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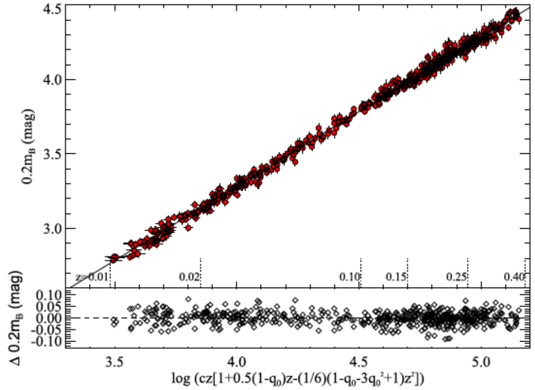
DISCORDANCE INTO CONCORDANCE
The standard cosmological model

- Standard cosmological model
- Observational evidences
- Issues: H_0
- Issues: Dark Matter
- Issues: Flatness
- Issues: The Lithium problem

Standard cosmological model

What do we know about universe?

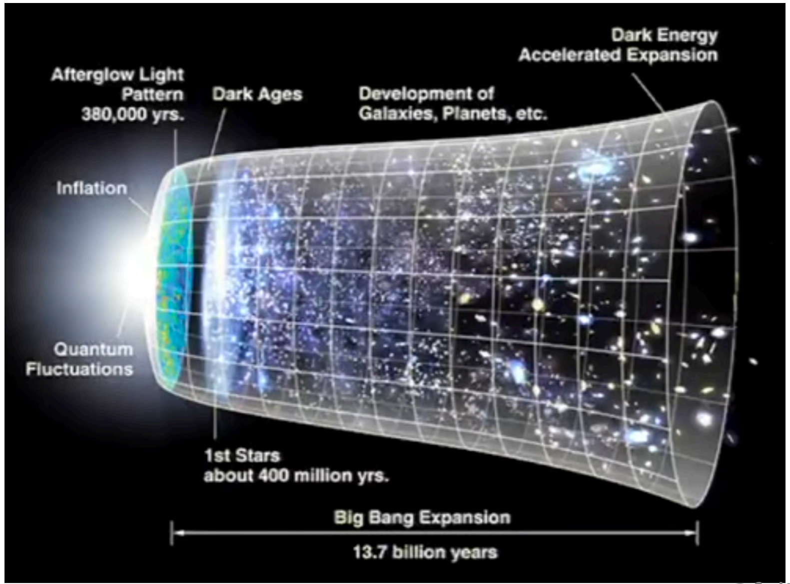


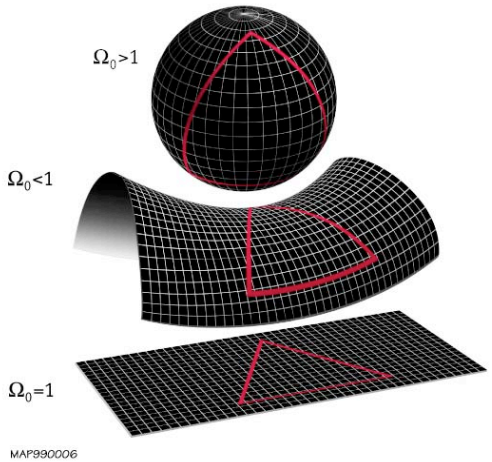
SCM pillars:

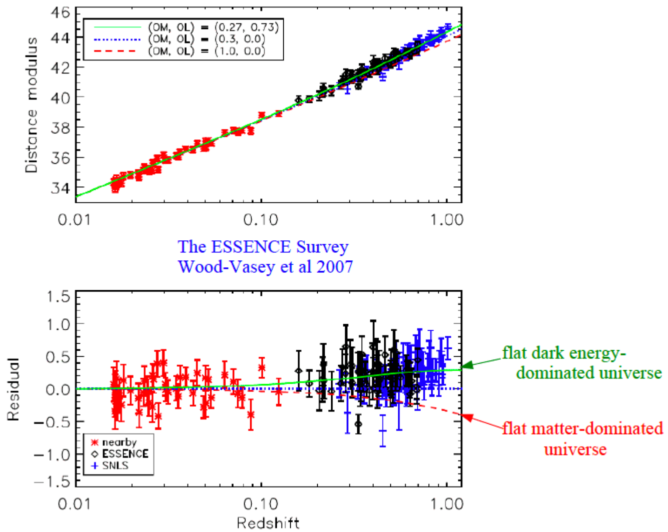
- universe is expanding ➡ Hubble law: $v_G = H_0 \, d_G$
- universe is cooling down

➡
  - universe was very hot at beginning: Big Bang (BB)
  - universe is filled with fossil radiation: Cosmic Microwave Background (CMB)

- universe is flat and is now accelerating (flatness and coincidence problems?)







The SCM

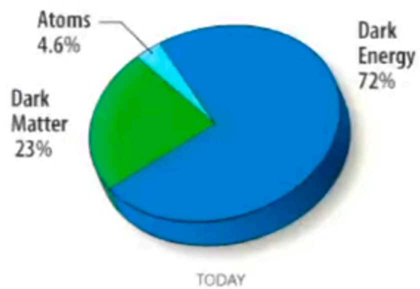
k = curvature parameter

Ingredients:

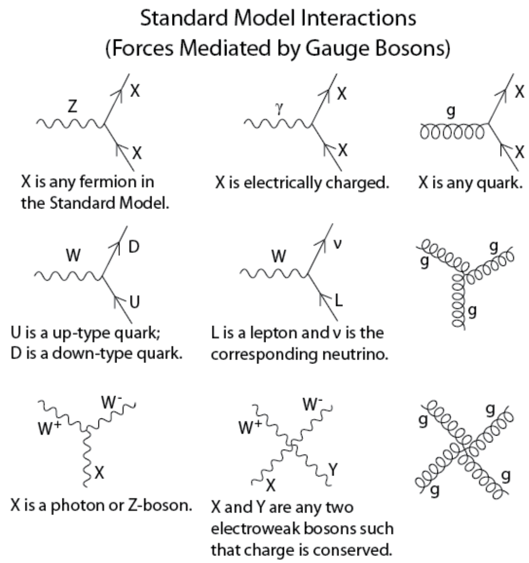
- GR + cosmological principle ➡ FLRW metric: $ds^2 = dt^2 - a^2\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$

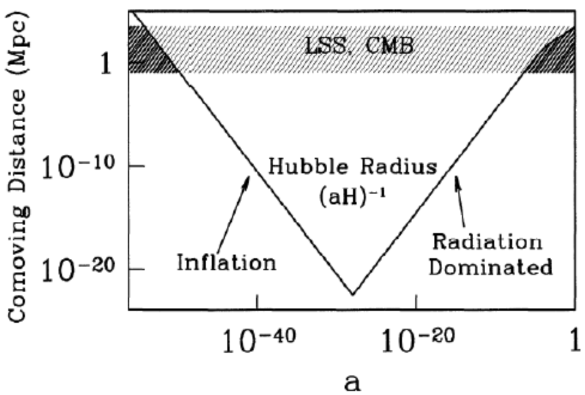
$$H \equiv \frac{\dot{a}}{a} \qquad H_0 \equiv \left(\frac{\dot{a}}{a}\right)_0 = 100\ h \text{ km/s Mpc}^{-1}$$

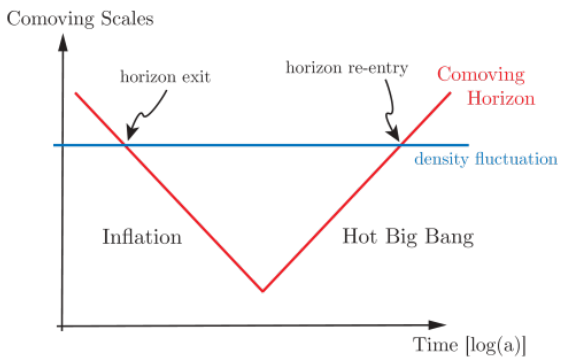
$$1 + z \equiv \frac{\lambda_o}{\lambda_e} \qquad a \equiv \frac{1}{1+z}$$



- universe components: DE, DM, baryons, (neutrinos, photons)
- microscopical physics: SM + possible extensions
- initial condition: inflation







The “concordance” ΛCDM

Our description of the universe is contained in six parameters:

