Cosmological Probes of Dark Radiation from Neutrino Mixing

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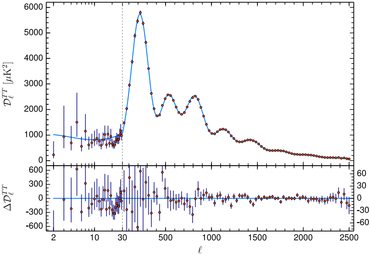
May 14, 2024

Based on
IJA, Aloni, Schöneberg 2404.16822

ΛCDM and the Hubble Tension

ΛCDM model



(from Planck 18 results, Aghanim et al 18)

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

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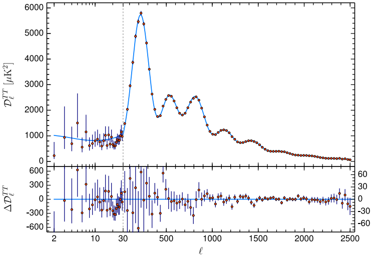

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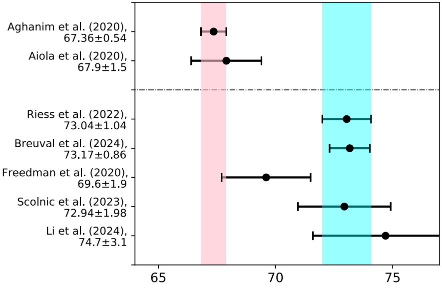
Known tension with some direct measurements of expansion rate H_0:



(adapted from Di Valentino et al 21)

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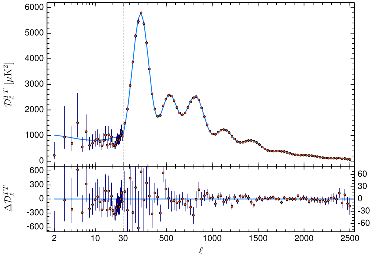

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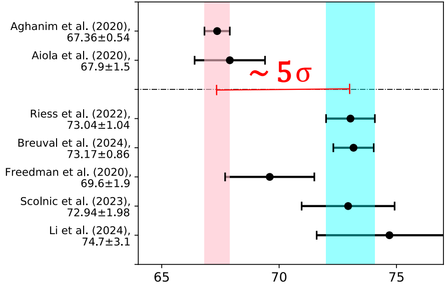

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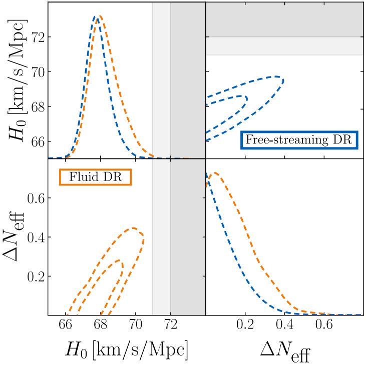
Simple Adjustment: Dark Relativistic Species ΔN_{eff}

Adding dark radiation to ΛCDM has been considered:

$$\Delta N_{\text{eff}} \equiv \rho_{\text{DR}}/\rho_{\nu,1} \quad (1)$$

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



(IJA + Notari + Rompineve 2404.15220)

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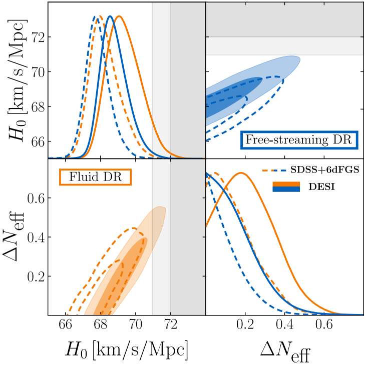
- ** Note updated constraints with DESI BAO



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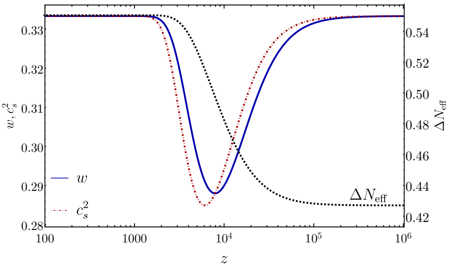
Dark Radiation with Mass Threshold (Step)

- Coupled light species, some with a mass m
- Gives rise to a relativistic sector with a step in abundance (Aloni et al 2021)
- Effect of step: high ℓ modes "see" smaller ΔN_{eff}



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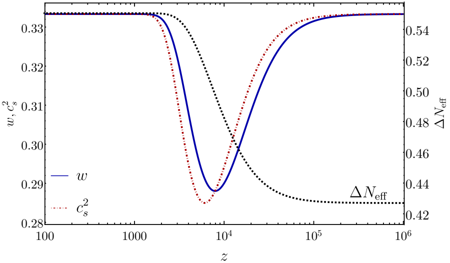
Constraint relaxes further

