On The “Hubble Tension”  
And How To Resolve It

Vivian Poulin
LUPM (France) and Johns Hopkins University

w/ T. Smith, T. Karwal and M. Kamionkowski 1811.04083
+ D. Grin 1806.10608
The Era of Precision Cosmology

20 years ago

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The Era of Precision Cosmology

10 years ago

Angular scale

\[ l(l+1)C_l / 2\pi \text{ [}\mu \text{K}^2]\]

Multipole moment \(l\)

[Graph showing angular scale and multipole moment with data from WMAP, Acbar, Boomerang, CBI, and VSA]
The Era of Precision Cosmology
The Era of Precision Cosmology

Very good agreement between all CMB data!
The Era of Precision Cosmology

And also with non-CMB data!

SN1a

BAO

Galaxy Clustering
The Era of Precision Cosmology

Astonishing success of $\Lambda$CDM Cosmology

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Planck alone</th>
<th>Planck + BAO</th>
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<tr>
<td>$\Omega_b h^2$</td>
<td>$0.02237 \pm 0.00015$</td>
<td>$0.02242 \pm 0.00014$</td>
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<td>$\ln(10^{10}A_s)$</td>
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Planck alone:
- 0.6% precision
- 1% precision
- 0.3% precision
- 13% precision
- 5% precision
- 0.5% precision
- 0.7% precision

E.g. 2015 data: TT +lowP reduced $\chi^2 = 1.004$
The Era of Precision Cosmology

Astonishing success of ΛCDM Cosmology

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As precision of data has increased, a certain number of “tensions” have emerged:

- $S8 = \sigma_8(\Omega_m/0.3)^{0.5}$ is higher at ~2-3σ than that measured by low-z probes (SZ cluster count, Weak Lensing surveys CFHTLenS, KiDS, DES...)

- Amplitude of lensing potential $C_{l\phi\phi}$ is higher than deduced from peak smoothing in TT/TE/EE at ~2σ.

**Potentially very interesting but still very premature...**
The Hubble Tension

3.8σ discrepancy between latest “direct” measurement from SH0ES and the value inferred from a fit of ΛCDM to Planck 2018

\[ H_0(\text{SH0ES}) = 73.52 \pm 1.62 \text{ km/s/Mpc} \]

Riess++ 1804.10655

\[ H_0(\Lambda\text{CDM}) = 67.27 \pm 0.60 \text{ km/s/Mpc} \]

Aghanim++ 1807.06209
Outline

- Is the Hubble Tension Real?
- Is it a “Hubble Tension” or “Sound Horizon” tension?
- Early Dark Energy Can Resolve The Hubble Tension
- Towards a new concordance model beyond $\Lambda$CDM?
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SYSTEMATICS??
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The Distance Ladder

absolute distance scale accessible

- solar system ($10^{-4}$ ly)
- nearby stars ($10^2$ ly)
- Milky Way ($10^7$ ly)
- nearby galaxies
- galaxy clusters ($10^{10}$ ly)

Hubble’s law: $d = \frac{V}{H_0}$

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The Distance Ladder

absolute distance scale accessible

solar system \((10^{-4}\text{ ly})\)

nearby stars \((10^2\text{ ly})\)

Venus

Sun

radar ranging

parallax

nearby galaxies \((10^7\text{ ly})\)

Milky Way

relative apparent brightness

surface temperature (K)

main-sequence fitting

Cepheids

luminosity

period

Tully–Fisher relation

distant standards

galaxy clusters \((10^{10}\text{ ly})\)

white dwarf supernovae

Hubble’s law: \(d = \frac{V}{H_0}\)

“calibrated” distances

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The Distance Ladder

GAIA will measure few*100’s of cepheids at μas precision by 2022 (currently ~ 50)
Could it be systematics in SN data?

