Probing the Recombination Era with CMB Anisotropies

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UCDAVIS

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1. Review of standard recombination
2. Constraining modified recombination
3. Results
4. Future work

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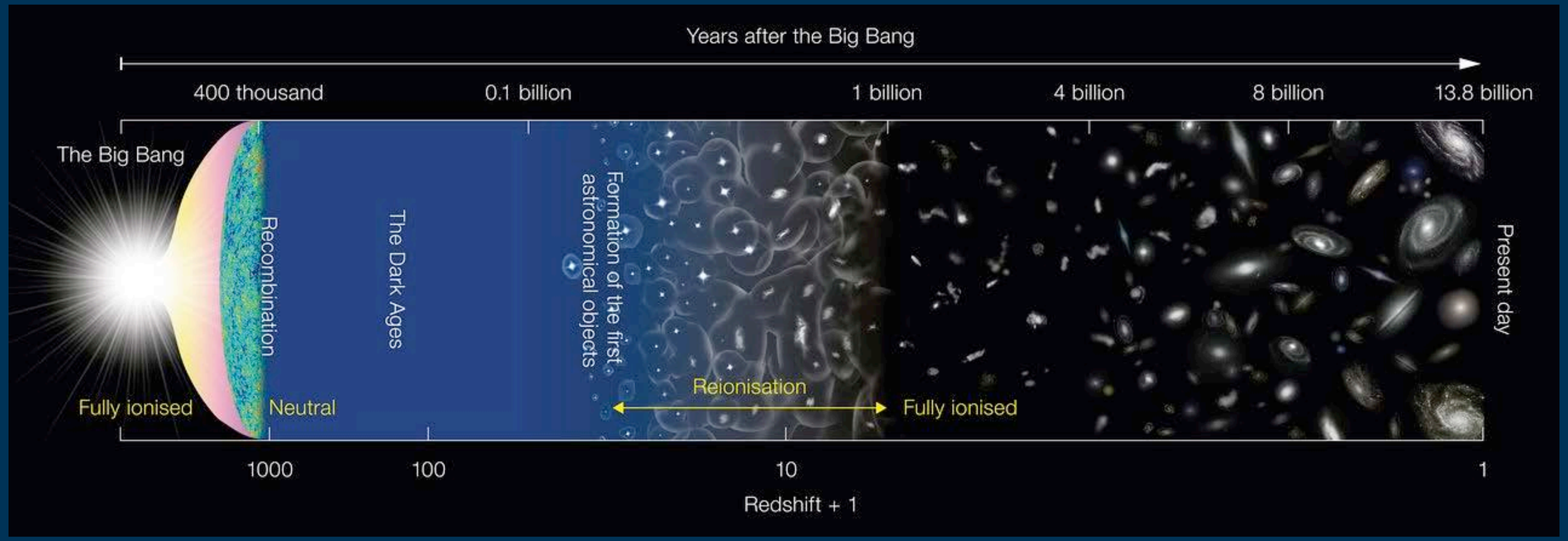

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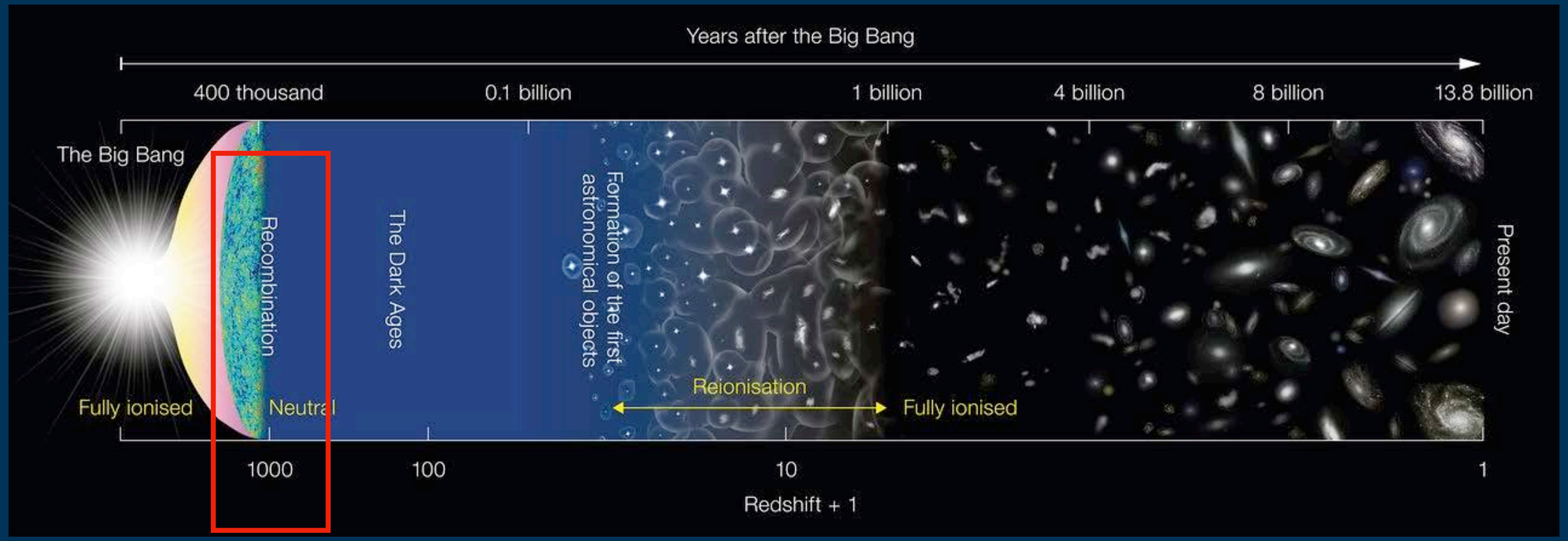

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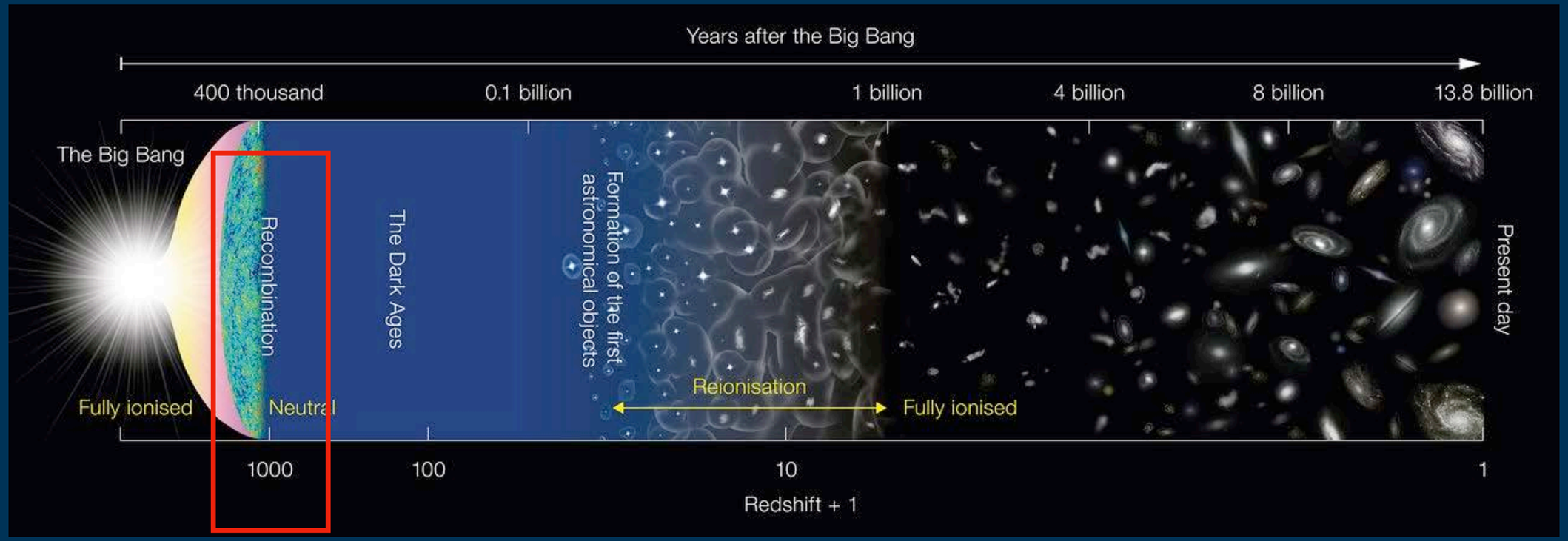


NAOJ

This situation persists until the universe has cooled enough to allow neutral atoms to form.

A simple model: equilibrium (Saha) recombination

Quantity of interest is the *ionization fraction* $X_e(z)$:

$$X_e = \frac{n_e}{n_p + n_H}$$

Assume equilibrium abundances of different species (HII, HI, HeI, etc…)

$$\frac{n_i}{n_j} = \exp\left(\frac{E_i - E_j}{T}\right)$$

Saha equation gives X_e as a function of T

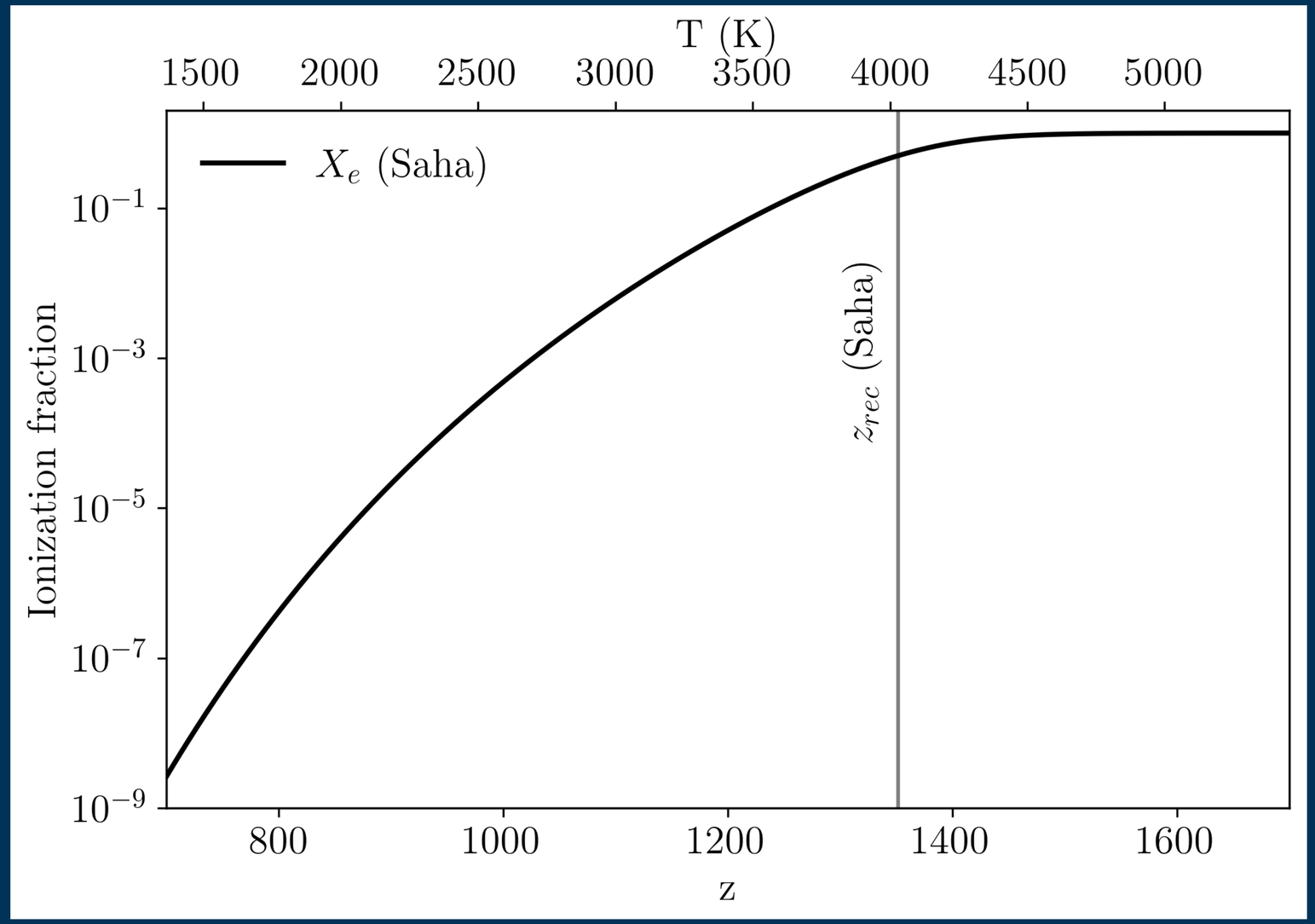
$$\left(\frac{1 - X_e}{X_e^2}\right)_{eq} = \frac{2\zeta(3)}{\pi^2}\left(\frac{2\pi T}{m_e}\right)^{3/2} \eta \exp\left(\frac{13.6\ \text{eV}}{T}\right)$$

In Saha recombination, hydrogen quickly settles into the ground state, with ionized and excited states negligible at late times (low redshifts).

$z_{rec} \sim 1350$

$T_{rec} \sim 3690$ K ~ 0.31 eV

$t_{rec} \sim 256{,}000$ years



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- The Thomson scattering rate $\Lambda_\gamma \sim \sigma_T X_e (n_p + n_H)$ depends on the ionization fraction.
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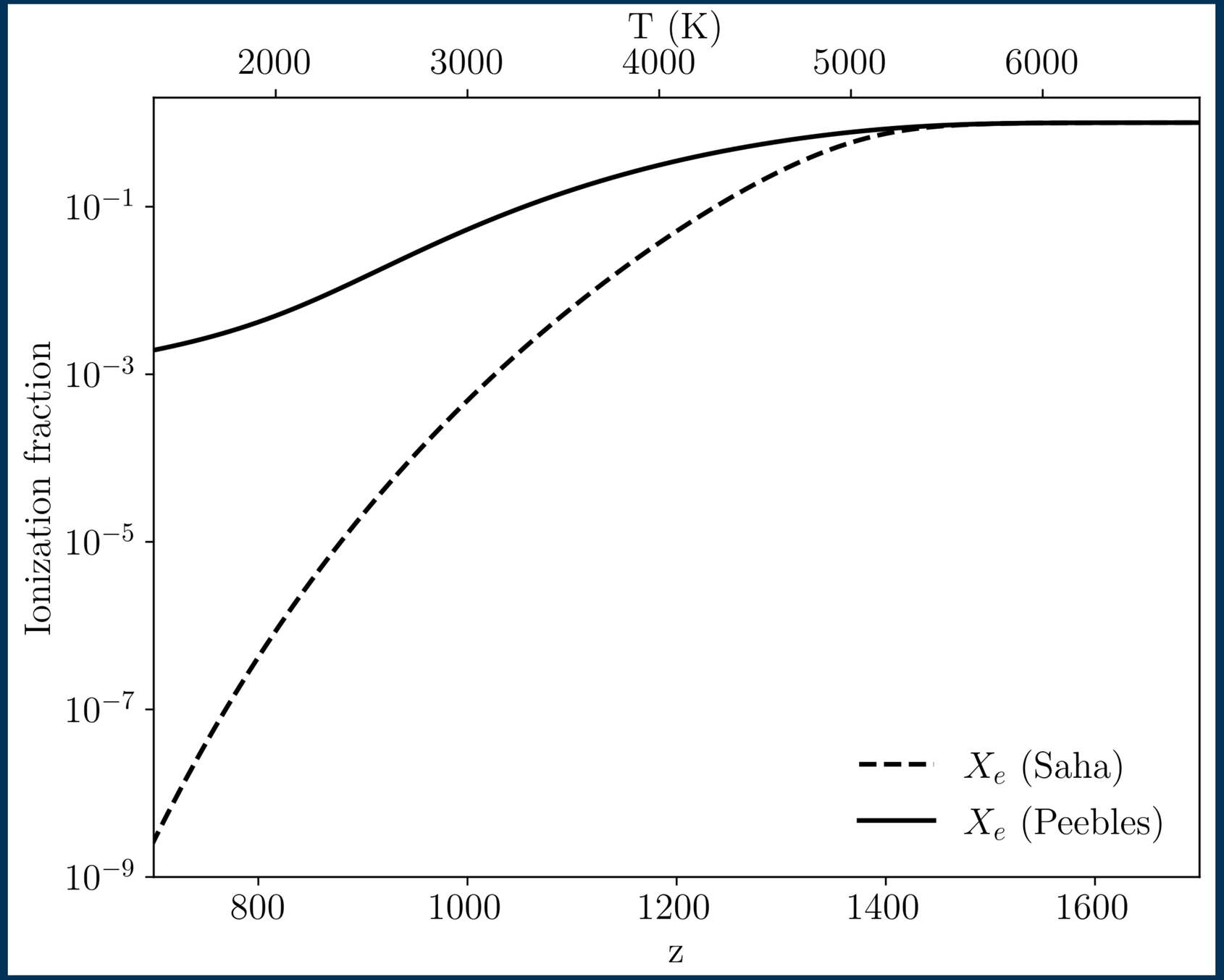
Peebles (1968) and Sunyaev, Kurt, and Zel'dovich (1968) gave the first qualitatively accurate picture using an effective three-level atom model.


