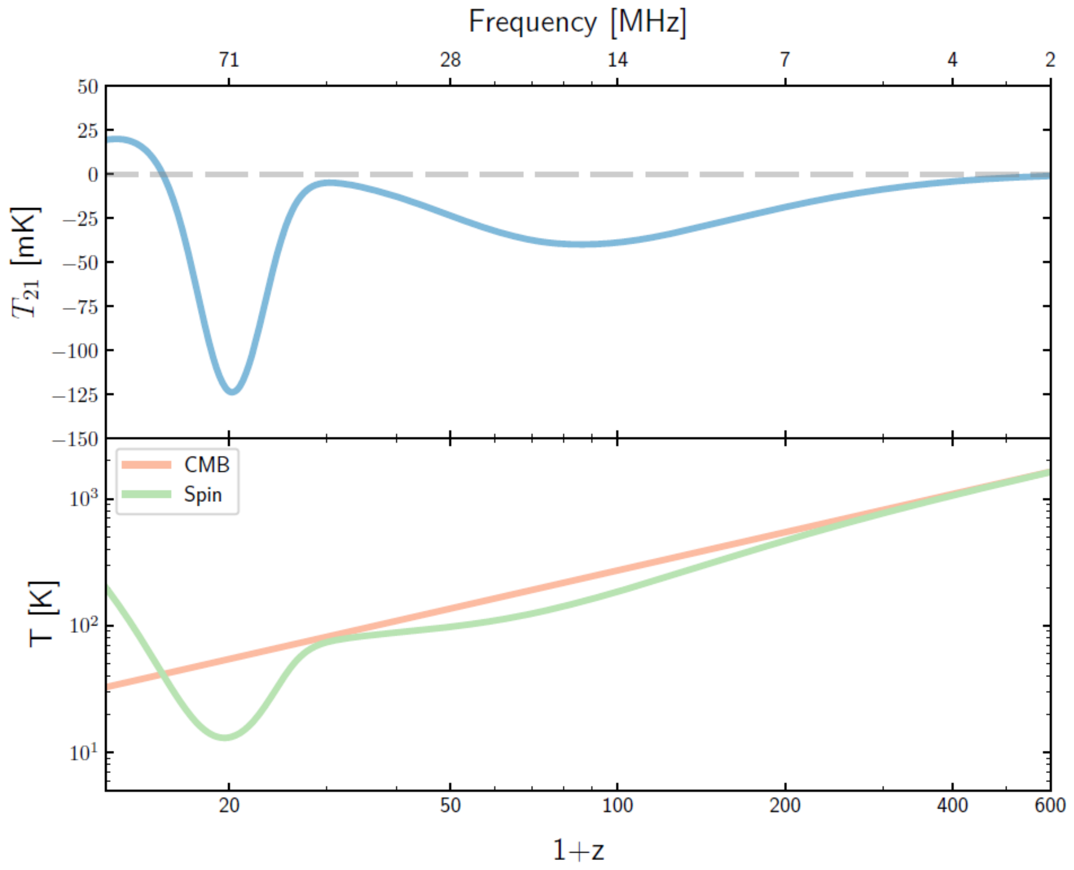


Introduction to 21-cm Cosmology

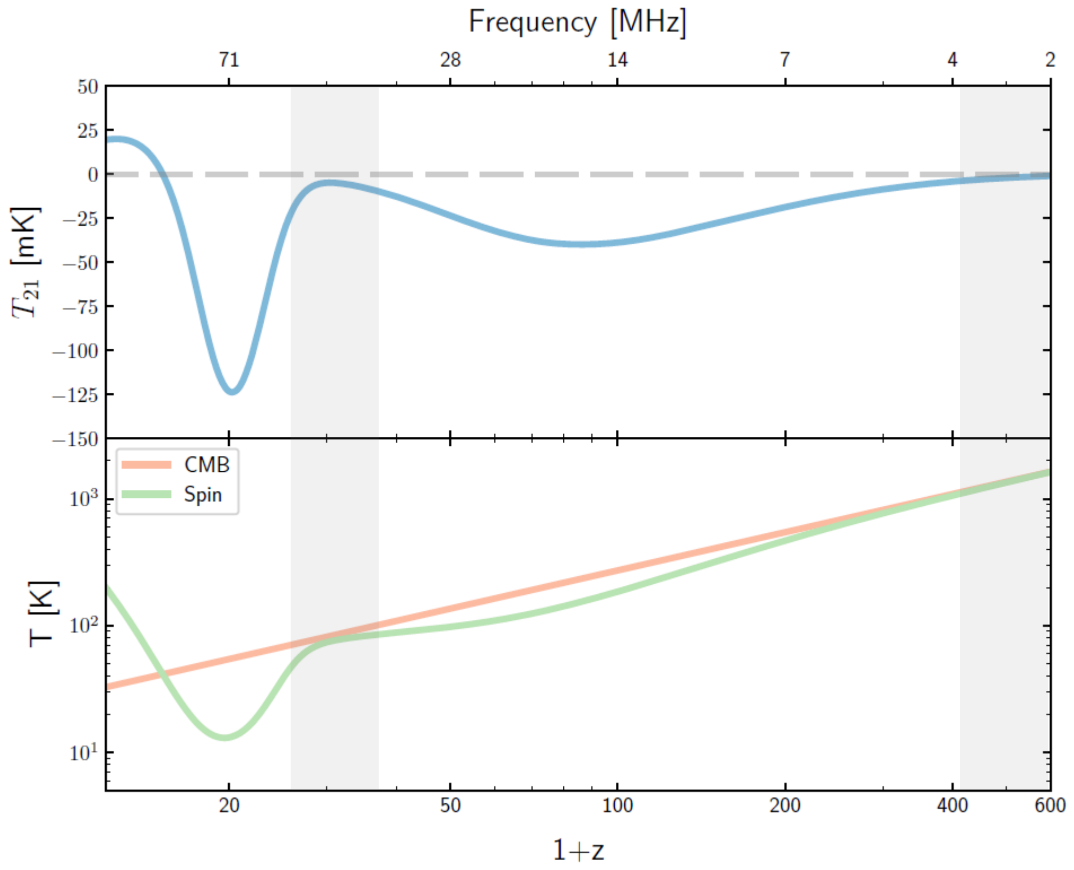
- Define the spin temperature

$$\frac{n_1}{n_0} = 3e^{-\frac{E_{21}}{T_S}}$$

$$T_S = T_\gamma \Rightarrow null\ signal$$

- Differential brightness temperature

$$T_{21} \propto T_S(z) - T_\gamma(z)$$



Introduction to 21-cm Cosmology

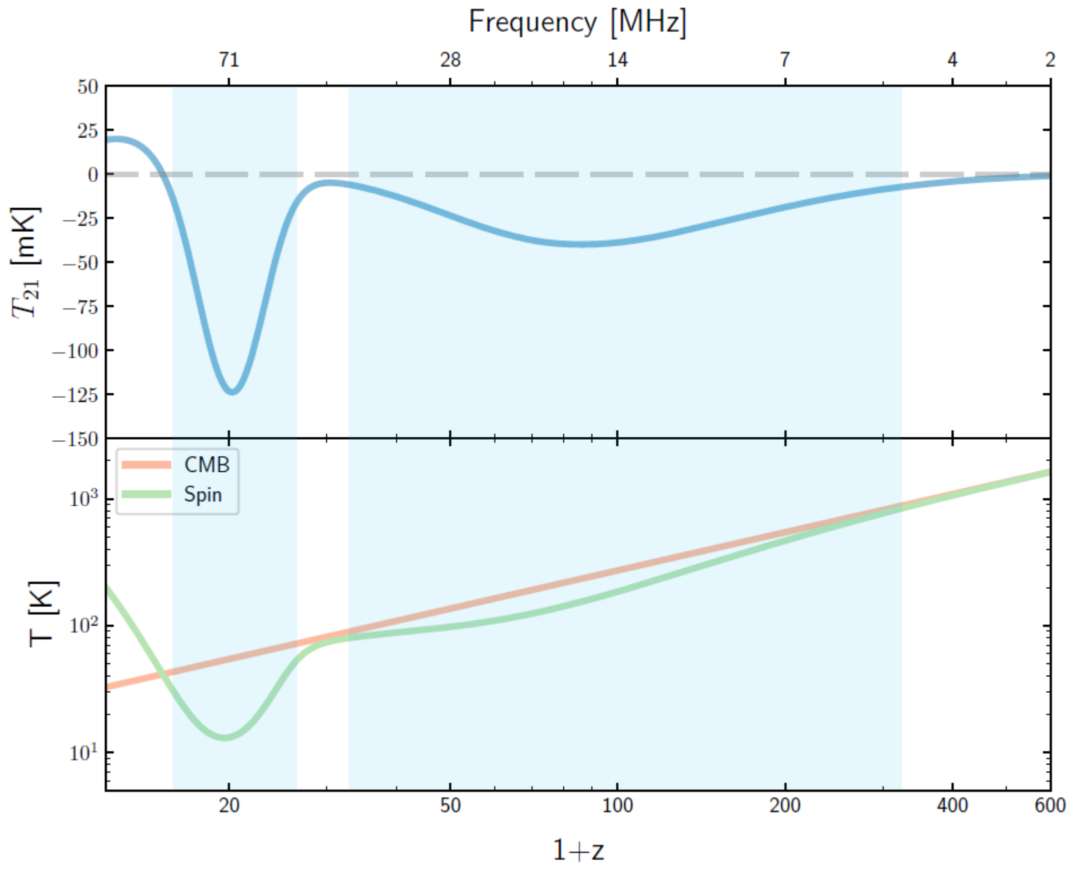
- Define the spin temperature

$$\frac{n_1}{n_0} = 3e^{-\frac{E_{21}}{T_s}}$$

$T_s < T_\gamma \Rightarrow absorption$

- Differential brightness temperature

$$T_{21} \propto T_s(z) - T_\gamma(z)$$



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- Define the spin temperature

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$T_s > T_\gamma \Rightarrow emission$ plot

