Sterile neutrinos in the Hubble and S_8 tension

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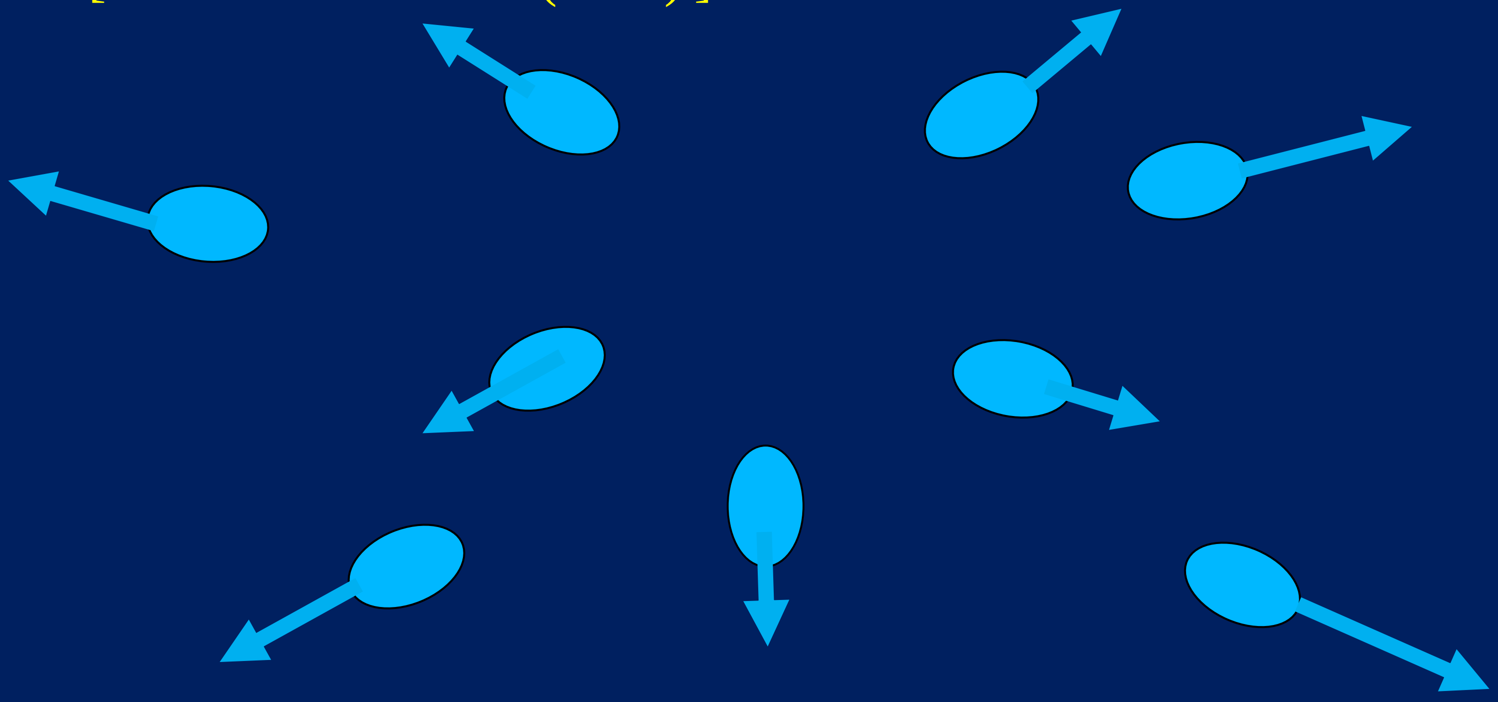
Refs: 2312.15435

§ Introduction

Success of Big Bang Cosmology

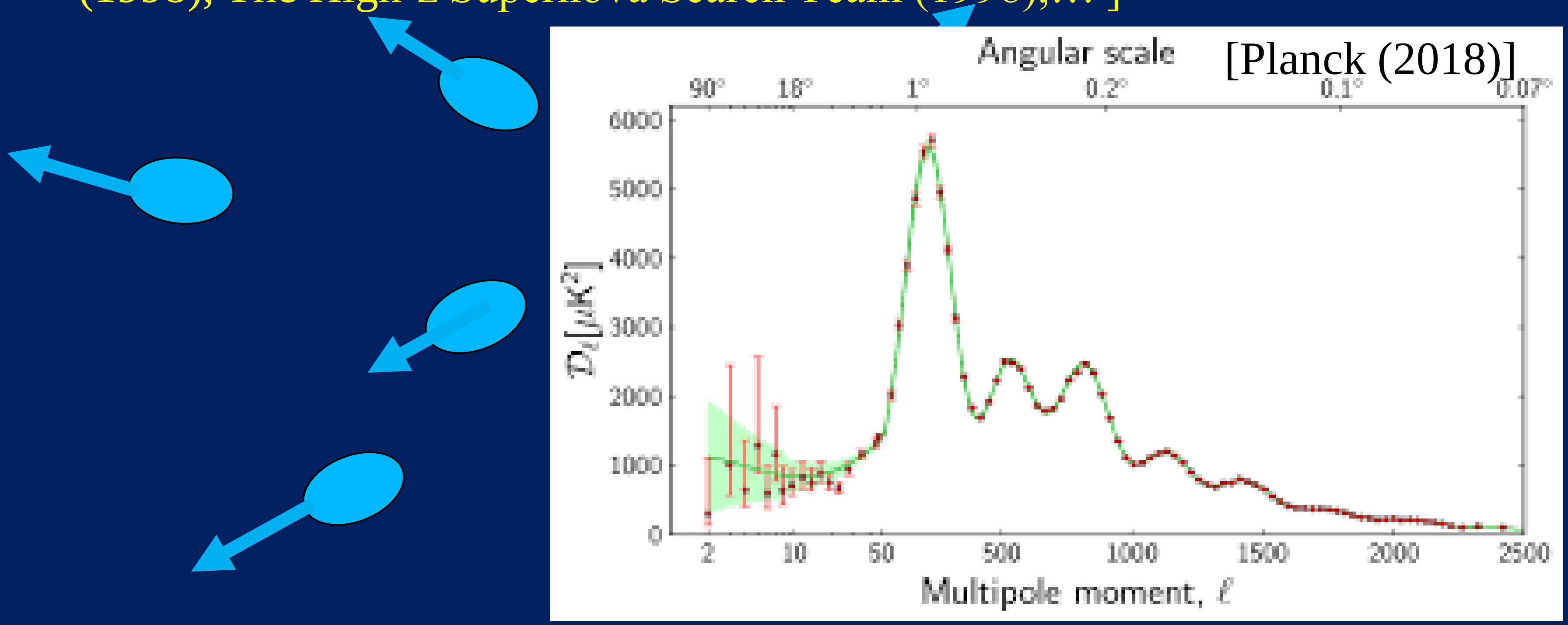
1. Cosmic Expansion [Hubble (1929)]
2. Big Bang Nucleosynthesis [Gamow (1946), Alpha et al (1948)]
3. Cosmic Microwave Background Radiation

   [Penzias and Wilson (1965)]



Success of
Λ-cold dark matter (CDM) model

1. Structure formation by CDM [1980's]
2. CMB fluctuation [COBE (1992),…]
3. Accelerated expansion [The Supernova Cosmology Project (1998), The High-z Supernova Search Team (1998),…]