- $\Delta N_{\rm eff} < 0.4$ (95% C.L.)
- $\rightarrow \Delta N_{\rm eff} < 0.55$



Neutrino Mixing Model

Consider dark radiation that mixes with standard model neutrinos:

- New component: dark fermion ν_d
  - Nonzero, but small ($\mathcal{O}$(eV)) mass m_{ν_d}
  - Nonzero mixing angle θ_0 with SM neutrinos ν
- New component: dark scalar ϕ
  - Massless $m_\phi = 0$
  - Strong self-interactions and with ν_d, coupling α_d

Three microphysical parameters: m_{ν_d}, θ_0, α_d

Background Evolution

- Begin with unpopulated dark sector
- Oscillations from $\nu \to \nu_d$ decohere because of strong interactions with ϕ, overall rate:

$$\Gamma_{\nu \to \nu_d} \approx P_{\rm osc}(\nu \to \nu_d) \times \Gamma_{\rm DS} \tag{2}$$

(Aloni et al 23)

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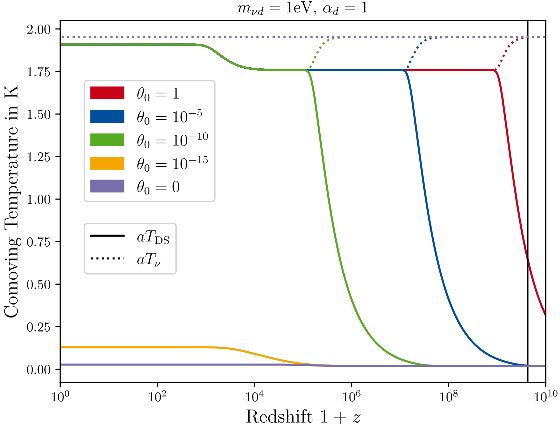
(Aloni et al 23)

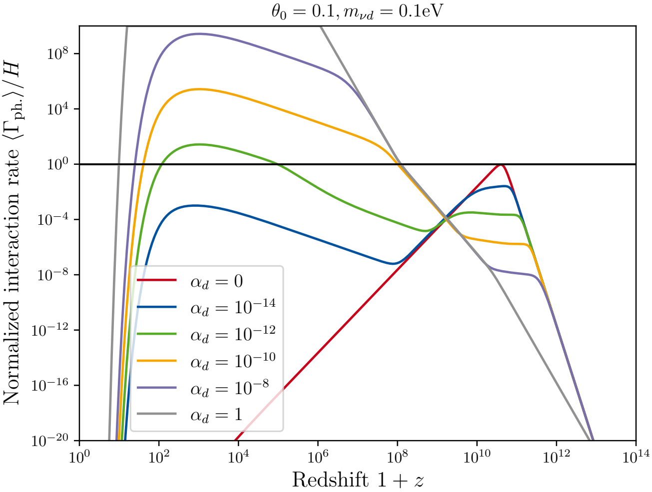
- Start to populate DS when $\Gamma/H \sim 1$ until reach thermal equilibrium
- At mass threshold, step occurs AND oscillations/ν interactions shut off

Dynamically Thermalized for wide range of θ_0

- Explains a mechanism for DR production after big bang nucleosvnthesis



Strong vs. Weak Coupling



1. Dark Radiation and the Hubble Tension
2. Dark Radiation from Neutrino Mixing
3. Results

Markov Chain Monte Carlo

Cosmologies are computed with modified Einstein-boltzmann solver `CLASS`: (Blas + Lesgourgues + Tram 11)

MCMC analysis using `MontePython`

(Audren et al 12, Brinckmann + Lesgourgues 18)

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Datasets considered:

- Baseline: CMB TT, TE, EE, and lensing from *Planck*, BAO from 6DFGS, BOSS, and WiggleZ, and Supernovae from *Pantheon+* (Aghanim et al 18 | Beutler et al 11, Ross et al 15, Alam et al 17 | Scolnic et al 22)

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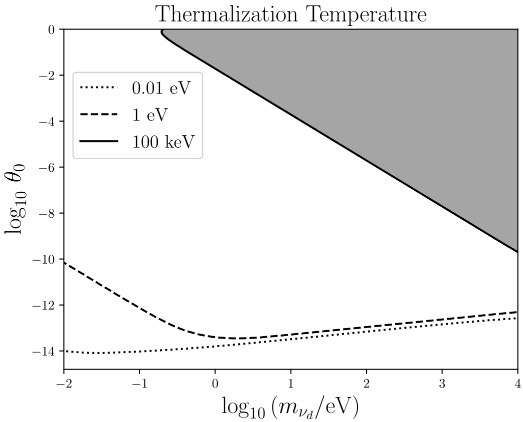
- +SH0ES: SH0ES measurement of instrinsic SNIa mag. (Riess et al 22) (combined consistently with Pantheon)

