Soundness of dark energy properties

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Laboratory of Theoretical Physics, University of Tartu
4 June 2020

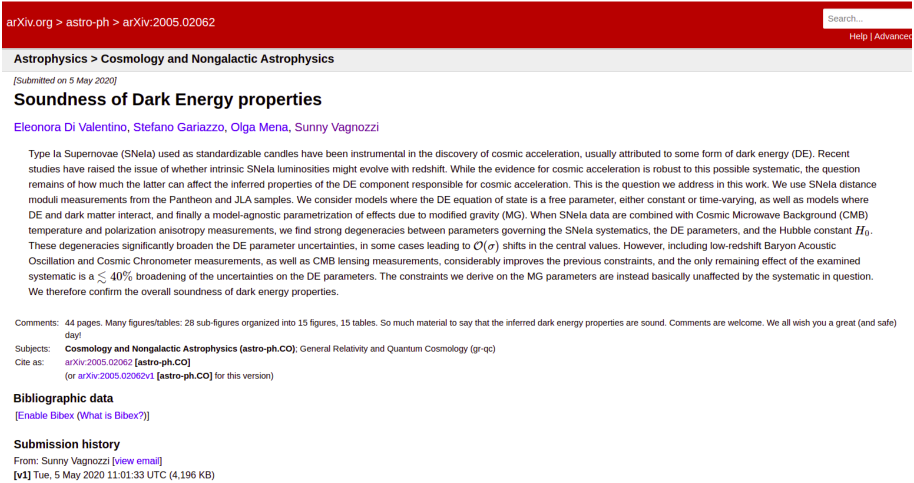
Soundness of dark energy properties

How robust are the dark energy properties we infer from cosmological data?

(against a possible systematic affecting interpretation of Supernovae data)

Caveat: to fit cosmological data one *always* assumes a (dark energy) model

Based on `arXiv:2005.02062`



Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 5 May 2020]

Soundness of Dark Energy properties

Eleonora Di Valentino, Stefano Gariazzo, Olga Mena, Sunny Vagnozzi

Type Ia Supernovae (SNeIa) used as standardizable candles have been instrumental in the discovery of cosmic acceleration, usually attributed to some form of dark energy (DE). Recent studies have raised the issue of whether intrinsic SNeIa luminosities might evolve with redshift. While the evidence for cosmic acceleration is robust to this possible systematic, the question remains of how much the latter can affect the inferred properties of the DE component responsible for cosmic acceleration. This is the question we address in this work. We use SNeIa distance moduli measurements from the Pantheon and JLA samples. We consider models where the DE equation of state is a free parameter, either constant or time-varying, as well as models where DE and dark matter interact, and finally a model-agnostic parametrization of effects due to modified gravity (MG). When SNeIa data are combined with Cosmic Microwave Background (CMB) temperature and polarization anisotropy measurements, we find strong degeneracies between parameters governing the SNeIa systematics, the DE parameters, and the Hubble constant H_0. These degeneracies significantly broaden the DE parameter uncertainties, in some cases leading to $\mathcal{O}(\sigma)$ shifts in the central values. However, including low-redshift Baryon Acoustic Oscillation and Cosmic Chronometer measurements, as well as CMB lensing measurements, considerably improves the previous constraints, and the only remaining effect of the examined systematic is a $\lesssim 40\%$ broadening of the uncertainties on the DE parameters. The constraints we derive on the MG parameters are instead basically unaffected by the systematic in question. We therefore confirm the overall soundness of dark energy properties.

Comments:	44 pages. Many figures/tables: 28 sub-figures organized into 15 figures, 15 tables. So much material to say that the inferred dark energy properties are sound. Comments are welcome. We all wish you a great (and safe) day!
Subjects:	**Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; General Relativity and Quantum Cosmology (gr-qc)
Cite as:	arXiv:2005.02062 **[astro-ph.CO]** (or arXiv:2005.02062v1 **[astro-ph.CO]** for this version)

Bibliographic data

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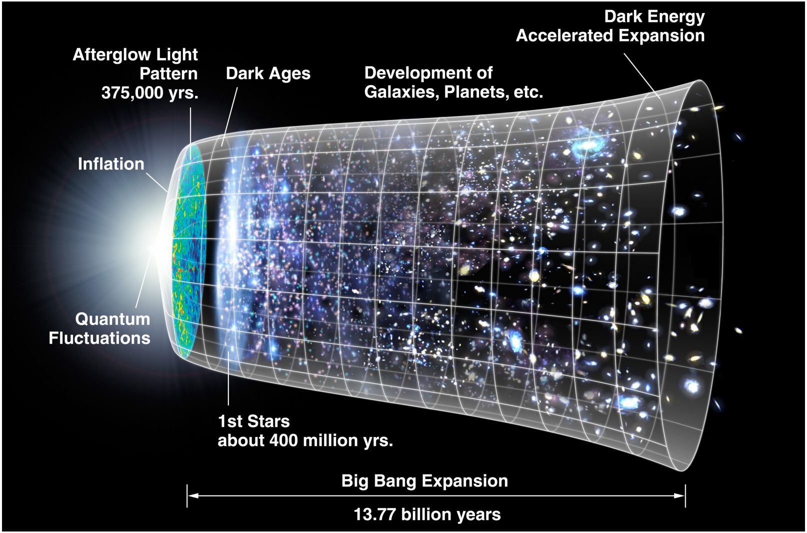
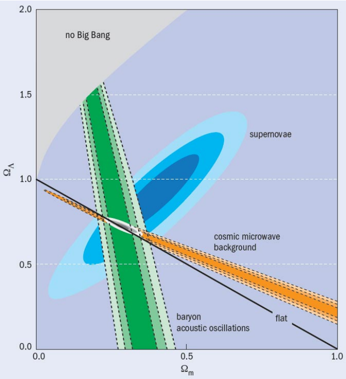
Submission history

From: Sunny Vagnozzi [view email]
[v1] Tue, 5 May 2020 11:01:33 UTC (4,196 KB)

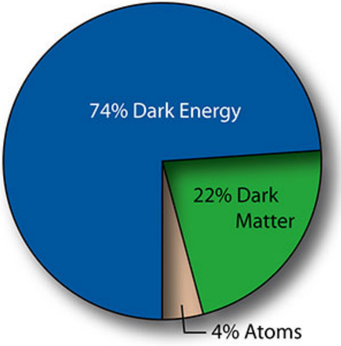
Cosmic acceleration



The standard model of cosmology: ΛCDM



Credits: Kowalski *et al.*, ApJ 686 (2008) 749



Credits: NASA

How to establish cosmic acceleration and test dark energy?

