

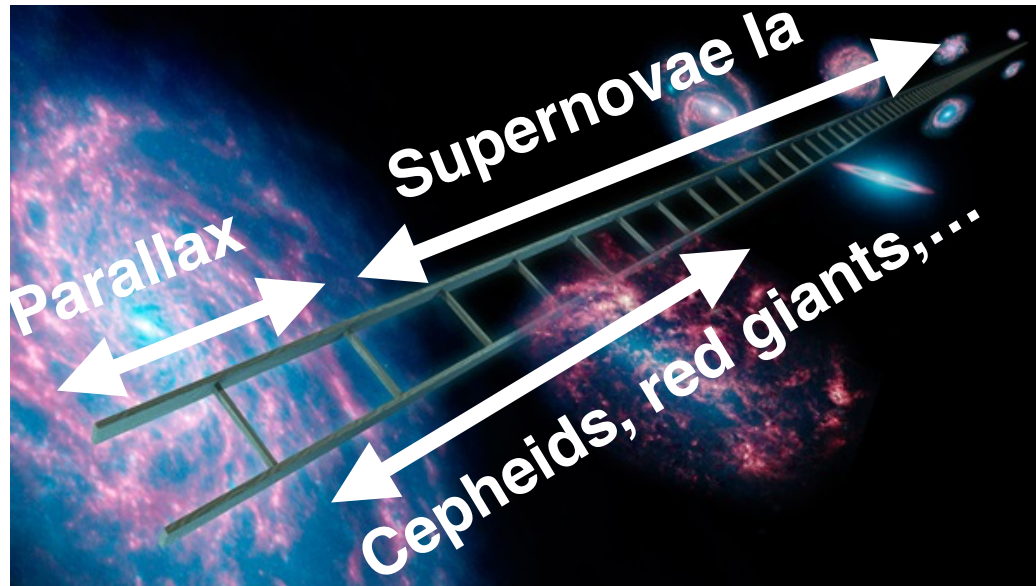
- 
- **Could cosmological tensions hint at non-standard DM properties?**

Involving Maria Archidiacono, Niklas Becker, Thejs Brinckmann, Manuel Buen-Abad, Stefan Heimersheim, Deanna Hooper, Misha Ivanov, Andrea Perez-Sanchez, Matteo Lucca, Nils Schöneberg, Sam Witte, + more senior collaborators...

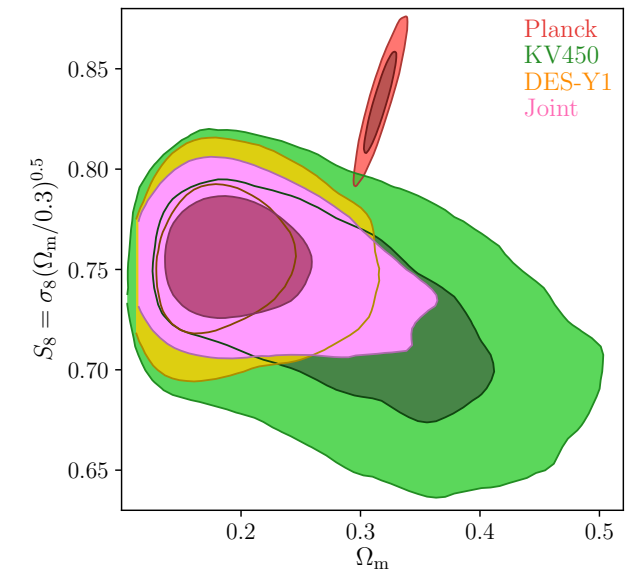
J. Lesgourgues

Institut für Theoretische Teilchenphysik und Kosmologie (TTK), RWTH Aachen University

H_0 and S_8 tensions



Local current expansion rate H_0 from distance ladder



Matter fluctuation amplitude S_8 from weak lensing

4 to 5σ

Repeated 2 to 3σ

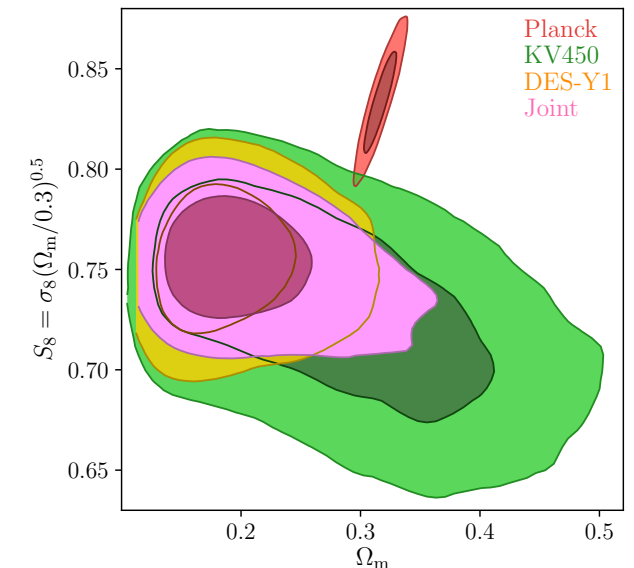
(H_0, S_8) reconstructed from most other datasets (Planck, BAO...), in model-dependent way, assuming Λ CDM

H_0 and S_8 tensions

Systematics in direct H_0 measurements
(Environnement-bias of SNIa close to
cepheids, variations in cepheids:
[Mortsell et al. 2105.11461](#), [2106.09400](#);
mass-sheet degeneracy of quasar time
delay analysis,...)

