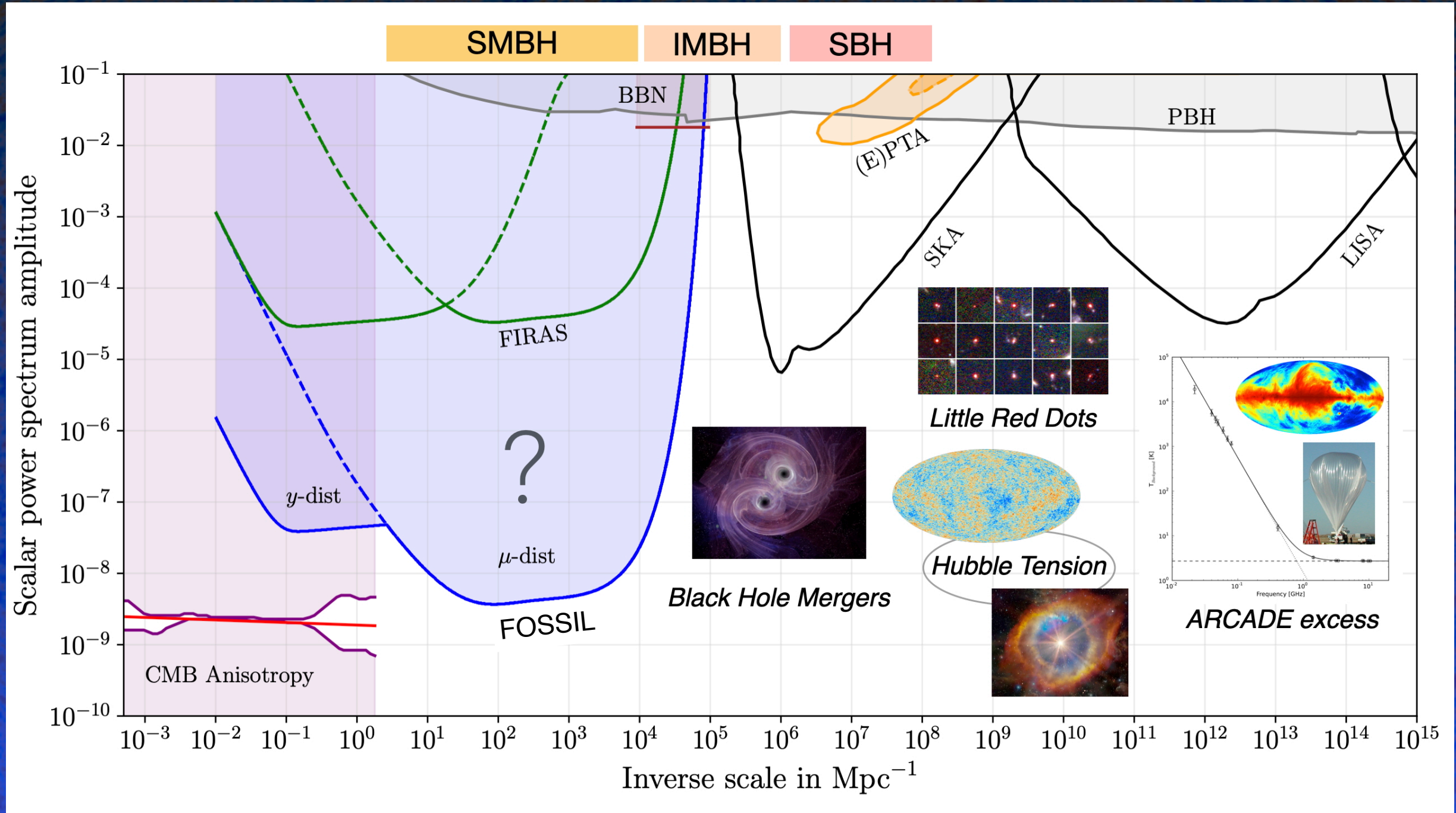
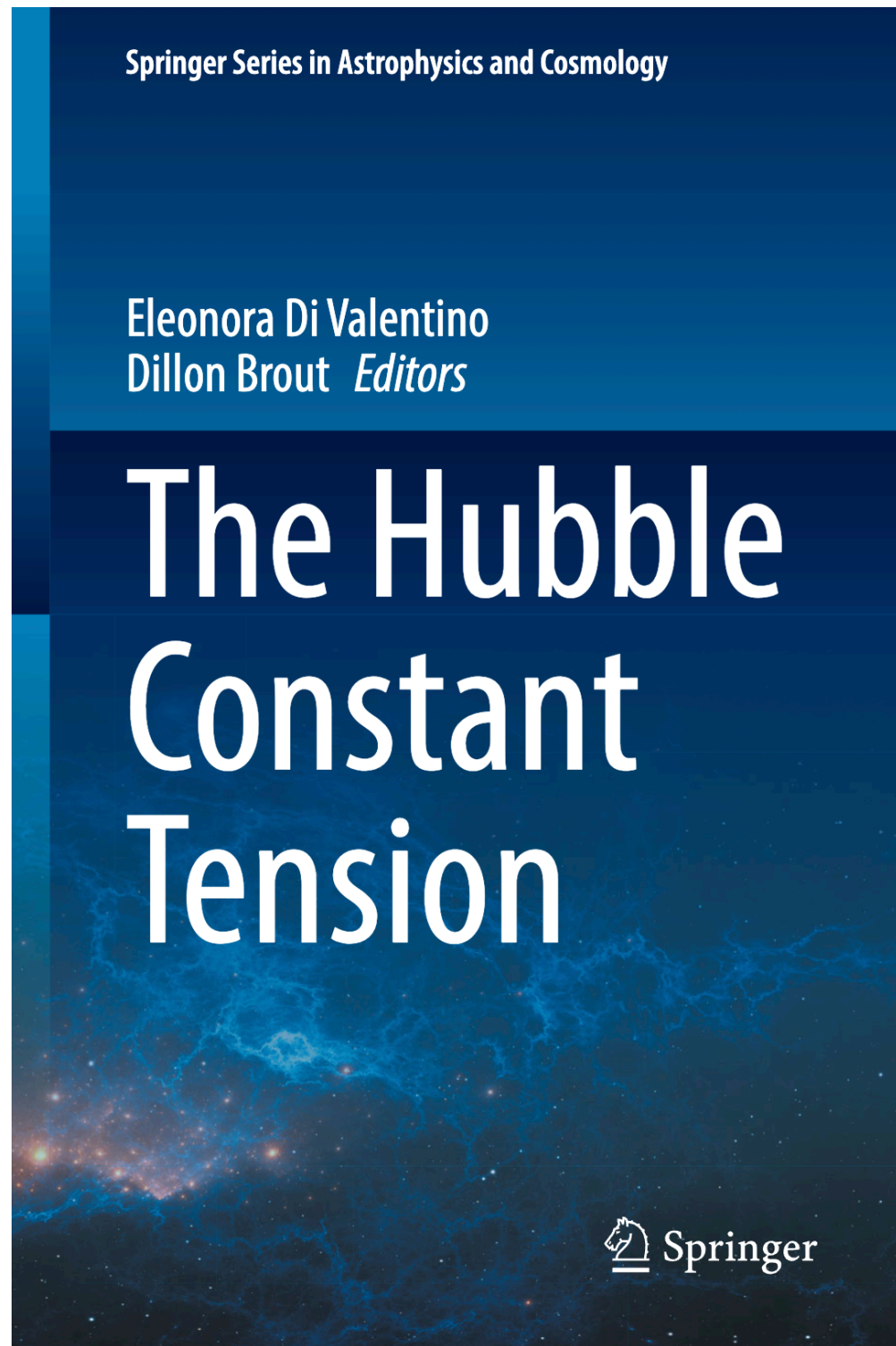


Modified recombination meets the Hubble tension



The Hubble tension has been persistent...

The Hubble tension has been persistent...



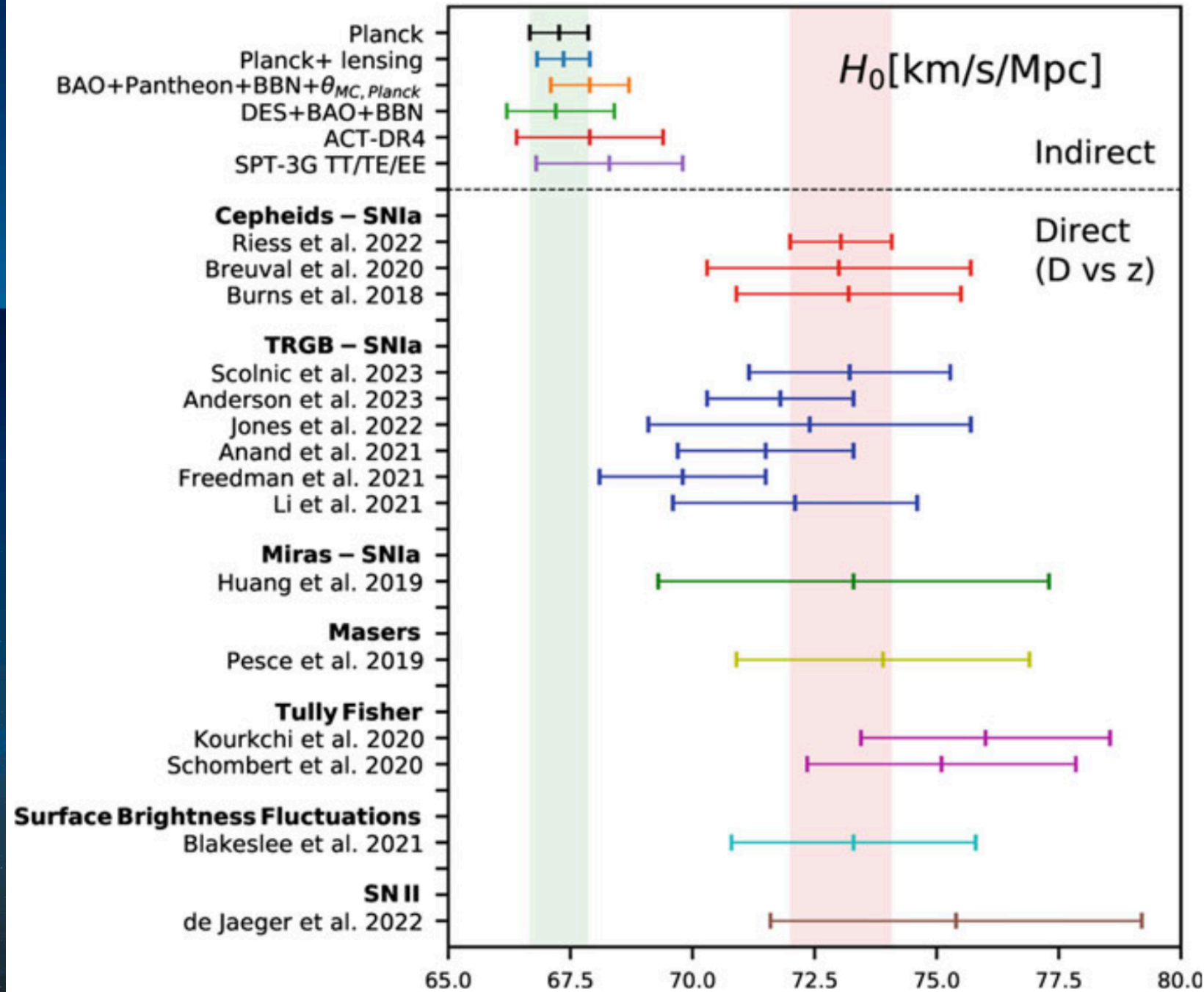
The Hubble tension has been persistent...

Springer Series in Astrophysics and Cosmology

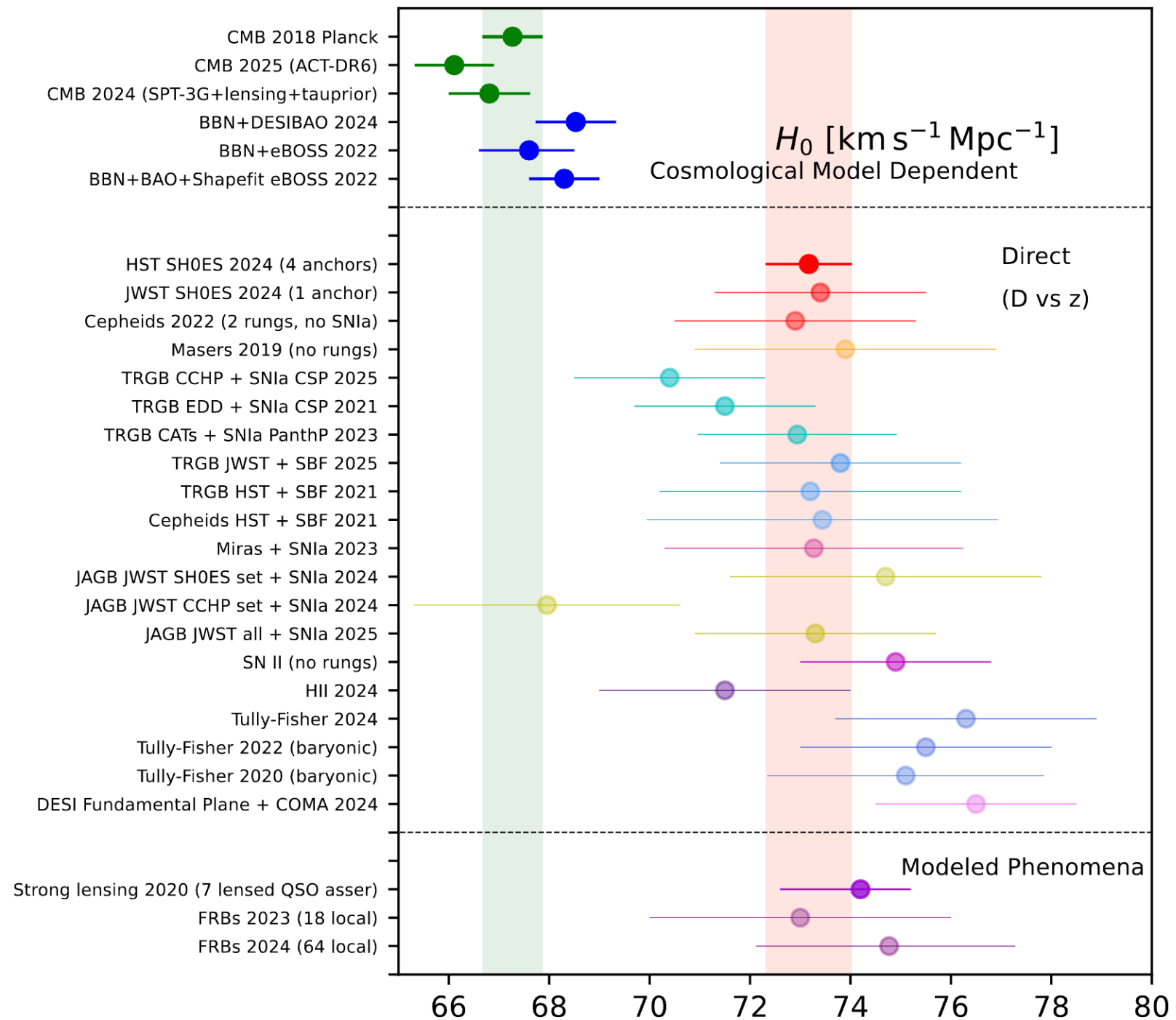
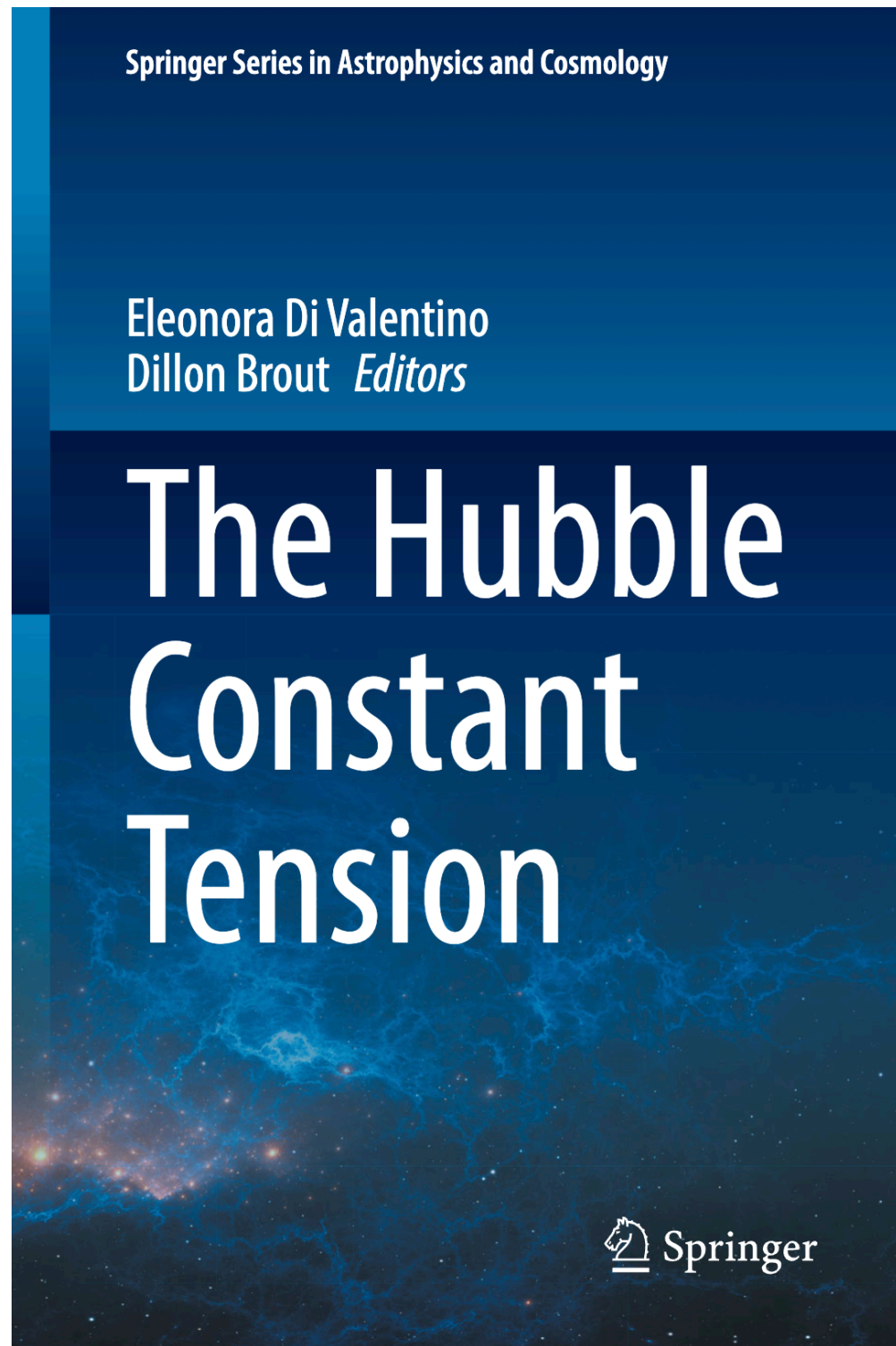
Eleonora Di Valentino
Dillon Brout *Editors*

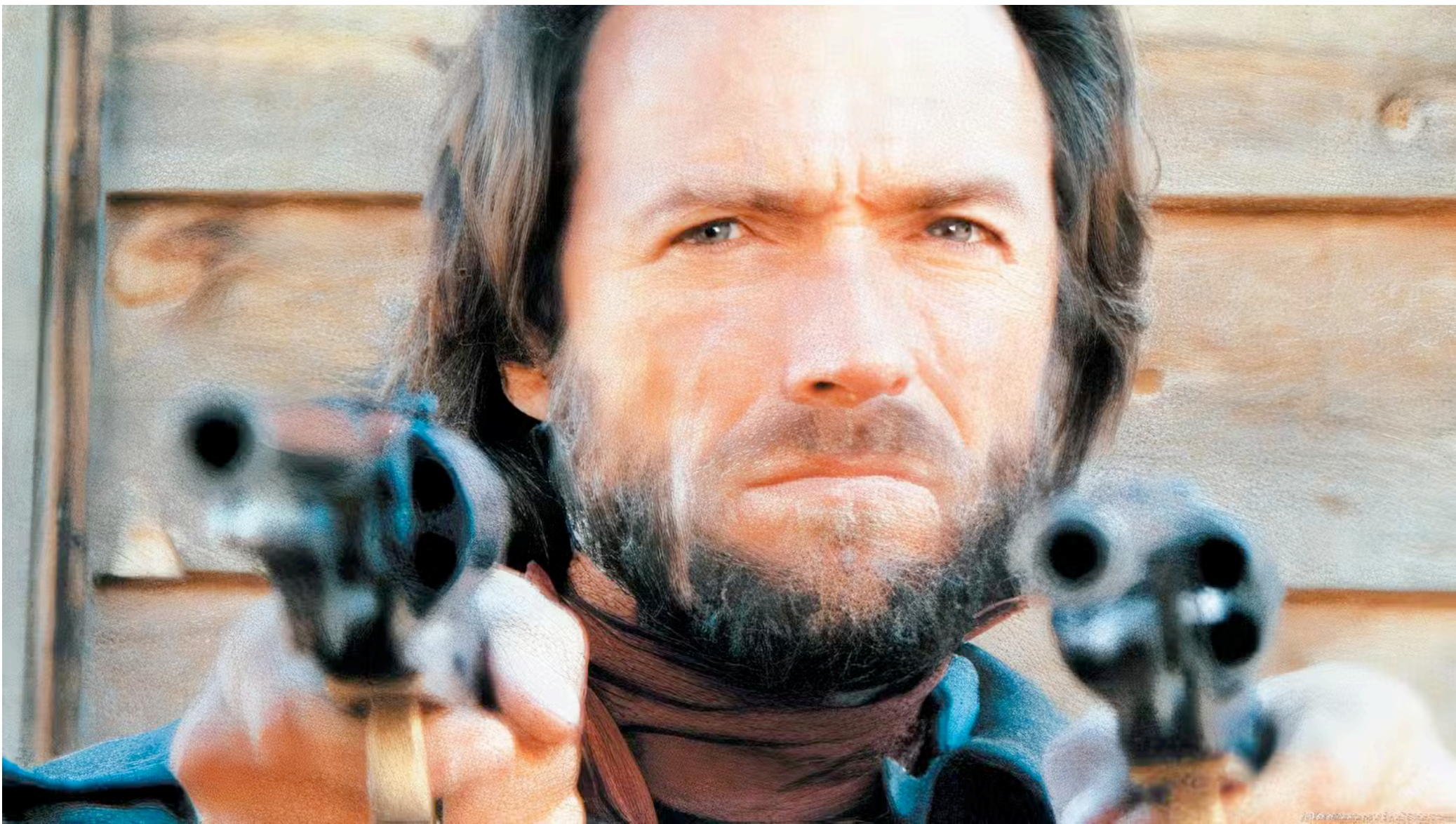
The Hubble Constant Tension

 Springer



The Hubble tension has been persistent...

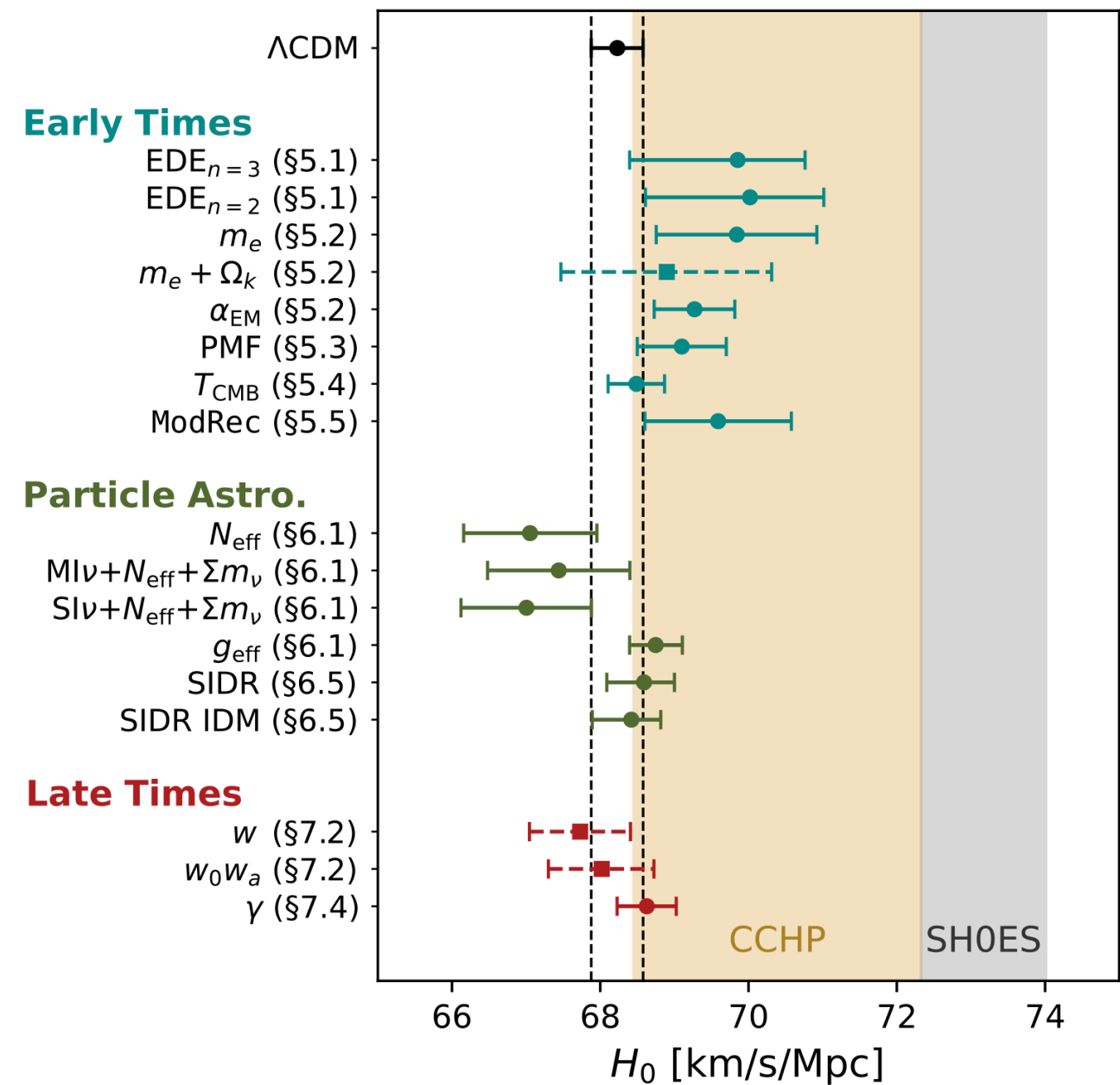
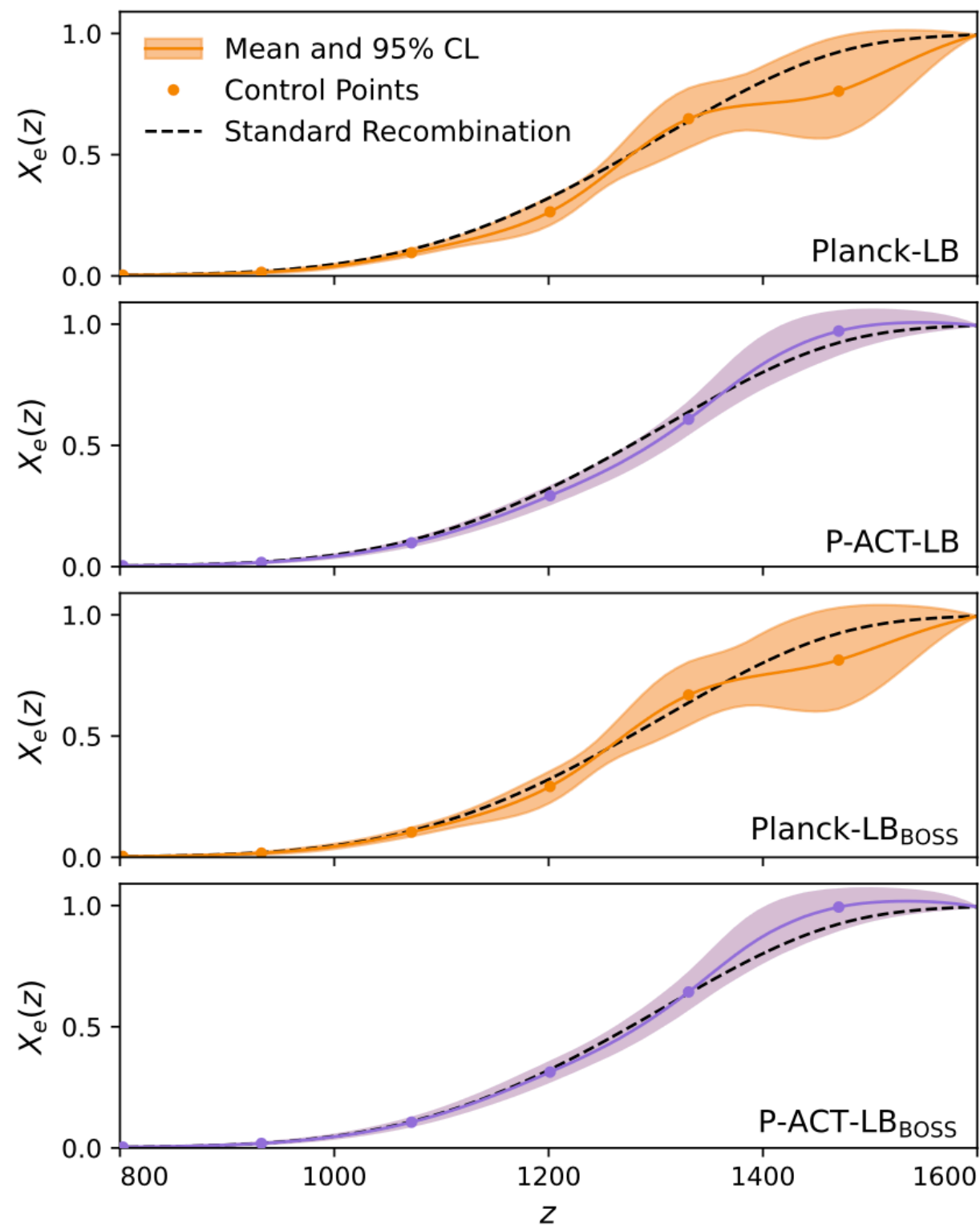




One of the *showdowns* at
CMB@60 meeting in Torino

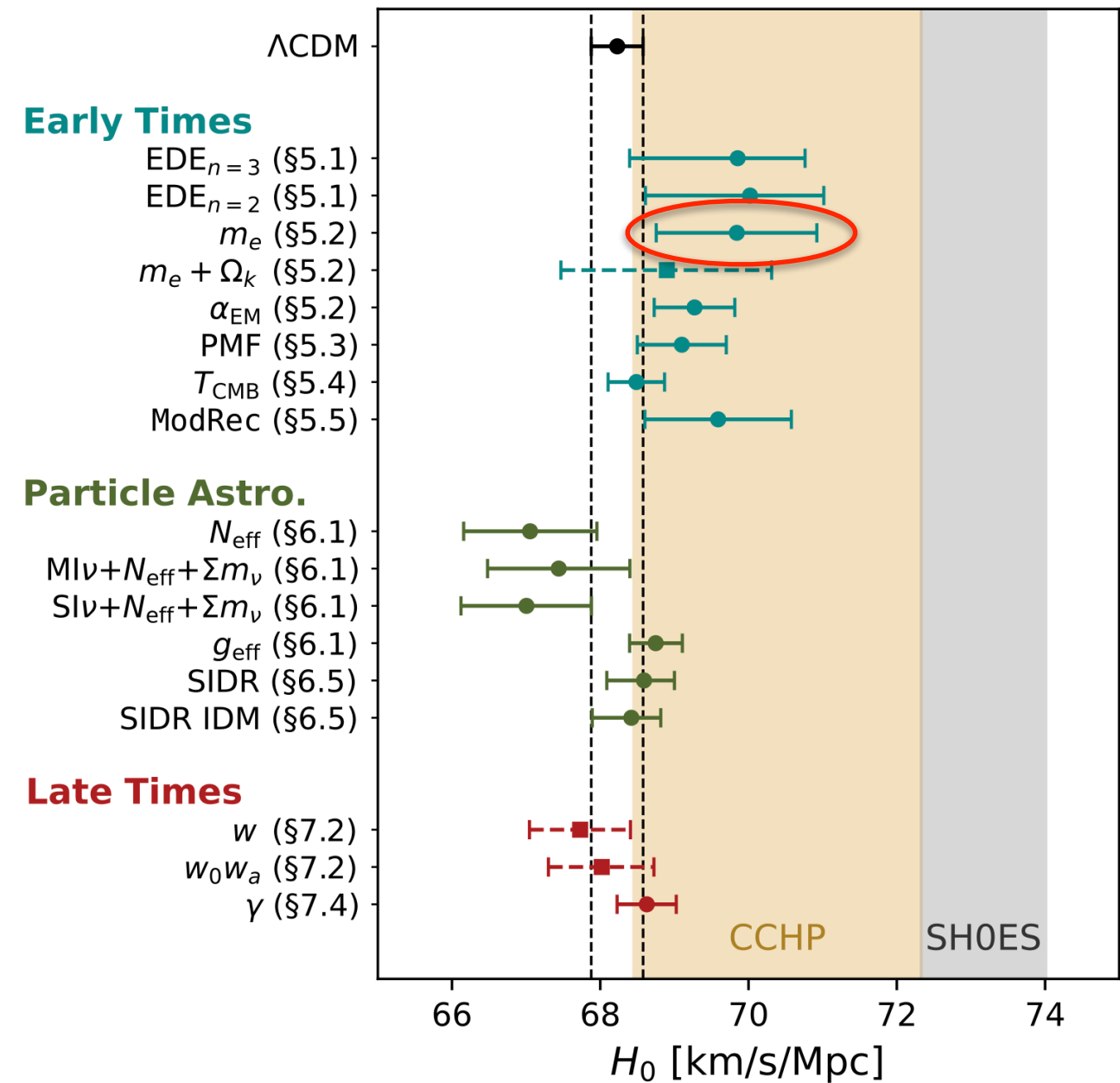
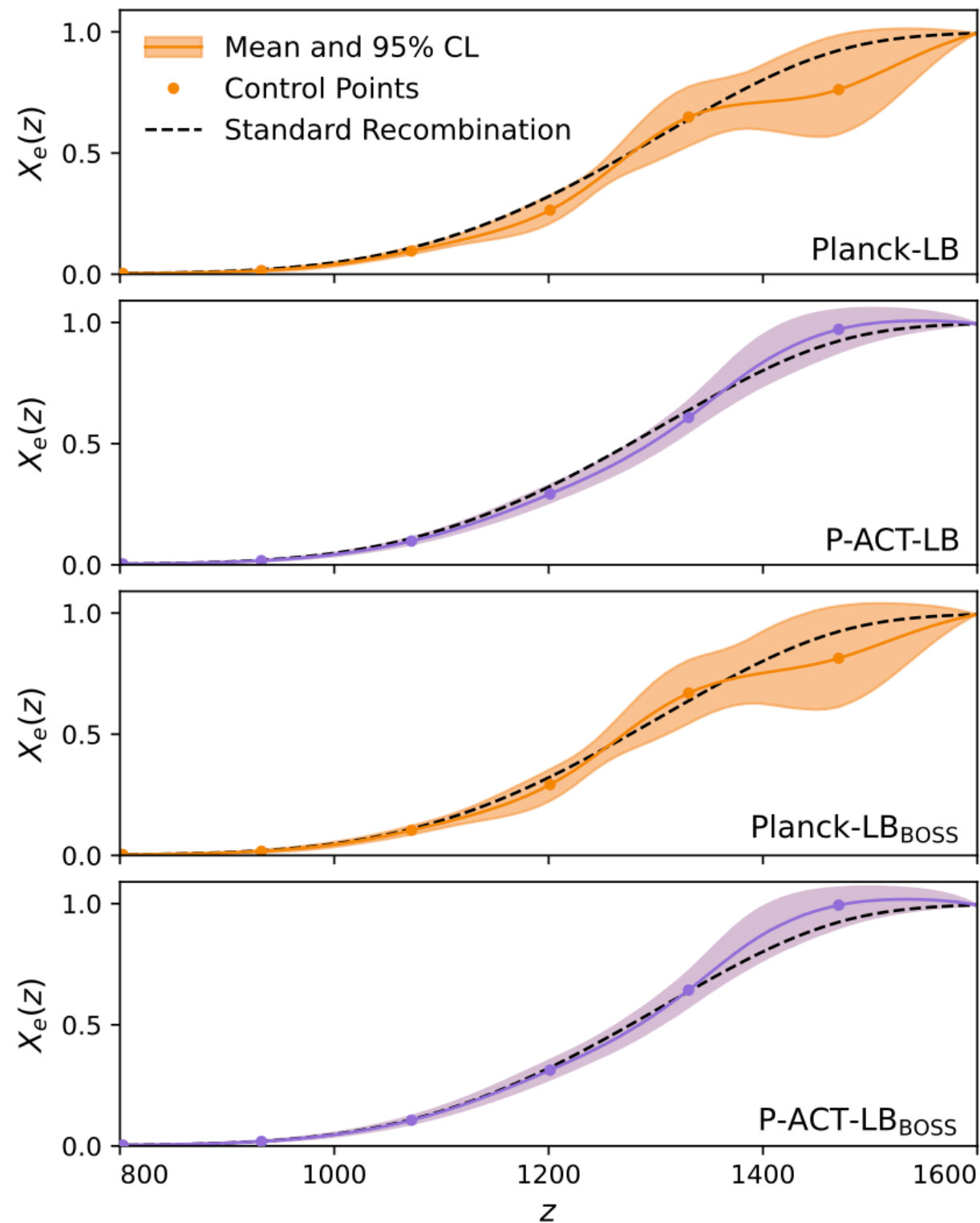


ACT Study of Extended Cosmological Models



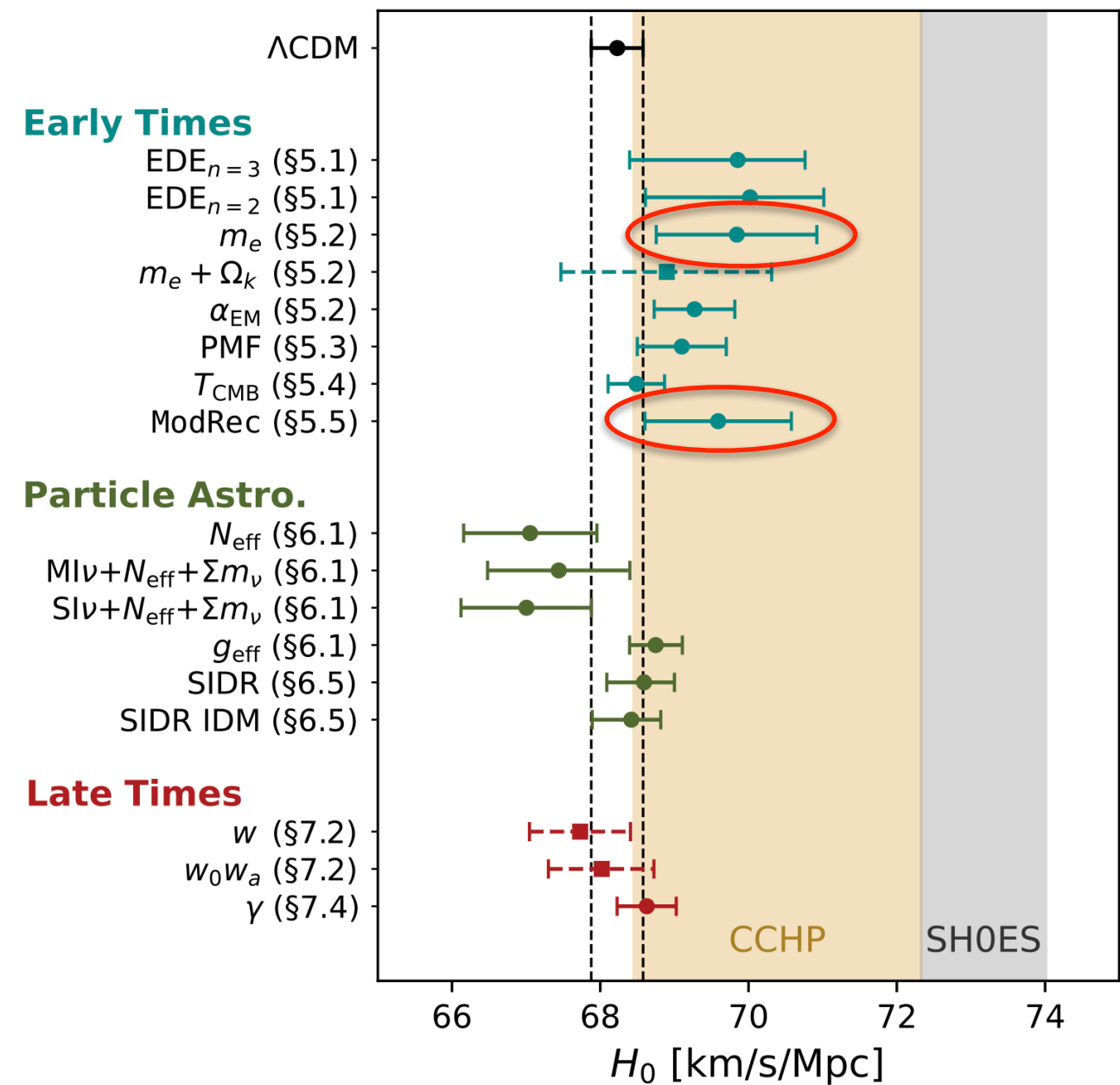
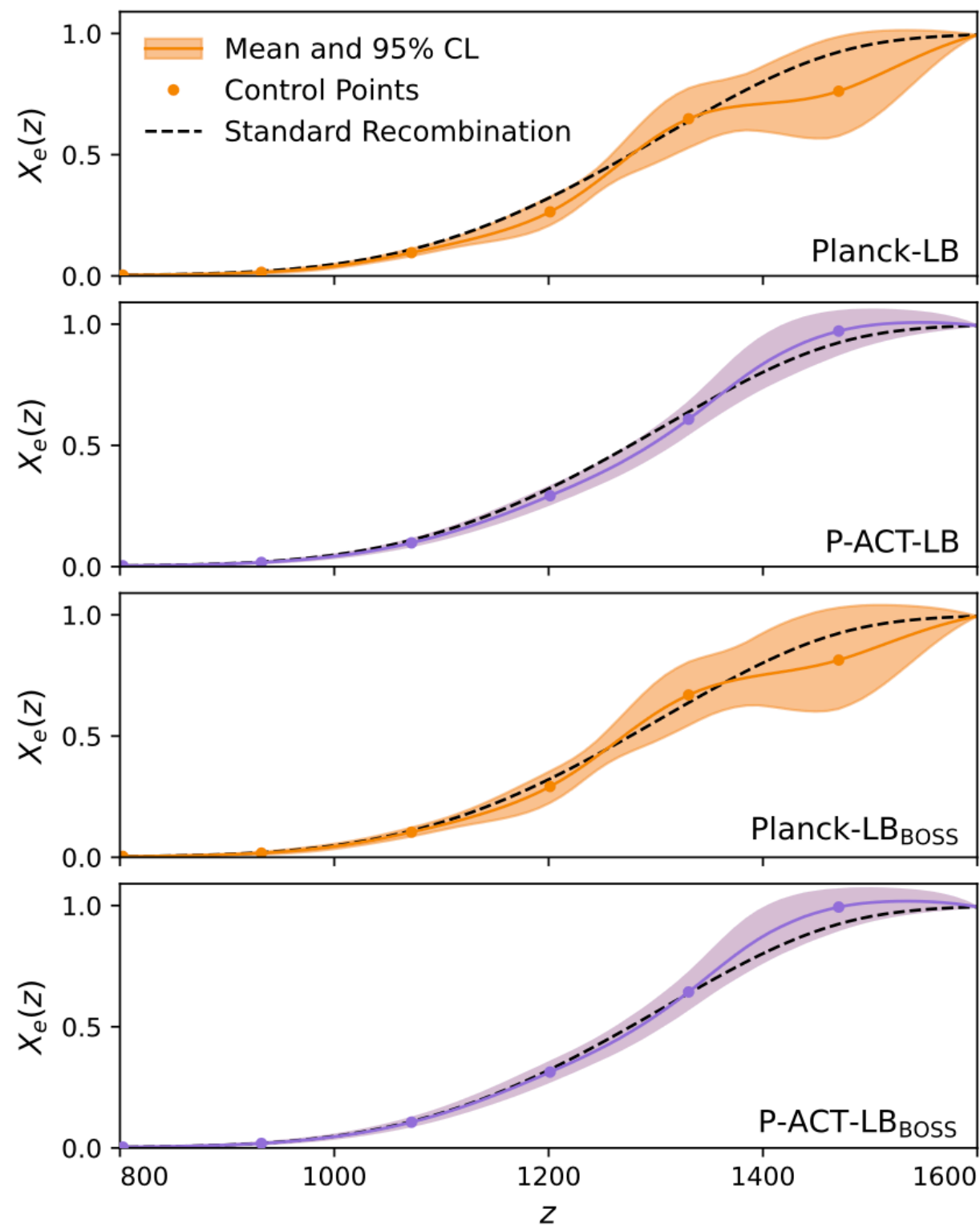
Modified recombination scenarios
do quite well in comparison to
other HT solutions!

ACT Study of Extended Cosmological Models



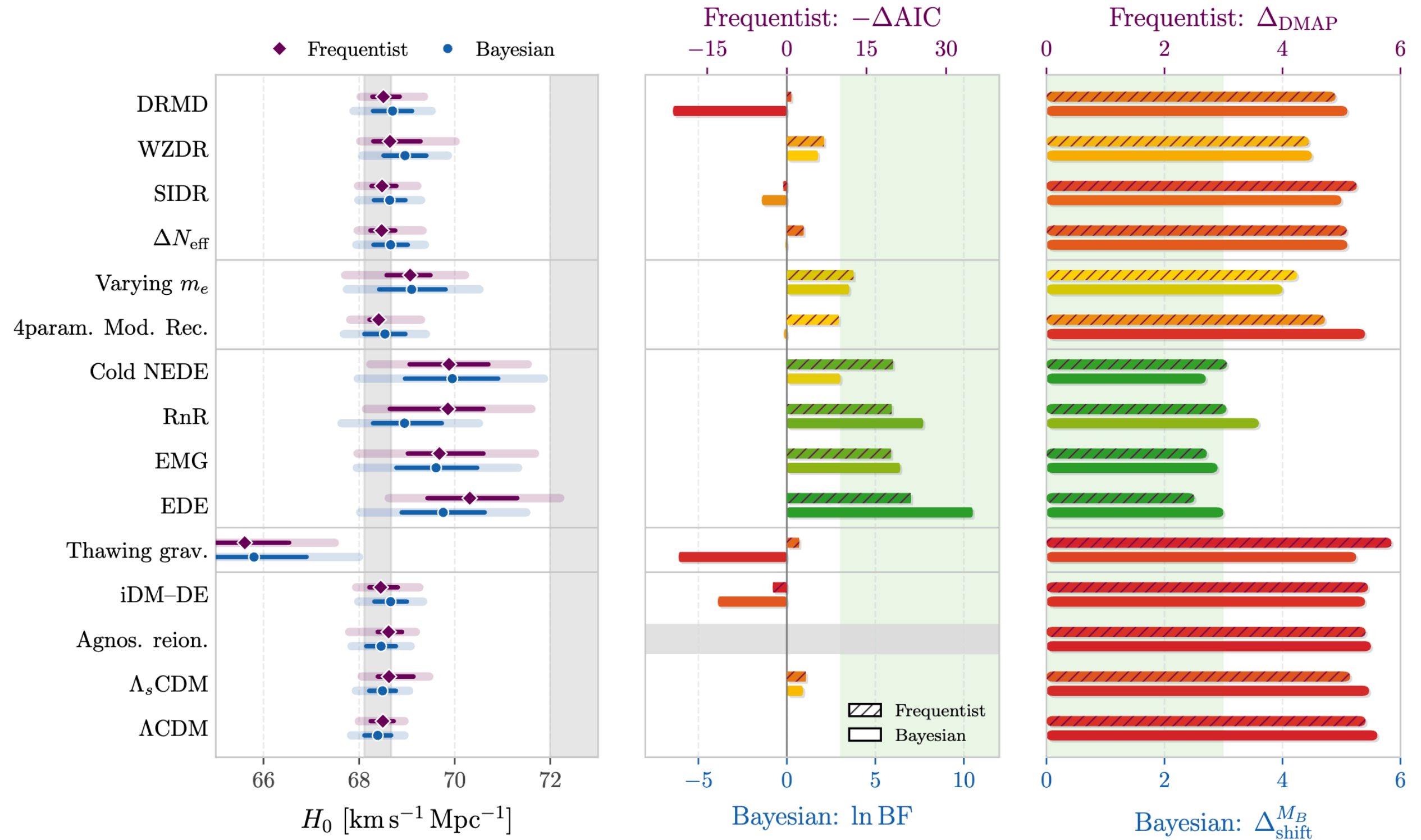
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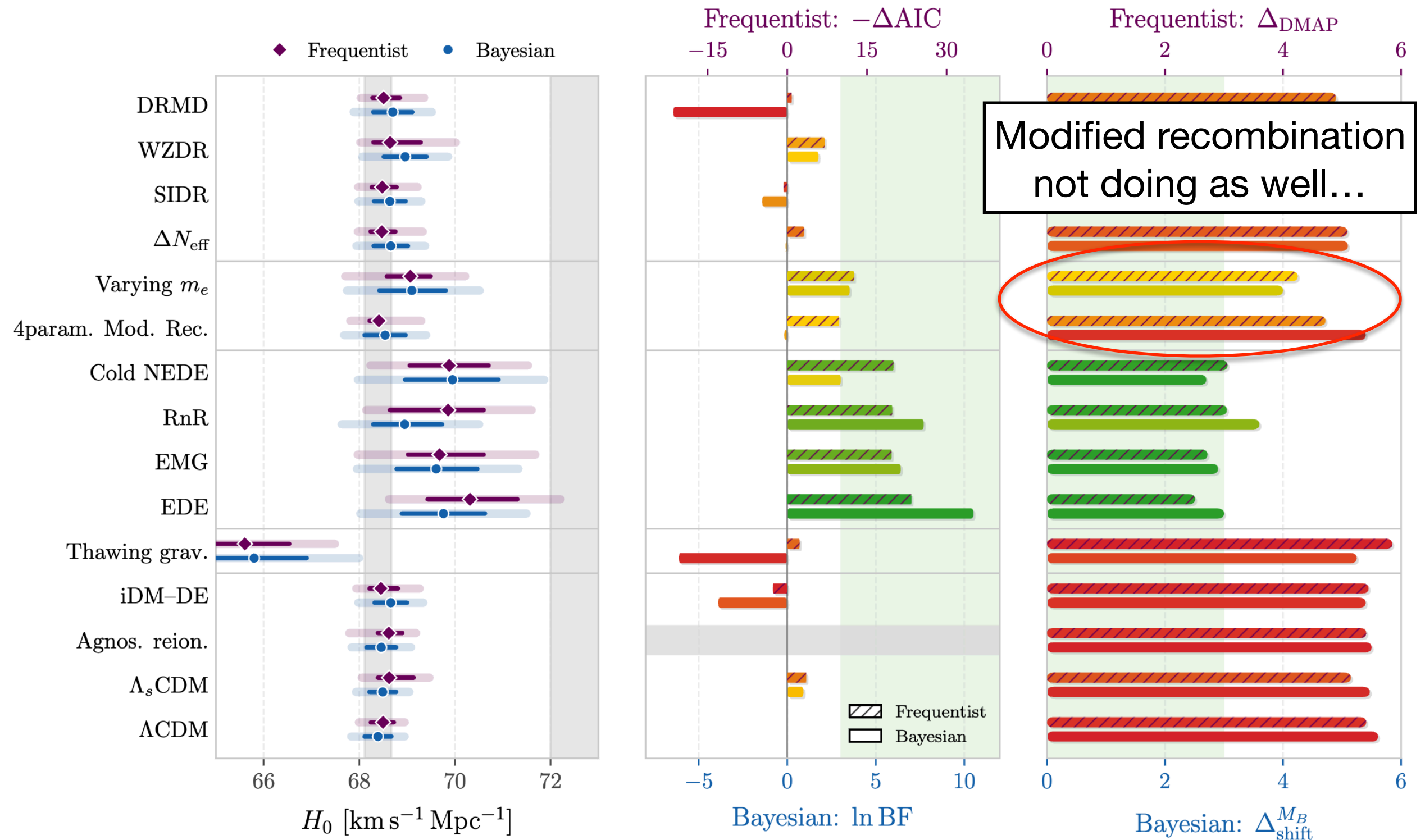


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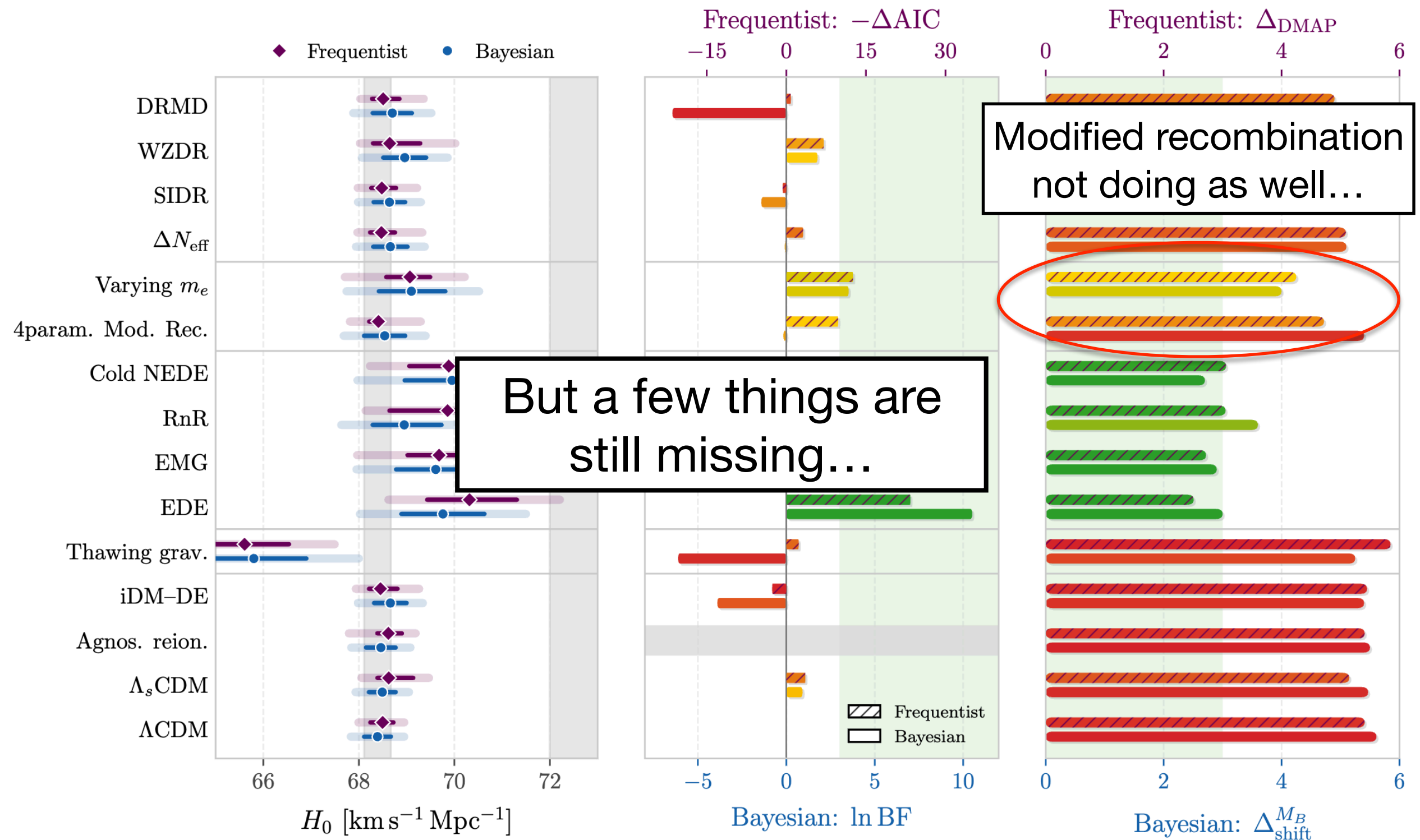
Lots of homework because of the world cups!



