A Ratio-Preserving Approach to Cosmological Concordance

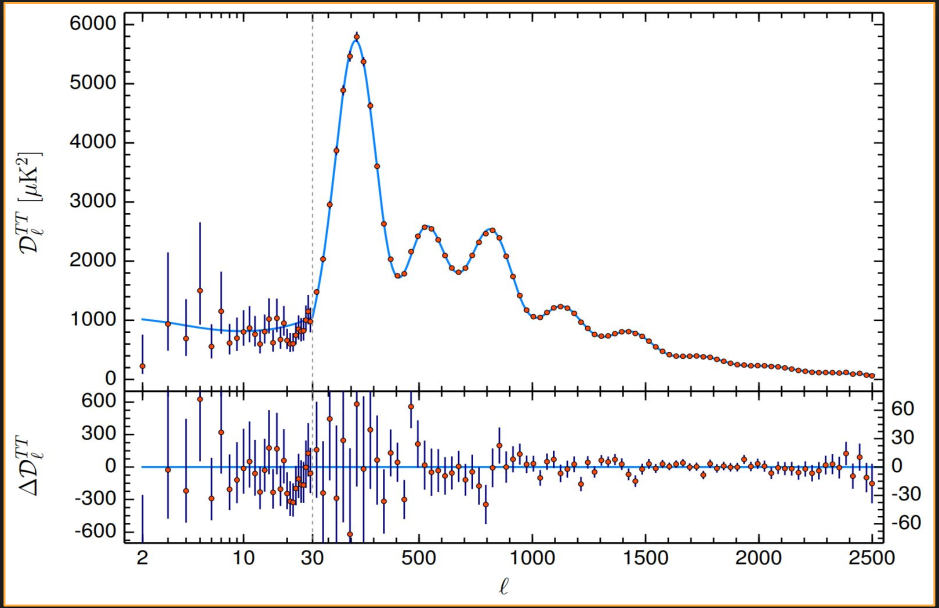
Kylar Greene

What is LCDM good at?

LCDM accurately predicts the observed anisotropies in the CMB.

What is LCDM good at?

LCDM accurately predicts the observed anisotropies in the CMB.

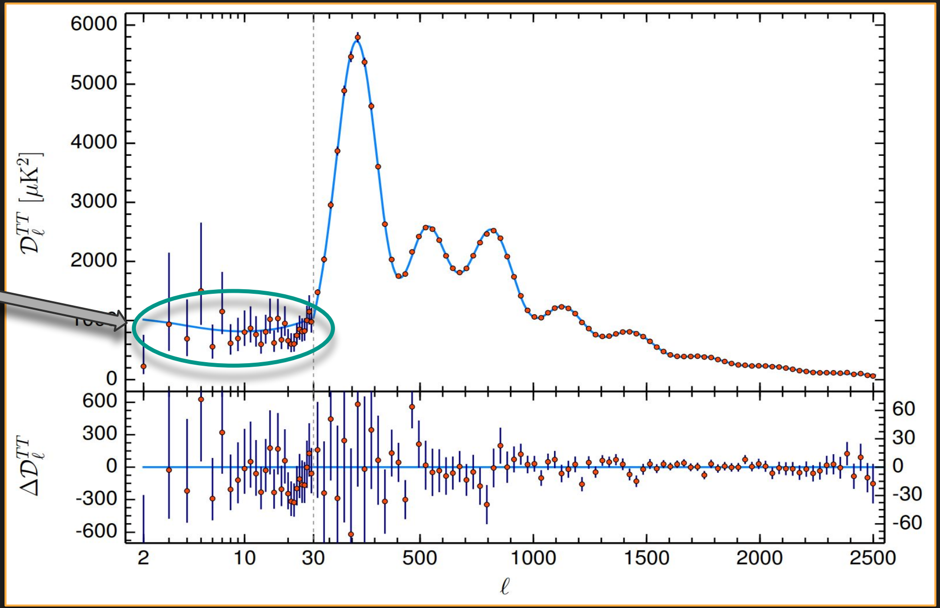


Planck 2018

What is LCDM good at?

LCDM accurately predicts the observed anisotropies in the CMB.

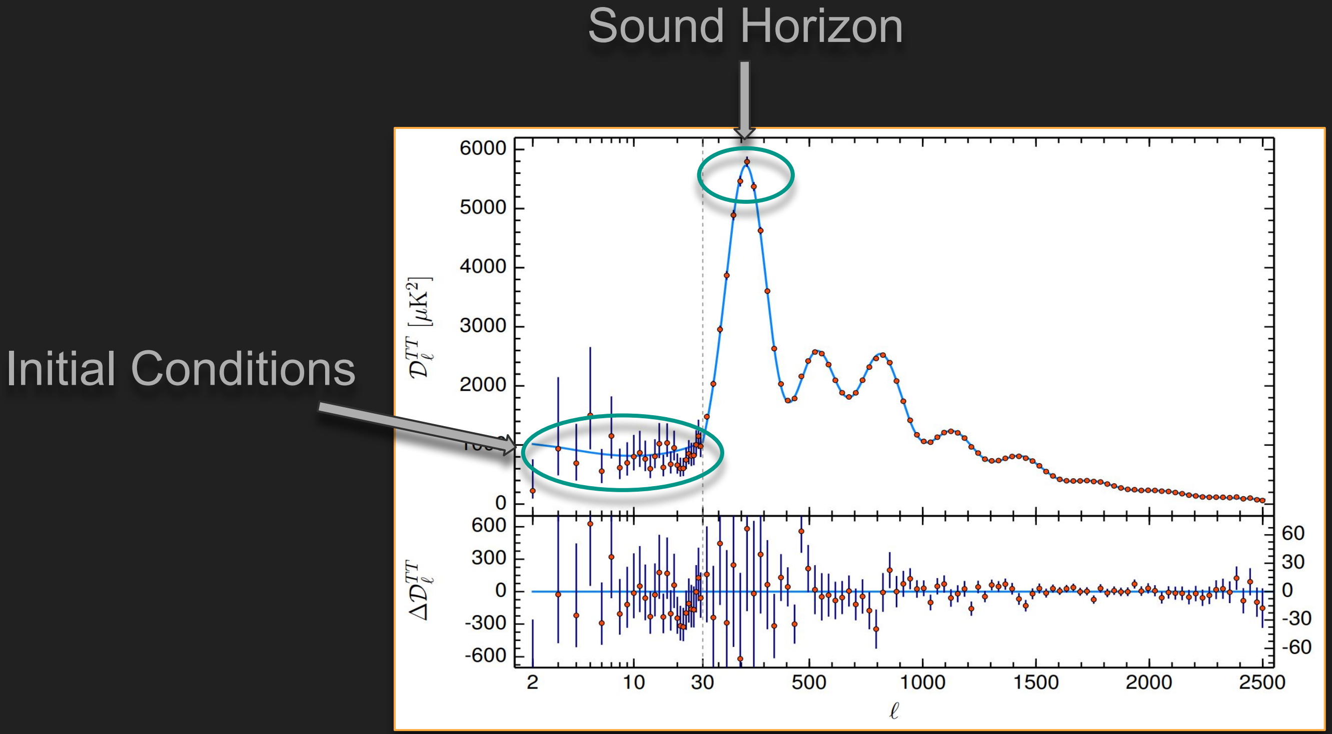
Initial Conditions



Planck 2018

What is LCDM good at?

LCDM accurately predicts the observed anisotropies in the CMB.



Planck 2018

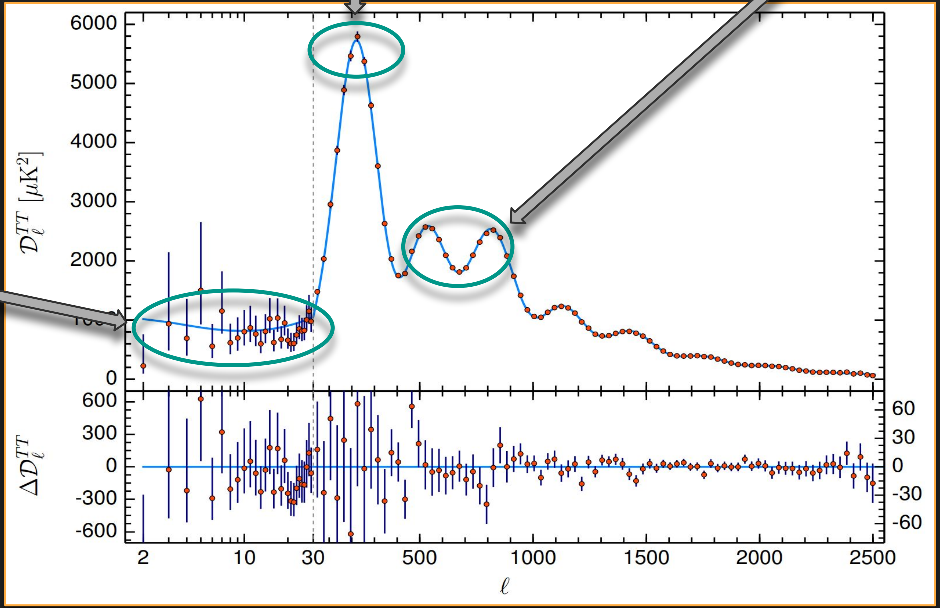
What is LCDM good at?

LCDM accurately predicts the observed anisotropies in the CMB.

