Reionization and the Hubble Constant: Correlations in the Cosmic Microwave Background

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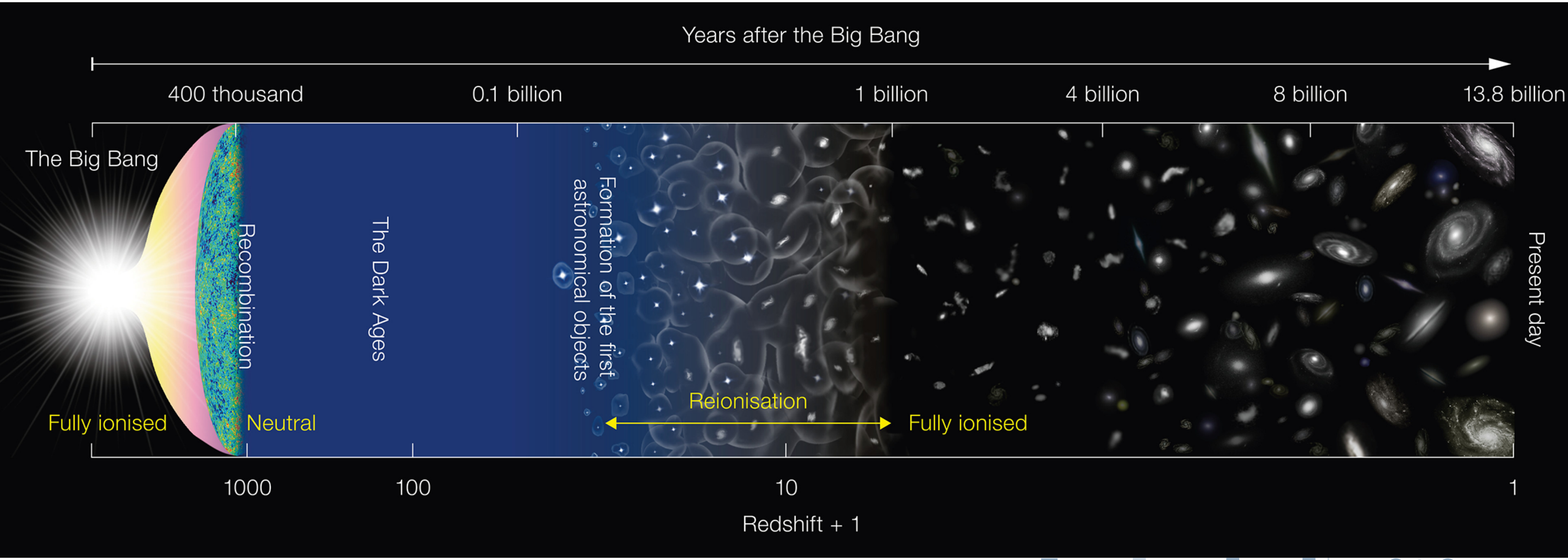
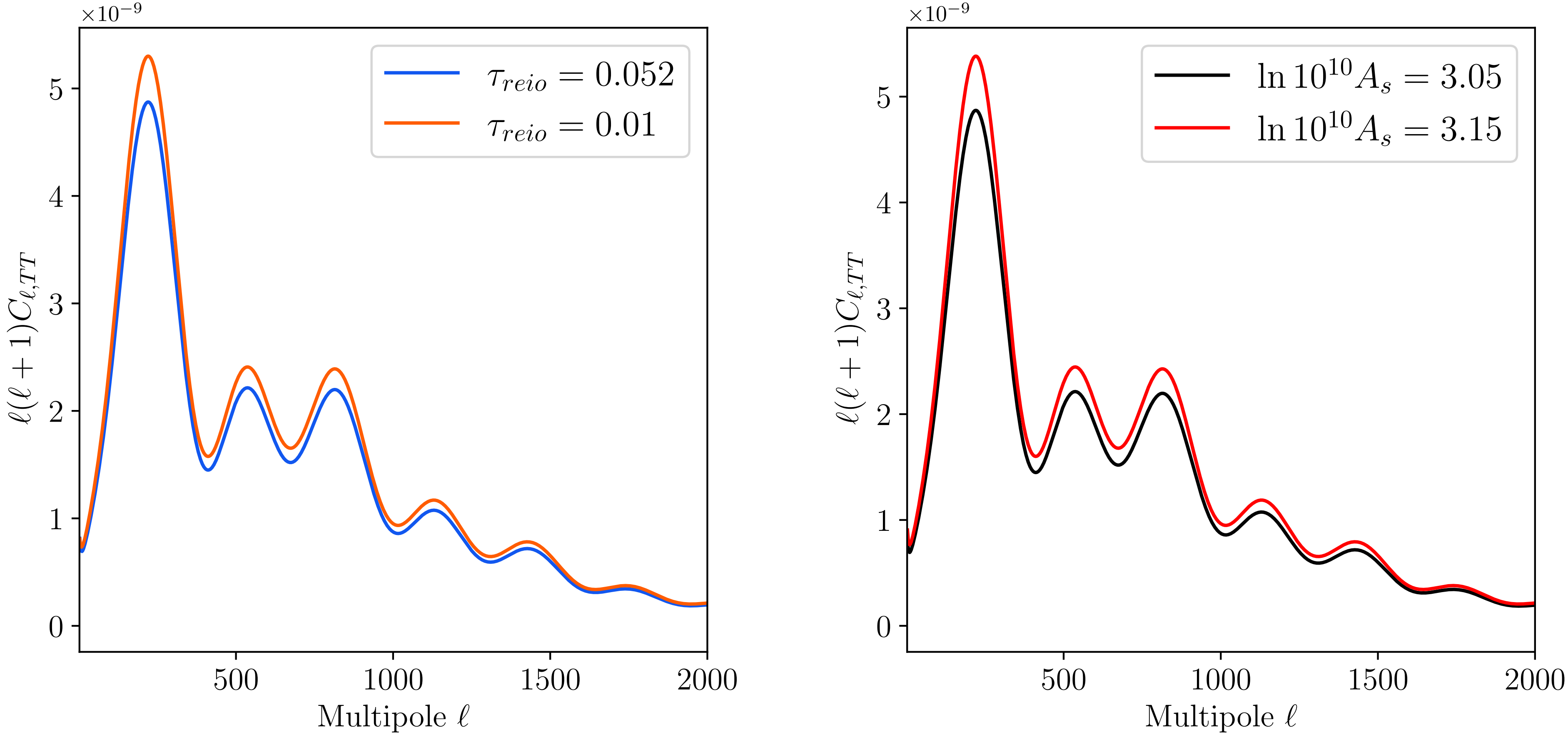
Reionization Epoch

- Reionization: $z \sim 20 - 5$
- $\tau_{\mathrm{reio}} \longrightarrow$ reionization optical depth

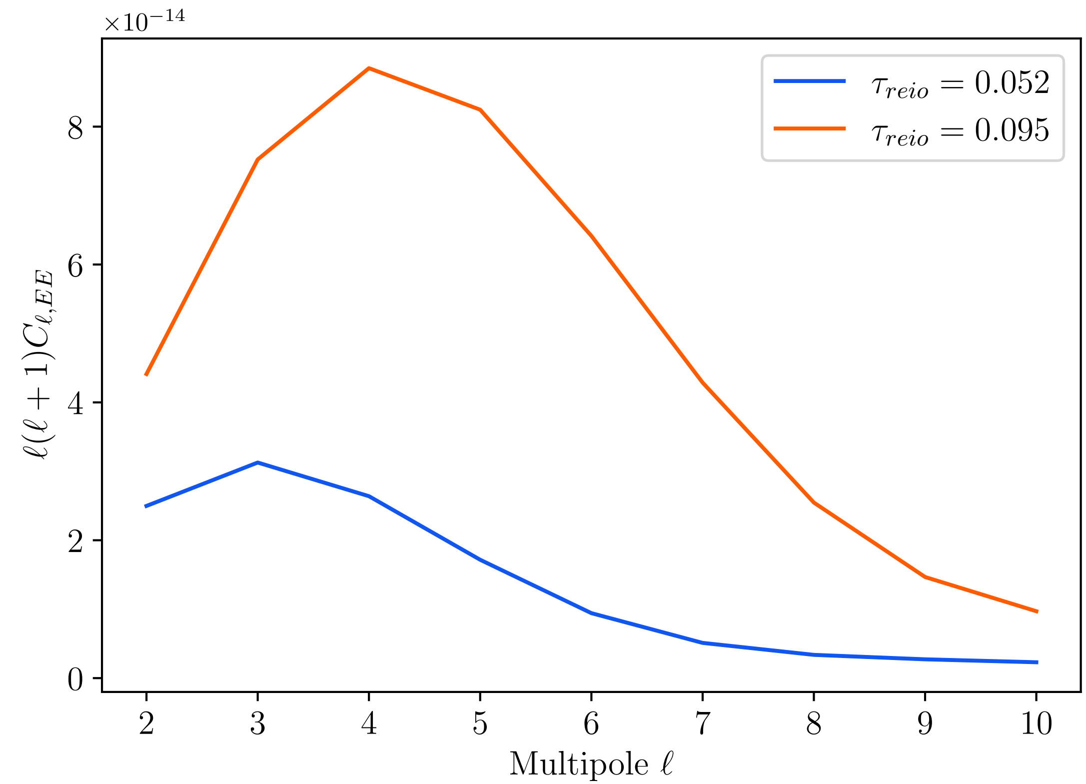


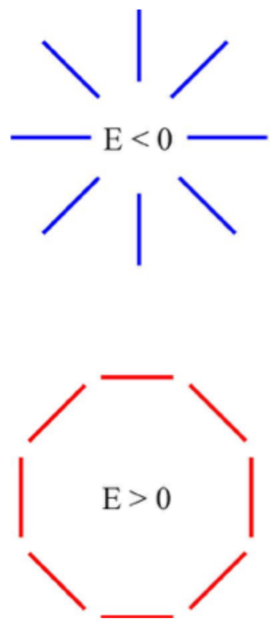
Effect of $\tau_{\rm reio}$ on CMB TT Spectrum



