Tension between the early and the late Universe on the Hubble constant measurements

lucas macri, on behalf of
the SH_0ES team (PI: adam riess)

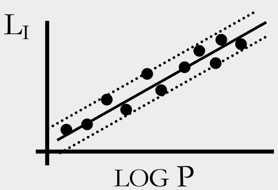
George P. & Cynthia Woods Mitchell Institute
for Fundamental Physics & Astronomy

Department of Physics & Astronomy
College of Arts & Sciences
Texas A&M University

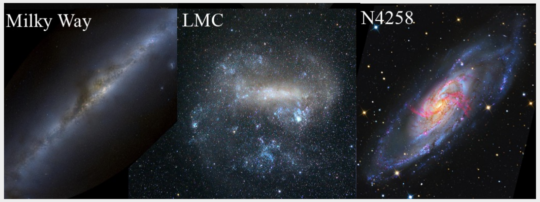
TEXAS A&M UNIVERSITY

SH$_0$ES DISTANCE LADDER

$H_0 = v/d$



"ANCHOR" GALAXIES

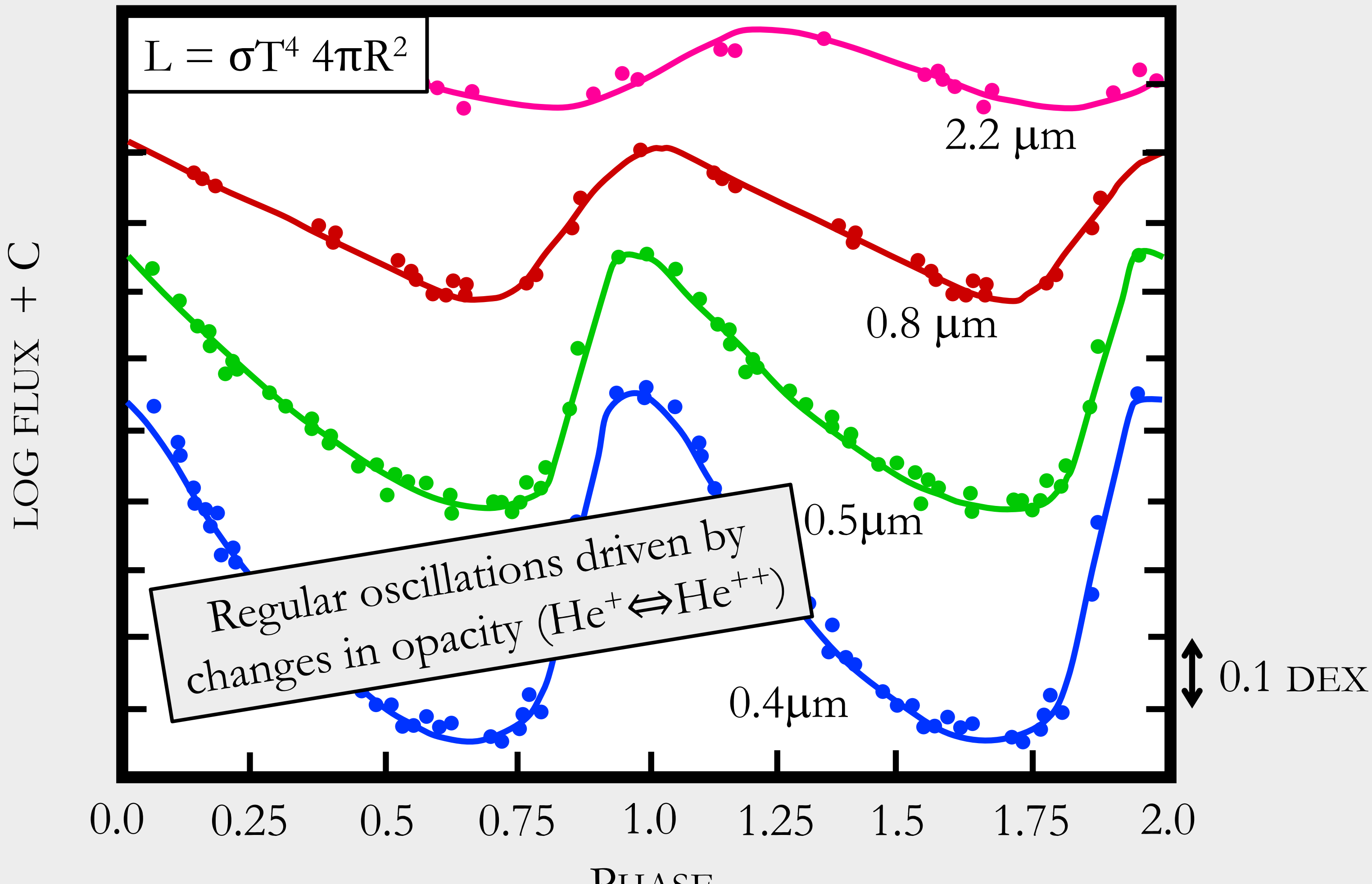


WELL-CHARACTERIZED CEPHEID SAMPLES

ACCURATE & PRECISE DISTANCES

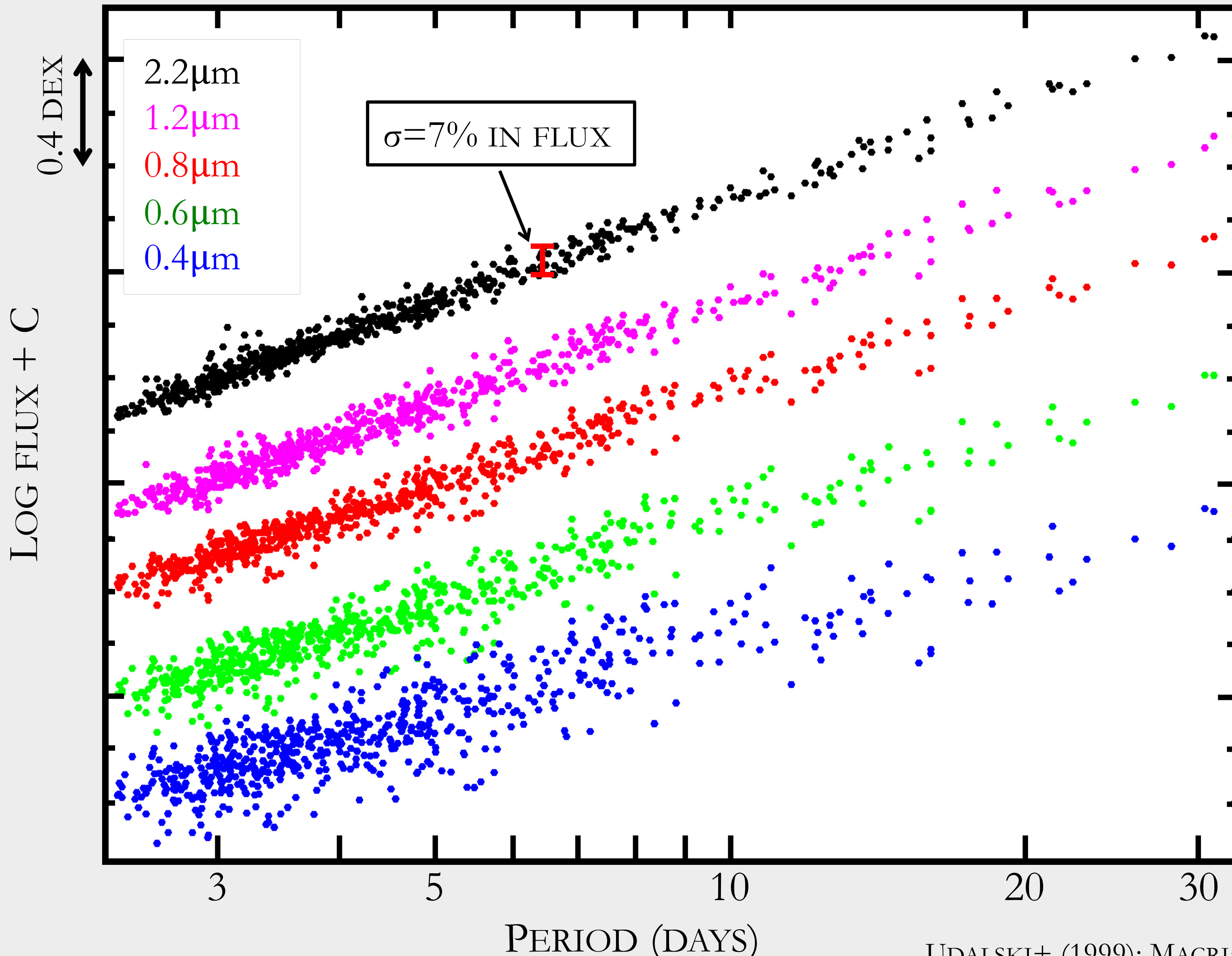
“Light curve” of a Cepheid

Brief (1% of lifetime, $10^{3\text{-}5}$ yrs) phase of stellar evolution for stars with masses ~4−15 $M_\odot$; regular pulsations with P~2−100d



after Madore & Freedman (1991)

