All Cosmology, All the Time

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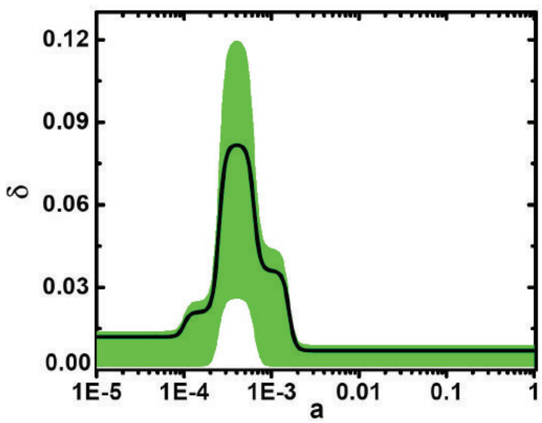
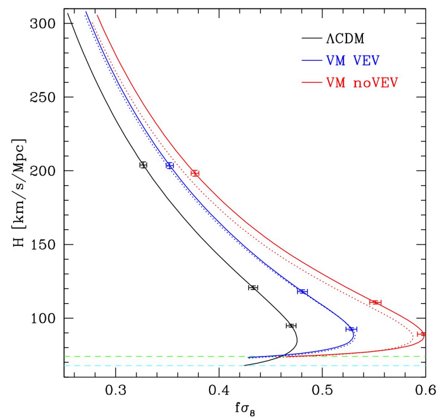
APCTP Lecture Series – 30 June 2020





What is the Standard Cosmological Model?

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This very much depends where people draw the line in "cosmology" or 'universe".

Cosmology as the global properties of the universe:

- **Smoothly connected** – we can get from here to there, and then to now. Not discrete.
- **Metric** – we can figure out how far it is from here to there and then to now.
- **Homogenous and isotropic** – Robertson-Walker metric: familiar territory!
- **Evolving** – expansion factor a(t).
- **Spatial curvature** – optional.

Cosmology as History

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Cosmology as the history of the universe:

- **Early hot dense state** – "Big Bang". Whether we start at the Planck energy, 10^{15} GeV, or 10^{3} GeV is a detail.
- **Matter/antimatter asymmetry** – ???
- **Radiation era** – primordial nucleosynthesis, degrees of freedom $g_\star$ (neutrino decoupling, electron/positron annihilation), CMB thermalization.
- **Matter era** – growth of structure (us!).
- **Cosmic acceleration** – "dark energy".

Cosmology as Contents

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Cosmology as the stuff *in* the universe:

- **Cosmic microwave background** – CMB structure (anisotropies, polarization, spectral distortions) is a rich probe of both history (including initial conditions, e.g. adiabatic) and the other contents.
- **Large scale structure** – density field, velocity field, acceleration (gravity) field.

Cosmology as the stuff in the stuff in the universe?

- Galaxies, clusters, assorted particles/fields (neutrinos, gravitational waves).

Properties of the stuff in the stuff?

- Cuspy cores, tidal streams, Cepheid pulsations, ...

Cosmologing is Hard

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But... the properties of the stuff in the stuff affect how/what we learn about the more fundamental stuff.

Example: Suppose you measure $T_{CMB}(z) \neq T_0(1+z)$?

Does this say the universe is not adiabatically expanding or that there is some systematic (e.g. molecular collisional excitations)?

Example: Suppose you measure $D_L(z) \neq (1+z)^2\, D_A(z)$?

Systematics in your different probes (e.g. galaxy selection function, Lyα metal contamination) or new physics (relation derived from 1. metricity, 2. geodesic completeness, 3. photons on null geodesics – conserved phase space density, 4. adiabatic expansion)?

Data Data Data!

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We need:

- Rigorous data
- Multiple probes
- Crosschecks
- Consistency at all cosmic times
- Check Expansion history and Growth history
  - And now Gravitational Waves!

H_0 Tension

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There is clear tension in H_0 values between certain probes, *taking the data at face value*.

There are some puzzles beyond the surface:

- Local measurements differ by more than 2σ depending on method, i.e. Cepheids vs tip of the red giant branch.
- It's not "early vs late" cosmology since BAO (+BBN or marginalizing over r_{drag}), i.e. no CMB, gives the same answer as CMB.
- Strong lensing time delays show a sharp transition between low and high H_0 around z ~ 0.4, albeit with a small sample.