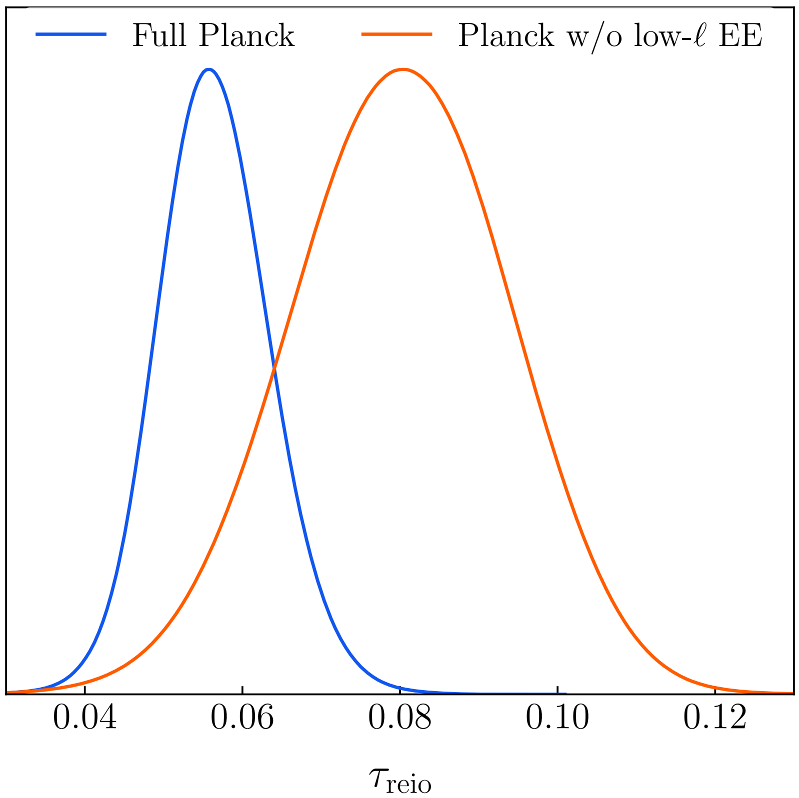
Probing $\tau_{\rm reio}$ with CMB EE spectra

- Thomson scattering of photons $\longrightarrow$ anisotropy in photon polarization
- Peak at $\ell < 10$, size depends on $\tau_{\rm reio}$
- low-ℓ EE spectra breaks $A_s e^{-2\tau_{\rm reio}}$ degeneracy
- $\tau_{\rm reio} = 0.0544^{+0.0070}_{-0.0081}$ at 68% C.L. (Planck 2018)





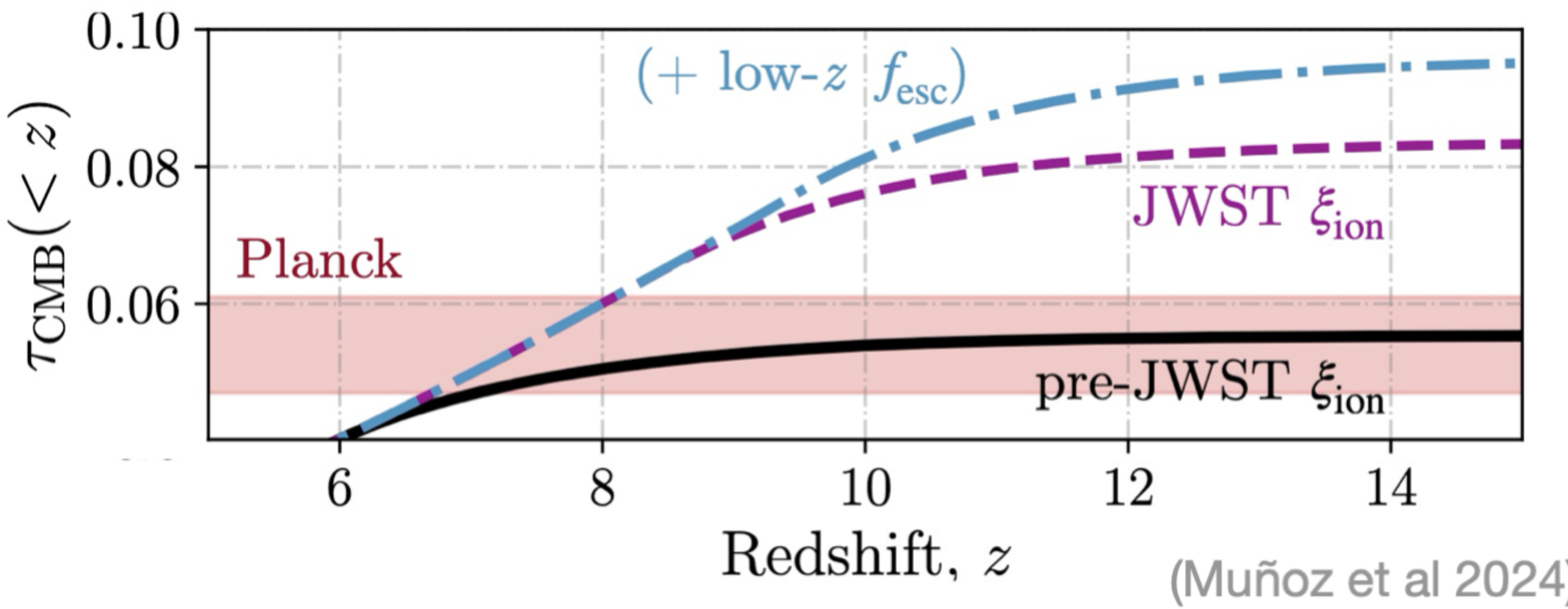
τ_{reio} Measurements of Planck: Small vs Large scale



- Full Planck data $\longrightarrow$ lower τ_{reio}

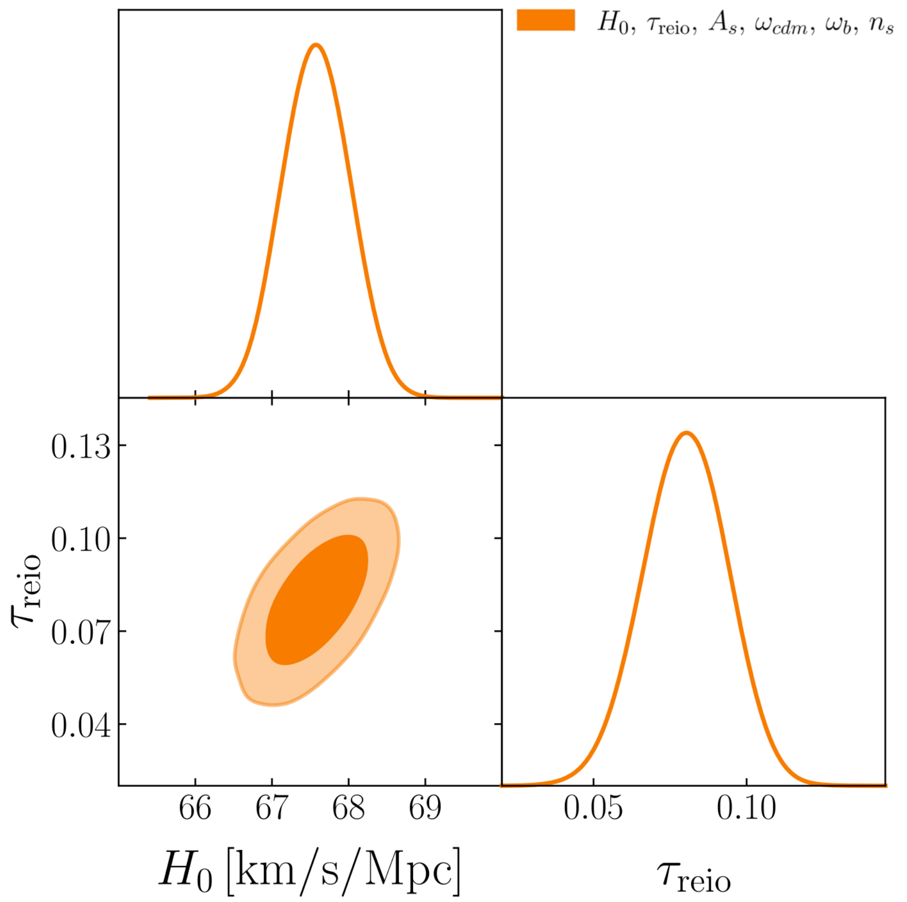
  (most precise measurement till date)
- Planck excluding large scale ($\ell < 30$) EE data $\longrightarrow$ higher τ_{reio}