§ Hubble (H_0) Tension

§ § Two ways of measurement of Hubble parameter

1. Hubble law（low z） by Red shift

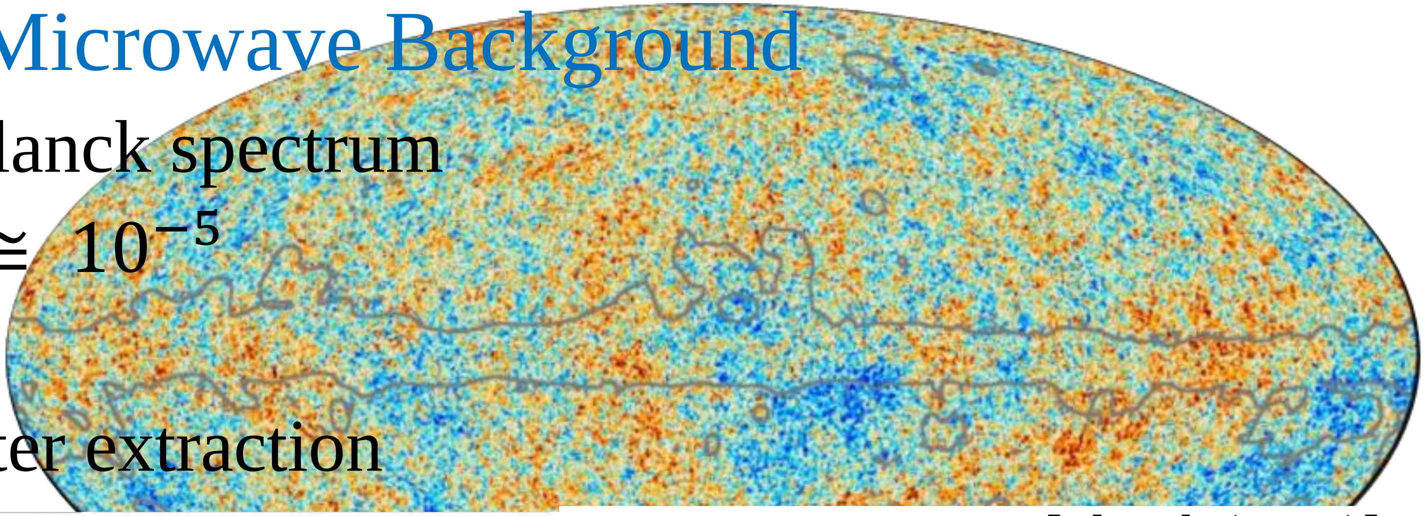
$$1 + z = \frac{\lambda_0}{\lambda_1} = \frac{a(t_0)}{a(t_1)}$$

$$H_0 d = z$$

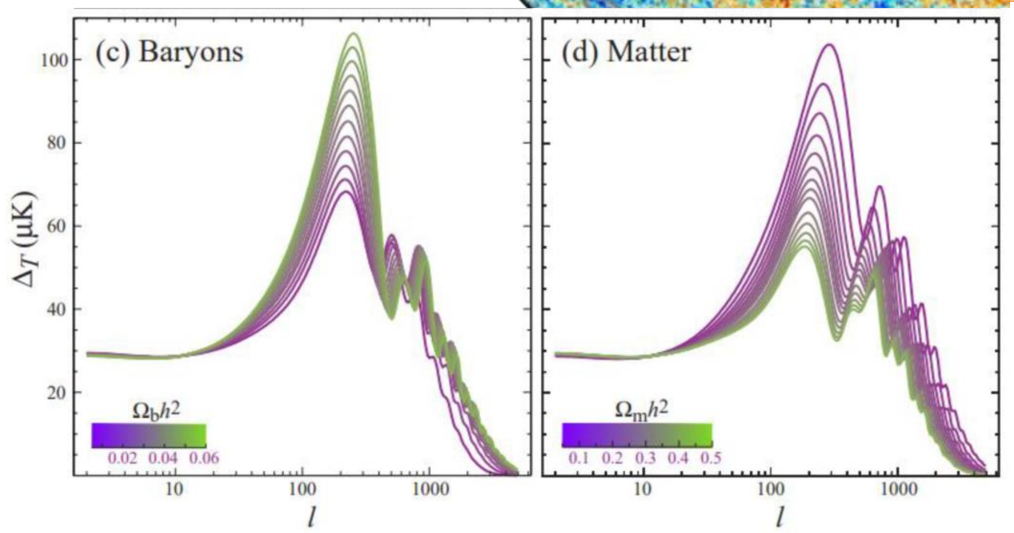
- SN + Cepheid ：SH0ES 73.04 ± 1.04 km/s/Mpc [Riess et al (2021)]
- SN + TRGB : 69.8 km/s/Mpc [Freedman et al (2019)]
- …

§ § Two ways of measurement of Hubble parameter

2. Cosmic Microwave Background

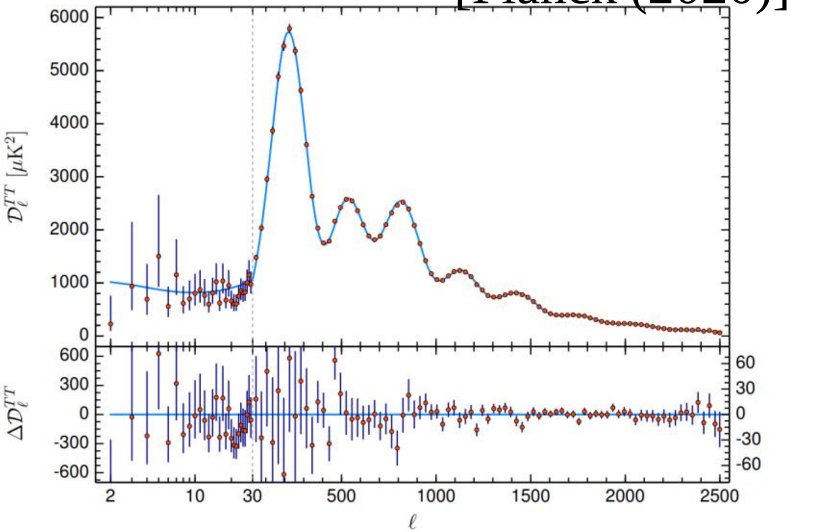


- 2.7K Planck spectrum
- $\delta T/T \cong 10^{-5}$
- Parameter extraction



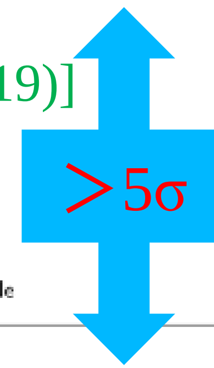
[Hu and Dodelson (2002)]

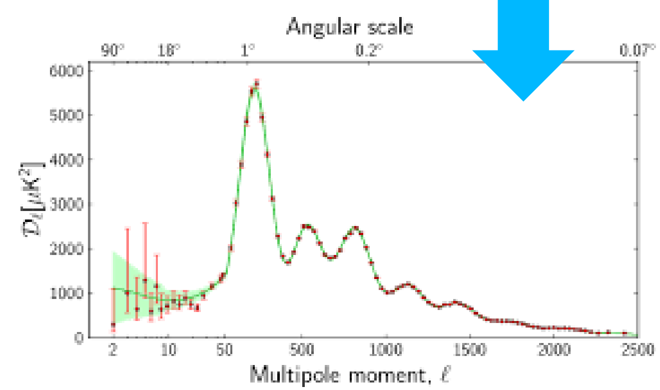
[Planck (2020)]



§ § Estimation of Hubble parameter

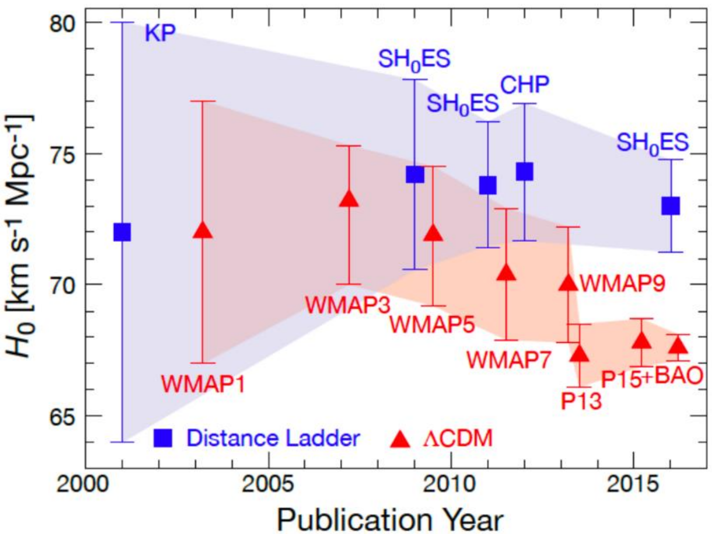
1. Hubble law（low z）
   - SN + Cepheid：SH0ES 73.04 ± 1.04 km/s/Mpc [Riess et al (2021)]
   - SN + TRGB : 69.8 km/s/Mpc [Freedman et al (2019)]
   - …