Always a good idea in cosmology: measure distances

Luminosity distance:

$$d_L(z) = (1+z)\frac{1}{H_0\sqrt{\Omega_K}}\sinh\left[H_0\sqrt{\Omega_K}\int_0^z\frac{dz'}{H(z')}\right]$$

Angular diameter distance:

$$d_A(z) = \frac{1}{1+z}\frac{1}{H_0\sqrt{\Omega_K}}\sinh\left[H_0\sqrt{\Omega_K}\int_0^z\frac{dz'}{H(z')}\right]$$

Standard candles and standard rulers

In practice “infer distances” = “measure fluxes or angles”

Fluxes:

$$d_L = \sqrt{\frac{L}{4\pi f}}$$

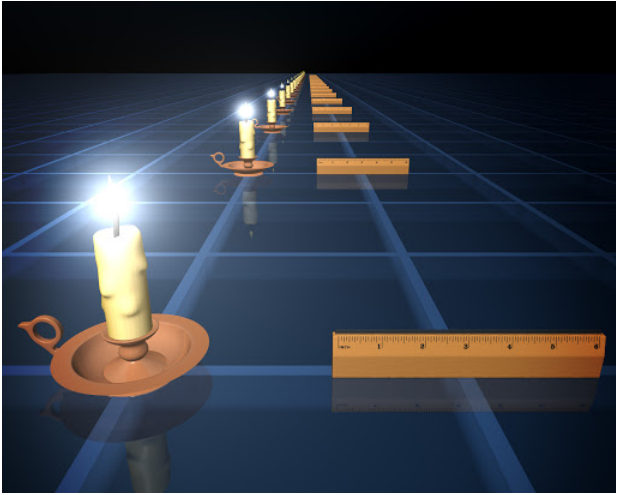
L=intrinsic luminosity

Angles:

$$d_A = \frac{x}{\theta}$$

x=intrinsic physical size

Standard candles and standard rulers



Credits: NASA/JPL-Caltech/R. Hurt (SSC)

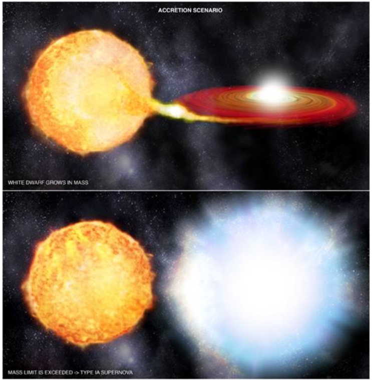
Type Ia Supernovae as standard candles

SNeIa: white dwarf accretes matter from a companion star, exceeds the Chandrasekhar mass limit ($\approx 1.4 M_\odot$), collapses, and explodes

$\implies$ mass of exploding star highly predictable

$\implies$ (peak) luminosity $\approx 4 \times 10^9 L_\odot$ highly predictable

$\implies$ SNeIa are excellent standard candles?



Credits: phys.org

Type Ia Supernovae as standard candles

We observe *distance moduli* μ:

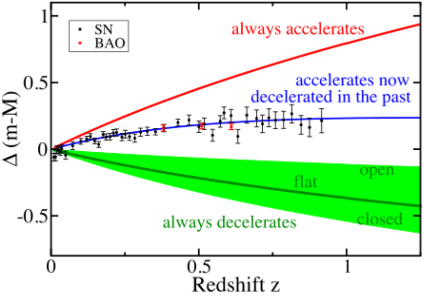
$$\mu = m_B - M_B = 5\log_{10}\left(\frac{d_L}{10\,\mathrm{pc}}\right)$$

m_B: observed (apparent) SNeIa magnitude

M_B: absolute (intrinsic) SNeIa magnitude

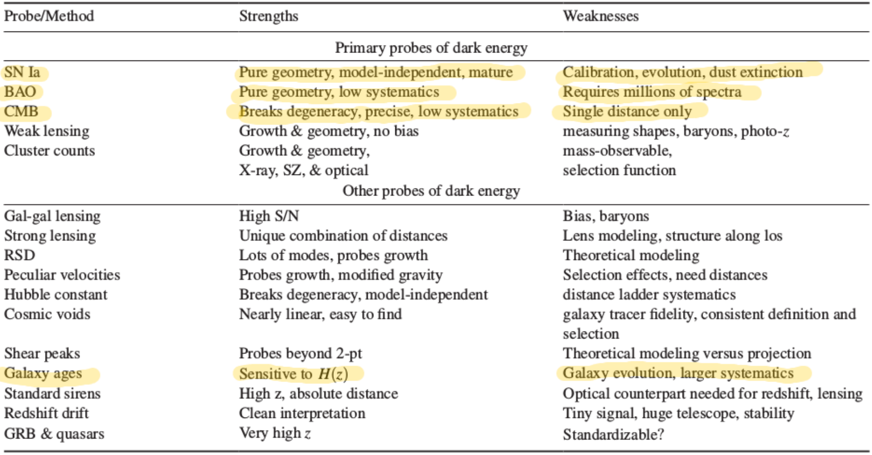
For a true class of standard candles, M_B would be the same across the whole class (get back to this later)

Schematic representation:



Not only SNeIa: evidence for cosmic acceleration is sound

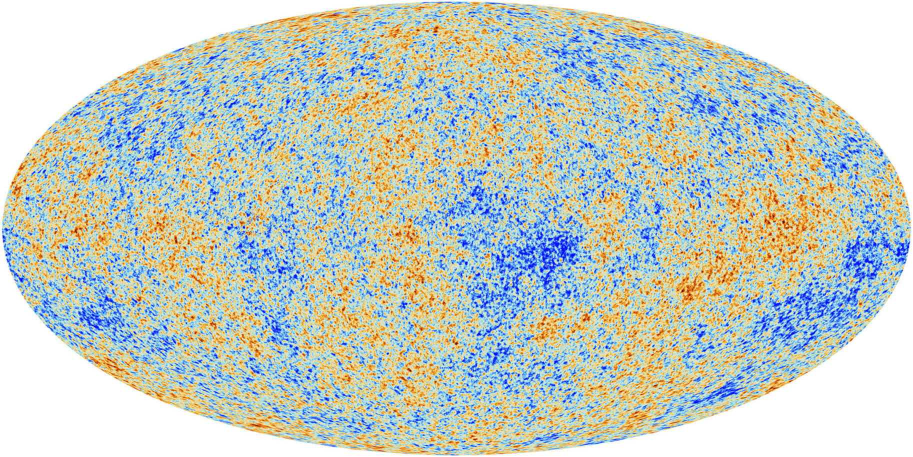
Evidence for cosmic acceleration does **not** only come from SNeIa



Probe/Method	Strengths	Weaknesses
	Primary probes of dark energy	
SN Ia	Pure geometry, model-independent, mature	Calibration, evolution, dust extinction
BAO	Pure geometry, low systematics	Requires millions of spectra
CMB	Breaks degeneracy, precise, low systematics	Single distance only
Weak lensing	Growth & geometry, no bias	measuring shapes, baryons, photo-z
Cluster counts	Growth & geometry, X-ray, SZ, & optical	mass-observable, selection function
	Other probes of dark energy	
Gal-gal lensing	High S/N	Bias, baryons
Strong lensing	Unique combination of distances	Lens modeling, structure along los
RSD	Lots of modes, probes growth	Theoretical modeling
Peculiar velocities	Probes growth, modified gravity	Selection effects, need distances
Hubble constant	Breaks degeneracy, model-independent	distance ladder systematics
Cosmic voids	Nearly linear, easy to find	galaxy tracer fidelity, consistent definition and selection
Shear peaks	Probes beyond 2-pt	Theoretical modeling versus projection
Galaxy ages	Sensitive to $H(z)$	Galaxy evolution, larger systematics
Standard sirens	High z, absolute distance	Optical counterpart needed for redshift, lensing
Redshift drift	Clean interpretation	Tiny signal, huge telescope, stability
GRB & quasars	Very high z	Standardizable?