- Sources of error are numerous (non-exhaustive list):
  - i) measurement of parallaxes.
  - ii) measurement of (apparent) magnitudes.
  - iii) calibration issues: are SN1 really standard candles?
  - iv) effect of local environment: could “local, young” cepheids be different from the “old, Hubble flow” cepheids?
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- High value of H0 is supported by numerous studies, including non-SH0ES ones.
  \[ \text{Cardina}++ 1611.06088, \text{Zhang}++ 1706.07573, \text{Feeney}++ 1707.00007, \text{Follin} & \text{Knox} 1707.01175 \]

- Environmental effects exist but cannot explain more than ~1% of the difference.
  \[ \text{Macpherson}++ 1807.01714, \text{Jones}++ 1805.05911 \]

- 5 different calibration methods all giving consistently high values of H0.
  \[ \text{see discussion in Riess}++ 1810.03526 \]
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- **Exists even with non-SN data**: Gravitational time delay of strongly lensed quasars is in (mild) tension with Planck.
  - \( H_0 = 72.5 \pm 2.1 \text{ km s}^{-1} \text{ Mpc}^{-1} \)
  - *Bonvin++ 1607.01790*, *S. Birrer++*, *1809.01274*

- **In the (near) future**: Gravitational wave standard sirens (~5 yrs) expect to get to 1km/s/Mpc.
  - *Mortlock++ 1811.11723*
Could it be systematics in Planck data?

- It is driven by residuals oscillations at $\ell > 800$ and the low-$\ell \sim 30$ deficit.

*Addison++ 1511.00055, Planck Col. 1608.02487*

**Figure:**

- $H_0$ graph with regions: $\ell < 2500$, $\ell < 2500 A_L$, $30 < \ell < 2500$, and $30 < \ell < 800$.
- $\omega_m$ graph with regions: $\ell < 800$, $\ell < 2500 A_L$, $\ell < 2500 \text{fixlens}$, $30 < \ell < 800$, and $30 < \ell < 2500$.

*TT + $\tau$ prior, 1σ error*
Could it be systematics in Planck data?

- It is driven by residuals oscillations at \( l > 800 \) and the low-\( l \sim 30 \) deficit. 

  \[ \text{Addison++ 1511.00055, Planck Col. 1608.02487} \]

- It exists with other CMB data: WMAP+SPT/ACT+BAO \( \sim 2.4\text{-}3.1\sigma \) with SH0ES.

- It exists even with non-CMB data! BAO+BBN \( \sim 3\sigma \) with SH0ES. 

  \[ \text{Addison++ 1707.06547} \]
$H_0$ from the CMB is model dependent

\[ \Omega_k \text{ free} \]
Planck measurement is strongly model dependent! baseline assumes “flat” universe

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Early/late universe physics are degenerate

- standard ruler in the sky: distance travelled by sound wave until recombination.
- problem: only angular scale of sound horizon is accessible

\[ \theta_s \approx \frac{r_s}{D_A} \]
Early/late universe physics are degenerate

- standard ruler in the sky: distance travelled by sound wave until recombination.
- problem: only angular scale of sound horizon is accessible $\theta_s = r_s/D_A$

**illustration: T. Smith**

- $r_s$ pre-recombination physics: DOES NOT depend on $H_0$, but on physical densities $\omega_x$
- $d_A$ angular diameter distance: post-recombination physics. $d_A \propto \omega_m^{-0.35}H_0^{-0.2}$
How does CMB data measure $H_0$?

It comes from the measurement of three angular scales: $\ell_s, \ell_d, \ell_{eq} \Rightarrow \theta_s, \theta_d, \theta_{eq}$

$\theta_s$ sound horizon at last scattering $\sim 1.0404$

(nb: any $\theta_x = r_x/D_A$)

e.g. Hu&White astro-ph/9609079, Hu++astro-ph/0006436
How does CMB data measure $H_0$?

- It comes from the measurement of **three angular scales**: $\ell_s$, $\ell_d$, $\ell_{eq} \Rightarrow \theta_s, \theta_d, \theta_{eq}$

$\theta_d$ photon diffusion length at last scattering $\sim 0.1609$

\[ \text{(nb: any } \theta_x = r_x/D_A) \]
How does CMB data measure H0?

- It comes from the measurement of three angular scales: $\ell_s, \ell_d, \ell_{eq} \rightarrow \theta_s, \theta_d, \theta_{eq}$

$\theta_{eq}$ horizon size at matter-radiation equality $\sim 0.81$

(n.b. any $\theta_x = r_x/D_A$)  

e.g. Hu&White astro-ph/9609079, Hu++astro-ph/0006436
A modified Dark-Energy sector?

