New Observational Constraints on Dark Sectors

October 2022

Tomer Volansky
Tel-Aviv University

[Peled, TV, *2022*]
[Barkana, Outmezguine, Redigolo, TV, *2018*]
[Liu, Outmezguine, Redigolo, TV, *2019*]
[Katz, Outmezguine, Redigolo, TV, *to appear*]
[Bloch, Outmezguine, Redigolo, Sun, TV, *work in progress*]
[Gouttenoire, Ruderman, Slone, TV, *work in progress*]

DALL·E

“How to find Dark Matter using astrophysics”

DALL·E

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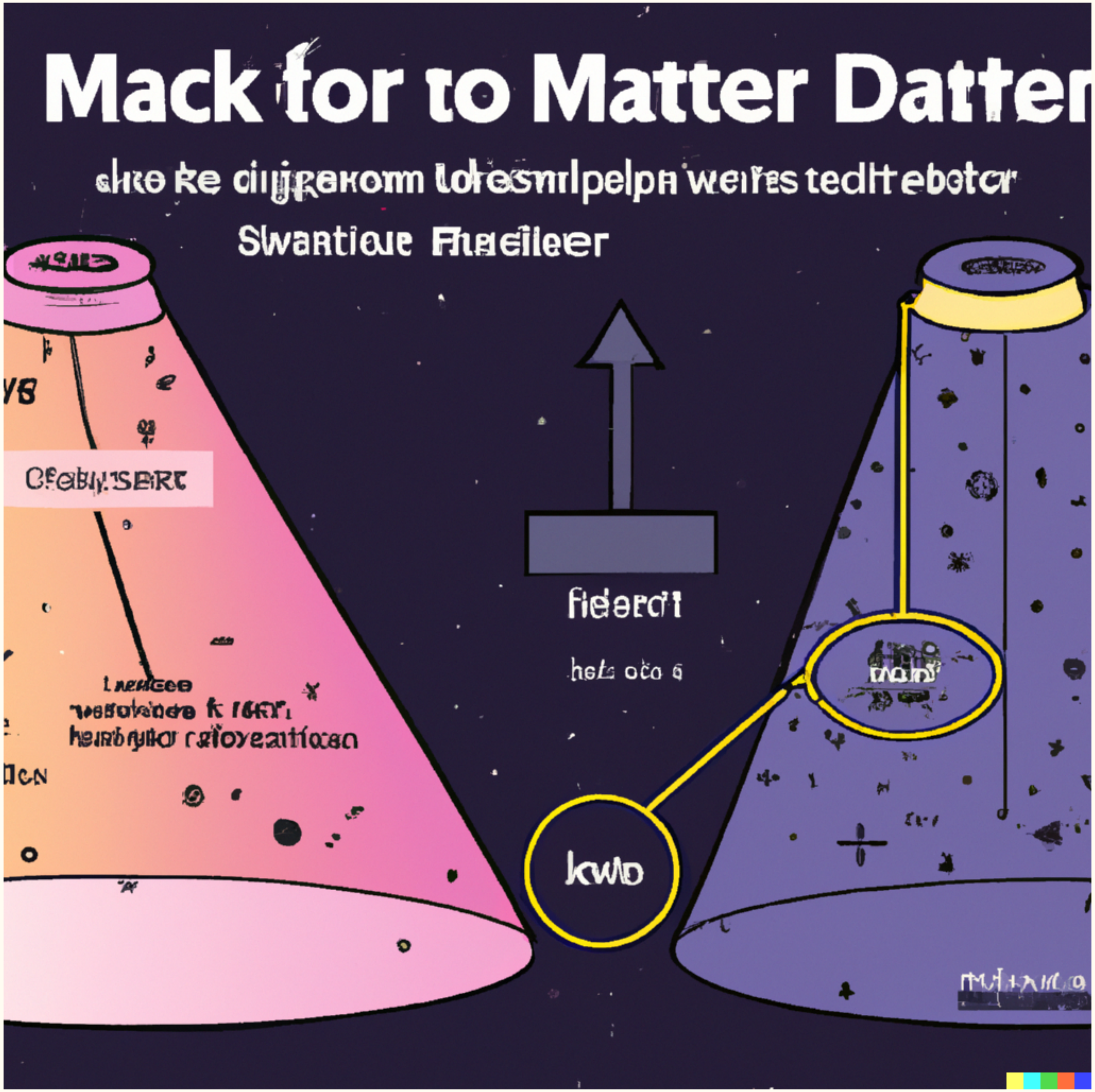


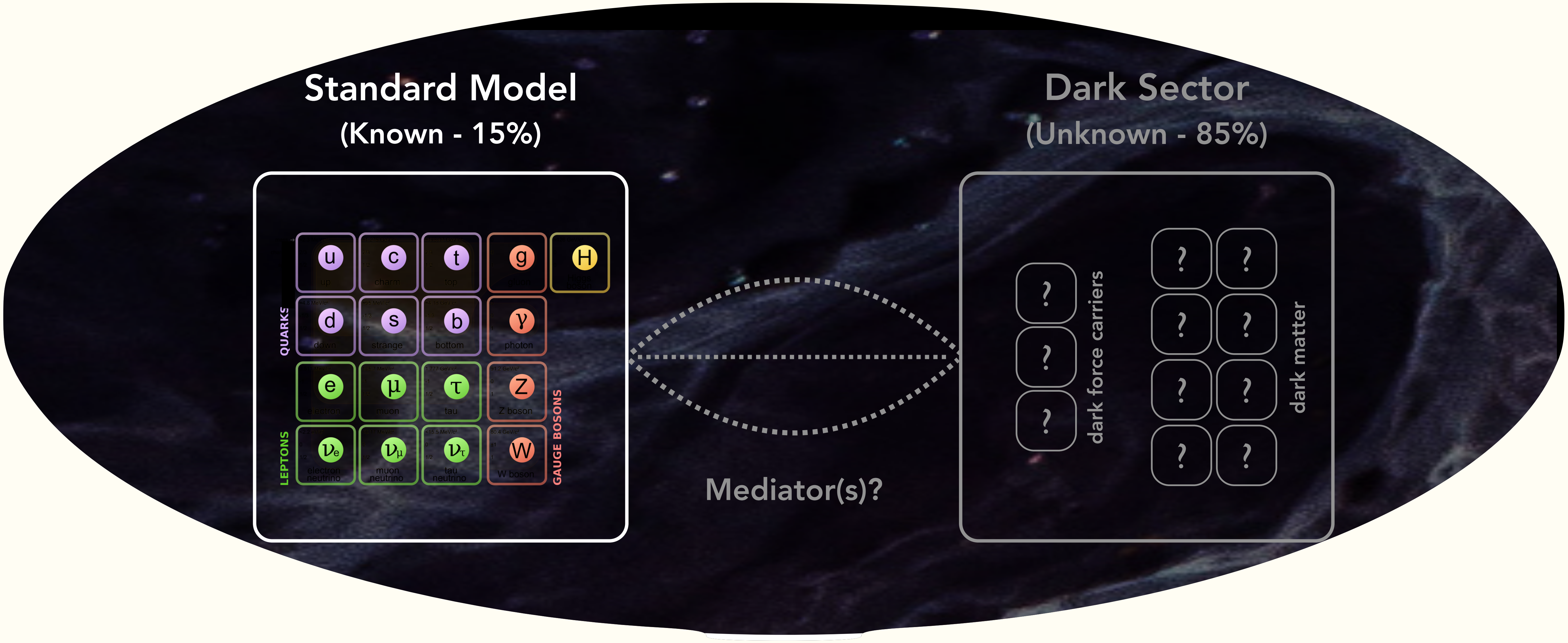
DALL·E

"Is there dark matter in Madrid?"

DALL·E

“logo for a dark matter experiment in an underground facility drawn in round Japanese style painting”

Motivation



Standard Model
(Known - 15%)

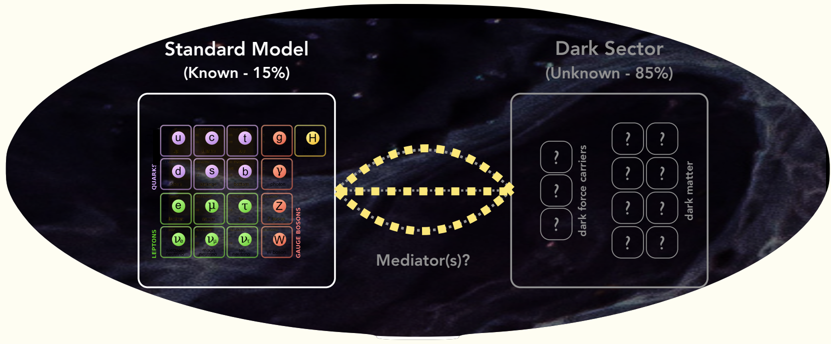
Dark Sector
(Unknown - 85%)

Mediator(s)?

Outline

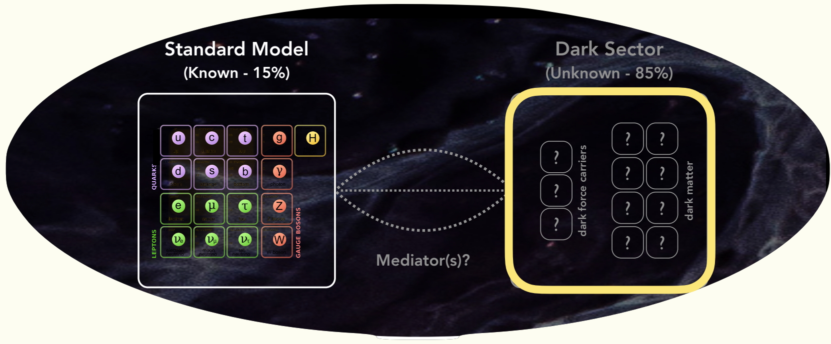
21-cm

Closing the gaps on strongly interacting DM



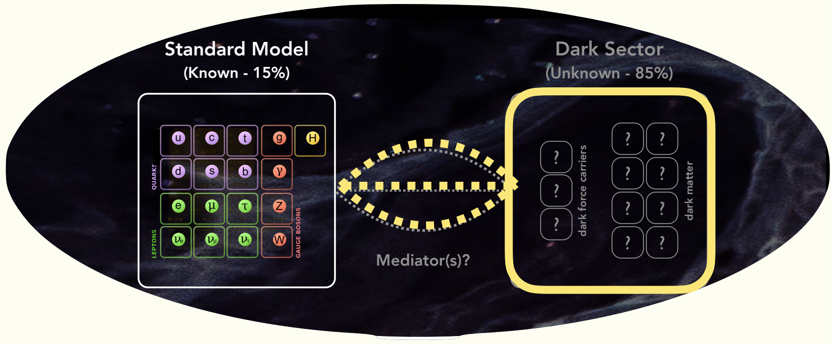
Double-lined Spectroscopic Binaries

Searching for Dissipative DM in Stars



General Dark Mediation

Environmental DM



Light Dark Matter in the Sky

21-cm Cosmology

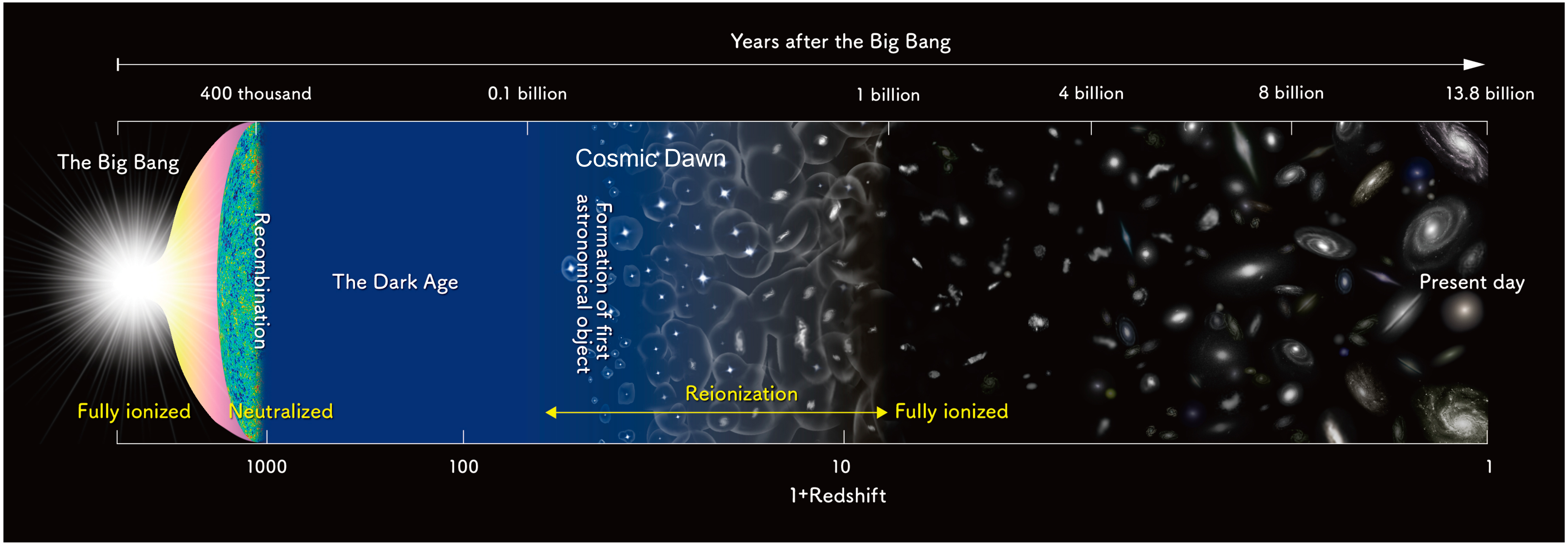
[Barkana, Outmezguine, Redigolo, TV, *2018*]

[Liu, Outmezguine, Redigolo, TV, *2019*]

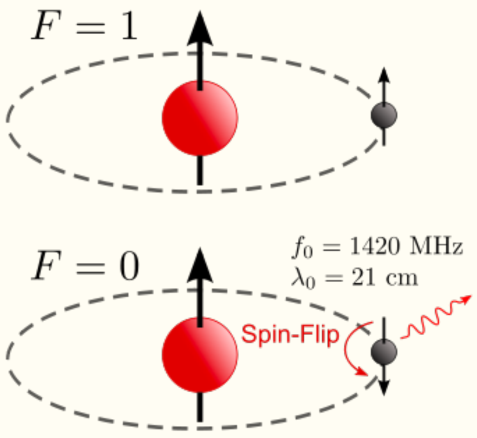
[Katz, Outmezguine, Redigolo, TV, *work in progress*]

21-cm Cosmology Basics

After recombination (z~1100): Baryon density is mostly hydrogen



21-cm (6x10^{-6} eV) line tracks the Hydrogen in the early universe.



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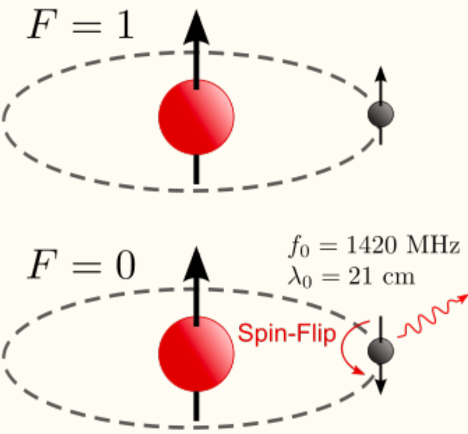


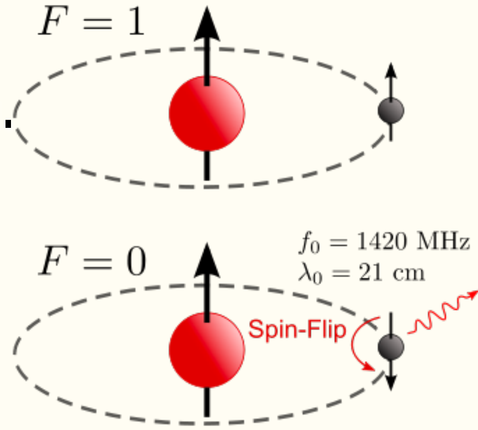
- The hydrogen is at its ground state, split by hyperfine interaction.

- Spin temperature is defined by:

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

- 3 effects change T_s:

21-cm Cosmology Basics



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  - H-H and H-e scattering:

$$C_{01} = \frac{g_1}{g_0} C_{10} e^{-E_{21}/T_{\rm gas}}$$

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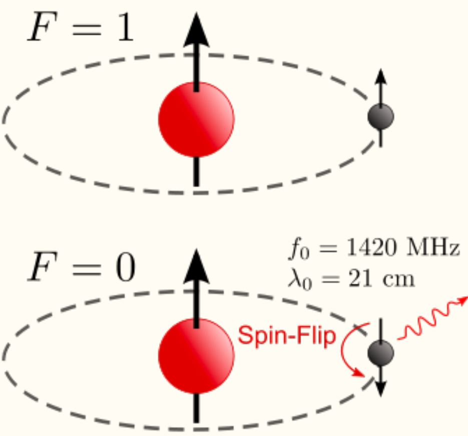

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  - Spontaneous and induced emission: $B_{10} = \frac{B_{01}}{3} = A_{10}\frac{T_{\mathrm{CMB}}}{E_{12}}$

$$A_{10} \approx 2.9 \times 10^{-15}\ \mathrm{sec}^{-1}$$

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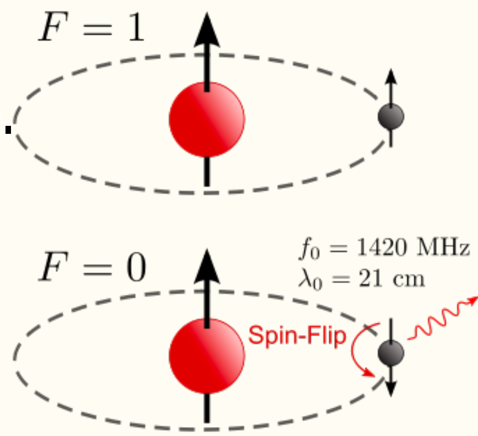

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  - Lyman radiation $L_{01} = \frac{g_1}{g_0} L_{10} e^{-E_{21}/T_c}$

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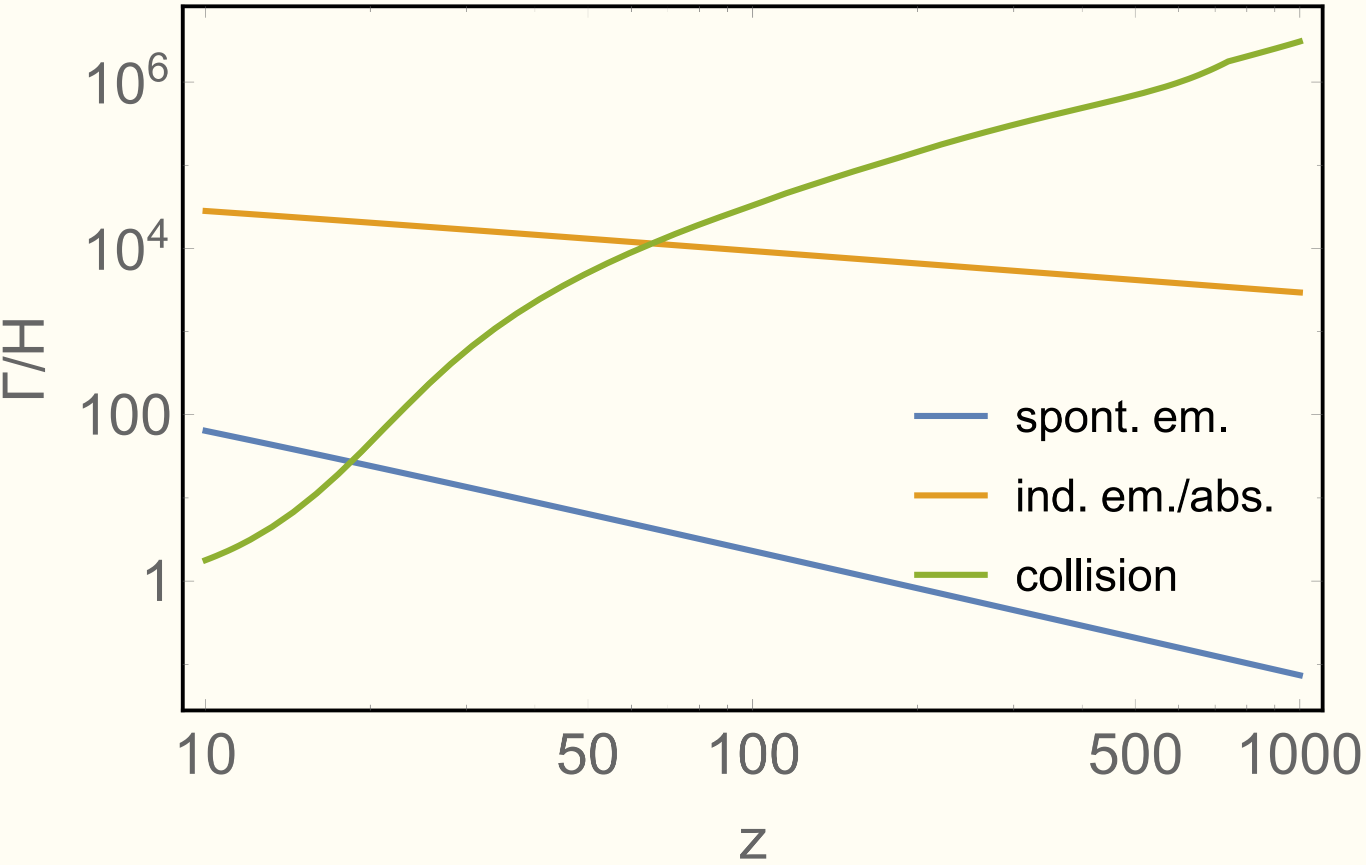

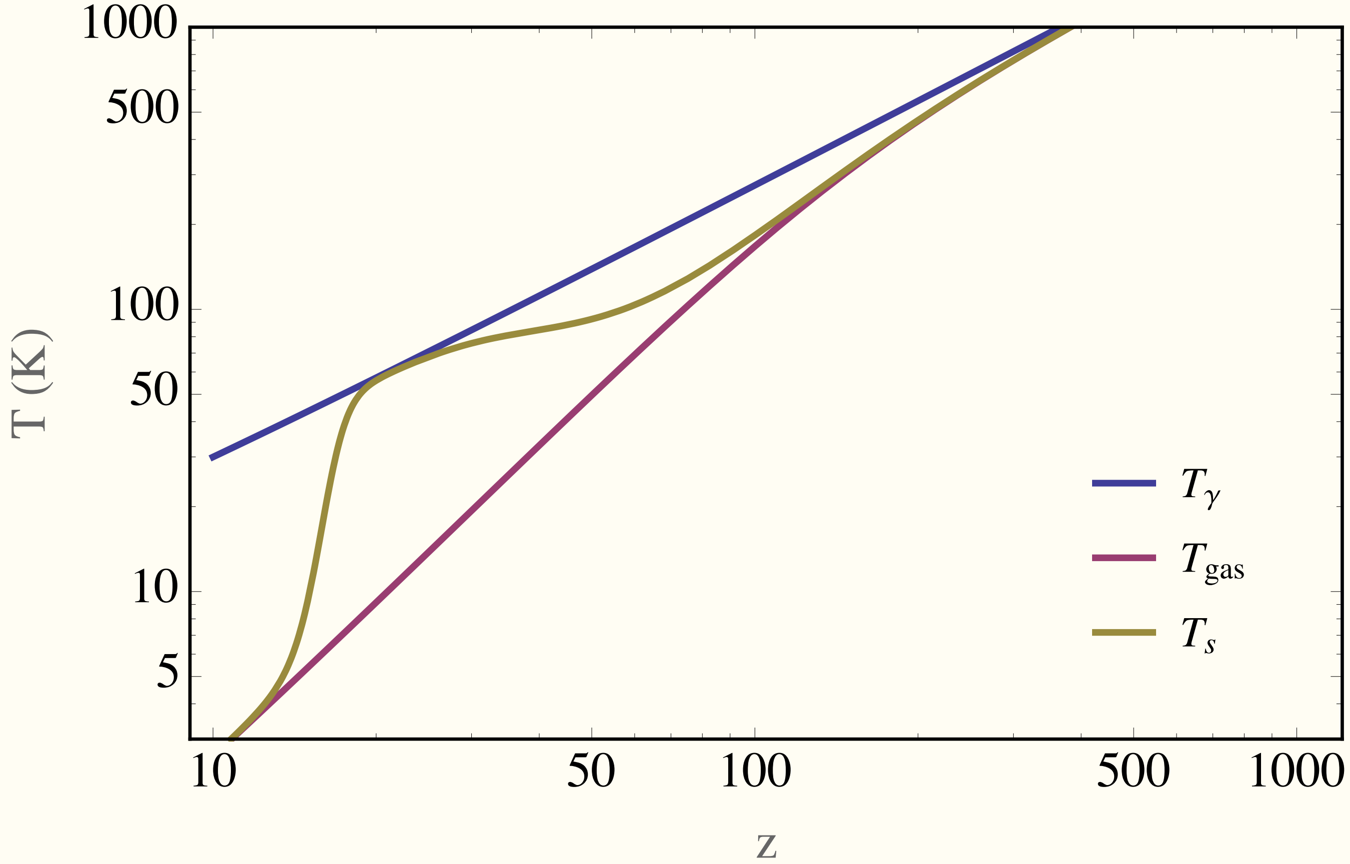

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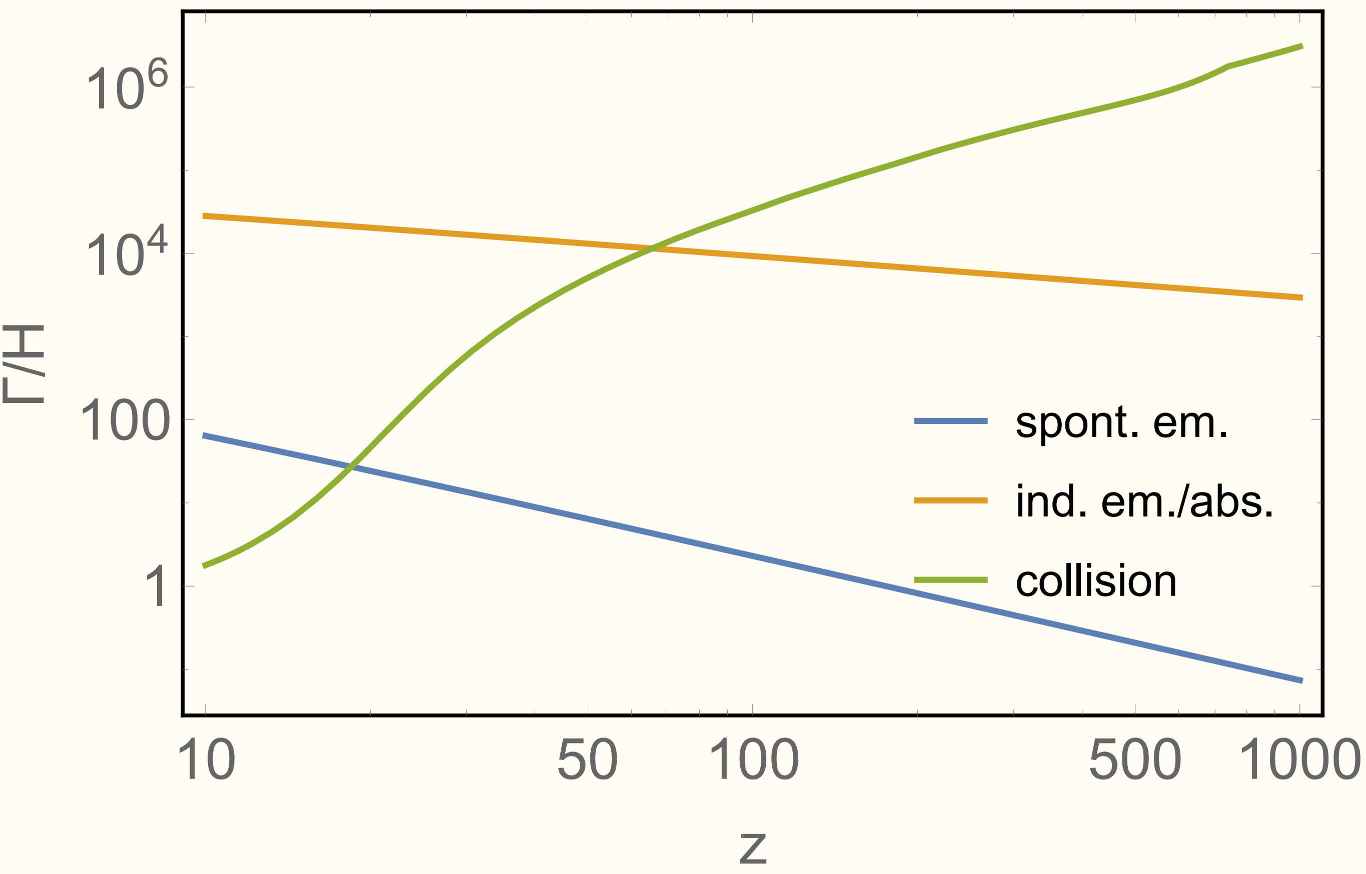
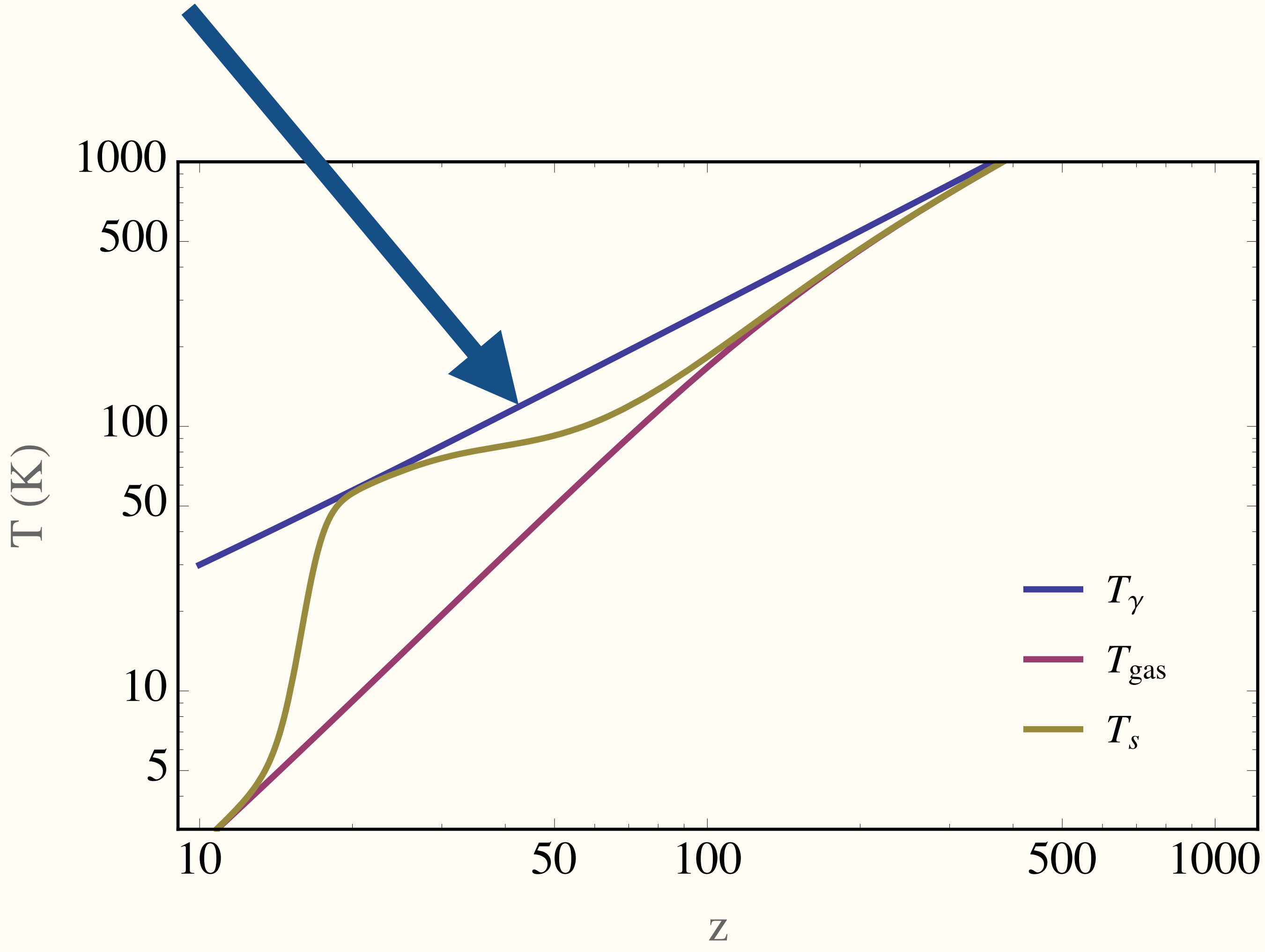
CMB Temperature





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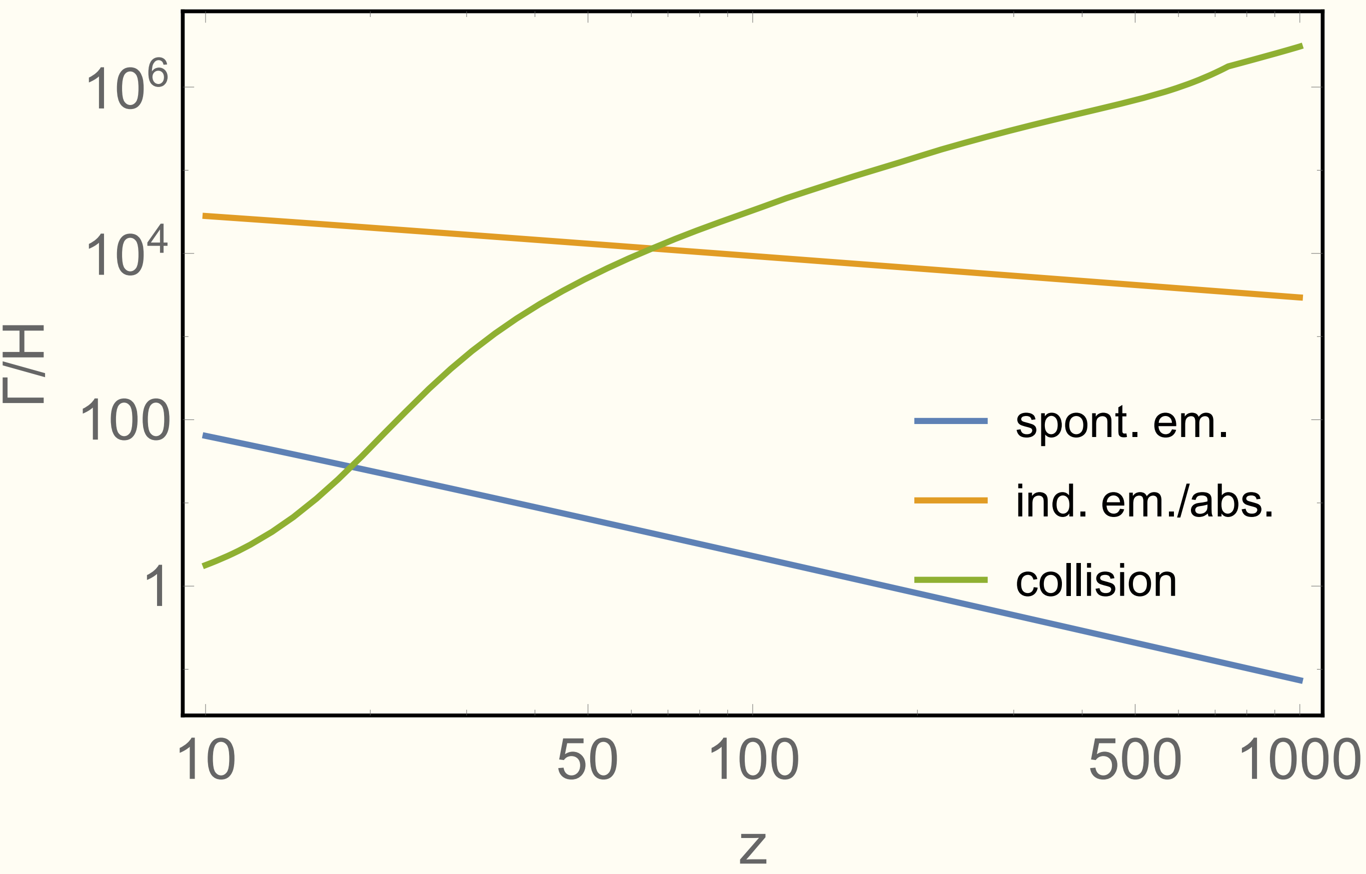
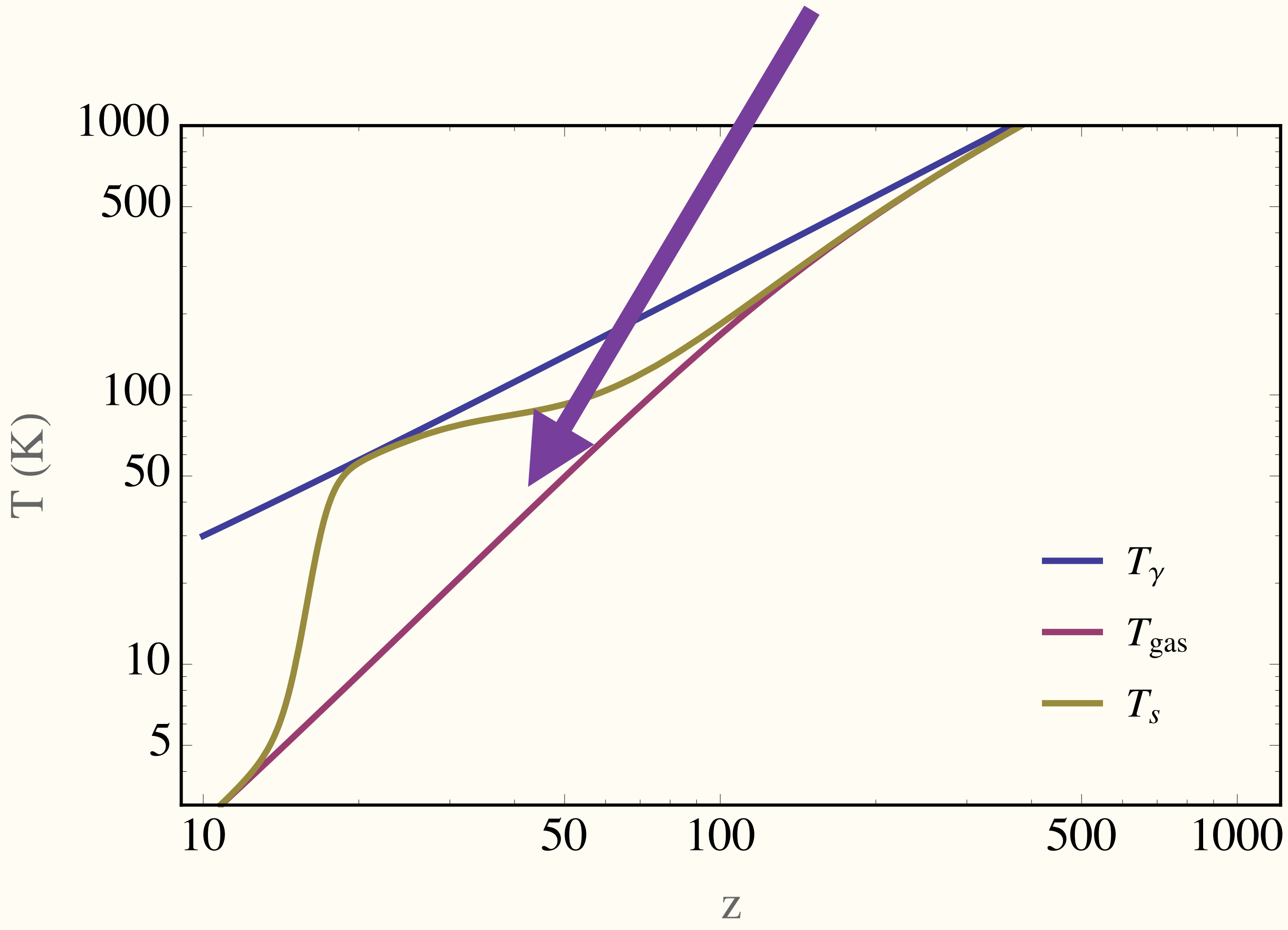


Gas Temperature



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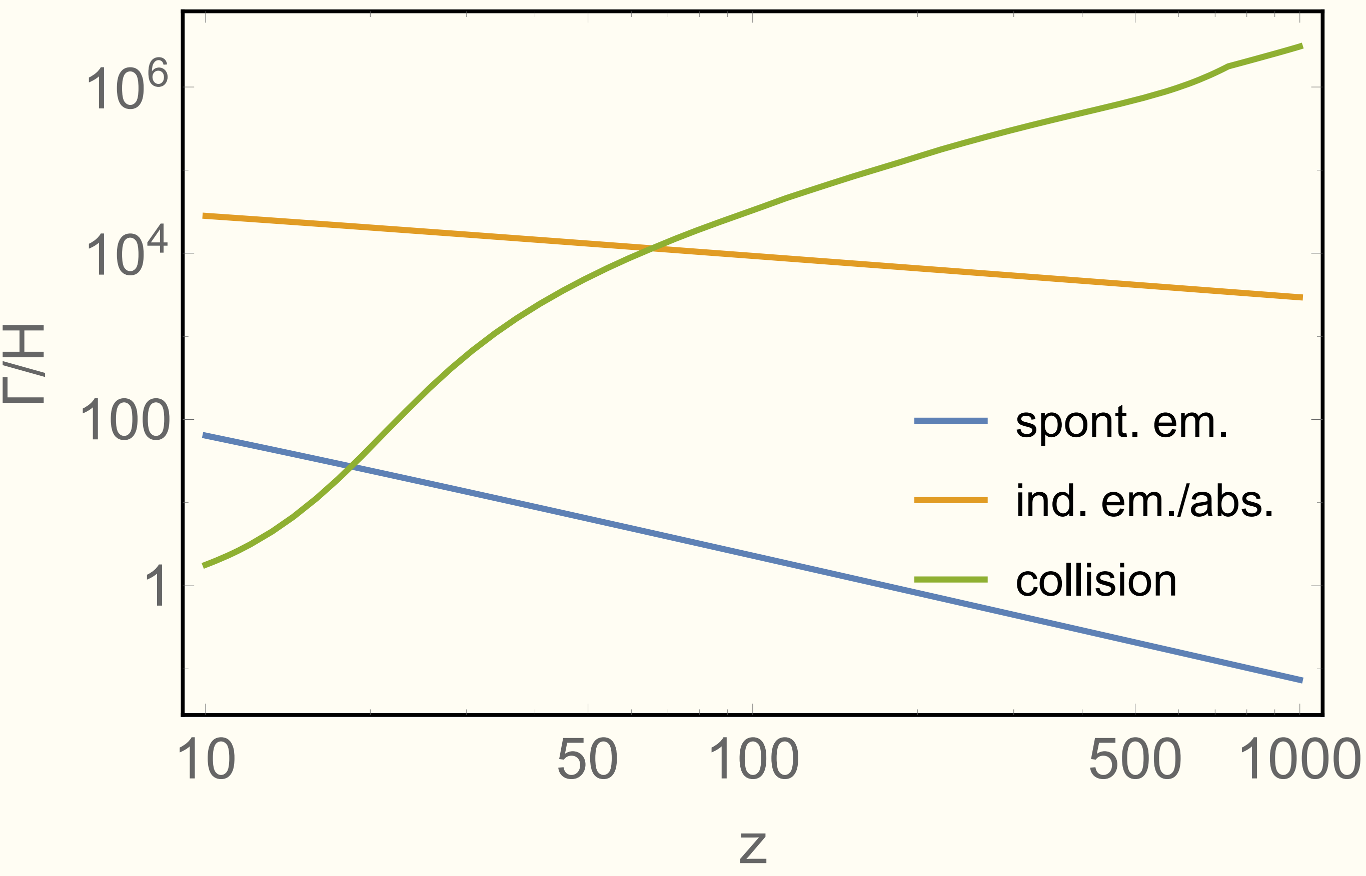
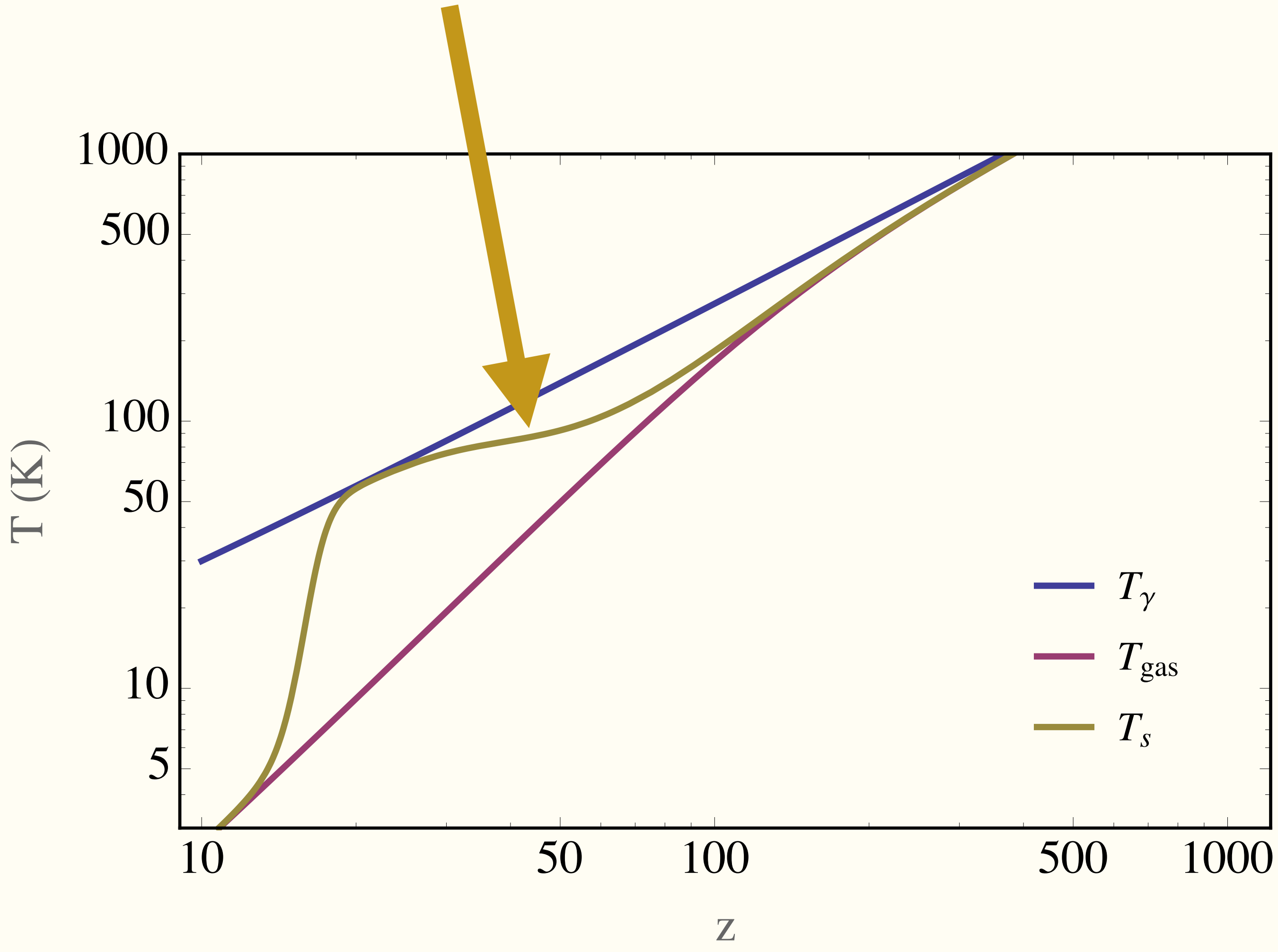


