Towards solutions to the Hubble problem beyond Einstein's Gravity

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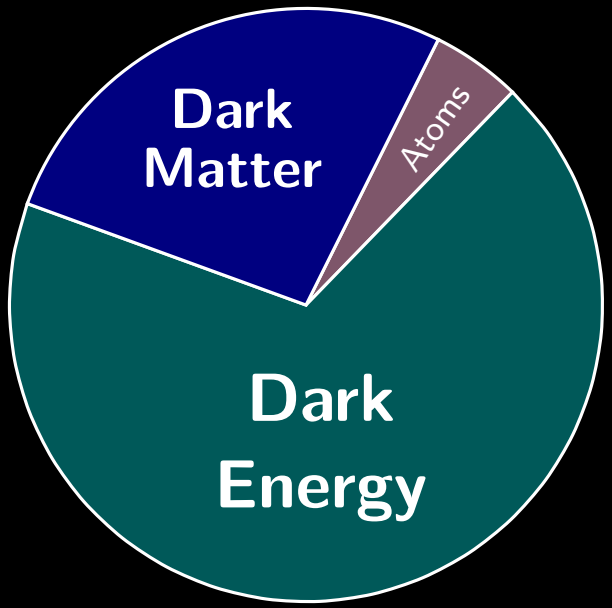
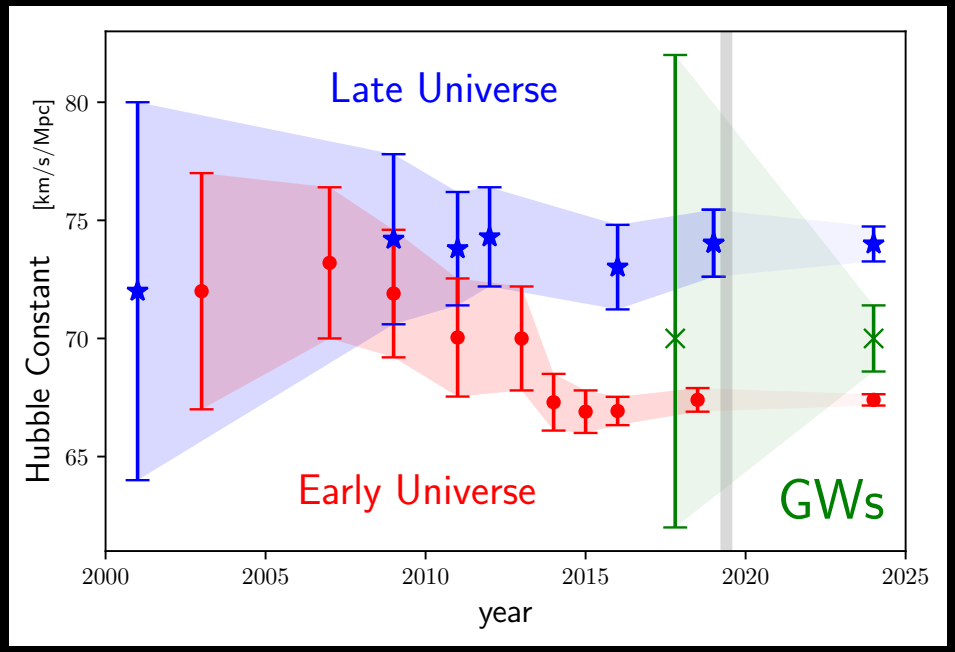
Hiring soon: `www.jobs.aei.mpg.de`

Cosmology & New physics



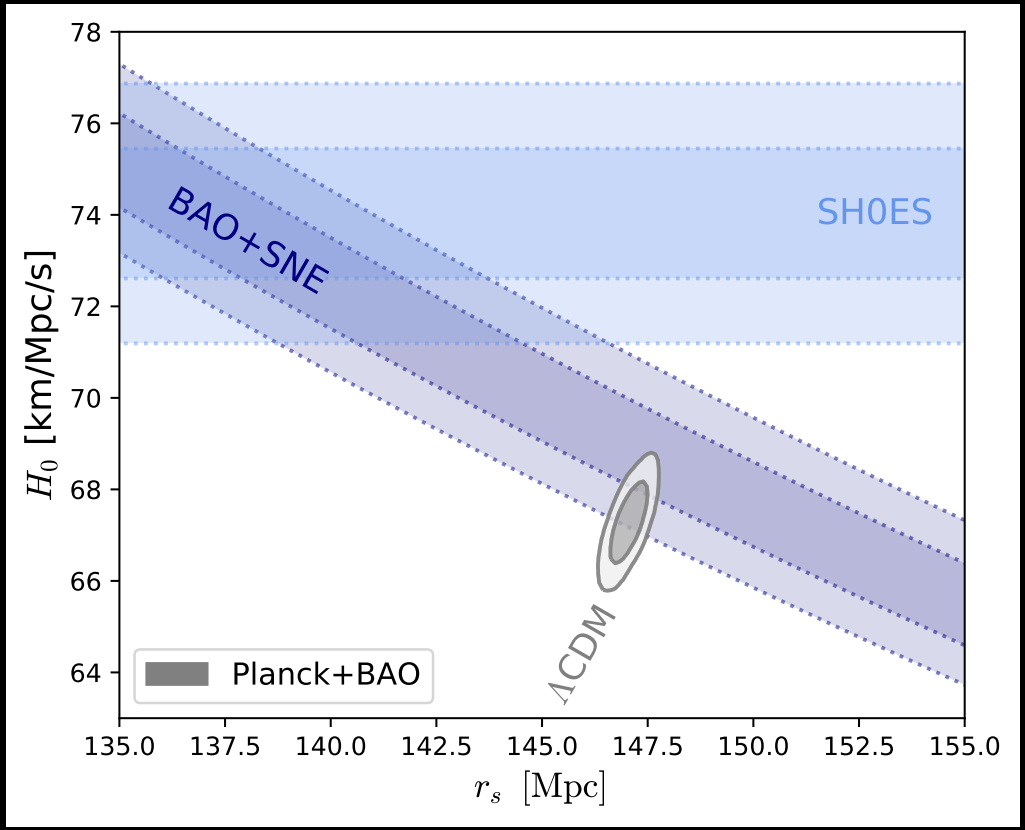


(Fredman '17, Ezquiaga & MZ '18)

- Succesful description of the Universe
- ΛCDM: 95% of our Universe unknown
- Datasets in tension: Hubble is high, lensing is low

Systematics or new new physics?

H_0 solutions early & late



(based on Knox & Millea '19)

$$\theta_* = \frac{r_s(z_*)}{D_M(z_*)}\,, \qquad r_s = \int dz \frac{c_s(z)}{H(z)}$$

Early H_0 solutions $\rightarrow$ Energy Injection at $z \sim z_{\rm eq}$

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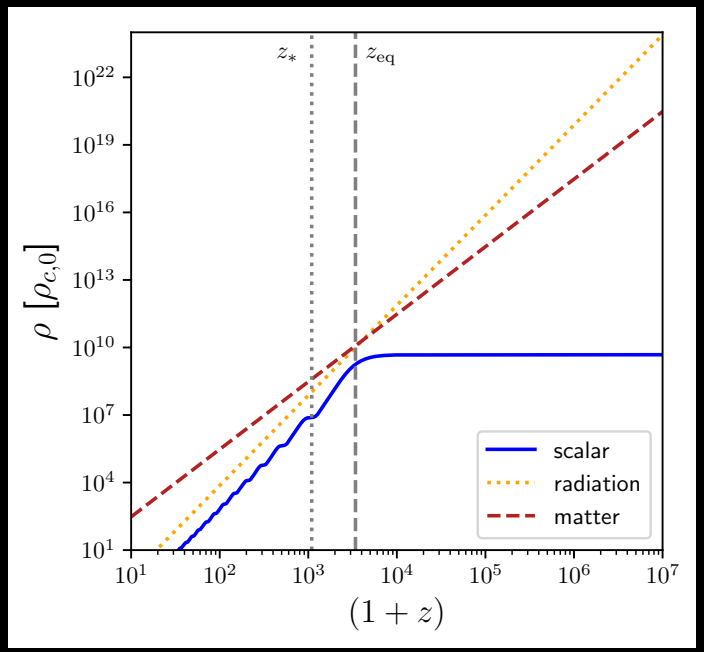
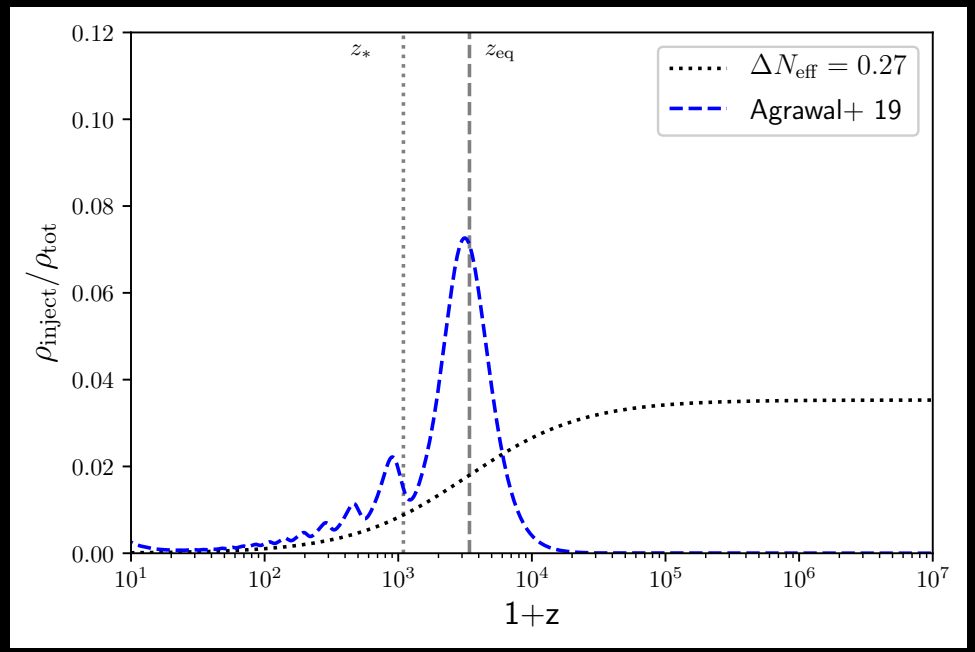




(Poulin+ 18, Agrawal+ '19, Smith+ '19)