"Leavitt law" in the LMC

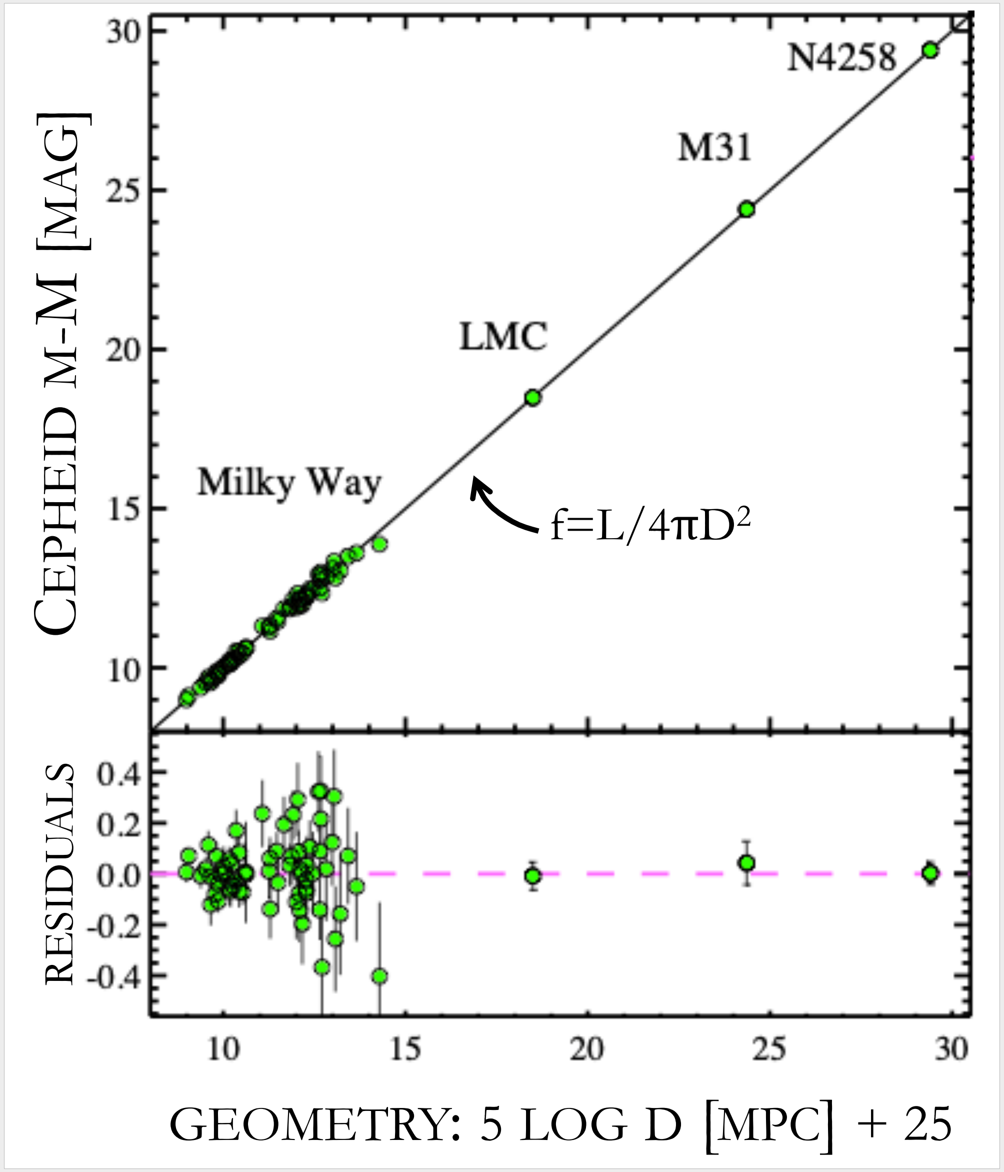


Udalski+ (1999); Macri+ (2015)

CEPHEID LUMINOSITIES

- Absolute calibration: several independent geometrical methods
- Trigonometric parallaxes to 75 Milky Way Cepheids **1.0%**
  - Sample will further increase and improve thanks to *Gaia*
- Distance to Large Magellanic Cloud (>1000 Cepheids) **1.3%**
  - Based on tight relation between flux density per unit angular area and surface temperature of stars
- Distance to galaxy Messier 106 (>600 Cepheids) **1.5%**
  - Based on near-Keplerian motions of water maser clouds orbiting supermassive black hole at galaxy center

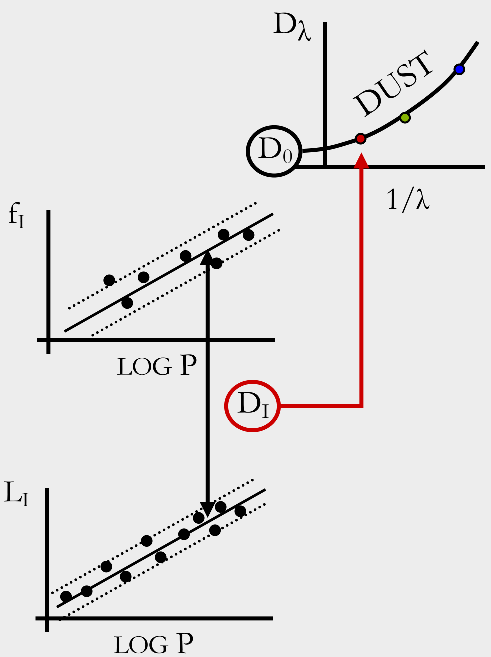
Cepheid luminosities



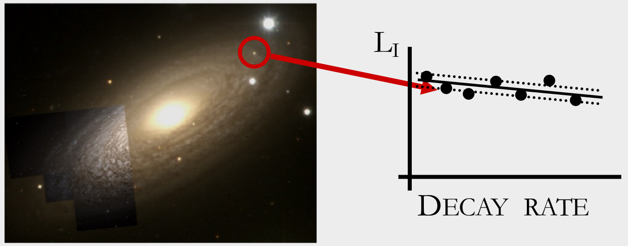
Riess, Yuan, Macri+ (2022)

SH_0ES DISTANCE LADDER

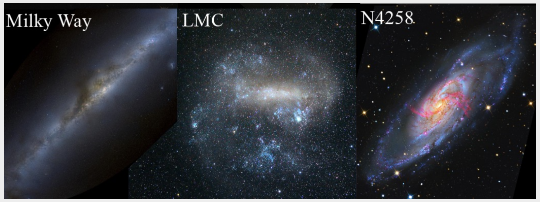
$H_0 = v/D$



SN host galaxies
(D<50 Mpc)



