Dark Radiation and Dark Energy and neutrinos with DESI 2024 BAO, and the H_0 tension

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Universitat de Barcelona

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

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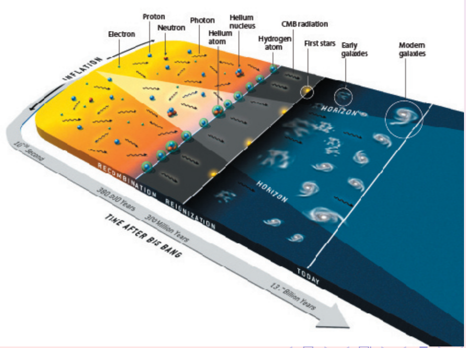
- Fluid pressure resists compression → acoustic oscillations
- Oscillations are frozen in when hydrogen forms (recombination): CMB photons emitted



CMB fluctuations

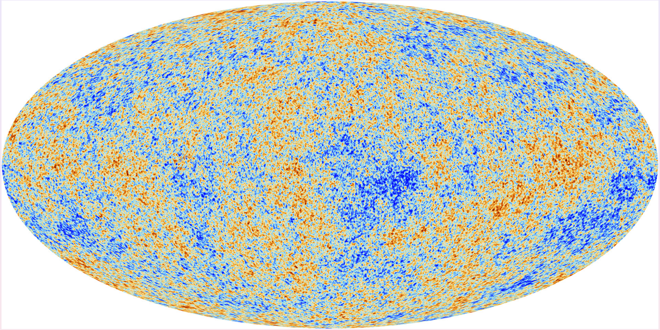


Figure: Credit: ESA and the Planck Collaboration

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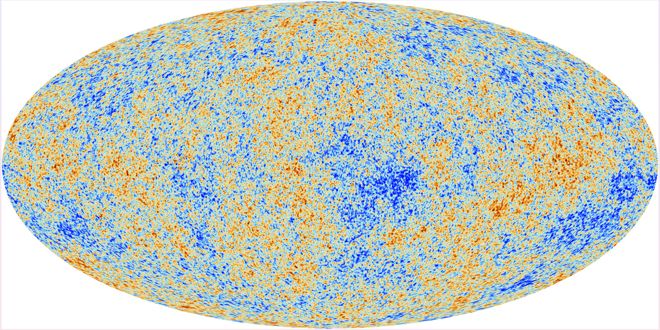

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- Preferred angular scale of $\theta_{\rm peak} \approx 1^\circ$

Sound horizon at CMB

- Sound horizon at decoupling r_d, length scale imprinted in CMB: distance that a sound wave can travel from big bang until decoupling:

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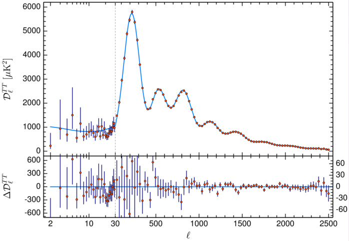
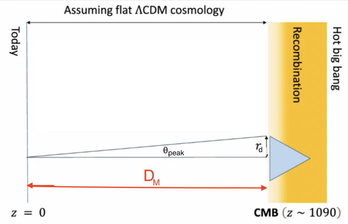
- "Standard ruler" of early universe, length scale stretched to ~ 150 Mpc today

Sound horizon in CMB and BAO

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





- 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)

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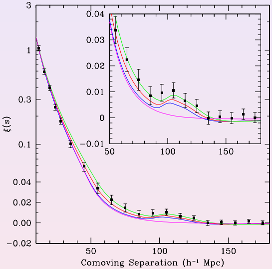

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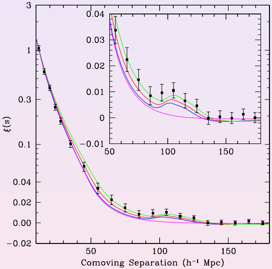

- $$\boxed{\Delta\theta = r_d / D_M(z)}$$

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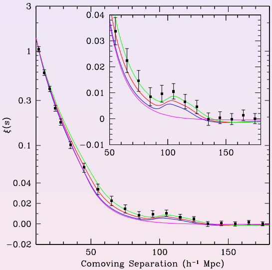

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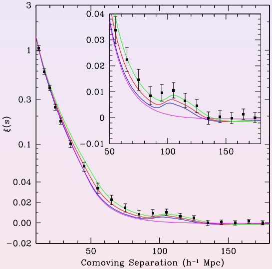
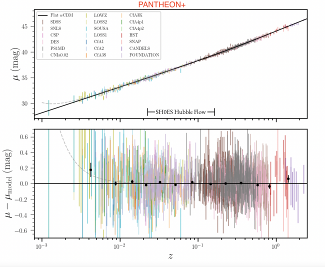


- $\boxed{\Delta\theta = r_d / D_M(z)}$
- Transverse comoving distance $D_M(z) = \int_0^z \frac{dz'}{H(z')}$
- Given a cosmological model $\implies r_d$

  $\implies$ BAO+CMB measure Distance D_M vs Redshift (z)
- Constrains $H(z)$

Supernovae



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- Assuming Type Ia SN have known intrinsic luminosity (standardized candles)

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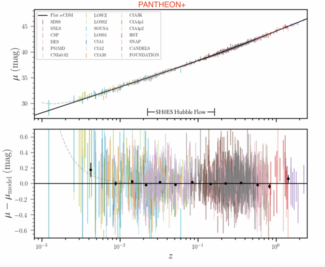