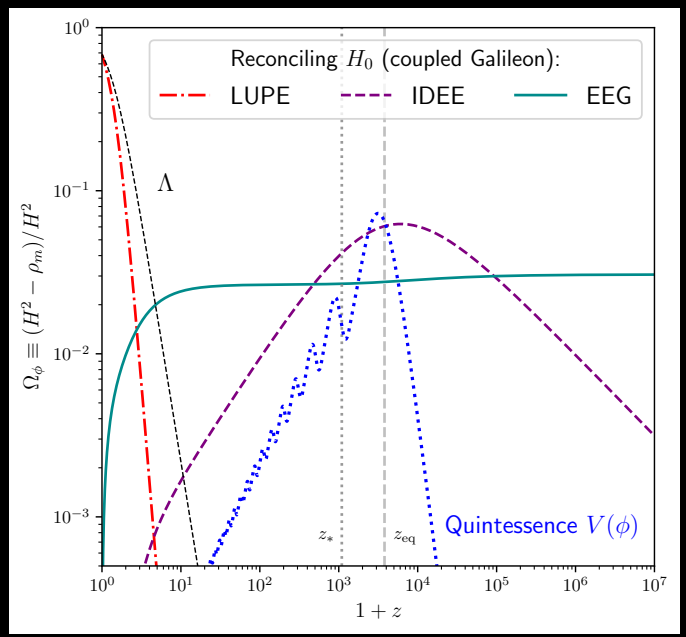
Early DE: $\mathcal{L} = \frac{1}{2}(\partial\phi)^2 - V(\phi)$ fine-tuned initial ϕ

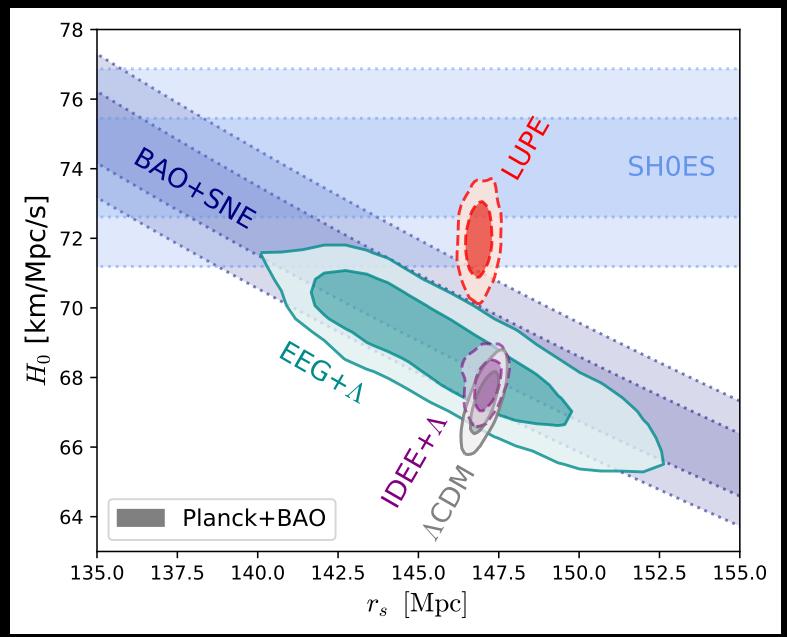
Mechanisms to reconcile H_0 beyond GR (MZ '20)

1) Late Universe Phantom Expansion (LUPE)

2) Imperfect Dark Energy at Equality (IDEE)

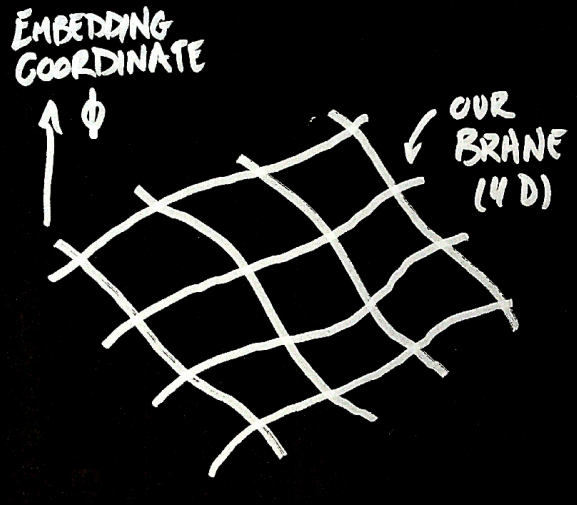
3) Enhanced Early Gravity (EEG)





Galileon gravity after GW170817 (Nicolis+ '08, Deffayet+ '09...)

- Small-scale limit of
  - Massive Gravity: $\phi \rightarrow$ helicity 0
  - DGP/extra dim: $\phi \leftrightarrow x^5$ coord.



- Recovers GR on small scales (Vainshtein Mechanism)

- Compatible with GW speed (e.g. Ezquiaga & MZ '17)

$$\mathcal{L} = \underbrace{C(\phi)}_{\text{coupling}} \frac{R}{2} + \frac{c_3}{H_0^2}(\partial\phi)^2\Box\phi + \frac{c_2}{2}(\partial\phi)^2$$

1 free function + 1 free parameter (rescaling ϕ) + 2$\times$ initial conditions

Coupled Galileons

$$\mathcal{L} = \underbrace{e^{\beta\phi}}_{M_*^2}\frac{R}{2} + \frac{c_3}{H_0^2}(\partial\phi)^2\Box\phi + \frac{c_2}{2}(\partial\phi)^2$$

$$H^2 = \frac{1}{M_*^2}\left(\rho_m + \hat{\rho}_\phi\right)$$

2 params & 2 initial conditions:

- $c_2 \to \hat{\Omega}_{\phi,0}$ (Gal. coupling)
- $\dot{\phi}_i \to \hat{\Omega}_{\phi,i}$ (kinetic energy)
- $\phi_i \to M^2_{*,i}$ (gravity strength)
- $\beta \to M^2_{*,0}$ (coupling strength)

($c_3 = -1$ via ϕ rescaling)

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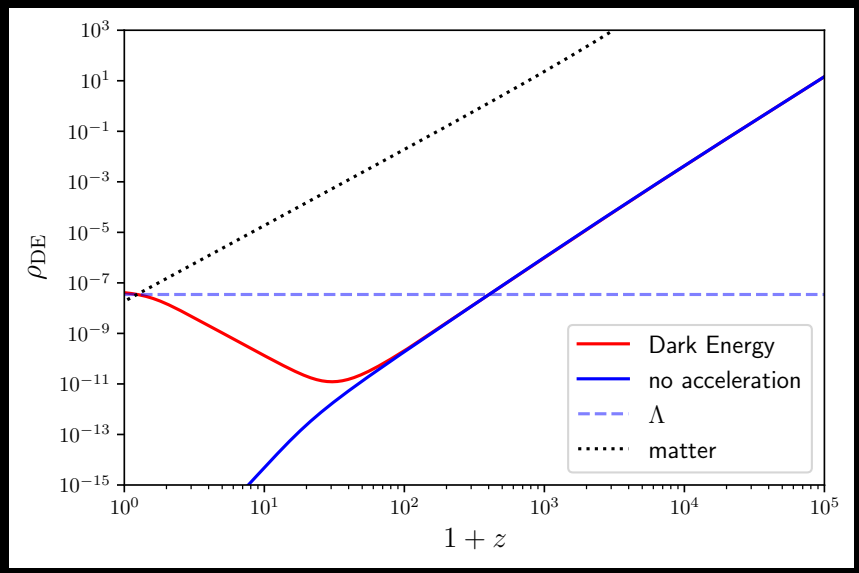

accelerating $c_2 < 0$ vs $c_2 < 0 + \Lambda$

1) Late-Universe Phantom Expansion (LUPE)

$$\mathcal{L} = \underbrace{e^{\beta\phi}}_{M_*^2}\frac{R}{2} + \frac{c_3}{H_0^2}(\partial\phi)^2\Box\phi + \frac{c_2}{2}(\partial\phi)^2$$