Sound Horizon

Baryon Loading
Radiation Driving

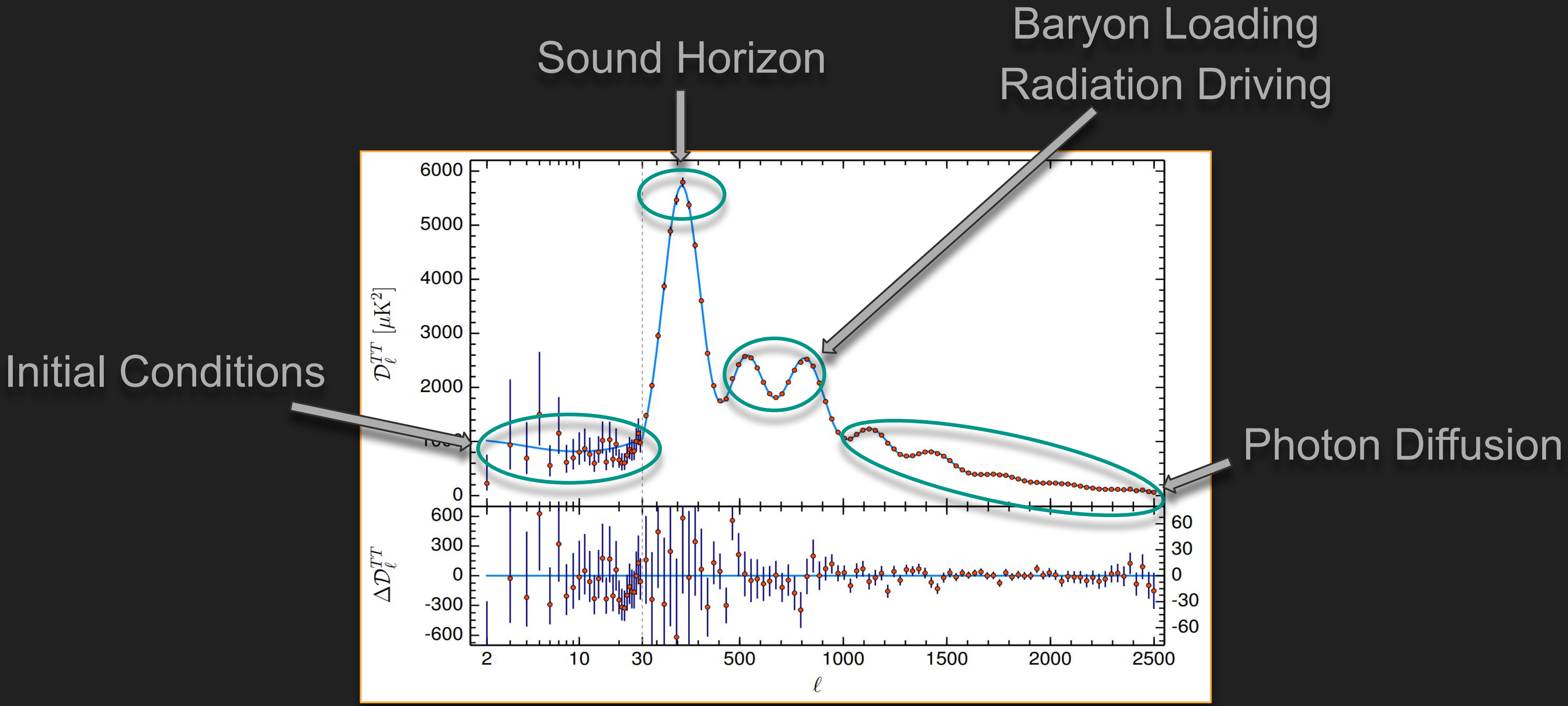
Initial Conditions



Planck 2018

What is LCDM good at?

LCDM accurately predicts the observed anisotropies in the CMB.



Planck 2018

Matter-Radiation Ratio

Matter-Radiation Ratio

$$z_{\text{eq}} = \frac{\rho_{m,0}}{\rho_{r,0}} - 1$$

Matter-Radiation Ratio

Radiation Domination

$$a(t) \approx t^{1/2}$$

$$\delta_{\mathrm{m}} \propto \ln(a)$$

$$z_{\mathrm{eq}} = \frac{\rho_{m,0}}{\rho_{r,0}} - 1$$

Matter-Radiation Ratio

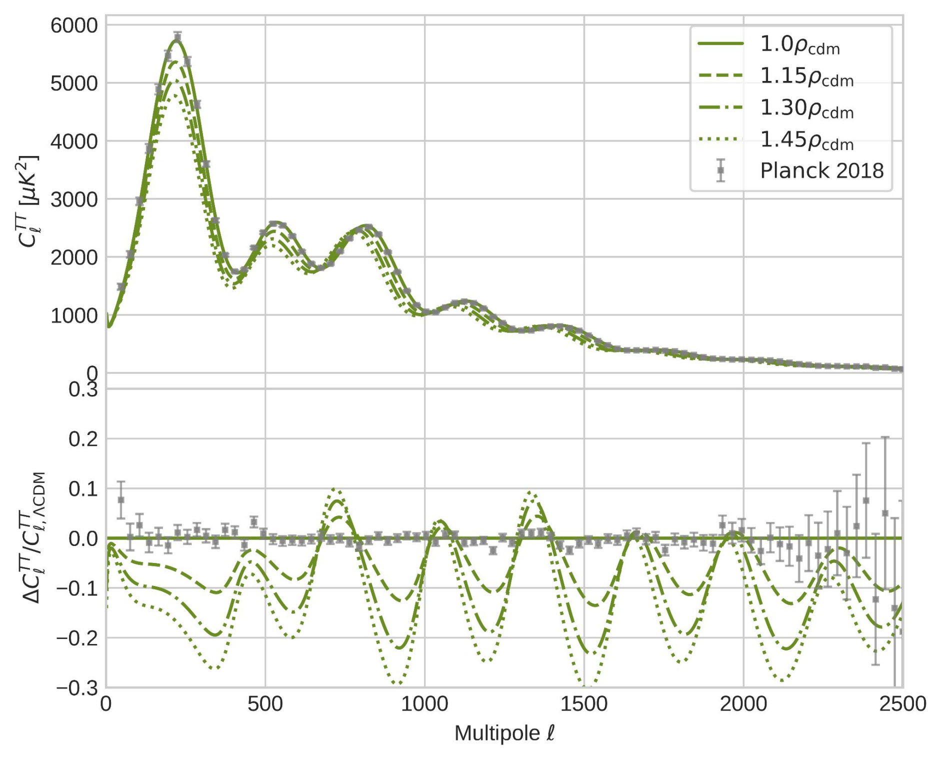
Radiation Domination	Matter Domination
$a(t) \approx t^{1/2}$	$a(t) \approx t^{2/3}$
$\delta_{\mathrm{m}} \propto \ln(a)$	$\delta_{\mathrm{m}} \propto a$

$$z_{\mathrm{eq}} = \frac{\rho_{m,0}}{\rho_{r,0}} - 1$$

Matter-Radiation Ratio

Radiation Domination	Matter Domination
$a(t) \approx t^{1/2}$	$a(t) \approx t^{2/3}$
$\delta_{\mathrm{m}} \propto \ln(a)$	$\delta_{\mathrm{m}} \propto a$

$$z_{\mathrm{eq}} = \frac{\rho_{m,0}}{\rho_{r,0}} - 1$$



Pressure Supported-Pressureless Matter Density

Pressure Supported-Pressureless Matter Density

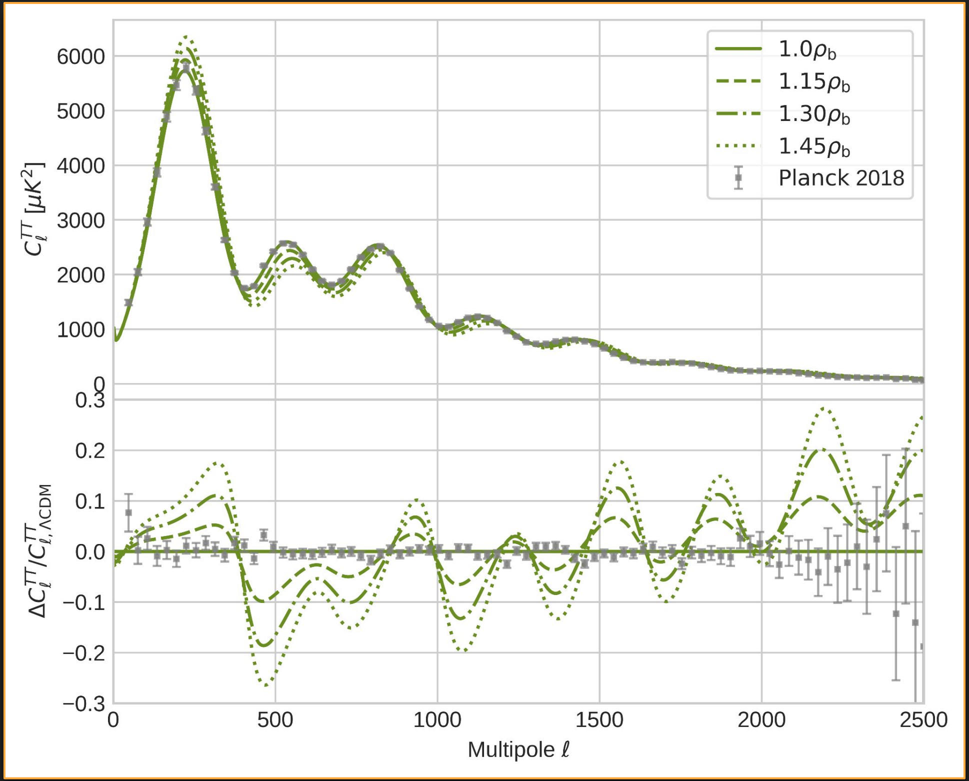
Dark matter and baryons form structure differently.

Odd peaks: compression
Even peaks: rarefication

Pressure Supported-Pressureless Matter Density

Dark matter and baryons form structure differently.

Odd peaks: compression
Even peaks: rarefication

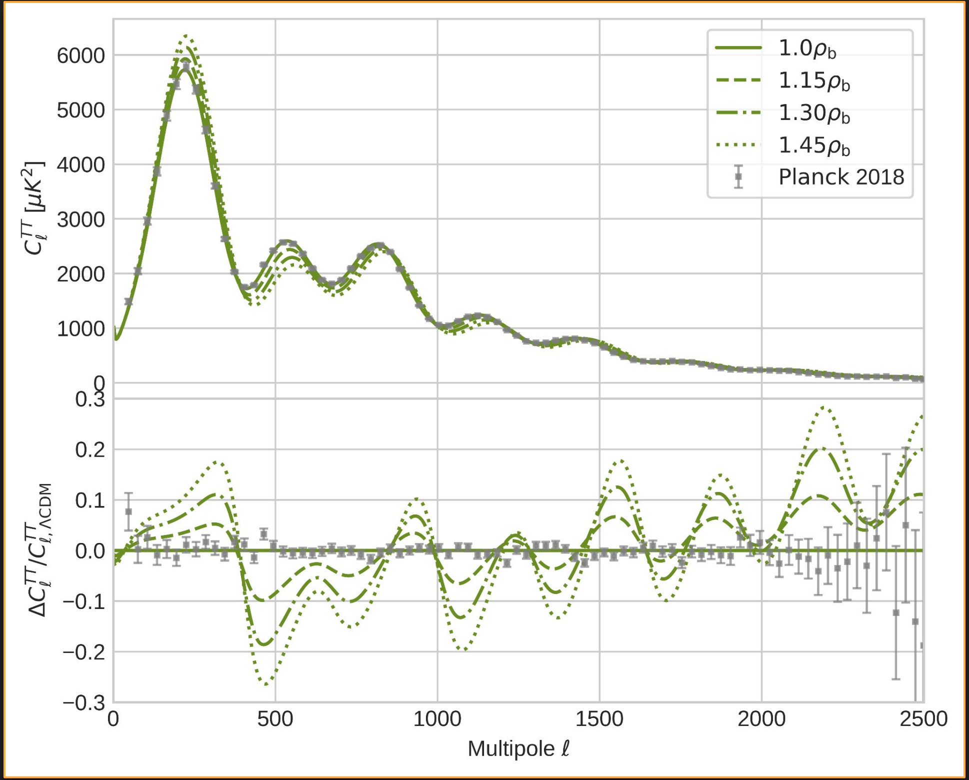


Pressure Supported-Pressureless Matter Density

Dark matter and baryons form structure differently.

