Sounds Discordant: Classical Distance Ladder and ΛCDM-based Determinations of the Cosmological Sound Horizon

Kevin Aylor  Mackenzie Joy  Marius Millea  Srini Raghunathan  Kimmy Wu

https://arxiv.org/abs/1811.00537 and ApJ

https://arxiv.org/abs/1908.03663 (PRD 2020)

The Hubble Hunter’s Guide  LK and Marius Millea
Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 10 Aug 2019 (v1), last revised 16 Sep 2019 (this version, v2)]

The Hubble Hunter's Guide

Lloyd Knox, Marius Millea

PHYSICAL REVIEW D
covering particles, fields, gravitation, and cosmology

Hubble constant hunter's guide

L. Knox and M. Millea
Phys. Rev. D 101, 043533 – Published 27 February 2020
The theoretical picture

Lloyd Knox
UC Davis
The Hubble constant / sound horizon problem

From “The Hubble Hunter’s Guide” (LK+Millea 2019)
Also see Bernal, Verde & Riess (2016), and Arendse et al. (2019)

SH0ES 2019 (Cepheids + Supernovae)
(no assumption of LCDM)

BOSS BAO + Pantheon SNe
(no assumption of LCDM*)

Planck (Assumes LCDM)

*assumes 5-parameter spline model for H(z) and zero mean curvature.
Also see Raveri et al. (2019).
The Hubble constant / sound horizon problem and opportunity for theorists

Goal:
Model X

- restores concordance
- is compelling and beautiful
- makes predictions…
- …that are subsequently confirmed

*assumes 5-parameter spline model for H(z) and zero mean curvature. Also see Raveri et al. (2019).
We have not yet found a Model X
Some papers on theoretical solutions published in past 9 months

Latest evidence for a late time vacuum-geodesic CDM interaction
Hogg, Natalie B.; Bruni, Marco; Crittenden, Robert and 2 more

Baryon-Interacting Dark Matter: heating dark matter and the emergence of galaxy scaling relations
Famaey, Benoit; Khoury, Justin; Penco, Riccardo and 1 more

Warm decaying dark matter and the hubble tension
Blinov, Nikita; Keith, Celeste; Hooper, Dan

Brans-Dicke cosmology with a $\Lambda$ - term: a possible solution to $\Lambda$ CDM tensions
Sola, Joan; Gomez-Valent, Adria; Cruz de Perez, Javier and 1 more

Can late dark energy transitions raise the Hubble constant?
Benevento, Giampaolo; Hu, Wayne; Raveri, Marco
9 2020JCAP...05..032P2020/05

Unified framework for Early Dark Energy from $\alpha$ -attractors
Braglia, Matteo; Emond, William T.; Finelli, Fabio and 2 more

Dark Energy with Phantom Crossing and the H0 tension
Di Valentino, Eleonora; Mukherjee, Ankan; Sen, Anjan A.

H0 tension or T0 tension?
Ivanov, Mikhail M.; Ali-Haïmoud, Yacine; Lesgourgues, Julien

Soundness of Dark Energy properties
Di Valentino, Eleonora; Gariazzo, Stefano; Mena, Olga and 1 more

Early Dark Energy from Massive Neutrinos as a Natural Resolution of the Hubble Tension
Sakstein, Jeremy; Trodden, Mark

Thermal friction as a solution to the Hubble tension
Berghaus, Kim V.; Karwal, Tanvi

Is the Hubble tension a hint of AdS phase around recombination?
Ye, Gen; Piao, Yun-Song

Updated fundamental constant constraints from Planck 2018 data and possible relations to the Hubble tension
Hart, Luke; Chluba, Jens

Interacting radiation after Planck and its implications for the Hubble Tension
Blinov, Nikita; Marques-Tavares, Gustavo

Gravity in the Era of Equality: Towards solutions to the Hubble problem without fine-tuned initial conditions
Zumalacarregui, Miguel

Reconciling Hubble Constant Discrepancy from Holographic Dark Energy
Dai, Wei-Ming; Ma, Yin-Zhe; He, Hong-Jian

Implications of a frame dependent dark energy for the spacetime metric, cosmography, and effective Hubble constant
Adler, Stephen L.

New Early Dark Energy
Niedermann, Florian; Sloth, Martin S.