$$H^2 = \frac{1}{M_*^2}\left(\rho_m + \hat{\rho}_\phi\right)$$

$$\hat{\Omega}_{\phi,0} = \frac{c_2^3}{216}\,, \quad c_2 < 0$$

- $c_2 \to \hat{\Omega}_{\phi,0}$ (Gal. coupling)
- $\dot{\phi}_i \to \hat{\Omega}_{\phi,i}$ (kinetic energy)
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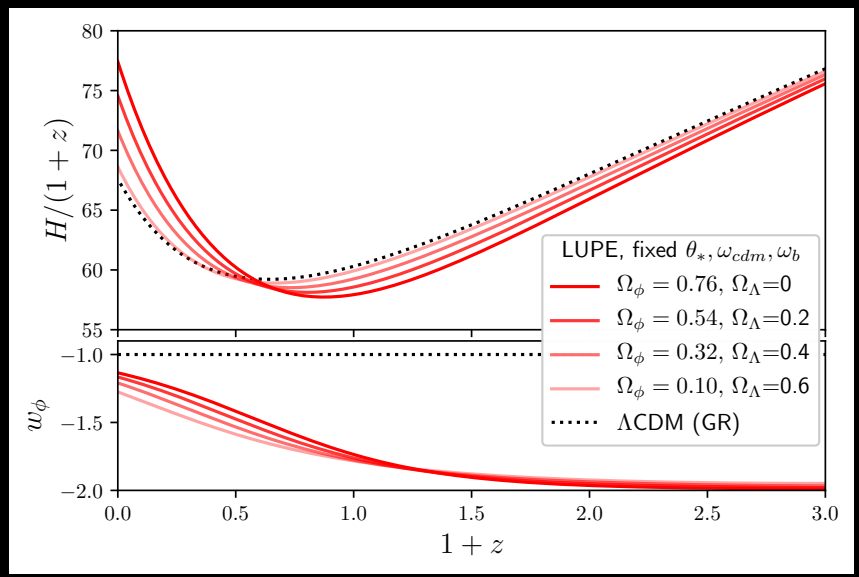
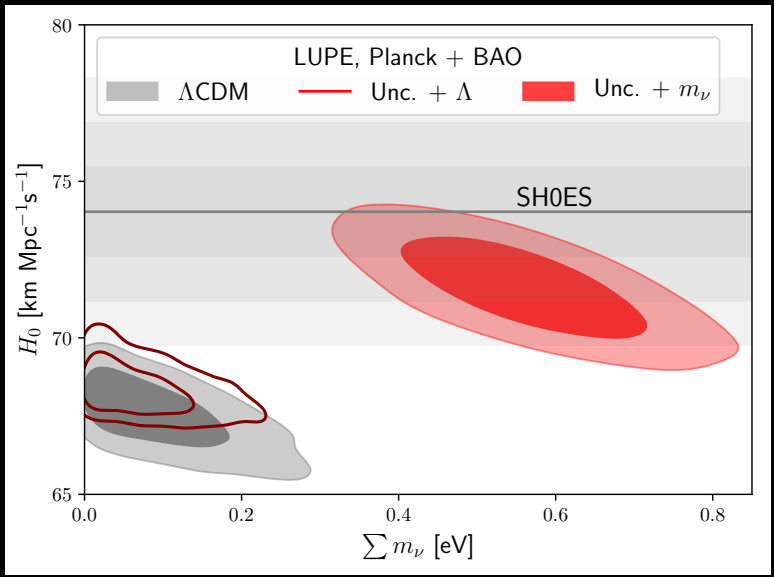
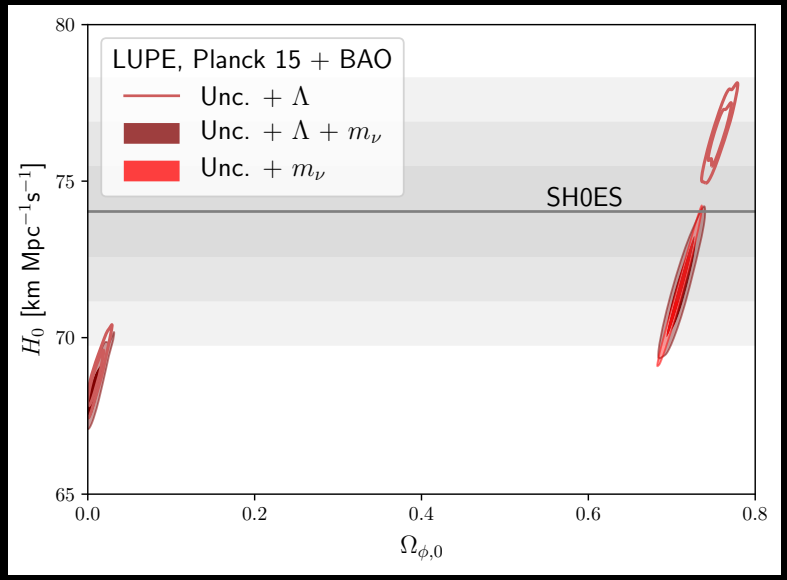


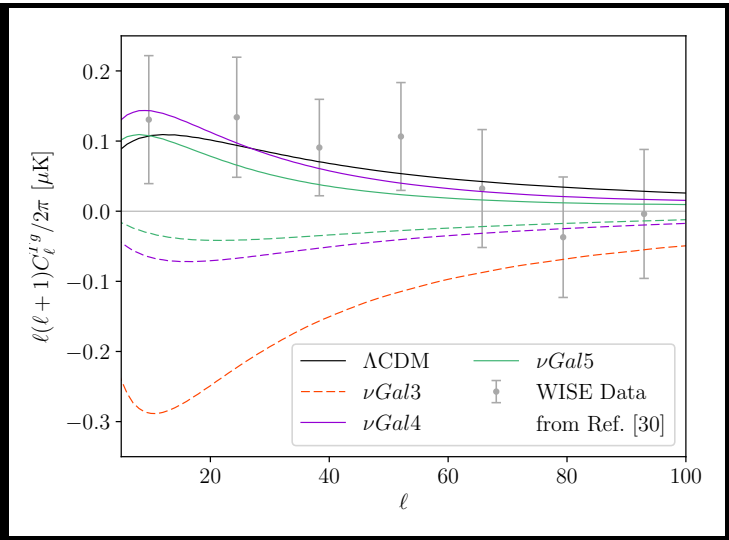
same r_s, change low z

LUPE constraints (MZ '20, Renk+ '17)

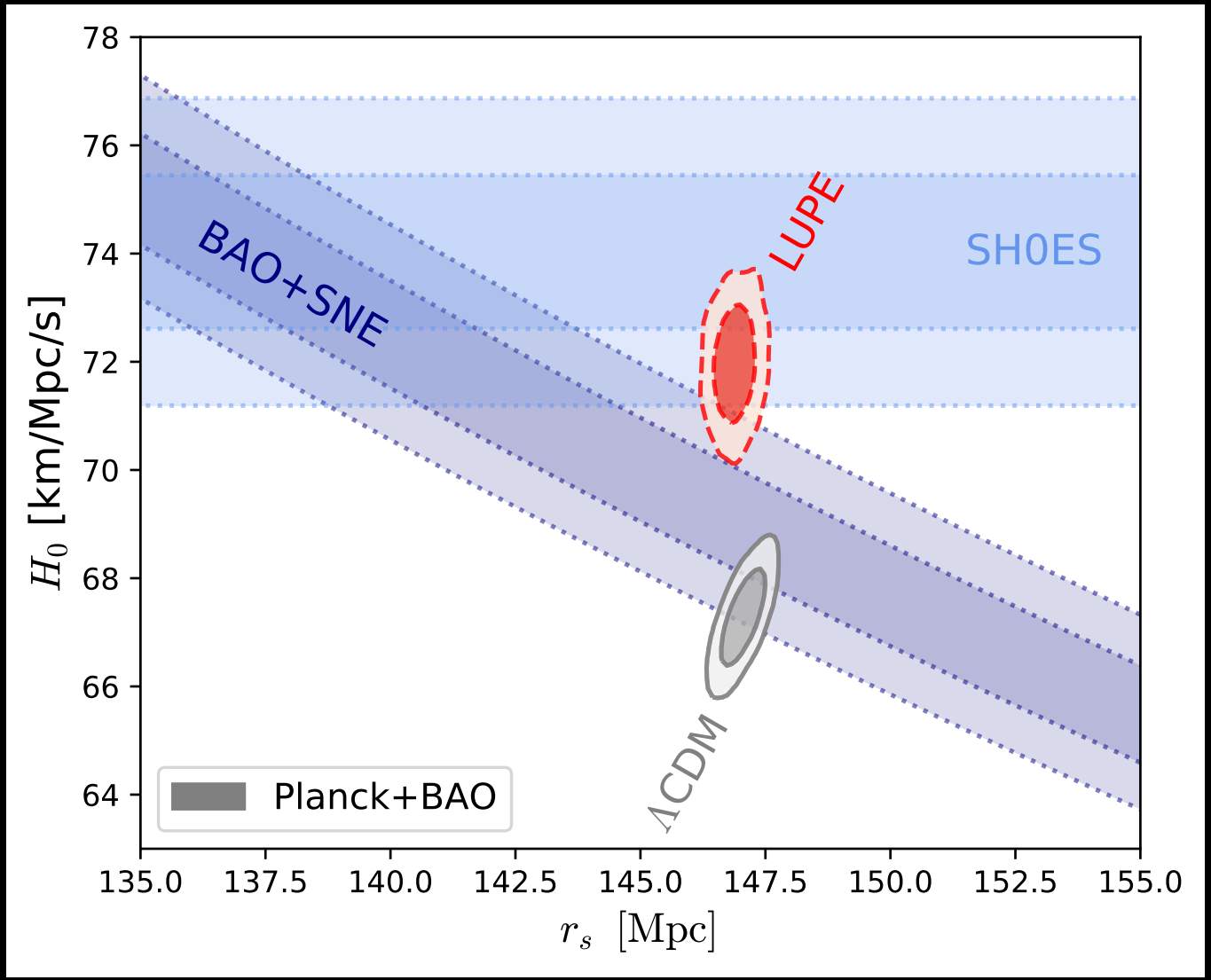




- Viable with $\sum m_\nu \sim 0.6$ eV
- One of $\Omega_{\phi,0}$, $\Omega_{\Lambda,0}$ dominates
- Ruled out by CMB×LSS (Renk+ '17)



Galileons in perspective



(MZ '20, based on Knox & Millea '19)

2) Imperfect Dark energy at Equality (IDEE)

$$\mathcal{L} = \underbrace{e^{\beta\phi}}_{M_*^2}\frac{R}{2} + \frac{c_3}{H_0^2}(\partial\phi)^2\Box\phi + \frac{c_2}{2}(\partial\phi)^2$$

$$H^2 = \frac{1}{M_*^2}\left(\rho_m + \hat{\rho}_\phi\right)$$

$$0 < w_\phi < \frac{1}{3}$$

- $c_2 \to \hat{\Omega}_{\phi,0}$ (Gal. coupling)
- $\dot{\phi}_i \to \hat{\Omega}_{\phi,i}$ (kinetic energy)
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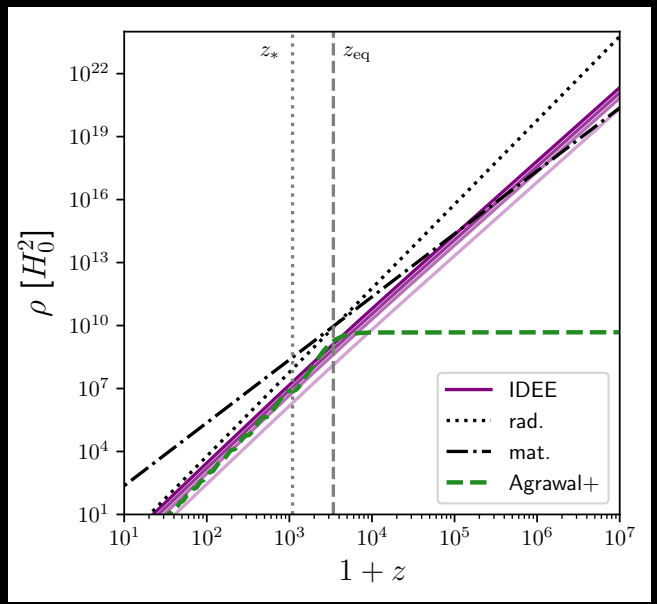
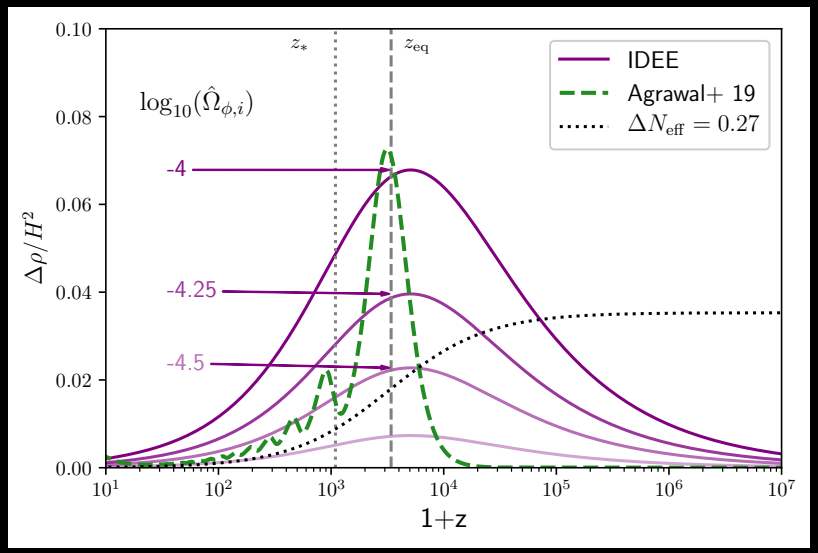
($c_3 = -1$ via ϕ rescaling)

