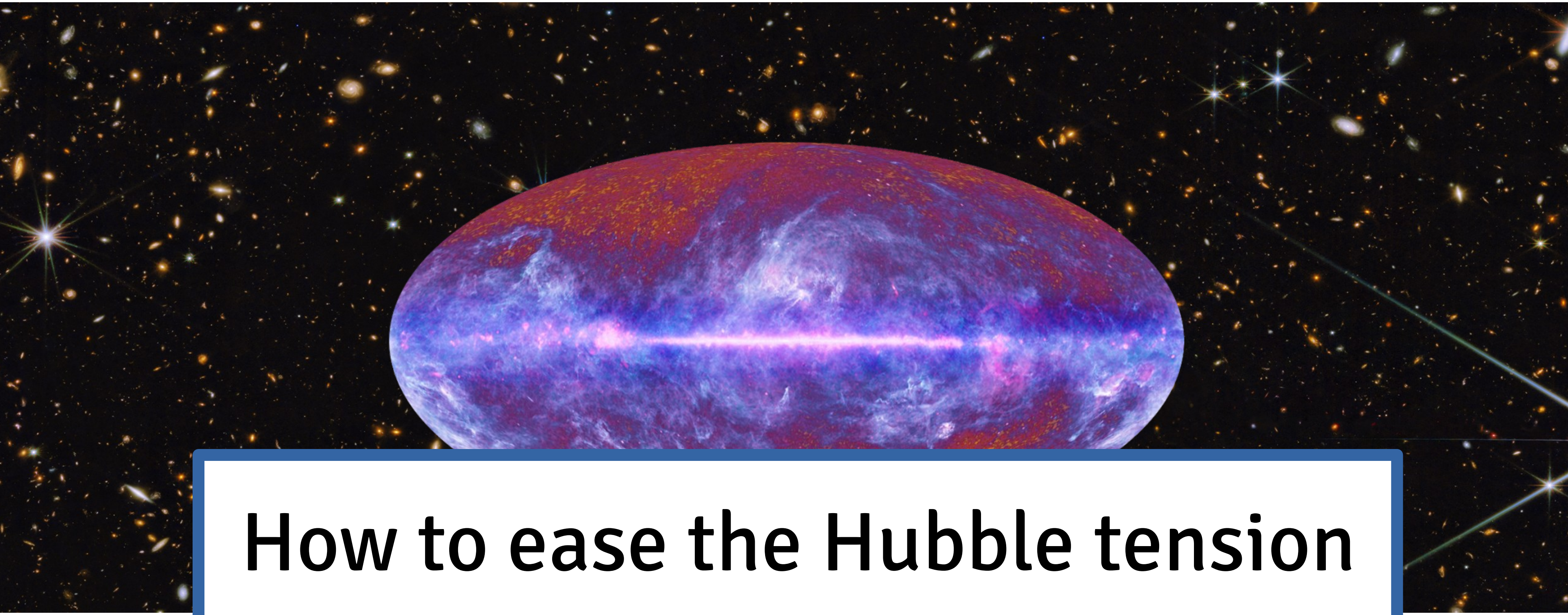
Nils Schöneberg

Florence, Monday 27.07.2026

nils.science@gmail.com

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN



How to ease the Hubble tension

https://plancksatellite.org.uk/science/ and https://science.nasa.gov/mission/webb/multimedia/images/#first-images

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Modified recombination is weird

Varying $m_e\,(+\;\Omega_k)$

(pass 3 of 3 tests)

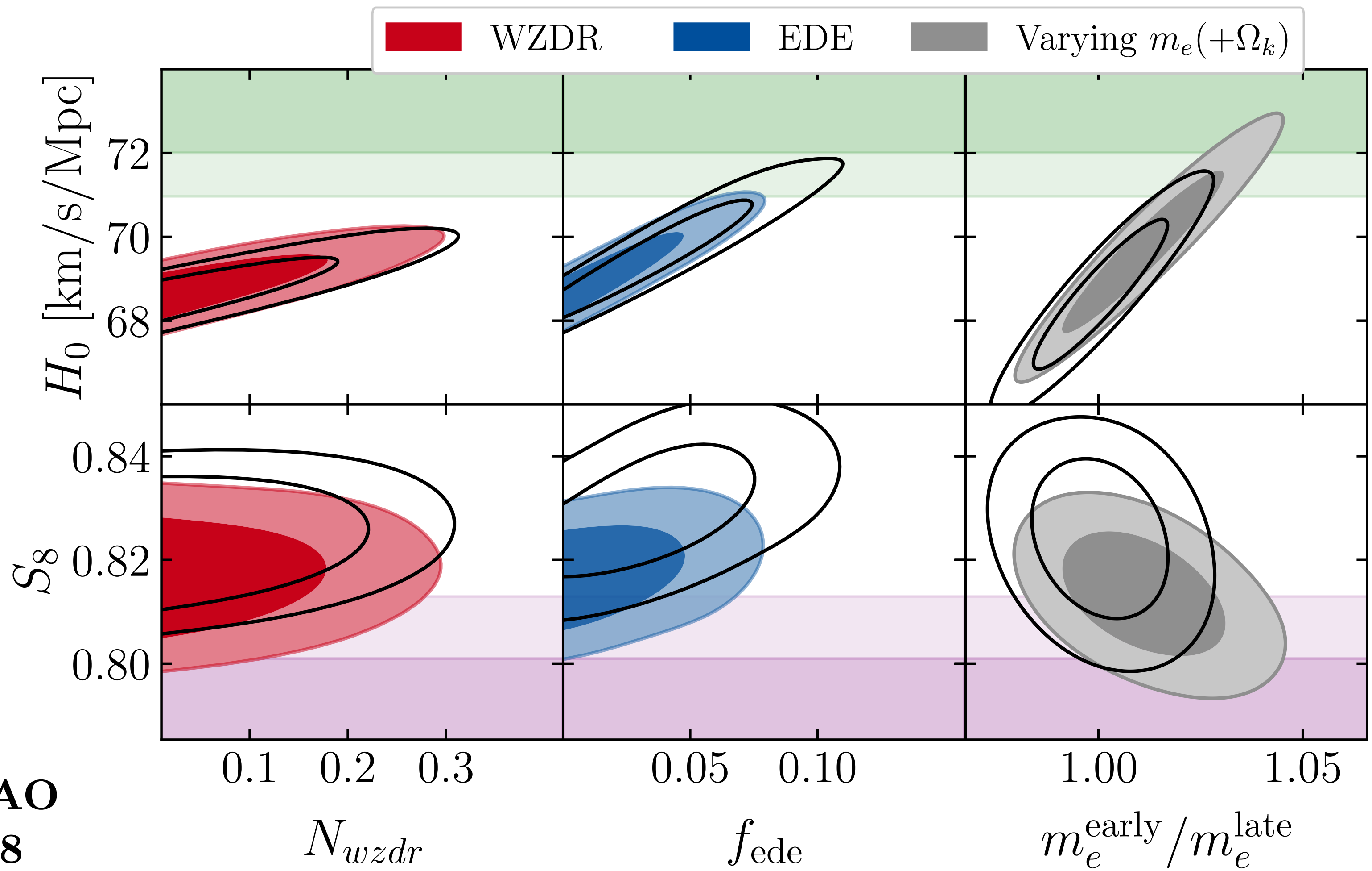
EDE, NEDE, EMG
Majoron, WZDR

(pass 2 of 3 tests)

Primordial B
SIDR

(pass 1 of 3 tests)

Modified recombination is weird



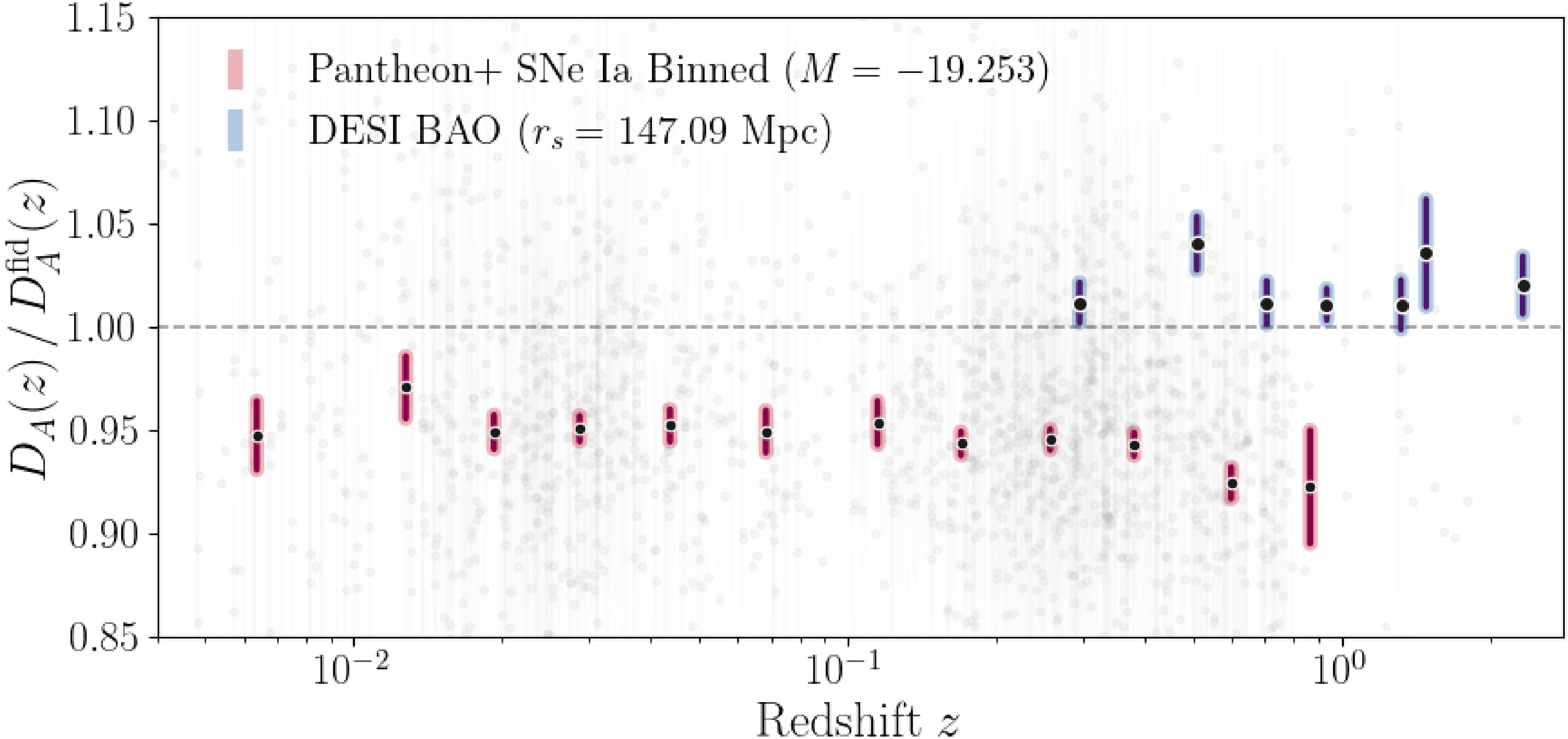
CMB+BAO +SN + S8

How does this model work?

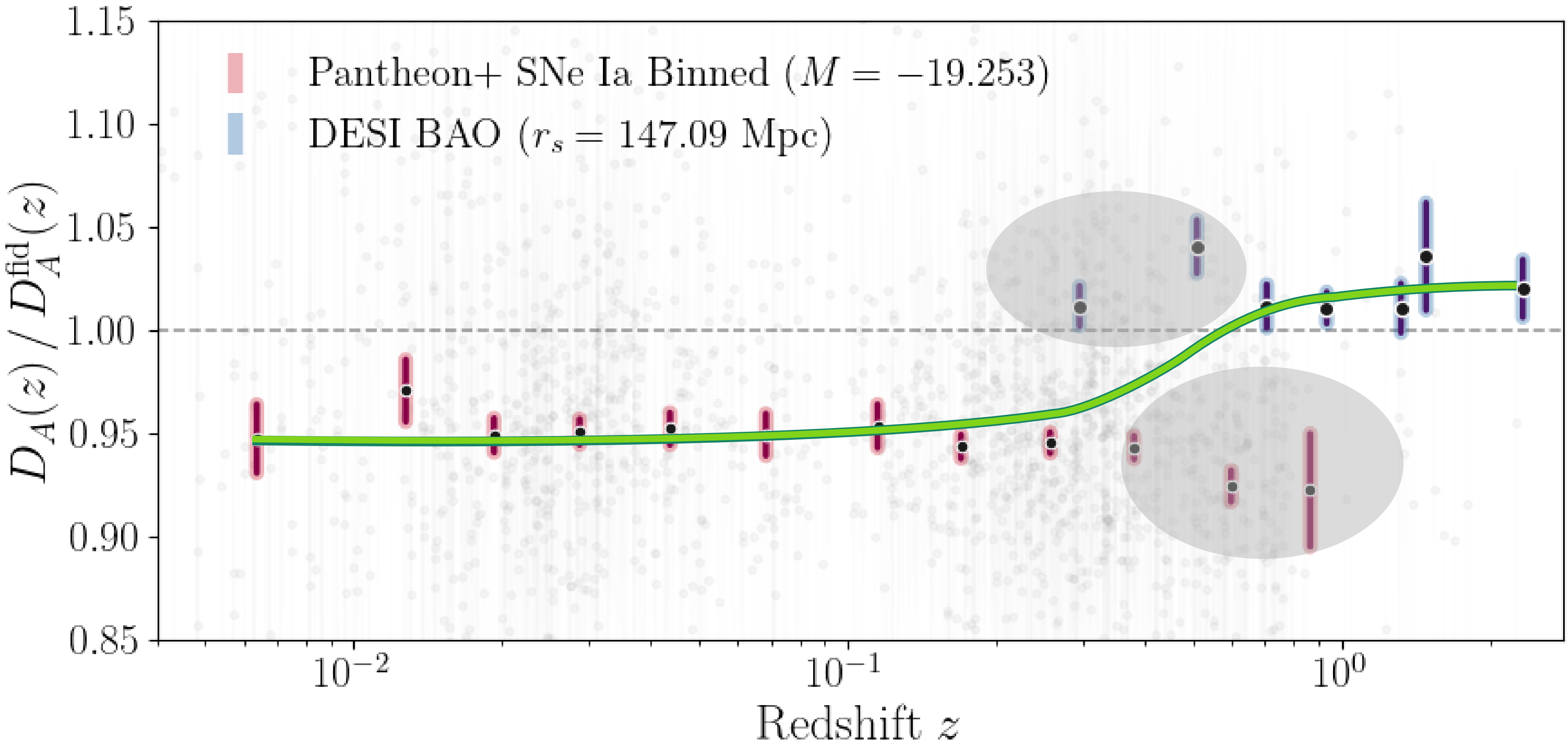
~~How does this model work?~~

How does *ANY* model work?

Cosmic calibrator tension



Cosmic calibrator tension



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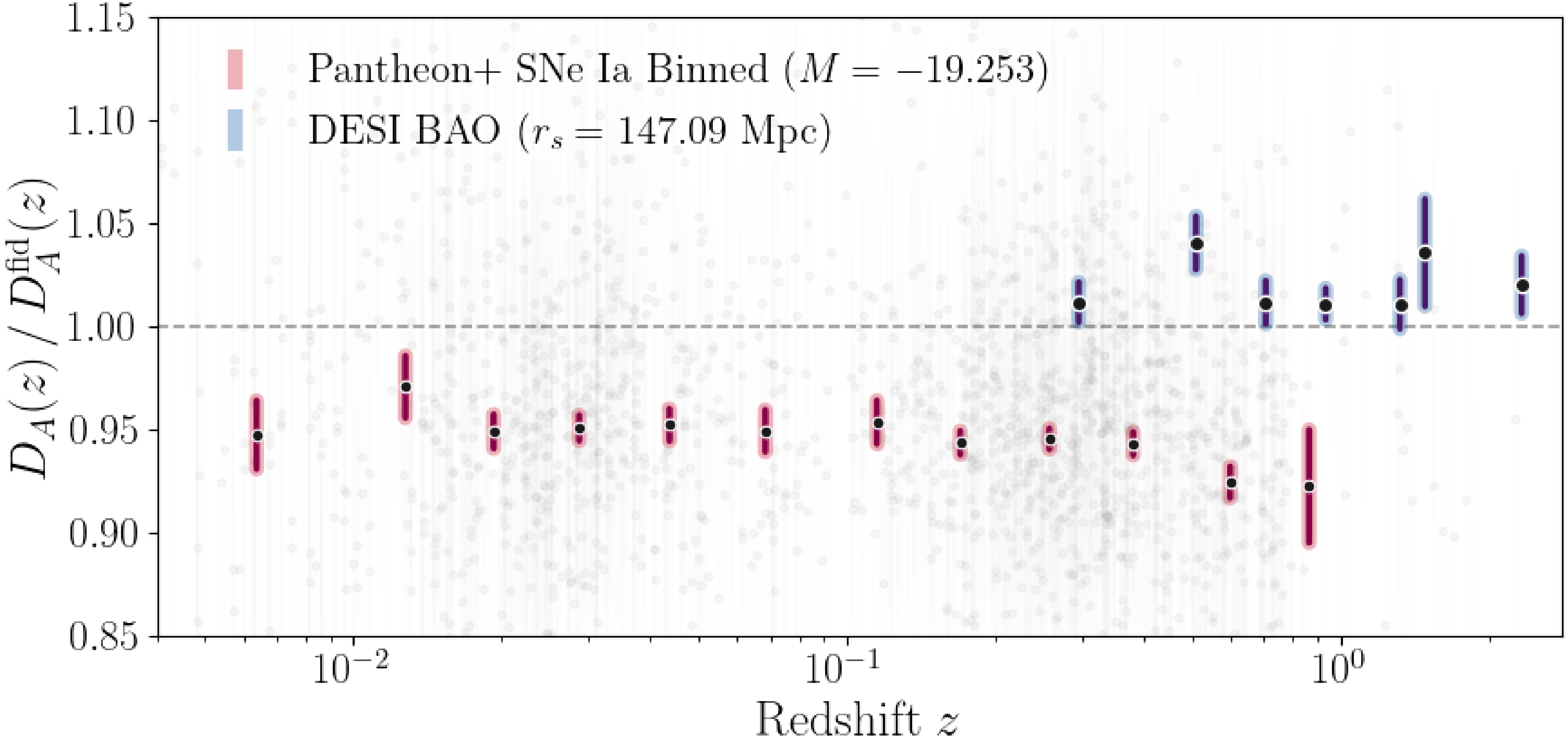
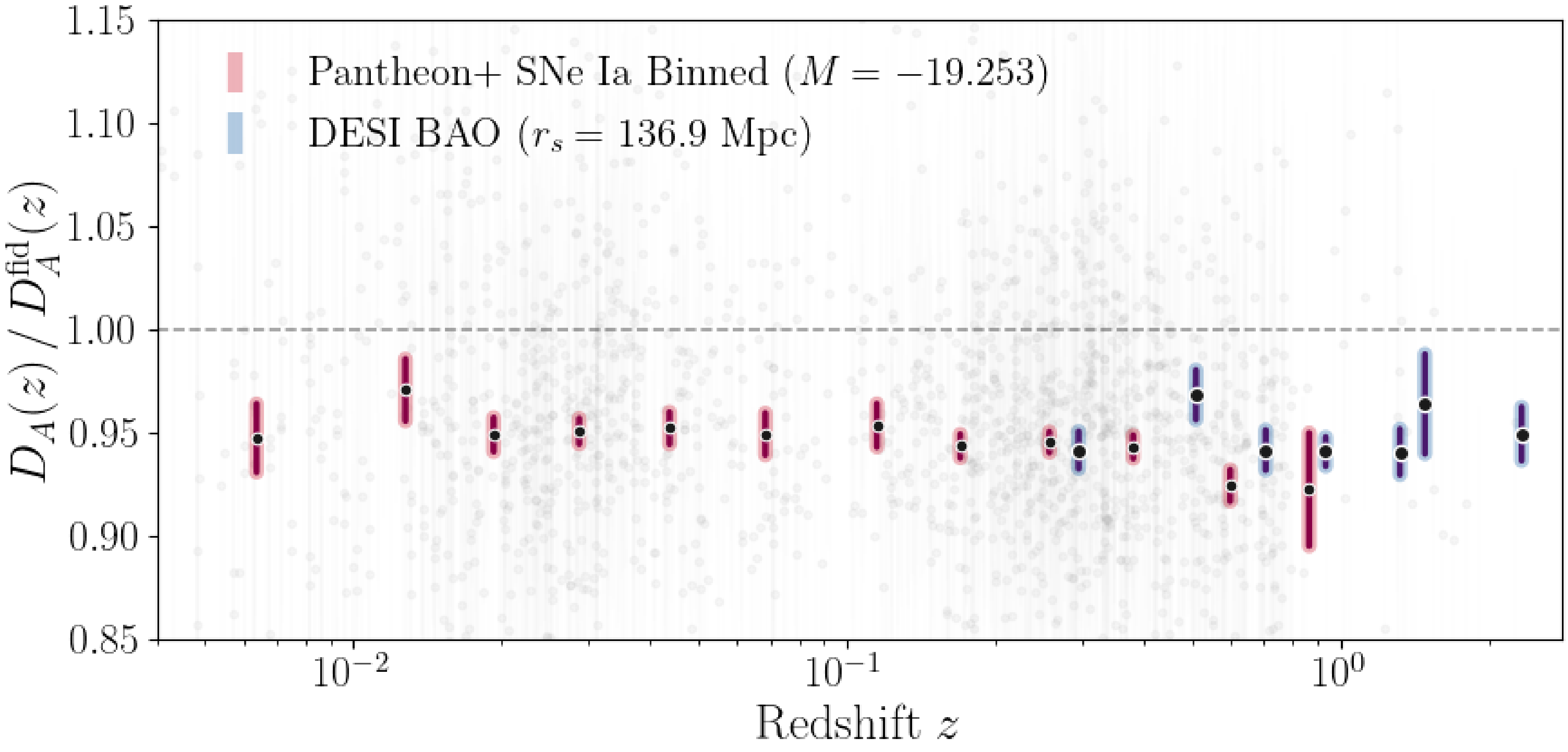
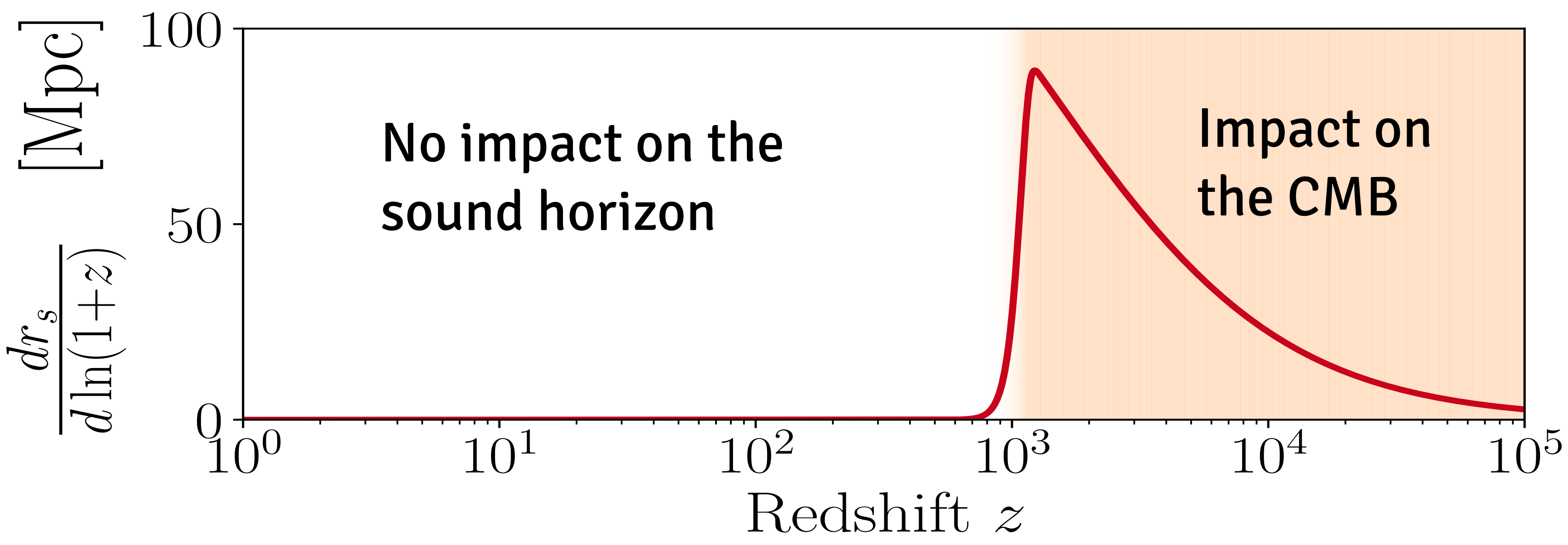


Cosmic calibrator tension



Cosmic calibrator tension

$$r_s = \int_{z_*}^{\infty} \frac{c_s(z)\mathrm{d}z}{H(z)}$$



Cosmic calibrator tension

$$r_s = \int_{z_*}^{\infty} \frac{\cancel{c_s(z)}\mathrm{d}z}{H(z)}$$

Group M

Groups R+E

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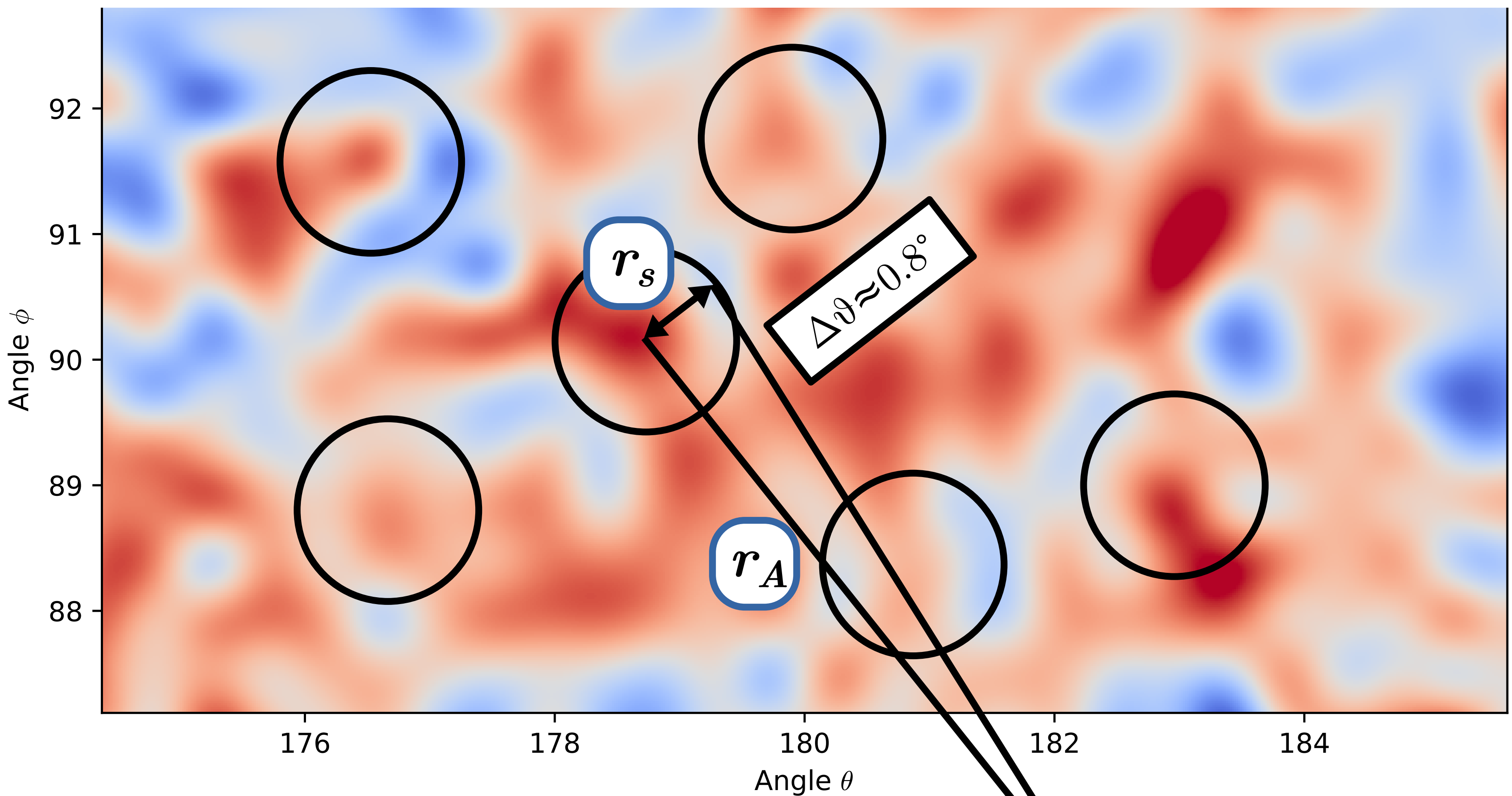
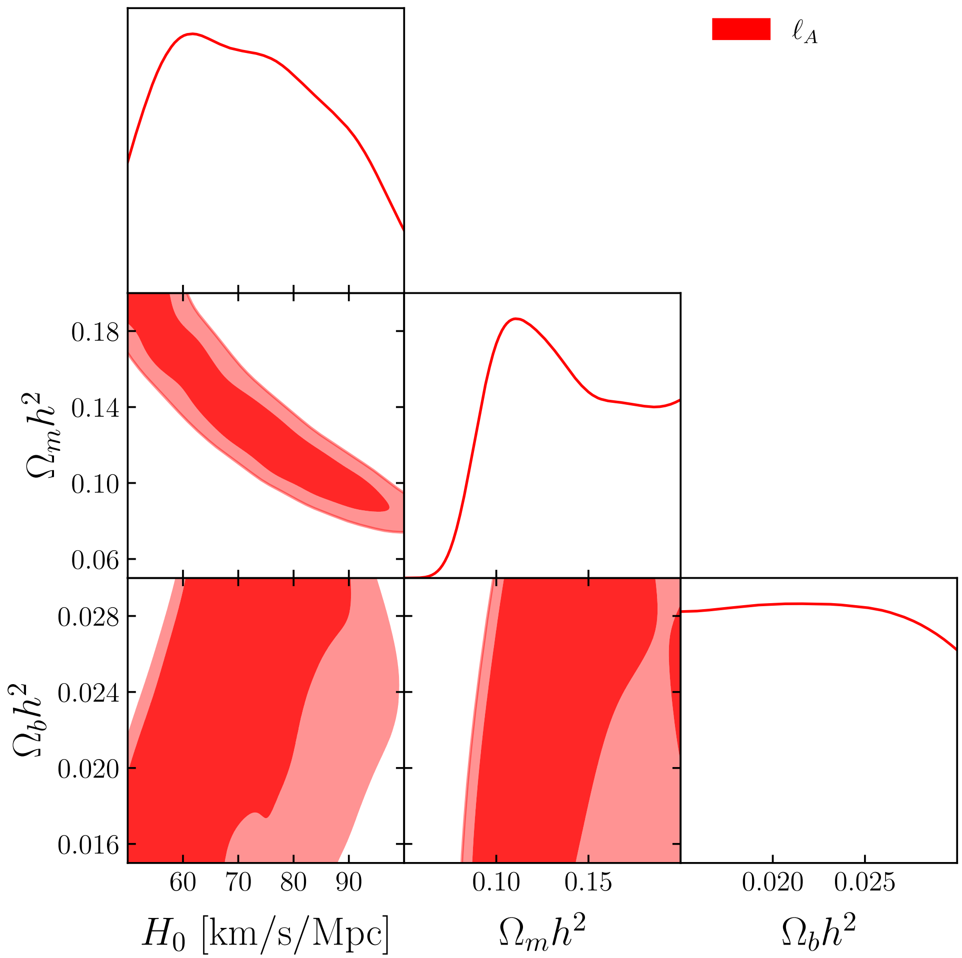
The CMB Anisotropies



$$\theta_s \approx r_s / r_A$$
$$r_A \propto H_0^{-1}$$

If you only had that scale...