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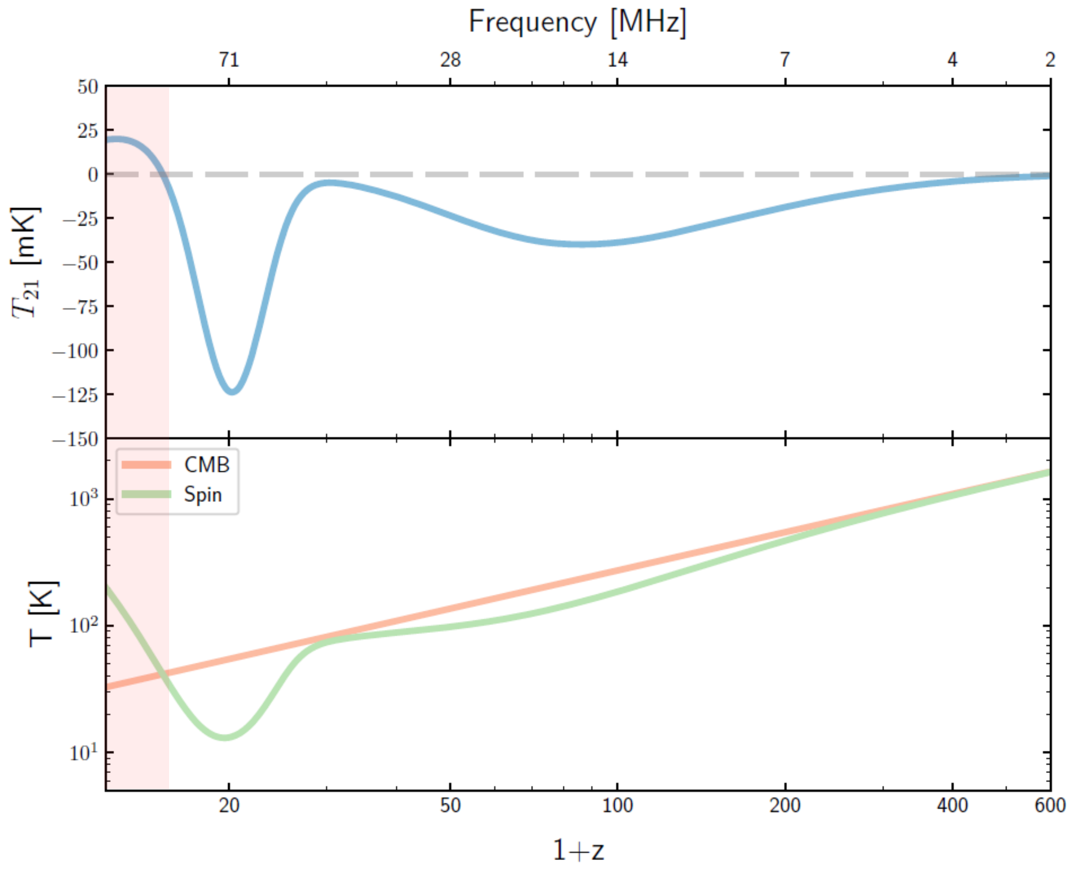
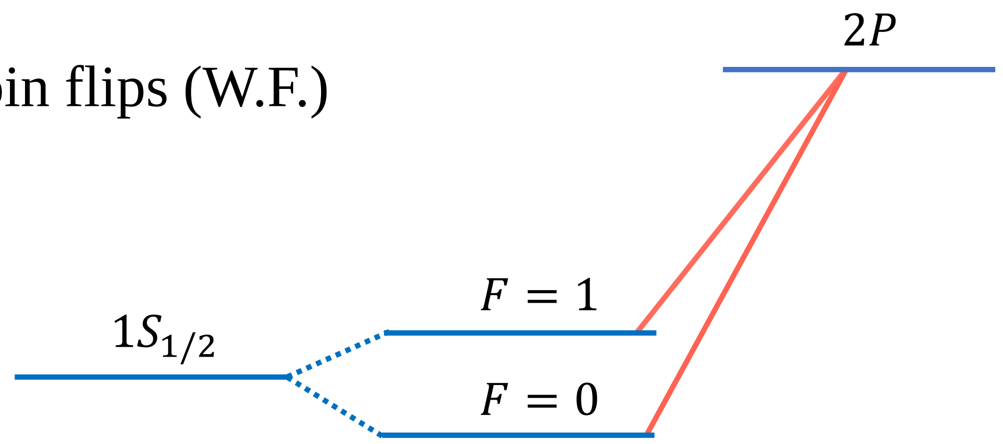


W.F. Coupling

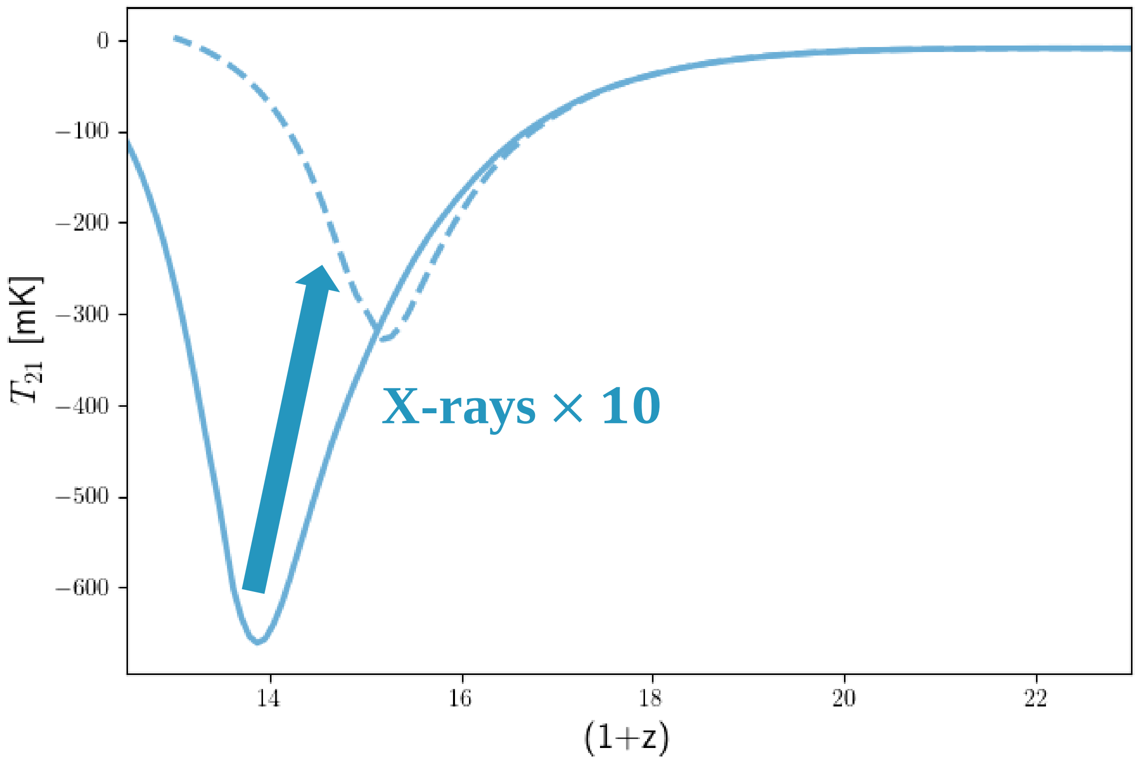
- $Ly\alpha$ photons emitted by the first luminous cause spin flips (W.F.)
- Energy transfer by recoil couple T_s and T_K