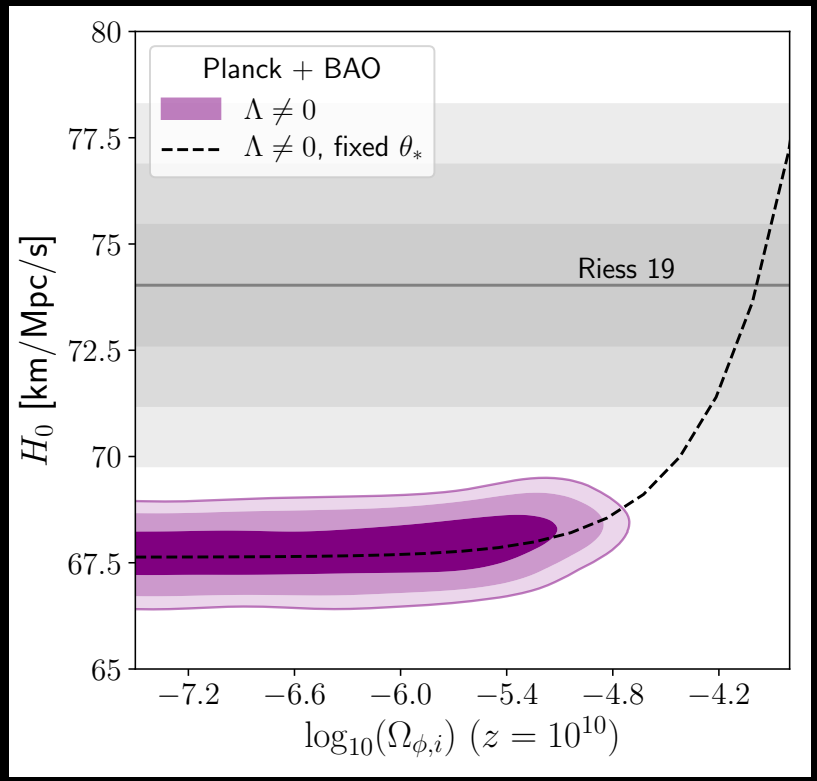


same low z, increase r_s

IDEE Constraints

(MZ '20)





- fix $H_0 \Leftrightarrow \hat{\Omega}_{\phi,i} \sim 10^{-4}$
- CMB+BAO: $\hat{\Omega}_{\phi,i} \lesssim 10^{-5}$
- Early MG $\alpha_B = \hat{\Omega}_\phi$

IDEE Constraints

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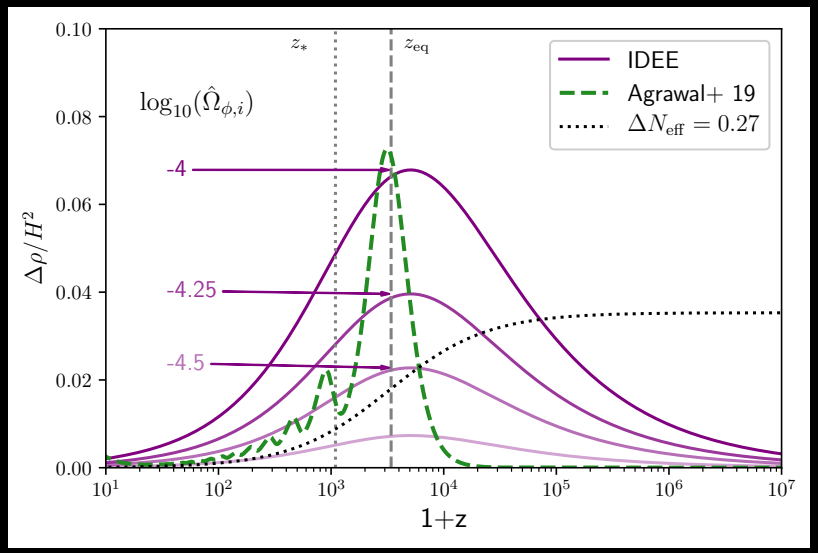

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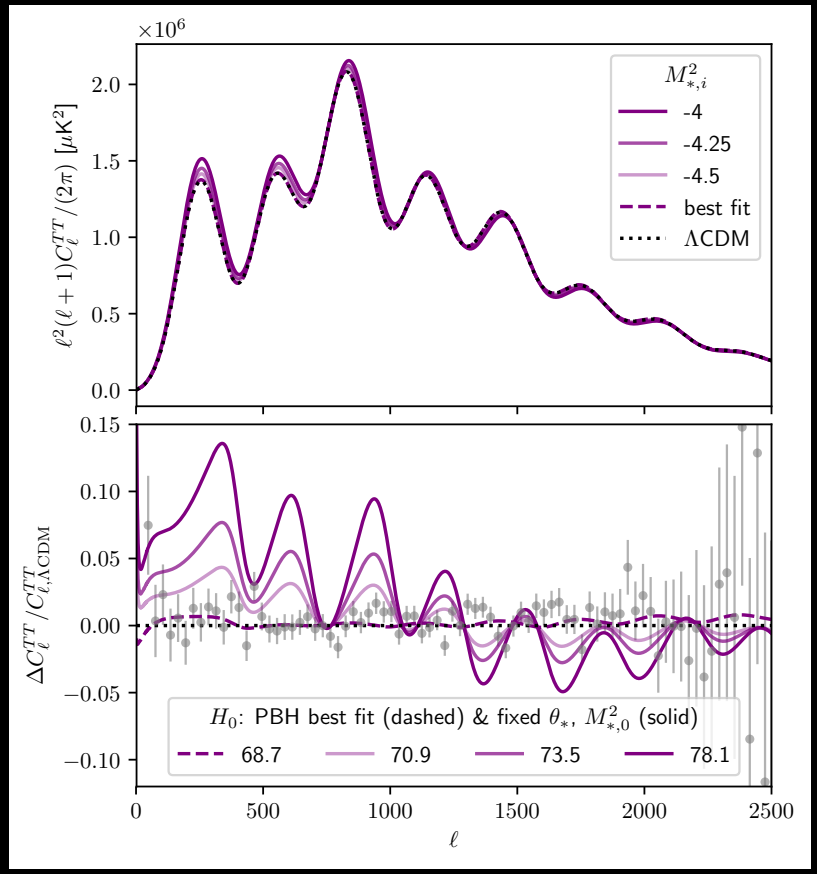

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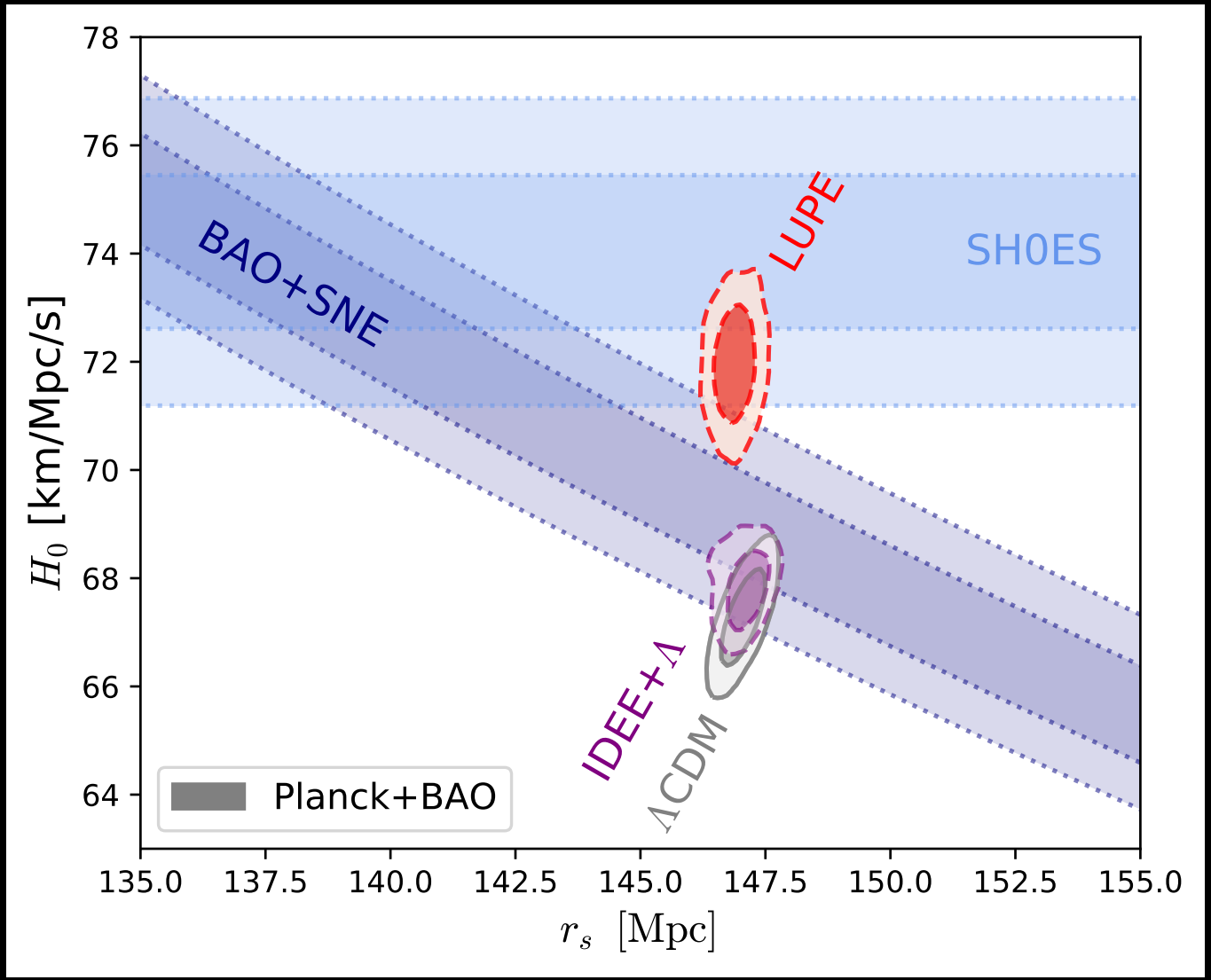

