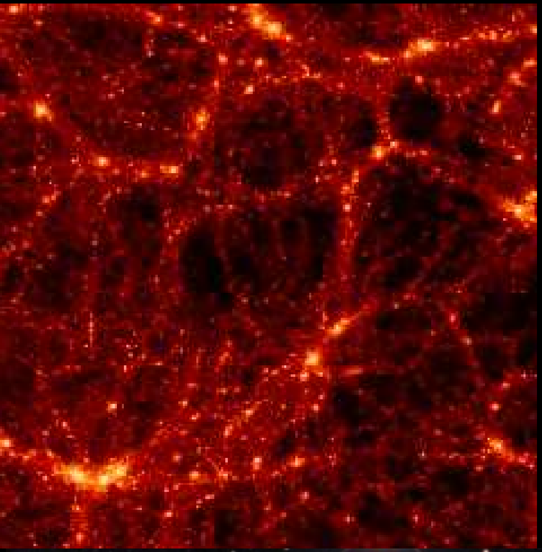
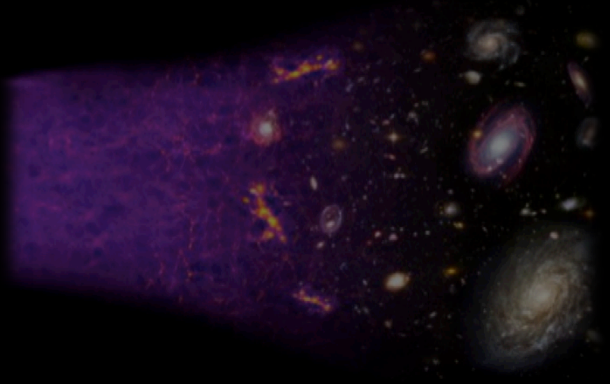
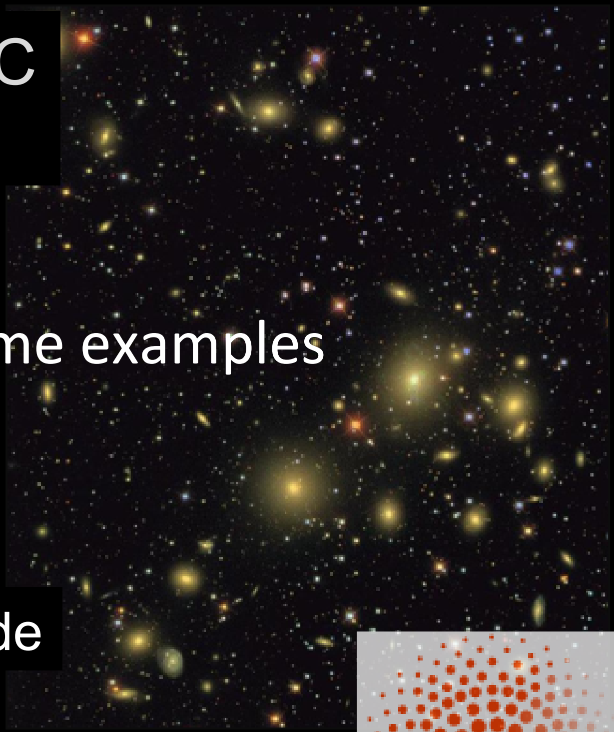




Licia Verde

ICREA & ICC-UB-IEEC
BARCELONA



Beyond precision cosmology, some examples

http://icc.ub.edu/~liciaverde

icrea Institució Catalana de Recerca i Estudis Avançats

ICCUB Institut de Ciències del Cosmos

UNIVERSITAT DE BARCELONA

erc

First decade or so of 2000: Precision cosmology

(WMAP, Boomerang, Acbar, …SDSS, 2dF, **Supernovae** etc..)

ΛCDM: The standard cosmological **model**

Just 6 numbers…..

describe the Universe composition and evolution

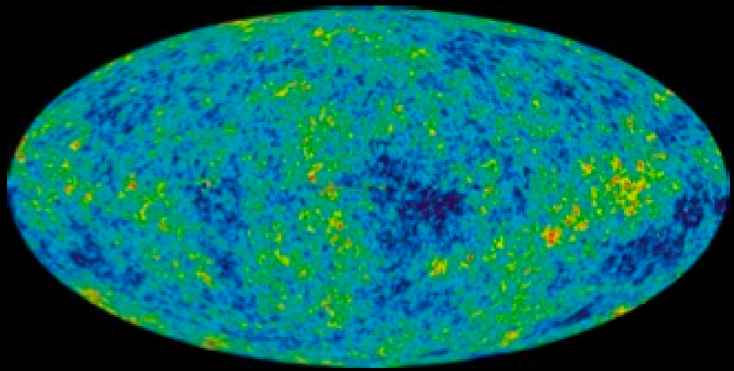
Homogenous background

$$\Omega_b, \Omega_c, \Omega_\Lambda, H_0, \tau$$

- atoms 4%
- cold dark matter 23%
- dark energy 73%

Λ? CDM?

Perturbations



$$A_s, n_s$$

- nearly scale-invariant
- adiabatic
- Gaussian

ORIGIN??

Context and overview

- Cosmology over the past 20 years has made the transition to *precision cosmology*
- Cosmology has now a *standard model.* The *standard cosmological model* only needs few parameters to describe origin composition and evolution of the Universe
- <u>Big difference between modeling and understanding</u>
- <u>Implies Challenges and opportunities</u>
- *Comology is special:* we can't make experiments, only observations. We have to use the entire Universe as a detector: the detector is given, we can't tinker with it.

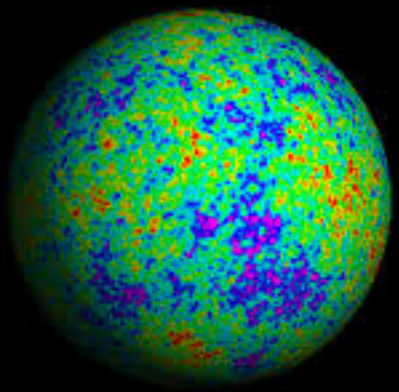
Can now do precision tests of fundamental physics with cosmological data

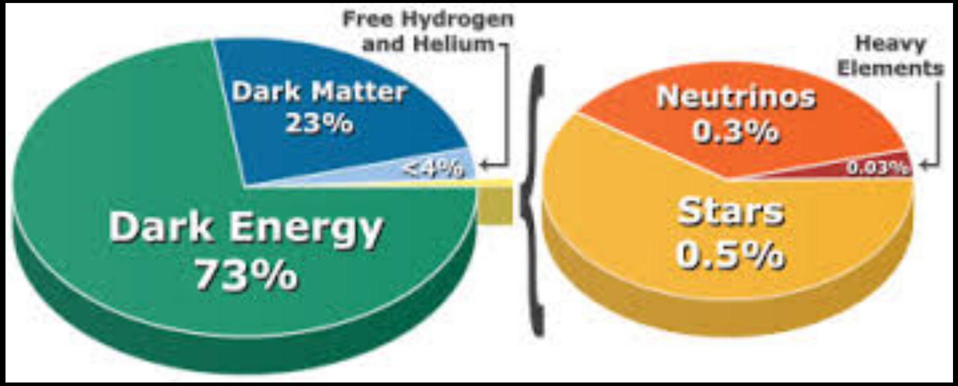
Wonderful agreement of new data with the ΛCDM model

* With some notable exceptions which are still up for discussion.

Is this the whole story?

- What is the 96% of the Universe?
- What set out the primordial perturbations?
- The model is “preposterous”, how can it be correct?
- Challenges and opportunities





It goes deeper than that

“We can’t live in a state of perpetual doubt, so we make up the best story possible and we live as if the story were true.”

Daniel Kahneman about theories

GR, big bang, choice of metric, nucleosynthesis, etc etc…

Cosmology tends to rely heavily on models (both for "signal" and "noise")

Essentially, all models are wrong , but some are useful
(Box and Draper 1987)

With ~1% precision, systematics become the name of the game

Systematics in the data
Systematics in the model (analysis)

Is it possible to be model independent? At what price?

In its infancy…

here’s some exploratory examples

The trouble with Ho; Bernal, LV, Riess, JCAP, 2016

The length of the local standard ruler; Verde, Bernal, Heavens, Jimenez 2017, MNRAS

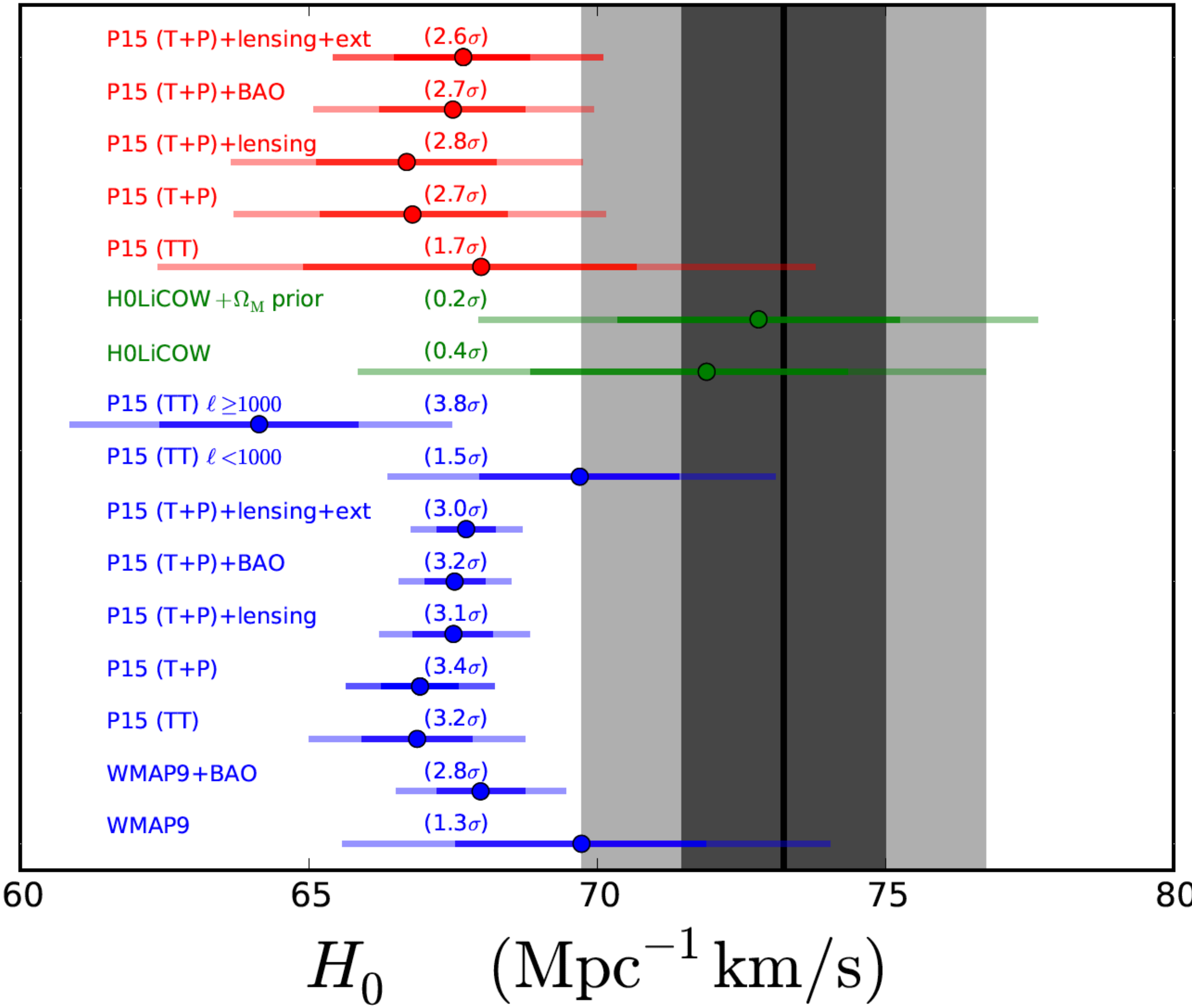
Early cosmology Constrained; Verde, Bellini et al. 2016(arxiv) 2017 JCAP

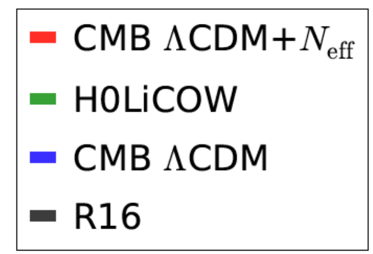
The trouble with H_0

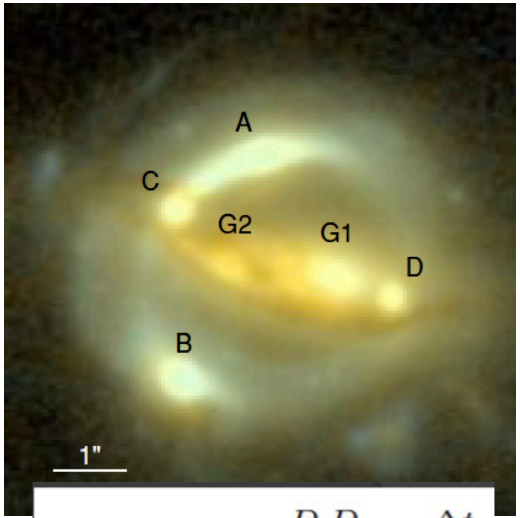
JL Bernal, LV,.A Riess, JACP 2016

- Direct measurement: 73.24 ± 1.74 km/s/Mpc (Riess et al 2016; verified with GAIA parallaxes)
- Planck (ΛCDM): 67.8± 0.9(66.9±0.6) km/s/Mpc
- Formally 3.4 σ, maybe we should pay attention
- Possibly worst with Planck low l polarization re-analysis

The landscape







$$D_{\Delta t} \equiv (1+z_l)\frac{D_l D_s}{D_{ls}} = \frac{\Delta t}{\Delta \phi}$$

Three avenues

Without invoking systematics (beside those declared by the authors themselves)

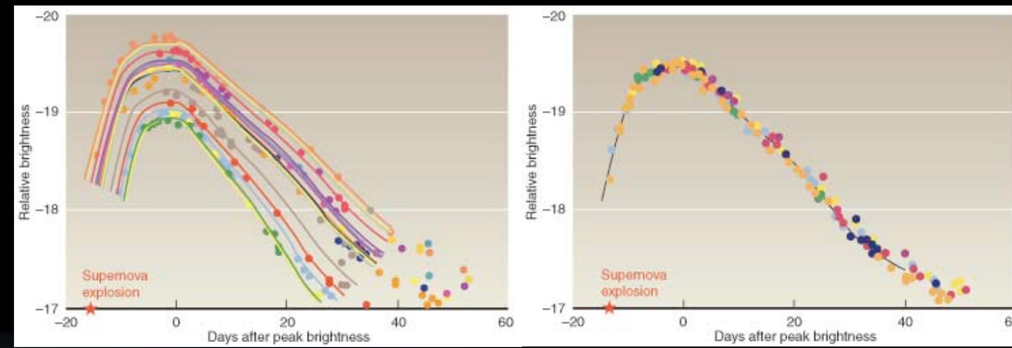
- Allow early cosmology to deviate from ΛCDM (unaltered late-time cosmology)
- Give freedom to late cosmology (unaltered early time physics*)
- <u>Model-independent</u>

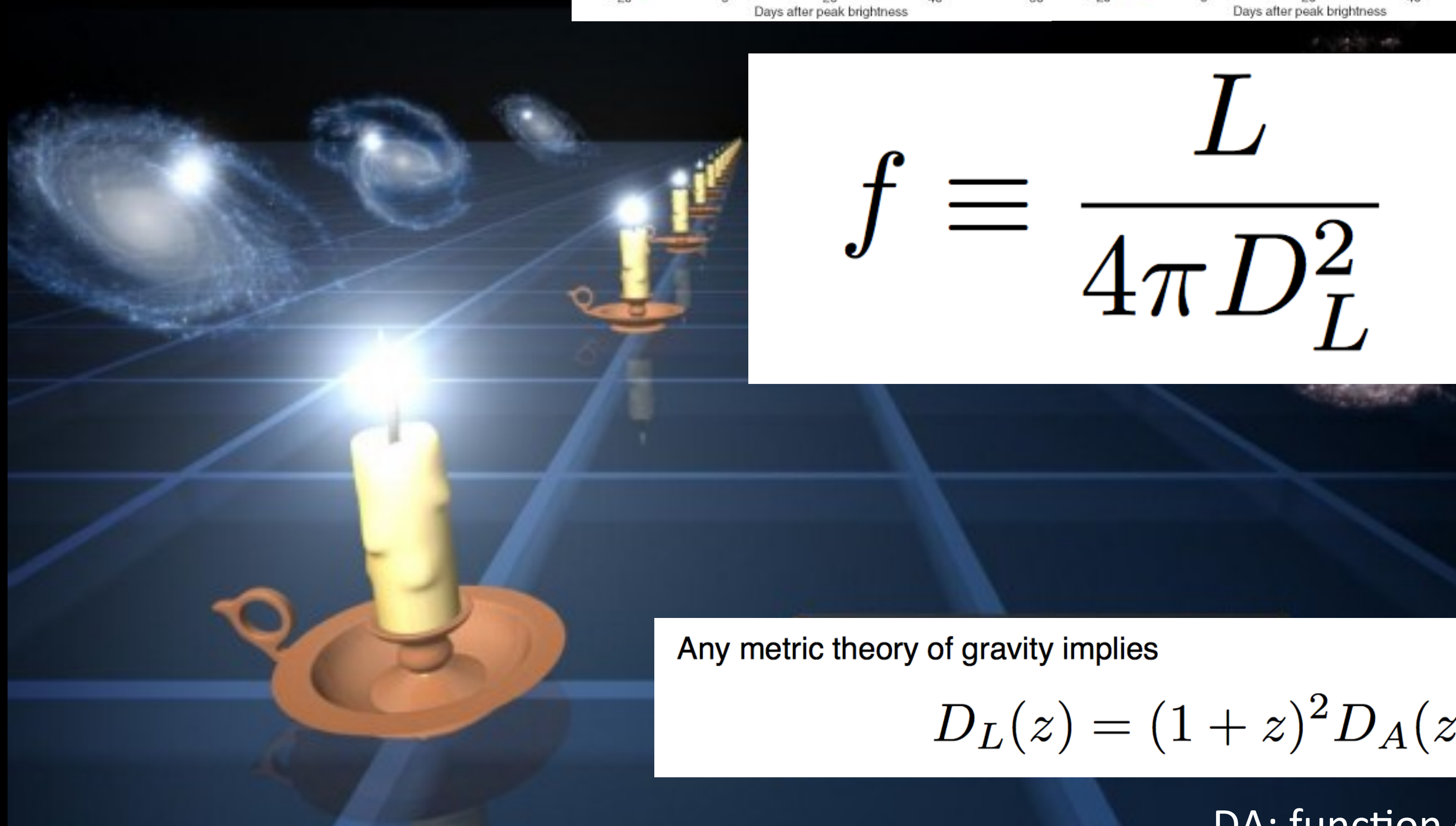
Data

- CMB: Planck TT, lowP, TEEE*, Lensing (even l>1000 or l<1000 for TT)#
- BAO: compilation 6dF, SDSS MGS, LOWZ, CMASS, WiggleZ
- SNe: JLA compilation
- Riess 2016 H_0 measurement

Addison et al. 2016, response of Planck team (Planck 2016)
* Planck high l polarization "ok for LCDM not ok beyond LCDM"

SNe : standard candles





$$f \equiv \frac{L}{4\pi D_L^2}$$

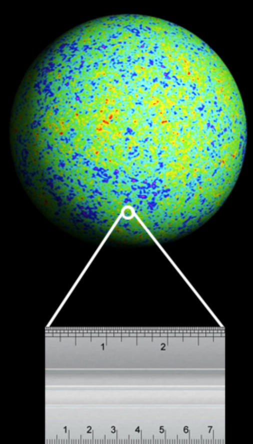
Any metric theory of gravity implies

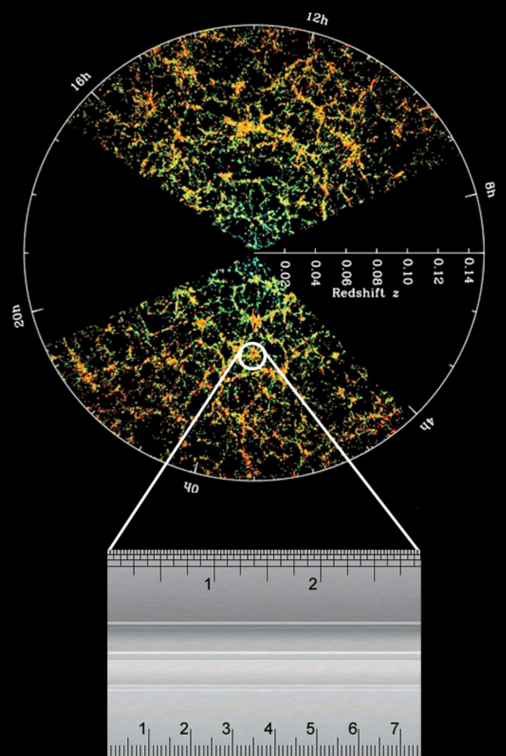
$$D_L(z) = (1+z)^2 D_A(z)$$

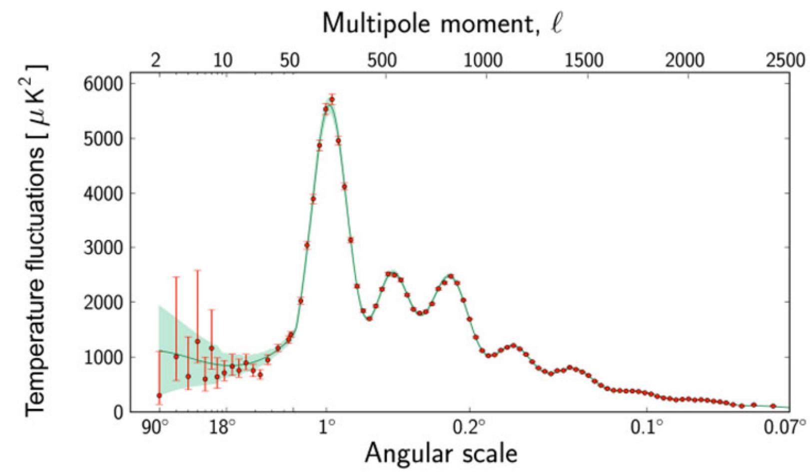
DA: function of geomerty and integral of 1/H

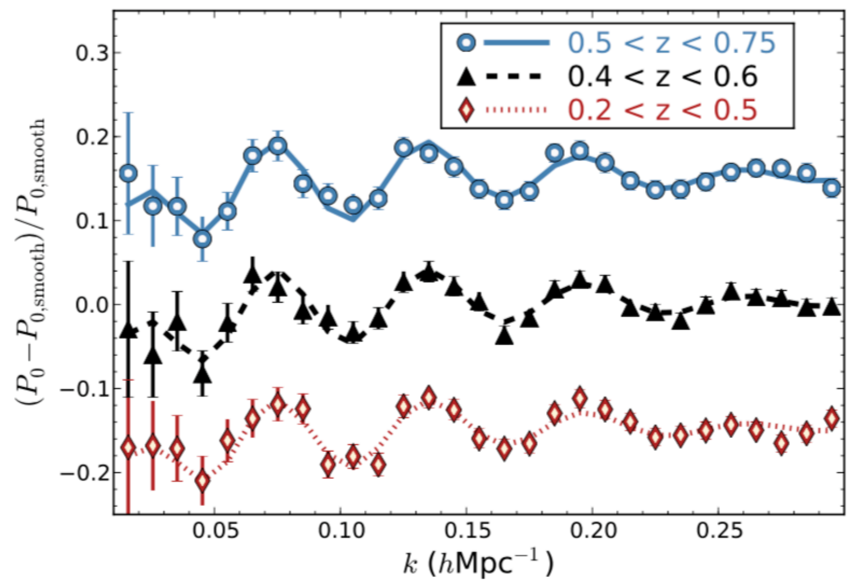
Since L is poorly known this is "uncalibrated", usually calibrated using measurements of H0

BAO



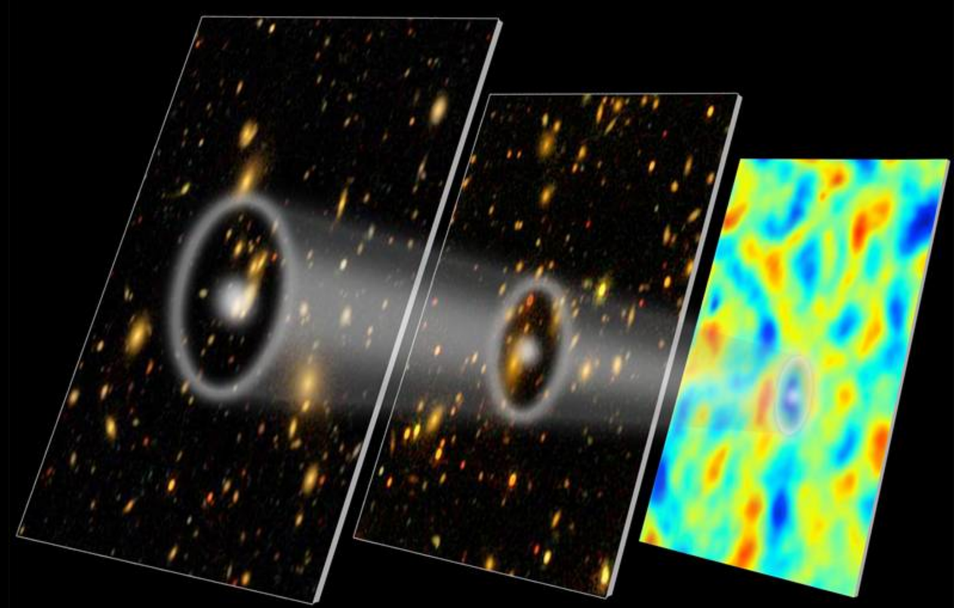

12h
16h
8h
20h
4h
0h
0.02 0.04 0.06 0.08 0.10 0.12 0.14
Redshift z


Multipole moment, ℓ
2 10 50 500 1000 1500 2000 2500
Temperature fluctuations [μK^2]
0 1000 2000 3000 4000 5000 6000
90° 18° 1° 0.2° 0.1° 0.07°
Angular scale


