Light Stepped Dark Sectors Face Cosmological Datasets

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Based on work with M.P. Hertzberg and F. Rompineve
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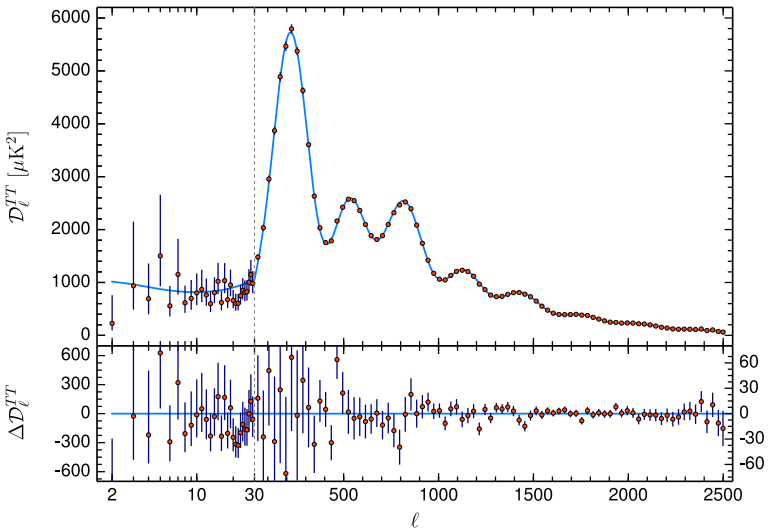
The ΛCDM Concordance (?) Model

ΛCDM model



(from Planck 18 results, Aghanim et al 18)

- 6 free parameters
- Agreement between CMB, BAO, LSS

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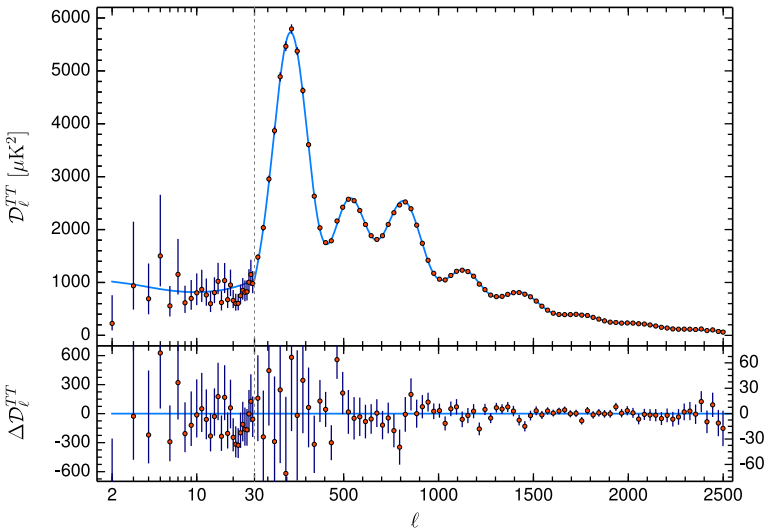

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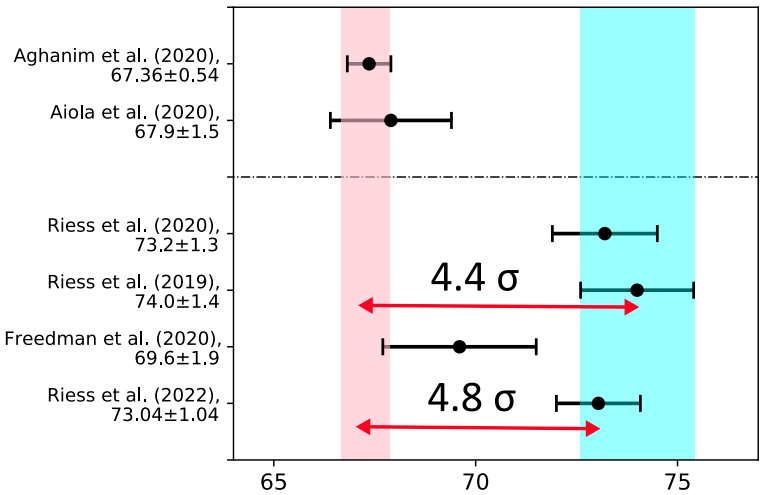
Tensions emerge with direct measurements:

H_0 tension with SH_0ES



(adapted from Di Valentino et al 21)