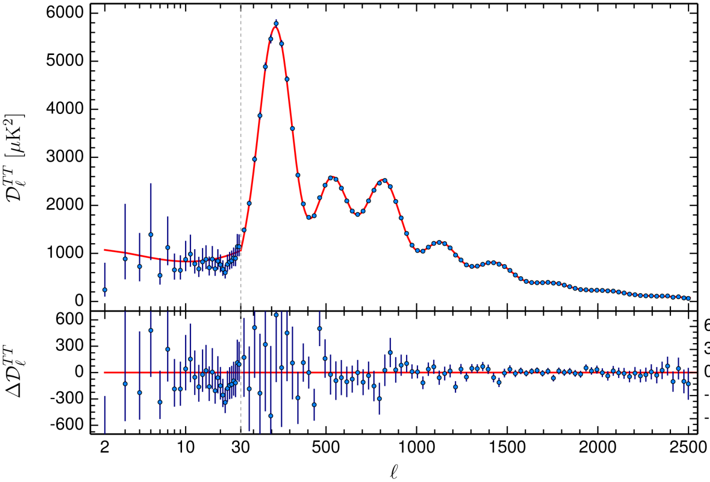
Huterer & Shafer, Rept. Prog. Phys. 81 (2018) 016901

Cosmic Microwave Background



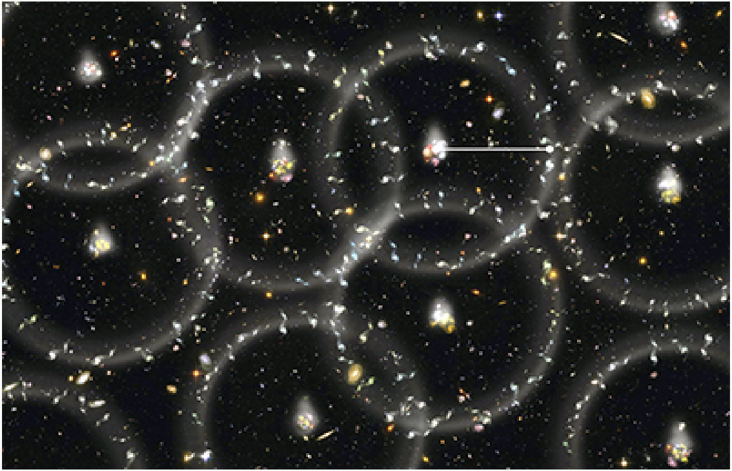
Credits: Planck collaboration

Cosmic Microwave Background



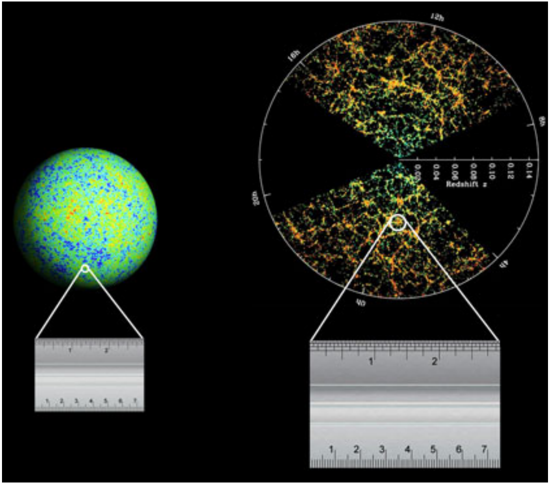
Credits: Planck collaboration

Baryon Acoustic Oscillations



Credits: BOSS collaboration

CMB and BAO as standard rulers



Credits: BOSS collaboration

Back to Type Ia Supernovae as standard candles...

We observe *distance moduli* μ:

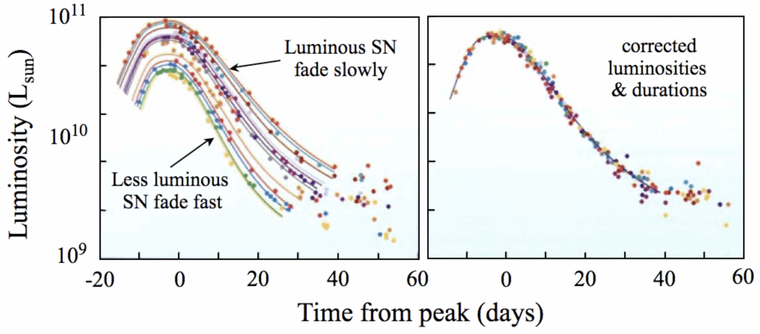
$$\mu = m_B - M_B = 5 \log_{10} \left(\frac{d_L}{10\,\mathrm{pc}} \right)$$

m_B: observed (apparent) SNeIa magnitude
M_B: absolute (intrinsic) SNeIa magnitude

For a true class of standard candles, M_B would be the same across the whole class

Type Ia Supernovae as standard(izable) candles

Can be standardized through *stretch* and *color* corrections. Mnemonic: "*broader is brighter, bluer is brighter*" Phillips, ApJ 413 (1993) L105; Riess *et al.*, ApJ 473 (1996) 88



Credits: John Lucey's website, Durham University

Type Ia Supernovae as standard(izable) candles

Practical modelling of the observed distance moduli:

$$\mu_{\text{obs}} = m_B - (M_B - \alpha X_1 + \beta C)$$

X_1: time stretch (related to broadness of light-curve)
C: colour at maximum brightness (intensity difference in two bands)
α and β: nuisance parameters (amplitude of stretch and color corrections)
M_B also becomes a nuisance parameter

Type Ia Supernovae as standard(izable) candles

What assumption is going into this modelling?