Odd peaks: compression
Even peaks: rarefication

Noticeable effects on CMB spectra when changing baryon density; odd peaks get amplified by baryon loading!

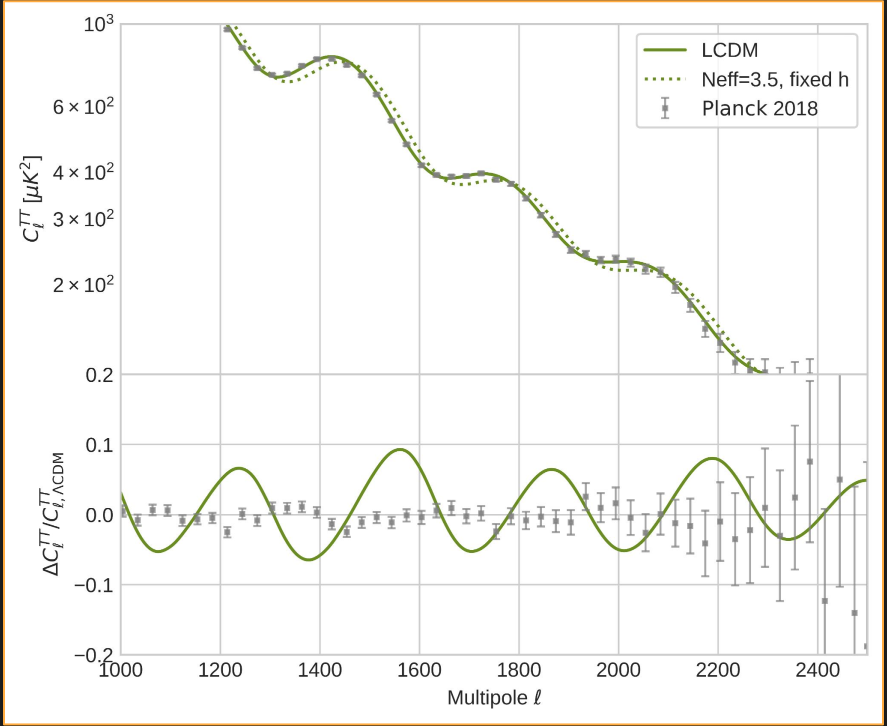


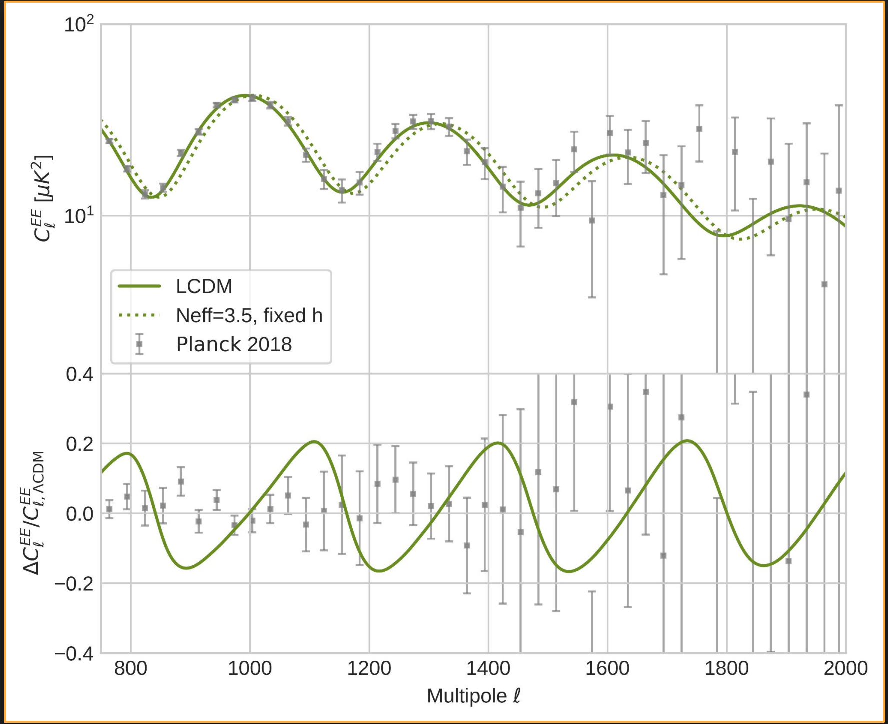
Fluid-Free streaming radiation density

Fluid-Free streaming radiation density

Phase and amplitude shift in spectra from different sound speeds.

Fluid-Free streaming radiation density





Phase and amplitude shift in spectra from different sound speeds.

Photon-Baryon number

Photon-Baryon number

Overall baryon number is conserved.

BBN and CMB agree on relative ratio of photons to baryons.

Photon-Baryon number

Overall baryon number is conserved.

BBN and CMB agree on relative ratio of photons to baryons.

$$\frac{n_b}{n_\gamma} = \eta \approx 10^{-10}$$

Photon-Baryon number

Overall baryon number is conserved.

BBN and CMB agree on relative ratio of photons to baryons.

$$\frac{n_b}{n_\gamma} = \eta \approx 10^{-10}$$

$$Y_\mathrm{P} = 0.2449 \pm 0.0040$$
$$D/H = 2.53 \pm 0.15 \times 10^{-5}$$

What kind of phenomenologies work?

What kind of phenomenologies work?

U(1) symmetry in the dark sector can satisfy all of these criteria

Includes:

1) Pressure supported matter
2) Pressureless Matter
3) Fluid radiation
4) Free streaming Radiation

What kind of phenomenologies work?

U(1) symmetry in the dark sector can satisfy all of these criteria

Includes:

1) Pressure supported matter
2) Pressureless Matter
3) Fluid radiation
4) Free streaming Radiation

For our purposes, we take electrons, protons, and photons forming a simple dark U(1) symmetry.

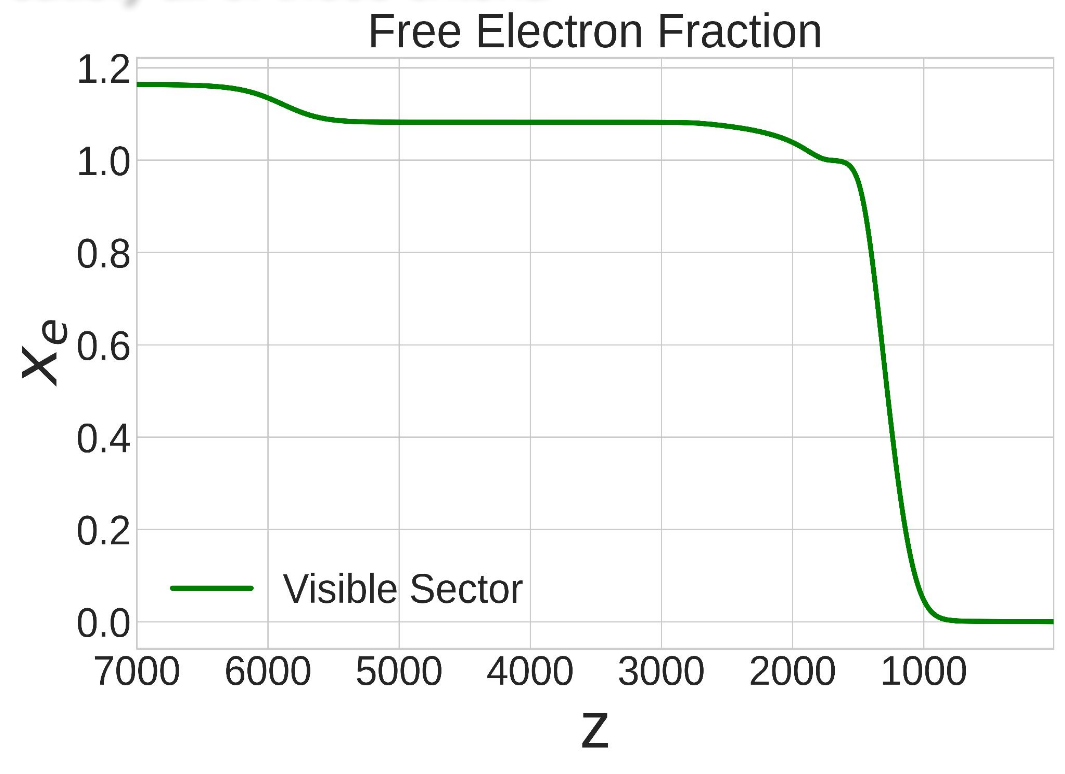
What kind of phenomenologies work?

U(1) symmetry in the dark sector can satisfy all of these criteria

Includes:

1) Pressure supported matter
2) Pressureless Matter
3) Fluid radiation
4) Free streaming Radiation

For our purposes, we take electrons, protons, and photons forming a simple dark U(1) symmetry.



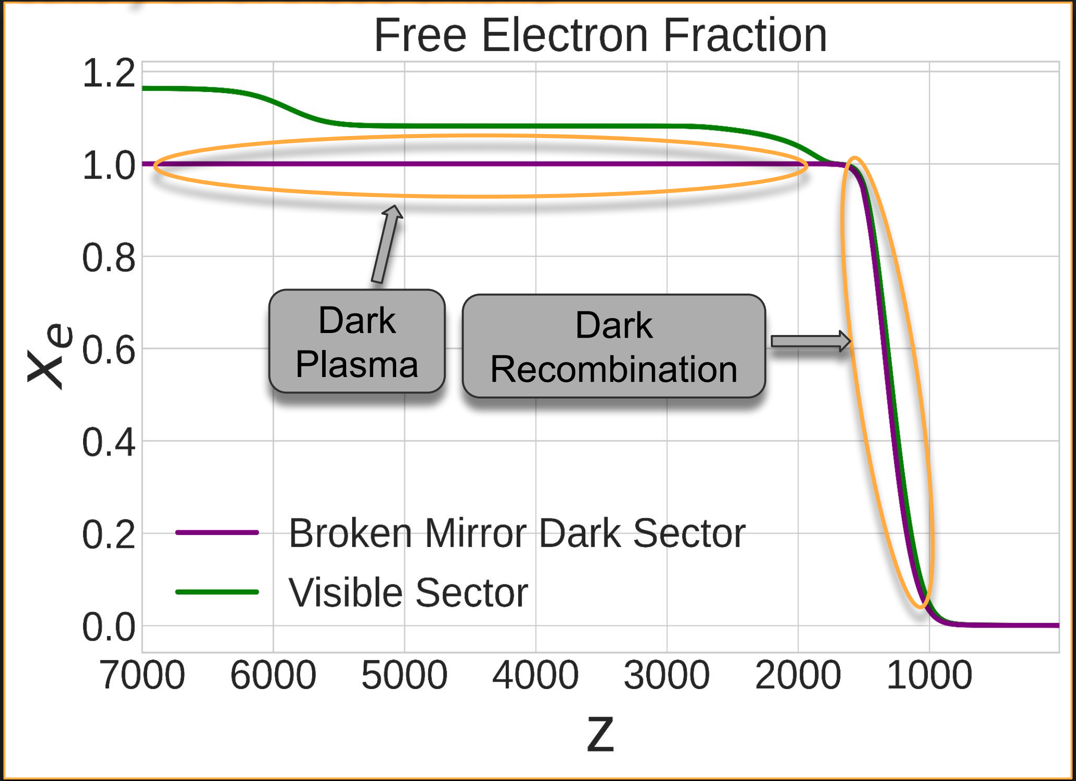
What kind of phenomenologies work?