0.5 < z < 0.75
0.4 < z < 0.6
0.2 < z < 0.5
$(P_0 - P_{0,\mathrm{smooth}})/P_{0,\mathrm{smooth}}$
−0.2 −0.1 0.0 0.1 0.2 0.3
0.05 0.10 0.15 0.20 0.25
k (hMpc^{-1})

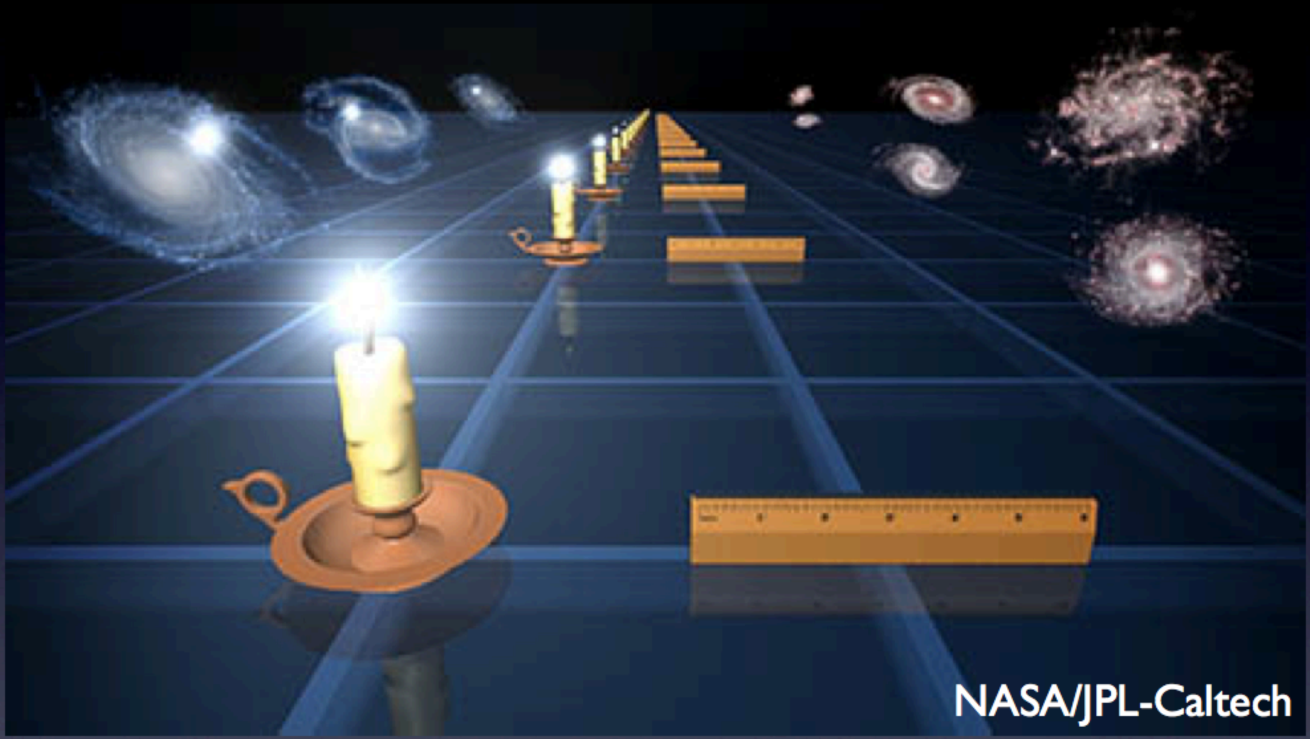
Baryon acoustic oscillations (BAO)
Standard ruler

- Physics: sound waves in early Universe propagate until radiation and matter decouple
- Imprints a scale - standard ruler
- Key Observable.
- Useful for:
  - geometry of Universe (Dark Energy equation of state, or modifications to GR)
  - early Universe physics (well known) sets it



CMB and early universe physics in LCDM constrain the standard ruler length to 0.2%

Standard candles & Standard rulers

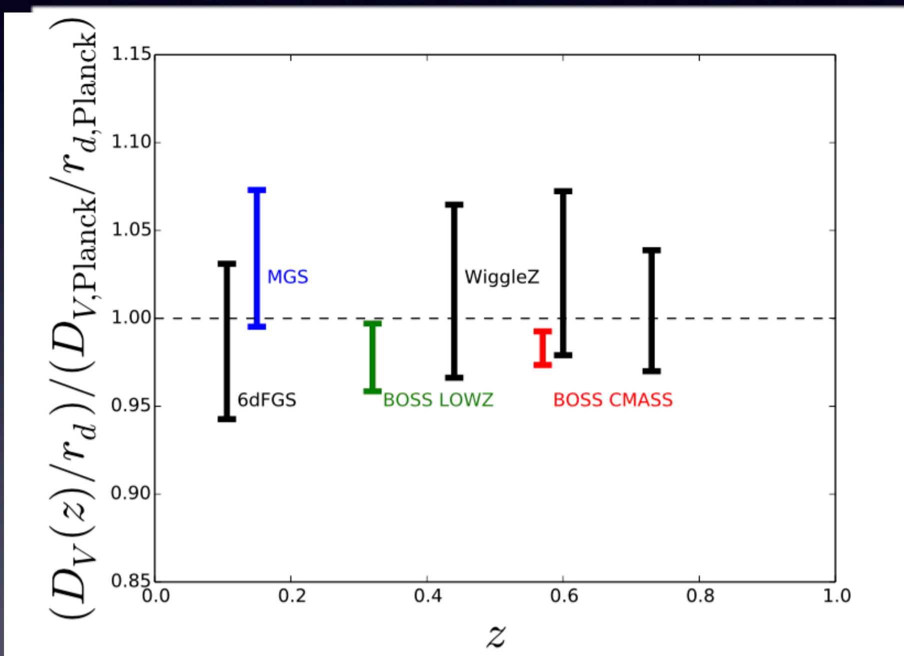


Type-Ia SNe measure
relative distances,
since there is large uncertainty
on the absolute magnitude M
of a fiducial SN

BAOs measure
absolute distances,
but depend on the value of
sound horizon r_{drag}

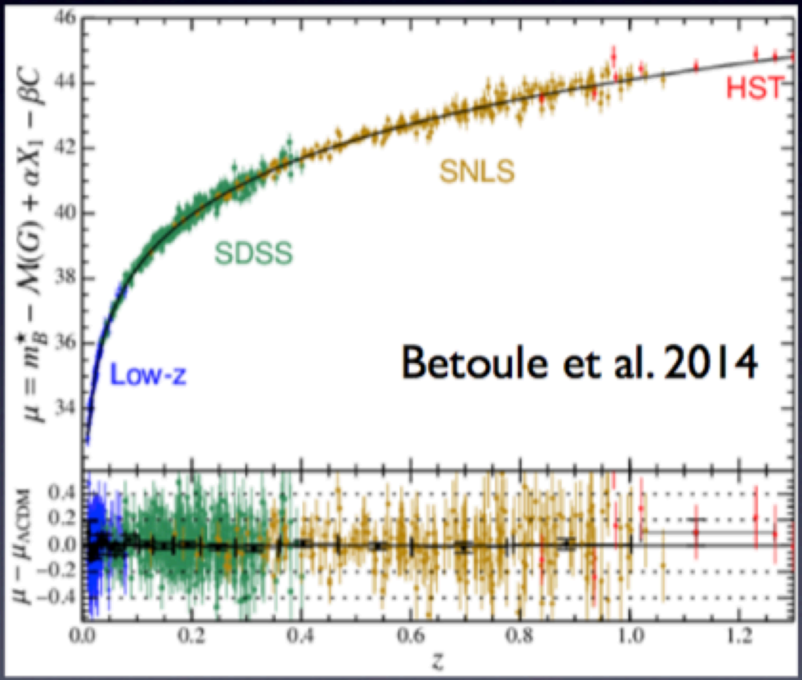
Visually

BAO + r_d



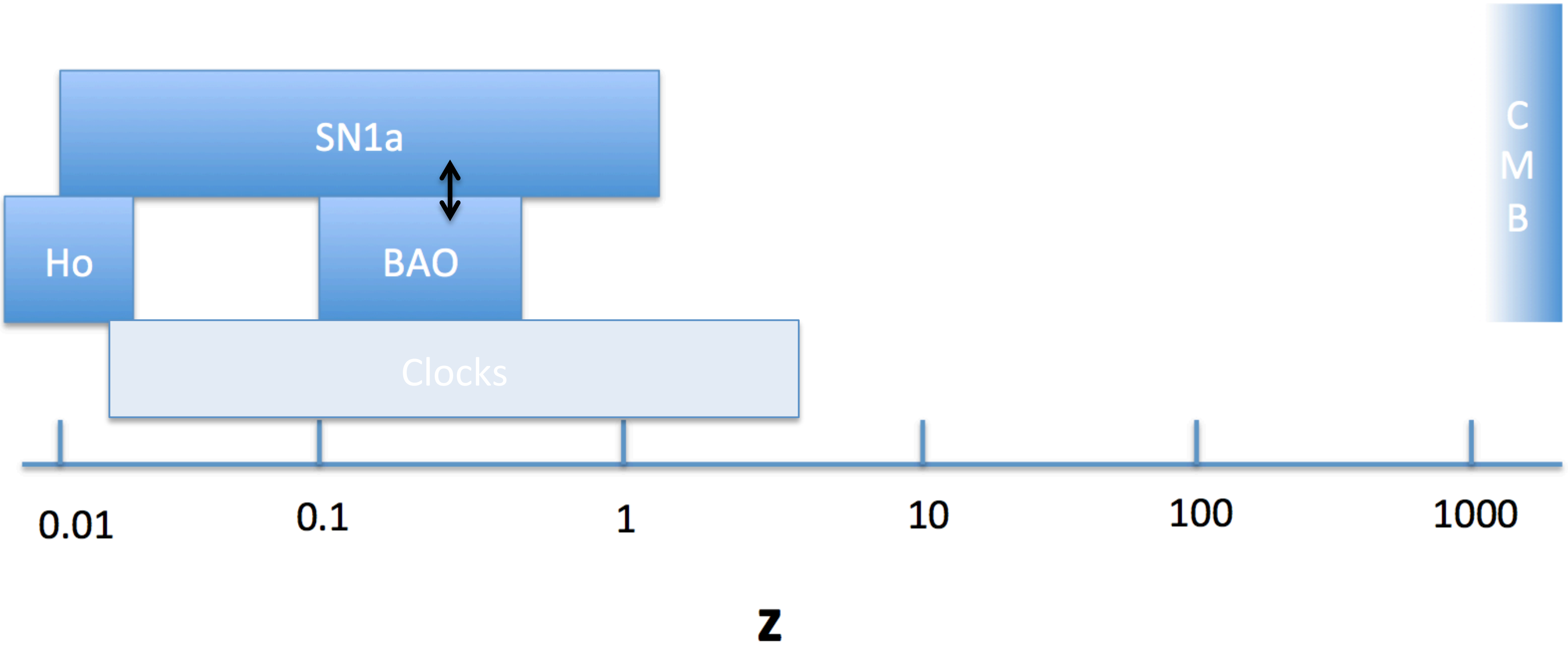
$D_V(z) = \{D_A(z)^2\, c\, z\, /H(z)\}^{1/3}$

SN



$\mu(z) = 25 + 5\log_{10} D_L(z)$

At glance: direct and inverse distance ladder



H0: Direct measurement: 73.24 ± 1.74 km/s/Mpc (Riess et al 2016)

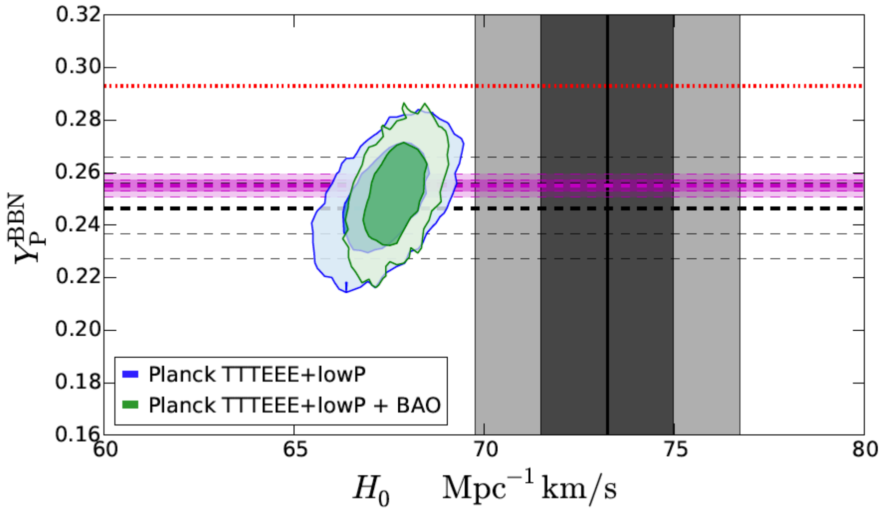
Low z anchor

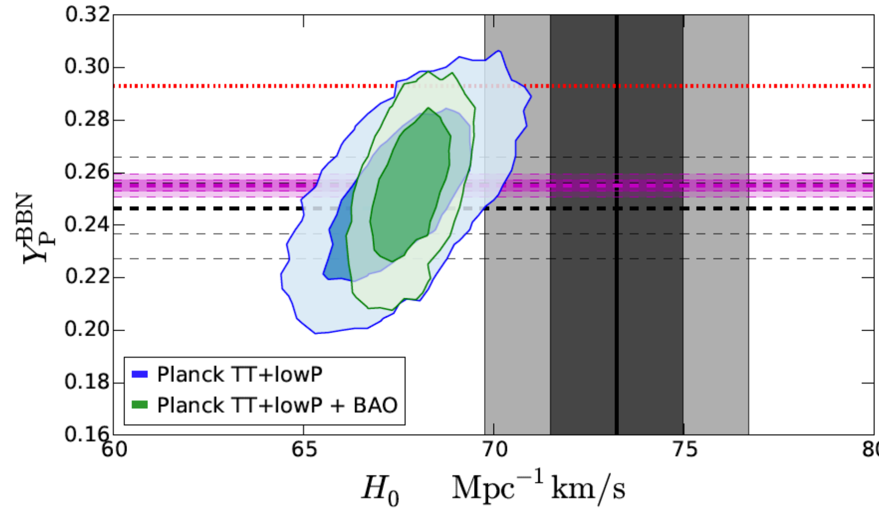
rd,
high z anchor

Cuesta et al 2014, Bernal et al 2016

Modify Early Universe physics: primordial helium fraction

Changes recombination history, affects the diffusion damping and redshift of last scattering





metal-poor HII regions

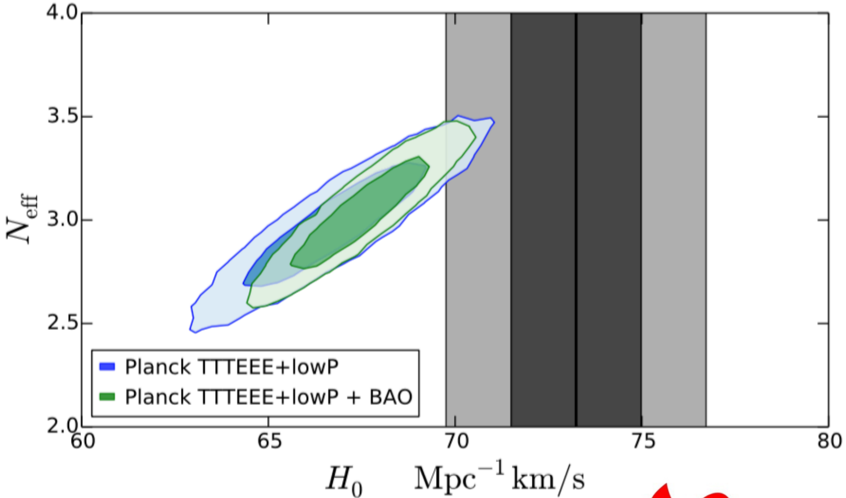
Aver et al 2013, MS dwarfs Casagrande et al 2003

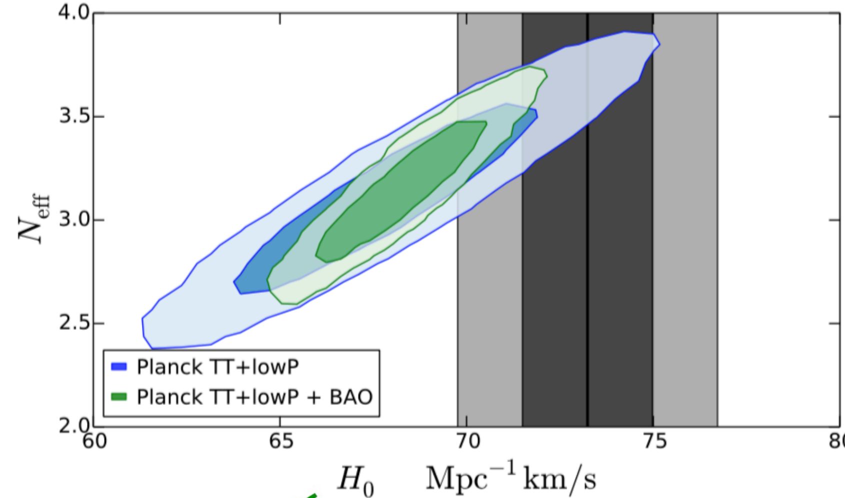
Izotov et al 2014

2 σ upper limit, initial Solar helium abundance

Serenelli Basu 2010

Modify Early Universe physics: early time expansion history, N_{eff}





Need ΔN_{eff}~0.4

Modify Early Universe physics: change also the perturbations

- N_{eff}, c_s c_{vis}

If all species have the same cs cvis, not much change

No evidence for relativistic species not being neutrinos

- What if you have three neutrinos + something else with different effective parameters (dark radiation)?

	$\Delta N_{\rm eff}$	c_s^2	$c_{\rm vis}^2$	H_0	$(\Omega_{\rm M}/0.3)^{0.5}\,\sigma_8$
lowP+ TTTEEE	< 0.36	$0.25^{+0.07}_{-0.15}$	$0.12^{+0.58}_{-0.11}$	$68.9^{+1.1}_{-0.9}$	$0.85^{+0.02}_{-0.02}$
lowP+ TTTEEE+CMB lensing	< 0.34	$0.24^{+0.10}_{-0.13}$	0.49 ± 0.33	$68.9^{+1.2}_{-0.9}$	$0.83^{+0.02}_{-0.01}$
lowP+ TTTEEE+CMB lensing+BAO	< 0.28	$0.26^{+0.09}_{-0.16}$	$0.28^{+0.45}_{-0.26}$	$68.7^{+0.6}_{-0.7}$	$0.84^{+0.01}_{-0.02}$
lowP + TT	< 0.76	$0.25^{+0.08}_{-0.10}$	$0.84^{+0.20}_{-0.51}$	$70.6^{+2.6}_{-2.0}$	$0.84^{+0.03}_{-0.04}$
lowP+ TT+CMB lensing	< 0.77	$0.27^{+0.07}_{-0.11}$	$0.81^{+0.19}_{-0.50}$	$71.3^{+1.9}_{-2.2}$	$0.82^{+0.02}_{-0.01}$
lowP+ TT+CMB lensing+BAO	< 0.44	$0.29^{+0.20}_{-0.16}$	$0.9^{+0.1}_{-0.7}$	$69.0^{+0.9}_{-0.8}$	$0.84^{+0.01}_{-0.02}$

What's that?

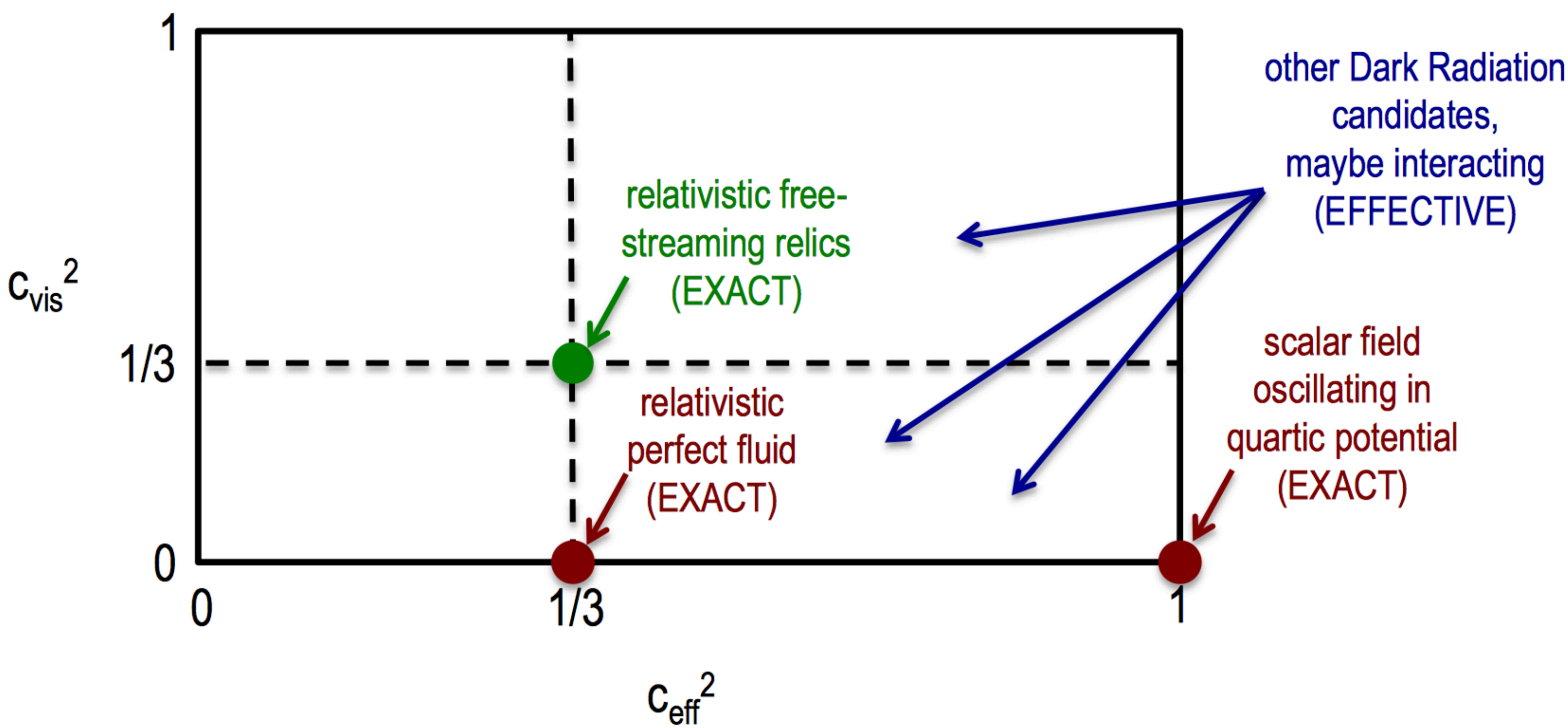
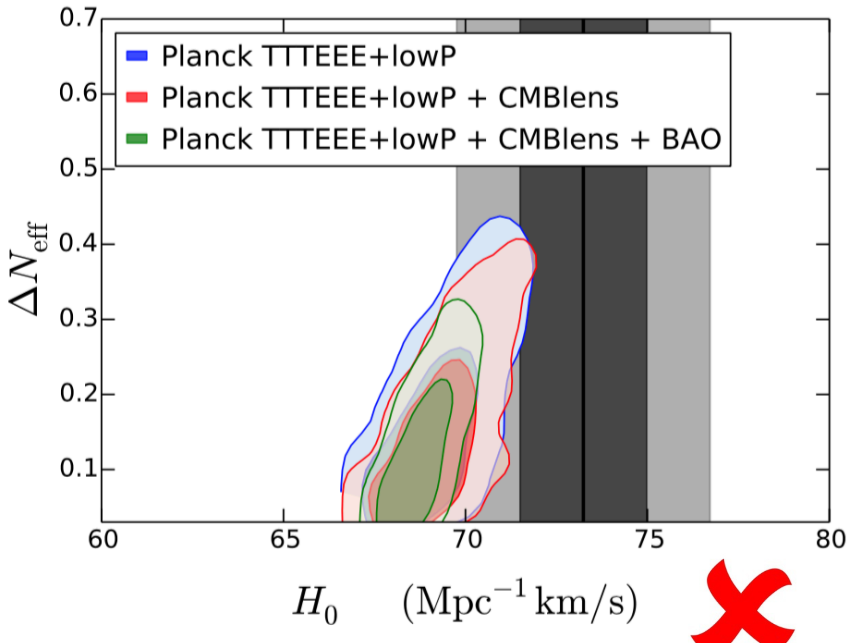
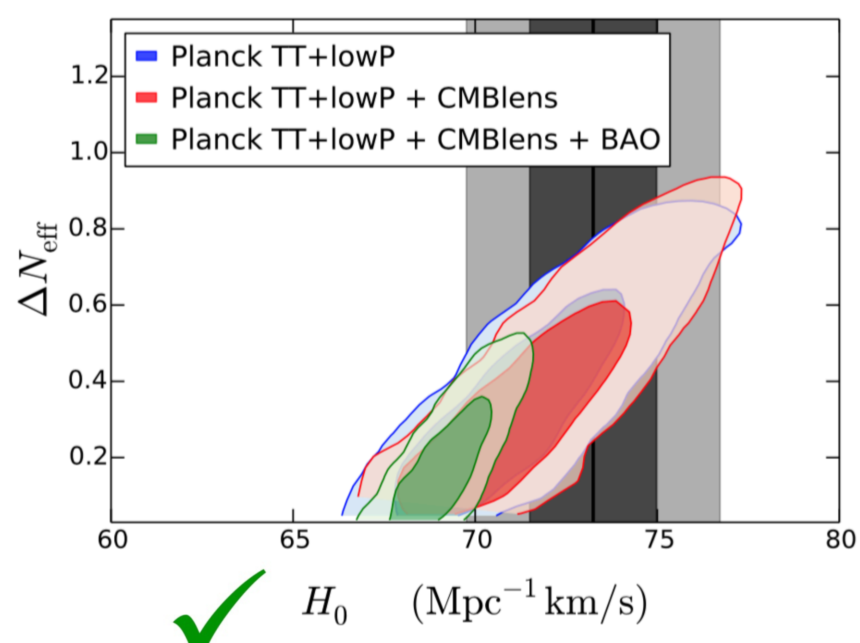


Fig courtesy of J. Lesgourgues

Modify Early Universe physics: change also the perturbations

- N_{eff}, c_s c_{vis}
- What if you have three neutrinos + something else with different effective parameters (dark radiation)?



