The Tensions of ΛCDM

and

(an ultra-late)

Gravitational Transition

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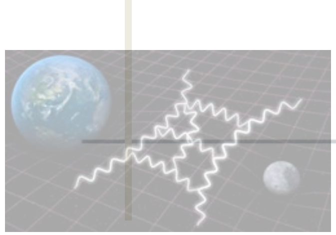
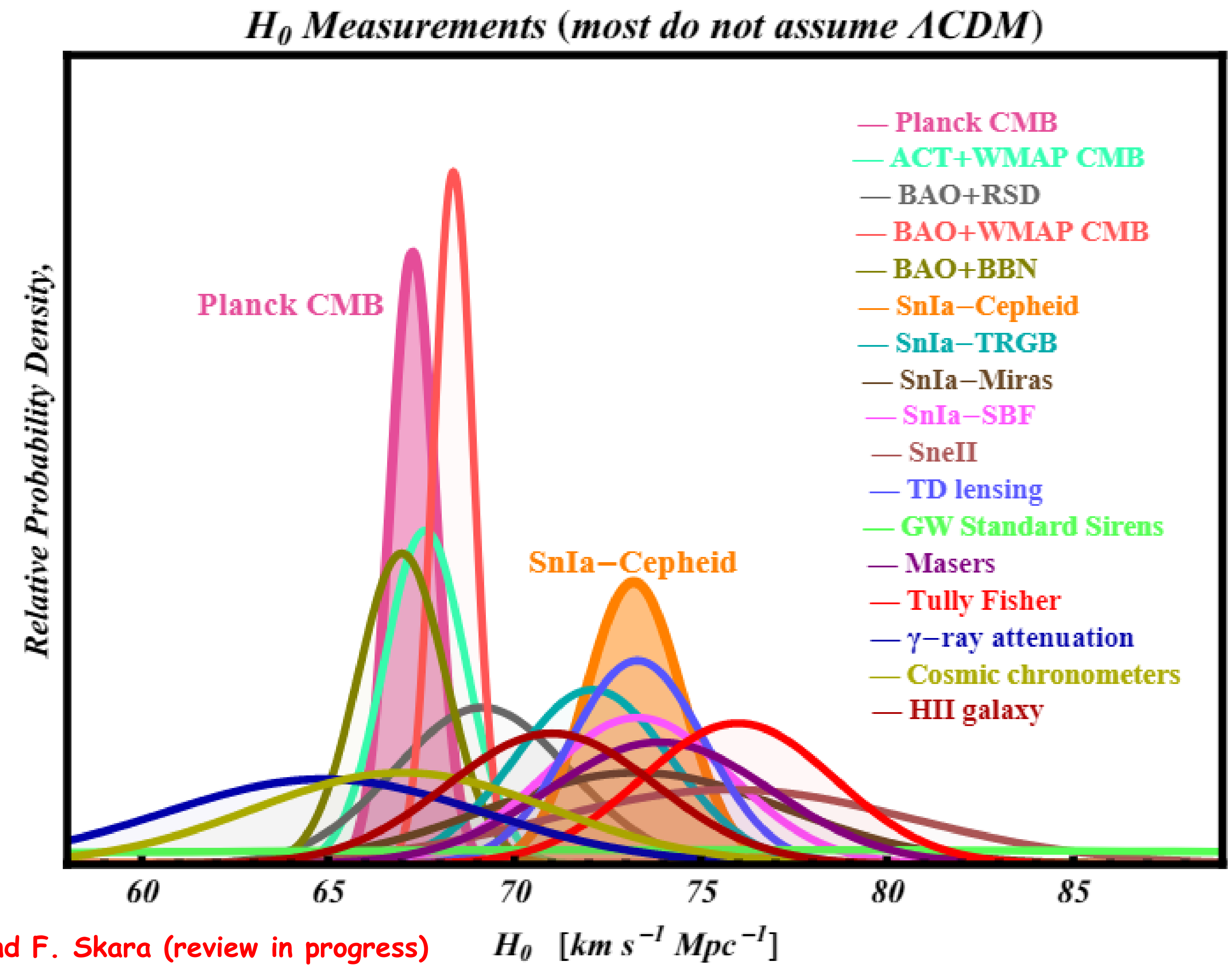
Download from: http://leandros.physics.uoi.gr/talks2021/grav-trans2.pdf

The Hubble tension



Q.: What is the feature that distinguishes the two Groups of H0 values?

Is it cosmic time or is it the assumption of distance ladder effects and fixed low z-high z gravitational physics?



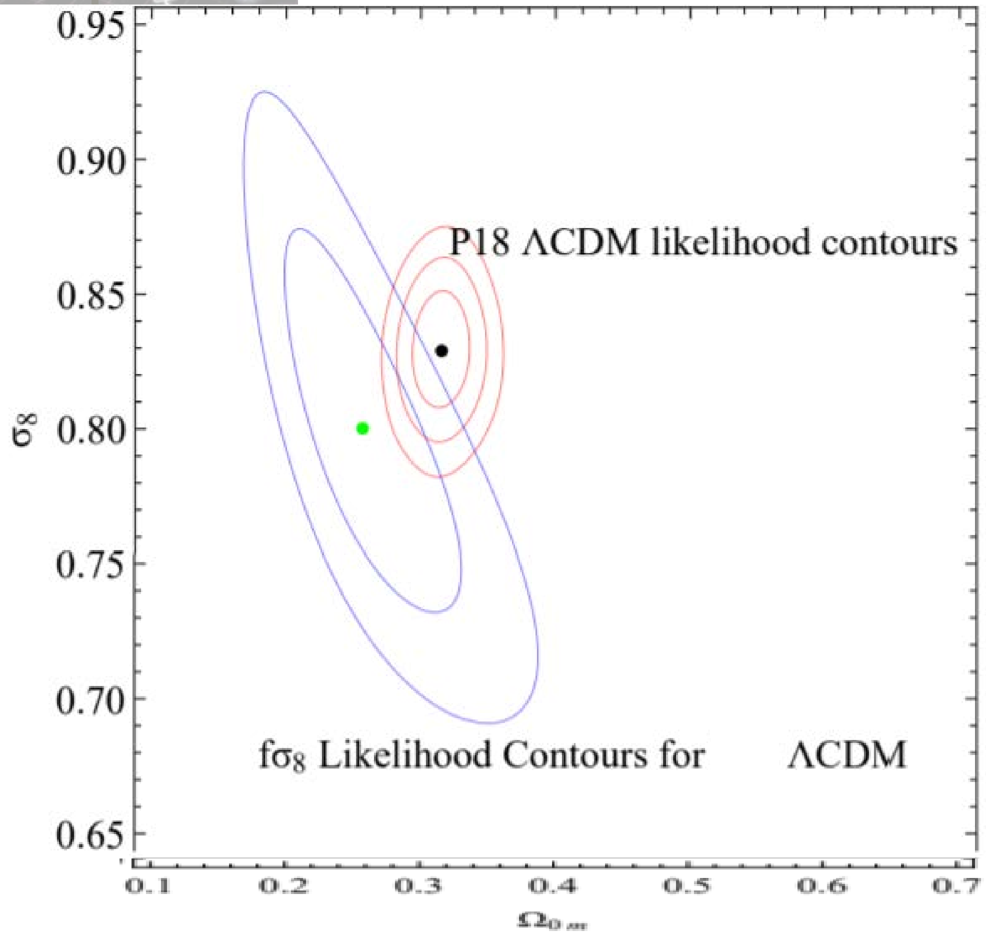
LP and F. Skara (review in progress)

The growth tension

A rapid transition of $G_{\rm eff}$ at $z_t \simeq 0.01$ as a solution of the Hubble and growth tensions

Valerio Marra, Leandros Perivolaropoulos (Feb 11, 2021)

e-Print: 2102.06012 [astro-ph.CO]

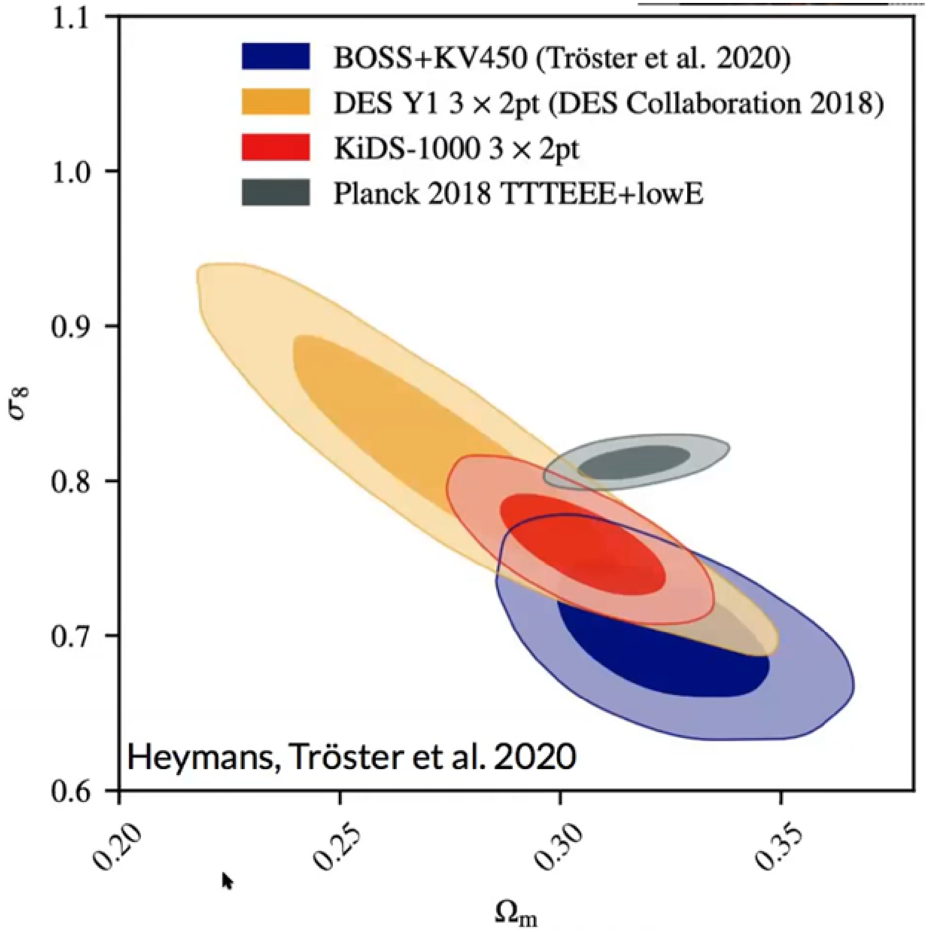


Redshift Space Distortions

KiDS-1000 Cosmology: Multi-probe weak gravitational lensing and spectroscopic galaxy clustering constraints

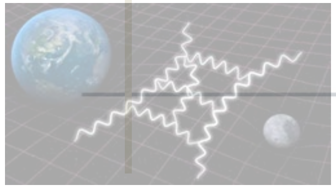
Catherine Heymans, Tilman Tröster, Marika Asgari, Chris Blake, Hendrik Hildebrandt et al. (Jul 30, 2020)

Published in: *Astron.Astrophys.* 646 (2021) A140 • e-Print: 2007.15632 [astro-ph.CO]



Weak Lensing

Degenerate measurable parameter combinations



H_0 measurement using sound horizon standard ruler (inverse distance ladder):

$$\theta_s = \frac{r_s}{D_A(z)} = \frac{H_0\, r_s}{\int_0^z \frac{dz}{E(z)}}$$

$$r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Assumptions: P18ΛCDM E(z), Standard expansion before z_{rec}

$$H_0^{P18} = 67.36 \pm 0.54 \text{ km s}^{-1}\text{Mpc}^{-1}$$

No dependence on G_{eff}.

H_0 measurement using distance ladder:

$$\mathcal{M} = M + 5log\frac{c/H_0}{Mpc} + 25$$

M depends on G_{eff}.

$$\mathcal{M}_{z>0.01} = 23.80 \pm 0.01$$

$$M^{R20}_{z<0.01} = -19.244 \pm 0.037$$

$$\mathcal{M} = M + 5log\frac{c/H_0}{Mpc} + 25$$

$$M_{z>0.01} = M^{R20}_{z<0.01}$$

$$G_{\text{eff}}(z < 0.01) = G_{\text{eff}}(z > 0.01)$$

$$H_0^{R20} = 73.2 \pm 1.3 \text{ km s}^{-1}\text{Mpc}^{-1} > H_0^{P18} = 67.36 \pm 0.54 \text{ km s}^{-1}\text{Mpc}^{-1}$$

H_0 Tension

Assumption: $G_{eff}(z<0.01) = G_{eff}(z>0.01)$

Growth of perturbations measurements: $\Omega_G \equiv \frac{G_{eff}}{G_{0,N}}\Omega_{0m}$ depends on G_{eff}.

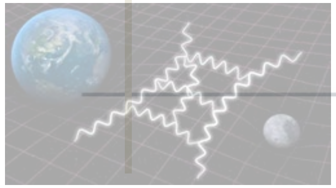
$$H^2\,\delta_m'' + \left(\frac{(H^2)'}{2} - \frac{H^2}{1+z}\right)\delta_m' \approx \frac{3}{2}(1+z)H_0^2\frac{G_{\text{eff}}(z)}{G_{N,0}}\,\Omega_{m,0}\,\delta_m$$

Growth Tension

$$\Omega_G \equiv \frac{G_{eff}}{G_{0,N}}\Omega_{0m} = 0.256 \pm 0.027 < \Omega_{0m}^{P18} = 0.3153 \pm 0.0073$$

Assumption: $G_{eff}(z) = G_{0,N}$

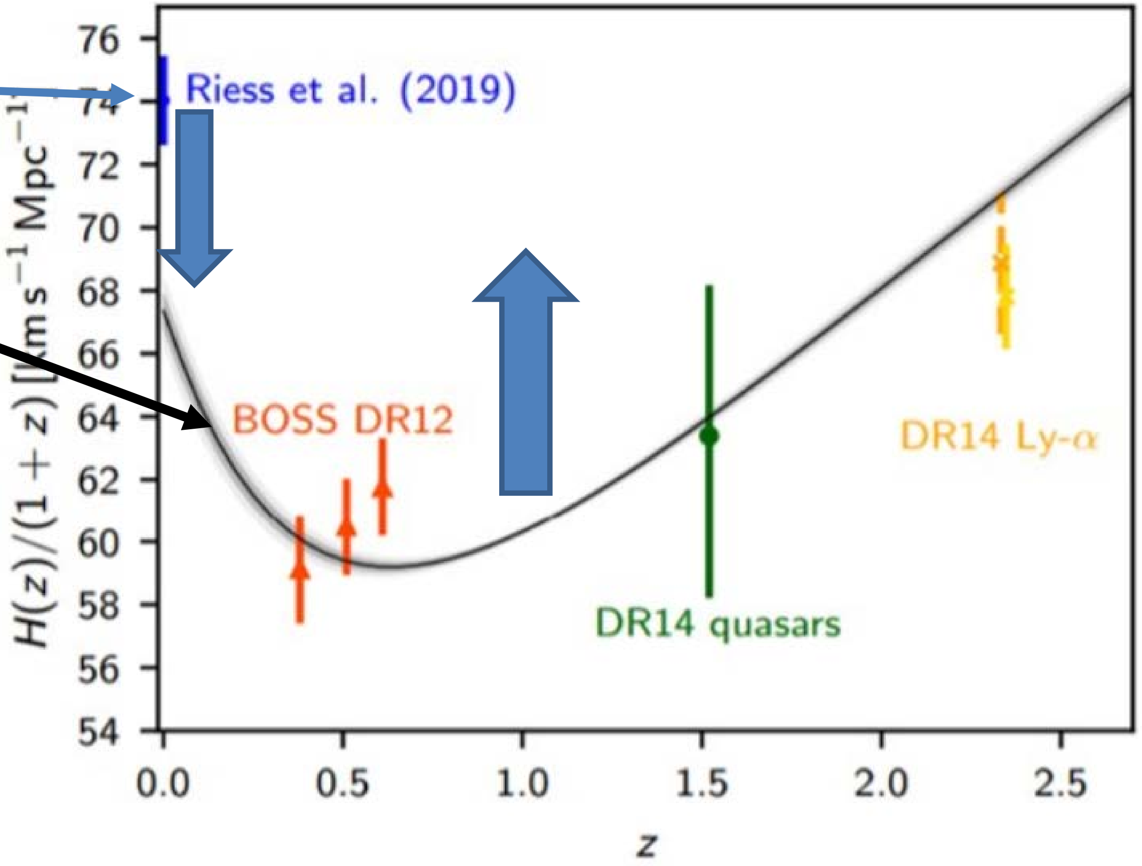
The Hubble Crisis Approaches



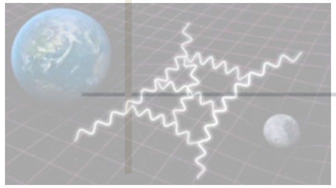
How can H(z) derived from late time calibrators (blue point) become consistent with H(z) derived from early time calibrator (black line)?

Change SnIa Intrinsic Luminosity.
(move blue point down)

Change sound horizon scale.
(shift black line up)



The Hubble Crisis Approaches

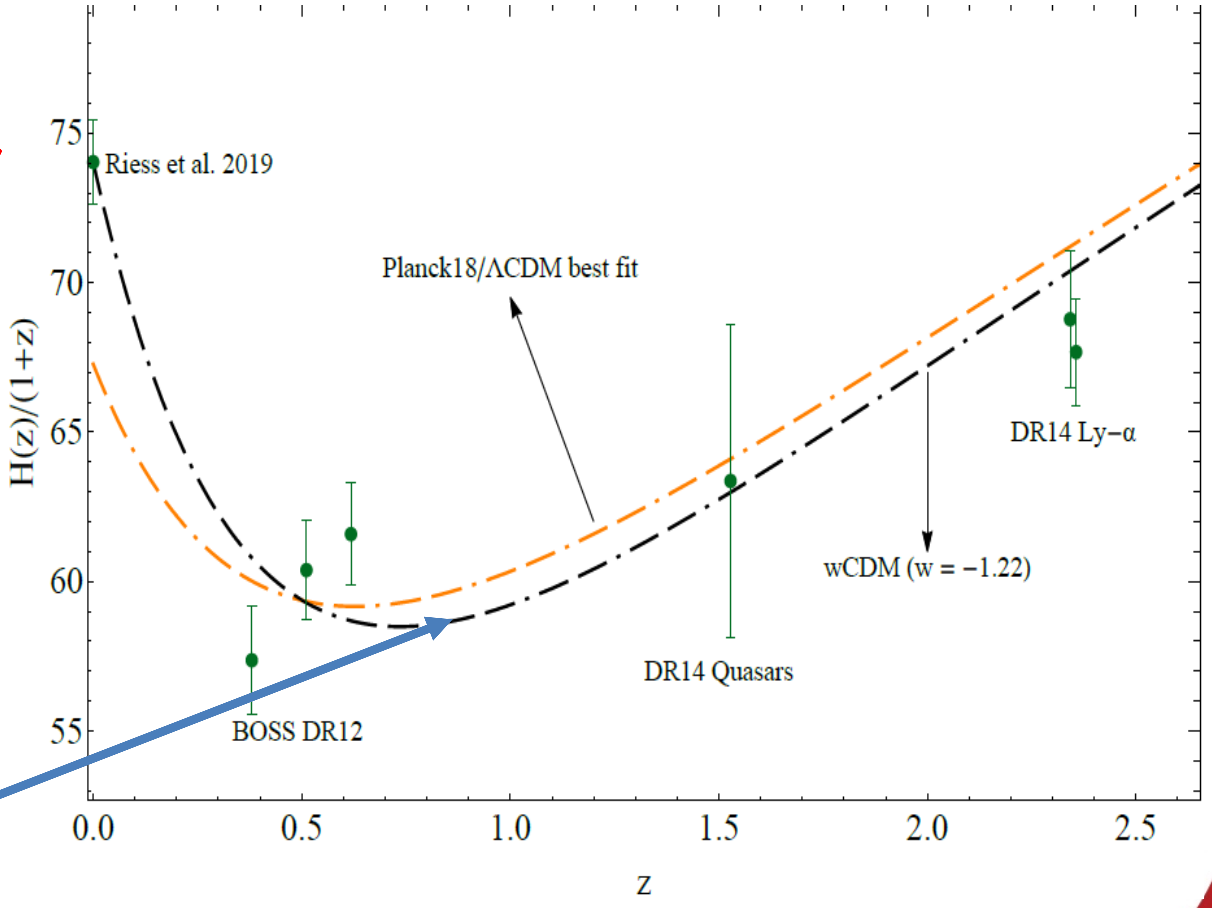


How can H(z) derived from late time calibrators (blue point) become consistent with H(z) derived from early time calibrator (black line)?

