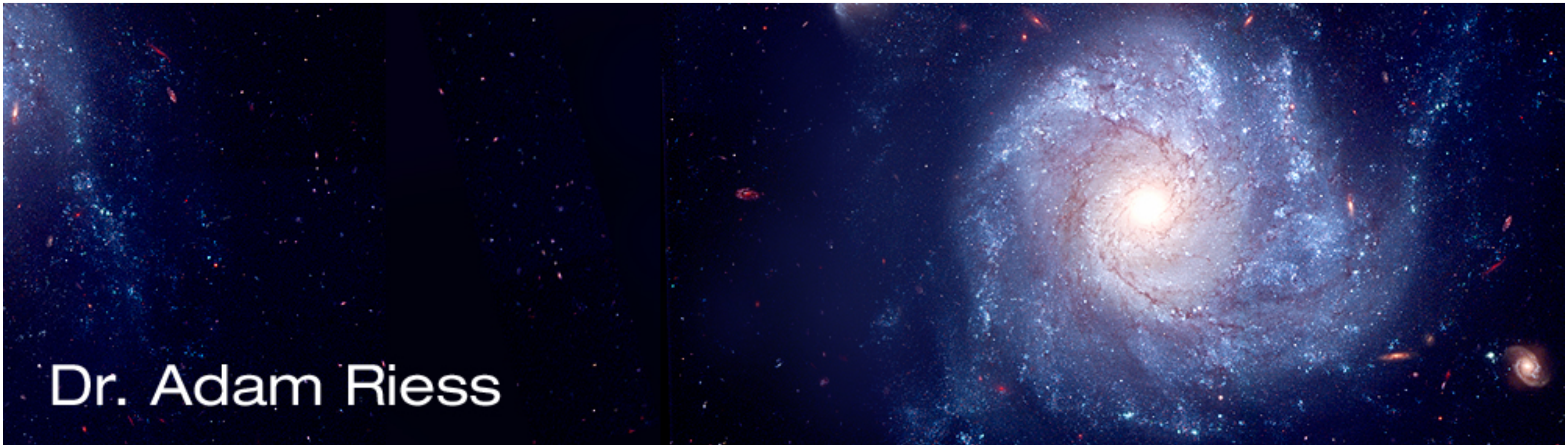



Johns Hopkins University
Space Telescope Science Institute

# New Measurements of the Expansion Rate of the Universe, Faster than we thought

$SH_0ES$ Team

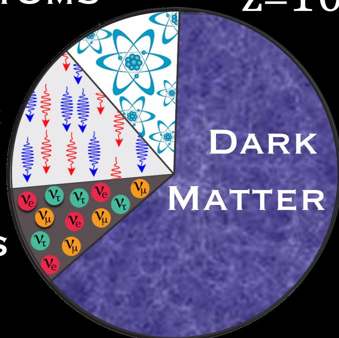
# Ultimate “End-to-end” test for ΛCDM, Predict and Measure $H_0$

Standard Model: (Vanilla) ΛCDM, 6 parameters + ansatz ($w$, $N_{eff}$, $\Omega_K$, etc)

ATOMS

PHOTONS

NEUTRINOS



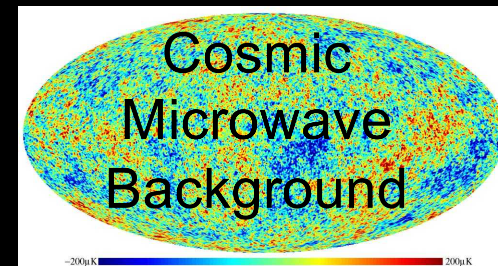

z=1000

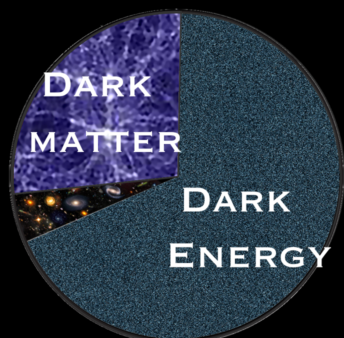
Predict physical size fluctuations, $r_s$, $\Omega_B$

Measure angular fluctuations (or $\Omega_B$)

Calibrate ΛCDM …

Big Bang

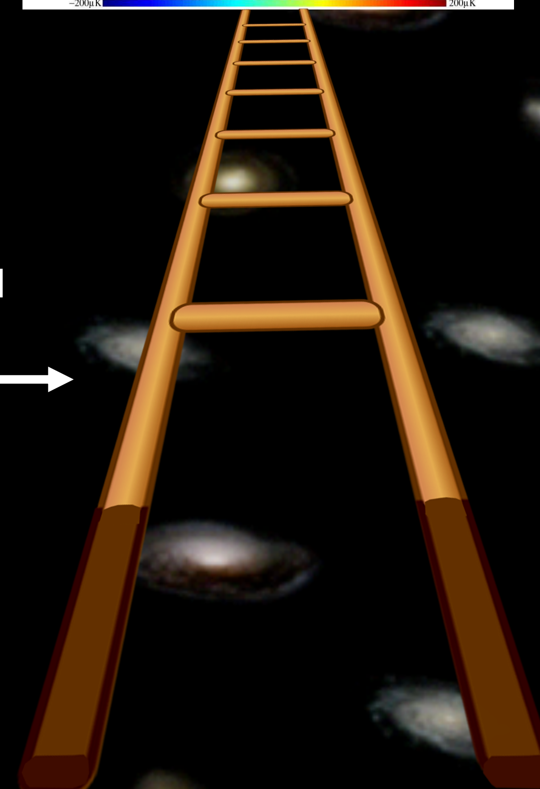


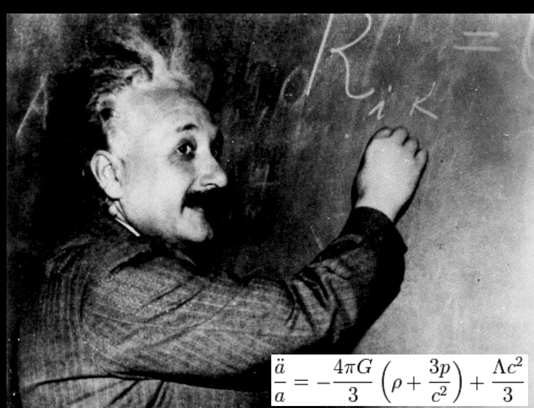




ATOMS

Now

Expansion history predicted
(“guard rails”, BAO, SNe)





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

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

# A Direct, Local Measurement of $H_0$ to percent precision

## The $SH_0ES$ Project (2005)

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

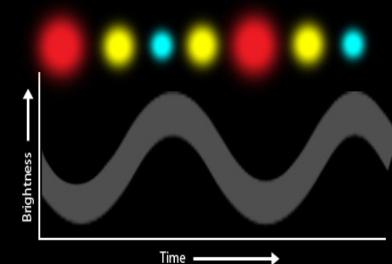
A. Riess, L. Macri, D. Scolnic, S. Casertano, A. Filippenko, W. Yuan, S. Hoffman, +

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

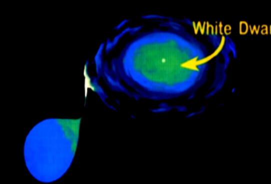
- A strong, simple ladder: $\boxed{\text{Geometry} \rightarrow \text{Cepheids} \rightarrow \text{SNe Ia}}$

Multiple ways

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.

--Reduce systematics w/ consistent data along ladder and NIR
--Thorough propagation of statistical and systematic
--HST Cycle 11-28, 17 competed GO proposals,~1000 orbits

# The $SH_0ES$ Project (2005)

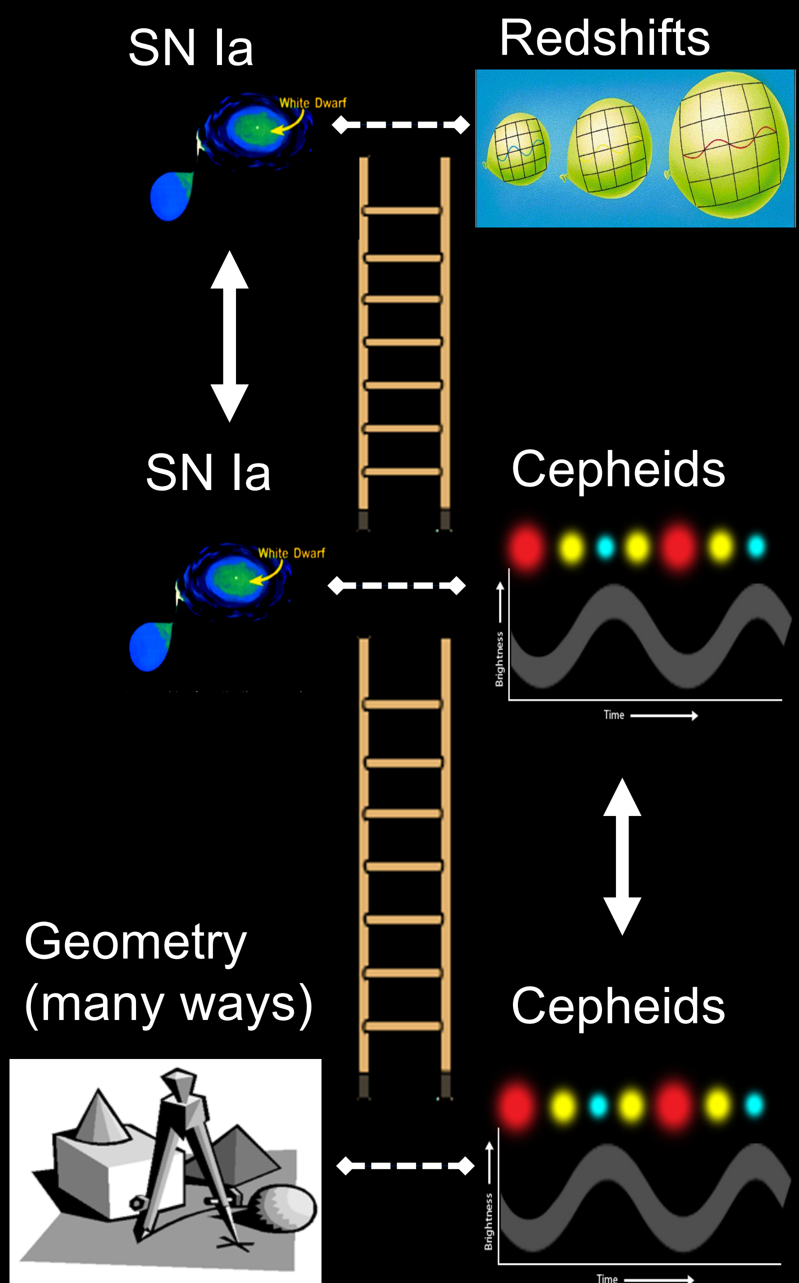
(Supernovae, $H_0$ for the dark energy Equation of State)