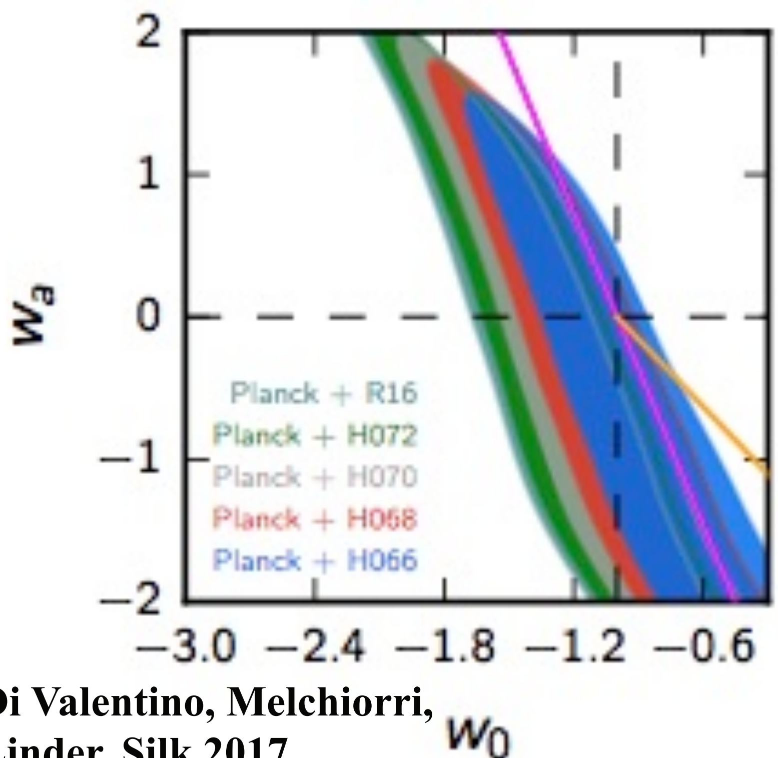
CMB and H_0

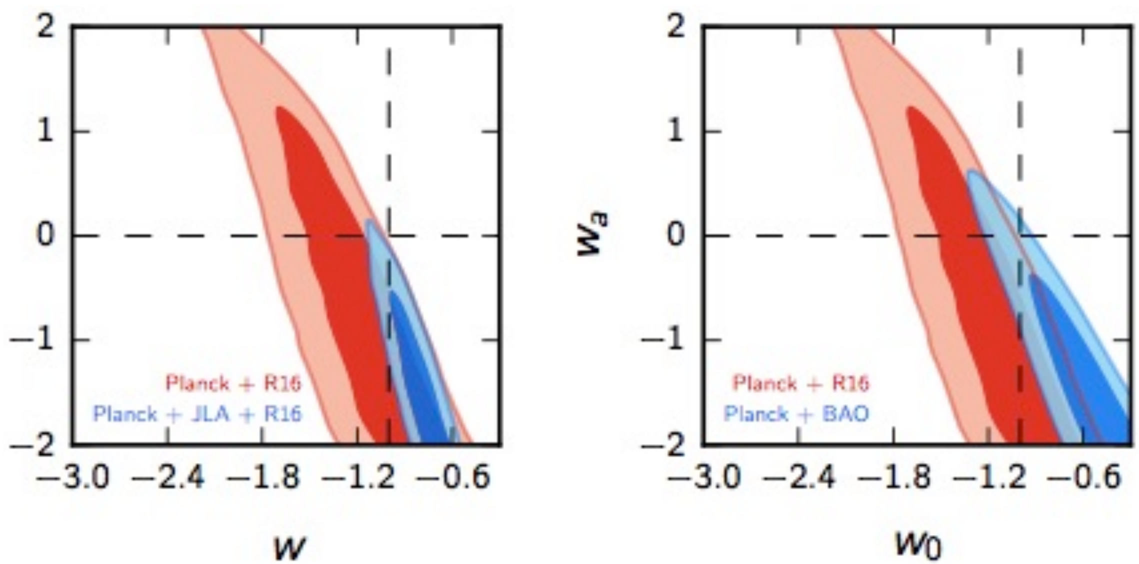
CMB data, fit in LCDM, gives "low" H_0 ~ 67.

