

Towards solutions to the Hubble problem beyond Einstein's Gravity

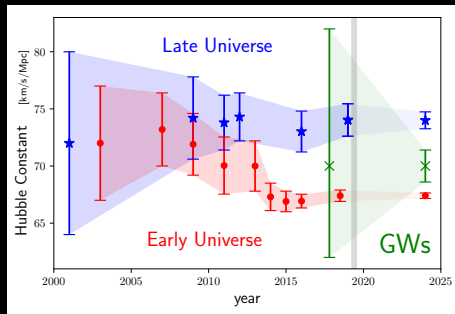
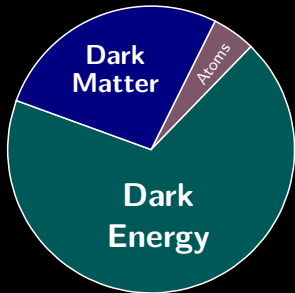
Miguel Zumalacárregui



Max Planck Institute for Gravitational Physics
(Albert Einstein Institute)
Berkeley Center for Cosmological Physics

August, 2020

Cosmology & New physics

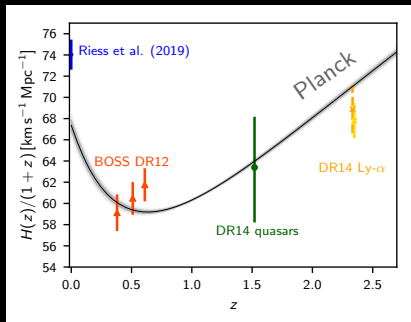
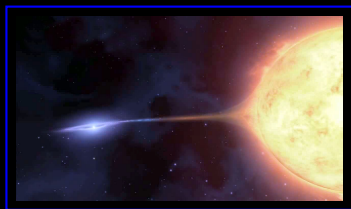


(Fredman '17, Ezquiaga & MZ '18)

- Successful description of the Universe
- Λ CDM: 95% of our Universe unknown
- Datasets in tension: Hubble is high, lensing is low

Systematics or new new physics?

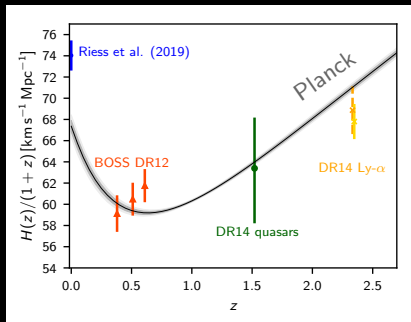
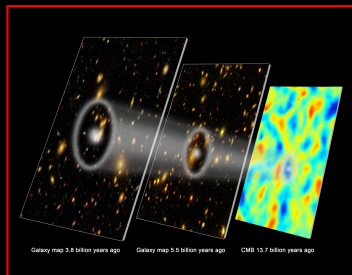
H_0 measurements: Early vs Late-universe



(Planck '18)

$$F = \frac{L}{(1+z)^2 D_M^2}, \quad D_M = \int_0^z \frac{dz'}{H(z')}$$

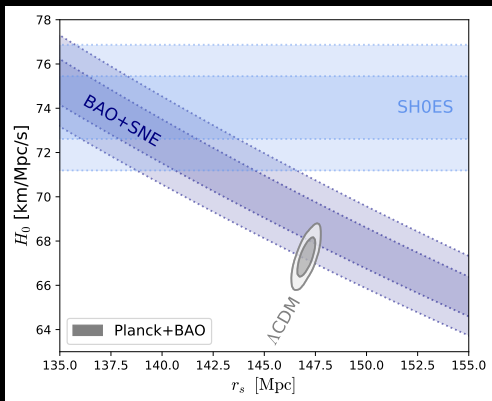
H_0 measurements: Early vs Late-universe



(Planck '18)