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(Unknown foregrounds, insufficient
instrument modelling)

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Small deviations from LCDM with new ingredients
(DM, DE, MG, magnetic fields, etc.),
or large-scale deviation from Friedmann model

Systematics in CMB
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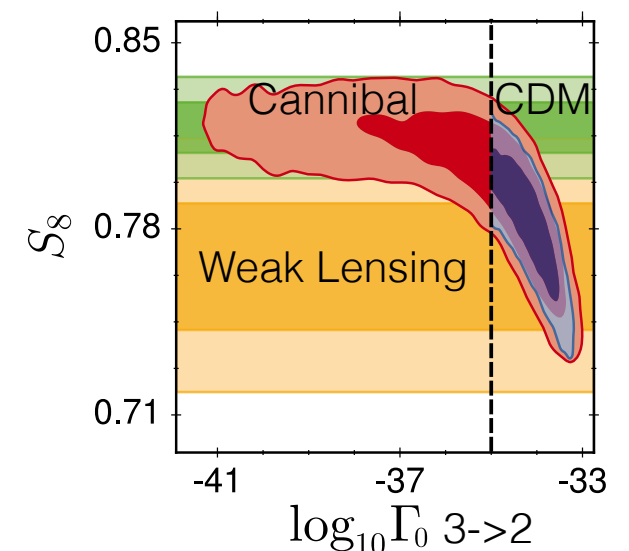
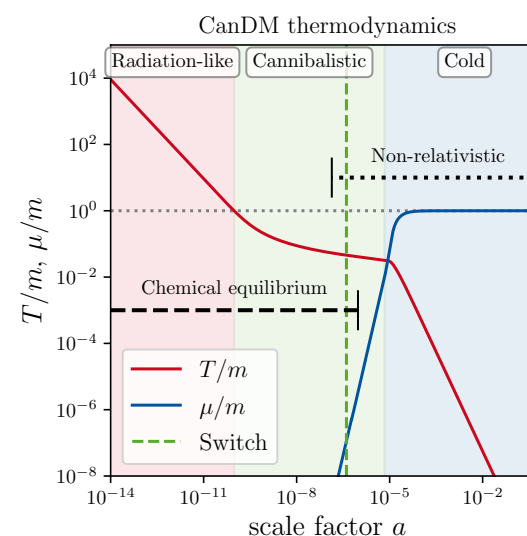
Solving the S_8 tension alone

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 $z \sim 1000$ and $z \sim 1$ into electromagnetic components: strong energy injection bounds; into neutrinos / dark radiation -> late ISW) (Audren et al. 1407.2418, Poulin et al. 1606.02073, DES 2011.04606, ...)

Works well:

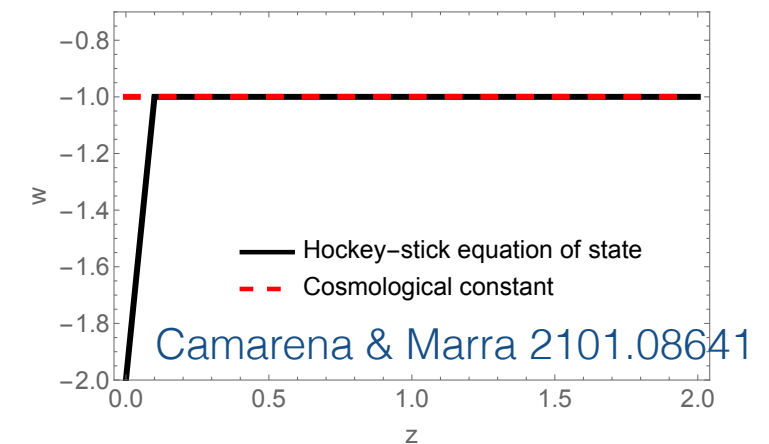
- Many Modified Gravity (MG) models (e.g. $f(R)$)
- Feebly interacting DM (with relativistic particles: photons or DR; collisional damping) (Becker et al. 2010.04074)
- Cold + Warm DM (small fraction of $\sim \text{keV}$ DM) (Boyarsky et al. 0812.0010)
- Long-lived CDM decaying into massless + massive but lighter particle; possible connection with Xenon-1T (Abellan et al. 2008.09615)
- Cannibal DM (inelastic scattering $3 \rightarrow 2$ causing slow transition from radiation-like to matter-like (Heimersheim et al. 2008.08486) \longrightarrow
- Connection with small-scale CDM crisis...



Solving the H_0 tension alone

Three avenues:

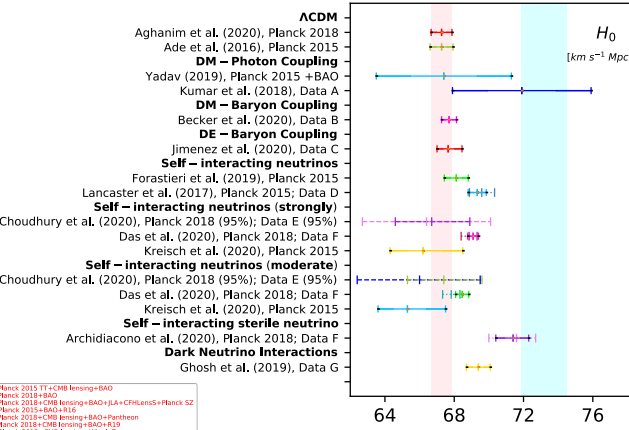
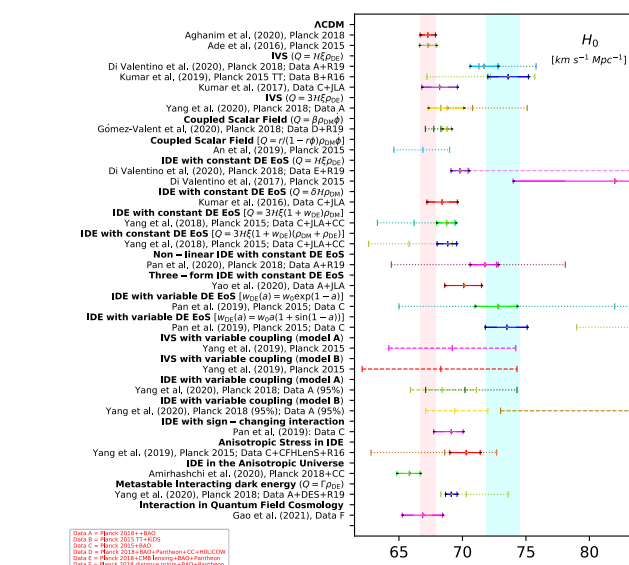
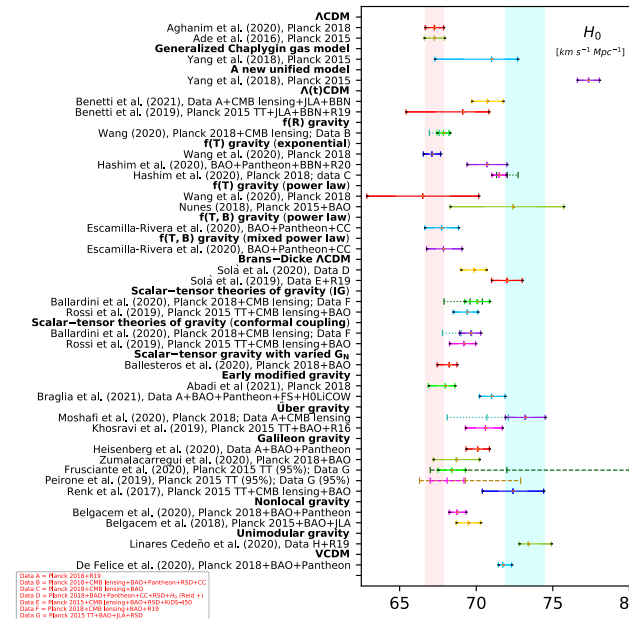
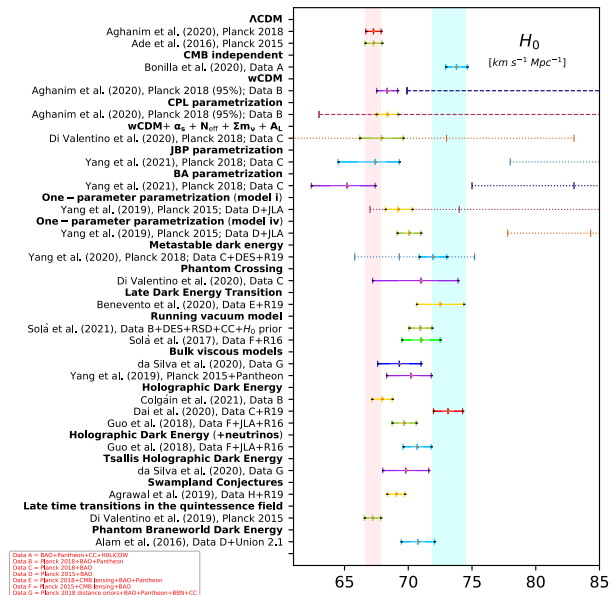
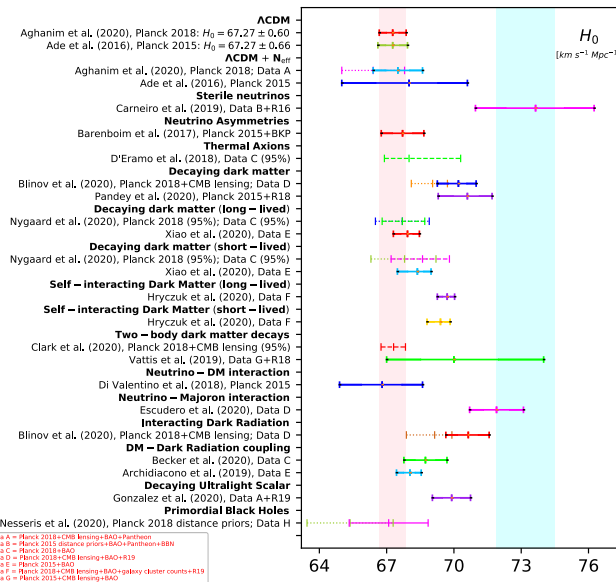
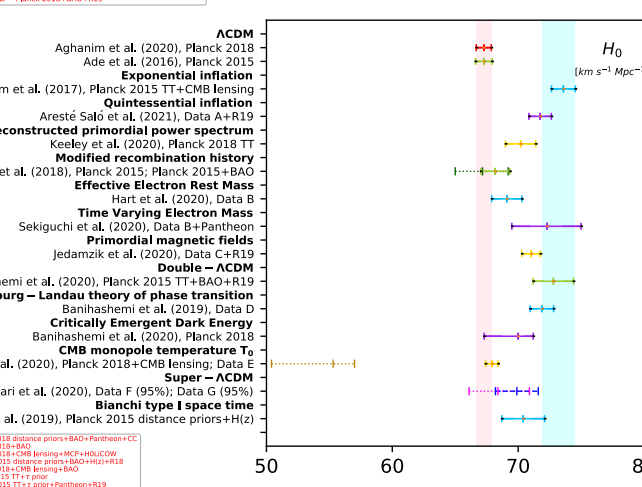
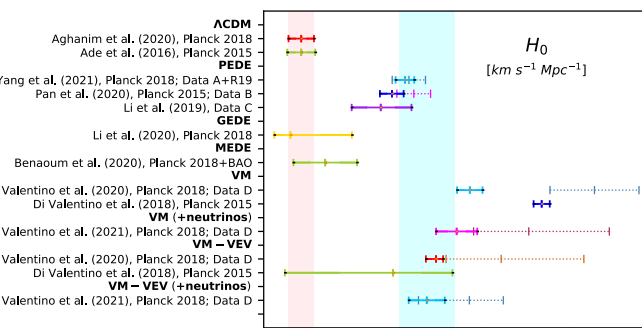
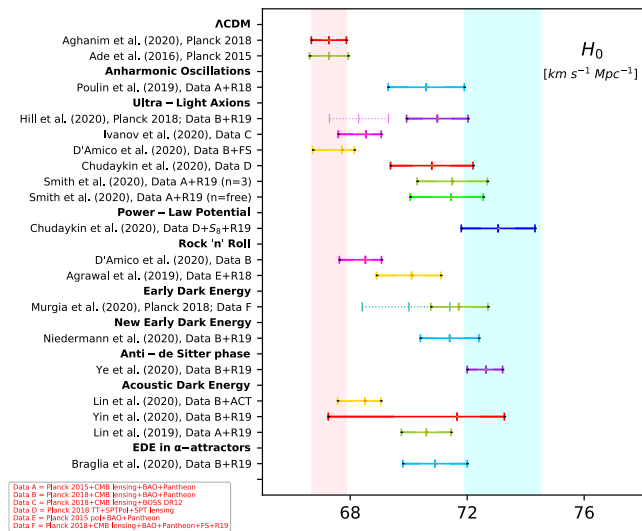
1. Change in **late cosmological evolution**, feature between $z \sim 0-0.1$ (SH0ES) and $z \sim 0.1-1.3$ (BAO/uncalibrated high- z SNIa)
 - **Difficulty:** simultaneous compatibility with all observables
2. **Increase N_{eff}** to change sound horizon r_s and make sound angular scale $\theta_s = r_s/d_A$ compatible with larger H_0
 - **Difficulty:** other ingredients must counteract other effects of increasing (N_{eff}, H_0): enhanced Silk damping, acoustic peak shift from neutrino drag...
 - \Rightarrow **new interactions** in dark sector and/or neutrino sector
 - self-interacting neutrinos: Lancaster et al. [1704.06657], Oldengott et al. [1706.02123], Kreisch et al. [1902.00534]...
 - DM scattering on DR: Buen-Abad et al. 1505.03542, 1708.09406; JL et al. 1507.04351)
3. Other changes in **early cosmological evolution**, still leading to shift in sound horizon r_s : early DE, early MG, primordial magnetic fields \rightarrow inhomogeneous recombination, running of fundamental constants...
 - Less constrained but **more ad hoc**?



