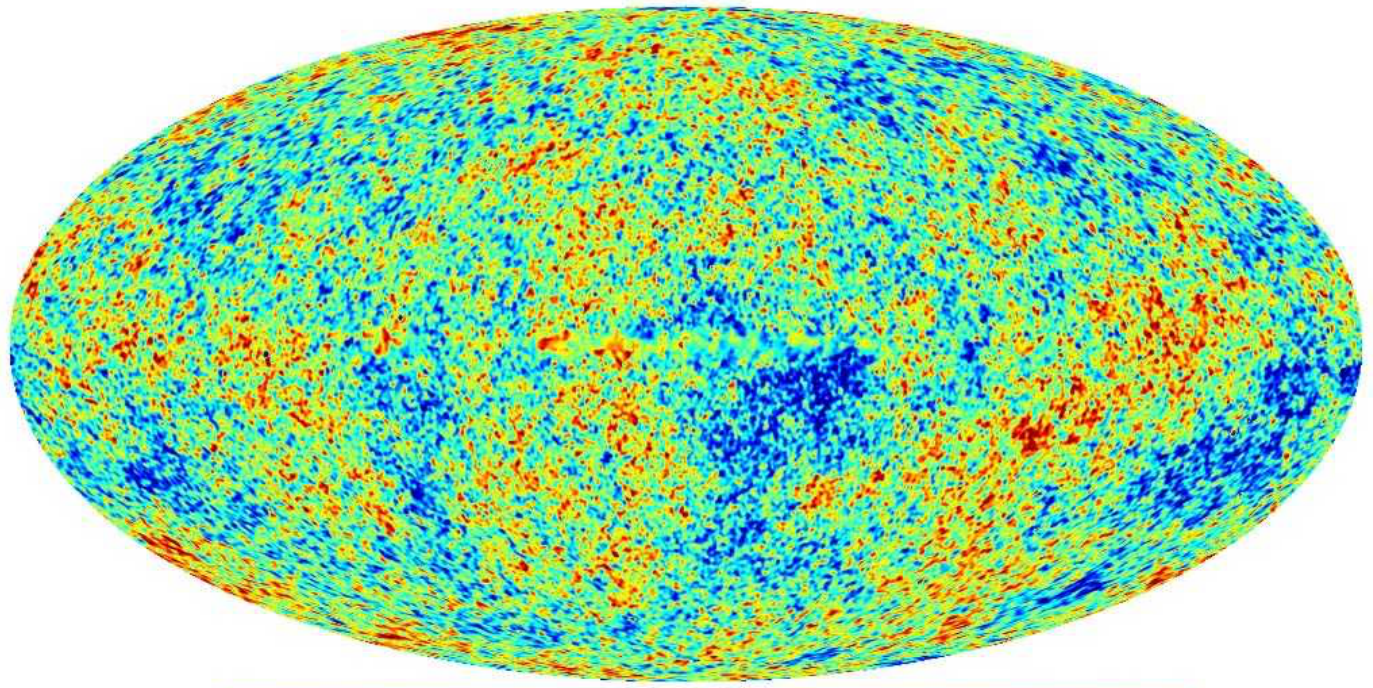
Searching for New Physics with Measurements of the Hubble Constant

D. Jones, on behalf of SH0ES
Einstein Fellow, UC Santa Cruz
Vulcano Workshop 2022

H_0: an End-to-End Test of the Cosmological Model

- Local expansion rate, H_0 can be predicted from the cosmic microwave background (~400K years after the big bang) and measured directly today

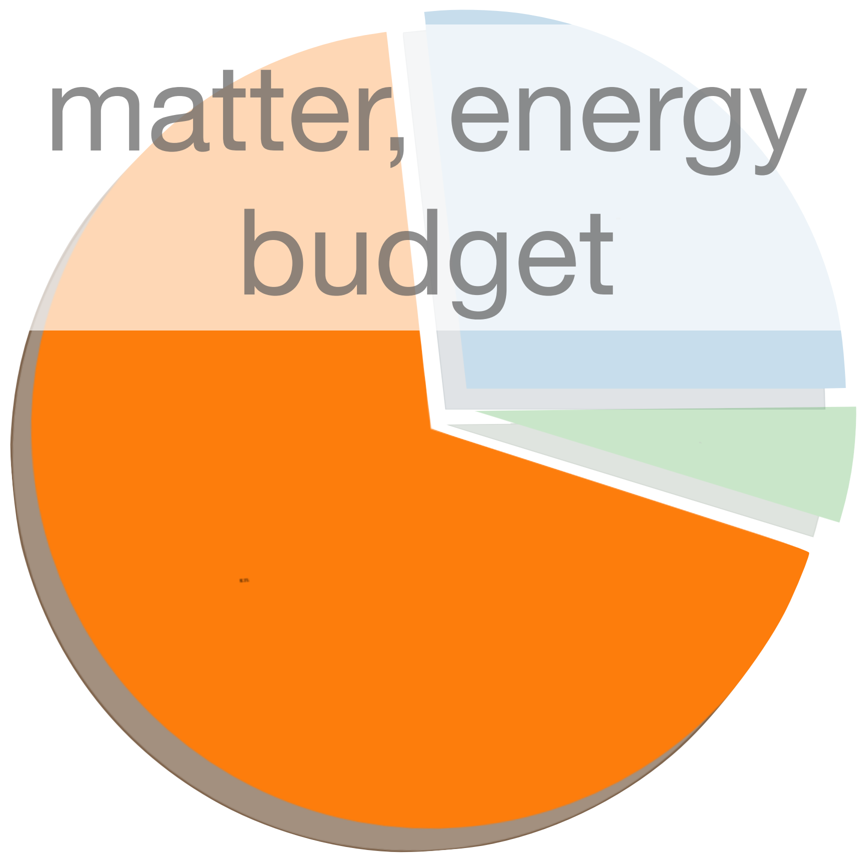
CMB Meas. of Sound Horizon

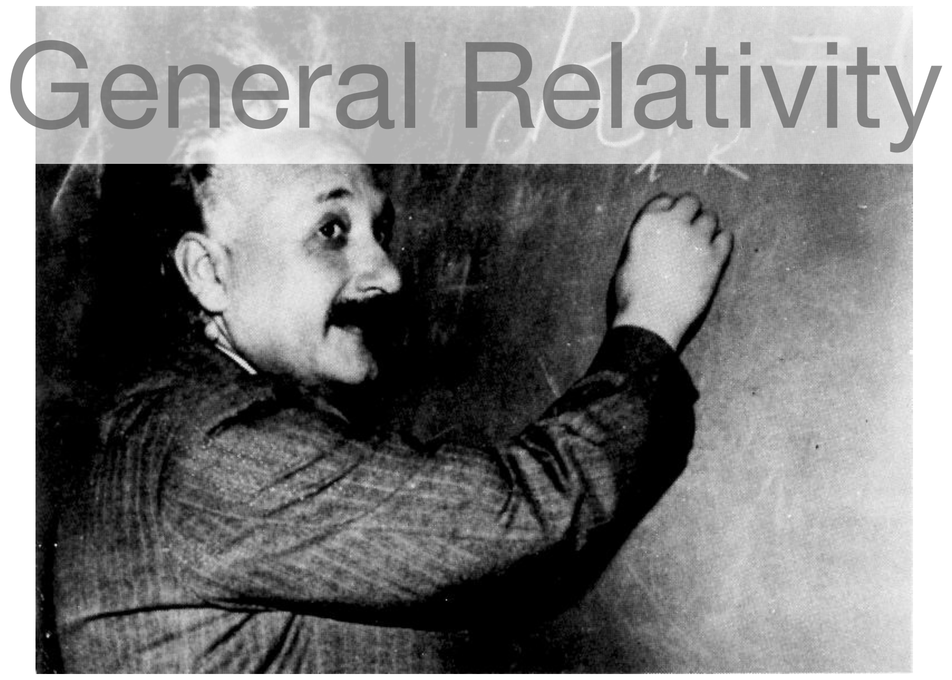


z=1100

$\sigma_{H0}(\Lambda CDM)=0.4\%$

+





+

13 billion years

→

H_0 = 67.5 +/- 0.4 km/s/ Mpc

Planck+18

H_0: an End-to-End Test of the Cosmological Model

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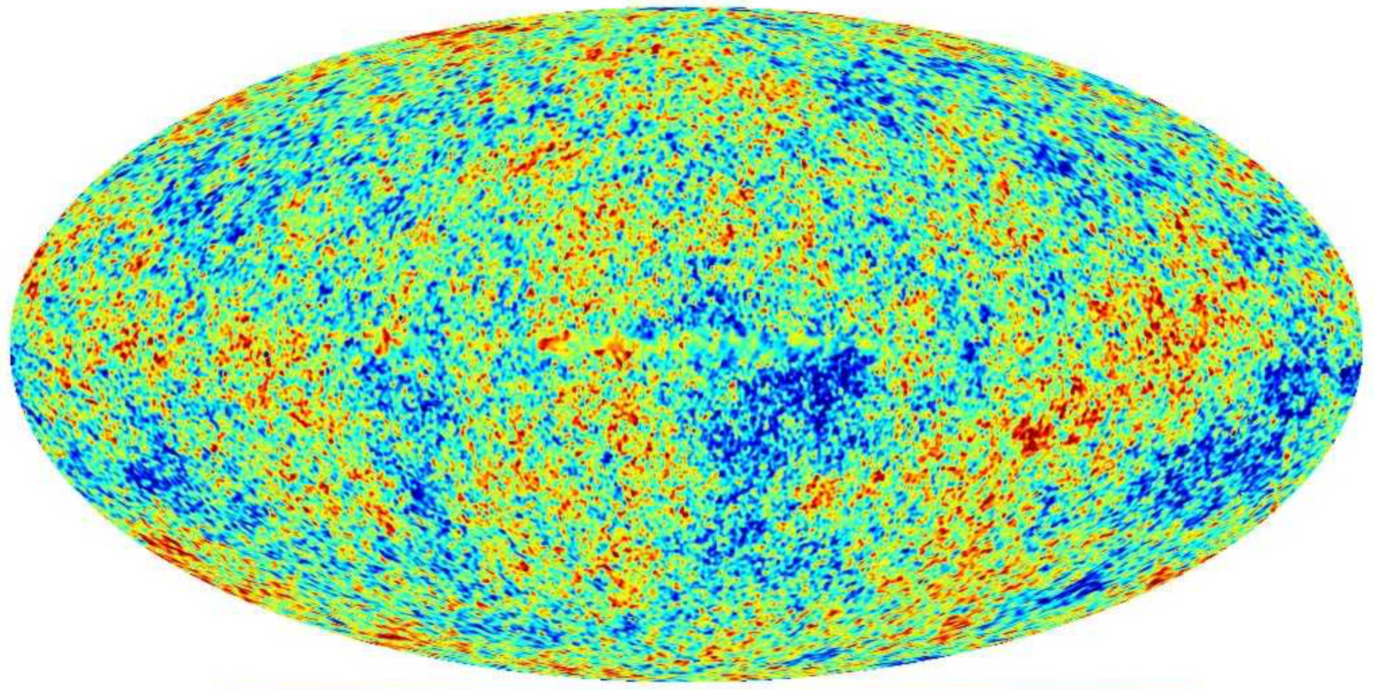
CMB Meas. of Sound Horizon



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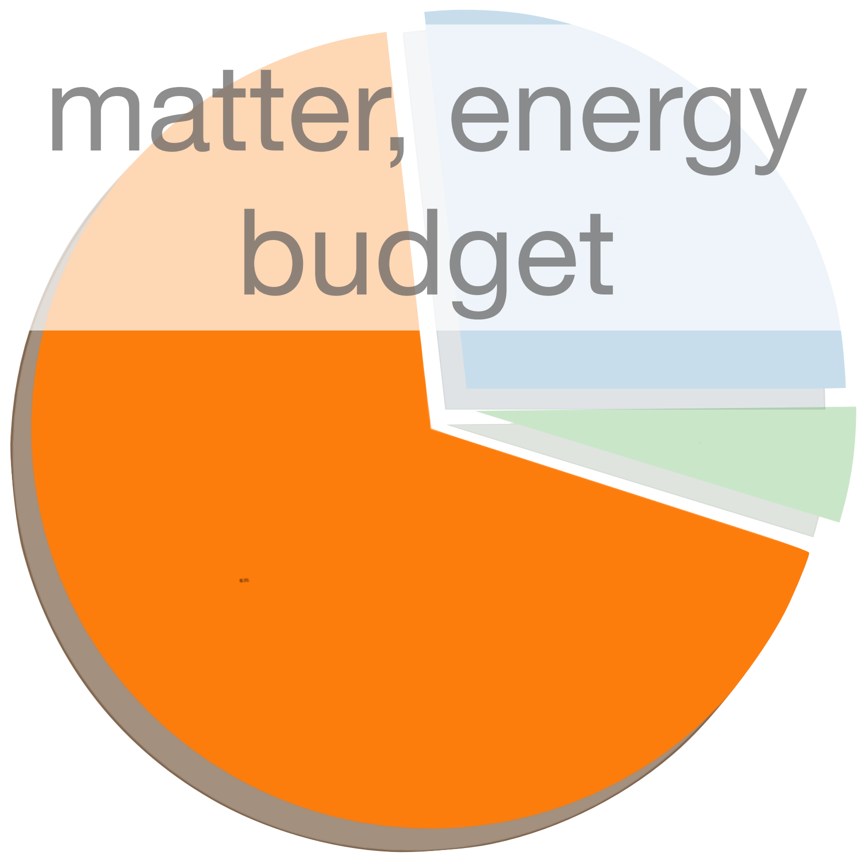
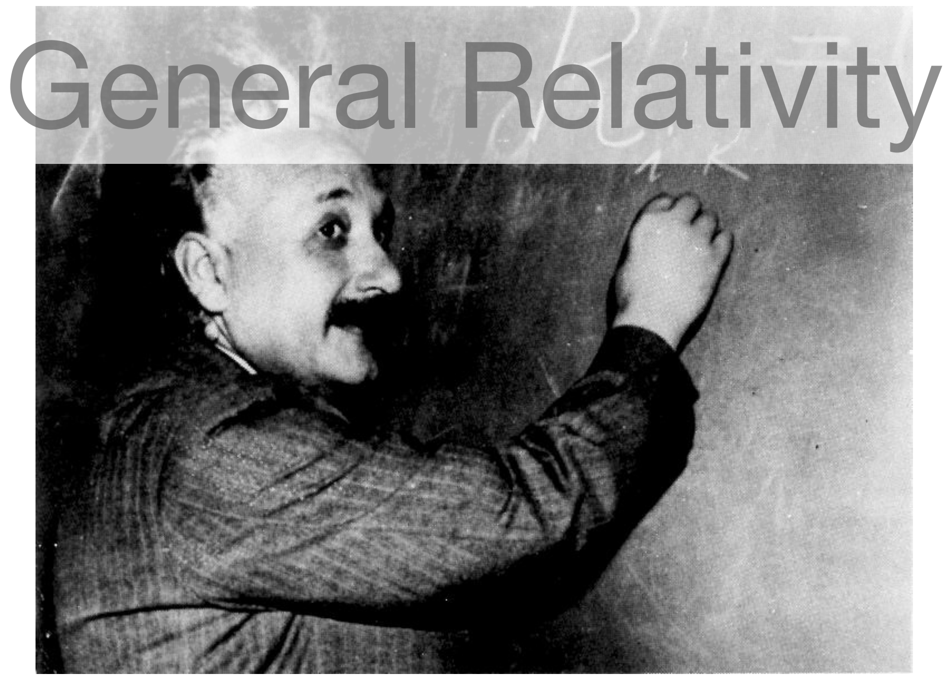


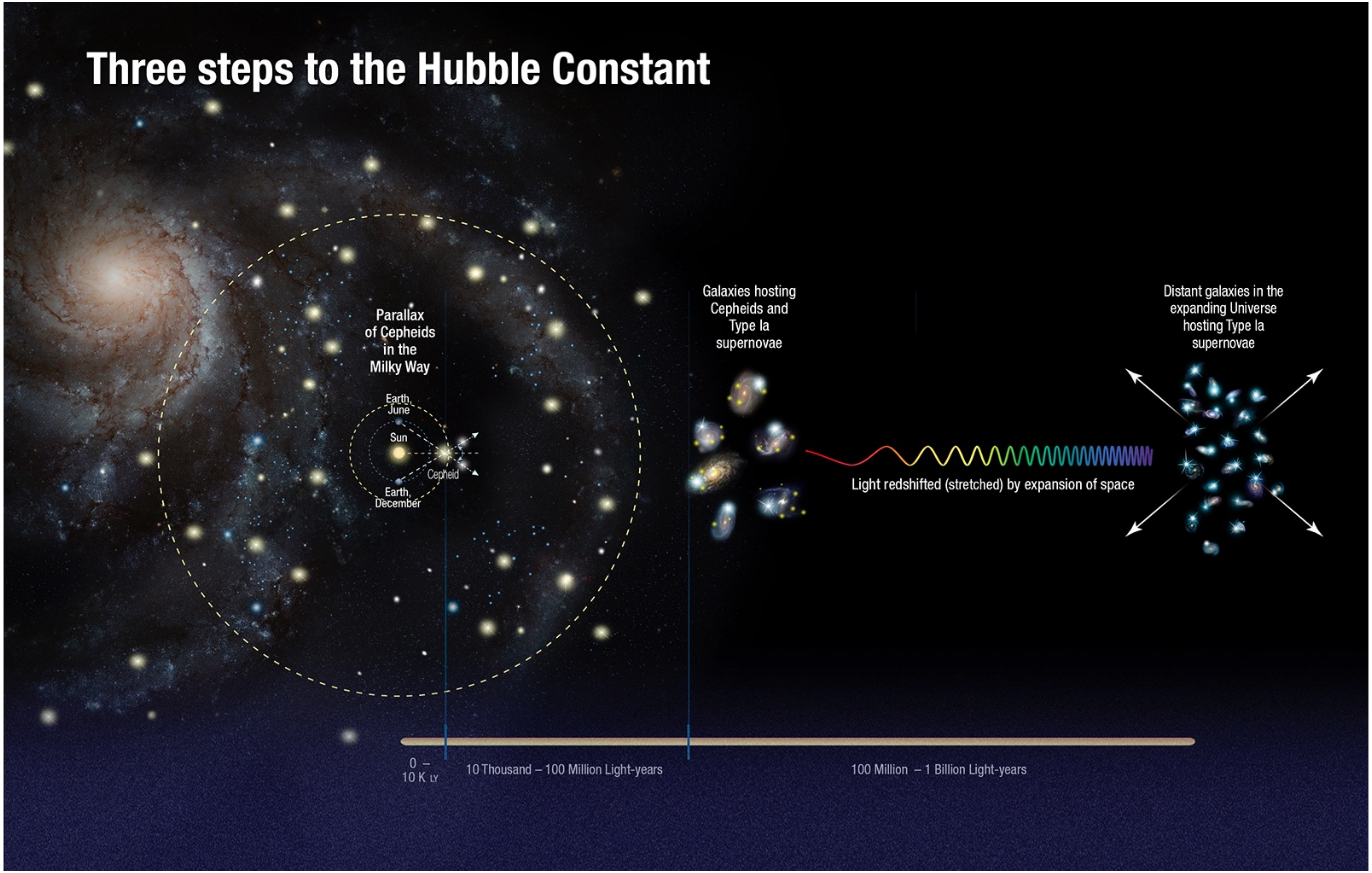


+

13 billion years → H_0 = 67.5 +/- 0.4 km/s/Mpc

If direct measurements disagree, that means knowledge of cosmology is wrong!

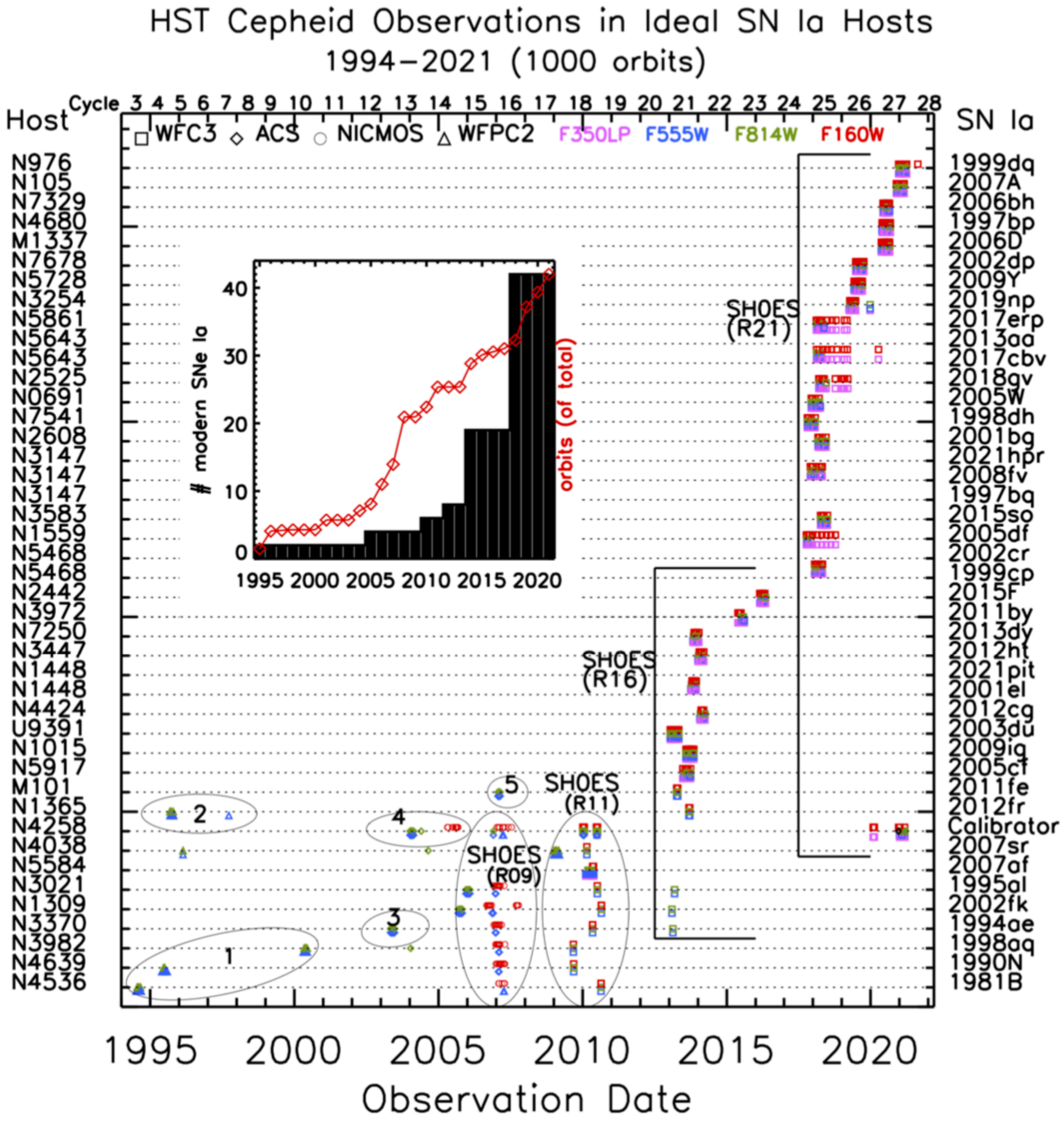
The Local Distance Ladder



hubblesite.org

The SH0ES Program

- Supernovae and H_0 for the Equation of State of dark energy
- Began in 2005 with the goal of a precise H_0 measurement
- Has now used more than 1,000 orbits of *HST* to measure Cepheids in SN Ia host galaxies (Proposal PIs: Riess, Jones, Foley, Whitmore)

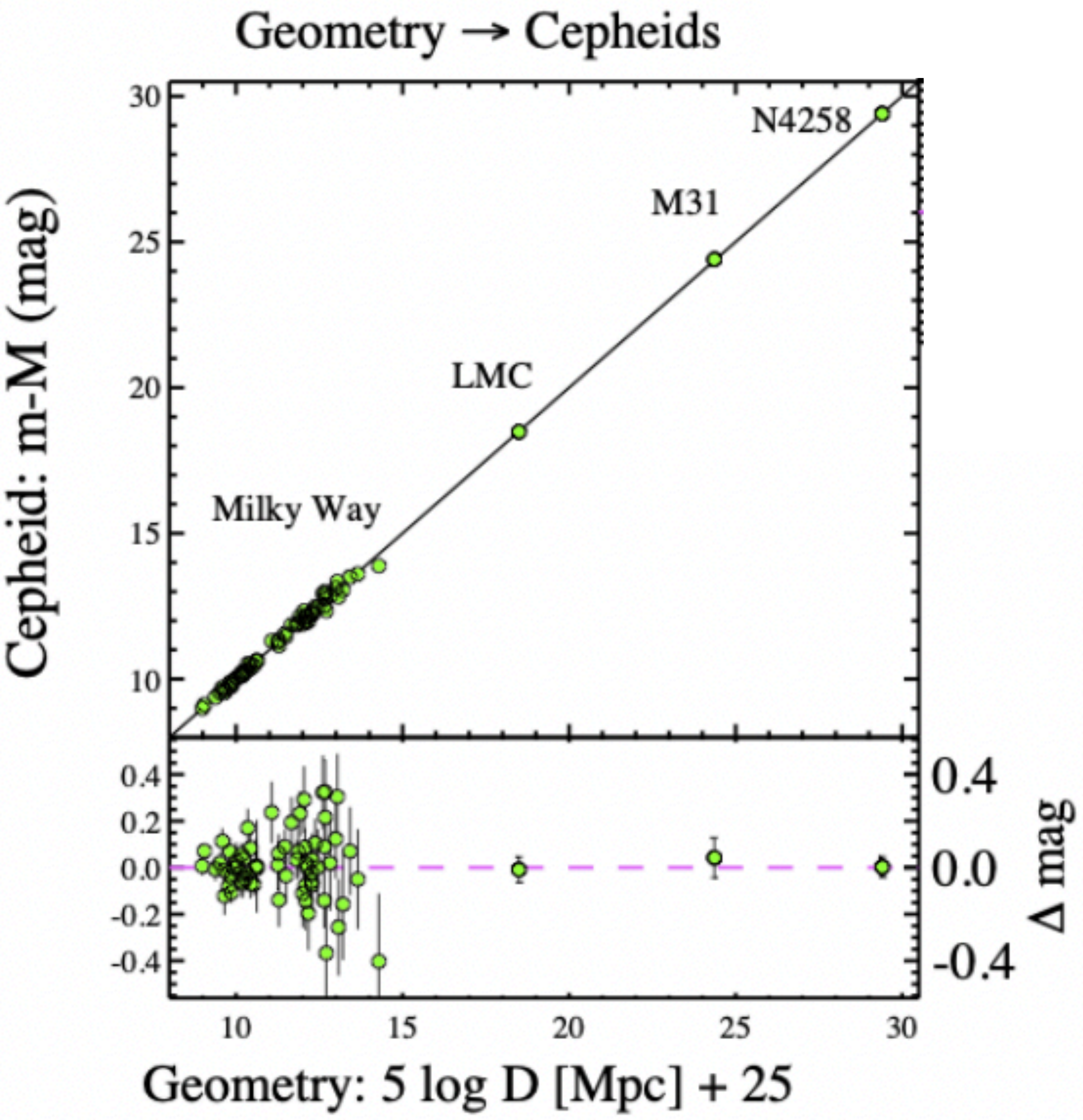


Riess+22 (incl. Jones)

The SH0ES Distance Ladder, 2022

1. Geometric distances to Cepheids

   There are 4 different anchors that span over 20 mags with <~2% error!



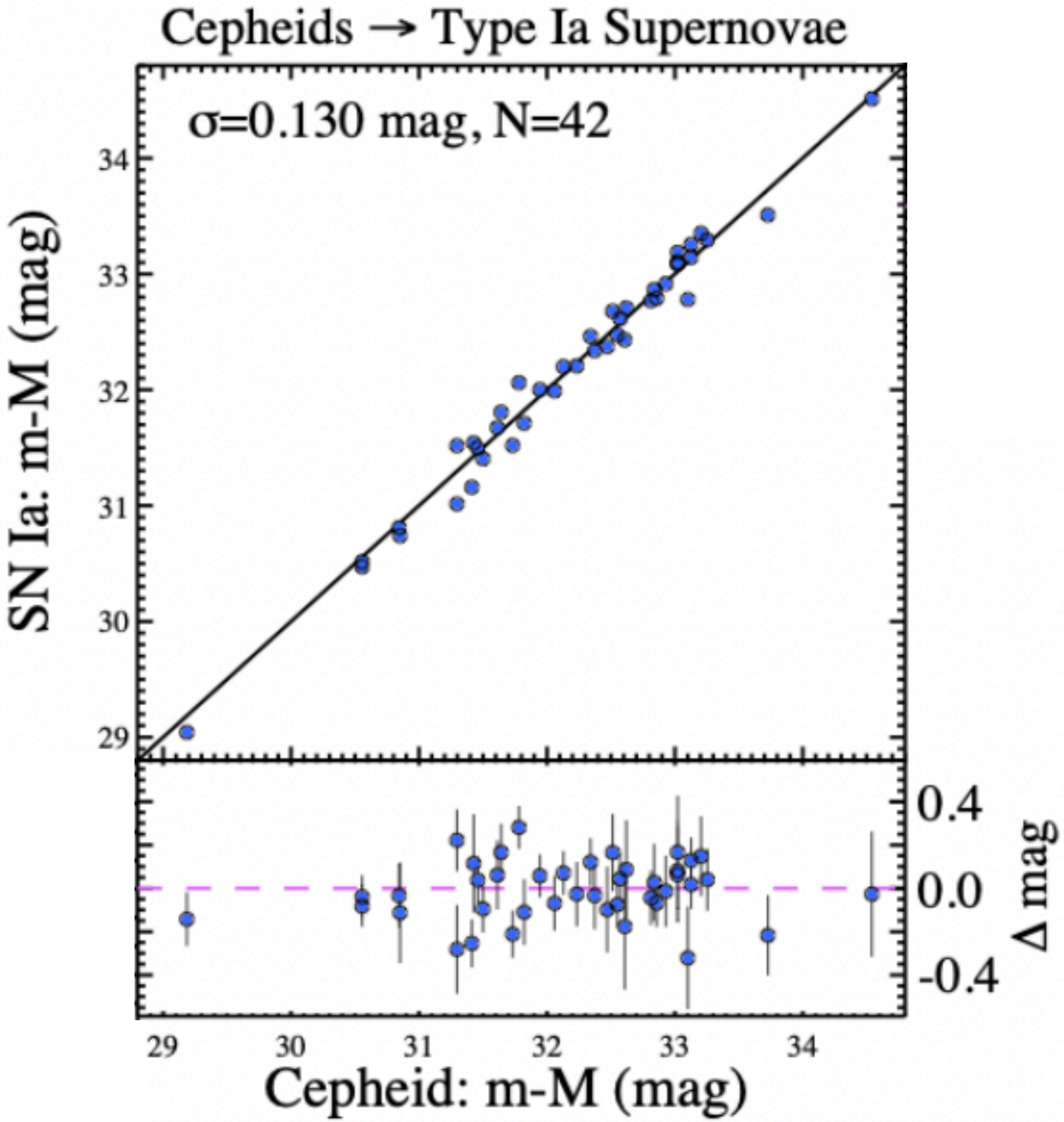
Riess+22 (incl. Jones)

The SH0ES Distance Ladder, 2022

1. Geometric distances to Cepheids

2. Cepheids in galaxies with SNe Ia

   Doubled the Cepheid sample with 42 Cepheid calibrators in Riess+22



Riess+22 (incl. Jones)