τ_{reio} from Recent Galaxy Surveys



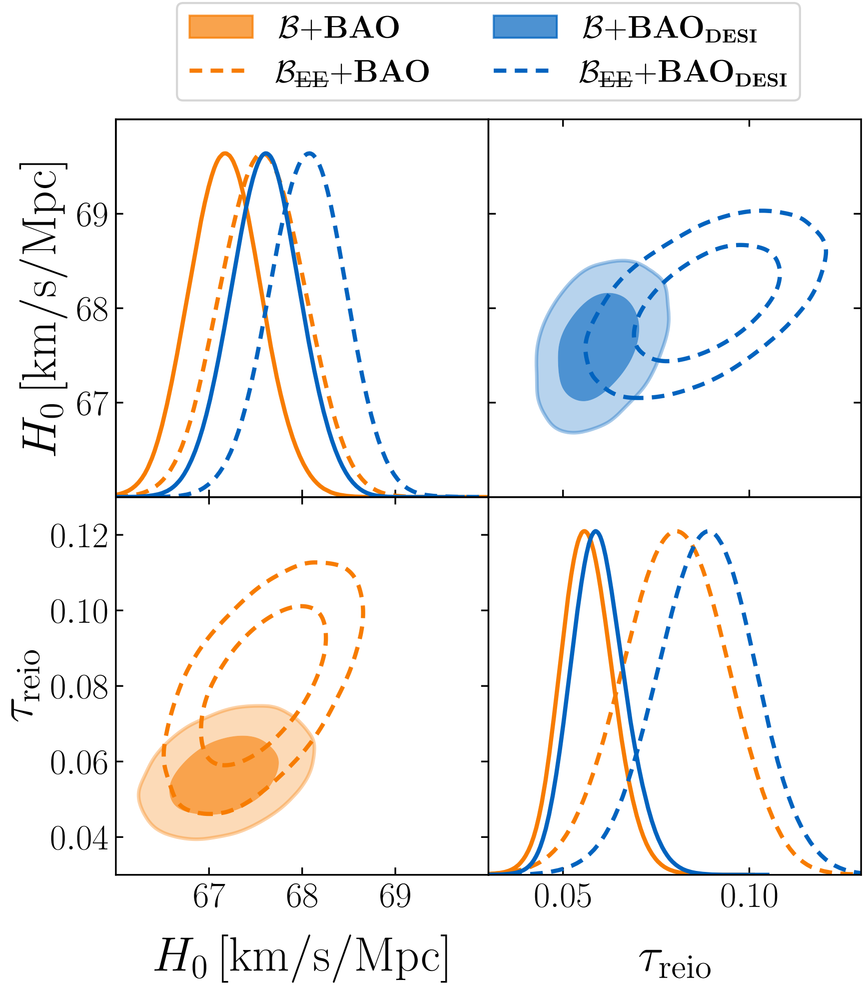
- JWST suggests:
  - $\uparrow$ ionizing efficiency
  - Enhanced population of galaxies ($z \gtrsim 9$)
- $\uparrow$ photon escape fraction
- Higher inferred value of $\tau_{\mathrm{reio}} \gtrsim 0.07$

$\tau_{\rm reio}$ and H_0



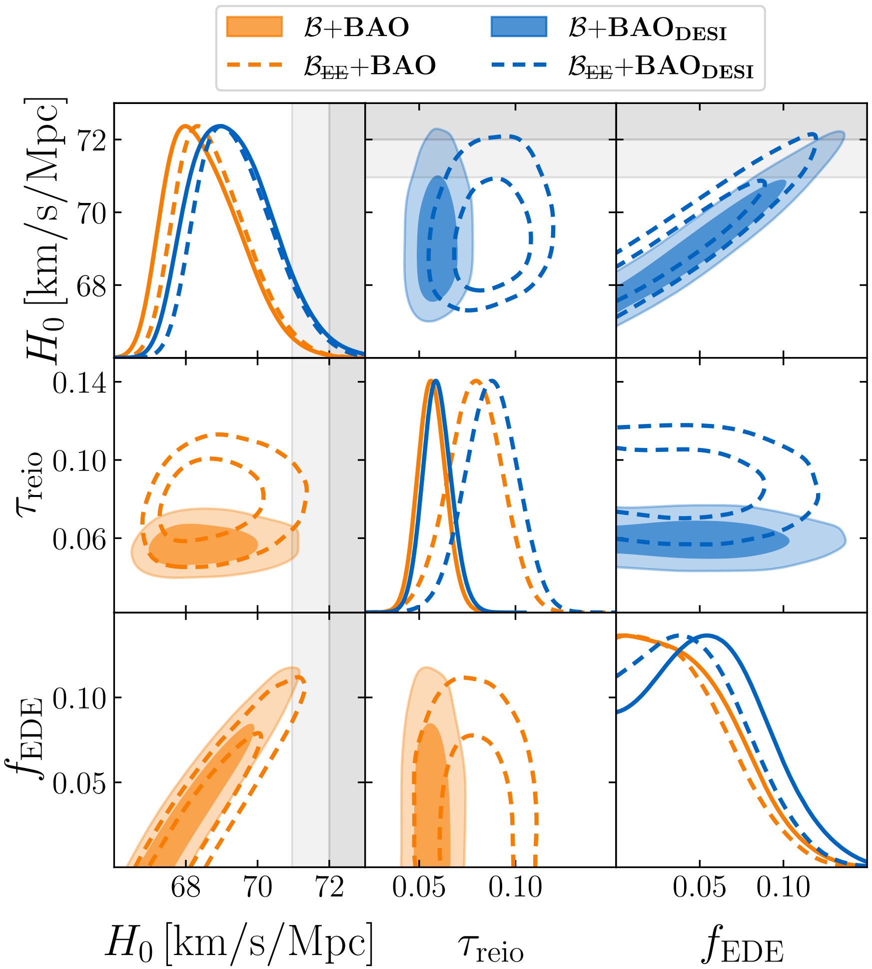
- Positive correlation between $\tau_{\rm reio}$ and H_0
- Impact on H_0 tension?

Results: ΛCDM Model



	H_0 (Tension)
$\mathcal{B}$+BAO	67.18 ± 0.38 (5.3σ)
	$\downarrow$
$\mathcal{B}_{\rm EE}$+BAO	67.58 ± 0.44 (4.8σ)
$\mathcal{B}$+BAO$_{\rm DESI}$	67.60 ± 0.37 (4.9σ)
	$\downarrow$
$\mathcal{B}_{\rm EE}$+BAO$_{\rm DESI}$	68.05 ± 0.40 (4.5σ)

Results: EDE Model



	H_0 (Tension)
$\mathcal{B}$+BAO	$68.52^{+0.77}_{-1.2}$ (3.5σ)
	↓
$\mathcal{B}_{\text{EE}}$+BAO	$68.78^{+0.74}_{-1.2}$ (3.3σ)
$\mathcal{B}$+BAO$_{\text{DESI}}$	$69.32^{+0.92}_{-1.3}$ (2.7σ)
	↓
$\mathcal{B}_{\text{EE}}$+BAO$_{\text{DESI}}$	$69.43^{+0.80}_{-1.2}$ (2.8σ)

Other Works

Increasing $\tau_{\rm reio}$ also helps with:

- alleviating negative neutrino mass, $\sum m_\nu$ bounds
- reduces preference for evolving dark energy model

(Jhaveri et al 2025, Sailer et al 2025)

Hi, I'm Praniti

BROWN

Hobbies:

Effect of τ_{reio} on CMB Temperature Spectrum

- CMB anisotropy $\Theta(\hat{n})$, along line of sight, $\hat{n}$ after reionization:

$$\begin{aligned} \Theta(\hat{n}) &\longrightarrow \Theta(\hat{n})e^{-\tau_{\text{reio}}} \\ \implies C_\ell^{TT} &\longrightarrow C_\ell^{TT} e^{-2\tau_{\text{reio}}} \end{aligned} \quad (1)$$

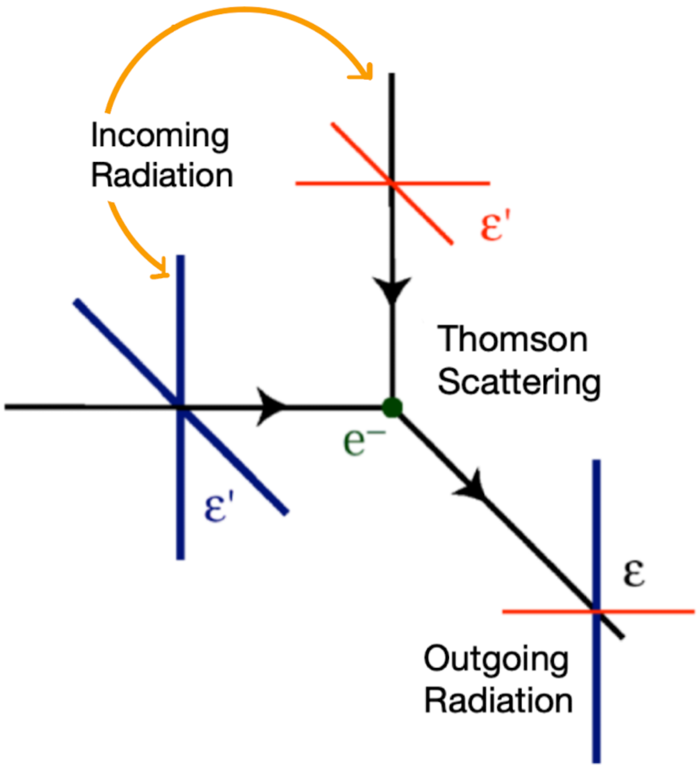
- Suppression occurs for multipoles: $\ell \gtrsim 100$
- Scales entering during reionization ($\ell \lesssim 100$) $\longrightarrow$ less supressed
- Effect of τ_{reio} degenerate with overall amplitude of the primordial power spectrum, A_s.

$$\implies \text{CMB TT spectrum measures } A_s e^{-2\tau_{\text{reio}}} \quad (2)$$

Scattering and Polarization

- Thomson-scattering differential cross-section:

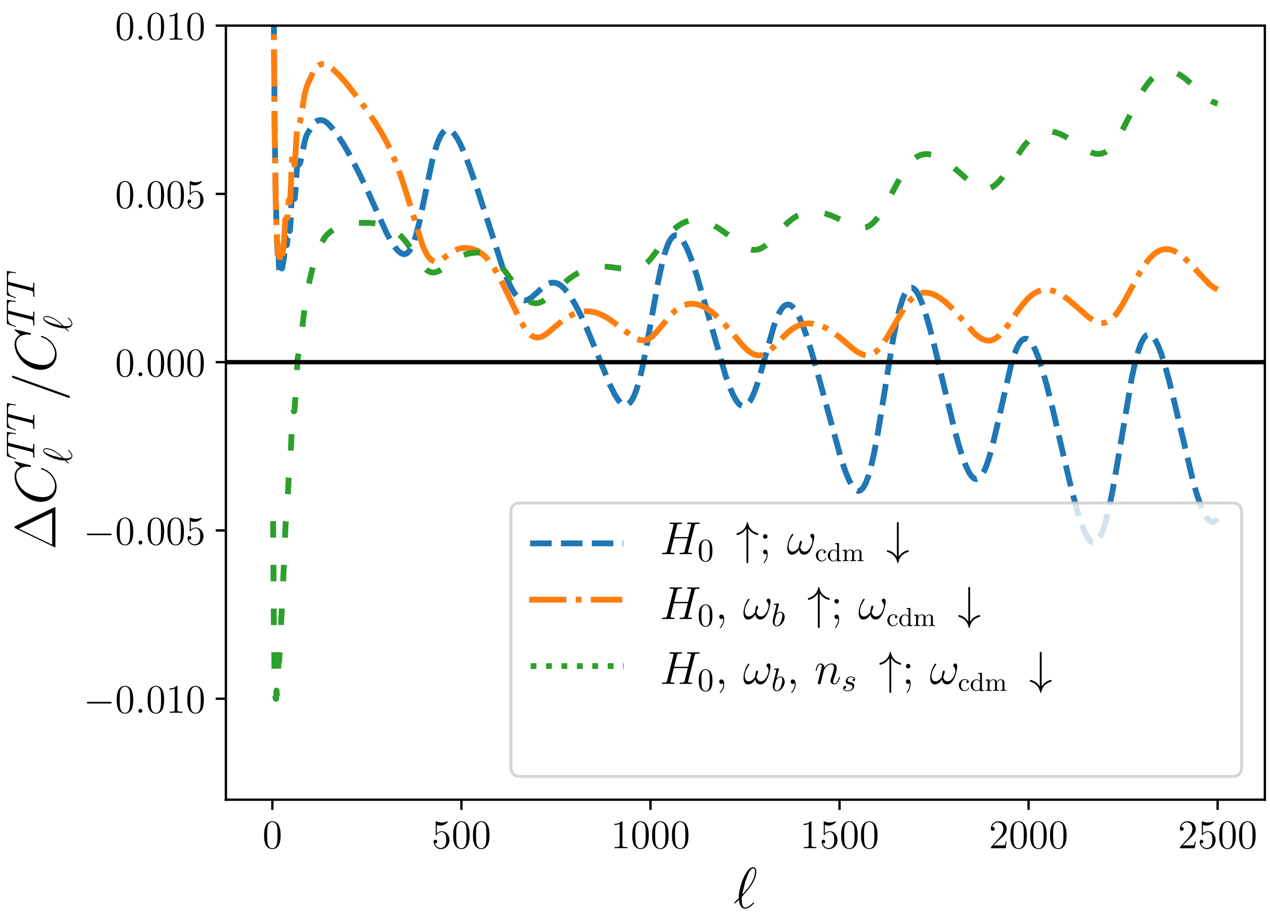
$$\frac{d\sigma}{d\Omega} \propto \left|\hat{\varepsilon} \cdot \hat{\varepsilon}'\right|^2$$



- Assuming incident radiation $\longrightarrow$ unpolarized

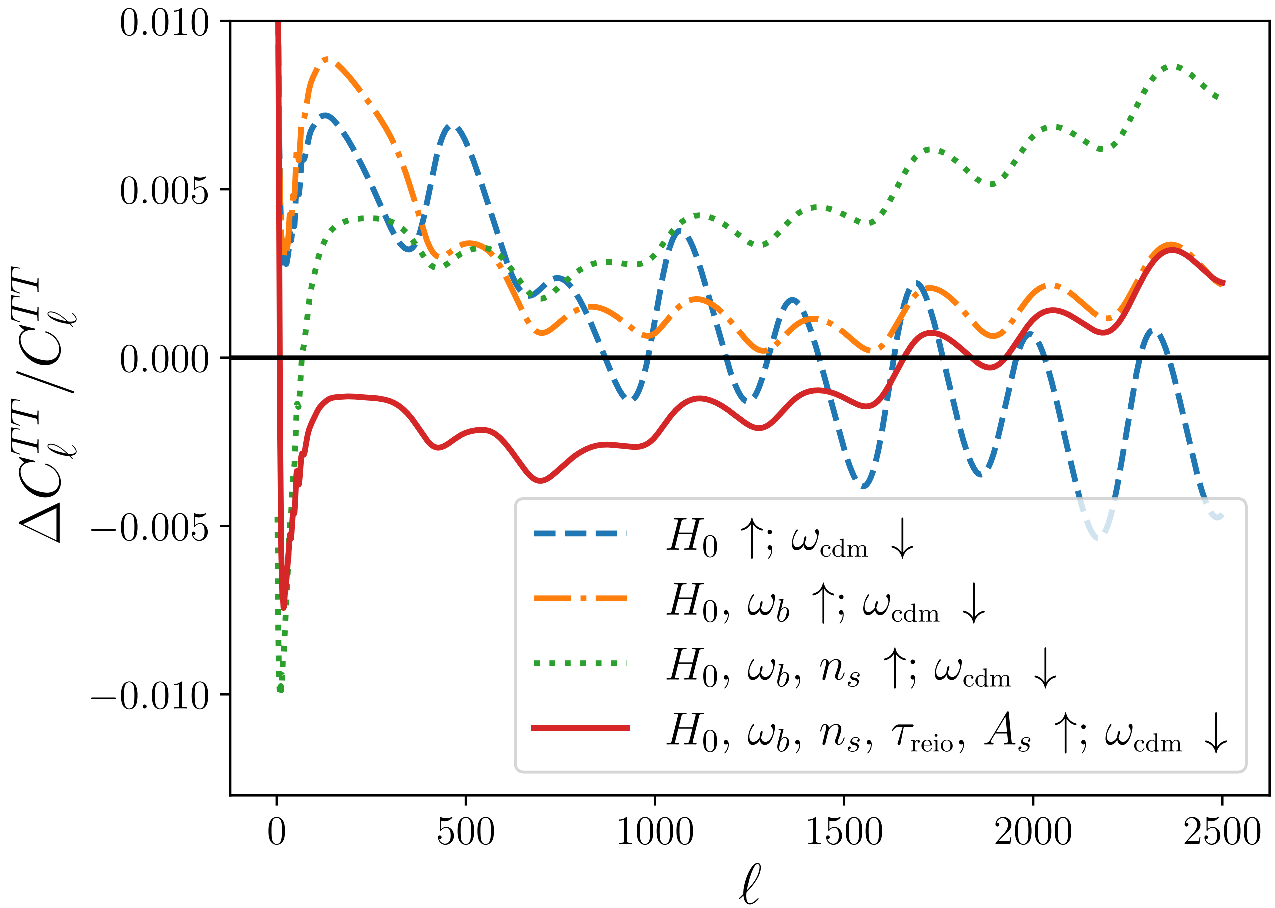
- Leads to anisotropy in the photon polarization.

$\tau_{\rm reio}$ - H_0 Correlation



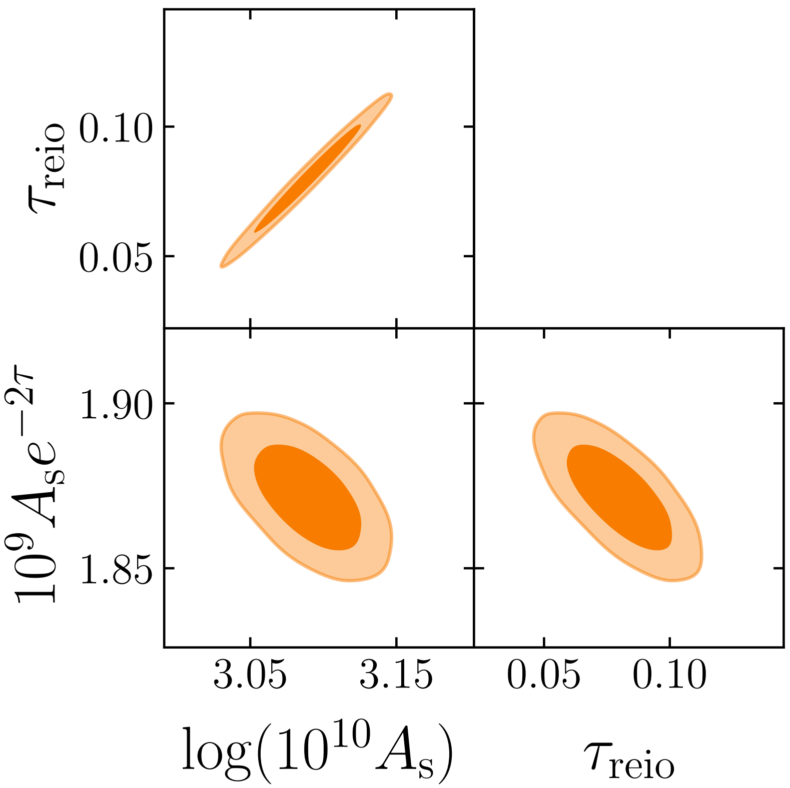
- Red-titled C_ℓ^{TT}: $n_s\uparrow$

$\tau_{\rm reio}$ - H_0 Correlation



- Overall Enhancement of C_ℓ^{TT}: $A_s \uparrow, \tau_{\rm reio} \uparrow$

Bonus: Breaking $A_s e^{-2\tau_{\rm reio}}$ Degeneracy



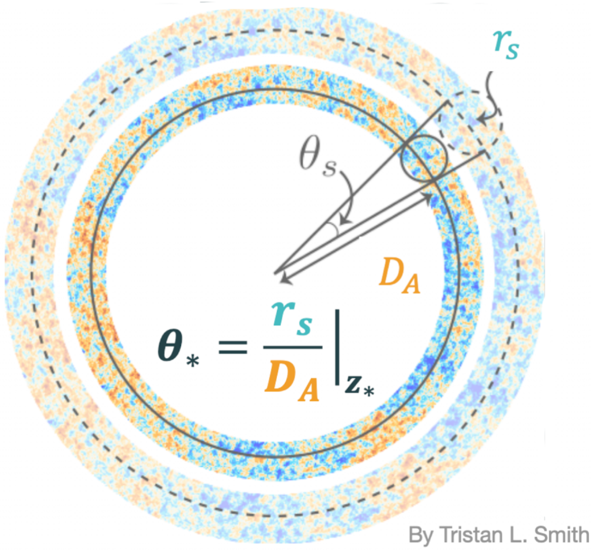
- Anti-correlation b/w A_s and $A_s e^{-2\tau_{\rm reio}}$
- Planck prefers $\uparrow A_s$ and $\uparrow \tau_{\rm reio}$ both

Inferences from Data and H_0 Tension

Datasets

- $\mathcal{B}$: Planck CMB + CMB lensing + Supernovae dataset.
- $\mathcal{B}_{\not{\text{EE}}}$: $\mathcal{B}$ with low-ℓ ($\ell < 30$) EE data removed.
- **BAO**: BAO from 6DFGS, BOSS, and SDSS BOSS.
- **BAO$_{\textbf{DESI}}$**: BAO measurements from DESI DR1.