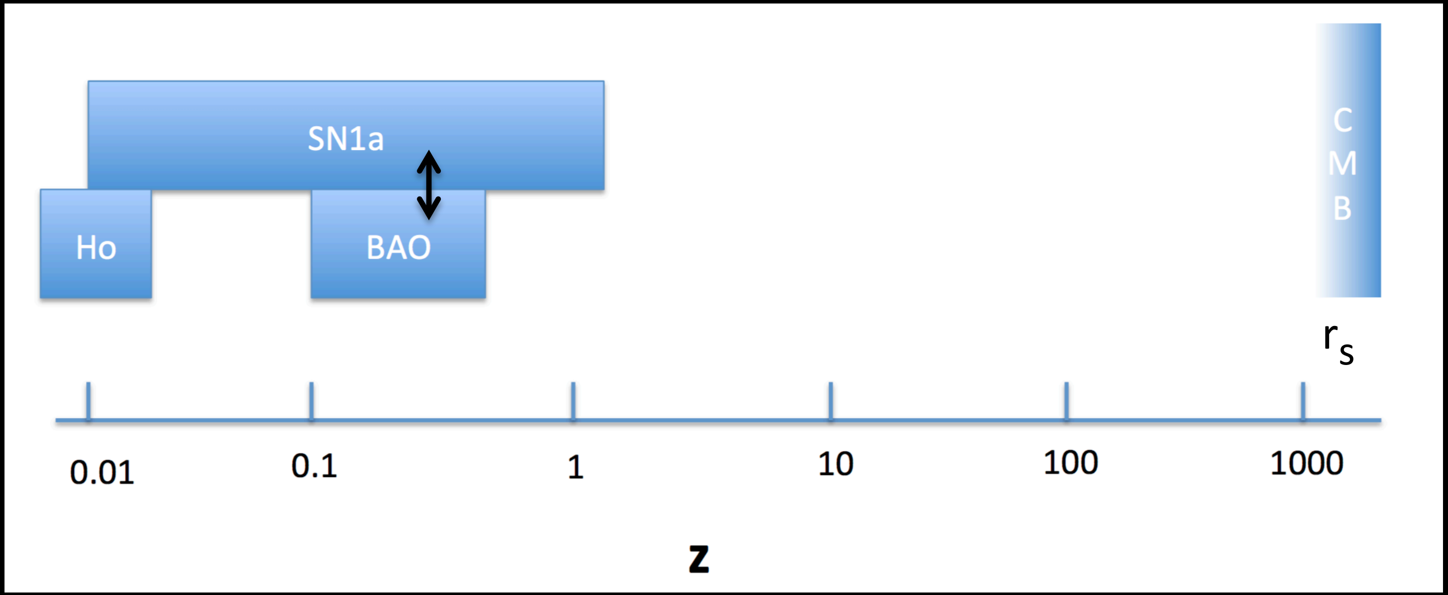


Changing late-time cosmology

- Spline reconstruction of the expansion history

$H(z)$ with 4 (5 with SNe) knots.

Direct and inverse cosmic distance ladder (Cuesta et al 2015)



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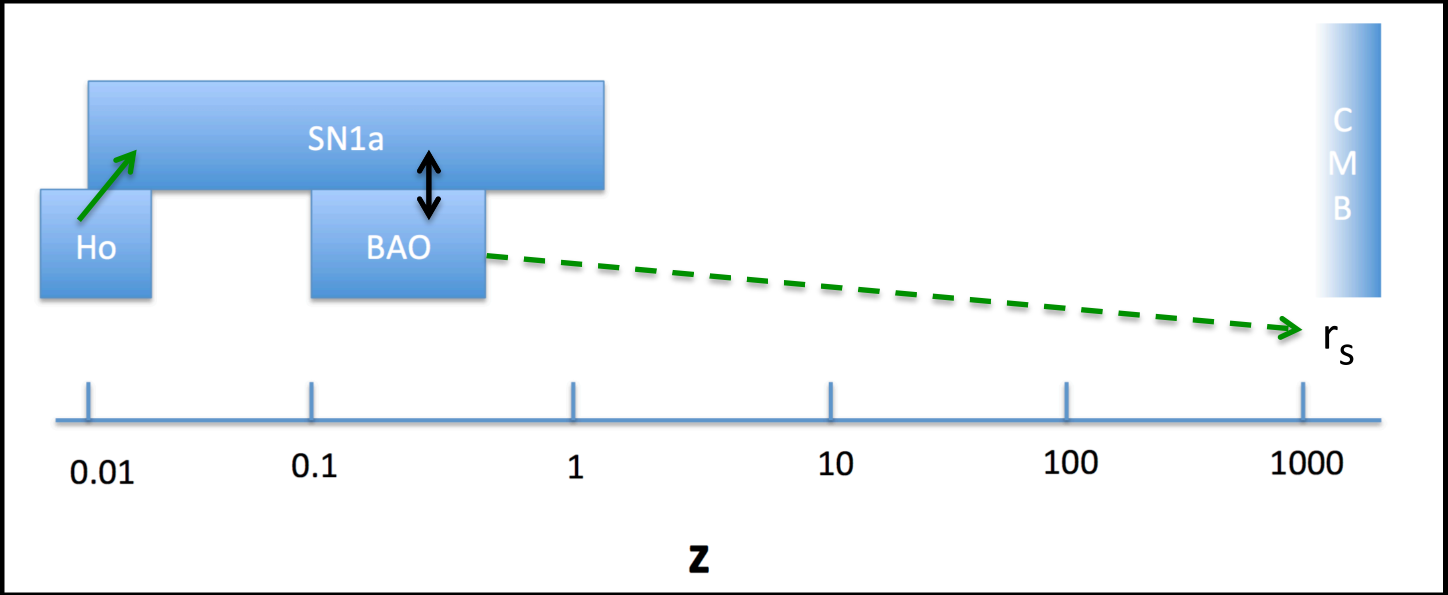
Direct cosmic distance ladder



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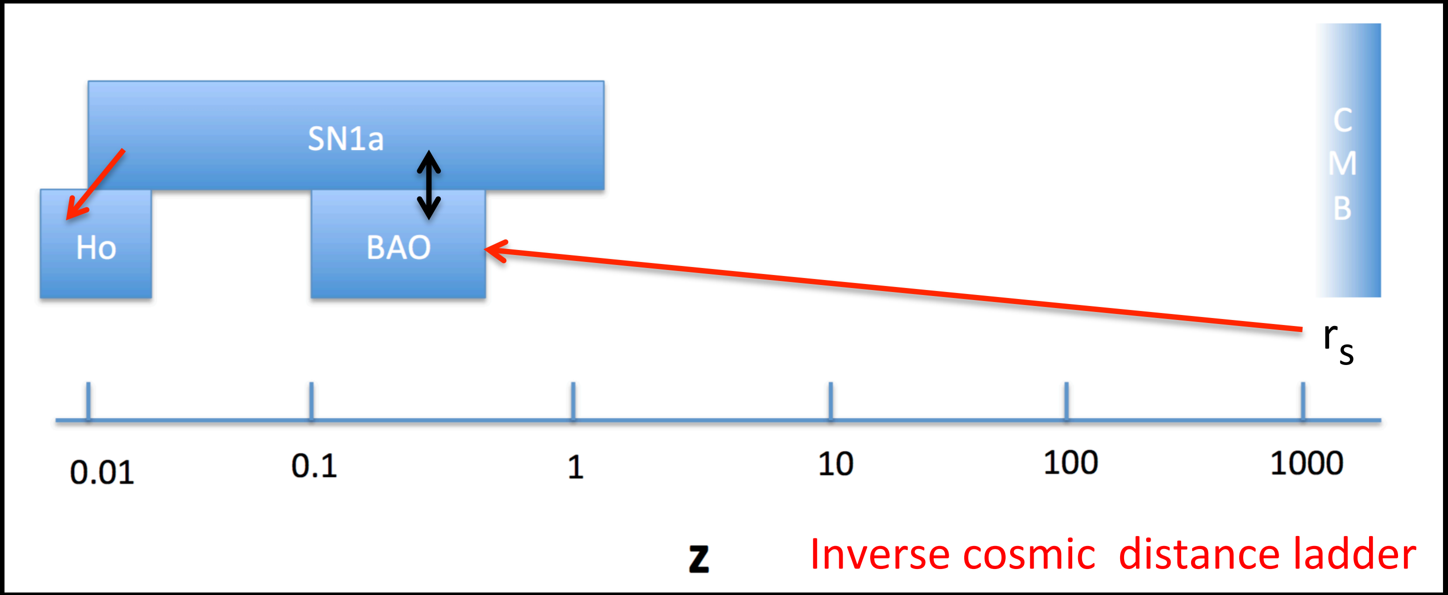

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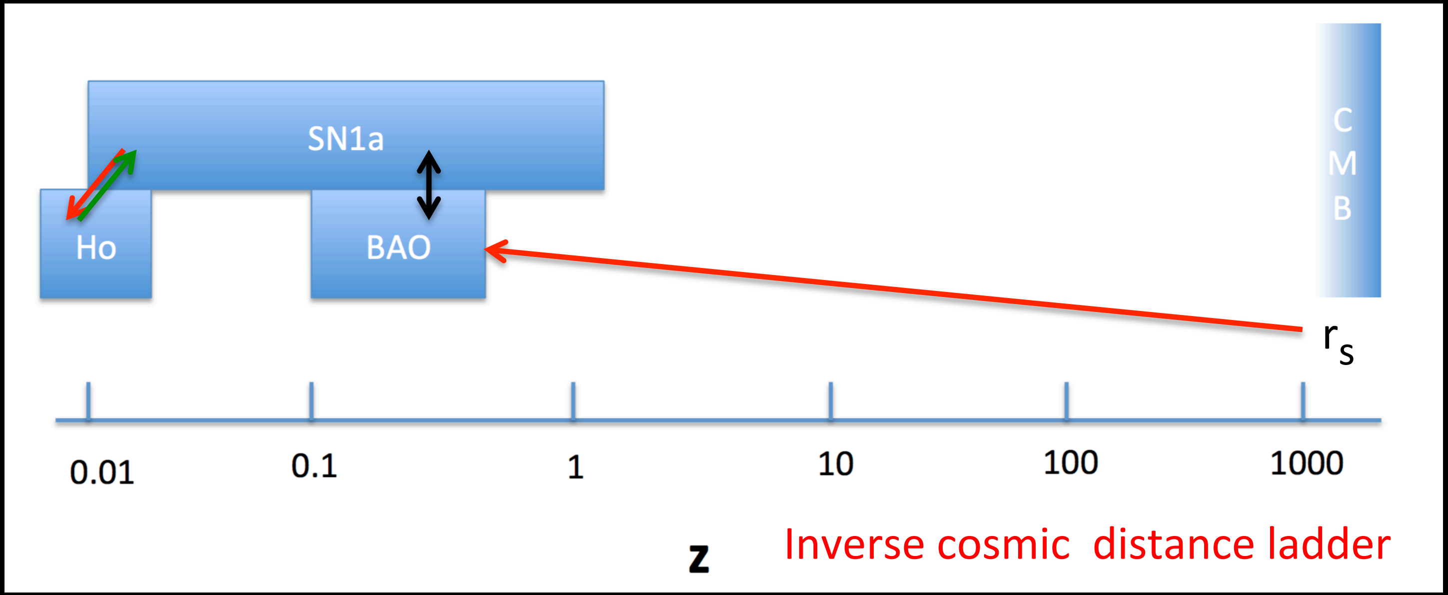
Direct cosmic distance ladder



Here is where in LCDM or its simple variations the two ladders do not match

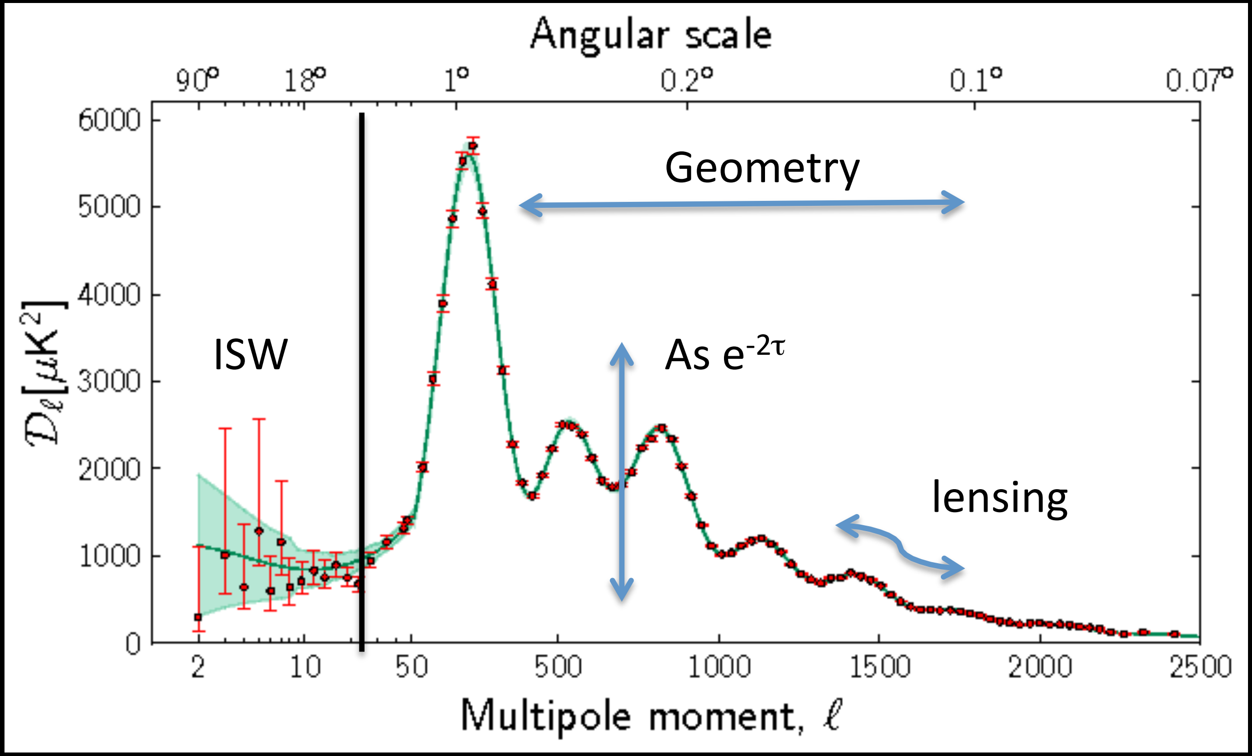
r_s from CMB independent from late time physics?

aside

Early cosmology constrained (Verde, Bellini, Pigozzo et al 2016.)

Based on Audren et al 2012

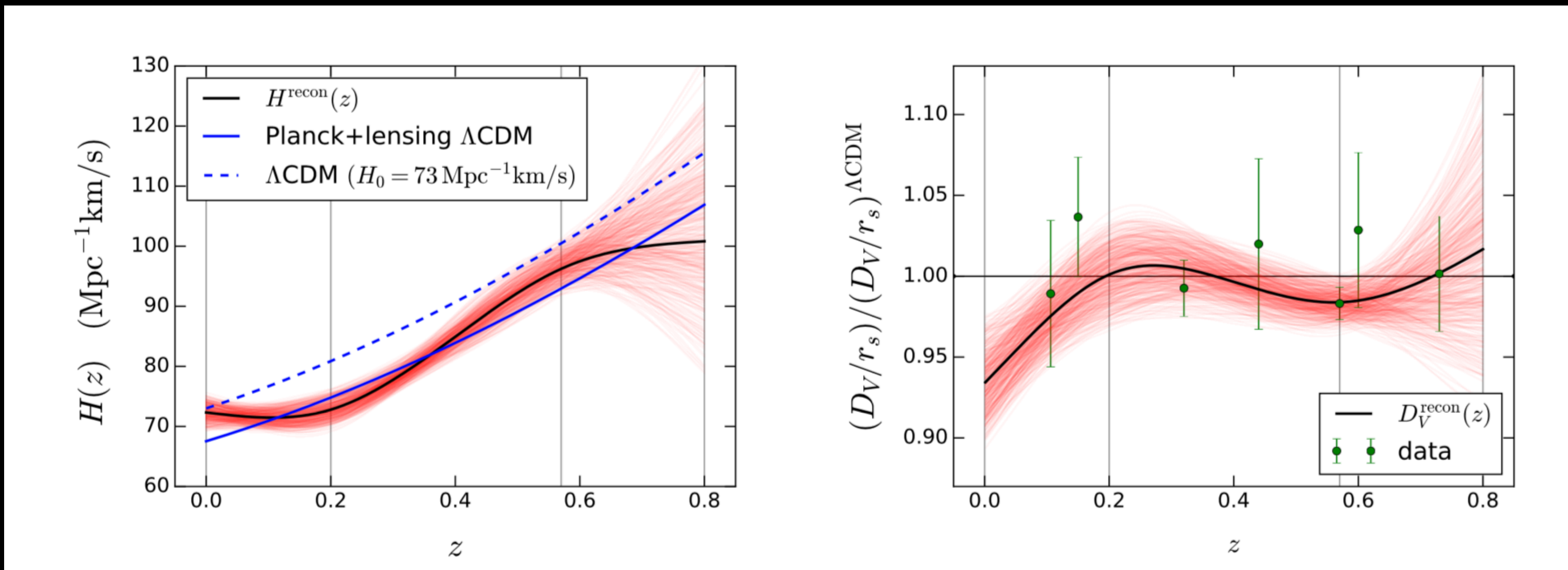
Late time effects in the CMB, combined with early time effects



The answer is yes: 147.0pm 0.34 Mpc (assume standard early time physics)

Towards model-independent

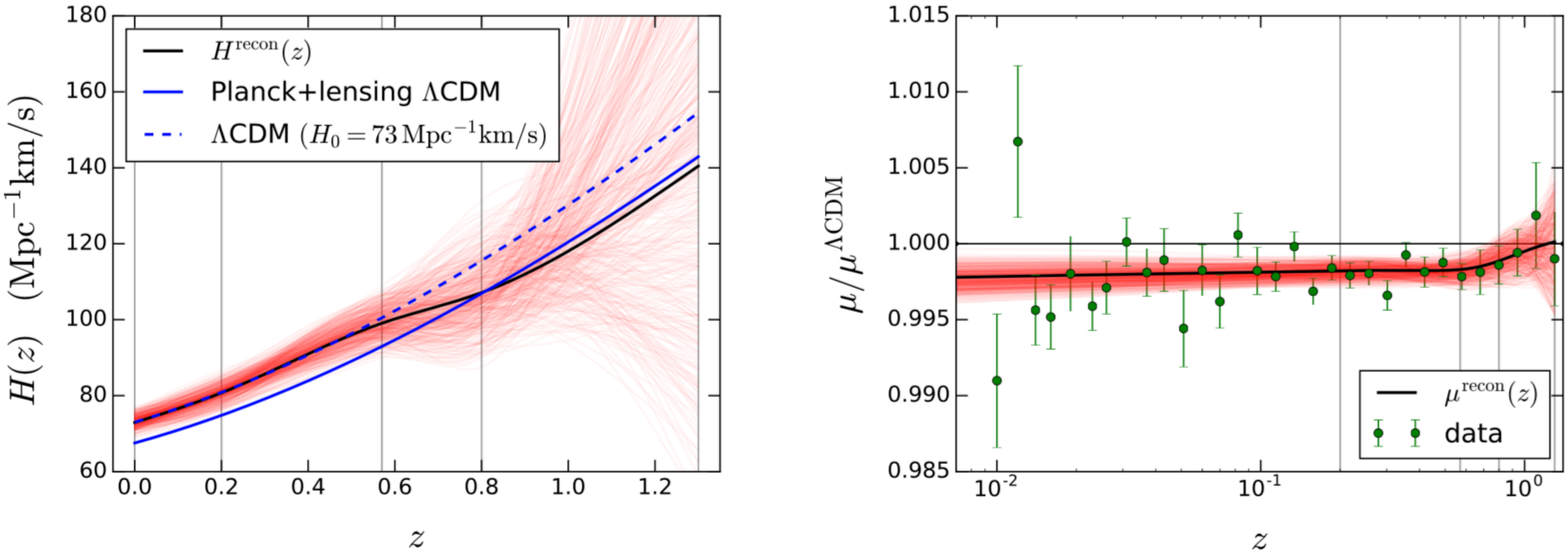
Ho+BAO+rs



Late time increased acceleration?