CMB data, fit in wCDM, does not constrain H_0.

However, CMB+BAO does, giving low value.

Very hard to get H_0>70 and fit combined probes.





Di Valentino, Melchiorri, Linder, Silk 2017

H0>70 requires phantom DE,
disfavored by CMB+BAO, CMB+SN

Two Outs

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Two ways out using the expansion history:

- **Late time transition – very sharp phantom excursion so distances aren't too affected.**
- **Early time transition – lower r_{drag} so H goes up. But must make sharp transition, removing early DE quickly to preserve CMB.**

Early Time Transition

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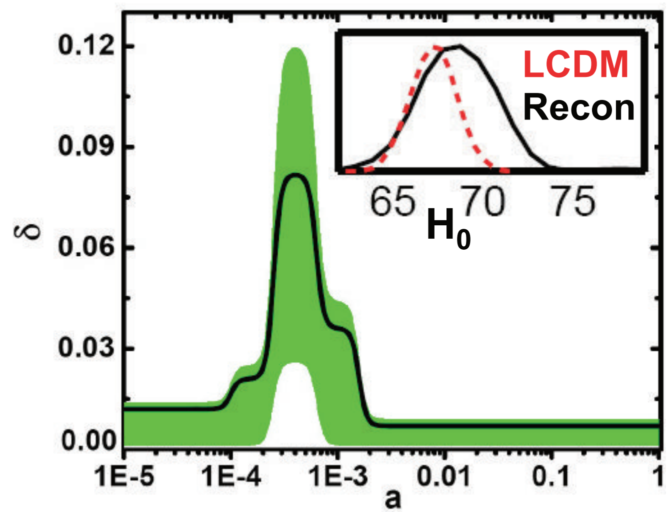
$r_{drag} \sim § \, dz \, c_s / H(z)$

Extra energy density raises H, lowers r_{drag}.

The degeneracy between r_{drag} and H_0 has long been known: Efstathiou & Bond 1998, Eisenstein & White 2004.

Hojjati, Linder, Samsing 2013 actually detected an early time transition and its effect on H_0!



Reconstruction from Planck13, WMAP9 data

The HLS approach has been rediscovered by Poulin+ 2019 and others.

Early transitions don't really work Hill+ 2003.07355.

Late Time Transition

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If we raise H(z), distances change. To keep distances viable, with larger H_0 need smaller H(z>0), i.e. less energy density.

Dark energy density has to suddenly appear – phantom $w < -1$.

- Phenomenological models, e.g. Li & Shafieloo 2019, 2020
- Fundamental theory – vacuum metamorphosis
  Parker & Raval 2000, Parker & Vanzella 2004, Caldwell+ 2006
- Emergent theory – ubergravity Khosravi+ 2019

Both VM and UG generalize Starobinsky R^2 gravity, VM by including loops to all orders, UG by "summing over states" giving an f(R) theory.

Does a Late Time Transition Work?

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With vacuum metamorphosis (same N_{par} as LCDM) one naturally gets $H_0 \sim 73$ for CMB+BAO or CMB+BAO+SN (no R19 used).