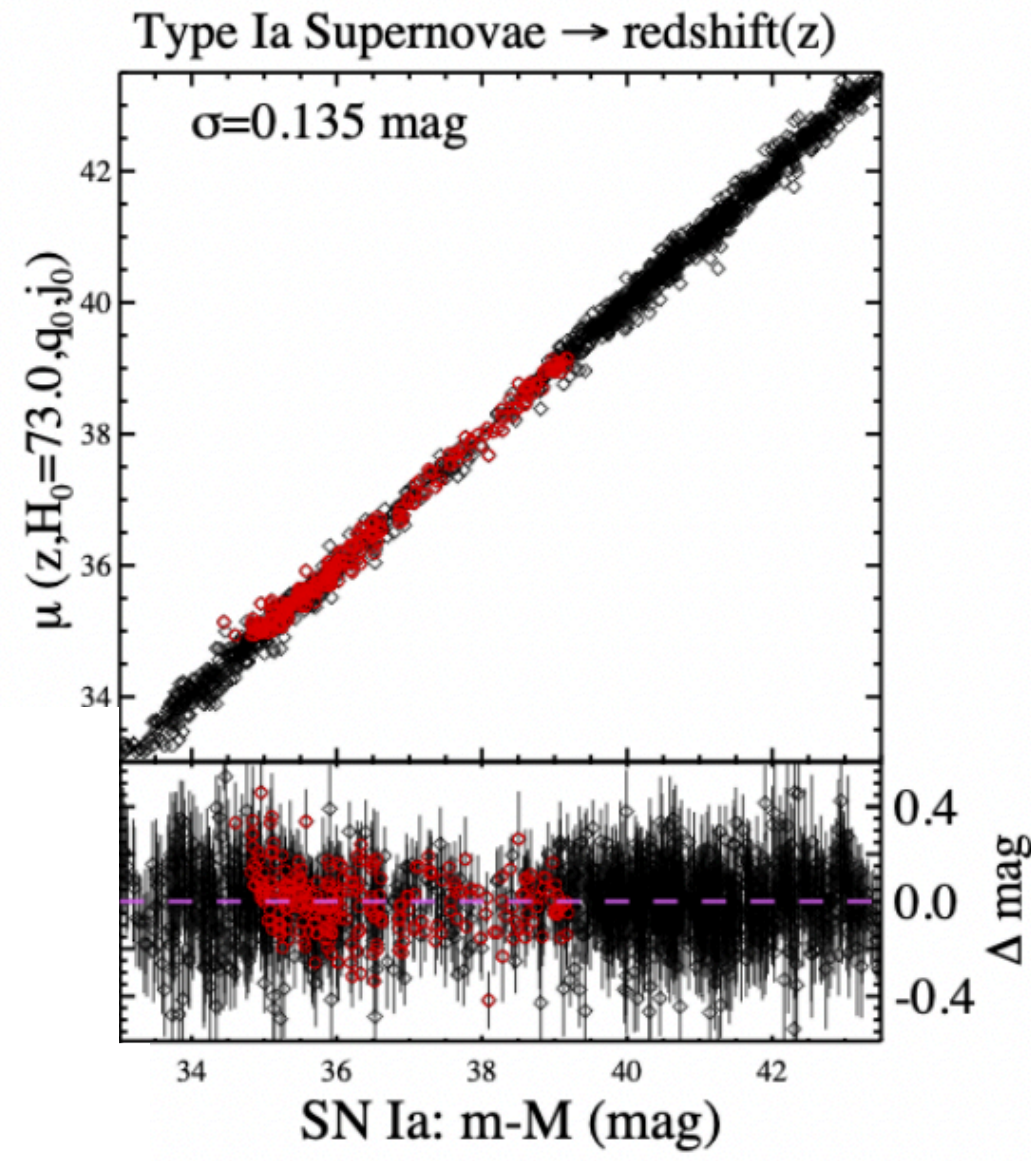
The SH0ES Distance Ladder, 2022

1. Geometric distances to Cepheids

2. Cepheids in galaxies with SNe Ia

3. SNe Ia in the Hubble flow

   Doubled the Hubble flow sample with 500+ SNe in Riess+22 with improved calibration and reduced selection biases (new samples from Foley+18, Jones+19)



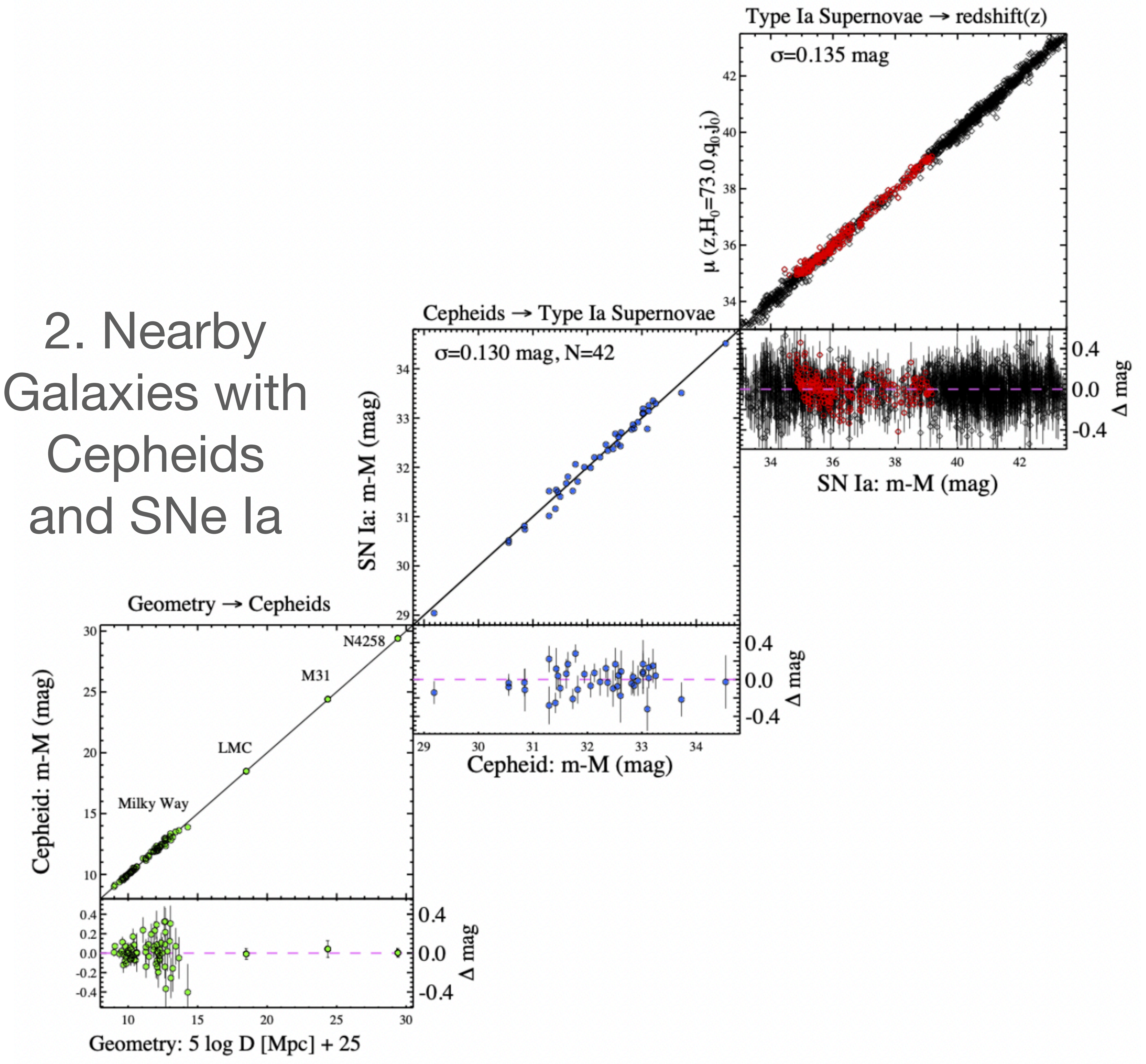
Riess+22 (incl. Jones)

The SH0ES Distance Ladder, 2022

1. Geometric Anchors

2. Nearby Galaxies with Cepheids and SNe Ia

3. SNe Ia in the Hubble flow

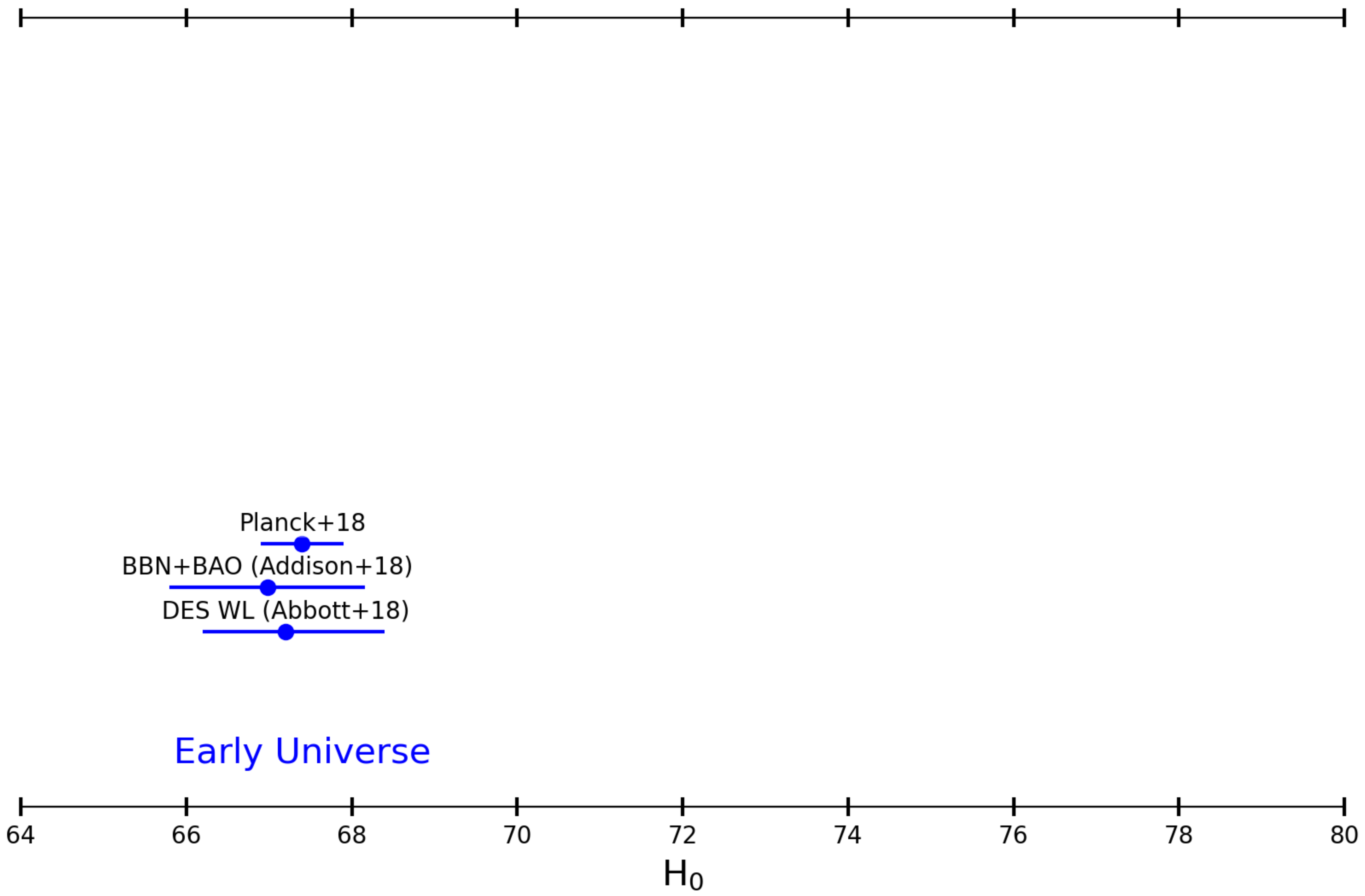


Local H_0 = 73.0 +/- 1.0 km/s/Mpc (Riess+22)

versus

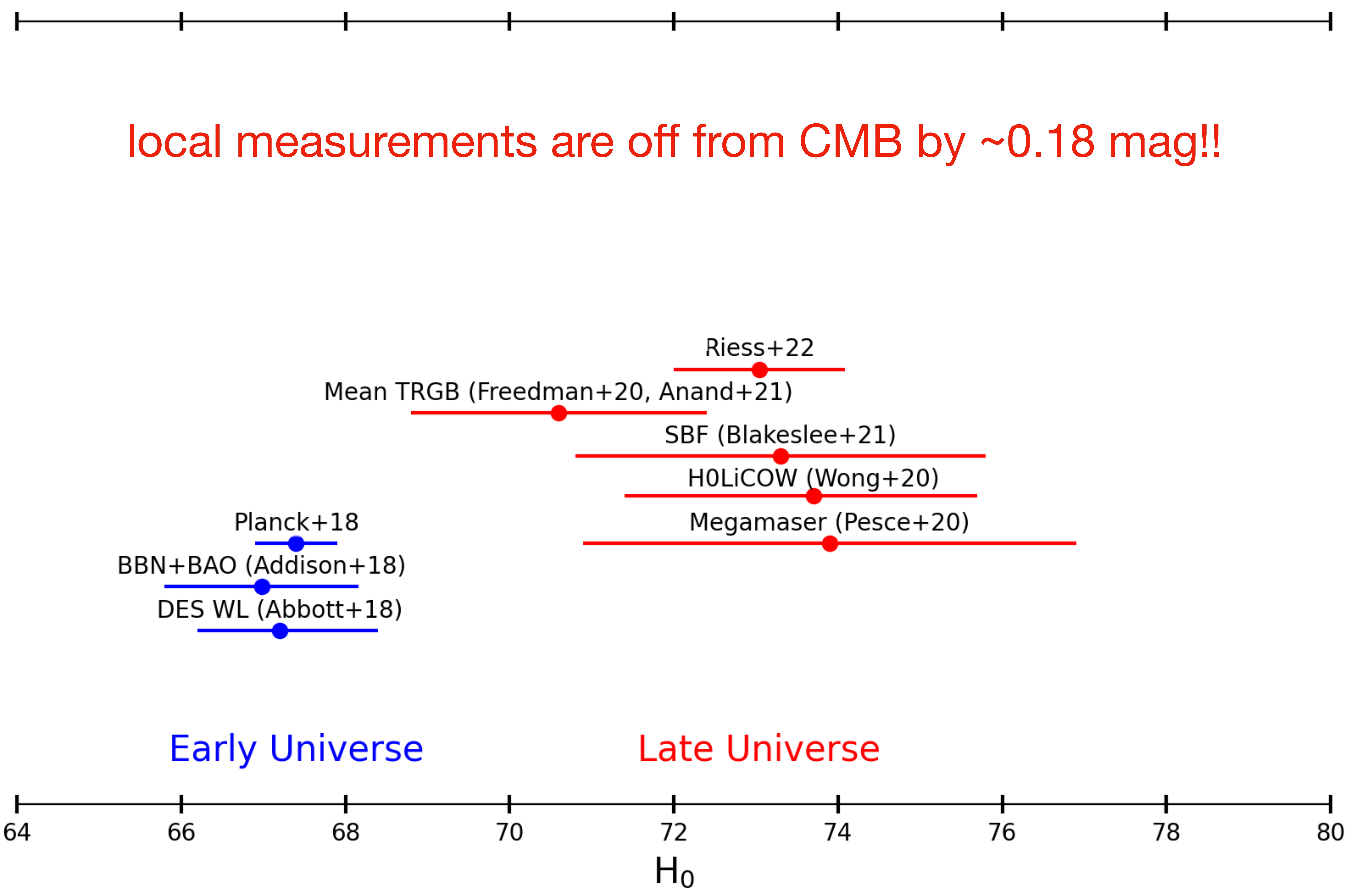
CMB H_0 = 67.5 +/- 0.4 km/s/Mpc

Tension in the Hubble Constant



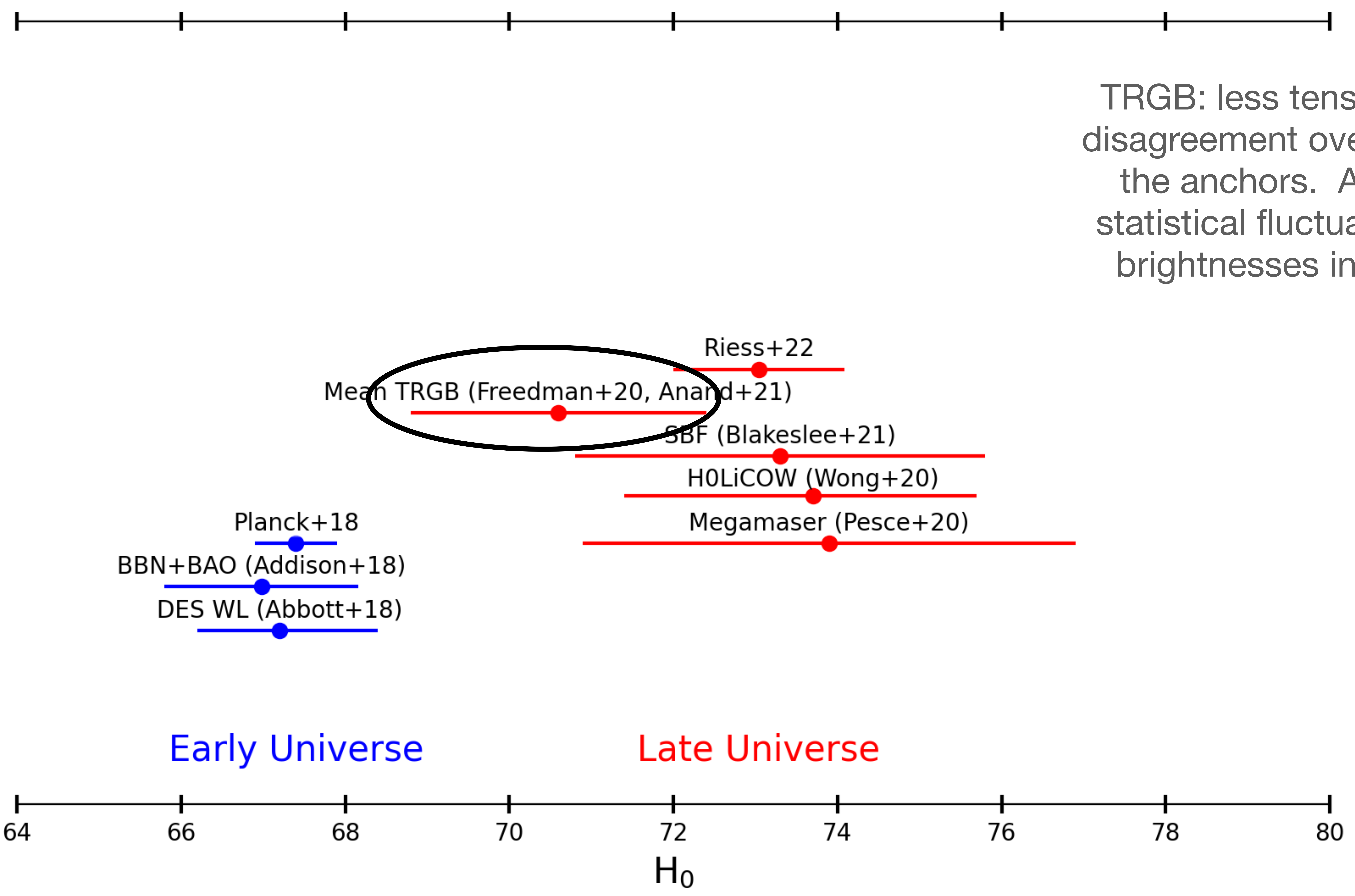
Tension in the Hubble Constant

local measurements are off from CMB by ~0.18 mag!!



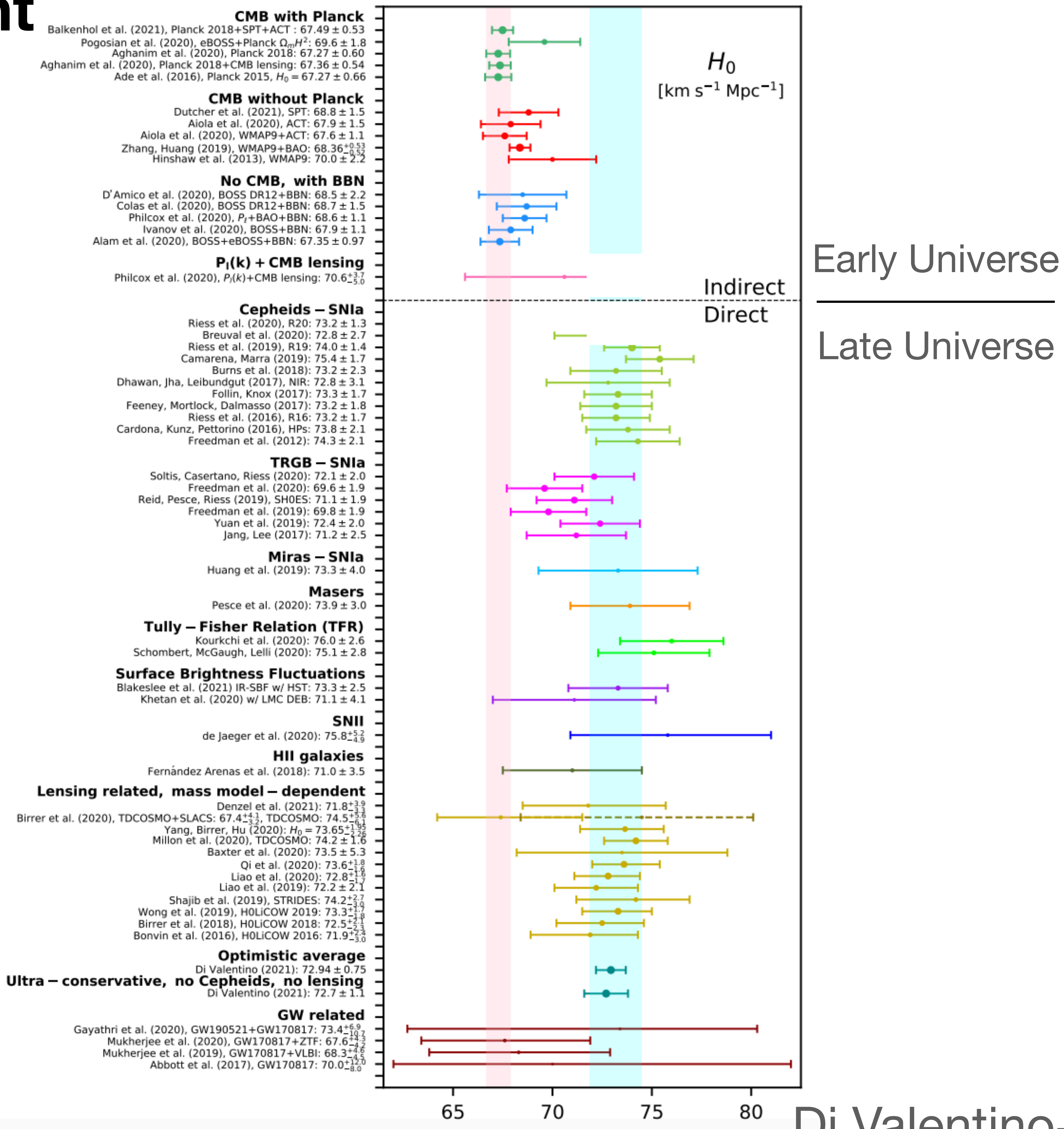
Tension in the Hubble Constant

TRGB: less tension, but some disagreement over calibration of the anchors. Also could be statistical fluctuation in the SN brightnesses in TRGB hosts



Tension in the Hubble Constant

- Includes TRGB, Miras, Masers, Tully-Fisher, Surface Brightness Fluctuations, SN II, Lensing Time Delays, Gravitational Waves



Di Valentino+21

Tension in the Hubble Constant

- Re-analyses of SH0ES haven't found anything very different in the past:
    - Follin & Knox 2017: modeling of cepheid systematics/photometry. H_0 =73.3 ± 1.7 (stat) km/s/Mpc.
    - Cardona et al. 2017: Bayesian hyper-parameters for outlier rejection. H_0 = 73.75 ± 2.11 km/s/Mpc.
    - Feeney et al. 2017: Bayesian hierarchical model, impact of non-gaussian likelihoods. H_0 = 72.72 ± 1.67 km/s/Mpc.
    - Zhang et al. 2017: Blinded, Bayesian hierarchical analysis of Riess+11. H_0 = 73.2 ± 3.1 (stat) ± 0.77 (sys) km/s/Mpc.
    - Burns 2018: Re-analysis of Cepheid data and new treatment of SNe Ia. H_0 = 73.2 ± 2.3 km/s/Mpc.
    - Javanmardi et al. 2021: independent confirmation of SH0ES NGC 5584 Cepheid distance with different photometry tools.

Tension in the Hubble Constant

Theorists are starting to have some fun

A Symmetry of Cosmological Observables, and a High Hubble Constant as an Indicator of a Mirror World Dark Sector

Francis-Yan Cyr-Racine,[1] Fei Ge,[2] and Lloyd Knox[2]

Early Dark Energy Can Resolve The Hubble Tension

Vivian Poulin[1], Tristan L. Smith[2], Tanvi Karwal[1], and Marc Kamionkowski[1]
[1]*Department of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, United States and*
[2]*Department of Physics and Astronomy, Swarthmore College, 500 College Ave., Swarthmore, PA 19081, United States*
(Dated: June 12, 2019)

Rock 'n' Roll Solutions to the Hubble Tension

Prateek Agrawal[1], Francis-Yan Cyr-Racine[1,2], David Pinner[1,3], and Lisa Randall[1]

Interacting dark energy in the early 2020s: a promising solution to the H_0 and cosmic shear tensions

Eleonora Di Valentino[a], Alessandro Melchiorri[b], Olga Mena[c], Sunny Vagnozzi[d]

Can Conformally Coupled Modified Gravity Solve The Hubble Tension?

Tal Abadi[1] and Ely D. Kovetz[1]
[1]*Department of Physics, Ben-Gurion University of the Negev, Be'er Sheva 84105, Israel*

Acoustic Dark Energy: Potential Conversion of the Hubble Tension

Meng-Xiang Lin,[1] Giampaolo Benevento,[2,3,1] Wayne Hu,[1] and Marco Raveri[1]

Alleviating the H_0 and σ_8 anomalies with a decaying dark matter model

Kanhaiya L. Pandey,[a] Tanvi Karwal[b] and Subinoy Das[c]

Oscillating scalar fields and the Hubble tension: a resolution with novel signatures

Tristan L. Smith[1], Vivian Poulin[2], and Mustafa A. Amin[3]

Constraining the Self-Interacting Neutrino Interpretation of the Hubble Tension

Nikita Blinov,[*] Kevin J. Kelly,[†] Gordan Krnjaic,[‡] and Samuel D. McDermott[§]
Fermi National Accelerator Laboratory, Batavia, IL, USA
(Dated: November 19, 2019)

Axion-Dilaton Destabilization and the Hubble Tension

Stephon Alexander[*] and Evan McDonough[†]
Brown Theoretical Physics Center, Brown University, Providence, RI, USA. 02912
and
Department of Physics, Brown University, Providence, RI, USA. 02912

Tension in the Hubble Constant

...and so is the media

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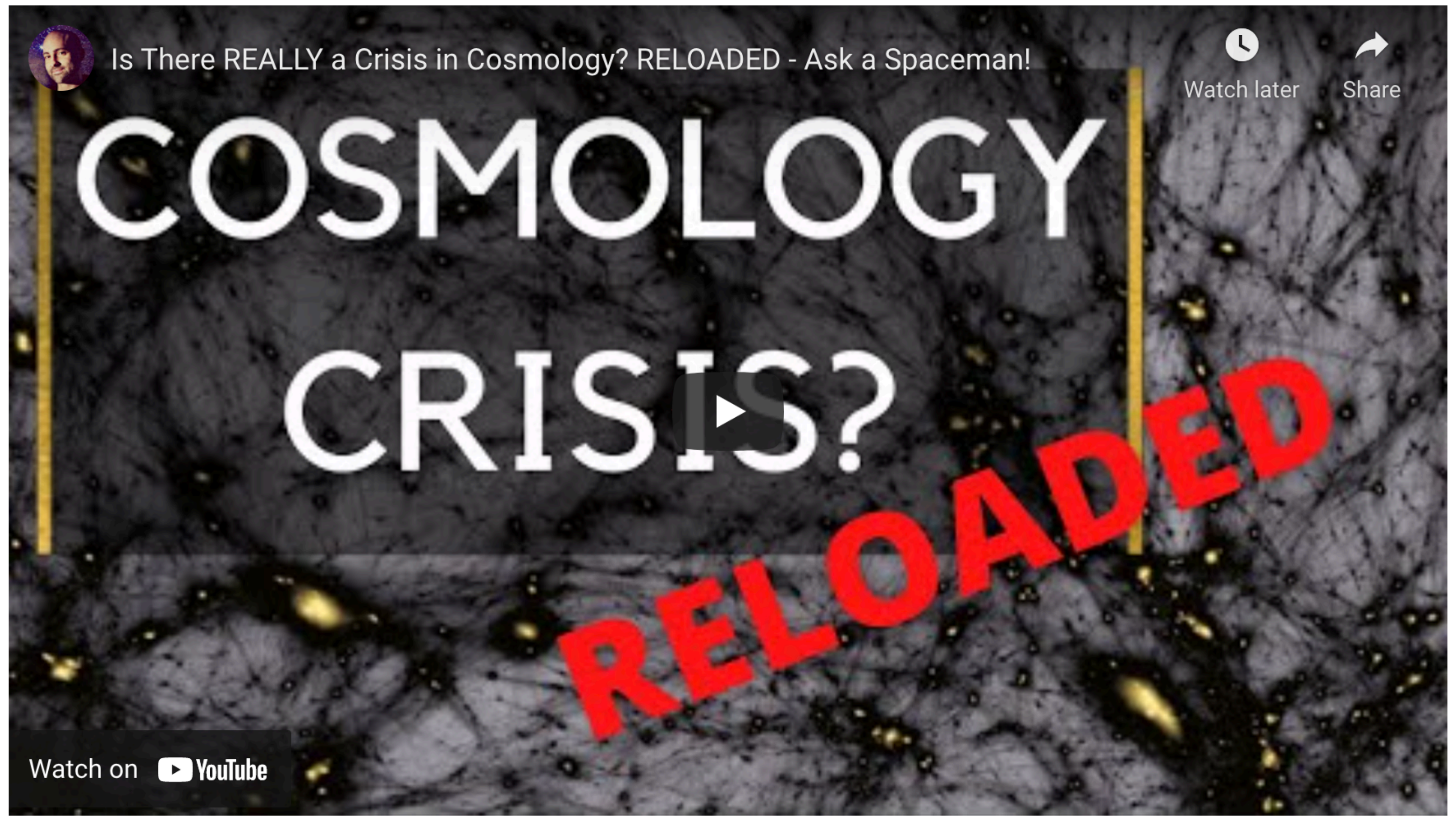
Beyond Earth

The universe is expanding faster than we thought

By Ashley Strickland, CNN
Published 2:52 PM EDT, Thu April 25, 2019



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A recharged debate over the speed of the expansion of the universe could lead to new physics

Cosmologists and astronomers have found a discrepancy in the Hubble constant from opposite ends of the universe

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SCIENCE

The Burning New Feud to Settle One of Physics' Biggest Questions

Quanta Magazine

Astronomers Get Their Wish, and the Hubble Crisis Gets Worse

We don't know why the universe appears to be expanding faster than it ... fast expansion of the universe, known as the Hubble tension.

Dec 17, 2020

Tension in the Hubble Constant

...and so is the media

CNN World Africa Americas Asia Australia China Europe India Middle East United Kingdom LIVE TV Edition

Beyond Earth

The universe is expanding faster than we thought

By Ashley Strickland, CNN
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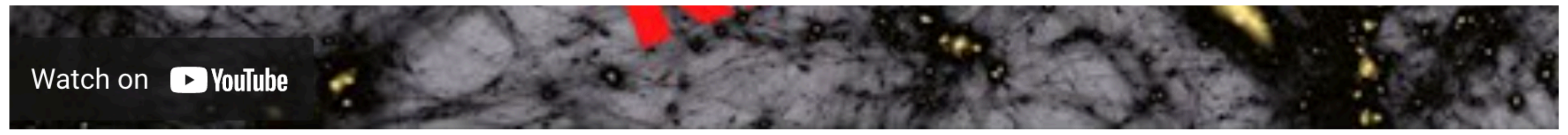
Science

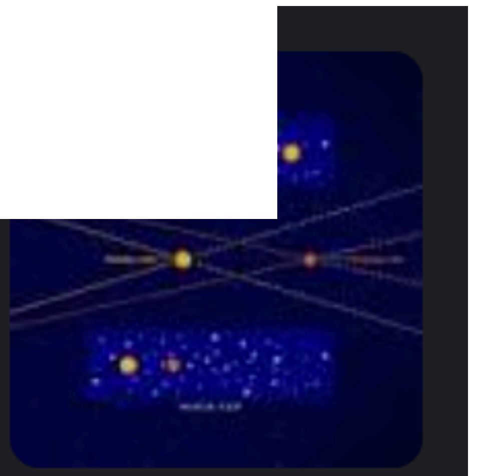
Scientists are baffled: What's up with the universe?