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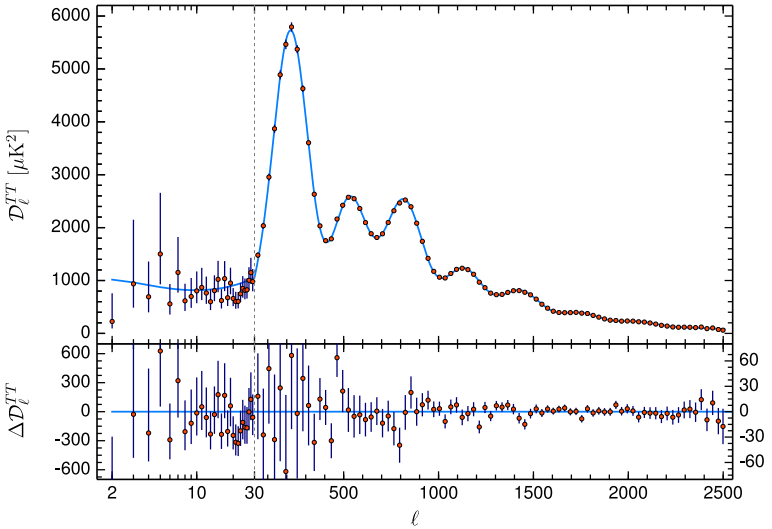
ΛCDM model



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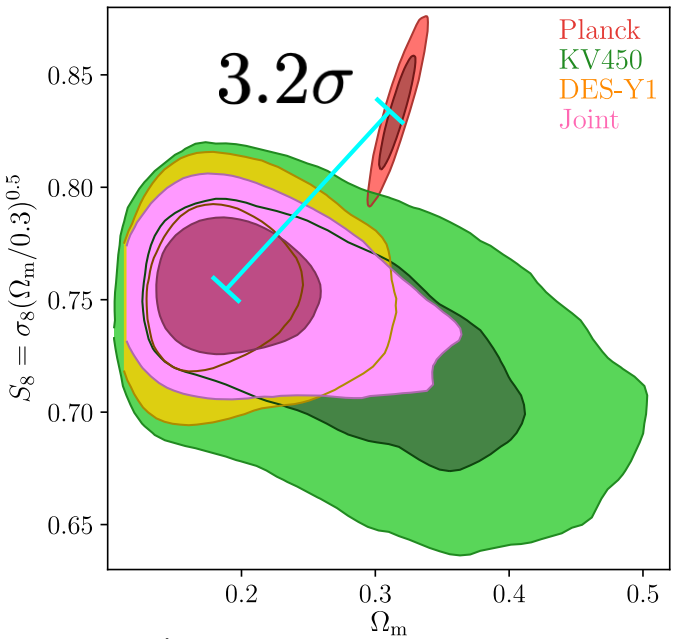
Tensions emerge with direct measurements:

S_8 tension with cosmic shear



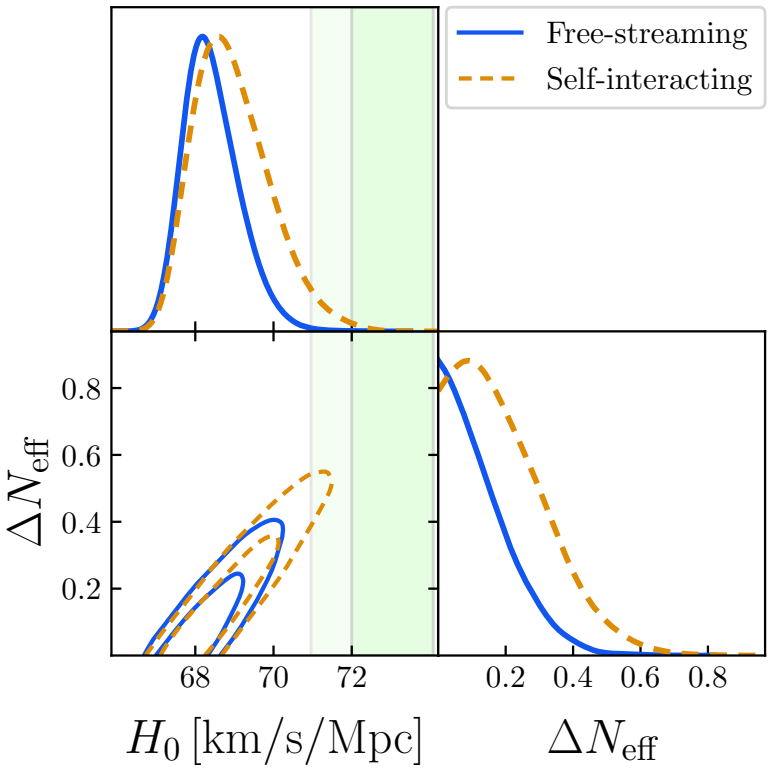
(Asgari et al 20)