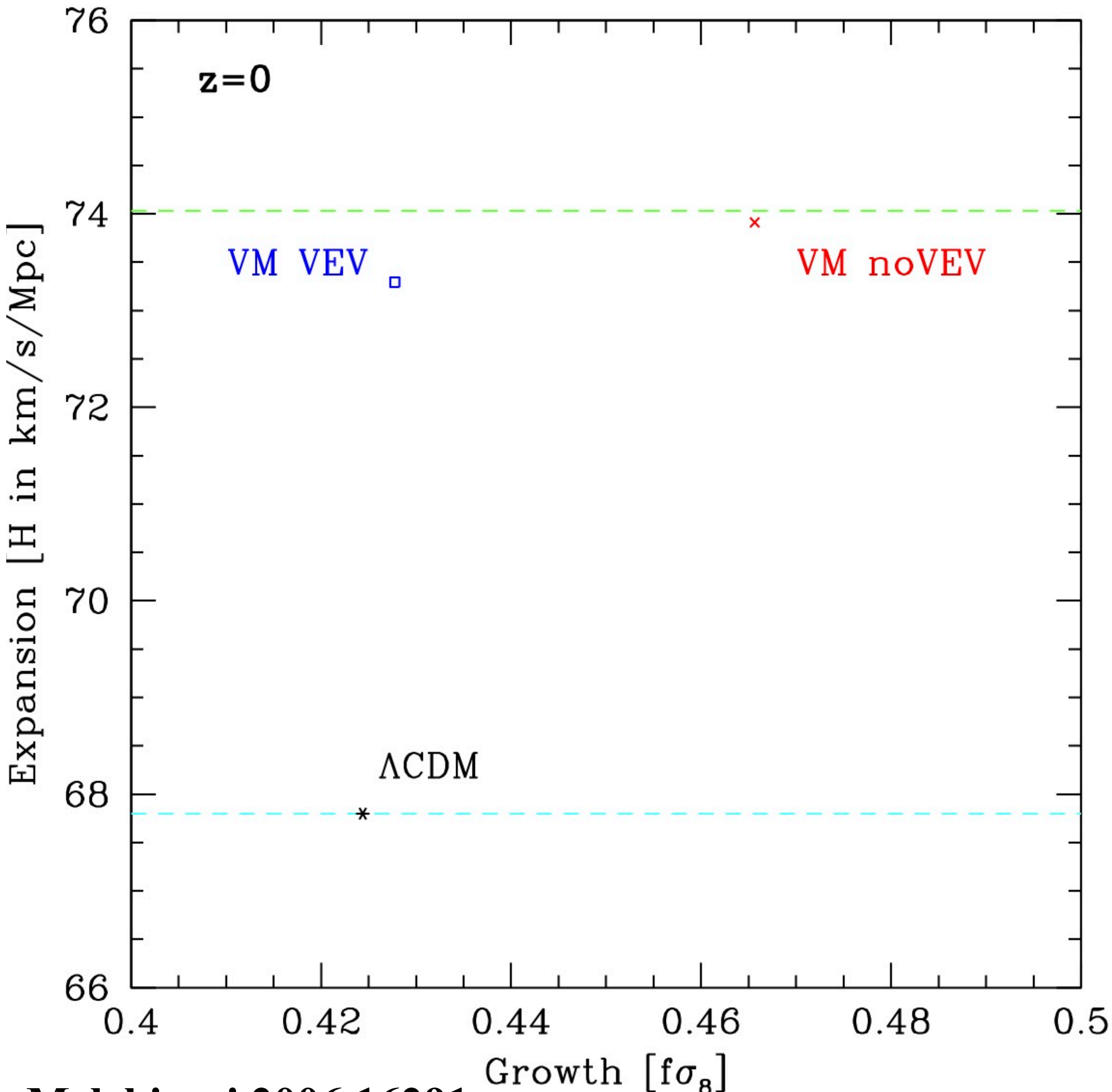
For a good fit to CMB, preserving $\Omega_m h^2$ means a lower $\Omega_m \sim 0.27$. That's ok.

However, it also gives a high amplitude for mass fluctuations $\sigma_8 \sim 0.88$. This is due to the reduced DE density (needed to get distances right) and so greater matter domination and growth.

That could be a problem. But $S_8 = \sigma_8(\Omega_m/0.3)^{0.5} \sim 0.83$. So for some probes (maybe weak lensing, not clusters) it may be at least as good as LCDM?

No Tension Today

VM gives H_0 ~ 73 while not making S_8 worse.