Lots of homework because of the world cups!



Lots of homework because of the world cups!



Itô calculus meets the Hubble tension: Effects of small-scale electron density fluctuations on the CMB anisotropies

Jens Chluba^{1★}, Geoffrey Vasil² and Richard Battye¹

¹*Jodrell Bank Centre for Astrophysics, School of Physics and Astronomy, The University of Manchester, Manchester M13 9PL, U.K.*

²*School of Mathematics and the Maxwell Institute for Mathematical Sciences, University of Edinburgh, EH9 3FD, U.K.*

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

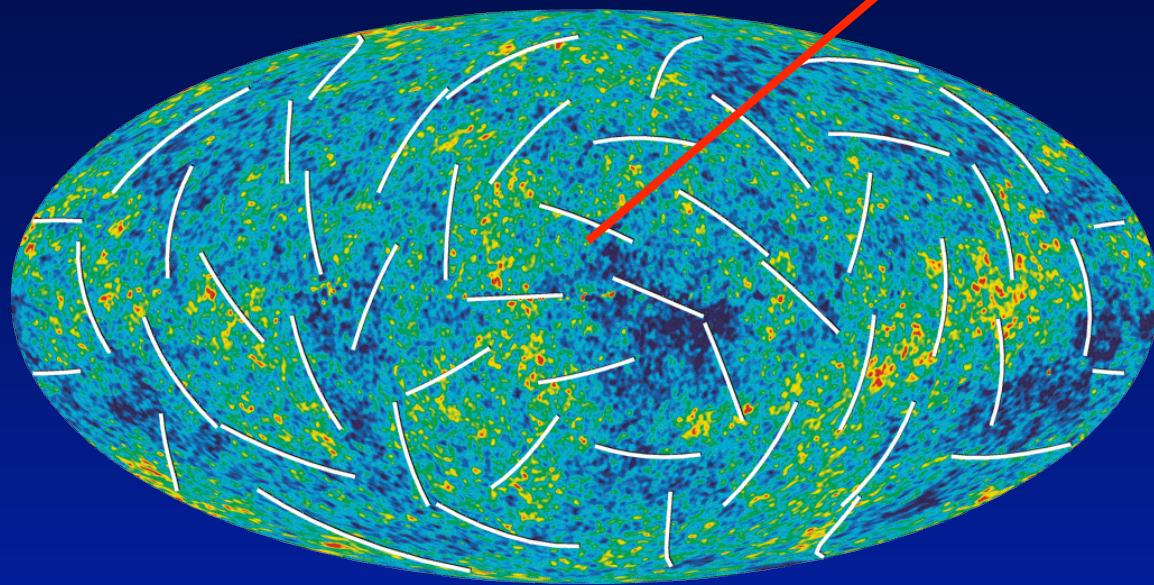
In this work, we develop a novel formalism to include the effect of electron density fluctuations at ultra small scales (well below the sound horizon at last scattering) on the observed anisotropies of the Cosmic Microwave Background (CMB). We treat the electron field as an independent stochastic variable and obtain the required ensemble-averaged photon Boltzmann equations using Itô calculus. Beyond changes to the average recombination history (which can be incorporated in the standard approach) our work identifies two new effects caused by the clumpiness of the medium. The first is a correction to the Thomson visibility function caused by correlations of the electron fluctuations along the line of sight, leading to an additional broadening of the visibility towards higher redshifts which causes extra damping and smearing of the CMB anisotropies. The second effect is a reduction of the effective scattering rate in the (pre-)recombination era that affects the photon transfer functions in a non-trivial manner. These new effects are subdominant in Λ CDM but can be significant in cosmologies with an early onset of structure formation (e.g., due to generation of enhanced small-scale power) as suggested by a number of indicators (e.g., the abundance of high redshift galaxies observed by JWST). We discuss the relevance of these new effects to the Hubble tension, finding that corrections which cannot be captured by simple modifications to the average recombination history arise. This highlights how important an understanding of the recombination process is in cosmological inference, and that a coordinated simulation and analysis campaign is required as part of the search for the origin of the various tensions in cosmology.

Key words: Cosmology - Cosmic Background Radiation; Cosmology - Theory

How does the recombination history enter all this?

CMB Sky → Cosmology

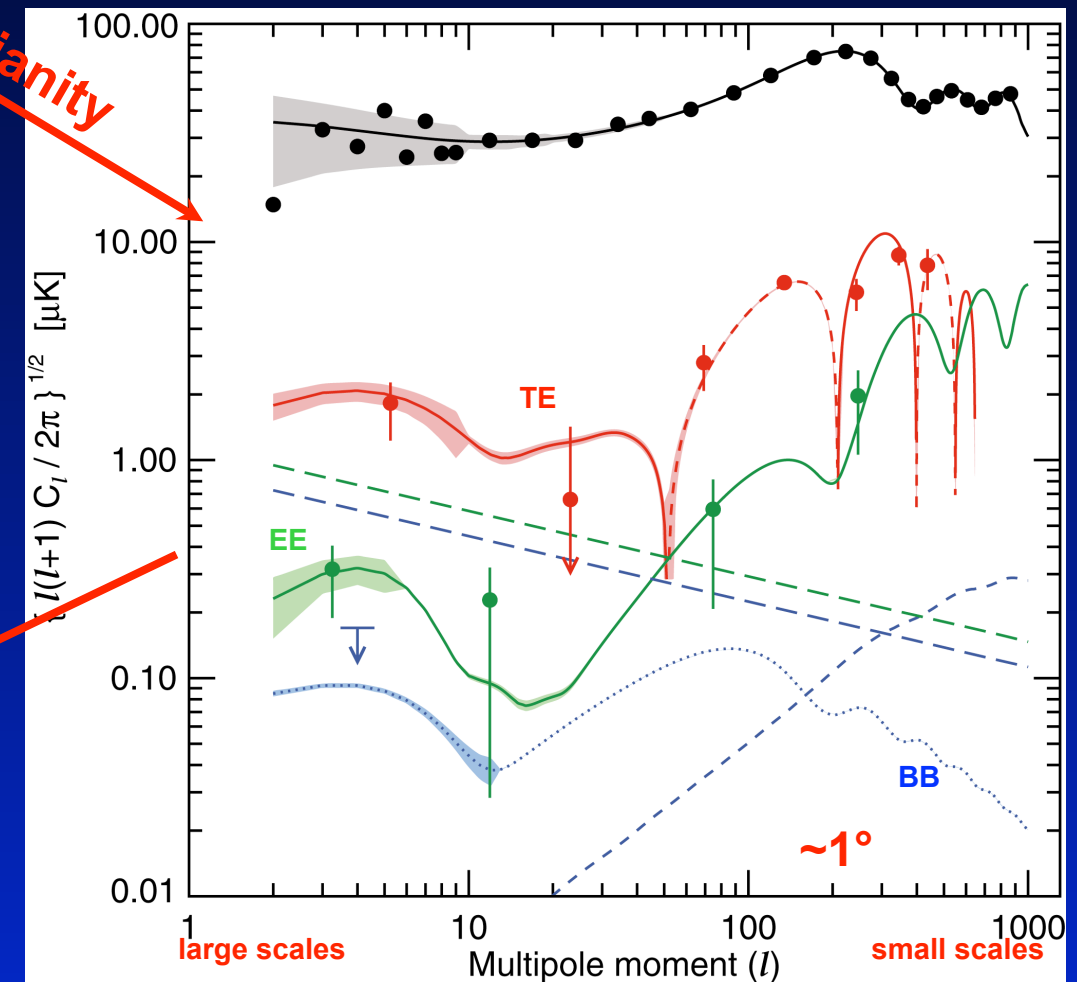
CMB Sky
(temperature & polarization)



a_{lm}

Gaussianity

Power spectra



Cosmological
Parameters

$\Omega_{\text{tot}}, \Omega_{\text{m}}, \Omega_{\text{b}}, \Omega_{\Lambda},$
 $h, \tau, n_{\text{s}}, \dots$

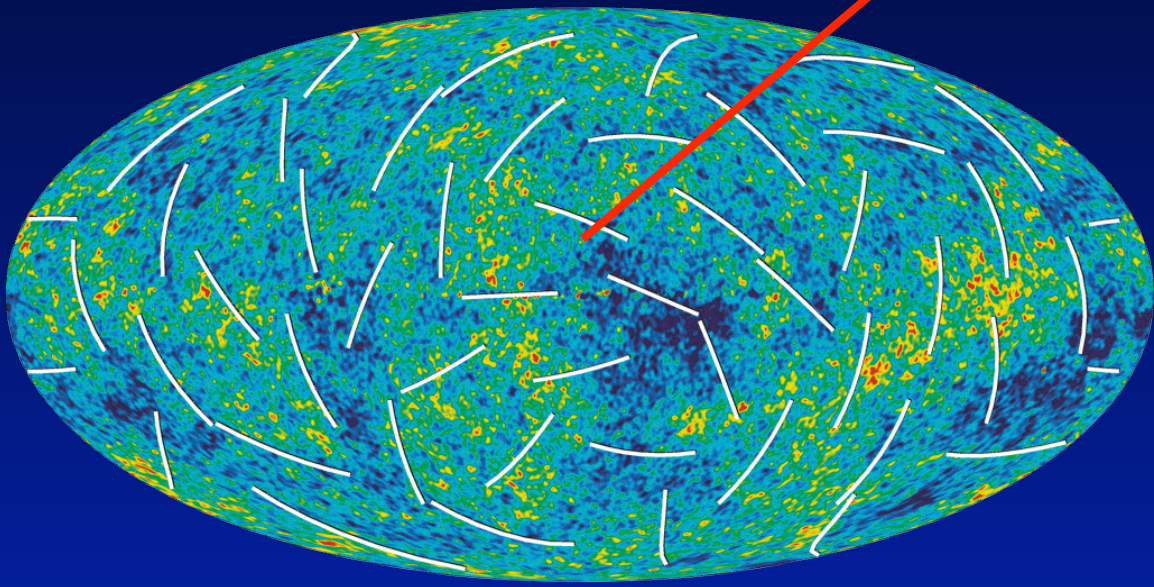
(Joint) analysis

Other cosmological Datasets:

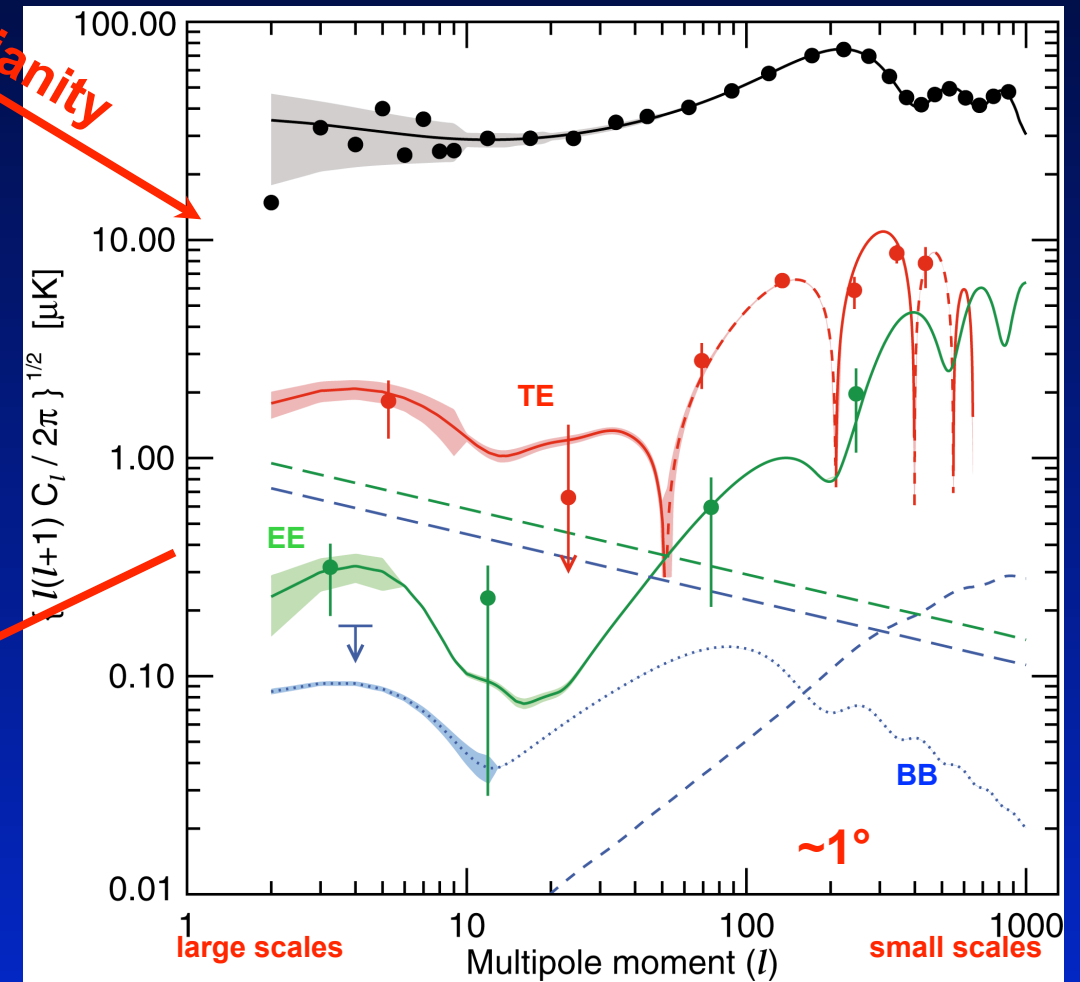
Supernovae, large-scale structure/BAO,
Lyman- α forest, weak lensing, ...

CMB Sky $\rightarrow$ Cosmology

CMB Sky (temperature & polarization)

 a_{lm} 
$$N_e(z)$$

Power spectra



Cosmological Parameters

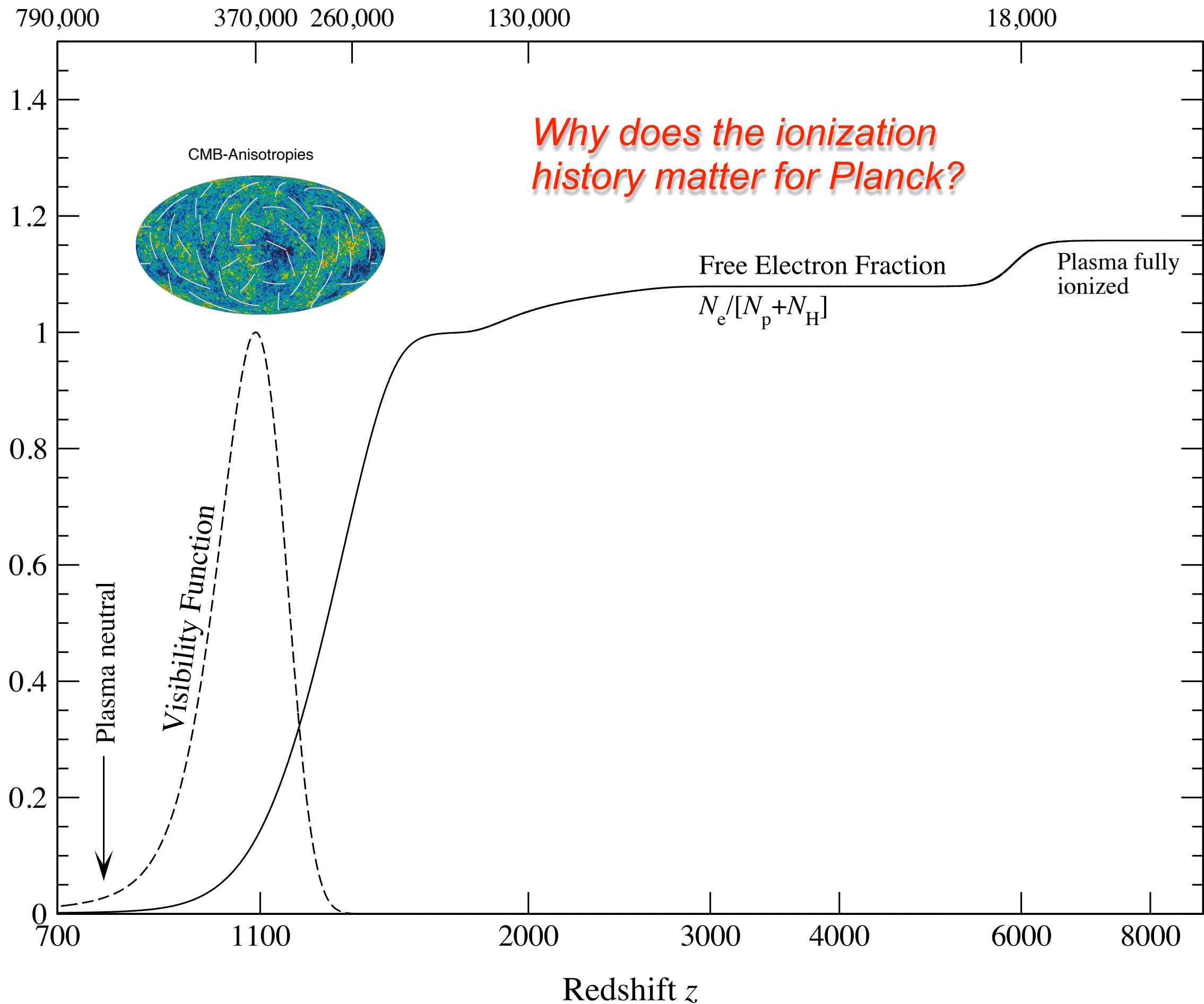
$$\Omega_{\text{tot}}, \Omega_{\text{m}}, \Omega_{\text{b}}, \Omega_{\Lambda},$$
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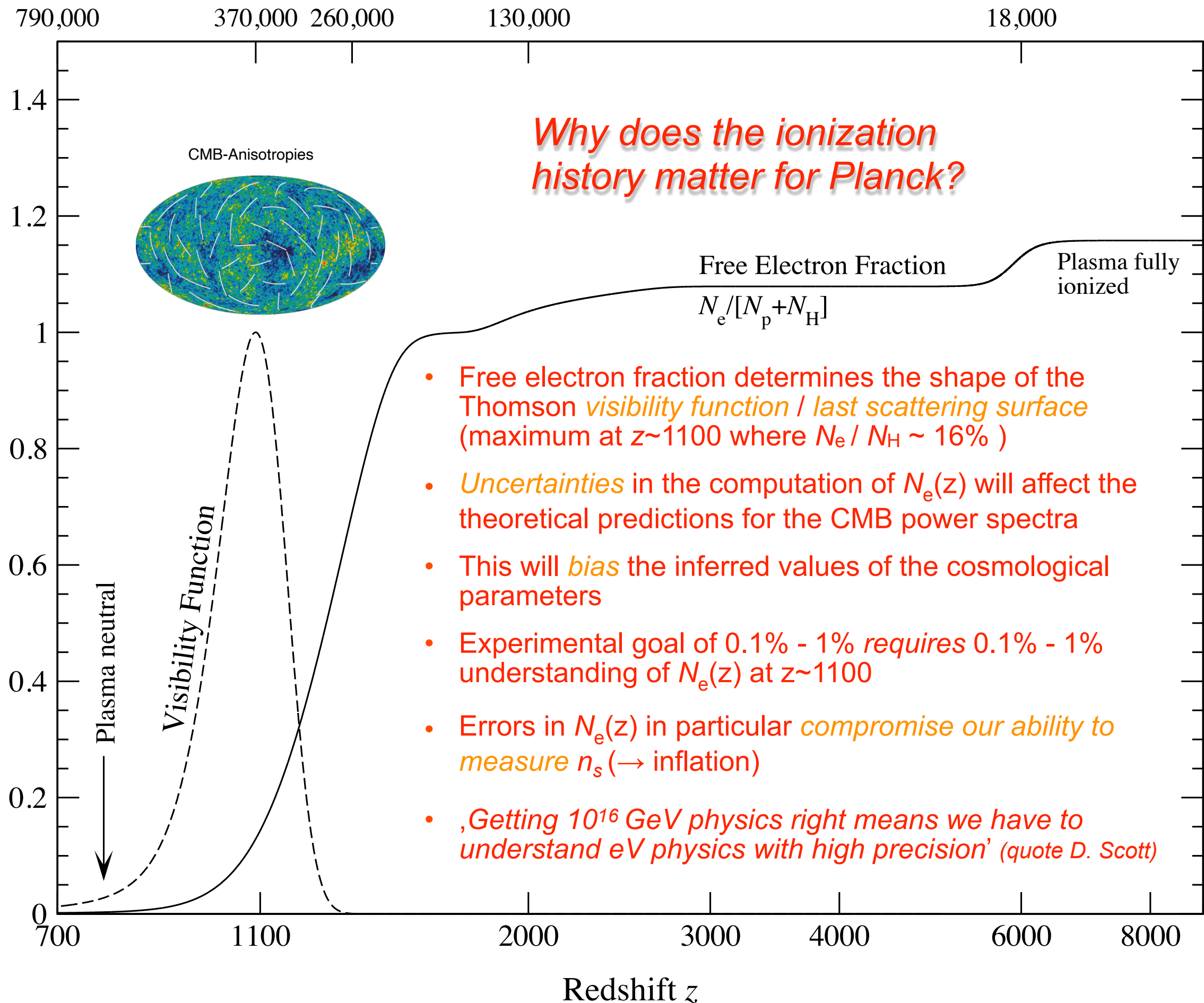
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Cosmological Time in Years



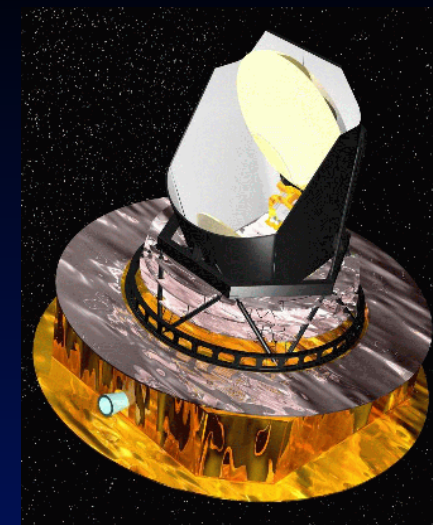
Cosmological Time in Years



Getting the job done for *Planck*

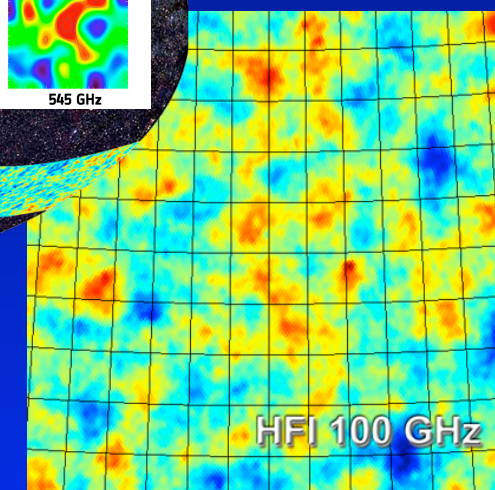
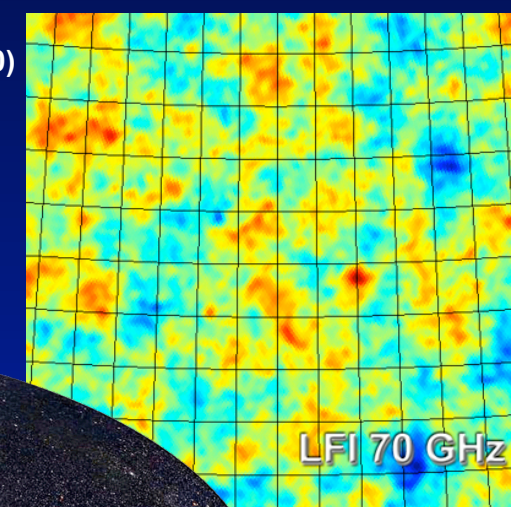
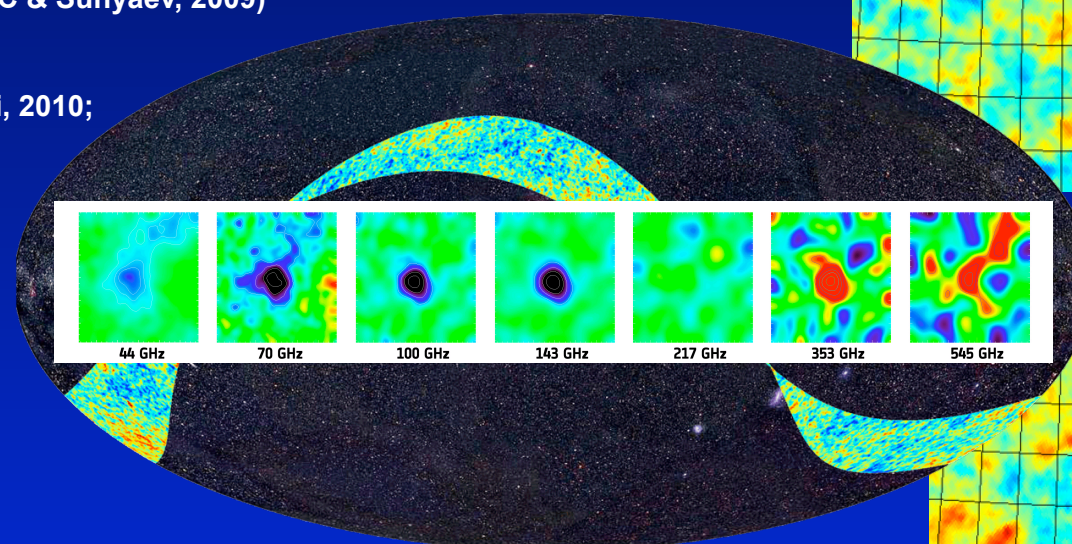
Hydrogen recombination

- Two-photon decays from higher levels
(Dubrovich & Grachev, 2005, Astr. Lett., 31, 359; Wong & Scott, 2007; JC & Sunyaev, 2007; Hirata, 2008; JC & Sunyaev 2009)
- Induced 2s two-photon decay for hydrogen
(JC & Sunyaev, 2006, A&A, 446, 39; Hirata 2008)
- Feedback of the Lyman- α distortion on the 1s-2s two-photon absorption rate
(Kholupenko & Ivanchik, 2006, Astr. Lett.; Fendt et al. 2008; Hirata 2008)
- Non-equilibrium effects in the angular momentum sub-states
(Rubiño-Martín, JC & Sunyaev, 2006, MNRAS; JC, Rubiño-Martín & Sunyaev, 2007, MNRAS; Grin & Hirata, 2009; JC, Vasil & Dursi, 2010)
- Feedback of Lyman-series photons ($\text{Ly}[n] \rightarrow \text{Ly}[n-1]$)
(JC & Sunyaev, 2007, A&A; Kholupenko et al. 2010; Haimoud, Grin & Hirata, 2010)
- Lyman- α escape problem (*atomic recoil, time-dependence, partial redistribution*)
(Dubrovich & Grachev, 2008; JC & Sunyaev, 2008; Forbes & Hirata, 2009; JC & Sunyaev, 2009)
- Collisions and Quadrupole lines
(JC, Rubiño-Martín & Sunyaev, 2007; Grin & Hirata, 2009; JC, Vasil & Dursi, 2010; JC, Fung & Switzer, 2011)
- Raman scattering
(Hirata 2008; JC & Thomas, 2010; Haimoud & Hirata, 2010)



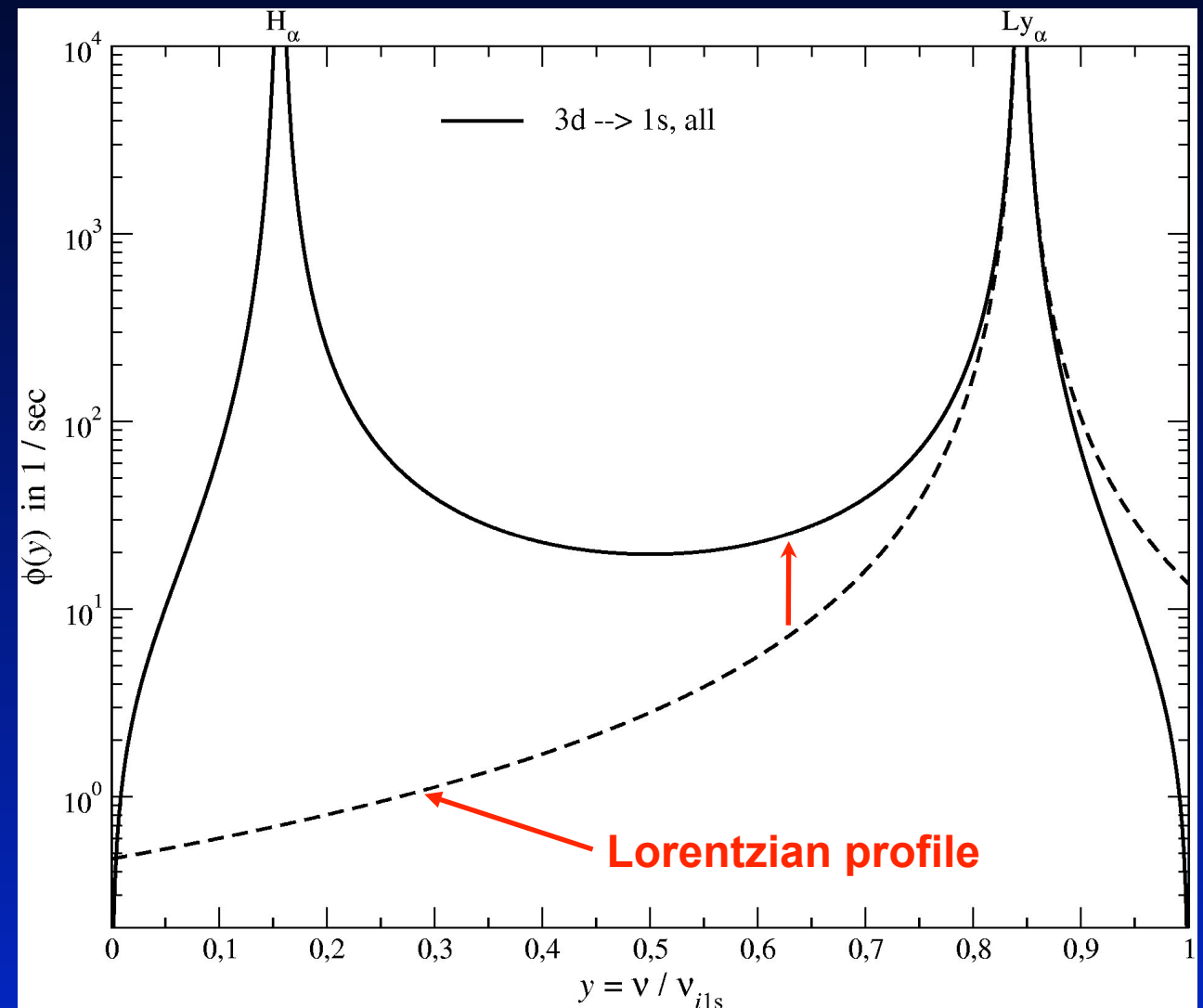
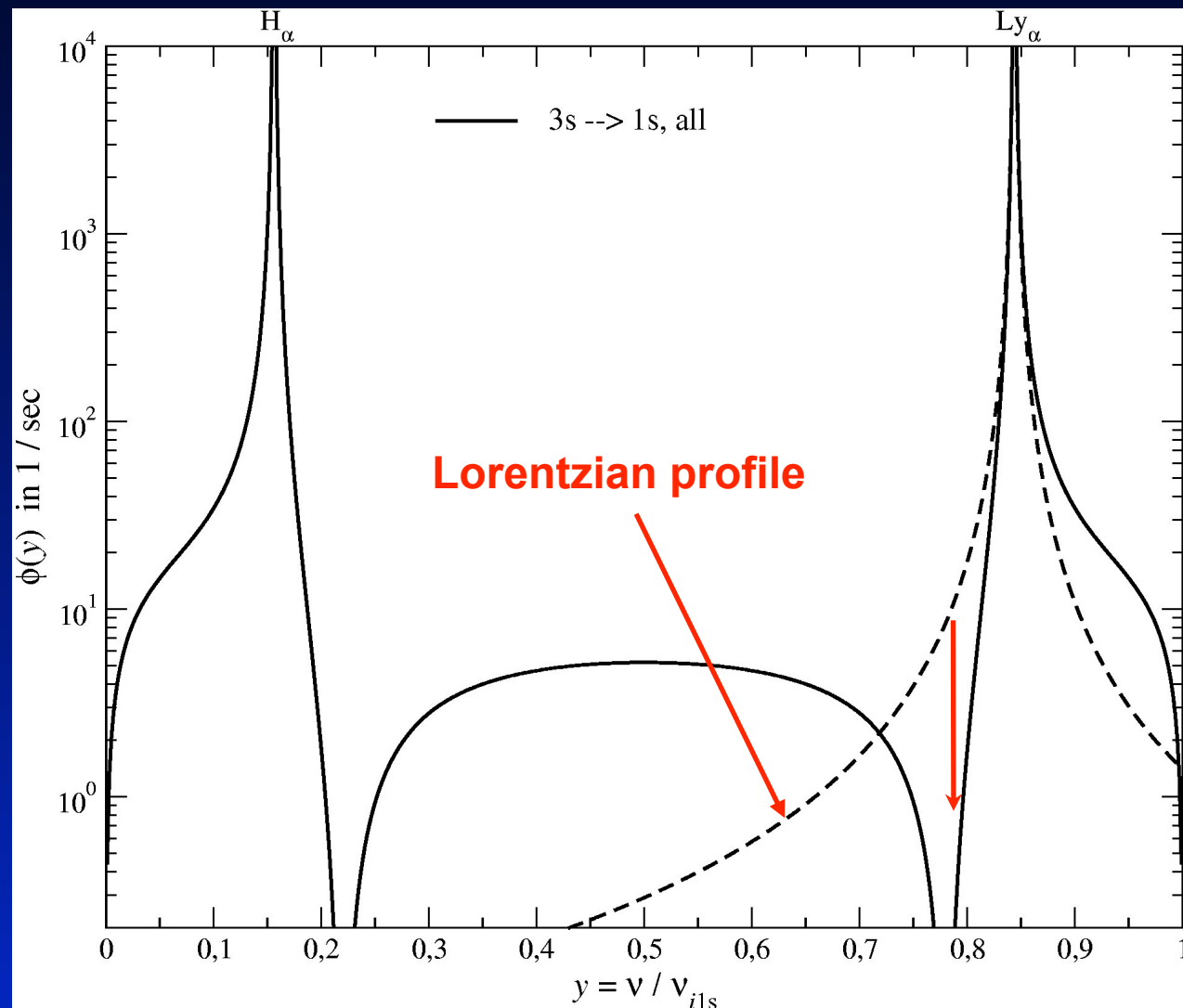
Helium recombination

- Similar list of processes as for hydrogen
(Switzer & Hirata, 2007a&b; Hirata & Switzer, 2007)
- Spin forbidden 2p-1s triplet-singlet transitions
(Dubrovich & Grachev, 2005, Astr. Lett.; Wong & Scott, 2007; Switzer & Hirata, 2007; Kholupenko, Ivanchik & Varshalovich, 2007)
- Hydrogen continuum opacity during He I recombination
(Switzer & Hirata, 2007; Kholupenko, Ivanchik & Varshalovich, 2007; Rubiño-Martín, JC & Sunyaev, 2007; JC, Fung & Switzer, 2011)
- Detailed feedback of helium photons
(Switzer & Hirata, 2007a; JC & Sunyaev, 2009, MNRAS; JC, Fung & Switzer, 2011)



$$\Delta N_e / N_e \sim 0.1 \%$$

3s and 3d two-photon decay spectrum

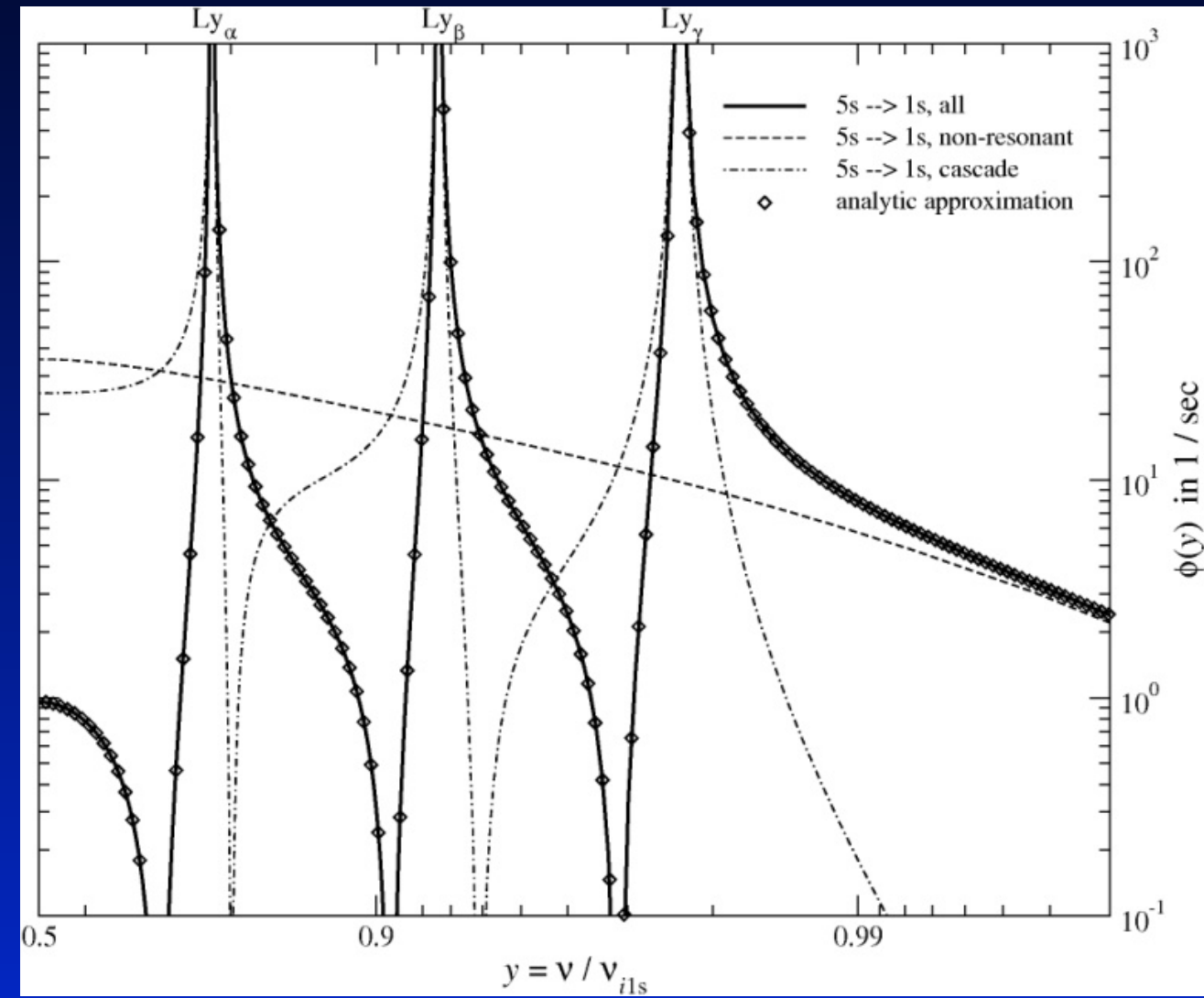
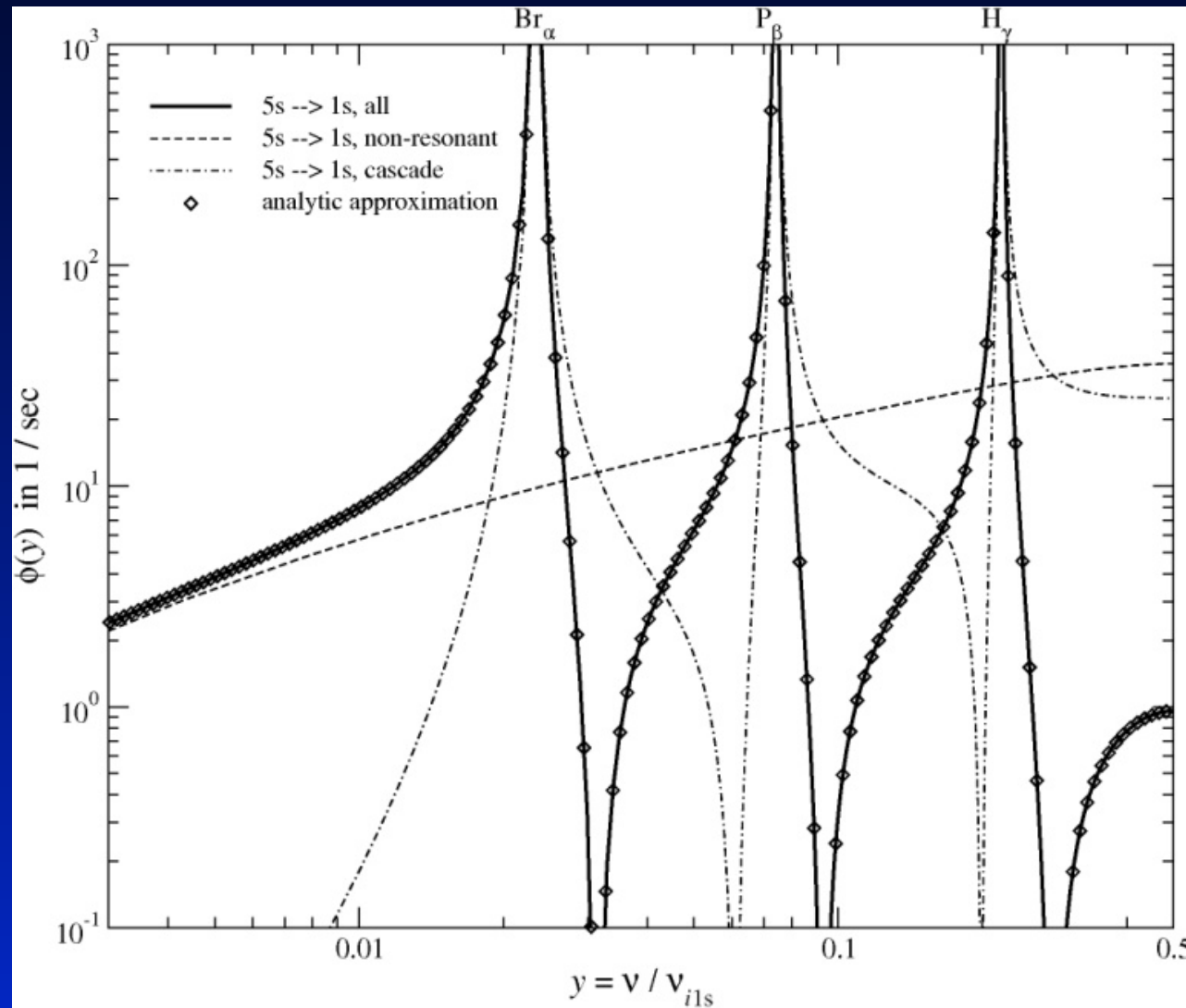


Direct Escape from optically thin regions:

→ HI -recombination is a bit *slower* due to 2γ -transitions from s-states

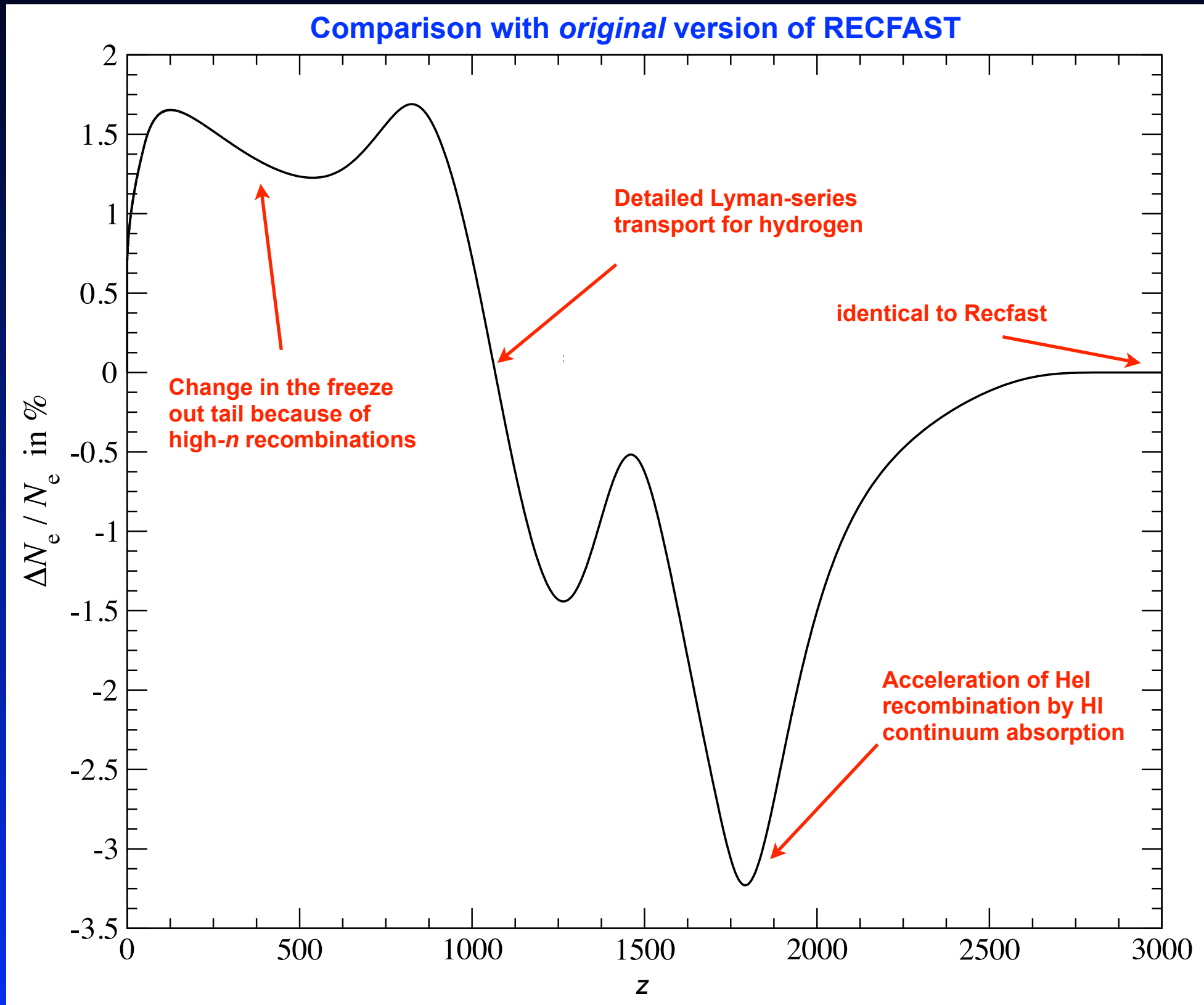
→ HI -recombination is a bit *faster* due to 2γ -transitions from d-states

5s two-photon decay spectrum

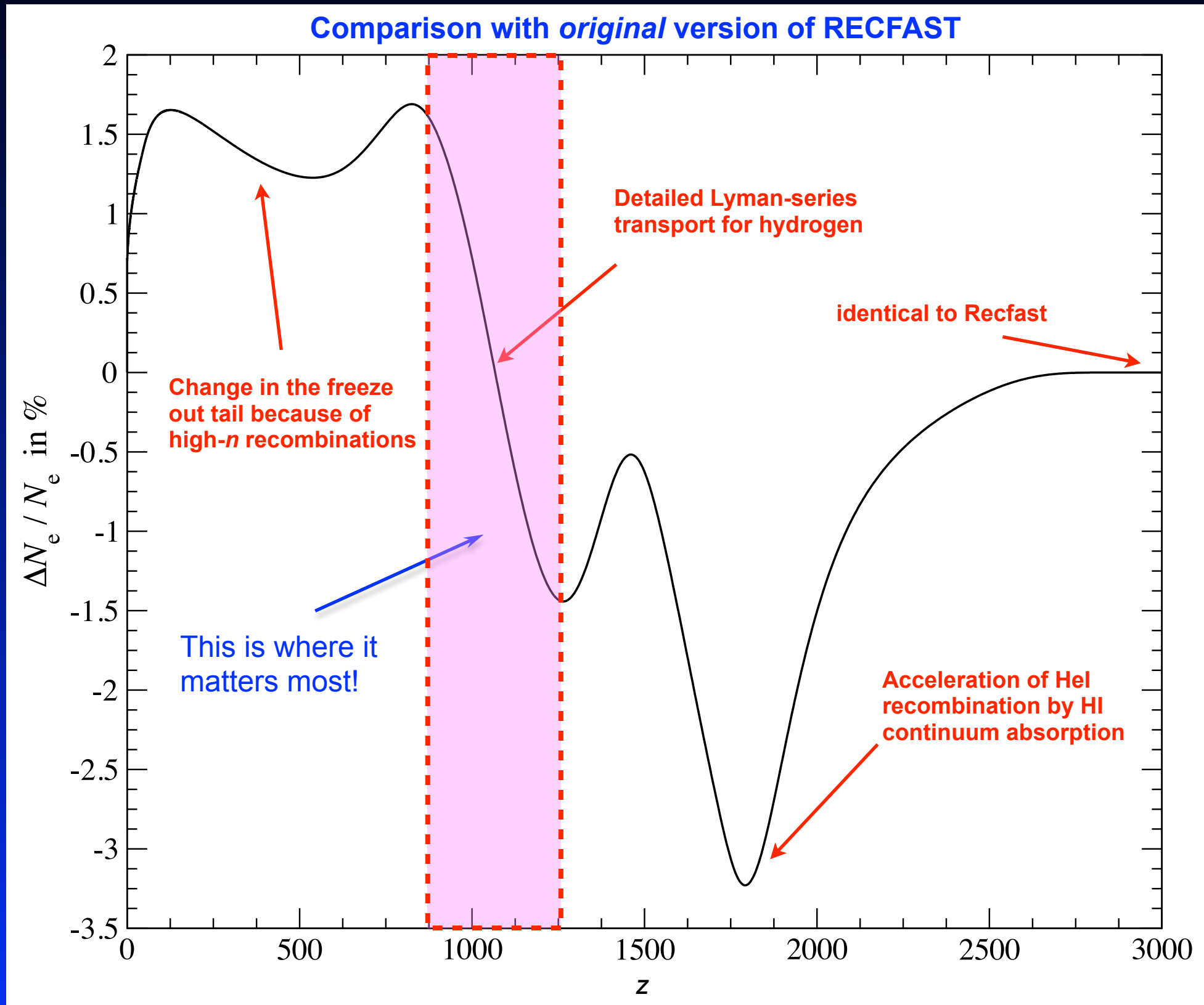


- matters become more complicated quickly
- splitting of resonance and non-resonant parts simplify the computation greatly
- luckily including these effects up to $n \sim 4-5$ is enough