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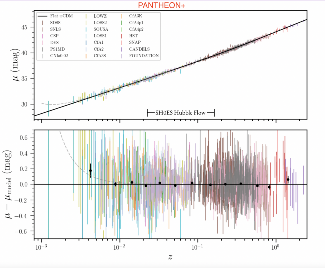

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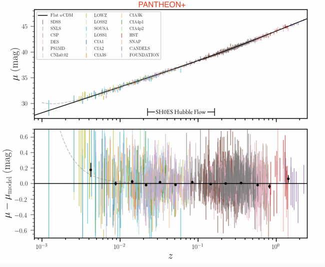

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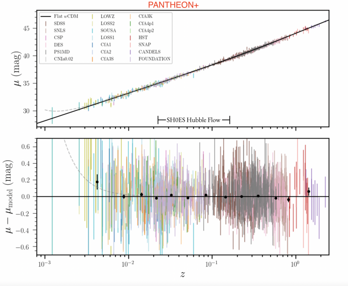
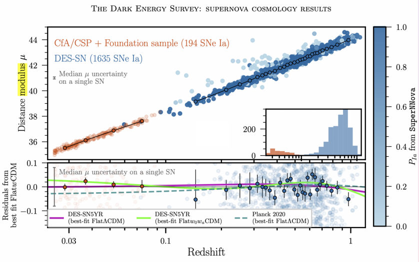
- Only if Intrinsic luminosity known (calibration) $\rightarrow$ H_0 is measured

Supernovae: Pantheon and DESY5

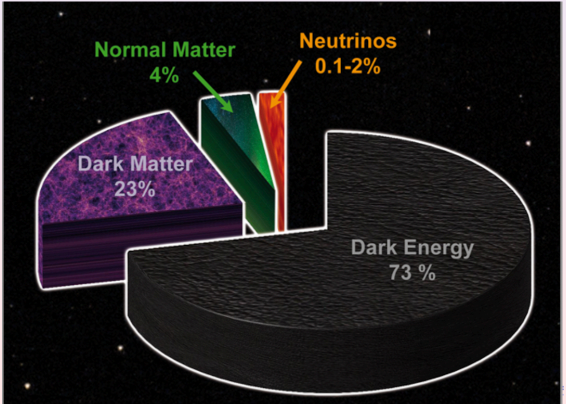




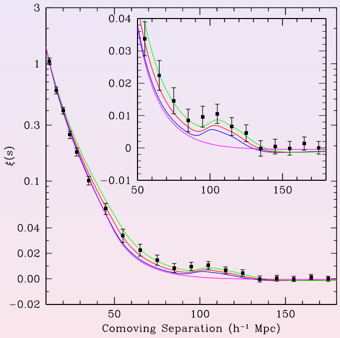
ΛCDM Concordance Model

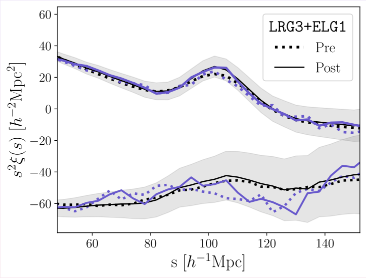
BAO + CMB + uncalibrated Supernovae: established the "Standard" ΛCDM cosmological model:

- Consistent with spatial flatness
- Requires Dark matter + Dark Energy



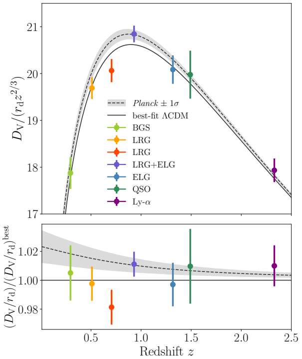
BAO from DESI 2024





(from SDSS, Eisenstein et al 05) (from DESI, Adame et al 24 (III))

Distance-redshift from DESI BAO



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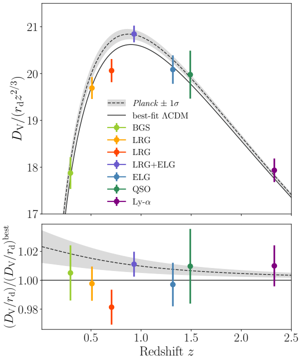

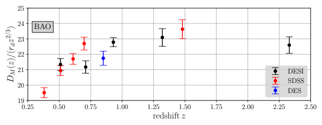

- Data point at $z \sim 0.7$ low.
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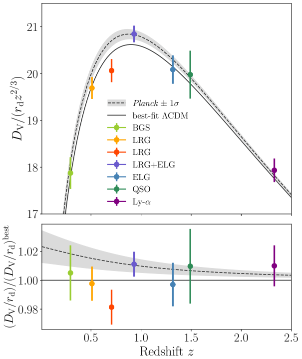

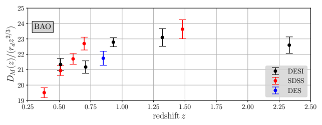

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Abbott et al. PRD 2024

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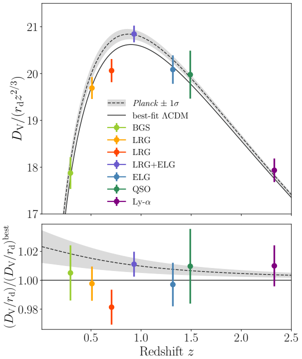

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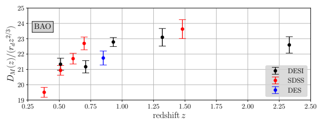