Spin Temperature



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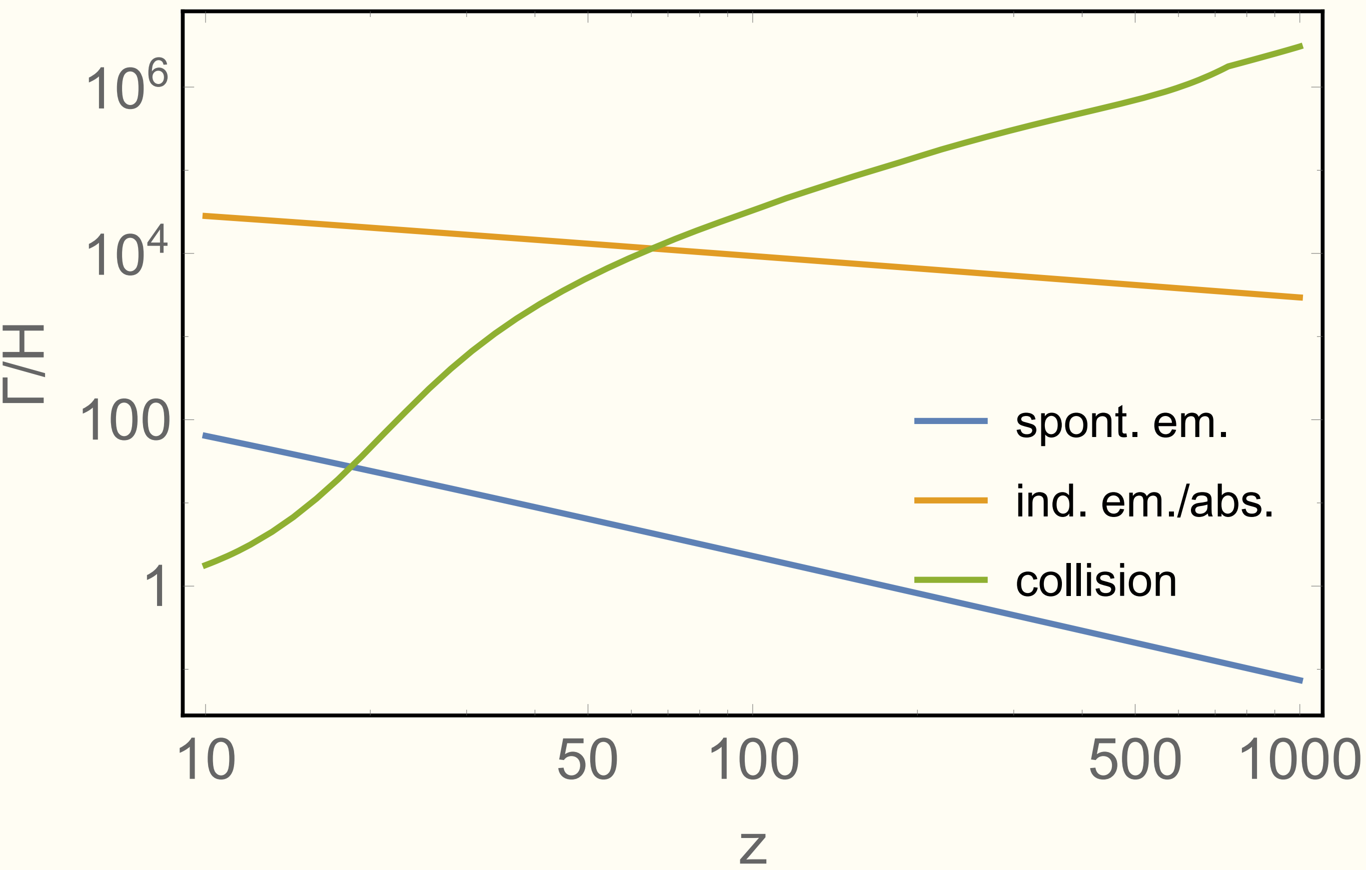

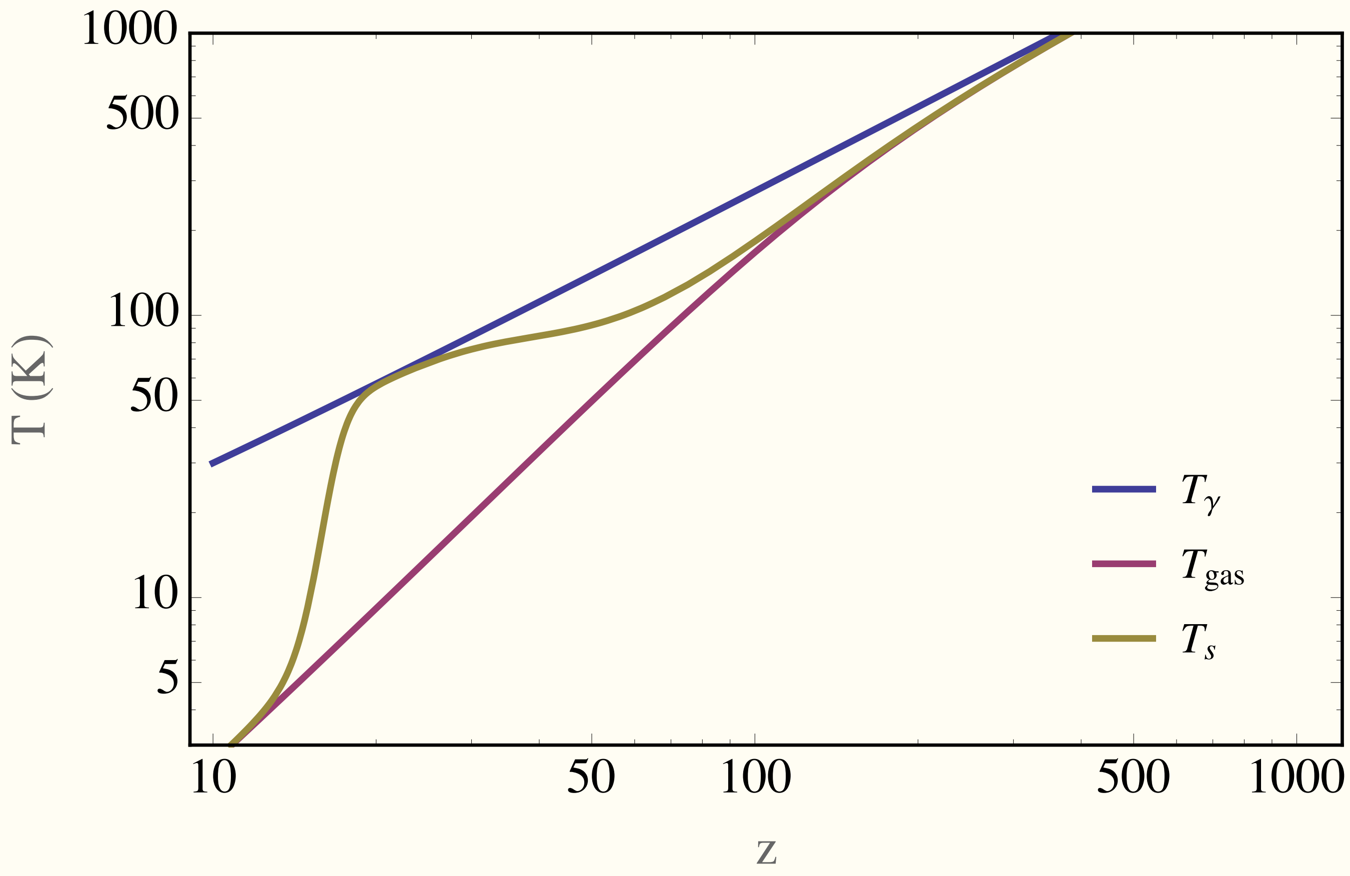

21-cm Cosmology Basics

- Boltzmann equation for the spin density:

$$\dot{n}_0 + 3Hn_0 = -n_0(C_{01} + B_{01} + L_{01}) + n_1(C_{10} + A_{10} + B_{10} + L_{10})$$

- Gives:

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_{\rm gas} T_{\rm gas}^{-1} + x_\alpha T_\alpha^{-1}}{1 + x_{\rm gas} + x_\alpha}$$

$$x_\alpha = \frac{E_{21}}{T_\gamma}\frac{L_{10}}{A_{10}}$$

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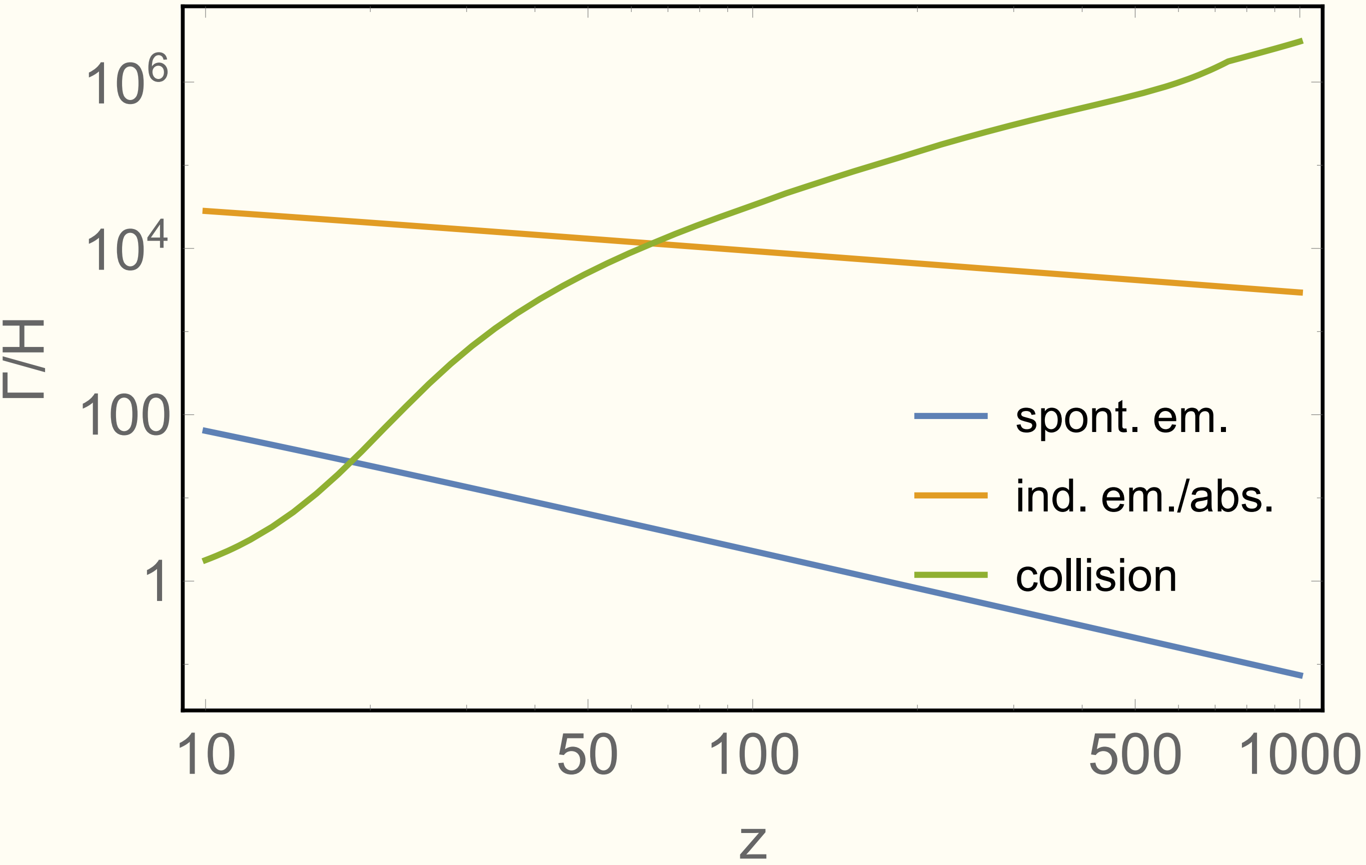

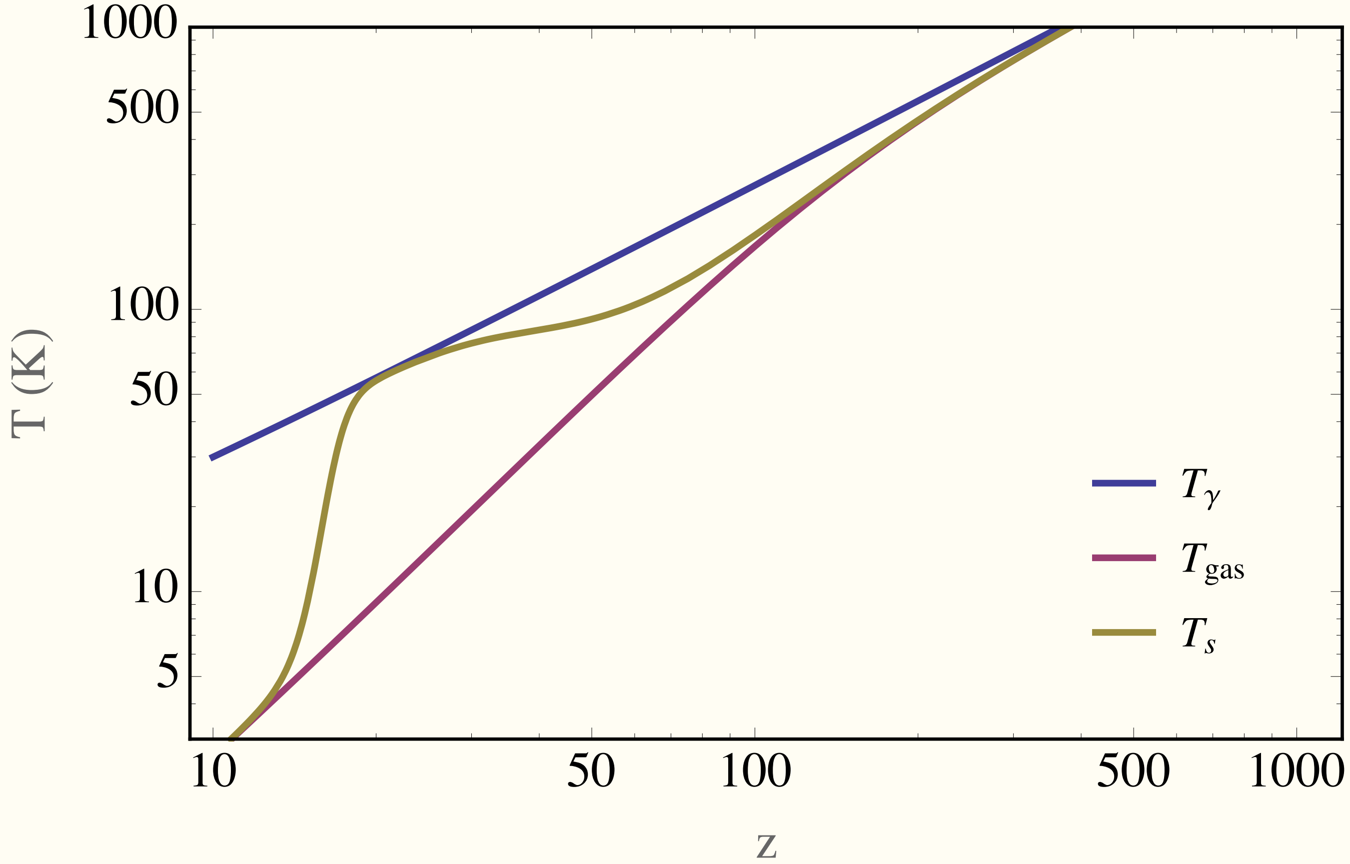

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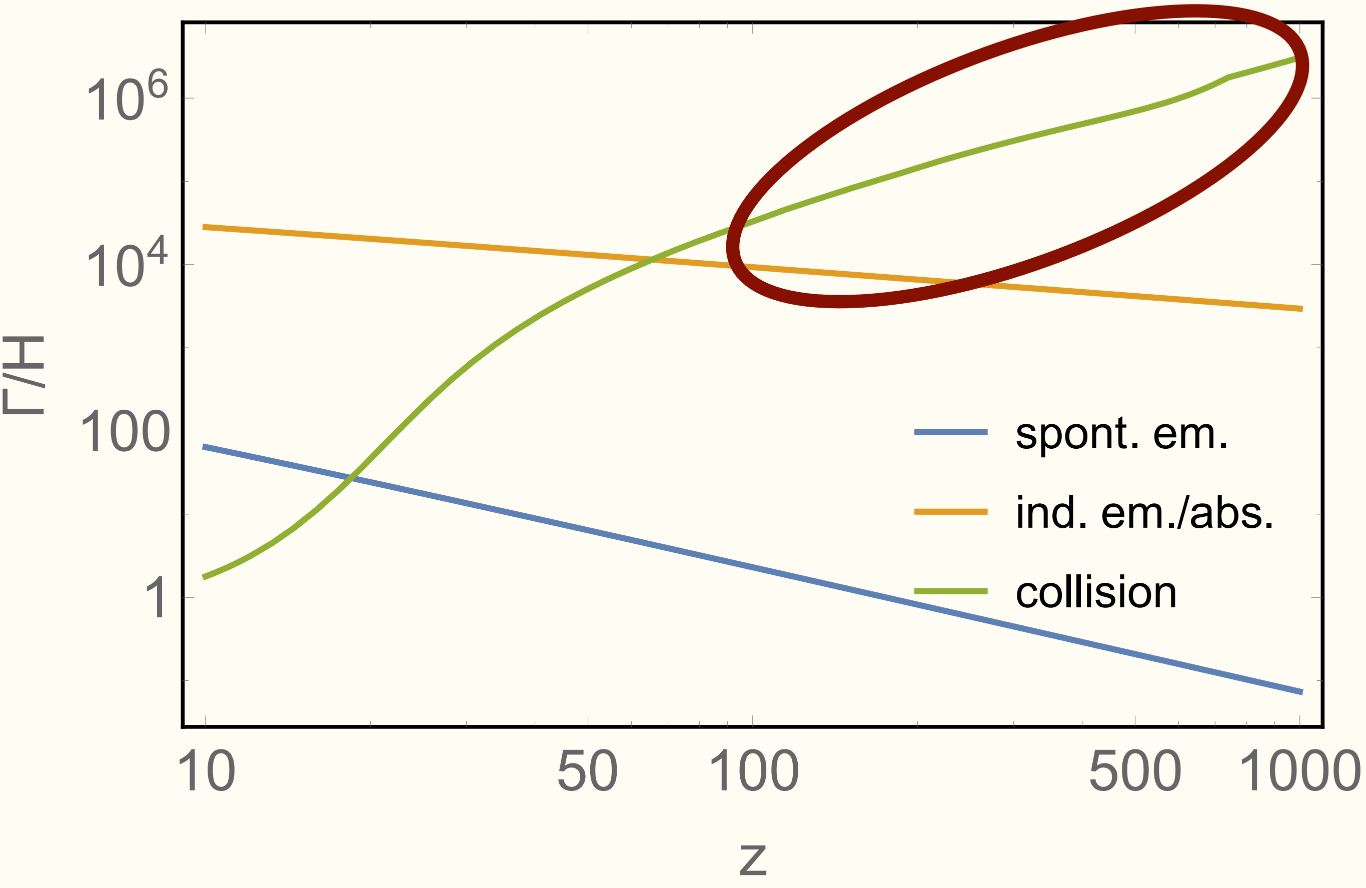
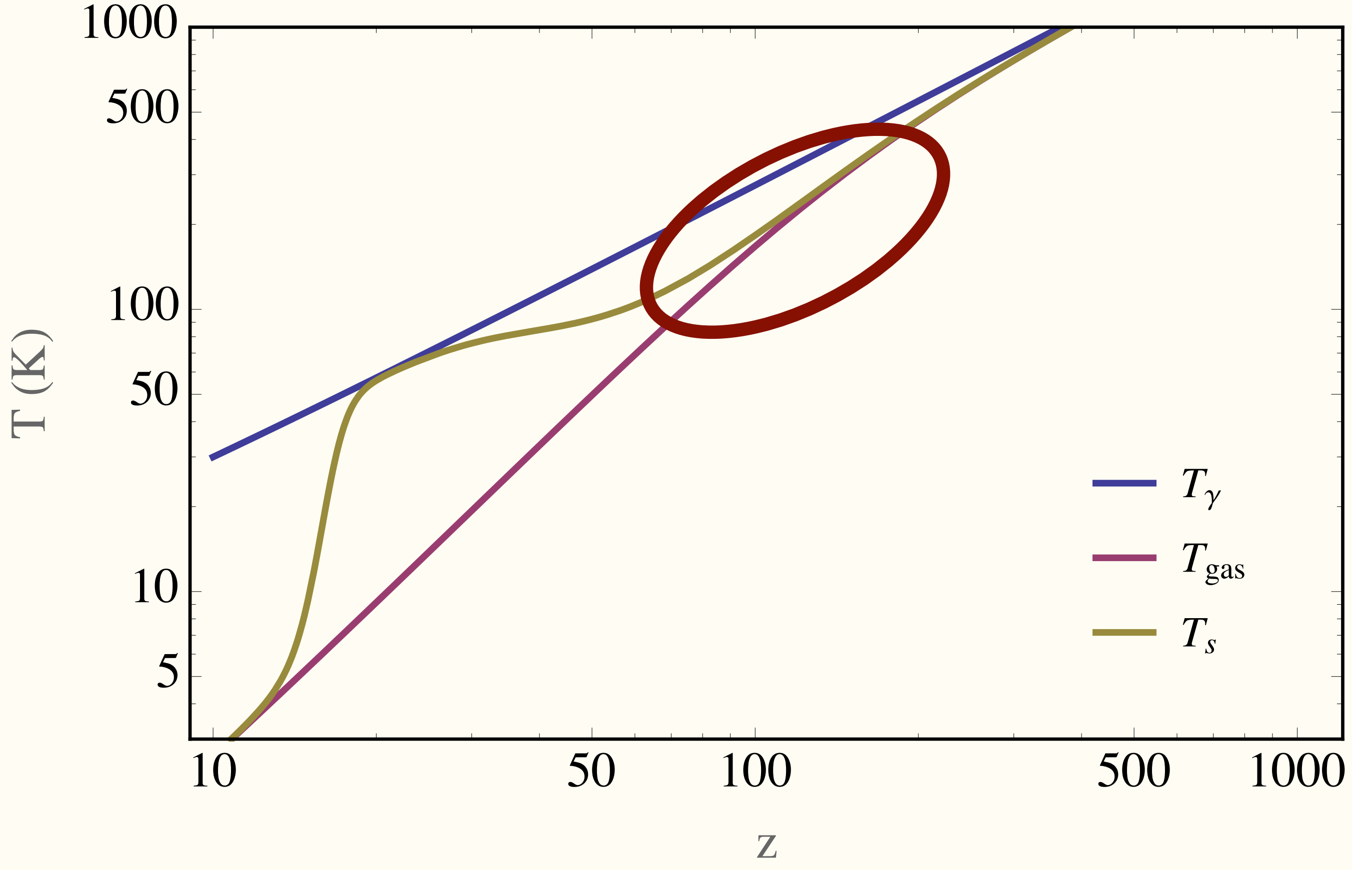
H-H & H-e Collisions





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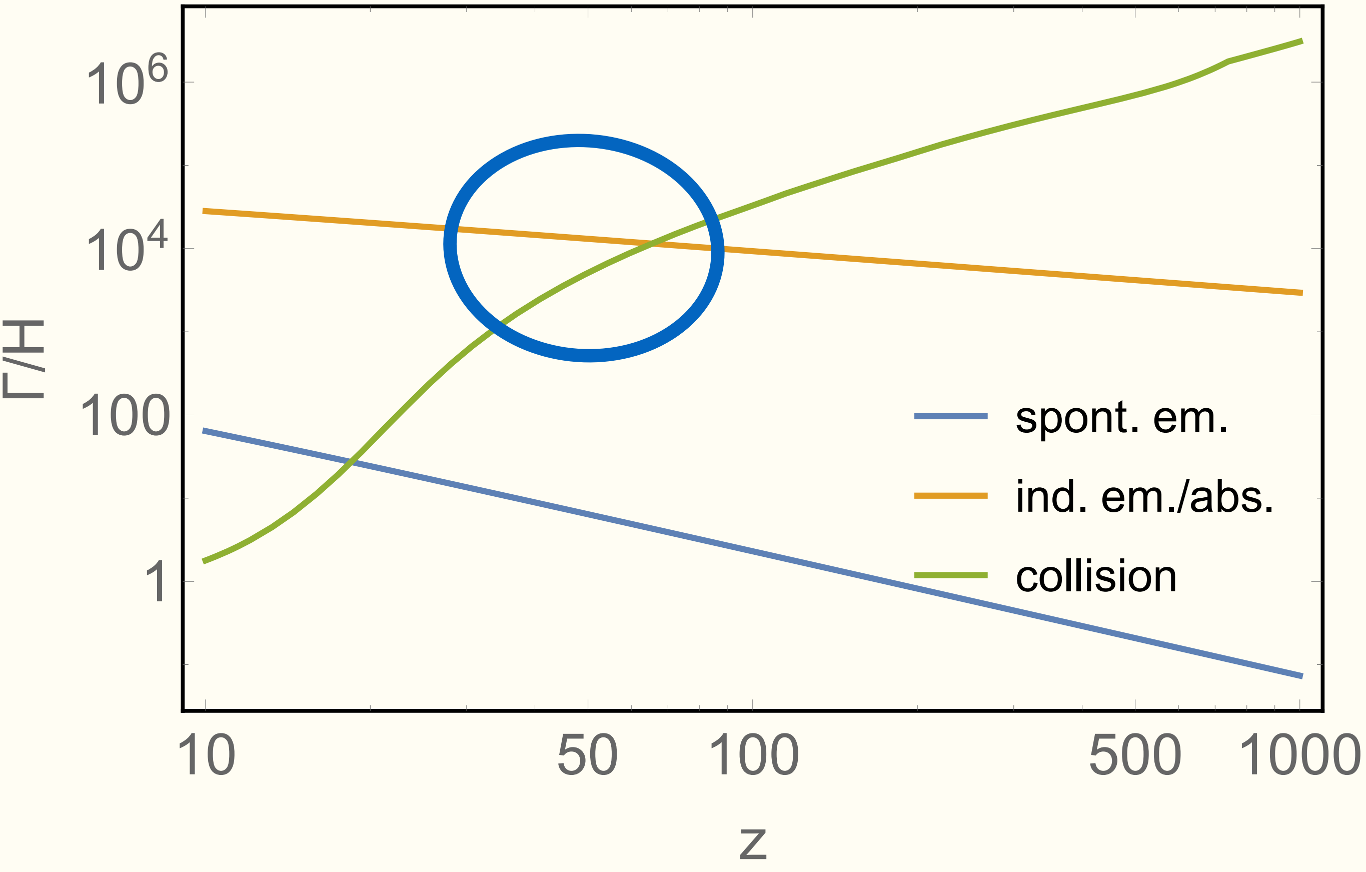
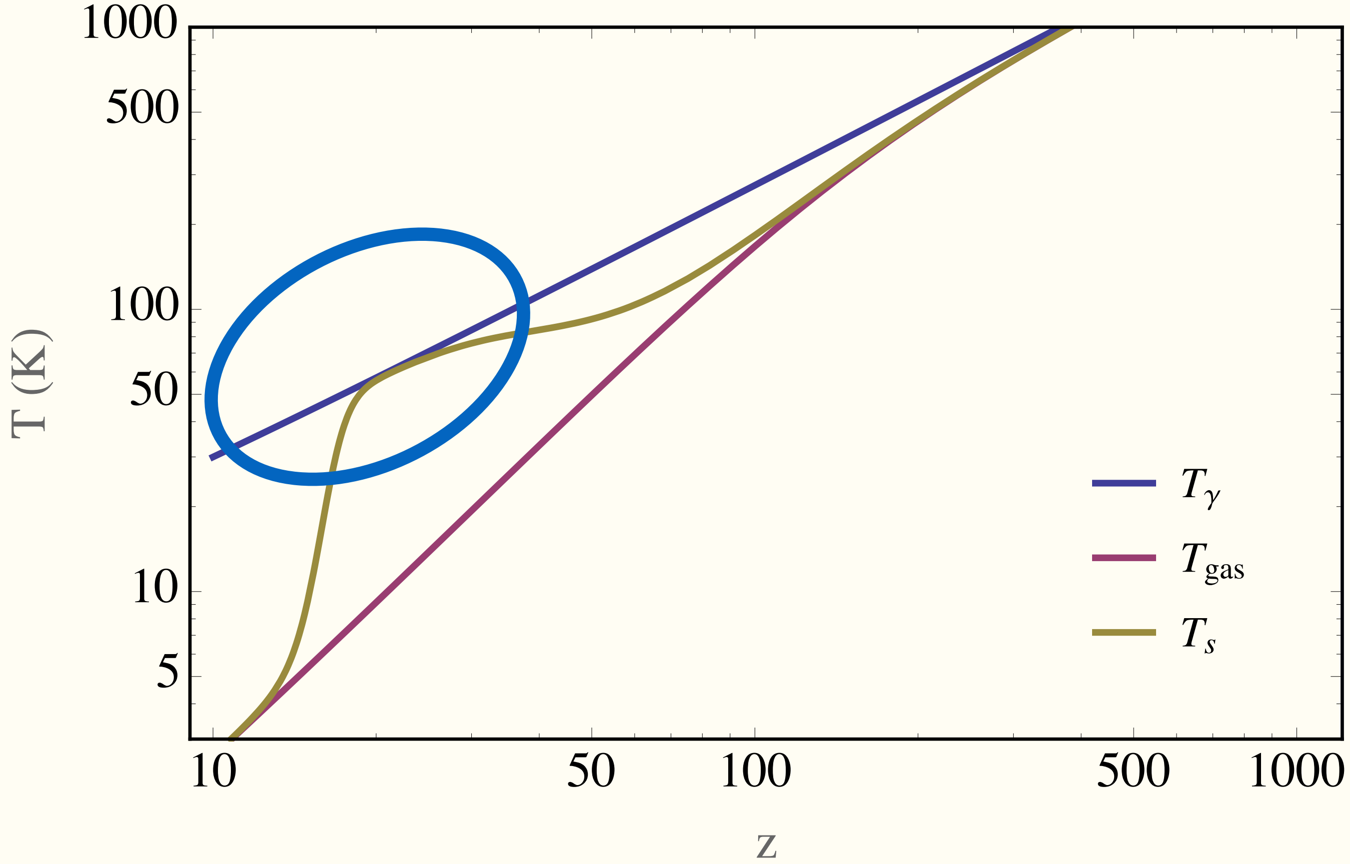
CMB-induced Emissions/Absorptions





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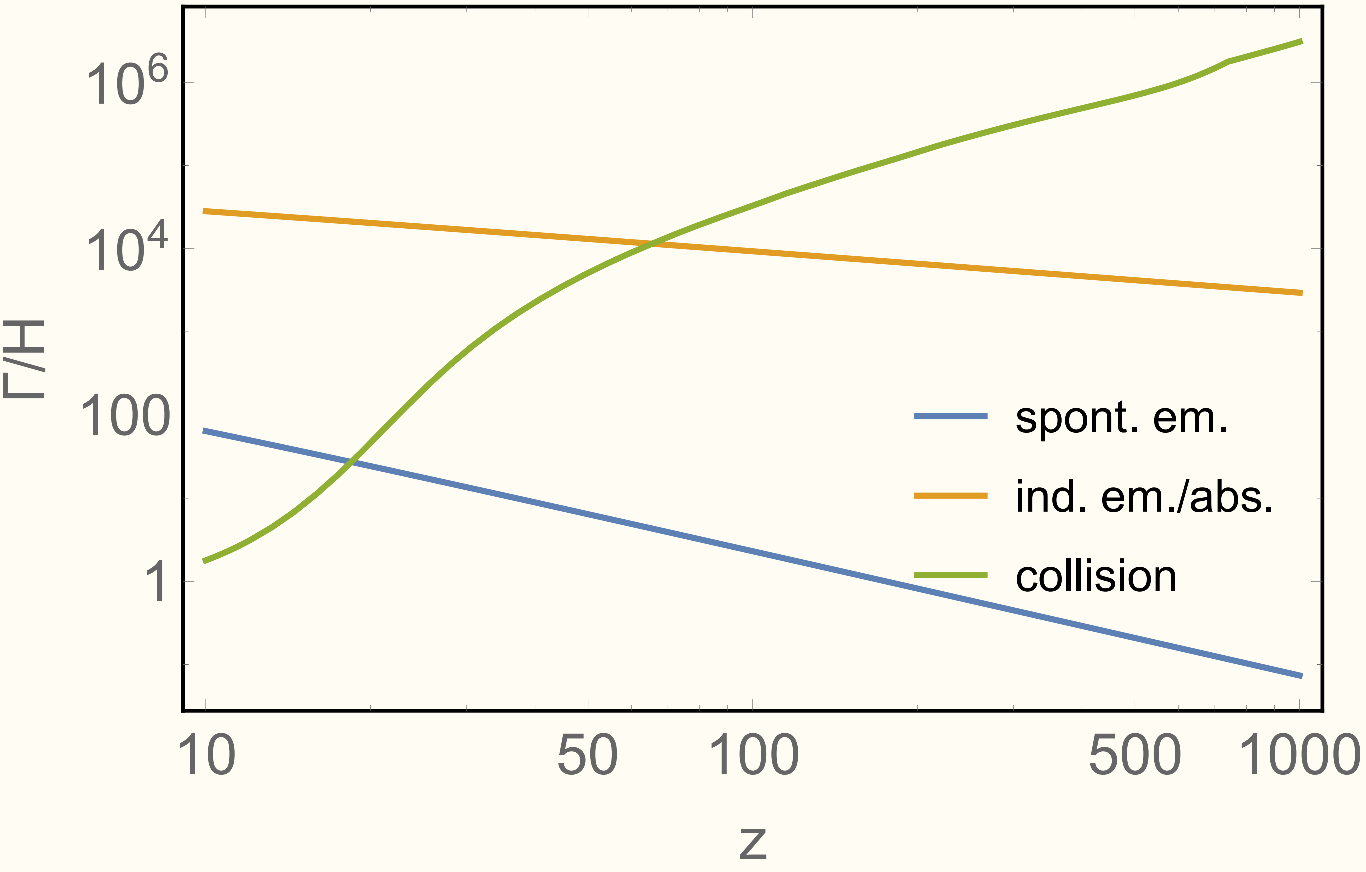
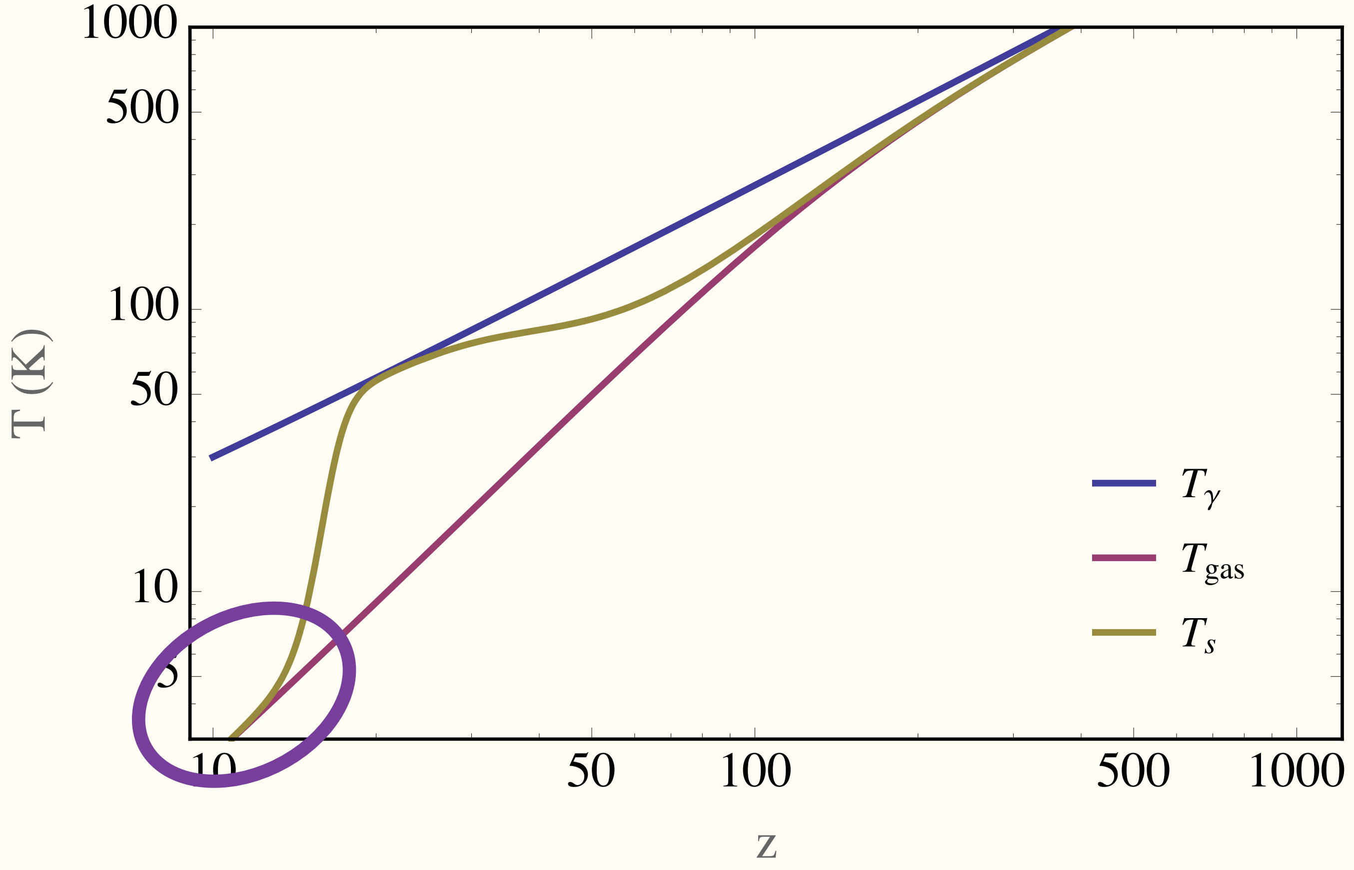
Lyman-α Radiation





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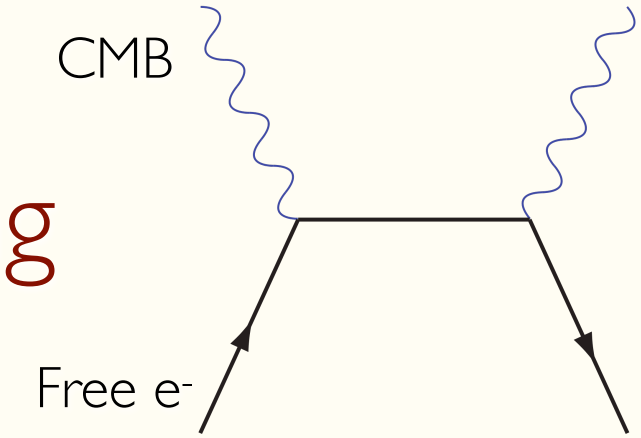
- Gives:

Compton scattering



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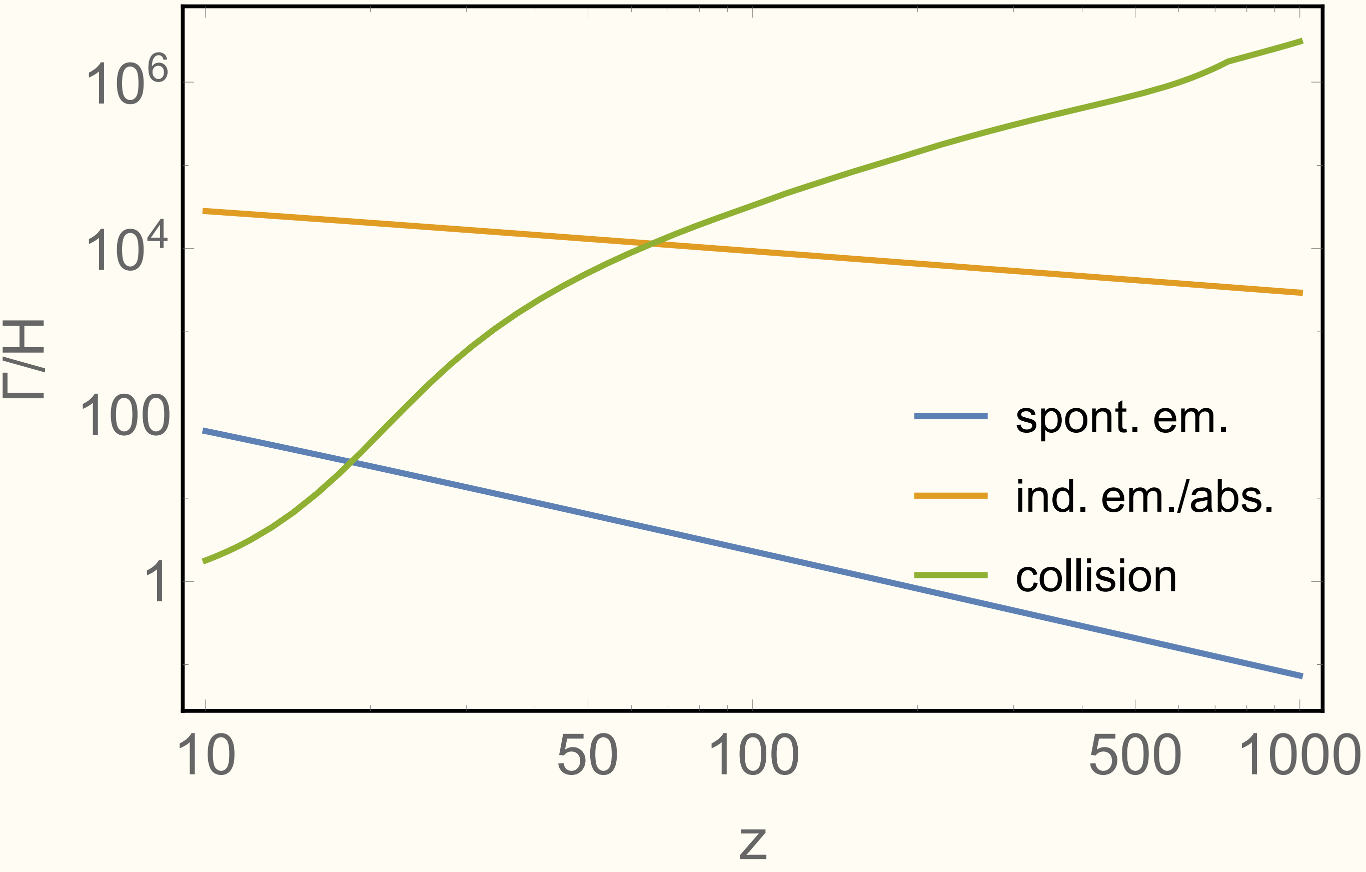

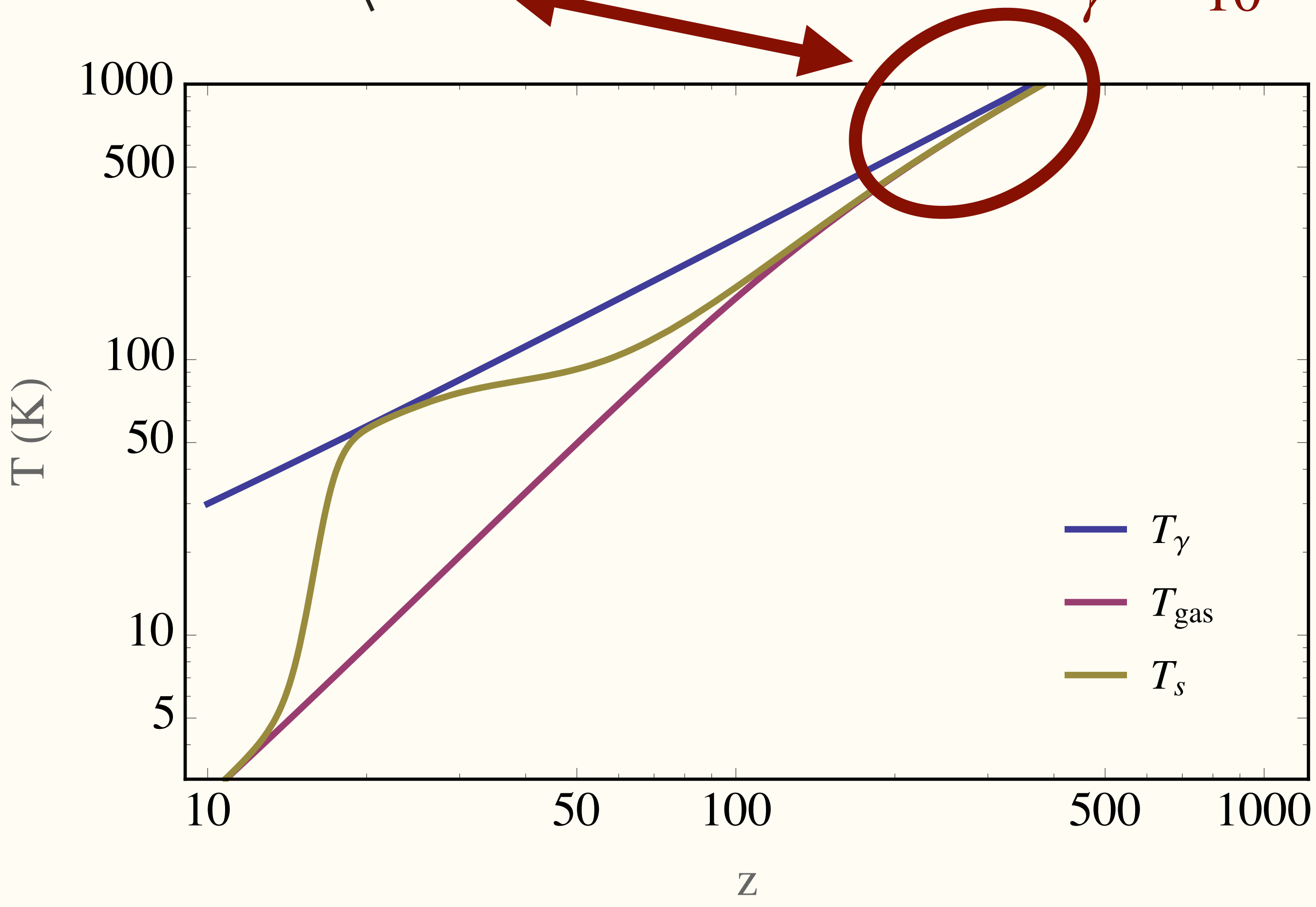

New Physics @ 21cm?