Cosmic Birefringence Test of the Hubble Tension
Capparelli, Ludovico M.; Caldwell, Robert R.; Melchiorri, Alessandro

The H0 tension: did a QCD meV axion emerge?
Cerdonio, Massimo
Some more

TeV scale leptogenesis with dark matter in non-standard cosmology
Mahanta, Devabrat; Borah, Debasish

A CMB search for the neutrino mass mechanism and its relation to the Hubble tension
Escudero, Miguel; Witte, Samuel J.

Scalar-tensor theories of gravity, neutrino physics, and the H0 tension
Ballardini, Mario; Braglia, Matteo; Finelli, Fabio and 3 more

Charged Dark Matter and the H0 tension
Beltrán Jiménez, Jose; Bettoni, Dario; Brax, Philippe

Cosmological evolution of light dark photon dark matter
McDermott, Samuel D.; Witte, Samuel J.

The Hubble tension and a renormalizable model of gauged neutrino self-interactions
Berbig, Maximilian; Jana, Sudip; Trautner, Andreas

An Examination of Geometrical and Potential Time Delays in Gravitational Lensing
Tsupko, Oleg Yu.; Bisnovatyi-Kogan, Gennady S.; Rogers, Adam and 1 more

A larger value for H0 by an evolving gravitational constant
Braglia, Matteo; Ballardini, Mario; Emond, William T. and 4 more

Relieving the Hubble tension with primordial magnetic fields
Jedamzik, Karsten; Pogosian, Levon

The H0 tension: ΔGN vs. ΔNeff
Ballesteros, Guillermo; Notari, Alessio; Rompineve, Fabrizio

The common origin of the Hubble tension and anomalous cold spots in the CMB
Kovács, András; Beck, Róbert; Szapudi, István and 3 more

Could the Hubble Tension be Pointing Towards the Neutrino Mass Mechanism?
Escudero, Miguel; Witte, Samuel J.

Oscillating scalar fields and the Hubble tension: A resolution with novel signatures
Smith, Tristan L.; Poulin, Vivian; Amin, Mustafa A.

Nonminimal dark sector physics and cosmological tensions
Di Valentino, Eleonora; Melchiorri, Alessandro; Mena, Olga and 1 more
SDSS MGS

SDSS LRG

VIPERS

FastSound

GAMA

WiggleZ

DR14 quasars

6dFGS

BOSS DR12

SDSS MGS

WiggleZ

DES (Dv)

BOSS

DR14 Ly-α/ quasars (Dv)

fσ8

0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

Z

0.2
0.3
0.4
0.5
0.6
0.7
0.8

$\Delta T_k / T_k$ [μK]

$\Delta T_k / T_k$ [μK]

$\Delta T_k / T_k$ [μK]

Multipole L

Planck 2018

SPTPOL 500d
PRIMORDIAL DEUTERIUM AT ONE PERCENT

Pettini, Cooke & Steidel

HIRES data

Kirkman et al. (2003) data

Normalized Flux

Velocity Relative to $z_{abs} = 2.525640$ (km s$^{-1}$)
We are finding these data to be highly constraining!
ΛCDM
if no photon diffusion

\[ \ell (\ell + 1) C_\ell / (2\pi) \mu K^2 \]

\[ \text{multipole moment } \ell \]
Other effects LCDM gets right

- Diffusion damping
- Radiation driving
- Baryon reduction of plasma pressure
- “neutrino cooling”
- Neutrino free streaming
- Gravitational lensing
- Early ISW, late ISW
- Polarization generation
Other effects LCDM gets right

- Diffusion damping
- Radiation driving
- Baryon reduction of plasma pressure
- “neutrino cooling”
- Neutrino free streaming
- Gravitational lensing
- Early ISW, late ISW
- Polarization generation

[also see Chu & Knox (2005)]
Determining $H_0$ from CMB Data in 3 steps

Step 1: Calibrating a Standard Ruler

Decoupling of baryons and photons

\[ adr = c_s dt \]

\[ r_s = \int_0^{t_d} c_s dt / a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)} \]

Need to know $c_s(a)$ and $H(a)$ to calibrate the ruler.
Determining $H_0$ from CMB Data

Step 1: Calibrating a Standard Ruler

\[
r_s = \int_0^{t_d} c_s dt / a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}
\]

Need to know $c_s(a)$ and $H(a)$ to calibrate the ruler.

\[
c_s^2 = \frac{\partial P}{\partial \rho} \quad \rho_b / \rho_\gamma
\]

\[
H^2(a) = \frac{8\pi G}{3} (\rho_\gamma + \rho_\nu + \rho_m)
\]
Determining $H_0$ from CMB Data