- Smaller distance $\Longrightarrow$ higher H_0

(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** (DES Collaboration, 2024) uncalibrated Supernovae
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Cosmologies computed with Einstein-Boltzmann code `CLASS`
MCMC analysis: `MontePython` +Cobaya

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  DESI 2024+SNe+CMB: preference for **time-varying Dark Energy** ? (Adame et al (DESI VI) 24)

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- Other methods include TRGB (tip of red giant branch), and recently JAGB (J-Branch Asymptotic Giant Branch stars)

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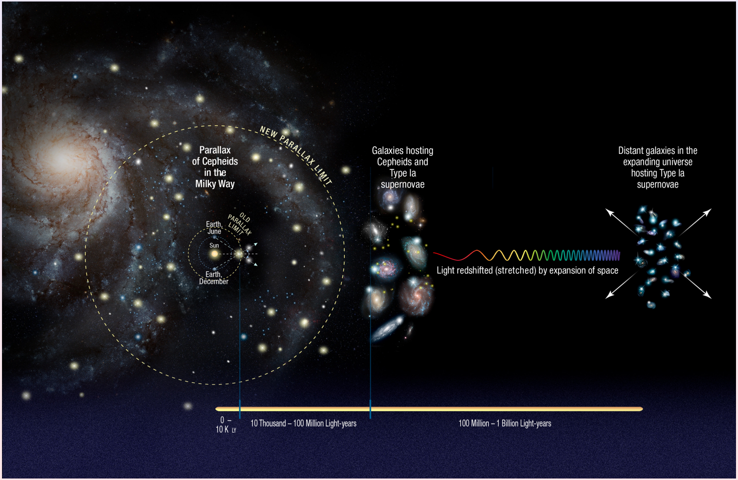
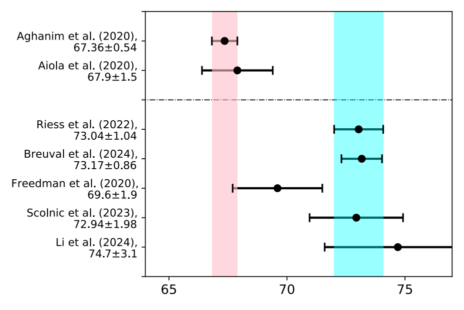


Credit: NASA, ESA, A. Feild (STScI), and A. Riess (STScI/JHU)

Disagreement in H_0 [km/s/Mpc]

Inferences from CMB in the ΛCDM model disagree with SH0ES



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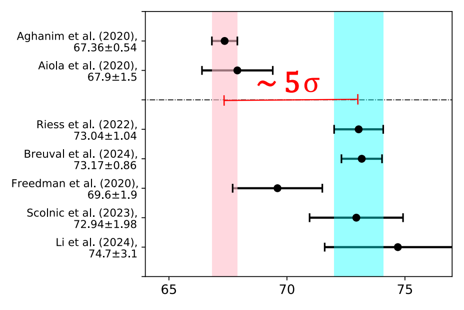

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- Freedman et al. 2408.06153 (CCHP): $H_0 = 69.96 \pm 1.05(\mathrm{stat}) \pm 1.12(\mathrm{sys})$ km/s/Mpc.
- Riess et al. (SH0ES): $H0 = 73.04 + -1.04$ km/s/Mpc

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- In light of new DESI 2024 BAO data, the status of tensions changes

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Dark Radiation (DR): extra light degrees of freedom

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- Almost negligible today
- Can be fermionic, bosonic, low mass, massless, interacting, non-interacting . . .
- Examples: thermal axions, gravitational waves, extra neutrinos, dark photons, etc....

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- We consider $\boxed{\Delta N_{\rm eff} > 0}$ flat **prior** (i.e. Standard Model neutrinos not altered)

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- DR $\Longrightarrow$ changes damping scale at large ℓ ("diffusion" damping)
- Freestreaming (FS) dark radiation $\Longrightarrow$ phase shift of the higher CMB peaks position

Dark Radiation: Free-Streaming

- Free-streaming radiation described by (Ma & Bertschinger '95)
    - Density contrast δ ($\ell = 0$)
    - Fluid Velocity, $\theta \equiv \partial_i v^i$ ($\ell = 1$)
    - Shear σ ($\ell = 2$)
    - $\ell > 2$

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  - $\ell > 2$
- Full "Boltzmann" hierarchy (must be truncated at some ℓ)

$$\begin{aligned}
\dot{\delta} &= -\frac{4}{3}\theta - \frac{2}{3}\dot{h}\,, && (\ell = 0) \\
\dot{\theta} &= k^2\left(\frac{1}{4}\delta - \sigma\right)\,, && (\ell = 1) \\
\dot{\sigma} &= \frac{4}{15}\theta - \frac{3}{10}k\,F_{\nu 3} + \frac{2}{15}\dot{h} + \frac{4}{5}\dot{\eta}\,, && (\ell = 2) \\
\dot{F}_{\nu\ell} &= \frac{k}{2\ell+1}\left[\ell F_{\nu(\ell-1)} - (\ell+1)F_{\nu(\ell+1)}\right]\,, && \ell \geq 3
\end{aligned}$$

- Synchronous gauge (h, η scalar parts of the spatial metric)

Dark Radiation: Fluid

- In an interacting fluid shear is driven to zero by fast interactions (faster than expansion):
  - Density contrast δ ($\ell = 0$)
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  - Shear $= 0$
- "Boltzmann" hierarchy (only $\ell = 0, 1$)

$$\begin{aligned} \dot{\delta} &= -\frac{4}{3}\theta - \frac{2}{3}\dot{h} \\ \dot{\theta} &= k^2 \left(\frac{1}{4}\delta - 0 \right) \end{aligned}$$