Di Valentino, Linder, Melchiorri 2006.16291

Jam Yesterday*

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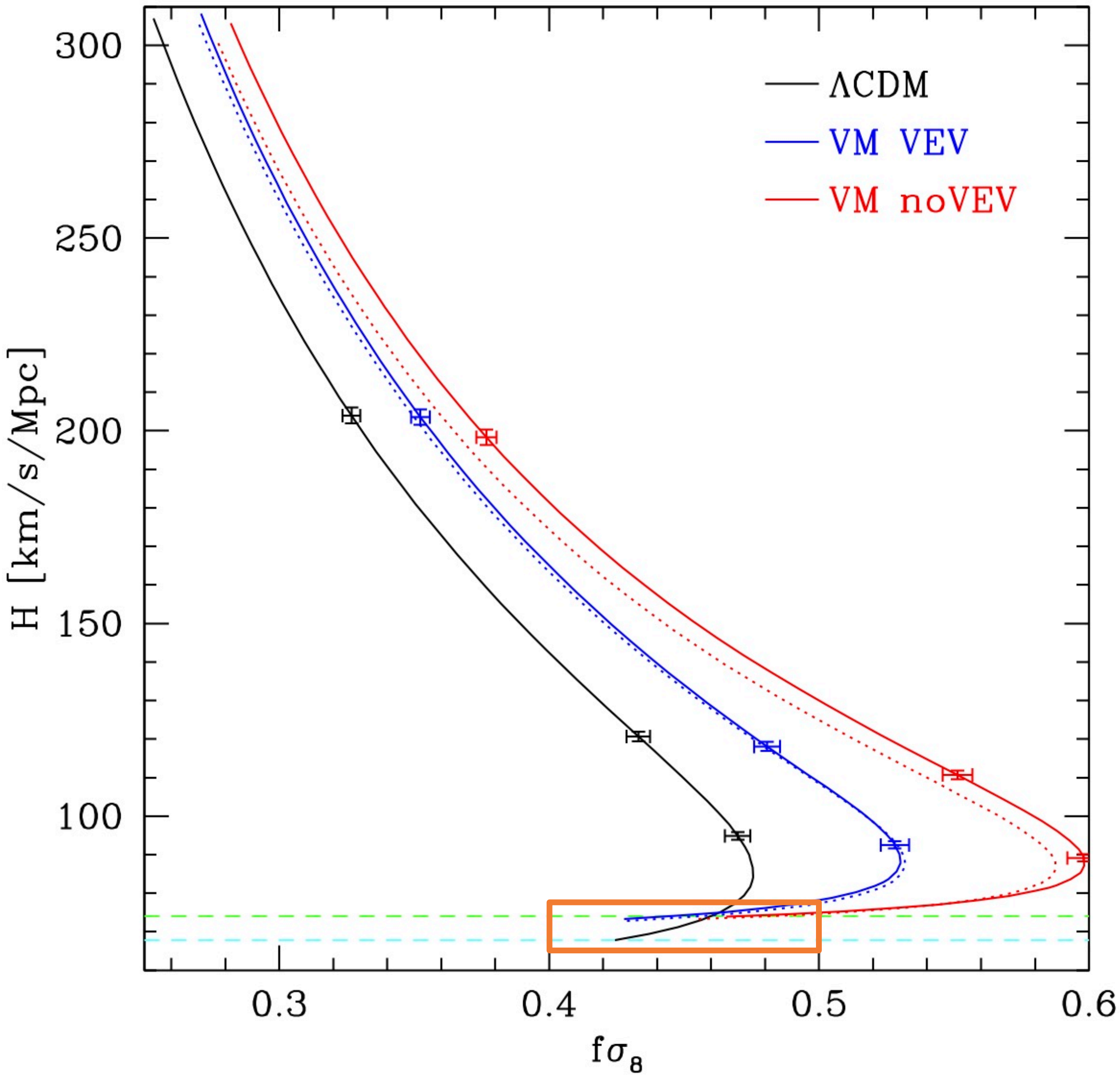
Focusing on 1 time is a bad idea. One has to take into account all cosmic times.



*** Lewis Carroll, Through the Looking-Glass and What Alice Found There**

Solution?

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Late time transitions don't really work.
(also see Benvenuto, Hu, Raveri 2002.11707)

As seen, early time transitions don't really work.

One has to take into account all the data.
One has to take into account all times.

It's not just H_0, it's $H(z)$. [Focusing on 1 number is a bad idea.]

It's not just Ω_m, it's $\Omega_m(z)$, i.e. $\sigma_8(z)$, $f\sigma_8(z)$.

How do we solve it? Raise H_0 but need to lower w, which raises σ_8, so need neutrinos/interactions, which changes... Epicycles? Or systematics?

New Cosmological Probes

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Can we open a new window on the cosmological framework?

Gravitational waves (as a new type of "stuff in the universe") can probe the cosmological model.

GW distances probe H_0, but it'll be a while until they reach the precision of current probes.

GW are great at probing "spacetime friction". This is like the Hubble friction that acts on LSS growth, but arises from $M_{Pl}(z)$. It damps the GW amplitude, changing the inferred distance $h \sim D_{GW}^{-1}$.

Is gravity the same at all cosmic times?