Solving the H_0 tension alone

Which work and which do not?

De Valentino et al. 2103.01183



Solving the H_0 tension alone

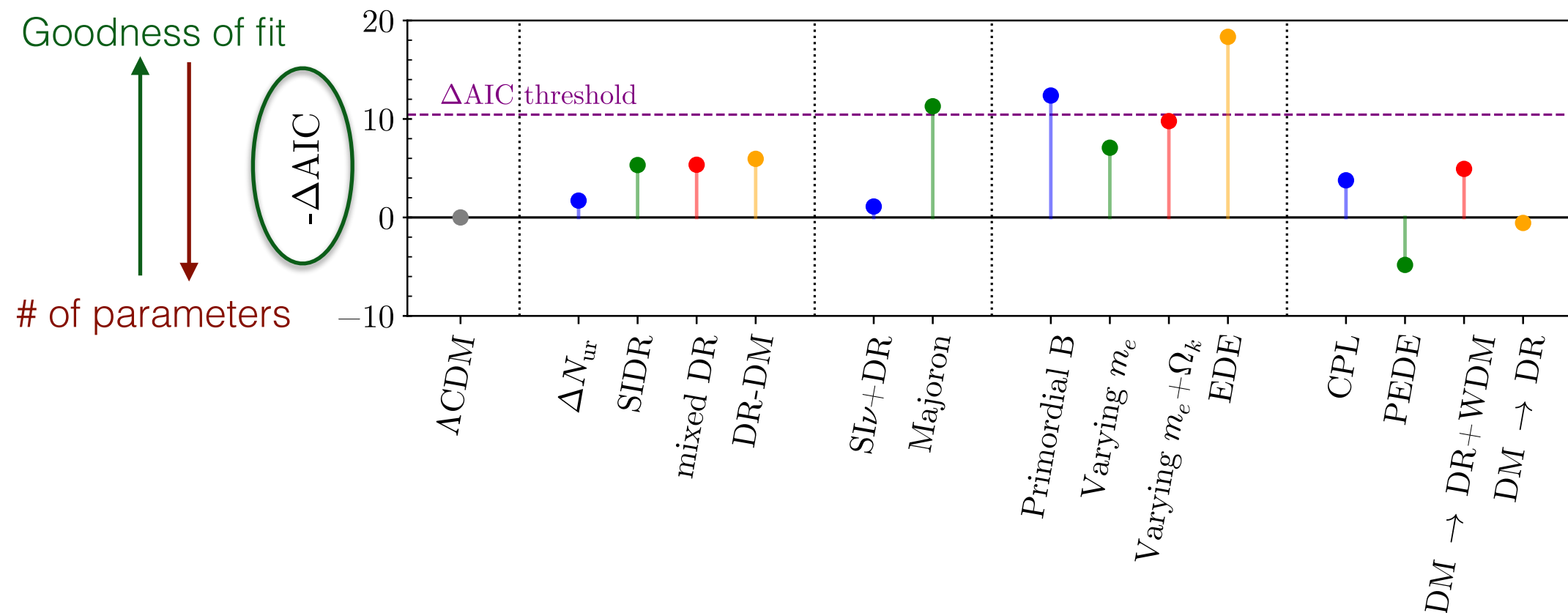
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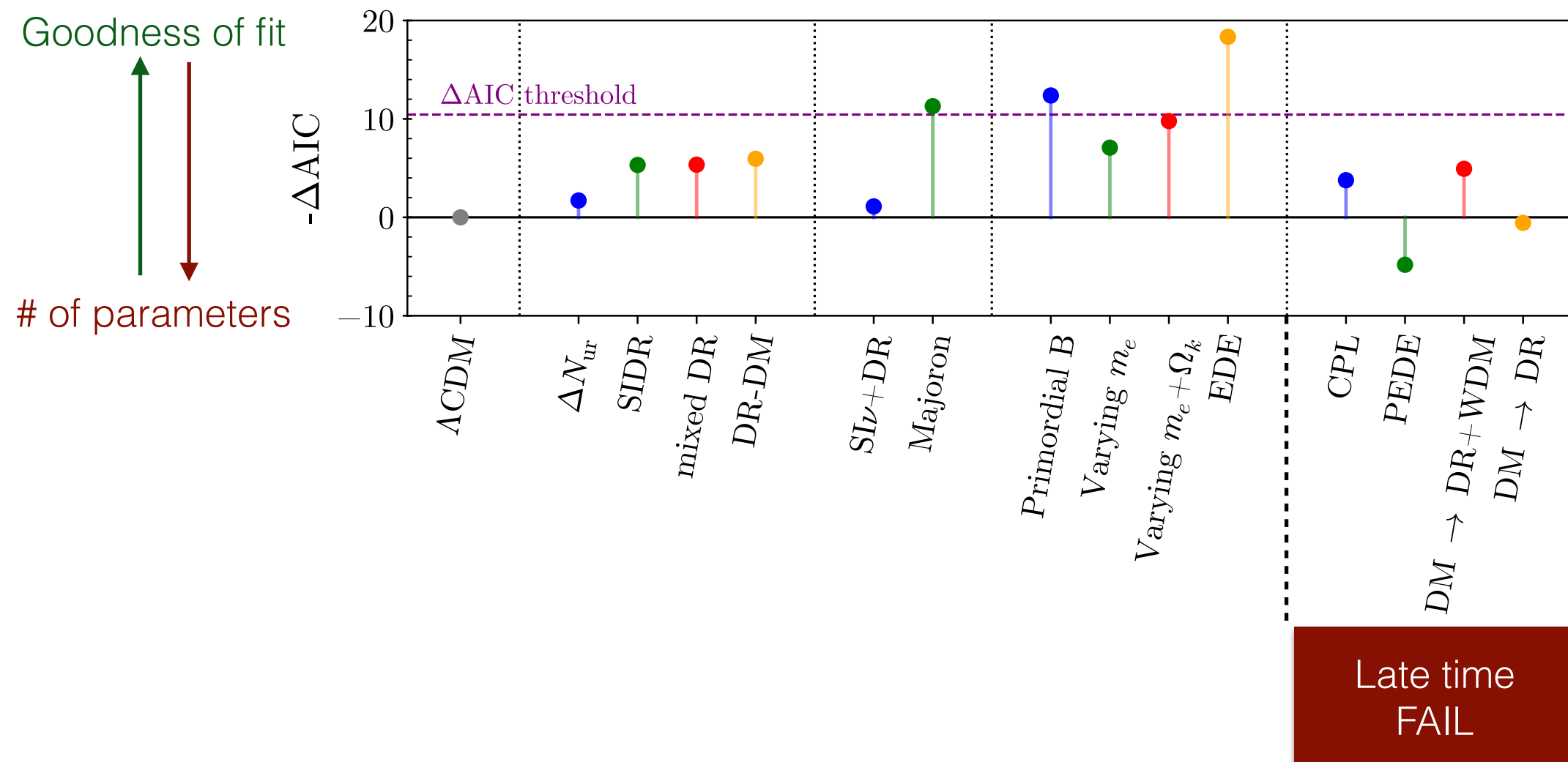
Solving the H_0 tension alone