Worse

We don't know why the universe appears to be expanding faster than it ... fast expansion of the universe, known as the Hubble tension.

Dec 17, 2020



NEWS | SPACE

A recharged debate over the speed of the expansion of the universe could lead to new physics

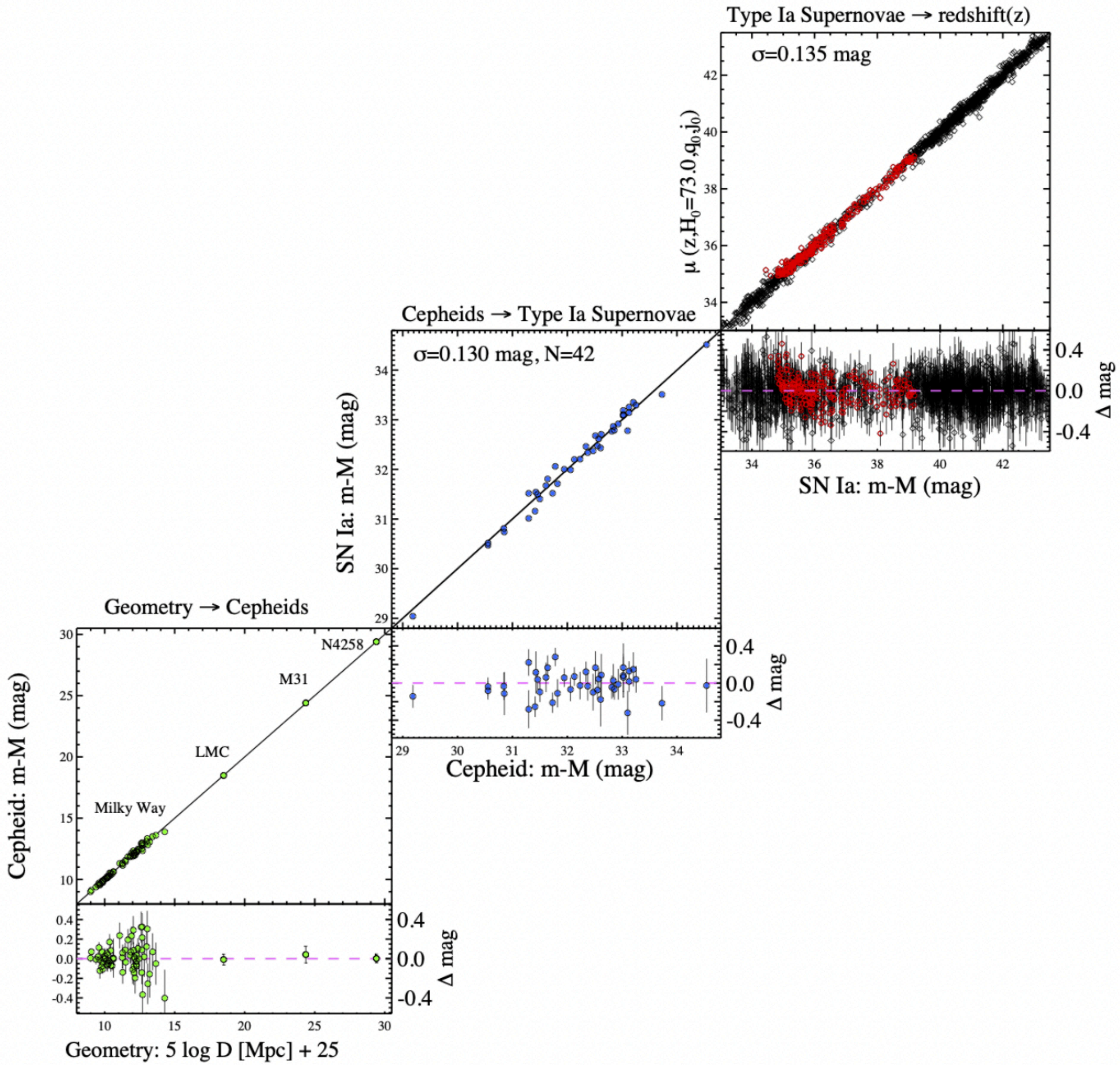
Cosmologists and astronomers have found a discrepancy in the Hubble constant from opposite ends of the universe

Could The H_0 Measurement Be Wrong?

- To measure an unbiased H_0, we need:

1. Accurate geometric distances
2. Consistent Cepheid distances between the first and second rungs of the distance ladder
3. Consistent SN Ia distances in the second and third rungs of the ladder
4. A reliable expansion history measurement in the third run (no voids/ non-LCDM)

- These are the **only** ways for systematic error to enter the measurement



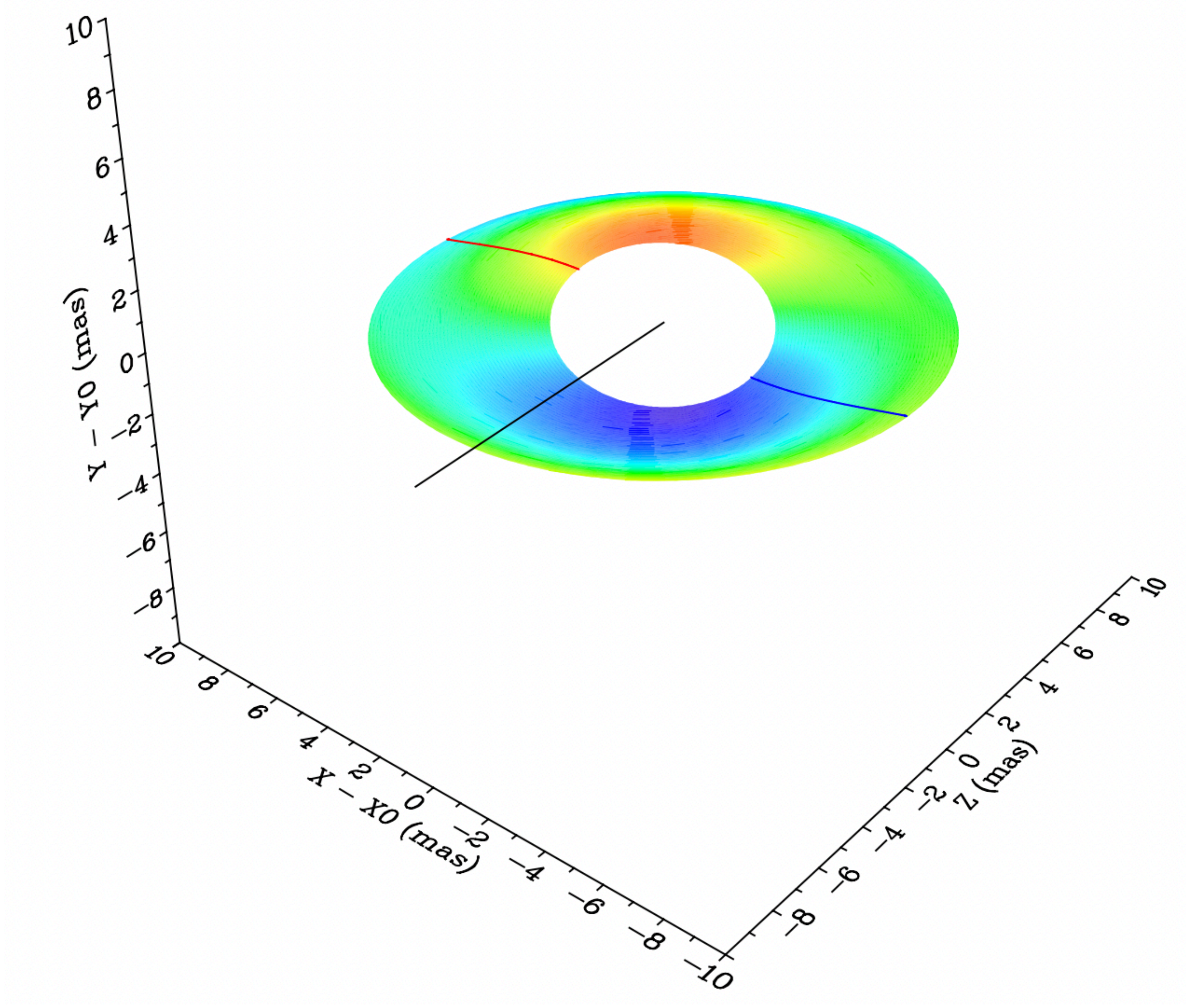
Could The H_0 Measurement Be Wrong?
1. Geometric Distances

- Three geometric anchors with **fully independent** systematics:

  1. NGC 4258 megamaser: H_0 = 72.51 +/- 1.54

  2. Milky Way Cepheid parallaxes: H_0 = 73.02 +/- 1.19

  3. LMC eclipsing binaries: H_0 = 73.59 +/- 1.36



NGC 4258 Maser Disk Model

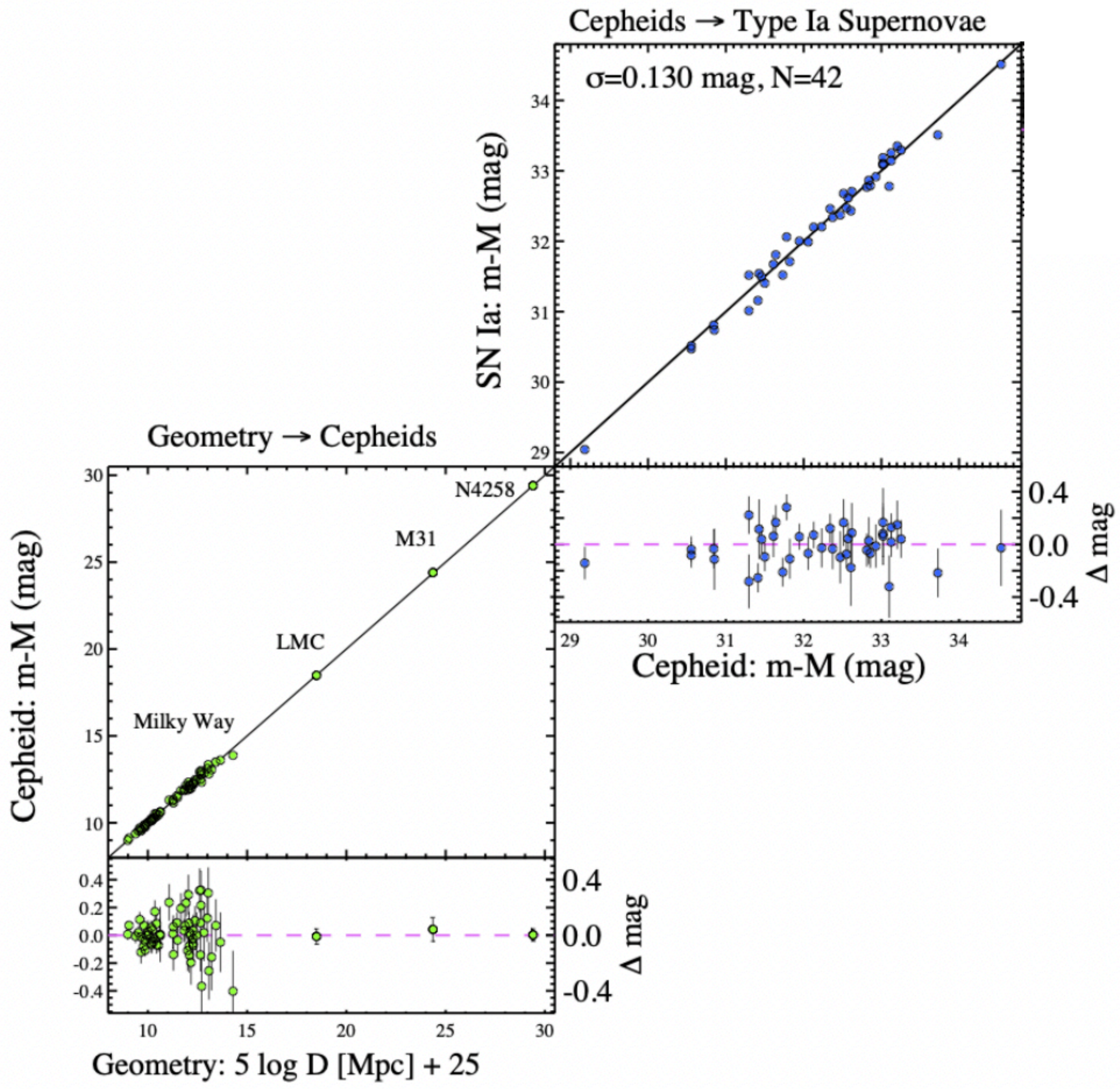
Humphreys+13

Could The H_0 Measurement Be Wrong?

2. Cepheid Distances

- Potential inconsistencies between first and second rung

  1. Calibration
  2. Metallicity
  3. Reddening Law
  4. Crowding



Could The H_0 Measurement Be Wrong?

2. Cepheid Distances

- Potential inconsistencies between first and second rung

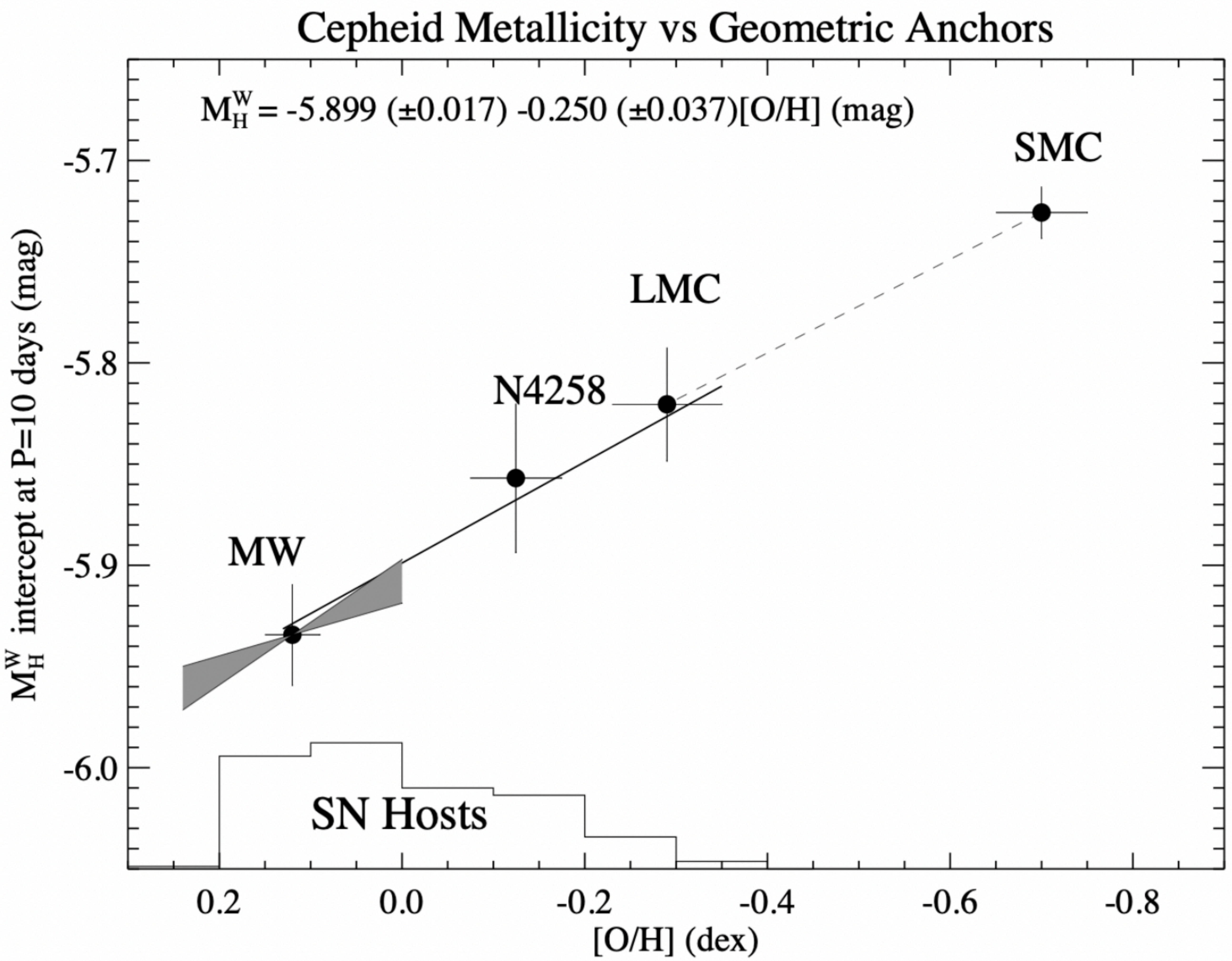
  1. Calibration

     - WFC3's *F160W* filter used for every Cepheid distance measurement, negating calibration uncertainties

     - Updated WFC3 count-rate nonlinearity correction improves the photometry further

Could The H_0 Measurement Be Wrong?
2. Cepheid Distances

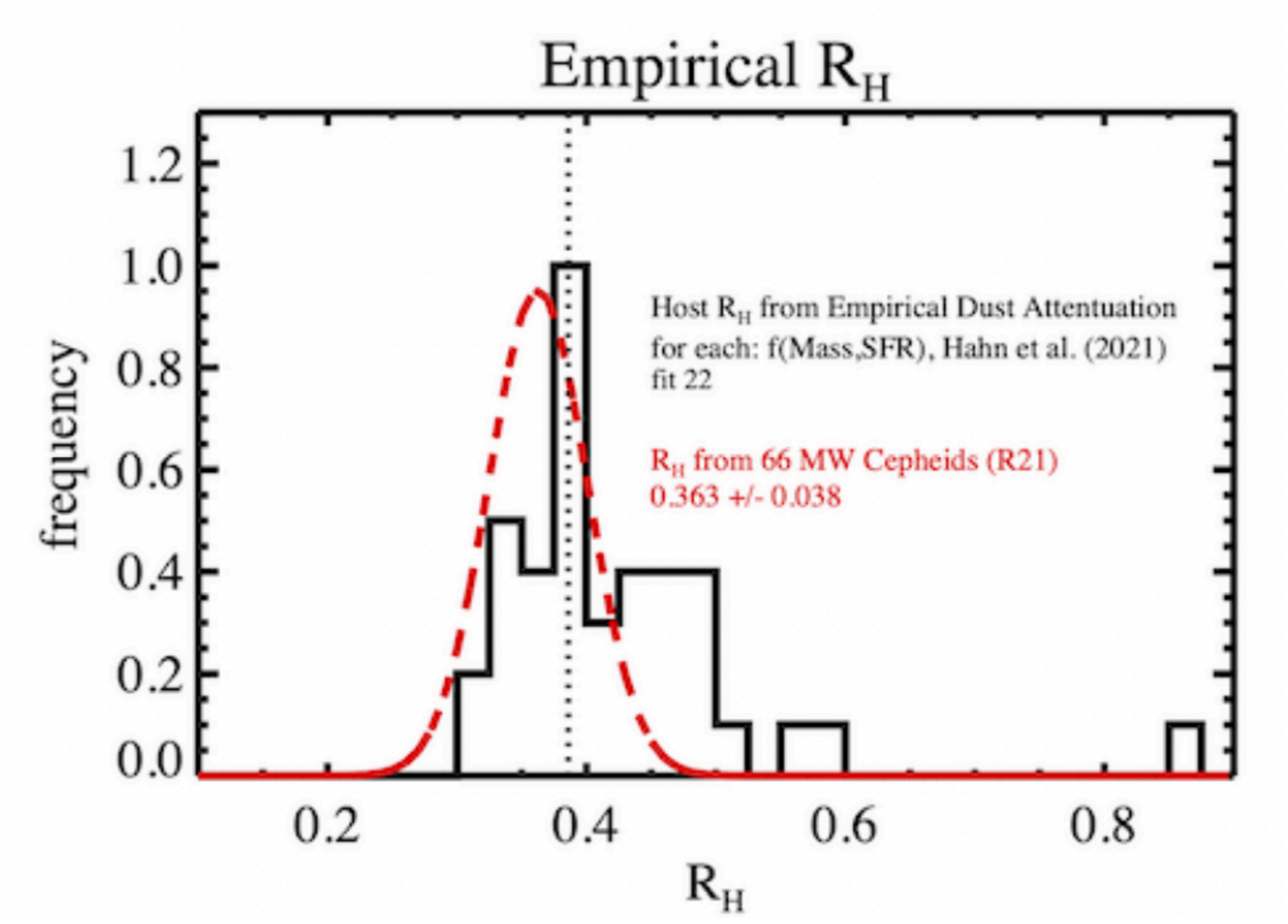
- Potential inconsistencies between first and second rung
  1. Calibration
  2. Metallicity
     - no significant offset between geometric anchor metallicity and calibrator metallicity
     - Anderson & Riess (2018) saw no significant H_0 bias caused by photometry of crowded Cepheids in binaries or open clusters in high-metallicity environments
     - H_0 posterior shows measurement doesn't depend on metallicity



Riess+22

Could The H_0 Measurement Be Wrong?
2. Cepheid Distances

- Potential inconsistencies between first and second rung
  1. Calibration
  2. Metallicity
  3. Reddening Law
     - Consistent H_0 measurements from $2.5 \lesssim R_V \lesssim 3.3$
     - Consistent H_0 measurements when allowing R_V to be a free global parameter
     - Consistent H_0 measurements when allowing R_V to vary for different hosts, after correcting for intrinsic Cepheid period-color relation

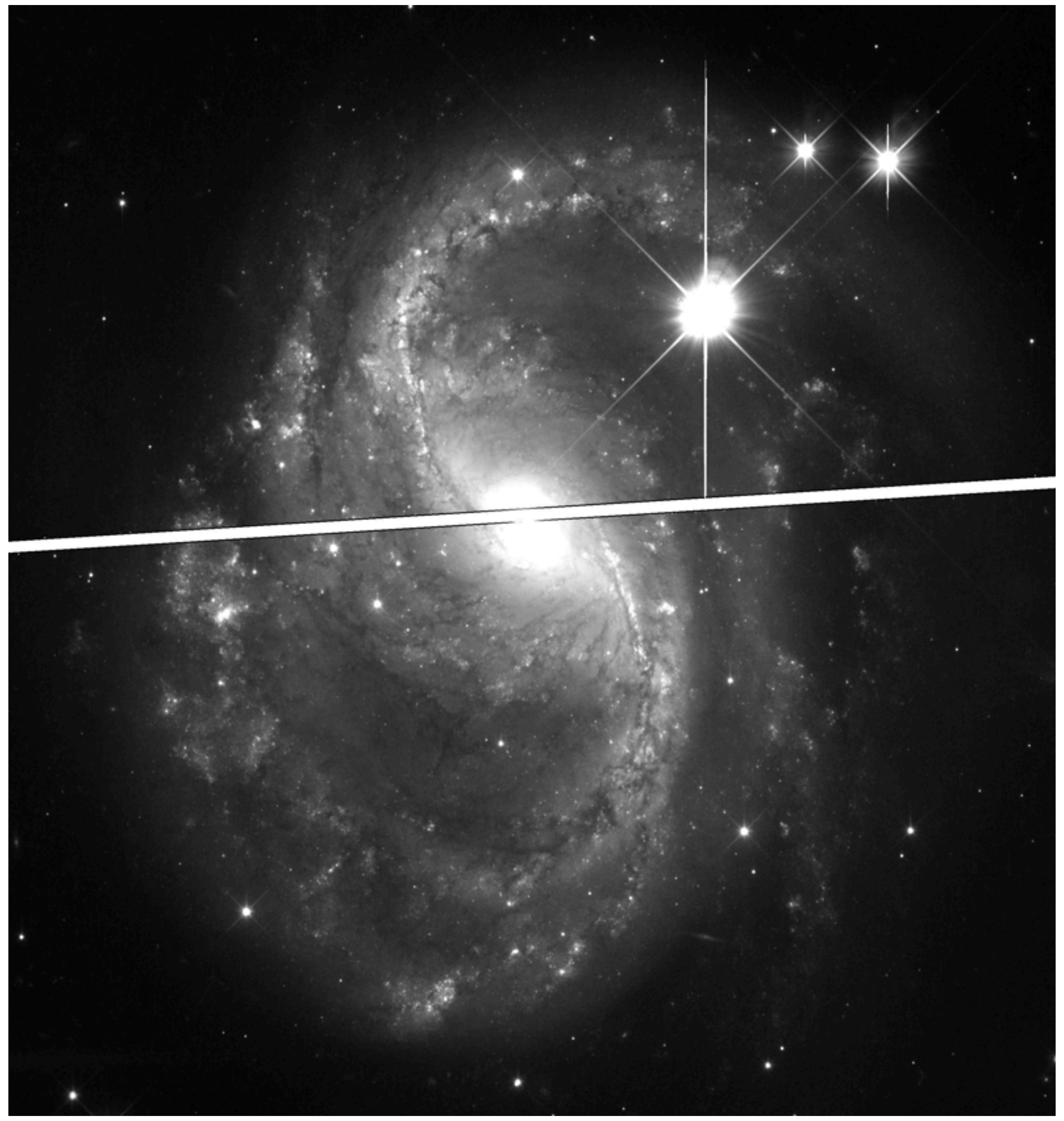


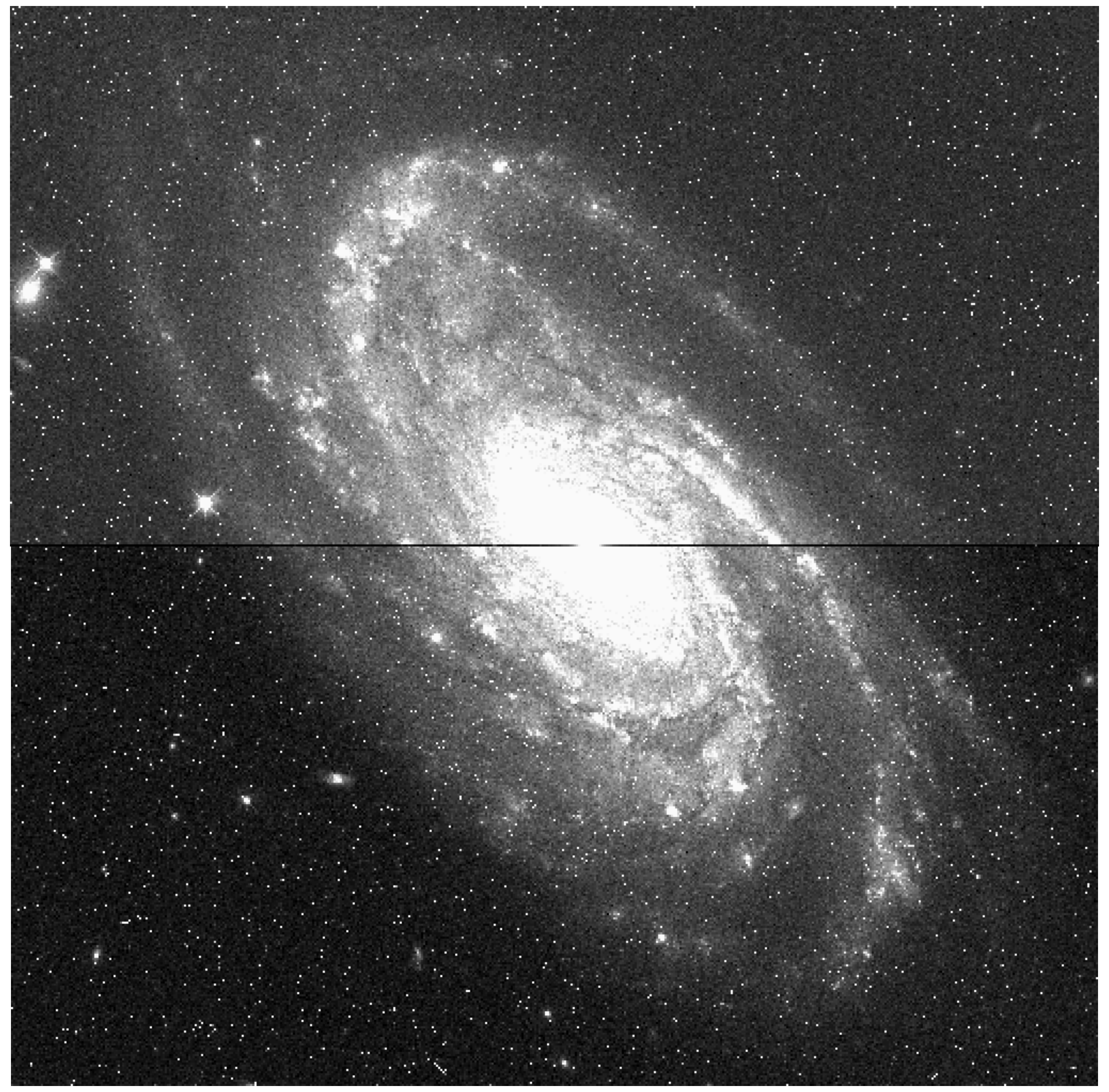
Riess+22

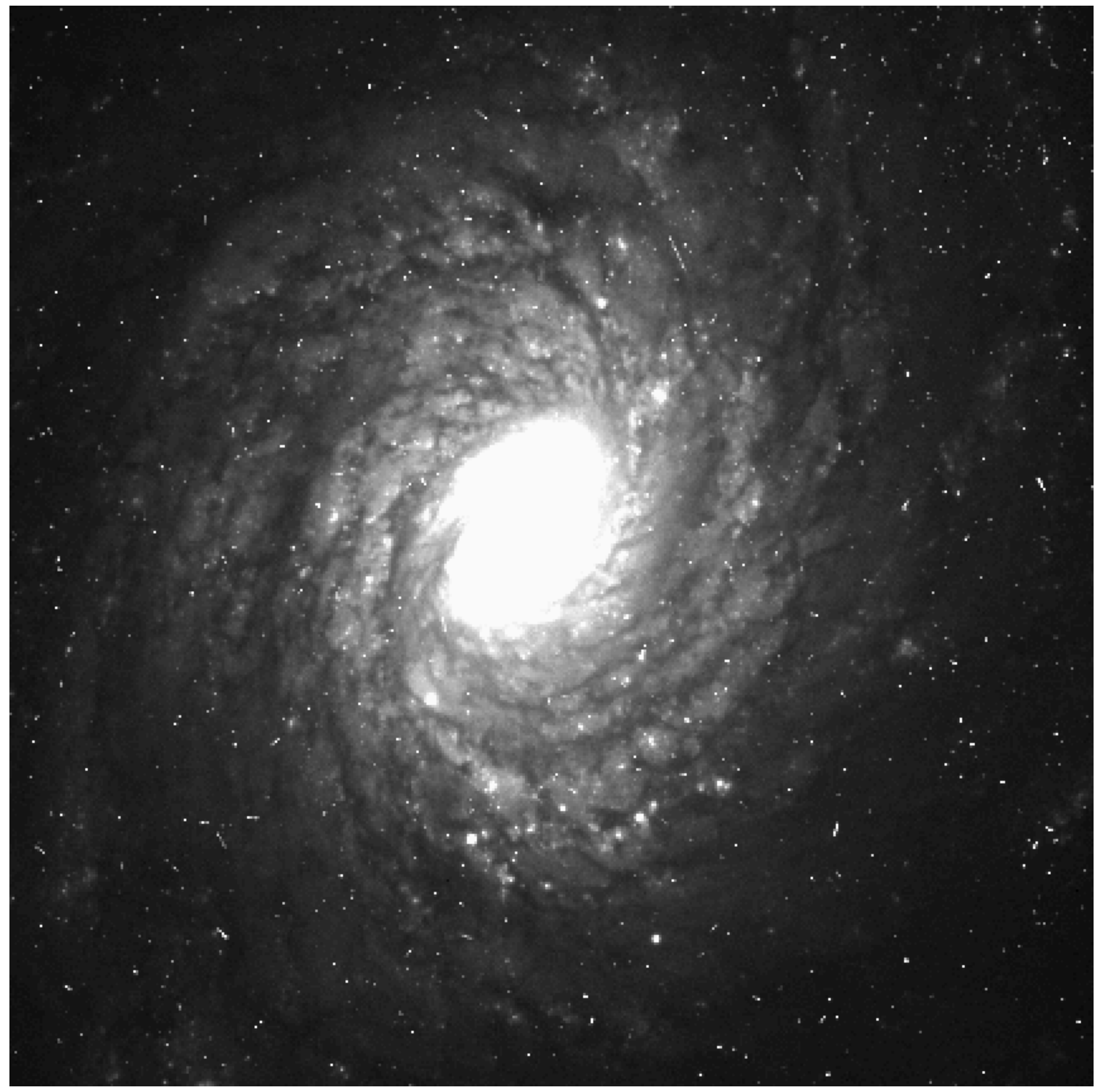
Could The H_0 Measurement Be Wrong?
2. Cepheid Distances