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

H_0 solutions early & late

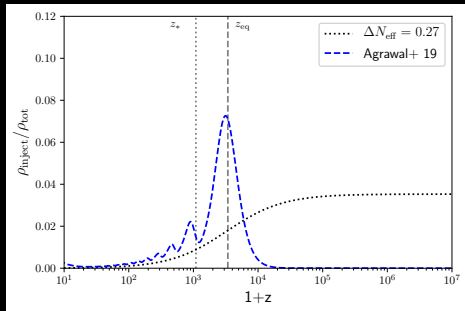
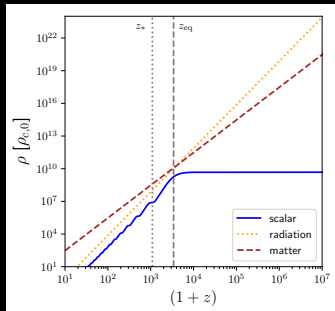


(based on Knox & Millea '19)

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

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

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



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

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

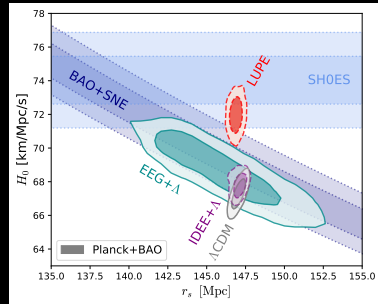
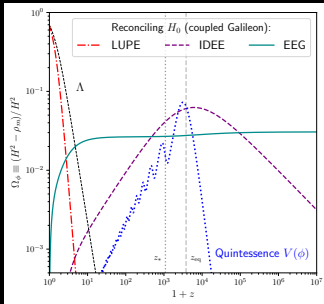
Mechanisms to reconcile H_0 beyond GR

(MZ '20)

1) Late Universe Phantom Expansion (LUPE) 🔍

2) Imperfect Dark Energy at Equality (IDEE) 💡

3) Enhanced Early Gravity (EEG) 🧠



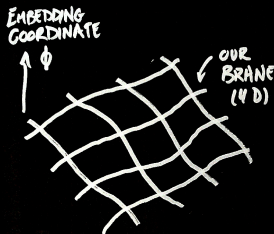
- Small-scale limit of
 - Massive Gravity: $\phi \rightarrow$ helicity 0
 - DGP/extra dim: $\phi \leftrightarrow x^5$ coord.

- Recovers GR on small scales
(Vainshtein Mechanism)

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

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

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



Coupled Galileons

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

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

2 params & 2 initial conditions:

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

($c_3 = -1$ via ϕ rescaling)

Coupled Galileons

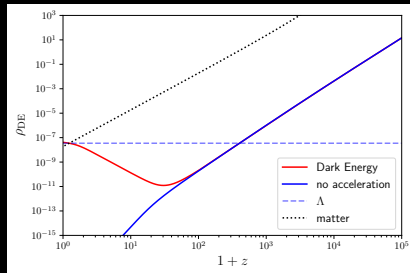
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accelerating $c_2 < 0$ vs $c_2 < 0 + \Lambda$

1) Late-Universe Phantom Expansion (LUPE)

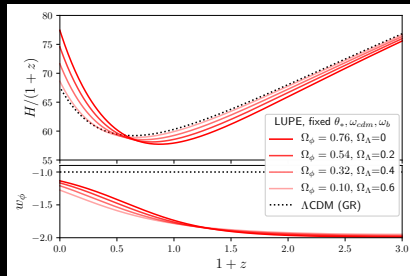
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$$H^2 = \frac{1}{M_*^2} (\rho_m + \hat{\rho}_\phi)$$

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

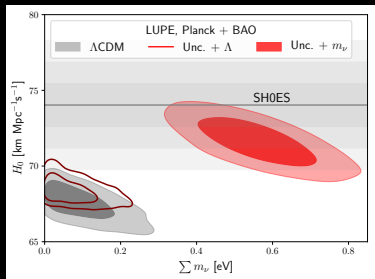
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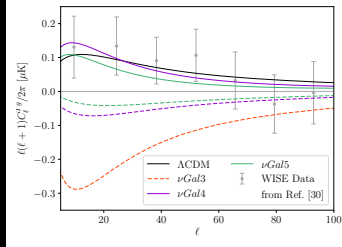
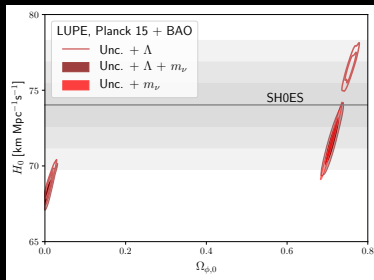