- Synchronous gauge (h, η scalar parts of the spatial metric)

Free-Streaming vs Fluid

- Free Streaming DR examples:
  - QCD Axion (see e.g. (AN + Rompineve +Villadoro PRL '24) for recent results)
  - Gravitational waves
  - Extra neutrinos
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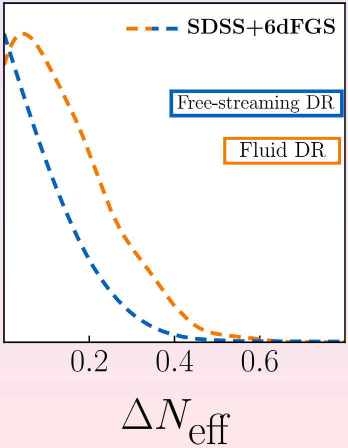
- Specific effects on perturbations:
  - FS case: phase shift of higher CMB peaks position, less clustering

DR Constraints *before* DESI (without SH0ES)

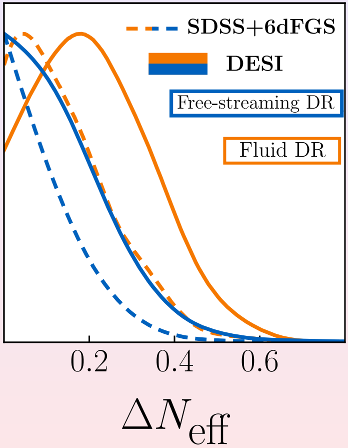


Combination of:

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

(Allali + AN + Rompineve 24)

With DESI (without SH0ES)



Combination of:

- CMB from **Planck18**
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- BAO from **SDSS+6DFGS**
- vs. from **DESI**

(Allali + AN + Rompineve 24)

Light Element Abundance Constraints (BBN)

Primordial element abundances are sensitive to the amount of radiation present during Big Bang Nucleosynthesis (BBN)

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$\rightarrow$ Updated constraints including BBN*:

(Aver et al 15, Cooke et al 18, Marcucci et al 16)

	Planck+DESI+Pantheon+	$+\mathbf{Y_{He}},\mathbf{D/H}$
Free-streaming	< 0.39	< 0.30
Fluid	$0.221^{+0.088}_{-0.18}$ (< 0.46)	< 0.37

(Allali + AN + Rompineve 24)

*Constraints sensitive to 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?

DR could be produced after BBN

Example: Decay of a Massive species at $\boxed{10\,\mathrm{eV} \ll T \ll \mathrm{MeV}}$.

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In this case:

- BBN constraints do not apply
- Abundance of free electrons not affected by DR
- We consider 4 cases:
  - Free-Streaming DR:
    1. present before BBN
    2. produced after BBN
  - Fluid DR:
    1. present before BBN
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DESI alleviates the H_0 tension

(Allali + AN + Rompineve 24)

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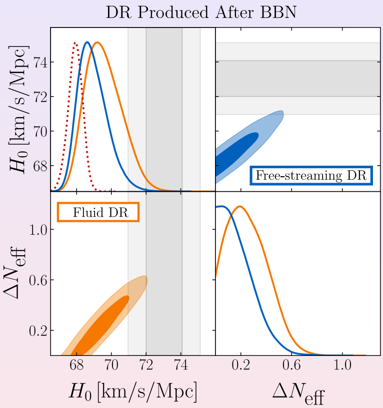

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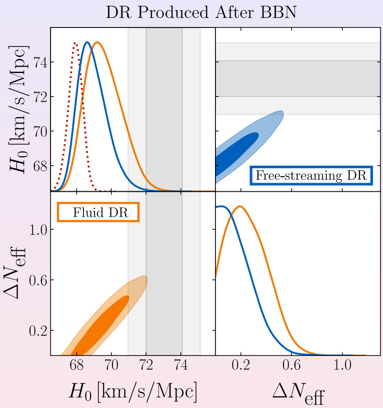
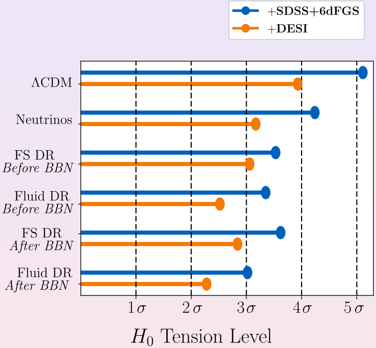
DESI alleviates the H_0 tension





(Allali + AN + Rompineve 24)

