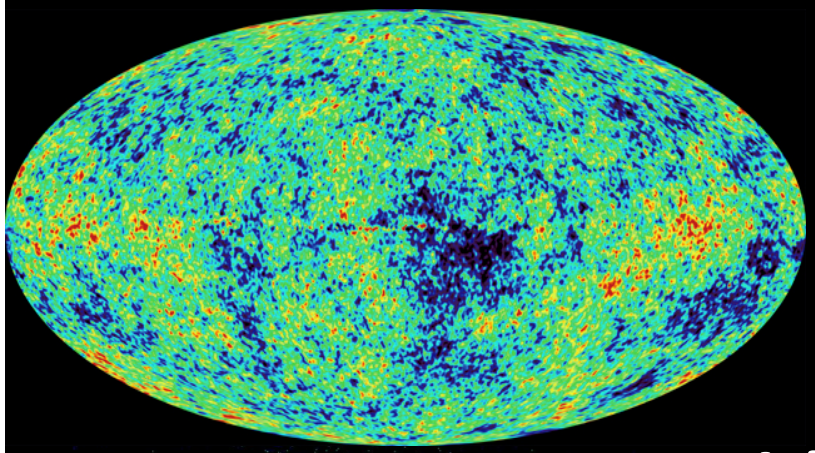
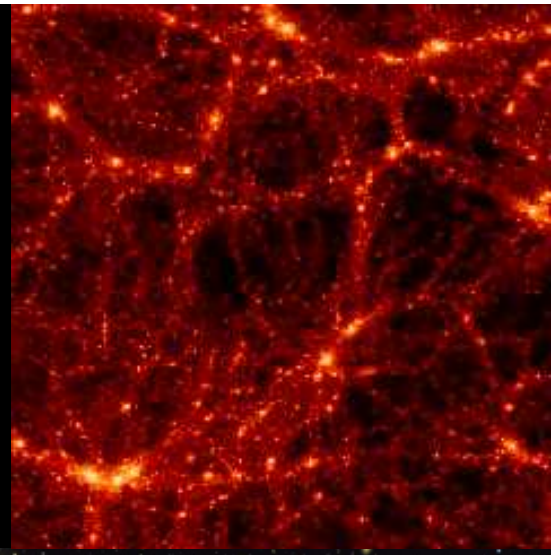
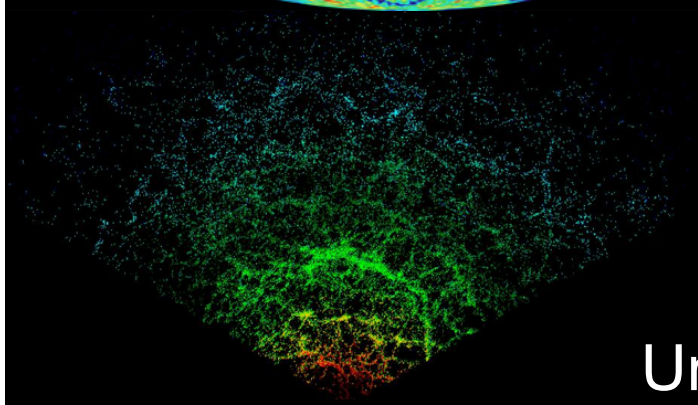
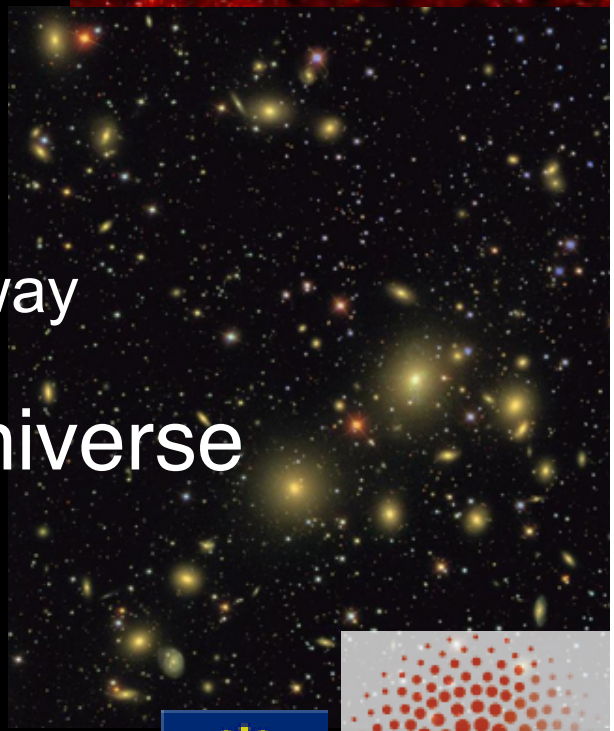
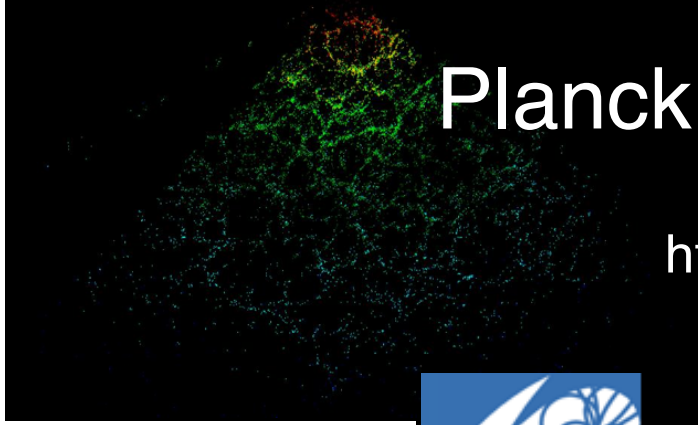










Licia Verde

ICREA & ICC-UB
Barcelona
University of Oslo, Norway

Planck and the local Universe

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

icrea Institució Catalana de Recerca i Estudis Avançats

ICCUB Institut de Ciències del Cosmos

UNIVERSITAT DE BARCELONA

IEEC

erc

Based on

The importance of local measurements for cosmology

Licia Verde[a,b], Raul Jimenez[a,b], Stephen Feeney[c]

Planck and the local Universe: quantifying the tension

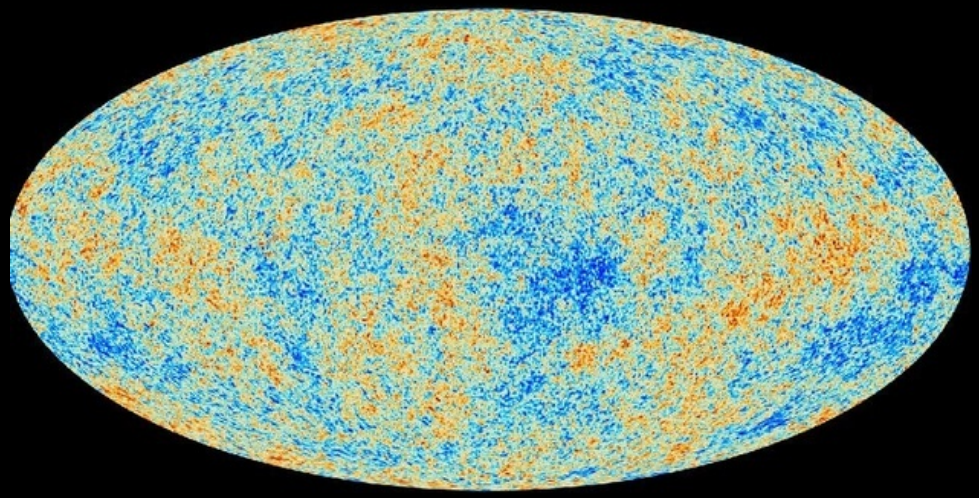
Licia Verde[a,b], Pavlos Protopapas[c,d], Raul Jimenez[a,b]

PHYSICS OF THE darkuniverse

Both in Physics of the Dark universe

CMB pros and cons

Clean, simple physics, exquisite precision

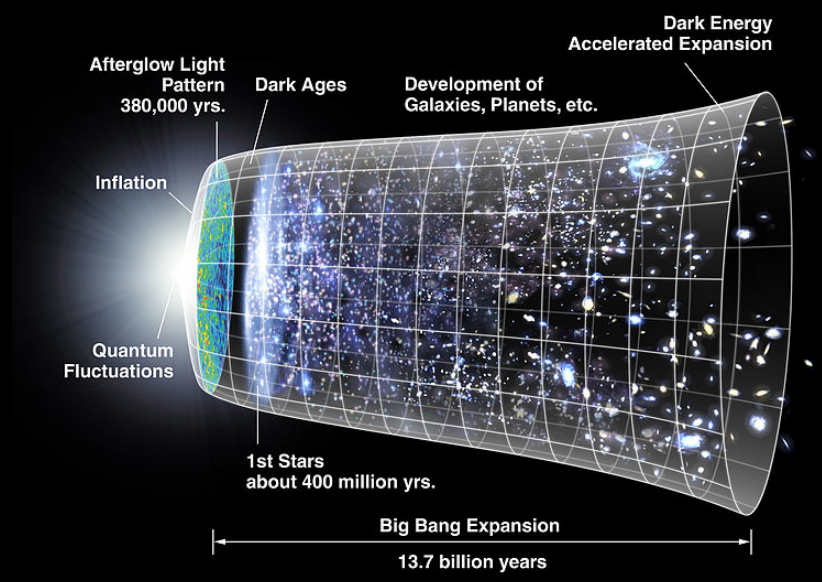


Measures the Universe at z ~ 1000
we want to think in terms of quantities at z=0
Ωm, $\Omega\Lambda$, Ωb, H0 etc.

This is highly model dependent

The importance of local measures

- CMB observations predominantly probe the physics of the early Universe up to a redshift of z ~ 1100



- These observations are then interpreted in terms of cosmological parameters defined at z = 0

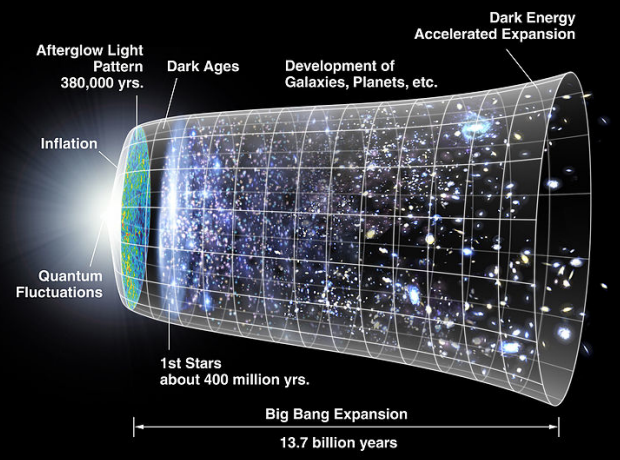
- This extrapolation is model-dependent

- Immense added value in measuring some of these parameters locally, in a way that is independent of the cosmological model.

- Examples H_0, age (t_0)

Local measurements

Less clean, (g)astrophysics, only few measurements



BUT cosmology-independent

- Immense added value in measuring some of these parameters locally, in a way that is independent of the cosmological model.

This is useful both for constraining parameters but also for asking:

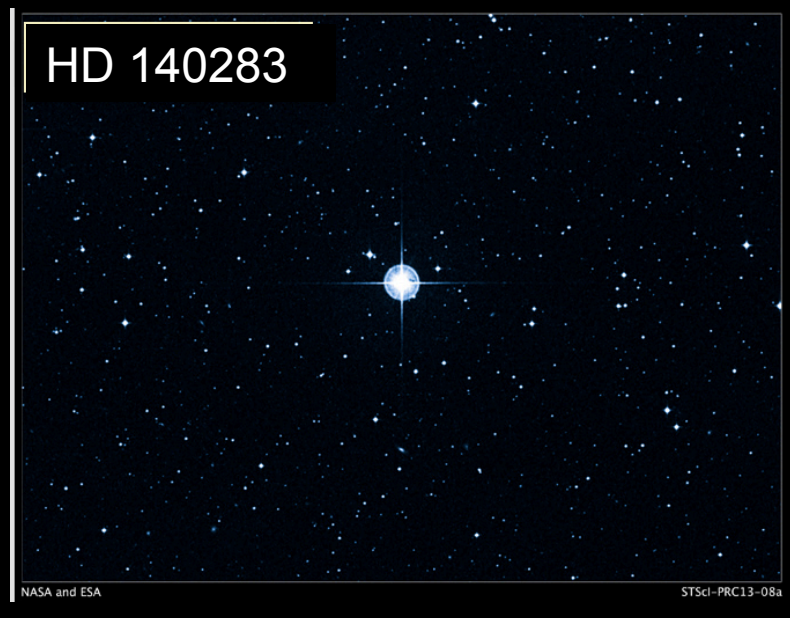
"Is there any indication that the standard (flat ΛCDM) cosmological model is inadequate or incomplete? "