Boltzmann solver $\longrightarrow$ CLASS, MCMC analysis $\longrightarrow$ Cobaya



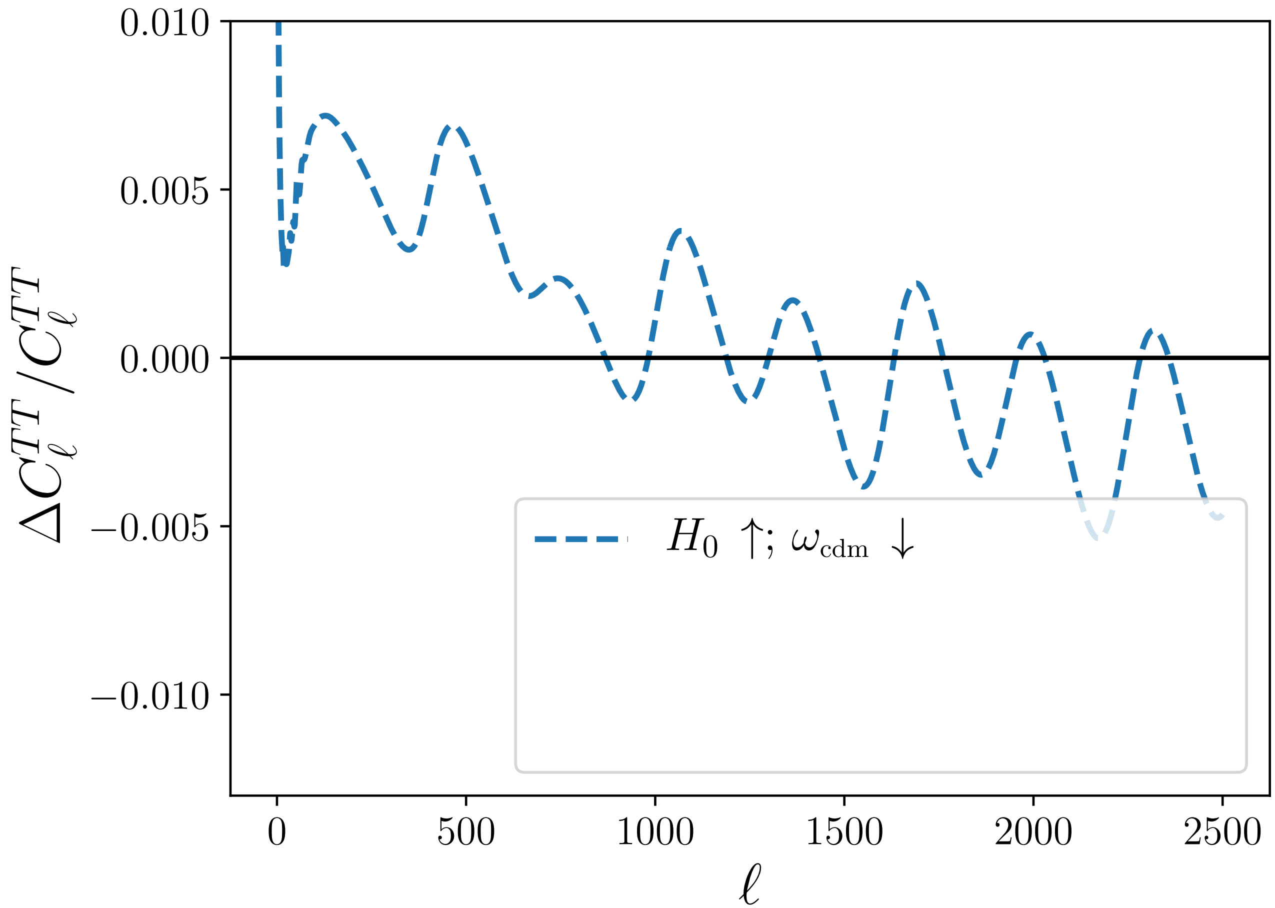
CMB measures angular sound horizon θ_s at recombination:

$$\theta_s = \frac{r_s}{D_A} = \frac{\int_{z_{\rm rec}}^{\infty} c_s dz/H(z)}{\int_0^{z_{\rm rec}} c dz/H(z)} \tag{3}$$

$$H^2(z) = (100\ \mathrm{km/s/Mpc})^2 \left[\omega_r(1+z)^4 + \omega_m(1+z)^3 + h^2 - \omega_m - \omega_r\right] \tag{4}$$

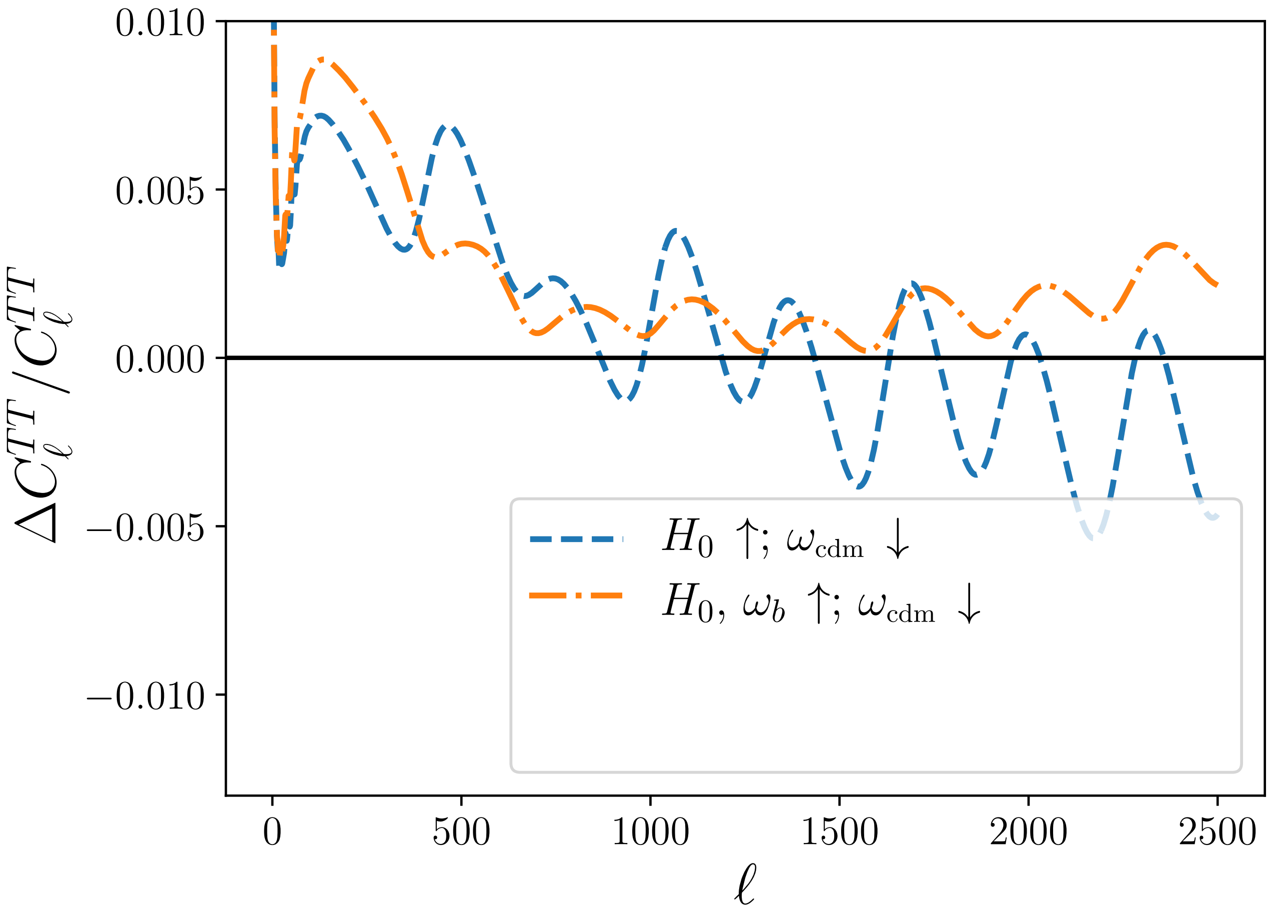
θ_s fixed by CMB $\longrightarrow H_0 \uparrow \implies \omega_m \downarrow$