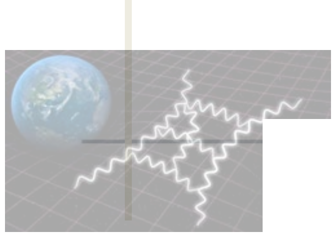
Change SnIa Intrinsic Luminosity.
(move blue point down)

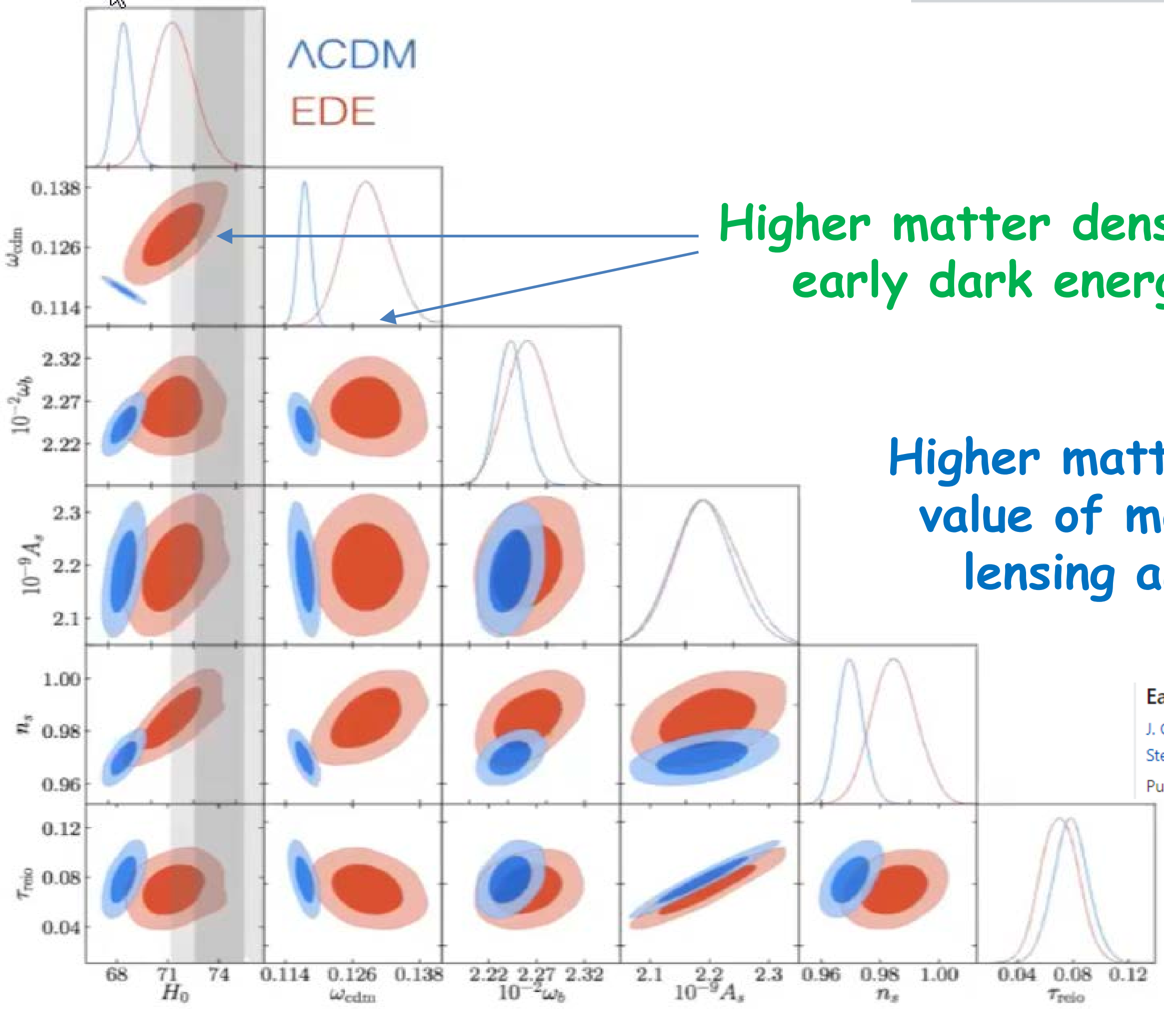
Change sound horizon scale.
(shift black line up)

Deform H(z) by eg dynamical dark energy.
(distort black line)



Problem Early Dark Energy worsens growth tension





Higher matter density is required to compensate for early dark energy effect after recombination.

Higher matter density contradicts the required low value of matter density at late times from weak lensing and growth data (growth tension gets worse).

Early dark energy does not restore cosmological concordance

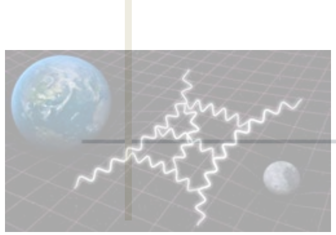
J. Colin Hill (Columbia U. (main) and Flatiron Inst., New York), Evan McDonough (Brown U. (main) and MIT), Michael W. Toomey (Brown U. (main)), Stephon Alexander (Brown U. (main)) (Mar 17, 2020)

Published in: *Phys.Rev.D* 102 (2020) 4, 043507 • e-Print: 2003.07355 [astro-ph.CO]

$$r_s = \int_{z_{rec}}^{\infty} \frac{dz\ c_s(z)}{H(z;\Omega_{0b}h^2,\Omega_{0\gamma}h^2,\Omega_{0CDM}h^2)}$$

$$\theta_s = \frac{r_s H_0}{\int_0^{z_{rec}} 1/E(z)}$$

Modifying the late H(z) evolution. Phantom Dark Energy



Q: Is it possible to keep the CMB anisotropy spectrum unaffected while changing H(z)?

A: Yes provided that we keep specific parameters unchanged:

These cosmological parameters fix to high accuracy the form of the CMB anisotropy spectrum

$$\Omega_m h^2 = 0.1430 \pm 0.0011$$
$$\Omega_b h^2 = 0.02237 \pm 0.00015$$
$$\Omega_r h^2 = (4.64 \pm 0.3)\ 10^{-5}$$
$$d_A = (100\ km\ sec^{-1}\ Mpc^{-1})^{-1}(4.62 \pm 0.08)$$

$$d_A = \int_0^{z_r} \frac{dz}{H(z)} = \int_0^{z_r} \frac{dz}{H_0\ E(z)}$$

General h(z)

Define:
h(z)=H(z)/100km/(sec Mpc),
h=h(z=0)

$$h(z) = \left[\Omega_{0r}\, h^2(1+z)^4 + \Omega_{0m}\, h^2(1+z)^3 + (h^2 - \Omega_{0m}h^2 - \Omega_{0r}h^2)\ f_{DE}(z)\right]^{1/2}$$

Fix to Planck best fits

allow to vary

Demand

Derive $f_{DE}(z)$

Fix h=0.74 (SnIa) $\int_0^{z_s} \frac{dz}{h(z;h=0.74,\Omega'_{0m},f_{de})} = \int_0^{z_s} \frac{dz}{h_{P\Lambda CDM}(z;h=0,67,\Omega_{0m})}$ ⟹ CMB spectrum = Planck Spectrum

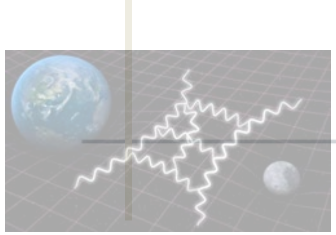
This method can be used to find general degeneracy relation between $f_{DE}(z)$ and H_0.
Fixing h(z=0)=h=0.74 gives infinite $f_{DE}(z)$, w(z) forms that can potentially resolve the H_0 problem.

H_0 tension, phantom dark energy, and cosmological parameter degeneracies

G. Alestas (Ioannina U.), L. Kazantzidis (Ioannina U.), L. Perivolaropoulos (Ioannina U.) (Apr 20, 2020)

Published in: *Phys.Rev.D* 101 (2020) 12, 123516 • e-Print: 2004.08363 [astro-ph.CO]

A general H(z) deformation (CPL)

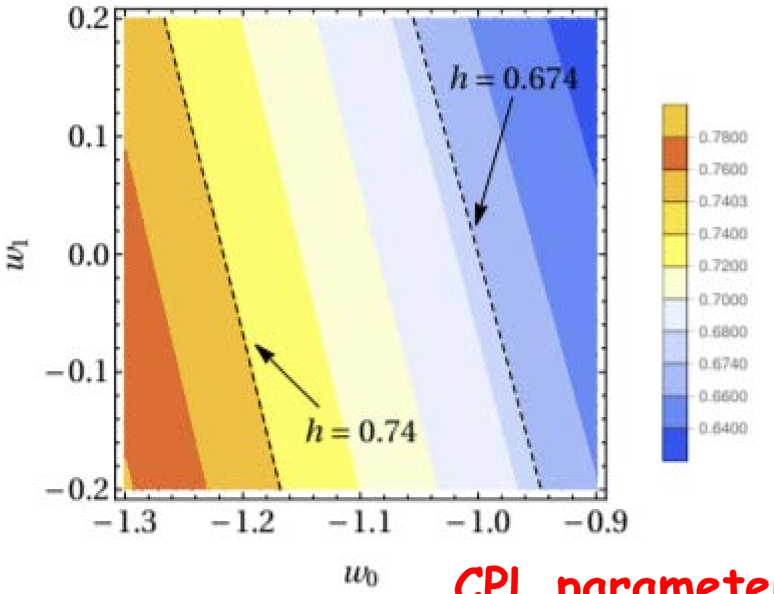


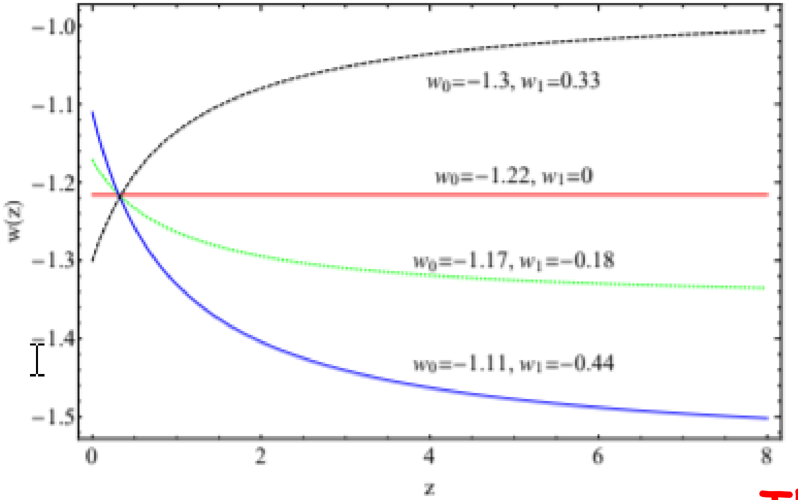
$$w = w_0 + w_1(1-a) = w_0 + w_1 z/(1+z)$$

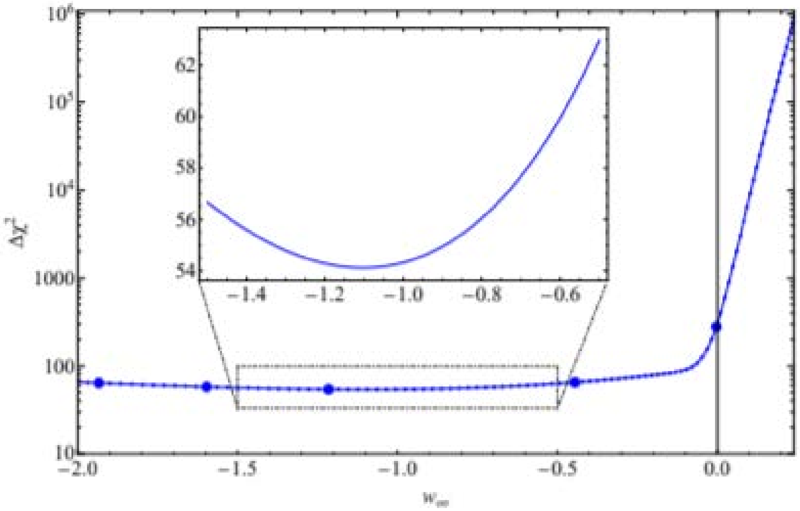
H(z) for CPL
$$H(z) = H_0\sqrt{\Omega_{0\mathrm{m}}(1+z)^3 + \Omega_{0\mathrm{r}}(1+z)^4 + (1-\Omega_{0\mathrm{m}}-\Omega_{0\mathrm{r}})(1+z)^{3(1+w_0+w_1)}e^{-3\frac{w_1 z}{1+z}}}$$

Hubble tension deformation:
$$\int_0^{z_s}\frac{dz}{h(z;h=0.74,\Omega'_{0m},f_{de})} = \int_0^{z_s}\frac{dz}{h_{P\Lambda CDM}(z;h=0,67,\Omega_{0m})}$$

$$\Delta\chi^2 = \chi^2_{\min-CPL} - \chi^2_{P18}$$



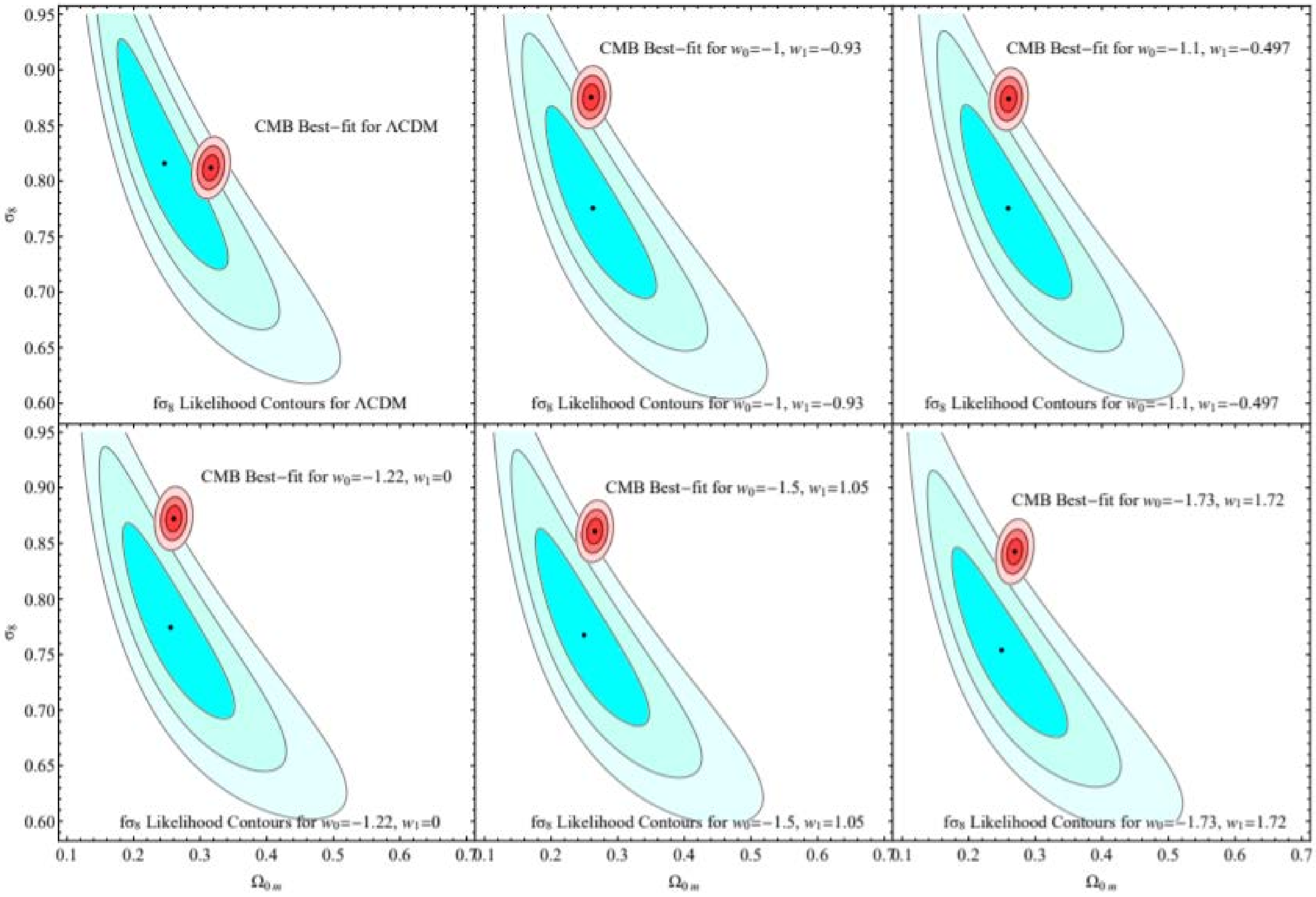




CPL parameters consistent with both CMB+local H_0.