U(1) symmetry in the dark sector can satisfy all of these criteria

Includes:

1) Pressure supported matter
2) Pressureless Matter
3) Fluid radiation
4) Free streaming Radiation

For our purposes, we take electrons, protons, and photons forming a simple dark U(1) symmetry.



Thomson scattering-Background Expansion Rate

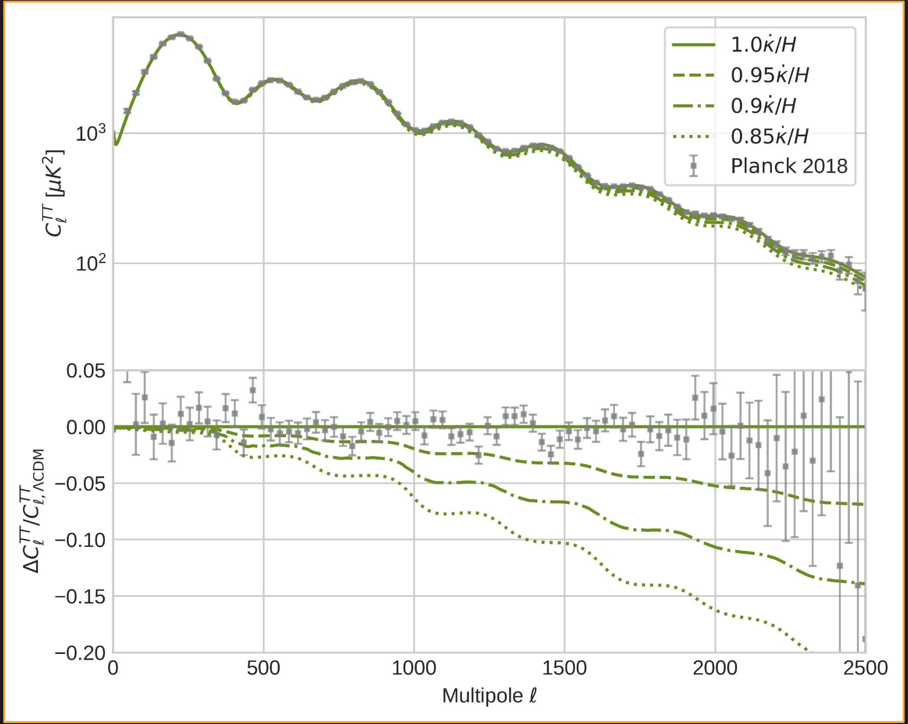
Thomson scattering-Background Expansion Rate

$$\frac{\dot{\kappa}}{H(a)}$$

Thomson scattering-Background Expansion Rate

$$\frac{\dot{\kappa}}{H(a)}$$

Increasing H(a) leads to more suppression on small scales



Thomson scattering-Background Expansion Rate

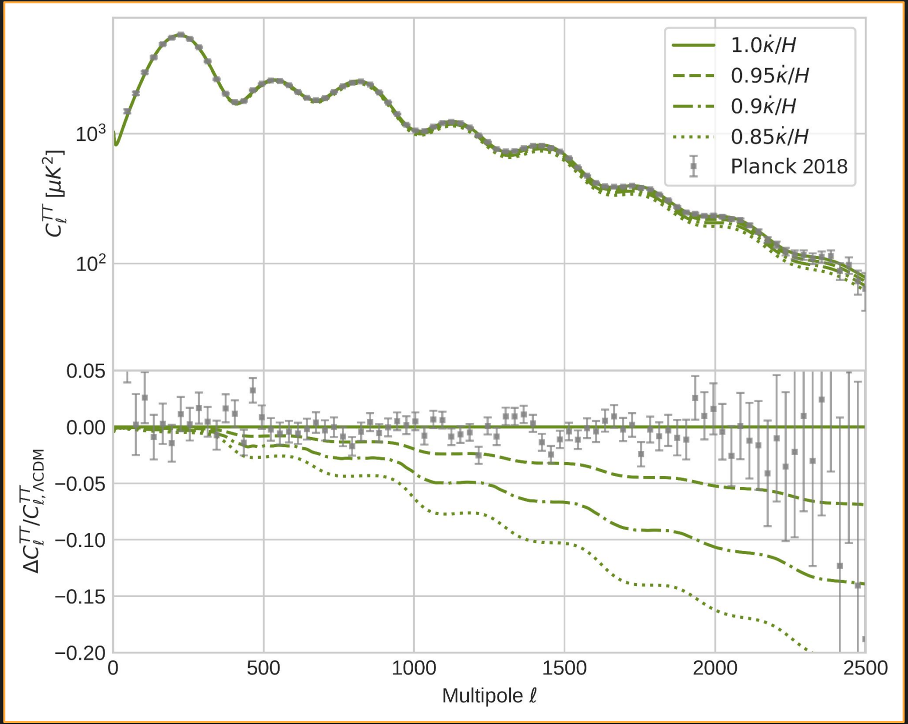
$$\frac{\dot{\kappa}}{H(a)}$$

Observables are insensitive to specific changes in fundamental constants as long as the binding energy is left invariant. (2306.06165)

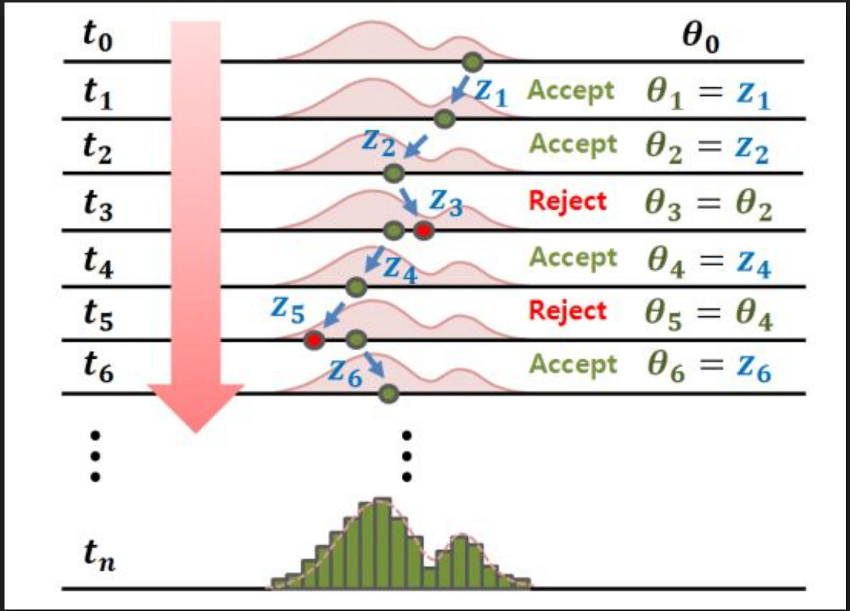
Hubble tension? Photon diffusion tension!

$$\alpha \xrightarrow{\lambda} \lambda^{1/6}\alpha$$
$$m_e \xrightarrow{\lambda} \lambda^{-1/3} m_e$$

Increasing H(a) leads to more suppression on small scales



Markov Chain Monte Carlo

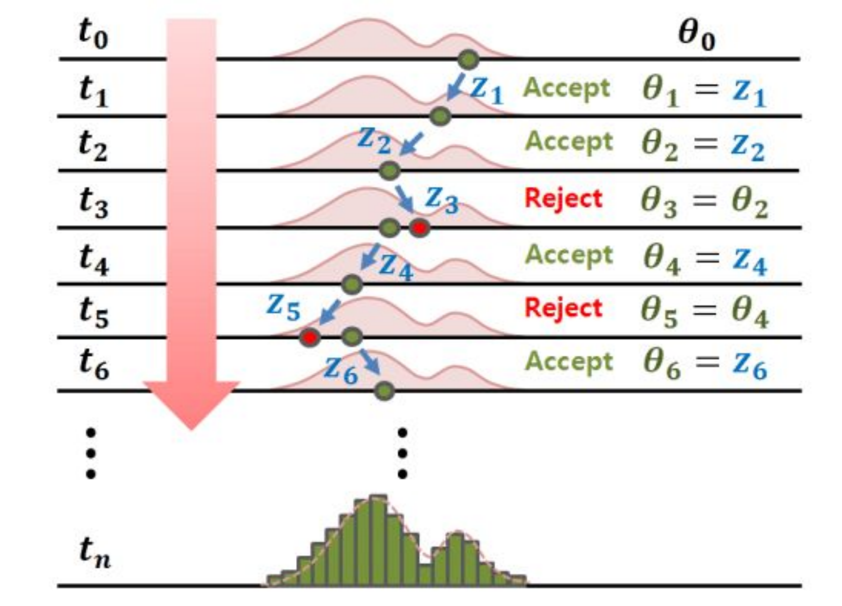


Seung-Seop Jin et al. (2019)

Markov Chain Monte Carlo

Likelihoods

- Planck 2018 TT,EE,TE,Lensing (CMB)
- BOSS DR12, SDSS DR7, 6dF Galaxy Survey (BAO)
- Pantheon+ Supernova
- Riess et al. 2022 observation of H_0



Seung-Seop Jin et al. (2019)