- Potential inconsistencies between first and second rung

  1. Calibration
  2. Metallicity
  3. Reddening Law
  4. Crowding
     - With HST-GO 16269 (PI: Jones), we doubled the maximum Cepheid distance compared to the last SH0ES analysis to look for crowding systematics





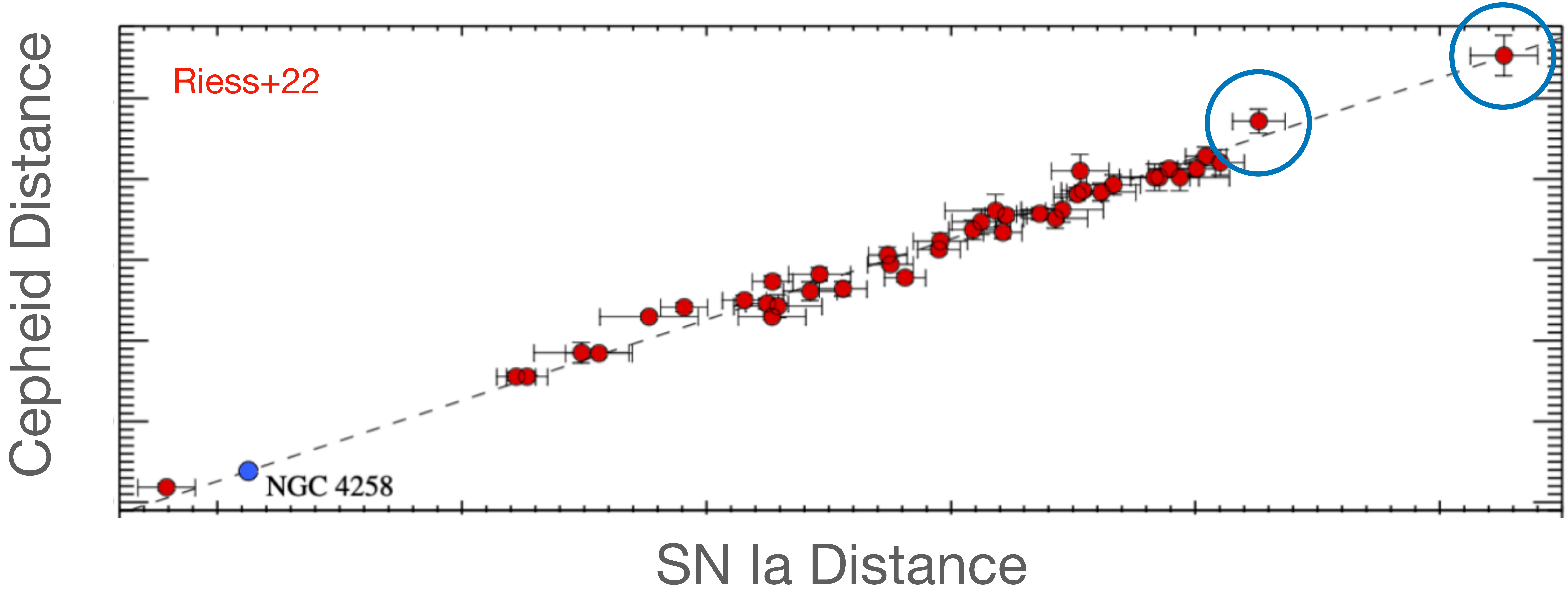


Jones+in prep

Improving the Measurement of H_0

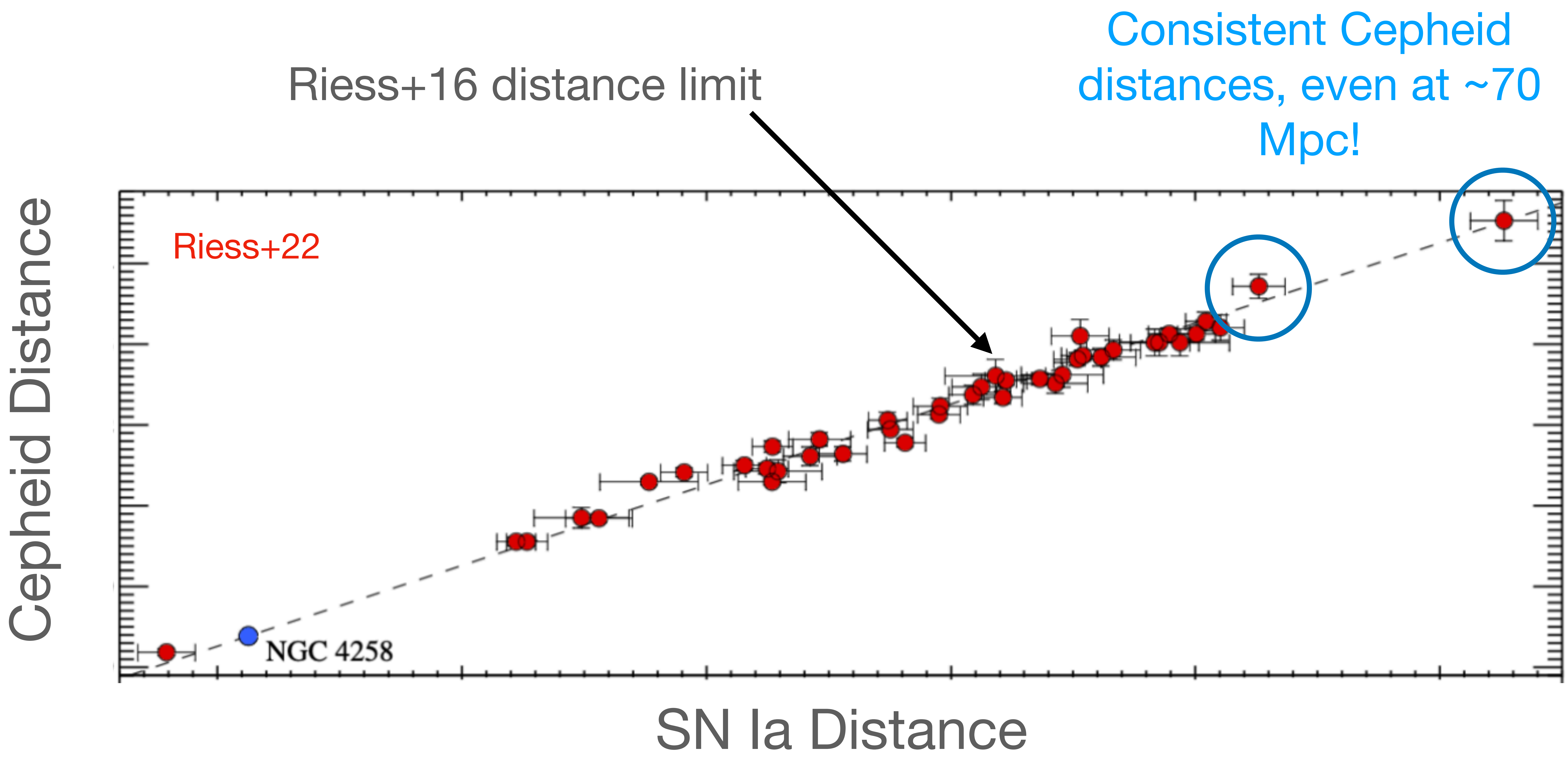
2. Cepheid Distances

Consistent Cepheid distances, even at ~70 Mpc!



Improving the Measurement of H_0

2. Cepheid Distances



Could The H_0 Measurement Be Wrong?

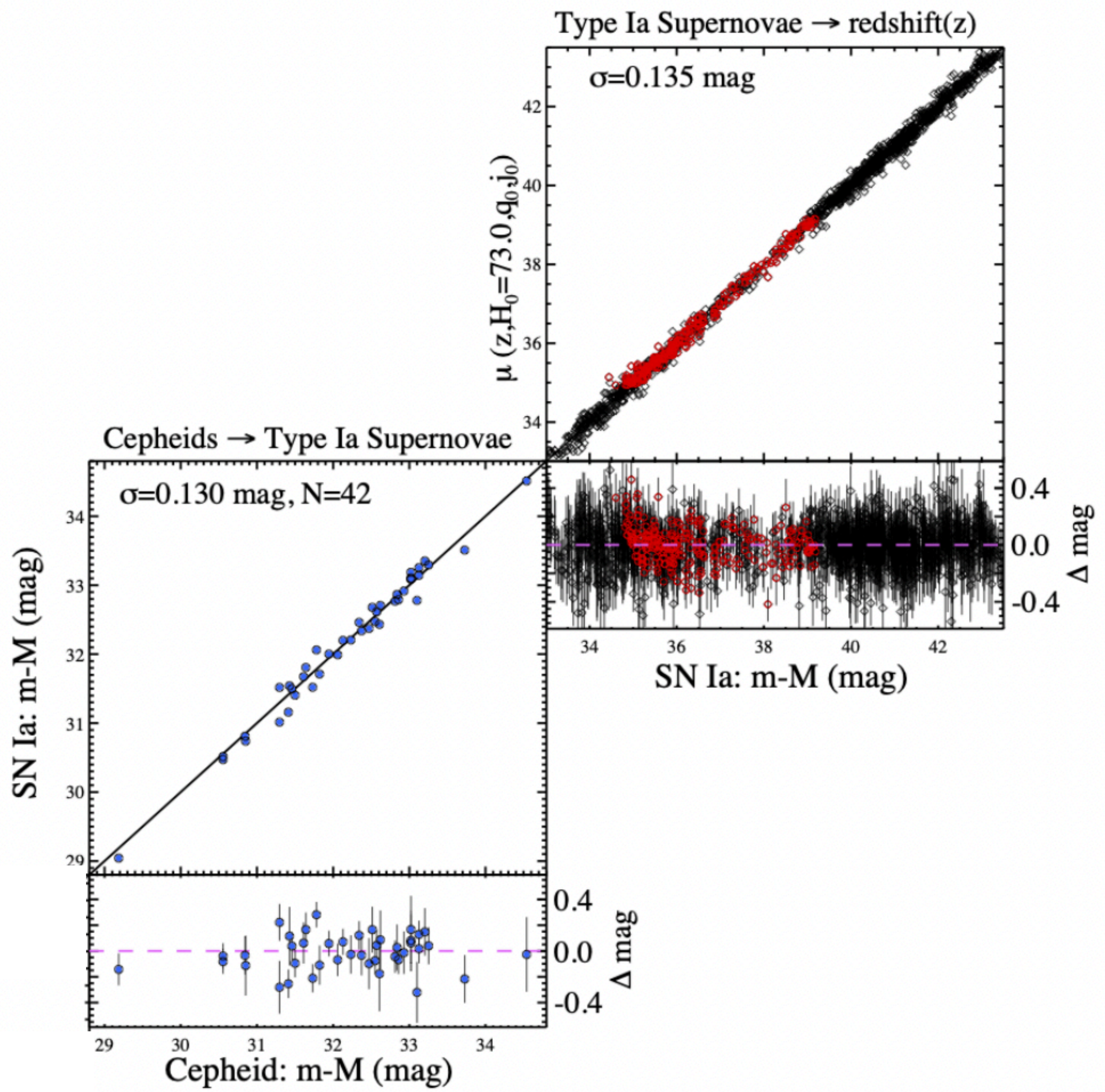
3. SN Distances

- Potential inconsistencies between second and third rung

  1. SN Progenitors ("host correction")
  2. Extinction Laws
  3. Calibration

- Expansion history biases

  4. Local Void
  5. Cosmological Model

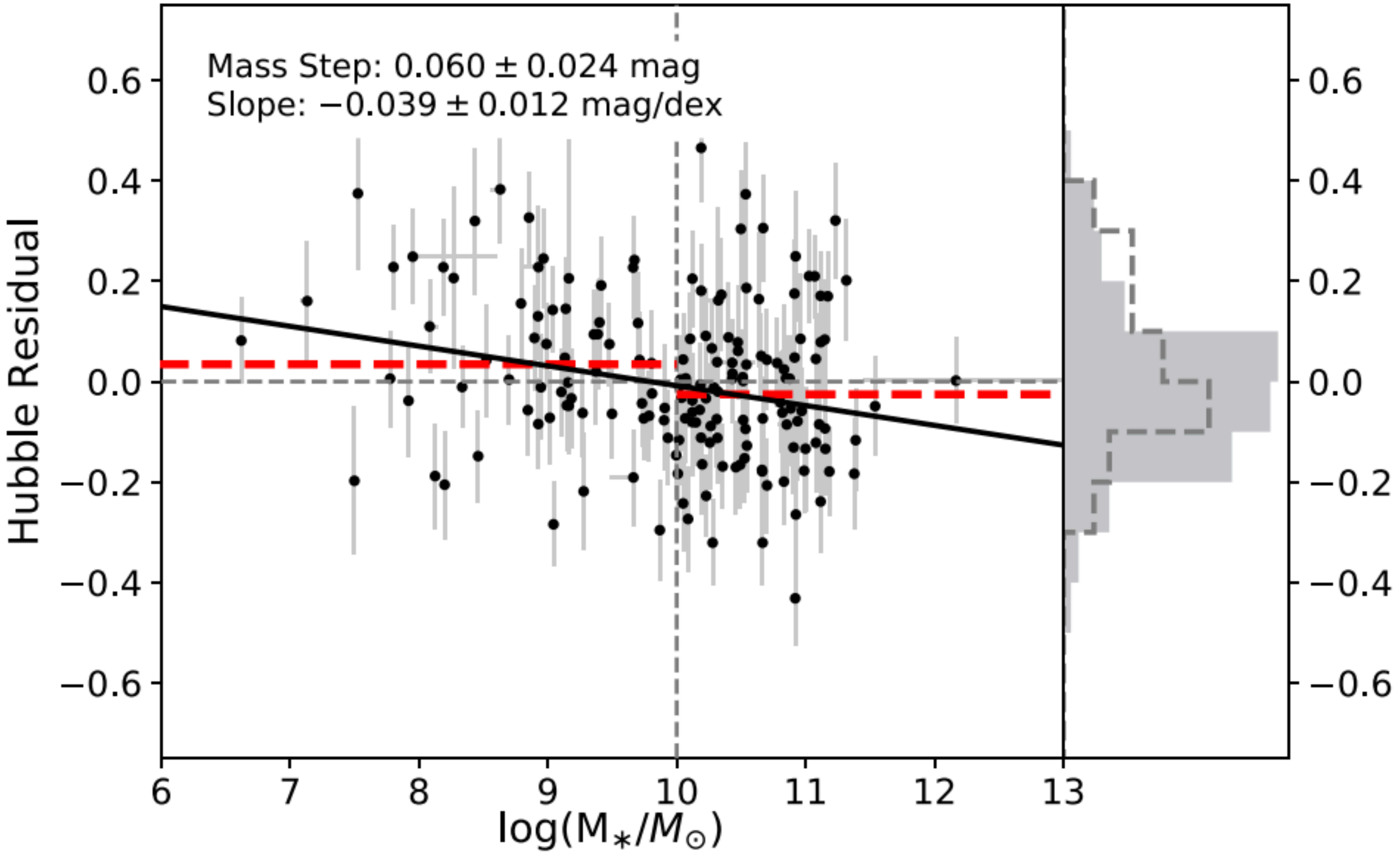


Could The H_0 Measurement Be Wrong?
3. SN Distances

- Potential inconsistencies between second and third rung

  1. SN Progenitors ("host correction")

     - SN Distance Measurements change depending on the mass of their host galaxies (Kelly+10, Lampeitl+10, Sullivan+10), cause unknown
     - Results in systematic uncertainties when second rung versus third rung galaxies have different demographics

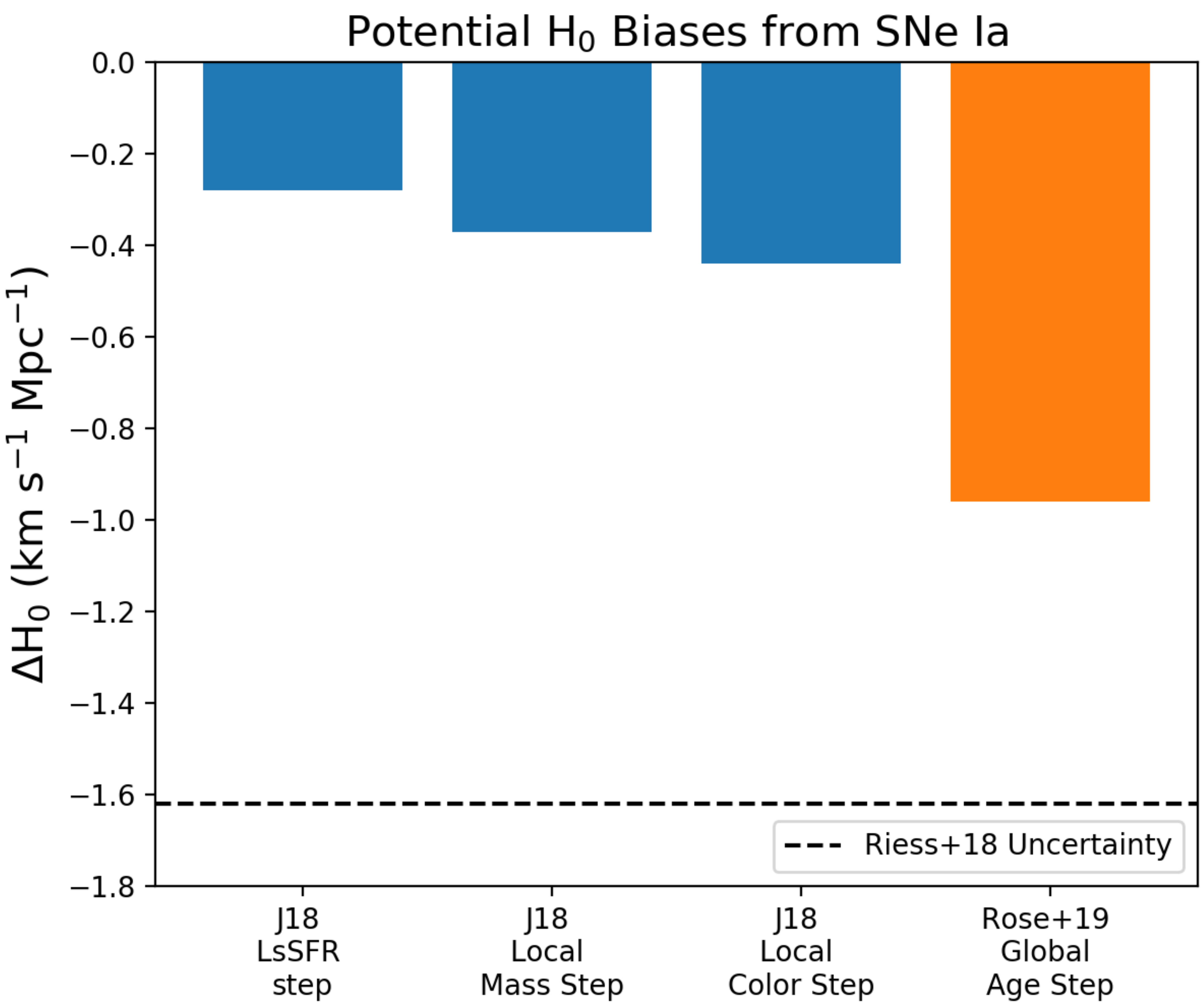


Jones+19

Could The H_0 Measurement Be Wrong?

3. SN Distances

- Potential inconsistencies between second and third rung
  1. SN Progenitors ("host correction")
     - A lot of recent work to rebuild the SN sample (Foundation; Jones+19)
     - In latest SH0ES paper, only late-type galaxies are used to mitigate selection effects
     - In Jones+18, we found alternative host corrections change H_0 by < 0.5%



Jones+18; Rose+19

Could The H_0 Measurement Be Wrong?
3. SN Distances

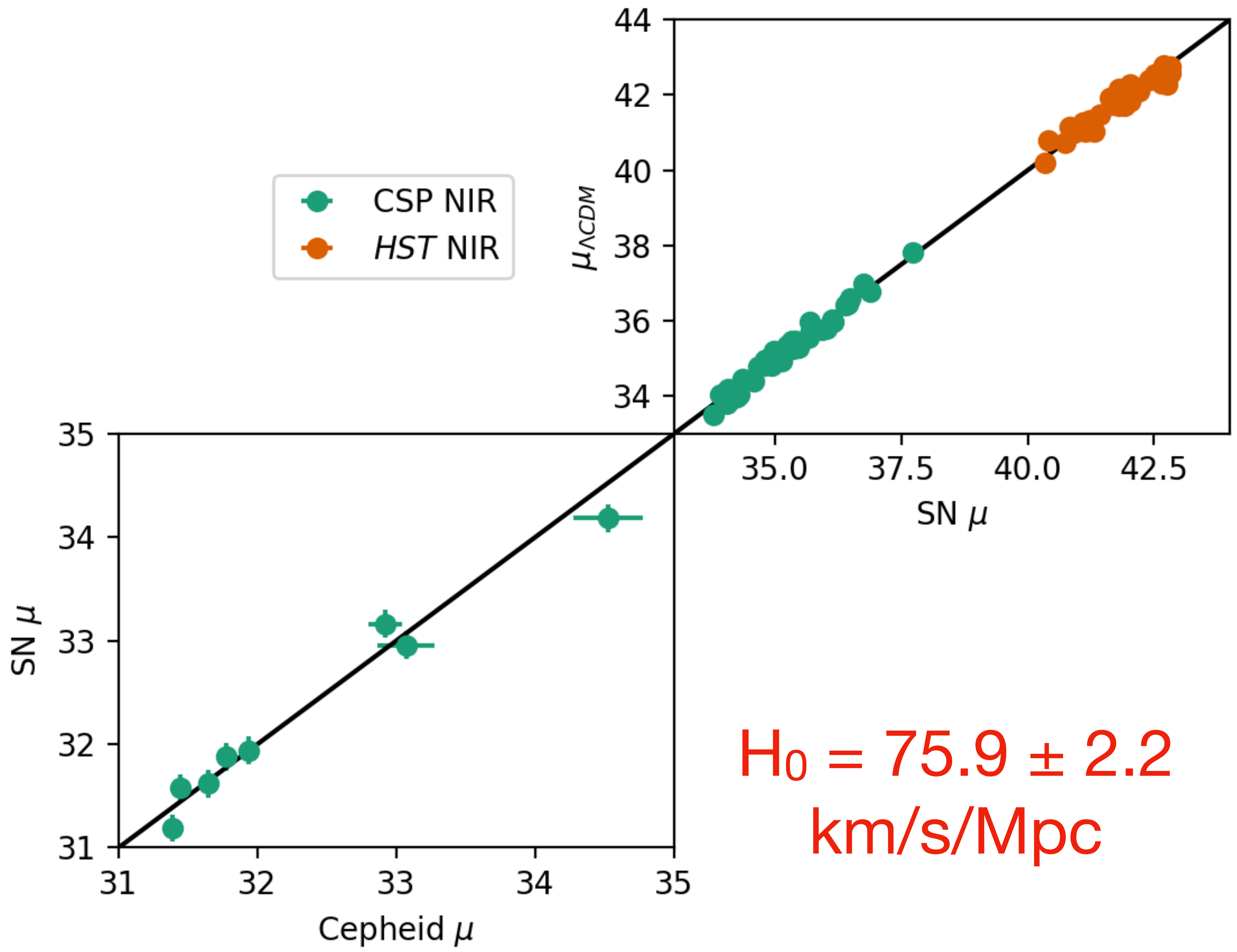
- Potential inconsistencies between second and third rung

  1. SN Progenitors ("host correction")

  2. Extinction Laws

     - Variation in extinction laws (e.g., Brout & Scolnic 2021; Wojtak & Hjorth 2022) between second and third-rung galaxies could affect H_0

     - But, NIR measurements of H_0 find consistent results (Jones+22, Galbany+22)



$H_0 = 75.9 \pm 2.2$ km/s/Mpc

Jones+22

Could The H_0 Measurement Be Wrong?

3. SN Distances

- Potential inconsistencies between second and third rung

  1. SN Progenitors (“host correction”)
  2. Extinction Laws
  3. Calibration

     - Foundation sample is significantly better calibrated, includes half of the Hubble flow sample and ~5 of the 42 H_0 calibrators
     - Excluding pre-2000 SN data changes H_0 by less than 0.5 km/s/Mpc

Sample Variant	H_0	err
No SDSS SNe	72.90	1.02
No CSP SNe	73.43	1.06
No literature SNe	73.47	1.05
No LOSS SNe	73.26	1.04
No SWIFT SNe	73.09	1.02
No CfA1/2 SNe	73.03	1.03
No CfA3/4 SNe	73.31	1.02
No Foundation SNe	73.46	1.03
No pre-2000 SNe	73.20	1.09

Could The H_0 Measurement Be Wrong?

4. Biased Expansion History

The Local Perspective on the Hubble Tension: Local Structure Does Not Impact Measurement of the Hubble Constant

W. D'Arcy Kenworthy[1], Dan Scolnic[2], and Adam Riess[1,3]

[1] Department of Physics and Astronomy, Johns Hopkins University, 3701 San Martin Drive, Baltimore, MD 21218, USA; wkenwor1@jhu.edu, darcy@darcykenworthy.com

[2] Department of Physics, Duke University, 120 Science Drive, Durham, NC 27708, USA

[3] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

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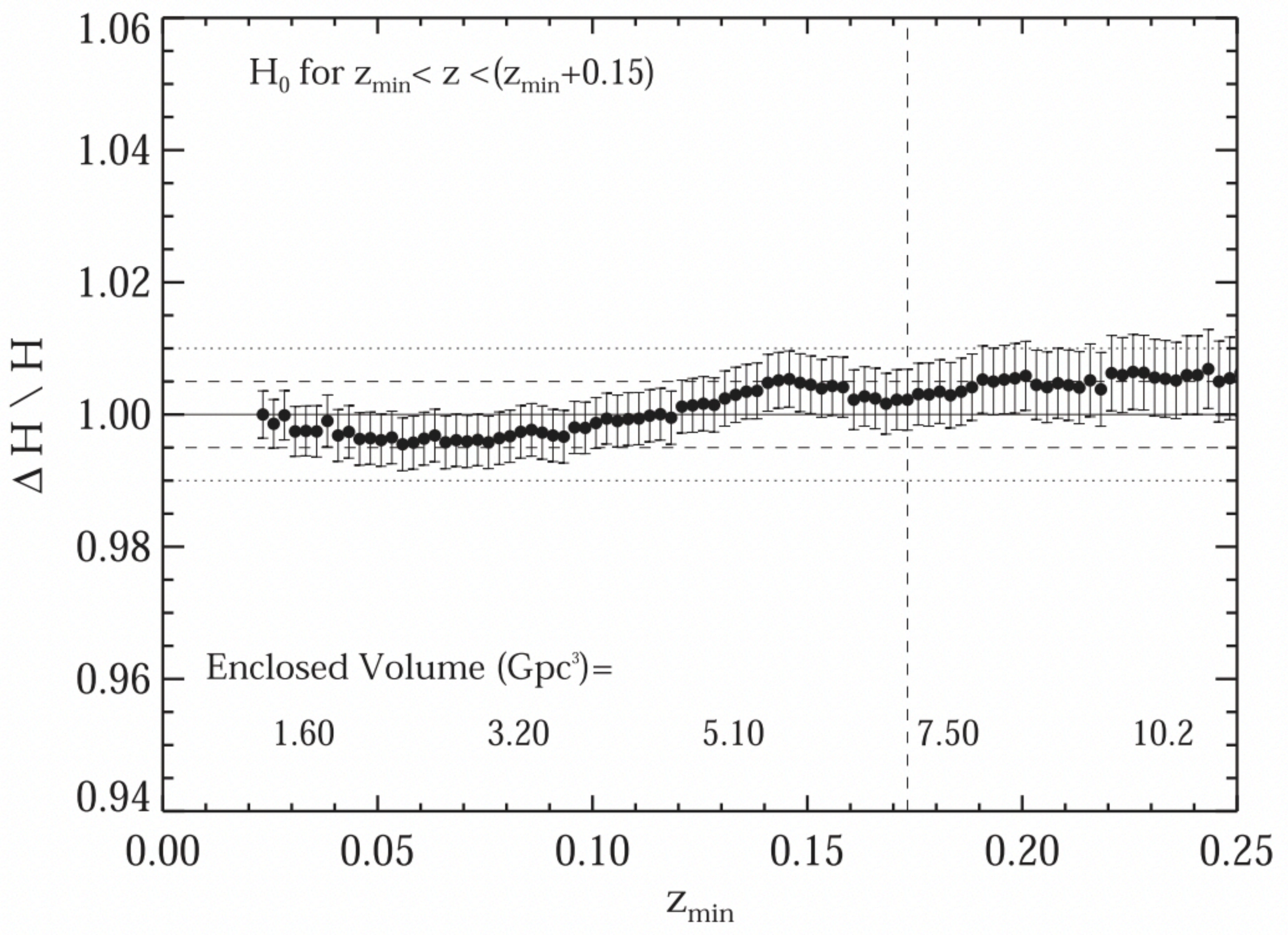
- Biases in the third rung

  1. Local Void

     - Kenworthy+19: H_0 insensitive to local structure at the 0.6% level

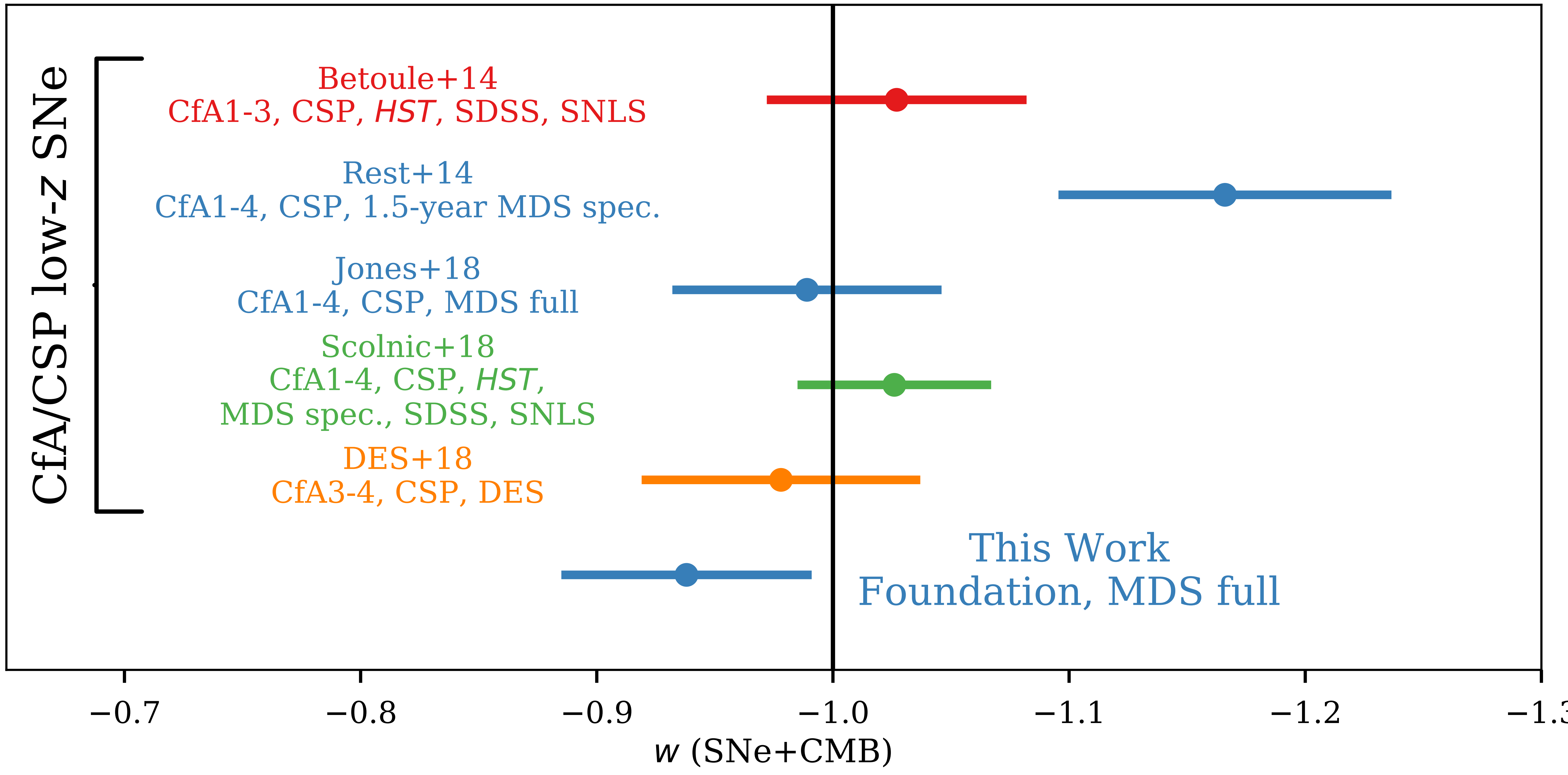
     - Riess+16 also shows no strong trends with minimum redshift for H_0 measurement



