A New Measurement of the Expansion Rate of the Universe, Hints of New Physics?
Ultimate “End-to-end” test for $\Lambda$CDM, Predict and Measure $H_0$

Standard Model of Cosmology, $\Lambda$CDM, 6 parameters

<table>
<thead>
<tr>
<th>Planets</th>
<th>Planets + Stars + Gas</th>
<th>Dark Matter</th>
<th>Dark Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05%</td>
<td></td>
<td>25%</td>
<td>70%</td>
</tr>
<tr>
<td>Stars</td>
<td>Gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5%</td>
<td>4%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Big Bang

Cosmic Microwave Background

$\Lambda$CDM

Predicted Now, $H_0 = 67.4 +/- 0.5$ km/s/Mpc
A Direct, Local Measurement of $H_0$ to percent precision

The SH$_0$ES Project (2005)
(Supernovae, $H_0$ for the dark energy Equation of State)

Measure $H_0$ to $\sim$1% percent precision empirically by:

- A clean, simple ladder: Geometry $\rightarrow$ Cepheids $\rightarrow$ SNe Ia
- Reducing systematic error with better data, better collection
- Thorough propagation of statistical and systematic errors
The Hubble Constant in 3 Steps: Present Data

1. Geometry → Cepheids
   - Cepheids → Type Ia Supernovae
   - 19 Calibrations
   - SN Ia: m-M (mag)
   - Cepheid: m-M (mag)

2. Galaxies hosting Cepheids and Type Ia supernovae
   - H₀ = 73.53 ± 1.62, Km s⁻¹ Mpc⁻¹
   - (Riess et al. 2018b)
   - 2.2% total uncertainty

3. Distant galaxies in the expanding Universe hosting Type Ia supernovae
   - Light redshifted (stretched) by expansion of space

*NEW*

Parallax of Cepheids in the Milky Way
Step 1: The Milky Way Cepheid P-L Relation

Two Potential Systematics:

- Difference in mean period, MW vs SN Ia hosts
- Inhomogeneous Cepheid photometry, MW vs SN Ia hosts

Most long period Cepheids D>2 Kpc requires higher precision parallaxes
Extending Parallax with HST WFC3 Spatial Scanning

Imaging: astrometry $\sigma_0=0.01$ pix
HST: 0.4mas, $\sim1\sigma$ @ 2 kpc
Two Features of Spatial Scans: Sampling and Jitter Removal

Extracted scan lines of stars from a single scan

- Jitter between lines is coherent, subtracted in line separations (vs time)
- Target scanned over ~4000 pix, improves SNR by factor of 10
- Reaching 20-40 μas
4 Years Later, New Parallaxes of Milky Way Cepheids, 3% Error in Mean

4 Years Later: Proper Motion subtracted, 8 MW Cepheid Parallax measurements 1.7<D<3.6 Kpc, error in mean=3.3%

50 Benchmark MW Cepheids all w/ HST Photometry, Long-Periods A “photometric bridge” for Gaia


Fast Scans 7.5”/s exp time~0.01 sec Error individual Cepheid mean D<1%

Final Gaia Parallaxes + HST Photometry $\rightarrow H_0 \sim 0.4\%$

$\{ \text{with 3 band HST photometry and} $

$\text{Periods > 10 days both matching}$

$\text{Cepheids HST sees in SN Ia hosts} \}$
### Step 1: Five Sources Geometric Cepheid Calibrations

<table>
<thead>
<tr>
<th>Independent Geometric Source</th>
<th>$\sigma$</th>
<th>$H_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 4258 H$_2$O Masers: Humphreys et al 2013, Riess et al 2016</td>
<td>2.6%</td>
<td>72.3</td>
</tr>
<tr>
<td>LMC 8 Late Detached Eclipsing Binaries: Pietrzynski et al. 2013</td>
<td>2.5%</td>
<td>72.0</td>
</tr>
<tr>
<td>Milky Way 10 HST FGS Short P Parallaxes: Benedict et al. 2007 --also Hipparcos (Van Leeuwen et al 2007)</td>
<td>2.2%</td>
<td>76.2</td>
</tr>
<tr>
<td>Milky Way 8 HST WFC3 SS Long P Parallaxes: Riess et al. 2018</td>
<td>3.3%</td>
<td>75.7</td>
</tr>
<tr>
<td>Milky Way 50 Gaia+HST, Long P Parallaxes: Riess et al. 2018</td>
<td>3.3%</td>
<td>73.7</td>
</tr>
</tbody>
</table>