Simple Adjustment: Dark Relativistic Species $\Delta N_{\rm eff}$

Adding dark radiation to ΛCDM has been considered:

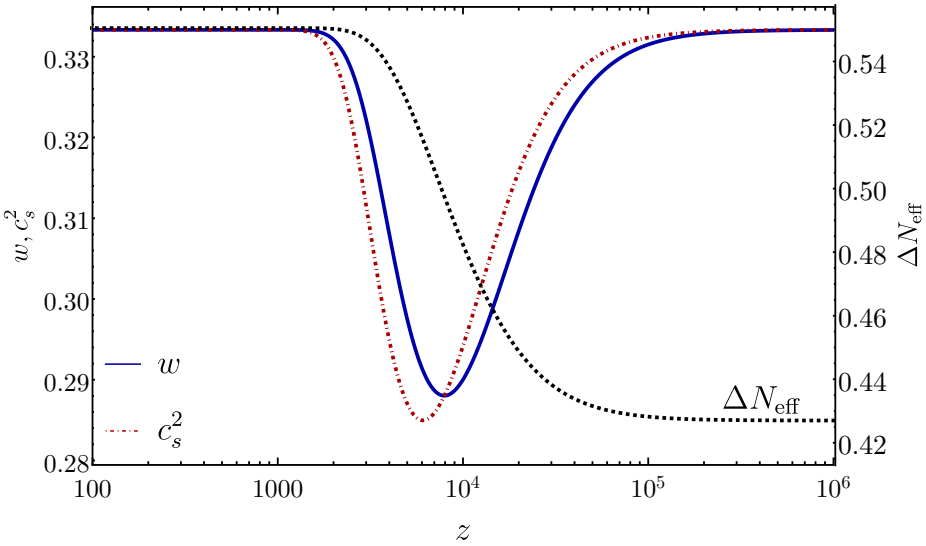
$$\Delta N_{\rm eff} \equiv \rho_{\rm DR}/\rho_{\nu,1} \tag{1}$$

- Free streaming radiation constrained heavily by CMB
- Strongly self-interacting a bit less, still constrained
- Known degeneracy with the value of H_0



Dark Radiation with Mass Threshold

- Coupled light species, some with a mass m ($\sim$ eV)
- Gives rise to a relativistic sector with a step in abundance (Aloni et al 2021)
- Affect of step: high ℓ modes "see" smaller $\Delta N_{\rm eff}$



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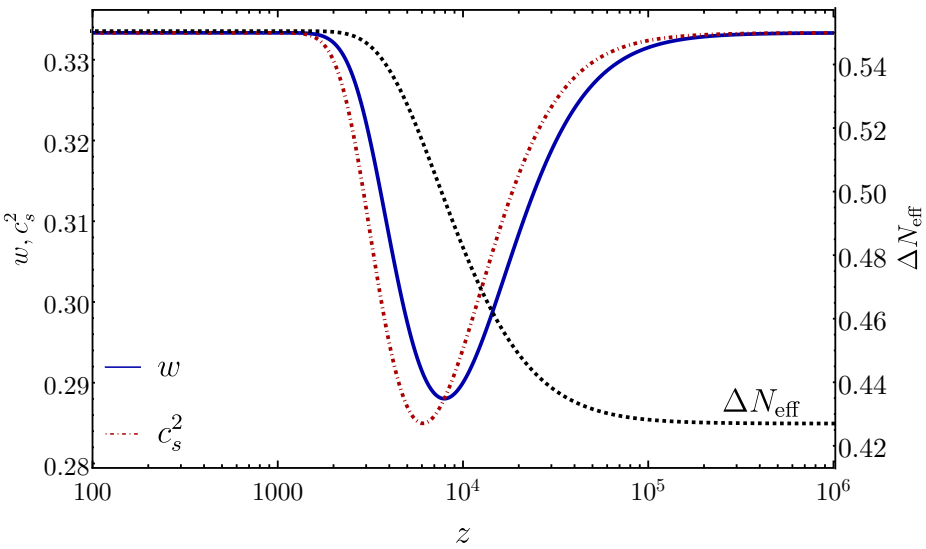
$$\frac{\Delta N_{\rm eff}^{\rm IR}}{\Delta N_{\rm eff}^{\rm UV}} = (1 + r_g)^{1/3} \quad (2)$$