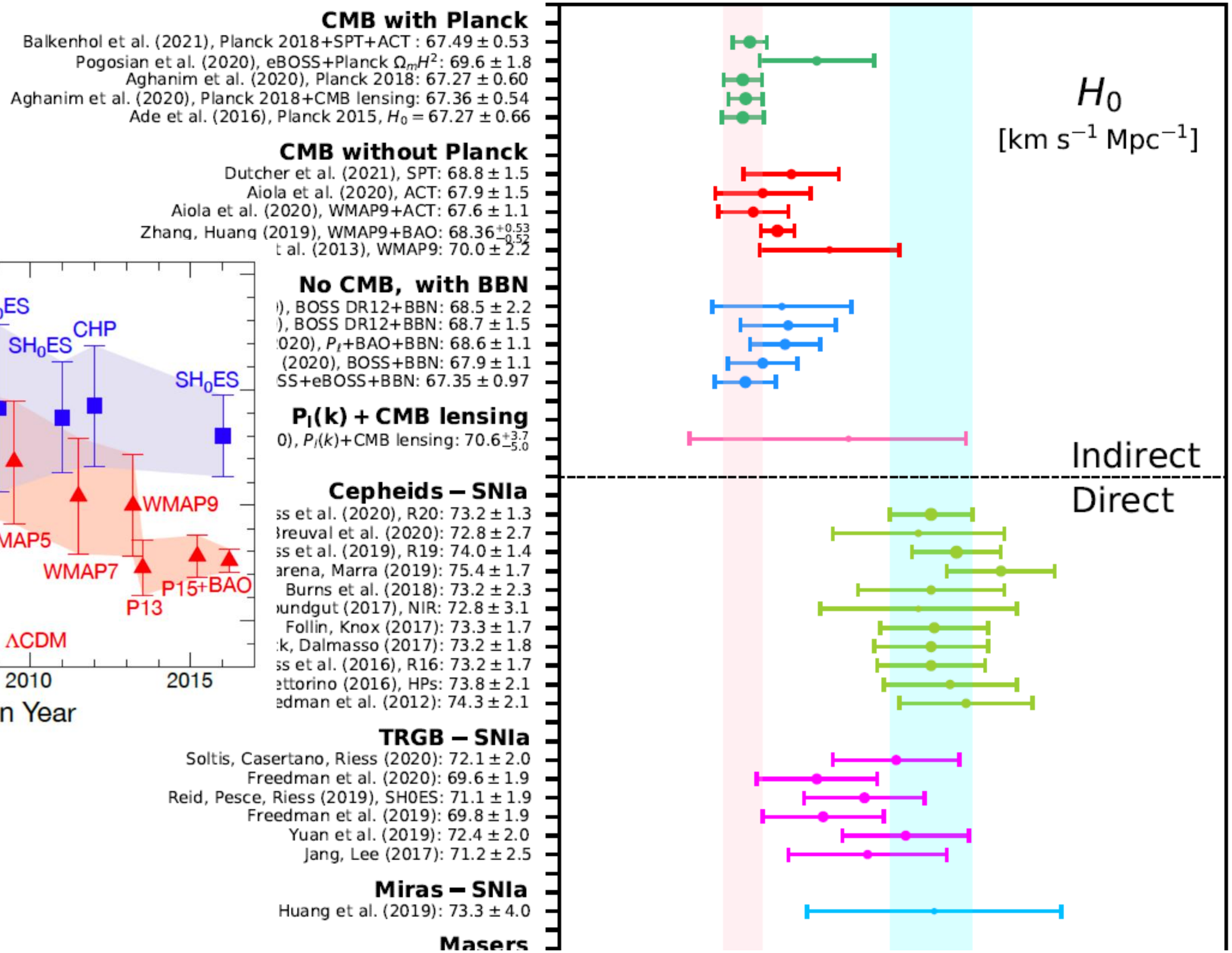




2. Cosmology（high z）
   - CMB 67.4 ± 0.4 km/s/Mpc [Planck (2020)]
   - BAO+BBN $68.3^{+1.1}_{-1.2}$ km/s/Mpc [Schoneberg et al (2019)]

Evolution of H_0: Summary





[Di Valentino et al (2021)]

§ § Challenging problem

Many models do not work [Schoneberg et al (2022)]

The H_0 Olympics: A fair ranking of proposed models

berg[a,*], Guillermo Franco Abellán[b], Andrea Pérez Sánchez[a], Samuel J. Wit
Poulin[b], Julien Lesgourgues[a]

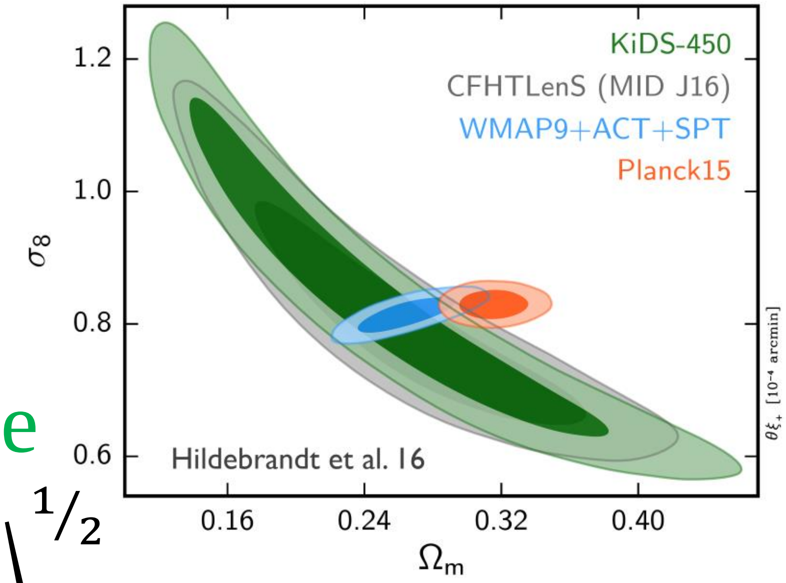
r Theoretical Particle Physics and Cosmology (TTK), RWTH Aachen University, D-520

Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist	
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	✗	0.00	0.00	✗	✗	
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	✗	-6.10	-4.10	✗	✗	
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	✗	-9.57	-7.57	✓	✓	3
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	✗	-8.83	-4.83	✗	✗	
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	✗	-8.92	-4.92	✗	✗	
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	✗	-4.98	1.02	✗	✗	
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓	2
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	✗	-11.42	-9.42	✓	✓	3
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓	1
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓	1

§ σ_8 (S_8) Tension

§ § σ_8 tension

- Matter fluctuation
  - $\delta(t, \boldsymbol{x}) := \frac{\rho(t,x)-\rho(t)}{\rho(t)}$



- Smoothed for $8h^{-1}$ Mpc scale
  - $\sigma_8 := \left\langle \left(\frac{\delta M}{M}\right)^2 \ (r = 8h^{-1}\,\mathrm{Mpc}) \right\rangle^{1/2}$
  - $S_8 = \sigma_8 \sqrt{\frac{\Omega_m}{0.3}}$
- Discrepancy between from Weak lensing (= 0.65-0.75 [Alsing et al CFHTLenS (2016), Hildebrandt et al KiDS-450 (2017), Khlinger et al KiDS-450 (2017)]) and Planck (0.81 [Planck (2018)])