Consistent Results, *Independent Systematics*
Step 2: Cepheids to Type Ia Supernovae

This is the $H_0$-Limiting Step: Number of SN Ia in Cepheid Range

Cumulative # Ideal SNe Ia

25 40 65 100 160

Mpc

Cepheid Mean (R mag, P=20 d)

Current SN Ia sample

HST+WFPC2

HST+WFC3

n=50?
n=37

n=19

KP, ~2001

% error towards $H_0$

HST Final? (0.8%)

Next (Cycle 25/26, 0.9%)

Now (Cycle 20 R16, 1.3%)

NGC 1309

SN2002fk

Lick Obs. 2002

HST ACS 2005
Cepheid V,I,H band Period-Luminosity Relationships: 19 hosts, 3 anchors

Geometric Anchors
Lower Systematics from *Differential* Flux Measurements

We reduce systematic errors by measuring all Cepheids with same instrument, filters, similar metallicity, period range, we correct for crowding and dust statistically

ANCHORS: NGC 4258 (and now MW, LMC)

geometric distance

19 SN Ia Hosts

All photometry in R16, all images in MAST archive

Cepheid composite LC’s, >2400
- Negligible sensitivity to metallicity in NIR
- Dependence on reddening laws 6x smaller than optical

We use H-band as primary +V,I

Key Project used V and I

Lowering *Systematics* with Near-IR Cepheid Observations

**LMC**

K 2.2μm  
J 1.2μm  
I 0.8μm  
V 0.6μm  
B 0.4μm

σ=0.08 MAG

UDALSKI+ (1999)  
MACRI+ (2015)
Step 3: Intercept of SN Ia Hubble Diagram: Distance vs Redshift

\[ a_B = \log cz \left\{ 1 + \frac{1}{2} [1 - q_0] z - \frac{1}{6} [1 - q_0 - 3q_0^2 + j_0] z^2 + O(z^3) \right\} - 0.2m_B^{0_B} \]

Kinematic Intercept equation

\( a_B = 0.71273 \pm 0.00176 \) (units log \( H_0 \)), 217 SNe Ia 0.023 < \( z < 0.15 \), \( q_0 = -0.55 \), \( j_0 = 1 \)

(see Burns et al. 2018—similar results with CSP SN sample, different SN fitter)
**Systematics R16: 23 Analysis Variants**

**Best Fit:**

$$5 \log \, H_0 = M_B^o + 5a_B + 25$$

**Planck + \Lambda CDM \Delta=0.20 \, \text{mag}$$

**Analysis Variants**

<table>
<thead>
<tr>
<th>Analysis Variants</th>
<th>$H_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Best Fit (R16, w/ HST, Gaia, R18=73.53)</td>
<td>73.24</td>
</tr>
<tr>
<td>Reddening Law: LMC-like ($R_V=2.5$, not 3.3)</td>
<td>73.15</td>
</tr>
<tr>
<td>Reddening Law: Bulge-like (N15)</td>
<td>73.39</td>
</tr>
<tr>
<td>No Cepheid Outlier Rejection (normally 2%)</td>
<td>73.49</td>
</tr>
<tr>
<td>No Correction for Cepheid Extinction</td>
<td>74.79</td>
</tr>
<tr>
<td>No Truncation for Incomplete Period Range</td>
<td>74.39</td>
</tr>
<tr>
<td>Metallic Gradient: None (normally fit)</td>
<td>73.30</td>
</tr>
<tr>
<td>Period-Luminosity: Single Slope</td>
<td>73.26</td>
</tr>
<tr>
<td>Period-Luminosity: Restrict to $P&gt;10$ days</td>
<td>71.64</td>
</tr>
<tr>
<td>Period-Luminosity: Restrict to $P&lt;60$ days</td>
<td>73.06</td>
</tr>
<tr>
<td>Supernovae $z&gt;0.01$ (normally $z&gt;0.023$)</td>
<td>73.38</td>
</tr>
<tr>
<td>Supernova Fitter: MLCS (normally SALT)</td>
<td>74.39</td>
</tr>
<tr>
<td>Supernova Hosts: Spiral (usually all types)</td>
<td>73.37</td>
</tr>
<tr>
<td>Supernova Hosts: Locally Star Forming</td>
<td>73.54</td>
</tr>
<tr>
<td>Cepheid Measurements: Optical Only</td>
<td>71.74</td>
</tr>
</tbody>
</table>
Error Budget for $H_0$ from 2016: 2.4% uncertainty, 2018: 2.2%