DESI alleviates the H_0 tension

Distance measurements

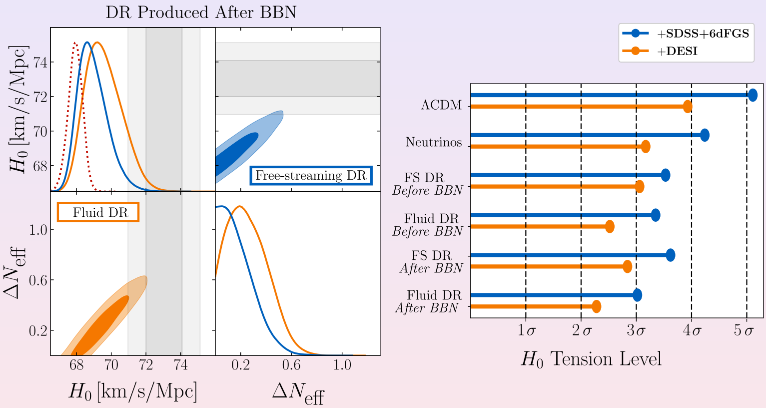
Hubble Tension

Dark Radiation

Dark Energy

DES5Y Supernovae

Neutrinos

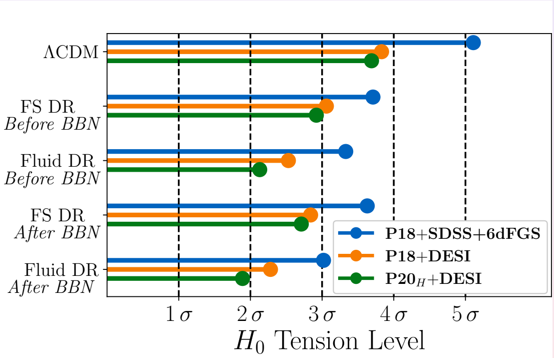


Lowest tension when DR is fluid, and when produced after BBN $\rightarrow$ slightly above 2σ

(Allali + AN + Rompineve 24)

More recent Planck '20 Likelihood

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



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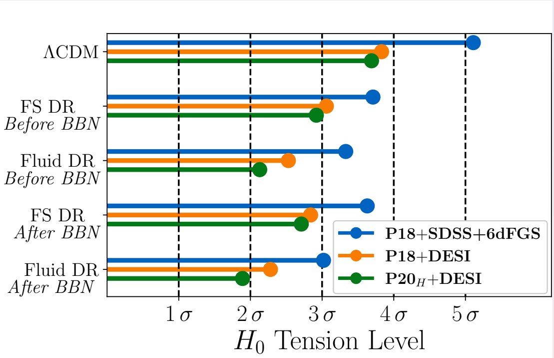

- Larger sky fraction
- Resolves "A_L anomaly" in CMB lensing
- Lower H_0 tension (down to 1.9σ)
- Combined fit with SH0ES can be justified

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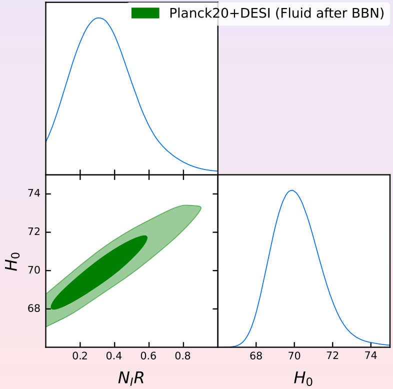
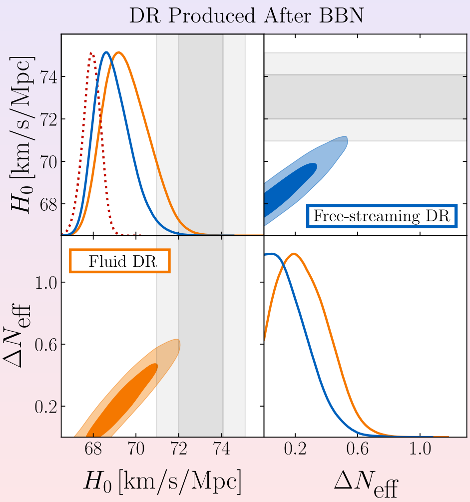


- H_0 tension down to 1.7σ

Increased H_0: adding SH0ES



P18+DESI+Pantheon+:

	H_0 (Tension)
ΛCDM	$67.93^{+0.44}_{-0.38}$ (3.9σ)
Fluid	$69.56^{+0.85}_{-1.2}$ (2.3σ)
FS	$68.94^{+0.63}_{-0.99}$ (2.8σ)

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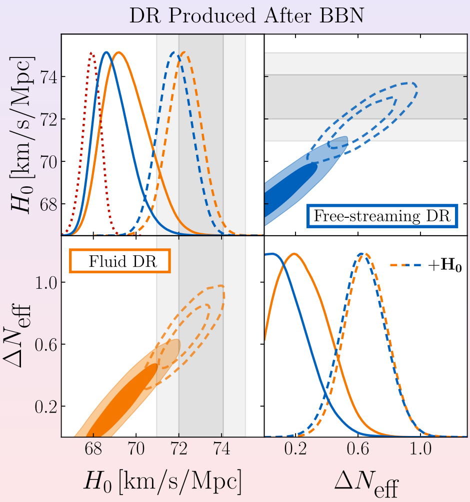

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ΛCDM	$67.93^{+0.44}_{-0.38}$ (3.9σ)
	↓
	$68.82^{+0.37}_{-0.39}$ (3.8σ)
Fluid	$69.56^{+0.85}_{-1.2}$ (2.3σ)
	↓
	72.25 ± 0.79 (0.6σ)
FS	$68.94^{+0.63}_{-0.99}$ (2.8σ)
	↓
	$71.82^{+0.78}_{-0.77}$ (0.9σ)

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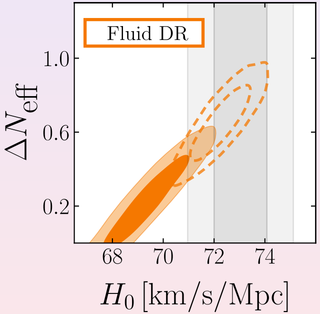

- Increased H_0

$$H_0 = 69.56^{+0.85}_{-1.2} \rightarrow 72.26^{+0.77}_{-0.78}$$
$$(2.3\sigma) \rightarrow (0.6\sigma)$$