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



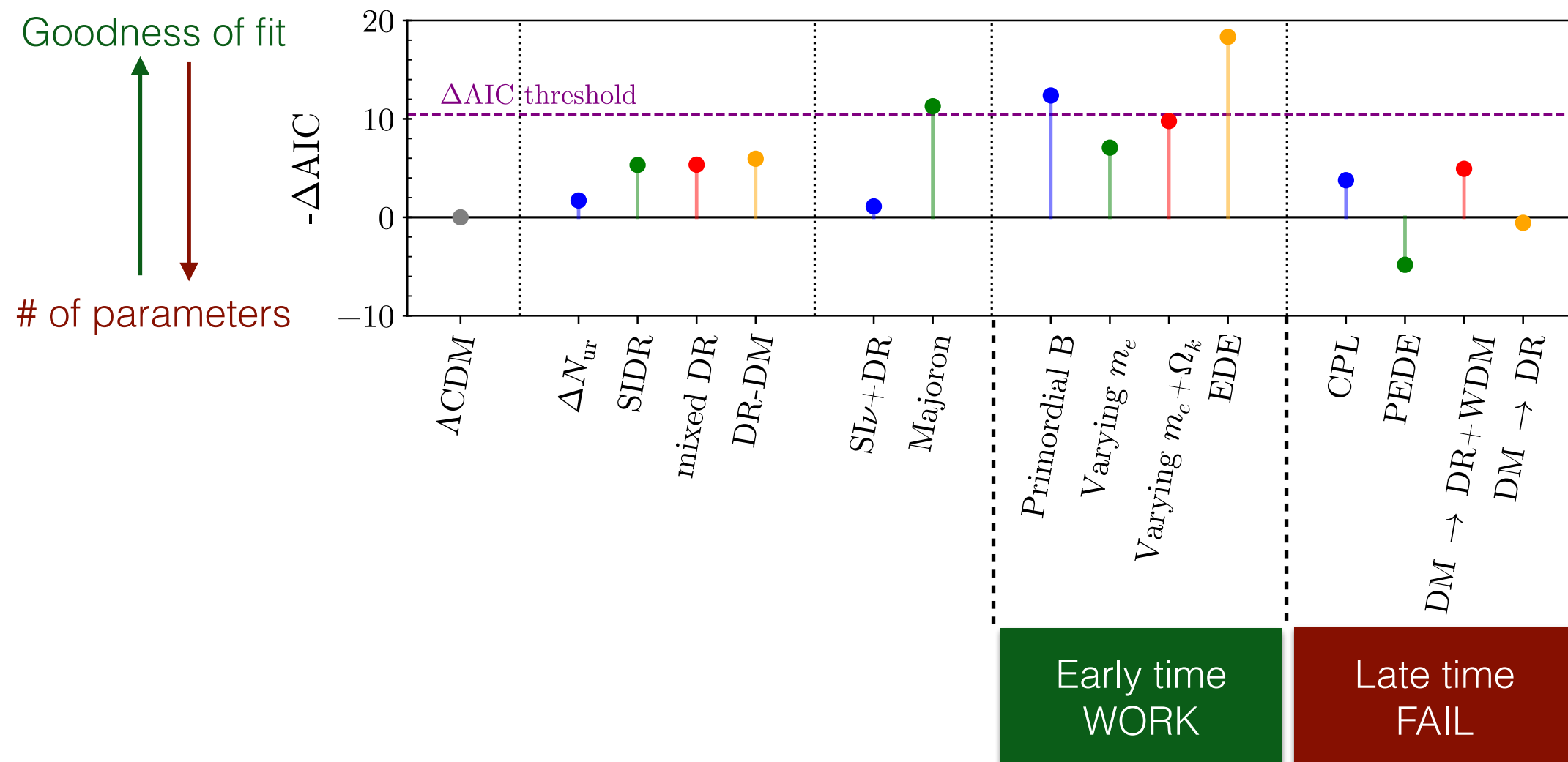
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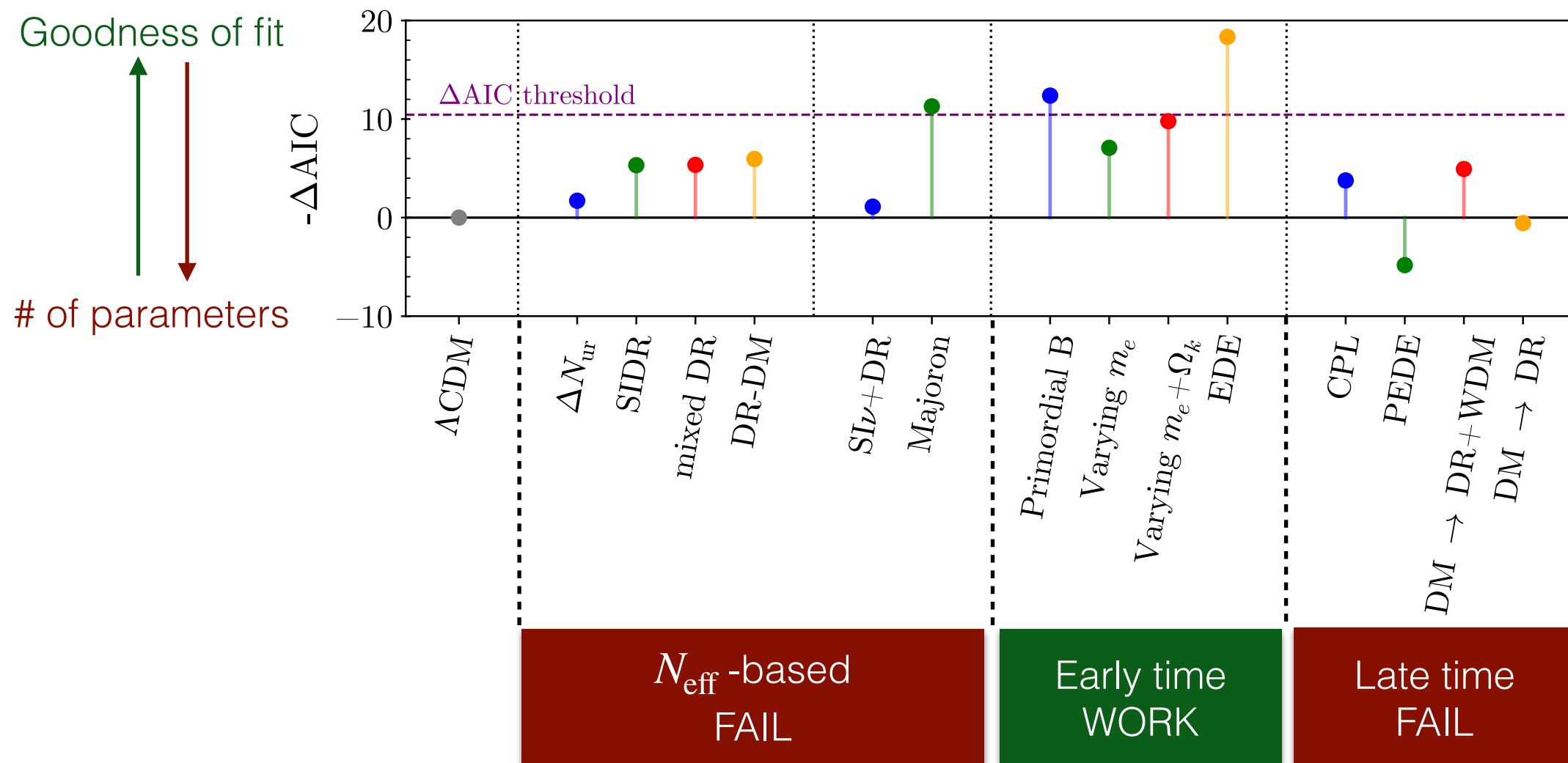
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Solving the H_0 tension alone