Local data

Riess et al'11: H_0=73.8 ± 2.4 Km/s/Mpc Systematic+ statistical

Freedman et al '12: H_0=74.3 ± 2.1 Km/s/Mpc Systematic-dominated

World-average: H_0=74.08 ± 2.25 Km/s/Mpc

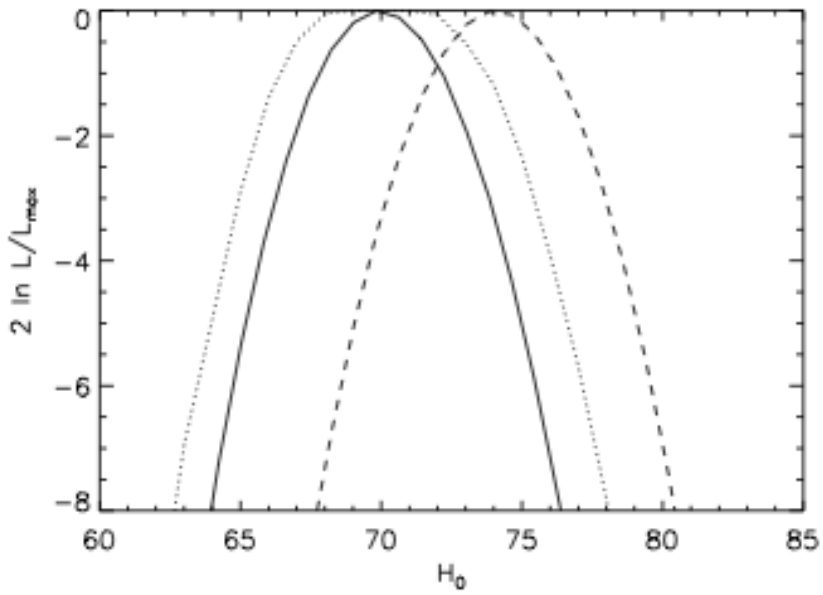


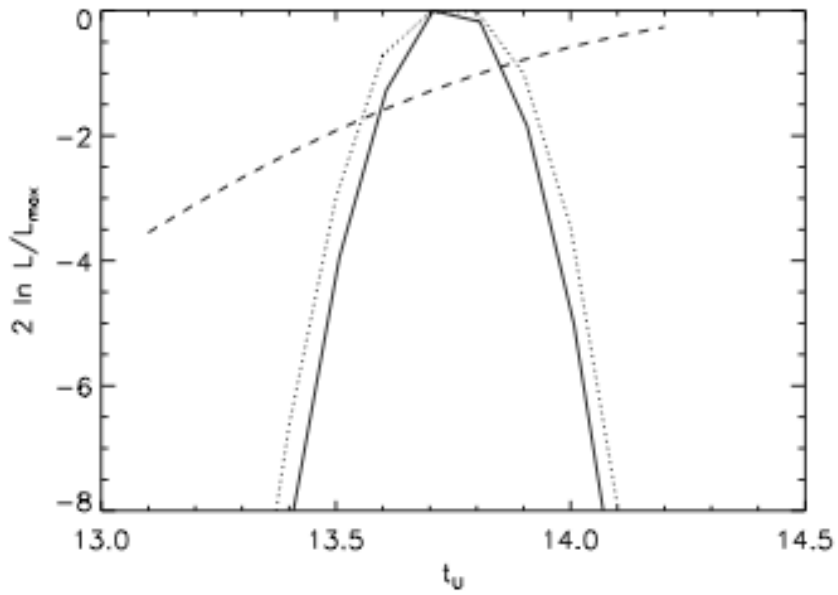
t_0= 14.46 ± 0.8

Systematic+ statistical

Bond et al 2013

WMAP9 ΛCDM

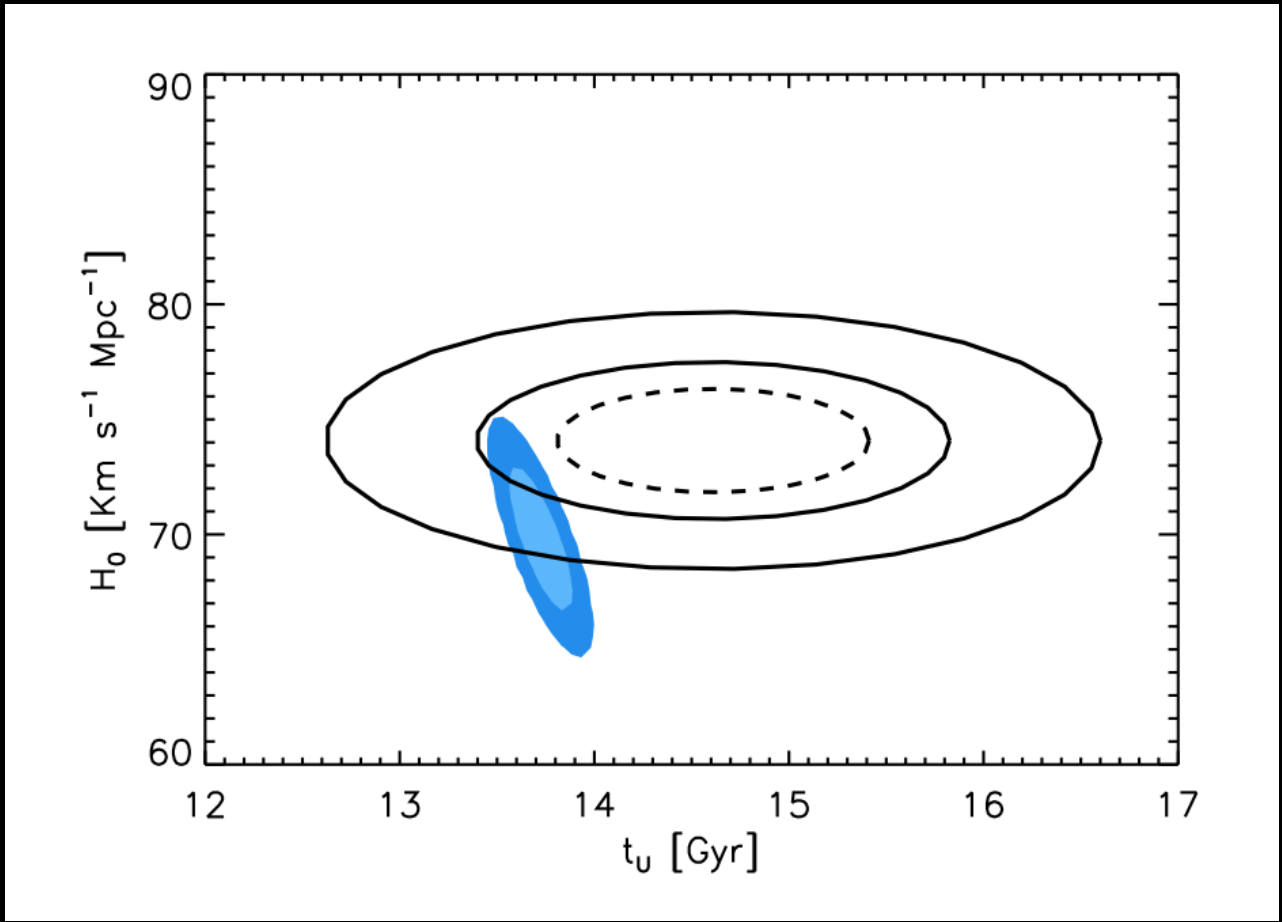




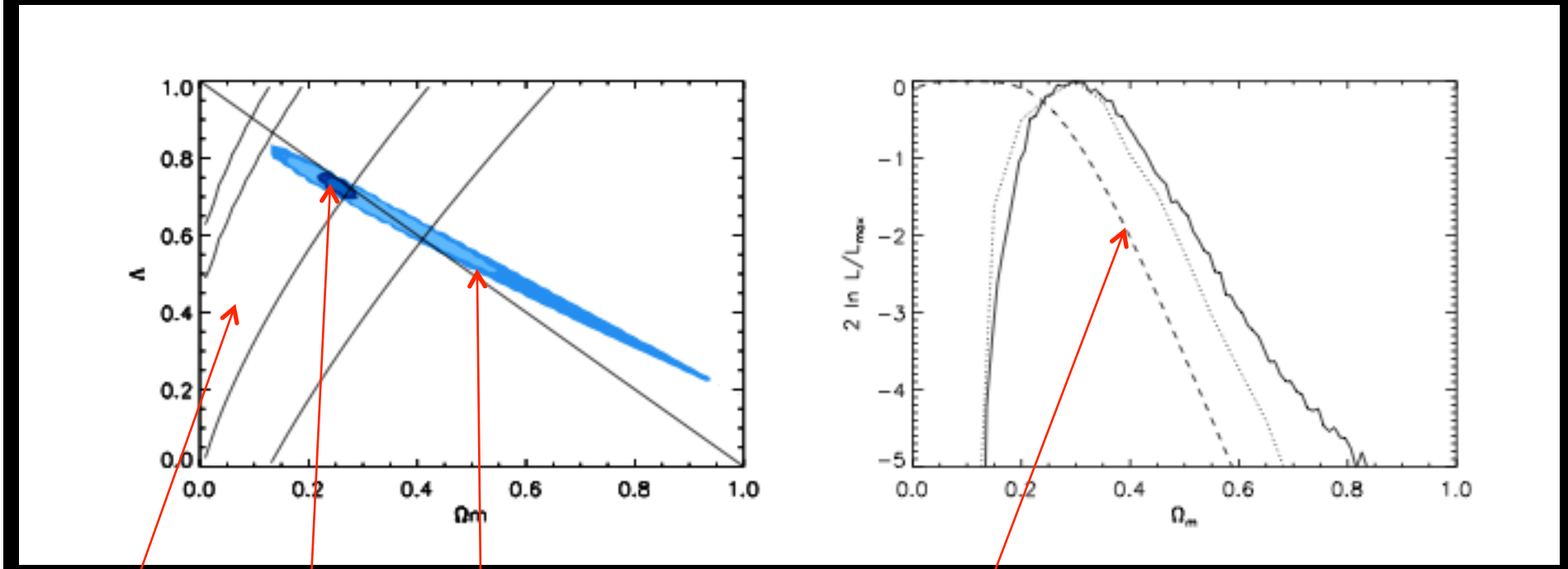
CMB

local

WMAP9 ΛCDM



Local vs CMB:
BROAD AGREEMENT in ΛCDM



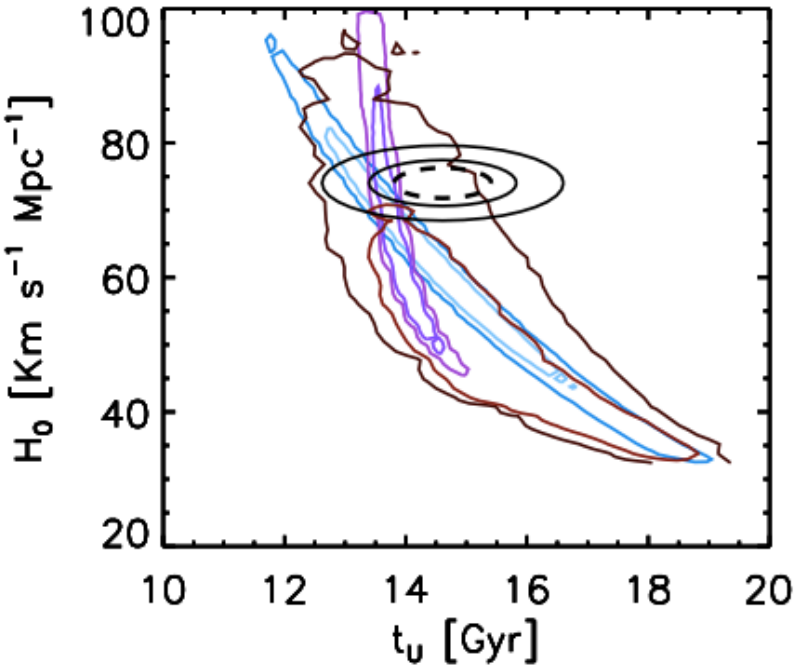
$t_u + H_0$

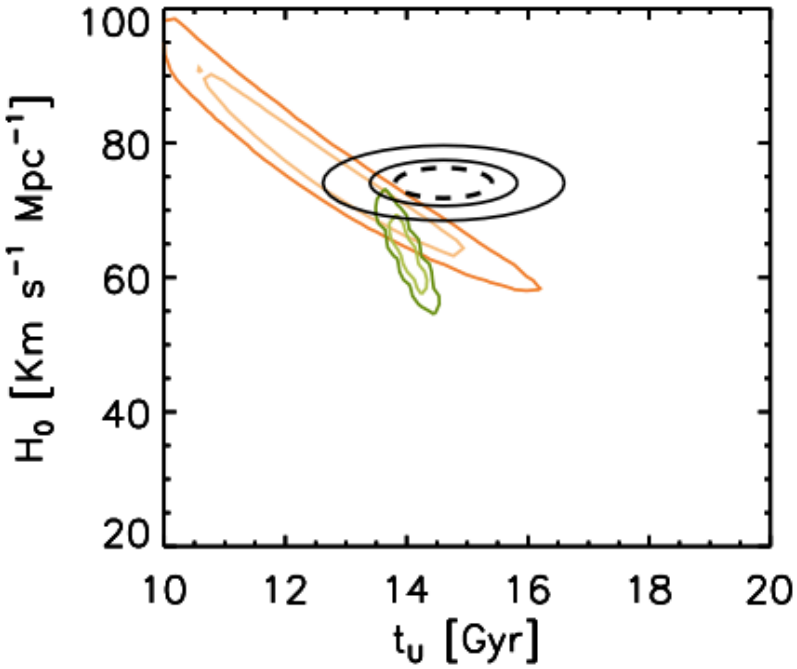
combination

CMB

$t_u + H_0$

WMAP9 ΛCDM extensions





+curvature

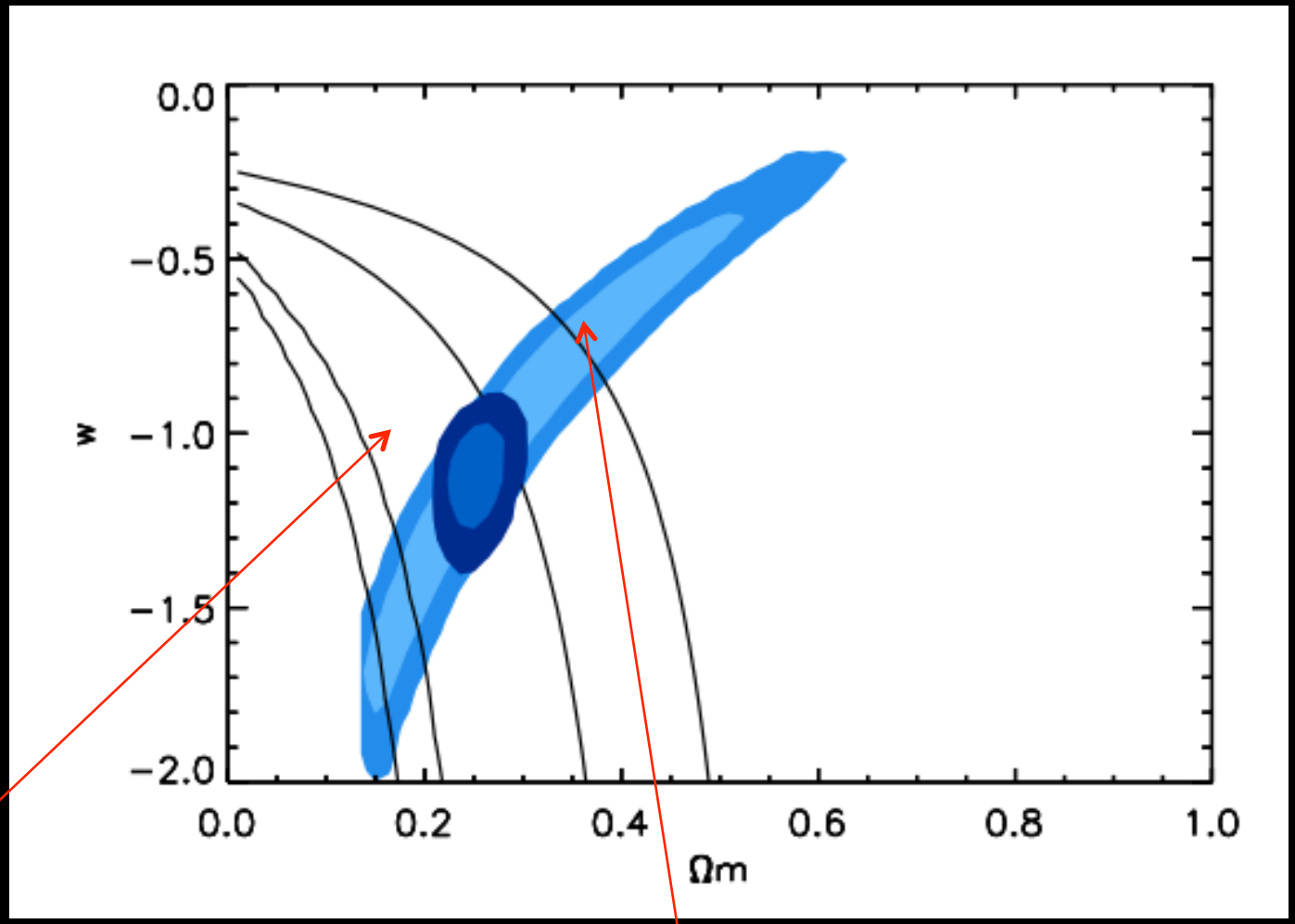
+ w ≠ -1

+ curvature and w ≠ -1

$+m_\nu$

$+N_{eff}$

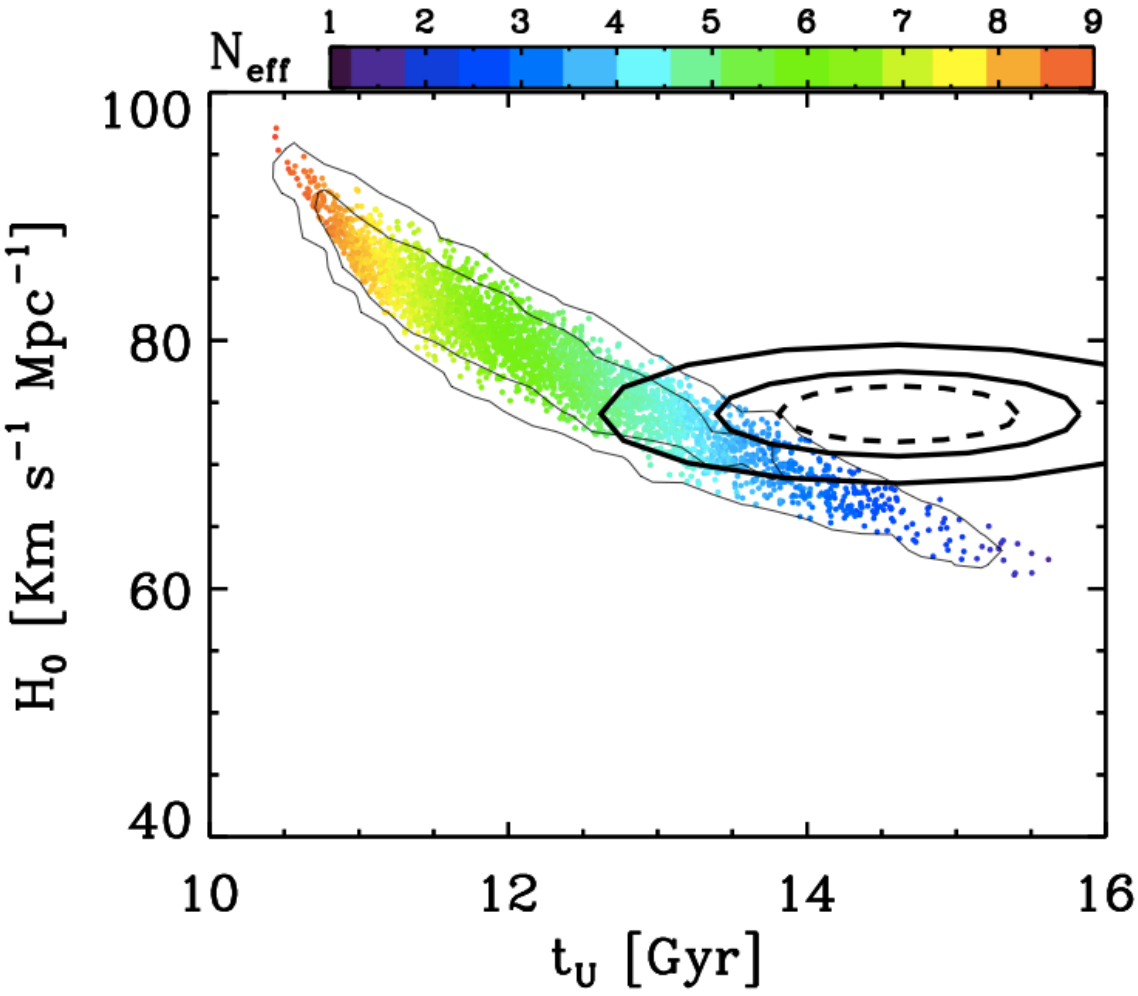
Dark energy w parameter



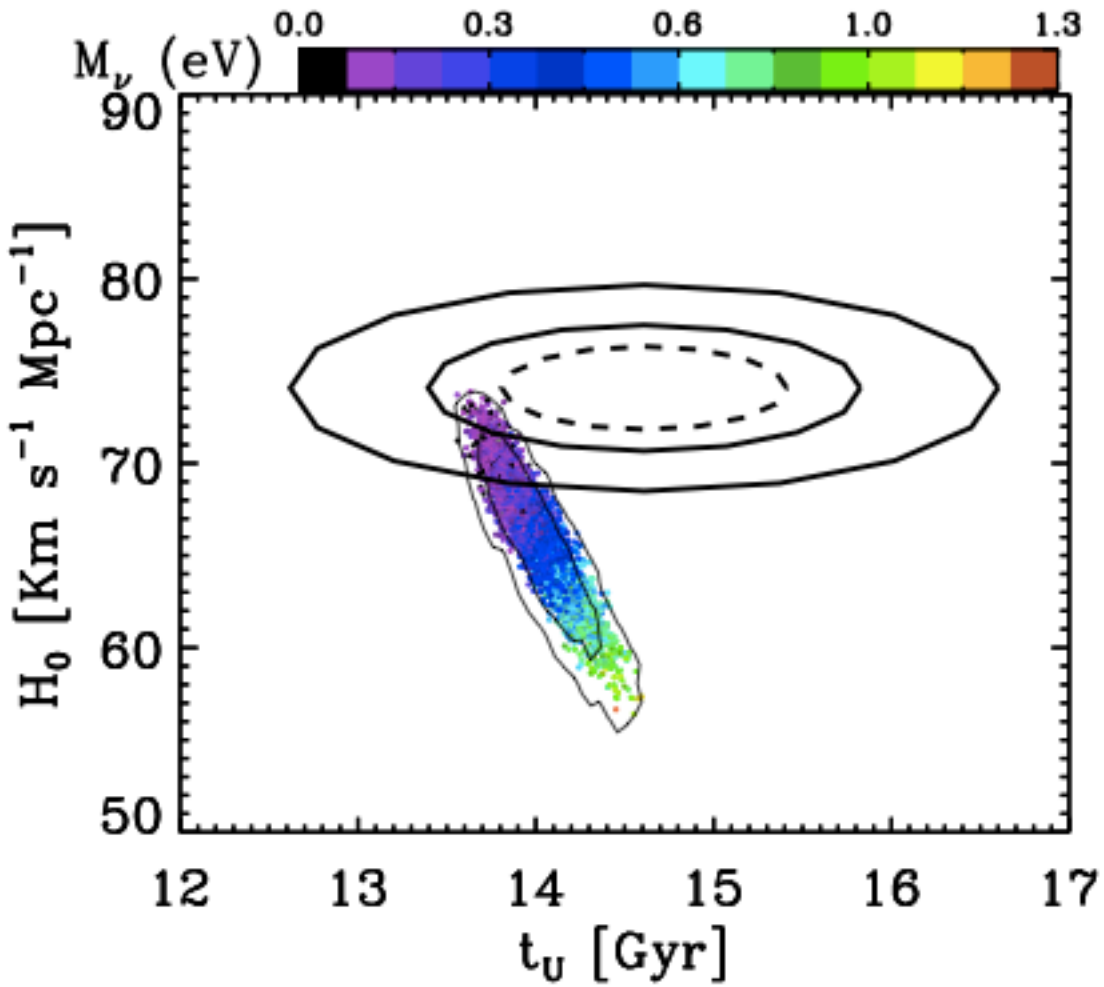
$t_u + H_0$

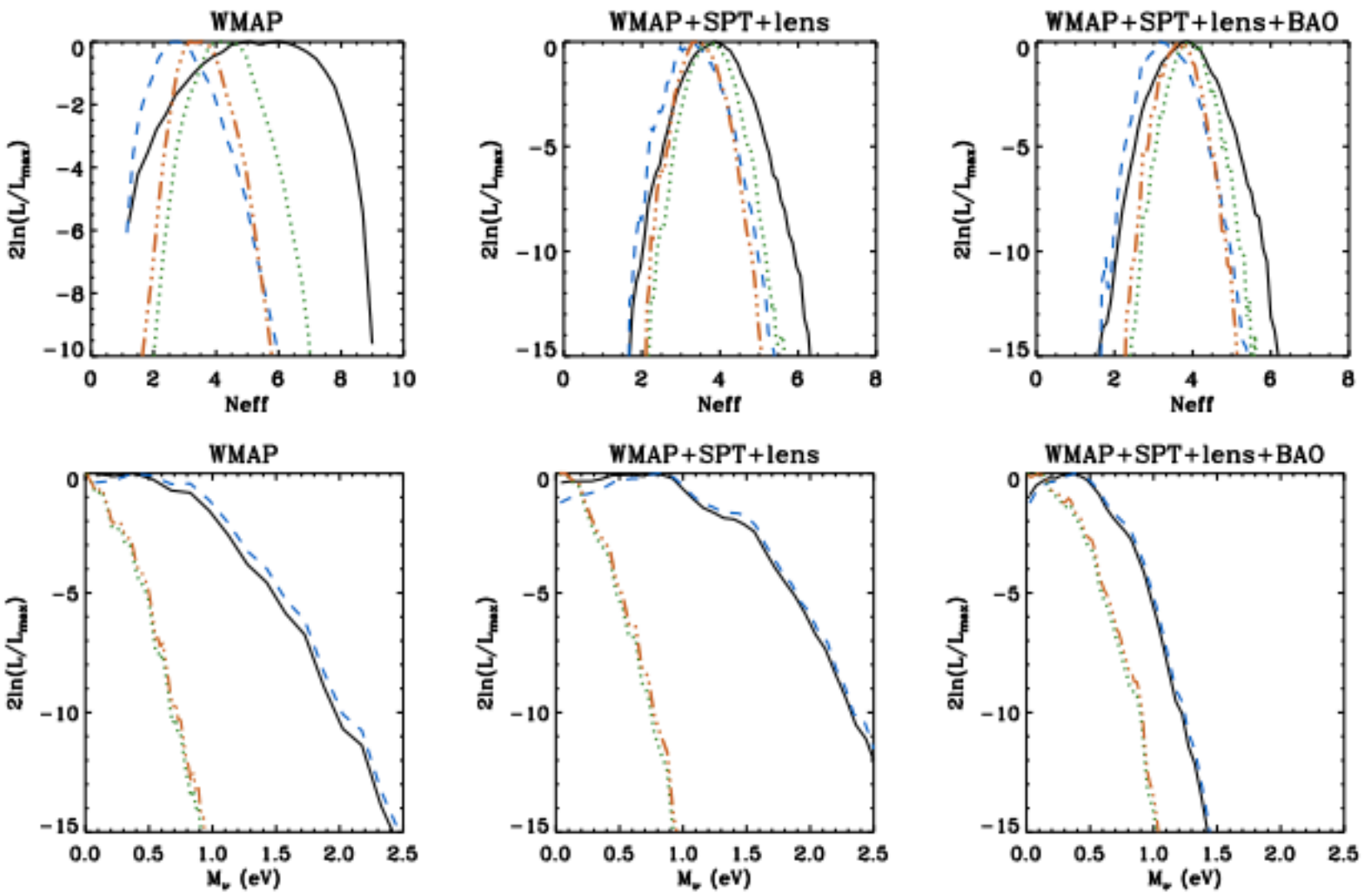
CMB

(pre Planck) N_{eff}



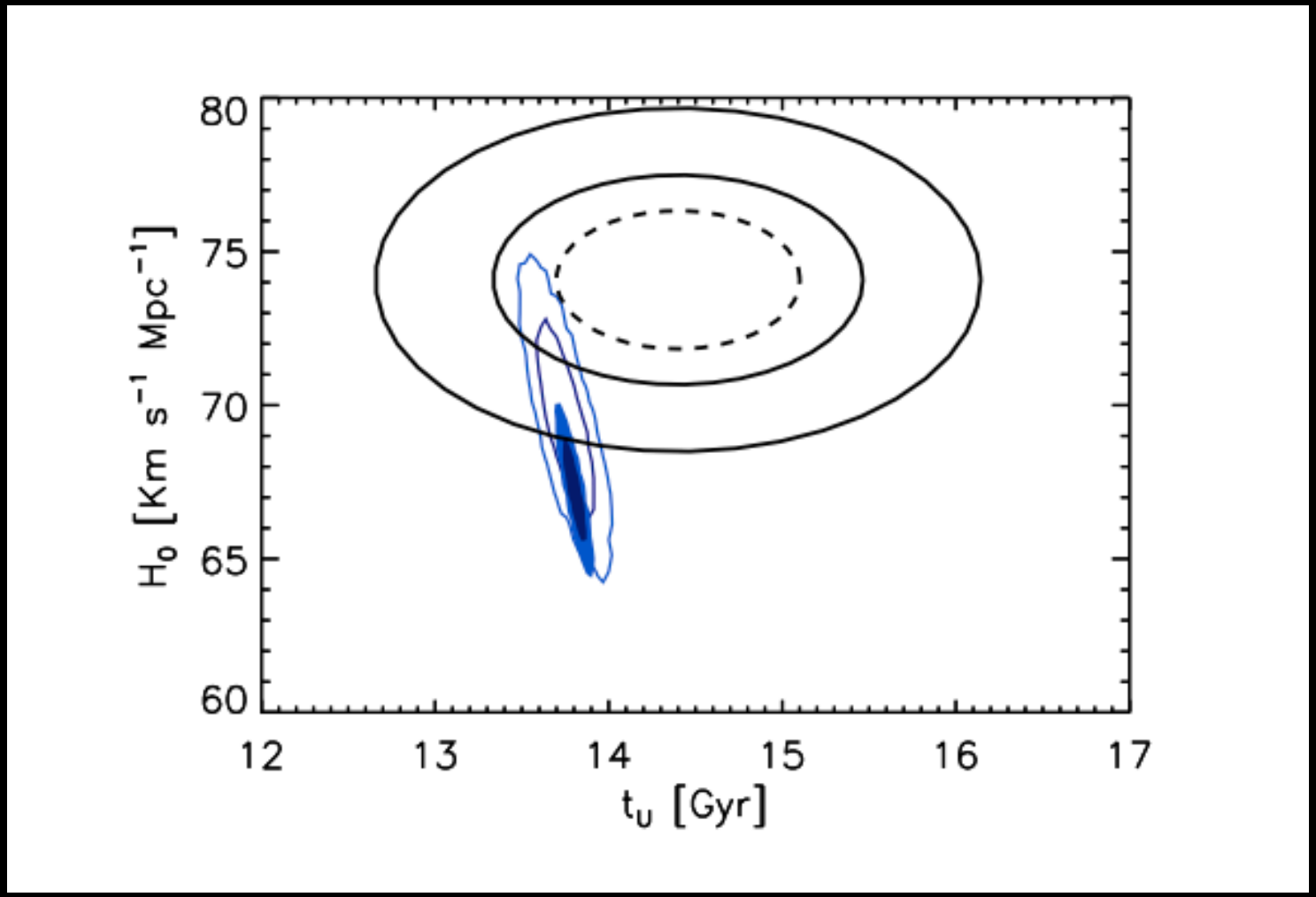
(pre Planck) M_ν





With T_U — With H_0 — both

Enter Planck



t_U updated with Gratton et al, Imbriani et al. to get 14.4 $^{+}_{-}$ 0.7 Gyr

Tension: how much?

Think in terms of evidence….

Cosmologists are (mostly) Bayesian

For model selection use Bayesian Evidence

$$E = \int \mathcal{L}(\theta)\Pr(\theta)d\theta$$

it does not focus on the best-fitting parameters of the model, but rather asks "of all the parameter values you thought were viable before the data came along, how well on average did they fit the data?"

Model averaged likelihood

RECALL:

$$\mathrm{P}(H \mid D) = \frac{\mathrm{P}(D \mid H)\mathrm{P}(H)}{\mathrm{P}(D)}$$

Bayes

$$\mathrm{P}(\boldsymbol{\theta} \mid D, H) = \frac{\mathrm{P}(D \mid \boldsymbol{\theta}, H)\mathrm{P}(\boldsymbol{\theta} \mid H)}{\mathrm{P}(D \mid H)}$$

Bayes, for parameter fitting

$$\mathcal{E} \equiv \mathrm{P}(D \mid H) = \int \mathrm{d}^n \boldsymbol{\theta} \mathrm{P}(D \mid \boldsymbol{\theta}, H)\mathrm{P}(\boldsymbol{\theta} \mid H)$$

Bayes for the MODEL itself

To compare two models
use RATIOS E_1/E_2: Bayes factors B_{12}

Interpretation

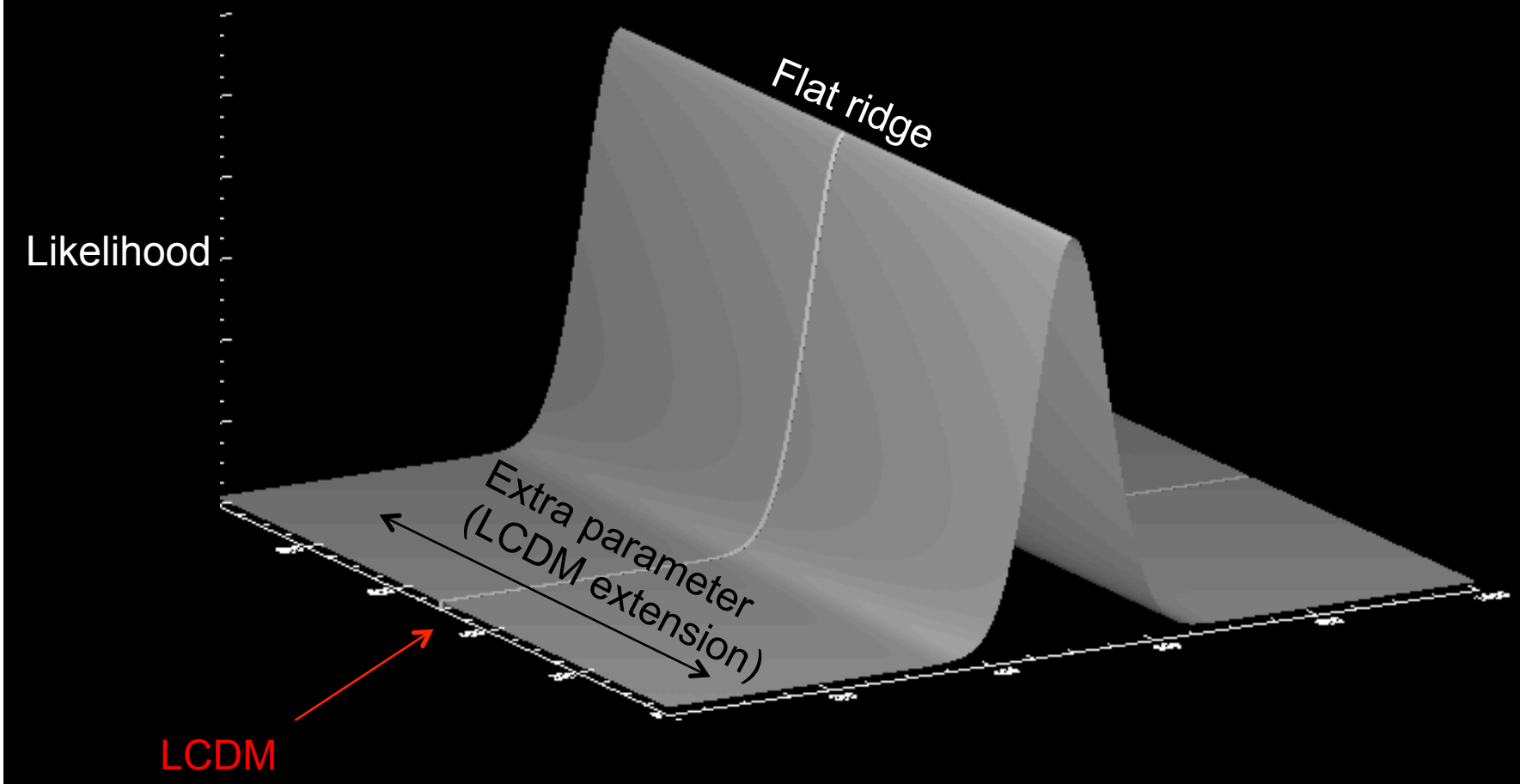
ln B12	interpretation	betting odds
< 1	not worth a bare mention, not significant	$< 3:1$
$1 - 2.5$	substantial	$\sim 3:1$
$2.5 - 5$	strong	$> 12:1$
> 5	highly significant	$> 150:1$

If you do: $\frac{\text{Simpler model}}{\text{Model extension}}$

Positive numbers favor the simpler model

Quiz

Imagine you have this situation:



What would the evidence ratio say?

solution

model 1 is the simpler model with parameter(s) ϕ
model 2 is the extension, ψ is the extra parameter(s)

$$
\begin{aligned}
E_2 &= \int\int \Pr(\boldsymbol{\phi}, \boldsymbol{\psi}|M_2)\Pr(\boldsymbol{d}|\boldsymbol{\phi}, \boldsymbol{\psi}, M_2)\,\mathrm{d}\boldsymbol{\phi}\,\mathrm{d}\boldsymbol{\psi} \\
&= \int \left[\int \Pr(\boldsymbol{\phi}, \boldsymbol{\psi}|M_2)\,\mathrm{d}\boldsymbol{\psi}\right] \Pr(\boldsymbol{d}|\boldsymbol{\phi}, M_1)\,\mathrm{d}\boldsymbol{\phi} \\
&= \int \Pr(\boldsymbol{\phi}|M_1)\Pr(\boldsymbol{d}|\boldsymbol{\phi}, M_1)\,\mathrm{d}\boldsymbol{\phi} \\
&= E_1.
\end{aligned}
$$

The evidence would be AGNOSTIC!

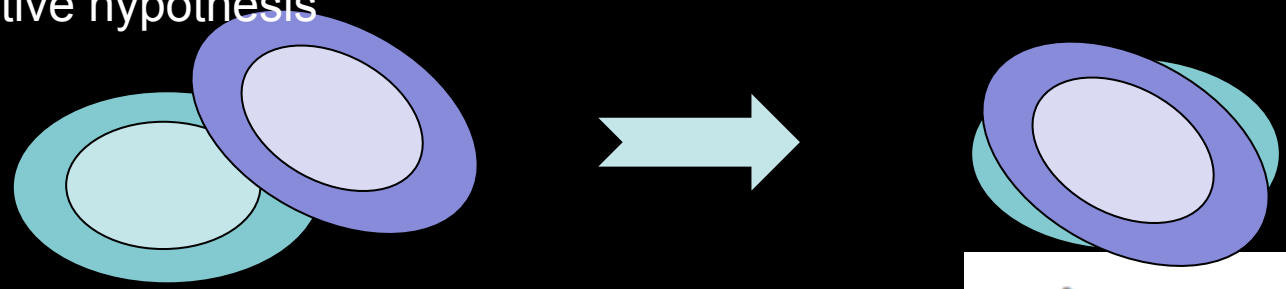
Tension: how much?

Think in terms of evidence.

$$\int P_A P_B dx = \lambda \int \mathcal{L}_A \mathcal{L}_B \pi_A \pi_B dx = \lambda \int \mathcal{L}_A \mathcal{L}_B \pi dx = \mathcal{E}\,.$$

$$\lambda^{-1} = \int \mathcal{L}_A \pi_A dx \int \mathcal{L}_B \pi_B dx'$$

Alternative hypothesis



Null hypothesis

$$\int \bar{P}_A \bar{P}_B dx = \bar{\mathcal{E}}|_{\mathrm{max}A=\mathrm{max}B}$$

Introduce:

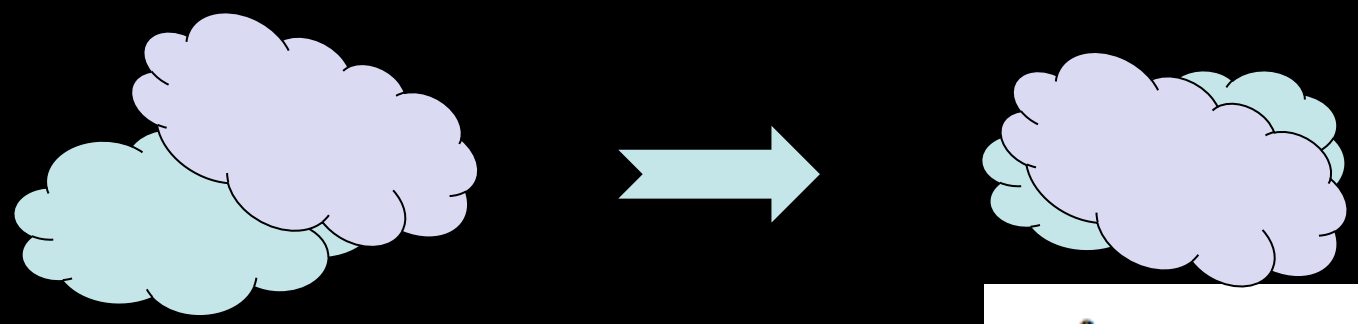
$$\mathcal{T} = \frac{\bar{\mathcal{E}}|_{\mathrm{max}A=\mathrm{max}B}}{\mathcal{E}}$$

Tension: how much?

Think in terms of evidence.

$$\int P_A P_B dx = \lambda \int \mathcal{L}_A \mathcal{L}_B \pi_A \pi_B dx = \lambda \int \mathcal{L}_A \mathcal{L}_B \pi dx = \mathcal{E}\,.$$

$$\lambda^{-1} = \int \mathcal{L}_A \pi_A dx \int \mathcal{L}_B \pi_B dx'$$



$$\int \bar{P}_A \bar{P}_B dx = \bar{\mathcal{E}}|_{\mathrm{max}A=\mathrm{max}B}$$

Introduce:

$$\mathcal{T} = \frac{\bar{\mathcal{E}}|_{\mathrm{max}A=\mathrm{max}B}}{\mathcal{E}}$$

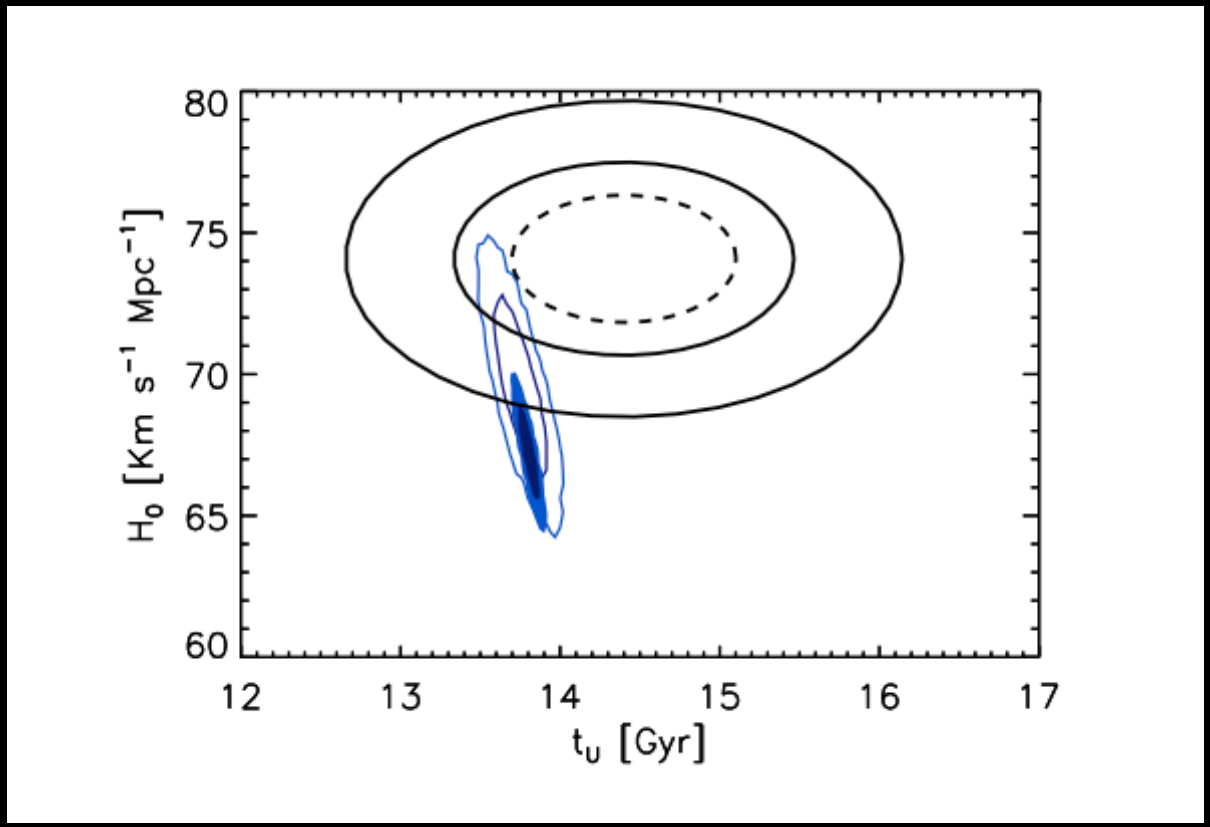
In other words

E1 can be seen as the Evidence for the joint distribution

now interpret it as one data set (A) gives you the prior
The evidence asks:
how well on average the parameters allowed by this prior within the model,
fit the data from experiment B?

gives additional information compared to the Bayes factor:
the Bayes factor will not tell if one (or both) models are bad fit to the combined data

Tension?



Odds: 1:53

Interpretation

$\ln \mathcal{T}$	interpretation	betting odds
< 1	not worth a bare mention, not significant	$< 3:1$
$1 - 2.5$	substantial	$\sim 3:1$
$2.5 - 5$	strong	$> 12:1$
> 5	highly significant	$> 150:1$

Table 1: The slightly modified Jeffreys' scale we use for interpreting the tension $\mathcal{T}$.