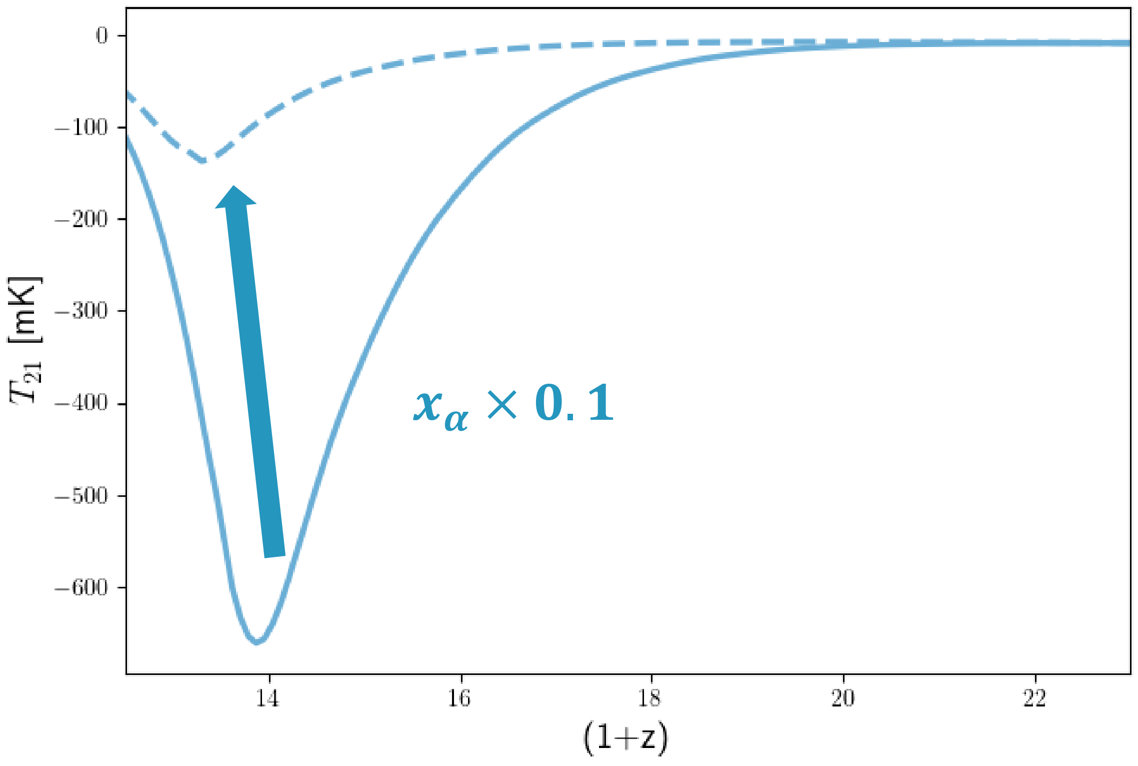
Counter Dark Cooling Effects

Dark Cooling Suppression

Heating effects counter cooling



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



Dark Cooling Suppression

Inefficient $Ly\alpha$ Coupling

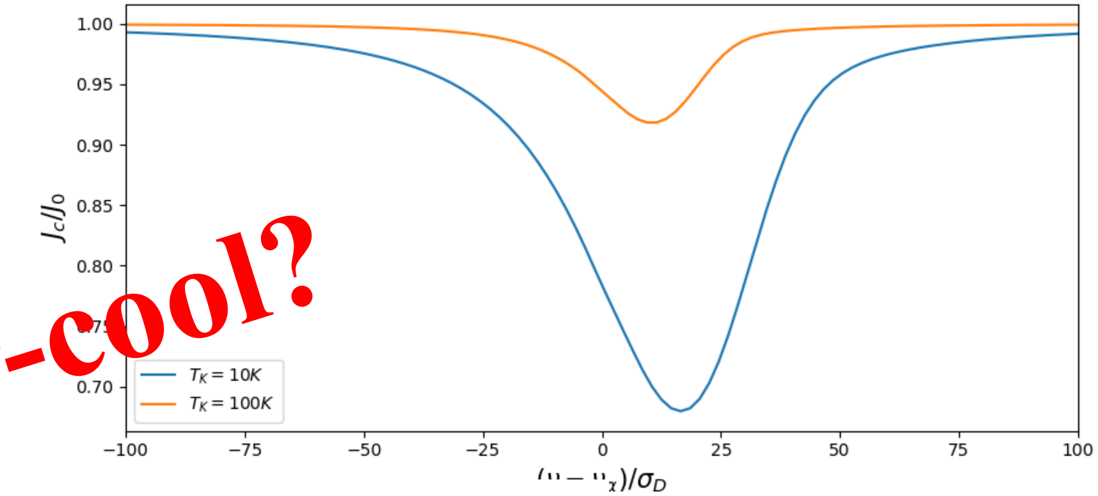
Photons around line center lose energy due to recoil with H

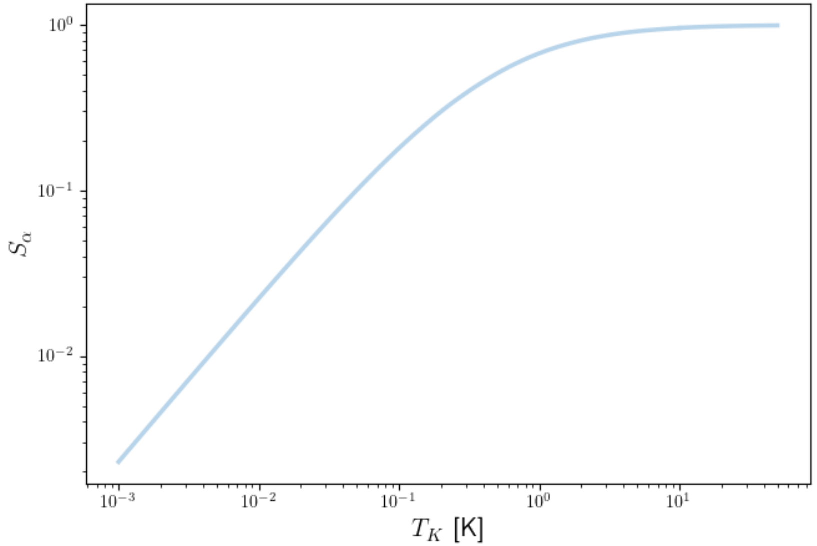
Intensity drops around line center

Inefficient $Ly\alpha$ coupling

$$x_\alpha = \frac{8\pi\lambda_{Ly\alpha}^2 \gamma T_\star}{9A_{10}T_\gamma} S_\alpha J_\alpha$$

What if we over-cool?