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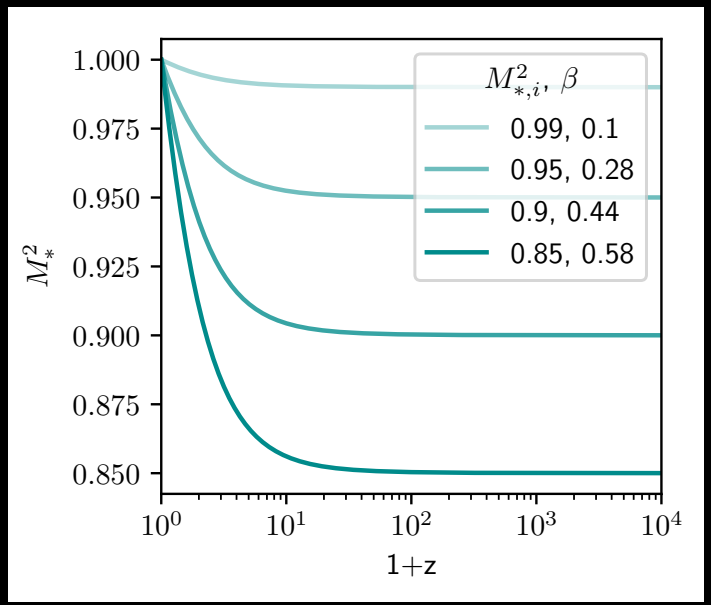
$$M^2_{*,i} < 1 \leq M^2_{*,0}$$



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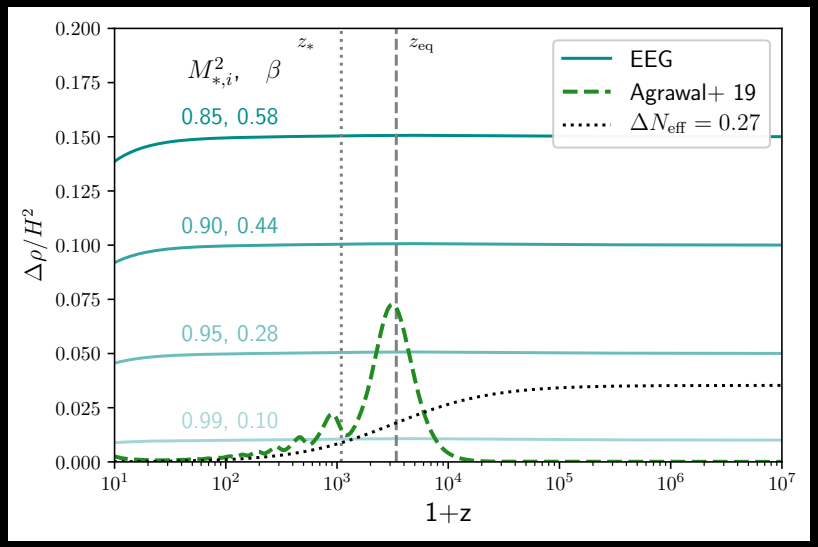
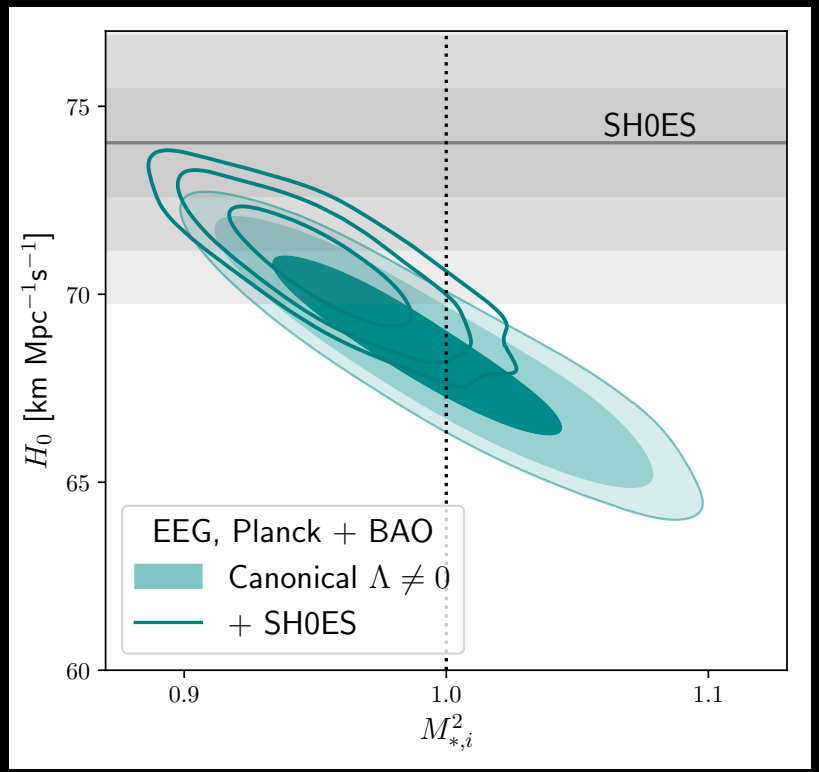
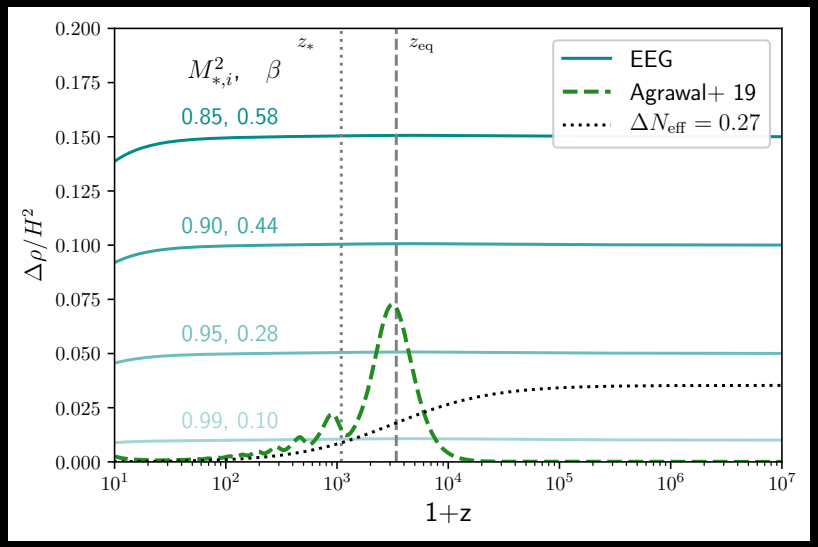
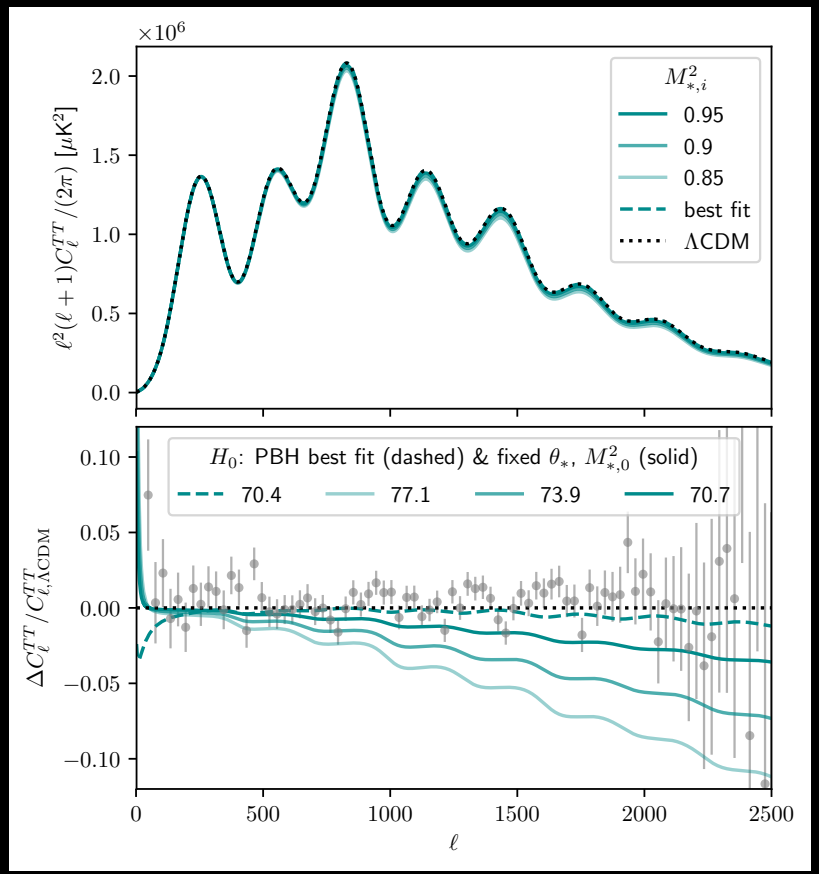




- Solve $H_0 \Leftrightarrow M^2_{*,i} \sim 0.95$
- CMB+BAO:
$$M^2_{*,i} = 0.988 \pm 0.035$$
- Degeneracy with $\omega_b, n_s, \cdots$

EEG Constraints (MZ '20)





