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Neutrino cosmology beyond LCDM

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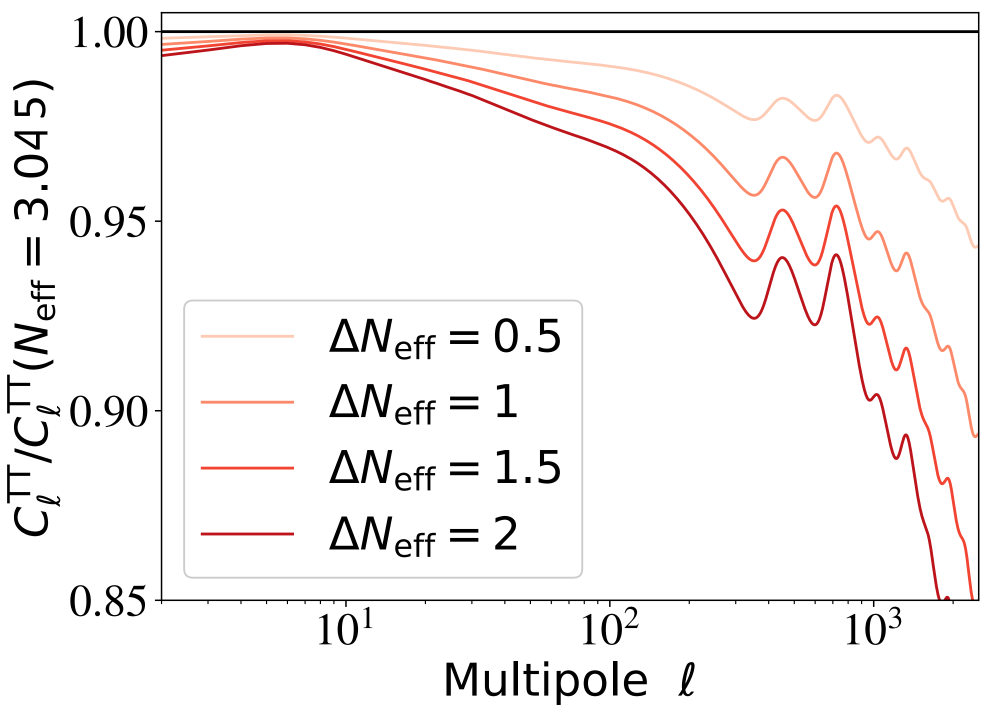
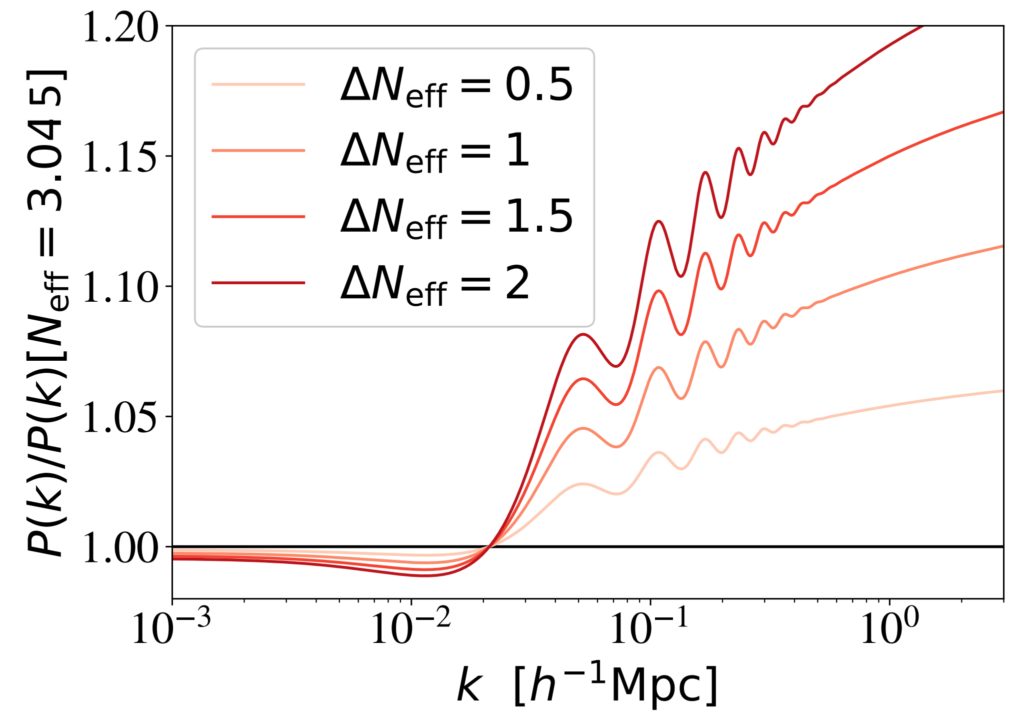
Plan

- Standard effect of $N_{\rm eff}$ and M_ν (3 minutes)
- Massive neutrino simulations for free! (2 minutes)
- Non-standard neutrino models inspired by:
  - H_0 tension: self-interacting nu, light majoron
  - S_8 tension: DR interacting with DM, heavy majoron
  - possible oscillation anomaly: secret interactions
  - Data preference for $M_\nu = 0$: decaying and mass-varying neutrinos
  - (3.5keV line and small-scale CDM crisis: keV sterile neutrinos)
- (Neutrino isocurvature modes)

Standard effects of $N_{\rm eff}$

$N_{\rm eff}$ = density of relativistic relics before photon decoupling, when standard neutrinos are still ultra-relativistic

