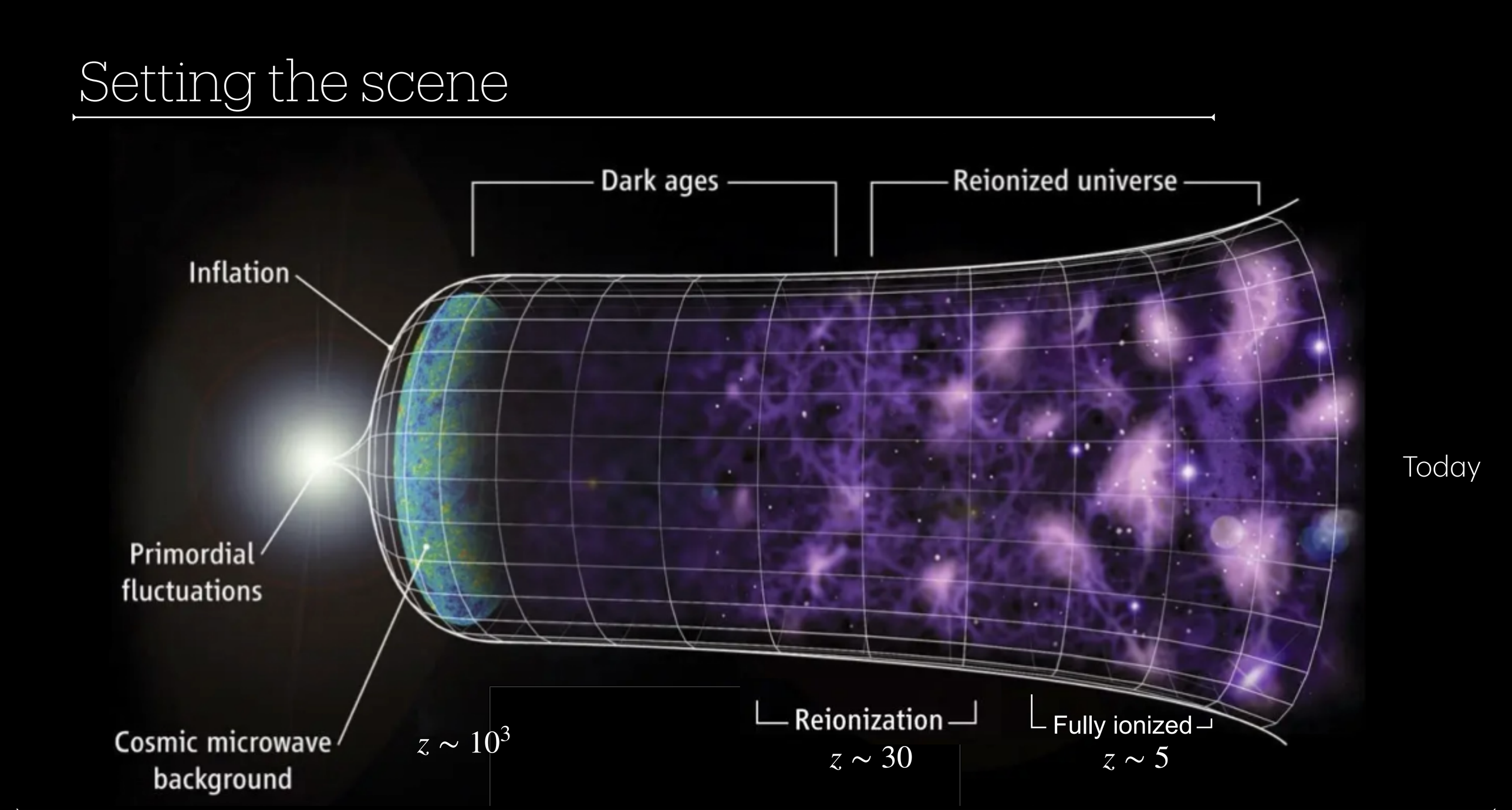
Boosting 21-cm Constraints on Dark Matter

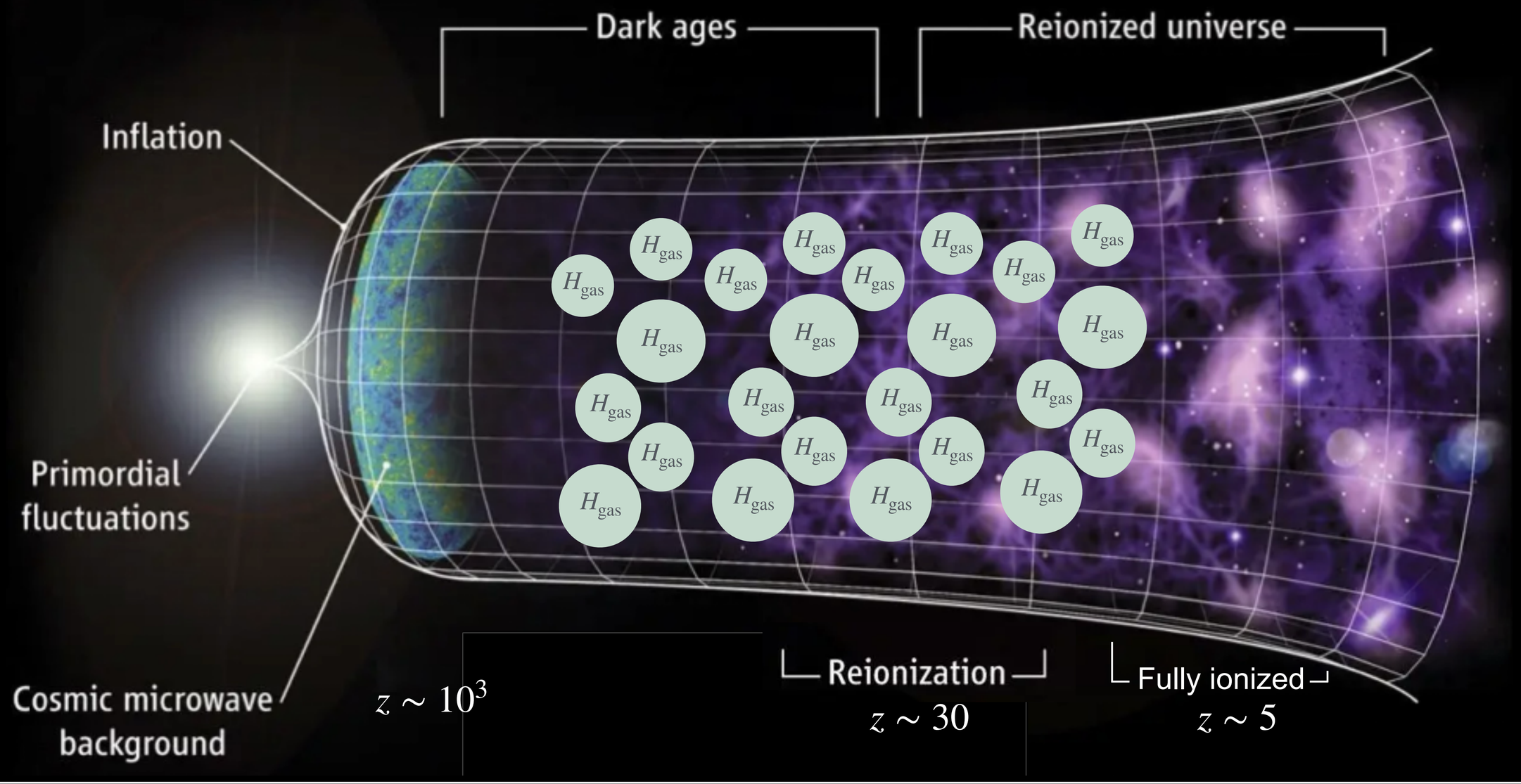
Including results from 2 very recent papers, in collaboration with:

- Rouven Essig (YITP, Stony Brook), Daniele Gaggero (INFN, Pisa), Sergio Palomares-Ruiz (IFIC, Valencia), Gregory Suczewski (YITP, Stony Brook), Mauro Valli (INFN, Rome). 2510.14877 — "Astrophysical Uncertainties…"
- Tracy Slatyer (MIT, Cambridge). 2510.26791 — "Boosting the cosmic 21-cm…"

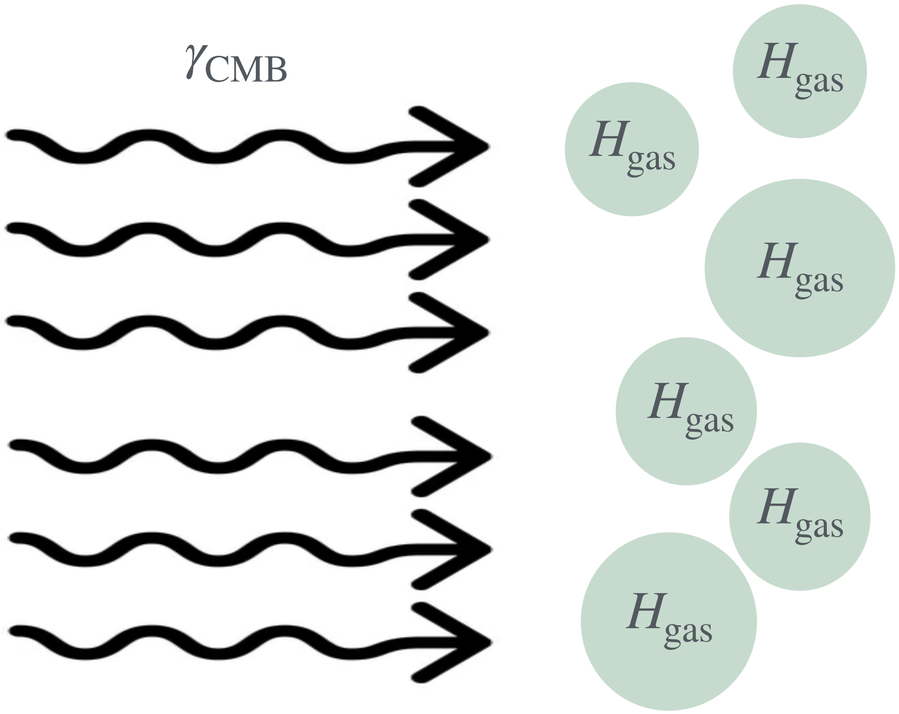
Setting the scene



Setting the scene — Neutral Hydrogen



The 21-cm signal



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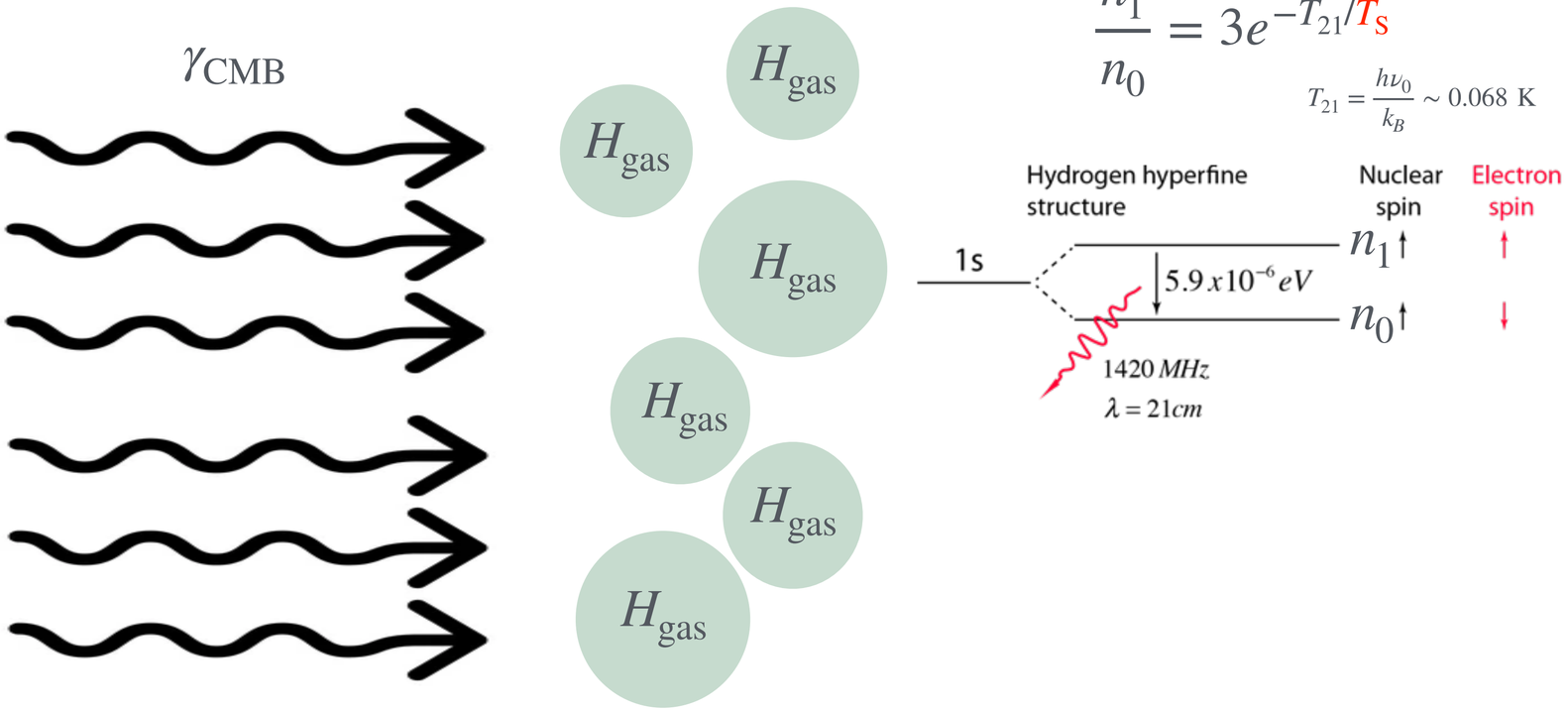

$$\frac{n_1}{n_0} = 3e^{-T_{21}/T_S}$$

$$T_{21} = \frac{h\nu_0}{k_B} \sim 0.068 \text{ K}$$

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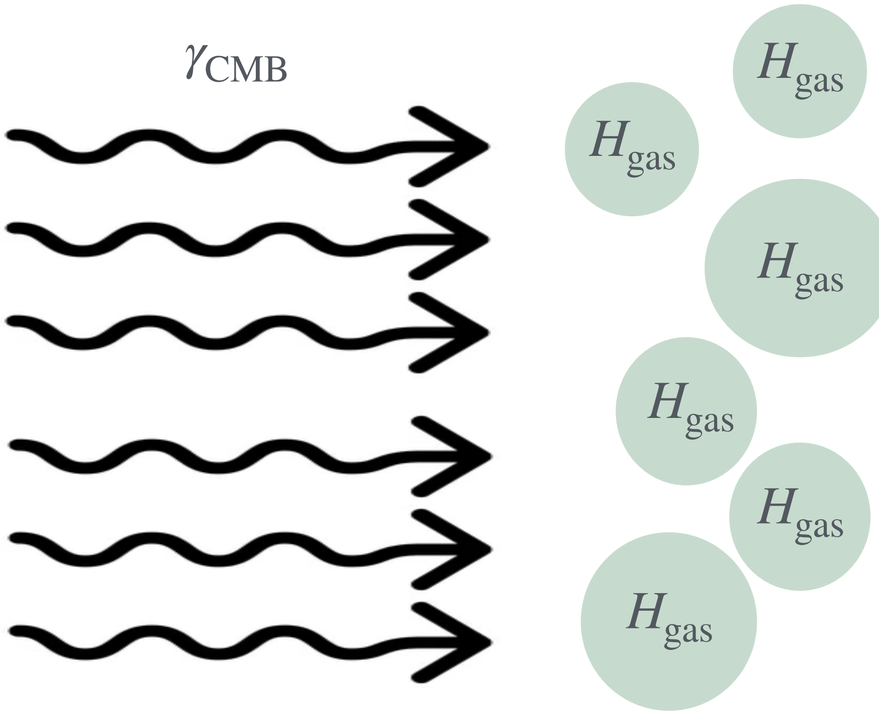

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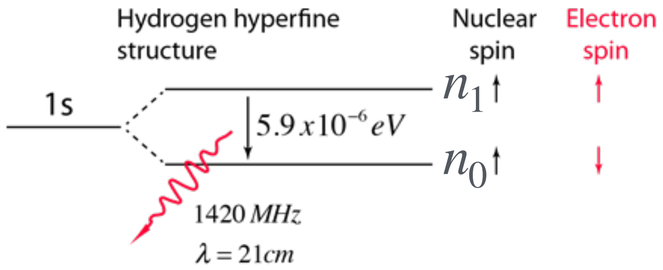

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_k T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_k + x_\alpha}$$

The 21-cm signal

CMB temperature

Gas kinetic temperature

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_k T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_k + x_\alpha}$$

UV dependent

X-ray dependent

The spin temperature is dictated by its (de)coupling to T_γ and T_K. This is determined by:

1. Absorption and emission of 21cm photons from and to the CMB
2. Collisional coupling between H atoms
3. Wouthuysen-Field Effect (Lyman-alpha photons)

21cm physics (a primer)

Differential brightness temperature

CMB temperature

$$\delta T_b \propto x_{\rm HI}\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}$$

Fraction of neutral hydrogen

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_k T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_k + x_\alpha}$$

Spin temperature

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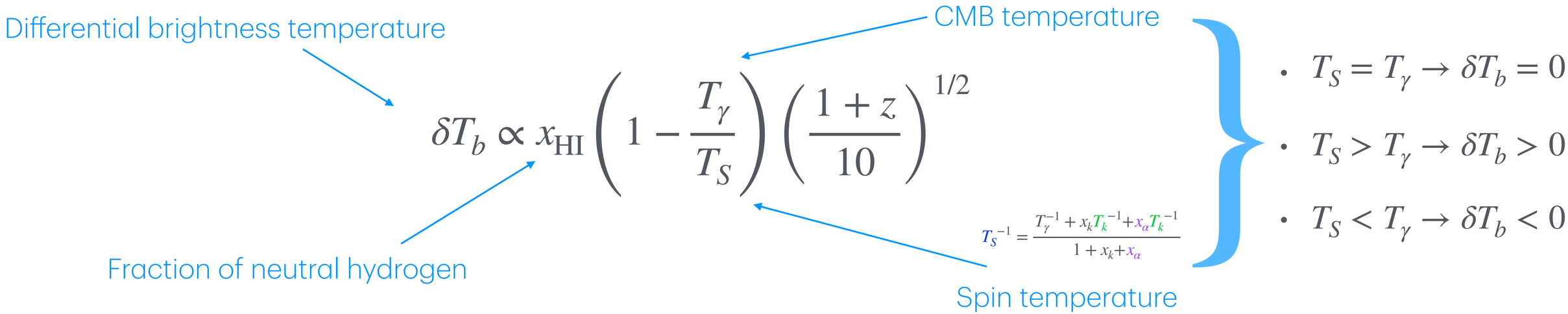
Spin temperature

- $T_S = T_\gamma \rightarrow \delta T_b = 0$
- $T_S > T_\gamma \rightarrow \delta T_b > 0$
- $T_S < T_\gamma \rightarrow \delta T_b < 0$

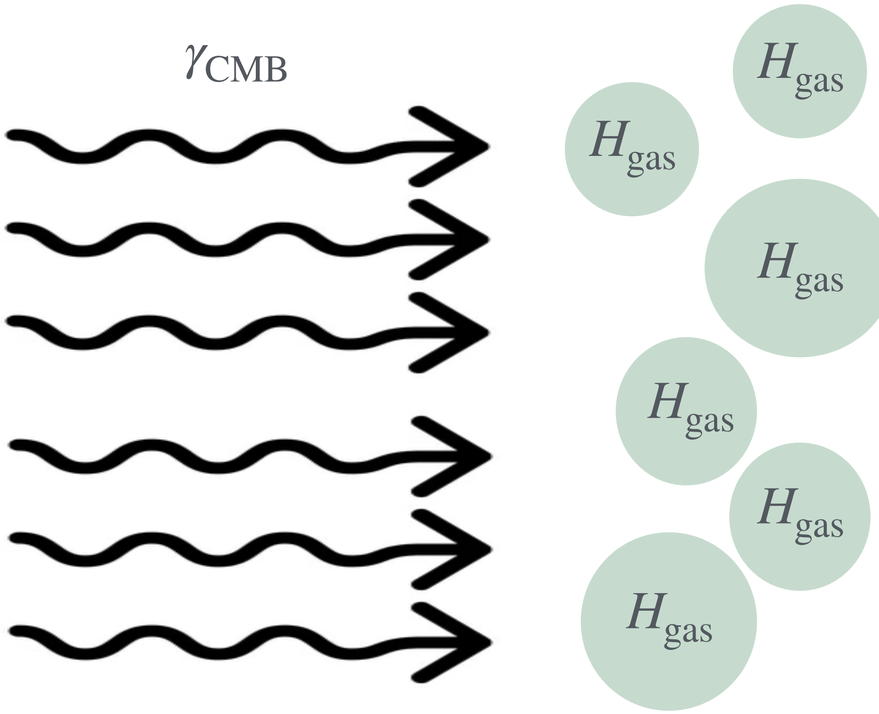
21cm physics (a primer)



The signal is dictated by T_γ / T_S!