The χ^2 problem of H(z) deformations
Poor fit to BAO+SnIa

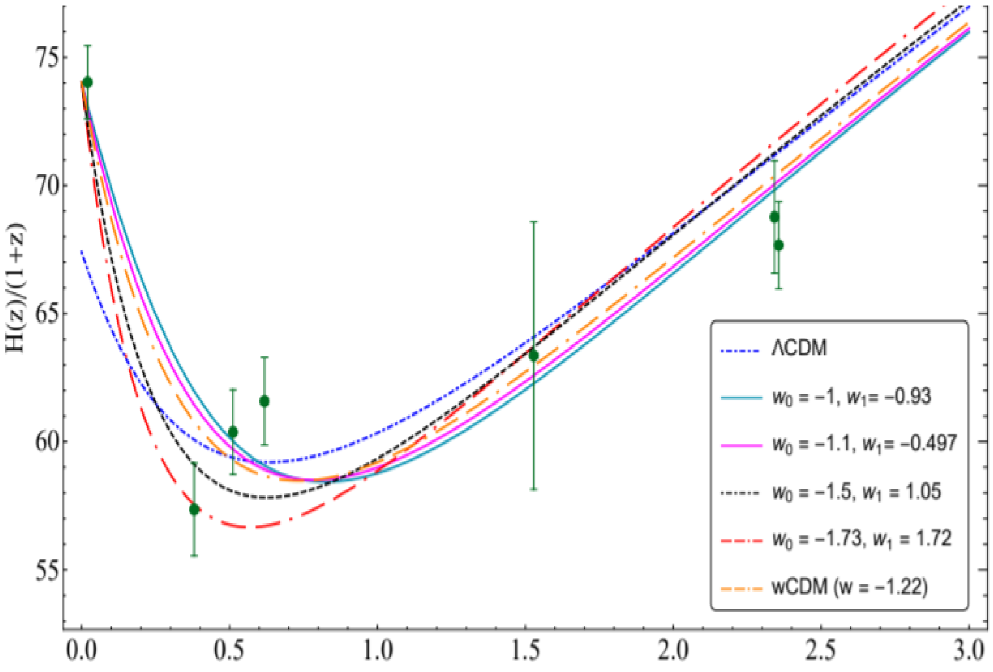
The growth problem of H(z) deformations



Late time approaches to the Hubble tension deforming $H(z)$, worsen the growth tension

George Alestas (Ioannina U.), Leandros Perivolaropoulos (Ioannina U.) (Mar 6, 2021)

e-Print: 2103.04045 [astro-ph.CO]



$$\int_0^{z_s} \frac{dz}{h(z; h=0.74, \Omega'_{0m}, f_{de})} = \int_0^{z_s} \frac{dz}{h_{P\Lambda CDM}(z; h=0,67, \Omega_{0m})}$$

$$H^2\,\delta_m'' + \left(\frac{(H^2)'}{2} - \frac{H^2}{1+z}\right)\delta_m' \approx \frac{3}{2}(1+z)H_0^2\frac{G_{\rm eff}(z)}{G_{N,0}}\,\Omega_{m,0}\,\delta_m$$

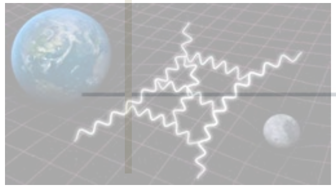
$$G_{\rm eff}(z) = G_{0,N}$$

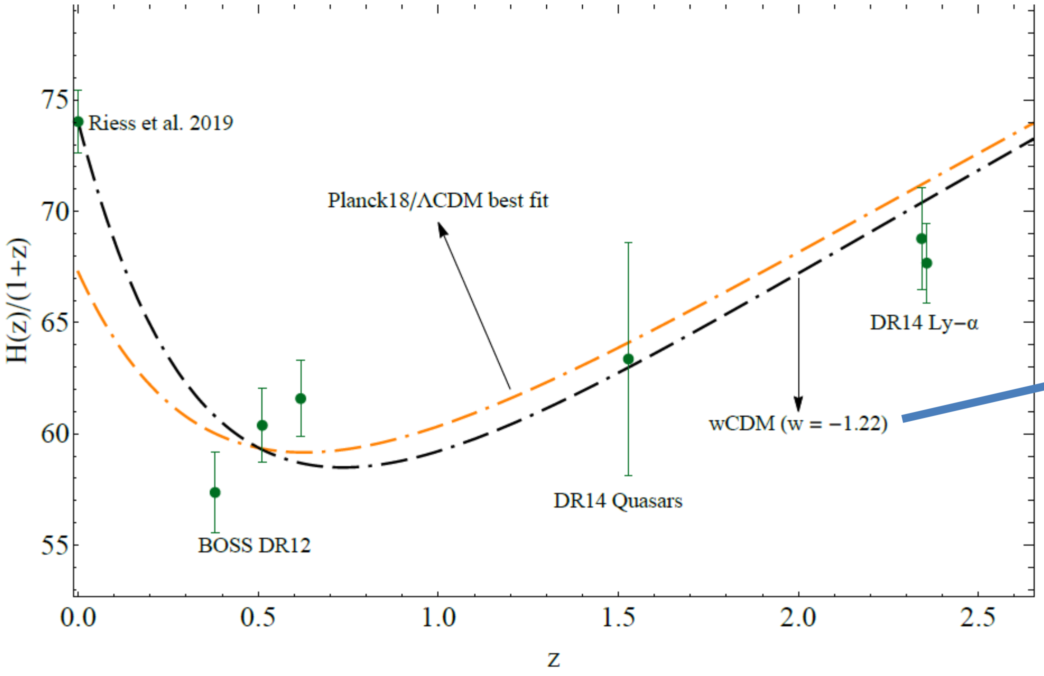
$$\omega_m \equiv \Omega_{0m}h^2$$

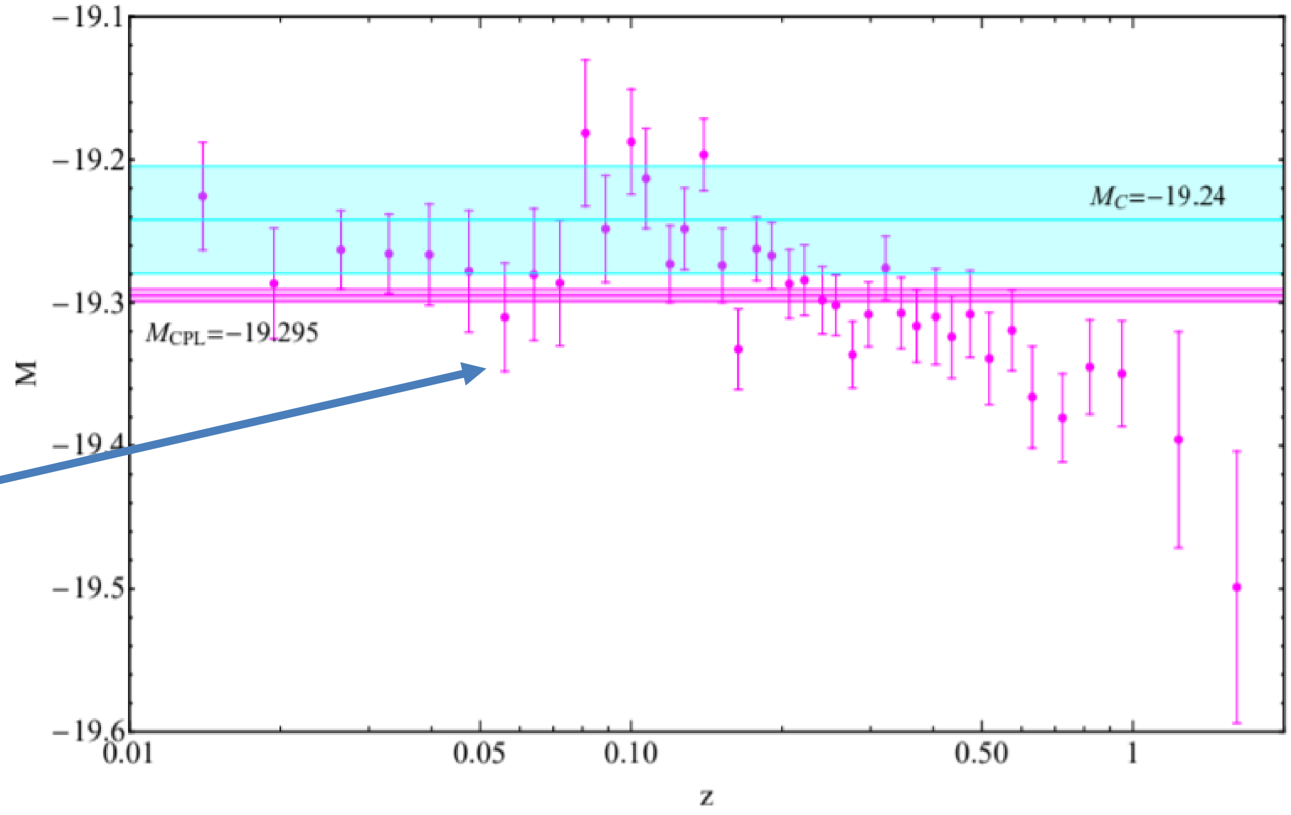
$$\Delta(a) = \frac{\delta(a)}{\delta(a_i)} = \exp\left[\omega_m^\gamma \int_{a_i}^{a} \frac{da'}{a'^{1+3\gamma}\,h(a')^{2\gamma}}\right]$$

$$\gamma = \frac{6-3(1+w_\infty)}{11-6(1+w_\infty)}$$

The M problem of H(z) deformations

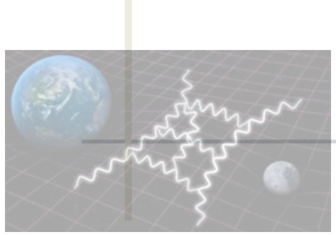






$$m(z_i) = M - 5\log_{10}[H_0 \cdot \mathrm{Mpc}/c] + 5\log_{10}(D_L(z_i)) + 25 \Rightarrow M_i = m(z_i) + 5\log_{10}\left[H_0^{R19} \cdot \mathrm{Mpc}/c\right] - 5\log_{10}(D_L(z_i)) - 25$$

A w-M Transition



A $w - M$ phantom transition at $z_t < 0.1$ as a resolution of the Hubble tension

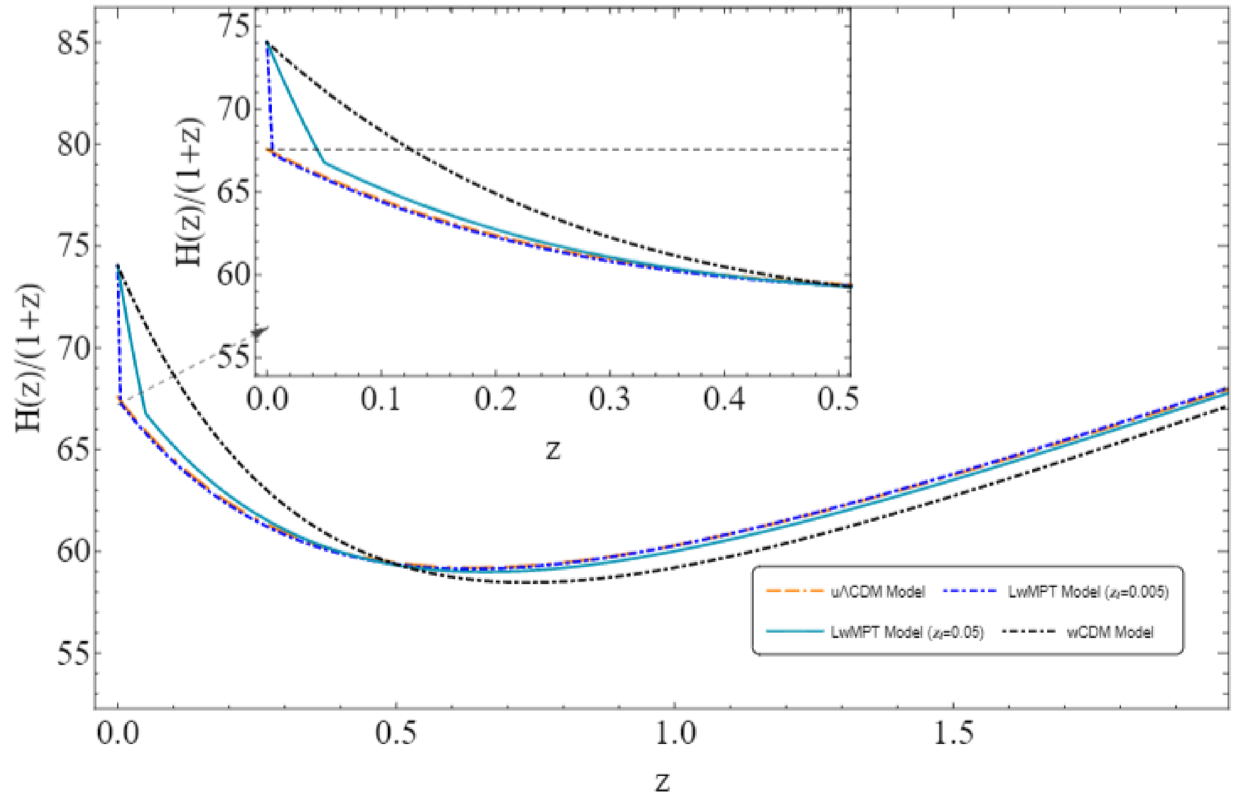
George Alestas (Ioannina U.), Lavrentios Kazantzidis (Ioannina U.), Leandros Perivolaropoulos (Ioannina U.) (Dec 27, 2020)

Published in: *Phys.Rev.D* 103 (2021) 8, 083517 • e-Print: 2012.13932 [astro-ph.CO]

H(z) for w-transition

$$h_w(z)^2 \equiv \omega_m(1+z)^3 + \omega_r(1+z)^4 + (h^2 - \omega_m - \omega_r)\left(\frac{1+z}{1+z_t}\right)^{3\,\Delta w} \qquad z < z_t$$

$$h_w(z)^2 \equiv \omega_m(1+z)^3 + \omega_r(1+z)^4 + (h^2 - \omega_m - \omega_r) \qquad z > z_t$$



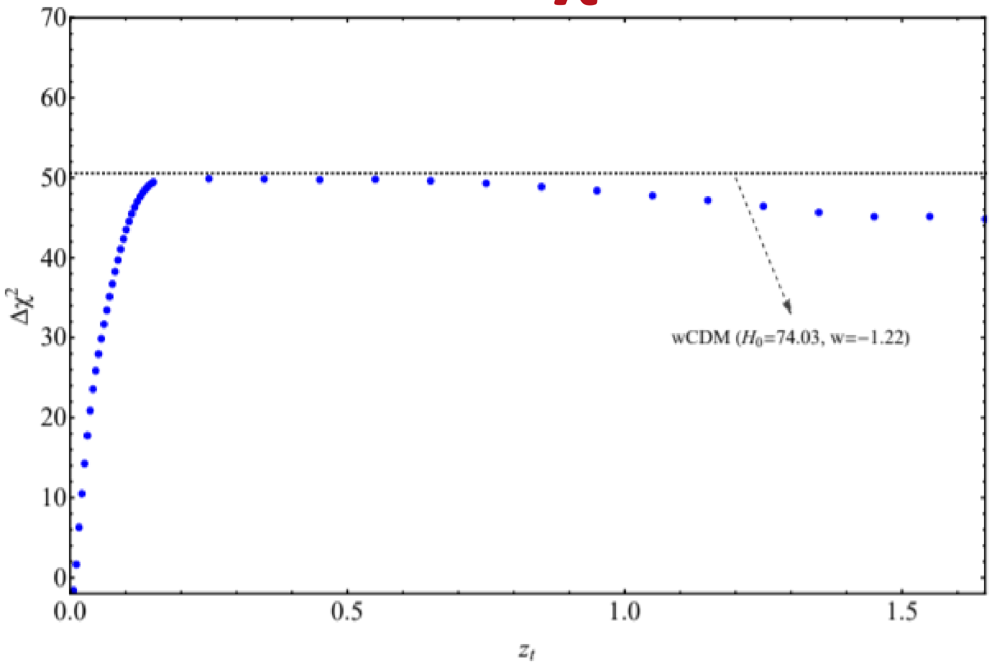
$$w(z) = -1 + \Delta w\, \Theta(z_t - z)$$

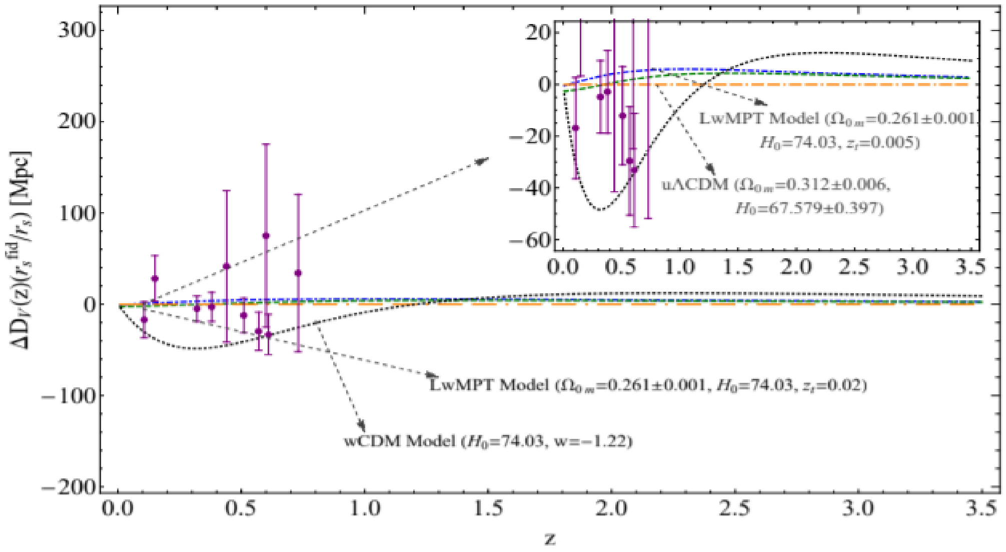
$$\Delta w = \frac{Log\left(h^2_{P18} - \omega_m\right) - Log\left(h^2_{R19} - \omega_m\right)}{3Log(1+z_t)}$$

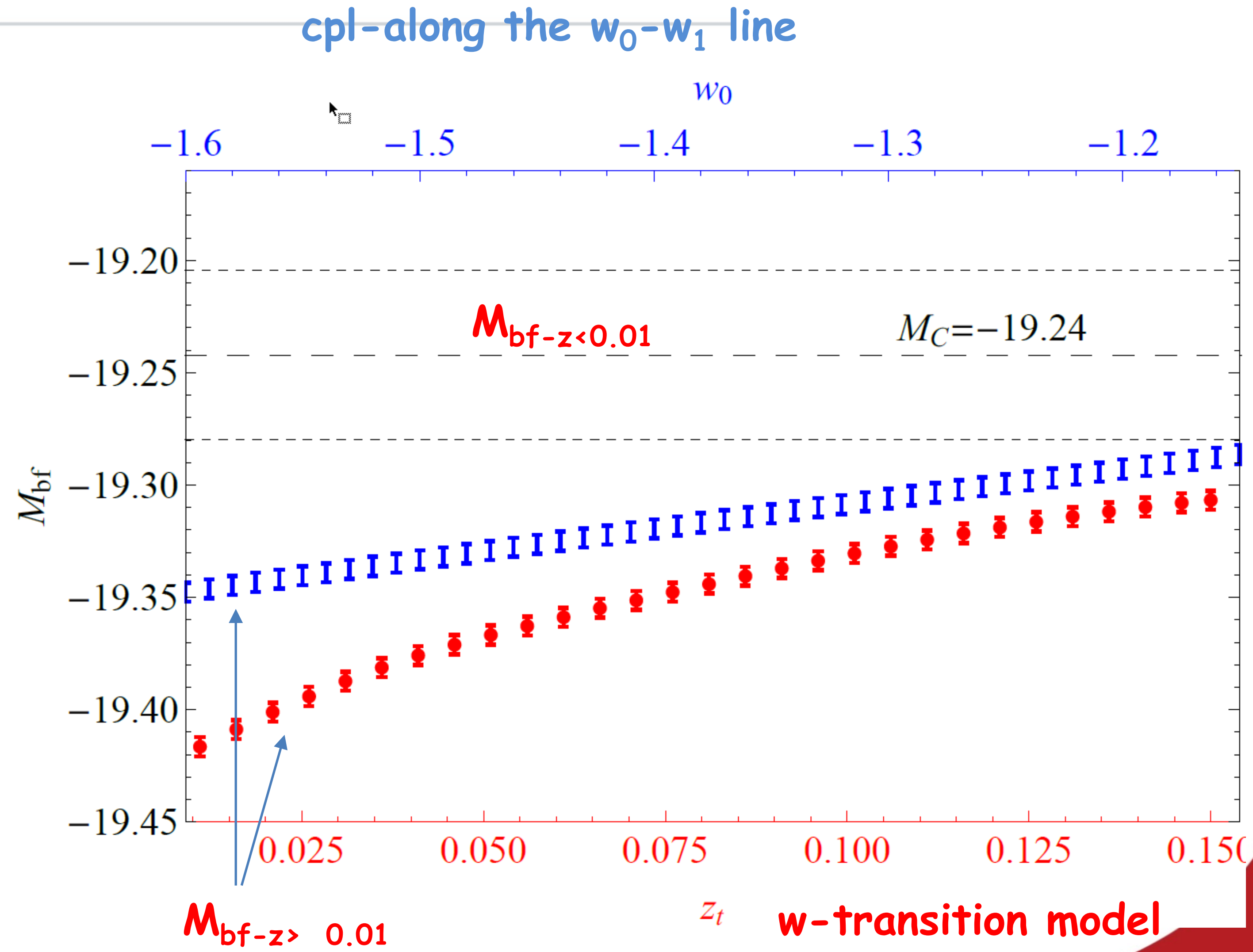
X^2 problem is resolved.
Growth tension is not worse.