Planck collaboration: 1807.06209

Parameter	TT+lowE 68% limits	TE+lowE 68% limits	EE+lowE 68% limits	TT,TE,EE+lowE 68% limits	TT,TE,EE+lowE+lensing 68% limits	TT,TE,EE+lowE+lensing+BAO 68% limits
$\Omega_b h^2$	0.02212 ± 0.00022	0.02249 ± 0.00025	0.0240 ± 0.0012	0.02236 ± 0.00015	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1206 ± 0.0021	0.1177 ± 0.0020	0.1158 ± 0.0046	0.1202 ± 0.0014	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04077 ± 0.00047	1.04139 ± 0.00049	1.03999 ± 0.00089	1.04090 ± 0.00031	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0522 ± 0.0080	0.0496 ± 0.0085	0.0527 ± 0.0090	$0.0544^{+0.0070}_{-0.0081}$	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10}A_s)$	3.040 ± 0.016	$3.018^{+0.020}_{-0.018}$	3.052 ± 0.022	3.045 ± 0.016	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9626 ± 0.0057	0.967 ± 0.011	0.980 ± 0.015	0.9649 ± 0.0044	0.9649 ± 0.0042	0.9665 ± 0.0038

background

initial conditions

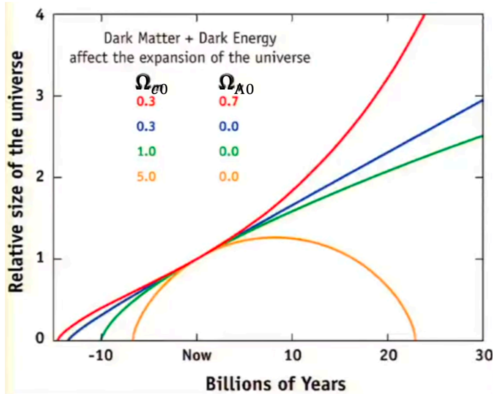
$$H^2 = \frac{8\,\pi G_N}{3}\rho_{tot} - \frac{k}{a^2}$$

$$\rho_{tot} = \rho_\Lambda + \rho_M + \rho_R$$

$$H^2 = \frac{8\,\pi G_N}{3}\rho_{tot} - \frac{k}{a^2} \quad \xrightarrow{k=0} \quad \rho_{c0} = \frac{3H_0^2}{8\,\pi G_N} = 1.88 \cdot 10^{-26} h^2\ \mathrm{kg/m^3}$$

$$\Omega_{i0} \equiv \frac{\rho_{i0}}{\rho_{c0}}$$

$$\Omega_{\Lambda 0} + \Omega_{c0} + \Omega_{b0} + \Omega_{\nu 0} + \Omega_{\gamma 0} + \Omega_{k0} = 1 \quad \Longleftrightarrow \quad \Omega_0 + \Omega_{k0} = 1$$



ΛCDM-model: Ω_k=0 and Ω_R is standard (known function of T_0).

Background: energy budget + CMB parameters. Initial conditions: inflation parameters.

Initial conditions: inflation

II Friedmann equation: ordinary matter/energy (positive pressure) decelerates.

$$H^2 = \frac{8\,\pi G_N}{3}\rho_{tot} - \frac{k}{a^2} \qquad\qquad \frac{\ddot{a}}{a} = -\frac{4\,\pi G_N}{3}(\rho_{tot} + 3p_{tot})$$

Inflation is a period of accelerated expansion, with a not ordinary equation of state

$$p_\Lambda = -\rho_\Lambda$$

Inflation solves several problems of cosmology (horizon, flatness, coincidence) and gives us (as a bonus) a theory for the formation of structures.

However, it makes only statistical predictions!

$$\delta(\vec{r},t) \equiv \frac{\rho_\mathrm{M}(\vec{r},t) - \rho_\mathrm{M0}(t)}{\rho_\mathrm{M0}(t)} \longrightarrow P(k,t) = \langle|\delta(\vec{r},t)|^2\rangle$$

Initial conditions are encoded in the form of the power spectrum at the inflation time

$$P(k,t_{inf}) = A_s\left(\frac{k}{k_0}\right)^{n_s-1} \longrightarrow P(k,t) = A_s\left(\frac{k}{k_0}\right)^{n_s-1} T^2(k,t)$$

Sigle scalar inflation: the predictions

- a flat universe, due to exponential expansion
- Gaussian primordial fluctuations, behaving as in flat space at asymptotic early time and short distances (Bunch-Davies initial conditions)
- Harrison-Zel'dovich-Peebles spectrum (almost scale invariant)

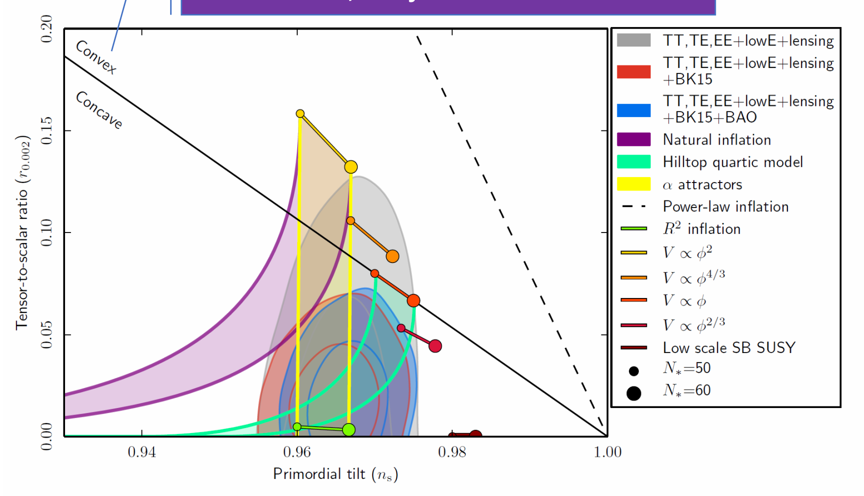
$$n_s \approx 1$$

- adiabatic initial conditions
- primordial gravitational waves

$$P_T(k, t_{inf}) = A_T \left(\frac{k}{k_0}\right)^{n_T}$$

$$r \equiv \frac{P_T(k_0)}{P_s(k_0)} \cong 0.1 \; \frac{\rho_{inf}}{(10^{16}\; GeV)^4}$$

F. Bouchet, Majorana lectures 2020



$$r < 0.06 \; (95\% CL)$$

Observational evidences

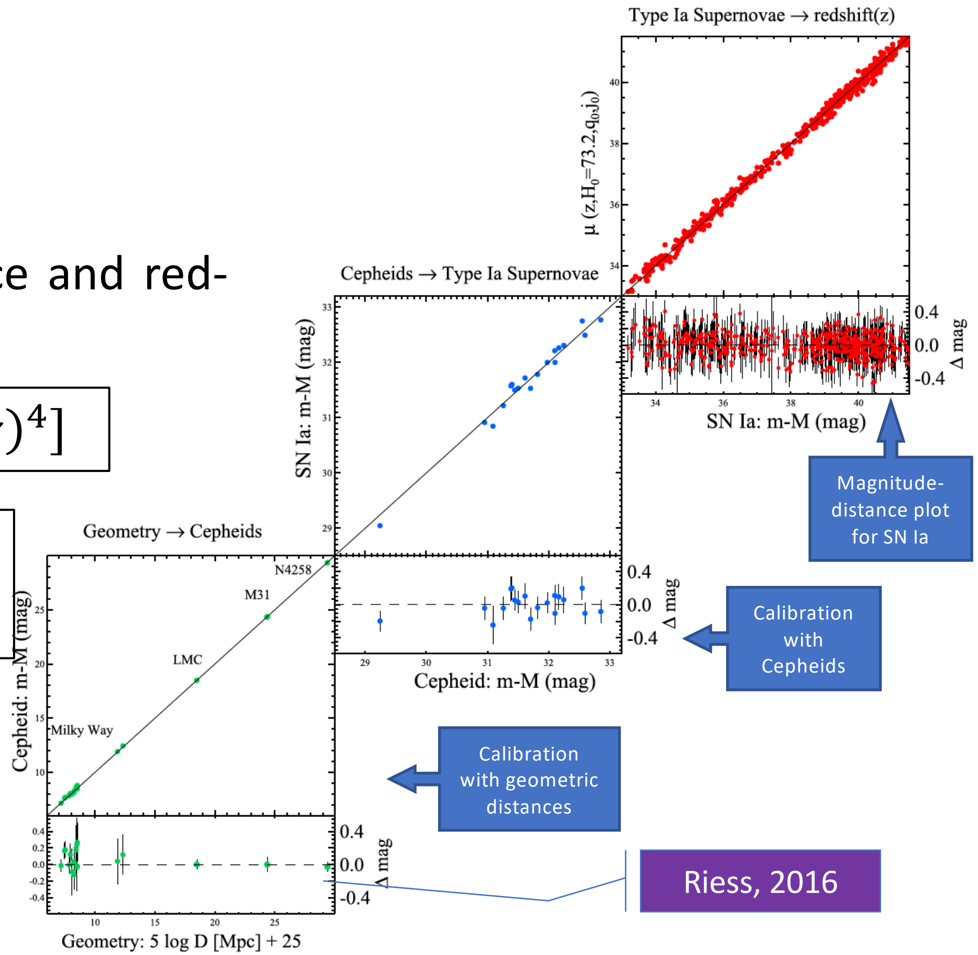
Hubble flow

H_0 comes mainly from a measure of distance and red-shift (but also time and red-shift)

$$H^2 = H_0^2[\Omega_{\Lambda 0} + \Omega_{M0}(1+z)^3 + \Omega_{R0}(1+z)^4]$$

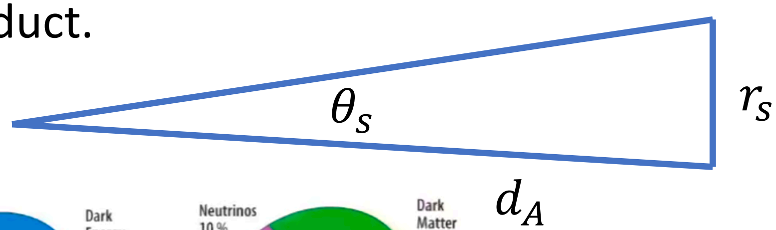
$$d = a_0\,\chi = \int_0^z \frac{dz'}{H(z')}$$

$$\delta t \cong \frac{\delta z}{H(z)(1+z)}$$



In the local universe distances can be measured by **standard candles**, like SN Ia, calibrated with Cepheids.