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_k T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_k + x_\alpha}$$

The 21-cm signal



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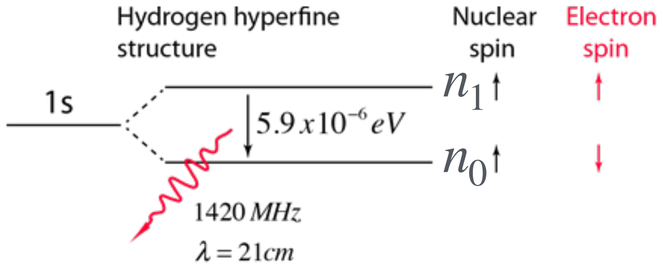
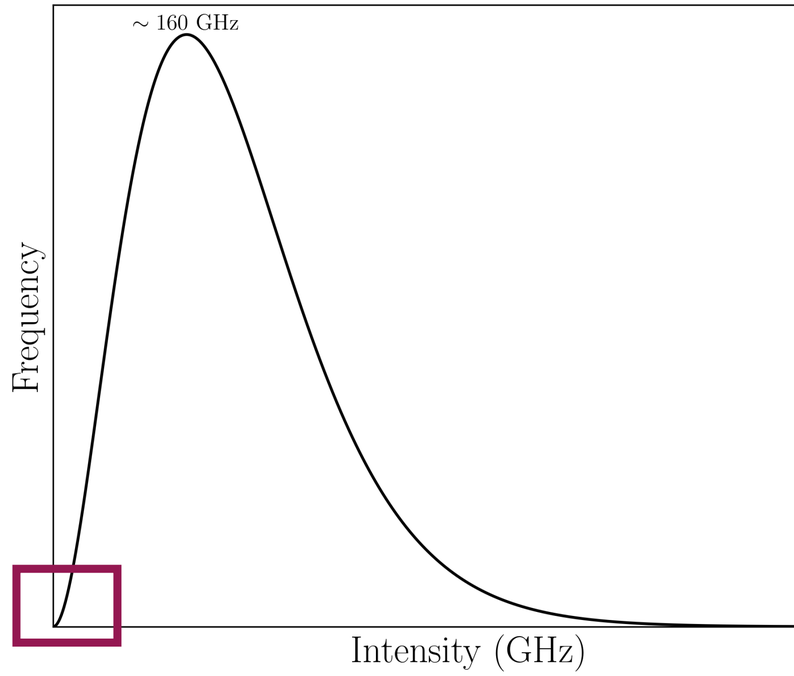
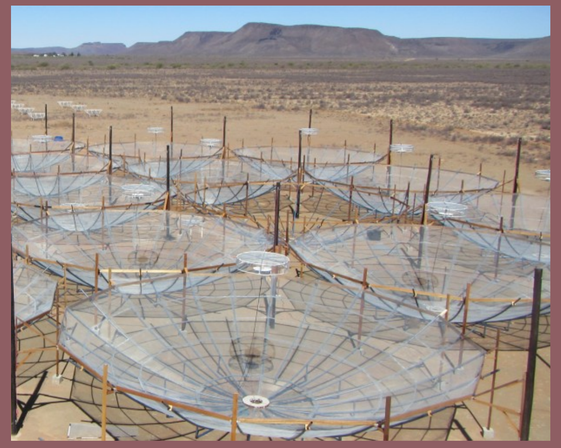




The 21-cm signal

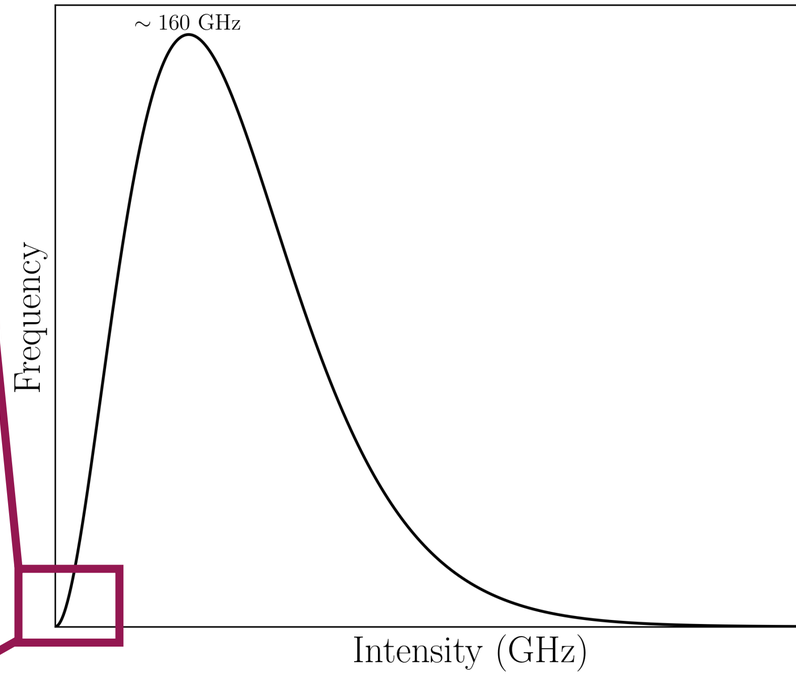
EDGES

SARAS



HERA

SKA



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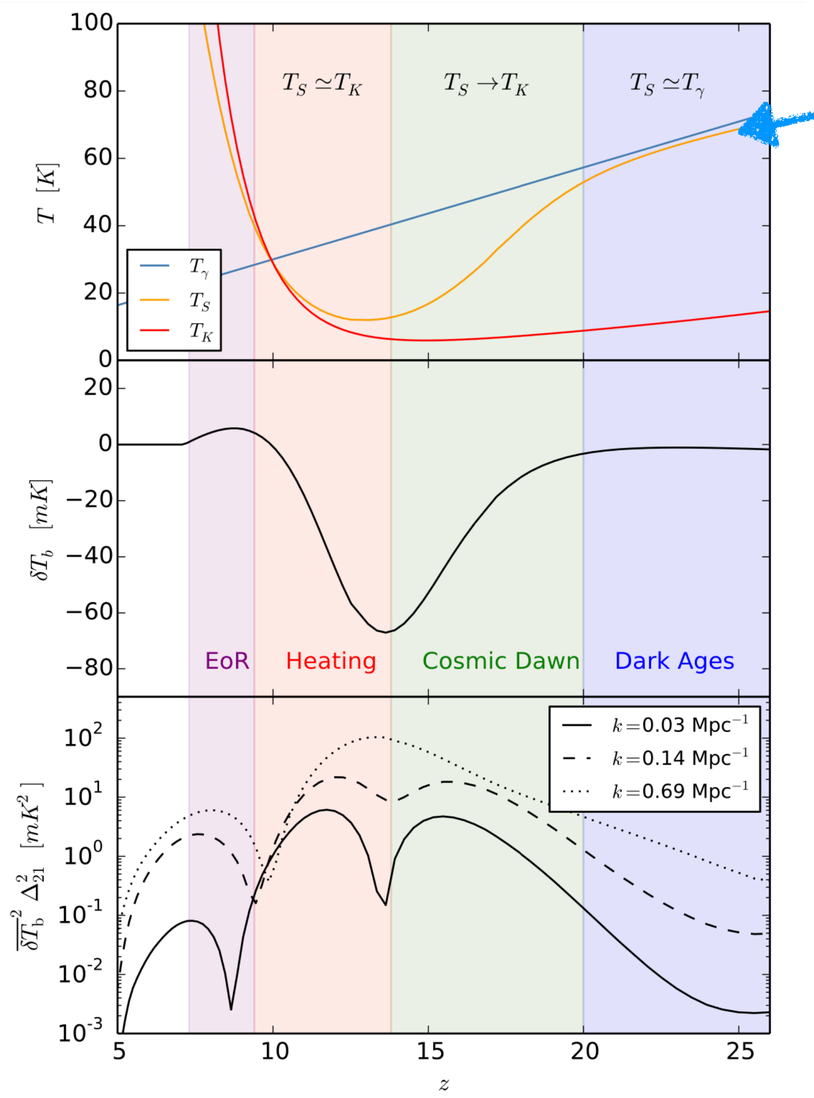
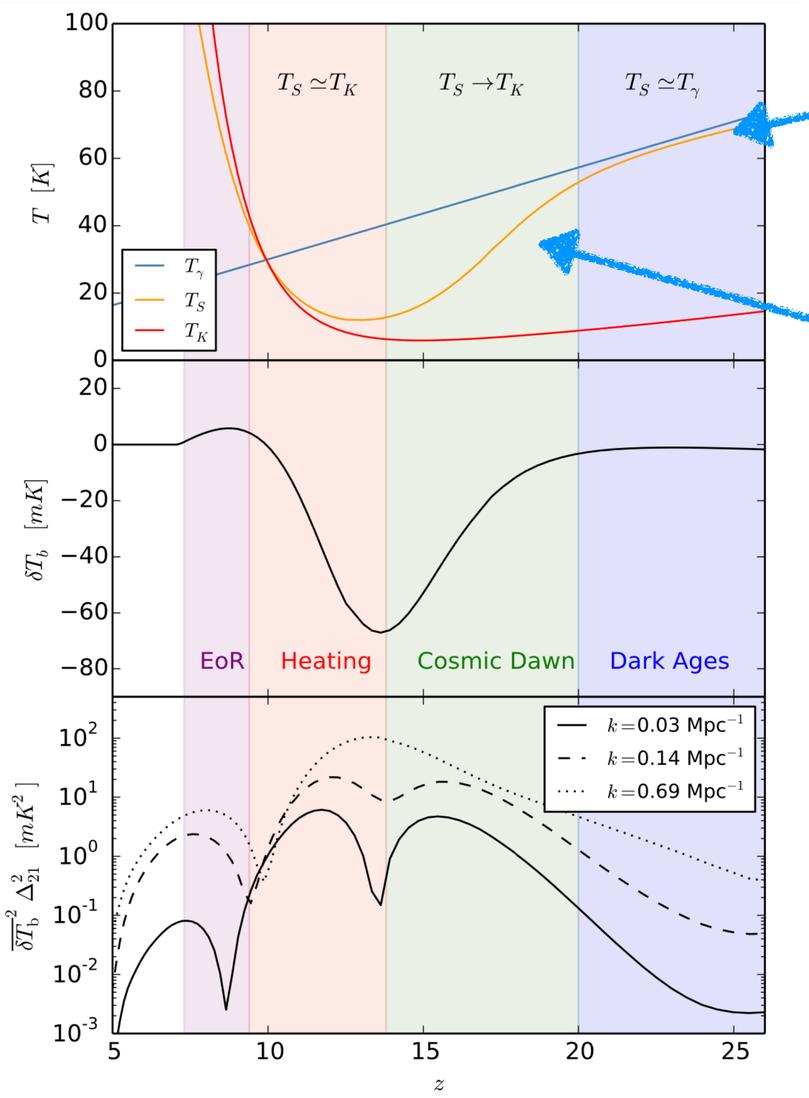


Villanueva-Domingo, PhD Thesis, 2021

Radiative coupling most efficient (too low densities for collisions) and $T_S \simeq T_\gamma$

21cm physics (a primer)



Villanueva-Domingo, PhD Thesis, 2021

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Lyman-alpha photons from first sources couples $T_S \to T_K$, through the WF effect

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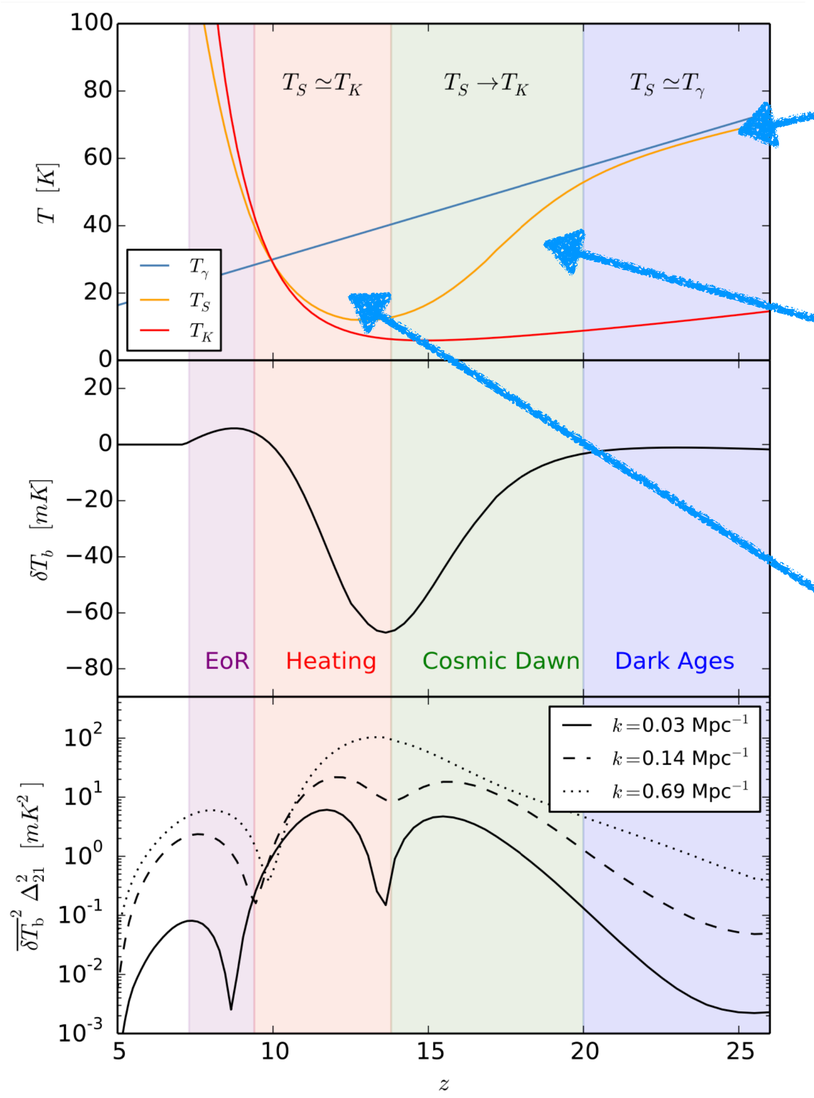

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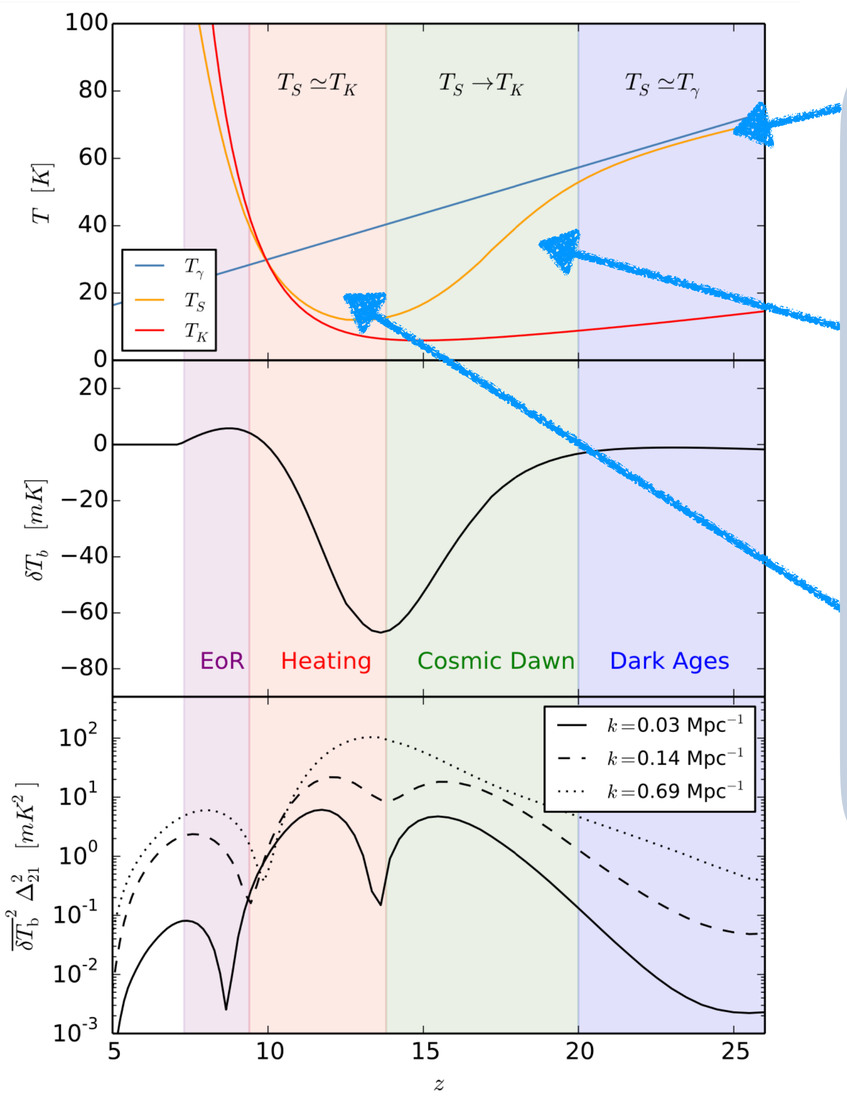
X-ray heating of the gas, where WF effect still couples $T_S \to T_K$. We see emission when $T_K > T_\gamma$

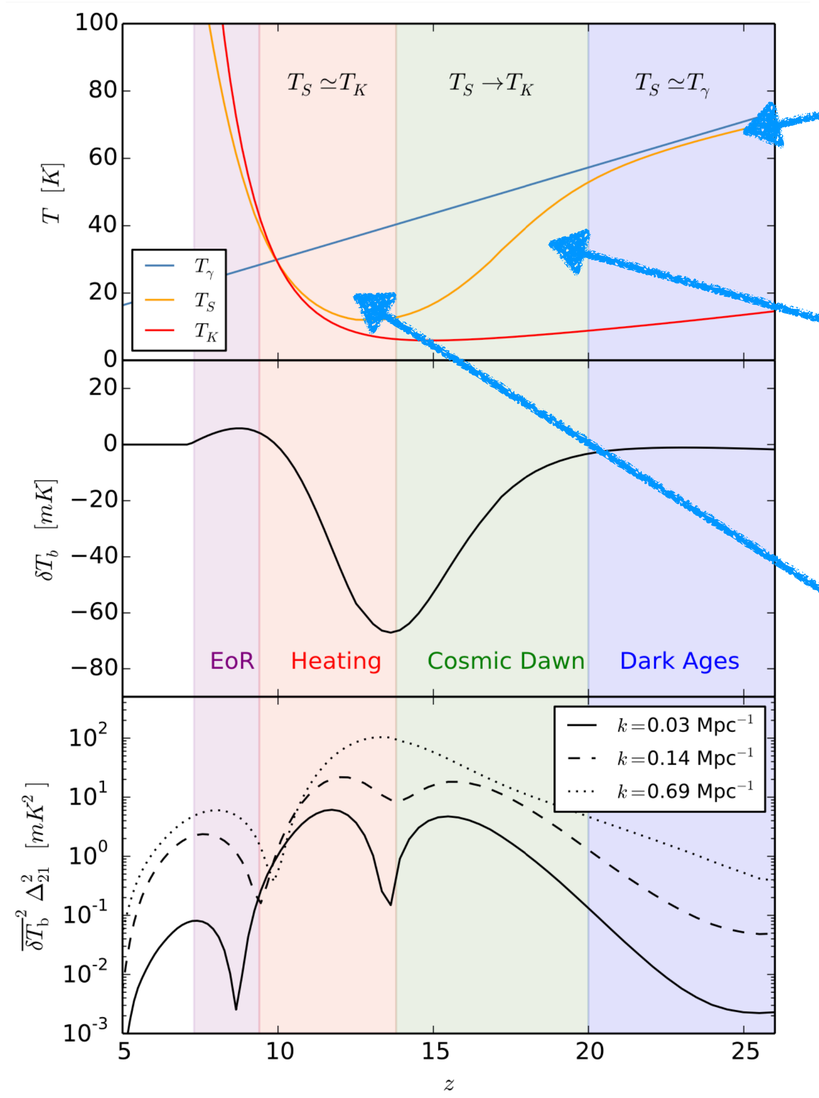
21cm physics (with exotics)



Villanueva-Domingo, PhD Thesis, 2021

Exotic Injections change two (measurable) things:

1. Extra heating of the gas



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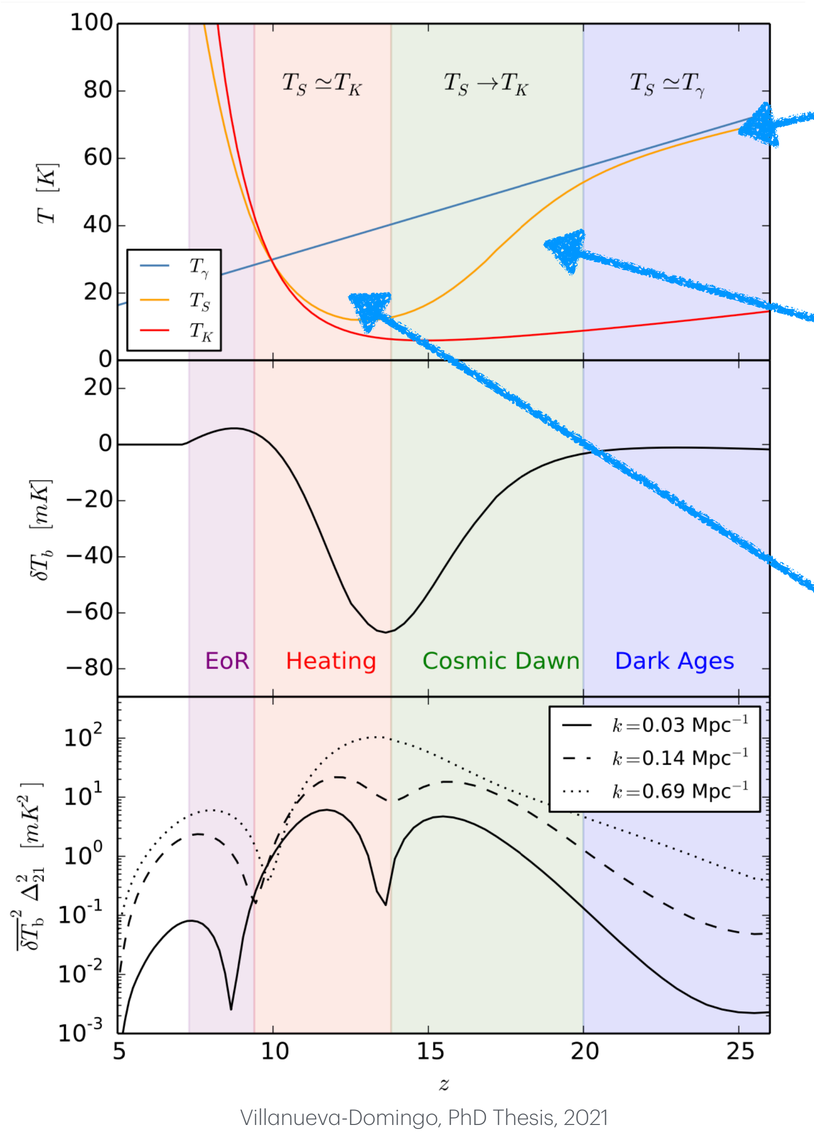
$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_k^{-1} + x_k T_k^{-1}}{1 + x_\alpha + x_k}$$