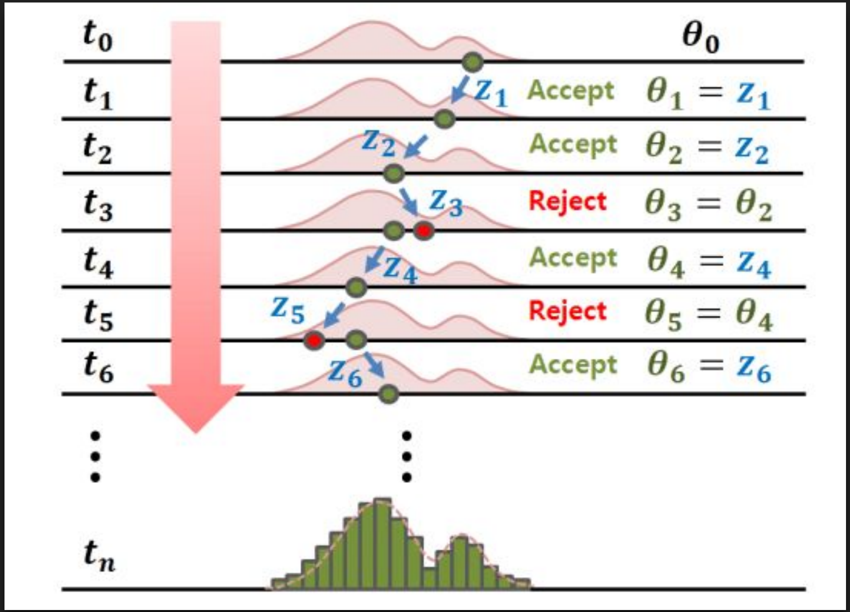
Markov Chain Monte Carlo

Likelihoods

- Planck 2018 TT,EE,TE,Lensing (CMB)
- BOSS DR12, SDSS DR7, 6dF Galaxy Survey (BAO)
- Pantheon+ Supernova
- Riess et al. 2022 observation of H_0

Parameters

- LCDM: $\rho_{\rm cdm}, \rho_{\rm b}, h, A_{\rm s}, n_{\rm s}, \tau_{\rm reio}$
- Mirror: $f_{\rm adm}, \xi_{\rm dark}$
- FCV: $m_{\rm e}, \alpha$
- $N_{\rm eff}$



Seung-Seop Jin et al. (2019)

CMB Spectra

Preserving cosmological ratios results in excellent CMB spectra agreement.

CMB Spectra

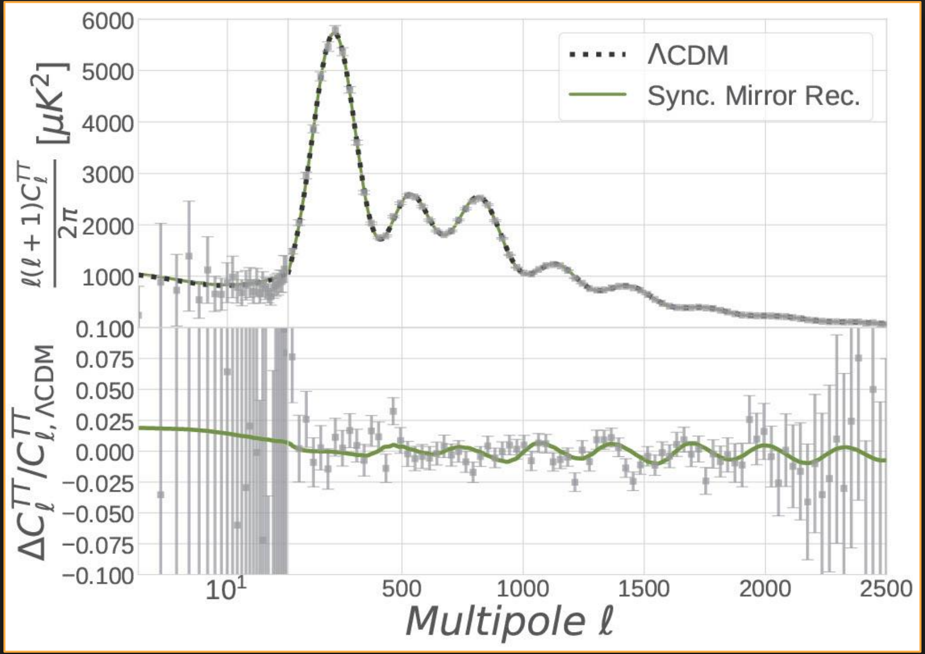
Preserving cosmological ratios results in excellent CMB spectra agreement.

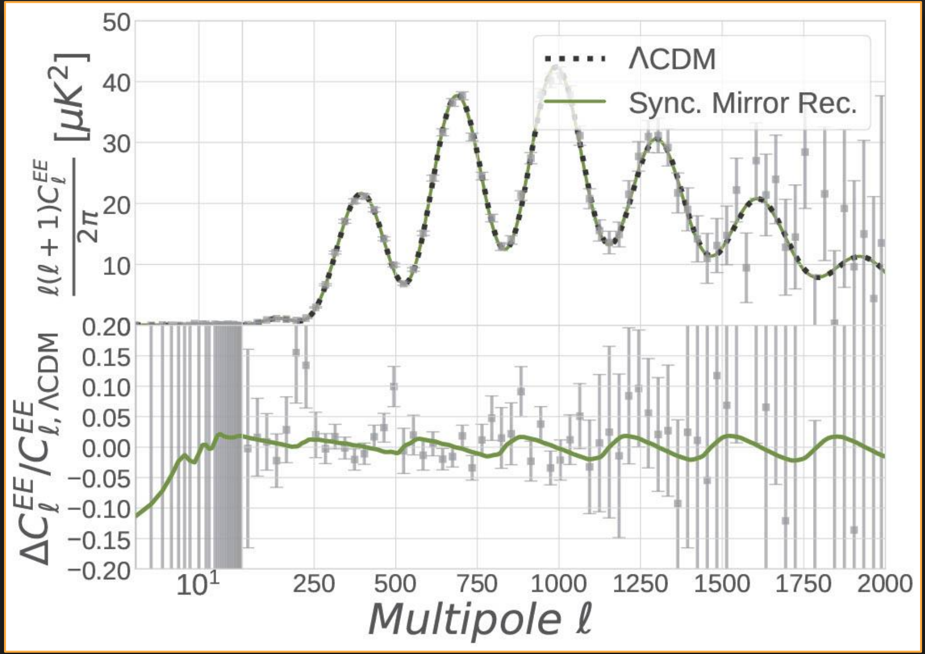
These spectra have an expansion rate H_0 = 73.8 km/s/Mpc.

CMB Spectra

Preserving cosmological ratios results in excellent CMB spectra agreement.

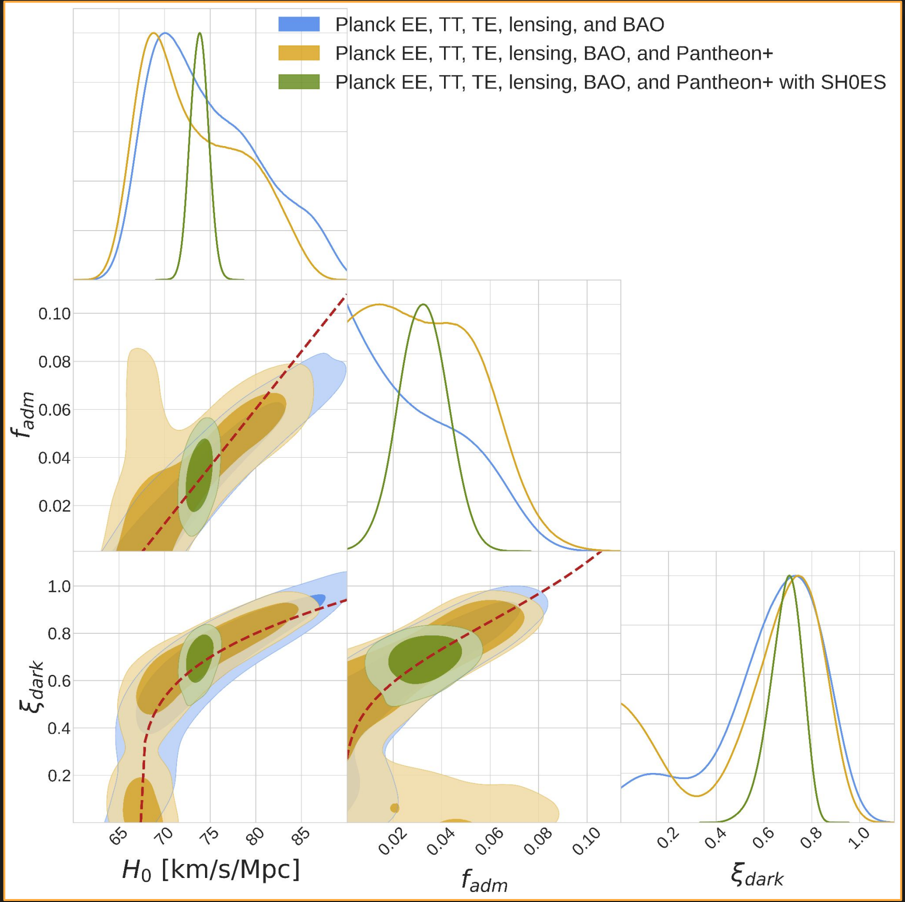
These spectra have an expansion rate H_0 = 73.8 km/s/Mpc.