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

## Measure $H_0$ to percent precision empirically by:

- A strong, simple ladder: Geometry → Cepheids → SNe Ia
- Reduce systematics w/ consistent data along ladder and NIR
- Thorough propagation of statistical and systematic errors
- HST Cycle 11-28, 17 competed GO proposals,~1000 orbits

# Distance Ladders: Simple & Empirical, Must be Consistent




**Hubble Flow:**
D~Gpc, z~0.1

**Cross-calibrate:**
D~10-40 Mpc

**Anchors:**
D~Kpc or Mpc

**Nutrition Facts**

Serving size 1 potato (148g/5.2oz)

**Amount per serving**
**Calories** **73**

**% Daily Value***

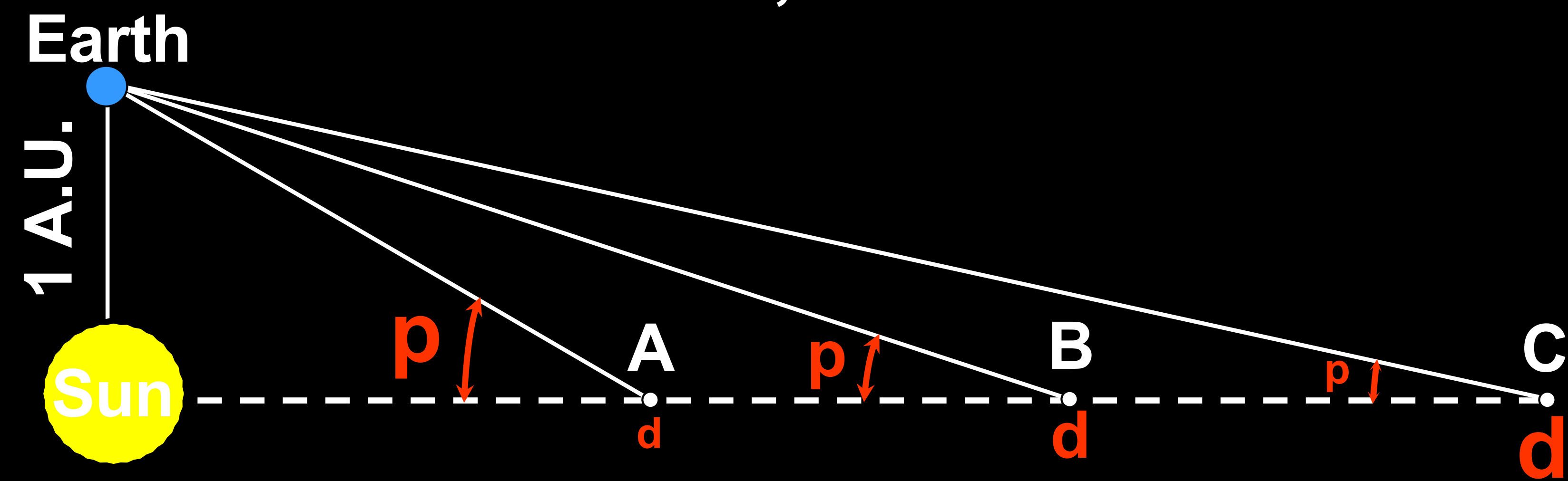
| | |
|---|---|
| Astrophysical modeling | 0% |
| General Relativity | <1% |
| LCDM | <1% |

**⚠ WARNING**

Same object types on different rungs must be standardized and measured <u>consistently</u>!

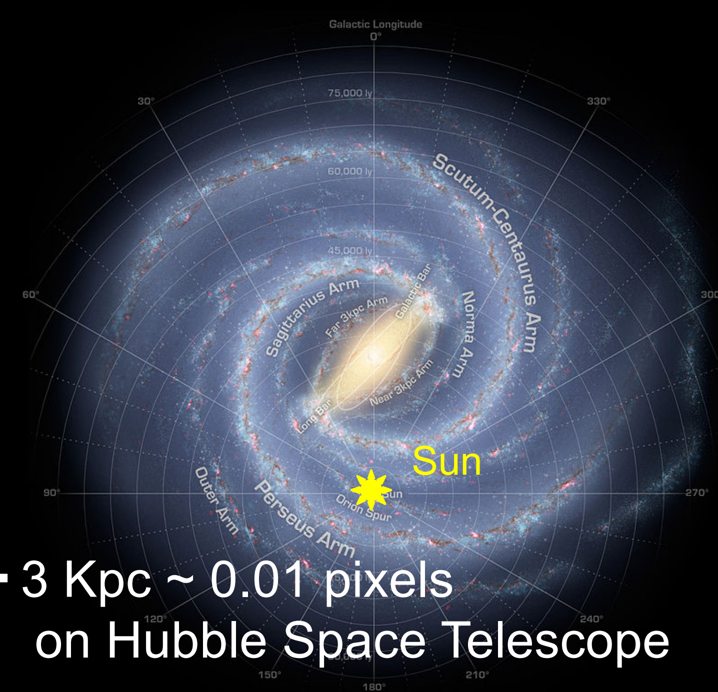
# Parallax in the Milky Way at Kiloparsec Distances

