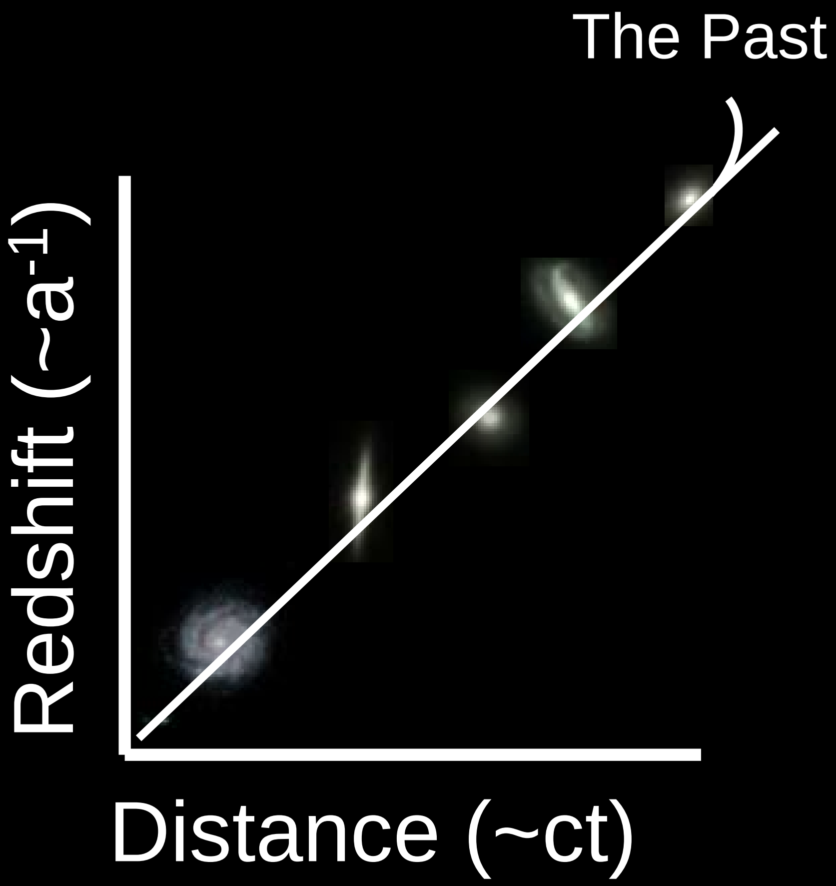
Dr. Adam Riess

Johns Hopkins University
Space Telescope Science Institute

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

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho_M}{3} + \frac{\Lambda}{3} - \frac{k}{a^2}$$

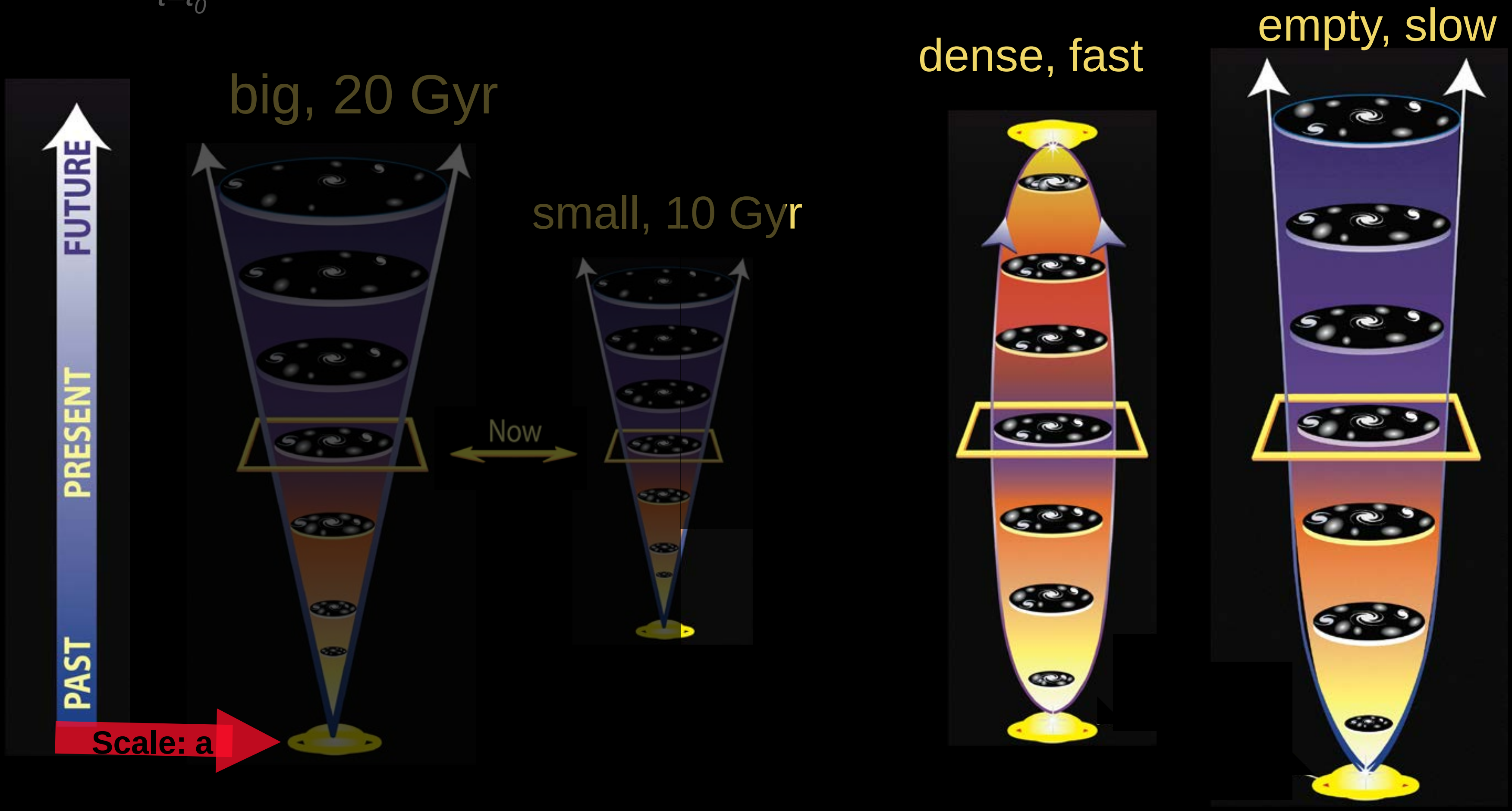
Before HST: Cosmology was the quest for two numbers

$$H_0 = \left.\frac{\dot{a}}{a}\right|_{t=t_0}$$

Present rate, size, age,
Key Project of HST!