"Anchor" galaxies



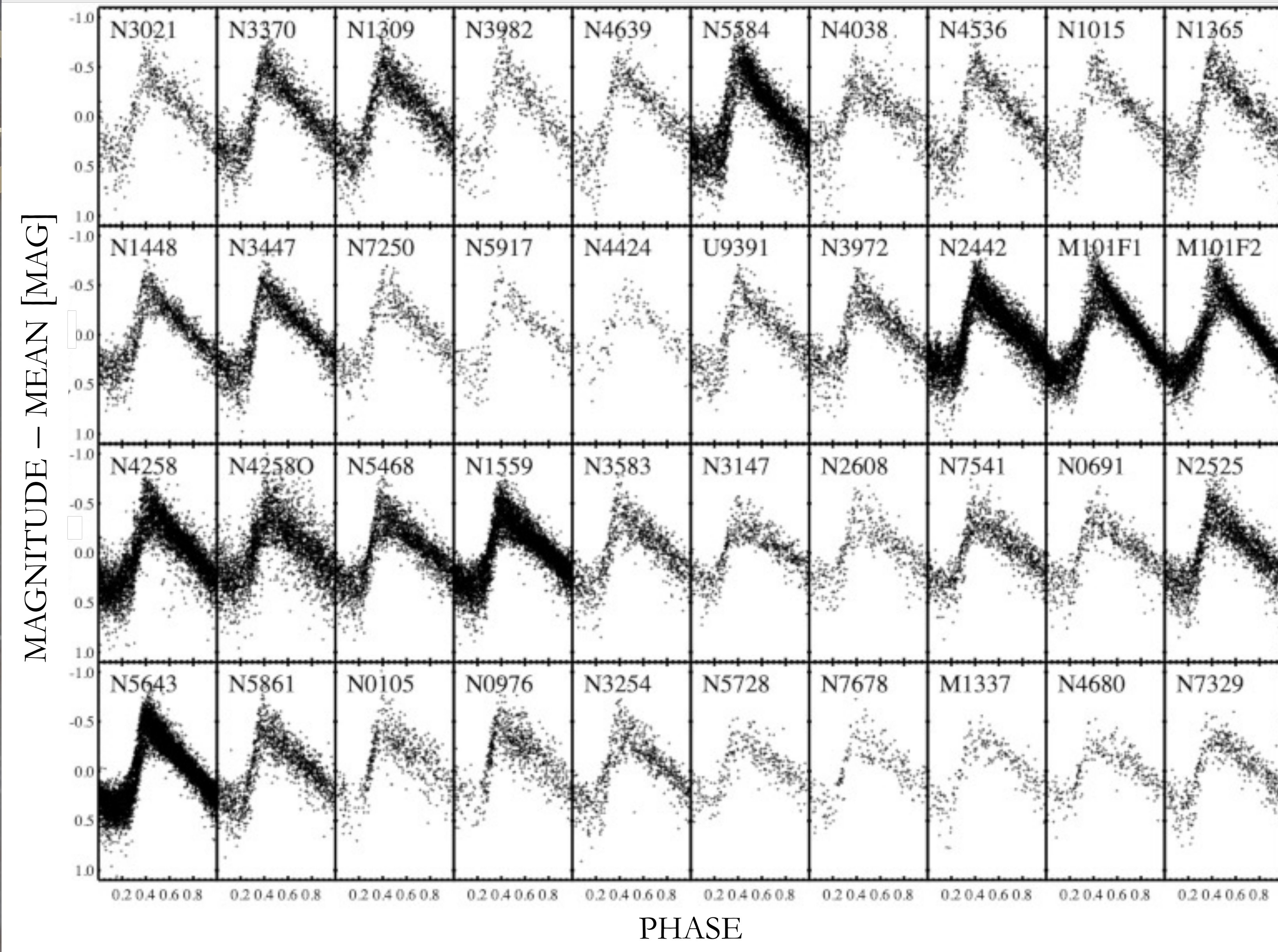
Well-characterized Cepheid samples

Accurate & precise distances

SH$_0$ES ANCHORS & SN HOST GALAXIES

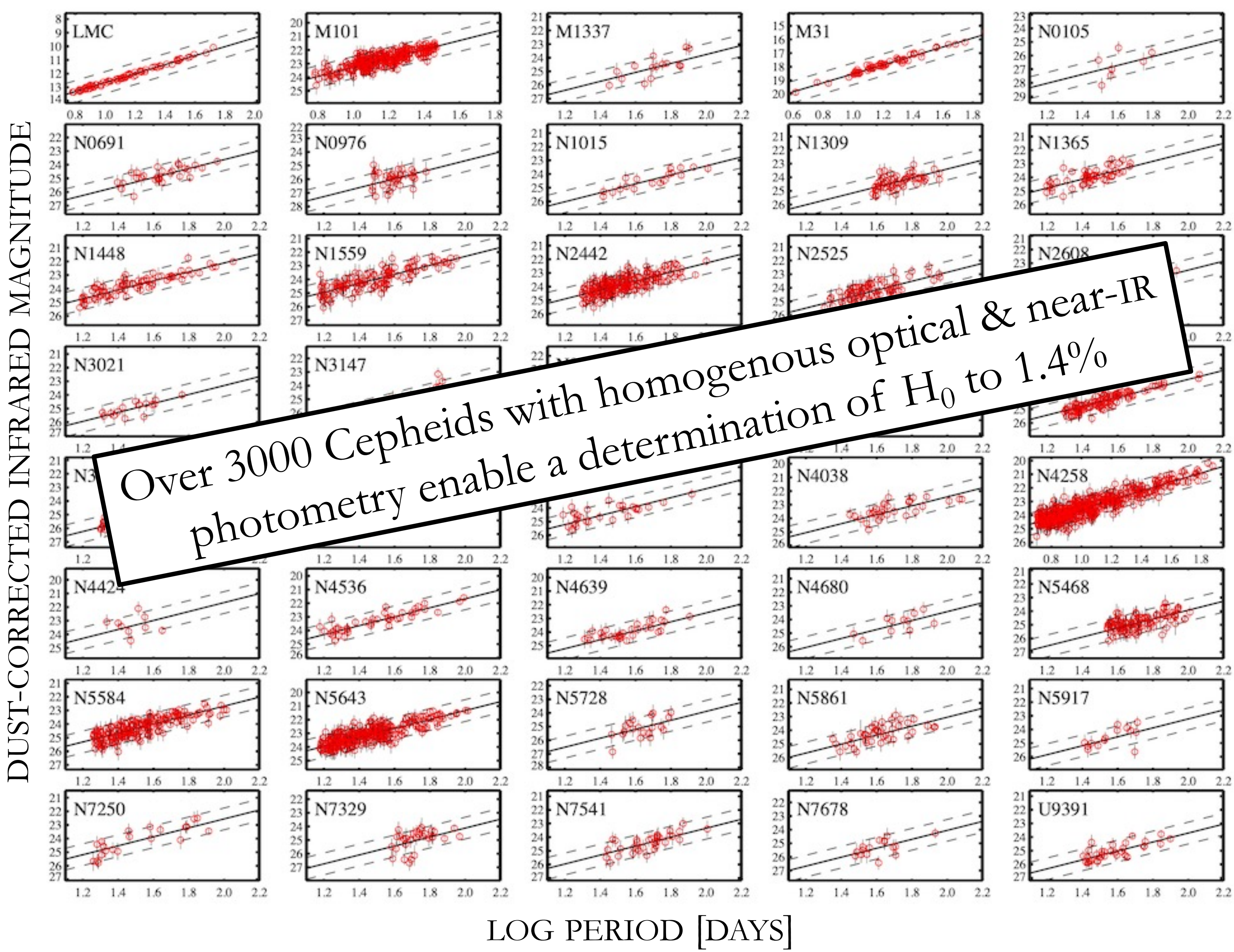
RIESS, YUAN, MACRI+ (2022)

SH$_0$ES Cepheid light curves



Riess, Yuan, Macri+ (2022)

SH$_0$ES "LEAVITT LAWS"

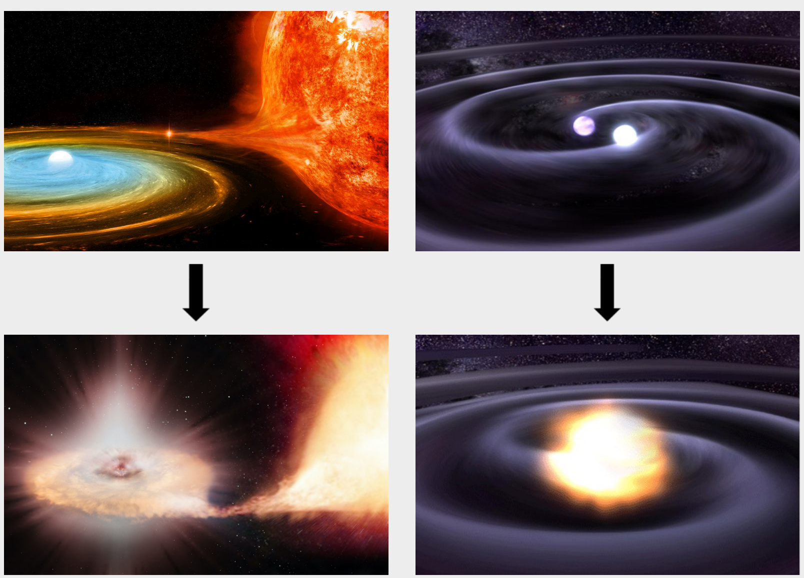


Over 3000 Cepheids with homogenous optical & near-IR photometry enable a determination of H$_0$ to 1.4%

RIESS, YUAN, MACRI+ (2022)

WHITE DWARF (IA) SUPERNOVAE

- Earth-sized degenerate C/O stellar core reaches $\sim 1.4 M_{\odot}$
  - Nature of "progenitor" unknown (2 white dwarfs, 1 white dwarf + giant)
  - $T_{max} > 5 \times 10^9$ K → nuclear statistical equilibrium → $\sim 0.4\ M_{\odot}\ {}^{56}Ni$
- Excellent secondary distance indicator (single SN → ±7%)
  - Based on empirically-determined corrections to light curve



NASA/CXC/Texas Tech/T. Maccarone; NASA/CXC/M. Weiss
ESA/C. Carreau; NASA/GSFC/T. Strohmayer; NASA/CXC/D. Berry

NASA/ESA/High-Z Supernova Search Team

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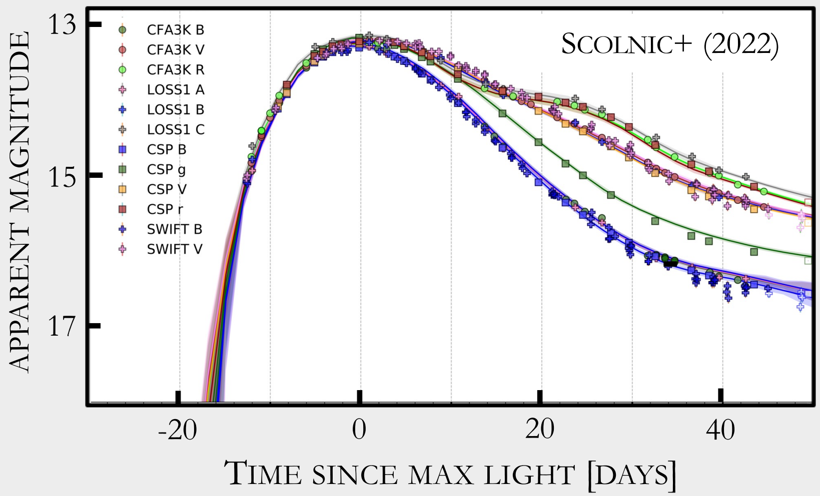
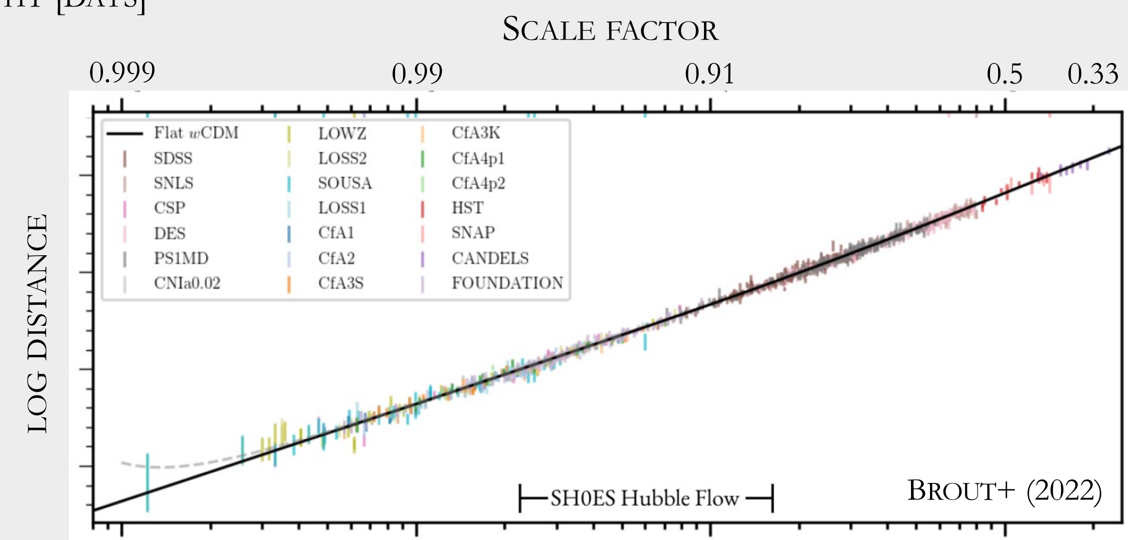
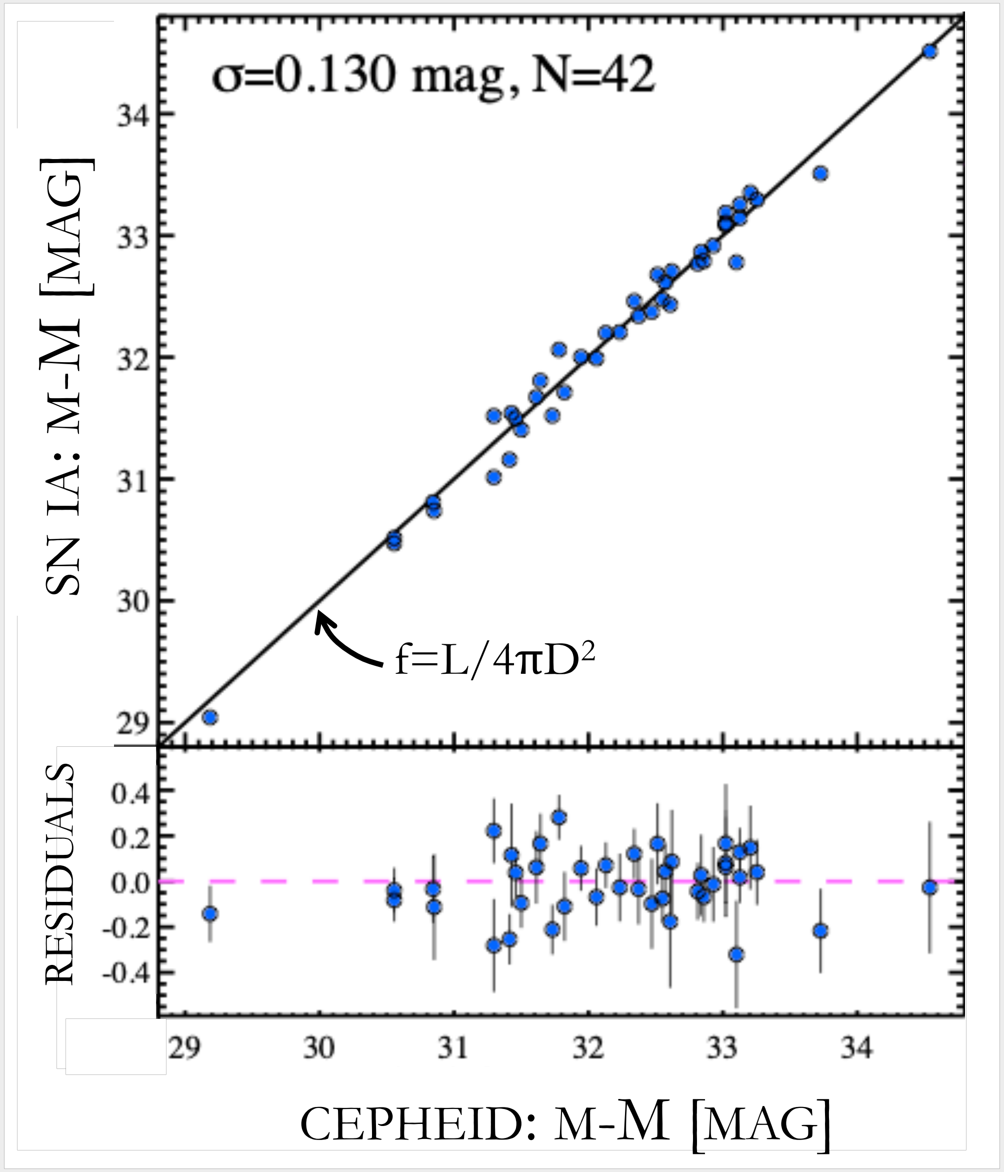