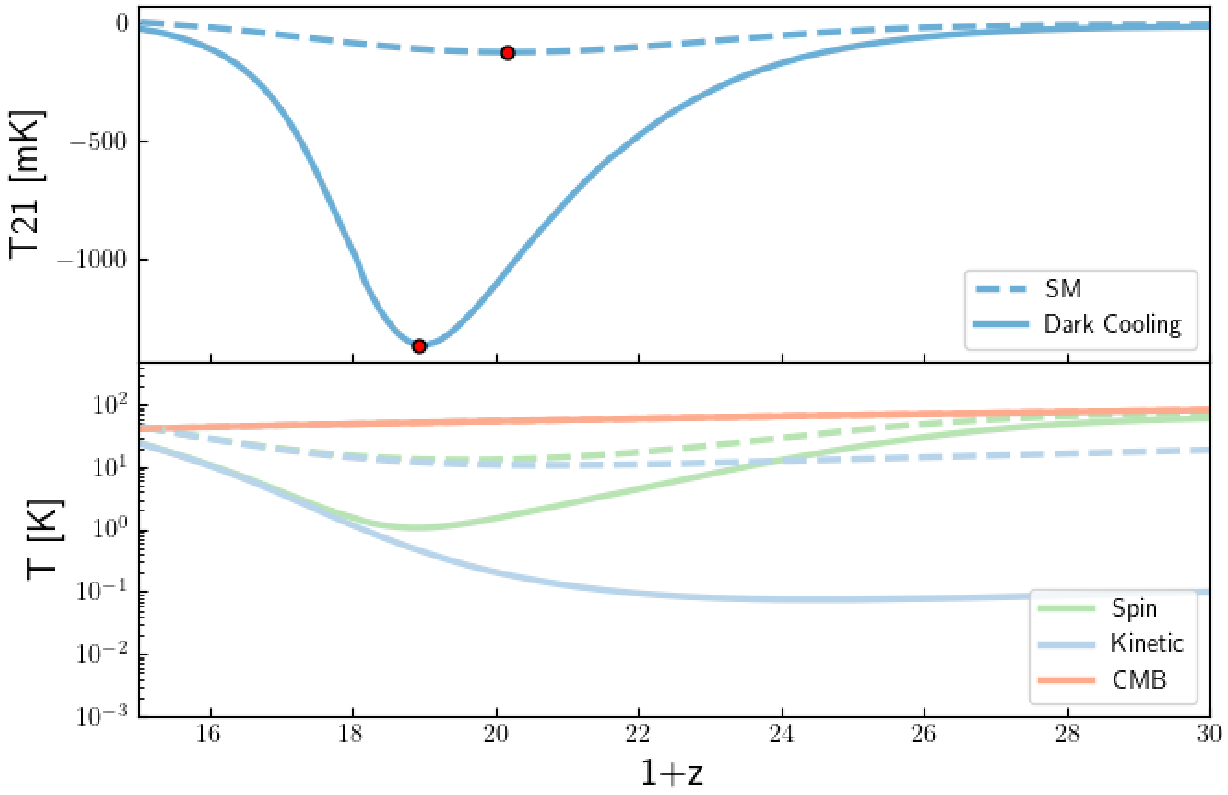




Dark Cooling Suppression

Inefficient $Ly\alpha$ Coupling

- Eventually enough $Ly\alpha$ photons are emitted
- Heating effects ⇒ moderate temperatures