Riess+16

Could The H_0 Measurement Be Wrong?
4. Biased Expansion History

- Biases in the third rung
  1. Local Void
  2. Cosmological Model
     - Not much current evidence for non-LCDM late-time expansion histories

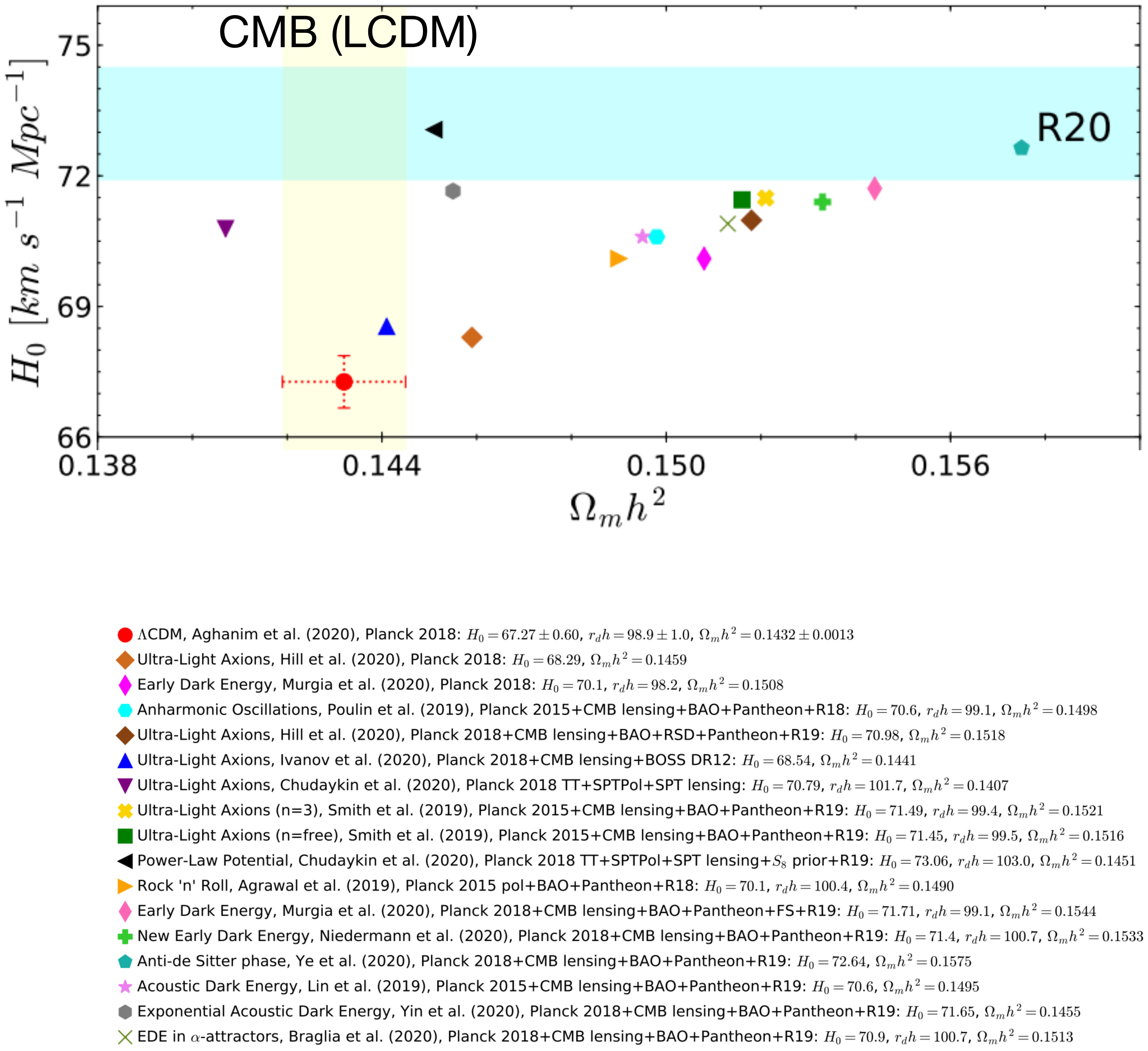


Brout+22: $w = -0.978^{+0.024}_{-0.031}$

Jones+19

Possible Theoretical Solutions

- In general, it is really tough to resolve the tension!
- Early dark energy, late-universe dark energy, extra relativistic species, coupled dark matter/dark energy are possibilities but many fail to fully solve the tension



Di Valentino+21

Possible Theoretical Solutions

- But maybe some hope from the CMB (or just more systematics!)

Hints of Early Dark Energy in *Planck*, SPT, and ACT data: new physics or systematics?

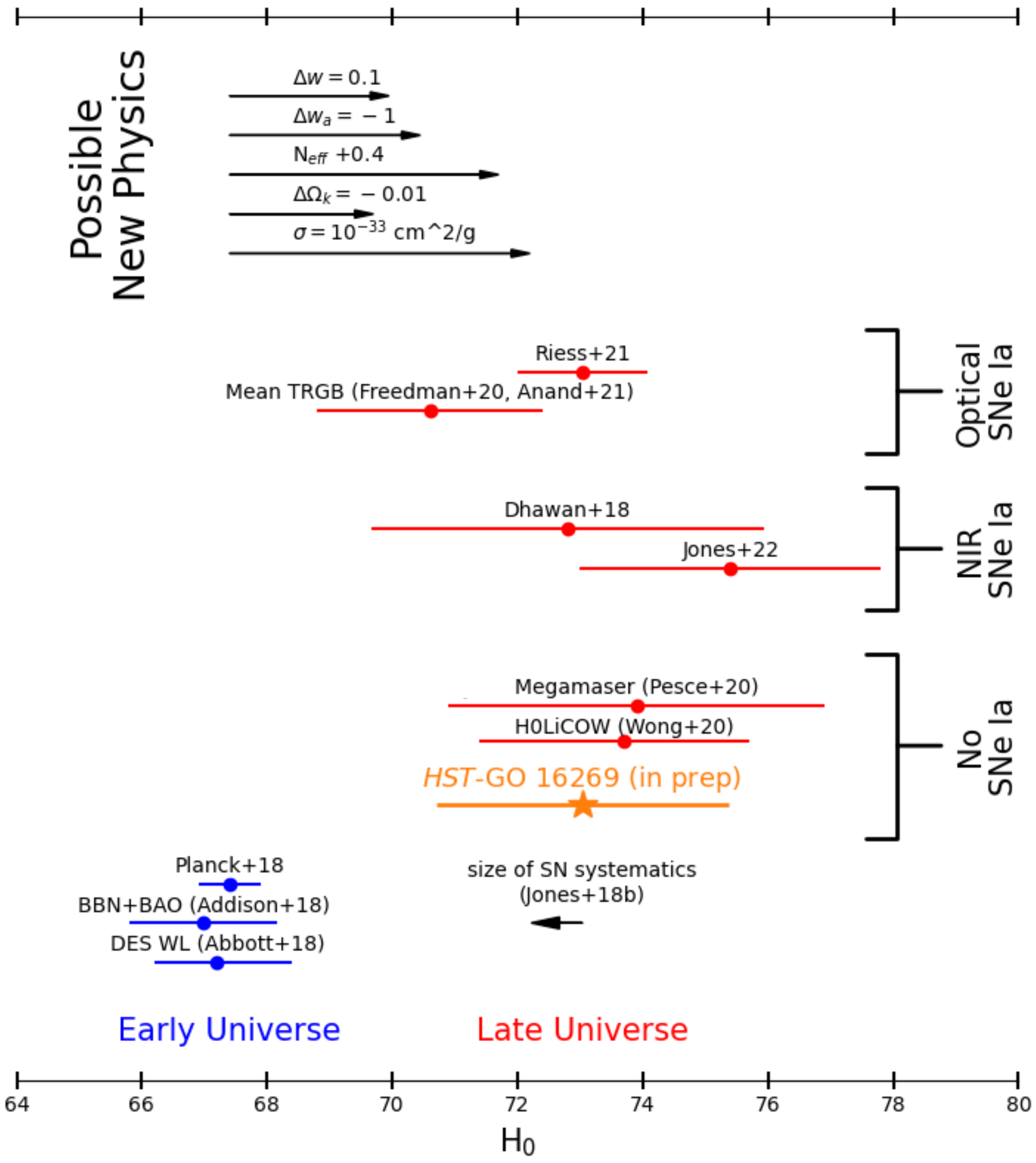
Tristan L. Smith,[1] Matteo Lucca,[2] Vivian Poulin,[3] Guillermo F. Abellan,[3] Lennart Balkenhol,[4] Karim Benabed,[5] Silvia Galli,[5] and Riccardo Murgia[3]

[1]*Department of Physics and Astronomy, Swarthmore College, Swarthmore, PA 19081, USA*
[2]*Service de Physique Théorique, Université Libre de Bruxelles, C.P. 225, B-1050 Brussels, Belgium*
[3]*Laboratoire Univers & Particules de Montpellier (LUPM), CNRS & Université de Montpellier (UMR-5299), Place Eugène Bataillon, F-34095 Montpellier Cedex 05, France*
[4]*School of Physics, University of Melbourne, Parkville, VIC 3010, Australia*
[5]*Sorbonne Université, CNRS, UMR 7095, Institut d'Astrophysique de Paris, 98 bis bd Arago, 75014 Paris, France*

We investigate constraints on early dark energy (EDE) using ACT DR4, SPT-3G 2018, *Planck* polarization, and restricted *Planck* temperature data (at $\ell < 650$), finding a 3.3σ preference ($\Delta\chi^2 = -16.2$ for three additional degrees of freedom) for EDE over ΛCDM. The EDE contributes

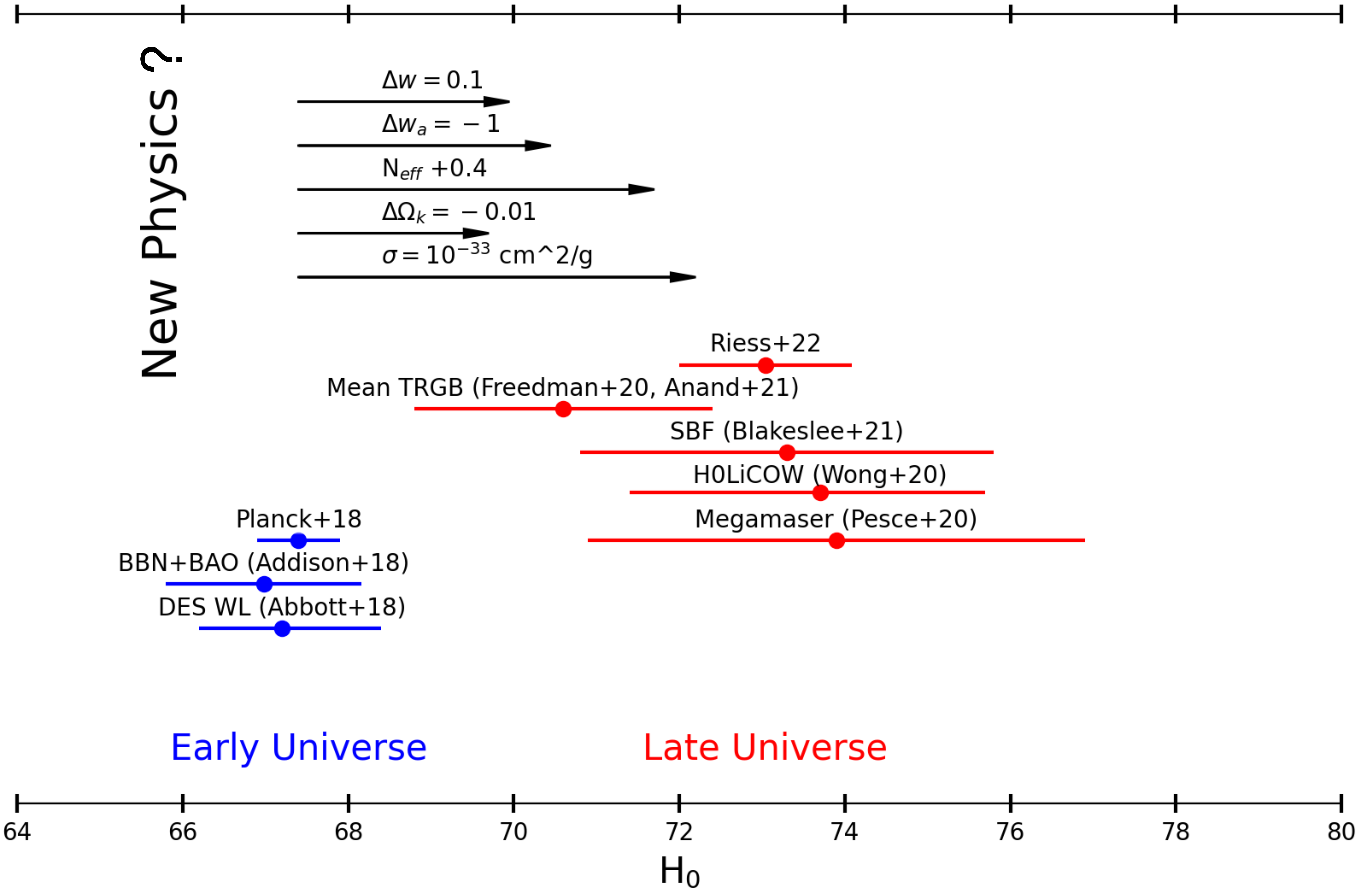
Conclusions

- New SH0ES results in 5.0-sigma tension with *Planck*, no sign yet that systematics can explain the tension
- In the process of improving Cepheid distances, improving the SN Ia sample, extending it to the NIR, and preparing for Rubin/ *Roman*



Extra Slides

Tension in the Hubble Constant



H_0: The Expansion Rate of the Nearby Universe

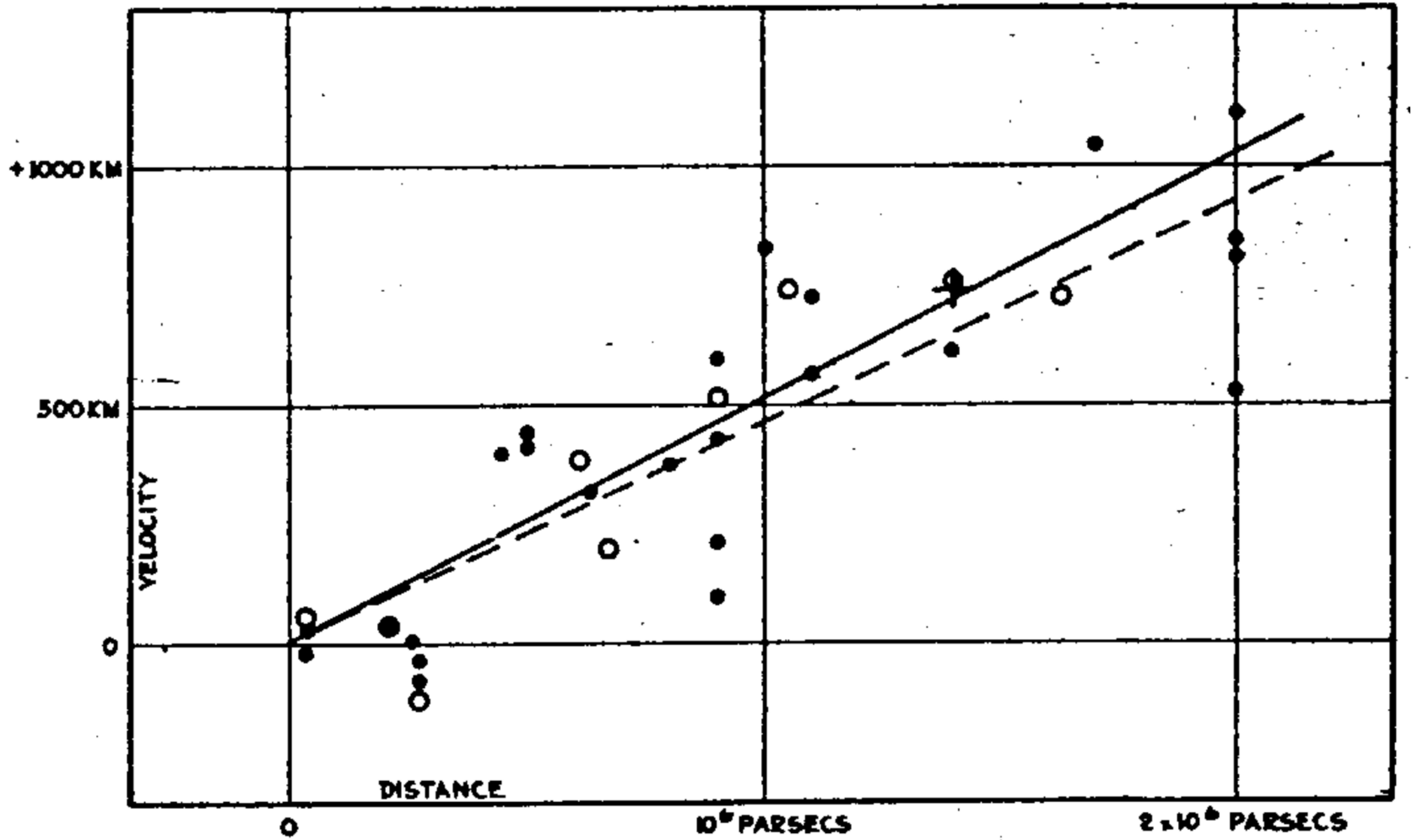
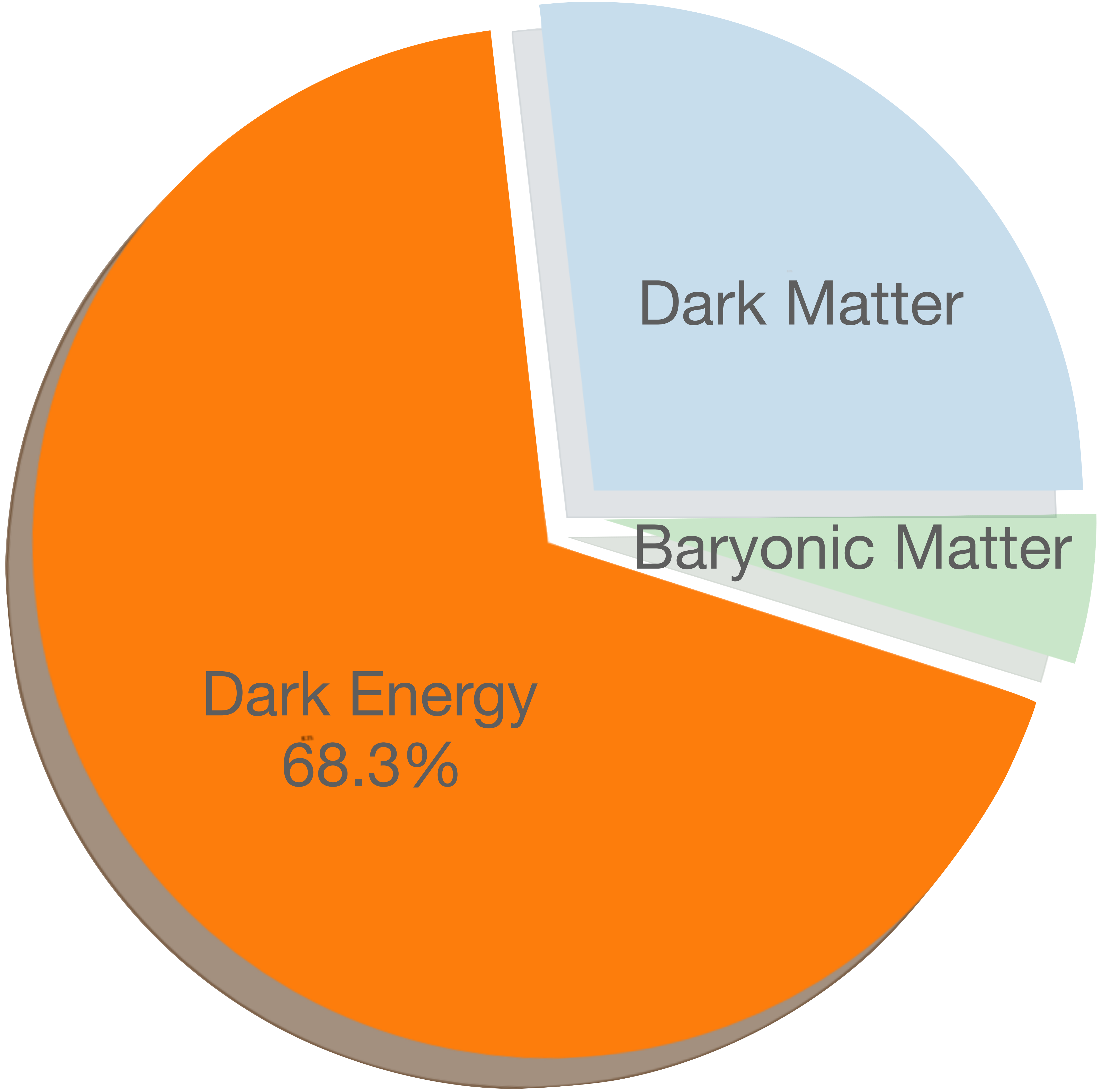


FIGURE 1

Hubble, 1929

H_0: The Expansion Rate of the Nearby Universe

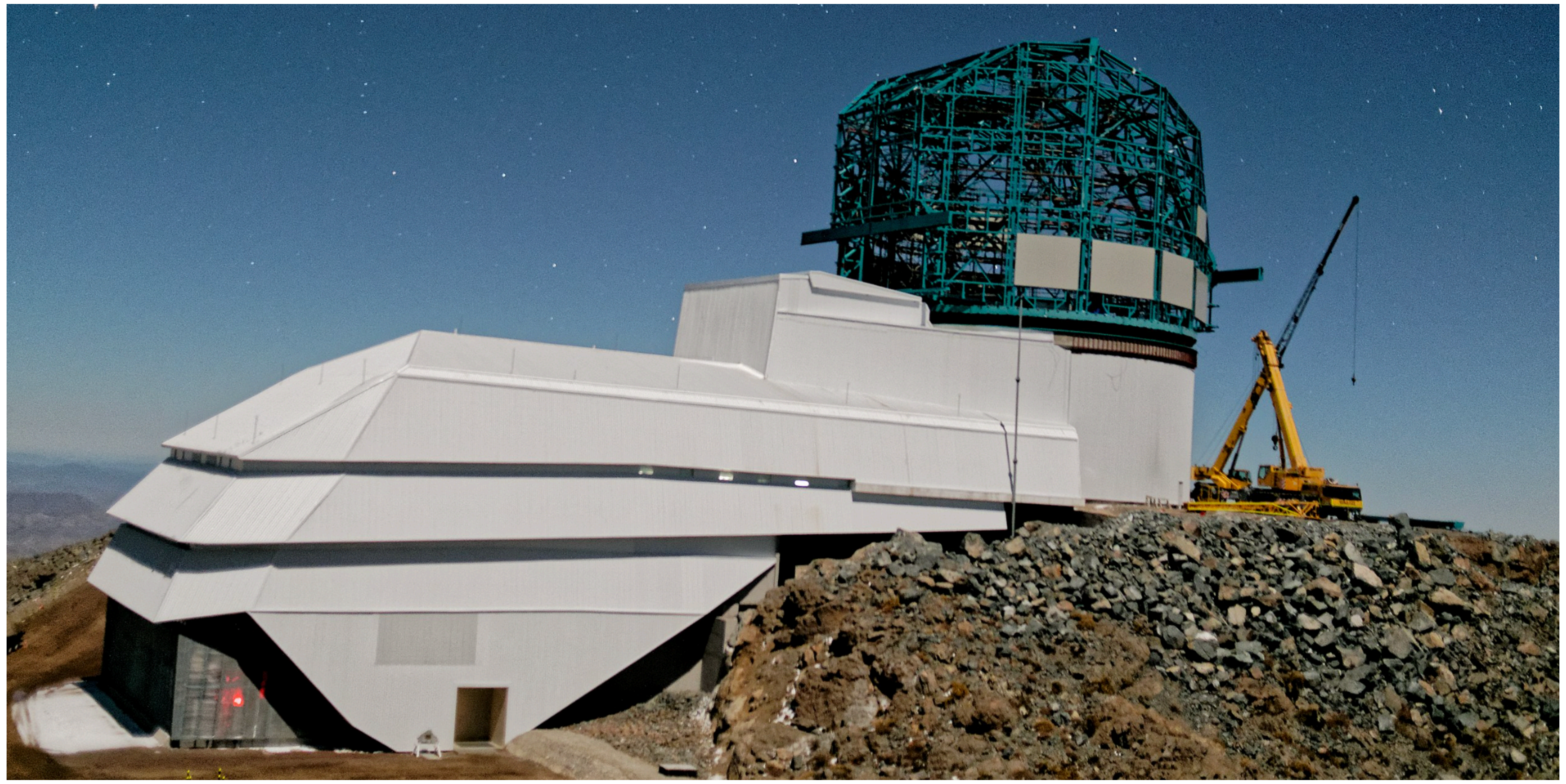
- Local expansion rate is a result of laws of physics and the composition of the universe



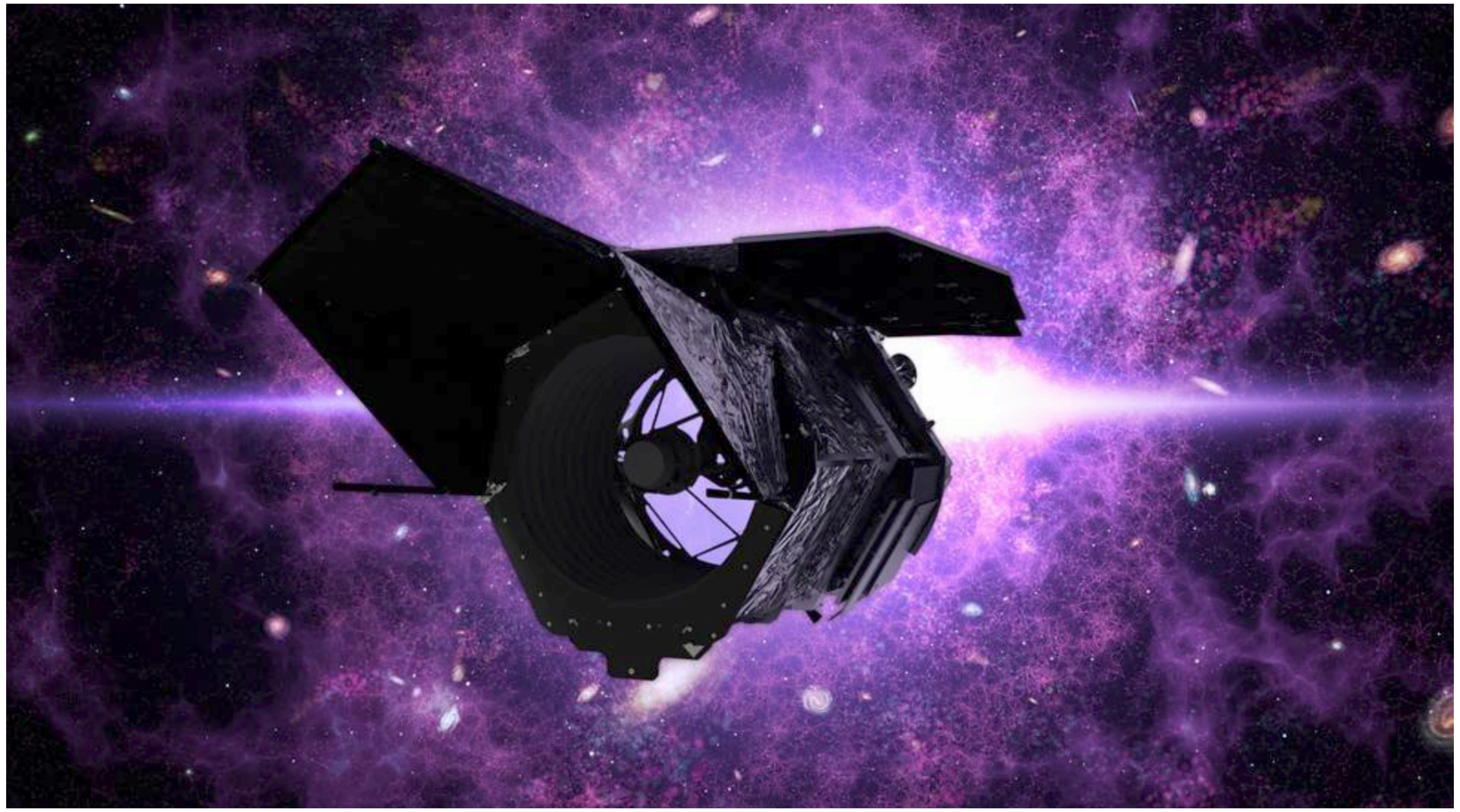
Planck+18

The Future H_0 Landscape

- Thousands of well-calibrated, homogenous SN Ia to re-build the Hubble flow SN sample from future surveys (LSST) and current (YSE; Jones+21)
- New second-rung distance indicators made possible by more *HST, JWST* data
- The *Roman Space Telescope* will refine the cosmological model
- Multi-messenger astronomy will provide a new path to H_0
- Along the way, new insights into transient physics and progenitors