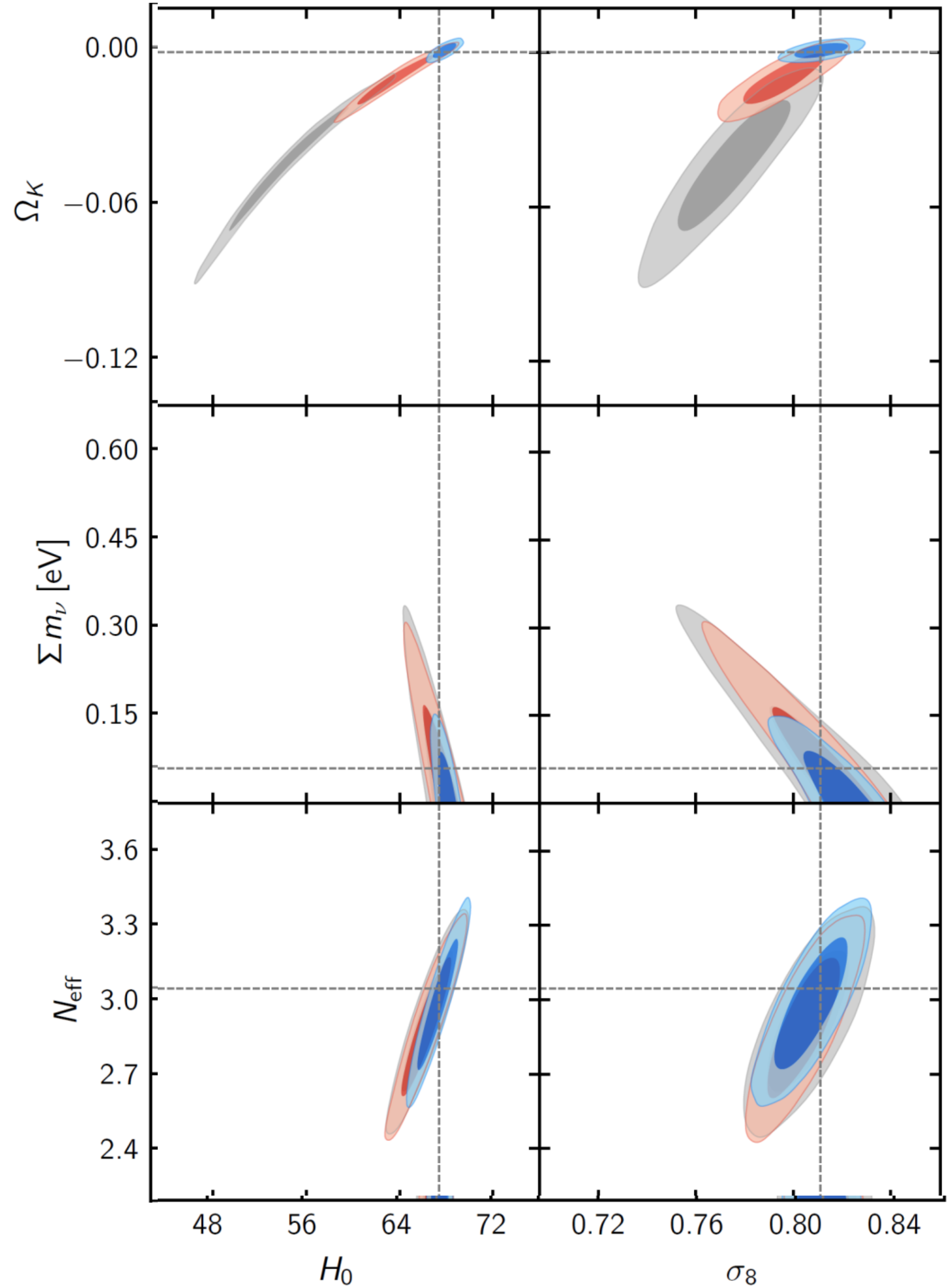
- The ΛCDM big bang (+inflation) cosmology works well.
- Some tensions exist.
  - Hubble parameters
  - Amplitude of matter fluctuation
  - …

Simple extensions

[Planck (2020)]

Planck TT,TE,EE+lowE *Planck* TT,TE,EE+lowE+lensing

Planck TT,TE,EE+lowE+lensing+BAO



H_0 and σ_8 are always anti-correlated

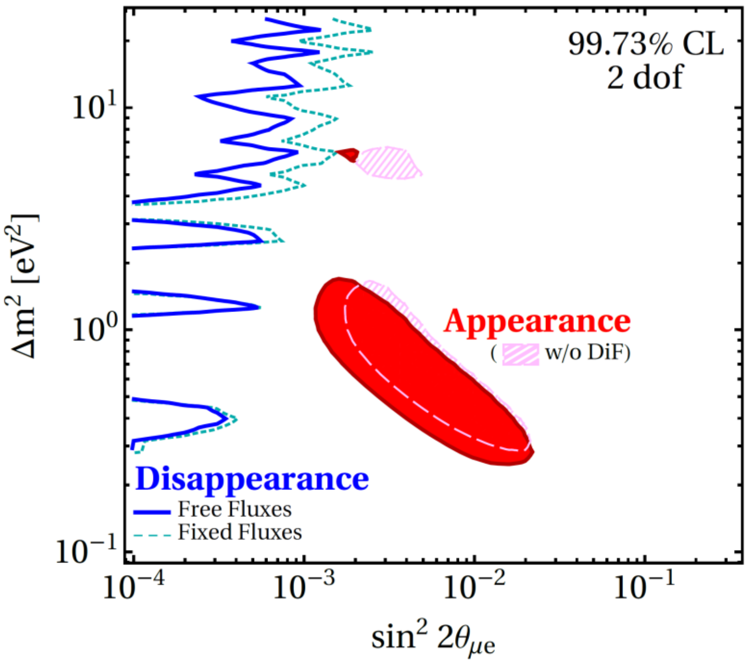
§ Neutrino, in particular, sterile neutrinos

§ Neutrinos

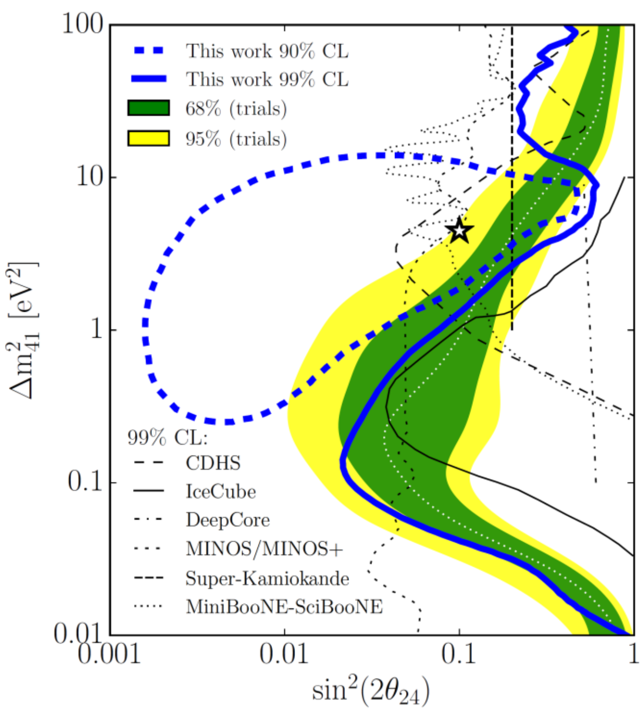
- The number of generation
  - 3 for left-handed (interact with the Z boson) by the LEP experiment
  - Invisible decay of the Z boson
- Neutrino oscillation and neutrino masses
  - Beyond the standard model
  - $\mathcal{O} = \frac{1}{\Lambda} L\Phi\Phi L$
- 2 independent Δm^2
  - Solar $\sim 10^{-5}\mathrm{eV}^2$ and atmospheric $\sim 10^{-3}\mathrm{eV}^2$
  - Another Δm^2 involves a sterile (no weak interacting), if there is.

§ Sterile neutrinos

- Tension between experiments…
- e.g.,
  - LSND/MiniBooNE vs others



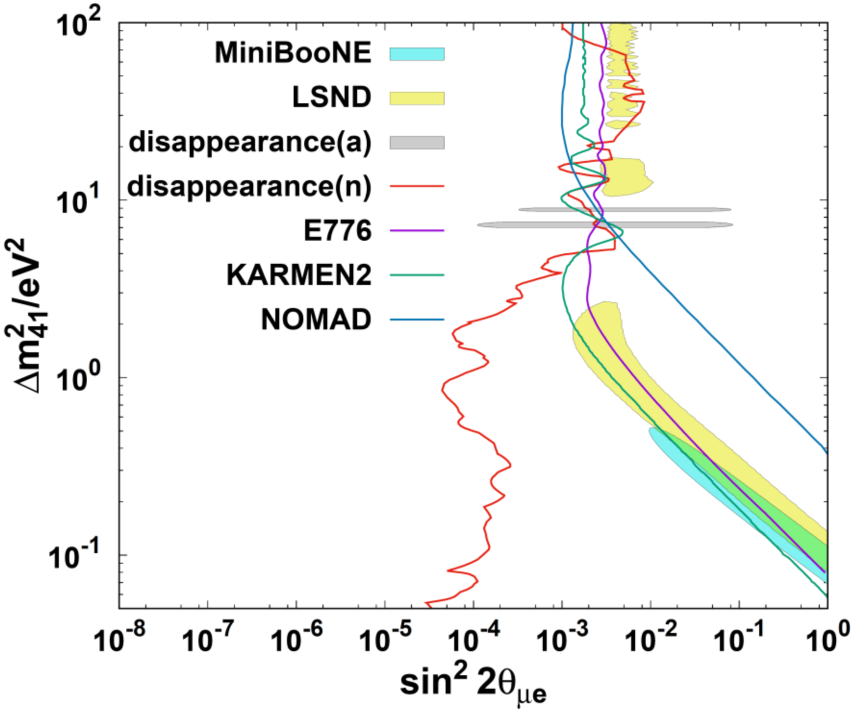
[Dentler et al (2018)]