$$q_0 = \left.\frac{-\ddot{a}}{aH_0^2}\right|_{t=t_0}$$

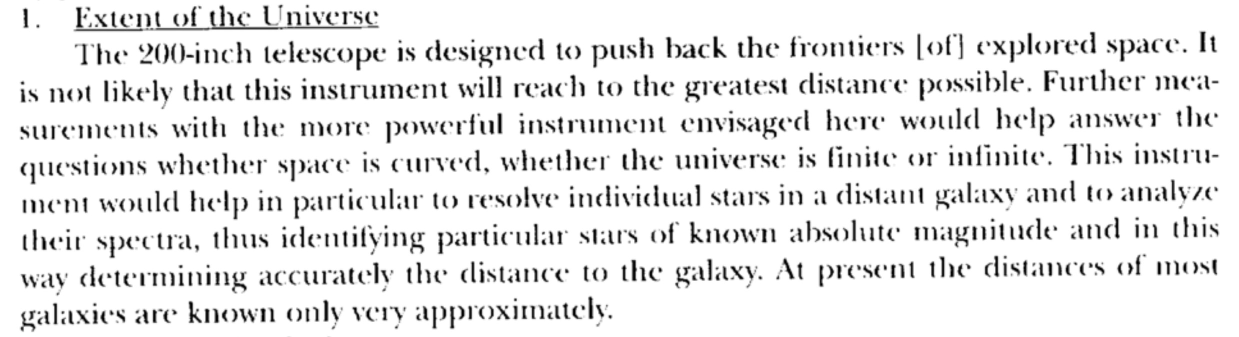
Deceleration by Ω_M (=$2q_0$), geometry, fate
origin, viability of inflation



1990's: Better D(z) with long range Standard Candles, SN Ia…

Original Objective of HST #1, Gauging the Universe

From Lyman Spitzer, 1946, RAND Report



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.

Colgate, S, ApJ, 1979

“Supernovae type I can perhaps be found to z=1 using the Space Telescope…to accurately determine q_0, the cosmological constant”

SN Ia Hubble Diagram; q_0, Accelerating Universe, Dark Energy!

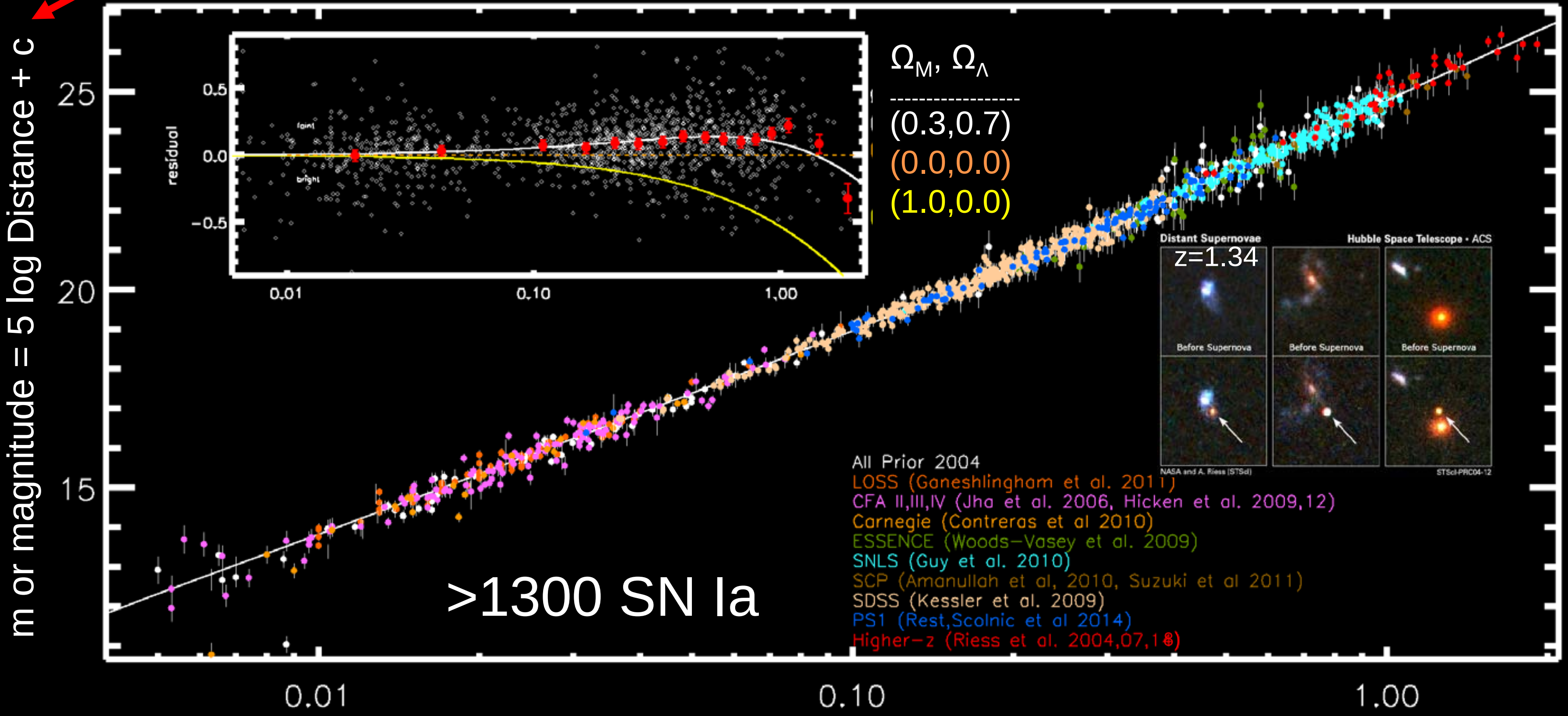
HST's Unique Contributions:

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"

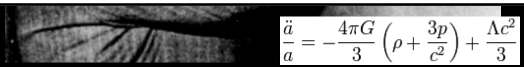
2007-present: WFC3: characterizing w(z), looking for unexpected

Independent of absolute distance, H_0 (2001: KP to 10%)