$$\mu_{\rm obs} = m_B - (M_B - \alpha X_1 + \beta C)$$

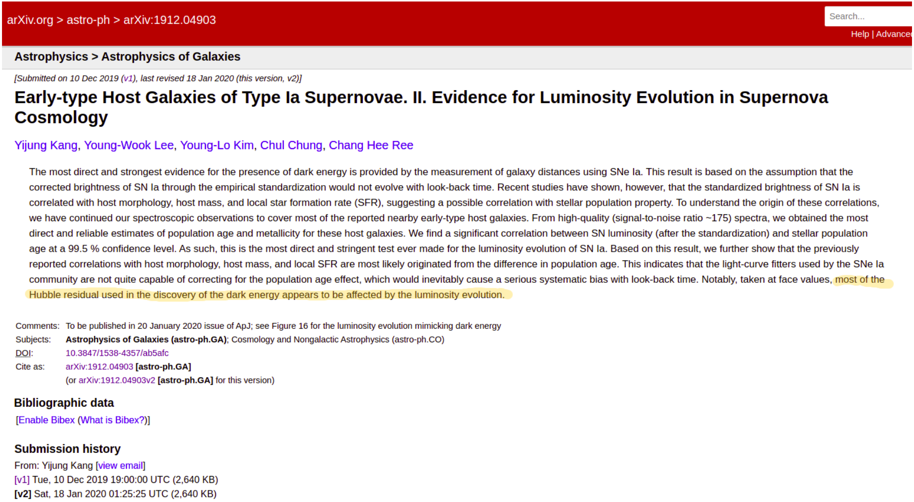
Intrinsic SNeIa luminosities do not evolve with redshift

or more explicitly

Two different SNeIa in different hosts, with the same C, X_1, and environmental properties, should on average have the same intrinsic luminosity, **independently of their redshift**

Do SNeIa intrinsic luminosities evolve with redshift?

Looks like it might be the case...



arXiv.org > astro-ph > arXiv:1912.04903

Astrophysics > Astrophysics of Galaxies

[Submitted on 10 Dec 2019 (v1), last revised 18 Jan 2020 (this version, v2)]

Early-type Host Galaxies of Type Ia Supernovae. II. Evidence for Luminosity Evolution in Supernova Cosmology

Yijung Kang, Young-Wook Lee, Young-Lo Kim, Chul Chung, Chang Hee Ree

The most direct and strongest evidence for the presence of dark energy is provided by the measurement of galaxy distances using SNe Ia. This result is based on the assumption that the corrected brightness of SN Ia through the empirical standardization would not evolve with look-back time. Recent studies have shown, however, that the standardized brightness of SN Ia is correlated with host morphology, host mass, and local star formation rate (SFR), suggesting a possible correlation with stellar population property. To understand the origin of these correlations, we have continued our spectroscopic observations to cover most of the reported nearby early-type host galaxies. From high-quality (signal-to-noise ratio ~175) spectra, we obtained the most direct and reliable estimates of population age and metallicity for these host galaxies. We find a significant correlation between SN luminosity (after the standardization) and stellar population age at a 99.5 % confidence level. As such, this is the most direct and stringent test ever made for the luminosity evolution of SN Ia. Based on this result, we further show that the previously reported correlations with host morphology, host mass, and local SFR are most likely originated from the difference in population age. This indicates that the light-curve fitters used by the SNe Ia community are not quite capable of correcting for the population age effect, which would inevitably cause a serious systematic bias with look-back time. Notably, taken at face values, most of the Hubble residual used in the discovery of the dark energy appears to be affected by the luminosity evolution.

Comments: To be published in 20 January 2020 issue of ApJ; see Figure 16 for the luminosity evolution mimicking dark energy
Subjects: **Astrophysics of Galaxies (astro-ph.GA)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO)
DOI: 10.3847/1538-4357/ab5afc
Cite as: arXiv:1912.04903 **[astro-ph.GA]**
(or arXiv:1912.04903v2 **[astro-ph.GA]** for this version)

Bibliographic data

[Enable Bibex (What is Bibex?)]

Submission history

From: Yijung Kang [view email]
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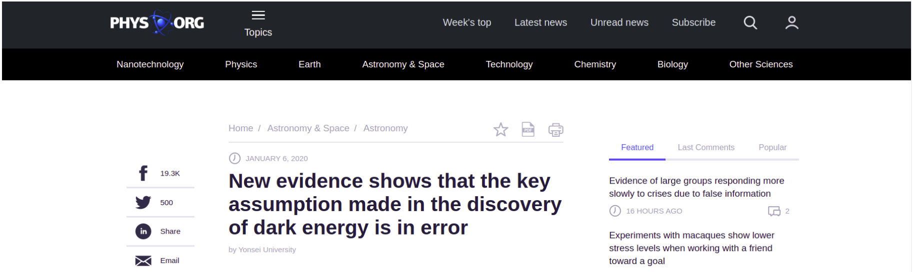
[v2] Sat, 18 Jan 2020 01:25:25 UTC (2,640 KB)

Kang *et al.*, ApJ 889 (2020) 8

Do SNeIa intrinsic luminosities evolve with redshift?

Lots of media attention...



JANUARY 6, 2020

New evidence shows that the key assumption made in the discovery of dark energy is in error

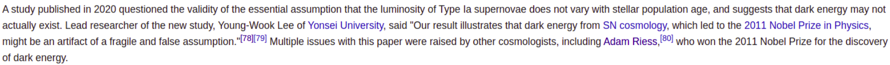
by Yonsei University

Evidence of large groups responding more slowly to crises due to false information

16 HOURS AGO 2

Experiments with macaques show lower stress levels when working with a friend toward a goal

Credits: phys.org

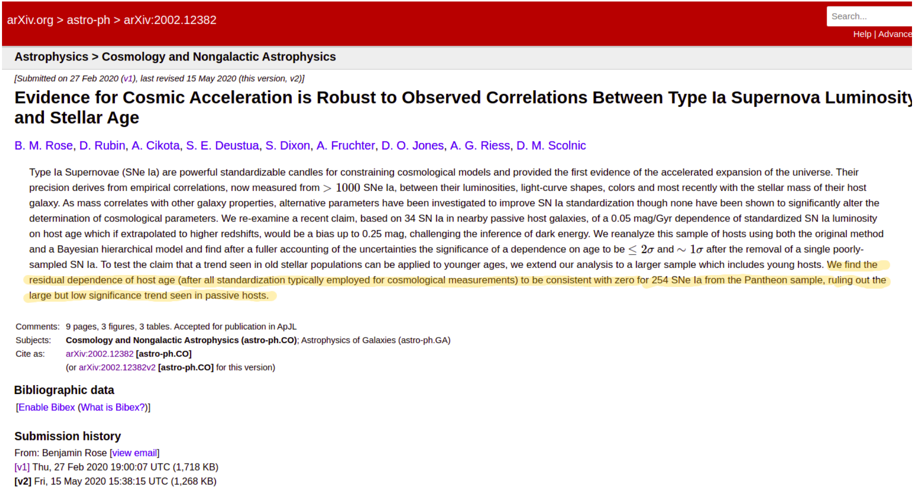


A study published in 2020 questioned the validity of the essential assumption that the luminosity of Type Ia supernovae does not vary with stellar population age, and suggests that dark energy may not actually exist. Lead researcher of the new study, Young-Wook Lee of Yonsei University, said "Our result illustrates that dark energy from SN cosmology, which led to the 2011 Nobel Prize in Physics, might be an artifact of a fragile and false assumption."[78][79] Multiple issues with this paper were raised by other cosmologists, including Adam Riess,[80] who won the 2011 Nobel Prize for the discovery of dark energy.

Credits: Wikipedia

Do SNeIa intrinsic luminosities evolve with redshift?

Response from Adam Riess' group...



Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 27 Feb 2020 (v1), last revised 15 May 2020 (this version, v2)]

Evidence for Cosmic Acceleration is Robust to Observed Correlations Between Type Ia Supernova Luminosity and Stellar Age

B. M. Rose, D. Rubin, A. Cikota, S. E. Deustua, S. Dixon, A. Fruchter, D. O. Jones, A. G. Riess, D. M. Scolnic

Type Ia Supernovae (SNe Ia) are powerful standardizable candles for constraining cosmological models and provided the first evidence of the accelerated expansion of the universe. Their precision derives from empirical correlations, now measured from > 1000 SNe Ia, between their luminosities, light-curve shapes, colors and most recently with the stellar mass of their host galaxy. As mass correlates with other galaxy properties, alternative parameters have been investigated to improve SN Ia standardization though none have been shown to significantly alter the determination of cosmological parameters. We re-examine a recent claim, based on 34 SN Ia in nearby passive host galaxies, of a 0.05 mag/Gyr dependence of standardized SN Ia luminosity on host age which if extrapolated to higher redshifts, would be a bias up to 0.25 mag, challenging the inference of dark energy. We reanalyze this sample of hosts using both the original method and a Bayesian hierarchical model and find after a fuller accounting of the uncertainties the significance of a dependence on age to be $\leq 2\sigma$ and $\sim 1\sigma$ after the removal of a single poorly-sampled SN Ia. To test the claim that a trend seen in old stellar populations can be applied to younger ages, we extend our analysis to a larger sample which includes young hosts. We find the residual dependence of host age (after all standardization typically employed for cosmological measurements) to be consistent with zero for 254 SNe Ia from the Pantheon sample, ruling out the large but low significance trend seen in passive hosts.

Comments:	9 pages, 3 figures, 3 tables. Accepted for publication in ApJL
Subjects:	**Cosmology and Nongalactic Astrophysics (astro-ph.CO)**; Astrophysics of Galaxies (astro-ph.GA)
Cite as:	arXiv:2002.12382 **[astro-ph.CO]**
	(or arXiv:2002.12382v2 **[astro-ph.CO]** for this version)

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[v2] Fri, 15 May 2020 15:38:15 UTC (1,268 KB)

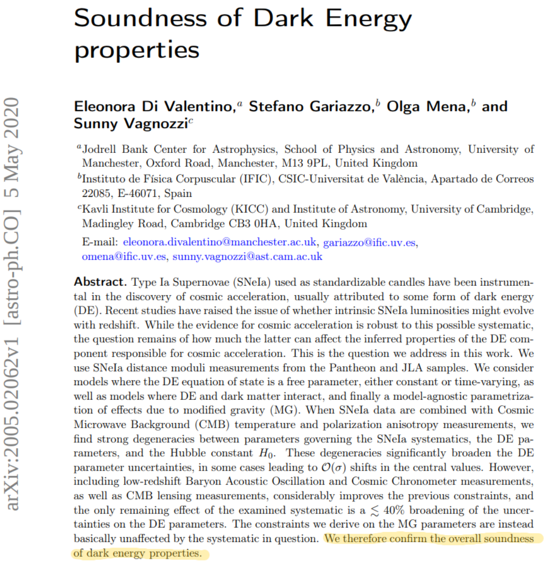
Rose *et al.*, arXiv:2002.12382

Do SNeIa intrinsic luminosities evolve with redshift?

Let's recap:

- Certainly some amount of redshift evolution/environmental dependence is undeniably present... (astrophysics is complicated!)
- ...but not in the size claimed by Kang *et al.*, which would undermine evidence for cosmic acceleration!
- So the real question is: *granted that cosmic acceleration exists*, are the properties we infer about dark energy/modified gravity robust to possible redshift-dependent intrinsic SNeIa luminosities?
- In some models, intrinsic SNeIa luminosities are actually *expected* to be z-dependent Calabrese *et al.*, PRD 89 (2014) 083509; Wright & Li, PRD 97 (2018) 083505

Are the properties of dark energy sound?



arXiv:2005.02062v1 [astro-ph.CO] 5 May 2020

Soundness of Dark Energy properties

Eleonora Di Valentino,[a] **Stefano Gariazzo,**[b] **Olga Mena,**[b] **and Sunny Vagnozzi**[c]

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[b]Instituto de Física Corpuscular (IFIC), CSIC-Universitat de València, Apartado de Correos 22085, E-46071, Spain
[c]Kavli Institute for Cosmology (KICC) and Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom

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Abstract. Type Ia Supernovae (SNeIa) used as standardizable candles have been instrumental in the discovery of cosmic acceleration, usually attributed to some form of dark energy (DE). Recent studies have raised the issue of whether intrinsic SNeIa luminosities might evolve with redshift. While the evidence for cosmic acceleration is robust to this possible systematic, the question remains of how much the latter can affect the inferred properties of the DE component responsible for cosmic acceleration. This is the question we address in this work. We use SNeIa distance moduli measurements from the Pantheon and JLA samples. We consider models where the DE equation of state is a free parameter, either constant or time-varying, as well as models where DE and dark matter interact, and finally a model-agnostic parametrization of effects due to modified gravity (MG). When SNeIa data are combined with Cosmic Microwave Background (CMB) temperature and polarization anisotropy measurements, we find strong degeneracies between parameters governing the SNeIa systematics, the DE parameters, and the Hubble constant H_0. These degeneracies significantly broaden the DE parameter uncertainties, in some cases leading to $\mathcal{O}(\sigma)$ shifts in the central values. However, including low-redshift Baryon Acoustic Oscillation and Cosmic Chronometer measurements, as well as CMB lensing measurements, considerably improves the previous constraints, and the only remaining effect of the examined systematic is a $\lesssim 40\%$ broadening of the uncertainties on the DE parameters. The constraints we derive on the MG parameters are instead basically unaffected by the systematic in question. We therefore confirm the overall soundness of dark energy properties.

Redshift-dependent intrinsic SNeIa luminosities

Phenomenological parametrization:

$$\mu_{\rm obs} = m_B - (M_B - \alpha X_1 + \beta C + \Delta m_{\rm evo}(z)) \;, \quad \Delta m_{\rm evo}(z) = \epsilon z^{\delta}$$

Tutusaus *et al.*, A&A 602 (2017) A73; A&A 625 (2019) A15

Q: how sound are the dark energy properties?

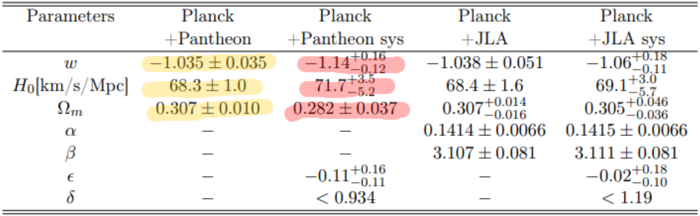
gets rephrased to

Q: within a given dark energy/modified gravity model described by some parameters, how do the inferred values of these parameters change by including $\Delta m_{\rm evo}(z)$ when modelling the observed SNeIa distance moduli?