Cumulative Changes to the Ionization History



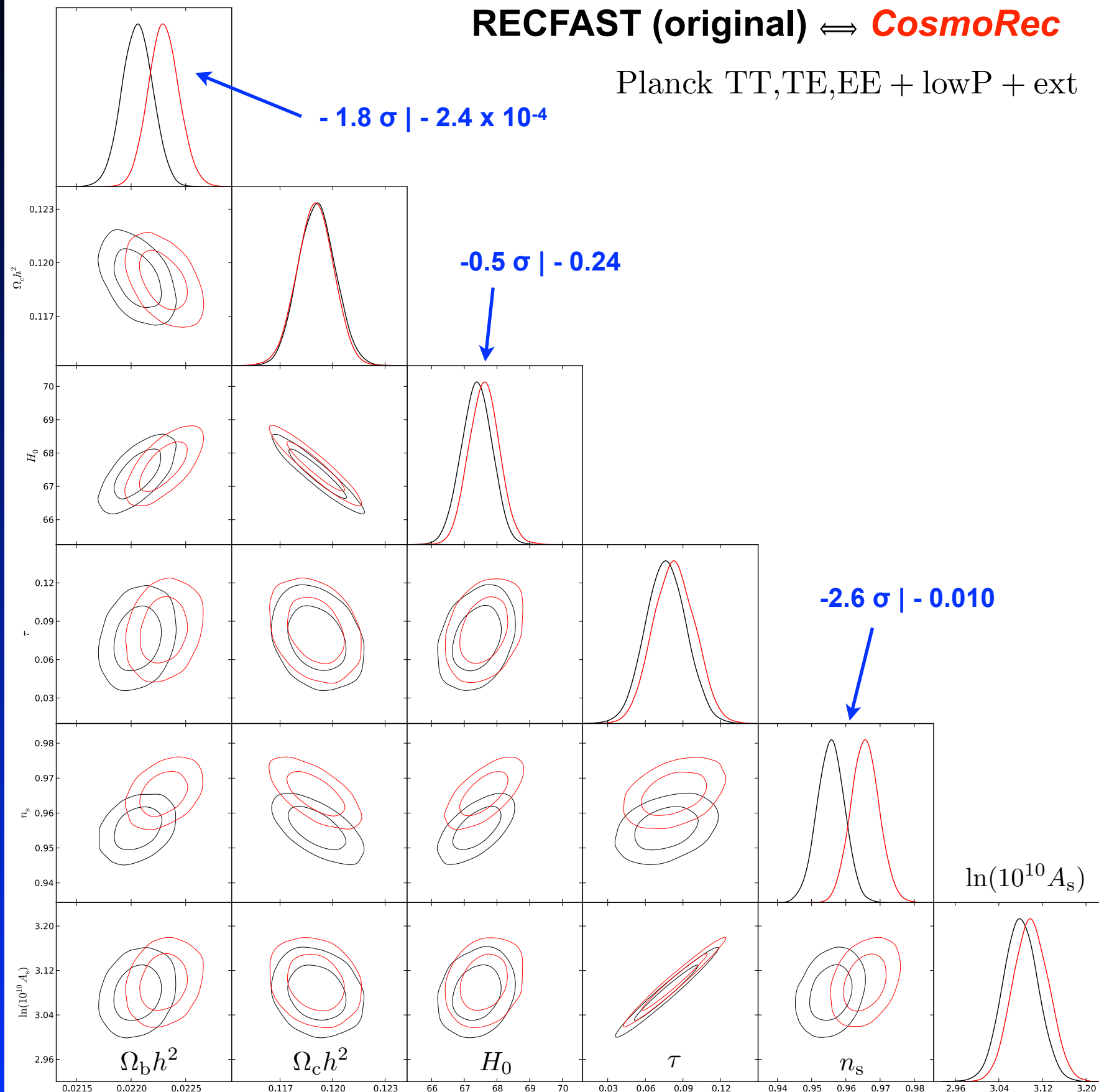
Cumulative Changes to the Ionization History



Biases as they *would* have been for *Planck*

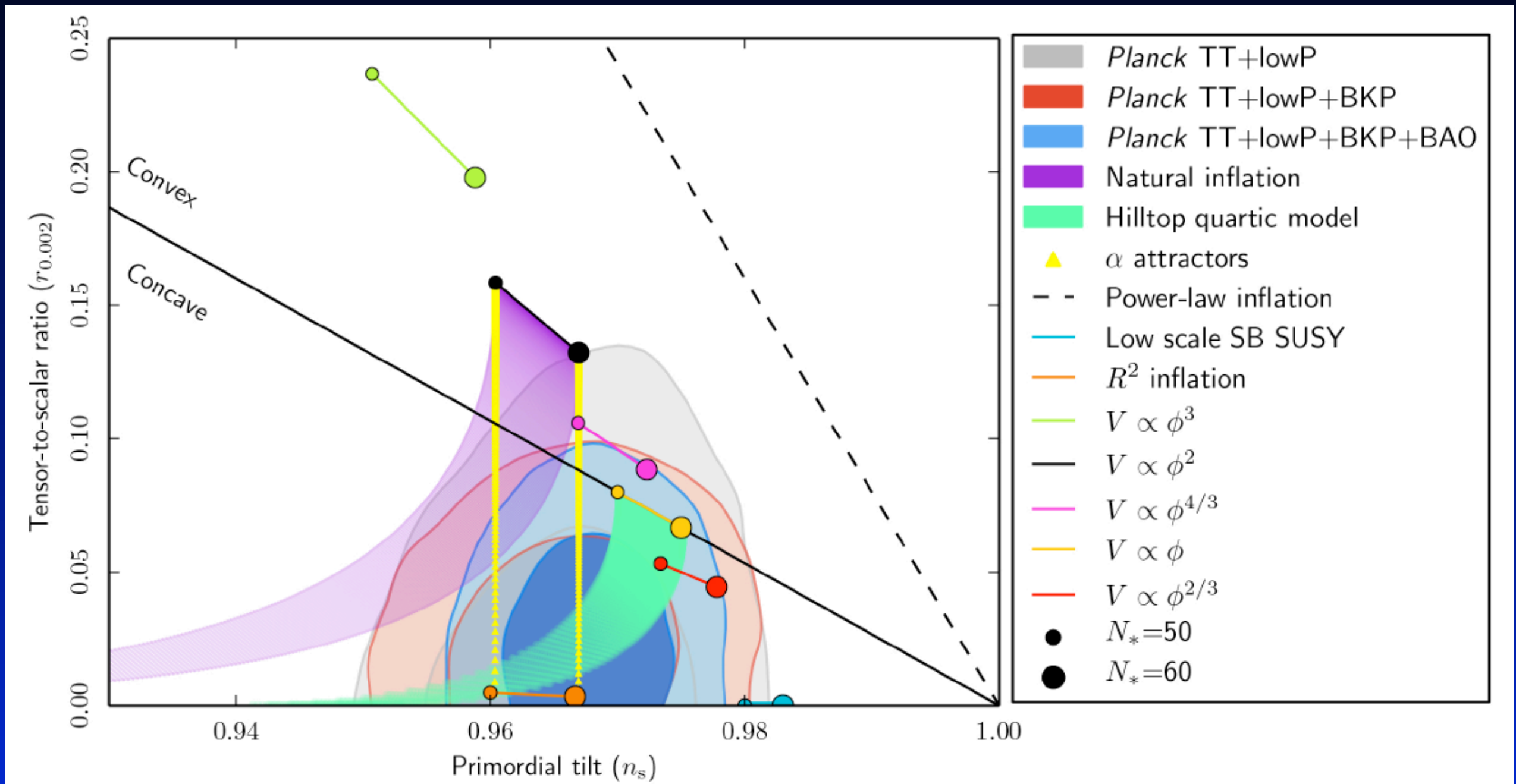
RECFAST (original) $\iff$ **CosmoRec**

Planck TT,TE,EE + lowP + ext



- Biases a little less significant with real *Planck* data
- absolute biases very similar
- In particular n_s would have been biased low
- Small effect on H_0

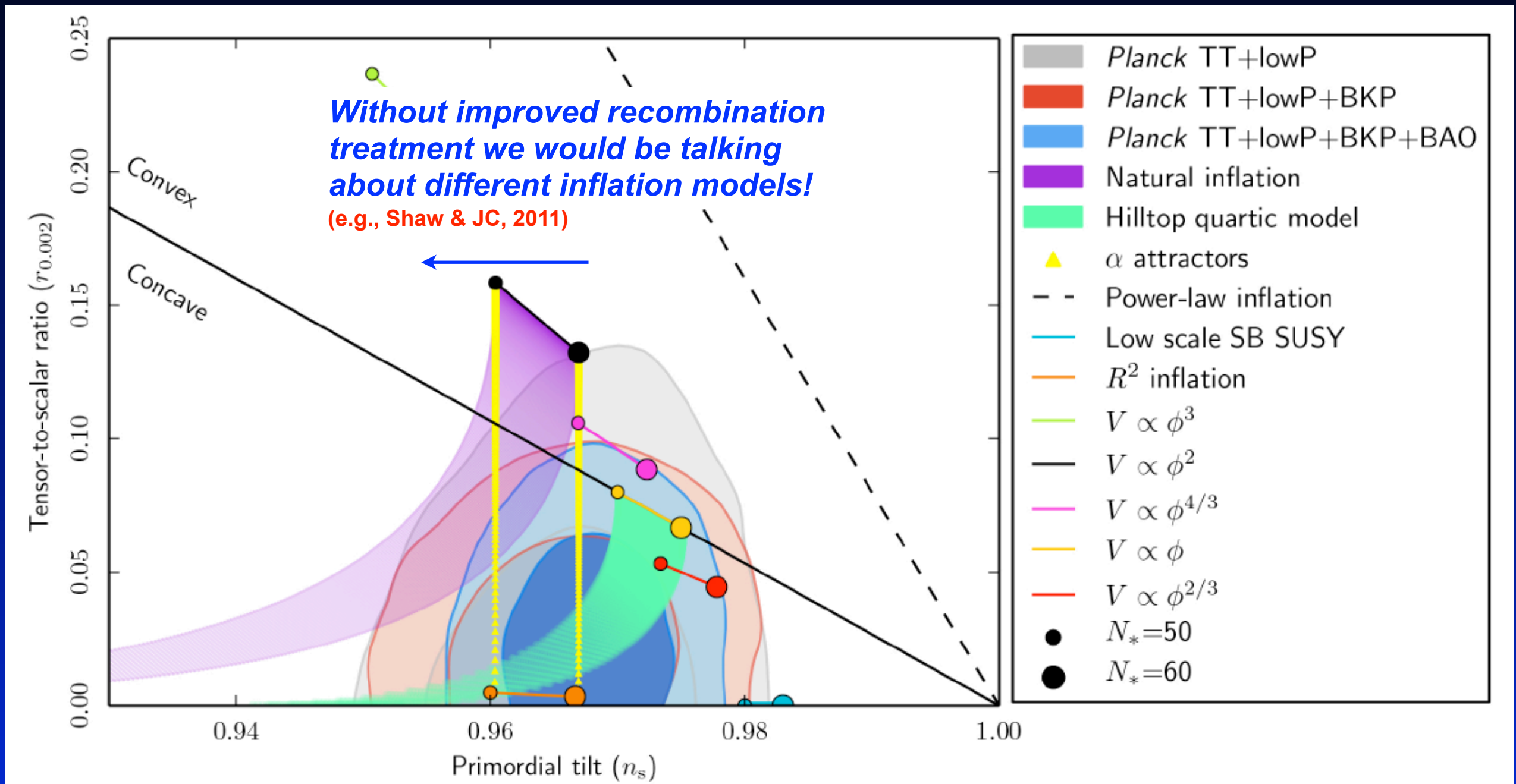
Importance of recombination for inflation constraints



Planck Collaboration, 2015, paper XX

- Analysis uses refined recombination model of CosmoRec

Importance of recombination for inflation constraints



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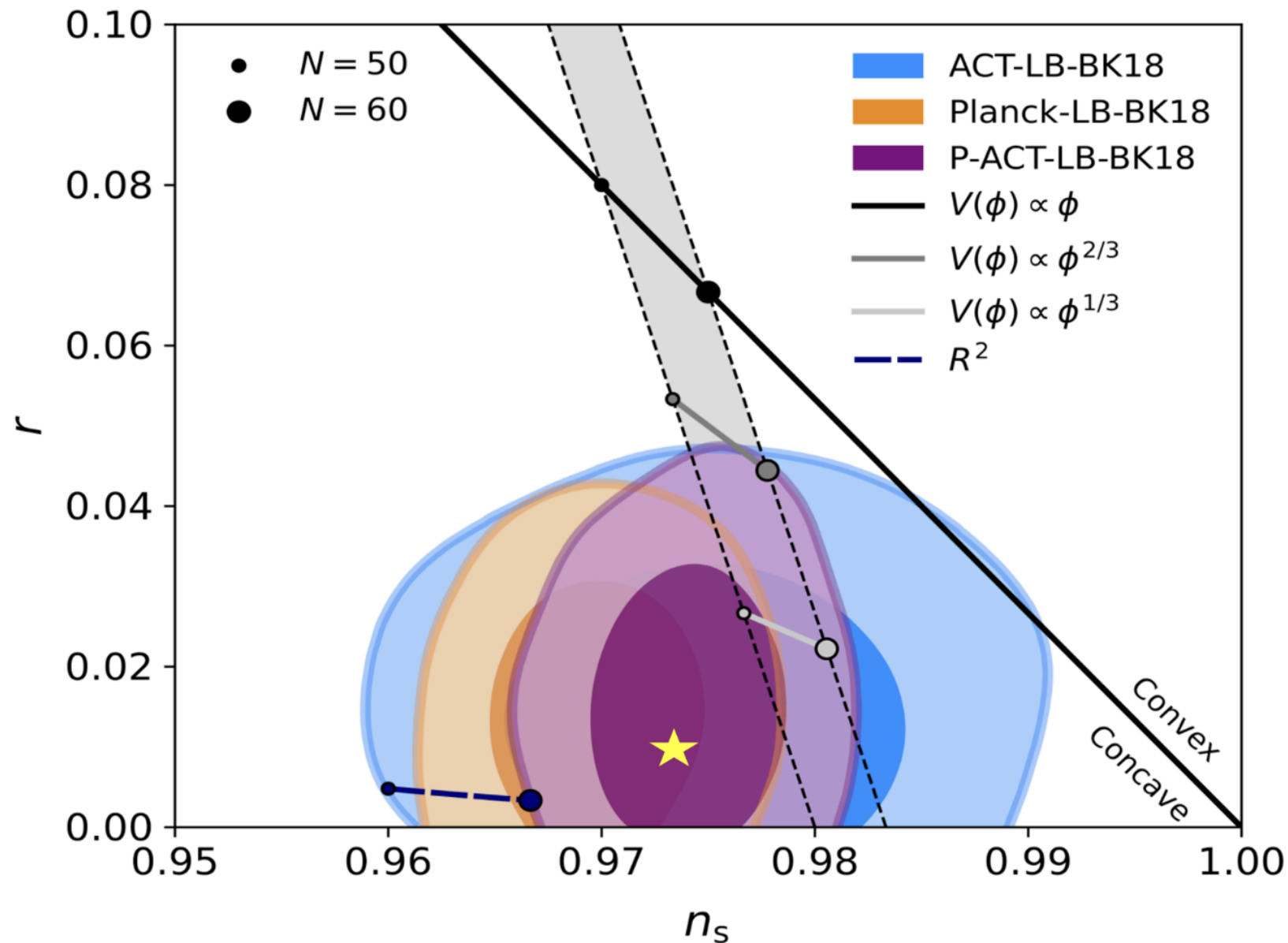
ACT, SPT, and chaotic inflation

Renata Kallosh¹, Andrei Linde¹ and Diederik Roest²

¹*Department of Physics and SITP, Stanford University,
Stanford, California 94305 USA and*

²*Van Swinderen Institute for Particle Physics and Gravity,
University of Groningen, 9747 AG Groningen, The Netherlands*

We show that the simplest generalization of the chaotic inflation model $\frac{1}{2}m^2\phi^2$ with nonminimal coupling to gravity $(1 + \phi)R$ provides a good match to the results of the latest data release of the Atacama Cosmology Telescope and South Pole Telescope, with $r \approx 10^{-2}$.



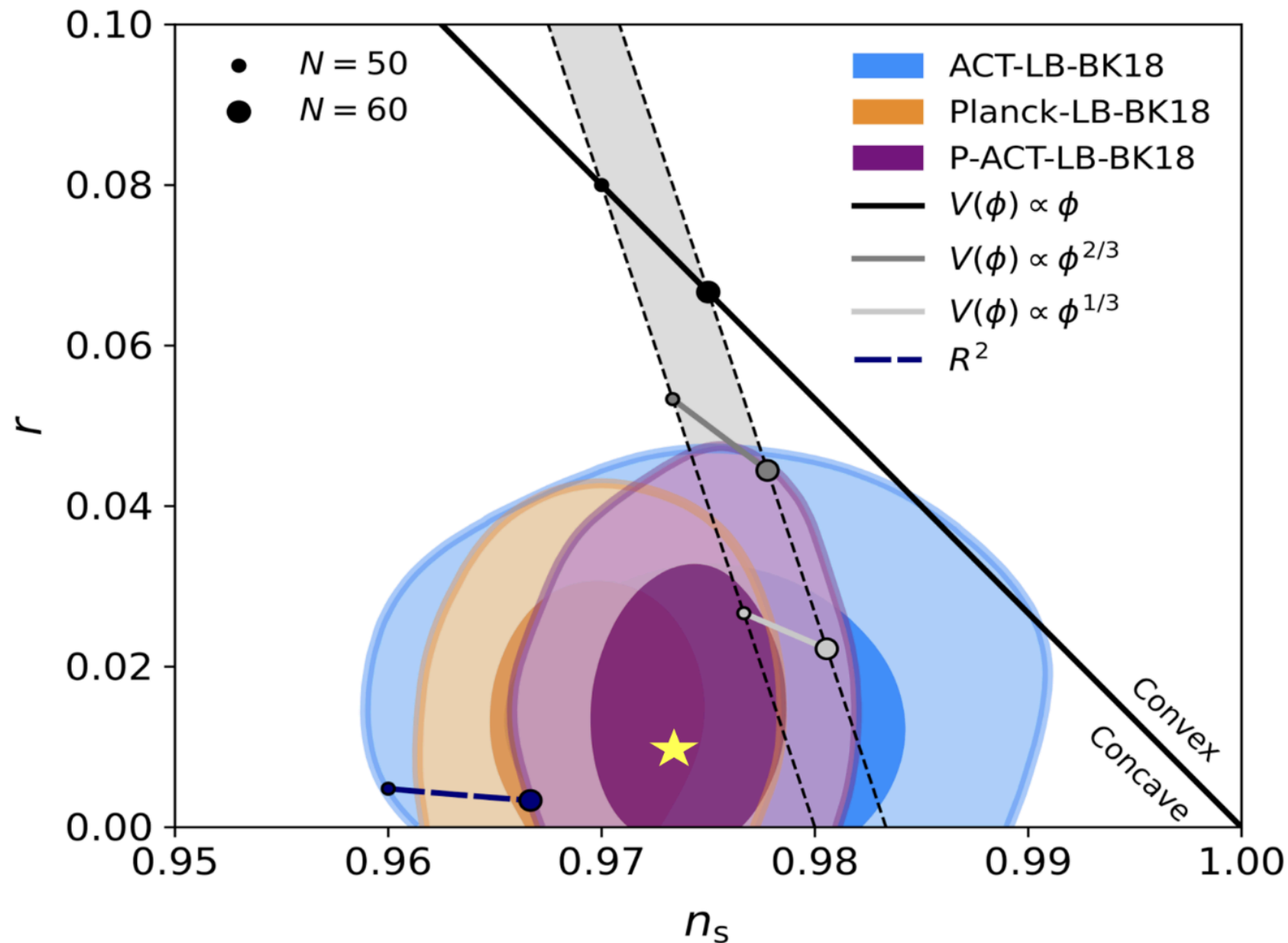
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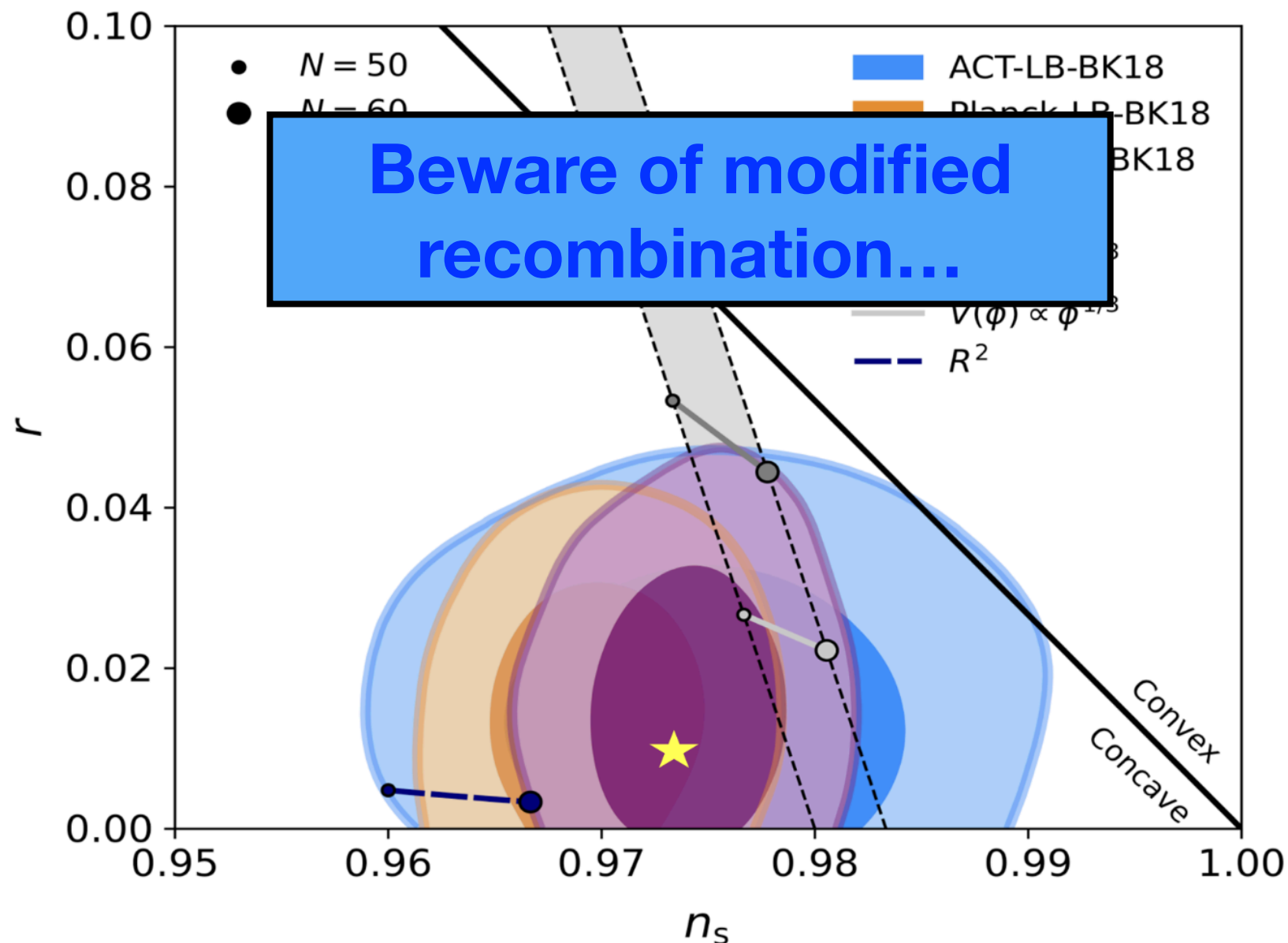
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What could be wrong then?

*** There are still a few standard processes that could contribute at ~0.1%...

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**Allowing for departures in either seems to
alleviate the Hubble tension!**

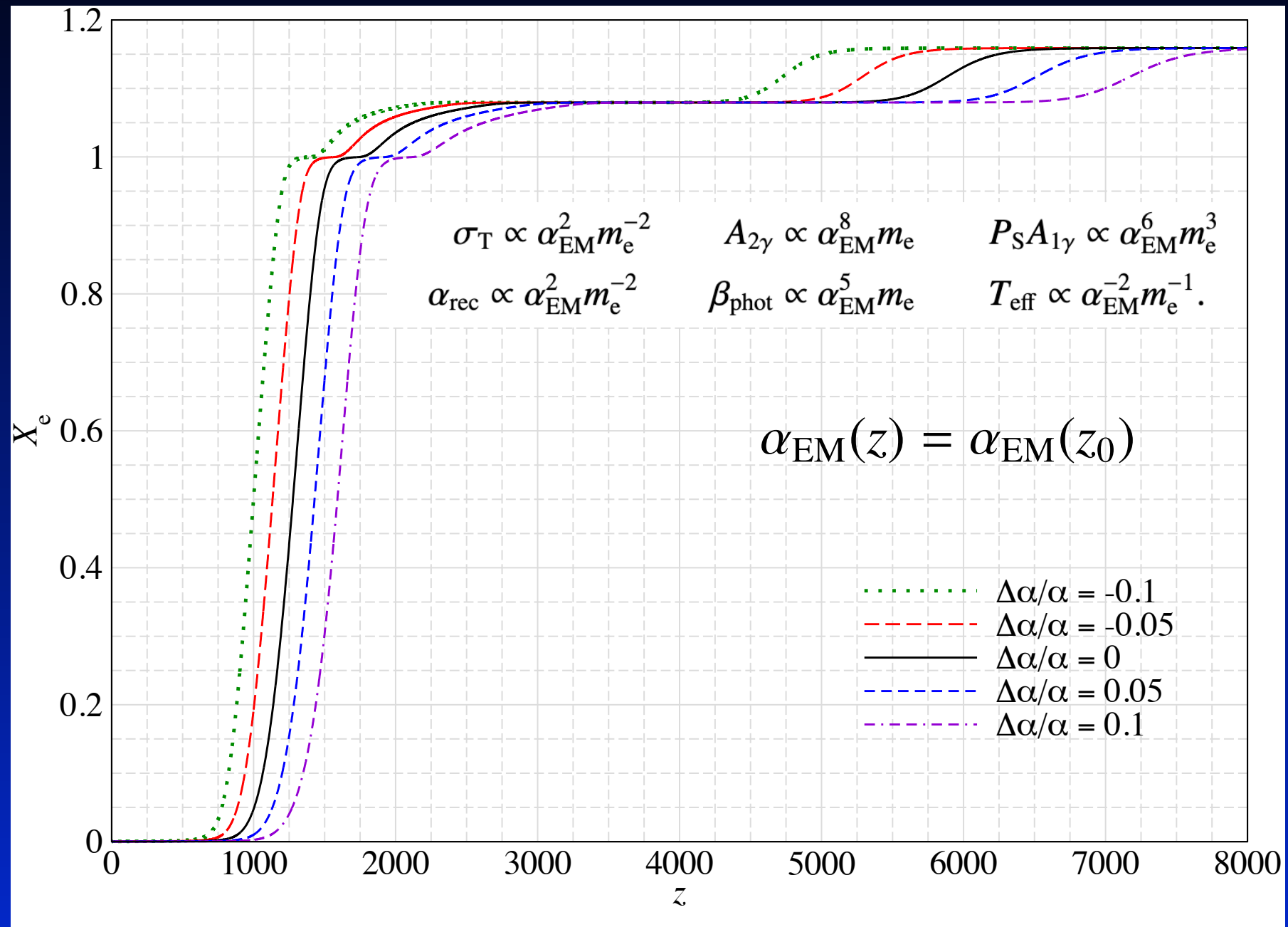
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Varying fundamental constants



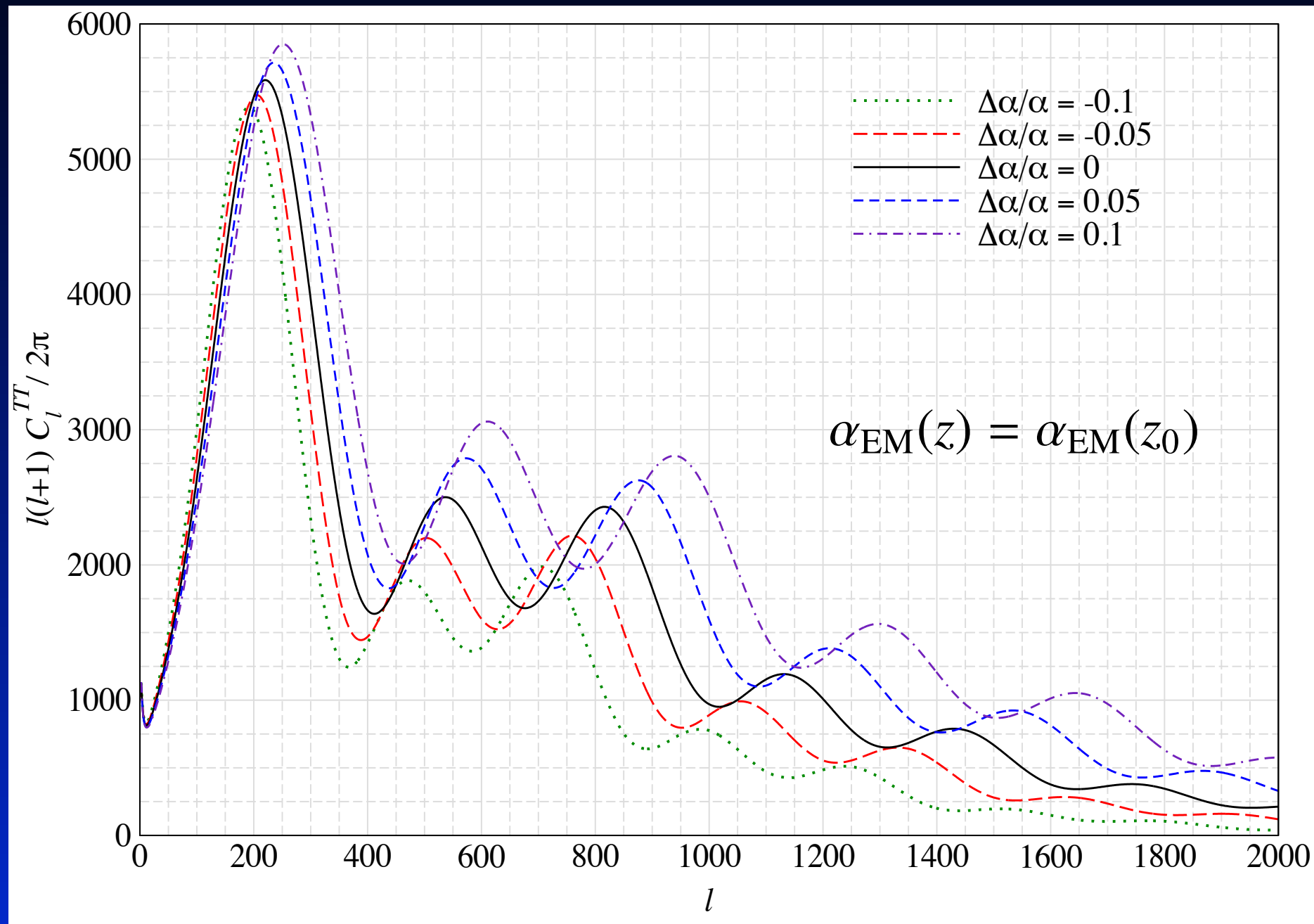
Luke Hart

Varying the fine-structure constants at recombination



- Constant change of α and m_e were frequently considered (e.g., Kaplinghat et al., 1999; Battye et al., 2001; Planck Collaboration, 2015)

Varying the fine-structure constants at recombination



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Constraints using Planck 2015

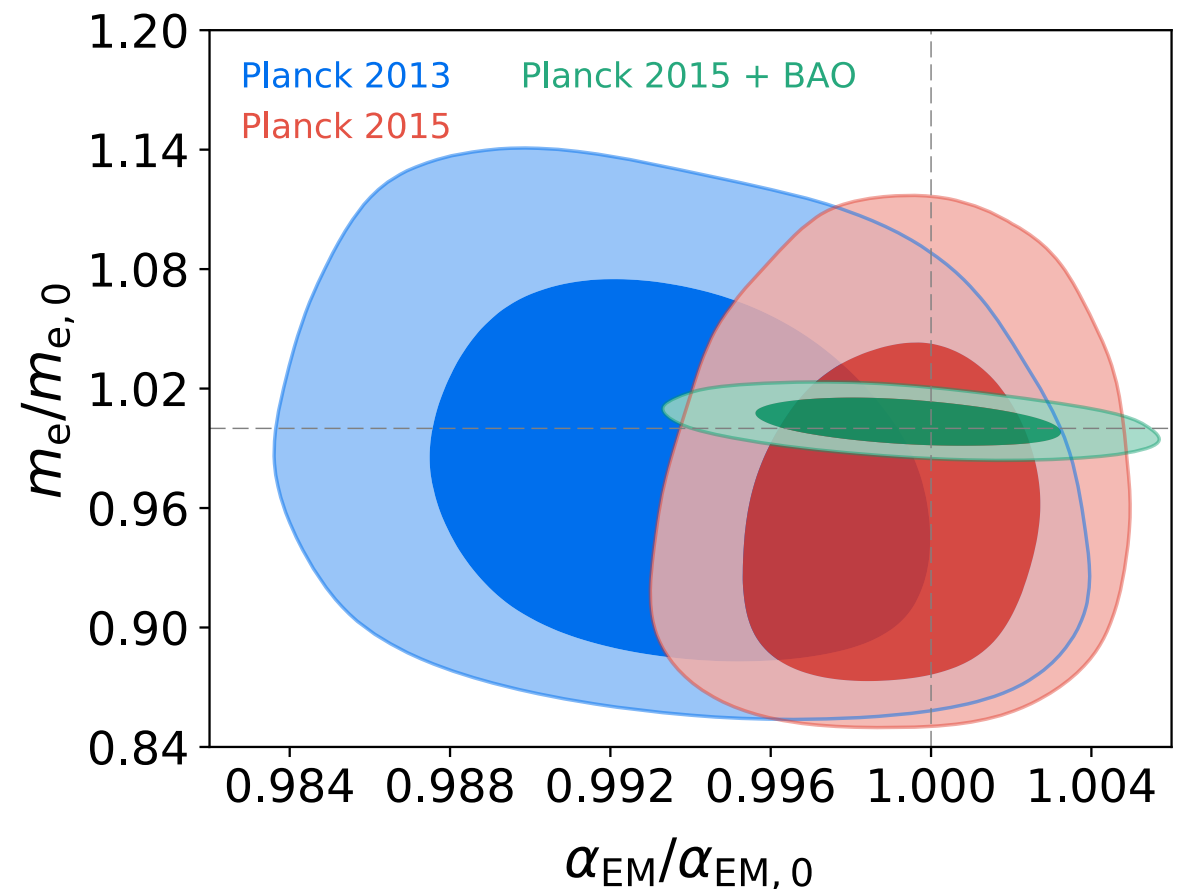
Parameter	Planck 2015	+ varying $\alpha_{\text{EM}}/\alpha_{\text{EM},0}$	+ varying p	+ varying $\alpha_{\text{EM}}/\alpha_{\text{EM},0}$ and p
$\Omega_b h^2$	0.02224 ± 0.00016	0.02225 ± 0.00016	0.02226 ± 0.00018	0.02223 ± 0.00019
$\Omega_c h^2$	0.1193 ± 0.0014	0.1191 ± 0.0018	0.1194 ± 0.0014	0.1193 ± 0.0020
$100\theta_{\text{MC}}$	1.0408 ± 0.0003	1.0398 ± 0.0035	1.0408 ± 0.0003	1.0406 ± 0.0051
τ	0.062 ± 0.014	0.063 ± 0.014	0.062 ± 0.014	0.063 ± 0.015
$\ln(10^{10} A_s)$	3.057 ± 0.025	3.060 ± 0.027	3.058 ± 0.026	3.059 ± 0.027
n_s	0.9649 ± 0.0047	0.9668 ± 0.0081	0.9663 ± 0.0060	0.9666 ± 0.0081
$\alpha_{\text{EM}}/\alpha_{\text{EM},0}$	–	0.9993 ± 0.0025	–	0.9998 ± 0.0036
p	–	–	0.0008 ± 0.0025	0.0007 ± 0.0036
H_0 [km s ⁻¹ Mpc ⁻¹]	67.5 ± 0.6	67.2 ± 1.0	67.5 ± 0.6	67.3 ± 1.4

- For α , Planck 2015 gives slight improvement over Planck 2013 because of polarization (~30%)

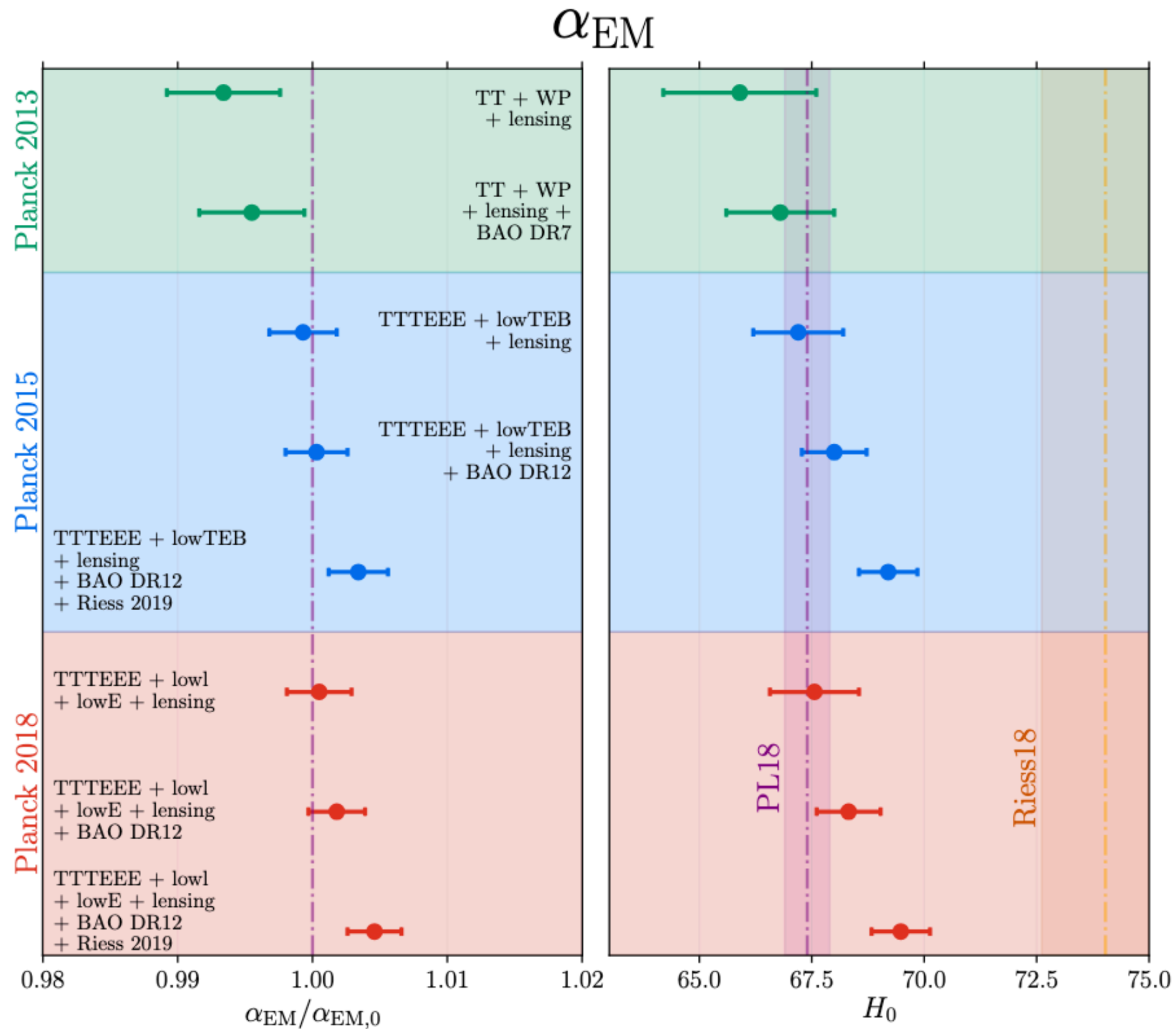
- Constraint on m_e asymmetric

$$m_e/m_{e,0} = 0.961^{+0.046}_{-0.072}$$

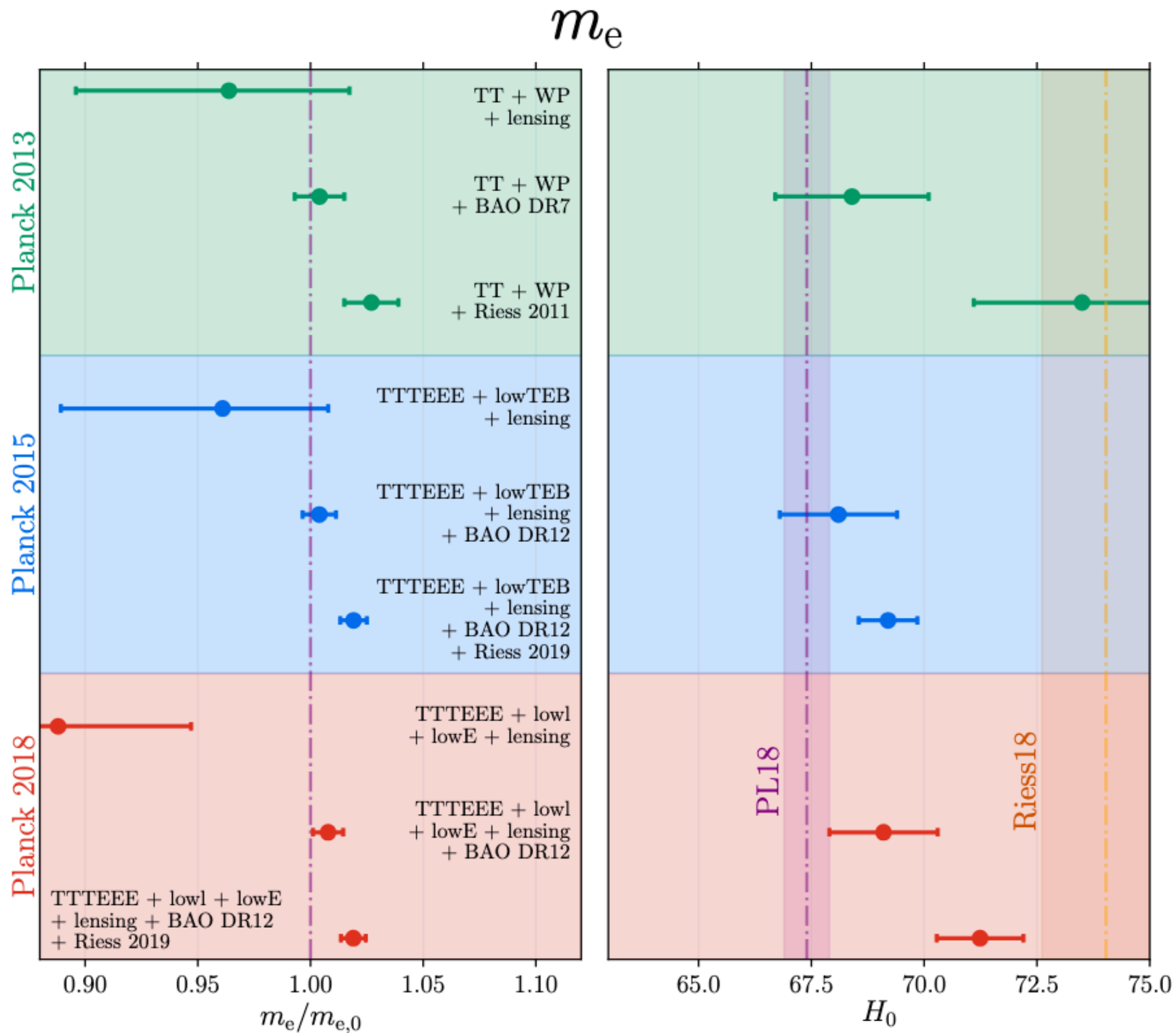
- BAO improves m_e constraint and allows breaking degeneracies between α and m_e



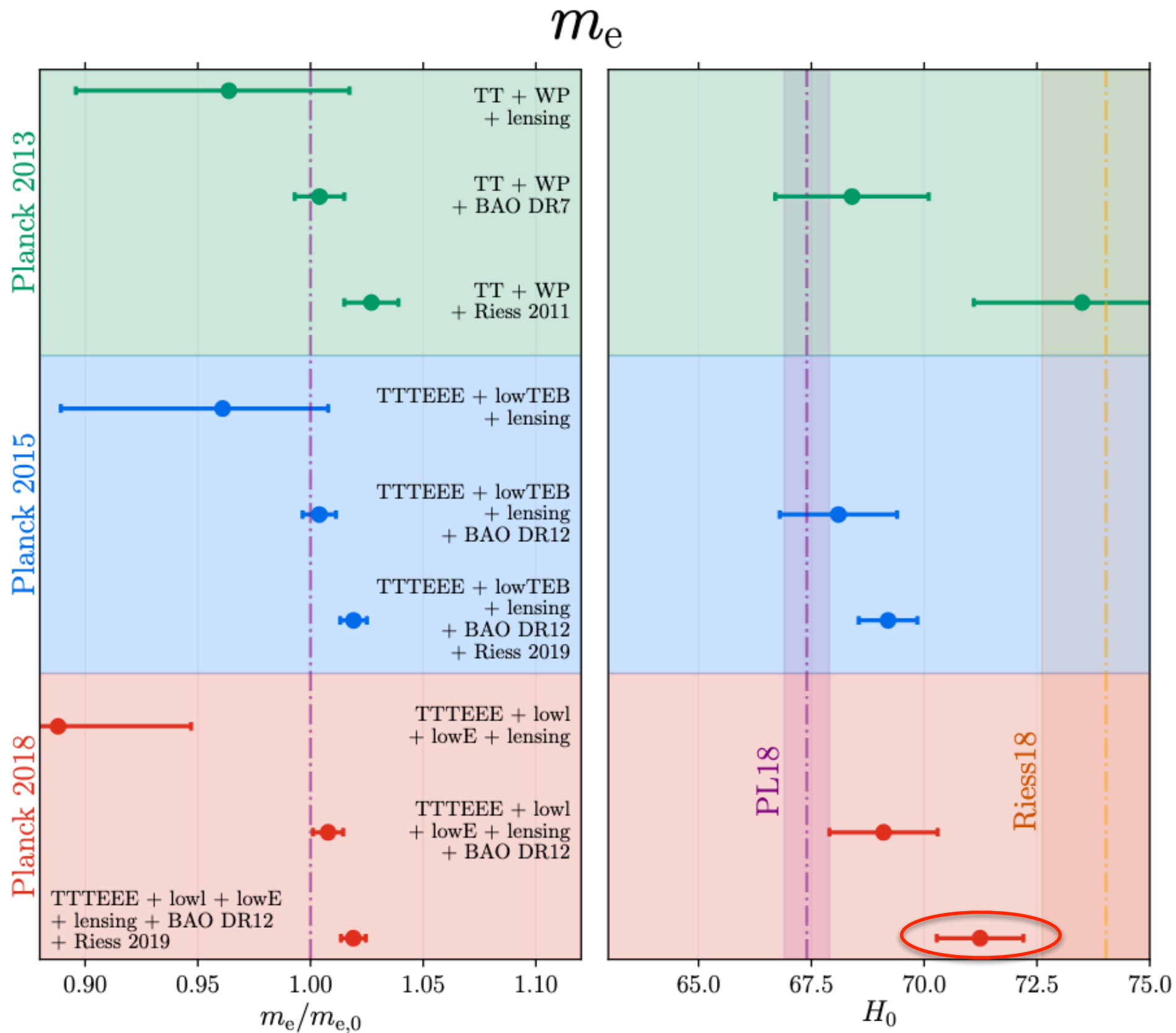
Possible link to the Hubble tension in 2019?



Possible link to the Hubble tension in 2018?

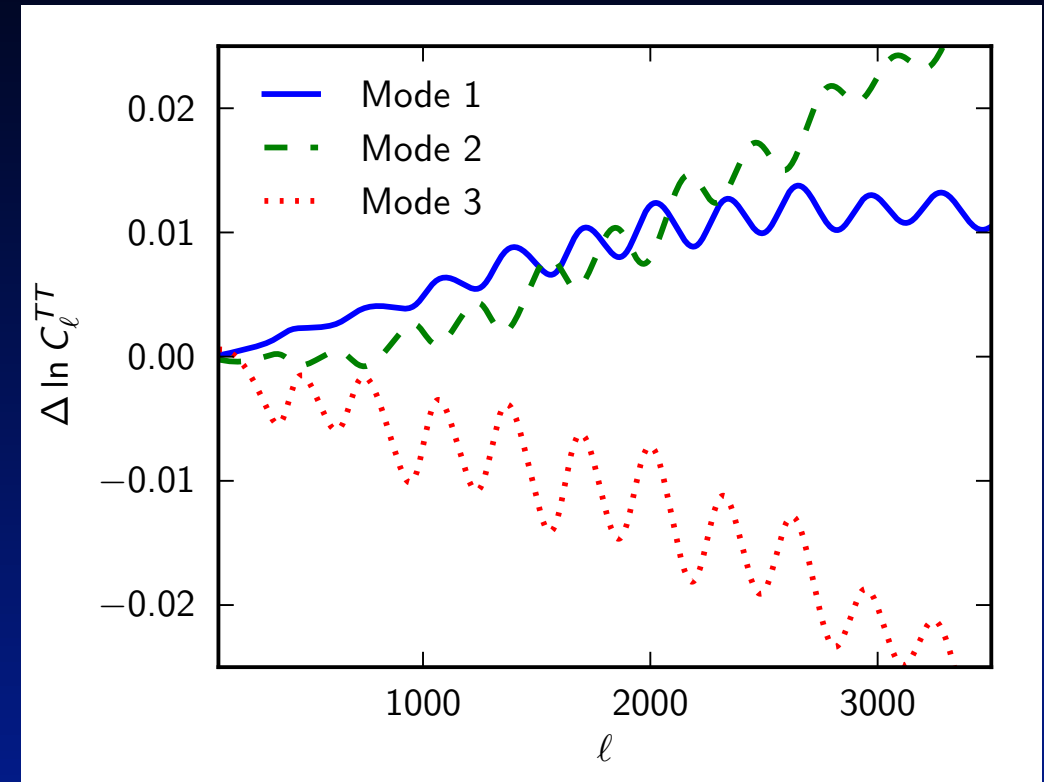
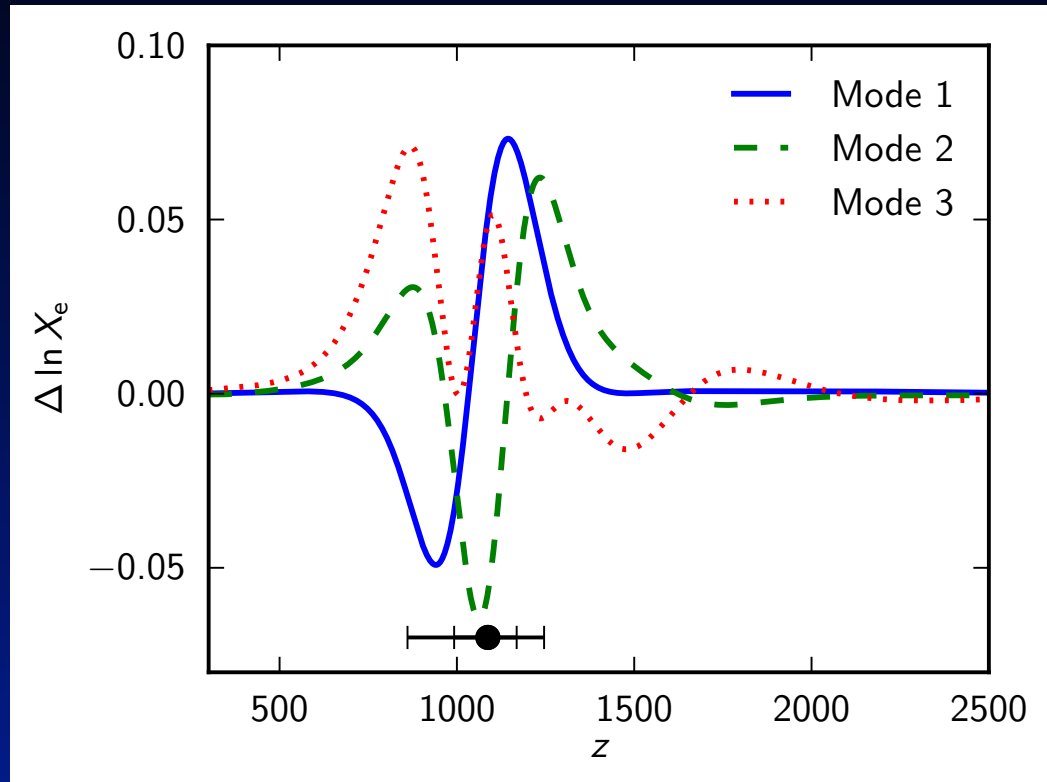


Possible link to the Hubble tension in 2018?



