Implications of DESI BAO measurements

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Based on:
I.Allali, AN, F.Rompineve 2404.15220
AN, M. Redi, A. Tesi, JCAP 11 (2024) 025
AN, M. Redi, A. Tesi, e-Print: 2411.11685
I. Allali, AN, e-Print: 2406.14554, JCAP (2024)

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Plasma Acoustic Oscillations in Early Universe

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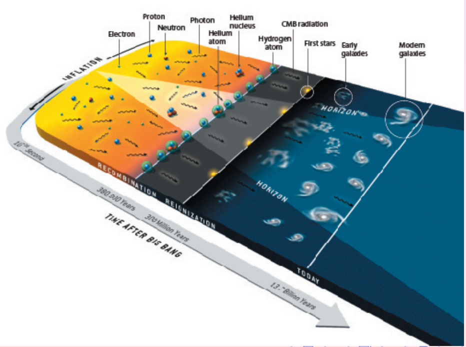
- Fluid pressure resists compression $\rightarrow$ acoustic oscillations
- Oscillations are frozen in when hydrogen forms (recombination): CMB photons emitted



CMB fluctuations

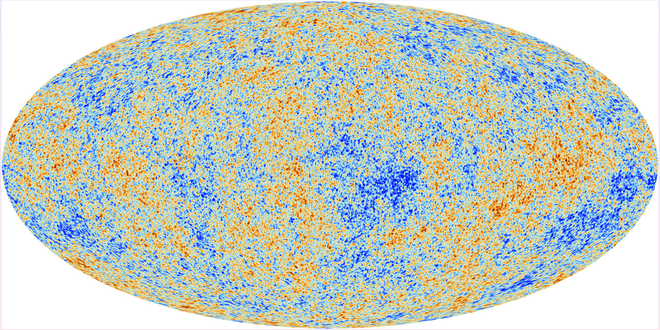


Figure: Credit: ESA and the Planck Collaboration

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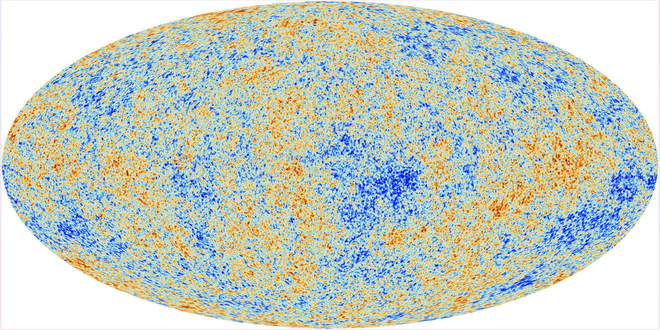

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- Preferred angular scale of $\theta_{\text{peak}} \approx 1^{\circ}$

Sound horizon at CMB

- Sound horizon at decoupling r_d, length scale imprinted in CMB:

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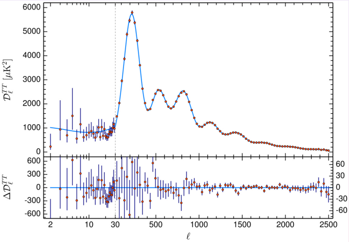
- "Standard ruler" of early universe, length scale stretched to $\sim$ 150 Mpc today

Sound horizon in CMB

- Length scale r_d corresponds to angular scale in CMB
  $\theta_{\mathrm{peak}} \sim 1/\ell_{\mathrm{peak}}$



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Dark Energy
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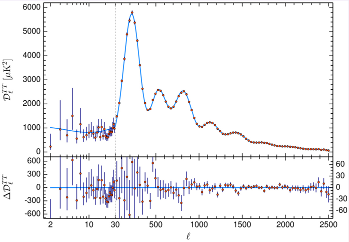

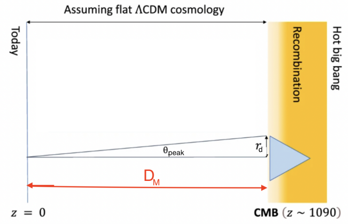

- Angular scale $\theta_{\rm peak} \approx 1^\circ \propto \dfrac{r_d}{D_M(z_{\rm decoupling})}$

  $\left(D_M(z) \equiv \int_0^z \frac{dz'}{H(z')}\right.$ "transverse distance" from observer to decoupling$)$