For LCDM,
Planck vs local Universe

$$\ln \mathcal{T} = 3.96$$

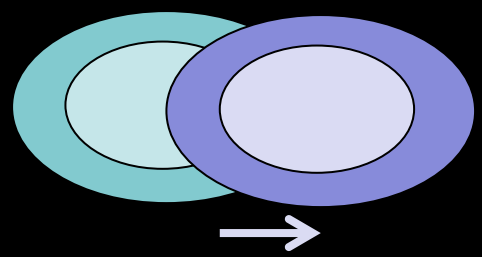
Odds ~ 1:50

Interpretation

$\ln \mathcal{T}$	interpretation	betting odds
< 1	not worth a bare mention, not significant	$< 3:1$
$1 - 2.5$	substantial	$\sim 3:1$
$2.5 - 5$	strong	$> 12:1$
> 5	highly significant	$> 150:1$

Table 1: The slightly modified Jeffreys' scale we use for interpreting the tension $\mathcal{T}$.

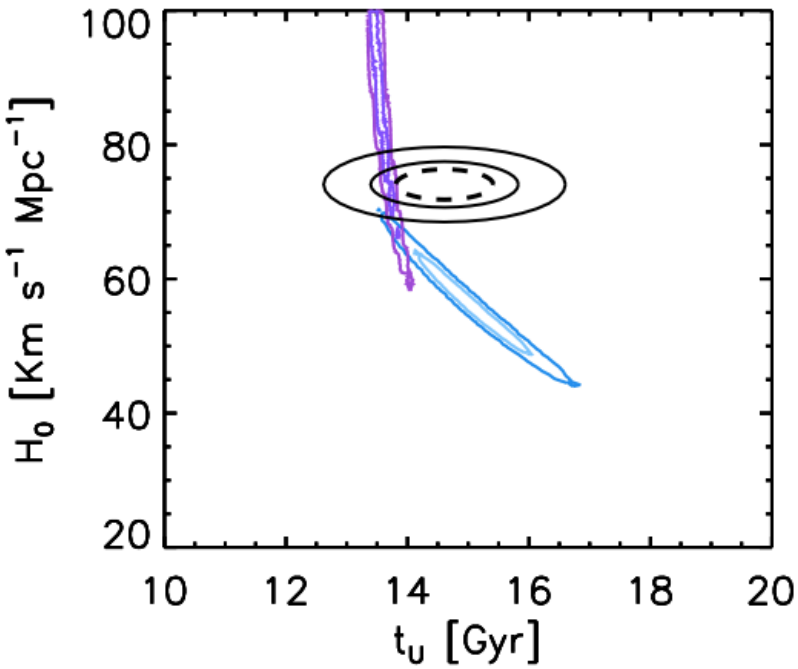
Keep in mind that:

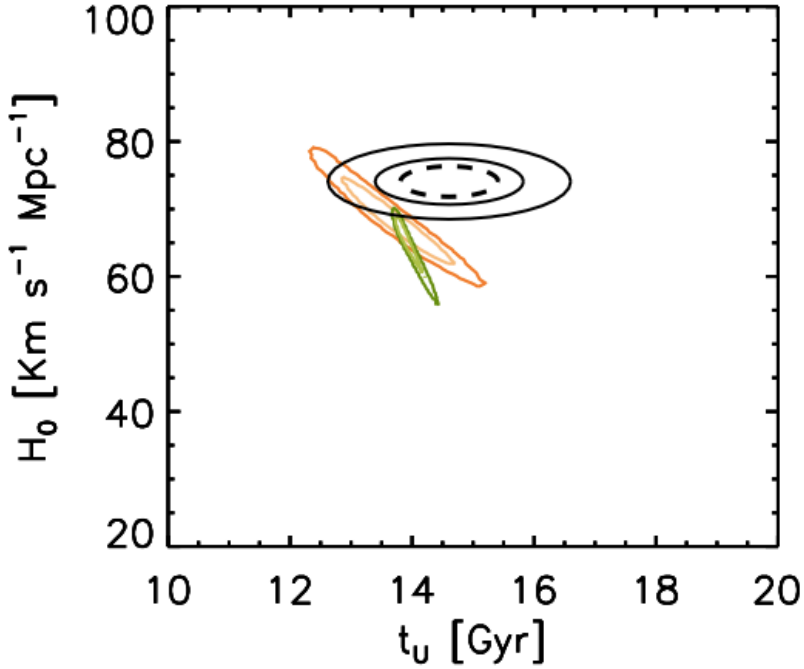


1	2 σ
2.5	3 σ
5	4.5 σ

3.98 sigmas

local measures with Planck





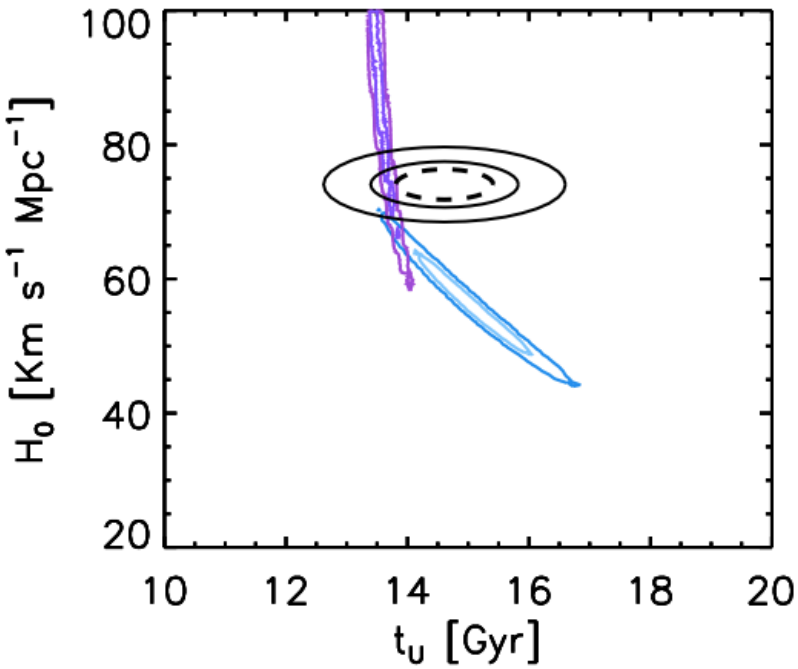
+curvature

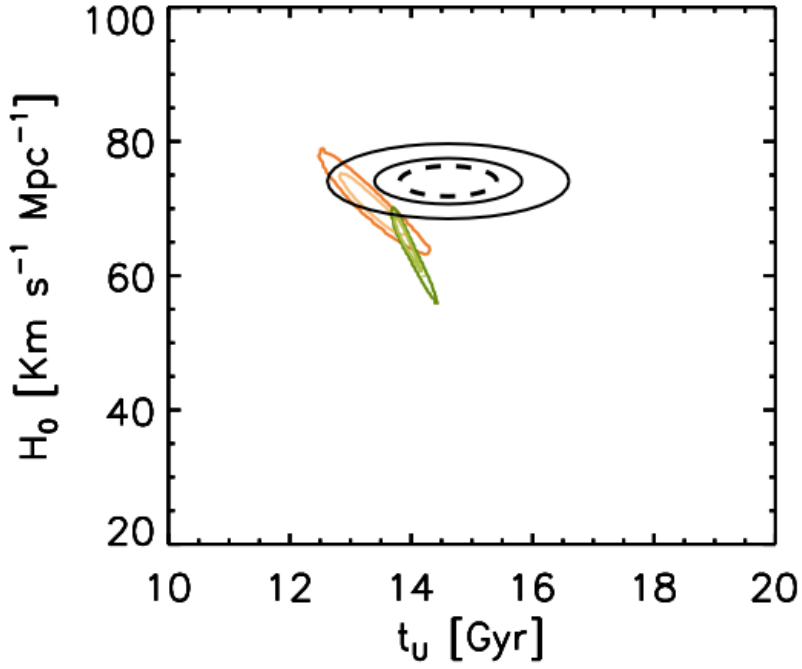
+ w ≠ -1

$+m_\nu$

$+N_{eff}$

local measures with Planck





+curvature

+ w ≠ -1

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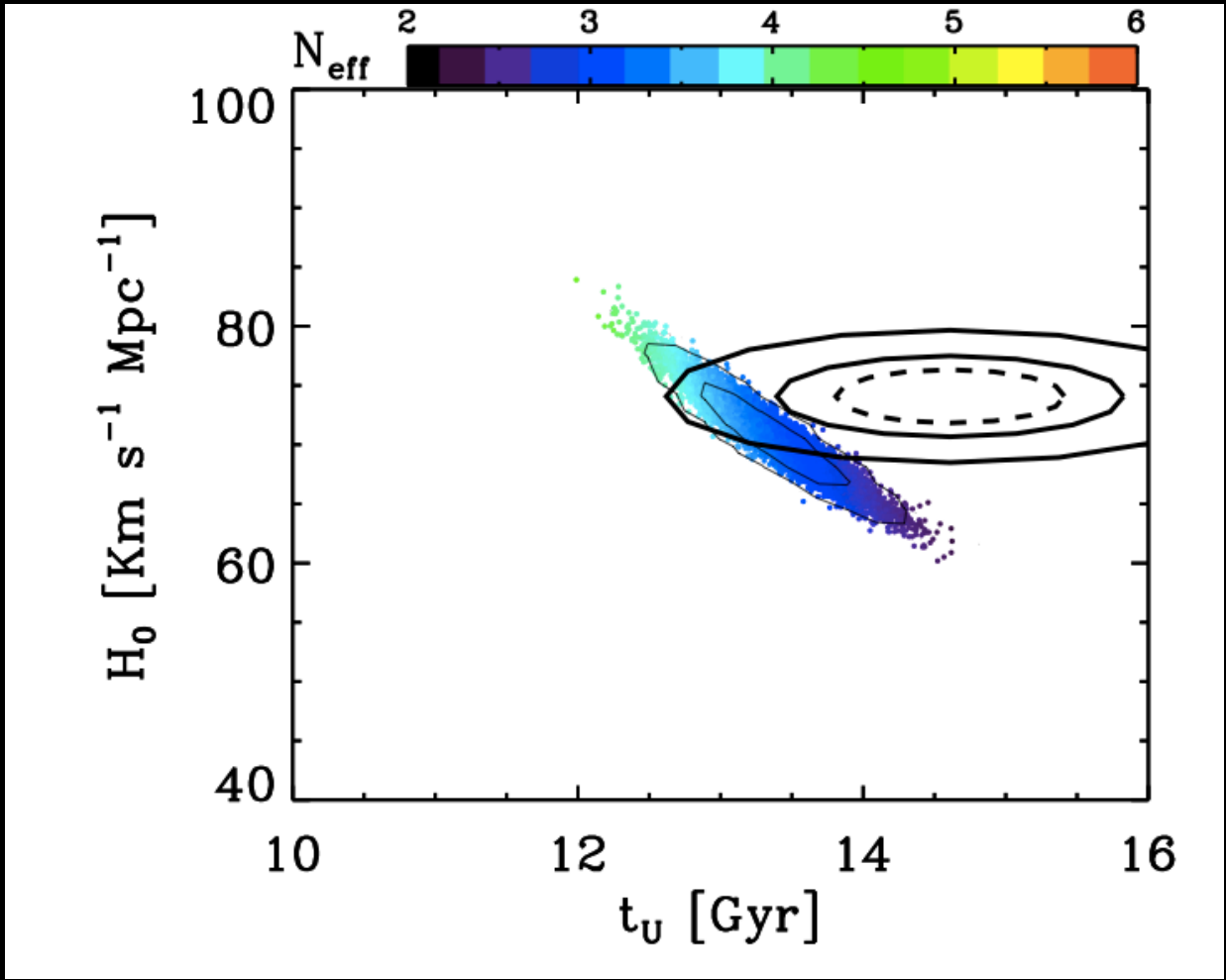
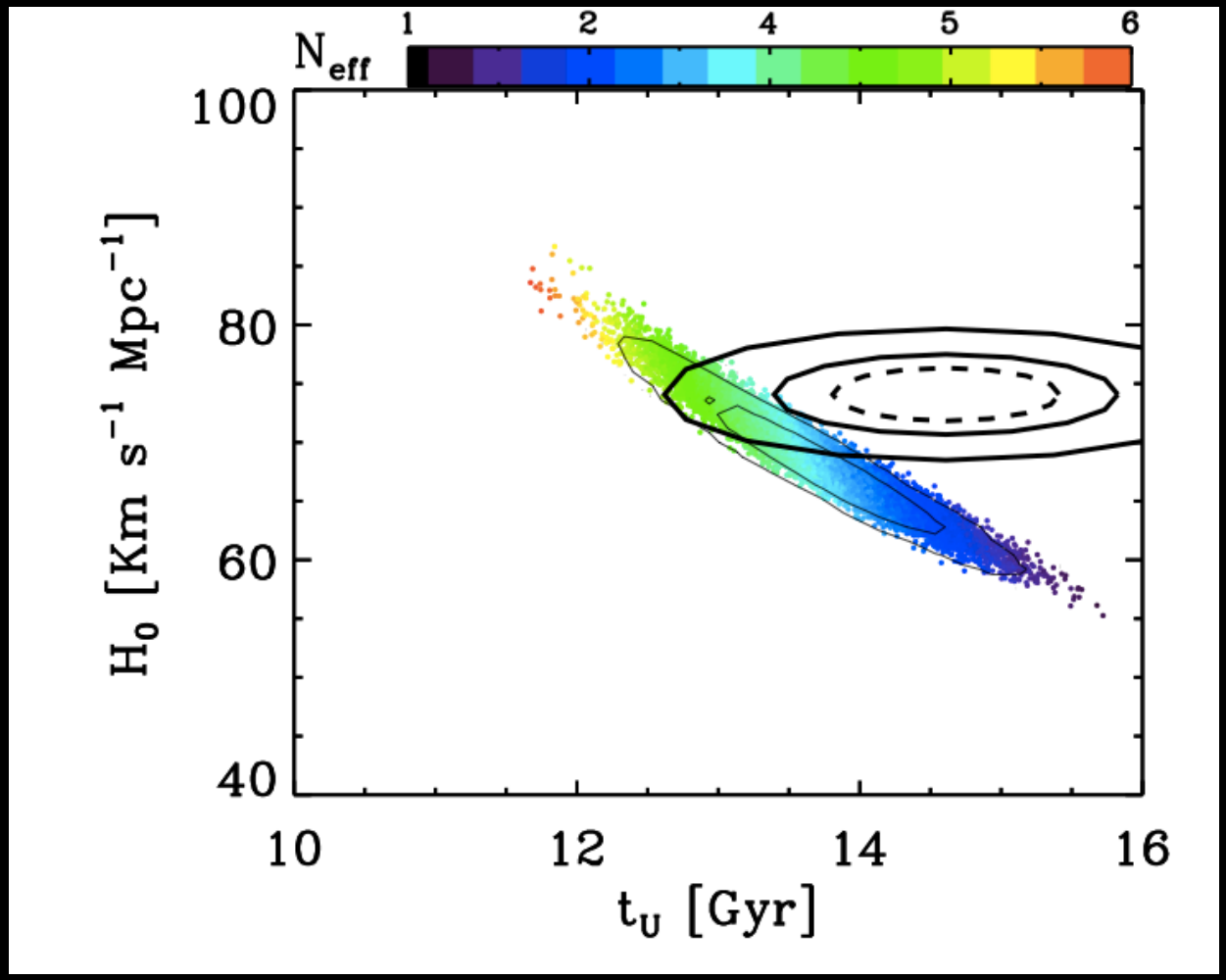
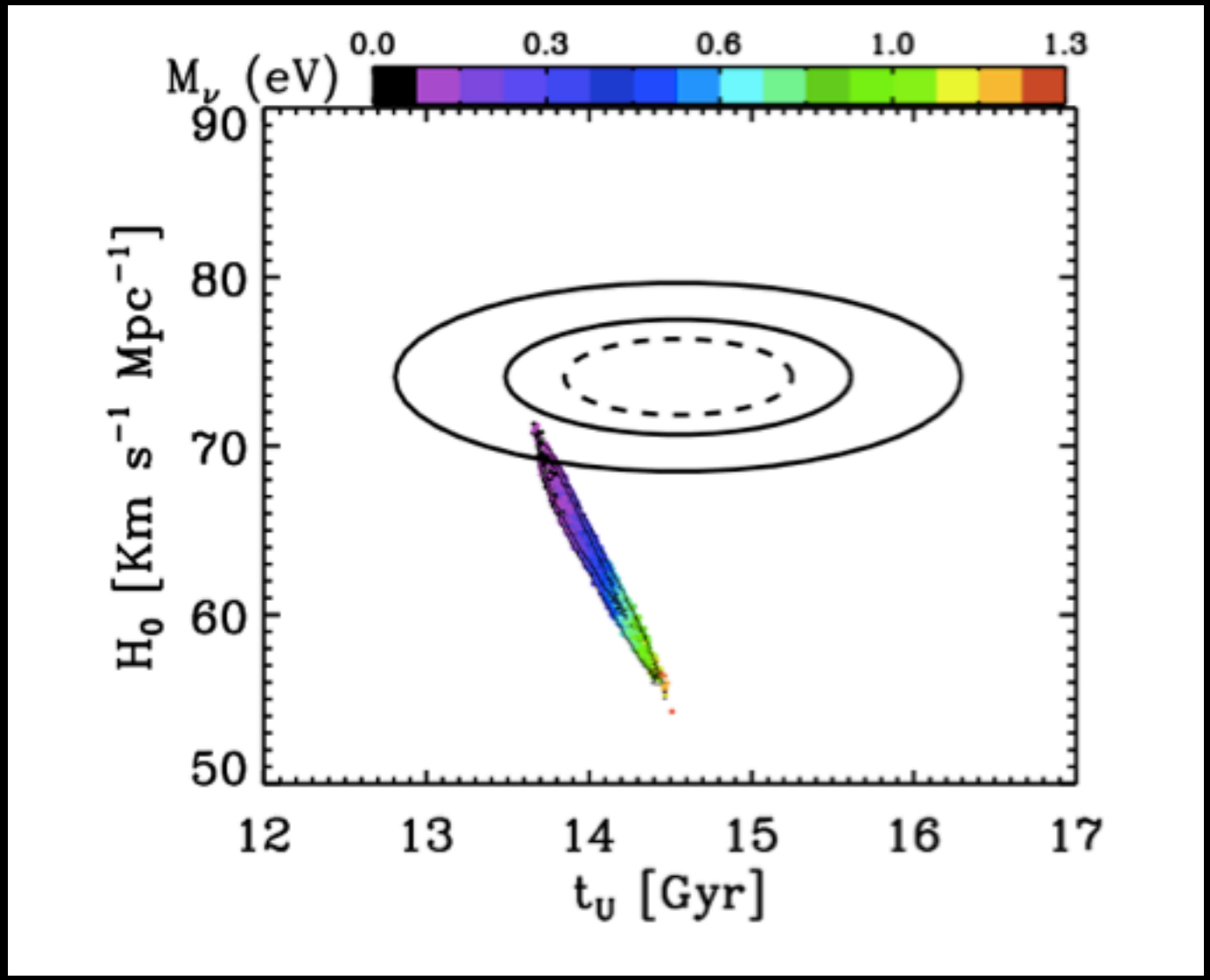
local measures with Planck