same r_s , change low z

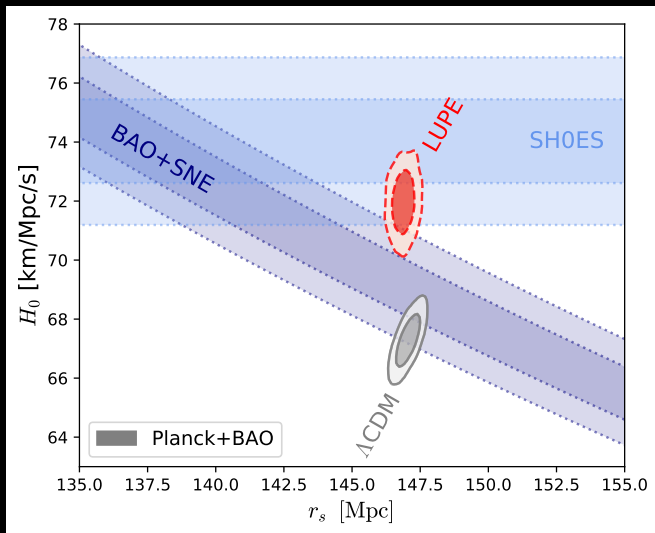
LUPE constraints (MZ '20, Renk+ '17)



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



Galileons in perspective



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

2) Imperfect Dark energy at Equality (IDEE)

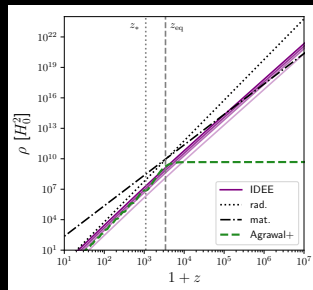
$$\mathcal{L} = \underbrace{e^{\beta\phi}}_{M_*^2} \frac{R}{2} + \frac{c_3}{H_0^2} (\partial\phi)^2 \square\phi + \frac{c_2}{2} (\partial\phi)^2$$

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

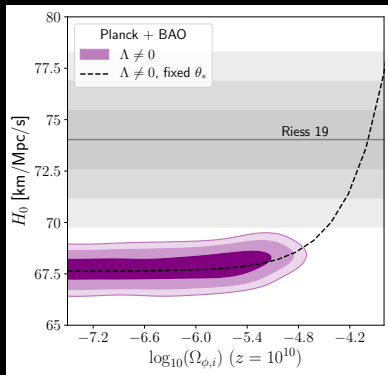
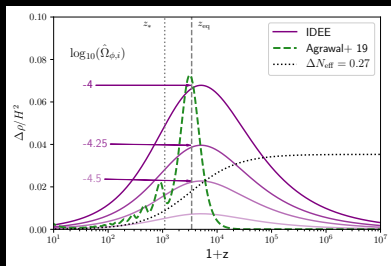
$$0 < w_\phi < \frac{1}{3}$$

- $c_2 \rightarrow \hat{\Omega}_{\phi,0}$ (Gal. coupling)
- $\dot{\phi}_i \rightarrow \hat{\Omega}_{\phi,i}$ (kinetic energy)
- $\phi_i \rightarrow M_{*,i}^2$ (gravity strength)
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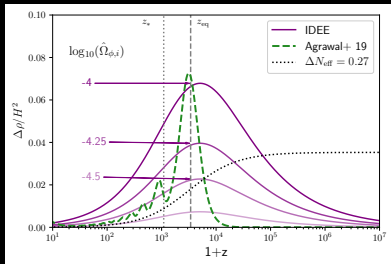
same low z , increase r_s