**Step 1: Calibrating a Standard Ruler**

$$r_s = \int_0^{t_d} c_s dt/a = \int_0^{a_d} c_s \frac{da}{a^2 H(a)}$$

Need to know $c_s(a)$ and $H(a)$ to calibrate the ruler.

$$c_s^2 = \frac{\partial P}{\partial \rho}$$

Pressure of plasma impacts peak morphology (odd/even height modulation)

$$H^2(a) = \frac{8\pi G}{3}(\rho_\gamma + \rho_\nu + \rho_m)$$

“Radiation Driving” effect (Hu & White 1997)
Determining $H_0$ from CMB Data

Step 2: Use the Ruler to Infer Distance

Measure this

$\theta_s$

Infer this

$D_A(z = 1100)$

Calculate this

$r_s$
Angular size of sound horizon can be determined from peak spacing

\[ \Delta k = \frac{\pi}{r_s} \]

\[ \Delta \ell = \frac{\pi}{\theta_s} \]
Determining $H_0$ from CMB Data

Step 2: Use the Ruler to Infer Distance

Measure this

$D_A(z = 1100)$

calculate this

$r_S$

Infer this

Infer this

Step 3:

$$D_A(z) = \int_0^z \frac{dz'}{H(z')}$$

To get the right $D_A$, only thing left in the model to adjust is the cosmological constant. With that done, we have $H(z)$. 
The Search for Model X
HHG in a nutshell: Model X probably includes a lowering of $r_s$ ...

Goal:
Model X

• restores concordance
• is compelling and beautiful
• makes predictions…
• …that are subsequently confirmed

*assumes 5-parameter spline model for $H(z)$ and zero mean curvature. Also see Raveri et al. (2019).
...and that means additional components must be important in this interval (Aylor et al. 2019)
H₀ Solutions: State of the Art

**Light Relics**

Self interacting
Lancaster, Cyr-Racine, LK, Pan (2017)
Kreisch et al. (2019)

Dark matter interacting
Buen-Abad et al. (2018)
Pan, Kaplinghat, LK (2018)
H₀ Solutions: State of the Art

Light Relics

Self interacting
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Dark matter interacting
Buen-Abad et al. (2018)
Pan, Kaplinghat, LK (2018)

Scalar Fields

"Early Dark Energy"

\[ V(\phi) \propto (1 - \cos \phi)^3 \]

"Acoustic Dark Energy"

Poulin et al. (2019), Agrawal et al. (2019), Alexander and McDonough (2019), Lin et al. (2019), Smith et al. (2019),
Warm Decaying Dark Matter and the Hubble Tension

Nikita Blinov\textsuperscript{a,b} Celeste Keith\textsuperscript{b,c} Dan Hooper\textsuperscript{a,b,c}
We are finding these data to be highly constraining!
(assuming LCDM)
Early Dark Energy Does Not Restore Cosmological Concordance

J. Colin Hill,1,2 Evan McDonough,3 Michael W. Toomey,4 and Stephon Alexander3

\[ f_{\text{EDE}} = \text{fraction of Early Dark Energy} \]
• Model X
  • restores concordance
  • is compelling and beautiful
  • makes predictions, that are subsequently confirmed

• We are still searching for Model X.

• LCDM sets a high bar — improving on its accomplishments across a variety of data sets is not easy.

• We suspect that Model X includes additional components important just prior to recombination.

• BAO is very important. So are a variety of other data sets.

• There are lots of things left to try

• Racial justice comments
  • Discover your own biases: https://implicit.harvard.edu/implicit/takeatest.html.
  • Echoing Beaton: #BlackinAstro week (https://tinyurl.com/blackinastrobites)
Or, truth could be here

Models with changes to LCDM at late times will not impact the sound horizon, but can split the difference between the orange and green constraints, achieving a semi-concordance.

See, for example, Keeley et al. 2019 in JCAP.