What about the M problem?

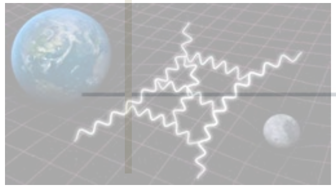
The χ^2 is resolved but the M problem worsens



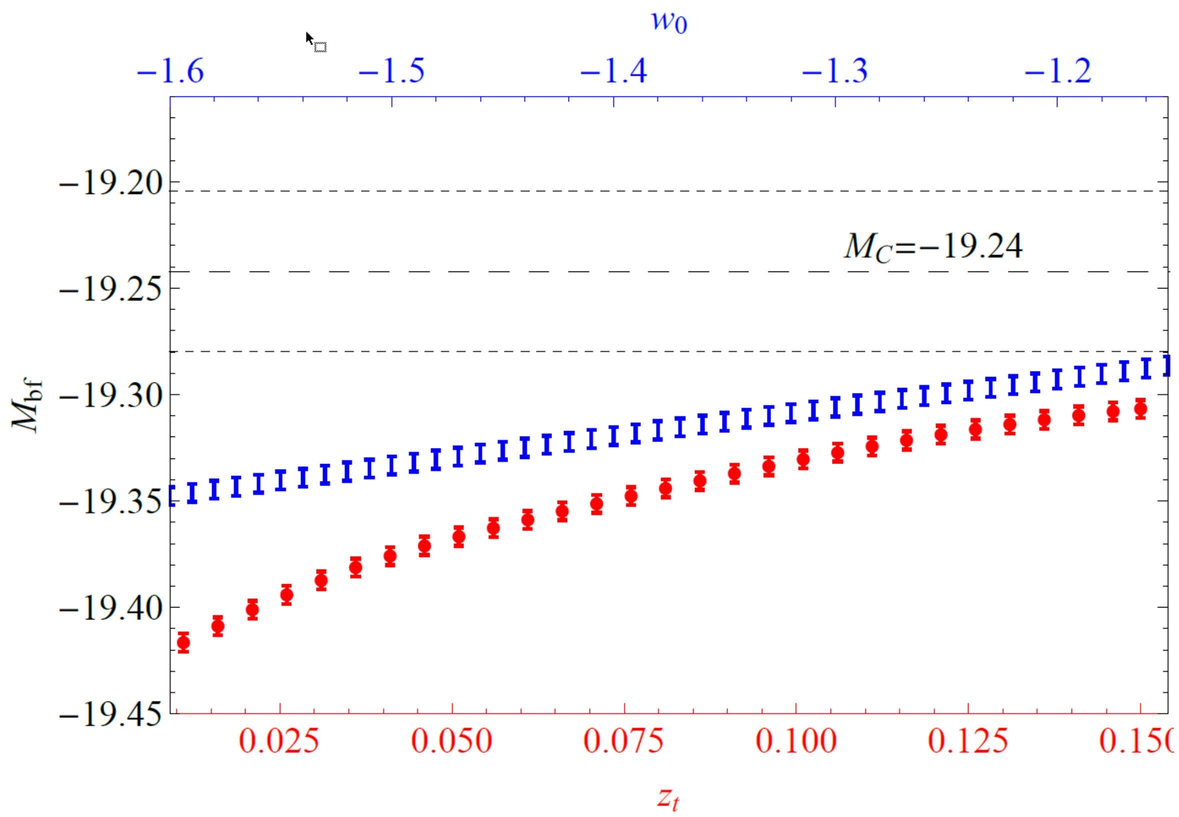


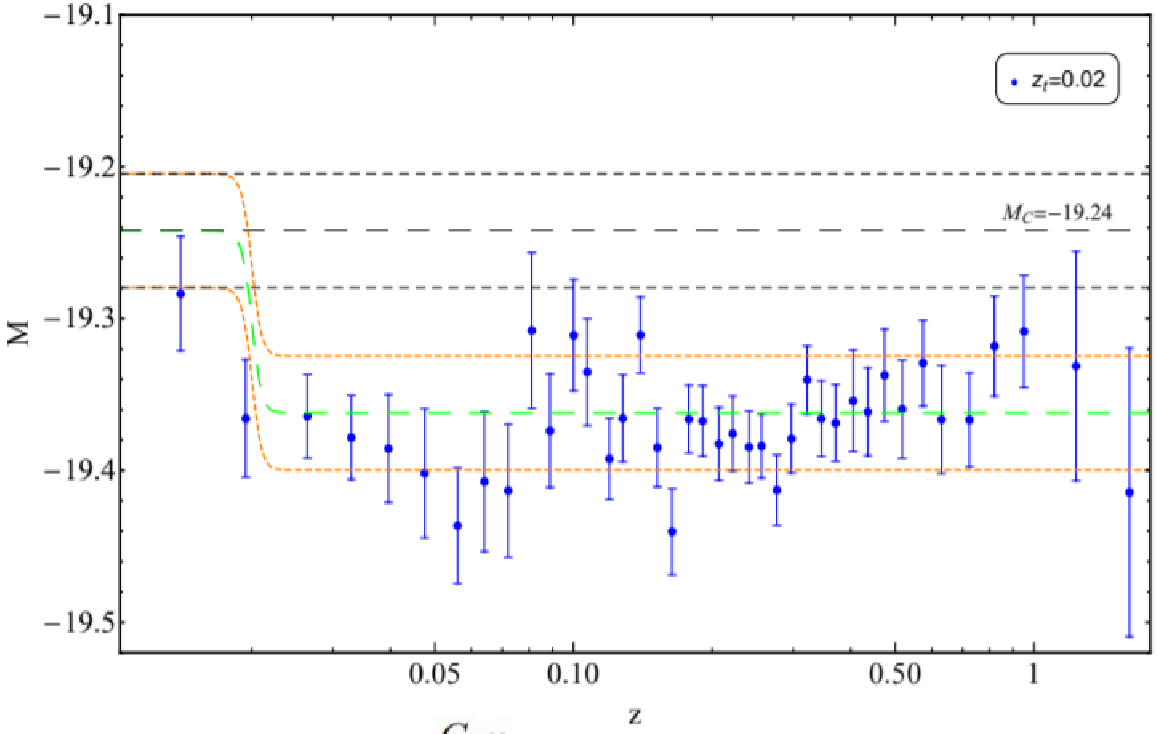


The M transition cures the M problem



$$M(z) = M_C + \Delta M \, \Theta(z - z_t)$$





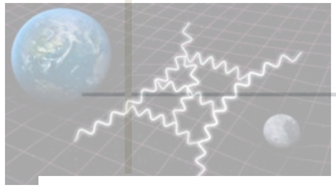
$$\mu \equiv \frac{G_{\rm eff}}{G_N}$$

$$L \sim G_{\rm eff}^b \;\Longrightarrow\; \Delta M = \frac{15}{4} \log_{10}(\mu)$$

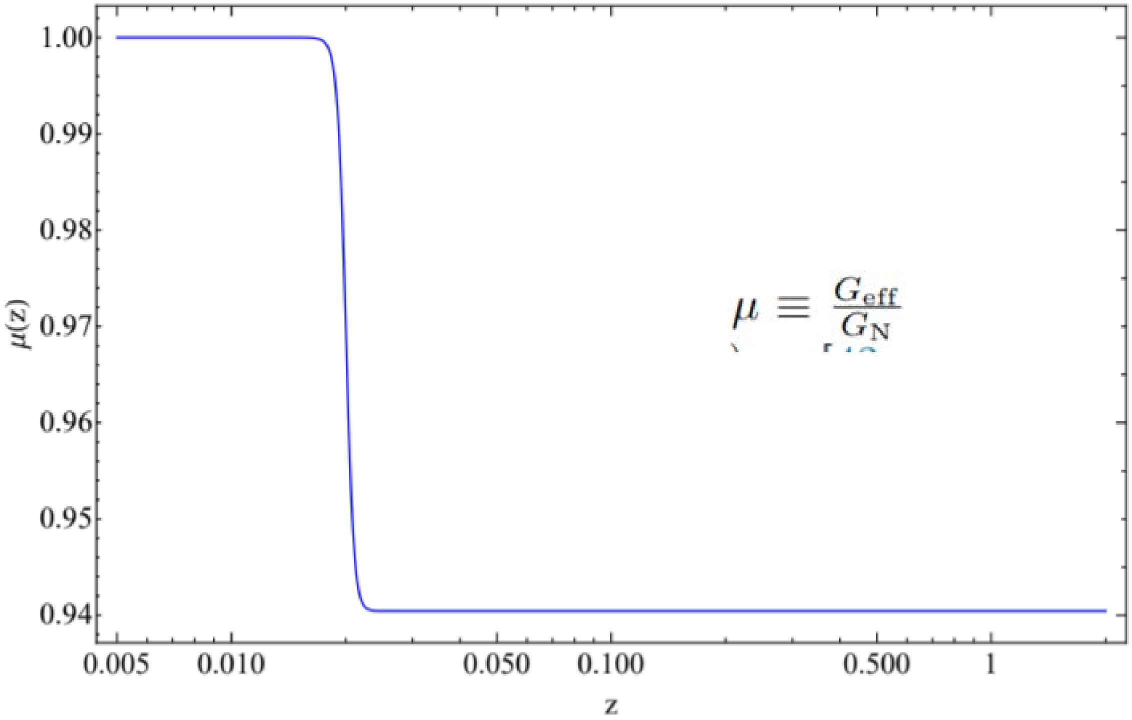
Q: What could cause an M transition?

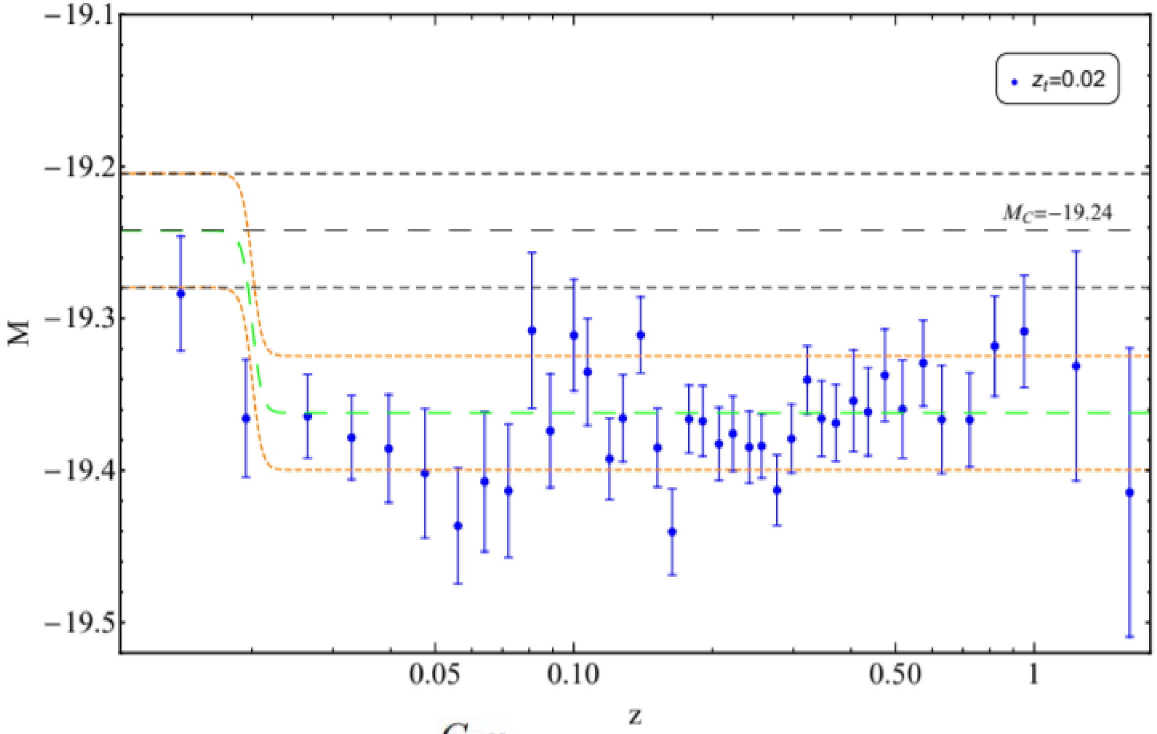
A: A 5-10% transition in G_{eff} less than 150 Myrs ago (z<0.01) $L \sim M_{Chandr} \sim G^{-3/2}$

The Gravitational Transition



$$M(z) = M_C + \Delta M\ \Theta(z - z_t)$$





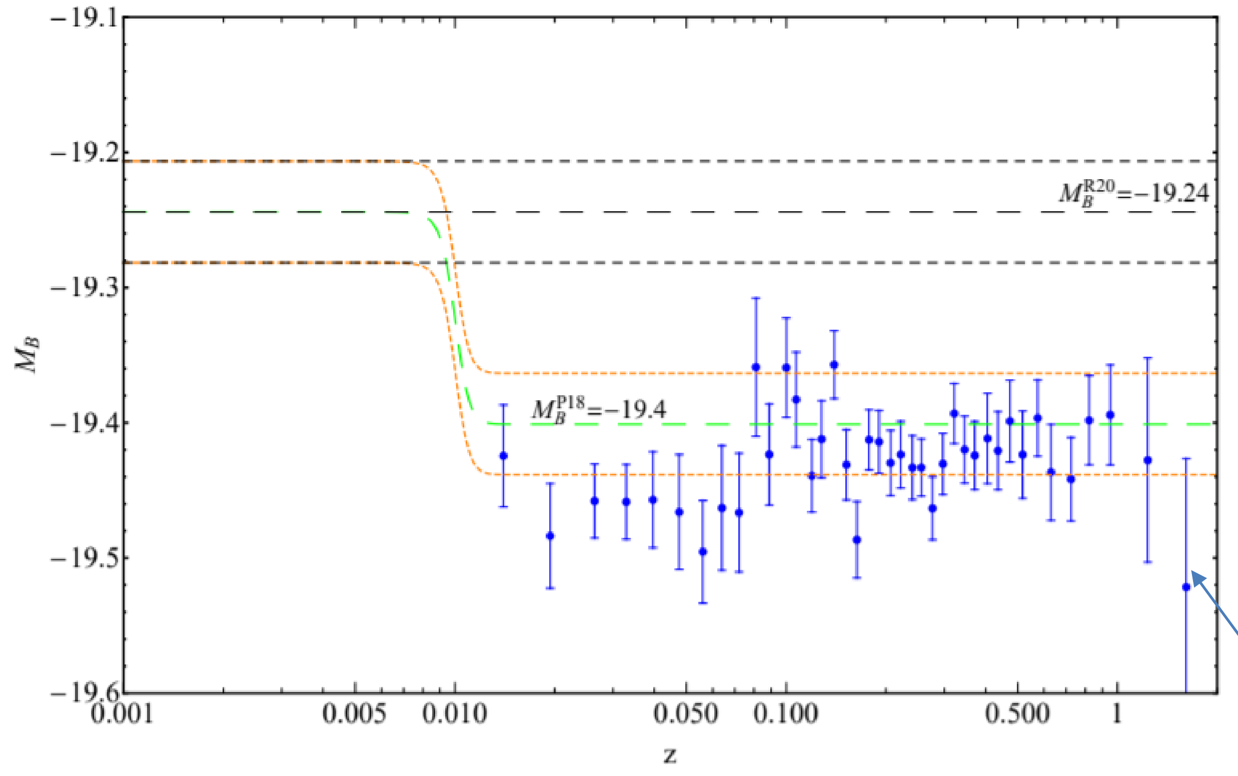
A 6% transition of G_{eff} is required for the reproduction of the required ΔM=0.1.

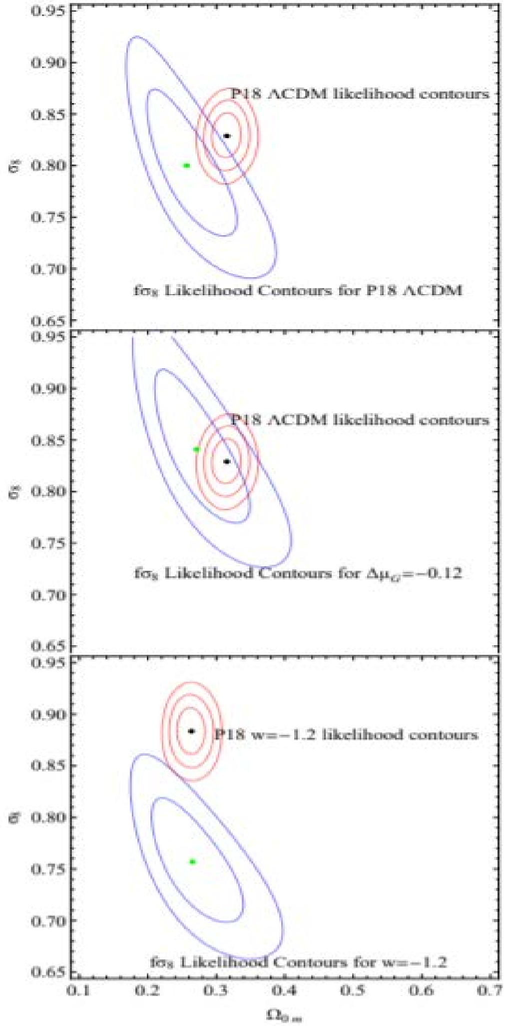
$$\mu \equiv \frac{G_{\rm eff}}{G_{\rm N}}$$

$$L \sim G_{\rm eff}^b \quad \Longrightarrow \quad \Delta M = \frac{15}{4} log_{10}\left(\mu\right)$$

$$L \sim M_{Chandr} \sim G^{-3/2}$$

The Pure M-transition model





The reduced value of G_{eff} allows for a larger value of Ω_{0m} thus resolving the growth tension

X^2 problem is resolved.
Growth tension resolved.
M problem resolved

A 12% transition of G_{eff} is required for the reproduction of the required ΔM=0.2 for a pure Planck/ΛCDM background.