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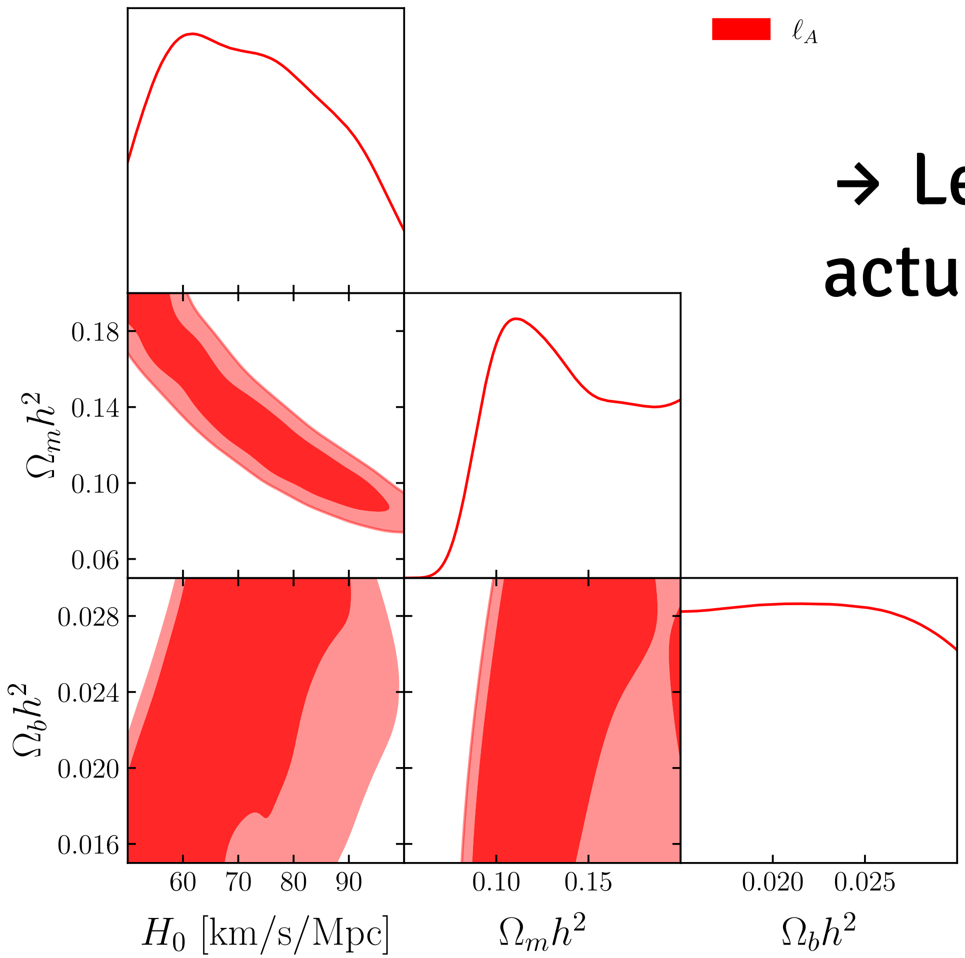
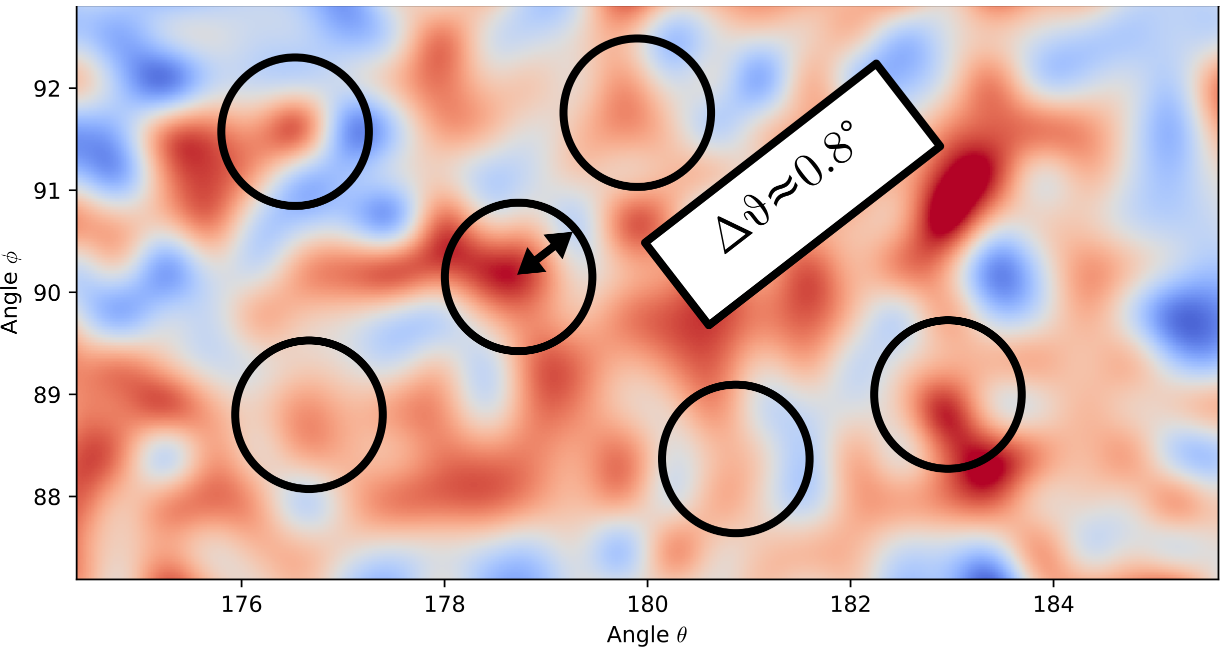
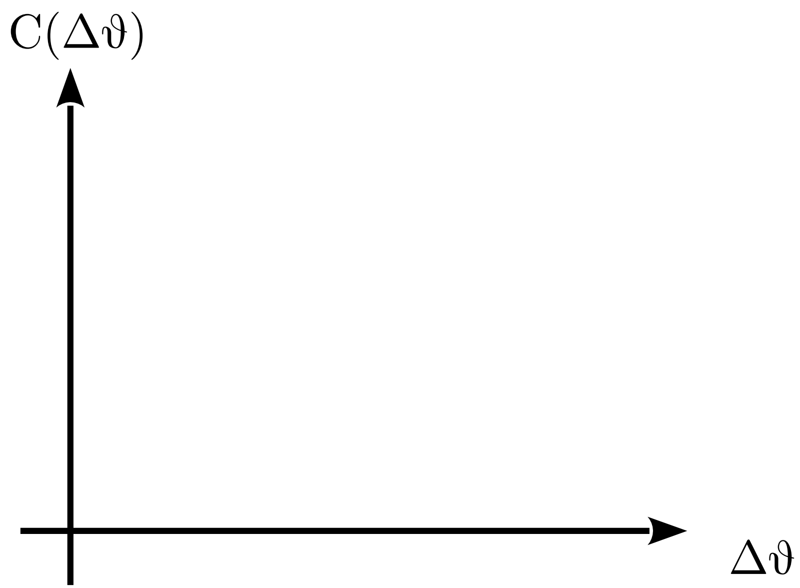


→ Let's see how it's actually done!

The CMB Anisotropies





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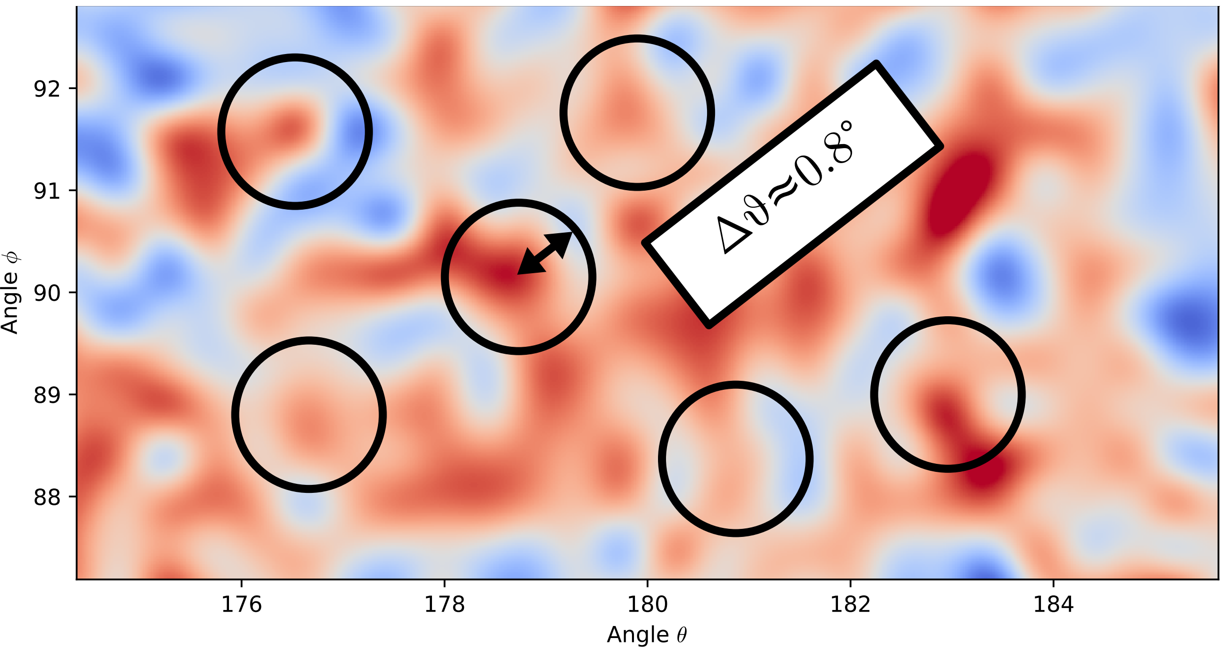

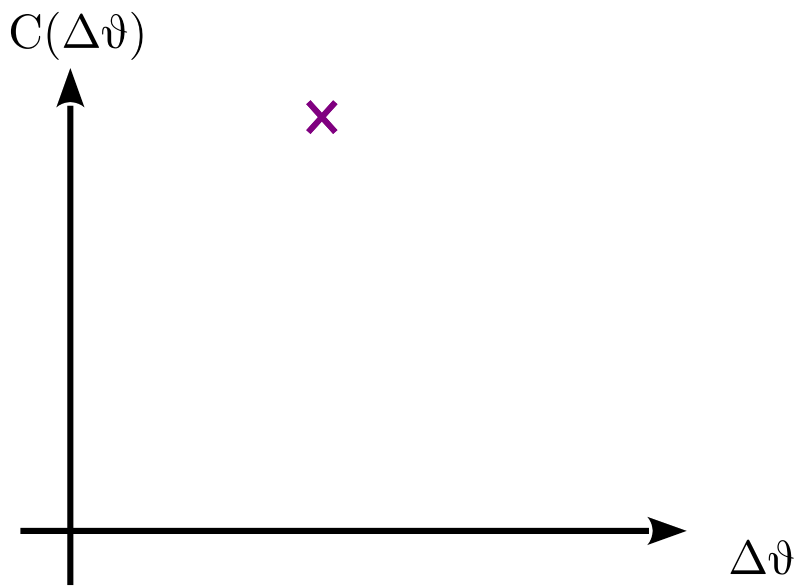

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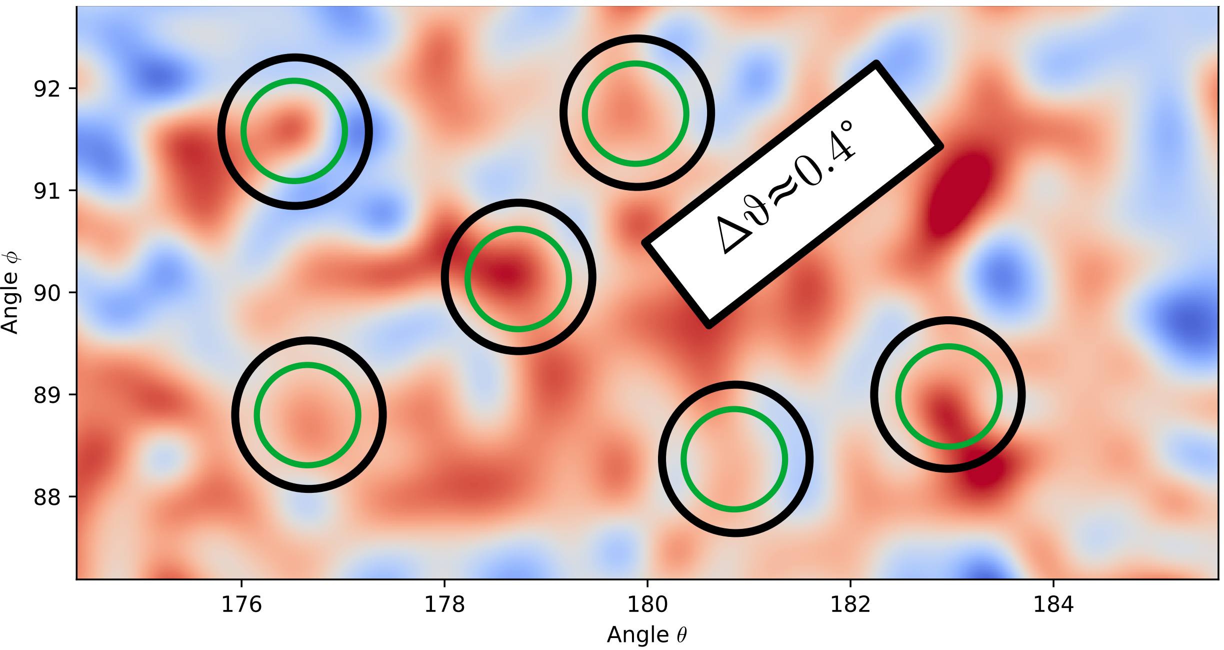

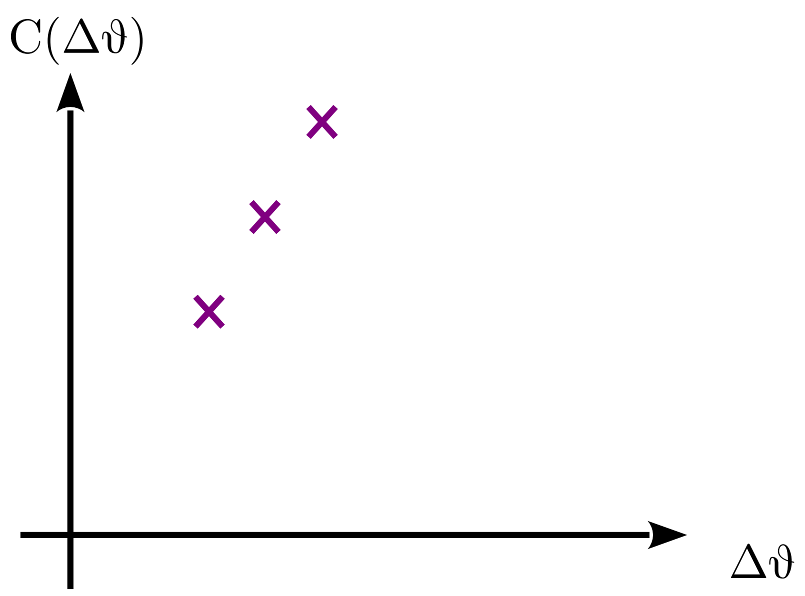

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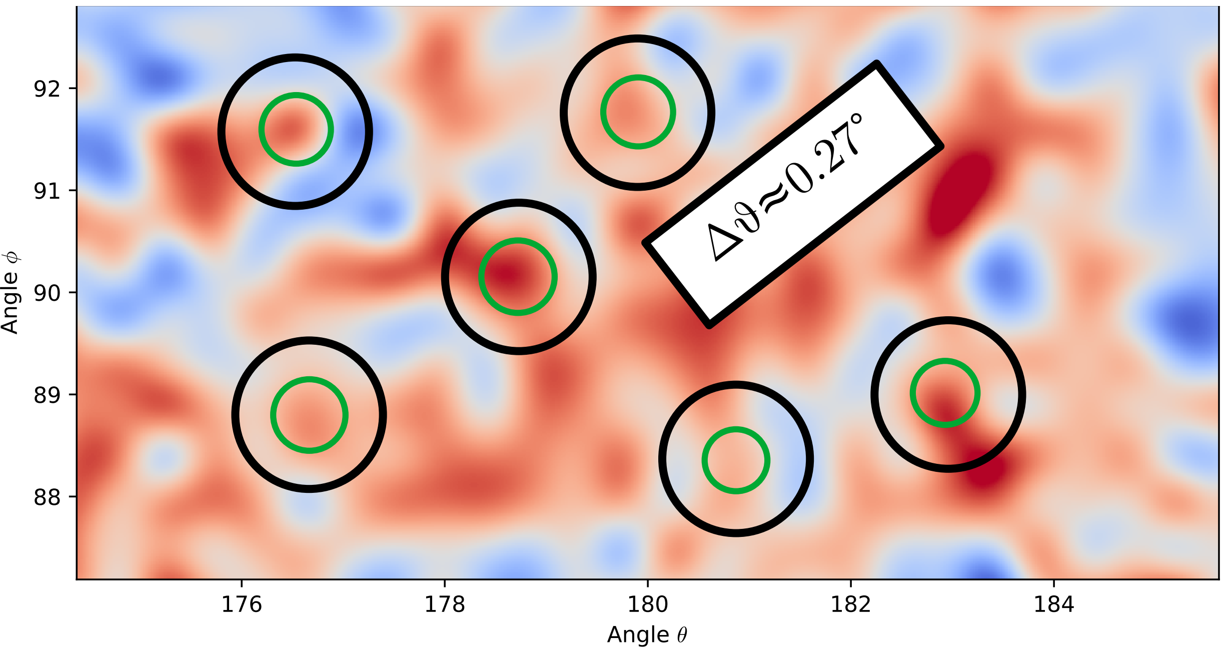
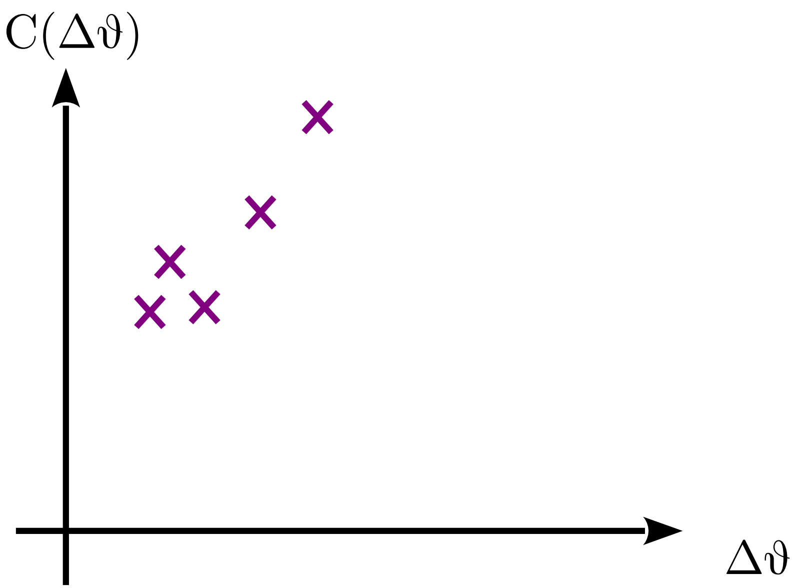
The CMB Anisotropies





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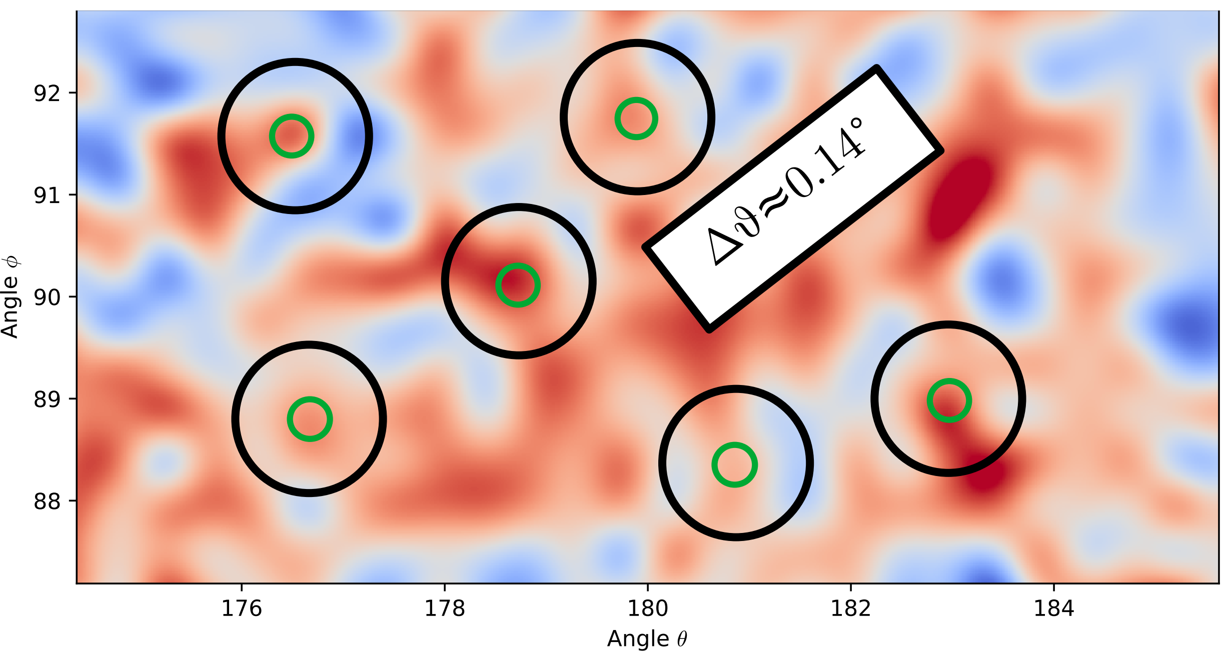

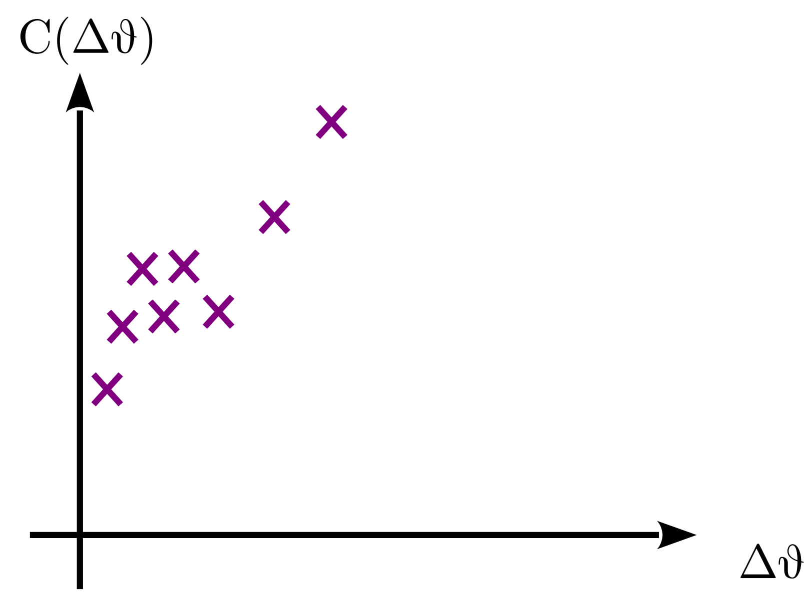

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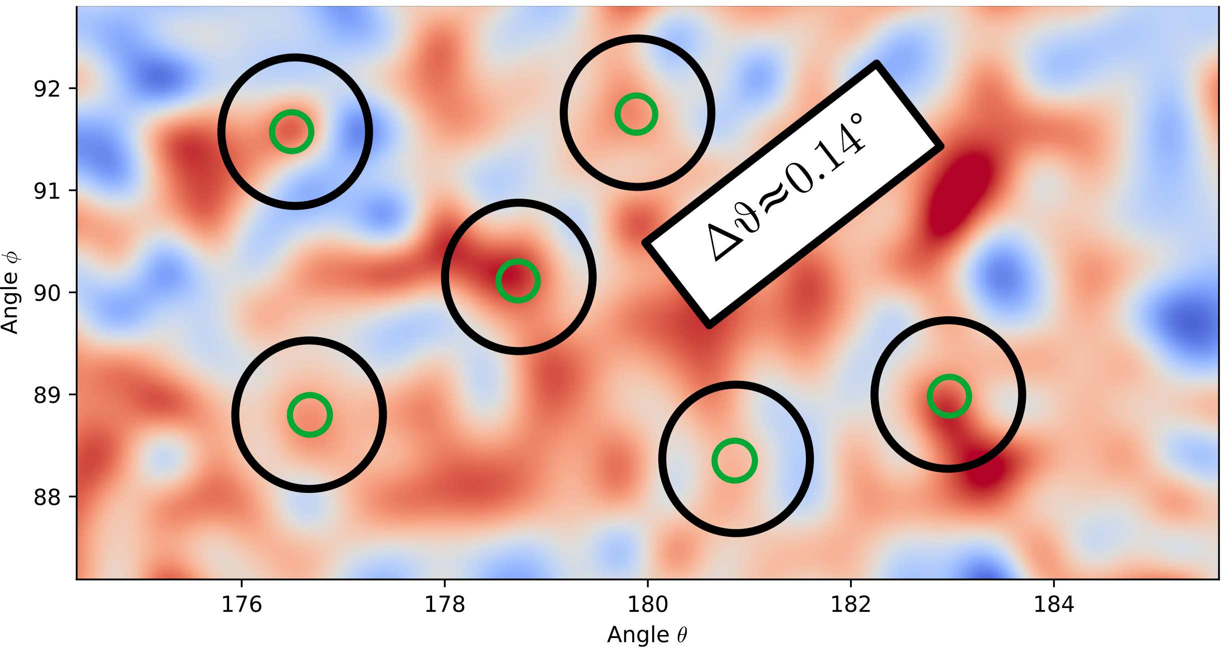
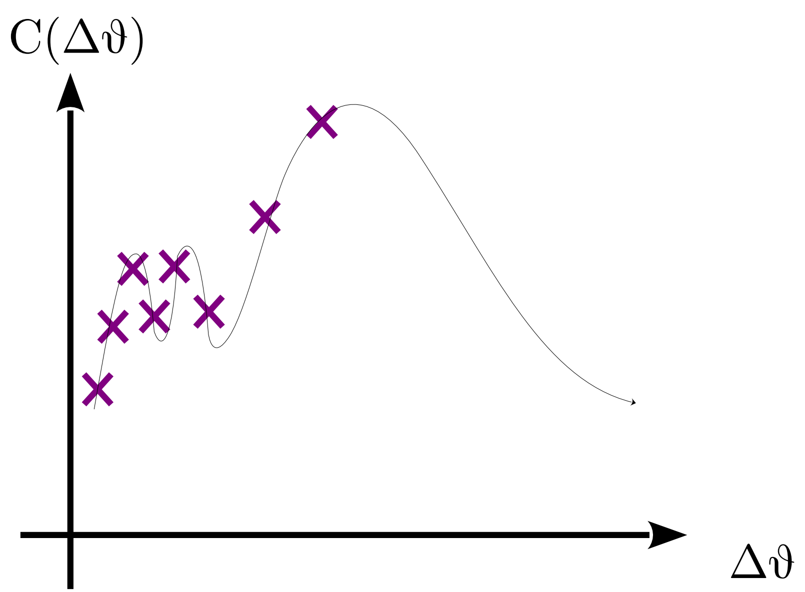
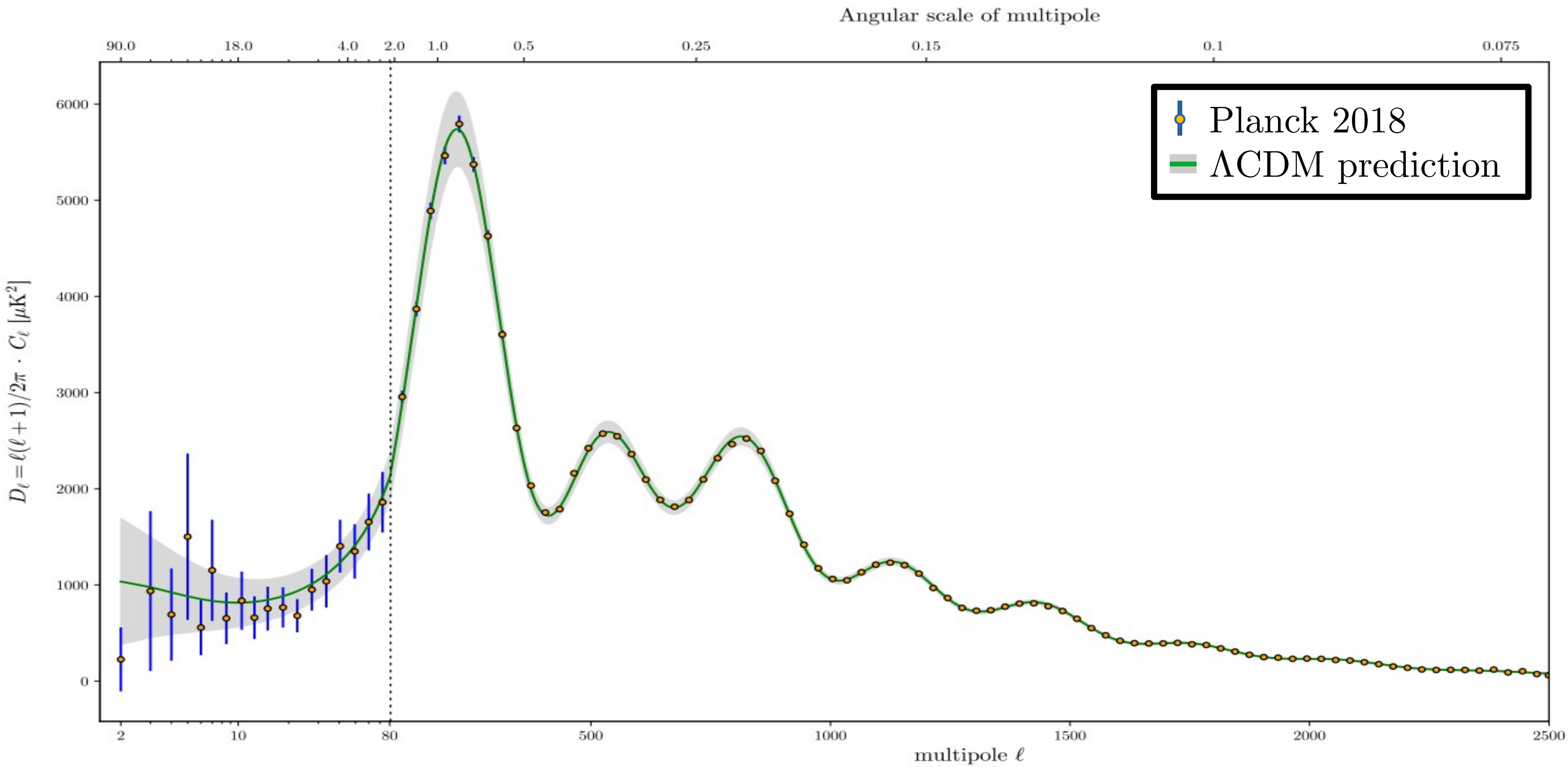


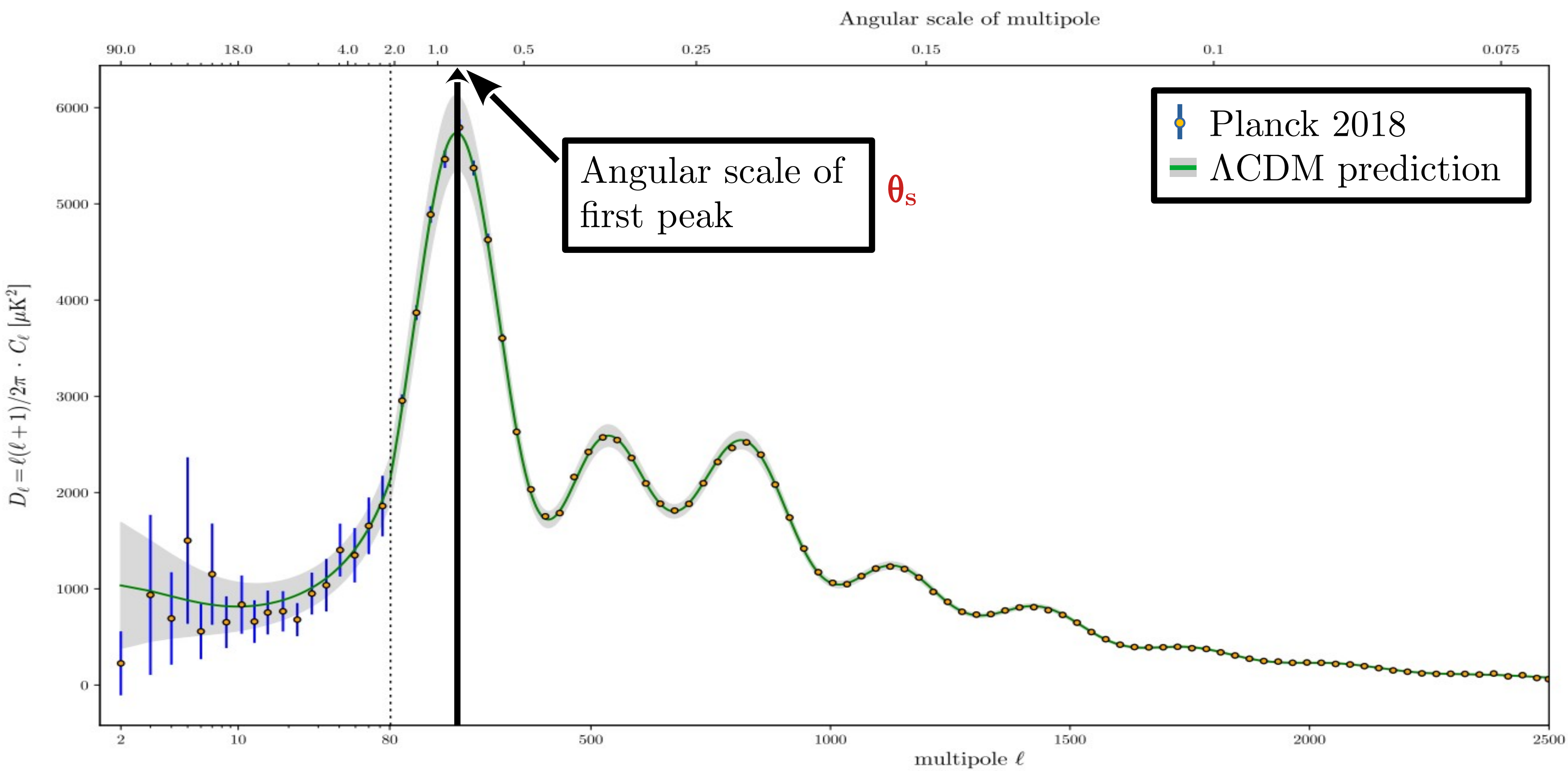


THE CMB



$$\ell \approx \pi/\Delta\vartheta$$

The CMB



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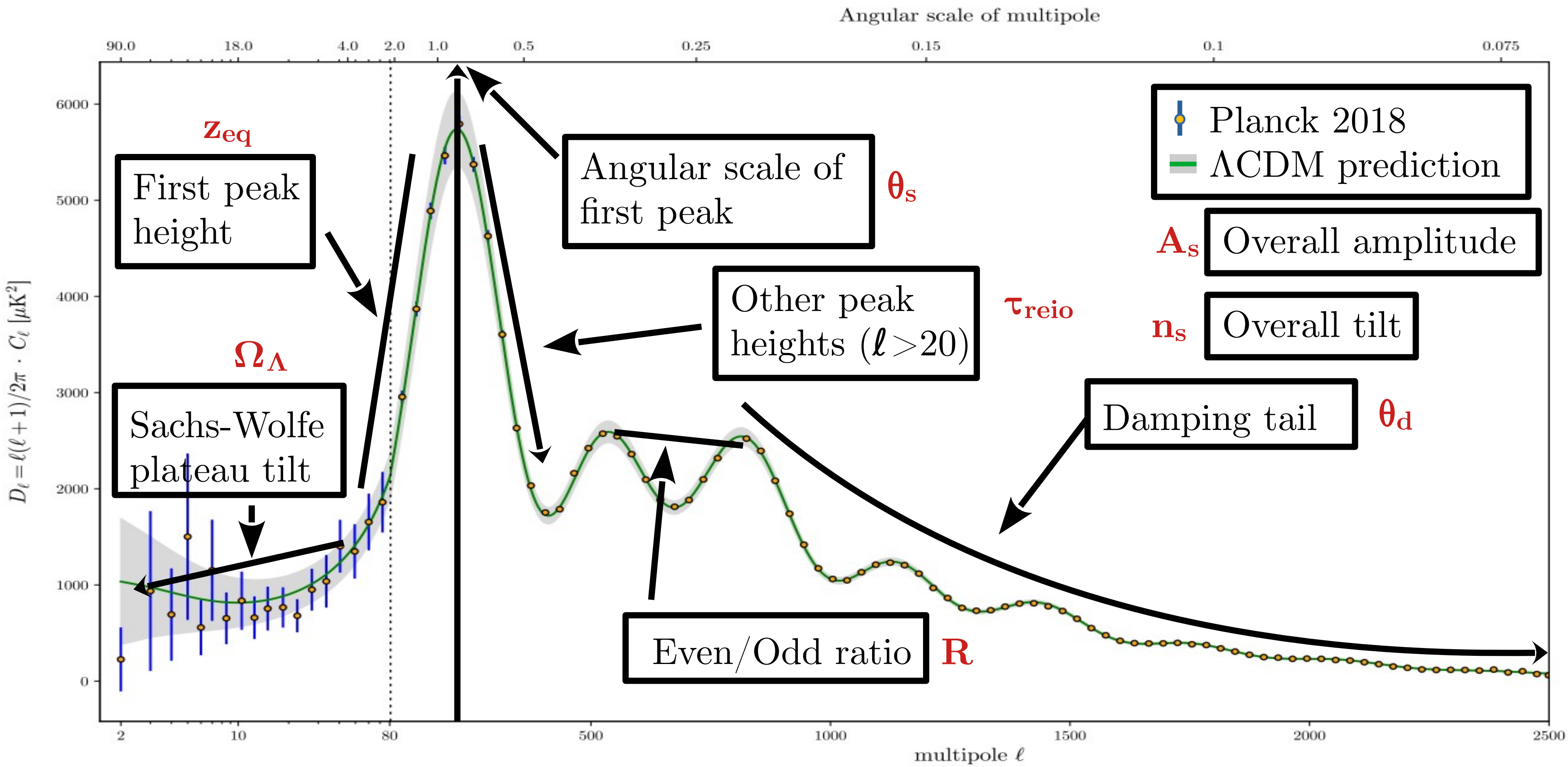