$\tau_{\rm reio}$ - H_0 Correlation



- Fix angular sound horizon: $H_0 \uparrow \implies \omega_{\rm cdm} \downarrow$

$\tau_{\rm reio}$ - H_0 Correlation



- Change in relative heights of even and odd peaks: $\omega_b \uparrow$

EISW Effect

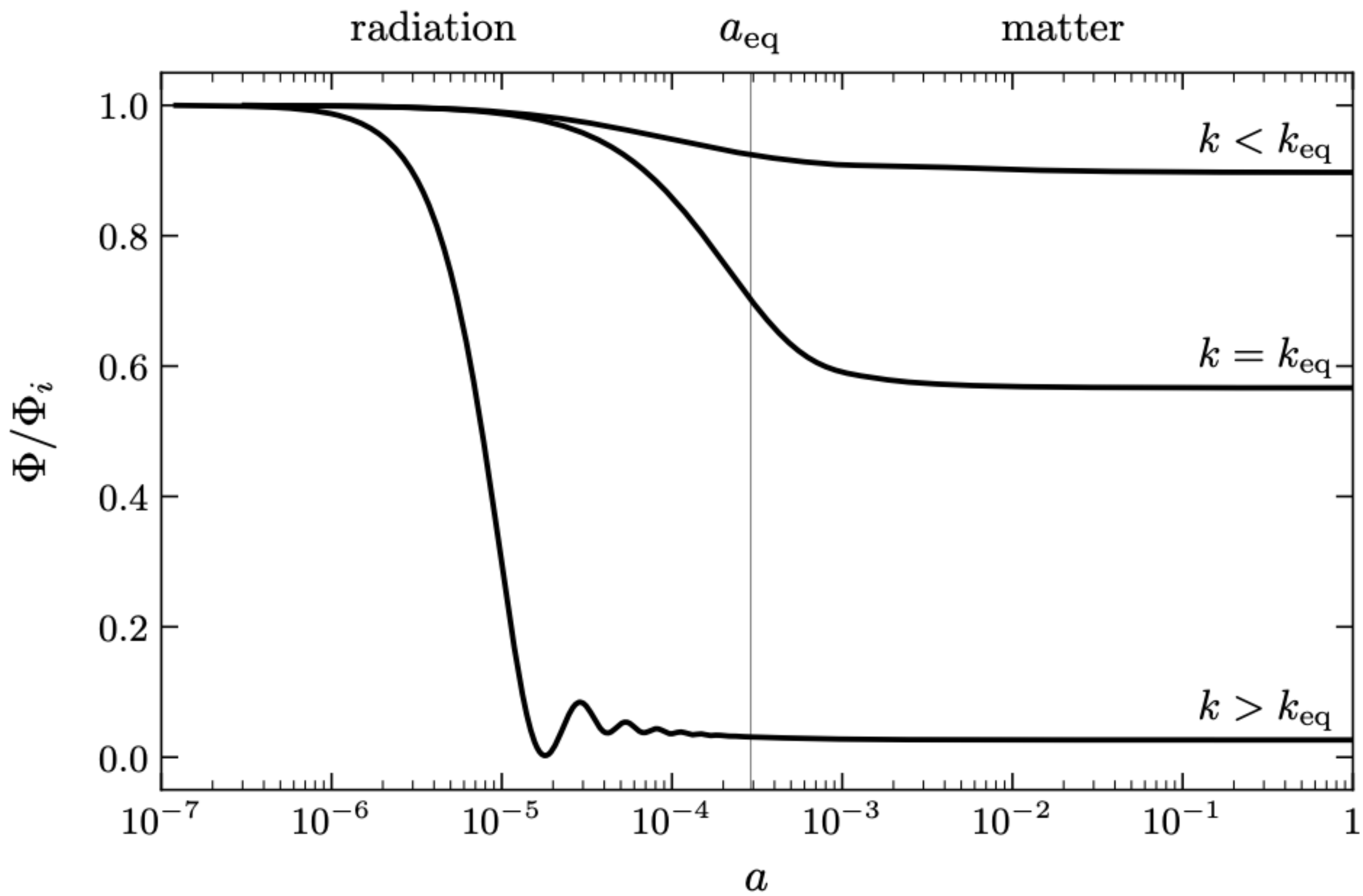


Figure: Maximum in variation in Φ for scales just entering the horizon

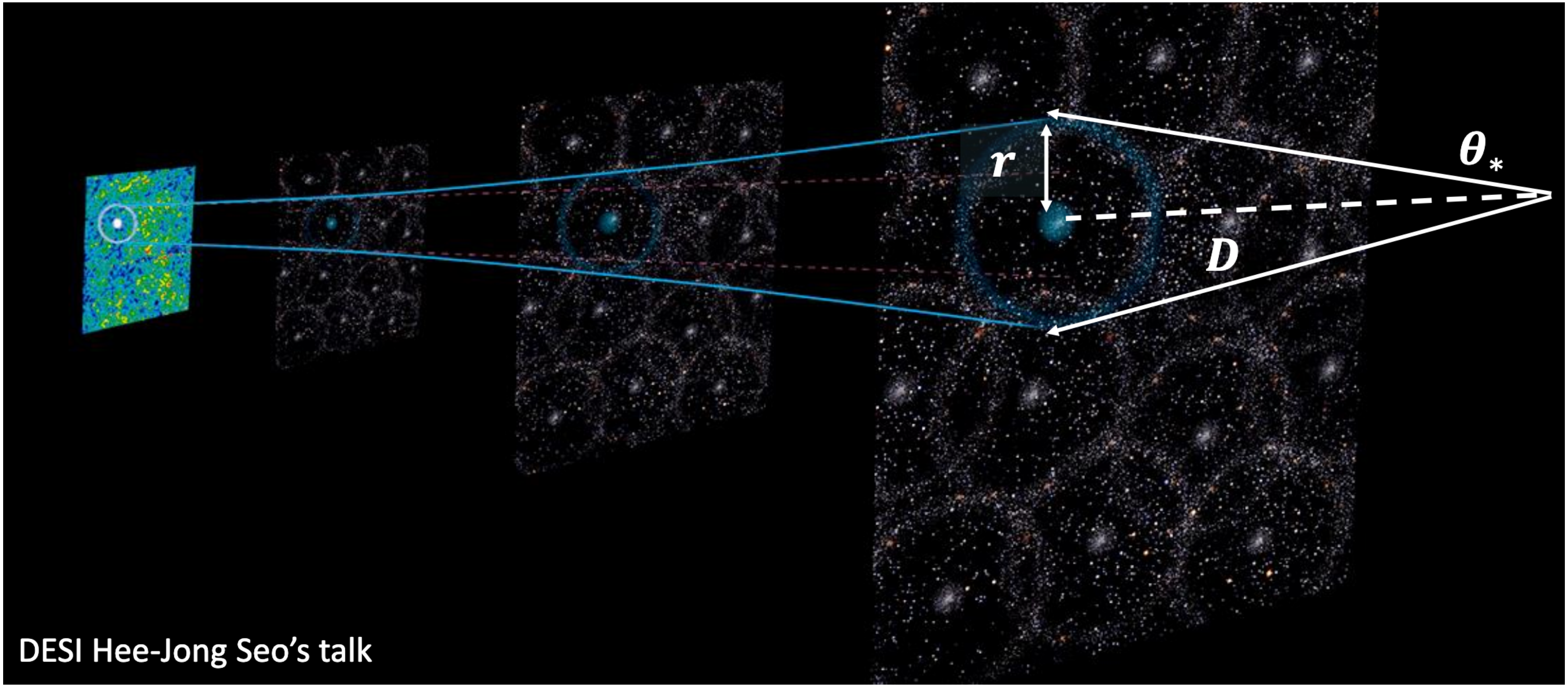
Early Dark Energy (EDE) Model

- New component parameterized by a scalar field, ϕ, with a potential:

$$
\begin{aligned}
V(\theta \equiv \phi/f) =& m^2 f^2 [1 - \cos(\theta)]^3 \\
m \longrightarrow & \text{ mass of scalar field} \\
f \longrightarrow & \text{ decay constant}
\end{aligned}
\tag{6}
$$

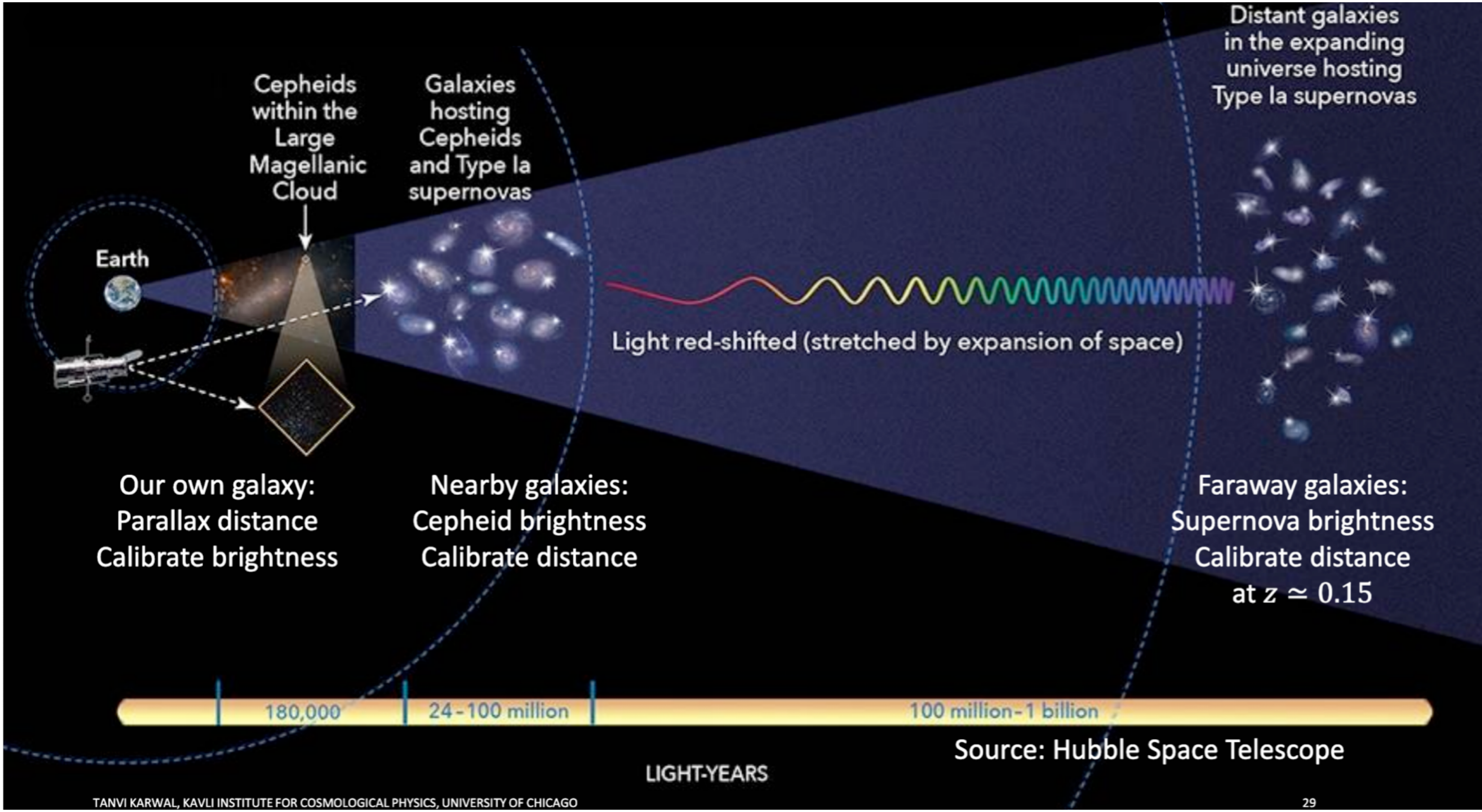
- Initially $\theta_i \to$ fixed, $\implies$ dark energy fluid, $w = -1$
- Begins oscillating at redshift, z_c when $H^2 \sim \partial_\theta^2 V(\theta)/f^2$, diluting faster than radiation.
- Decays around recombination: does not affect late-time dynamics.
- Free parameters:
  1. Critical scale factor, $a_c = 1/(1 + z_c)$
  2. $f_{\rm EDE}$: fraction contributed by EDE to the total energy density at z_c