SnIa luminosities in the context of a Planck/ΛCDM background

$$\mu \equiv \frac{G_{\rm eff}}{G_N}$$

$$L \sim G_{\rm eff}^b \Rightarrow \Delta M = \frac{15}{4} log_{10}(\mu)$$

$$L \sim M_{Chandr} \sim G^{-3/2}$$

A rapid transition of $G_{\rm eff}$ at $z_t \simeq 0.01$ as a solution of the Hubble and growth tensions

Valerio Marra, Leandros Perivolaropoulos (Feb 11, 2021)

e-Print: 2102.06012 [astro-ph.CO]

Tully-Fisher Data

Tully-Fisher relation: Baryonic mass of galaxies proportional to power (s~4) of rotation velocity

$$v^2 = G_{\rm eff} M/R \implies v^4 = (G_{\rm eff} M/R)^2 \sim M\ S\ G_{\rm eff}^2 \quad \Rightarrow \quad M_B = A_B v_{rot}^s \qquad A_B \sim G^{-2} S^{-1}$$

Q: Is there a hint for a transition of the best fit value of A_B at some $z_t<0.01$ (D<40Mpc)?

Tully-Fisher dataset: Updated SPARC database (Lelli et al. 2019,2016), 118 (D, M_B, v_{rot}) datapoints

Split in two subsets: Σ_1: $D > D_c$, Σ_2: $D < D_c$.

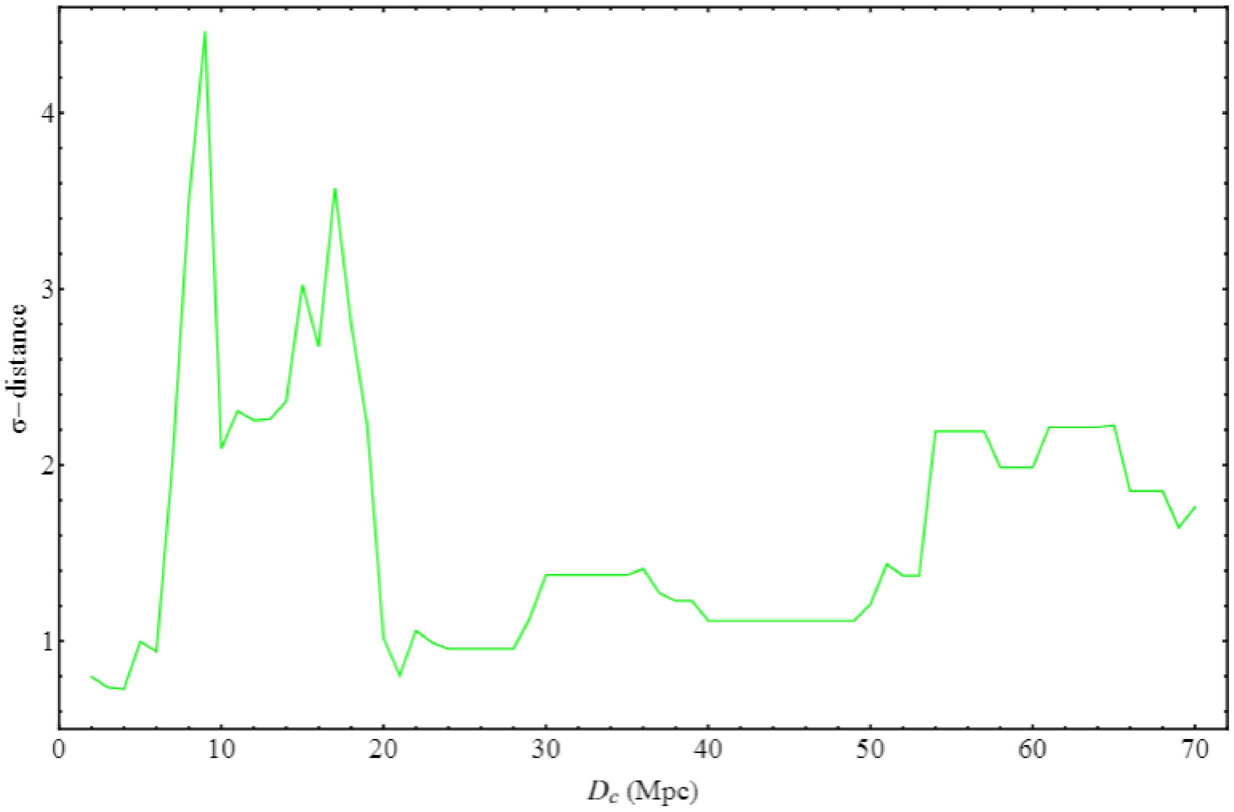
Find σ-between the best fit parameters of each subset.

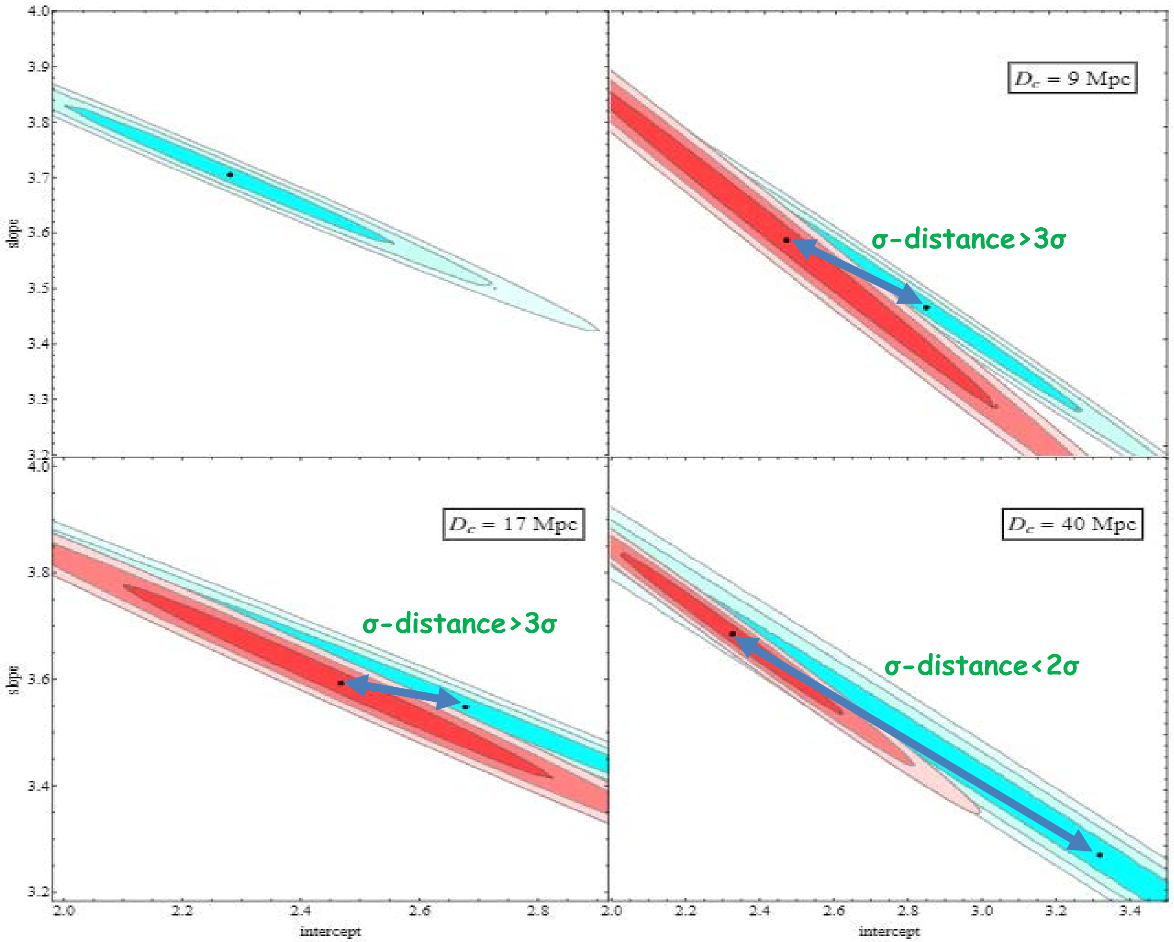
$$log M_B = s\, log v_{rot} + \log A_B \equiv s\ y + b$$

Tully-Fisher Data: Hints for transition

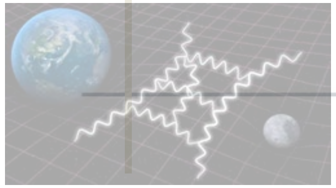
Split in two subsets: Σ_1: $D>D_c$, Σ_2: $D<D_c$.

Find σ-between the best fit parameters of each subset.





Tully-Fisher Data: Hints for transition



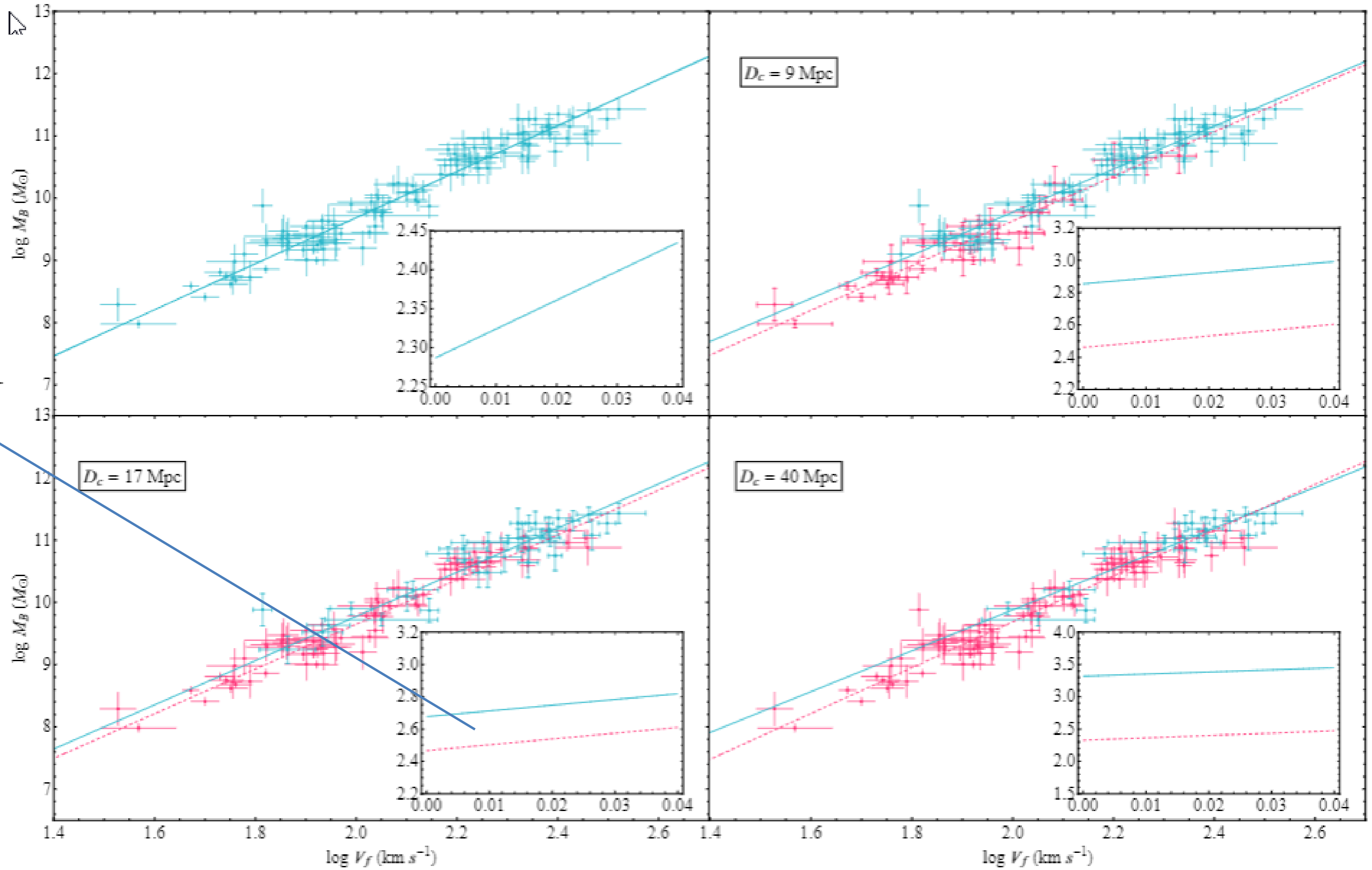
Split in two subsets: Σ_1: $D>D_c$, Σ_2: $D<D_c$.

Find σ-between the best fit parameters of each subset.

$$\log M_B = s \log v_{rot} + \log A_B \equiv s\ y + b$$

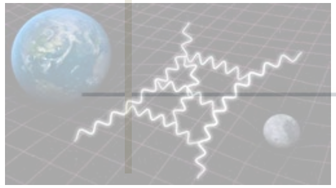
$$A_B \sim G^{-2} S^{-1}$$

$$\frac{\Delta A_B}{A_B} = -2\frac{\Delta G_{eff}}{G_{eff}} \implies \frac{\Delta G_{eff}}{G_{eff}} \simeq -0.1$$



Galaxies further away have higher A_B by 20% and thus lower G_{eff} by about 10% (3σ distance).

Other hints for transition: Cepheid luminosities



LP, F. Skara in preparation

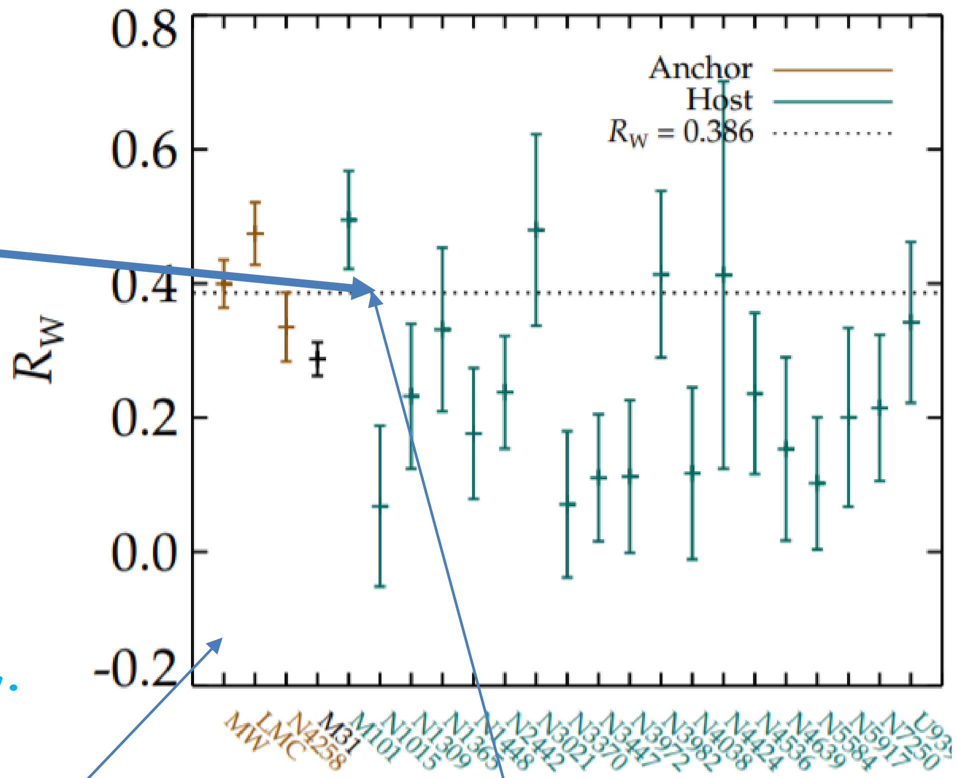
Cepheid star luminosities:

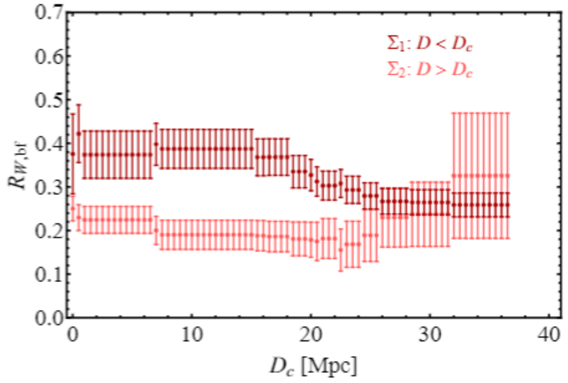
Hints for a luminosity transition

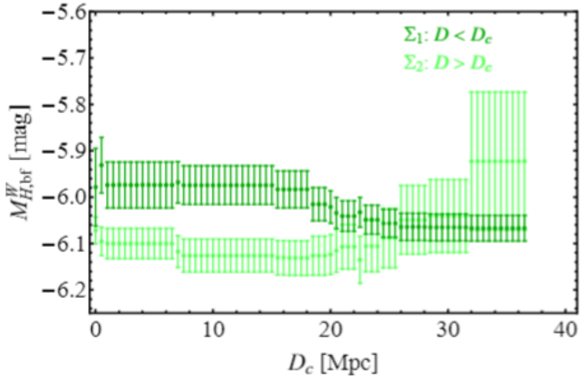
$$m^{\rm W}_{{\rm H},i,j} = \mu_i + M^{\rm W}_{\rm H} + b_{\rm W}[{\rm P}]_{i,j} + Z_{\rm W}[{\rm M/H}]_{i,j},$$

$$m^{\rm W}_{\rm H} \equiv m_{\rm H} - R_{\rm W}\,({\rm V-I})$$

Fit of Cepheid host dust extinction coefficient R_W.