Synchronous Recombination: Dark Sector

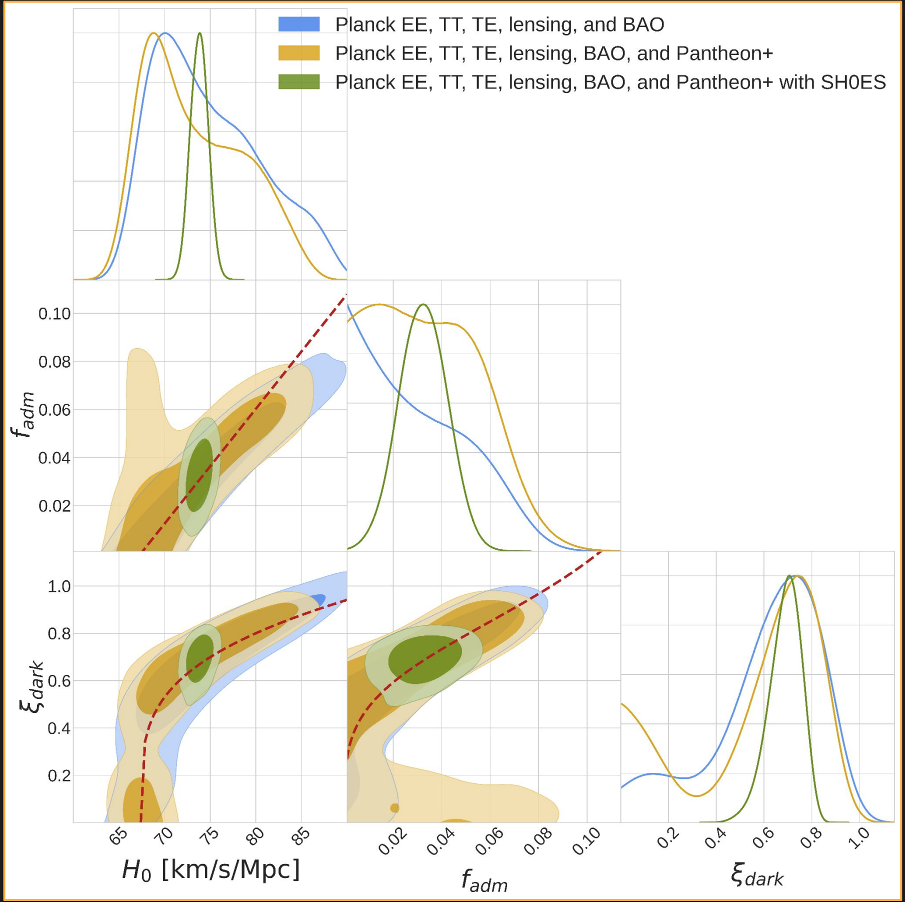
Synchronous Recombination: Dark Sector



Synchronous Recombination: Dark Sector

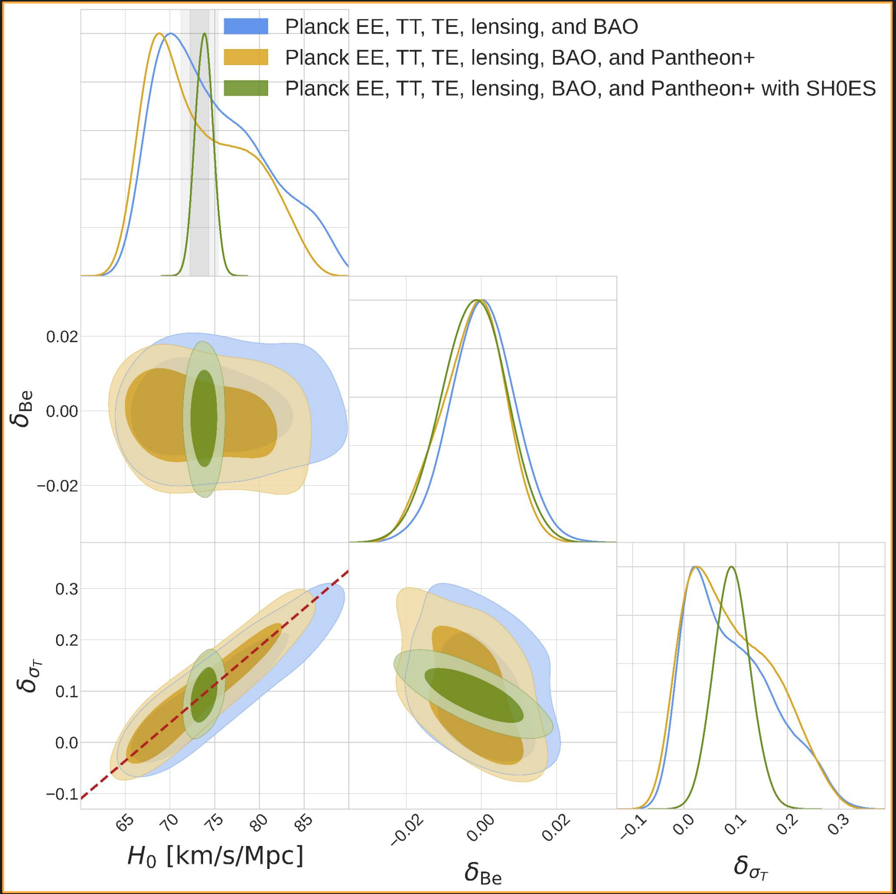
Red dashed line indicates ratio preserving direction direction.

Sampler explores broad range of H_0 when no anchor is present.

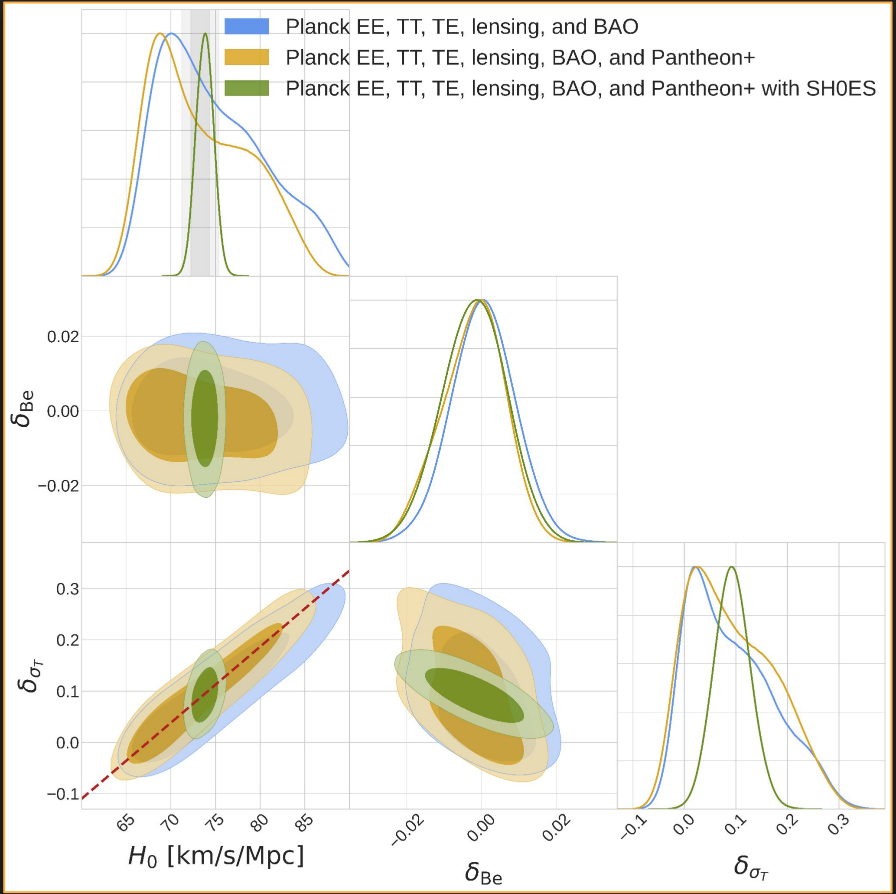


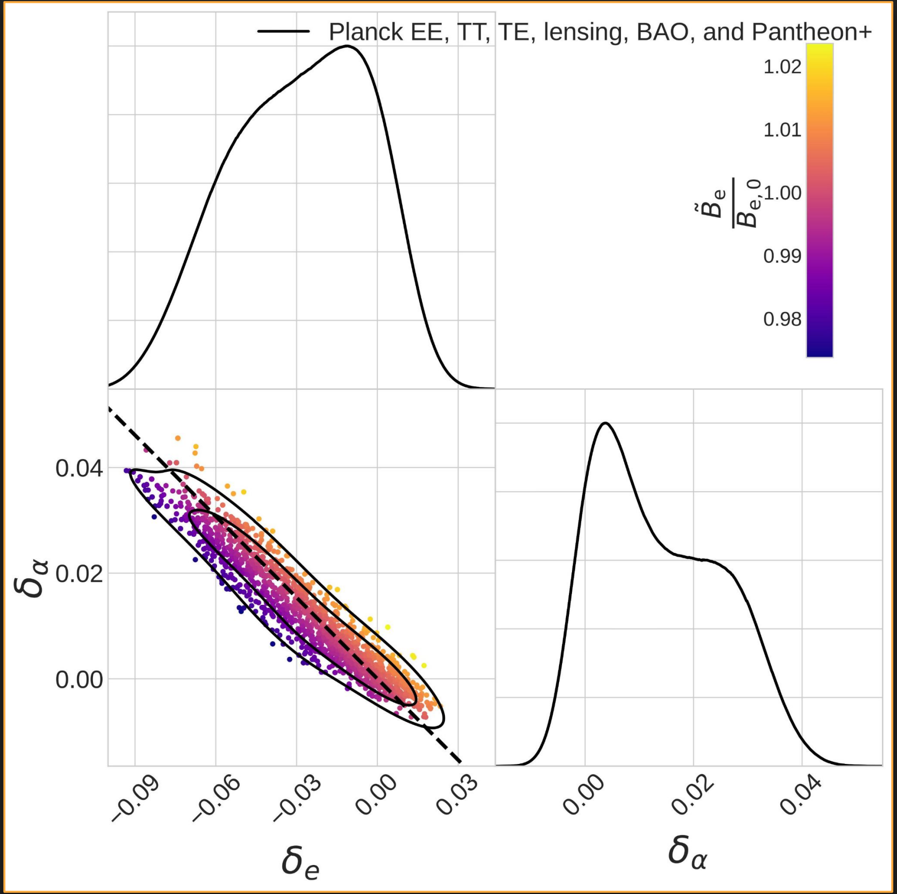
Synchronous Recombination: FCV

Synchronous Recombination: FCV



Synchronous Recombination: FCV

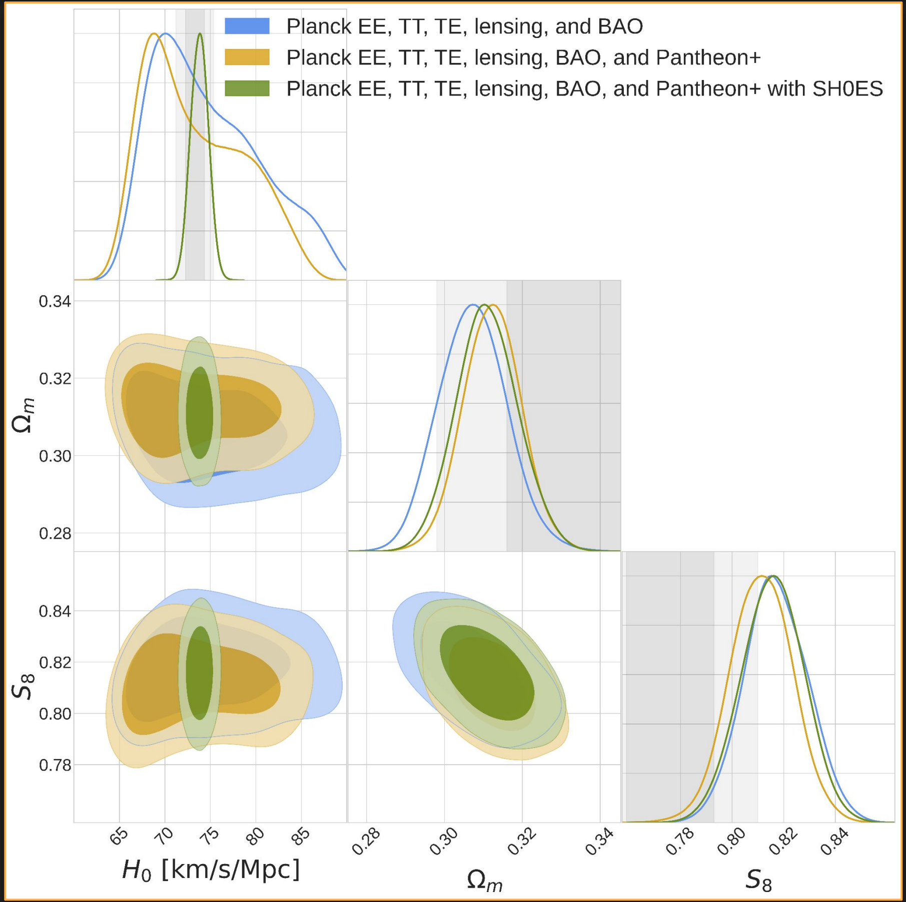




Synchronous Recombination: Observables

Synchronous Recombination: Observables

1) Tension in H_0 is removed.
2) No issues with matter density.
3) S_8 is still… peculiar.