T (K)
2000
3000
4000
5000
6000
Ionization fraction
10^{-1}
10^{-3}
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10^{-9}
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z
X_e (Saha)
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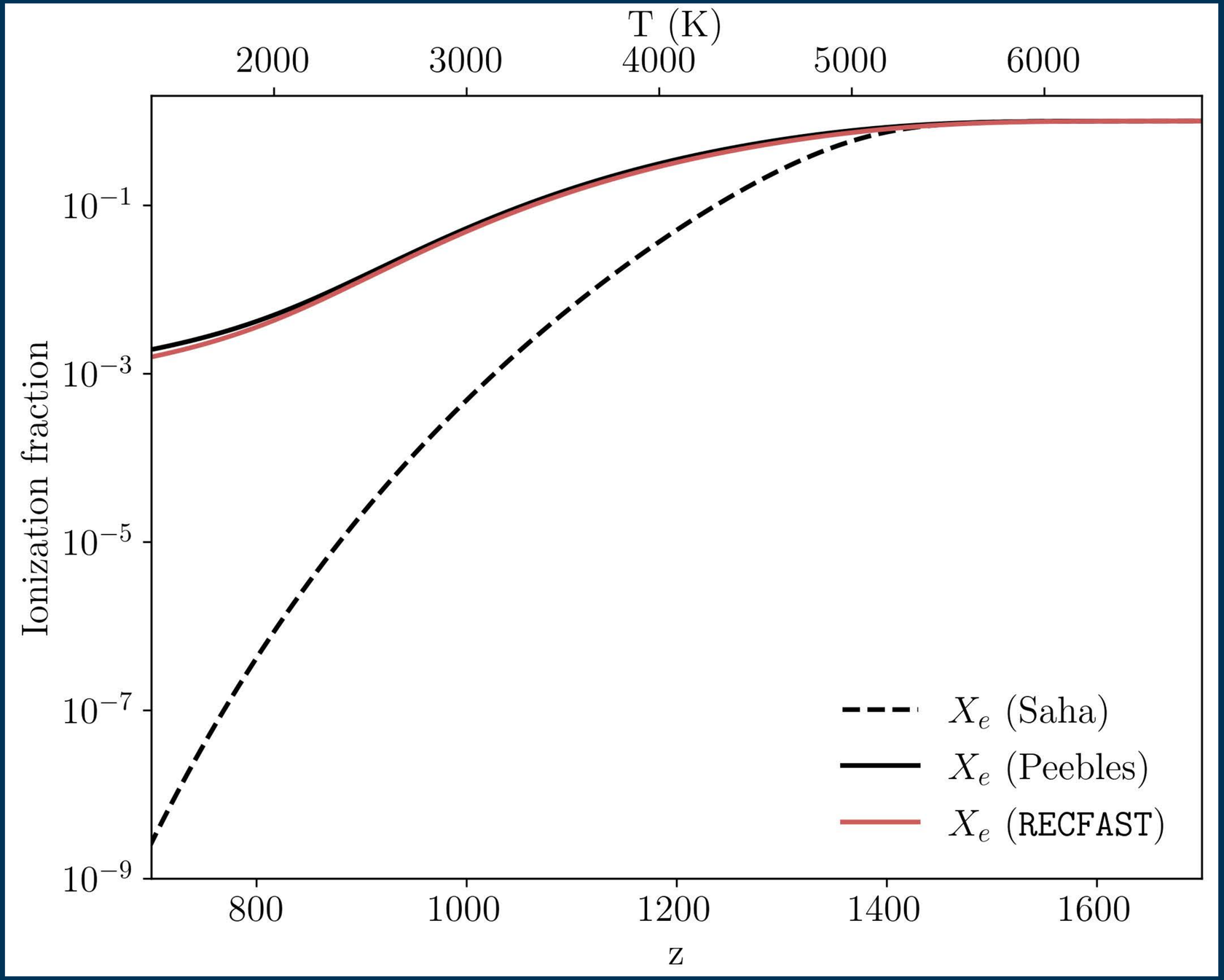
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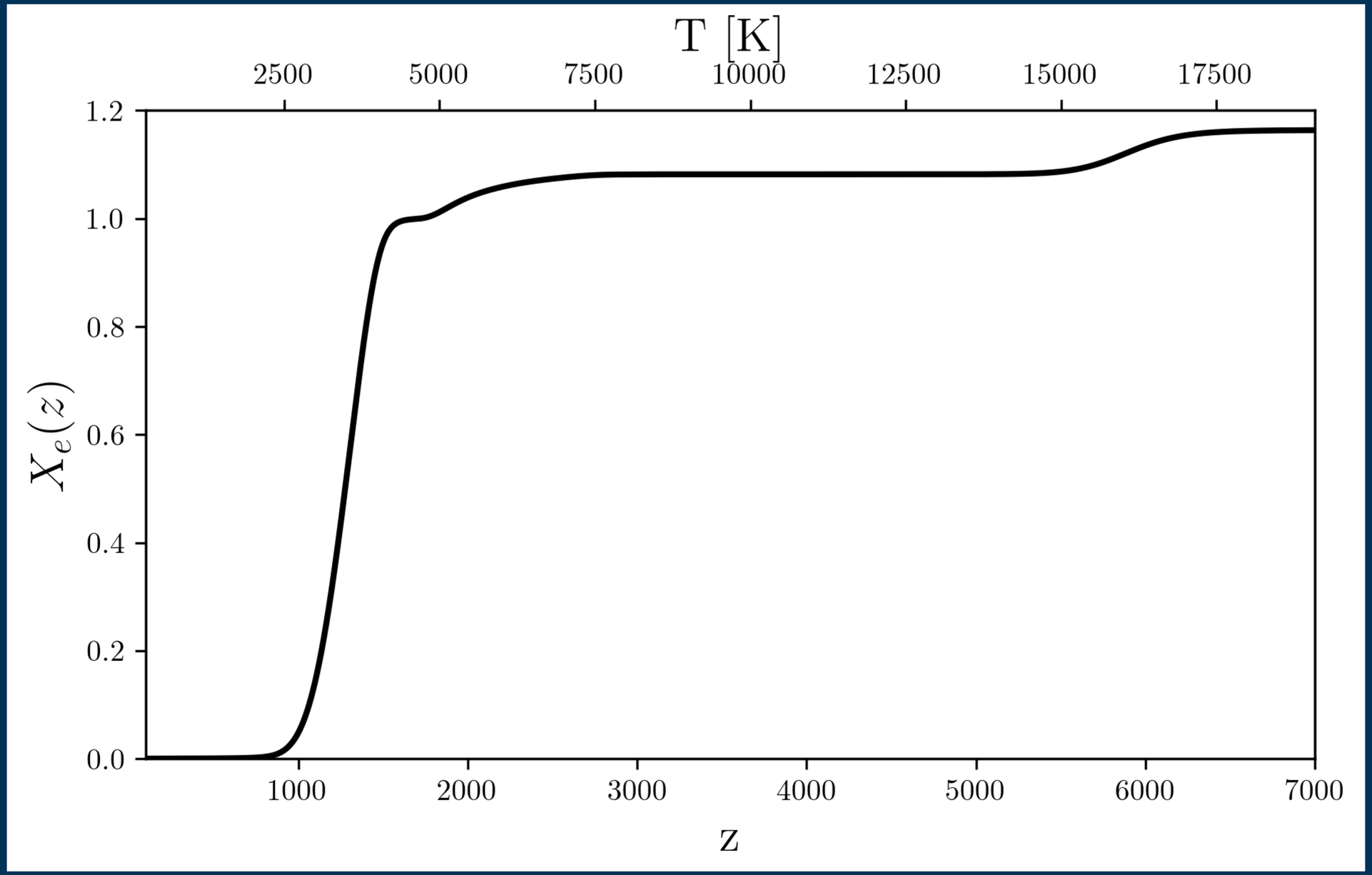
The takeaway from this is that **standard recombination is well understood!**



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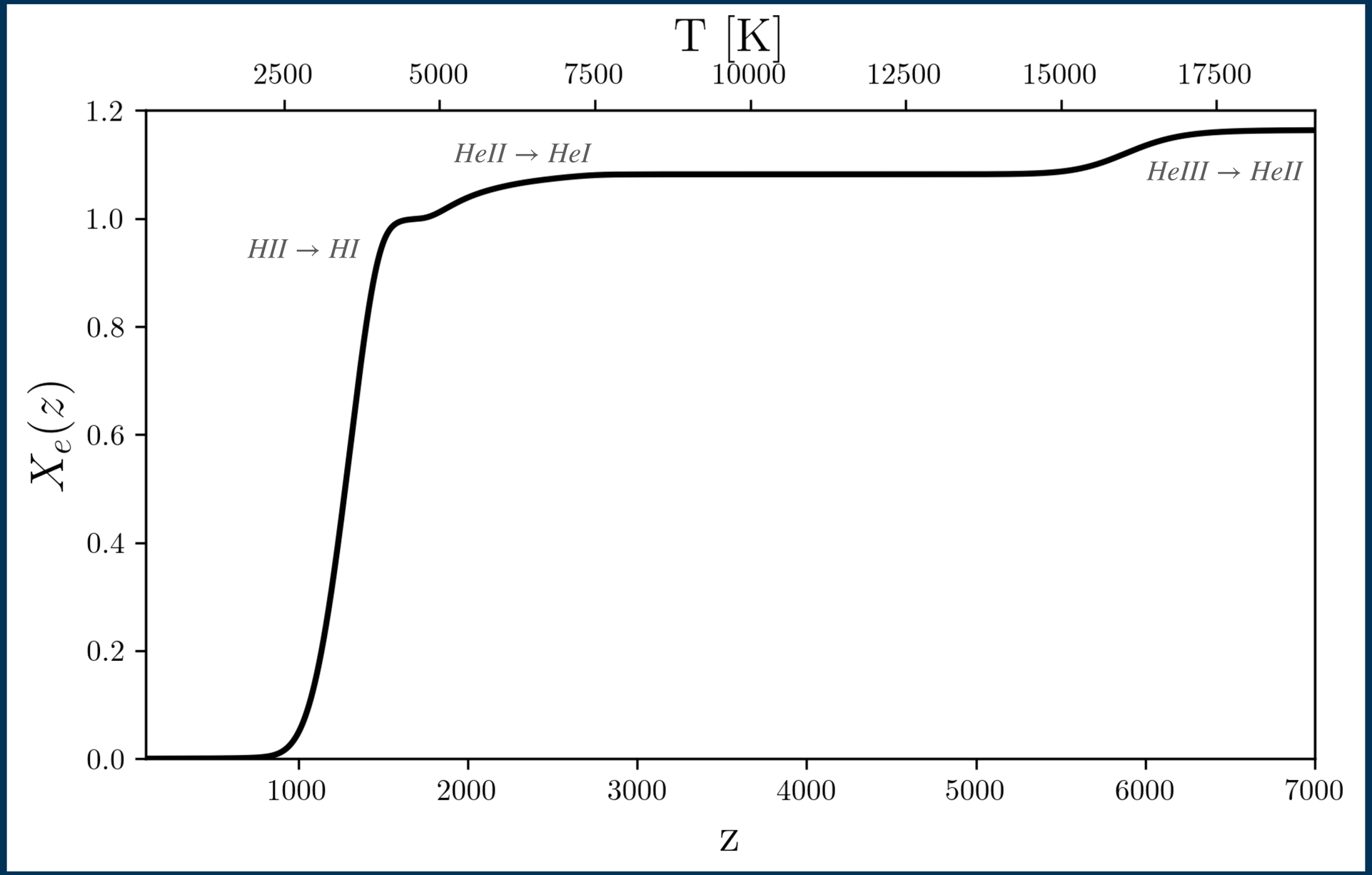

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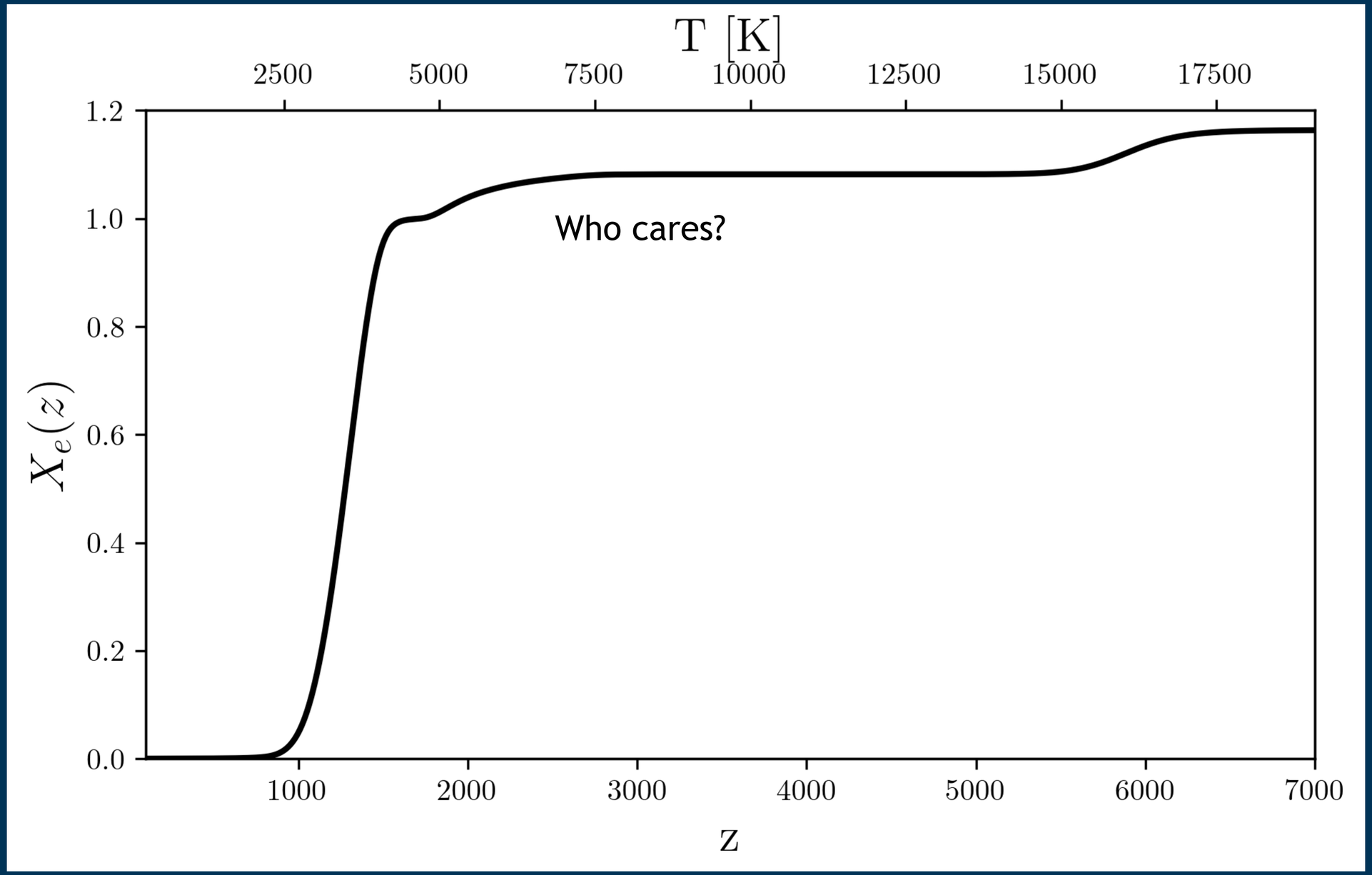

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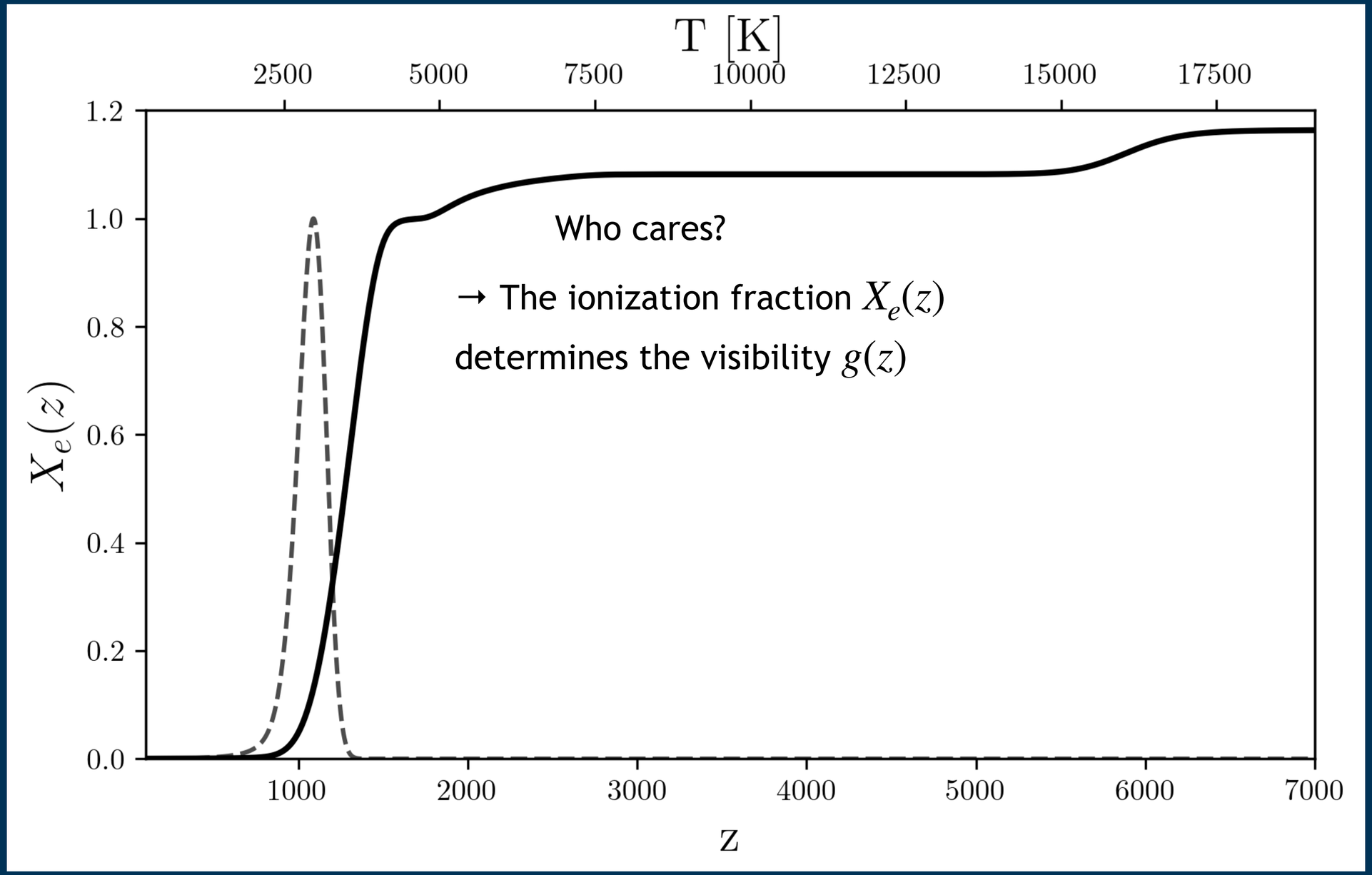