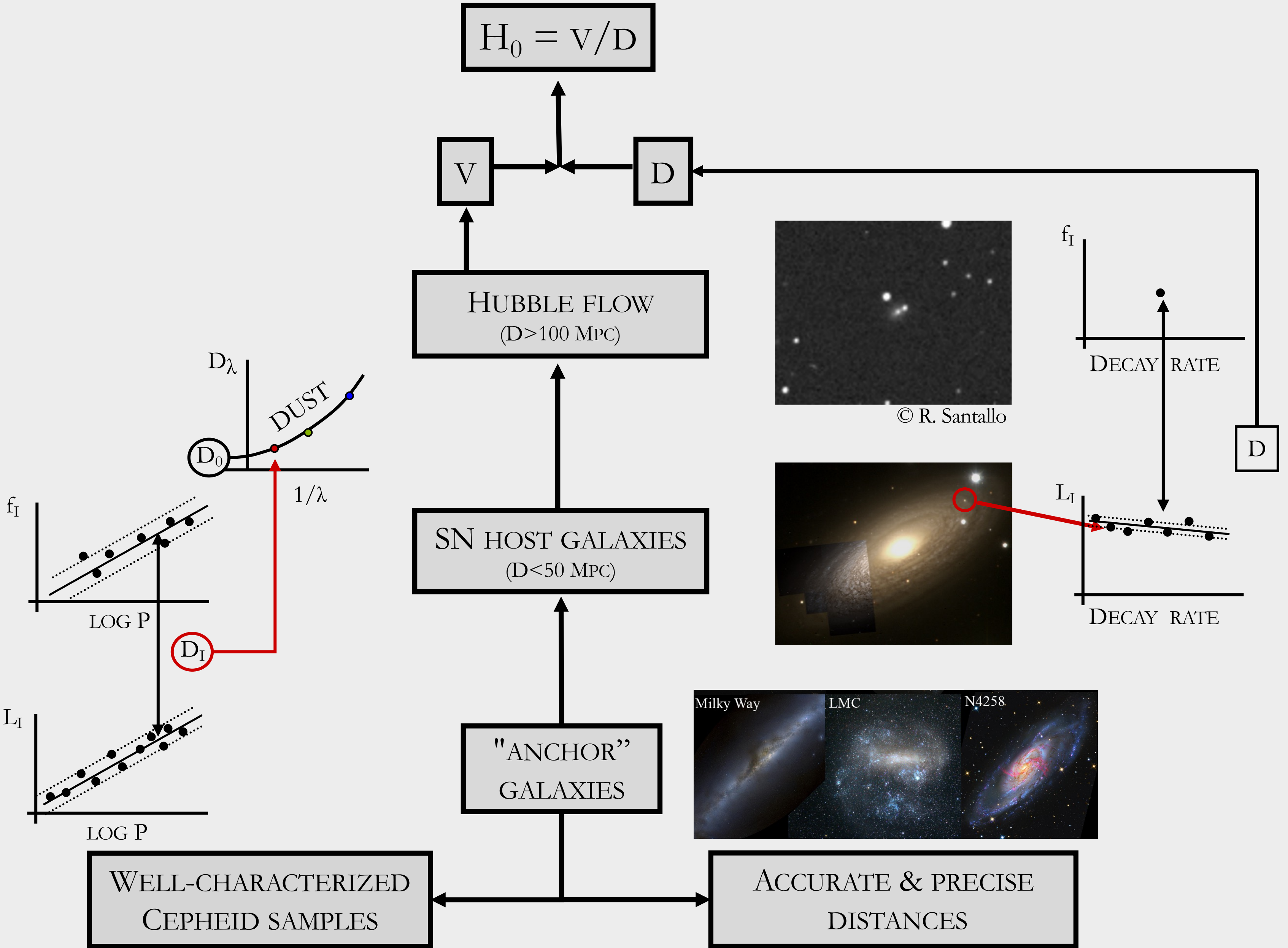


WD (IA) SUPERNOVAE LUMINOSITY

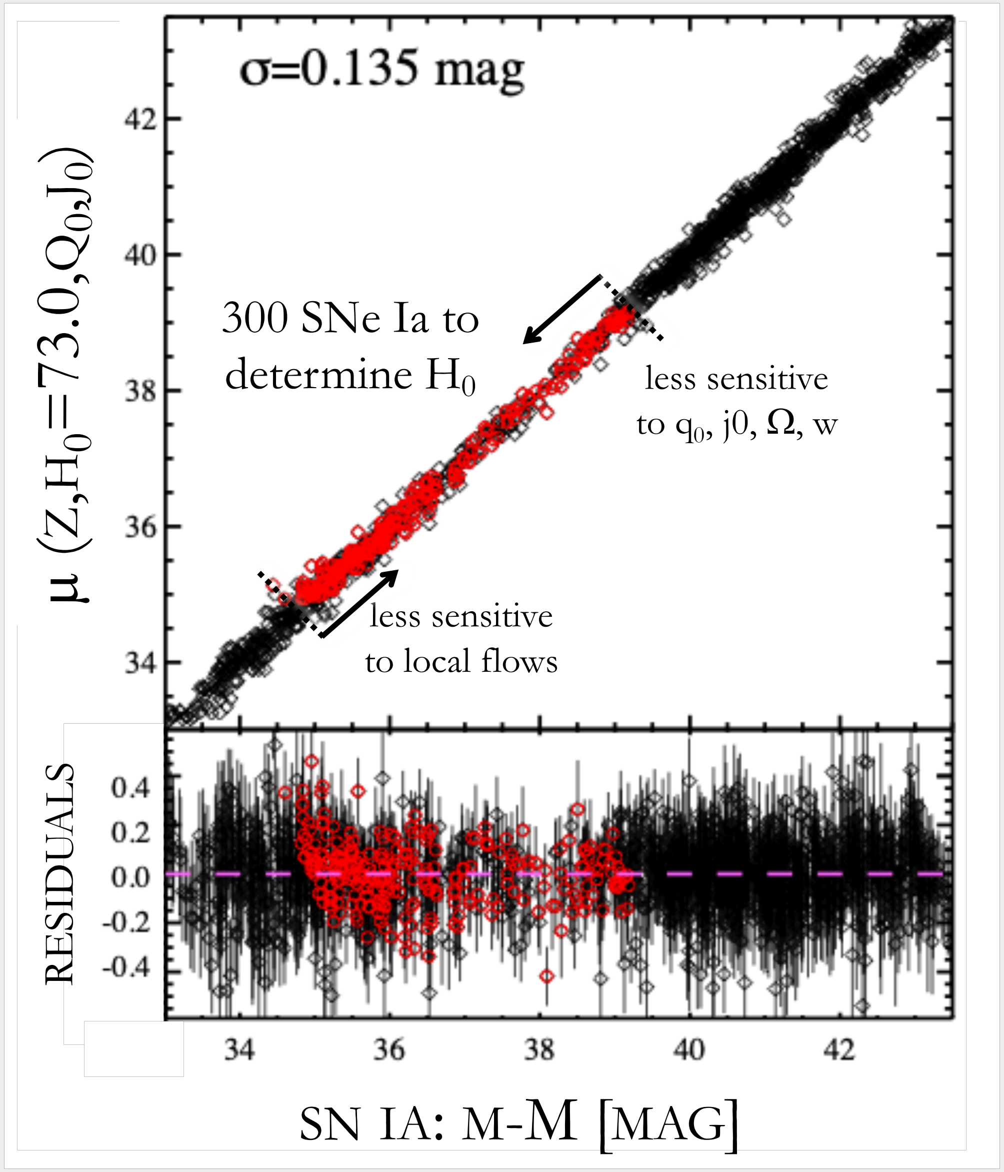


RIESS, YUAN, MACRI+ (2022)