*w*CDM model

Fit for constant dark energy equation of state $w \neq -1$ (in ΛCDM $w = -1$)

Consider only CMB+SNeIa data

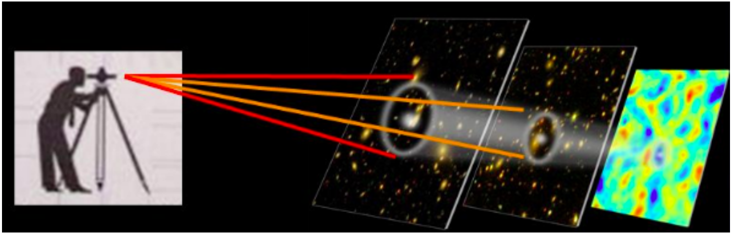


Parameters	Planck +Pantheon	Planck +Pantheon sys	Planck +JLA	Planck +JLA sys
w	-1.035 ± 0.035	$-1.14^{+0.16}_{-0.12}$	-1.038 ± 0.051	$-1.06^{+0.18}_{-0.11}$
H_0[km/s/Mpc]	68.3 ± 1.0	$71.7^{+3.5}_{-5.2}$	68.4 ± 1.6	$69.1^{+3.0}_{-5.7}$
Ω_m	0.307 ± 0.010	0.282 ± 0.037	$0.307^{+0.014}_{-0.016}$	$0.305^{+0.046}_{-0.036}$
α	–	–	0.1414 ± 0.0066	0.1415 ± 0.0066
β	–	–	3.107 ± 0.081	3.111 ± 0.081
ϵ	–	$-0.11^{+0.16}_{-0.11}$	–	$-0.02^{+0.18}_{-0.10}$
δ	–	< 0.934	–	< 1.19

Naïvely we see huge shifts: dark energy properties are not sound?

Geometrical degeneracy

CMB data alone is “not good enough” to constrain dark energy because of the *geometrical degeneracy*

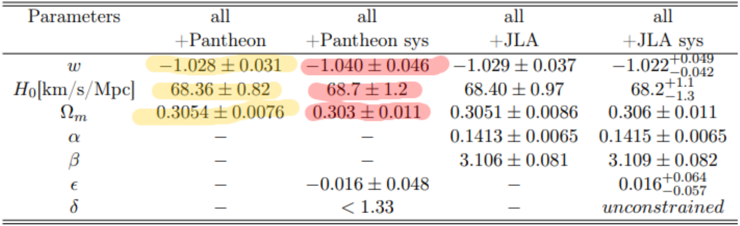


Credits: Daniel Eisenstein

Combining CMB with BAO data or anything which measures $H_0/H(z)$ gives much better constraints on dark energy!

wCDM model

Considering CMB+SNeIa+CMB lensing+BAO+cosmic chronometer data

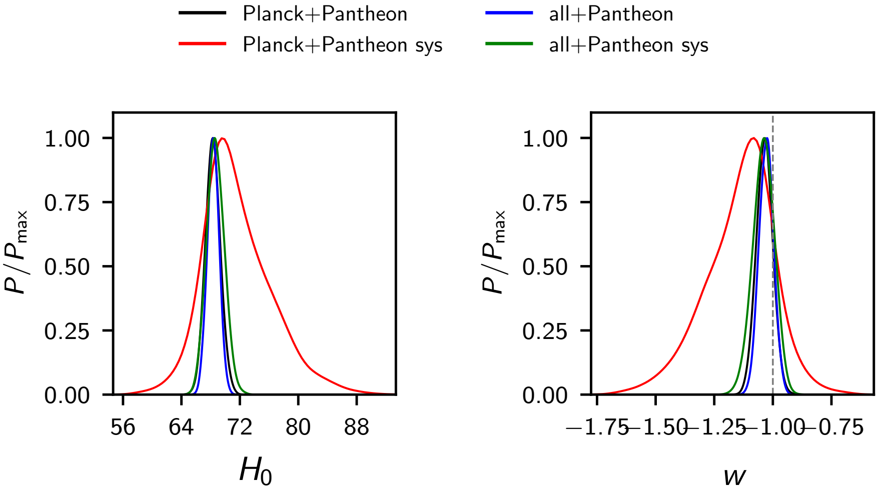


Parameters	all +Pantheon	all +Pantheon sys	all +JLA	all +JLA sys
w	-1.028 ± 0.031	-1.040 ± 0.046	-1.029 ± 0.037	$-1.022^{+0.049}_{-0.042}$
H_0[km/s/Mpc]	68.36 ± 0.82	68.7 ± 1.2	68.40 ± 0.97	$68.2^{+1.1}_{-1.3}$
Ω_m	0.3054 ± 0.0076	0.303 ± 0.011	0.3051 ± 0.0086	0.306 ± 0.011
α	–	–	0.1413 ± 0.0065	0.1415 ± 0.0065
β	–	–	3.106 ± 0.081	3.109 ± 0.082
ϵ	–	-0.016 ± 0.048	–	$0.016^{+0.064}_{-0.057}$
δ	–	< 1.33	–	*unconstrained*

- The previous huge shifts have been reduced
- What is left is $\lesssim 40\%$ broadening of uncertainties

wCDM model

Perhaps easier to understand graphically...

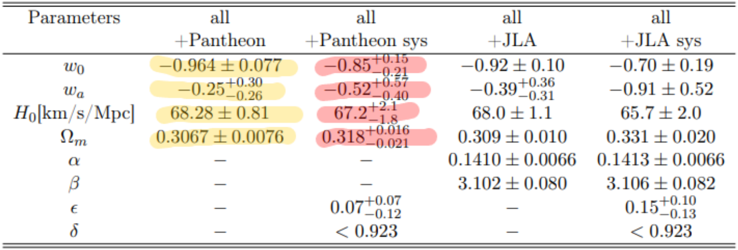


CPL model

Allow for time-varying equation of state:

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

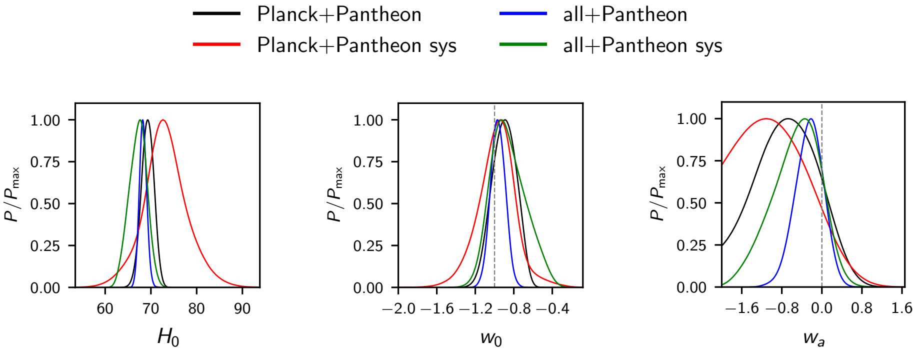
Chevallier & Polarski, IJMPD 10 (2001) 213; Linder, PRL 90 (2003) 091301



