Title: The Present Expansion rate of the Universe, Evidence of New Physics?

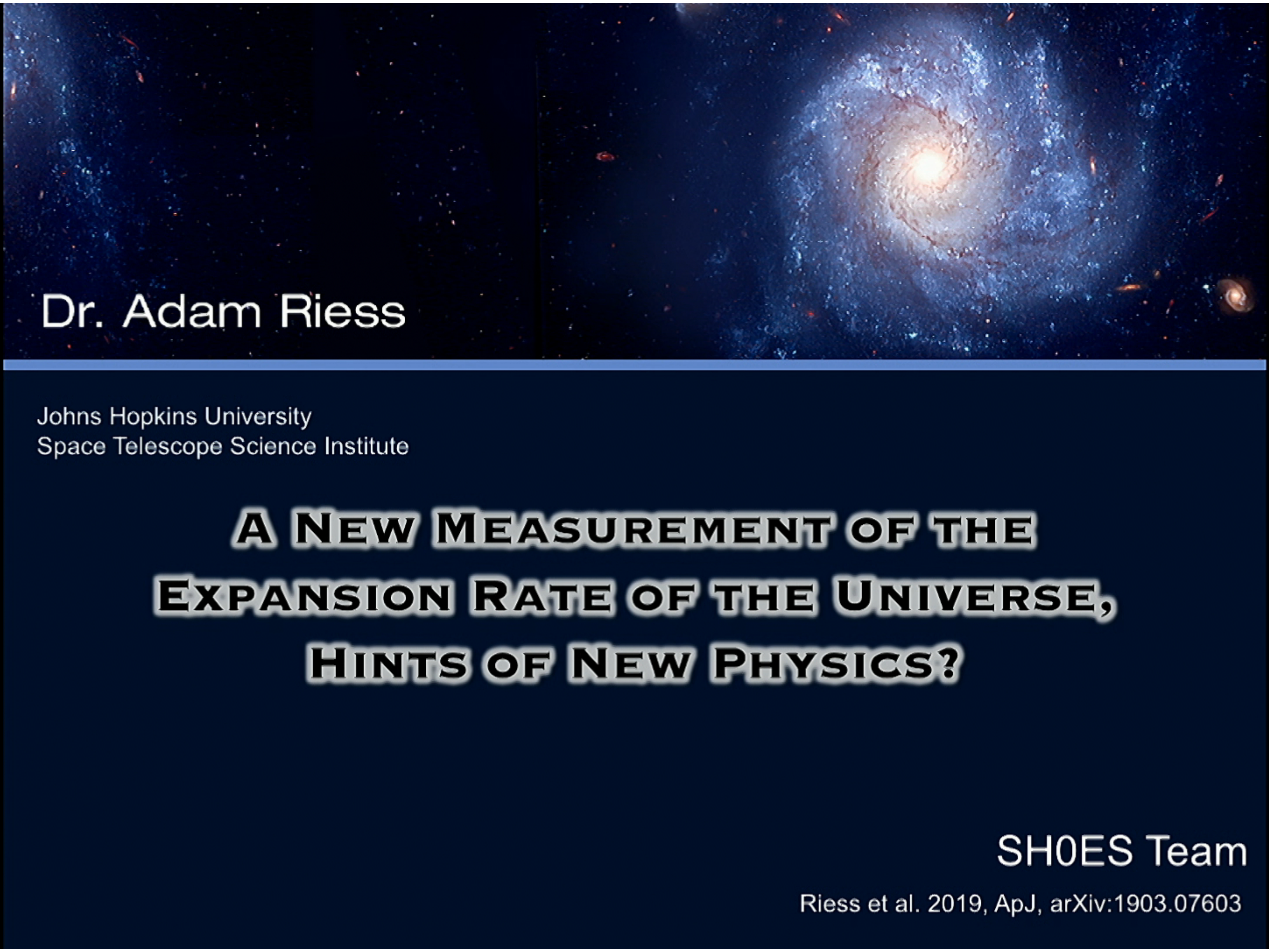
Speakers: Adam Riess

Series: Colloquium

Date: September 04, 2019 - 2:00 PM

URL: http://pirsa.org/19090086

Abstract: The Hubble constant remains one of the most important parameters in the cosmological model, setting the size and age scales of the Universe. Present uncertainties in the cosmological model including the nature of dark energy, the properties of neutrinos and the scale of departures from flat geometry can be constrained by measurements of the Hubble constant made to higher precision than was possible with the first generations of Hubble Telescope instruments. A streamlined distance ladder constructed from infrared observations of Cepheids and type Ia supernovae with ruthless attention paid to systematics now provide <2% precision and offer the means to do much better. By steadily improving the precision and accuracy of the Hubble constant, we now see evidence for significant deviations from the standard model, referred to as LambdaCDM, and thus the exciting chance, if true, of discovering new fundamental physics such as exotic dark energy, a new relativistic particle, or a small curvature to name a few possibilities. I will review recent and expected progress.



Dr. Adam Riess

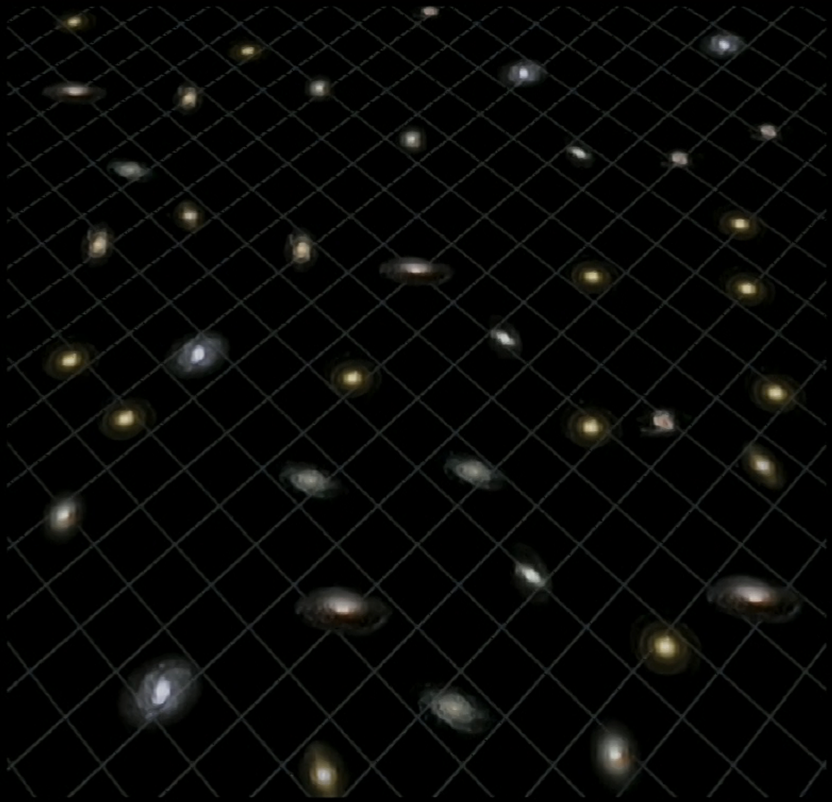
Johns Hopkins University
Space Telescope Science Institute

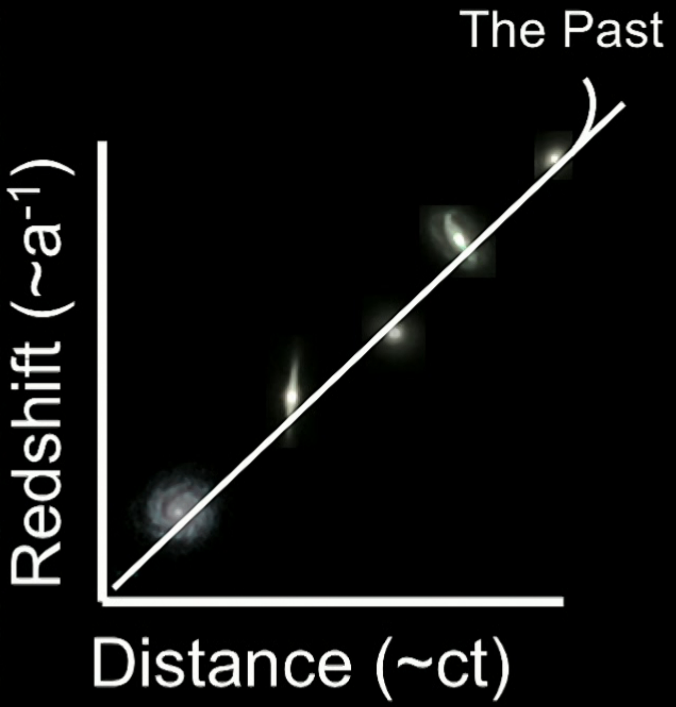
A New Measurement of the Expansion Rate of the Universe, Hints of New Physics?

SH0ES Team

Riess et al. 2019, ApJ, arXiv:1903.07603

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

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

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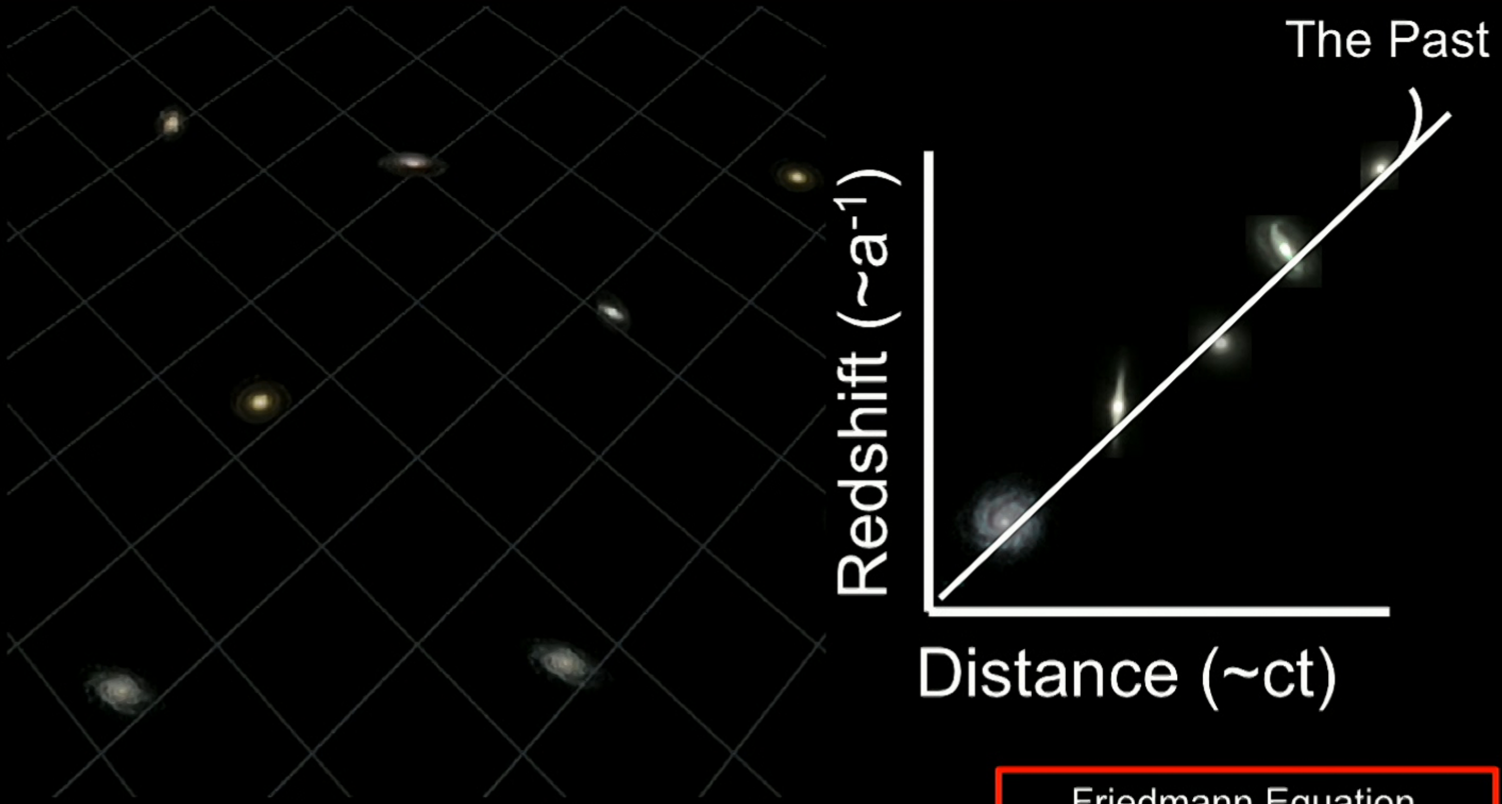

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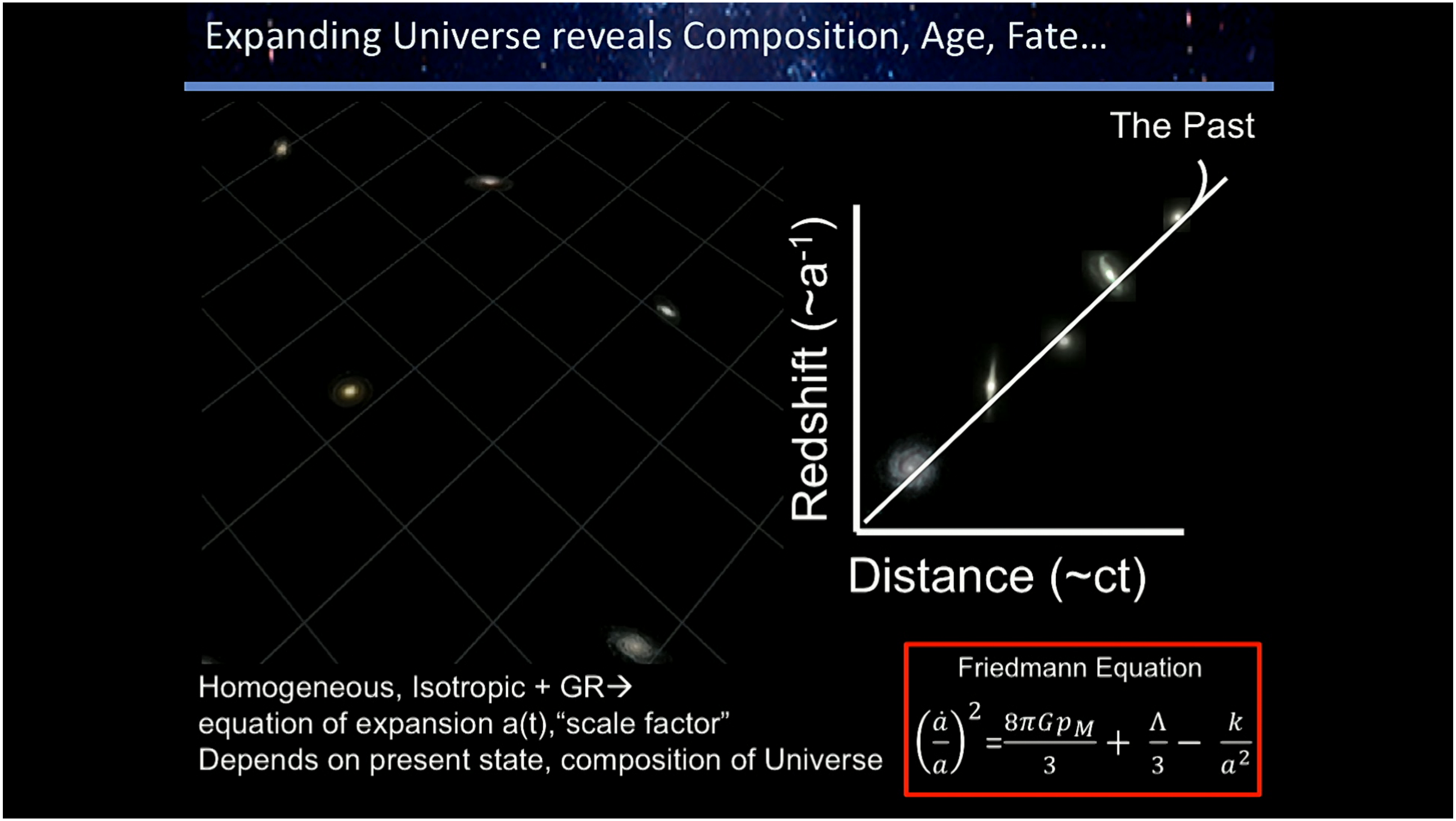

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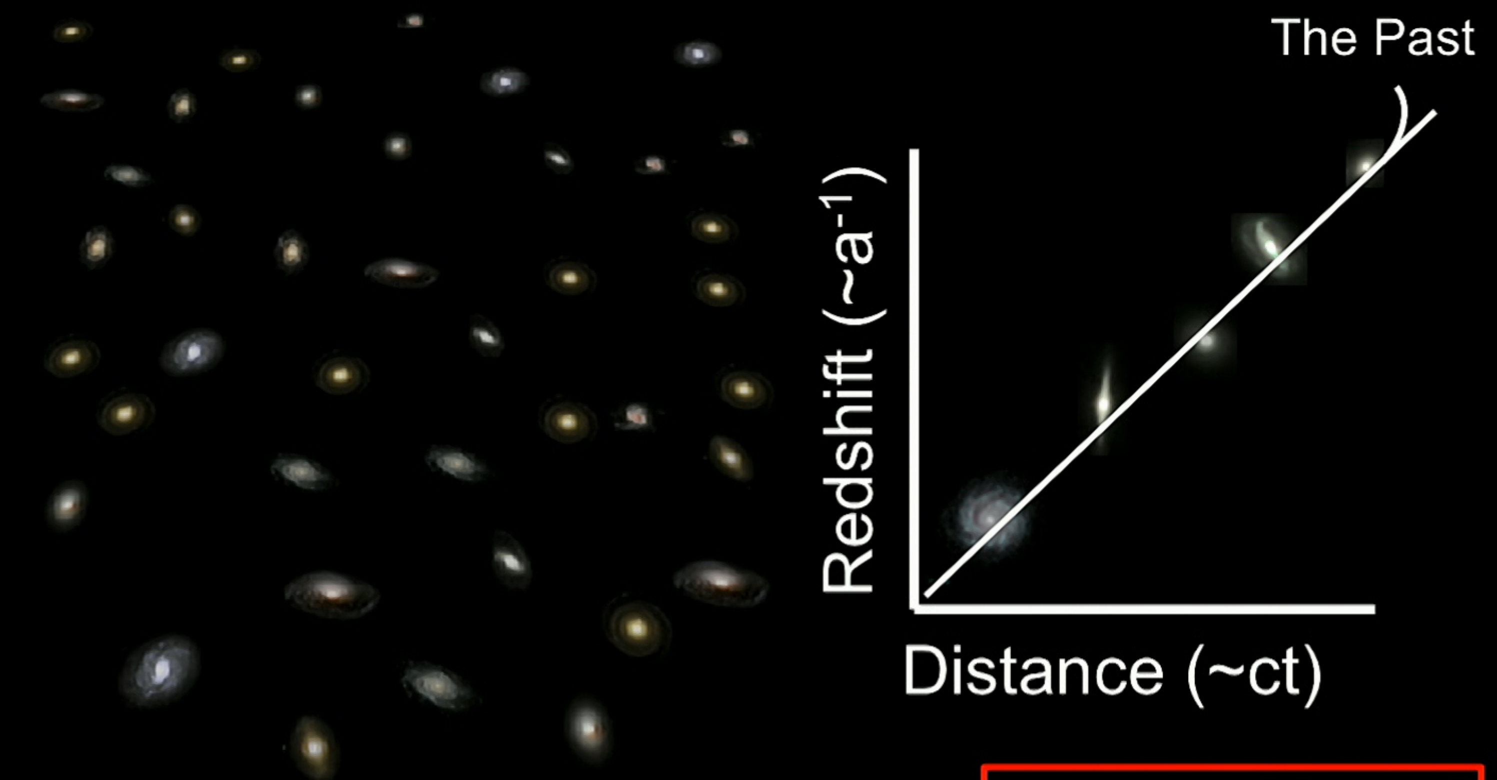

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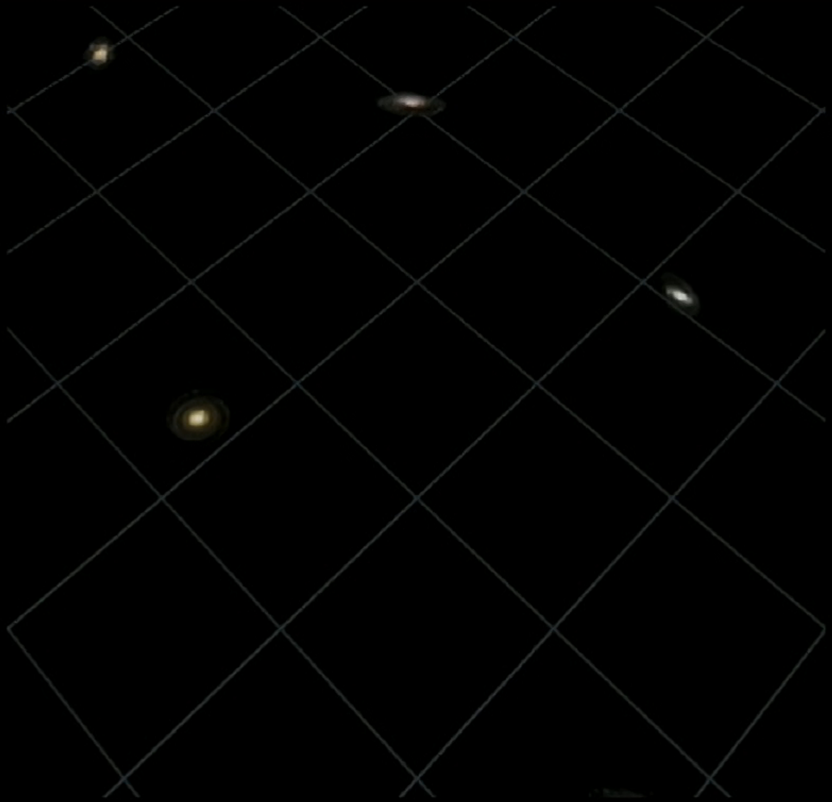

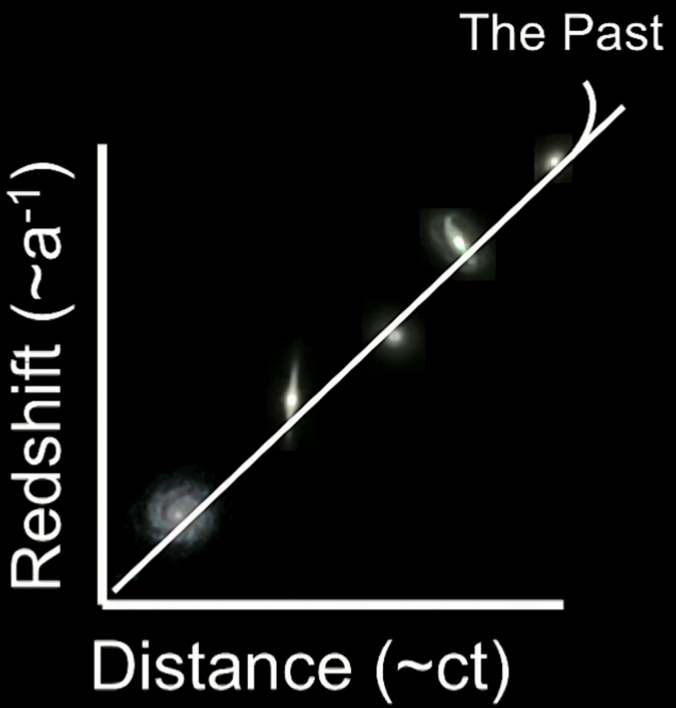

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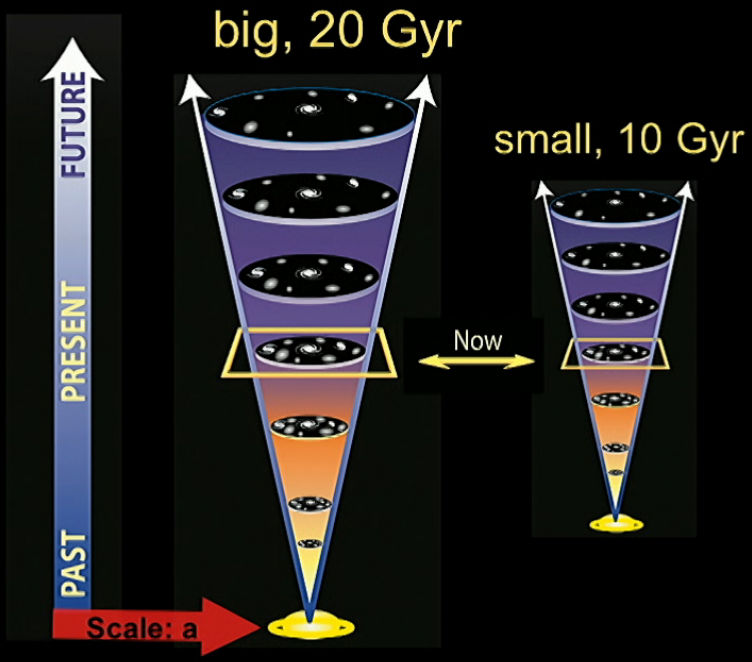
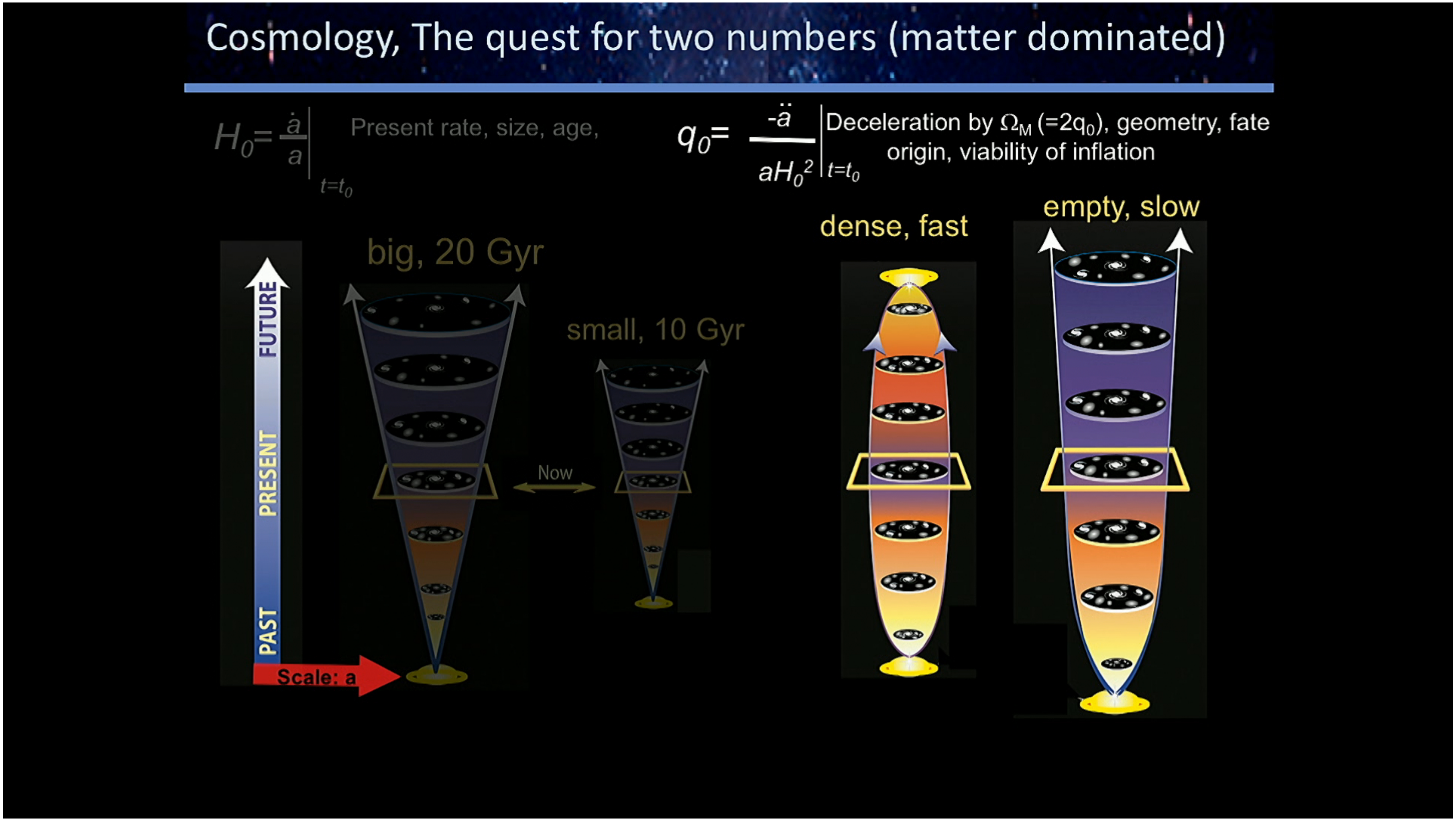
Cosmology, The quest for two numbers (matter dominated)

$$H_0 = \left.\frac{\dot{a}}{a}\right|_{t=t_0}$$ Present rate, size, age,





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$$H_0 = \frac{\dot{a}}{a}\Big|_{t=t_0}$$ Present rate, size, age,

$$q_0 = \frac{-\ddot{a}}{aH_0^2}\Big|_{t=t_0}$$ Deceleration by Ω_M (=$2q_0$), geometry, fate origin, viability of inflation

