Cosmic Expansion Seen by HST,
"Standing on the Shoulders of Giants"
Expanding Universe reveals Composition, Age, Fate...

Homogeneous, Isotropic + GR →

equation of expansion \( a(t) \), “scale factor”

Depends on present state, composition of Universe

Friedmann Equation

\[
\left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G \rho_M}{3} + \frac{\Lambda}{3} - \frac{k}{a^2}
\]
Before HST: Cosmology was the quest for two numbers

$H_0 = \frac{\dot{a}}{a}$ \quad Present rate, size, age, Key Project of HST!

$q_0 = \frac{-\ddot{a}}{aH_0^2}$ \quad Deceleration by $\Omega_M (=2q_0)$, geometry, fate

origin, viability of inflation

big, 20 Gyr

small, 10 Gyr

dense, fast

empty, slow

1990’s: Better D(z) with long range Standard Candles, SN Ia…
1. Extent of the Universe

The 200-inch telescope is designed to push back the frontiers [of] explored space. It is not likely that this instrument will reach to the greatest distance possible. Further measurements with the more powerful instrument envisaged here would help answer the questions whether space is curved, whether the universe is finite or infinite. This instrument would help in particular to resolve individual stars in a distant galaxy and to analyze their spectra, thus identifying particular stars of known absolute magnitude and in this way determining accurately the distance to the galaxy. At present the distances of most galaxies are known only very approximately.

“Supernovae type I can perhaps be found to $z=1$ using the Space Telescope...to accurately determine $q_0$, the cosmological constant”
HST’s Unique Contributions:
1996-2001: WFPC2, follow-up some grnd SNe Ia at z<1, best data
2001-2007: ACS+NIC2: find SN Ia at z>1, confirming “turn-over”
2007-present: WFC3: characterizing w(z), looking for unexpected

SN Ia Hubble Diagram; q₀, Accelerating Universe, Dark Energy!

Independent of absolute distance, H₀ (2001: KP to 10%)

Ωₘ, Ωₐ

(0.3,0.7)
(0.0,0.0)
(1.0,0.0)

>1300 SN Ia

m or magnitude = 5 log Distance + c

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Att Prior 2004
LOSS (González-Gaitán et al. 2013)
CFA III, IV (Jha et al. 2006, Hicken et al. 2009, 12)
Cornegle (Contreras et al. 2010)
ESSENCE (Woods-Vasey et al. 2009)
SNLS (Guy et al. 2010)
SGP (Amanullah et al. 2010; Suzuki et al. 2011)
SDSS (Kessler et al. 2009)
PSI (Rest, Scalzo et al 2014)
Higher–z (Riess et al. 2004, 07, 14)
2010’s: “End-to-end” test for ΛCDM, Predict and Measure $H_0$

Standard Model of Cosmology, ΛCDM, 6 parameters

- Cosmic Microwave Background
- Big Bang

Planck Predicted, $H_0 = 67.4 +/- 0.5$ km/s/Mpc
The SH$_{0}$ES Project (2005)
(Supernovae, H$_0$ for the dark energy Equation of State)

Measure H$_0$ to percent precision purely **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
   - 5 Sources
   - Cepheids → Type Ia Supernovae
   - 19 Calibrations

2. HST

3. Type Ia Supernovae → redshift(z)
   - 300 SNe
   - $H_0 = 74.03 \pm 1.42, \text{Km s}^{-1} \text{Mpc}^{-1}$ (Riess et al. 2019)

1.9% total uncertainty
≠ CMB + ΛCDM!

Riess et al. 2019

Parallax of Cepheids in the Milky Way

Light redshift (stretched by expansion of space)
Milky Way Cepheid P-L Relation, Now w/ HST photometry, Long Periods

Milky Way PL Relation

Final Gaia Parallaxes + HST Photometry → $H_0 \approx 0.4\%$

} with 3 band HST photometry and Periods > 10 days both matching Cepheids HST sees in SN Ia hosts
**Independent Geometric Source**

<table>
<thead>
<tr>
<th>Source</th>
<th>Authors</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></td>
<td>2.6%</td>
<td>72.3</td>
</tr>
<tr>
<td>LMC 20 Late Detached Eclipsing Binaries: Pietrzyński et al. 2019</td>
<td>+70 HST LMC Cepheids: Riess et al (2019)</td>
<td>1.3%</td>
<td>74.2</td>
</tr>
<tr>
<td>Milky Way 10 HST FGS Short P Parallaxes: Benedict et al. 2007</td>
<td>--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></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></td>
<td>3.3%</td>
<td>73.7</td>
</tr>
</tbody>
</table>

Consistent Results (1.3$\sigma$), *Independent Systematics*
Step 2: Cepheids to Type Ia Supernovae

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

- Now (Cycle 20, R16, 1.3%)
  - $n=50$?
  - $n=38$
  - $n=19$

- Next (Cycle 25/26, 0.9%)
- HST Final? (0.8%)
- Now (Cycle 20 R16, 1.3%)

KP, ~2001
Cepheid V,I,H band Period-Luminosity Relationships: 19 hosts, 3 anchors

Geometric Anchors

S H O S T S
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

Cepheid composite LC’s, >2400

\[ \begin{align*}
\Delta \text{mag} & = -0.5 \quad 0.0 \quad +0.5 \\
\end{align*} \]
Lowering Systematics: Near-IR Cepheid Observations + HST, Now in LMC!

- Negligible sensitivity to metallicity in NIR (F160W)
- Dependence on reddening laws 6x smaller than optical

We use F160W-band as primary +F555W,F814W

Key Project used F555W and F814W

\[ \sigma = 0.07 \]  
\[ \sigma = 0.30 \]

Riess et al. (2019), arxiv:190307603
How does this compare to the CMB measurements?

Main improvements
Since 2016:
- Anchors—MW parallaxes, LMC DEB distance, matched Cepheid photometry, WFC3 CRNL
$H_0$: Measured Late vs. Predicted from Early Universe

NEW PHYSICS (Poulin et al 2018)
1930-1950:
$H_0 > 300 \text{ km s}^{-1} \text{ Mpc}^{-1} \rightarrow t_0 \sim \text{Gyr} << \text{age of Earth}$
Why? Two populations of stars! Early and late, poor and rich.

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

2010’s:
$H_0 = 74 \pm 1.4 \rightarrow 4.4\sigma$ higher than Planck CMB+$\Lambda$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.