## Stars are far, Parallax is small !



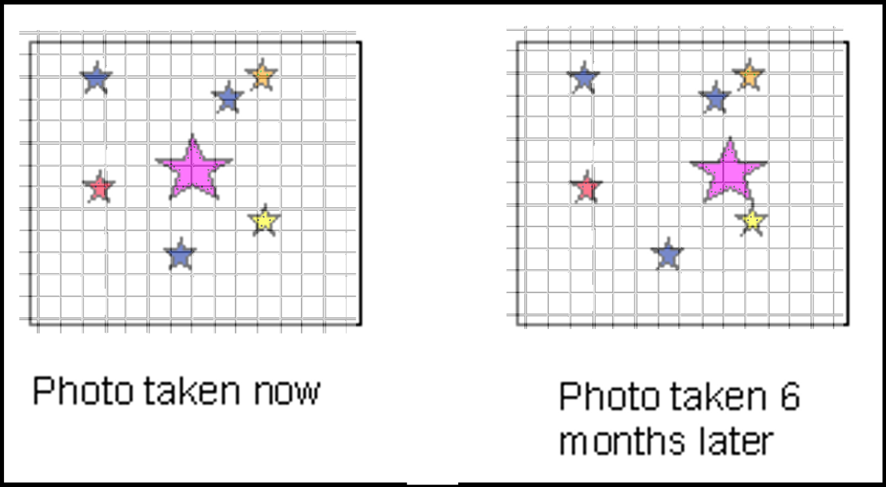

$$\boxed{d\ (\mathrm{kpc}) = \frac{1}{p\ (\mathrm{milliarcsec})}}$$

Nearly all long-period (P>10 days)
MW Cepheids D > kpc




3 Kpc ~ 0.01 pixels
on Hubble Space Telescope

# Extending Parallax with WFC3 Spatial Scanning

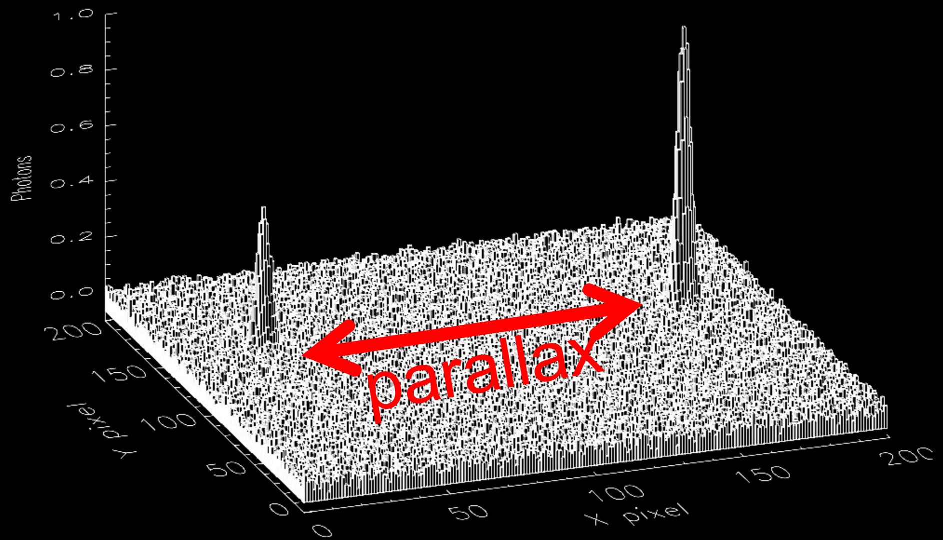


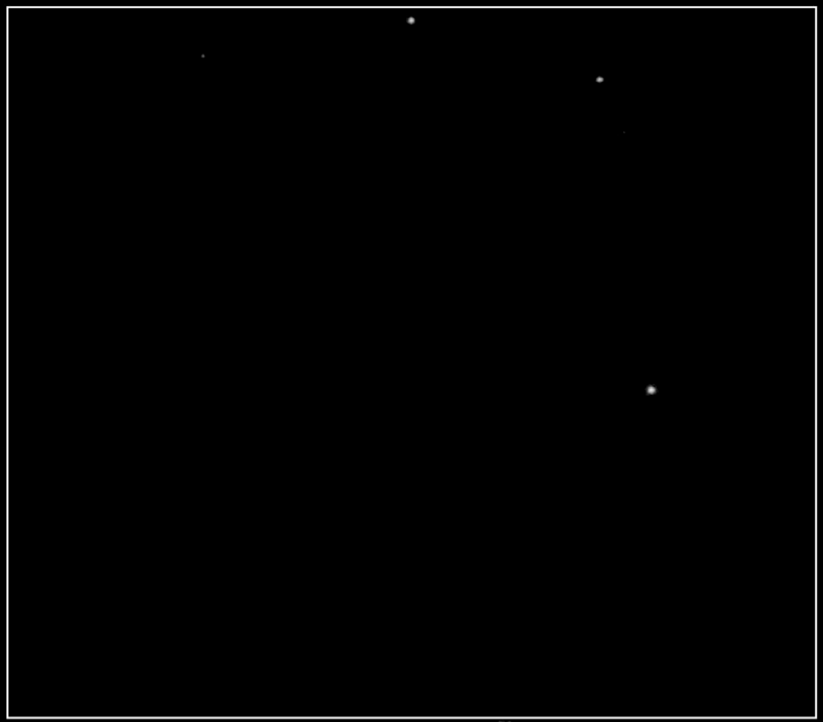


Imaging, precision=0.01 pix

WFC3: ~1σ @ 3 kpc

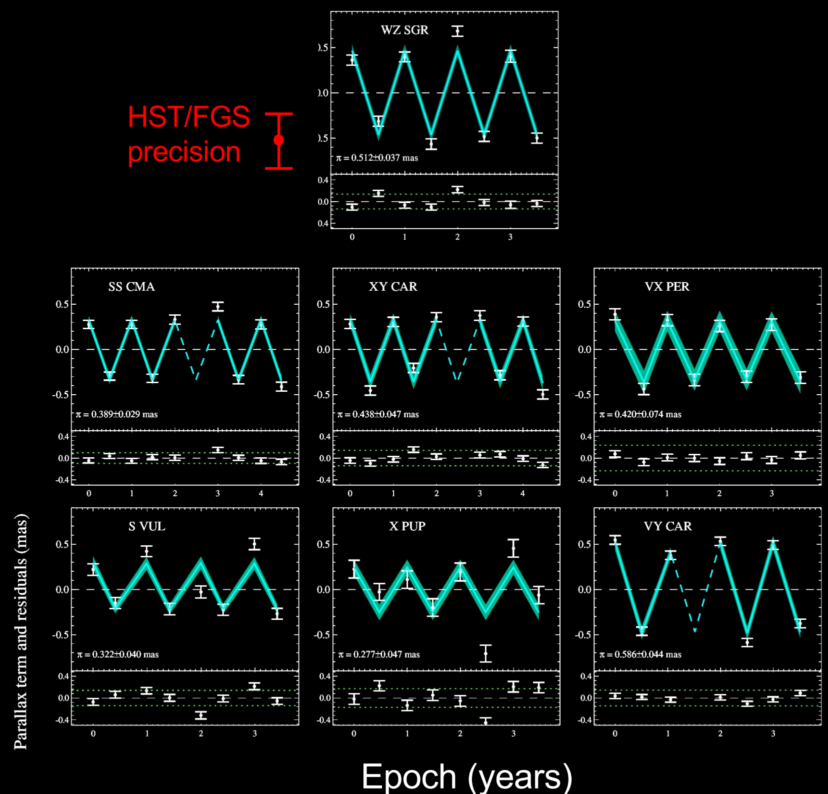
Sc



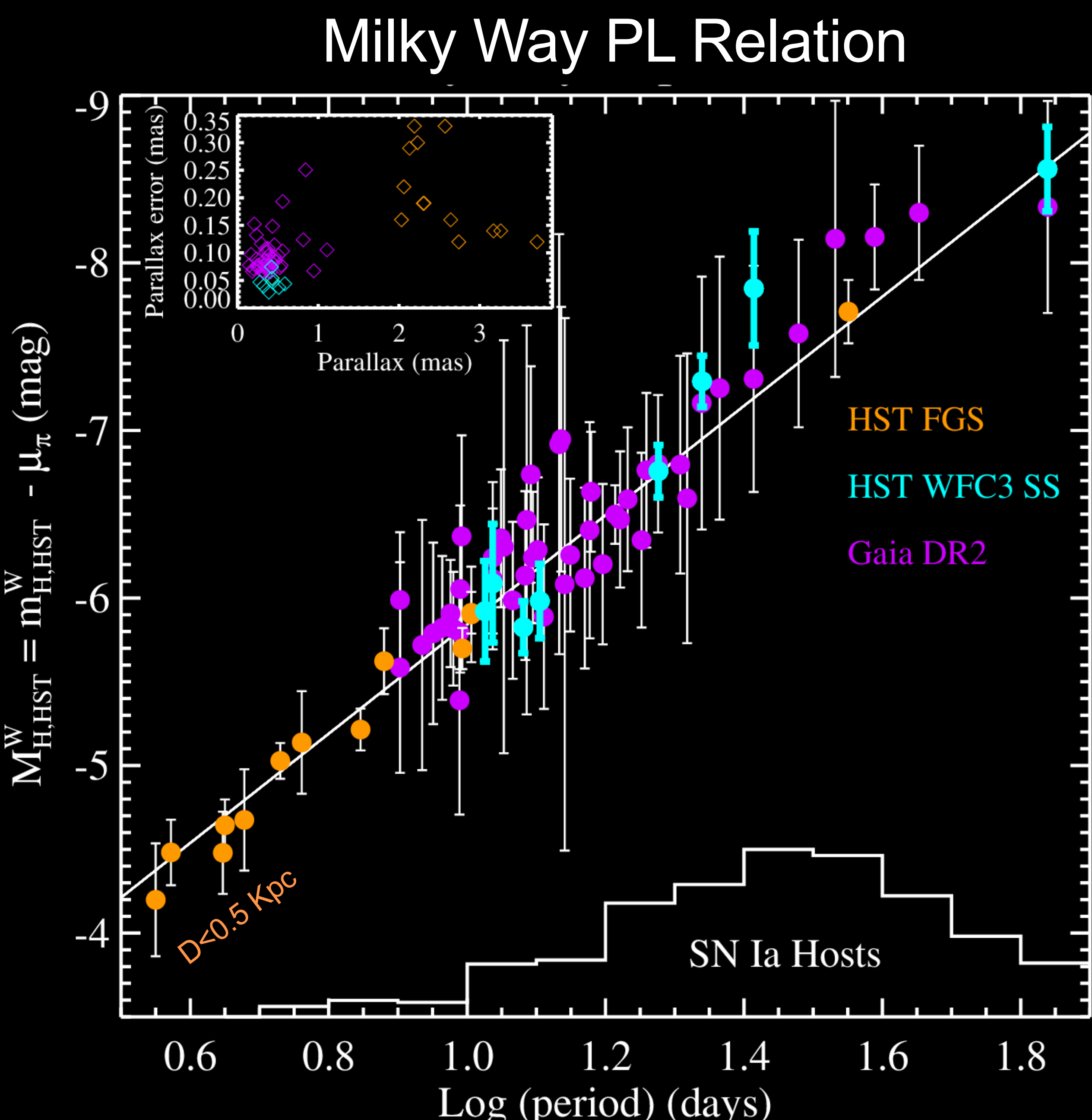
# New Tool: WFC3 Spatial scanning for long range parallaxes, photometry

WFC3 Spatial Scanning→ 20-40 $\mu$as
4 Years Later: Proper Motion subtracted,
8 MW long-P Cepheid Parallaxes
1.7<D<3.6 Kpc, error in mean=3.3%




Riess et al. (2018a), ApJ, 855,136

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




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

}

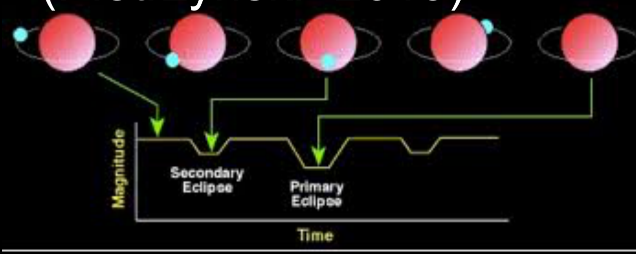
Periods > 10 days matching Cepheids HST sees in SN Ia hosts

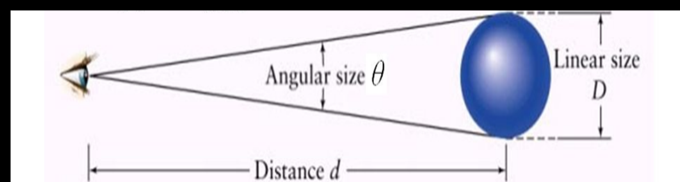
Gaia EDR3! In prep

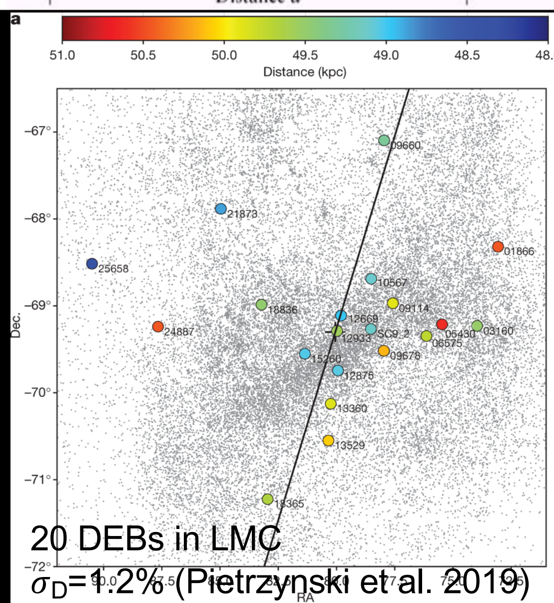
# Three Sources of Geometric Distances to Calibrate Cepheids

## Parallax in Milky Way (WFC3 SS, HST FGS, Gaia)


## Detached Eclipsing Binaries in LMC
(Pietrzynski+2019)

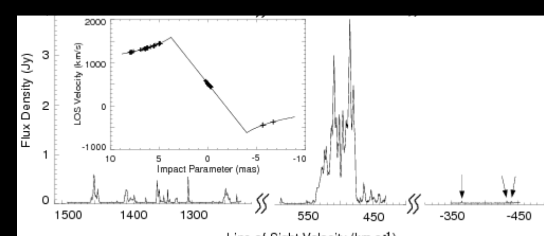



20 DEBs in LMC
$\sigma_D$=1.2% (Pietrzynski et al. 2019)

## Masers in NGC 4258, Keplerian Motion
(Reid+2019)

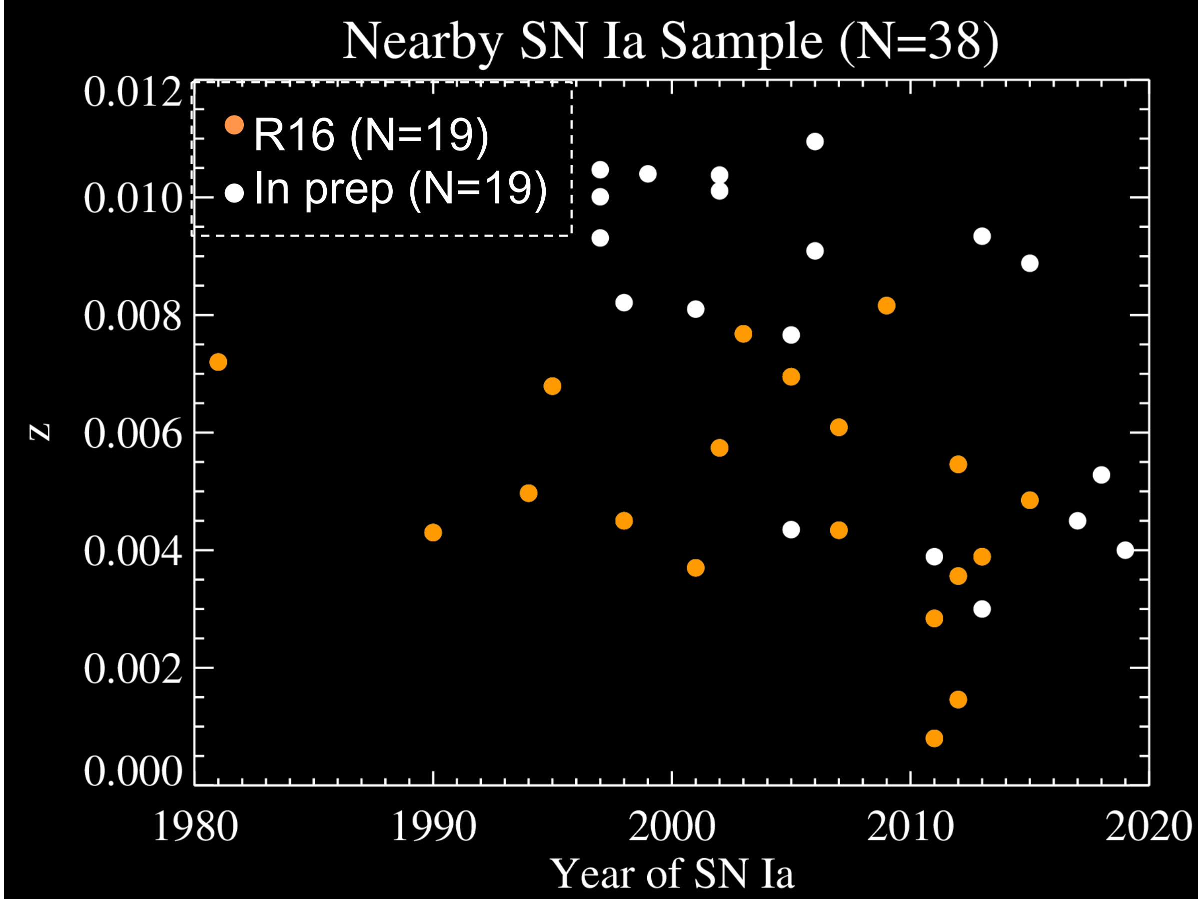
# Step 2: Cepheids to Type Ia Supernovae