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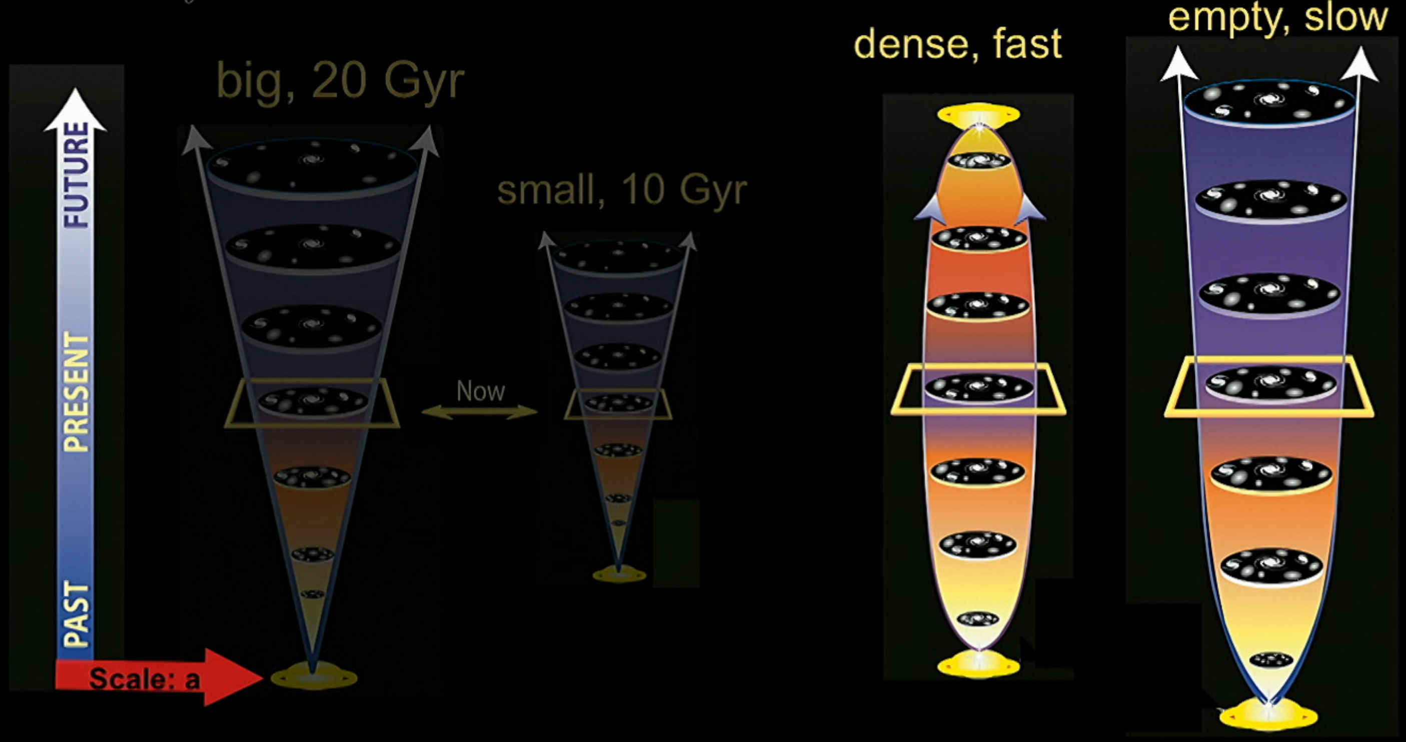
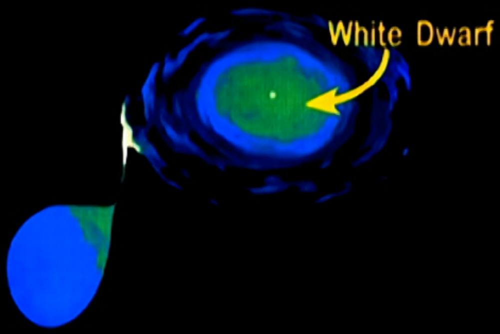


1990's: Better D(z) with long range Standard Candles…

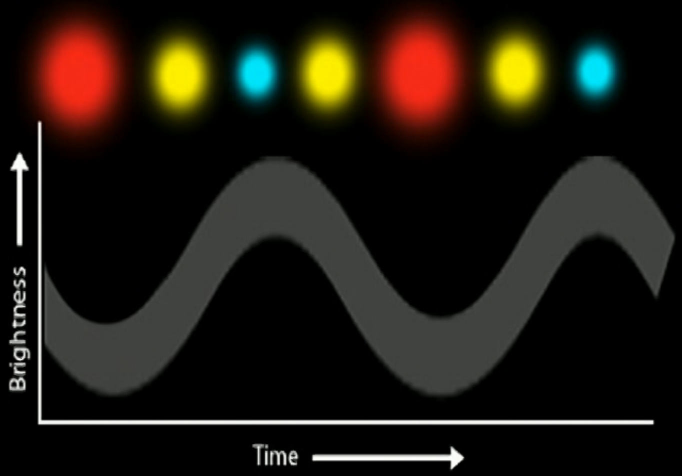
SN Ia and Cepheids: Standardized Candles for long range, *relative* distances

Type Ia Supernovae, Exploding Stars, $10^9\ L_\odot$



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

Cepheids, Pulsating Stars, $10^5\ L_\odot$
Period-Luminosity relation



Standard Candles: The Distant, the Dim, and the Dusty

Bright=near faint=far

but not all the same…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Standard Candles: The Distant, the Dim, and the Dusty

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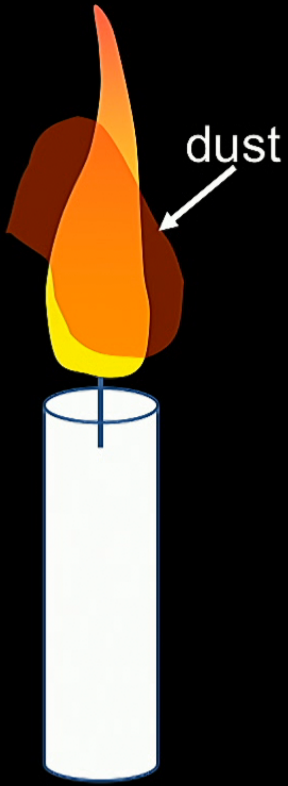

faint & red=not so far!

Standard Candles: The Distant, the Dim, and the Dusty

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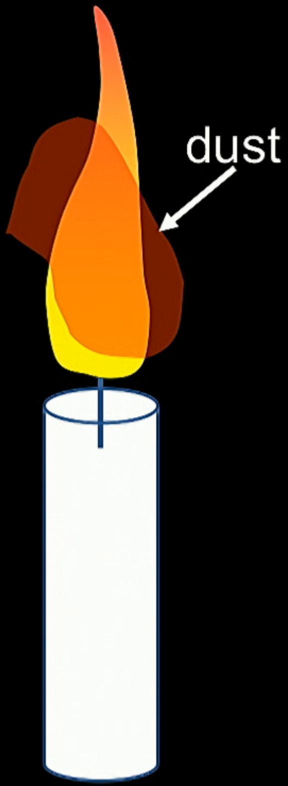

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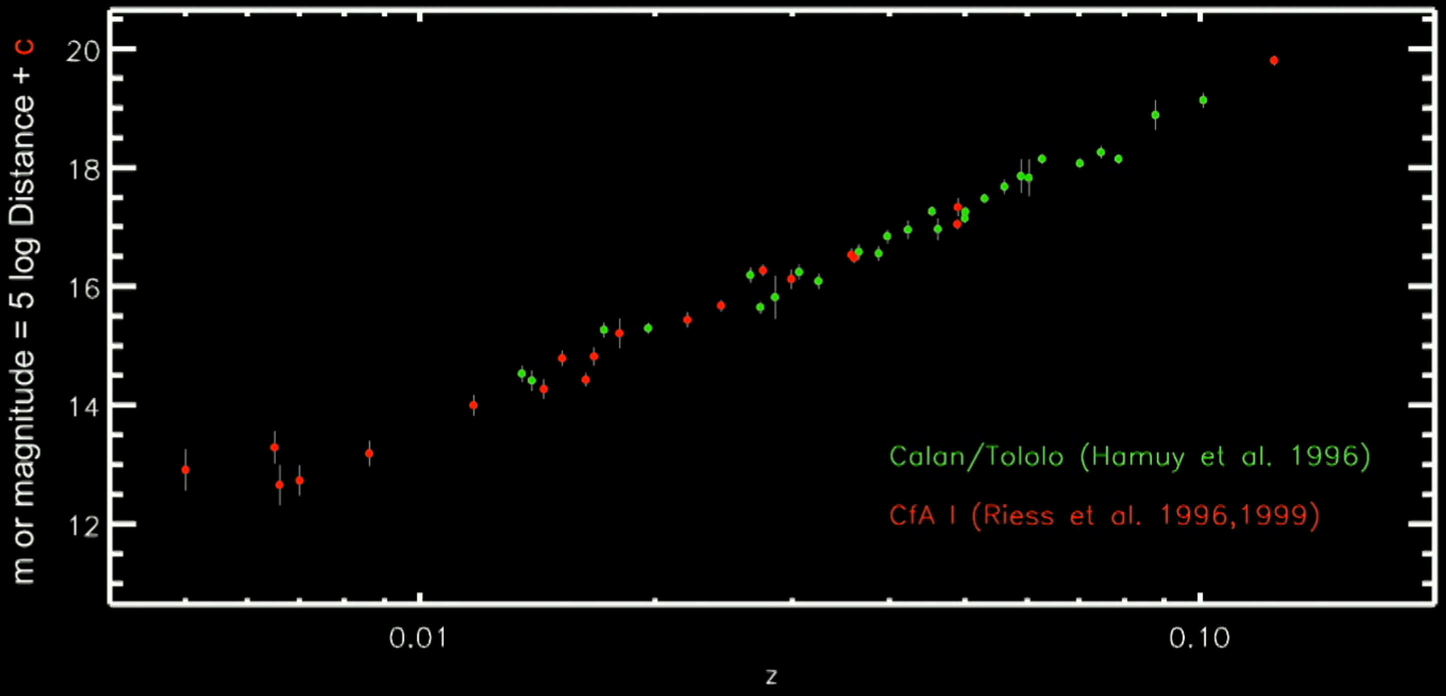
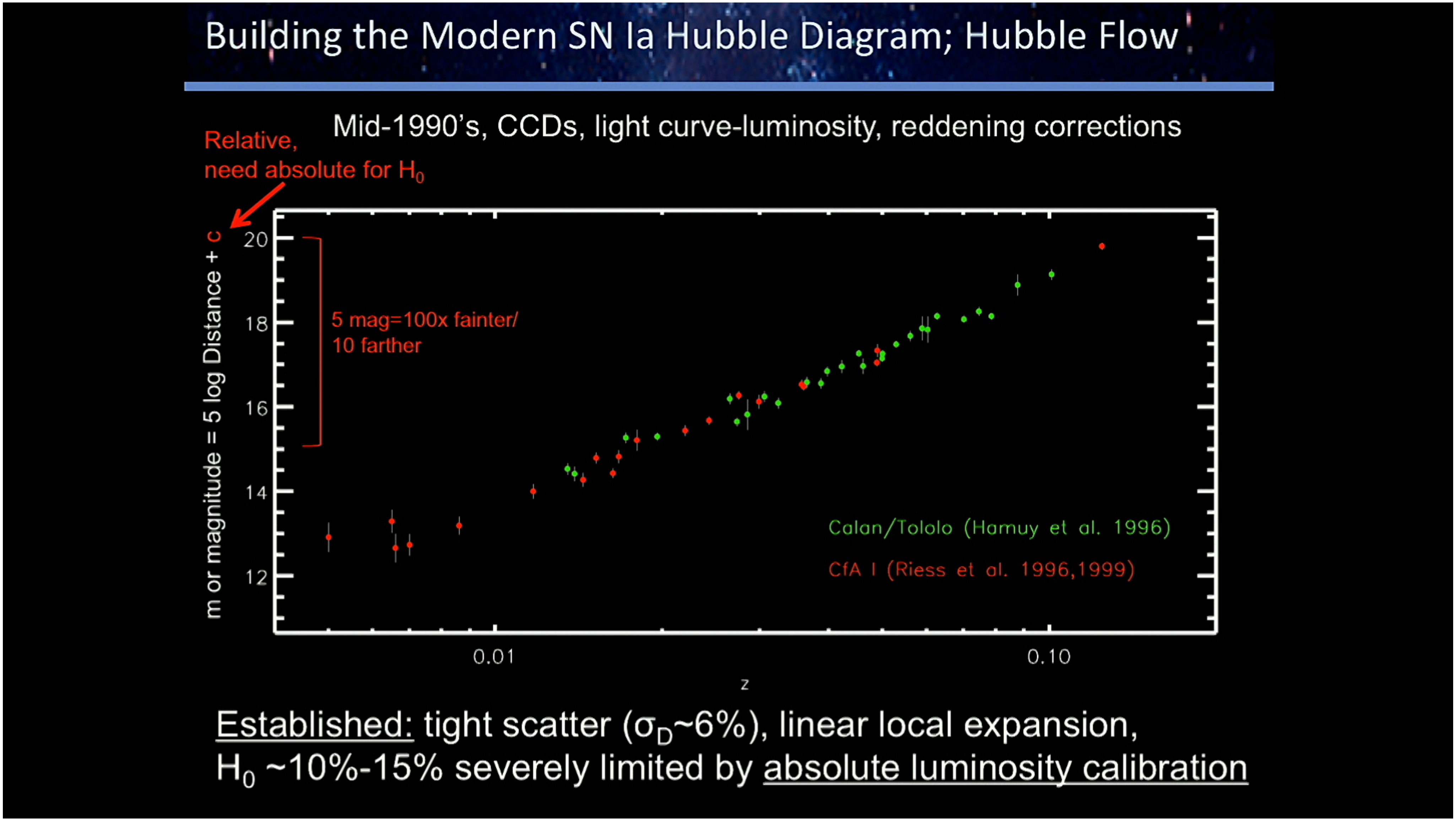
SN Ia Luminosity-color-light curve shape correlations 1990’s sharpened distances

Building the Modern SN Ia Hubble Diagram; Hubble Flow

Mid-1990's, CCDs, light curve-luminosity, reddening corrections



<u>Established:</u> tight scatter (σ_D~6%), linear local expansion,
H_0 ~10%-15% severely limited by <u>absolute luminosity calibration</u>



Building the Modern SN Ia Hubble Diagram; Hubble Flow

Mid-1990's, CCDs, light curve-luminosity, reddening corrections

Relative,
need absolute for H_0

Established: tight scatter (σ_D~6%), linear local expansion,
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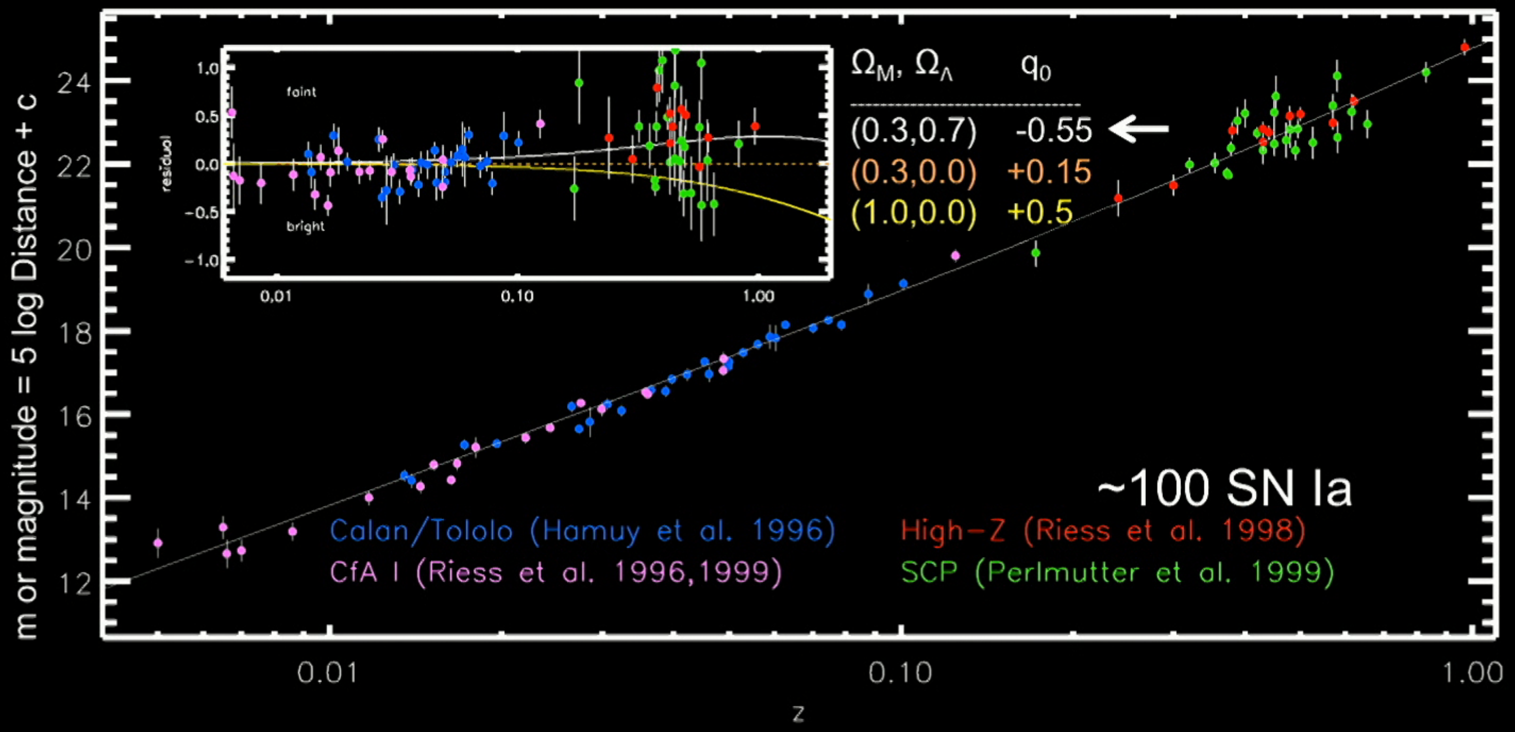
Building the Modern SN Ia Hubble Diagram; Acceleration!

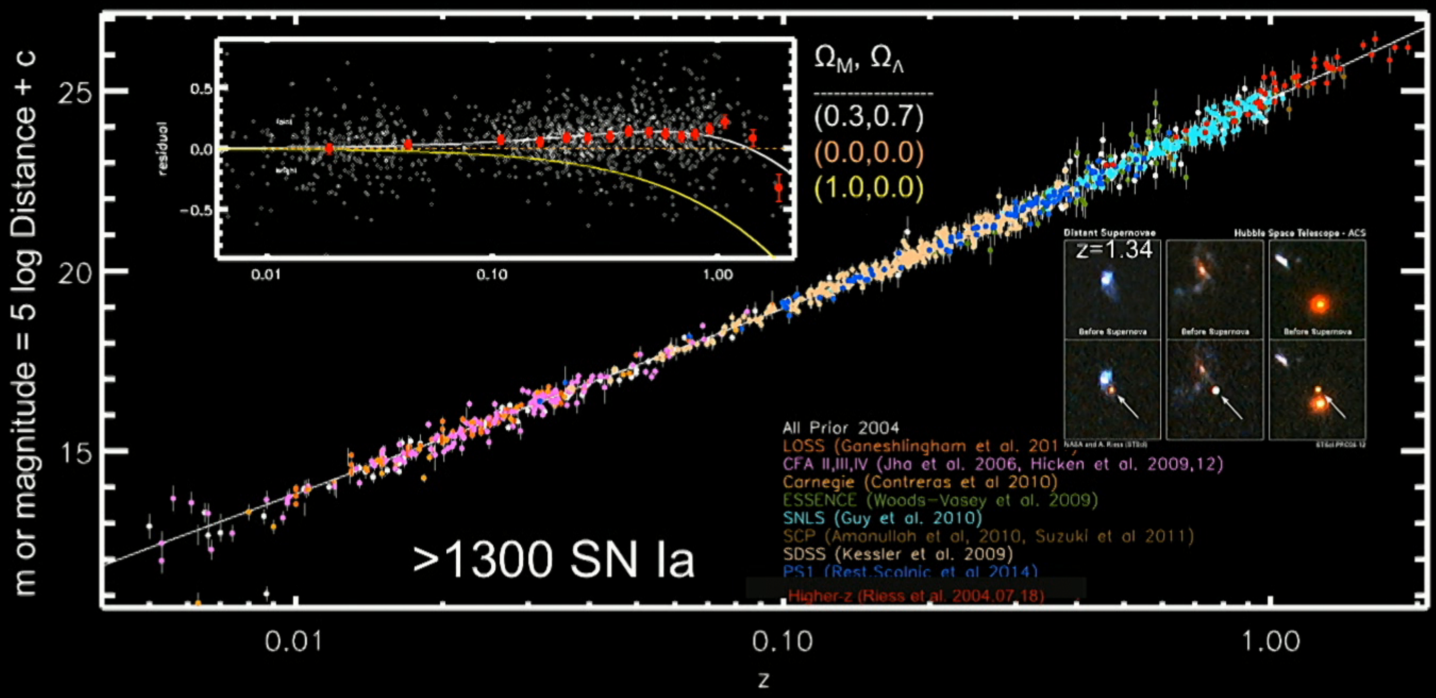
1998: SN discoveries at z~0.5 from large format CCDs



Established: Two Teams: $q_0<0$!, presence of dark energy, no “known unknown”

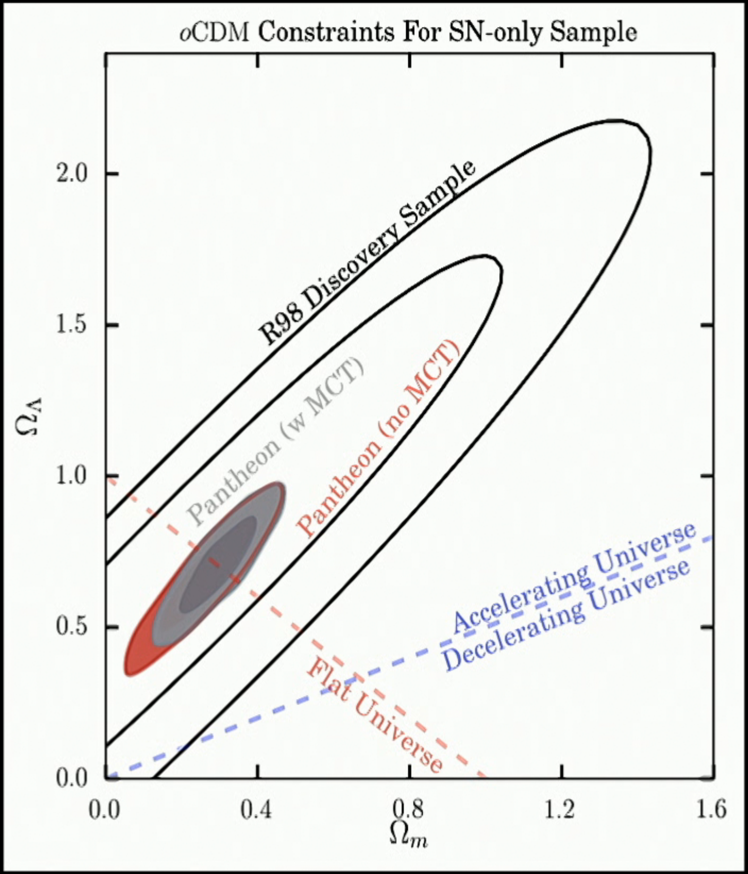
The Modern SN Ia Hubble Diagram; Confirm, Characterize

2004-present: *Massive* ground surveys z<1 and z>1 with HST



Established: not astrophysical dimming (grey dust, evolution), decelerating before accelerating, looks like lambda to ~10%

2019 State of the Art SN Ia Cosmology from Pan-STARRS, HST



- ~20 years ago vs "Pantheon Sample" uniform calibration of 1050 SNe Ia (Scolnic et al. 2018)
- 6σ evidence for DE from SN alone (no priors Ω_M or k), evidence becomes <u>much much</u> stronger w/ BAO, CMB

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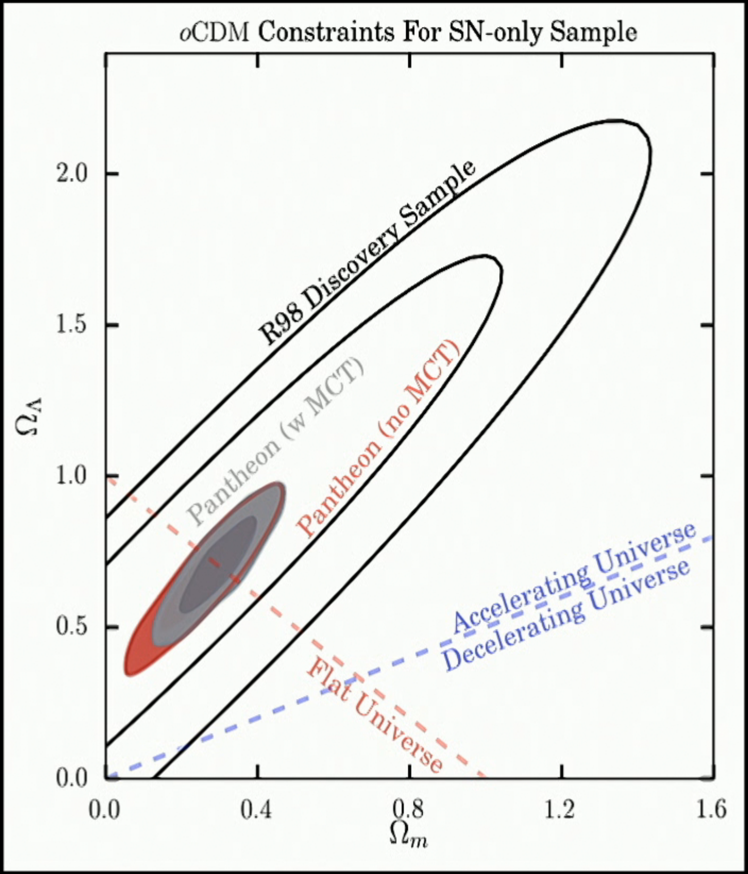

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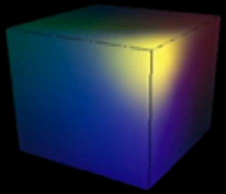
Why Does the Universe Appear to be Accelerating?