Towards model-independent

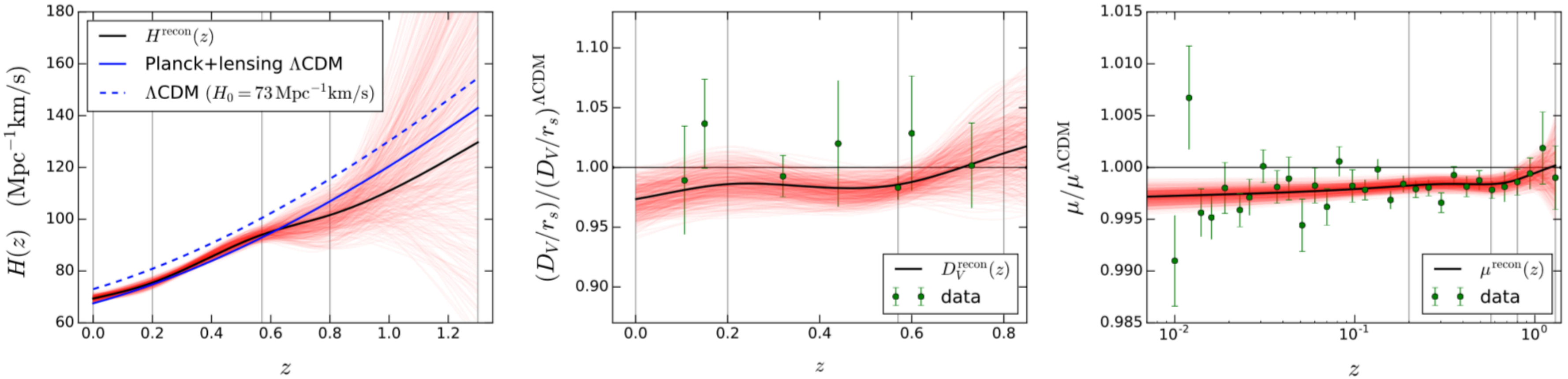
Ho+SNe



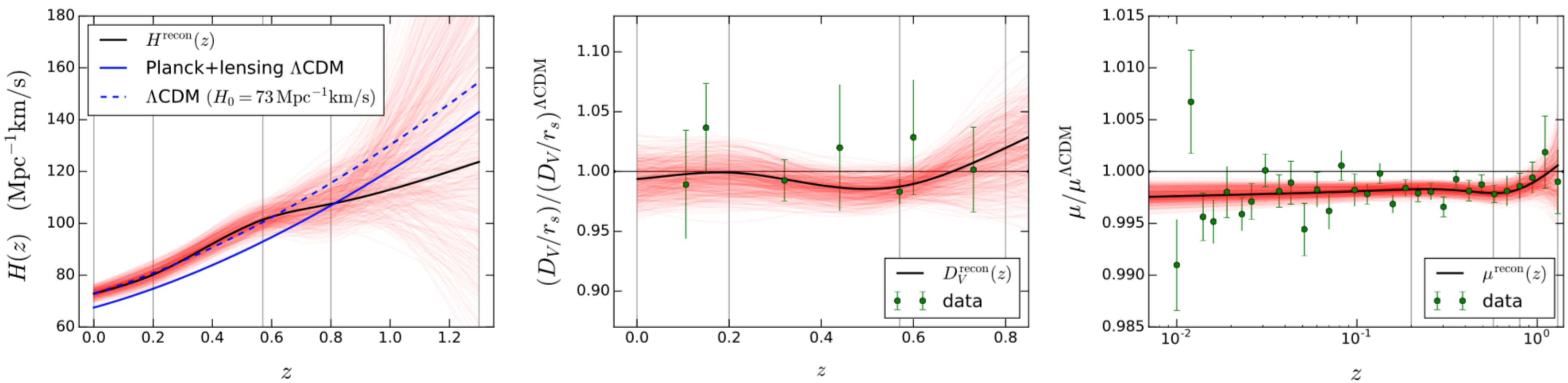
Late time increased acceleration? nope

Towards model-independent

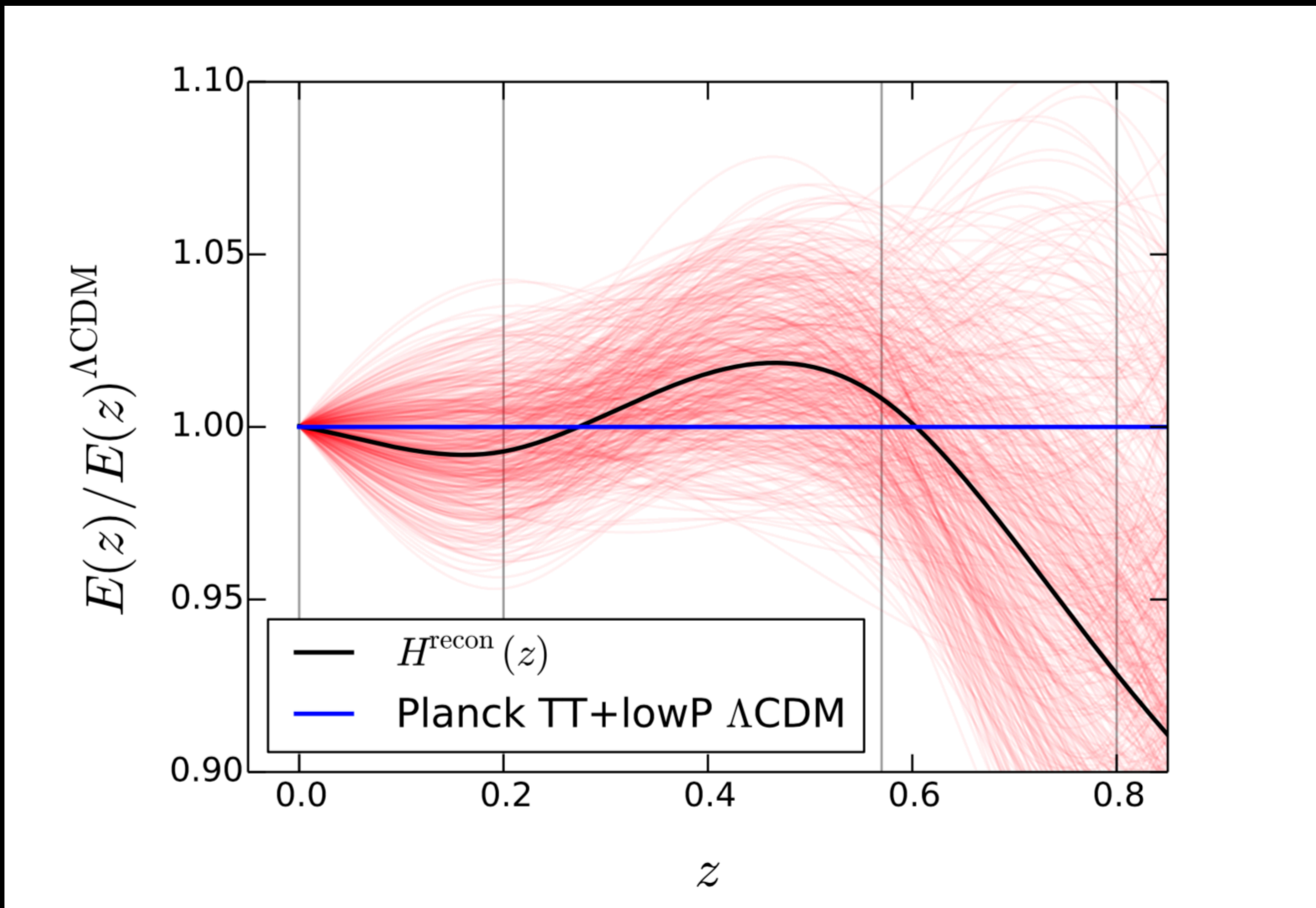
Ho+BAO+ SNe +rs



Ho+BAO+ Sne

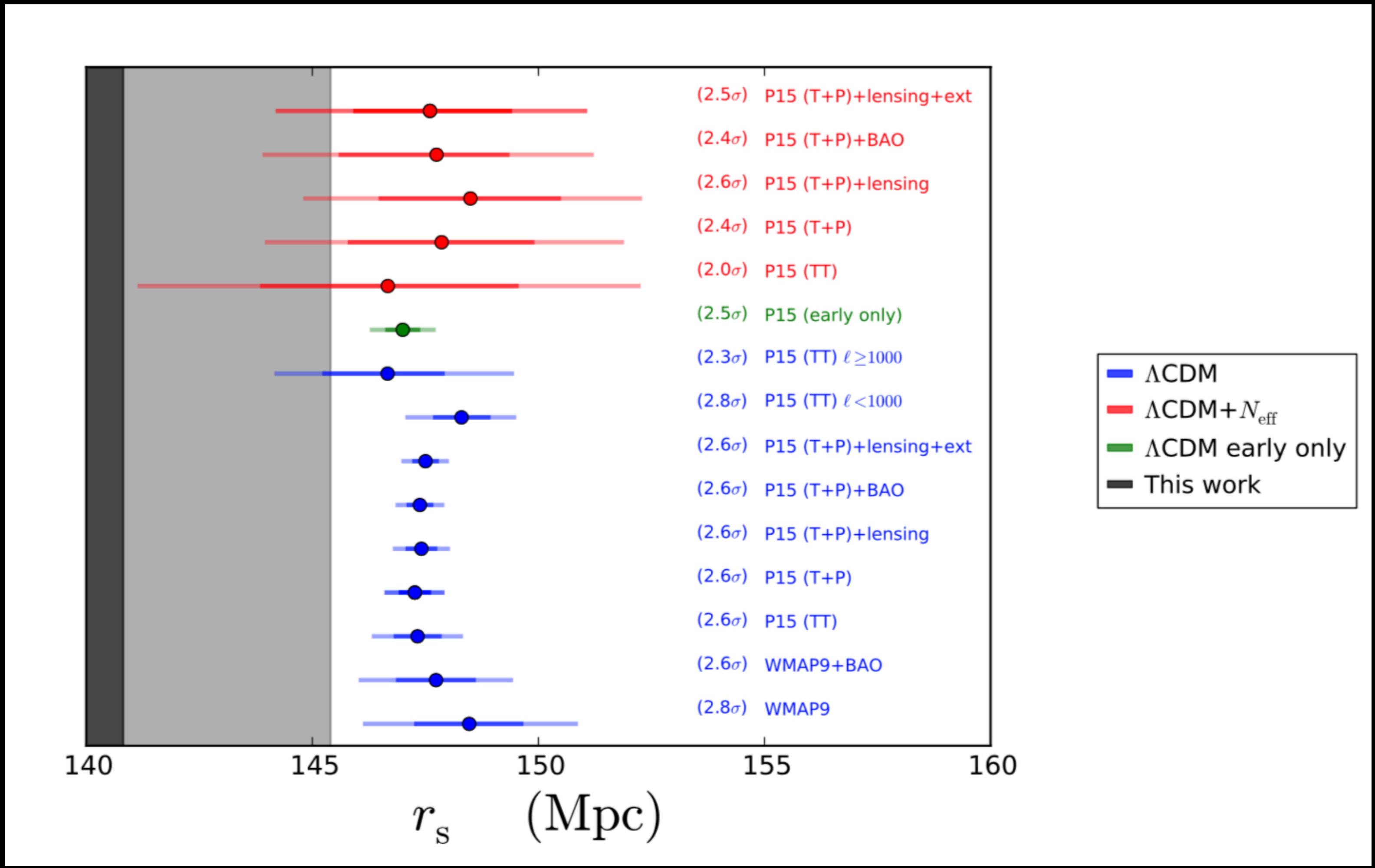


The SHAPE of expansion history is well constrained



The issue is with the normalization

The H_0 problem as a r_s problem



In a nutshell

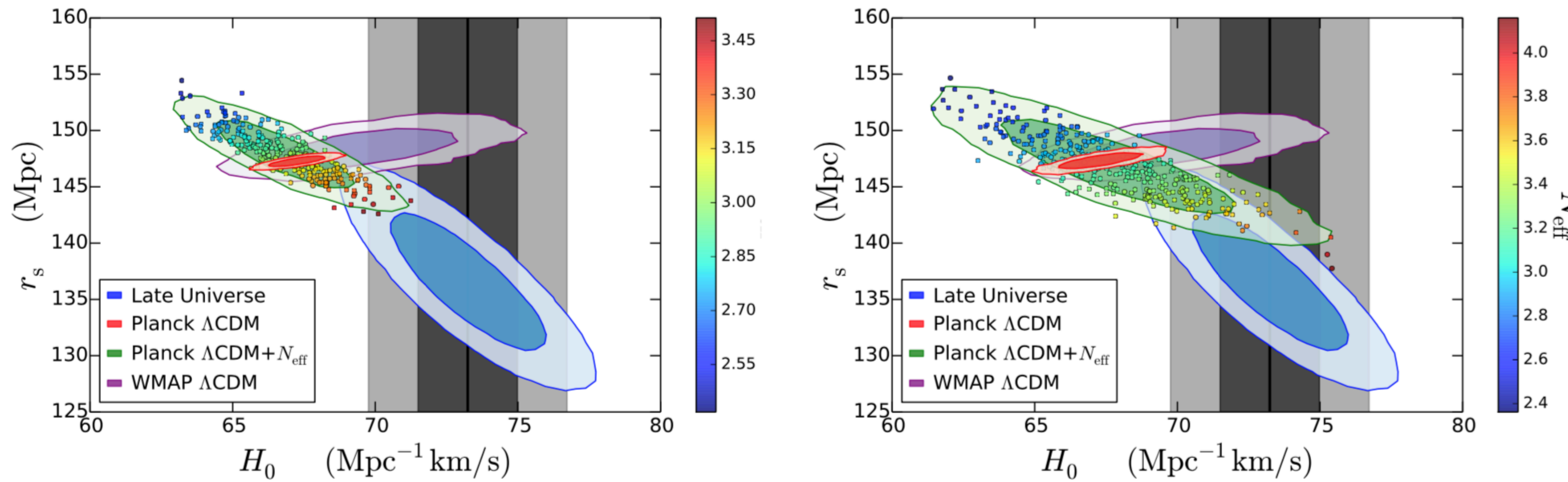
The H0 problem is an anchor problem (either at z=0 or at z=1100), which cannot be solved by tweaking (or bending) the expansion history

It can be solved by changing rs (thus early time physics) but polarization data impose some tight limits.

Why so much interest in Neff…

With high l polarization

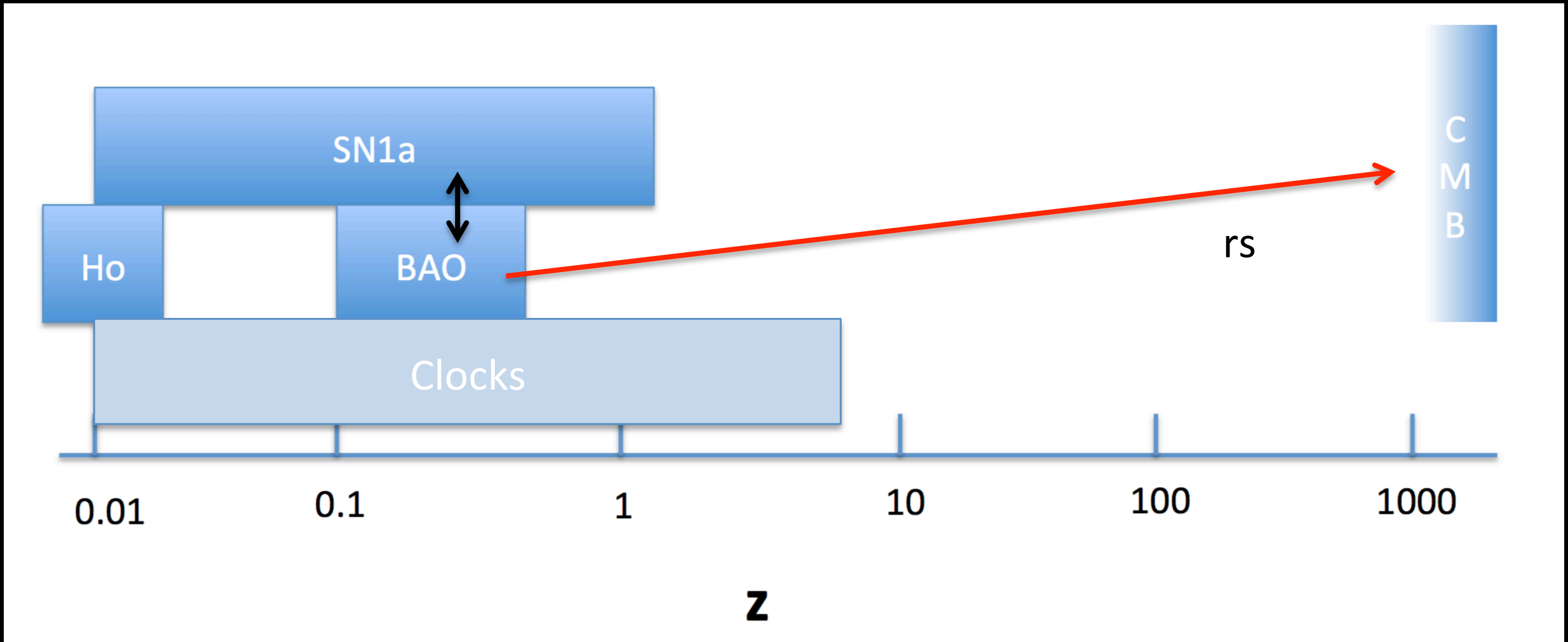
w/o high l polarization



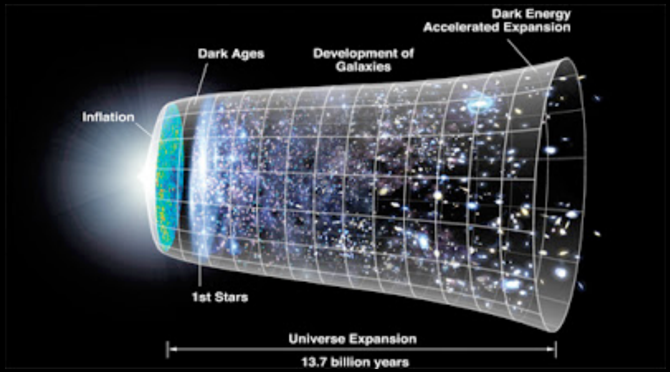
ΔNeff ~0.4 fixes everything but is disfavored by high l Planck polarization

The low redshift standard ruler

Verde, Bernal et al 2016



BAO Physics

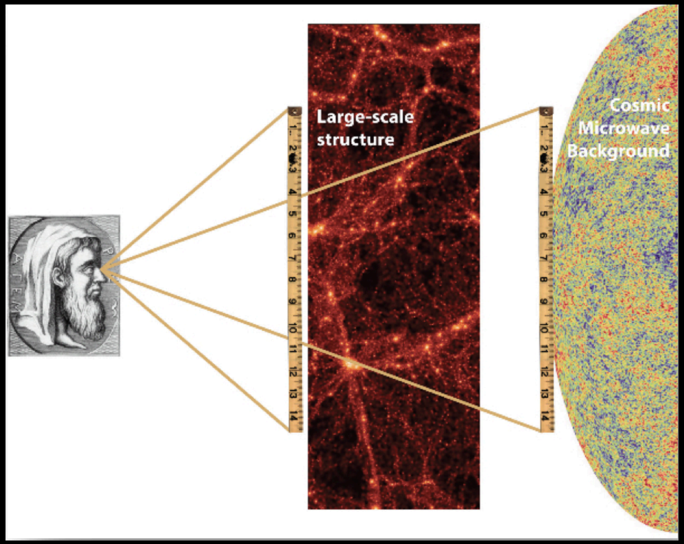


- *Theoretical* prediction depends on physics at z ~ 1000 (recombination)
- *Measured* size of BAO ruler depends on cosmology at z < a few
- Some aspects of recombination physics are set at z ~ 10^9. (Helium abundance)
- We can test a complete model with data from all of these 3 very different epochs (1 minute, 400,000 yr, 10^{10} years)
- If the model is wrong at one epoch, parameter inference (relevant to physics at another epoch) may be incorrect

How long is the standard ruler?

Normally model-dependent

$$r_s = \int_0^{t_*} \frac{c_s(t)}{1+z} dt = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)} dz$$



"Only" measure angles

$$\theta = r_d / D_A$$

The geometry can be measured with a standard ruler whose length is not necessarily important

Can we measure how long it is in a model independent way?

(so we can use it to test models)

A. Heavens, R. Jimenez, LV , PRL 2014, arXiv:1409.6217

PS similar philosophy of Sutherland 2012 MNRAS (model-dependent way)

How long is the standard ruler?

$$\theta = r_d / D_A$$

From the Robertson-Walker metric:

$$ds^2 = c^2 dt^2 - R^2(t)\{dr^2 + S_k^2(r)[d\theta^2 + \sin^2\theta d\phi^2]\}$$

$$S_k(r) = \sin(r), r, \sinh(r) \text{ for } k = 1, 0, -1$$

$$D_A(z) = (1+z)^{-1} R_0 S_k\left(\frac{\chi(z)}{R_0}\right) \qquad \chi(z) = c\int_0^z \frac{dz'}{H(z')}$$

$$H(z) = \dot{R}/R$$

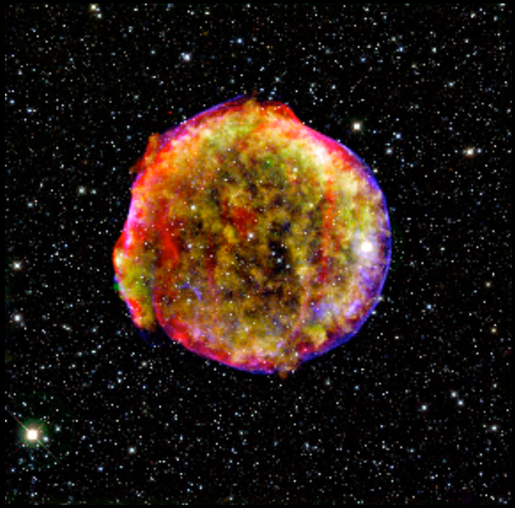
No GR; just symmetry (isotropy, homogeneity)

And the existence of a standard ruler, of course (standard candles etc..)

No need to use a model for the nearby Universe - use data

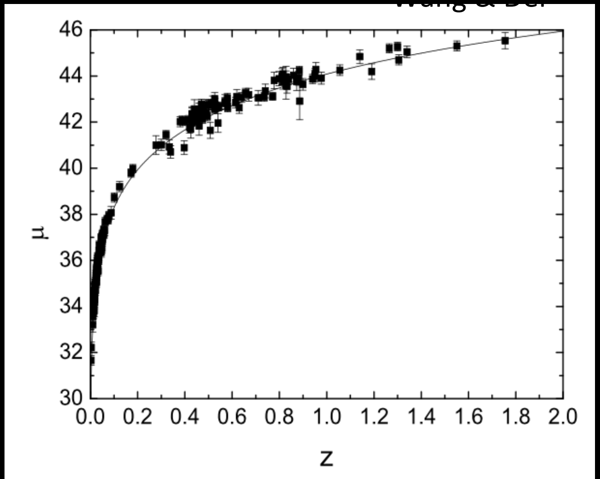
Type IA supernovae: standard candles.
Measure 'Luminosity Distance'

$$f \equiv \frac{L}{4\pi D_L^2}$$



Any (Riemannian) metric theory of gravity implies

$$D_L(z) = (1+z)^2 D_A(z)$$



JLA sample, Betoule et al 2014

Probes of the expansion history

Standard clocks

Old elliptical galaxies have stellar populations well described by a single age.

Differential ages give

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

(ignores spread in formation time in comparison with Hubble time)

Simon et al. 2005, Stern et al. 2010, Moresco et al. 2012, 2015, 2016

And, of course, H0

(Riess et al. 2016)

Basic model parameters and assumptions

Assume only:

Cosmological Principle (Homogeneity, Isotropy)

A metric theory of gravity

Smooth expansion history

Equation of state (of dark energy etc) is not assumed

Independent of Cosmological Model

Late-time data , z<1.3(1.8) tells us the length of the standard ruler.

Physics of the early Universe sets it

The low redshift standar ruler

Parameters (8 or 10)

Ruler length

Supernova magnitude (log[luminosity])

Inverse curvature radius of Universe, $c/(R_0 H_0)$ (i.e., in units of H_0/c ~ 1/size of observable Universe)

1/H(z) at 5 (7) different redshifts from 0 to 1.3 (1.8) (linearly interpolate in between)

8(10) parameters. Improper uniform priors.
Monte Carlo Markov Chain with ~10^7 points.
Gelman-Rubin convergence: R = 1+O(0.0001)

Results

Two ways to report the low redshift standard ruler

If only SNe and BAO: $r_s h$

If add Ho (or H(z) e.g., Clocks): r_s

Results

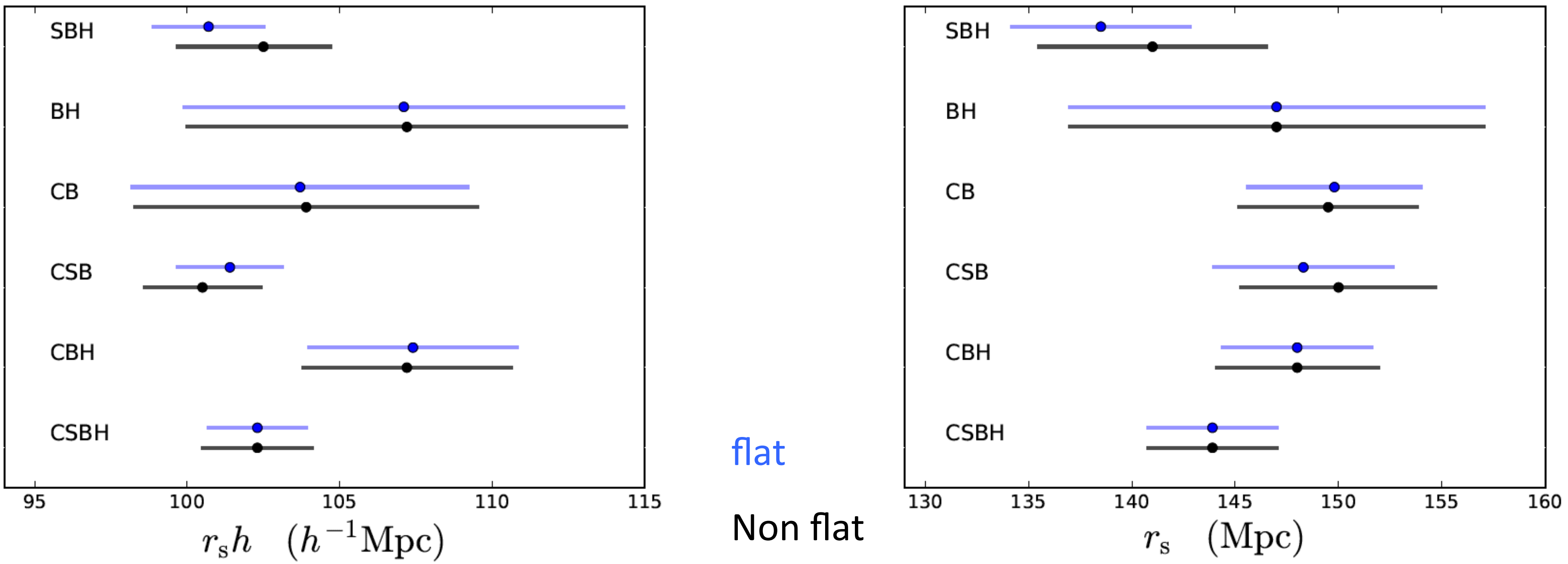
Data	$r_s^h[h^{-1}\mathrm{Mpc}]$	$r_s[\mathrm{Mpc}]$	H_0	ΔM	$\Omega_k = k(c/H_0R_0)^2$
SBH	$102.0 \pm 2.5(^{+2.2}_{-2.8})$	140.8 ± 4.9	72.8 ± 1.8	0.079 ± 0.083	$-0.49 \pm 0.64 \left(-0.99^{+0.86}_{-0.26}\right)$
BH	107.2 ± 7.2	147 ± 10	73.0 ± 1.8	N/A	unconstrained
SB	101.0 ± 2.3	unconstrained	unconstrained	unconstrained	0.07 ± 0.61
CB	103.9 ± 5.6	149.5 ± 4.3	69.6 ± 4.2	N/A	unconstrained
CSB	100.5 ± 1.9	150.0 ± 4.7	67.0 ± 2.5	-0.090 ± 0.079	0.36 ± 0.41
CBH	107.2 ± 3.4	148.0 ± 3.9	72.5 ± 1.7	N/A	unconstrained
CSBH	102.3 ± 1.8	143.9 ± 3.1	71.1 ± 1.5	0.028 ± 0.047	$-0.03 \pm 0.31 \left(-0.08^{+0.32}_{-0.28}\right)$
SBH	100.7 ± 1.8	138.5 ± 4.3	72.8 ± 1.8	0.083 ± 0.061	flat
BH	107.1 ± 7.2	147 ± 10	73.0 ± 1.8	N/A	flat
SB	101.2 ± 1.8	unconstrained	unconstrained	unconstrained	flat
CB	103.7 ± 5.5	149.8 ± 4.2	69.2 ± 4.0	N/A	flat
CSB	101.4 ± 1.7	148.3 ± 4.3	68.5 ± 2.1	-0.047 ± 0.064	flat
CBH	107.4 ± 3.4	148.0 ± 3.6	72.6 ± 1.7	N/A	flat
CSBH	102.3 ± 1.6	143.9 ± 3.1	71.1 ± 1.4	0.026 ± 0.043	flat

2% measure

Planck, LCDM: 147.27 ± 0.31 Mpc

The low redshift standar ruler

Results



Without H_0 or clocks only r_s h is constrained

In a nutshell

It is possible to measure the standard ruler from low redshift observations in a model-independent way without making any assumptions about gravity, GR, dark energy, or early time physics etc.