In the primordial universe distances can be measured by **standard rulers**, like the sound horizon size at recombination. H_0 is not a parameter of the model but a by-product.



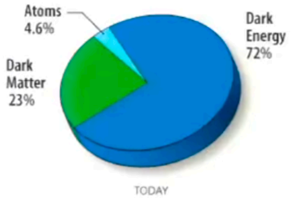
$$r_s = \int_{z_r}^{\infty} \frac{c_s\,dz}{H(z)}$$

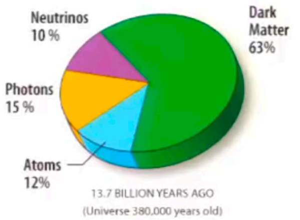
early times

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

late times

$$z_r \cong 1100$$





Big Bang Nucleosynthesis

At about 1 s from the BB, when temperature is ~ 1 MeV, protons and neutrons form light nuclides (mainly H, ^{4}He, and trace amount of the others).

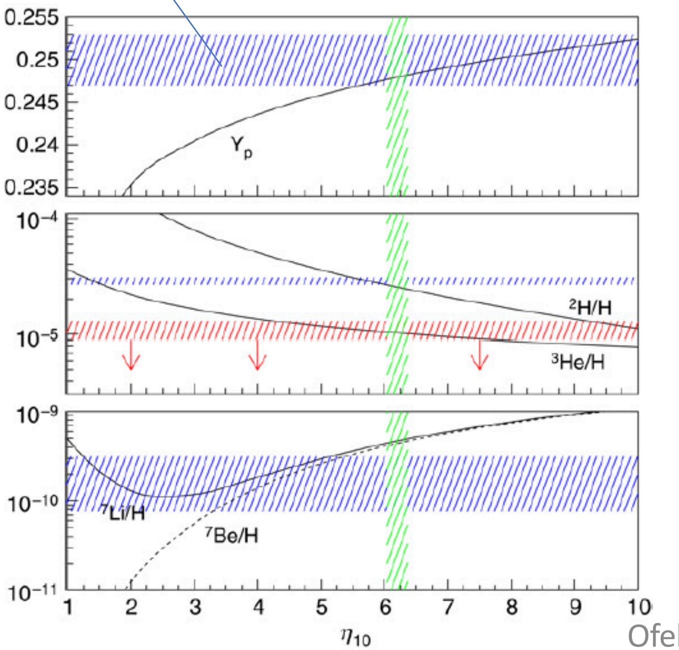
In the standard BB cosmology, the final element yields depends only on one parameter, the amount of baryons, $\Omega_b h^2$, which is encoded in a time-independent quantity

$$\eta = \frac{n_b}{n_\gamma} \approx 6 \cdot 10^{-10}$$

$$\Omega_b h^2 \approx \frac{\eta \cdot 10^{10}}{273.3\,(1 + 0.01\,Y_p)} \frac{T_0}{2.72\,K}$$

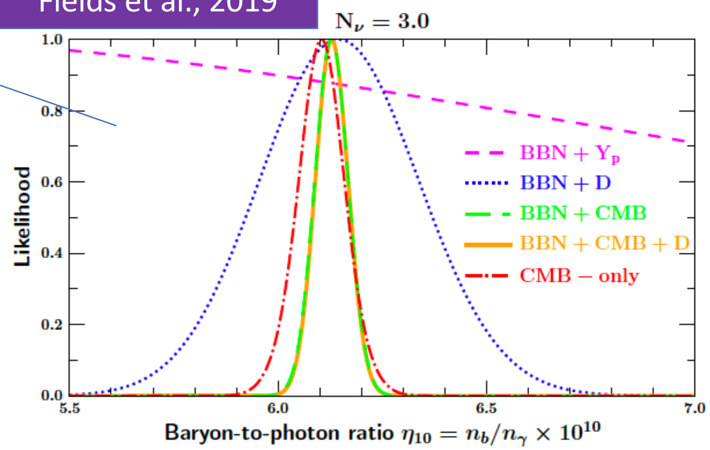
^{4}He mass fraction

Schramm plot



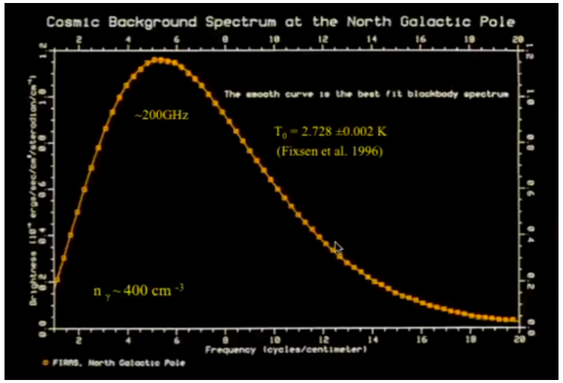
Standard BBN (no extensions of the SM of particles) gives a prediction in fair agreement with the independent prediction from CMB.

Fields et al., 2019



Cosmic Microwave Background

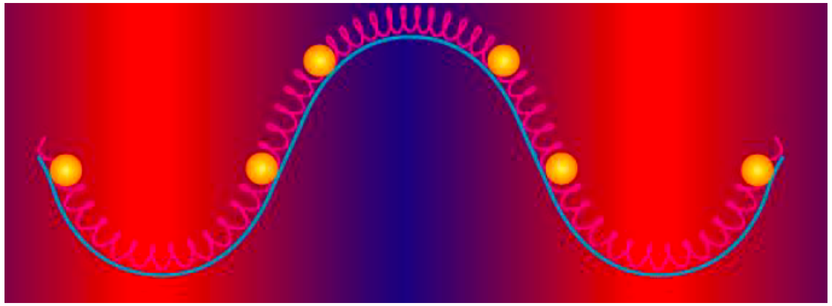
Perfect black body with a temperature of 2.73 K and tiny fluctuations of relative amplitude 10^{-5}.

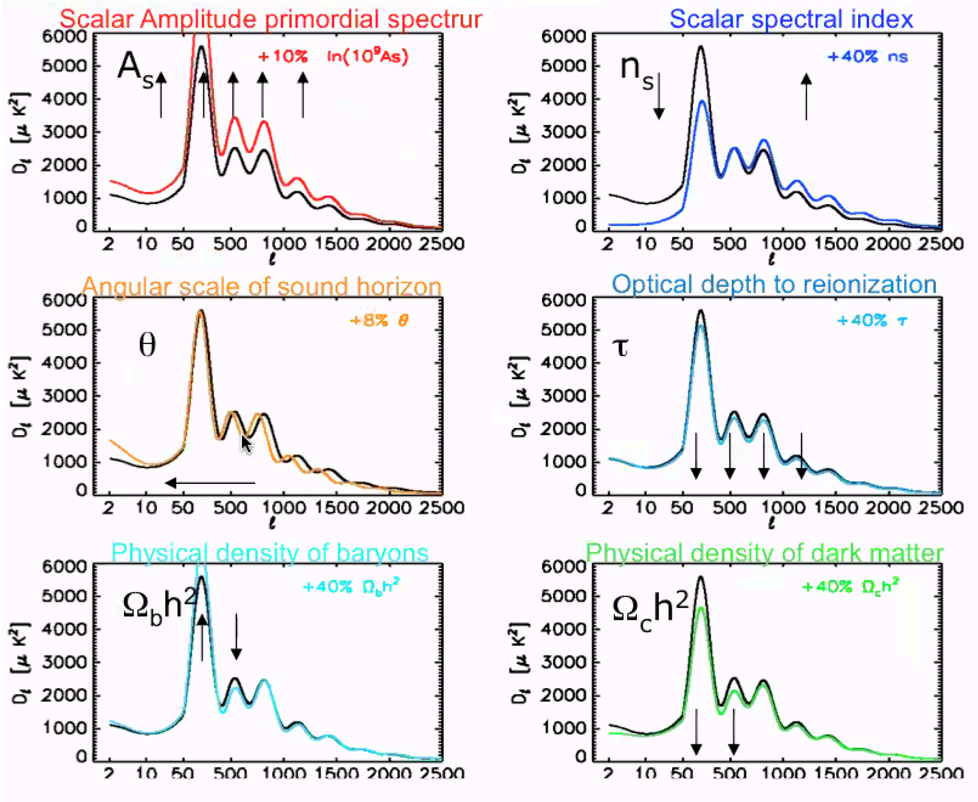


Newtonian theory of perturbation

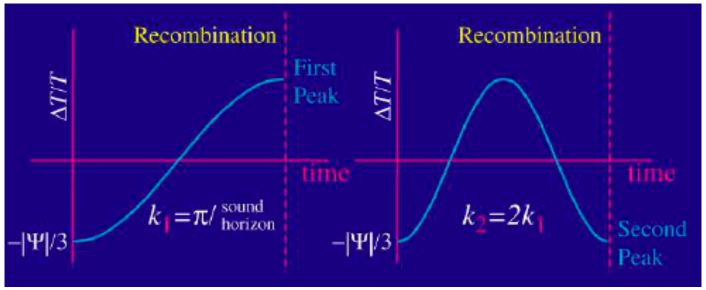
$$\ddot{\delta}_k + 2H\dot{\delta}_k + \left(k^2 c_s^2 - 4\,\pi\, G_N\, \rho_{bgd}\right)\delta_k = 0$$

Matter fluctuations are coupled to radiation ones.