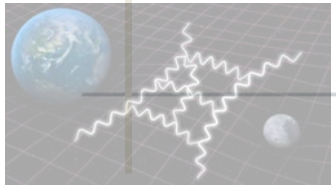
Distance ~ 10-20Mpc z~0.005

The Hubble Tension Bites the Dust: Sensitivity of the Hubble Constant Determination to Cepheid Color Calibration

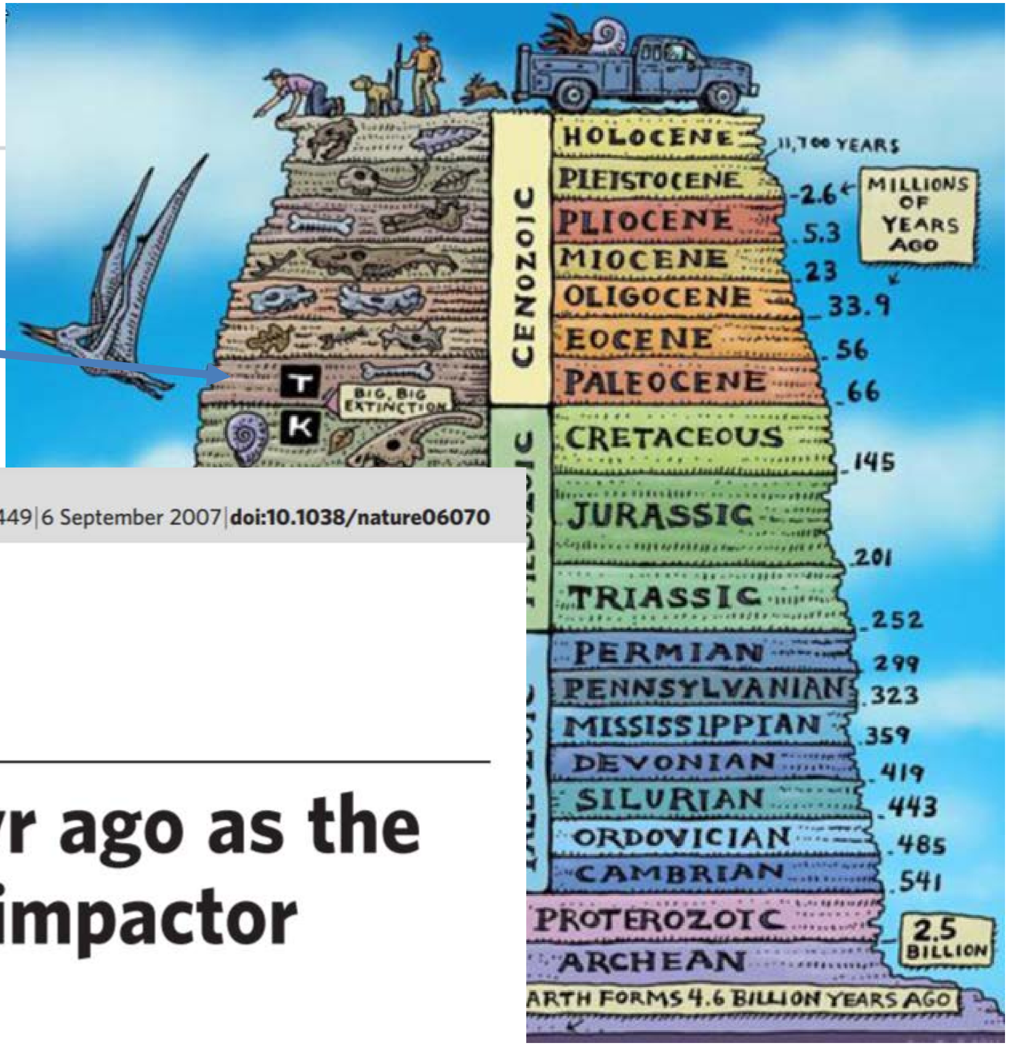
Edvard Mortsell, Ariel Goobar, Joel Johansson, Suhail Dhawan (May 24, 2021)

e-Print: 2105.11461 [astro-ph.CO]

Speculation: Extinction of Dinosaurs



Massive extinction: K/T Impactor



nature Vol 449|6 September 2007|doi:10.1038/nature06070

ARTICLES

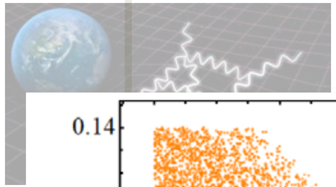
An asteroid breakup 160 Myr ago as the probable source of the K/T impactor

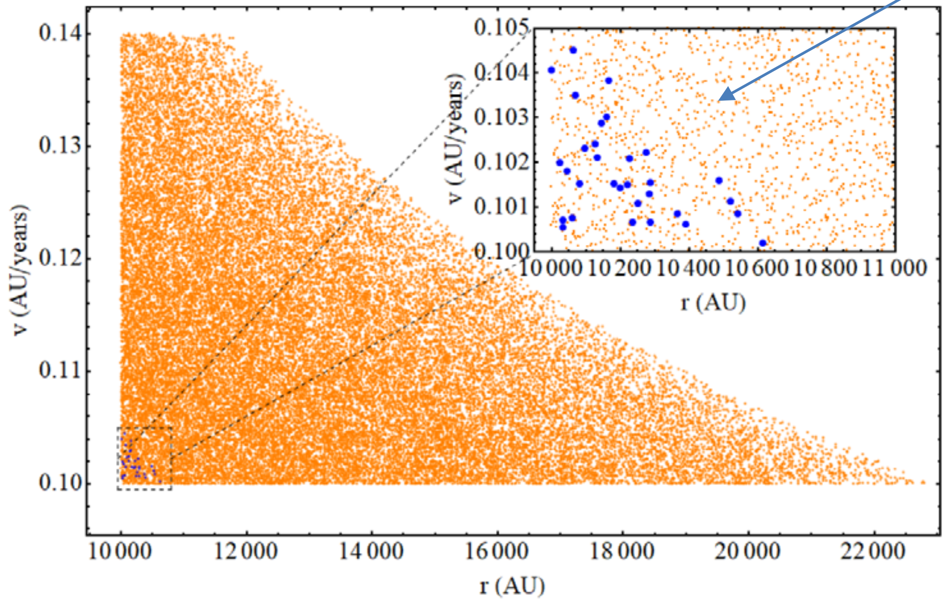
William F. Bottke[1], David Vokrouhlický[1,2] & David Nesvorný[1]

The terrestrial and lunar cratering rate is often assumed to have been nearly constant over the past 3 Gyr. Different lines of evidence, however, suggest that the impact flux from kilometre-sized bodies increased by at least a factor of two over the long-term average during the past ~100 Myr. Here we argue that this apparent surge was triggered by the catastrophic disruption of the

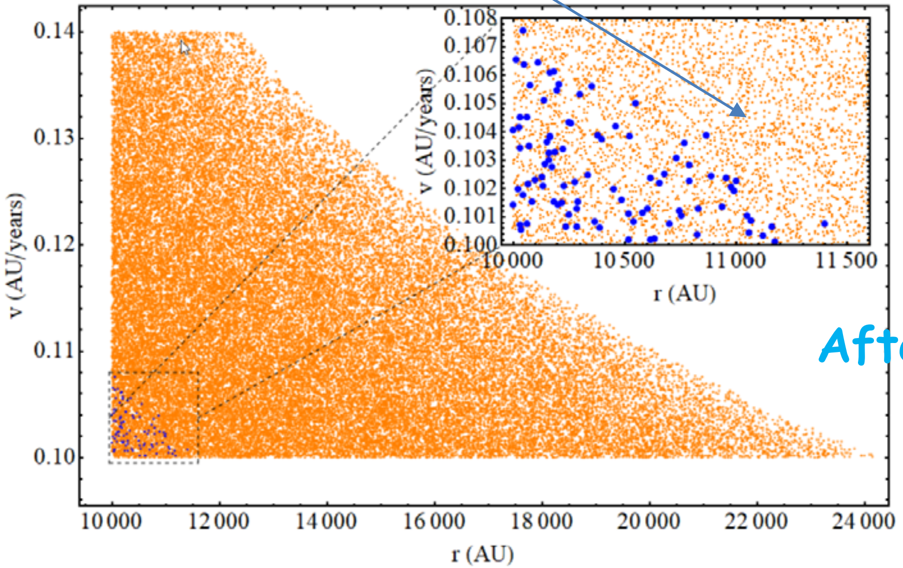
Perturbed Comets that Hit the Solar System

Comets that hit the solar system after a given set of random velocity perturbations.

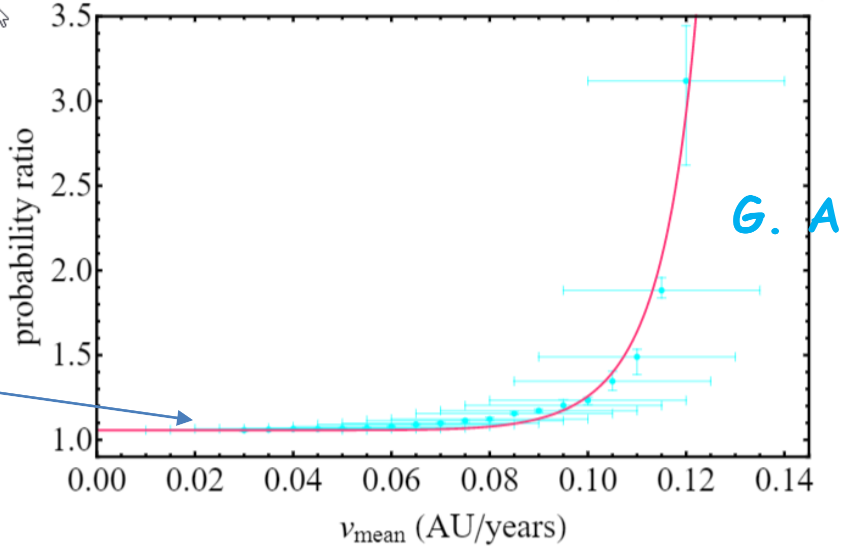




Before a 10% gravitational transition.



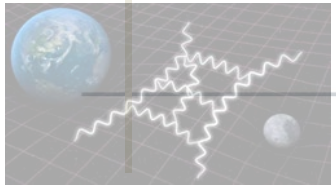
After a 10% gravitational transition.



G. Alestas, LP in progress

Larger velocity perturbations of comets can lead to large probability enhancement for entering the solar system after a gravitational transition.

Conclusion



Late time H(z) deformation approaches to the Hubble tension suffer from 3 problems: the χ^2 problem, the growth tension worsening and the M problem.

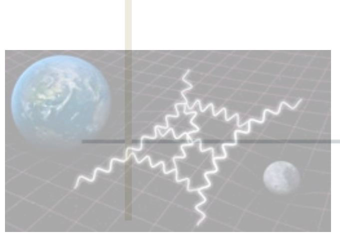
These problems are avoided if the H(z) deformation is replaced by a sudden diming of the SnIa intrinsic luminosity occurring less than 150 million years ago (z_t<0.01).

Such a diming may be due to a sudden increase of the strength G_{eff} of gravitational interactions by about 10% at z_t<0.01. This is a viable and testable conjecture.

There are hints for such a transition in recent Tully-Fisher data which probe the dynamics of galaxies at low z.

Corresponding hints exist in other types of astrophysical data (Cepheid, Comet impact rates).

Viability of a gravitational transition



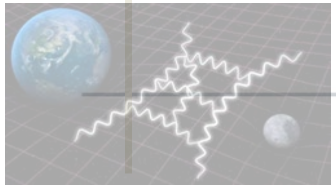
Method	$\frac{\Delta G_{eff}}{G_{eff}}\big\|_{max}$	$\frac{\dot{G}_{eff}}{G_{eff}}\big\|_{max}$ (yr^{-1})	time scale (yr)	References
Lunar ranging		1.47×10^{-13}	24	Hofmann & Müller (2018)
Solar system		7.8×10^{-14}	50	Pitjeva & Pitjev (2013)
Pulsar timing		3.1×10^{-12}	1.5	Deller et al. (2008)
Orbits of binary pulsar		1.0×10^{-12}	22	Zhu et al. (2019)
Ephemeris of Mercury		4×10^{-14}	7	Genova et al. (2018)
Exoplanetary motion		10^{-6}	4	Masuda & Suto (2016)
Hubble diagram SnIa	0.1	1×10^{-11}	$\sim10^{8}$	Gaztañaga et al. (2009)
Pulsating white-dwarfs		1.8×10^{-10}	0	Córsico et al. (2013)
Viking lander ranging		4×10^{-12}	6	Hellings et al. (1983)
Helioseismology		1.6×10^{-12}	4×10^{9}	Guenther et al. (1998)
Gravitational waves	8	5×10^{-8}	1.3×10^{8}	Vijaykumar et al. (2020)
Paleontology	0.1	2×10^{-11}	4×10^{9}	Uzan (2003)
Globular clusters		35×10^{-12}	$\sim10^{10}$	Degl'Innocenti et al. (1996)
Binary pulsar masses		4.8×10^{-12}	$\sim10^{10}$	Thorsett (1996)
Gravitochemical heating		4×10^{-12}	$\sim10^{8}$	Jofre et al. (2006)
Big Bang Nucleosynthesis*	0.05	4.5×10^{-12}	1.4×10^{10}	Alvey et al. (2020)
Anisotropies in CMB*	0.095	1.75×10^{-12}	1.4×10^{10}	Wu & Chen (2010)

Marginally viable if $G_N=G_{eff}$ and assuming $$\Delta M = \frac{15}{4}\, log_{10}\,(\mu)$$

Any of these may need to be modified (more studies are needed)

Search for hints of gravitational transition in other astrophysical data

The large scale tensions of the standard model



1. **The Hubble crisis (5σ):** Local direct measurements of H_0 are in 5σ tension with CMB indirect measurements of H_0. (Planck CMB: H_0=67.4, SnIa+Cepheids: 74.03 (5σ, 9%))

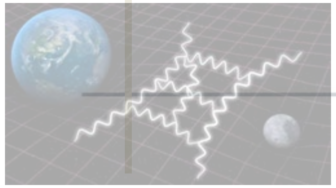
2. **The growth tension (2-3σ):** Direct measurements of the growth rate of cosmological perturbations (weak lensing, peculiar velocities, cluster counts) indicate a lower growth rate than that indicated by Planck-ΛCDM (lower matter density).

3. **CMB anisotropy anomalies (2-3σ):** Lack of power on large angular scales, small vs large scales tension (different best fit values of cosmological parameters), cold spot anomaly, hemispherical temperature variance asymmetry, preference for odd parity correlations etc.

4. **Cosmic Dipoles (2-4σ):** Fine structure constant dipole (quasar spectra), quasar density dipole, large scale velocity bulk flow.

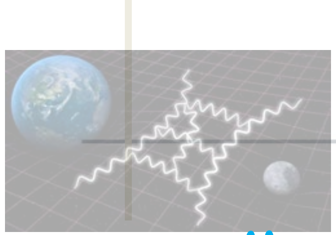
5. **The Lithium problem (2-4σ):** Measurements of old, metal-poor stars in the Milky Way's halo find 5 times less lithium that BBN predicts.

Structure of talk



1. The Hubble tension, measurable degenerate parameter combinations and the three classes of models
2. The growth tension
3. The sound horizon scale modification class and the growth tension
4. The H(z) deformation class and its three problems
5. The SnIa luminosity transition and the three problem resolution.
6. Gravitational transition in the Tully-Fisher data?
7. Conclusions – The road ahead

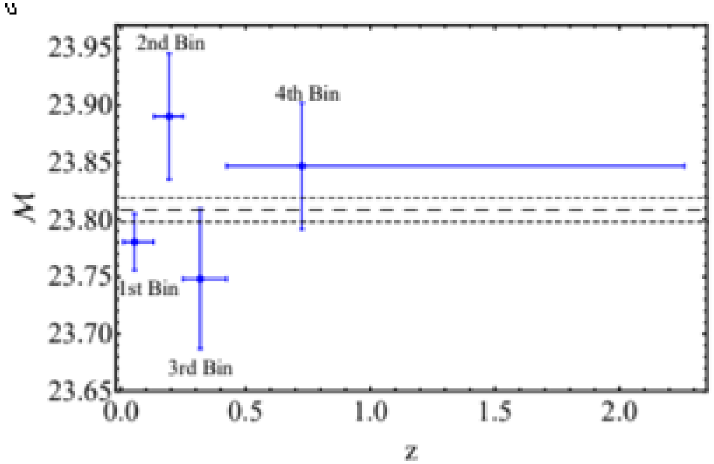
SnIa luminosity and effects of gravity



$$m_{th}(z) = M + 5\,log_{10}\left(D_L(z)\right) + 5\,log_{10}\left(\frac{c/H_0}{1Mpc}\right) + 25$$

Measured parameter combination by uncalibrated SnIa: $\mathcal{M} = M + 5log\dfrac{c/H_0}{Mpc}$

What could be the cause of a possible M variation with redshift?



Modified gravity: $L \sim M_{Chandr} \sim G^{-3/2}$ $\Rightarrow$ $M - M_0 = \dfrac{15}{4}\log\left(\dfrac{G}{G_0}\right)$

Bounds on the possible evolution of the gravitational constant from cosmological type Ia supernovae

E. Gaztanaga (INAOE, Puebla and Barcelona, IEEC), E. Garcia-Berro (Barcelona, Polytechnic U. and Barcelona, IEEC), J. Isern (Barcelona, IEEC), E. Bravo (Barcelona, Polytechnic U. and Barcelona, IEEC), I. Dominguez (Granada U., Theor. Phys. Astrophys.) (Apr, 2001)

Published in: *Phys.Rev.D* 65 (2002) 023506 • e-Print: astro-ph/0109299 [astro-ph]

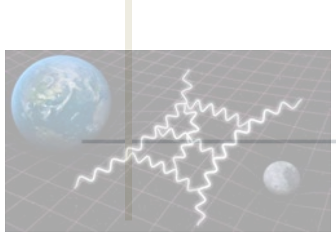
Is gravity getting weaker at low z? Observational evidence and theoretical implications

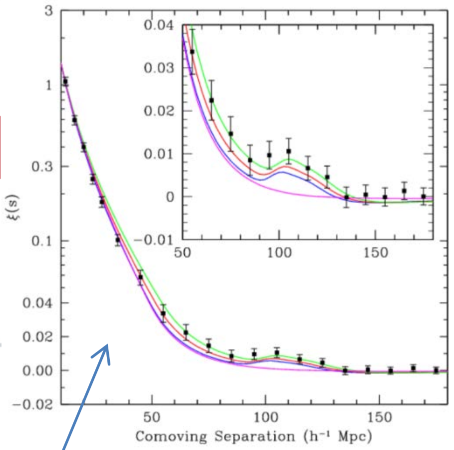
Lavrentios Kazantzidis (Ioannina U.), Leandros Perivolaropoulos (Ioannina U.) (Jul 6, 2019)

e-Print: 1907.03176 [astro-ph.CO]

Invited contribution for the White Paper of COST CA-15117 project `CANTATA' (Cosmology and Astrophysics Network for Theoretical Advances and Training Actions) `Observational Discriminators' section. The numerical analysis files that were used for the production of the figures may be downloaded from http://leandros.physics.uoi.gr/cantata-wp/wp-num-analysis.zip

Measuring H_0-H(z) with a stand early time calibrators





Sound Horizon at Recombination Standard Ruler (Early Universe):

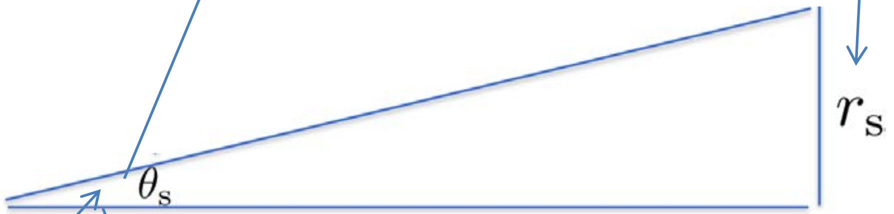
$$r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Depends on ρ_b, ρ_γ and ρ_{CDM}

r_s=147.6 Mpc from Planck and BBN values of ρ_b, ρ_γ and ρ_{CDM}

inferred

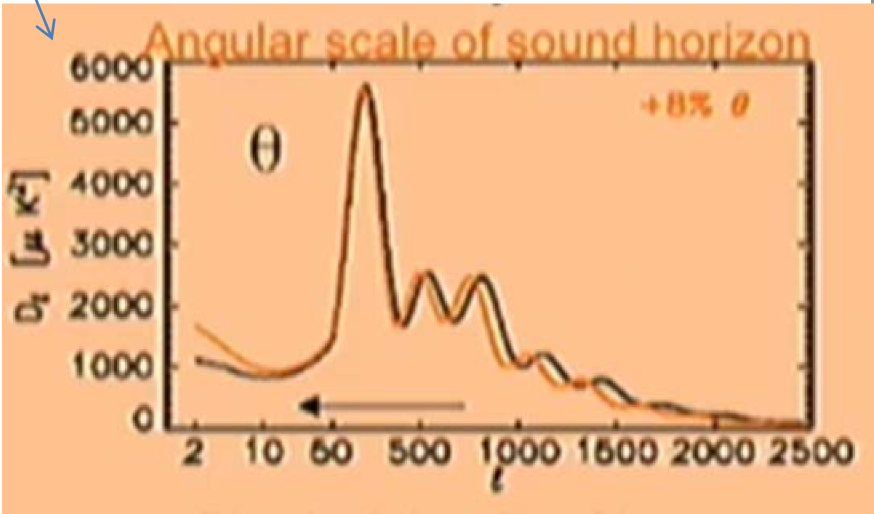
calculated



measured

$$\theta_s = \frac{r_s}{D_A(z)}$$

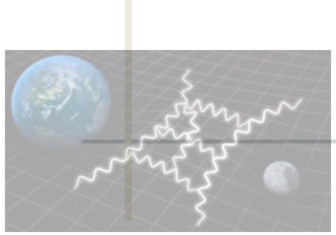
comoving



$$E(z) = \left[\Omega_{0m}(1+z)^3 + (1-\Omega_{0m})\right]^{\frac{1}{2}}$$

Degeneracy between r_s and H_0 and E(z).