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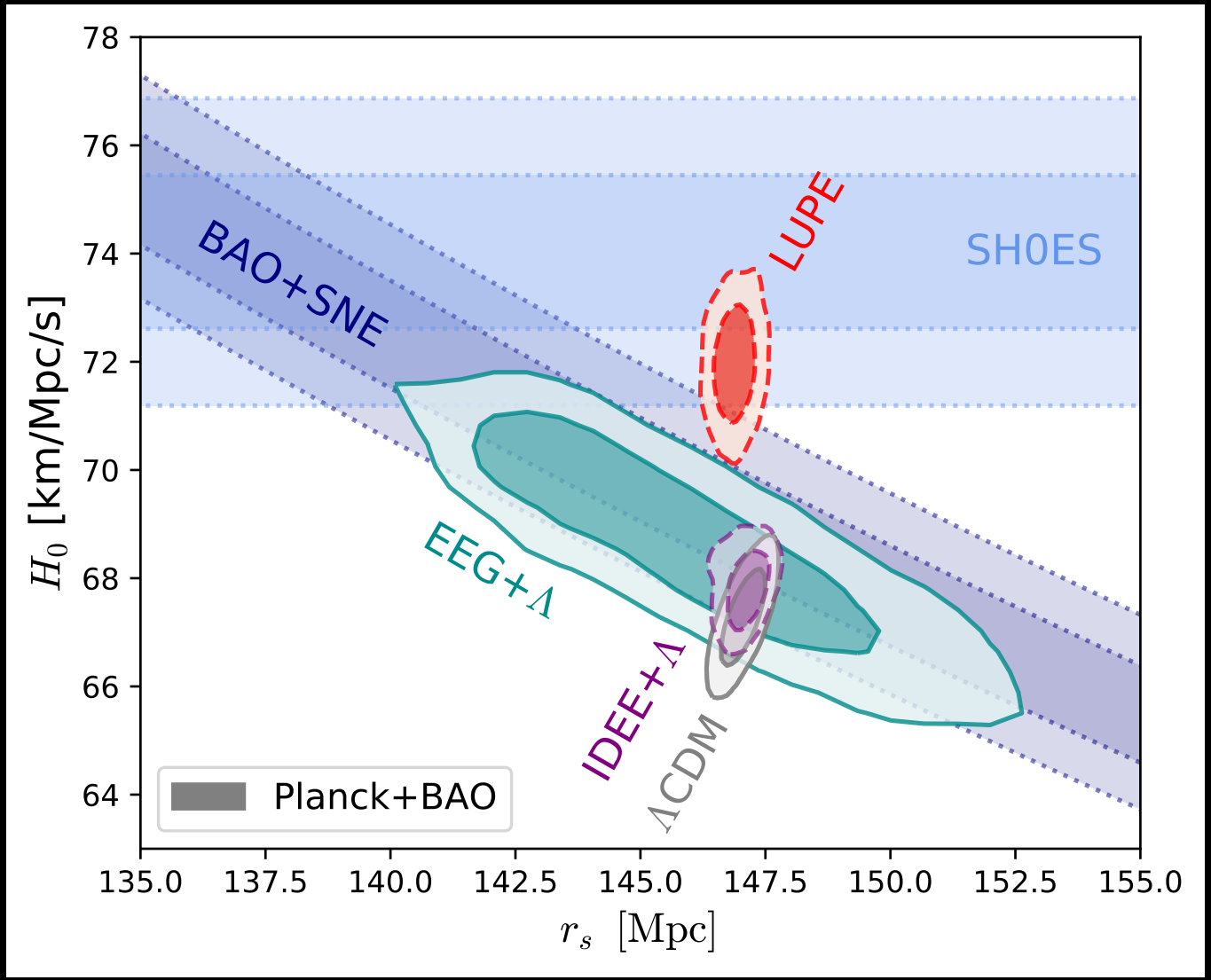
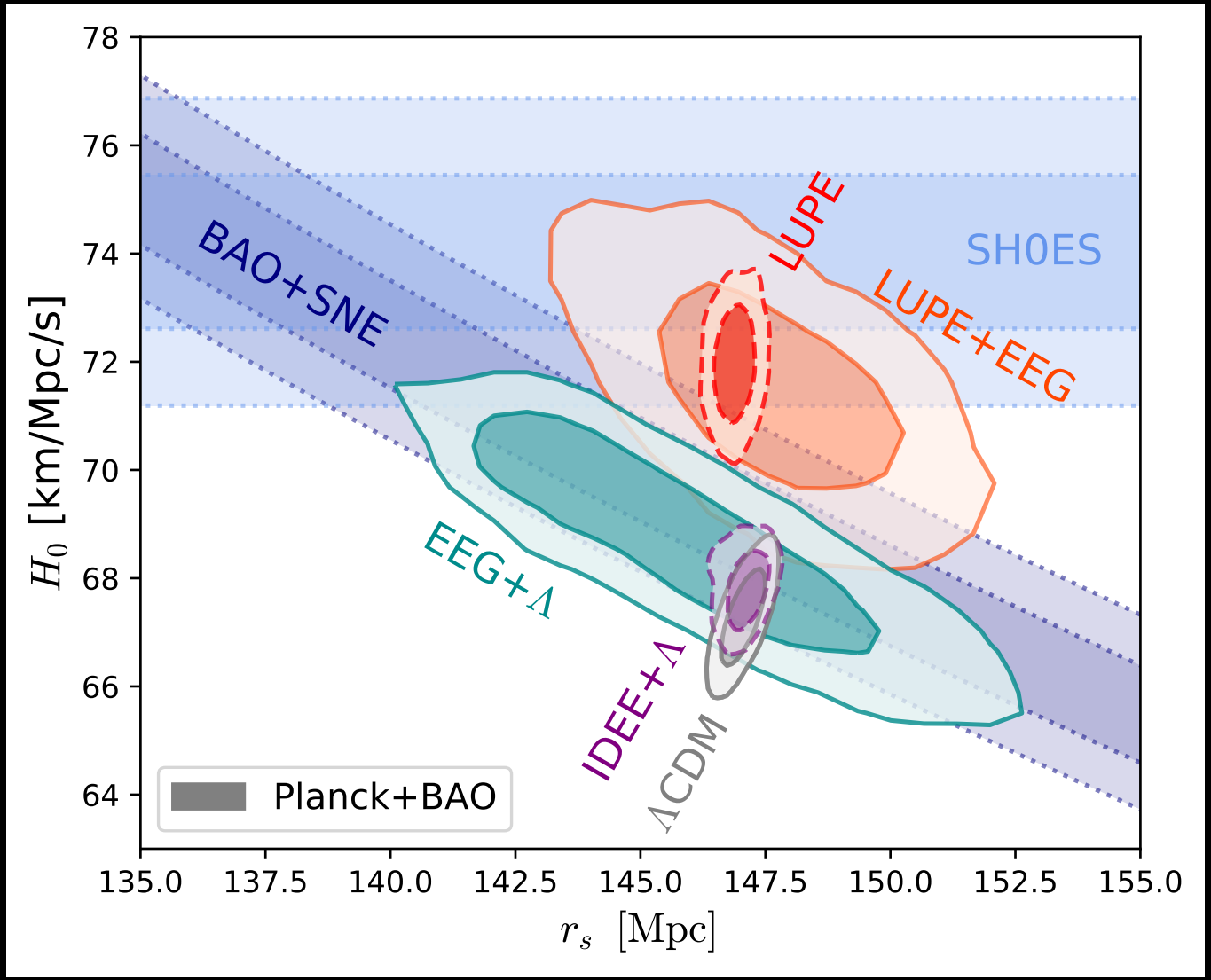


(MZ '20, based on Knox & Millea '19)

Combining multiple solutions



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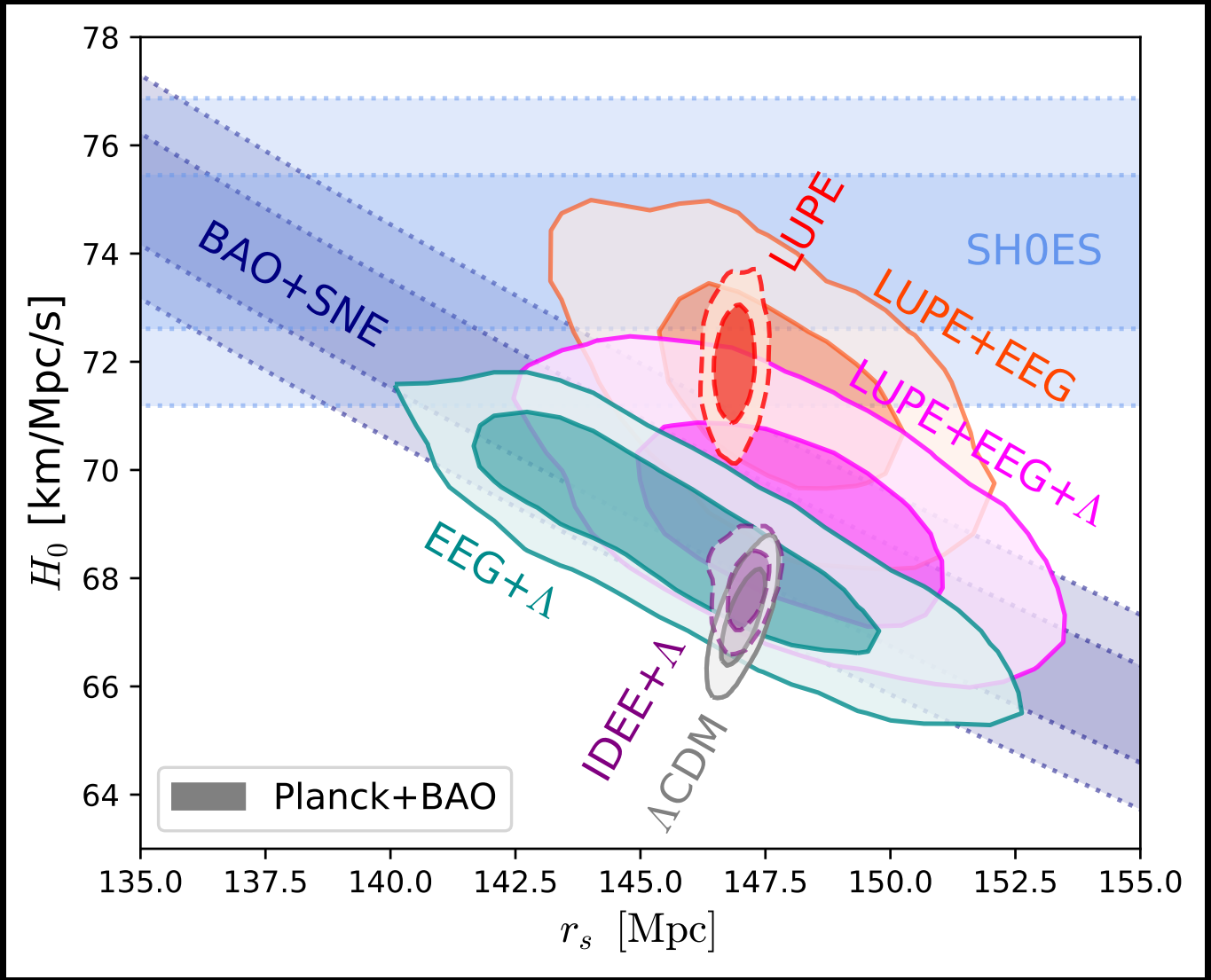

