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Planck and the local Universe

http://icc.ub.edu/~liciaverde
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$^{a,b}$

Both in Physics of the Dark universe
CMB pros and cons

Clean, simple physics, exquisite precision

Measures the Universe at $z \sim 1000$
we want to think in terms of quantities at $z=0$
$\Omega_m, \Omega_\Lambda, \Omega_b, H_0$ 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 $z \sim 1100$.

- 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 ($t_0$).
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 $\Lambda$CDM) cosmological model is inadequate or incomplete? “
Local data

Riess et al’11: $H_0=73.8 \pm 2.4$ Km/s/Mpc  Systematic+ statistical

Freedman et al ‘12: $H_0=74.3 \pm 2.1$ Km/s/Mpc  Systematic-dominated

World-average: $H_0=74.08 \pm 2.25$ Km/s/Mpc

HD 140283

t$_0=14.46 \pm 0.8$  Systematic+ statistical

Bond et al 2013
WMAP9 $\Lambda$CDM
Local vs CMB: BROAD AGREEMENT in $\Lambda CDM$
WMAP9 $\Lambda$CDM extensions

+ curvature
+ $w \neq -1$
+ curvature and $w \neq -1$

$+m_v$
$+N_{\text{eff}}$
Dark energy $w$ parameter

$w$ vs $\Omega_m$

$\tau + H_0$

CMB
(pre Planck) $N_{\text{eff}}$
(pre Planck) $M_\nu$
Enter Planck

t\textsubscript{U} updated with Gratton et al, Imbriani et al. to get 14.4 \pm 0.7 Gyr
Tension: how much?

Think in terms of evidence….

Cosmologists are (mostly) Bayesian

For model selection use Bayesian Evidence

\[ E = \int \mathcal{L}(\theta)\text{Pr}(\theta)d\theta \]

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:

\[ P(H | D) = \frac{P(D | H)P(H)}{P(D)} \]

Bayes

\[ P(\theta | D, H) = \frac{P(D | \theta, H)P(\theta | H)}{P(D | H)} \]

Bayes, for parameter fitting

\[ \mathcal{E} \equiv P(D | H) = \int d^n \theta P(D | \theta, H)P(\theta | H) \]

Bayes for the MODEL itself

To compare two models
use RATIOS \( E_1/E_2 \): Bayes factors \( B_{12} \)
If you do:  
Simpler model  
Model extension  
Positive numbers favor the simpler model

<table>
<thead>
<tr>
<th>$\ln B12$</th>
<th>interpretation</th>
<th>betting odds</th>
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Quiz

Imagine you have this situation:

What would the evidence ratio say?

**LCDM**

Likelihood

Flat ridge

Extra parameter (LCDM extension)

LCDM
solution

model 1 is the simpler model with parameter(s) $\phi$
model 2 is the extension, $\psi$ is the extra parameter(s)

$$
E_2 = \int \int \Pr(\phi, \psi|M_2) \Pr(d|\phi, \psi, M_2) \, d\phi \, d\psi \\
= \int \left[ \int \Pr(\phi, \psi|M_2) \, d\psi \right] \Pr(d|\phi, M_2) \, d\phi \\
= \int \Pr(\phi|M_1) \Pr(d|\phi, M_1) \, d\phi \\
= E_1.
$$

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

Introduce:

\[ \mathcal{T} = \frac{\bar{\mathcal{E}}|_{\text{max}A=\text{max}B}}{\mathcal{E}} \]

Null hypothesis
Tension: how much?

Think in terms of evidence.

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

\[ \lambda^{-1} = \frac{1}{\int \mathcal{L}_A \pi_A dx \int \mathcal{L}_B \pi_B dx} \]

Introduce:

\[ \mathcal{T} = \frac{\mathcal{E}|_{\text{max}A=\text{max}B}}{\mathcal{E}} \]
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

For LCDM,
Planck vs local Universe

\[ \ln \mathcal{T} = 3.96 \]

Odds \(~ 1:50\)

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

Interpretation

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Table 1: The slightly modified Jeffreys’ scale we use for interpreting the tension $\tau$.