Value so measured is in agreement with CMB-LCDM except for SBH combination

The error-bars are still factor 6-7 larger than that of CMB-inferred value in LCDM
The error bars are however (slightly) smaller that CMB-inferred ones for NeffLCDM model.
Can be used to constrain Neff

Error on rs dominated by error on H0

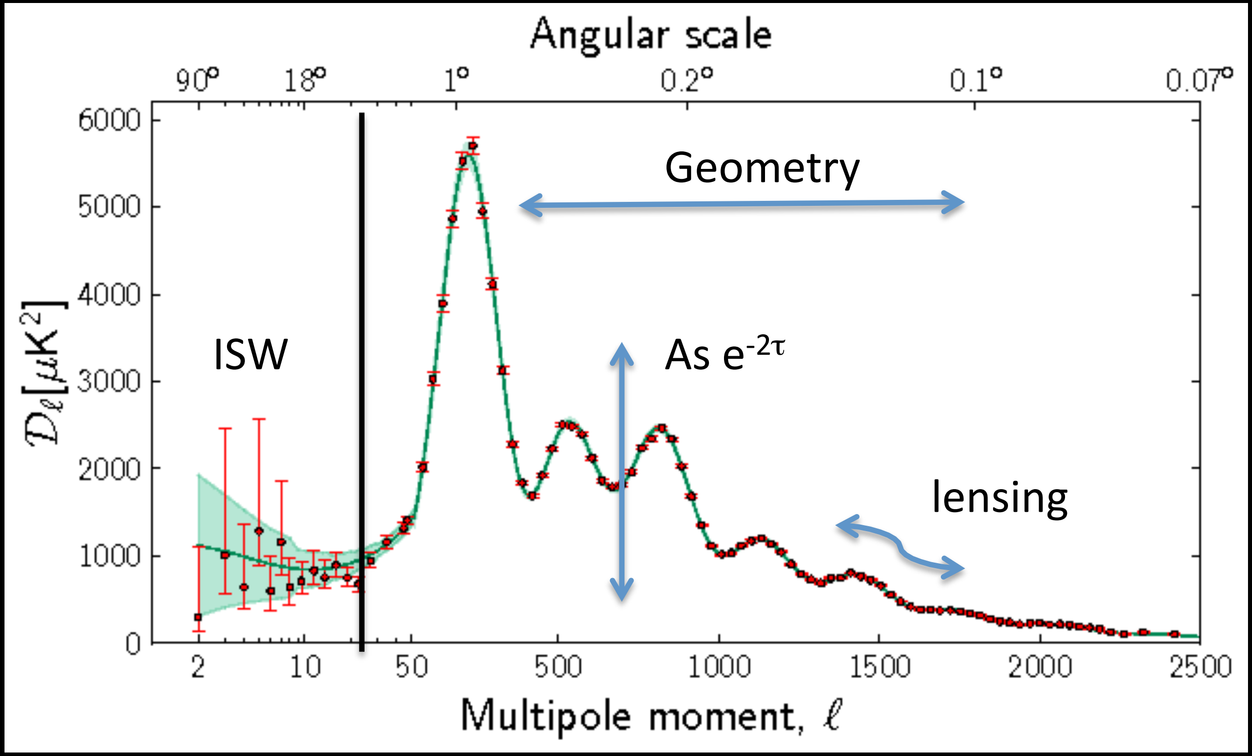
r_s from CMB independent from late time physics?

Parameters, physics

Early cosmology constrained (Verde, Bellini, Pigozzo et al.)

Based on Audren et al 2012

Late time effects in the CMB, combined with early time effects



Early cosmology

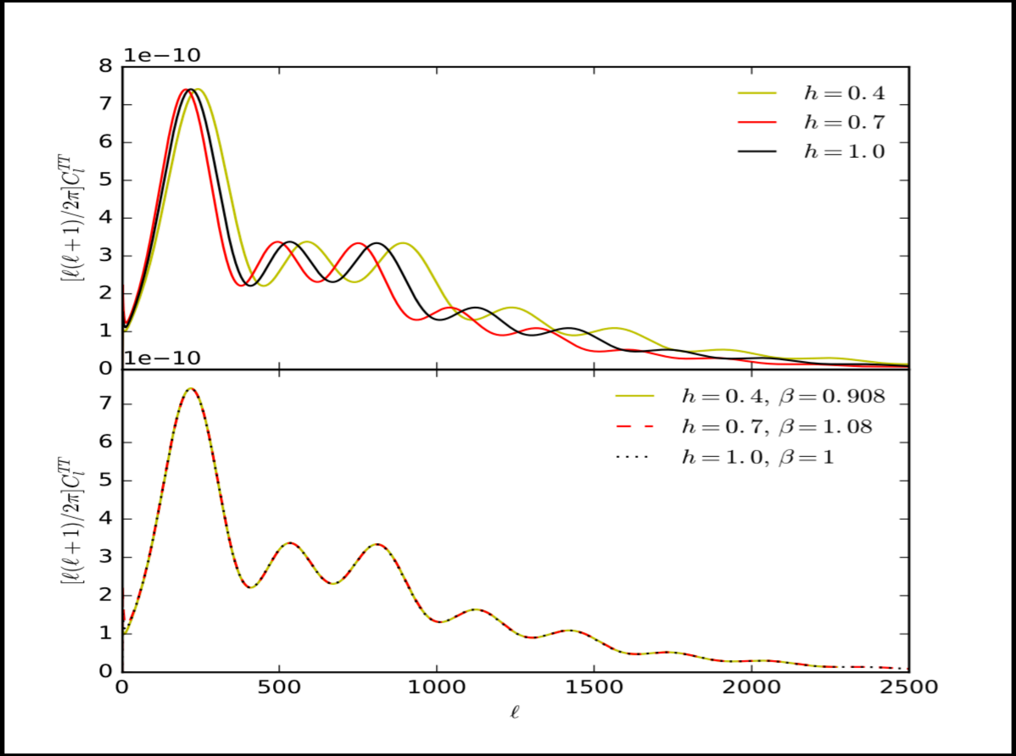
r_s from CMB independent from late time physics?

Early cosmology constrained (Verde, Bellini, Pigozzo et al.)

Based on Audren et al 2012

Late time effects in the CMB

geometry



Late time

Cancel with

$$C_\ell^{TT} \rightarrow C_{\beta\ell}^{TT}.$$

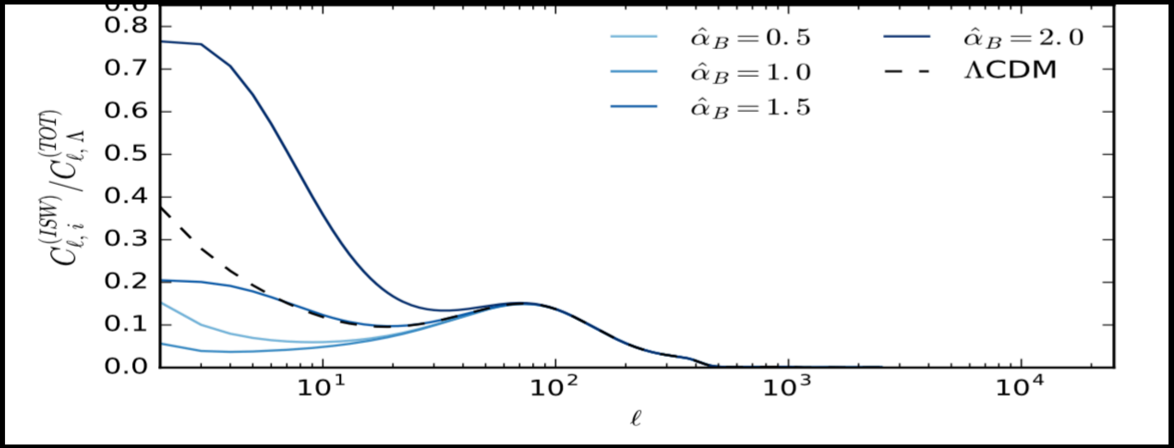
Early cosmology

r_s from CMB independent from late time physics?

Recipe to remove Late time effects in the CMB

Based on Audren et al 2012

ISW



Neglect low l

This procedure has some limitations

Early cosmology

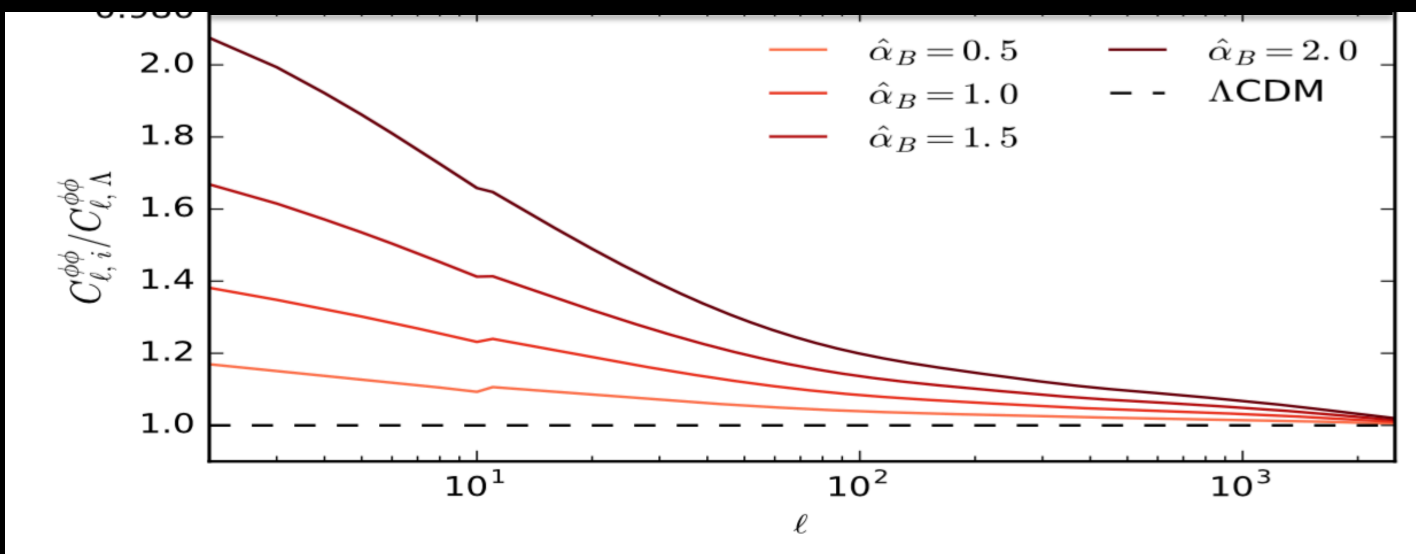
r_s from CMB independent from late time physics?

Early cosmology constrained (Verde, Bellini, Pigozzo et al.)

Based on Audren et al 2012

Late time effects in the CMB

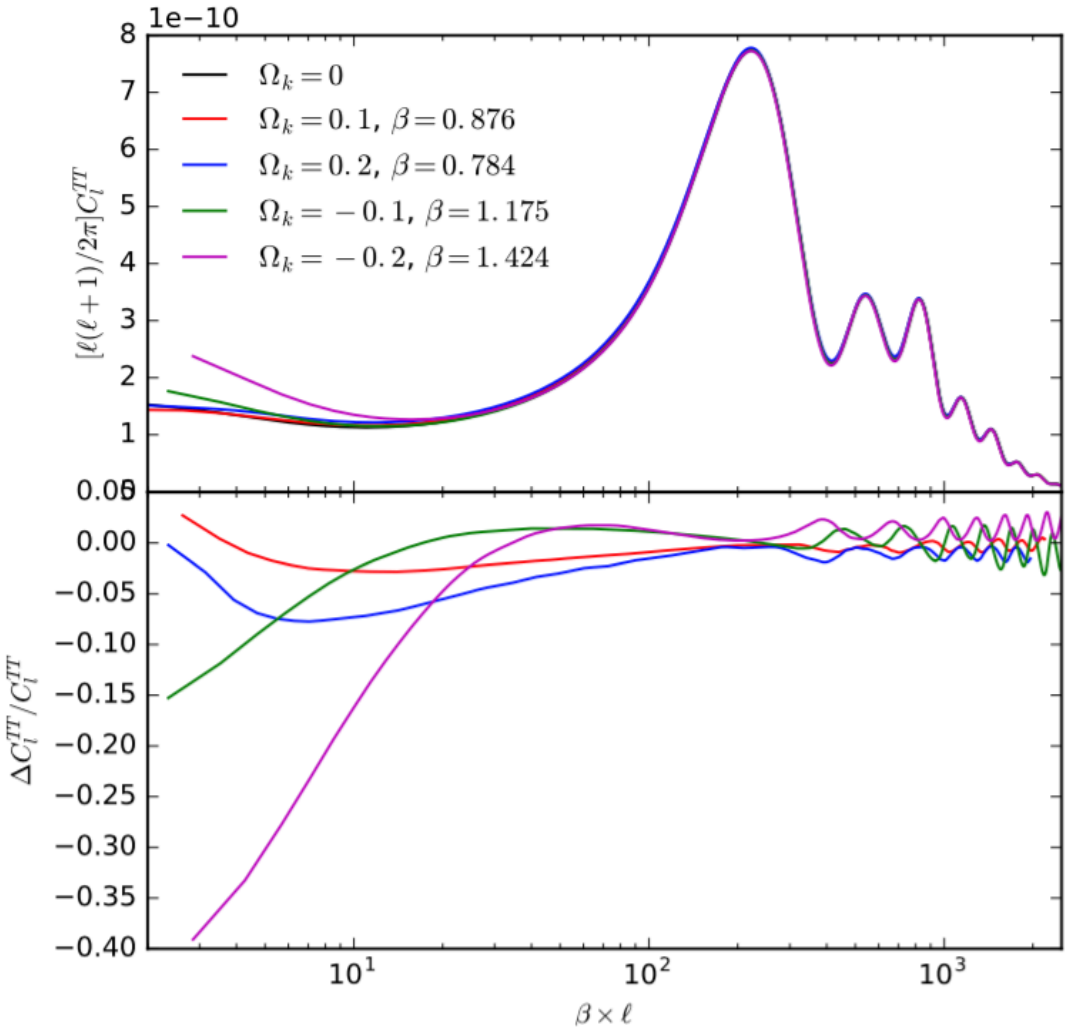
Lensing potential



$$\phi(k,z) \longrightarrow A_{lp}\left(\frac{k}{k_{lp}}\right)^{n_{lp}} \phi(k,z)$$

Early cosmology

Dark energy “hardened” constraints



More powerful than r_s only

now analise data so that the late-time information is removed*

We consider:

LCDM: standard 6-parameters model

DE fld: dark energy fluid.perfect fluid, $w<0$ and $c_s=1$

K: LCDM but non flat (recall that CMB constraints on flatness come from late-time effects)

nu:3 neutrinos but c_{eff} and c_{vis} are free parameters

Matteriation: extra fluid with $0<w<1/3$, no perturbations effect only on the background

*dark-energy “hardened" CMB prior

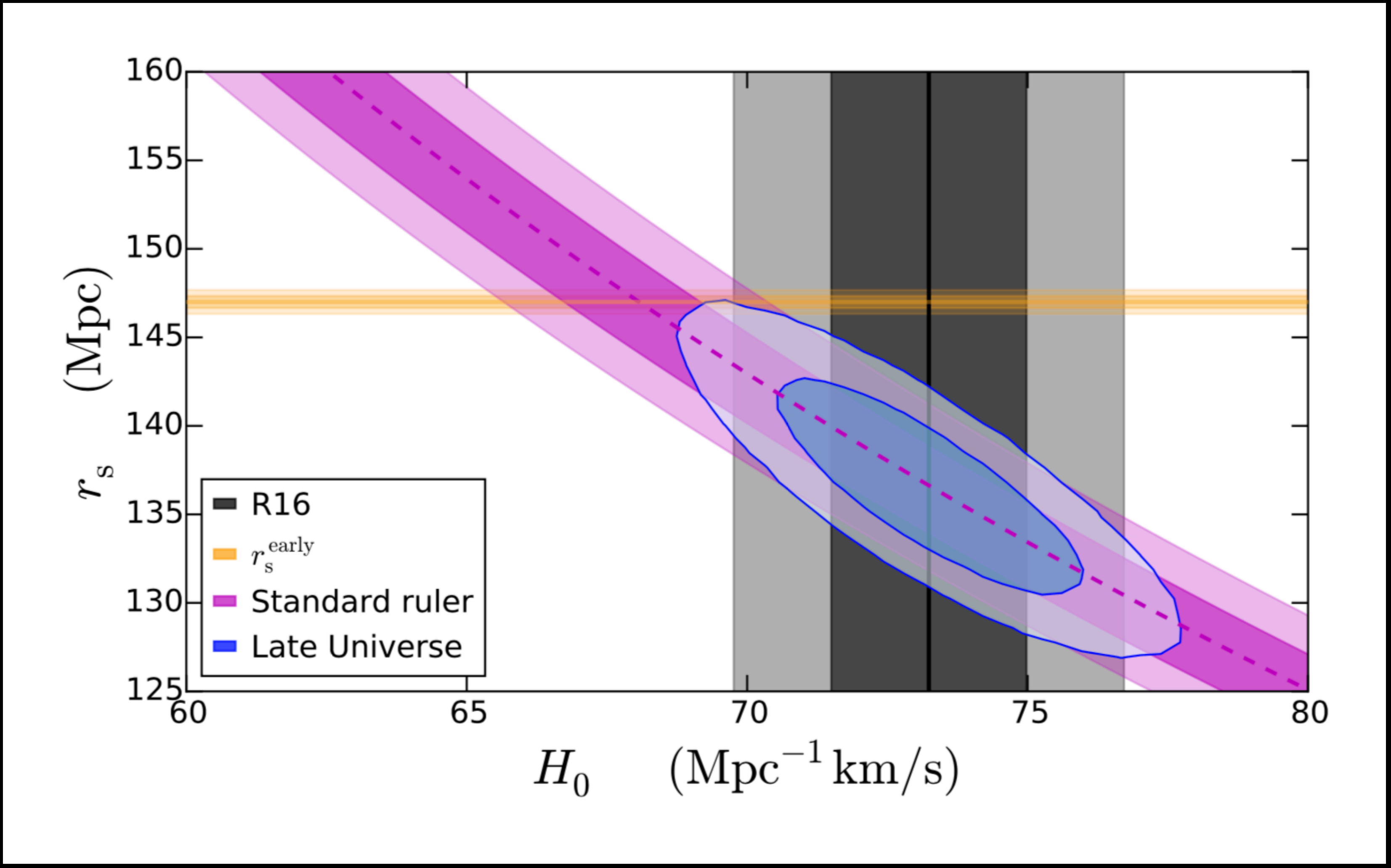
	LCDM	DE fld	k	nu	matteriation
$10\Omega_b^{\rm rec}$	$1.187^{+0.034}_{-0.034}$	$1.186^{+0.034}_{-0.034}$	$1.188^{+0.036}_{-0.034}$	$1.205^{+0.047}_{-0.047}$	$1.185^{+0.035}_{-0.033}$
$10\Omega_{\rm cdm}^{rec}$	$6.378^{+0.071}_{-0.070}$	$6.379^{+0.071}_{-0.070}$	$6.376^{+0.071}_{-0.075}$	$6.378^{+0.071}_{-0.072}$	$6.351^{+0.082}_{-0.085}$
$H_{\rm rec}$ [Mpc^{-1}]	$5.197^{+0.045}_{-0.045}$	$5.198^{+0.046}_{-0.045}$	$5.196^{+0.046}_{-0.047}$	$5.12^{+0.14}_{-0.14}$	$5.193^{+0.046}_{-0.048}$
n_s	$0.964^{+0.010}_{-0.010}$	$0.964^{+0.010}_{-0.010}$	$0.964^{+0.011}_{-0.011}$	$0.956^{+0.023}_{-0.023}$	$0.966^{+0.011}_{-0.011}$
$e^{-2\tau}A_s$	$1.879^{+0.024}_{-0.025}$	$1.879^{+0.026}_{-0.026}$	$1.876^{+0.025}_{-0.026}$	$1.871^{+0.072}_{-0.070}$	$1.875^{+0.026}_{-0.026}$
$10^9\Omega_\Lambda^{rec}$	$1.29^{+0.12}_{-0.12}$	-	$1.66^{+1.38}_{-1.46}$	$1.24^{+0.17}_{-0.17}$	$1.31^{+0.13}_{-0.12}$
$10^4\Omega_k^{\rm rec}$	-	-	$0.27^{+1.17}_{-1.24}$	-	-
$10^3\Omega_{\rm fld}^{\rm rec}$	-	$0.039^{+0.197}_{-0.039}$	-	-	$2.50^{+3.40}_{-2.50}$
$w_{\rm fld}^0$	-	$-1.15^{+0.44}_{-0.73}$	-	-	$0.05^{+0.10}_{-0.05}$
$N_{\rm eff}$	-	-	-	$2.77^{+0.47}_{-0.46}$	-
$c_{\rm eff}^2$	-	-	-	$0.33^{+0.01}_{-0.01}$	-
$c_{\rm vis}^2$	-	-	-	$0.34^{+0.10}_{-0.10}$	-
$z_{\rm rec}$	$1089.0^{+0.5}_{-0.5}$	$1089.0^{+0.5}_{-0.5}$	$1089.0^{+0.5}_{-0.6}$	$1088.7^{+0.6}_{-0.6}$	$1089.0^{+0.5}_{-0.5}$
r_d^s	$147.35^{+0.66}_{-0.66}$	$147.34^{+0.66}_{-0.66}$	$147.37^{+0.68}_{-0.69}$	$150.0^{+4.8}_{-4.7}$	$147.47^{+0.69}_{-0.71}$
χ^2_{min}	2456	2454	2456	2454	2455

1%

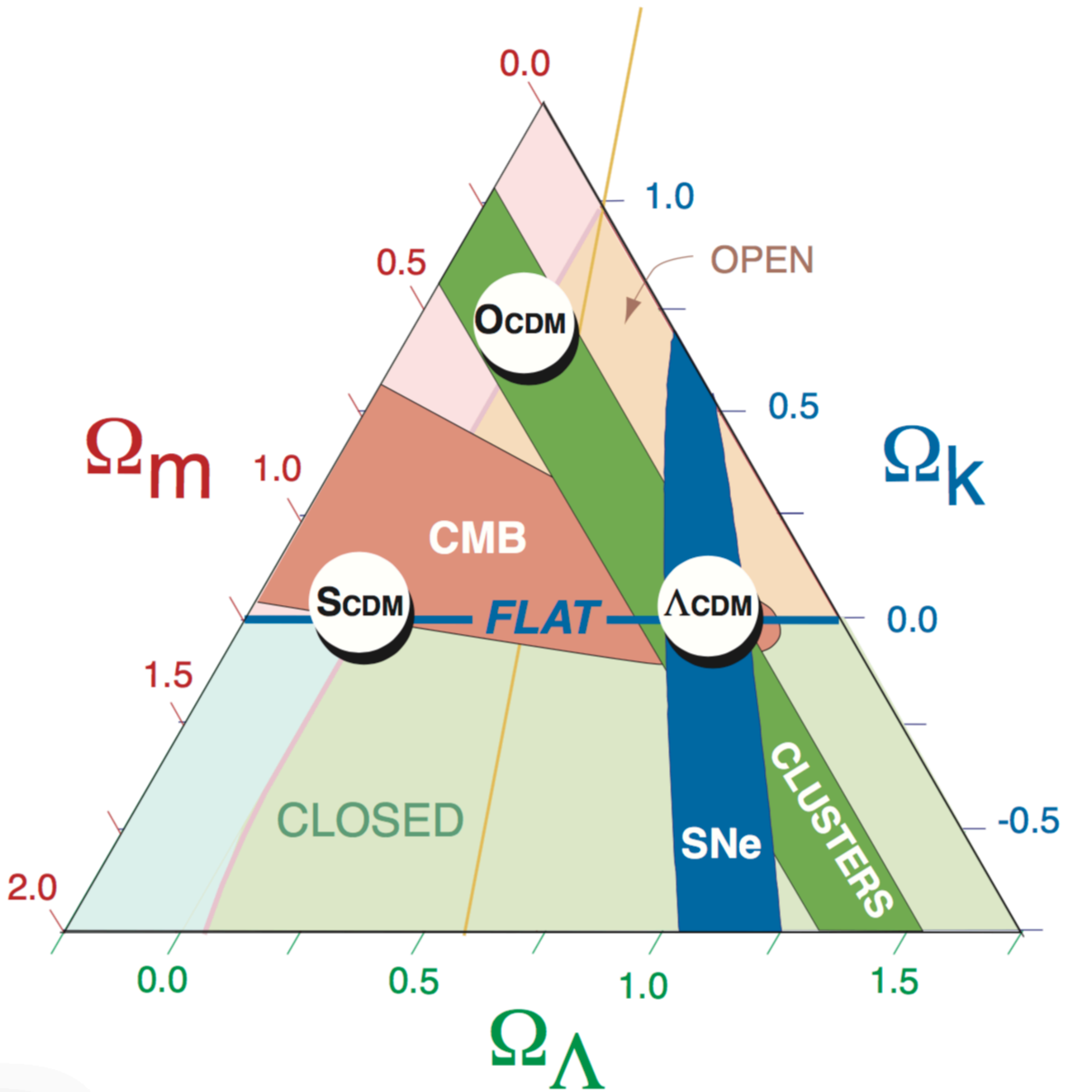
Bounds are 95% C.L.