- $h$ increases but $d_A^*(z^*)$ must be kept constant: **decrease $\Omega_{DE}$ at $z < z^*$**

\[
\theta_X \equiv \frac{r_X}{d_A} \quad d_A^*(z^*) = \int_0^{z^*} \frac{dz}{100\sqrt{\omega_M (1 + z)^3 + \Omega_{DE}(z) h^2}}
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$$

- Requires phantom crossing (stability of perturbations?)
- JLA favors "flat" expansion history / BAO favors oscillation: 2$\sigma$ residual tension
The H0 tension is a $r_s$ tension

One can deduce the co-moving sound horizon $r_s$ from H0 and BAO $r_s$ from CMB needs to decrease by $\sim 10$ Mpc

- H0LiCOW+SNe+BAO ($\Lambda$CDM)
- Cepheids+SNe+BAO ($\Lambda$CDM)
- Cepheids+SNe+BAO (Spline, $\Omega_k = 0$)

Planck
- TT+lowE
- TE+lowE
- EE+lowE
- TT ($\ell < 800$)
- TT ($\ell > 800$)
- WMAP9+SPT+ACT
- SPT-SZ+\tau
- SPTpol+\tau
- ACTpol+\tau
- BAO+BBN

Planck+3G(TT,TE,EE+lensing)

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How to solve the Hubble tension

- $r_s$ does not reach 10Mpc before ~ 25000 in $\Lambda$CDM
- $r_s$ receives most of its contribution close to recombination

\[ r_s = \int_{\infty}^{z^*} \frac{c_s(z)}{H(z)} dz \]

$\Lambda$CDM prediction
How to solve the Hubble tension

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decrease $c_s$: DM-photon scattering? DM-b scattering?

Boddy, Gluscevic, VP++1808.00001
How to Resolve the Hubble tension

decrease $z^*$: modified recombination physics?

Chiang & Slozar 1811.03624

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increase $H(z)$: Neff? Early Dark Energy?

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V. Poulin - LUPM & JHU

Stony Brook - 01/24/19
How to Resolve the Hubble tension

decrease $z^*$: modified recombination physics?

$\text{Neff} \sim 3.5$ is needed

$\text{increase } H(z): \text{Neff? Early Dark Energy?}$

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$Bodd\mathring{\text{y}}, \text{Gluscevic, VP++1808.00001}$

$\int_{\infty}^{z^*} dz \frac{c_s(z)}{H(z)}$

$Bernal++ 1607.05617$
How to Resolve the Hubble tension

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• Neff $\sim 3.5$ is needed: disfavored by Planck high-l polarization and BAO

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- decrease $z^*$: modified recombination physics?
- decrease $c_s$: DM-photon scattering? DM-b scattering?
- increase $H(z)$: Neff? Early Dark Energy?

Neff ~ 3.5 is needed: disfavored by Planck high-$l$ polarization and BAO

\[ r_s = \int_{\infty}^{z^*} dz \frac{c_s(z)}{H(z)} \]

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V. Poulin - LUPM & JHU  Stony Brook - 01/24/19
Scalar field and Early Dark Energy

Initially slowly-rolling field (due to Hubble friction) that later dilutes faster than matter

\[ \ddot{\phi} + 3H\dot{\phi} + \frac{dV_n(\phi)}{d\phi} = 0 \]

\[ \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_n(\phi), \quad P_\phi = \frac{1}{2}\dot{\phi}^2 - V_n(\phi) \]
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We use the GDM formalism with:

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\begin{cases}
    \Omega_{EDE}(z \gg z_c) = \Omega_{EDE}(z_c) \\
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\(n=1: \text{matter, } n=2: \text{radiation, etc.}\)

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\(GDM: \text{Hu astro-ph/9801234}\)
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GDM: Hu astro-ph/9801234

Realized in (at least) two models:

One with oscillating potential ("axion-like") and a simple linear potential

\[ V(\phi) \propto \phi^{2n} \]

VP++1806.10608; Karwal, VP++(in prep)
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- This allows us to treat perturbations in the fluid consistently: this is essential to the success of the solution.