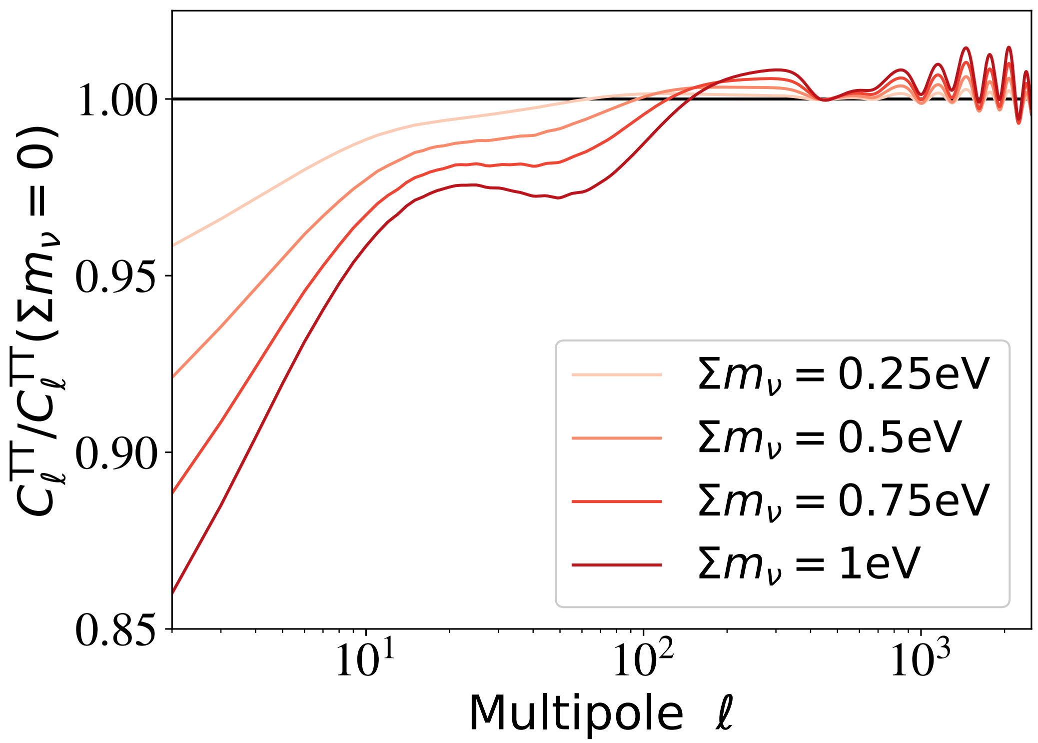


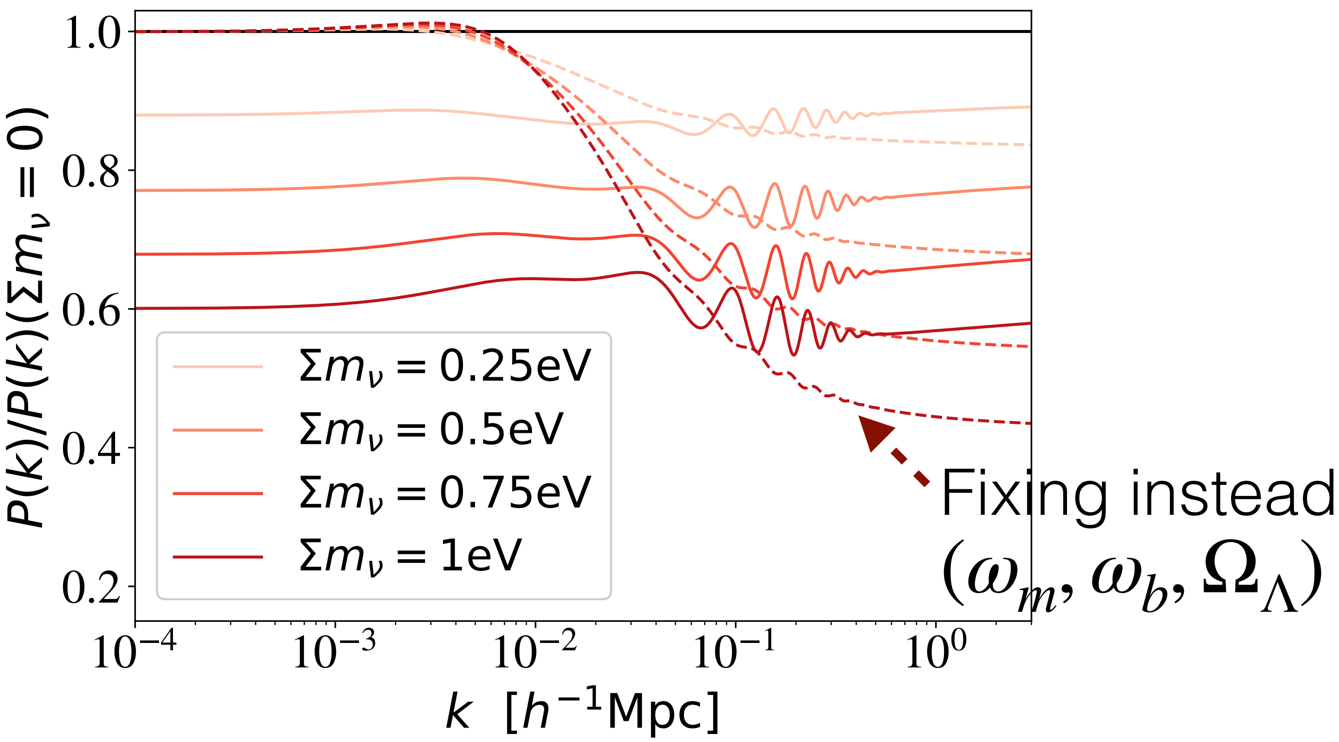


Fixing $(z_{\rm eq}, \omega_b, \theta_s)$: small shift of CMB and BAO peak amplitude and position (neutrino drag), extra Silk damping (compensation by H_0), enhanced small-scale P(k) shape (compensation by H_0)

Standard effects of M_ν and $N_{\rm eff}$

M_ν = mass summed over three mass eigenstates





Fixing $(z_{\rm eq}, \omega_b, \theta_s)$: CMB lensing, dip from early ISW (ν NR transition), late ISW (change in z_Λ), suppressed P(k) (free-streaming + compensation by H_0)