Strong Coupling Regime $\alpha_d \geq 1$



(IJA, Aloni, Schöneberg 24)

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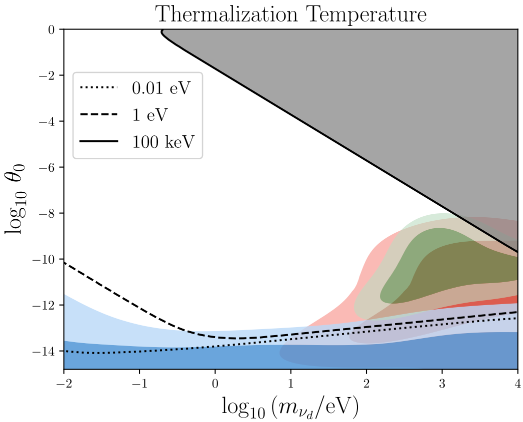
- Data constrain thermalization to after CMB



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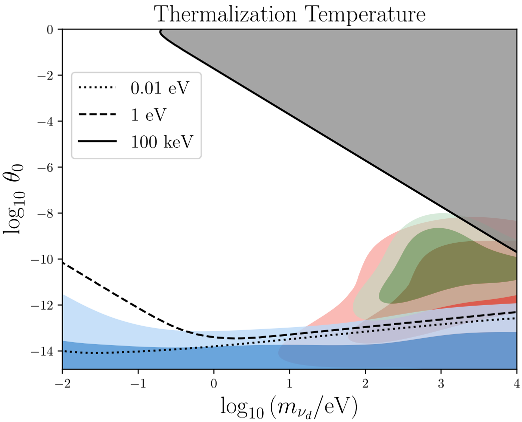
Strong Coupling Regime $\alpha_d \geq 1$

- Data constrain thermalization to after CMB
- In constrast with previous studies showing preference for ν interactions (e.g. Kreisch et al 19 | Camarena et al 23 | He et al 23)



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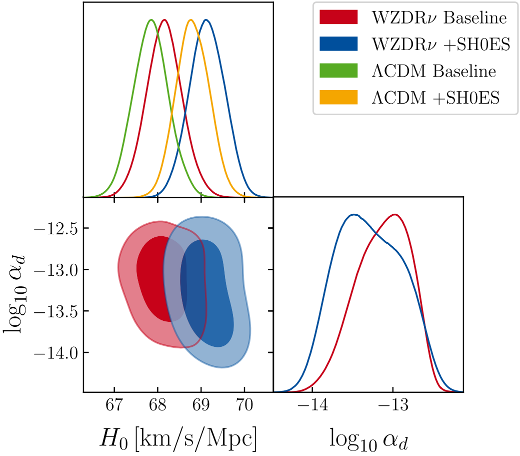
Neutrino Anomalies?

- Anomalies in ν oscillations prefer dark neutrino
- E.g. MiniBoonE/MicroBoonE with $m = 0.5$ eV, $\theta_0 = 0.09$
  (Aguilar-Arevalo et al 22)



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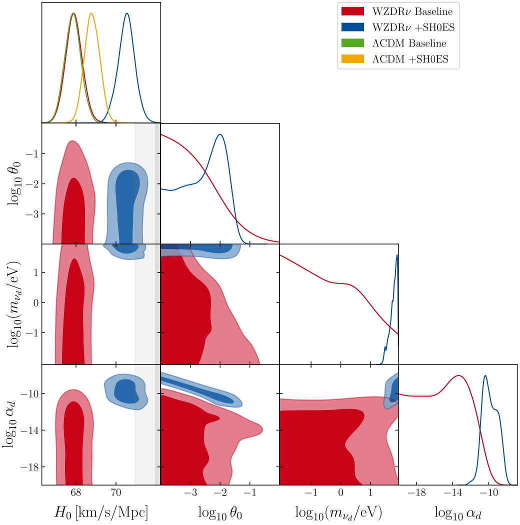
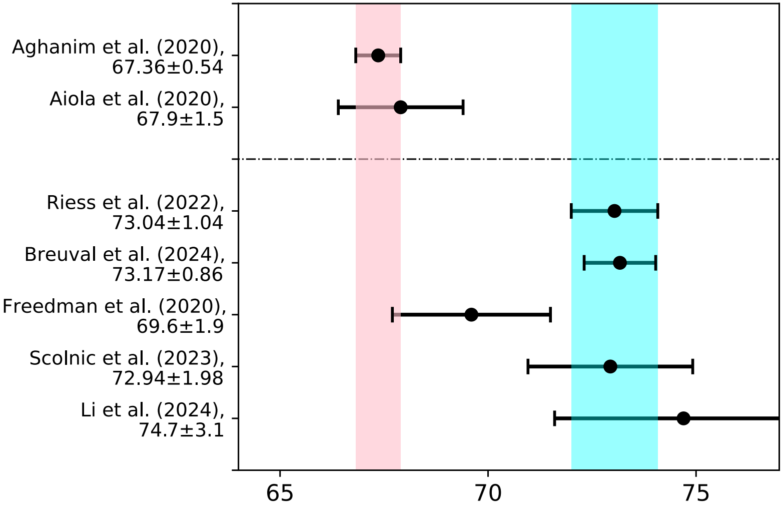
Weak Coupling Limit and the Hubble Tension