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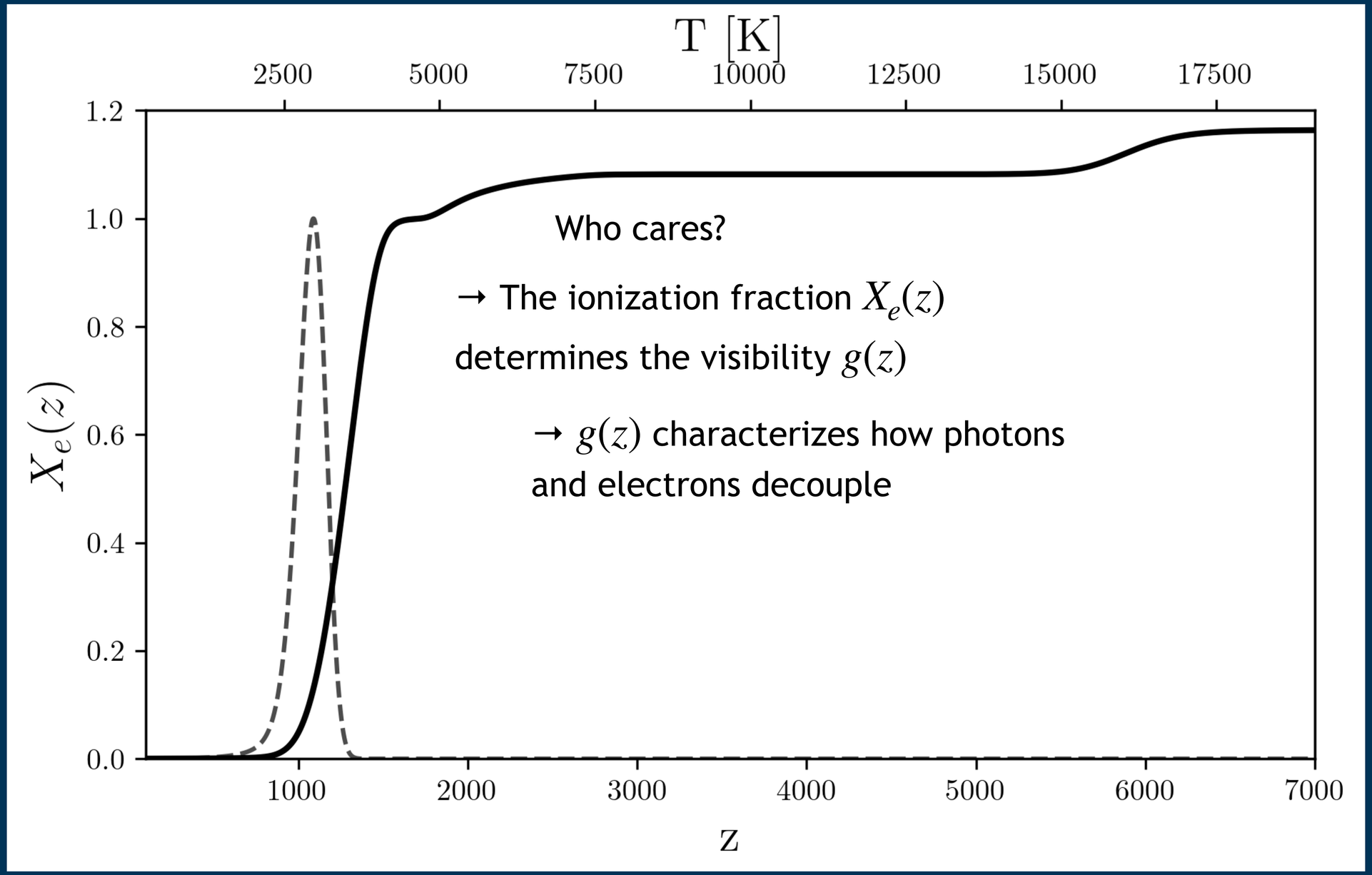

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→ The ionization fraction $X_e(z)$ determines the visibility $g(z)$

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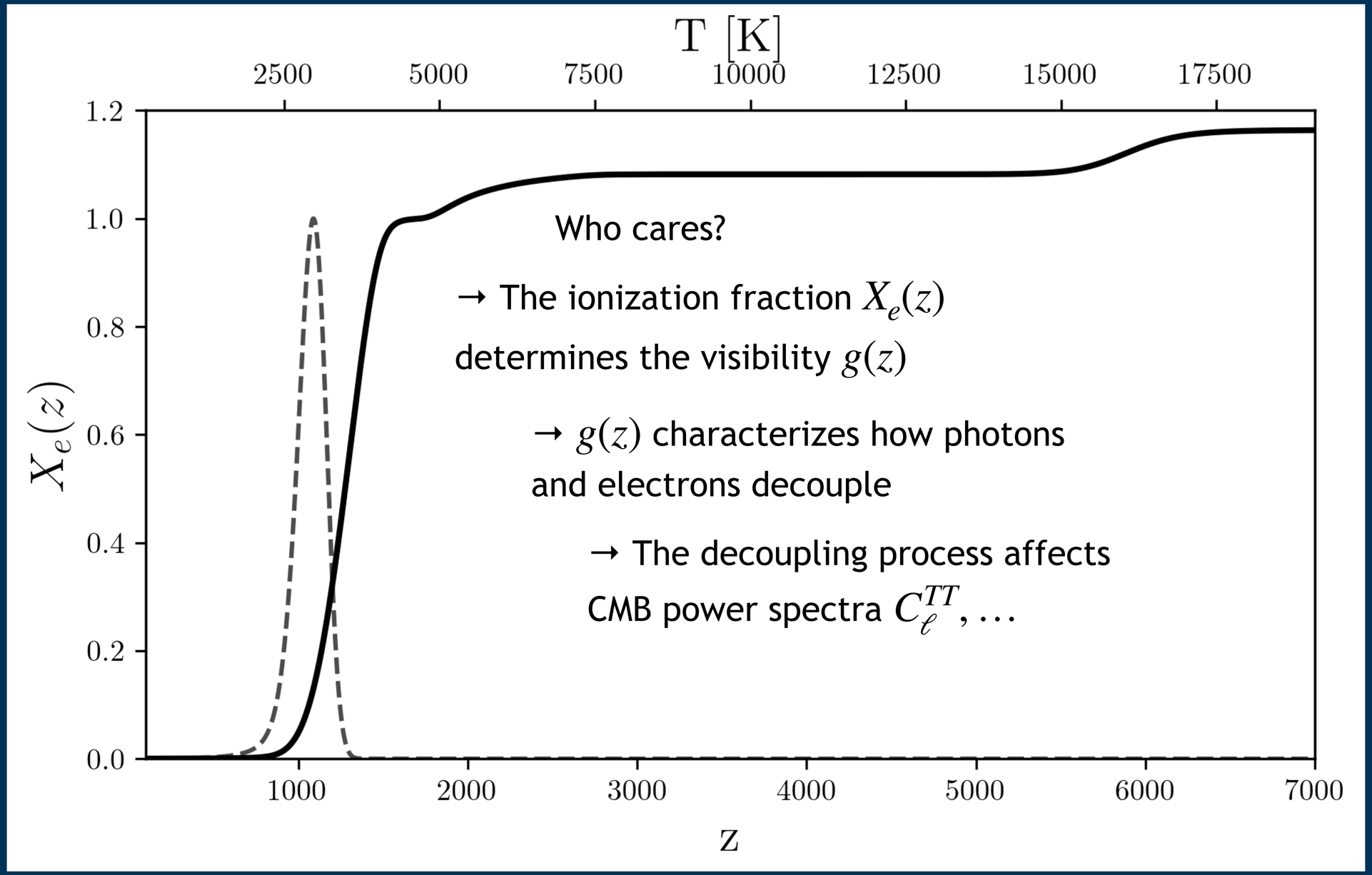

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→ The decoupling process affects CMB power spectra $C_\ell^{TT}, \ldots$

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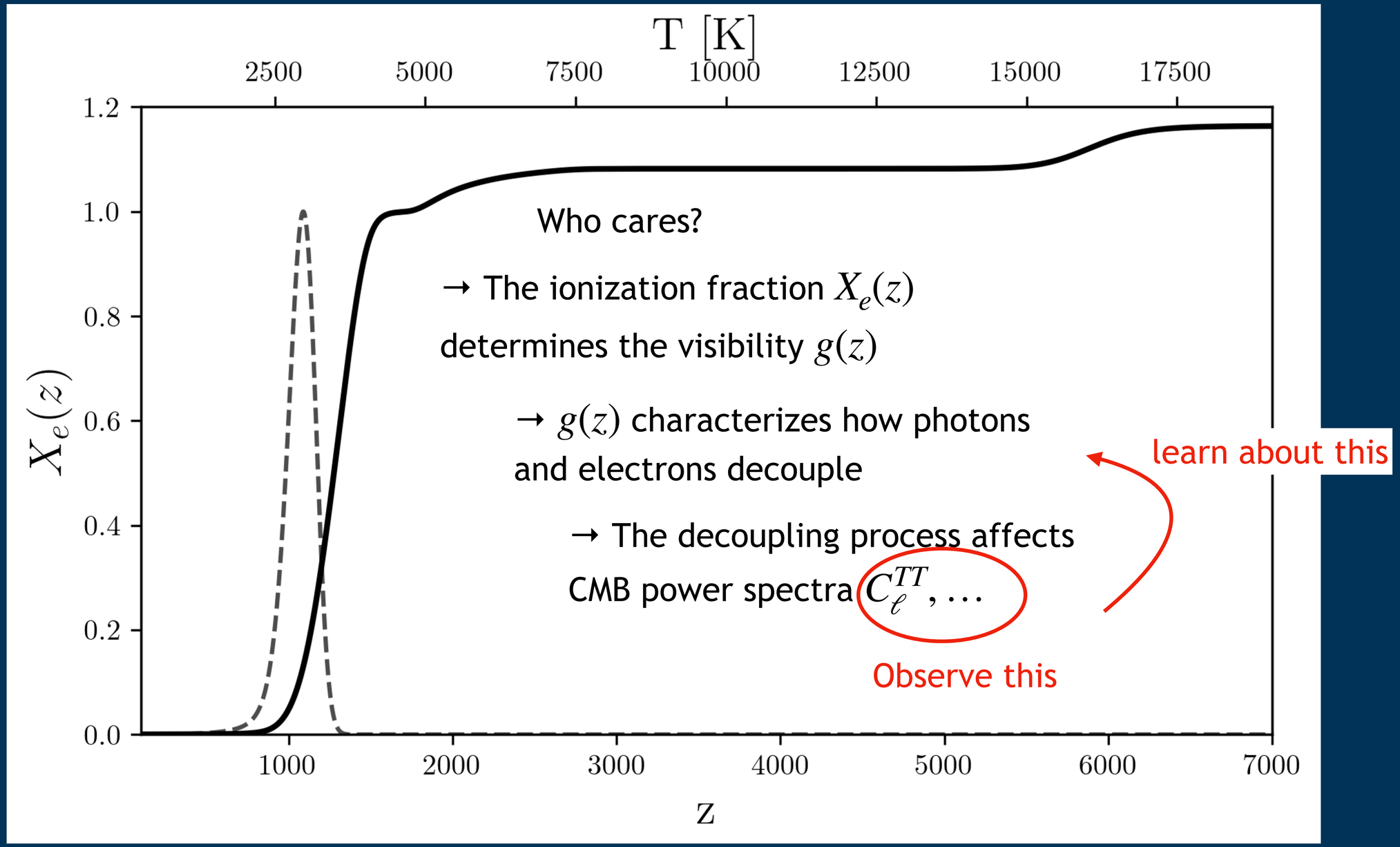
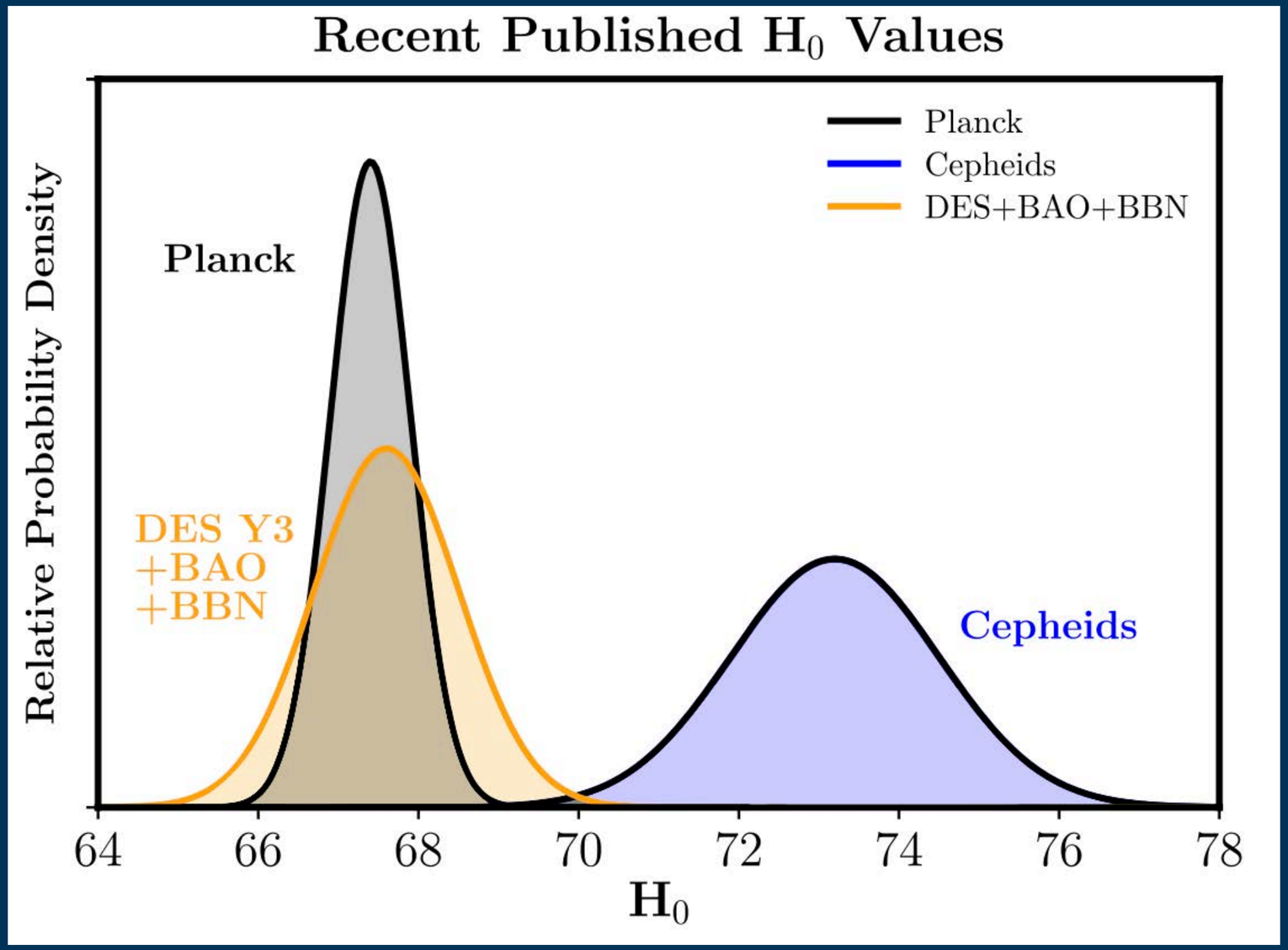