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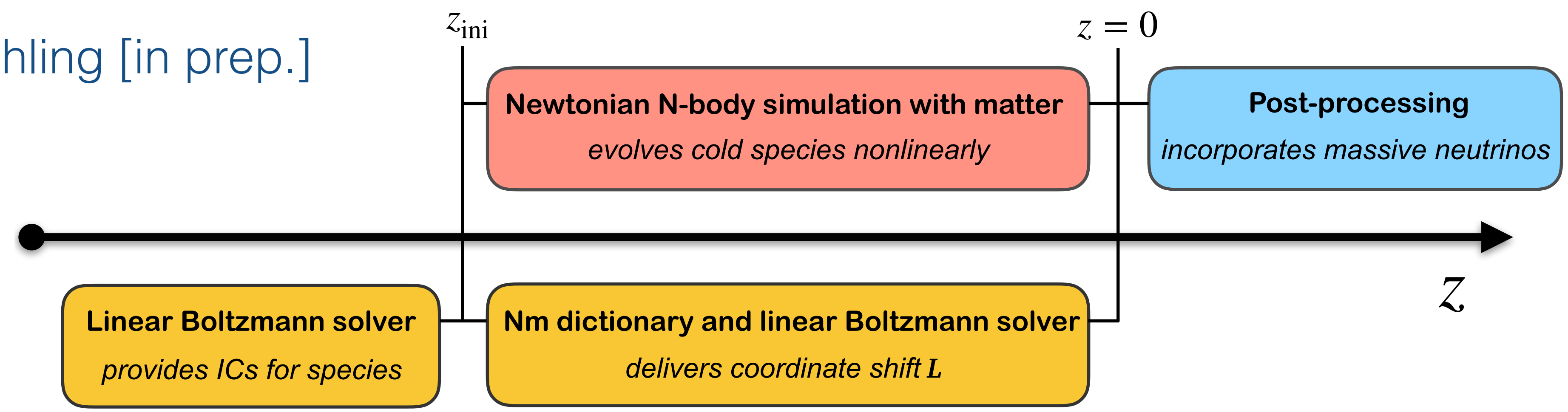
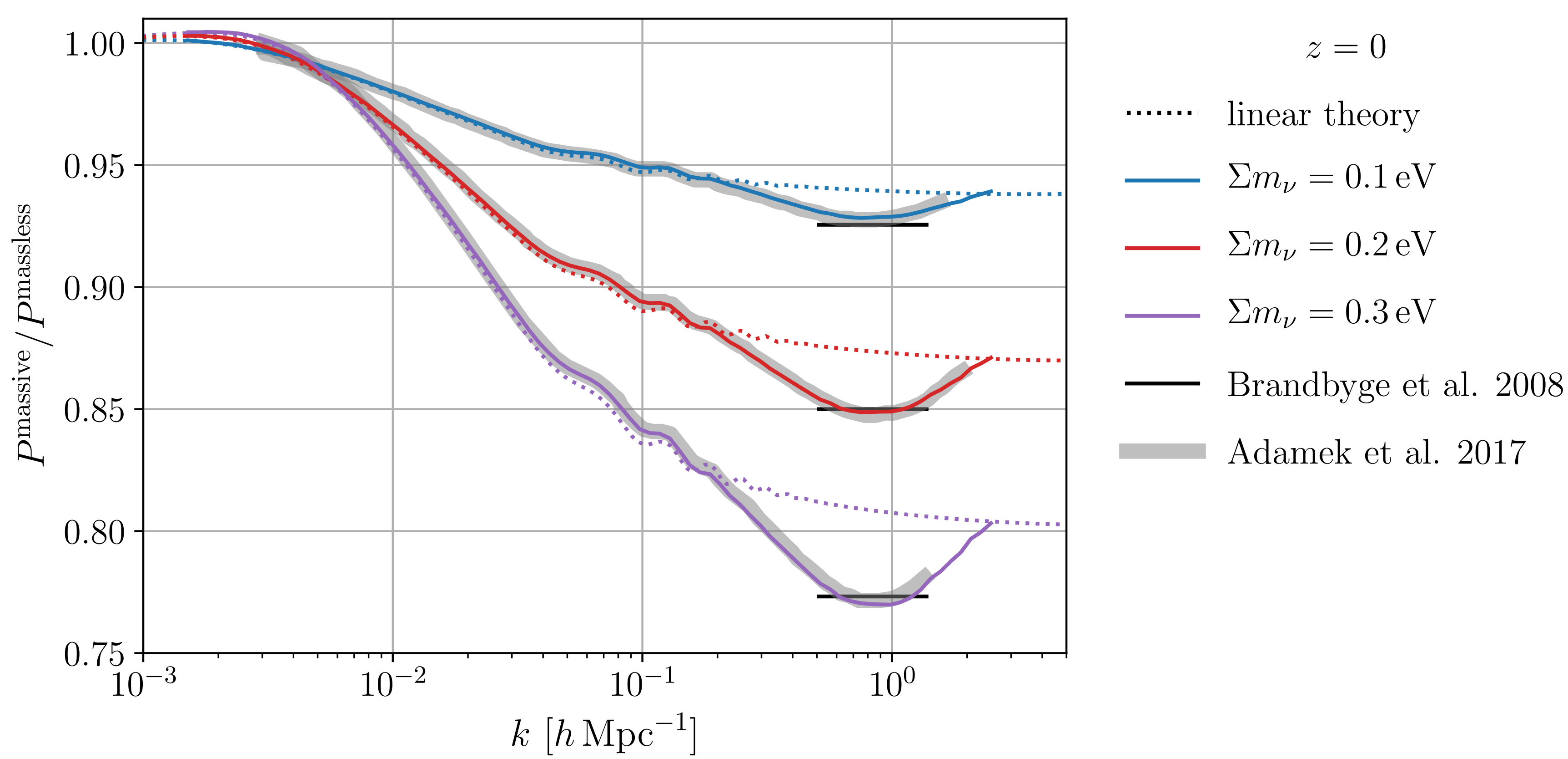
N-body simulations with M_ν for free

Partmann, Fidler, Rampf, Hahn 2003.07387: Gevolution/Gadget-2 + CLASS

Fidler, Heuschling [in prep.]





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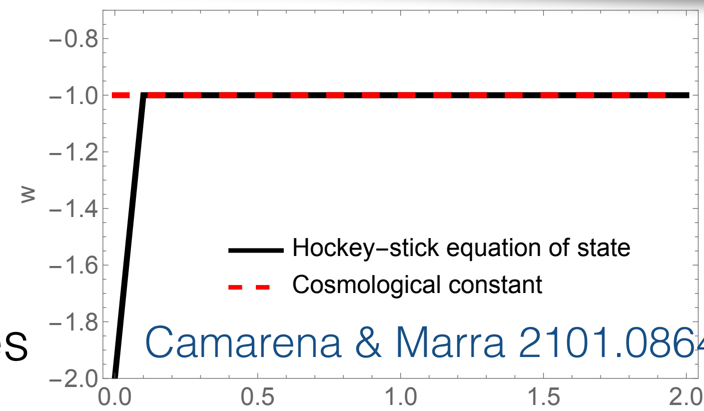
H0 tension and neutrinos



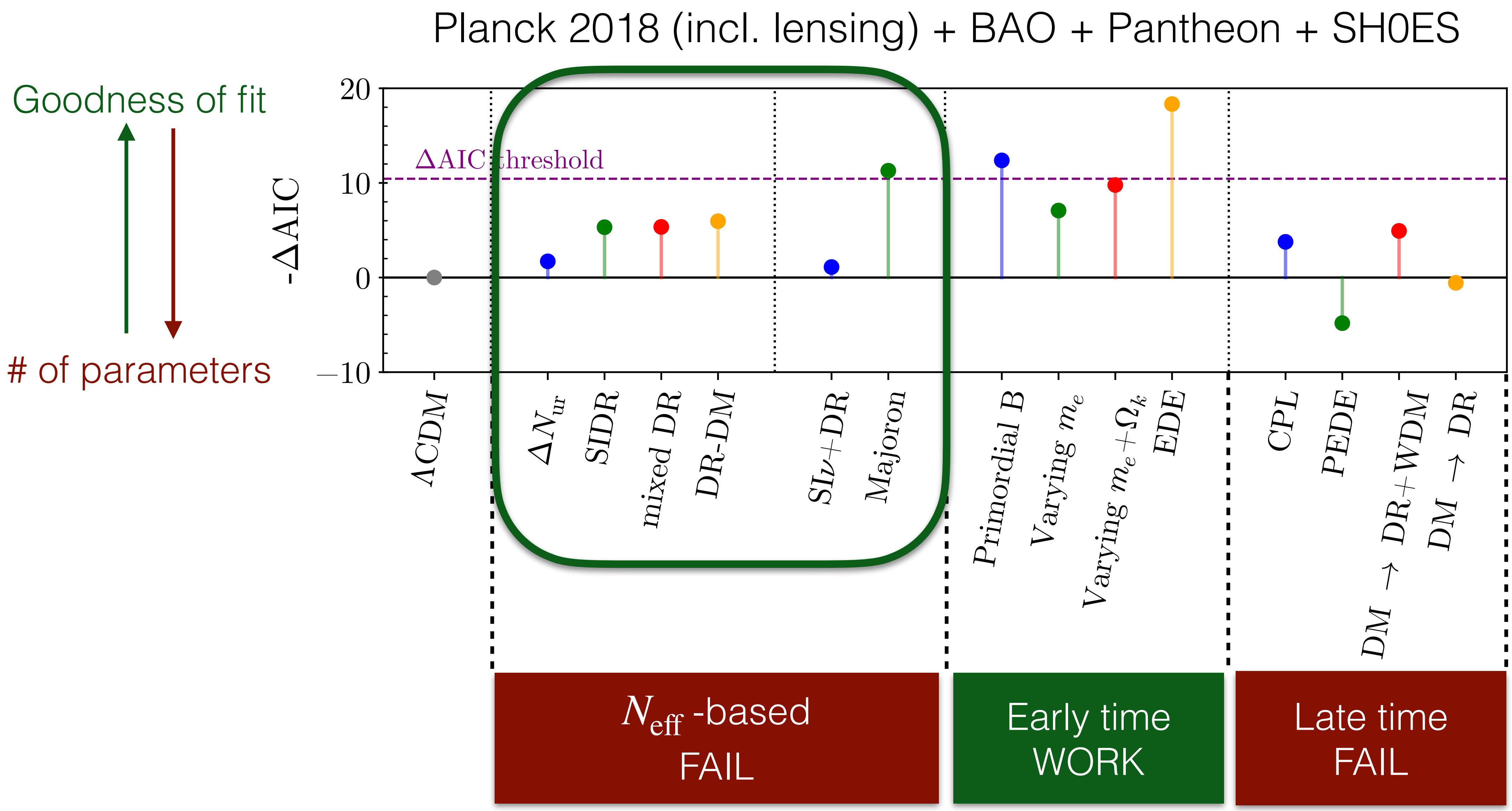
Three avenues:

1. Change in late cosmological evolution, feature between z~0-0.1 (SH0ES) and z~0.1-1.3 (BAO/high-z SNIa)
   - Difficulty: simultaneous compatibility with all observables

2. Increase $N_{\rm eff}$ to change sound horizon r_s and make sound angular scale $\theta_s = r_s/d_A$ compatible with larger H_0
   - Difficulty: other ingredients must counteract other effects of increasing $(N_{\rm eff}, H_0)$: enhanced Silk damping, acoustic peak shift from neutrino drag… ⇒ new interactions in dark sector and/or neutrino sector
     - Self-interacting DR, potentially also interacting with DM: Buen-Abad et al. 1505.03542, 1708.09406; JL et al. 1507.04351
     - self-interacting neutrinos: Lancaster et al. [1704.06657], Oldengott et al. [1706.02123], Kreisch et al. [1902.00534]…
     - Neutrinos coupled to Majoron: Escudero & Witte 1909.04044, 2004.01470, 2103.03249

3. Other changes in early cosmological evolution, still leading to shift in sound horizon r_s: early DE, early MG, primordial magnetic fields-> inhomogeneous recombination, running of fundamental constants…
   - Less constrained but more ad hoc?

H0 tension and neutrinos



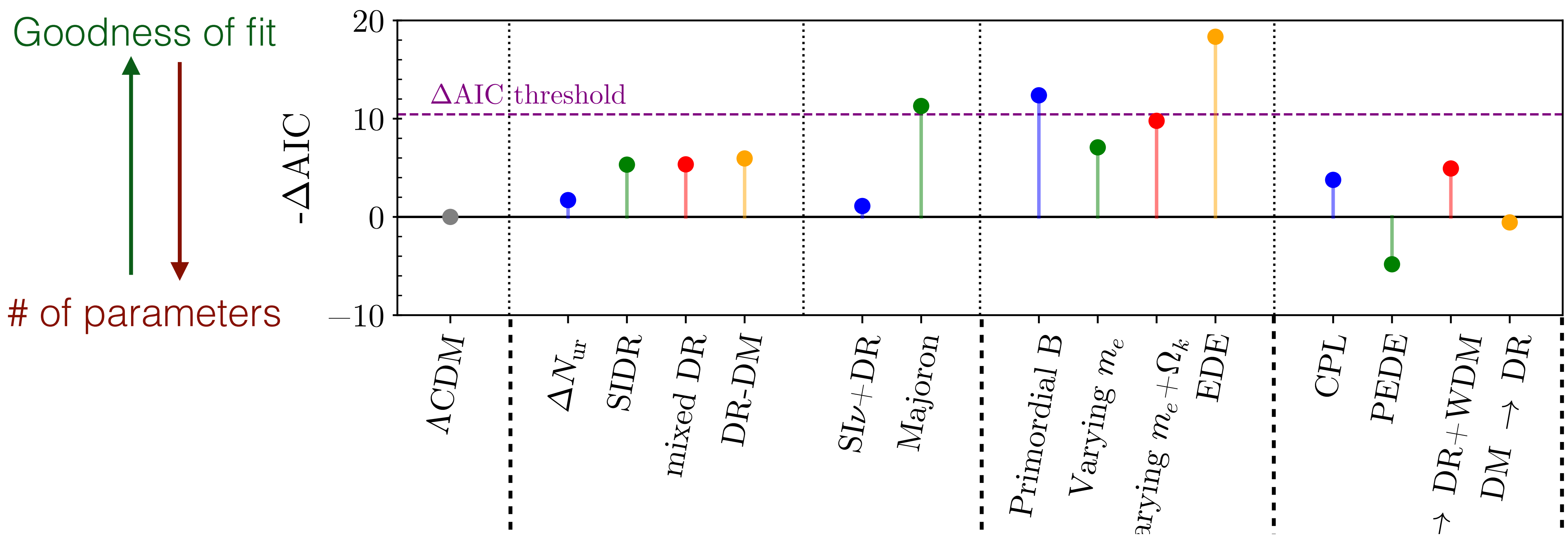
excepted one
Majoron-motivated model

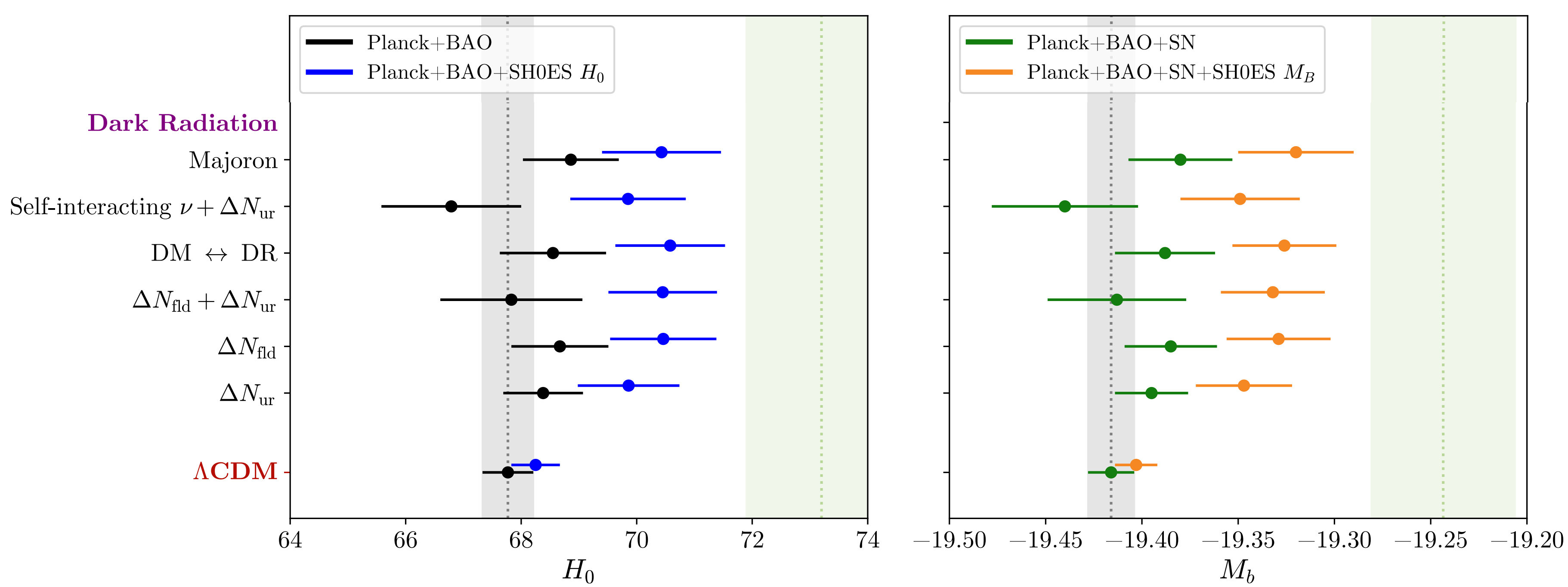
Bad news for:

- Self-interacting neutrinos
- DM scattering on self-coupled DR

H0 tension and neutrinos

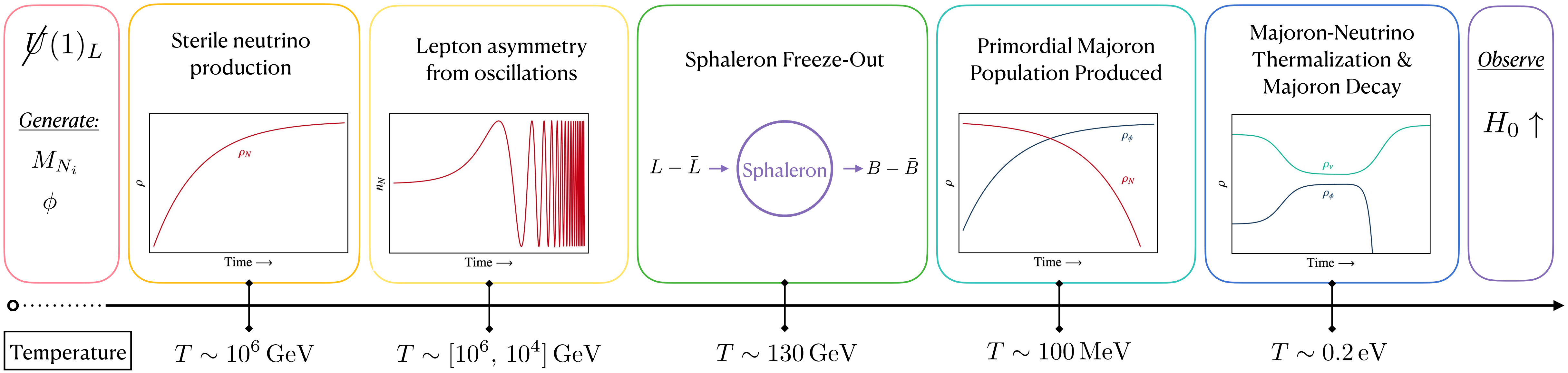
Planck 2018 (incl. lensing) + BAO + Pantheon + SH0ES





(light) Majoron scenario of Escudero & Witte 1909.04044, 2004.01470, 2103.03249:

- O(eV)-mass Majoron ϕ = pseudo-Goldstone of spontaneously broken $U(1)_L$
- small Yukawa-like couplings to active neutrinos
- $T \sim \phi$: interactions between majoron and active neutrinos (inverse neutrino decay):
  - Majoron thermalize and contribute to $N_{\rm eff}$,
  - active neutrinos do not free-stream
- $T < \phi$: Majoron decays into active neutrinos, which free-stream



H0 tension and neutrinos

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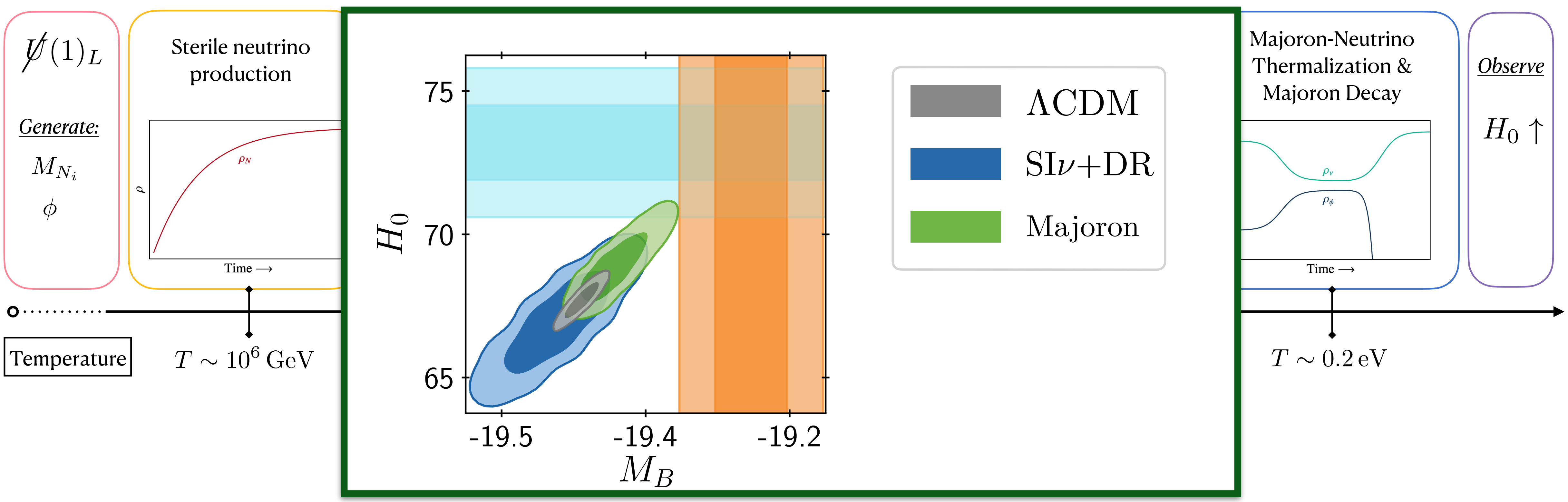
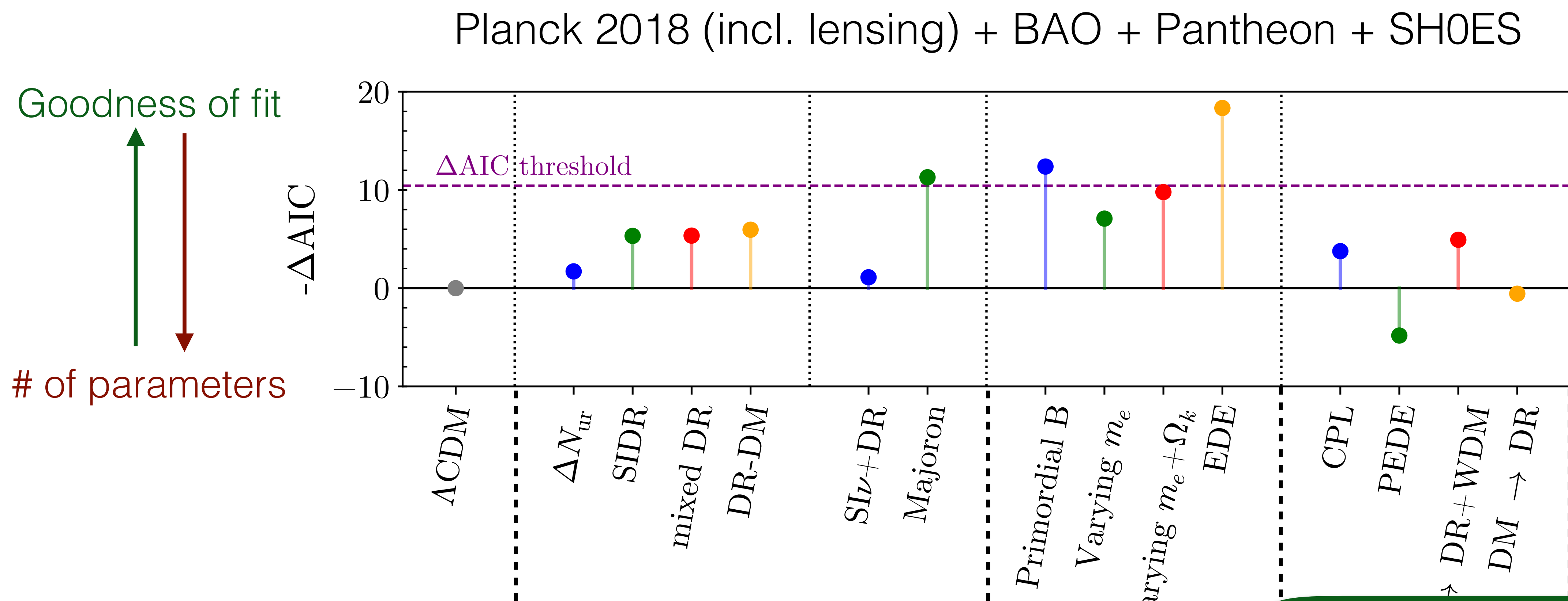
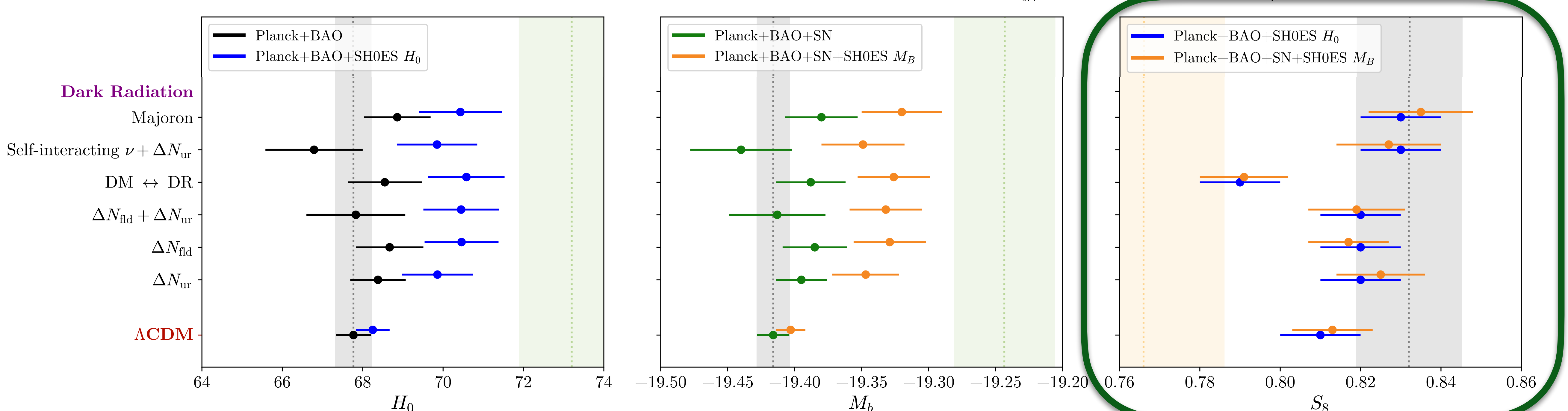