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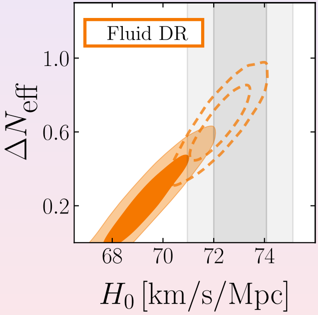

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- Evidence for dark radiation ($\sim 5\sigma$)

$$\boxed{\Delta N_{\rm eff} = 0.65 \pm 0.13}$$

Comparison with ΛCDM

- Much better fit than ΛCDM

$$\boxed{\Delta\chi^2 = -24.7}$$

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

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- $\Delta AIC \equiv \Delta\chi^2 + 2\Delta p$, Akaike Information Criterion, penalized by extra parameters

-

$$\boxed{\Delta \mathrm{AIC} = -22.7}$$

Δ AIC Range	Interpretation
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Table: AIC Thresholds (Burnham & Anderson, 2002)

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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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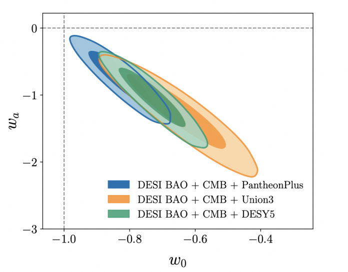

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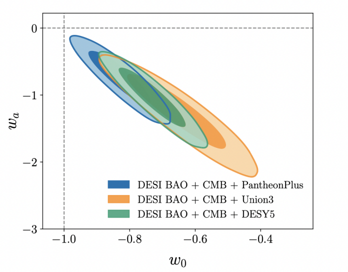

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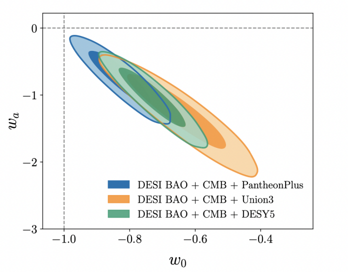

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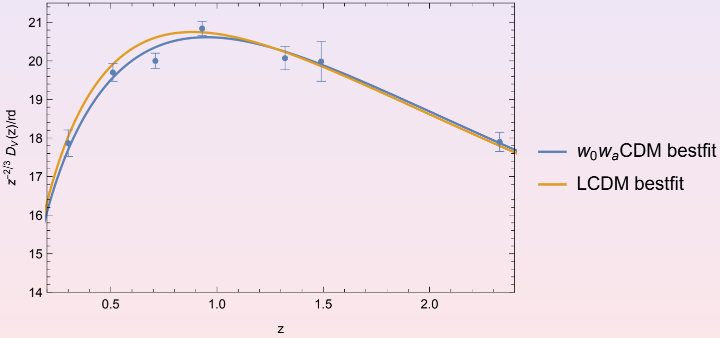

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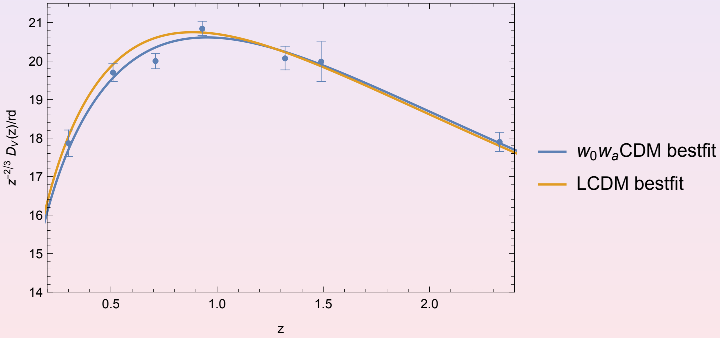

- Supernovae crucial too: Pantheon (2.5σ) vs DES5Y (3.9σ)

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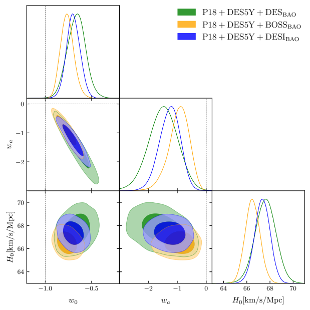

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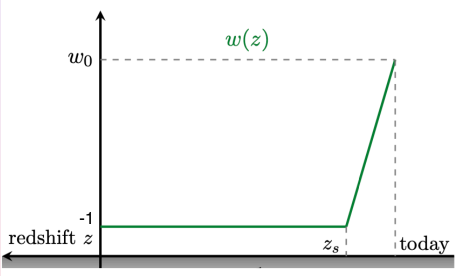

Figure: "Ramp" model

- 2 parameters: w_0 and z_s

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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- Can be embedded in healthy 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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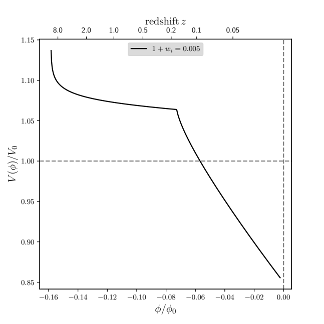

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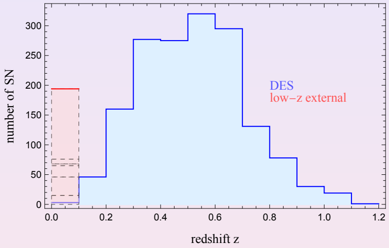
- Supernova (DES5Y dataset) fit also very important!
- We attempted a combination of Pantheon+ with DESYR5 by removing common SNe