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

w≡p/ρ

w=1 radiation
w=0 matter
w=-1 vacuum energy (3D)



1. Vacuum Energy, the cosmological constant: ΛCDM

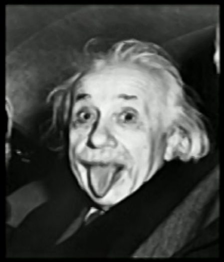
QM: constant energy of empty space, GR: repulsive gravity of Λ

Test: $w(z)=-1$, Existence Proof: Higgs Field

2. Dynamical dark energy

Potential energy of scalar field filling space

Test: $w_0 \neq -1$ or $dw/dz \neq 0$, Existence Proof: Inflation



3. Modification to GR

GR fails at long range (i.e., as a→1)

Test: w(z) depends on scale (i.e., different in H(z) and g(z))

New Game; assume Model=plain ΛCDM and hunt for departures

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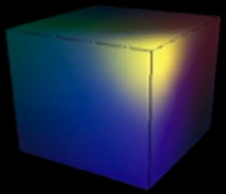

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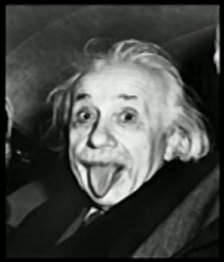

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GR fails at long range (i.e., as $a \rightarrow 1$)

Test: $w(z)$ depends on scale (i.e., different in $H(z)$ and $g(z)$)

New Game; assume Model=plain ΛCDM and hunt for departures


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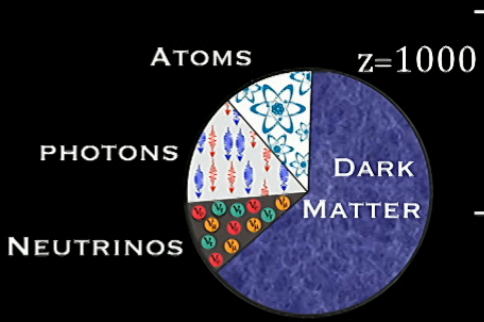
Ultimate "End-to-end" test for ΛCDM, Predict and Measure H_0

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

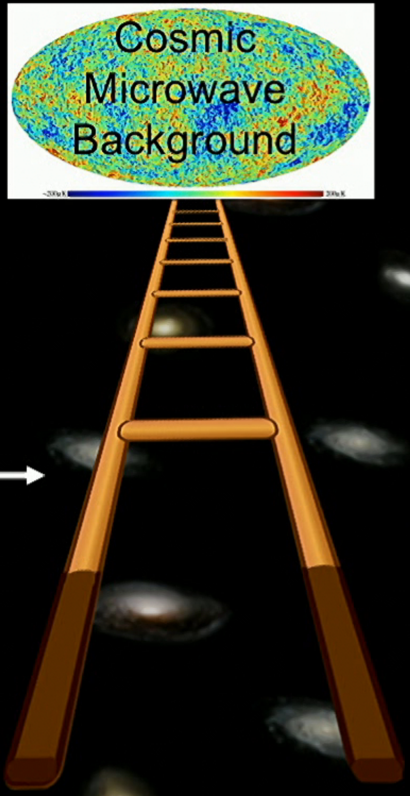


Predict physical size fluctuations, r_s, Ω_B →

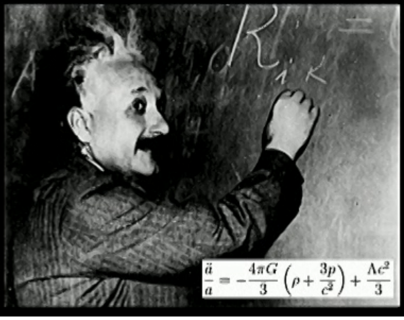
← Measure angular fluctuations (or Ω_B)

Calibrate ΛCDM …

Big Bang



Expansion history predicted
("guard rails", BAO, SNe) →



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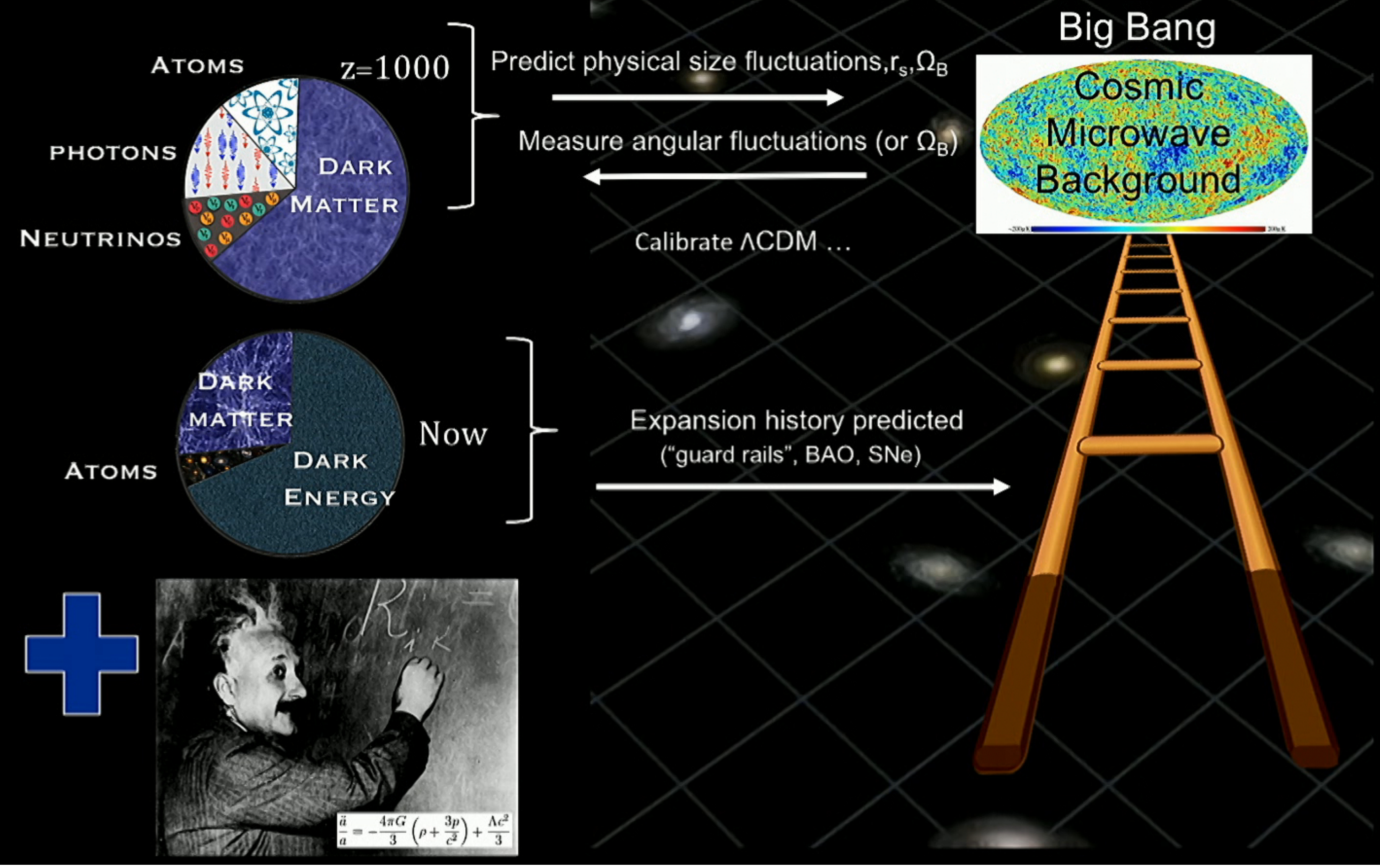

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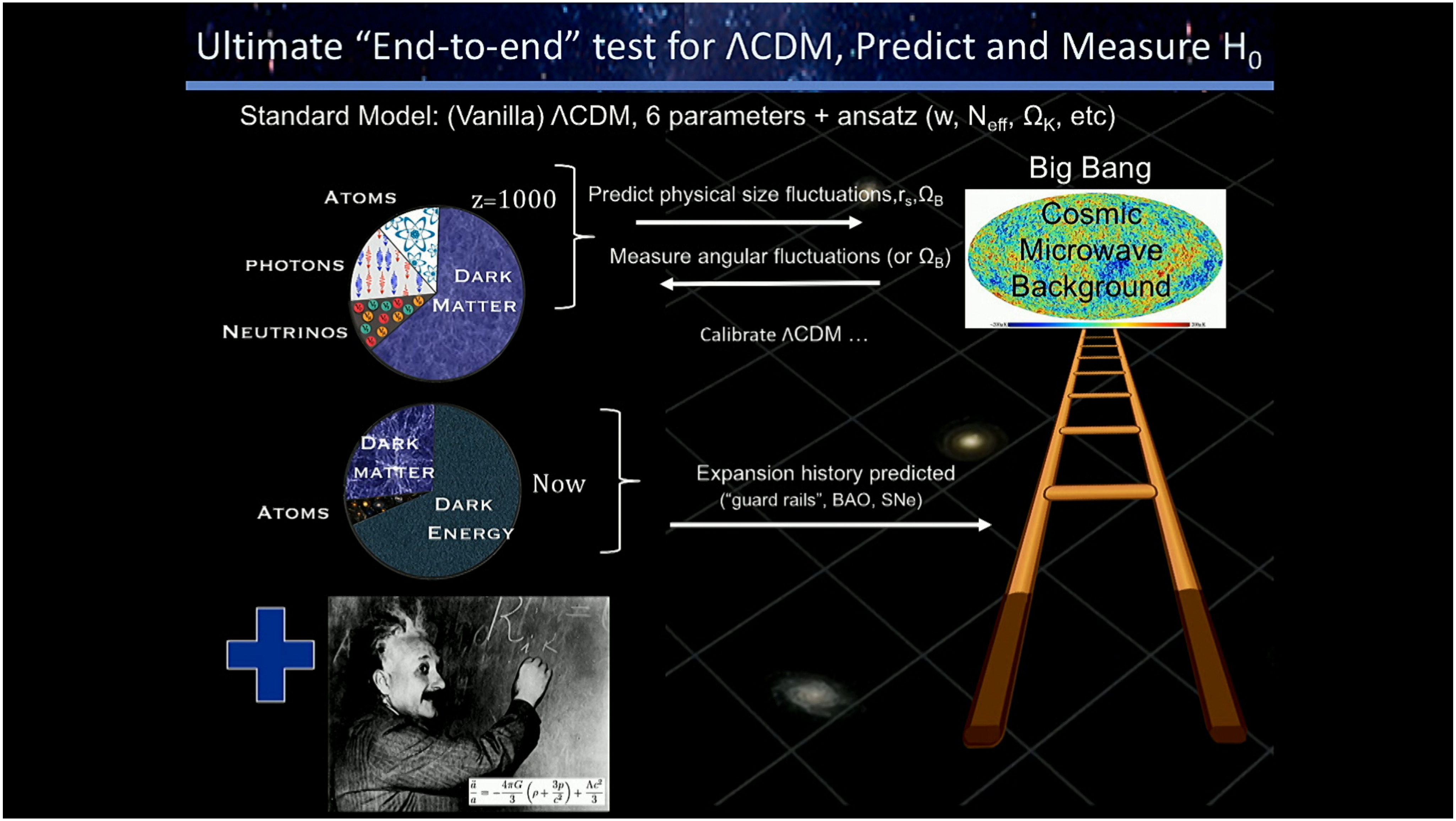

Ultimate "End-to-end" test for ΛCDM, Predict and Measure H_0

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

ATOMS

z=1000

PHOTONS

DARK MATTER

NEUTRINOS

Predict physical size fluctuations, r_s, Ω_B

Measure angular fluctuations (or Ω_B)

Calibrate ΛCDM …

Big Bang

Cosmic Microwave Background

DARK MATTER

ATOMS

DARK ENERGY

Now

Expansion history predicted

("guard rails", BAO, SNe)

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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)

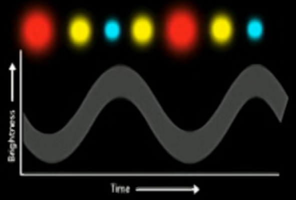
A. Riess, L. Macri, S. Casertano, D. Scolnic, A. Filippenko, W. Yuan, S. Hoffman, et al

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

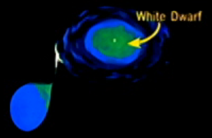
- A strong, simple ladder: Geometry → Cepheids → SNe Ia

Multiple ways

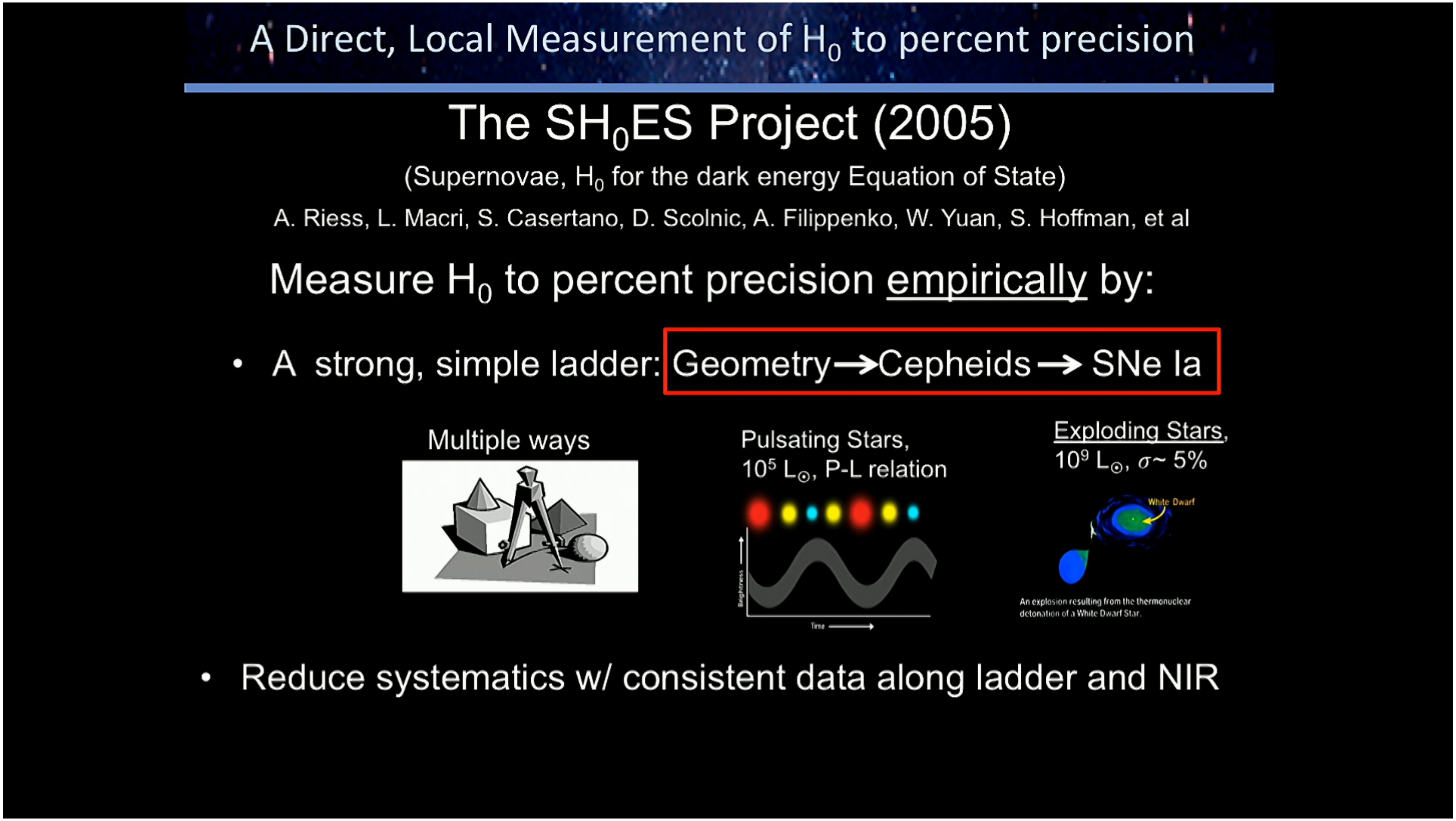
Pulsating Stars,
10^5 $L_\odot$, P-L relation



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



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



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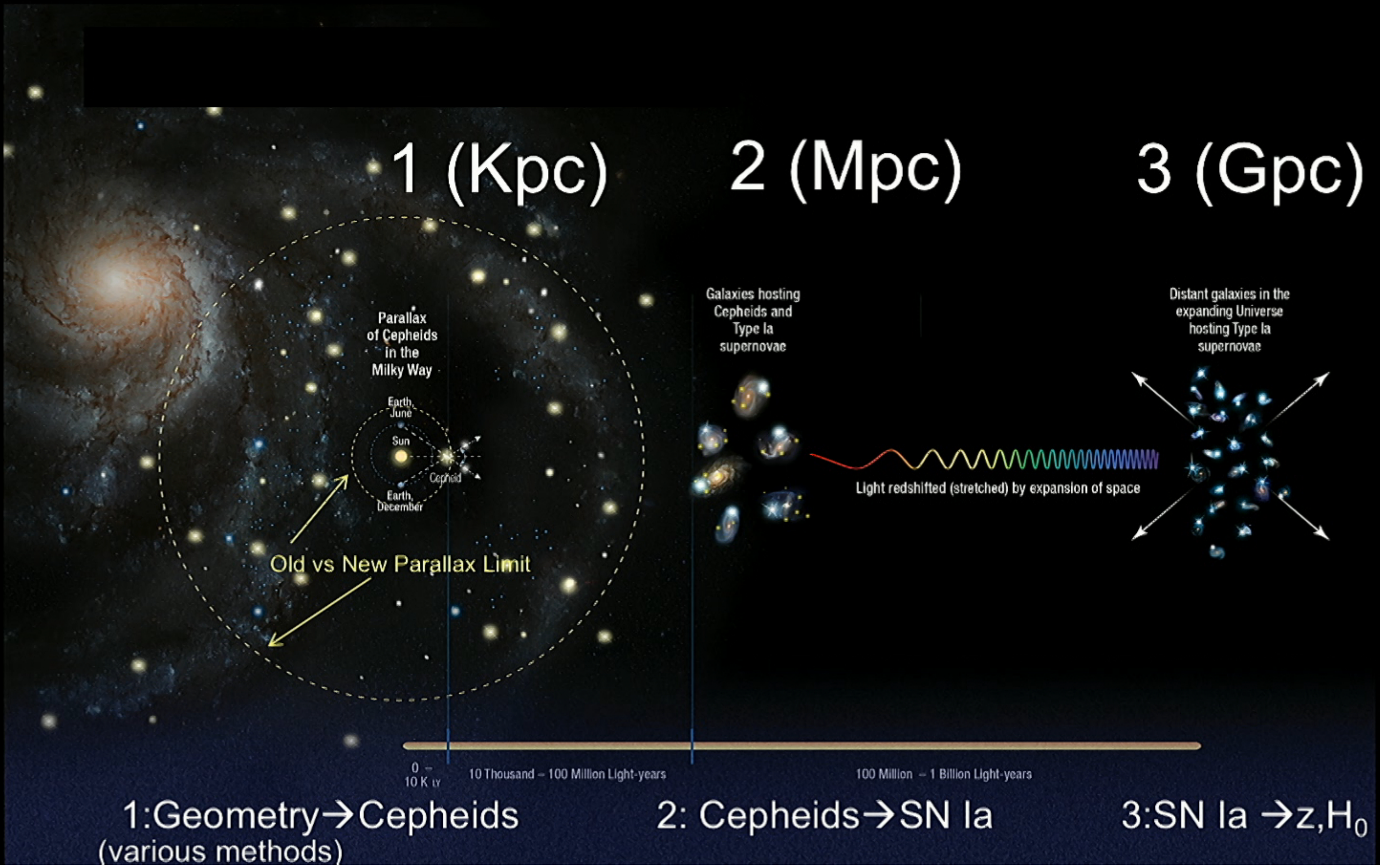
An explosion resulting from the thermonuclear detonation of a White Dwarf Star.

- Reduce systematics w/ consistent data along ladder and NIR

Our route: 3 Steps to H_0

[redacted]



1 (Kpc) 2 (Mpc) 3 (Gpc)

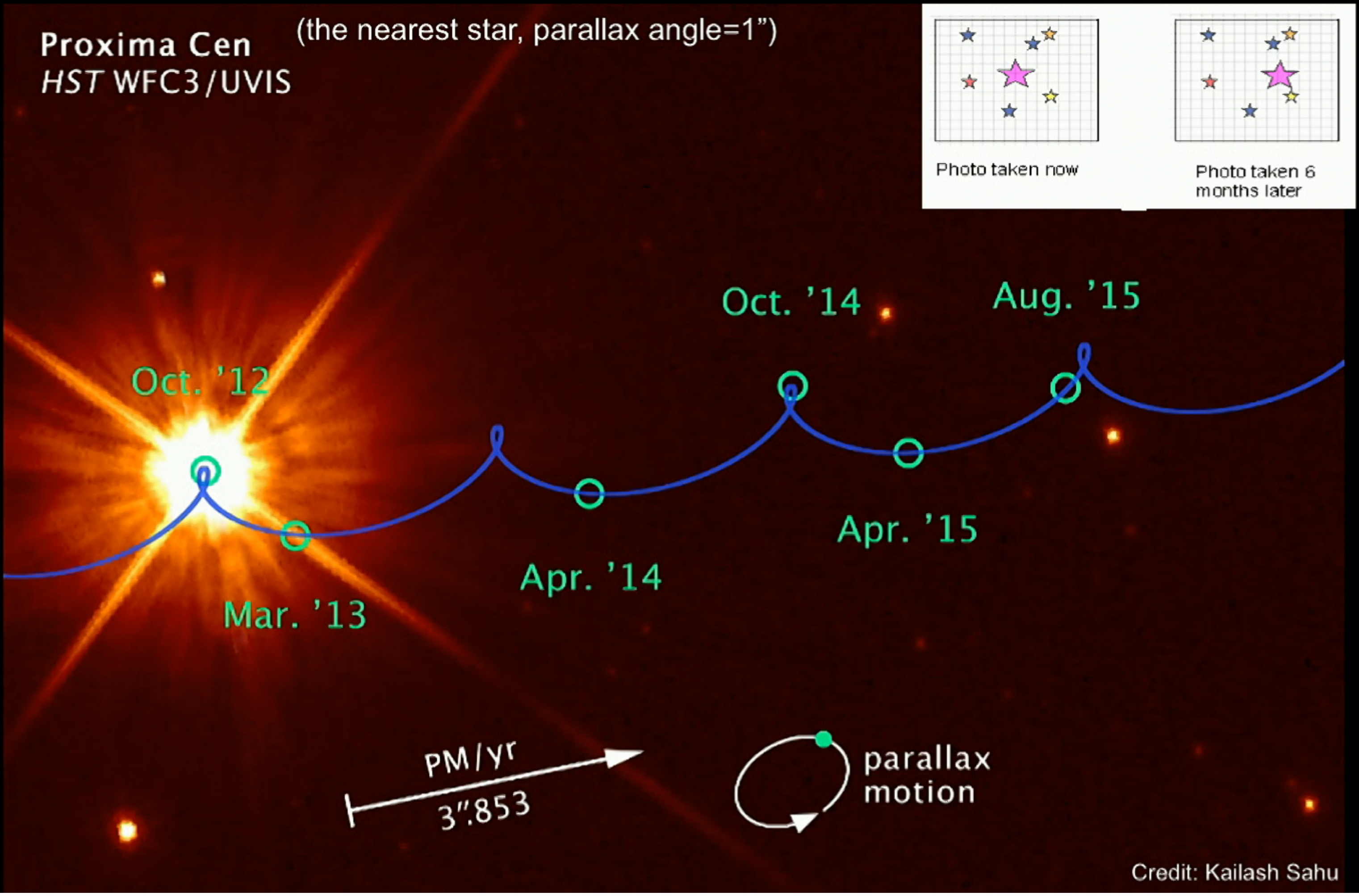
1:Geometry→Cepheids
(various methods)

2: Cepheids→SN Ia

3:SN Ia →z,H_0

Stars are far, Parallax is small !