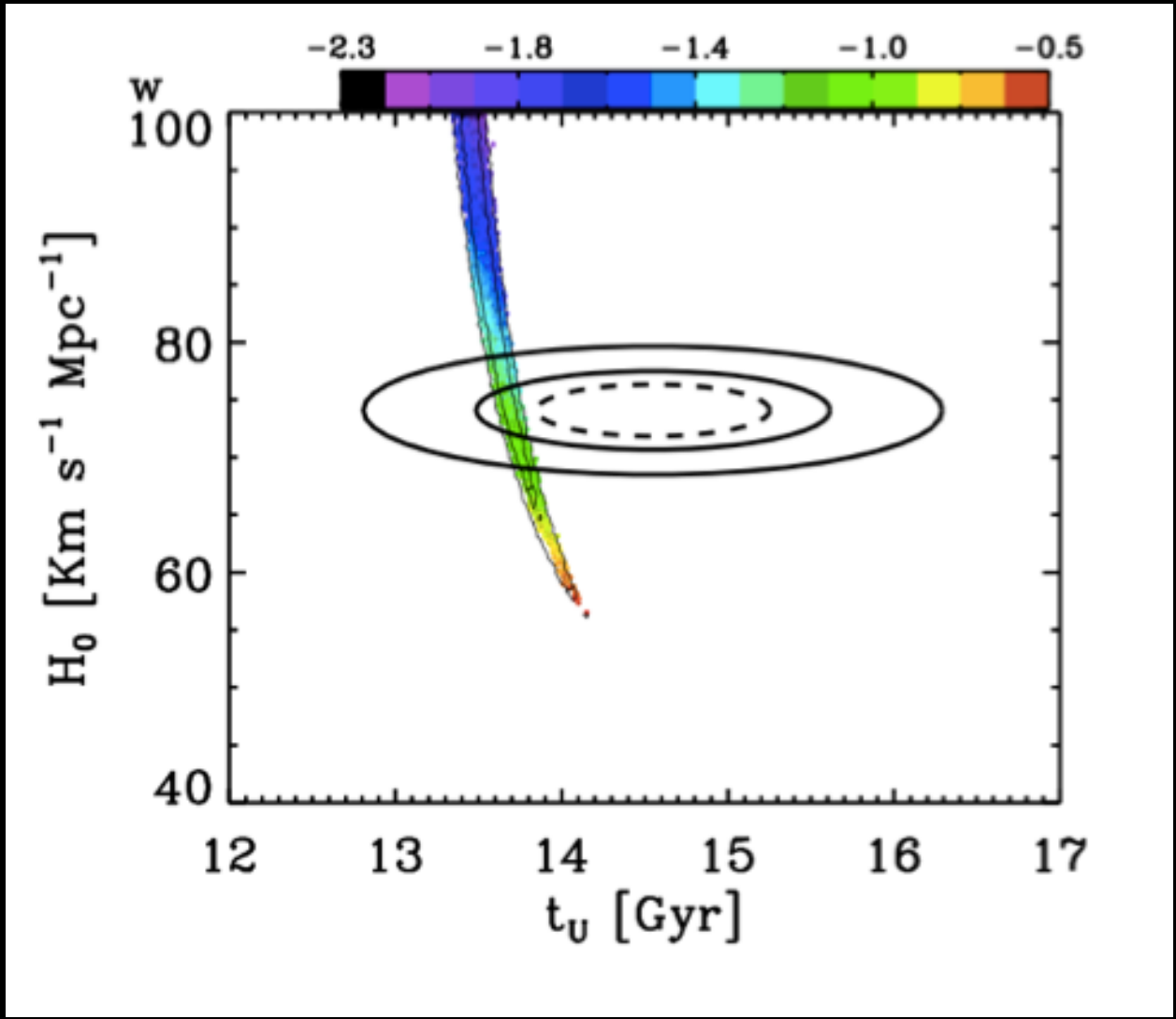
local measures with Planck



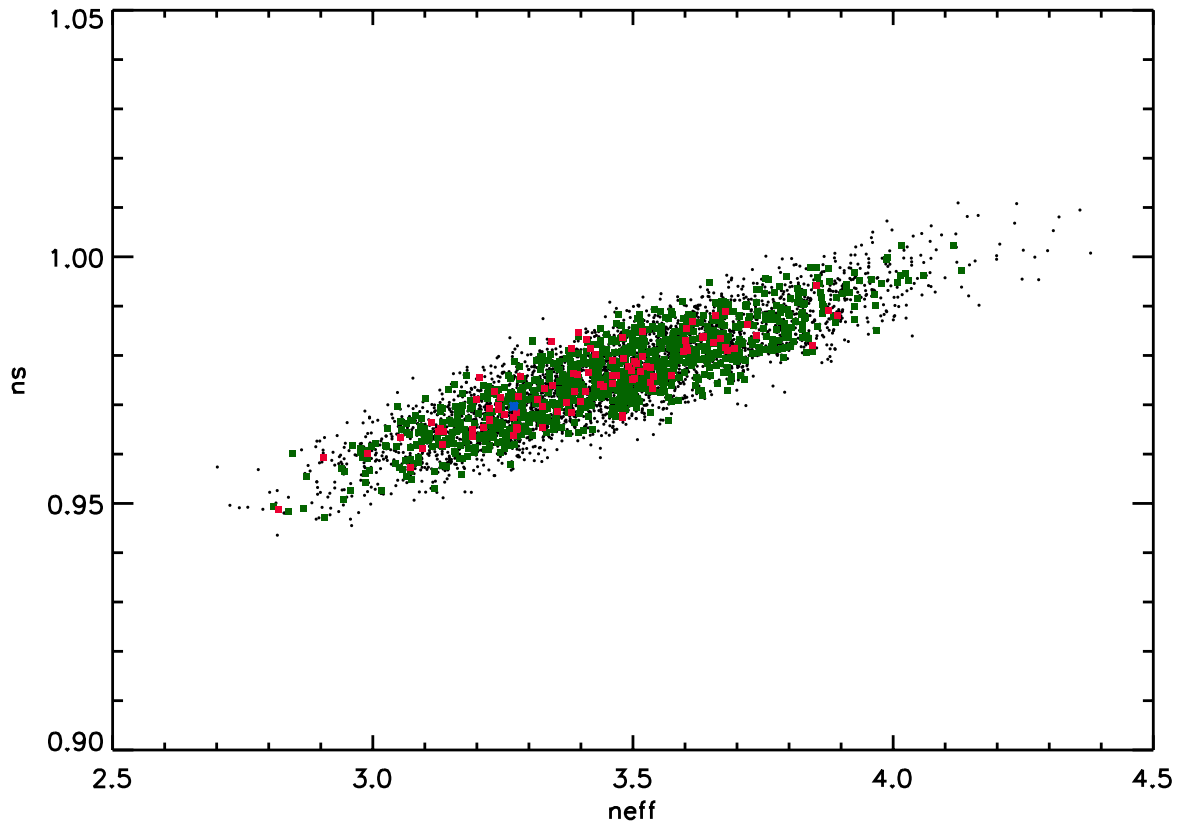
local measures with Planck



local measures with Planck



What about n_s?



Black: delta log like 3
Green: delta log like 2
Red: delta log like 1
Blue: the max

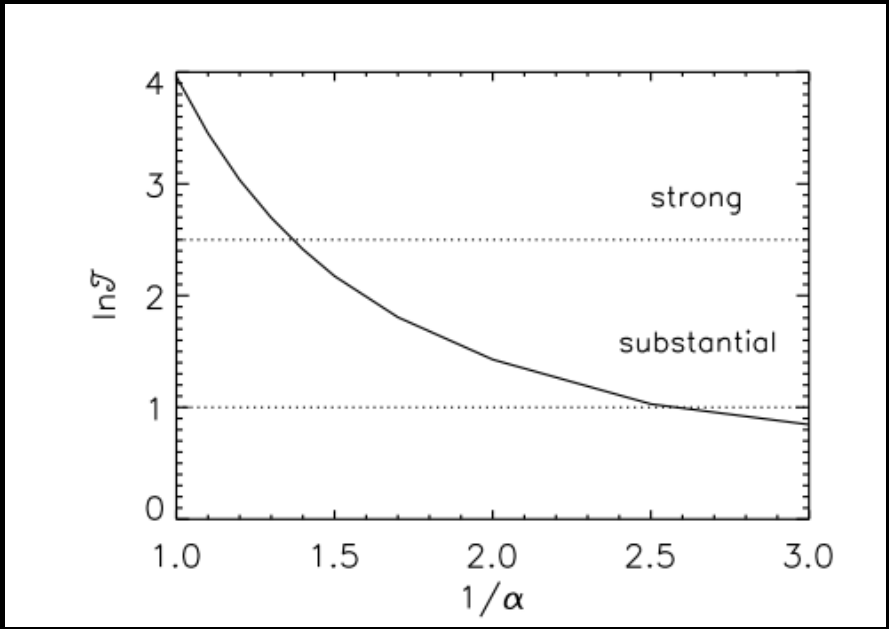
Planck

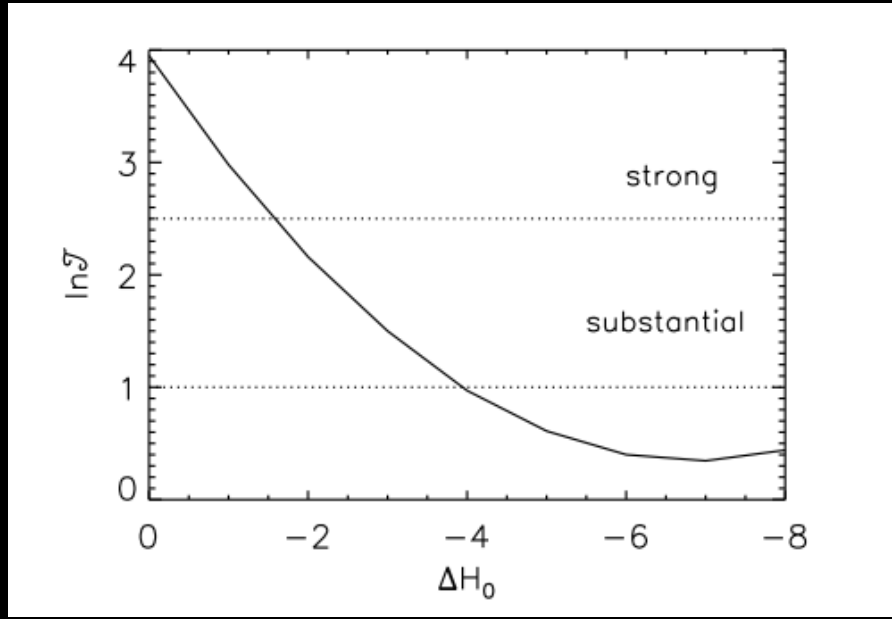
Yp not varied

Must go to $\Delta\chi^2$=4: Neff is 4 ns~1

And now what?

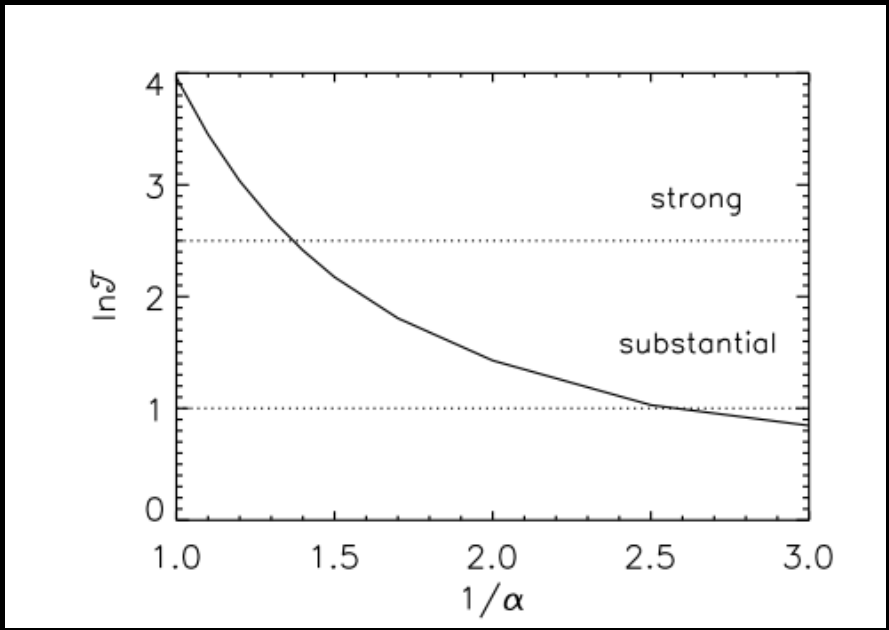
Option a)
some errors are under-estimated. Let' us just pick on H0 and explore the consequences (see if we can live with them)

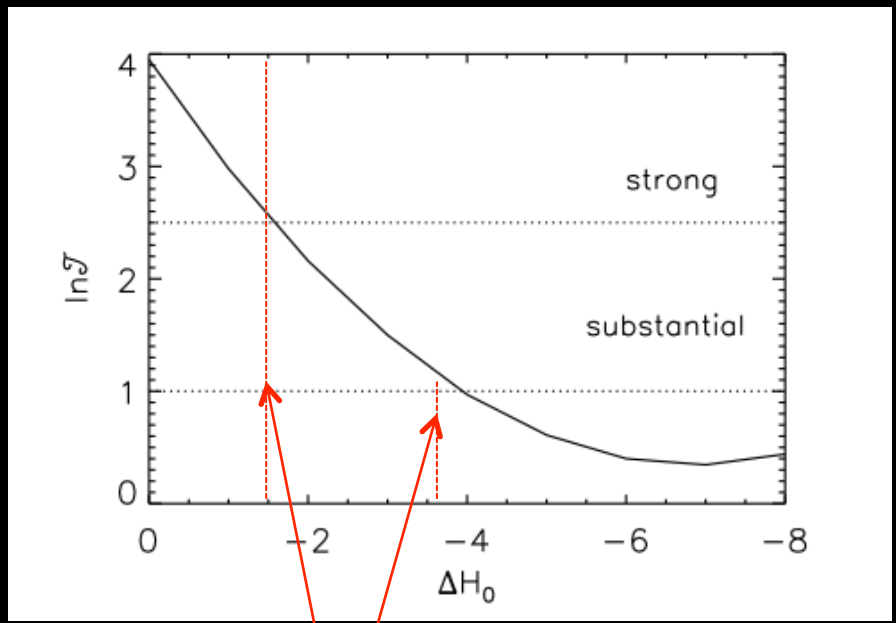




And now what?

Option a)
some errors are under-estimated. Let' us just pick on H0 and explore the consequences (see if we can live with them)





Efstathiou 2013

And now what?

Option b) the model is not quite right

and explore the consequences (see if we can live with them)

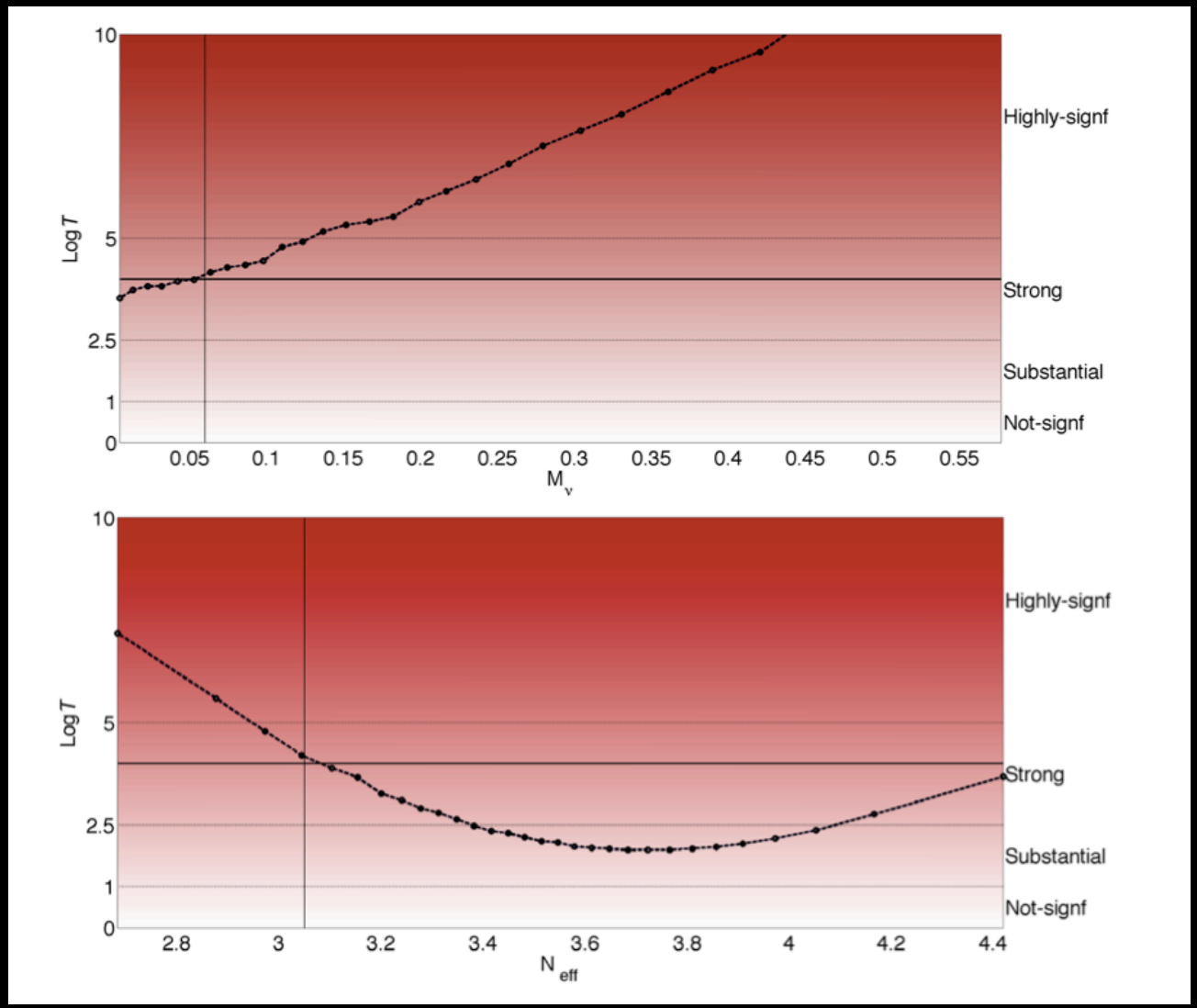
Which extension should one consider?

model extension	w	Ω_k	$N_{\rm eff}$	M_ν	$N_{\rm eff} + Y_P$
$\ln \mathcal{T}$	0.74	5.24	1.94	4.5	2.2
$\ln E_{\Lambda CDM}/E_{\rm extension}$	-0.72	3.70	-0.27(P)	3.45	1.93(P)

Remember LCDM ln $\mathcal{T}$= 3.96

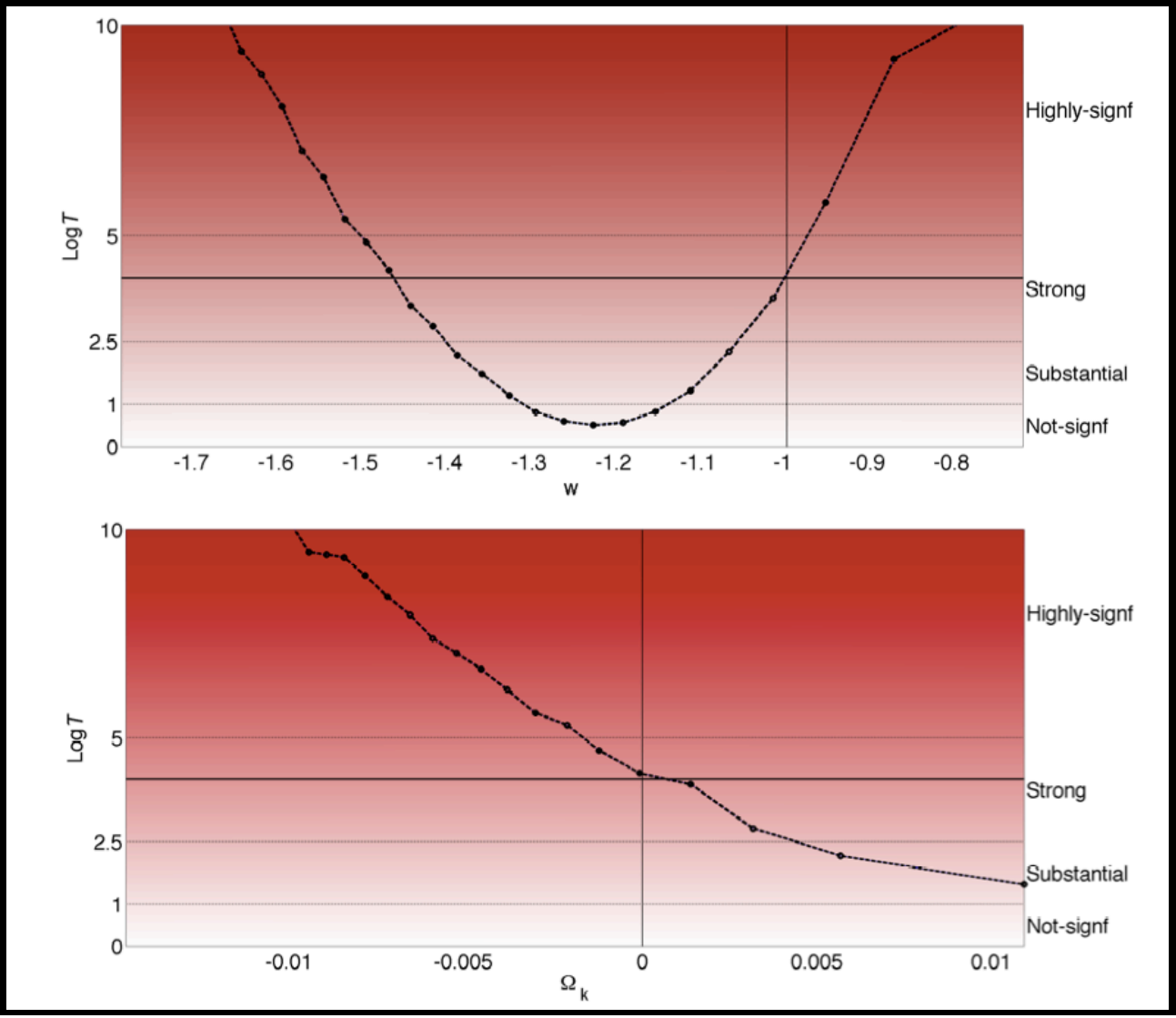
Option b) the model is not quite right

Implications for model parameters



Option b) the model is not quite right

Implications for model parameters



Option b) the model is not quite right

Implications for model parameters

Neutrino mass <0.15 eV for tension not to be highly significant (1:150)