2010’s: “End-to-end” test for ΛCDM, Predict and Measure H_0

Standa



$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

Planck Predicted, H_0=67.4+/-0.5 km/s/Mpc

After KP: Direct Measurement of H_0 to percent precision

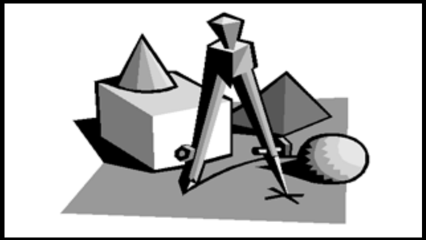
The SH_0ES Project (2005)

(Supernovae, H_0 for the dark energy Equation of State)

A. Riess, L. Macri, S. Casertano, D. Scolnic, A. Filippenko, W. Yuan, S. Hoffman, et al

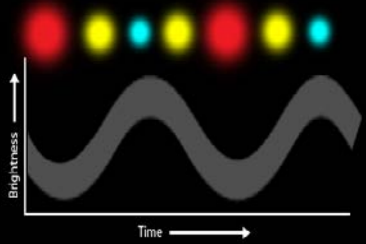
Measure H_0 to percent precision purely <u>empirically</u> by:

- A clean, simple ladder: Geometry → Cepheids → SNe Ia



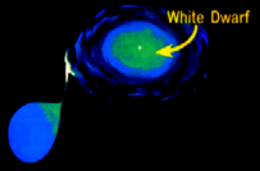
→

Pulsating Stars,
10^5 $L_\odot$, P-L relation



→

<u>Exploding Stars</u>,
10^9 $L_\odot$, $\sigma \sim 5\%$

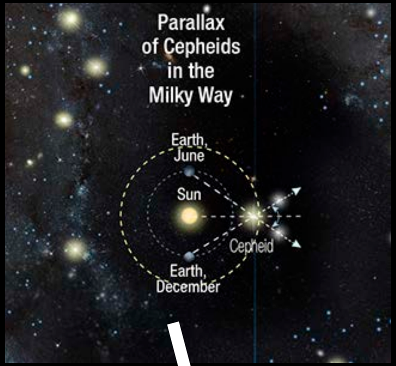


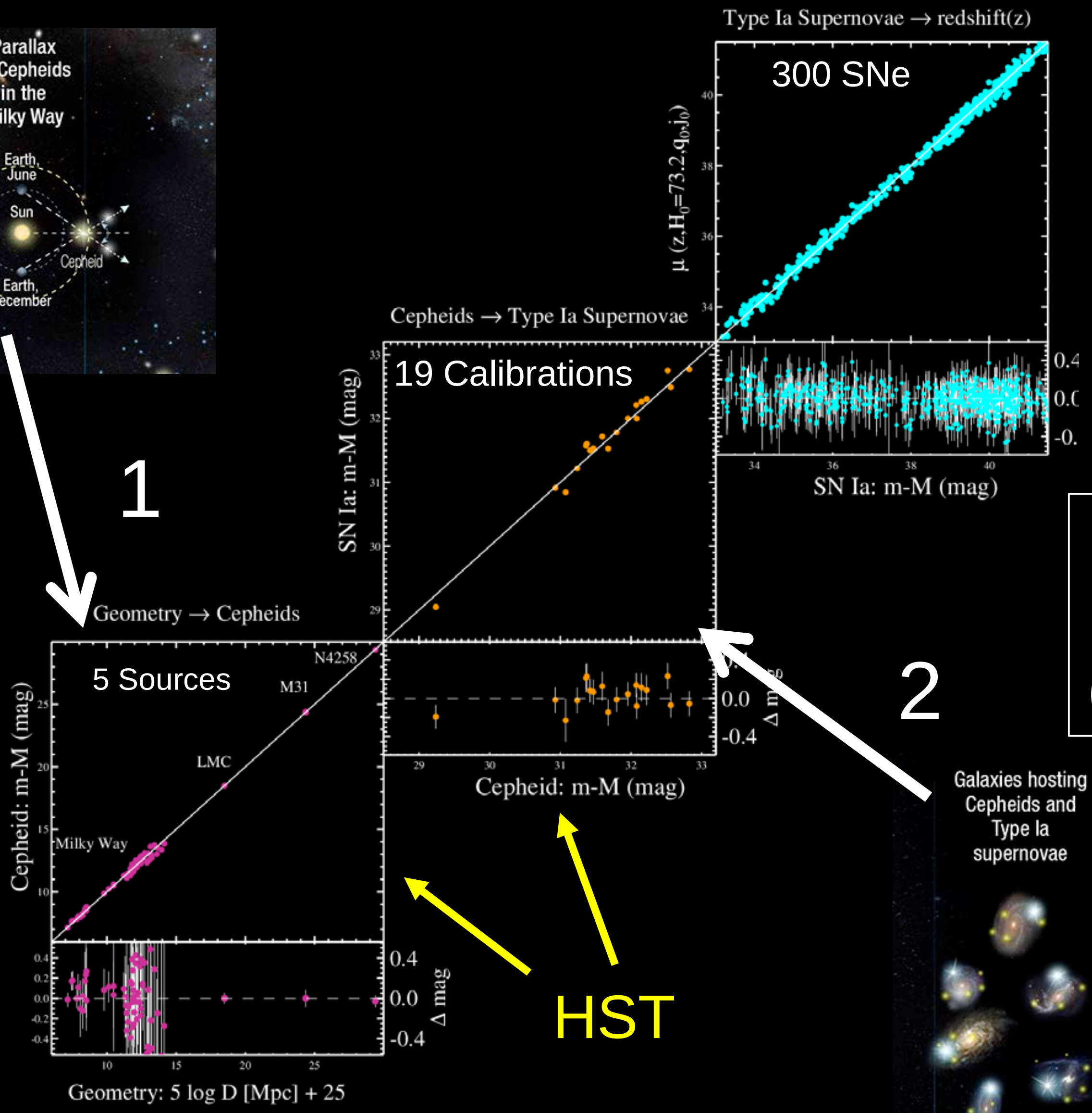
An explosion resulting from the thermonuclear detonation of a White Dwarf Star.