An interlude: The Hubble tension



Adapted from Freedman 2021

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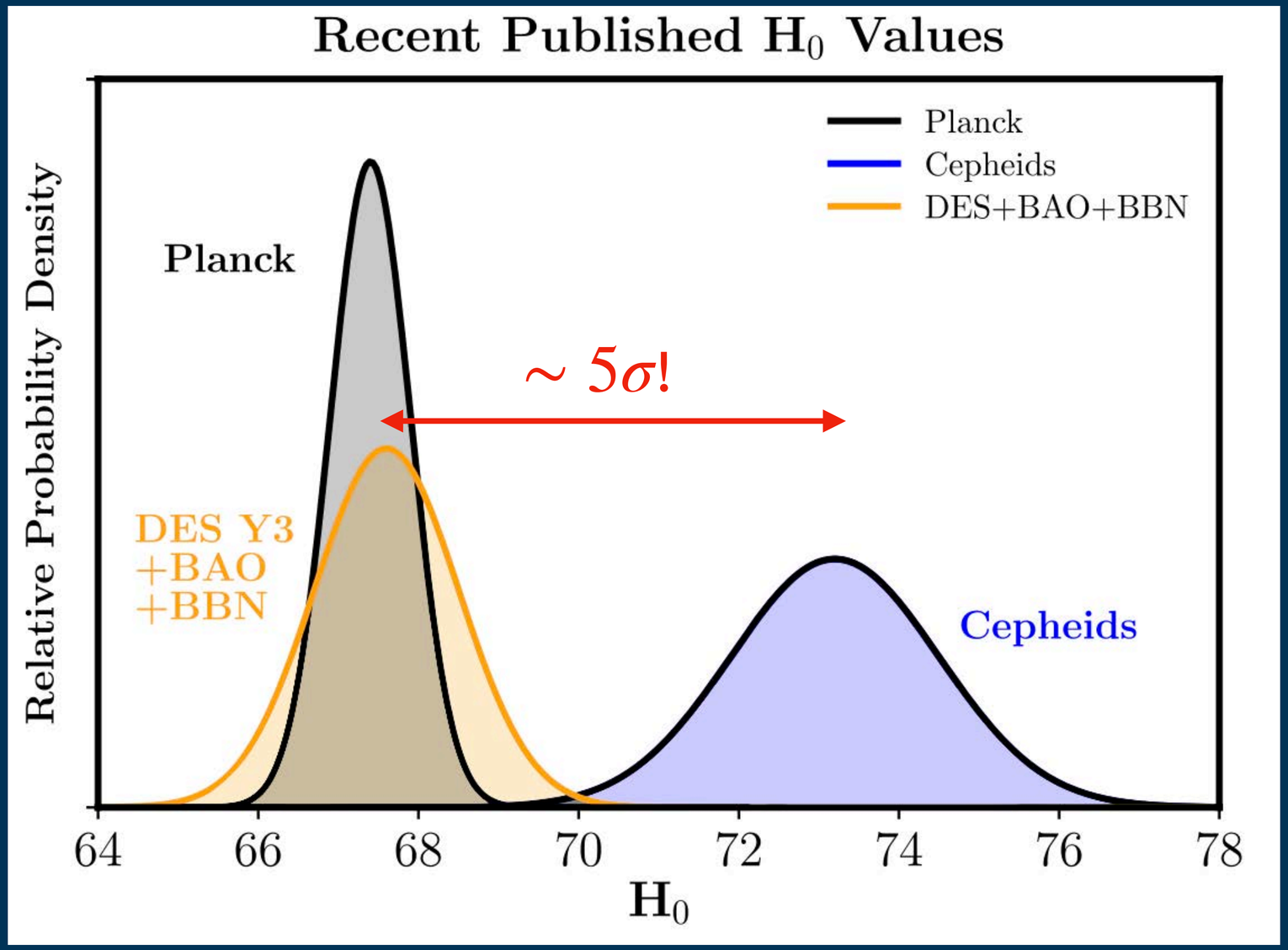

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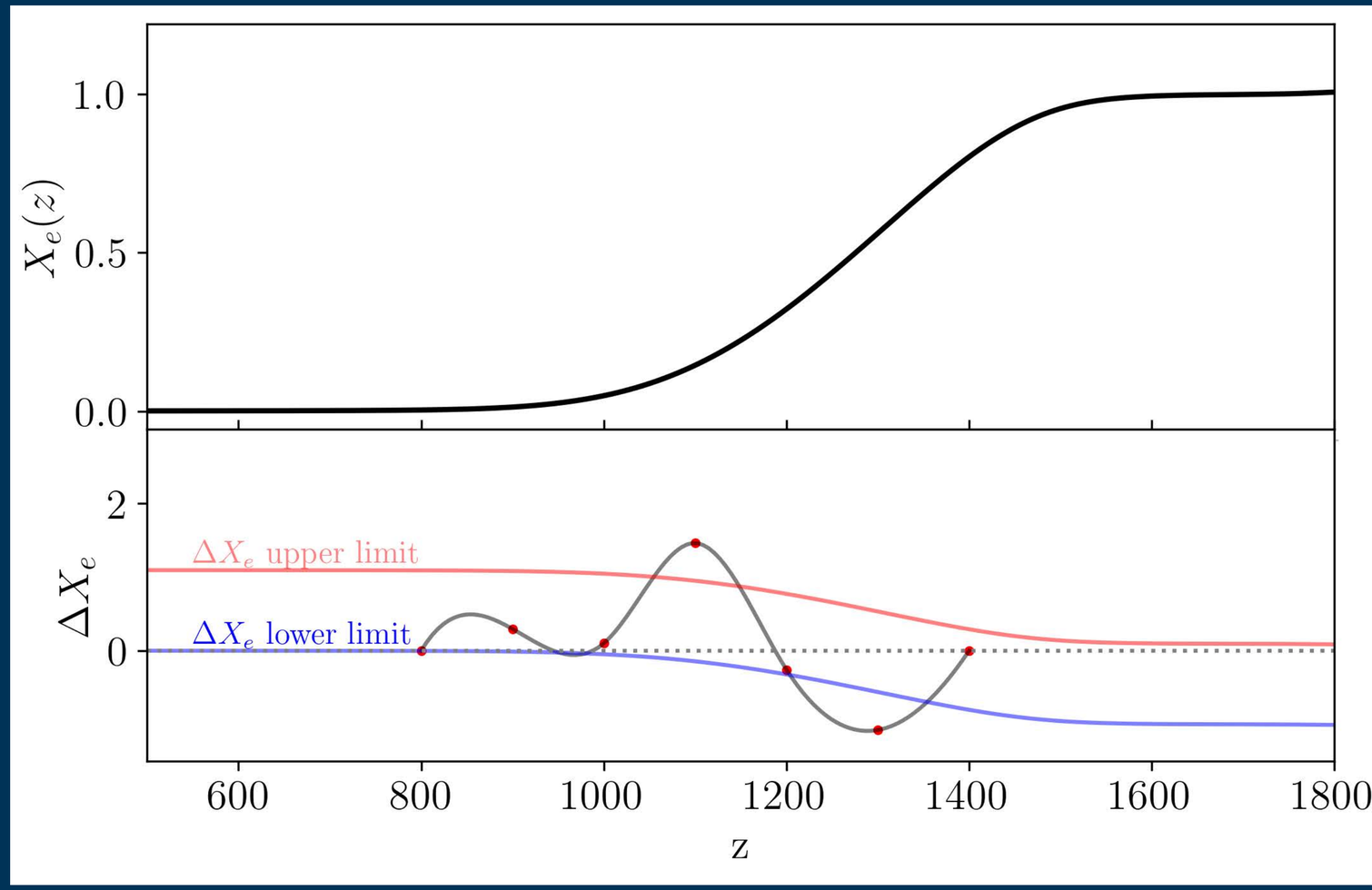

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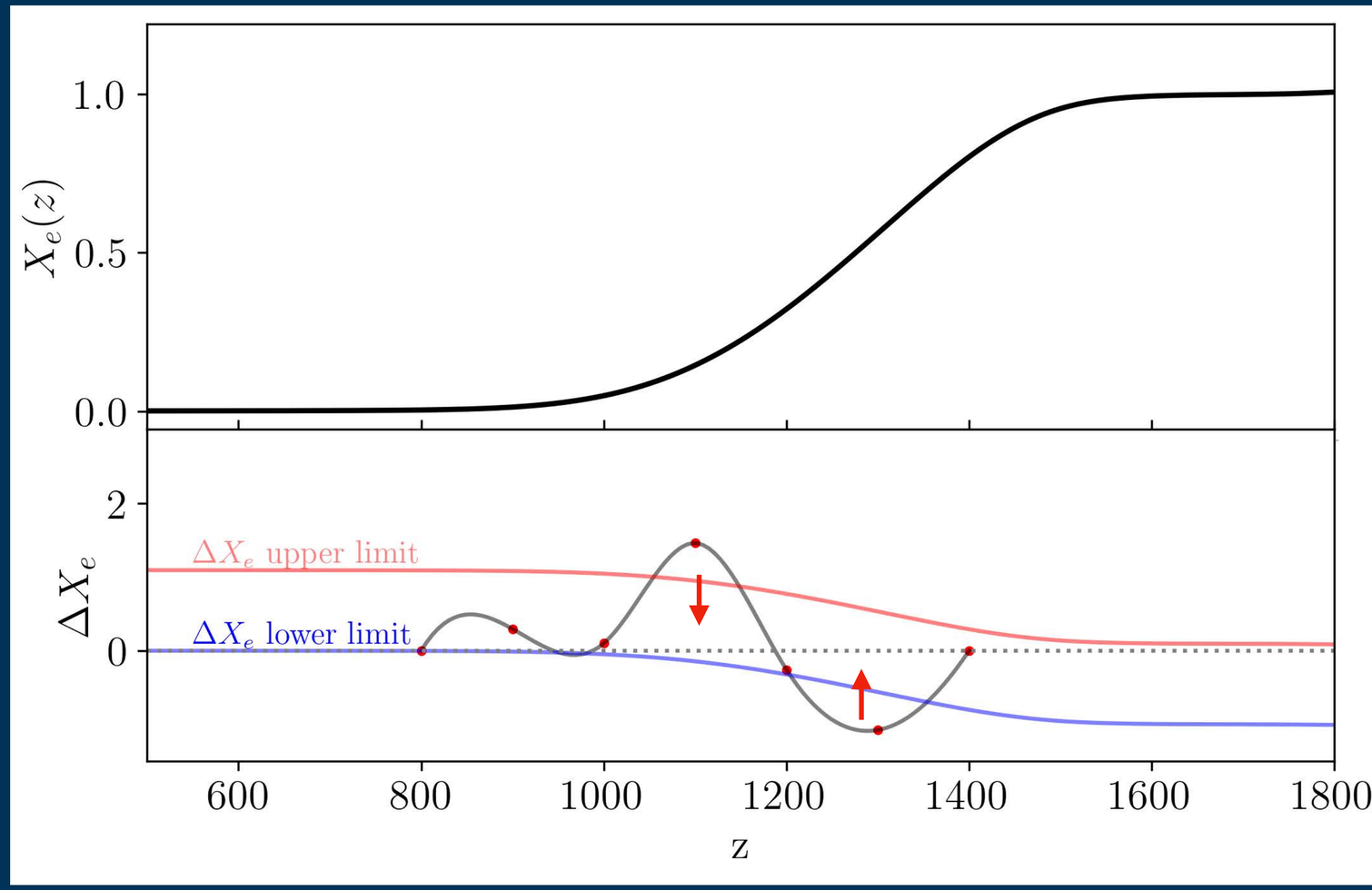

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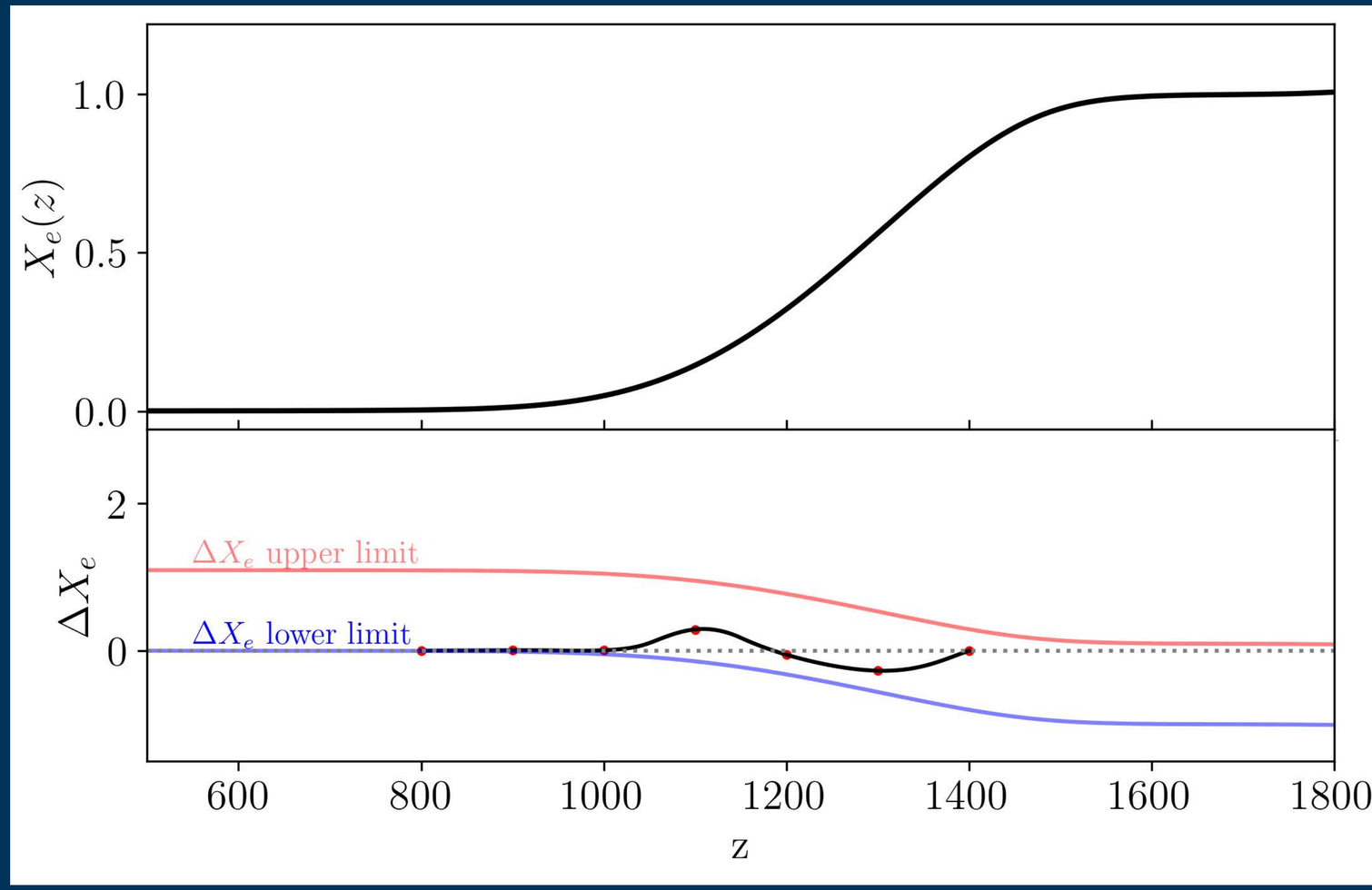

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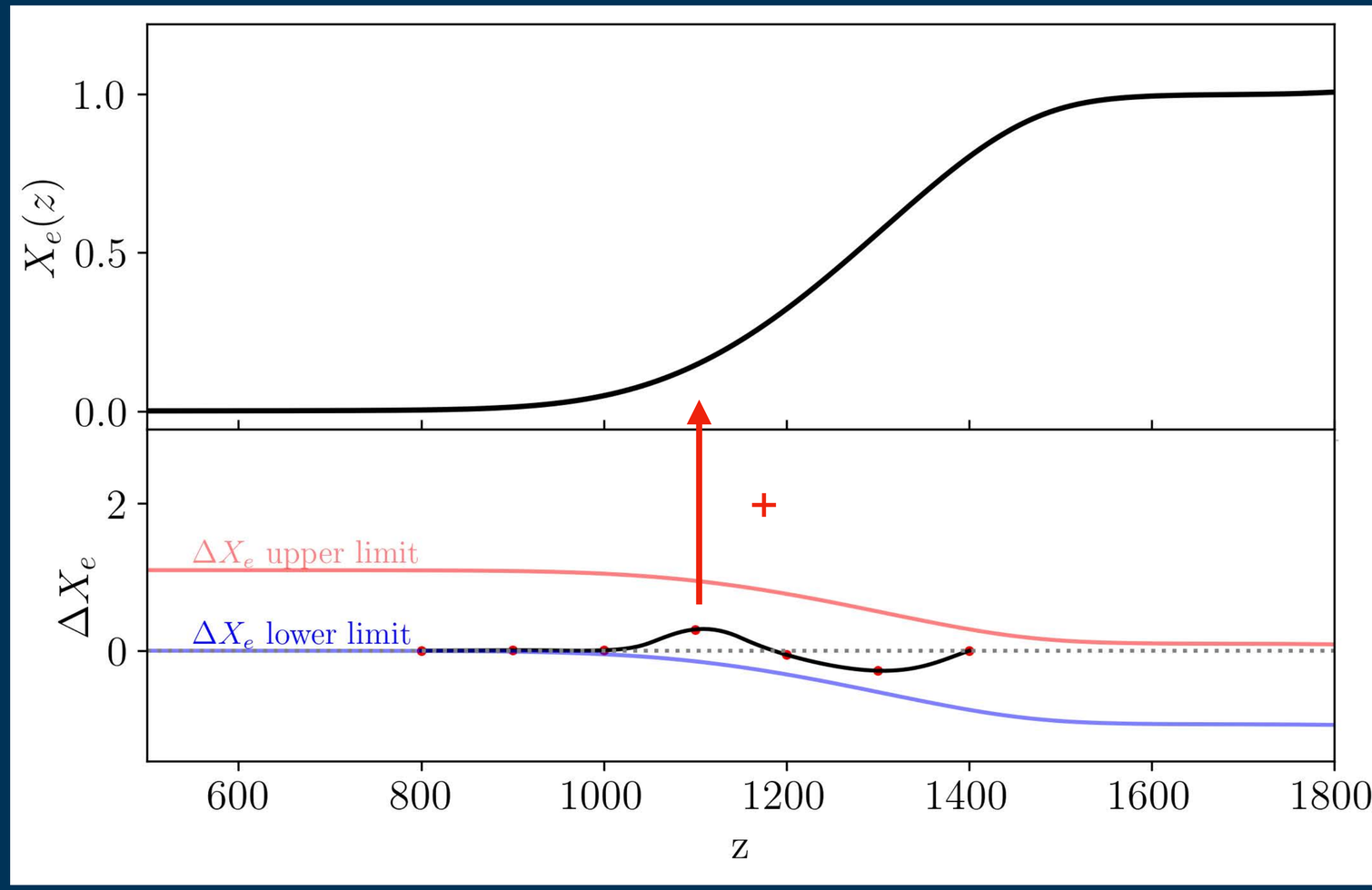