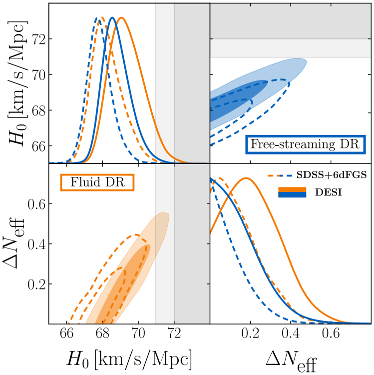
Summary

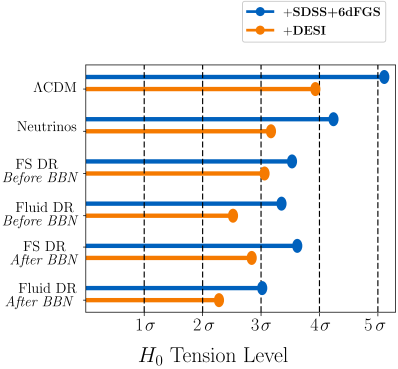
- Dark Radiation is known to alleviate Hubble tension, even preferred by new data
- DR with mass threshold can do better
- Production after BBN is attractive feature: thermalization via neutrino interactions
- Late thermalization preferred by data, early allowed with early decoupling (strong coupling)
- Provides unique partial thermalization regime preferred by data (weak coupling)

H_0 Tension


Aghanim et al. (2020),
67.36±0.54
Aiola et al. (2020),
67.9±1.5
Riess et al. (2022),
73.04±1.04
Breuval et al. (2024),
73.17±0.86
Freedman et al. (2020),
69.6±1.9
Scolnic et al. (2023),
72.94±1.98
Li et al. (2024),
74.7±3.1
65
70
75

DESI Constraints on DR and H_0 tension

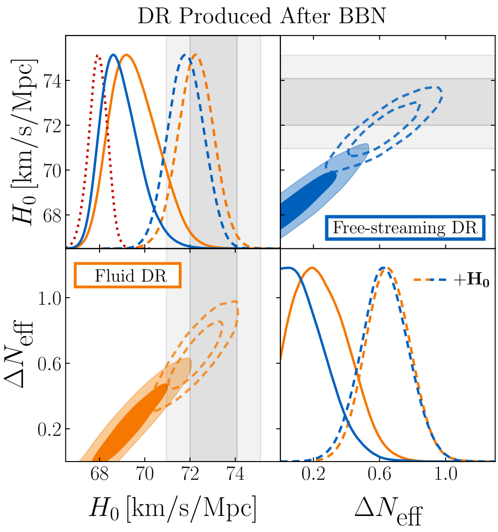




Lowest tension when DR is fluid, and when produced after BBN
→ justifies a combined fit with SH0ES

(IJA + Notari + Rompineve 24)

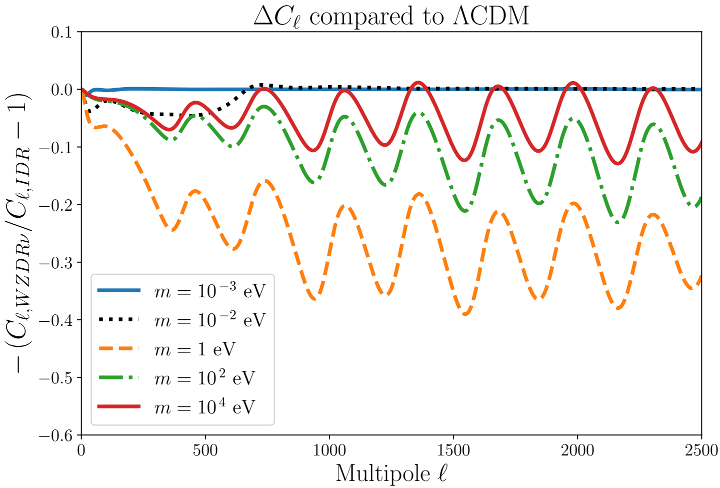
Hubble Tension in light of DESI + DR



	H_0 (Tension)
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)

(IJA + Notari + Rompineve 24)