Keep in mind that:

1
2.5
5
2 $\sigma$
3 $\sigma$
4.5 $\sigma$

3.98 sigmas
local measures with Planck

\[ \pm \text{curvature} \]
\[ +w \neq -1 \]
local measures with Planck

+ curvature

+ $w \neq -1$

$+m_v$

$+N_{\text{eff}}$
local measures with Planck
local measures with Planck
local measures with Planck
local measures with Planck
What about $n_s$?

Planck

Yp not varied

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

Black: delta log like 3
Green: delta log like 2
Red: delta log like 1
Blue: the max
And now what?

Option a)
some errors are under-estimated. Let’ us just pick on $H_0$
and explore the consequences (see if we can live with them)
And now what?

Option a)
some errors are under-estimated. Let’s 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?

<table>
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<tr>
<th>model extension</th>
<th>$w$</th>
<th>$\Omega_k$</th>
<th>$N_{\text{eff}}$</th>
<th>$M_\nu$</th>
<th>$N_{\text{eff}} + Y_P$</th>
</tr>
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<tbody>
<tr>
<td>$\ln T$</td>
<td>0.74</td>
<td>5.24</td>
<td>1.94</td>
<td>4.5</td>
<td>2.2</td>
</tr>
<tr>
<td>$\ln \frac{E_{\Lambda \text{CDM}}}{E_{\text{extension}}}$</td>
<td>-0.72</td>
<td>3.70</td>
<td>-0.27(P)</td>
<td>3.45</td>
<td>1.93(P)</td>
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Remember LCDM $\ln T = 3.96$
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

w ~ -1.2 makes tension not significant!

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

Amerson 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:

\[ \int P_A P_B dx = \lambda \int L_A L_B \pi_A \pi_B dx = \lambda \int L_A L_B \pi dx = \varepsilon. \]

\[ \lambda^{-1} = \int L_A \pi_A dx \int L_B \pi_B dx \]

\[ \int P_A P_B dx = \varepsilon_{\text{maxA=maxB}} \]

Introduce:

\[ \mathcal{T} = \frac{\varepsilon_{\text{maxA=maxB}}}{\varepsilon} \]

Just in higher dimensions, not 2 measurements any more but ~ 7
With new BOSS measurements
Multi Dimensional Tension

$\Lambda CDM \ \ln T = 2.05, \ T = 7.7$
$\Lambda CDM \ln T' = 2.0, T' = 7.4$
$\Lambda CDM \ \ln T' = 2.0, \ T' = 7.5$
\[ \Lambda CDM \text{ ln } T = 2.4, \ T = 11.6 \]
Interpretation

Keep in mind that:

- $\ln \mathcal{T}$
- $< 1$: not worth a bare mention, not significant
- $1 - 2.5$: substantial
- $2.5 - 5$: strong
- $> 5$: highly significant

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Keep in mind that:

- 1
- 2.5
- 5

$2 \sigma$
$3 \sigma$
$4.5 \sigma$
$\Lambda$CDM $\ln T' = 0.34, T' = 1.4$
With Wiggle z re-analysis

$\Lambda \text{CDM}$ $\ln T = 2.39$, $T = 10.9$

Kazin et al arXiv:1401.0358
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 $z_{\text{min}} \leq z \leq z_{\text{max}}$ corresponds to the range of observation of [2]. Also shown is the 1-$\sigma$ emerald band relative to the value $H_0^{\text{local}}/H_0^{\text{CMB}} - 1$, which shows the 2.4$\sigma$ tension between CMB and local measurements of the Hubble constant.

Voids and halos

Wojitak et al 2013

and Local group-like

Wojitak et al 2013
Information theory

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

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?

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<th>$w_b$</th>
<th>$w_c$</th>
<th>$n_s$</th>
<th>$H_0$</th>
<th>age</th>
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<td>1D for parameter</td>
<td>1.35</td>
<td>1.63</td>
<td>1.09</td>
<td>1.21</td>
<td>0.83</td>
</tr>
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<td>$\Lambda$CDM Extension</td>
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$+h_{\text{high}L}$

$+\text{lensing}$
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)

?????