3.4<Neff<4.1 reduce tension to substantial (better than 1:12)
(NO value makes it not significant)

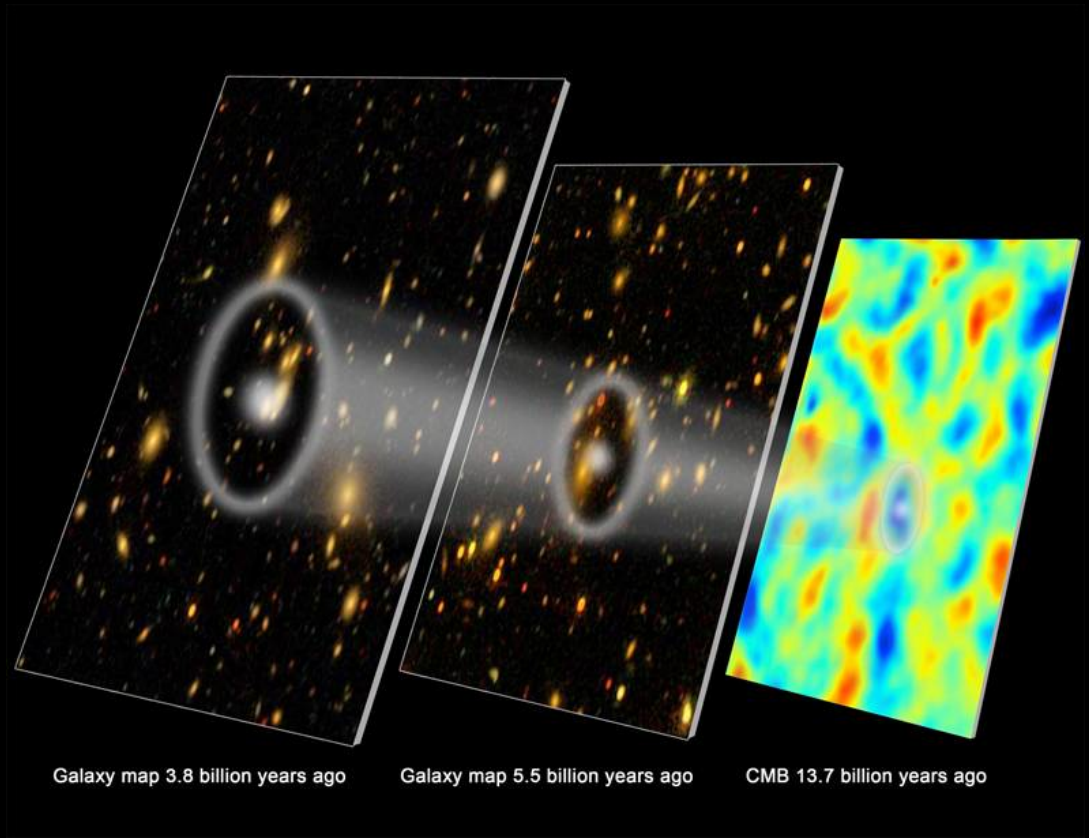
Neff>4.6 makes tension highly significant

However there are other data out there which do not support this interpretation

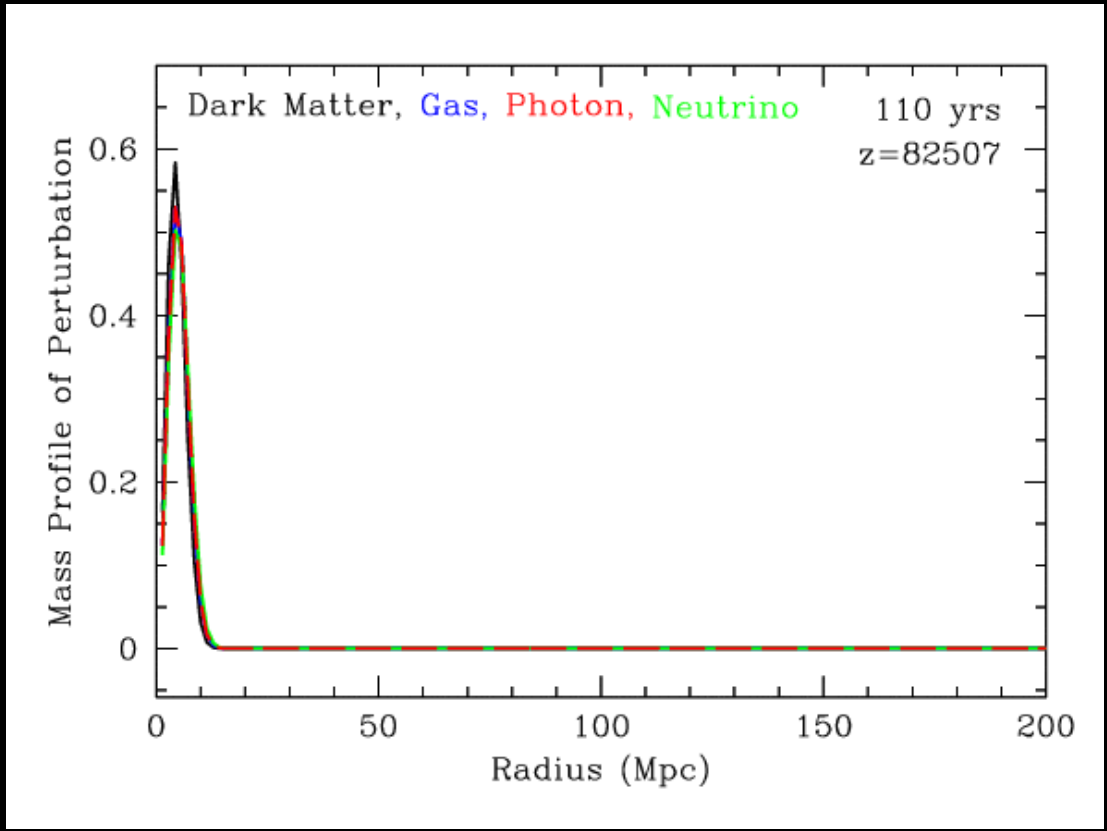
w ~ -1.2 makes tension not significant!

Beyond local

Still (quasi-)model independent



BAO

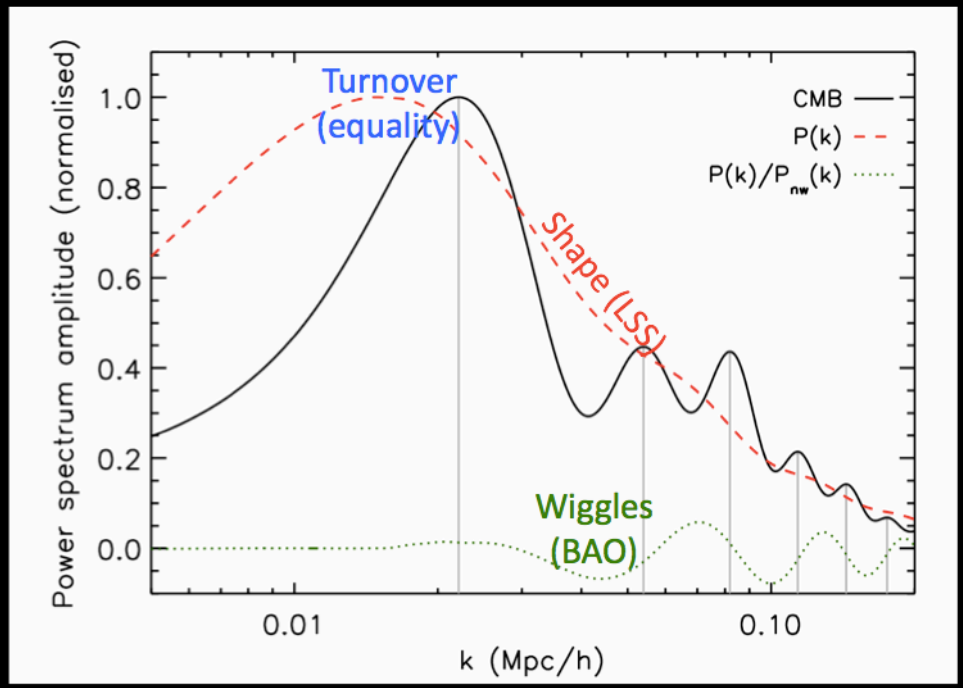


Animation courtesy of D. Eisenstein

BAO

Still quasi-model independent

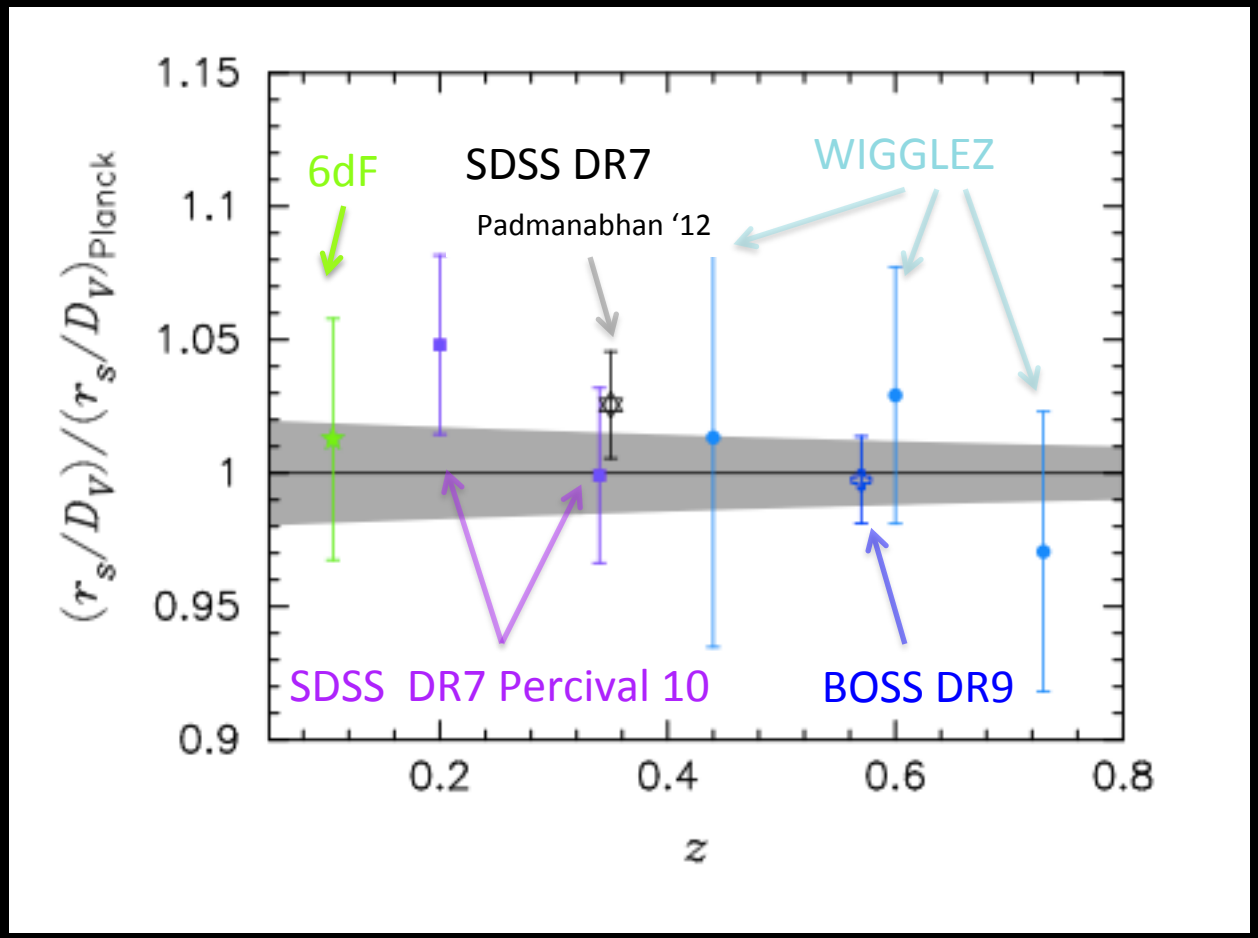
Features of power spectrum (compared to CMB)



From: T. Davis

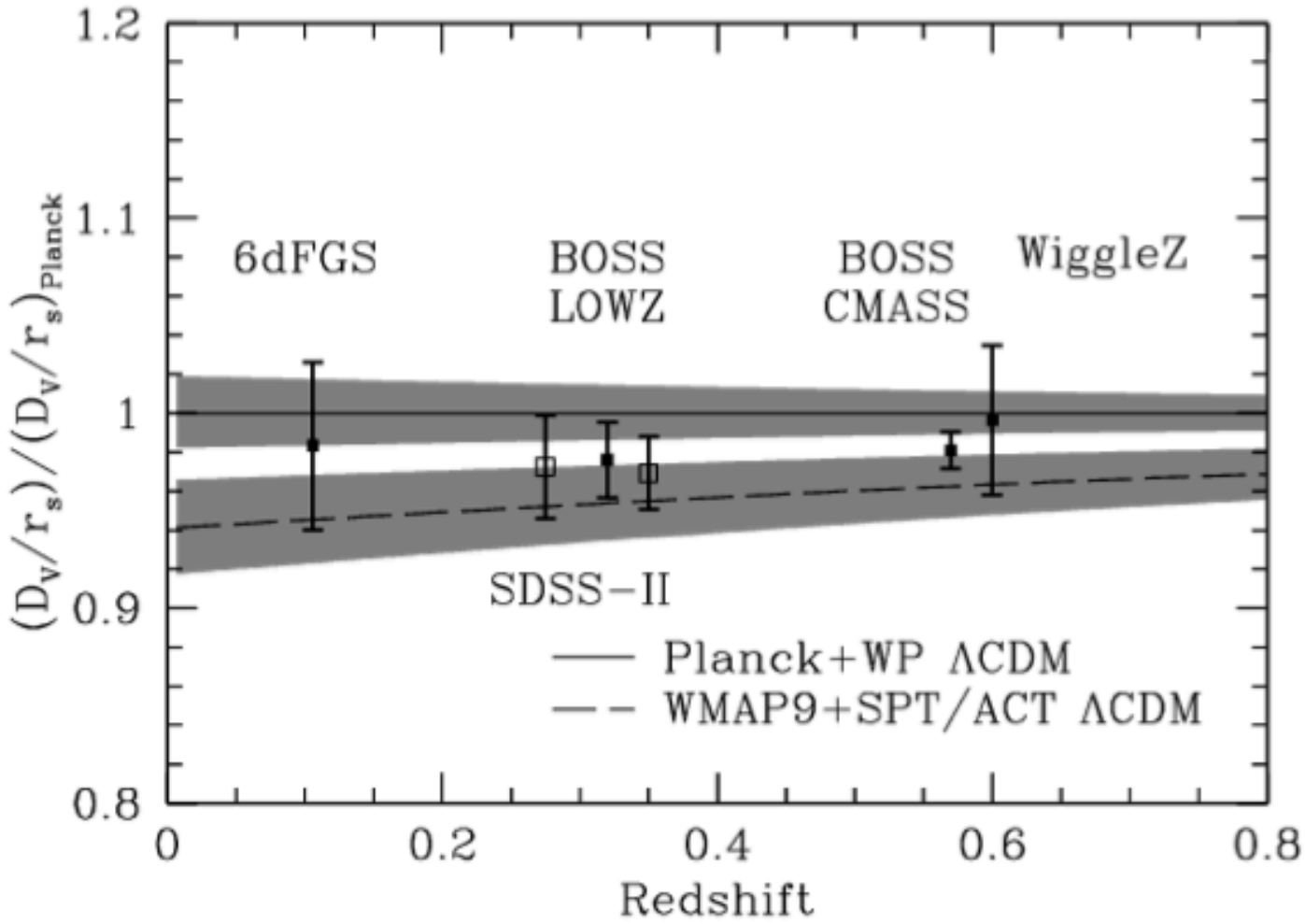
Example of BAO

From the Planck cosmological parameters paper: almost the state of the art



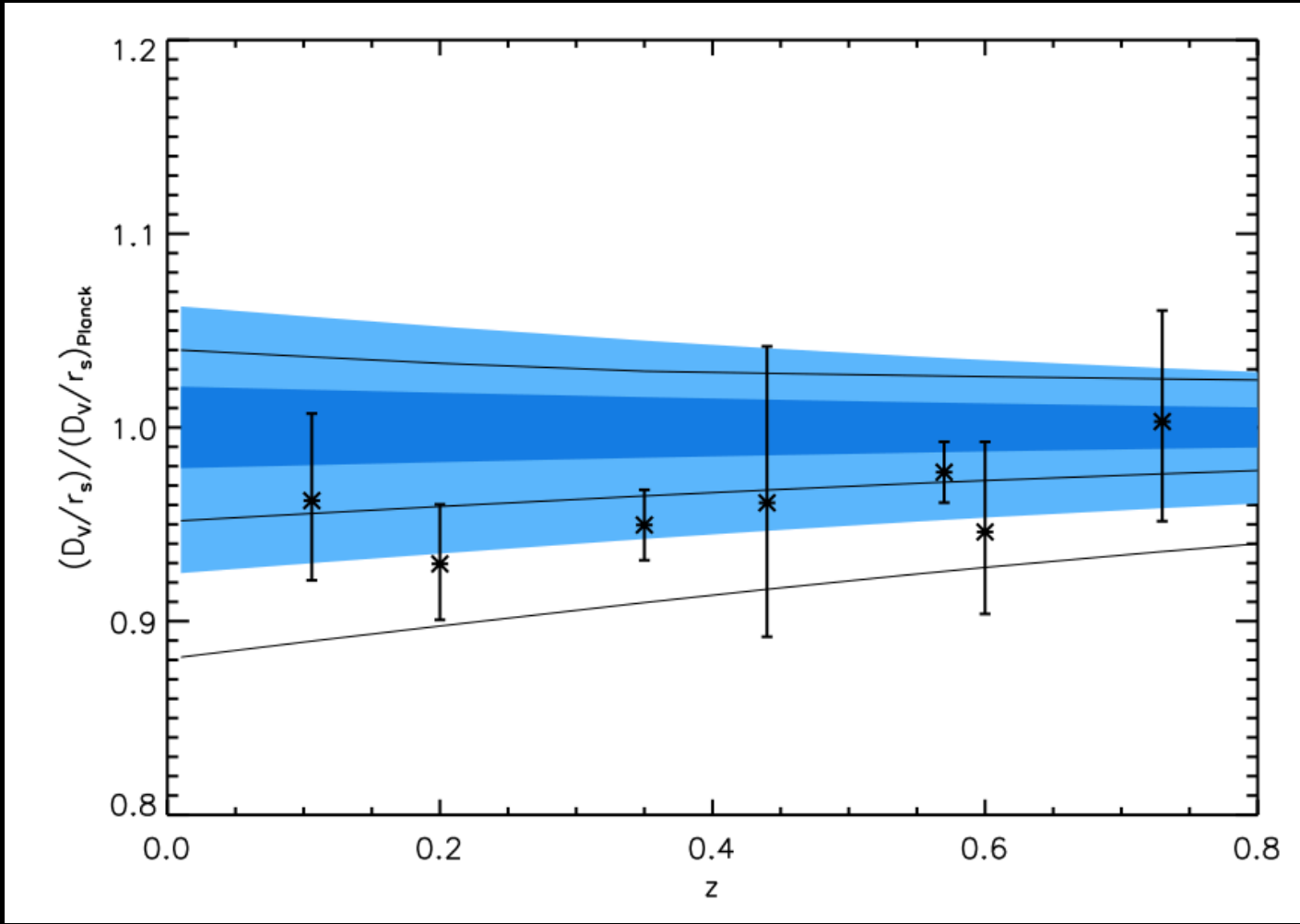
Adapted from Planck collaboration, 2013, paper XVI

NEWER



Amderson et al. SDSSII Boss collab. 2013, arXiv:1312.4877

Woops, what was that?