Sound horizon in matter distribution

- Same sound horizon scale r_d imprinted also in the galaxy distribution at late times
- "Standard ruler" visible also in galaxy correlations
- Baryon Acoustic Oscillations (BAO)

Measuring BAO

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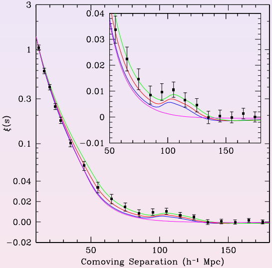

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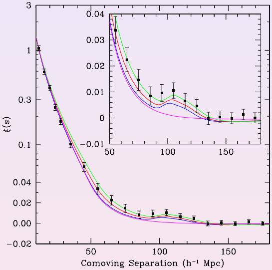

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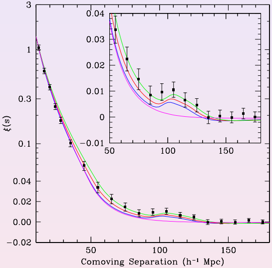

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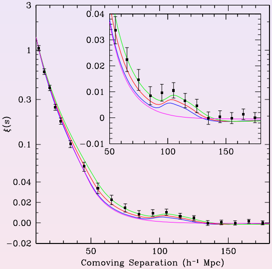

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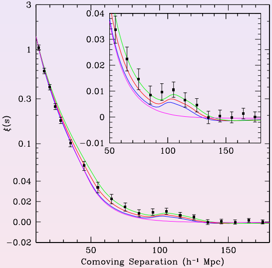

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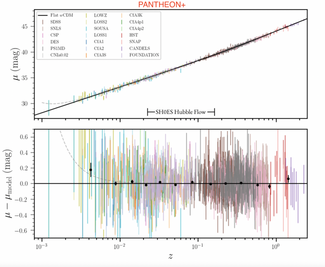
- Transverse comoving distance $D_M(z) = \int_0^z \frac{dz'}{H(z')}$
- Given a cosmological model $\implies r_d$
  $\implies$ BAO+CMB measure Distance D_M vs Redshift (z)
- Constrains $H(z)$

Supernovae



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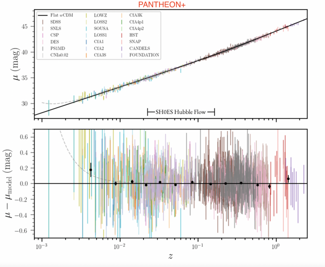

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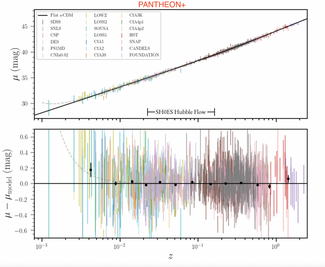

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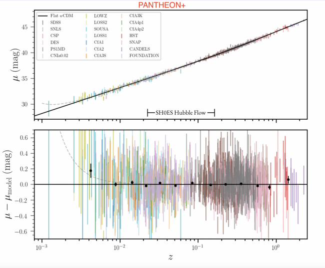

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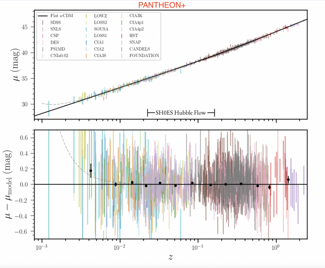

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- The constant c contains both H_0 and intrinsic luminosity
- Only if Intrinsic luminosity known (calibration) $\rightarrow$ H_0 is measured

ΛCDM Concordance Model

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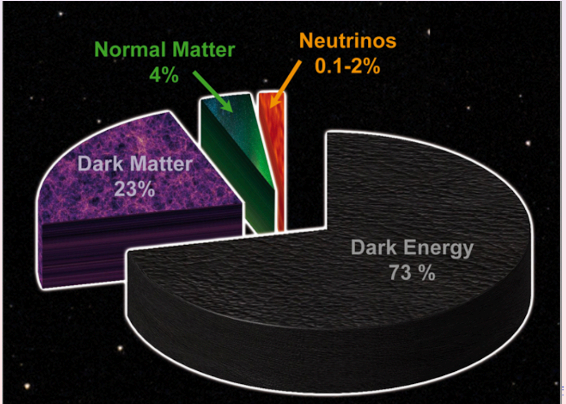