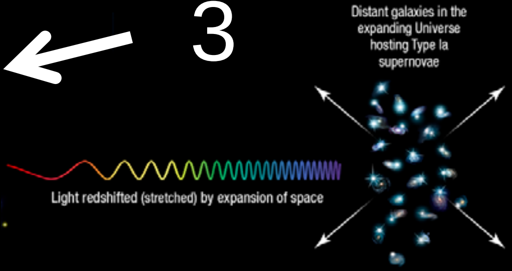
- Reducing systematic error with better data, better collection

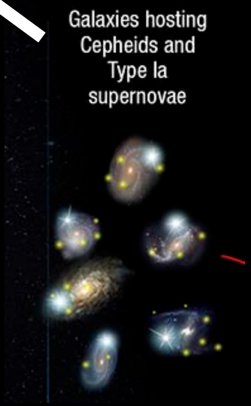
- Thorough propagation of statistical and systematic errors

The Hubble Constant in 3 Steps: Present Data







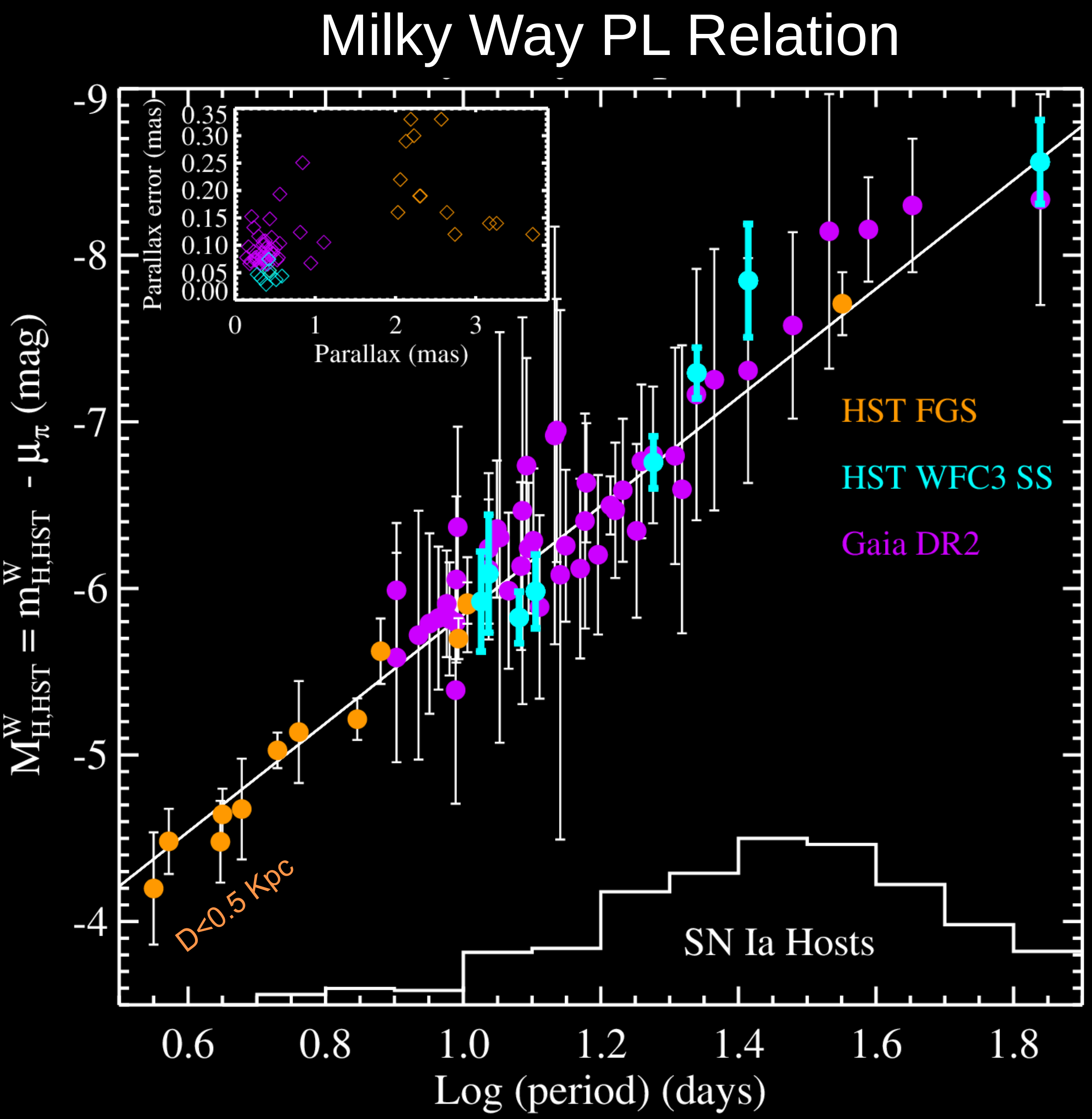


H_0=74.03 +/- 1.42,
Km s^{-1} Mpc^{-1}
(Riess et al. 2019)

1.9% total uncertainty

$\neq$ CMB + ΛCDM !

Milky Way Cepheid P-L Relation, Now w/ HST photometry, Long Periods



Final Gaia Parallaxes + HST Photometry→ H_0~0.4%!