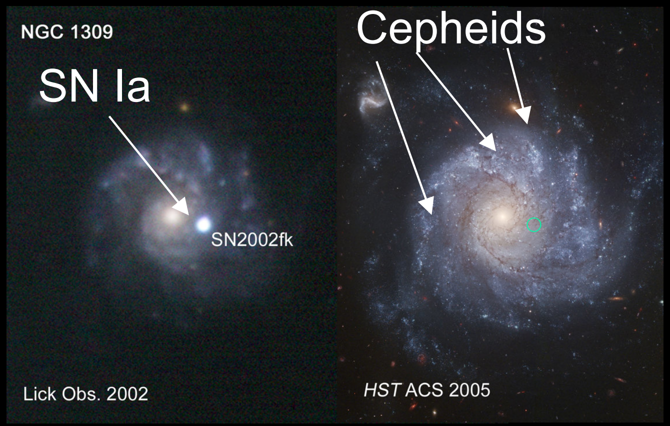
Number nearby SN Ia limits $H_0$ precision, $\sigma = \frac{6\%}{\sqrt{N}}$

SN Ia  Requirements: $A_V$<0.5, normal, pre-max, digital

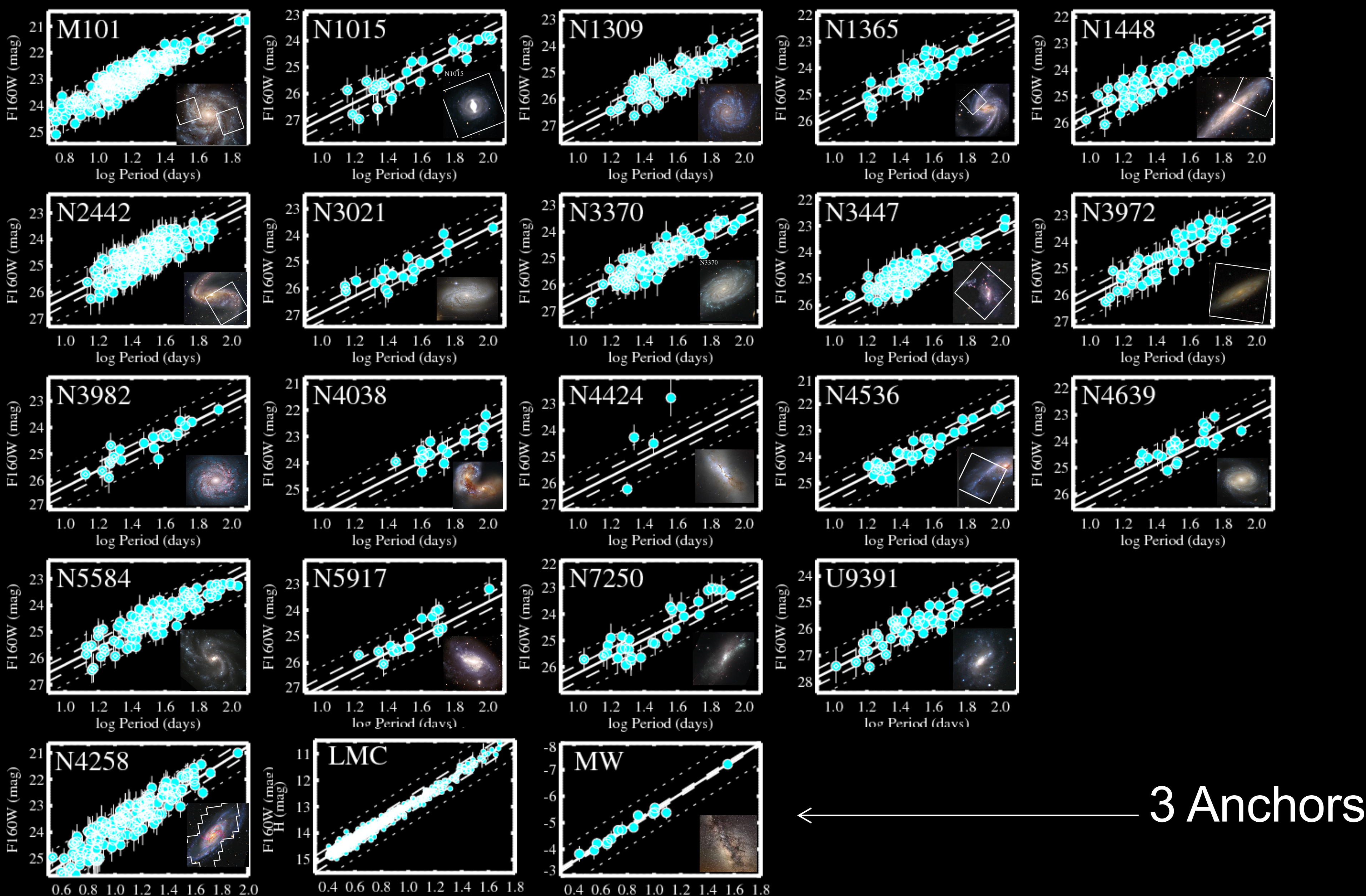
Host Requirements: Late-type, z≤0.01, not-edge on

2020 Complete sample (new ones @ 1.5/yr)



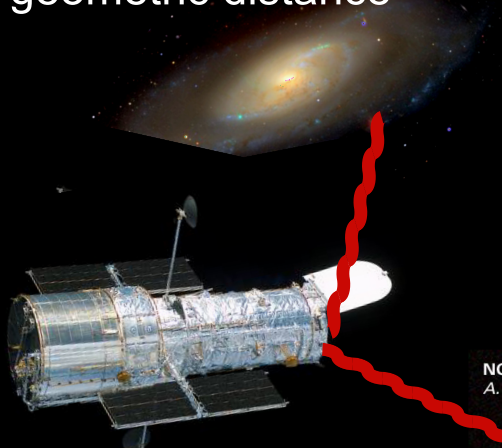
# Cepheid V,I,H band Period-Luminosity Relationships: 19 hosts, 3 anchors



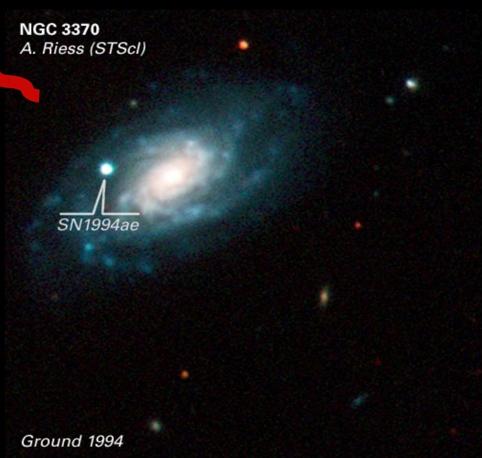
# Lower Systematics from *Differential* Flux Measurements

To reduce systematic errors: measure all Cepheids with same instrument, filters, similar metallicity, period range

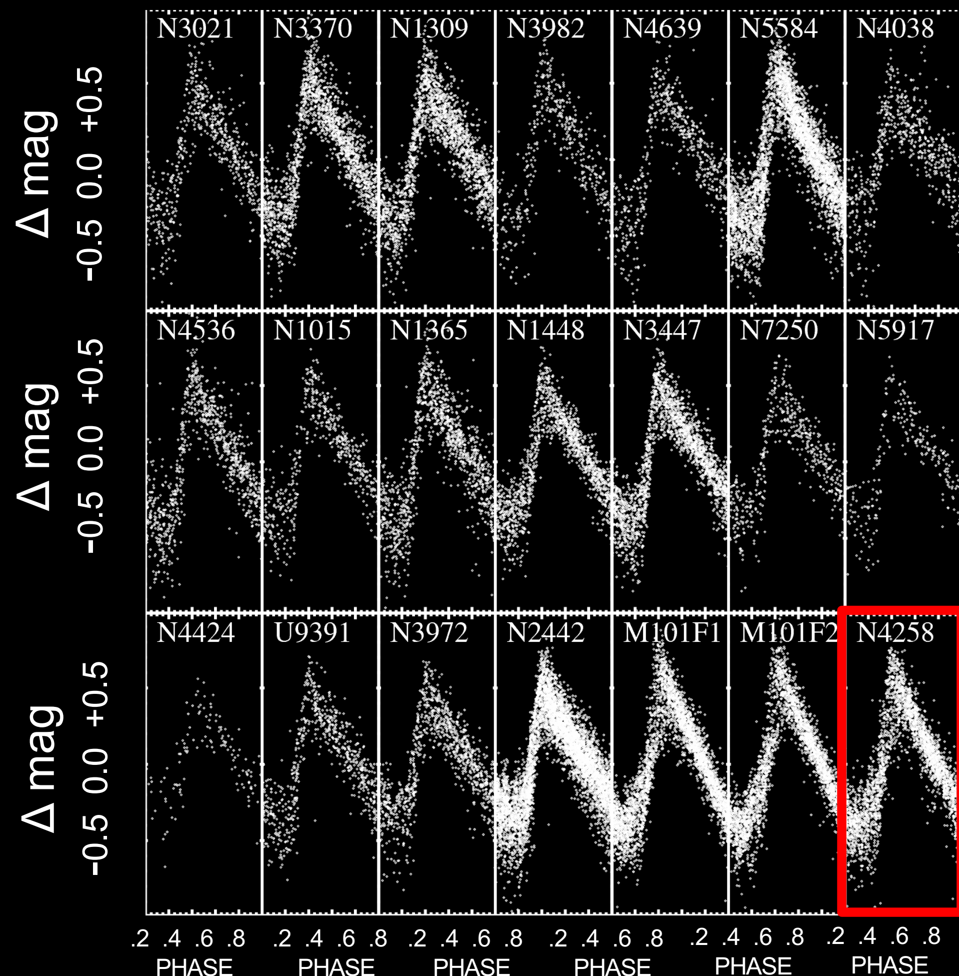
ANCHORS: NGC 4258, MW, & LMC geometric distance