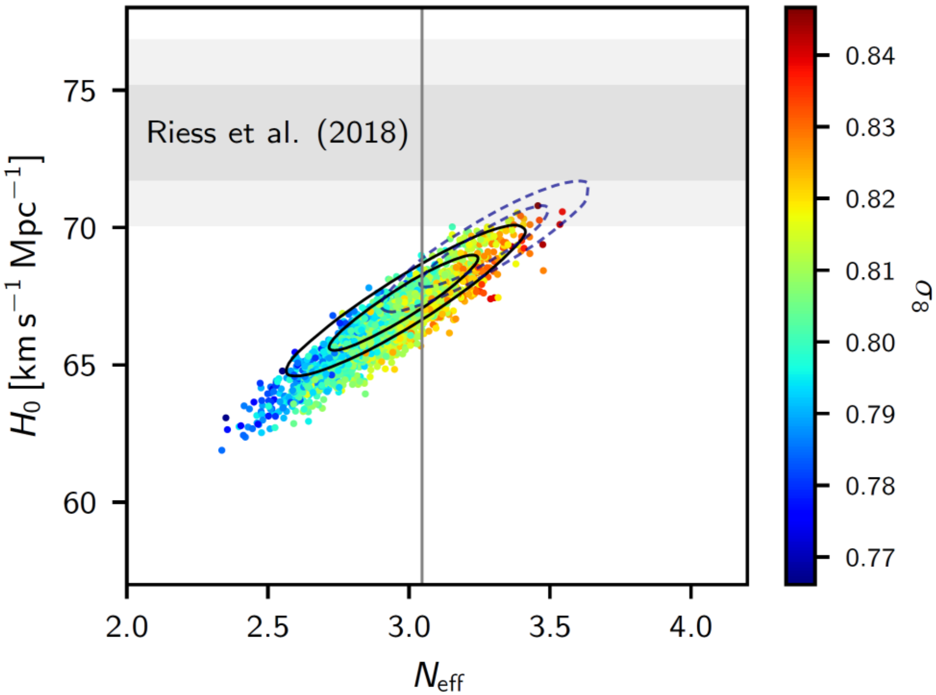
  - IceCube [IceCube (2020)]
  - …

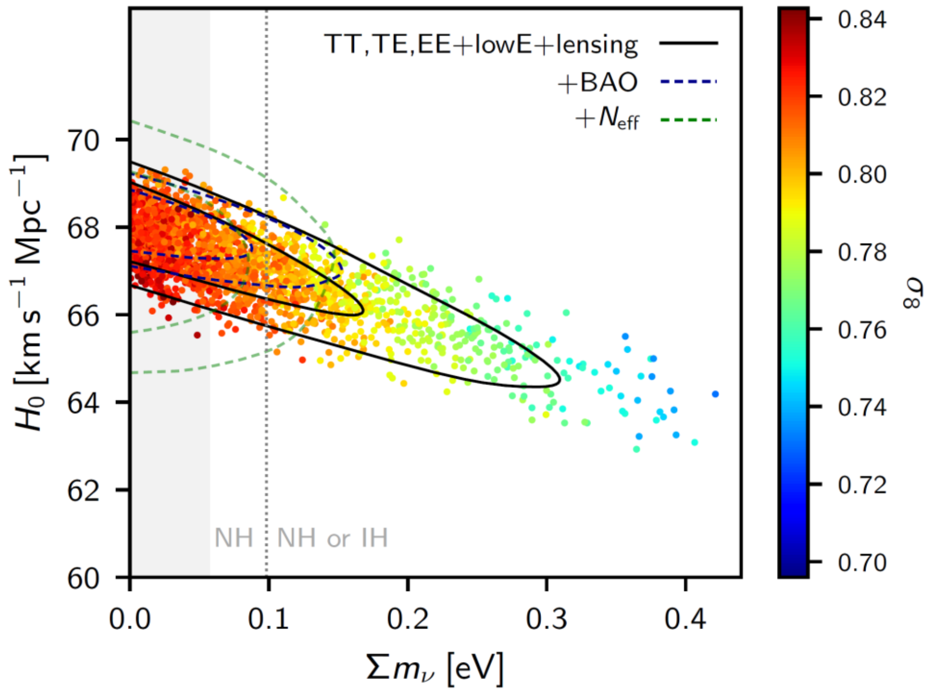
§ Sterile neutrinos

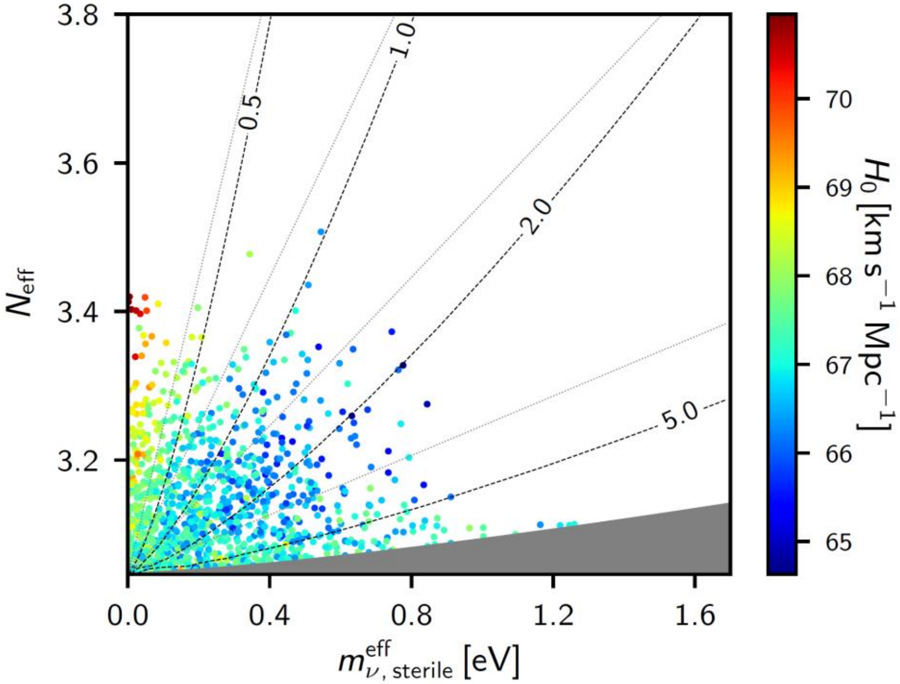
- Tension between experiments…
- e.g.,
  - LSND/MiniBooNE vs others [Dentler et al (2018)]
  - IceCube [IceCube (2020)]
  - Neutrino-4 and IceCube [Yasuda (2022)]