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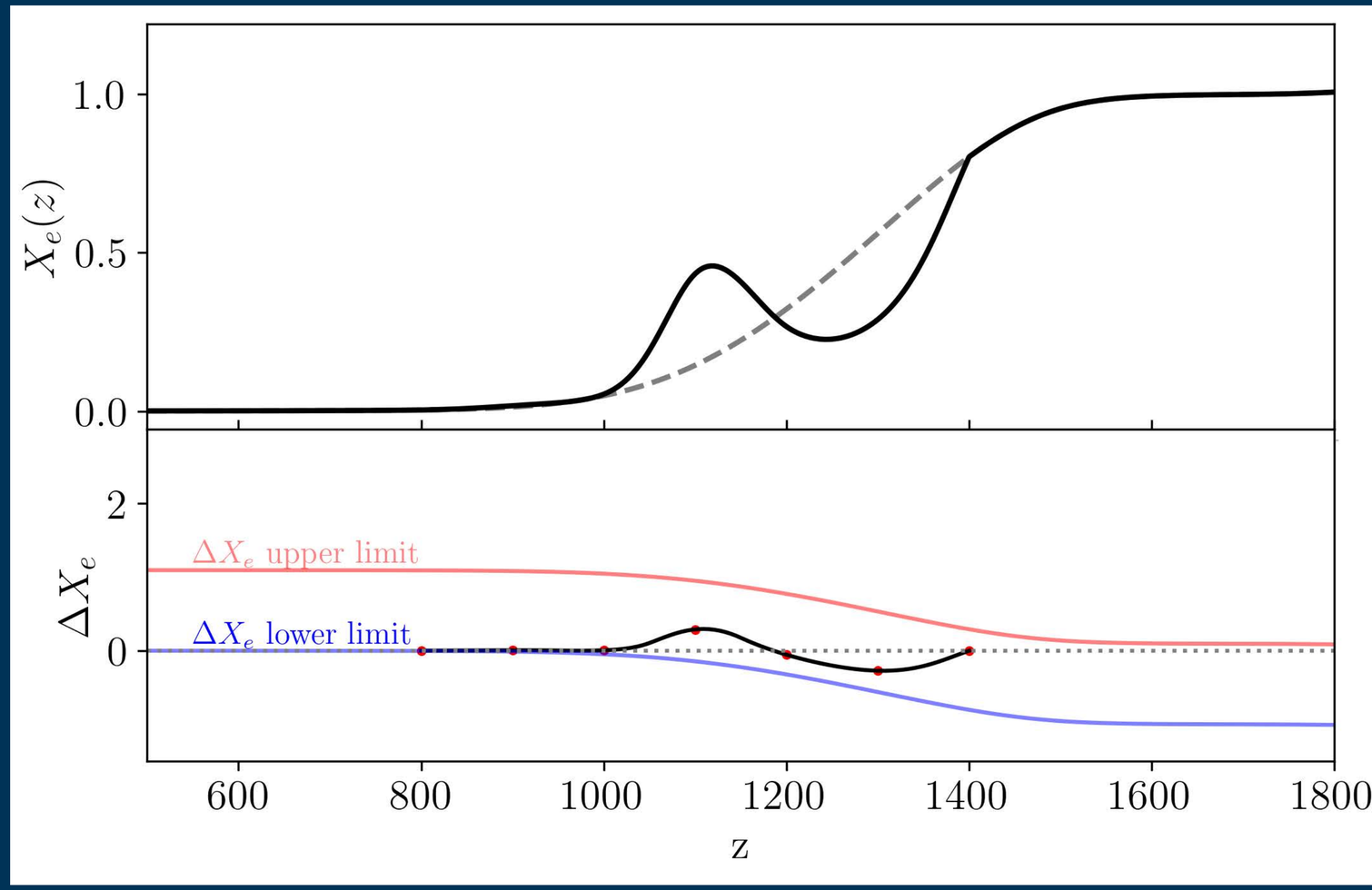
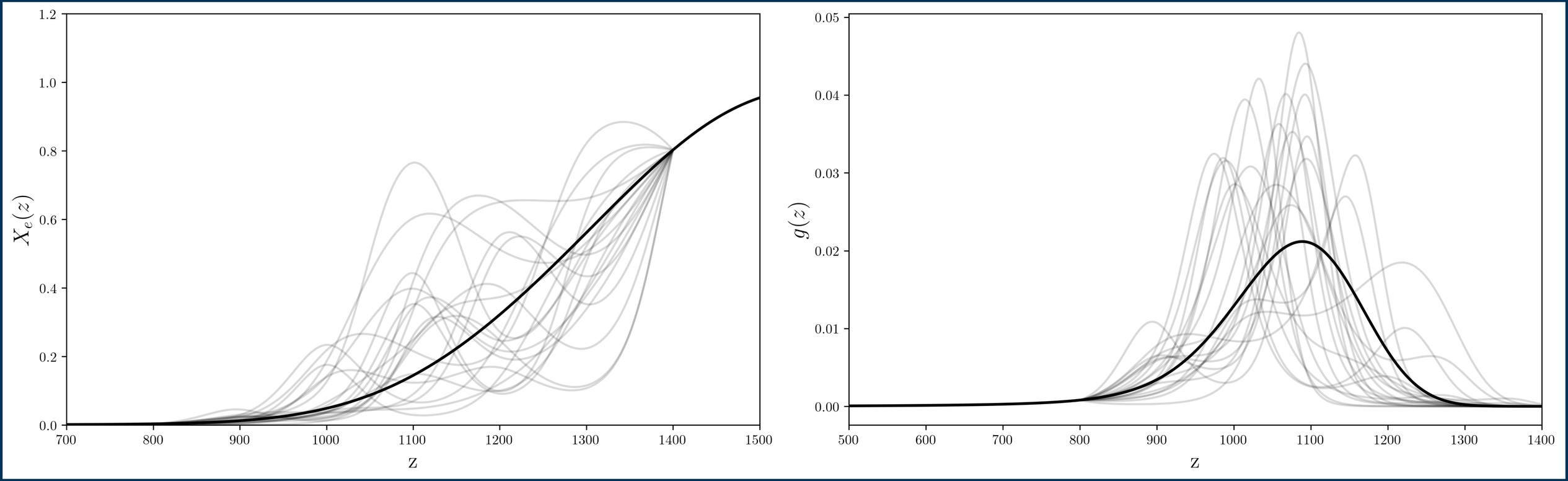


Using this model of modified recombination (ModRec) we can achieve very general deviations from the standard scenario.



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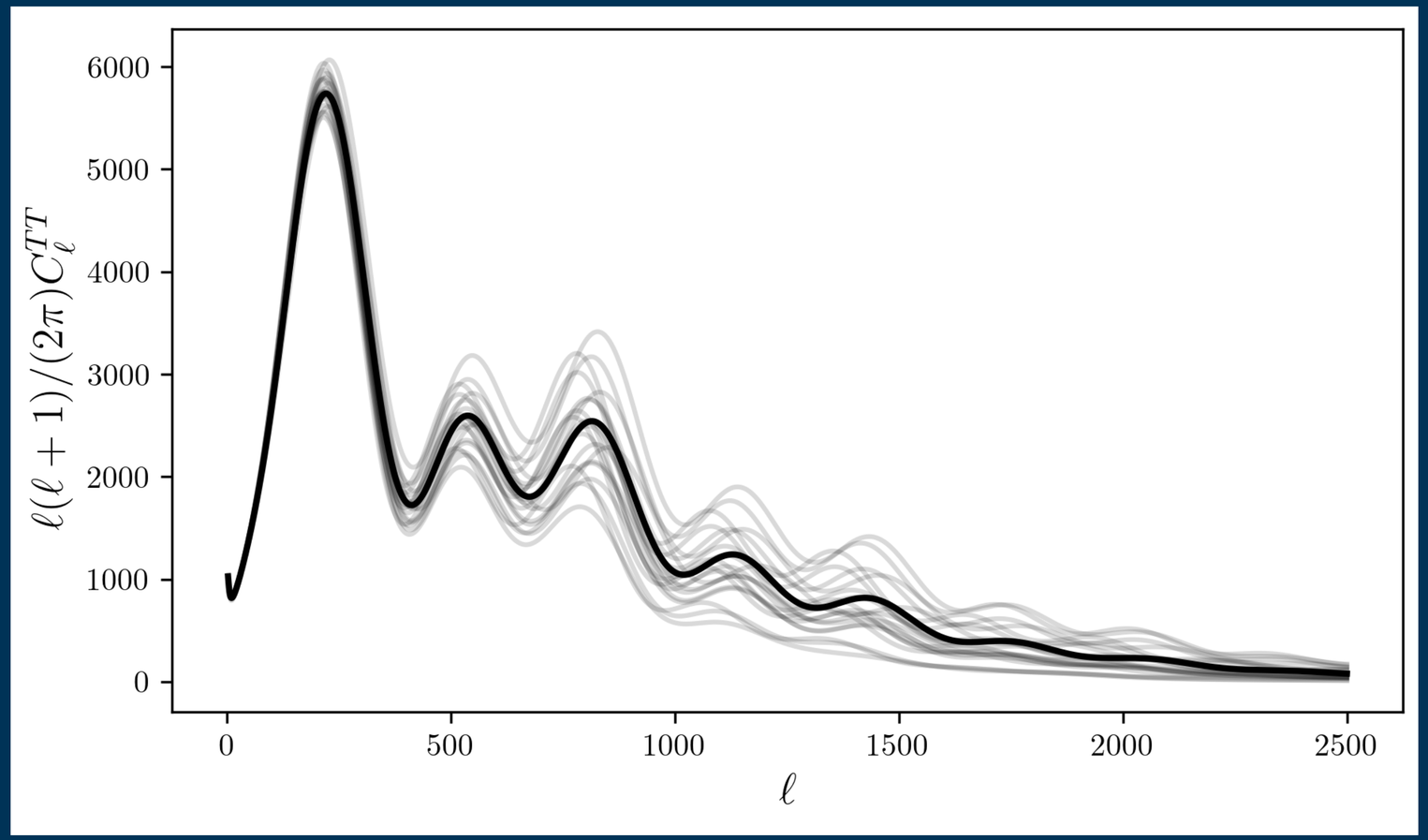

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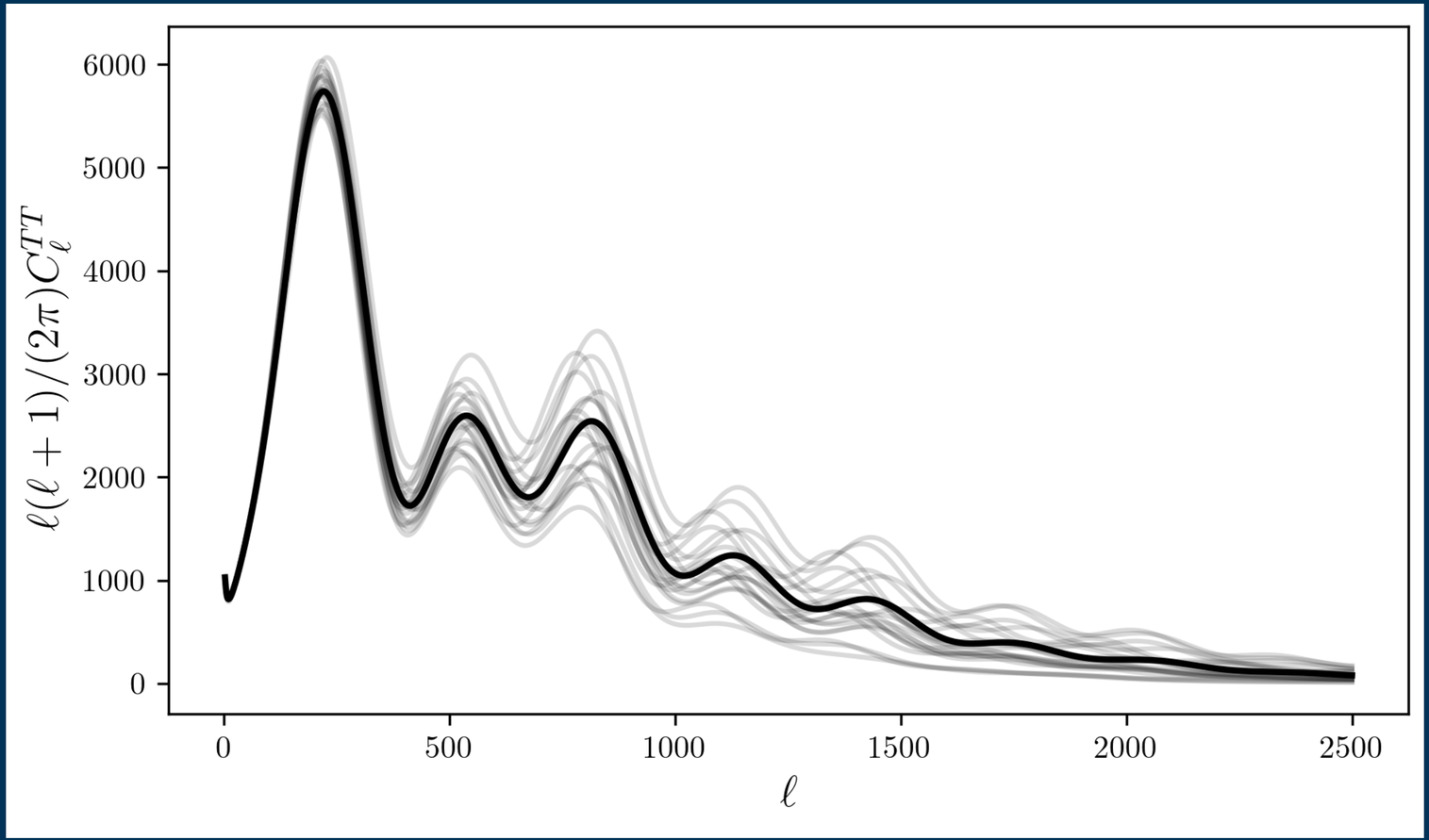

NB: Previous studies do not allow for such freedom — most assume a) small perturbations and/or b) linear response of the likelihood to changes in recombination. It turns out this is overly restrictive!