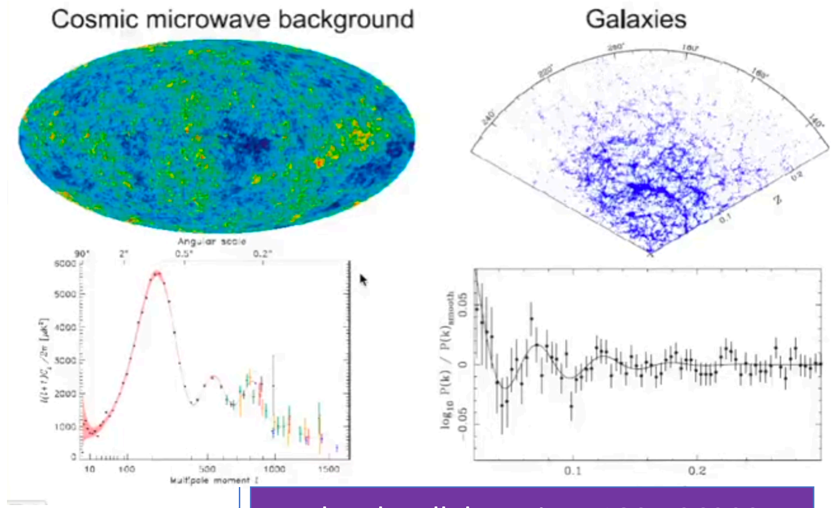
First peak: first maximal compression
Second peak: first maximal decompression



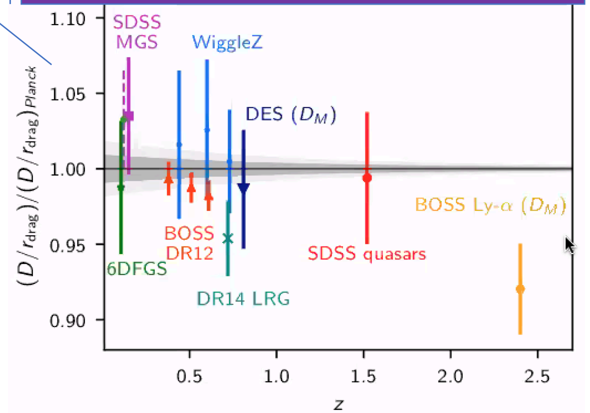
Other observational data

- Large Scale Structure
- Gravitational lensing
- Galaxy rotational curves
- X-ray emission in clusters
- Supernovae IA
- …
- Baryon Acoustic Oscillations

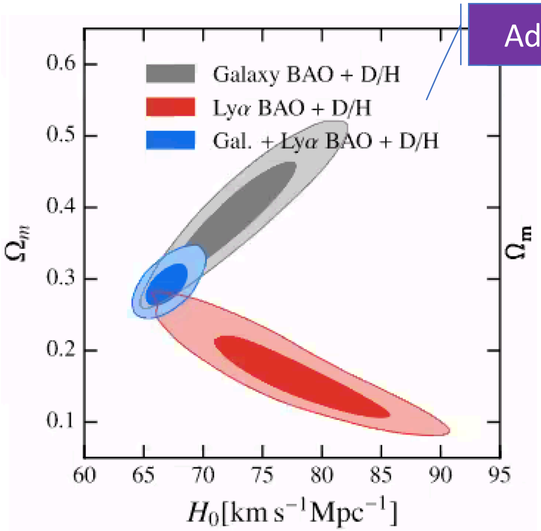
These are the same oscillations seen in CMB but at different redshifts.



Planck collaboration: 1807.06209



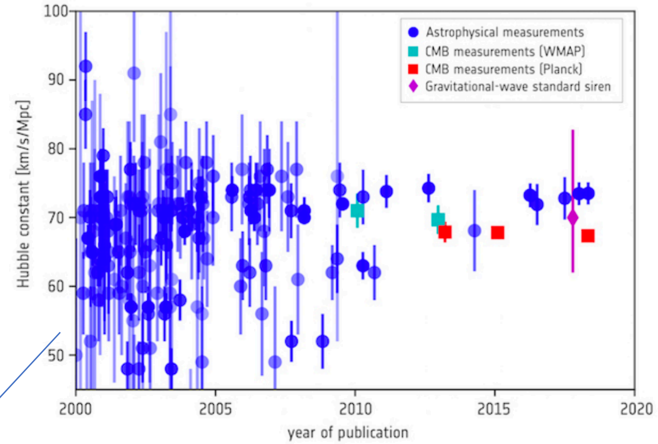
Addison et al., ApJ 2018



For CMB-independent determination of H_0, BAO experiments can use the baryons density coming from BBN and break the degeneracy with Ω_M using data at different red-shifts.

Issues: H_0

The problem: increasingly precise measures of H0 show a tension between local and primordial determinations.



ESA/Planck Collaboration, 2018

Planck collaboration: 1807.06209

$H_0 = 67.36 \pm 0.54$ km/s Mpc^{-1} (0.8%)

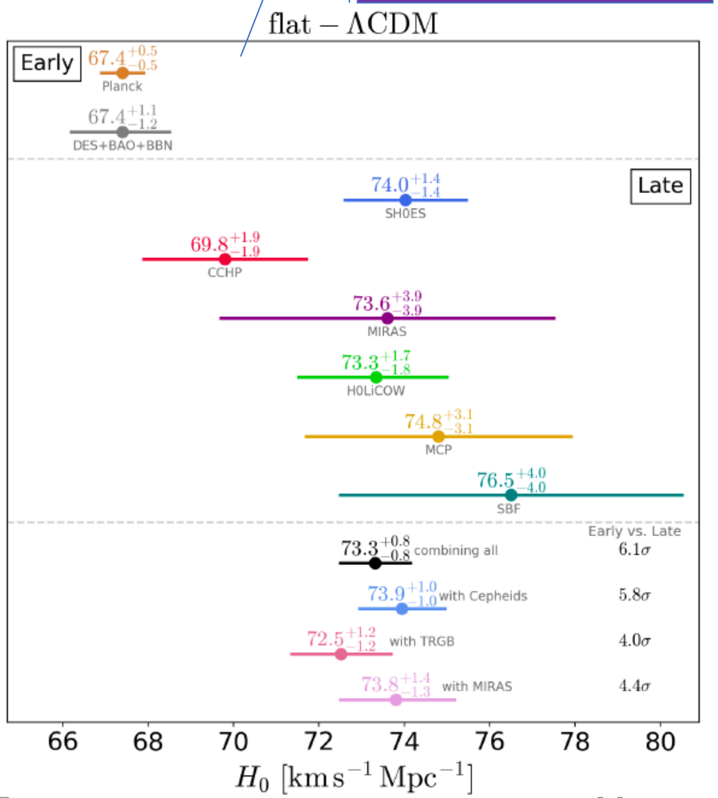
$H_0 = 74.03 \pm 1.42$ km/s Mpc^{-1} (1.9%)

Riess et al, 2019

4.4σ

SH0ES collaboration, 2017

Verde et al., 2019



An H_0 problem?

Early universe issues:

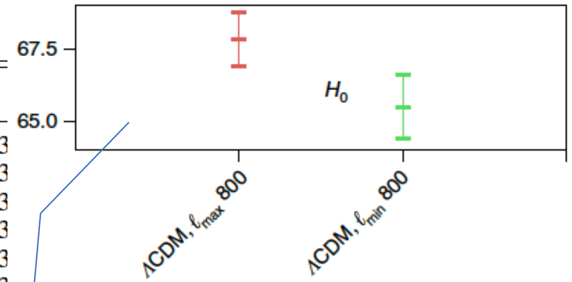
✓ despite several improvements in data analysis, Planck H_0 was very stable

✓ in all "classical" extensions of the base ΛCDM, H_0 is "low"

✓ all CMB experiments (not only Planck) gives "low" H_0; moreover, CMB-independent BAO calibrated with BBN still gives low H_0

✗ small difference between the small and high multipole data determination of H_0

✗ tensions in ΛCDM model that could be the smoking gun for some shortcoming? (A_{lens} in Planck, BAO at z<1 and Ly-α at high z)