How can NP affect 21-cm?

$$T_{21} = \frac{1}{1+z}\left(T_s - T_{\rm CMB}\right)\left(1 - e^{-\tau}\right)$$

$$\tau \simeq \frac{3\lambda_{21}^2 A_{10} n_{\rm H}}{16 T_s H(z)}$$

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- Non-standard CMB spectrum
  - Additional astrophysical sources (e.g. radio-loud quasars)
  - New physics contribution (e.g. decay to hidden photons)

[Feng, Holder, 2018]

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- Suppressed Ts
  - Cool gas
    - Alternate cosmological history (e.g. new stable charged particles)
    - Dark cooling

[Falkowski,Petraki, 2018; Baxter,Hill, 2018]

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      [Lambiase,Mohanty, 2018]
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Dark Cooling

- DM is initially very cold.
- Can interact directly with baryons and cool it down.
- Cooling described by Boltzmann eqs.:

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

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Redshift

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Compton scattering

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$$\dot{Q}^I_{\rm gas} \sim -x_I\Gamma_{\chi I}\Delta E_I + \frac{d}{dt}\frac{\mu_{\chi I}v^2_{\rm rel}}{2}$$

DM scattering

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- Can interact directly with baryons and cool it down.
- Cooling described by Boltzmann eqs.:

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

$$\dot{Q}^I_{\rm gas} \sim -x_I \Gamma_{\chi I} \Delta E_I + \frac{d}{dt}\frac{\mu_{\chi I} v^2_{\rm rel}}{2}$$

- Two implications:
    - DM scattering rate must compete with Compton: Large cross-section
    - For $m_{\rm DM}$>$m_{\rm proton}$ cooling is not sufficient (small heat capacity): Light DM

Dark Cooling

Large cross-section

+

Light DM

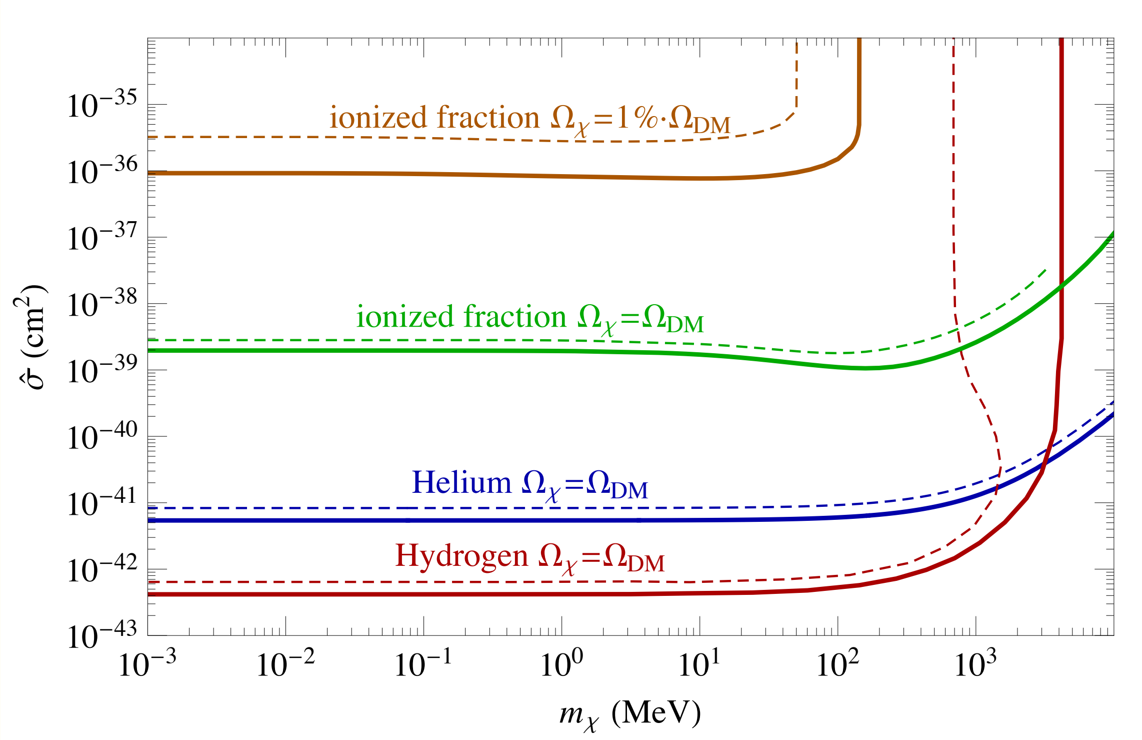
Dark Cooling

$$\sigma^I = \hat{\sigma}^I v_{\text{rel}}^{-4}$$

Large cross-section

+

Light DM



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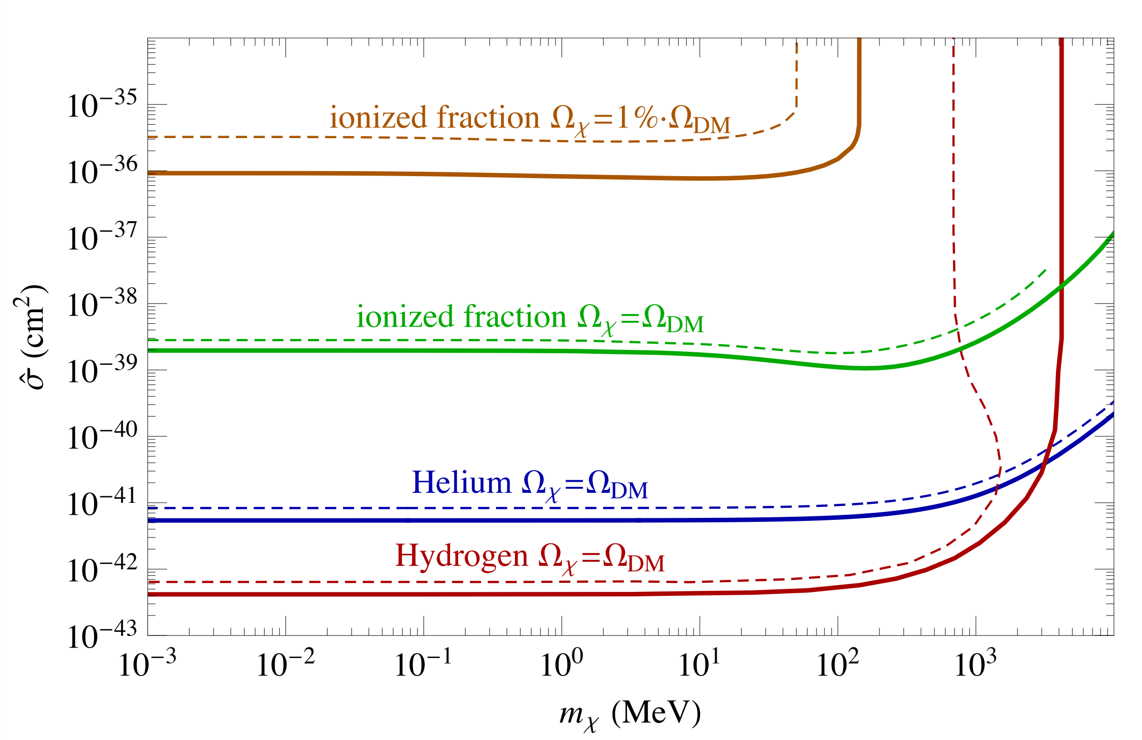

Long Range Force
(light mediator)

$$m_\phi \lesssim \mu_I v_{\rm rel} \simeq 1 \text{ keV} \cdot \frac{\mu_I}{1 \text{ GeV}}$$

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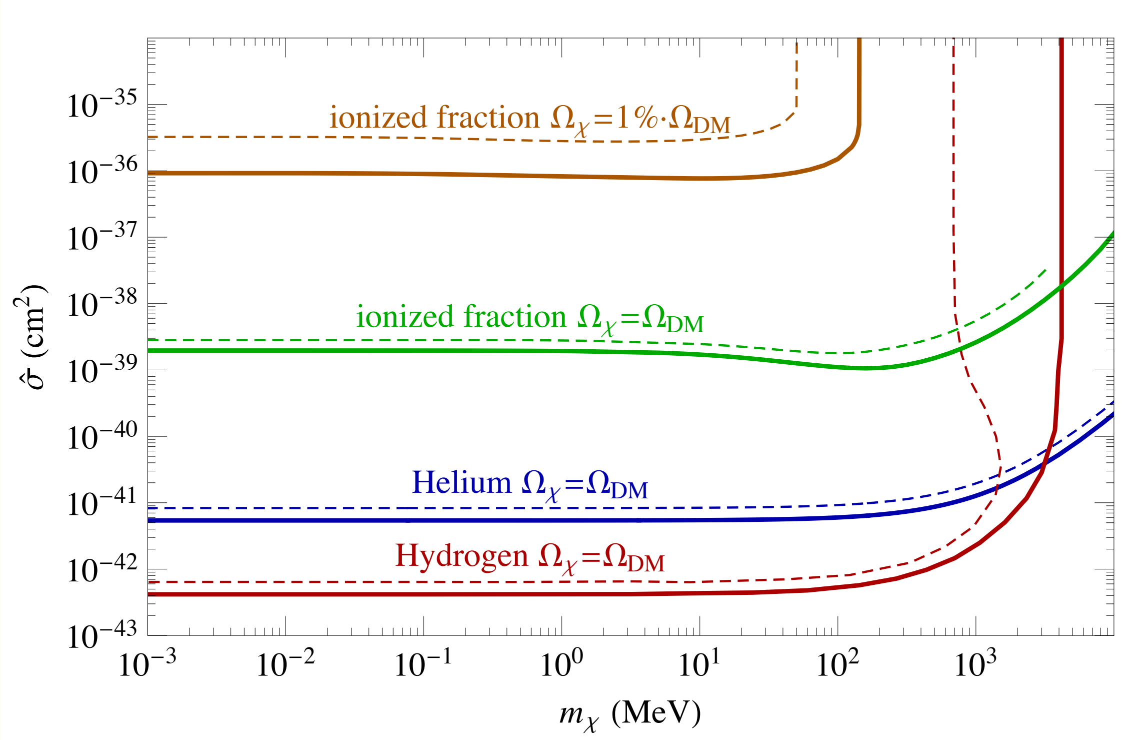

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$$m_\phi \lesssim \mu_I v_{\rm rel} \simeq 1\ {\rm keV} \cdot \frac{\mu_I}{1\ {\rm GeV}}$$

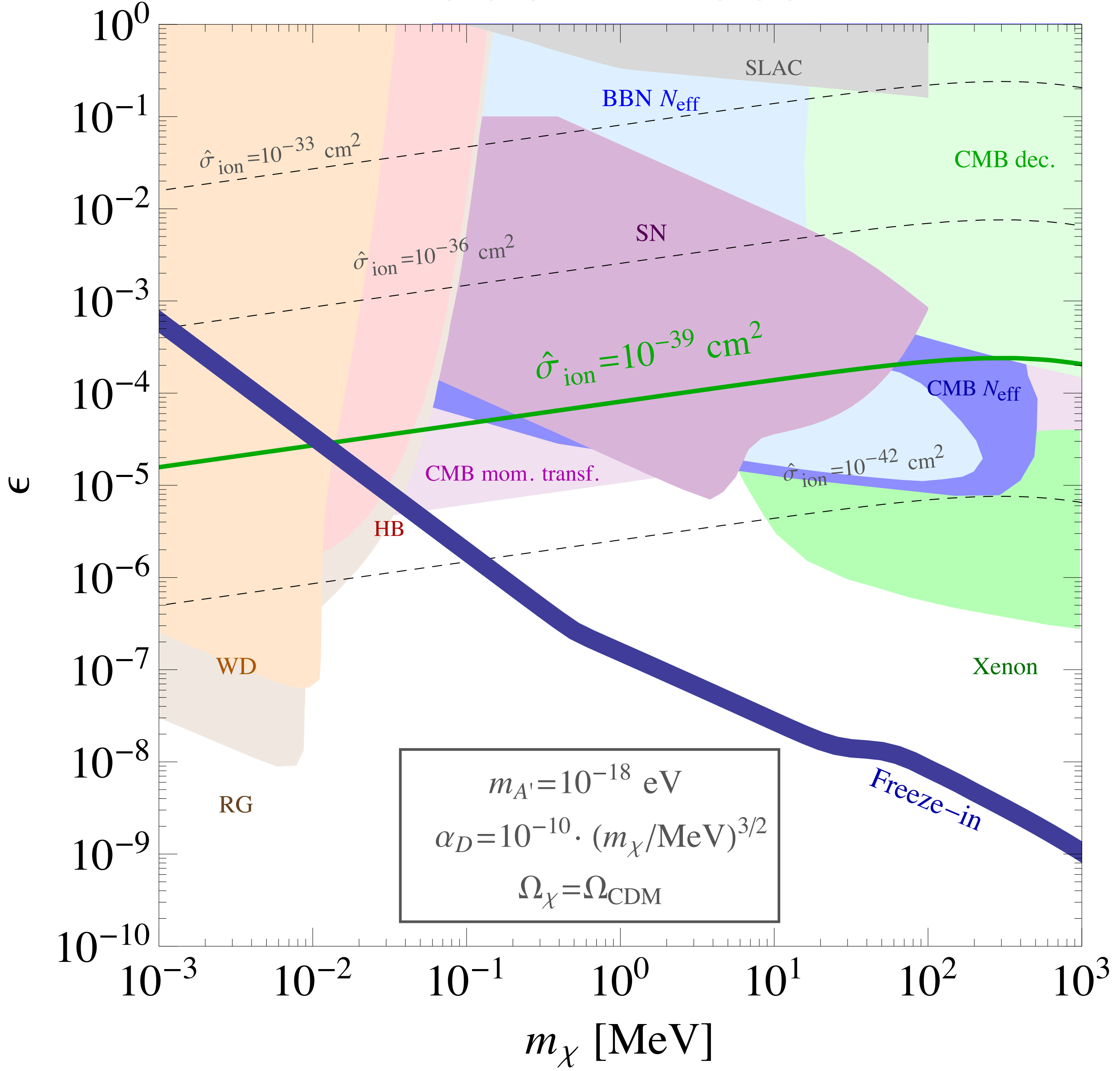
Unscreened

or

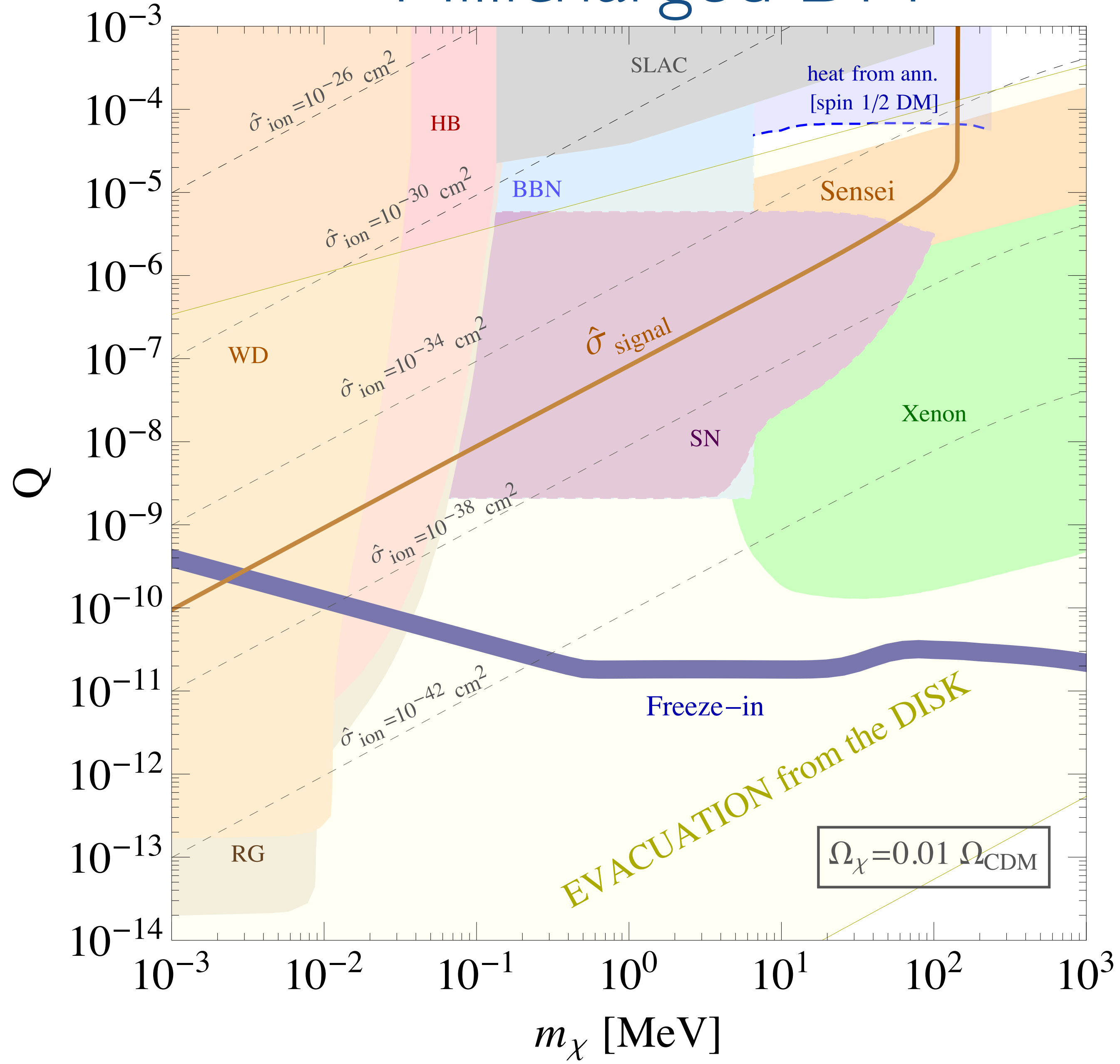
Screened?

Models of Strongly Interacting Light DM

Hidden Photon



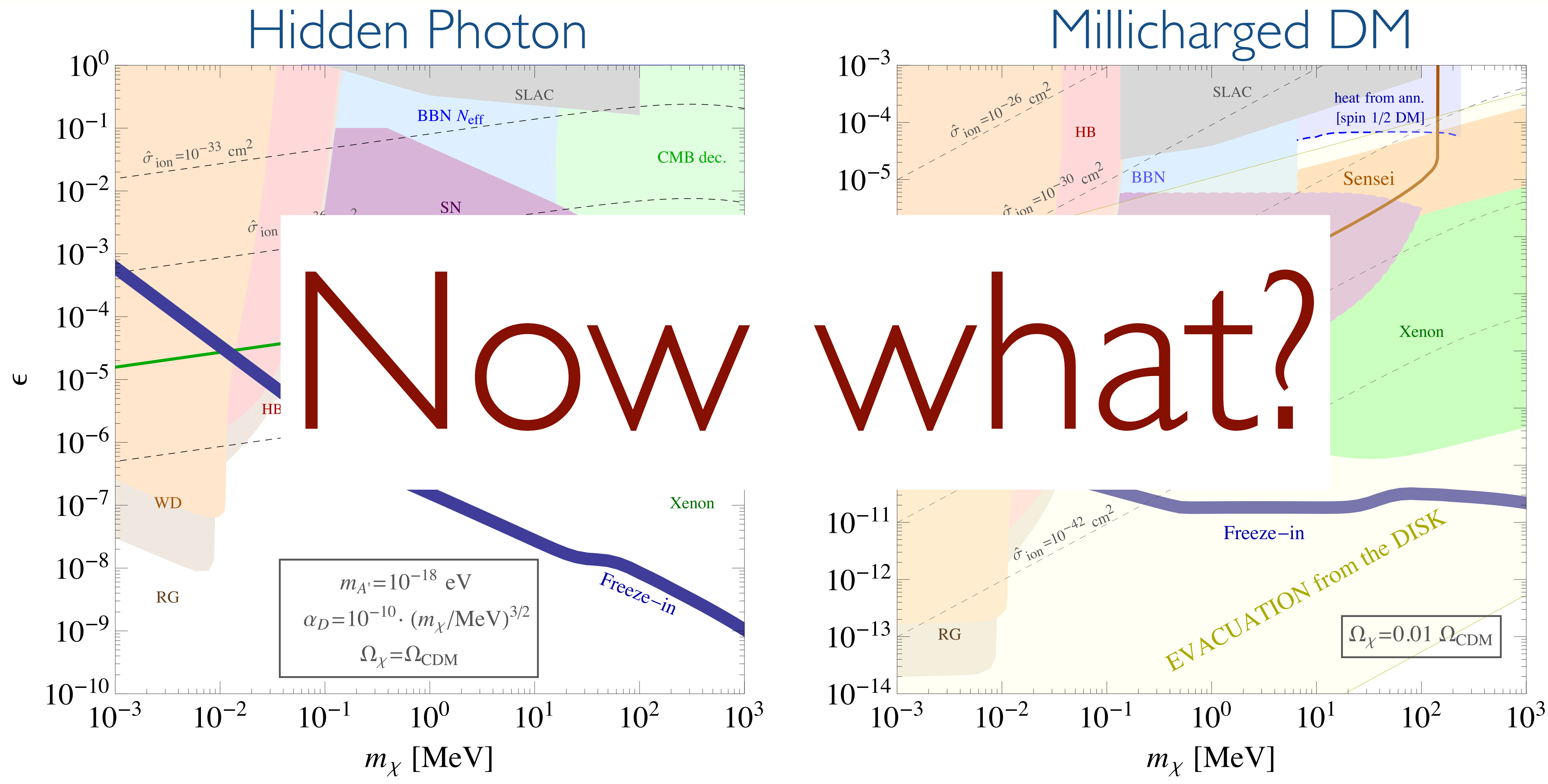
Millicharged DM



[Barkana,Outmezguine,Redigolo,TV, 2018]

DM interacting via (hidden) photon is unlikely to explain EDGES.

Models of Strongly Interacting Light DM



Now what?

[Barkana,Outmezguine,Redigolo,TV, 2018]

DM interacting via (hidden) photon is unlikely to explain EDGES.

Millicharged DM is Back!

- The problem in original idea:
    - Constraints from CMB imply mDM density is low ($\Omega_{\rm mDM} < 4 \times 10^{-3}\Omega_{\rm DM}$).
    - Small fraction can only cool a little - small heat capacity.

Millicharged DM is Back!

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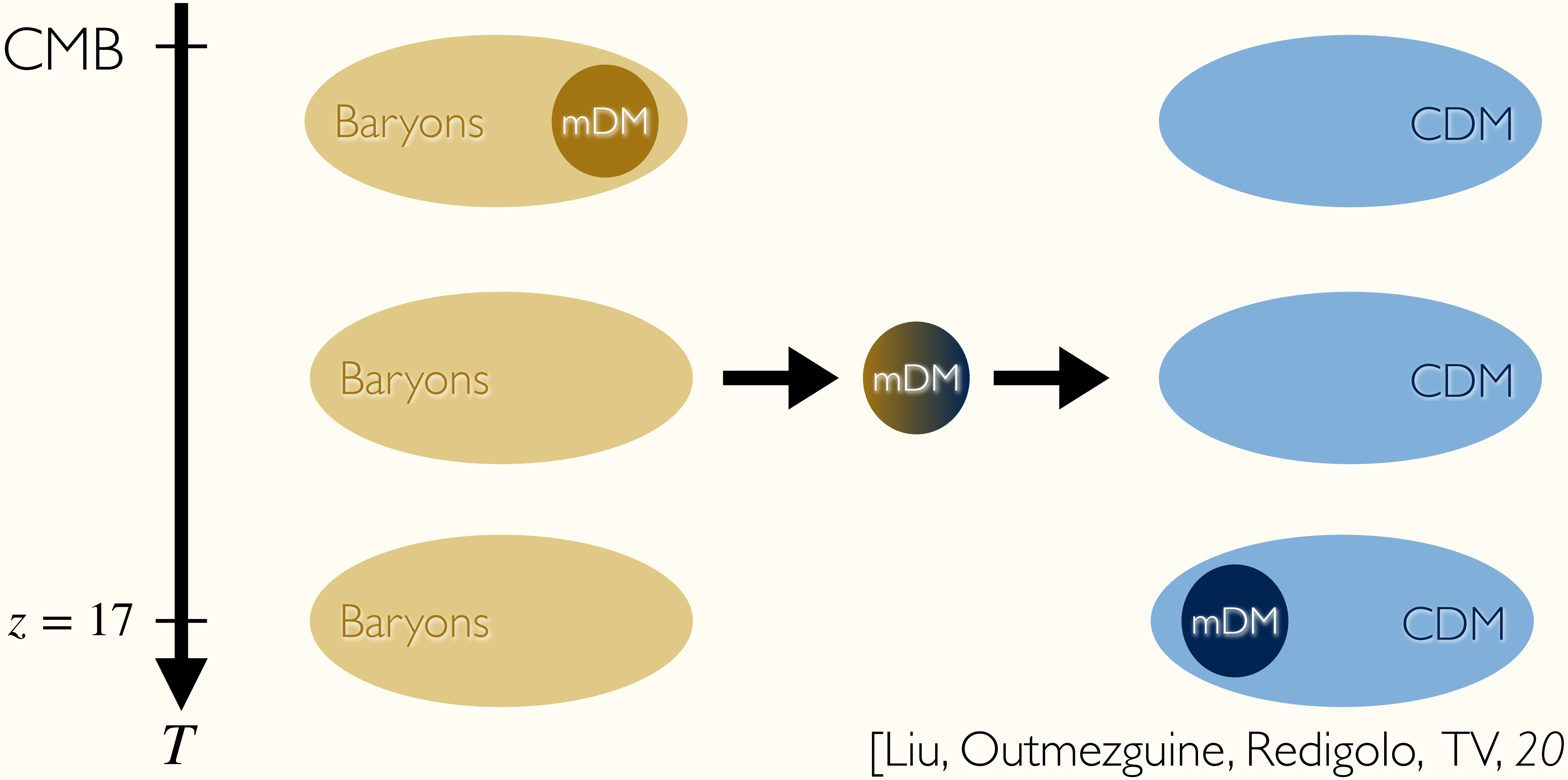
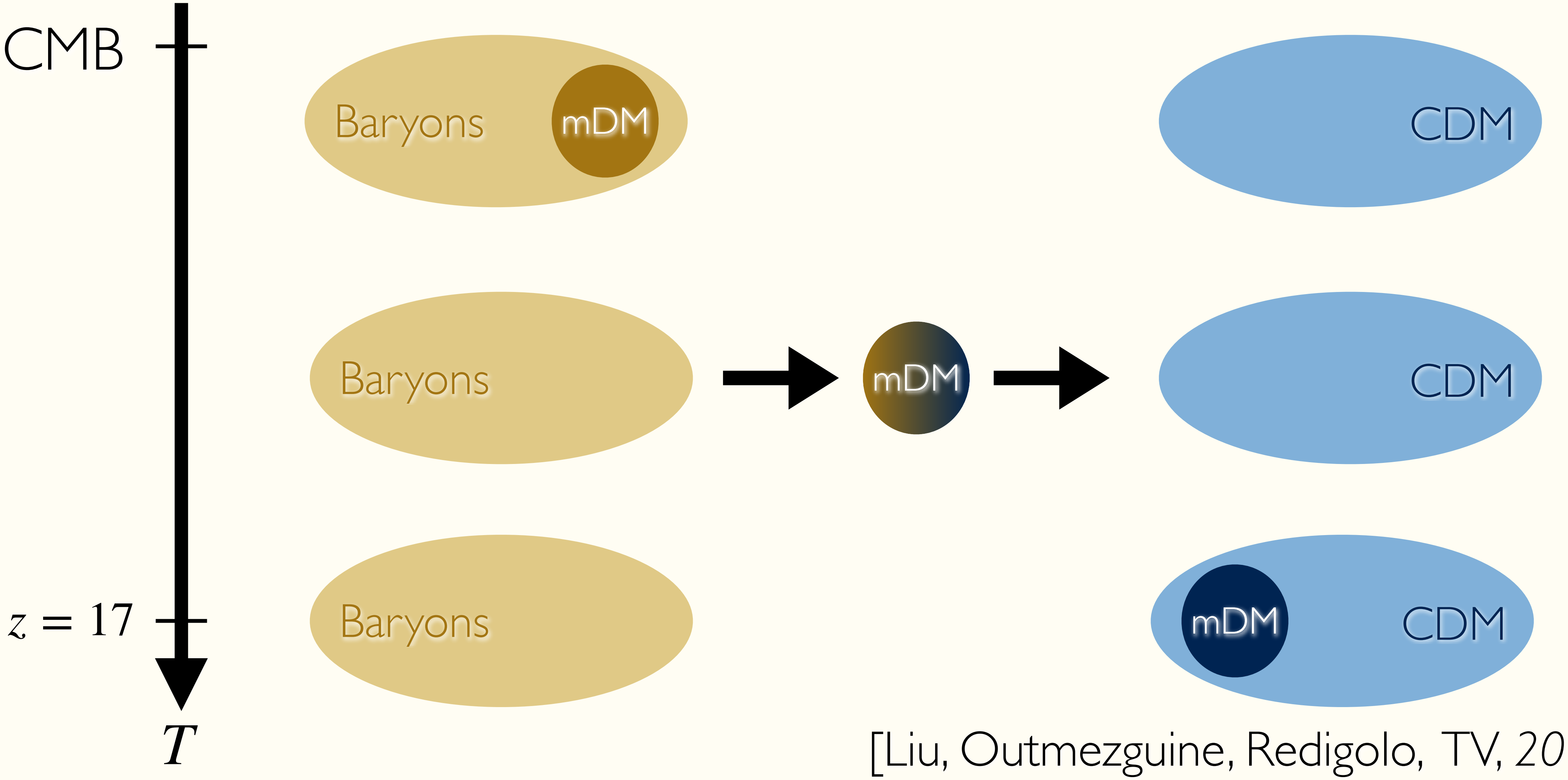
    - Constraints from CMB imply mDM density is low ($\Omega_{\rm mDM} < 4 \times 10^{-3}\Omega_{\rm DM}$).
    - Small fraction can only cool a little - small heat capacity.
- New idea:



[Liu, Outmezguine, Redigolo, TV, *2019*]

Millicharged DM is Back!



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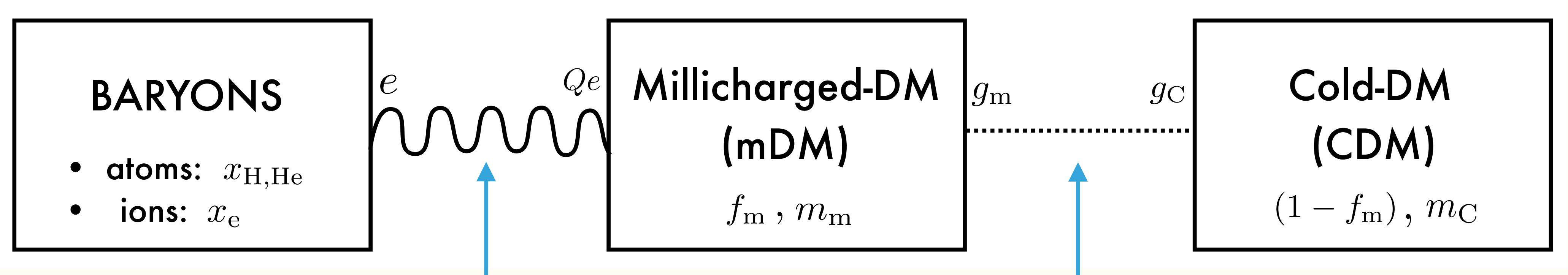


BARYONS

- atoms: $x_{\mathrm{H,He}}$
- ions: x_{e}

e Qe

Millicharged-DM (mDM)

$f_{\mathrm{m}}\,,\, m_{\mathrm{m}}$

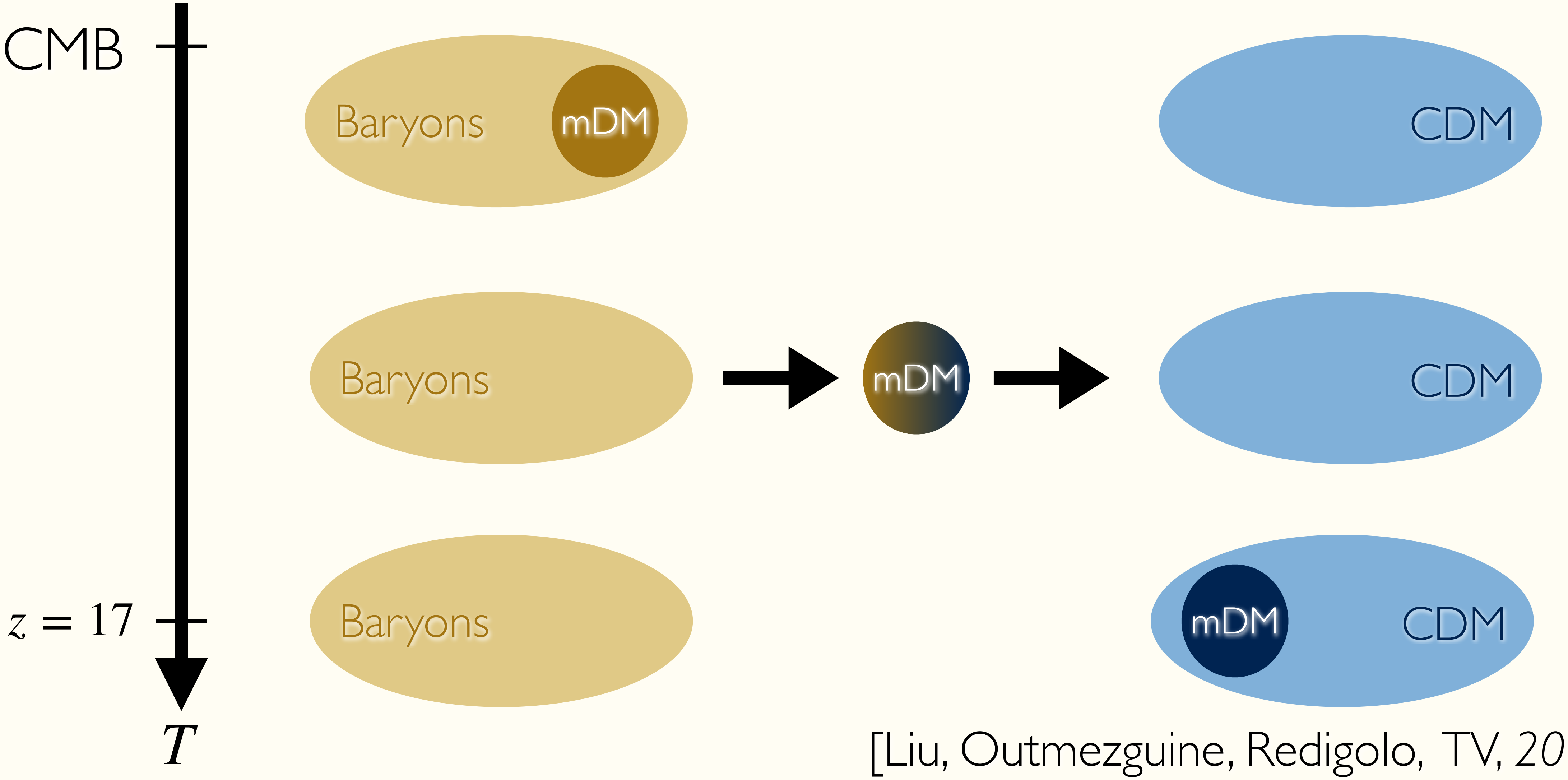
g_{m} g_{C}

Cold-DM (CDM)

$(1-f_{\mathrm{m}})\,,\, m_{\mathrm{C}}$

$\Gamma_{mb} \propto x_e v_{\mathrm{rel}}^{-4}$

$\Gamma_{mC} \propto v_{\mathrm{rel}}^{-4}$



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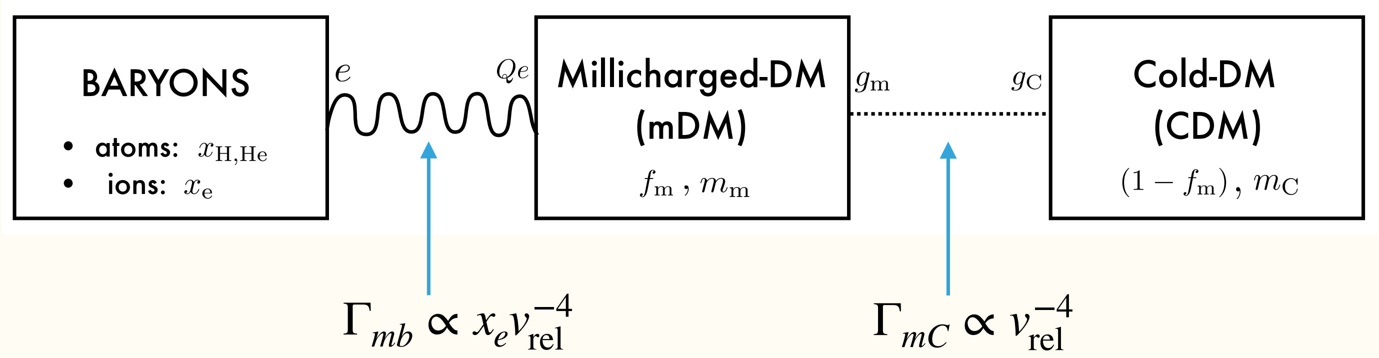

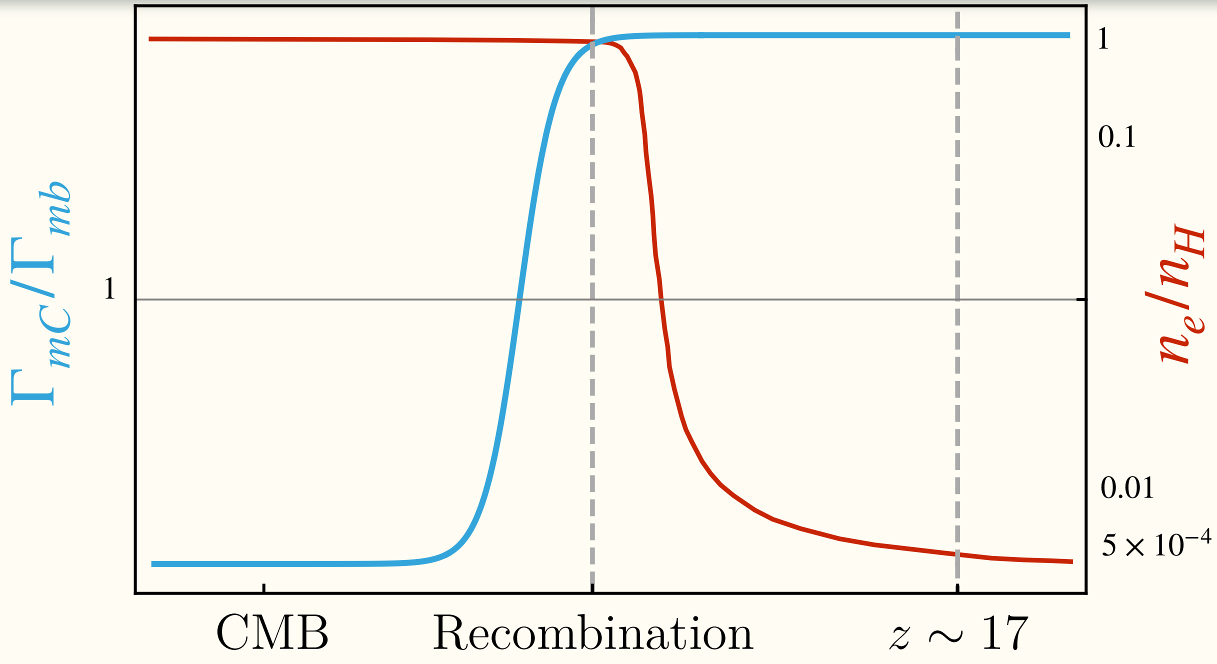

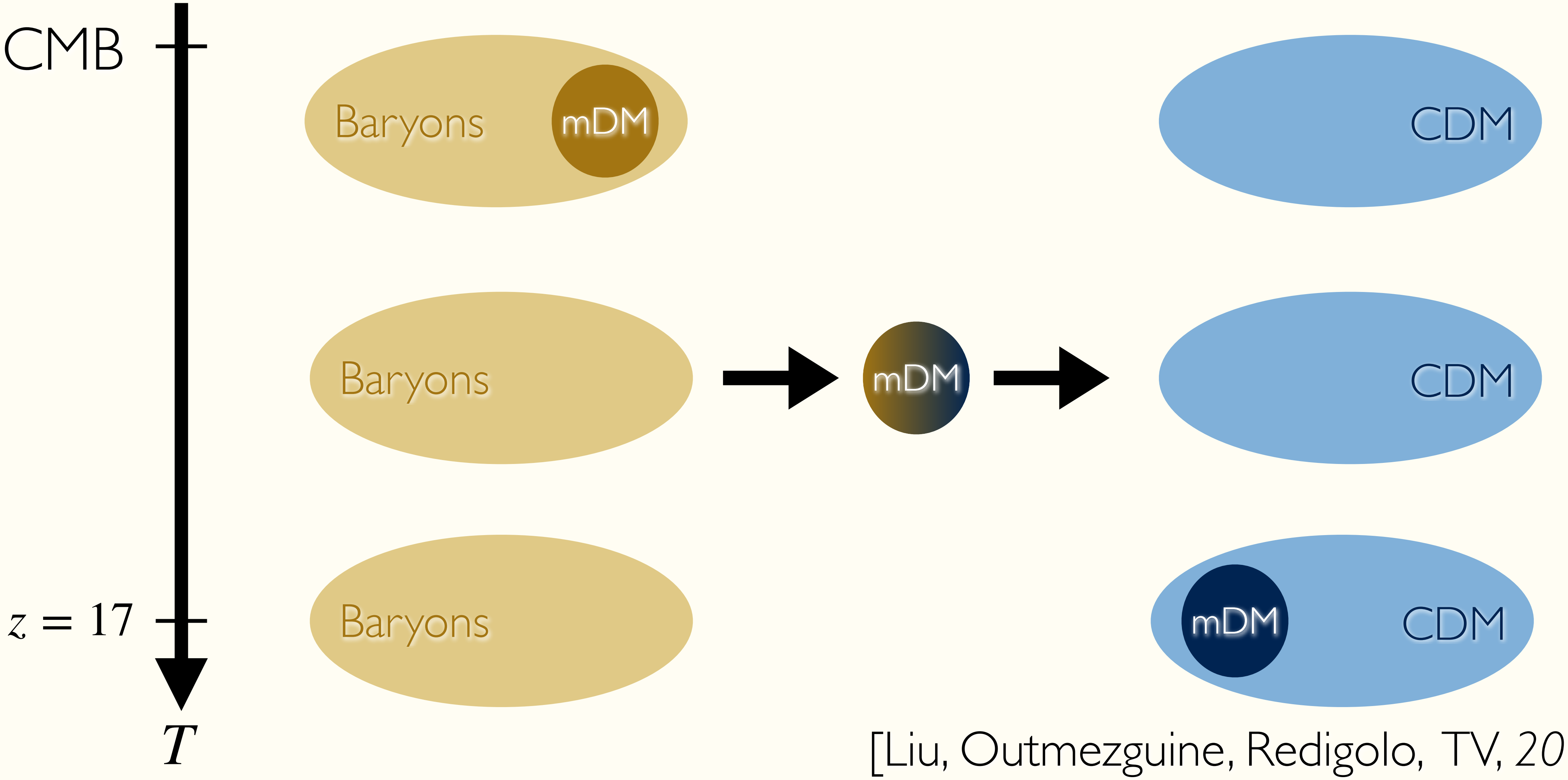

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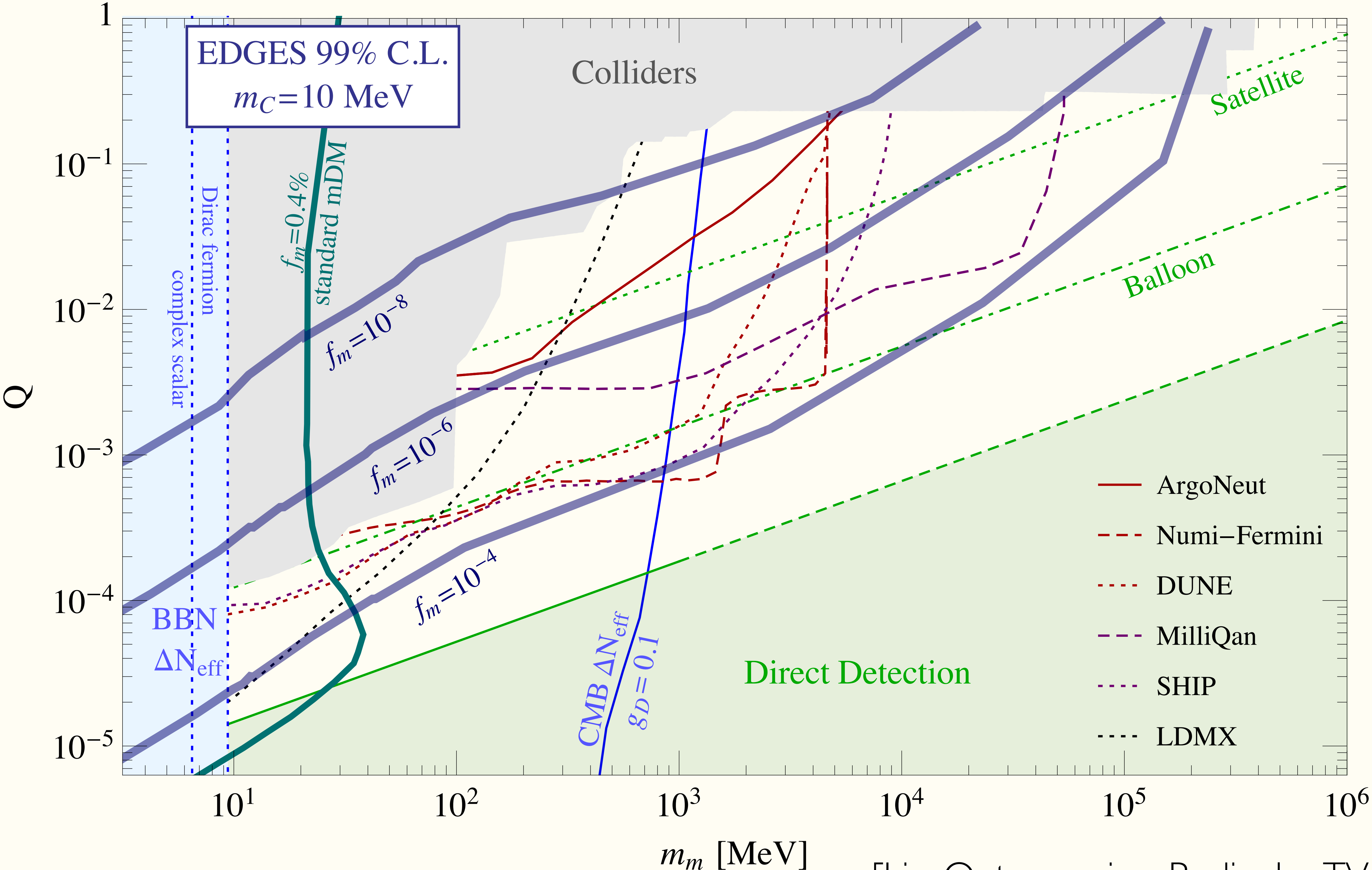
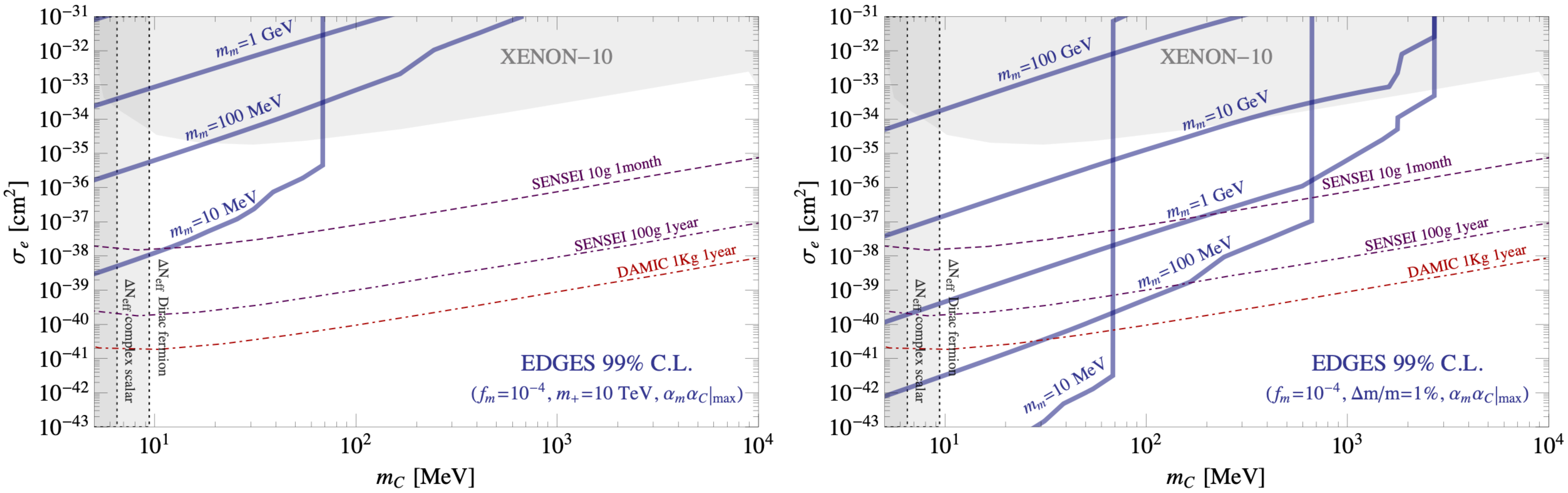
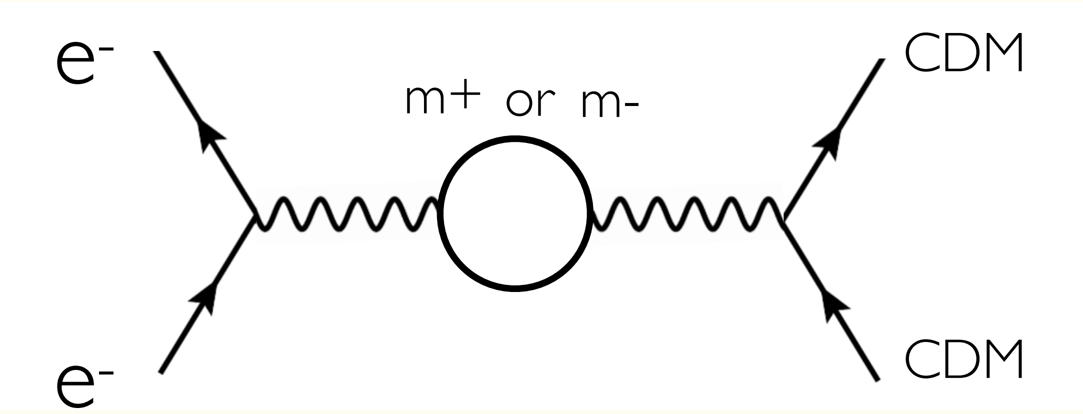
Millicharged DM is Back!



[Liu, Outmezguine, Redigolo, TV, *2019*]

CDM Direct Detection





$$\Longrightarrow \quad \bar{\sigma}_e \simeq \frac{8Q^2\alpha_{\rm C}\alpha_{\rm m}}{\alpha_{\rm EM}^2\mu_{em}^2}\left(\log\frac{m_+}{m_-}\right)^2$$

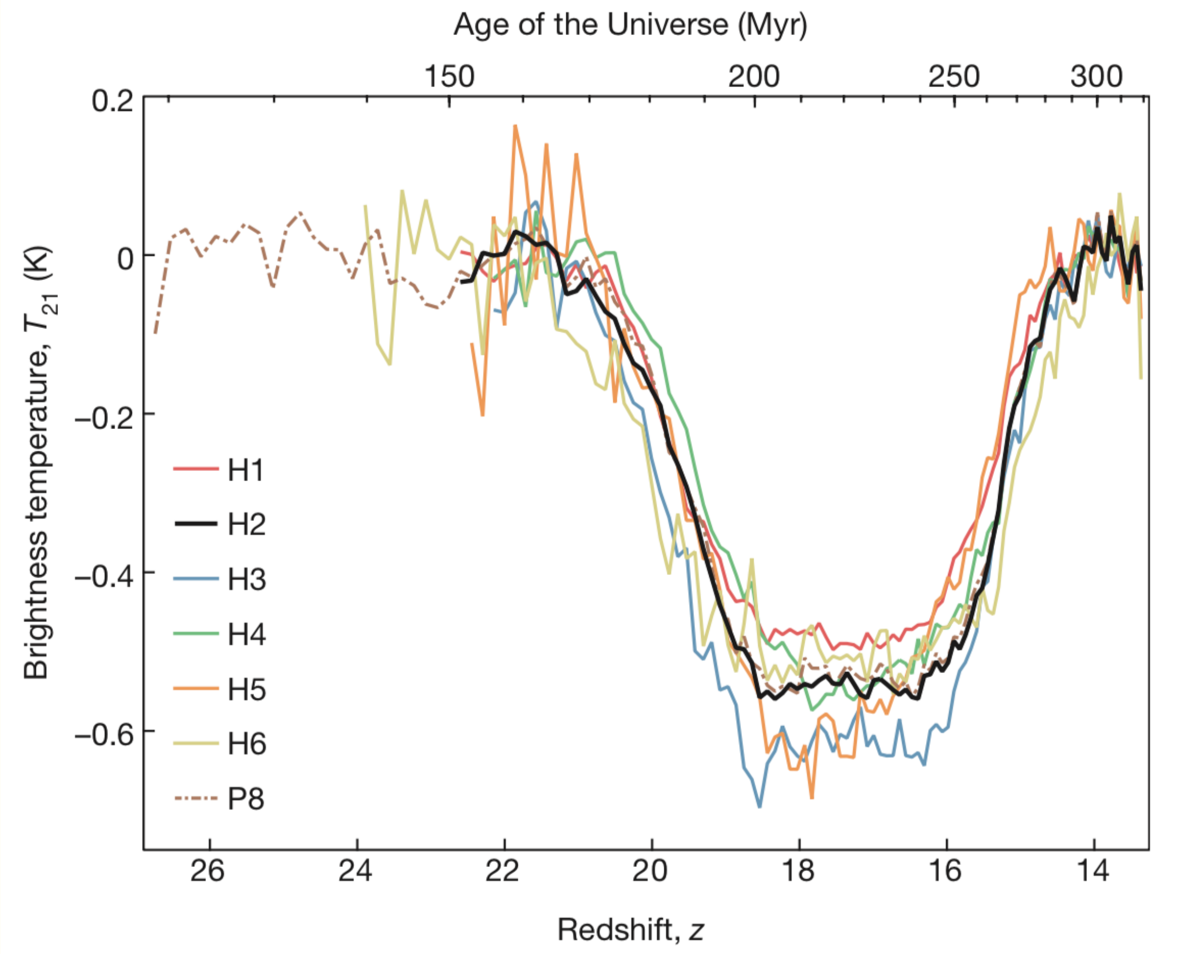
[Liu, Outmezguine, Redigolo, TV, *2019*]

Can we constrain the millicharged DM model?