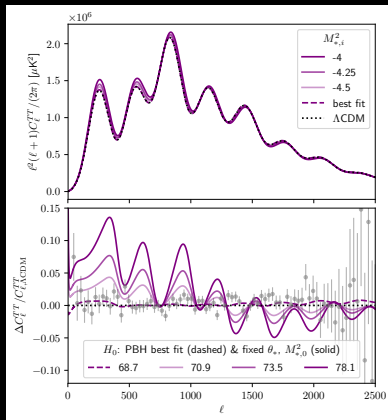
- fix $H_0 \Leftrightarrow \hat{\Omega}_{\phi,i} \sim 10^{-4}$
- CMB+BAO: $\hat{\Omega}_{\phi,i} \lesssim 10^{-5}$
- Early MG $\alpha_B = \hat{\Omega}_{\phi}$

IDEA Constraints

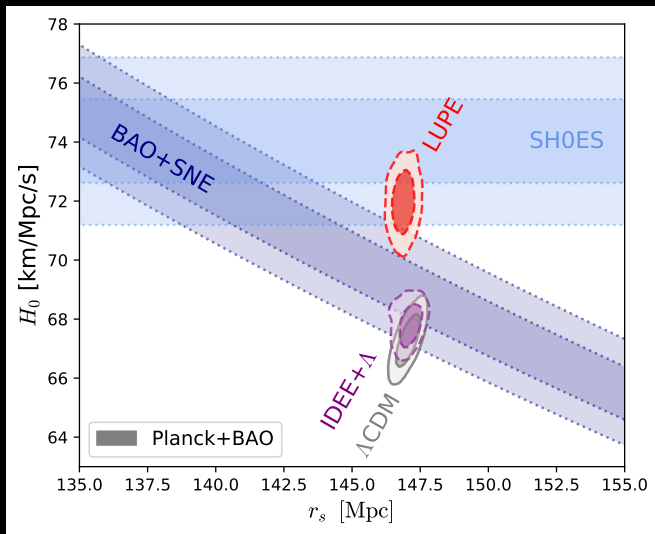
(MZ '20)



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Galileons in perspective



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

3) Enhanced Early Gravity (EEG)

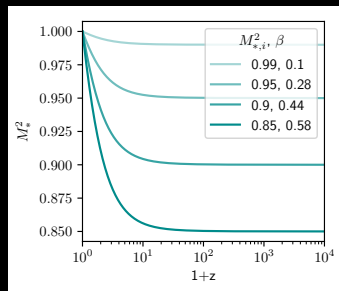
$$\mathcal{L} = \underbrace{e^{\beta\phi}}_{M_*^2} \frac{R}{2} + \frac{c_3}{H_0^2} (\partial\phi)^2 \square\phi + \frac{c_2}{2} (\partial\phi)^2$$

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

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

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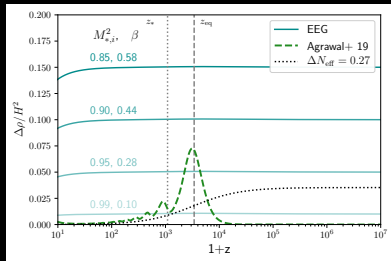
($c_3 = -1$ via ϕ rescaling)



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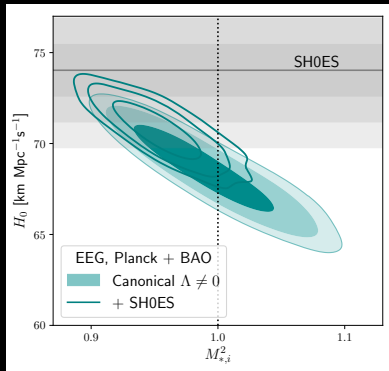
EEG Constraints

(MZ '20)