Low m_{ν_d} Limit



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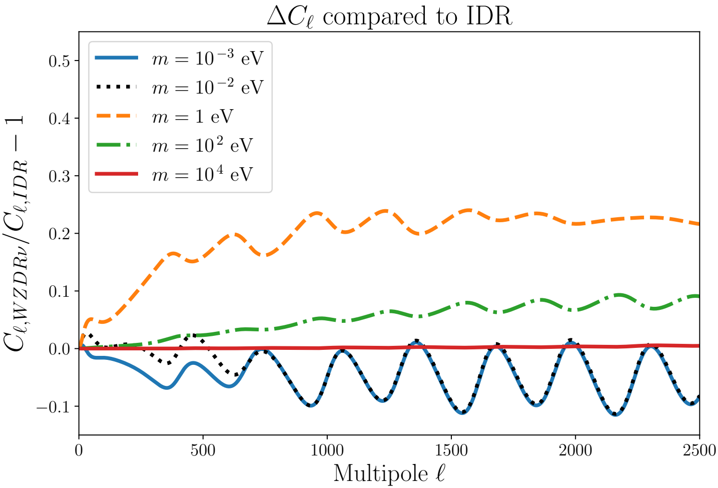


Boltzmann Equations

$$\frac{\partial f_\nu}{\partial \ln a} - p\frac{\partial f_\nu}{\partial p} = -\frac{\langle \Gamma_{\rm ph.} \rangle}{H}\left(f_\nu - f_{\nu d}\right) \ , \tag{3}$$

$$\frac{\partial f_{\nu d}}{\partial \ln a} - p\frac{\partial f_{\nu d}}{\partial p} = \frac{g_\nu}{g_{\nu d}}\frac{\langle \Gamma_{\rm ph.} \rangle}{H}\left(f_\nu - f_{\nu d}\right) + C_{\nu_d - \phi}[f_{\nu_d}, f_\phi] \ , \tag{4}$$

$$\frac{\partial f_\phi}{\partial \ln a} - p\frac{\partial f_\phi}{\partial p} = -\frac{g_{\nu d}}{g_\phi} C_{\nu_d - \phi}[f_{\nu_d}, f_\phi] + C_{\phi^n}[f_\phi] \ , \tag{5}$$

Background Evolution/Thermalization

$$\frac{\partial \ln T_\nu}{\partial \ln a} + 1 = -\frac{1}{4}\frac{\langle \Gamma_{\text{ph.}} \rangle}{H}\left[1 - \frac{R_{3,\nu_d}}{R_{3,\nu_d,[T\to T_\nu]}}\right] , \tag{6}$$

$$\frac{\partial \ln T_{\rm DS}}{\partial \ln a} + \frac{\rho_{\rm DS} + P_{\rm DS}}{\rho_{\rm DS} + R_{0,DS}} = \frac{\rho_\nu}{3(\rho_{\rm DS} + R_{0,DS})}\frac{\langle \Gamma_{\text{ph.}} \rangle}{H}\left[1 - \frac{R_{3,\nu_d}}{R_{3,\nu_d,[T\to T_\nu]}}\right] . \tag{7}$$

$$3R_{n,\,\xi} \equiv \frac{g_\xi}{(2\pi)^3}\int_0^\infty \mathrm{d}^3p \left[\frac{E^3}{p^2}\right]\left(\frac{p}{E}\right)^n f_\xi(E,\,T) \;, \tag{8}$$

Neutrino Perturbations

$$\frac{\partial \delta_\nu}{\partial \tau} + \frac{4}{3}\theta_\nu - 4\dot{\phi}_{CN} = -4\mathcal{H}\left[\frac{\partial \ln(aT_\nu)}{\partial \ln a}\right]\delta_\nu - a\left\langle\Gamma_{\text{ph.}}\right\rangle\left[\delta_\nu - \frac{4\delta_{\rm DS}}{3(1+w_{R_0,DS})}\right] , \tag{9}$$

$$\frac{\partial \theta_\nu}{\partial \tau} - k^2\left[\frac{1}{4}\delta_\nu - \sigma_\nu\right] + k^2\,\psi_{CN} = -4\mathcal{H}\left[\frac{\partial \ln(aT_\nu)}{\partial \ln a}\right]\theta_\nu + a\left\langle\Gamma_{\text{ph.}}\right\rangle(\theta_{\rm DS} - \theta_\nu) , \tag{10}$$

$$\frac{\partial F_\nu^\ell}{\partial \tau} - \frac{k}{2\ell+1}\left[\ell\, F_\nu^{\ell-1} - (\ell+1)F_\nu^{\ell+1}\right] = -4\mathcal{H}\left[\frac{\partial \ln(aT_\nu)}{\partial \ln a}\right]F_\nu^\ell - a\left\langle\Gamma_{\text{ph.}}\right\rangle F_\nu^\ell \quad , \ \ell \geq 2 , \tag{11}$$