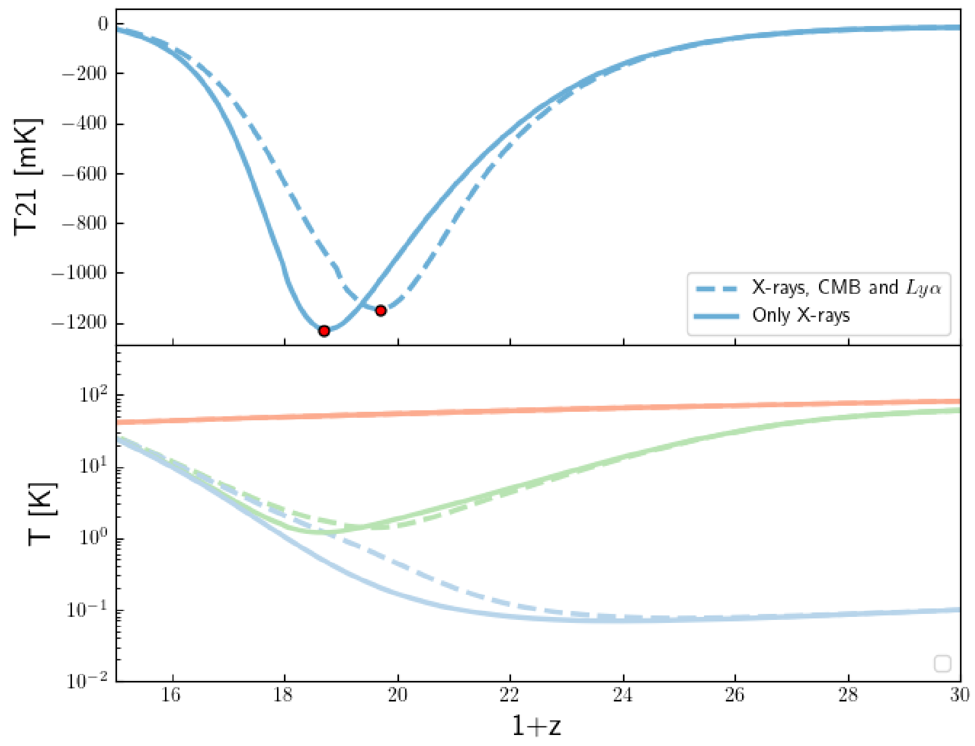
Dark Cooling Suppression

Heating

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

Enhanced at low T_K

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



Dark cooling – Standard scenario

Long range interactions $m_\phi < \mu_I v_{rel} \approx 1KeV \frac{\mu_I}{1GeV}$ ⇒ $m_\phi < 1/r_{Bohr}$

⇓

Interactions do not probe the constituents of atoms

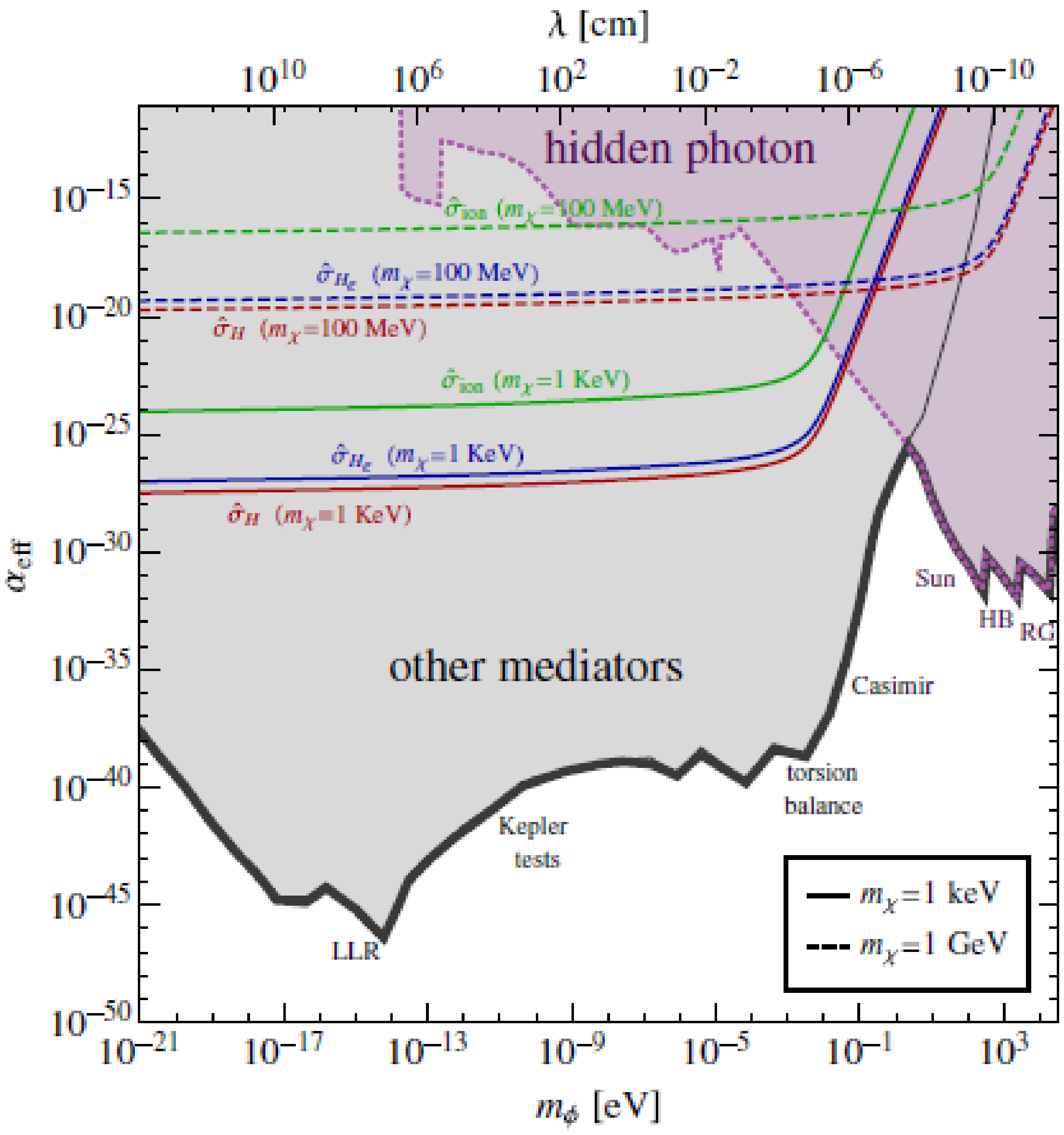
⇐

Screened or unscreened?

- Hidden photon
- Millicharged DM

- Yukawa coupling scalar mediator
- B-L coupling scalar or vector mediator

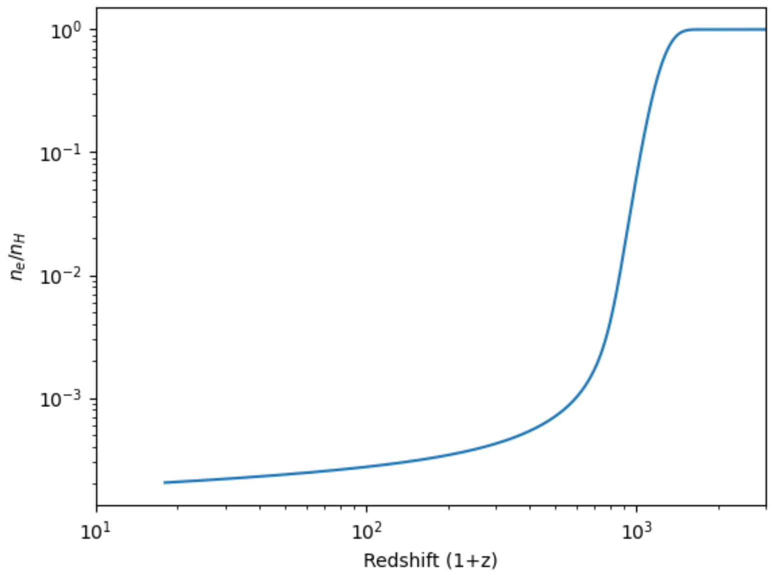
Dark cooling – Standard scenario



[Barkana, Outmezguine, Redigolo, Volansky, 2018]