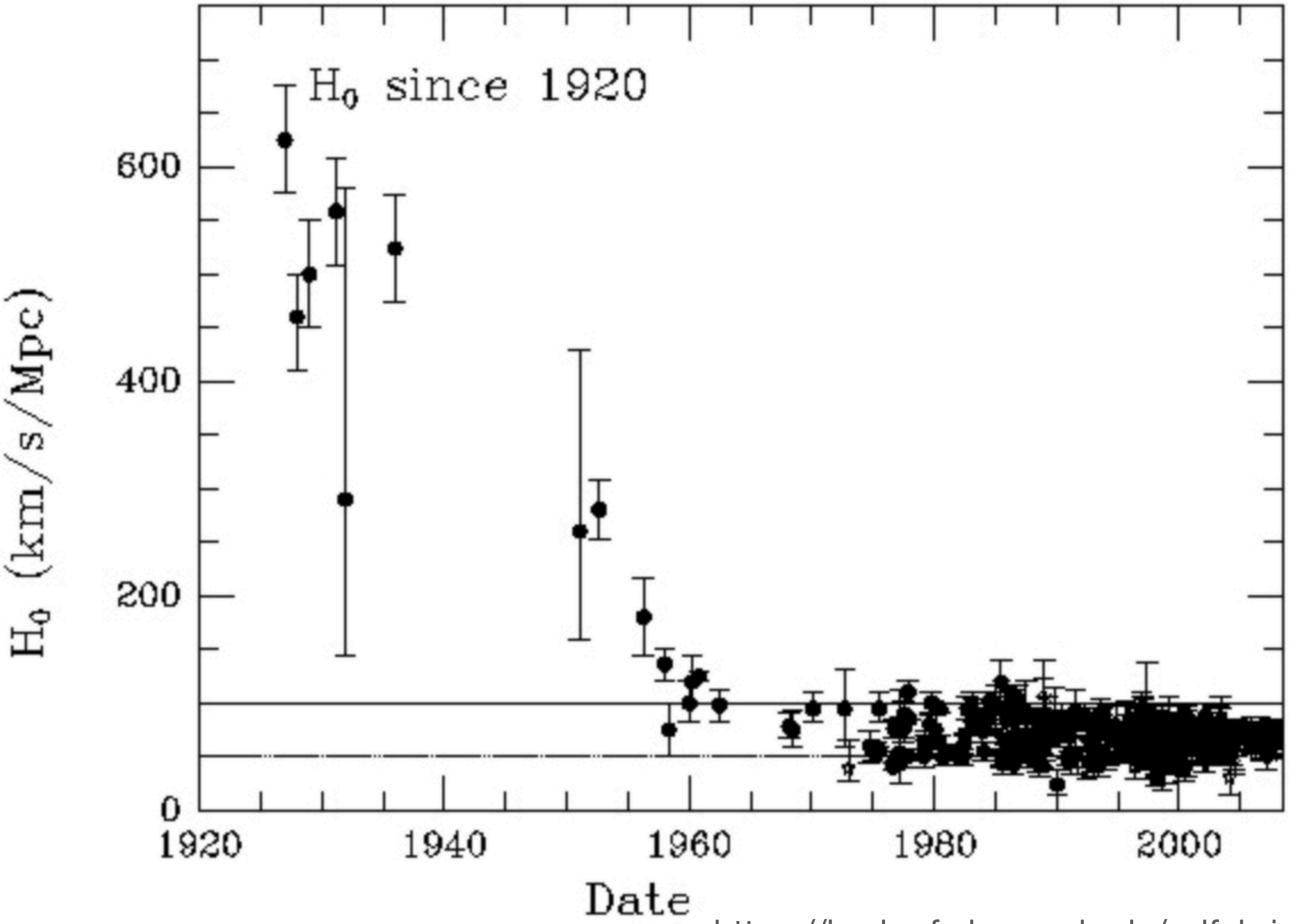


Vera Rubin Observatory



Nancy Grace Roman Space Telescope

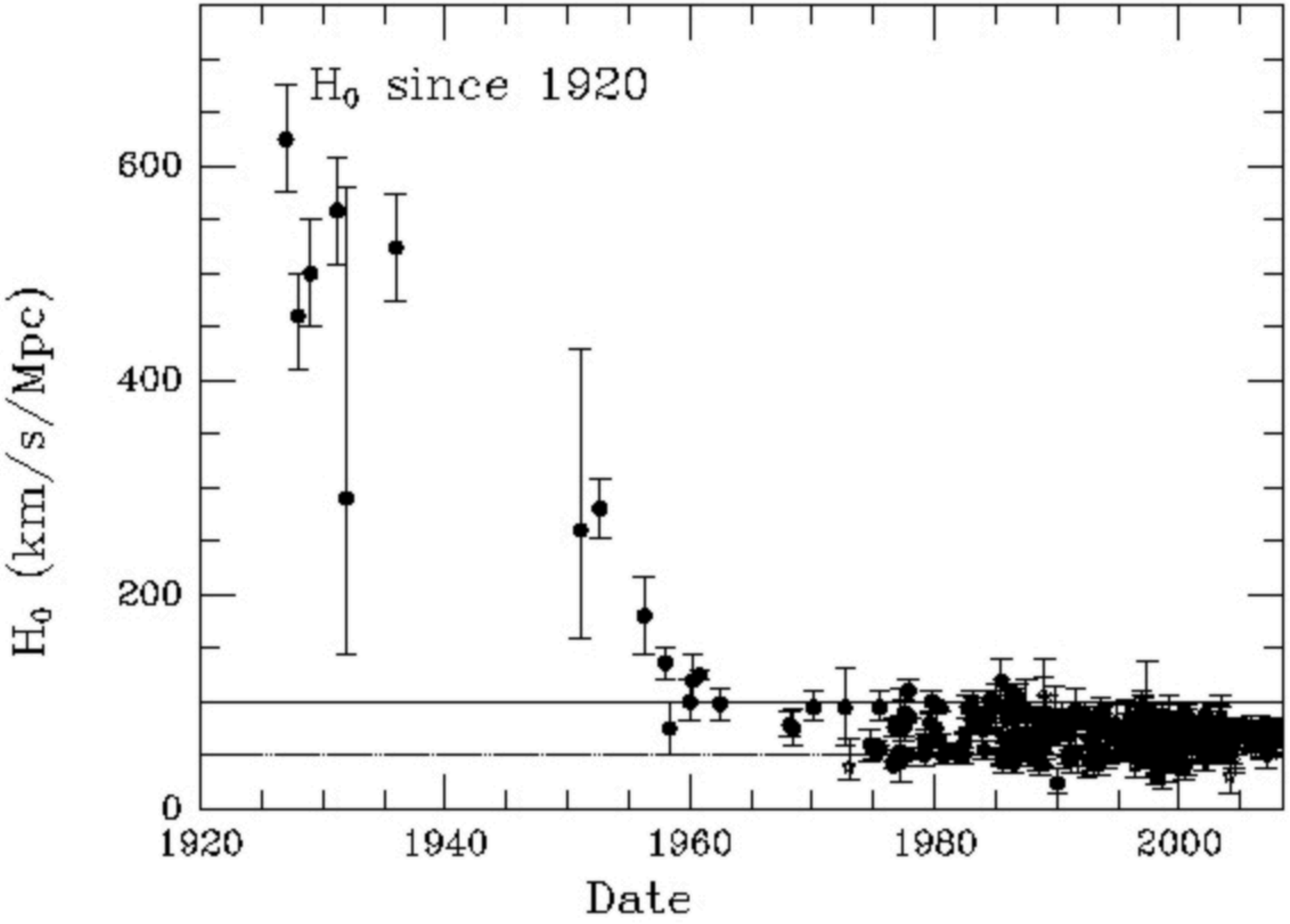
History of Measuring the Hubble Constant



https://lweb.cfa.harvard.edu/~dfabricant/huchra/hubble/

History of Measuring the Hubble Constant

- A few controversies:
  - 1950s: discovery of two types of Cepheids dropped H_0 from 500 down to ~100 km/s/Mpc



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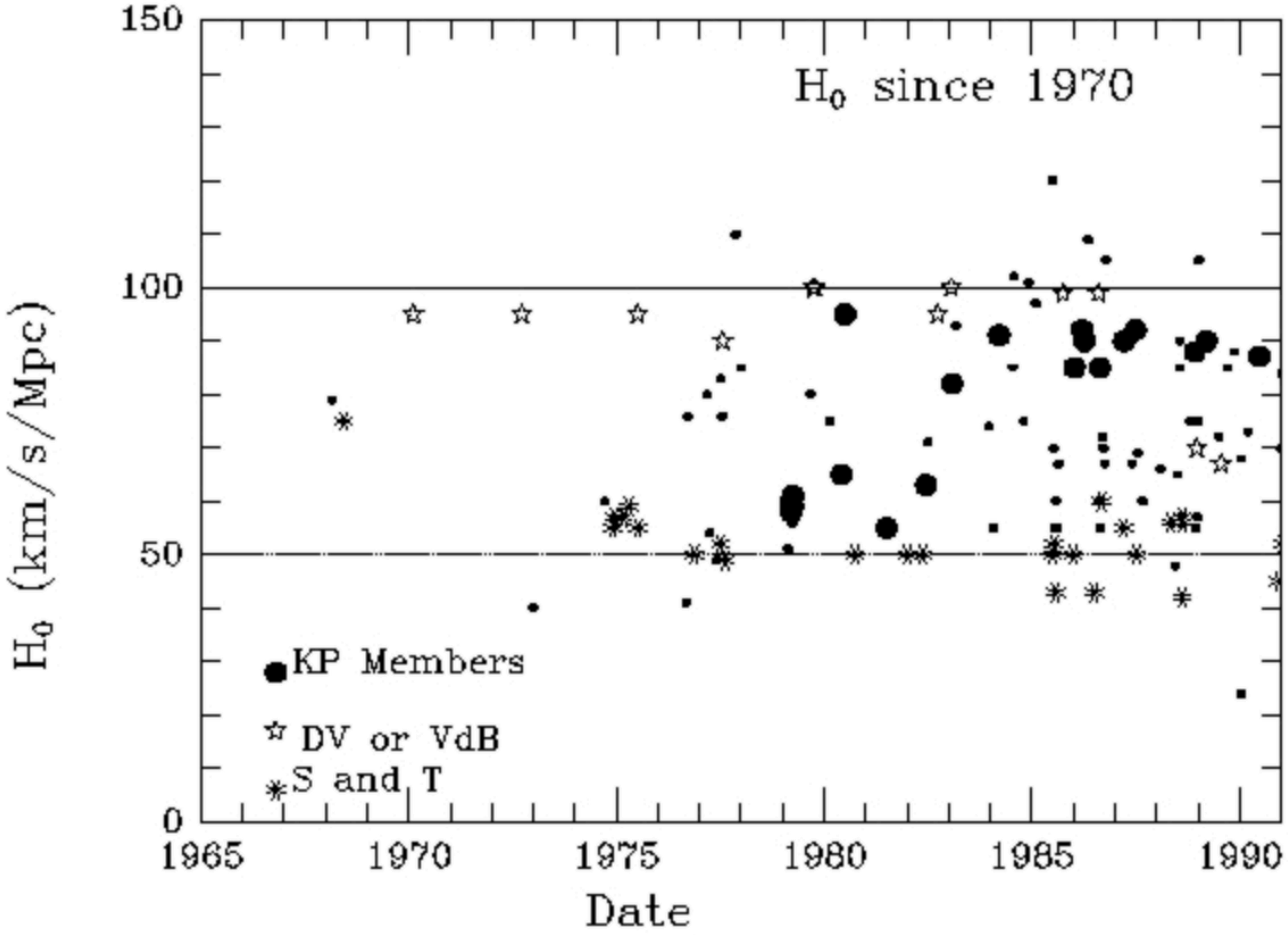
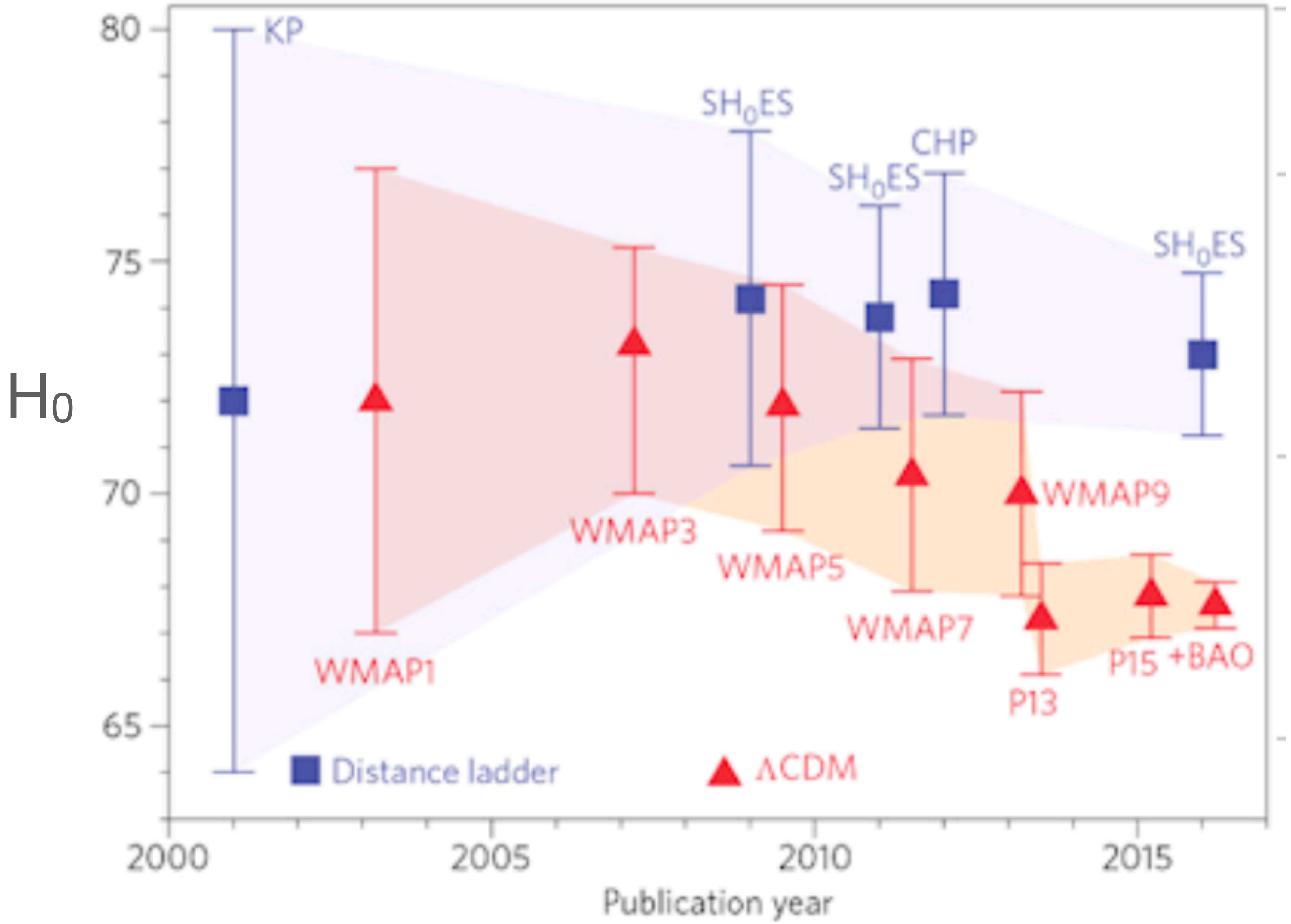


Huchra 2008

History of Measuring the Hubble Constant

- A few controversies:
  - 1950s: discovery of two types of Cepheids dropped H_0 from 500 down to ~100 km/s/Mpc
  - 1990s: discovery of dark energy helped to resolve controversy between the predicted age of the universe from estimated matter density and measured globular cluster ages
  - 2020s: ????

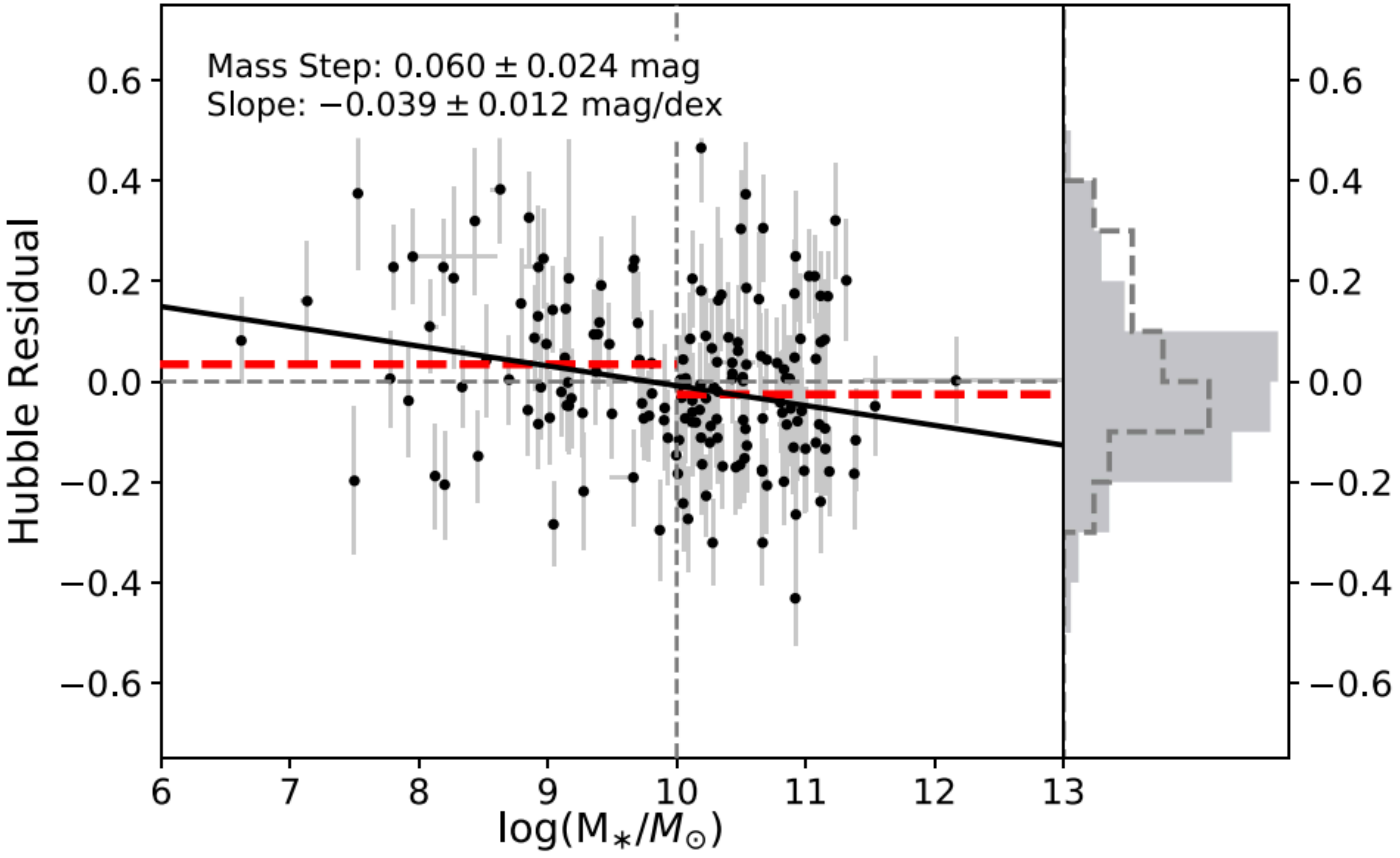


Could The H_0 Measurement Be Wrong?
3. SN Distances

- Potential inconsistencies between second and third rung

  1. SN Progenitors ("host correction")

     - SN Distance Measurements change depending on the mass of their host galaxies (Kelly+10, Lampeitl+10, Sullivan+10)
     - Possible reasons: changing progenitor metallicities, explosion mechanisms, or dust laws
     - Results in systematic uncertainties when second rung versus third rung galaxies have different demographics

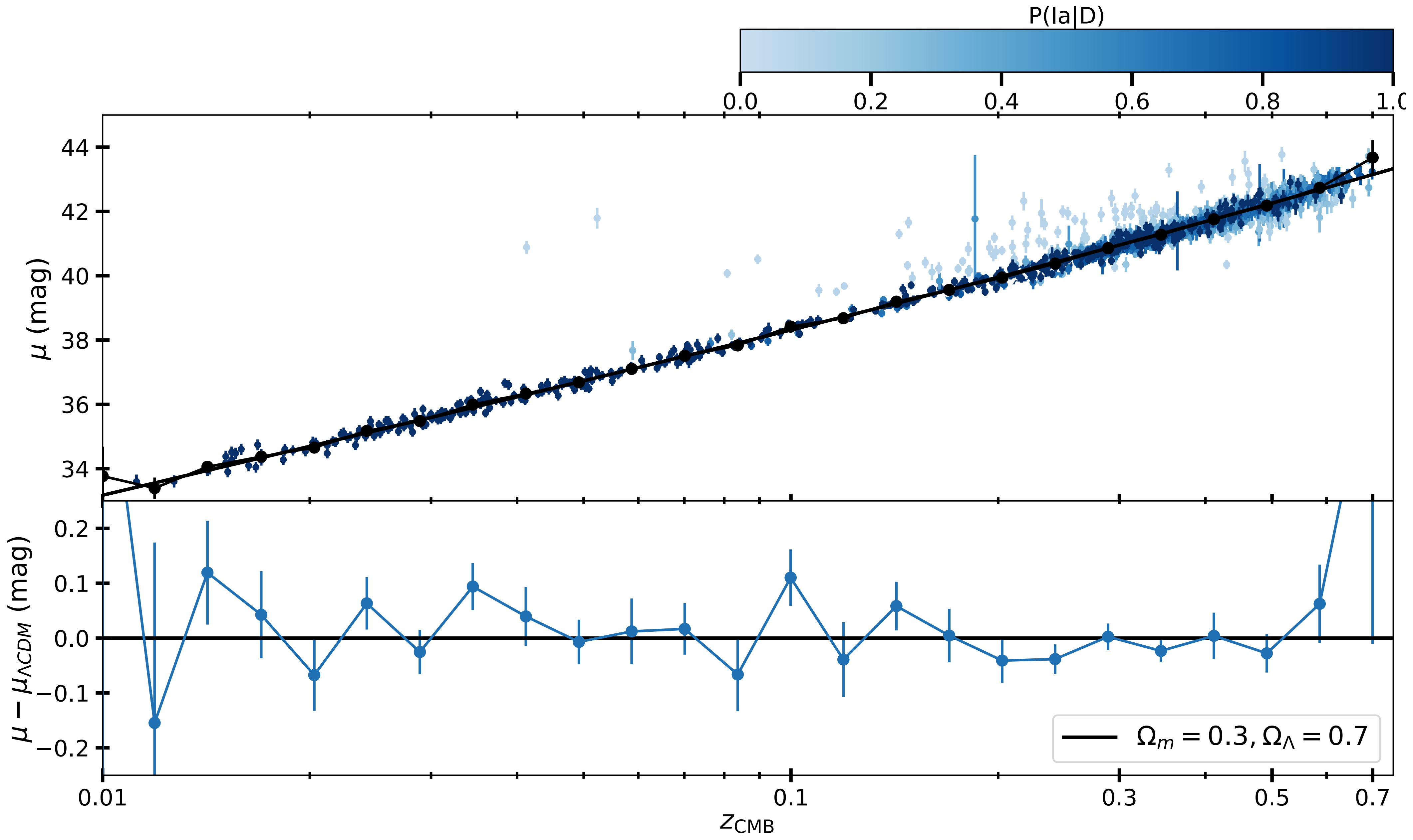


Jones+19

The Foundation Supernova Survey
SN Follow-up with Pan-STARRS

- 2015-2018, rebuilding the low-*z* SN sample for Rubin and *Roman*
- Observed ~350 z < 0.1 SN Ia on the Pan-STARRS telescope (largest low-z cosmology sample)
- mmag-level photometric calibration, well-tested reduction and analysis pipeline
- ~5 Cepheid calibrators
- primarily follows SNe from untargeted surveys

~1400 SNe from Pan-STARRS, spanning 5+Gyr of cosmic history
Jones+19

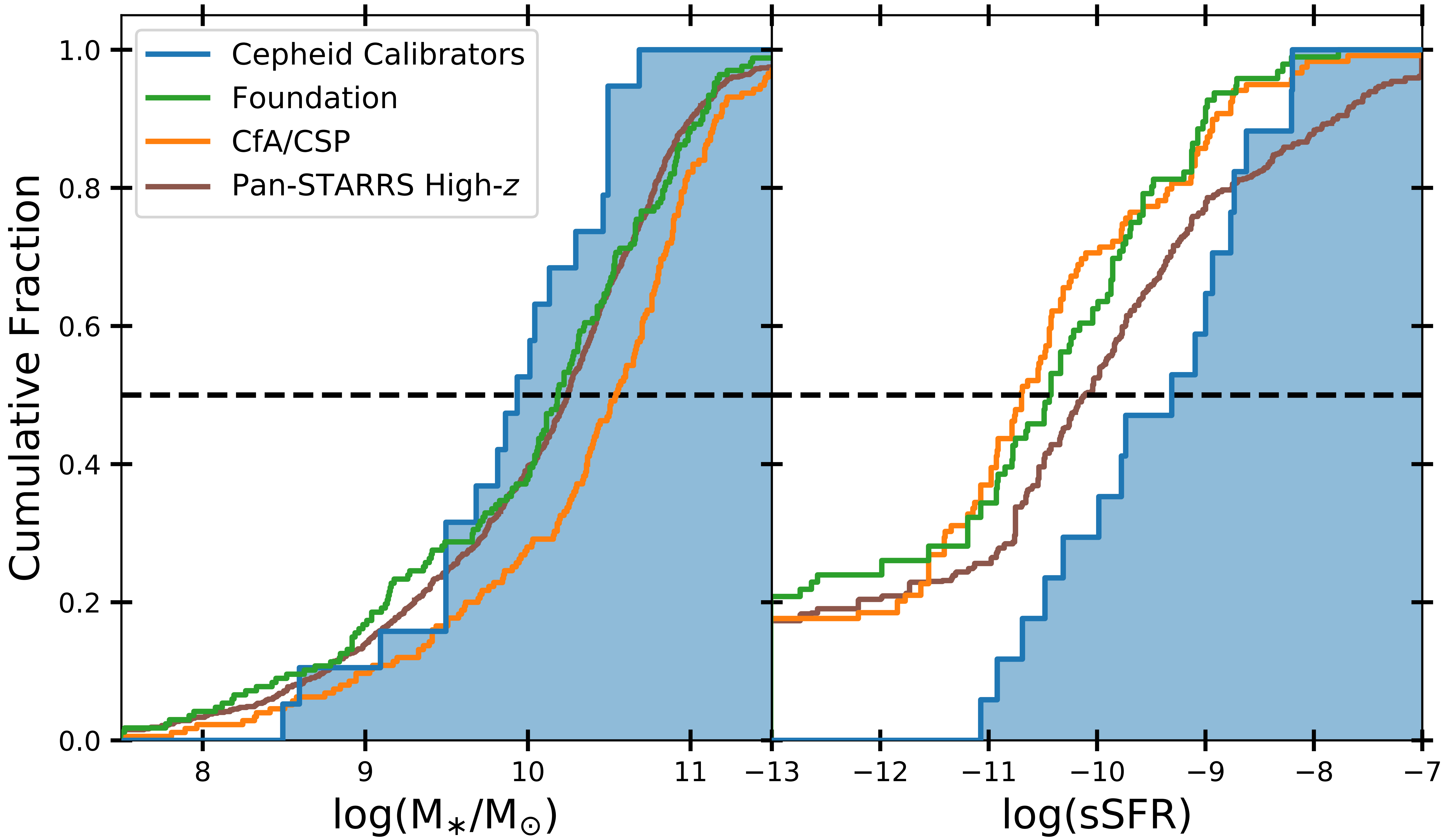


Foundation Publications:
First Data Release: Foley+18
Host Galaxies: Jones+18b
Dark Energy: Jones+19
Photospheric Velocities: Dettman+21

Publications using Foundation:
Dust Laws: Thorp+21
Pantheon+: Peterson+21, Brownsberger+21, Brout+22, Riess+22
Growth of Structure: Boruah+19, Stahl+21
Host Galaxies: too many to list

The Foundation Supernova Survey
SN Follow-up with Pan-STARRS

- **Better sample for measuring H_0**: Foundation host demographics are closer to those of galaxies with SN Ia and Cepheid distances

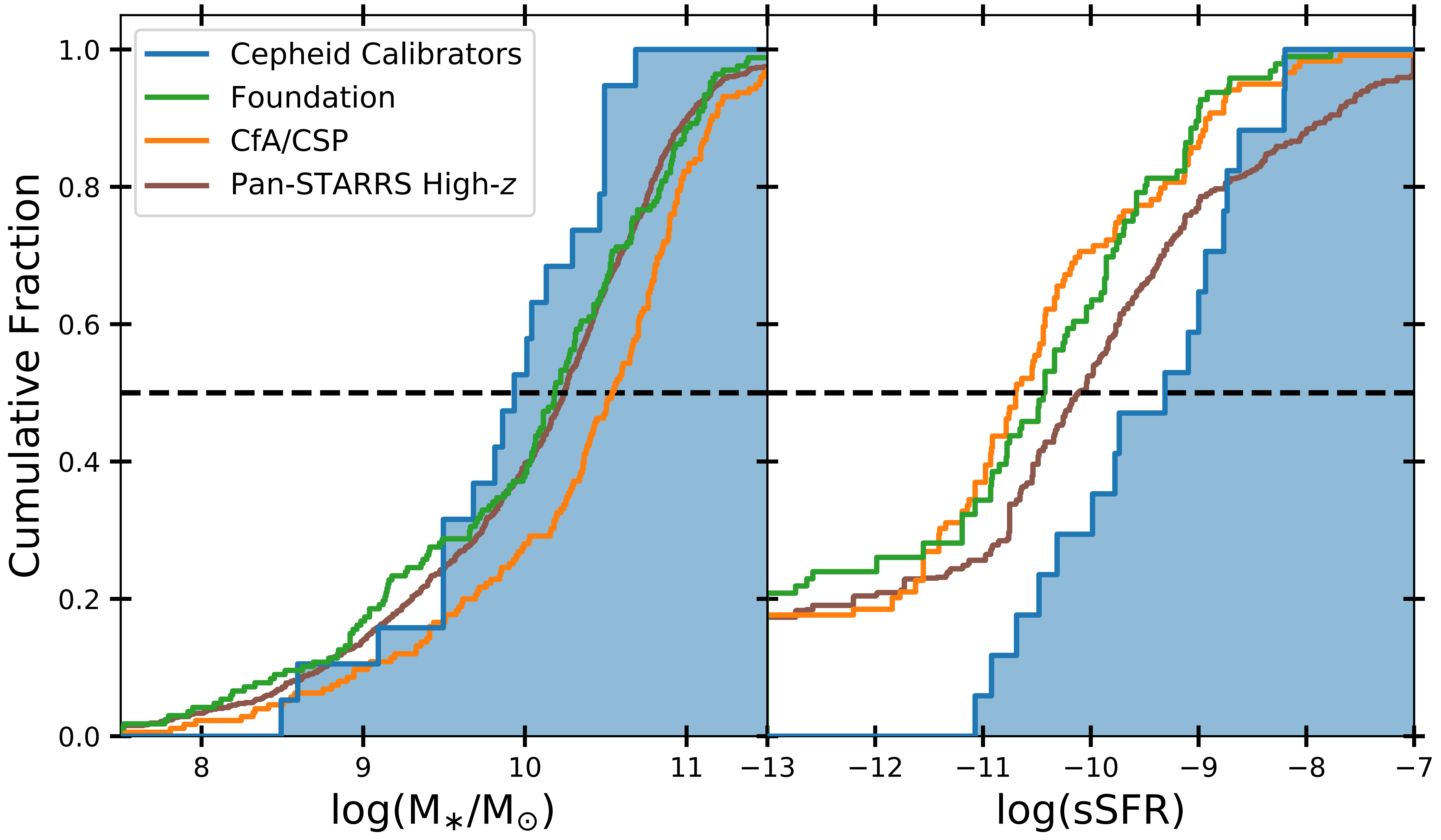


Jones+18b, Jones+19

The Foundation Supernova Survey

SN Follow-up with Pan-STARRS

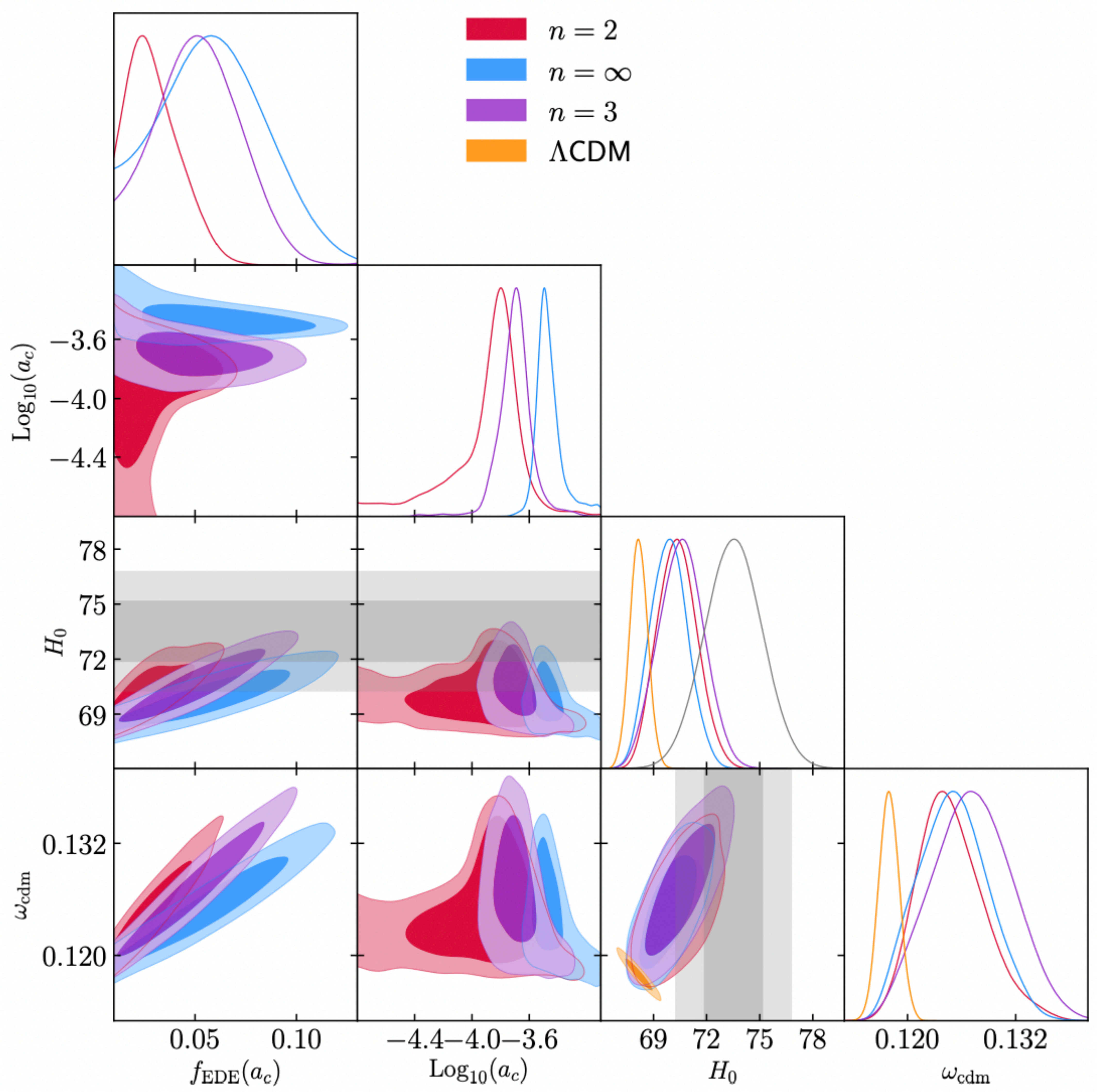
- **Better sample for measuring H_0**: Foundation host demographics are closer to those of galaxies with SN Ia and Cepheid distances.
- In latest SH0ES paper, **only late-type galaxies are used** as a second step to mitigate these selection effects
- In Jones+18, found alternative "host" corrections change H_0 by < 0.5%