DS Perturbations

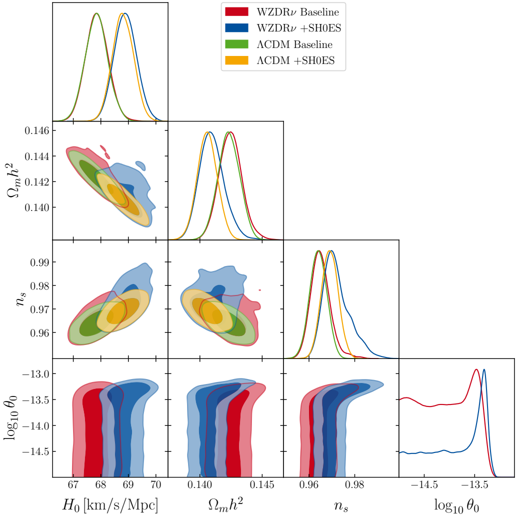
$$\frac{\partial \delta_{\rm DS}}{\partial \tau} + (1 + w_{\rm DS}) \left(\theta_{\rm DS} - 3\dot{\phi}_{CN}\right) + 3\mathcal{H}\left(c^2_{s,DS} - w_{\rm DS}\right)\delta_{\rm DS}$$
$$= 4\mathcal{H}\left[\frac{\partial \ln(aT_\nu)}{\partial \ln a}\frac{\rho_\nu}{\rho_{\rm DS}}\right]\delta_{\rm DS} + a\langle\Gamma_{\rm ph.}\rangle\frac{\rho_\nu}{\rho_{\rm DS}}\left[\delta_\nu - \frac{4\delta_{\rm DS}}{3(1 + w_{R_0,DS})}\right], \quad (12)$$

$$\frac{\partial \theta_{\rm DS}}{\partial \tau} - k^2\frac{c^2_{s,DS}}{1 + w_{\rm DS}}\delta_{\rm DS} + \mathcal{H}\left(1 - 3c^2_{s,DS}\right)\theta_{\rm DS} + k^2\psi_{CN}$$
$$= 4\mathcal{H}\left[\frac{\partial \ln(aT_\nu)}{\partial \ln a}\frac{\rho_\nu}{\rho_{\rm DS}}\right]\theta_{\rm DS} + a\langle\Gamma_{\rm ph.}\rangle\left[\frac{4\rho_\nu}{3(\rho_{\rm DS} + P_{\rm DS})}\right](\theta_\nu - \theta_{\rm DS}) \quad (13)$$

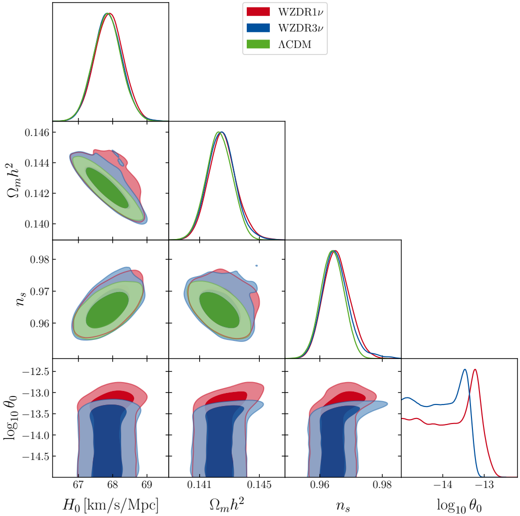
Interaction Rate

$$\langle \Gamma_{\text{ph.}} \rangle = \frac{\frac{1}{4}\sin^2 2\theta_0 \left(3c_\Gamma T_\nu^5 G_F^2 + \alpha_d^2 \frac{T_d^2}{T_\nu} \right)}{\left(\cos 2\theta_0 + \alpha_d \frac{T_d^2}{m_{\nu d^2}} + 18 c_V \frac{G_F^2 T_\nu^5}{m_{\nu d}^2} \right)^2 + \sin^2 2\theta_0} \times e^{-m_{\nu d}/T_\nu} \ . \tag{14}$$

Strong 3 ν


WZDRν Baseline
WZDRν +SH0ES
ΛCDM Baseline
ΛCDM +SH0ES
0.146
0.144
0.142
0.140
Ω_m h^2
0.99
0.98
0.97
0.96
n_s
−13.0
−13.5
−14.0
−14.5
log10 θ0
67
68
69
70
0.140
0.145
0.96
0.98
−14.5
−13.5
H0 [km/s/Mpc]
Ω_m h^2
n_s
log10 θ0