§ § Neutrino in cosmology

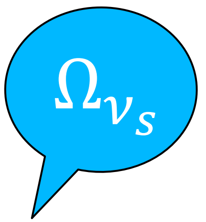






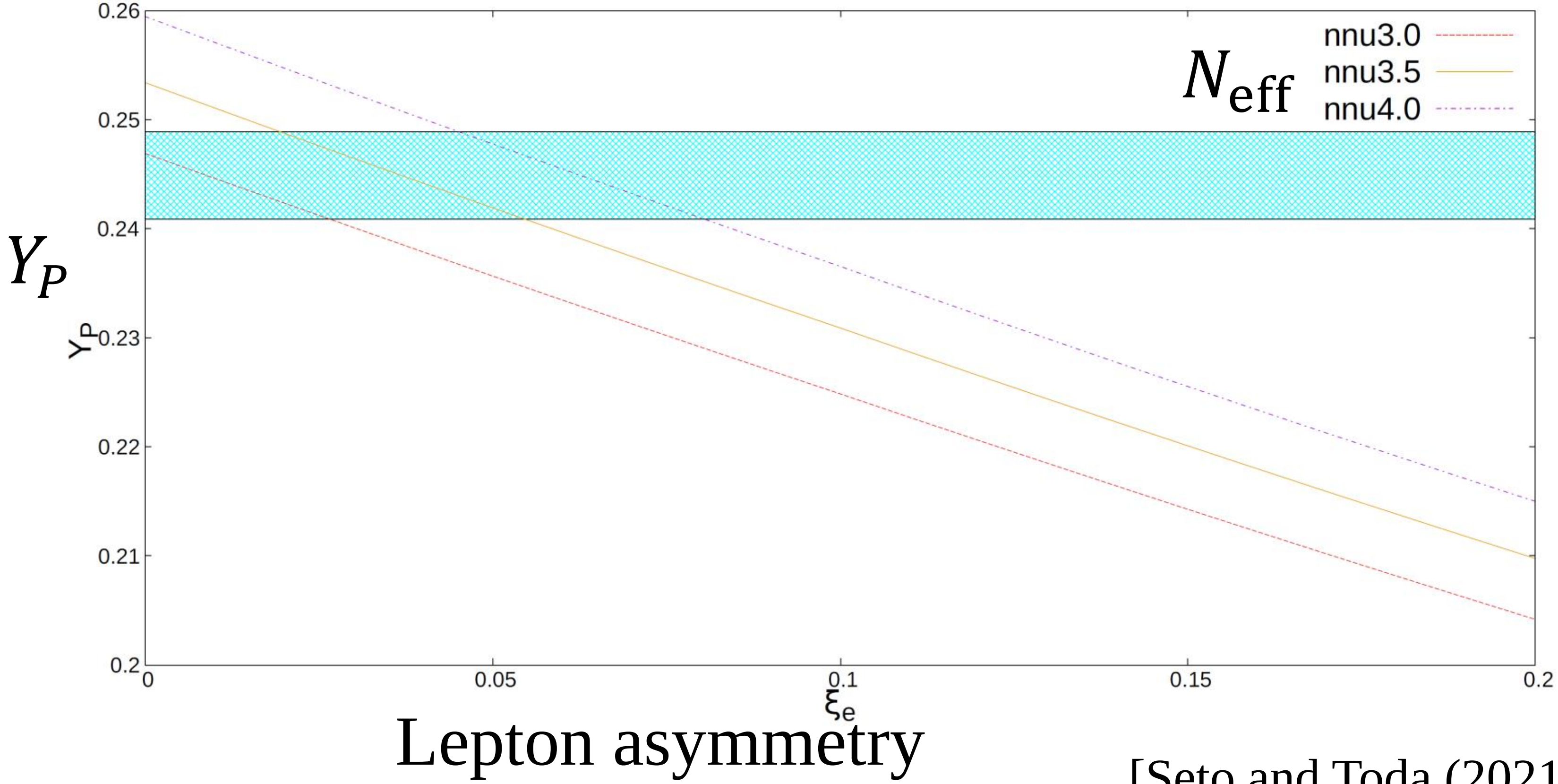
[Planck (2020)]

- Neutrino's effects on structure formation
  - N_{eff}
  - Free streaming



- $m_{\nu,\text{sterile}}^{\text{eff}} = \Delta N_{\text{eff}}{}^{4/3} m_{\nu,\text{sterile}}^{\text{thermal}}$

- Neutrino's effects on BBN
  - N_{eff}
  - Too much Helium
  - Can be partly compensated by lepton asymmetry [Beaudet and Goret (1976),…]



[Seto and Toda (2021)]

§ § Sterile neutrinos

- Confront with cosmology
- For $\mathcal{O}(1)$eV mass and $\mathcal{O}(0.1)$ mixing
  - $N_{\mathrm{eff}} \cong 4$ by thermalization [Di Bari (2002), Bager et al (2003), ..]
  - Free streaming as hot dark matter

  - Way out for free streaming problem ?
  - Generalization of EOS of dark energy [Kristiansen and Elgaroy (2011)]
  - $f(R)$ gravity energy [Motohashi, Starobinsky, and Yokoyama (2010)]

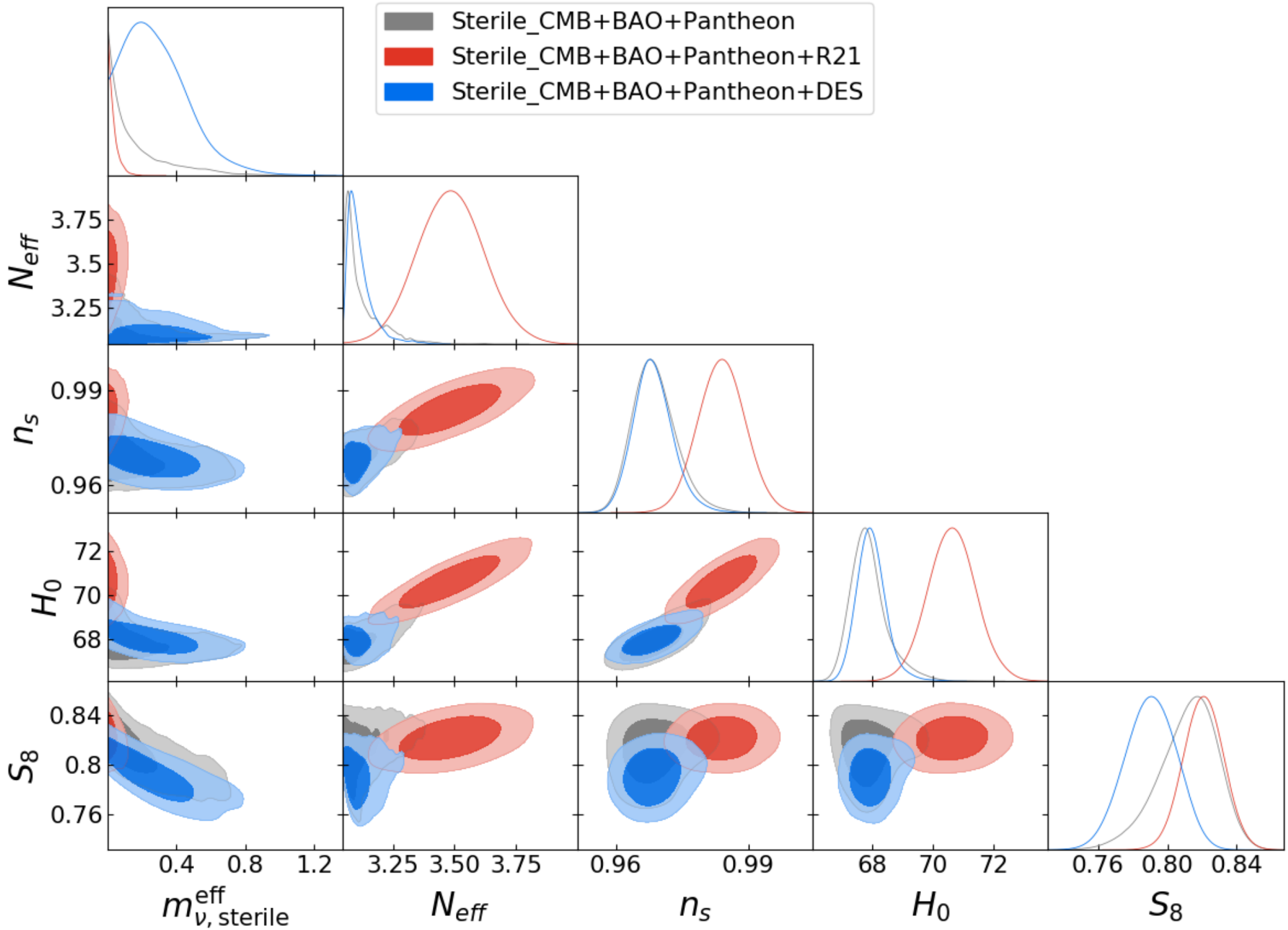
§ Cosmology with sterile neutrinos and one more parameter

[With Pan, Takahashi and Toda (2312.15435)]