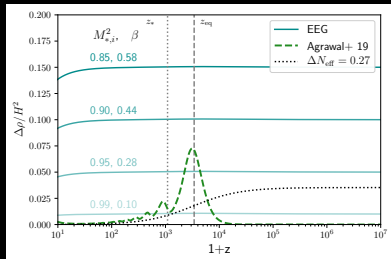
- Solve $H_0 \Leftrightarrow M_{*,i}^2 \sim 0.95$
- CMB+BAO:

$$M_{*,i}^2 = 0.988 \pm 0.035$$
- Degeneracy with ω_b, n_s, \dots

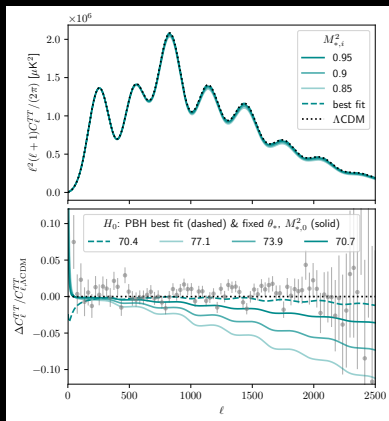


EEG Constraints

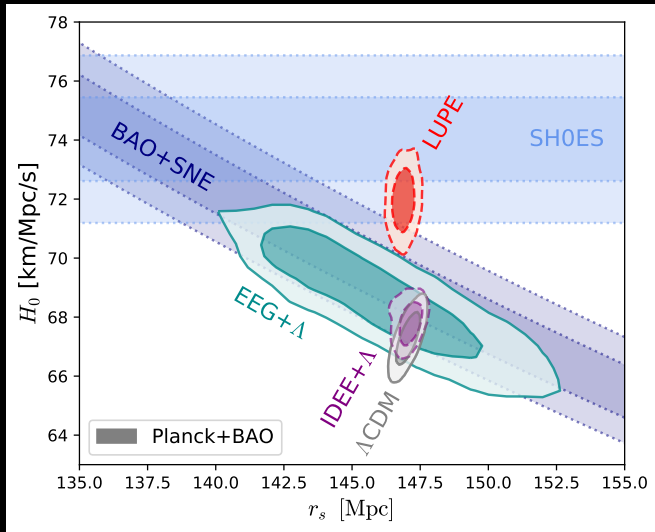
(MZ '20)



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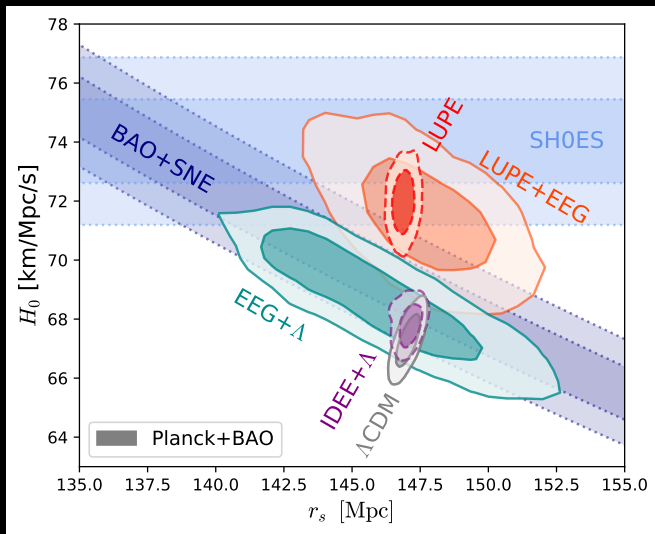


Galileons in perspective



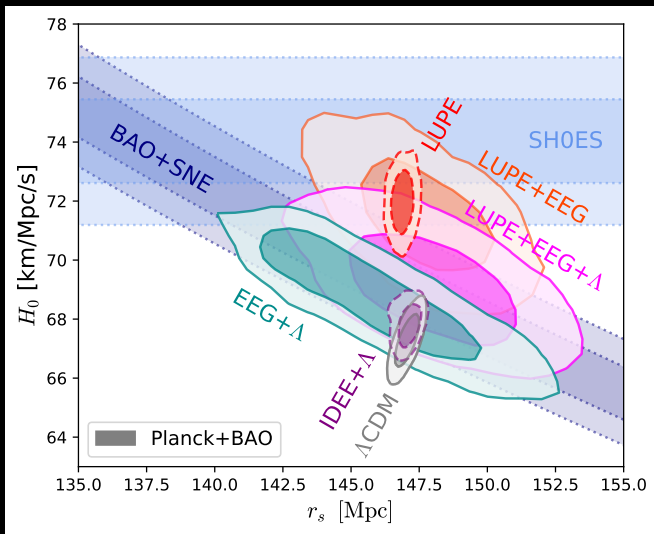
(MZ '20, based on Knox & Millea '19)