Parameter estimation is done with MCMC, however…

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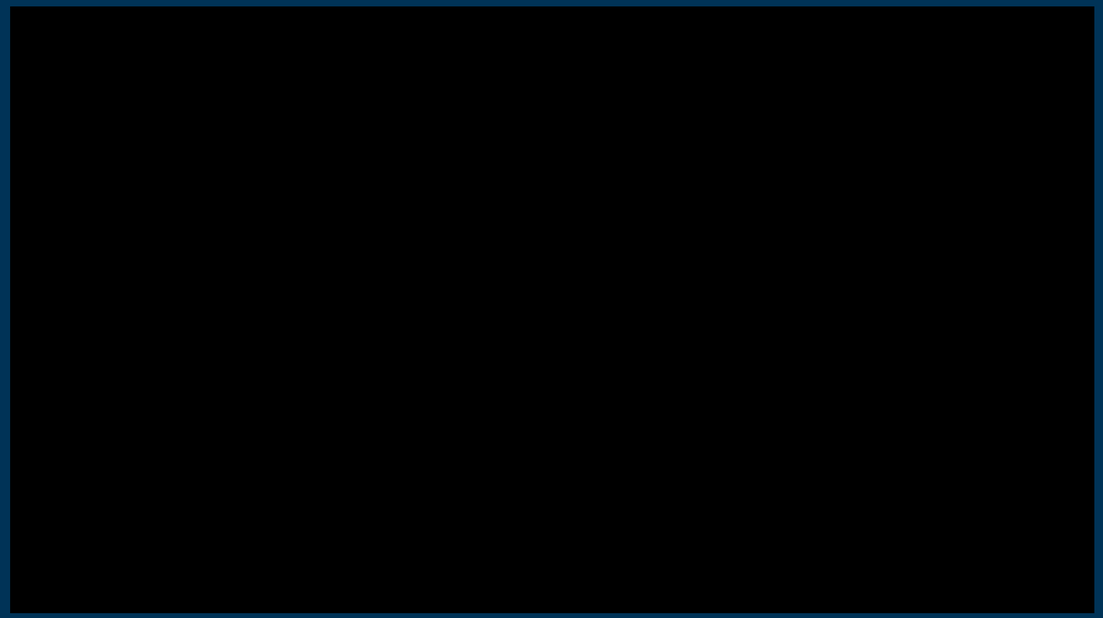
$$\{\omega_b, \omega_c, H_0, \ldots\} \rightarrow$$



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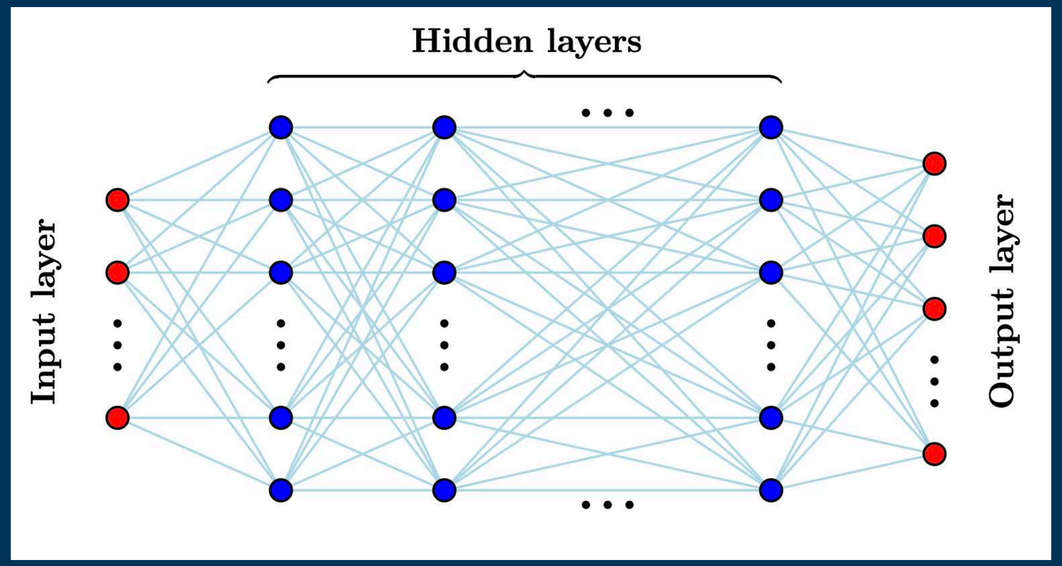

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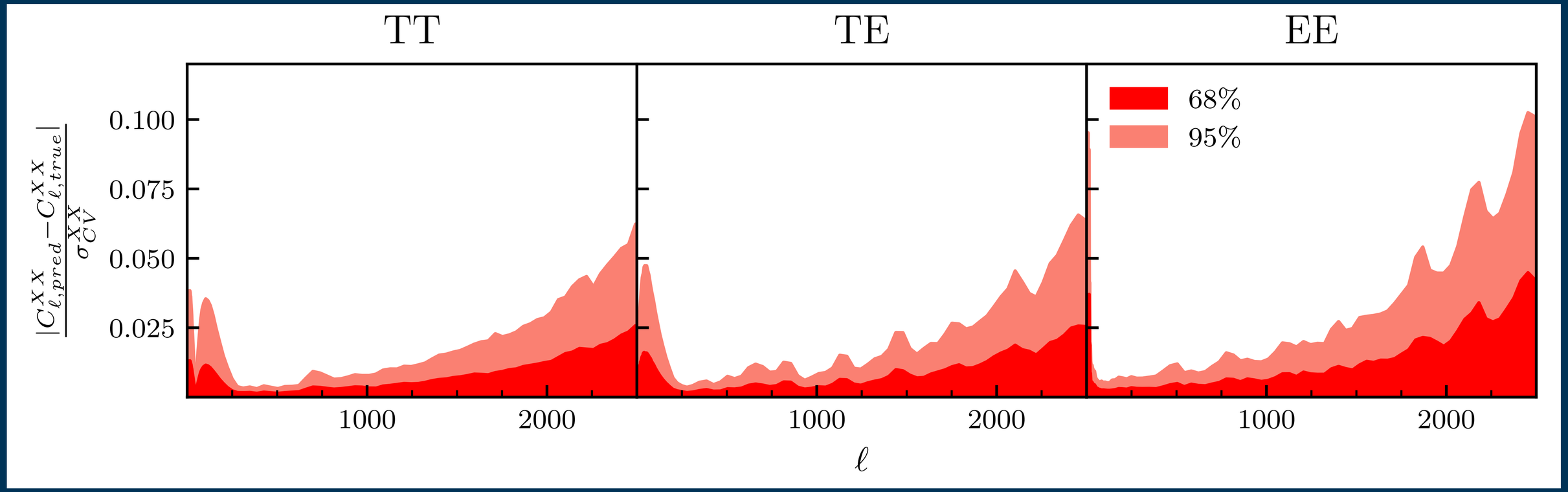

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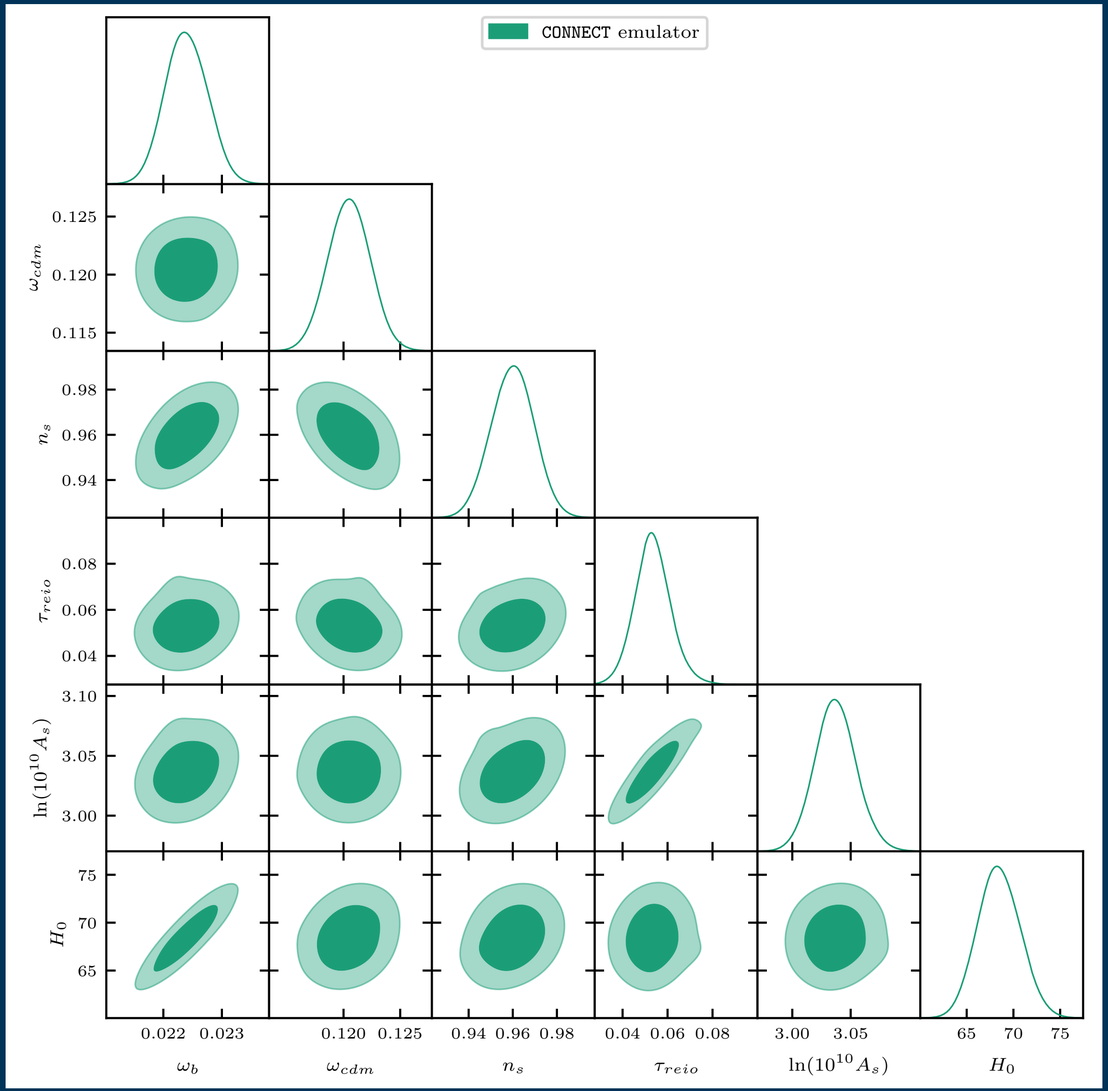
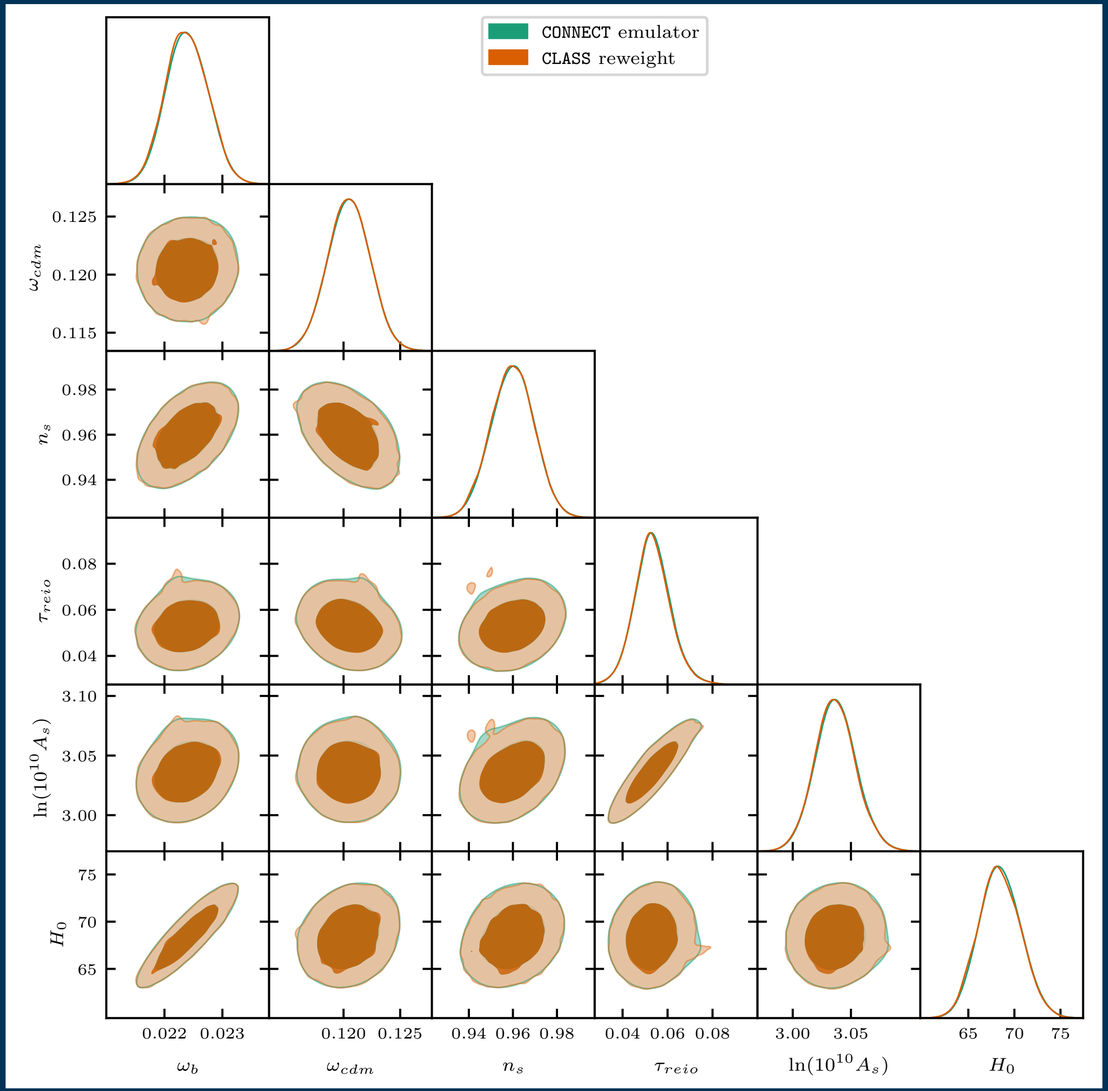
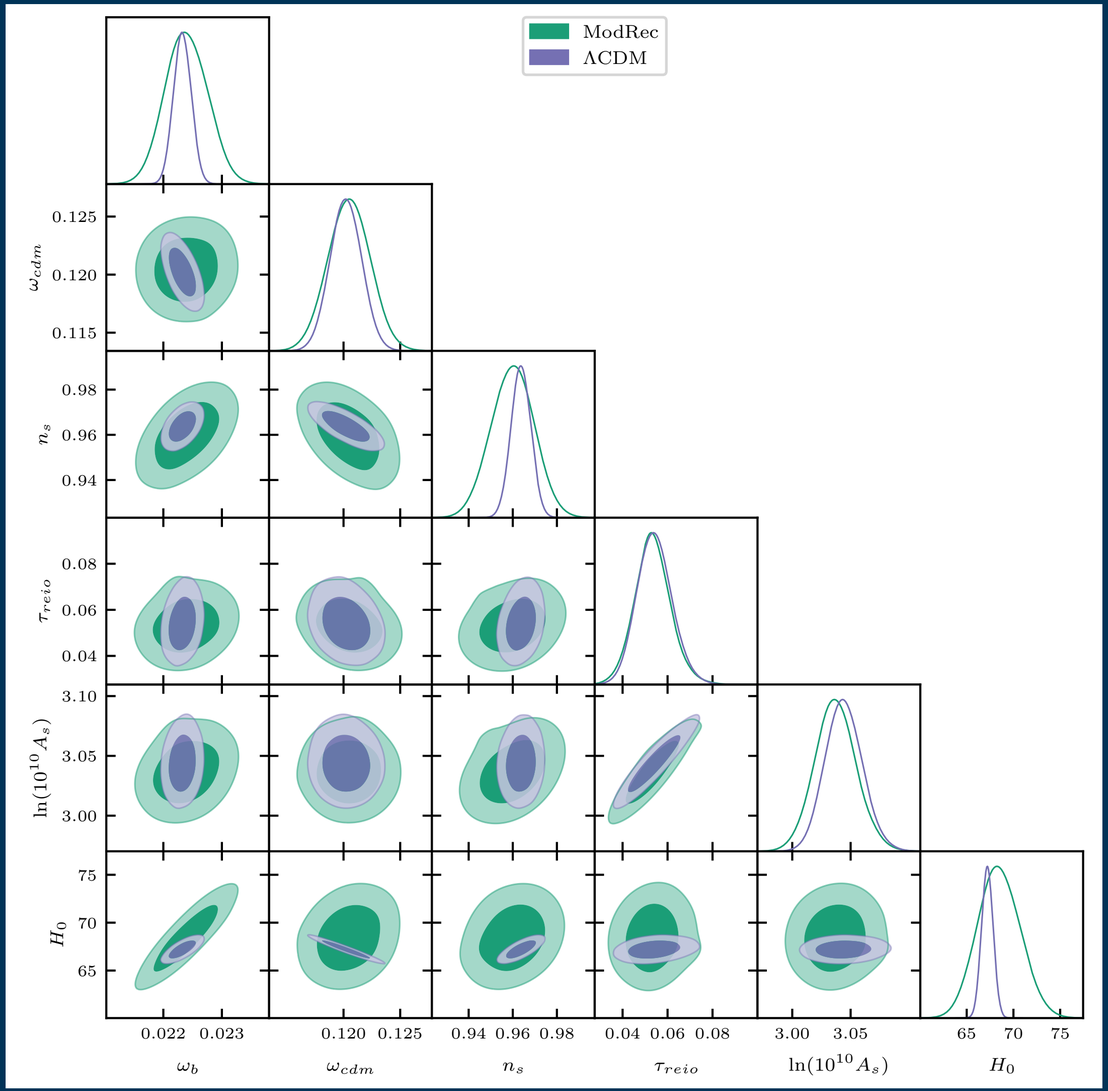
We ran an MCMC to jointly estimate standard cosmological parameters along with ModRec parameters. Our data set was Planck 2018 (TTTEEE+lowE+lowT)



First, we verify that our emulator is accurate enough for this task by thinning the sample and recomputing likelihoods using the “true” power spectra



Unlike analyses using approximations, we find that parameter constraints are significantly weakened, in some cases more than doubling!