EDGES

[Bowman et al., 2018]

$$T_{21} = \frac{1}{1+z}\left(T_s - T_{\rm CMB}\right)\left(1 - e^{-\tau}\right)$$



$$T_{21}^{EDGES}(z \simeq 17) = -500^{+200}_{-500}\ {\rm mK}$$

EDGES

[Bowman et al., 2018]

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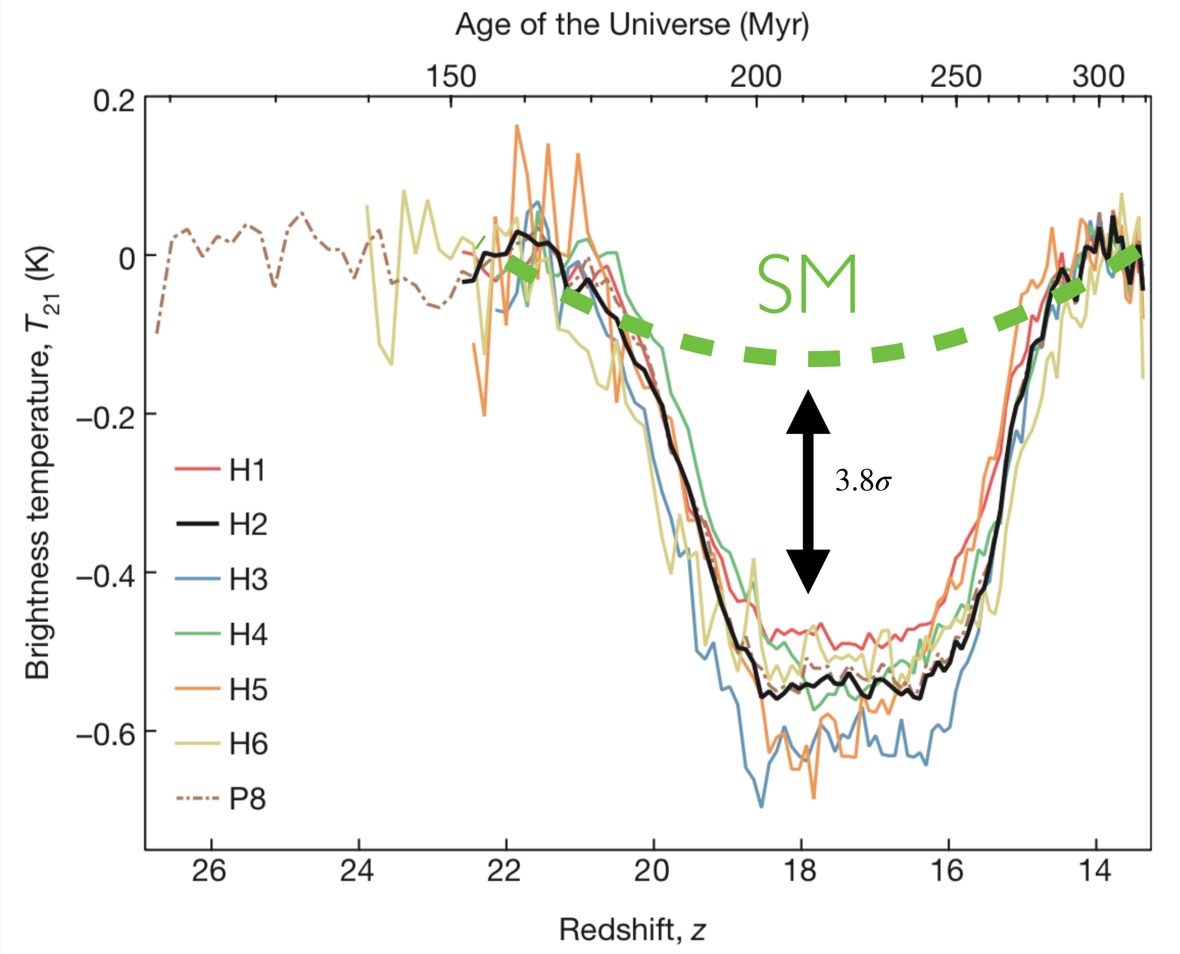
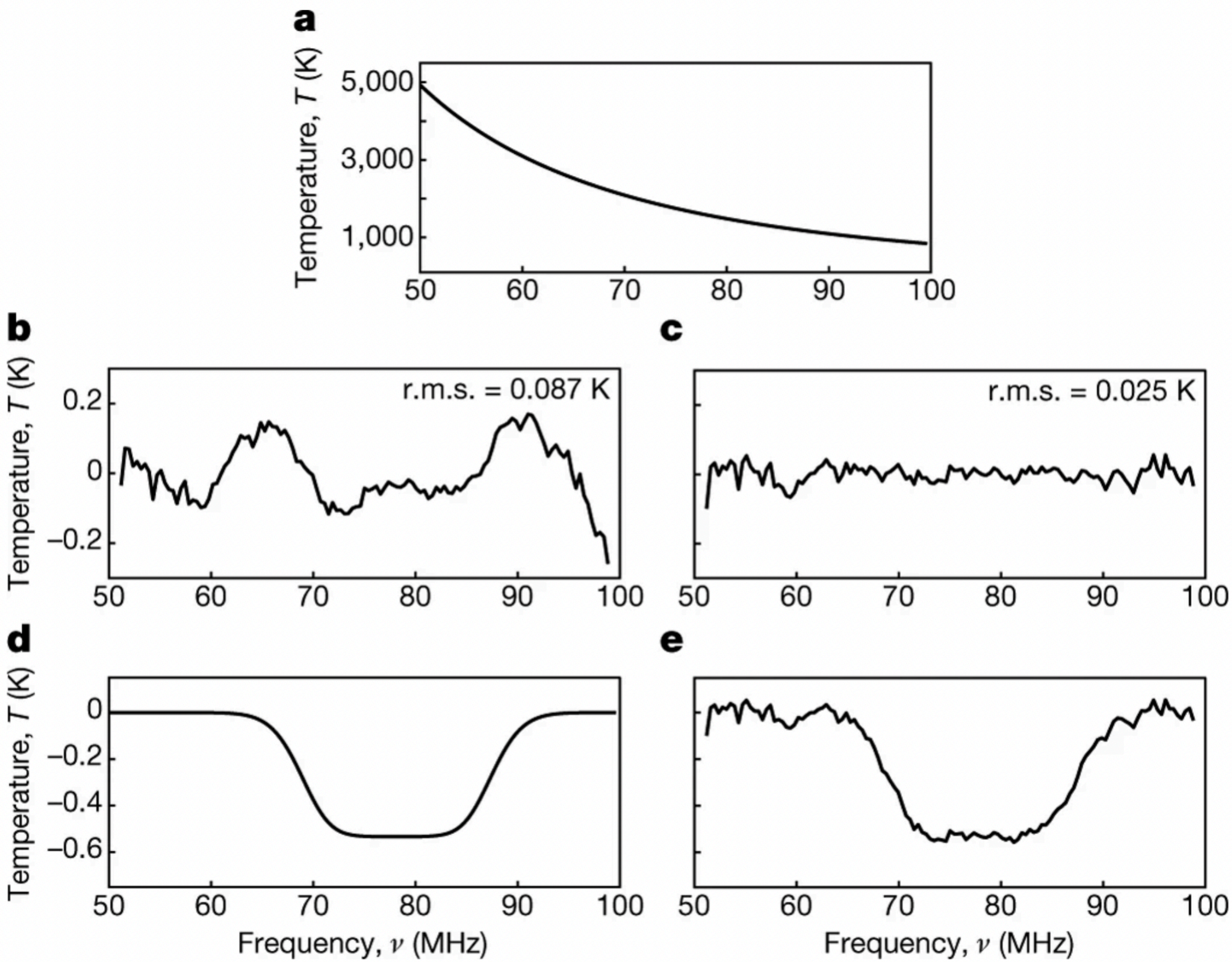


$$T_{21}^{EDGES}(z \simeq 17) = -500^{+200}_{-500}\ \text{mK}$$

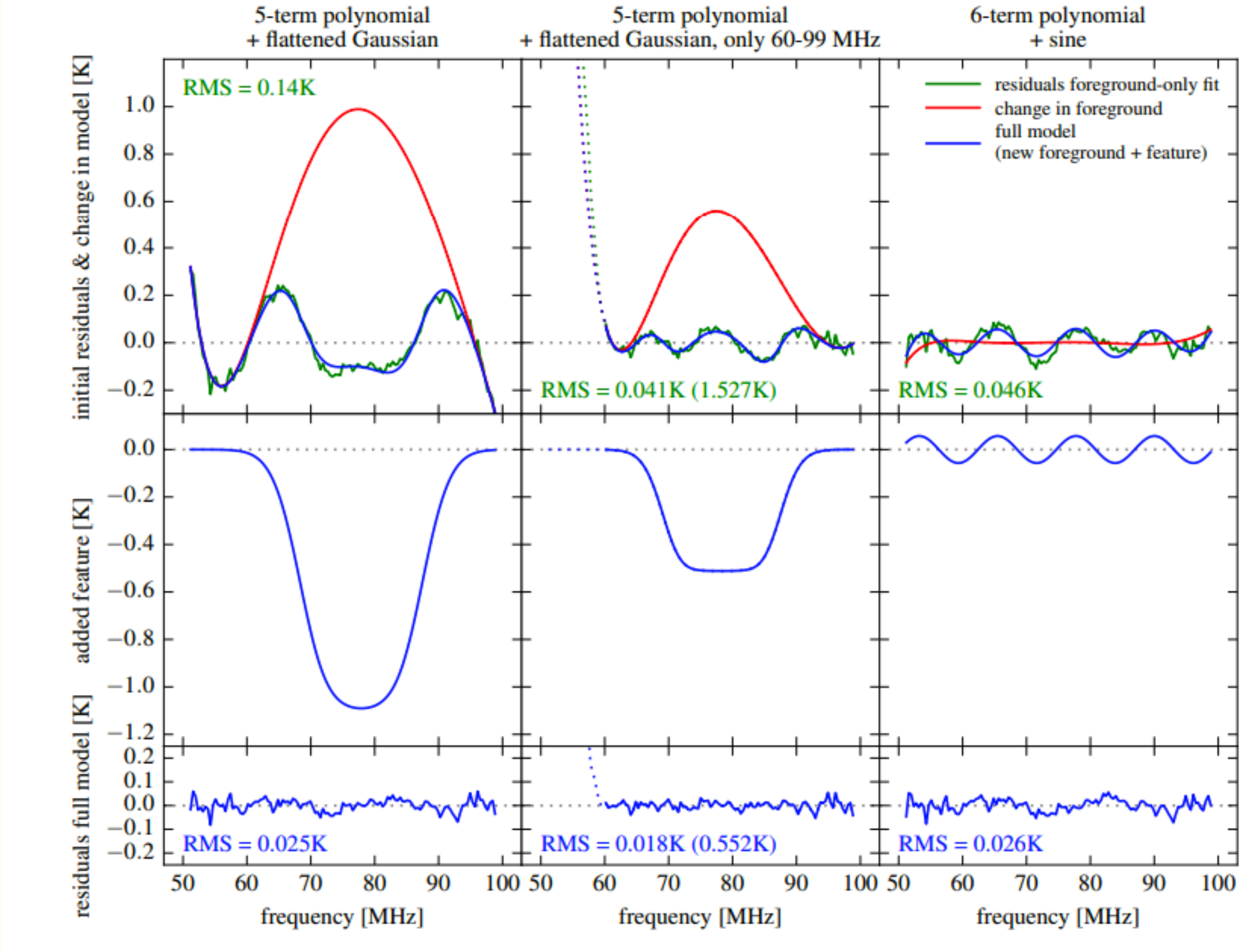
$$T_{21}^{SM}(z = 17) \gtrsim -220\ \text{mK}$$

EDGES



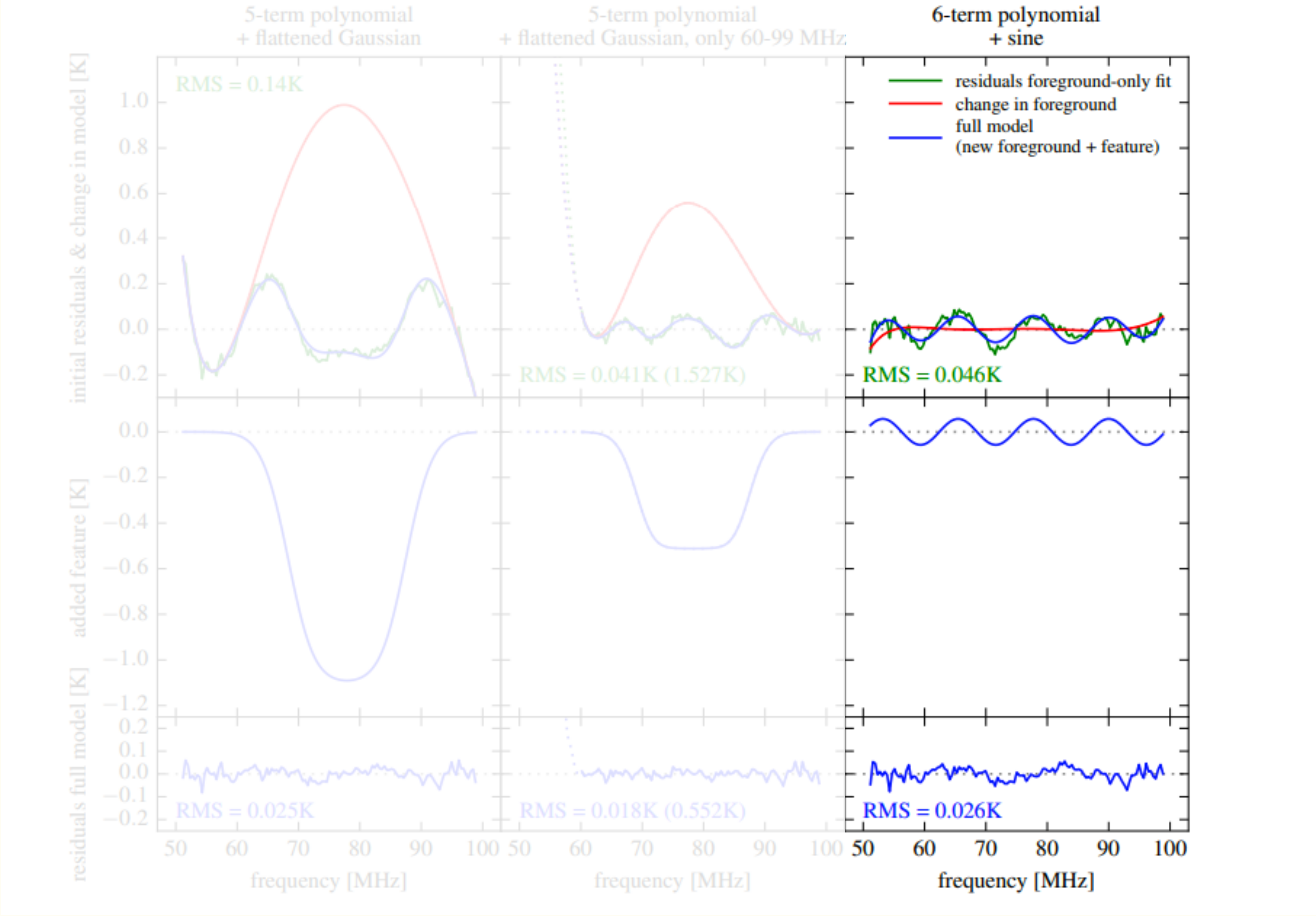
a, Measured spectrum for the reference dataset after filtering for data quality and radio-frequency interference. The spectrum is dominated by Galactic synchrotron emission. **b**, **c**, Residuals after fitting and removing only the foreground model (**b**) or the foreground and 21-cm models (**c**). **d**, Recovered model profile of the 21-cm absorption, with a signal-to-noise ratio of 37, amplitude of 0.53 K, centre frequency of 78.1 MHz and width of 18.7 MHz. **e**, Sum of the 21-cm model (**d**) and its residuals (**c**).

EDGES: Back to Reality



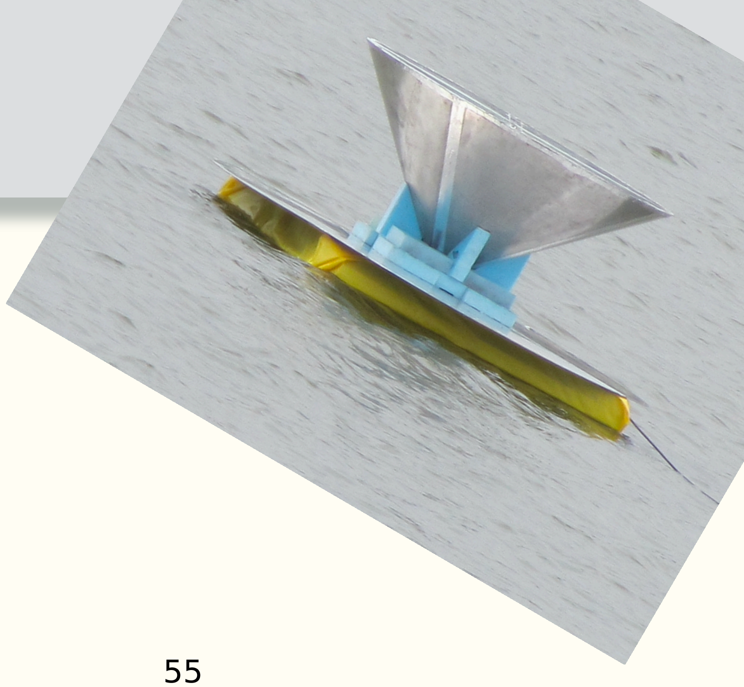
[Hills,Kulkarni,Meerburg,Puchwein, 2018]

EDGES: Back to Reality



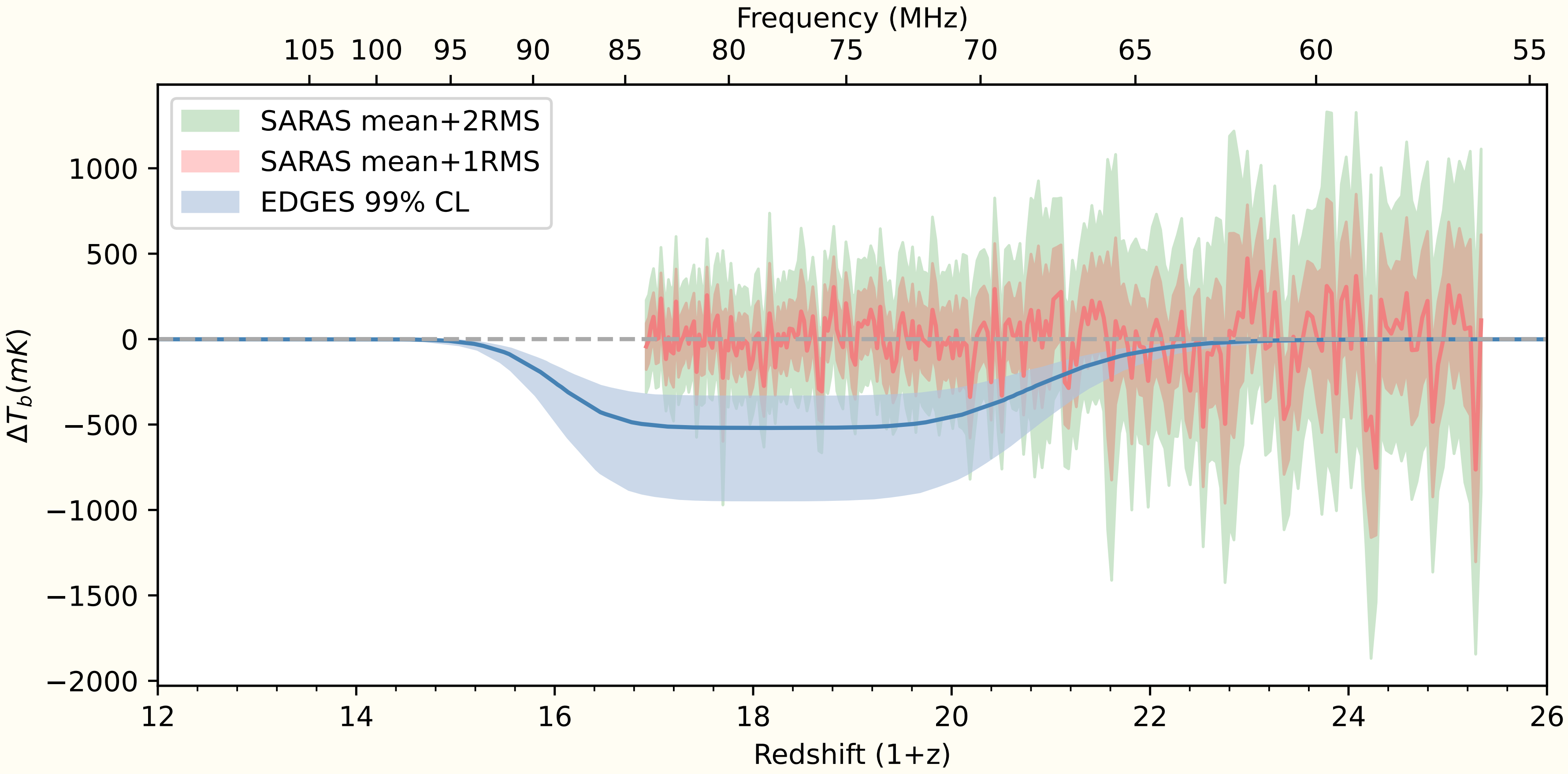
[Hills,Kulkarni,Meerburg,Puchwein, 2018]

SARAS 3



Inconsistent with EDGES!

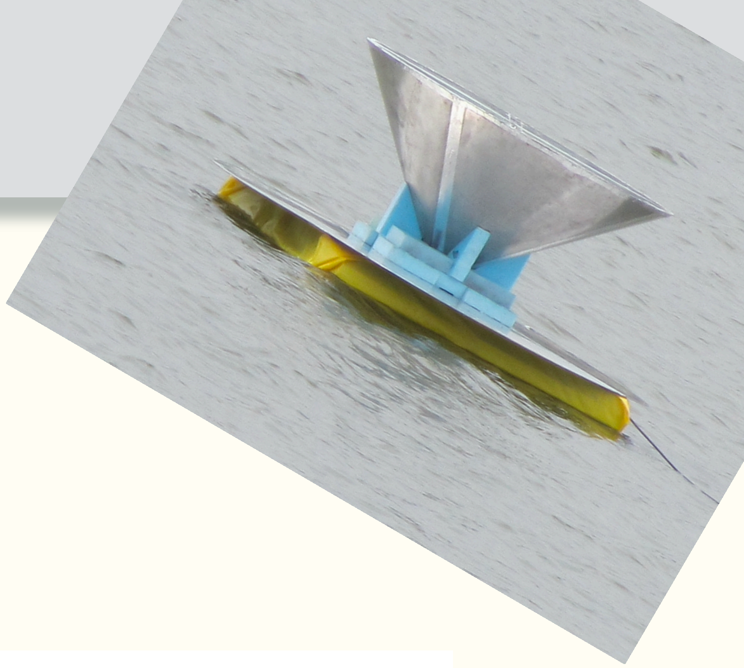
[SARAS 3, 2112.06778]



Suggested problem with EDGES:

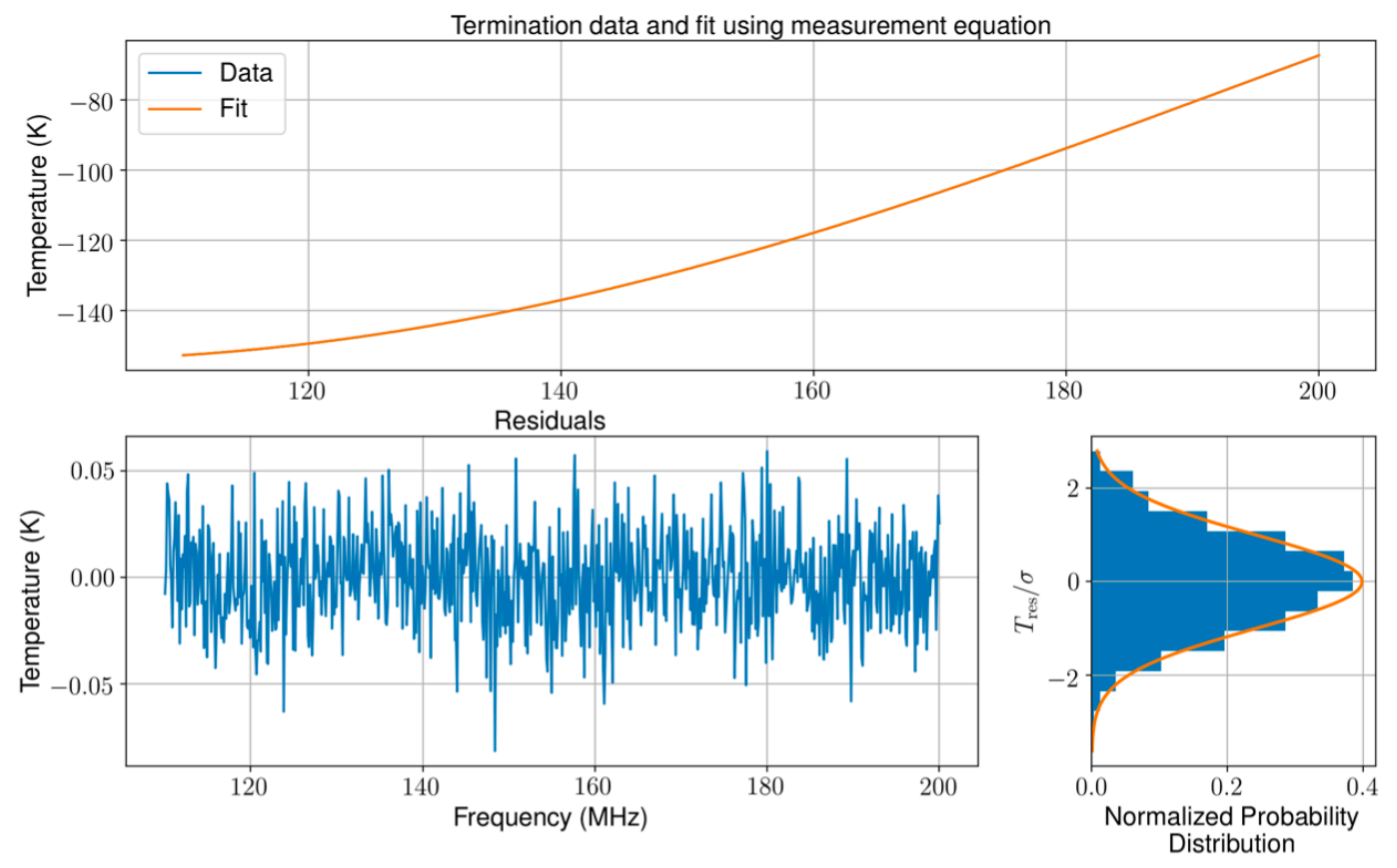
Inhomogeneous grounds under the detector, causing a 12.5 MHz systematic noise.

SARAS 2

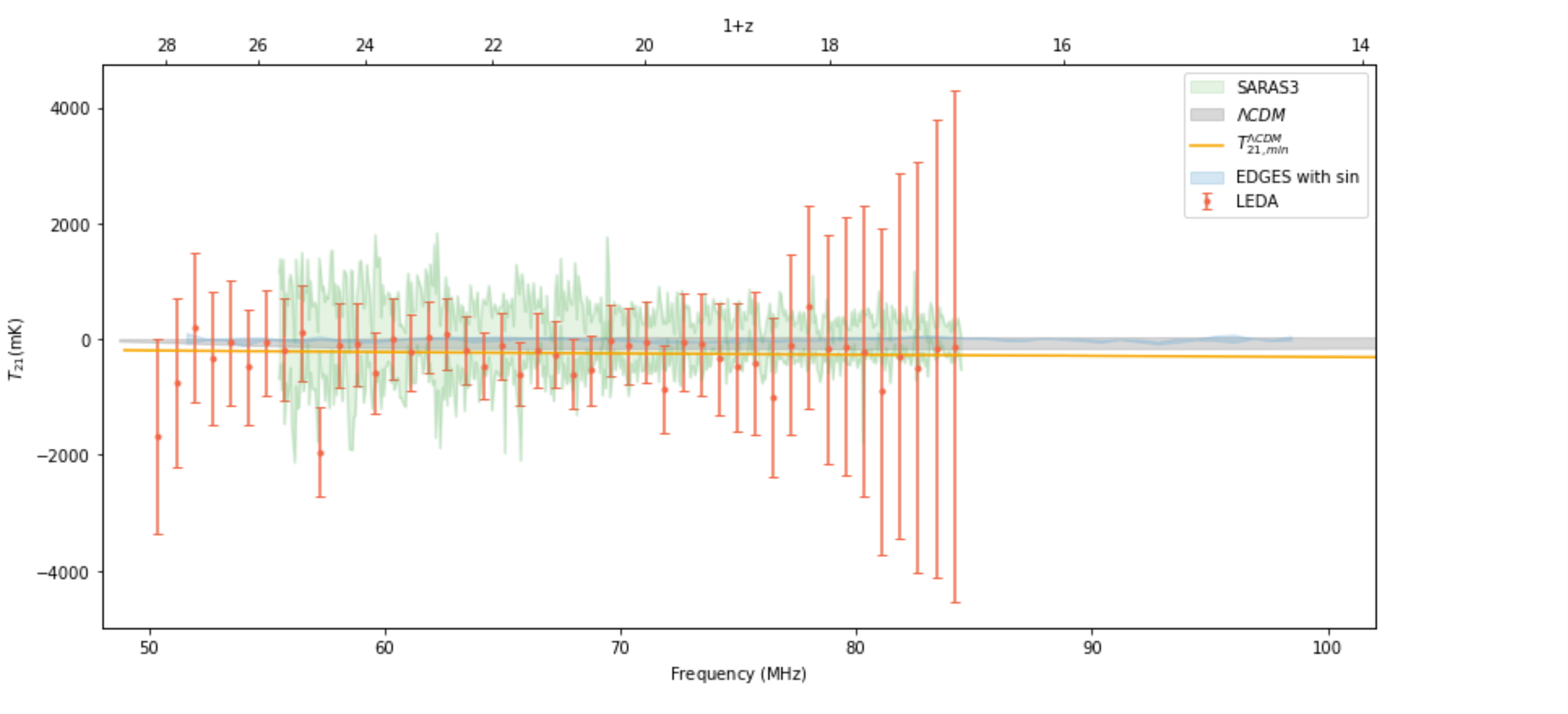


Inconsistent with EDGES!

[SARAS 2, 2018]



21-cm Experiments: Current Status



What are the implications?

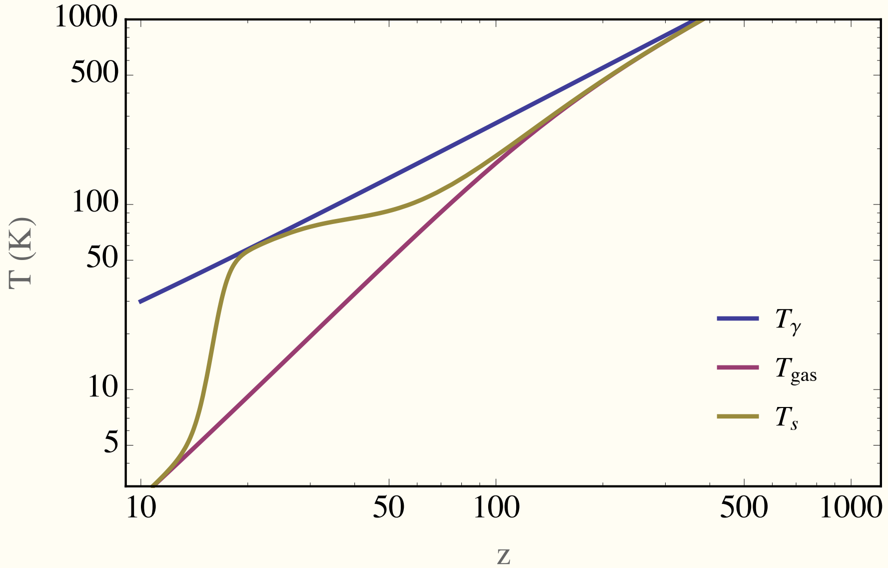
Now what?

For EDGES we've ignored the real physics: X-rays and Ly-α radiation

- For theorists, explaining a signal is **easy**: Ignore all systematic uncertainties and show it's physically possible.

- Placing constraints is **hard**: Figure out all astrophysical and systematic uncertainties and derive a conservative bound.

- With EDGES we made an important simplifying assumption:
  - Maximal Lyman-α that couples gas to spin temperature.
  - No heating from X-rays (dominant source via photoionization)



Now what?

Lyman-α

Finite efficiency that drops as the gas cools

Important implications for dark imprints on 21-cm signal

X-Rays

Large astrophysical uncertainties that affect the 21-cm predictions and constraints.

Understanding Lyman-α

UV starlight plays a crucial role in 21-cm

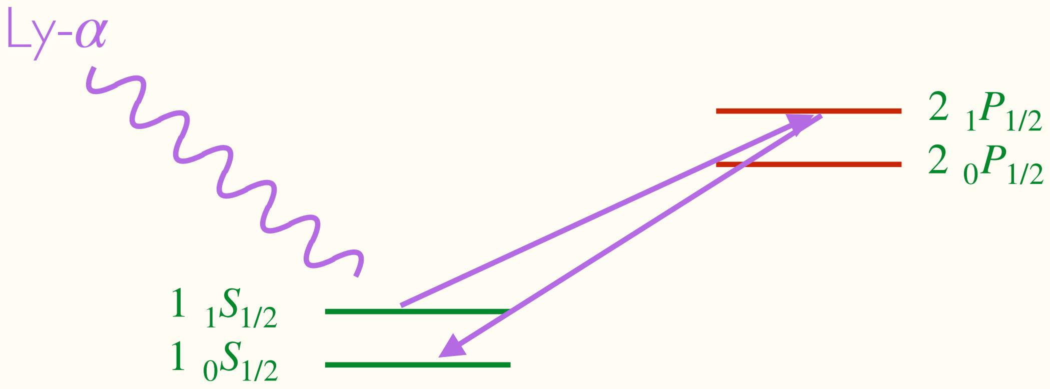
Affect 21-cm spectrum via the Wouthuysen-Field (WTF) effect:

Understanding Lyman-α

UV starlight plays a crucial role in 21-cm

Affect 21-cm spectrum via the Wouthuysen-Field (WTF) effect:

Raman scattering



Understanding Lyman-α

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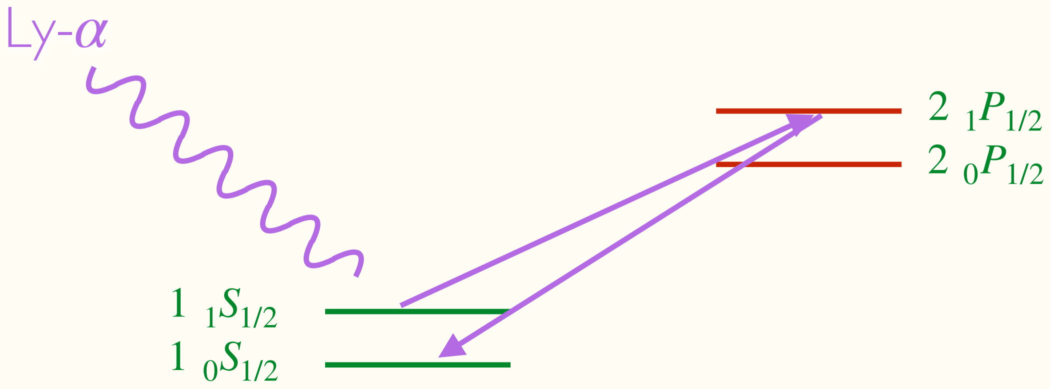

Doppler shift implies energy exchange with HI

Understanding Lyman-α

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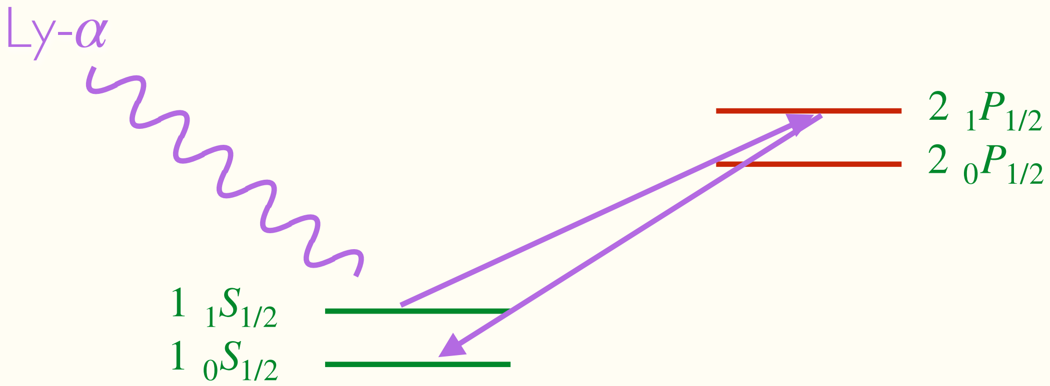
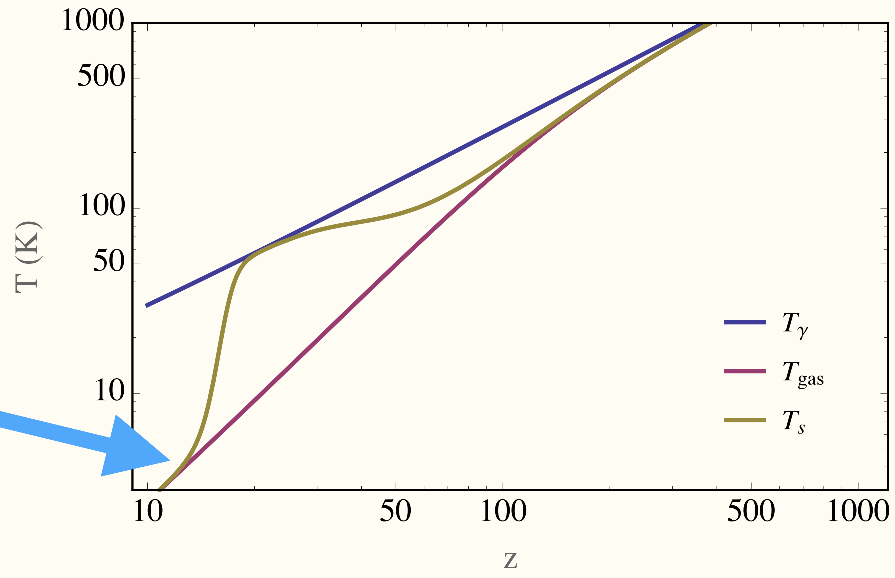


Doppler shift implies energy exchange with HI

Thermalization between T_s and $T_{\rm gas}$



Understanding Lyman-α

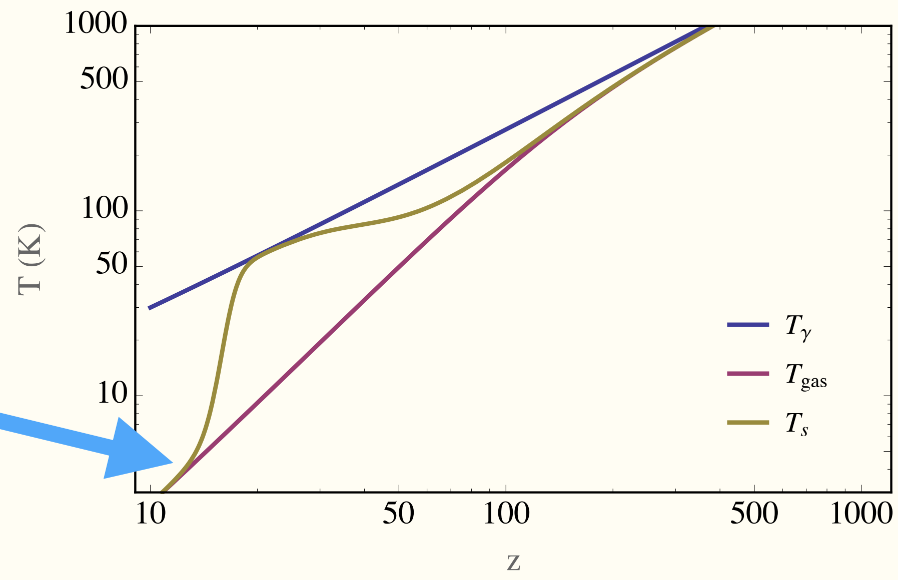
UV starlight plays a crucial role in 21-cm

WTF effect implies:

Absorption signal if HI is cold
(adiabatic expansion or other cooling effects)

Emission signal if HI is hot
(X-ray heating)

Thermalization between T_s and $T_{\rm gas}$



Understanding Lyman-α

Efficiency of WTF strongly depends on T_{gas}

Recall:

$$T_s^{-1} = \frac{T_\gamma^{-1} + x_{\text{gas}} T_{\text{gas}}^{-1} + x_\alpha T_\alpha^{-1}}{1 + x_{\text{gas}} + x_\alpha}$$

$$x_\alpha = \frac{E_{21}}{T_\gamma} \frac{L_{10}}{A_{10}}$$

Understanding Lyman-α

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Photon flux

Absorption Cross-section

Understanding Lyman-α

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So effect of Ly-α directly depends on the flux at around the absorption line

Understanding Lyman-α

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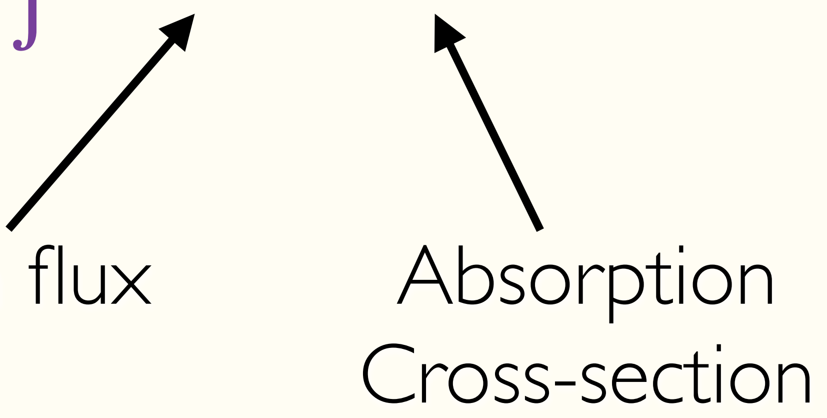

Photon flux

Absorption Cross-section

So effect of Ly-α directly depends on the flux at around the absorption line

$$x_\alpha = \frac{E_{21}}{T_\gamma} \frac{L_{10}}{A_{10}} = S_\alpha \frac{J_\alpha}{\bar{J}}$$

S_α - WTF effective coupling

J_α - Flux around absorption peak without radiative transfer

Understanding Lyman-α

$$x_\alpha = \frac{E_{21}}{T_\gamma}\frac{L_{10}}{A_{10}} = S_\alpha \frac{J_\alpha}{\bar{J}}$$

How do we find S_α ?