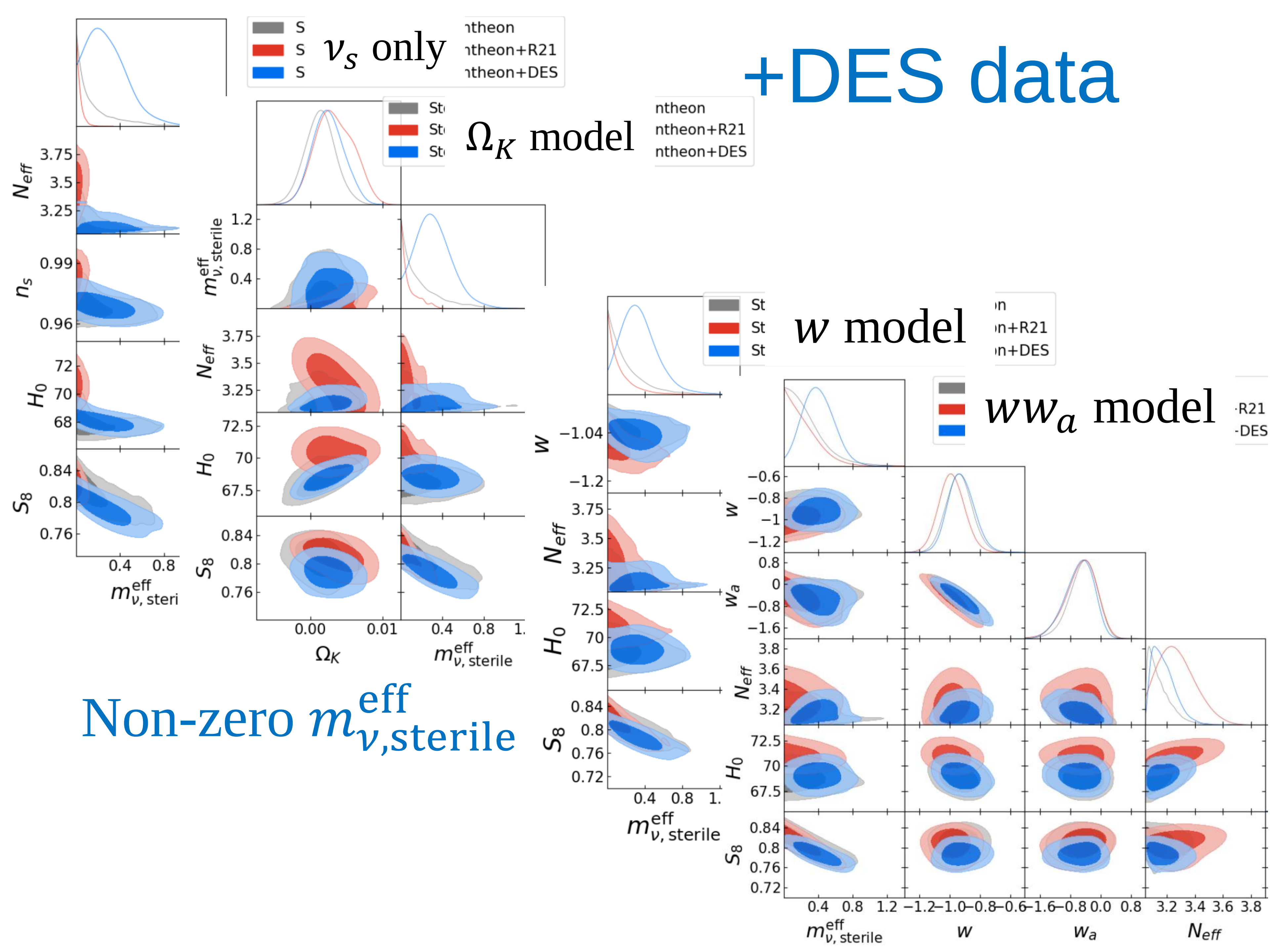
Models

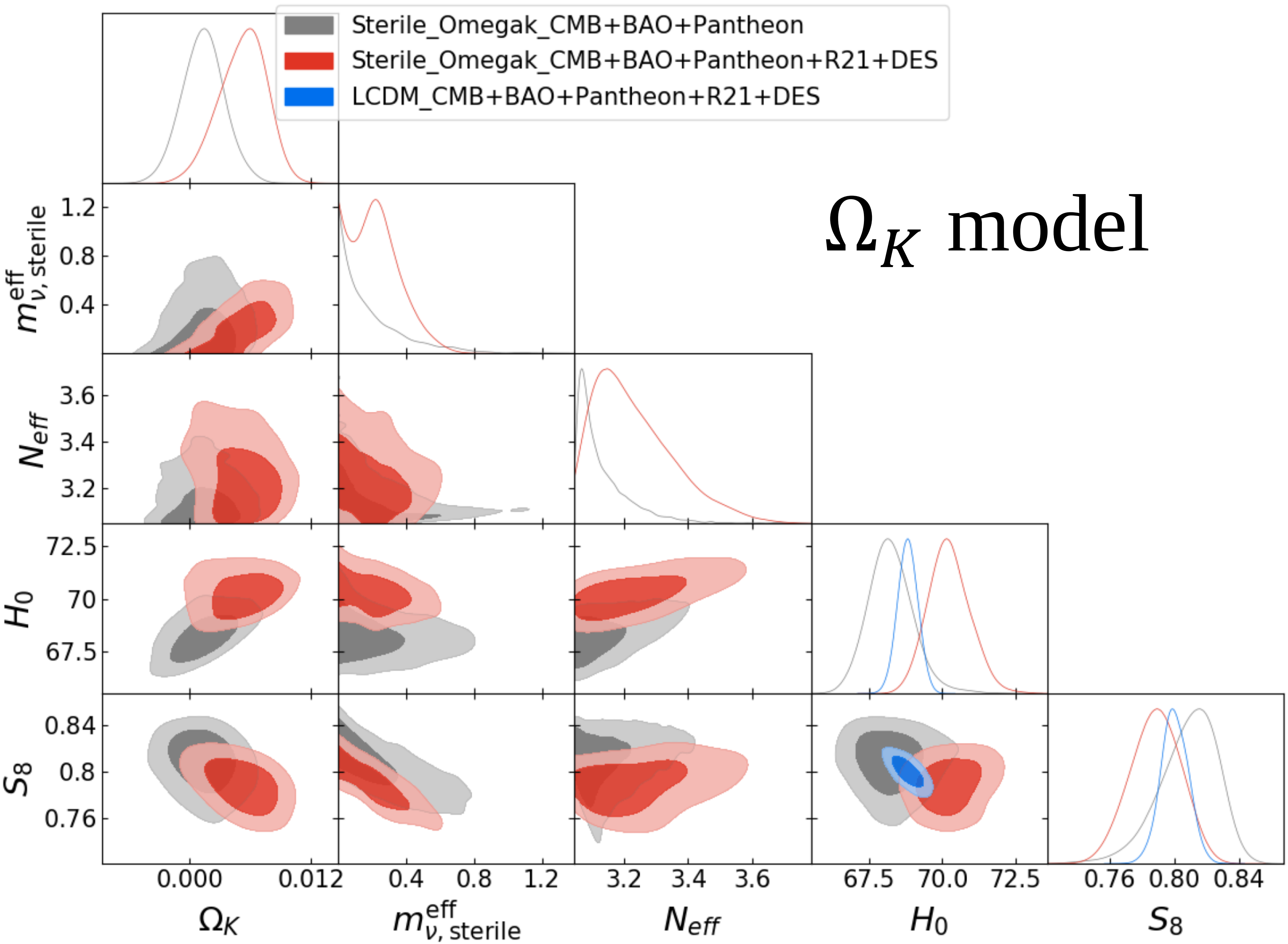
- ΛCDM
- ΛCDM + sterile neutrino
- $\Omega_K \Lambda$CDM + sterile neutrino
- wCDM + sterile neutrino
- $w w_a$CDM + sterile neutrino
  - CPL parametrization [Chevallier and Polarski (2001), Linder (2003)]