(the nearest star, parallax angle=1")



Credit: Kailash Sahu

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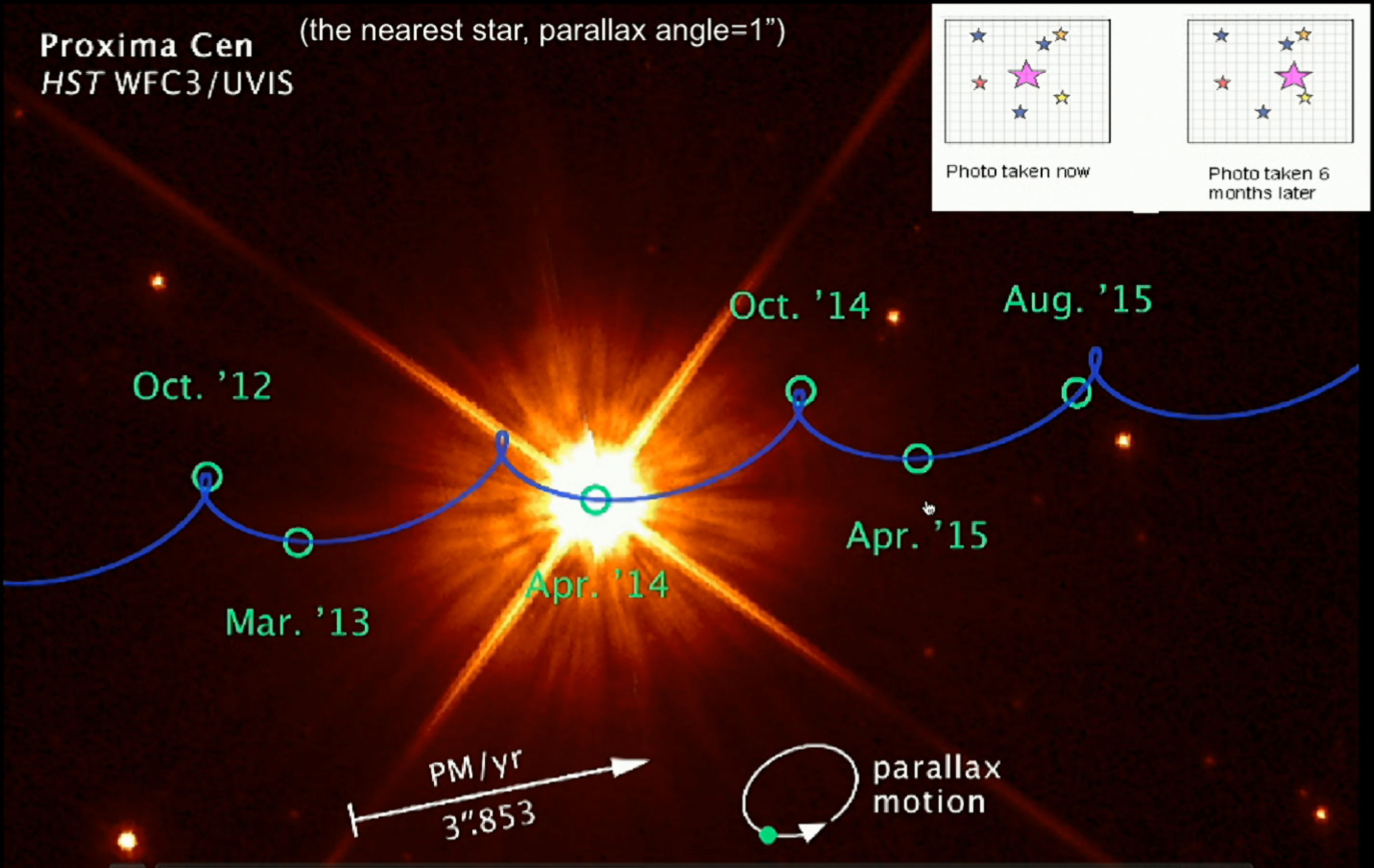

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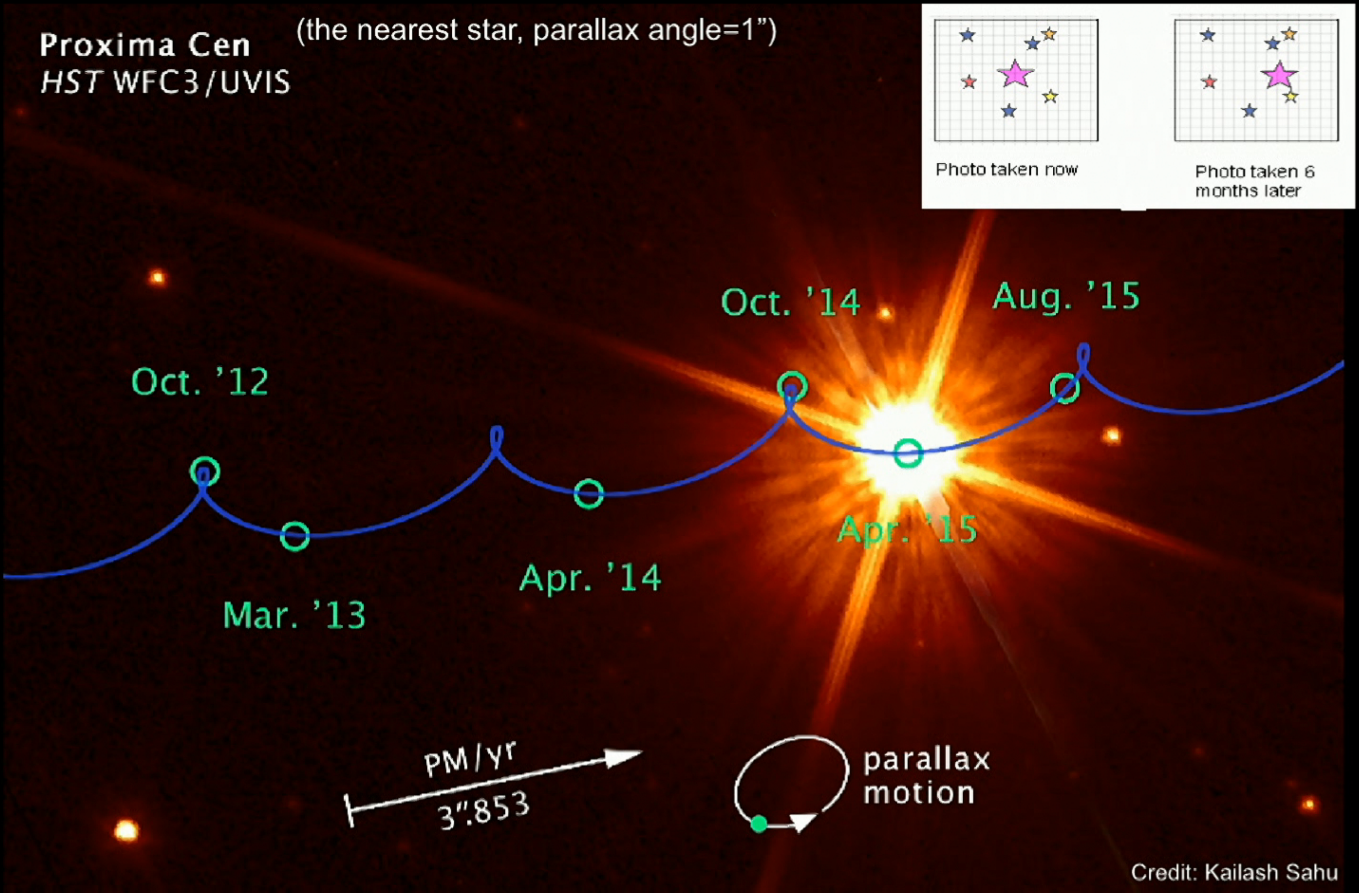

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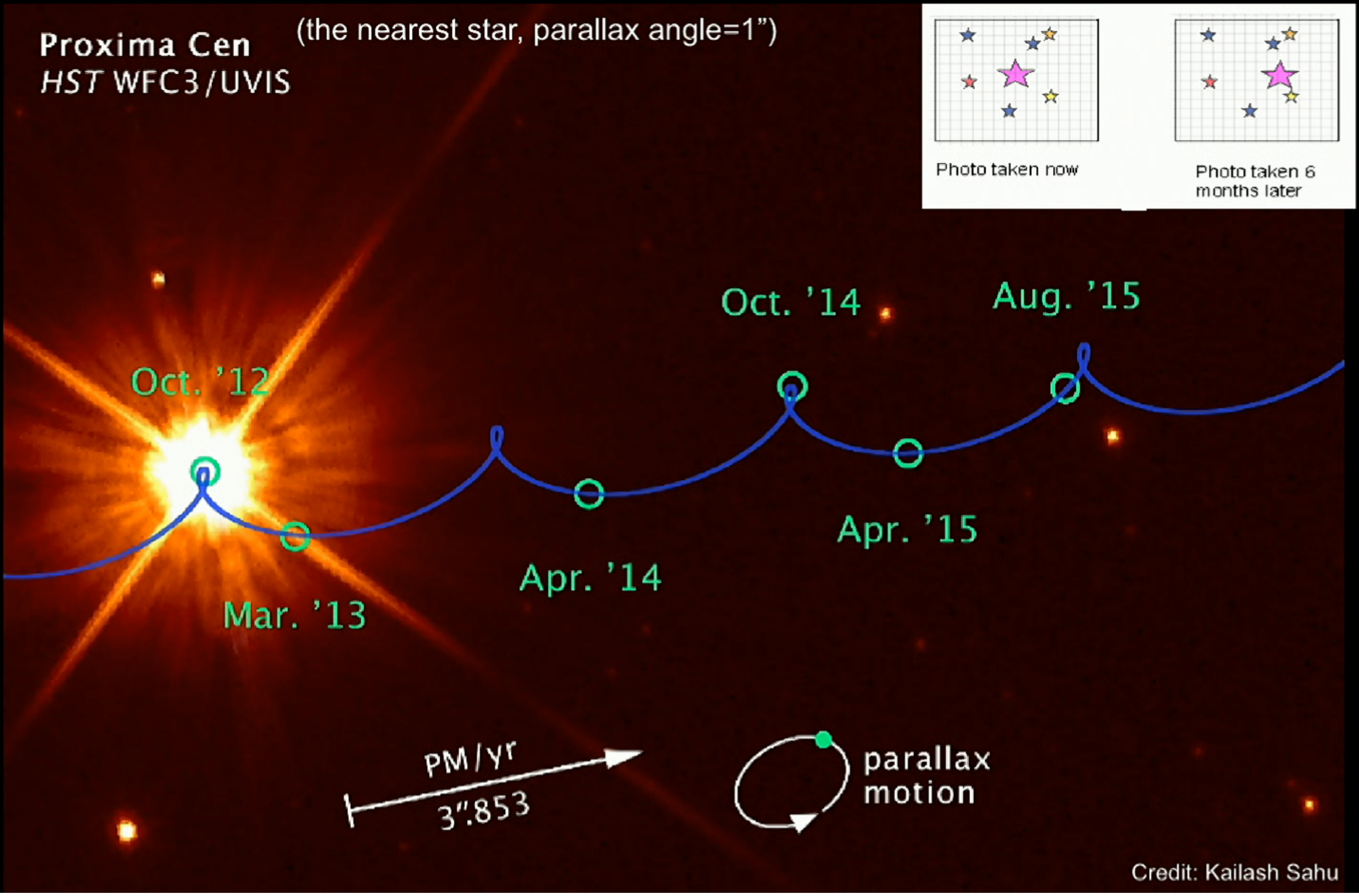
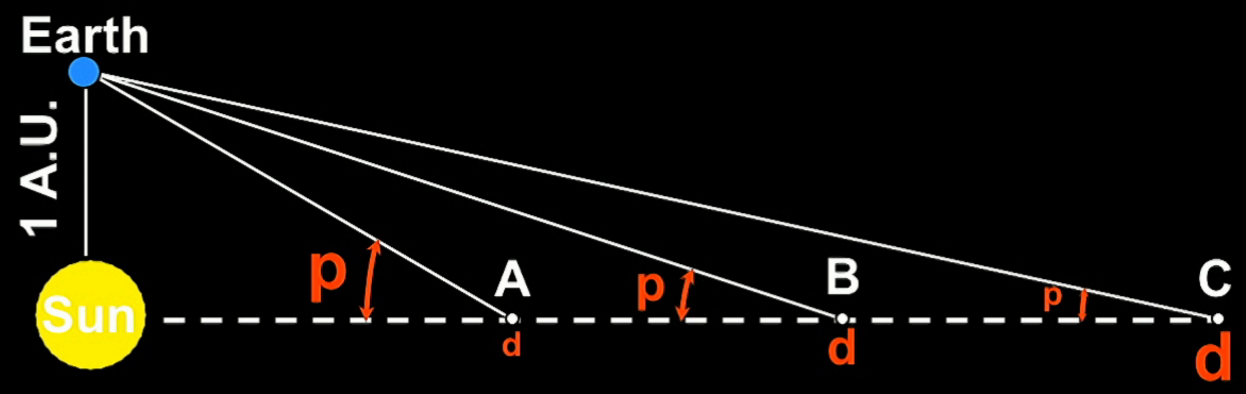


Credit: Kailash Sahu

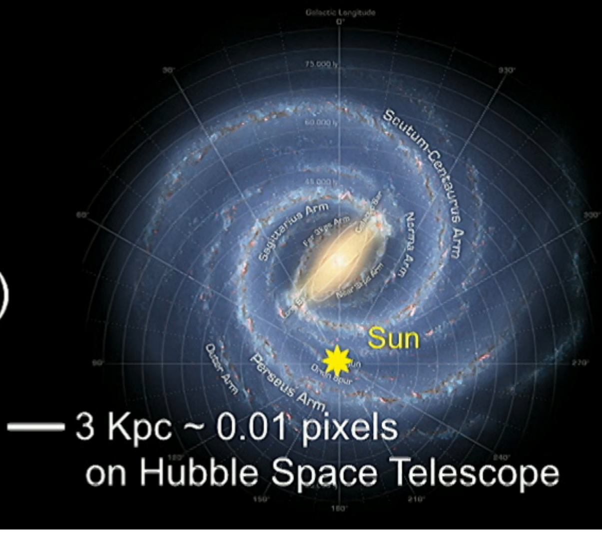
Scale of the Milky Way is Kiloparsecs

As distance increases, parallax decreases



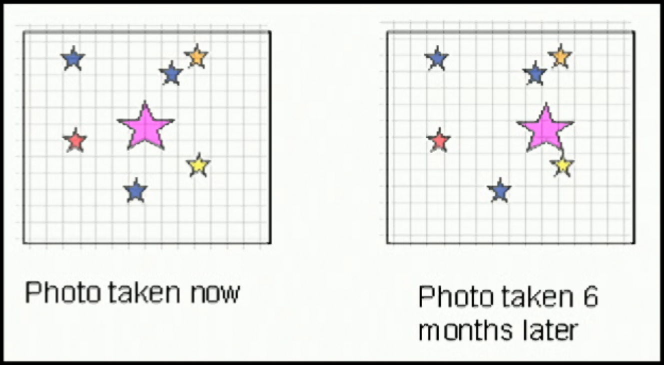
$$d\ (\text{kpc}) = \frac{1}{p\ (\text{milliarcsec})}$$

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

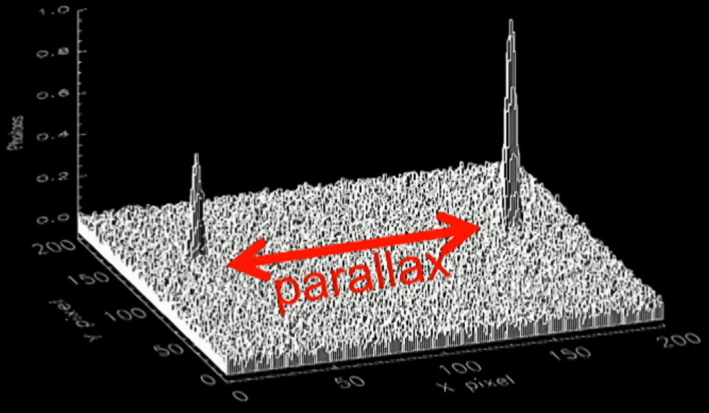


3 Kpc ~ 0.01 pixels
on Hubble Space Telescope

Extending Parallax with WFC3 Spatial Scanning



Imaging, precision=0.01 pix
WFC3: ~1σ @ 3 kpc



Extending Parallax with WFC3 Spatial Scanning

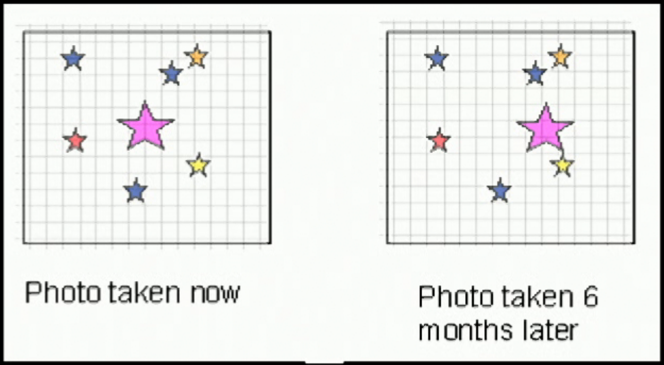
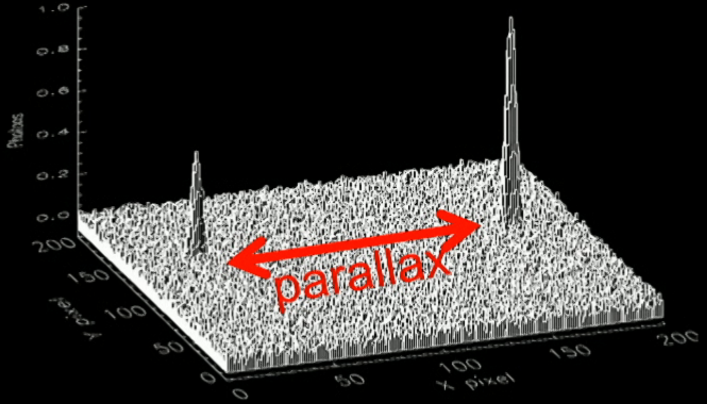


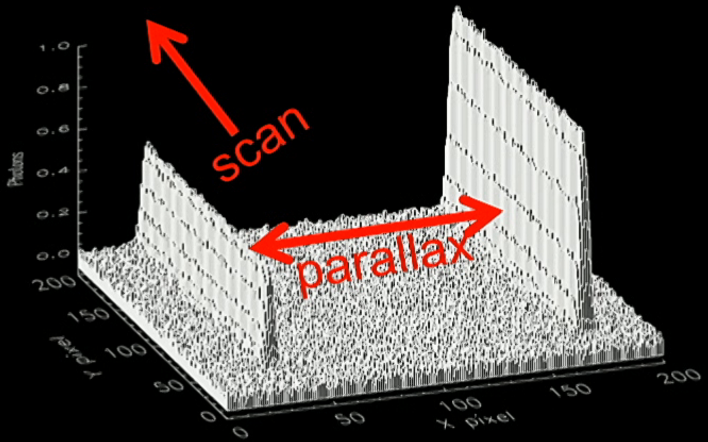
Photo taken now

Photo taken 6 months later

Imaging, precision=0.01 pix
WFC3: ~1σ @ 3 kpc

Scanning, σ_θ=0.01/√N samples pix





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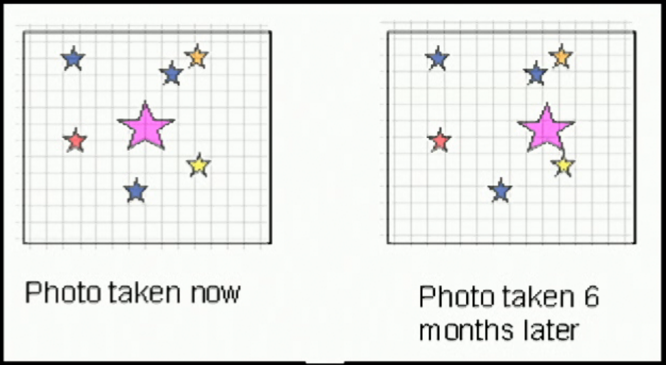
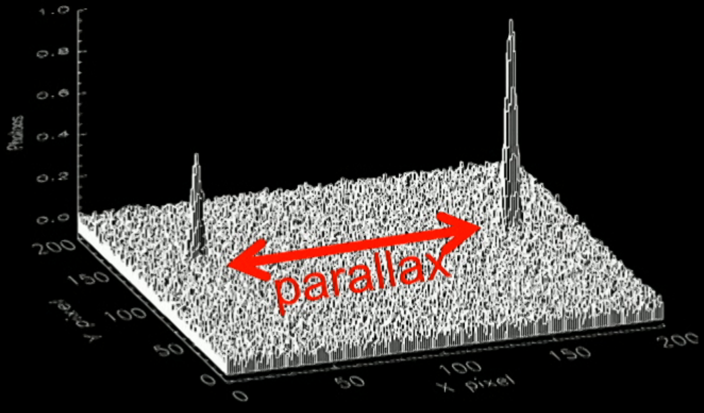
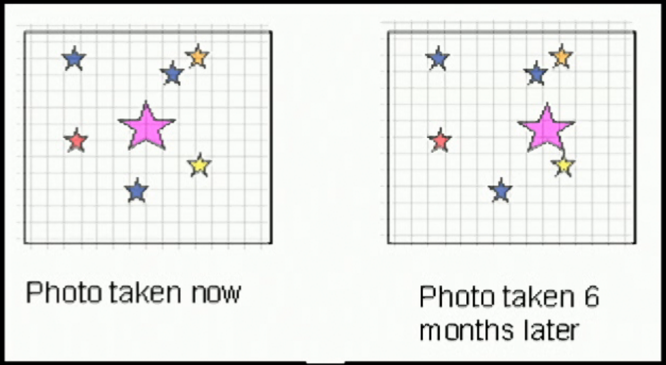


Imaging, precision=0.01 pix
WFC3: ~1σ @ 3 kpc

Sc

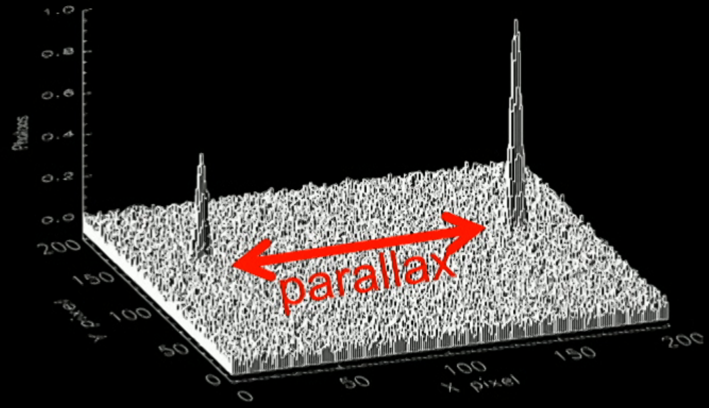


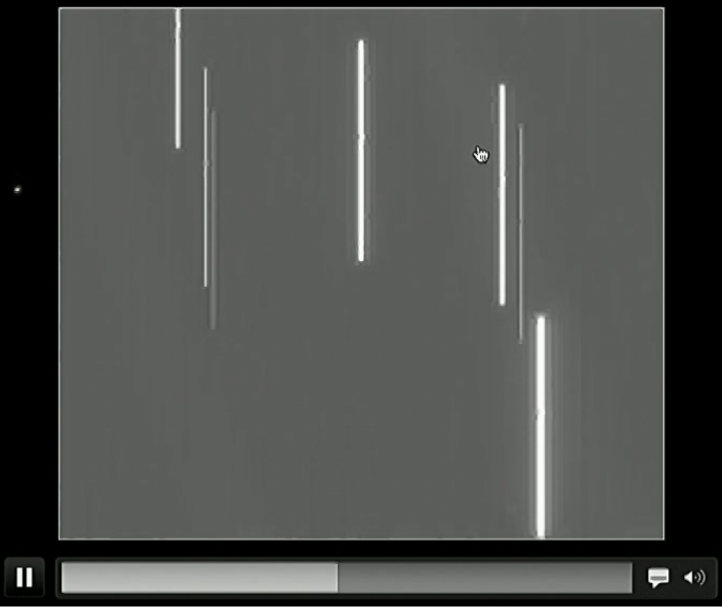
Extending Parallax with WFC3 Spatial Scanning



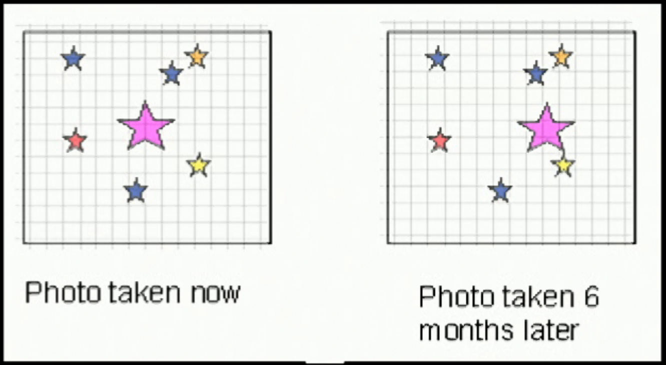
Imaging, precision=0.01 pix
WFC3: ~1σ @ 3 kpc

Sc





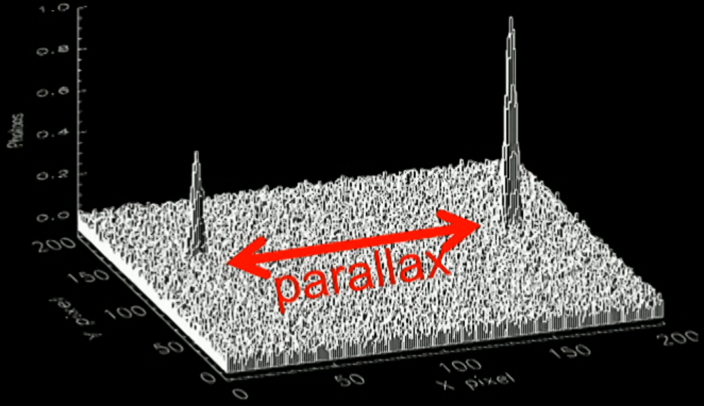
Extending Parallax with WFC3 Spatial Scanning

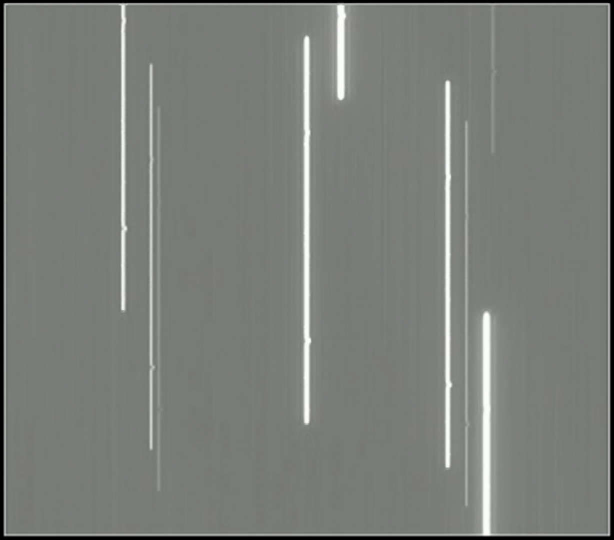


Imaging, precision=0.01 pix

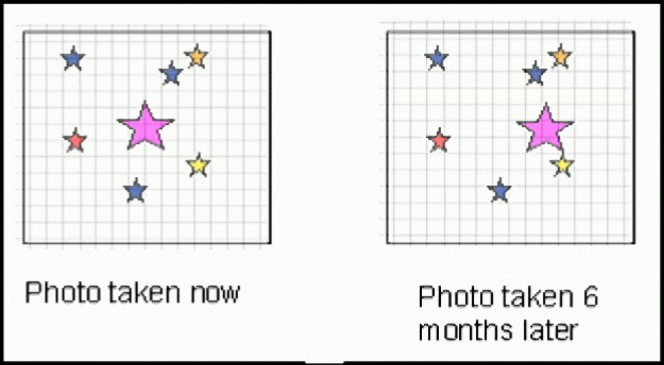
WFC3: ~1σ @ 3 kpc

Sc





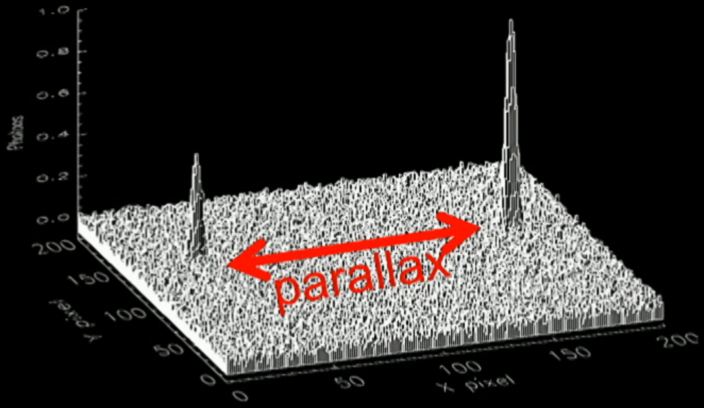
Extending Parallax with WFC3 Spatial Scanning

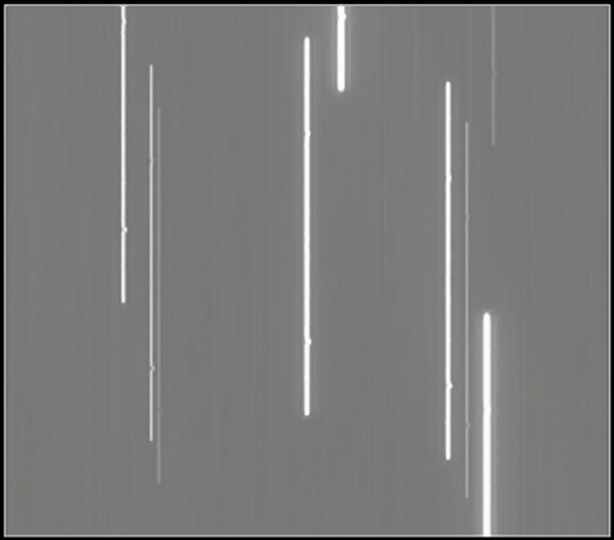


Riess, Casertano, Mackenty et al (2014)
Casertano, AGR, Anderson et al (2016)