Parameters	all +Pantheon	all +Pantheon sys	all +JLA	all +JLA sys
w_0	-0.964 ± 0.077	$-0.85^{+0.15}_{-0.21}$	-0.92 ± 0.10	-0.70 ± 0.19
w_a	$-0.25^{+0.30}_{-0.26}$	$-0.52^{+0.57}_{-0.40}$	$-0.39^{+0.36}_{-0.31}$	-0.91 ± 0.52
H_0[km/s/Mpc]	68.28 ± 0.81	$67.2^{+2.1}_{-1.8}$	68.0 ± 1.1	65.7 ± 2.0
Ω_m	0.3067 ± 0.0076	$0.318^{+0.016}_{-0.021}$	0.309 ± 0.010	0.331 ± 0.020
α	–	–	0.1410 ± 0.0066	0.1413 ± 0.0066
β	–	–	3.102 ± 0.080	3.106 ± 0.082
ϵ	–	$0.07^{+0.07}_{-0.12}$	–	$0.15^{+0.10}_{-0.13}$
δ	–	< 0.923	–	< 0.923

Again we see a broadening of uncertainties (larger, about $\lesssim 100\%$)

CPL model



Planck+Pantheon
all+Pantheon
Planck+Pantheon sys
all+Pantheon sys
$P/P_{\rm max}$
1.00
0.75
0.50
0.25
0.00
60
70
80
90
H_0
$P/P_{\rm max}$
1.00
0.75
0.50
0.25
0.00
−2.0
−1.6
−1.2
−0.8
−0.4
w_0
$P/P_{\rm max}$
1.00
0.75
0.50
0.25
0.00
−1.6
−0.8
0.0
0.8
1.6
w_a

Interacting dark energy

Couple continuity equations of dark matter and dark energy:

$$\dot{\rho}_c + 3H\rho_c = Q$$
$$\dot{\rho}_x + 3H(1+w)\rho_x = -Q$$

Common (phenomenological) choice: For example Gavela *et al.*, JCAP 0907 (2007) 034

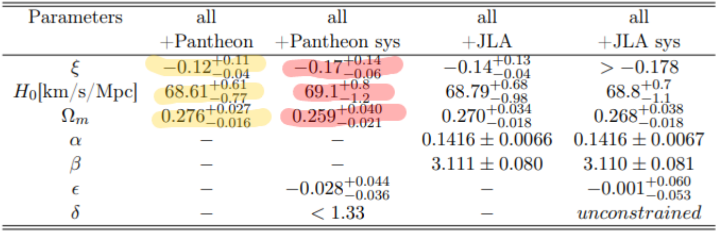
$$Q = 3H\xi\rho_x$$

Three possibilities:

- $w \approx -1$, $\xi < 0$: *coupled vacuum* ($\xi\Lambda$CDM)
- $w > -1$, $\xi < 0$: *coupled quintessence* (ξqCDM)
- $w < -1$, $\xi > 0$: *coupled phantom* (ξpCDM)

These models may help with the so-called Hubble tension, see e.g. Di Valentino, Melchiorri, Mena, SV, PRD 101 (2020) 063502

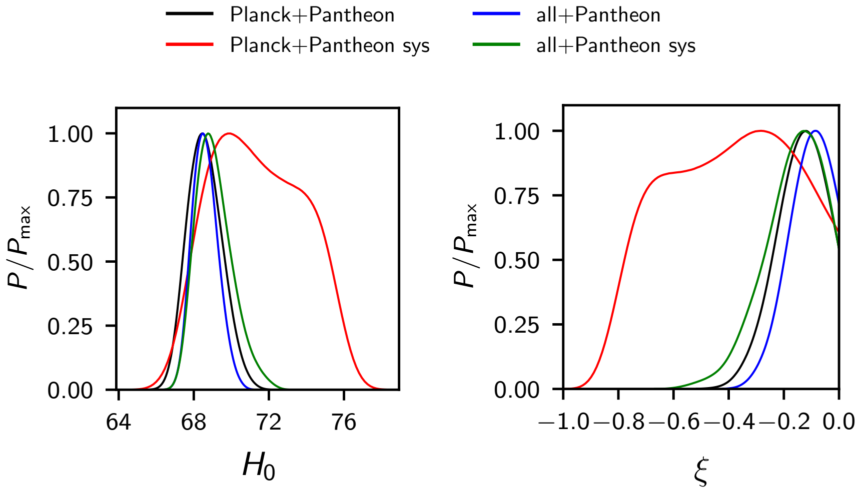
Coupled vacuum model



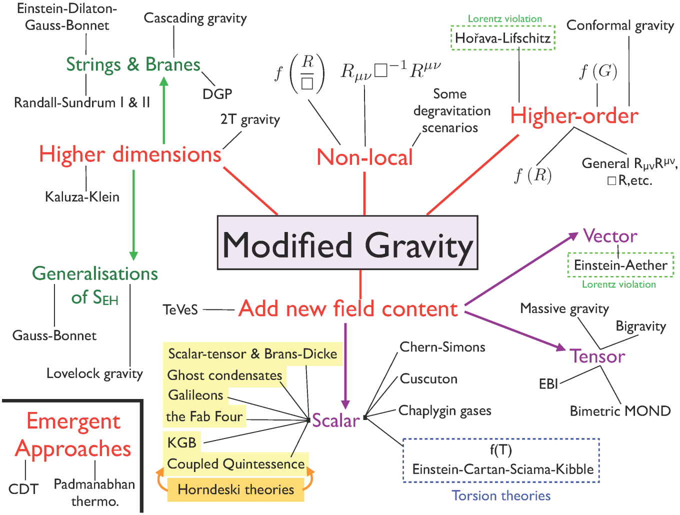
Parameters	all +Pantheon	all +Pantheon sys	all +JLA	all +JLA sys
ξ	$-0.12^{+0.11}_{-0.04}$	$-0.17^{+0.14}_{-0.06}$	$-0.14^{+0.13}_{-0.04}$	> -0.178
H_0[km/s/Mpc]	$68.61^{+0.61}_{-0.77}$	$69.1^{+0.8}_{-1.2}$	$68.79^{+0.68}_{-0.98}$	$68.8^{+0.7}_{-1.1}$
Ω_m	$0.276^{+0.027}_{-0.016}$	$0.259^{+0.040}_{-0.021}$	$0.270^{+0.034}_{-0.018}$	$0.268^{+0.038}_{-0.018}$
α	–	–	0.1416 ± 0.0066	0.1416 ± 0.0067
β	–	–	3.111 ± 0.080	3.110 ± 0.081
ϵ	–	$-0.028^{+0.044}_{-0.036}$	–	$-0.001^{+0.060}_{-0.053}$
δ	–	< 1.33	–	*unconstrained*

Again we see a broadening of uncertainties (smaller, about $\lesssim 30\%$)

Coupled vacuum model



Modified gravity



Modified Gravity

Higher dimensions
- Strings & Branes
  - Einstein-Dilaton-Gauss-Bonnet
  - Cascading gravity
  - Randall-Sundrum I & II
  - DGP
- 2T gravity
- Kaluza-Klein
- Generalisations of S_{EH}
  - Gauss-Bonnet
  - Lovelock gravity

Non-local
- $f\left(\frac{R}{\Box}\right)$
- $R_{\mu\nu}\Box^{-1}R^{\mu\nu}$
- Some degravitation scenarios

Higher-order
- Lorentz violation: Hořava-Lifschitz
- Conformal gravity
- $f(G)$
- $f(R)$
- General $R_{\mu\nu}R^{\mu\nu}$, $\Box R$,etc.

