A New Measurement of the Expansion Rate of the Universe and a Path to 1% with Gaia

Expanding Universe reveals Composition, Age, Fate...

Homogeneous, Isotropic + GR → equation of expansion $a(t)$, "scale factor"
Depends on present state and composition of Universe

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G \rho_M}{3} + \frac{\Lambda}{3} - \frac{k}{a^2}$$
Cosmology, The quest for two numbers (matter dominated)

\[ H_0 = \frac{\dot{a}}{a} \mid _{t=t_0} \]

Present rate, size, age,

\[ q_0 = \frac{-\ddot{a}}{aH_0^2} \mid _{t=t_0} \]

Deceleration by \( \Omega_M (=2q_0) \), geometry, fate

origin, viability of inflation

big, 20 Gyr

dense, fast

small, 10 Gyr

empty, slow

1990’s: Building of Modern SN Ia Hubble diagram…
Bright=near \quad faint=far

but not all the same…

faint \quad \& \quad red=not \ so \ far!

SN Ia Luminosity-color-light curve shape correlations…1990’s
Building the Modern SN Ia Hubble Diagram; Hubble Flow

Mid-1990’s, CCDs, light curve, reddening corrections

Established: tight scatter ($\sigma_D \sim 6\%$), linear local expansion, $H_0 \sim 10\%-15\%$ severely limited by luminosity calibration
Building the Modern SN Ia Hubble Diagram; Acceleration!

1998: SN discoveries at z~0.5 from large format CCDs

Established: $q_0 < 0$, presence of dark energy, no known unknown
Established: not astrophysical dimming (grey dust, evolution), decelerating before accelerating, looks like lambda to ~10%
Why Does the Universe Appear to be Accelerating?

1. Vacuum Energy, the cosmological constant: $\Lambda$CDM
   - Constant energy of empty space (e.g., Higgs), feature of QM+GR
   - Test: $w(z) = -1$

2. Dynamical dark energy
   - A scalar field fills space (e.g., “inflation-lite”), rolling down potential
   - Test: $w_0 \neq -1$ or $dw/dz \neq 0$

3. Modification to GR
   - GR fails at long range (i.e., as $a \to 1$)
   - Test: $w(z)$ depends on scale (i.e., different in $H(z)$ and $g(z)$)

New Game; assume Model=plain $\Lambda$CDM and hunt for departures

$$q_0 = \frac{\Omega_M}{2} + (1 + 3w) \frac{\Omega_{DE}}{2}$$

$w \equiv p/\rho$
- $w=1$ radiation
- $w=0$ matter
- $w=-1$ vacuum energy (3D)
Ultimate “End-to-end” test for \( \Lambda \)CDM, Predict and Measure \( H_0 \)

The Standard Model of Cosmology, \( \Lambda \)CDM

- Planets 0.05%
- Planets+Stars+Gas
- Dark Matter: 25%
- Dark Energy: 70%
- Dark Energy
- Stars 0.5%
- Gas 4%

Big Bang

CMB, \( z=1000 \)
\( \sigma_D(\Lambda \)CDM\)=0.4%

Sound Horizon

\[ D(z) = D_* - \int_z^{z_*} \frac{dz}{H(z)} \]

Now

\( z=0, \sigma_{H_0}=1\% \)
The SH0ES Project (2005)
(Supernovae, $H_0$ for the dark energy Equation of State)

A. Riess, L. Macri, S. Casertano, A. Filippenko, S. Hoffman, S. Jha

$$\sigma_w \approx 2 \sigma_H$$ (after WMAP, Planck)

Measure $H_0$ to percent level precision through:

- 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
Our route: 3 Steps to $H_0$

1 (Kpc)  
Parallax of Cepheids in the Milky Way  
Old vs New Parallax Limit

2 (Mpc)  
Galaxies hosting Cepheids and Type Ia supernovae  
Light redshifted (stretched) by expansion of space

3 (Gpc)  
Distant galaxies in the expanding Universe hosting Type Ia supernovae

1: Geometry $\rightarrow$ Cepheids  
2: Cepheids $\rightarrow$ SN Ia  
3: SN Ia $\rightarrow z, H_0$
Step 1: Extending Parallax with WFC3 Spatial Scanning

WFC3-UVIS, 0.01 pixel=0.4 mas \( \sim 2\sigma @ 2 \text{ kpc} \)

Imaging, PSF \( \sigma_\theta=0.01 \text{ pix} \)

Scanning, \( \sigma_\theta=0.01/\sqrt{N \text{ samples pix}} \)

Riess, Casertano, Mackenty et al (2014)
Then we extract scan lines, row-by-row...
Two Features of Spatial Scans: Repetition and Jitter Removal

Average all scan lines to produce oversampled “reference line”

Jitter between lines is coherent, subtracted in line separations (vs time). Approach is doubly differential.