$\ell \approx \pi/\Delta\vartheta$

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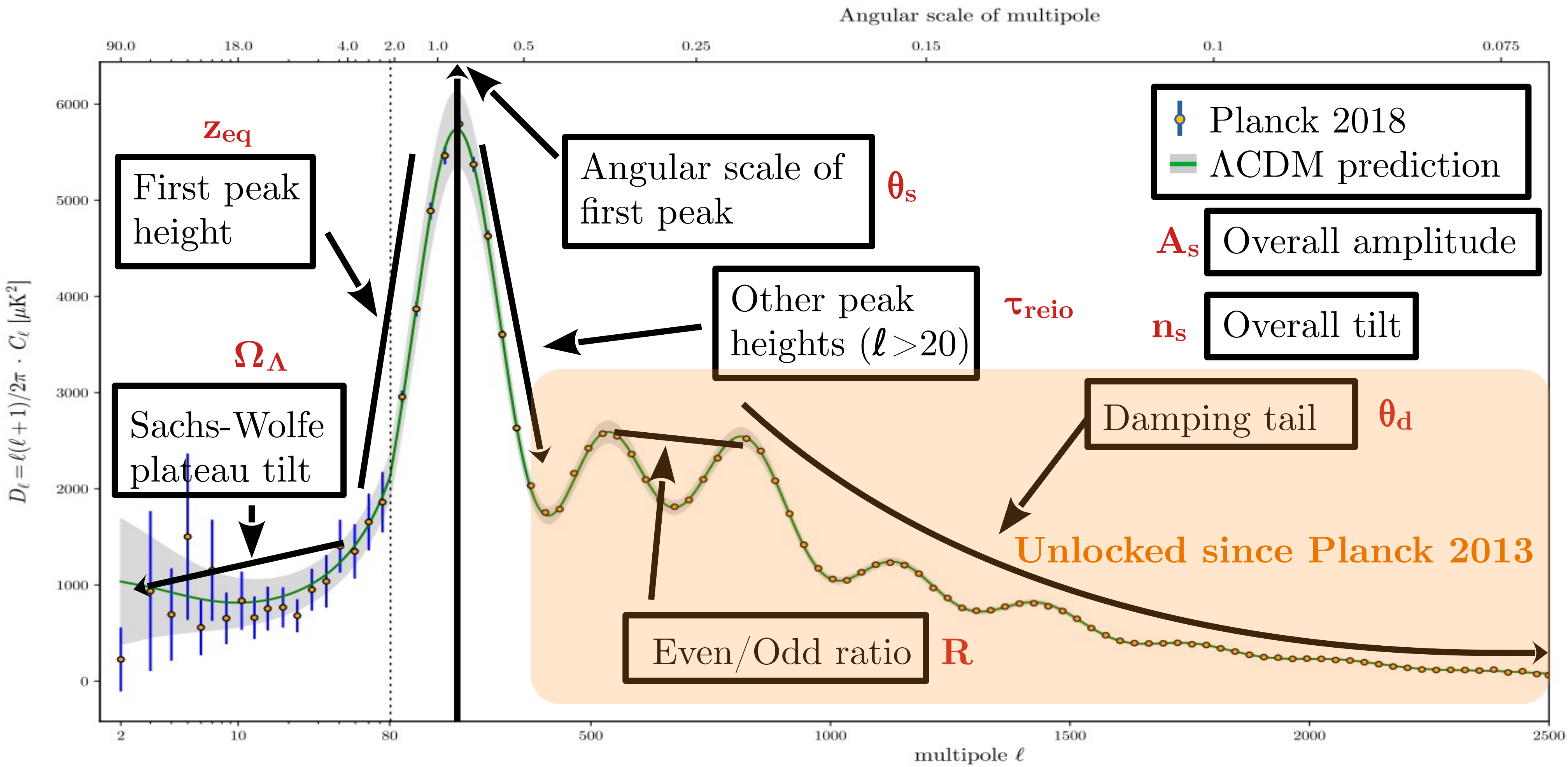

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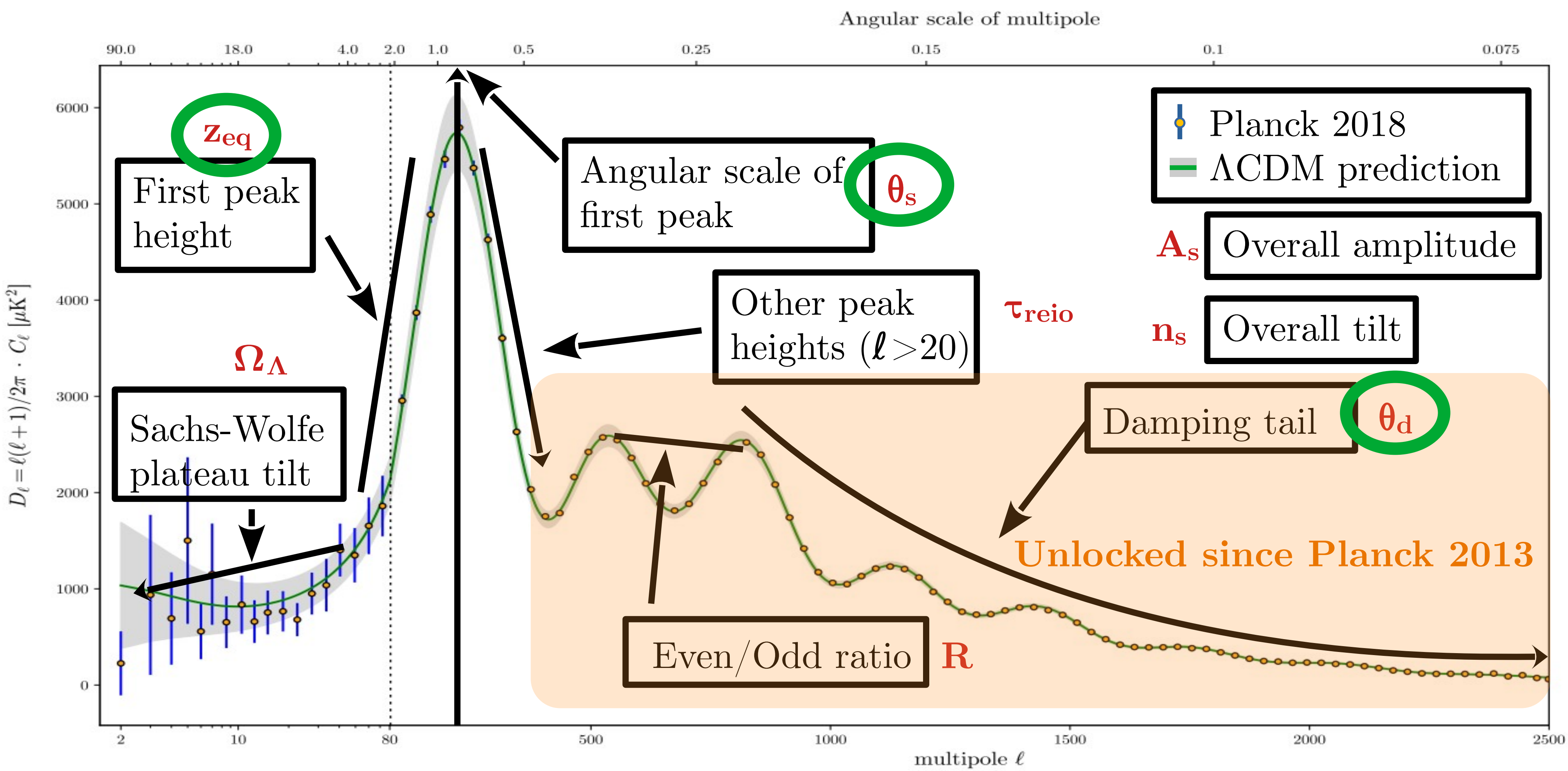
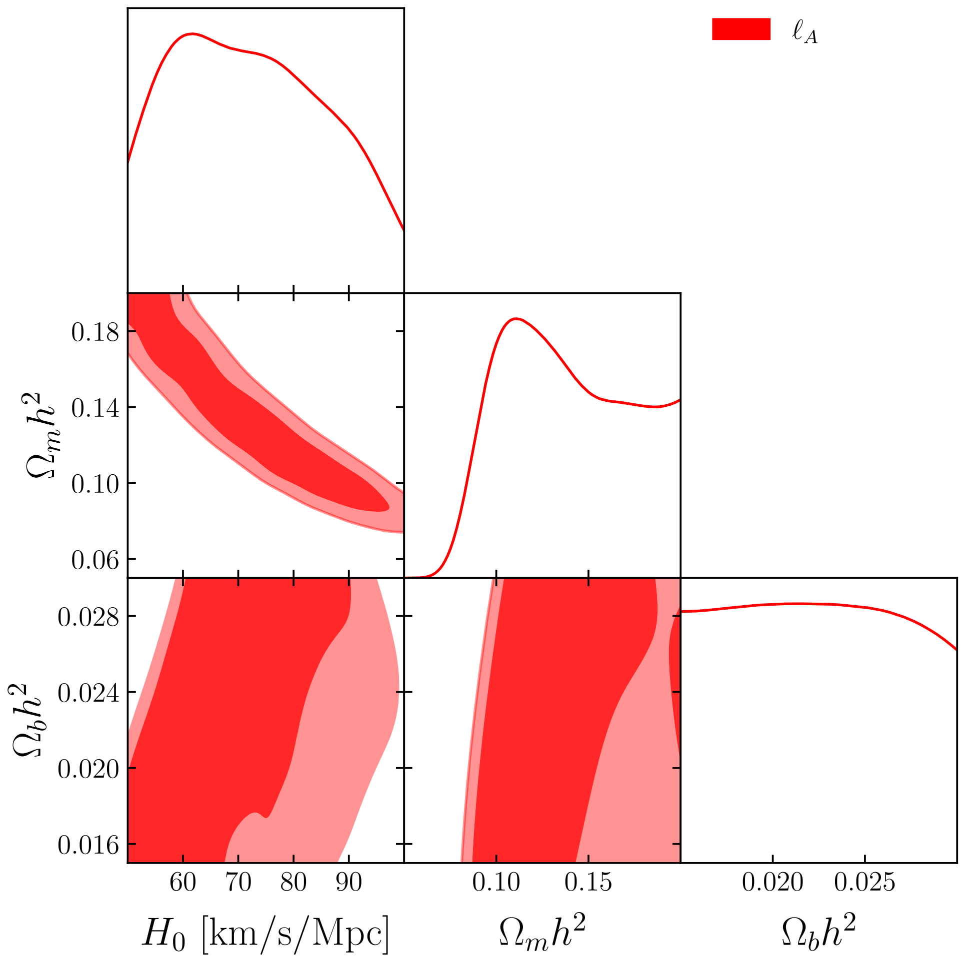


$\ell \approx \pi/\Delta\vartheta$

If you only had those scales...



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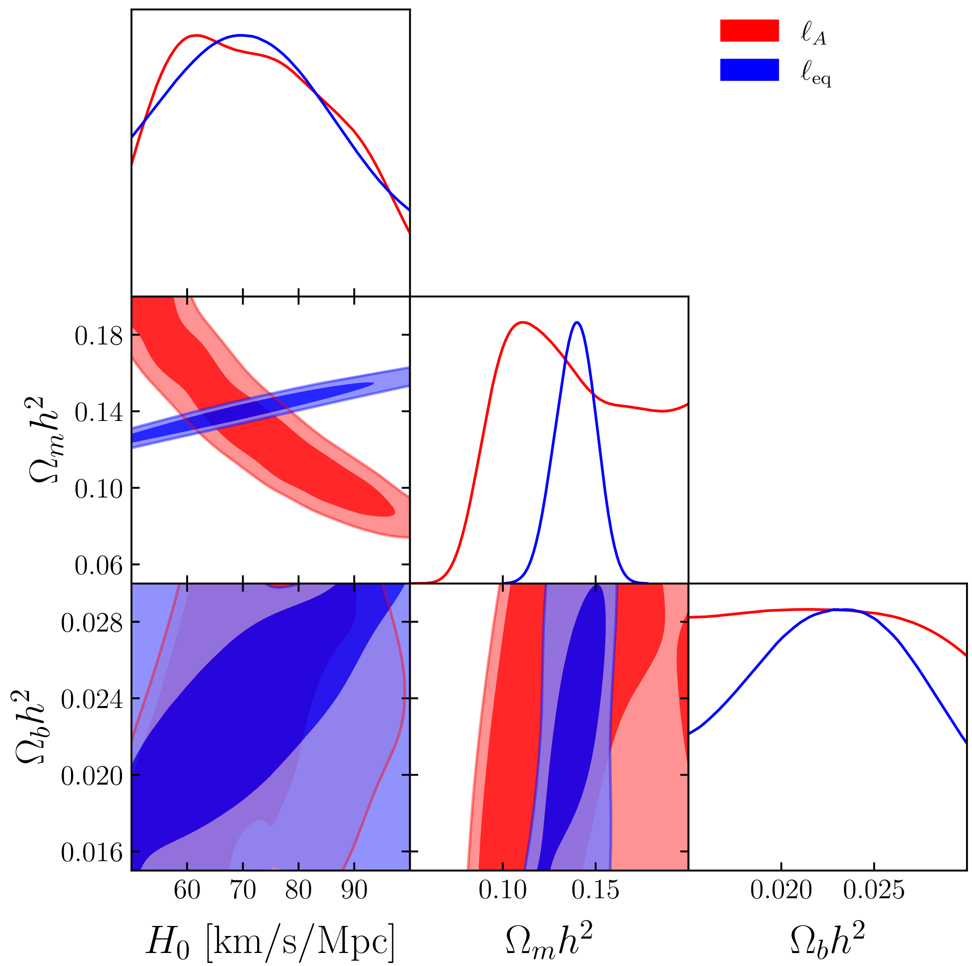

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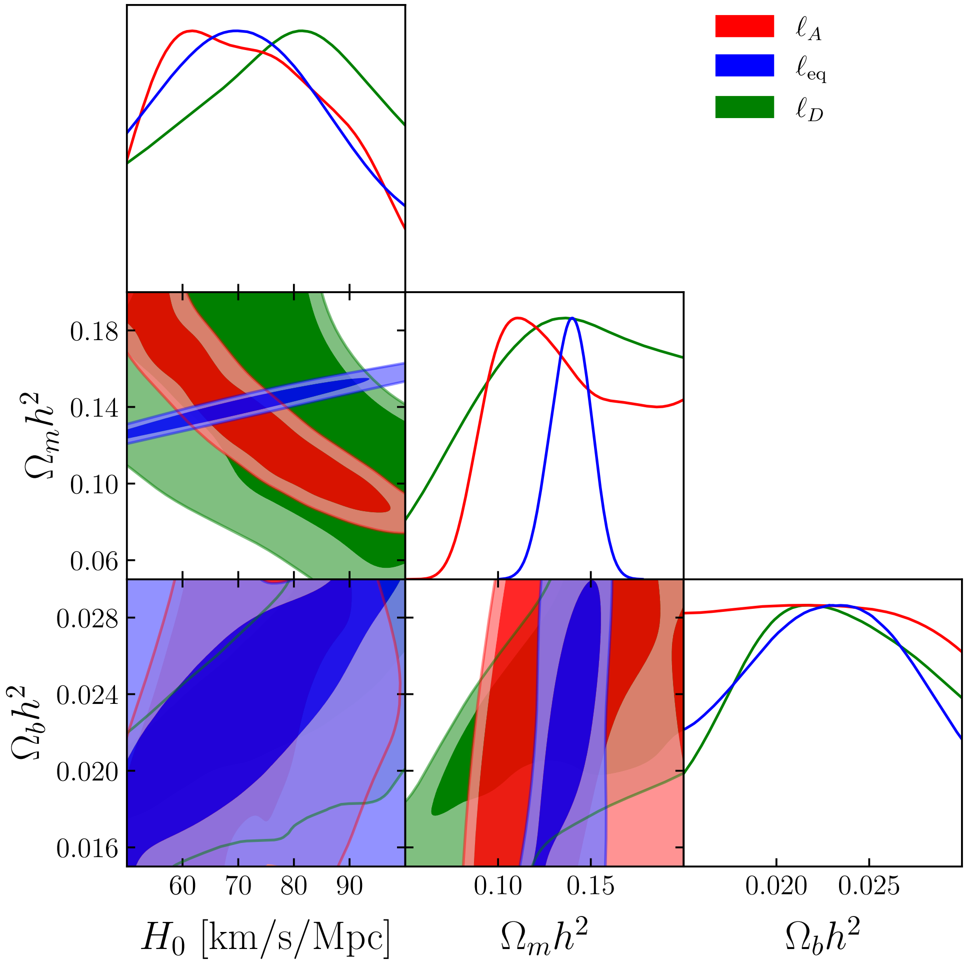

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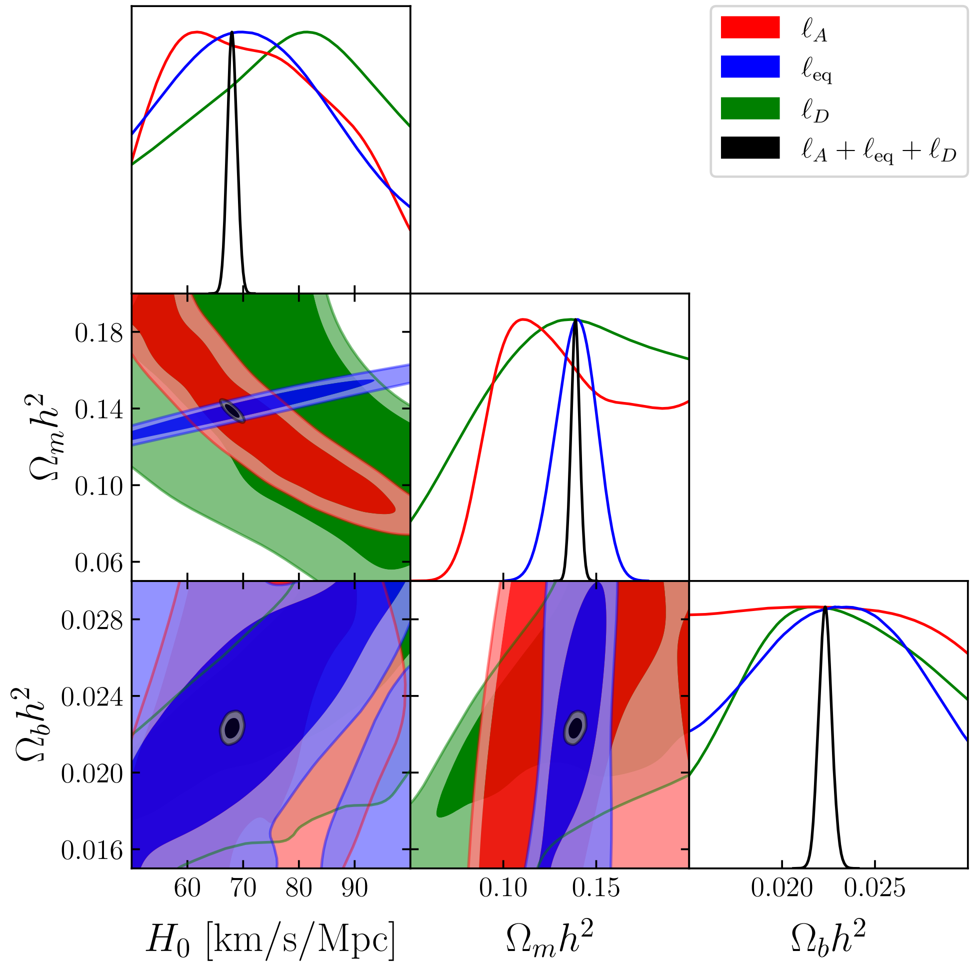

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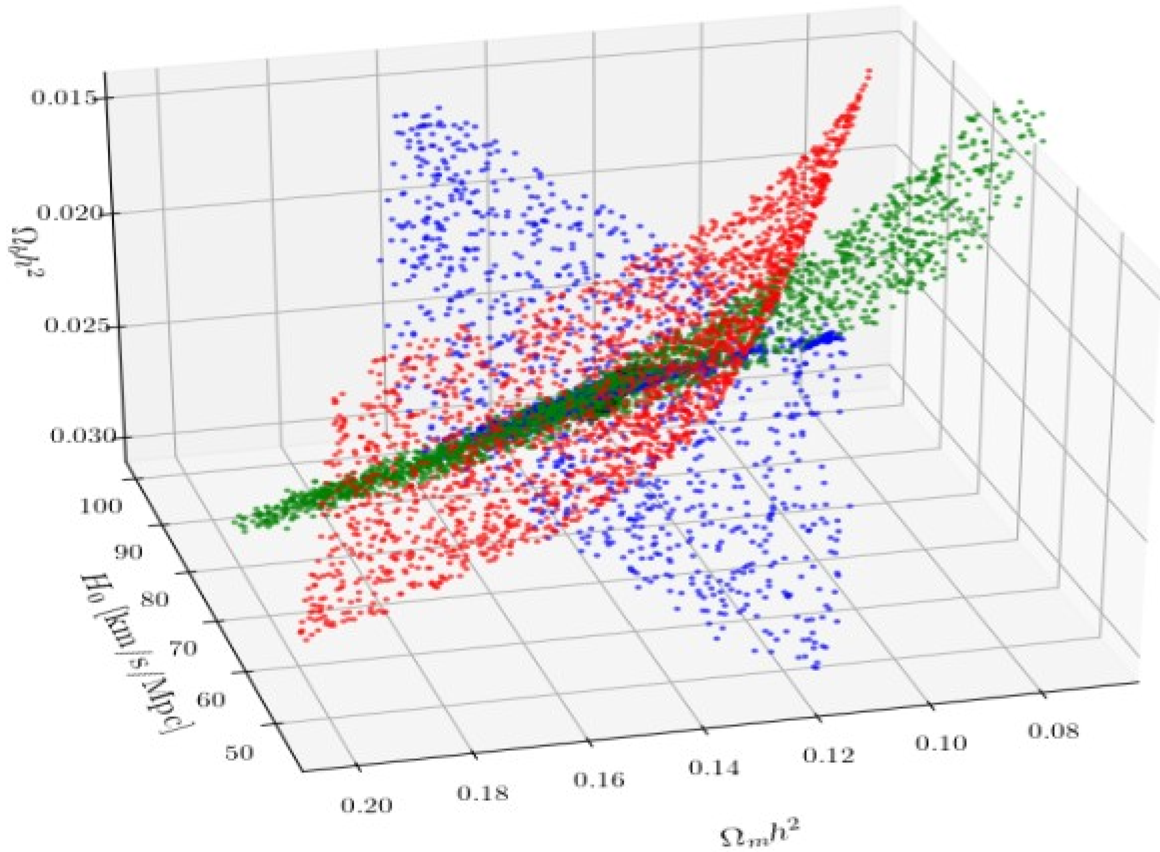

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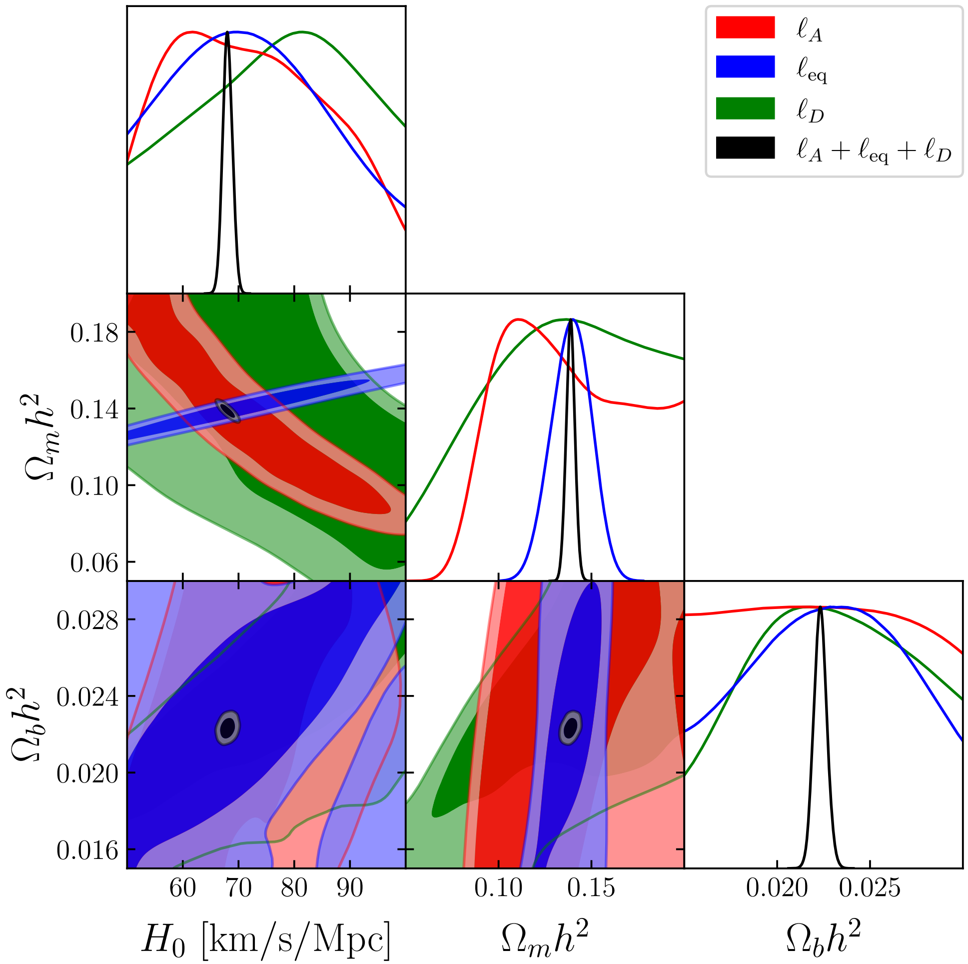

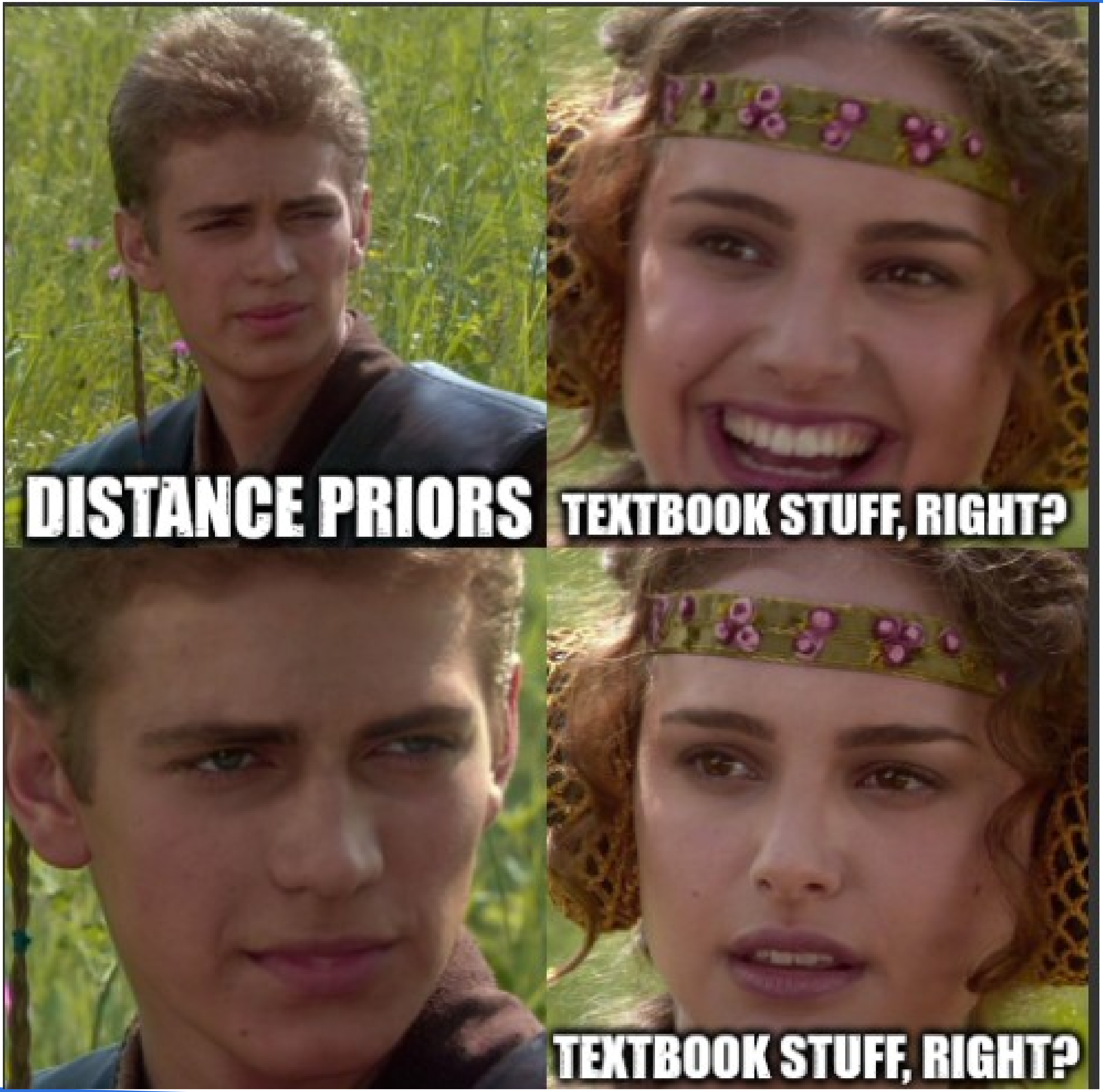
DISTANCE PRIORS
TEXTBOOK STUFF, RIGHT?
TEXTBOOK STUFF, RIGHT?