SH$_0$ES DISTANCE LADDER



SUPERNOVAE IN HUBBLE FLOW



RIESS, YUAN, MACRI+ (2022)

SH$_0$ES ANALYSIS

- Standard candles (Cepheids, SNe Ia)
  - Used empirically – no astrophysical modeling involved
- All Cepheid observations use same telescope (*HST*) and cameras
  - Nullifies calibration systematics (zeropoint, color terms)
- All SNe data uniformly calibrated and analyzed
  - Brout+2022 (2112.03864); Scolnic+2022 (2112.03863)
- All data publicly available
  - https://pantheonplussh0es.github.io

Perform simultaneous fit to retain interdependence of data and parameters

Measurements

Cepheids in SN hosts

Cepheids in Anchors

SNe in Cepheid hosts

External constraints

SNe in Hubble flow

$$
\begin{pmatrix}
m^W_{H,1} \\
.. \\
m^W_{H,\mathrm{nh}} \\ \hline
m^W_{H,\mathrm{N4258}} - \mu_{0,\mathrm{N4258}} \\
m^W_{H,\mathrm{M31}} \\
m^W_{H,\mathrm{LMC}} - \mu_{0,\mathrm{LMC}} \\ \hline
m^0_{B,1} \\
.. \\
m^0_{B,\mathrm{ncc}} \\ \hline
M^W_{H,1,\mathrm{HST}} \\
M^W_{H,1,\mathrm{Gaia}} \\
0 \\
0 \\
0 \\ \hline
m^0_{B,1} - 5\log cz_1\{\} - 25 \\
.. \\
m_{B,\mathrm{nhf}} - 5\log cz_{\mathrm{nhf}}\{\} - 25
\end{pmatrix}
=
$$

Regression Matrix

$$
\left(\begin{array}{cccccccccccc}
1 & .. & 0 & 0 & 1 & 0 & 0 & \log P_{N,1} - 1 & 0 & [\mathrm{O/H}]_{N,1} & 0 & 0 \\
.. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & 0 \\
0 & .. & 1 & 0 & 1 & 0 & 0 & \log P_{N,\mathrm{nh}} - 1 & 0 & [\mathrm{O/H}]_{N,\mathrm{nh}} & 0 & 0 \\ \hline
0 & .. & 0 & 1 & 1 & 0 & 0 & \log P_{\mathrm{N4258}} - 1 & 0 & [\mathrm{O/H}]_{\mathrm{N4258}} & 0 & 0 \\
0 & .. & 0 & 0 & 1 & 0 & 1 & \log P_{\mathrm{M31}} - 1 & 0 & [\mathrm{O/H}]_{\mathrm{M31}} & 0 & 0 \\
0 & .. & 0 & 0 & 1 & 1 & 0 & \log P_{\mathrm{LMC}} - 1 & 0 & [\mathrm{O/H}]_{\mathrm{LMC}} & 1 & 0 \\ \hline
1 & .. & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
.. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & 0 \\
0 & .. & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ \hline
0 & .. & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & .. & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & .. & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & .. & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & .. & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ \hline
0 & .. & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1 \\
.. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. \\
0 & .. & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & -1
\end{array}\right)
$$

Free Parameters

$$
* \begin{pmatrix}
\mu_{0,1} \\
.. \\
\mu_{0,\mathrm{nh}} \\
\Delta\mu_{\mathrm{N4258}} \\
M^W_{H,1} \\
\Delta\mu_{\mathrm{LMC}} \\
\mu_{M31} \\
b_W \\
M^0_B \\
Z_W \\
\Delta\mathrm{zp} \\
5\log \mathrm{H}_0
\end{pmatrix}
$$

Absolute Host Distances

ΔD (N4258)

Cepheid Luminosity

ΔD(LMC)

ΔD(M31)

P-L slope

SN Ia Luminosity

Metallicity, Cepheid

Zeropoint, LMC

H_0

Covariance Matrix

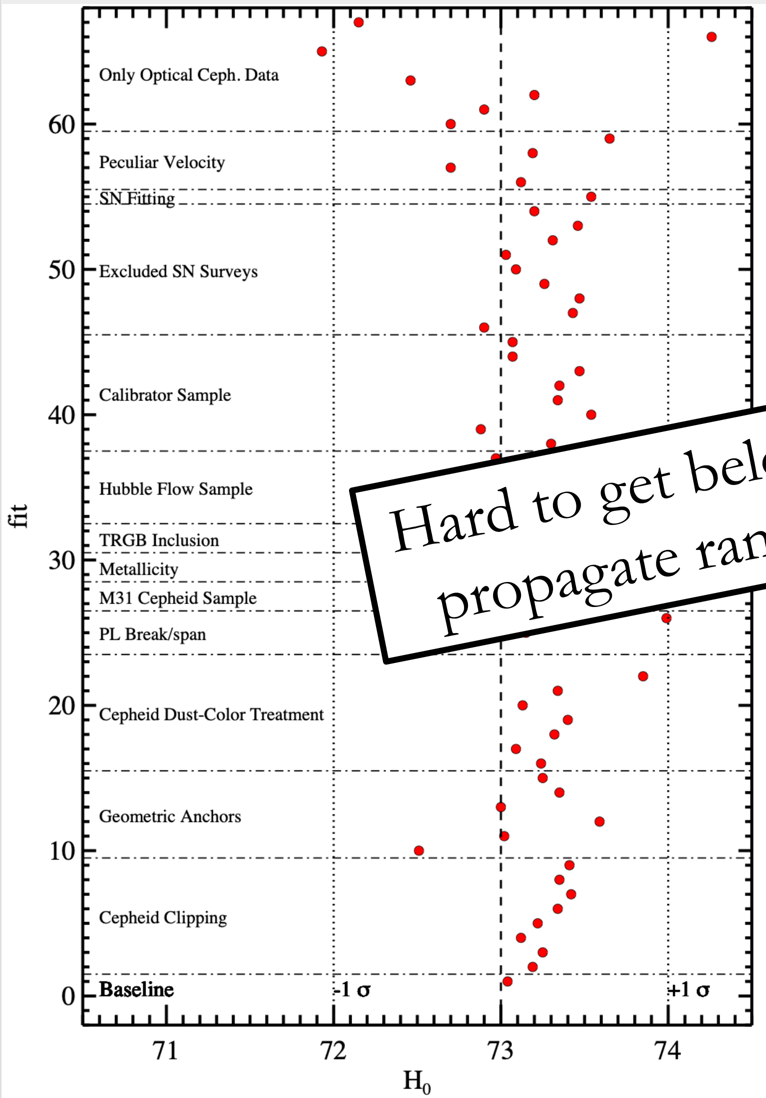
$$
\left(\begin{array}{cccccccccccccccc}
\sigma^2_{\mathrm{tot},1} & .. & Z_{\mathrm{cov}} & Z_{\mathrm{cov}} & 0 & 0 & 0 & .. & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .. & 0 \\
.. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. \\
Z_{\mathrm{cov}} & .. & \sigma^2_{\mathrm{tot,nh}} & Z_{\mathrm{cov}} & 0 & 0 & 0 & .. & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .. & 0 \\ \hline
Z_{\mathrm{cov}} & .. & Z_{\mathrm{cov}} & \sigma^2_{\mathrm{tot,N4258}} & 0 & 0 & 0 & .. & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .. & 0 \\
0 & .. & 0 & 0 & \sigma^2_{\mathrm{tot,M31}} & 0 & 0 & .. & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .. & 0 \\
0 & .. & 0 & 0 & 0 & \sigma^2_{\mathrm{tot,LMC}} & 0 & .. & 0 & 0 & 0 & 0 & 0 & 0 & 0 & .. & 0 \\ \hline
0 & .. & 0 & 0 & 0 & 0 & \sigma^2_{m_{\mathrm{B}},1} & .. & \mathrm{SN_{cov}} & 0 & 0 & 0 & 0 & 0 & \mathrm{SN_{cov}} & .. & \mathrm{SN_{cov}} \\
.. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. \\
0 & .. & 0 & 0 & 0 & 0 & \mathrm{SN_{cov}} & .. & \sigma^2_{m_{\mathrm{B}},\mathrm{ncc}} & 0 & 0 & 0 & 0 & 0 & \mathrm{SN_{cov}} & .. & \mathrm{SN_{cov}} \\ \hline
0 & .. & 0 & 0 & 0 & 0 & 0 & .. & 0 & \sigma^2_{\mathrm{HST}} & 0 & 0 & 0 & 0 & 0 & .. & 0 \\
0 & .. & 0 & 0 & 0 & 0 & 0 & .. & 0 & 0 & \sigma^2_{\mathrm{Gaia}} & 0 & 0 & 0 & 0 & .. & 0 \\
0 & .. & 0 & 0 & 0 & 0 & 0 & .. & 0 & 0 & 0 & \sigma^2_{\mathrm{grnd}} & 0 & 0 & 0 & .. & 0 \\
0 & .. & 0 & 0 & 0 & 0 & 0 & .. & 0 & 0 & 0 & 0 & \sigma^2_{\mu,\mathrm{N4258}} & 0 & 0 & .. & 0 \\
0 & .. & 0 & 0 & 0 & 0 & 0 & .. & 0 & 0 & 0 & 0 & 0 & \sigma^2_{\mu,\mathrm{LMC}} & 0 & .. & 0 \\ \hline
0 & .. & 0 & 0 & 0 & 0 & \mathrm{SN_{cov}} & .. & \mathrm{SN_{cov}} & 0 & 0 & 0 & 0 & 0 & \sigma^2_{m_{\mathrm{B}},z,1} & .. & \mathrm{SN_{cov}} \\
.. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. \\
0 & .. & 0 & 0 & 0 & 0 & \mathrm{SN_{cov}} & .. & \mathrm{SN_{cov}} & 0 & 0 & 0 & 0 & 0 & \mathrm{SN_{cov}} & .. & \sigma^2_{m_{\mathrm{B}},z,\mathrm{nhf}}
\end{array}\right)
$$

$$5\log \mathrm{H}_0 = M_B^0 + 5a_B + 25$$

Riess, Yuan, Macri+ (2022)

Analysis Variants

12 categories, 67 variants, bifurcations, extensions, etc.