- 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)

DES5Y Supernovae



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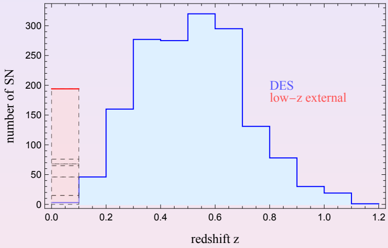

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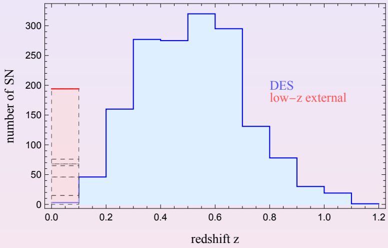

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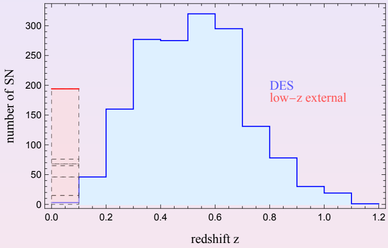

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- Efstathiou, 2408.07175: low z sample of DES5Y has an offset, compared to same SNe in Pantheon

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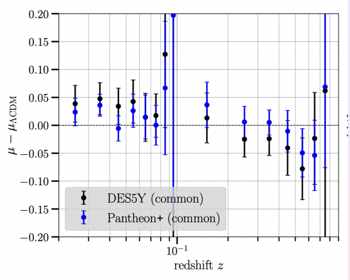

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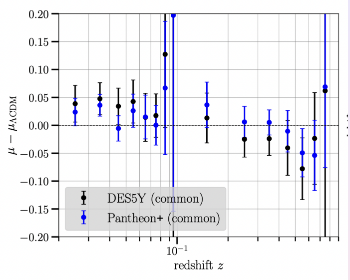

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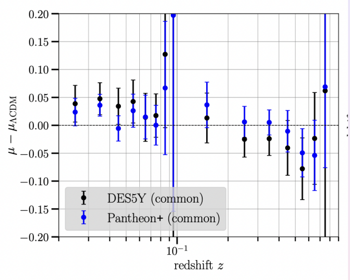

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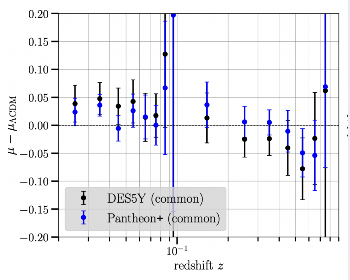

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DES5Y Supernovae

Dataset	$\chi^2_{\rm min}(w_0w_a{\rm CDM})$	ΛCDM exclusion
P18+DESI$_{\rm BAO}$+DES5Y	4431	3.9σ
P18+DESI$_{\rm BAO}$+Pantheon+	4205	2.5σ
P18+DESI$_{\rm BAO}$+$\overline{\rm DES5Y}$ + Pantheon+	5550	2.5σ
P18+DESI$_{\rm BAO}$+$\overline{\rm Pantheon+}$ + DES5Y	5569	3.8σ

- Evidence driven by the old low-z SNe **reanalyzed** by DES collaboration

DES5Y Supernovae

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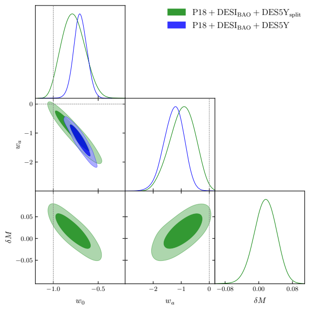
- Evidence for evolving DE vanishes (1.7σ)



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  1. half of the offset compared to Pantheon, is due to better bias subtraction in DES5Y
  2. When treating DESY5 with old bias subtraction
     $3.9\sigma \rightarrow 3.3\sigma$

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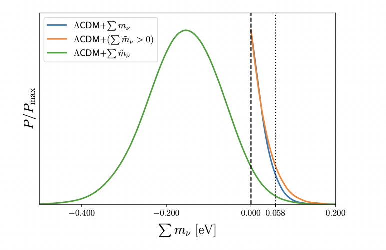
  - Problem: preference for "negative" neutrino masses



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

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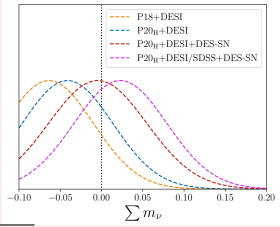
- More Positive neutrino masses preferred, as it should be



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Neutrino masses bound from DESI

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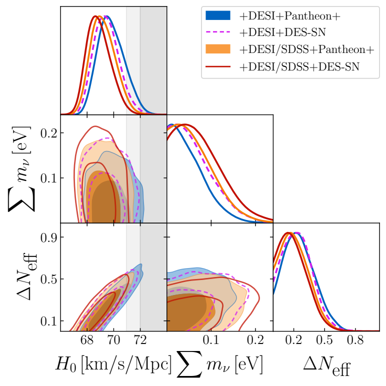
- Central value gets close to expectation (0.05 eV) from normal hierarchy: 0.04 eV