GDM: Hu astro-ph/9801234

\[ n=1: \text{matter}, \quad n=2: \text{radiation}, \text{etc.} \]

plot by T. Karwal

VP++1806.10608; Karwal, VP++(in prep)

This allows us to treat perturbations in the fluid consistently: this is essential to the success of the solution.

background only: Karwal&Kamionkowski 1608.01309
We also include linear perturbations!

\[ \ddot{\phi}_1 + 3H \dot{\phi}_1 + \left( \frac{k^2}{a^2} + V'' \right) \phi_1 = (\dot{A} + 3\dot{H}_L - k/aB)\phi_0 - 2AV' \]

WKB approx.

fluid with \( c_s^2, c_a^2 \) & \( w \)

\[ \dot{\delta}_a = - \left[ u_a + (1 + w_a)\frac{\dot{h}}{2} \right] - 3(c_s^2 - w_a)H\delta_a \]
\[ -9(c_s^2 - c_a^2)H\frac{u_a}{k^2}, \]
\[ \ddot{u}_a = -(1 - 3c_s^2)Hu_a + 3H(w_a - c_a^2)u_a + c_s^2k^2\delta_a. \]

1 hour
1 sec!
Perturbations are important

no perturbations: Karwal&Kamionkowski 1608.01309
Early Dark Energy In Cosmological Data?

CMB+BAO+Pantheon+SH0ES
Early Dark Energy In Cosmological Data?

- CMB+BAO+Pantheon+SH0ES

![Graph showing Early Dark Energy In Cosmological Data](image)
Early Dark Energy In Cosmological Data?

- CMB+BAO+Pantheon+SH0ES

For $n >= 2$: $\sim 2\sigma$ detection

$$f_{\text{EDE}}(z_c) \equiv \frac{\rho_{\text{EDE}}(z_c)}{\rho_{\text{tot}}(z_c)} \sim 5 \pm 2\%$$

$$z_c \sim 4000 - 7000$$
Early Dark Energy In Cosmological Data?

- CMB+BAO+Pantheon+SH0ES

- For $n >= 2$: $\sim 2\sigma$ detection

$$f_{EDE}(z_c) \equiv \frac{\rho_{EDE}(z_c)}{\rho_{tot}(z_c)} \sim 5 \pm 2\%$$

- $z_c \sim 4000 - 7000$

- strong increase in $\omega_{cdm}$
Why \( z_c \sim 5000? \)

Change in \( r_s, r_s/r_D, \) Peak Height \(-vs-\) \( a_c \)

- \( r_s = \) sound horizon
- \( r_D = \) damping scale
- \( PH = \) Peak Height

\[
\begin{align*}
\log_{10}(a_c) & \quad \quad \text{for } n = 2 \\
\log_{10}(a_c) & \quad \quad \text{for } n = 3 \\
\log_{10}(a_c) & \quad \quad \text{for } n \rightarrow \infty
\end{align*}
\]
Why $z_c \sim 5000$?

Change in $r_s$, $r_s/r_D$, Peak Height -vs- $a_c$

- $r_s$ = sound horizon
- $r_D$ = damping scale
- PH = Peak Height

- Favored region maximizes the $r_s$ decrease and minimizes $r_s/r_D$ shift.
Why $z_c \sim 5000$?

Change in $r_s$, $r_s/r_D$, Peak Height - vs - $a_c$

- Favored region maximizes the $r_s$ decrease and minimizes $r_s/r_D$ shift.
- From requiring $\delta r_s \sim 10$ Mpc; $\delta(r_s/r_D)\sim 0$: Neff is disfavored; n=3 fairs slightly better.

$r_s = \text{sound horizon}$  
$r_D = \text{damping scale}$  
$PH = \text{Peak Height}$
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- From requiring $\delta r_s \sim 10$ Mpc; $\delta(r_s/r_d) \sim 0$: Neff is disfavored; n=3 fairs slightly better.
- Increase in Peak Height (and $\theta_{eq}$) is compensated via increase in $\omega_{cdm}$.
### Some Statistics

- Slight preference for $n=3$. ‘‘Definite’’ evidence according to Jeffrey’s scale.