Target scanned over ~4000 pix, Improves SNR by up to ~40 (or 10 for correlated errors on scales of 40 pix), Reaching 20-40 μas

Dispersion 1.45 mas, error in the mean 25.4 μas

Separation between two scans (#5,104)
The millipixel (40 µas) challenge: scanning systematics

A lot moves at the millipixel level!
Proper Motion subtracted, Parallax measurements field stars & Cepheid

Cepheid
At 3 kpc, 4 years
$\sigma = 27 \mu\text{as}$

Also: NGC 4258 Masers 3.0% → 2.6%, LMC DEBs, M31 DEBs,
Future: 20 New MW Parallaxes, Gaia…

Reduction to Absolute: e.g., Red giant at 8 Kpc, 0.4 mag spec $\pi \rightarrow 25 \mu\text{as}$

Riess et al. (2014)
Casertano et al. (2016)
Step 2: Cepheids to Type Ia Supernovae

1. Discard *photographic* data, SN 1895B, 1937C, 1960F 1974G, & unreliable i.e. all but 2-3 used by Key Project, Sandage et al., Freedman et al.

Previously limited by 20 Mpc Cepheid range of WFPC2…
Step 2: Better Data-SN Ia

- ACS (2002), WFC3 (2009) doubled range, 8X as many possible

- Using only reliable SN Ia data—i.e., digital data, multiband light curves 4 bands, pre-max, normal spectra, low extinction $A_V < 0.5$.

$\text{m} - 19.35 + 5 \log(H_0/70)$

SHOES Calibration Sample,
(N=8 Riess et al 2011, N=19 in progress)
Step 2: Increasing the Sample of SN Ia Calibrators

New HST Program w/ WFC3 NIR+wide filters 3x speed, n=8 → n=19

NEW! NEW! NEW! NEW! NEW! NEW! NEW! NEW! NEW! NEW! NEW! NEW! NEW! NEW! NEW! NEW! NEW! NEW!
Homogeneous Cepheid *data* for anchors and SN Hosts: same instruments, same filters, same metallicity, period range

ANCHOR: NGC 4258, 2.6% geometric distance

19 SN Ia Hosts

Cepheid composite LC’s, >2400
Inclination ➔ crowding of more distant host

Random phase

HST PHAT Survey; Riess et al. 2012, Wagner-Kaiser et al 2015
Cepheid NIR Period-Luminosity Relationships: 19 hosts, 4 anchors
Step 3: Intercept of SN Ia Hubble Diagram: Distance vs Redshift

\[ a_B = \log(cz) \left\{ 1 + \frac{1}{2} [1 - q_0] z - \frac{1}{6} [1 - q_0 - 3q_0^2 + j_0] z^2 + O(z^3) \right\} - 0.2m^0_B \]
Simultaneous Fit: Retain interdependence of data and parameters

**Measurements**

Cepheids in SN hosts

Cepheids in Anchors

SN Ia

Geometric Distance Priors

\[
\begin{pmatrix}
\Delta D (N4258) \\
\mu_{0,1} \\
\Delta \mu_{N4258} \\
M_{H,1}^W \\
\Delta \mu_{LMC} \\
\mu_{M31} \\
b \\
M_B^0 \\
Z_W \\
\Delta zp \\
b_l
\end{pmatrix}
\]