Jones+18b, Jones+19

Possible Theoretical Solutions

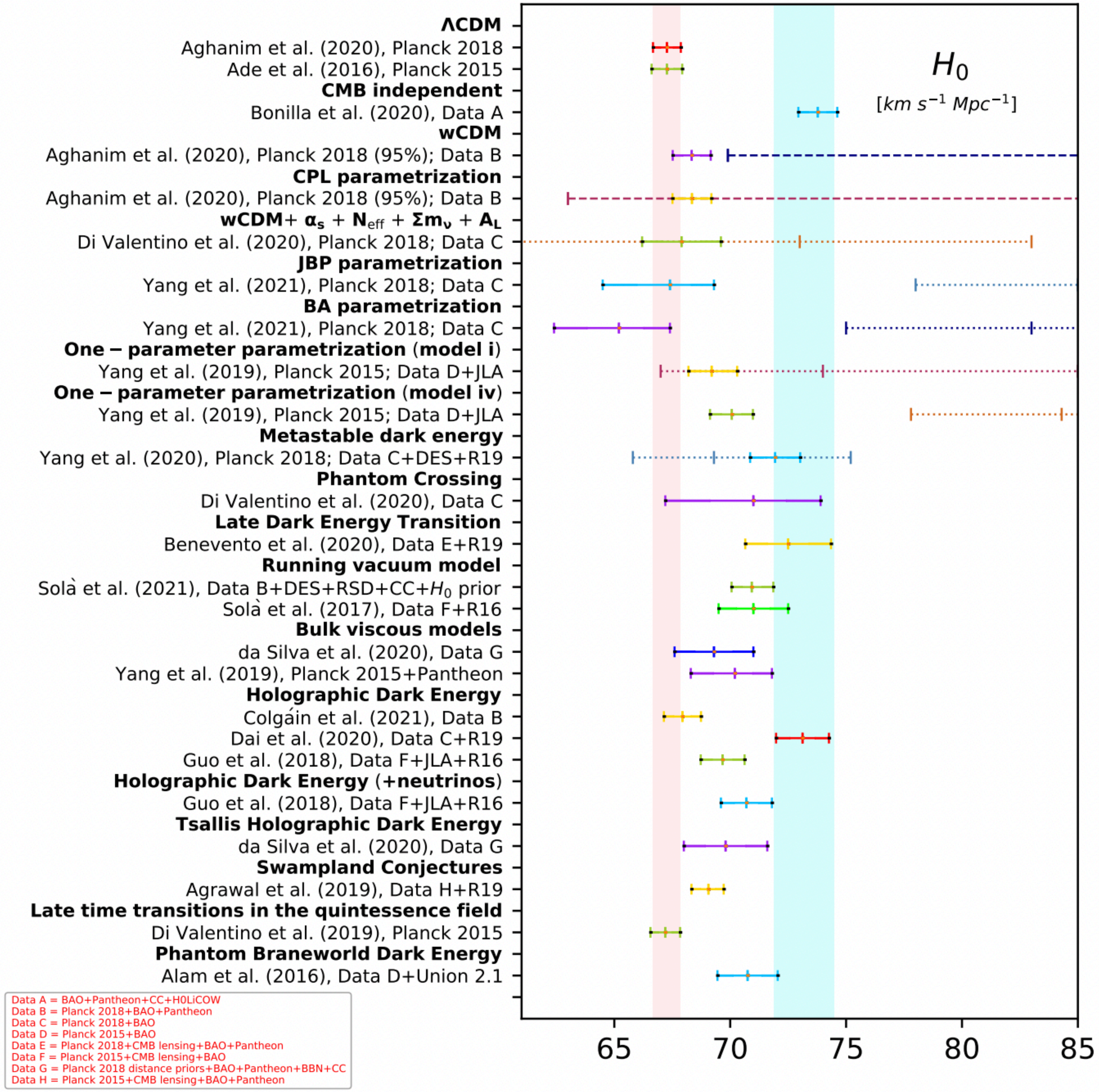
- Early Dark Energy
  - Dark energy component before recombination reduces the sound horizon size
  - Also suppresses clustering (increases S8 tension), and could have a “coincidence” problem



Poulin+2019

Possible Theoretical Solutions

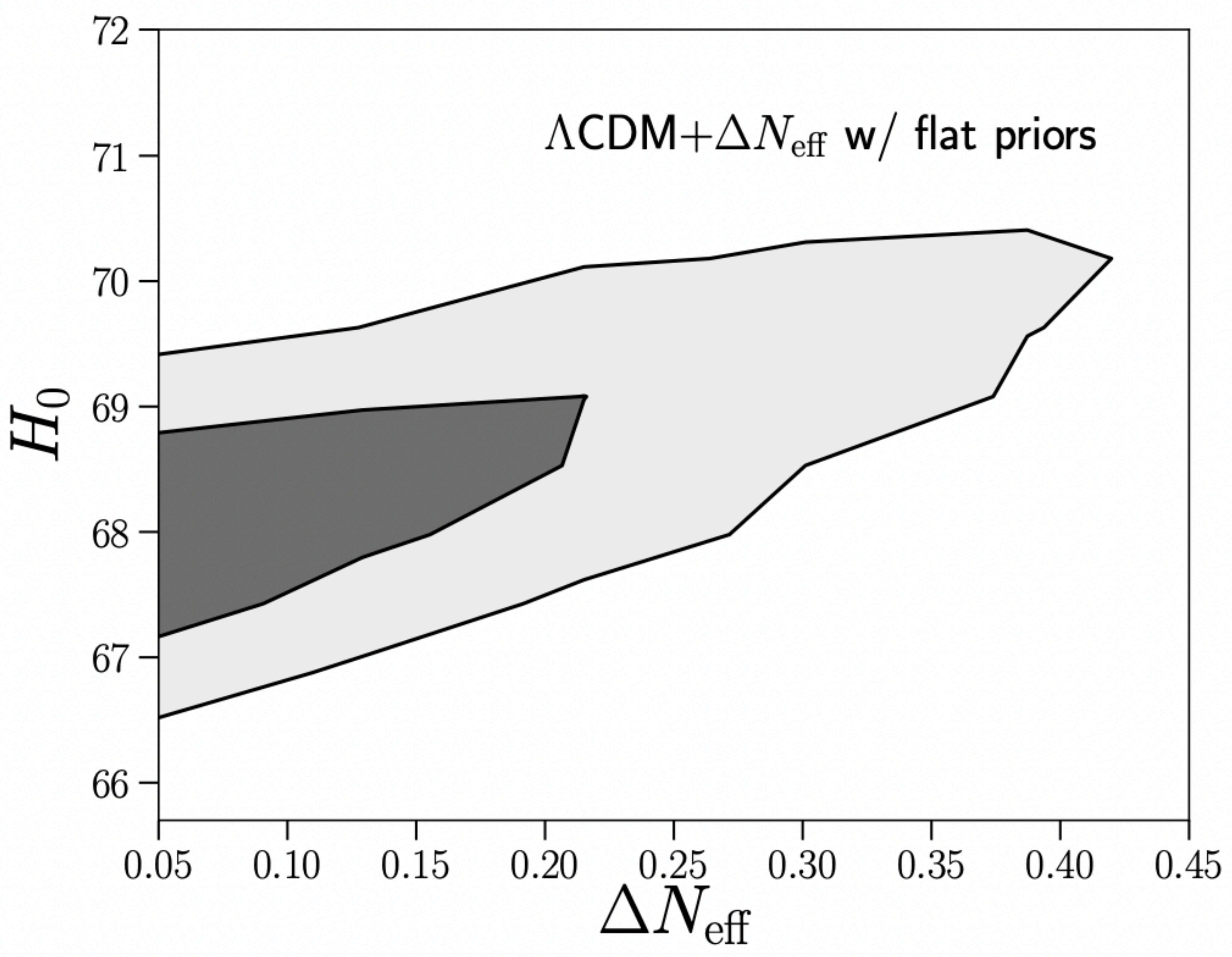
- Late-Universe Dark Energy
  - Observational constraints ~rule out most wCDM models as source of the tension
  - But some dynamical dark energy models have more flexibility to solve tension



Di Valentino+21

Possible Theoretical Solutions

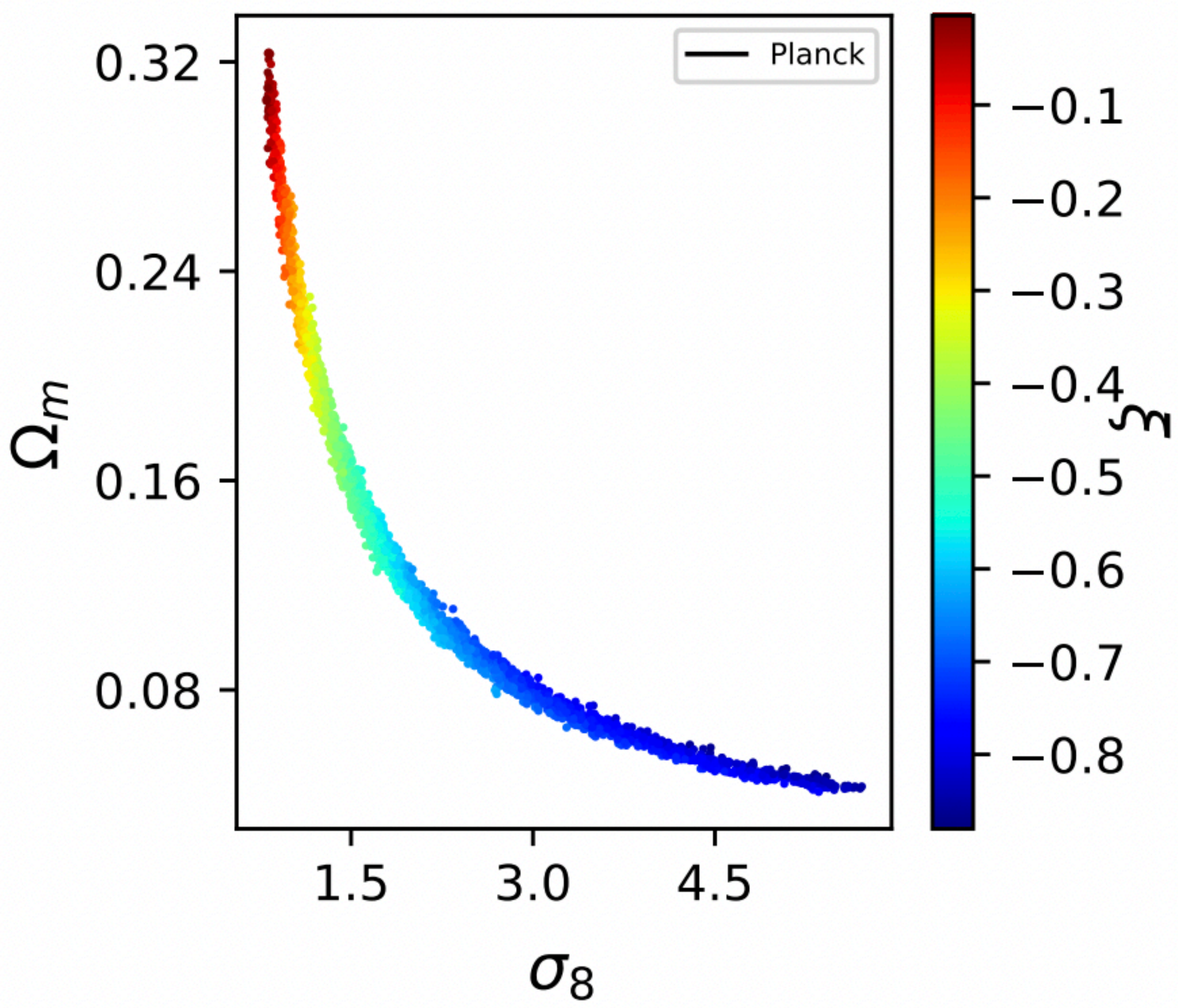
- Extra Relativistic Species
  - Sterile neutrinos could increase N_{eff} and therefore change the sound horizon size
  - Axion models can also increase N_{eff} while remaining compatible with CMB



D'Eramo+18

Possible Theoretical Solutions

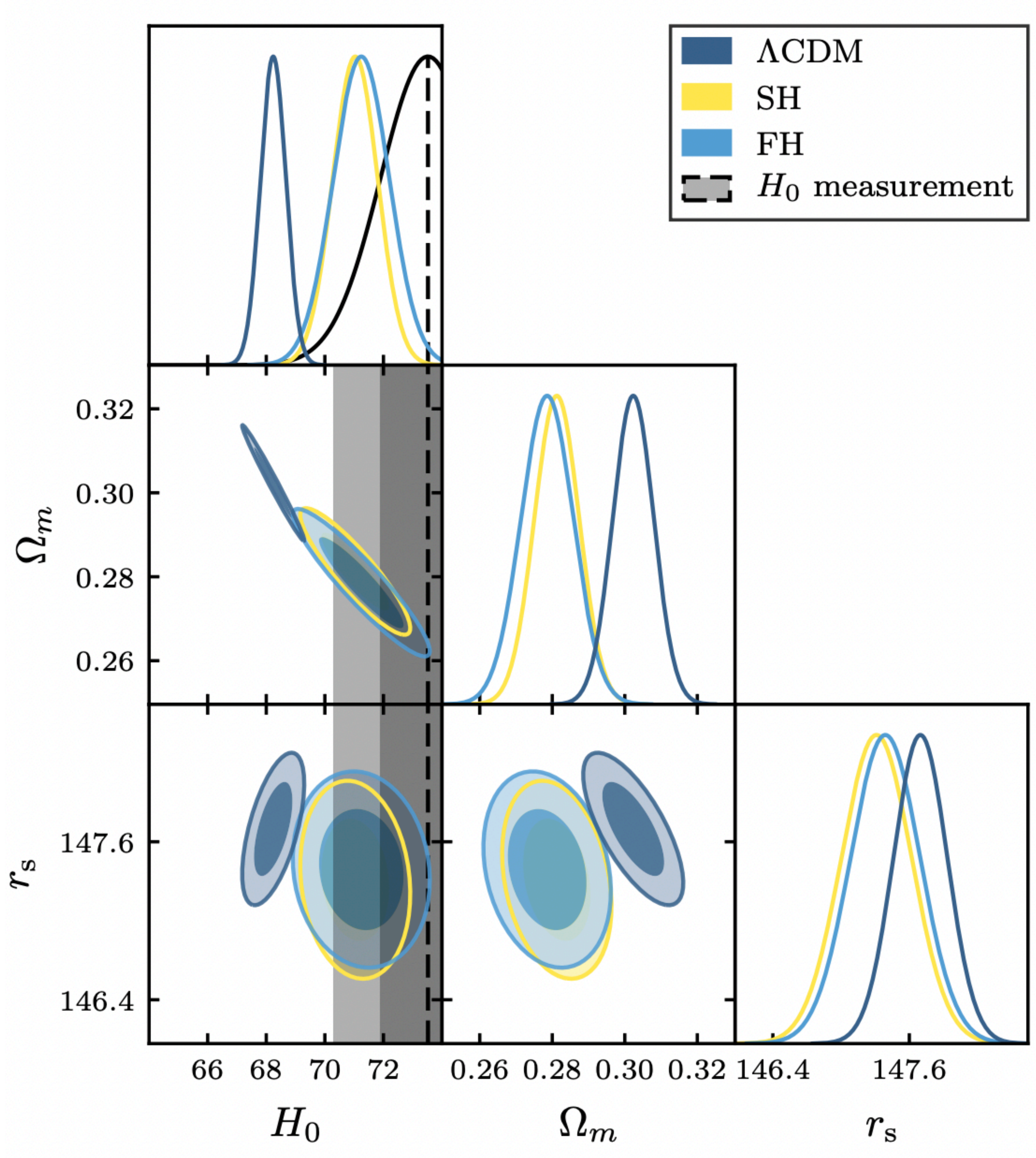
- Coupled Dark Matter/ Dark Energy
  - Could potentially solve both S8 and H_0 tensions
  - Unclear if they can match all SN Ia, BAO data



Di Valentino+20

Possible Theoretical Solutions

- Modified Gravity
  - Early time modifications change evolution of fluctuations in the gravitational potential, affecting CMB temperature, polarization, lensing predictions
  - Late-time modifications smooth out CMB acoustic peaks
  - But sometimes have trouble matching the full expansion history data including SN Ia and BAO



Raveri 2020

The Local Distance Ladder
Geometric Distances

- Parallaxes

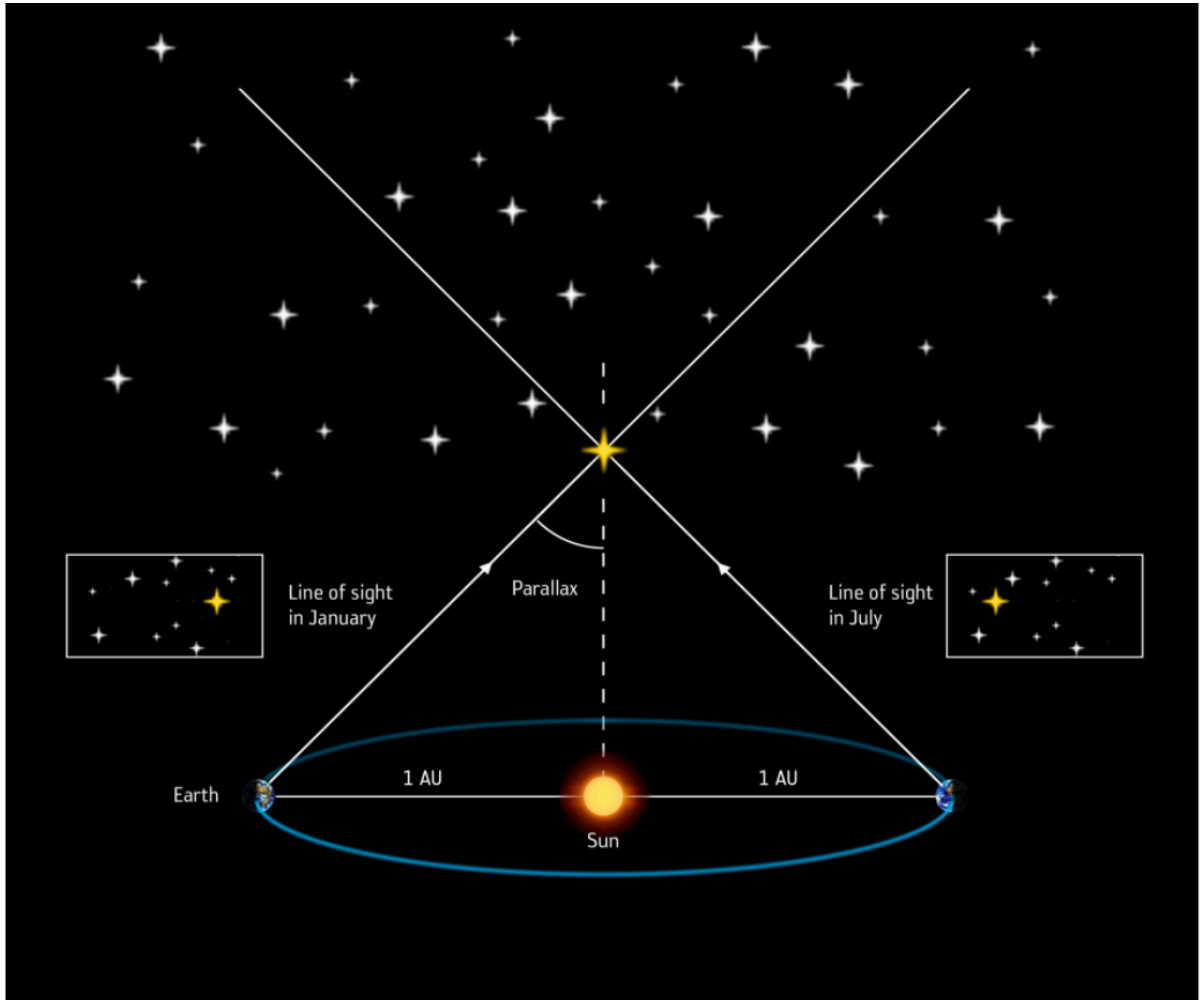


Image credit: European Space Agency

The Local Distance Ladder
Geometric Distances

- Parallaxes
- Eclipsing Binaries

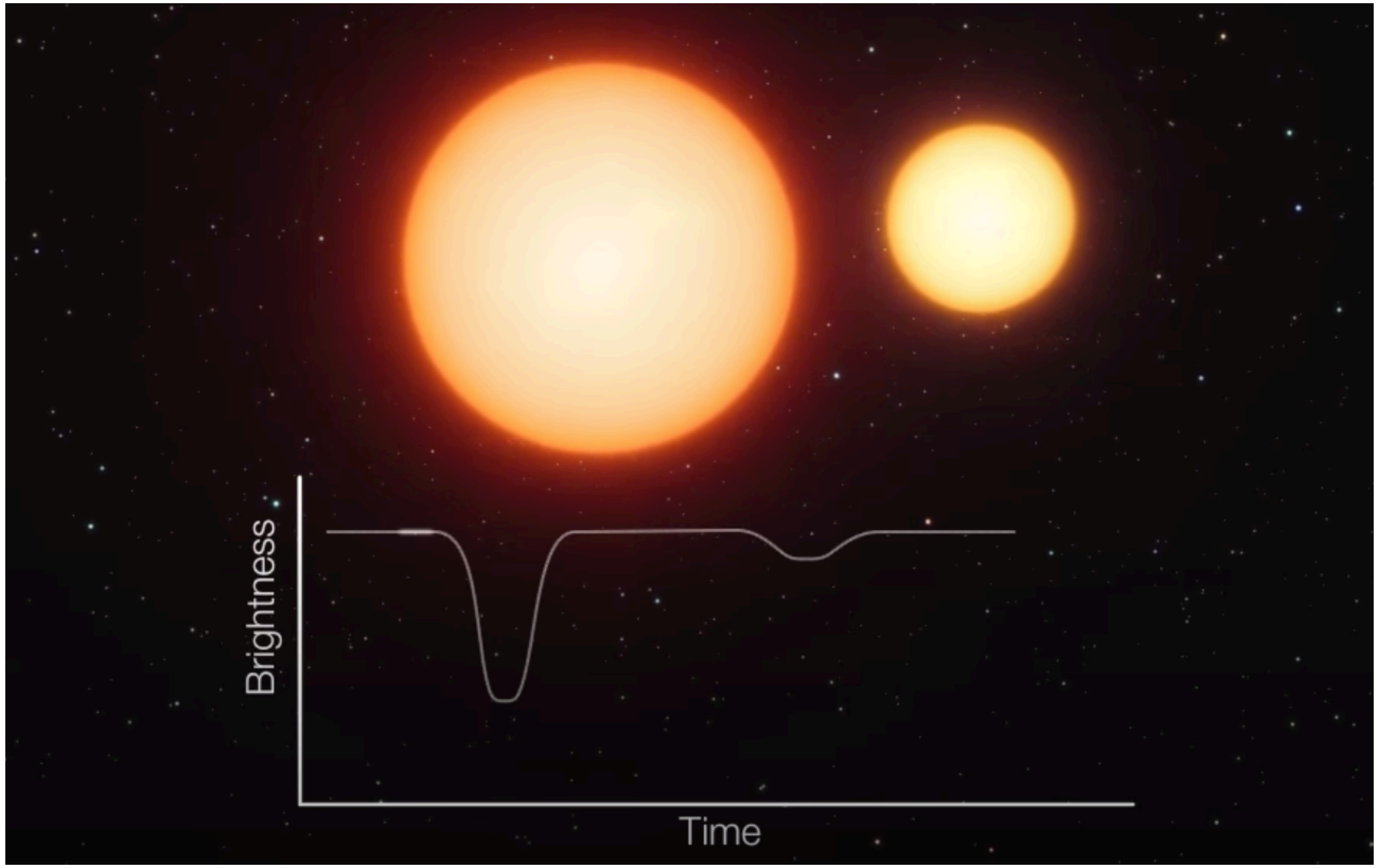
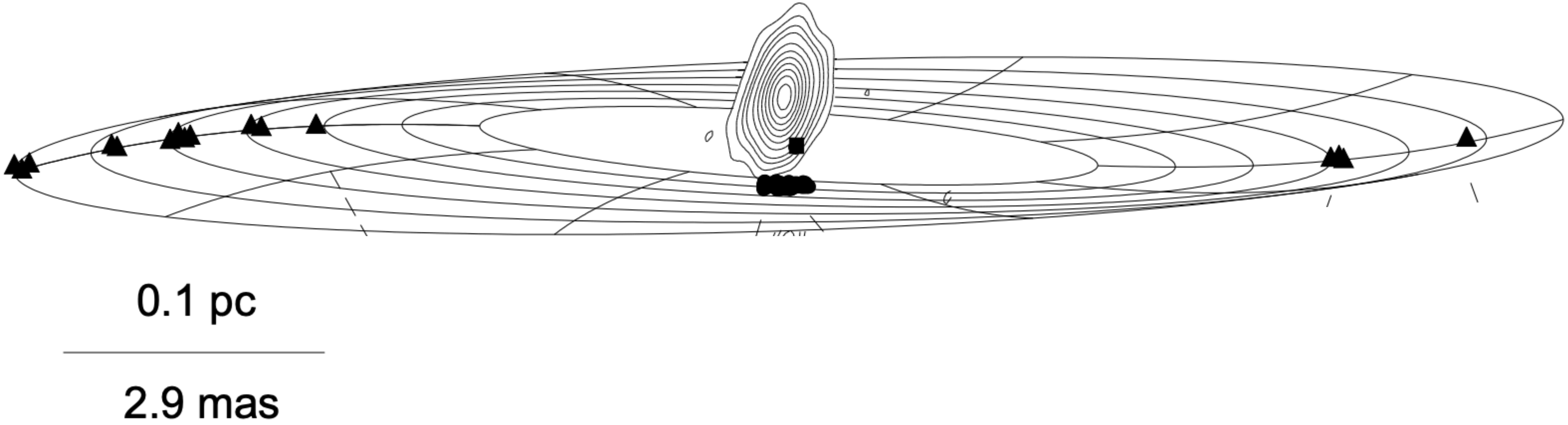


Image credit: European Southern Observatory

The Local Distance Ladder
Geometric Distances

- Parallaxes
- Eclipsing Binaries
- NGC 4258 Megamaser

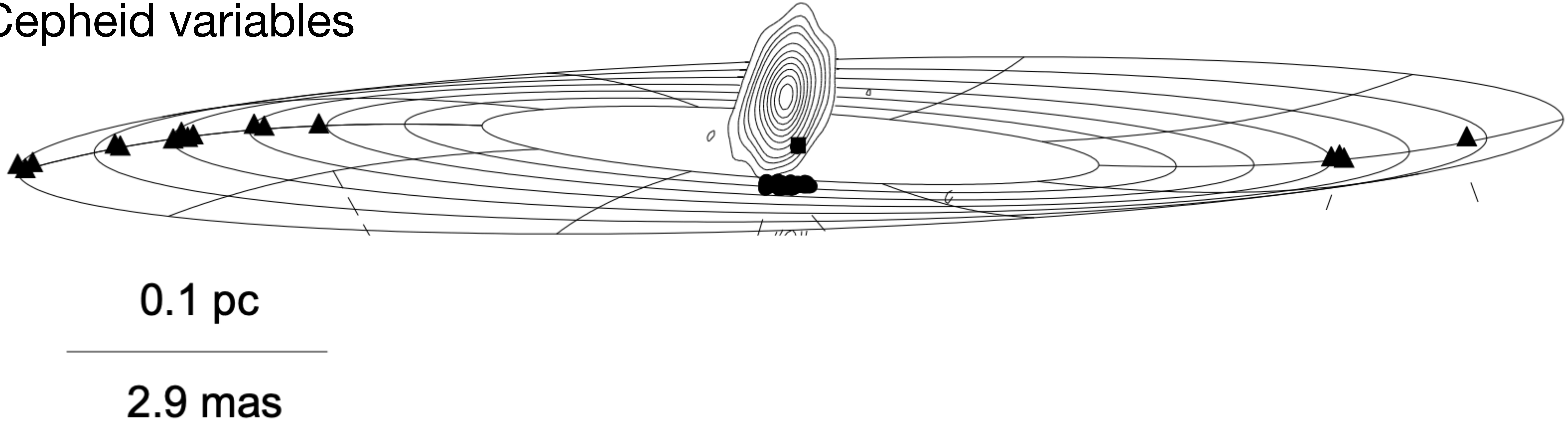


Herrnstein+1999

The Local Distance Ladder
Geometric Distances

- Parallaxes
- Eclipsing Binaries
- NGC 4258 Megamaser

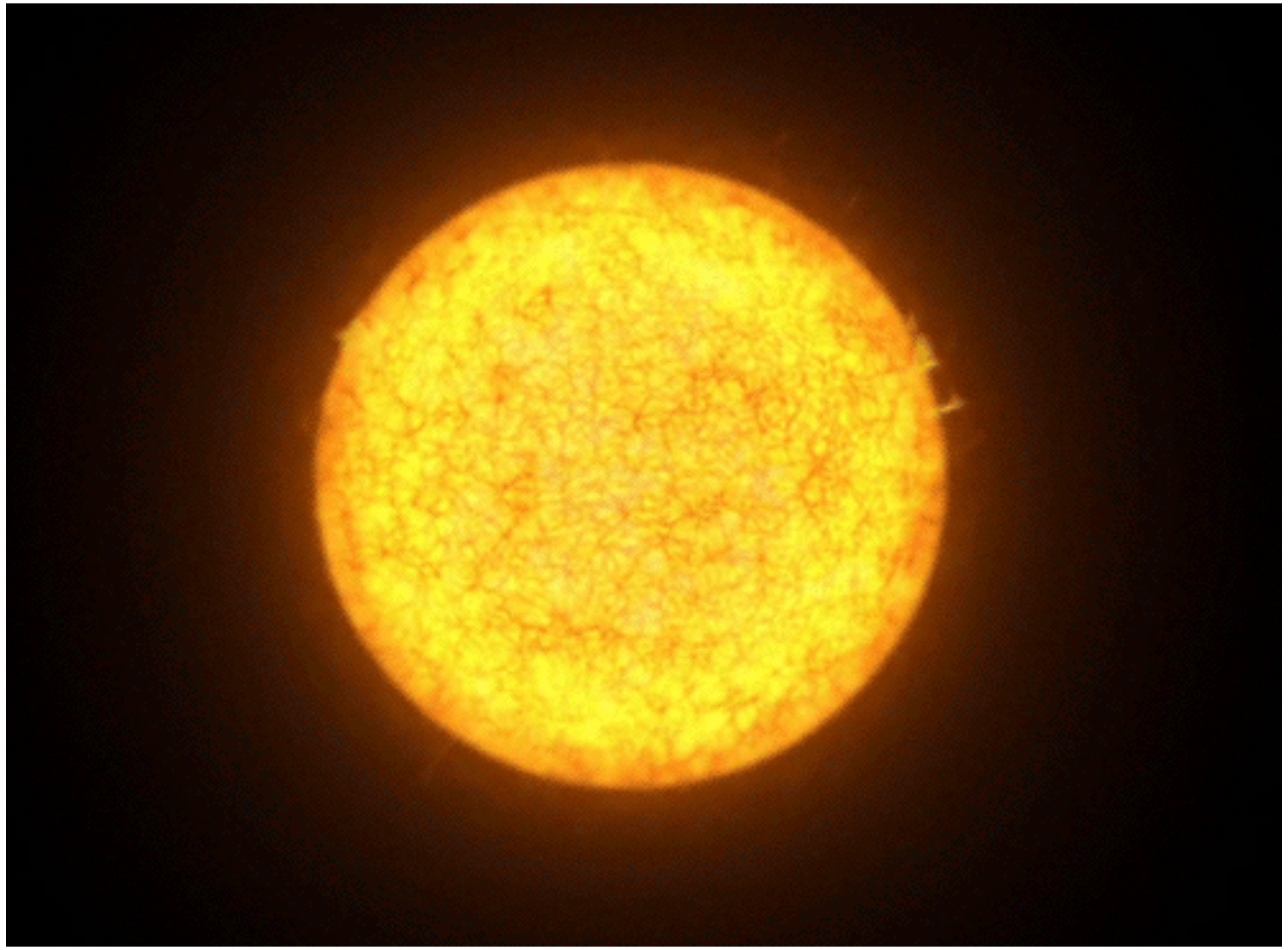
  -> Each of the geometric distances above calibrate the luminosity of Cepheid variables