Di Valentino et al., Nature Astr., 2020

Parameter(s)	$\Omega_b h^2$	$\Omega_c h^2$	$100\theta_{MC}$	H_0	n_s	
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3
$dn_s/d\ln k$	0.02240 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.53	0.9641 ± 0.0044	3
$dn_s/d\ln k, r$	0.02243 ± 0.00015	0.1199 ± 0.0012	1.04093 ± 0.00030	67.44 ± 0.54	0.9647 ± 0.0044	3
$d^2n_s/d\ln k^2, dn_s/d\ln k$	0.02237 ± 0.00016	0.1202 ± 0.0012	1.04090 ± 0.00030	67.28 ± 0.56	0.9625 ± 0.0048	3
N_{eff}	0.02224 ± 0.00022	0.1179 ± 0.0028	1.04116 ± 0.00043	66.3 ± 1.4	0.9589 ± 0.0084	[illegible]
$N_{eff}, dn_s/d\ln k$	0.02216 ± 0.00022	0.1157 ± 0.0032	1.04144 ± 0.00048	65.2 ± 1.6	0.950 ± 0.011	3.03
Σm_ν	0.02236 ± 0.00015	0.1201 ± 0.0013	1.04088 ± 0.00032	$67.1^{+1.2}_{-0.67}$	0.9647 ± 0.0043	3.04
$\Sigma m_\nu, N_{eff}$	0.02223 ± 0.00023	0.1180 ± 0.0029	1.04113 ± 0.00044	$66.0^{+1.8}_{-1.6}$	0.9587 ± 0.0086	3.038 ± 0.017
$m^{eff}_{\nu,\,sterile}, N_{eff}$	$0.02242^{+0.00014}_{-0.00016}$	$0.1200^{+0.0032}_{-0.0020}$	$1.04074^{+0.00033}_{-0.00029}$	$67.11^{+0.63}_{-0.79}$	$0.9652^{+0.0045}_{-0.0056}$	$3.050^{+0.014}_{-0.016}$
α_{-1}	0.02238 ± 0.00015	0.1201 ± 0.0015	1.04087 ± 0.00043	67.30 ± 0.67	0.9645 ± 0.0061	3.045 ± 0.014
w_0	0.02243 ± 0.00015	0.1193 ± 0.0012	1.04099 ± 0.00031	...	0.9666 ± 0.0041	3.038 ± 0.014
Ω_K	0.02249 ± 0.00016	0.1185 ± 0.0015	1.04107 ± 0.00032	$63.6^{+2.1}_{-2.3}$	0.9688 ± 0.0047	$3.030^{+0.017}_{-0.015}$
Y_P	0.02230 ± 0.00020	0.1201 ± 0.0012	1.04067 ± 0.00055	67.19 ± 0.63	0.9621 ± 0.0070	3.042 ± 0.016
Y_P, N_{eff}	0.02224 ± 0.00022	$0.1171^{+0.0042}_{-0.0049}$	1.0415 ± 0.0012	$66.0^{+1.7}_{-1.9}$	0.9589 ± 0.0085	3.036 ± 0.018
A_L	0.02251 ± 0.00017	0.1182 ± 0.0015	1.04110 ± 0.00032	68.16 ± 0.70	0.9696 ± 0.0048	3.0

Planck collaboration: 1807.06209

An H_0 problem?

Late universe issues:

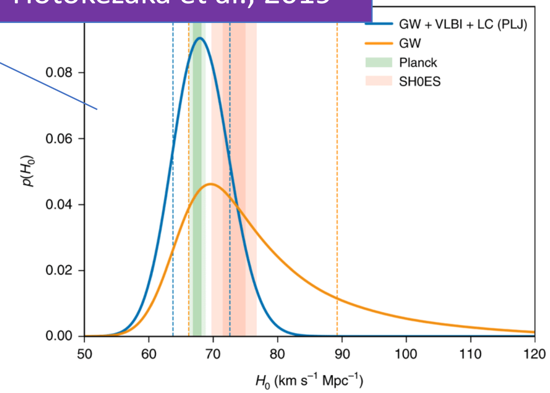
✗ distance ladder is based on different astrophysical calibrations and systematics can be somehow underestimated. SN from Riess et al. are in young environment (where they usually are fainter) while distant ones are expected to be a mix. Taking this into account might bring their central value to 70 km/s Mpc^{-1}.

✗ a different SN calibration, by TRGB, gives a smaller H_0 determination, in between CMB and Cepheids one, and in agreement with both (?systematics claimed, still discussed)

✗ different physical explanations (super-void) does not fit with ΛCDM

✓ GW technique very promising but for the moment larger uncertainties, $H_0 = 70.3 \pm^{5.3}_{5.0}$ km /s Mpc^{-1}.

Hotokezaka et al., 2019



Then:

- Despite the efforts at present no systematic effects can reconcile the discrepancy
- New physics could be involved? Not easy to find explanations without disturbing agreement with all existing data
- Time will judge...

Issues: Dark Matter

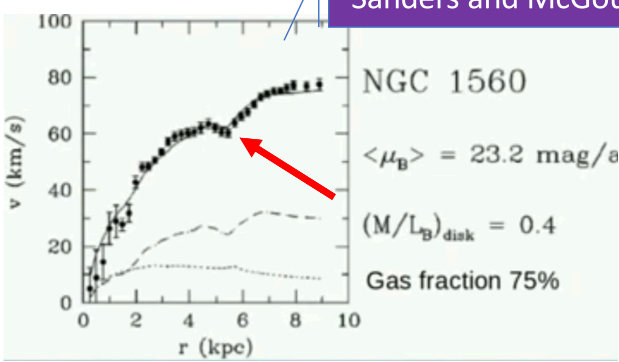
The problem: is DM really there or only an "ad hoc" invention for explaining some anomalies? Indeed, there are classical small scale challenges to DM: cusp/core, missing satellites, too-big-to-fail.

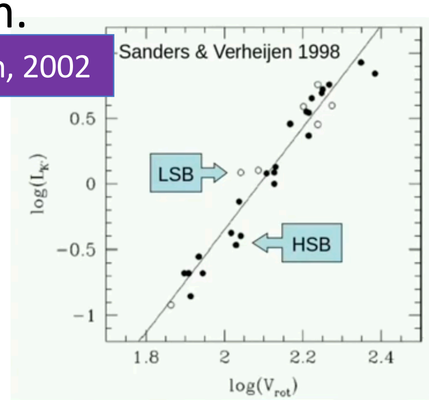
MOND (Milgrom, 1983) based on the observation that, in galaxies, DM appears only when gravity acceleration is below a fixed value, $a_0 \approx 1.2 \cdot 10^{-8}$ cm/s^2. Then, the hypothesis is that below this value Newtonian dynamics breaks down.

$$a = \frac{\sqrt{G_N M a_0}}{r} \qquad a \ll a_0$$

A war with no holds barred!

Sanders and McGough, 2002





van Dokkum et al., Nature 2018

LETTER

doi:10.1038/nature25767

A galaxy lacking dark matter

Pieter van Dokkum[1], Shany Danieli[1], Yotam Cohen[1], Allison Merritt[1,2], Aaron J. Romanowsky[3,4], Roberto Abraham[5], Jean Brodie[4], Charlie Conroy[6], Deborah Lokhorst[5], Lamiya Mowla[1], Ewan O'Sullivan[6] & Jielai Zhang[5]

LSB galaxies are claimed to be in MOND regime since stars are far apart and acceleration lower → they should exhibit a sizable DM component → LSB galaxy without DM considered a falsification of MOND.

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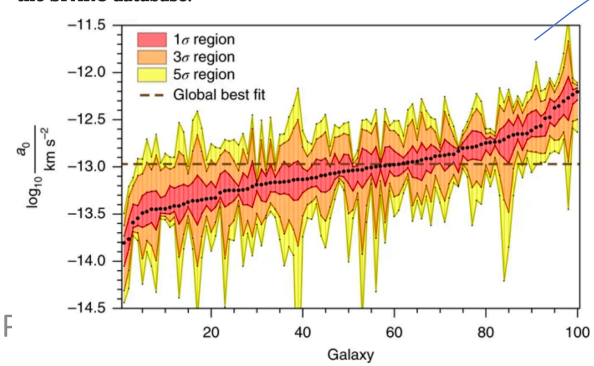
Received 2019 March 20; revised 2019 July 1; accepted 2019 July 6; published 2019 July 19

Abstract

A second galaxy "missing dark matter" (NGC 1052-DF4) has been reported recently. Here we show, using the location of the tip of the red giant branch (TRGB), that the distance to this galaxy is 14.2 ± 0.7 Mpc. This locates the galaxy 6 Mpc closer than previously determined. We also analyze the distances to the brightest galaxies in the field of view of NGC 1052. We find that this field is populated by two groups of galaxies in projection: one dominated by NGC 1052 and NGC 1047 at ~19 Mpc, and another group containing NGC 1042 and NGC 1035 (as well as [KKS2000]04 and NGC 1052-DF4) at ~13.5 Mpc. At a distance of 13.5 Mpc the globular clusters of NGC 1052-DF4 have the same properties as globular clusters in the Milky Way and other dwarf galaxies.

Monelli and Trujillo, ApJ 2018

Fig. 1: Posterior probability distributions of a_0 for the galaxies of the SPARC database.



Rodrigues et al., Nature Astr. 2018

Using the same data Rodrigues et al. and McGaugh et al. make opposite claims. What changes is the prior.