BAO Measurements

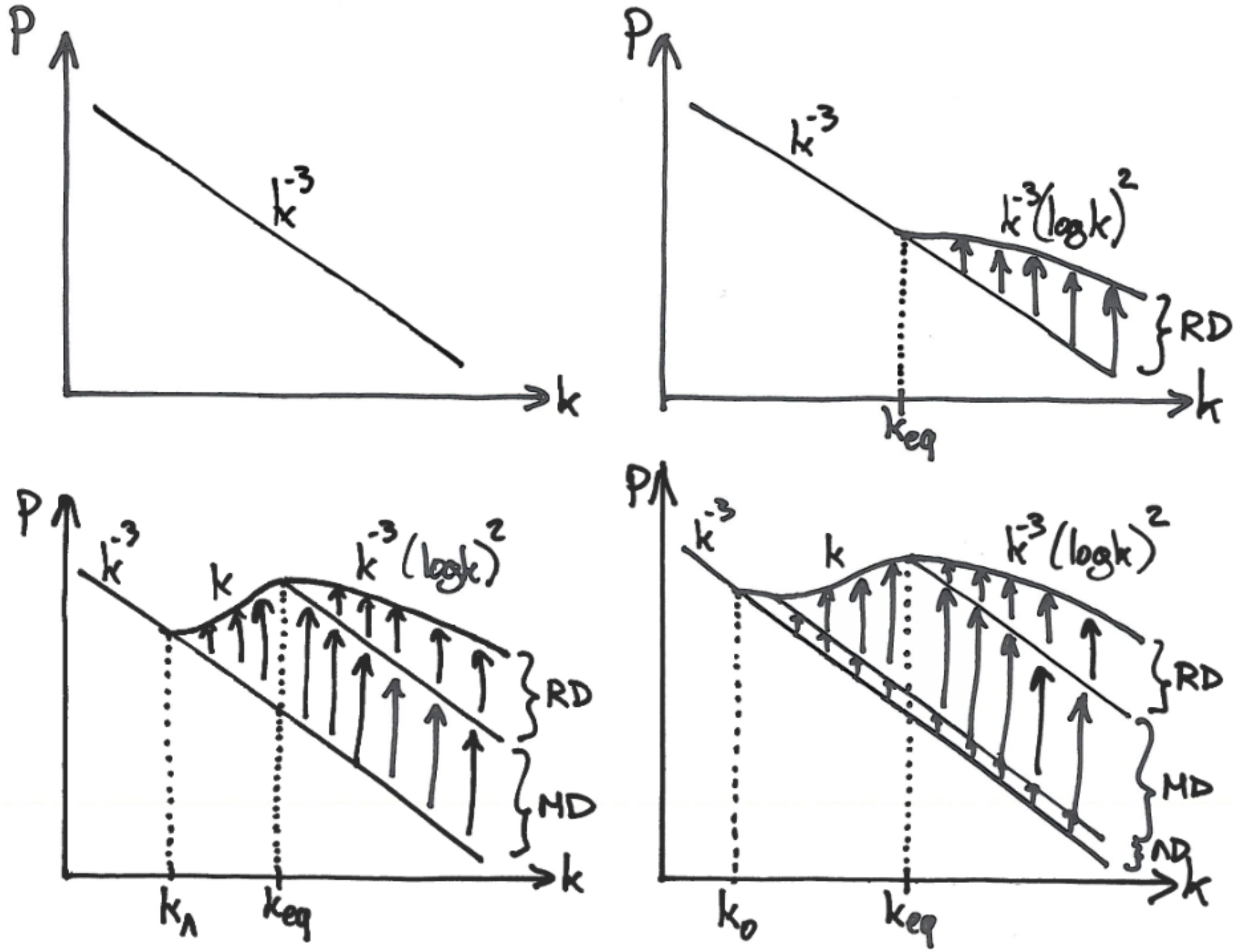


Baryon acoustic oscillations trace the same physics as the CMB at nearer redshifts

Supernovae Distance Ladder



Matter Power Spectrum



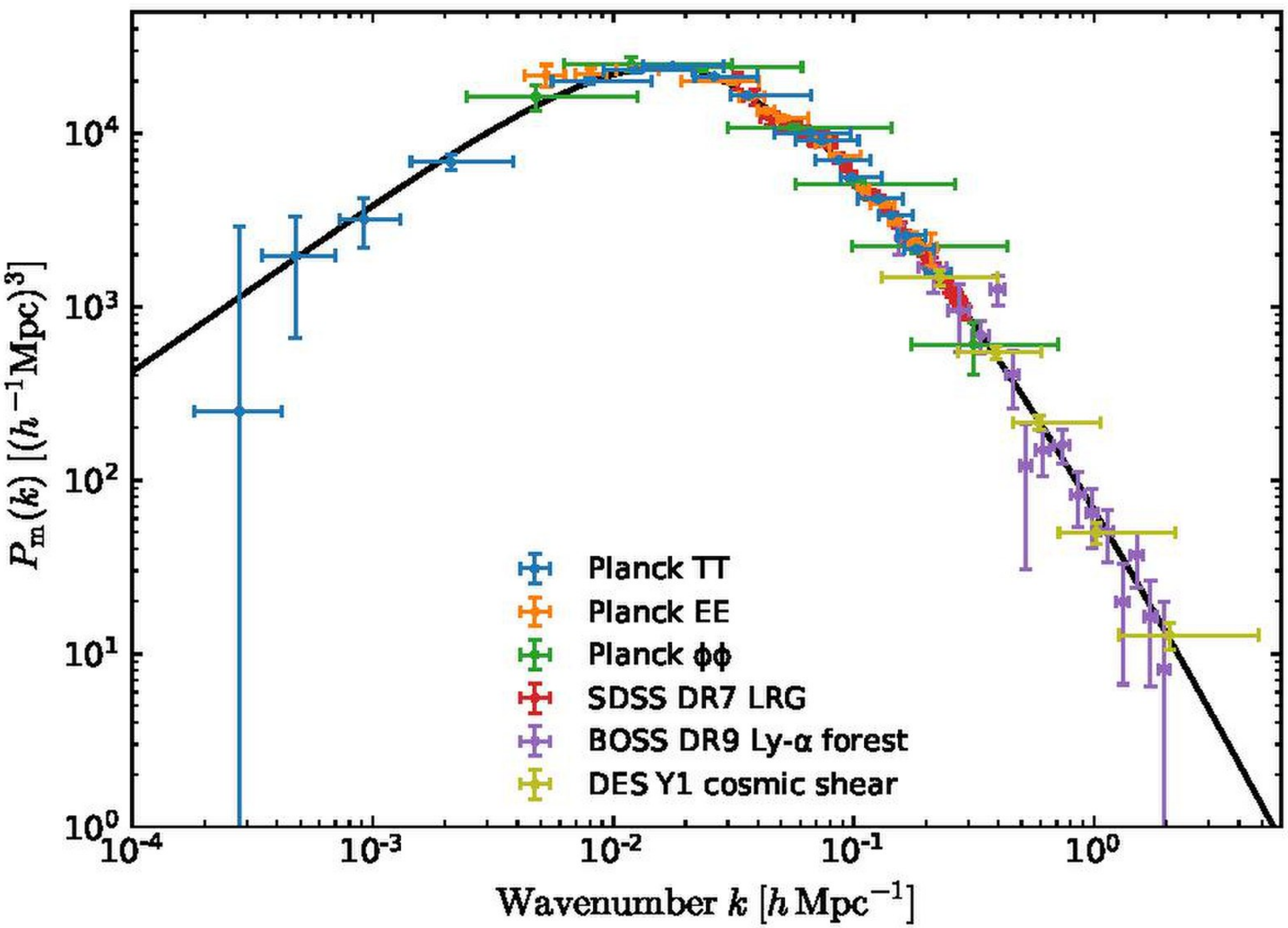
Matter Power Spectrum for different eras (Lesgourges lectures at TASI)

Matter Power spectrum

Table 2. Independent leading effects controlling the shape of the matter power spectrum $P(k)$ in the minimal ΛCDM model.

	Effect	Relevant quantity	Parameter
(P1)	scale of the maximum	$k_{\rm eq}$	$\omega_{\rm m}, \Omega_\Lambda$
(P2)	slope for $k \gg k_{\rm eq}$ and BAO amplitude	$\Omega_{\rm b}/\Omega_{\rm cdm}$	$\omega_{\rm b}, \omega_{\rm m}$
(P3)	BAO scale	$r_{\rm s}(\eta_{\rm drag})$	$\omega_{\rm b}, \omega_{\rm m}$
(P4)	Global amplitude	amplitude of primordial spectrum and duration of ΛD	$A_{\rm s}, \Omega_\Lambda$
(P5)	Global tilt	tilt of primordial spectrum	$n_{\rm s}$

Matter Power Spectrum: Observations



Photon Polarization Modes

Dark Radiation (DR) Model

- Additional light degrees of freedom which remain ultra-relativistic until after the epoch of recombination.