19 SN Ia Hosts




Cepheid composite LC's, >2400



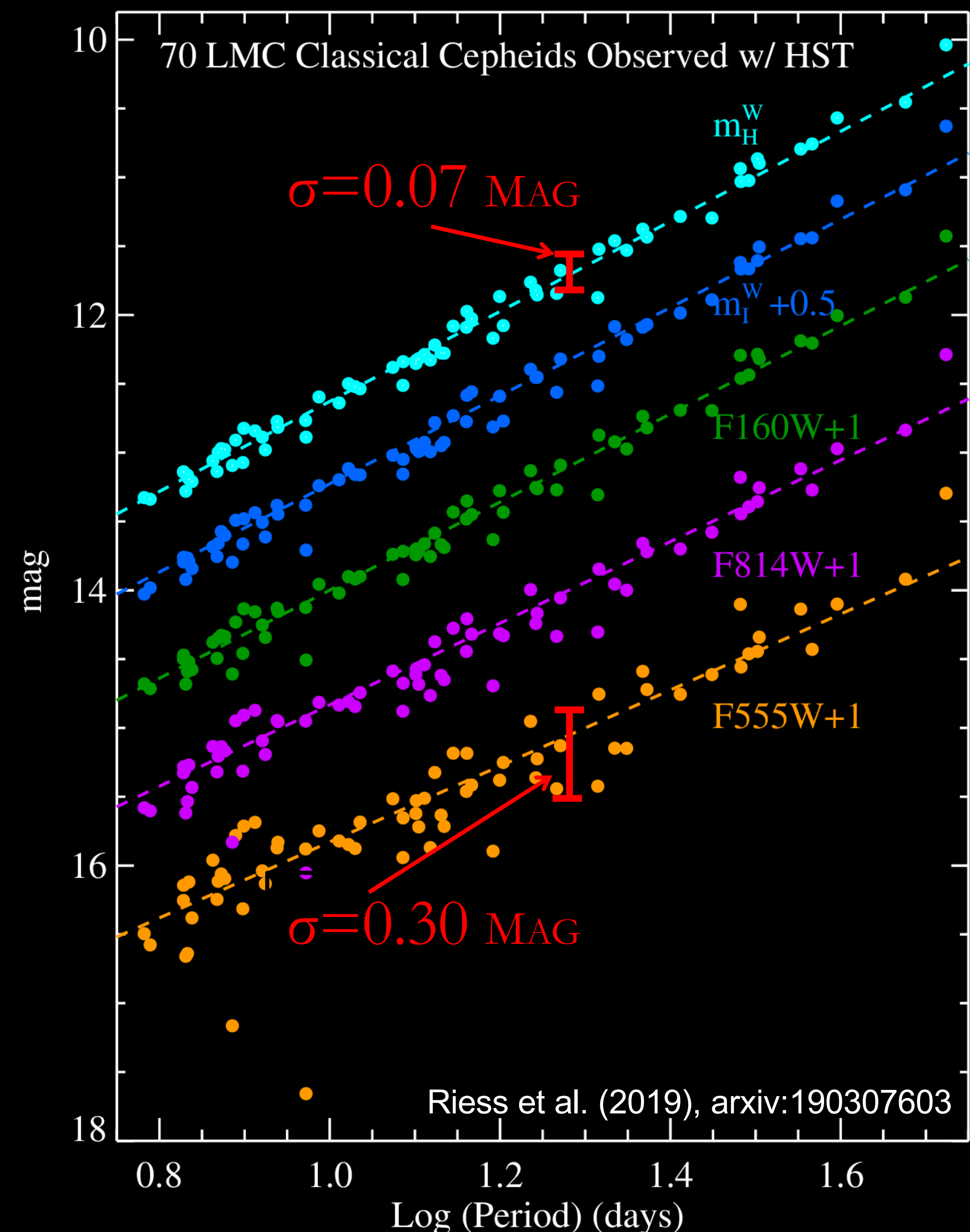
# Lowering Systematics: Near-IR Cepheid Observations + HST, Now in LMC!

-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



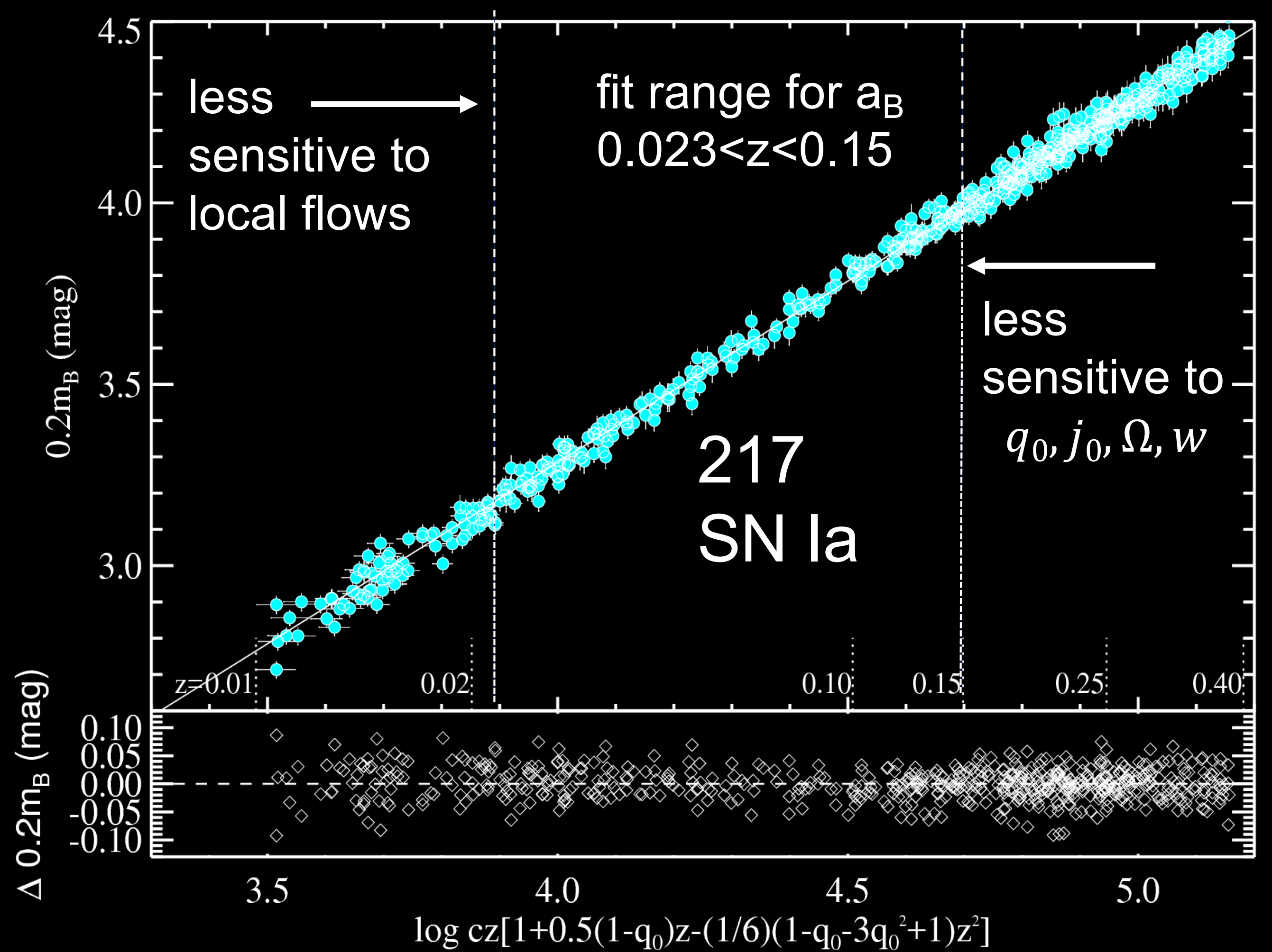


Leavitt

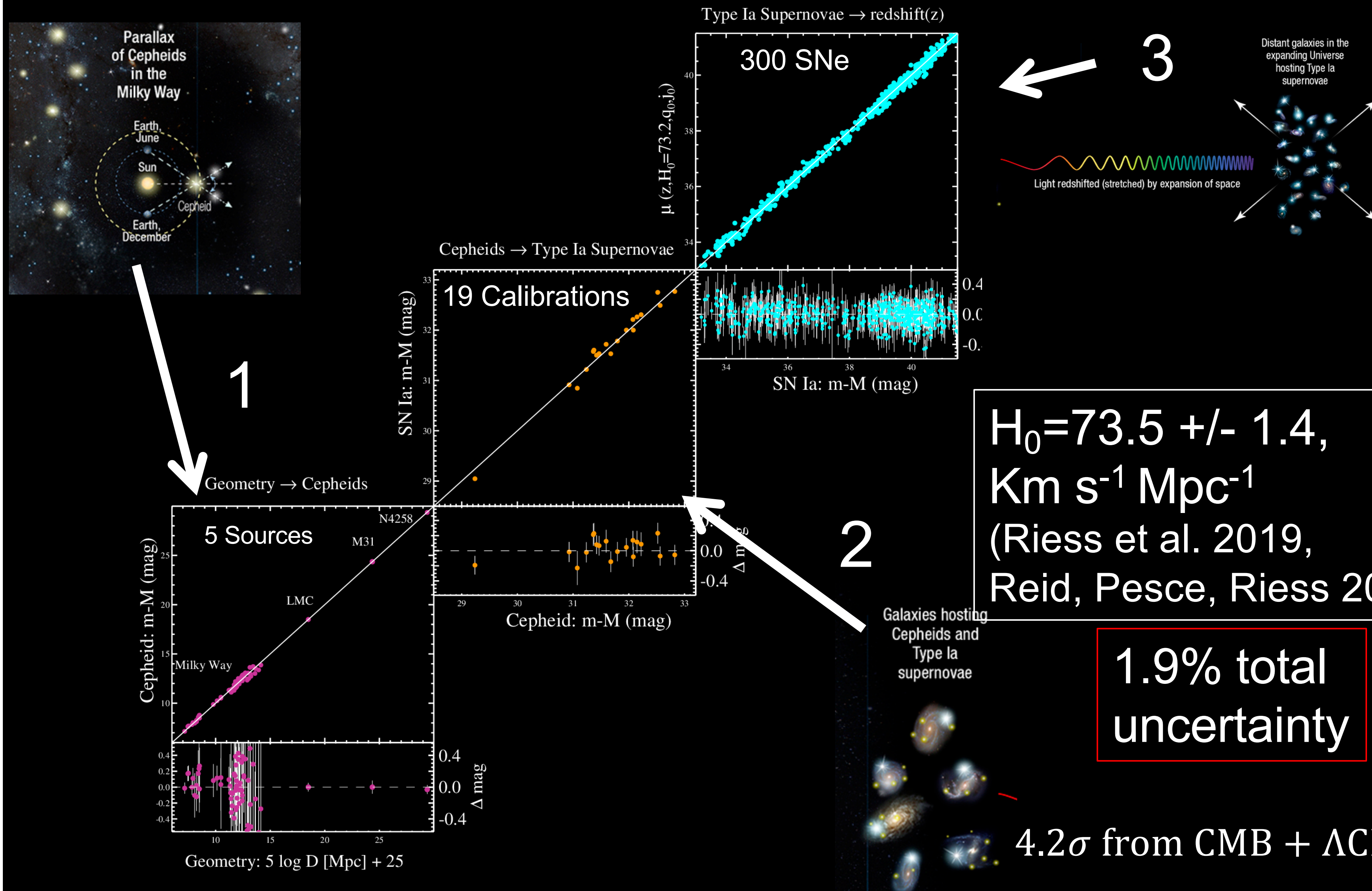
# Step 3: Intercept of SN Ia Hubble Diagram: Distance vs Redshift

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

Kinematic Intercept equation



# The Hubble Constant in 3 Steps: Present Data




$H_0$=73.5 +/- 1.4, Km $s^{-1}$ $Mpc^{-1}$
(Riess et al. 2019, Reid, Pesce, Riess 2019)

1.9% total uncertainty

$4.2\sigma$ from CMB + $\Lambda$CDM !