2. Extra Lyman-alpha photons (new)



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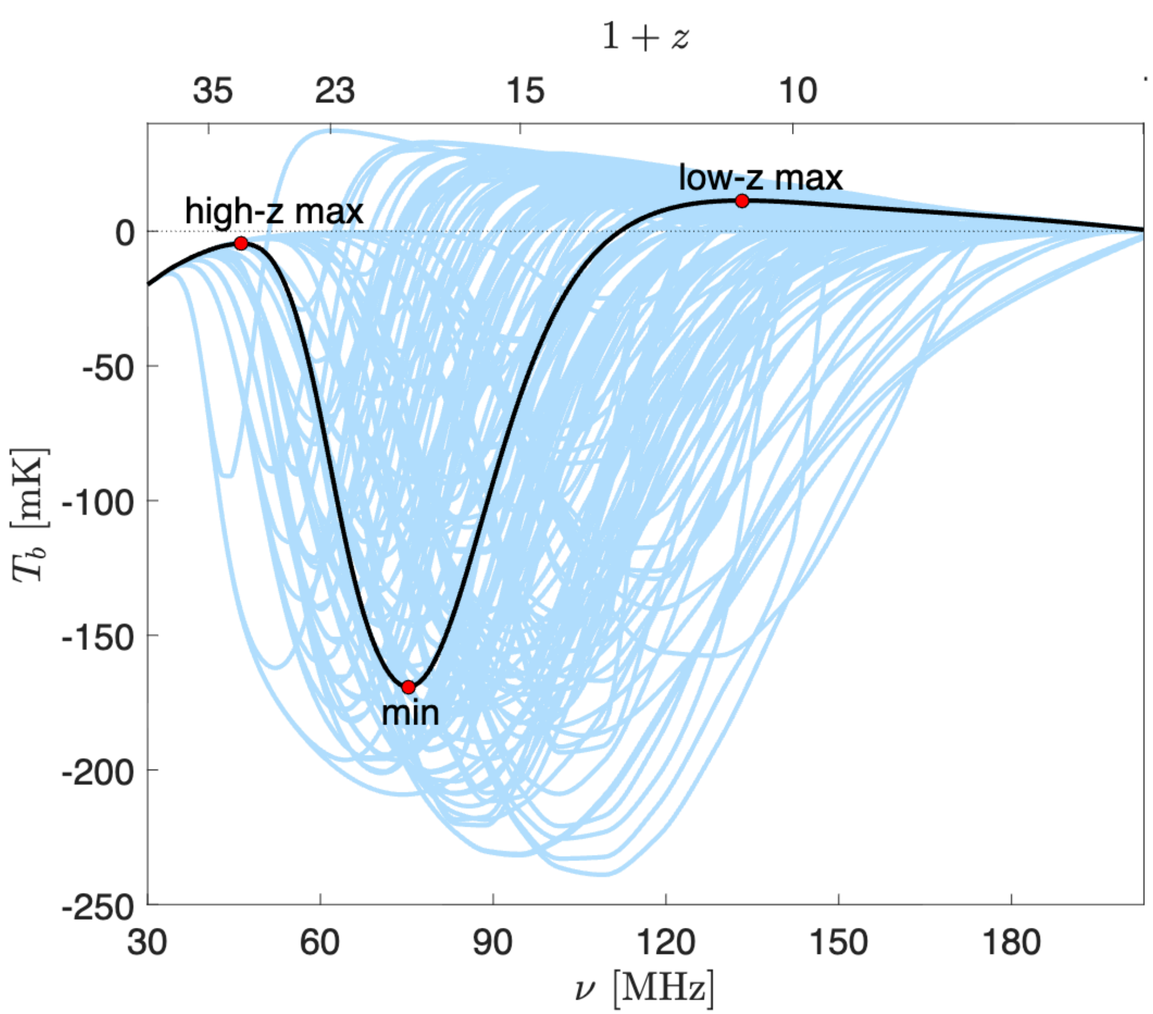
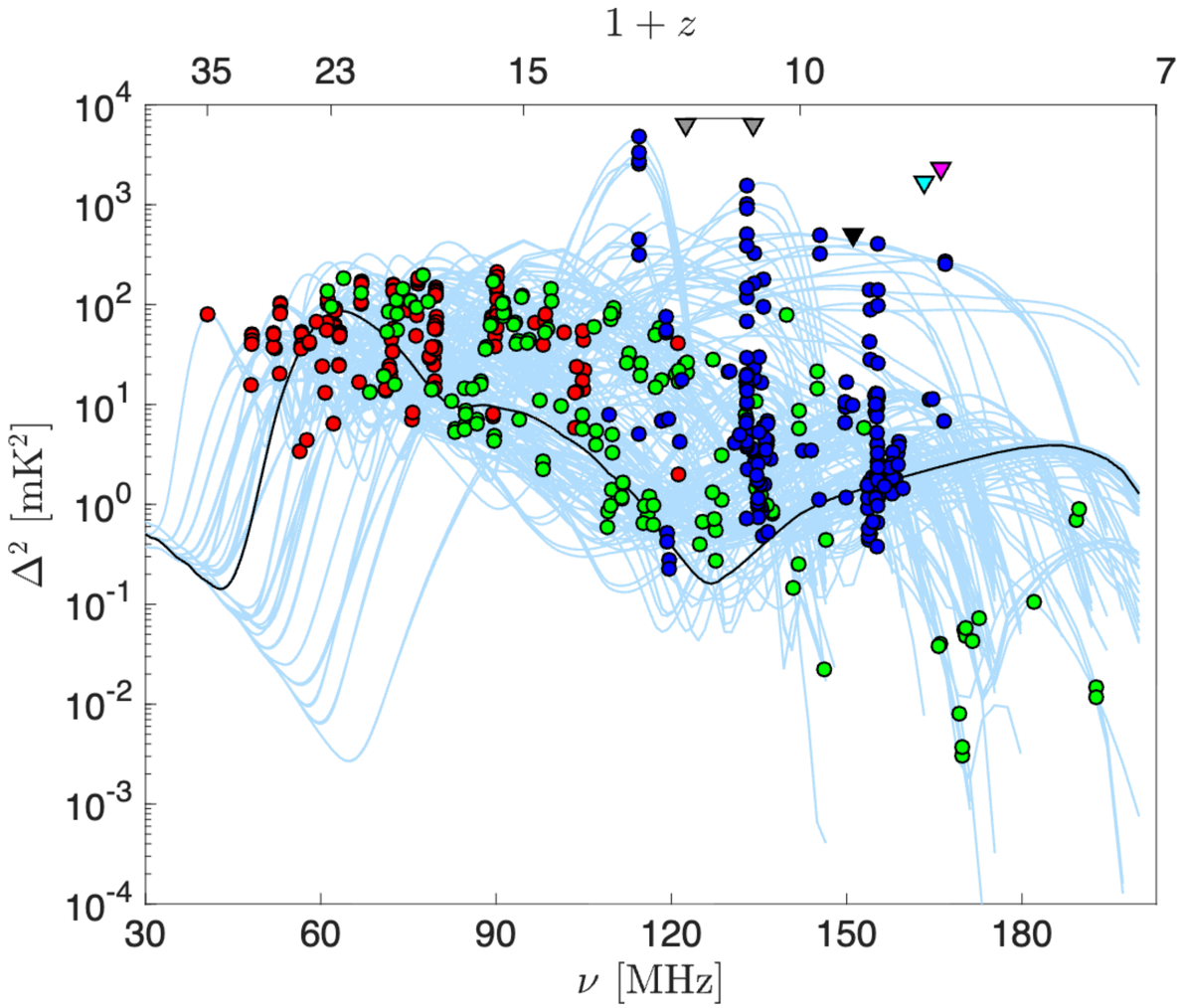
$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_k^{-1} + x_k T_k^{-1}}{1 + x_\alpha + x_k}$$

The signal space from "standard" astrophysics is wide





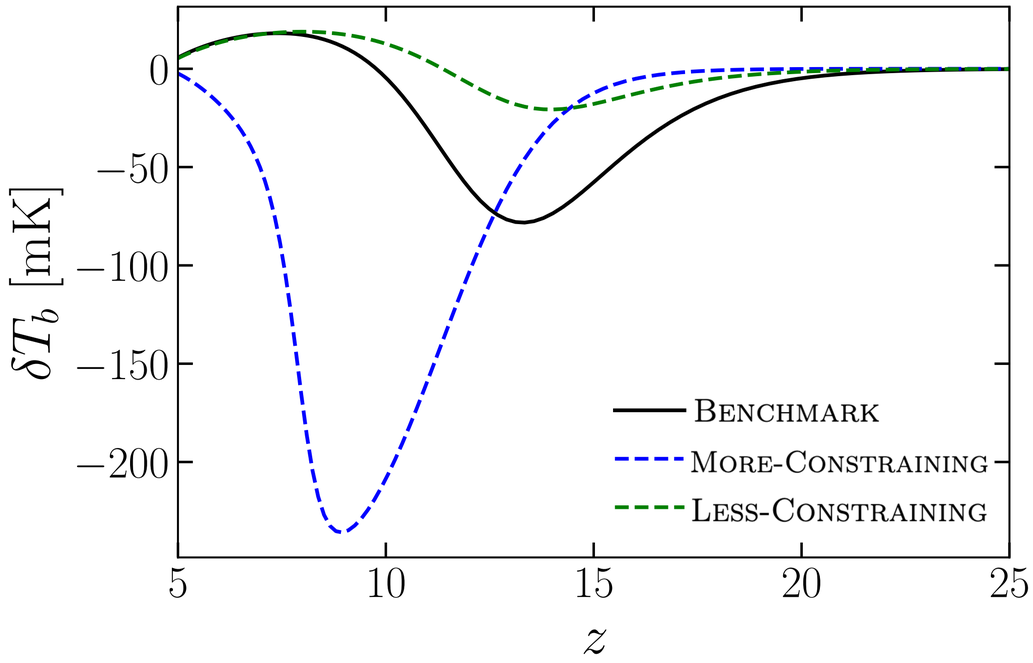
1709.02122

- redshift of the Lyα coupling
- moment of the heating transition
- midpoint of reionization

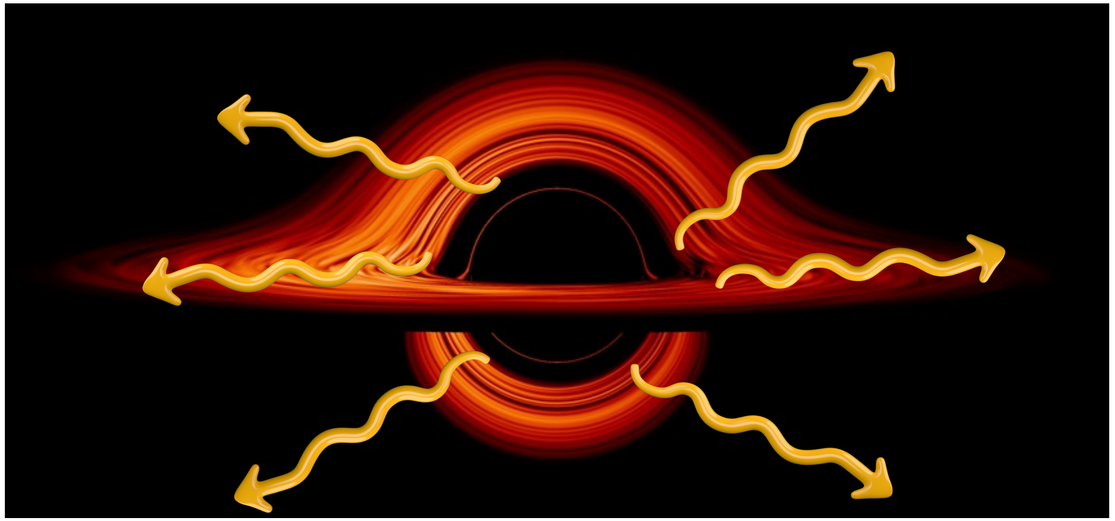
Independent constraints on astrophysics

- UVLFs [1809.08995,2003.04442, 2110.13919, etc.]
- CMB optical depth [1809.08995, 2502.03525, etc.]
- Chandra X-ray and HERA additional heating [2502.03525, 2108.07282, etc.]
- Starburst99 Synthesis models (+ more recent)

Astrophysical parameter	BENCHMARK	LESS-CONSTRAINING	MORE-CONSTRAINING
N_α	9690	3×10^3	4×10^4
$\log_{10}\, L_X/\dot{M}_* \; [\frac{\text{erg}}{\text{s}} \frac{\text{yr}}{M_\odot}]$	40.5	41	39.5
$T_{\text{vir}}\; [K]$	10^4	10^4	10^5



Accreting PBHs: A typical heating signal



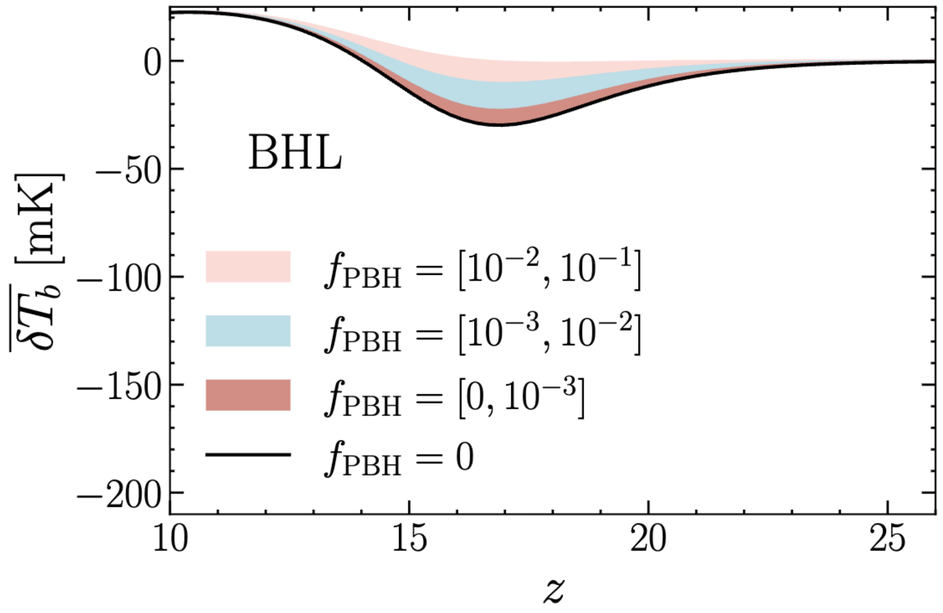
[Image from Jeremy Schnittman - NASA]

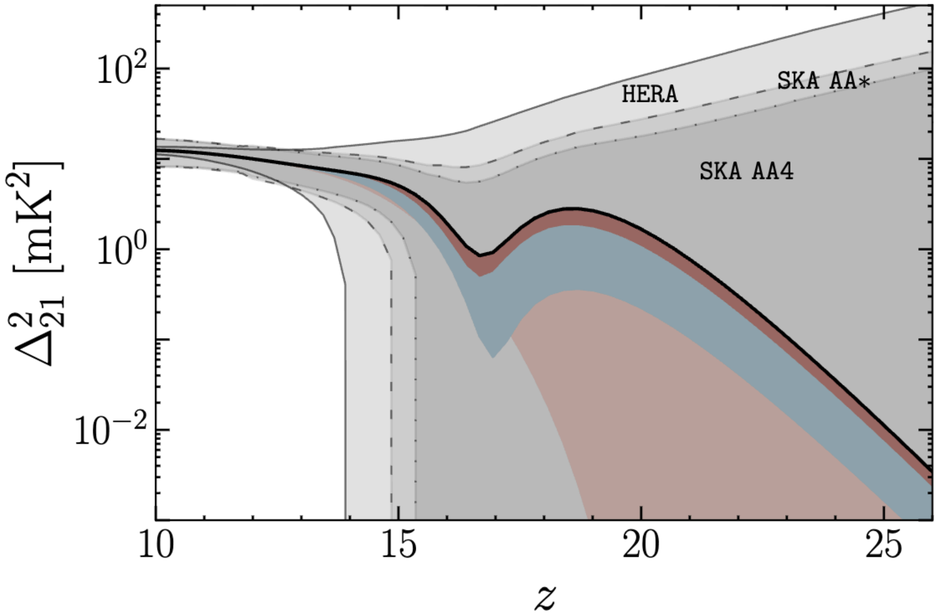
$$L = \epsilon \left(\dot{M}\right) \dot{M} c^2$$

$$\left.\frac{\mathrm{d}^2 E}{\mathrm{d}V\ \mathrm{d}t}\right|_{\mathrm{inj}} = L f_{\mathrm{PBH}} \frac{\rho_{\mathrm{DM}}}{M}$$

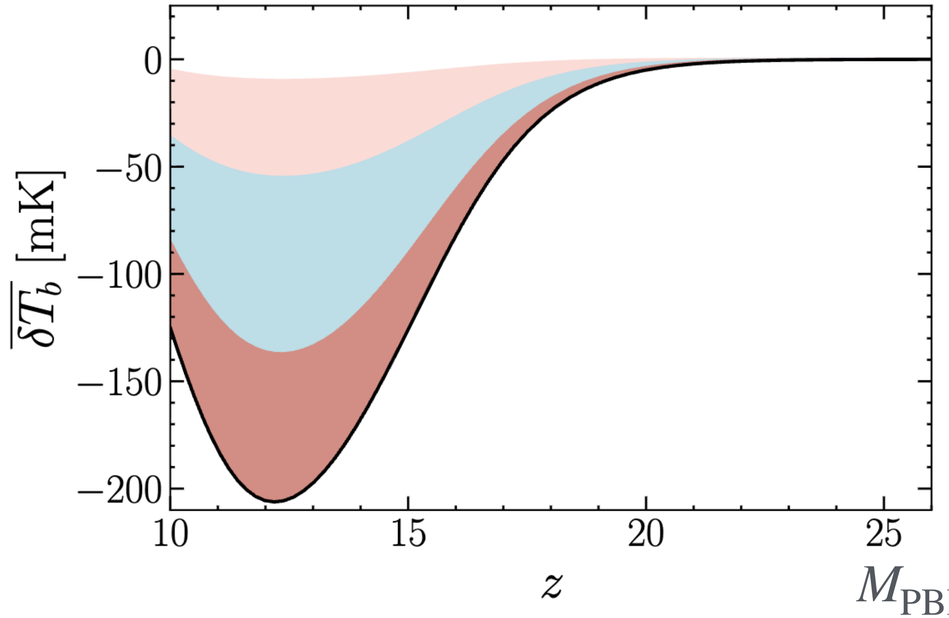
Details in [2403.18895, 2510.14877]

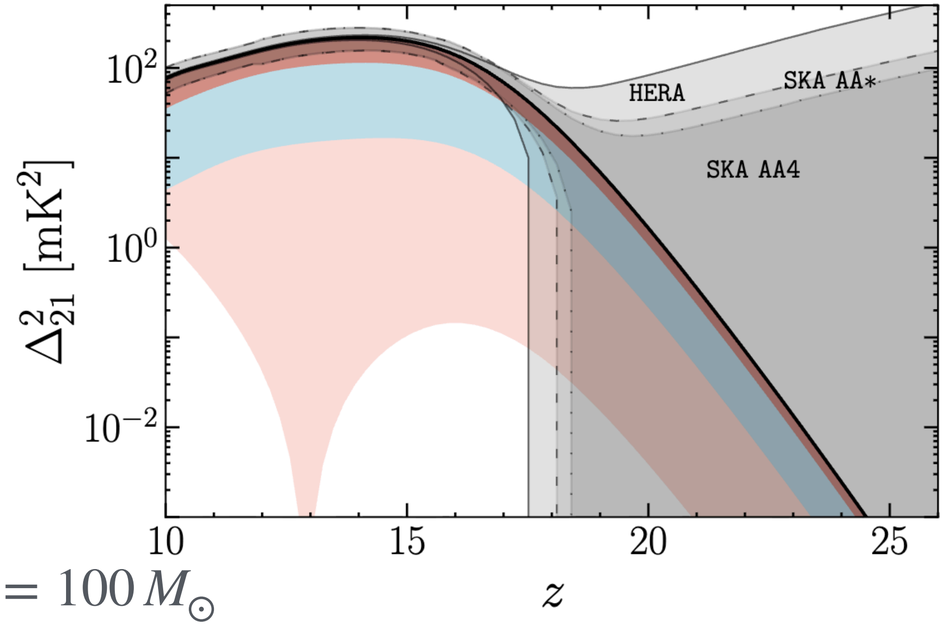
LESS-CONSTRAINING SCENARIO: $N_\alpha = 3 \times 10^3$, $L_X = 10^{41}\,\mathrm{erg\,s^{-1}}\,M_\odot^{-1}\,\mathrm{yr}$, $T_{\rm vir} = 10^4\,\mathrm{K}$.