Note H at recombination…

The H_0-r_s relation

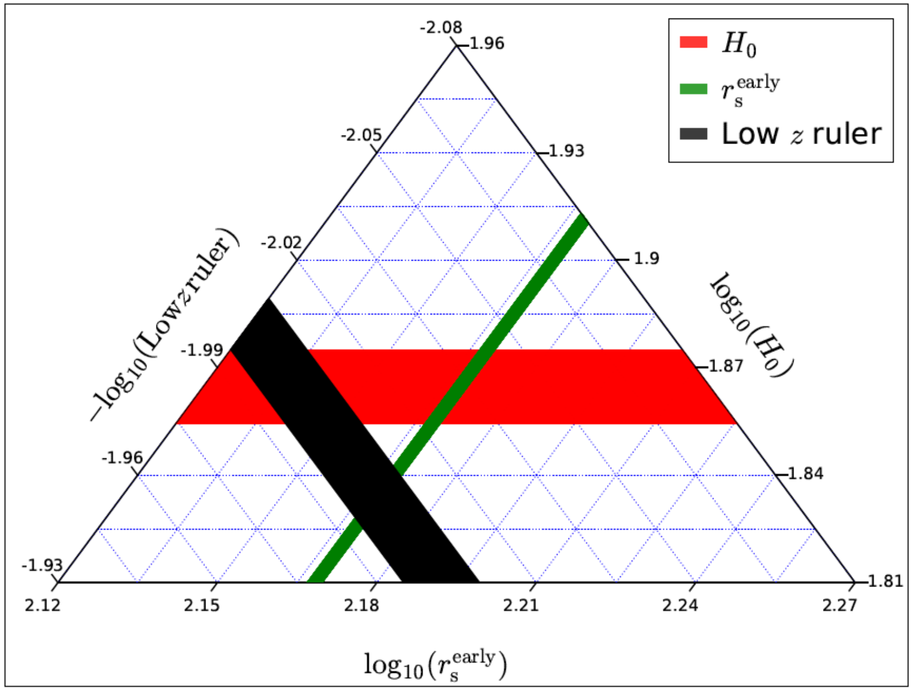


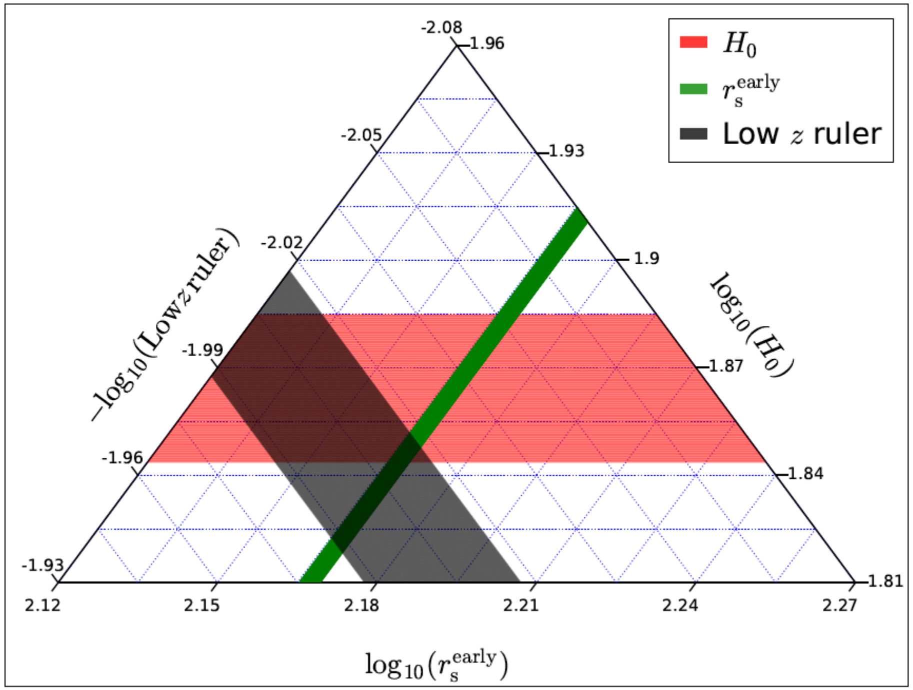
The cosmic triangle (last millenium)



Bachall et al 1999

The (new) cosmic triangle





1 σ

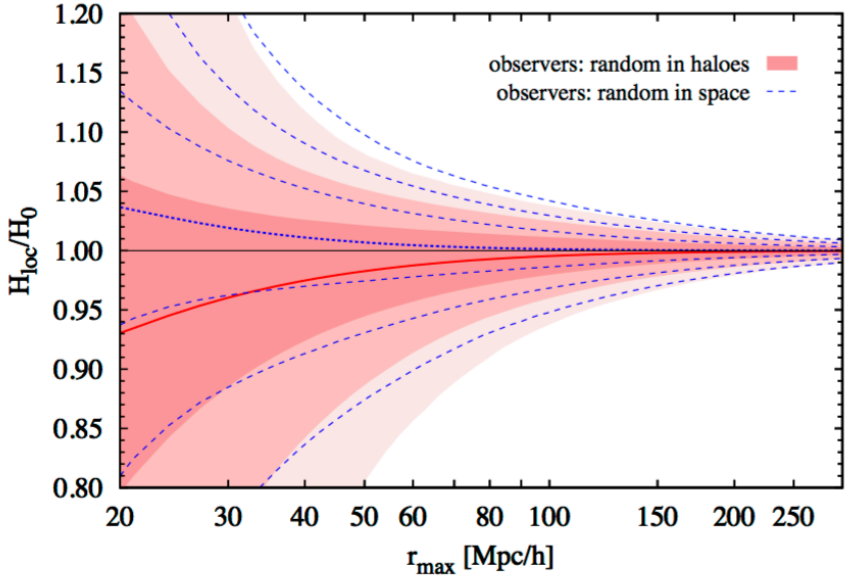
2 σ

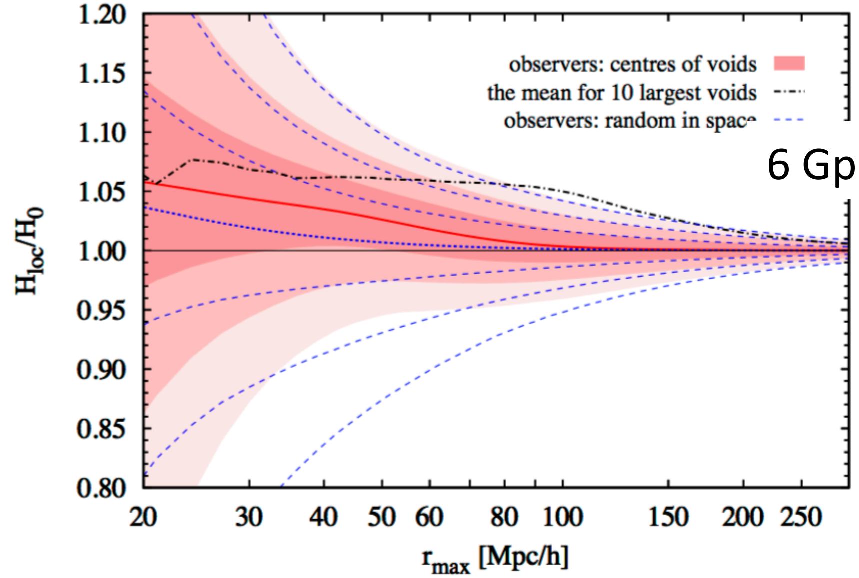
In summary

- The ``Ho trouble": It is a mis-match of anchors no evidence for strange expansion history.
- Can shift Ho or r_s. (keep this in mind if looking for new physics)
- ΔNeff~0.4 would do (if no Planck polarization)
- More better data are coming in

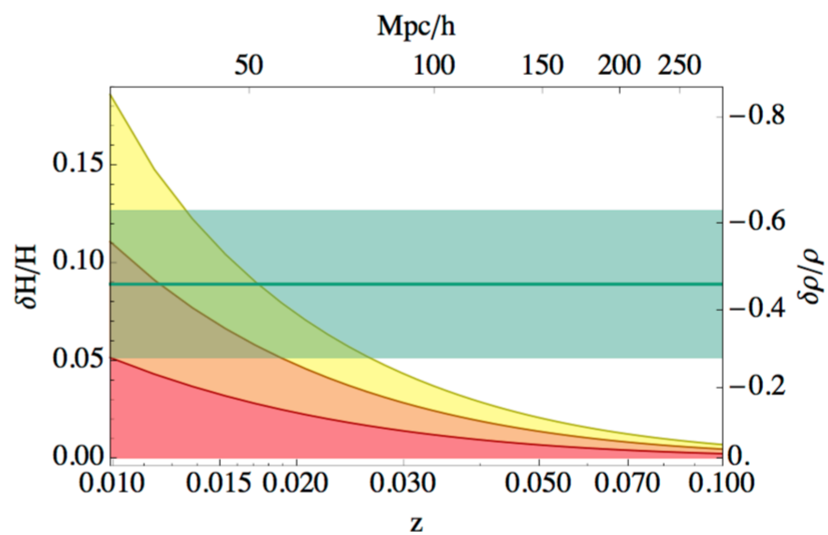
Void (underdensity by -0.57 out to 300 Mpc) Romano 2017, see also Wotjak et al 2013

A Void?





6 Gpc/h

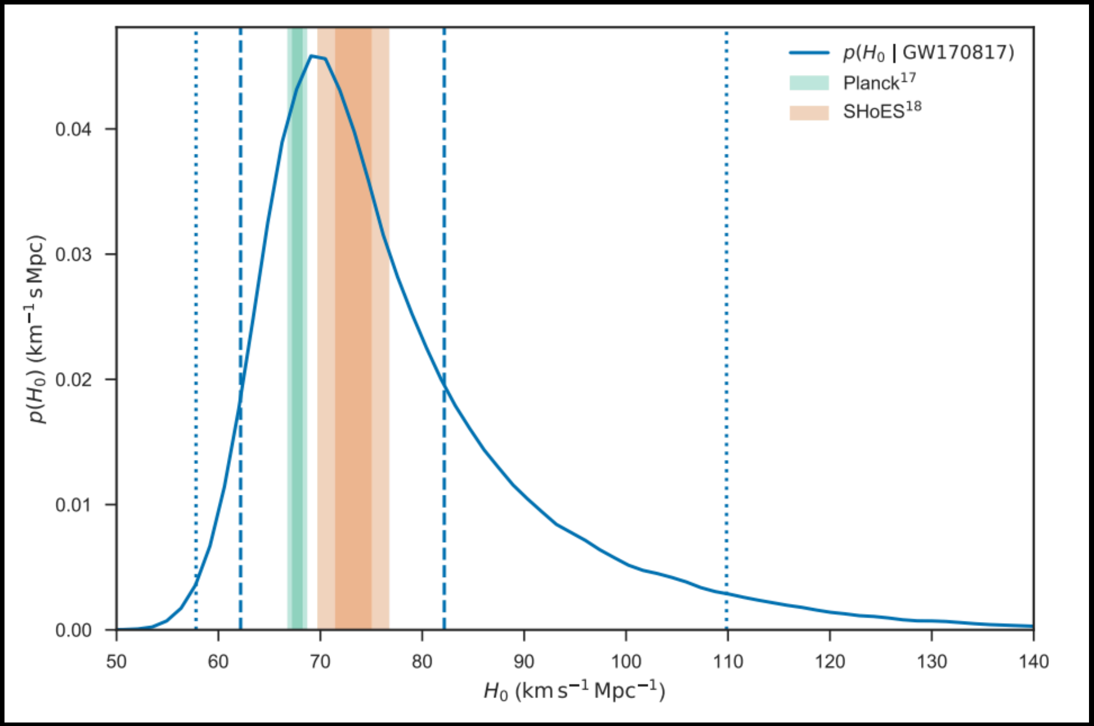


Wotjak et al 2013
arXiv:1312.0276

And…KSZ would be HUGE

Marra et al 2013
(Linear theory)

Standard sirens to the rescue (with some patience)

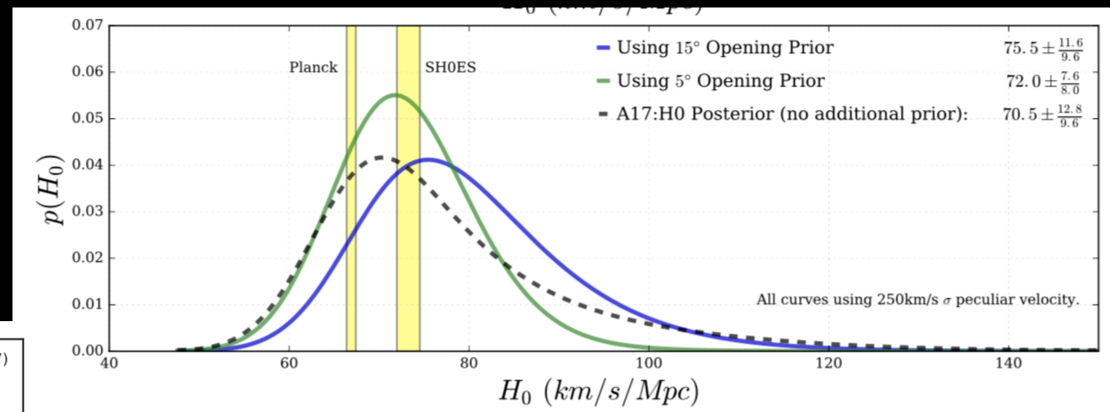


LIGO Nature paper last week

70(+12-8) Km/s/Mpc

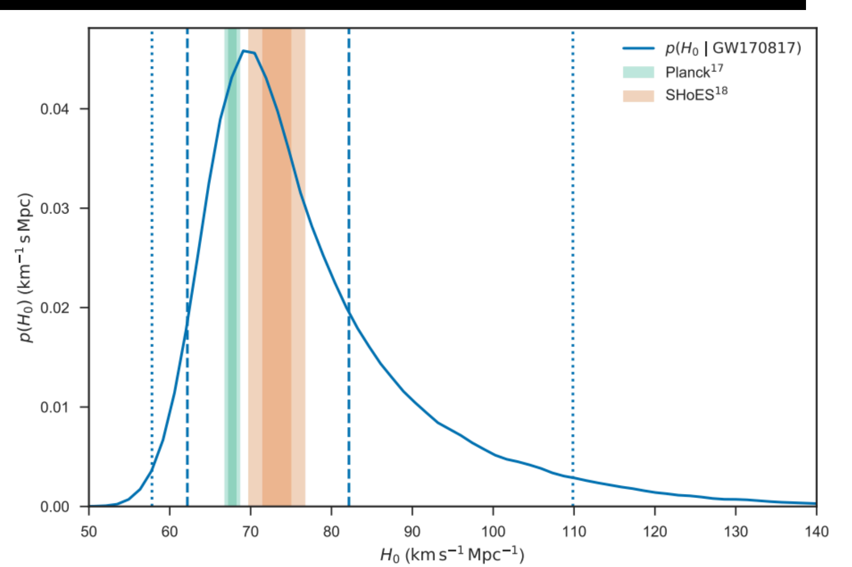
14% error

Standard sirens to the rescue (with some patience)



[arXiv:1710.06426](https://arxiv.org/abs/1710.06426)

They claim one needs 70-50 events...



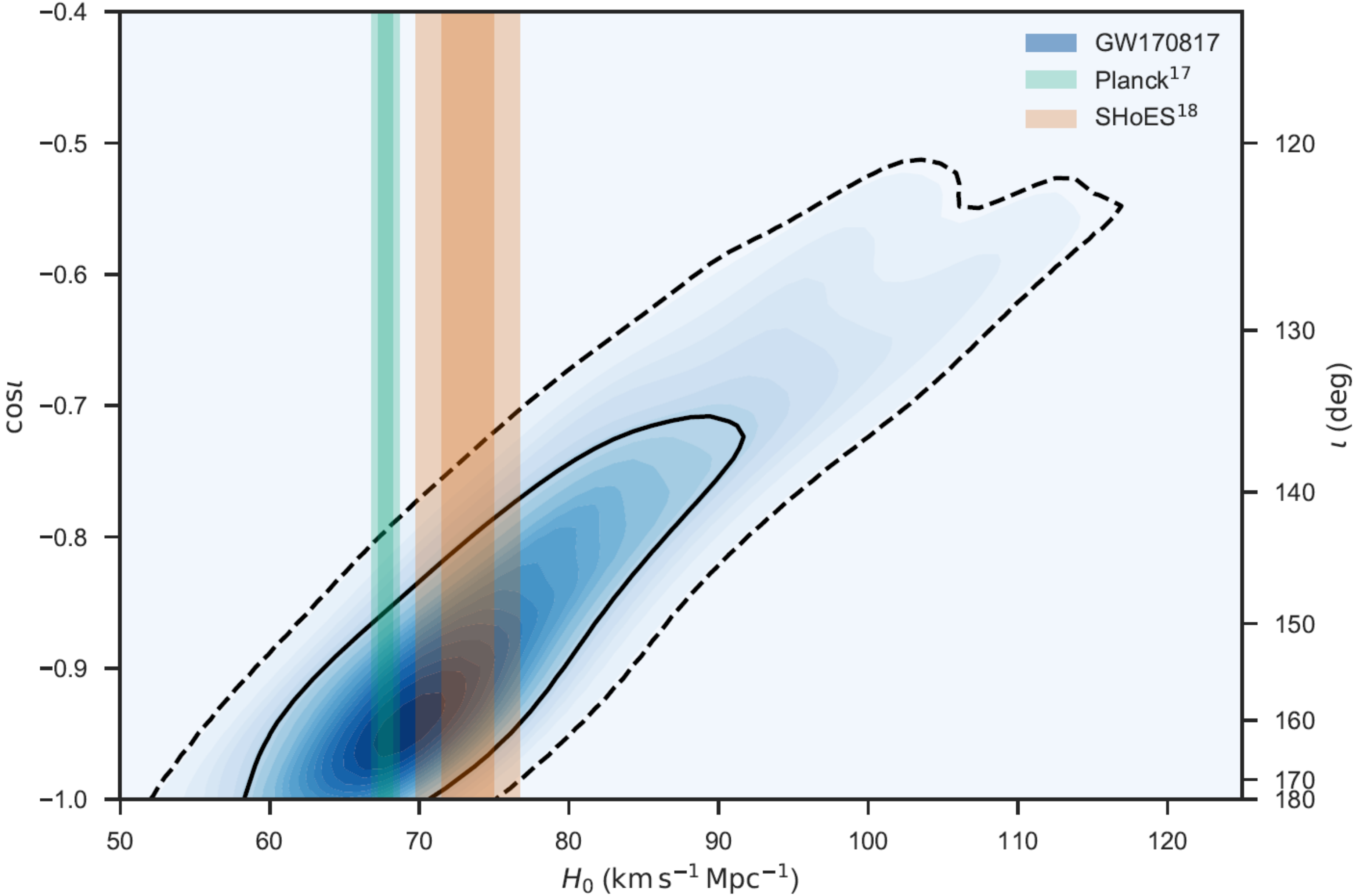
LIGO Nature paper last week

70(+12-8) Km/s/Mpc

Final conclusions

- Systematic errors are not only in the measurement but also in the interpretation (the adopted underlying model). Cosmology is special.
- It would be good to have a principled framework to deal with systematics errors (for another time)
- Concentrated on difference between “constraining model’s parameters” and “understanding”
- Attempt to be model-independent. Some examples of possible approaches.

END


GW170817
Planck[17]
SHoES[18]
cos ι
ι (deg)
H_0 (km s^{-1} Mpc^{-1})
−0.4
−0.5
−0.6
−0.7
−0.8
−0.9
−1.0
120
130
140
150
160
170
180
50
60
70
80
90
100
110
120

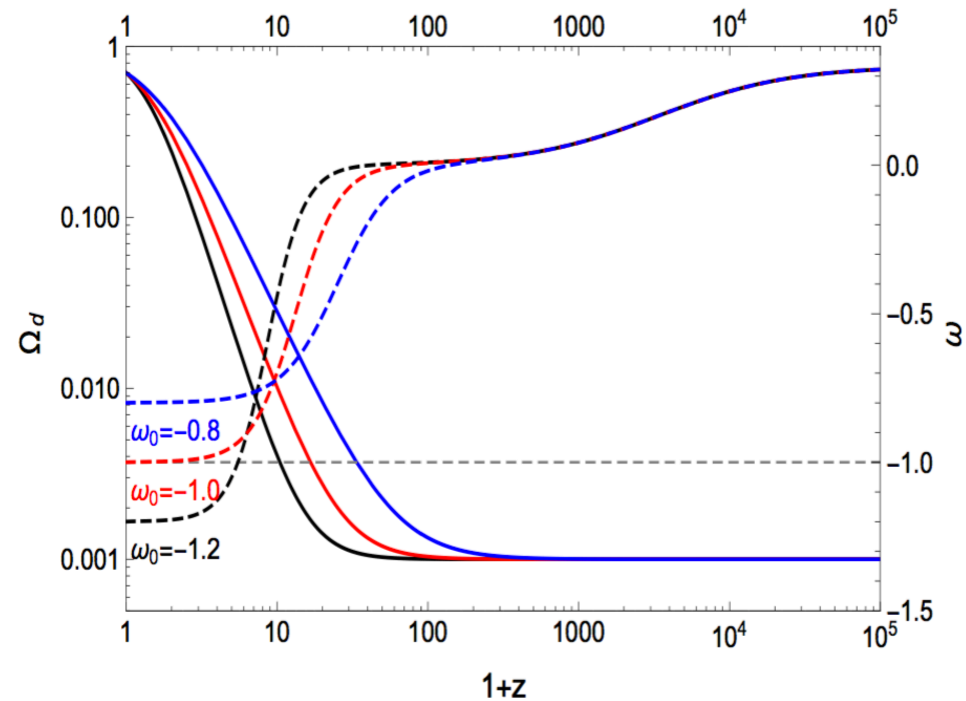
Example: an early dark energy model

Doran,Robers 2006

constant fraction of early dark energy Ωd,e until a transition at recent times.

$$\frac{H^2(a)}{H_0^2} = \frac{\Omega_{\rm m,0}a^{-3} + \Omega_{\rm rel,0}a^{-4}}{1-\Omega_{\rm d}(a)},$$

$$\Omega_{\rm d}(a) = \frac{\Omega_{\rm d,0} - \Omega_{\rm d,e}(1-a^{-3w_0})}{\Omega_{\rm d,0} + \Omega_{\rm m,0}a^{3w_0}} + \Omega_{\rm d,e}(1-a^{-}\quad ,$$

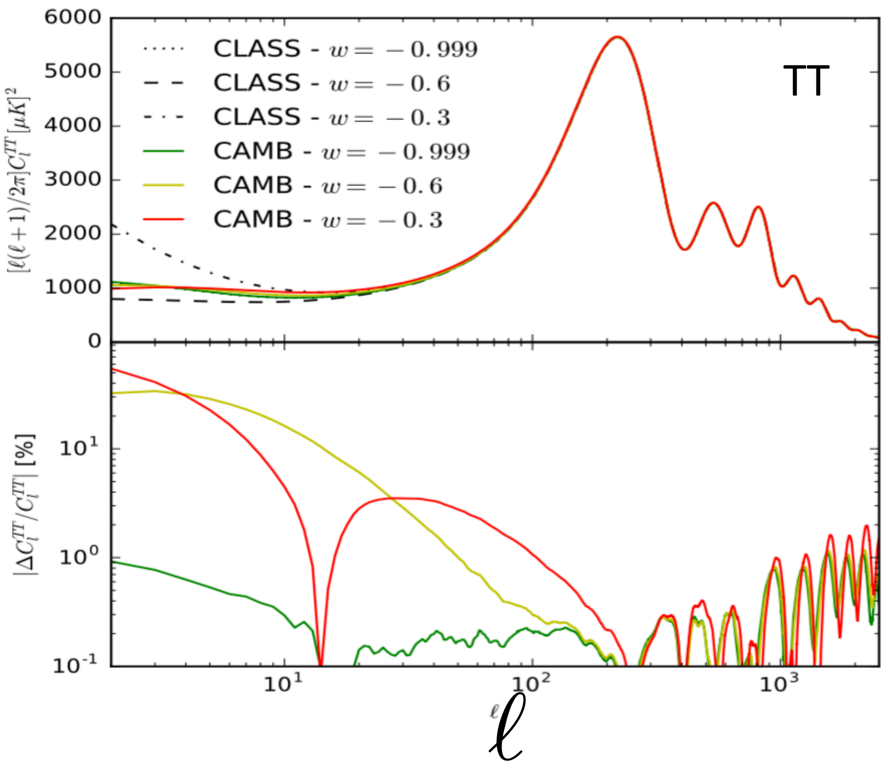


Ωm,0 = 0.3, Ωd,0 ≈ 0.7, Ωd,e = 0.001 and zeq = 3570.