From “The Hubble Hunter’s Guide” (LK+Millea 2019)
Matter density variation in LCDM

SH0ES 2019 (Cepheids + Supernovae) (no assumption of LCDM)

BOSS BAO + Pantheon SNe (no assumption of LCDM*)

Planck (Assumes LCDM)

*assumes 5-parameter spline model for H(z) and zero mean curvature. Also see Raveri et al. (2019).
Some Scalar Field Results

Dataset = Planck 2015 T+E+phi + SHOES + BAO + Pantheon

Lin, Benvenuto, Hu & Raveri (2019)
The Hubble constant / sound horizon problem

Models that do not change the matter content we place in the ‘Confusion Sowing’ category

SH0ES 2019 (Cepheids + Supernovae)
(no assumption of LCDM)

BOSS BAO + Pantheon SNe
(no assumption of LCDM*)

Planck (Assumes LCDM)

*assumes 5-parameter spline model for $H(z)$ and zero mean curvature. Also see Raveri et al. (2019).

From “The Hubble Hunter’s Guide” (LK+Millea 2019)
The Hubble Hunter’s Guide*

Categories of Solution

|                | Post-recombination                                      | Pre-recombination                                      |
|----------------|--------------------------------------------------------|--------------------------------------------------------|
| **High $r_s$** | 1) H(z) wiggles                                        | 1) Confusion sowing                                     |
|                | 2) Axion brightening                                    | 2) Sound speed reduction                                |
|                | 3) New physics impacting (some) Cepheids               | 3) Reduction of conformal time to recombination         |
| **Low $r_s$**  | 1) Confusion sowing                                     |                                                        |
|                | 2) Post-recombination evolution of BAO feature         |                                                        |

*with apologies to J. Gunion *et al.*

[https://arxiv.org/abs/1908.03663](https://arxiv.org/abs/1908.03663)
# The Hubble Hunter’s Guide*

## Categories of Solution

| High $r_s$ | Post-recombination | Pre-recombination |
|------------|---------------------|-------------------|
| 1) H(z) wiggles |
| 2) Axion brightening |
| 3) New physics impacting (some) Cepheids |
| Low $r_s$ | 1) Confusion sowing |
| 2) Post-recombination evolution of BAO feature |

1) Confusion sowing
2) Sound speed reduction
3) Reduction of conformal time to recombination

*with apologies to J. Gunion *et al.*

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Marius Millea on Monday

[https://arxiv.org/abs/1908.03663](https://arxiv.org/abs/1908.03663)
The Hubble Hunter’s Guide

Categories of Solution

Reduction of conformal time to recombination

A) High-temperature recombination
B) Photon cooling/conversion
C) Increasing $H(z)$ with additional components:
   1. Light Relics
   2. Early/Acoustic Dark Energy

Chiang & Slosar (2019)
Hart & Chluba (2018)
Categories of Solution

Reduction of conformal time to recombination

A) High-temperature recombination
B) Photon cooling/conversion
C) Increasing H(z) with additional components:
   1. Light Relics
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Chiang & Slosar (2019)
Hart & Chluba (2018)
Warm Decaying Dark Matter and the Hubble Tension

Nikita Blinov,\textsuperscript{a,b} Celeste Keith,\textsuperscript{b,c} Dan Hooper\textsuperscript{a,b,c}

Evolution of Background Densities

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram.png}
\end{figure}
The Sound Horizon in Galaxy Surveys Too

Image credit: Eric Huff (BOSS, SPT)

SDSS-BOSS:
\[ \theta_s(a=0.64) = (4.19 +/- 0.07) \text{ deg} \]

Planck:
\[ \theta_s(a=9.166 \times 10^{-4}) = (0.59672 +/- 0.00035) \text{ deg} \]

(numbers from 2013)

(Scale factor, a, is equal to 1 today)
Using Cepheid-calibrated supernovae to determine the sound horizon

$\Delta D_A(z)/D_{A,\Lambda CDM}(z)$

$D_A(z)$ [Mpc]

$\Delta D(z)/D_{A,\Lambda CDM}(z)$

$z$

$H_0 = 73.52 \pm 1.62 \text{ km/sec/Mpc}$

SNe=Pantheon (Scolnic et al. 2018), cal. by R18:

$\Lambda CDM$

Spline

BAO, $r_s=138.09$ Mpc

SNe, $M=-19.26$

See also Bernal, Verde, and Riess 2016,
Verde et al. 2017
See also Bernal, Verde, and Riess 2016, Verde et al. 2017

Model: $\Lambda$CDM

"Sounds Discordant", Aylor, Joy, LK, Millea, Raghunathan & Wu (2018)
“Sounds Discordant”, Aylor, Joy, LK, Millea, Raghunathan & Wu (2018)
See also Bernal, Verde, and Riess 2016, Verde et al. 2017