### 2.2% Total Uncertainty

<table>
<thead>
<tr>
<th>TERM</th>
<th>KP LMC</th>
<th>R09 4258</th>
<th>R11 ALL</th>
<th>R16 ALL</th>
<th>R18 ALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anchor Distance</td>
<td>5.0</td>
<td>3.0</td>
<td>1.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Cepheid reddening, zpts (anchor-to-hosts)</td>
<td>4.5</td>
<td>0.3</td>
<td>1.4</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>P-L slope, d log P (anchor-to-hosts)</td>
<td>4.0</td>
<td>0.5</td>
<td>0.6</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Cepheid metallicity (anchor-to-hosts)</td>
<td>3.0</td>
<td>1.1</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>WFPC2 CTE, long-vs-short zeropoints</td>
<td>3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean of SN IA calibrators</td>
<td>2.5</td>
<td>2.5</td>
<td>1.9</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Mean of P-L in anchor</td>
<td>2.5</td>
<td>1.5</td>
<td>0.8</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Mean of P-L in SN hosts</td>
<td>1.5</td>
<td>1.5</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>SN IA m-z relation</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Analysis Systematics (from 23 variants)</td>
<td>NA</td>
<td>1.3</td>
<td>1.1</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total, % error $H_0$</strong></td>
<td><strong>10</strong></td>
<td><strong>4.8</strong></td>
<td><strong>3.3</strong></td>
<td><strong>2.4</strong></td>
<td><strong>2.2</strong></td>
</tr>
</tbody>
</table>

**SH0ES, Riess et al 2005: 73.0  2009: 74.2  2011: 73.8  2016: 73.2  2018: 73.5**

**KP: (Freedman et al. 2001/12: 72.0/74.0)**

How does this compare to the CMB measurements?
**NEW PHYSICS**

**H$_0$: Measured Late vs. Predicted from Early Universe**

- **DE not $\Lambda$**
- **Sterile $\nu$**
- **curvature**
- **DM inter.**
- **early DE** (Poulin et al. 2018)

- Early
  - Planck18+ACDM
  - BAO+BBN $^2$H
  - BAO+ACTPol,SPT,WMAP

- Late
  - R16 (SHOES)
  - Reanalysis of R16 (C16,FK17,FM18)
  - HOLiCOW-4 lenses (Birrer18)
  - SN Ia NIR (JUL17,CSP B18)
  - Gaia DR2,HST $\pi$ (R18a,b: SHOES)

* >4 $\sigma$ with constraint on Gaia DR2 zp offset
Cepheid Alternatives: VS. TRGB and VS O-rich Miras

Internal consistency: 5 tests absolute vs geometry, 19 tests relative vs. SNe Ia

Cepheids VS TRGB
in 10 SN Ia Hosts + N4258
Cepheids: Riess et al. 2016,
TRGB: Hatt, WLF et al (2018),
Jang, Lee et al (2017/8), CCHP
using same zeropoint