3 pheno parameters:

- Late time $\Delta N_{\rm eff}^{\rm IR}$
- Redshift of step z_t (determined by m)
- Step size r_g



Motivation for this Analysis

Stepped Dark radiation models are interesting and deserve study:

- The potential to solve tensions well
- Simple and well-motivated particle physics modeling is rare

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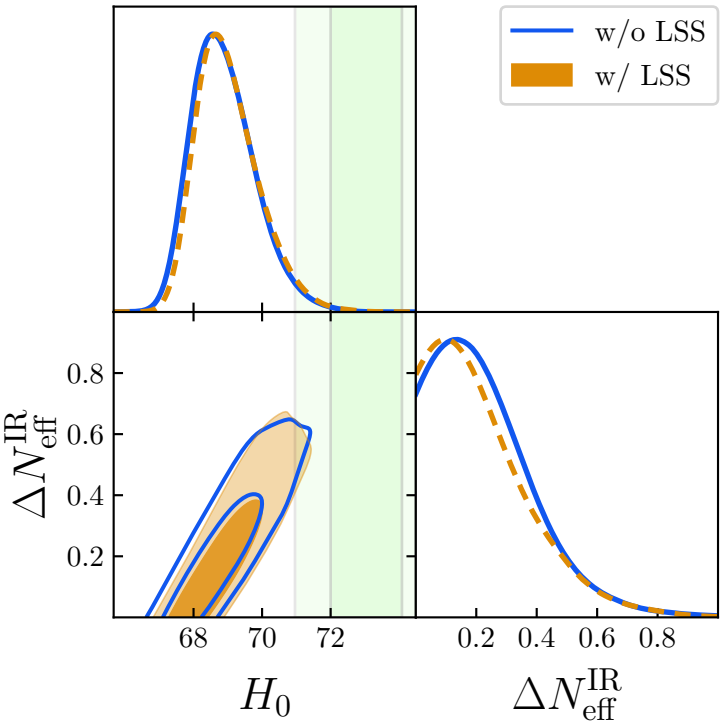
Extending the Analysis

1. Including LSS data: has been shown to constrain other models (e.g. EDE (Hill et al 20 | Ivanov et al 20 | D'Amico et al 20 | Smith et al 20))
2. Conservative analysis: broad priors and all parameters free (different than previous choices (Aloni et al 21 | Joseph et al 22))

Testing Against LSS, Preliminary Results

- LSS data does not significantly impact $\Delta N_{\rm eff}$ constraint



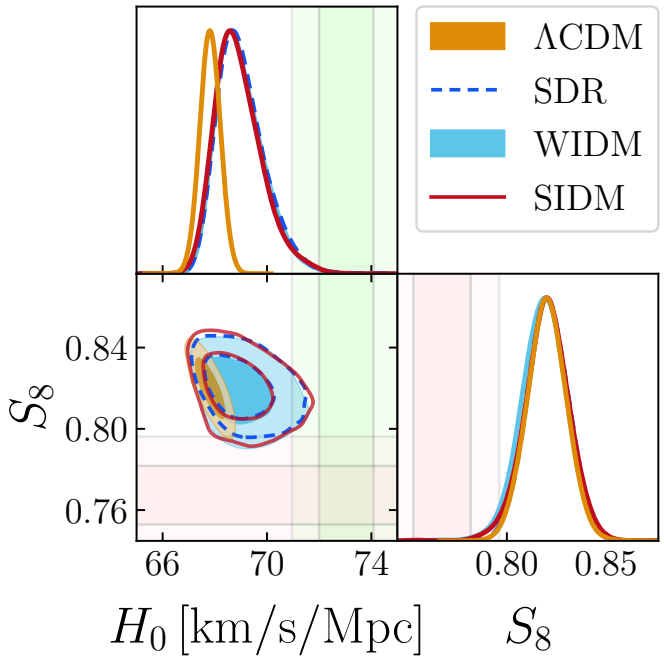
Planck + BAO + Pantheon fit w/o and w/ LSS