Measuring H_0–H(z) with standard candles: late time calibrators



Fit SnIa Standard Candles for H_0 , z<0.1:

fit with kinematic expansion (z<0.1)

$$D_L(z, q_0) = cz\left[1 + \frac{1}{2}(1 - q_0)z\right]$$

$$m_{th}(z) = M + 5\,log_{10}\left[\frac{d_L(z)}{Mpc}\right] + 25$$

$$d_L = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

$$D_L(z) = \frac{H_0\, d_L(z)}{c}$$

$$m_{th}(z) = M + 5\,log_{10}\,(D_L(z)) + 5\,log_{10}\left(\frac{c/H_0}{1Mpc}\right) + 25$$

measure

measure locally (z<0.01, 40Mpc) using relative distance indicators (eg Cepheids)

fit

Degeneracy between M (measured at z<0.01) and H_0 (fit at z>>>>>>> 0.01).

Fit for H(z) and cosmological parameters (Ω_{0m}) z_{max}~2.

Parametrize H(z): $$H(z)^2 = H_0^2\left[\Omega_{0m}(1+z)^3 + (1 - \Omega_{0m})\right]$$

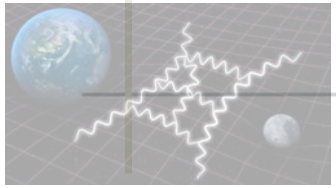
$$m_{th}(\Omega_{0m}, \mathcal{M}) = 5\,log_{10} D_L(z; \Omega_{0m}) + \mathcal{M}(M, H_0)$$

$$D_L(z, \Omega_{0m}) = c(1+z)\int_0^z \frac{dz'}{\left[\Omega_{0m}(1+z')^3 + (1 - \Omega_{0m})\right]^{1/2}}$$

Minimize: $$\chi^2(\mathcal{M}, \Omega_{0m}) = \sum_i \left[\frac{m_{obs,i} - m_{th}(z_i; \Omega_{0m}, \mathcal{M})}{\sigma_i^2}\right]$$

$$\mathcal{M} = M + 5log\frac{c/H_0}{Mpc} + 25$$

Subhorizon Growth of Matter Perturbations



The dynamical linear growth of perturbations $\delta_m(z,\Omega_{m0})$:

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G_{\rm eff}\, \rho\, \delta_m \approx 0$$

$$\delta_m \equiv \frac{\delta\rho}{\rho}$$

$$H^2 = \frac{8\pi G_N}{3}\rho$$

$$H^2\, \delta_m'' + \left(\frac{(H^2)'}{2} - \frac{H^2}{1+z}\right)\delta_m' \approx \frac{3}{2}(1+z)H_0^2\frac{G_{\rm eff}(z)}{G_{N,0}}\, \Omega_{m,0}\, \delta_m$$

$$F_G = G_{eff}\frac{m_1 m_2}{r^2}$$

$$H(z) = H_0^{\rm P18}\sqrt{\Omega_{0m}(1+z)^3 + 1 - \Omega_{0m}}$$

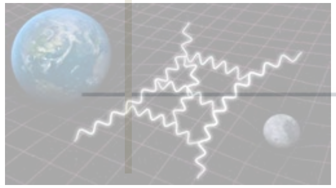
Example: Scalar-Tensor theories

$$S = \frac{1}{16\pi G_*}\int d^4x\sqrt{-g}\Big(F(\Phi)\; R - Z(\Phi)\; g^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi - 2U(\Phi)\Big) + S_m[\psi_m; g_{\mu\nu}]\;.$$

$$G_N \equiv G_*/F \qquad G_{\rm eff} \equiv \frac{G_*}{F}\left(\frac{2ZF + 4(dF/d\Phi)^2}{2ZF + 3(dF/d\Phi)^2}\right)$$

Scalar tensor gravity in an accelerating universe
Gilles Esposito-Farese (Marseille, CPT and DARC, Meudon), D. Polarski (Tours U. and DARC, Meudon and Montpellier U.) (Sep, 2000)
Published in: *Phys.Rev.D* 63 (2001) 063504 • e-Print: gr-qc/0009034 [gr-qc]

Observational Probe of Perturbation Growth



Growth rate: $f(a) = \frac{d\ln\delta}{d\ln a}$

Density rms fluctuations within spheres of radius R = 8h^{-1}Mpc $\sigma(a) = \sigma_8 \frac{\delta(a)}{\delta(1)}$

Bias free combination: $f\sigma_8(a) \equiv f(a)\cdot\sigma(a) = \frac{\sigma_8}{\delta(1)}\, a\, \delta'(a)$, $b = \frac{\delta_g}{\delta}$

34 $f\sigma_8(z)$ datapoints from RSD survey measurements (each assuming different fiducial cosmology), 18 of them robust-independent

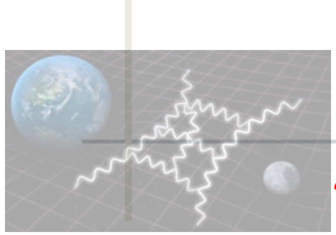
Construct theoretically predicted $f\sigma_8(a,\sigma_8,\Omega_{0m})$: $f\sigma_8(a) \equiv f(a)\cdot\sigma(a) = \frac{\sigma_8}{\delta(1)}\, a\, \delta'(a)$

Construct $\chi^2(\sigma_8,\Omega_{0m})$: $V^i(z_i,p^j) = f\sigma_{8,i} - f\sigma_8(z_i,p^j)$ $\chi^2_{growth} = V^i\, C^{-1}_{ij}\, V^j$,

Tension of the E_G statistic and redshift space distortion data with the Planck - ΛCDM model and implications for weakening gravity
F. Skara (Ioannina U.), L. Perivolaropoulos (Ioannina U.) (Nov 24, 2019)
Published in: Phys.Rev.D 101 (2020) 6, 063521 • e-Print: 1911.10609 [astro-ph.CO]

Tension and constraints on modified gravity parametrizations of $G_{\rm eff}(z)$ from growth rate and Planck data
Savvas Nesseris (Madrid, IFT), George Pantazis (Ioannina U.), Leandros Perivolaropoulos (Patras U.) (Mar 30, 2017)
Published in: Phys.Rev.D 96 (2017) 2, 023542 • e-Print: 1703.10538 [astro-ph.CO]

Modifying the early time calibrator: Early Dark Energy



Assumption Modified: Standard expansion before z_{rec}

Calculated: $r_s = \int_{z_{rec}}^{\infty} \frac{dz\, c_s(z)}{H(z; \rho_b, \rho_\gamma, \rho_{CDM})}$

$$\theta_s = \frac{r_s H_0}{\int_0^{z_{rec}} 1/E(z)}$$

Deduced

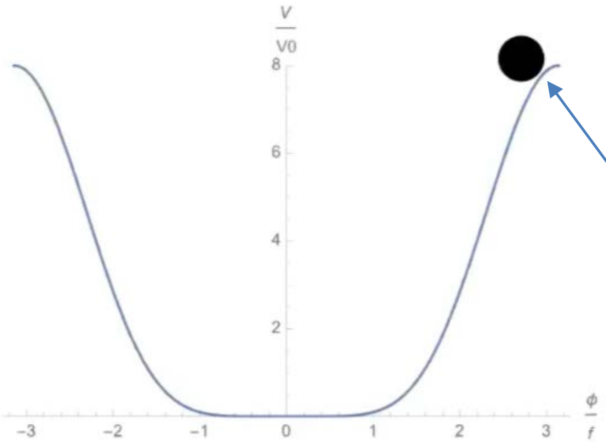
Measured (CMB anisotropy spectrum peaks)

$$E(z)^2 = \Omega_{0m}(1+z)^3 + (1-\Omega_{0m})$$

Decrease sound horizon using more rapid expansion before recombination (Dark Energy):

$$r_s = \int_{z_{rec}}^{\infty} \frac{dz\, c_s(z)}{H(z; \rho_b, \rho_\gamma, \rho_{CDM}, \rho_{DE})}$$

Increases early expansion rate and thus decreases r_s.



Initially H>>m (field frozen)

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

Early Dark Energy Can Resolve The Hubble Tension

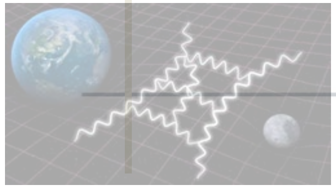
Vivian Poulin (Johns Hopkins U.), Tristan L. Smith (Swarthmore Coll.), Tanvi Karwal (Johns Hopkins U.), Marc Kamionkowski (Johns Hopkins U.) (Nov 9, 2018)

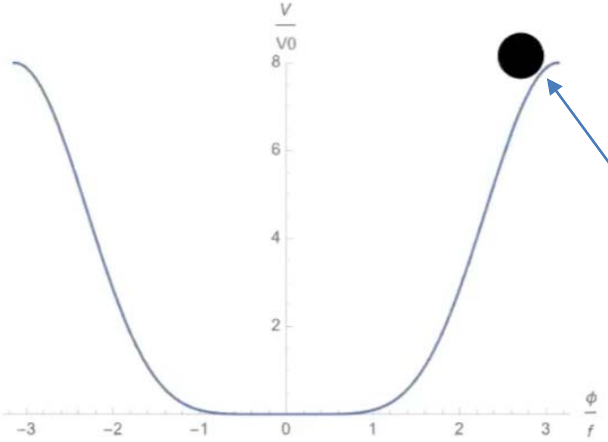
Published in: *Phys.Rev.Lett.* 122 (2019) 22, 221301 • e-Print: 1811.04083 [astro-ph.CO]

Early Dark Energy

Field energy must dissipate faster than matter to avoid spoiling other data

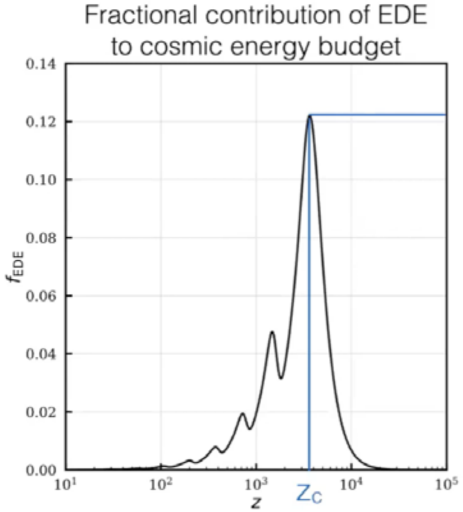
$$V(\phi) = m^2 f^2 \left(1 - \cos\left(\phi/f\right)\right)^n \Rightarrow w_\phi = \frac{n-1}{n+1}$$

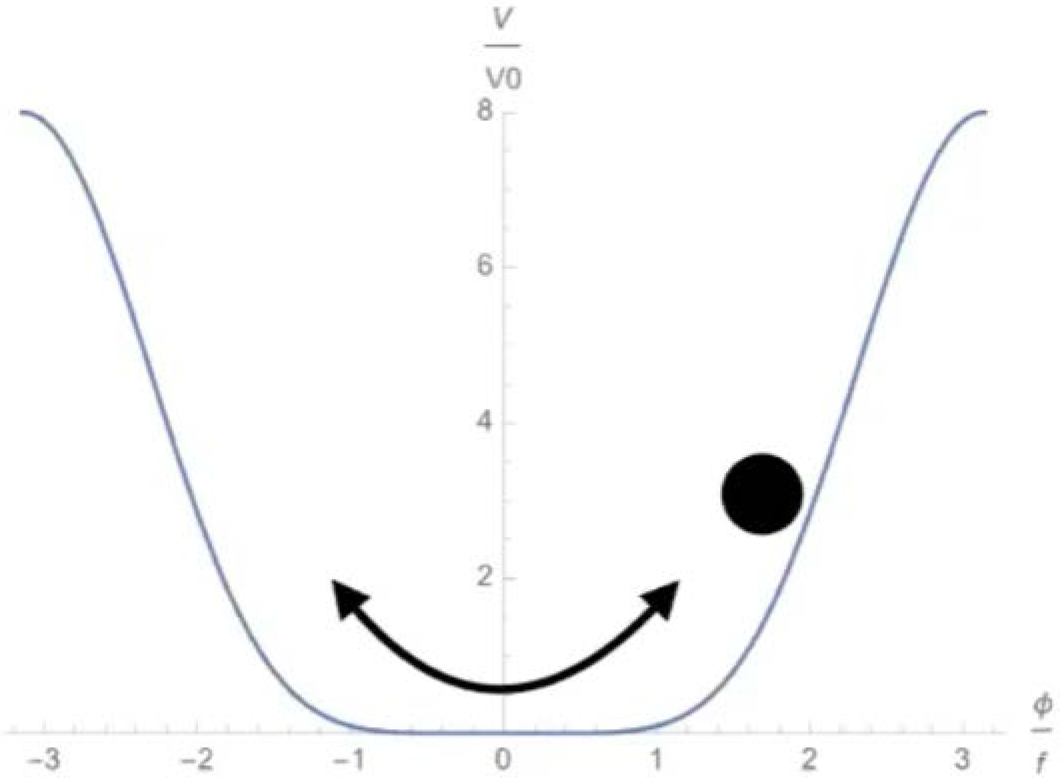




$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

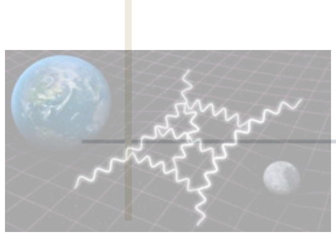
Initially H>>m (field frozen)



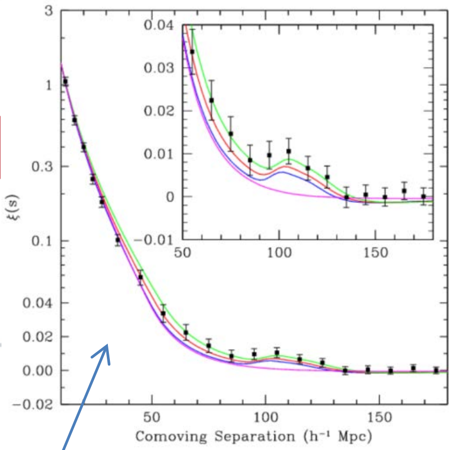


When H~m the field rolls down its potential (mass dominates Hubble friction).

This happens when $z=z_{rec}$ ($m \sim 10^{-27}$ eV)



Measuring H_0-H(z) with a standard early time calibrators

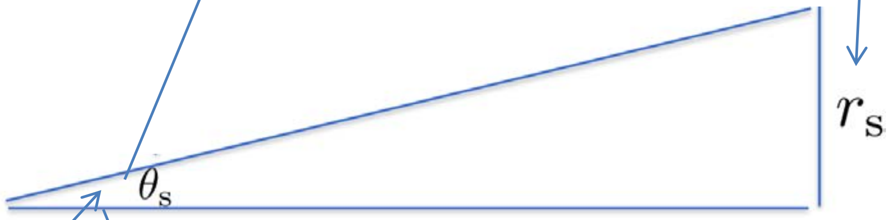


calculated

Sound Horizon at Recombination Standard Ruler (Early Universe):

$$r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Depends on ρ_b, ρ_γ and ρ_{CDM}



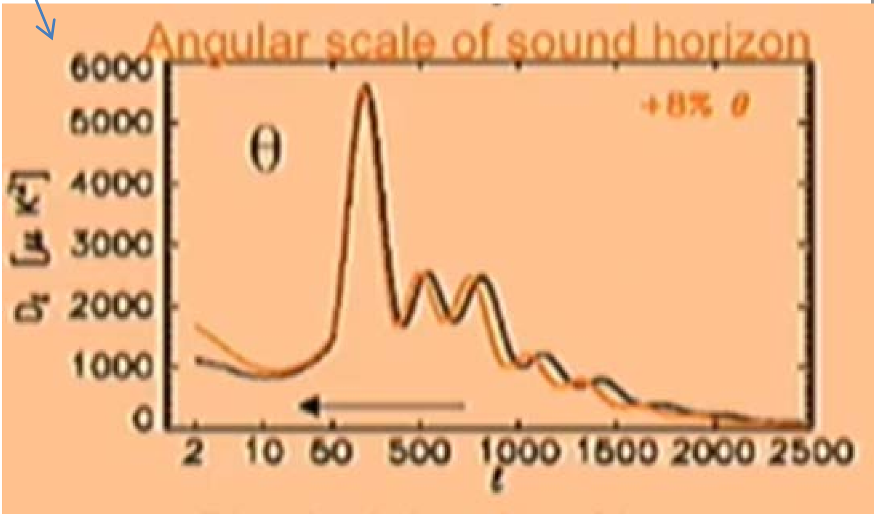
$D_A(z = 1100)$

r_s=147.6 Mpc from Planck and BBN values of ρ_b, ρ_γ and ρ_{CDM}

inferred

measured

$$\theta_s = \frac{r_s}{D_A(z)}$$

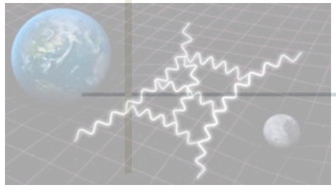


comoving

$$E(z) = \left[\Omega_{0m}(1+z)^3 + (1-\Omega_{0m})\right]^{\frac{1}{2}}$$

Degeneracy between r_s and H_0 and E(z).

Measuring H_0–H(z) with standard candles: late time calibrators



Fit SnIa Standard Candles for H_0 , z<0.1:

fit with kinematic expansion (z<0.1)

$$D_L(z,q_0) = cz\left[1+\frac{1}{2}(1-q_0)z\right]$$

$$m_{th}(z) = M + 5\,log_{10}\left[\frac{d_L(z)}{Mpc}\right] + 25$$

$$d_L = c(1+z)\int_0^z \frac{dz'}{H(z')}$$

$$D_L(z) = \frac{H_0\, d_L(z)}{c}$$

$$m_{th}(z) = M + 5\,log_{10}\left(D_L(z)\right) + 5\,log_{10}\left(\frac{c/H_0}{1Mpc}\right) + 25$$

measure

measure locally (z<0.01, 40Mpc) using relative distance indicators (eg Cepheids)

fit

Degeneracy between M (measured at z<0.01) and H_0 (fit at z>>>>>>> 0.01).

Fit for H(z) and cosmological parameters (Ω_{0m}) z_{max}~2.