If not, then $D_{GW}(z) \neq D_{EM}(z)$.

Gravity at all Cosmic Times

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If gravity is not the same at all cosmic times then

$$D_{GW}(z) \neq D_{EM}(z)$$

That's one important check. Precision with single events is not great (and need counterpart) so will (eventually) do statistically (just as we do with, e.g., supernovae, BAO, strong lenses).

But changing gravity also affects LSS growth.

This gives an important crosscheck: a deviation from GR in one predicts a specific deviation in the other.

Growth and GW together

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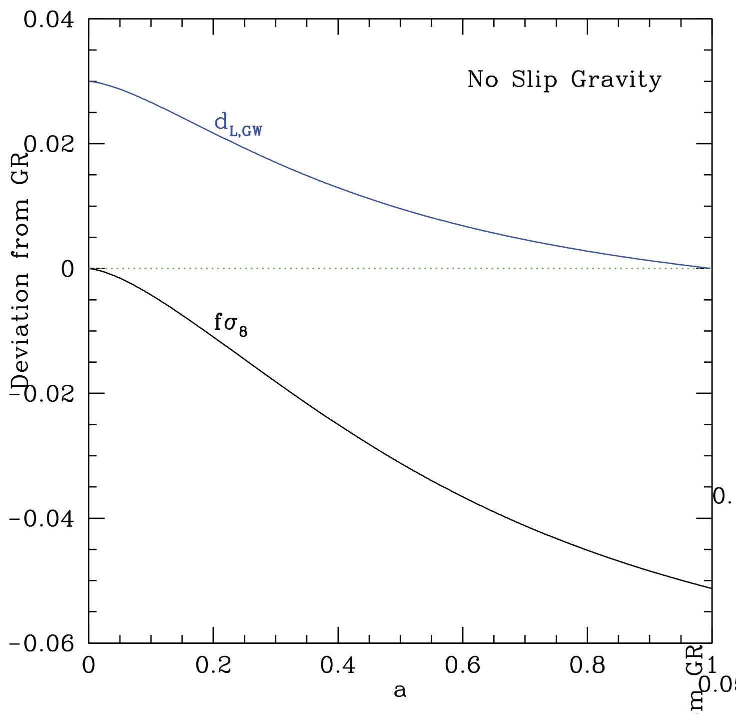
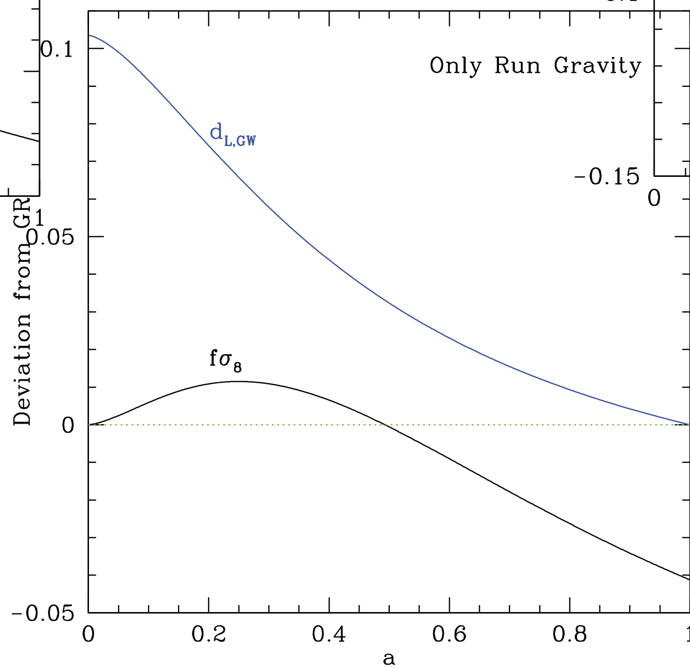
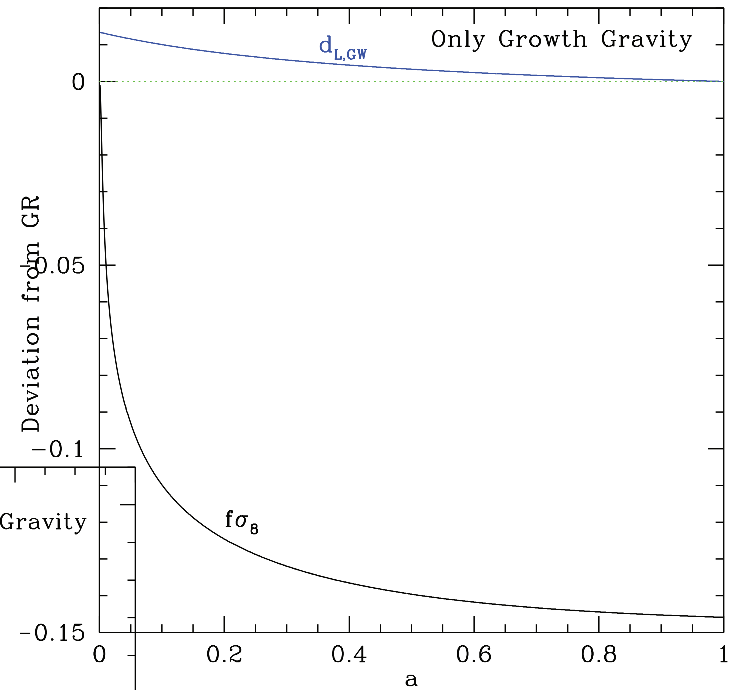
A deviation in GR in one can be crosschecked in the other, with different systematics.