*Simultaneous Fit: Retain interdependence of data and parameters

# Robust? Seven Sources of Cepheid Geometric Calibration

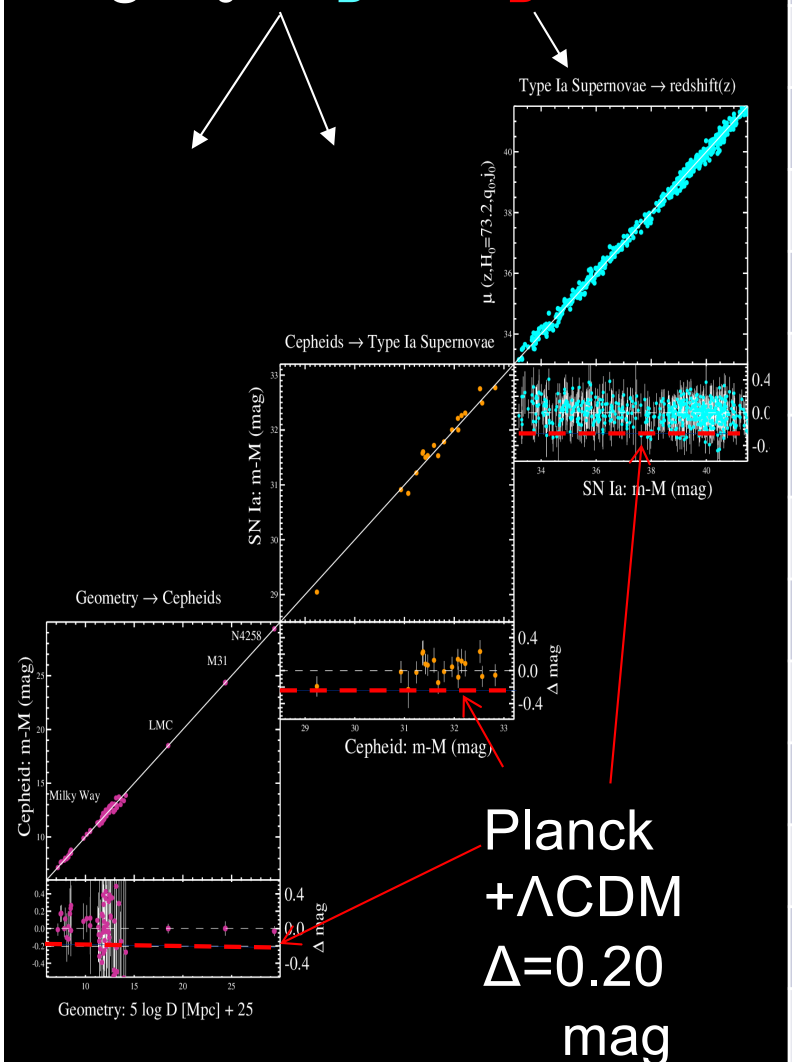
| Independent Geometric Source | $\sigma_D$ | $H_0$ |
|---|---|---|
| NGC 4258 $H_20$ Masers: Reid, Pesce, Riess 2019 | 1.5% | 72.0 |
| LMC 20 Detached Eclipsing Binaries: Pietzrynski+ 2019 + 70 HST LMC Cepheids: Riess+(2019) AGREES WITH GAIA EDR3 | 1.3% | 74.2 |
| Milky Way 10 HST FGS Short P Parallaxes: Benedict+2007 --also Hipparcos (Van leeuwen et al 2007) | 2.2% | 76.2 |
| Milky Way 8 HST WFC3 SS Long P Parallaxes: Riess+ 2018 | 3.3% | 75.7 |
| Milky Way 50 Gaia+HST, Long P Parallaxes: Riess+ 2018 | 3.3% | 73.7 |
| Milky Way Short P Cepheid Binary Gaia Companion Parallax: Breuval+20 | 3.8% | 72.7 |
| Milky Way Short P Cepheid Cluster Gaia Parallax: Breuval+20 | 3.2% | 73.6 |

Consistent Results ($\leq 2\sigma$), *Independent Systematics*

# Systematics? 23 Analysis Variants—we propagate variation to error

## Best Fit:

$$5\log H_0 = M_B^0 + 5a_B + 25$$




| Analysis Variants | $H_0$ |
|---|---|
| Best Fit (2019) | 73.5 |
| Reddening Law: LMC-like ($R_V$=2.5, not 3.3) | 73.4 |
| Reddening Law: Bulge-like (N15) | 73.9 |
| No Cepheid Outlier Rejection (normally 2%) | 73.8 |
| No Correction for Cepheid Extinction | 75.2 |
| No Truncation for Incomplete Period Range | 74.6 |
| Metallicity Gradient: None (normally fit) | 74.0 |
| Period-Luminosity: Single Slope | 73.8 |
| Period-Luminosity: Restrict to P>10 days | 73.7 |
| Period-Luminosity: Restrict to P<60 days | 74.1 |
| Supernovae z>0.01 (normally z>0.023) | 73.7 |
| Supernova Fitter: MLCS (normally SALT) | 75.4 |
| Supernova Hosts: Spiral (usually all types) | 73.6 |
| Supernova Hosts: Locally Star Forming | 73.8 |
| Optical Cepheid Data only (no NIR) | 72.0 |

## Frequently Asked Questions: technical, see backup slide

- Could we live in a giant void (9% in $H_0$)?
  No, LSS Theory and SN Ia mag-z limit $\sigma$~0.6% in $H_0$

  Odderskov et al. (2016) , Wu & Huterer (2017), Kenworthy, Scolnic, Riess 2019

- Is HST WFC3-IR flux scale linear to 1%?
  Yes, calibrated to $\sigma$=0.3% in $H_0$ across 15 mag

  Riess, Narayan, Calamida 2019

- Does Cepheid crowding compromise accuracy?
  No, amplitude data confirms locality of crowding

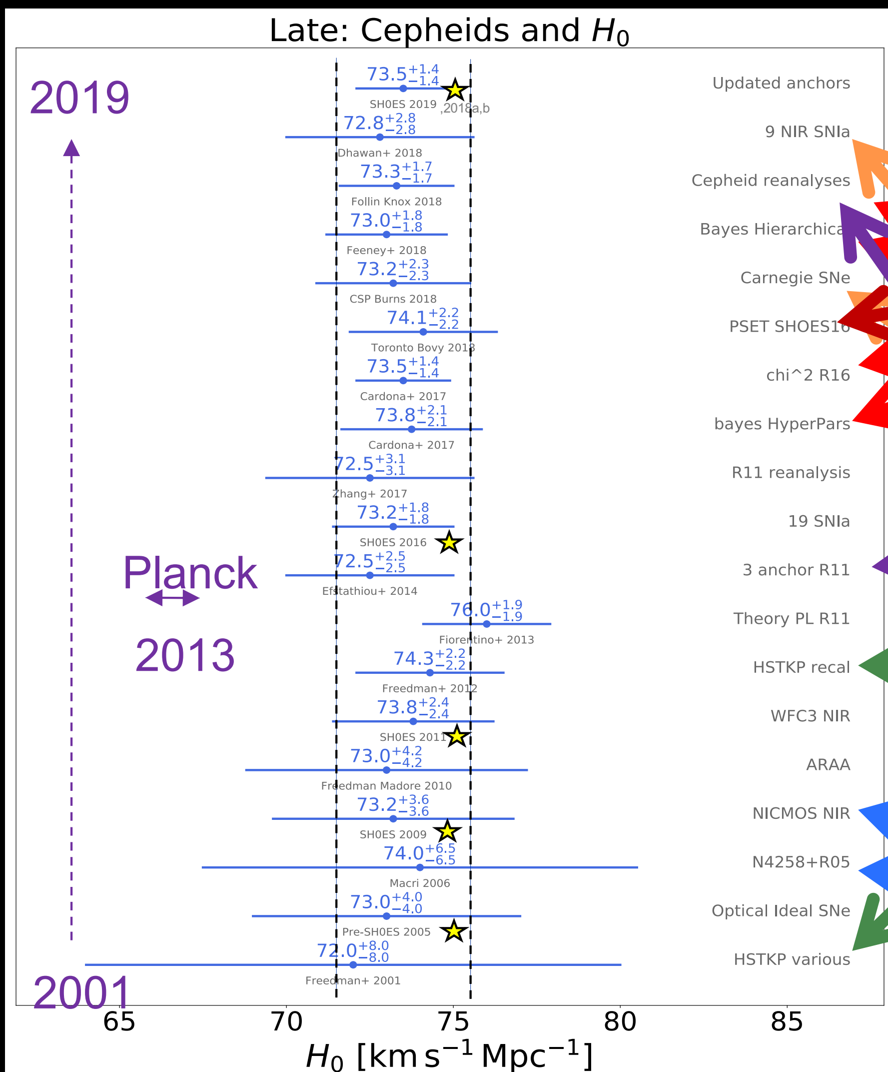
  Riess, Yuan, Casertano, Macri, Scolnic 2020

- Is there a difference in SN Ia at ends of distance ladder?
  No, correlations of Hubble residuals < $\sigma$=0.3% in $H_0$

  Jones et al 2018

# Cepheids+SN Ia Ladder, Most Widely Replicated: 2001-2019

Why Cepheids? Advantages: 1) longest-range 2) most calibrations 3) consistent photometry along ladder 4) most tested…




$SH_0ES$ results (★) *cumulative* but compared to present… consistent

grad student problem set! (Toronto)