- $\Delta N_{\rm eff} < 0.546$ w/o LSS
- $\Delta N_{\rm eff} < 0.550$ w/ LSS

Implemented with modified version of `CLASS`: (Blas + Lesgourgues + Tram 11)
MCMC analysis using `MontePython` (Audren et al 12, Brinckmann + Lesgourgues 18)
EFTofLSS likelihood from `PyBird`: (D'Amico + Senatore + Zhang 20)

Tensions

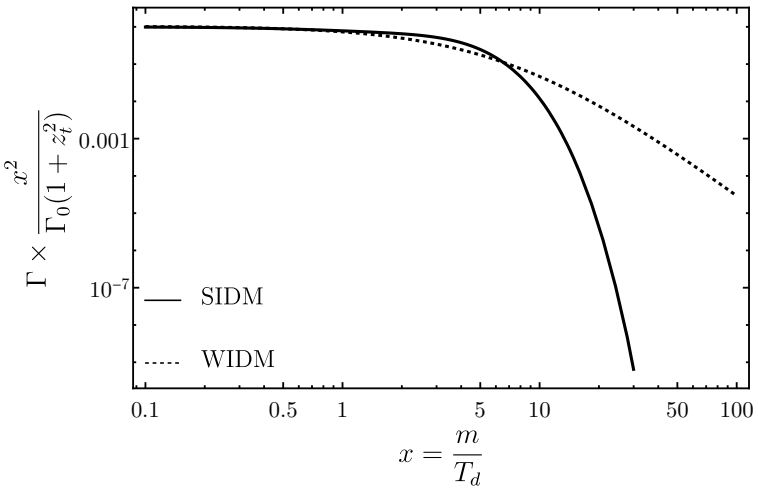
H_0 tension: $\sim 3\,\sigma$ tension across various measures

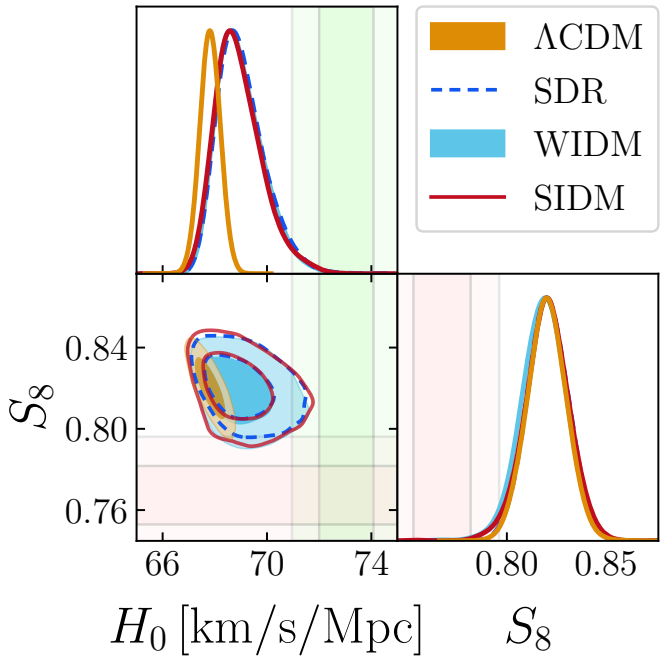


Tensions

H_0 tension: $\sim 3\,\sigma$ tension across various measures

- Include interacting dark matter (2 params)





- S_8 tension ($\sim 2.7\,\sigma$) slightly better than ΛCDM ($\sim 3\,\sigma$)
- Fit to data: not convincingly better than ΛCDM ($\Delta\chi^2 \sim -1$)

Conclusions

- Dark radiation models with mass threshold (step) are interesting
- Better particle physics embedding than competitive models

Conclusions

Analysis including LSS data:

- Does not alter relaxed $\Delta N_{\rm eff}$ constraint, or tensions

Conservative analysis raises questions about:

- Compatibility of datasets with SH_0ES and S_8 ($3\,\sigma$ tensions)
- Evidence over alternatives, especially ΛCDM (small $\Delta\chi^2$)

Monte Carlo Markov Chain

Models implemented using modified version of `CLASS`:

(Blas + Lesgourgues + Tram 11)

MCMC analysis using `MontePython`, adding datasets:

(Audren et al 12, Brinckmann + Lesgourgues 18)