Dark Energy Spectroscopic Instrument (DESI)

- Measures BAO in galaxies, quasars, and Lyman-α forest
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(Adame et al 24 (DESI III, VI), Abareshi et al 22)

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With respect to previous BAO measurements (6dFGS, BOSS, eBOSS, SDSS, WiggleZ)

- 40 million target galaxies and quasars (vs. $\sim 3-4$ million)
- Aim to increase precision on distance $5-10\times$
- Extended redshift range

(Adame et al 24 (DESI III, VI), Abareshi et al 22)

Distance-redshift from DESI

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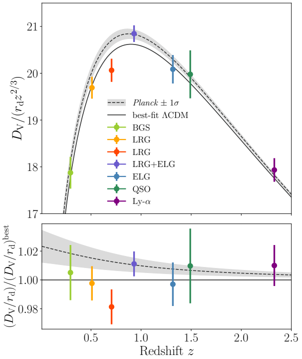

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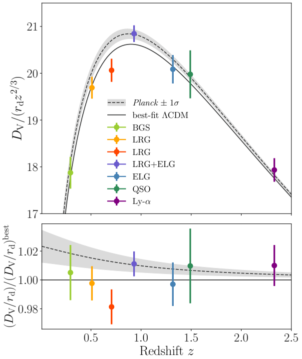

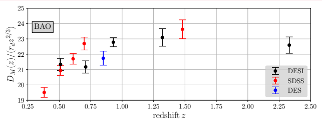

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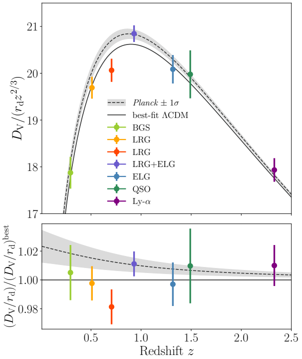

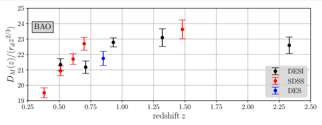

- Data point at $z \sim 0.7$ low.
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- Consistent with another 2024 BAO measurement at $z = 0.85$ (DES)

Abbott et al. PRD 2024

(from DESI, Adame et al 24)

Extract Cosmological Parameters

Datasets considered ('baseline'):

- **Planck18**: CMB (+ lensing) from *Planck* (Aghanim et al 18)
- **Pantheon+** (Scolnic et al 22) or **DESYR5** Uncalibrated Supernovae
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- With SH0ES: which model has lowest tension?
  - New physics at Early Time: Dark Radiation (Allali, AN, Rompineve arXiv:2404.15220)

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Cosmology without SH0ES: varying Dark Energy?

- A generic fluid evolves as:

$$\boxed{\dot{\rho} + 3H(1+w)\rho = 0}$$

- $w \equiv \frac{p}{\rho}$ equation of state ($w = 0$ Matter, $w = \frac{1}{3}$ radiation)

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- But data seem to favor $w < -1$! ((Adame et al (DESI VI) 24)) (ρ grows with expansion?!)

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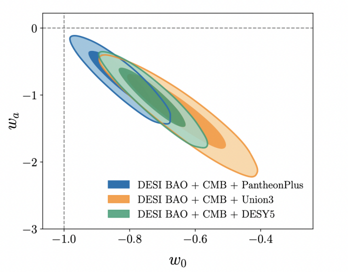

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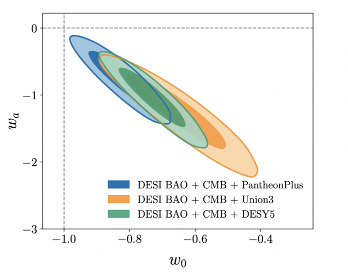

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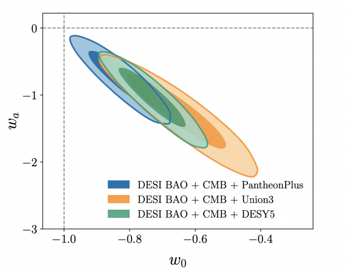