Parametrize H(z): $H(z)^2 = H_0^2\left[\Omega_{0m}(1+z)^3 + (1-\Omega_{0m})\right]$

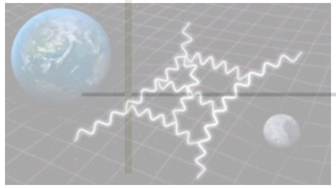
$$m_{th}(\Omega_{0m},\mathcal{M}) = 5\,log_{10} D_L(z;\Omega_{0m}) + \mathcal{M}(M,H_0)$$

$$D_L(z,\Omega_{0m}) = c(1+z)\int_0^z \frac{dz'}{\left[\Omega_{0m}(1+z')^3+(1-\Omega_{0m})\right]^{1/2}}$$

Minimize: $\chi^2(\mathcal{M},\Omega_{0m}) = \sum_i \left[\frac{m_{obs,i} - m_{th}(z_i;\Omega_{0m},\mathcal{M})}{\sigma_i^2}\right]$

$$\mathcal{M} = M + 5log\frac{c/H_0}{Mpc} + 25$$

Subhorizon Growth of Matter Perturbations



The dynamical linear growth of perturbations $\delta_m(z,\Omega_{m0})$:

$$\ddot{\delta}_m + 2H\dot{\delta}_m - 4\pi G_{\text{eff}}\,\rho\,\delta_m \approx 0$$

$$\delta_m \equiv \frac{\delta\rho}{\rho}$$

$$H^2 = \frac{8\pi G_N}{3}\rho$$

$$H^2\,\delta_m'' + \left(\frac{(H^2)'}{2} - \frac{H^2}{1+z}\right)\delta_m' \approx \frac{3}{2}(1+z)H_0^2\frac{G_{\text{eff}}(z)}{G_{N,0}}\,\Omega_{m,0}\,\delta_m$$

$$F_G = G_{eff}\frac{m_1 m_2}{r^2}$$

$$H(z) = H_0^{\text{P18}}\sqrt{\Omega_{0m}(1+z)^3 + 1 - \Omega_{0m}}$$

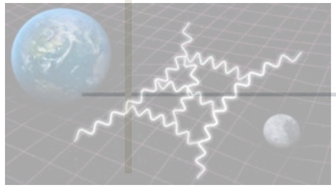
Example: Scalar-Tensor theories

$$S = \frac{1}{16\pi G_*}\int d^4x\sqrt{-g}\Big(F(\Phi)\,R - Z(\Phi)\,g^{\mu\nu}\partial_\mu\Phi\partial_\nu\Phi - 2U(\Phi)\Big) + S_m[\psi_m; g_{\mu\nu}]\,.$$

$$G_N \equiv G_*/F \qquad G_{\text{eff}} \equiv \frac{G_*}{F}\left(\frac{2ZF + 4(dF/d\Phi)^2}{2ZF + 3(dF/d\Phi)^2}\right)$$

Scalar tensor gravity in an accelerating universe
Gilles Esposito-Farese (Marseille, CPT and DARC, Meudon), D. Polarski (Tours U. and DARC, Meudon and Montpellier U.) (Sep, 2000)
Published in: *Phys.Rev.D* 63 (2001) 063504 • e-Print: gr-qc/0009034 [gr-qc]

Observational Probe of Perturbation Growth



Growth rate: $f(a) = \frac{dln\delta}{dlna}$

Density rms fluctuations within spheres of radius R = 8h^{-1}Mpc $\sigma(a) = \sigma_8 \frac{\delta(a)}{\delta(1)}$

Bias free combination: $f\sigma_8(a) \equiv f(a) \cdot \sigma(a) = \frac{\sigma_8}{\delta(1)} \, a \, \delta'(a)$, $b = \frac{\delta_g}{\delta}$

34 $f\sigma_8(z)$ datapoints from RSD survey measurements (each assuming different fiducial cosmology), 18 of them robust-independent

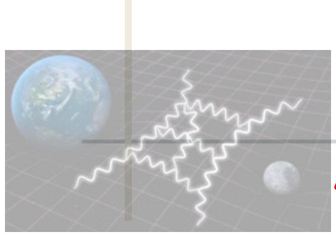
Construct theoretically predicted $f\sigma_8(a, \sigma 8, \Omega_{0m})$: $f\sigma_8(a) \equiv f(a) \cdot \sigma(a) = \frac{\sigma_8}{\delta(1)} \, a \, \delta'(a)$

Construct $\chi^2(\sigma 8, \Omega_{0m})$: $V^i(z_i, p^j) = f\sigma_{8,i} - f\sigma_8(z_i, p^j)$ $\chi^2_{growth} = V^i \, C^{-1}_{ij} \, V^j,$

Tension of the E_G statistic and redshift space distortion data with the Planck - ΛCDM model and implications for weakening gravity
F. Skara (Ioannina U.), L. Perivolaropoulos (Ioannina U.) (Nov 24, 2019)
Published in: *Phys.Rev.D* 101 (2020) 6, 063521 • e-Print: 1911.10609 [astro-ph.CO]

Tension and constraints on modified gravity parametrizations of $G_{\rm eff}(z)$ from growth rate and Planck data
Savvas Nesseris (Madrid, IFT), George Pantazis (Ioannina U.), Leandros Perivolaropoulos (Patras U.) (Mar 30, 2017)
Published in: *Phys.Rev.D* 96 (2017) 2, 023542 • e-Print: 1703.10538 [astro-ph.CO]

Modifying the early time calibrator: Early Dark Energy



Assumption Modified: Standard expansion before z_{rec}

Calculated: $r_s = \int_{z_{rec}}^{\infty} \frac{dz\, c_s(z)}{H(z; \rho_b, \rho_\gamma, \rho_{CDM})}$

Deduced

$$\theta_s = \frac{r_s H_0}{\int_0^{z_{rec}} 1/E(z)}$$

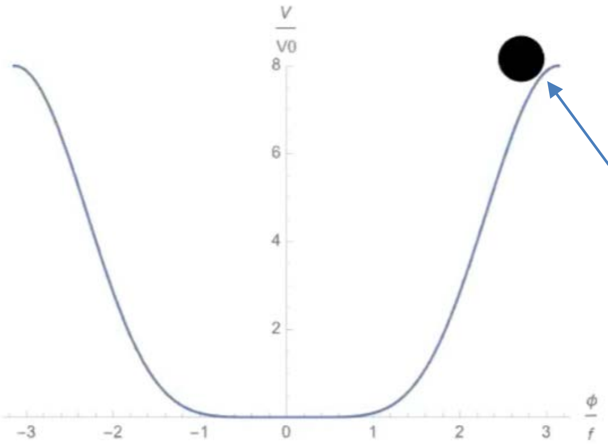
Measured (CMB anisotropy spectrum peaks)

$$E(z)^2 = \Omega_{0m}(1+z)^3 + (1 - \Omega_{0m})$$

Decrease sound horizon using more rapid expansion before recombination (Dark Energy):

$$r_s = \int_{z_{rec}}^{\infty} \frac{dz\, c_s(z)}{H(z; \rho_b, \rho_\gamma, \rho_{CDM}, \rho_{DE})}$$

Increases early expansion rate and thus decreases r_s.



Initially H>>m (field frozen)

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

Early Dark Energy Can Resolve The Hubble Tension

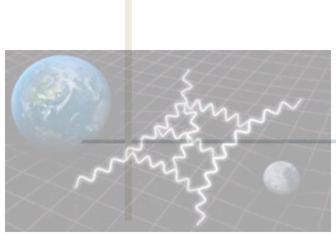
Vivian Poulin (Johns Hopkins U.), Tristan L. Smith (Swarthmore Coll.), Tanvi Karwal (Johns Hopkins U.), Marc Kamionkowski (Johns Hopkins U.) (Nov 9, 2018)

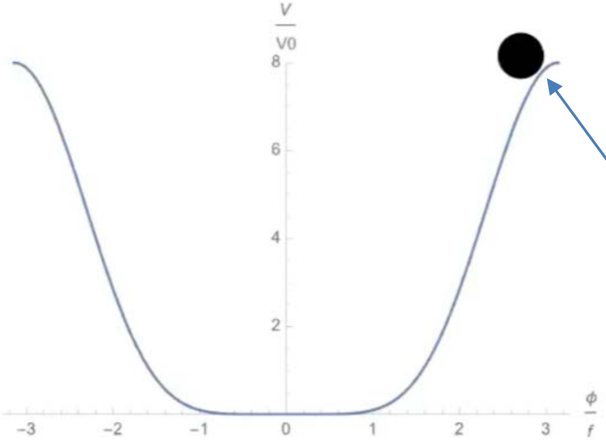
Published in: *Phys.Rev.Lett.* 122 (2019) 22, 221301 • e-Print: 1811.04083 [astro-ph.CO]

Early Dark Energy

Field energy must dissipate faster than matter to avoid spoiling other data

$$V(\phi) = m^2 f^2 \left(1 - \cos(\phi/f)\right)^n \Rightarrow w_\phi = \frac{n-1}{n+1}$$

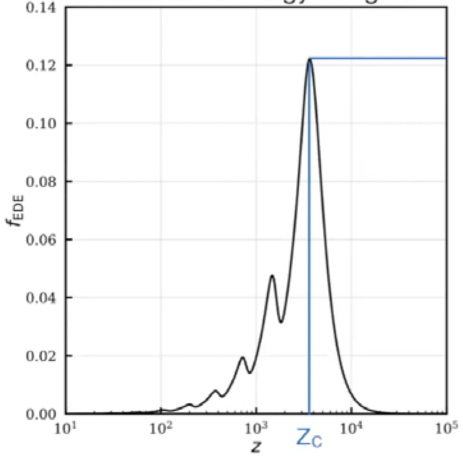


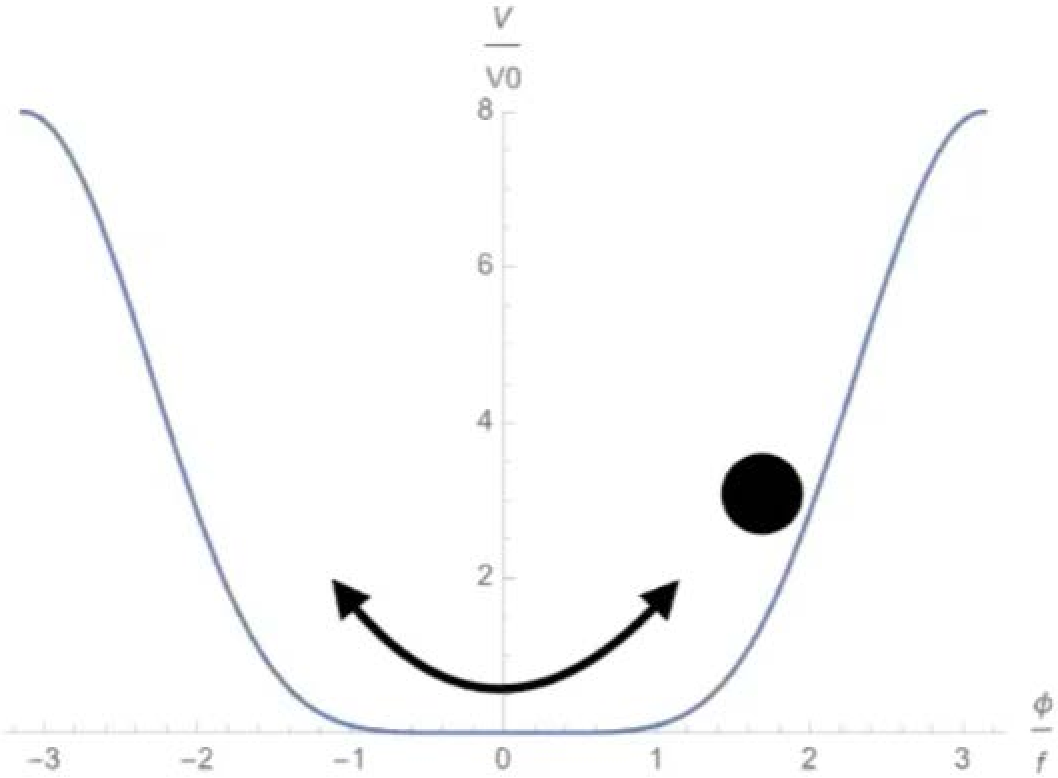


$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

Initially H>>m (field frozen)

Fractional contribution of EDE to cosmic energy budget

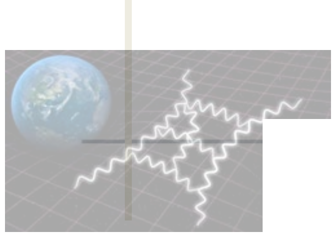


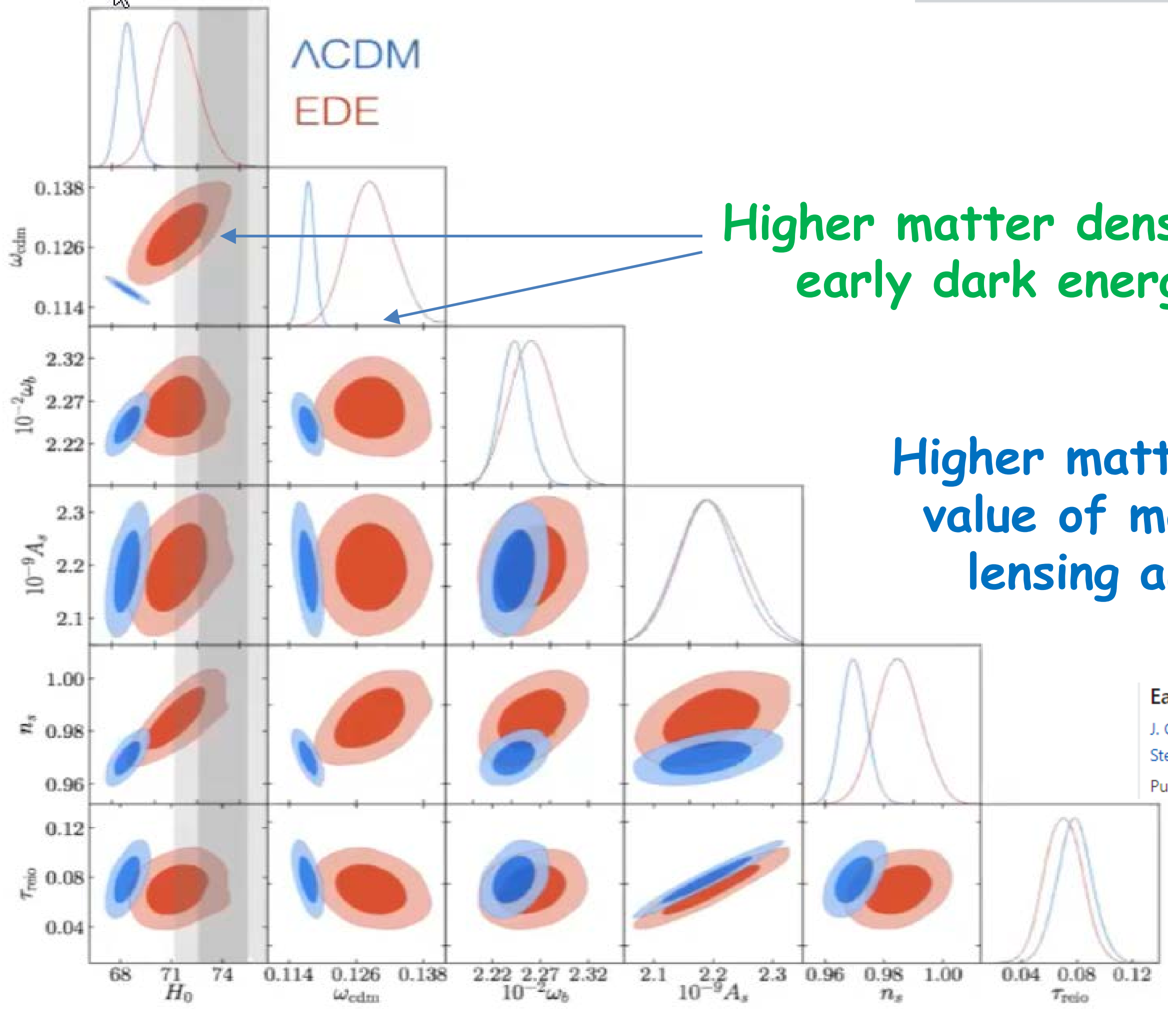


When H~m the field rolls down its potential (mass dominates Hubble friction).

This happens when $z=z_{rec}$ ($m \sim 10^{-27}$ eV)

Problem Early Dark Energy worsens growth tension





Higher matter density is required to compensate for early dark energy effect after recombination.

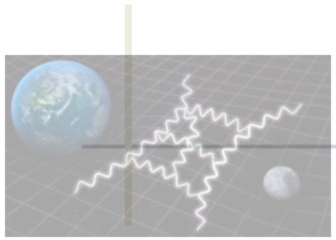
Higher matter density contradicts the required low value of matter density at late times from weak lensing and growth data (growth tension gets worse).

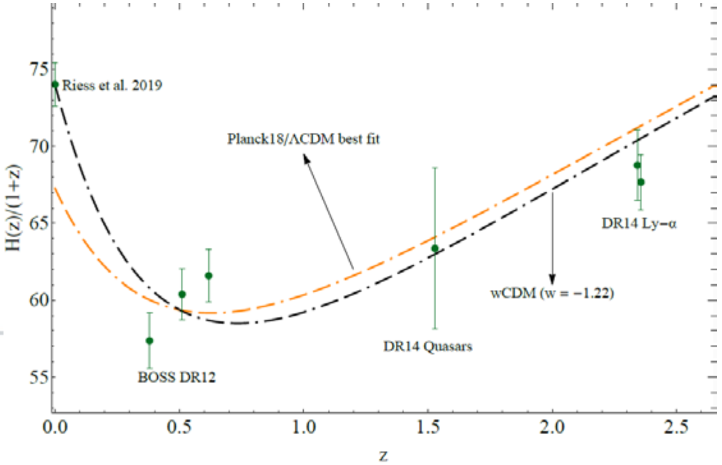
Early dark energy does not restore cosmological concordance

J. Colin Hill (Columbia U. (main) and Flatiron Inst., New York), Evan McDonough (Brown U. (main) and MIT), Michael W. Toomey (Brown U. (main)), Stephon Alexander (Brown U. (main)) (Mar 17, 2020)

Published in: *Phys.Rev.D* 102 (2020) 4, 043507 • e-Print: 2003.07355 [astro-ph.CO]

Special case Ⅰ: wCDM





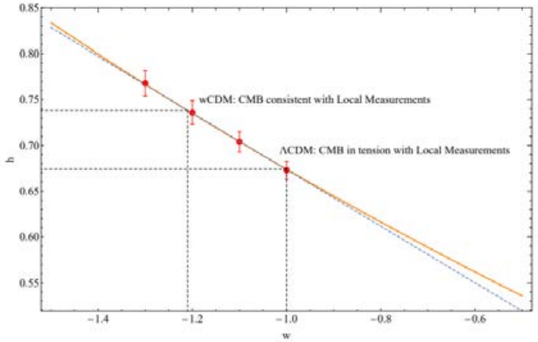
H(z) for wCDM

$$h(z;w)^2 = \left[\Omega_{0m}h^2(1+z)^3 + \Omega_{0r}h^2(1+z)^4 + (h^2 - \Omega_{0m}h^2 - \Omega_{0r}h^2)(1+z)^{3(1+w)}\right]$$

$$\Omega_m h^2 = 0.1430 \pm 0.0011$$
$$\Omega_b h^2 = 0.02237 \pm 0.00015$$
$$\Omega_r h^2 = (4.64 \pm 0.3)\ 10^{-5}$$

$$\int_0^{z_{rec}} \frac{dz}{h(z)} = \int_0^{z_{rec}} \frac{dz}{h_{Planck}(z)}$$

$$h(w) \approx -0.3093w + 0.3647$$



For h=0.74 this gives w=-1.22

This value of w corresponds to h=0.74 and CMB spectrum identical with Planck/ΛCDM.

H_0 tension, phantom dark energy, and cosmological parameter degeneracies

G. Alestas (Ioannina U.), L. Kazantzidis (Ioannina U.), L. Perivolaropoulos (Ioannina U.) (Apr 20, 2020)

Published in: *Phys.Rev.D* 101 (2020) 12, 123516 • e-Print: 2004.08363 [astro-ph.CO]