$$w(a) = w + w_a \left(1 - \frac{a}{a_0}\right) = w + \frac{z}{1+z} w_a,$$

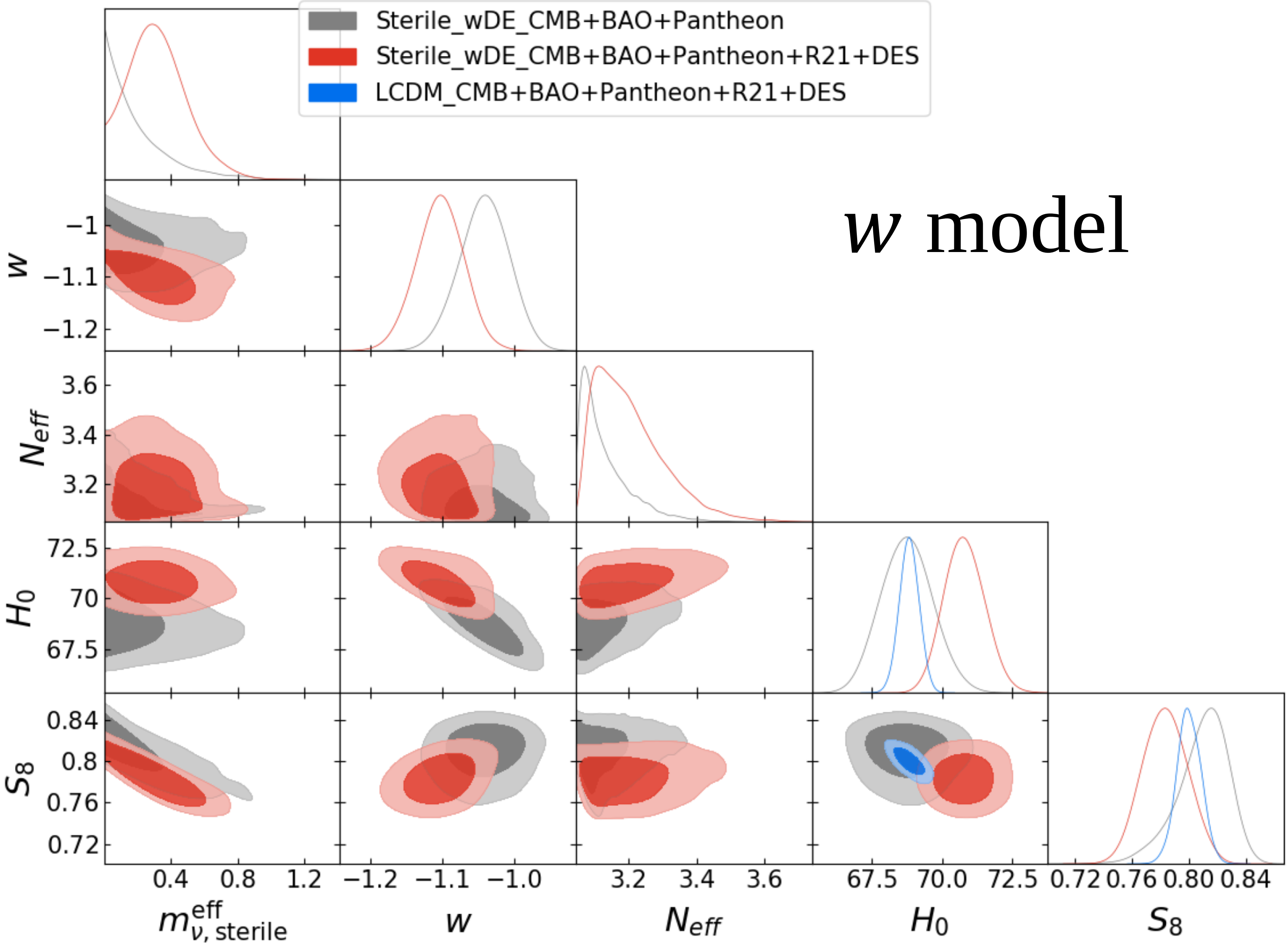


Sterile_CMB+BAO+Pantheon
Sterile_CMB+BAO+Pantheon+R21
Sterile_CMB+BAO+Pantheon+DES
N_{eff}
3.75
3.5
3.25
n_s
0.99
0.96
H_0
72
70
68
S_8
0.84
0.8
0.76
0.4
0.8
1.2
$m_{\nu,\,\mathrm{sterile}}^{\mathrm{eff}}$
3.25
3.50
3.75
N_{eff}
0.96
0.99
n_s
68
70
72
H_0
0.76
0.80
0.84
S_8

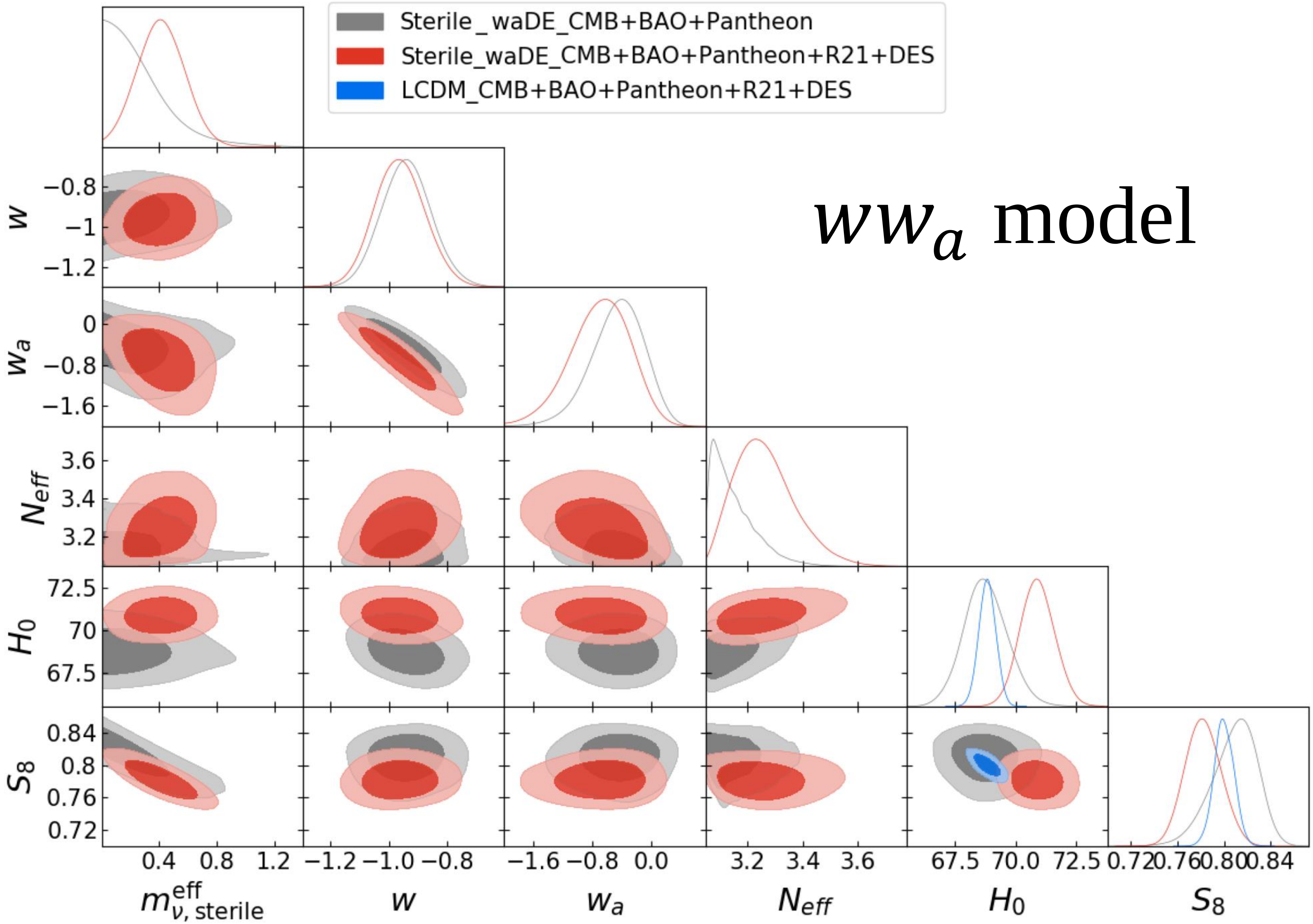

+DES data
ν_s only
Ω_K model
w model
ww_a model
Non-zero $m^{\mathrm{eff}}_{\nu,\mathrm{sterile}}$
ntheon
ntheon+R21
ntheon+DES
N_{eff}
n_s
H_0
S_8
w
w_a
Ω_K
$m^{\mathrm{eff}}_{\nu,\,\mathrm{sterile}}$



Sterile_Omegak_CMB+BAO+Pantheon
Sterile_Omegak_CMB+BAO+Pantheon+R21+DES
LCDM_CMB+BAO+Pantheon+R21+DES
Ω_K model
$m^{\rm eff}_{\nu,\,\rm sterile}$
N_{eff}
H_0
S_8
Ω_K



Sterile_wDE_CMB+BAO+Pantheon
Sterile_wDE_CMB+BAO+Pantheon+R21+DES
LCDM_CMB+BAO+Pantheon+R21+DES
w model
$m_{\nu,\,\mathrm{sterile}}^{\mathrm{eff}}$
w
N_{eff}
H_0
S_8



Sterile_waDE_CMB+BAO+Pantheon
Sterile_waDE_CMB+BAO+Pantheon+R21+DES
LCDM_CMB+BAO+Pantheon+R21+DES
$m_{\nu,\,\mathrm{sterile}}^{\mathrm{eff}}$
w
w_a
N_{eff}
H_0
S_8

ww_a model

§ Summary

- Conclusion depends on data sets
- Planck+BAO+SNe
  - All models are consistent with the standard ΛCDM.
- Planck+BAO+SNe+DES
  - Non-zero sterile neutrino mass favored
- Planck+BAO+SNe+DES+R21
  - Non-zero sterile neutrino mass favored for ww_a model
  - Upper bound on sterile neutrino mass for other models
  - Slightly $\Omega_K > 0$ (negative spatial curvature) favored