- Baseline: Planck18 + BAO + Pantheon
  (Aghanim et al 18 | Beutler et al 11, Ross et al 15, Alam et al 17 | Scolnic et al 19)
- + FS: Adding EFTofLSS (via `PyBird`)
  (D'Amico + Senatore + Zhang 20)
- $+S_8$: Adding priors on S_8 from KiDS-100 ($0.759^{+0.024}_{-0.021}$) and DES-Y3 ($0.772^{+0.018}_{-0.017}$)
  (Asgari et al 21) (Amon et al 22)
- $+M_b$: Adding prior on M_b from SH_0ES (-19.253±0.027)
  (Riess et al 22)

For tension, using combined $S_8 = 0.767 \pm 0.014$

Tensions

Fitting to CMB + BAO + SN

Tension with H_0:

	ΛCDM	SDR
Tension	$5.6\,\sigma$	$3.0\,\sigma$
$\Delta\chi^2$	—	-1.4
$Q^{H_0}_{\rm DMAP}$	$5.7\,\sigma$	$2.7\,\sigma$
$\Delta{\rm AIC}^{H_0}$	—	-20.7

Tension with S_8:

	ΛCDM	WIDM	SIDM
Tension	$3.2\,\sigma$	$2.9\,\sigma$	$3.2\,\sigma$
$\Delta\chi^2$	—	-1.8	$+0.1$
$Q^{S_8}_{\rm DMAP}$	$3.5\,\sigma$	$2.9\,\sigma$	$3.5\,\sigma$
$\Delta{\rm AIC}^{S_8}$	—	$+4.8$	$+10.6$

$\Delta\chi^2 \equiv \chi^2 - \chi^2_{\Lambda CDM}$

$Q^{H_0 \text{ or } S_8}_{\rm DMAP} \equiv \sqrt{\chi^2_{+H_0 \text{ or } S_8} - \chi^2}$

$\Delta{\rm AIC}^{H_0 \text{ or } S_8} \equiv \Delta\chi^2_{+H_0 \text{ or } S_8} + \#$ of free parameters

Tensions

Fitting to CMB + BAO + SN + LSS

Tension with H_0:

	ΛCDM	SDR
Tension	$5.5\,\sigma$	$2.9\,\sigma$
$\Delta\chi^2$	—	-1.6
$Q^{H_0}_{\rm DMAP}$	$5.5\,\sigma$	$2.7\,\sigma$
$\Delta{\rm AIC}^{H_0}$	—	-18.7

Tension with S_8:

	ΛCDM	WIDM	SIDM
Tension	$3.0\,\sigma$	$2.6\,\sigma$	$2.7\,\sigma$
$\Delta\chi^2$	—	-0.6	-1.0
$Q^{S_8}_{\rm DMAP}$	$3.0\,\sigma$	$2.8\,\sigma$	$2.6\,\sigma$
$\Delta{\rm AIC}^{S_8}$	—	$+7.9$	$+6.4$

$\Delta\chi^2 \equiv \chi^2 - \chi^2_{\Lambda CDM}$

$Q^{H_0 \text{ or } S_8}_{\rm DMAP} \equiv \sqrt{\chi^2_{+H_0 \text{ or } S_8} - \chi^2}$

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Tensions

Fitting to CMB + BAO + SN + LSS + H_0

Tension with H_0:

	ΛCDM	SDR
Tension	$4.6\,\sigma$	$1.3\,\sigma$
$\Delta\chi^2$	—	-24.7

$\Delta\chi^2 \equiv \chi^2 - \chi^2_{\Lambda CDM}$

Tensions

Fitting to CMB + BAO + SN + LSS + S_8

	ΛCDM	WIDM	SIDM
Tension with H_0	$5.0\,\sigma$	$2.6\,\sigma$	$2.8\,\sigma$
Tension with S_8	$2.2\,\sigma$	$1.5\,\sigma$	$1.8\,\sigma$
$\Delta\chi^2$	—	-2.1	-3.6

$\Delta\chi^2 \equiv \chi^2 - \chi^2_{\Lambda CDM}$

Tensions

Fitting to CMB + BAO + SN + LSS + S_8 + H_0

	ΛCDM	WIDM	SIDM
Tension with H_0	$4.5\,\sigma$	$1.1\,\sigma$	$0.9\,\sigma$
Tension with S_8	$1.6\,\sigma$	$1.4\,\sigma$	$1.7\,\sigma$
$\Delta\chi^2$	—	-26.9	-18.1

$\Delta\chi^2 \equiv \chi^2 - \chi^2_{\Lambda CDM}$