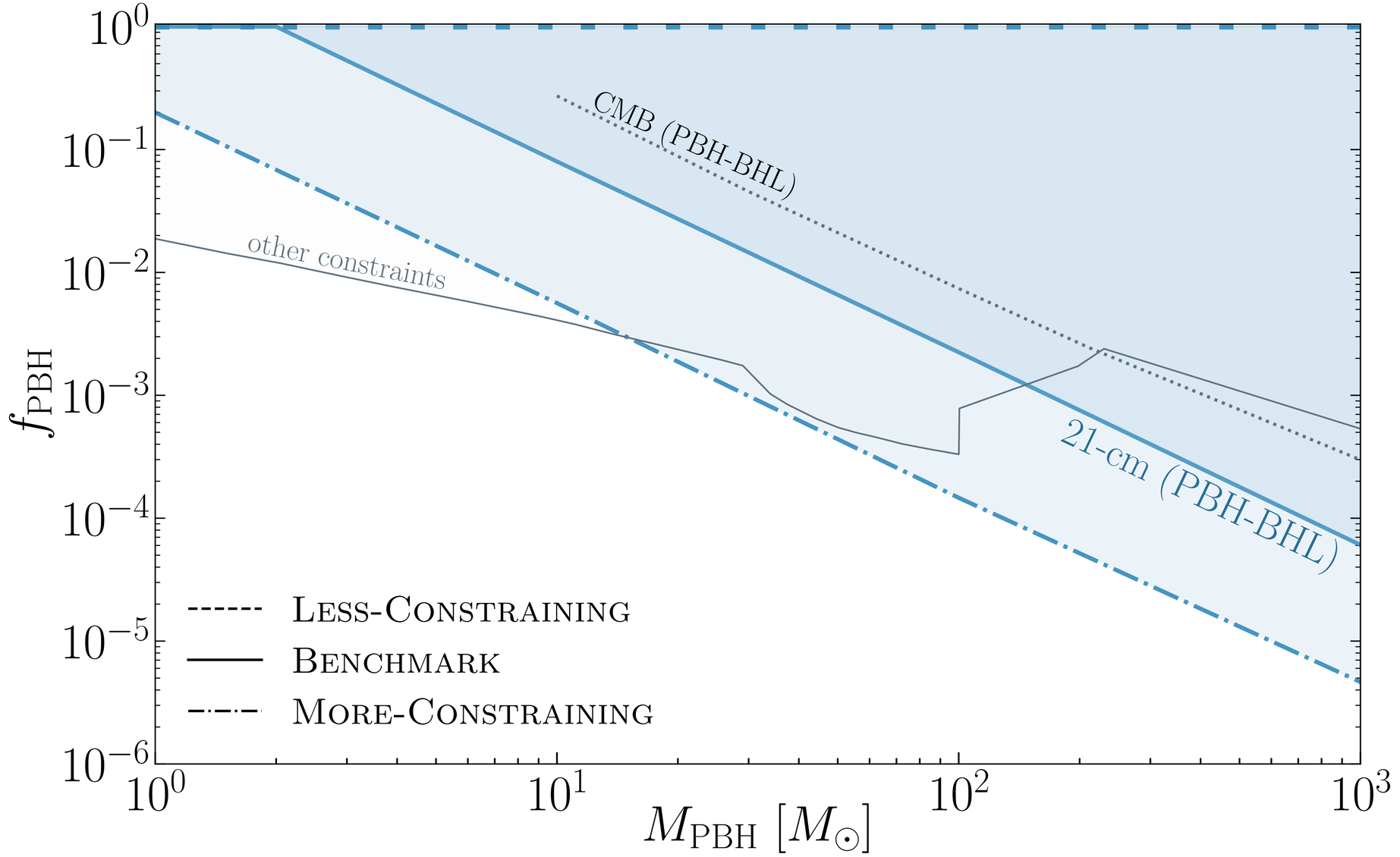
MORE-CONSTRAINING SCENARIO: $N_\alpha = 4 \times 10^4$, $L_X = 10^{39.5}\,\mathrm{erg\,s^{-1}}\,M_\odot^{-1}\,\mathrm{yr}$, $T_{\rm vir} = 10^5\,\mathrm{K}$.





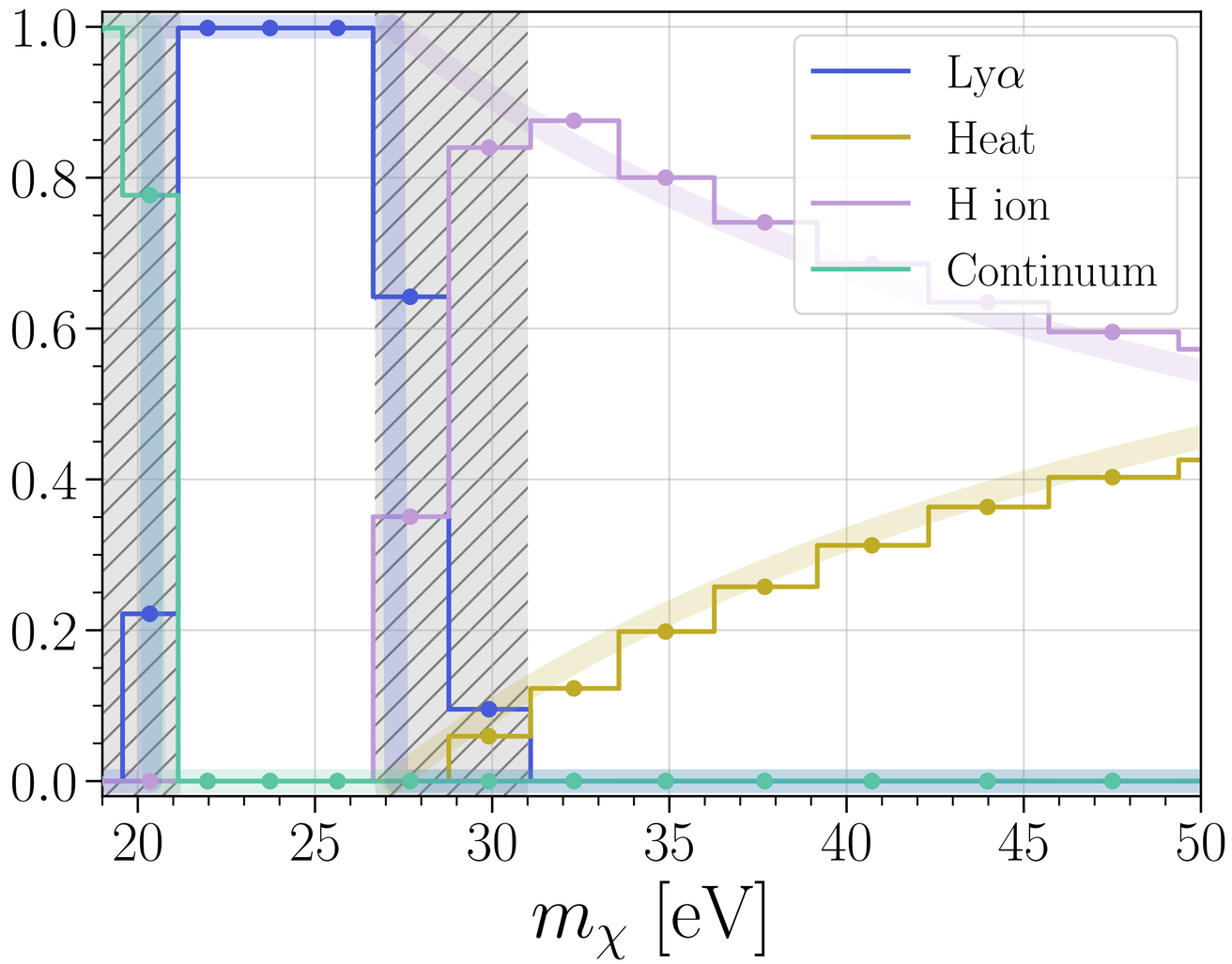
$M_{\rm PBH} = 100\,M_\odot$

The astrophysical scenario matters!



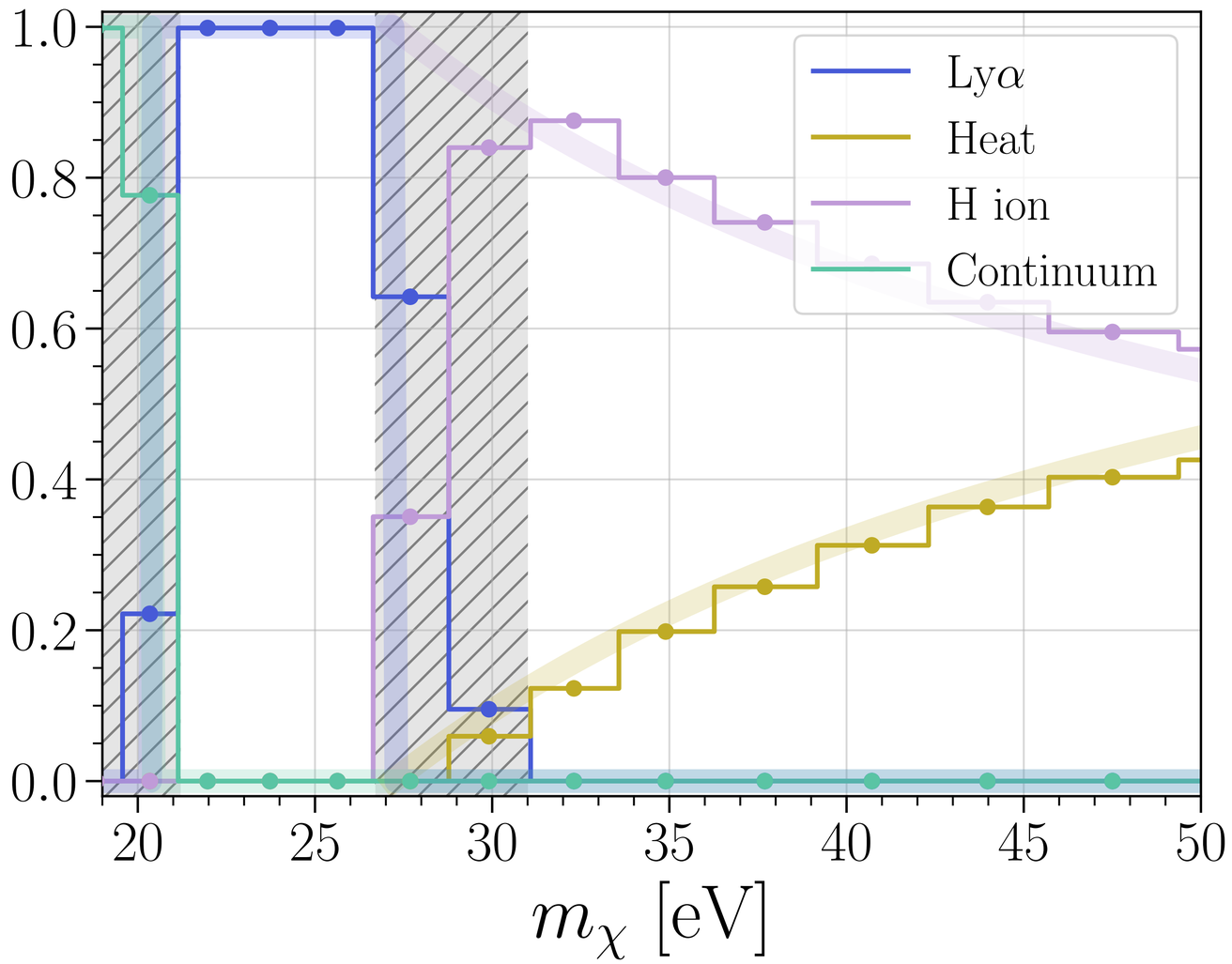
Consider Lyman-α instead of heating

Lyman-alpha from particle (e.g. axion) decay



$$\chi \to \gamma\gamma$$

Lyman-alpha from particle (e.g. axion) decay



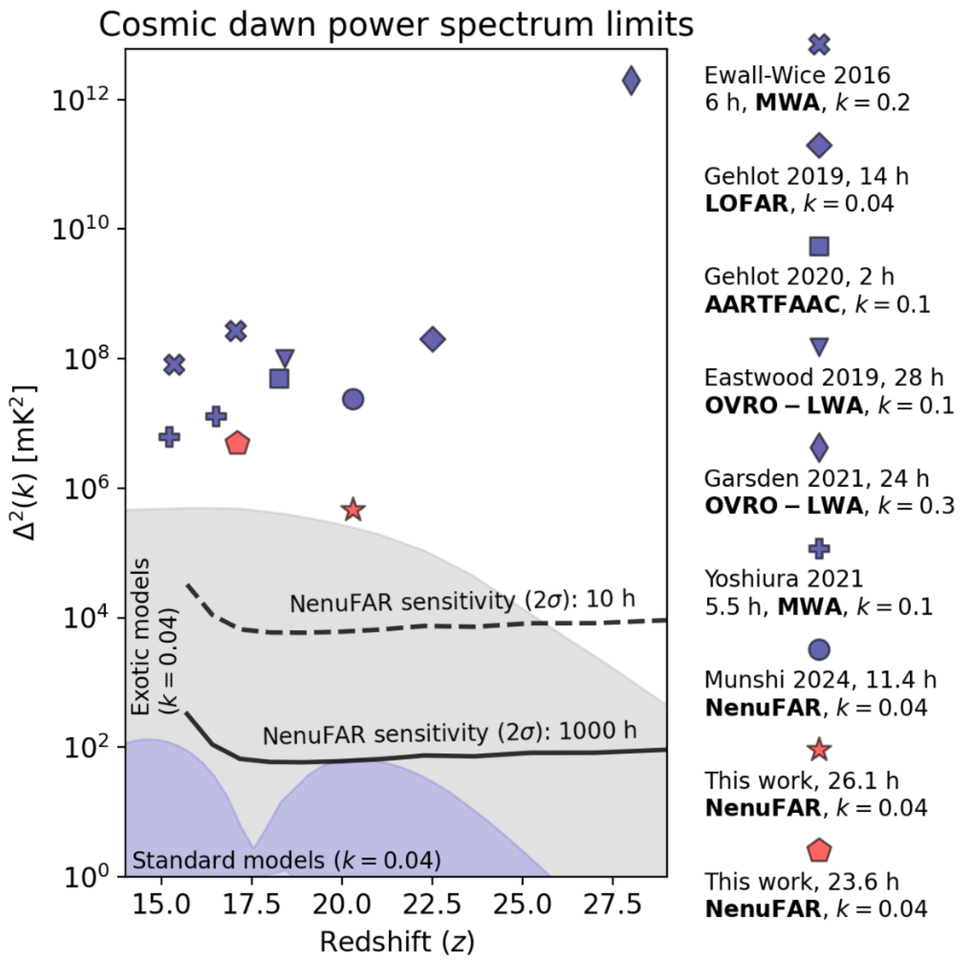
$$\chi \to \gamma\gamma$$

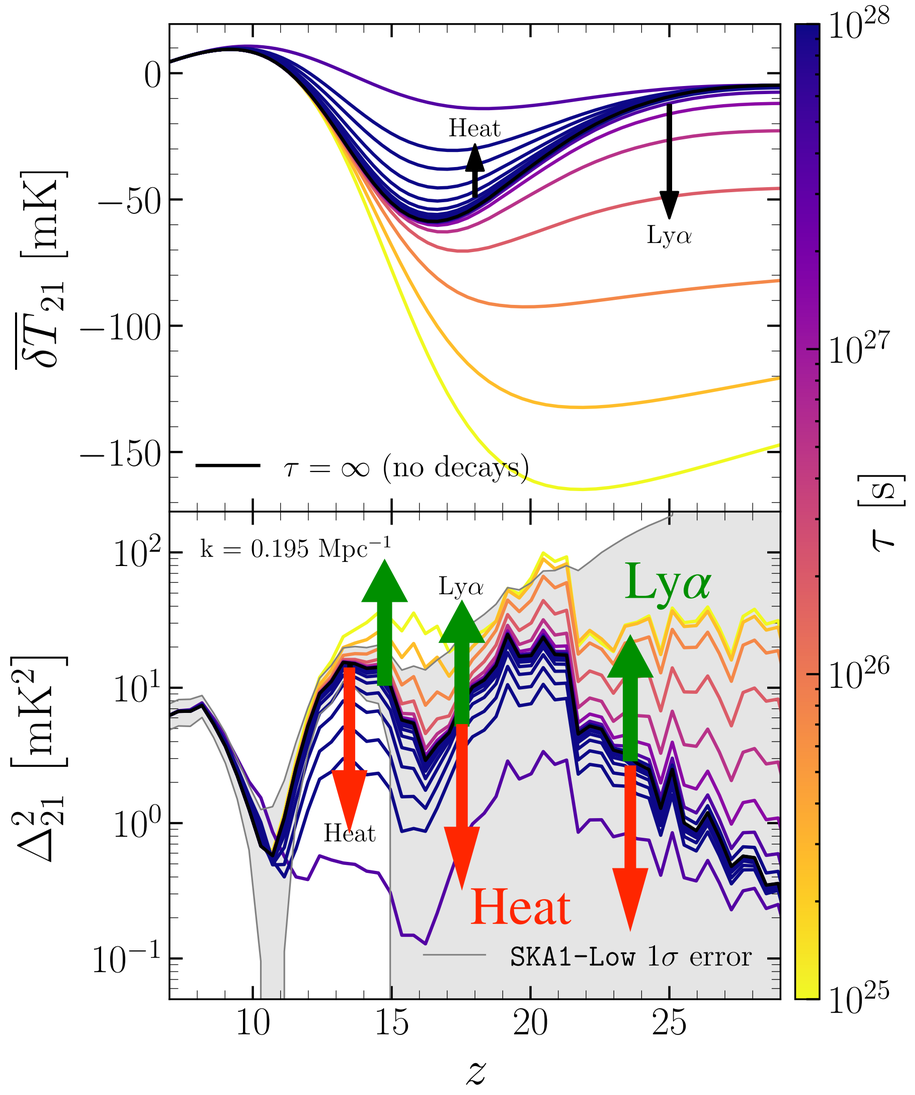
$$T_S^{-1} = \frac{T_\gamma^{-1} + x_k T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_k + x_\alpha}$$

extra Lyman-α (new)

extra heating (old)

Back to the 21-cm signal





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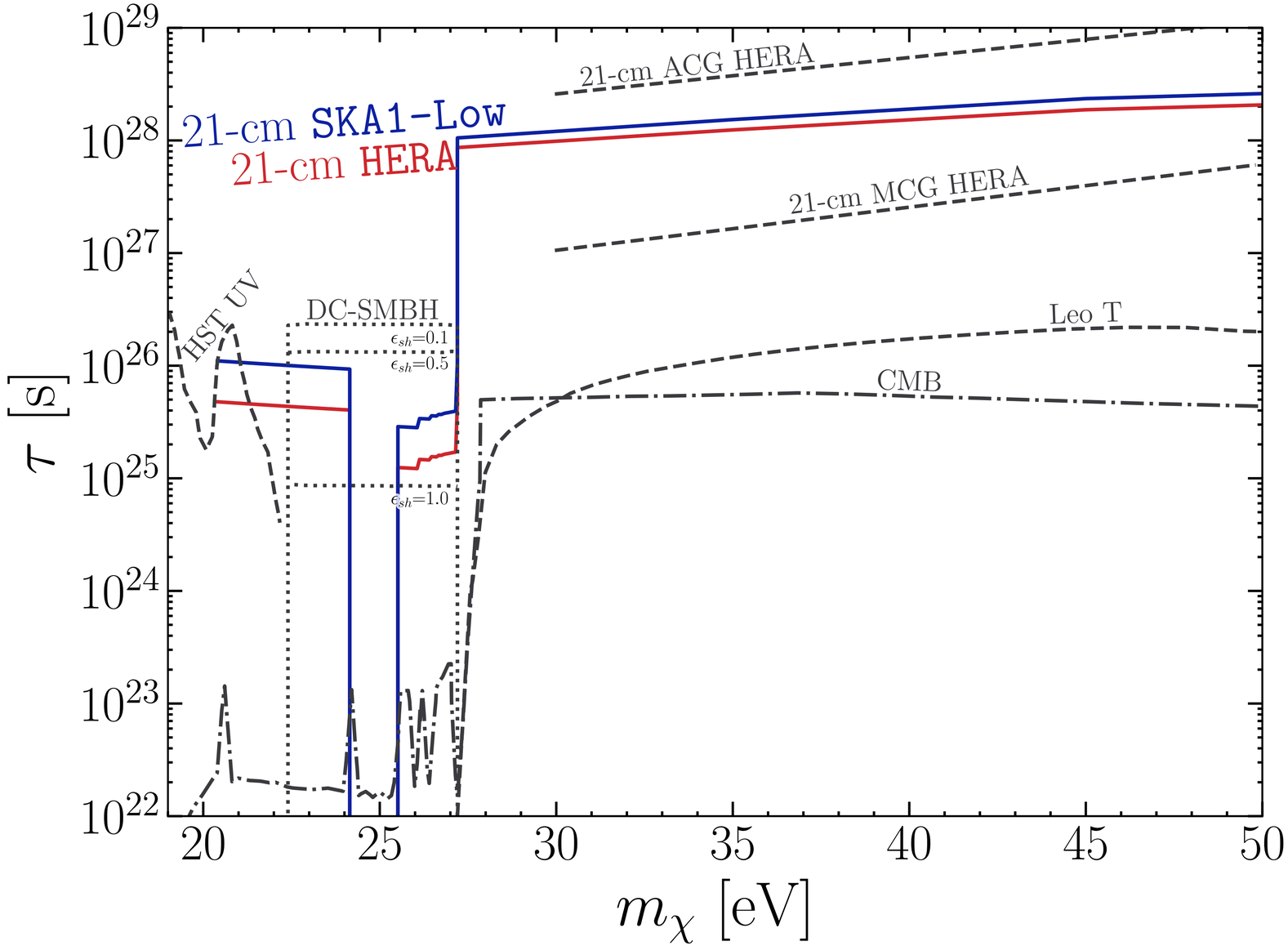
Fiducial scenario bound