Write down Boltzmann Eq. describing the absorption and reemission

Hard to solve - instead expand to arrive at a Fokker-Planck Eq.:

$$\frac{\partial}{\partial \nu}\left(-A\,J_\nu + D\frac{\partial\,J_\nu}{\partial \nu}\right) + C\psi(\nu) = 0$$

Understanding Lyman-α

$$\frac{\partial}{\partial \nu}\left(-A\, J_\nu + D\frac{\partial J_\nu}{\partial \nu}\right) + C\psi(\nu) = 0$$

Understanding Lyman-$\boldsymbol{\alpha}$

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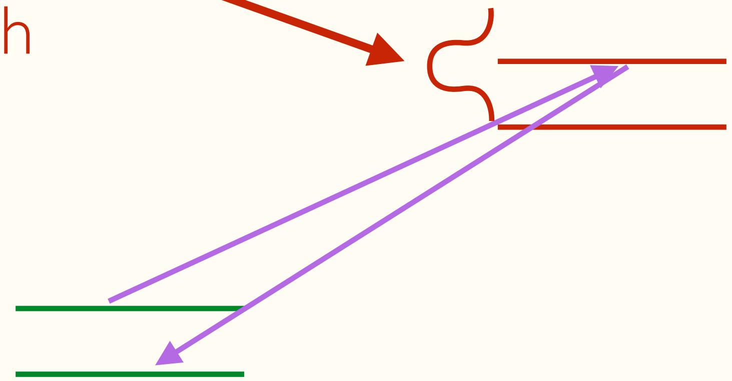
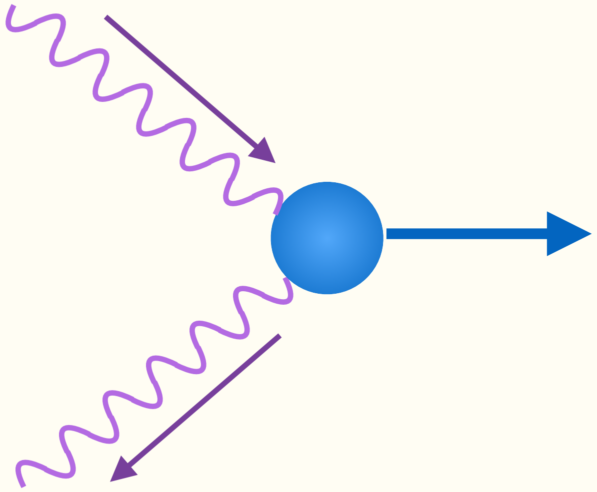


Diffusion due to
$T_{\rm gas}$-dependent, finite width

Understanding Lyman-α

$$\frac{\partial}{\partial\nu}\left(-A\,J_\nu + D\frac{\partial J_\nu}{\partial\nu}\right) + C\psi(\nu) = 0$$

Frequency drift due to T_{gas}-dependent recoil



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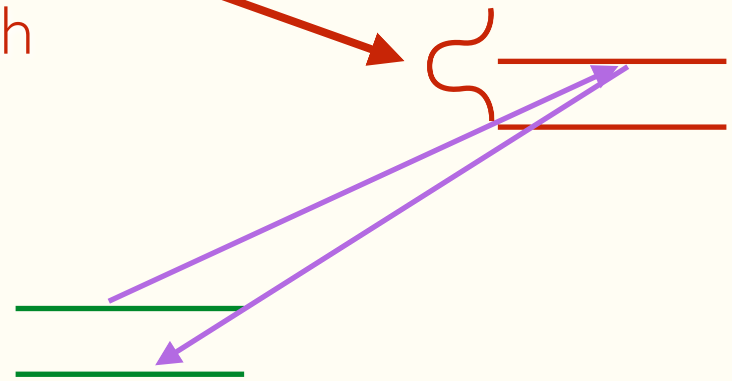

Understanding Lyman-α

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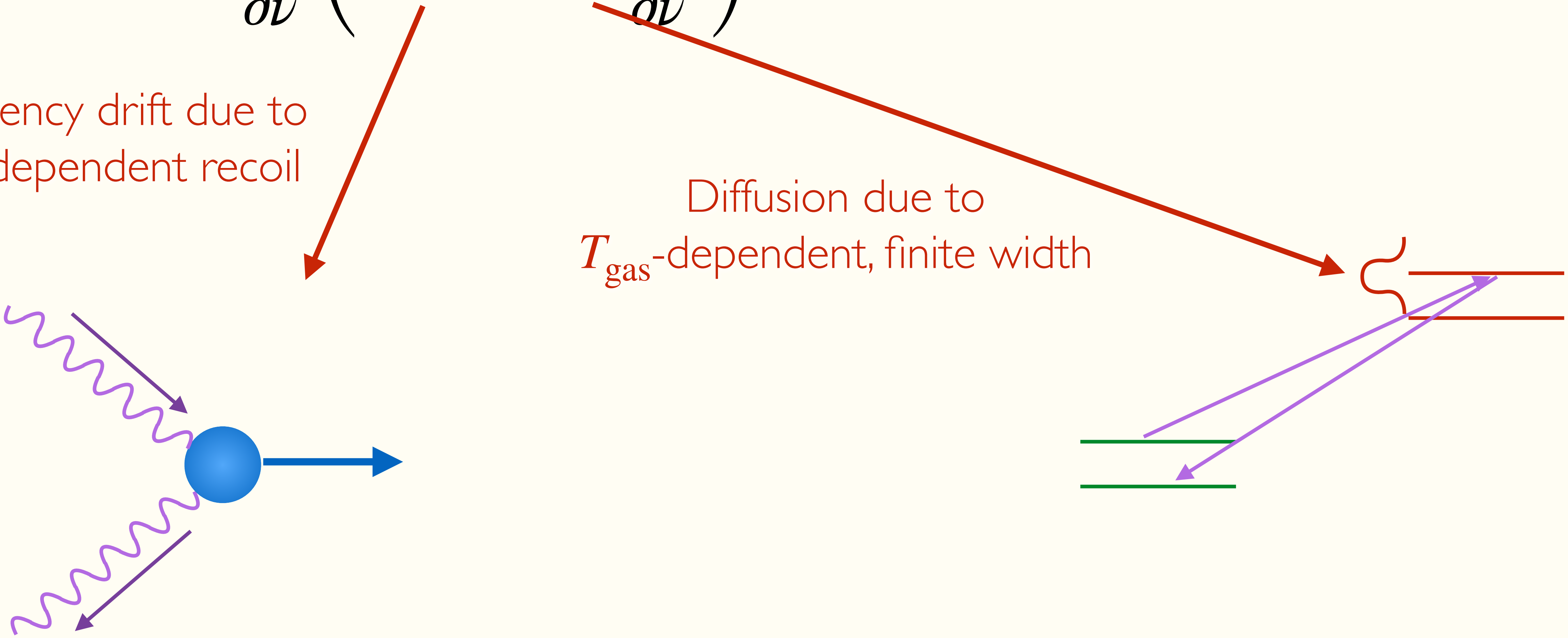


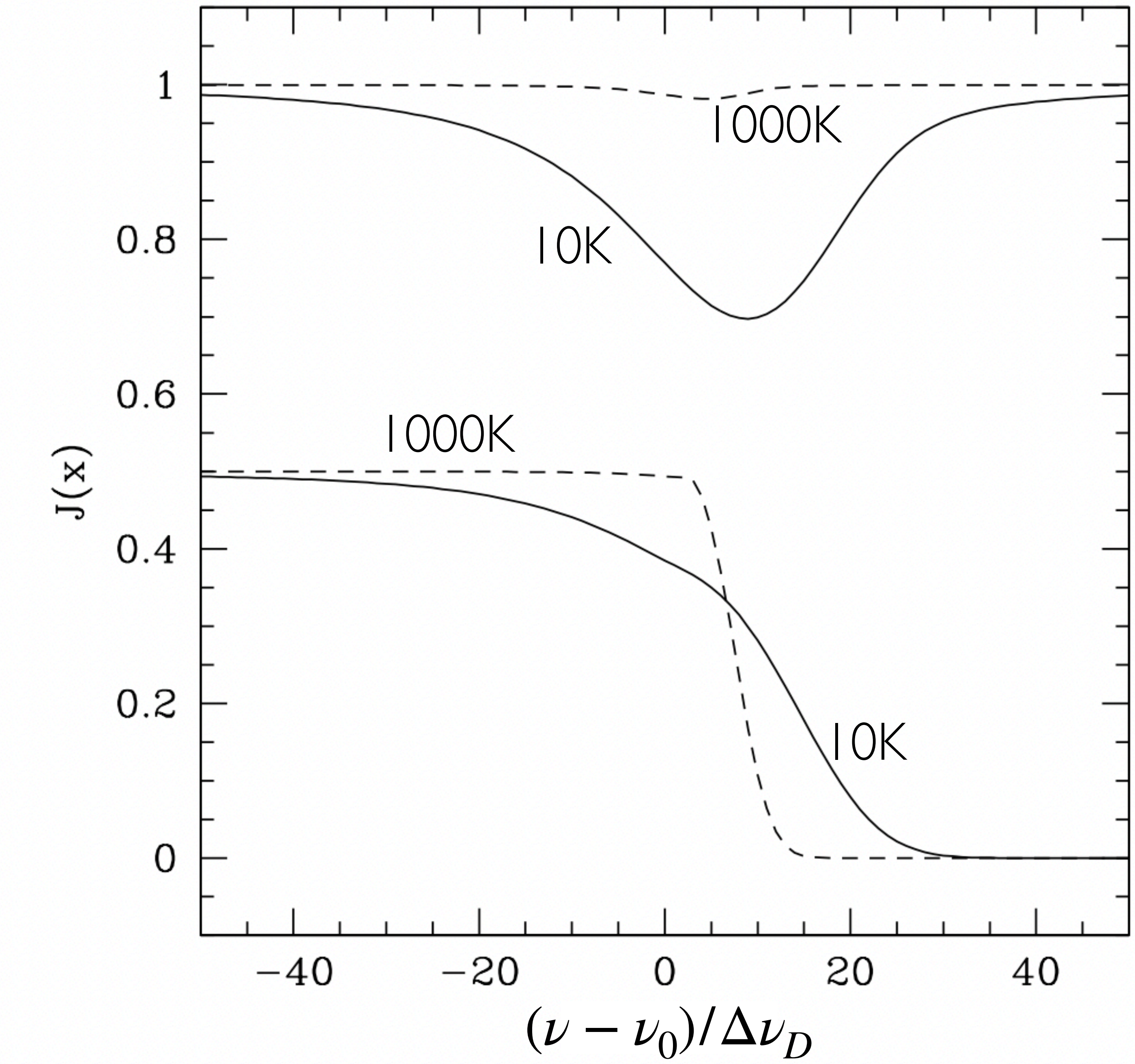
Frequency drift due to T_{gas}-dependent recoil

Diffusion due to T_{gas}-dependent, finite width

Expect a T_{gas}-dependent absorption peak in photon flux around Ly-α line

Understanding Lyman-α

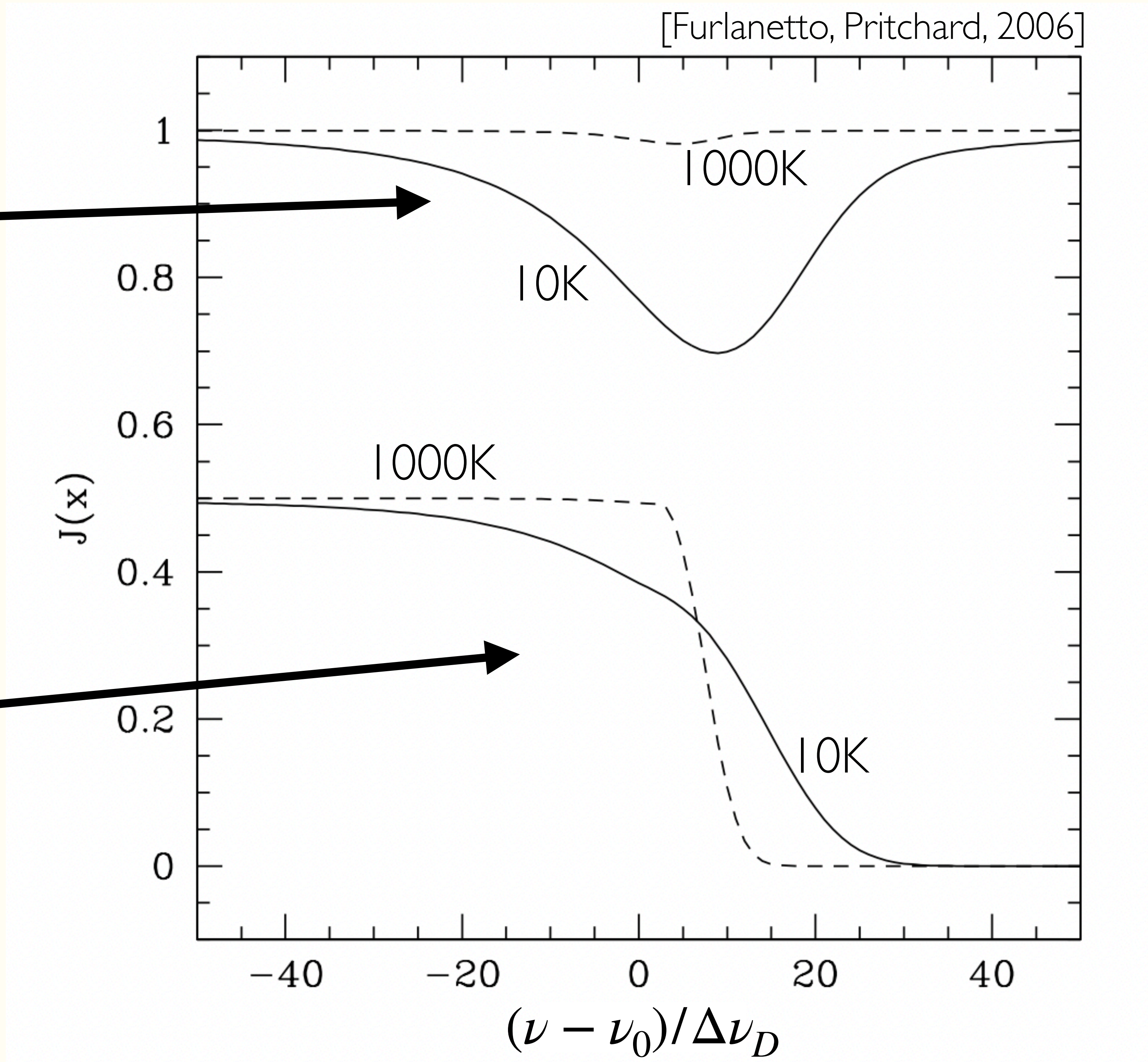
[Furlanetto, Pritchard, 2006]



Expect a T_{gas}-dependent absorption peak

in photon flux around Ly-α line

Understanding Lyman-α



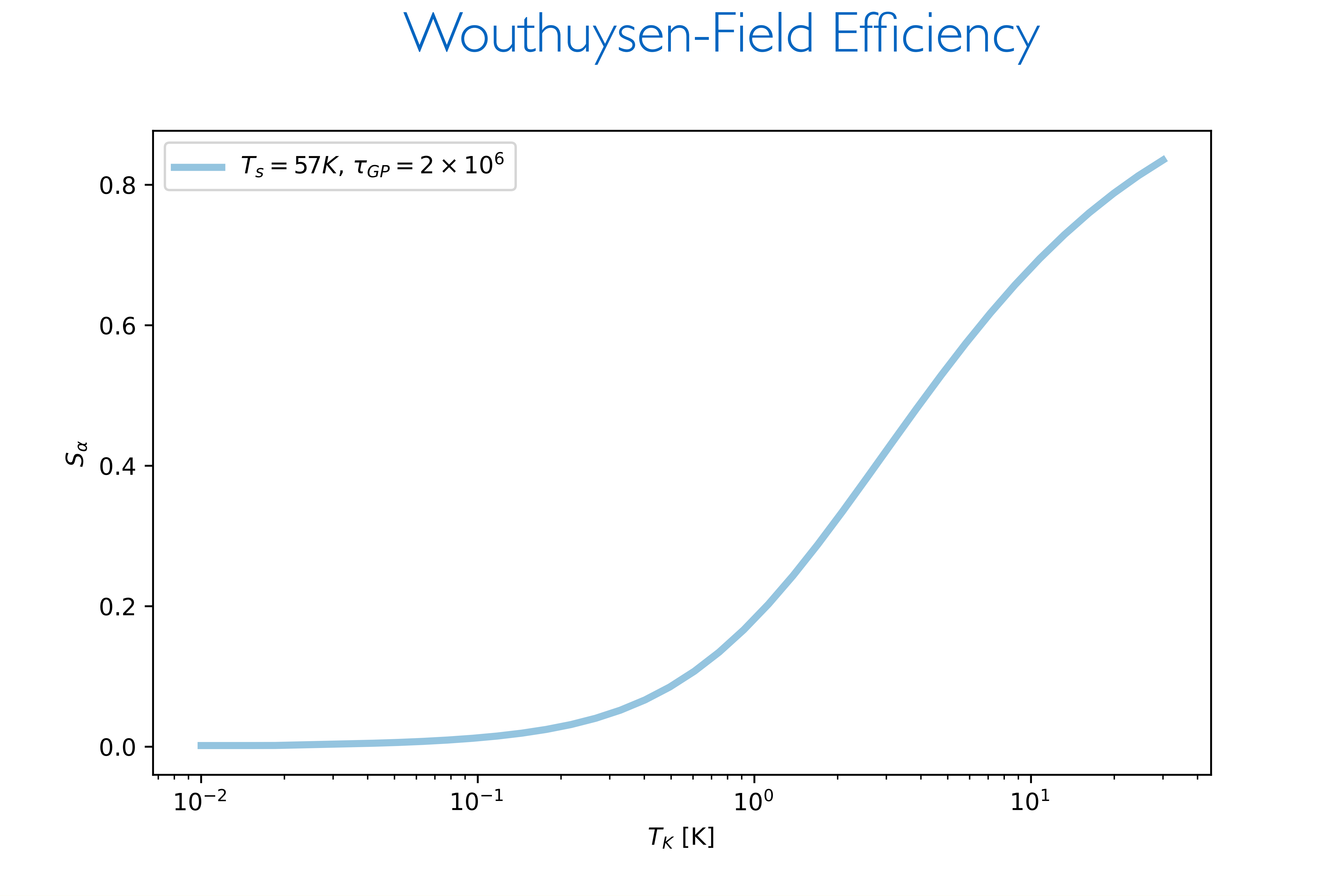
[Furlanetto, Pritchard, 2006]

Continuum (redshifted) photon spectrum

Injected photon spectrum

Expect a T_{gas}-dependent absorption peak in photon flux around Ly-α line

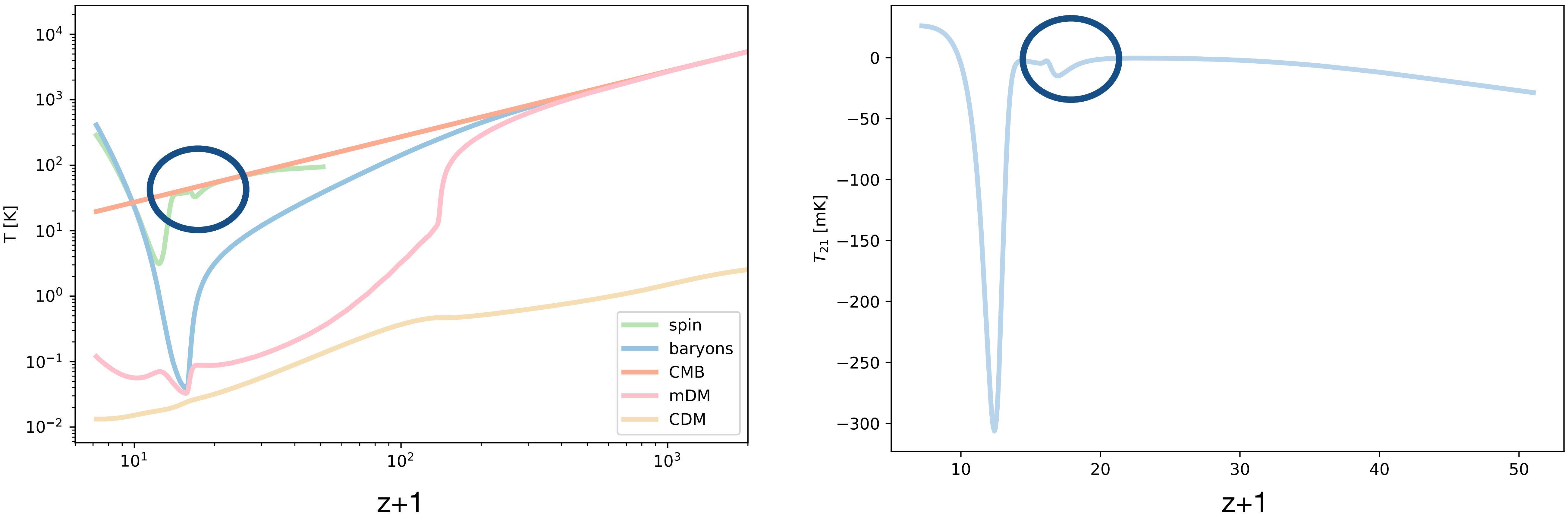
Understanding Lyman-α



Strong DM cooling of hydrogen will not efficiently cool T_s

WTF Effect: DM Implications

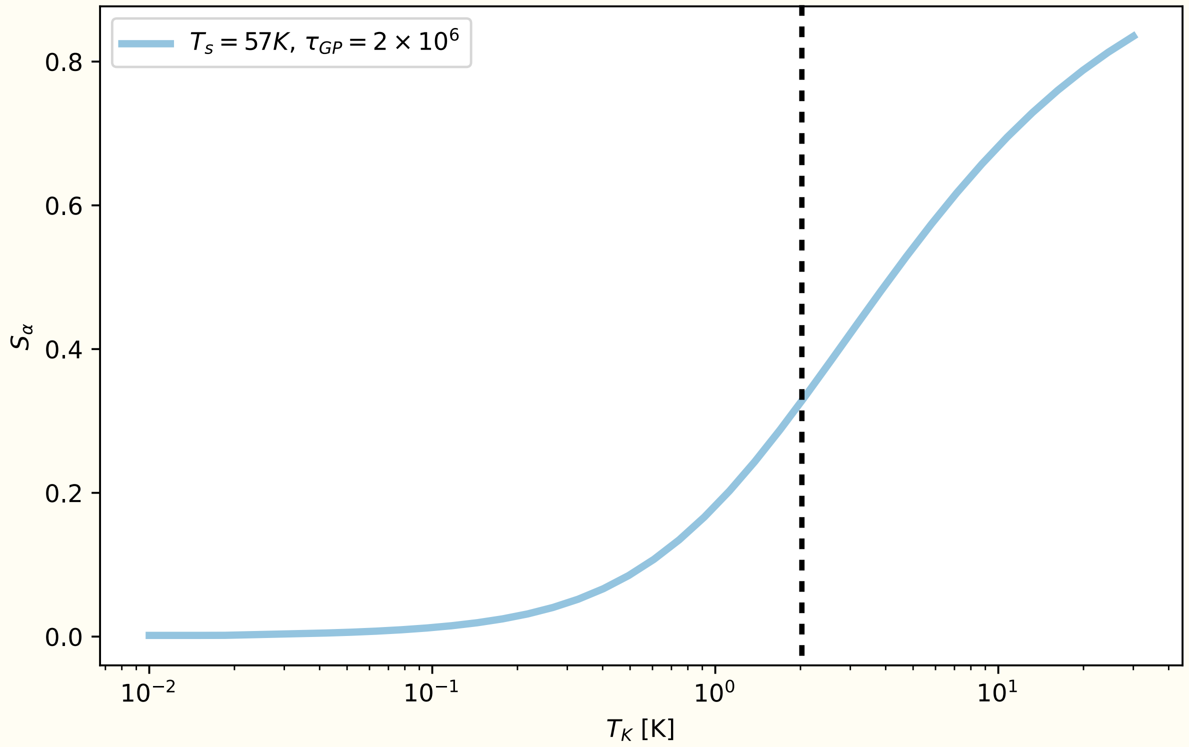
Finite Cooling: T_s affected only shortly until gas is cooled too much



Another dip predicted due to DM cooling

WTF Efficiency: Many complications

S_α only calculated for $T > 2$ K



Below Fokker-Planck approximation does not hold

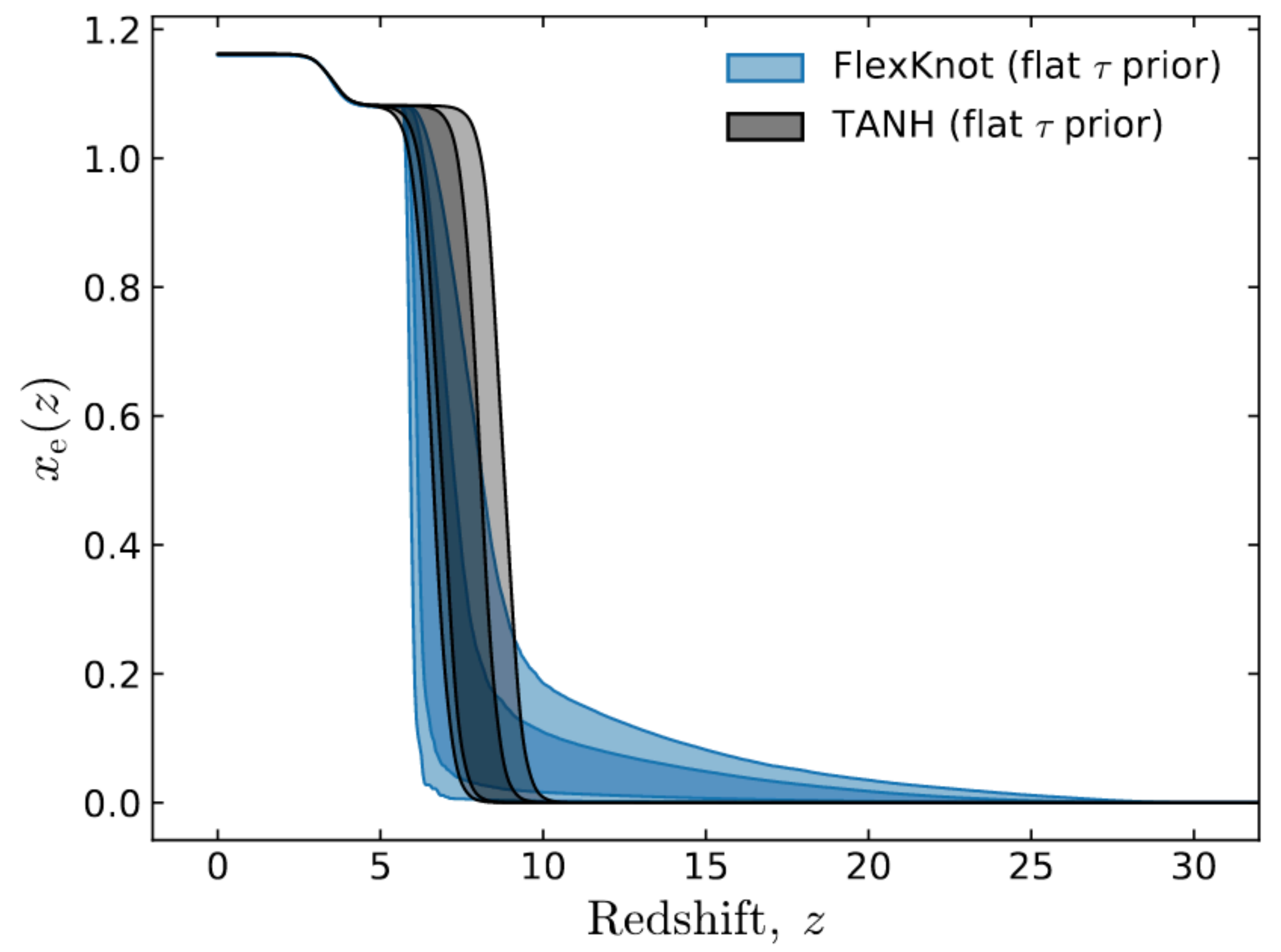
Need to solve full Boltzmann Eq. (hard!)

Not expected to change qualitative features but could still be important.

Work in progress..

WTF Efficiency: Many complications

Reionization



Understanding X-Rays

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

Redshift

Compton scattering

DM scattering

Understanding X-Rays

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$$\dot{Q}_{\rm X-ray} \sim f_{\rm atoms}\ \Gamma_{\rm X-ray}\ \Delta E\ \epsilon_{\rm heat} = f_{\rm atoms}\int d\nu\ \sigma(\nu)\ \Phi_{\rm X-ray}(\nu)\ \ \Delta E(\nu)\epsilon_{\rm heat}$$

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Key difficulty: How do we estimate $\Phi_{\rm X-ray}$?

Understanding X-Rays

- Extracted indirectly.
- Flux (and luminosity) strongly depends on the Star Formation Rate (SFR):

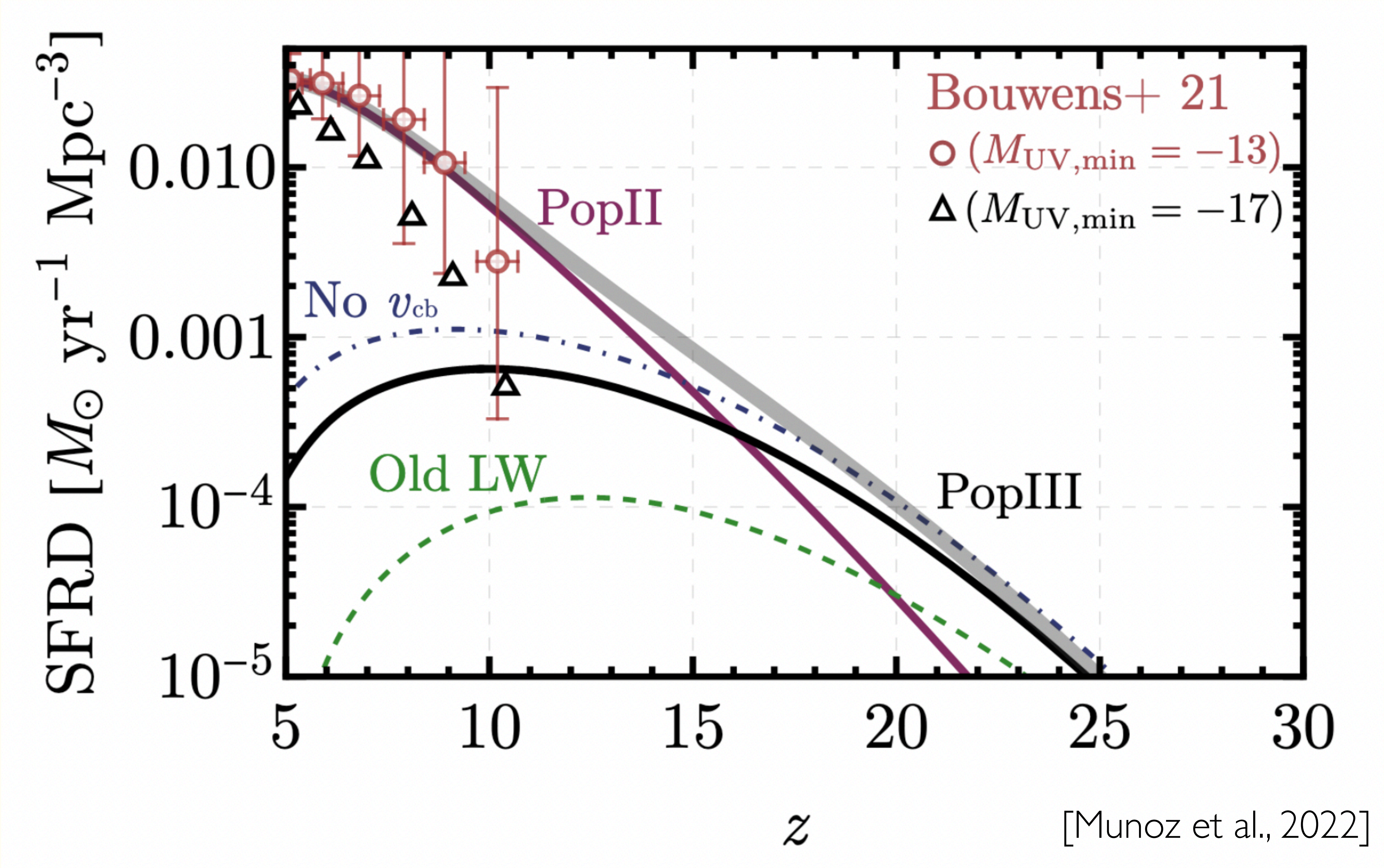
$$L_\nu(z) = \Gamma_{\rm SFR}(z) \left.\frac{d^2E}{d\nu dM}\right|_{\nu 0} \left(\frac{\nu}{\nu_0}\right)^{-\alpha}$$

- α depends on source: starbursts, SNR and mini-quasars.
- $\Gamma_{\rm SFR}(z)$ depends on minimal halo size and cooling mechanism:

$$\Gamma_{\rm SFR}(z) \sim \frac{d}{dt}\int_{M_{\rm min}}^{\infty} dm' m' \frac{dN}{dm'}\ \epsilon_{\rm SF}(z, m')$$

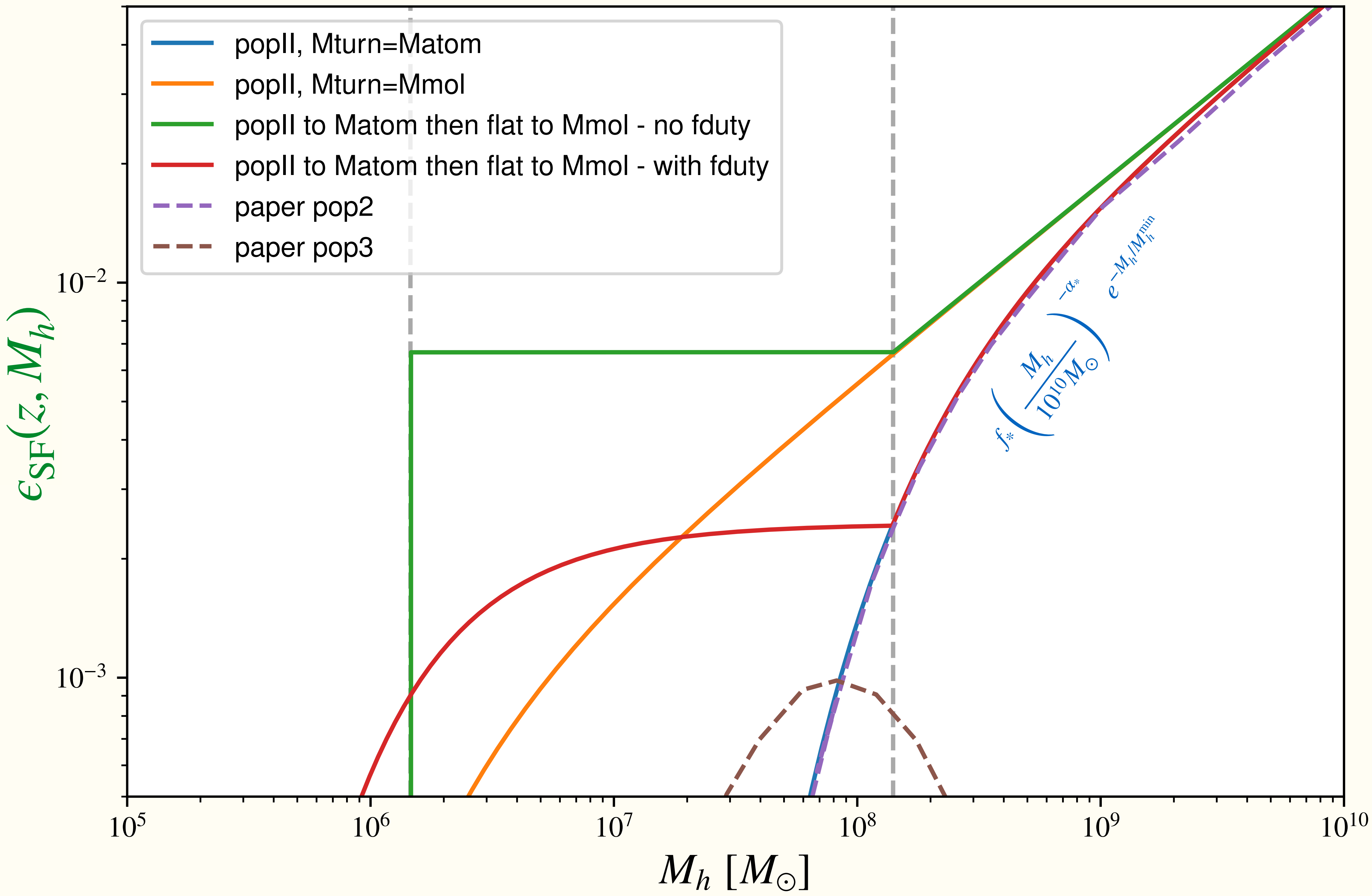
Model-Dependent!!

Star Formation Efficiency



[Munoz et al., 2022]

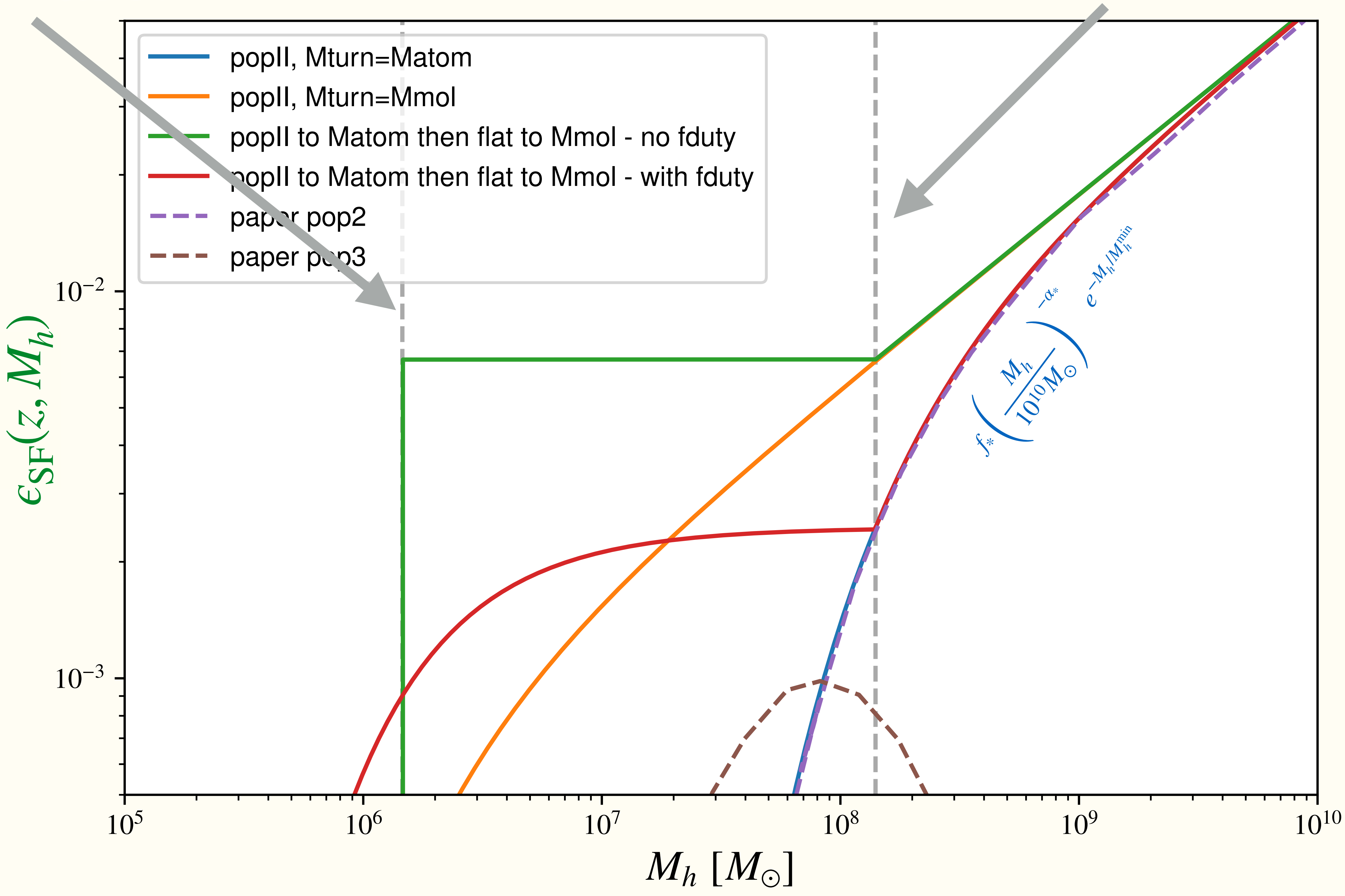
Star Formation Efficiency



Star Formation Efficiency

Molecular cooling
$T_{\rm vir} \simeq 0.1$ eV

Atomic cooling
$T_{\rm vir} \simeq 1$ eV



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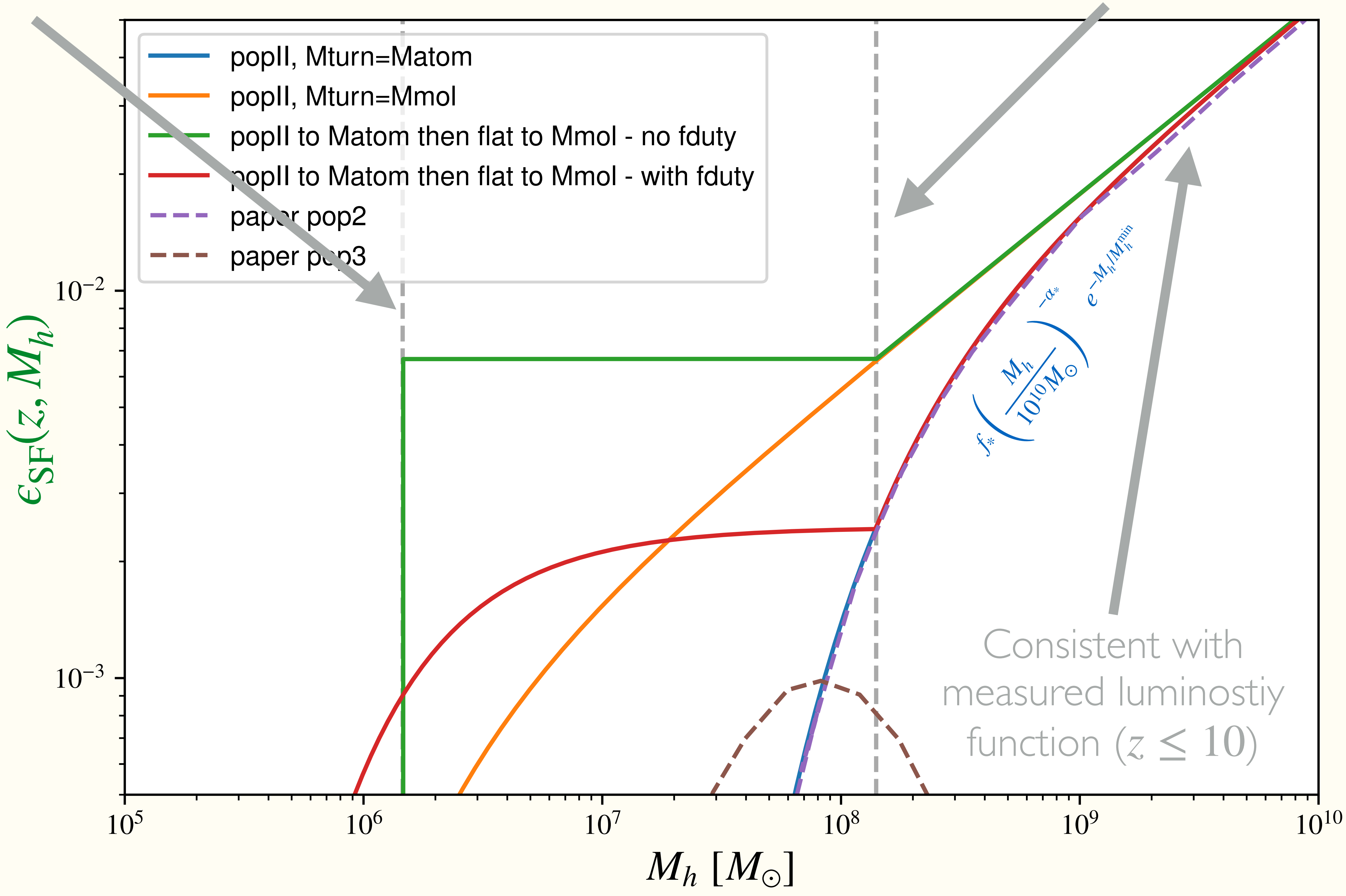
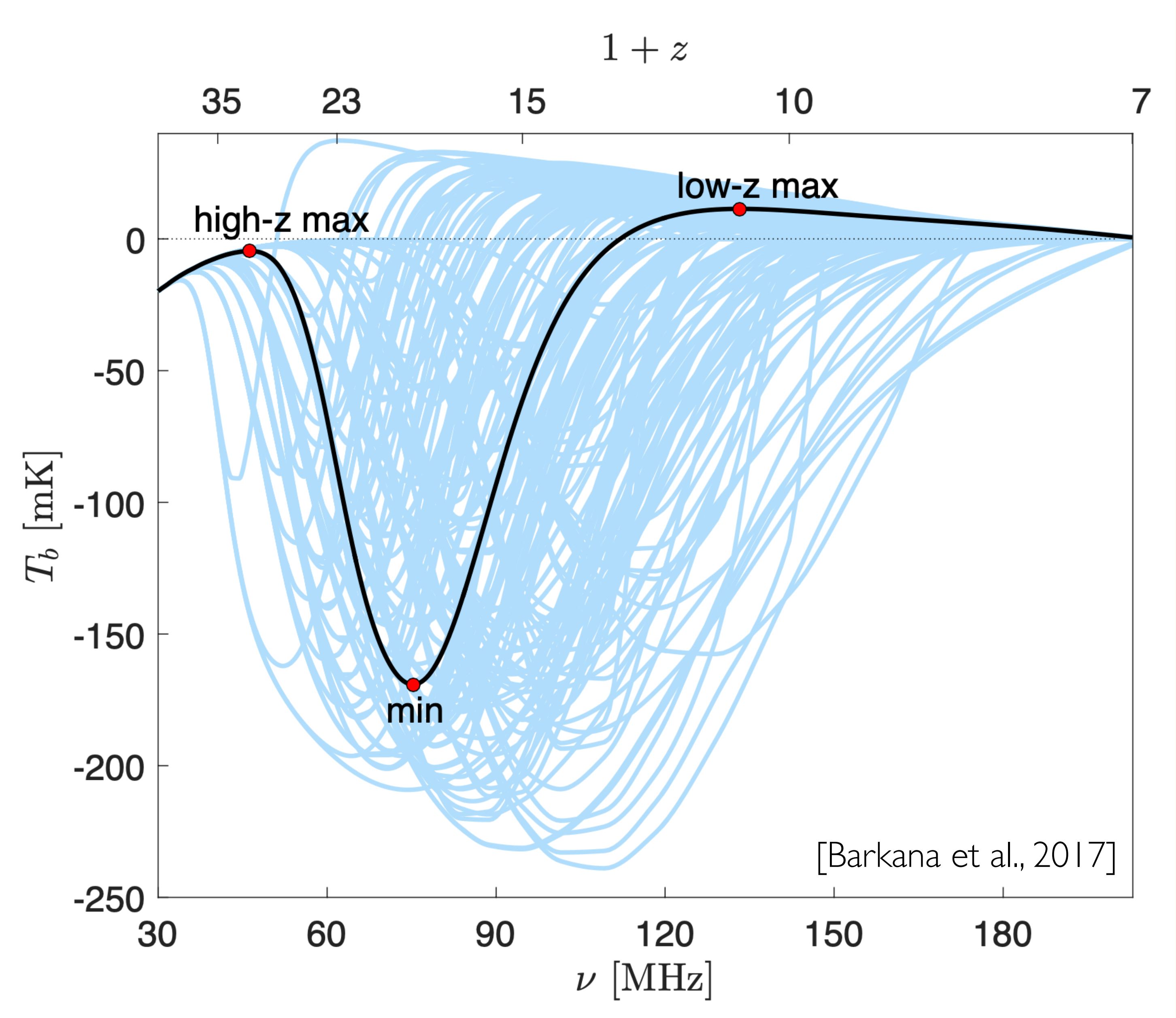


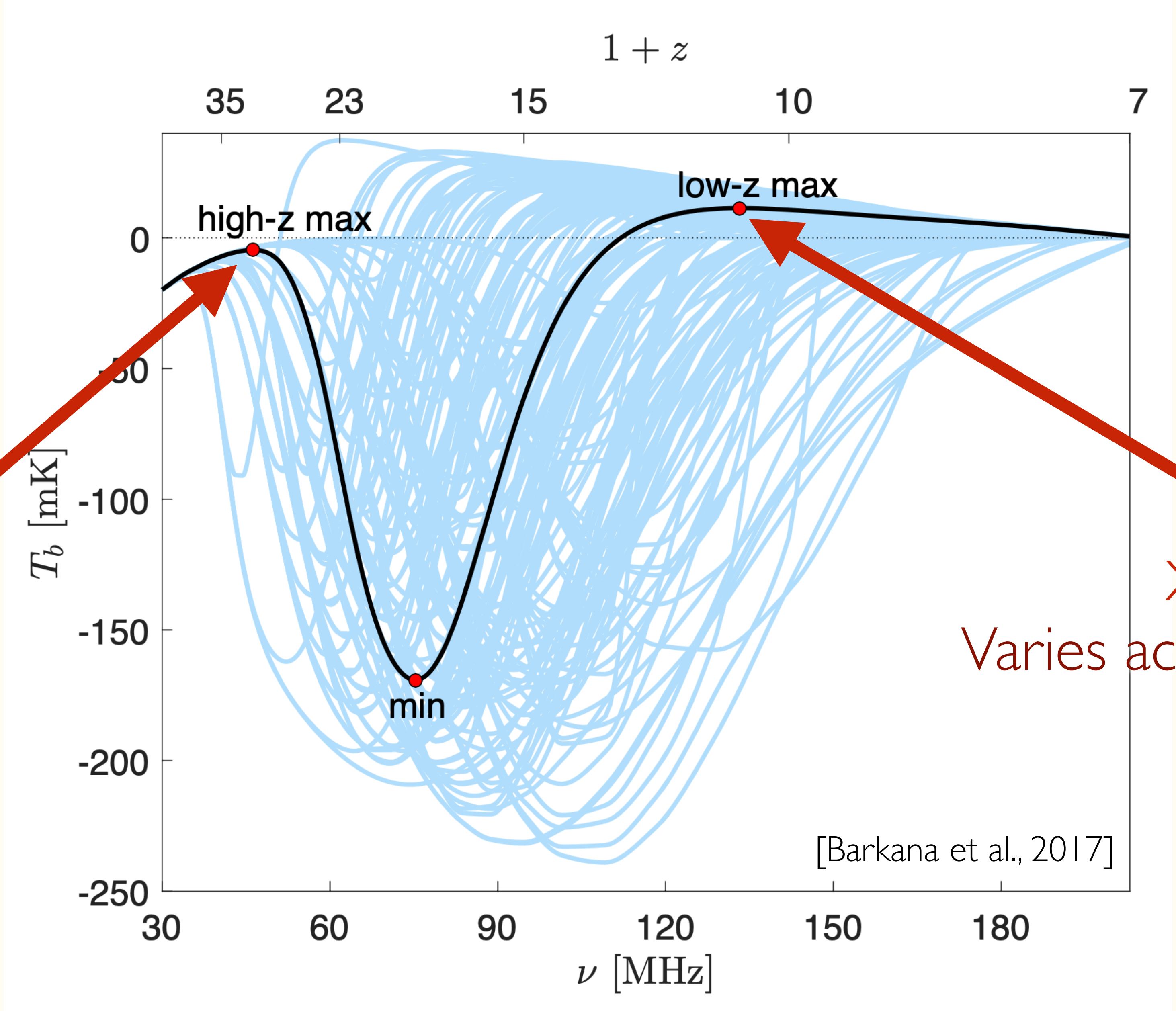
Consistent with
measured luminostiy
function ($z \leq 10$)

What do we know about X-rays?



[Barkana et al., 2017]

What do we know about X-rays?



[Barkana et al., 2017]

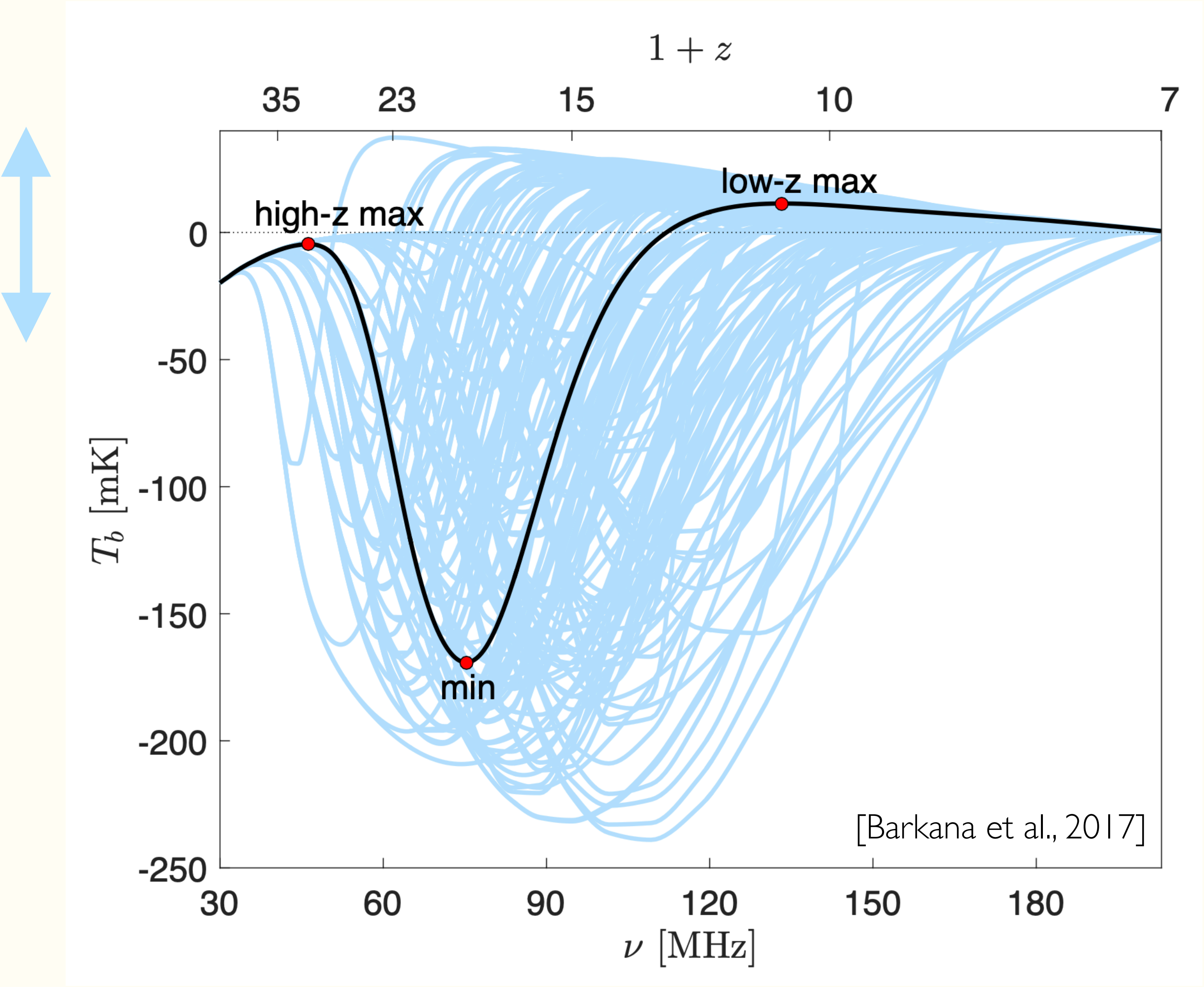
Coupled to CMB

X-ray heating

Varies according to spectrum

What do we know about X-rays?