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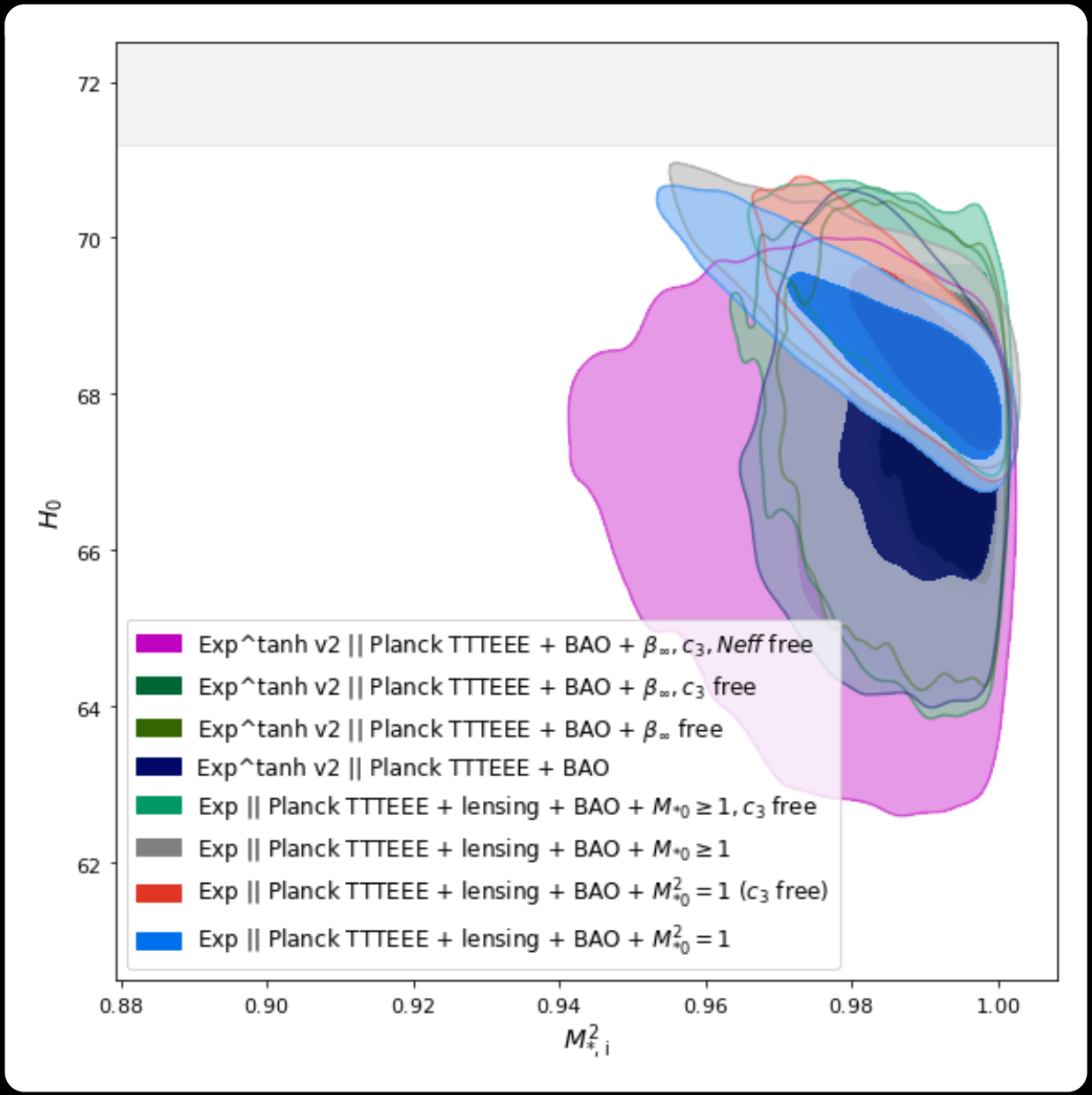
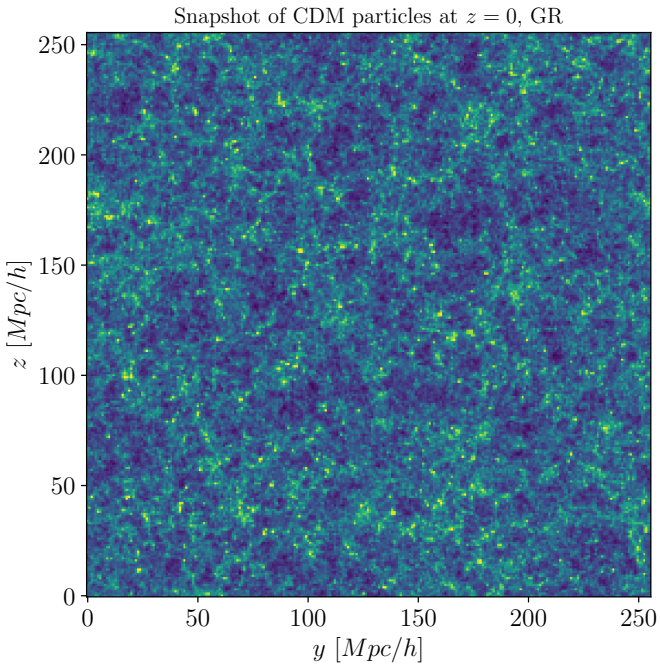
Refining the model

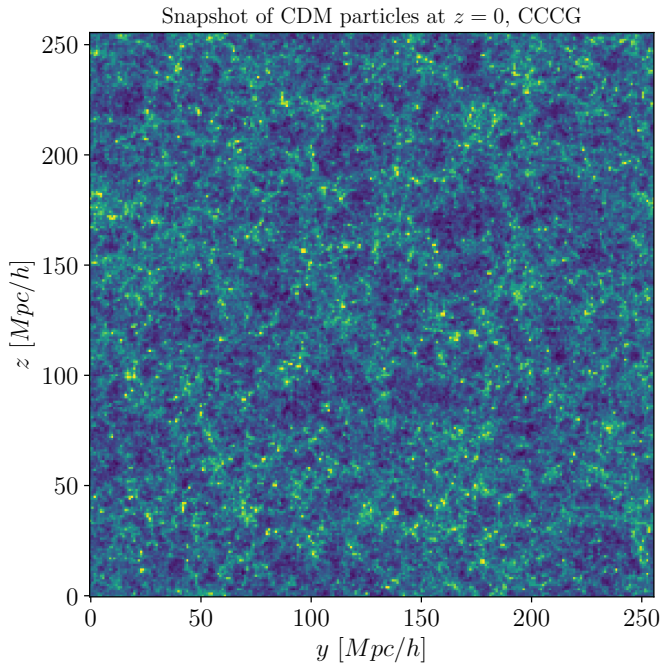
(credit C. Garcia-Garcia)

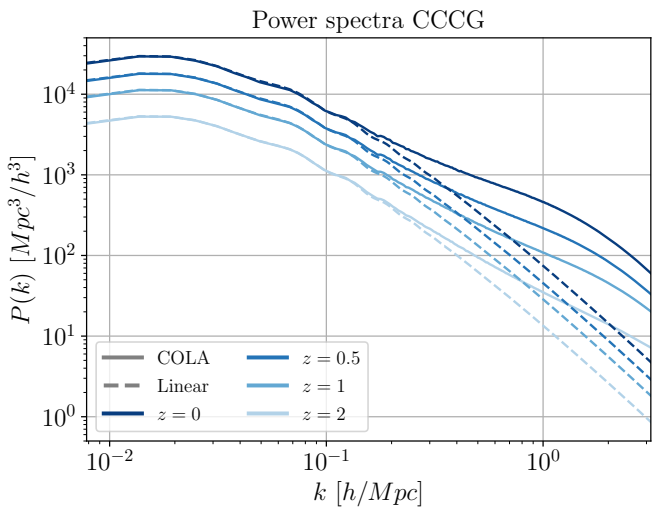


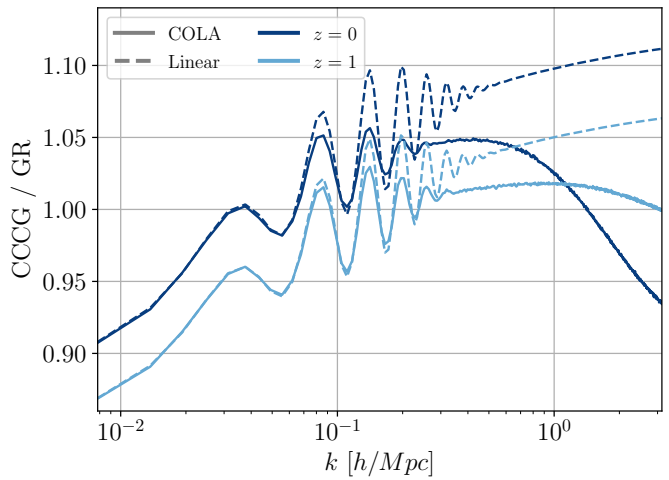
EEG Simulations

(credit G. Brando)