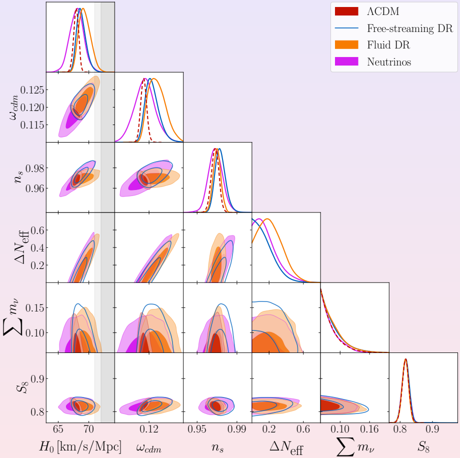


EXTRA SLIDES

Fluid Dark Radiation Produced After BBN

Parameter	**P18+DESI +Pantheon_Plus**	**P18+DESI +Pantheon_Plus+H_0**	**ΛCDM**
$100\omega_b$	$2.266\ (2.263)^{+0.015}_{-0.019}$	$2.299\ (2.305)^{+0.015}_{-0.015}$	$2.264\ (2.275)^{+0.013}_{-0.013}$
ω_{cdm}	$0.1229\ (0.1254)^{+0.0023}_{-0.0034}$	$0.1291\ (0.1303)^{+0.0028}_{-0.0028}$	$0.11682\ (0.11669)^{+0.00083}_{-0.00083}$
$\ln 10^{10}A_s$	$3.049\ (3.041)^{+0.015}_{-0.015}$	$3.045\ (3.053)^{+0.016}_{-0.016}$	$3.061\ (3.07)^{+0.015}_{-0.016}$
n_s	$0.9689\ (0.9666)^{+0.0037}_{-0.0037}$	$0.9716\ (0.9759)^{+0.0035}_{-0.0035}$	$0.9723\ (0.9732)^{+0.0037}_{-0.0036}$
τ_{reio}	$0.0607\ (0.057)^{+0.0071}_{-0.0081}$	$0.0627\ (0.0679)^{+0.0073}_{-0.0083}$	$0.0651\ (0.0666)^{+0.0074}_{-0.0085}$
$\Delta N_{\rm eff}$	$0.26\ (0.34)^{+0.11}_{-0.21}$	$0.65\ (0.73)^{+0.13}_{-0.14}$	–
$\sum m_\nu$	< 0.137	< 0.149	< 0.099
H_0 [km/s/Mpc]	$69.56\ (69.82)^{+0.85}_{-1.2}$	$72.25\ (73.0)^{+0.79}_{-0.79}$	$68.82\ (68.98)^{+0.37}_{-0.39}$
S_8	$0.815\ (0.825)^{+0.010}_{-0.011}$	$0.809\ (0.812)^{+0.011}_{-0.011}$	$0.8017\ (0.8045)^{+0.0096}_{-0.010}$
M_b	$-19.374\ (-19.365)^{+0.026}_{-0.037}$	$-19.298\ (-19.276)^{+0.024}_{-0.021}$	$-19.398\ (-19.392)^{+0.011}_{-0.011}$
H_0 GT	2.59σ	0.6σ	3.82σ
H_0 IT	2.28σ	0.6σ	3.8σ
$\Delta\chi^2$	-0.4	-24.7	-
ΔAIC	$+1.6$	-22.7	-

P18+DESI+Pantheon Plus, Before BBN



$S_8 = 0.790^{+0.018}_{-0.014}$ DES Y3 + KiDS-1000

$S_8 = 0.836 \pm 0.035$ DESI FS+BAO+BBN+n_{s10}

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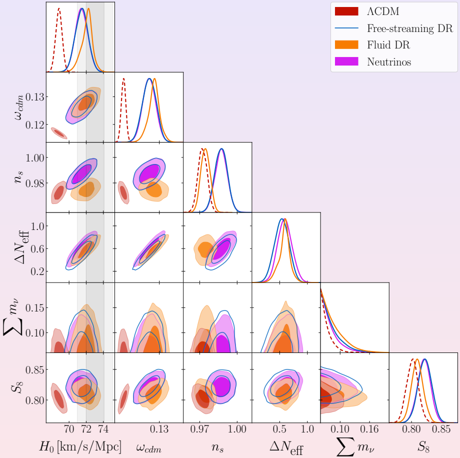

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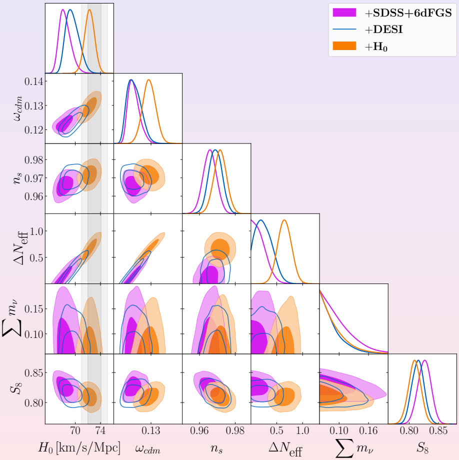

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Early Dark Energy with DESI BAO

- $V(\phi) = m^2 f^2 (1 - cos(\phi/f))^3$, with P18+CMB lensing+DESI BAO (Qu et al. 2404.16805)
  - $H_0 = 69.14^{+0.68}_{-1.1} \mathrm{kms^{-1}Mpc^{-1}}$
  - 3.1σ Gaussian Tension
- $V(\phi) = m^2 f^2 (1 - cos(\phi/f))^2$, with P18+CMB lensing+DESI BAO+SDSS BAO (O.Seto and Y.Toda, Phys.Rev.D 110 (2024),
  - $H_0 = 69.19^{+0.6}_{-0.84} \mathrm{kms^{-1}Mpc^{-1}}$
  - 3.2σ Gaussian Tension