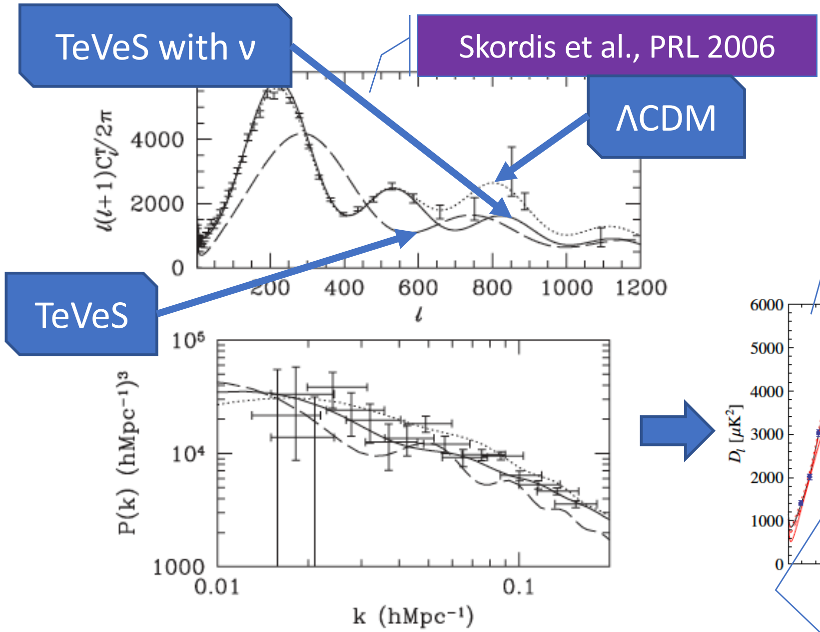
A relativistic covariant MOND?

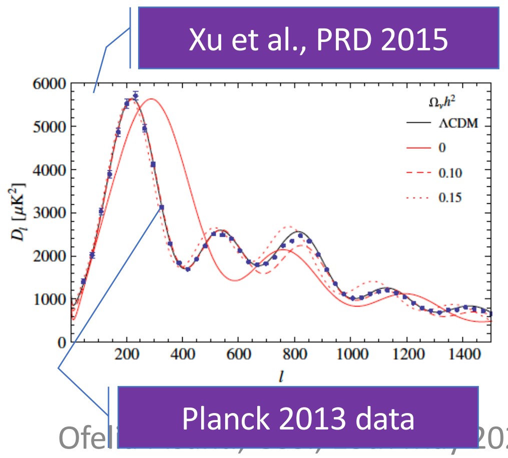
MOND competitive with “local description” but what about the primordial universe? Expansion history, CMB, power spectrum...

Bekenstein, 2004: proposal to embedded MOND in a Tensor-Vector-Scalar model of gravity

- ordinary matter couples to the **disformally transformed metric** $\tilde{g}_{\mu\nu}$ with DM
- GWs couple to $g_{\mu\nu}$ without DM

TeVeS can make predictions on CMB, PS, ...





...but, at the end, it has been falsified.

Boran et al., PRD 2018

GW170817 falsifies dark matter emulators

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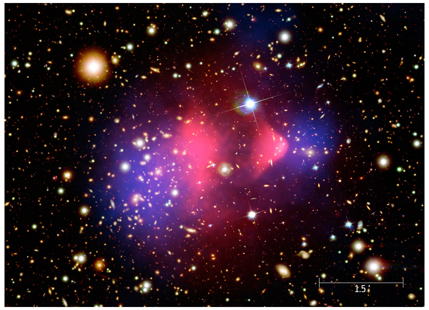
(Received 25 October 2017; published 13 February 2018)

A DM problem?



- MOND/DM dispute proposes again the old debate: in presence of an anomaly, should one modify the laws of nature (perihelion of Mercury) or search for some other of matter (discovery of Neptune)?

✓ MOND very performant in explaining galaxy dynamics, but...

✗ cluster of galaxies remain a challenge (e.g. Bullet Cluster), and...

✗ TeVeS, where MOND was embedded in, not so performant (CMB, but especially BAO) and after all based on different kind of DM, and...

✗ GW detection falsifies modified gravity models where GW and matter couple to different metrics, but...

✓ there are other extensions: bi-metric MOND, non-local MOND, ...

Then:

- Occam razor would suggest that for the moment MOND less satisfying than DM
- things to be clarified: why does MOND work so well with galaxies? $a_0 \sim cH_0$, a new fundamental mass scale in physics? modified gravity or GR?

Issues: Flatness

The problem:

Di Valentino et al., Nature Astronomy, 2020

- “Two datasets in major tension with Planck: H_0 (Riess et al, 2019) and weak lensing (Hildebrandt et al., 2017)”
- These tensions worsen and new tensions arise if flat universe hypothesis is abandoned

a cosmological crisis hidden under the flat carpet of the universe?

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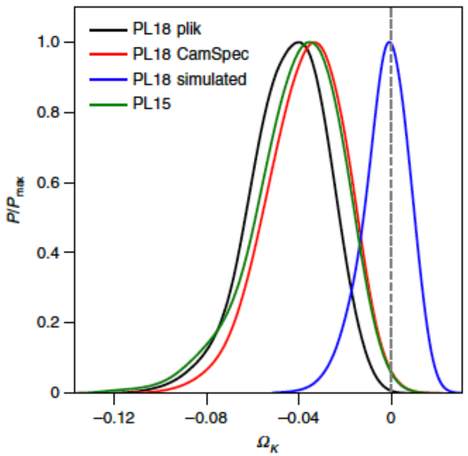

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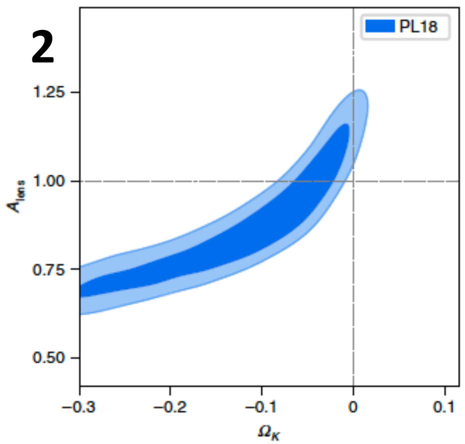

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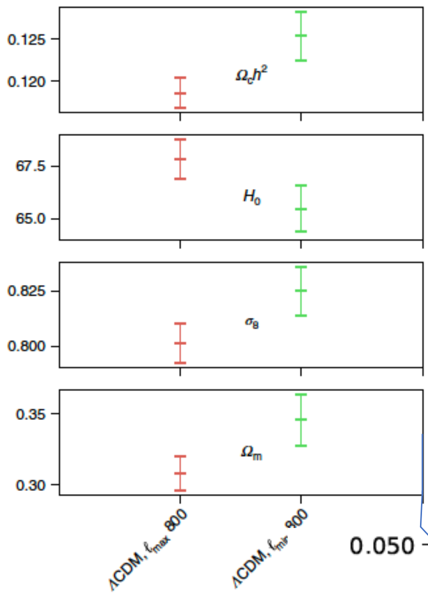

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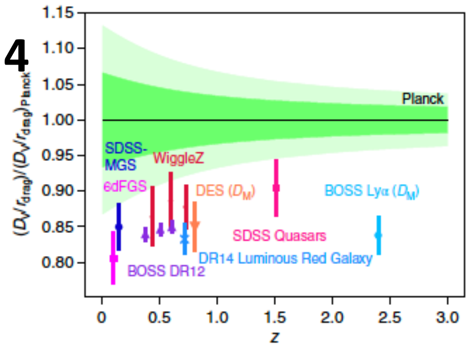
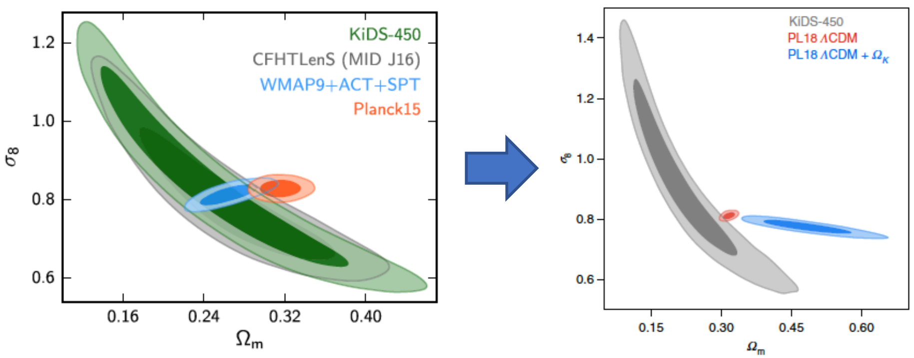


Di Valentino et al., arXiv:2003.04935



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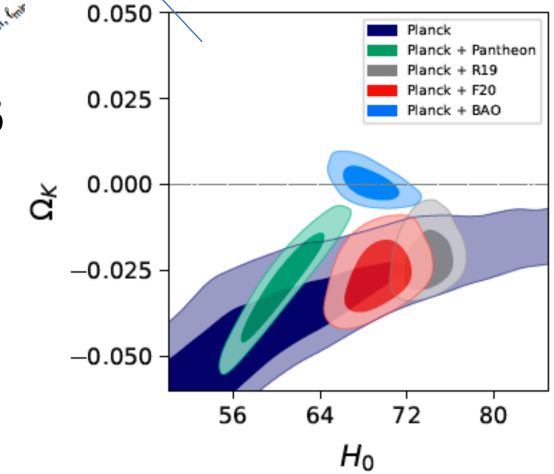
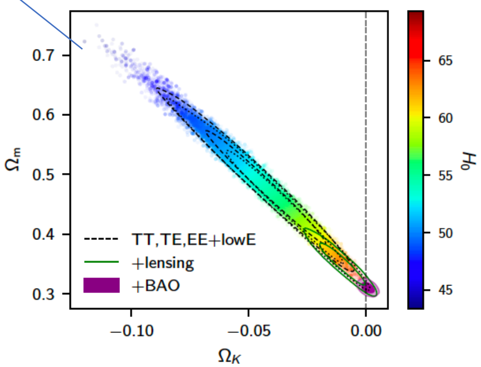


An Ω_k problem?