5th force

Screened



Cooling is dominated by the small ionized fraction

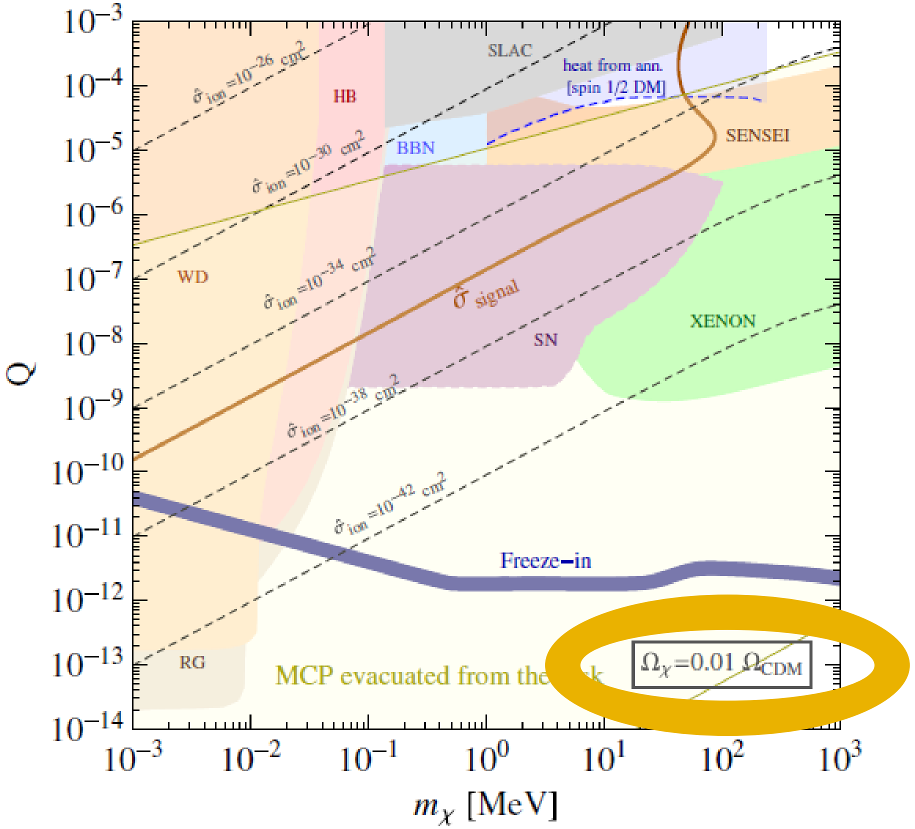
Dark cooling – Standard scenario

[Barkana, Outmezguine, Redigolo, Volansky, 2018]

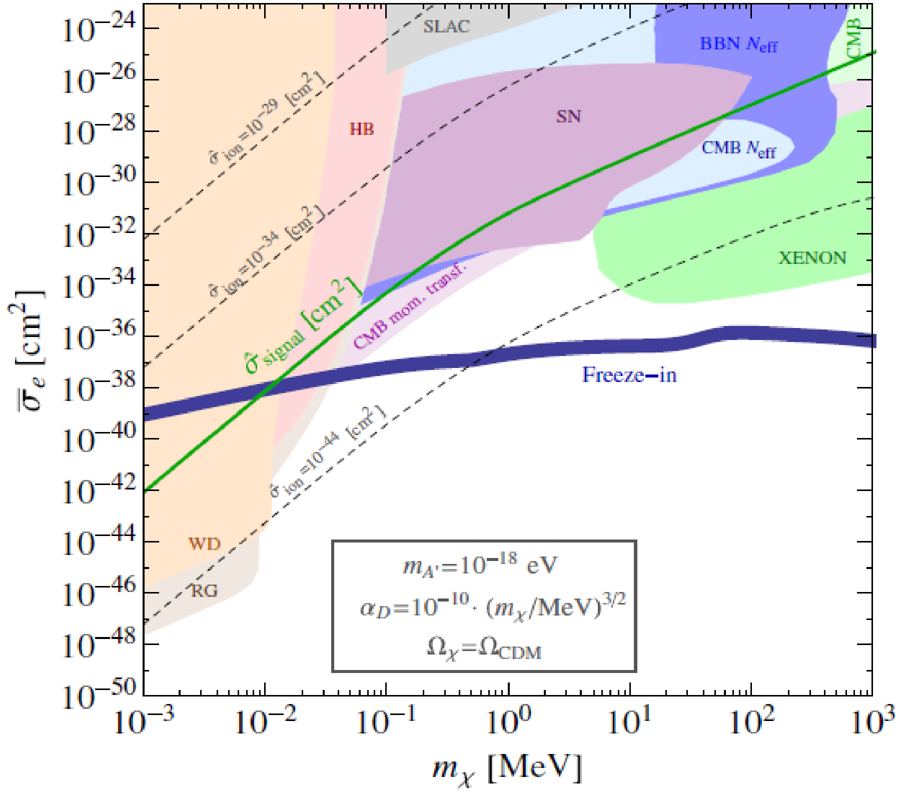
The mediator must be either the SM's photon or a Hidden photon.