What does the data tell us about the recombination history?

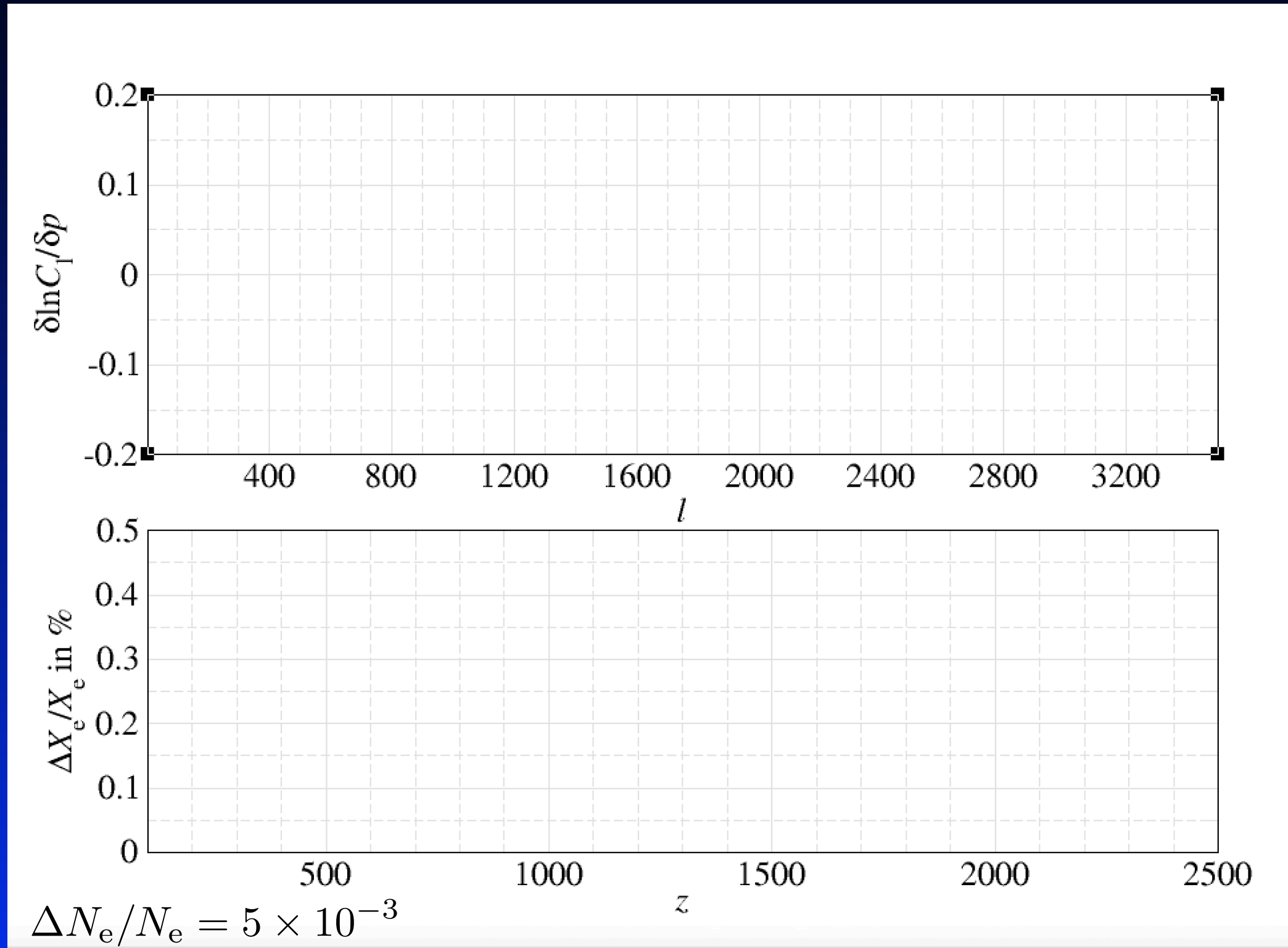
PCA analysis with Planck 2015



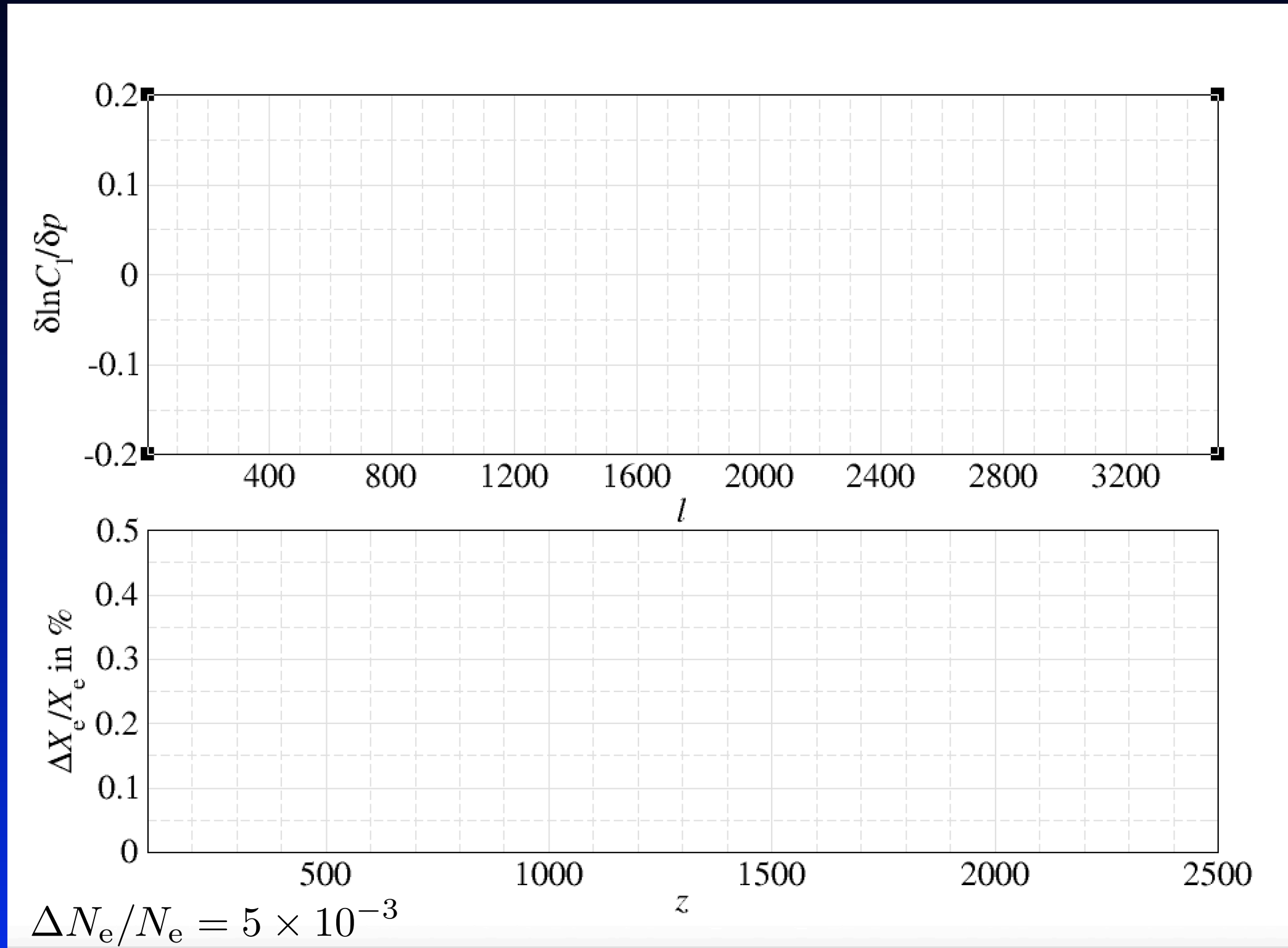
- Planck data is *consistent* with standard recombination
- Non-trivial statement, even if it is expected!
- Improvement in next release

Parameter	+ 1 mode	+ 2 modes	+ 3 modes
$\Omega_b h^2$	0.02229 ± 0.00017	0.02237 ± 0.00018	0.02237 ± 0.00019
$\Omega_c h^2$	0.1190 ± 0.0010	0.1186 ± 0.0011	0.1187 ± 0.0012
H_0	67.64 ± 0.48	67.80 ± 0.51	67.80 ± 0.56
τ	0.065 ± 0.012	0.068 ± 0.013	0.068 ± 0.013
n_s	0.9667 ± 0.0053	0.9677 ± 0.0055	0.9678 ± 0.0067
$\ln(10^{10} A_s)$	3.062 ± 0.023	3.066 ± 0.024	3.066 ± 0.024
μ_1	-0.03 ± 0.12	0.03 ± 0.14	0.02 ± 0.15
μ_2	...	-0.17 ± 0.18	-0.18 ± 0.19
μ_3	...	...	-0.02 ± 0.88

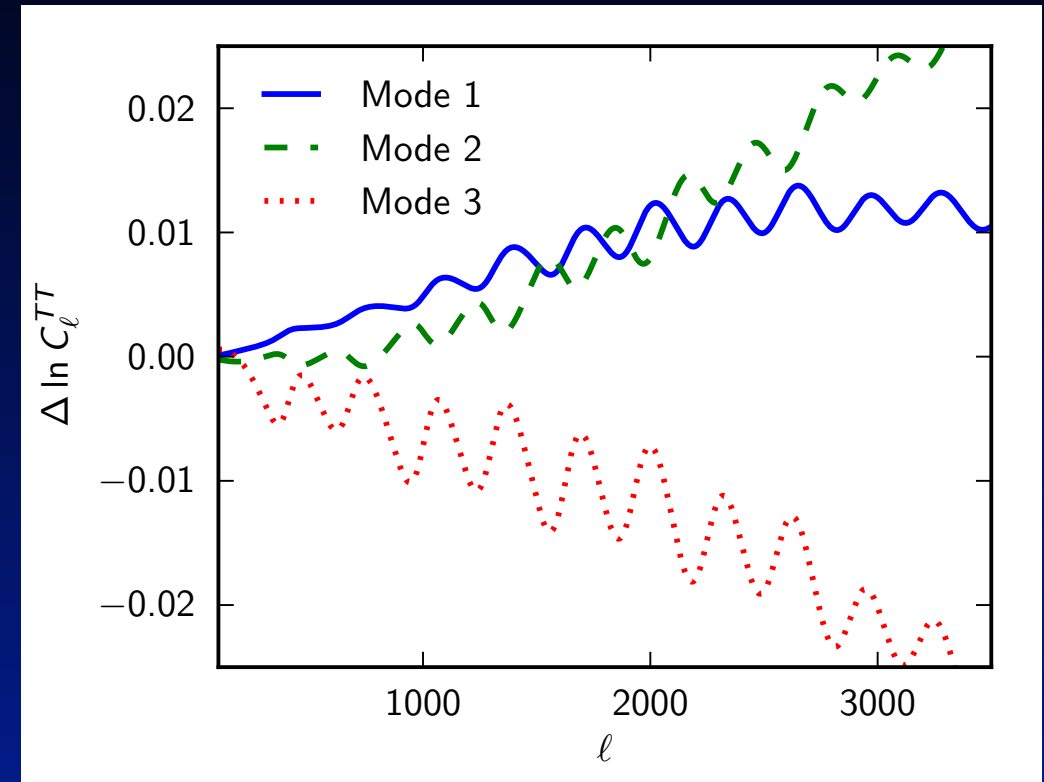
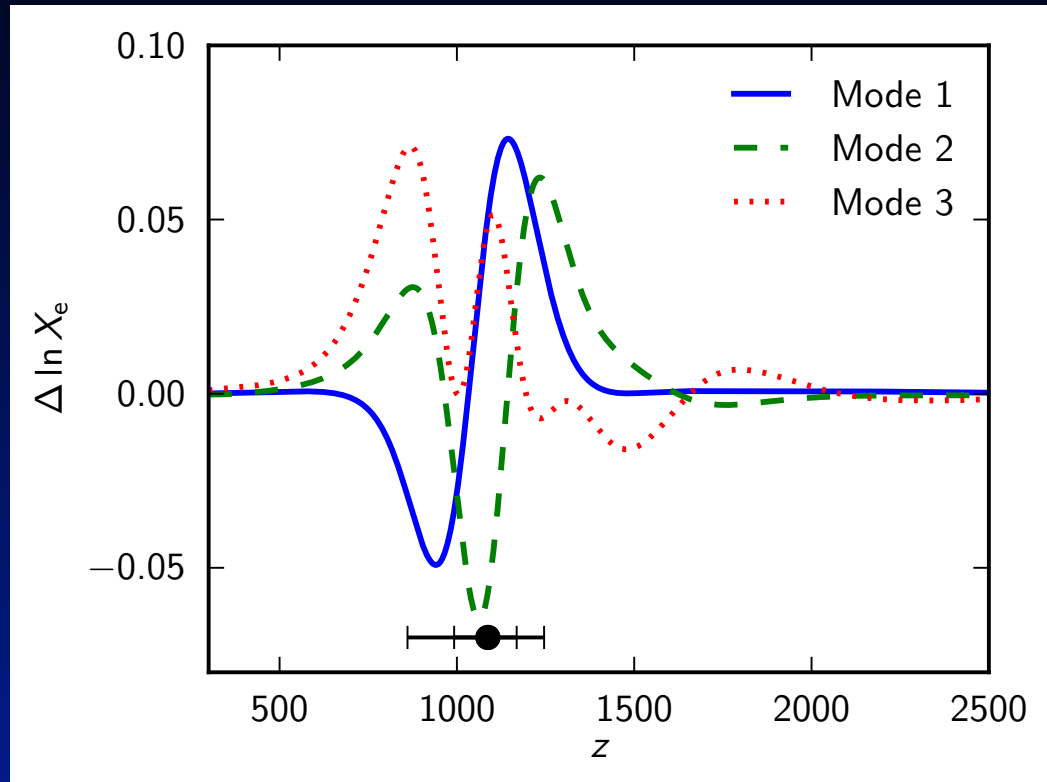
Power spectrum response at different redshifts



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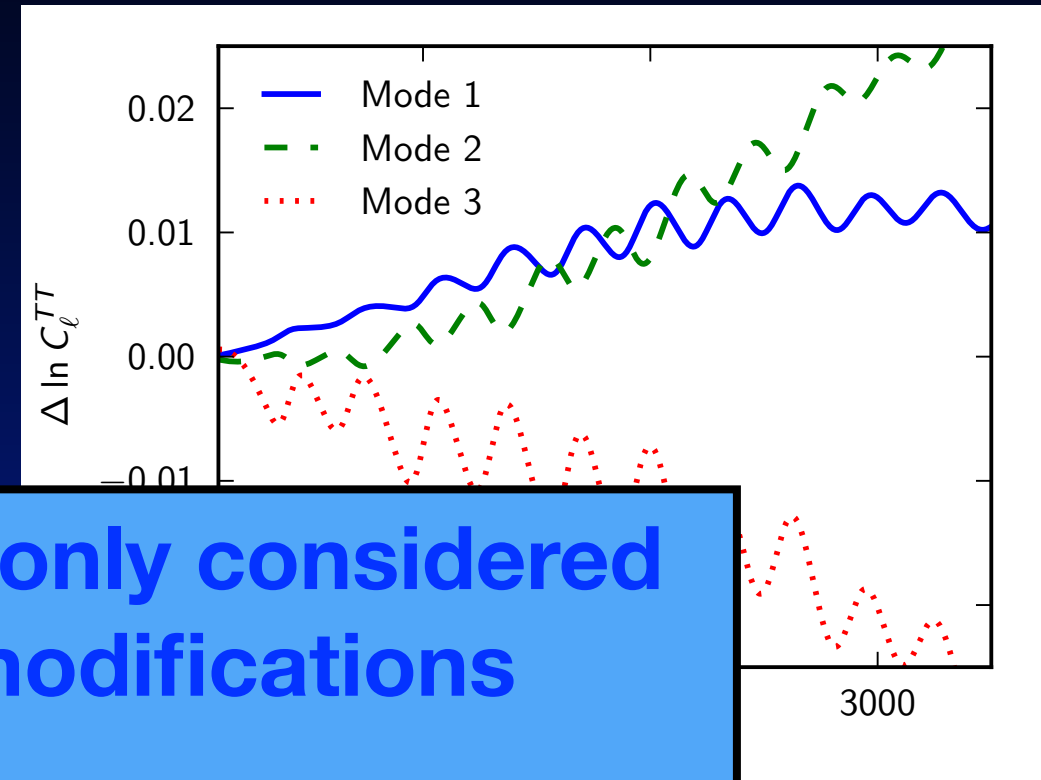
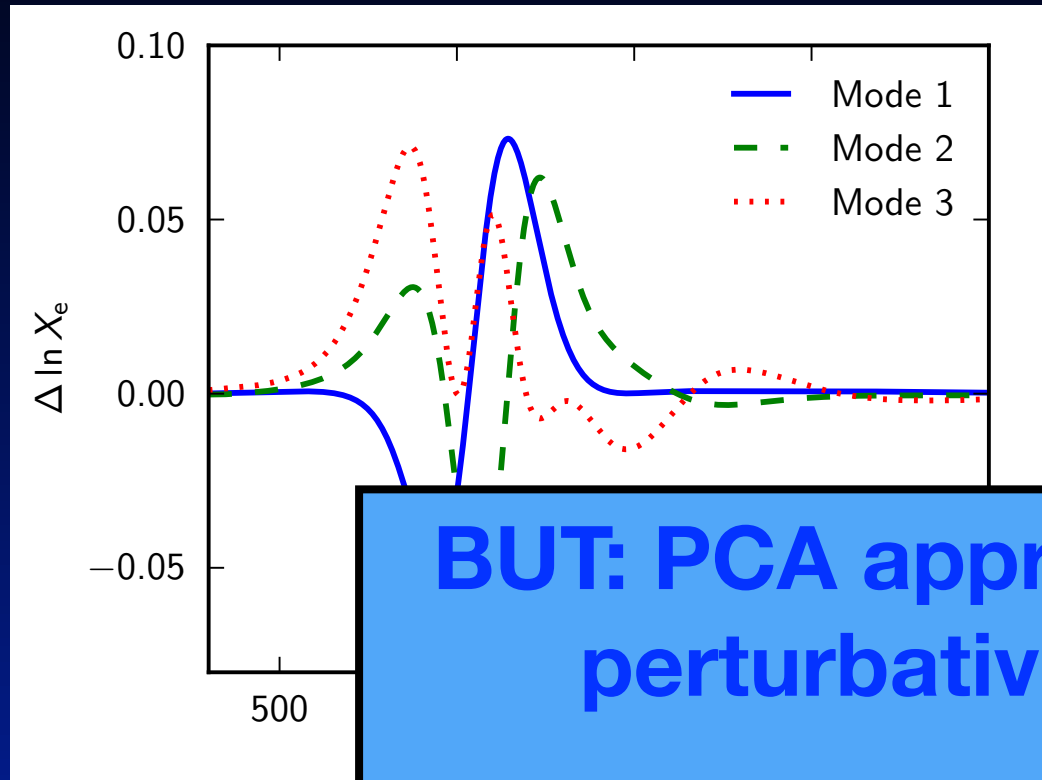
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$\ln(10^{10} A_s)$	3.062 ± 0.023	3.066 ± 0.024	3.066 ± 0.024
μ_1	-0.03 ± 0.12	0.03 ± 0.14	0.02 ± 0.15
μ_2	...	-0.17 ± 0.18	-0.18 ± 0.19
μ_3	...	...	-0.02 ± 0.88

PCA analysis with Planck 2015



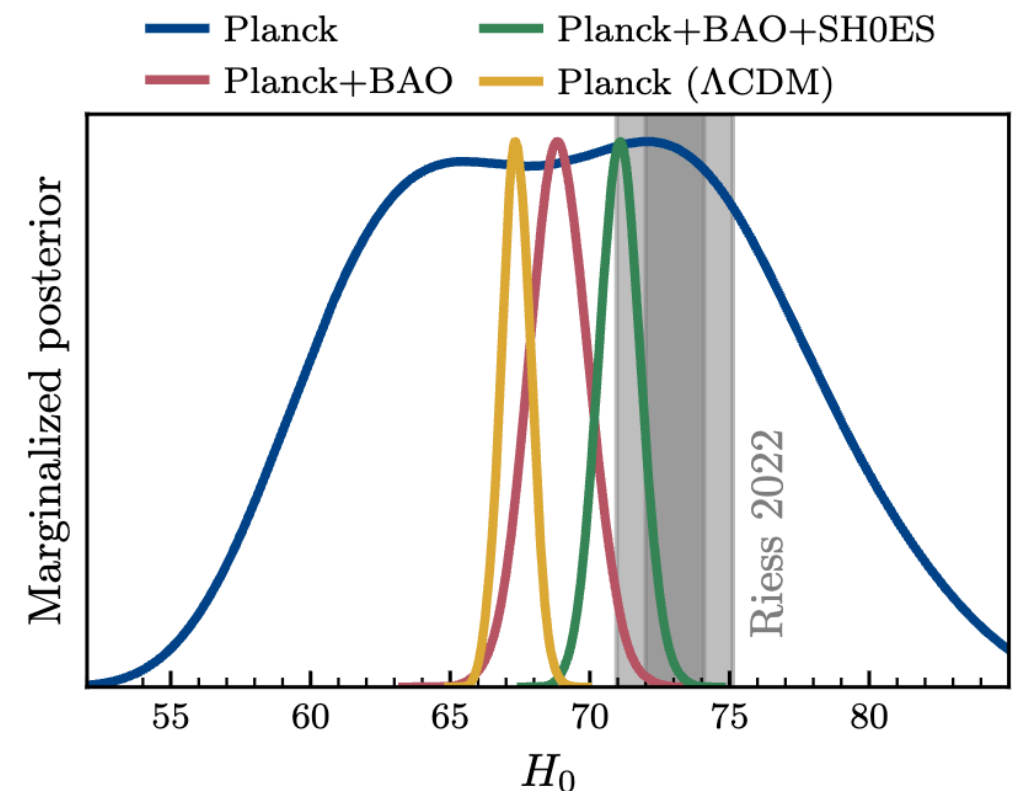
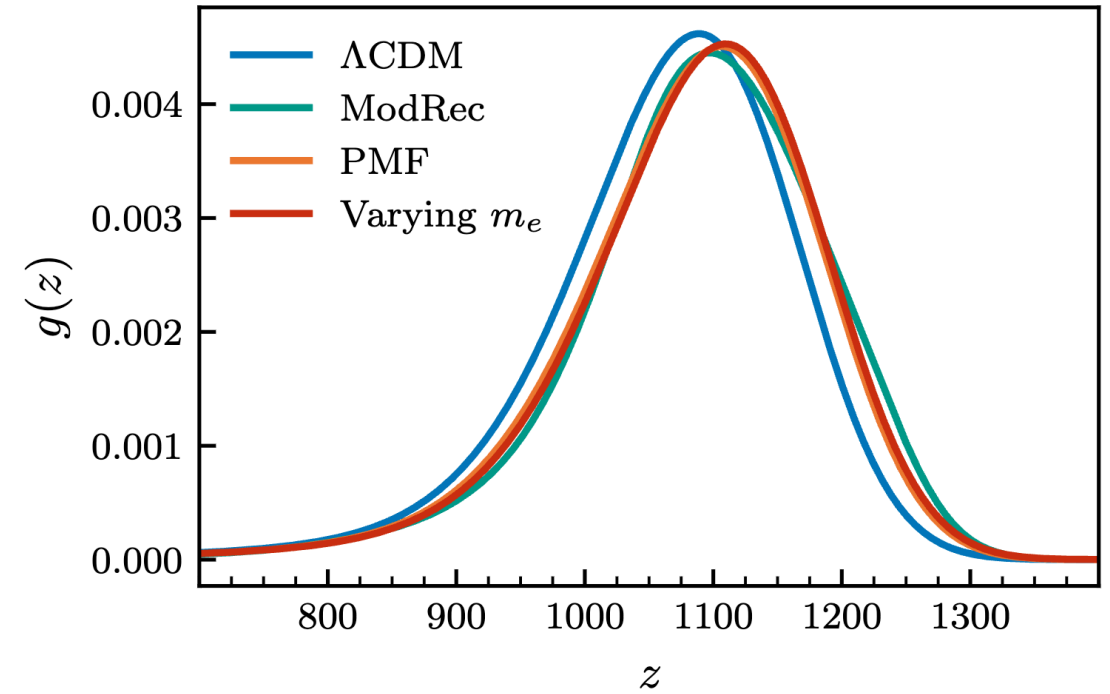
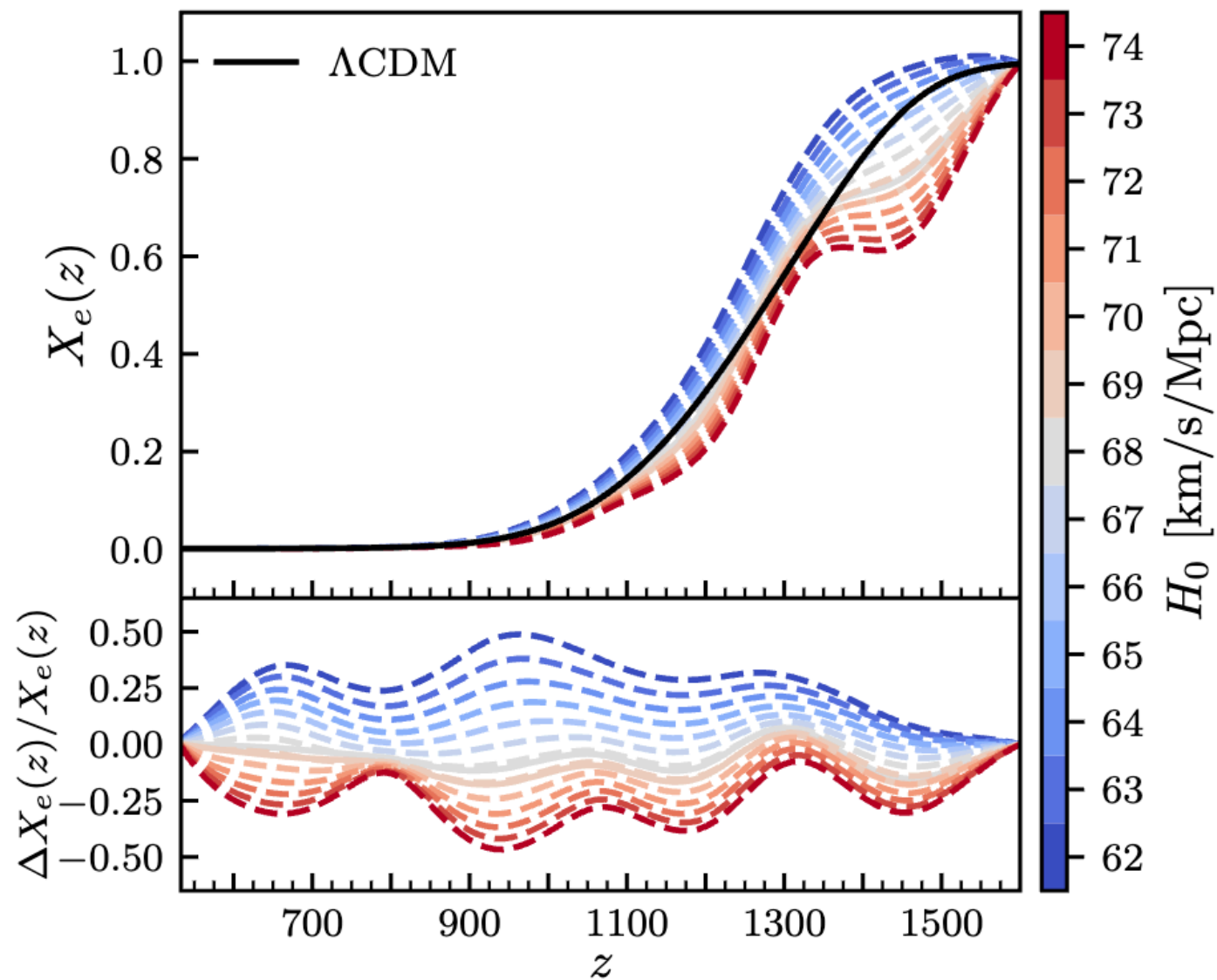
BUT: PCA approach only considered perturbative X_e modifications

Also: was never tried when combined with SN data...

- Planck data with standard recombination
- Non-trivial statement, even if it is expected!
- Improvement in next release

			+ 3 modes
$\Omega_b h^2$	0.02229 ± 0.00017	0.02237 ± 0.00018	0.02237 ± 0.00019
$\Omega_c h^2$	0.1190 ± 0.0010	0.1186 ± 0.0011	0.1187 ± 0.0012
H_0	67.64 ± 0.48	67.80 ± 0.51	67.80 ± 0.56
τ	0.065 ± 0.012	0.068 ± 0.013	0.068 ± 0.013
n_s	0.9667 ± 0.0053	0.9677 ± 0.0055	0.9678 ± 0.0067
$\ln(10^{10} A_s)$	3.062 ± 0.023	3.066 ± 0.024	3.066 ± 0.024
μ_1	-0.03 ± 0.12	0.03 ± 0.14	0.02 ± 0.15
μ_2	...	-0.17 ± 0.18	-0.18 ± 0.19
μ_3	...	...	-0.02 ± 0.88

Cosmological data seems to be preferring early recombination scenarios!

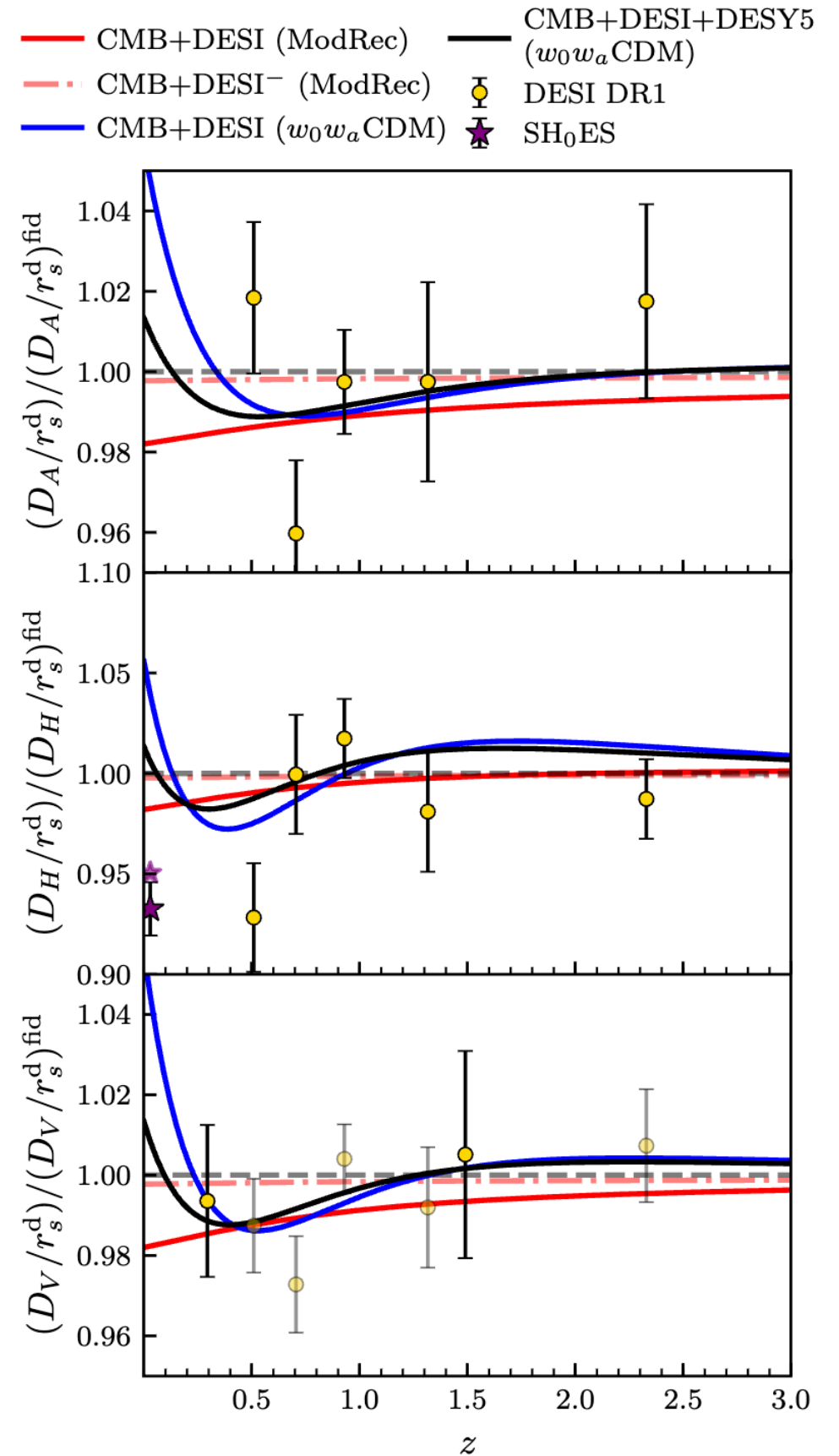
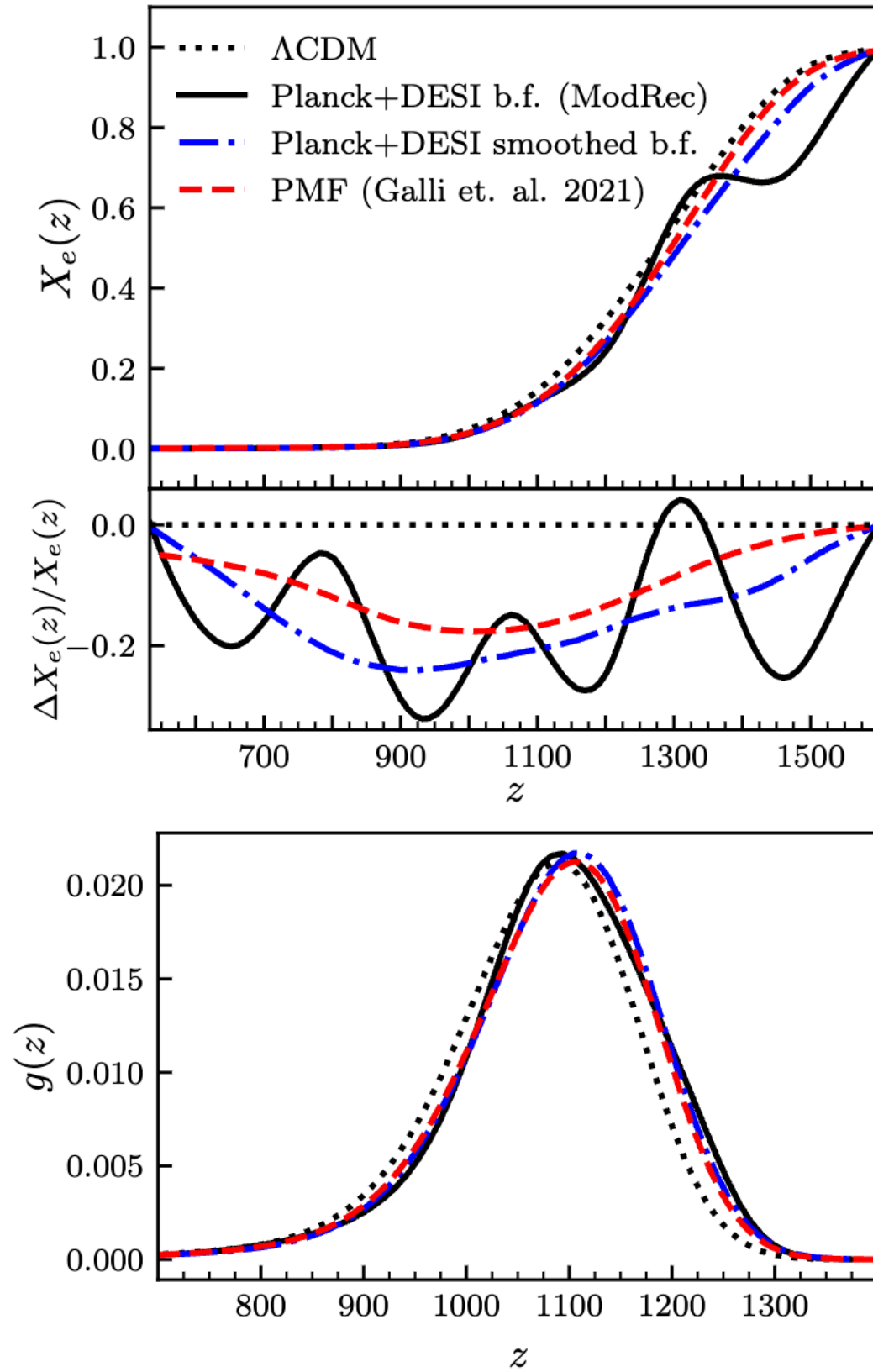


Model-independent reconstruction of free electron fraction using Emulators

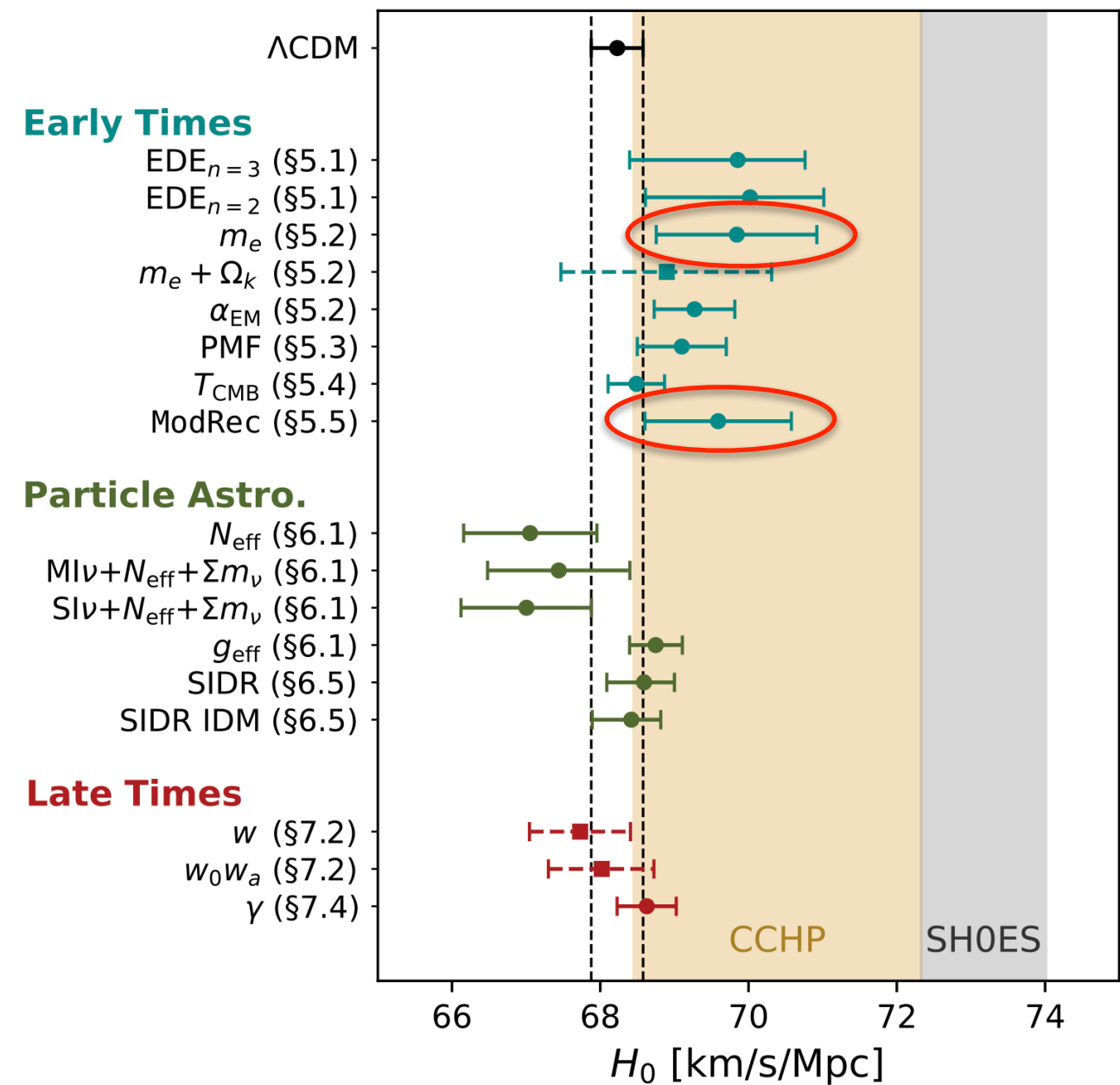
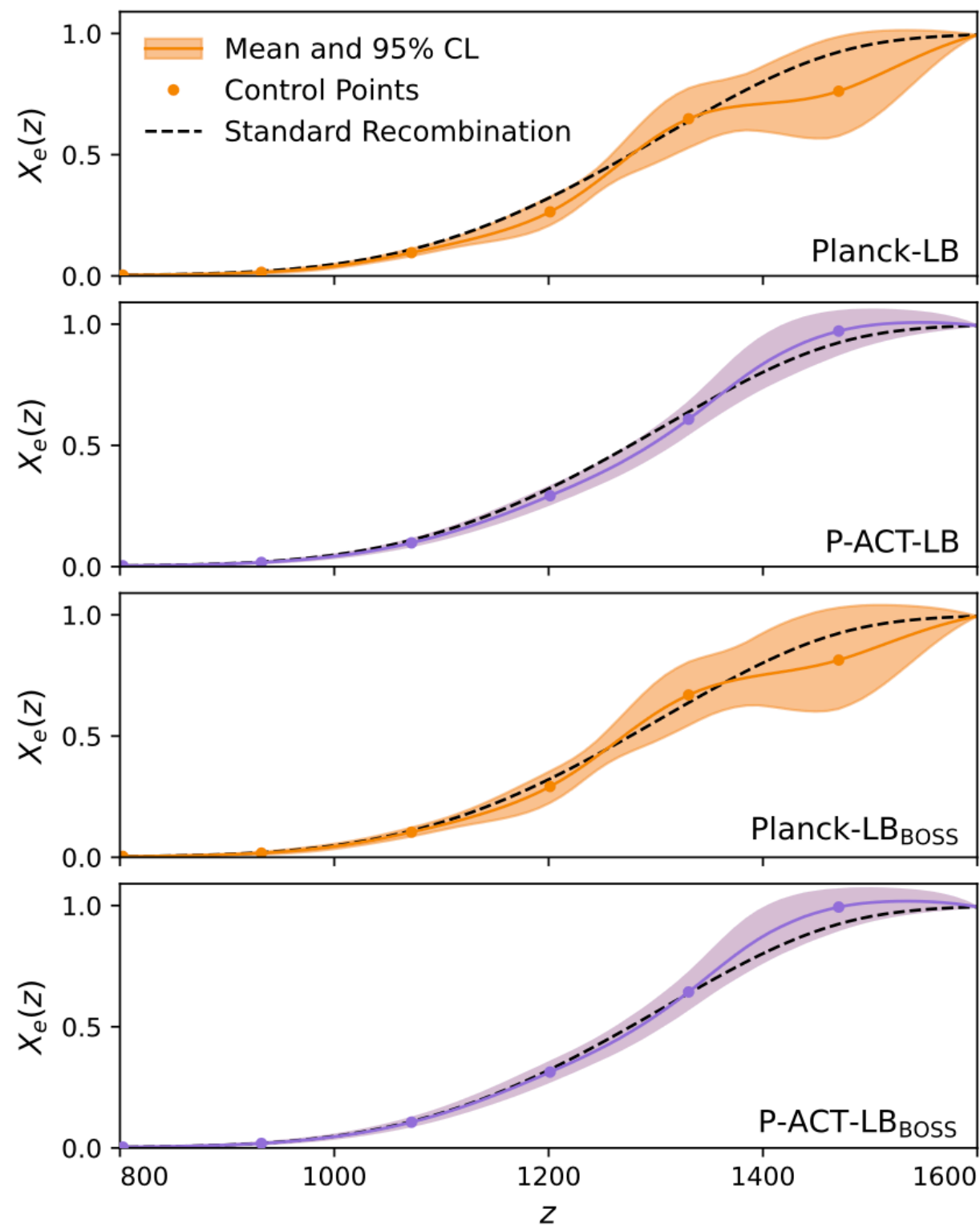
[Lynch, Knox & JC, ArXiv:2406.10202](#)

[Lynch, Knox & JC, ArXiv:2404.05715](#)

Reconstruction in light of DESI

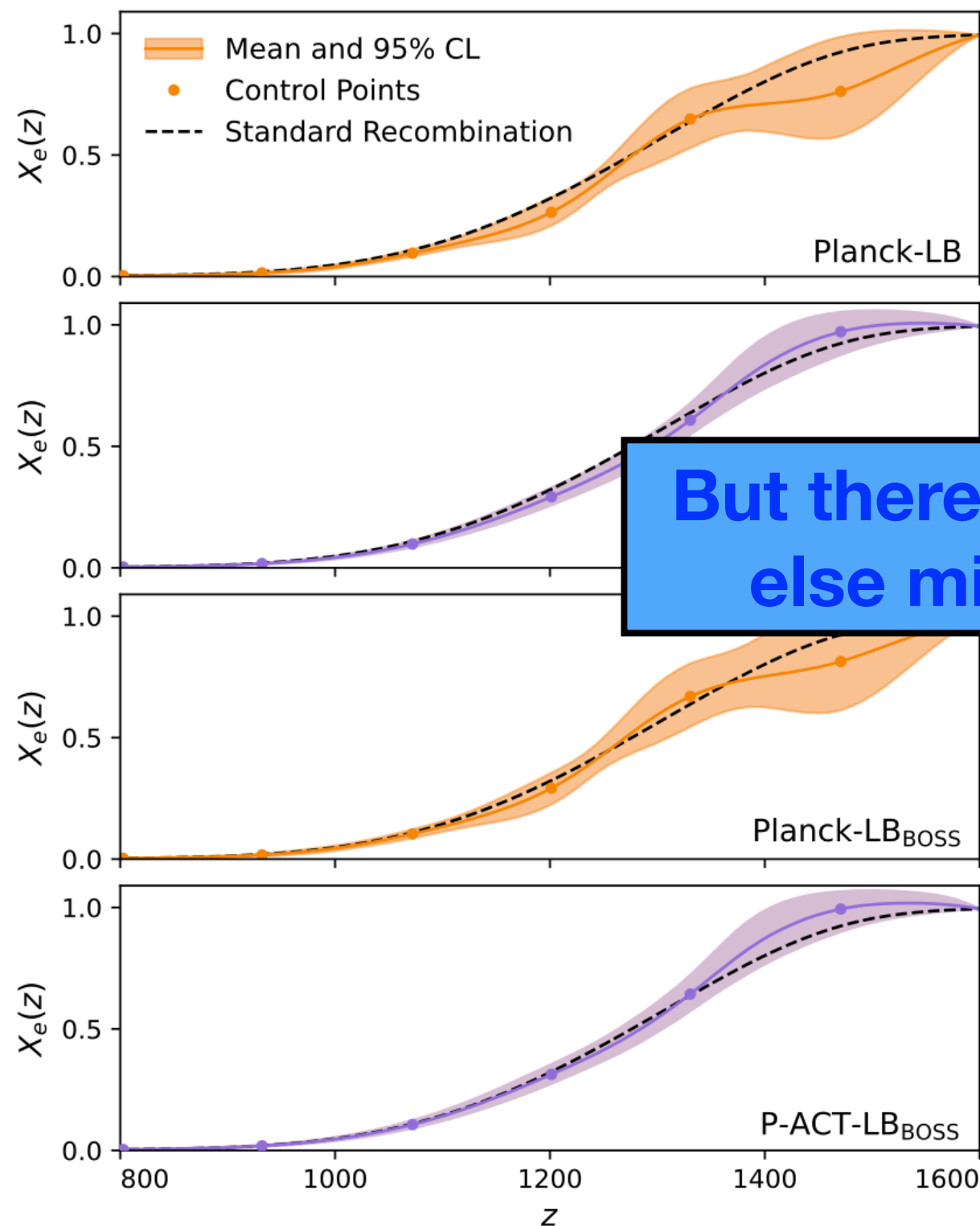


ACT Study of Extended Cosmological Models



Modified recombination scenarios
do quite well in comparison to
other HT solutions!

ACT Study of Extended Cosmological Models



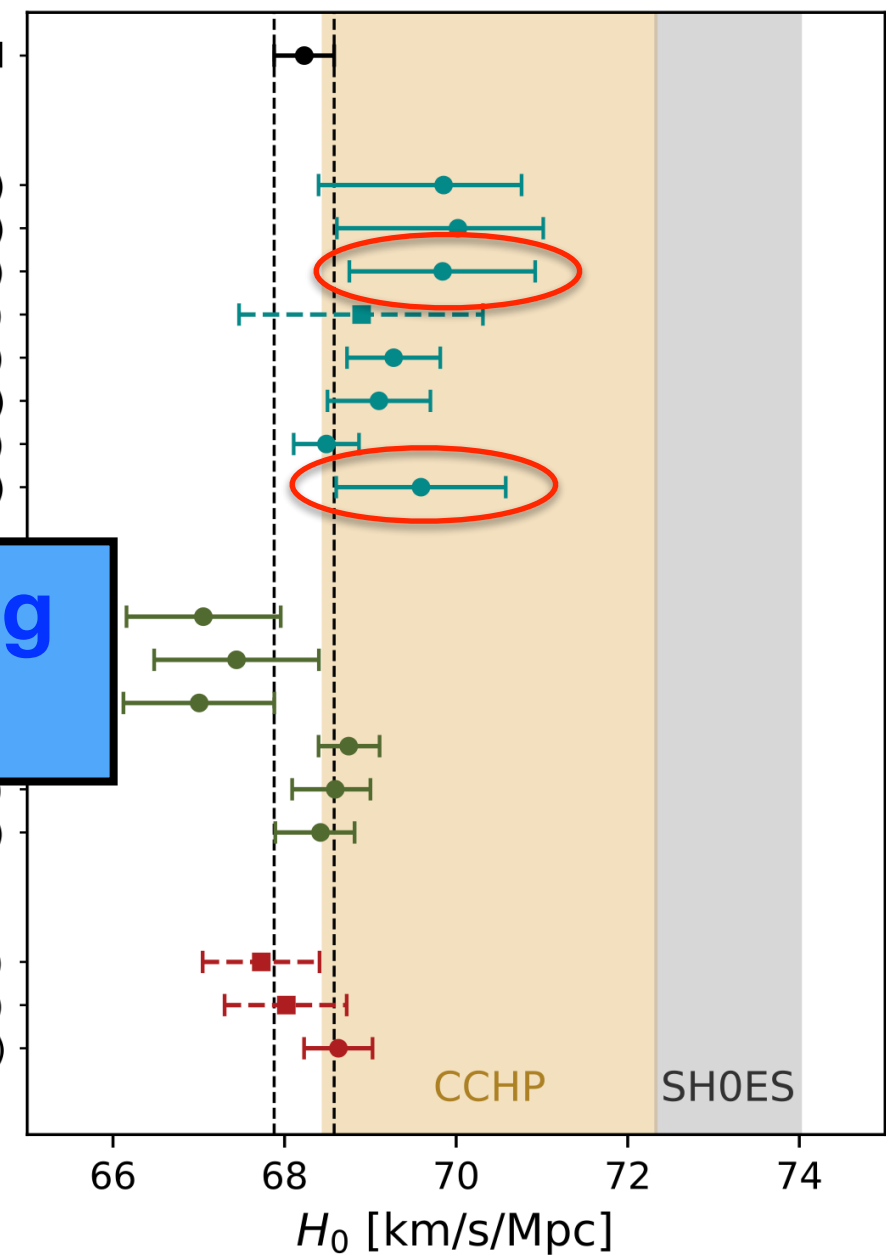
But there is something else missing here!