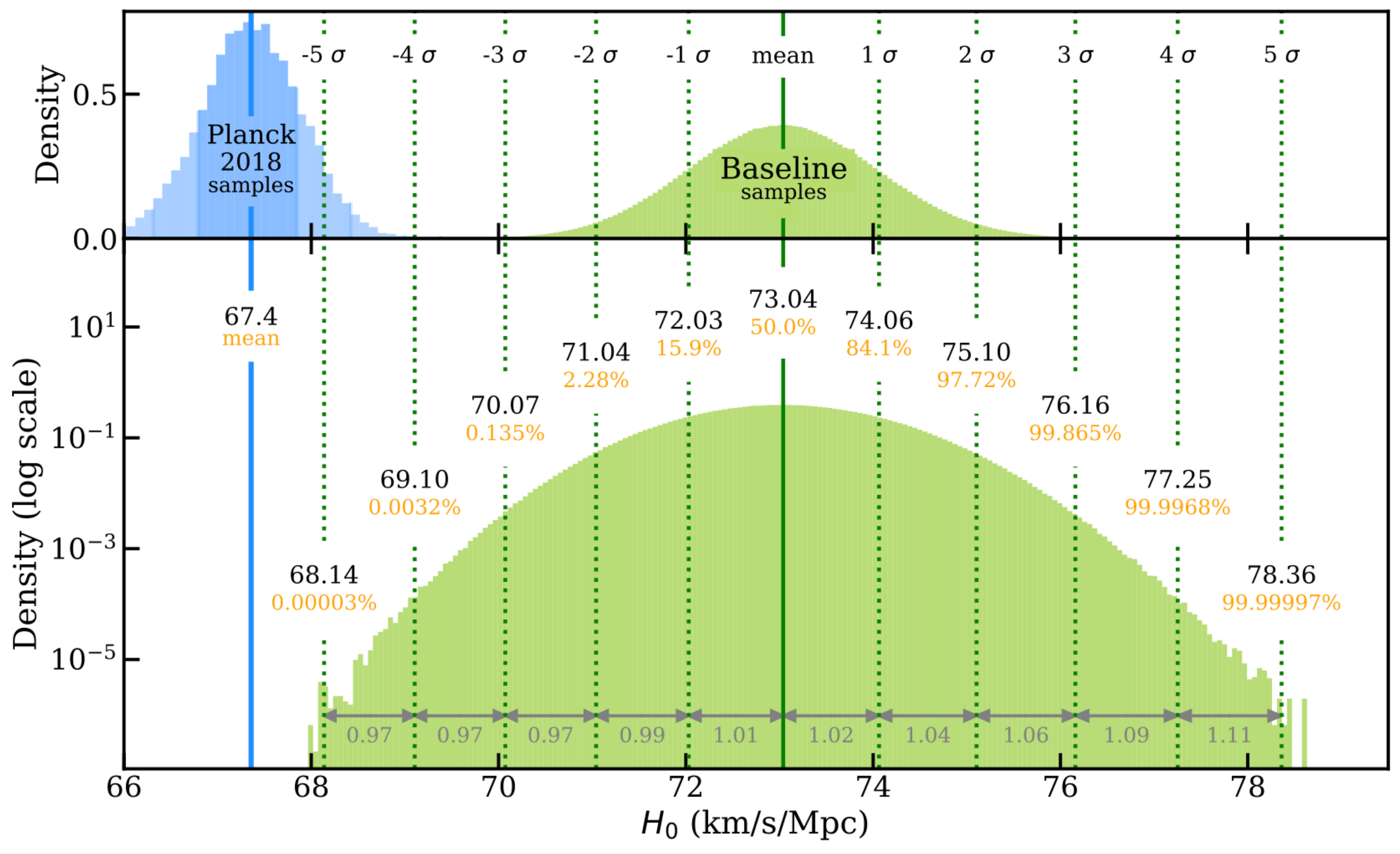
- Optical Cepheid data only 72.7
- Diff. pec. vel map or none 73.1,72.7
- SN scatter ind. wave+mass step 73.5
- No pre-2000 SNe 73.2
- Closest half hosts 73.1
- Most crowded half 73.4
- Least 73.3
- 73.4
- 73.3
- TRGB (consistently) jointly 72.5
- No metallicity term 73.5
- Break in PL at P=10 days 72.7
- No dust correction 74.8
- Individual host dust law 73.9
- Free param dust law 73.3
- Low R_V=2.5 dust law 73.2
- Two of three anchors 73.0,73.4,73.2
- No outlier rejection 73.4

Hard to get below 72.5 or above 73.5;
propagate range as extra systematic

Riess, Yuan, Macri+ (2022)

BASELINE FIT: H_0=73.04±1.04 KM/S/MPC

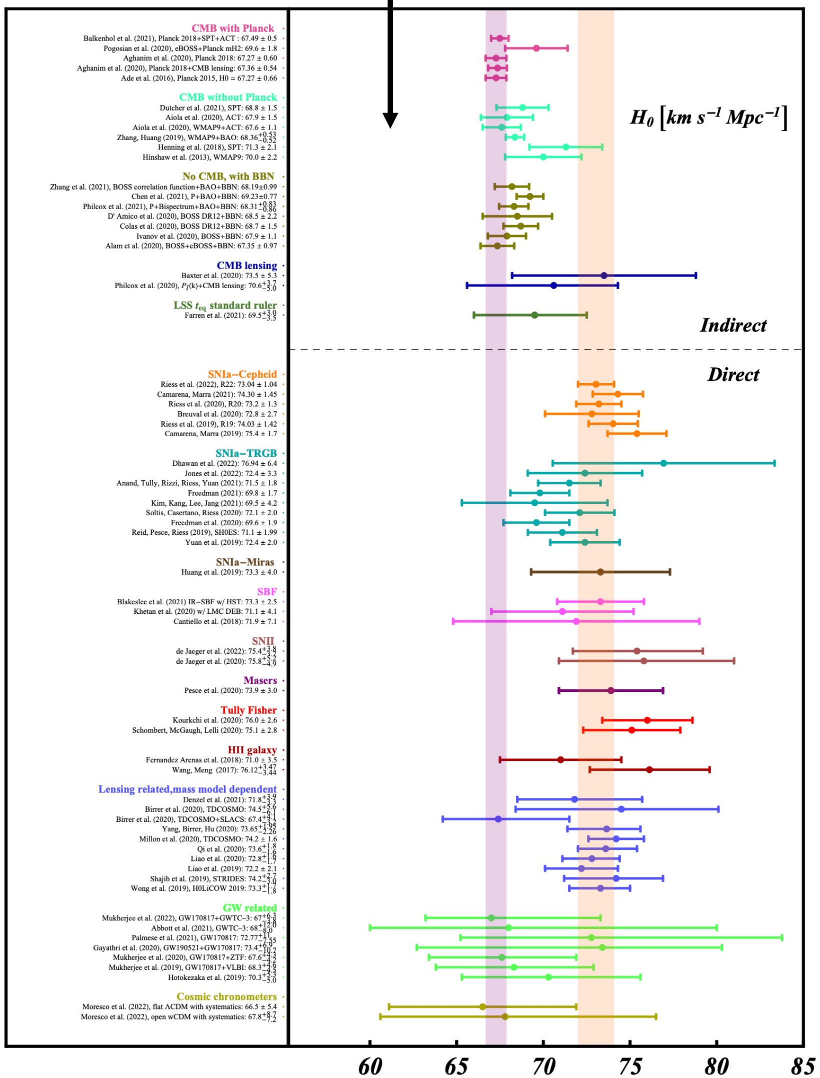
includes systematics; 5.0σ from Planck+ΛCDM; χ^2_ν=1.03, N=3500



RIESS, YUAN, MACRI+ (2022)

H_0 TENSION

WHY IS THERE NO PRECISE LATE-UNIVERSE H_0 < EARLY-UNIVERSE?



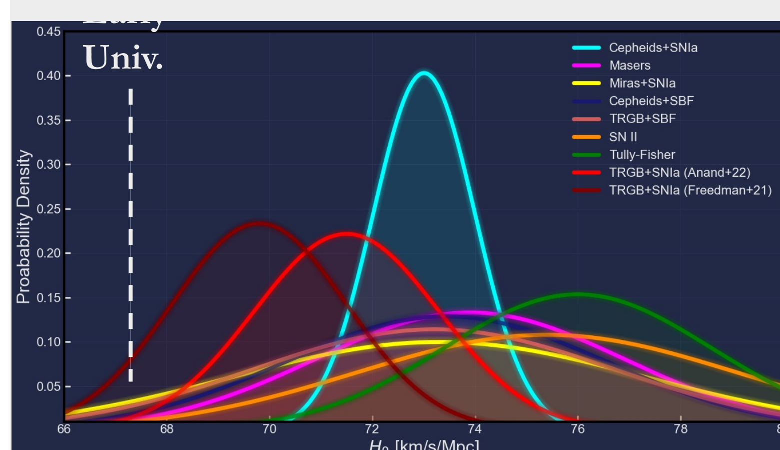
DI VALENTINO+2022 (2103.01183)

Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Cosmology Intertwined:
A Review of the Particle Physics, Astrophysics, and Cosmology
Associated with the Cosmological Tensions and Anomalies

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

The most precise and referenced distance ladders are consistent



NEW PHYSICS IN DARK SECTOR?