Add new field content
- TeVeS
- Vector
  - Einstein-Aether (Lorentz violation)
- Tensor
  - Massive gravity
  - Bigravity
  - EBI
  - Bimetric MOND
- Scalar
  - Scalar-tensor & Brans-Dicke
  - Ghost condensates
  - Galileons
  - the Fab Four
  - KGB
  - Coupled Quintessence
  - Horndeski theories
  - Chern-Simons
  - Cuscuton
  - Chaplygin gases
  - Torsion theories: f(T), Einstein-Cartan-Sciama-Kibble

Emergent Approaches
- CDT
- Padmanabhan thermo.

Credits: Tessa Baker

Modified gravity

Widely used μ-Σ-η parametrization: Bertschinger & Zukin, PRD 78 (2008) 024015

$$k^2\Psi = -4\pi a^2 G\mu(k,a)\rho\delta$$
$$-k^2(\Psi+\Phi) = 8\pi a^2 G\Sigma(k,a)\rho\delta$$
$$\eta(k,a) = \frac{\Phi}{\Psi}$$

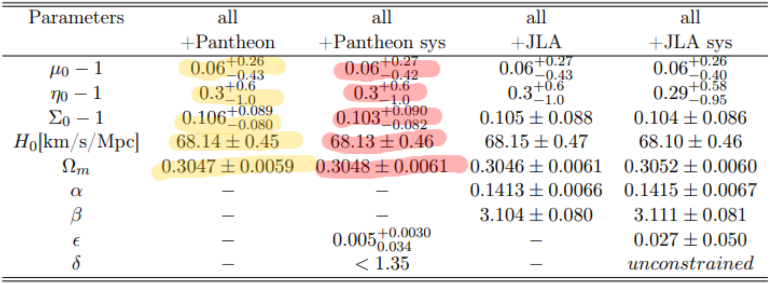
$\mu, \Sigma, \eta \neq 1$ is generically a signature of modified gravity theories

We work with the widely-used *phenomenological* parametrization:

$$\mu(k,a) = 1 + E_{11}\Omega_x(a)\,, \quad \eta(k,a) = 1 + E_{22}\Omega_x(a)\,, \quad \Sigma \equiv \frac{\mu(1+\eta)}{2}$$

Planck collaboration, A&A 594 (2016) A14

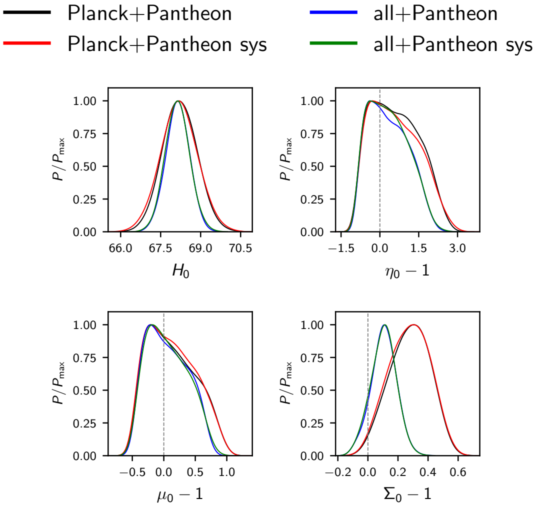
(Phenomenological) modified gravity (parametrization)



Parameters	all +Pantheon	all +Pantheon sys	all +JLA	all +JLA sys
$\mu_0 - 1$	$0.06^{+0.26}_{-0.43}$	$0.06^{+0.27}_{-0.42}$	$0.06^{+0.27}_{-0.43}$	$0.06^{+0.26}_{-0.40}$
$\eta_0 - 1$	$0.3^{+0.6}_{-1.0}$	$0.3^{+0.6}_{-1.0}$	$0.3^{+0.6}_{-1.0}$	$0.29^{+0.58}_{-0.95}$
$\Sigma_0 - 1$	$0.106^{+0.089}_{-0.080}$	$0.103^{+0.090}_{-0.082}$	0.105 ± 0.088	0.104 ± 0.086
H_0[km/s/Mpc]	68.14 ± 0.45	68.13 ± 0.46	68.15 ± 0.47	68.10 ± 0.46
Ω_m	0.3047 ± 0.0059	0.3048 ± 0.0061	0.3046 ± 0.0061	0.3052 ± 0.0060
α	–	–	0.1413 ± 0.0066	0.1415 ± 0.0067
β	–	–	3.104 ± 0.080	3.111 ± 0.081
ϵ	–	$0.005^{+0.0030}_{0.034}$	–	0.027 ± 0.050
δ	–	< 1.35	–	*unconstrained*

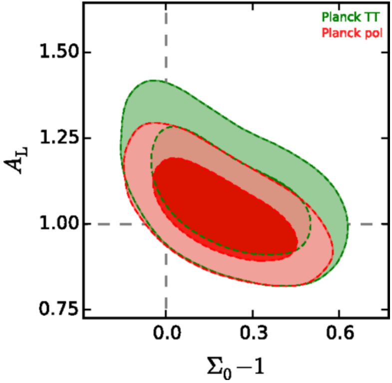
No noticeable effect of SNeIa systematics

(Phenomenological) modified gravity (parametrization)

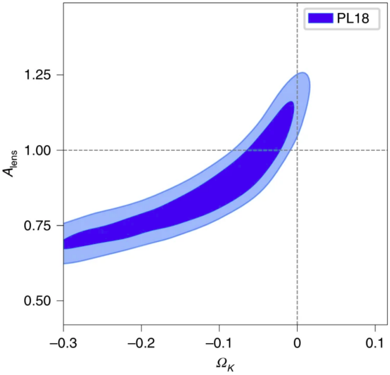


Apparent preference for modified gravity?

Comes from the so-called A_{lens} anomaly and is related to the apparent *Planck* preference for a closed Universe



Di Valentino, Melchiorri, Silk, PRD 93 (2016) 023513



Di Valentino, Melchiorri, Silk, Nat. Astron. 4 (2019) 196

Conclusions

Dark energy properties are sound

(against a possible redshift-dependence of intrinsic SNeIa luminosities)

(caveat: valid for the specific models and phenomenological parametrizations of dark energy, modified gravity, and redshift evolution of intrinsic SNeIa luminosities we have considered)