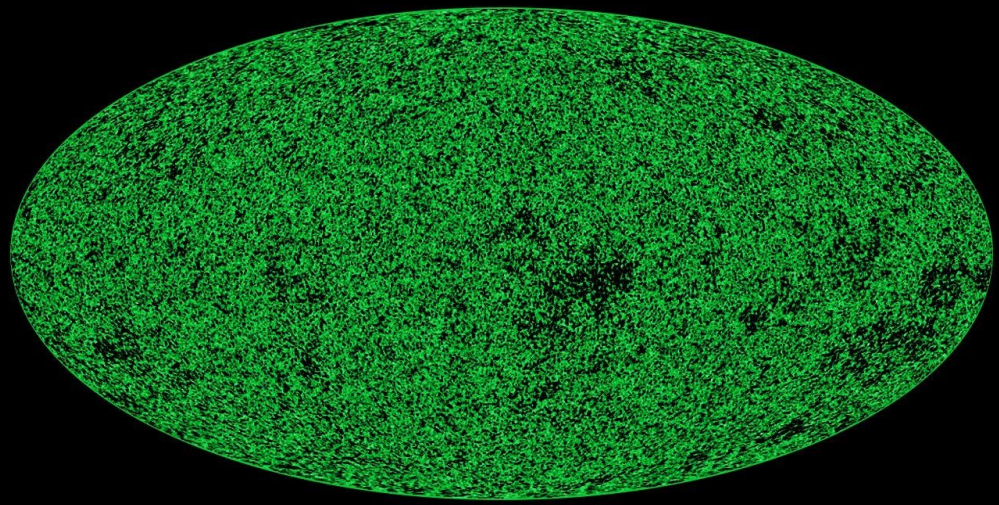
Conclusions

- H_0 tension: systematics or new physics?
- Minimal Galileon solutions *(constrained by)*
  - Late Universe Phantom Expansion *(ISW, SNe)*
  - Imperfect DE at Equality *(Planck)*
  - Enhanced Early Gravity *($\dot{G}/G$)*
- Moderate H_0 tension improvement: $4.4\sigma \rightarrow 2.6\sigma$

  Further model building needed
- Probes weak in ΛCDM critical beyond GR (c_g, ISW, $\dot{G}/G$)
- Testing gravity is easier than ever! www.hiclass-code.net

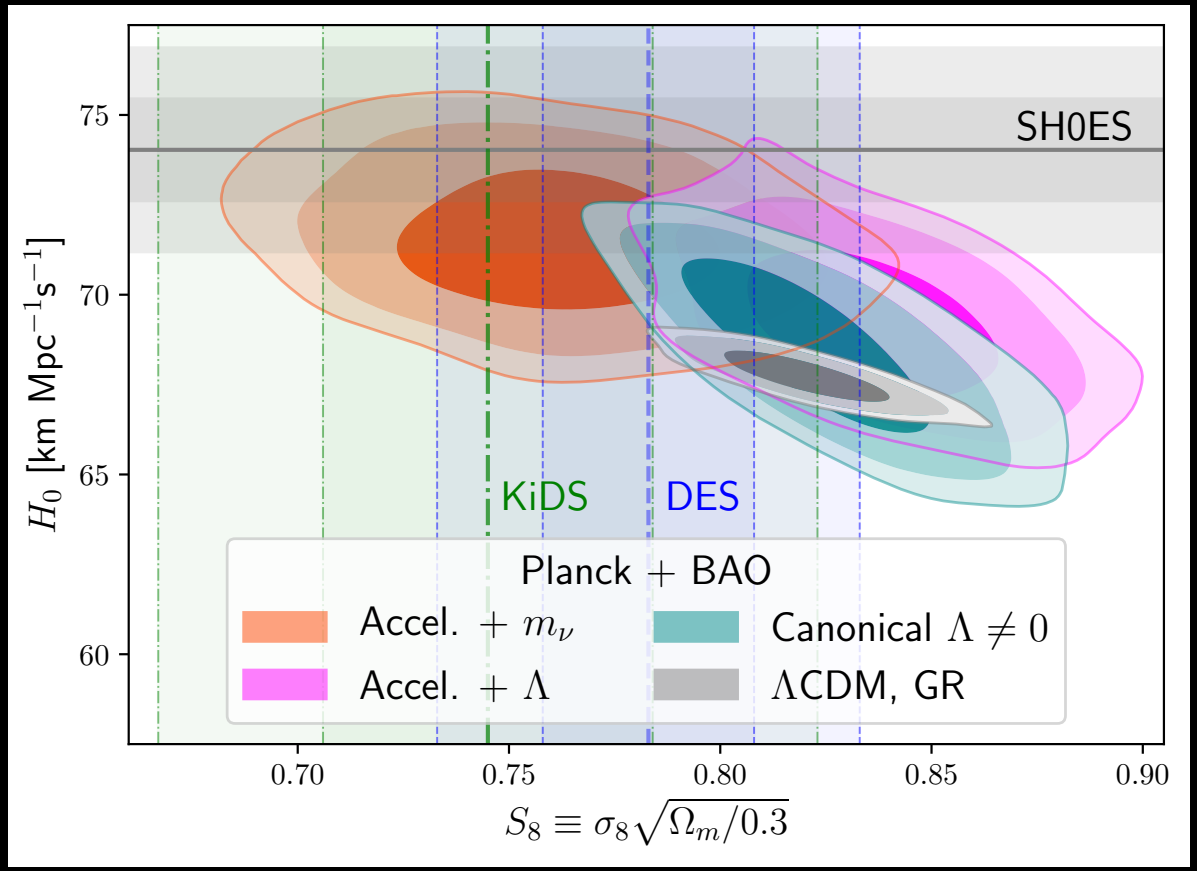
Thanks!

Backup Slides



PLANCK

Weak Lensing tension



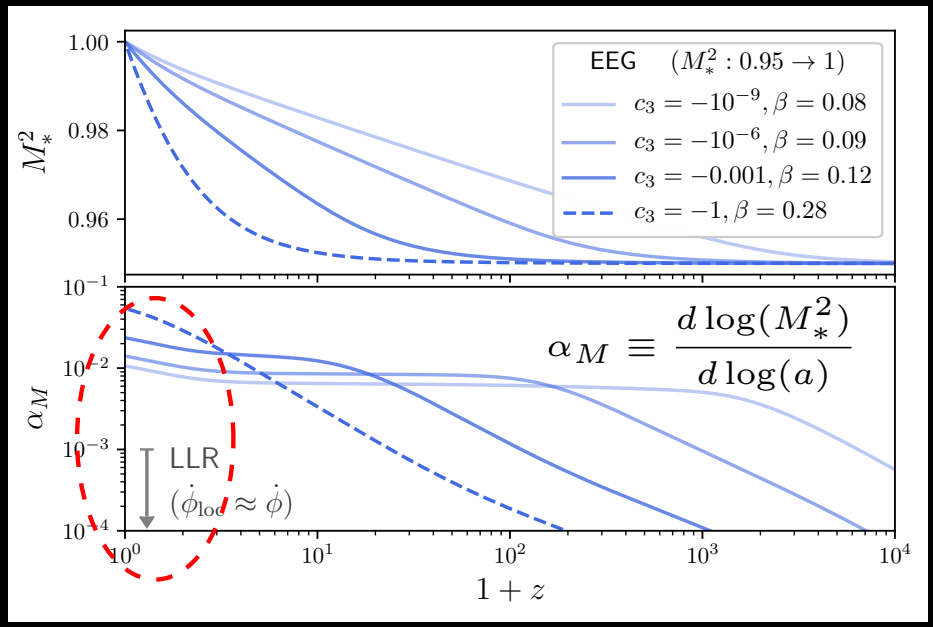
- Low S_8 in galaxy lensing surveys for ΛCDM
- EEG: H_0, S_8 anti-correlated ✓

EEG & Local gravity

Tests:

- Scalar forces
- Local strenght of gravity
- G_N time variation

e.g. Lunar Laser Ranging



Local vs Global evolution

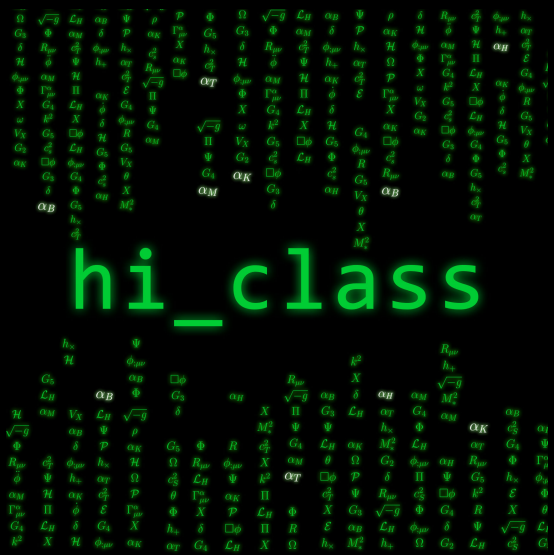
$$\phi_{\rm loc}(\vec{x},t) \begin{cases} \approx \dot{\phi}(t) & \text{(ruled out}^* \text{ for } C = e^{\beta\phi}) \\ \ll \dot{\phi}(t) & \text{(screening, viable?)} \end{cases}$$

* see Burrage & Dombrowski '20

Horndeski in the Cosmic Linear Anisotropy Solving System

Goals: $\begin{cases} \star \text{ DE/MG predictions in as much detail as } \Lambda\text{CDM} \\ \star \text{ public tool, valid for a large class of theories} \end{cases}$

New version!



www.hiclass-code.net

(MZ+ '16, Bellini+ '19)

1. Flexibility: Many available theories
   - $\star$ Easy to add/modify!
   - $\rightarrow$ Models defined by Lagrangian
2. Accuracy: precision cosmology
   - $\star$ Tested to $\mathcal{O}(0.1\%)$ (Bellini+ '17)
     against EFTCAMB $+\cdots$
   - $\rightarrow$ MG initial conditions + isocurvature
3. Speed: sample parameter space
   - $\rightarrow$ Flexible approximation scheme

hi_class in practice

$$\left.\begin{array}{c} G_2,\, G_3,\, G_4,\, G_5 \\ \phi(t_0),\, \dot{\phi}(t_0) \end{array}\right\} \longrightarrow \left\{\begin{array}{c} \text{Kineticity } \alpha_K \\ \text{Braiding } \alpha_B \\ M_p \text{ running } \alpha_M \\ \text{Tensor speed } \alpha_T \end{array}\right\} \longrightarrow \left\{\begin{array}{c} D_A(z) \\ C_\ell \\ P(k) \\ \dots \end{array}\right.$$

a) Full theory + IC $\rightarrow$ Now Available!

b) *or* Parameterize $w(z), \alpha_i(z)$

Full theory has more info

- **Background $\rightarrow$ address H_0 problem!**
- Non-linear effects
- Other regimes: GWs, strong gravity, Solar System...