Direct comparison with Planck's paper figure

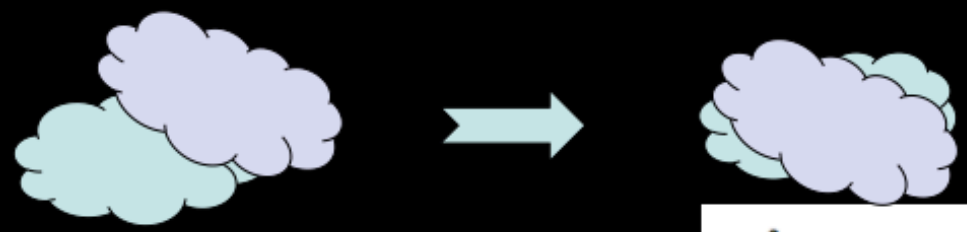
Multi Dimensional Tension

Tension: how much?

Think in terms of evidence.

$$\int P_A P_B dx = \lambda \int \mathcal{L}_A \mathcal{L}_B \pi_A \pi_B dx = \lambda \int \mathcal{L}_A \mathcal{L}_B \pi dx = \mathcal{E}\,.$$

$$\lambda^{-1} = \int \mathcal{L}_A \pi_A dx \int \mathcal{L}_B \pi_B dx'$$



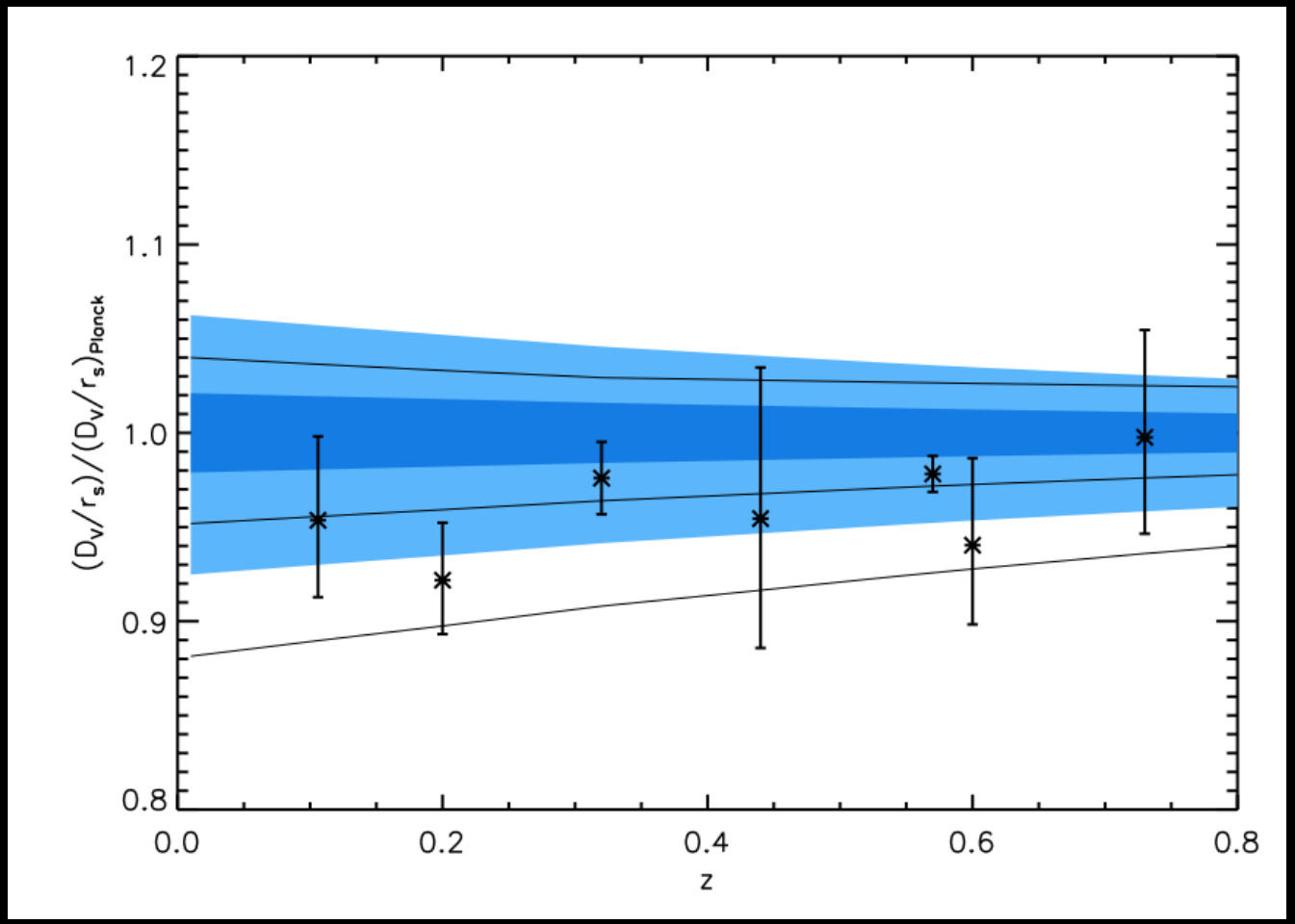
$$\int \bar{P}_A \bar{P}_B dx = \bar{\mathcal{E}}|_{\mathrm{max}A=\mathrm{maxB}}$$

Introduce:

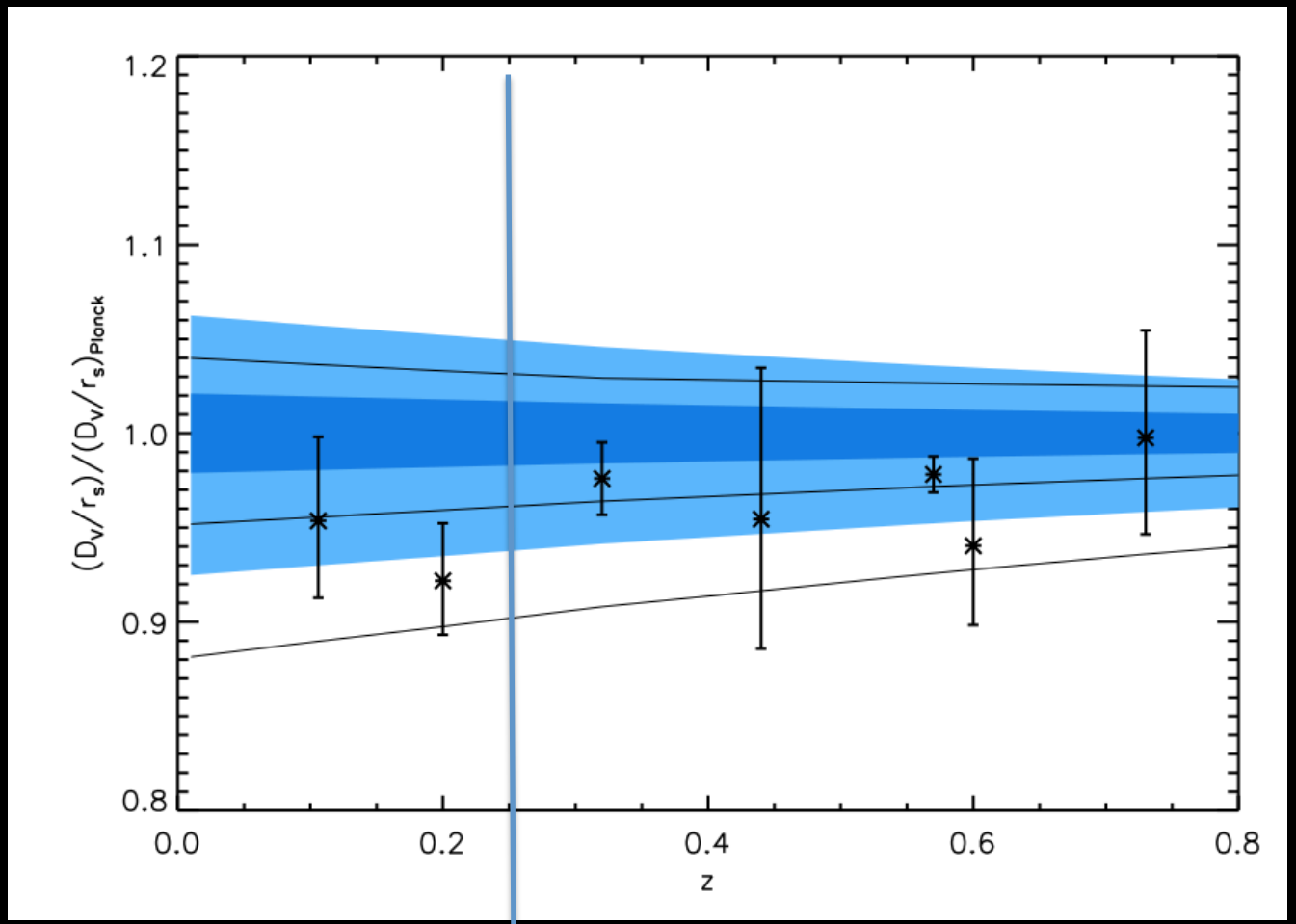
$$\mathcal{T} = \frac{\bar{\mathcal{E}}|_{\mathrm{max}A=\mathrm{maxB}}}{\mathcal{E}}$$

Just in higher dimensions, not 2 measurements any more but ~ 7

With new BOSS measurements

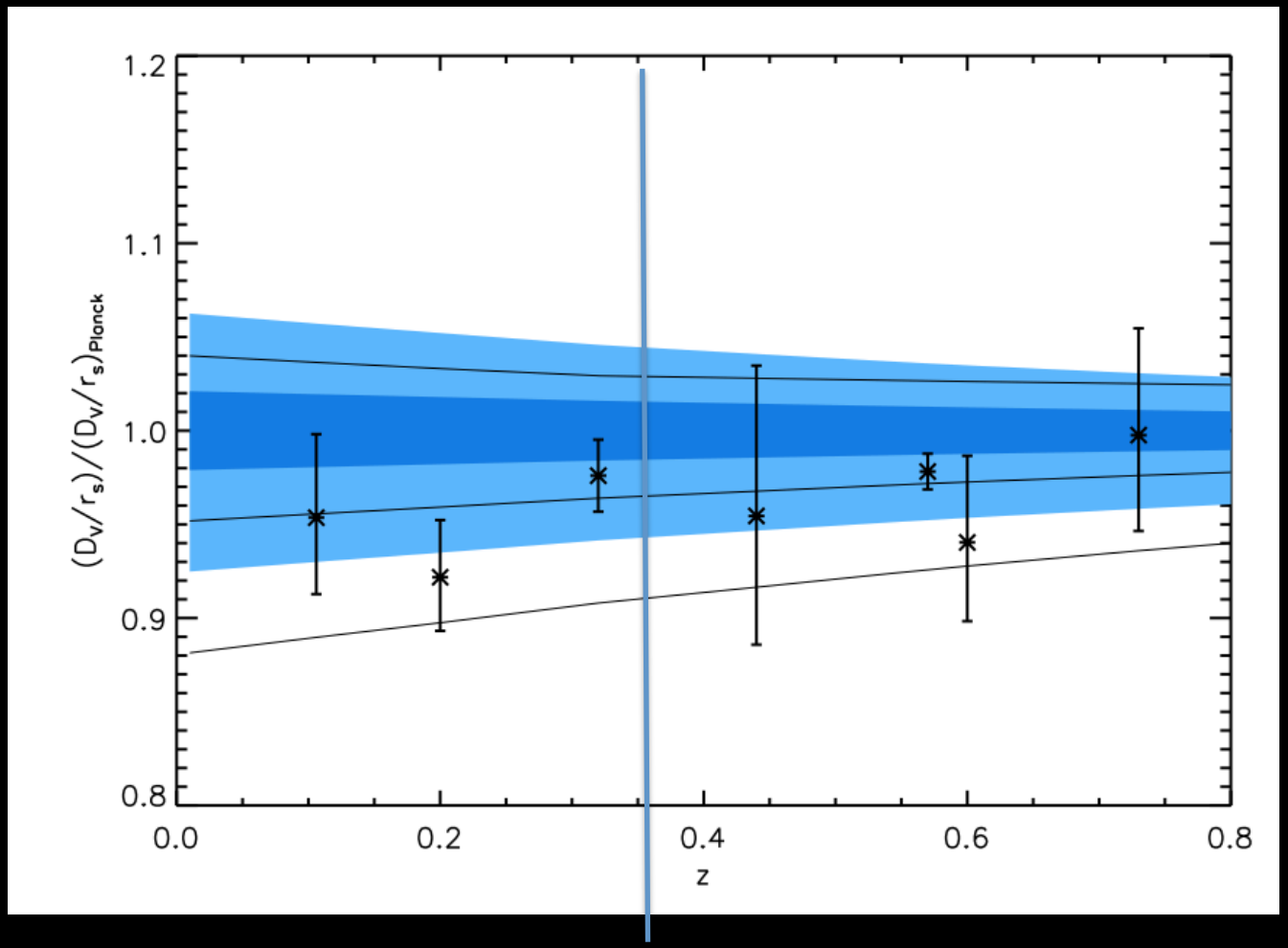


Multi Dimensional Tension



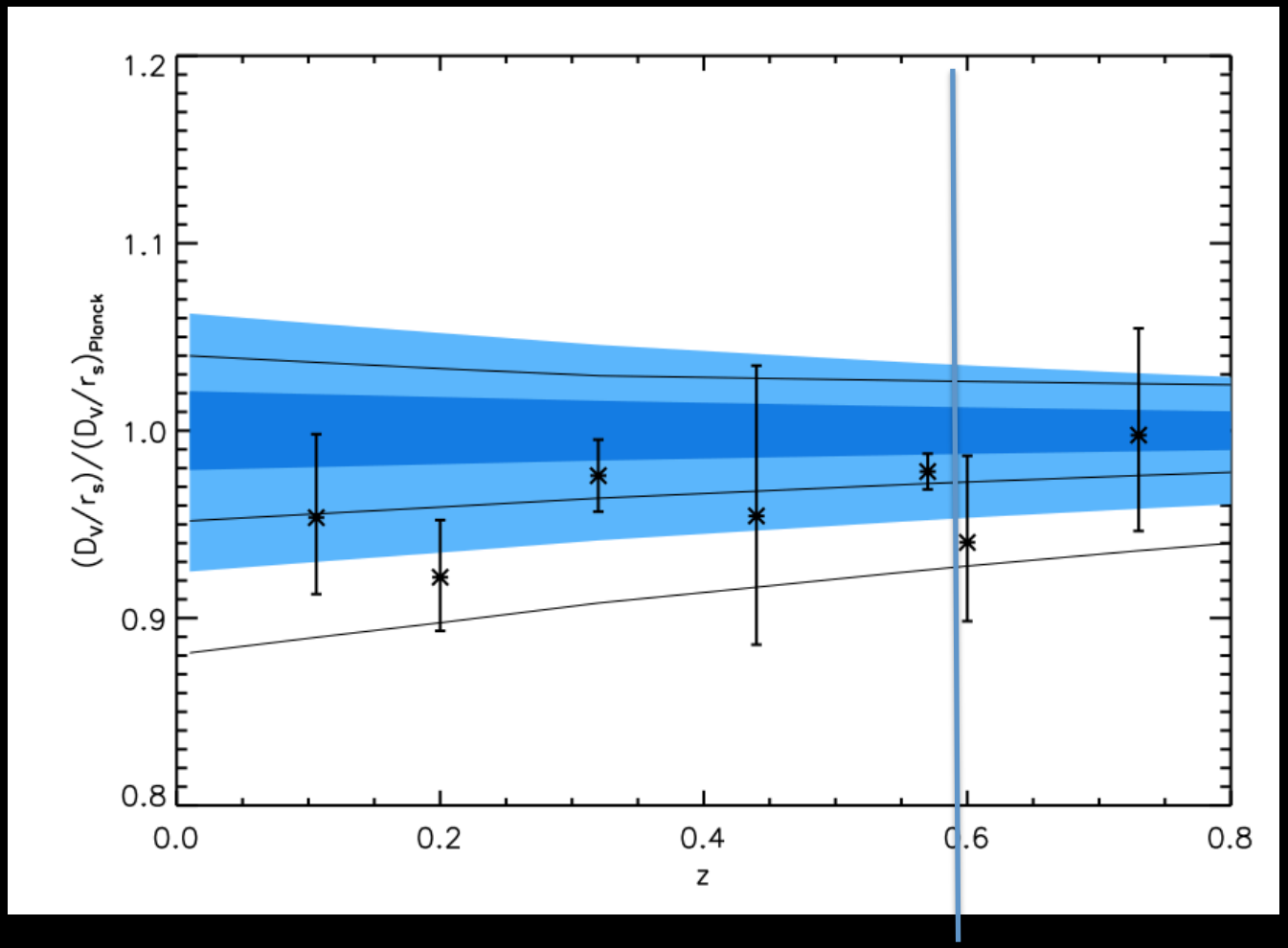
ΛCDM ln $\mathcal{T}$= 2.05, $\mathcal{T}$=7.7