Reviews: Schöneberg+2022 (2107.10291); Di Valentino+2022 (2103.01183)

"H0 Olympics"

Model	ΔN_{param}	$\Delta\chi^2$	ΔAIC		One test passed	
ΛCDM	0	0.00	0.00	✗	✗	
ΔN_{ur}	1	−6.10	−4.10	✗	✗	
SIDR	1	−9.57	−7.57	✓	✓	3
mixed DR	2	−8.83	−4.83	✗	✗	
DR-DM	2	−8.92	−4.92	✗	✗	
SIν+DR	3	−4.98	1.02	✗	✗	
Majoron	3	−15.49	−9.49	✓	✓	2
primordial B	1	−11.42	−9.42	✓	✓	3
varying m_e	1	−12.27	−10.27	✓	✓	1
varying m_e+Ω_k	2	−17.26	−13.26	✓	✓	1
EDE	3	−21.98	−15.98	✓	✓	2
NEDE	3	−18.93	−12.93	✓	✓	2
EMG	3	−18.56	−12.56	✓	✓	2
CPL	2	−4.94	−0.94	✗	✗	
PEDE	0	2.24	2.24	✗	✗	
GPEDE	1	−0.45	1.55	✗	✗	
DM → DR+WDM	2	−0.19	3.81	✗	✗	
DM → DR	2	−0.53	3.47	✗	✗	

<u>Not so good</u>: decaying dark matter, w<-1, Swampland

<u>Better</u>: early dark energy, sterile and/or self-interacting ν's, evolving e^- mass, primordial B fields, early recombination

<u>Best</u>: <your idea here>

"The Hubble Hunter's Guide" (Knox and Millea, 2019) "Most Likely": Increased expansion rate pre-recombination reduces sound horizon by 5-8%

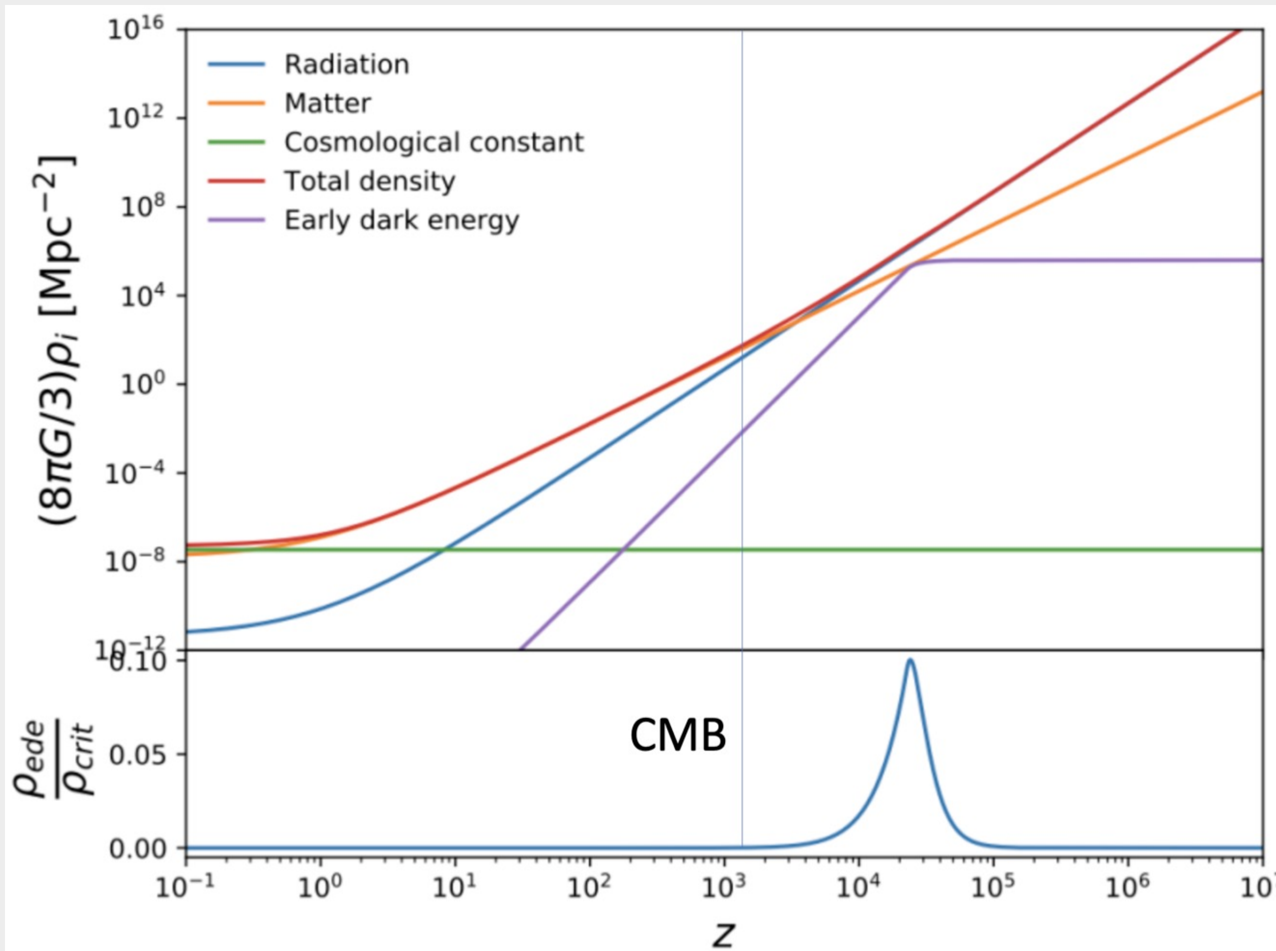
Mechanisms: Early dark energy or sterile (and/or self-interacting) neutrinos

Claims: not worse fit to CMB, should produce new CMB features for next stage

SLIDE COURTESY OF A. RIESS

Early Dark Energy?

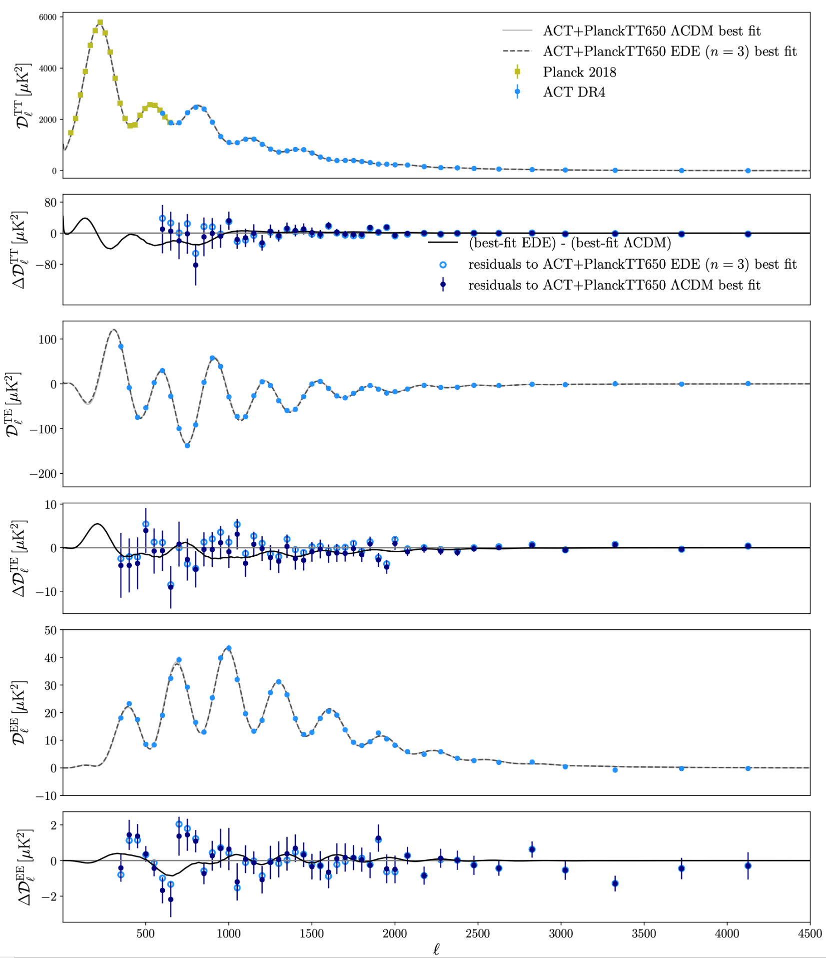
- Energy density contributes ~10% briefly before recombination
- Energy density later decays faster than radiation, leaving late evolution of Universe unchanged



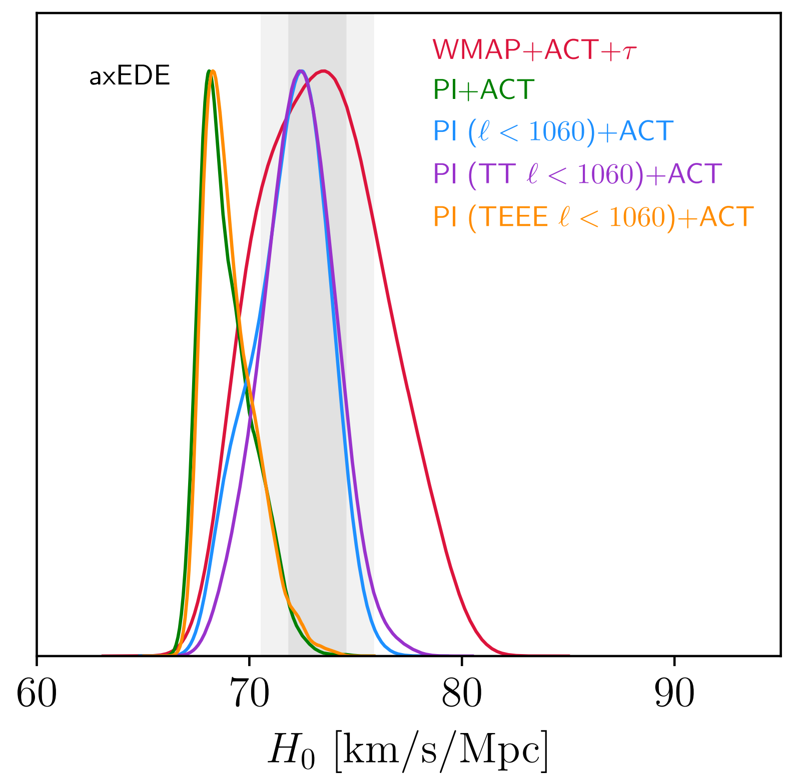
Kamionkowski & Riess, ARAA, in press (2211.04492)

EARLY DARK ENERGY?