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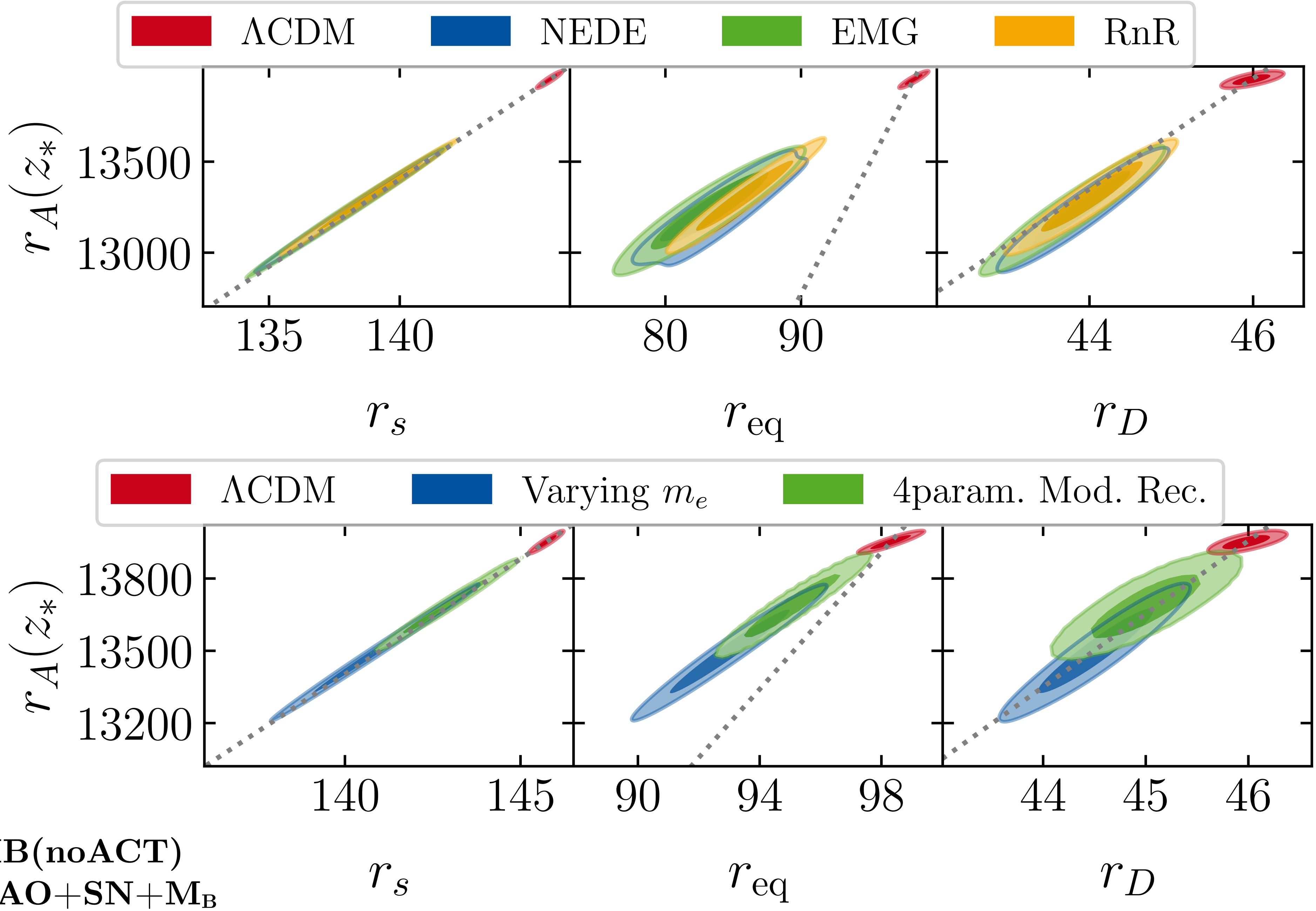
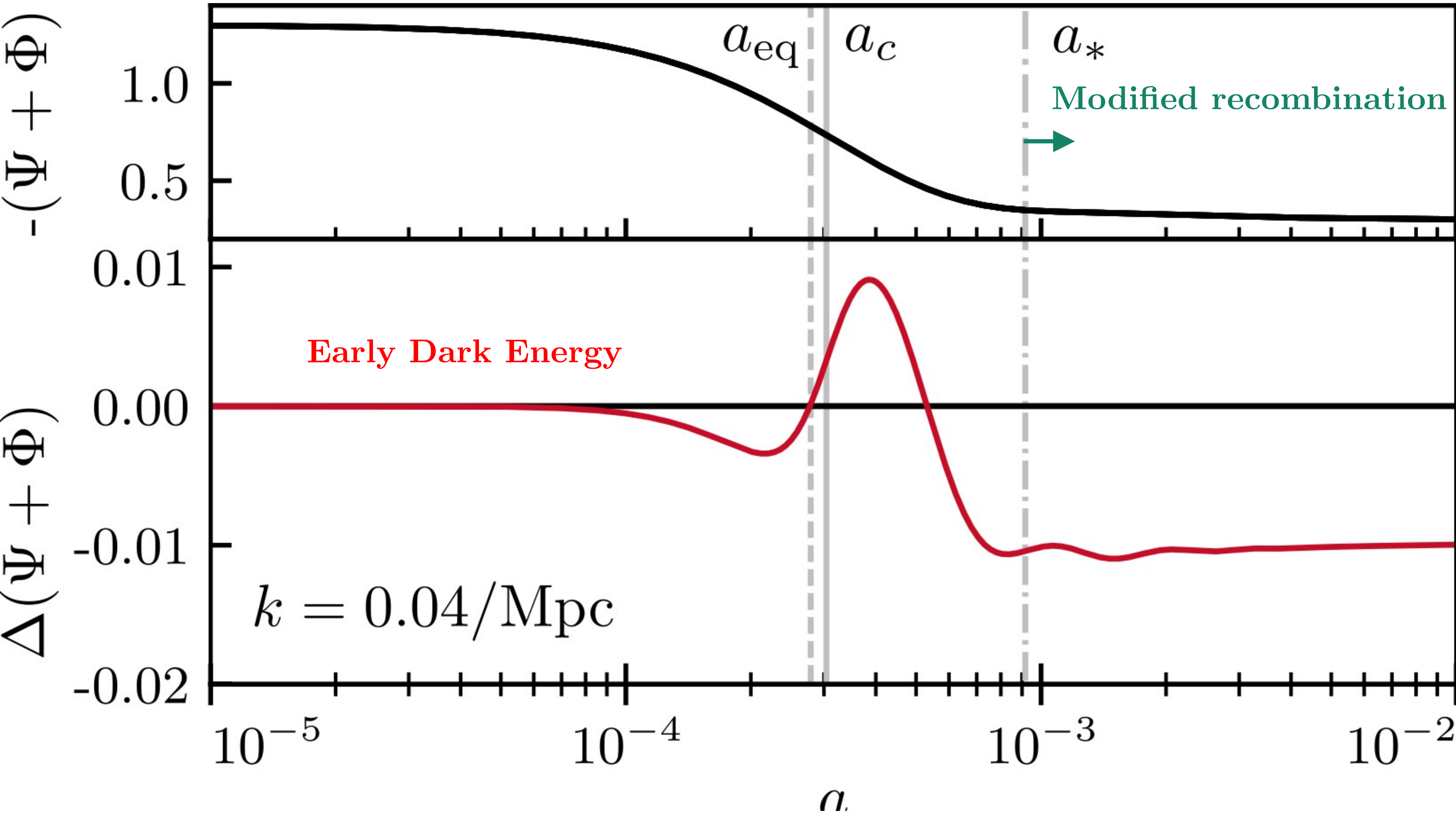


CMB(noACT)
+BAO+SN+M_B


-(Ψ + Φ)
1.0
0.5
a_{eq}
a_c
a_*
Modified recombination
0.01
0.00
-0.01
-0.02
Early Dark Energy
Δ(Ψ + Φ)
$k = 0.04/\mathrm{Mpc}$
10^{-5}
10^{-4}
10^{-3}
10^{-2}
a

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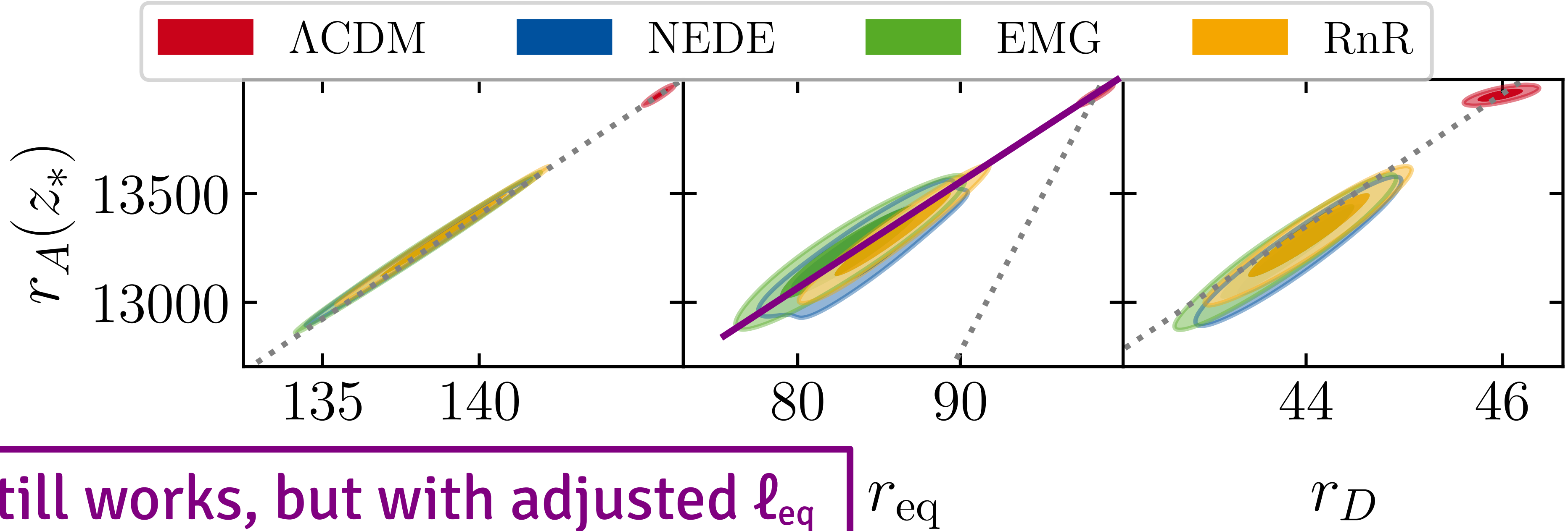
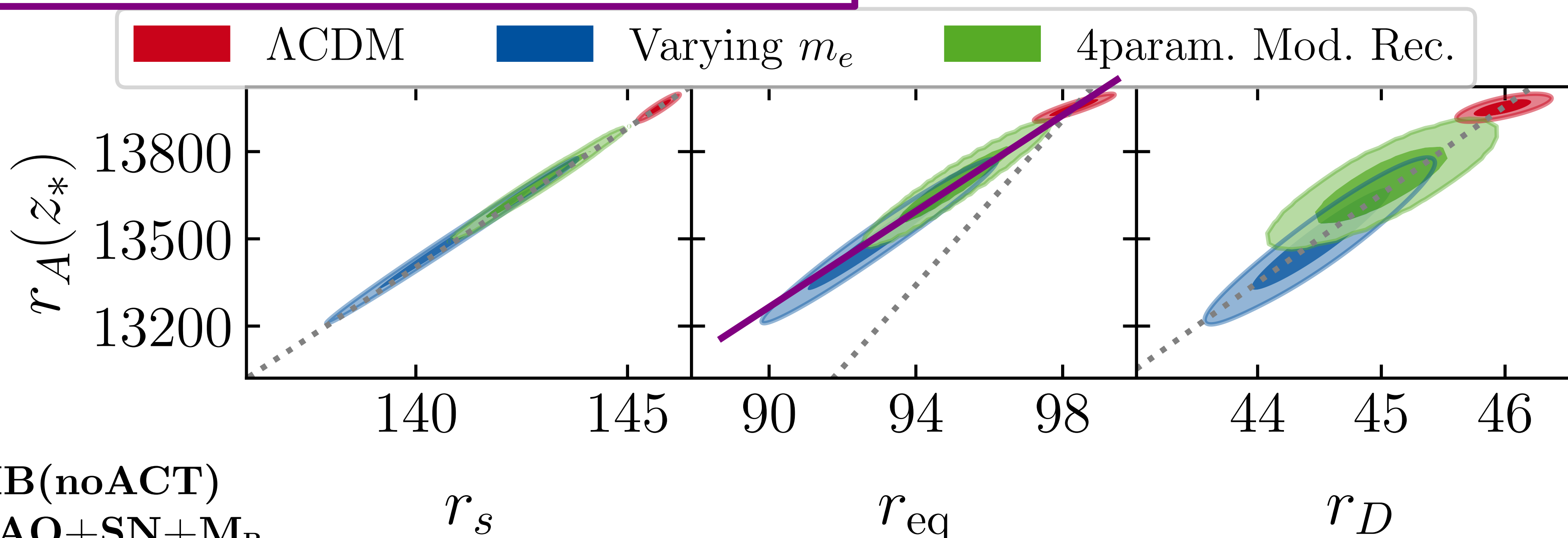


Still works, but with adjusted $\ell_{\rm eq}$



CMB(noACT)
+BAO+SN+M$_B$

Plan

I. Discuss picture with ℓ_{eq} fixed

II. Adjust ℓ_{eq}

III. Explain peculiar features

Plan

Only for recombination models
(otherwise we'll be here all day)

I. Discuss picture with ℓ_{eq} fixed

II. Adjust ℓ_{eq}

III. Explain peculiar features

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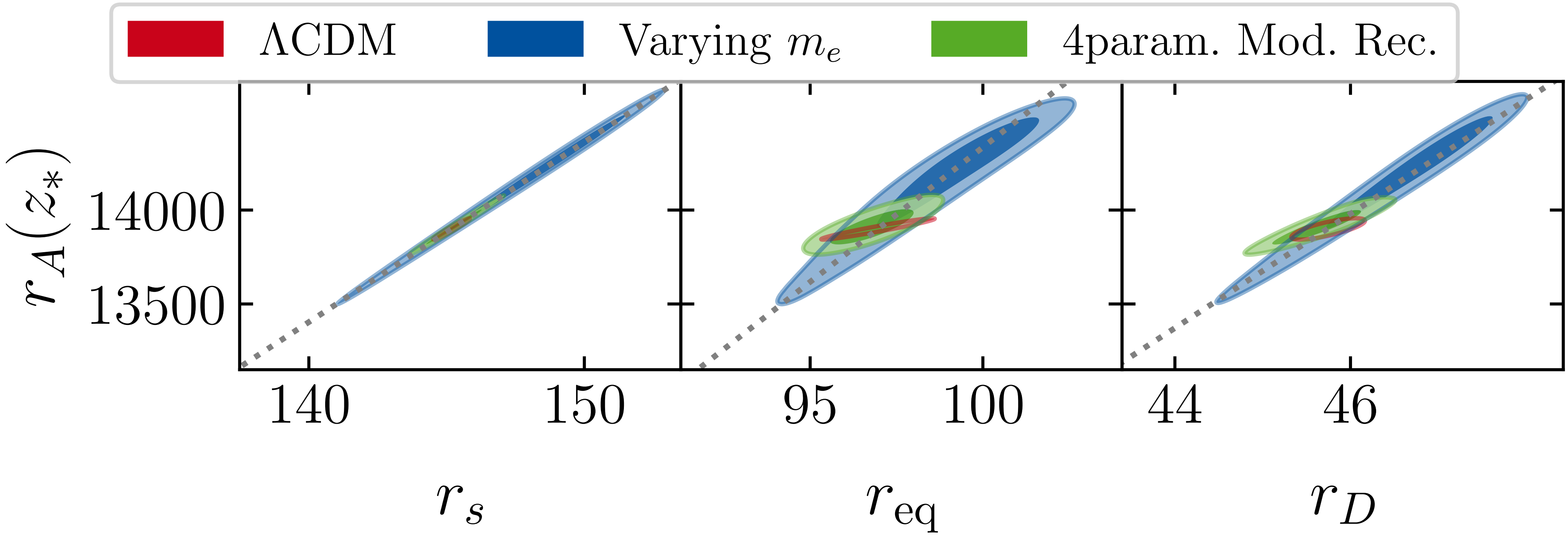
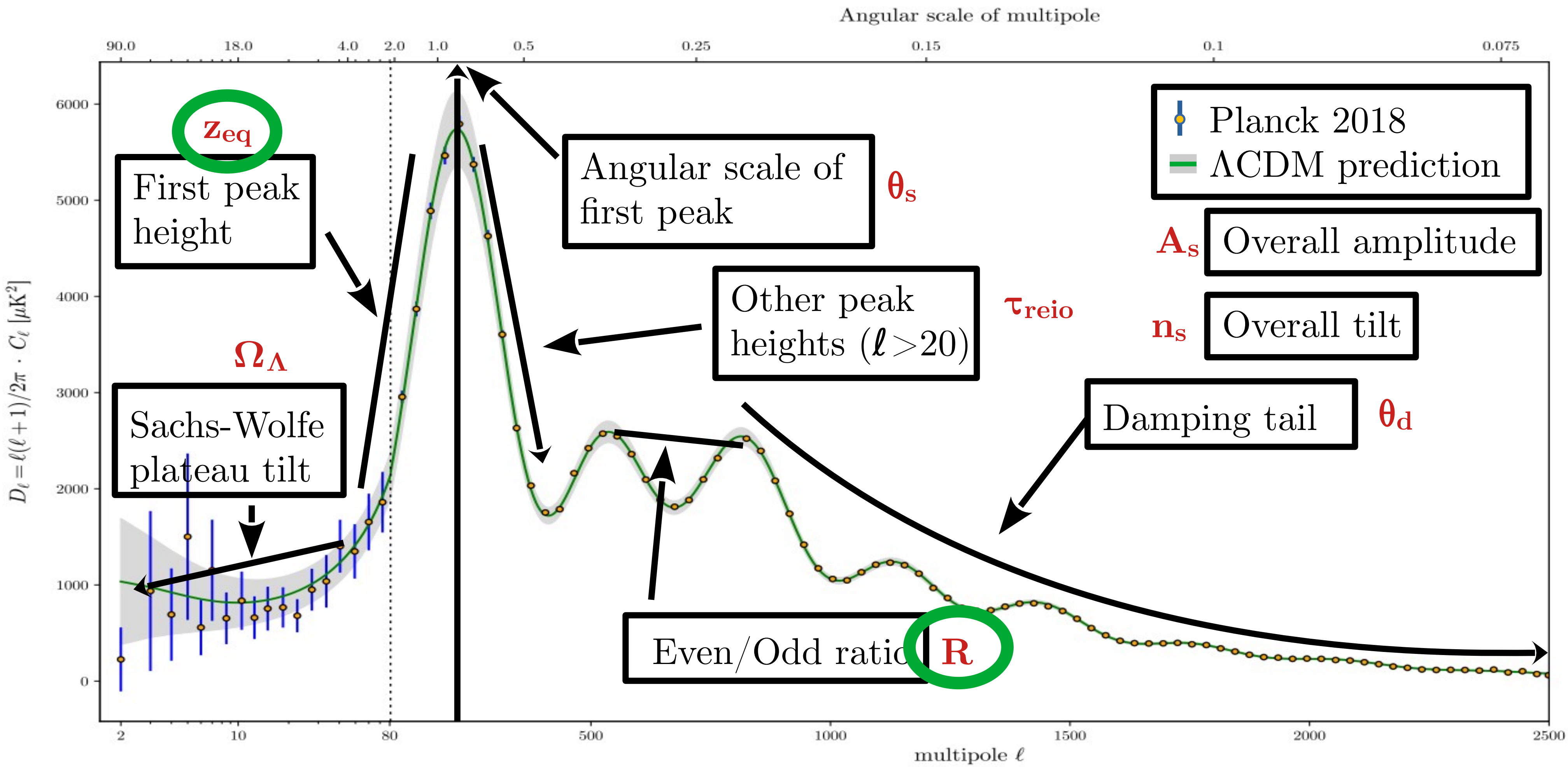


Fixed equality is "natural" direction without BAO+SN

Shifting $\ell_{\rm eq}$ requires "extra effort"

The CMB



$\ell \approx \pi/\Delta\vartheta$

The little solution that could

At CMB times, we need same baryon-to-photon and matter-to-radiation ratios

even-to-odd peak

gravitational boost of BAO

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At CMB times, we need same baryon-to-photon and matter-to-radiation ratios

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gravitational boost of BAO

$$R = \frac{3}{4}\frac{\omega_b}{\omega_\gamma} \cdot a$$

The little solution that could

At CMB times, we need same baryon-to-photon and matter-to-radiation ratios

even-to-odd peak

gravitational boost of BAO

$$R = \frac{3}{4}\frac{\omega_b}{\omega_\gamma} \cdot a \qquad R_* = \frac{3}{4}\frac{\omega_b}{\omega_\gamma} \cdot a_* \overset{!}{=} \text{constant}$$

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$$R = \frac{3}{4}\frac{\omega_b}{\omega_\gamma} \cdot a \qquad R_* = \frac{3}{4}\frac{\omega_b}{\omega_\gamma} \cdot a_* \overset{!}{=} \text{constant}$$

$$\Rightarrow \omega_b \propto a_*^{-1}$$

The little solution that could

At CMB times, we need same baryon-to-photon and matter-to-radiation ratios

even-to-odd peak

gravitational boost of BAO

$$R \to \omega_b \propto a_*^{-1}$$

The little solution that could

At CMB times, we need same baryon-to-photon and matter-to-radiation ratios

even-to-odd peak

gravitational boost of BAO

$$\frac{\rho_m}{\rho_r} \approx \omega_m a/\omega_r$$

$$R \to \omega_b \propto a_*^{-1}$$

The little solution that could

At CMB times, we need same baryon-to-photon and matter-to-radiation ratios

even-to-odd peak

gravitational boost of BAO

$$\frac{\rho_m}{\rho_r} \approx \omega_m a/\omega_r \qquad \left.\frac{\rho_m}{\rho_r}\right|_{a=a_*} \approx \omega_m a_*/\omega_r \stackrel{!}{=} \text{constant}$$

$$R \to \omega_b \propto a_*^{-1}$$

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At CMB times, we need same baryon-to-photon and matter-to-radiation ratios

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$$\Rightarrow \omega_m \propto a_*^{-1}$$

$$R \rightarrow \omega_b \propto a_*^{-1}$$

The little solution that could

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

The little solution that could

What about r_s?

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

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The little solution that could

What about r_s?

$$r_s = \int_0^{\eta_*} c_s \mathrm{d}\eta$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_s?

$$r_s = \int_0^{\eta_*} c_s \mathrm{d}\eta = \int_{z_*}^{\infty} \frac{c_s \mathrm{d}z}{H(z)}$$

$$R \rightarrow \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \rightarrow \omega_m \propto a_*^{-1}$$

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What about r_s?

$$r_s = \int_0^{\eta_*} c_s \mathrm{d}\eta = \int_{z_*}^{\infty} \frac{c_s \mathrm{d}z}{H(z)} \propto \int_{z_*}^{\infty} \frac{1}{\sqrt{3(1+R)}} \frac{1}{\sqrt{(\rho_m/\rho_r + 1)\cdot \rho_r}} \mathrm{d}z$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

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$$r_s \propto \int_{z_*}^{\infty} \frac{1}{\sqrt{\rho_r}} \mathrm{d}z$$

$$\boxed{R \to \omega_b \propto a_*^{-1}}$$

$$\boxed{\rho_m/\rho_r \to \omega_m \propto a_*^{-1}}$$

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$$r_s \propto \int_{z_*}^{\infty} \frac{1}{\sqrt{\rho_r}} \mathrm{d}z$$

$$\rho_r \propto a^{-4} \qquad \mathrm{d}z = -\frac{\mathrm{d}a}{a^2}$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_s?

$$r_s = \int_0^{\eta_*} c_s \mathrm{d}\eta = \int_{z_*}^{\infty} \frac{c_s \mathrm{d}z}{H(z)} \propto \int_{z_*}^{\infty} \frac{1}{\sqrt{3\cancel{(1+R)}}} \frac{1}{\sqrt{\cancel{(\rho_m/\rho_r+1)}\cdot\rho_r}} \mathrm{d}z$$

$$r_s \propto \int_{z_*}^{\infty} \frac{1}{\sqrt{\rho_r}} \mathrm{d}z \propto \int_0^{a_*} a^2 \cdot \frac{\mathrm{d}a}{a^2}$$

$\rho_r \propto a^{-4}$ $\mathrm{d}z = -\frac{\mathrm{d}a}{a^2}$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_s?

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$$r_s \propto \int_{z_*}^{\infty} \frac{1}{\sqrt{\rho_r}} \mathrm{d}z \propto \int_0^{a_*} a^2 \cdot \frac{\mathrm{d}a}{a^2} = \int_0^{a_*} \mathrm{d}a = a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

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$$r_s \propto \int_{z_*}^{\infty} \frac{1}{\sqrt{\rho_r}} \mathrm{d}z \propto \int_0^{a_*} a^2 \cdot \frac{\mathrm{d}a}{a^2} = \int_0^{a_*} \mathrm{d}a = a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

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The little solution that could

$$r_s \propto a_*$$

(this is the reason why it's a H_0 model)

$$R \rightarrow \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \rightarrow \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_{eq} ?

$r_s \propto a_*$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

The little solution that could

What about r_{eq} ?

$$r_{\mathrm{eq}} \propto \frac{1}{k_{\mathrm{eq}}}$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_{eq}?

$$r_{\rm eq} \propto \frac{1}{k_{\rm eq}} \propto \frac{1}{a_{\rm eq} H_{\rm eq}}$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_{eq}?

$$r_{\mathrm{eq}} \propto \frac{1}{k_{\mathrm{eq}}} \propto \frac{1}{a_{\mathrm{eq}} H_{\mathrm{eq}}} \propto \frac{1}{\sqrt{\omega_m a_{\mathrm{eq}}^{-1} + \omega_r a_{\mathrm{eq}}^{-2}}}$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about $r_{\rm eq}$?

$$r_{\rm eq} \propto \frac{1}{k_{\rm eq}} \propto \frac{1}{a_{\rm eq} H_{\rm eq}} \propto \frac{1}{\sqrt{\omega_m a_{\rm eq}^{-1} + \omega_r a_{\rm eq}^{-2}}} \propto \frac{1}{\sqrt{2\omega_r a_{\rm eq}^{-2}}}$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_{eq}?

$$r_{\rm eq} \propto \frac{1}{k_{\rm eq}} \propto \frac{1}{a_{\rm eq} H_{\rm eq}} \propto \frac{1}{\sqrt{\omega_m a_{\rm eq}^{-1} + \omega_r a_{\rm eq}^{-2}}} \propto \frac{1}{\sqrt{2\omega_r a_{\rm eq}^{-2}}} \propto a_{\rm eq}$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_{eq} ?

$$r_{\rm eq} \propto \frac{1}{k_{\rm eq}} \propto \frac{1}{a_{\rm eq} H_{\rm eq}} \propto \frac{1}{\sqrt{\omega_m a_{\rm eq}^{-1} + \omega_r a_{\rm eq}^{-2}}} \propto \frac{1}{\sqrt{2\omega_r a_{\rm eq}^{-2}}} \propto a_{\rm eq}$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_{eq}?

$$\left.\frac{\omega_m a}{\omega_r}\right|_{a=a_{\rm eq}} \stackrel{!}{=} 1$$

$$r_{\rm eq} \propto \frac{1}{k_{\rm eq}} \propto \frac{1}{a_{\rm eq} H_{\rm eq}} \propto \frac{1}{\sqrt{\omega_m a_{\rm eq}^{-1} + \omega_r a_{\rm eq}^{-2}}} \propto \frac{1}{\sqrt{2\omega_r a_{\rm eq}^{-2}}} \propto a_{\rm eq}$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_{eq}?

$$\left.\frac{\omega_m a}{\omega_r}\right|_{a=a_{eq}} \overset{!}{=} 1 \qquad a_{eq} = \omega_r/\omega_m$$

$$r_{eq} \propto \frac{1}{k_{eq}} \propto \frac{1}{a_{eq}H_{eq}} \propto \frac{1}{\sqrt{\omega_m a_{eq}^{-1} + \omega_r a_{eq}^{-2}}} \propto \frac{1}{\sqrt{2\omega_r a_{eq}^{-2}}} \propto a_{eq}$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

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The little solution that could

What about r_{eq} ?

$$\left.\frac{\omega_m a}{\omega_r}\right|_{a=a_{eq}} \stackrel{!}{=} 1 \qquad a_{eq} = \omega_r/\omega_m \propto a_*$$

$$r_{eq} \propto \frac{1}{k_{eq}} \propto \frac{1}{a_{eq}H_{eq}} \propto \frac{1}{\sqrt{\omega_m a_{eq}^{-1} + \omega_r a_{eq}^{-2}}} \propto \frac{1}{\sqrt{2\omega_r a_{eq}^{-2}}} \propto a_{eq}$$

$$r_s \propto a_*$$

$$R \rightarrow \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \rightarrow \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_{eq} ?

$$\left.\frac{\omega_m a}{\omega_r}\right|_{a=a_{eq}} \stackrel{!}{=} 1 \qquad a_{eq} = \omega_r/\omega_m \propto a_*$$

$$r_{eq} \propto \frac{1}{k_{eq}} \propto \frac{1}{a_{eq}H_{eq}} \propto \frac{1}{\sqrt{\omega_m a_{eq}^{-1} + \omega_r a_{eq}^{-2}}} \propto \frac{1}{\sqrt{2\omega_r a_{eq}^{-2}}} \propto a_{eq}$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_{eq} ?

$$\left.\frac{\omega_m a}{\omega_r}\right|_{a=a_{\rm eq}} \stackrel{!}{=} 1 \qquad a_{\rm eq} = \omega_r/\omega_m \propto a_*$$

$$r_{\rm eq} \propto \frac{1}{k_{\rm eq}} \propto \frac{1}{a_{\rm eq} H_{\rm eq}} \propto \frac{1}{\sqrt{\omega_m a_{\rm eq}^{-1} + \omega_r a_{\rm eq}^{-2}}} \propto \frac{1}{\sqrt{2\omega_r a_{\rm eq}^{-2}}} \propto a_{\rm eq} \propto a_*$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

$r_{\mathrm{eq}} \propto a_*$

$r_s \propto a_*$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

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The little solution that could

What about r_D ?

$r_{\mathrm{eq}} \propto a_*$

$r_s \propto a_*$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

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THE LITTLE SOLUTION THAT COULD

What about r_D ?

$$r_D \propto 1/k_D$$

$$r_{\mathrm{eq}} \propto a_*$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_D?

Sekiguchi & Takahashi (2007.03381)

$$r_D \propto 1/k_D \propto \ldots$$

$$r_{\text{eq}} \propto a_*$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

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The little solution that could

What about r_D?

$$r_D \propto 1/k_D \propto \ldots \propto \frac{a_*^{3/2}}{\sqrt{\omega_b \sigma_T (1-Y_{\mathrm{He}})}}$$

$$r_{\mathrm{eq}} \propto a_*$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_D?

$$r_D \propto 1/k_D \propto \ldots \propto \frac{a_*^{3/2}}{\sqrt{\omega_b \sigma_T (1-Y_{\mathrm{He}})}}$$

$$r_D \propto {a_*}^2/\sqrt{\sigma_T}$$

$$r_{\mathrm{eq}} \propto a_*$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

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The little solution that could

What about r_D?

$$r_D \propto 1/k_D \propto \ldots \propto \frac{a_*^{3/2}}{\sqrt{\omega_b \sigma_T (1-Y_{\mathrm{He}})}}$$

$$r_D \propto {a_*}^2/\sqrt{\sigma_T}$$

$$r_{\mathrm{eq}} \propto a_*$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

What about r_D?

$$r_D \propto 1/k_D \propto \ldots \propto \frac{a_*^{3/2}}{\sqrt{\omega_b \sigma_T (1-Y_{\mathrm{He}})}}$$

$$r_D \propto {a_*}^2/\sqrt{\sigma_T} = a_* \cdot a_*/\sqrt{\sigma_T}$$

$$r_{\mathrm{eq}} \propto a_*$$

$$r_s \propto a_*$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The little solution that could

$r_{\mathrm{eq}} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

The natural direction

- Modified recombination scenarios “want” to follow these directions

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

The natural direction

- Modified recombination scenarios “want” to follow these directions

→ This means we can explain what works and what doesn’t !

$r_{\mathrm{eq}} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

The natural direction

- Modified recombination scenarios “want” to follow these directions

→ This means we can explain what works and what doesn’t !

$\rightarrow$ Data can force us off preferred direction (increasing $\ell_{\rm eq}$)
$\rightarrow$ Importantly $\mathrm{r_s}$, $\mathrm{r_D}$ scalings stay the same!

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \rightarrow \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \rightarrow \omega_m \propto a_*^{-1}$

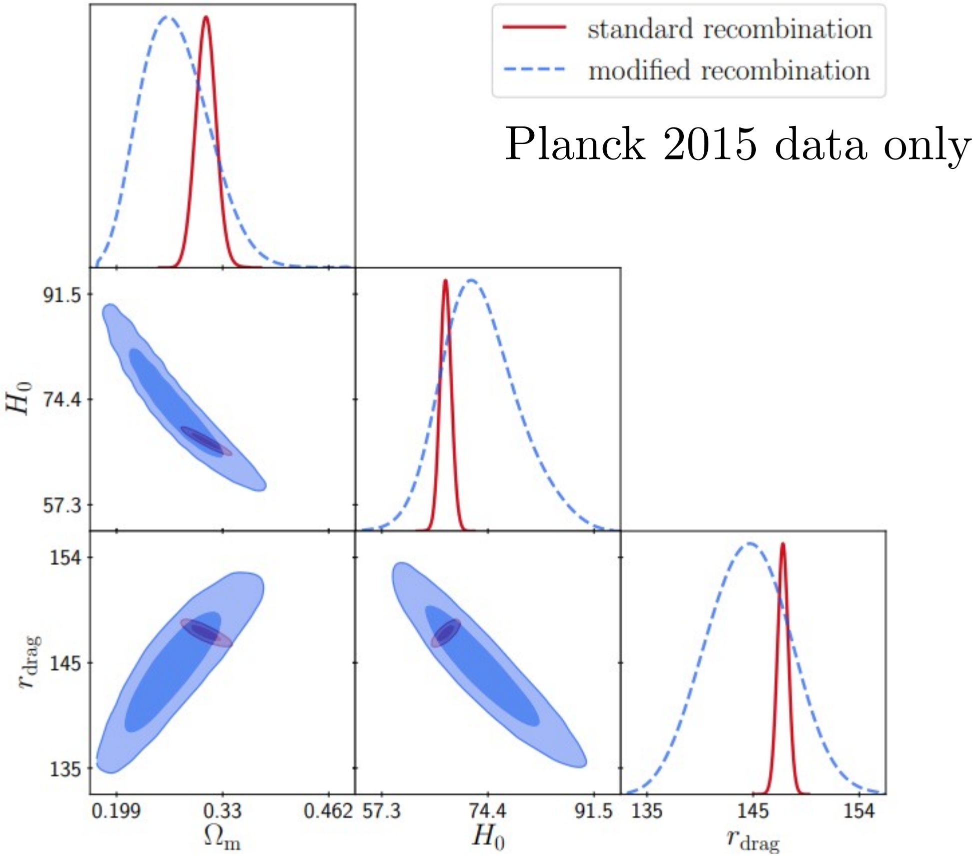
Explaining our first mysteries

Explaining our first mysteries

For this, a bit of history :)

Explaining our first mysteries

- Early exploratory work in Chiang & Slosar (1811.03624)



Explaining our first mysteries

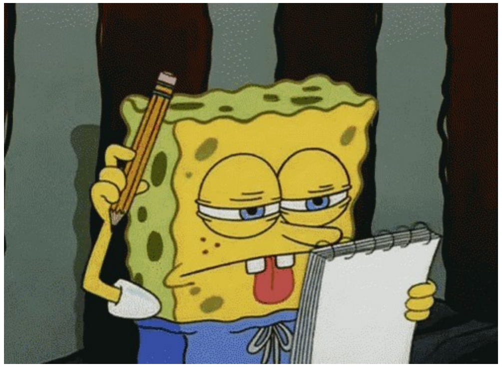
Liu+2020 (1912.00190)

Can Non-standard Recombination Resolve the Hubble Tension?

Miaoxin Liu, Zhiqi Huang,* Xiaolin Luo, Haitao Miao, Naveen K. Singh, and Lu Huang

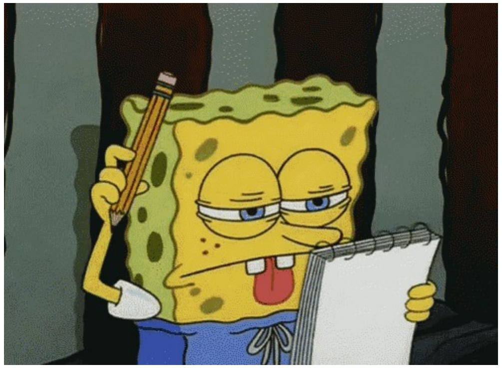
School of Physics and Astronomy, Sun Yat-sen University, 2 Daxue Road, Tangjia, Zhuhai, China

Thus, the Hubble tension is very robust against perturbations of recombination history, unless exotic physics modifies the atomic constants during the recombination epoch.