Previous work: placed constraints using principal component analysis (had to assume small perturbations and a linear response from the likelihood)

Parameter	$\Lambda\mathrm{CDM} + q_i$	$\Lambda\mathrm{CDM}$
ω_b	0.02239 ± 0.00036	0.02233 ± 0.00015
ω_{cdm}	0.1205 ± 0.0019	0.1202 ± 0.0014
n_s	0.9599 ± 0.0097	0.9637 ± 0.0045
τ_{reio}	0.0534 ± 0.0080	$0.0543^{+0.0072}_{-0.0082}$
$\ln(10^{10} A_s)$	3.037 ± 0.018	3.044 ± 0.016
H_0	68.5 ± 2.3	67.21 ± 0.62
q_1	$-0.22^{+0.25}_{-0.21}$	–
q_2	0.012 ± 0.096	–
q_3	-0.14 ± 0.19	–
q_4	$-0.03^{+0.15}_{-0.11}$	–
q_5	$-0.02^{+0.30}_{-0.46}$	–

This work

Parameter	+ 1 mode	+ 2 modes	+ 3 modes
$100\Omega_b h^2$ . . .	2.241 ± 0.016	2.241 ± 0.018	2.239 ± 0.018
$\Omega_c h^2$	0.1191 ± 0.0009	0.1192 ± 0.0010	0.1192 ± 0.0010
H_0	67.72 ± 0.43	67.72 ± 0.44	67.84 ± 0.45
τ	0.054 ± 0.007	0.055 ± 0.007	0.055 ± 0.007
n_s	0.9667 ± 0.0051	0.9668 ± 0.0050	0.9657 ± 0.0051
$\ln(10^{10} A_s)$ . .	3.042 ± 0.015	3.042 ± 0.014	3.040 ± 0.015
μ_1	0.02 ± 0.12	0.01 ± 0.12	0.03 ± 0.13
μ_2	. . .	0.01 ± 0.17	0.05 ± 0.17
μ_3	. . .	. . .	-0.84 ± 0.69

Planck 2018

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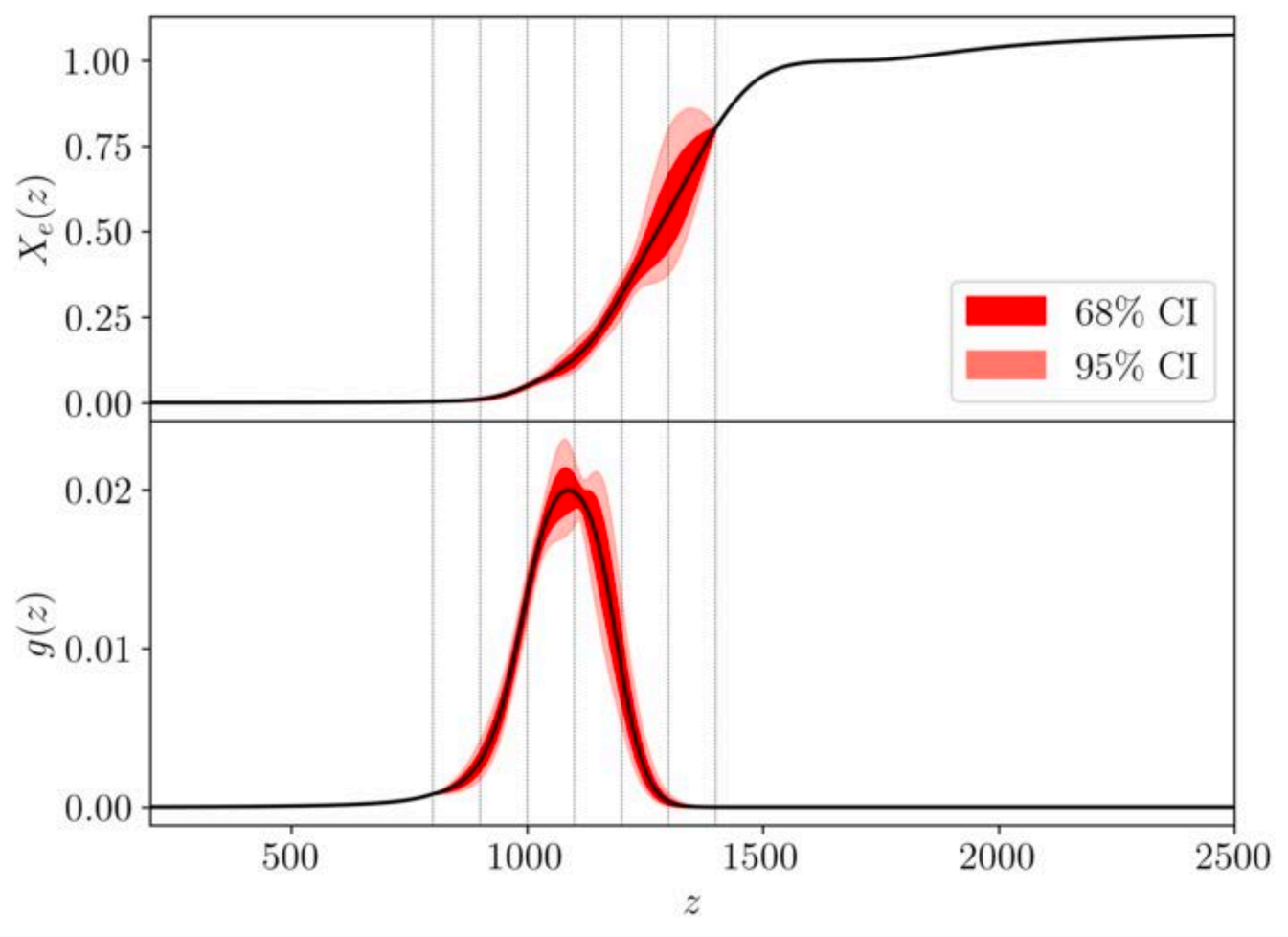
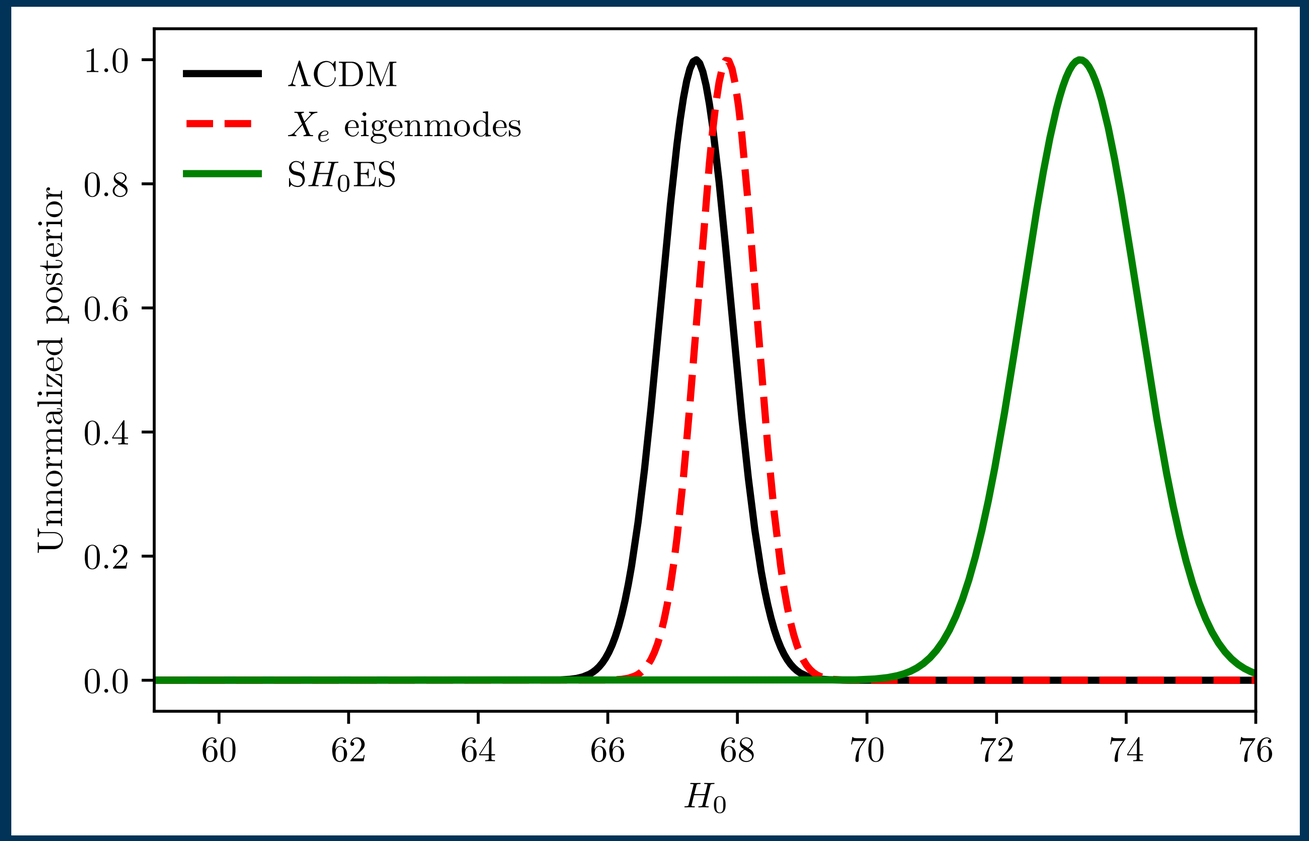
Planck 2018

We find a range of recombination histories consistent with the data. Both $X_e(z)$ and $g(z)$ could have deviated significantly from their fiducial values



The increased freedom in recombination can alleviate the Hubble tension. One way to do this is by increasing uncertainty:



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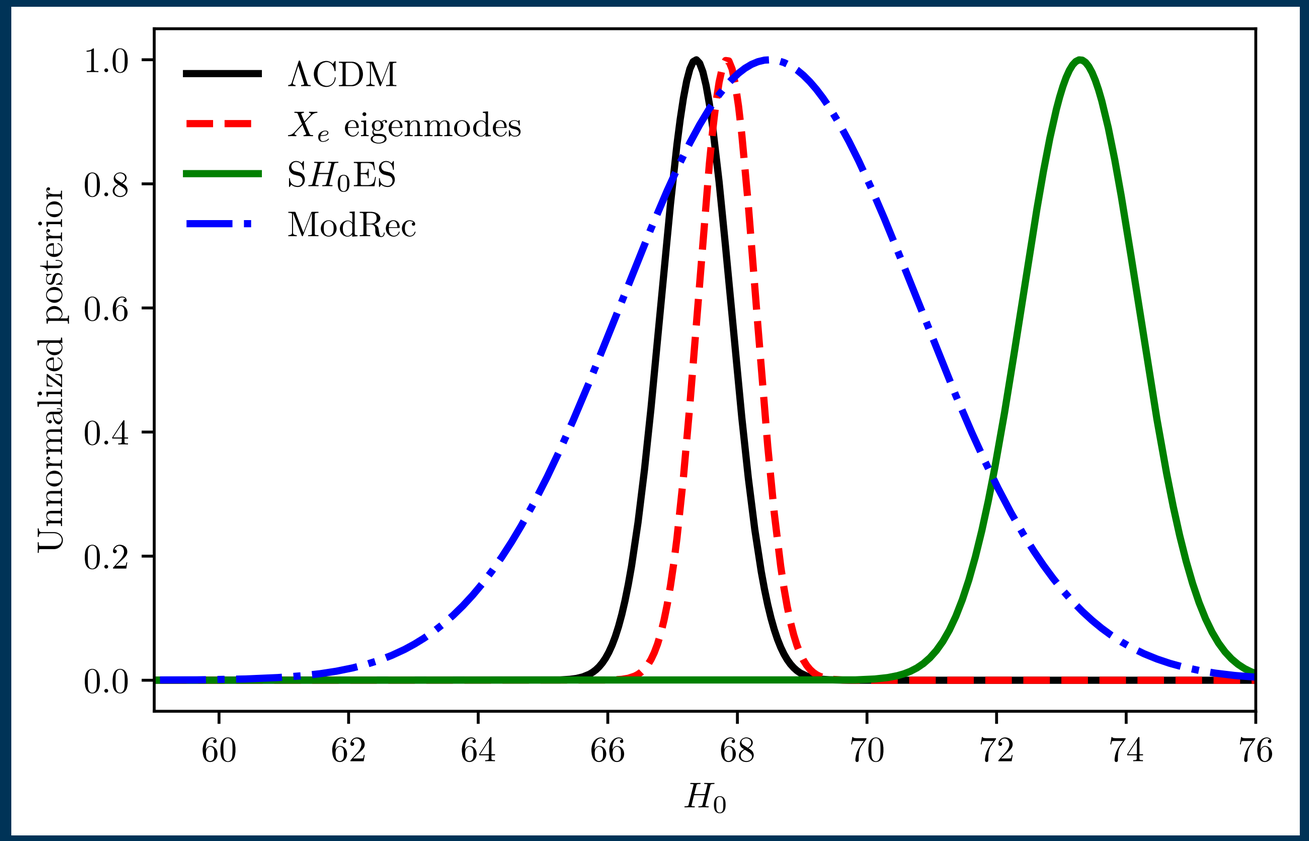
SH0ES measurement:

$H_0 = 73.29 \pm 0.90$ km/s/Mpc

The increased freedom in recombination can alleviate the Hubble tension. One way to do this is by increasing uncertainty:



Parameter	$\Lambda\mathrm{CDM} + q_i$	$\Lambda\mathrm{CDM}$
ω_b	0.02239 ± 0.00036	0.02233 ± 0.00015
ω_{cdm}	0.1205 ± 0.0019	0.1202 ± 0.0014
n_s	0.9599 ± 0.0097	0.9637 ± 0.0045
τ_{reio}	0.0534 ± 0.0080	$0.0543^{+0.0072}_{-0.0082}$
$\ln(10^{10} A_s)$	3.037 ± 0.018	3.044 ± 0.016
H_0	68.5 ± 2.3	67.21 ± 0.62
q_1	$-0.22^{+0.25}_{-0.21}$	–
q_2	0.012 ± 0.096	–
q_3	-0.14 ± 0.19	–
q_4	$-0.03^{+0.15}_{-0.11}$	–
q_5	$-0.02^{+0.30}_{-0.46}$	–

SH$_0$ES measurement:

$H_0 = 73.29 \pm 0.90$ km/s/Mpc

Just by increasing uncertainty, H_0 tension is reduced to ~2σ

However, we can also find models which fit the data well and deliver a high H_0.

Selection criteria: $\chi^2_{\text{model}} - \chi^2_{\text{bf},\Lambda CDM} < 0$

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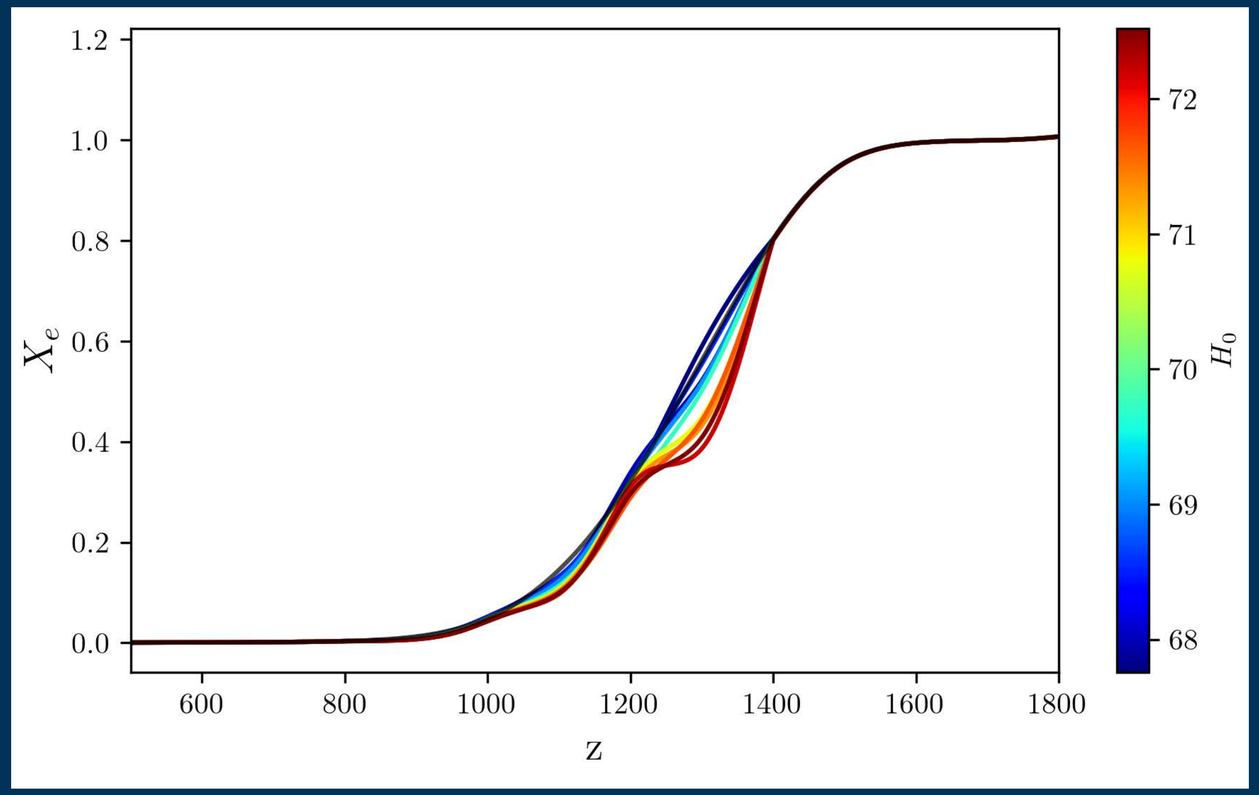