"Sounds Discordant", Aylor, Joy, LK, Millea, Raghunathan & Wu (2018)
See also Bernal, Verde, and Riess 2016, Verde et al. 2017

"Sounds Discordant", Aylor, Joy, LK, Millea, Raghunathan & Wu (2018)
Outline

• LCDM predictions of $H_0$

• The important role of BAO in stabilizing those predictions, and pointing toward solutions

• Measurements of $H_0$

• The Hubble Hunter’s Guide (to potential model solutions)
Determining $H_0$ from CMB Data

Step 2: Use the Ruler to Infer Distance

Measure this

$\theta_S$

Infer this

$D_A(z = 1100)$

Calculate this

$r_S$

$D_A(z = 1100)$
Baryon Acoustic Oscillations

Measure this: $\theta_s(z_1)$

$D_A(z_1)$

$\mathcal{r}_s$

Calculate this

Infer this
Measure this

\[ \theta_s(z_2) \]

\[ D_A(z_2) \]

Calculate this

\[ r_s \]

...or this
Baryon Acoustic Oscillations

Or turn it around...

Measure this

$\theta_s(z_2)$

$D_A(z_2)$

Infer this

$r_s$

Determine from Cepheid-calibrated supernovae

Bernal et al. 2016, Verde et al. 2017, Aylor et al. 2019
Using Cepheid-calibrated supernovae to determine the sound horizon

SNe=Pantheon (Scolnic et al. 2018), cal. by R18: $H_0 = 73.52 \pm 1.62 \, \text{km/sec/Mpc}$

BAO = BOSS galaxy BAO (Alam et al. 2017)

See also Bernal, Verde, and Riess 2016, Verde et al. 2017
The sound horizon — Hubble constant plane

BOSS BAO + Pantheon SNe
(no assumption of LCDM*)

SH0ES 2019 (Cepheids + Supernovae)
(no assumption of LCDM)

Planck (Assumes LCDM)

For consistency with BAO + Cepheid-calibrated supernovae ==> need alternative model with lower sound horizon (Aylor et al. 2019)

*assumes 5-parameter spline model for H(z) and zero mean curvature. Also see Raveri et al. (2019).
LK & Millea (2019), also see Bernal et al. (2016) and Verde et al. (2017)

The sound horizon — Hubble constant plane

**BOSS BAO + Pantheon SNe**
(no assumption of LCDM*)

**SH0ES 2019 (Cepheids + Supernovae)**
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**Planck** (Assumes LCDM)

For consistency with BAO + Cepheid-calibrated supernovae ==> need alternative model with lower sound horizon (Aylor et al. 2019)

**Sound Horizon**

*assumes 5-parameter spline model for H(z) and zero mean curvature. Also see Raveri et al. (2019).
Adding additional components not a panacea: it’s hard to make the data consistent with $H_0 > 70$ (Agrawal, Cyr-Racine, Pinner & Randall).

Why?

A model with “early dark energy”
Radiation-driving envelope altered ==> LCDM-based analyses will find angular-scale dependent inferences of matter density

Matter Density

Planck (TT $\ell > 800$)
Planck (TT $\ell < 800$)

See also
Addison et al. (2016)

Planck PIP LI (2017)
Is this 2.3 sigma discrepancy (Planck PIP LI 2017, see also Addison et al. 2016) a consequence of additional component that is important just prior to recombination?

Radiation-driving envelope altered ==> LCDM-based analyses will find angular-scale dependent inferences of matter density
CMB-S4 will have great sensitivity to the contents of the primordial plasma during the last two decades of expansion prior to recombination.
Future probes of light relics

CMB-S4 Science Case, Reference Design and Project Plan
(https://arxiv.org/abs/1907.04473)
Future probes of light relics

CMB-S4 Science Case, Reference Design and Project Plan (https://arxiv.org/abs/1907.04473)
Figure 10. 2D Posterior distributions of \(\{\log_{10}(z_c), f_{\text{EDE}}(z_c)\}\) and \(\{H_0, f_{\text{EDE}}(z_c)\}\) reconstructed from a fit to simulated Planck data and CMB-S4. The fiducial model has \(\{H_0 = 72\ \text{km/s/Mpc}, f_{\text{EDE}}(z_c) = 0.115, \log_{10}(z_c) = 3.53\}\).
A Group Hug at CERN in 2013