Early Times

Λ CDM
EDE_{n=3} (§5.1)
EDE_{n=2} (§5.1)
 m_e (§5.2)
 $m_e + \Omega_k$ (§5.2)
 α_{EM} (§5.2)
PMF (§5.3)
 T_{CMB} (§5.4)
ModRec (§5.5)

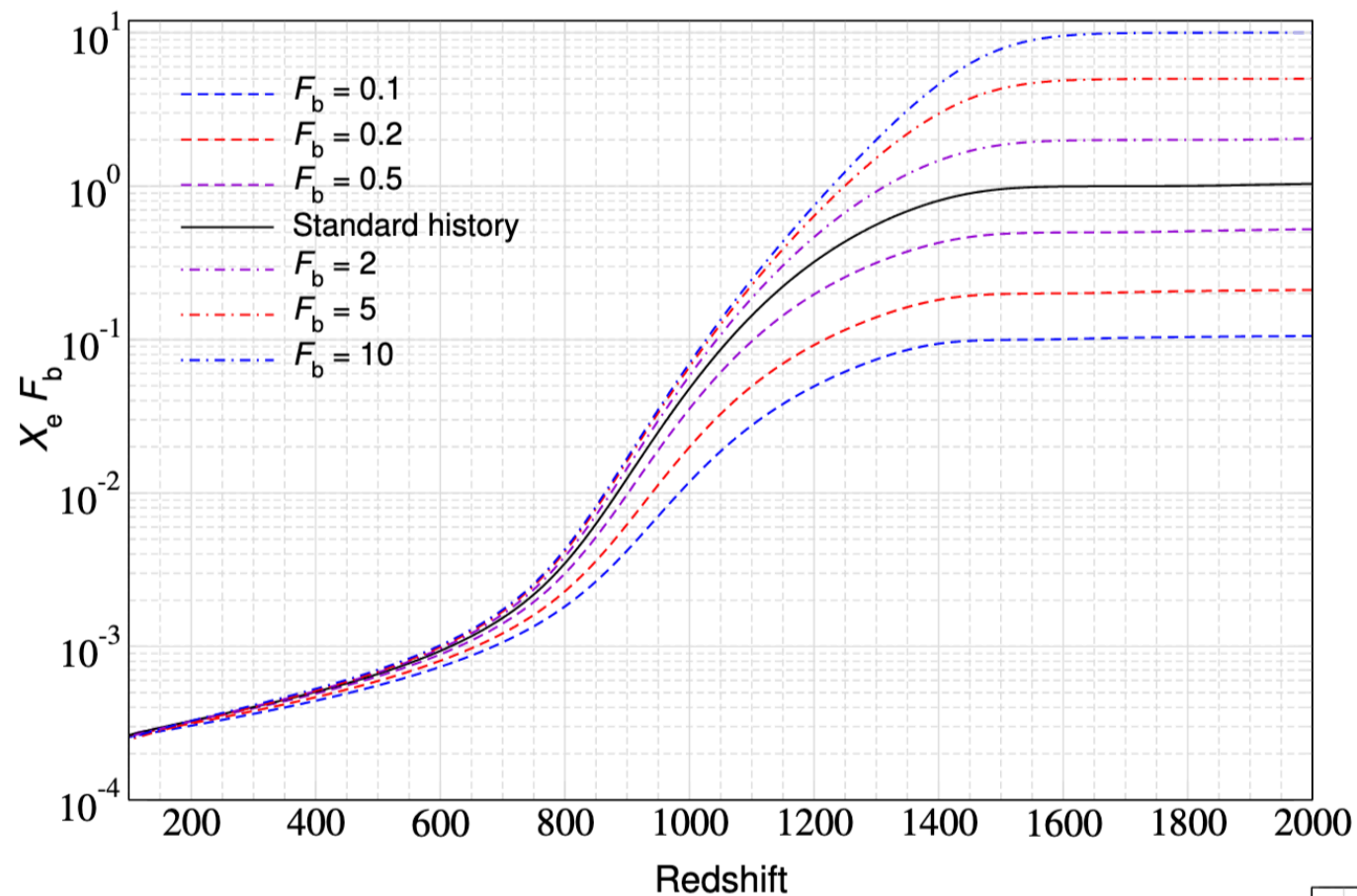
Late Times

SIDR (§6.5)
SIDR IDM (§6.5)
 w (§7.2)
 $w_0 w_a$ (§7.2)
 γ (§7.4)



Modified recombination scenarios do quite well in comparison to other HT solutions!

What if the Universe is lumpy at recombination?

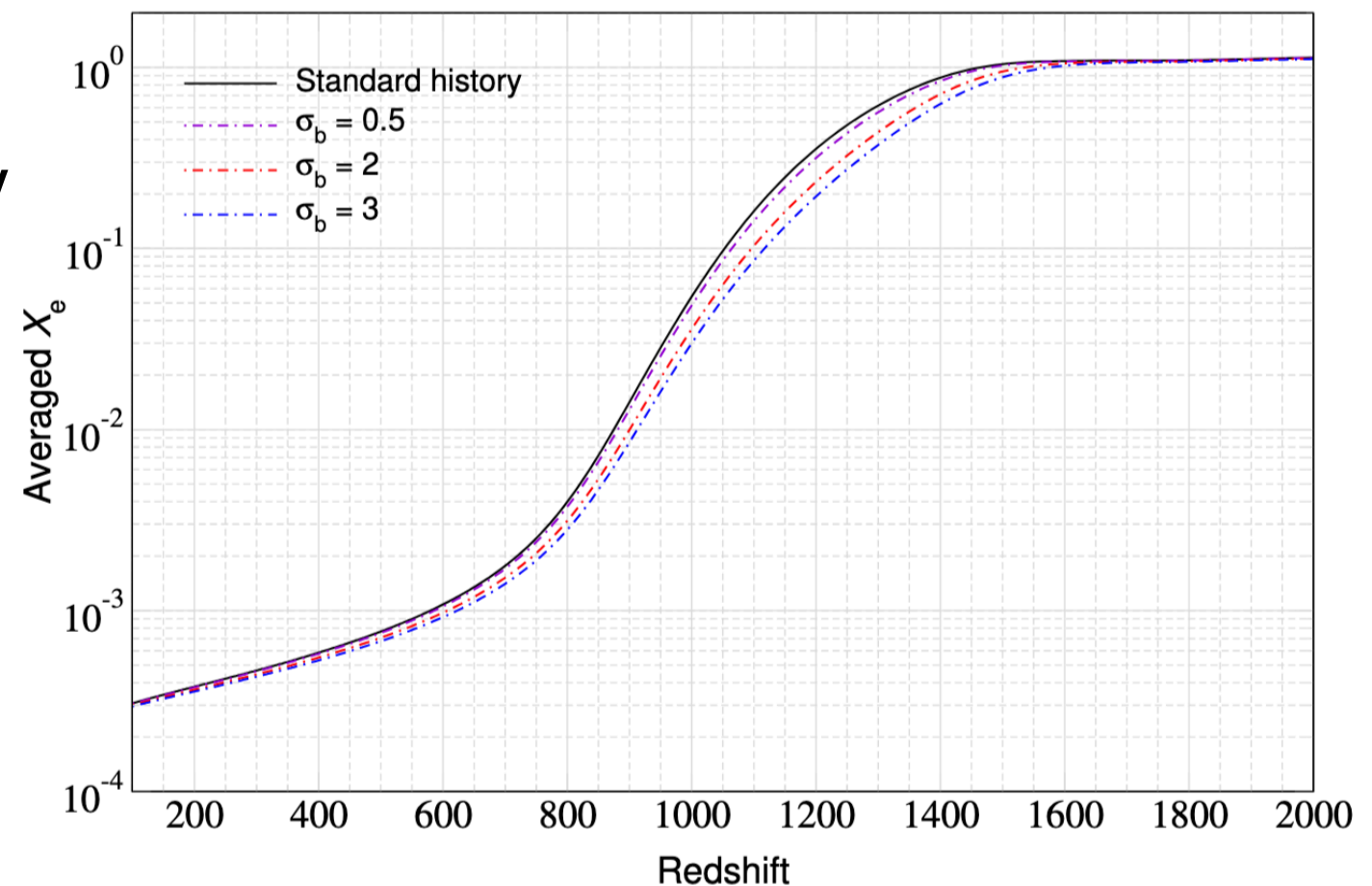


Some patches will recombine faster some more slowly...

Modifications are non-linear

Average history is modified, typically leading to *early recombination*

This is consistent with the reconstructions...



What if the Universe is lumpy at recombination?

Second effect coming from the coherence scale of the fluctuations!

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$$\begin{aligned}\langle f \rangle &= \langle \exp(-\tau) \rangle = \left\langle \exp \left(- \int_{\eta}^{\eta_0} \bar{\Gamma} (1 + \delta_e) d\eta' \right) \right\rangle \\ &= \bar{f}(\eta) \int \exp \left[-\Delta\eta \bar{\Gamma}(\eta) \cdot \delta_e(\eta) \right] \mathcal{P}(\delta_e) d\delta_e^N \\ &= \bar{f}(\eta) \exp \left[\frac{\Delta\eta^2}{2} \bar{\Gamma}^T(\eta) \mathbf{C} \bar{\Gamma}(\eta) \right]\end{aligned}$$

$$\bar{\Gamma} = \sigma_T \bar{N}_e a$$

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$$\langle f \rangle = \bar{f}(\eta) \exp \left[\sum_i \frac{\Delta\eta^2}{2} \sigma_i^2 \bar{\Gamma}_i^2 \right] \rightarrow \bar{f}(\eta)$$

$$\bar{\Gamma} = \sigma_T \bar{N}_e a$$

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$$\bar{\Gamma} = \sigma_T \bar{N}_e a$$

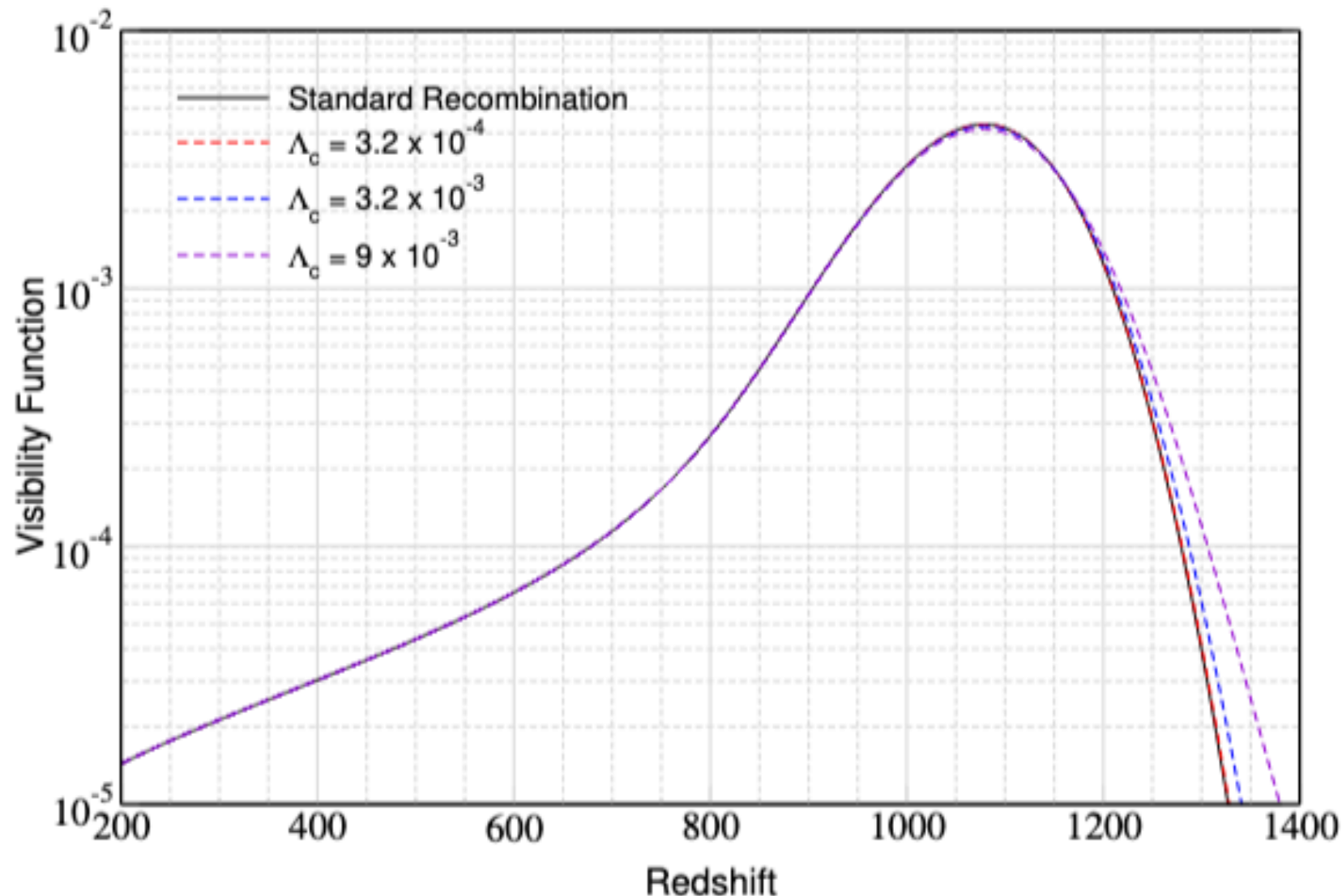
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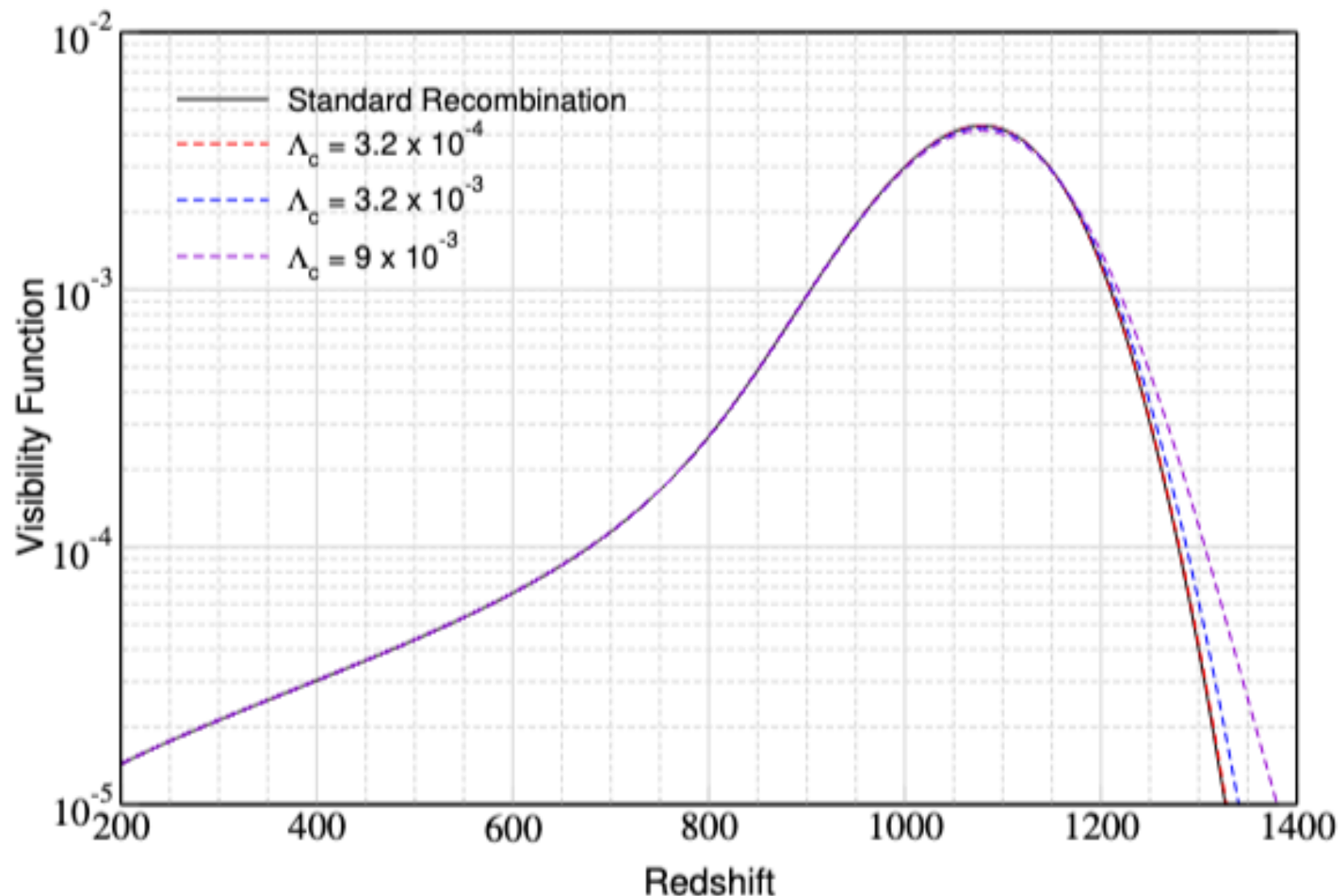
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$$\begin{aligned}\langle f \rangle &= \langle \exp(-\tau) \rangle = \left\langle \exp \left(- \int_{\eta}^{\eta_0} \bar{\Gamma} (1 + \delta_e) d\eta' \right) \right\rangle \\ &= \bar{f}(\eta) \int \exp \left[-\Delta\eta \bar{\Gamma}(\eta) \cdot \delta_e(\eta) \right] \mathcal{P}(\delta_e) d\delta_e^N \\ &= \bar{f}(\eta) \exp \left[\frac{\Delta\eta^2}{2} \bar{\Gamma}^T(\eta) \mathbf{C} \bar{\Gamma}(\eta) \right]\end{aligned}$$

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$$\tau_c = \Delta\eta_c \bar{\Gamma}$$

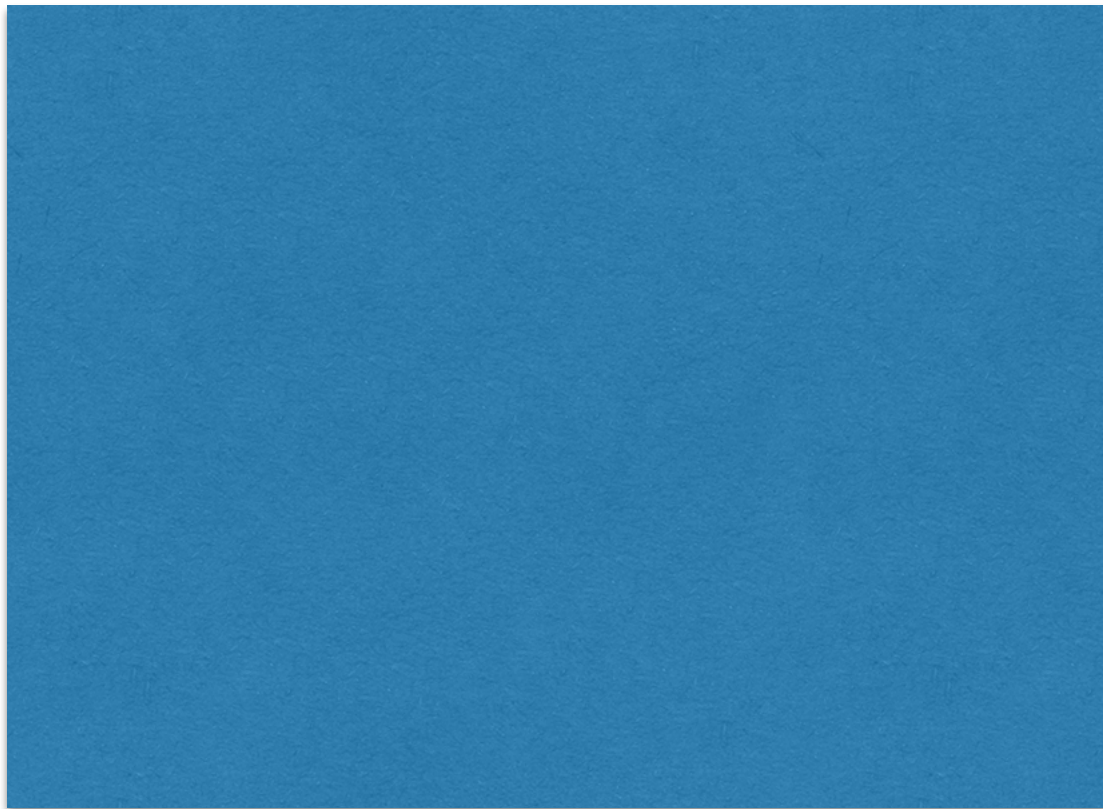
$$\zeta_e = \tau_c \sigma_e^2$$

$$\bar{\Gamma} = \sigma_T \bar{N}_e a$$

Additional effects of baryon clumping at very small scales

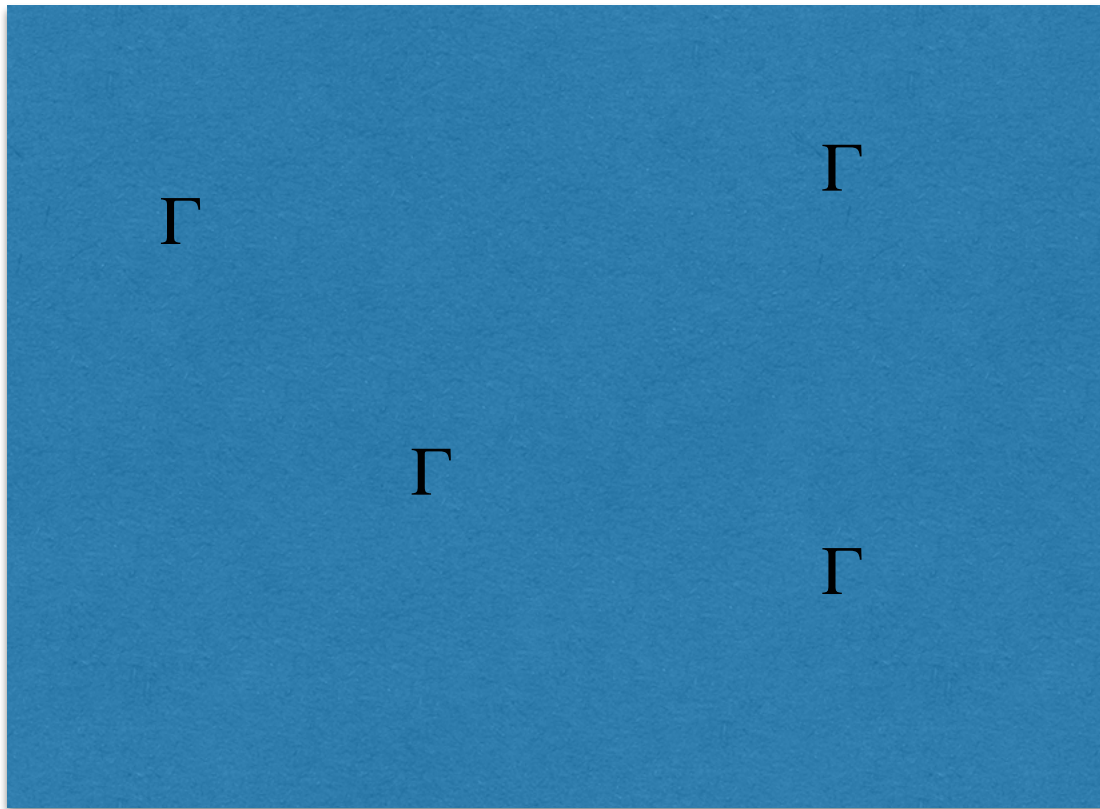
Additional effects of baryon clumping at very small scales

Uniform medium



Additional effects of baryon clumping at very small scales

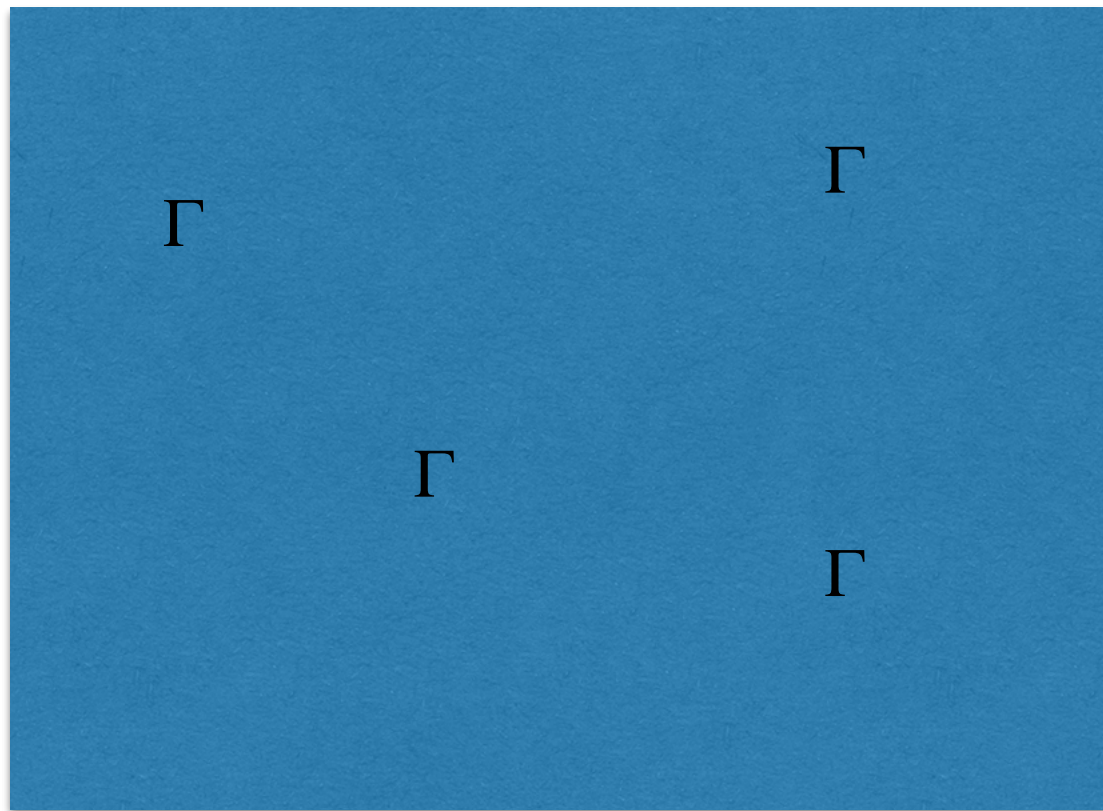
Uniform medium



$$\Gamma = \sigma_T \bar{N}_e a$$

Additional effects of baryon clumping at very small scales

Uniform medium

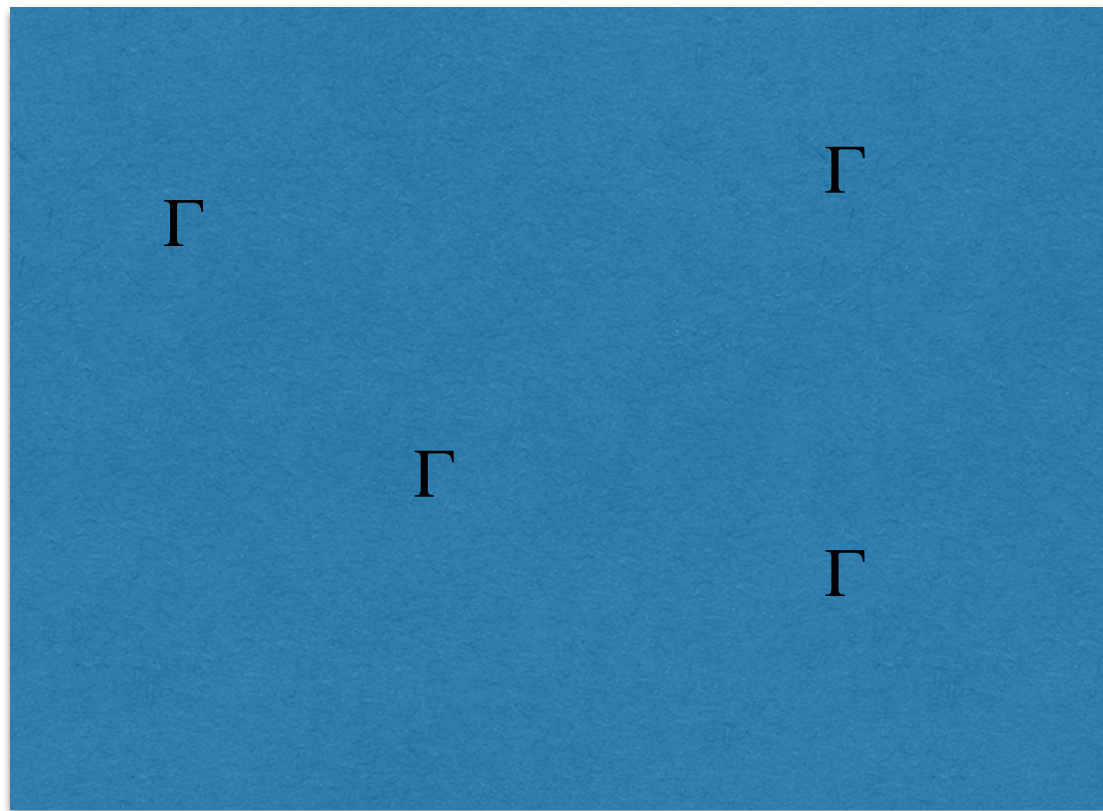


$$\Gamma = \sigma_T \bar{N}_e a$$

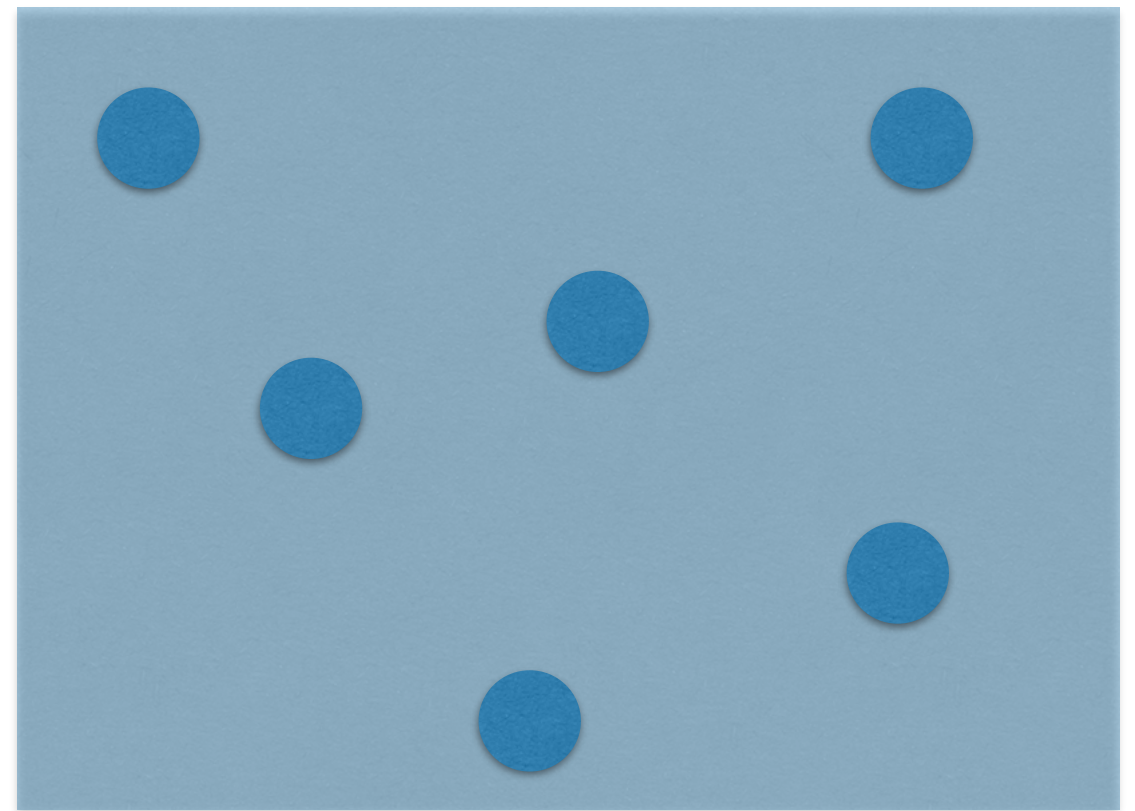
Average
recombination
history

Additional effects of baryon clumping at very small scales

Uniform medium



Clumpy medium

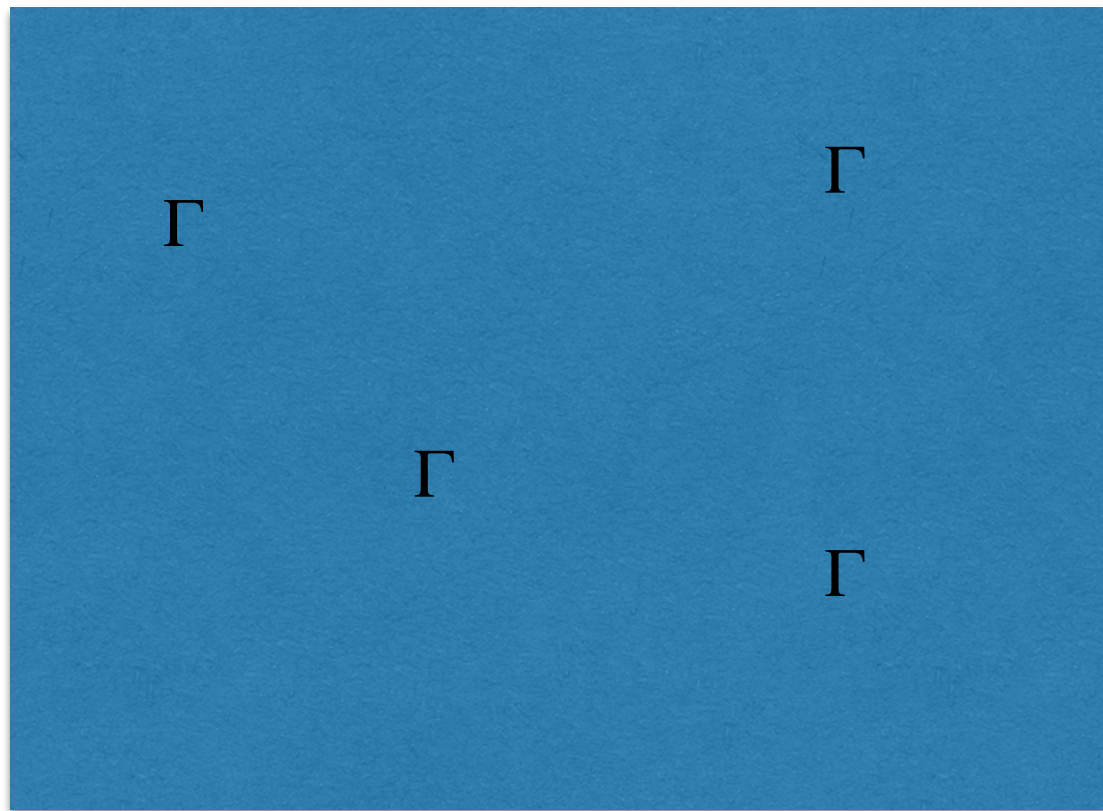


$$\Gamma = \sigma_T \bar{N}_e a$$

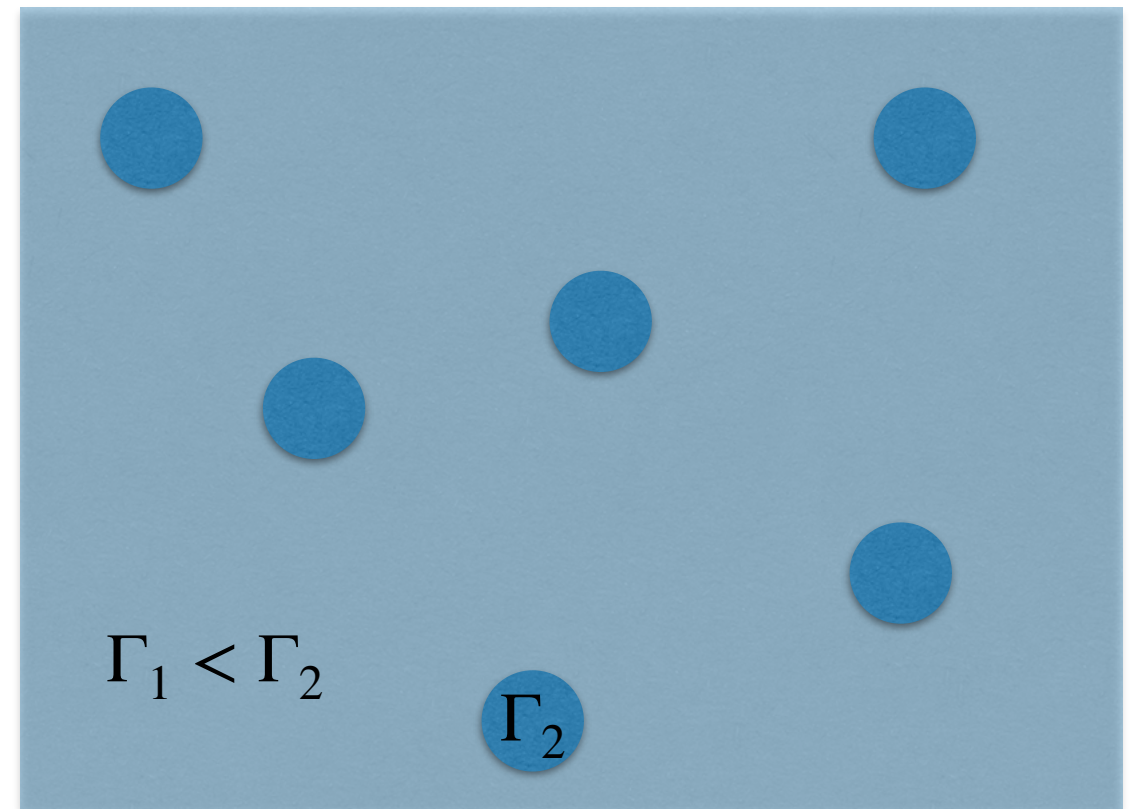
Average
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history

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Uniform medium



Clumpy medium

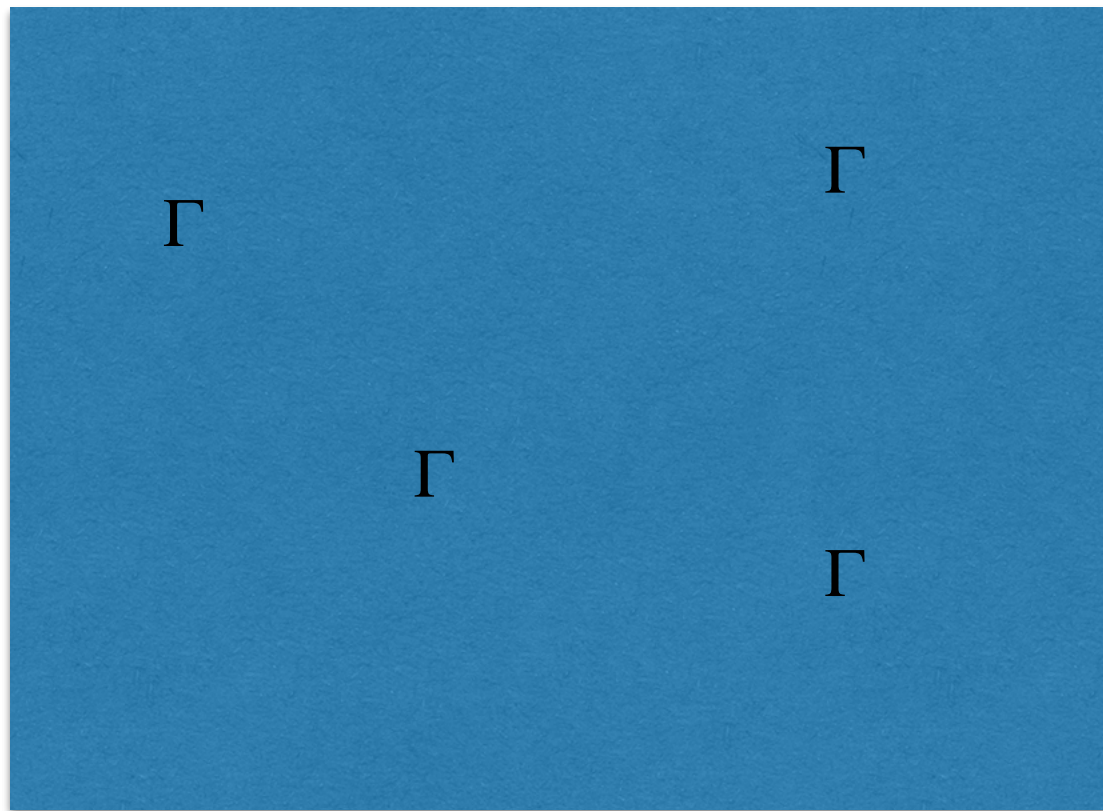


$$\Gamma = \sigma_T \bar{N}_e a$$

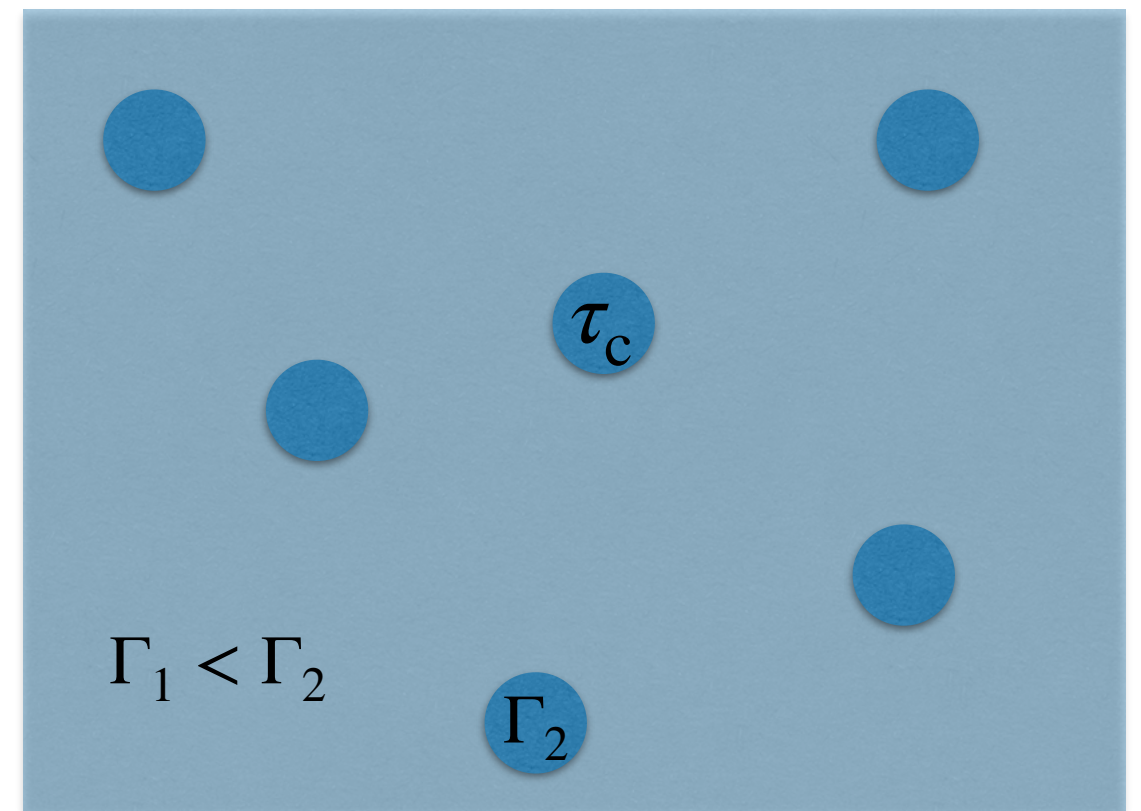
Average
recombination
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Clumpy medium

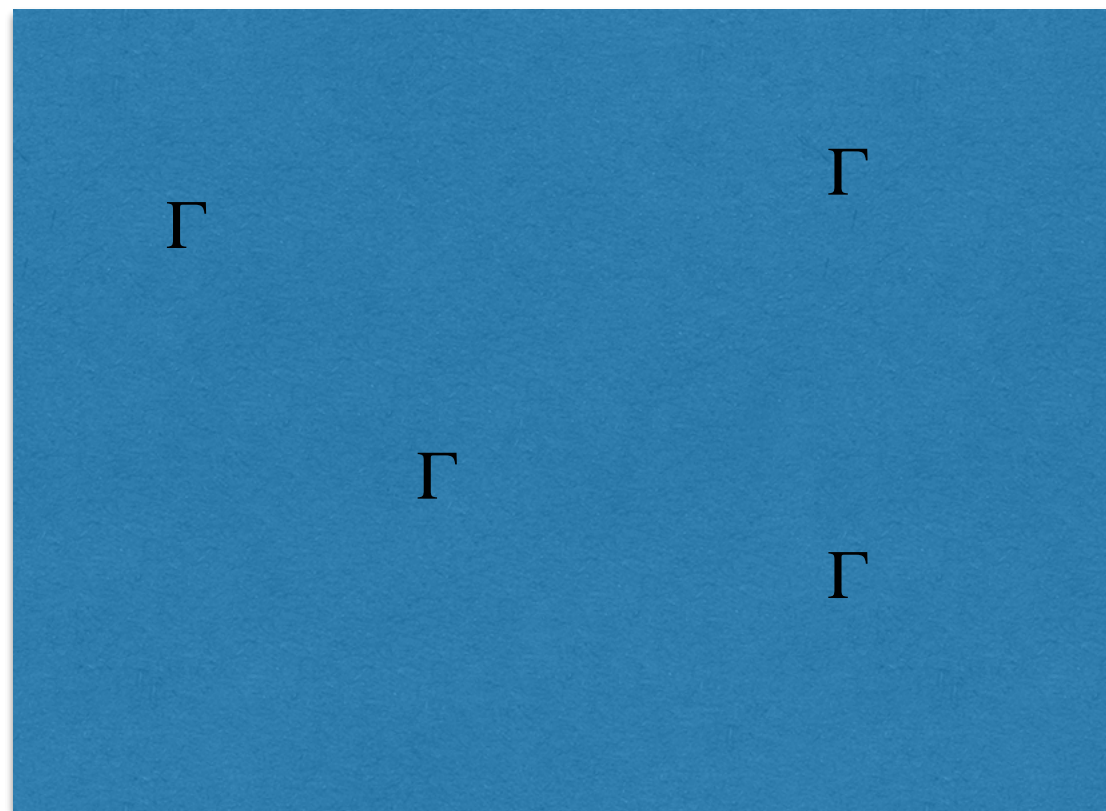


$$\Gamma = \sigma_T \bar{N}_e a$$

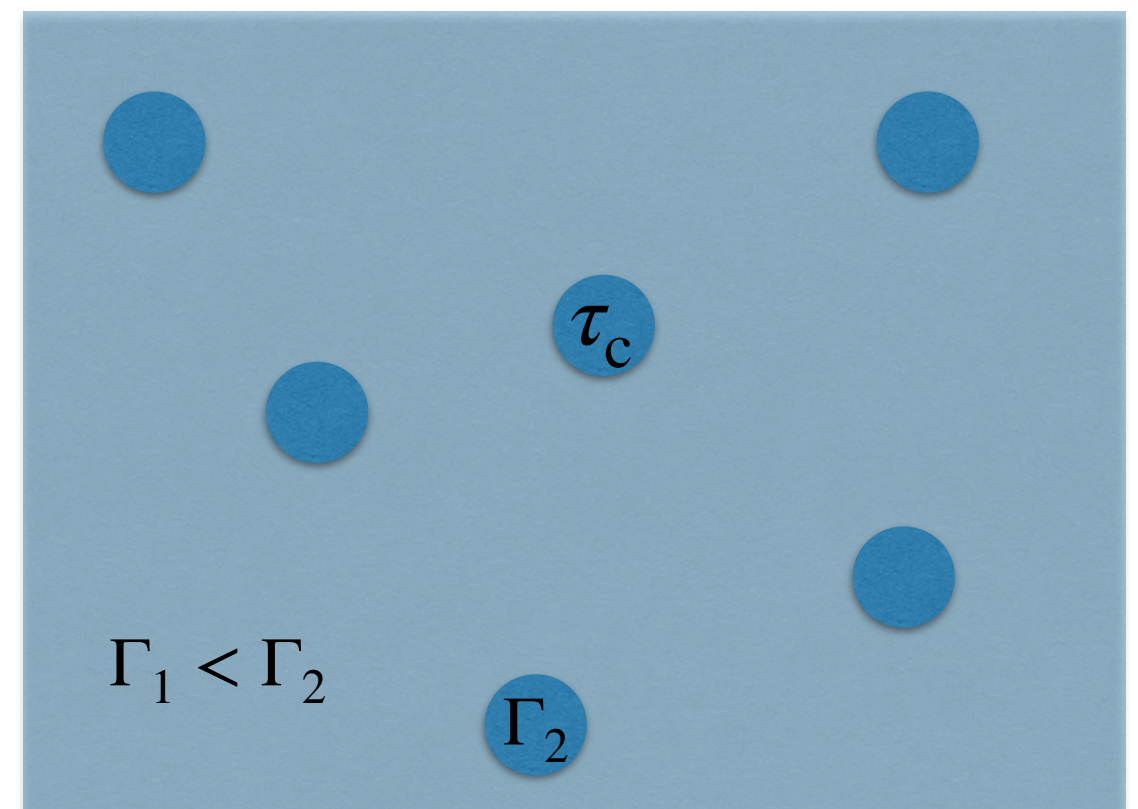
Average
recombination
history

Additional effects of baryon clumping at very small scales

Uniform medium



Clumpy medium



$$\Gamma = \sigma_T \bar{N}_e a$$

Average
recombination
history

$$\Gamma \approx \sigma_T \bar{N}_e a [1 - \zeta_e]$$

$$\zeta_e = \tau_c \sigma_e^2$$

Optical depth
across coherence
length

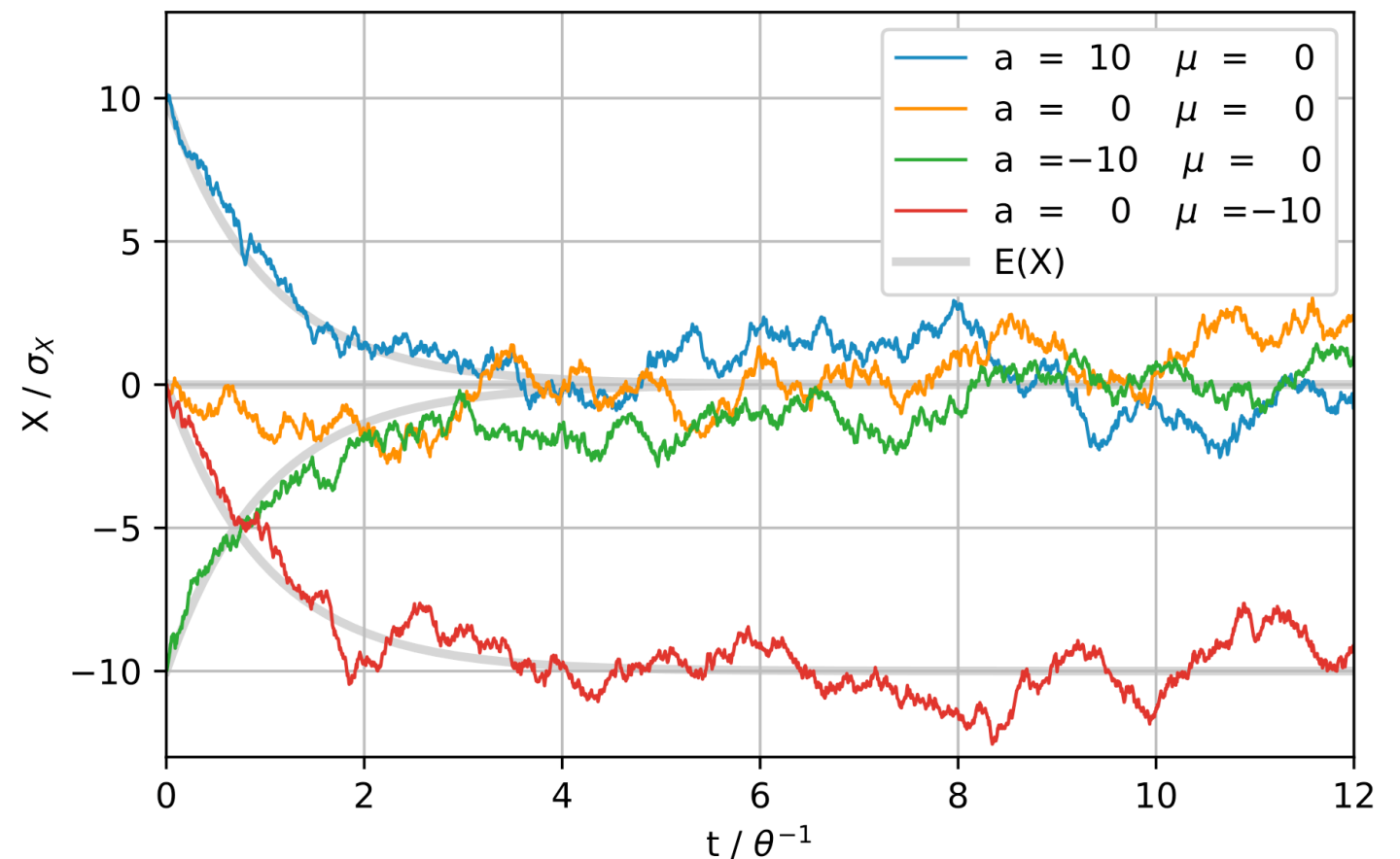
Electron variance

What if the Universe is lumpy at recombination?