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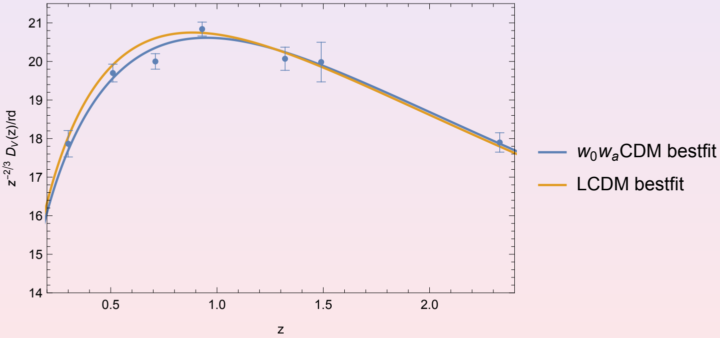

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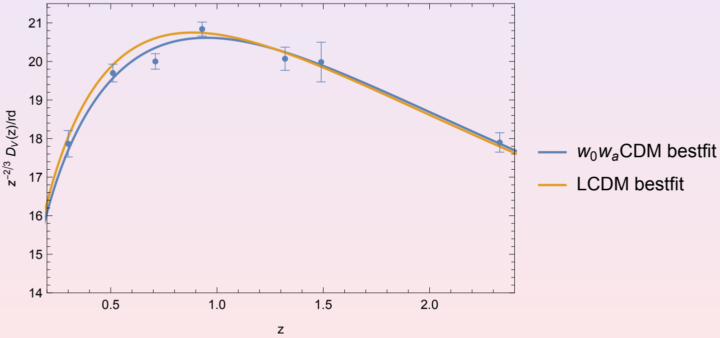

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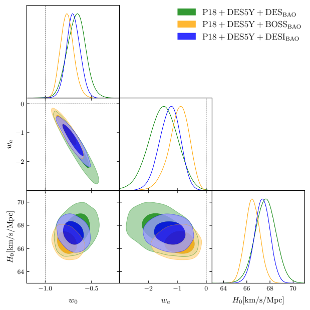

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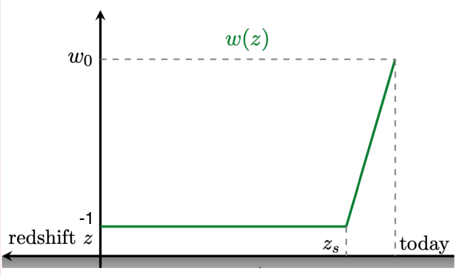

Figure: "Ramp" model

Ramp model

P18+DESI BAO+ DES5Y Supernovae:

$w_0 w_a$**CDM**	w_0	w_a	H_0 **[km/s/Mpc]**	$\Delta\chi^2$
	$-0.71^{+0.069}_{-0.073}$	$-1.13^{+0.35}_{-0.29}$	$67.43^{+0.65}_{-0.67}$	-18

Ramp	w_0	z_s	H_0 **[km/s/Mpc]**	$\Delta\chi^2$
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- $\Delta AIC \equiv \Delta\chi^2 + 2\Delta p$, Akaike Information Criterion, penalized by extra parameters
- $\Delta AIC|_{\rm RAMP} = -8$ vs. ΛCDM

Δ **AIC Range**	**Interpretation**
$\Delta AIC \leq 2$	Models considered equivalent.
$4 \leq \Delta AIC \leq 7$	Moderate evidence
$\Delta AIC > 10$	Strong evidence

Table: AIC Thresholds (Burnham & Anderson, 2002)

Ramp model

P18+DESI BAO+ DES5Y Supernovae:

$w_0 w_a$**CDM**	w_0	w_a	H_0 **[km/s/Mpc]**	$\Delta\chi^2$
	$-0.71^{+0.069}_{-0.073}$	$-1.13^{+0.35}_{-0.29}$	$67.43^{+0.65}_{-0.67}$	-18

Ramp	w_0	z_s	H_0 **[km/s/Mpc]**	$\Delta\chi^2$
	$-0.53^{+0.16}_{-0.36}$	$0.25^{+0.031}_{-0.21}$	$66.15^{+0.63}_{-0.65}$	-12

where: $\Delta\chi^2 \equiv \chi^2_{\rm model} - \chi^2_{\Lambda\rm CDM}$.