Imaging, precision=0.01 pix
WFC3: ~1σ @ 3 kpc

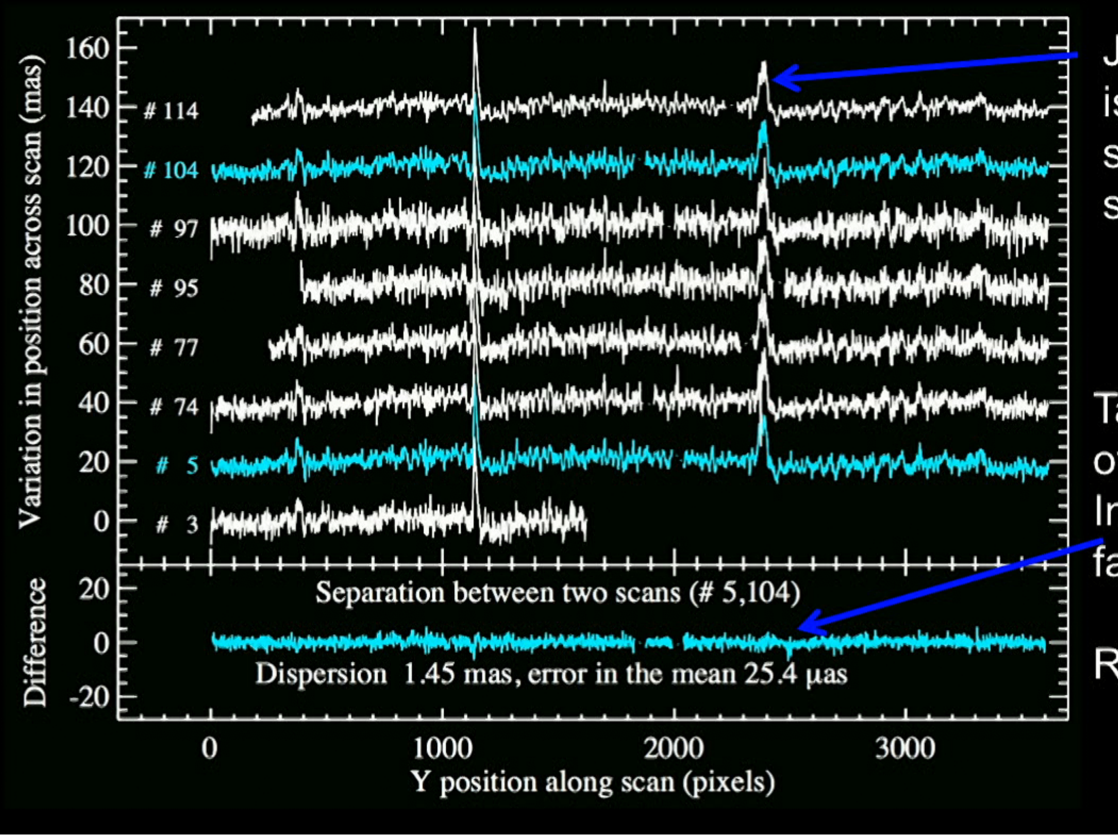
Sc





Two Features of Spatial Scans: Sampling and Jitter Removal

Extracted scan lines of stars from a single scan



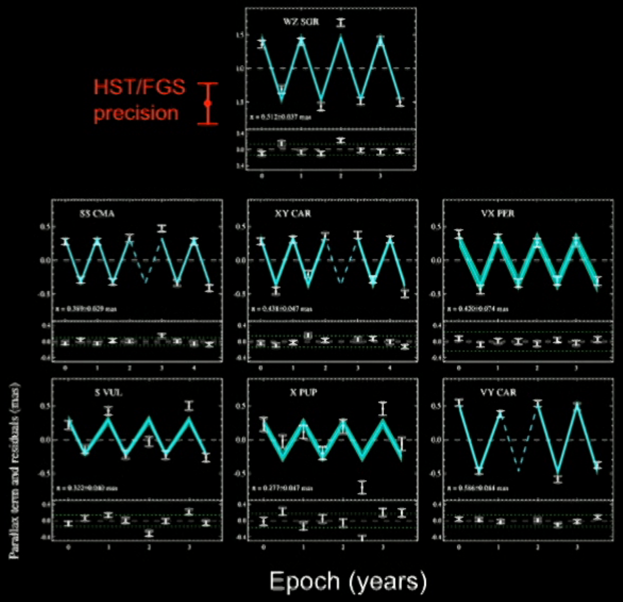
Jitter between lines is *coherent*, subtracted in line separations (vs time)

Target scanned over ~4000 pix, Improves SNR by factor of 10

Reaching 20-40 μas

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

WFC3 Spatial Scanning→ 20-40 μas
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

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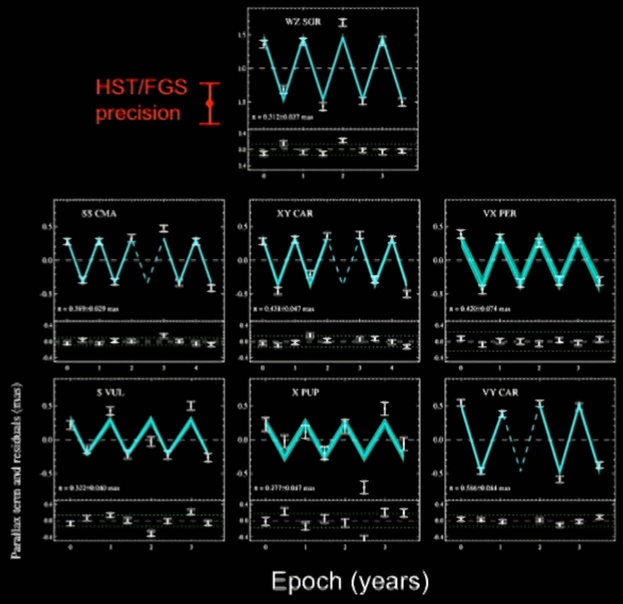

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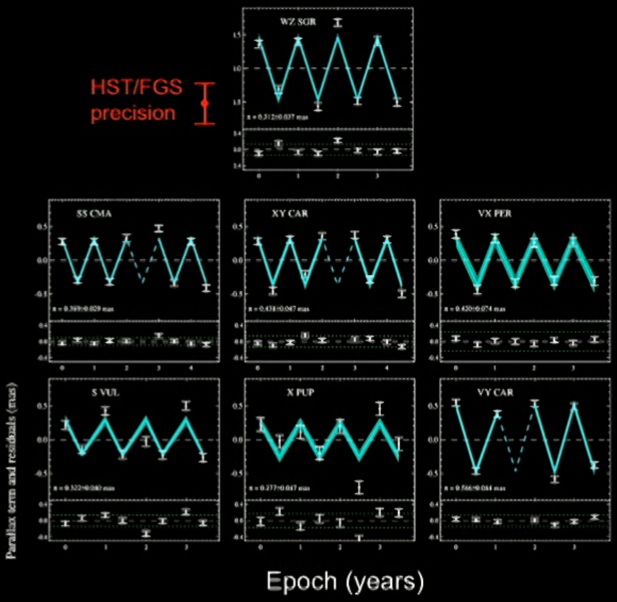
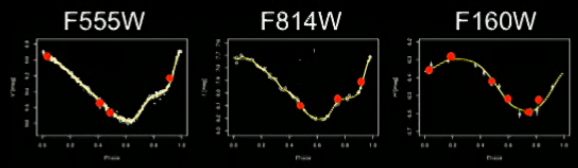
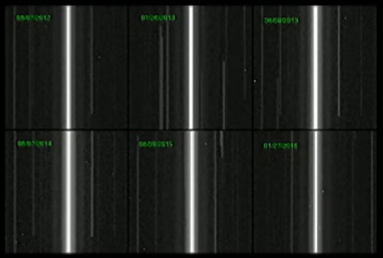


Riess et al. (2018a), ApJ, 855,136

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





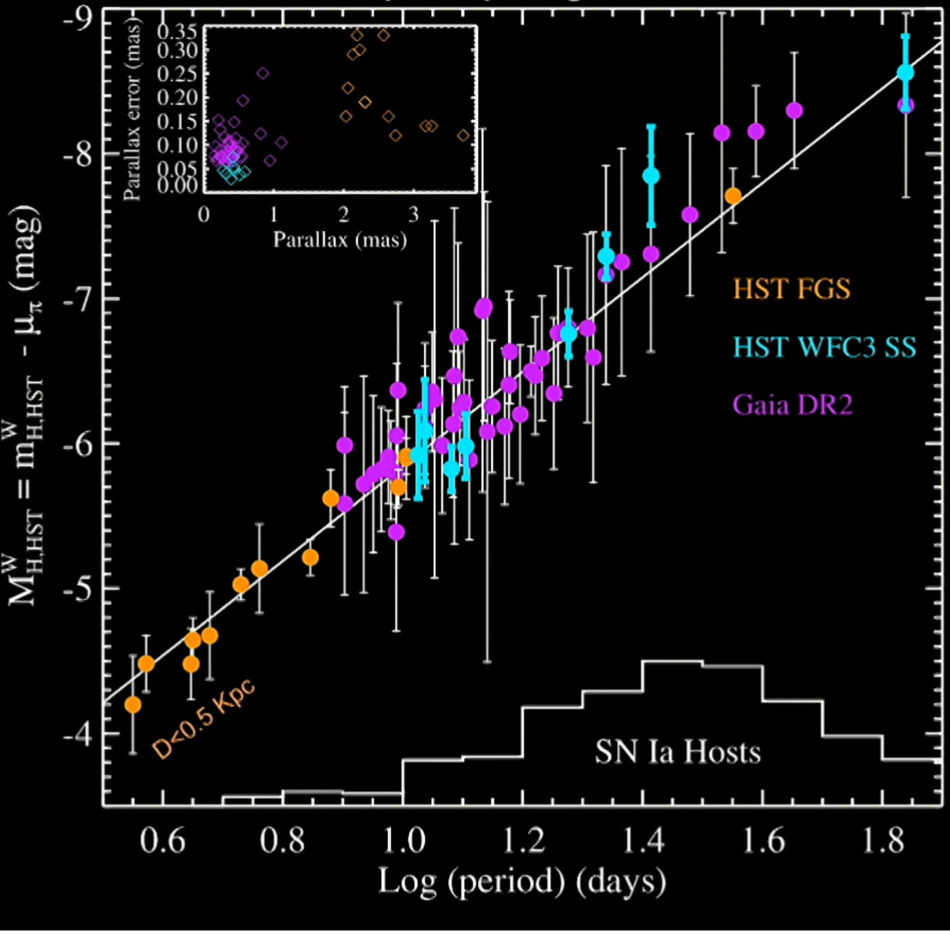
Fast Scans 7.5”/s exp time~0.01 sec
Error individual Cepheid mean D<1%

w/ Gaia DR2, error in mean=3.3%
Riess et al. (2018b), ApJ, 861, 126

More in Cycle 27 to help resolve Gaia
zeropoint, reach 1% distance calibration

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

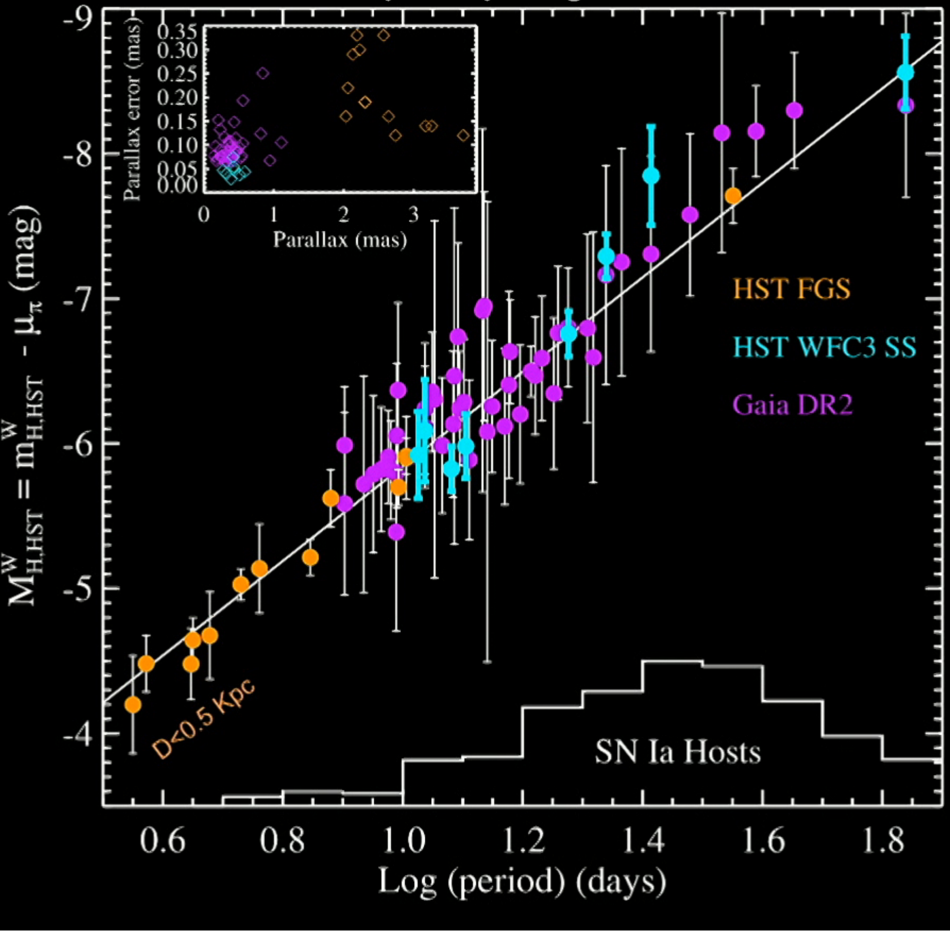
Milky Way PL Relation



}

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

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



Milky Way PL Relation

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

}

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

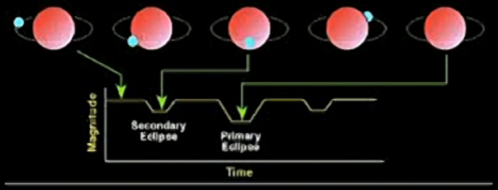
Three Sources of Geometric Distances to Calibrate Cepheids

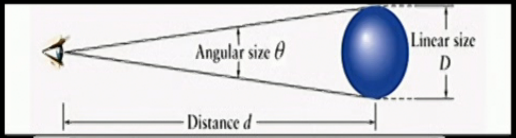
Parallax in Milky Way (WFC3 SS, HST FGS, Gaia)

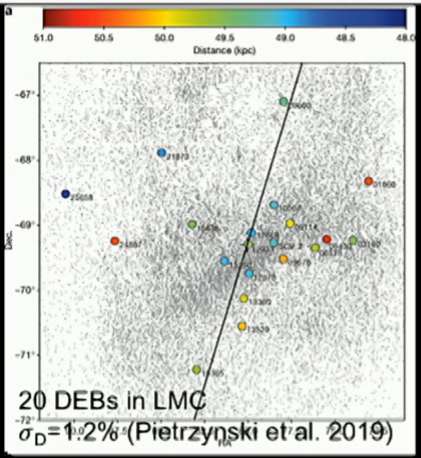
Three Sources of Geometric Distances to Calibrate Cepheids

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

Detached Eclipsing Binaries in LMC







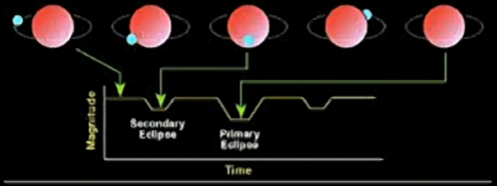
20 DEBs in LMC

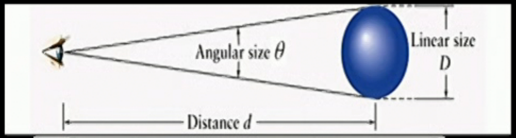
σ_D=1.2% (Pietrzynski et al. 2019)

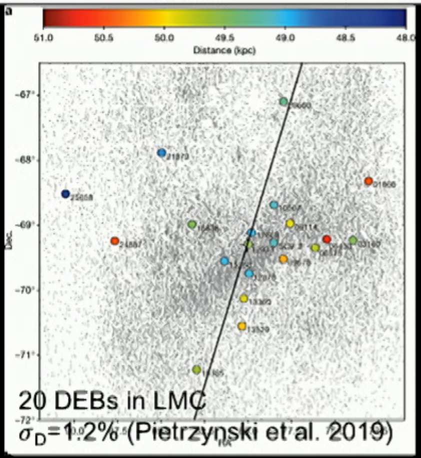
Three Sources of Geometric Distances to Calibrate Cepheids

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

Detached Eclipsing Binaries in LMC







20 DEBs in LMC

σ_D=1.2% (Pietrzynski et al. 2019)

Masers in NGC 4258, Keplerian Motion


nature

INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

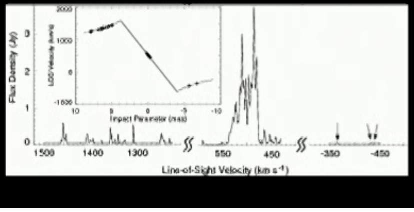
Volume 373 No. 6510 12 January 1995 $8.50

Zooming in on a black hole

Dynamics of HIV-1 infection

The Pope and embryology

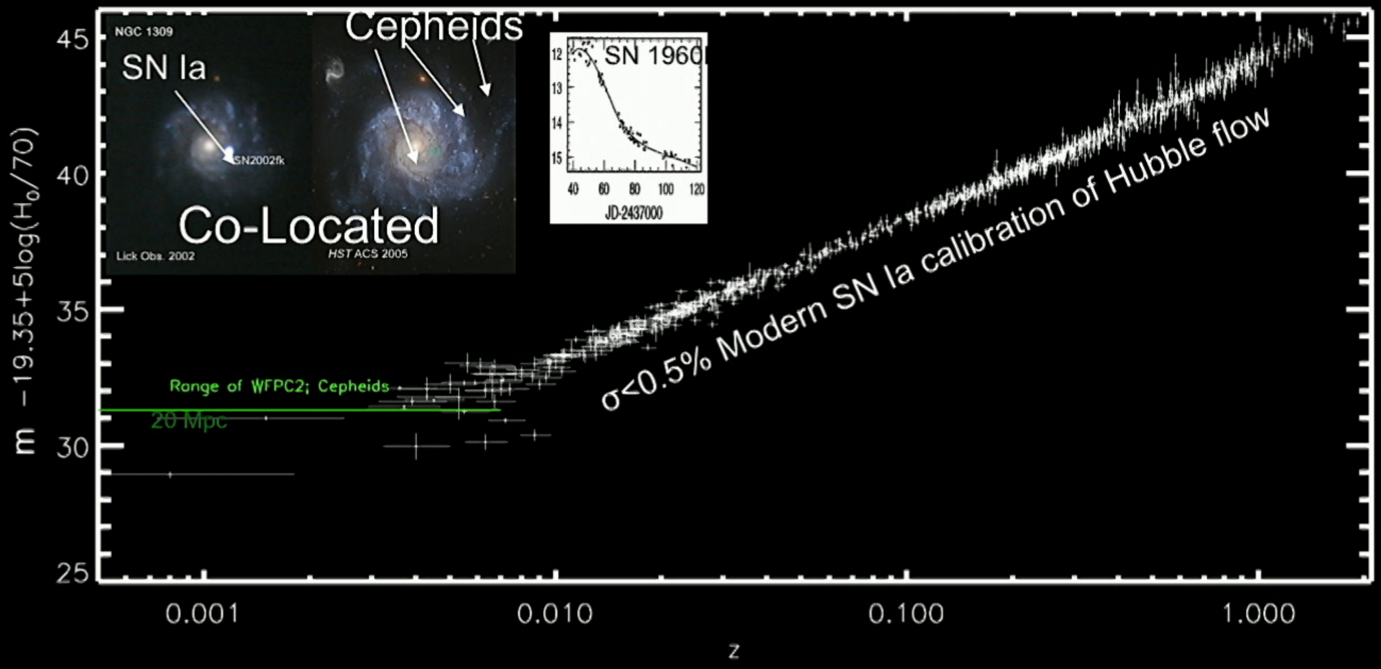
Multi-ring impact basins



Step 2: Cepheids to Type Ia Supernovae

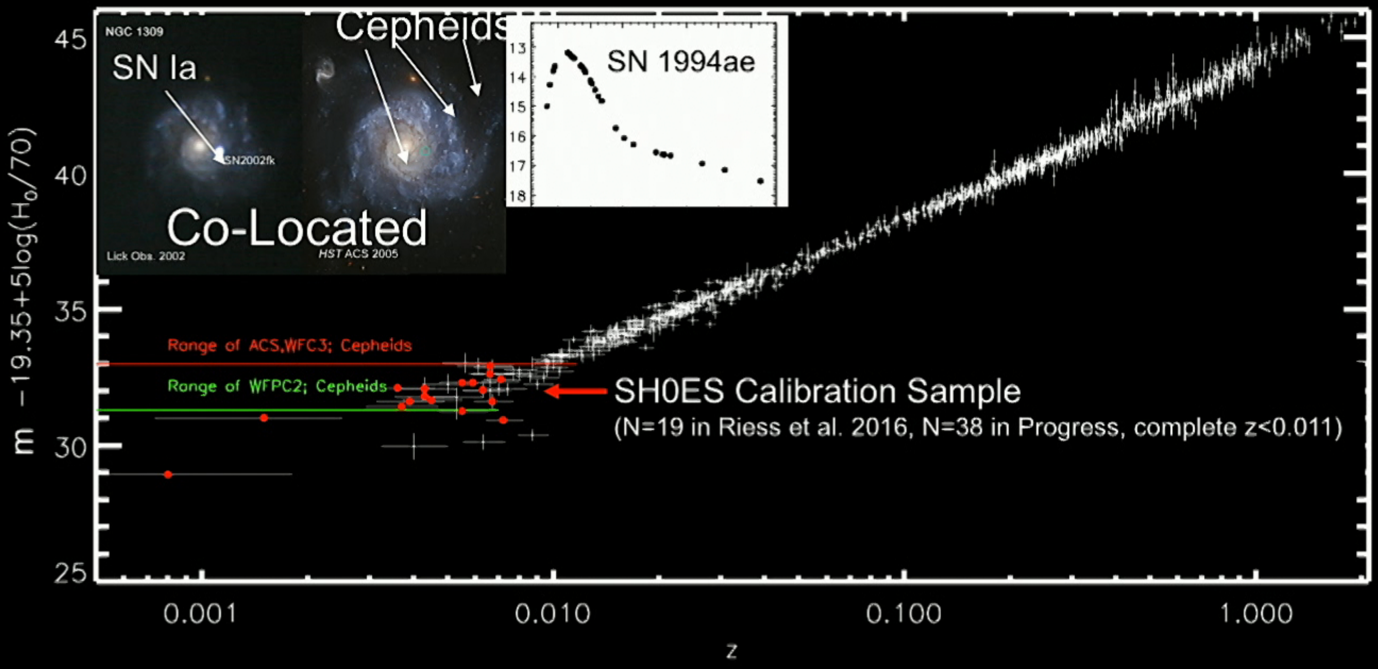
1.Discard *photographic* data, SN 1895B, 1937C, 1960F 1974G, & unreliable
i.e. all but 2-3 used by Key Project Freedman et al. 2001,2012, Sandage et al.,

Previously limited by 20 Mpc Cepheid range of WFPC2…

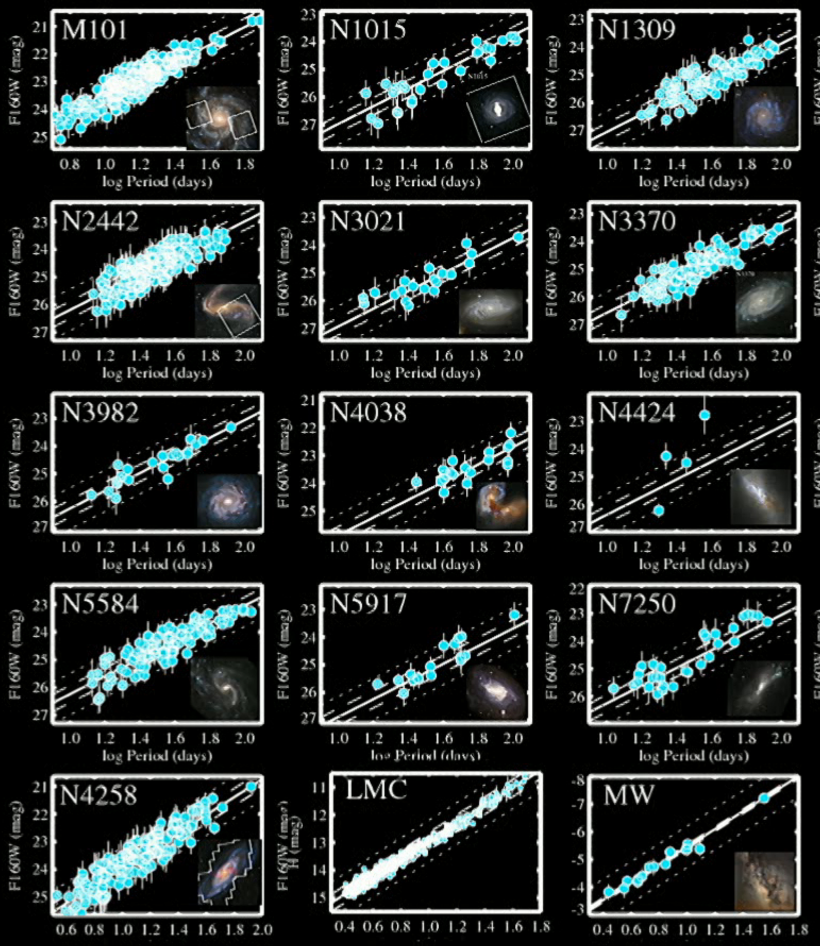


Step 2: Better Data-SN Ia

- 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).