- Hill+22 (2109.04451): 3σ detection of EDE in ACT+*Planck*+BAO
- Poulin+21 (2109.06229): "More accurate TT at $\ell \gtrsim 2500$ and EE at $300<\ell<500$ will play a crucial role in differentiating EDE models"



HILL+(2022)

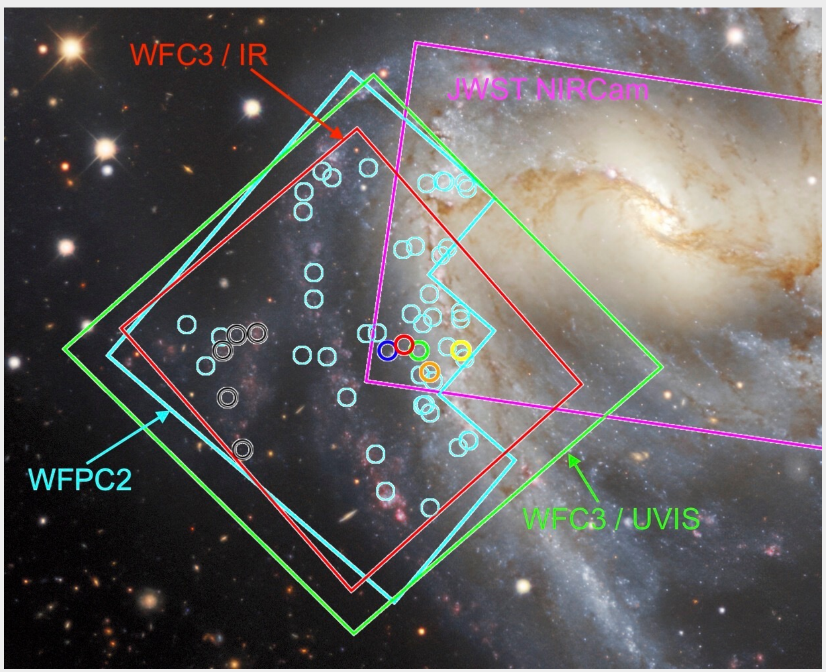


POULIN, SMITH & BARTLETT (2021)

Next steps for SH_0ES

- *JWST* Cepheids in hosts of 9 SNe Ia + N4258 → $\sigma(H_0)$~2%
- First (serendipitous) observations of Cepheids with *JWST* in N1365 bodes well! (Yuan+2022, 2209.09101)

13-Aug-2022, *JWST* NIRCAM N1365 (host of SN 2012fr), F200W



JWST: far better NIR resolution! that yields HST vis. resolution w/HST NIR low dust

0.55 µM

HST VIS

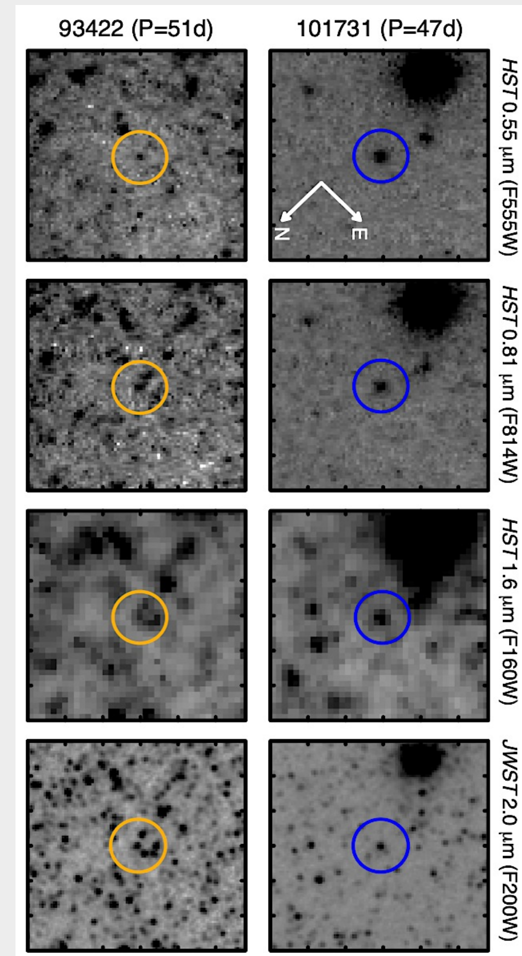
0.81 µM

HST NIR

1.6 µM

JWST NIR

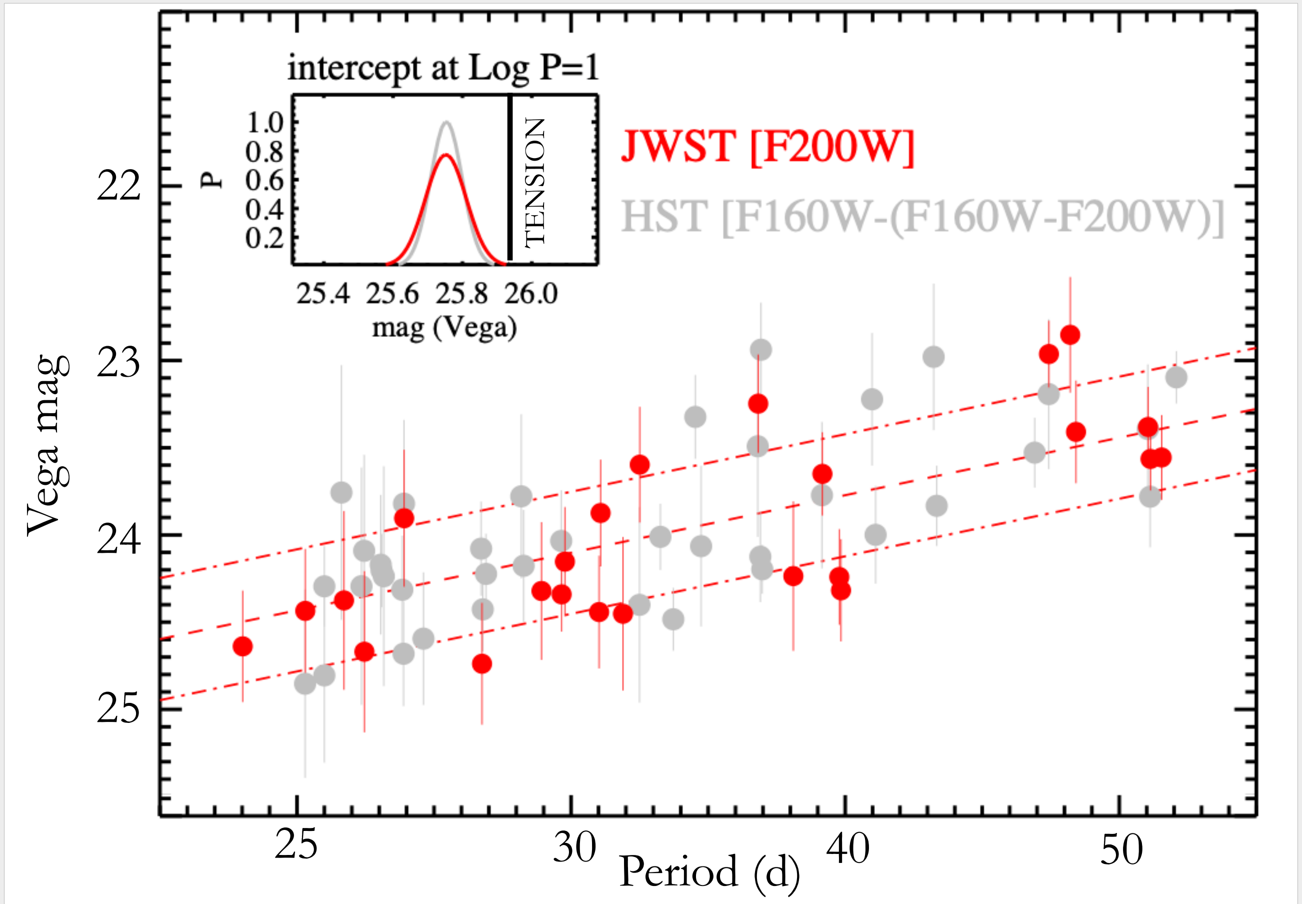
2 µM



Yuan, Riess, Casertano & Macri (2022)

First Cepheids with *JWST*

- Not optimal: depth, location, random phase, λ, calibration…
- PSF photometry, calibrated w/P330E (HST standard)
- P-L intercepts: JWST: 25.76±0.06 mag; HST: 25.75±0.05 mag
- No evidence HST "biased bright" at ~0.2 mag level



Yuan, Riess, Casertano & Macri (2022)

Summary

- SH_0ES project: calibration of modern, high-quality SNe Ia using Cepheids in the near-infrared
  - $H_0 = 73.04 \pm 1.04$ km s^{-1} Mpc^{-1} ; $\sigma(H_0) = 10\% \rightarrow 1.4\%$
- 5σ diff wrt ΛCDM → New dark-sector Physics?
  - $4\text{-}6\sigma$ regardless of combination of cosmological probes
  - New pre-recombination Physics most promising solution
- Next steps
  - *JWST* Cepheids (approved program) + 9 SNe Ia: $\sigma(H_0) \sim 2\%$
  - *Gaia* DR4/5: Calibrate Cepheids to 0.4% (now 1%)
  - Eagerly await CMB-S4!