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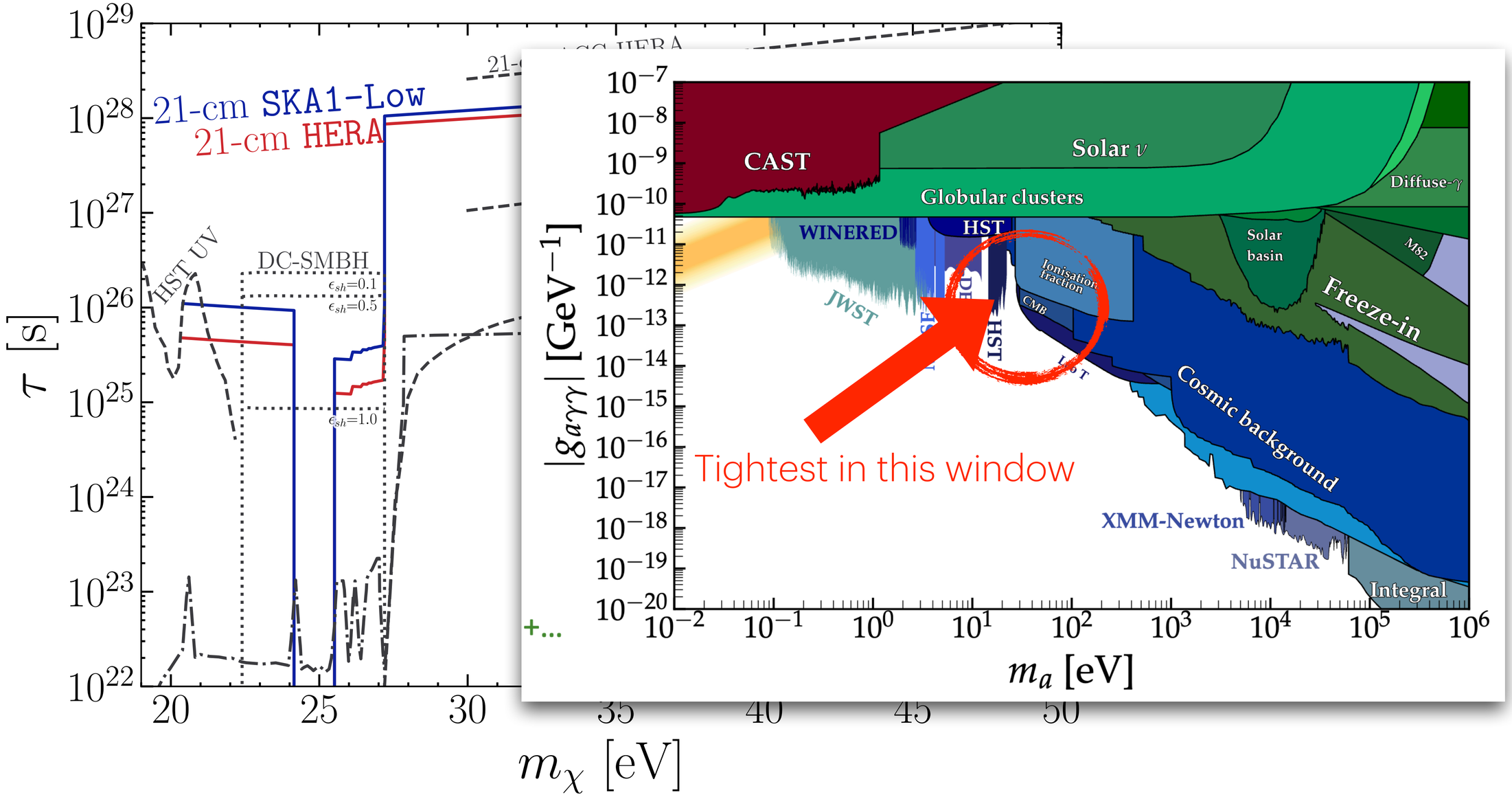
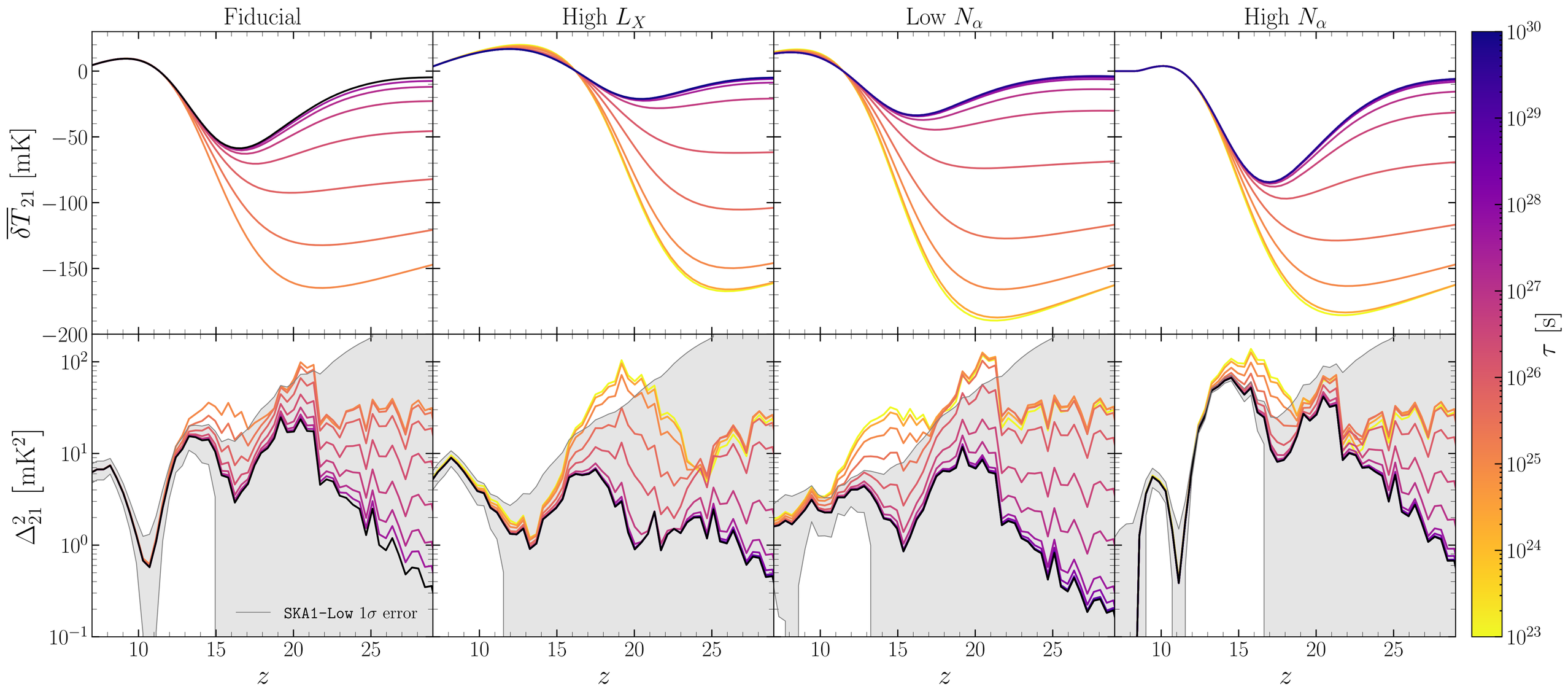


What if astrophysics is "unfavourable"

Scenario	$L_X/\dot{M}_*$	$N_{\rm ion}^{\rm ACG}$	$N_{\rm Ly\alpha}^{\rm ACG}$	$N_{\rm ion}^{\rm MCG}$	$N_{\rm Ly\alpha}^{\rm MCG}$
Fiducial	$10^{40.5}$	5×10^3	1.1×10^4	4.4×10^4	4.8×10^3
High L_X	$10^{41.5}$	5×10^3	1.1×10^4	4.4×10^4	4.8×10^3
Low N_α	$10^{40.5}$	1×10^3	2.2×10^3	2×10^4	2.1×10^3
High N_α	$10^{40.5}$	2×10^4	4.4×10^4	8×10^4	8.7×10^3



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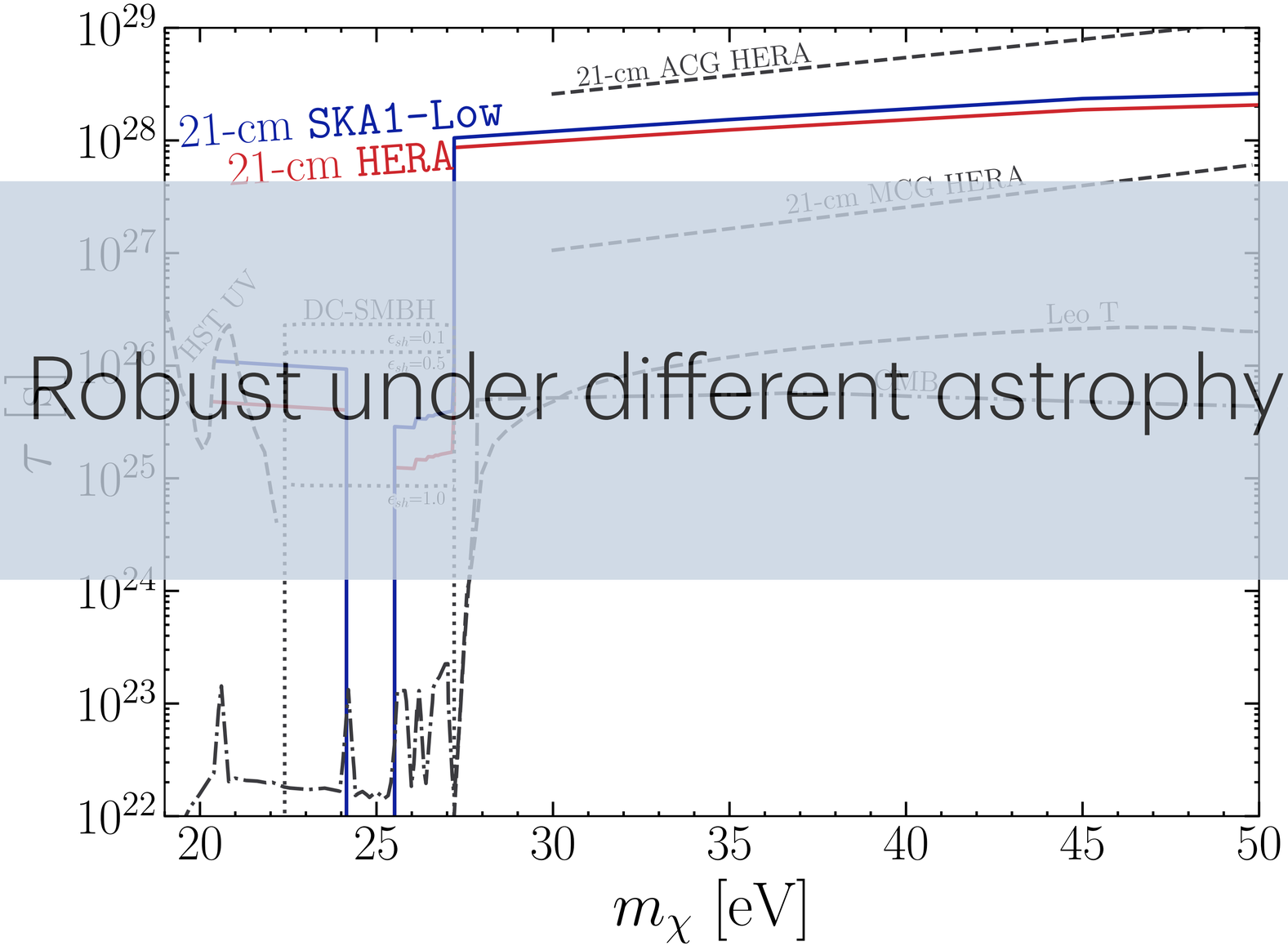
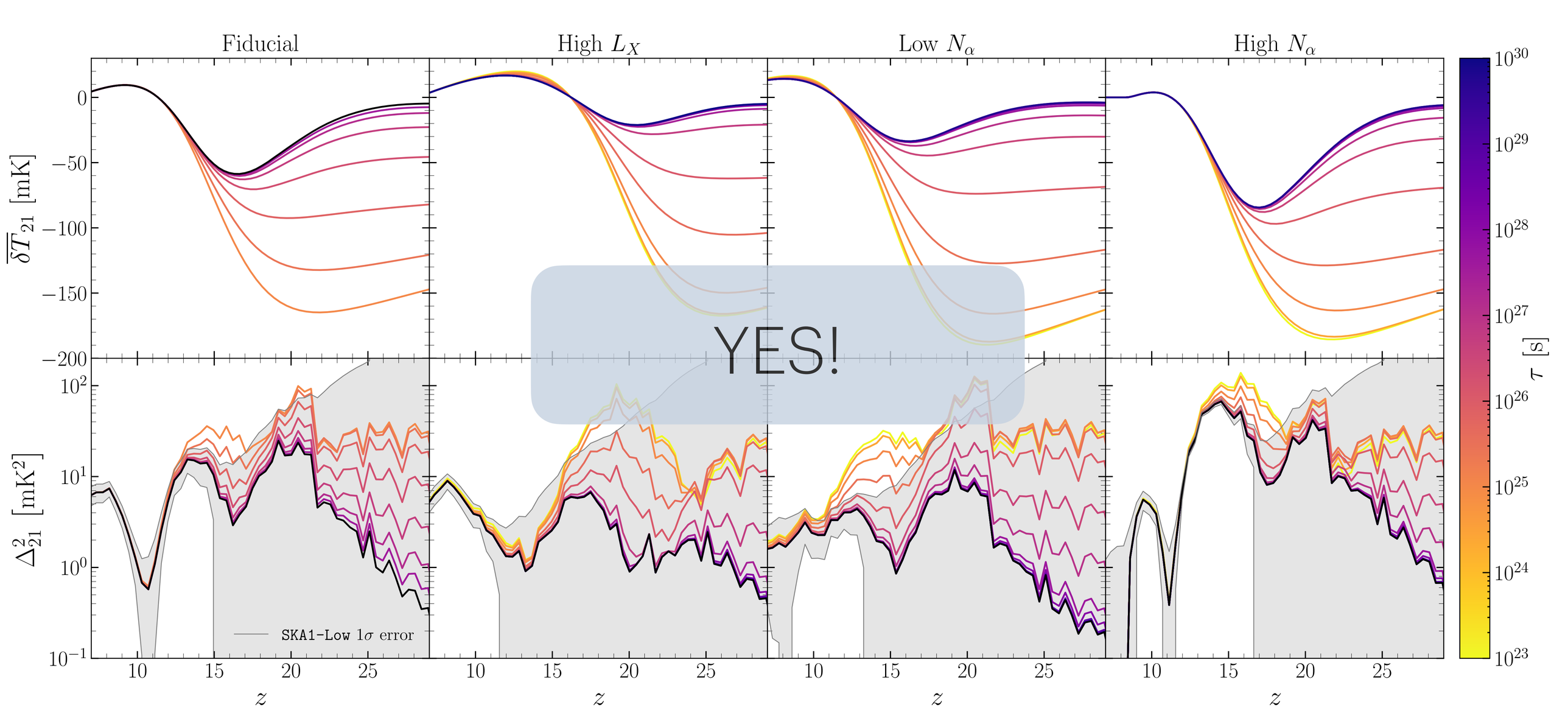


Robust under different astrophysics?

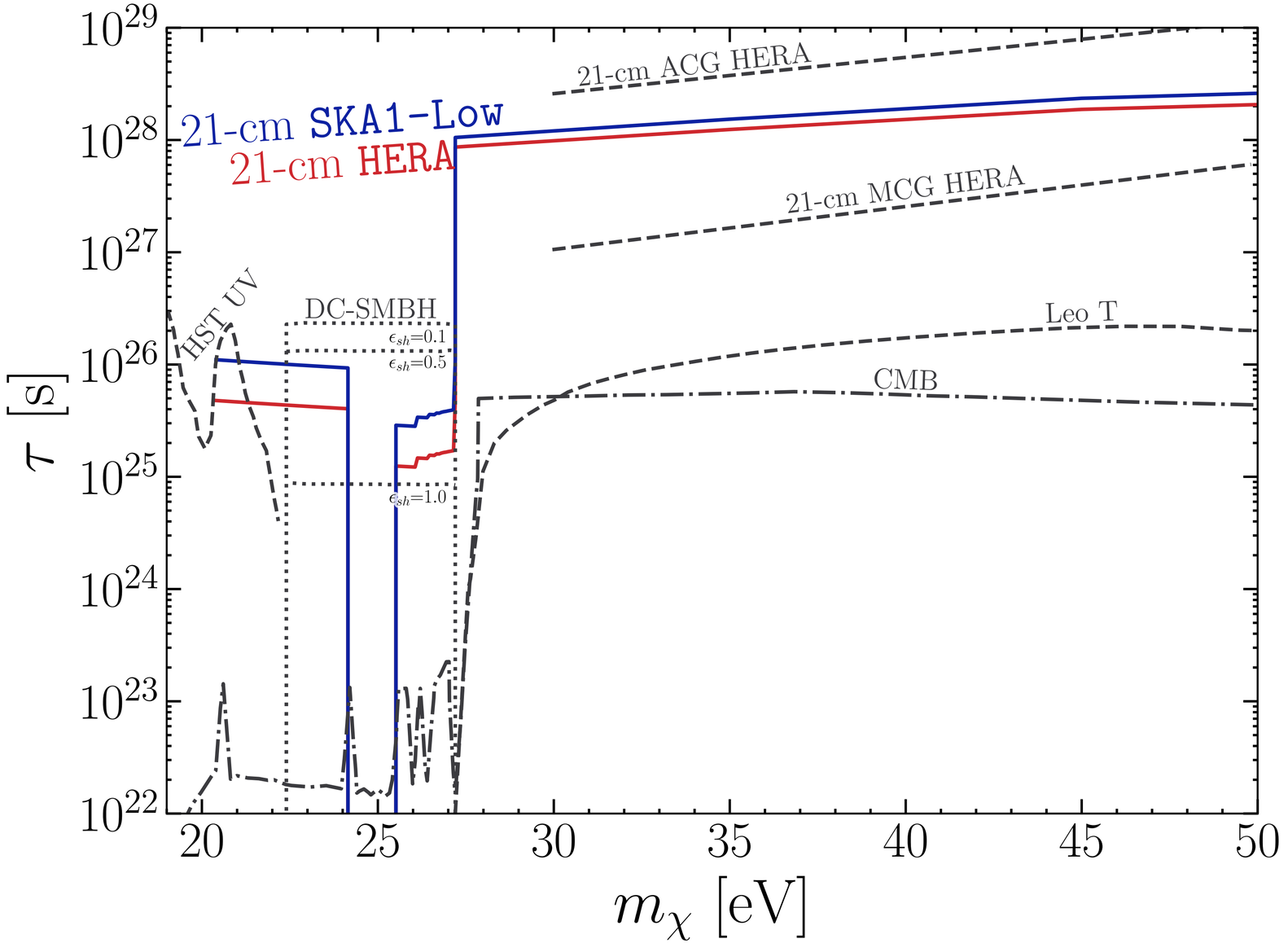


$m_\chi = 20.4\,\mathrm{eV}$

	Fiducial	**High L_X**	**High N_α**	**Low N_α**
τ_{95} [s]	1.1×10^{26}	5.2×10^{25}	2.2×10^{26}	1.1×10^{26}

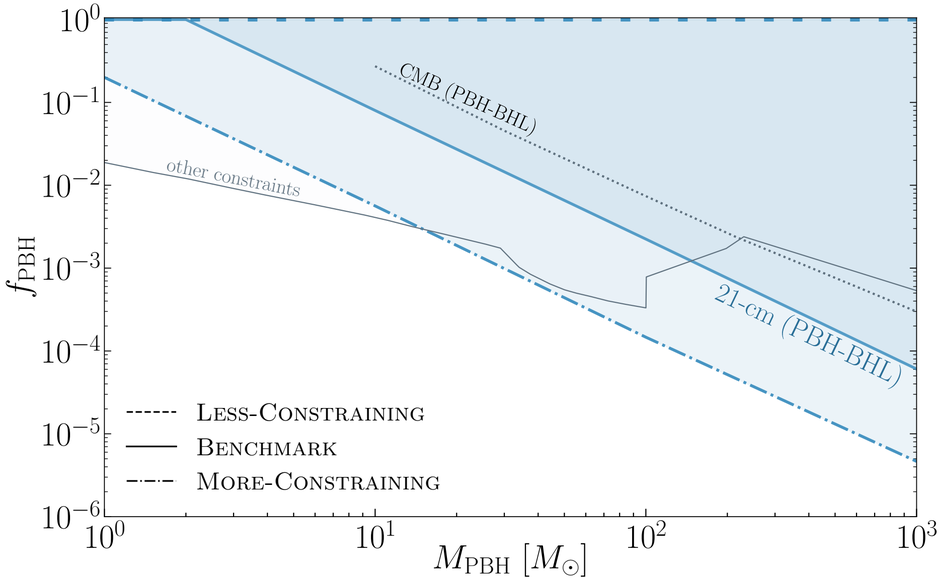
What else can we learn from this?