S8 tension and neutrinos

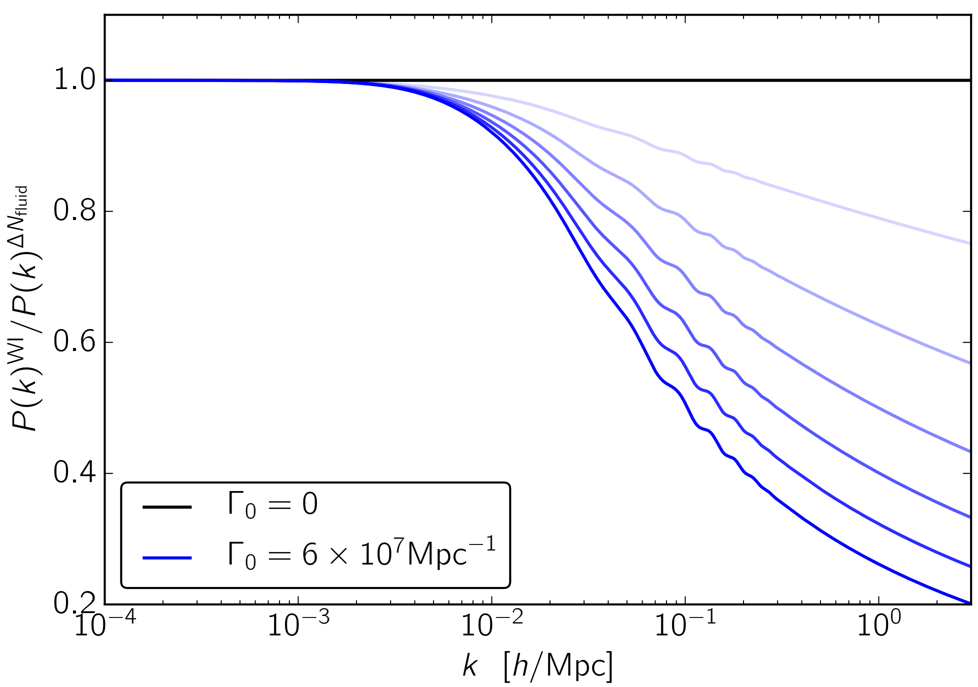




- DR interacting with DM with momentum exchange rate $\propto T^2$
  (Buen-Abad et al. 1505.03542, 1708.09406; JL et al. 1507.04351; Archidiacono et al. 1907.01496)

Assets:

- Ingredients are all-in-one
- Derived from concrete DS set ups (dark gauge group + gauge bosons + charged fermions)
- Distinct prediction for P(k,z)



Issues:

- $N_{\rm eff}$ in conflict with BBN+Helium: need additional mechanism
- Solves either: S_8 fully but H_0. partially.