Multi Dimensional Tension



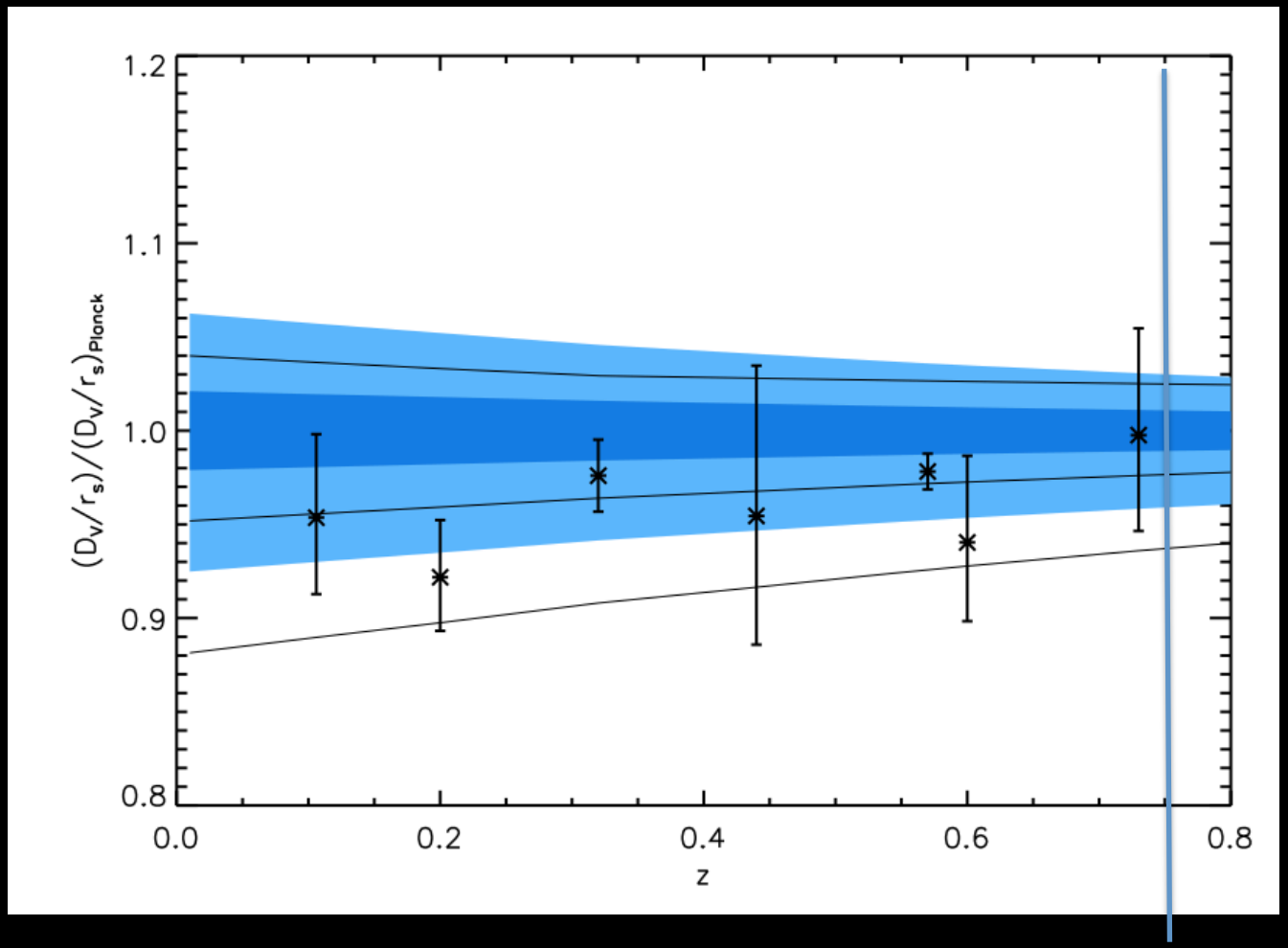
ΛCDM ln $\mathcal{T}$= 2.0, $\mathcal{T}$=7.4

Multi Dimensional Tension



ΛCDM ln $\mathcal{T}$= 2.0, $\mathcal{T}$=7.5

Multi Dimensional Tension



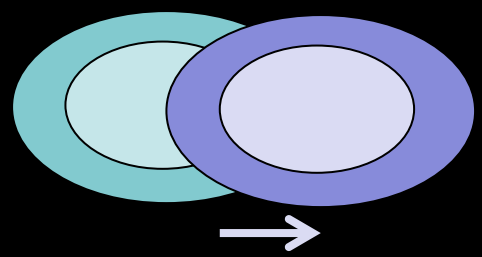
ΛCDM ln $\mathcal{T}$= 2.4, $\mathcal{T}$=11.6

Interpretation

$\ln \mathcal{T}$	interpretation	betting odds
< 1	not worth a bare mention, not significant	$< 3:1$
$1 - 2.5$	substantial	$\sim 3:1$
$2.5 - 5$	strong	$> 12:1$
> 5	highly significant	$> 150:1$

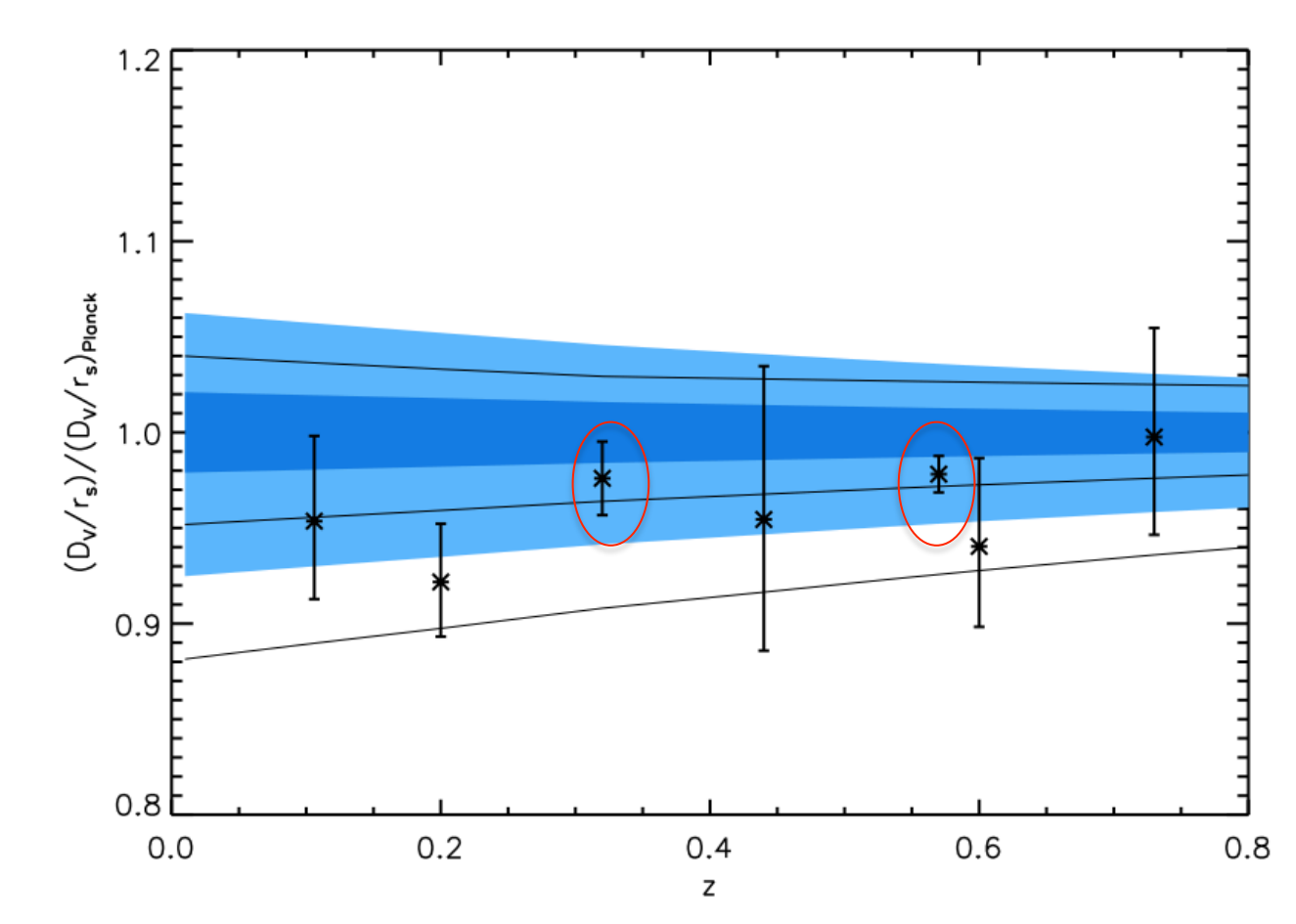
Table 1: The slightly modified Jeffreys' scale we use for interpreting the tension $\mathcal{T}$.

Keep in mind that:



1	2 σ
2.5	3 σ
5	4.5 σ

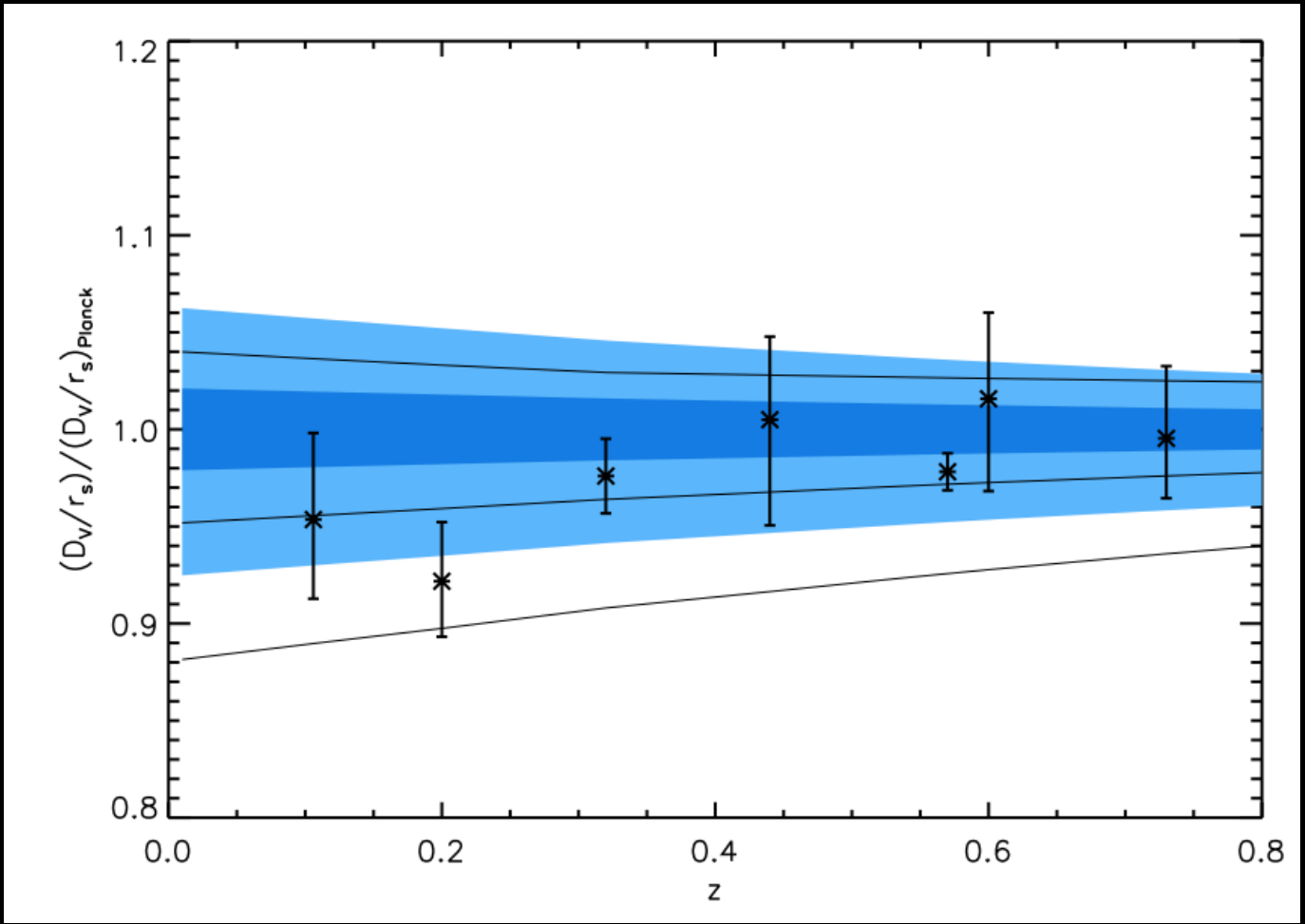
BOSS only



ΛCDM ln $\mathcal{T}$= 0.34, $\mathcal{T}$=1.4

With Wiggle z re-analysis

Kazin et al arXiv:1401.0358



ΛCDM ln $\mathcal{T}$= 2.39, $\mathcal{T}$=10.9

Voids

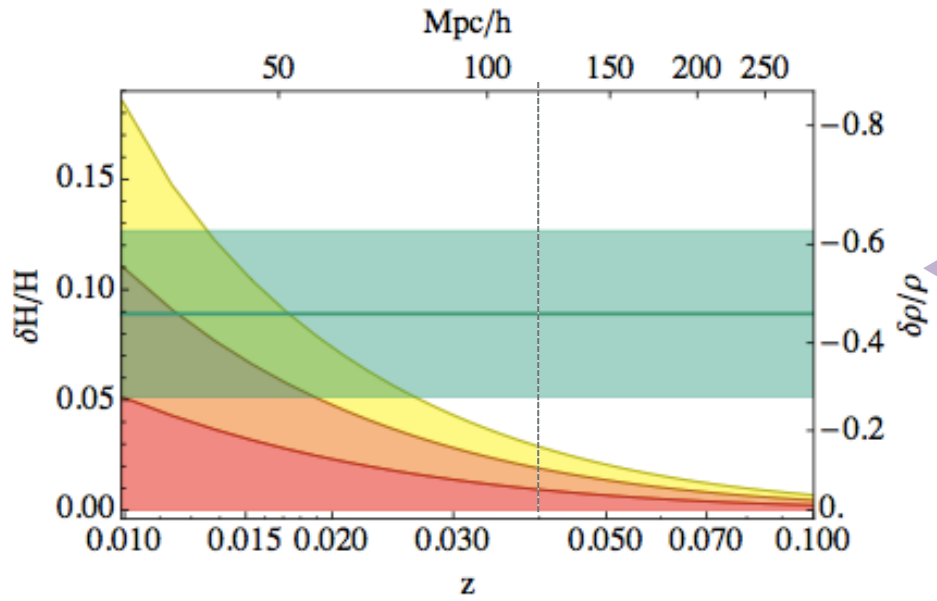
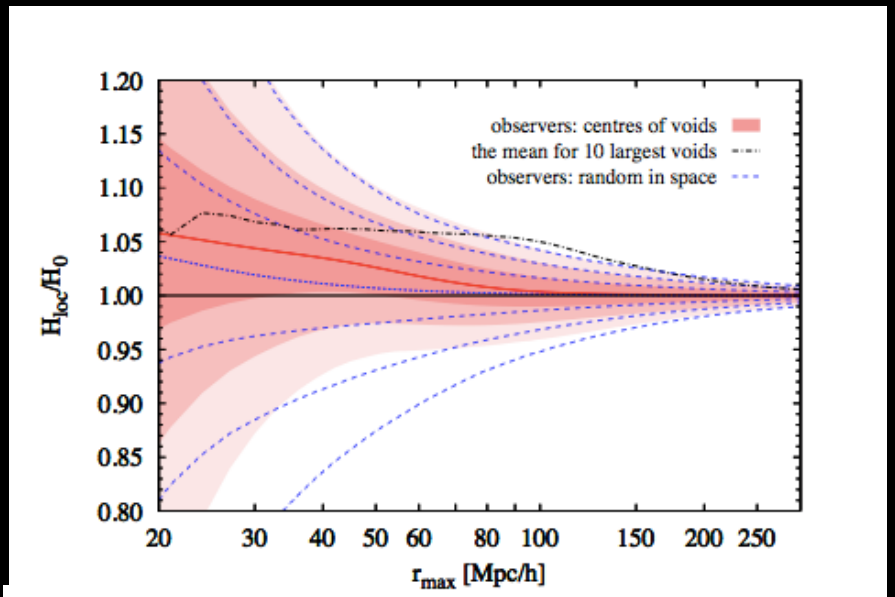
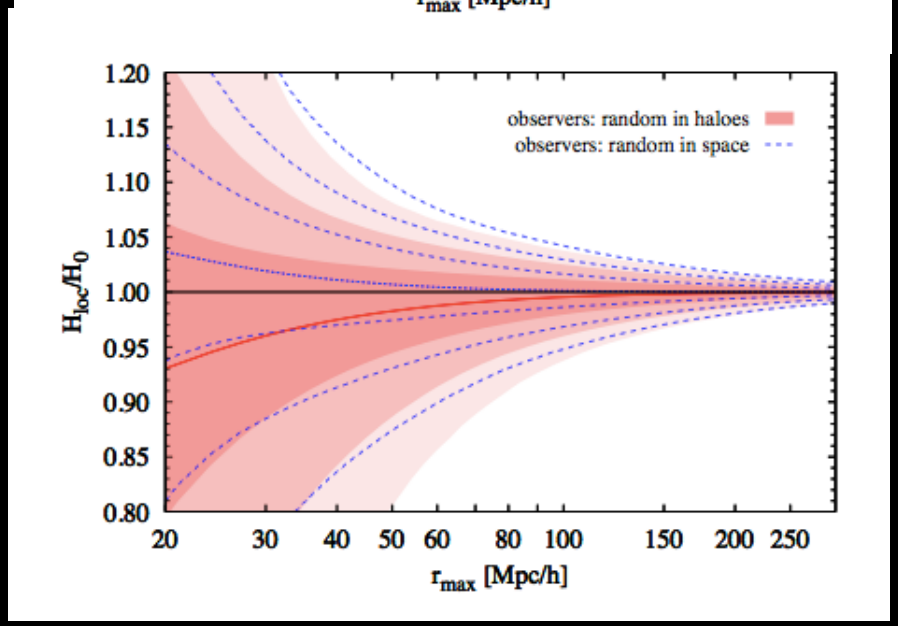


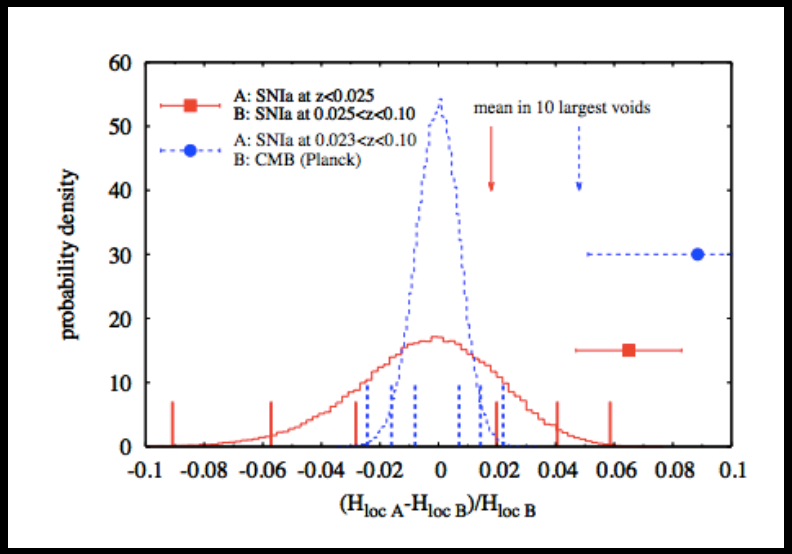
Figure 2. The 68%, 95% and 99.7% confidence-level probabilities of gaussian matter fluctuations (right vertical axis) and consequently of the local Hubble parameter (left vertical axis), as a function of co-moving size of the matter fluctuation (top ticks) or, equivalently, redshift (bottom ticks). The relation between $\delta H/H$ and $\delta\rho/\rho$ is given by Eq. (1). The range $z_{\rm min} \leq z \leq z_{\rm max}$ corresponds to the range of observation of [2]. Also shown is the 1-σ emerald band relative to the value $H_0^{\rm local}/H_0^{\rm CMB} - 1$, which shows the 2.4$\sigma$ tension between CMB and local measurements of the Hubble constant.

Marra et al (2013),
Keenan et al (2013)

Voids and halos







and Local group-lik…e

Wojitak et al 2013

Information theory

$$D_{KL}(\mathcal{P}||\mathcal{W}) = \int_x \log_2 \left(\frac{\mathcal{P}(x)}{\mathcal{W}(x)} \right) \mathcal{P}(x) dx$$

Kullback-Leibler divergence

How much new information, in bits, has Planck added to WMAP ?
Or: How many bits you need to get from WMAP posteriors to Planck posteriors?

ΛCDM	w_b	w_c	n_s	H_0	age
1D for parameter	1.35	1.63	1.09	1.21	0.83

ΛCDM Extension	Ω_k	w	$N_{\rm eff}$	M_ν
1D for parameter	0.67	1.05	1.70	0.39
$+highL$	0.82	1.18	1.90	0.91
$+lensing$	1.07	1.15	1.94	0.38

Conclusions

- There is added value in measuring locally cosmological quantities
- (Hard)
- presented the “Tension”
- Ho and Planck are in tension within the LCDM
- Blame the model or blame the observations?

Discussion

What other cosmology-independent measurements of cosmological quantities ?

BAOs (can be “massaged” to be)

H(z)

Redshift drift (M. Martinelli)

Nucleosynthesis/light elements abundance (P. Creminelli)

?????