Change in
star formation
efficiency
& total X-ray
luminosity



[Barkana et al., 2017]

What do we know about X-rays?

Change in minimal halo size &
star formation efficiency

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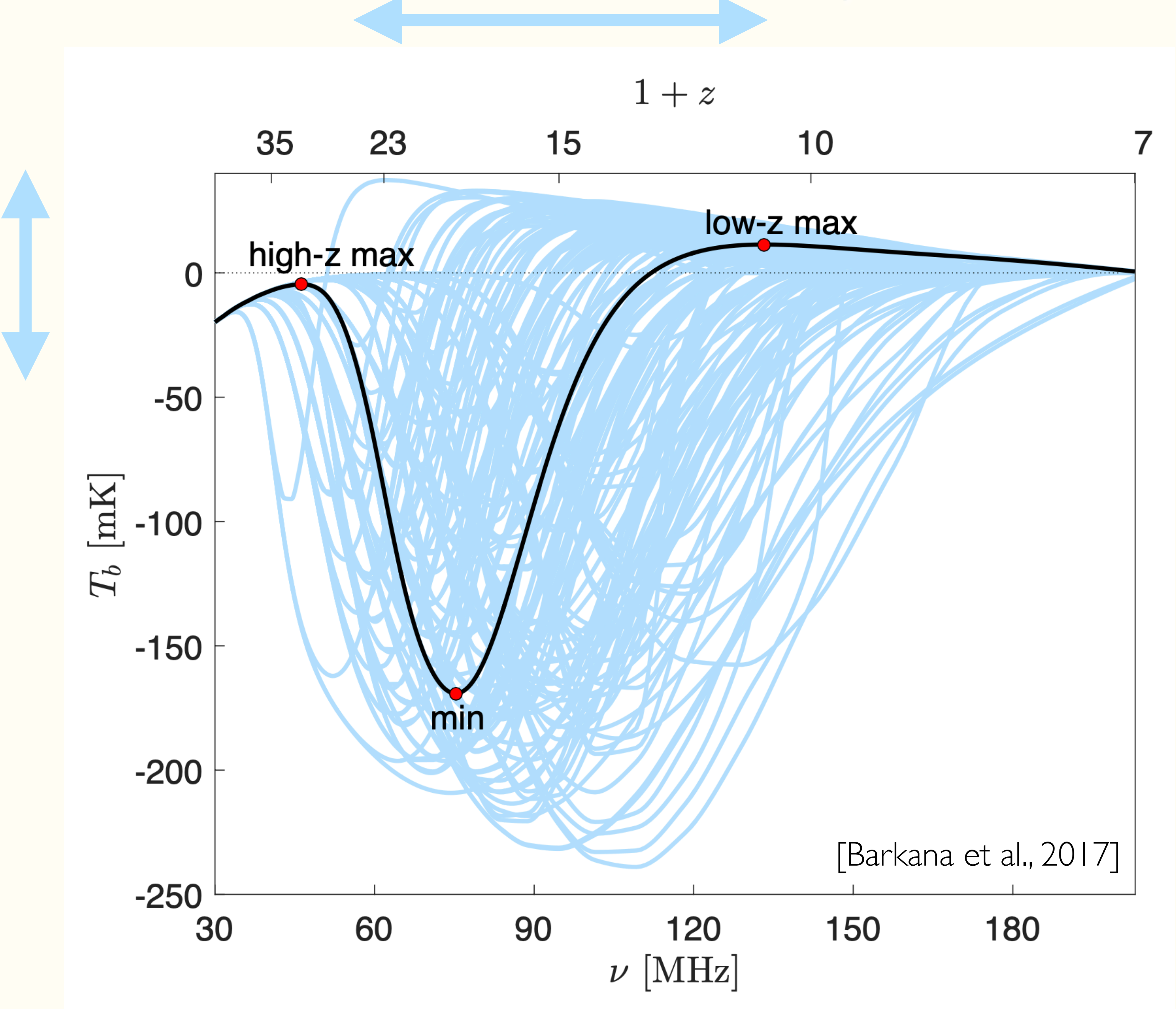
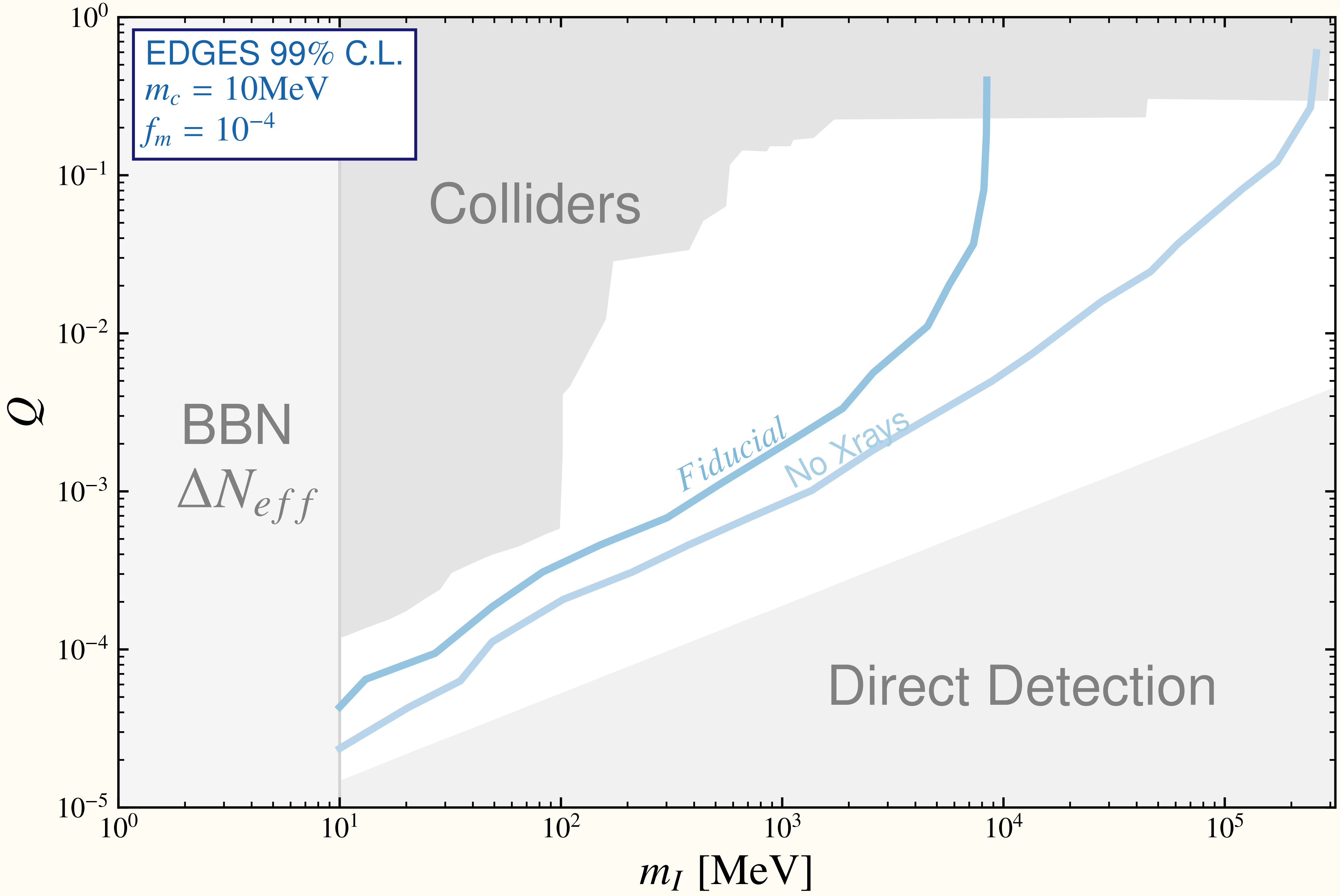


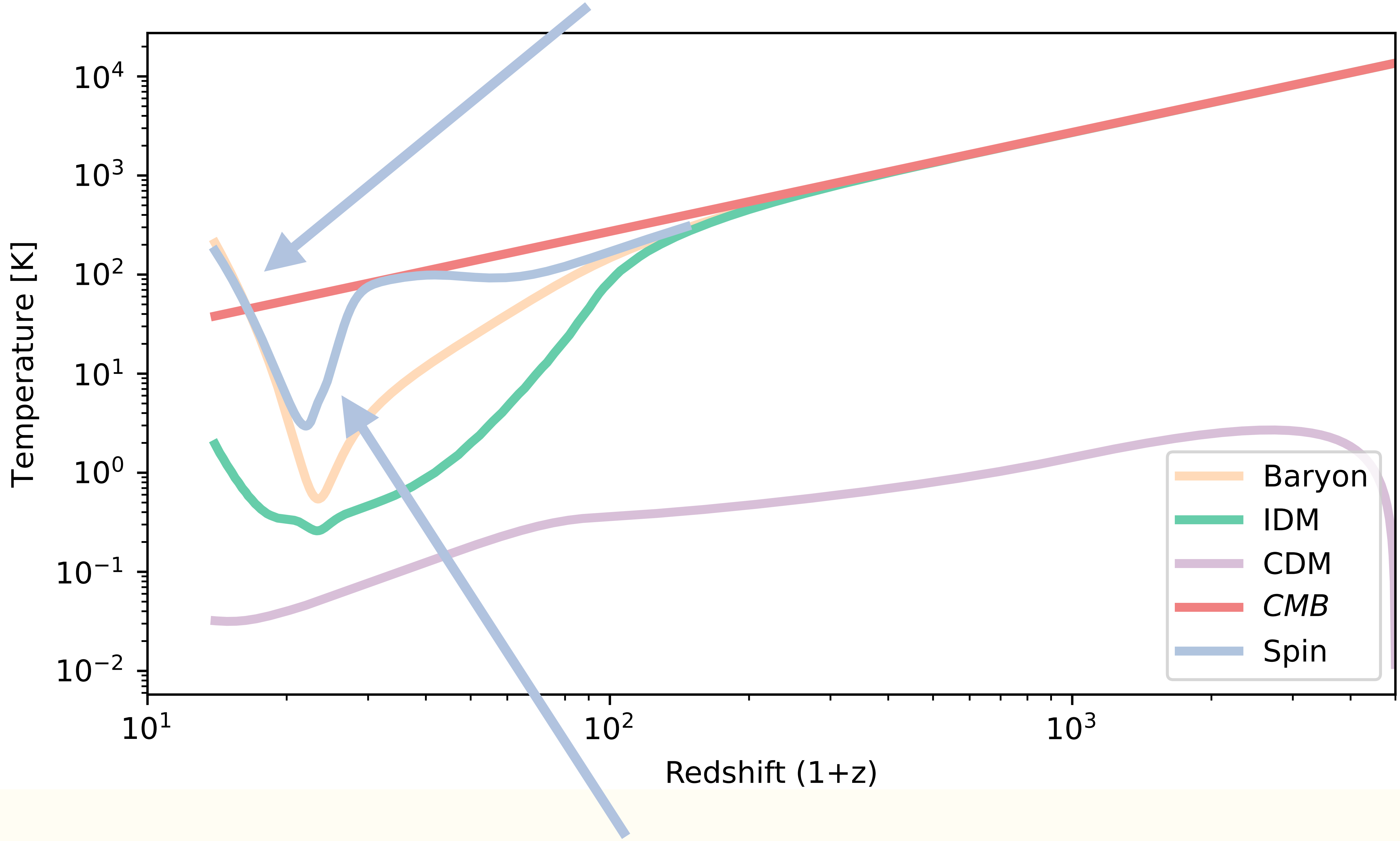
[Barkana et al., 2017]

X-Ray Matters!



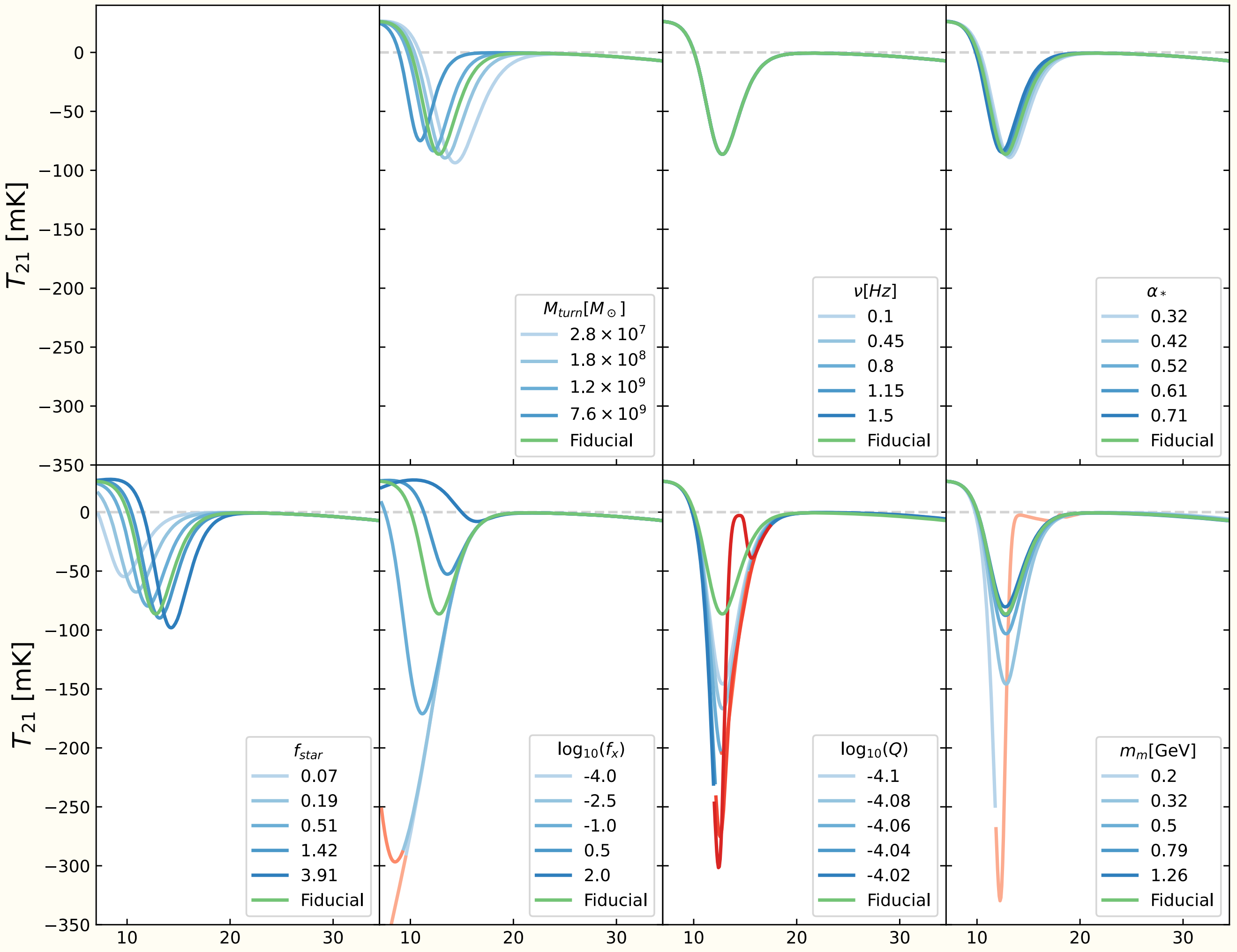
3-Fluid Dynamics

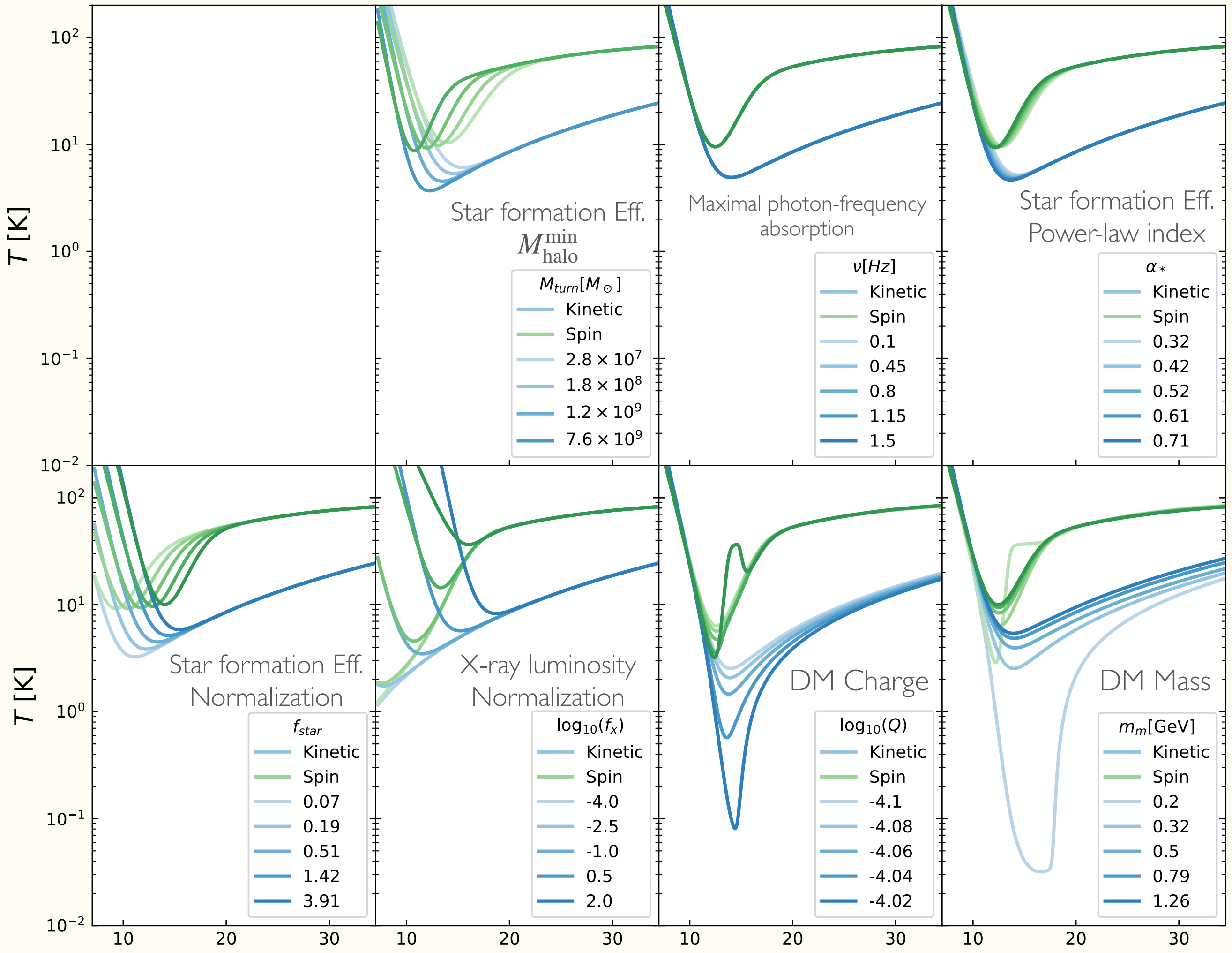
Heating up
(X-Ray)



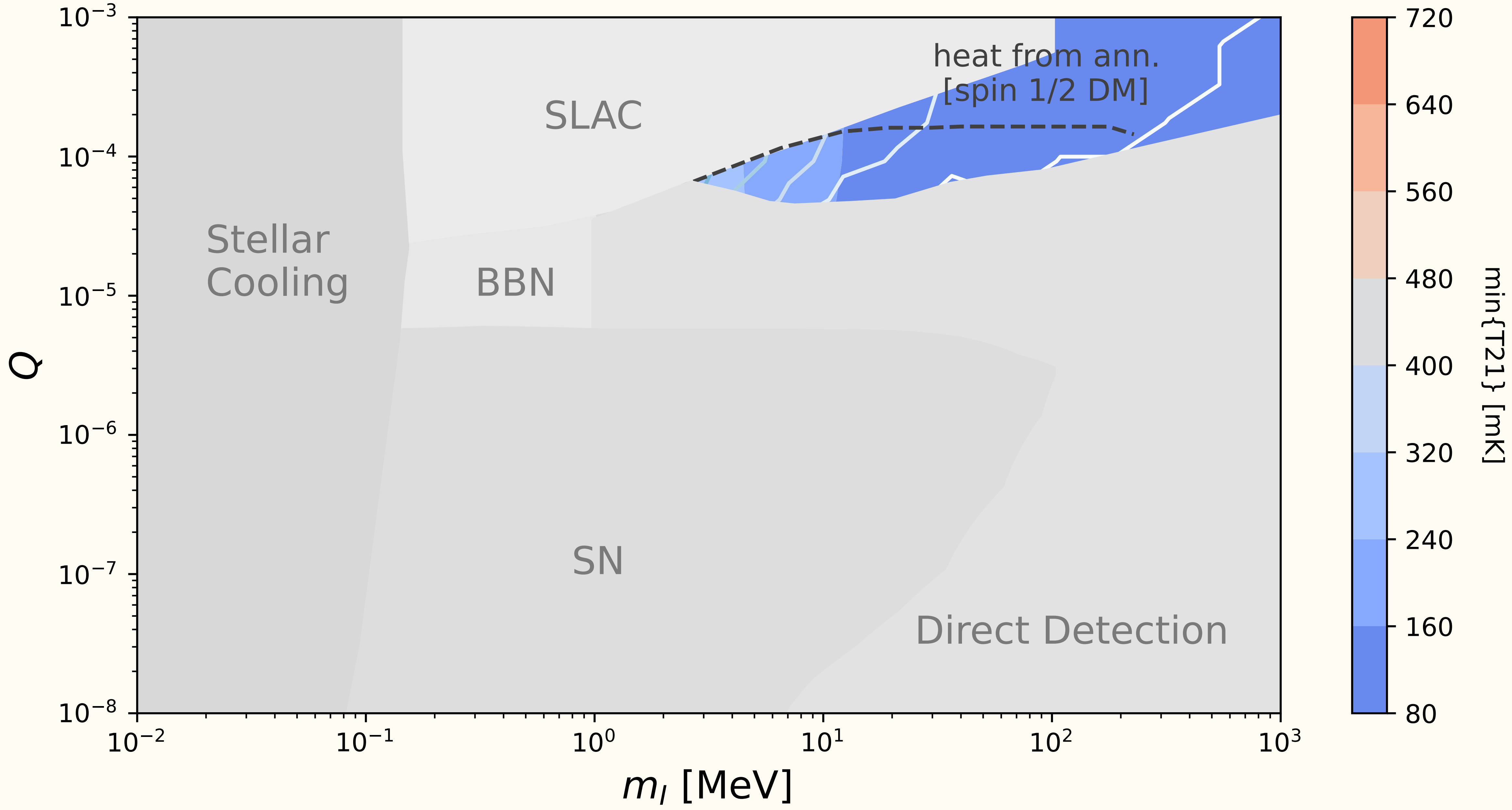
Doesn’t couple to baryons
(Finite Ly-α radiation efficiency)

Parameter Scans





Millicharged DM - 2 Fluids



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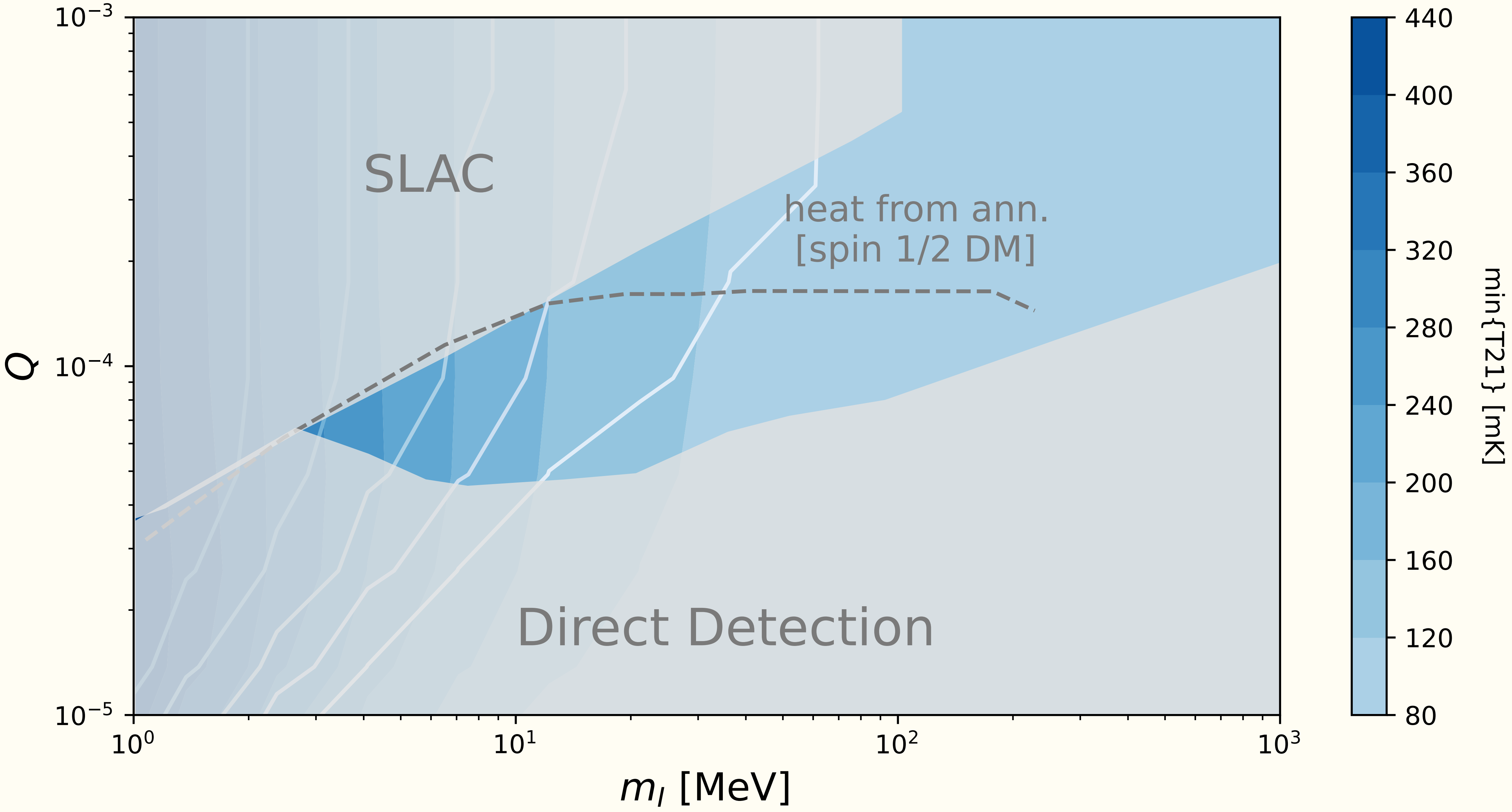
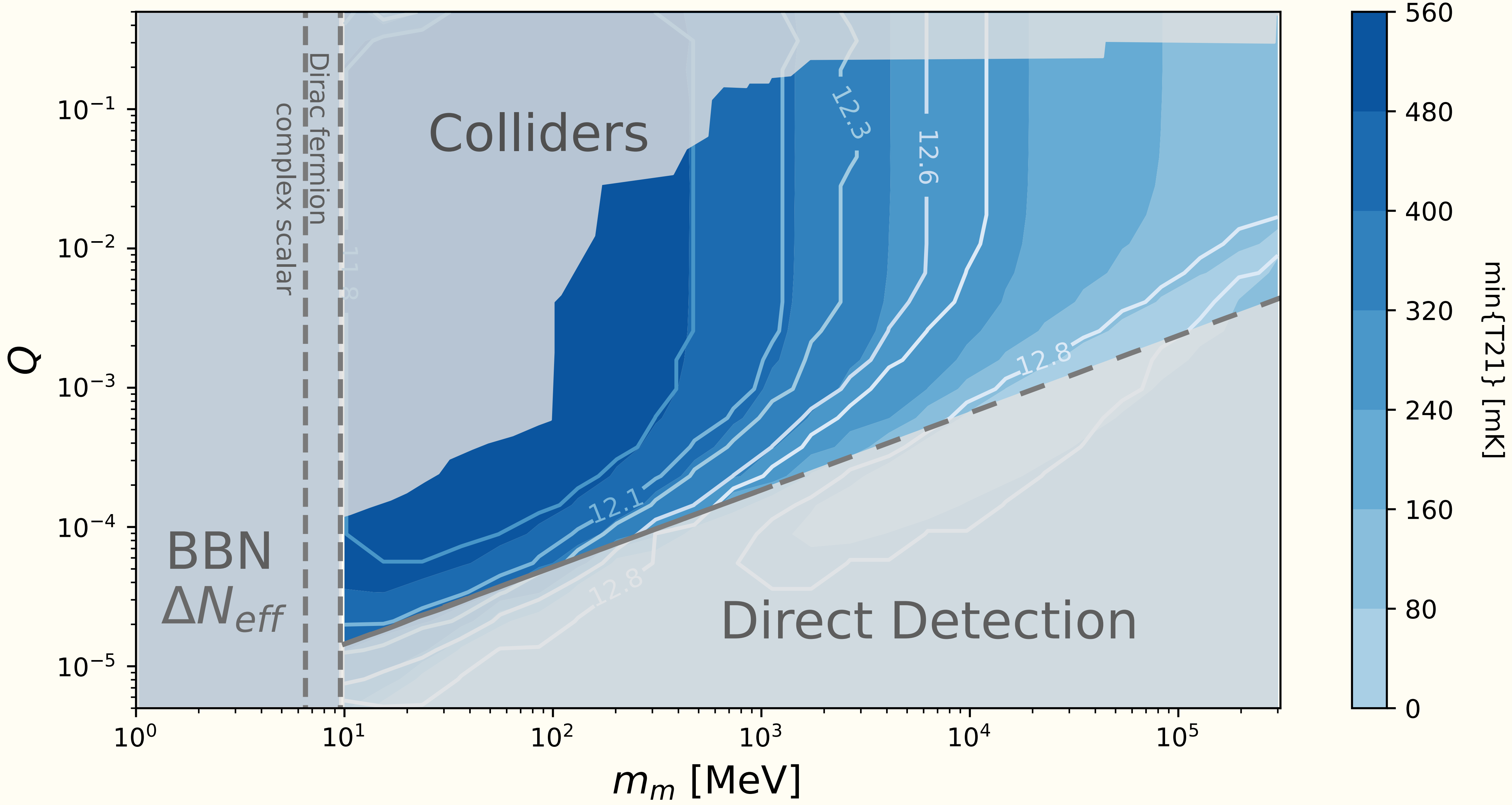


Millicharged DM - 3 Fluids



How Much DM is Hiding Inside Stars?

[Peled, TV, *2022*]

Nightmare Scenario

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2$$

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

$$\rho_\phi \propto a^{-3}$$

We'll never find this kind of DM!

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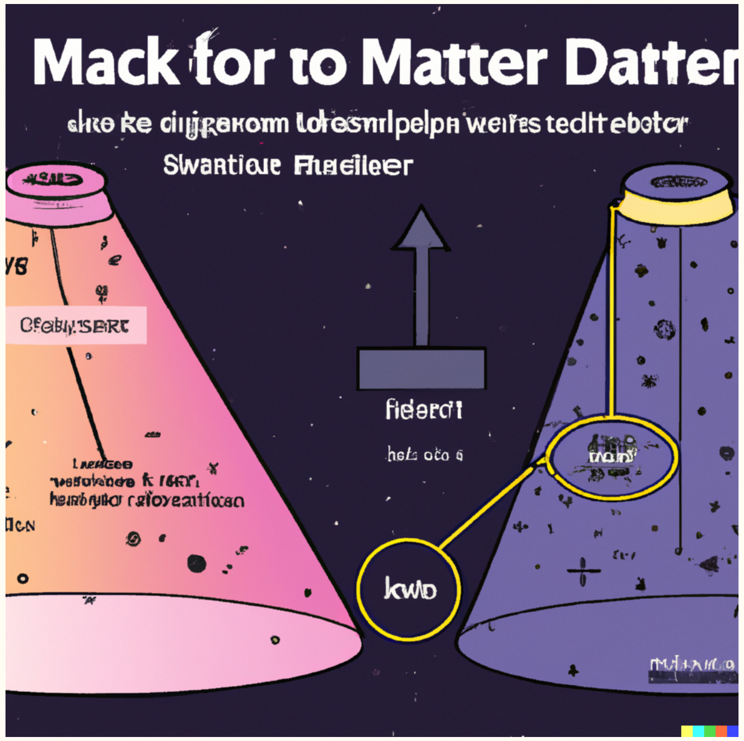

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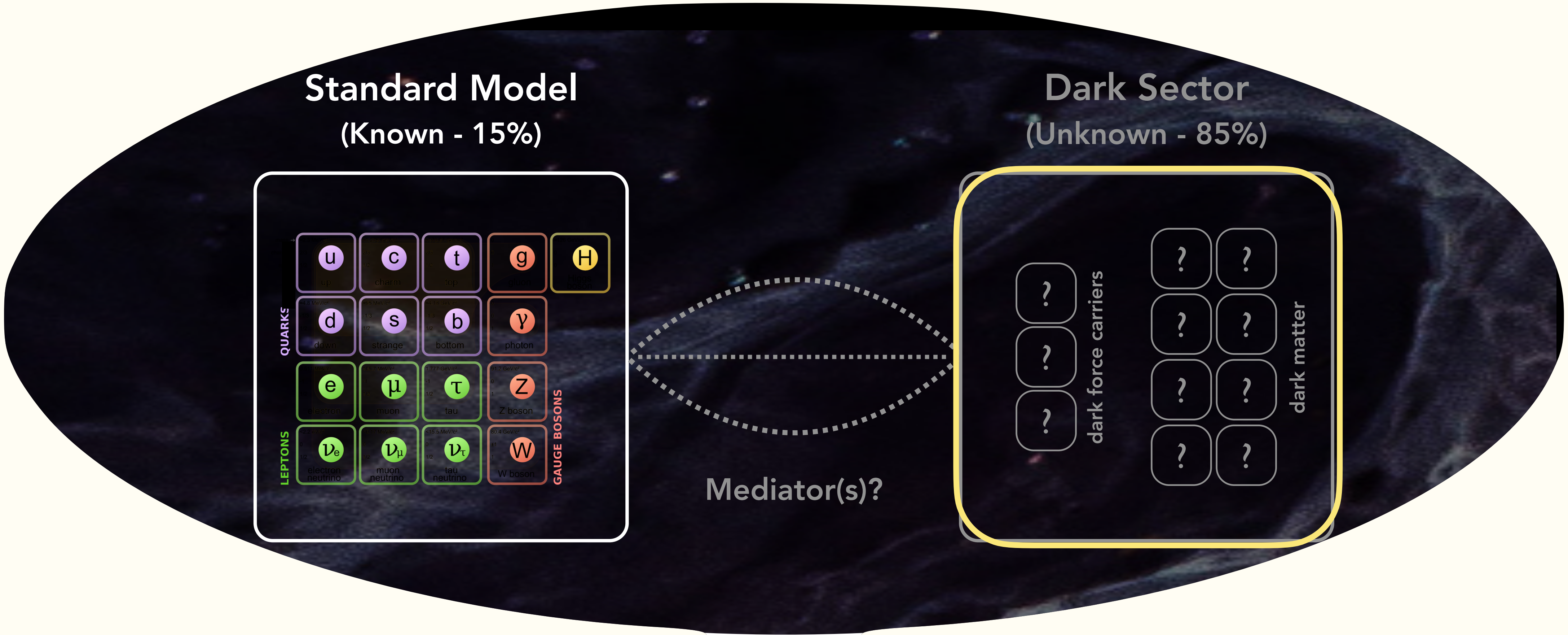


Standard Model

(Known - 15%)

Dark Sector

(Unknown - 85%)

Mediator(s)?

dark force carriers

dark matter

Motivation: Nightmare Scenario

- The models we discussed above, and many other models predict dissipative DM.

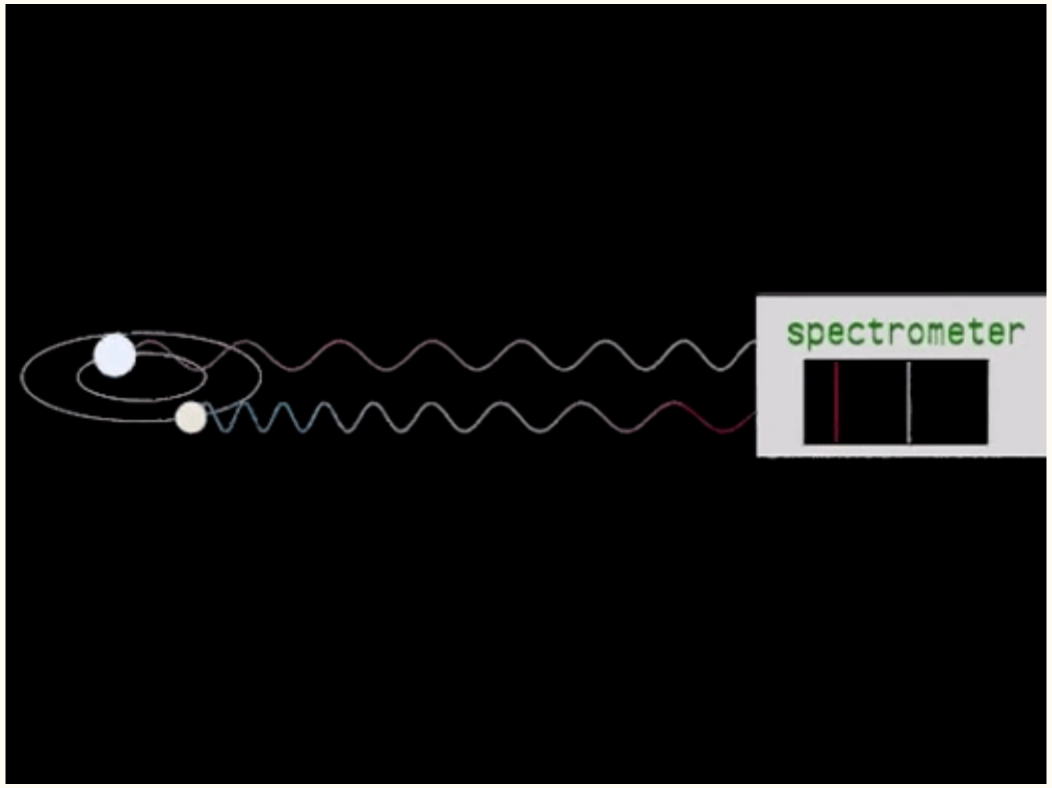
- Dissipative DM can fall into a disk and fragment into even smaller objects.

- But then it's possible DM fall into stars during their formation and early evolution.

How Much DM in Stars?

Double-lined Spectroscopic Binaries (SB2s)

- For a certain type of binaries, we have a lot of information.
- If we observe the oscillating spectral red/blueshift of each star, we can extract both velocities.



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- Using Kepler's 3rd law:

$$\frac{M_{1,2}^3 \sin^3 i}{(M_1 + M_2)^2} = \frac{V_{2,1}^3 \tilde{P}(1 - e^2)^{\frac{3}{2}}}{2\pi G_N}$$

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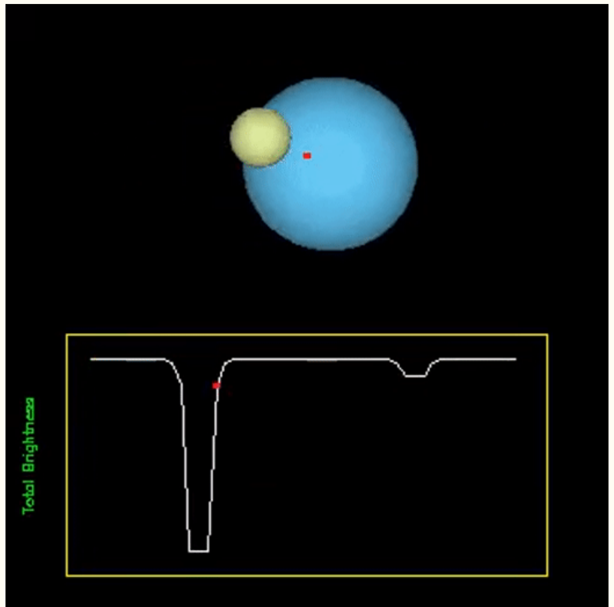
- If we also see the eclipse, we know (roughly) the inclination.



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For eclipsing SB2s we know the gravitational masses of the stars

Mass-Luminosity Relation (MLR)

What about the luminous (baryonic) mass?

Mass continuity: $$\frac{\partial r}{\partial m_b} = \frac{1}{4\pi r^2 \rho_b}$$

Hydrostatic equilibrium: $$\frac{\partial P}{\partial m_b} = -\frac{G_N m_b(r)}{4\pi r^4}$$

Energy transport: $$\frac{\partial T}{\partial m_b} = -\frac{T}{P}\frac{G_N m_b(r)}{4\pi r^4}\nabla$$

Thermal equilibrium: $$\frac{\partial l}{\partial m_b} = \epsilon$$

Equation of state: $$P = P_{\text{gas}} + P_{\text{rad}} = \frac{k_B}{m_p \mu}\rho_b T + \frac{1}{3}aT^4$$

Mass-Luminosity Relation (MLR)

What about the luminous (baryonic) mass?

Add Dark Matter: $\boxed{q(r) \equiv \frac{m_{\mathrm{tot}}(r)}{m_b(r)}}$

Mass continuity: $\frac{\partial r}{\partial m_b} = \frac{1}{4\pi r^2 \rho_b}$

Hydrostatic equilibrium: $\frac{\partial P}{\partial m_b} = -\frac{G_N m_b(r)\, q(r)}{4\pi r^4}$

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Mass-Luminosity Relation (MLR)

- Solution to these equations is unnecessarily model-dependent.
- To extract functional form use homologous (or ''self-similar'') stellar model.
- Center concept:

  Internal structure is self-similar and depends on a dimensionless parameter

$$\xi = \frac{m_b}{M_b} = \frac{m_b'}{M_b'} \qquad\qquad \frac{r(\xi)}{R} = \frac{r'(\xi)}{R'}$$

- Implies scaling relations, e.g.:

$$P = f_1(\xi) P_\star$$
$$r = f_2(\xi) R_\star$$
$$T = f_4(\xi) T_\star$$

- Those can be plugged into the equations to obtain algebraic relations.

Mass-Luminosity Relation (MLR)

Example: star with with radiative diffusion and dominant gas pressure

$$L \propto \begin{cases} QM_{\mathrm{tot}}^3 & \text{gas pressure} \\ M_{\mathrm{tot}} & \text{radiation pressure} \end{cases}$$

Mass-Luminosity Relation (MLR)

Example: star with with radiative diffusion and dominant gas pressure

$$L \propto \begin{cases} Q M_{\rm tot}^3 & \text{gas pressure} \\ M_{\rm tot} & \text{radiation pressure} \end{cases}$$

All possibilities can be captured by the MLR parametrization:

$$\boxed{L = \eta\, Q^{\omega} M_{\rm tot}^{\alpha}} \qquad Q \equiv \frac{M_{\rm tot}}{M_b}$$

Luminosity depends on a combination of the luminous mass and dark matter

Mass-Luminosity Relation (MLR)

$$\boxed{L = \eta\, Q^{\omega} M_{\text{tot}}^{\alpha}}$$

Problem: MLR seems strange since $L \to \infty$ as $Q \to \infty$.

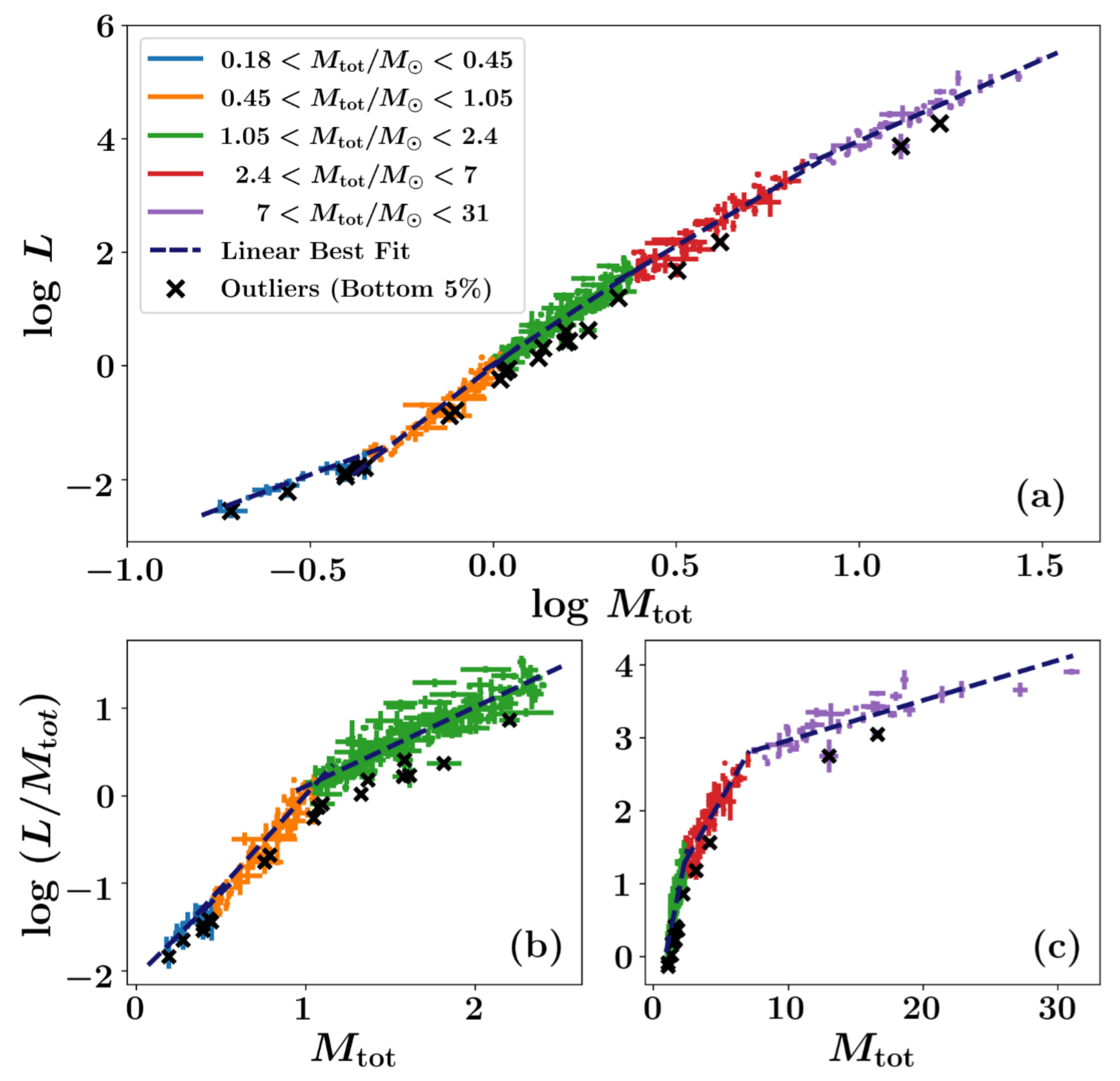
Answer:

1. Since $T \propto Q^{\#}$, temperature also rises to the point where radiation pressure dominates for which $L \propto Q^{0}$.

2. Stellar lifetime is, $\tau \propto \dfrac{M_b}{L} \propto Q^{-4}$. For large Q, lifetime is too short to be consistent with data.

$$0 < Q - 1 \ll 1$$

SB2s: The Eker Catalogue



Statistical Model

MLR Model: $L = \eta \, Q^{\omega} \, M_{\mathrm{tot}}^{\alpha}$

Model suffers from 2 flat directions.