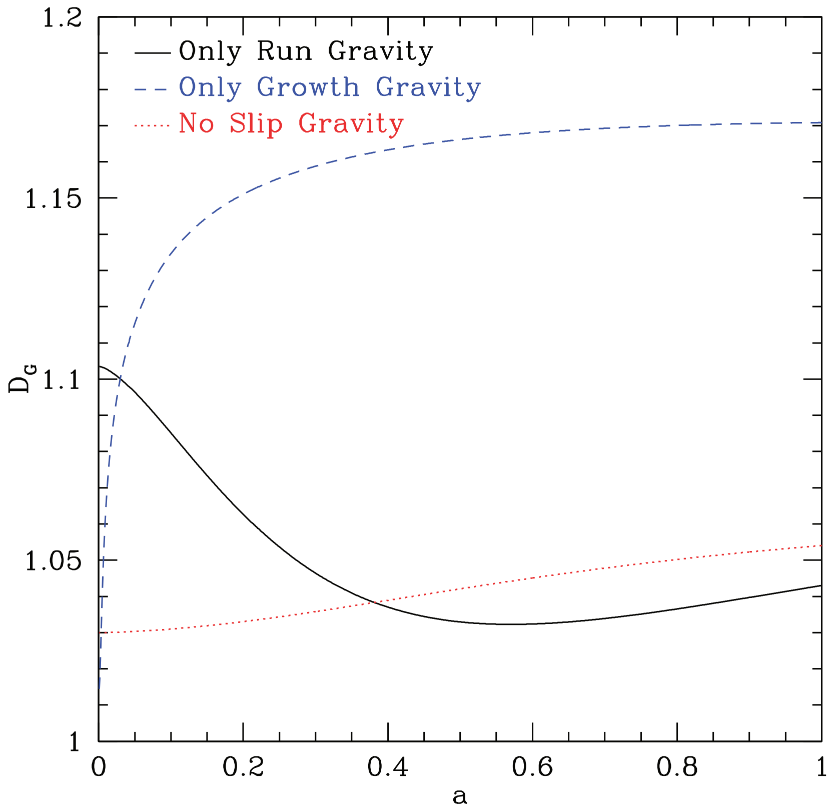
Linder 2003.10453

New Statistic – D_G

Quantify the conjoined information on GR deviation:

$$D_G(a) = \frac{d_{L,\mathrm{GW}}^{\mathrm{MG}} / d_L^{\mathrm{GR}}}{f\sigma_8^{\mathrm{MG}} / f\sigma_8^{\mathrm{GR}}}$$

For GR this is 1 for all z. For MG model it has a specific redshift dependence predicted.



Summary

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The cosmological framework is multilayered, with strong support for the deepest foundations.

LCDM works quite well, and it's not clear where "tensions" would be addressed.

All cosmology, all the time!

Early or late time transitions unlikely as the answer.

- ***Why are there ~10's times more papers on unusual theories than on data systematics?***

New probes are always welcome.

Is gravity the same at all cosmic times?

- ***New statistic D_G: GW vs growth – predictive.***