Different analyses

Different SNe, wavelength

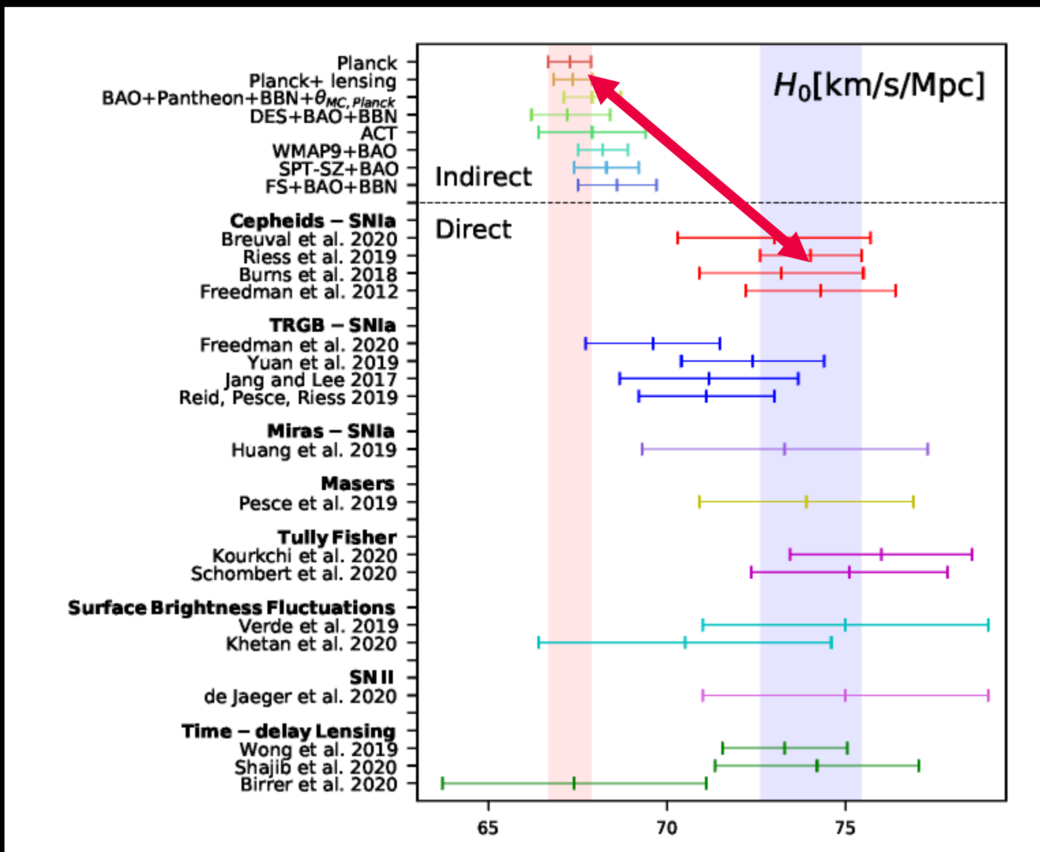
"Planck People"

Different Team (KP), photometry, Cepheids, wavelengths

Different HST Instruments

# The Hubble Constant ~~Tension~~, ~~Discrepancy~~, Problem, ~~Crisis~~

## Status late 2020




Compilation from Di Valentino(2020)

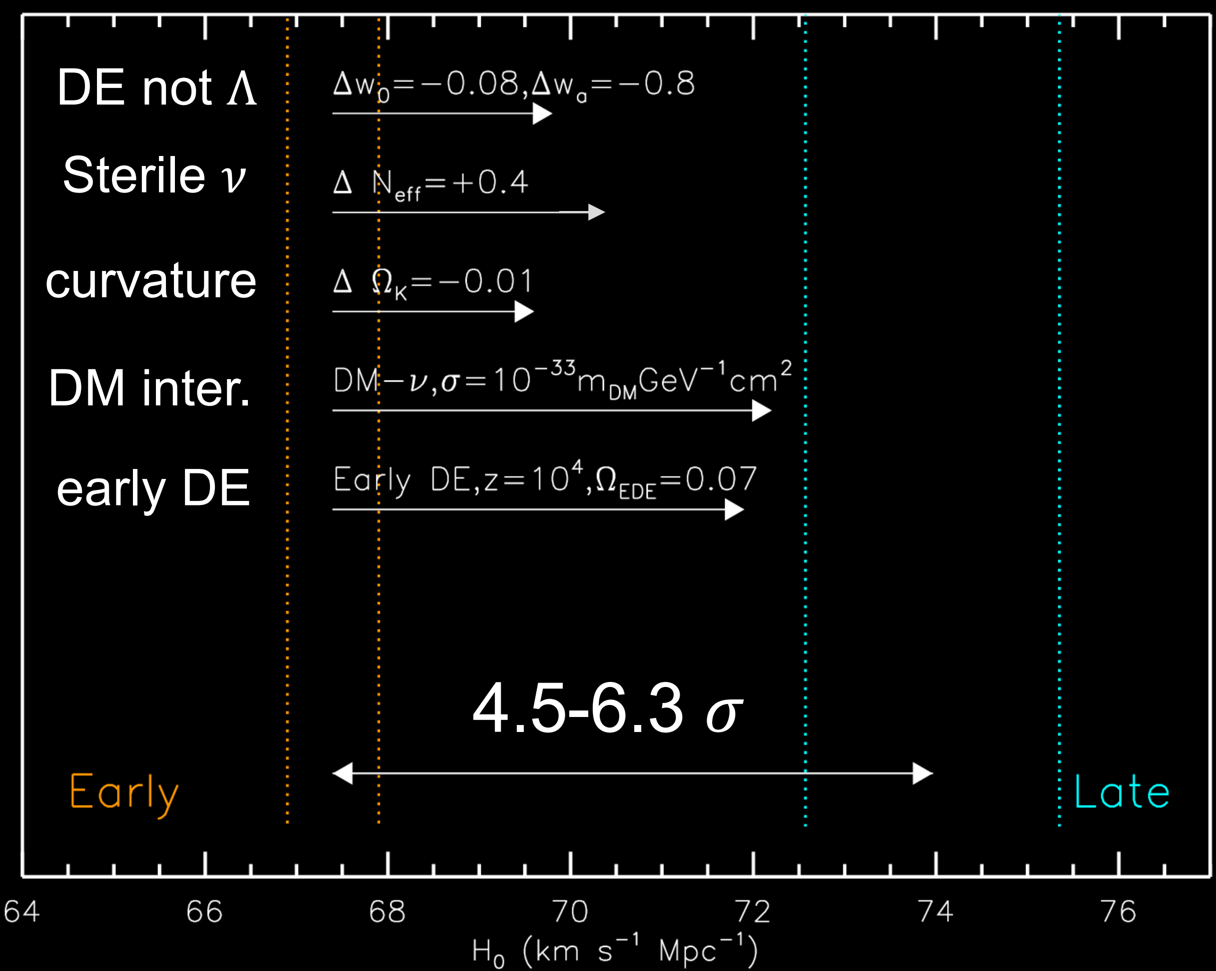
## KITP 2019 (Verde, Treu, Riess 2019)

*“does not appear to depend on the use of any one method, team or source”*

No Cepheids: 4.5-5.3$\sigma$
No TRGB: 5.7-6.3$\sigma$
No lens: 5.0$\sigma$
No SN Ia: 4.9$\sigma$
No Cepheids or TRGB: 5.3$\sigma$
No Planck: 4.4-4.9$\sigma$
No CMB: 4.0-4.5$\sigma$
(Riess 2019, Nature Reviews)

# Cause Early vs Late Difference? Newton: “Feign No Hypothesis”

NEW PHYSICS ?




“The Hubble Hunter’s Guide”, Knox and Millea, 2019: “Most Likely”: Increase Expansion Rate Pre-recombination->reduce sound horizon by 5-8%

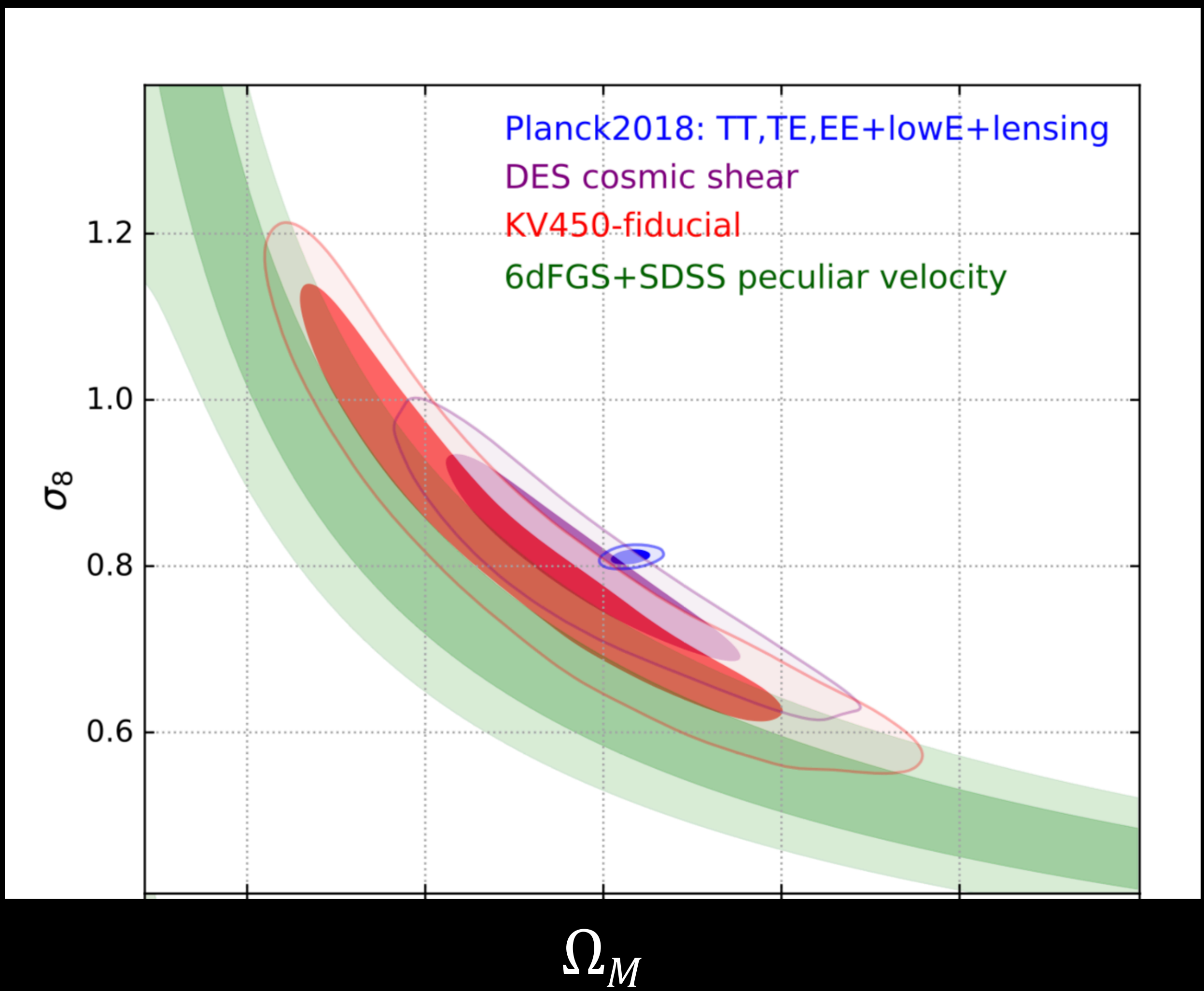
Mechanisms: Early DE or sterile (self-interacting) neutrinos

Claims: better fit to CMB, new CMB features, cosmic birefringence as evidence of CMB coupling to EDE/ALPs or pNG Boson (Capparelli+20, Fujita+20)?