Strong 1 ν


WZDR1ν
WZDR3ν
ΛCDM
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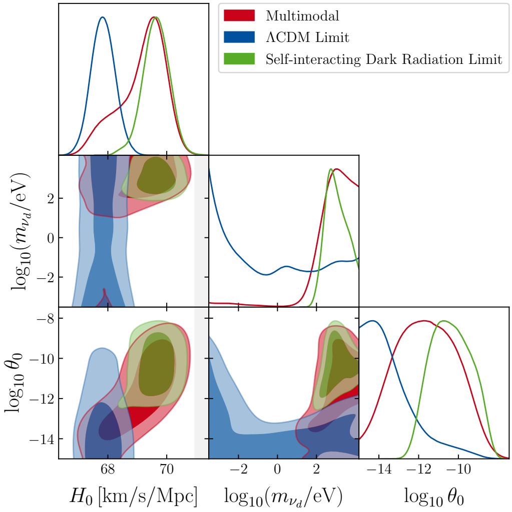
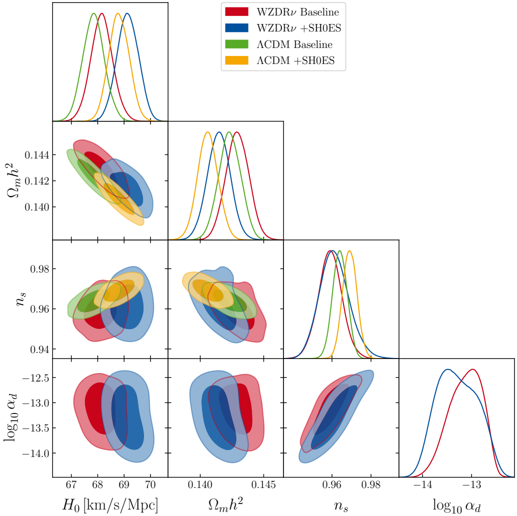
H0 [km/s/Mpc]
Ω_m h^2
n_s
log10 θ0

Strong Bimodal



Anomaly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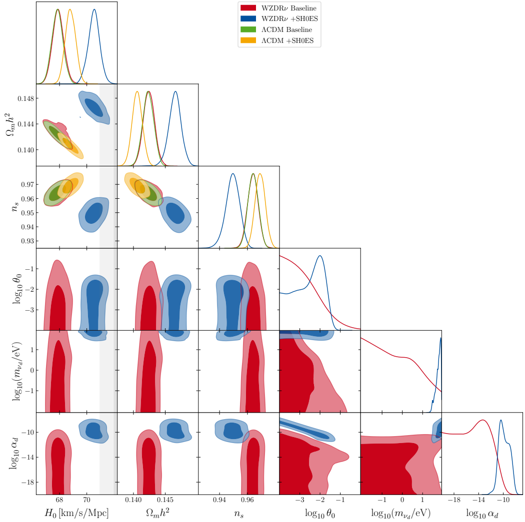
Weak 3 ν


WZDRν Baseline
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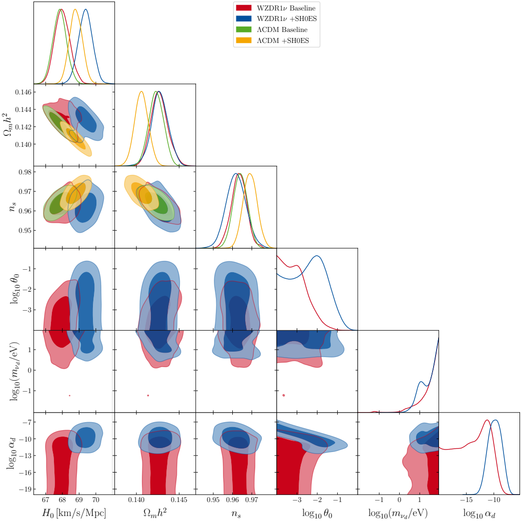
ΛCDM Baseline
ΛCDM +SH0ES
$\Omega_m h^2$
n_s
$\log_{10}\theta_0$
$\log_{10}(m_{\nu_d}/\mathrm{eV})$
$\log_{10}\alpha_d$
H_0 [km/s/Mpc]

Weak 1 ν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$\Omega_m h^2$
n_s
$\log_{10}\theta_0$
$\log_{10}(m_{\nu_d}/\mathrm{eV})$
$\log_{10}\alpha_d$
H_0 [km/s/Mpc]

Model	Dataset	Best-fit χ^2	$\Delta\chi^2$
ΛCDM	baseline	4192.1	0
	baseline+SH0ES	4102.3	0
$\alpha_d = 1$, narrow prior	baseline	4191.5	-0.6
	baseline+SH0ES	4102.0	-0.3
$\alpha_d = 1$, 1ν interaction	baseline	4189.3	-1.8
$\alpha_d = 1$, broad prior	baseline	4191.2	-0.9
$\alpha_d = 1$, IDR limit	baseline	4195.2	$+3.1$
$\alpha_d = 1$, multimodal	baseline	4193.1	$+1.0$
Anomaly	baseline	4191.8	-0.3
	baseline+SH0ES	4099.7	-2.6
narrow prior	baseline	4190.5	-1.6
	baseline+SH0ES	4091.4	-10.9
	baseline	4190.3	-1.8
	baseline+SH0ES	4087.6	-14.7
1ν interaction	baseline	4191.3	-0.8
	baseline+SH0ES	4093.4	-8.9