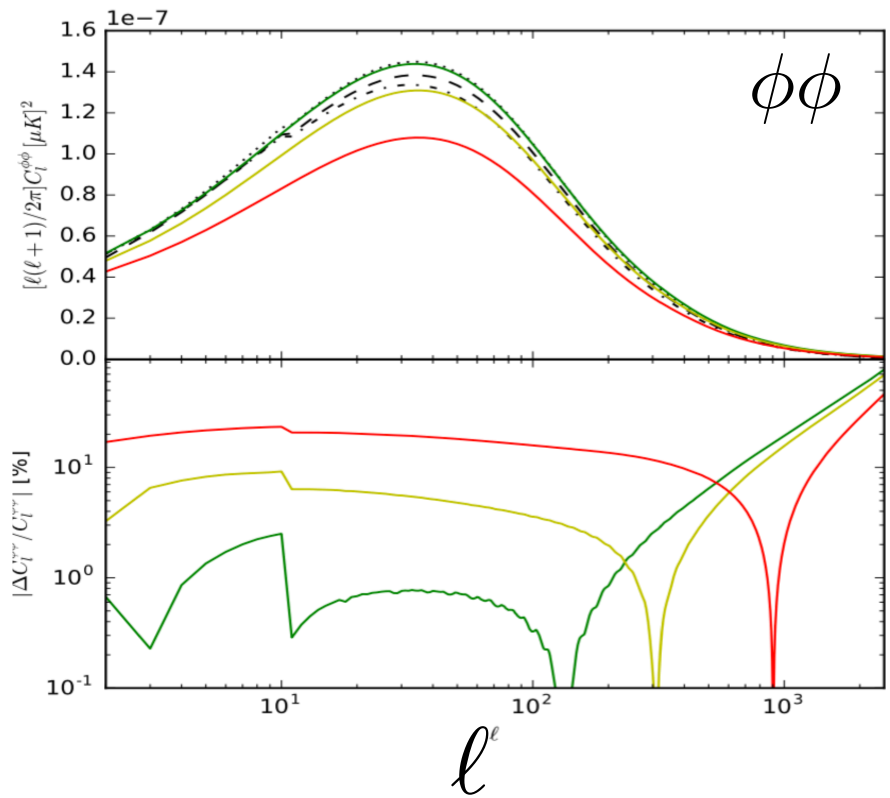
Effect of dark energy perturbations

CAMB (includes perturbations*) CLASS (does not, Background only)

ISW

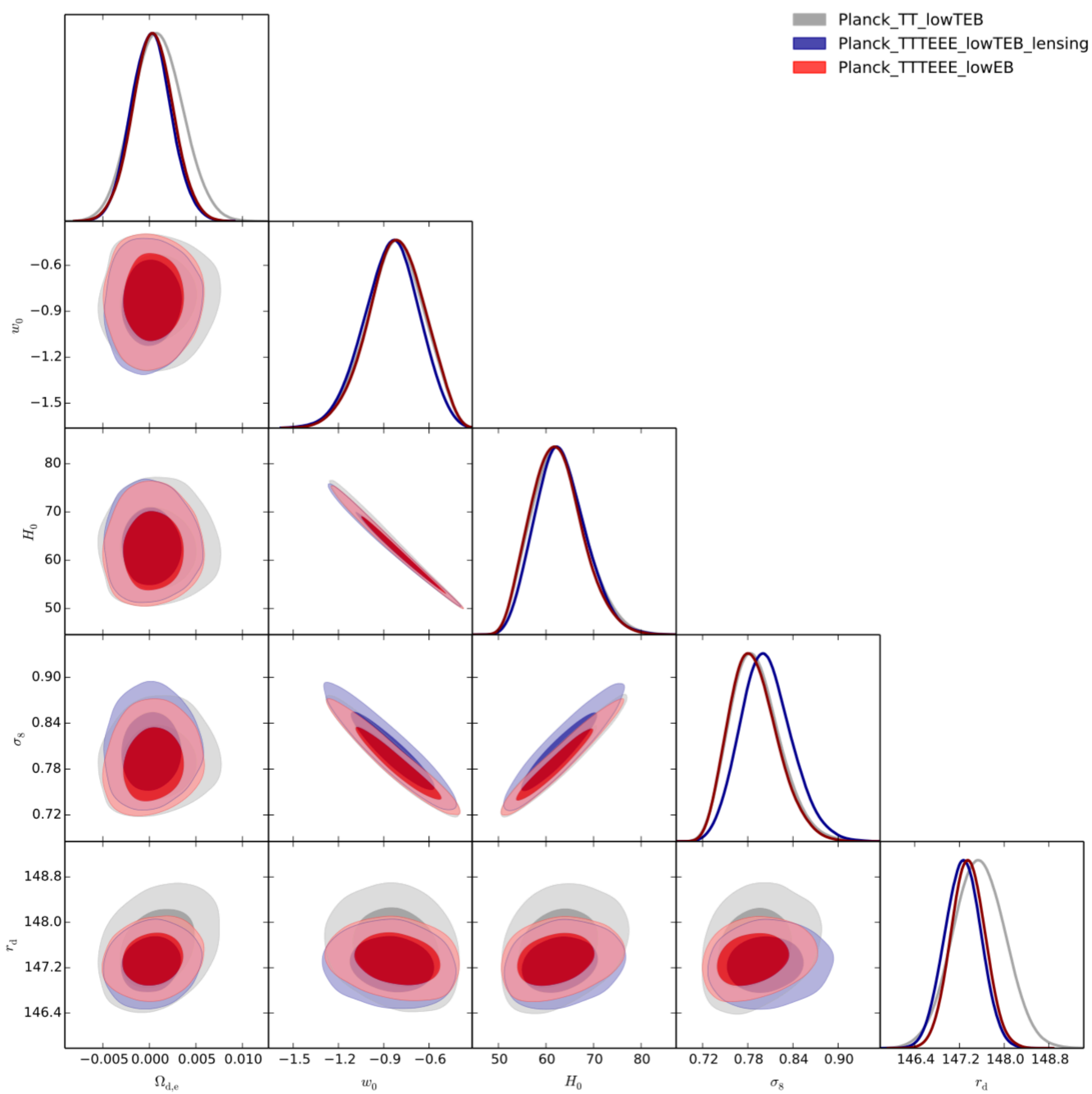


LENSING

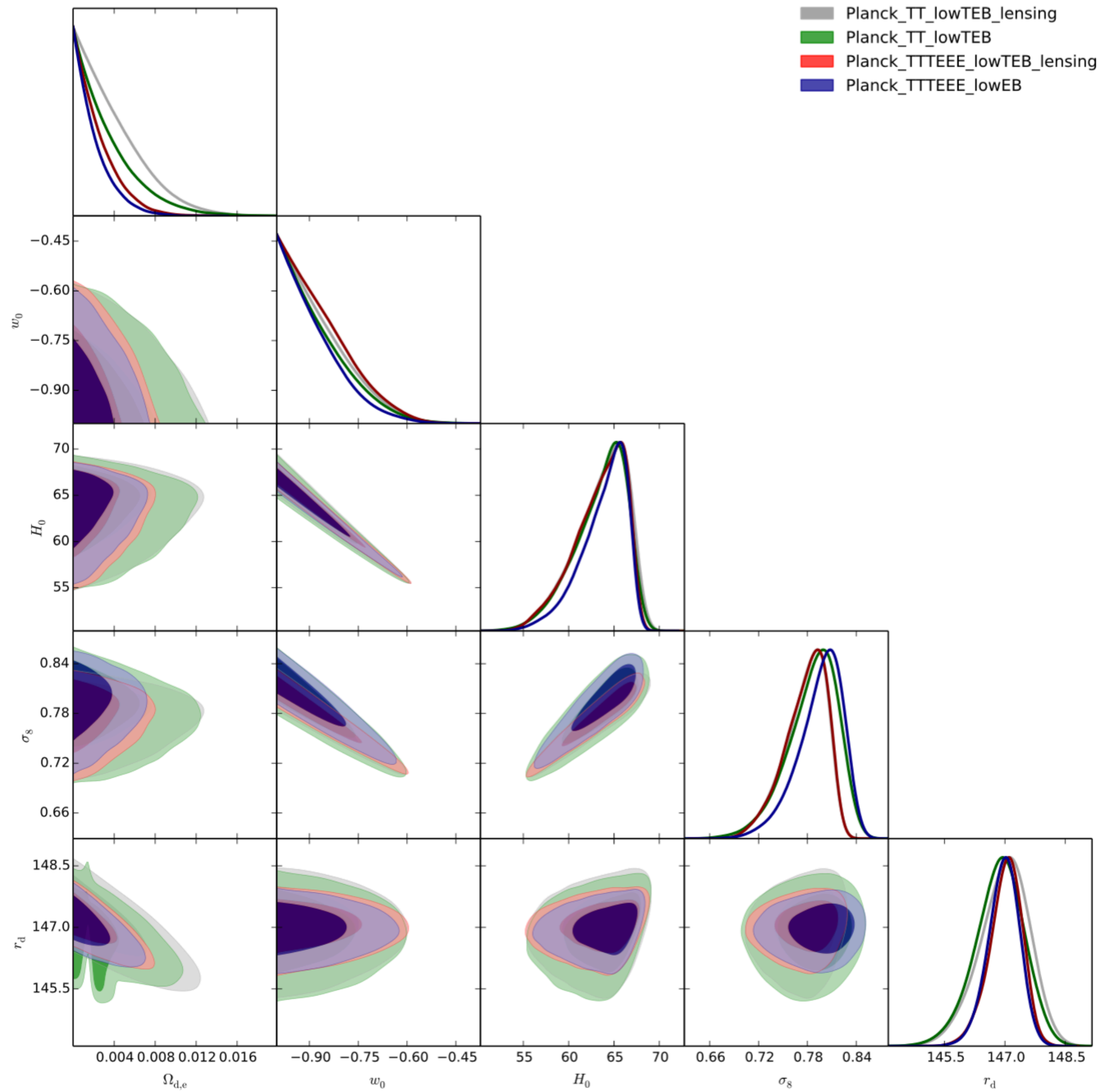


*sound speed c2s = 1 and no anisotropic stress.

Effect on cosmological parameters



Effect on cosmological parameters

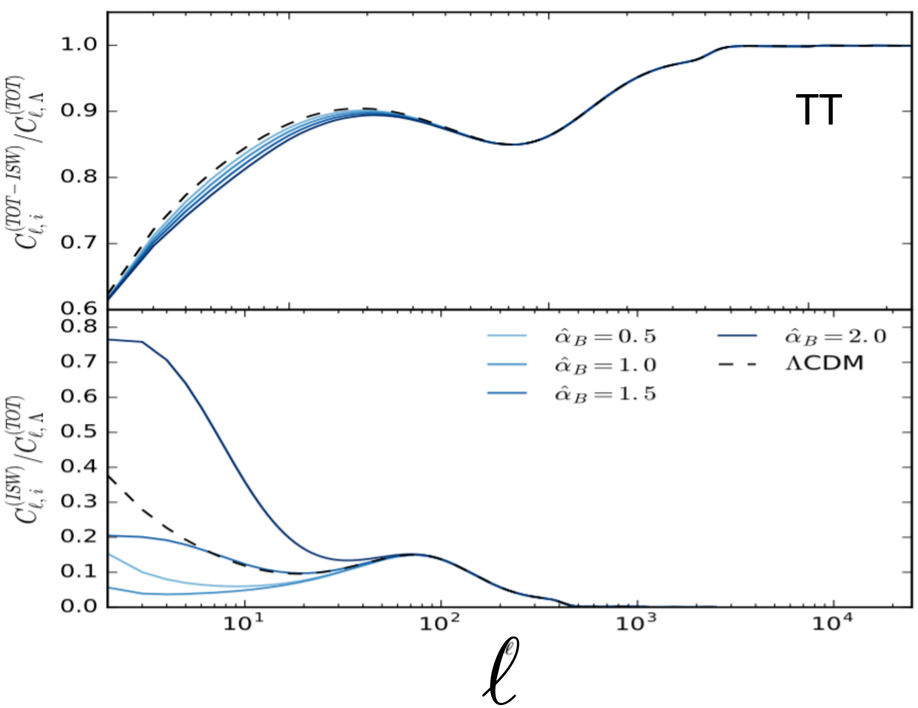


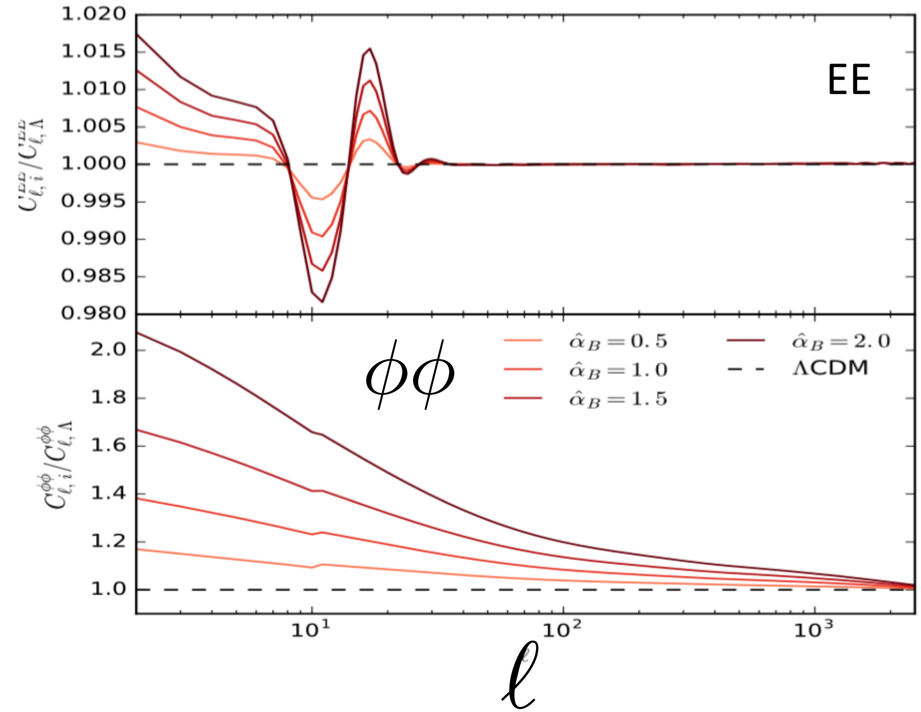
Effect on cosmological parameters

Parameter	TT	TT_lens	TTTEEE	TTTEEE_lens	Code
$10^3\Omega_{\mathrm{d,e}}$	< 9.240	< 9.80	< 5.53	< 6.25	CAMB
	–	$0.9^{+5.4}_{-5.1}$	$0.2^{+4.4}_{-4.2}$	$0.4^{+4.4}_{-4.3}$	CLASS
w_0	< -0.69	< -0.68	< -0.72	< -0.68	CAMB
	–	$-0.82^{+0.36}_{-0.36}$	$-0.85^{+0.34}_{-0.37}$	$-0.82^{+0.36}_{-0.36}$	CLASS
σ_8	$0.786^{+0.057}_{-0.065}$	$0.778^{+0.046}_{-0.055}$	$0.795^{+0.051}_{-0.060}$	$0.778^{+0.046}_{-0.055}$	CAMB
	–	$0.790^{+0.067}_{-0.063}$	$0.805^{+0.069}_{-0.067}$	$0.788^{+0.065}_{-0.060}$	CLASS
r_d [Mpc]	$146.9^{+1.2}_{-1.0}$	$147.0^{+1.2}_{-1.3}$	$146.96^{+0.73}_{-0.84}$	$147.01^{+0.80}_{-0.88}$	CAMB
	–	$147.55^{+0.93}_{-0.92}$	$147.26^{+0.63}_{-0.64}$	$147.36^{+0.60}_{-0.59}$	CLASS
H_0 [km s^{-1} Mpc^{-1}]	$63.5^{+4.9}_{-6.1}$	$63.6^{+5.0}_{-6.2}$	$63.7^{+4.3}_{-5.6}$	$63.4^{+4.8}_{-6.0}$	CAMB
	–	$62.8^{+11.1}_{-10.8}$	$63.1^{+10.6}_{-10.3}$	$62.3^{+10.7}_{-10.4}$	CLASS

Separating late-early effects…

ISW



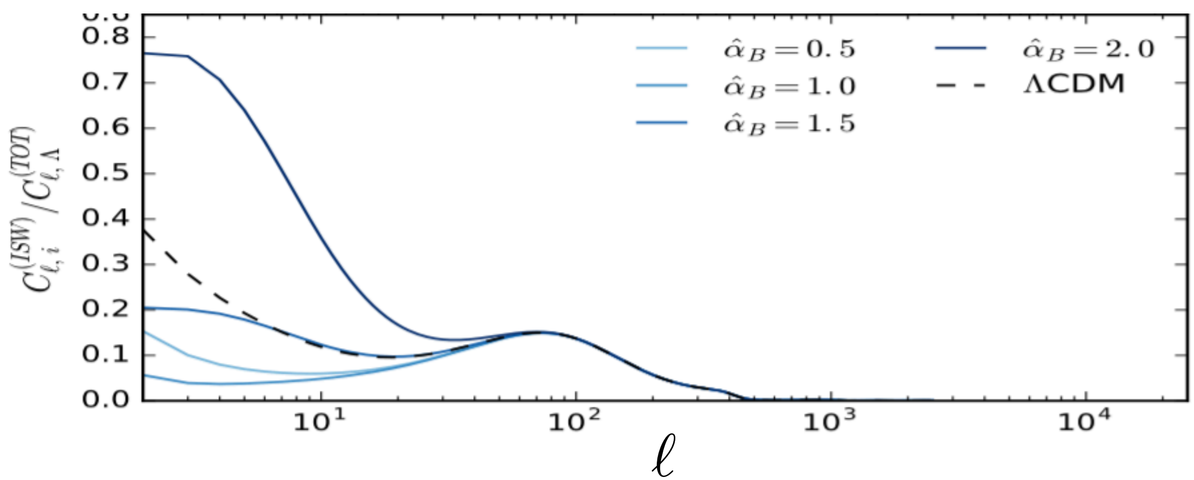


LENSING

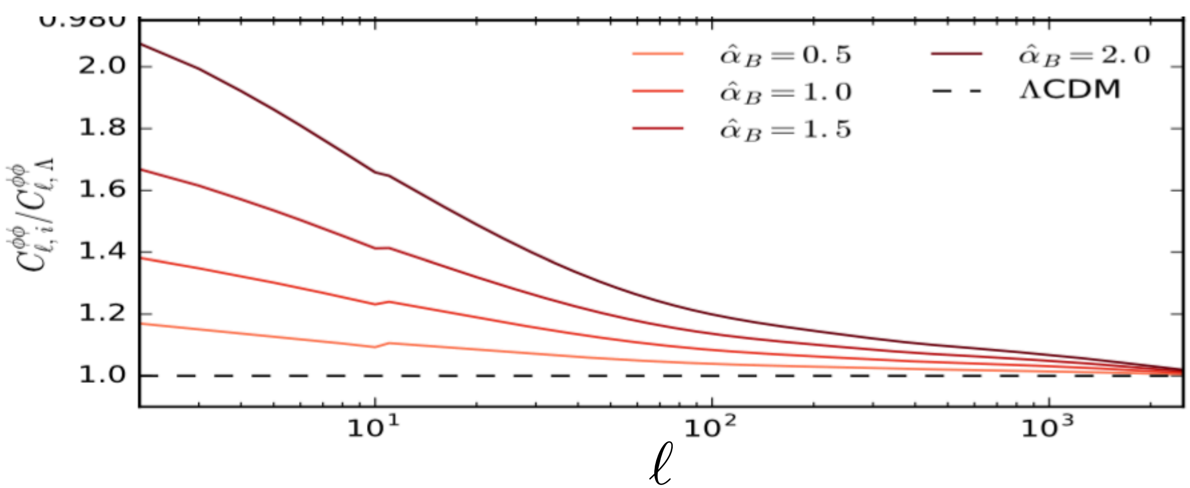
Hi-class: Zumalacrregui et al 2016; Bellini, Sawicki 2014

Separating early-late effects

Follow: Vonlanthen et al 2010, and Audren et al 2013



Ignore ℓ< 30

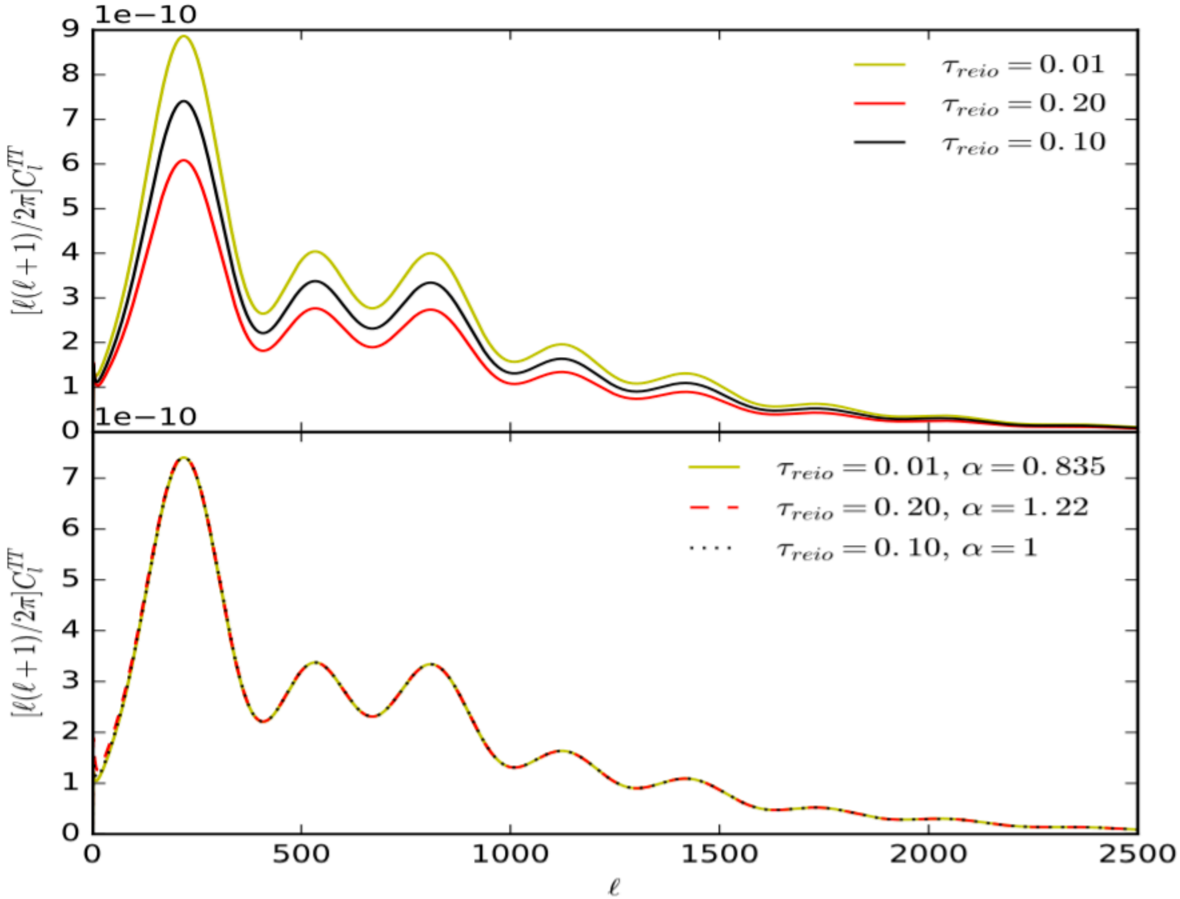


Rescale Newtonian potential and marginalize

$$\phi(k,z) \longrightarrow A_{lp}\left(\frac{k}{k_{lp}}\right)^{n_{lp}} \phi(k,z)$$