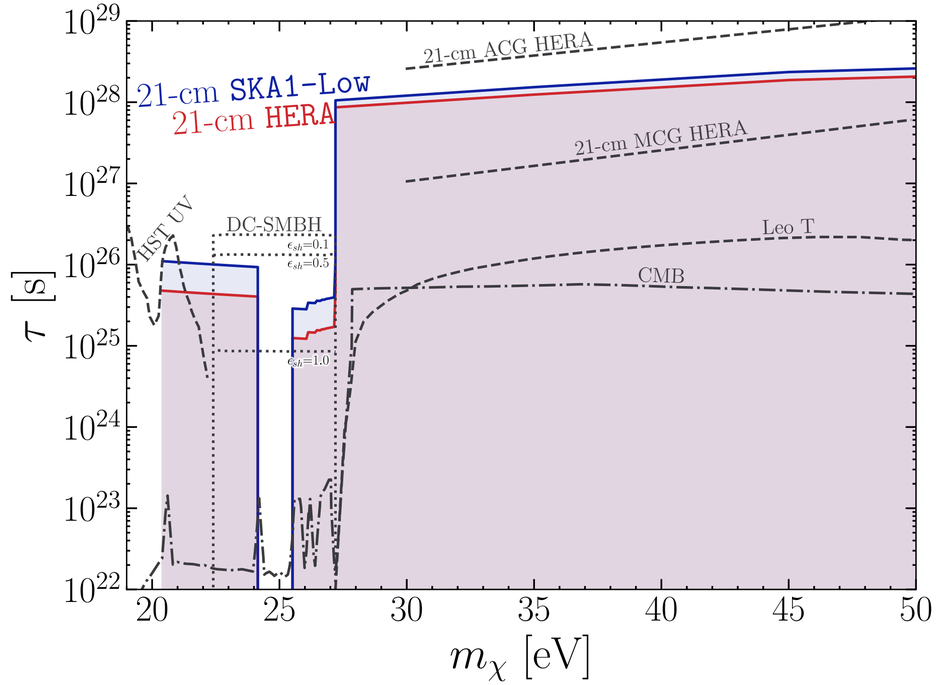
- Other DM candidates at different scales may emit efficiently in to Lyman-band
- Astrophysics robust probes?
- Dark Ages signal even more robust to these signatures (future lunar detectors)



Summary

- The uncertainties on the astrophysics, entering in the null hypothesis, is the most important systematic for 21-cm forecasts
- Lyman-alpha from dark matter can help!

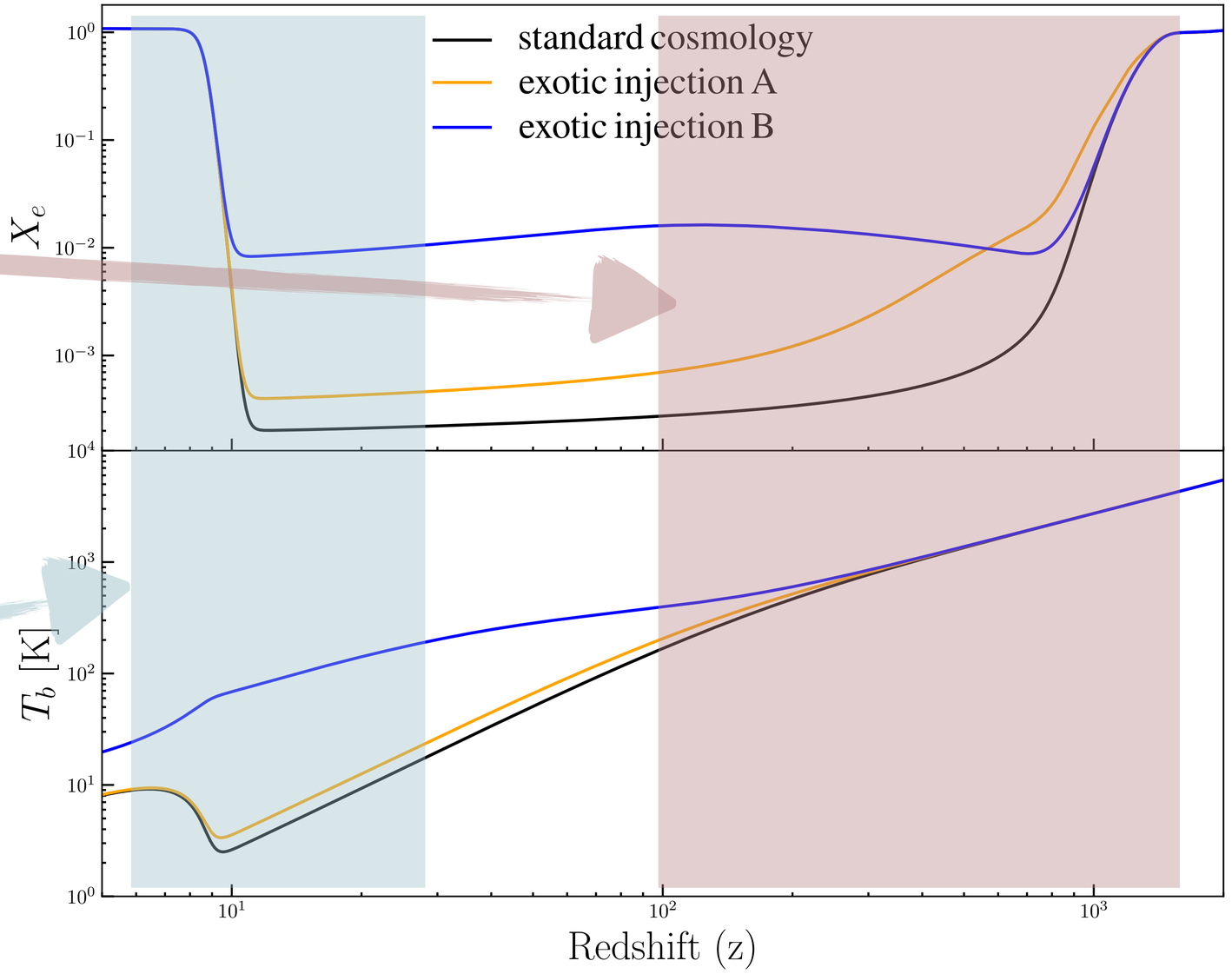




A1: CMB and 21-cm Signal

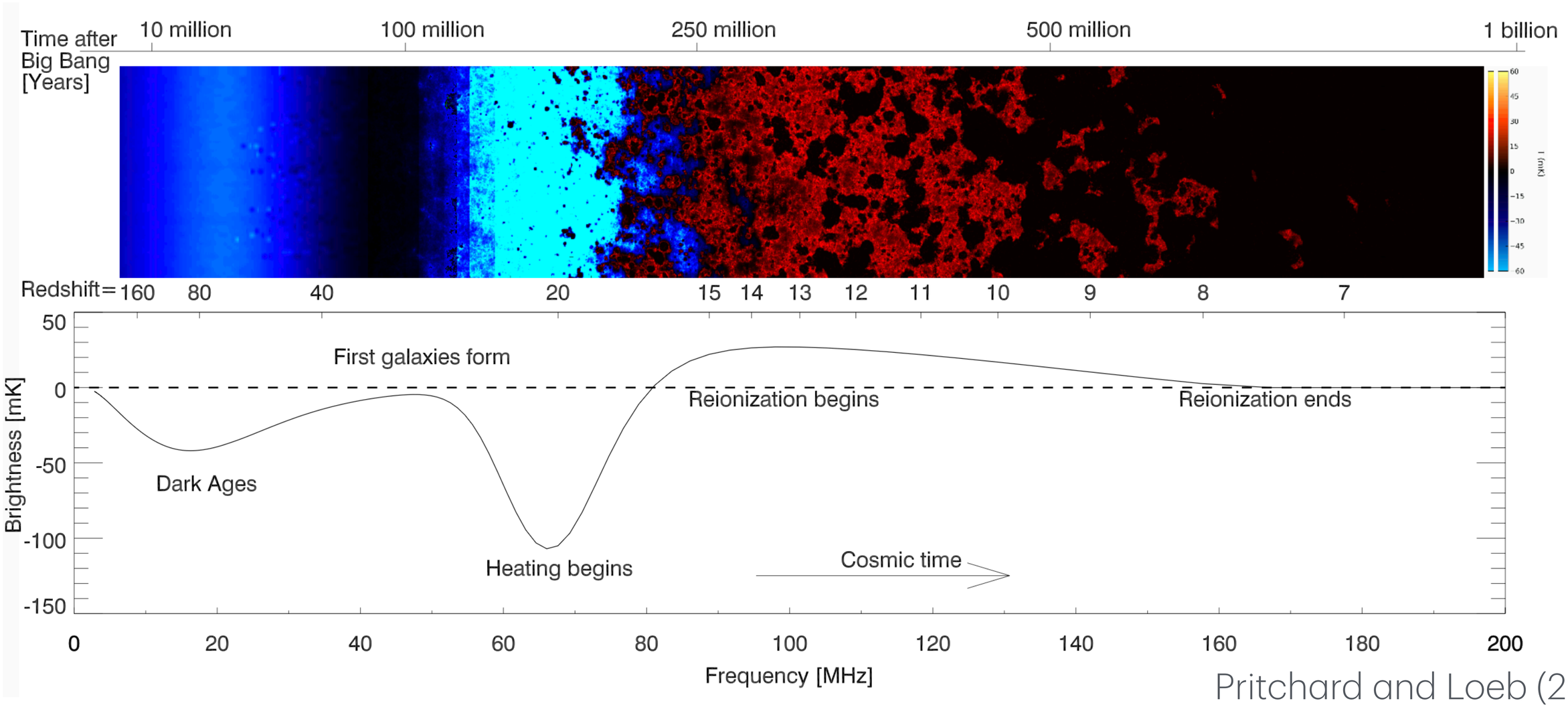
CMB

21-cm Signal



$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_c^{-1} + x_k T_k^{-1}}{1 + x_\alpha + x_k}$$

$$\delta T_b \simeq 27 \text{ mK } x_{\rm HI}(1+\delta)\left(1 - \frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}$$

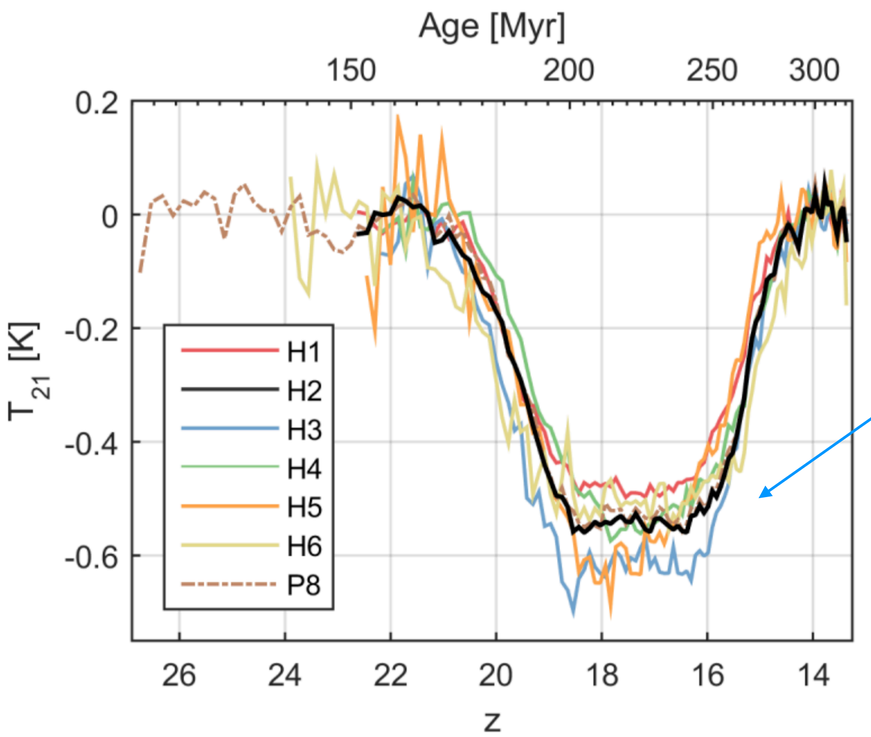


Pritchard and Loeb (2012)

A3: The EDGES affair

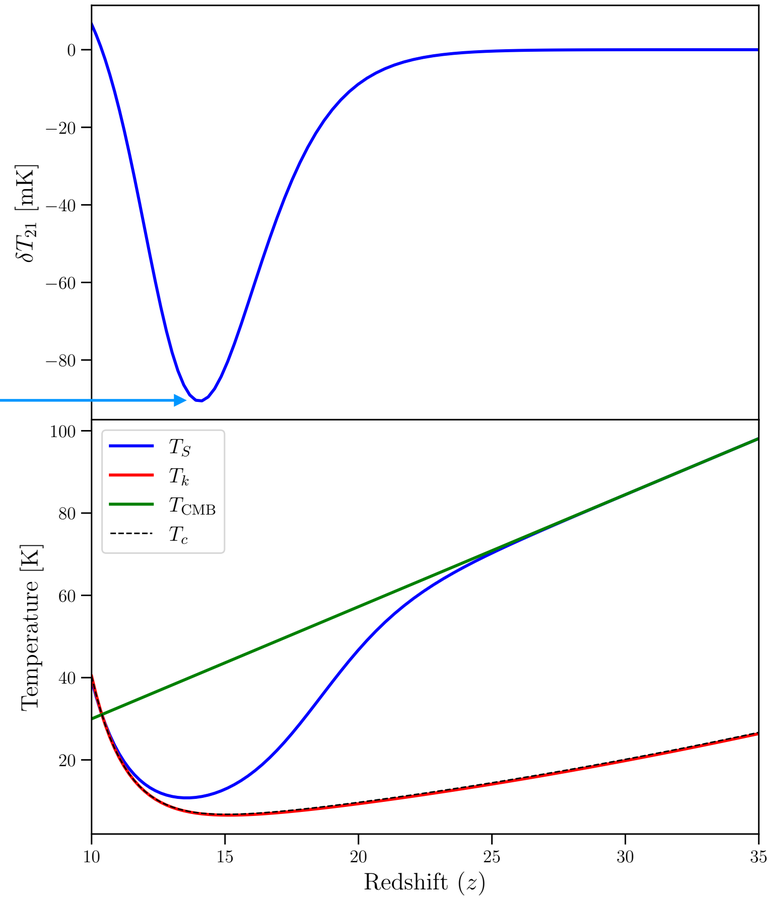
An absorption profile centred at 78 MHz in the sky-averaged spectrum [10.1038/nature25792]

$$\delta T_b \simeq 27\ \mathrm{mK}\ x_{\mathrm{HI}}(1+\delta)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}$$

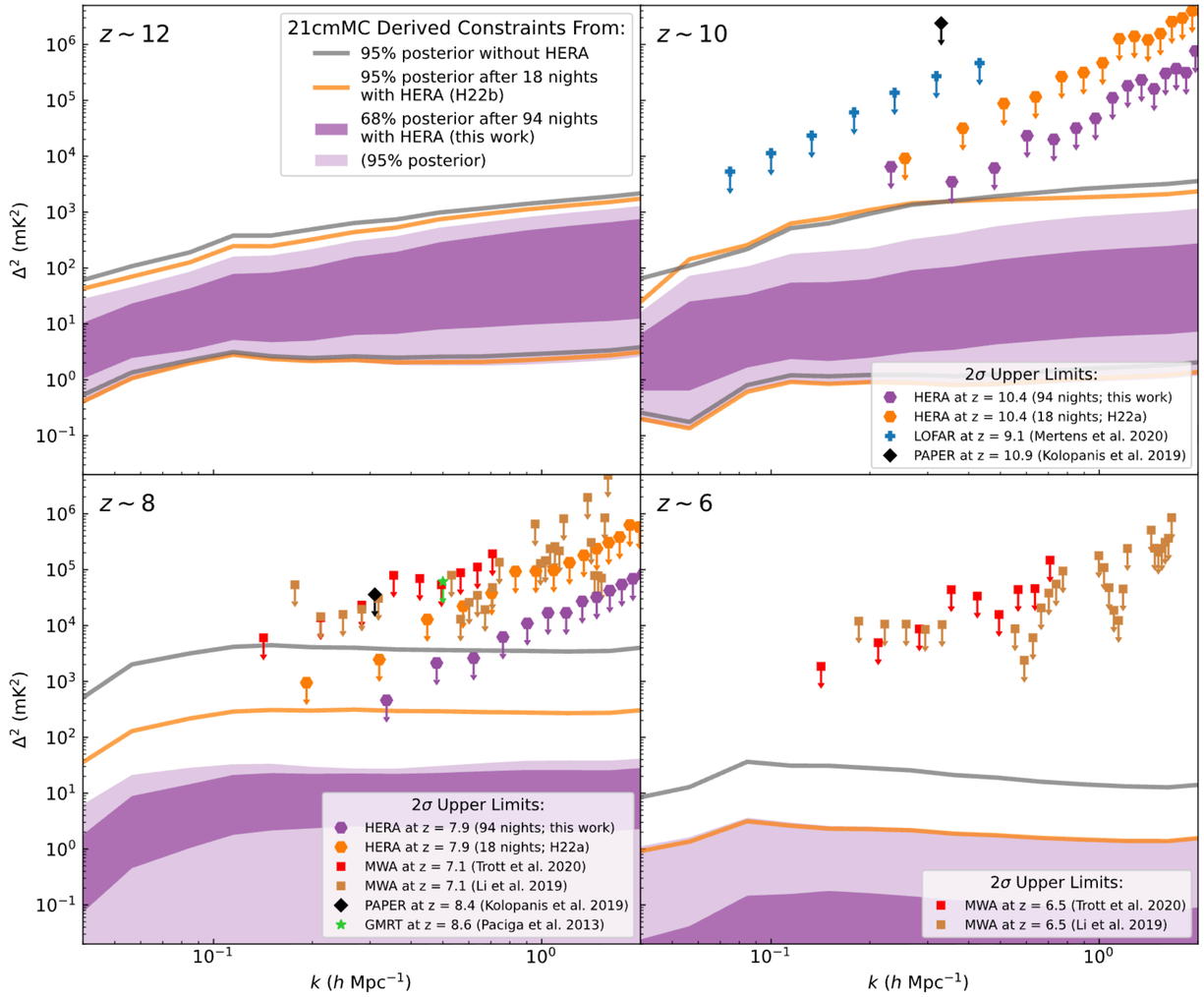


EDGES is too low!