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

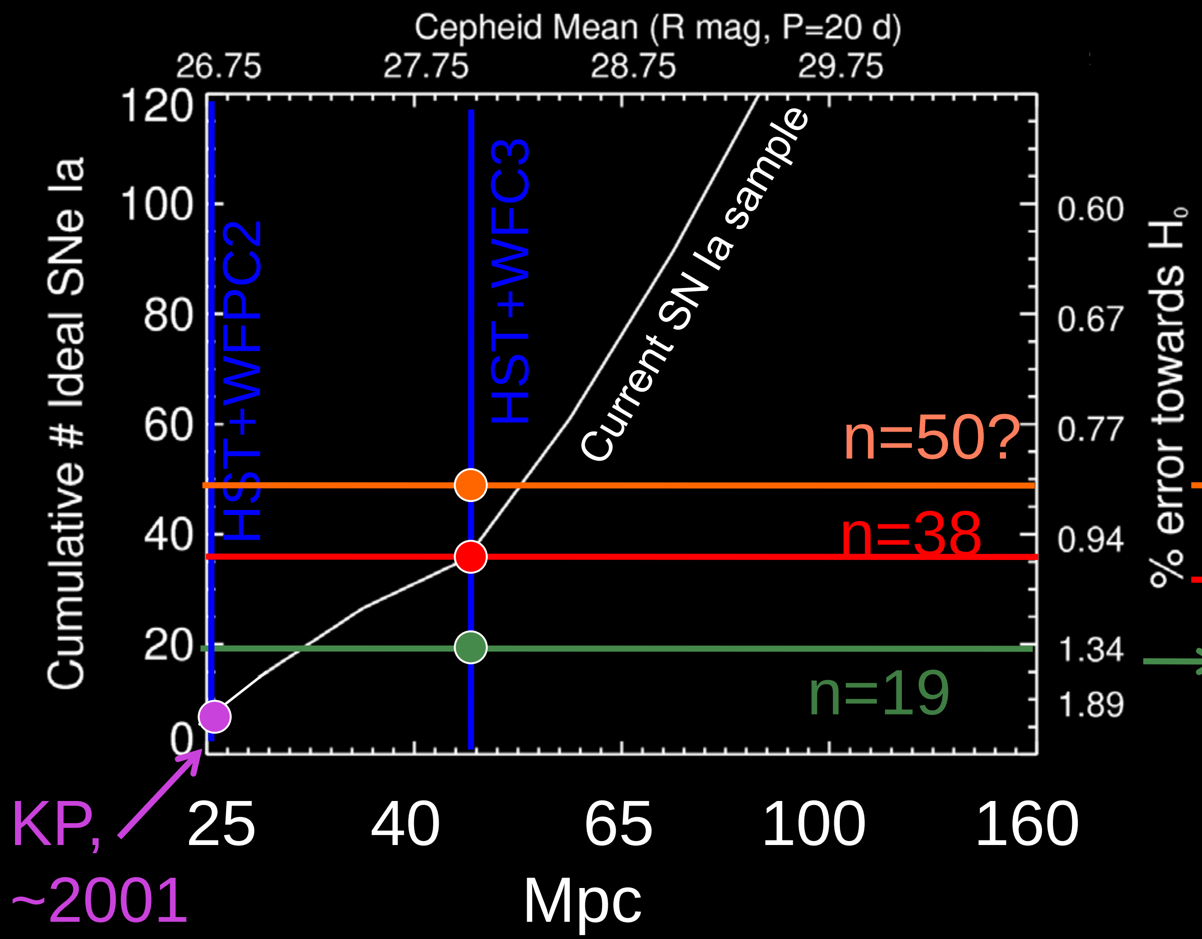
Robust? Five Sources of Cepheid Geometric Calibration

	Independent Geometric Source	**σ**	**H_0**
	NGC 4258 H_20 Masers: Humphreys et al 2013, Riess et al 2016	2.6%	72.3
NEWER	LMC 20 Late Detached Eclipsing Binaries: Pietzrynski et al. 2019 +70 HST LMC Cepheids Riess et al (2019)	1.3%	74.2
	Milky Way 10 HST FGS Short P Parallaxes: Benedict et al. 2007 --also Hipparcos (Van leeuwen et al 2007)	2.2%	76.2
NEW	Milky Way 8 HST WFC3 SS Long P Parallaxes: Riess et al. 2018	3.3%	75.7
NEW	Milky Way 50 Gaia+HST, Long P Parallaxes: Riess et al. 2018	3.3%	73.7

Consistent Results (1.3σ), *Independent Systematics*

Step 2: Cepheids to Type Ia Supernovae

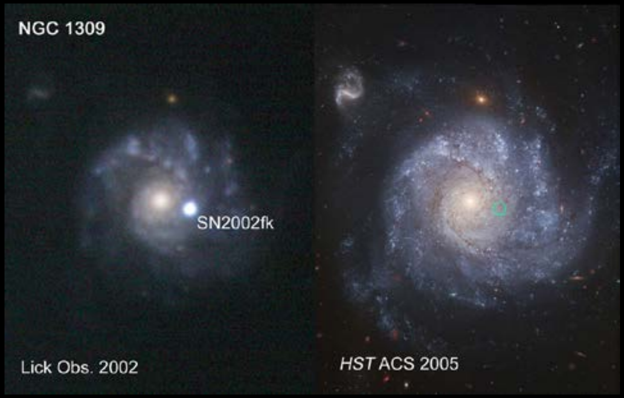
This is the H_0-Limiting Step: Number of SN Ia in Cepheid Range