<table>
<thead>
<tr>
<th>Datasets</th>
<th>$\Lambda$CDM</th>
<th>$n = 2$</th>
<th>$n = 3$</th>
<th>$n = \infty$</th>
<th>$N_{\text{eff}}$</th>
</tr>
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<td>\textit{Planck} high-$\ell$</td>
<td>2449.5</td>
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<td>10493.1</td>
<td>10494.4</td>
<td>10493.8</td>
</tr>
<tr>
<td>\textit{Planck} lensing</td>
<td>9.2</td>
<td>9.6</td>
<td>10.0</td>
<td>10.1</td>
<td>9.8</td>
</tr>
<tr>
<td>BAO-low $z$</td>
<td>1.7</td>
<td>1.8</td>
<td>2.3</td>
<td>1.7</td>
<td>2.7</td>
</tr>
<tr>
<td>BAO-high $z$</td>
<td>1.8</td>
<td>1.9</td>
<td>2.1</td>
<td>1.9</td>
<td>2.0</td>
</tr>
<tr>
<td>Pantheon</td>
<td>1027.1</td>
<td>1026.9</td>
<td>1027.2</td>
<td>1027.3</td>
<td>1027.1</td>
</tr>
<tr>
<td>SH0ES</td>
<td>11.1</td>
<td>4.7</td>
<td>0.92</td>
<td>4.2</td>
<td>3.9</td>
</tr>
<tr>
<td>\text{Total $\chi^2_{\text{min}}$}</td>
<td>13995.1</td>
<td>13985.1</td>
<td>13980.8</td>
<td>13985.4</td>
<td>13991.2</td>
</tr>
<tr>
<td>$\Delta \chi^2_{\text{min}}$</td>
<td>0</td>
<td>-10</td>
<td>-14.3</td>
<td>-9.7</td>
<td>-3.9</td>
</tr>
<tr>
<td>$\Delta \log B$</td>
<td>0</td>
<td>-0.51</td>
<td>+2.51</td>
<td>+2.41</td>
<td>-0.44</td>
</tr>
</tbody>
</table>

- \textit{Planck} Only: Very slight improvement.

\[ \chi^2_{\text{high-$\ell$}} \simeq 2446.2, \quad \chi^2_{\text{low-$\ell$}} \simeq 10495.9, \quad \chi^2_{\text{lensing}} \simeq 9.4 \]
Future CMB experiments can probe the model

Oscillations in EE would definitely be detected by CoRE/ SO / CMB-S4

© A. Lewis
Future H0 measurements can help too

what if we had Planck+BAO+Pantheon+

\[ H_0 = 73.4 \pm 1 \text{ km s}^{-1} \text{ Mpc}^{-1} \]

\[ \Delta \chi^2 = 14 \]

\[ \Delta \chi^2 (\text{Planck}) = +2 \]

**EDE**

V. Poulin - LUPM & JHU

Stony Brook - 01/24/19
Towards a new concordance model?

Planck 2013 data already hinted at accelerated expansion history around $a \sim 5 \times 10^{-4}$!

\[ H^2(a) = \frac{8\pi G}{3} \left[ \rho_m(a) + \rho_r(a) + \rho_\Lambda \right] [1 + \delta(a)] \]

Hojjati, Linder, Samsing 1304.3724

Here Planck TT 2013 + WMAP EE and TE, to be confirmed with 2018 data…
Some lessons to be learned

- If the “Hubble Tension” is confirmed by other local H0 measurements, the EDE solution represents the best possible “early-universe” solution.

- There are many open questions with the potential presence of such an EDE phase.

- Obvious “fine tuning” issues: why would it need to kick right around matter-radiation equality? why in such amount?
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- If the “Hubble Tension” is confirmed by other local H0 measurements, the EDE solution represents the best possible “early-universe” solution.

- There are many open questions with the potential presence of such an EDE phase.

- Obvious “fine tuning” issues: why would it need to kick right around matter-radiation equality? why in such amount?

  ΛCDM already has similar issues!

- The ‘coincidence problem’: why now? Structure cannot grow in CC dominated universe.

- Hierarchy problem: why is this scale \((0.002 \text{ eV})^4\) so different from Weak / Planck scales?
A New Understanding Of $\Lambda$?

- Accelerated expansion era might be related to each other. What if there were more of such era to be discovered?