Model	Dataset	H_0	$\Omega_m h^2$	n_s	$\log_{10}(\theta_0)$	$\log_{10}(\alpha_d)$	$\log_{10}(m_{\nu d}/\mathrm{eV})$
ΛCDM	baseline	67.84 ± 0.41	0.14232 ± 0.00088	0.9641 ± 0.0037	—	—	—
	+SH0ES	68.81 ± 0.39	0.14059 ± 0.00080	0.9691 ± 0.0037	—	—	—
narrow prior	baseline	67.86 ± 0.41	$0.14246^{+0.00089}_{-0.00092}$	$0.9651^{+0.0040}_{-0.0043}$	< -13	—	Unconstrained
	+SH0ES	68.89 ± 0.41	0.14096 ± 0.00098	$0.9722^{+0.0061}_{-0.0056}$	< -13	—	Unconstrained
1ν interaction	baseline	67.90 ± 0.42	0.14254 ± 0.00093	0.9654 ± 0.0043	< -13	—	Unconstrained
broad prior	baseline	67.84 ± 0.41	0.14232 ± 0.00085	0.9641 ± 0.0037	< -11	—	Unconstrained
IDR limit	baseline	69.64 ± 0.44	0.14735 ± 0.00092	0.9559 ± 0.0045	-10.4 ± 1.1	—	$3.01^{+0.64}_{-0.54}$
multimodal	baseline	$69.17^{+0.74}_{-0.89}$	$0.1460^{+0.0019}_{-0.0025}$	0.9566 ± 0.0055	-11.6 ± 1.7	—	> 1.5
Anomaly	baseline	68.15 ± 0.41	0.14293 ± 0.00091	0.9590 ± 0.0059	—	-13.12 ± 0.35	—
	+SH0ES	69.14 ± 0.41	0.14146 ± 0.00088	0.9613 ± 0.0074	—	$-13.29^{+0.47}_{-0.44}$	—
narrow prior	baseline	68.19 ± 0.49	0.1434 ± 0.0012	0.9643 ± 0.0062	< -1.2	$-13.3^{+1.2}_{-1.0}$	$0.11^{+0.48}_{-0.59}$
	+SH0ES	69.63 ± 0.49	0.1440 ± 0.0015	0.9738 ± 0.0047	< -1.5	$-12.72^{+0.52}_{-0.44}$	$0.60^{+0.14}_{-0.11}$
	baseline	67.90 ± 0.42	0.14244 ± 0.00088	0.9639 ± 0.0038	< -1.3	< -11	Unconstrained
	+SH0ES	70.53 ± 0.41	$0.14653^{+0.00093}_{-0.00095}$	$0.9494^{+0.0050}_{-0.0048}$	< -1.6	-9.84 ± 0.93	1.77 ± 0.13
1ν interaction	baseline	68.00 ± 0.46	0.14268 ± 0.00099	0.9633 ± 0.0040	< -2.0	< -9.7	> 0.40
	+SH0ES	69.38 ± 0.42	$0.14273^{+0.00100}_{-0.00095}$	0.9619 ± 0.0051	< -1.1	-9.8 ± 1.3	> 0.72

SDR Background

$$w(z) \equiv \frac{p(z)}{\rho(z)}, \quad c_s^2(z) \equiv \frac{dp(z)/dz}{d\rho(z)/dz}, \tag{15}$$

$$r_g \equiv \frac{g_*^{z\gg z_t} - g_*^{z\ll z_t}}{g_*^{z\ll z_t}} = \left(\frac{\Delta N_{\rm eff}^{\rm IR}}{\Delta N_{\rm eff}^{\rm UV}}\right)^3 - 1, \tag{16}$$

$$T_d^{\rm IR,UV} \simeq 0.5 \left(\frac{2}{g_*^{\rm IR,UV}}\right)^{\frac{1}{4}} \left(\frac{\Delta N_{\rm eff}^{\rm IR,UV}}{0.3}\right)^{\frac{1}{4}} T_{\rm SM}. \tag{17}$$

SDR Perturbations

$$\dot{\delta} = -(1+w)(\theta + \frac{\dot{h}}{2}) - 3\mathcal{H}(c_s^2 - w)\delta \tag{18}$$

$$\dot{\theta} = -\mathcal{H}(1-3w)\theta - \frac{\dot{w}}{1+w}\theta + \frac{c_s^2}{1+w}k^2\delta - k^2\sigma \tag{19}$$