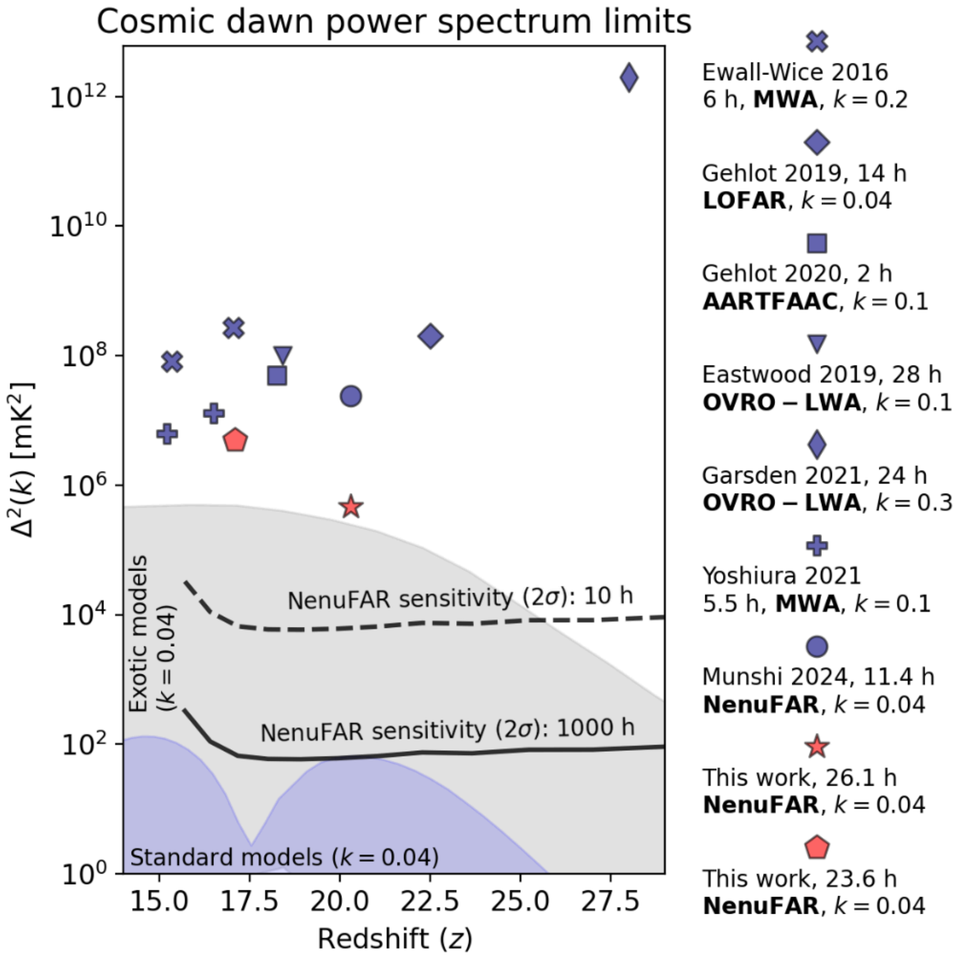
Standard scenario with POP II stars



A4: Power spectrum status - HERA and NenuFAR

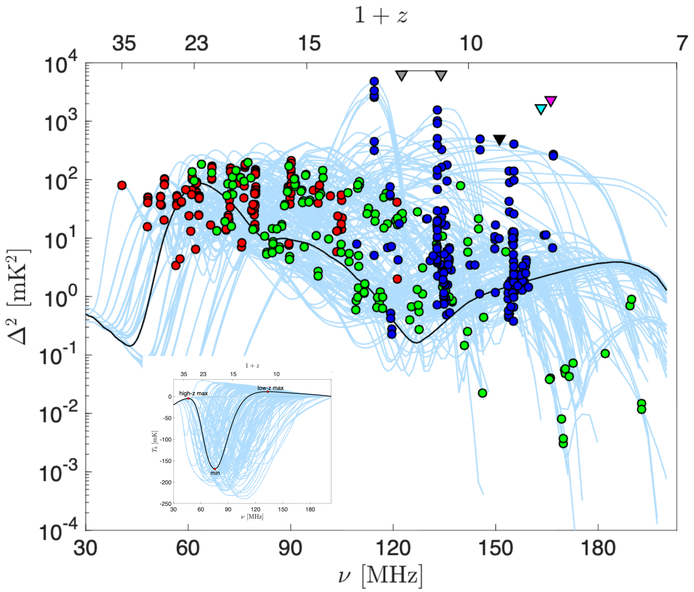


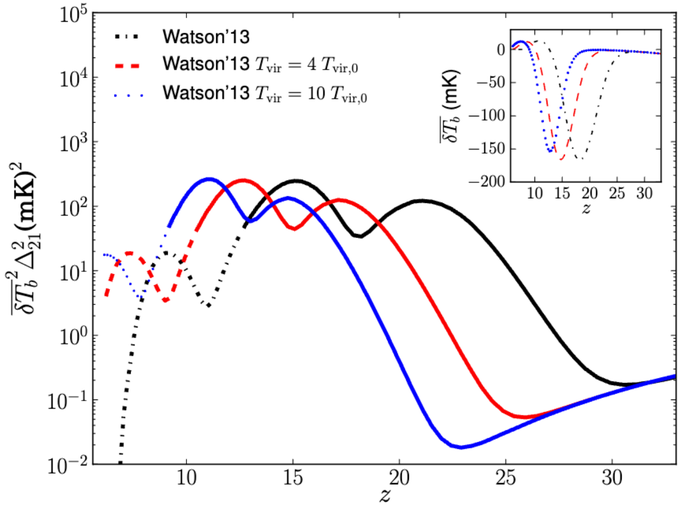
2210.04912



2507.10533

A5: Systematics related to astrophysics



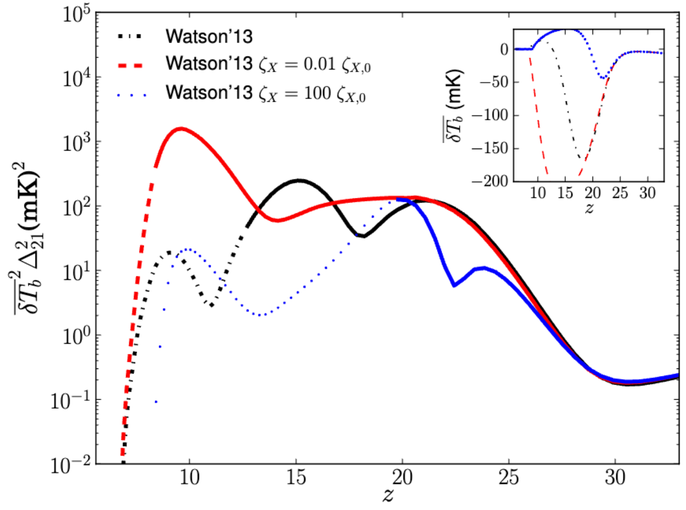


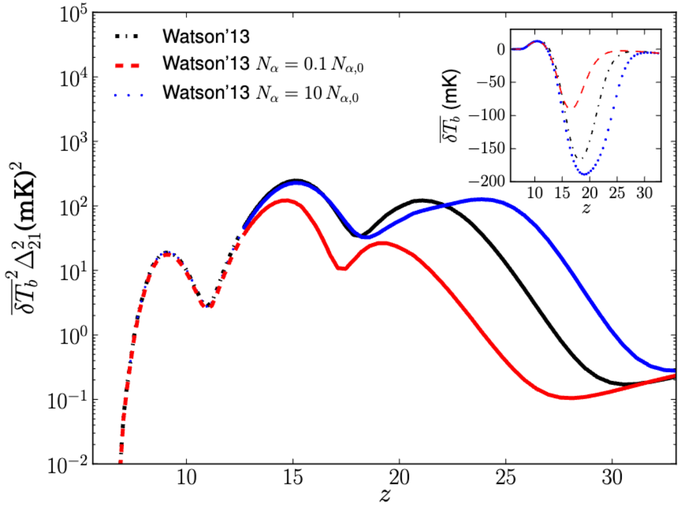
Virial Temperature

$$\mathrm{SFR} \propto \exp\left(-\frac{M_{\rm turn}}{M_h}\right)$$

$$M_{\rm turn} \propto T_{\rm vir}^{3/2}$$

X-Ray Luminosity

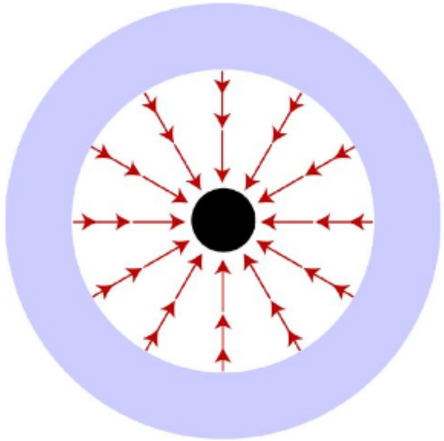




Lyman Alpha

[Laura Lopez-Honorez+2016]

A6: BHL

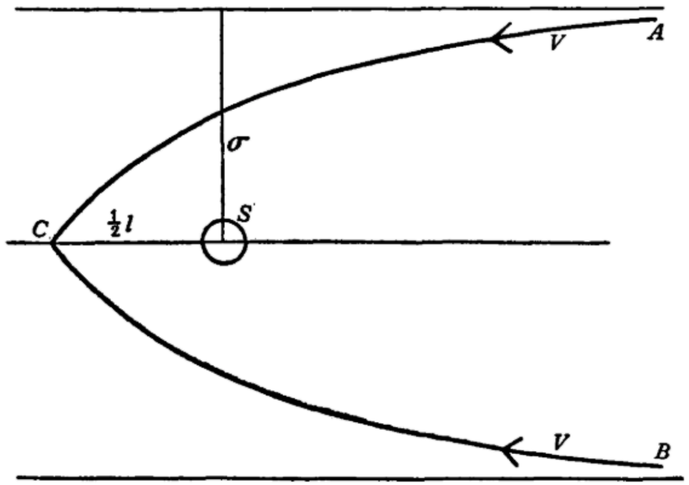


Steady state spherical

H. Bondi (1952)

$$\dot{M}_{\rm BHL} = 4\pi\lambda \frac{(GM_{\rm PBH})^2 \rho_{\rm b}}{\left(v_{\rm BH}^2 + c_{\rm s}^2\right)^3}$$

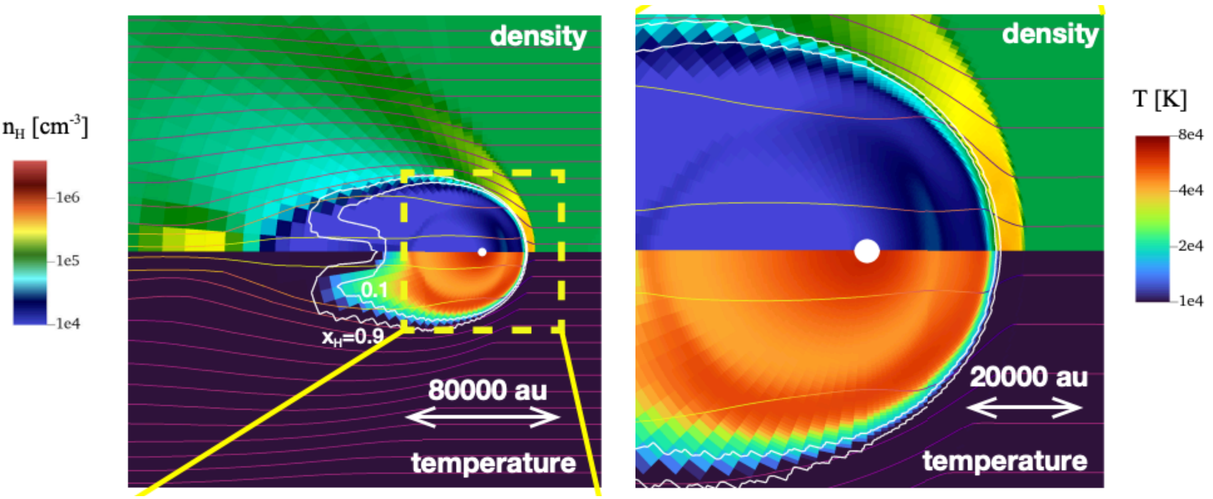
Ballistic limit



Hoyle, F., & Lyttleton, R. A. (1939)

"It seems likely that it represents the order of magnitude of the accretion rate" - Bondi 1952

A6.1: PR

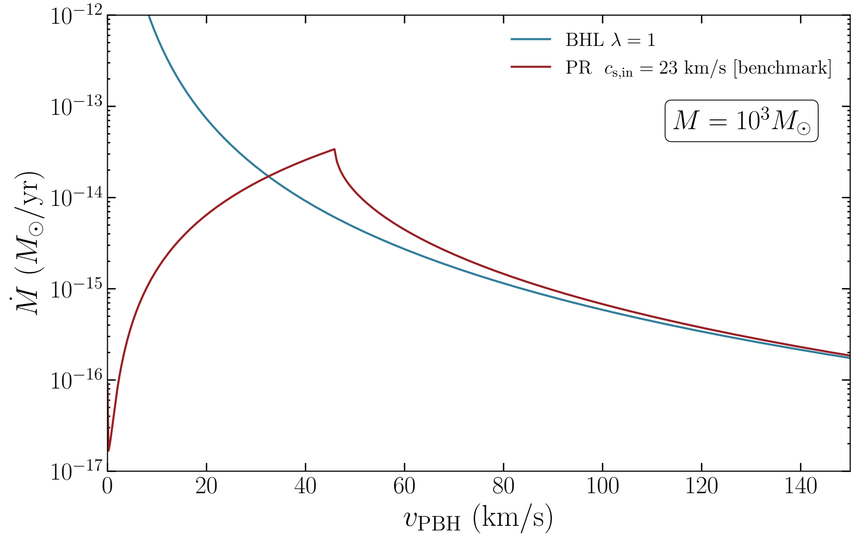


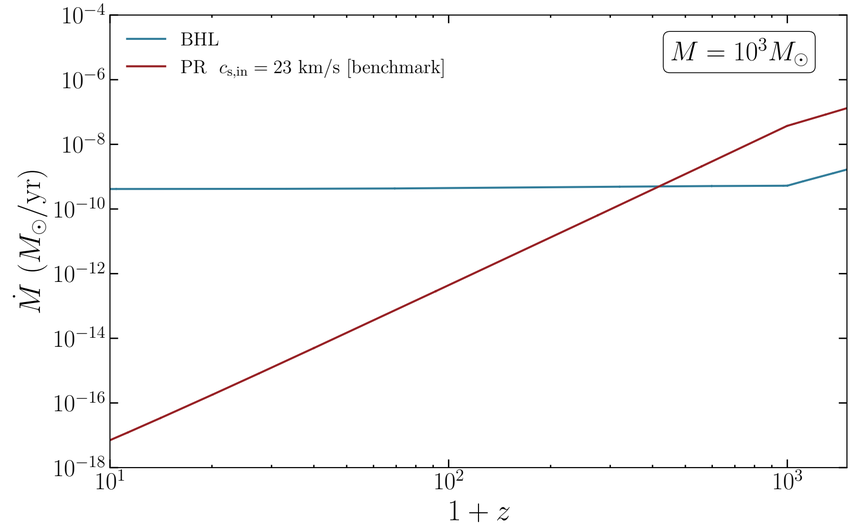
$$\dot{M}_{\rm PR} = 4\pi\rho_{\rm in}\frac{(GM_{\rm PBH})^2}{(v_{\rm in}^2 + c_{\rm s,in}^2)^{3/2}}$$

Fixed by Euler's equations at the ionisation front

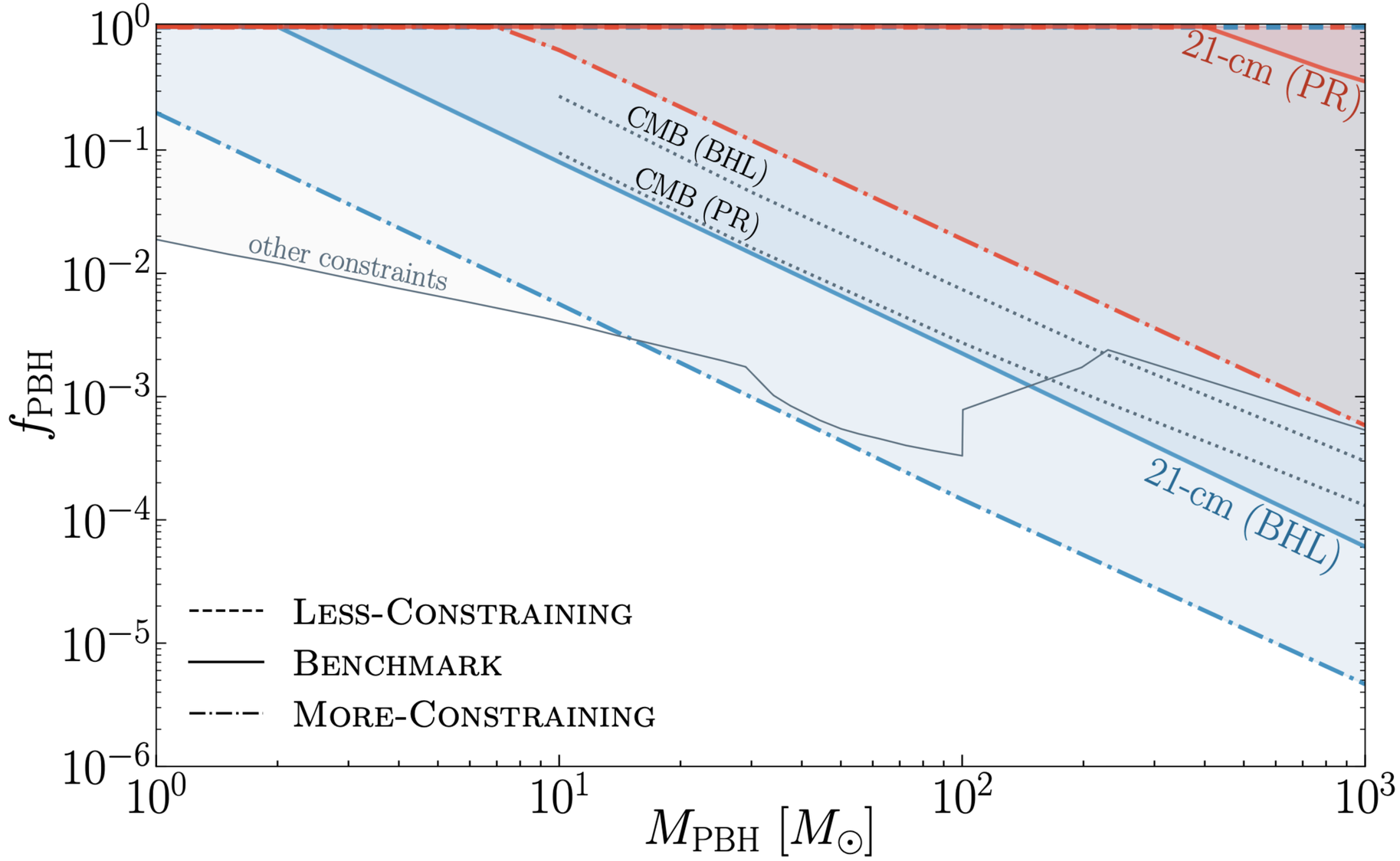
Free parameter parametrising temperature in the ionised region

Park and Ricotti 2013: numerical simulations + semi-analytic formula including radiative feedback.



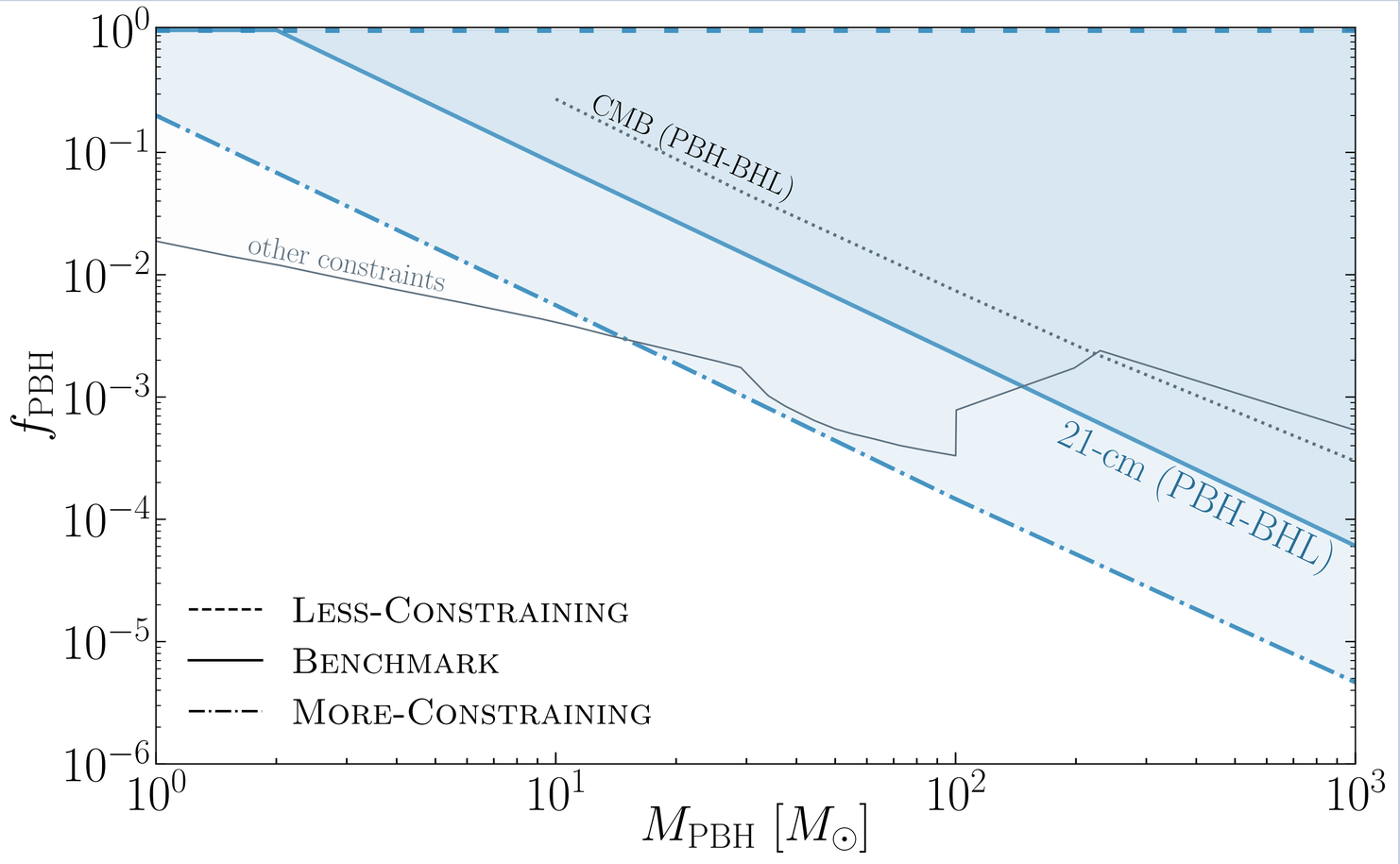


A6.2: PR bound


21-cm (PR)
CMB (BHL)
CMB (PR)
other constraints
21-cm (BHL)
Less-Constraining
Benchmark
More-Constraining
$f_{\rm PBH}$
$M_{\rm PBH}\ [M_\odot]$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^0
10^1
10^2
10^3

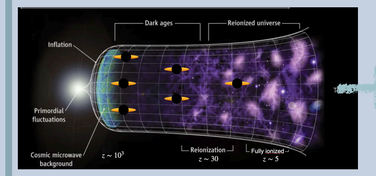
A7: How to perform a forecast

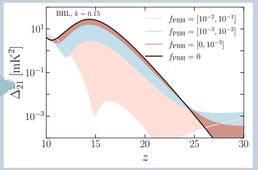
4. Perform your MCMC, or Fisher Forecast, or compute the likelihood given a fiducial signal, varying only $f_{\rm PBH}$