$$\frac{d\sigma}{d\Omega} = \frac{\bar{\sigma}}{4\pi}|F(q^2)|^2 = \frac{\bar{\sigma}}{4\pi}|f_{DM}(q^2)|^2|f_{SM}(q^2)|^2$$

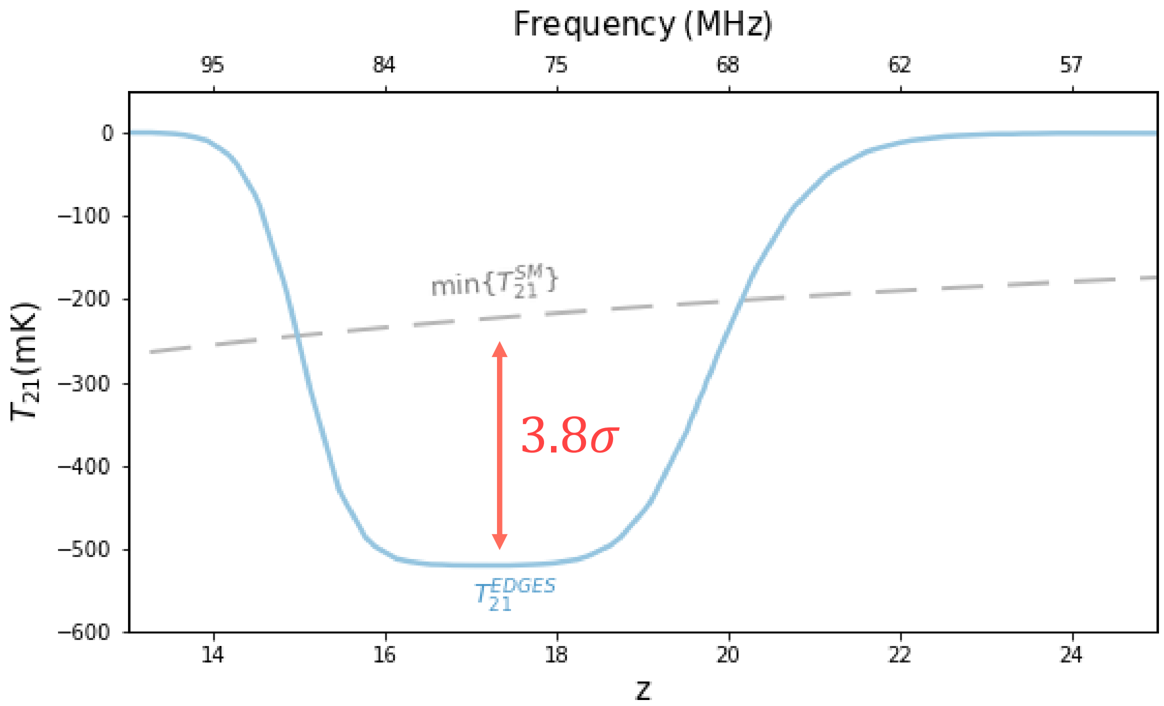
SM photon – millicharged DM

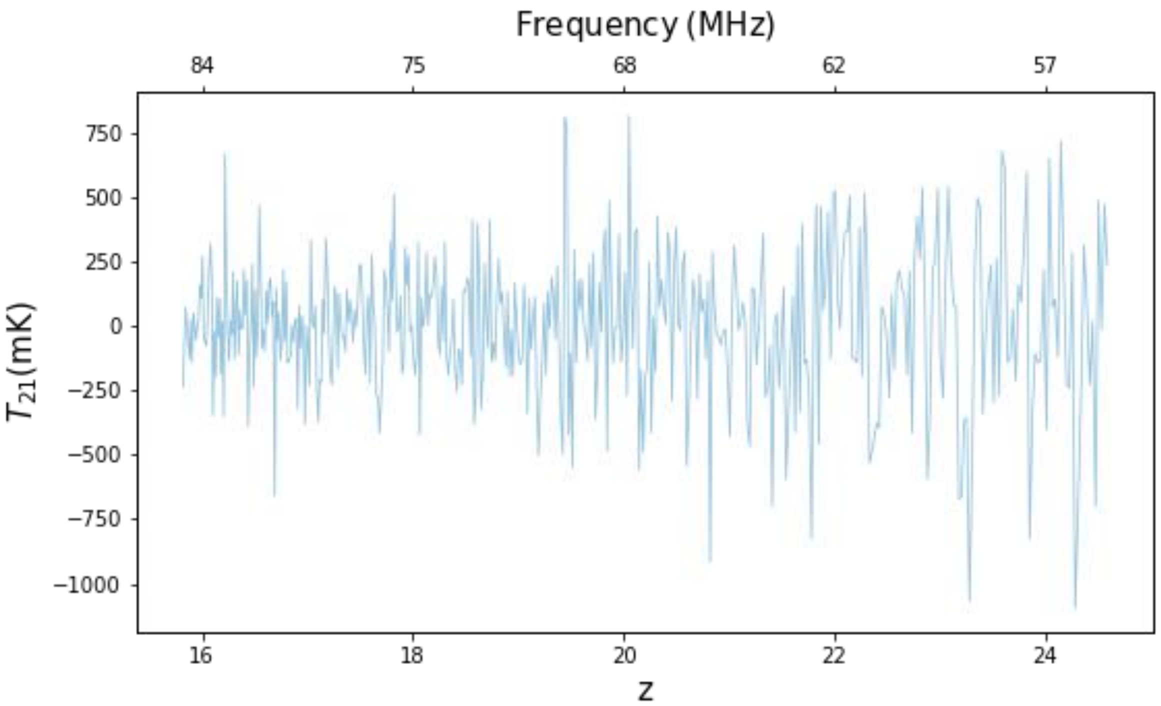


Hidden photon



Measurements





- EDGES collaboration – anomalous absorption at cosmic dawn