Third effect on Photon transfer functions can be treated using Itô calculus!

Ornstein-Uhlenbeck process

$$d\delta_e = -\alpha(\eta) \delta_e d\eta + \sigma(\eta) dW$$



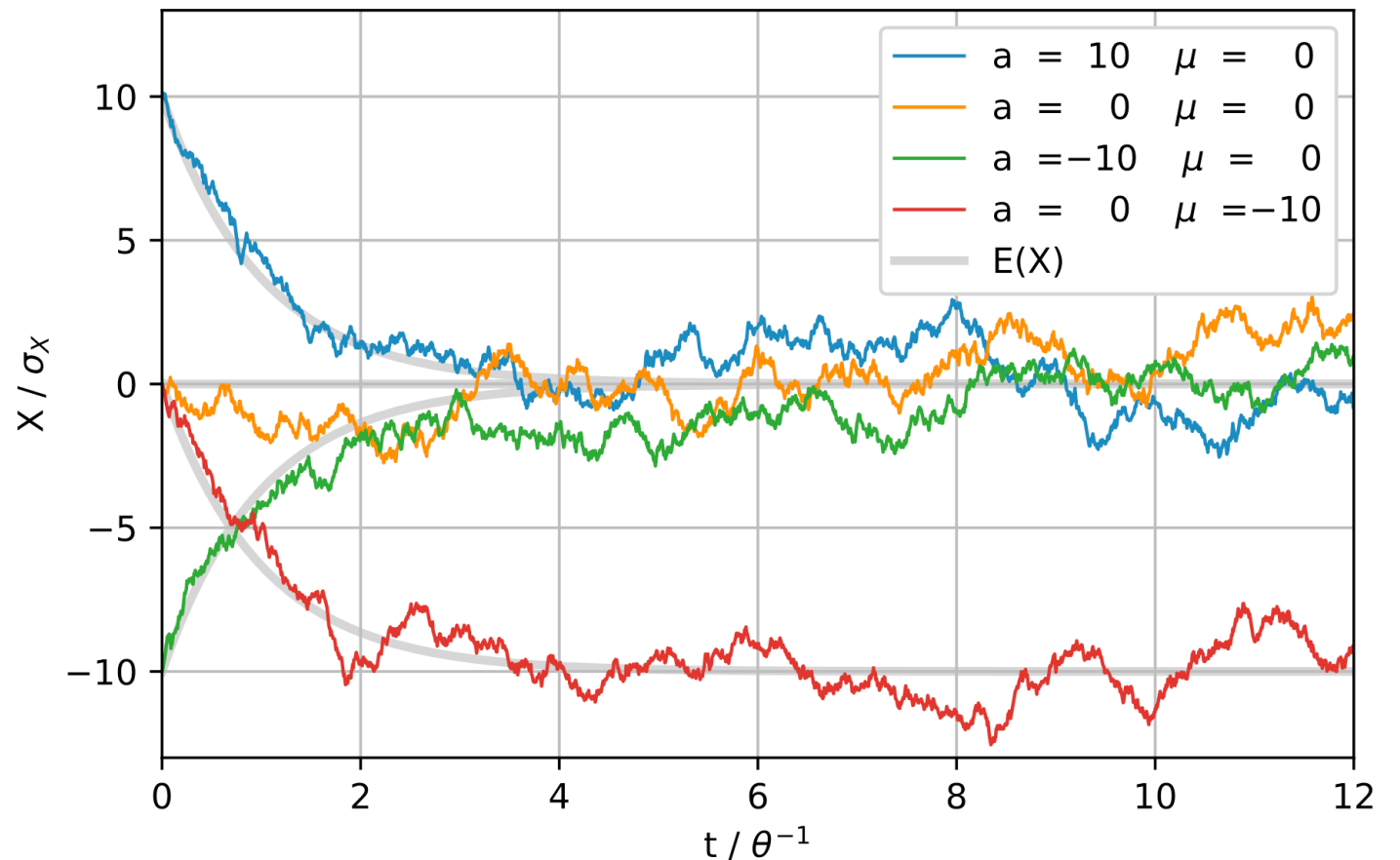
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$$\frac{df}{d\eta} = \lim_{\Delta\eta \rightarrow 0} \frac{f(\eta + \Delta\eta) - f(\eta)}{\Delta\eta}$$



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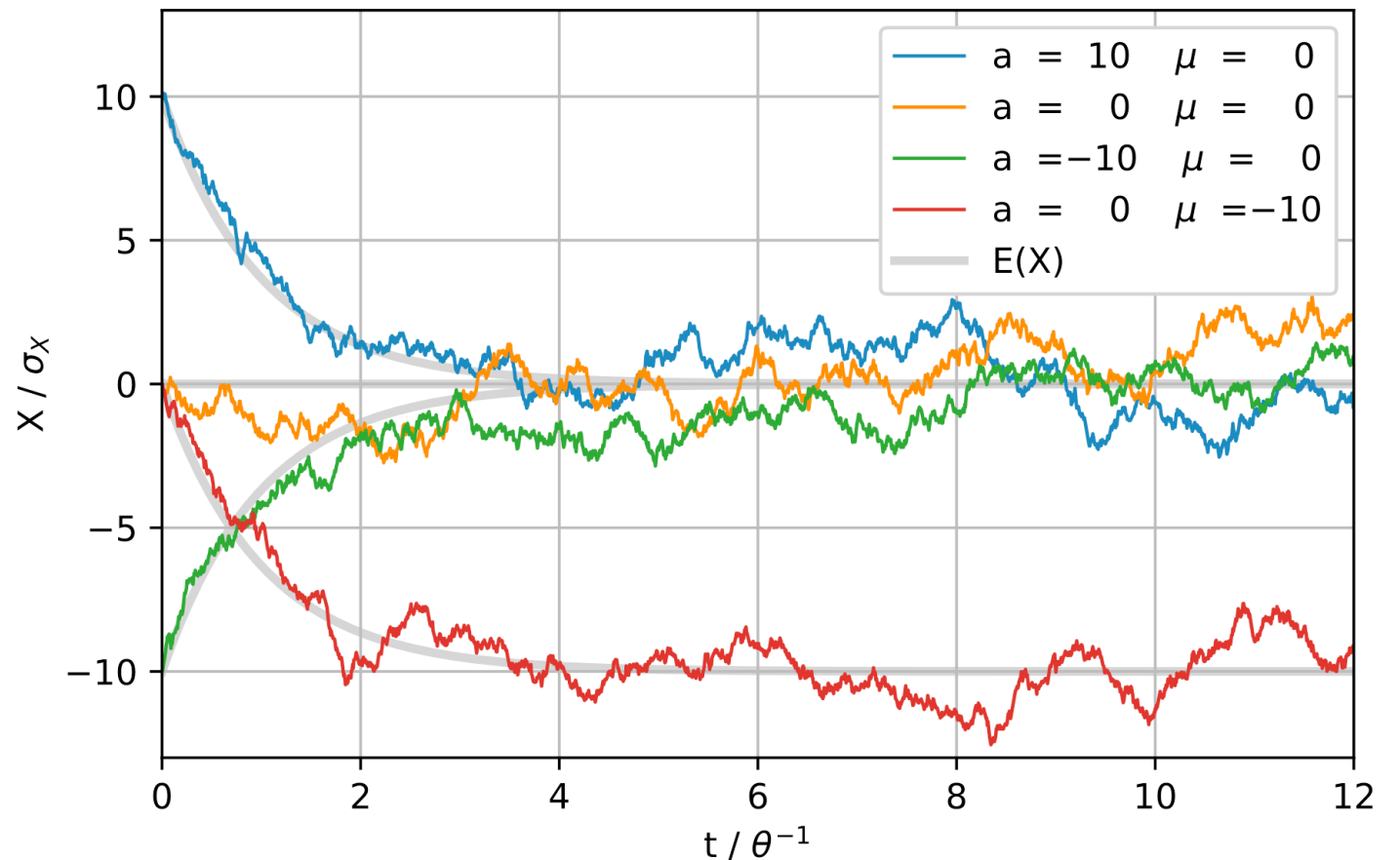
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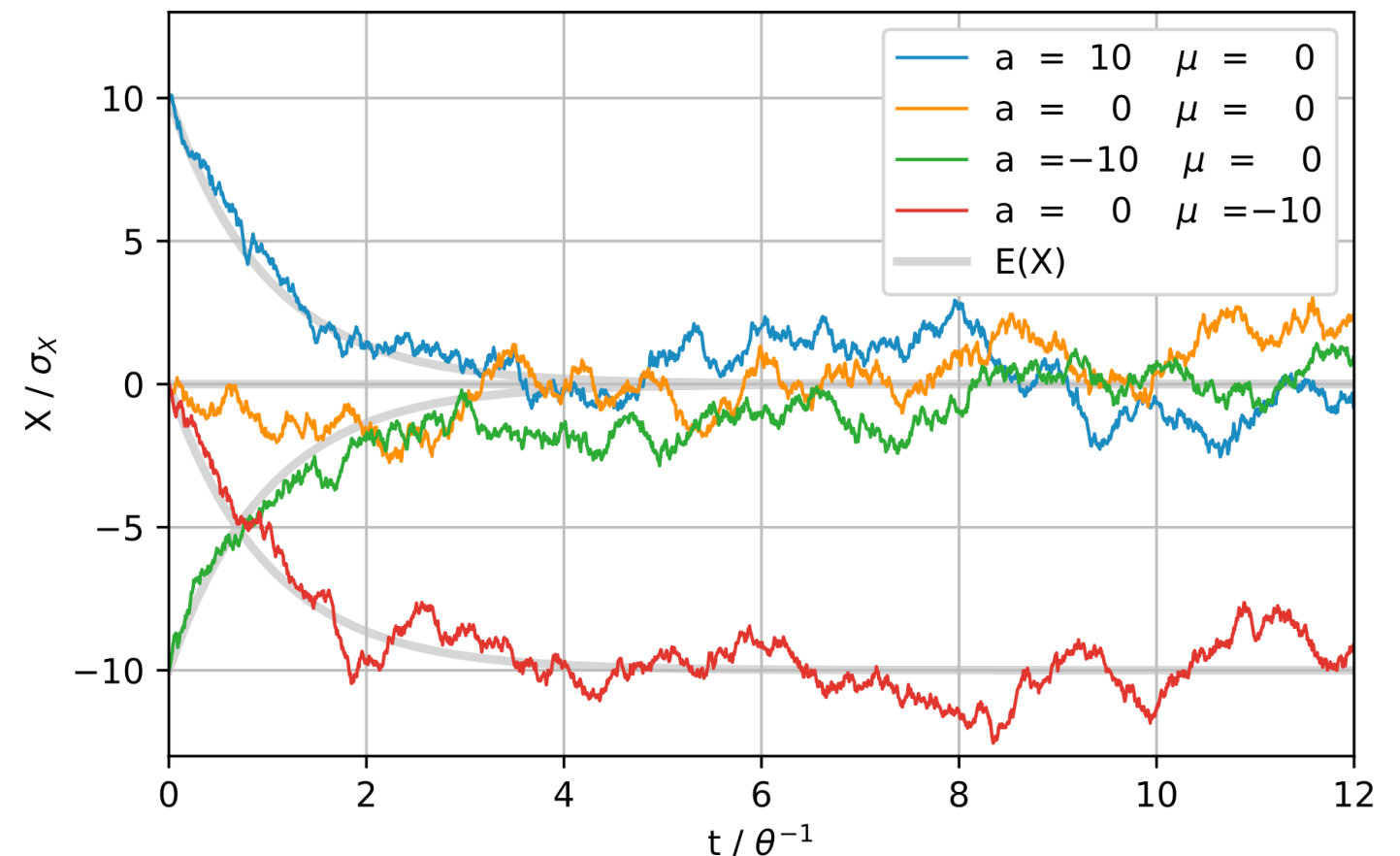
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$$\left\langle \frac{df}{d\eta} \right\rangle = \left\langle \lim_{\Delta\eta \rightarrow 0} \frac{f(\delta_e(\eta + \Delta\eta)) - f(\delta_e(\eta))}{\Delta\eta} \right\rangle = ???$$

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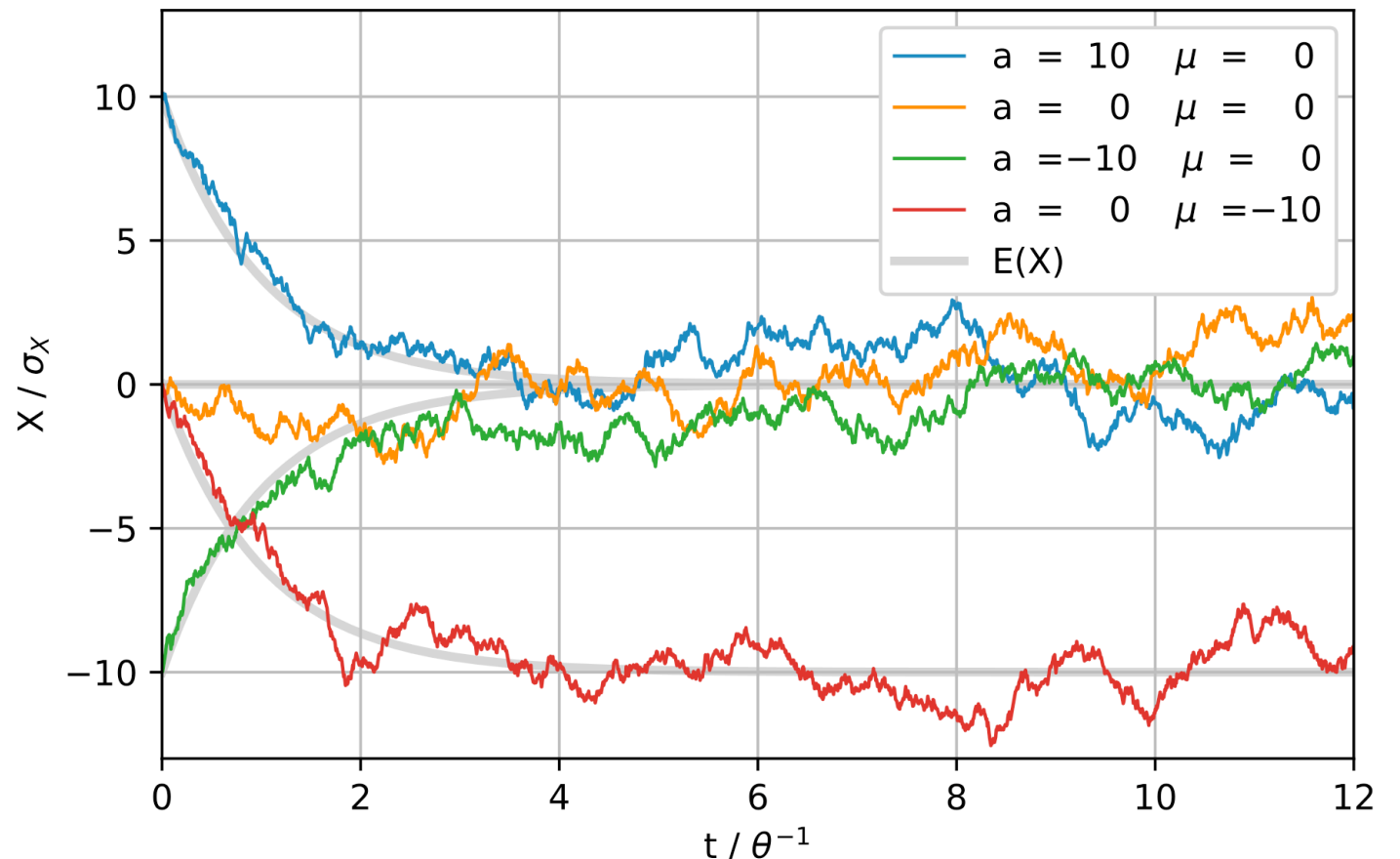
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Picks up new terms from $\langle dW dW' \rangle \neq 0$

New terms in Boltzmann equation using Ito calculus

$$\partial_{\eta} v_b = k\Psi - \mathcal{H}v_b + \frac{3\bar{\Gamma}}{R} \{1 - f_1(\tau_c, \sigma_e)\} \left[\Theta_1 - \frac{v_b}{3} \right], \quad (82)$$

$$\partial_{\eta} \Theta_1 = \frac{k}{3} \Theta_0 - \frac{2k}{3} \Theta_2 + \frac{k}{3} \Psi - \bar{\Gamma} \{1 - f_1(\tau_c, \sigma_e)\} \left[\Theta_1 - \frac{v_b}{3} \right],$$

$$\partial_{\eta} \Theta_2 = \frac{2k}{5} \Theta_1 - \frac{3k}{5} \Theta_3 - \frac{9}{10} \bar{\Gamma} \{1 - f_2(\tau_c, \sigma_e)\} \Theta_2,$$

$$\partial_{\eta} \Theta_{\ell \geq 3} = \frac{k\ell}{2\ell + 1} \Theta_{\ell-1} - \frac{k(\ell + 1)}{2\ell + 1} \Theta_{\ell+1} - \bar{\Gamma} \{1 - f_3(\tau_c, \sigma_e)\} \Theta_{\ell},$$

New terms in Boltzmann equation using Ito calculus

$$\begin{aligned}\partial_\eta v_b &= k\Psi - \mathcal{H}v_b + \frac{3\bar{\Gamma}}{R} \{1 - f_1(\tau_c, \sigma_e)\} \left[\Theta_1 - \frac{v_b}{3} \right], \quad (82) \\ \partial_\eta \Theta_1 &= \frac{k}{3} \Theta_0 - \frac{2k}{3} \Theta_2 + \frac{k}{3} \Psi - \bar{\Gamma} \{1 - f_1(\tau_c, \sigma_e)\} \left[\Theta_1 - \frac{v_b}{3} \right], \\ \partial_\eta \Theta_2 &= \frac{2k}{5} \Theta_1 - \frac{3k}{5} \Theta_3 - \frac{9}{10} \bar{\Gamma} \{1 - f_2(\tau_c, \sigma_e)\} \Theta_2, \\ \partial_\eta \Theta_{\ell \geq 3} &= \frac{k\ell}{2\ell + 1} \Theta_{\ell-1} - \frac{k(\ell + 1)}{2\ell + 1} \Theta_{\ell+1} - \bar{\Gamma} \{1 - f_3(\tau_c, \sigma_e)\} \Theta_\ell,\end{aligned}$$

New terms in Boltzmann equation using Ito calculus

$$\begin{aligned}
 \partial_\eta v_b &= k\Psi - \mathcal{H}v_b + \frac{3\bar{\Gamma}}{R} \{1 - f_1(\tau_c, \sigma_e)\} \left[\Theta_1 - \frac{v_b}{3} \right], \quad (82) \\
 \partial_\eta \Theta_1 &= \frac{k}{3} \Theta_0 - \frac{2k}{3} \Theta_2 + \frac{k}{3} \Psi - \bar{\Gamma} \{1 - f_1(\tau_c, \sigma_e)\} \left[\Theta_1 - \frac{v_b}{3} \right], \\
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 \partial_\eta \Theta_{\ell \geq 3} &= \frac{k\ell}{2\ell + 1} \Theta_{\ell-1} - \frac{k(\ell + 1)}{2\ell + 1} \Theta_{\ell+1} - \bar{\Gamma} \{1 - f_3(\tau_c, \sigma_e)\} \Theta_\ell,
 \end{aligned}$$

Gaussian
fluctuations

$$f_e^G(\tau_*, \sigma_e) = \tau_* \sigma_e^2 \exp(-\tau_*^2 \sigma_e^2), \quad (83a)$$

$$f_1(\tau_c, \sigma_e) = f_e^G\left(\frac{1+R}{R} \tau_c, \sigma_e\right), \quad (83b)$$

$$f_2(\tau_c, \sigma_e) = f_e^G\left(\frac{9}{10} \tau_c, \sigma_e\right), \quad (83c)$$

$$f_3(\tau_c, \sigma_e) = f_e^G(\tau_c, \sigma_e), \quad (83d)$$

New terms in Boltzmann equation using Ito calculus

$$\partial_{\eta} v_b = k\Psi - \mathcal{H}v_b + \frac{3\bar{\Gamma}}{R} \{1 - f_1(\tau_c, \sigma_e)\} \left[\Theta_1 - \frac{v_b}{3} \right], \quad (82)$$

$$\partial_{\eta} \Theta_1 = \frac{k}{3} \Theta_0 - \frac{2k}{3} \Theta_2 + \frac{k}{3} \Psi - \bar{\Gamma} \{1 - f_1(\tau_c, \sigma_e)\} \left[\Theta_1 - \frac{v_b}{3} \right],$$

$$\partial_{\eta} \Theta_2 = \frac{2k}{5} \Theta_1 - \frac{3k}{5} \Theta_3 - \frac{9}{10} \bar{\Gamma} \{1 - f_2(\tau_c, \sigma_e)\} \Theta_2,$$

$$\partial_{\eta} \Theta_{k\ell} = \frac{k\ell}{k(\ell+1)} \Theta_{k\ell+1} - \bar{\Gamma} \{1 - f_{k\ell}(\tau_c, \sigma_e)\} \Theta_{k\ell},$$

New terms not degenerate with changes in average recombination history!

Gaussian
fluctuations

$$f_e^G(\tau_*, \sigma_e) = \tau_* \sigma_e^2 \exp(-\tau_*^2 \sigma_e^2), \quad (83a)$$

$$f_1(\tau_c, \sigma_e) = f_e^G\left(\frac{1+R}{R} \tau_c, \sigma_e\right), \quad (83b)$$

$$f_2(\tau_c, \sigma_e) = f_e^G\left(\frac{9}{10} \tau_c, \sigma_e\right), \quad (83c)$$

$$f_3(\tau_c, \sigma_e) = f_e^G(\tau_c, \sigma_e), \quad (83d)$$

Changes to CMB power spectra

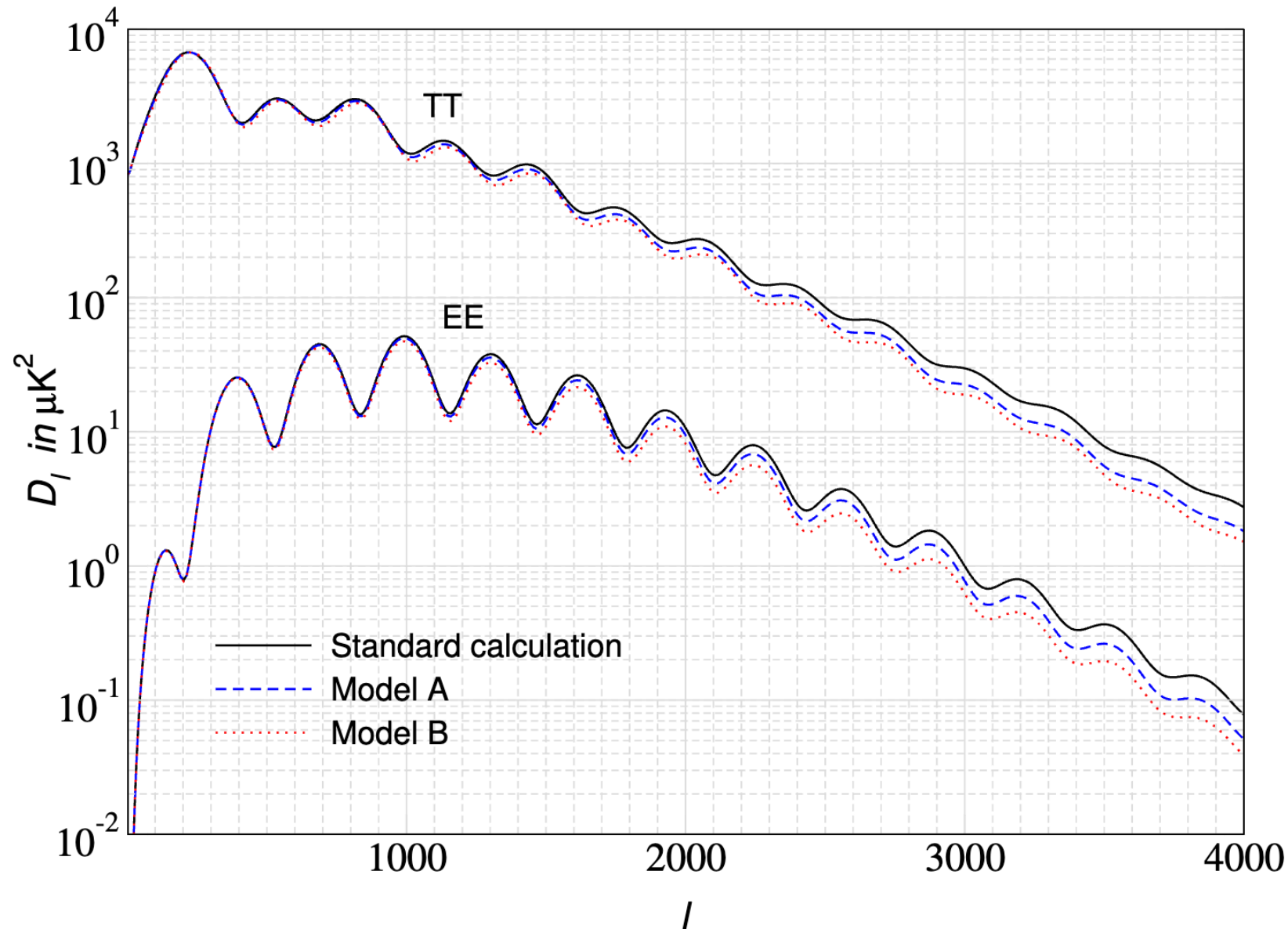
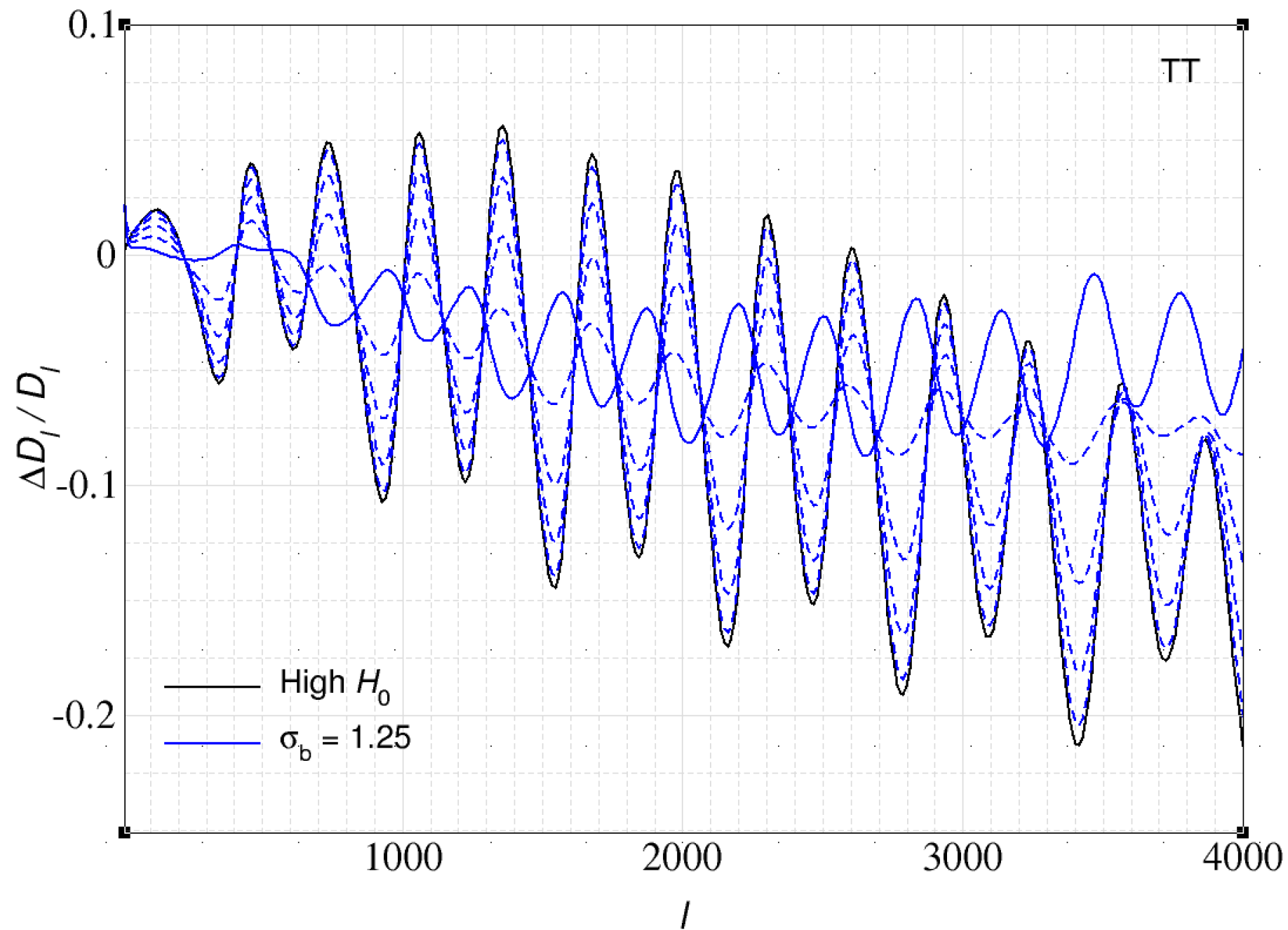


Figure 17. CMB TT and EE power spectra, $D_\ell = \ell(\ell + 1)C_\ell/2\pi$. The solid black lines show the standard Λ CDM computation. The other cases were computed using the log-normal modified BH setup. For Model A, we use a setup similar to Fig. 8 with $\sigma_e(z) = 1$ and $\tau_c = 0.01$ at $z = 1100$ and scaling Eq. (98). Model B is similar to the scenario shown in Fig. 15 with $\sigma_e(z) = 1$ and $\tau_c = 0.1$ at $z = 1100$ with scaling Eq. (99) for $z_s = 1200$ and $\gamma_s = 2$.

Illustration of potential for solving Hubble tension



Stay tuned for full data constraints....

Preliminary

How well do these models do?

Preliminary

Preliminary

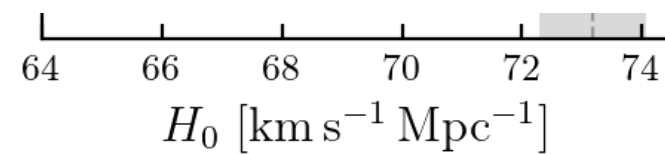
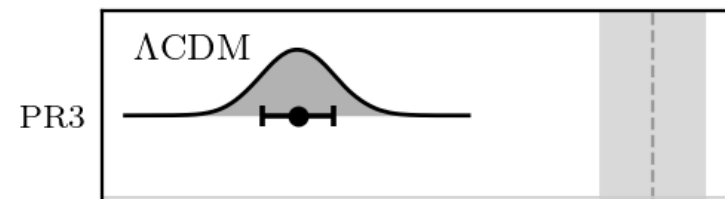


Gabriel Lynch

Preliminary

How well do these models do?

Preliminary



Preliminary



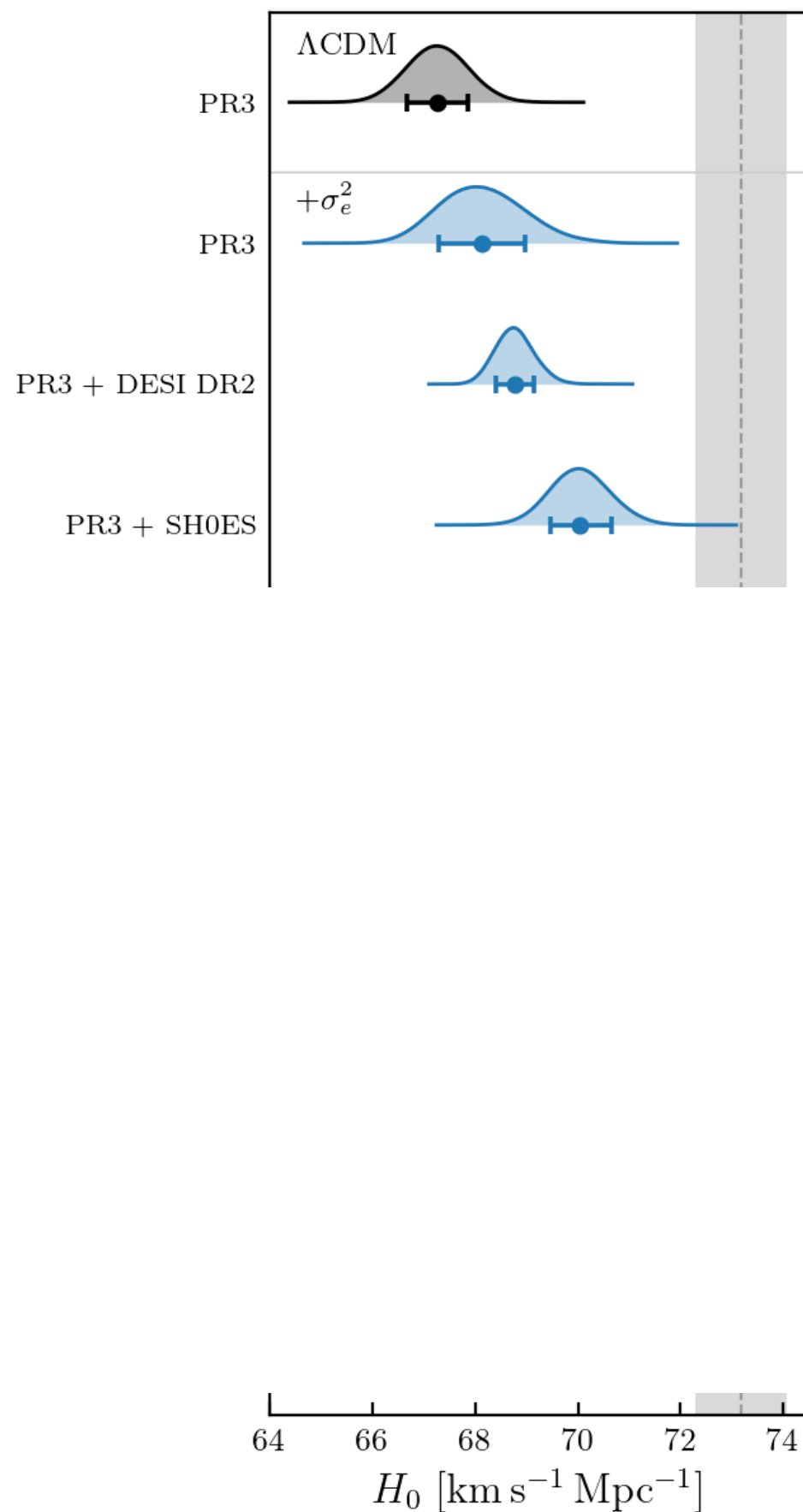
Gabriel Lynch

Lynch et al. 2026 in prep

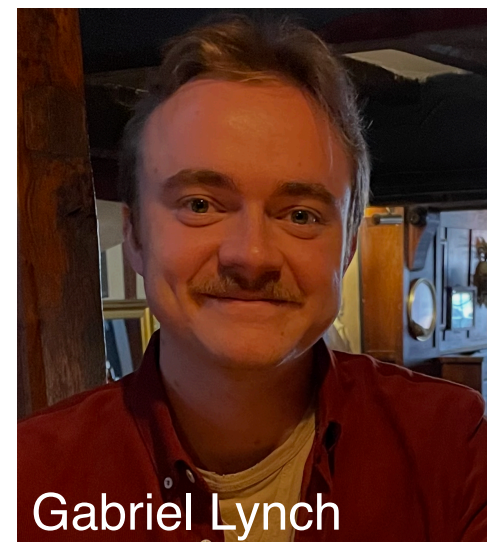
Preliminary

How well do these models do?

Preliminary



Preliminary



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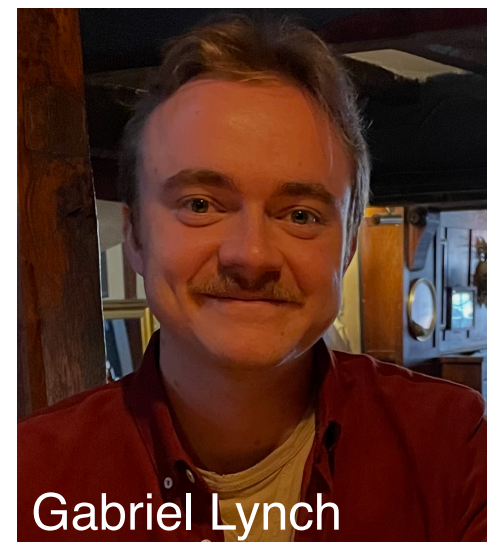
Lynch et al. 2026 in prep

Preliminary

How well do these models do?

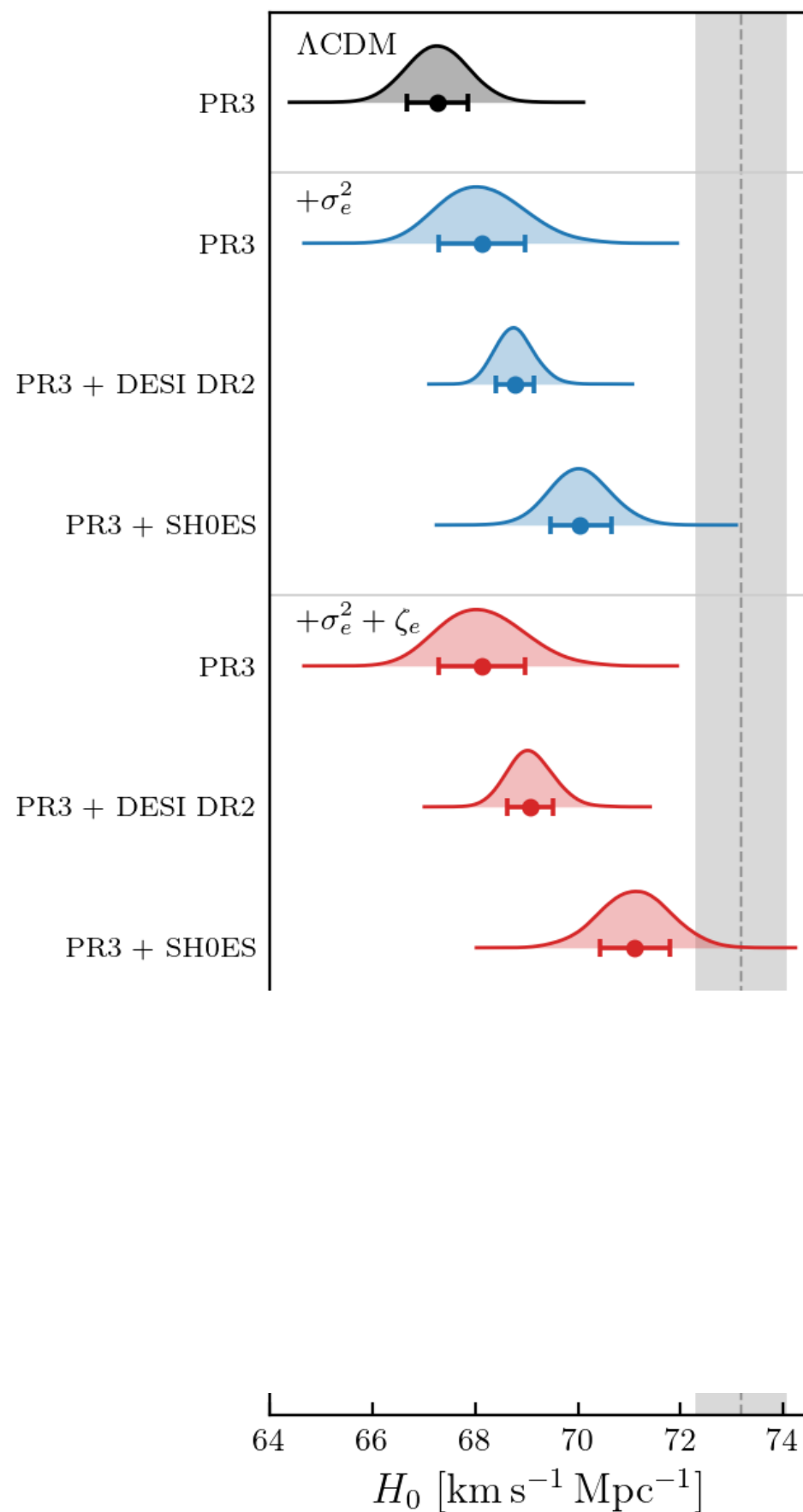
Preliminary

Preliminary



Gabriel Lynch

Lynch et al. 2026 in prep



Preliminary

How well do these models do?

Preliminary

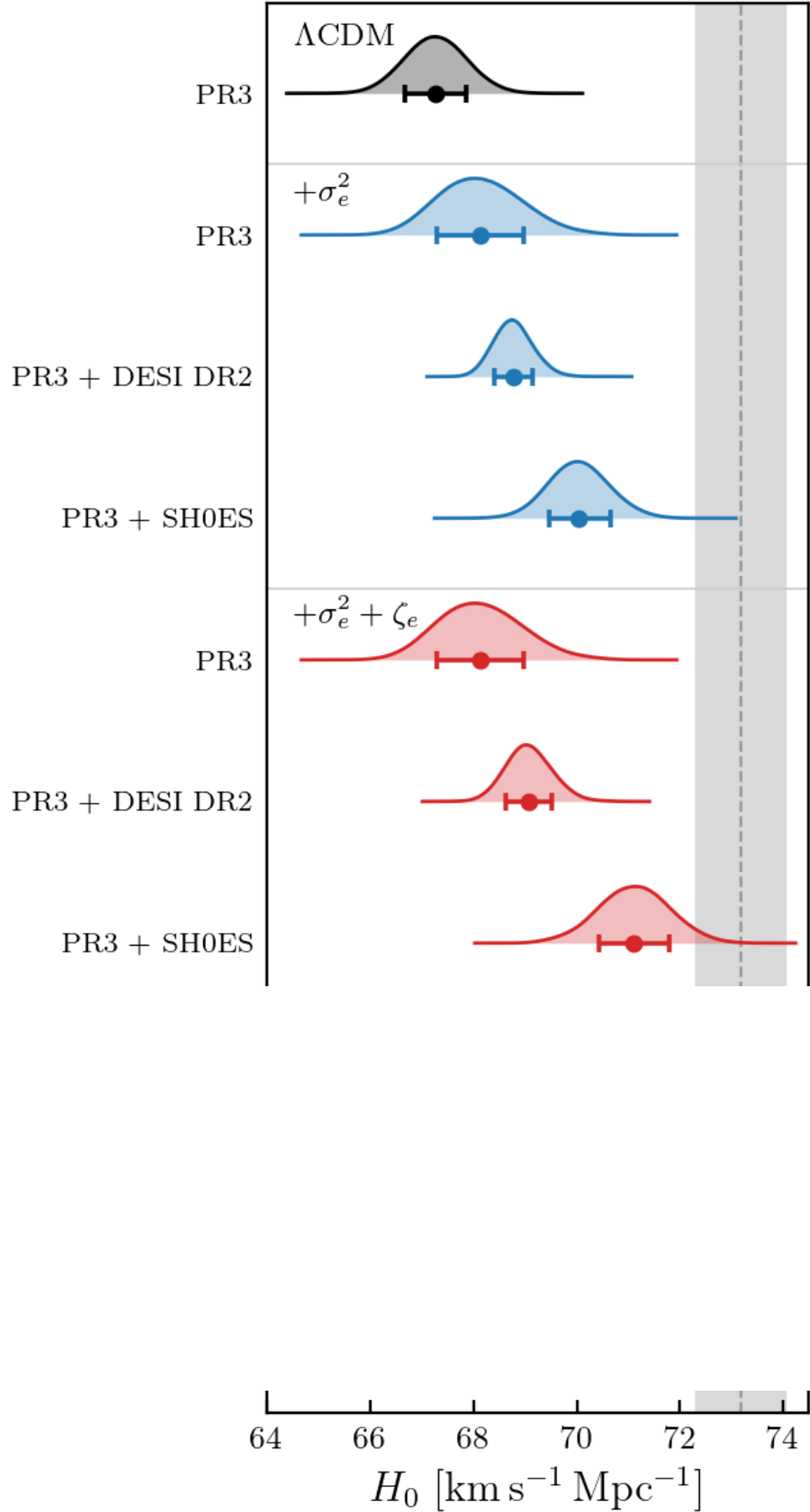


TABLE III.

Model	Dataset	H_0 [km/s/Mpc]	$\langle \delta_e^2 \rangle$	$\Delta\chi_{\text{CMB}}^2$	$\Delta\chi_{\text{ext}}^2$	$\Delta\bar{D}$	Δp_D	ΔDIC
$+\sigma_e^2$	PR3	67.6 ± 0.7	< 0.27	-0.06	—	+1.28	+1.88	+3.2
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	PR3 + SH0ES	71.1 ± 0.7	0.825 ± 0.31	+0.44	-15.08	-13.00	+2.53	-10.5

Preliminary



Gabriel Lynch

Preliminary

How well do these models do?

Preliminary

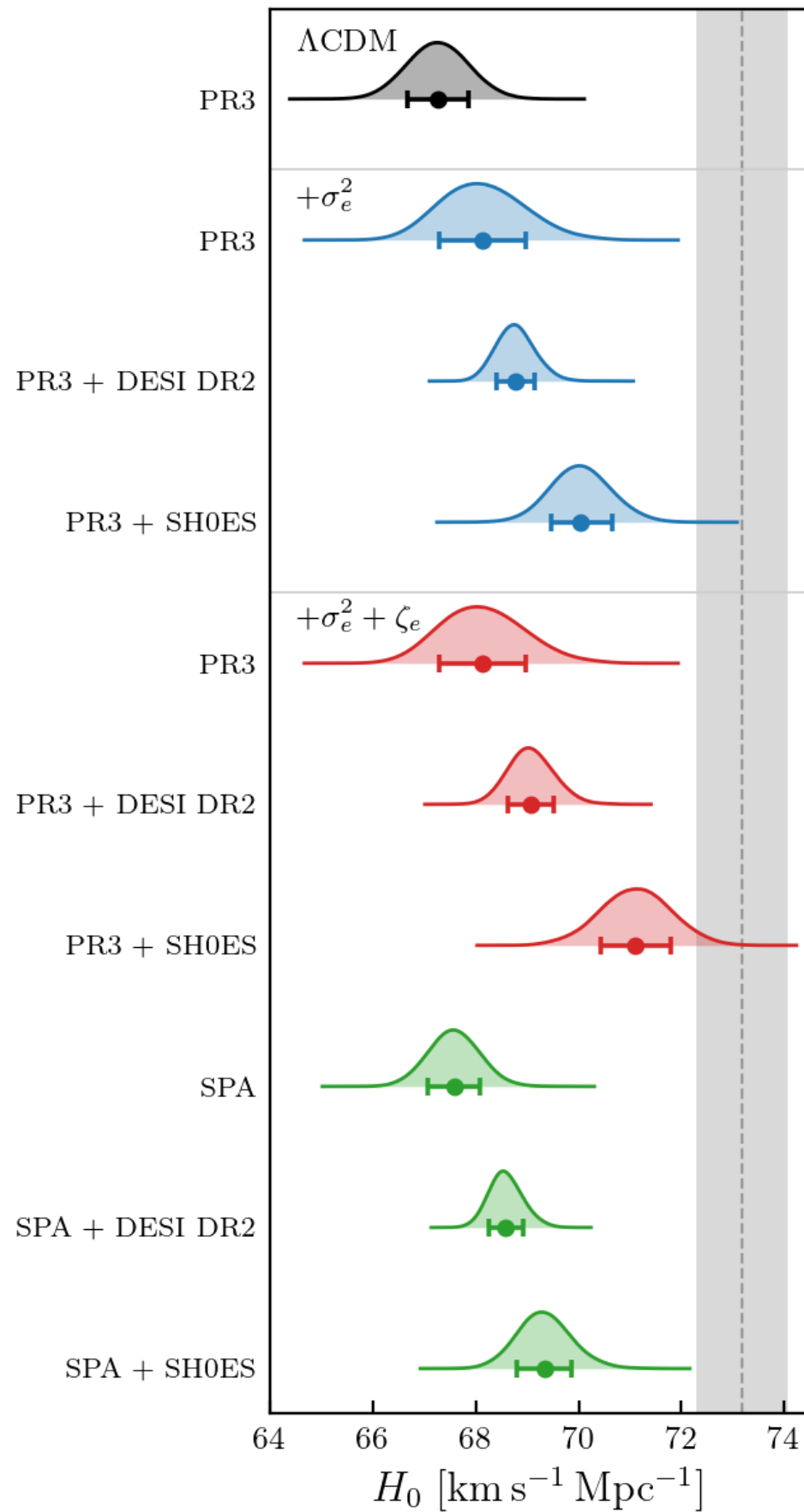
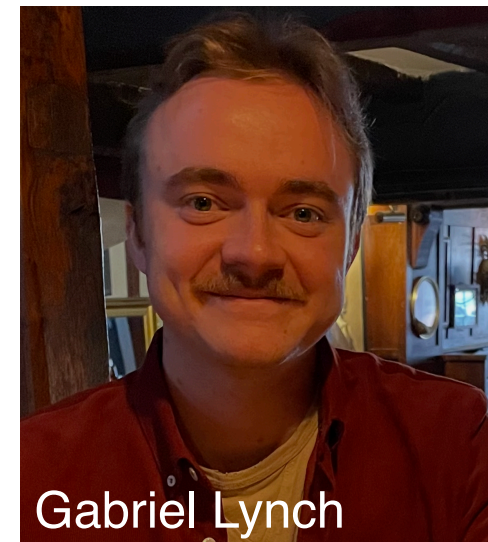


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Preliminary



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Lynch et al. 2026 in prep

Preliminary

How well do these models do?