Explaining our first mysteries

$$z_* \approx \underbrace{\frac{E_{\rm binding}}{T_{\rm cmb}}}_{\rm naive} \cdot \underbrace{\frac{1}{40}}_{\text{Saha }(\eta_{\rm b})} \cdot \underbrace{0.75}_{\rm non-equilibrium} \approx 1080$$



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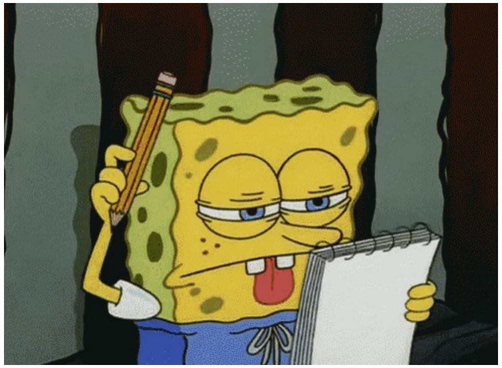
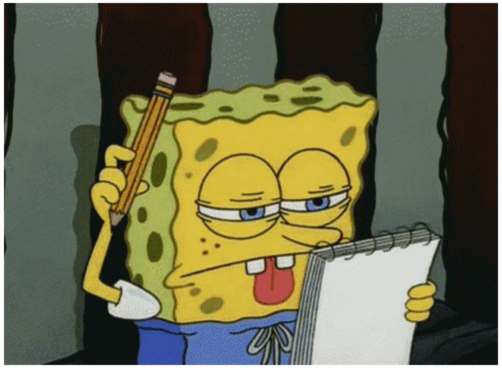
Explaining our first mysteries

$$z_* \approx \underbrace{\frac{E_{\mathrm{binding}}}{T_{\mathrm{cmb}}}}_{\text{naive}} \cdot \underbrace{\frac{1}{40}}_{\text{Saha } (\eta_{\mathrm{b}})} \cdot \underbrace{0.75}_{\text{non-equilibrium}} \approx 1080$$



Explaining our first mysteries

$$z_* \approx \underbrace{\frac{E_{\text{binding}}}{T_{\text{cmb}}}}_{\text{naive}} \cdot \underbrace{\frac{1}{40}}_{\text{Saha }(\eta_{\text{b}})} \cdot \underbrace{0.75}_{\text{non}-\text{equilibrium}} \approx 1080$$



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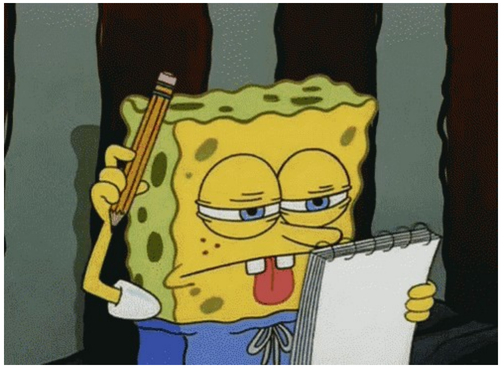
Explaining our first mysteries

$$E_{\rm binding} = \frac{1}{2} m_e \alpha^2 \approx 13.6\mathrm{eV}$$

$$z_* \approx \underbrace{\frac{E_{\rm binding}}{T_{\rm cmb}}}_{\rm naive} \cdot \underbrace{\frac{1}{40}}_{\text{Saha } (\eta_{\rm b})} \cdot \underbrace{0.75}_{\text{non-equilibrium}} \approx 1080$$



Explaining our first mysteries

$$E_{\text{binding}} = \frac{1}{2} m_e \alpha^2 \approx 13.6\text{eV}$$

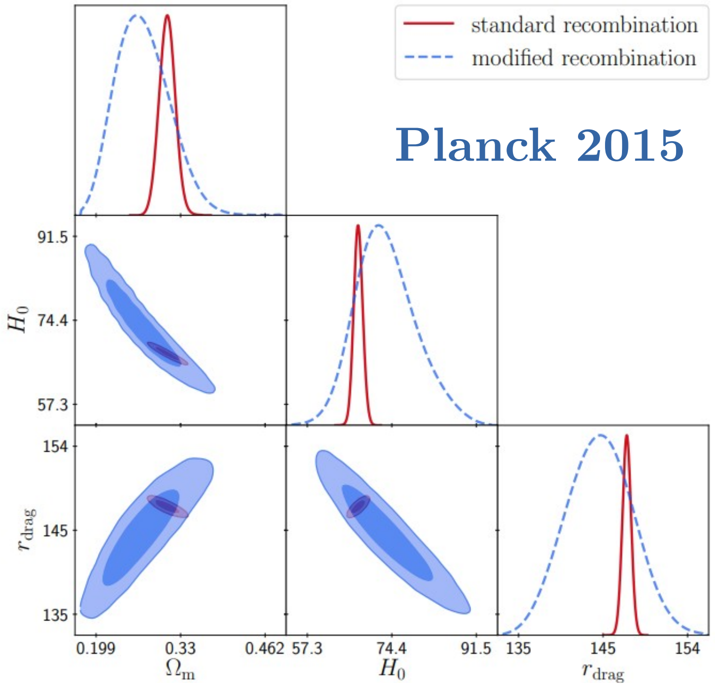
Explaining our first mysteries

$$E_{\mathrm{binding}} = \frac{1}{2} m_e \alpha^2 \approx 13.6\mathrm{eV}$$

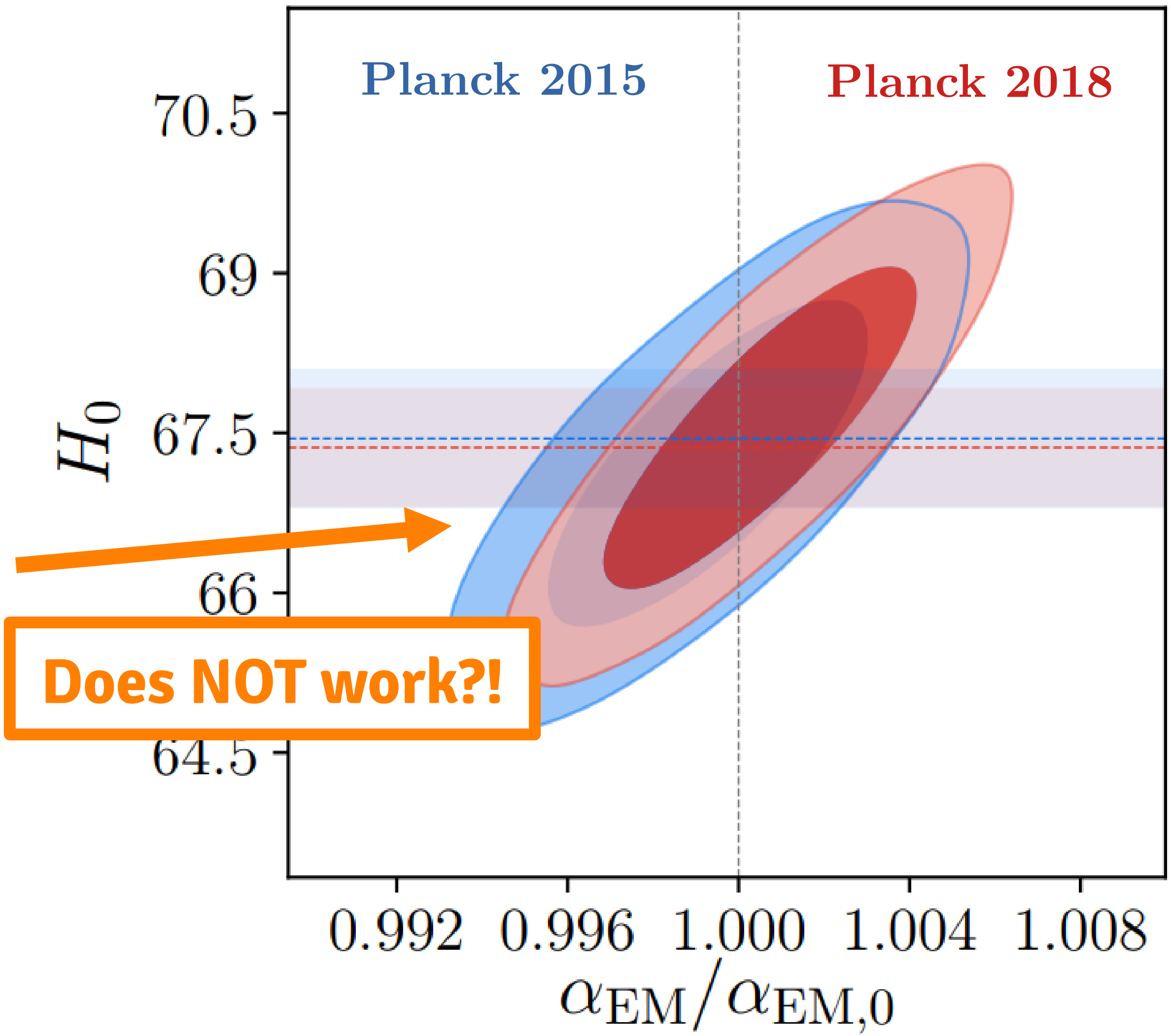
$$\mathcal{L} = \ldots + -\frac{1}{4} B_F(\phi) F_{\mu\nu} F^{\mu\nu}$$

$$\Rightarrow \quad \frac{\Delta\alpha}{\alpha_0} = (B_F(\phi))^{-1} - 1$$

Explaining our first mysteries



Hart & Chluba (1912.03986)



The natural direction

$r_{\mathrm{eq}} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

The natural direction

$$\boxed{(a_*)^{-1} \propto z_* \propto E_{\text{binding}} \propto m_e \alpha^2}$$

$$a_* \propto \alpha^{-2}$$

$$a_* \propto m_e^{-1}$$

$$r_{\text{eq}} \propto a_*$$

$$r_s \propto a_*$$

$$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The natural direction

$$\boxed{(a_*)^{-1} \propto z_* \propto E_{\text{binding}} \propto m_e \alpha^2}$$

$$a_* \propto \alpha^{-2}$$

$$a_* \propto m_e^{-1}$$

$$\boxed{\sigma_T \propto \frac{\alpha^2}{m_e^2}}$$

$$r_{\text{eq}} \propto a_*$$

$$r_s \propto a_*$$

$$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The natural direction

$$\boxed{(a_*)^{-1} \propto z_* \propto E_{\mathrm{binding}} \propto m_e \alpha^2}$$

$$a_* \propto \alpha^{-2}$$

$$a_* \propto m_e^{-1}$$

$$\boxed{\sigma_T \propto \frac{\alpha^2}{m_e^2}}$$

$$a_*/\sqrt{\sigma_T} \propto \alpha^{-3}$$

$$\frac{a_*}{\sqrt{\sigma_T}} \propto \frac{m_e^{-1}}{\sqrt{m_e^{-2}}} \propto const$$

$$r_{\mathrm{eq}} \propto a_*$$

$$r_s \propto a_*$$

$$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The natural direction

$a_*/\sqrt{\sigma_T} \propto \alpha^{-3}$ ⟶ Bad for CMB damping !

$a_*/\sqrt{\sigma_T} \propto const$ ⟶ Perfect for CMB damping !

$r_{\mathrm{eq}} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

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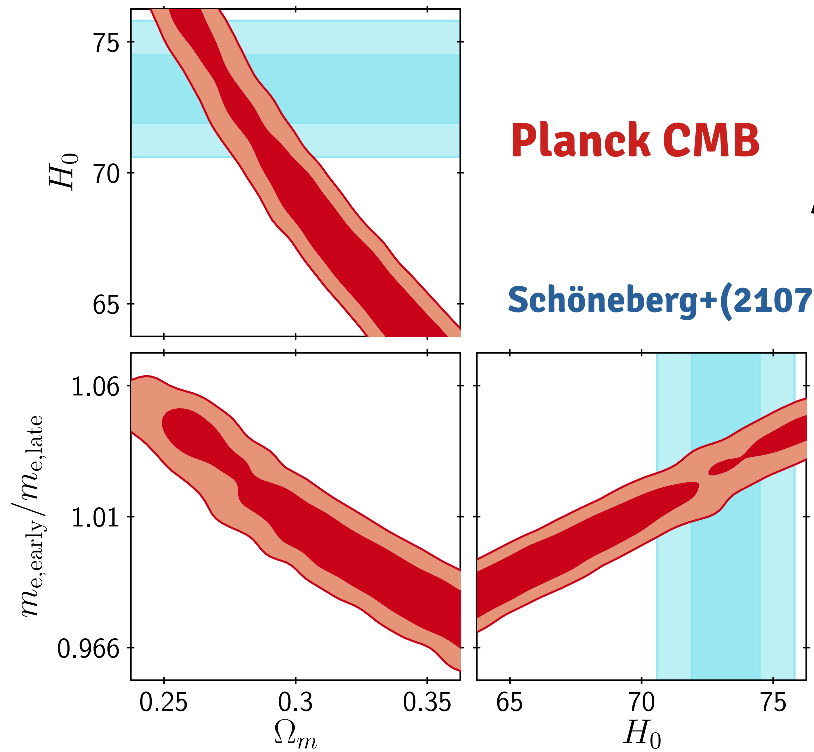
The natural direction



Planck CMB

Any value of H_0 is allowed!

Schöneberg+(2107.10291)

$r_{\mathrm{eq}} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

Solving Mysteries

Mysteries solved:

- Why does α fail where m_e succeeds? → σ_T scaling

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

Solving Mysteries

Can other models also shift σ_T ?

Yes, but...

$r_{\text{eq}} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

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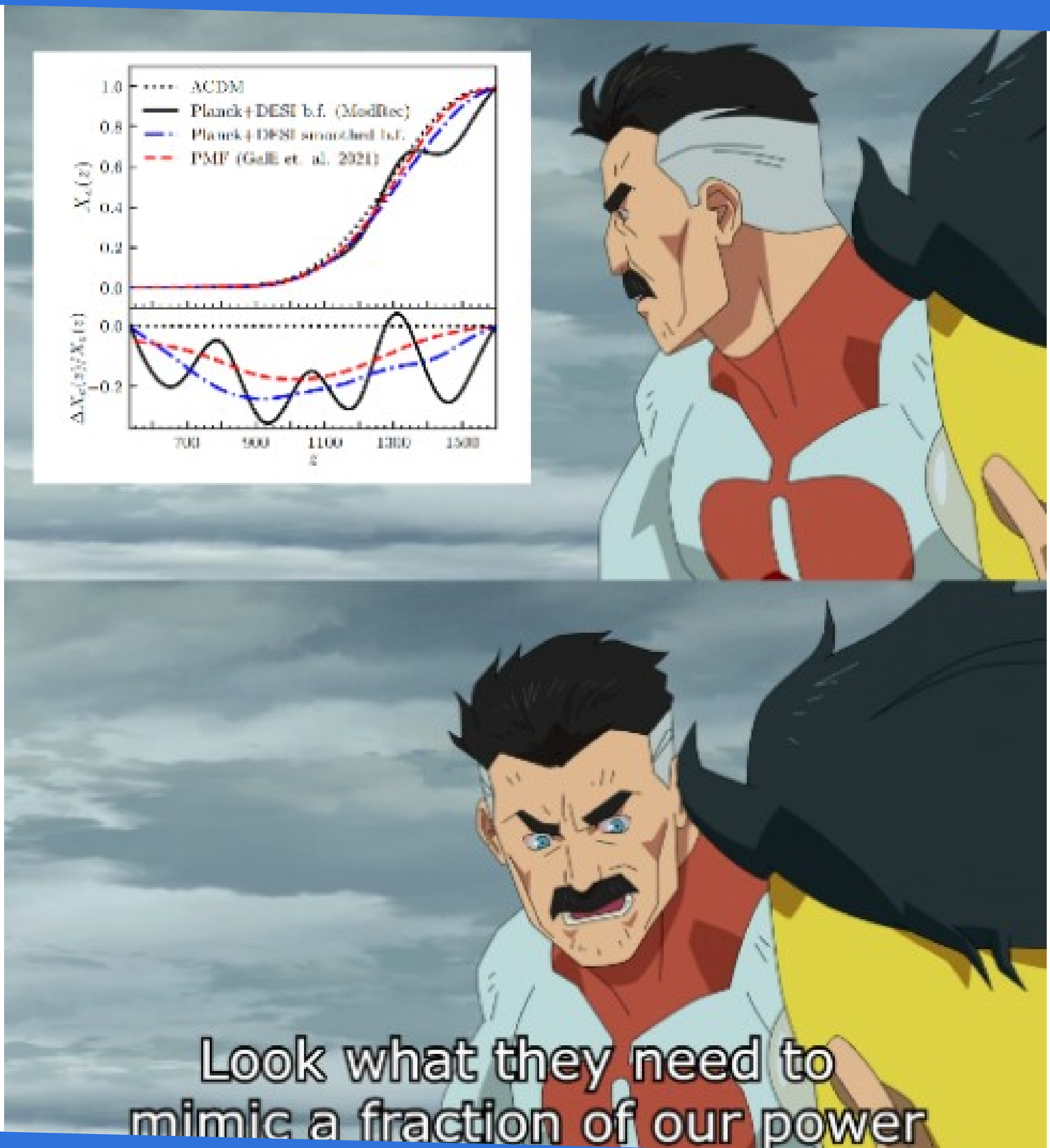

Solving Mysteries

Can other models also shift σ_T ?

Yes, but it's not trivial/by default

$r_{\mathrm{eq}} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

Solving Mysteries

Can other models also shift σ_T ?

Yes, but it's not trivial/by default

Frequentist vs Bayesian!

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

Solving Mysteries

Mysteries solved:
- Why does α fail where m_e succeeds? → σ_T scaling
- Why did 4-param mod. rec. fail? → σ_T scaling + simple

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

Solving Mysteries

Mysteries solved:

- Why does α fail where m_e succeeds? → σ_T scaling
- Why did 4-param mod. rec. fail? → σ_T scaling + simple
- Why does DESI love it?

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

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Solving Mysteries

Schöneberg & Vacher (2407.16845)

$\Delta m_e/m_{e,0}$	P18+DESI	1.21 ± 0.63	70.03 ± 1.06	2.0	this work
$\Delta m_e/m_{e,0} + \Omega_k$	P18+DESI	2.52 ± 1.85	70.94 ± 1.23	1.3	this work, see also [16]
$\Delta m_e/m_{e,0} + \Omega_k$	P18+DESI+PanPLUS	1.88 ± 0.52	71.61 ± 1.00	1.0	this work
$\Delta m_e/m_{e,0} + w_0/w_a$	P18+DESI	1.53 ± 0.63	70.30 ± 1.34	1.6	this work
$\Delta m_e/m_{e,0} + w_0/w_a$	P18+DESI+PanPLUS	0.72 ± 0.84	69.38 ± 2.17	1.5	this work

?!?!? 3σ preference

Without SH0ES we get a <2σ Hubble tension?!

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

Solving Mysteries

To answer this mystery:

→ Parameter changes!

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

Solving Mysteries

To answer this mystery:

→ Parameter changes!

$$\theta_s = \frac{r_s}{r_A(z_*)}$$ measured at 0.03% uncertainty

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

The natural direction

Parameter changes:

$$r_A \propto \int_{a_*}^{1} \frac{1}{\sqrt{\omega_m a^{-3} + h^2}}$$

Assumption:
ΛCDM-like expansion history at low-z

$$r_A \overset{!}{\propto} a_*$$

$r_{\mathrm{eq}} \propto a_*$ $r_s \propto a_*$ $r_D \propto a_*$

$R \to \omega_b \propto a_*^{-1}$ $\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

The natural direction

Parameter changes:

$$r_A \propto \int_{a_*}^{1} \frac{1}{\sqrt{\omega_m a^{-3} + h^2}}$$

<u>Assumption:</u>
ΛCDM-like expansion history at low-z

$$r_A \overset{!}{\propto} a_* \qquad \Rightarrow h \overset{!}{\propto} a_*^{-3.23}$$

$$r_{\rm eq} \propto a_*$$

$$r_s \propto a_*$$

$$r_D \propto a_*$$

$$R \rightarrow \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \rightarrow \omega_m \propto a_*^{-1}$$

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The natural direction

<u>Assumption:</u>
ΛCDM-like expansion history at low-z

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_*$

$h \overset{!}{\propto} a_*^{-3.23}$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

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The natural direction

$$a_* \propto m_e^{-1}$$

$$a_* \propto z_*^{-1} \propto E_{\rm bin}^{-1} \propto m_e^{-1}$$

<u>Assumption:</u>
ΛCDM-like expansion history at low-z

$$r_{\rm eq} \propto a_*$$

$$r_s \propto a_*$$

$$r_D \propto a_*$$

$$h \overset{!}{\propto} a_*^{-3.23}$$

$$R \rightarrow \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \rightarrow \omega_m \propto a_*^{-1}$$

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The natural direction

$$\boxed{\Omega_m h^2 \propto a_*^{-1}}$$

Assumption:
ΛCDM-like expansion history at low-z

$r_\mathrm{eq} \propto a_*$

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$R \rightarrow \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \rightarrow \omega_m \propto a_*^{-1}$

The natural direction

$\boxed{\Omega_m h^2 \propto a_*^{-1}}$ $\Omega_m \propto a_*^{5.26} \propto h^{-1.7}$

$\boxed{h \propto a_*^{-3.23}}$

Assumption:
ΛCDM-like expansion history at low-z

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_*$

$h \overset{!}{\propto} a_*^{-3.23}$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

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The natural direction

$$\Omega_m h^2 \propto a_*^{-1}$$

$$h \propto a_*^{-3.23}$$

$$\Omega_m \propto h^{-1.7}$$

We haven't used a m_e-specific law!

Assumption:
ΛCDM-like expansion history at low-z

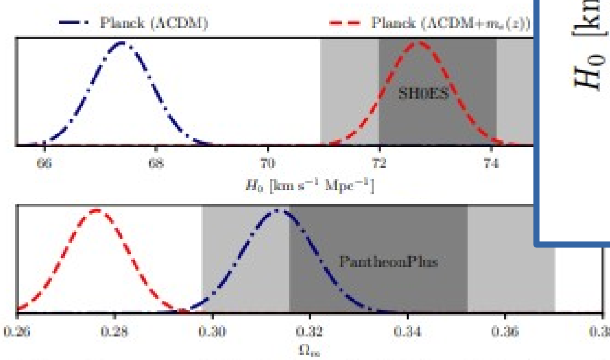
$r_{\rm eq} \propto a_*$ | $r_s \propto a_*$ | $r_D \propto a_*$ | $h \overset{!}{\propto} a_*^{-3.23}$

$R \to \omega_b \propto a_*^{-1}$ | $\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

The natural direction

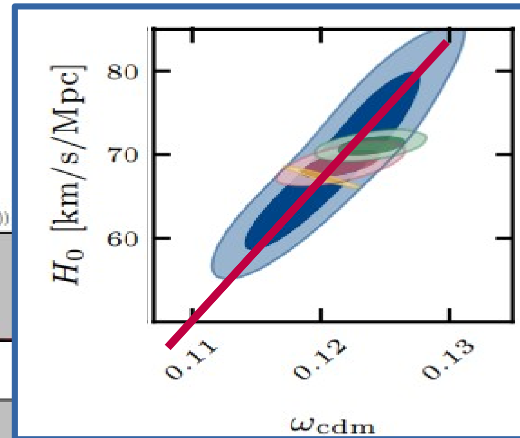
$$h \approx 1.07 h_{\rm fid}$$
$$\Omega_m \approx 0.89 \Omega_{m,\rm fid}$$

$$\Omega_m h^2 \propto a_*^{-1}$$
$$h \propto a_*^{-3.23}$$
$$\Omega_m \propto h^{-1.7}$$



Lee+2212.04494

Free-form reconstruction of m_e



Lynch+2404.05715

Free-form reconstruction of ionization x_e

Assumption:
ΛCDM-like expansion history at low-z

$r_{\rm eq} \propto a_*$ | $r_s \propto a_*$ | $r_D \propto a_*$ | $h \overset{!}{\propto} a_*^{-3.23}$

$R \to \omega_b \propto a_*^{-1}$ | $\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$

The natural direction

$$\Omega_m h^2 \propto a_*^{-1}$$

$$h \propto a_*^{-3.23}$$

$$\boxed{\Omega_m \propto h^{-1.7}}$$

Assumption:
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$R \rightarrow \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \rightarrow \omega_m \propto a_*^{-1}$

The natural direction

$$\Omega_m h^2 \propto a_*^{-1}$$

$$\boxed{h \propto a_*^{-3.23}}$$

$$\boxed{\Omega_m \propto h^{-1.7}}$$

$$r_s \cdot h \propto a_*^{-2.23}$$

<u>Assumption:</u>
ΛCDM-like expansion history at low-z

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$$R \rightarrow \omega_b \propto a_*^{-1}$$

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The natural direction

$$\Omega_m h^2 \propto a_*^{-1}$$

$$h \propto a_*^{-3.23}$$

$$\Omega_m \propto h^{-1.7}$$

$$r_s \cdot h \propto a_*^{-2.23} \propto h^{0.7}$$

<u>Assumption:</u>
ΛCDM-like expansion history at low-z

$$r_{\mathrm{eq}} \propto a_* \qquad r_s \propto a_* \qquad r_D \propto a_* \qquad h \overset{!}{\propto} a_*^{-3.23}$$

$$R \to \omega_b \propto a_*^{-1} \qquad \rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

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The natural direction

$$\Omega_m h^2 \propto a_*^{-1}$$

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The natural direction

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THE NATURAL DIRECTION

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$$h \propto a_*^{-3.23}$$

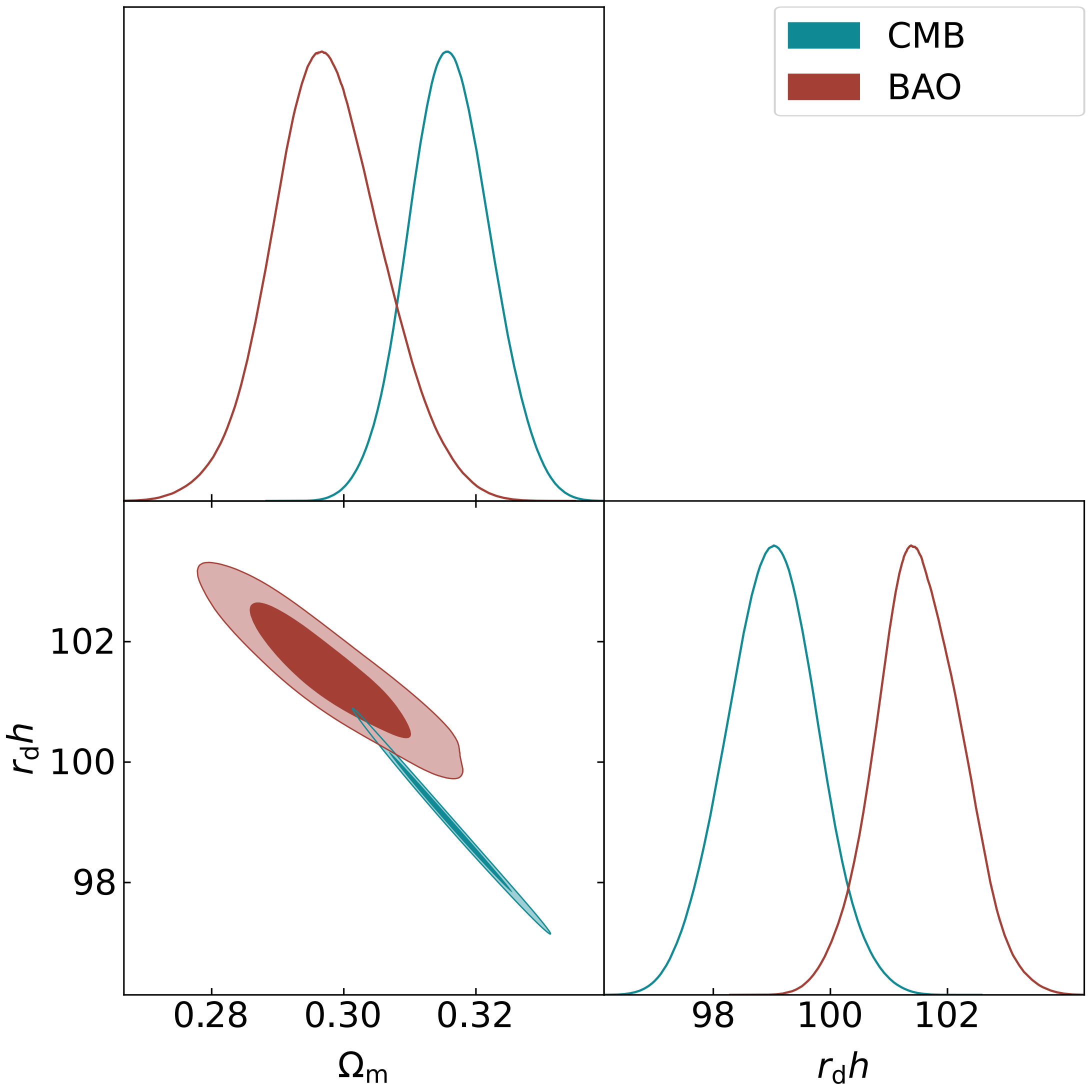
$$\boxed{\Omega_m \propto h^{-1.7}}$$

$$\boxed{r_s \cdot h \propto h^{0.7}}$$

$$r_{\mathrm{eq}} \propto a_*$$

$$r_s \propto$$

$$R \to \omega_b \propto a_*^{-1}$$



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The natural direction

$$\Omega_m h^2 \propto a_*^{-1}$$

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$r_{\rm eq} \propto a_*$

$r_s \propto$

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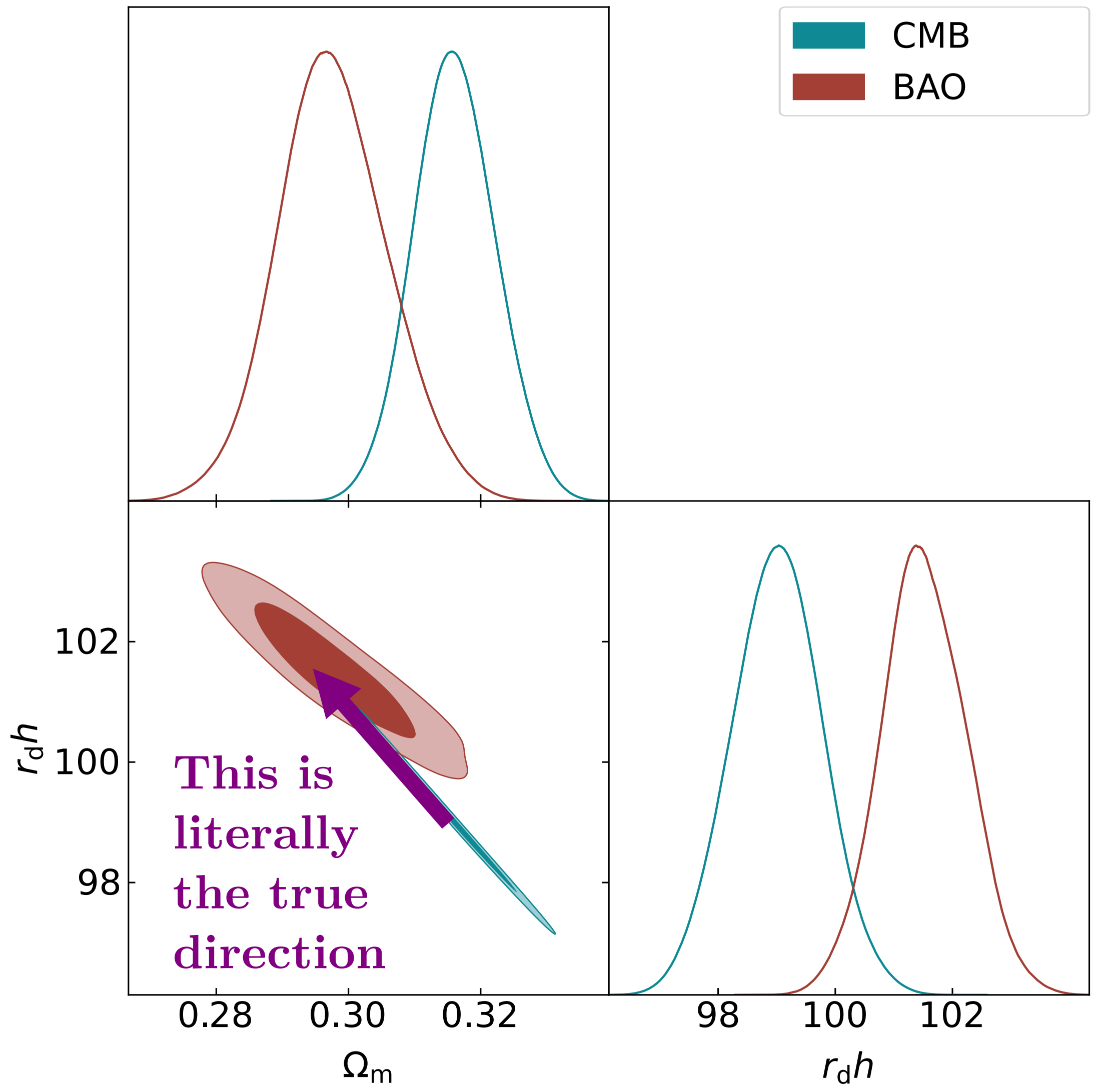

Solving Mysteries

Mysteries solved:

- Why does α fail where m_e succeeds? → σ_T scaling
- Why did 4-param mod. rec. fail? → σ_T scaling + simple
- Why does DESI love it? → Reduces Ω_m, increases h r_s

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \to \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$


BAO WEIRDNESS
THAT'S JUST ONE THING, RIGHT?
THAT'S JUST ONE THING, RIGHT?