- $\Delta AIC \equiv \Delta\chi^2 + 2\Delta p$, Akaike Information Criterion, penalized by extra parameters
- $\Delta AIC|_{\rm RAMP} = -8$ vs. ΛCDM

Δ **AIC Range**	**Interpretation**
$\Delta AIC \leq 2$	Models considered equivalent.
$4 \leq \Delta AIC \leq 7$	Moderate evidence
$\Delta AIC > 10$	Strong evidence

Table: AIC Thresholds (Burnham & Anderson, 2002)

- Can be embedded in scalar field model (“quintessence”)

Ramp potential

- Given any $w(a) > -1 \implies$ Scalar field with potential $V(\phi)$ can be reconstructed

(see Z.-K. Guo, N. Ohta, and Y.-Z. Zhang, Phys. Rev. D, 2005)

$$\rho = \frac{\dot{\phi}^2}{2} + V(\phi)\,, \qquad p = \frac{\dot{\phi}^2}{2} - V(\phi)\,, \qquad w = p/\rho$$

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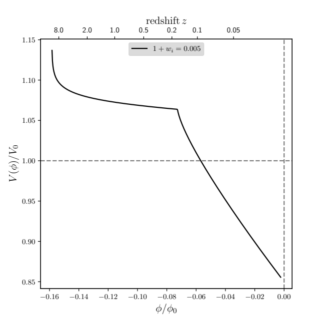

Figure: "Ramp" model

Role of Supernovae

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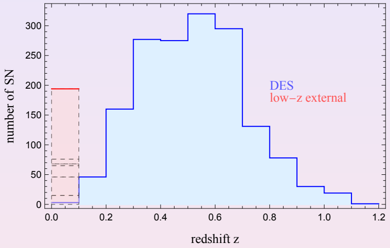
- Pantheon+: collection of SNe from many catalogues

- DES5Y: (almost) single experiment
  - About 1600 DES SNe at high-z ($z > 0.1$)
  - Supplemented with old low redshift sample ($\sim$ 190 SNe) at low z

DES5Y Supernovae



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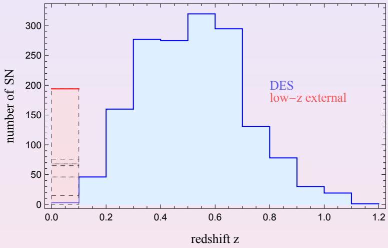

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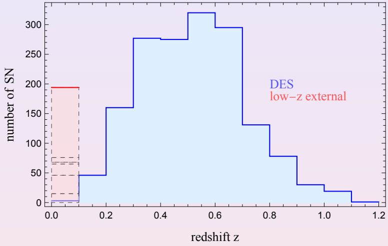

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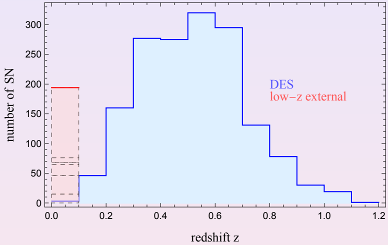

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- Efstathiou, 2408.07175: low z sample of DES5Y has an offset compared to same SNe in Pantheon

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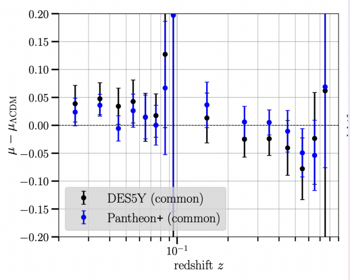

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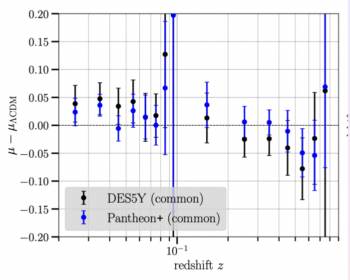

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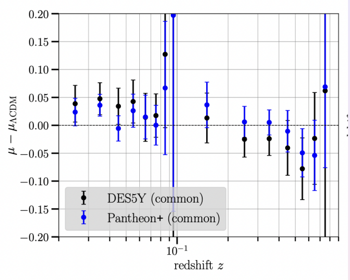

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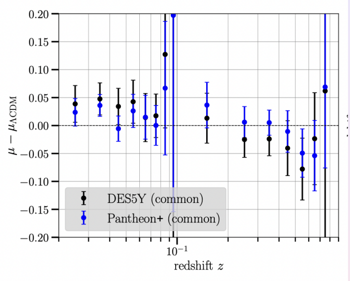

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DES5Y Supernovae

Dataset	$\chi^2_{\rm min}(w_0 w_a{\rm CDM})$	**ΛCDM exclusion**
P18+DESI$_{\rm BAO}$+DES5Y	4431	3.9σ
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- Something needs to be clarified...