# Another Early vs Late Tension? Matter clumpiness, $\sigma_8$

RMS matter fluctuation, $\sigma_8$ , (r=8 $h^{-1}$ Mpc), 0.8 Early vs late divide

~3 $\sigma$ from lensing and peculiar velocities, independently




6dFGS+SDSS

Said, K et al 2020, MNRAS,497, 1275

"…deviates by more than 3σ from the latest Planck CMB measurement. Our results favour … a Hubble constant $H_0 > 70$ km $s^{-1}$ $Mpc^{-1}$ or a fluctuation amplitude $\sigma_8 < 0.8$ or some combination of these. "

# Can We Believe Measurements without Explanation?

Don't sweep "problems" under the rug


"Problems" are often clues!

~~Precession of Mercury~~ Solved!

~~Solar Neutrino Problem~~ Solved!

~~Missing Baryon Problem~~ Solved!

Lithium Problem

CMB Cold Spot

Flat rotation curves/
what/where is dark matter?

Accelerating Universe/
why Λ so small?

# Can We Believe Explanation without hypothesis (*how*)?

Present data provides formidable challenge!

"Its New Physics"—constrained precise H(z) data, CMB high-l

"Its Systematics"—many measures, many independent rungs, duplicate measurements, Copernican principle

I don't think so.

Reasons for optimism:

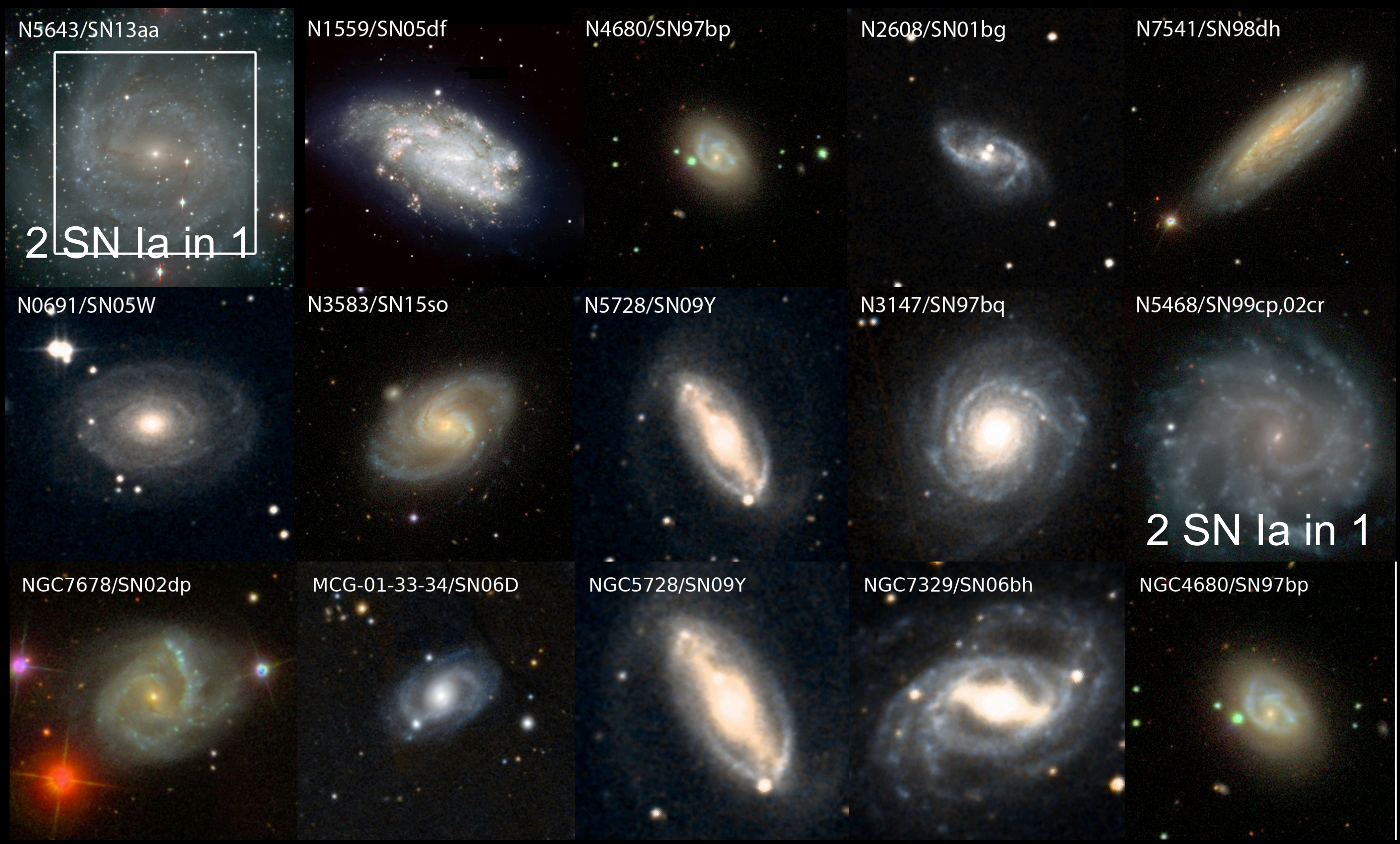
New data: LIGO, DESI, Roman, Rubin, Euclid, JWST, Simons, S4

New clues: Early vs late $\sigma_8$, Cosmic Birefringence?, BBN ?

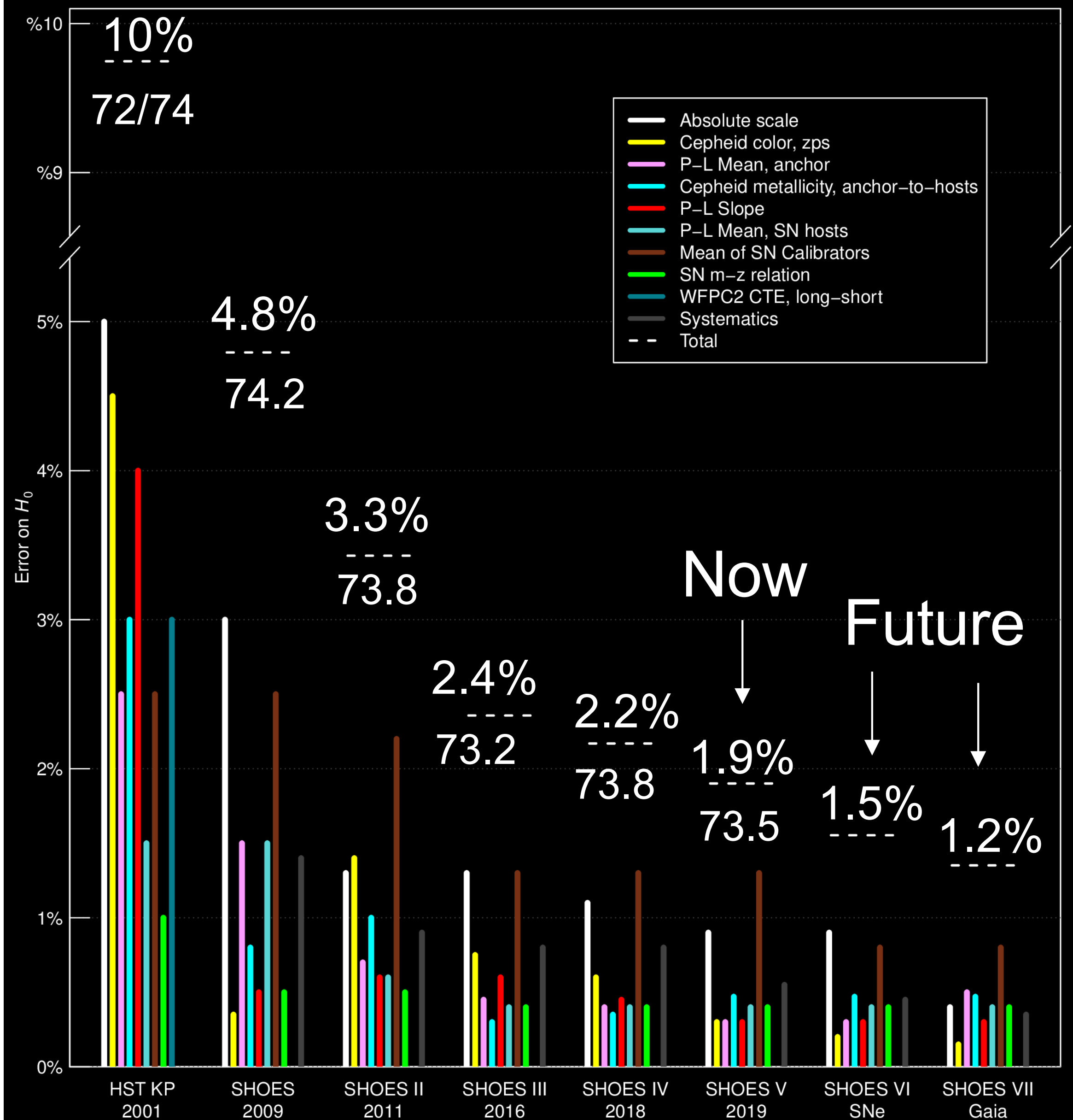
Big Playground: Lambda CDM is 95% dark, quantum gravity

# Next Steps: Increasing Number of SN-Cepheid Calibrations

## *NEW* SHOES Large HST Programs, Cycles 25,26,28
## 24 more Cepheid-SN Ia Calibrators underway, to reach total=43, + Cepheids to Coma!



# Future Prospects…




- **New low-z SN samples**
- **Doubling SN Calibrator sample, 19→40**
- **Gaia EDR3 !!!**
- LIGO $H_0$ (Late Universe)
- DESI,LSST,WFIRST,Euclid →better w(z)
- Next generation CMB: signatures (e.g., EDE)
- Stay tuned…

# Final Thoughts

- Discrepancy is ~5$\sigma$ (4-6) $\sigma$ (depending on combination)
  No Late Universe measurements lower than any Early
- Appears robust, requires <u>multiple</u> catastrophic failures to avoid
- <u>Very interesting!</u> (unless your Bayesian prior on $\Lambda$CDM > 5 $\sigma$)
- Feign No Hypothesis, let's follow evidence, find the *how*
- Universe may be more clever than we are *now*