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

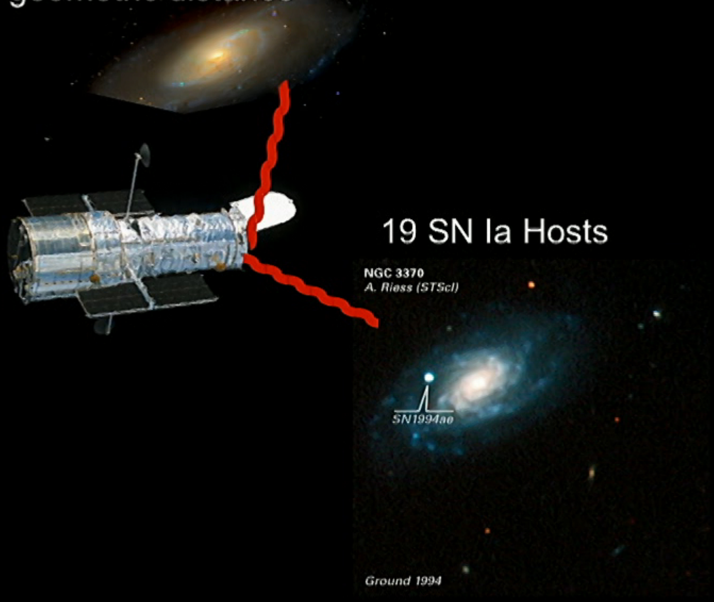


3 Anchors

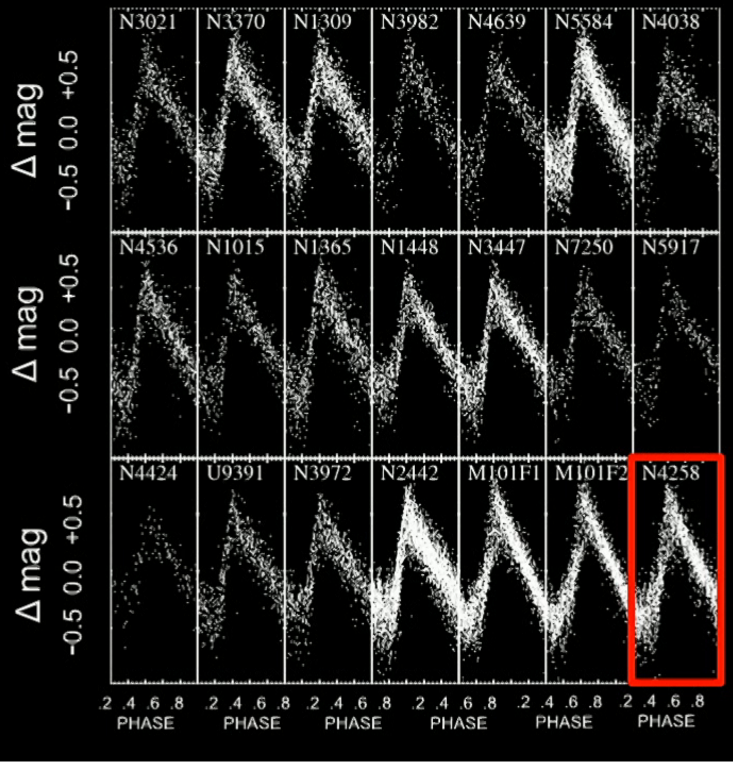
Lower Systematics from *Differential* Flux Measurements

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

ANCHORS: NGC 4258, MW, & LMC geometric distance



Cepheid composite LC's, >2400



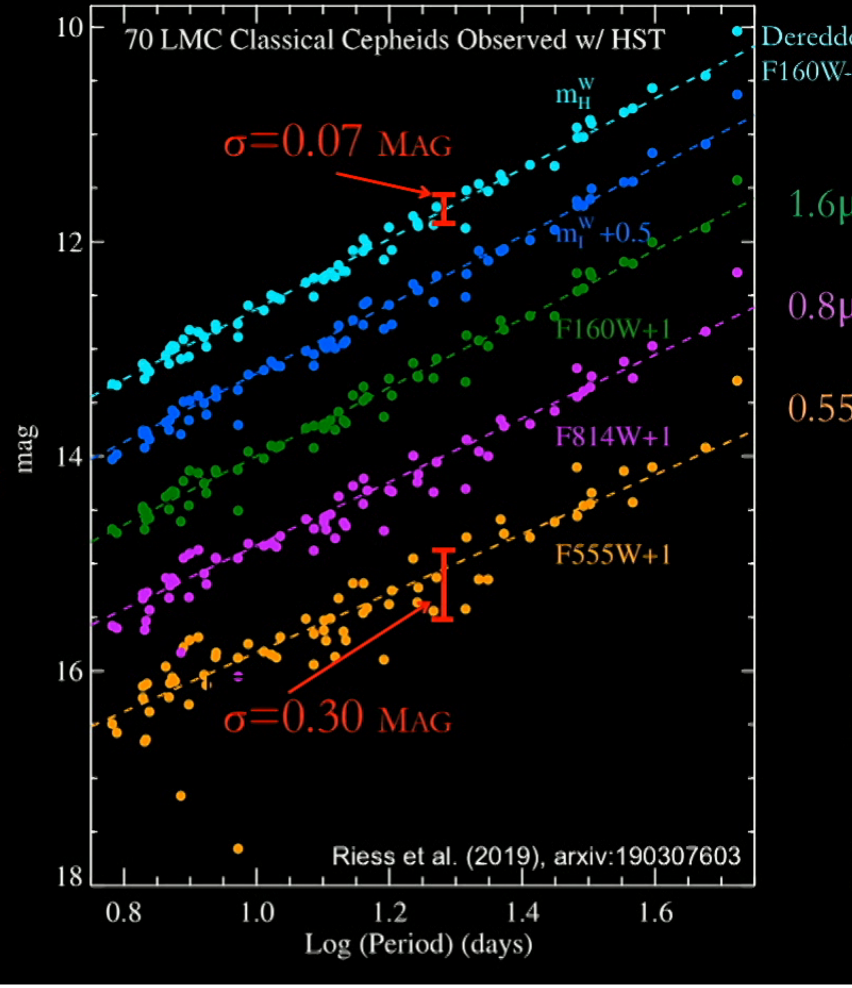
Lowering Systematics: Near-IR Cepheid Observations + HST, Now in LMC!

-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



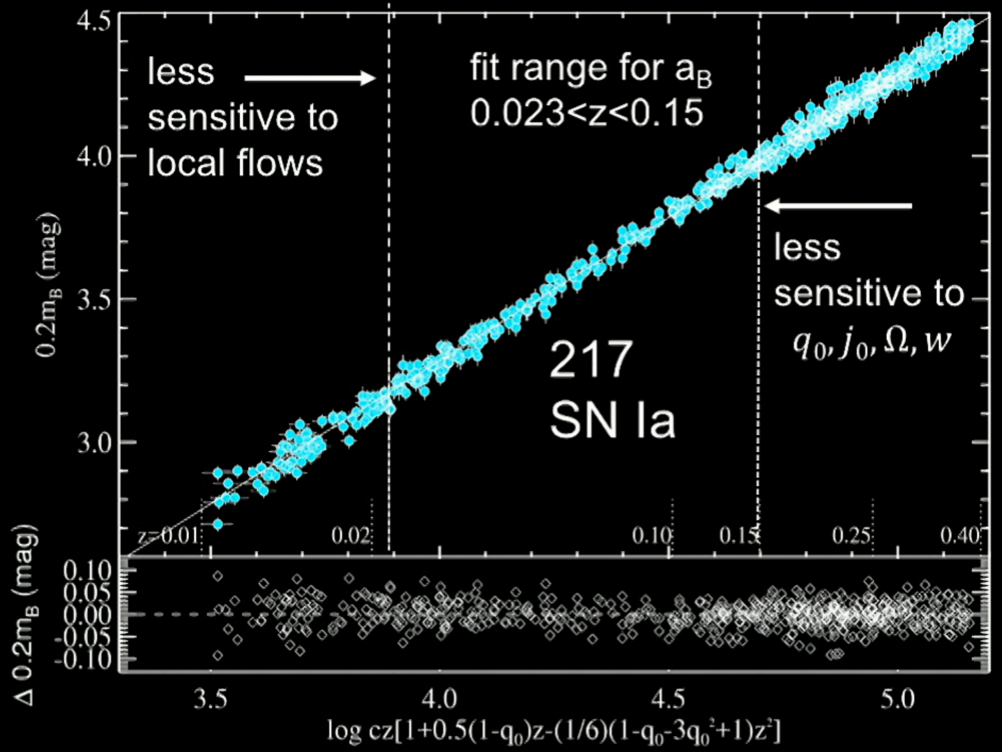
Riess et al. (2019), arxiv:190307603

Leavitt

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

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

Kinematic Intercept equation

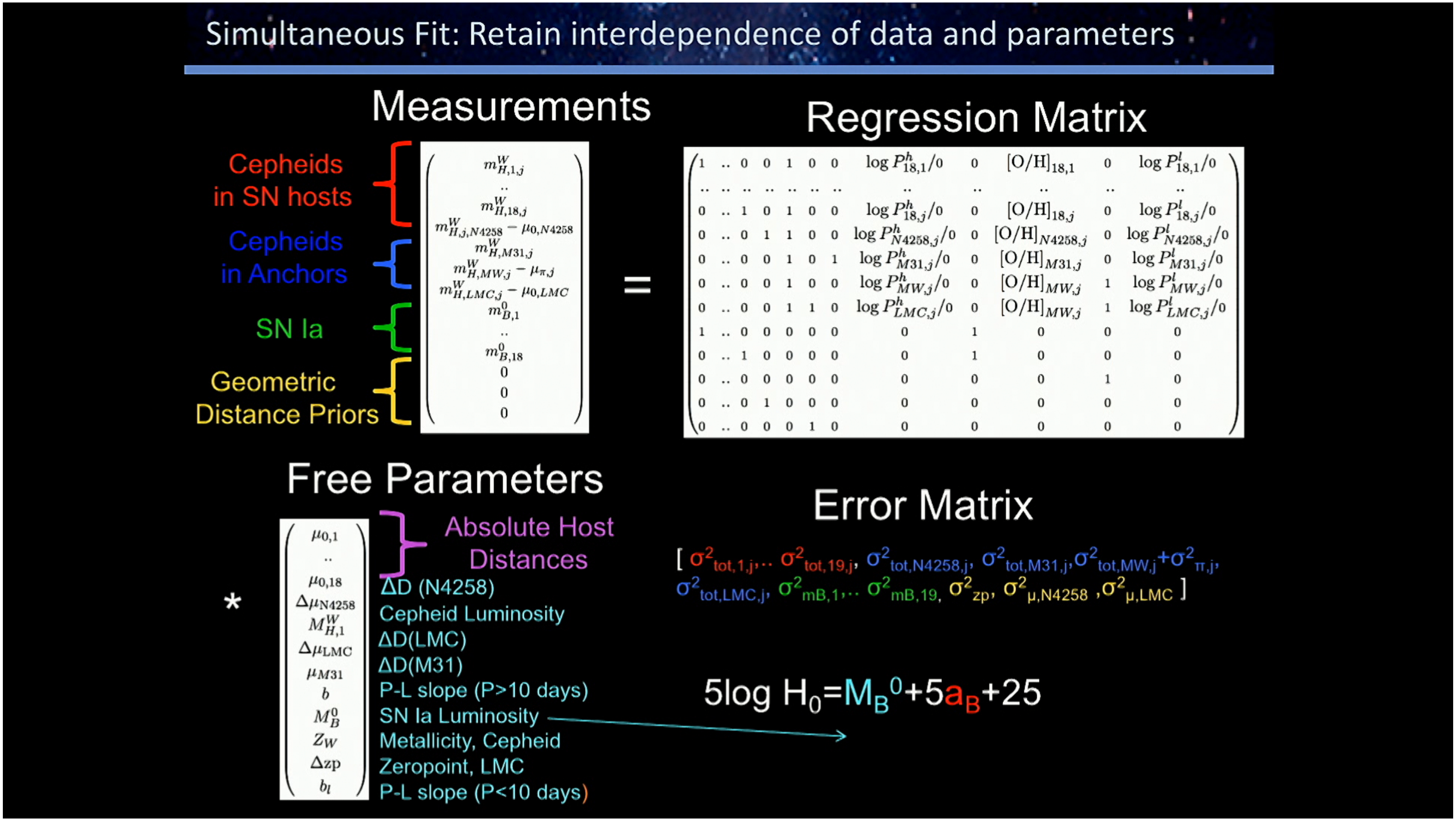


less sensitive to local flows

fit range for a_B 0.023<z<0.15

217 SN Ia

less sensitive to q_0, j_0, Ω, w



Simultaneous Fit: Retain interdependence of data and parameters

Measurements

Cepheids in SN hosts

Cepheids in Anchors

SN Ia

Geometric Distance Priors

$$\begin{pmatrix} m^W_{H,1,j} \\ .. \\ m^W_{H,18,j} \\ m^W_{H,j,N4258} - \mu_{0,N4258} \\ m^W_{H,M31,j} \\ m^W_{H,MW,j} - \mu_{\pi,j} \\ m^W_{H,LMC,j} - \mu_{0,LMC} \\ m^0_{B,1} \\ .. \\ m^0_{B,18} \\ 0 \\ 0 \\ 0 \end{pmatrix} =$$

Regression Matrix

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

Free Parameters

$$* \begin{pmatrix} \mu_{0,1} \\ .. \\ \mu_{0,18} \\ \Delta\mu_{\mathrm{N4258}} \\ M^W_{H,1} \\ \Delta\mu_{\mathrm{LMC}} \\ \mu_{M31} \\ b \\ M^0_B \\ Z_W \\ \Delta\mathrm{zp} \\ b_l \end{pmatrix}$$

Absolute Host Distances

ΔD (N4258)

Cepheid Luminosity

ΔD(LMC)

ΔD(M31)

P-L slope (P>10 days)

SN Ia Luminosity →

Metallicity, Cepheid

Zeropoint, LMC

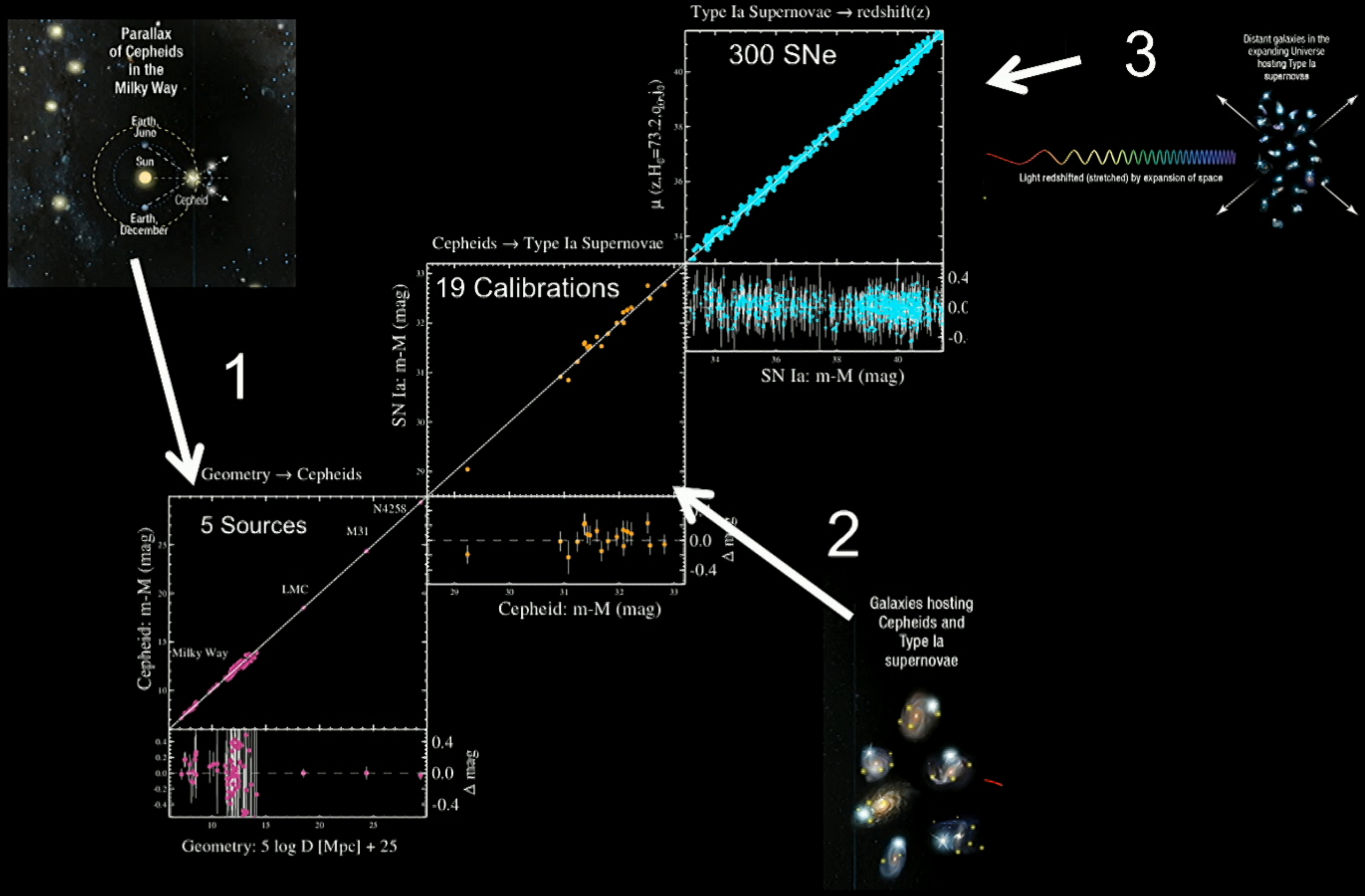
P-L slope (P<10 days)

Error Matrix

$[\ \sigma^2_{\mathrm{tot},1,j}, ..\ \sigma^2_{\mathrm{tot},19,j},\ \sigma^2_{\mathrm{tot,N4258},j},\ \sigma^2_{\mathrm{tot,M31},j}, \sigma^2_{\mathrm{tot,MW},j} + \sigma^2_{\pi,j},$
$\sigma^2_{\mathrm{tot,LMC},j},\ \sigma^2_{\mathrm{mB},1}, ..\ \sigma^2_{\mathrm{mB},19},\ \sigma^2_{\mathrm{zp}},\ \sigma^2_{\mu,\mathrm{N4258}}\ , \sigma^2_{\mu,\mathrm{LMC}}\ ]$

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

The Hubble Constant in 3 Steps: Present Data



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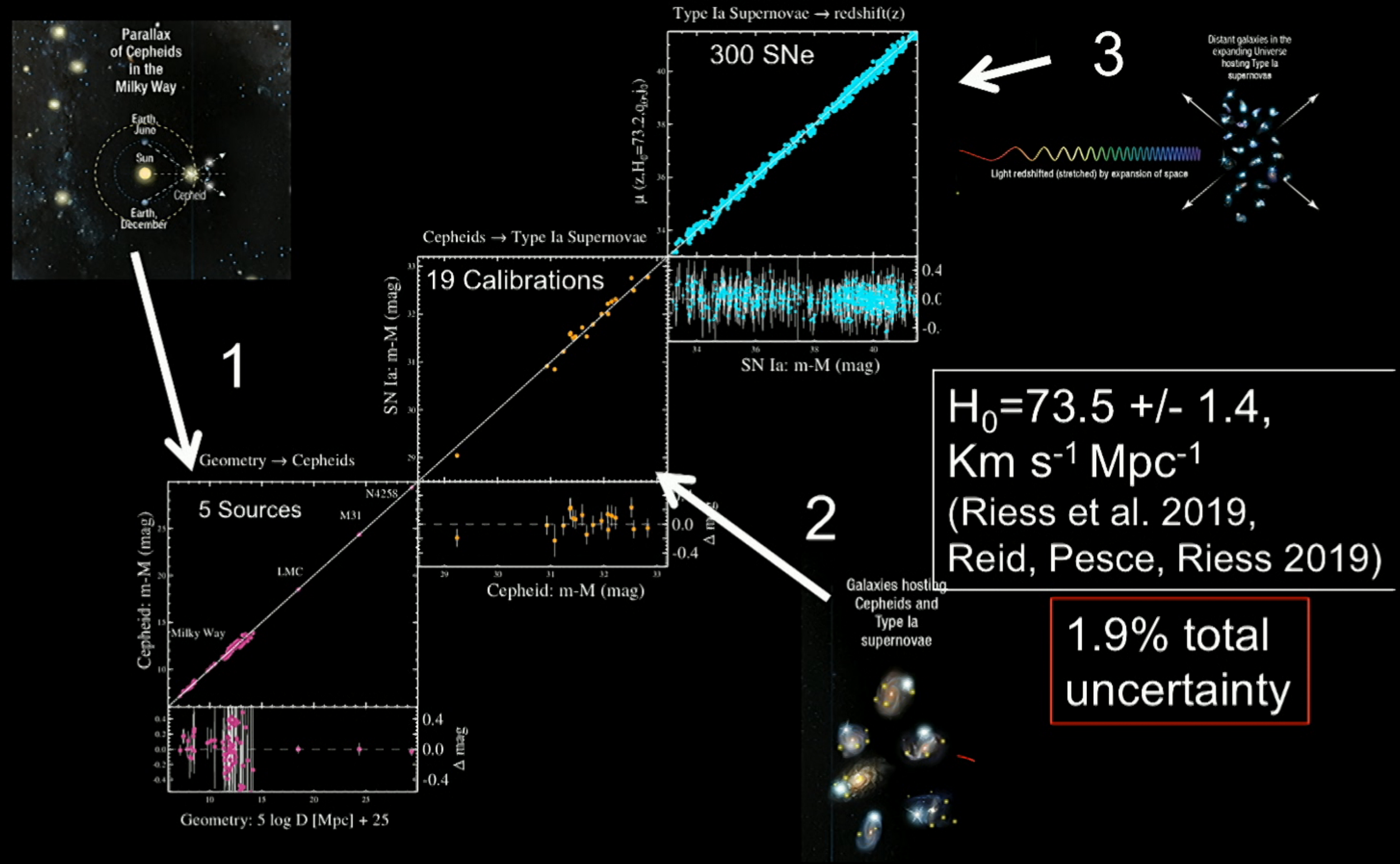
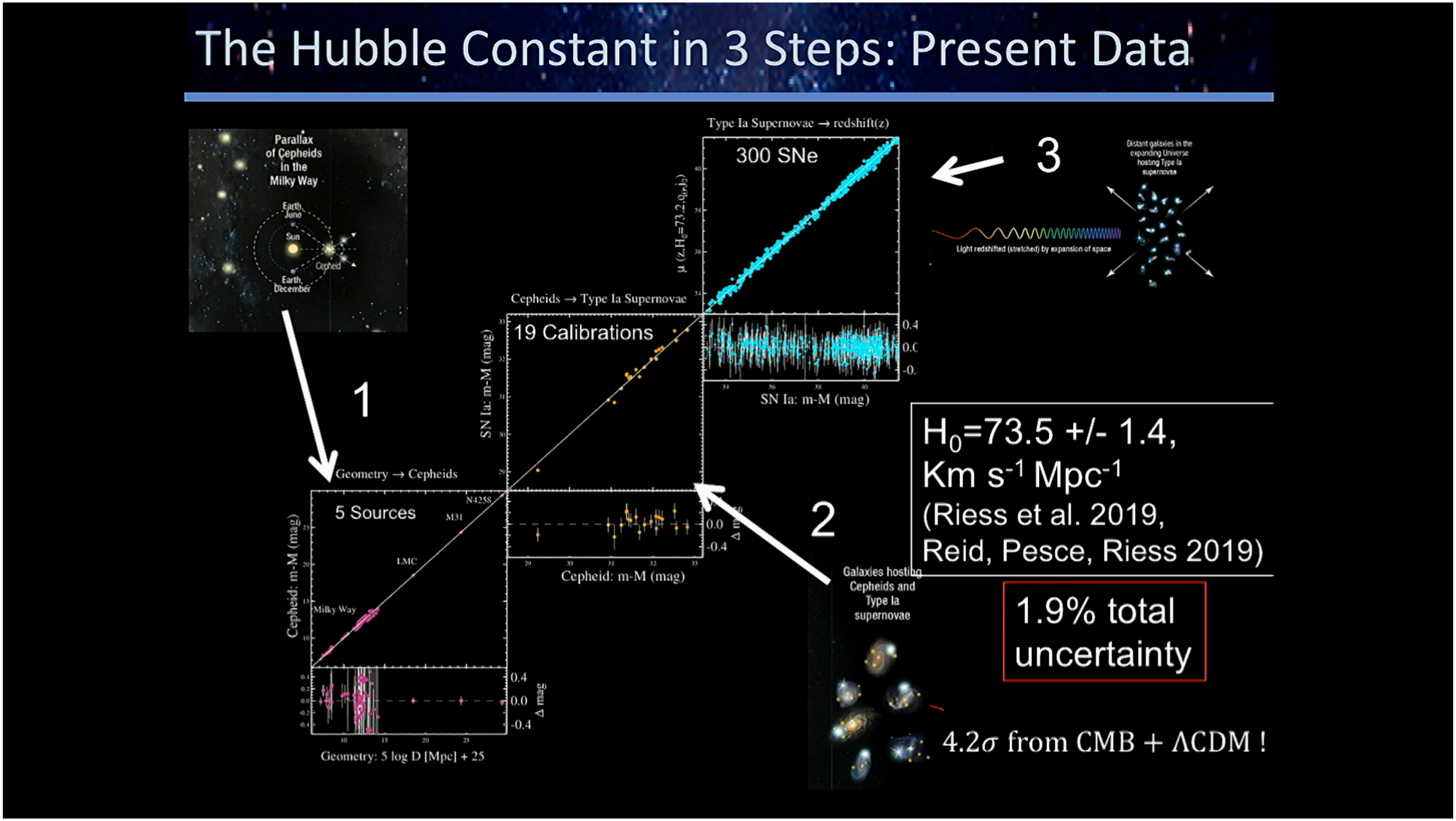


H_0=73.5 +/- 1.4,
Km s^{-1} Mpc^{-1}
(Riess et al. 2019,
Reid, Pesce, Riess 2019)

1.9% total
uncertainty

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

4.2σ from CMB + ΛCDM !