Methodological issues:

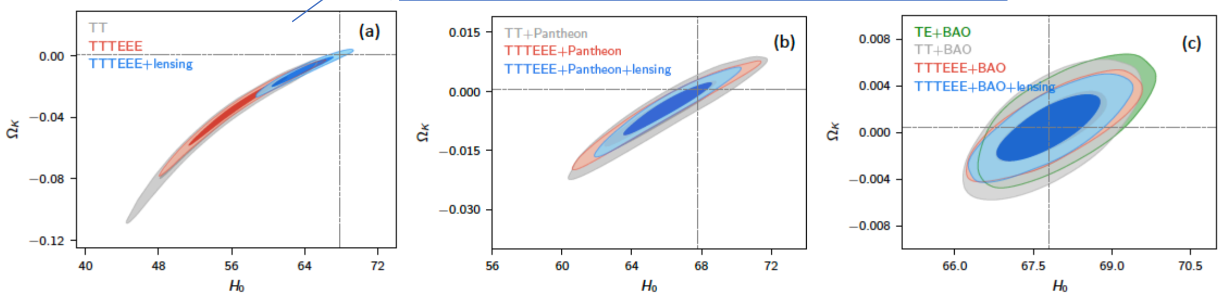
- Planck likelihood almost flat in Ω_k ➡ Planck is blind to Ω_k. Then, which priors are reasonable? Issues: flat prior? posterior dependence on the prior?
- In choosing a prior, which parameters are the dataset sensitive to? For example, Planck is very sensitive to H_0, like SN. In this case, one cannot combine the two, because incompatible. But Planck and BAO are both sensitive to H_0 and compatible.

Planck collaboration: 1807.06209



When **independent** and **compatible** datasets are considered (lensing, BAO) the degeneracy is broken and the flatness restored.

Efstathiou&Gratton, arXiv: 2002.06892



- Occam razor: the model with the minimal number of inconsistencies. Instead: H_0 is worse, σ_8 is worse, BAO disagrees with Planck...

The problem:

Di Valentino et al., Nature Astronomy, 2020

- "Two datasets in major tension with Planck: H_0 (Riess et al, 2019) and weak lensing (Hildebrandt et al., 2017)"
- These tensions worsen and new tensions arise if flat universe hypothesis is abandoned

a cosmological crisis? maybe not

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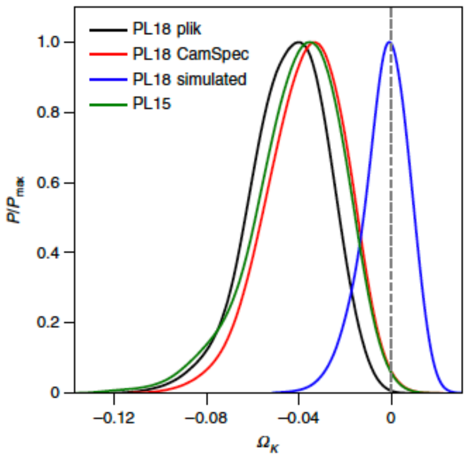

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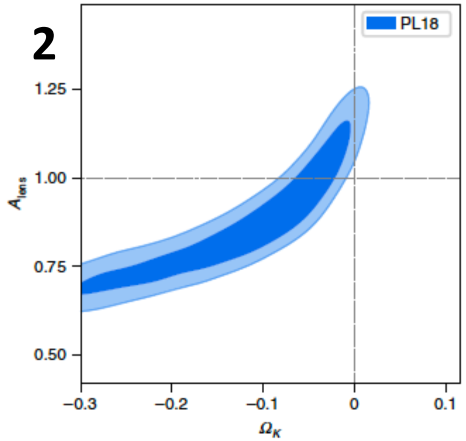

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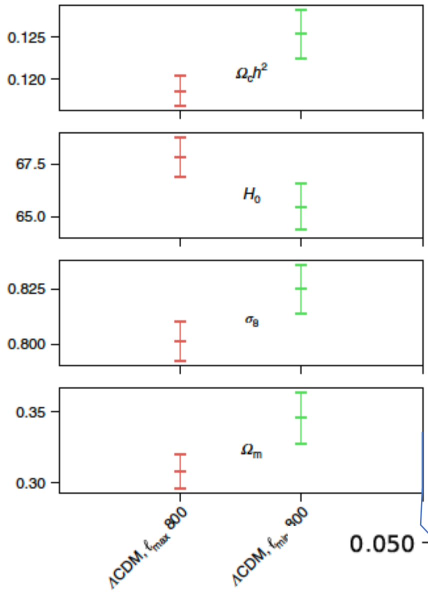

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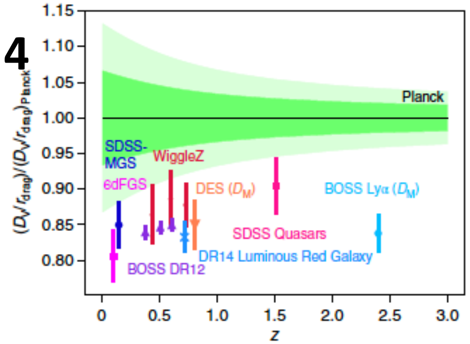
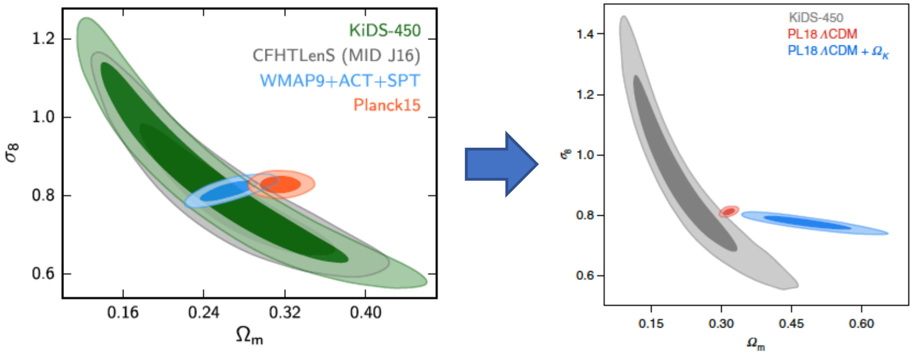


Di Valentino et al., arXiv:2003.04935



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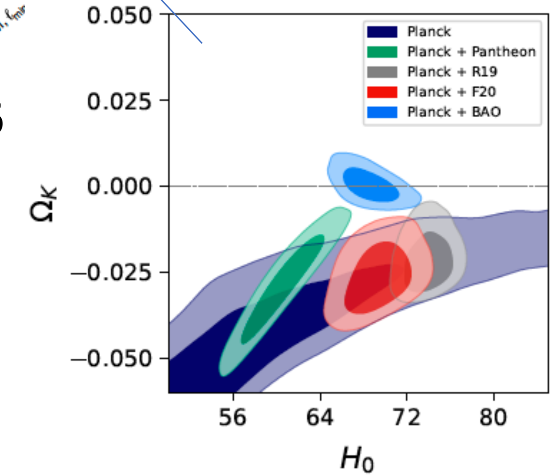


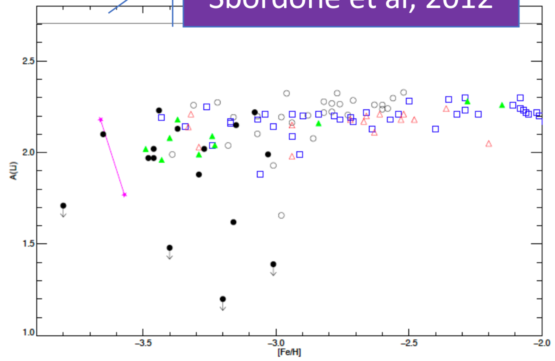
Issues: The Lithium problem

The problem: No consistency region in the Schramm plot between predicted and observed value of ^{7}Li. If calculated at $\eta_{10,CMB}$:

$$\left(\frac{^7Li}{H}\right)_{BBN} = (4.70 \pm 0.06) \cdot 10^{-10}$$

$$\left(\frac{^7Li}{H}\right)_{Spite} = (1.6 \pm 0.3) \cdot 10^{-10}$$

even if higher values come from ISM (2012) and OC stars (2013).