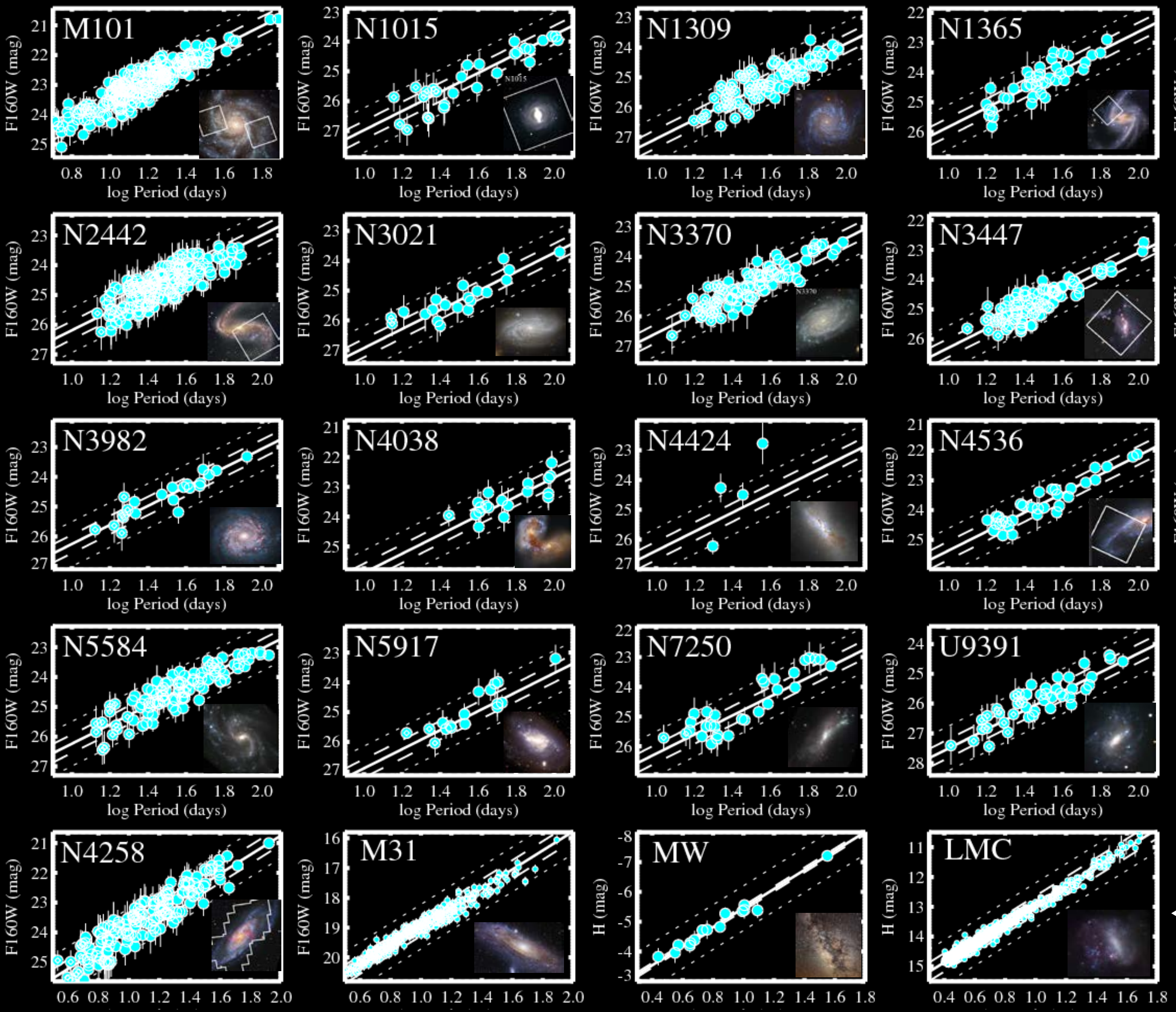
→ **HST Final? (0.8%)**

→ Next (Cycle 25/26, 0.9%)

→ Now (Cycle 20 R16,1.3%)



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



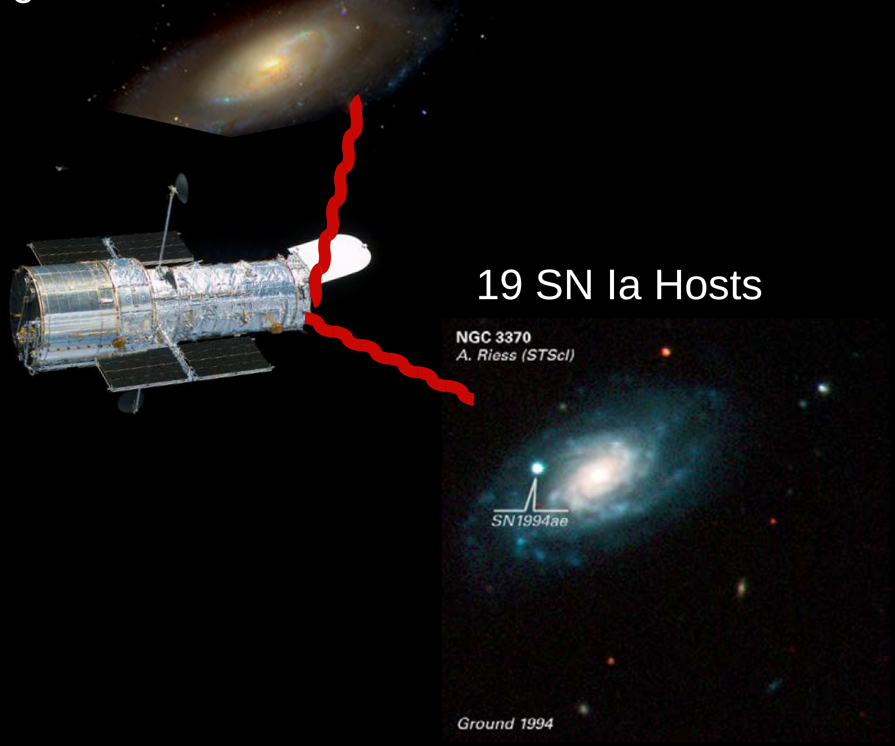
SN HOSTS

Geometric Anchors

Lower Systematics from *Differential* Flux Measurements

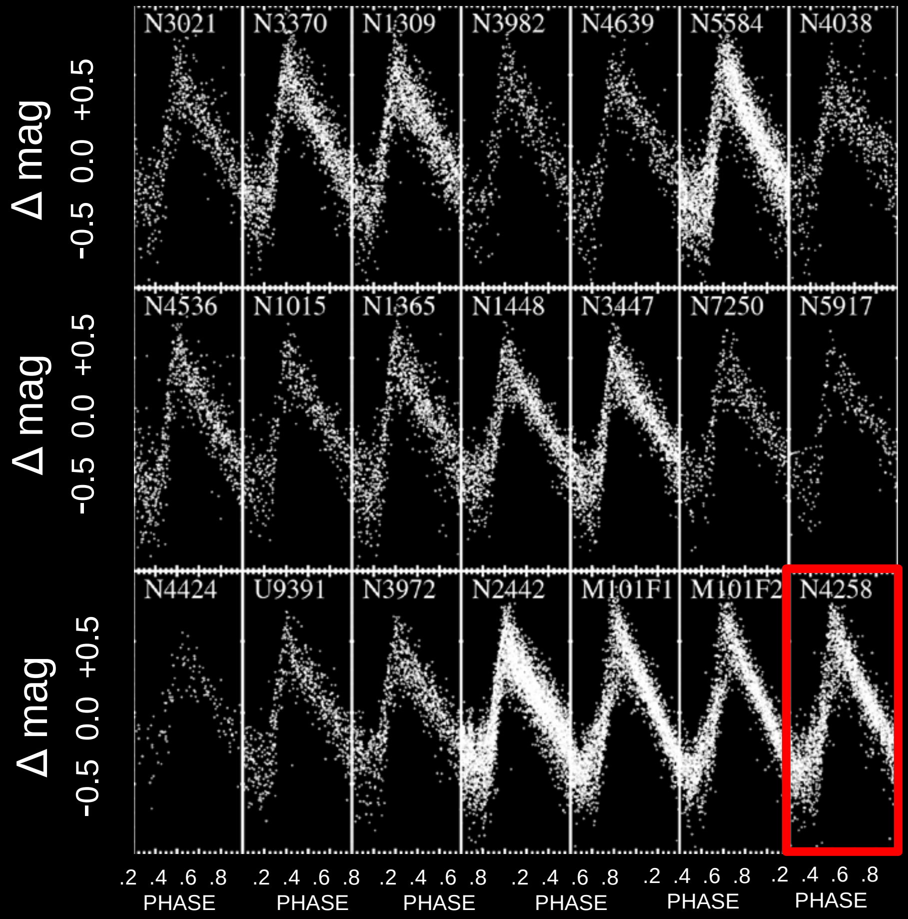
We reduce systematic errors by measuring all Cepheids with same instrument, filters, similar metallicity, period range, we correct for crowding and dust statistically