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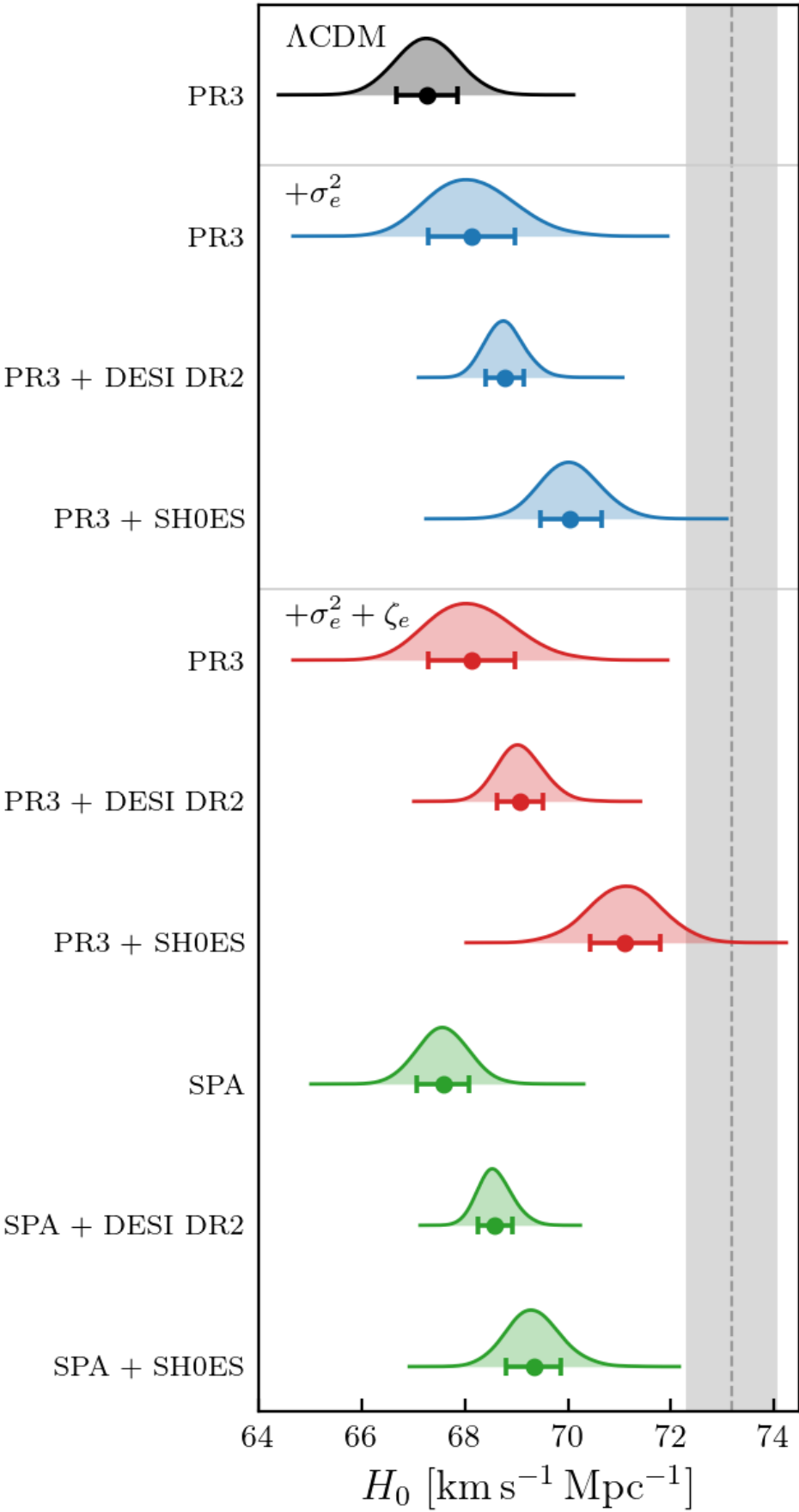


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	SPA + DESI DR2	68.6 ± 0.3	< 0.3	TBD	TBD	+2.28	+2.60	+4.9
	SPA + SH0ES	69.3 ± 0.5	0.278 ± 0.15	+3.10	-7.99	-1.36	+2.49	+1.1

Preliminary



Gabriel Lynch

Preliminary

How well do these models do?

Preliminary

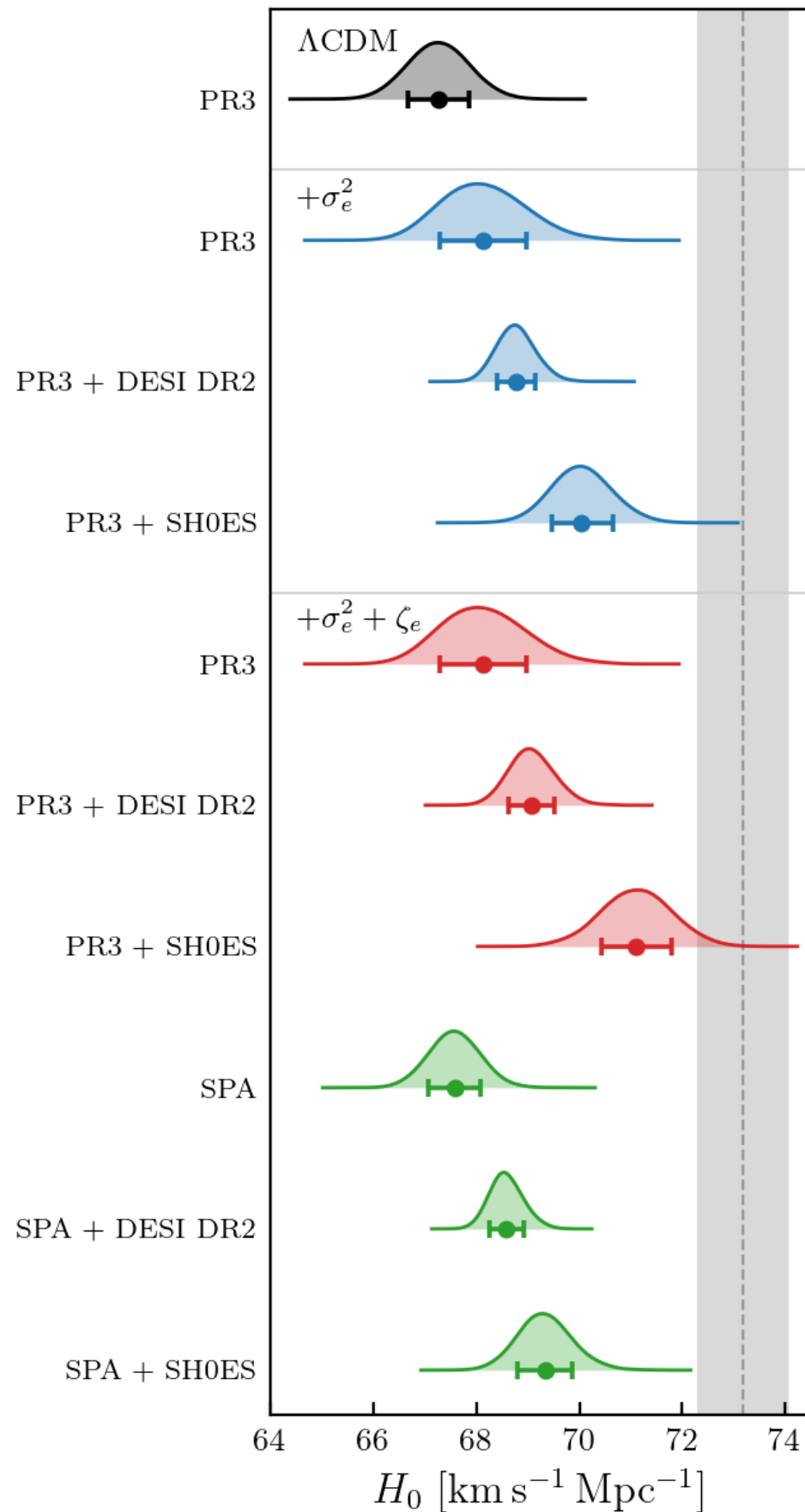
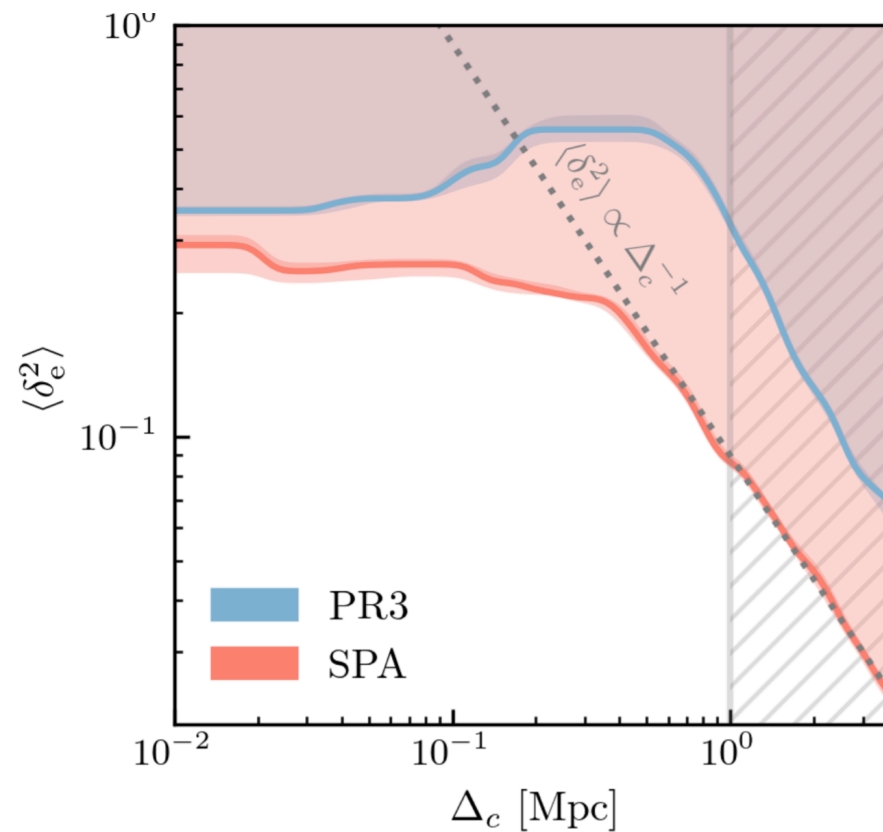


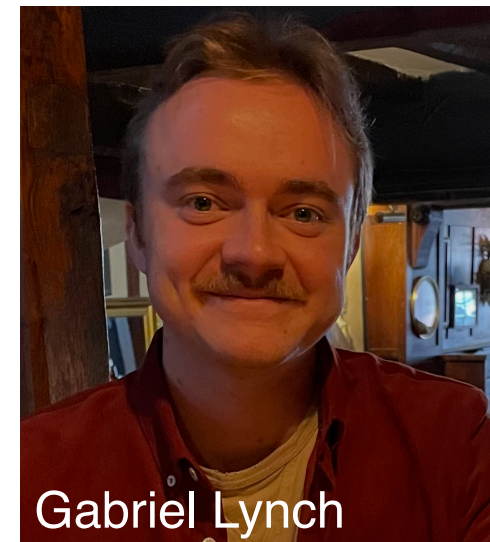
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Novel constraints on the variance and coherence length of small-scale fluctuations during recombination

Preliminary



Preliminary

How well do these models do?

Preliminary

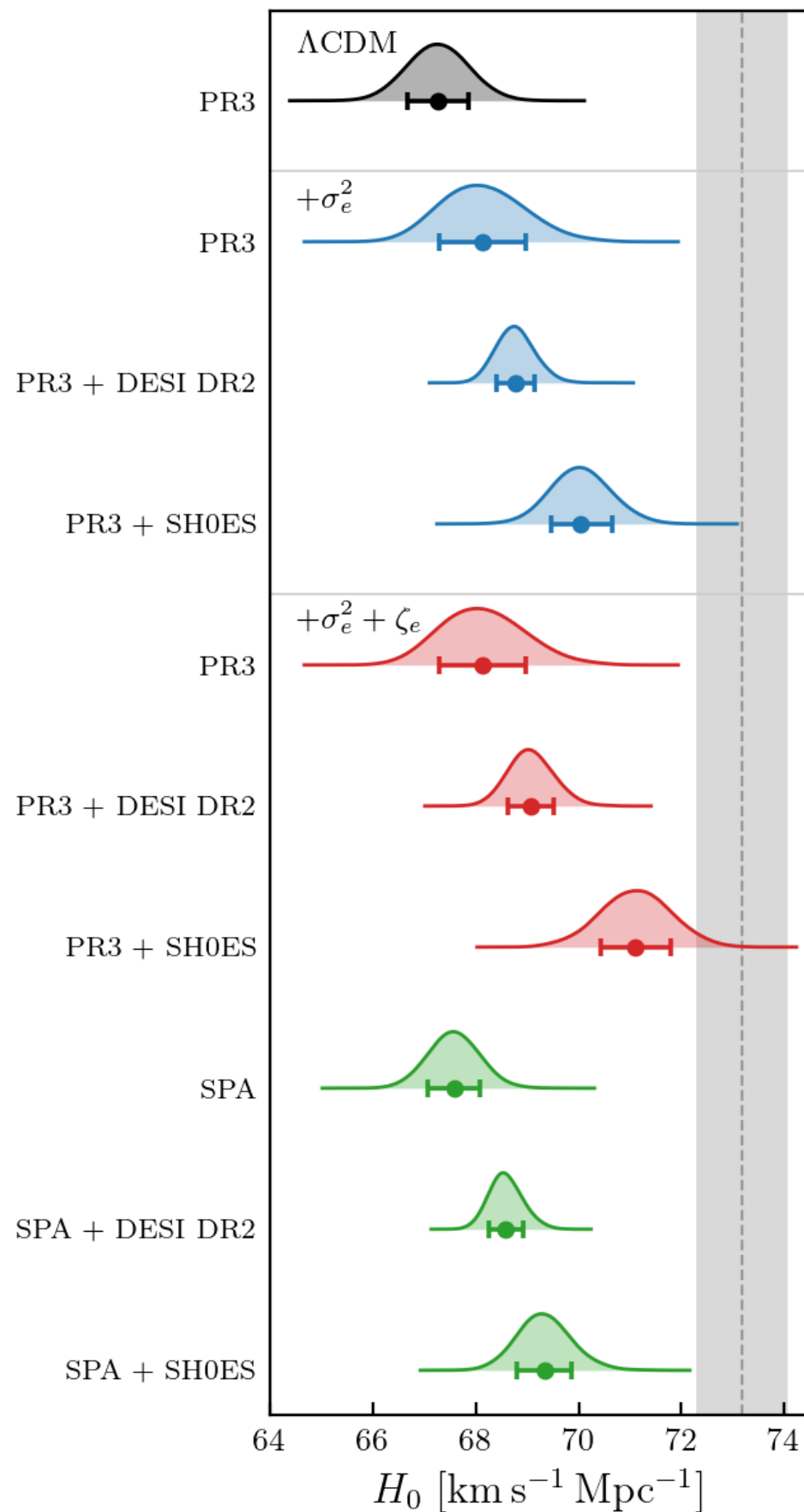
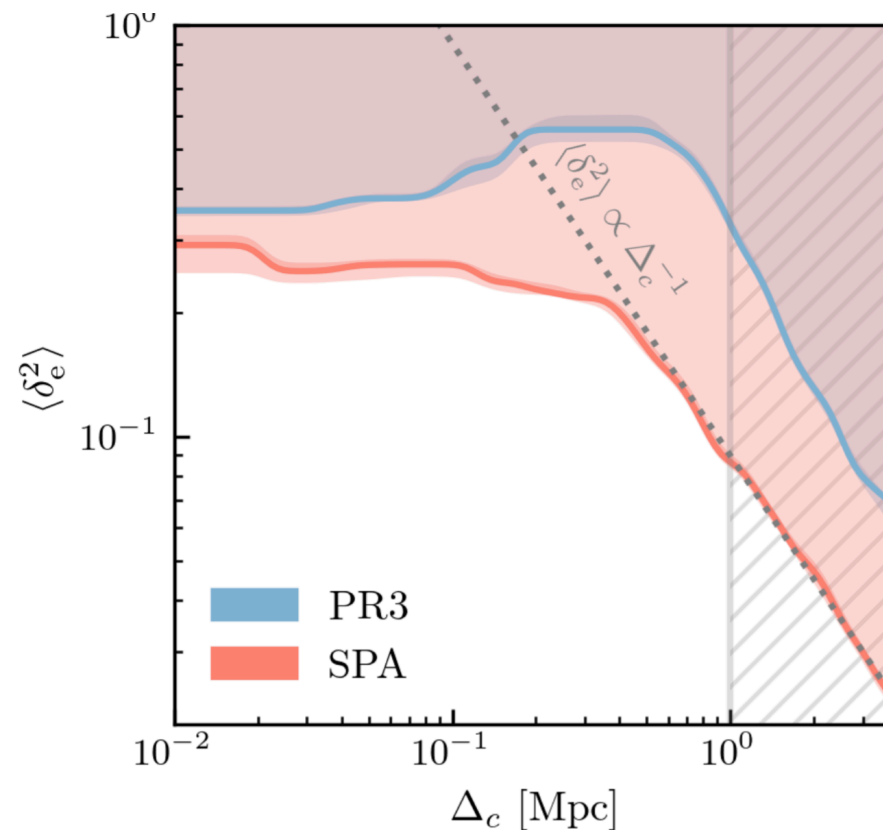


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Novel constraints on the variance and coherence length of small-scale fluctuations during recombination

Still some loopholes left...

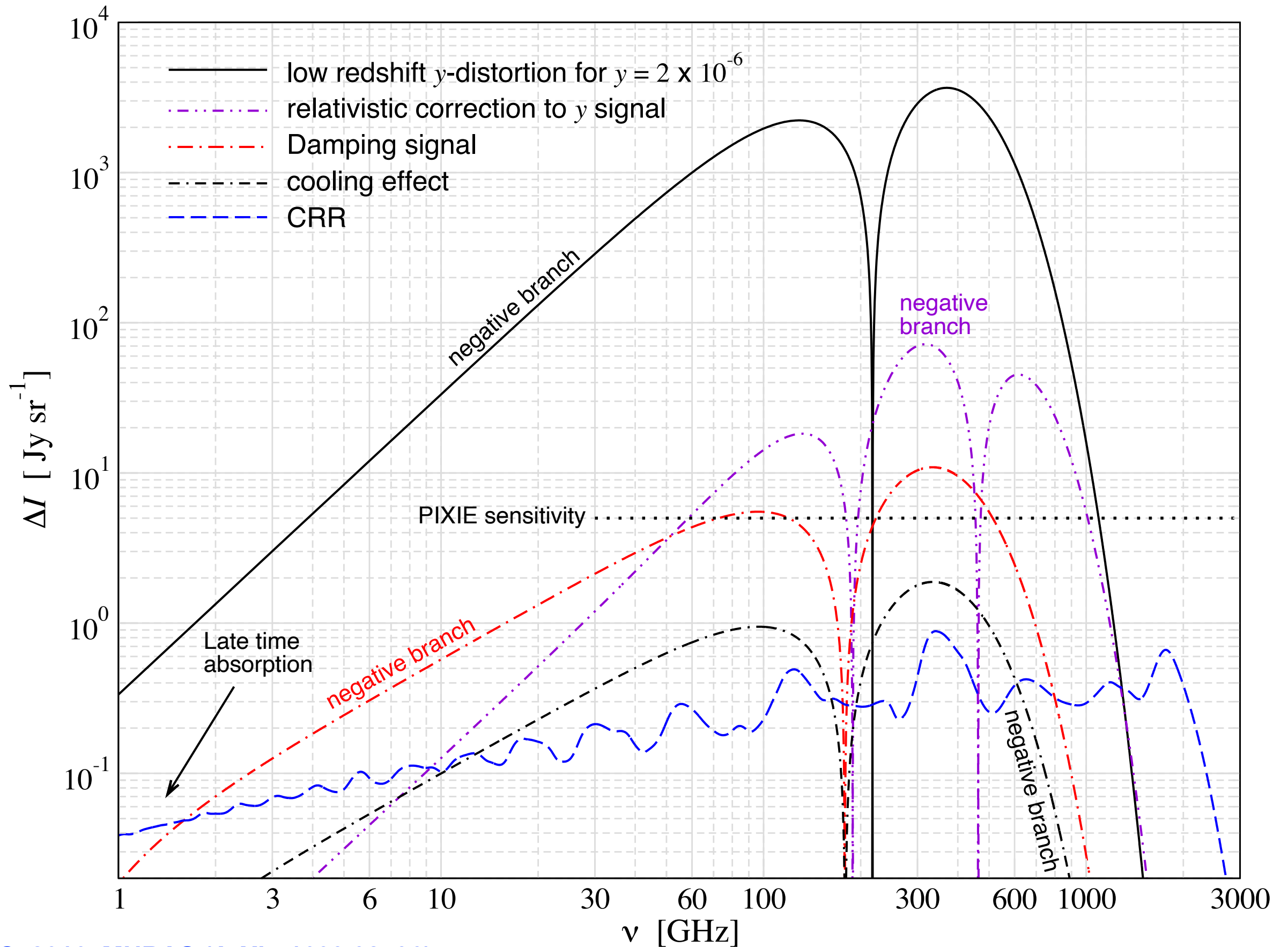


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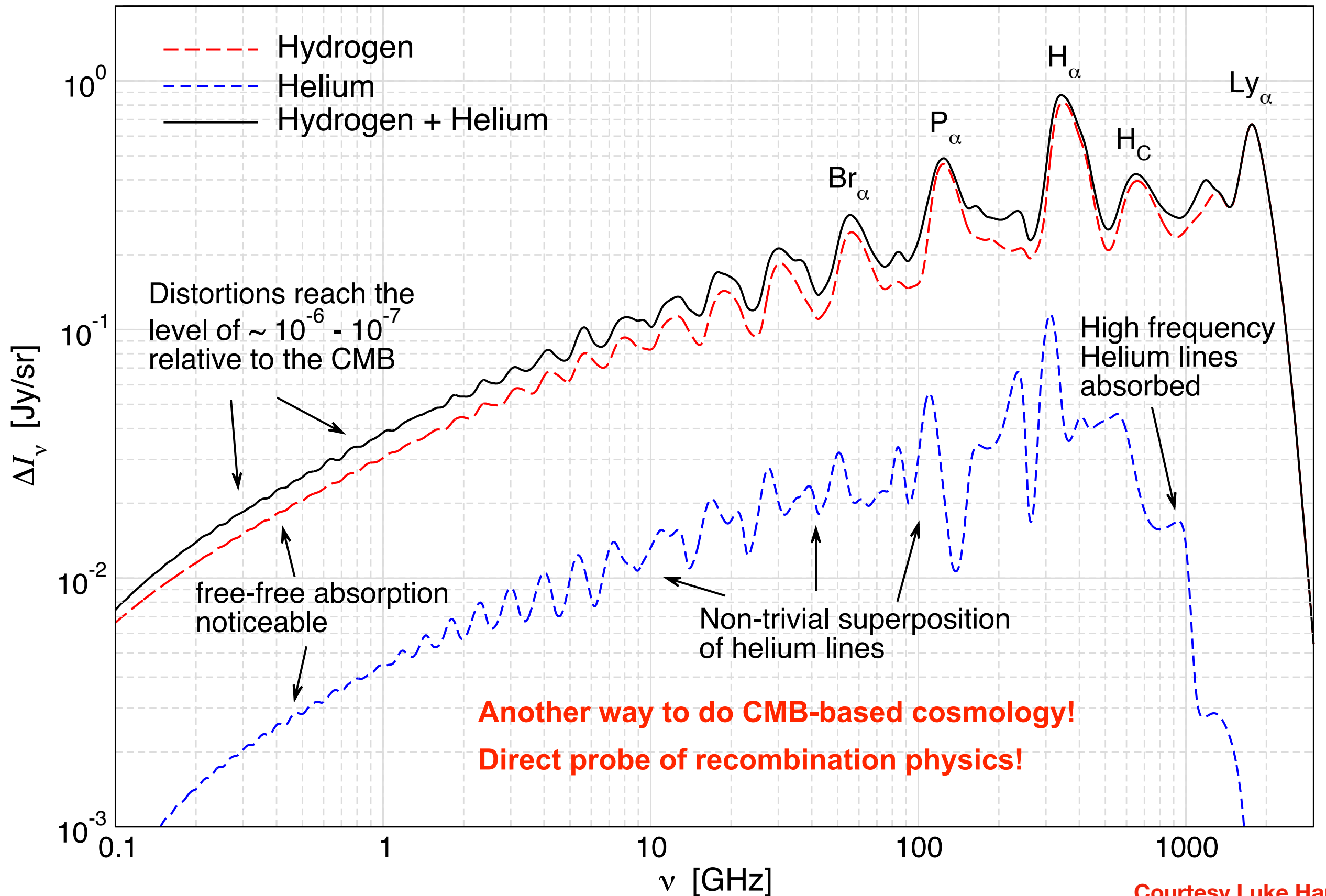
Lynch et al. 2026 in prep

*Directly Testing recombination with the
cosmological recombination radiation*

Average Λ CDM spectral distortions

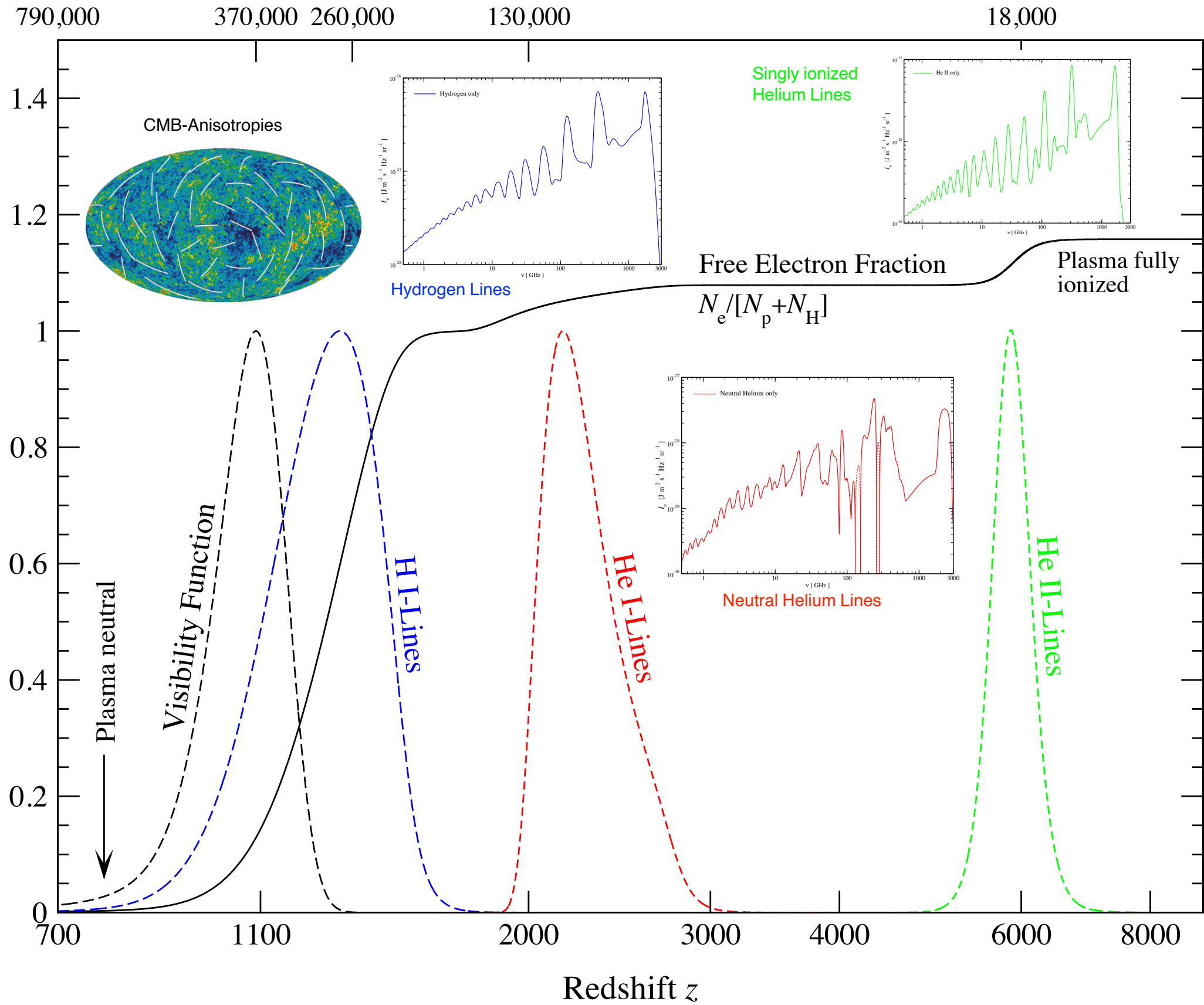


Cosmological Recombination Radiation

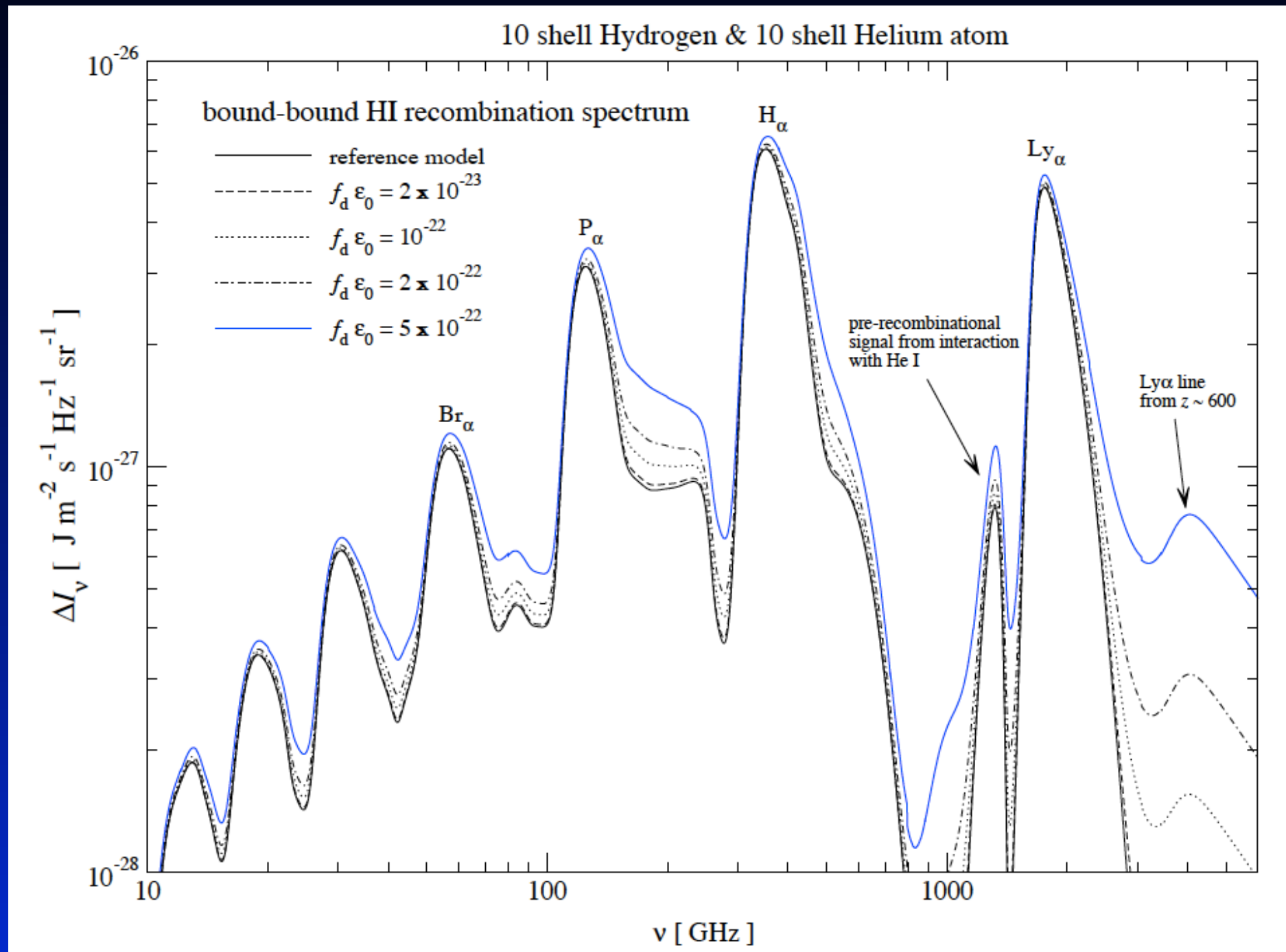


Courtesy Luke Hart

Cosmological Time in Years



Dark matter annihilations / decays

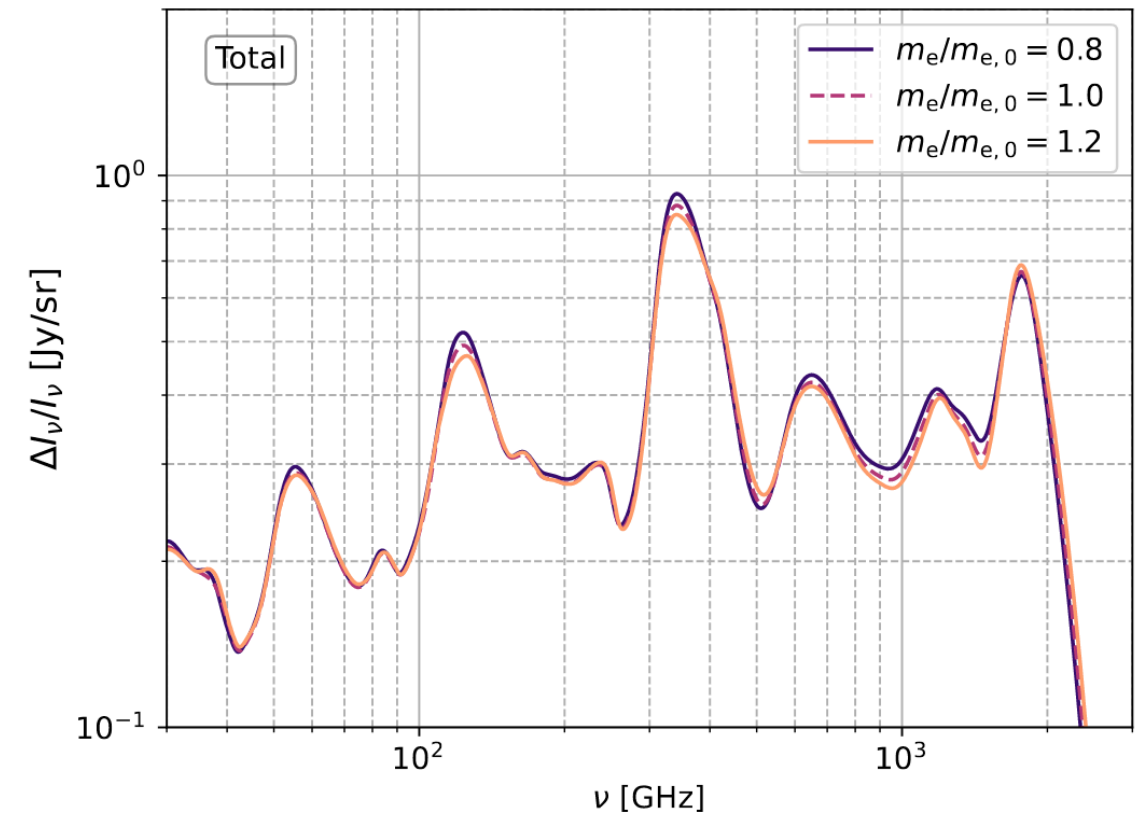
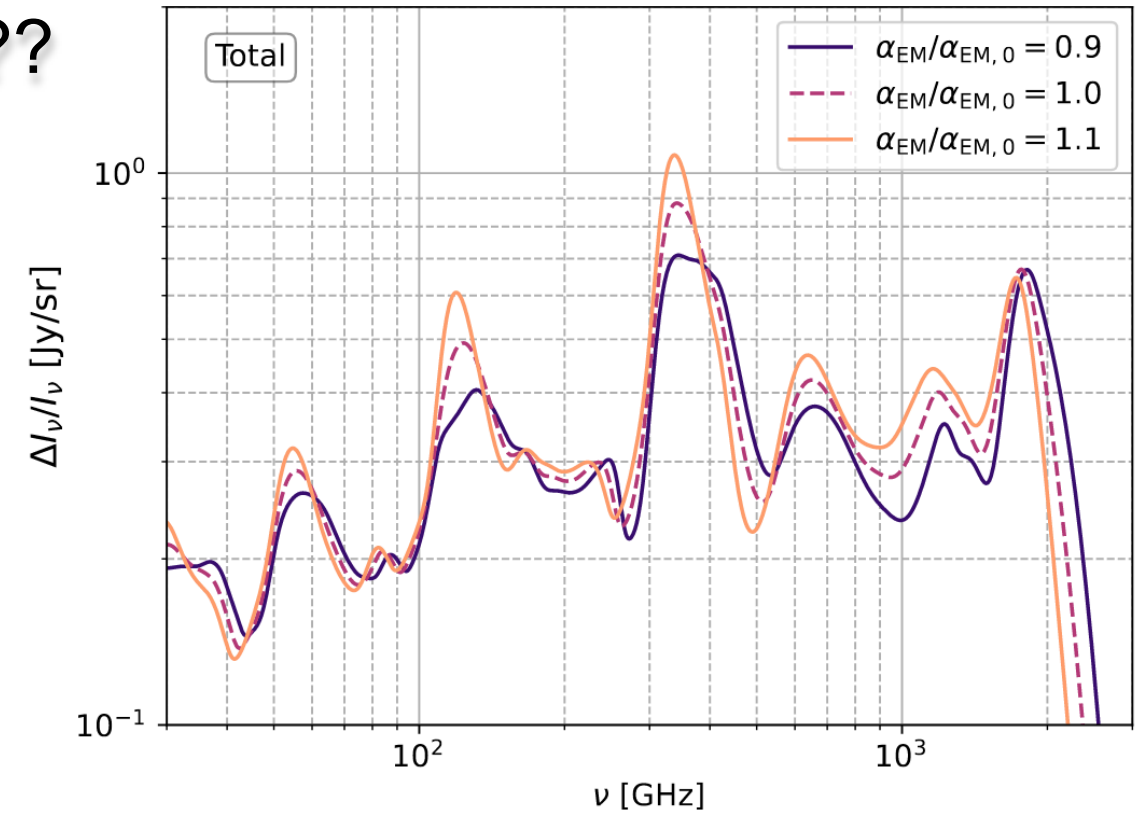
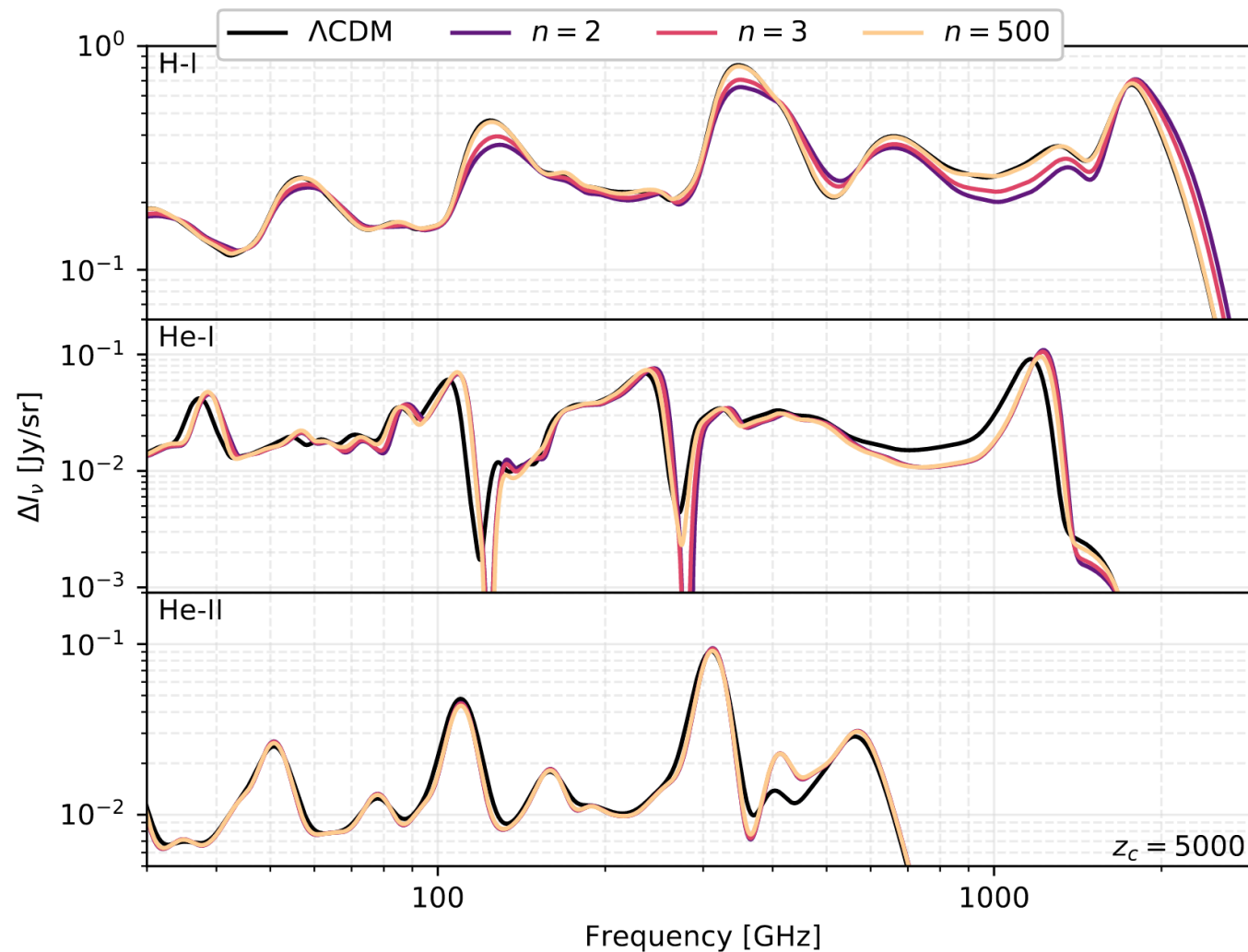


JC, 2009, arXiv:0910.3663

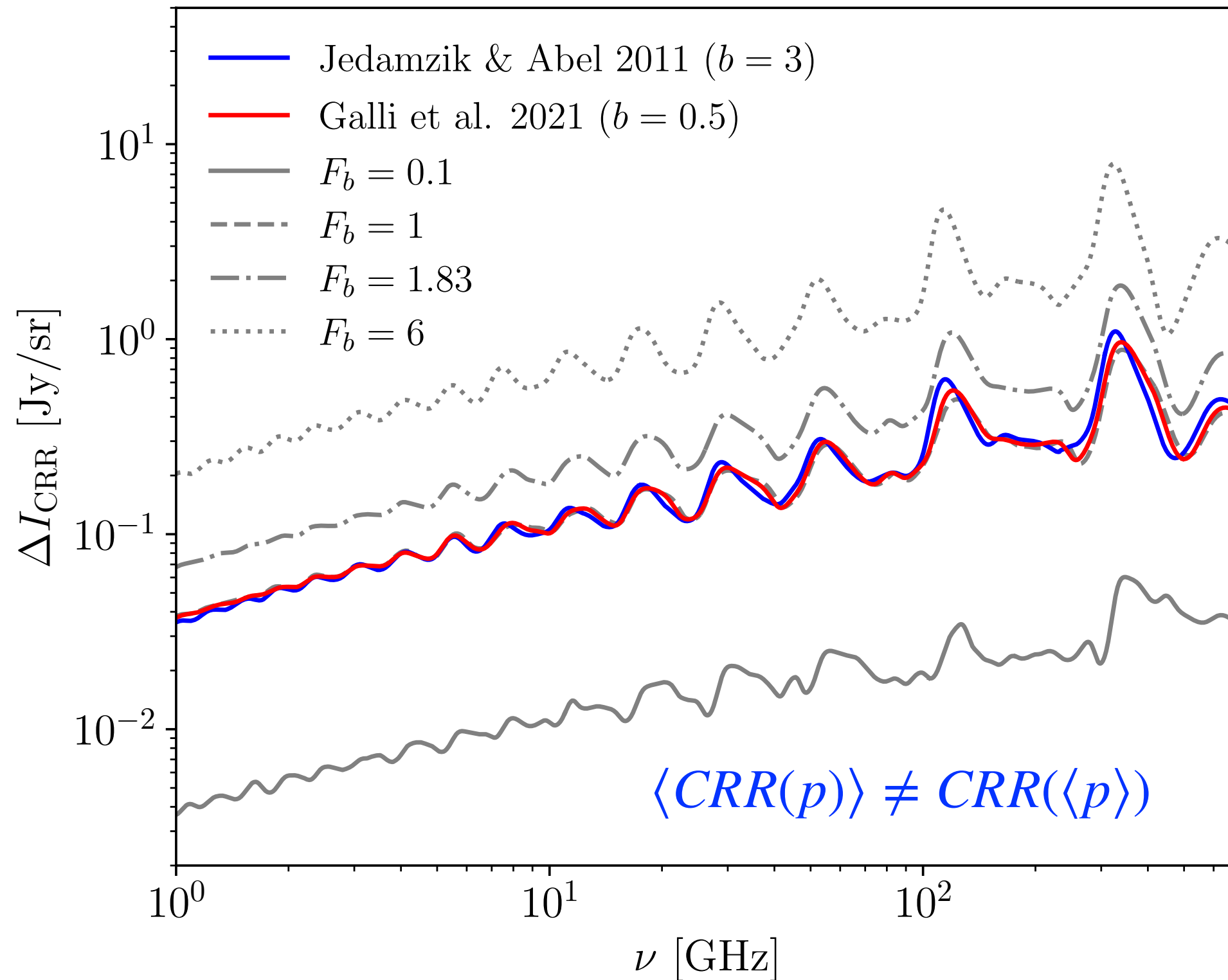
- Additional photons at all frequencies
- Broadening of spectral features
- Shifts in the positions

Testing the origin of the Hubble tension with the CRR

- Hubble tension persists... New Physics??
- H_0 Olympics identified EDE, Primordial Magnetic fields and varying m_e models as best solutions!
- These should affect the CRR!