**Regression Matrix**

\[
\begin{pmatrix}
\begin{pmatrix}
1 & 0 & 0 & 1 & 0 & 0 & \log P^h_{18,1} / 0 & 0 & [O/H]_{18,1} & 0 & \log P^l_{18,1} / 0 \\
.. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. \\
0 & 1 & 0 & 1 & 0 & 0 & \log P^h_{18,2} / 0 & 0 & [O/H]_{18,2} & 0 & \log P^l_{18,2} / 0 \\
0 & 0 & 1 & 1 & 0 & 0 & \log P^h_{N4258,j} / 0 & 0 & [O/H]_{N4258,j} & 0 & \log P^l_{N4258,j} / 0 \\
0 & 0 & 0 & 1 & 0 & 1 & \log P^h_{M31,j} / 0 & 0 & [O/H]_{M31,j} & 0 & \log P^l_{M31,j} / 0 \\
0 & 0 & 0 & 1 & 0 & 0 & \log P^h_{MW,j} / 0 & 0 & [O/H]_{MW,j} & 1 & \log P^l_{MW,j} / 0 \\
0 & 0 & 0 & 1 & 1 & 0 & \log P^h_{LMC,j} / 0 & 0 & [O/H]_{LMC,j} & 1 & \log P^l_{LMC,j} / 0
\end{pmatrix}
\end{pmatrix}
\]

**Free Parameters**

\[
\begin{pmatrix}
\sigma^2_{\text{tot},1,j} & \sigma^2_{\text{tot},19,j} & \sigma^2_{\text{tot},N4258,j} & \sigma^2_{\text{tot},M31,j} + \sigma^2_{\mu,1,j} & \sigma^2_{\text{tot},MW,j} & \sigma^2_{\text{tot},LMC,j} & \sigma^2_{\mu,1,j} & \sigma^2_{\mu,LMC,j} & \sigma^2_{mB,1} & \sigma^2_{mB,19} & \sigma^2_{zp}
\end{pmatrix}
\]

\[
5 \log H_0 = M_B^0 + 5a_B + 25
\]
The Hubble Constant in just 3 Steps..reduced systematics

\[ H_0 = 73.24 \pm 1.74, \text{ Km s}^{-1} \text{ Mpc}^{-1} \]

2.4% total uncertainty
## Analysis Variants, Anchors

<table>
<thead>
<tr>
<th>Anchor</th>
<th>Value (km/sec/Mpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preferred</strong></td>
<td></td>
</tr>
<tr>
<td>NGC4258+MW+LMC</td>
<td>73.24+/-.174</td>
</tr>
<tr>
<td>NGC4258+MW+LMC+M31</td>
<td>73.46+/-.171</td>
</tr>
<tr>
<td>NGC 4258: Masers</td>
<td>72.25+/-.251</td>
</tr>
<tr>
<td>MW: 15 Cepheid Parallaxes</td>
<td>76.18+/-.237</td>
</tr>
<tr>
<td>LMC: 8 Late-type DEBs</td>
<td>72.04+/-.267</td>
</tr>
<tr>
<td>M31: 2 Early-type DEBs</td>
<td>74.50+/-.327</td>
</tr>
<tr>
<td>No NIR: N4258+MW+LMC</td>
<td>71.56+/-.249</td>
</tr>
<tr>
<td><strong>One anchor</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Four anchors</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Optical only</strong></td>
<td></td>
</tr>
</tbody>
</table>

Cardona, Kunz, Pettorino 2016
Analysis Variants, Additional Systematics

23 Variants:
- Reddening law,
- Metallicity,
- SN fitters,
- z range,
- Host types,
- PL breaks,
- PL range
- Outliers, etc
Error Budget for $H_0$ from 2016; 2.4% uncertainty

$H_0 = 73.24 \pm 1.74 \text{ km/s/Mpc}$ (Riess et al. 2016)

<table>
<thead>
<tr>
<th>TERM</th>
<th>KP LMC %</th>
<th>R09 4258 %</th>
<th>R11 ALL %</th>
<th>R16 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>
</tr>
<tr>
<td>Cepheid reddening, zeropoints (anchor-to-hosts)</td>
<td>4.5</td>
<td>0.3</td>
<td>1.4</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>
</tr>
<tr>
<td>Cepheid metallicity dependence (anchor-to-hosts)</td>
<td>3.0</td>
<td>1.1</td>
<td>1.0</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>
</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>
</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>
</tr>
<tr>
<td>Mean of P-L in SN hosts</td>
<td>1.5</td>
<td>1.5</td>
<td>0.6</td>
<td>0.7</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>
</tr>
<tr>
<td>Analysis Systematics</td>
<td>NA</td>
<td>1.3</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Total, % error $H_0$</td>
<td>10</td>
<td>4.8</td>
<td>3.3</td>
<td>2.4</td>
</tr>
</tbody>
</table>

How does this compare to the CMB measurements?
New Physics?