Conclusions

- LCDM is hard to improve on because it predicts five important ratios very well.

Conclusions

- LCDM is hard to improve on because it predicts five important ratios very well.
- Atomic dark matter with a dark radiation component can add energy to Universe while preserving these ratios.

Conclusions

- LCDM is hard to improve on because it predicts five important ratios very well.
- Atomic dark matter with a dark radiation component can add energy to Universe while preserving these ratios.
- Mirror sector recombination is a plausible approach to the Hubble tension:

$$H_0 = 73.80 \pm 1.02 \text{ km/s/Mpc}$$

$$\Delta\chi^2 = -35.72 \qquad +5 \text{ free params}$$

Conclusions

- LCDM is hard to improve on because it predicts five important ratios very well.
- Atomic dark matter with a dark radiation component can add energy to Universe while preserving these ratios.
- Mirror sector recombination is a plausible approach to the Hubble tension:

$$H_0 = 73.80 \pm 1.02 \text{ km/s/Mpc}$$

$$\Delta\chi^2 = -35.72 \qquad +5 \text{ free params}$$

- Asynchronous mirror recombination prefers to happen between the end of Helium recombination and the beginning of hydrogen recombination.

Conclusions

- LCDM is hard to improve on because it predicts five important ratios very well.
- Atomic dark matter with a dark radiation component can add energy to Universe while preserving these ratios.
- Mirror sector recombination is a plausible approach to the Hubble tension:

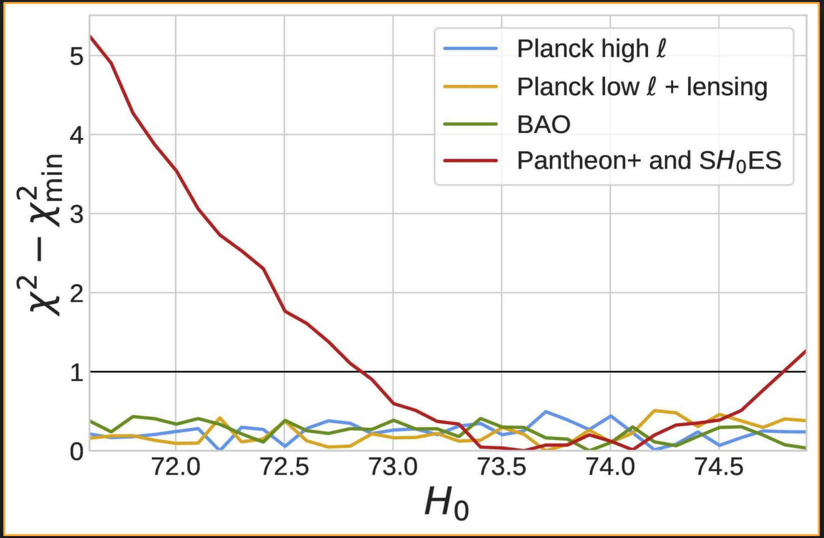
$$H_0 = 73.80 \pm 1.02 \text{ km/s/Mpc}$$

$$\Delta\chi^2 = -35.72 \qquad +5 \text{ free params}$$

- Asynchronous mirror recombination prefers to happen between the end of Helium recombination and the beginning of hydrogen recombination.
- Based on 2403.05619, K. Greene & F.Y. Cyr-Racine

Thank you!

Profile Likelihood



CMB and BAO data remain consistent for enhanced values of H_0 while cosmological ratios are preserved along the FFAT direction.

System requires a calibrator/anchor measurement: local measurement of H_0 by SH_0ES.

	ΛCDM	Synchronous Recombination	Asynchronous Recombination
Planck High ℓ	2347.79	2343.97	2342.18
Planck Low ℓ TT	22.63	24.16	23.89
Planck Low ℓ EE	396.95	396.09	396.05
Planck Lensing	8.85	8.62	8.70
BOSS DR12	3.57	4.28	4.41
BOA low z	2.32	1.23	1.198
Pantheon+SH_0ES	1319.44	1287.49	1287.45
$\Delta\chi^2$	0	-35.72	-37.65

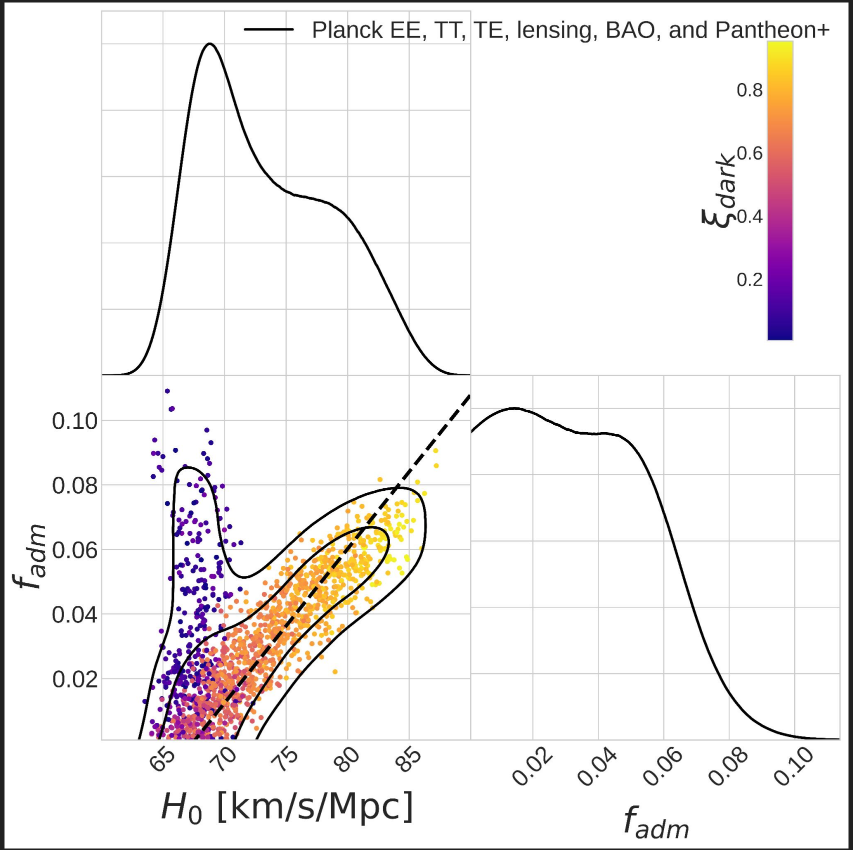
Warm mittens with cold thumbs

Warm mittens with cold thumbs

The sampler has revealed a large prior volume effect where ADM behaves as CDM in cold dark sectors.

Warm mittens with cold thumbs

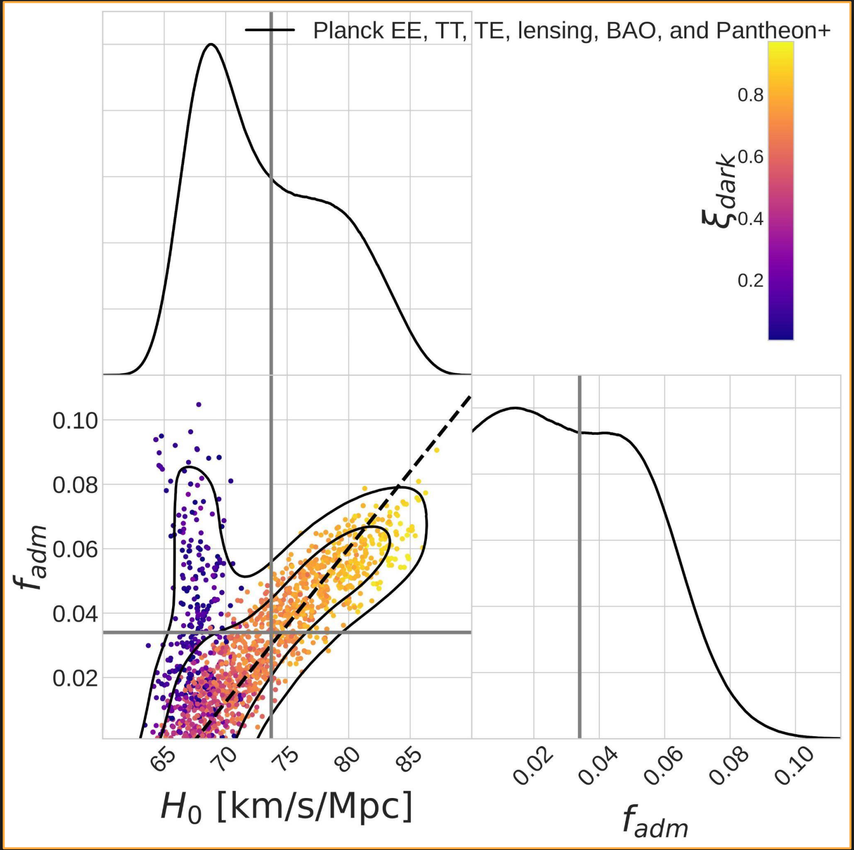
The sampler has revealed a large prior volume effect where ADM behaves as CDM in cold dark sectors.