Cepheid-TRGB=0.029 +/- 0.026 mag
~8σ from Planck at -0.20 mag

O-Rich Miras
Variable AGB stars, large
amplitudes, long periods

LMC to NGC 4258,
Consistent with Cepheids
Huang et al. (2018)
Miras in SN Ia hosts in prep
FAQ: Is local $H_0$ (0.0233<z<0.15) = global $H_0$? Yes to 0.5%

- We already correct for local (peculiar) flows derived from 2M++ density field
- Expect local-to-global $\Delta H_0$ N-body sims in Gpc$^3$ box, SN, z $\rightarrow \Delta H$~0.3% Odderskov et al. (2016) and Wu & Huterer (2017)
- We can use SN Hubble diagram to look for change in $H_0$ with z

Planck=+9%

$\times$ Shanks et al (2018)

$3 \sigma$

$2 \sigma$

$1 \sigma$

Kenworthy et al 2018, In prep

Suggestion we live in giant void (z<0.07; KBC 2013, Shanks et al. 2018), SN data rejects 4.5 $\sigma$
Increasing Number of SN-Cepheid Calibrations

*NEW* SHOES Large HST Programs, Cycles 25,26
18 more Cepheid-SN Ia Calibrators underway,
to reach total=37

*N5643/SN13aa* N1559/SN05df N4680/SN97bp N2692/SN01bg N7541/SN98dh

N0691/SN05w N3583/SN15so N5728/SN99Y N3147/SN97bg N5468/SN99cp.02cr

NGC7678/SN02dp MCG-01-33-34/SN06D NGC5728/SN99Y NGC7329/SN06bh NGC4680/SN97bp

2 SN Ia in 1 2 SN Ia in 1

*Cepheids and Miras, Same data*
**NEW** Linearity: Can HST WFC3-IR Flux Scale Support 1%?

"Flux Calibration Ladder"

- 2MASS Asterisms
- MW Cepheids
- LMC Cepheids
- DA WDs

0.3% Non-linearity, corrected

*if* 3.0% Non-linearity (NIC2 F110W)

Cepheids: MW→ SN hosts,

\[ \sigma = 7 \text{ dex} \times 0.0008 \text{ mag/dex} = 0.006 \text{ mag} \rightarrow 0.3\% \text{ in } H_0 \]
H_0 is easier than q_0

SN Ia Hubble diagram
(Pantheon Set-Scolnic et al 2018)
0.01<z<2, 1100 Sne Ia
ΔCDM residuals <0.04 mag

Measuring w,q_0 requires
comparing z~0.05 to z~1.0
Sys: evolution, K-corrs, zps

Measuring H_0 requires
Comparing z~0 to z~0.05
Same surveys, no evolution, negligible K-corrections,
no zeropoint changes.
Much easier!
Breakthroughs When Local $H_0$ was too high. This time?

1930-1950:
$H_0 > 300 \text{ km s}^{-1} \text{ Mpc}^{-1} \rightarrow t_0 \sim \text{Gyr} \ll \text{age of Earth}$
Why? Two populations of stars! Early and late, poor and rich.

1990’s*:
$60 < H_0 < 85 + \Omega_M = 1 \rightarrow t_0 \text{ (10 Gyr)} \ll \text{oldest stars (14 Gyr)}$
Why? Dark energy! $\Omega_M \sim 0.3$, $\Lambda \sim 0.7$

2010’s:
$H_0 = 73.5 \pm 1.6 \rightarrow 3.8\sigma \text{ higher than Planck CMB+} \Lambda \text{CDM}$
What will be discovered?

* Internally inconsistent measures of $H_0$ indicated systematics not new features
Takeaways

• Universe now appears to be expanding ~9% (+/- 2.2%) faster than-expected based $\Lambda$CDM+Planck CMB

• There are independent checks on each measurement so, either a *conspiracy* of errors or a new feature of LCDM

• We anticipate significant improvements in these measurements in just the next few years which may reveal the cause.

• With additional measurements HST and Gaia can enable a 1% measurement of $H_0$, a benchmark for constraining the cosmological model.

Ask me about host galaxy environmental effects (Backup Slides)