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excepted one
Majoron-motivated model

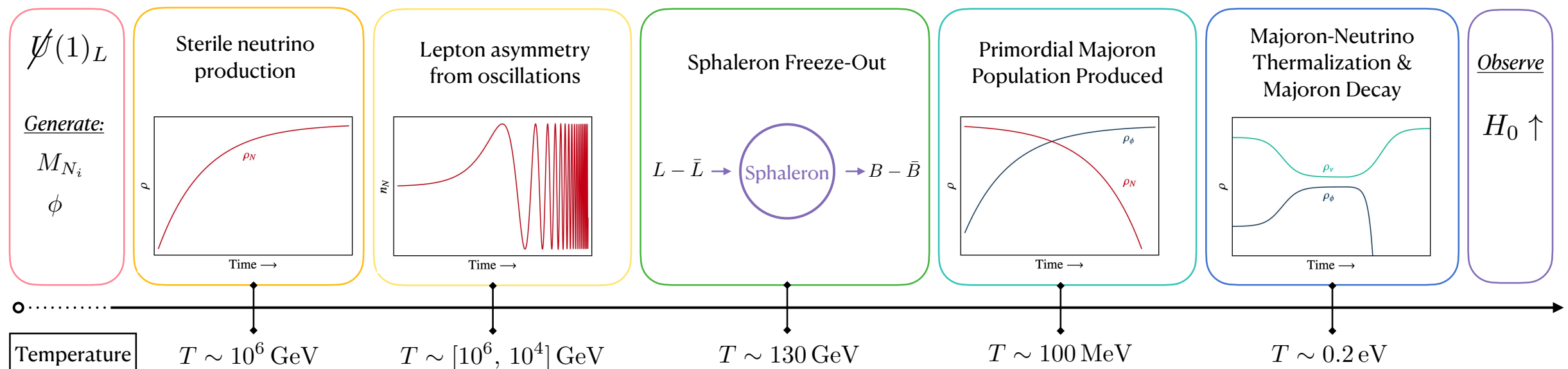
Bad news for:

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

Solving the H_0 tension alone

Majoron scenario of Escudero & Witte 1909.04044, 2004.01470, 2103.03249:

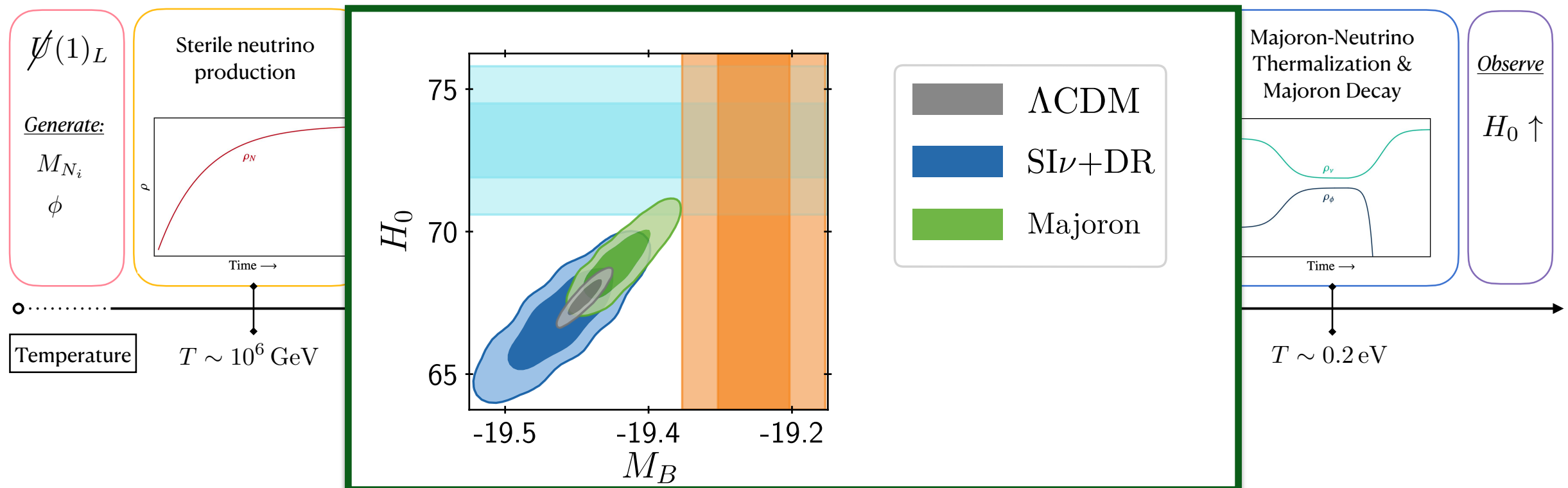
- O(eV)-mass Majoron ϕ = pseudo-Goldstone of spontaneously broken $U(1)_L$
- small Yukawa-like couplings to active neutrinos
- $T \sim \phi$: interactions between majoron and active neutrinos (inverse neutrino decay):
 - Majoron thermalize and contribute to N_{eff} ,
 - active neutrinos do not free-stream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