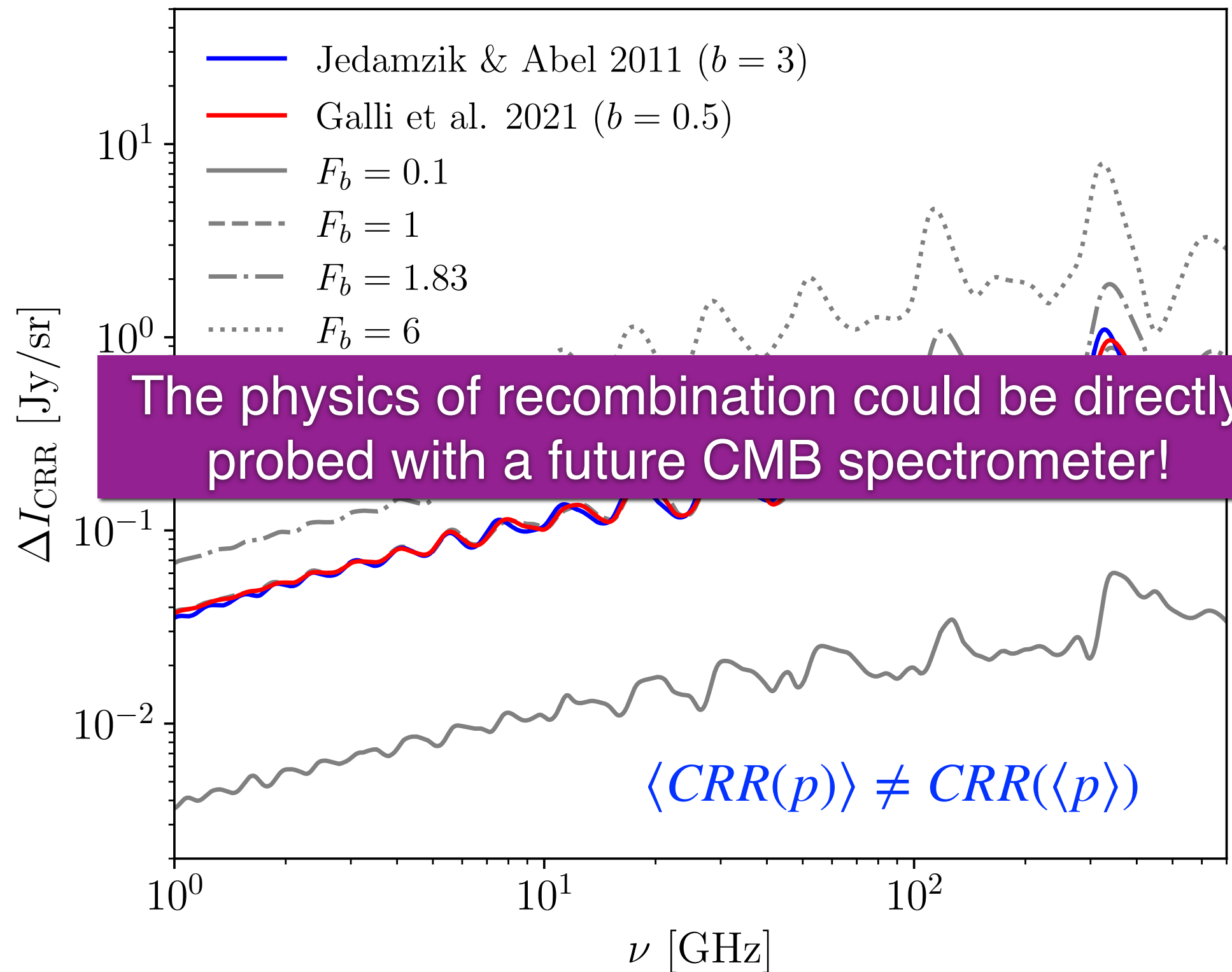


Spatial variations from PMF could be seen with CRR



Using new CRR emulator CRRfast which also models variance terms

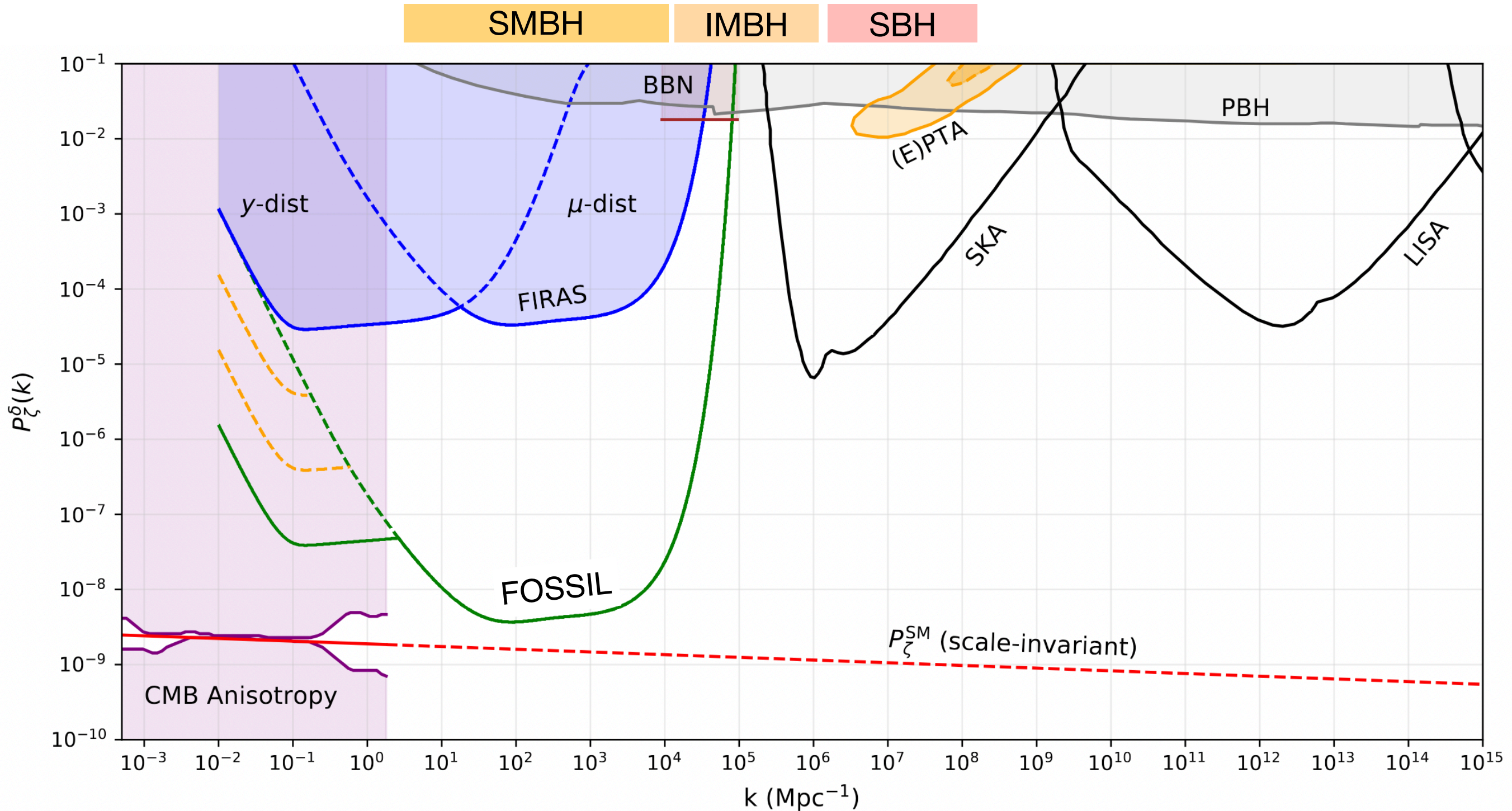
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New Probes of the small-scale Universe

Small-scale power constraints and PBH formation



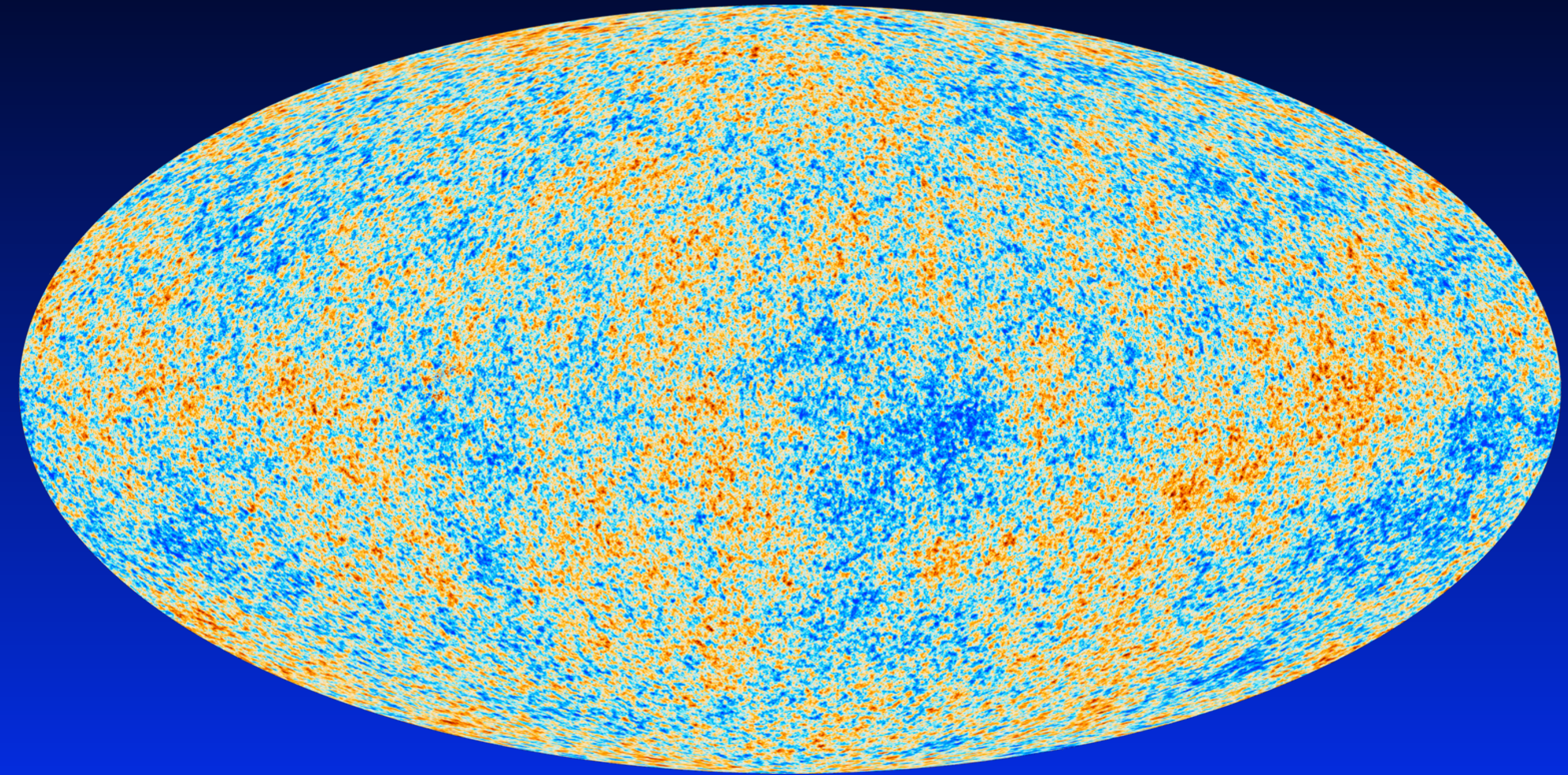
JC, Khatri & Sunyaev, 2012

JC, Erickcek & Ben-Dayan, 2012

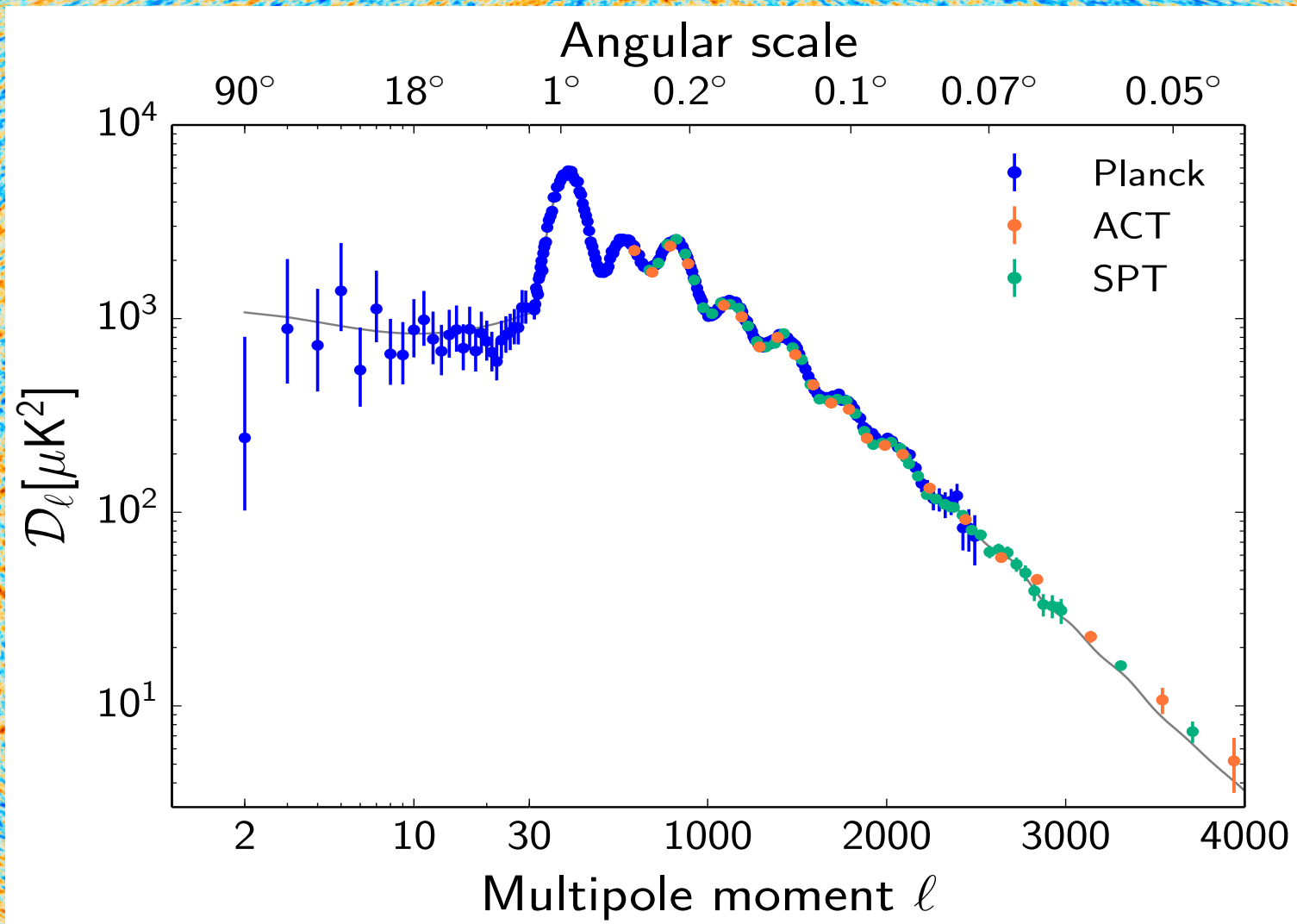
Jeong et al., 2014

Cyr et al., 2023, ArXiv:2309.02366

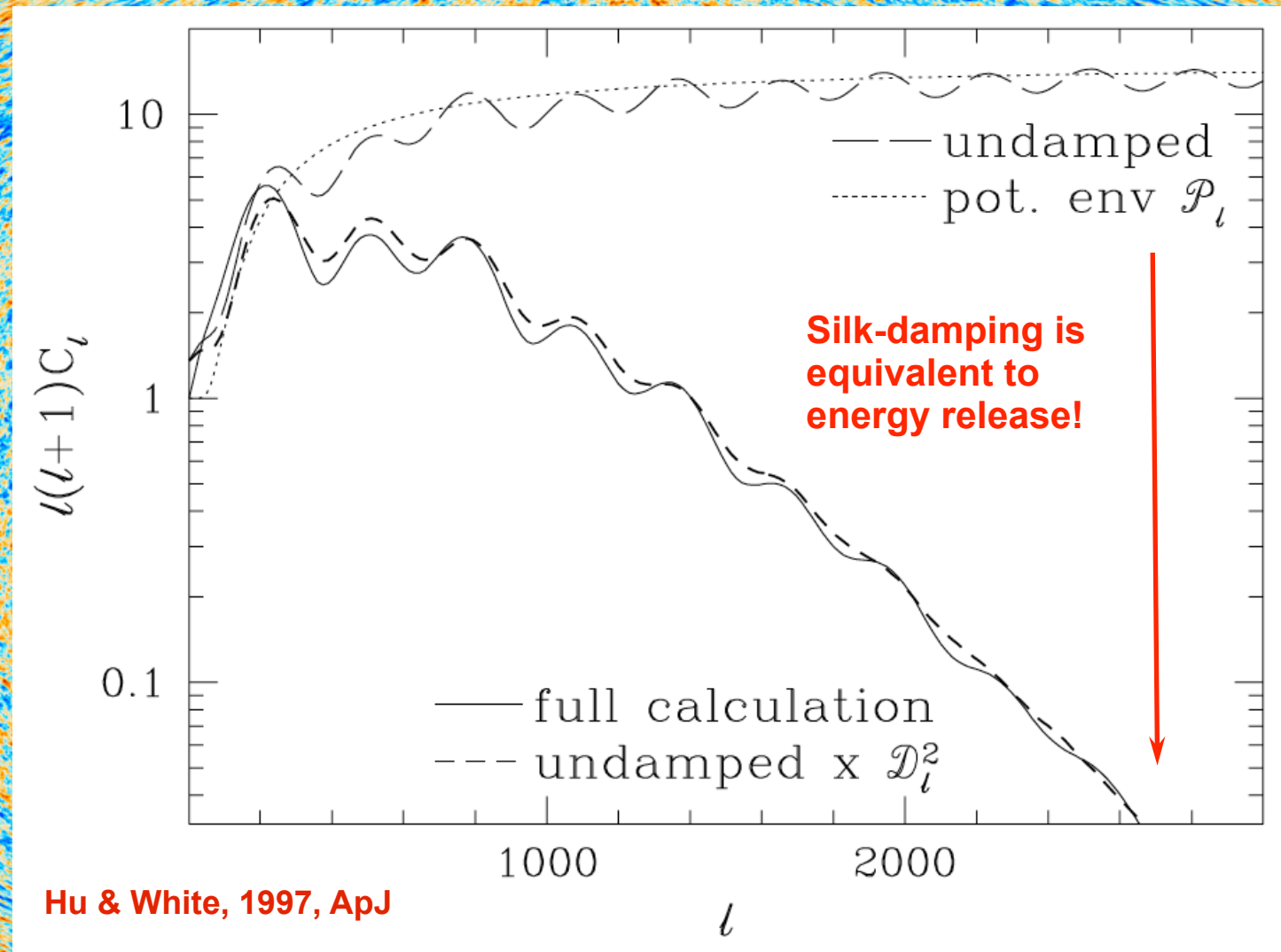
Dissipation of small-scale acoustic modes



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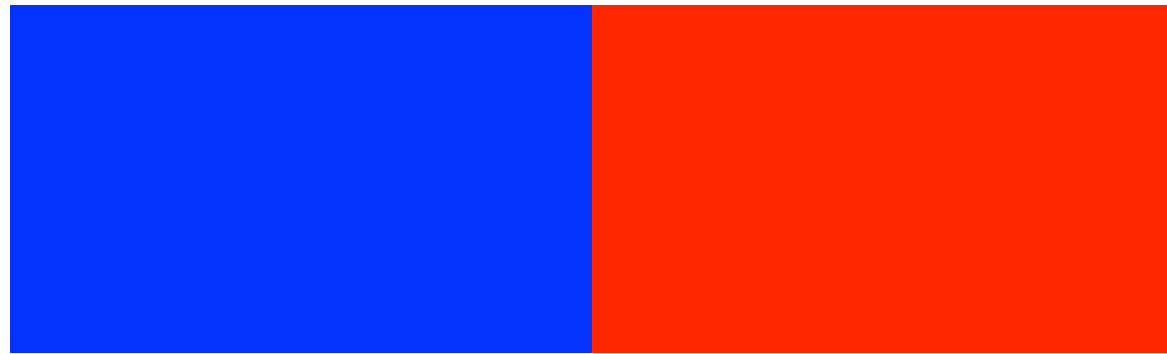
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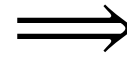
Ideas go back to Sunyaev & Zeldovich, 1970

Distortion due to mixing of blackbodies

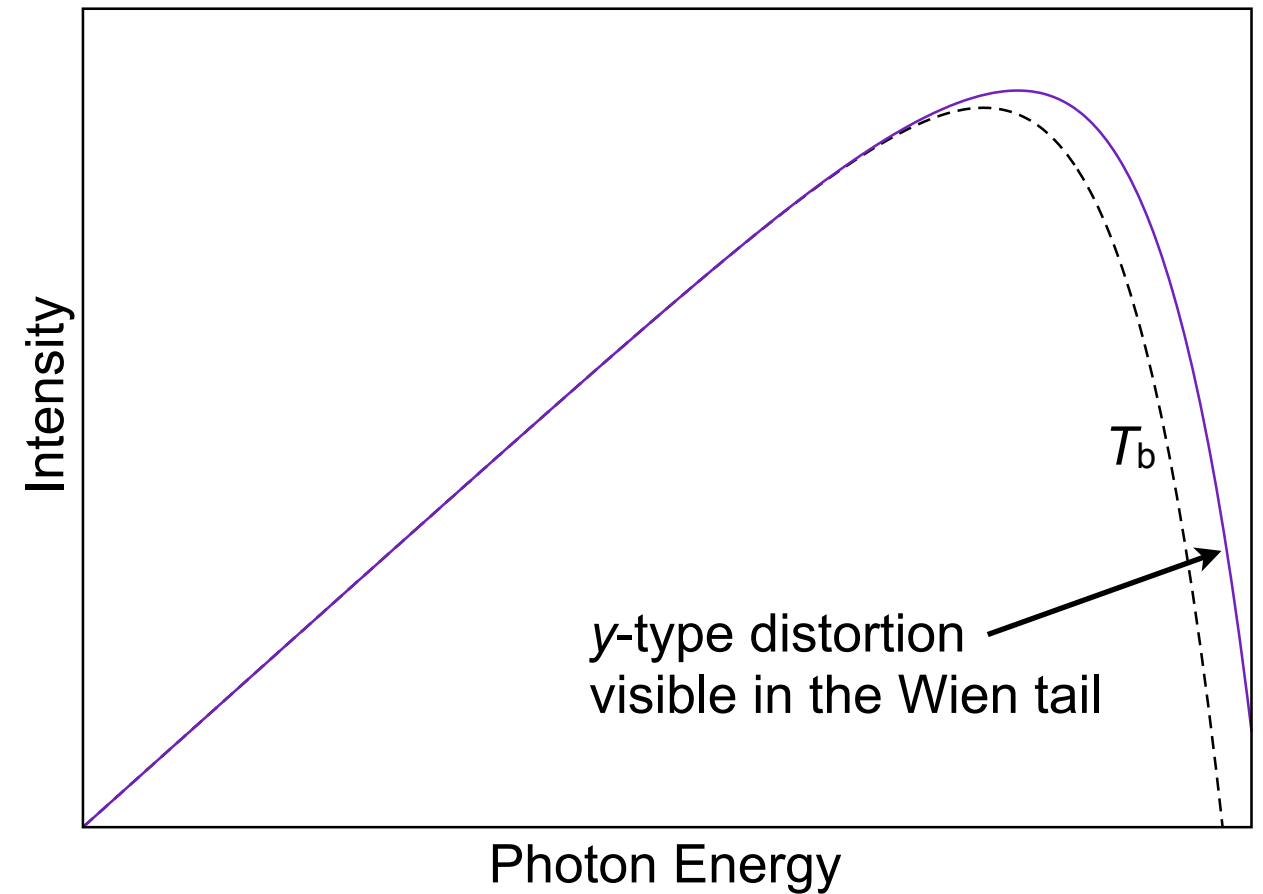
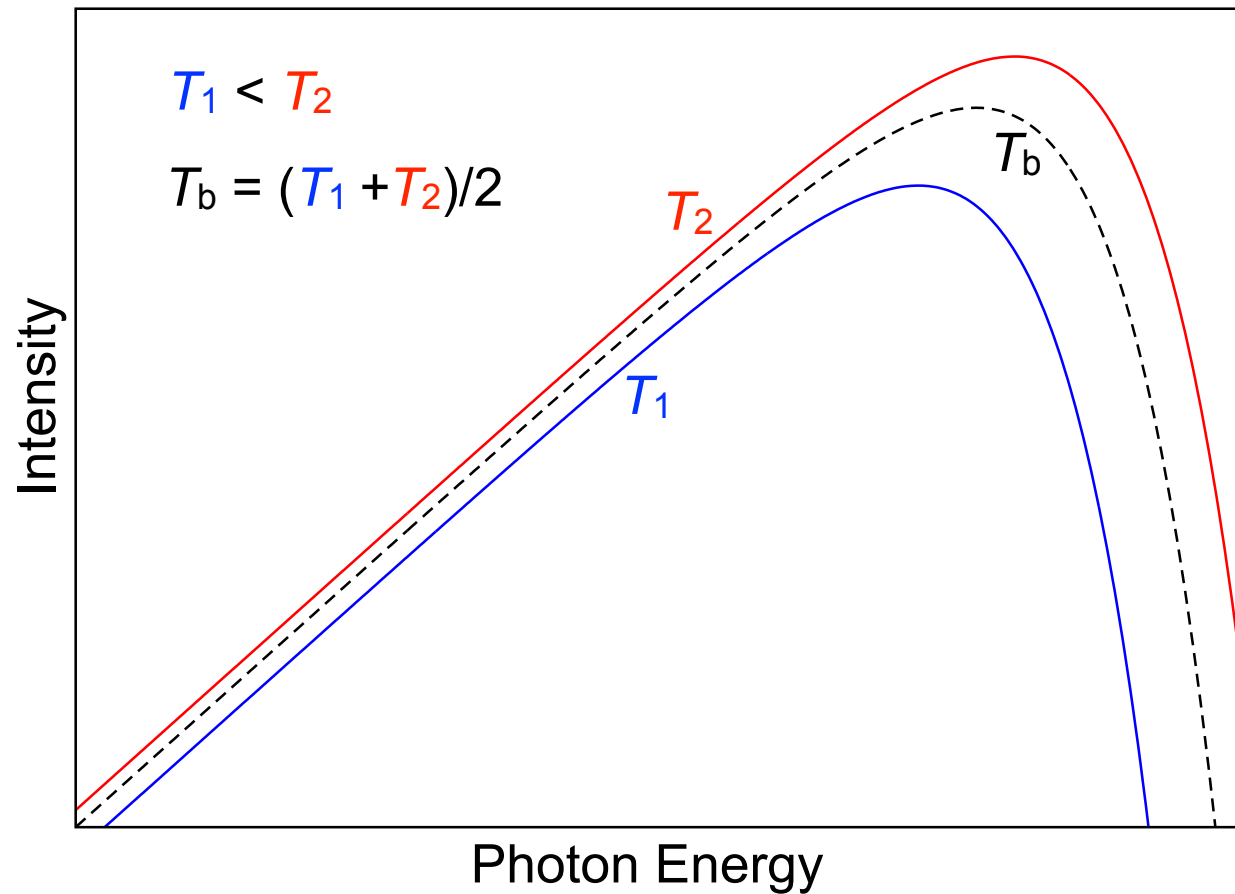
Blackbody spectra



Photon mixing

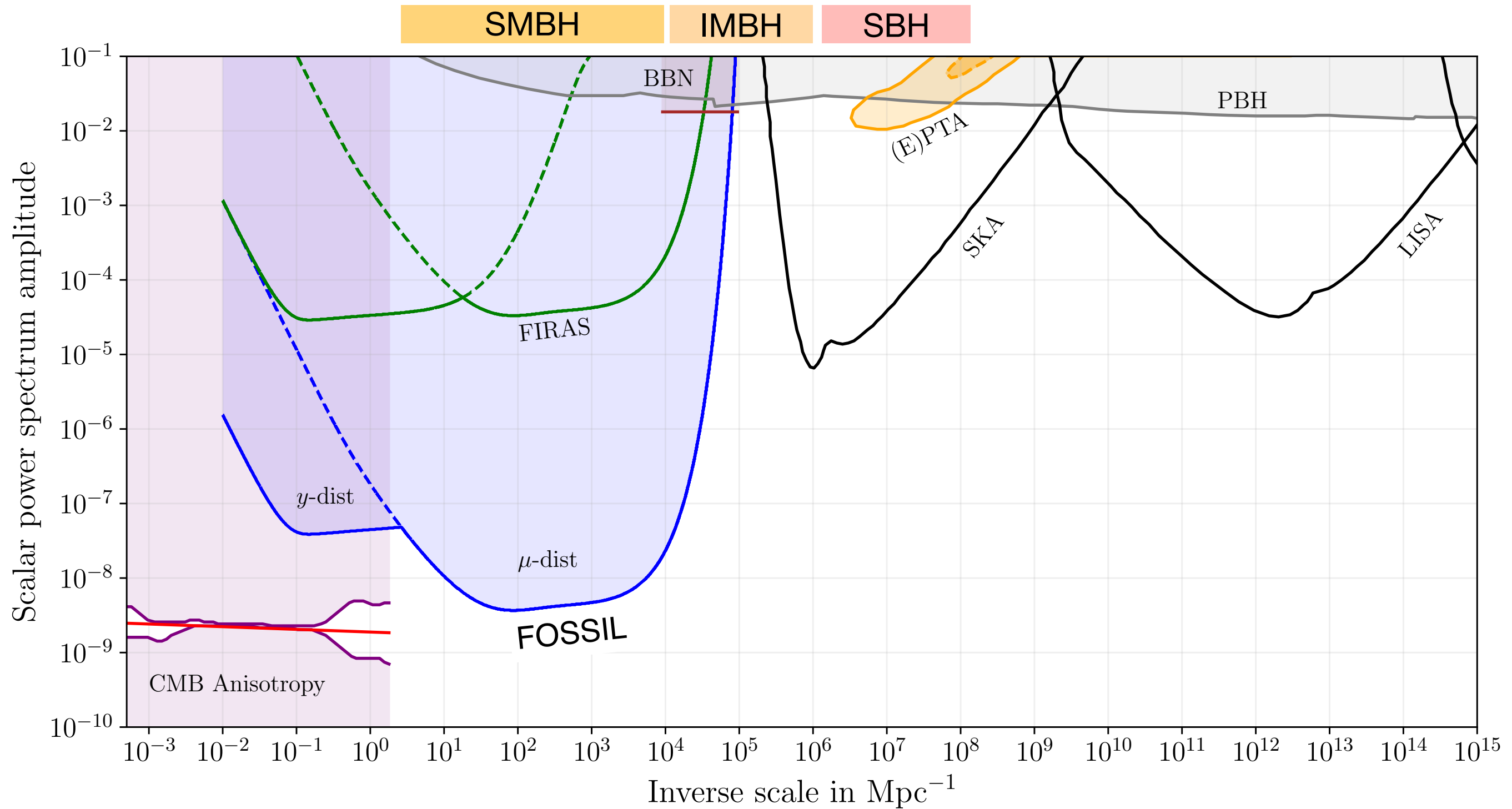


Blackbody + y -distortion



Mixing is mediated by Thomson scattering $\Rightarrow$ Silk damping

Exploring the small-scale Universe



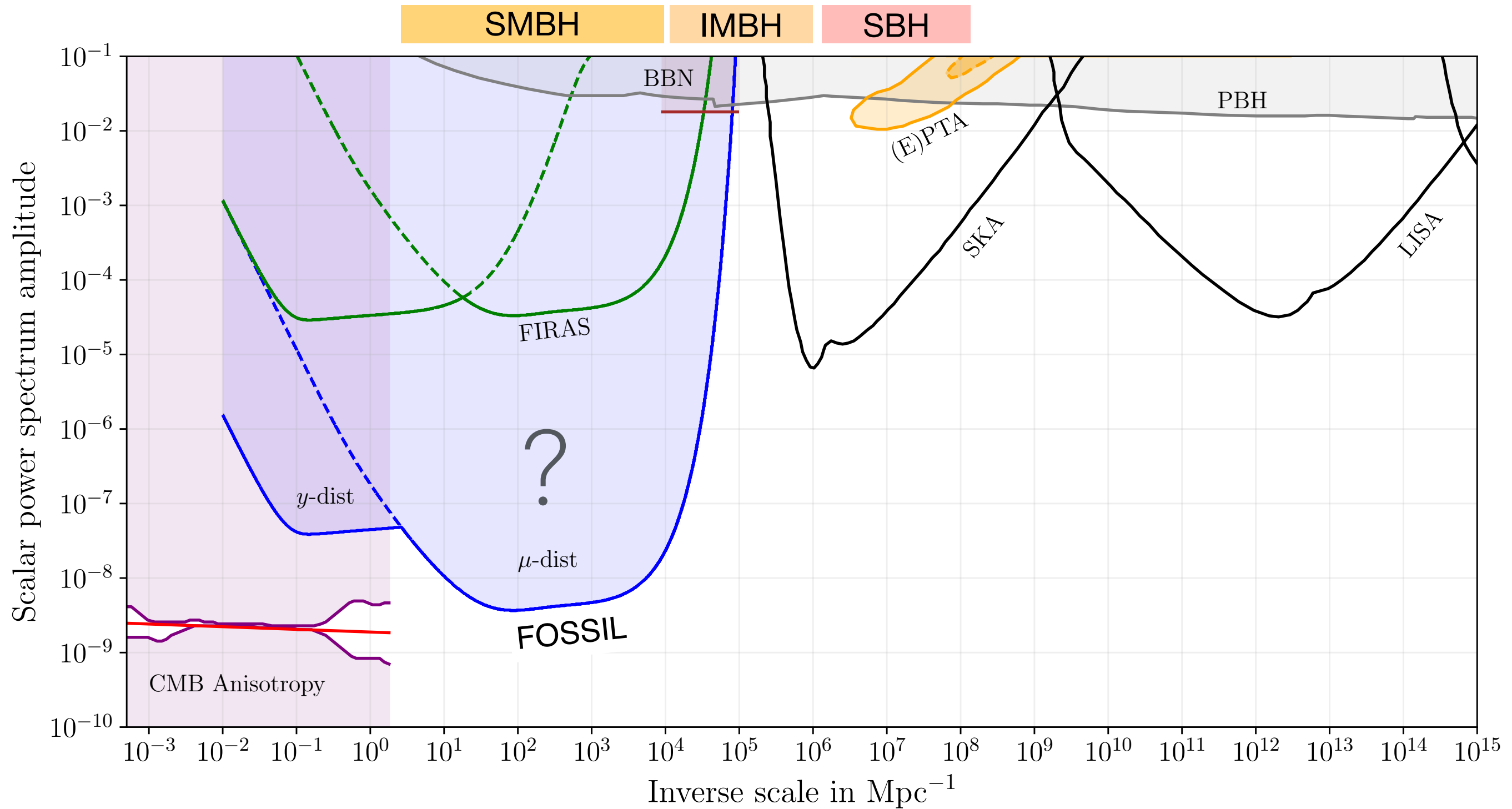
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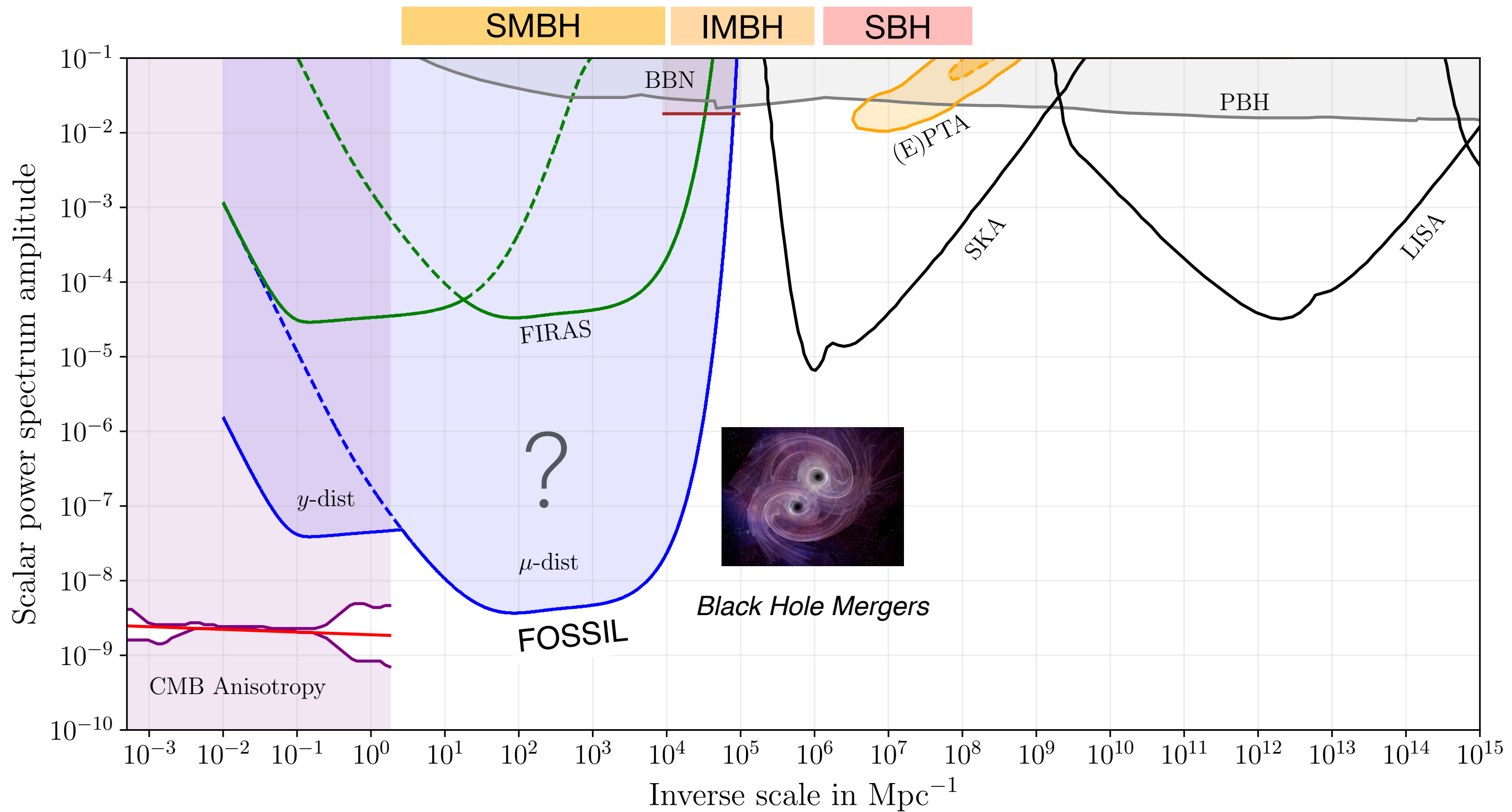
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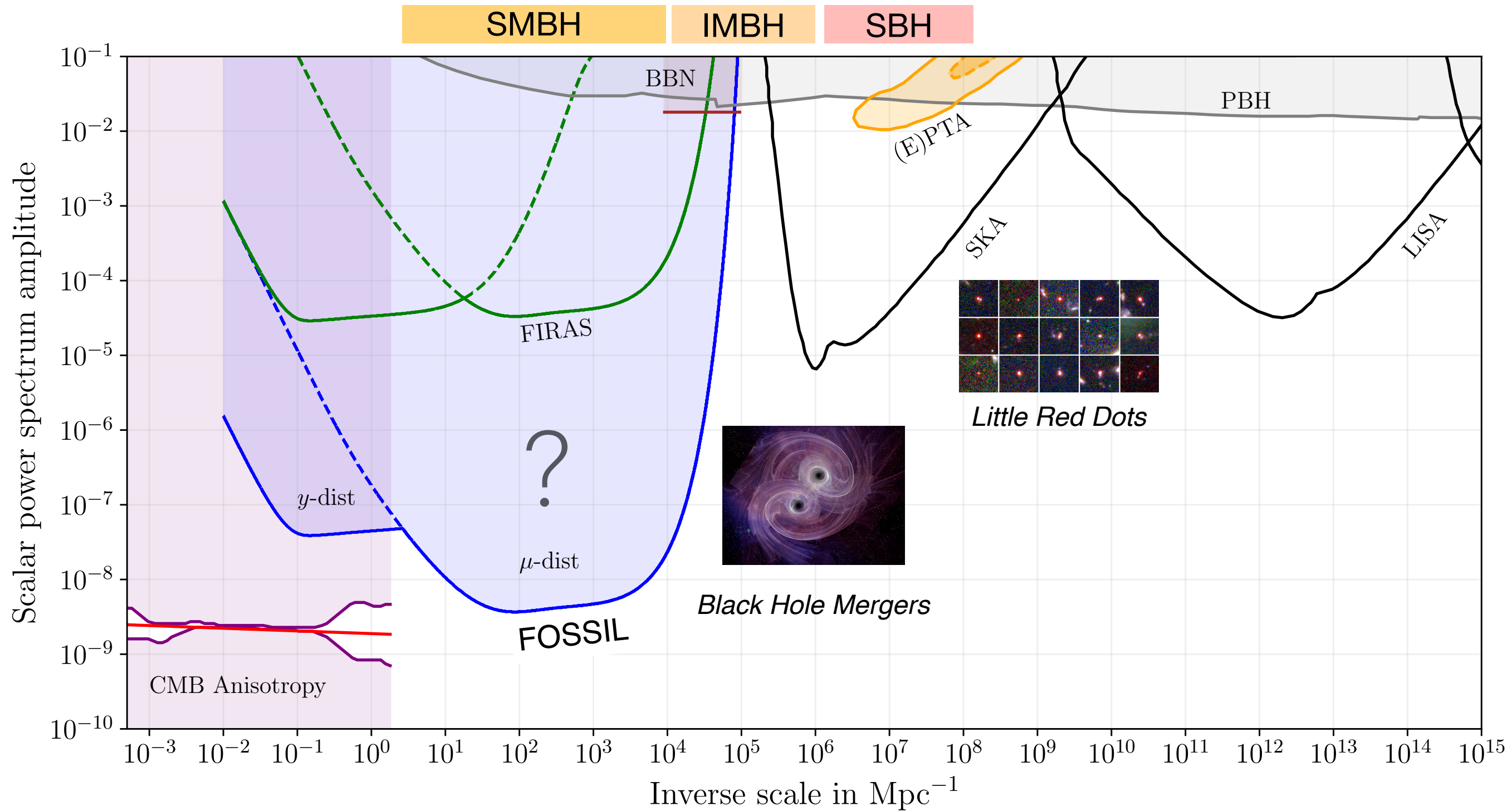
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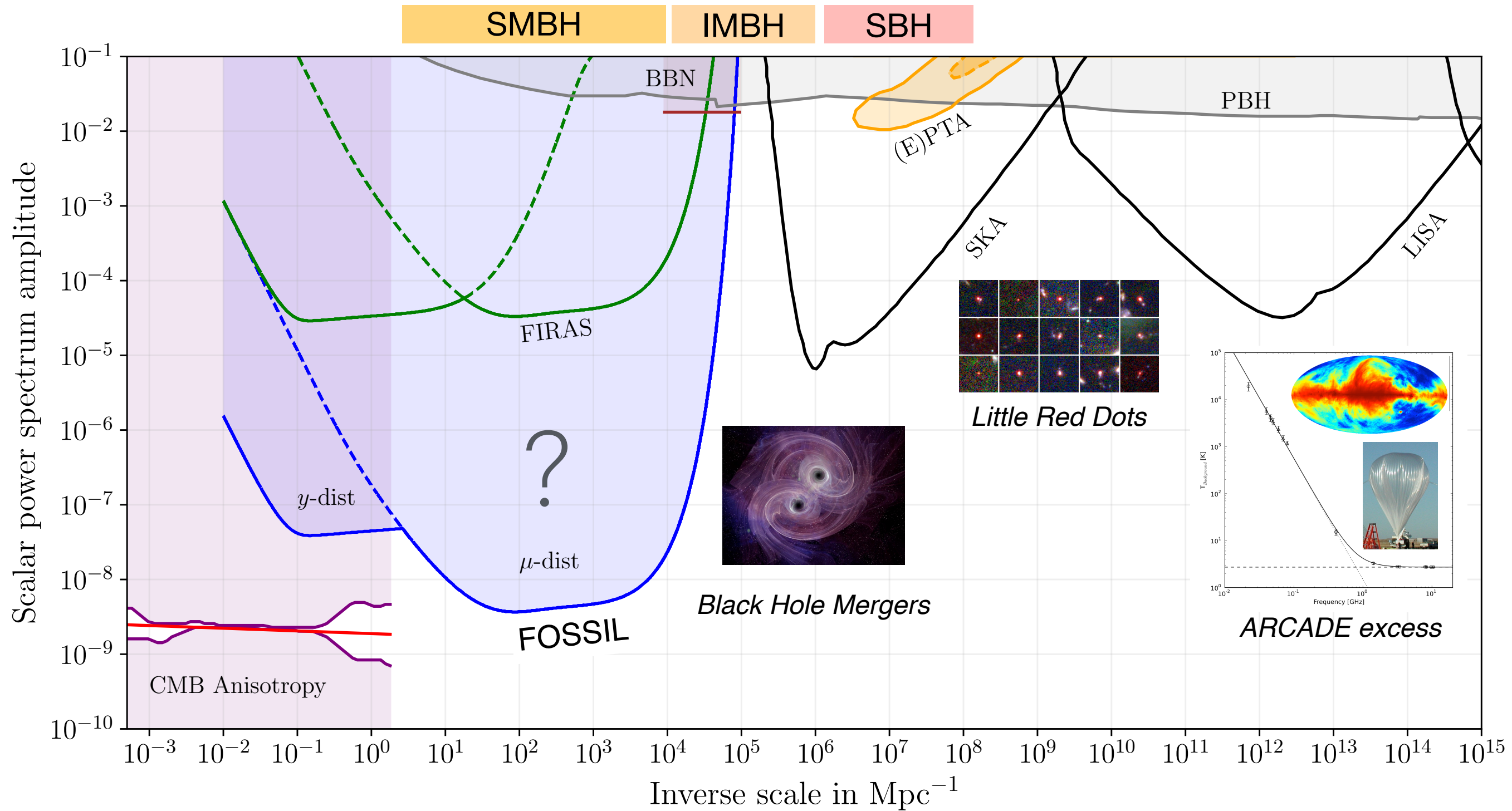
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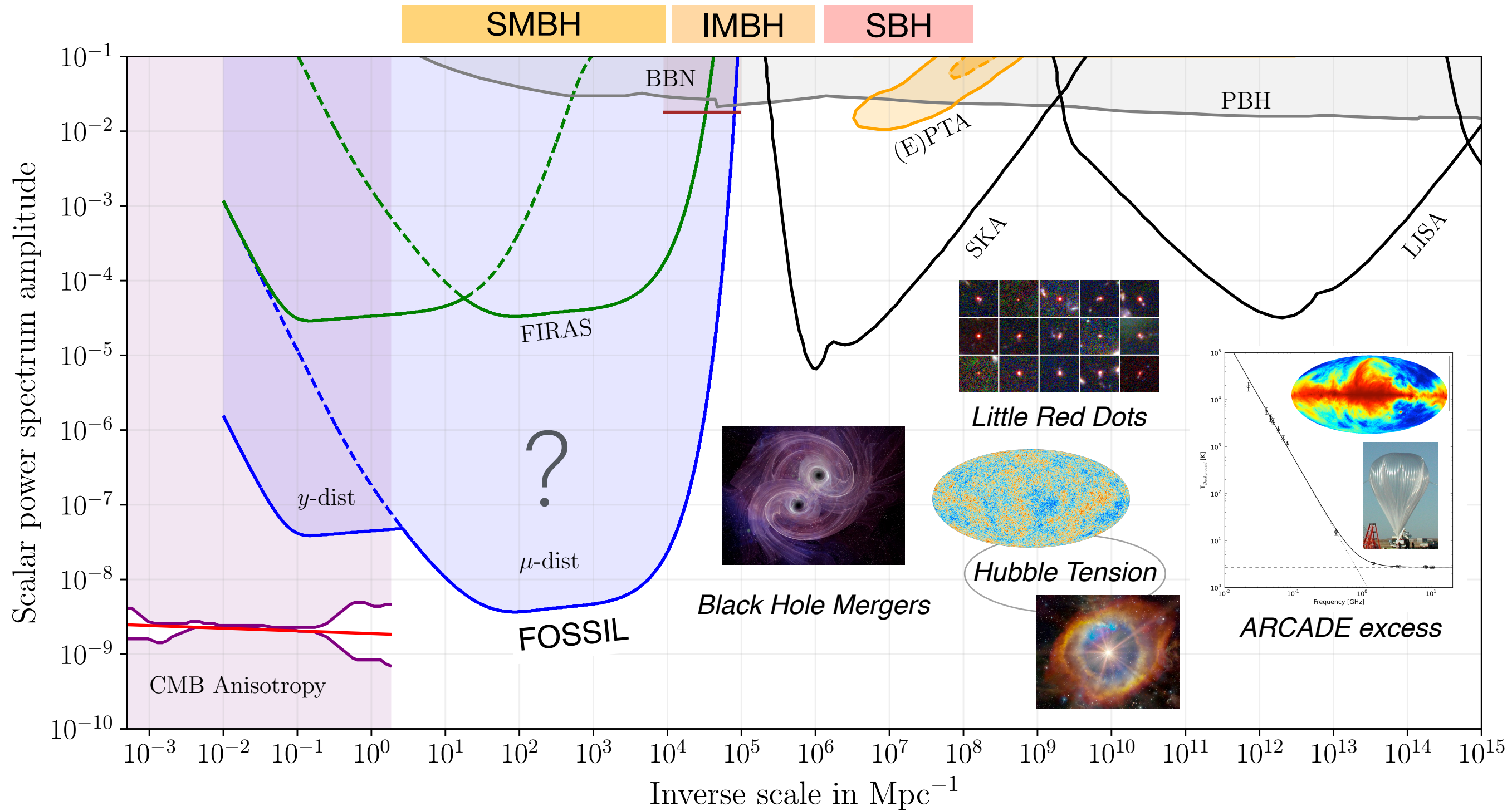
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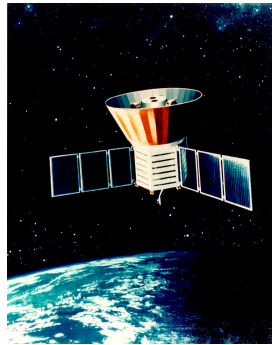
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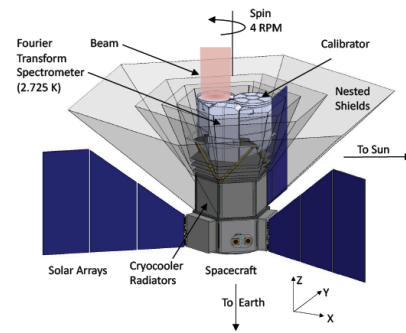
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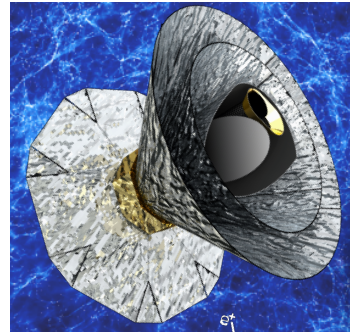
History of distortion experiments and proposals



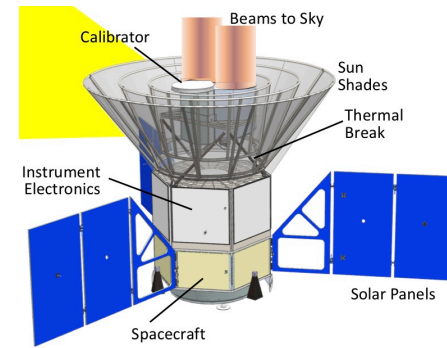
COBE/FIRAS
Mather & Fixsen



PIXIE
Kogut & Fixsen



PRISM
De Bernardis



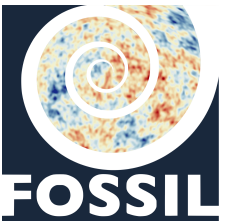
PIXIE
Kogut & Fixsen

(PIXIE)

Super-PIXIE



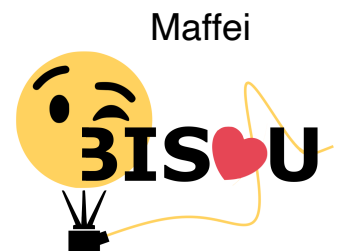
Aghanim



Aghanim



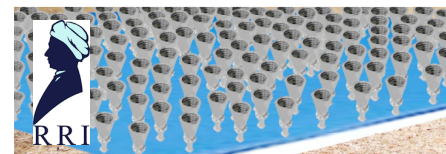
ARCADE 2
Kogut & Fixsen



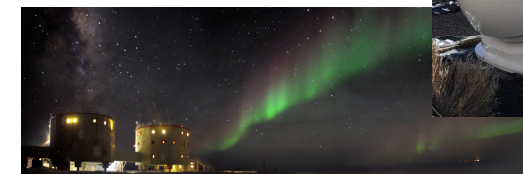
Maffei



Gervasi, Zannoni & Tartari



APSE Ra
Subrahmanyam & Rao



COSMO
De Bernardis, Masi & Battistelli



TMS
Rubiño-Martin

1989

2008

2011

2013

2015

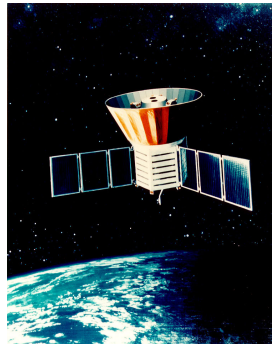
2016

2018

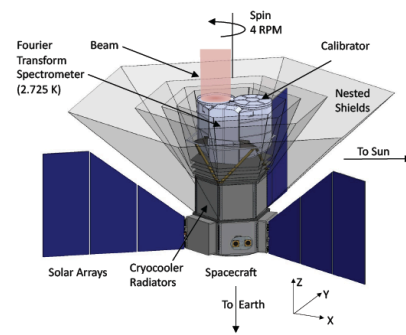
2022



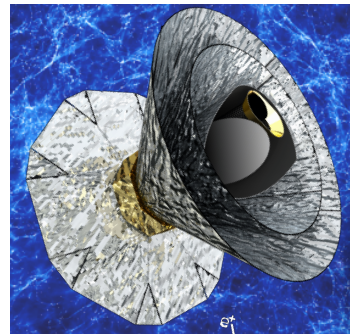
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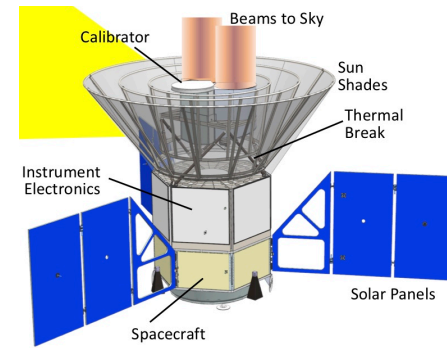
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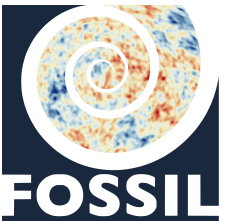
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(PIXIE)

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Aghanim

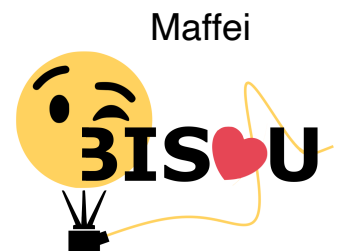
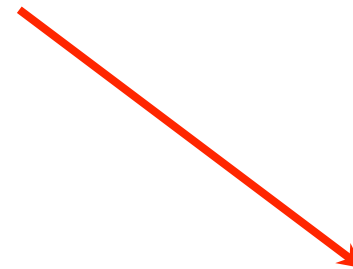


Aghanim



ARCADE 2
Kogut & Fixsen

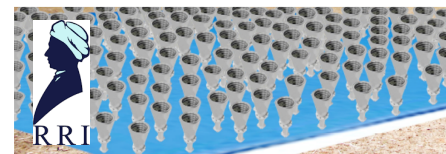
Not just fiction
anymore!



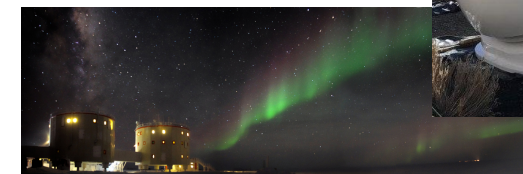
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Rubiño-Martin

1989



2008

2011

2013

2015

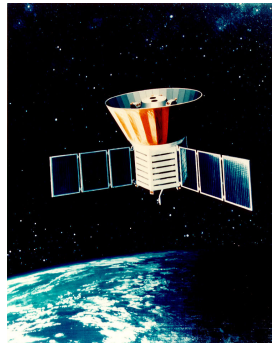
2016

2018

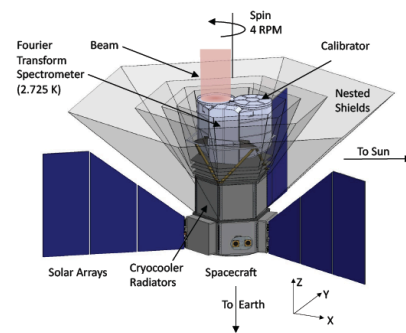
2022



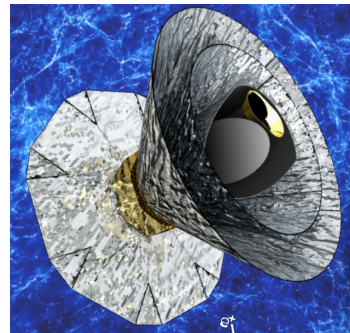
History of distortion experiments and proposals



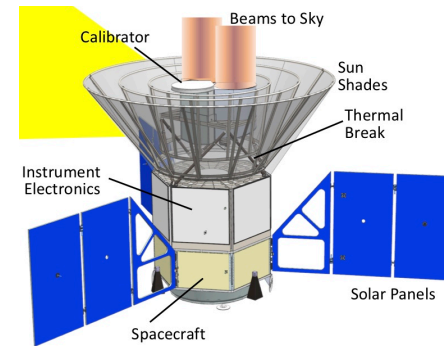
COBE/FIRAS
Mather & Fixsen



PIXIE
Kogut & Fixsen



PRISM
De Bernardis



PIXIE
Kogut & Fixsen

(PIXIE)

Super-PIXIE

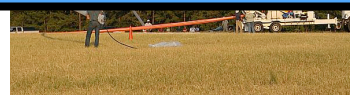
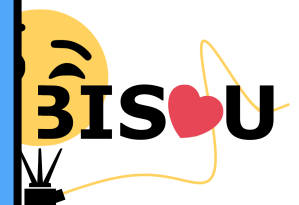


Aghanim



TMS and COSMO in construction!
BISOU officially in Phase A!
FOSSIL in step 2 of M8 selection!

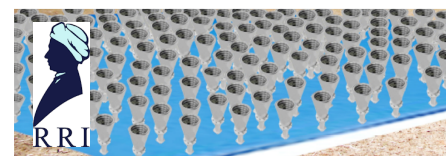
Maffei



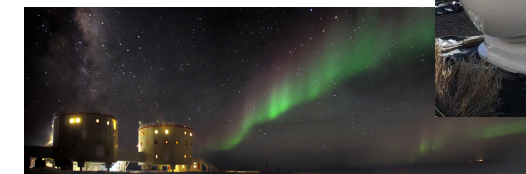
ARCADE 2
Kogut & Fixsen



Gervasi, Zannoni & Tartari



APSERa
Subrahmanyam & Rao



COSMO
De Bernardis, Masi & Battistelli



TMS
Rubiño-Martin

1989

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2022



Conclusions

- We live in an amazing era with lots of high precision data now and in the future
- We can “park the Hubble tension” but we should *not* forget it in the ongoing discussions!
- The small scale Universe is one of the places we have not constrained as much as we make believe
- Modifying recombination physics is one of the conservative ways of augmenting our cosmological model
 - Is excess lensing possibly also related? Another Ito problem to solve?
 - Could larger τ also be linked?
More small scale structures $\rightarrow$ earlier reionization?

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Still much to do and it could be many things!