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- Evidence vanishes (1.7σ)

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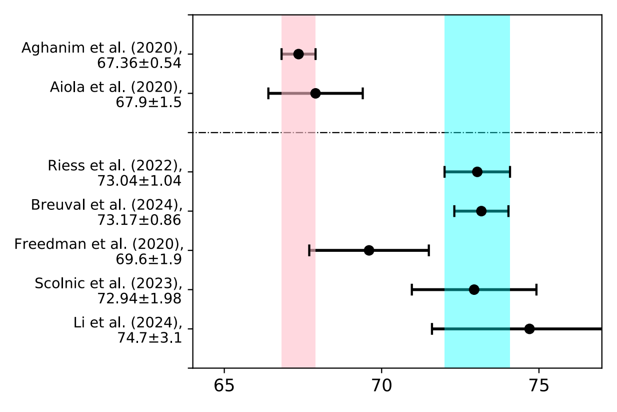

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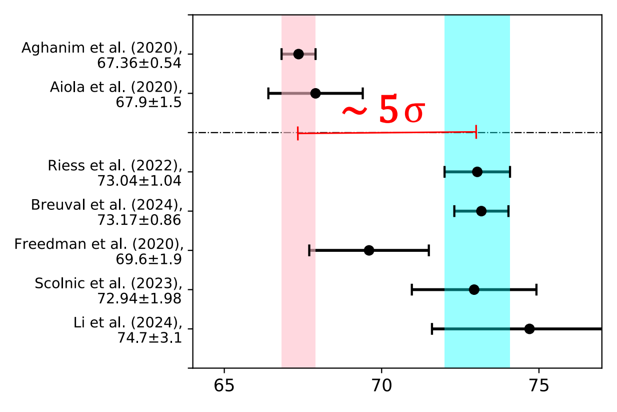

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- In light of new BAO data (DESI 2024), we reassessed the status of tensions

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Dark Radiation (DR): extra light degrees of freedom

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- Can be fermionic, bosonic, low mass, massless, interacting, non-interacting ...
- Examples: thermal axions, gravitational waves, etc....

Dark Radiation (DR): extra light degrees of freedom

DR parameterized as an "effective number of extra neutrino species"

$$N_{\mathrm{eff}} \equiv (\rho_\nu + \rho_{\mathrm{DR}})/\rho_{\nu,1}$$

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- Extra light degrees of freedom contribute as $N_{\text{eff}} = 3.044 + \Delta N_{\text{eff}}$
- We consider $\Delta N_{\text{eff}} > 0$

Relic light particle abundance ($\Delta N_{\rm eff}$) from decoupling

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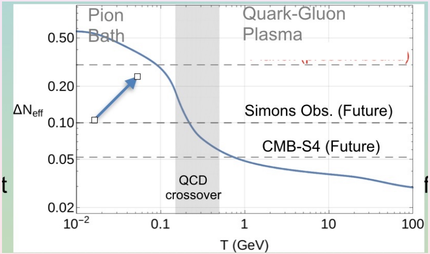
- Low $T_{\rm DECOUPLING} \implies$ largest possible $\Delta N_{\rm eff}$:



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Other effects on CMB fluctuations (beyond r_d)

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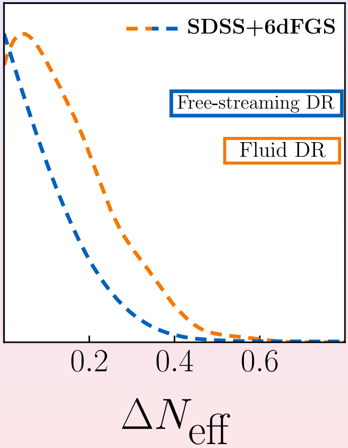
- Freestreaming (FS) dark radiation $\implies$ phase shift of the higher CMB peaks position