- **Dark Energy**
  \[ \Delta w_\Lambda = -0.1 \]

- **Dark Radiation**
  \[ \Delta N_{\text{eff}} = +0.4 \]

- **Curved Space**
  \[ \Delta \Omega_K = -0.01 \]

- **DM-Rad Interaction**
  \[ \Delta \sigma = 10^{-33} \]

- **Planck vs WMAP vs l?**

* "If a persuasive case can be made that a direct measurement of \( H_0 \) conflicts with these estimates, then this will be strong evidence for additional physics beyond the base \( \Lambda \)CDM model." -Planck Team Paper, 2015
How Big is the Difference between our $H_0$ and Planck CMB+$\Lambda$CDM?

$H_0 = 73.24 \pm 1.74$, Km s$^{-1}$ Mpc$^{-1}$

2.4% total uncertainty

Planck +$\Lambda$CDM

$\Delta = 0.2$ mag
Is local $H_0$ (0.02<z<0.15) same as global $H_0$?

- empirically model $H(z)$ w/ kinematic terms $q_0$, $j_0$ derived from high-z SN Ia
- correct z for local (peculiar) flows derived from 2M++ density field (Carrick et al. 2015)

Test: explore larger volume, $z_{\text{min}}$<z<$z_{\text{min}}$+0.15, $\Delta H_0 < 0.4$

- N-body sims in 700 Mpc box $\Rightarrow$ 0.3% (Odderskov et al. (2016))
Evidence for a systematic error in the Planck CMB data?

Claimed 2.5 σ Tension Between Halves of Planck CMB data, \(\ell>1000\) vs \(\ell<1000\) (WMAP)

Planck Team, arXiv: 1608.02487—"2.5 σ like 1.8 σ for 6 parameters”, but we measure \(H_0\)!

\[
\begin{align*}
H_0 & \quad 70 \pm 10 \quad 70 \pm 10 \\
0.3 & \quad 0.3 \quad 0.3 \quad 0.3 \\
0.06 & \quad 0.07 \quad 0.08 \quad 0.09
\end{align*}
\]
H$_0$+Cepheid P-L relation (R16) predicts MW parallaxes $\sigma \sim 20\mu$as, 10x precision of Gaia DR1 for $\sim 210$ Cepheids

Casertano, Riess, Bucciarelli, Lattanzi arXive:1609.05175, submitted A&A (DR1+2 days)

DR1 parallaxes good ($zp=1\pm19\mu$as), errors overestimated $\sim 20\%$, average of $210 \rightarrow H_0 = 73.0 \text{ km/sec/Mpc}$, 2.5-3 $\sigma$ tension with Planck
H\textsubscript{0} to 1%? Anchored by 60 “Best” Milky Way Long Period Cepheids

Gaia(2022), $\sigma_\pi < 10\mu$as

- Gaia to measure 60 “best” MW Cepheids w/ $\sigma_\pi < 10\mu$as parallaxes, Net: $\sigma_D = 3\%$ per Cepheid (with scatter) $\rightarrow$ 3\% / $\sqrt{60} = 0.4\% = \sigma_H$
- MUST measure 60 MW Cepheids on HST zpt or will add $\sigma_H = 1.5\%$!
Reaching 1% in $H_0$...2% in $w$, 20% in $w'$, 0.002 in $\Omega_K$, 0.08 in $N_{\text{eff}}$

- **2011**: 3.3%
  - 8 SN hosts
  - Short-period Galactic Cepheids + NGC 4258

- **2017**: 1.8%
  - 19 SN hosts
  - 20+ Galactic Cepheids
  - With HST Parallax, Photometry

- **2022(?)**: 1.0%
  - ~50 SN hosts (HST+JWST)
  - 60+ Galactic Cepheids
  - (Gaia astrometry + HST photometry)

Powerful complement to CMB Stage IV (Manzotti et al. 2016)
And stay alert for systematics along the way...
Takeaways

• Universe now appears to be expanding ~9% (+/- 2.4%) faster than-expected based $\Lambda$CDM+Planck CMB. This is surprising!

• If not an error, could be a vital clue pertaining to the 95% of the Universe (i.e., the dark sector) we don’t understand.

• We anticipate significant improvements in these measurements in just the next few years which may reveal the cause of the now “peppy Universe”.

• With additional measurements HST, Gaia and JWST can enable a 1% measurement of $H_0$. 