Separating early-late effects

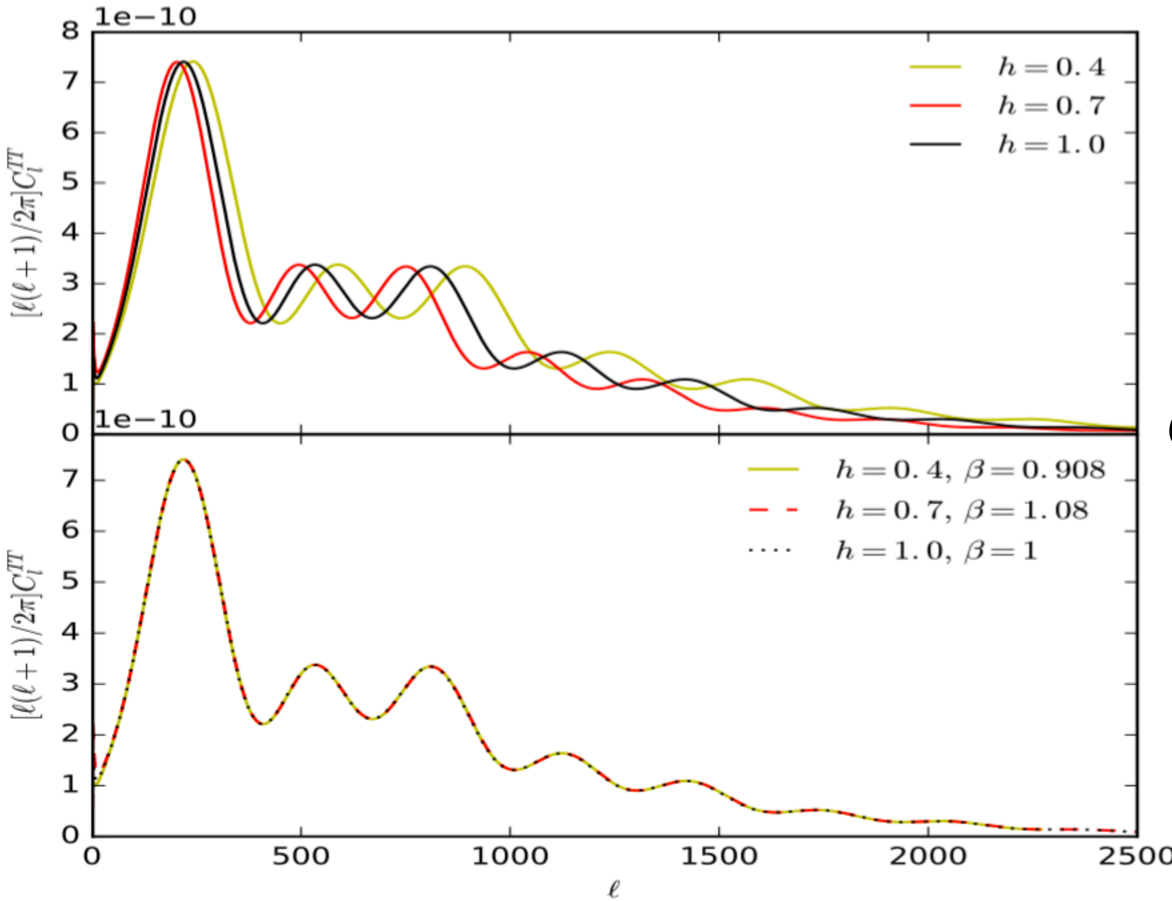
REIONIZATION



Renormalization at high ell (→As)

Separating early-late effects

Distance to last scattering or geometry or expansion history…



$$C_\ell \longrightarrow C_{\beta\ell}$$

And now we go wild…

Several models:

- LCDM
- DE fld : Lambda replaced by standard perfect fluid, $c_s^2=1$, $w<0$, constant
- k: allow curvature
- nu: a LCDM with non standard neutrinos that have free c_s^2 c_{vis}^2
- matteriation: there is a (dark) fluid with $0<w<1/3$

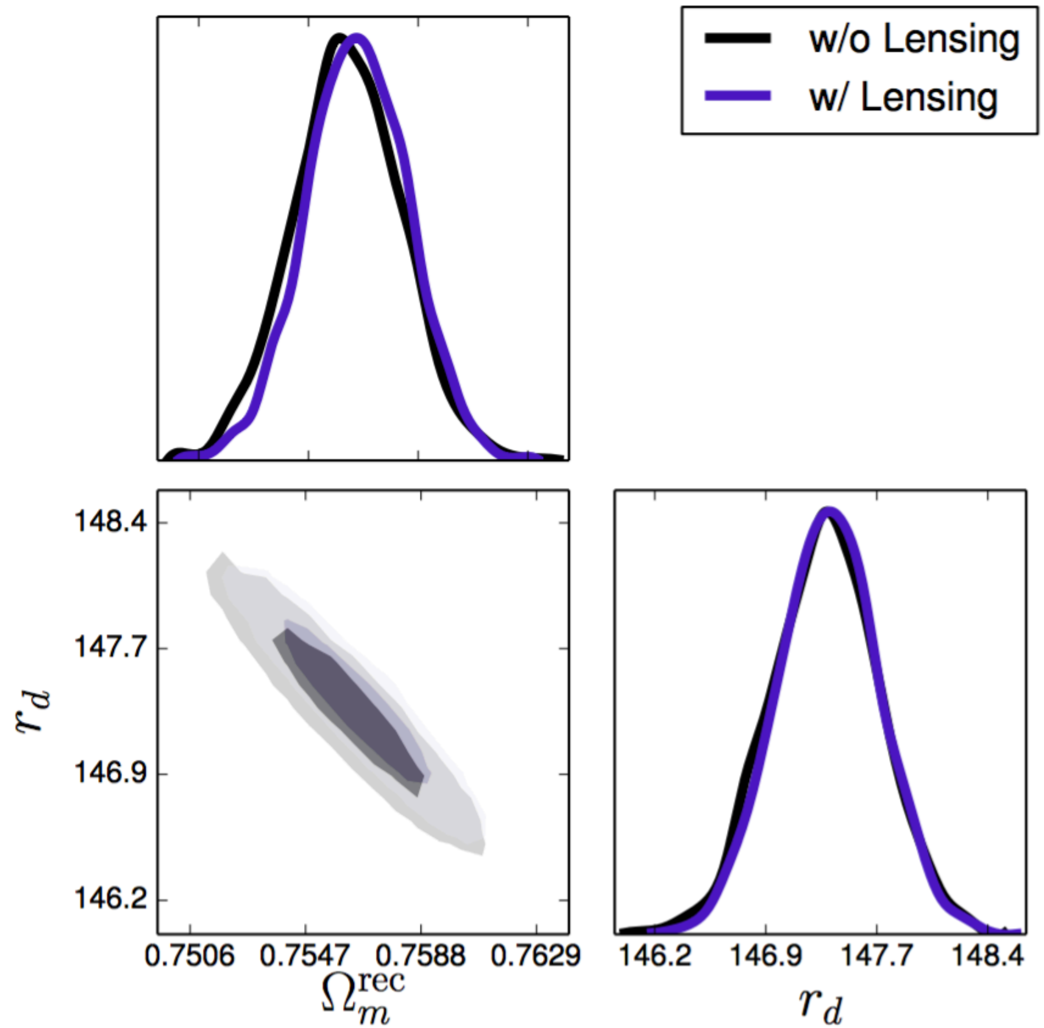
Warning: for values of $\Omega_{\Lambda,0} > 0.8$ The ISW removal procedure is not sufficent

We should cut more low multiploes but constraints degrade rapidly ….

But relevant parameters do not show degeneracy with $\Omega_{\Lambda,0}$

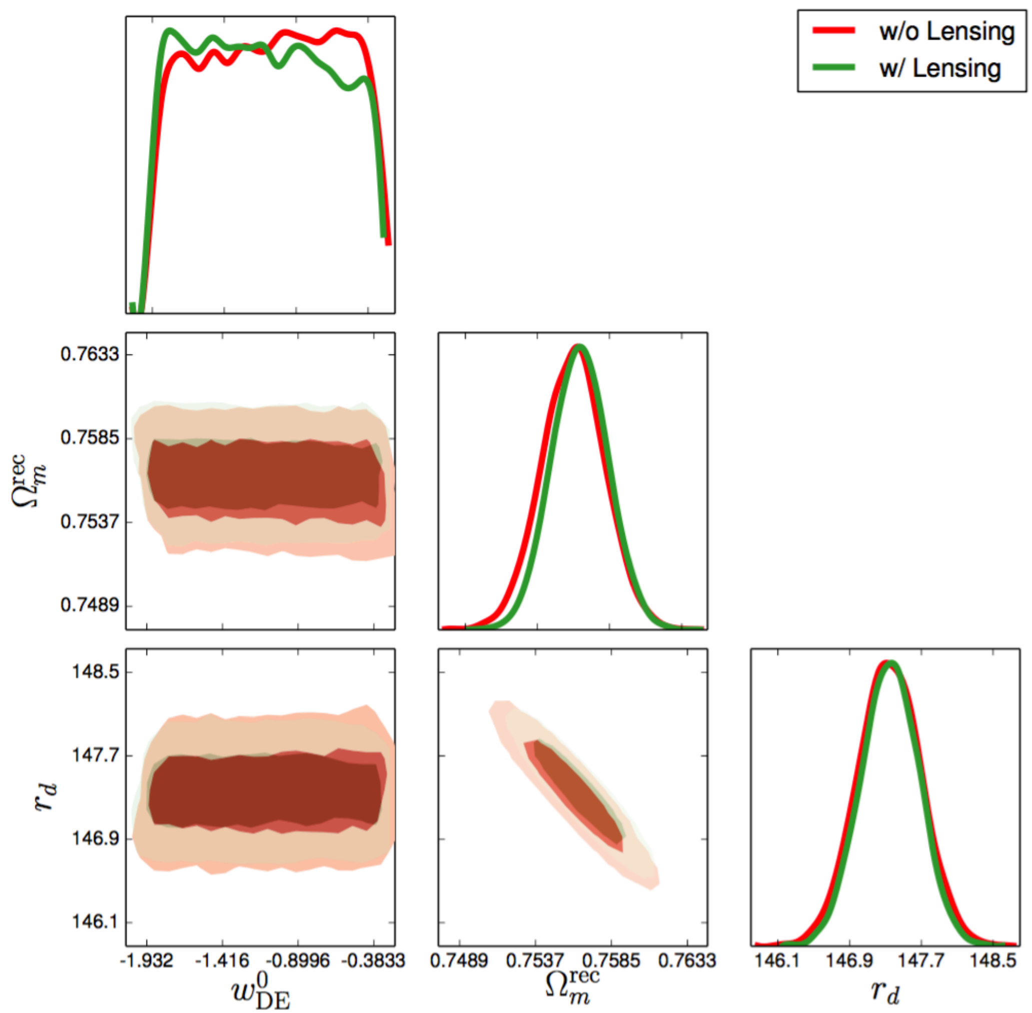
So constraints are not affected

Results: LCDM

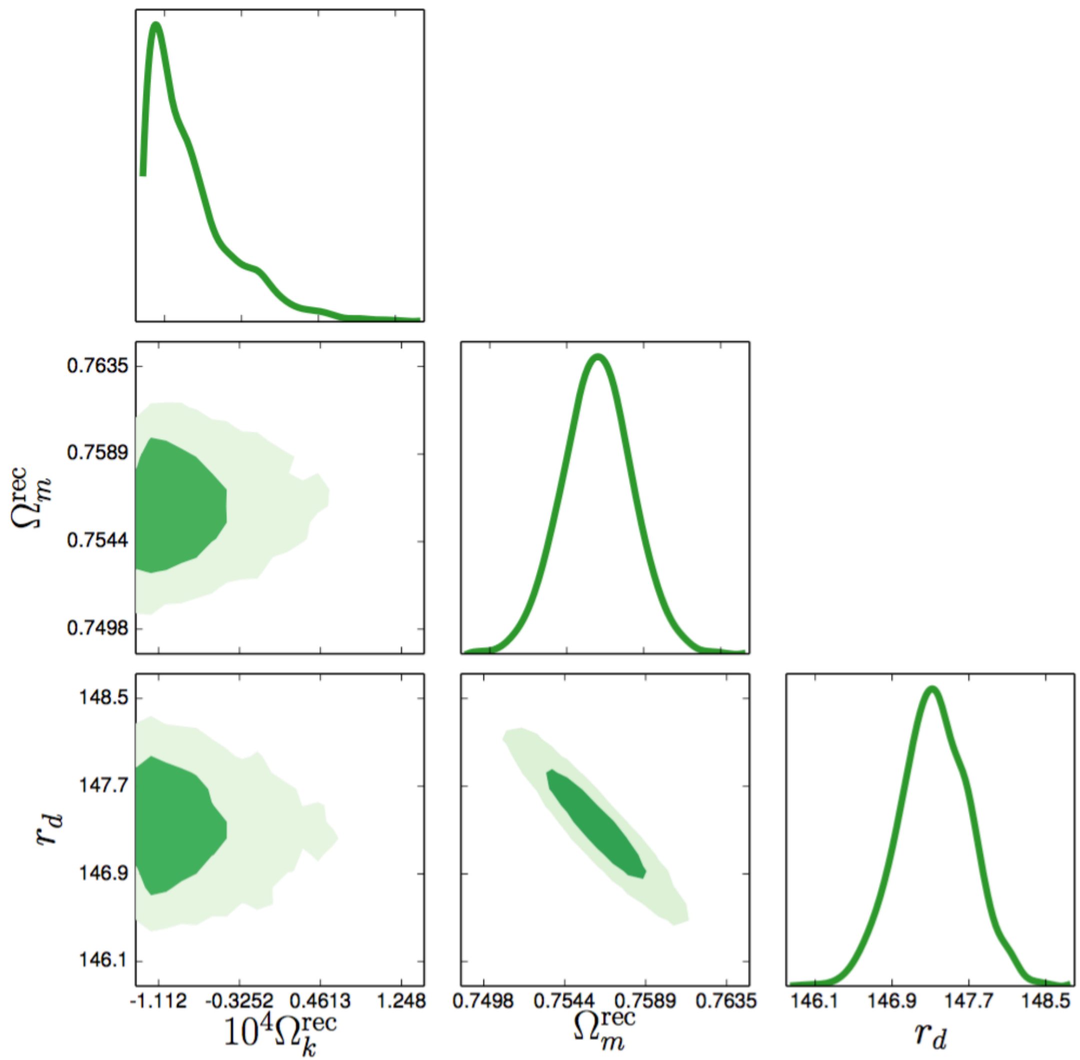


Results: DEfld

DE fld : Lambda replaced by standard perfect fluid, c_s^2=1, w<0, constant



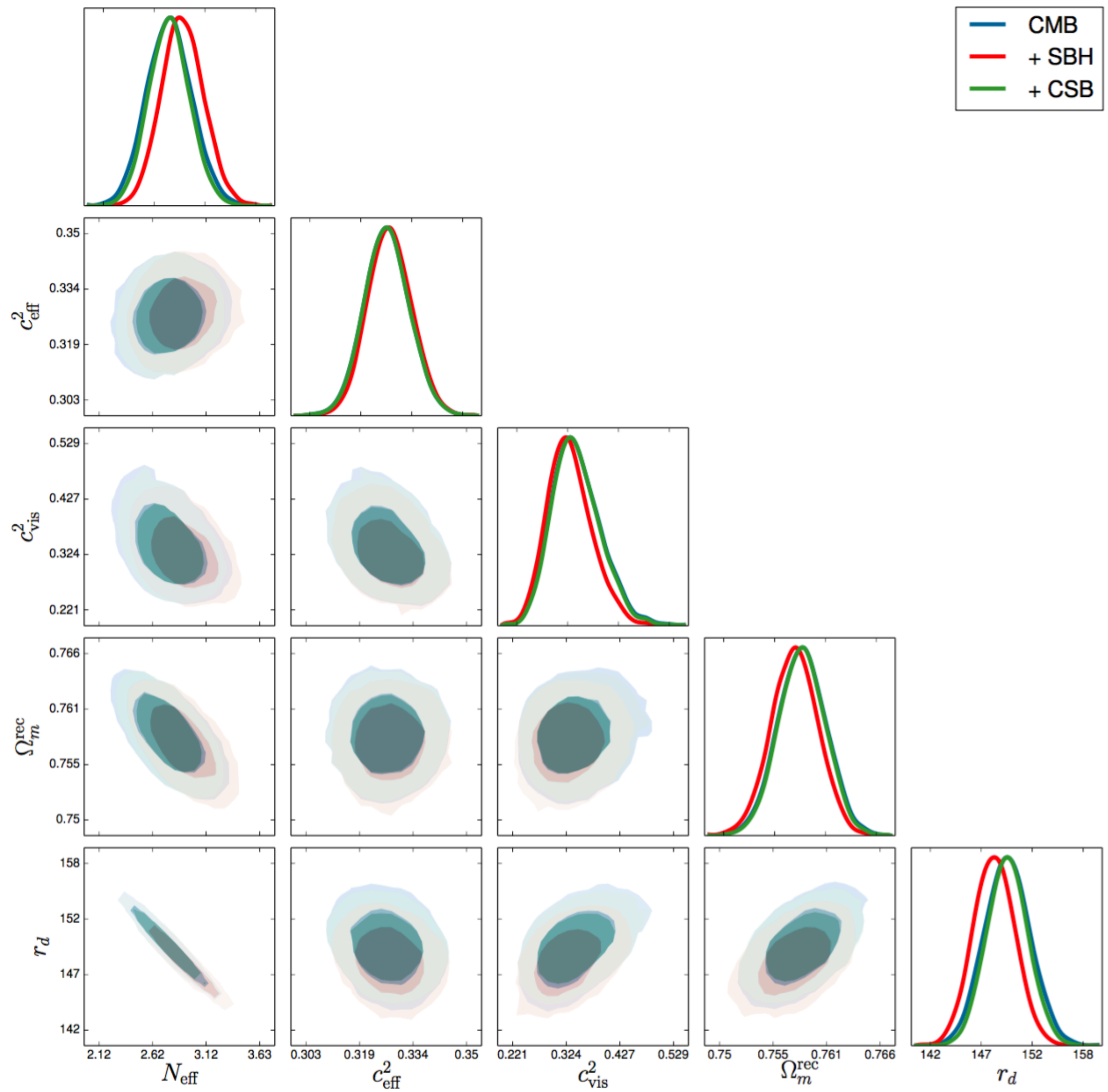
Results: k



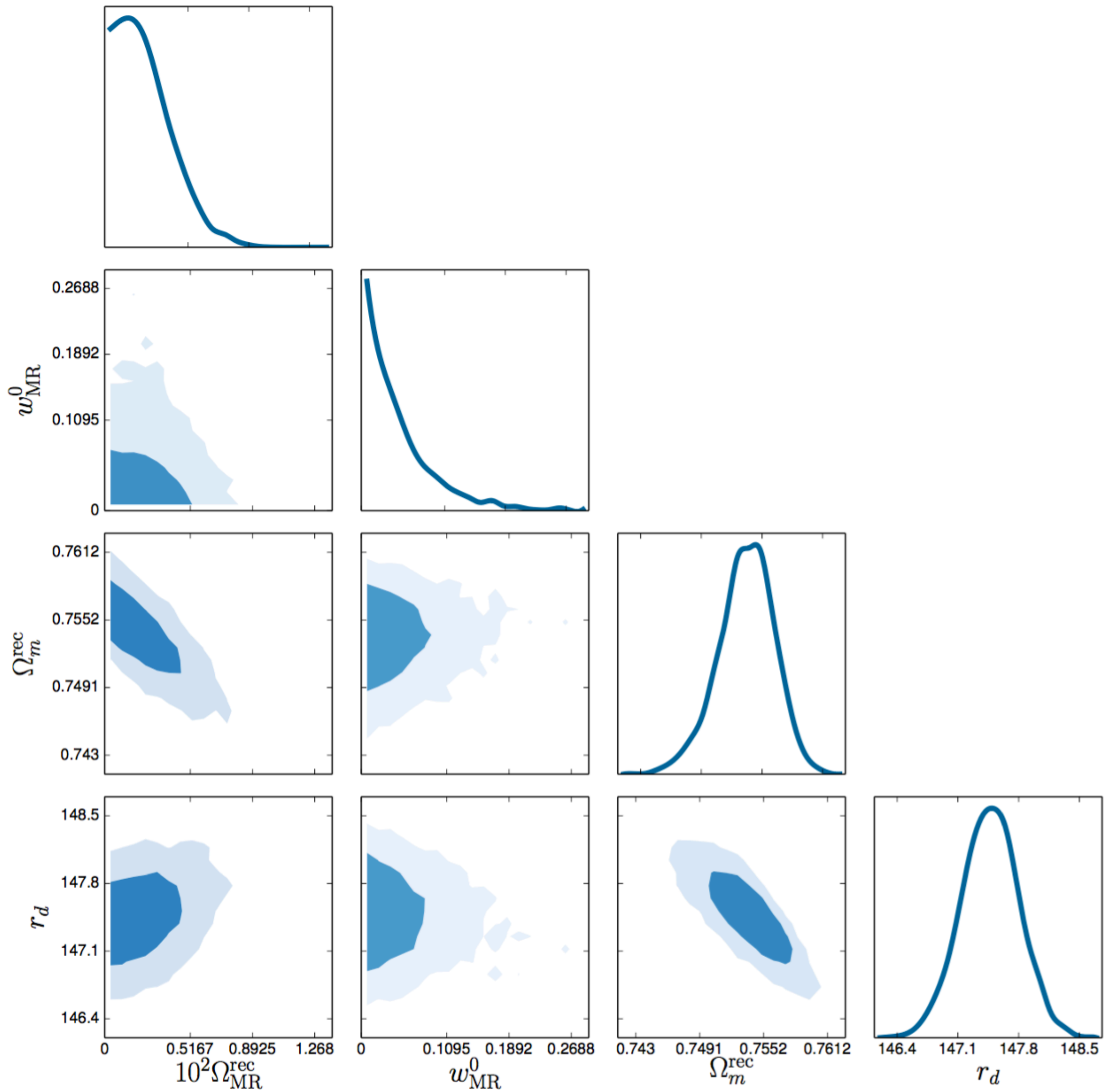
0.7635
0.7589
0.7544
0.7498
$\Omega_m^{\rm rec}$
148.5
147.7
146.9
146.1
r_d
-1.112
-0.3252
0.4613
1.248
$10^4\Omega_k^{\rm rec}$
0.7498
0.7544
0.7589
0.7635
$\Omega_m^{\rm rec}$
146.1
146.9
147.7
148.5
r_d

Results: nu

nu: a LCDM with non standard neutrinos that have free c_s^2 c_{vis}^2



Results: matteriation



Results: summary

	LCDM	DE fld	k	nu	matteriation
$10\Omega_b^{rec}$	$1.187^{+0.034}_{-0.034}$	$1.186^{+0.034}_{-0.034}$	$1.188^{+0.036}_{-0.034}$	$1.205^{+0.047}_{-0.047}$	$1.185^{+0.035}_{-0.033}$
$10\Omega_{cdm}^{rec}$	$6.378^{+0.071}_{-0.070}$	$6.379^{+0.071}_{-0.070}$	$6.376^{+0.071}_{-0.075}$	$6.378^{+0.071}_{-0.072}$	$6.351^{+0.082}_{-0.085}$
H_{rec} [Mpc^{-1}]	$5.197^{+0.045}_{-0.045}$	$5.198^{+0.046}_{-0.045}$	$5.196^{+0.046}_{-0.047}$	$5.12^{+0.14}_{-0.14}$	$5.193^{+0.046}_{-0.048}$
n_s	$0.964^{+0.010}_{-0.010}$	$0.964^{+0.010}_{-0.010}$	$0.964^{+0.011}_{-0.011}$	$0.956^{+0.023}_{-0.023}$	$0.966^{+0.011}_{-0.011}$
$e^{-2\tau} A_s$	$1.879^{+0.024}_{-0.025}$	$1.879^{+0.026}_{-0.026}$	$1.876^{+0.025}_{-0.026}$	$1.871^{+0.072}_{-0.070}$	$1.875^{+0.026}_{-0.026}$
$10^4\Omega_k^{rec}$	-	-	$0.27^{+1.17}_{-1.24}$	-	-
$10^3\Omega_{fld}^{rec}$	-	$0.039^{+0.197}_{-0.039}$	-	-	$2.50^{+3.40}_{-2.50}$
w_{fld}^0	-	$-1.15^{+0.44}_{-0.73}$	-	-	$0.05^{+0.10}_{-0.05}$
N_{eff}	-	-	-	$2.77^{+0.47}_{-0.46}$	-
c_{eff}^2	-	-	-	$0.33^{+0.01}_{-0.01}$	-
c_{vis}^2	-	-	-	$0.34^{+0.10}_{-0.10}$	-
z_{rec}	$1089.0^{+0.5}_{-0.5}$	$1089.0^{+0.5}_{-0.5}$	$1089.0^{+0.5}_{-0.6}$	$1088.7^{+0.6}_{-0.6}$	$1089.0^{+0.5}_{-0.5}$
r_d^s	$147.35^{+0.66}_{-0.66}$	$147.34^{+0.66}_{-0.66}$	$147.37^{+0.68}_{-0.69}$	$150.0^{+4.8}_{-4.7}$	$147.47^{+0.69}_{-0.71}$
χ^2_{min}	2456	2454	2456	2454	2455

1%

Bounds are 95%