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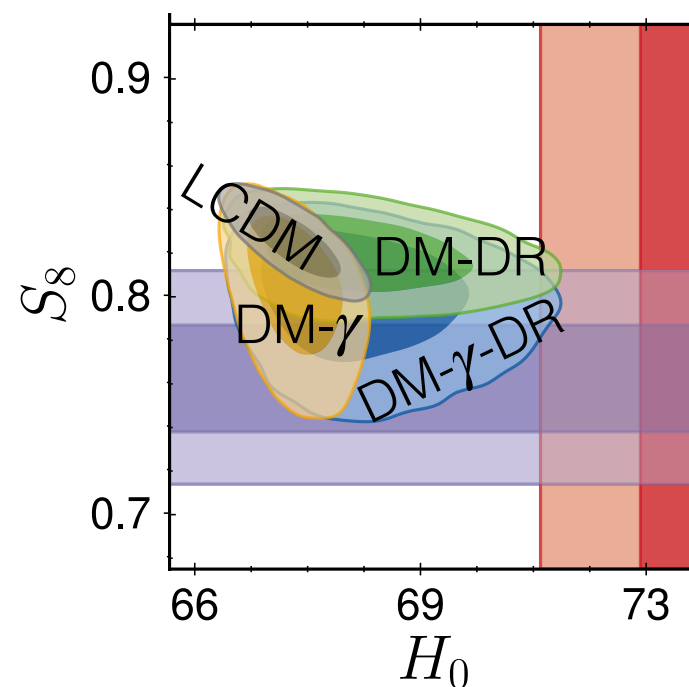
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Solving both tensions?

No known models convincingly solving both tensions!

- Most models ease one tension at expense of making other worse... few exceptions, e.g.:
- DM interacting with DR helps with both tensions (but not enough)
- DM interacting with DR *and* photons works better ([Becker et al. 2010.04074](#))
E.g. DM may interact with dark photon, mixed with visible photon...



- More studies required (e.g. Majoron + sizeable active neutrino mass)

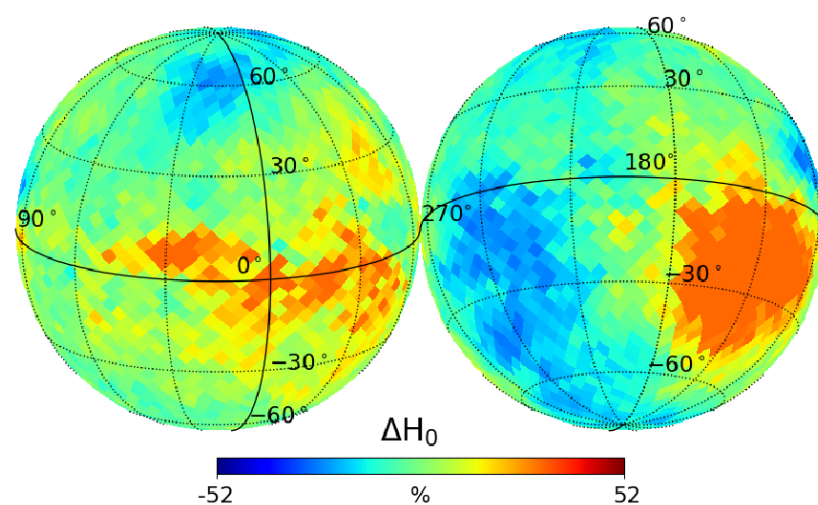
Conclusions

Hope that one or more tension **solved by systematics!**

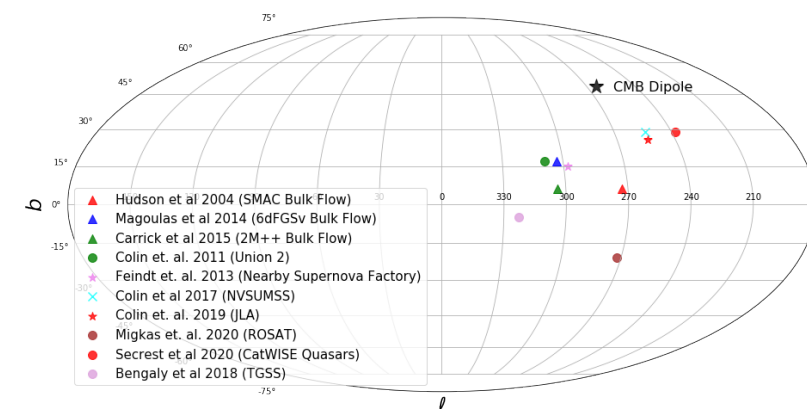
Reassuring that **we cannot fit anything?** ...

If tensions do not settle with systematics:

- Previous models: predictions for **next-generation CMB/LSS** (e.g. EDE, Majoron, shifted recombination...)
- Chance to learn about **new particle physics**, tests it in laboratory? (e.g. DM interactions, Majoron)
- Revisit models **beyond Friedmann?** Large-scale inhomogeneity?



Fosalba & Gaztanaga 2011.00910



Kinematic dipole / CMB dipole mismatch
Secrest et al. 2009.14826; 2105.09790, 2106.03119