DR Constraints before DESI (without SH0ES)

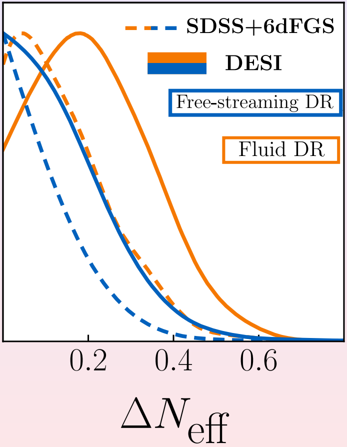


Combination of:

- CMB from **Planck18**
- Supernovae from **Pantheon+**
- BAO from **SDSS+6DFGS**

(Allali + AN + Rompineve 24)

Updated Constraints from DESI (without SH0ES)



Combination of:

- CMB from **Planck18**
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- vs. from **DESI**

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Light Element Abundance Constraints (BBN)

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→ Constraints on $\Delta N_{\rm eff}$ with and without these data*
(Aver et al 15, Cooke et al 18, Marcucci et al 16)

	Planck+DESI+Pantheon+	**+Y_{He},D/H**
Free-streaming	< 0.386	< 0.295
Fluid	$0.221^{+0.088}_{-0.18}$ (< 0.461)	< 0.365

(Allali + AN + Rompineve 24)

*Constraints sensitive to the choice of data for, e.g. the Y_{He} measurement (e.g. Aver et al 15 vs. Izotov et al 14)

DR produced before or after BBN?

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We consider 4 cases:

- Free-Streaming DR:
  1. present before BBN
  2. produced after BBN
- Fluid DR:
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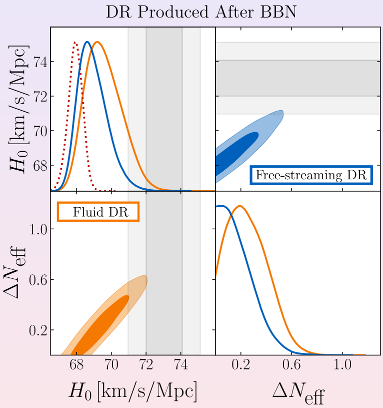

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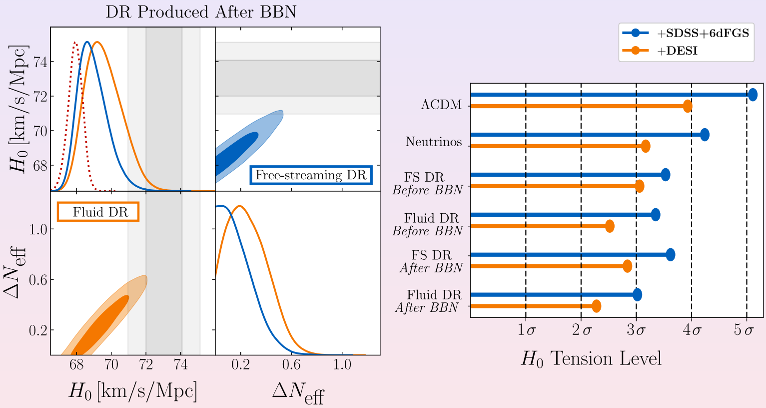

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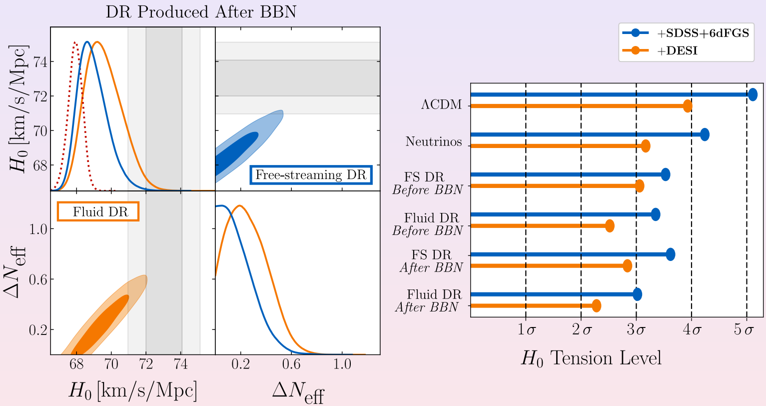
DESI BAO
Dark Energy
DES5Y Supernovae
H_0 Tension
Dark Radiation