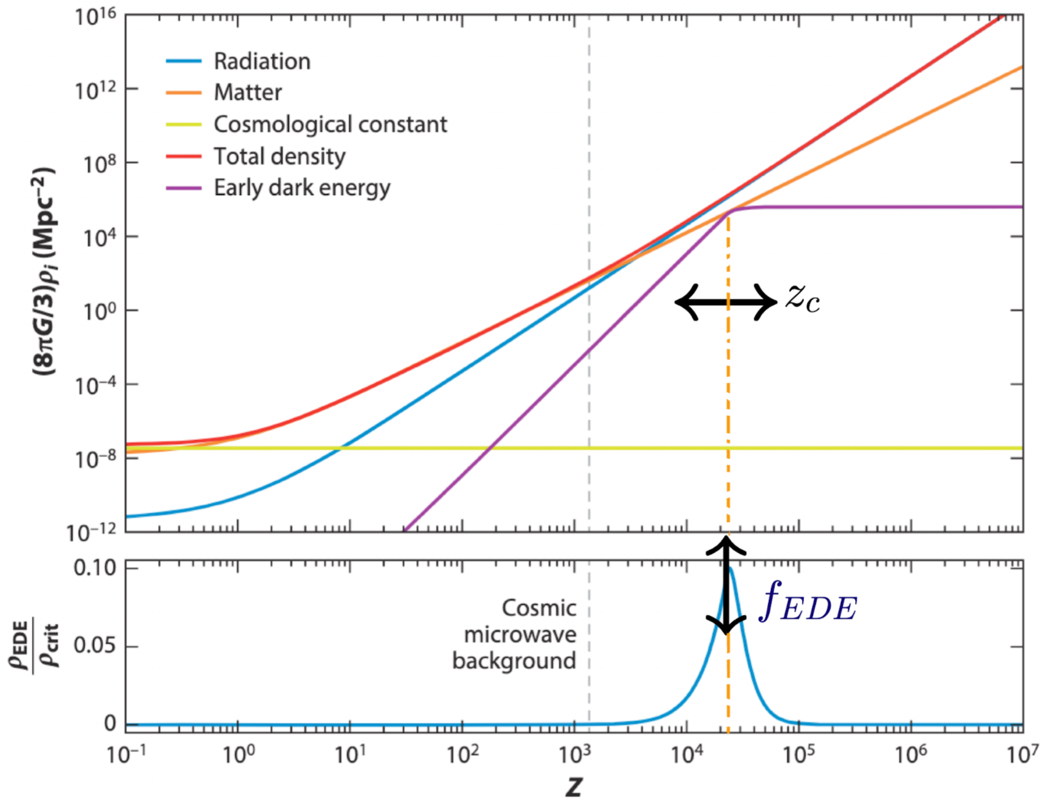
$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma \qquad (7)$$

$$\rho_r \longrightarrow \text{radiation energy density}$$

$$\rho_\gamma \longrightarrow \text{photon energy density}$$

- The total relativistic degrees of freedom, $N_{\rm eff}$ is a free parameter.
- Two different DR scenarios:
  1. Free-Streaming Dark Radiation (FSDR): interaction rate, $\Gamma \ll H$.
  2. Self-Interacting Dark Radiation (SIDR): interaction rate, $\Gamma \gg H$.

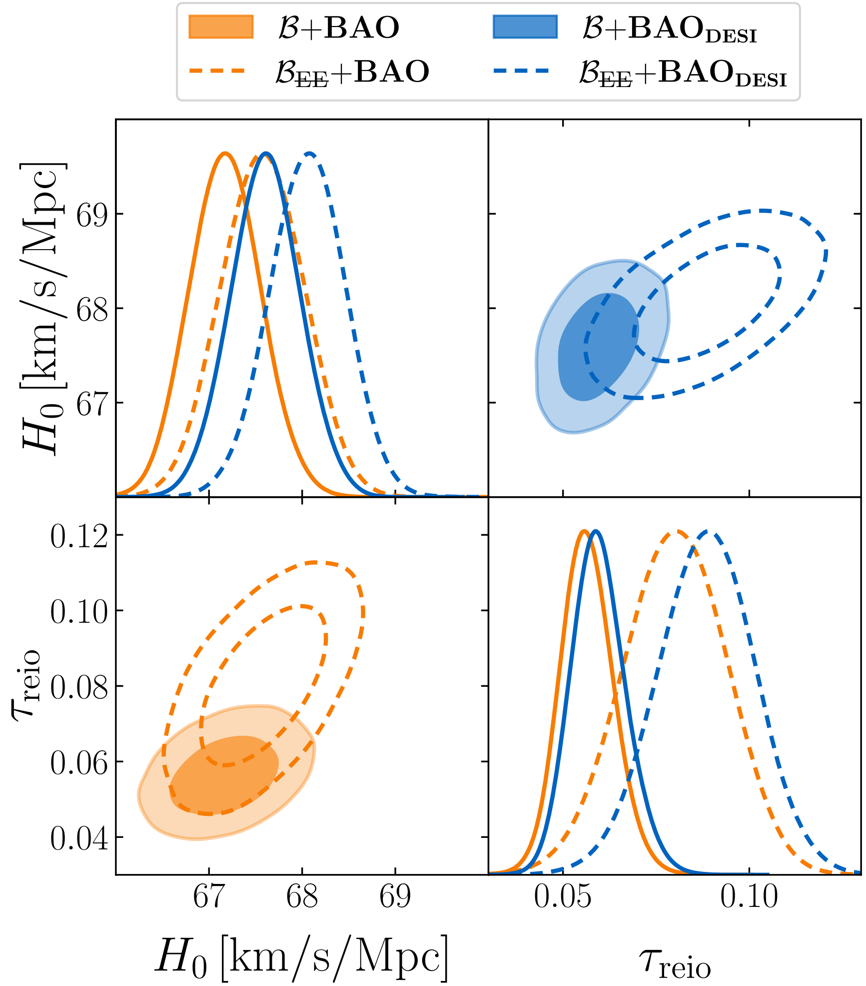
Early Dark Energy (EDE) Model



(Kamionkowski et al 2023)

- Λ-like behaviour initially
- Starts diluting away faster than radiation at z_c
- Localised peak in $f_{\text{EDE}} = \frac{\rho_{EDE}}{\rho_{total}}$ at z_c

Results: ΛCDM Model



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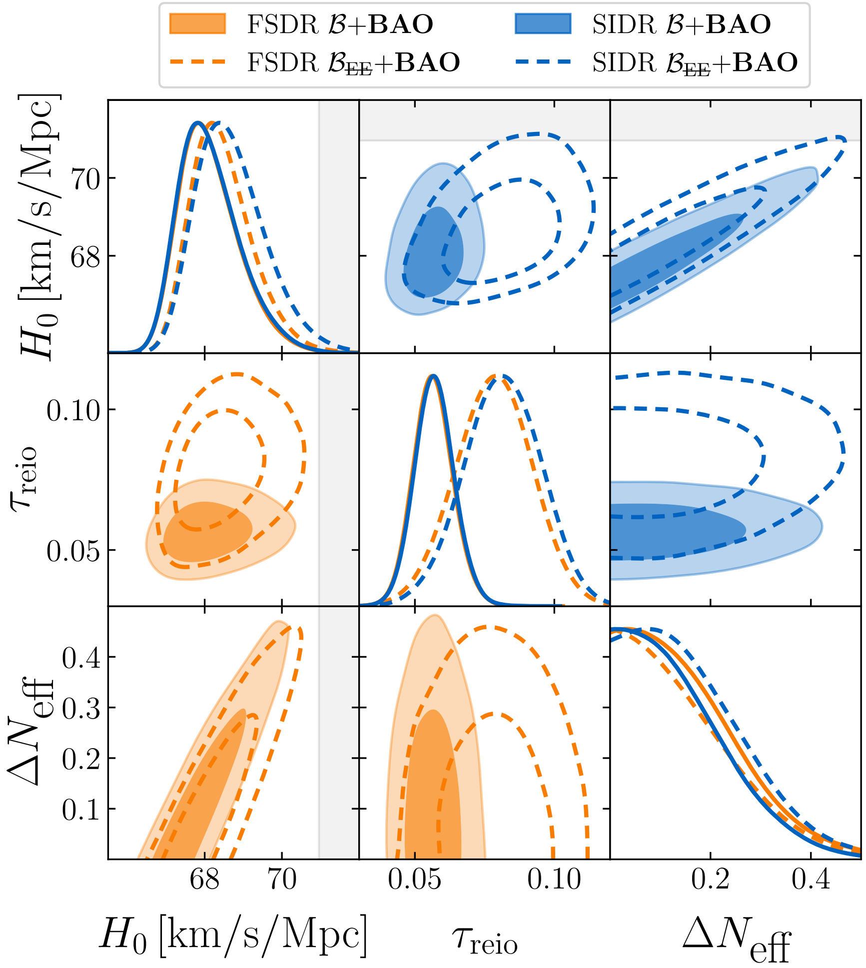
Results: DR Models



	H_0 (Tension)
FSDR	
$\mathcal{B}$+BAO	$68.13^{+0.58}_{-0.92}$ (4.1σ)
	↓
$\mathcal{B}_{\not{\rm EE}}$+BAO	$68.45^{+0.60}_{-0.91}$ (3.8σ)
SIDR	
$\mathcal{B}$+BAO	$68.14^{+0.59}_{-0.94}$ (4.1σ)
	↓
$\mathcal{B}_{\not{\rm EE}}$+BAO	$68.69^{+0.69}_{-1.1}$ (3.5σ)