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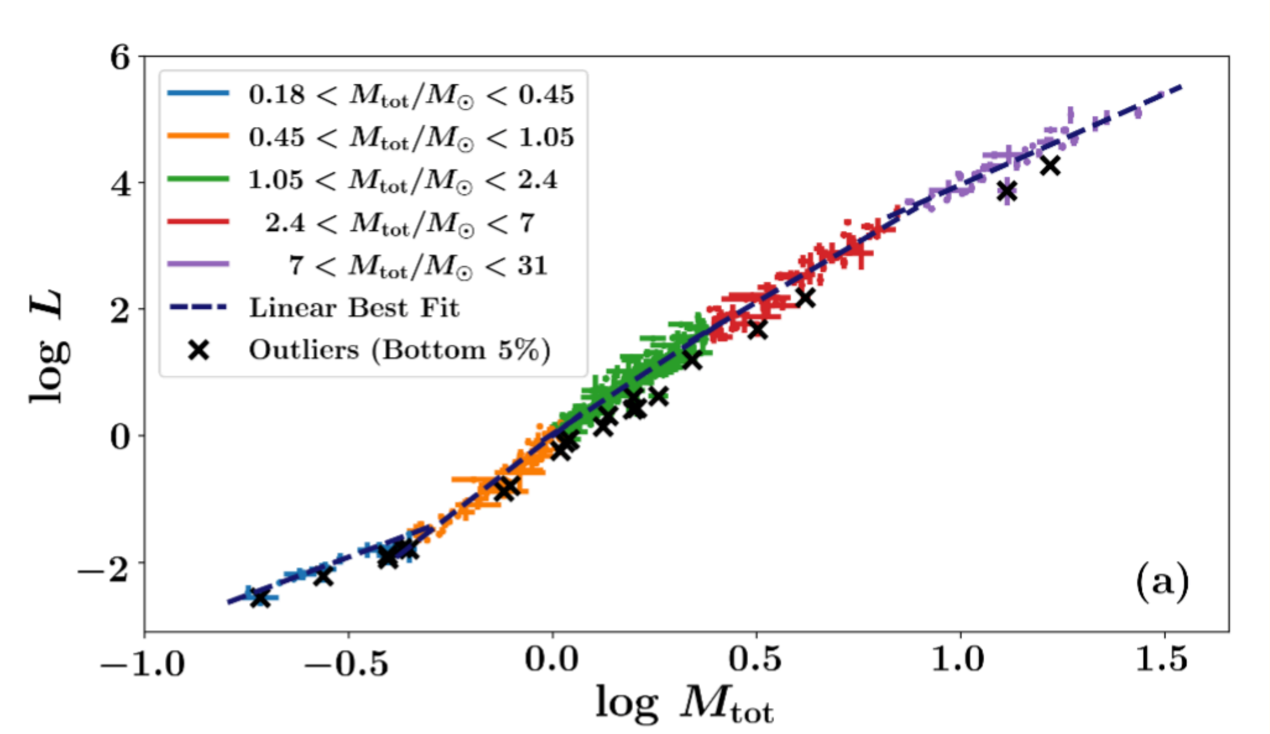
Solution: 1. One value of ω per mass regime ($0.8 \leq \omega \leq 1$)



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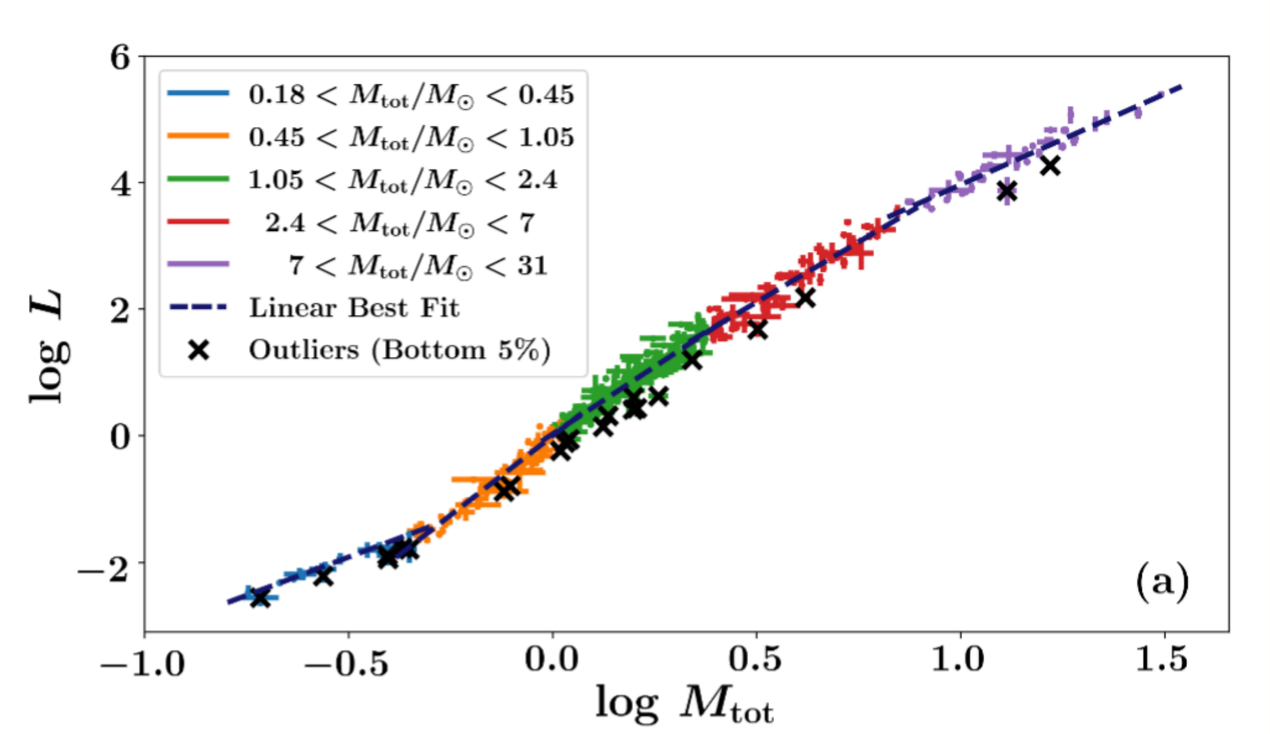
2. To disentangle η and Q, identify anomalously low-luminosity stars and assume no DM.



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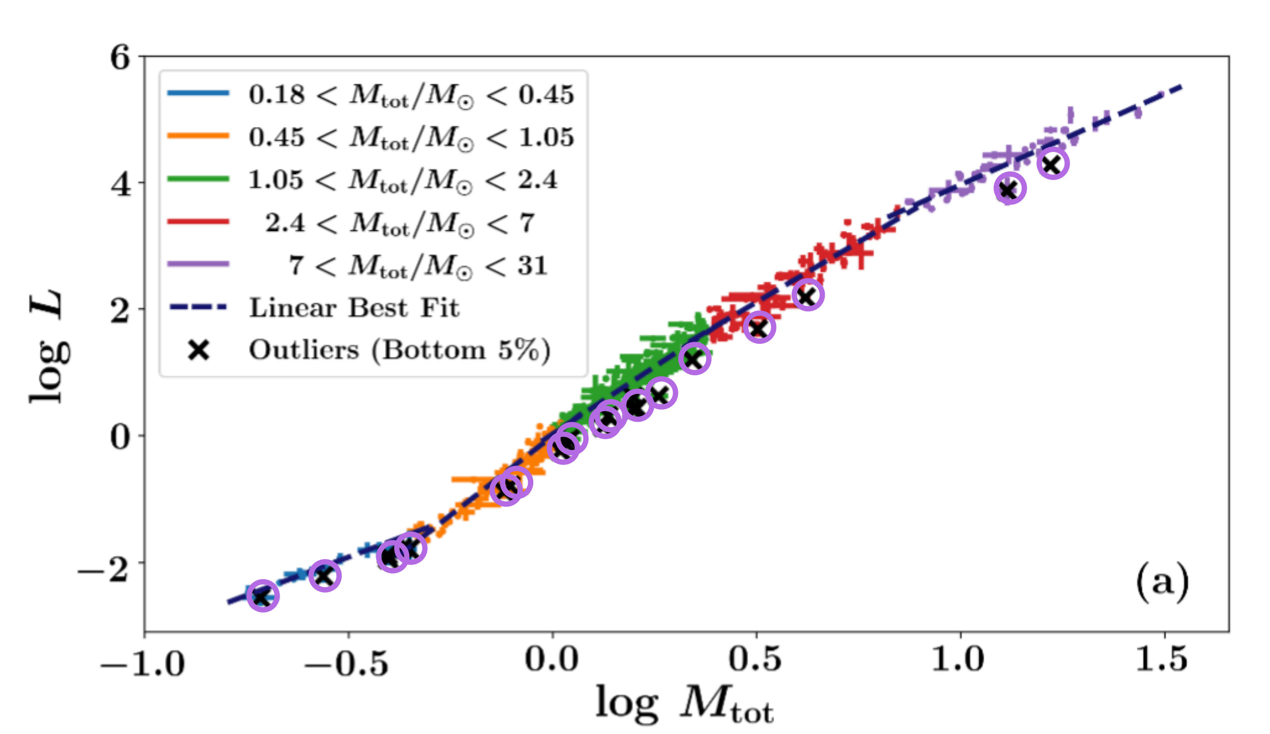


Statistical Model

MLR Model: $$L = \eta\, Q^{\omega}\, M_{\mathrm{tot}}^{\alpha}$$

Statistical Model takes into account astrophysical variability of stars:

$$\log L + \delta \log L = \log(\eta + \delta\eta) + \omega \log(Q + \delta Q) + (\alpha + \delta\alpha)\log(M_{\mathrm{tot}} + \delta M_{\mathrm{tot}})$$

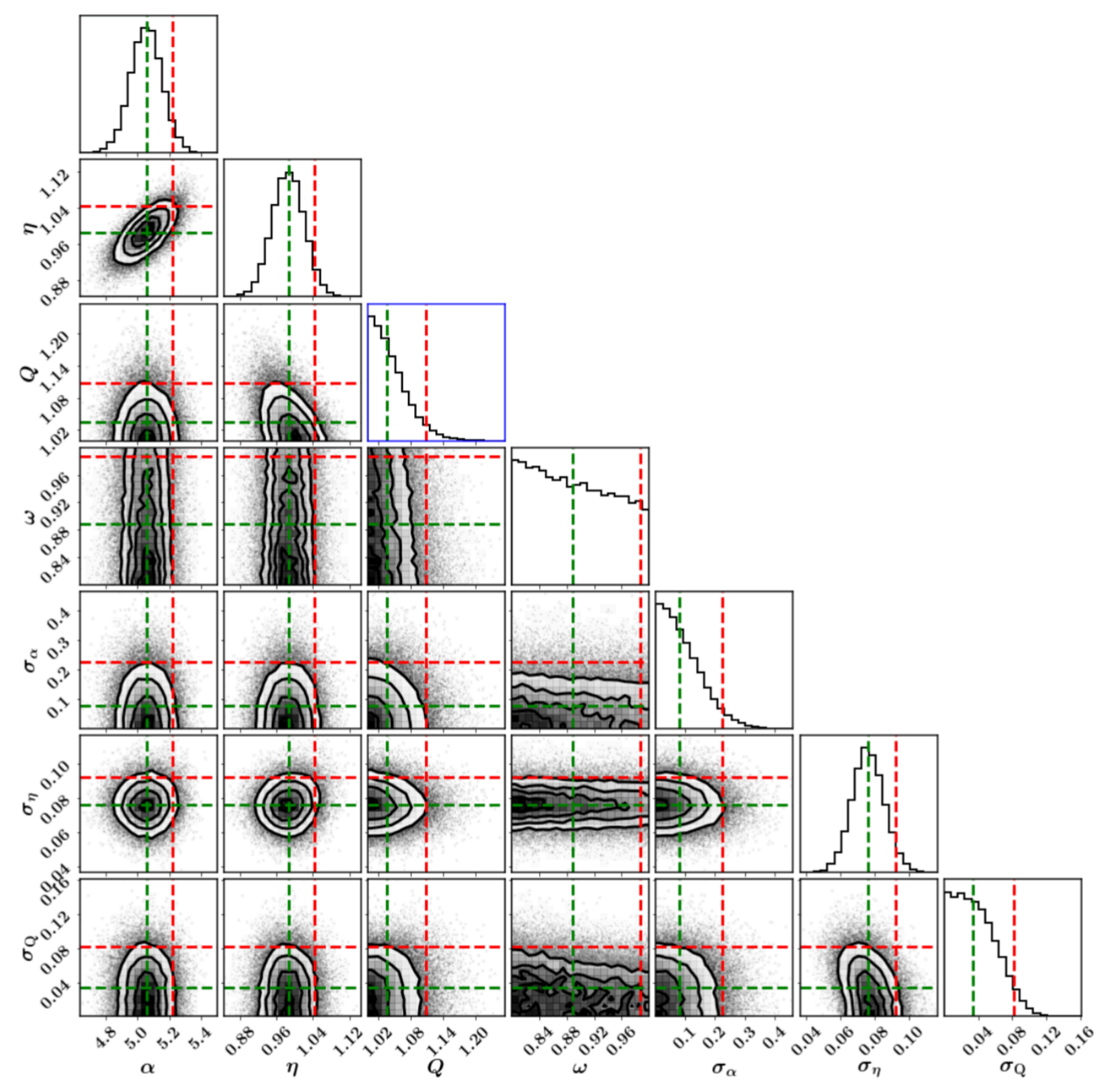
Profile likelihood ratio:

$$\mathscr{L}(\alpha, \sigma_\alpha, \eta, \sigma_\eta, Q, \sigma_Q, \omega \mid \{M_{\mathrm{tot_i}}, \sigma_{M_{\mathrm{tot_i}}}, \log L_i, \sigma_{\log L_i}\}_{i=1}^{n}) =$$

$$= \prod_{i=1}^{n} \int d\delta M_{\mathrm{tot_i}}\, d\delta\alpha_i\, d\delta\eta_i\, d\delta Q_i\, d\delta \log L_i\;\, G(\delta M_{\mathrm{tot_i}} \mid \sigma_{M_{\mathrm{tot_i}}})\, G(\delta\alpha_i \mid \sigma_\alpha)\, G(\delta\eta_i \mid \sigma_\eta) G(\delta Q_i \mid \sigma_Q)\, G(\delta \log L_i \mid \sigma_{\log L_i})$$

$$\delta\left(\delta \log L_i - \left[\log \eta + \frac{\delta\eta_i}{\eta} + \omega\, \left(\log Q + \frac{\delta Q_i}{Q}\right) + (\alpha + \delta\alpha_i)\left(\log M_{\mathrm{tot_i}} + \frac{\delta M_{\mathrm{tot_i}}}{M_{\mathrm{tot_i}}}\right) - \log L_i\right]\right)$$

Constraints: DM inside Stars



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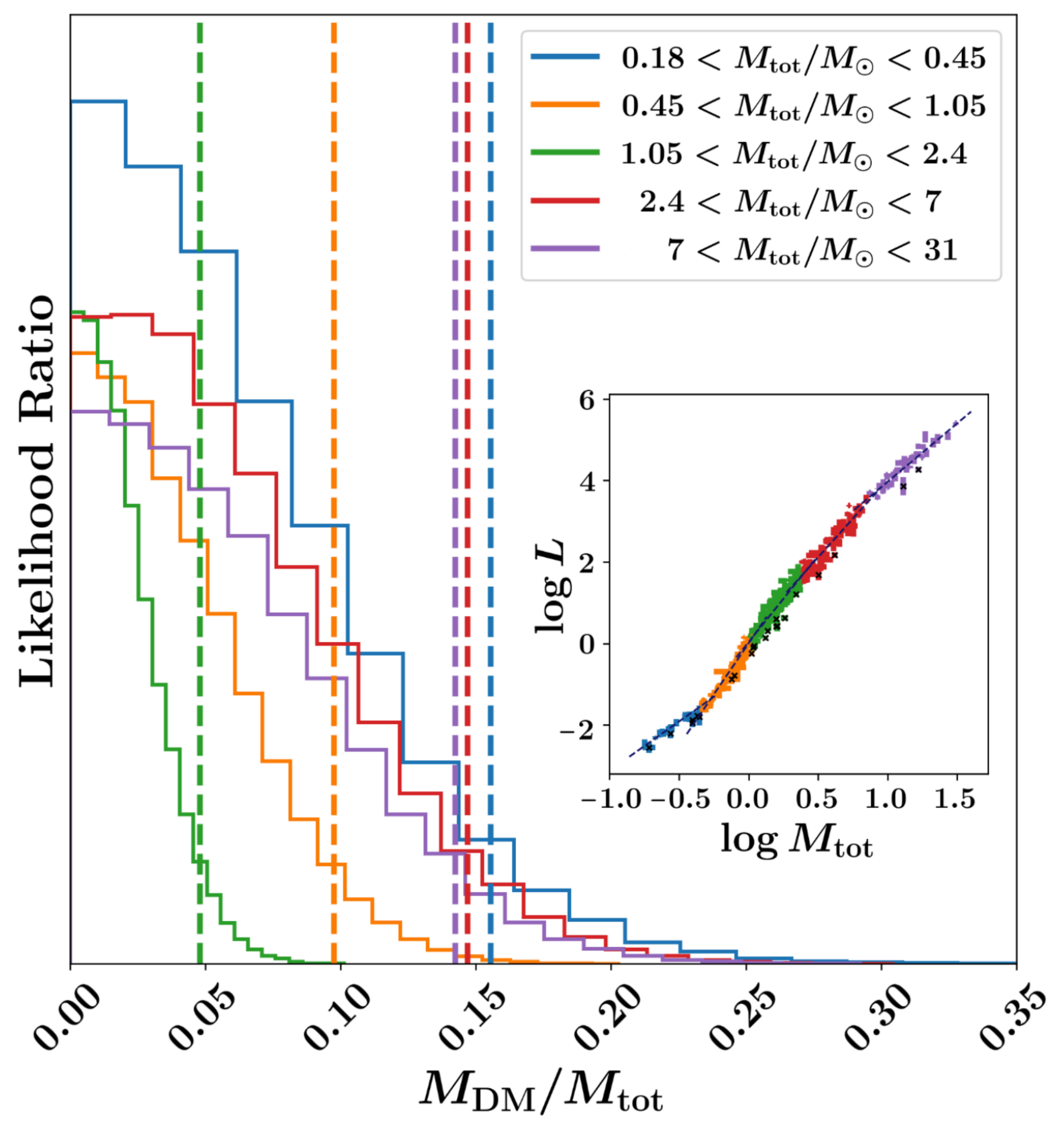


What's Next?

Quite strong constraints ($< 5\,\%$) from limited data

Can significantly improve with Gaia data?

Use limits to constrain Dissipative or asymmetric DM models

In particular place constraints on presence of a DM disk

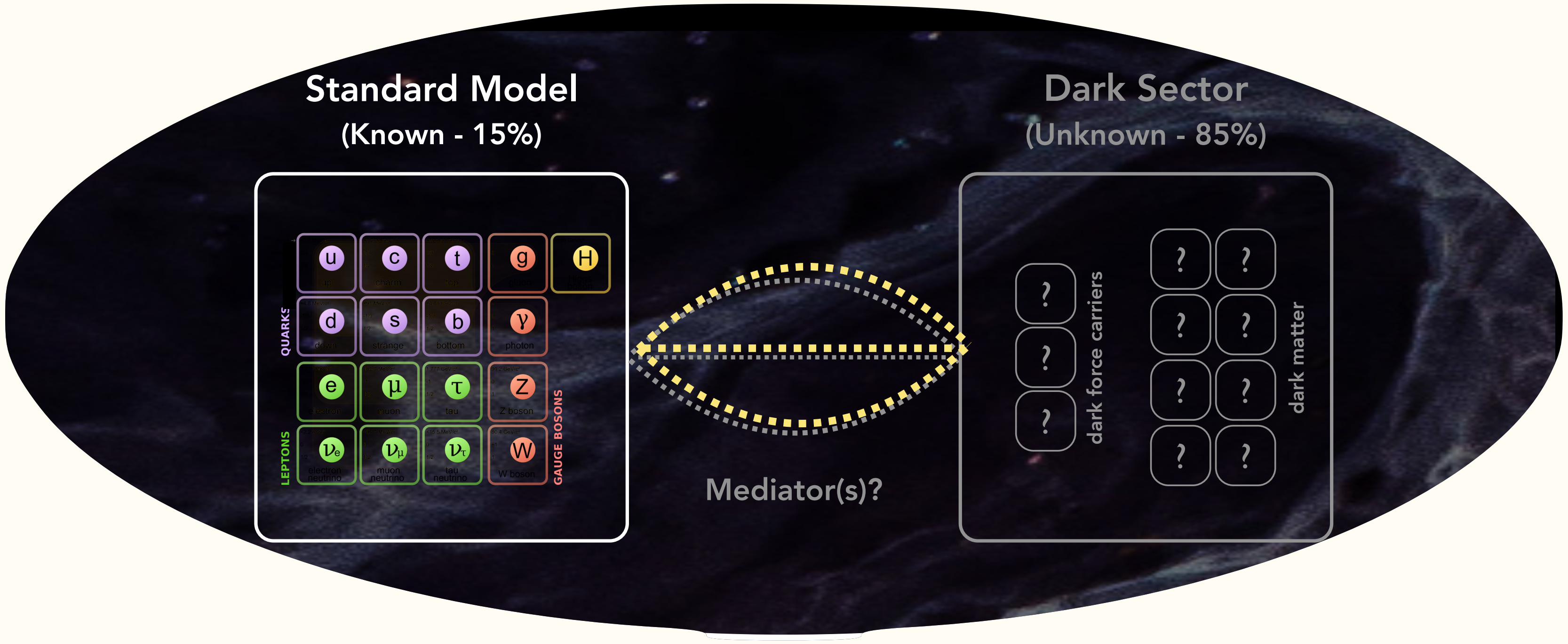
General Dark Mediation
&
Environmental Dark Matter

[Bloch, Outmezguine, Redigolo, Sun, TV, *work in progress*]

[Gouttenoire, Ruderman, Slone, TV, *work in progress*]

Skip

What did we learn?



Models typically studied (especially for direct-detection) use very limited number of mediation schemes:
light vector or point-like interaction (few other exceptions).

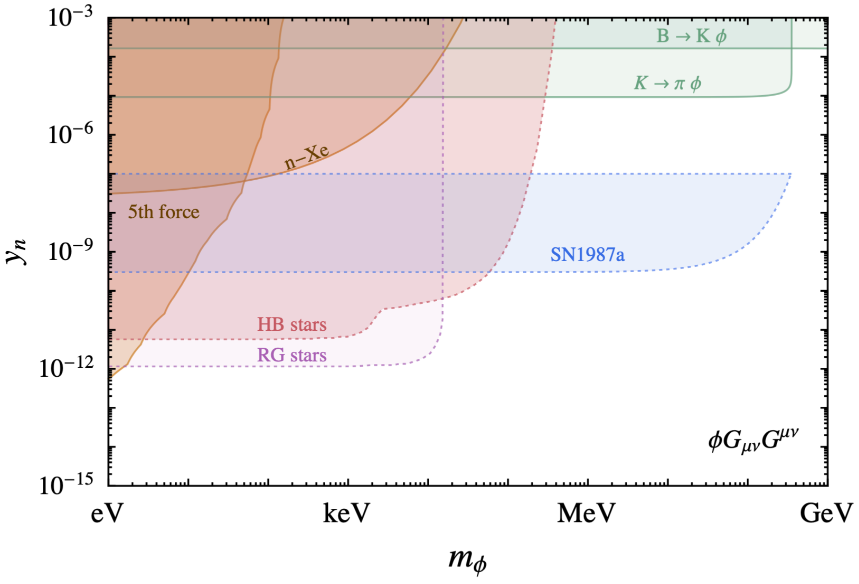
Why?

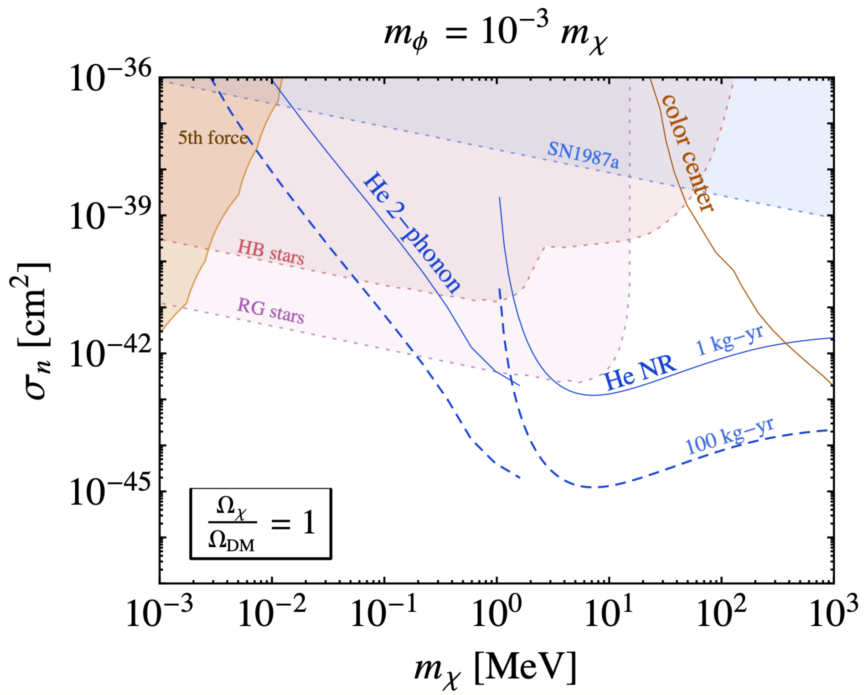
Stellar Cooling constraints!

Vanilla Scalar and Vector Mediators

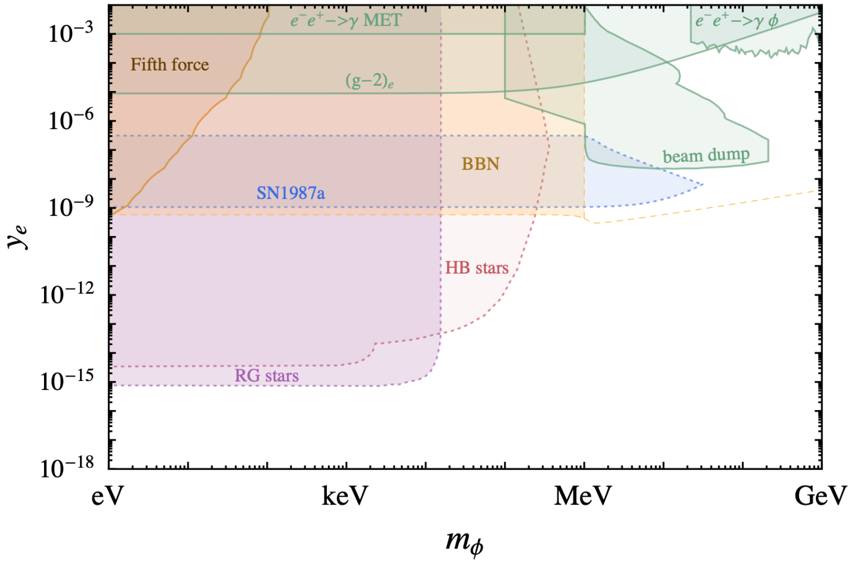
[Knapen, Lin, Zurek, 2017]

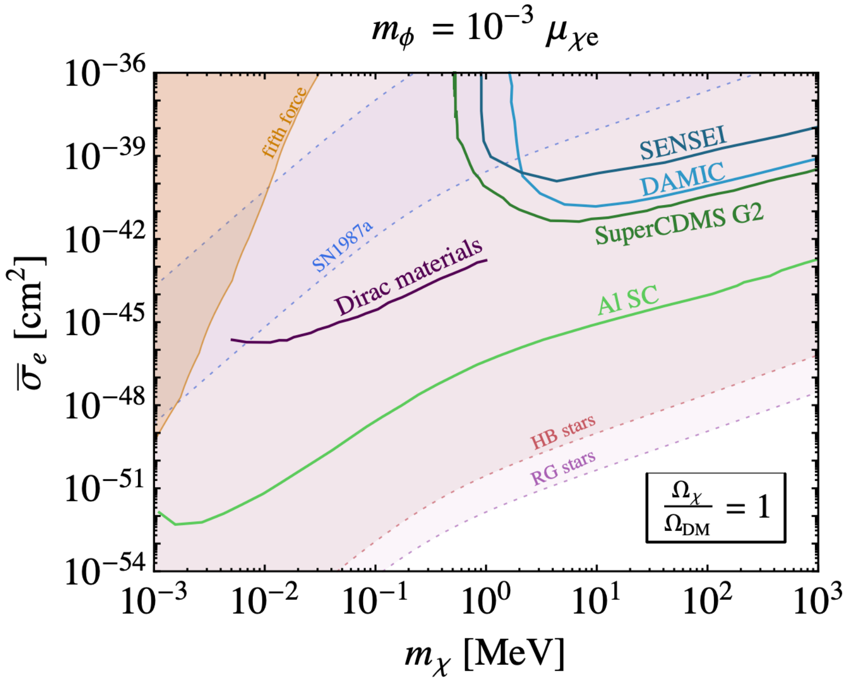
Hadrophilic Scalar



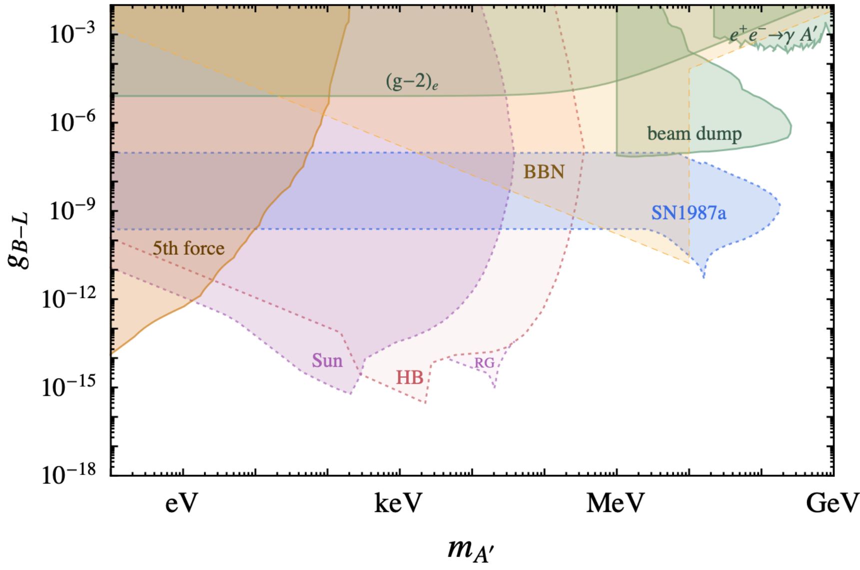


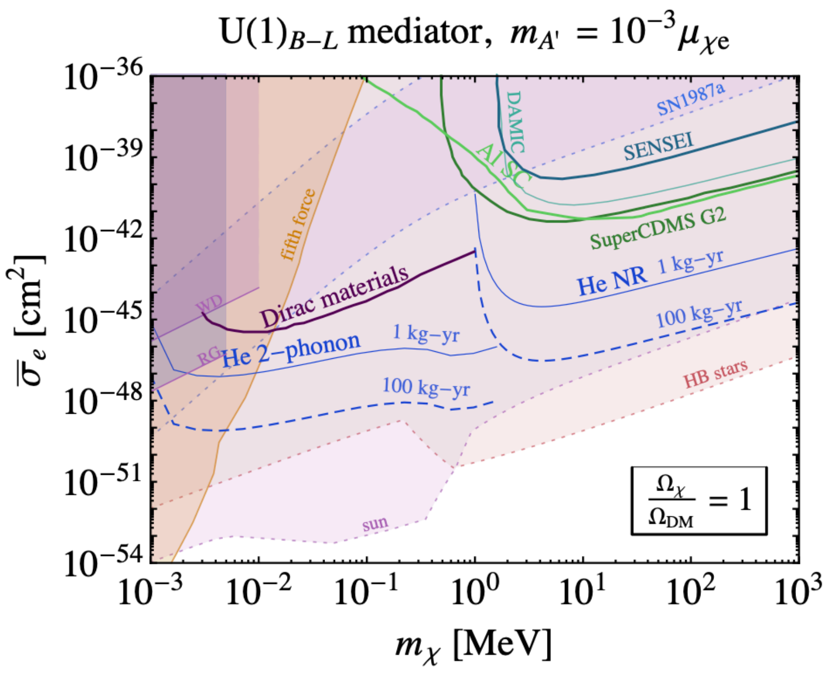
Leptophilic Scalar





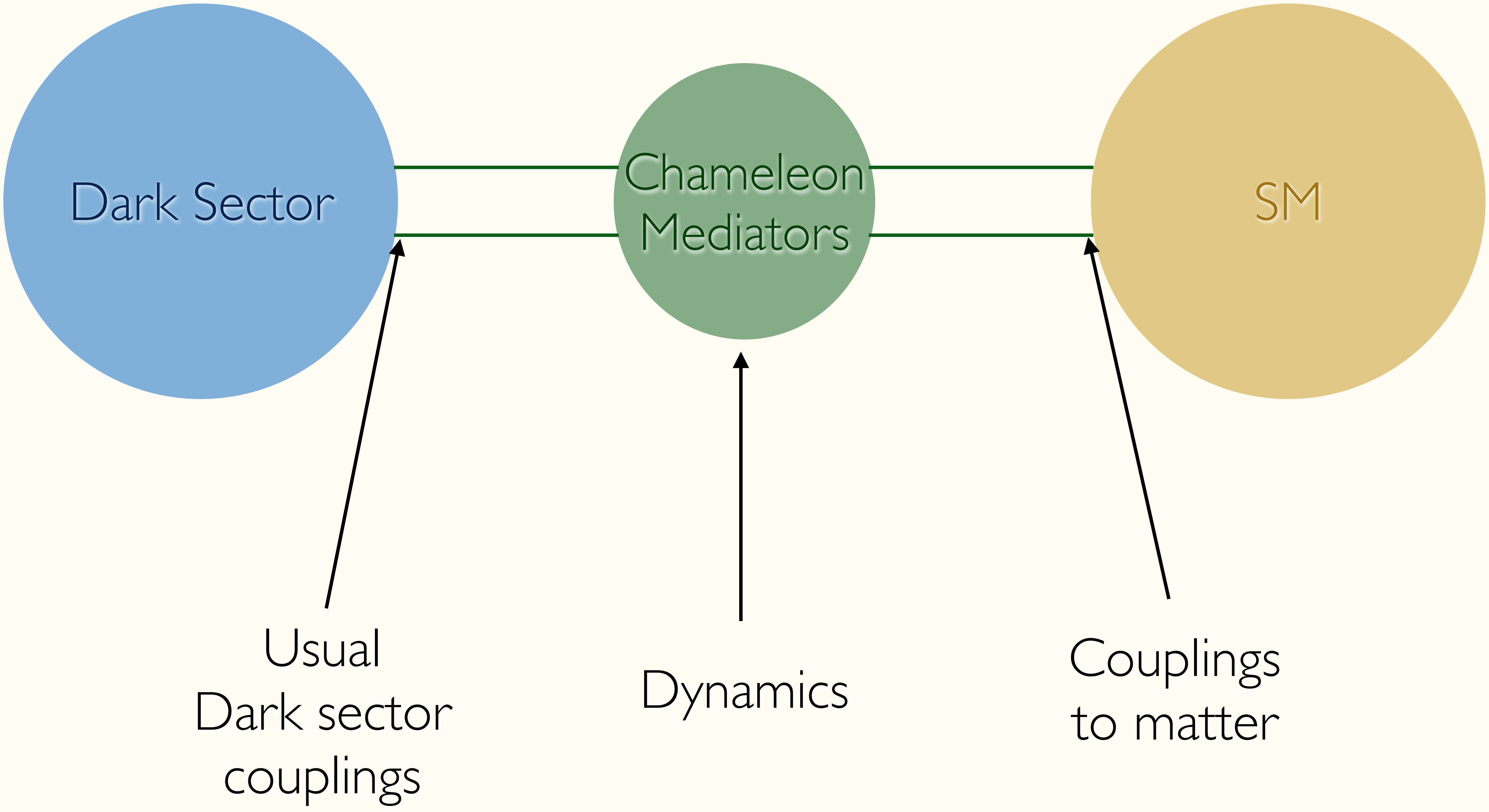
B-L Vector





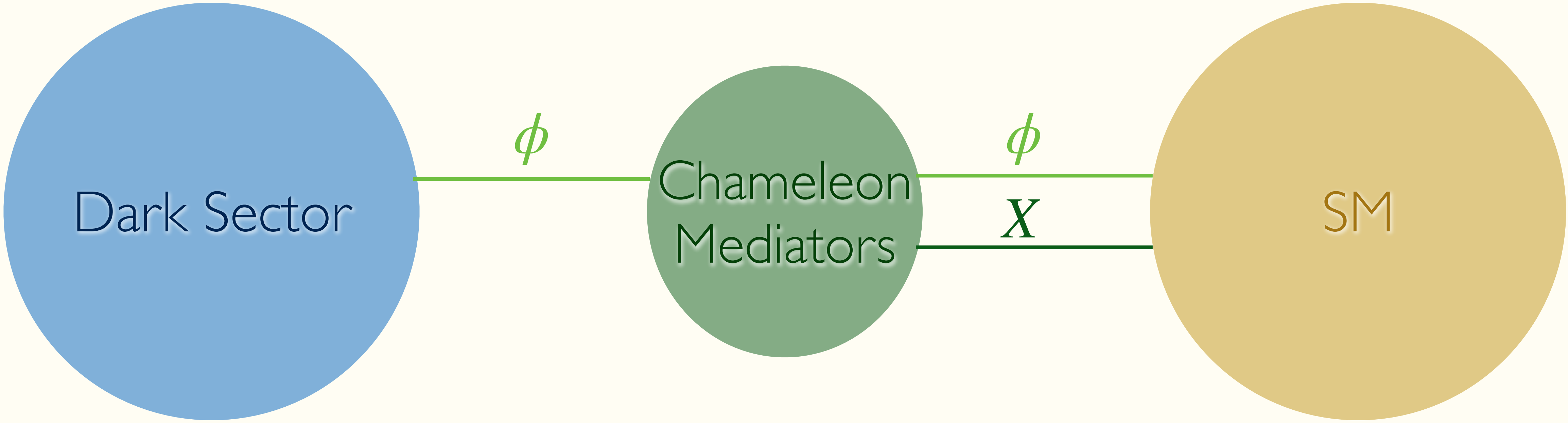
Chameleon Mediators?

[Bloch, Outmezguine, Redigolo, Sun, TV, *work in progress*]



Example: Weakly Coupled Symmetron

[Bloch, Outmezguine, Redigolo, Sun, TV, *work in progress*]



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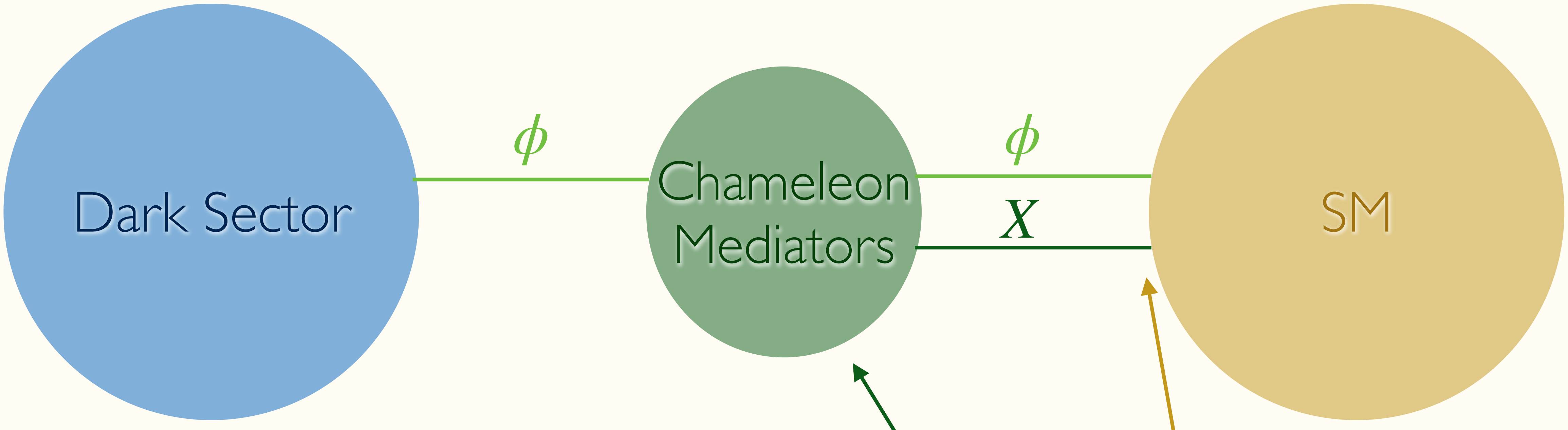

$$\frac{1}{2}\left(m_X^2 - \frac{\rho}{M_X^2}\right)X^2 + \frac{1}{4}\lambda_X X^4$$

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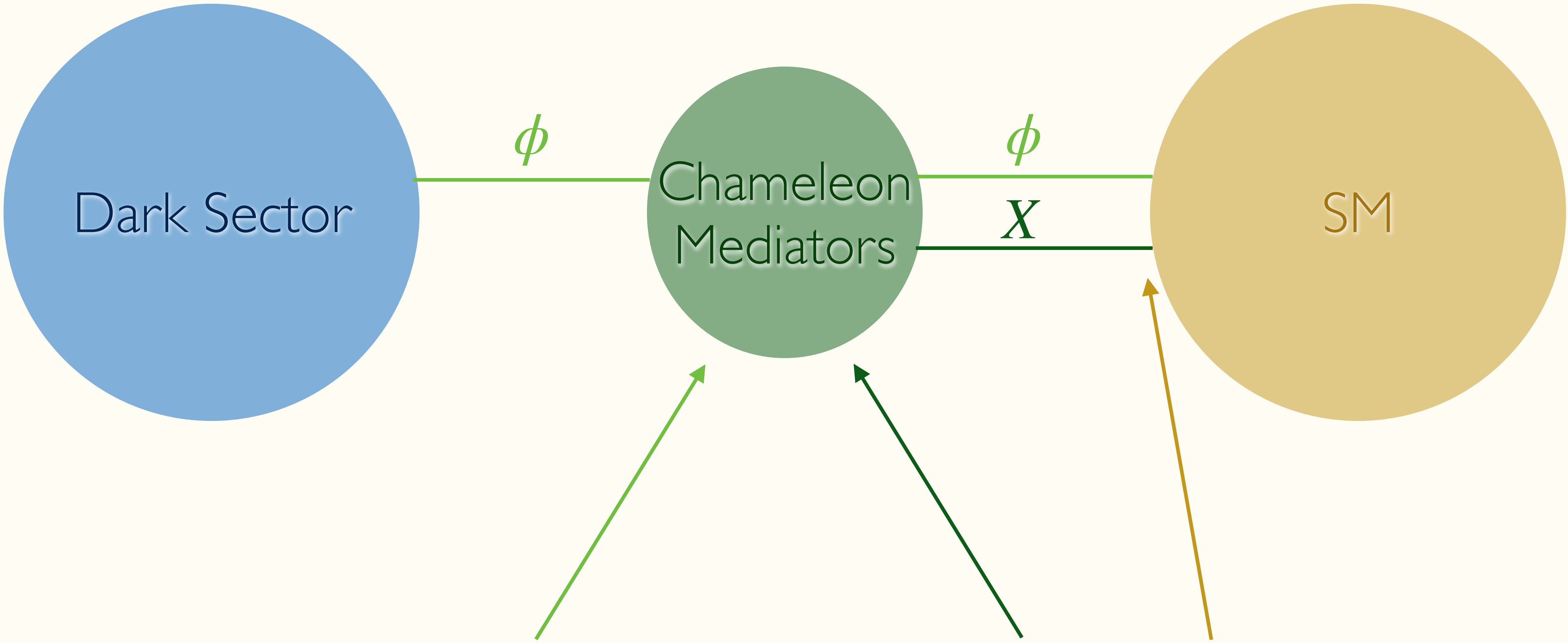


Dark Sector

ϕ

Chameleon Mediators

ϕ

X

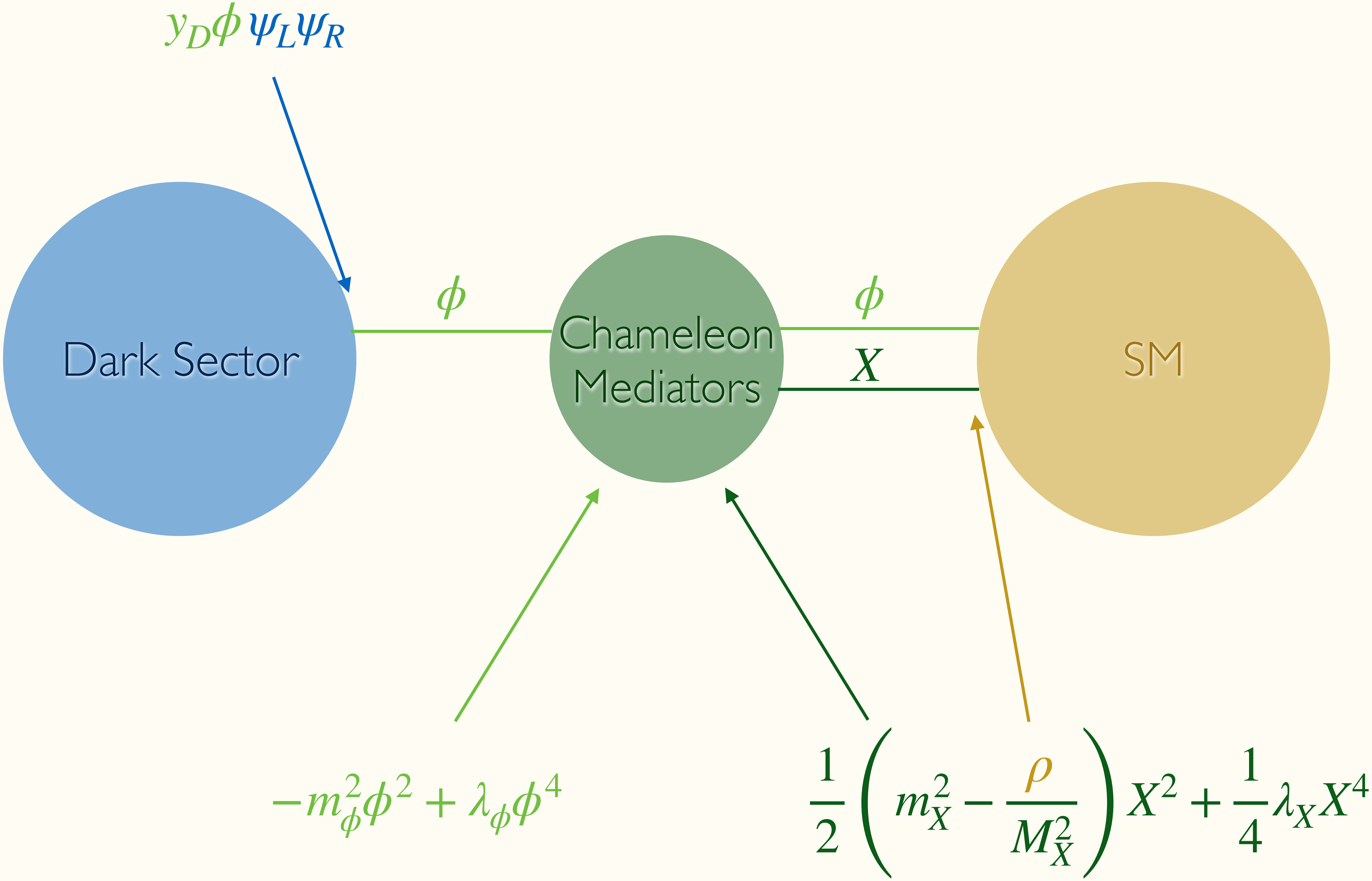
SM

$$-m_\phi^2\phi^2 + \lambda_\phi\phi^4$$

$$\frac{1}{2}\left(m_X^2 - \frac{\rho}{M_X^2}\right)X^2 + \frac{1}{4}\lambda_X X^4$$

Example: Weakly Coupled Symmetron

[Bloch, Outmezguine, Redigolo, Sun, TV, *work in progress*]



$y_D \phi \psi_L \psi_R$

ϕ

Dark Sector

Chameleon Mediators

ϕ

X

SM

$-m_\phi^2 \phi^2 + \lambda_\phi \phi^4$

$$\frac{1}{2}\left(m_X^2 - \frac{\rho}{M_X^2}\right) X^2 + \frac{1}{4}\lambda_X X^4$$