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The natural direction

Claim: Model does not affect σ_8 much (only BAO, baryon suppression)

$$\Omega_m h^2 \propto a_*^{-1}$$

$$h \propto a_*^{-3.23}$$

$$\boxed{\Omega_m \propto h^{-1.7}}$$

$$\boxed{r_s \cdot h \propto h^{0.7}}$$

<u>Assumption:</u>
ΛCDM-like expansion history at low-z

$$r_{\mathrm{eq}} \propto a_*$$

$$r_s \propto a_*$$

$$r_D \propto a_*$$

$$h \overset{!}{\propto} a_*^{-3.23}$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The natural direction

Claim: Model does not affect σ_8 much
(only BAO, baryon suppression)

$$S_8 \propto h^{-0.86}$$

$$\Omega_m \propto h^{-1.7}$$

$$r_s \cdot h \propto h^{0.7}$$

Assumption:
ΛCDM-like expansion history at low-z

$$r_{\rm eq} \propto a_*$$

$$r_s \propto a_*$$

$$r_D \propto a_*$$

$$h \overset{!}{\propto} a_*^{-3.23}$$

$$R \to \omega_b \propto a_*^{-1}$$

$$\rho_m/\rho_r \to \omega_m \propto a_*^{-1}$$

The natural direction

S_8 from $0.83 \to 0.81$

$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5} = 0.789^{+0.012}_{-0.012}$

DES Y6 3x2pt

$S_8 \equiv \sigma_8\sqrt{\Omega_m/0.3} = 0.815^{+0.016}_{-0.021}$

KiDS legacy

$\boxed{S_8 \propto h^{-0.86}}$

$\boxed{\Omega_m \propto h^{-1.7}}$

$\boxed{r_s \cdot h \propto h^{0.7}}$

Assumption:
ΛCDM-like expansion history at low-z

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

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$R \to \omega_b \propto a_*^{-1}$

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Solving Mysteries

Mysteries solved:

- Why does α fail where m_e succeeds? → σ_T scaling
- Why did 4-param mod. rec. fail? → σ_T scaling + simple
- Why does DESI love it? → Reduces Ω_m, increases h r_s
- Why does S_8 data love it? → Reduces S_8

$r_{\rm eq} \propto a_*$

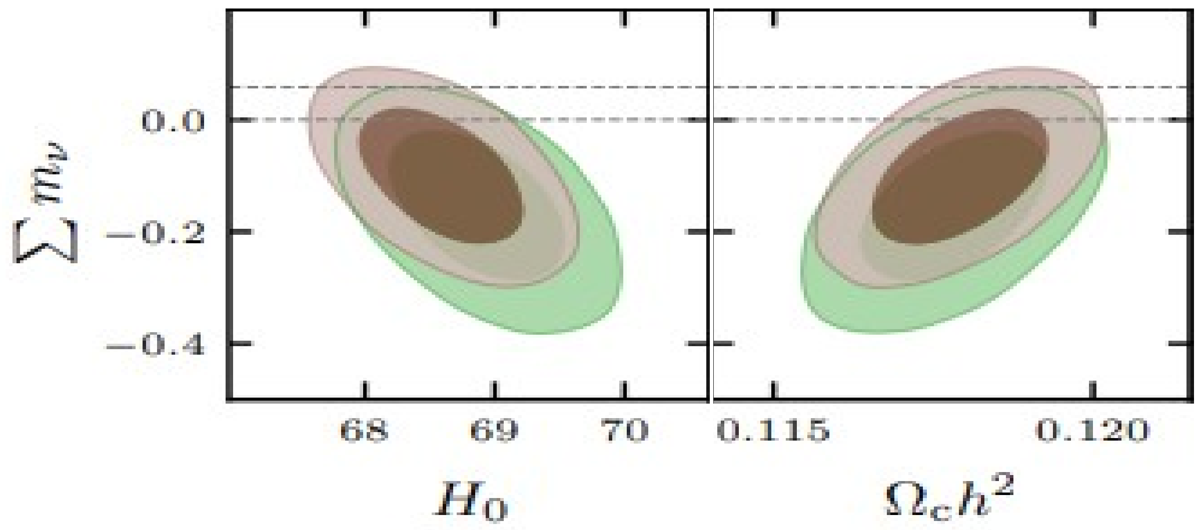
$r_s \propto a_*$

$r_D \propto a_* \cdot (a_*/\sqrt{\sigma_T})$

$R \rightarrow \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \rightarrow \omega_m \propto a_*^{-1}$


BAO, S8
THAT'S JUST
TWO THINGS, RIGHT?
THAT'S JUST
TWO THINGS, RIGHT?



Neutrino mass is preferred negative in order to get Ω_m smaller

More neutrinos → more lensing → less Ω_m required

If only there was another way to get to low Ω_m ...

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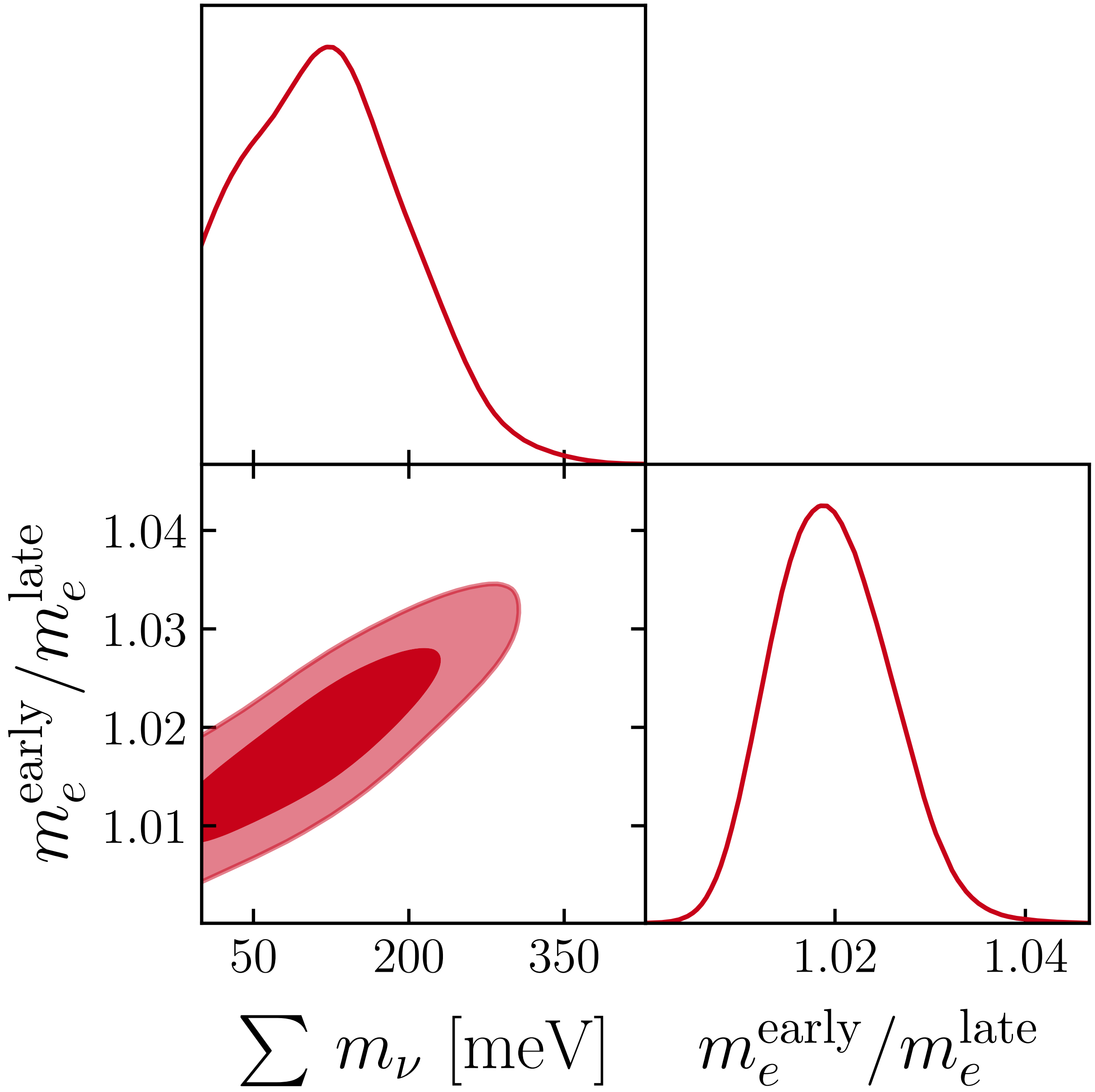


Solving Mysteries

Mysteries solved:

- Why does α fail where m_e succeeds? → σ_T scaling
- Why did 4-param mod. rec. fail? → σ_T scaling + simple
- Why does DESI love it? → Reduces Ω_m, increases h r_s
- Why does S_8 data love it? → Reduces S_8
- Why do neutrinos love it? → Allows small Ω_m at $m_\nu > 0$

Solving Mysteries

Mysteries solved:

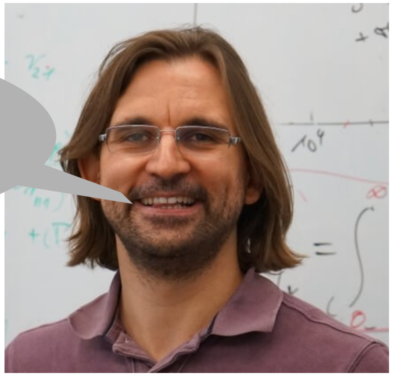
- Why does α fail where m_e succeeds? → σ_T scaling
- Why did 4-param mod. rec. fail? → σ_T scaling + simple
- Why does DESI love it? → Reduces Ω_m, increases h r_s
- Why does S_8 data love it? → Reduces S_8
- Why do neutrinos love it? → Allows small Ω_m at $m_\nu > 0$

=> Most of these not specific to m_e model !
(only σ_T scaling)

Solving Mysteries

- We need more investigations into modified recombination
- We need to solve σ_T scaling better than just complicated x_e history

Already on it with Ito



=> Most of these not specific to m_e model !
(only σ_T scaling)

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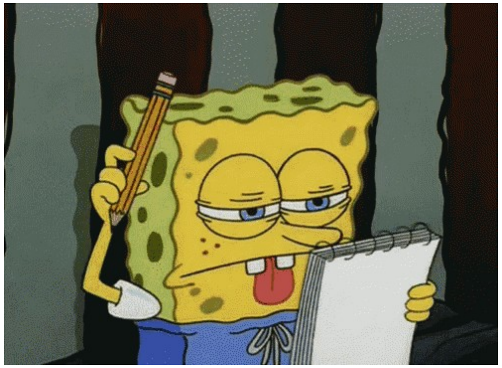
Explaining our first mysteries

$$z_* \approx \underbrace{\frac{E_{\mathrm{binding}}}{T_{\mathrm{cmb}}}}_{\mathrm{naive}} \cdot \underbrace{\frac{1}{40}}_{\mathrm{Saha}\ (\eta_{\mathrm{b}})} \cdot \underbrace{0.75}_{\mathrm{non-equilibrium}} \approx 1080$$



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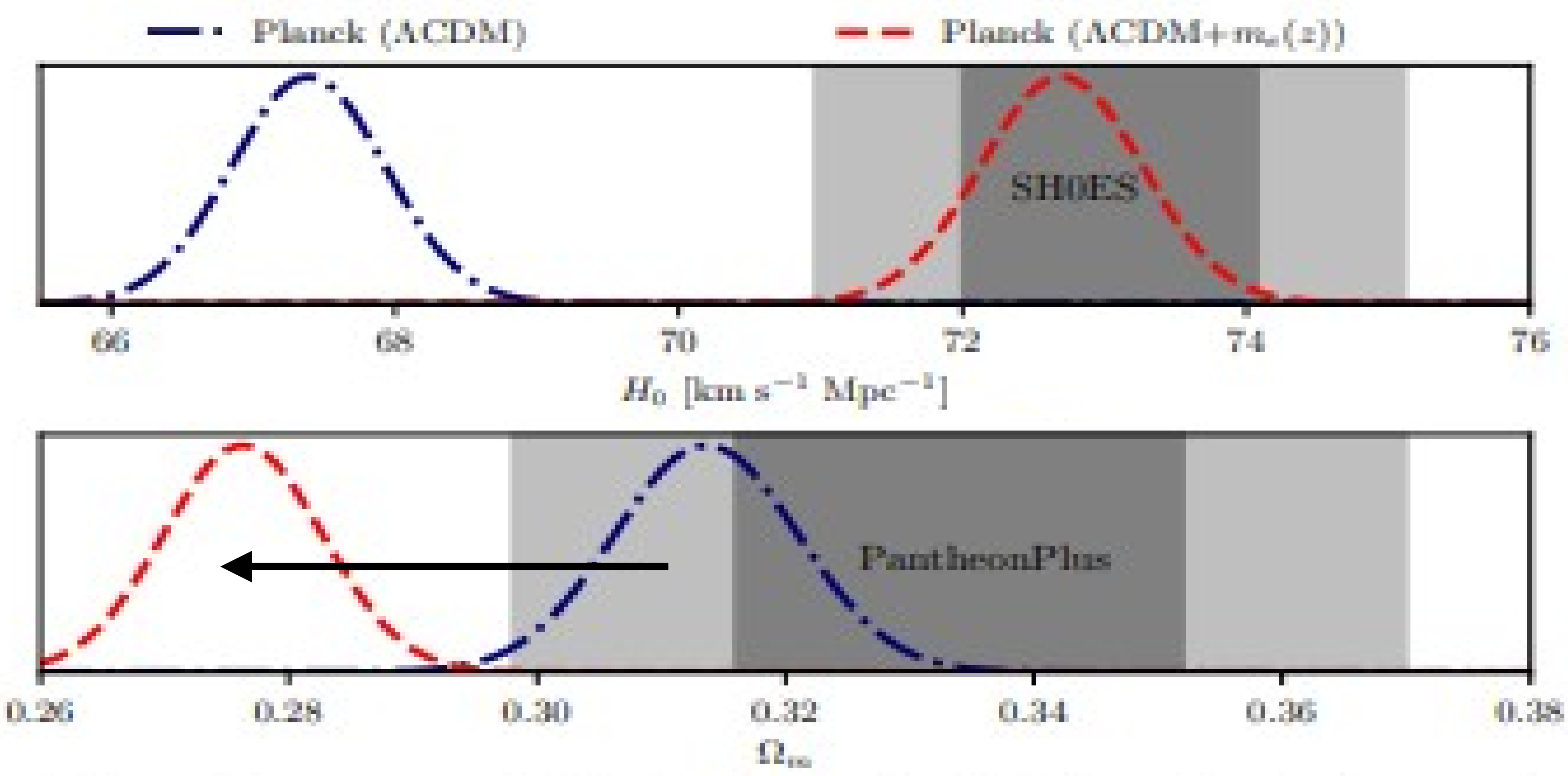

Lee+2212.04494

Supernova data does not like this type of models

By changing ℓ_{eq} we satisfy supernovae

→ Cost = play with other CMB parameters to balance first peaks (n_s, τ_{reio}, A_s, ...)

(not actually "liked",
e.g. disappears if we get rid of SN or satisfy otherwise)

↑

Supernova data does not like this type of models

Use curvature:

- Confuses supernovae data

Supernova data does not like this type of models

Use curvature:

- Confuses supernovae data

- Breaks angular diameter distance scaling

Supernova data does not like this type of models

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The natural direction

Curvature allows shallower slopes between h and a_*

$S_8 \propto h^{-0.86}$

$\Omega_m \propto h^{-1.7}$

$r_s \cdot h \propto h^{0.7}$

Assumption:
ΛCDM-like expansion history at low-z

$r_{\rm eq} \propto a_*$

$r_s \propto a_*$

$r_D \propto a_*$

$h \overset{!}{\propto} a_*^{-3.23}$

$R \rightarrow \omega_b \propto a_*^{-1}$

$\rho_m/\rho_r \rightarrow \omega_m \propto a_*^{-1}$

Use curvature:

- Confuses supernovae data

- Breaks angular diameter distance scaling

→ Breaks $\Omega_m \propto h^{-1.7}$

Use curvature:

- Confuses supernovae data
- Breaks angular diameter distance scaling

→ Breaks $\Omega_m \propto h^{-1.7}$

Careful: Curvature well constrained by CMB + BAO + SN

Use curvature:

- Confuses supernovae data

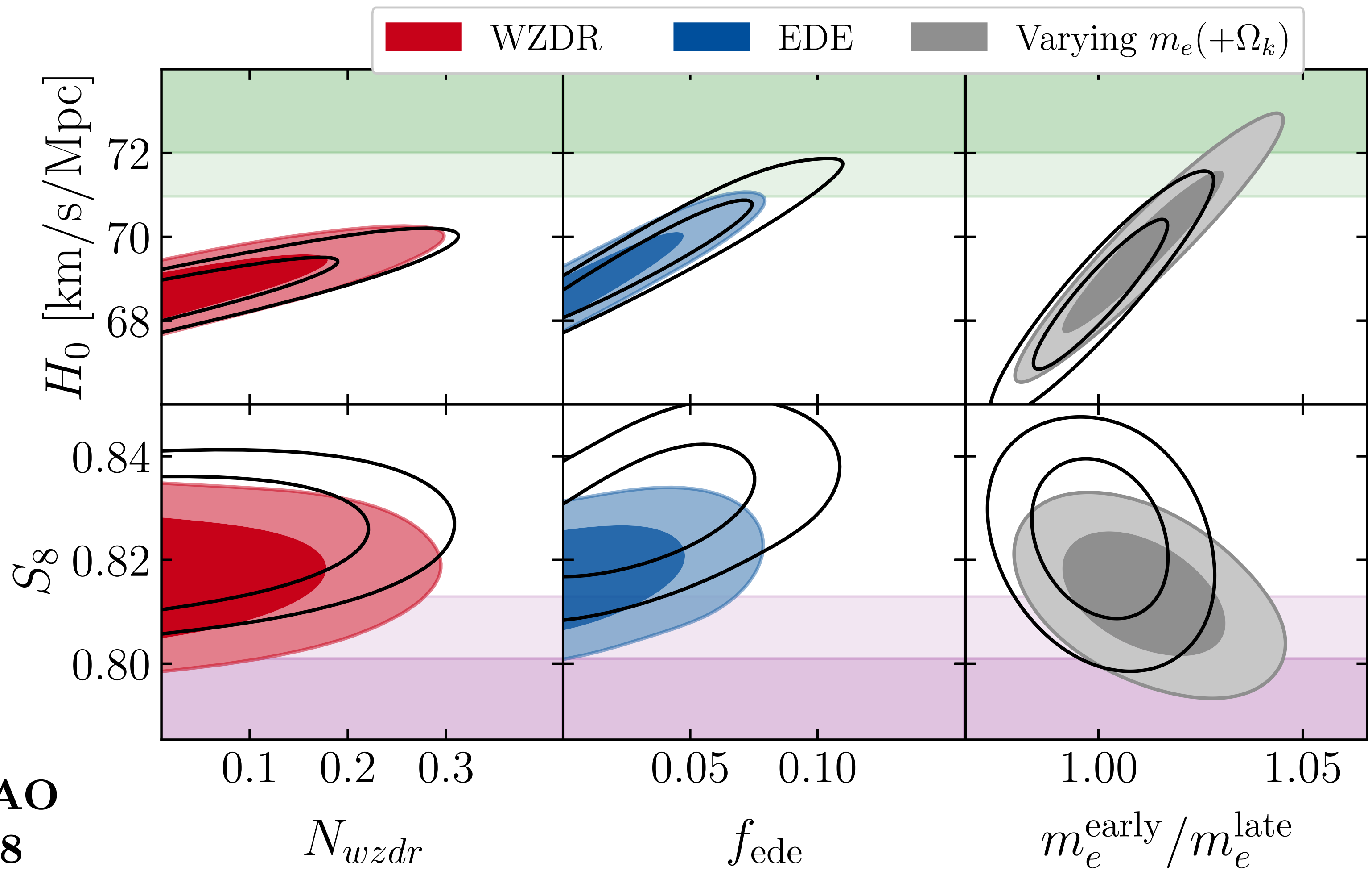
- Breaks angular diameter distance scaling

→ Breaks $\Omega_m \propto h^{-1.7}$

Careful: Curvature well constrained by CMB + BAO + SN

Curvature is *not* the only extension doing this !

Modified recombination is weird



CMB+BAO +SN + S8

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It's not a viable model

It's not a viable model

- We are using it as:

m_{e} = modified recombination + σ_{T} scaling

- It's just the *simplest* implementation of this mechanism!

(That does not make it realistic, of course)

It's not a viable model

- **Why not?** $h \propto m_e^{3.23} \Rightarrow \Delta m_e / m_e \simeq 2\%$

It's not a viable model

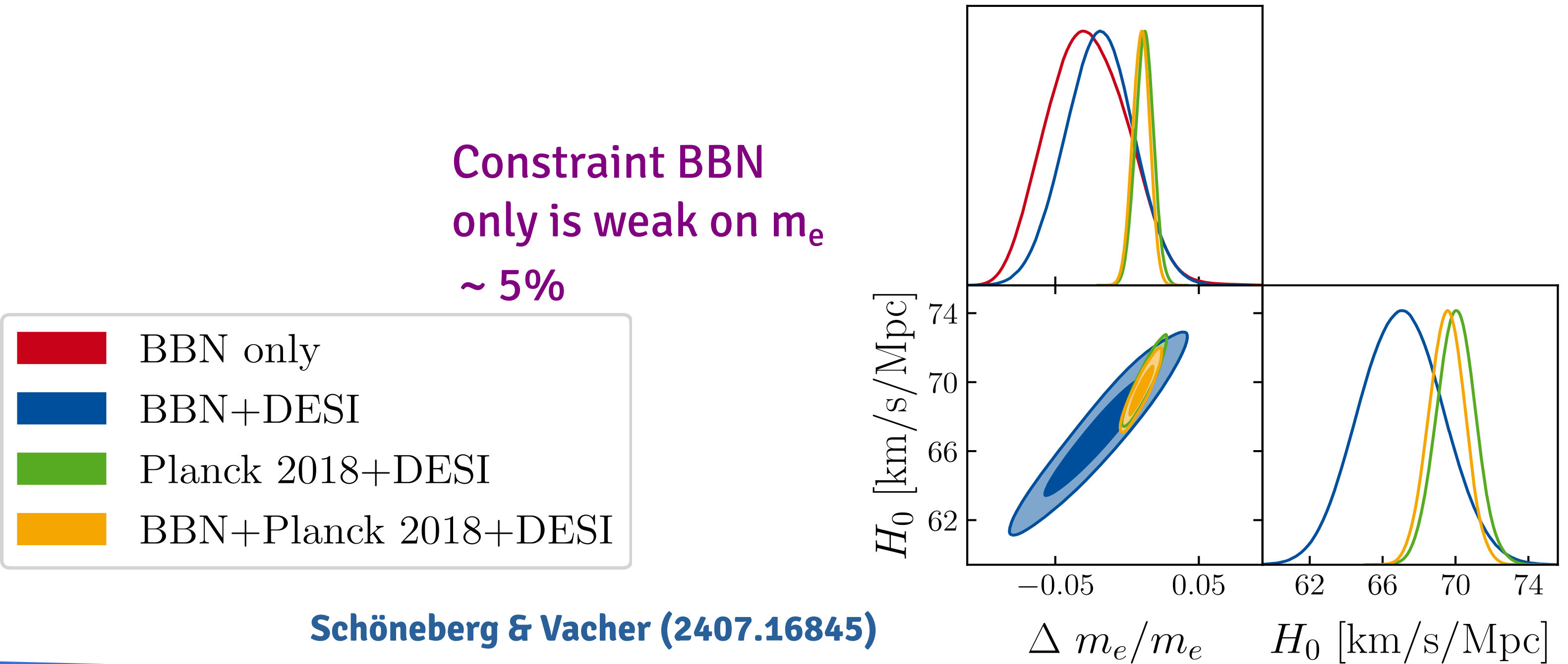
- **Why not?** $h \propto m_e^{3.23} \Rightarrow \Delta m_e / m_e \simeq 2\%$
  - BBN constraints (m_e influences weak rates, β decay)

It's not a viable model

- **Why not?** $h \propto m_e^{3.23} \Rightarrow \Delta m_e/m_e \simeq 2\%$
  - BBN constraints (m_e influences weak rates, β decay)

No big difference from BBN

Constraint BBN only is weak on m_e ~ 5%



Schöneberg & Vacher (2407.16845)

BBN Constraints

Garramone+(2602.05720)

D+^{4}He (PDG)	NACRE II	0.982 ± 0.029
	PRIMAT	$1.015^{+0.023}_{-0.013}$

D+^{4}He (LBT)	NACRE II	$0.986^{+0.013}_{-0.011}$
	PRIMAT	$0.994^{+0.017}_{-0.009}$

About 2% level constraint on m_e, but value depends a bit on adopted He4 constraints

→ PDG would be fine with it

BBN Constraints

Difference: also assumptions about G_F

→ V_{ud} Cabbibo angle and/or g_A nucleon axial coupling

→ Need a full UV-complete theory to compute QCD corrections to g_A from m_e variations

=> We cannot model-independently constrain m_e variations easily…

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It's not a viable model

- **Why not?** $h \propto m_e^{3.23} \Rightarrow \Delta m_e / m_e \simeq 2\%$
  - BBN constraints (m_e influences weak rates, β decay)
  - Direct quasar constraints?
    - Not necessarily sensitive enough (too low z to catch it)
    - Requires a model of how m_e shifts back to standard value

$$\left(\frac{\Delta\mu}{\mu}\right)_{Radio} = -0.24 \pm 0.09\, ppm$$

$$\left(\frac{\Delta\mu}{\mu}\right)_{Optical} = 2.9 \pm 1.9\, ppm\, ;$$

Martins (1709.02923)

$$\mu \propto m_e^{-1}$$

$$m_e(z_q) = (1 + 0.24 \cdot 10^{-6}) m_e^{\mathrm{late}}$$

It's not a viable model

- Why not? $h \propto m_e^{3.23} \Rightarrow \Delta m_e/m_e \simeq 2\%$
  - BBN constraints ($m_{\rm e}$ influences weak rates, β decay)
  - Direct quasar constraints?
    - Not necessarily sensitive enough (too low z to catch it)
    - Requires a model of how $m_{\rm e}$ shifts back to standard value
    - Might actually be beneficial…

It's not a viable model

- Why not? $h \propto m_e^{3.23} \Rightarrow \Delta m_e/m_e \simeq 2\%$
  - BBN constraints (m_e influences weak rates, β decay)
  - Direct quasar constraints? → Not really

It's not a viable model

- Why not? $h \propto m_e^{3.23} \Rightarrow \Delta m_e/m_e \simeq 2\%$
  - BBN constraints (m_e influences weak rates, β decay)
  - Direct quasar constraints? → Not really
  - Atomic clock constraints?
    - Again requires a model of how m_e settles back
    - Constraint strength (2407.16845): $|(\Delta m_e/m_e)_{z_\mathrm{CMB}}| \lesssim (2.3 \pm 1.6)\%$, (Order of magnitude estimate!)
    - Weakened by even small curvature presence

It's not a viable model

- Why not? $h \propto m_e^{3.23} \Rightarrow \Delta m_e/m_e \simeq 2\%$
  - BBN constraints (m_e influences weak rates, β decay)
  - Direct quasar constraints? → Not really
  - Atomic clock constraints? → Very barely no

It's not a viable model

- Why not? $h \propto m_e^{3.23} \Rightarrow \Delta m_e / m_e \simeq 2\%$
  - BBN constraints (m_e influences weak rates, β decay)
  - Direct quasar constraints? → Not really
  - Atomic clock constraints? → Very barely no
  - Fifth force constraints?

It's not a viable model

- Why not? $h \propto m_e^{3.23} \Rightarrow \Delta m_e / m_e \simeq 2\%$
  - BBN constraints (m_e influences weak rates, β decay)
  - Direct quasar constraints? → Not really
  - Atomic clock constraints? → Very barely no
  - Fifth force constraints?
    - Weiner+ argues in **2502.04432** that no (quadratic coupling)
    - Others argue that still yes due to e.g. loop corrections
    - Above my pay grade to judge

It's not a viable model

- Why not? $h \propto m_e^{3.23} \Rightarrow \Delta m_e/m_e \simeq 2\%$
  - BBN constraints (m_e influences weak rates, β decay)
  - Direct quasar constraints? → Not really
  - Atomic clock constraints? → Very barely no
  - Fifth force constraints? → Maybe?

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It's not a viable model

- Why not? $h \propto m_e^{3.23} \Rightarrow \Delta m_e / m_e \simeq 2\%$
  - BBN constraints (m_e influences weak rates, β decay)
  - Direct quasar constraints? → Not really
  - Atomic clock constraints? → Very barely no
  - Fifth force constraints? → Maybe?
  - Cannot be realized?
    - Appears possible, multiple options even
    - Yukawa (Randall-Sundrum), Higgs vacuum change
    - Maybe even GUT/extra dimensions, Symmetron (2201.03127)

It's not a viable model

- Why not? $h \propto m_e^{3.23} \Rightarrow \Delta m_e/m_e \simeq 2\%$
  - BBN constraints (m_e influences weak rates, β decay)
  - Direct quasar constraints? → Not really
  - Atomic clock constraints? → Very barely no
  - Fifth force constraints? → Maybe?
  - Cannot be realized? → Probably can be

It's not a viable model

- So far no definite conclusion reached on UV theory

- However, importantly, we are using it as:
  m_e = modified recombination + σ_T scaling

- It's just the *simplest* implementation of this mechanism!

How to differentiate it from EDE

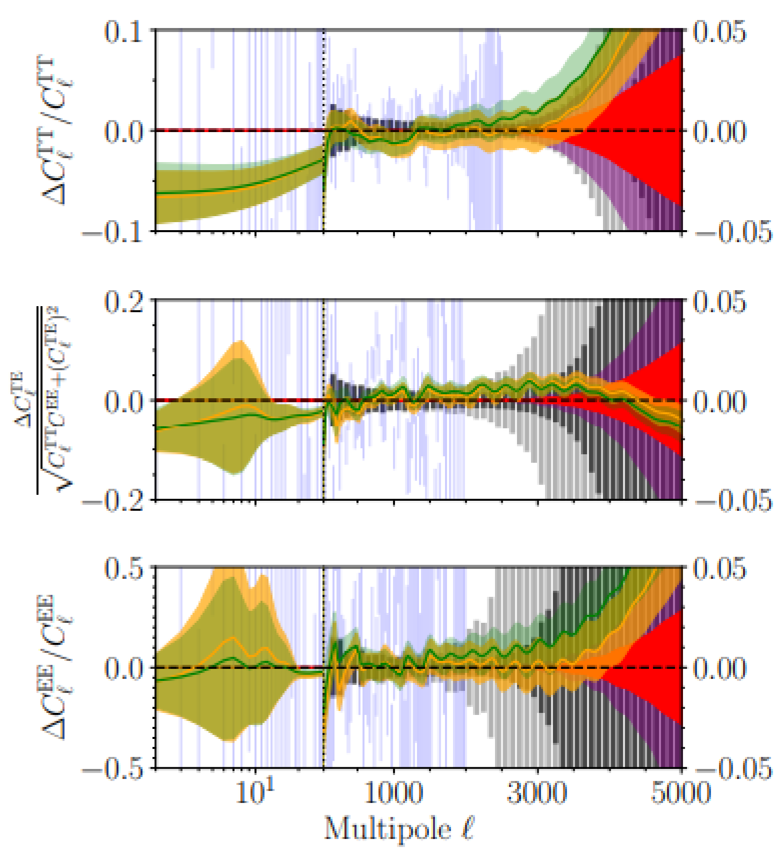


Figure 2. Same as figure 1 but for EDE (orange) fluid-like EDE model (green).

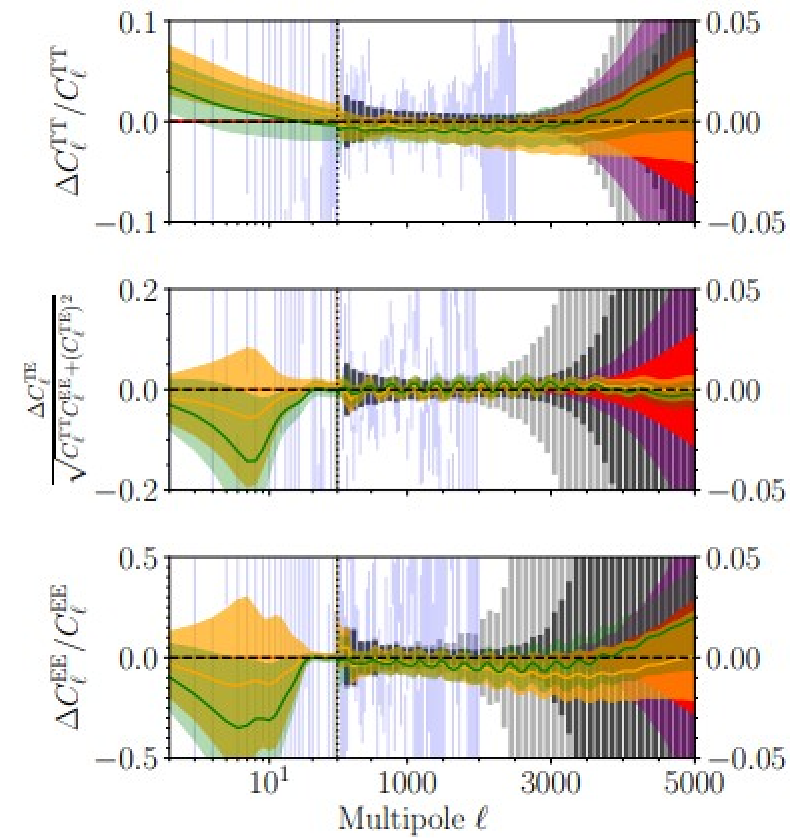
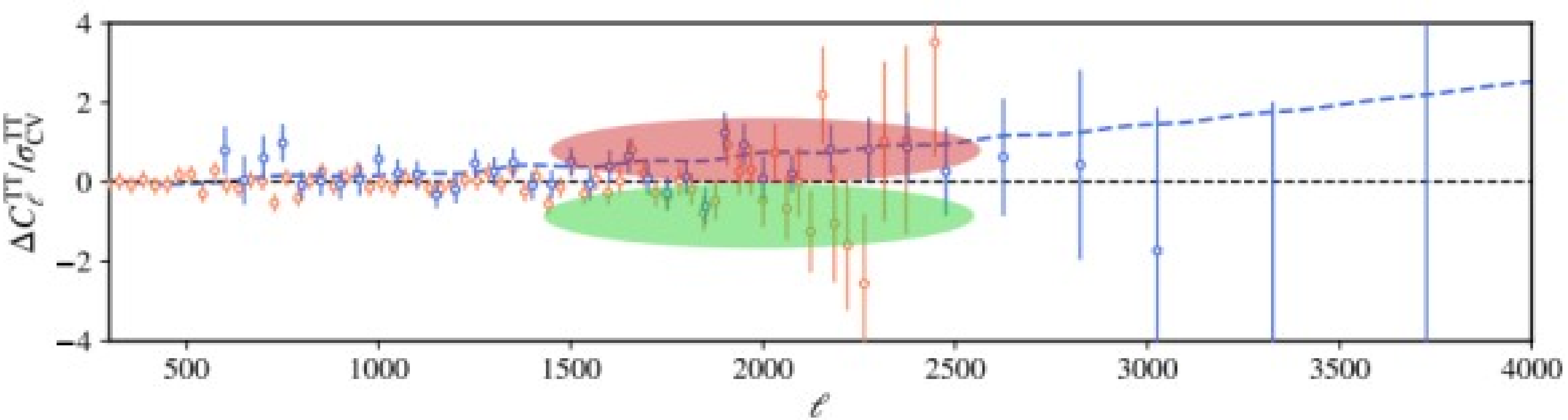


Figure 4. As in figure 1, but for a model with a time-variation of the electron mass. We show the predictions for the baseline model in orange and with additional curvature allowed in green.