ANCHORS: NGC 4258 (and now MW, LMC) geometric distance



19 SN Ia Hosts

Cepheid composite LC's, >2400



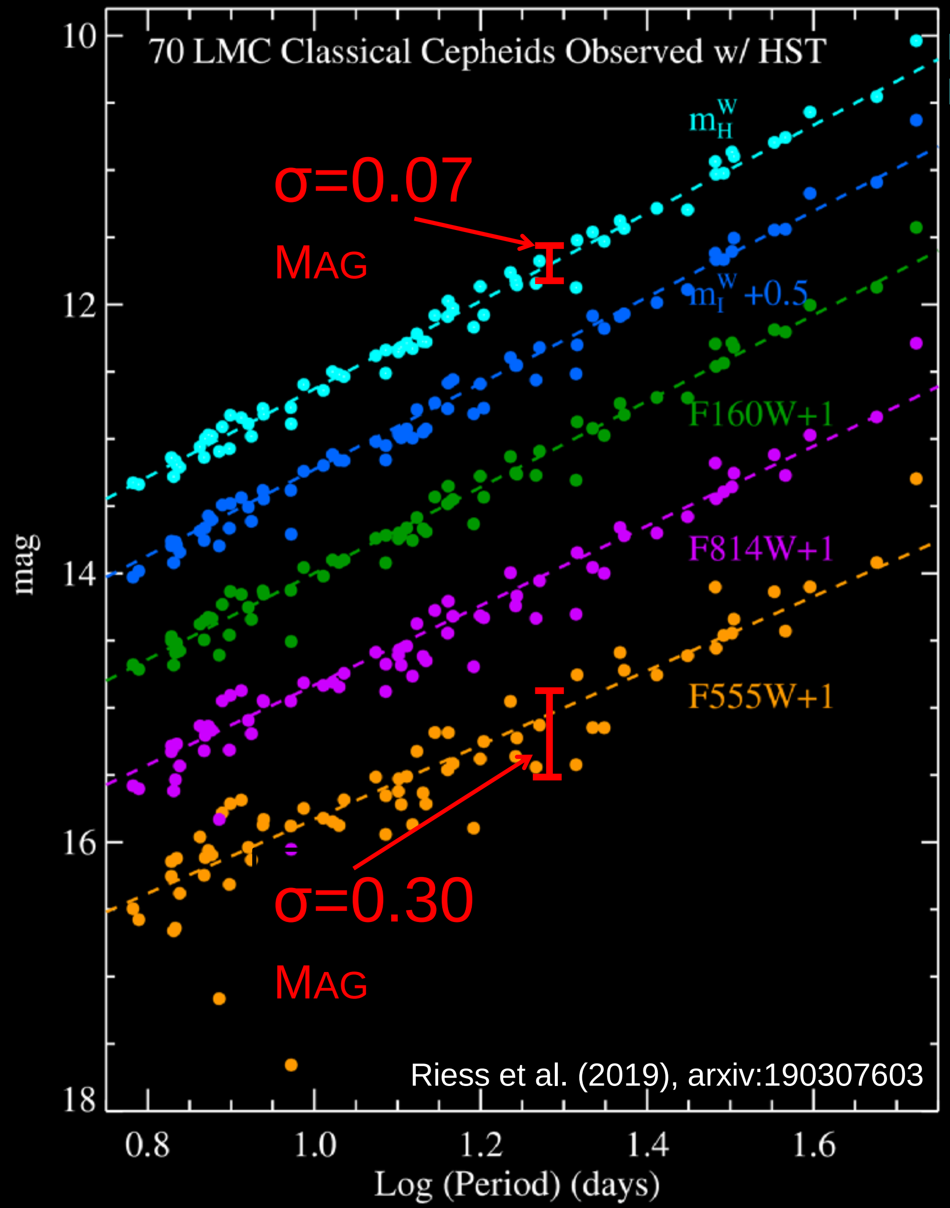
Lowering Systematics: Near-IR Cepheid Observations + HST, Now in LMC!