- Is their one field with a complicated potential or many fields with simple potentials?

  e.g. Dodelson++astro-ph/0002360, Griest astro-ph/0202052, Kamionkowski++1409.0549
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Conclusions

H_0 from local measurement is in 3.8σ tension with LCDM-inferred value from Planck: this tension also exists with non-SN and non-CMB data! It is a tension between our understanding of the early and late universe.

This tension can be recast as a sound-horizon tension: CMB r_s too high by 10Mpc.
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- A Hubble-frozen scalar field acting like Early Dark Energy until $z\sim 5000$ with $f(z_c)\sim 5\%$ and diluting faster than radiation later can solve the Hubble tension.

- CMB, BAO and Pantheon data are fitted just as well as in LCDM (or even better? TBC). “Definite” evidence for $n\geq 3$ in Bayesian terms.
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- If this is the “correct” solution: there might be new ways of interpreting $\Lambda$ and inflation.
And the winner is?

Thank you!
Back Up
Should we detect 5% EDE with Planck?

Fiducial = best fit model with EDE. Optimistic Planck + SH0ES cannot see it at >2sig.
How does CMB data measure $H_0$?

$$\theta_X \equiv \frac{r_X}{d_A}$$

e.g. Hu&White astro-ph/9609079, Hu++astro-ph/0006436
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- physical scale: pre-recombination physics;
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post-recombination physics $d_A \propto \omega_M^{-0.35} H_0^{-0.2}$

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Fig. 5. Constraints on parameters of the base-$\Lambda$CDM model from the separate Planck Collaboration: Cosmological parameters

Notations:

- $\theta_X$ angular diameter distance
- $r_X$ comoving distance to redshift $r_X$
- $d_A$ angular diameter distance
- $H_0$ Hubble constant
- $\omega_M$ matter density
- $\omega_X$ total density
- $\Omega_c h^2$ cold dark matter density

References:


Planck 2018
How does CMB data measure H0?

- Physical scale: pre-recombination physics; DOES NOT depend on H0, but on physical densities \( \omega_X \)

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Measurements of the absolute Peak Height and Peak Height ratios allow to measure \( \omega_b, \omega_M \) and infer a value of H0.
How does CMB data measure \( H_0 \)?

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Typical (background) dynamics of ULA

$m = 10^{-26}$ eV
Typical (background) dynamics of ULA

Hubble friction wins: field is frozen

$\Omega_\Theta$

$m = 10^{-26}$ eV

$10^{11}$

$10^{10}$

$10^{9}$

$10^{8}$

$10^{7}$

$10^{6}$

$10^{2}$

$10^{3}$

$10^{4}$

$10^{5}$

$n = 1$

$n = 2$

$n = 3$

radiation

CDM
Typical (background) dynamics of ULA

\[ m = 10^{-26} \text{ eV} \]

Hubble friction wins: field is frozen

\[ m > 3H: \text{the field rolls down and oscillates} \]
Typical (background) dynamics of ULA

VP, Smith, Grin, Karwal, Kamionkowski; 1806.10608

Hubble friction wins: field is frozen

$m > 3H$: the field rolls down and oscillates

$n = 1$ matter; $n = 2$ radiation; $n = 3$ faster than radiation

$m = 10^{-26}$ eV
Typical (background) dynamics of ULA

Key Idea: Early Dark Energy can increase expansion rate and solve various tensions. Once the field becomes dynamical, it dilutes away (the faster the better)!

VP, Smith, Grin, Karwal, Kamionkowski; 1806.10608
When is the WKB approximation valid?

- Our WKB approximation requires oscillation time-scale $\ll$ Hubble time-scale.

- The oscillation time-scale can be obtained from requiring that energy is conserved over several oscillations (no friction).

$$\frac{\omega}{H} \propto \begin{cases} a^{(5-n)/(1+n)} & a < a_{eq}, \\ a^{6/(1+n)-3/2} & a > a_{eq}, \end{cases}$$

- This ratio increases with time for $n < 5$ during radiation domination and for $n < 3$ for matter domination.

- The condition $\omega > H$ holding at all time requires $n < 3$.

See also Johnson and Kamionkowski, 0805.1748.
Comparison with full KG calculation

- Without perturbations, precision is >3% given Planck constraints. Planck is ~1% precise!
- With perturbations, sub-percent agreement: 1h vs 1sec computation time!