How to differentiate it from EDE

See also Talk by Rodrigo Calderon



ACT data likes EDE-like upturn

→ ACT data does not like me

Further confirmation with SO

Summary

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Summary

- It's weird but exciting (toy model!)
- Natural direction:
  - $\boxed{\Omega_m \propto h^{-1.7}}$ $\boxed{r_s \cdot h \propto h^{0.7}}$ $\boxed{S_8 \propto h^{-0.86}}$
  - Liked by BAO data, S_8 data, neutrinos
- SN data does not like direction
  - Increasing ℓ_{eq} helps (playing with other parameters)
  - Using curvature helps
- ACT data doesn't like it, BBN maybe bad, quasar no constraint, atomic clock no constraint, fifth force maybe
- Model motivation hard (but not impossible → Higgs, Yukawa)

BACKUP SLIDES

The nail in the coffin

- Maybe the model can be ‘revived’ ?
- Vacher & Schöneberg (2403.02256) suggests: Most likely not

Generic bound $\Delta\alpha/\alpha$ at $5\cdot10^{-4}$ **

** : Applying to non-fine-tuned single scalar fields

The nail in the coffin

- → To be re-cycled for m_e constraints (!)

The nail in the coffin

- Idea: Use scalar field kinetics

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3 decades of time
with a speed 3/2

→ 3·3/2 = **4.5 decades** possible

Impossible to get 6 decades of deceleration

The nail in the coffin

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$$\Delta\alpha/\alpha(z_*) < 5\cdot 10^4 \cdot \left.\frac{\mathrm{d}\ln\alpha}{\mathrm{d}\ln a}\right|_{z=0}$$

$= 10^{4.7}$ **Primarily MD**

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$$\Delta\alpha/\alpha(z_*) < 5\cdot 10^{-4}$$ Stronger than CMB!

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$$\dot{\phi} = \underbrace{Ca^{-3}}_{\text{Cannot slow down faster!}} - \underbrace{a^{-3}\int \frac{a^3}{H}\frac{\mathrm{d}V}{\mathrm{d}\phi}\mathrm{d}\ln a}_{\text{Let's deal with this later!}}$$

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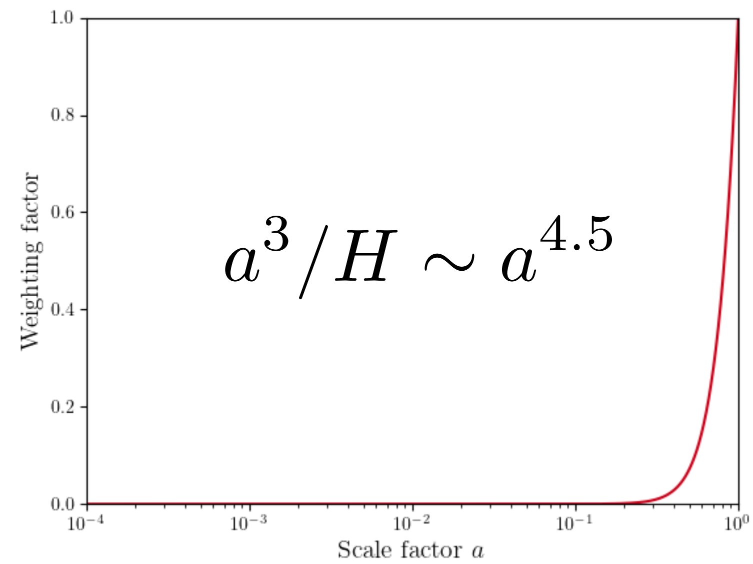

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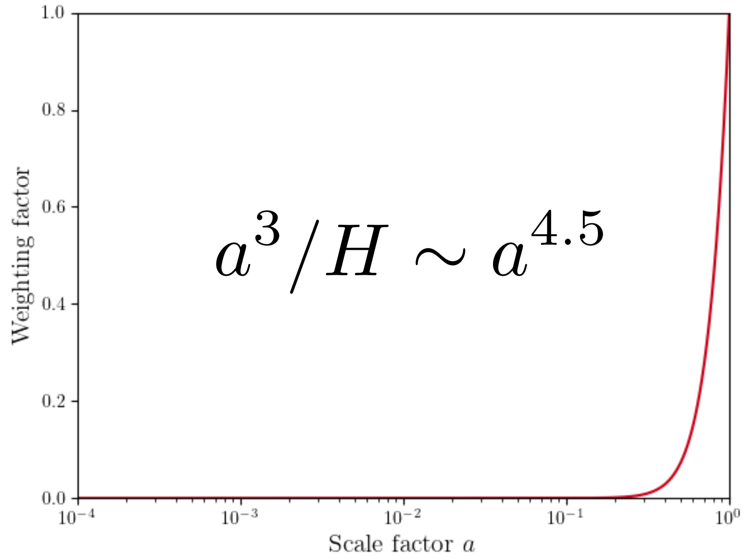

$a \gtrsim 0.2$

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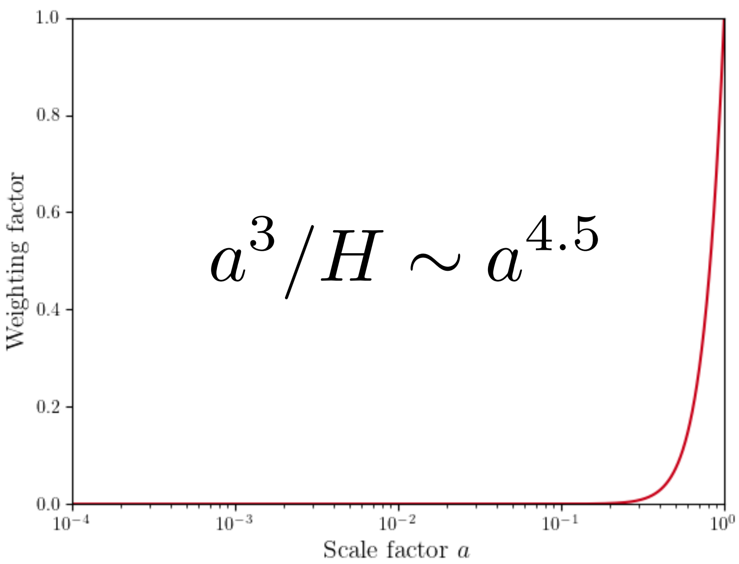

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Cannot slow down faster!

Requires extreme finetuning!
(only relevant towards a → 1)

The problem with alpha

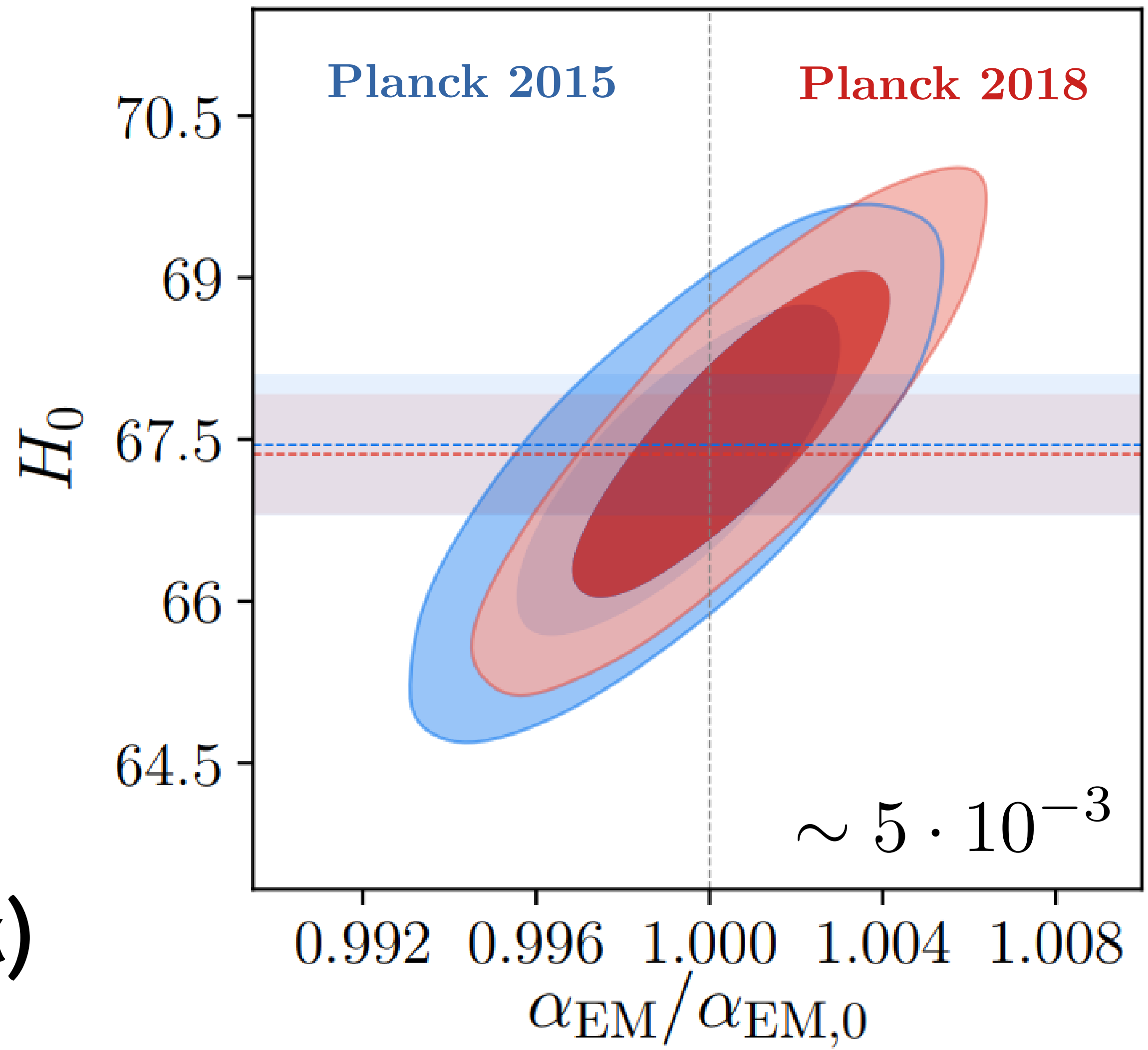
- Not a good solution!

- Why?

  → Silk damping

  (let's come back)

Hart & Chluba (1912.03986)



GETTING RID OF IT

- Single field kinetic constraint?

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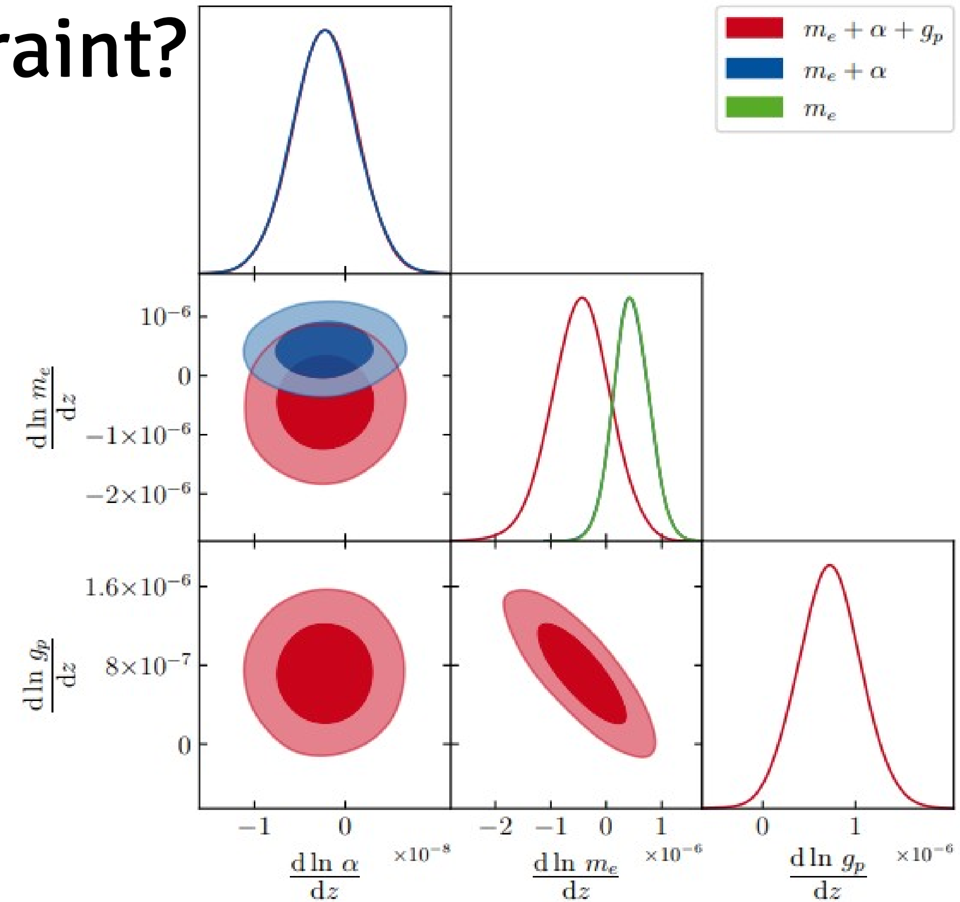
Getting rid of it

Schöneberg & Vacher (2407.16845)

- Single field kinetic constraint?

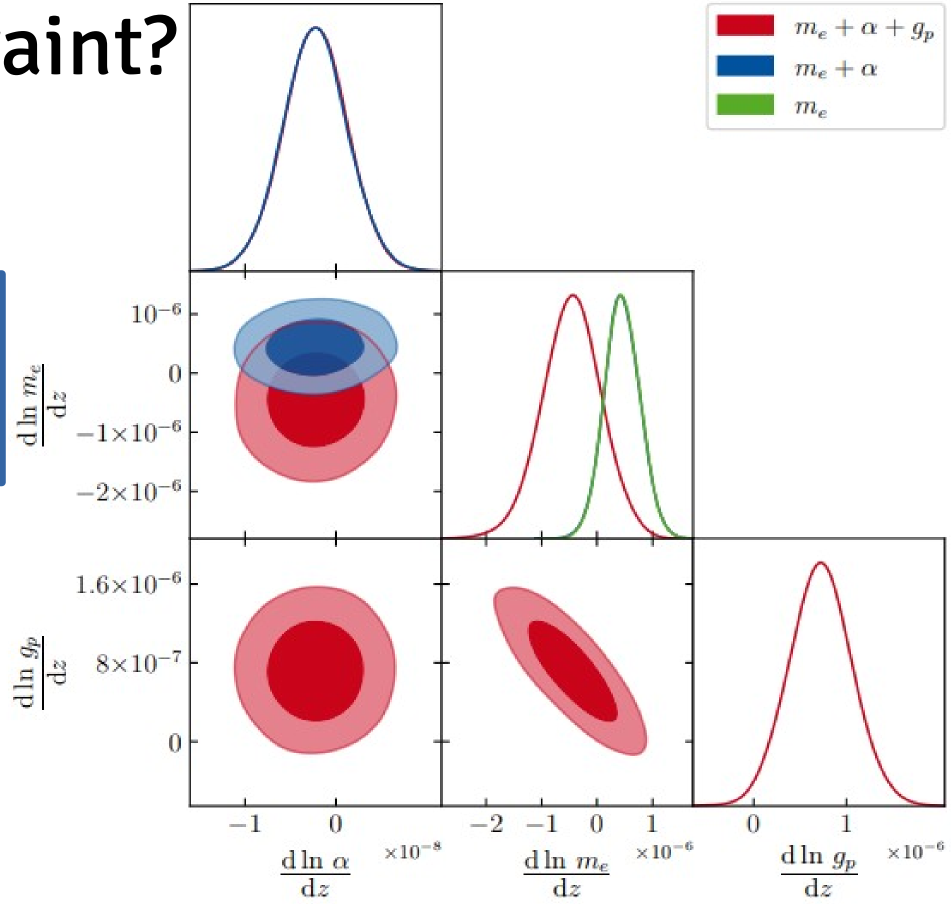


GETTING RID OF IT

Schöneberg & Vacher (2407.16845)

- Single field kinetic constraint?
- Less sensitivity to m_e

$$\boxed{\frac{\mathrm{d}\ln\alpha}{\mathrm{d}z} \sim 10^{-8} \quad \text{vs} \quad \frac{\mathrm{d}\ln m_e}{\mathrm{d}z} \sim 10^{-6}}$$



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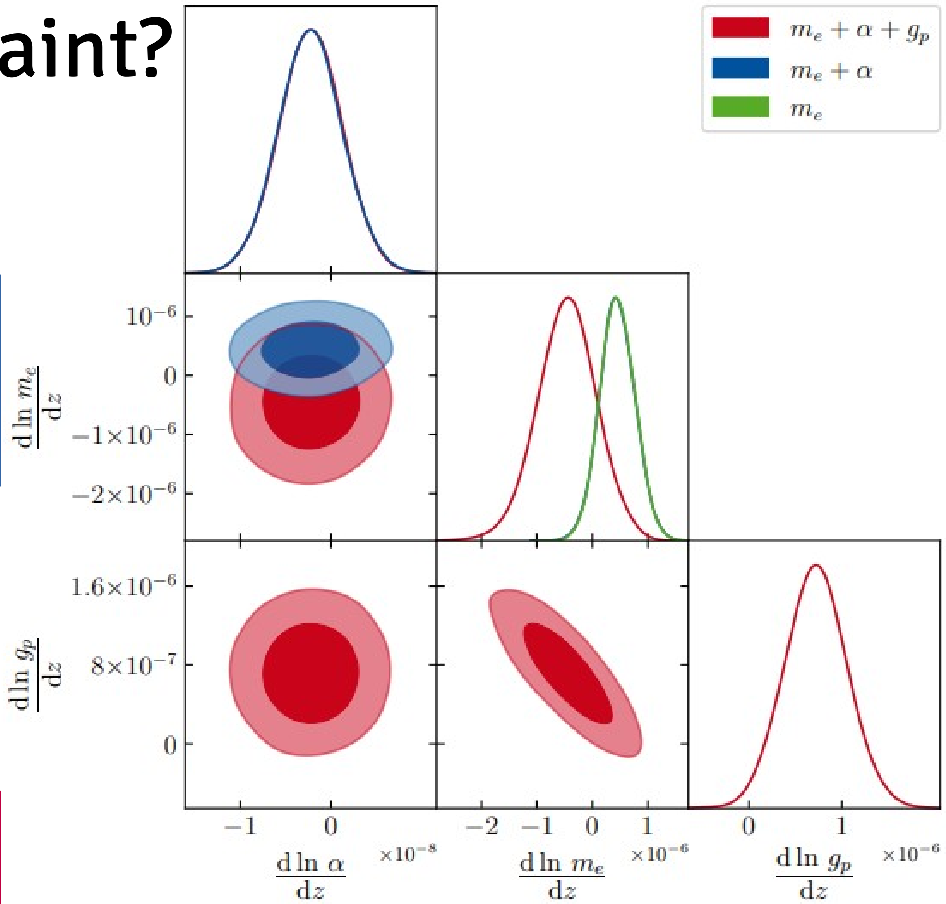
Two EM transitions → α

EM and hyperfine transitions → α and μ

$\mu = m_p/m_e$

$$\rightarrow \boxed{\begin{array}{ccc} 5\cdot 10^{-4} & \text{vs} & 5\cdot 10^{-2} \\ \Delta\alpha/\alpha & & \Delta m_e/m_e \end{array}}$$



The little solution that could

- Same problem for m_e?

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The little solution that could

- Same problem for m_e? No!

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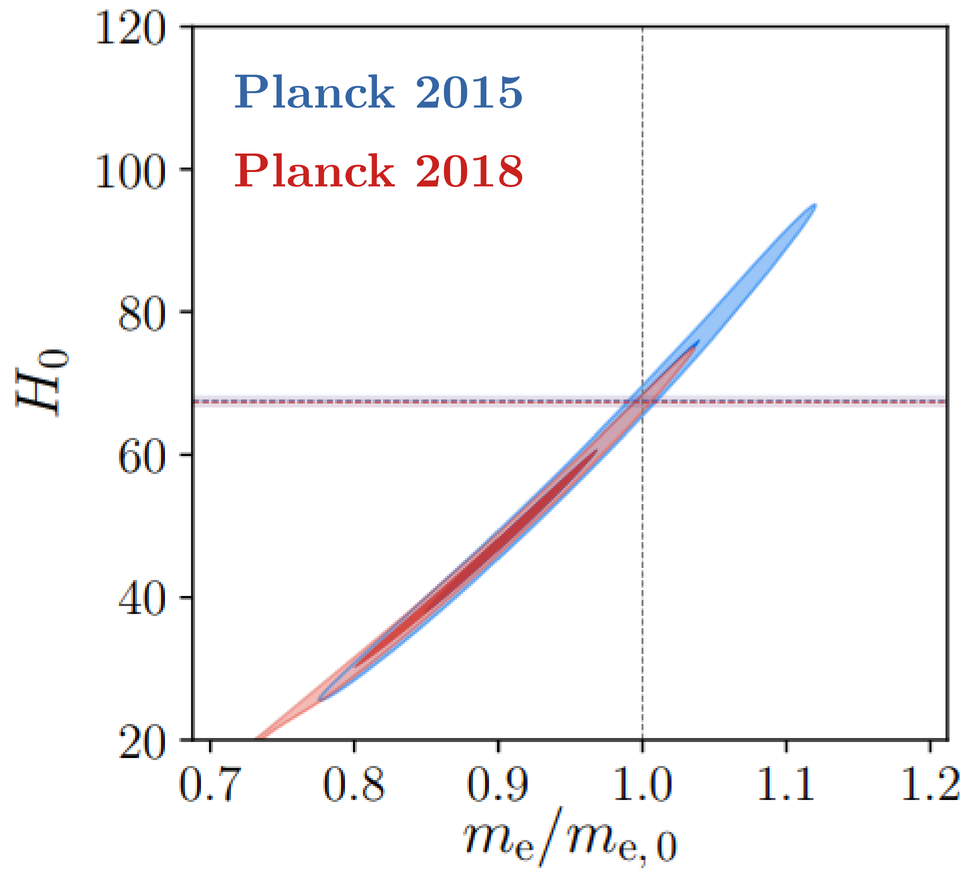

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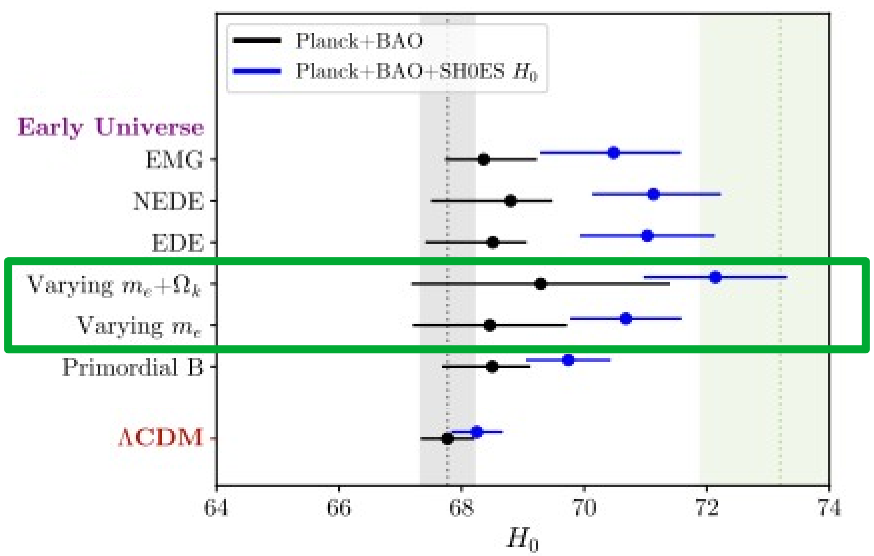
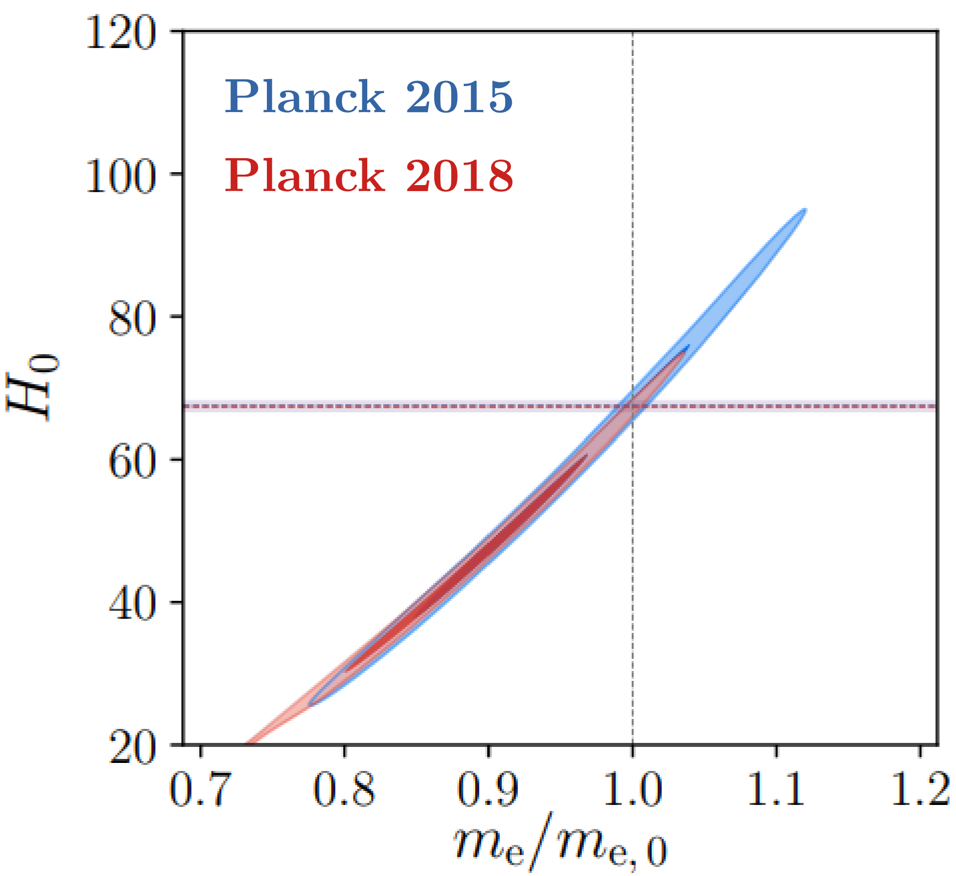
Schöneberg+ (2107.10291)



Gold medal in H_0 olympics?!

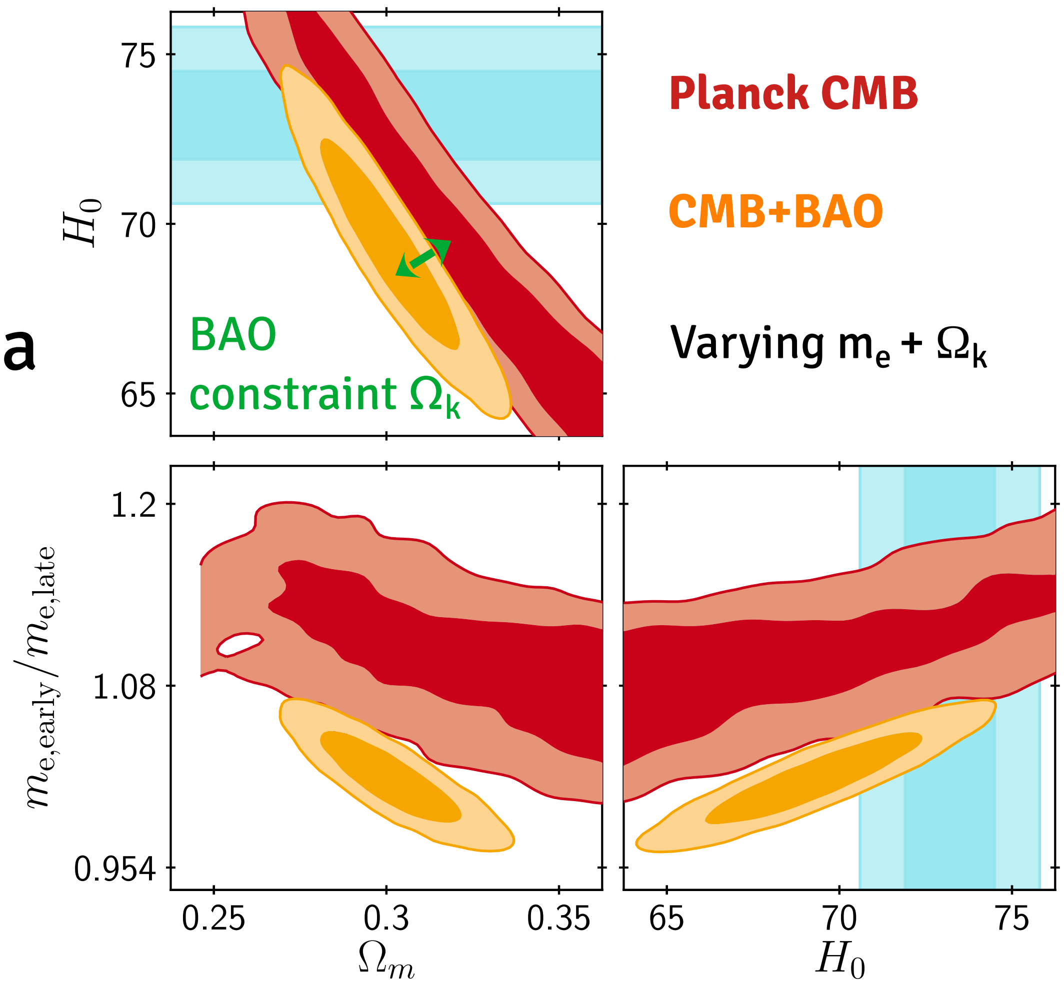
Hart & Chluba (1912.03986)



The little solution that could

Schöneberg+ (2107.10291)

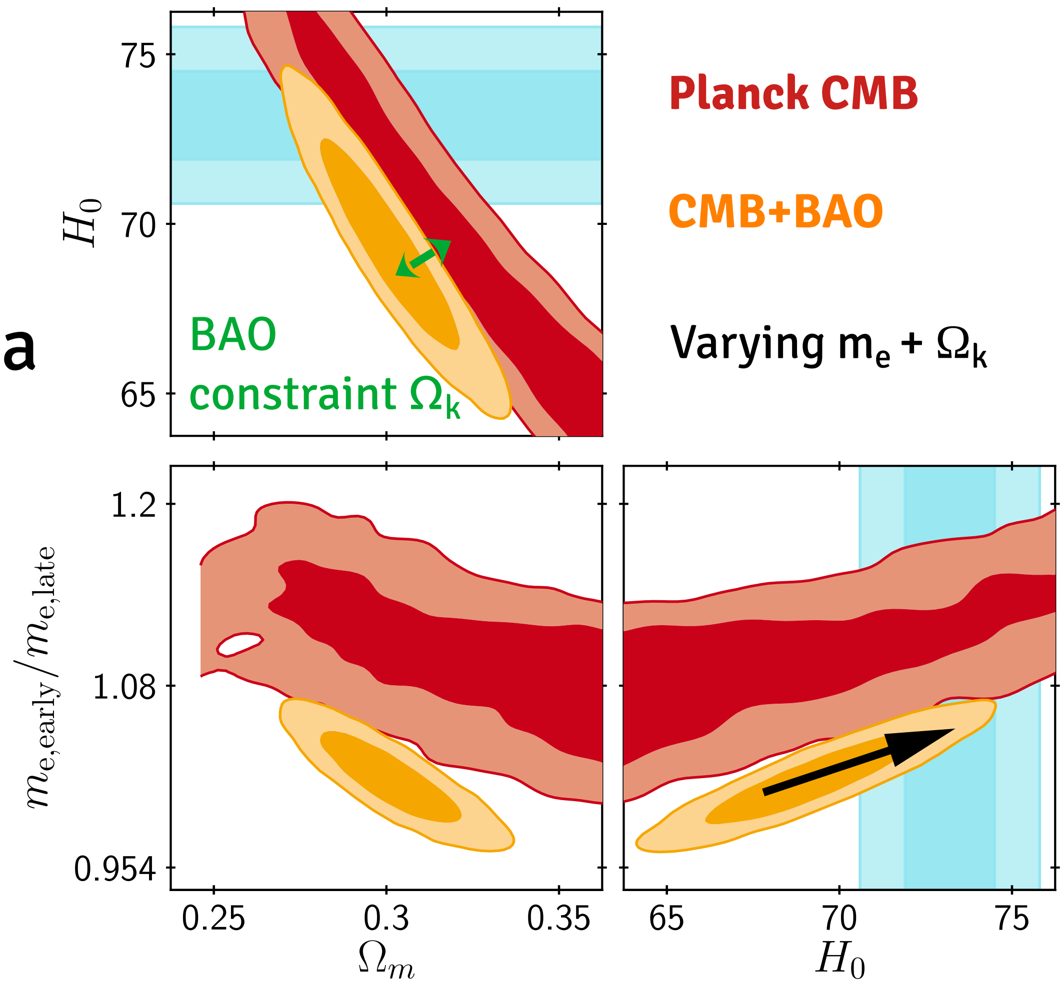
- Double trouble:
  - Ω_k breaks $\quad h \propto a_*^{-3.23}$
  - Ω_k 'confuses' BAO/SN data



The little solution that could

- Double trouble:
  - Ω_k breaks $h \propto a_*^{-3.23}$
  - Ω_k ‘confuses’ BAO/SN data
- → Works ‘well enough’ for current constraints