Warm mittens with cold thumbs

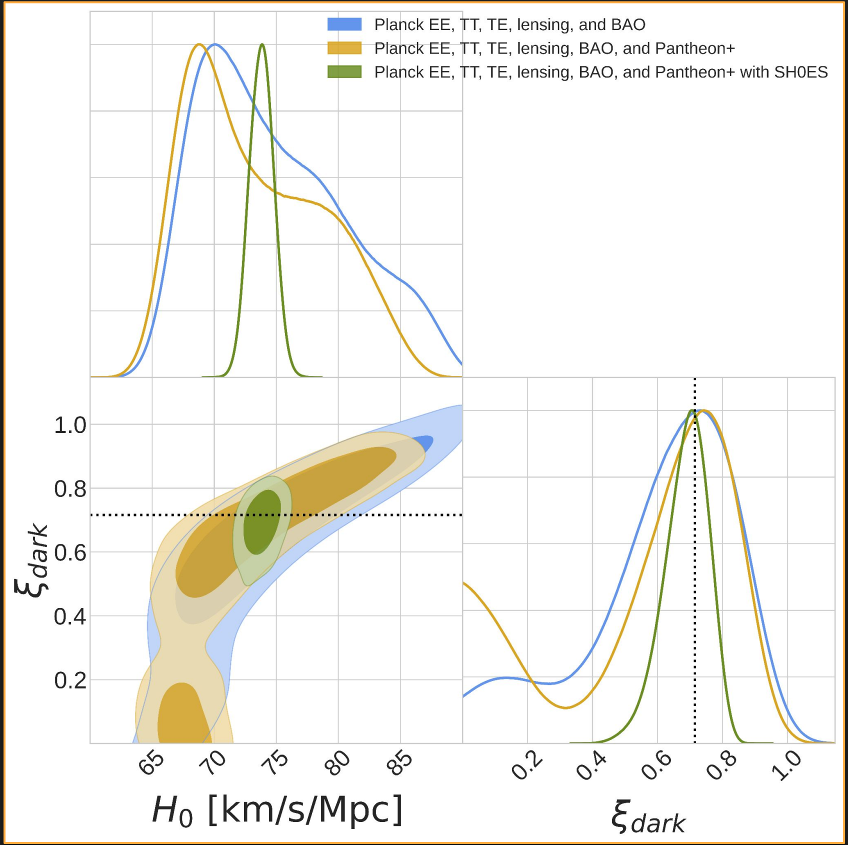
The sampler has revealed a large prior volume effect where ADM behaves as CDM in cold dark sectors.

Influences shape of 1D posteriors.



A dark sector temperature coincidence

A dark sector temperature coincidence

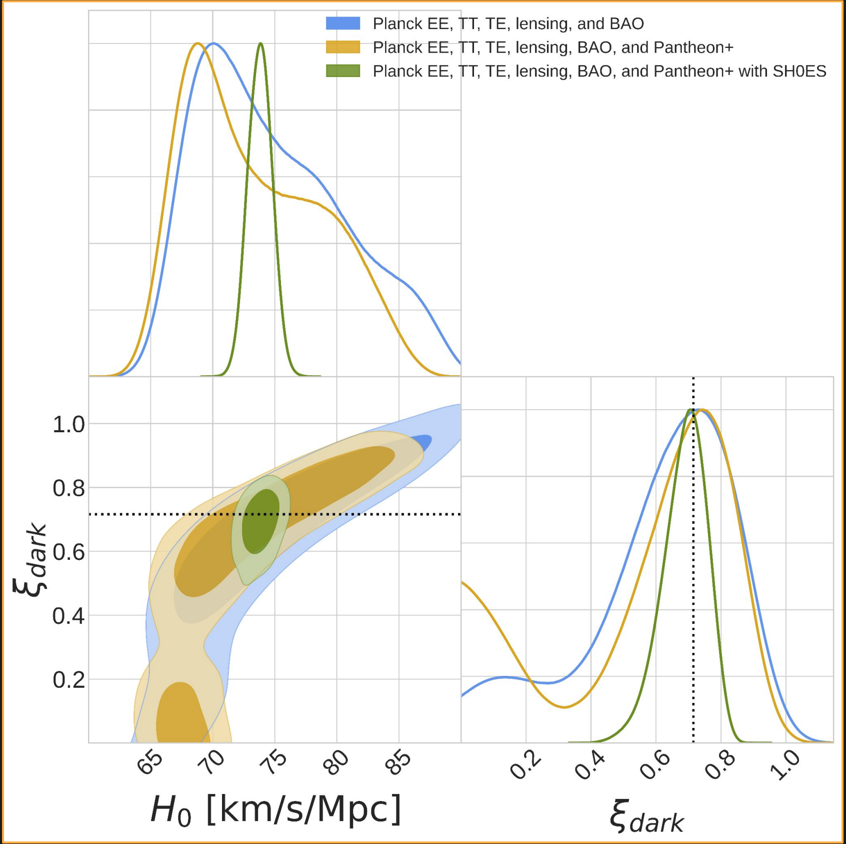


A dark sector temperature coincidence

Bestfit dark sector temperature: **1.88 K**

Predicted background neutrino temperature: **1.95 K**

Perhaps the dark sector was in thermal contact before electron-positron annihilation or has maintained contact with just neutrinos?



Asynchronous Recombination

$$\frac{r_{\mathrm{Be}}}{\xi_{\mathrm{dark}}} = \frac{\frac{B_{\mathrm{e,d}}}{B_{\mathrm{e}}}}{\frac{T_{\gamma,d}}{T_{\gamma}}}$$

Asynchronous Recombination

$$\frac{r_{\mathrm{Be}}}{\xi_{\mathrm{dark}}} = \frac{\frac{B_{\mathrm{e,d}}}{B_{\mathrm{e}}}}{\frac{T_{\gamma,d}}{T_{\gamma}}}$$

= 1: synchronous recombination

< 1: later asynchronous recombination

> 1: earlier asynchronous recombination

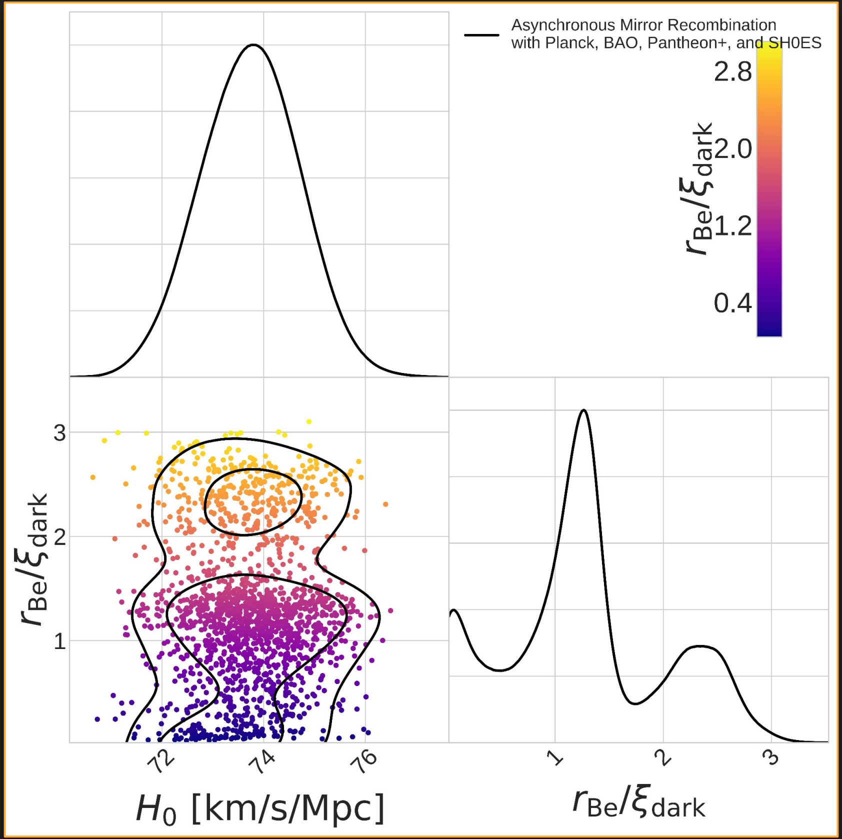
Asynchronous Recombination

$$\frac{r_{\mathrm{Be}}}{\xi_{\mathrm{dark}}} = \frac{\frac{B_{\mathrm{e,d}}}{B_{\mathrm{e}}}}{\frac{T_{\gamma,d}}{T_{\gamma}}}$$

= 1: synchronous recombination

< 1: later asynchronous recombination

> 1: earlier asynchronous recombination

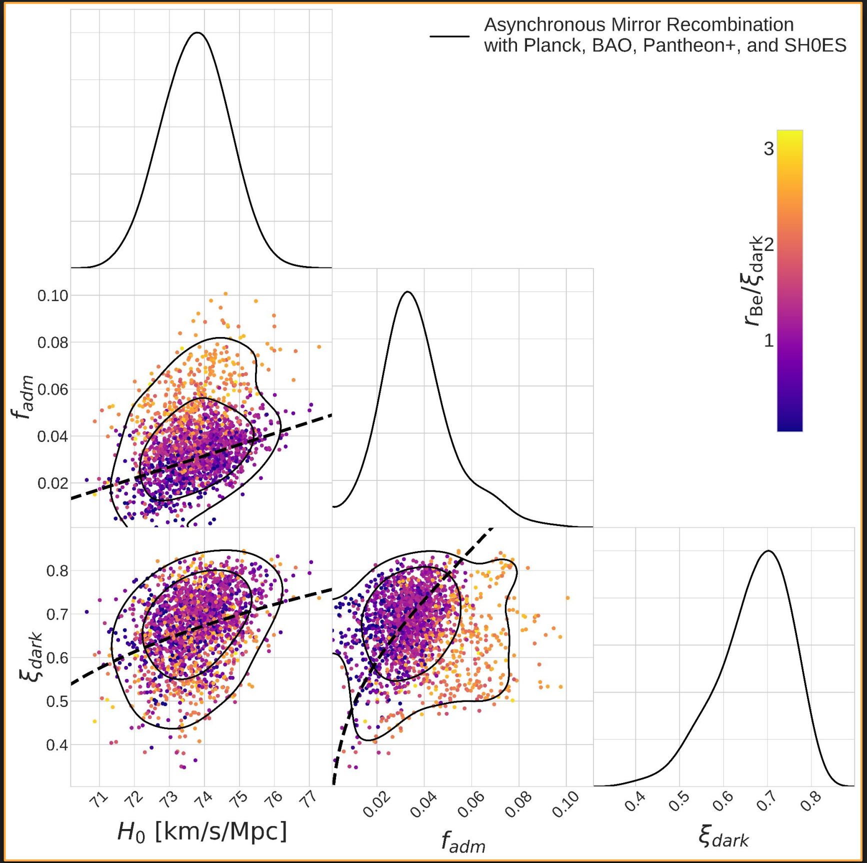


Asynchronous Recombination: Dark Sector

Black dashed lines indicate ratio preserving direction.

Only considering likelihood with SH_0ES in this plot.

Earlier dark recombination likes more atomic dark matter.



Asynchronous Recombination: Observables

No correlation between timing of dark recombination and observable tensions.

Largely the same story as the visible sector.