S8 tension and neutrinos

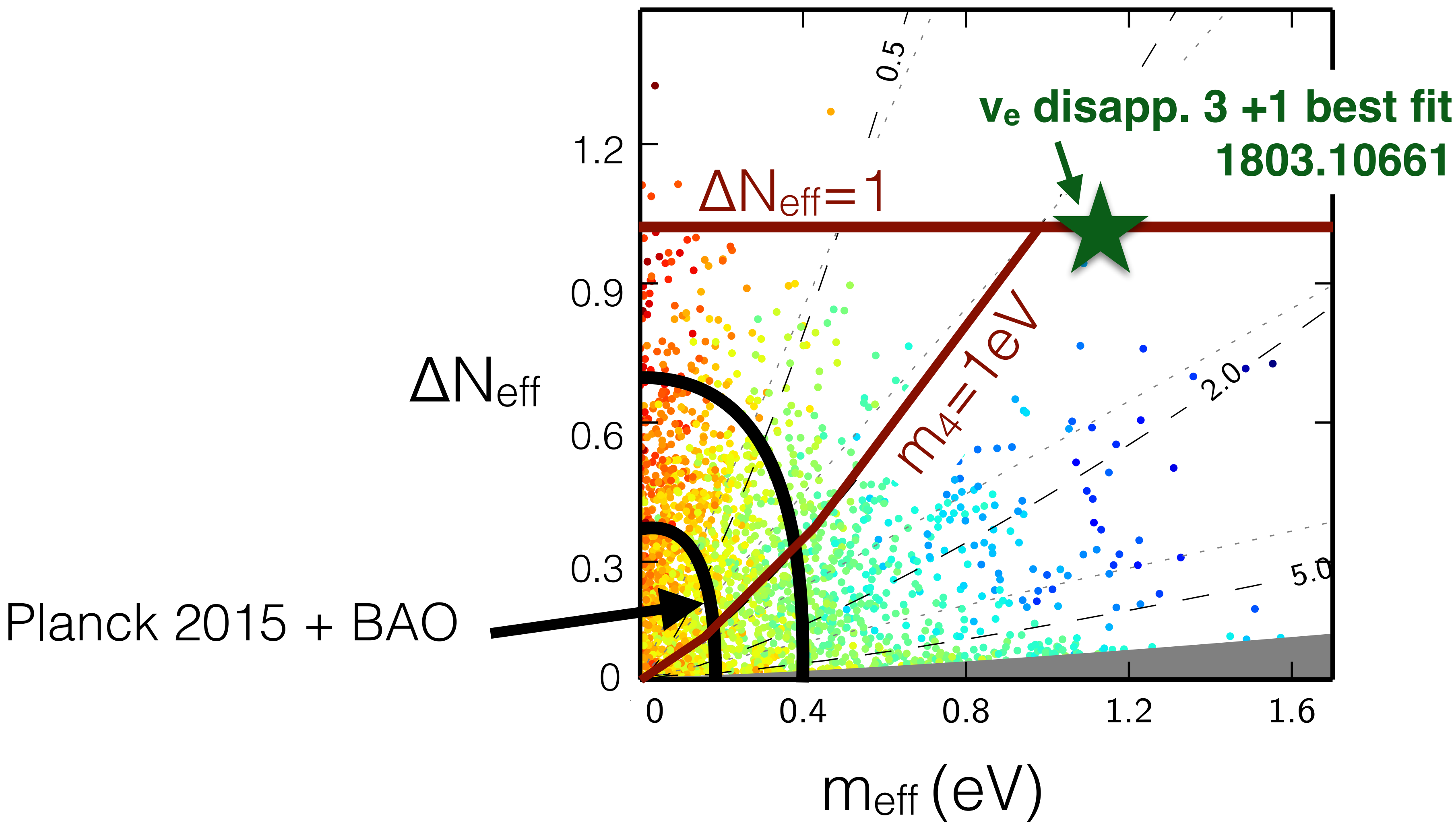
Does not work:

- Standard neutrino mass $\sum m_\nu$ (z_{NR} close to z_{dec} -> early ISW; not enough CMB lensing)
- Most decaying DM models (decay between z~1000 and z~1 into electromagnetic components: strong energy injection bounds; into neutrinos / dark radiation -> late ISW) (Chudaykin et al. 1602.08121, Poulin et al. 1606.02073, DES 2011.04606, …)

Works well:

- Many Modified Gravity (MG) models (e.g. f(R))
- Feebly interacting DM (with relativistic particles: photons or DR; collisional damping) (Becker et al. 2010.04074)
- Cold + Warm DM (small fraction of ~keV DM) (Boyarsky et al. 0812.0010)
- Long-lived CDM decaying into massless+massive but lighter particle; possibly (heavier) Majoron decaying into active + sterile neutrinos; possible connection with (heavier) Majoron and with Xenon-1T (Abellan et al. 2008.09615); not a solution to Hubble tension
- Cannibal DM (inelastic scattering 3->2 causing slow transition from radiation-like to matter-like (Heimersheim et al. 2008.08486)
- Connection with small-scale CDM crisis…

Neutrino oscillation anomalies



Neutrino oscillation anomalies

How to suppress the ν_4 density in both relativistic and non-relativistic regimes?

- Low-temperature reheating — Gelmini et al. 2014, de Salas et al. 2015
- Leptonic asymmetry and resonant oscillations… *issues with BBN* (μ_e)

  Di Bari et al. 2001; …; Hannestad, Tambora & Tram 2012; Mirizzi et al. 2012; Saviano et al. 2013
- NSI (need to pass bounds on fifth force and SN energy loss…)
  - ν_4 interacts with (dark) gauge boson

    Dasgupta, Kopp 2015 ; Saviano et al. 2014; Mirizzi et al. 2014; Chu, Dasgupta, Kopp 2015
  - ν_4 interacts with (dark) pseudoscalar

    Hannestad et al. 2013; Saviano et al. 2014; Archidiacono et al. 2016, 2020
    - ν_4 production is suppressed, ϕ-ν_s recouple —> neutrinos as relativistic fluid *(maybe testable with future CMB data)*, ν_4 annihilate into ϕ at late times…