-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



σ=0.07 MAG

σ=0.30 MAG

Riess et al. (2019), arxiv:190307603

Dereddened: F160W-0.386(F555W-F814

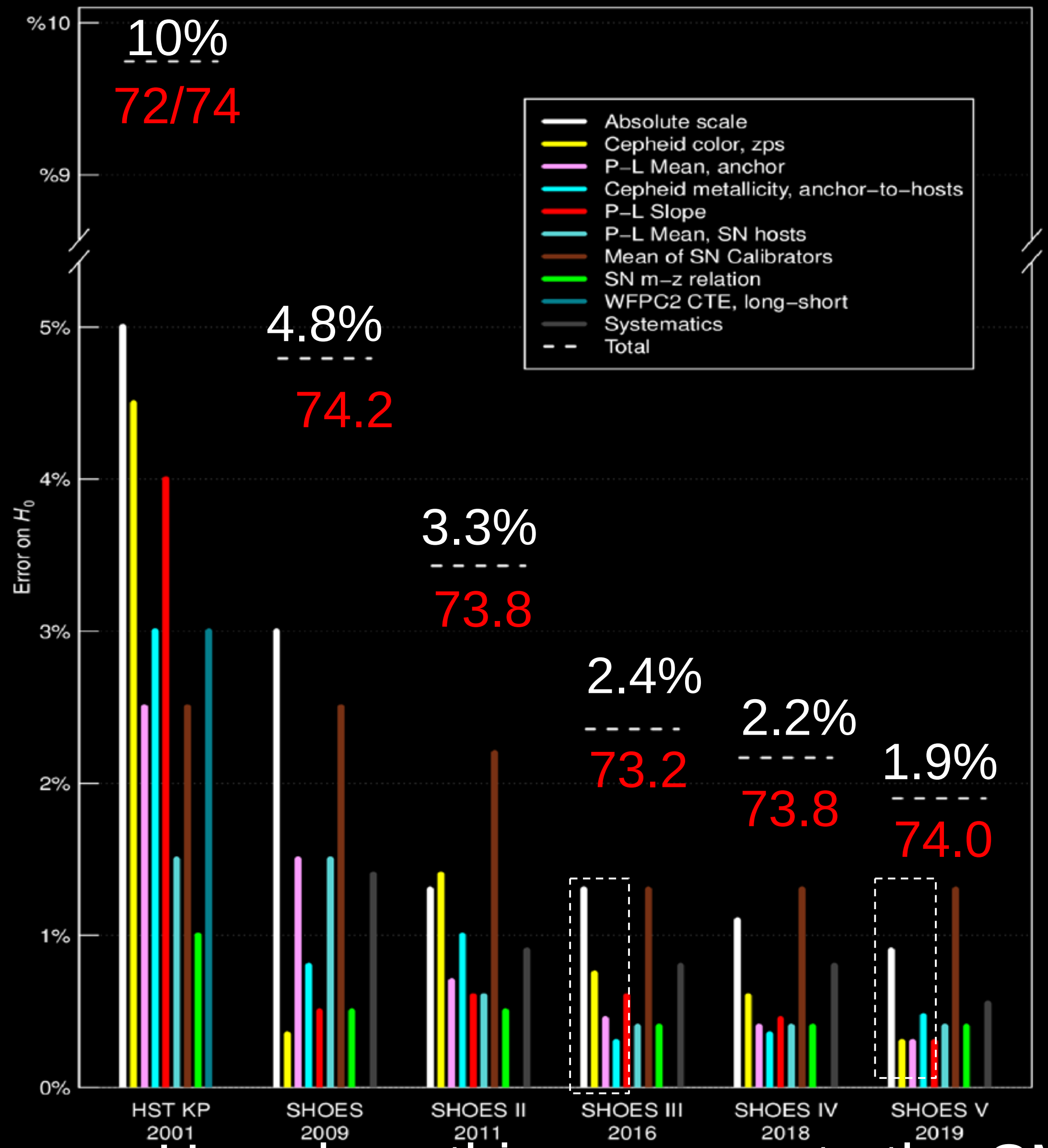
1.6⌠m

0.8⌠m

0.55⌠m

Leavitt

HST Distance Ladder Error Budgets for H_0 (w/ SN+Cepheids) 2001-2019

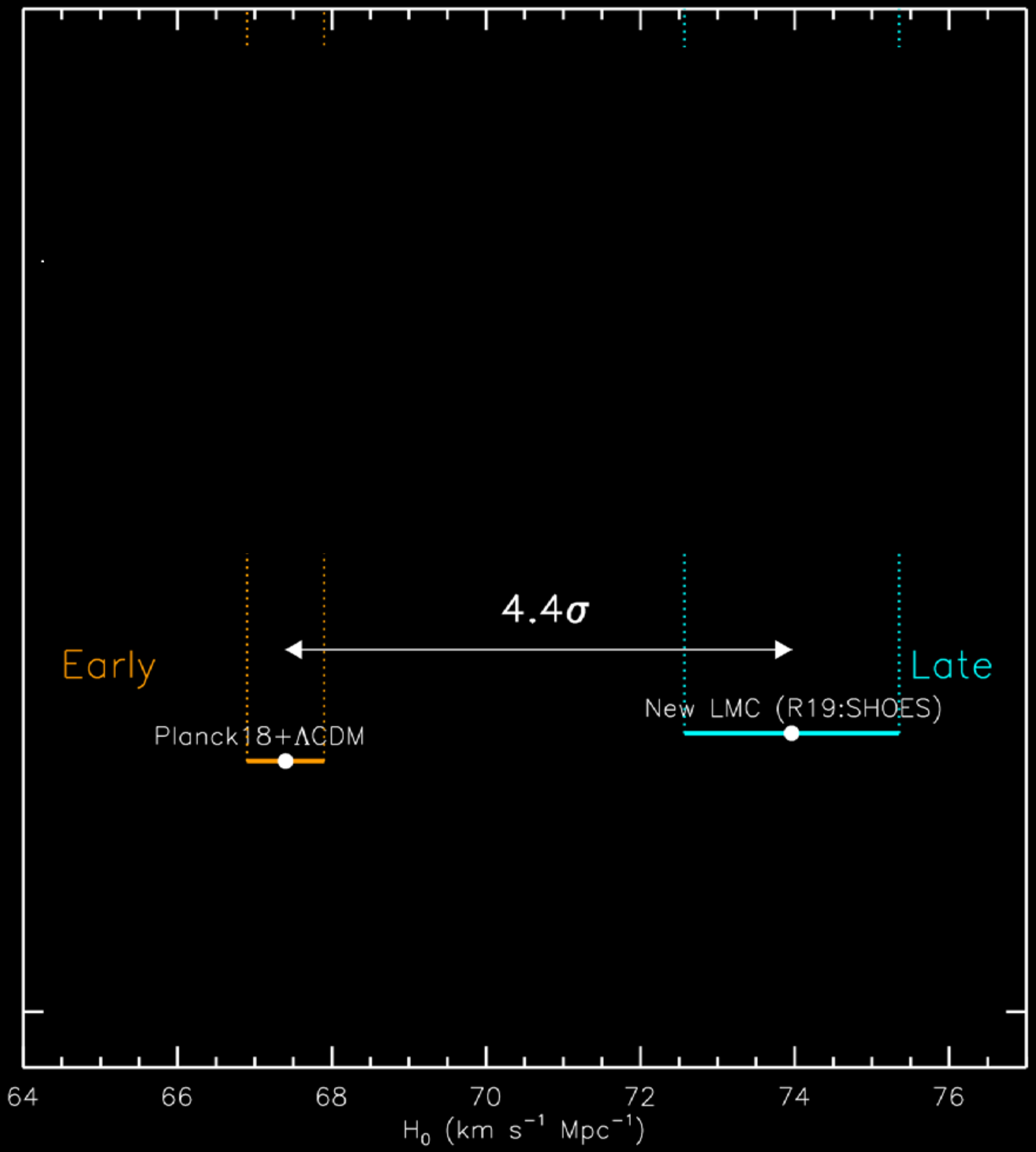


Main improvements Since 2016:
Anchors—MW parallaxes, LMC DEB distance, matched Cepheid photometry, WFC3 CRNL

How does this compare to the CMB measurements?

H_0 : Measured Late vs. Predicted from Early Universe

NEW
PHYSICS

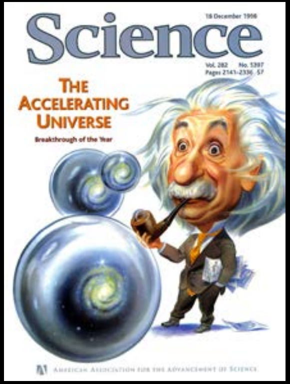


Breakthroughs When Local H_0 was too high. This time?

1930-1950:

$H_0 > 300$ km s^{-1} $Mpc^{-1} \rightarrow t_0 \sim$Gyr << 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 Gyr) << 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+ΛCDM

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 ΛCDM+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.