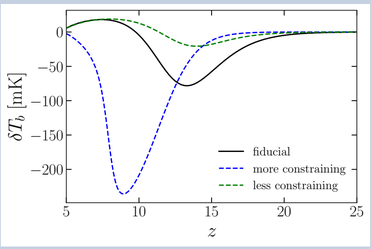
1. Implement PBH accretion by modifying

`CLASS + ZEUS21`





2. Choose a fiducial set of astrophysics parameters for your null hypothesis. We use (N_α, L_{40} and $T_{\rm vir}$).



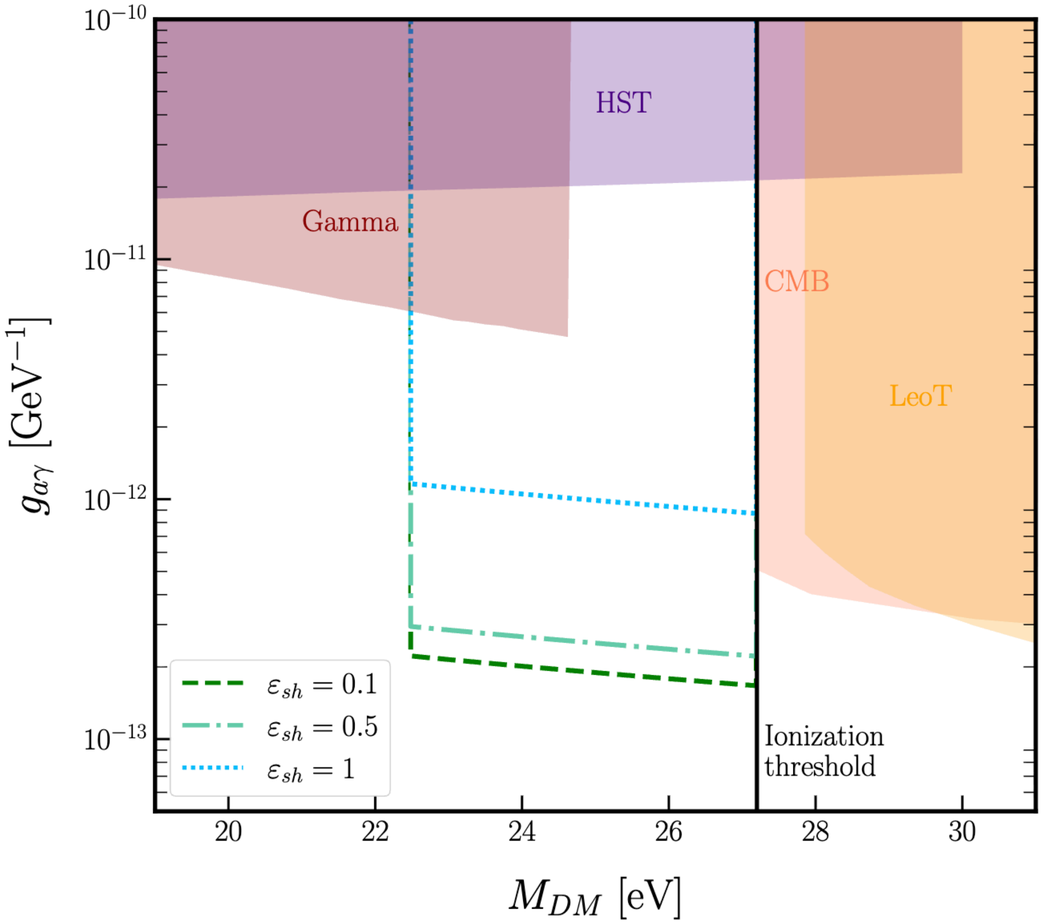
3. Definite a **Gaussian multivariate** likelihood containing the **null hypothesis**, and sensitivities of SKA at 1080 hours of observation using

`21cmSense`

$$\log \mathscr{L} = -\frac{1}{2}\sum_{i=1}^{n}\frac{(x_i - \mu_i^{\rm NULL})^2}{\sigma_i^2}$$

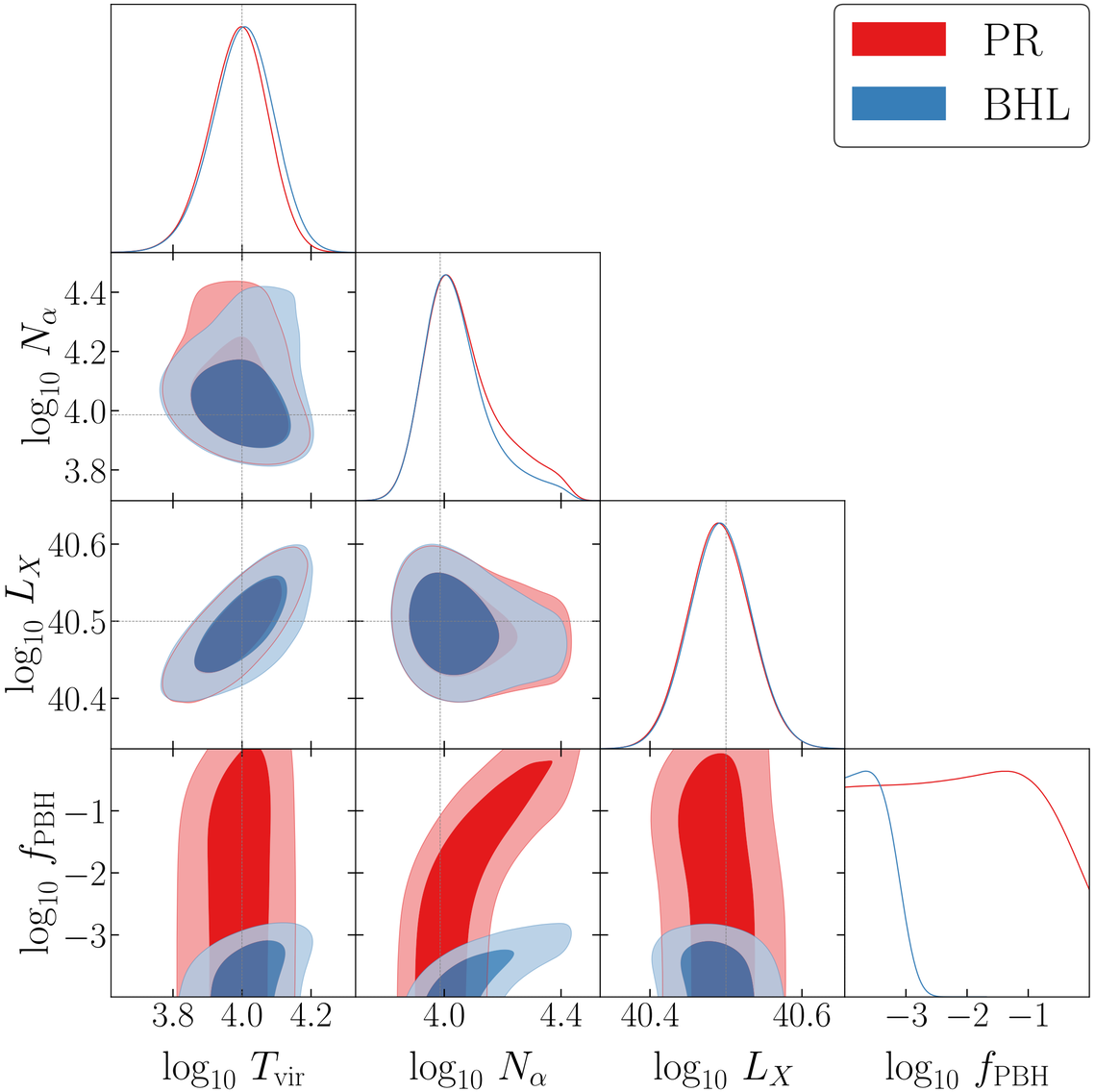
A8: What else can these Lyman-series photons do?

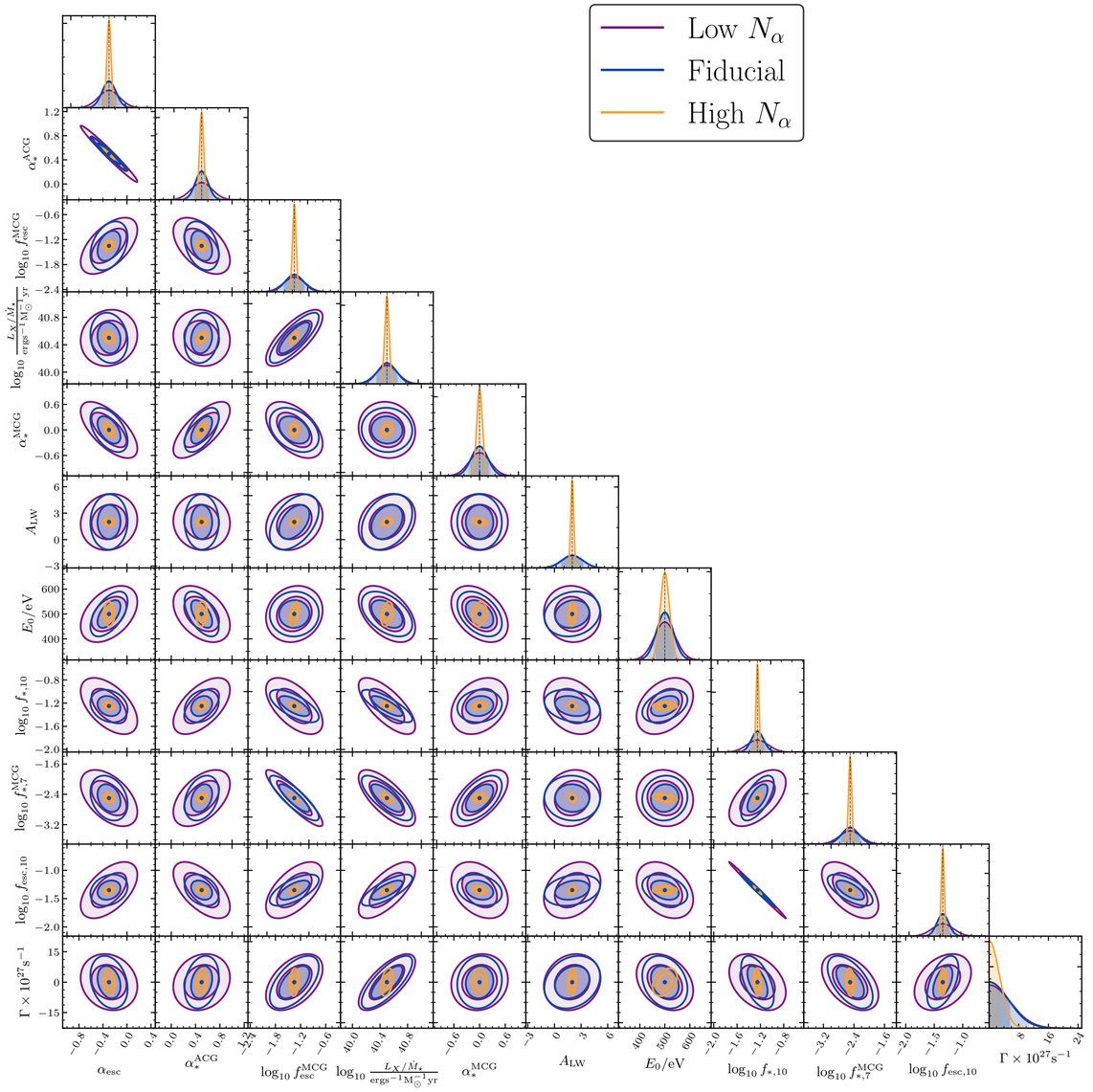
- Lyman-Werner photons (11.2-13.6 eV) suppress formation of molecular hydrogen
  - Direct collapse of pristine hydrogen to form SMBHs



2404.03909

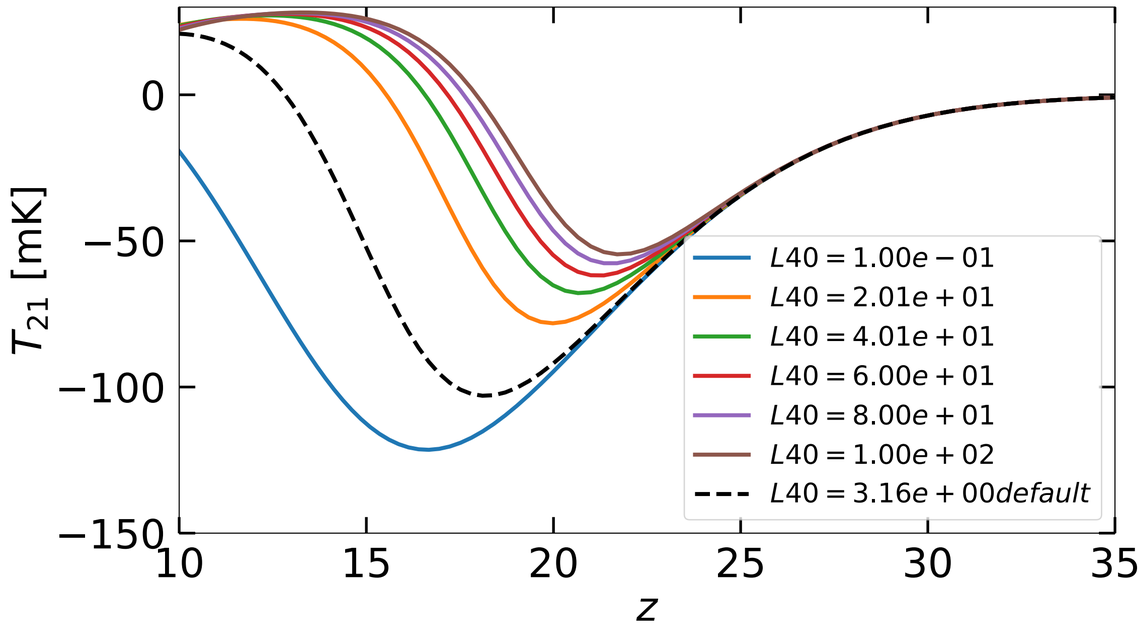
A9: Correlations between parameters



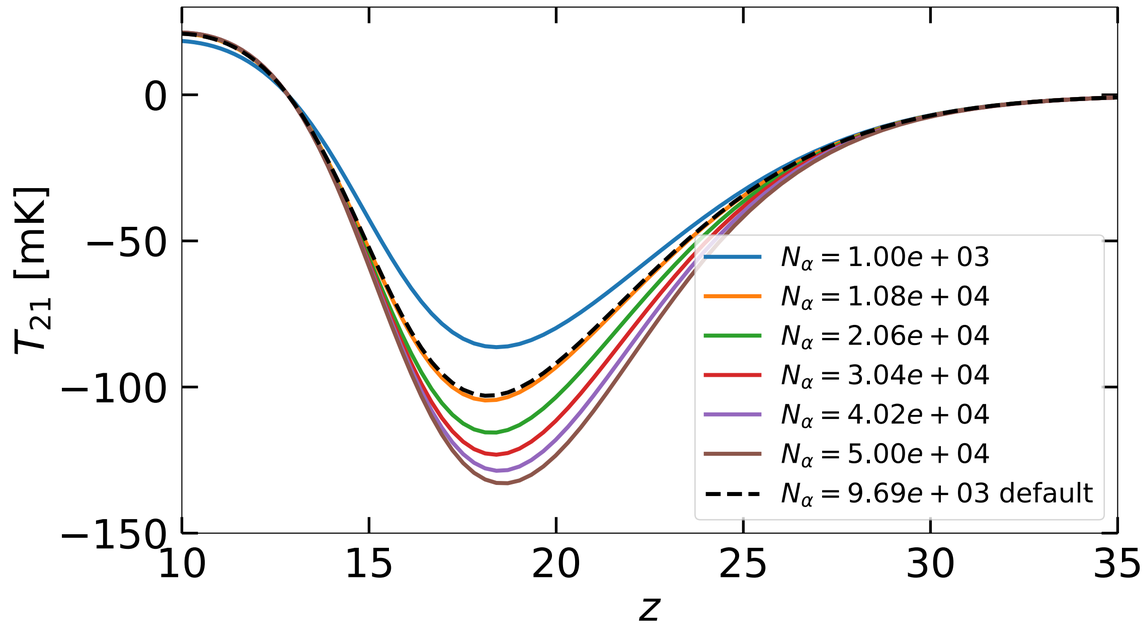


A10: X-rays and Lyman-alpha

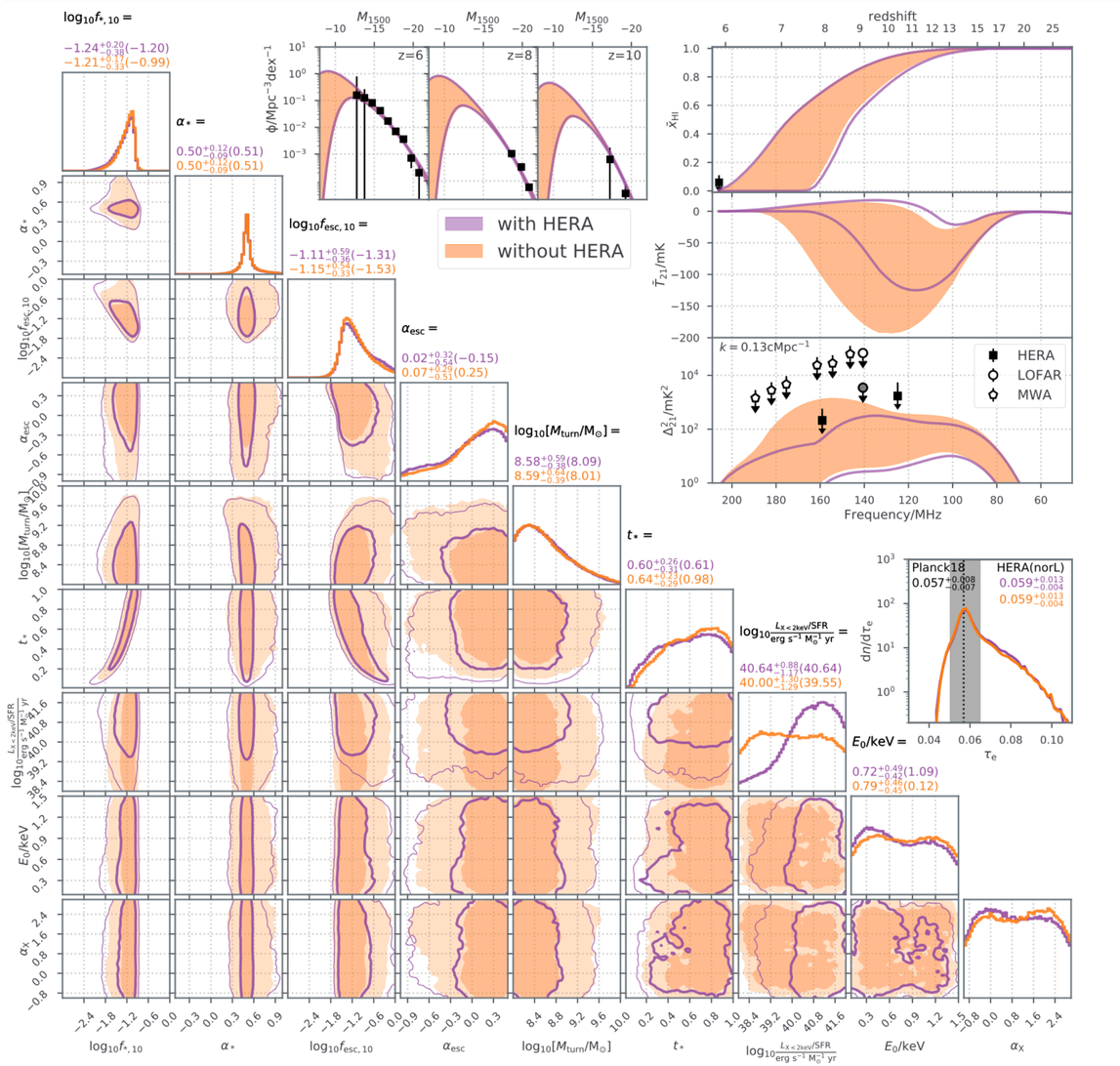
- **X-ray heating of the gas**

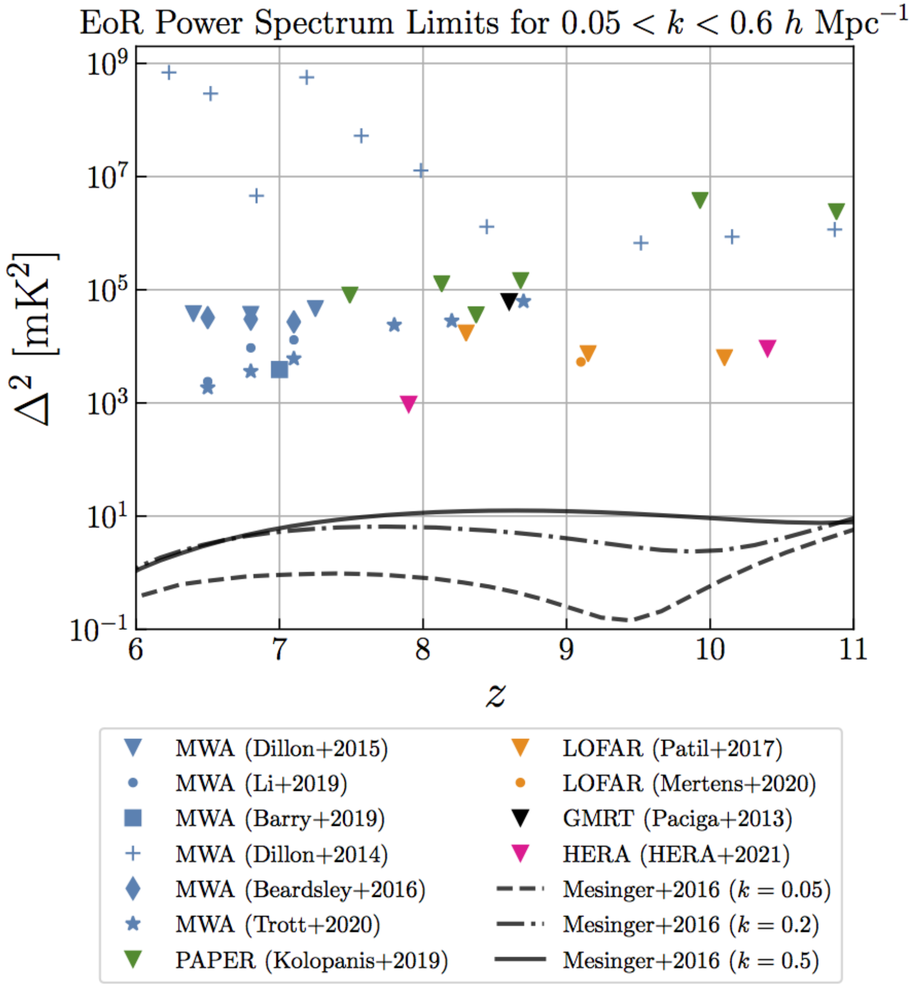


- **Lyman-alpha coupling to the gas**



A11: Hera Collaboration 2021+2022





A12: Evolution equations

$$\frac{dX_e(z)}{dz} = \frac{1}{(1+z)H(z)}(R(z) - I(z) - I_X(z))$$

$$\frac{dT_b}{dz} = \frac{1}{1+z}\left[2T_b + \gamma(T_b - T_{CMB})\right] + K_h$$

$$J_\alpha = J_\alpha^{\text{astro}} + J_\alpha^{\text{DM}}$$