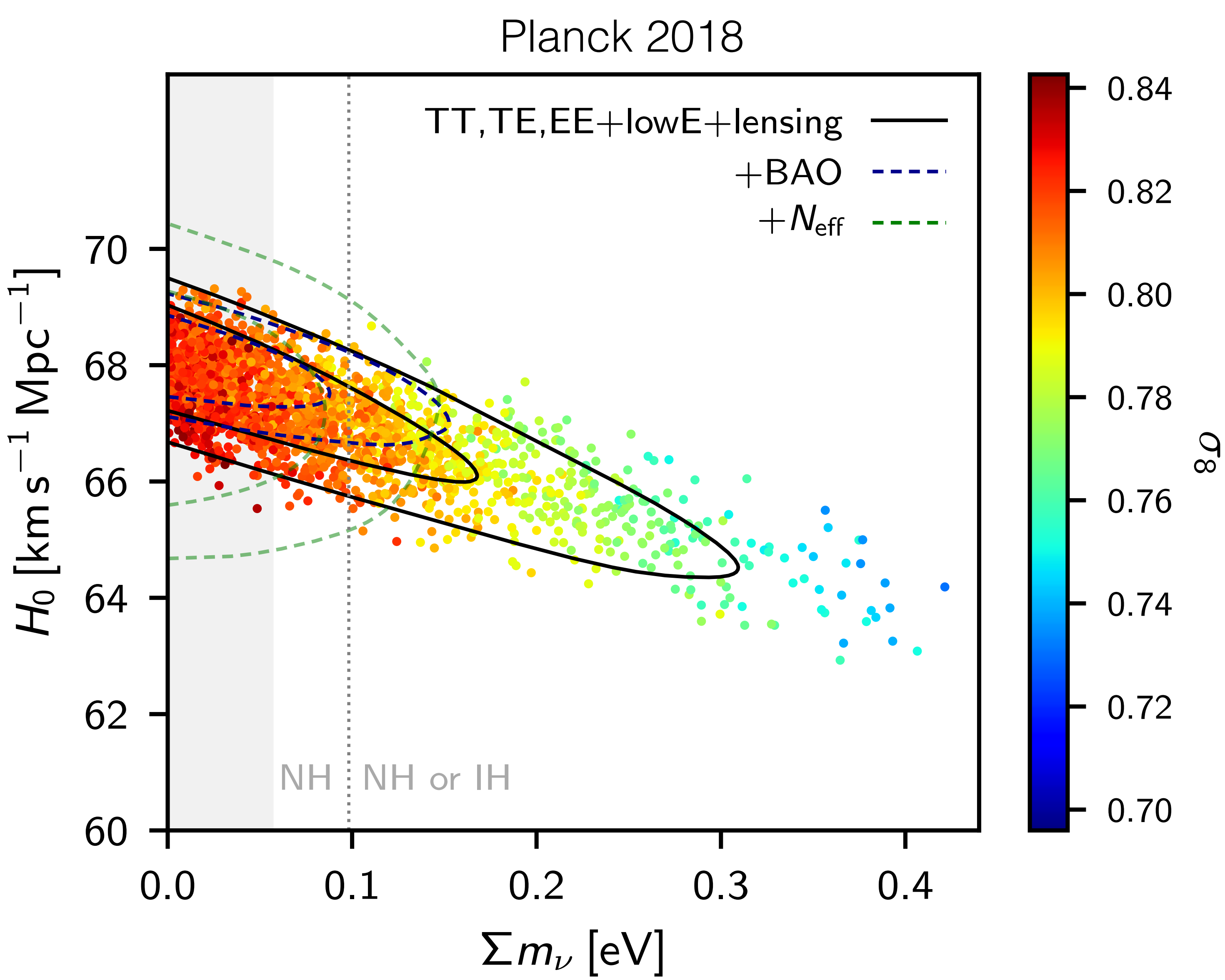
Neutrino oscillation anomalies

eV-mass sterile neutrino with secret interactions : Archidiacono et al. 2006.12885

	Vanilla	Pseudo	Thermal
Parameter	Planck TTTEEE + lensing + BAO		
$\Delta N_{\rm eff}$	< 0.14	< 0.41	1
m_s [eV]	n.c.	< 1.03	< 0.28
H_0 [km/s/Mpc]	$68.1^{+0.4}_{-0.5}$	$70.0^{+0.7}_{-1.1}$	$73.3^{+0.8}_{-0.7}$
n_s	$0.966^{+0.004}_{-0.004}$	$0.944^{+0.005}_{-0.006}$	$0.999^{+0.004}_{-0.004}$

- 95% bound compatible with neutrino disappearance.
- High Hubble rate at the same time.
- But priors in this model do not incorporate plain LCDM. Best fit degraded by $\Delta\chi^2 = 13$ w.r.t. LCDM (despite 2 additional parameters).

Absence of preliminary evidence for neutrino mass



Could be statistical fluke, but isn't the data trending towards $M_\nu < 0.06$ eV ?

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Absence of preliminary evidence for neutrino mass

- Invisible neutrino decay into:
  - lighter neutrino ($\ll 0.1$ eV) + scalar (Majoron again!). Barenboim et al. 2011.01502. Joint bounds on decaying neutrino lifetime and mass (which could be arbitrarily large).
  - Same in the framework of see-saw (more constrained). Escudero et al. 2007.04994. $M_\nu \leq 1$ eV still possible.
  - Dark Radiation. Chacko et al. 2002.08401: could be probed by Euclid if decay takes place late enough.
- Mass-varying neutrinos coupled to scalar field (Fardon et al. astro-ph/0309800). Mass varies with time and location. Instability problems (small-scale neutrino lumps, Wetterich et al.).
- Neutrino mass generated at late times (phase transition after recombination, Dvali and Funcke 1602.03191). Lorenz et al. 1811.01991, 2102.13618. No significant evidence for the model, but bound relaxed to $M_\nu \leq 1.4$ eV. Solves S_8 tension (no impact on H_0).

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keV-mass sterile neutrinos

Review in Drewes et al. 1807.07938

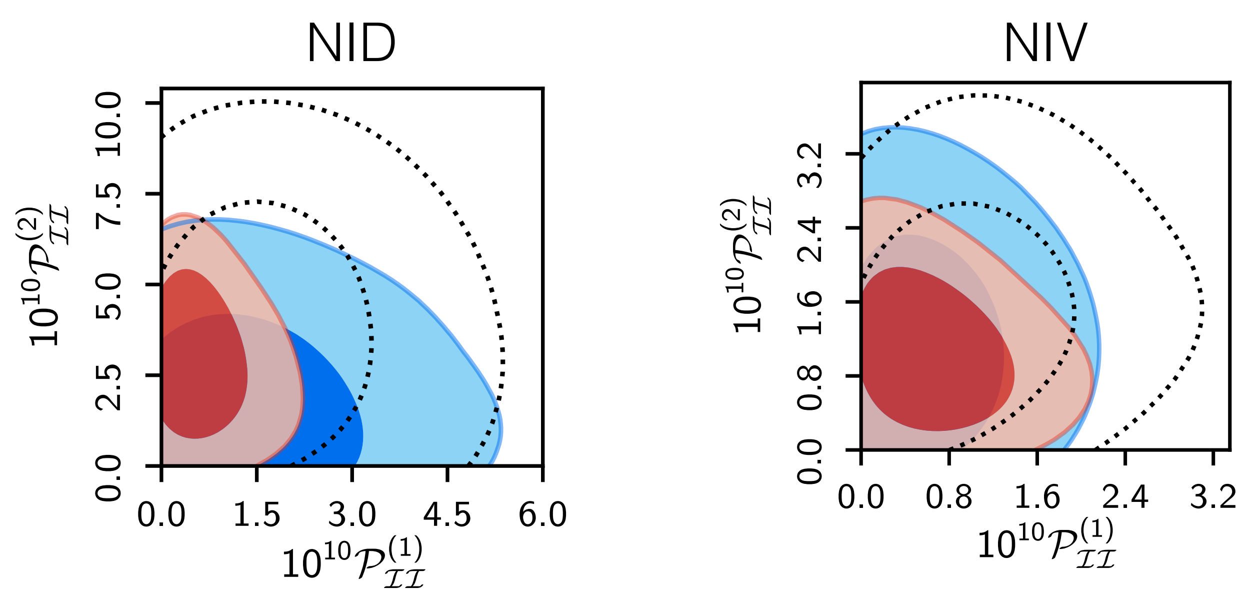
- Sterile neutrino = elegant candidate for DM
- WDM: potential solution to CDM small-scale crisis
- Lyman-alpha bounds partially evaded by resonant production (more like mixed C+WDM than usual thermal WDM)
- 3.5keV line in X-ray data potentially explained by radiative decay $N \longrightarrow \nu + \gamma$ of 7keV sterile neutrinos

neutrino isocurvature modes

- Neutrino Isocurvature Density (NID) mode
- Neutrino Isocurvature Velocity (NIV) mode
- Unknown tilt, unknown correlation with adiabatic mode

None are significantly favored by Planck 2018 TTTEEE + lensing, although they do improve the chi χ^2 by ~ 5 (small reduction of small-scale power):

small-scale amplitude



Large-scale amplitude

- Can always be used to add or remove power at both edges of CMB range of scales