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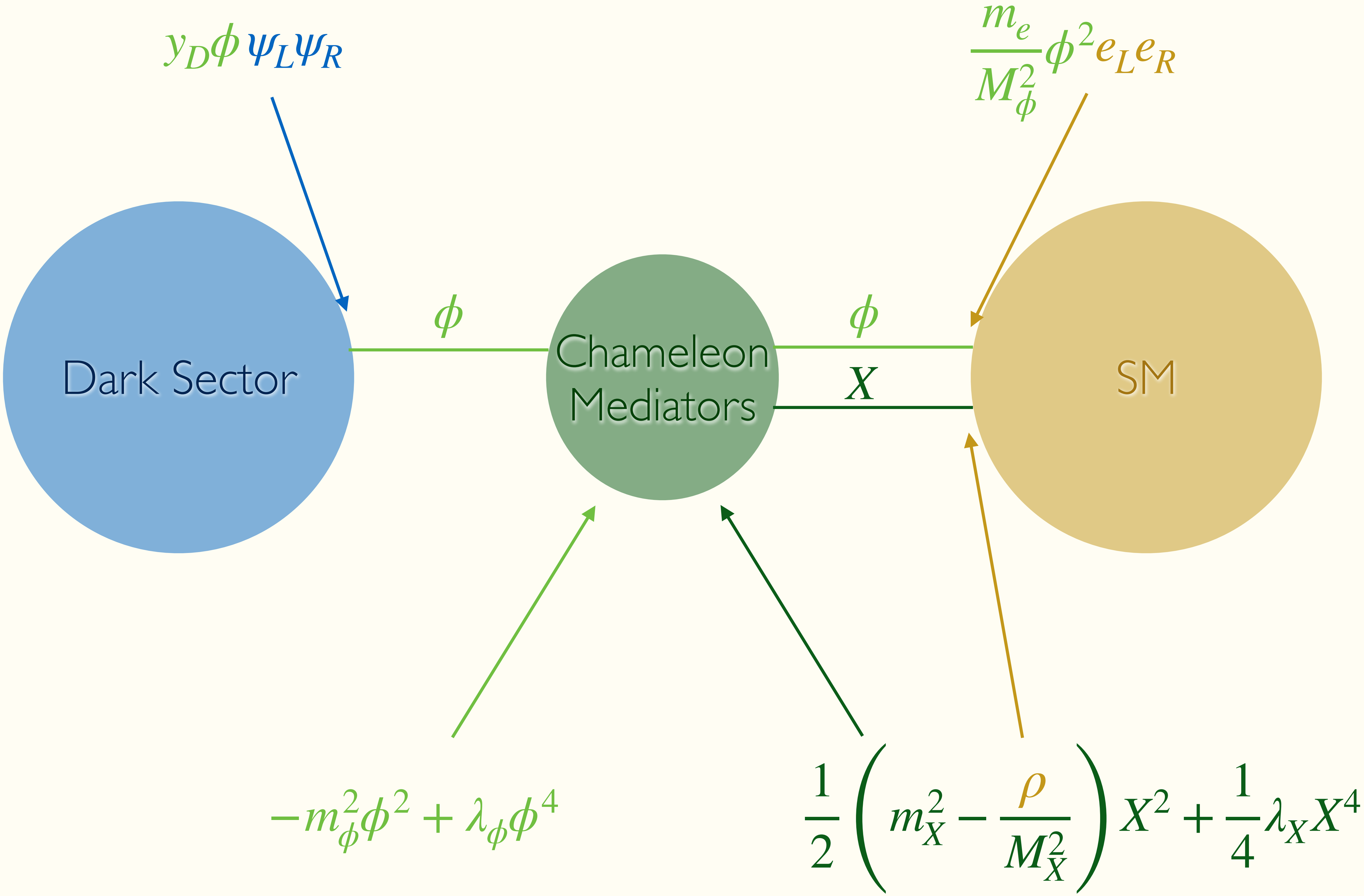

$y_D \phi \, \psi_L \psi_R$

$\frac{m_e}{M_\phi^2} \phi^2 e_L e_R$

Dark Sector

ϕ

Chameleon Mediators

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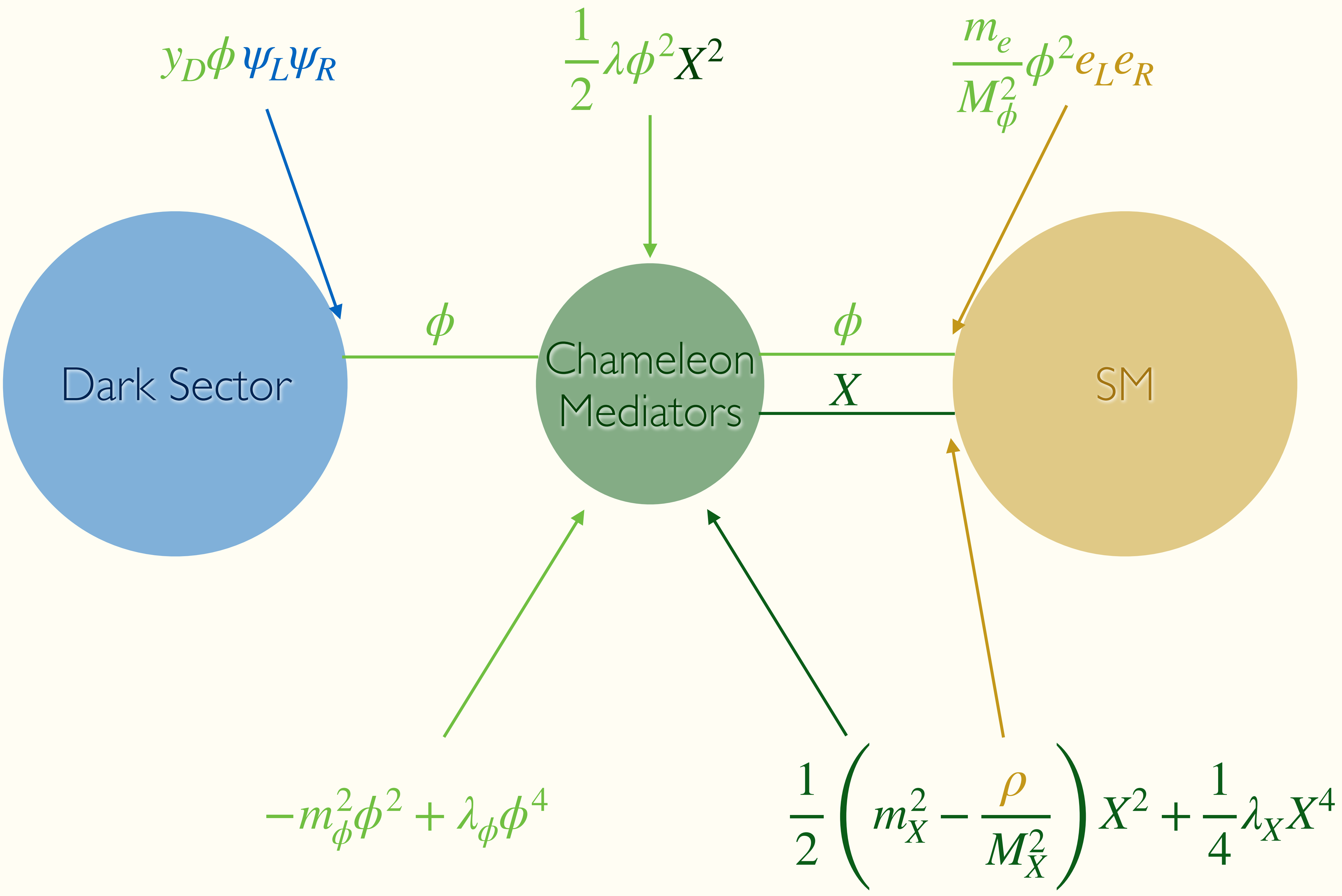

$y_D\phi\,\psi_L\psi_R$

$\frac{1}{2}\lambda\phi^2X^2$

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Example: Weakly Coupled Symmetron

[Bloch, Outmezguine, Redigolo, Sun, TV, *work in progress*]

$y_D \phi \psi_L \psi_R$

$\frac{1}{2}\lambda \phi^2 X^2$

$\frac{m_e}{M_\phi^2}\phi^2 e_L e_R$

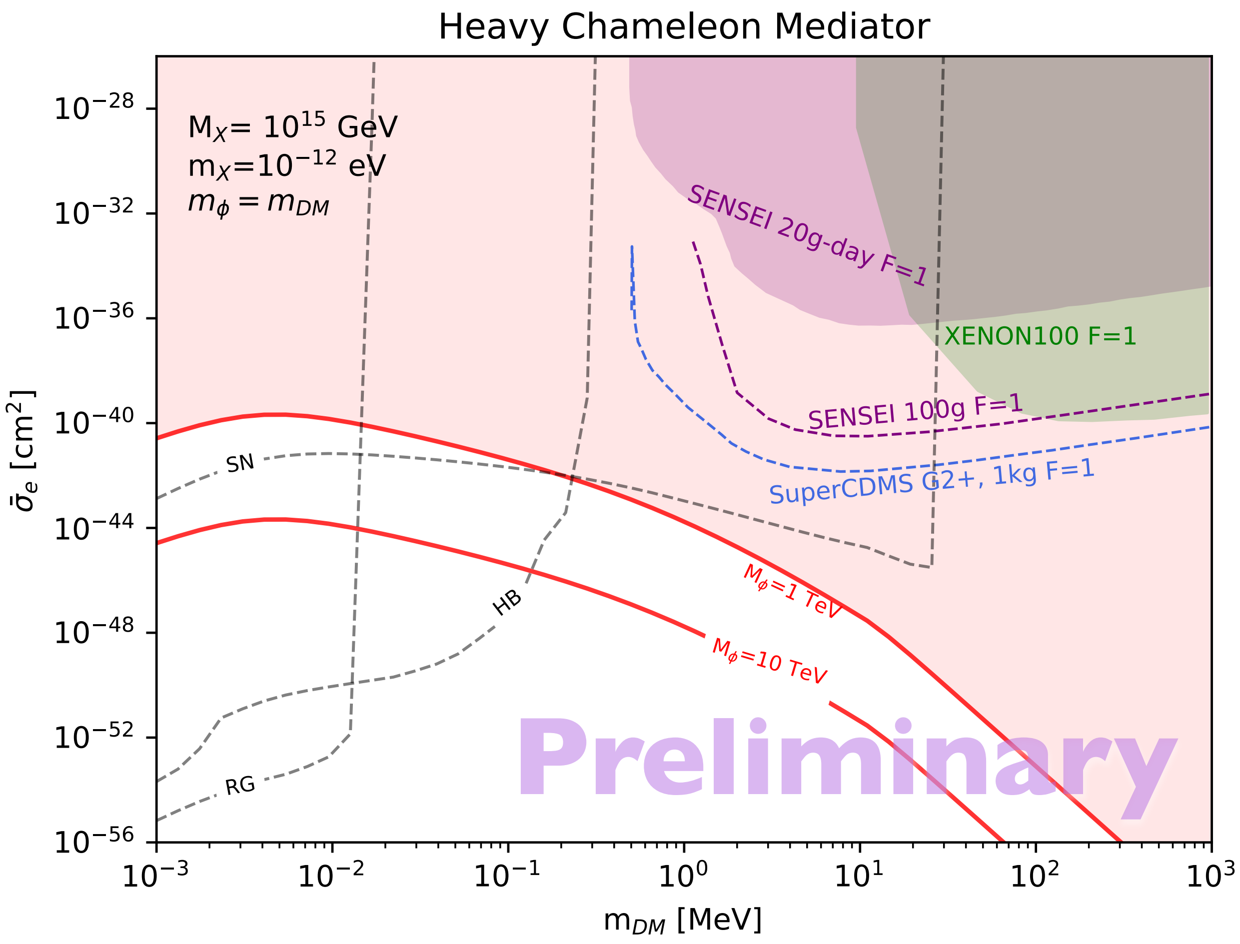
Earth	$\langle X \rangle = 0$	$\langle \phi \rangle \neq 0$	Significant scattering
Star	$\langle X \rangle \neq 0$	$\langle \phi \rangle = 0$	Suppressed production

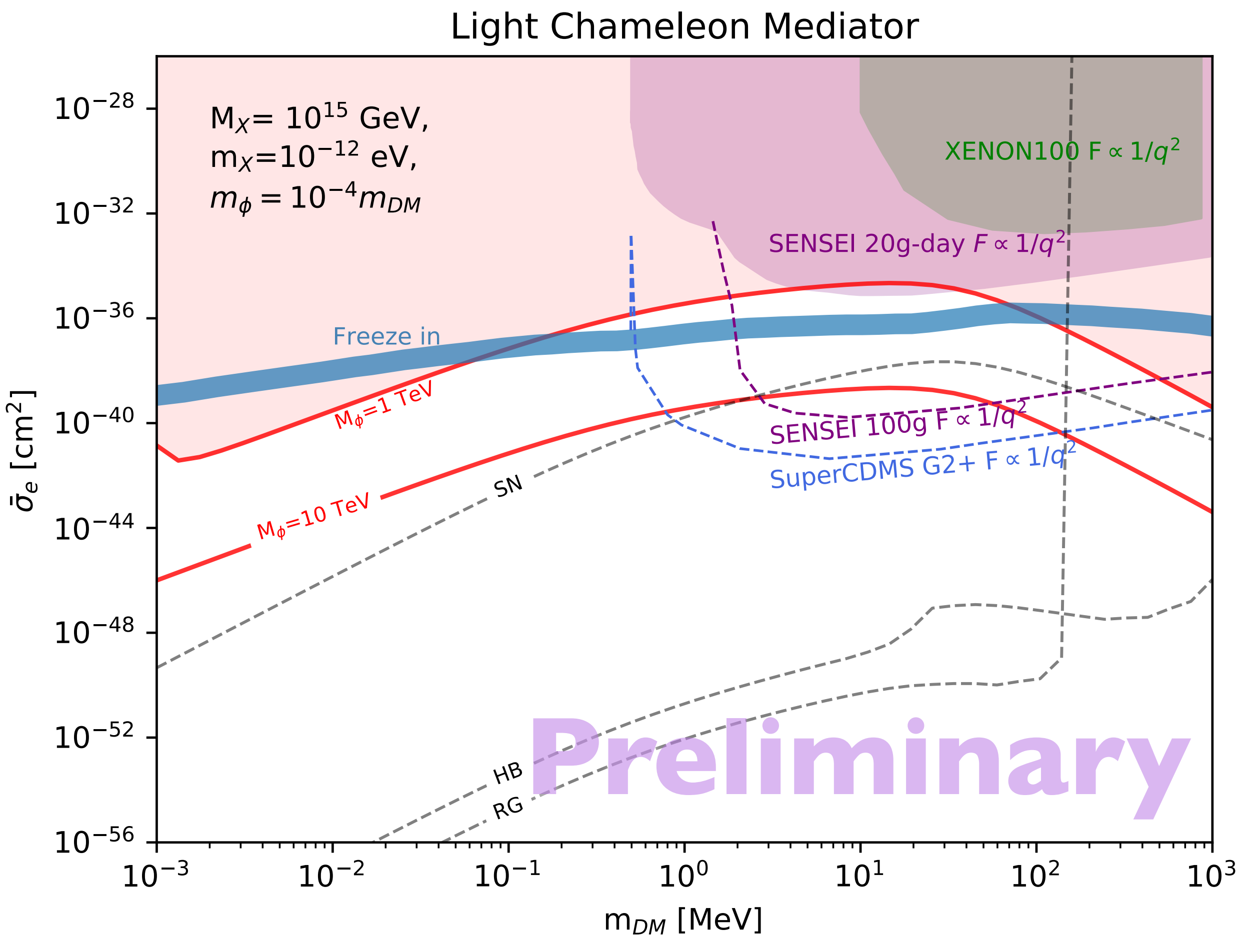
$-m_\phi^2 \phi^2 + \lambda_\phi \phi^4$

$$\frac{1}{2}\left(m_X^2 - \frac{\rho}{M_X^2}\right) X^2 + \frac{1}{4}\lambda_X X^4$$

Example: Weakly Coupled Symmetron

[Bloch, Outmezguine, Redigolo, Sun, TV, *work in progress*]





General Dark Mediation?

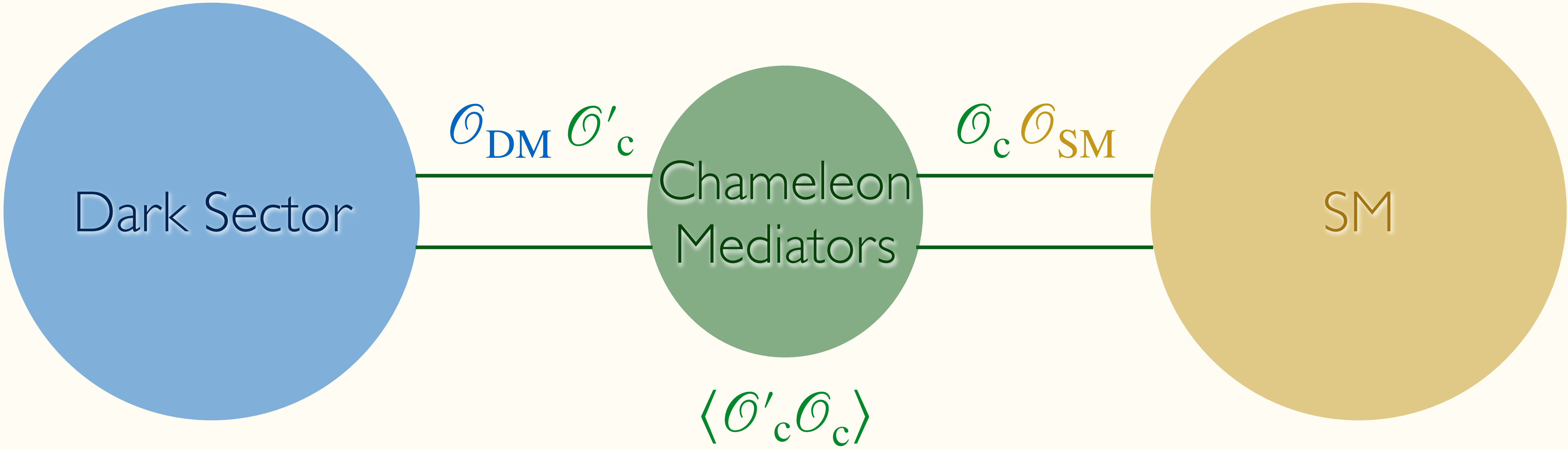
[Bloch, Outmezguine, Redigolo, Sun, TV, *work in progress*]

What's the catch?

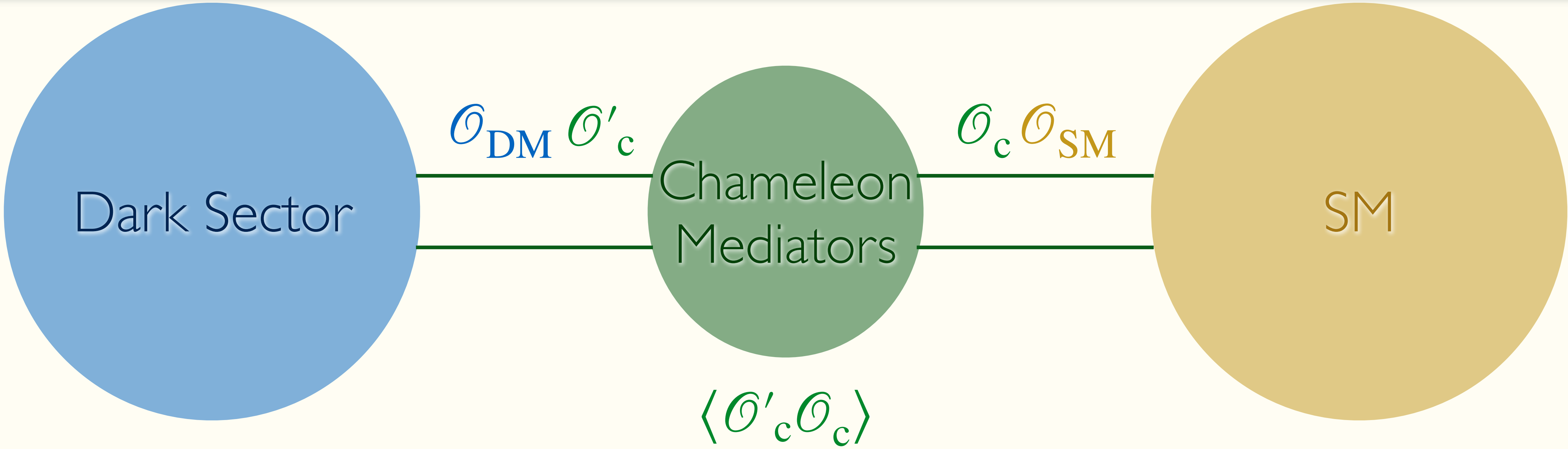
- The example has several constraints and requires very small (but natural) couplings. Is it unique?

Generalization?

- Can be generalized. Strongly coupled models likely better.



General Dark Mediation?



Dark Sector

$\mathcal{O}_{\mathrm{DM}}\,\mathcal{O}'_{\mathrm{c}}$

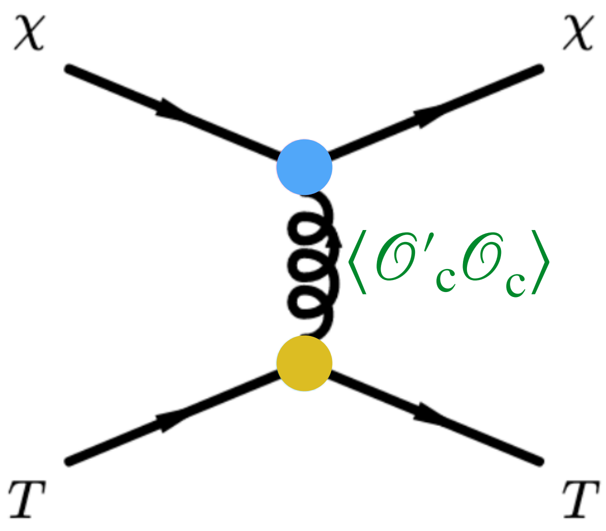
Chameleon Mediators

$\mathcal{O}_{\mathrm{c}}\,\mathcal{O}_{\mathrm{SM}}$

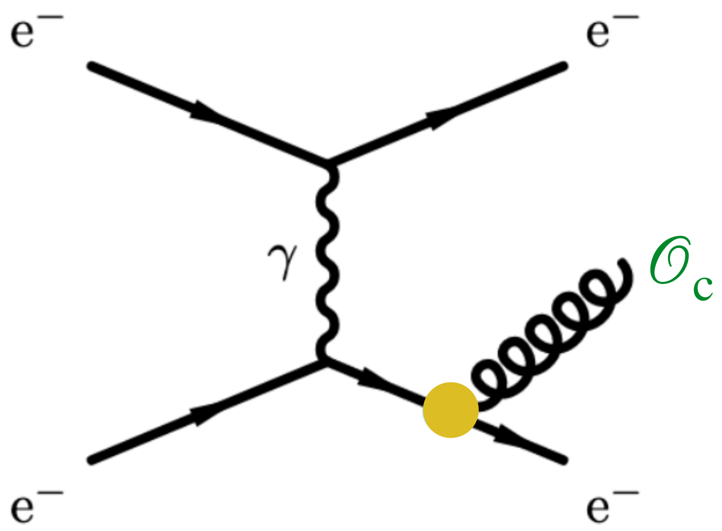
SM

$\langle \mathcal{O}'_{\mathrm{c}} \mathcal{O}_{\mathrm{c}} \rangle$

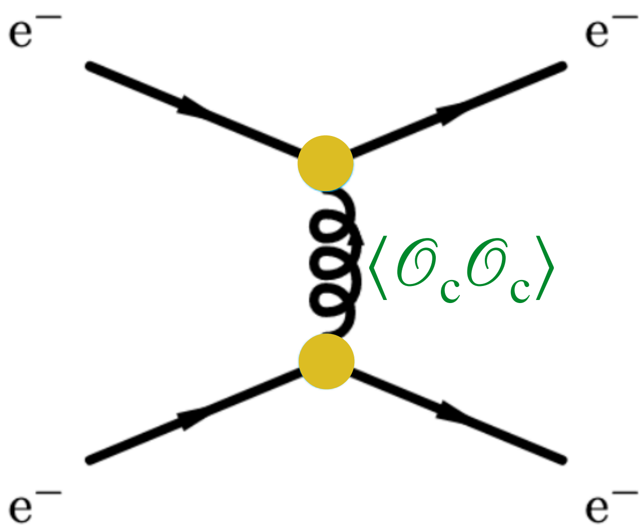
Direct Detection



Stellar Cooling



Long-range force



Massless Mediation Sector

2 things can change

$\langle \mathcal{O}_{\mathbf{SM}} \rangle \neq 0$ inside stars

↓

OPE behavior of correlation functions change

$$\langle 0 | T \mathcal{O}_1(-q) \mathcal{O}_2(q) | 0 \rangle = a_1(q^2) \cdot \mathbf{1} + \sum_i a_i(q^2) \langle \mathcal{O}_i \rangle \ldots$$

Massless Mediation Sector

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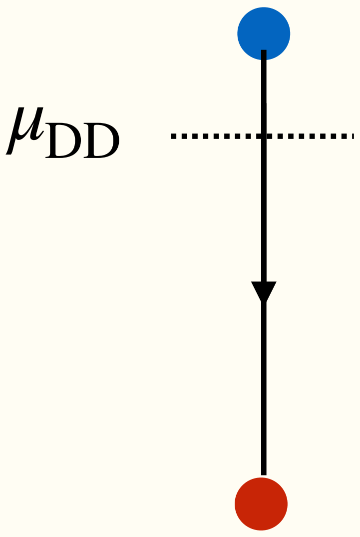
Anomalous dimensions of operators can change



$$\frac{c_1}{\Lambda^{d_1 - 1}} \mathcal{O}_1 \bar{e} e + \frac{c_2}{\Lambda^{d_2 - 1}} \mathcal{O}_2 \bar{\psi}_D \psi$$

Massless Mediation Sector

2 things can change

$\langle \mathcal{O}_{\mathrm{SM}} \rangle \neq 0$ inside stars

OPE behavior of correlation functions change

$$\langle 0 | T\mathcal{O}_1(-q)\mathcal{O}_2(q) | 0 \rangle = a_1(q^2)\cdot \mathbf{1} + \sum_i a_i(q^2)\langle \mathcal{O}_i \rangle\ldots$$

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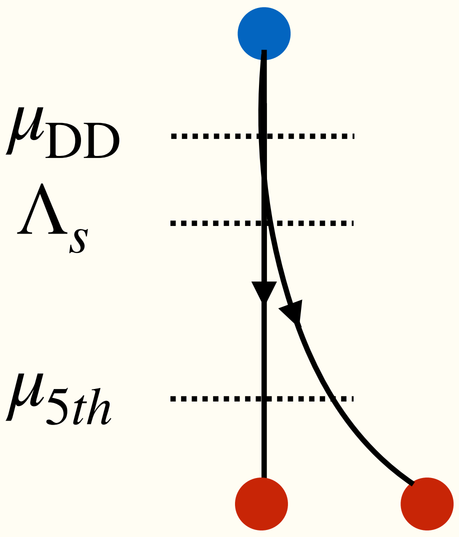
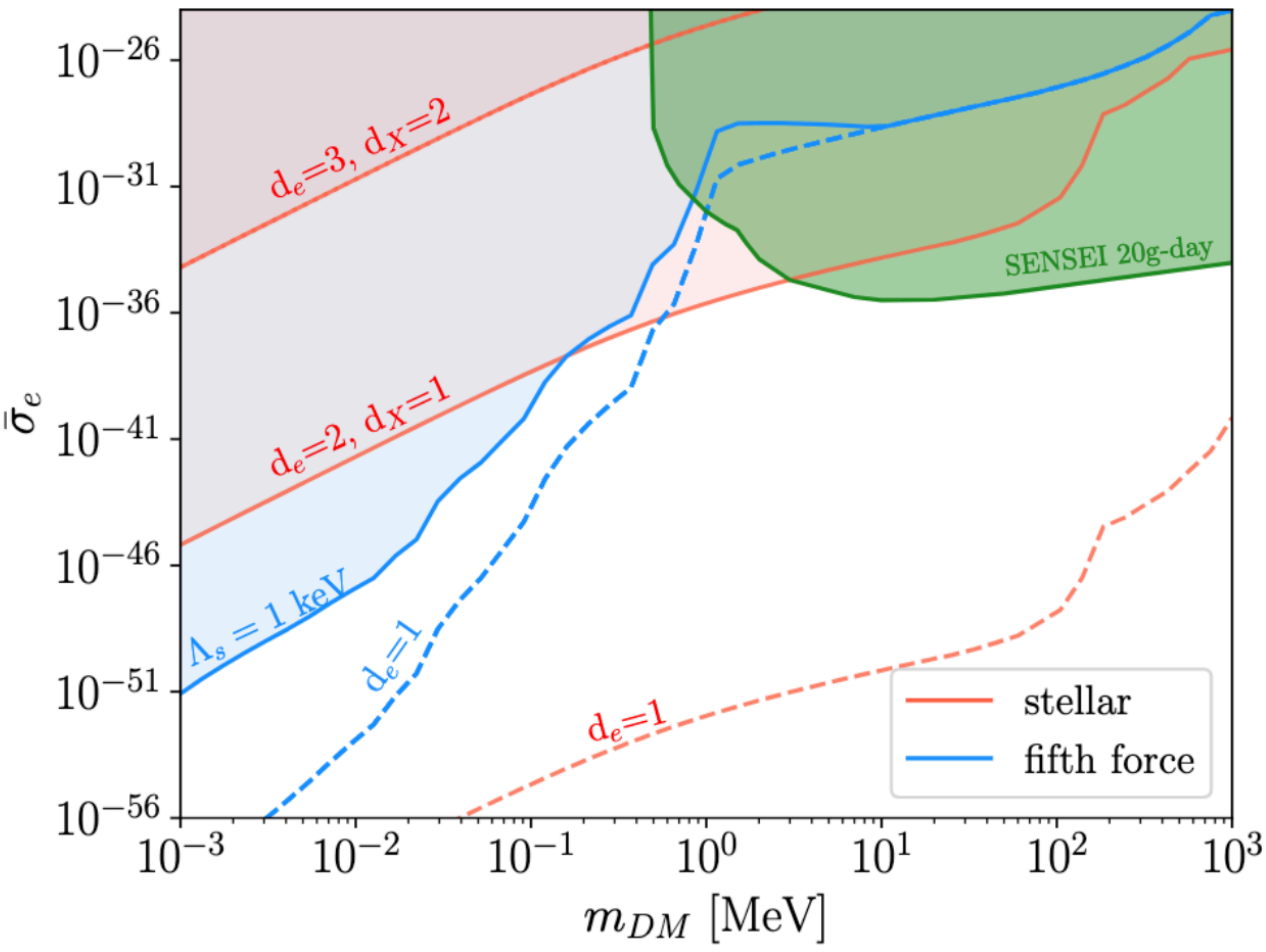


$$\left(\frac{\mu}{\Lambda_s}\right)^{\gamma_1/2}\frac{c_1}{\Lambda^{d_1-1}}\mathcal{O}_1\bar{e}e+\left(\frac{\mu}{\Lambda_s}\right)^{\gamma_2/2}\frac{c_2}{\Lambda^{d_2-1}}\mathcal{O}_2\bar{\Psi}_D\Psi$$

Massless Mediation Sector

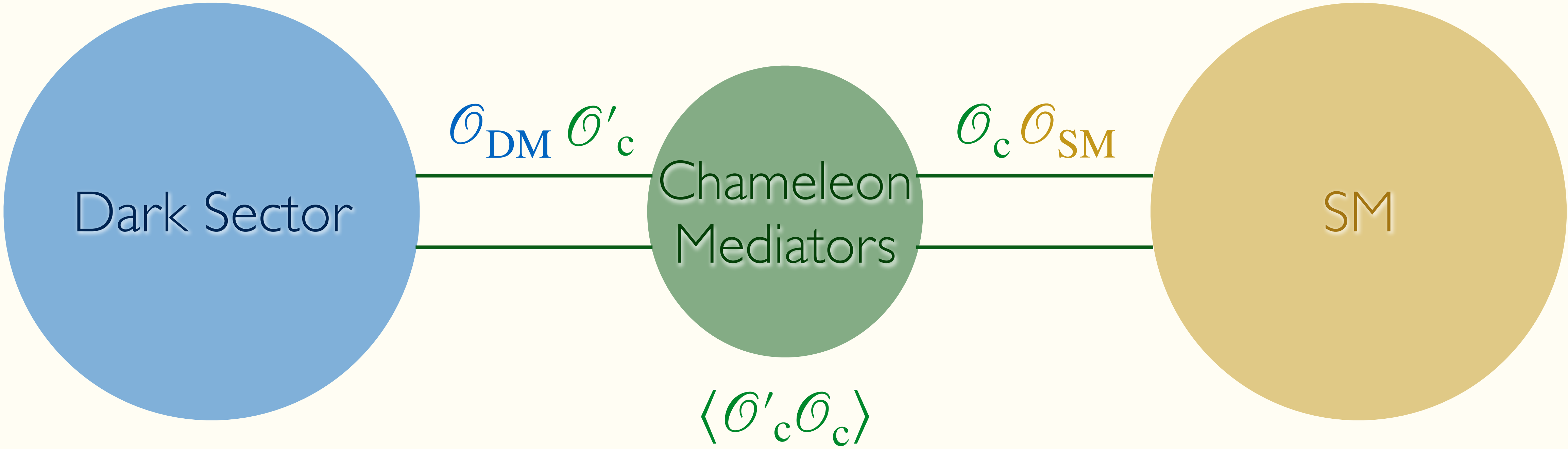


[Bloch, Outmezguine, Redigolo, Sun, TV, *work in progress*]

General Dark c-Mediation?

[Bloch, Outmezguine, Redigolo, Sun, TV, *work in progress*]

- Numerous applications:
    - Ameliorate direct detection.
    - New DM form factors, $F_{\text{DM}} \sim q^{-\alpha}$.
    - Implication for production mechanism? [Hong, Kurup, Perelstein, 2022]
    - Could change cosmology - different couplings at large temperatures (e.g. 21cm predictions)
    - More?



More General Environmental Effects

DM interactions with environment can influence its behavior

Relevant for structure formation

Example: CDM (χ) + light component (ϕ)

$$\mathscr{L} = -m_\chi^2 |\chi|^2 - m_{\phi,0}^2 |\phi|^2 - \lambda |\phi|^2 |\chi|^2$$

For simplicity assume: $m_{\phi,0} \ll m_\chi$

$$\rho_\phi \ll \rho_\chi \sim \rho_{\rm DM}$$

Then: $$m_\phi^2 = m_{\phi,0}^2 + \lambda\chi^2 = m_{\phi,0}^2 + \lambda \frac{\rho_{\rm DM}}{m_\chi^2}$$

More General Environmental Effects

To solve: Write down the EOM and take $\psi = \sqrt{2m_{\phi,0}}\phi e^{im_{\phi,0}t}$

Obtain the Schrodinger-Poisson Eqs.:

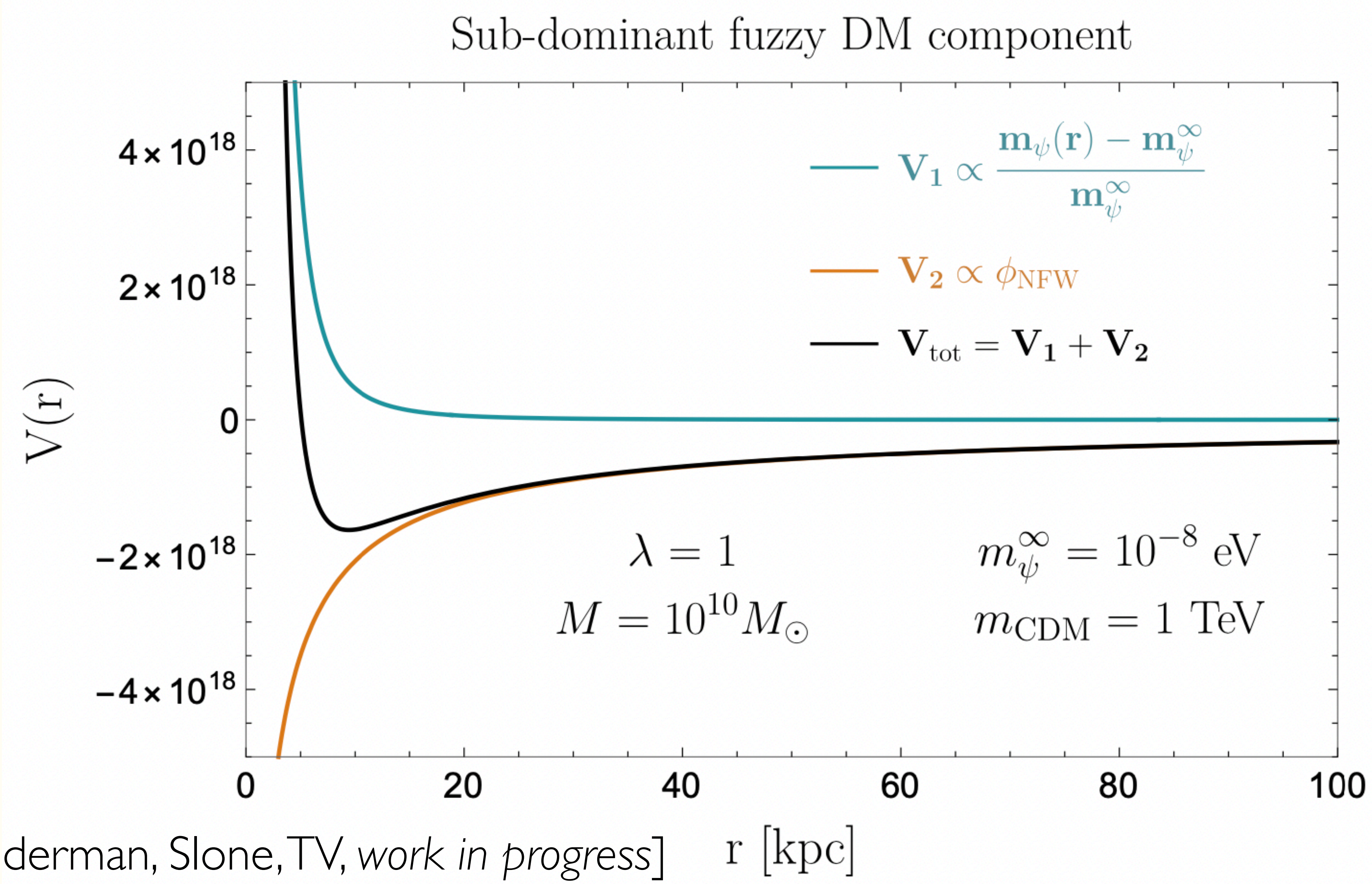
$$\boxed{i\partial_t\psi + \frac{\nabla^2\psi}{2m_0} - \frac{(m(r) - m_0)}{2}\psi - \frac{g_2|\psi|^2}{4m_0^2}\psi - (2m_0 - m(r))\Phi\psi \simeq 0.}$$

$$\boxed{\nabla^2\Phi = 4\pi G\left[m_\chi|\chi|^2 + (2m_0 - m(r))|\psi|^2\right].}$$

More General Environmental Effects

$$i\partial_t\psi + \frac{\nabla^2\psi}{2m_0} - \frac{(m(r)-m_0)}{2}\psi - \frac{g_2|\psi|^2}{4m_0^2}\psi - (2m_0 - m(r))\Phi\psi \simeq 0.$$

$$\nabla^2\Phi = 4\pi G\left[m_\chi|\chi|^2 + (2m_0 - m(r))|\psi|^2\right].$$

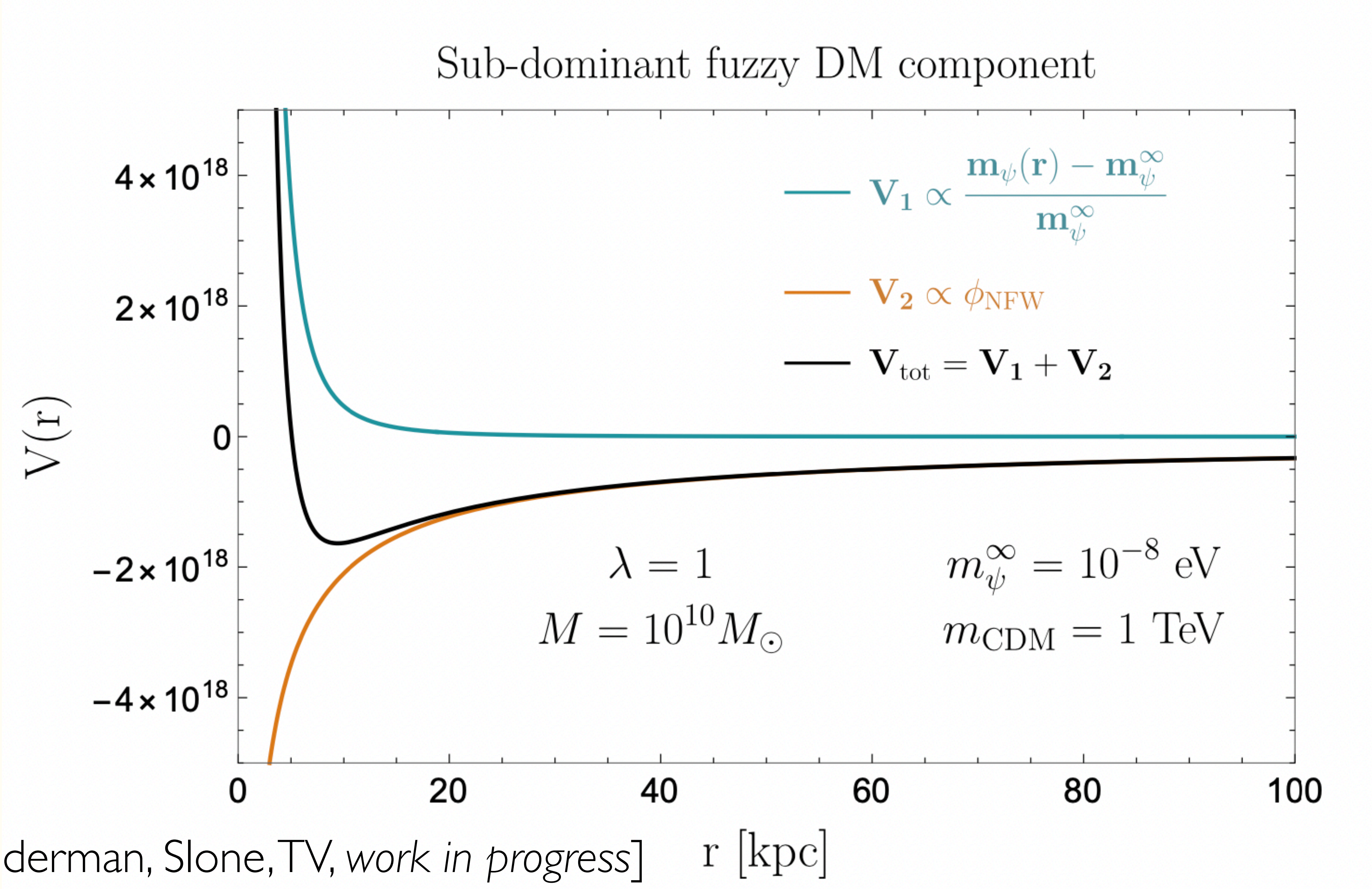


[Gouttenoire, Ruderman, Slone, TV, *work in progress*]

More General Environmental Effects

The light component is predicted to have a core

Possible solution to small-scale problems.



[Gouttenoire, Ruderman, Slone, TV, *work in progress*]

More General Environmental Effects

The light component is predicted to have a core

Possible solution to small-scale problems.

Much more to do

Analyze with dominant light component

Possible couplings to baryons (diversity problem / baryonic Tully-Fisher)

Other constraints?

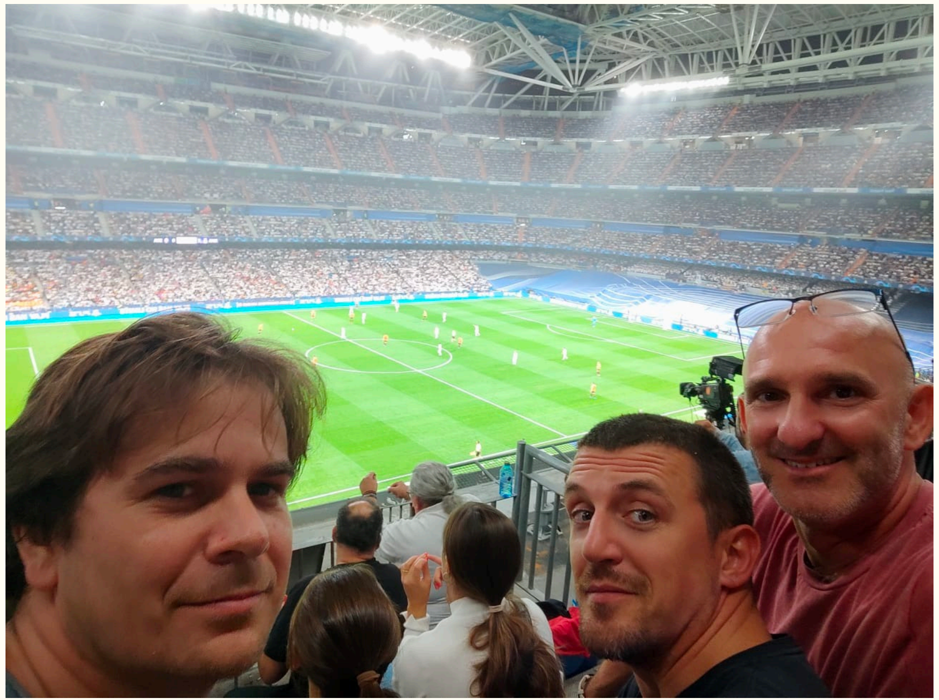
Conclusions

Astrophysical and cosmological data present opportunities to search for non-trivial DM

Could be DM that interacts with visible sector (e.g. 21-cm)
Or DM that does not interact with visible sector (e.g. SB2s, enDM)

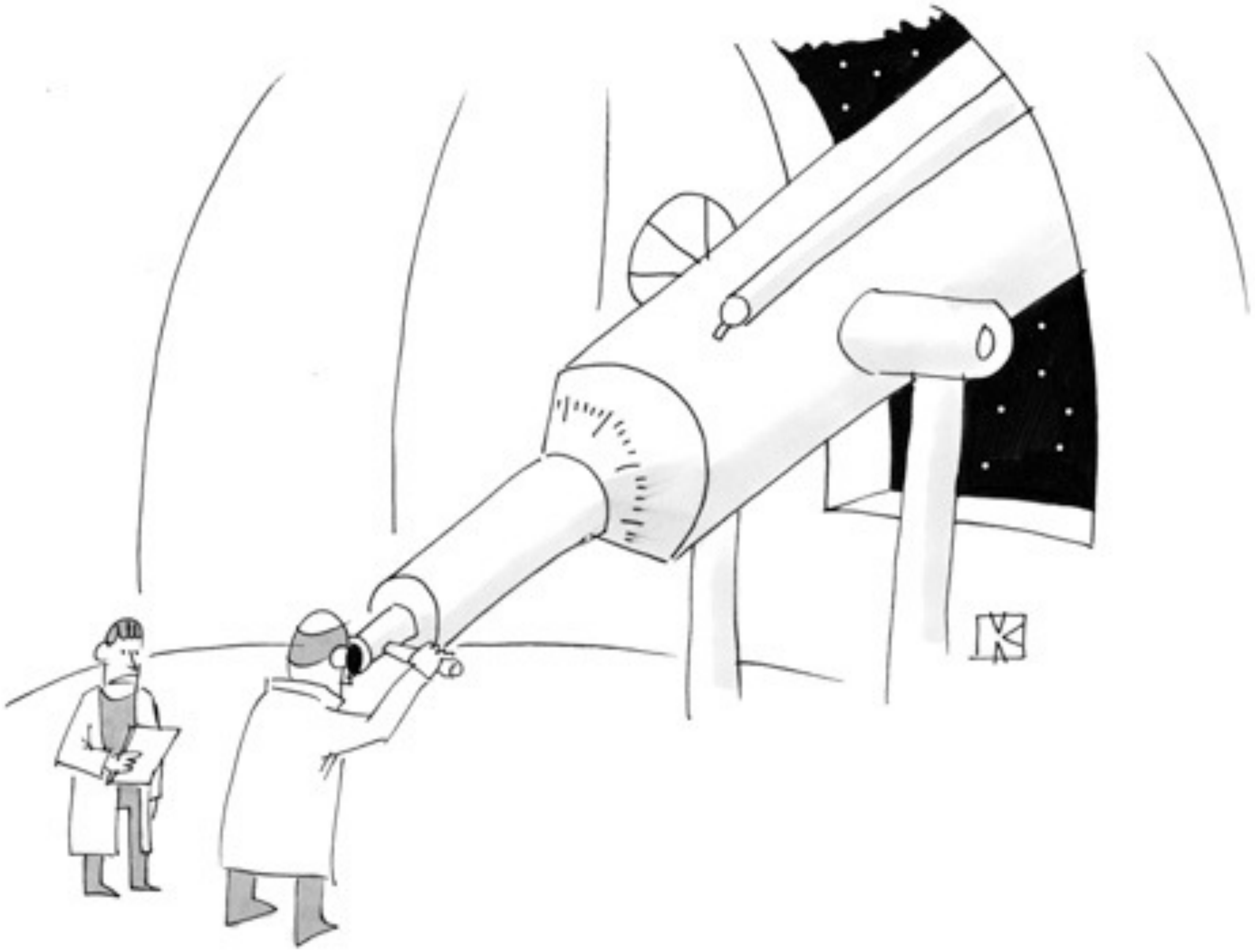
Lots more to do!

Have fun while you're at it



Far too many mysteries to solve. Can't stop now!

To be continued...



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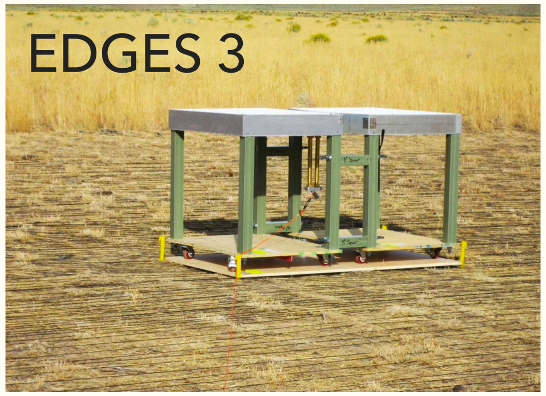
"That isn't dark matter, sir—you just forgot to take off the lens cap."

Backup Slides

Future 21-cm Experiments

Many(!) experiments

Global signal



Fluctuations