Lowest tension when DR is fluid, and when produced after BBN $\rightarrow$ slightly above 2σ

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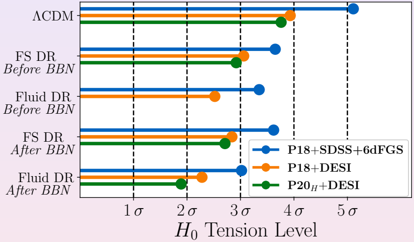
More recent Planck '20 Likelihood

We also use a more recent Planck '20 Likelihood ('Hillipop+Lollipop')+BAO+Pantheon:



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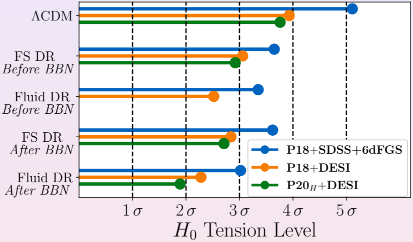

- Larger sky fraction
- Resolves an inconsistency ("A_L anomaly") in CMB lensing
- Lower H_0 tension (down to $1.87\ \sigma$)
- Justifies a combined fit with SH0ES

Consequence: adding SH0ES

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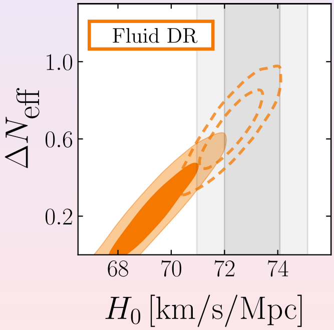

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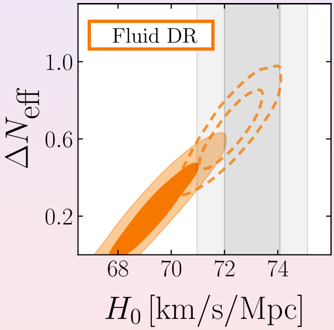

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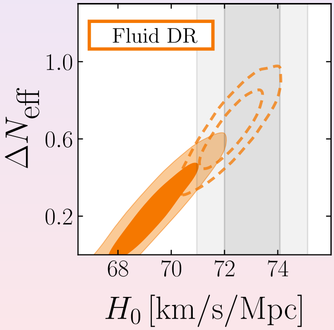

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$$\Delta\chi^2 = -24.7\,, \quad \Delta\mathrm{AIC} = -22.7$$

(Allali + AN + Rompineve 24)

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EXTRA SLIDES

Neutrino masses detection from Cosmology

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  - Inverted hierarchy:
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Neutrino masses detection from Cosmology

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  - Transition: Dark radiation $\to$ Dark matter
  - Other effect: Free-streaming $\implies$ large velocities $\implies$ they erase overdensities on small scales in the matter distribution

Neutrino masses bound from DESI

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  (at 2σ, with a prior $\sum m_\nu > 0$) (from DESI, Adame et al 24)

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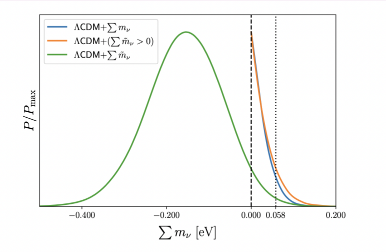
  - Problem: preference for "negative" neutrino masses



(N. Craig, D. Green, J. Meyers and S. Rajendran, arXiv:2405.00836.)

Neutrino masses bound from DESI 2024

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I. Allali, AN 2024, 2406.14554 [astro-ph.CO]

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DESI BAO

Dark Energy

DES5Y Supernovae

H_0 Tension

Dark Radiation

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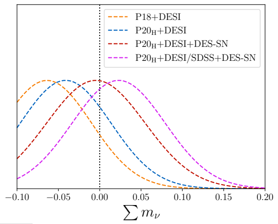
- More Positive neutrino masses preferred,



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Neutrino masses bound from DESI

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Neutrino masses bound from DESI

- In the Fluid Dark Radiation model even more positive
- Central value gets close to expectation (0.05 eV) from normal hierarchy: ~ 0.04 eV