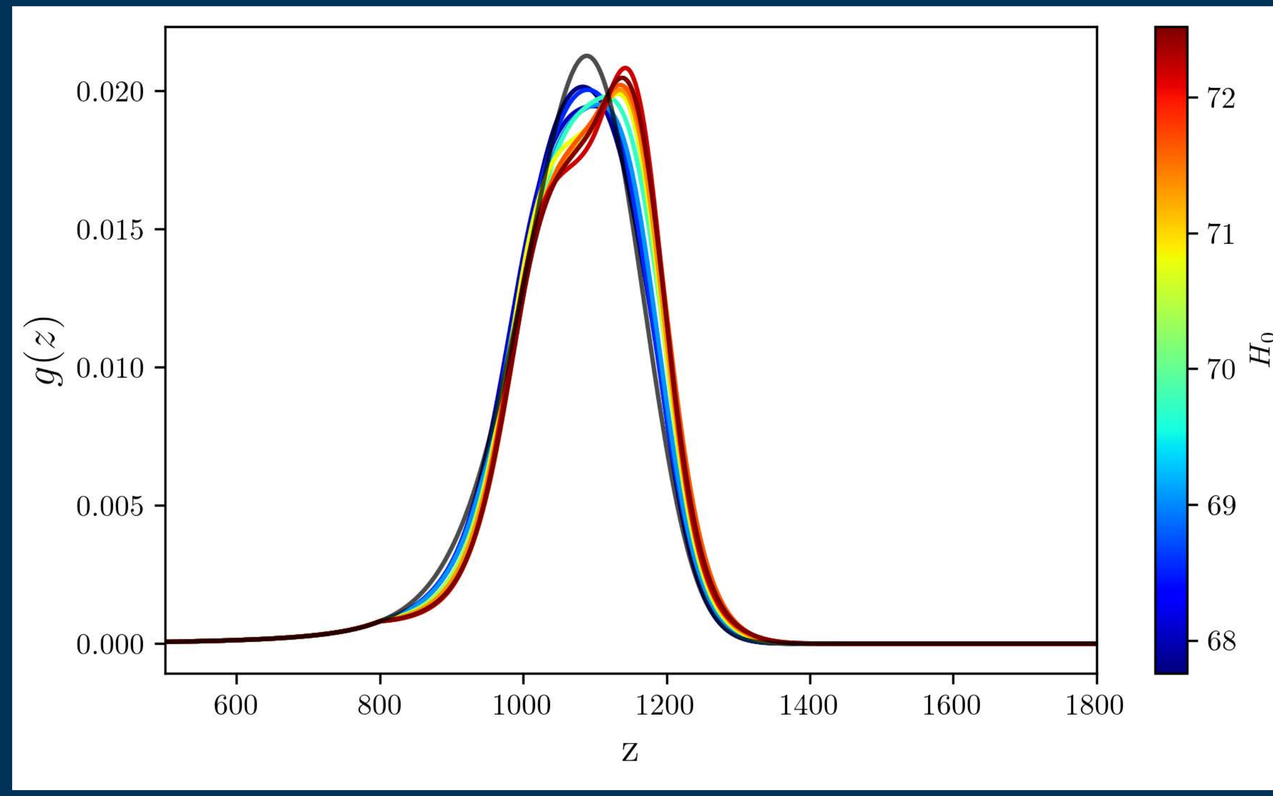

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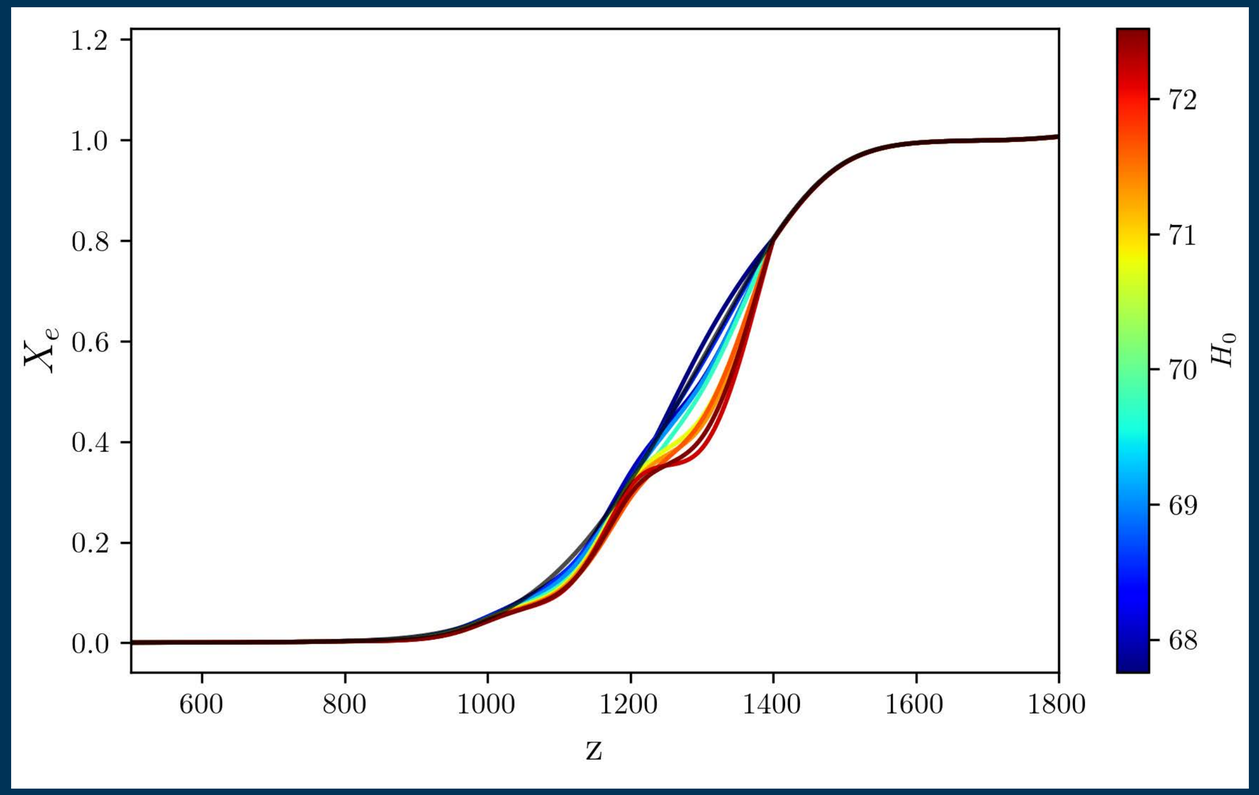
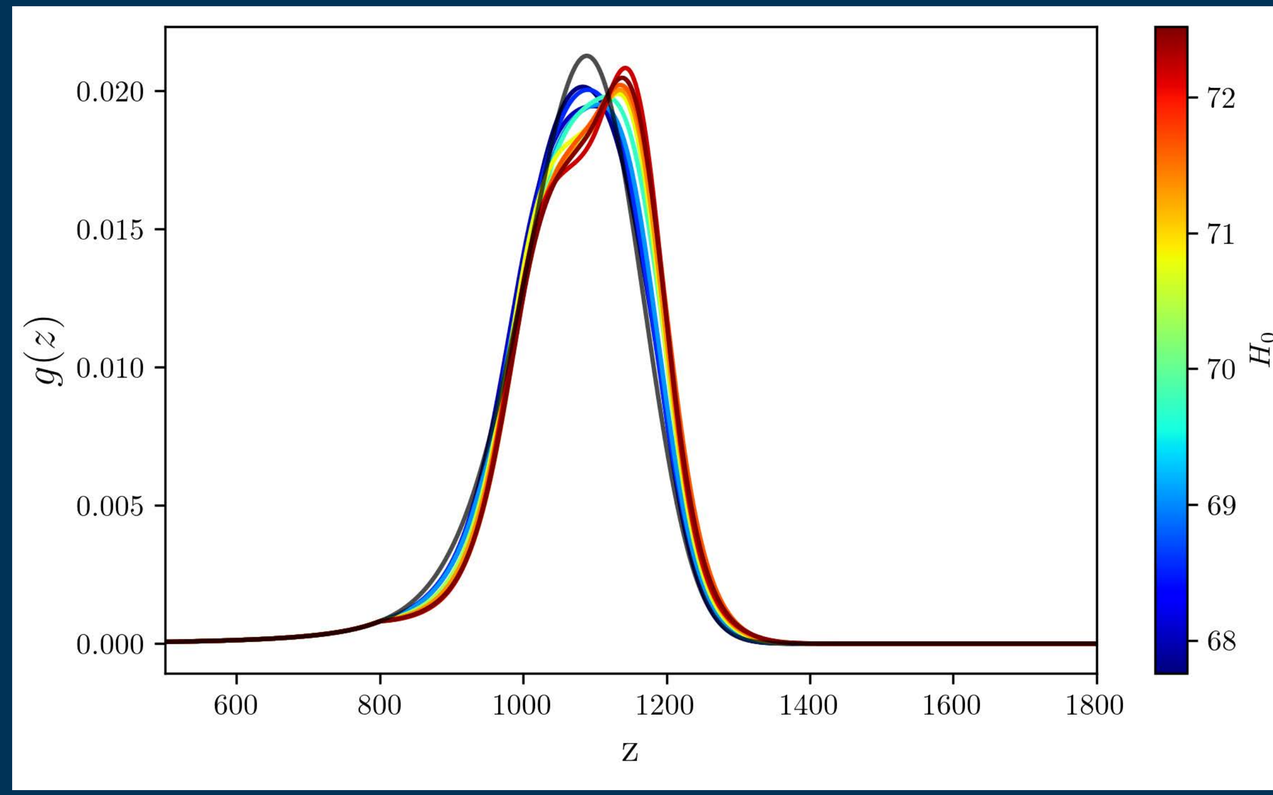
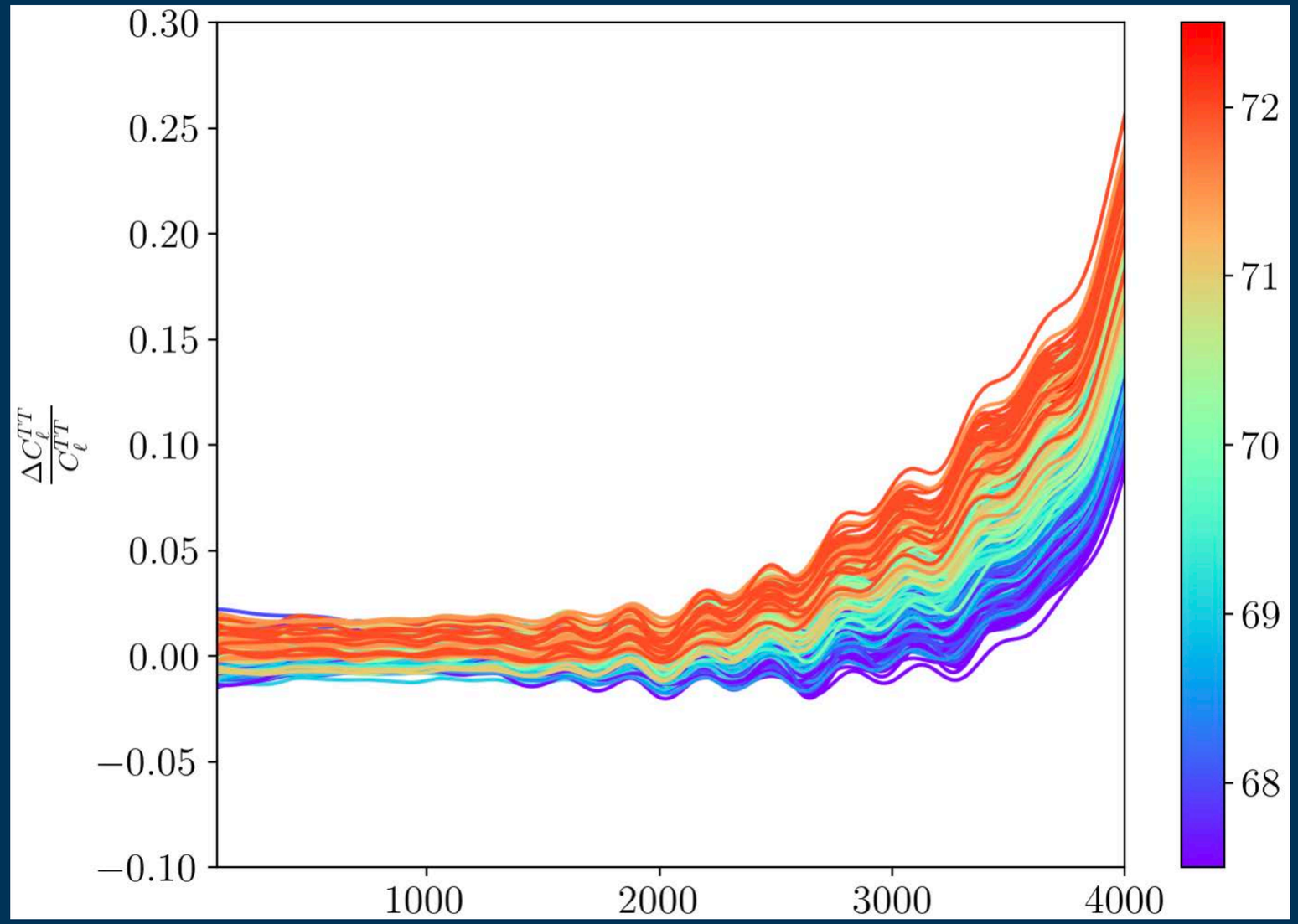


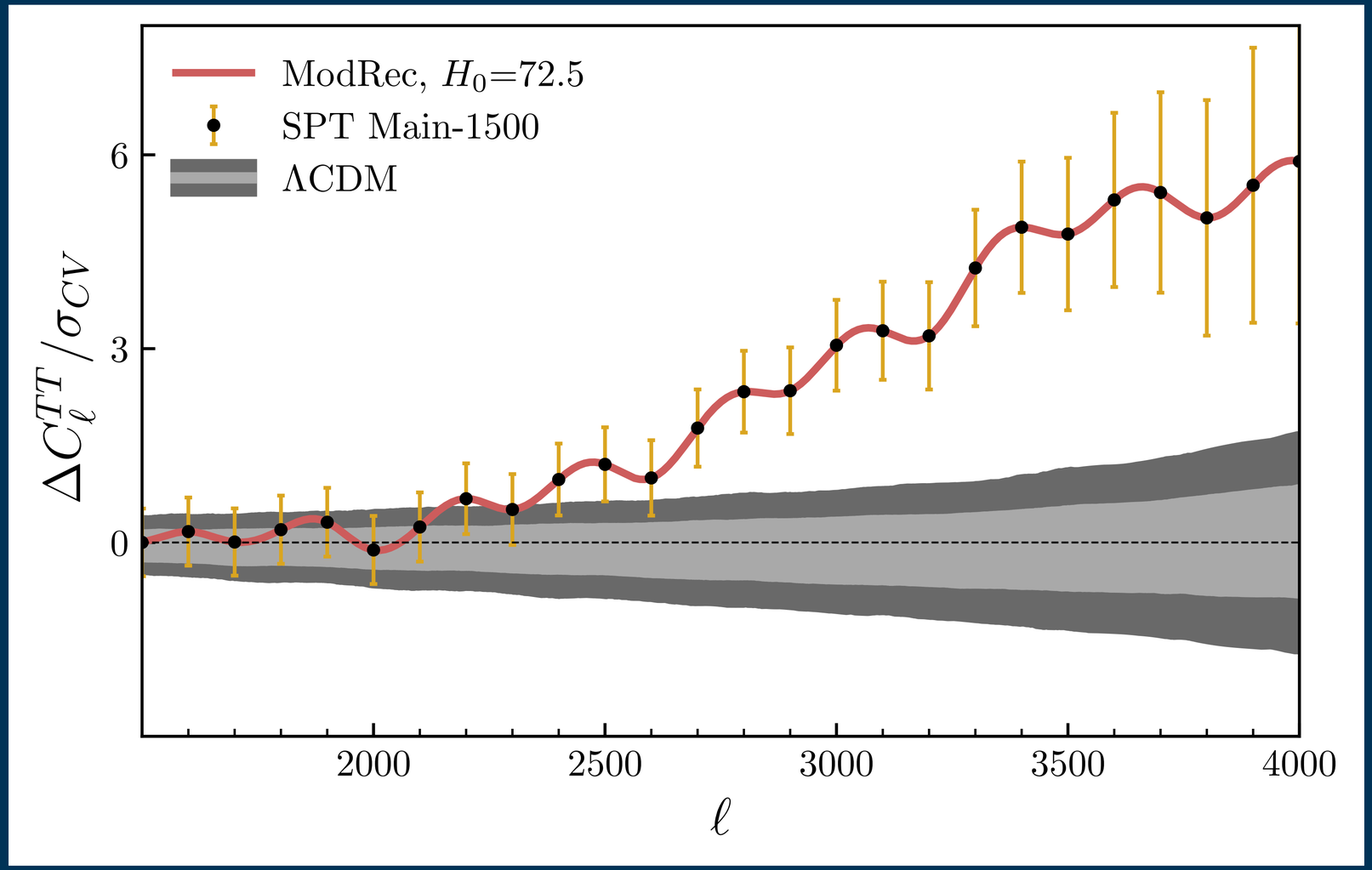


Provides a clear target for model builders: make recombination look like this and you have solved the Hubble tension. Might not be easy to do!

Planck data only probes multipoles out to $\ell \sim 2500$, so larger variations are unconstrained at very small scales



But these small scale deviations will be constrained by upcoming (this year?) data from SPT-3G.



Key takeaways:

- The linear response approximation is overly restrictive for the recombination problem
- The data still allow for very different recombination histories
- The Hubble tension can be addressed via modifications to recombination
- Recombination can be more tightly constrained with high resolution measurements of CMB power spectra — many of these recombination histories will soon be ruled out