Sbordone et al, 2012

Three approaches:

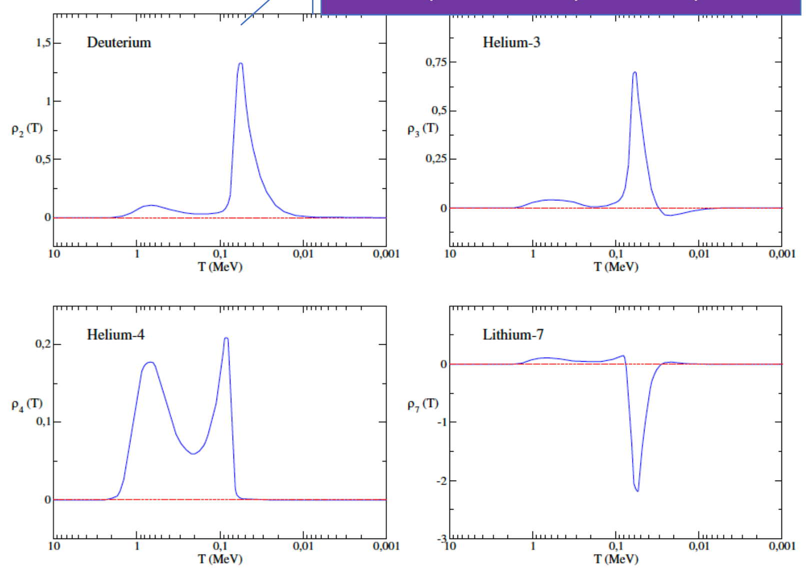
- astrophysical solution: systematics. Li destroyed by convective motion is a not convincing explanation. Moreover: why no points above the plateau?
- nuclear physics solution: overproduction of ^{7}Be

  $^4\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma$ more important than $^4\mathrm{He} + {}^3\mathrm{H} \rightarrow {}^7\mathrm{Li} + \gamma$

  Missing or hill measured reactions? Unknown resonances? All explored solutions seems not likely (see, e.g. Broggini et al., JCAP, 2012).
- new physics solution: many of them!
  - neutron injection (see e.g. Coc et al, 2015)
  - photon injection (see e.g. Salvati et al., 2017)
  - new particles interacting with ^{7}Be (see e.g. Pospelov et al., 2016)
  - non-standard evolution of η_{10}, such that $\eta_{10,BBN} \neq \eta_{10,CMB}$
  - ...

New physics: two examples

Bambi, Giannotti, Villante, 2005



Change the expansion rate.

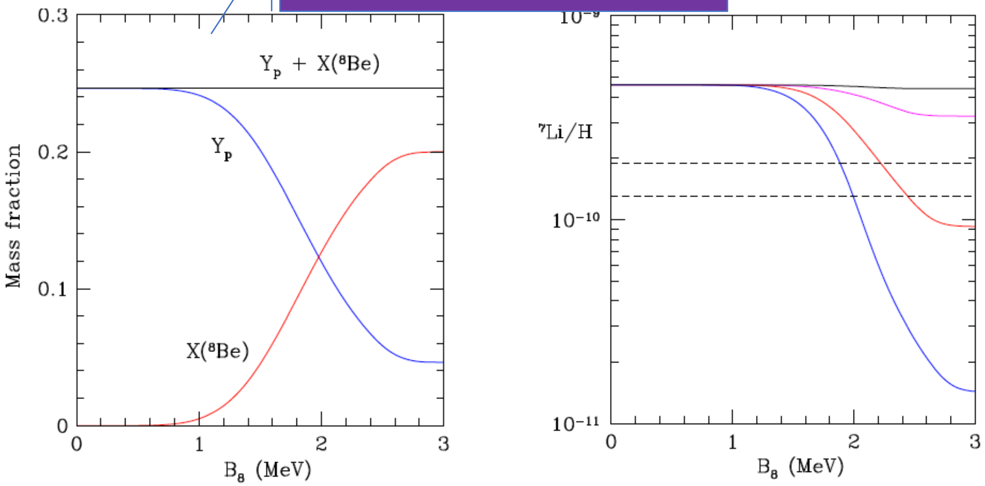
Good: Lithium decreases

Bad:

- in the same time window Deuterium increases
- how realize such a fine-tuned change?

Changing constants of Nature seems to work (Coc et al., 2007): biggest effect is from binding energy of D. Intriguing possibility: stabilize ^{8}Be.

Scherrer and Scherrer, 2017



1. B_8 increase

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{8}\mathrm{Be}$$

2. decreased ^{7}Li synthesis
3. B_8 goes back

$$^{8}\mathrm{Be} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$$

It works. But: unnatural B_8 required, hard to achieve with screening effects.

A ^{7}Li problem?

- old formulation: Observations present a plateau value, with negligible dispersion, 3-5 smaller than BBN prediction; no known fine-tuned astrophysical mechanism can explain such value
- present formulation: Observations present a "roof" value, with negligible dispersion, 3-5 smaller than BBN prediction at high/intermediate metallicity and a "meltdown" at low ones; no known astrophysical mechanism can explain such features → we don't understand Lithium, then...
- the use of the Spite plateau value as the primordial one is not advisable
- recent (higher) observations in different environment have great potential to shed light on the ^{7}Li problem, could point to "no problem at all"
- in the meantime, the nuclear physics approach to the problem seems the less promising (nuclear physics very constrained)
- new physics approach is a very beaten path, we can have fun by writing and reading a lot of exotic solutions!

Conclusions

- standard cosmological model in good shape but...
- the general impression is that it is too much phenomenological: we put a little bit of this and a little bit of that (and most of our ingredients are dark...)
- false notes in the symphony push us towards new efforts for distinguish between statistics/systematics or new physics (and probably new physics will help to go deeper)
- CMB is the framework where the largest number of cosmological parameters can be determined in one shot
  - ➡ it is natural that anomalies jump out in CMB
  - it is encouraging that still all works so well
- this talk: H_0 problem seems the more serious anomaly, DM should be improved at small scales (modifying gravity?), closed universe indications seem to come from incorrect methodology, the ^{7}Li problem could be not a problem at all
- the future will tell: new experiments/tecnique very important

Backup slides

GW measure of H_0

GW sources accompanied by e.m. counterparts offer an independent standard siren measurement of H_0, without the need of assuming a cosmological model and independently of a distance ladder.

- the GW waveform reconstruction allows for the determination of the luminosity distance; to determine the distance, the signal has to be observed by a worldwide network of three, and preferably four, detectors, by measuring both the response of the detectors and the delays between the arrival times of the signal at different detectors (Schutz, Nature 1986)
- the observation of the e.m. signal gives the red-shift of the source

Note that because GW source is relatively nearby the random relative motions of galaxies, known as peculiar velocities, need to be taken into account

DM small scale problems

- **Core-cusp** problem. High-resolution simulations show that the mass density profile for CDM halos increases toward the center, scaling approximately as $\rho_{DM} \propto r^{-1}$ in the central region (cusp). However, many observed rotation curves of disk galaxies (mainly dwarf and LSB galaxies) prefer a constant (cored) density profile $\rho_{DM} \propto r_0$.
- **Diversity** problem. Contrary to what expected, disk galaxies with the same maximal velocity have core density that varies by a factor $\mathcal{O}(10)$.
- **Missing satellite** problem. CDM halos are rich with substructure, since they grow via hierarchical mergers of smaller halos that survive the merger process. Observationally, however, the number of small galaxies in the Local Group are far fewer than the number of predicted sub-halos.
- **Too-big-to-fail** problem. Massive sub-halos are expected to form stars and should host observable galaxies, but observations of dwarf galaxies in Andromeda and the Local Group find discrepancies with these expectations.

TeVeS

Matter metric and Einstein metrics connected using scalar and vector fields.

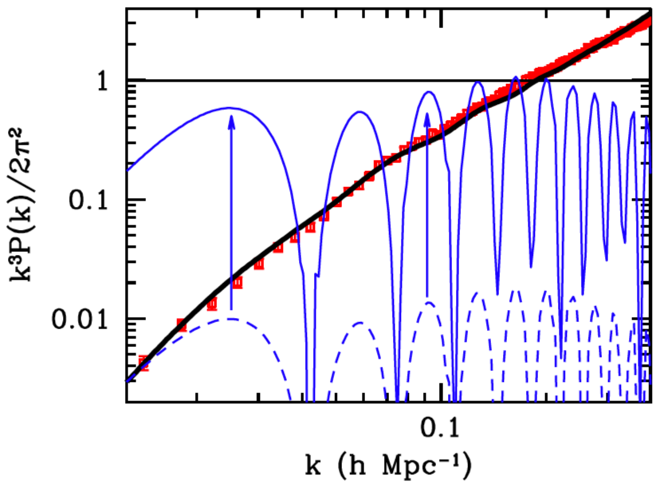
$$g_{\mu\nu} = e^{-2\phi}\tilde{g}_{\mu\nu} - 2\sinh(2\phi)A_\mu A_\nu$$

Friedmann equation similar to the standard one, with an effective gravitational constant.

$$H^2 = \frac{8\,\pi G_{eff}}{3}(\rho + \rho_\phi)$$

$$G_{eff} = \frac{G_N\, e^{-4\phi}}{\left(1 + \frac{d\phi}{d\log a}\right)^2}$$

TeVeS (solid blue curve) solves the no structure problem of no DM universe (dashed blue curve) by modifying gravity to enhance the perturbations (amplitude enhancement shown by arrows). While the amplitude can now exceed unity, the spectrum has pronounced Baryon Acoustic Oscillations, in violent disagreement with the data from the Sloan Digital Sky Survey (red points).



A_{lens}

- lensed CMB spectrum is a smoothed version of the unlensed one: $C_l \cdot C_l^{\psi}$
- lensing comes directly (4-pt function, non-Gaussian signal)
- for investigating consistency, a phenomenological parameter, A_{lens}
- 2.1-2.8σ anomaly

$$A_L = 1.243 \pm 0.096 \quad (68\,\%,\ \textit{Planck}\ \mathrm{TT{+}lowE}),$$

- most likely explanation is statistical (no systematics seems to explain this)
- the anomaly “can be seen” in directions having analogous effects on data, Ω_k-A_{lens} connection because in a closed universe more matter would imply larger lensing