Combining multiple solutions



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Combining multiple solutions



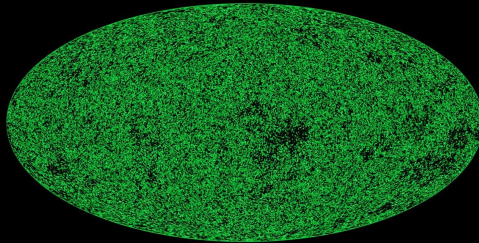
(MZ '20, based on Knox & Millea '19)

Conclusions

- H_0 tension: systematics or new physics?
- Minimal Galileon solutions *(constrained by)*
 - Imperfect DE at Equality *(Planck)*
 - Enhanced Early Gravity *(\dot{G}/G)*
 - Late Universe Phantom Expansion *(ISW, SNe)*
- Moderate H_0 tension improvement: $4.4\sigma \rightarrow 2.6\sigma$
Further model building needed
- Probes weak in Λ CDM critical beyond GR (c_g , ISW, \dot{G}/G)
- Testing gravity is easier than ever! www.hiclass-code.net

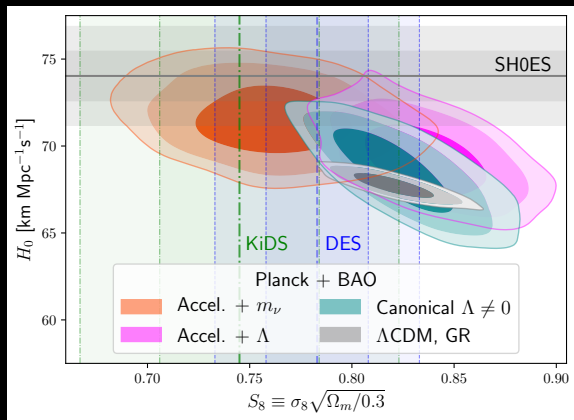
Thanks!

Backup Slides



PLANCK

Weak Lensing tension



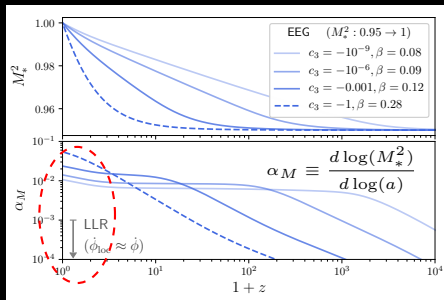
- Low S_8 in galaxy lensing surveys for Λ CDM
- EEG: H_0, S_8 anti-correlated ✓

EEG & Local gravity

Tests:

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

e.g. Lunar Laser Ranging



Local vs Global evolution

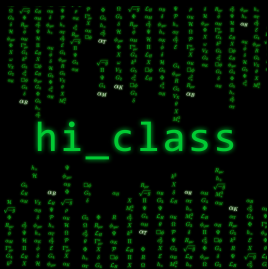
$$\phi_{\text{loc}}(\vec{x}, t) \begin{cases} \approx \dot{\phi}(t) & (\text{ruled out}^* \text{ for } C = e^{\beta\phi}) \\ \ll \dot{\phi}(t) & (\text{screening, viable?}) \end{cases}$$

* see Burrage & Dombrowski '20

Horndeski in the Cosmic Linear Anisotropy Solving System

Goals: {
★ DE/MG predictions in as much detail as Λ CDM
★ public tool, valid for a large class of theories

New version!



www.hiclass-code.net

(MZ+ '16, Bellini+ '19)

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

hi_class in practice

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

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...