Robust? Five Sources of Cepheid Geometric Calibration

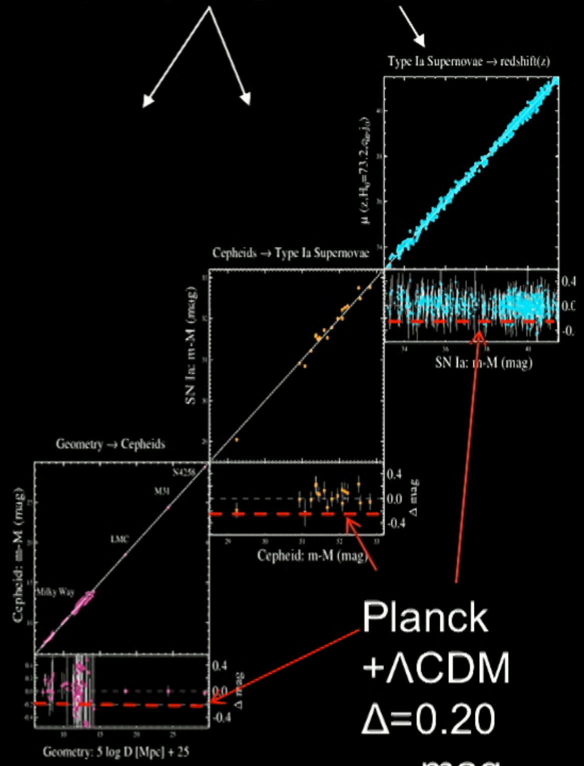
Independent Geometric Source	σ_D	H_0	Δ_{all}
NGC 4258 $H_2$0 Masers: Reid, Pesce, Riess 2019	1.5%	72.0	-1.5±1.1
LMC 20 Detached Eclipsing Binaries: Pietzrynski+ 2019 + 70 HST LMC Cepheids: Riess+(2019)	1.3%	74.2	+0.7±1.0
Milky Way 10 HST FGS Short P Parallaxes: Benedict+2007 --also Hipparcos (Van leeuwen et al 2007)	2.2%	76.2	+2.7±1.6
Milky Way 8 HST WFC3 SS Long P Parallaxes: Riess+ 2018	3.3%	75.7	+2.2±2.4
Milky Way 50 Gaia+HST, Long P Parallaxes: Riess+ 2018	3.3%	73.7	+0.2±2.4

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

Systematics? 23 Analysis Variants—we propagate variation to error

Best Fit:

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

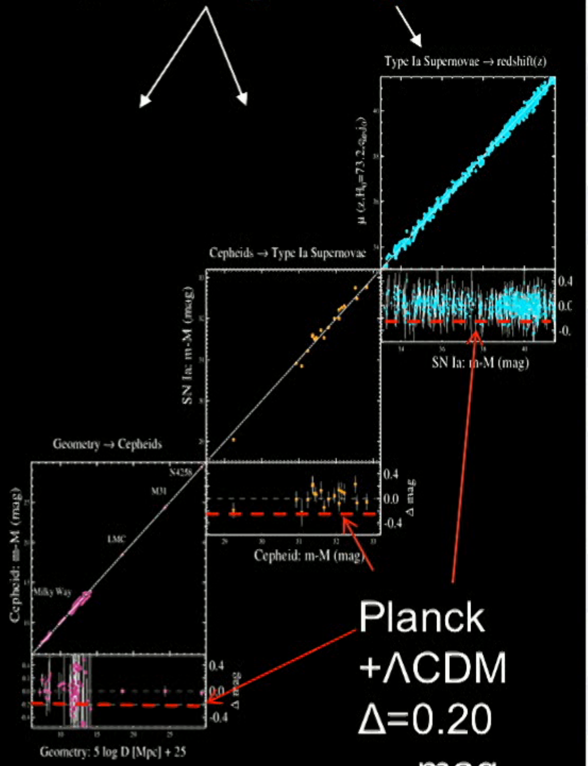


Planck
+ΛCDM
Δ=0.20
mag

Systematics? 23 Analysis Variants—we propagate variation to error

Best Fit:

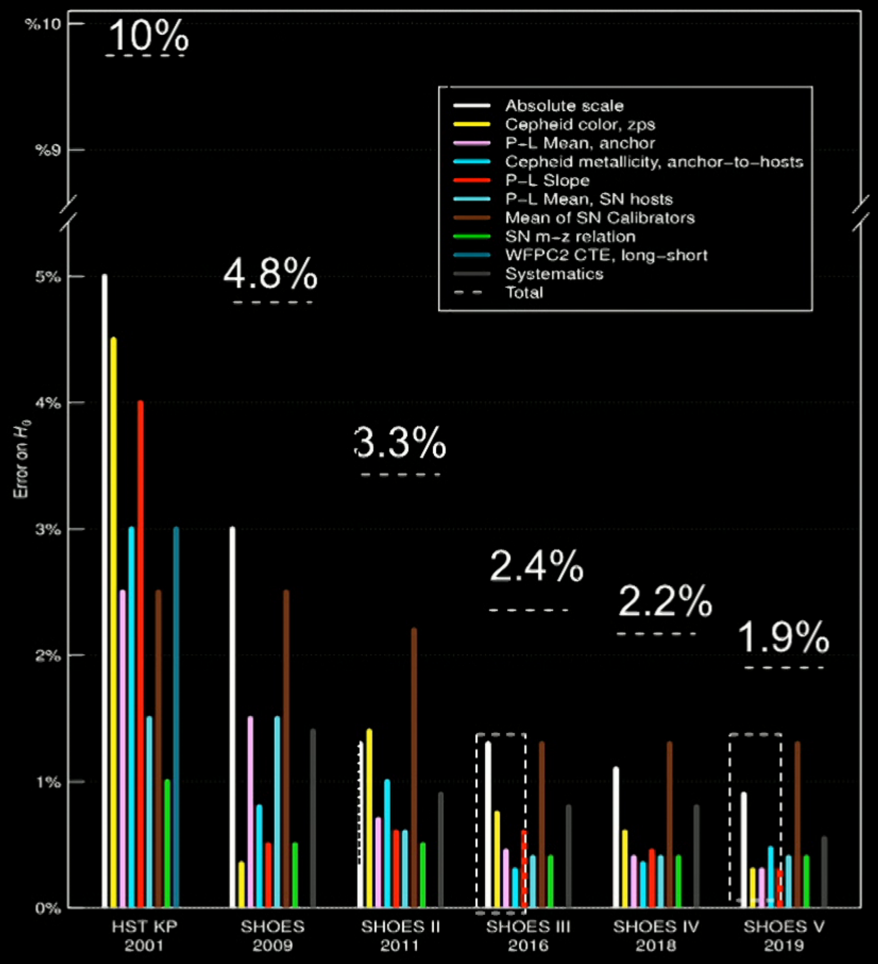
$5\log H_0 = M_B^0 + 5a_B + 25$



Planck +ΛCDM Δ=0.20 mag

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

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

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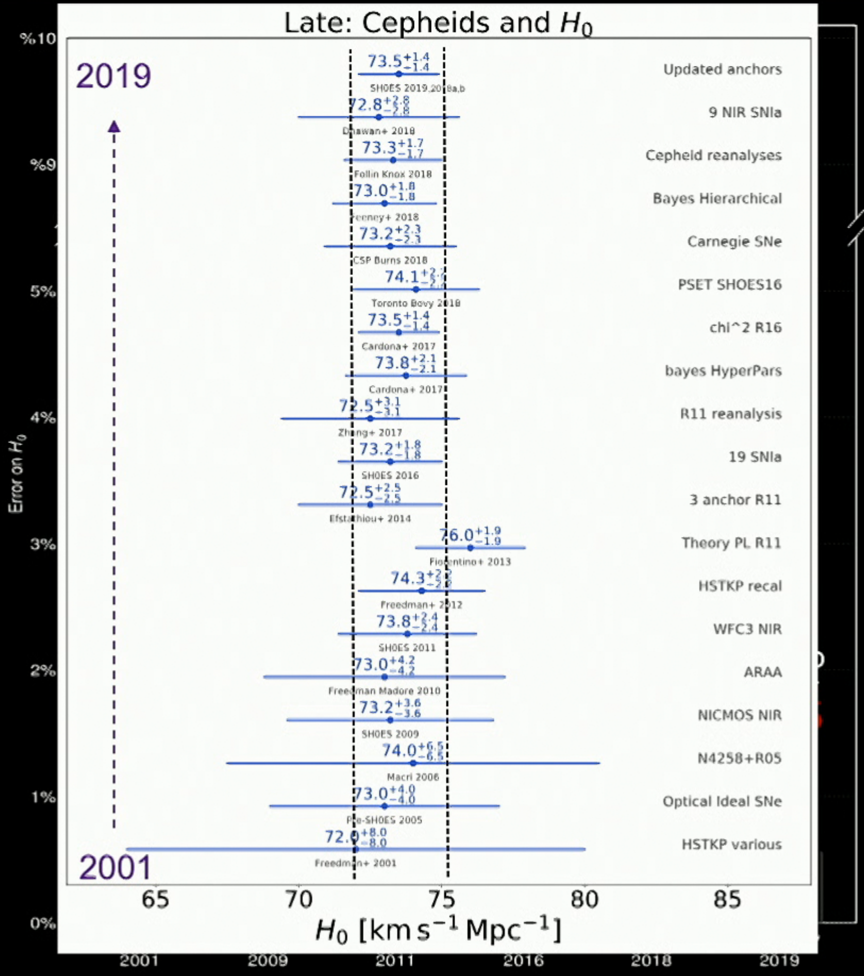

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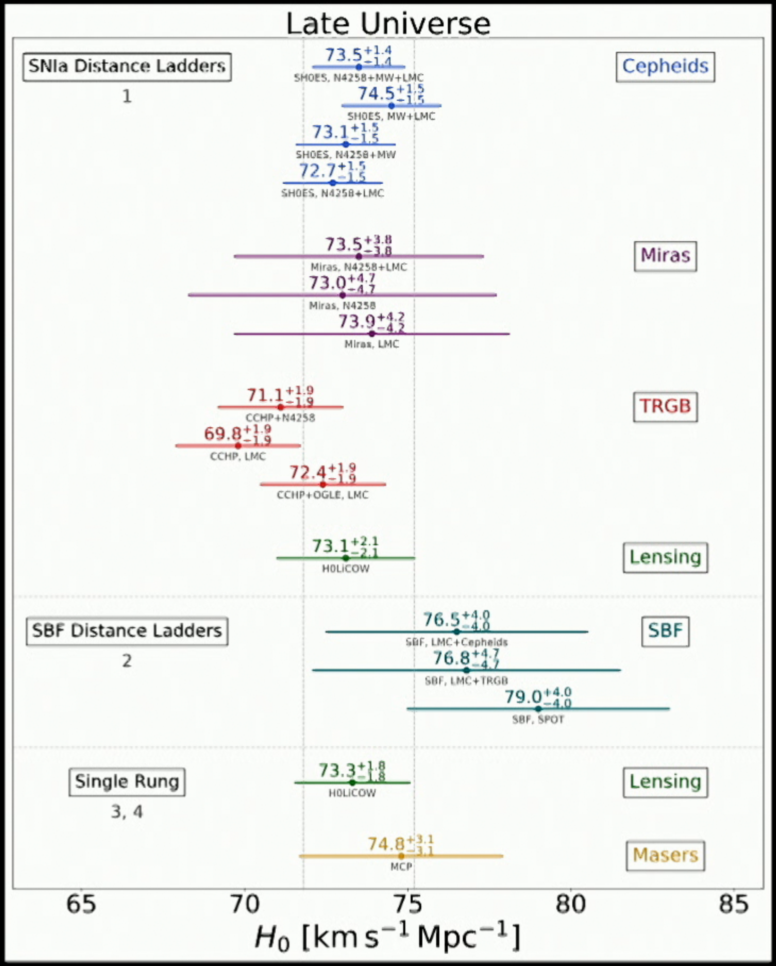
Late Universe H_0

Review by Verde, Treu, Riess (2019)



Naïve Combo: 73 +/- 1 but some covariance so…

Prix Fixe Menu

One from 1 & 2
+3+4+
one peremptory
challenge

Late Universe H_0

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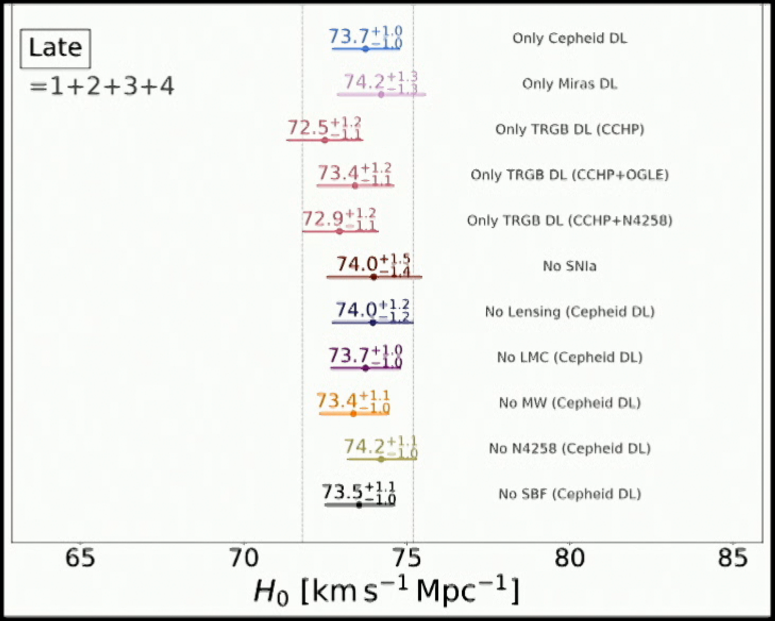

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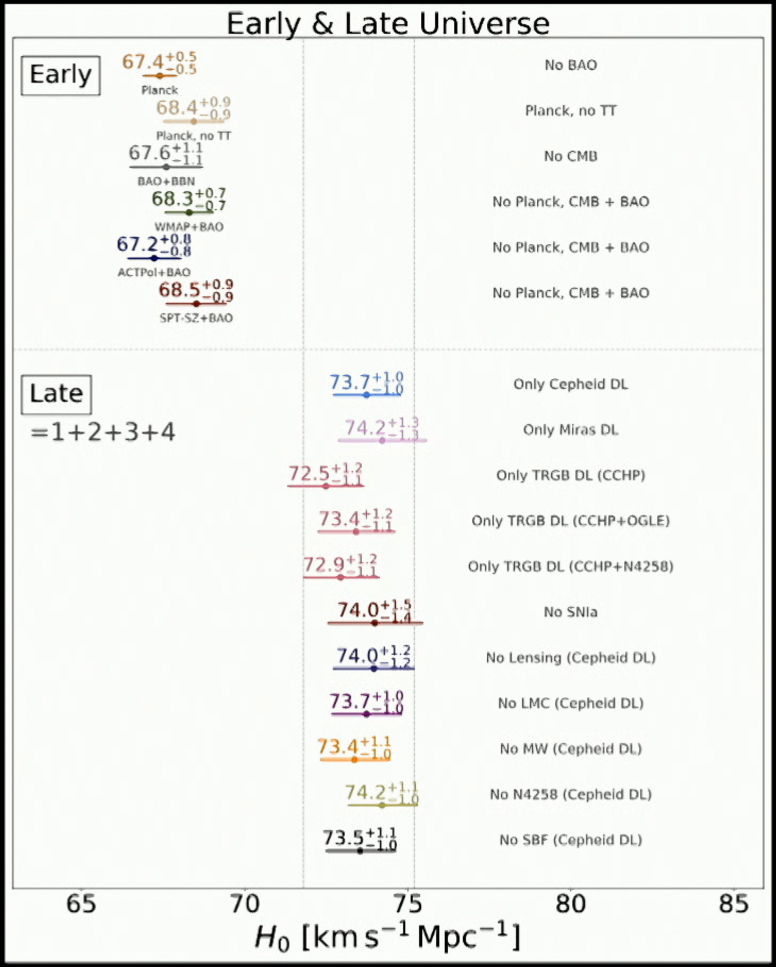

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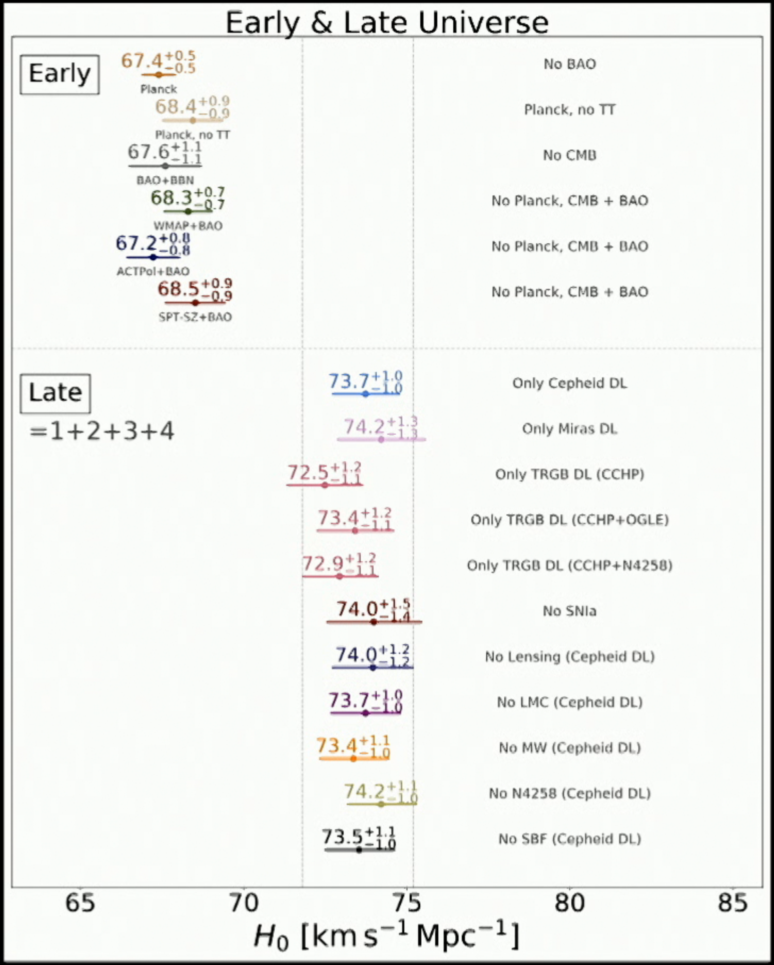

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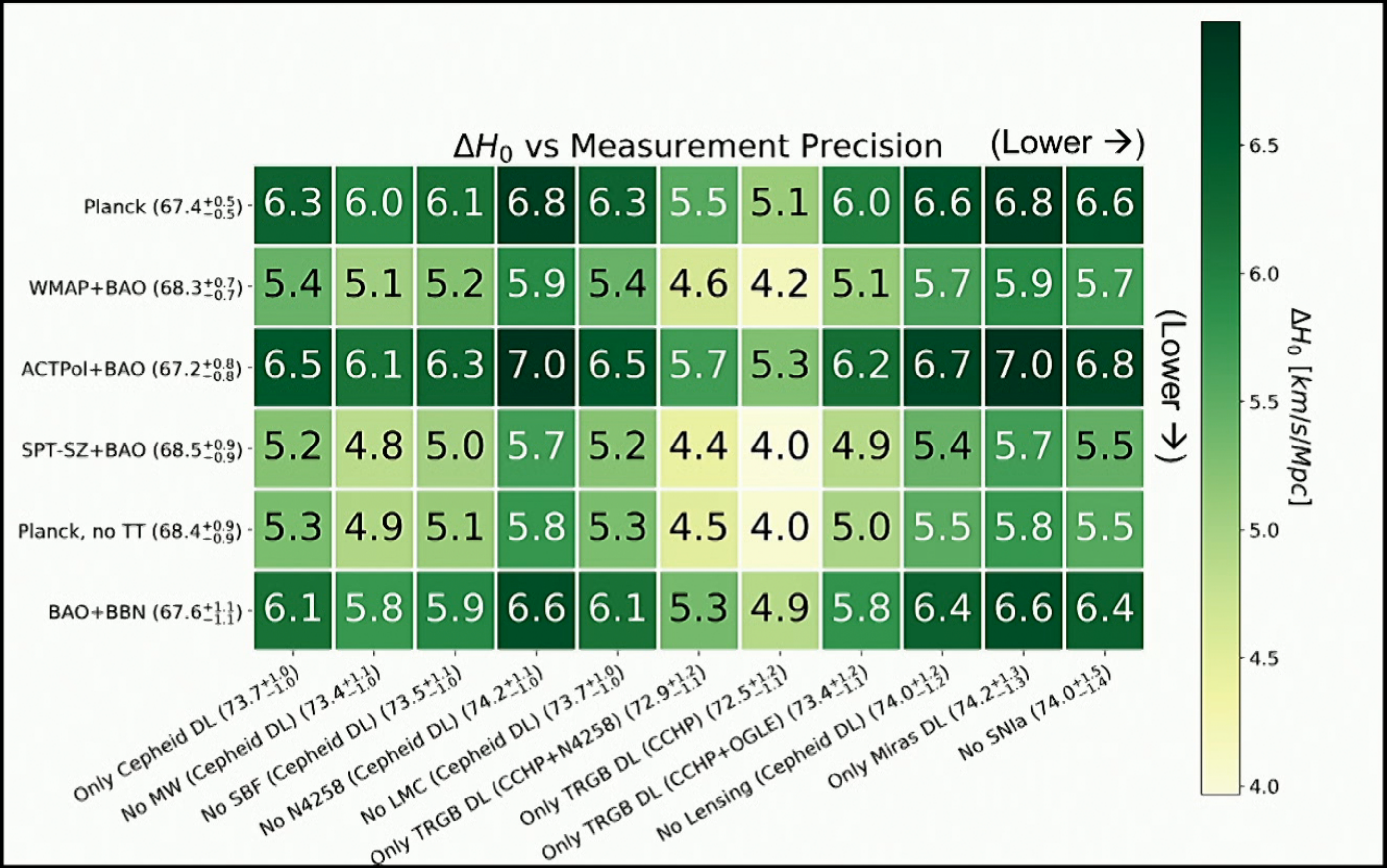
challenge

The Tension Matrix

Review by Verde, Treu, Riess (2019)

E
A
R
L
Y



ΔH_0 vs Measurement Precision (Lower →)

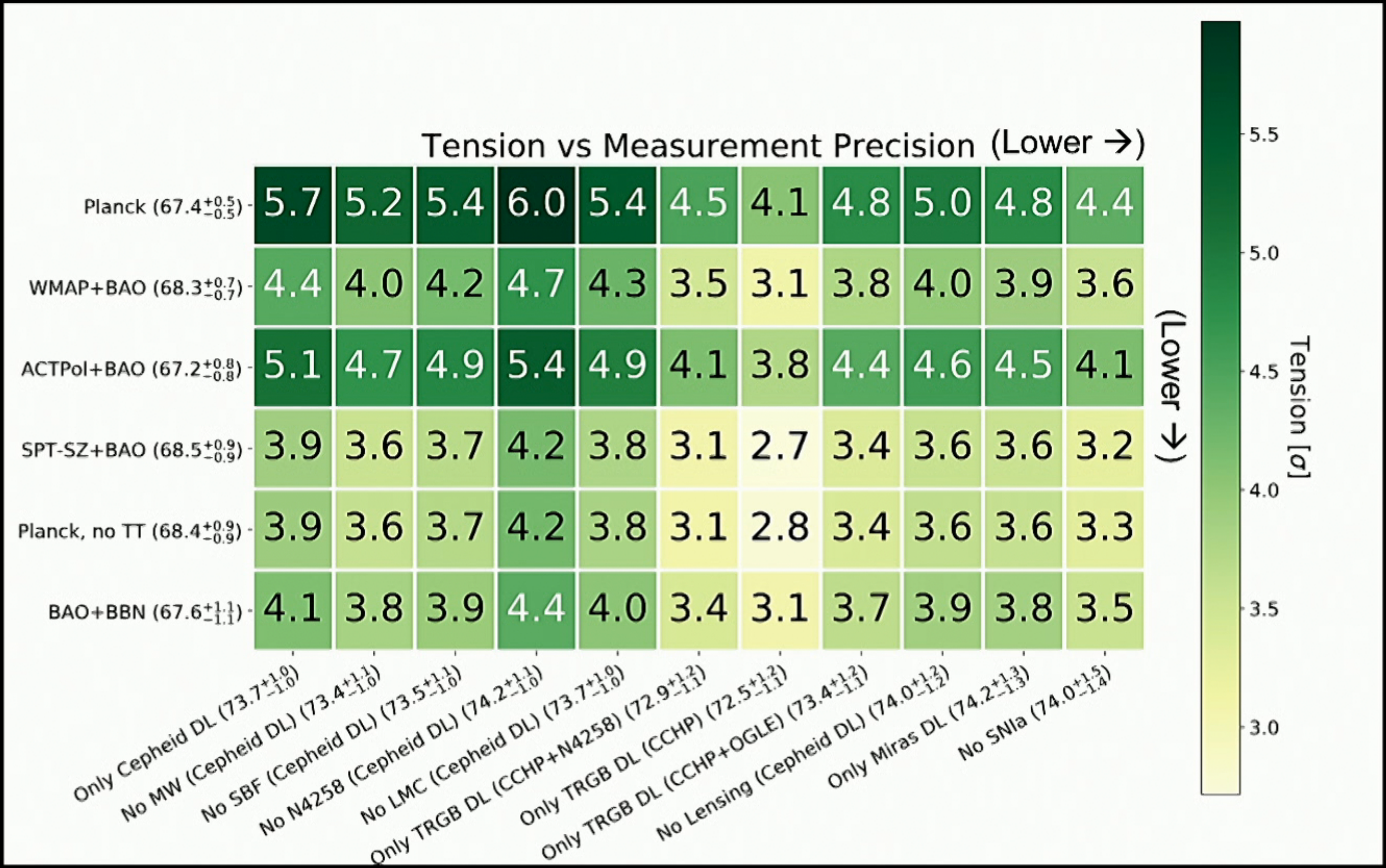
	Only Cepheid DL ($73.7^{+1.0}_{-1.0}$)	No MW (Cepheid DL) ($73.4^{+1.1}_{-1.0}$)	No SBF (Cepheid DL) ($73.5^{+1.1}_{-1.0}$)	No N4258 (Cepheid DL) ($74.2^{+1.1}_{-1.0}$)	No LMC (Cepheid DL) ($73.7^{+1.0}_{-1.0}$)	Only TRGB DL (CCHP+N4258) ($72.9^{+1.2}_{-1.1}$)	Only TRGB DL (CCHP) ($72.5^{+1.2}_{-1.1}$)	Only TRGB DL (CCHP+OGLE) ($73.4^{+1.2}_{-1.1}$)	No Lensing (Cepheid DL) ($74.0^{+1.2}_{-1.2}$)	Only Miras DL ($74.2^{+1.3}_{-1.3}$)	No SNIa ($74.0^{+1.5}_{-1.4}$)
Planck ($67.4^{+0.5}_{-0.5}$)	6.3	6.0	6.1	6.8	6.3	5.5	5.1	6.0	6.6	6.8	6.6
WMAP+BAO ($68.3^{+0.7}_{-0.7}$)	5.4	5.1	5.2	5.9	5.4	4.6	4.2	5.1	5.7	5.9	5.7
ACTPol+BAO ($67.2^{+0.8}_{-0.8}$)	6.5	6.1	6.3	7.0	6.5	5.7	5.3	6.2	6.7	7.0	6.8
SPT-SZ+BAO ($68.5^{+0.9}_{-0.9}$)	5.2	4.8	5.0	5.7	5.2	4.4	4.0	4.9	5.4	5.7	5.5
Planck, no TT ($68.4^{+0.9}_{-0.9}$)	5.3	4.9	5.1	5.8	5.3	4.5	4.0	5.0	5.5	5.8	5.5
BAO+BBN ($67.6^{+1.1}_{-1.1}$)	6.1	5.8	5.9	6.6	6.1	5.3	4.9	5.8	6.4	6.6	6.4

LATE UNIVERSE

The Tension Matrix

Review by Verde, Treu, Riess (2019)

EARLY



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ACTPol+BAO ($67.2^{+0.8}_{-0.8}$)	5.1	4.7	4.9	5.4	4.9	4.1	3.8	4.4	4.6	4.5	4.1
SPT-SZ+BAO ($68.5^{+0.9}_{-0.9}$)	3.9	3.6	3.7	4.2	3.8	3.1	2.7	3.4	3.6	3.6	3.2
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LATE UNIVERSE

The Tension Matrix

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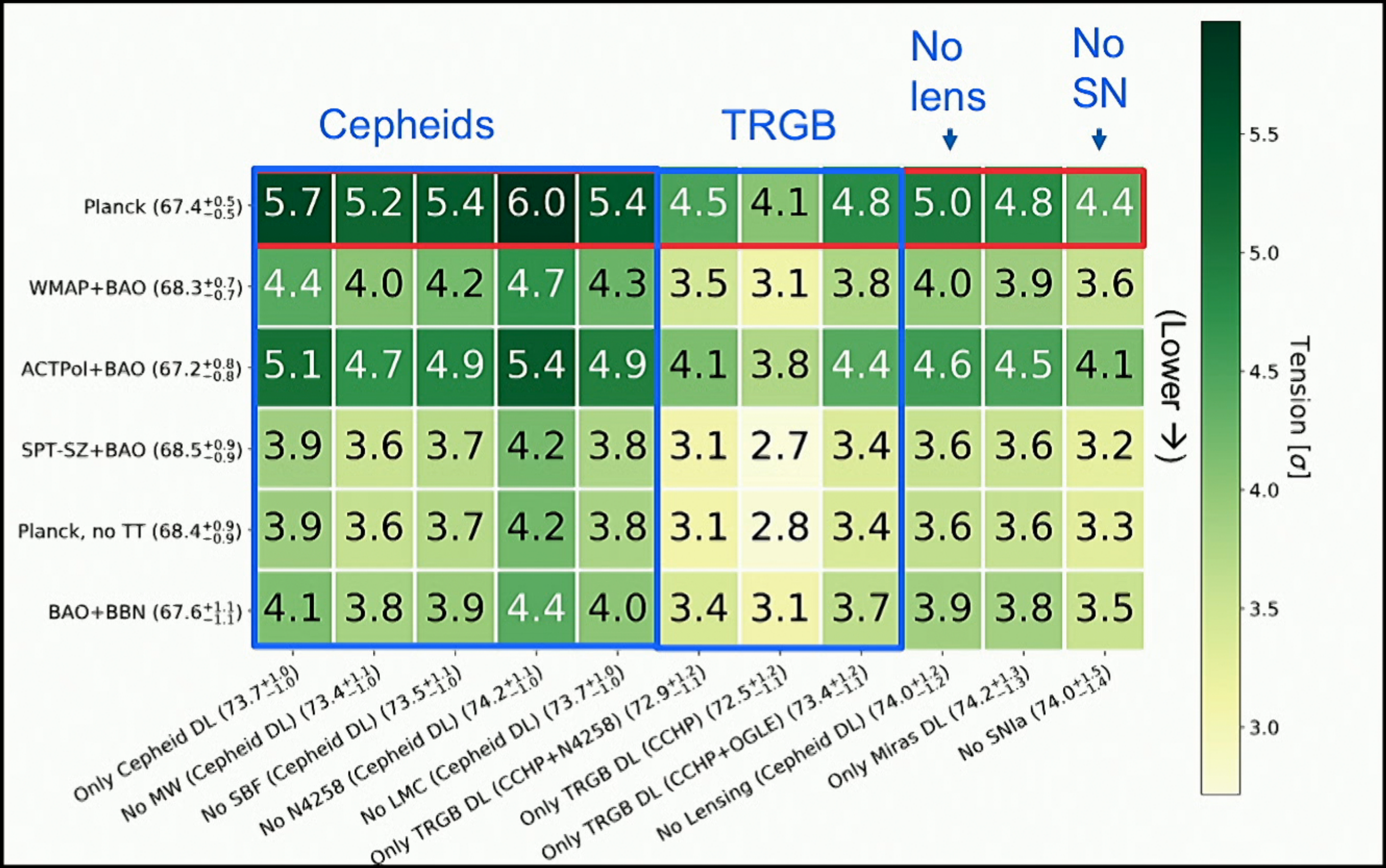