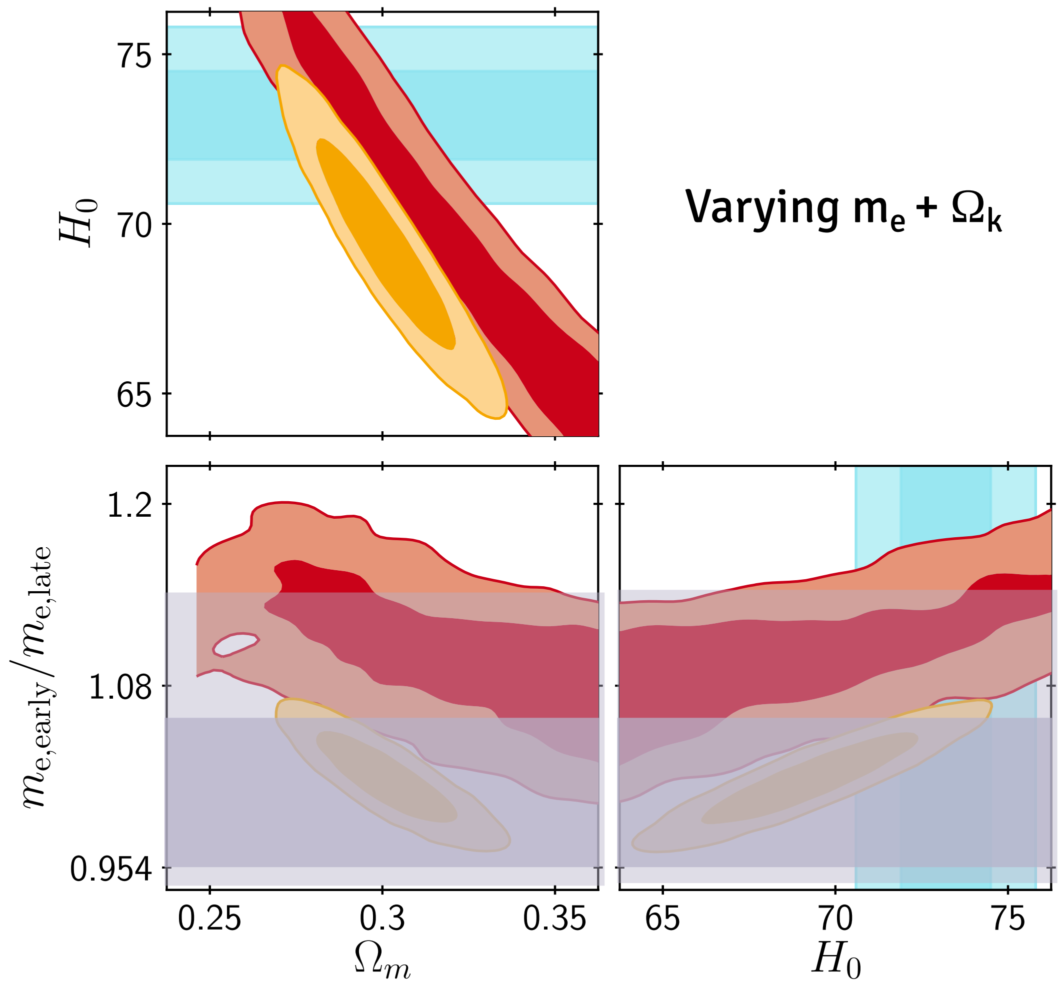
Schöneberg+ (2107.10291)



The little solution that could

Schöneberg+ (2107.10291)

- $5\ 10^{-2}$ is not good enough



Varying $m_e + \Omega_k$

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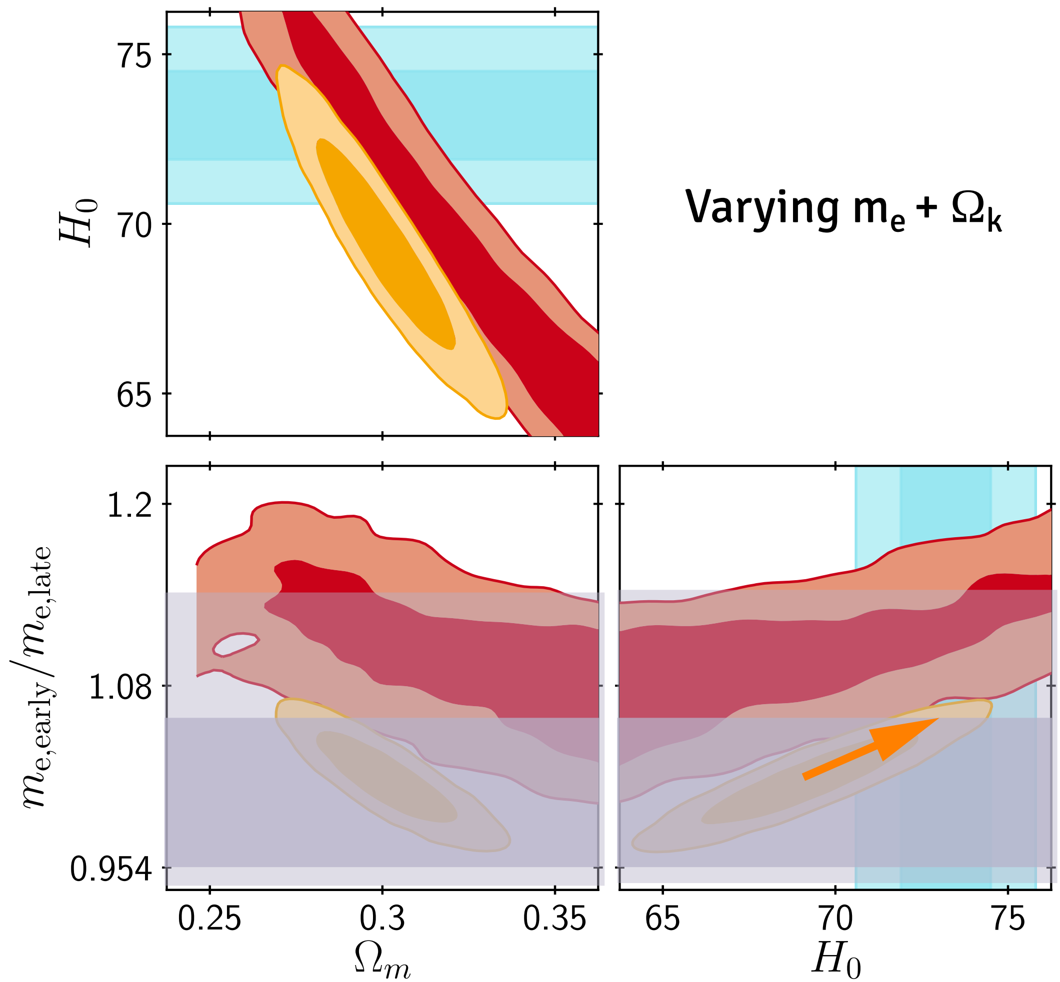

Varying $m_e + \Omega_k$

GETTING RID OF IT

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- New DESI data?

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Getting rid of it

- Single field kinetic constraint? → No
- New DESI data? → Even favored!
- BBN data?!

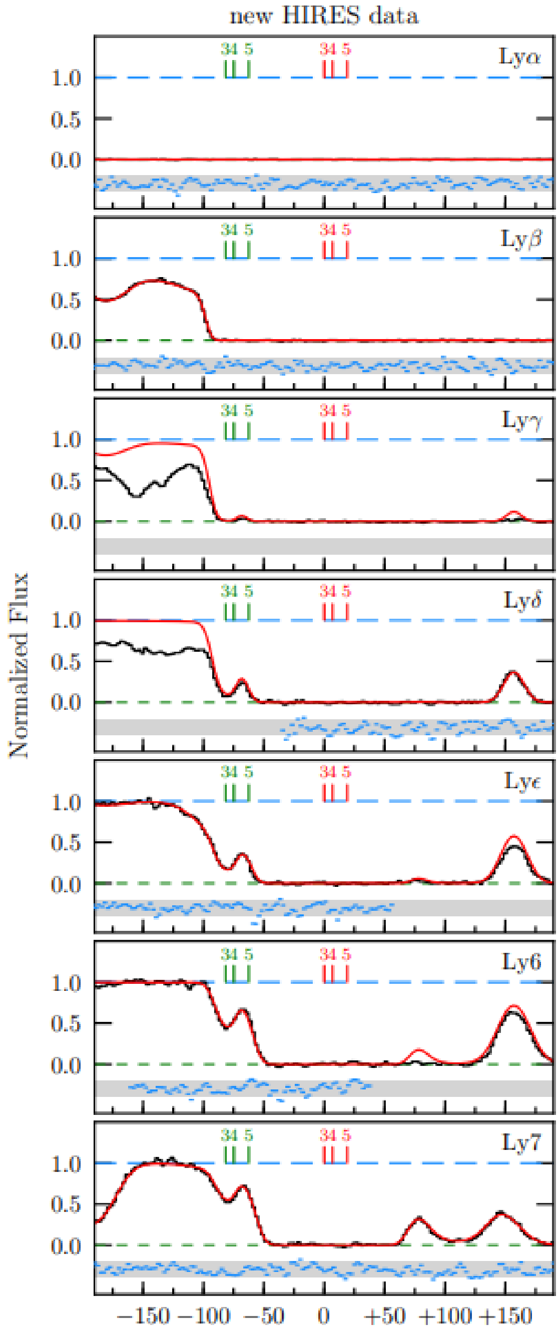
Interlude

Gruber price cosmology 2025:
Ryan Cooke, Max Pettini $\rightarrow$ D/H measurement

$$E_{\text{bind}} = \frac{1}{2} m_e \alpha^2 \longrightarrow E_{\text{bind}} = \frac{1}{2} \mu_e \alpha^2 = \frac{1}{2} \frac{m_e m_{\text{nucleus}}}{m_e + m_{\text{nucleus}}} \alpha^2$$

$$\lambda_{\text{Deuterium}} \approx \lambda_H \cdot \left(\frac{1 + m_e/m_D}{1 + m_e/m_H} \right) \approx \lambda_H \cdot \left(1 - \frac{1}{2} \frac{m_e}{m_p} \right) \approx \lambda_H \cdot 99.97\%$$

$$\delta\lambda/\lambda \sim 100\text{km/s}$$



INTERLUDE

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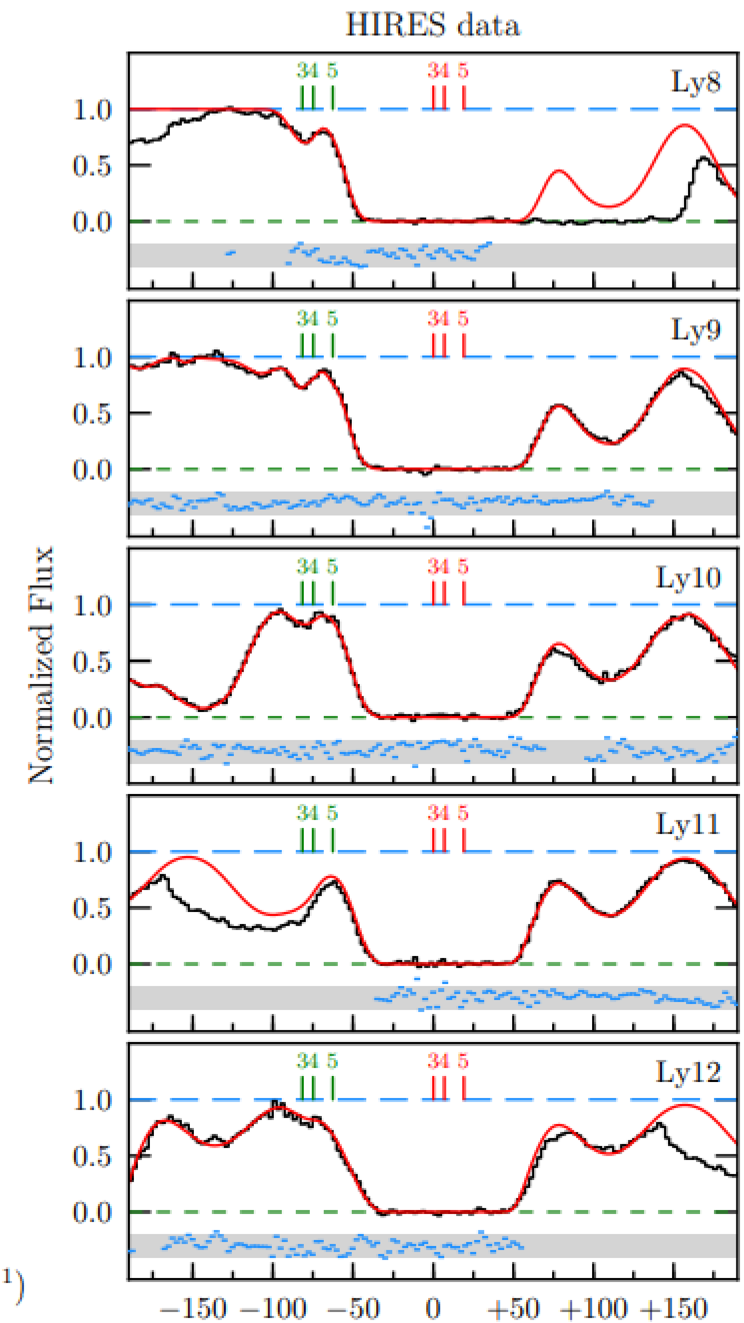

Velocity Relative to $z_{\rm abs} = 2.525640$ (km s^{-1})

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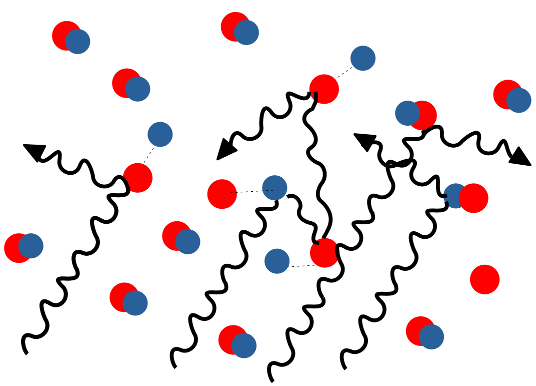
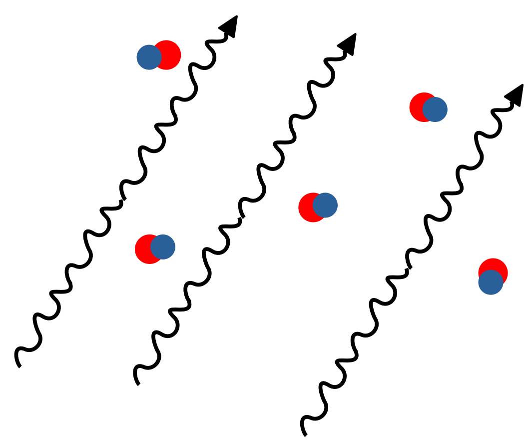
INTERLUDE

more baryons →
easier/earlier D burning →
hotter D burning →
more violent fusion →
less final D/H leftover





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→ $\Omega_b h^2$ prior

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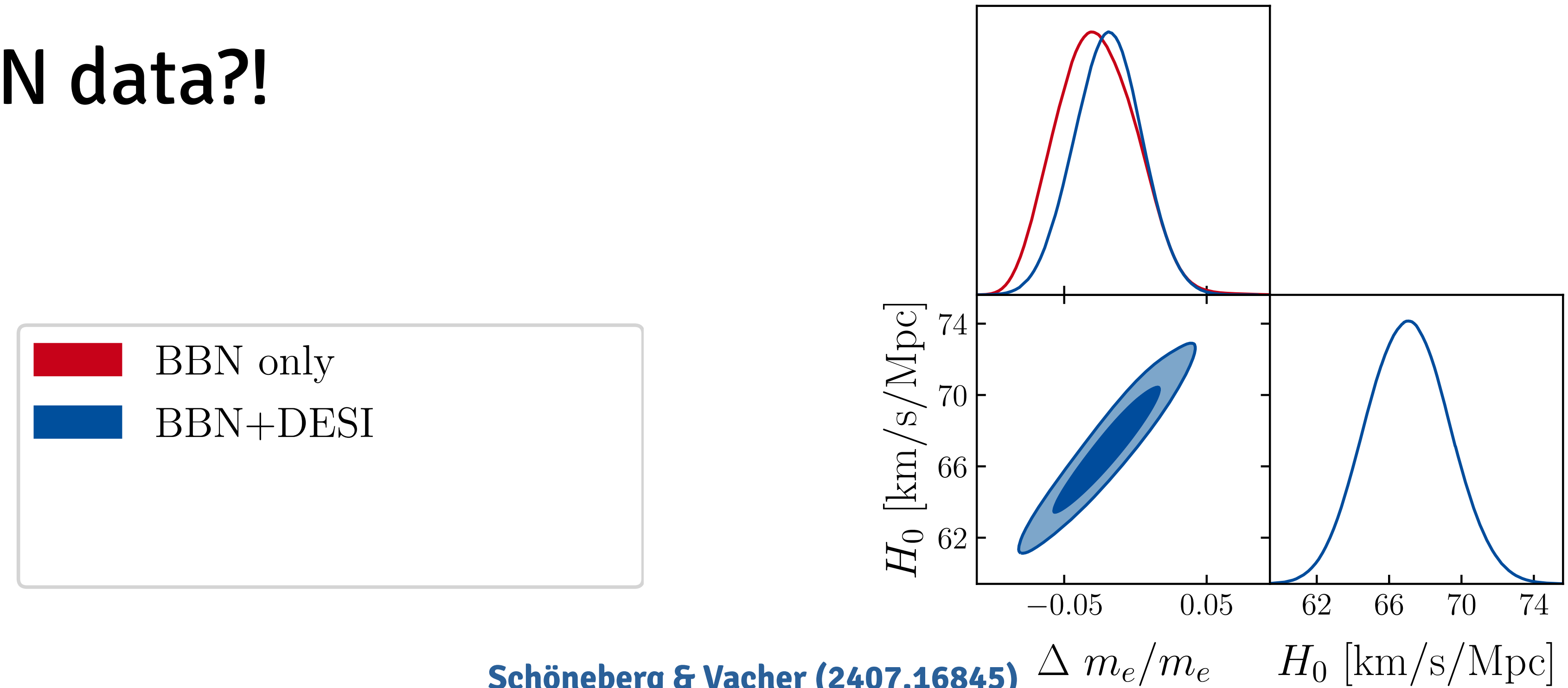

Schöneberg & Vacher (2407.16845)

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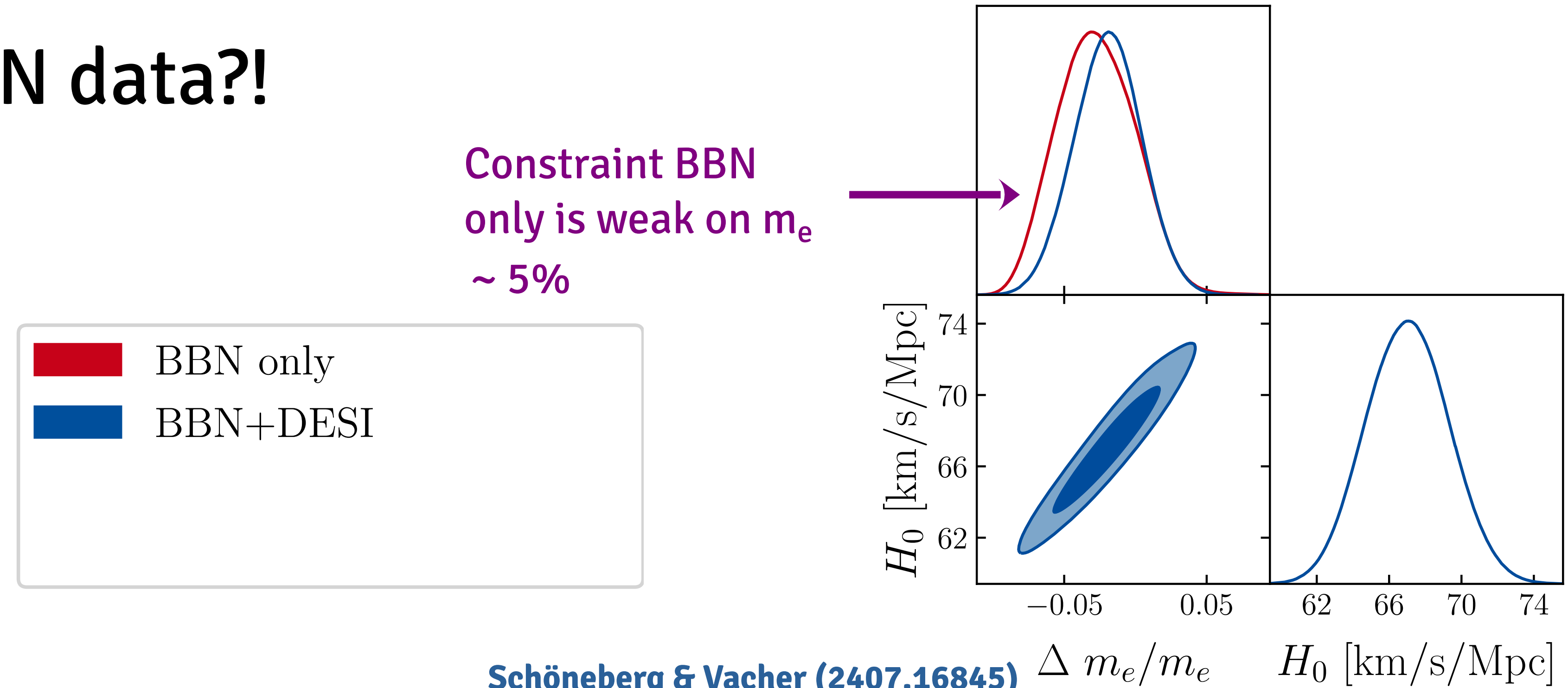
Constraint BBN only is weak on m_e ~ 5%



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No big difference from BBN

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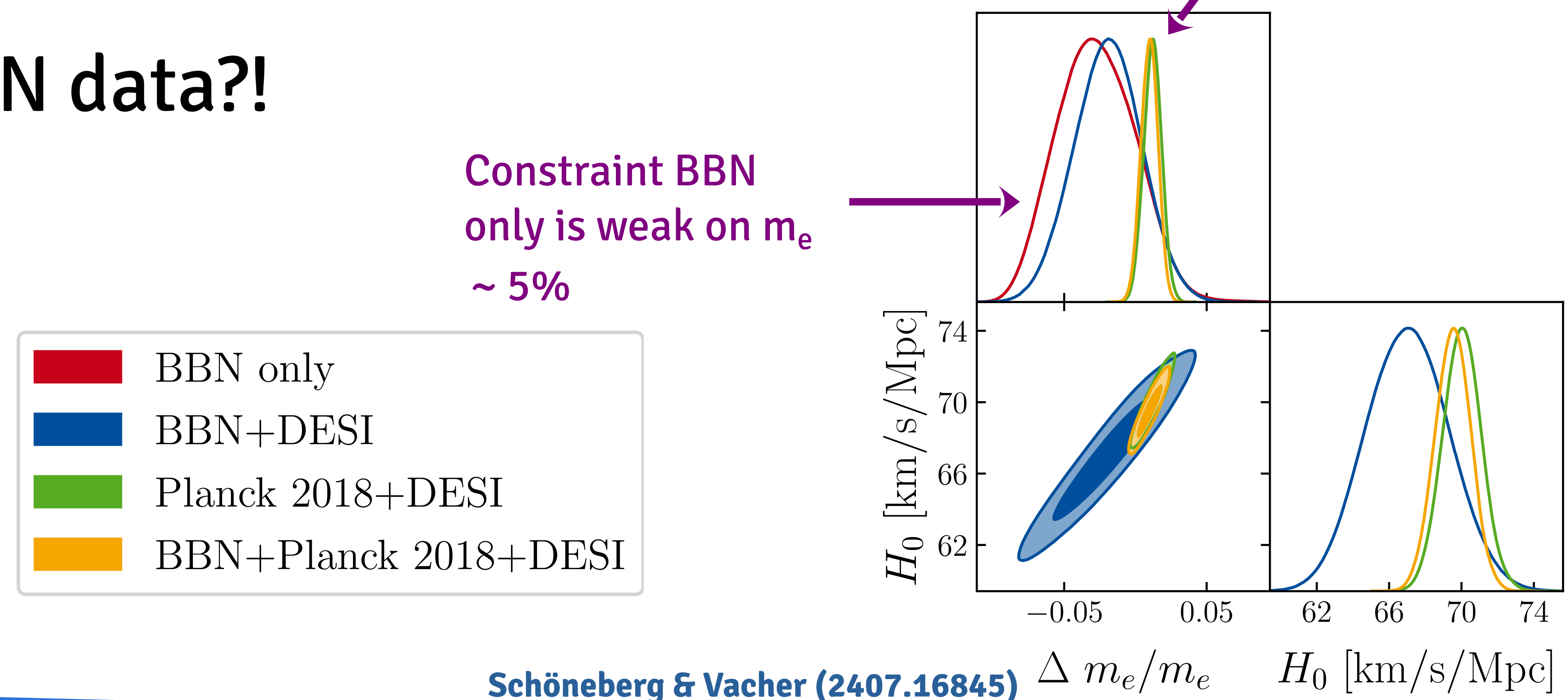

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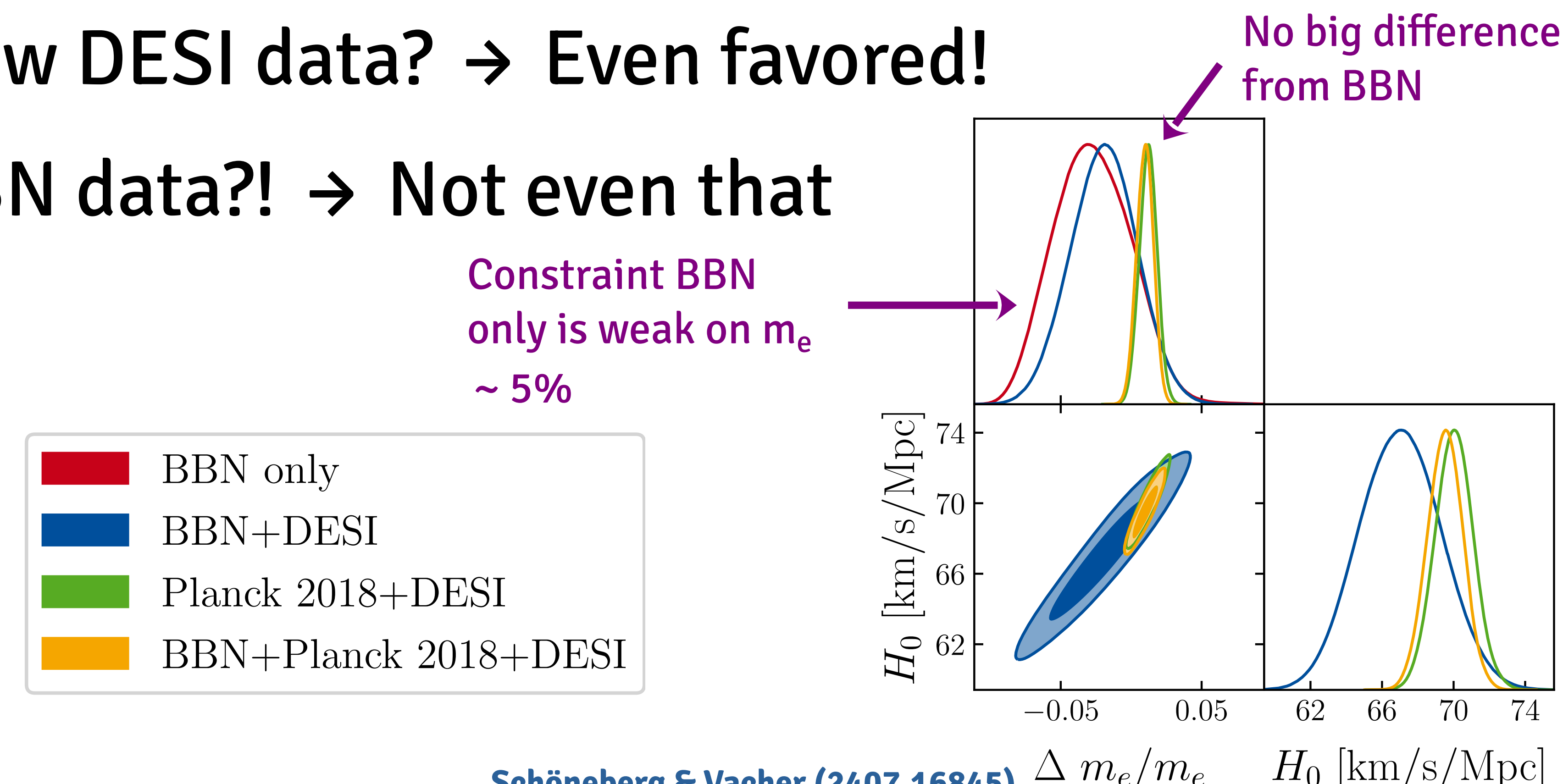

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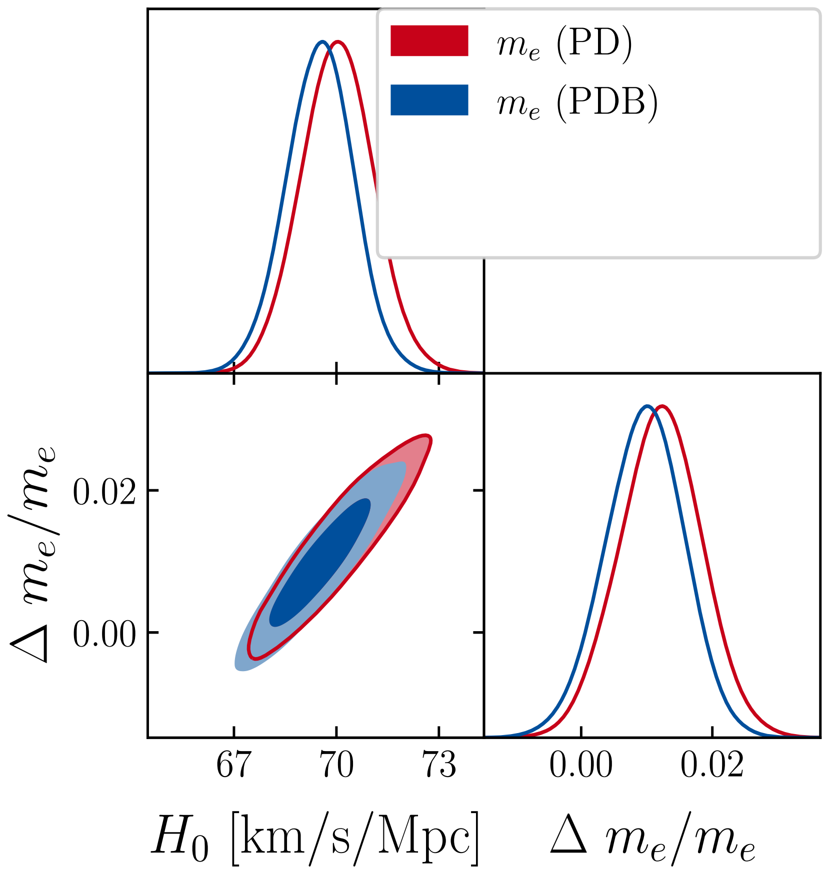
- Varying m_e is like a 

Getting rid of it

- Even with extensions, doesn't look much worse



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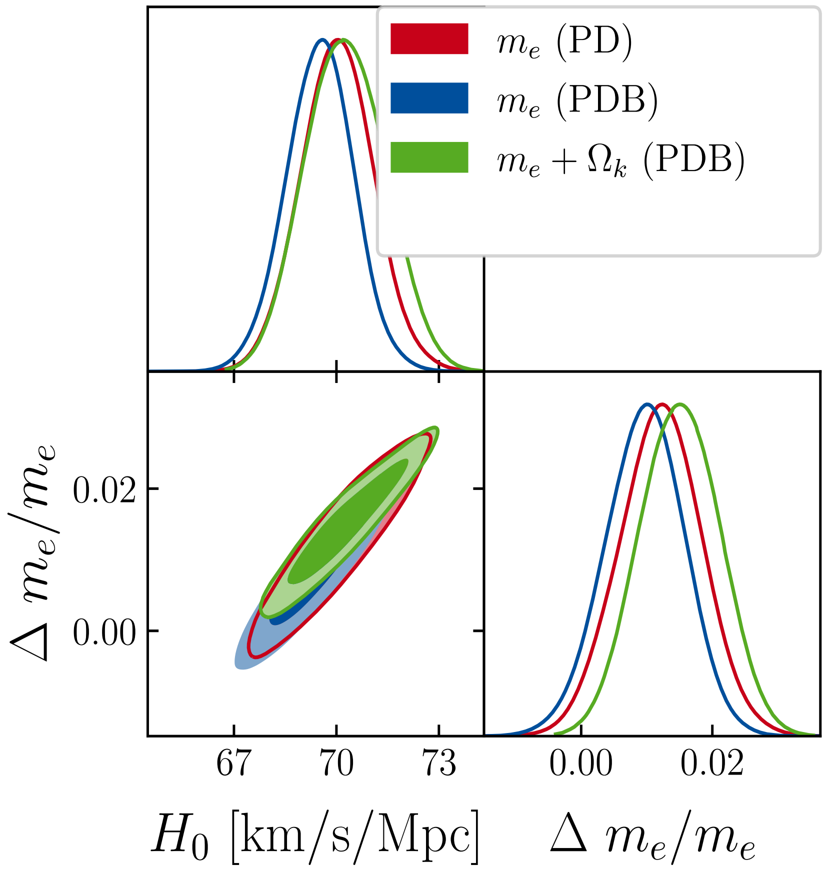

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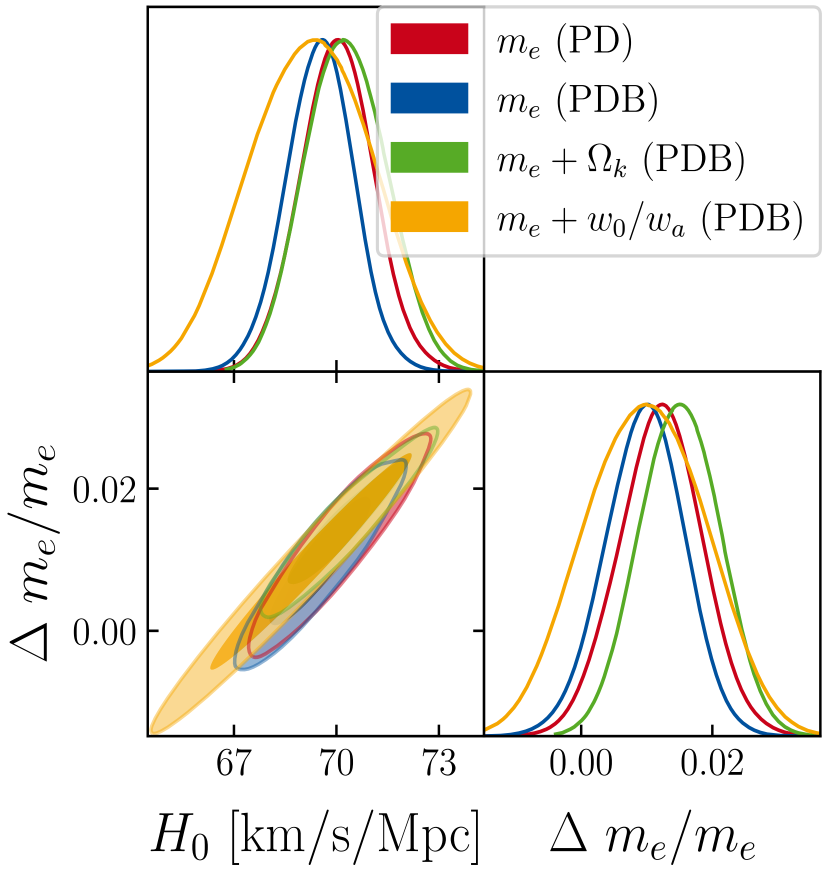

Schöneberg & Vacher (2407.16845)

How to differentiate it from EDE

- Different CMB
- Different cosmological parameters → structure growth → galaxy clustering + weak lensing