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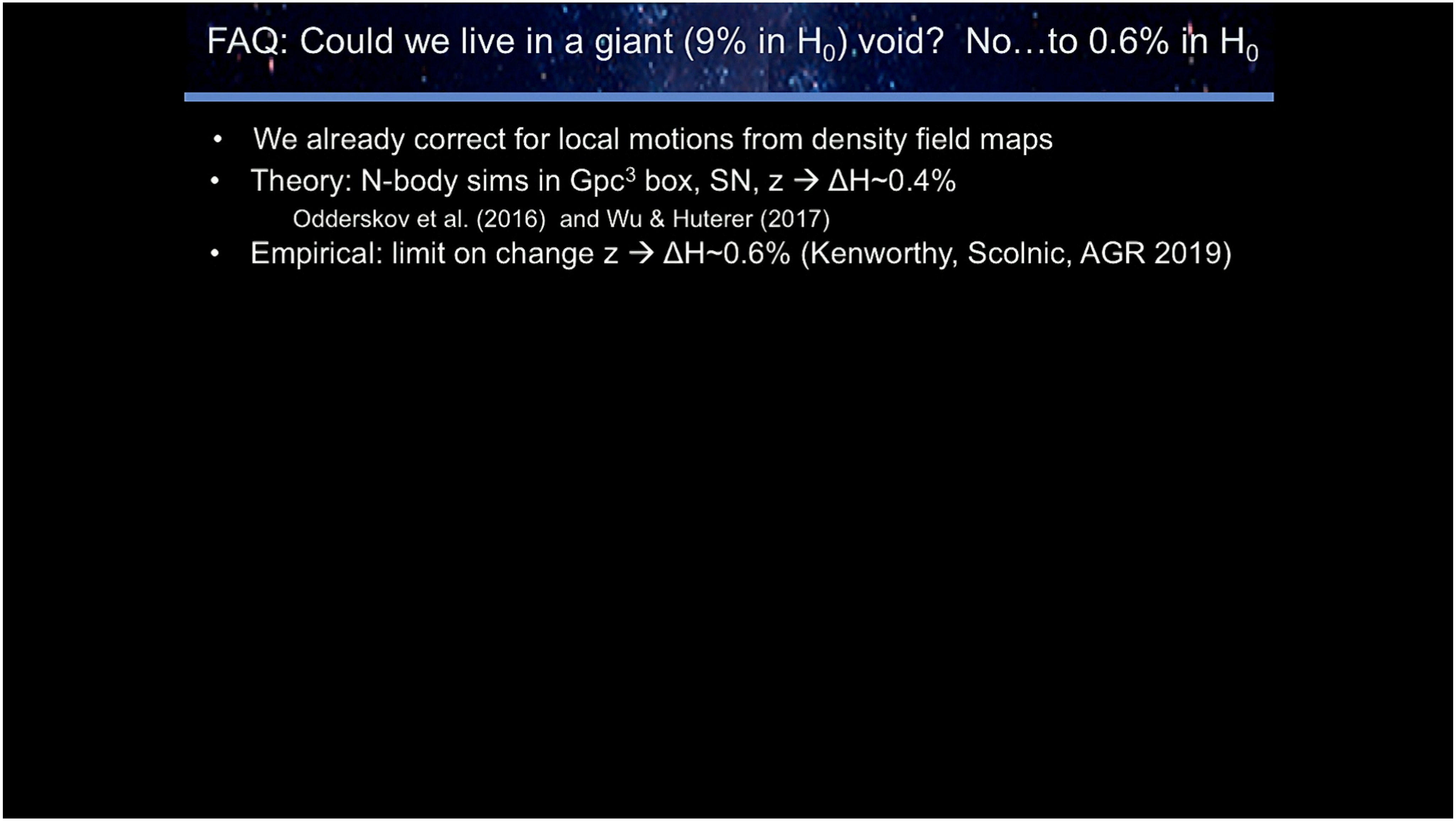
EARLY

LATE UNIVERSE



FAQ: Could we live in a giant (9% in H_0) void? No…to 0.6% in H_0

- We already correct for local motions from density field maps
- Theory: N-body sims in Gpc^3 box, SN, z → $\Delta H \sim 0.4\%$
  Odderskov et al. (2016) and Wu & Huterer (2017)
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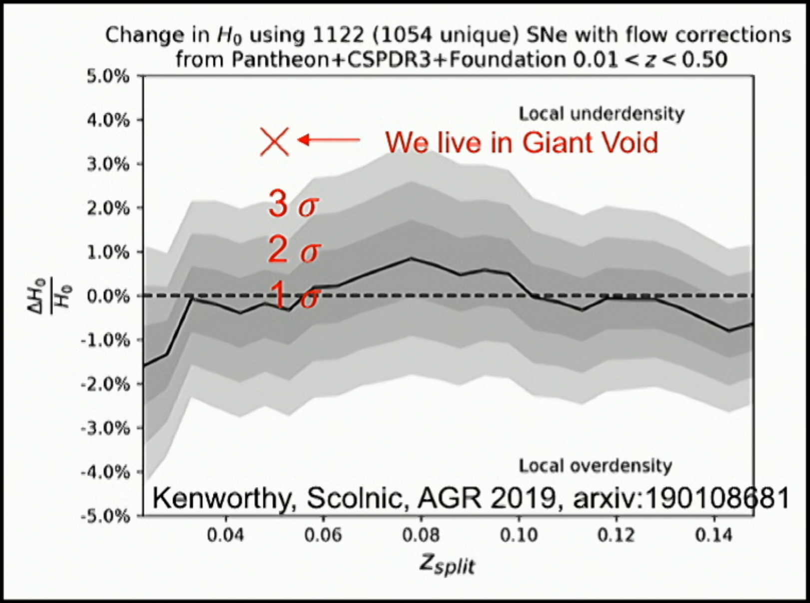
Planck=+9% ↑



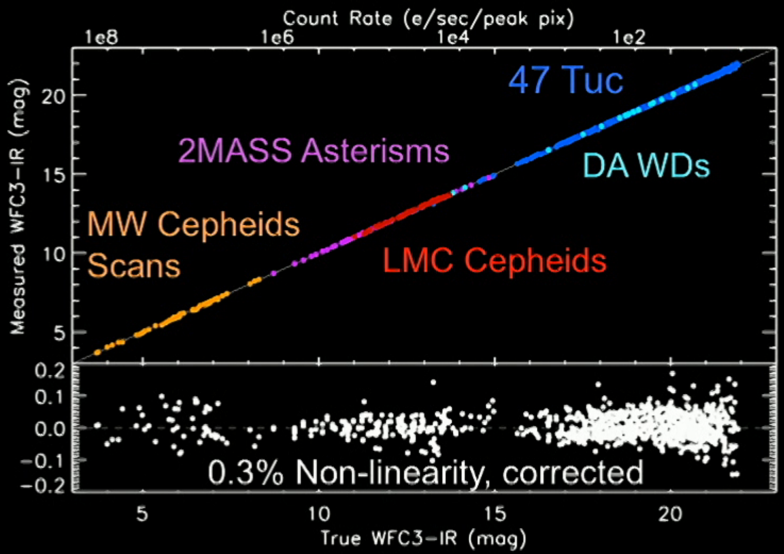
Change in H_0 using 1122 (1054 unique) SNe with flow corrections from Pantheon+CSPDR3+Foundation $0.01 < z < 0.50$

Kenworthy, Scolnic, AGR 2019, arxiv:190108681

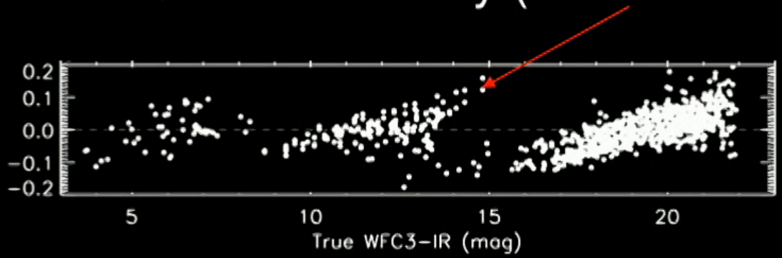
Suggestion we live in 3.5% H_0 void (z<0.07; KBC 2013, Shanks et al. 2018), SN data rejects 4.5 σ

FAQ: Is HST WFC3-IR Flux Scale Linear to 1%?

“Flux Calibration Ladder”



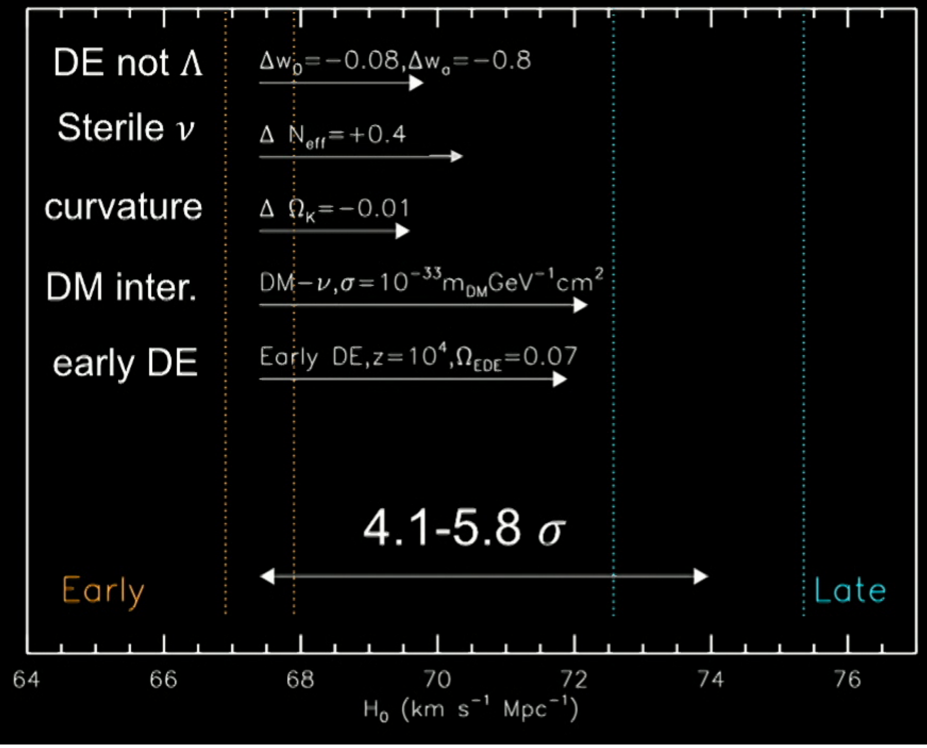
if 3.0% Non-linearity (NIC2 F110W)



Cause of Early vs Late Difference?

"Combining independent approaches in the late universe yields tension with the early Universe…4.1σ and 5.8σ…discrepancy not dependent on any one method, team, or source." July 15-17, 2019 KITP @ UCSB
Verde, Treu, Riess, arxiv:190710625

NEW
PHYSICS



“Most Likely”: Increasing Expansion Rate Pre-recombination

“The Hubble Hunter’s Guide”, Knox and Millea, 2019

Best--New components increase H(z) before recombination (scalar fields, Neutrinos+interactions) →earlier recombination, lower sound horizon. New features in CMB (excess scatter in ω_m vs scale). Claims of better fit to CMB (not worse!) Poulin+2018, Agrawal+2019, Lin+2019, Kreisch+2018

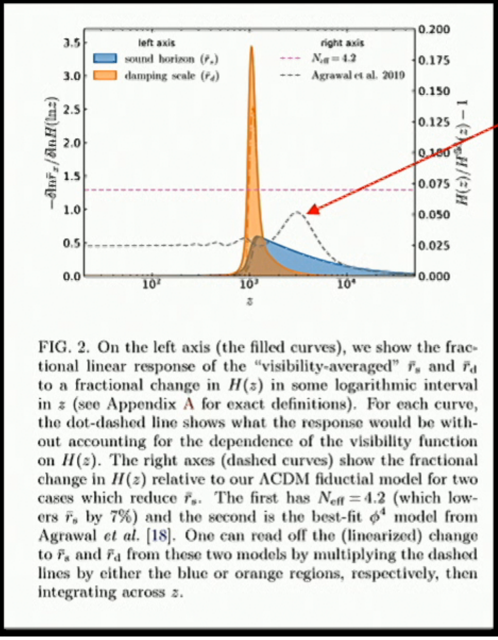


FIG. 2. On the left axis (the filled curves), we show the fractional linear response of the “visibility-averaged” $\bar{r}_s$ and $\bar{r}_d$ to a fractional change in $H(z)$ in some logarithmic interval in z (see Appendix A for exact definitions). For each curve, the dot-dashed line shows what the response would be without accounting for the dependence of the visibility function on $H(z)$. The right axes (dashed curves) show the fractional change in $H(z)$ relative to our ΛCDM fiducial model for two cases which reduce $\bar{r}_s$. The first has $N_{\rm eff} = 4.2$ (which lowers $\bar{r}_s$ by 7%) and the second is the best-fit ϕ^4 model from Agrawal *et al.* [18]. One can read off the (linearized) change to $\bar{r}_s$ and $\bar{r}_d$ from these two models by multiplying the dashed lines by either the blue or orange regions, respectively, then integrating across z.

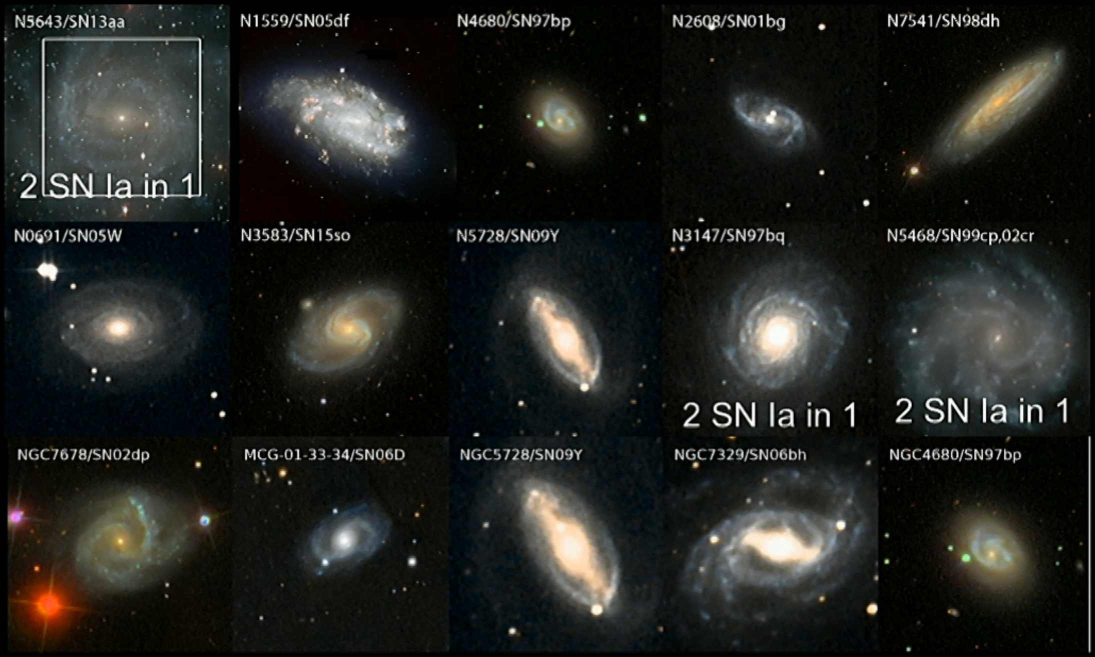
Scalar field
Dark energy
Increases
Expansion, lowers
Sound horizon

Next Steps: Increasing Number of SN-Cepheid Calibrations

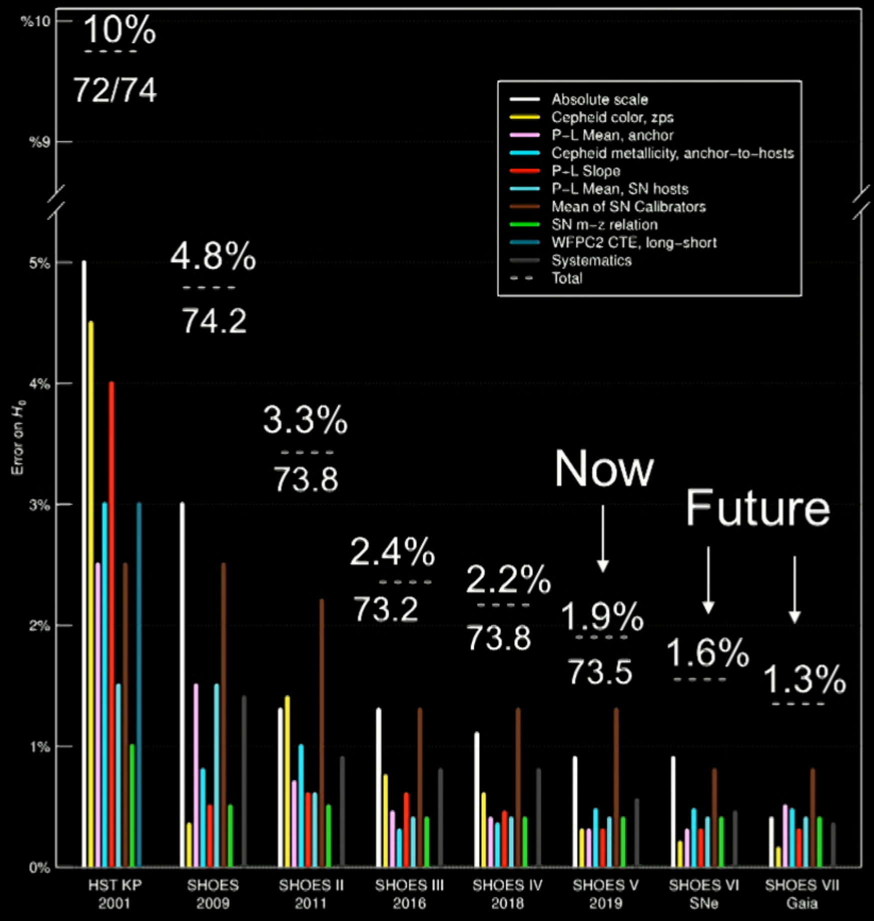
NEW SHOES Large HST Programs, Cycles 25,26

19 more Cepheid-SN Ia Calibrators underway,

to reach total=38



Future Prospects…



- **New low-z SN samples**
- **Doubling SN Calibrator sample, 19→38 (2019?)**
- **Gaia DR3 (2020?)**
- LIGO H_0 (Late Universe)
- DESI,LSST,WFIRST,Euclid →better w(z)
- Next generation CMB: signatures (e.g., EDE)
- Stay tuned…

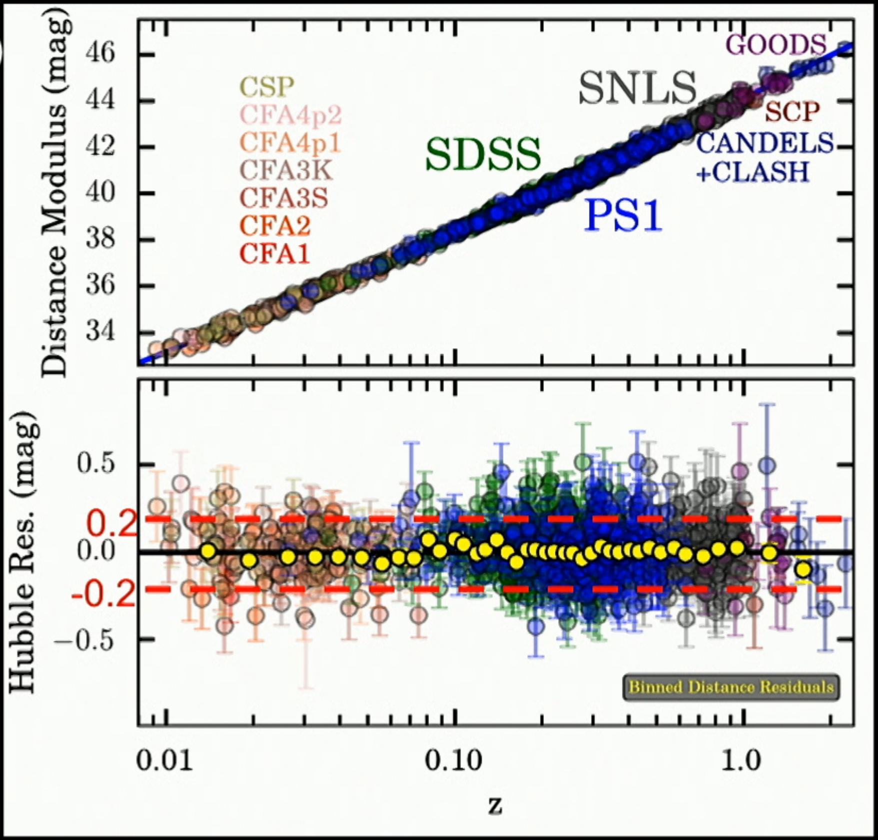
H_0 is easier than q_0

SN Ia Hubble diagram

(Pantheon Set-Scolnic et al 2018)

0.01<z<2, 1100 Sne Ia

ΛCDM residuals <0.04 mag

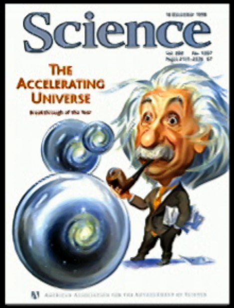


Breakthroughs When Local H_0 was too high. This time?

1930-1950:

$H_0 > 300$ km s^{-1} Mpc^{-1} → t_0 ~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:

$H_0 = 73.5 +/- 1.4 \rightarrow 4.1-5.8\sigma$ higher than Planck CMB+ΛCDM ?

What will be discovered ?

Takeaways

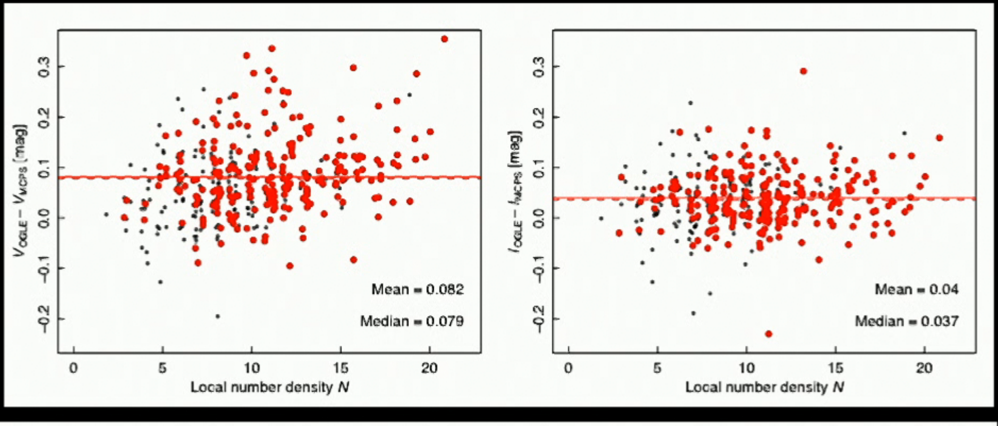
- Universe now appears to be expanding ~9% (+/- 2%) faster-than-expected based ΛCDM+Planck CMB. Confidence=~5 σ Many crosschecks, not dependent on source, method, Team

- If not conspiracy of errors, could be a *clue* pertaining to the 95% of the Universe (i.e., the dark sector) we don't understand. (& Universe younger, ~13 Gyr not ~14 Gyr)

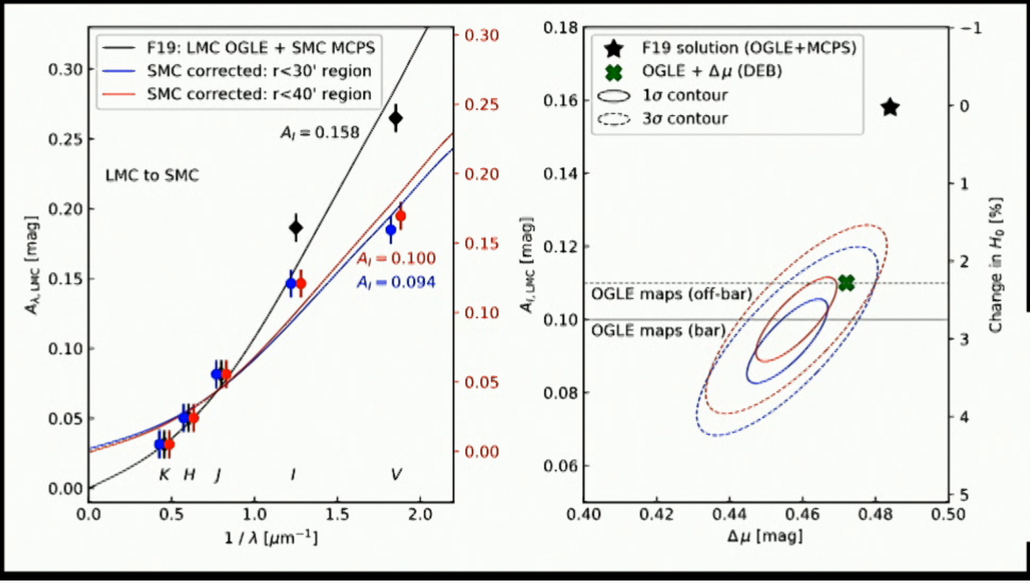
- We anticipate significant improvements in these measurements in just the next few years which may reveal the cause.

- With additional measurements HST and Gaia can approach a 1% measurement of H_0, a benchmark for constraining the cosmological model. More CMB, LIGO, etc.

Yuan et al, arxiv: 1908.00993



MCPS (Zaritsky et al 2002)
And OGLE III (Udalski et al 2012)
differ by 0.04 mag I, 0.08 mag V
Mostly due to blending
Biases LMC extinction by 0.06 mag



OGLE Reddeing Maps