Herrnstein+1999

The Local Distance Ladder
Cepheids

- Pulsates radially, varying in both diameter and temperature and brightness changes with a well-defined stable period and amplitude.
- Direct relationship between luminosity and pulsation period (h/t Henrietta Swan Leavitt)
- Many Cepheids per (star-forming) galaxy



Credit: NASA, ESA

The Local Distance Ladder
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- Led to discovery of expanding universe

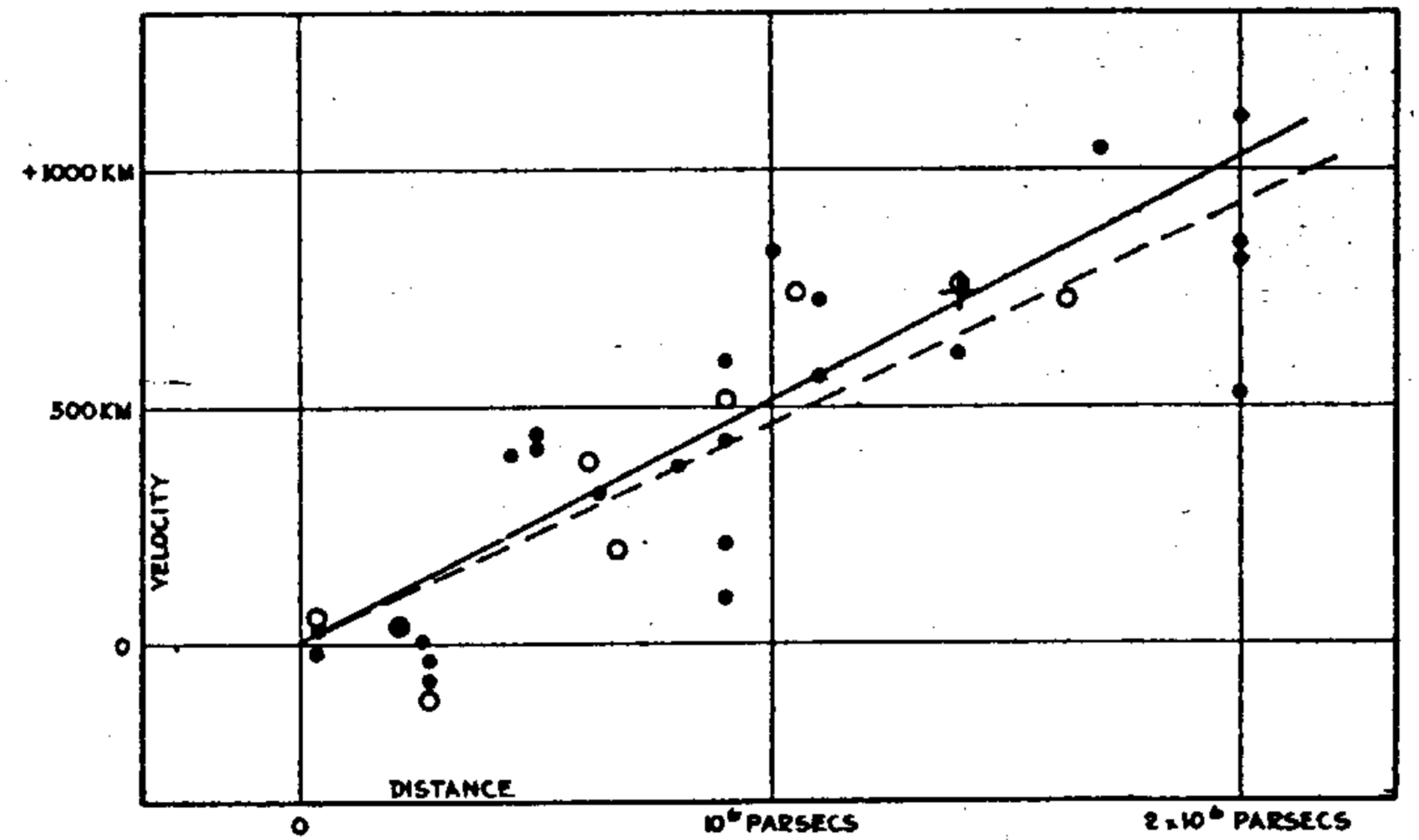


FIGURE 1

Hubble, 1929

The Local Distance Ladder
Cepheids

- Pulsates radially, varying in both diameter and temperature and brightness changes with a well-defined stable period and amplitude.
- Direct relationship between luminosity and pulsation period (h/t Henrietta Swan Leavitt)
- Many Cepheids per (star-forming) galaxy
- Led to discovery of expanding universe
- Cepheids are used to calibrate the luminosity of Type Ia supernovae

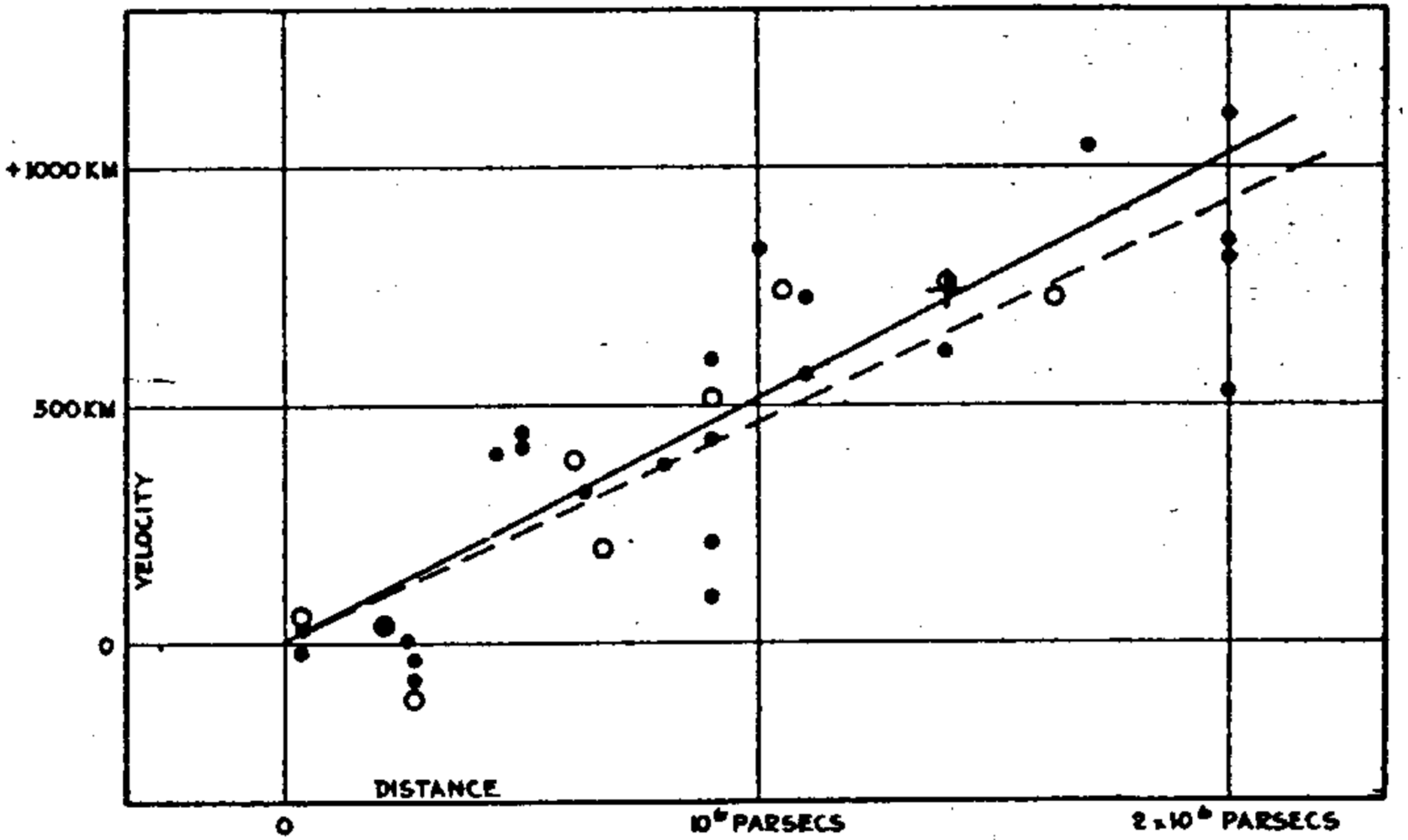


FIGURE 1

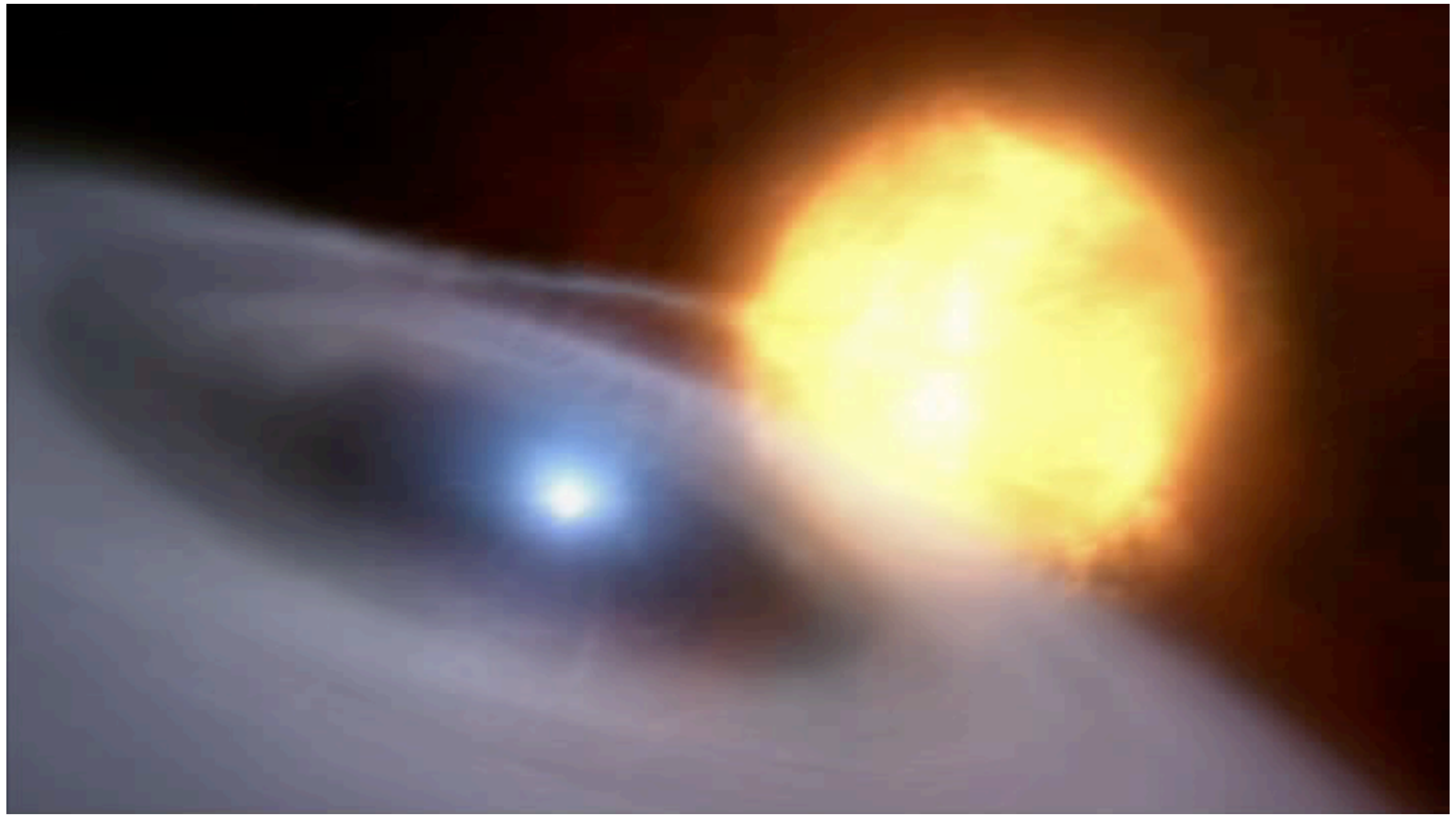
Hubble, 1929

The Local Distance Ladder
SNe Ia

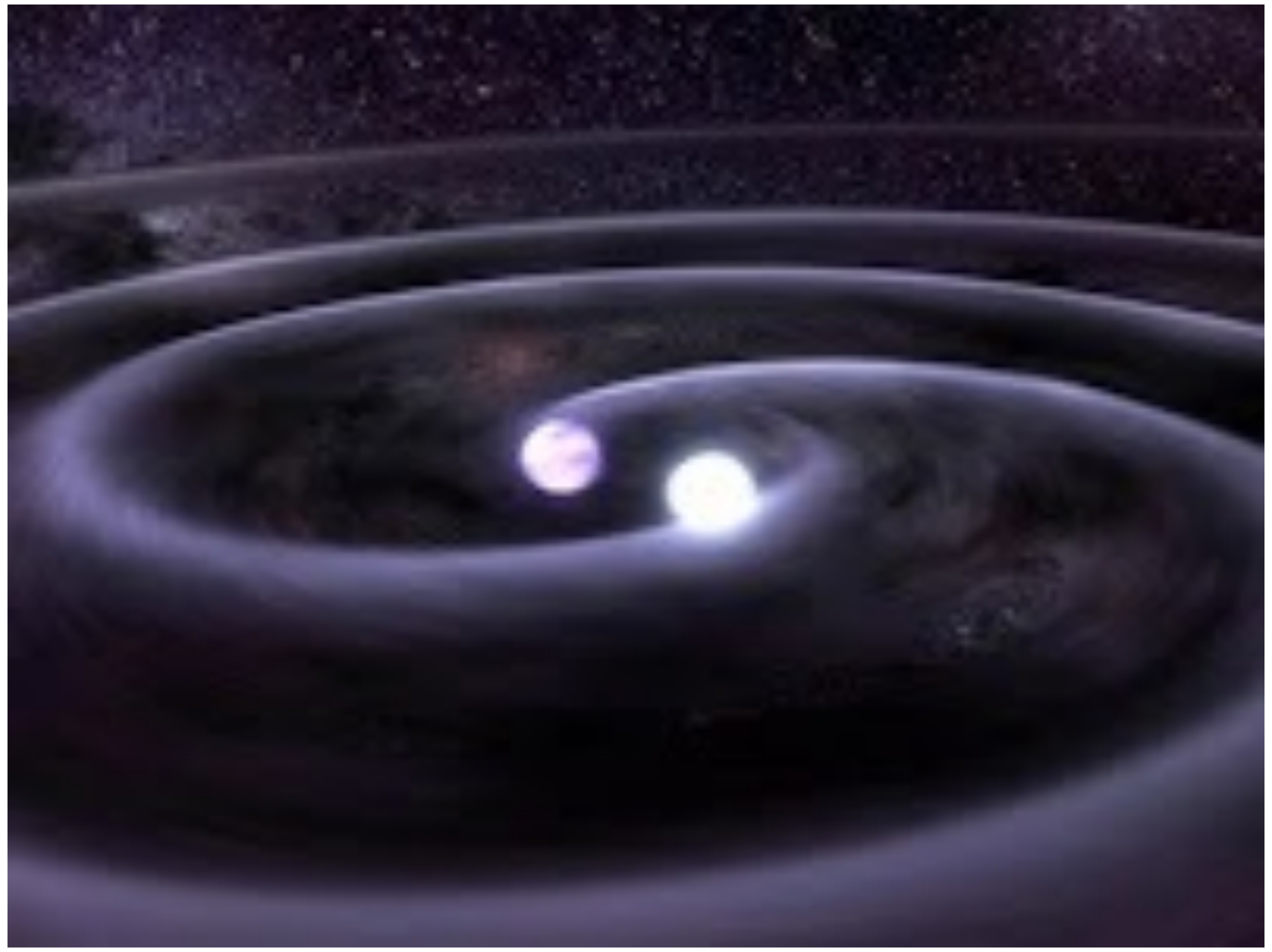
- SNe Ia are formed by detonation of a Carbon/ Oxygen white dwarf, but progenitor system unclear

Possible Progenitor Systems

white dwarf accreting mass from giant star



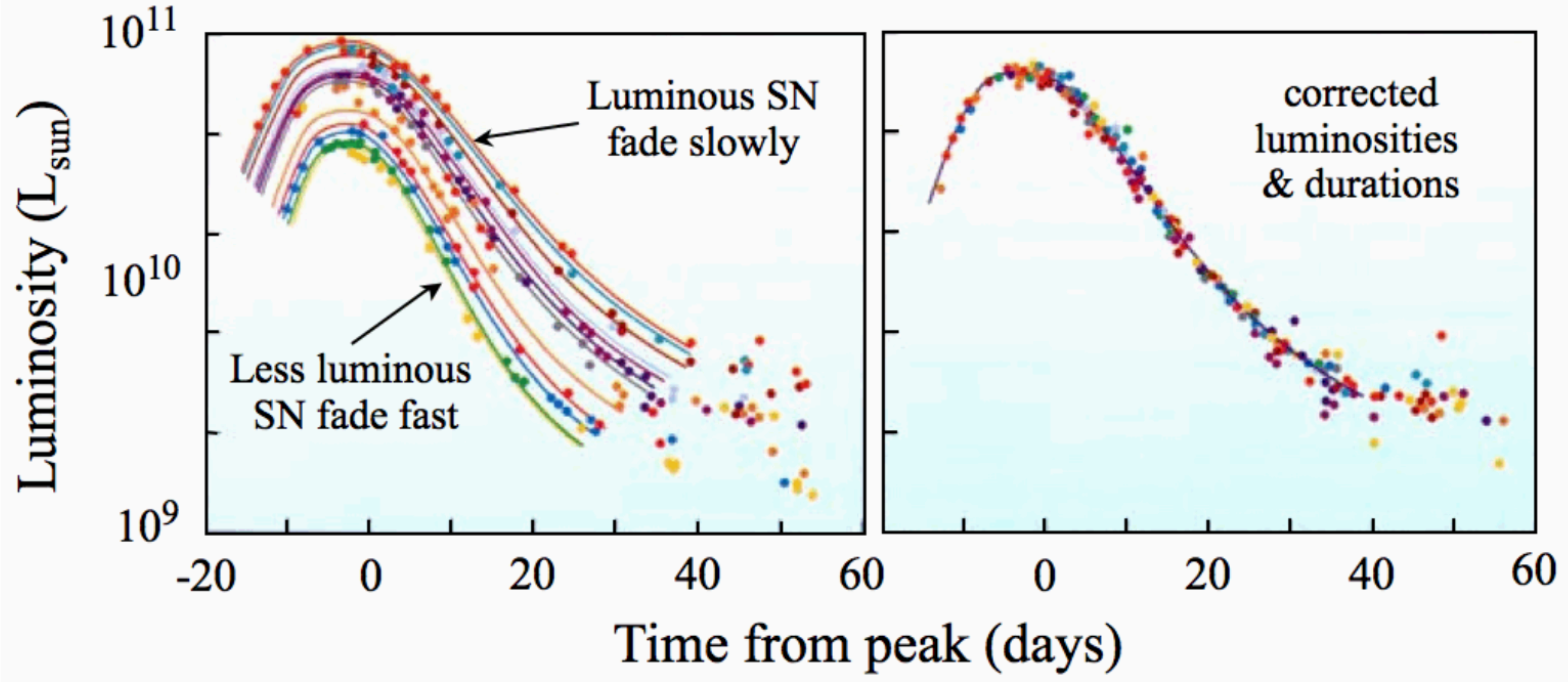
two white dwarfs merge due to grav. radiation



credit: ESO

The Local Distance Ladder
SNe Ia

- SNe Ia are formed by detonation of a Carbon/Oxygen white dwarf, but progenitor system unclear
- SN Ia are empirically standardizable



The Local Distance Ladder

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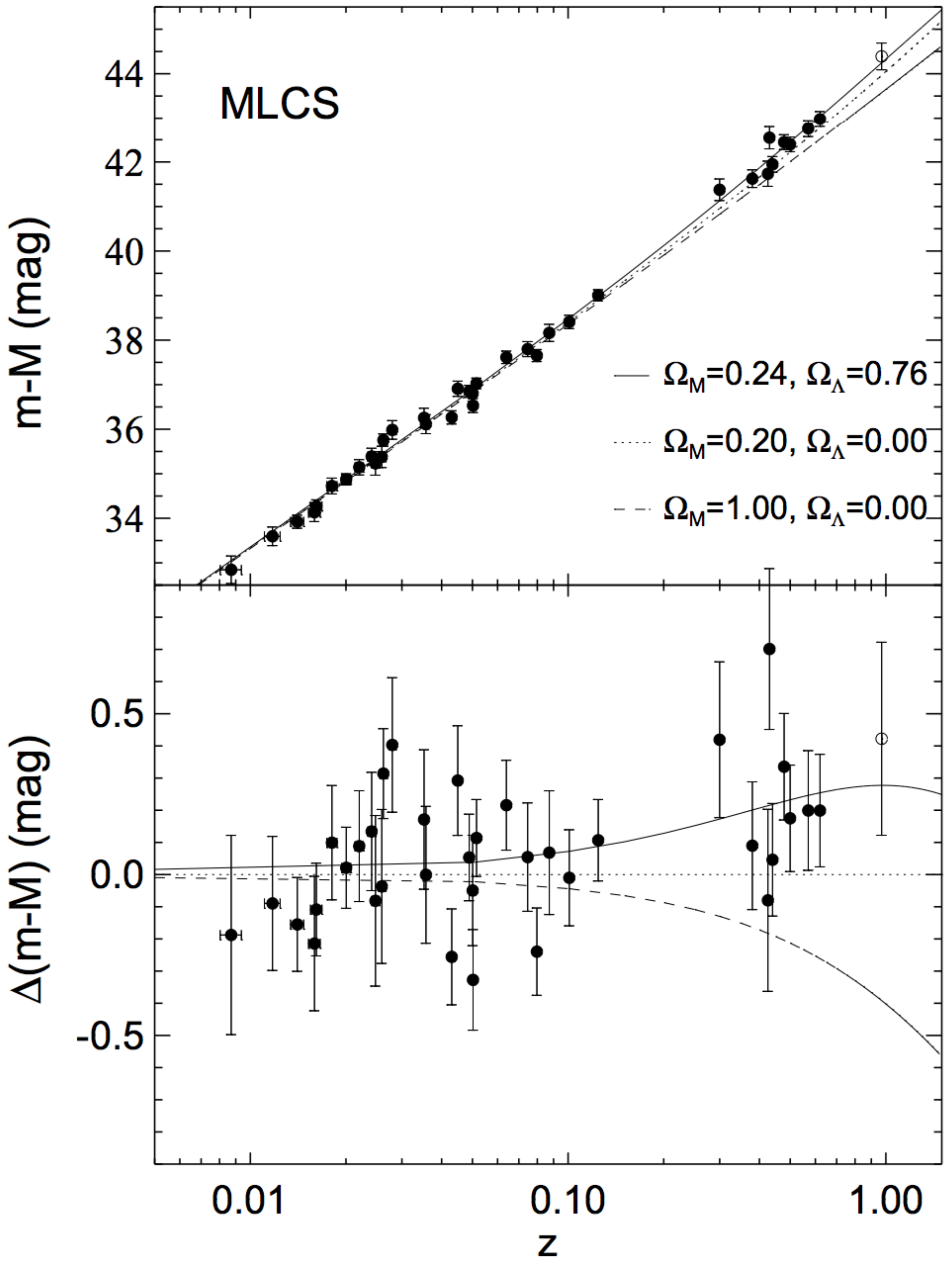

Riess+98

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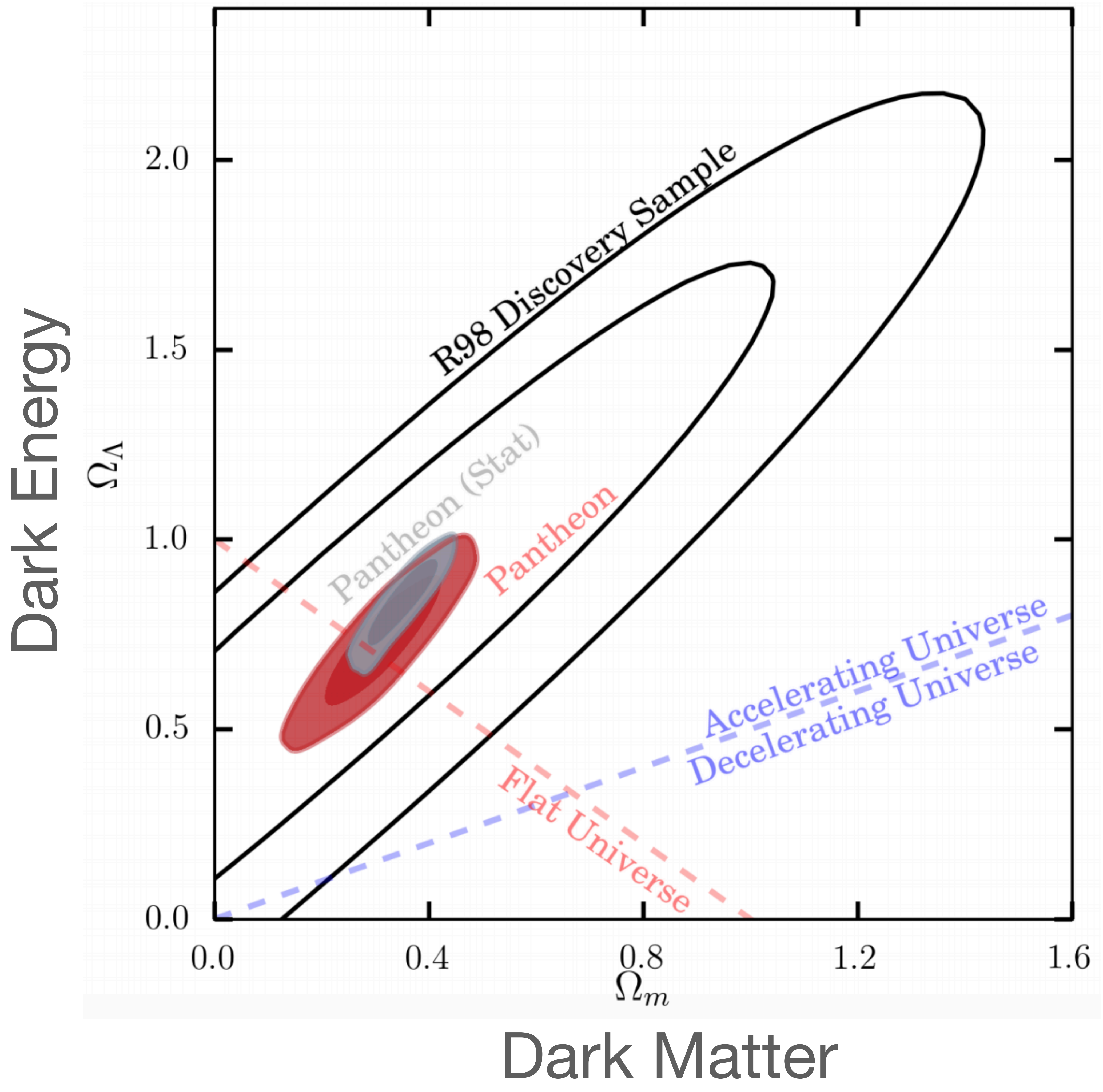

Scolnic, Jones+18

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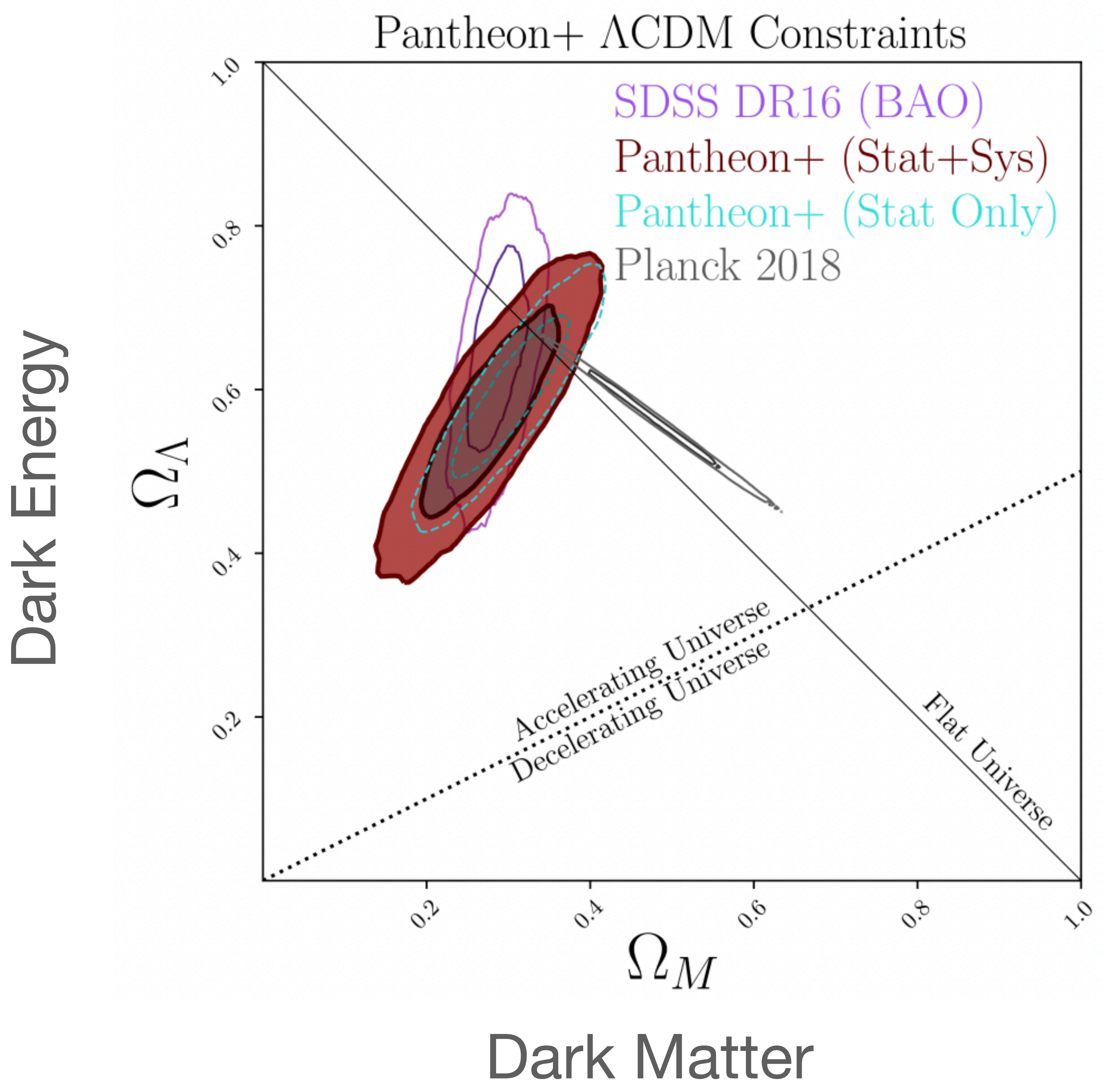
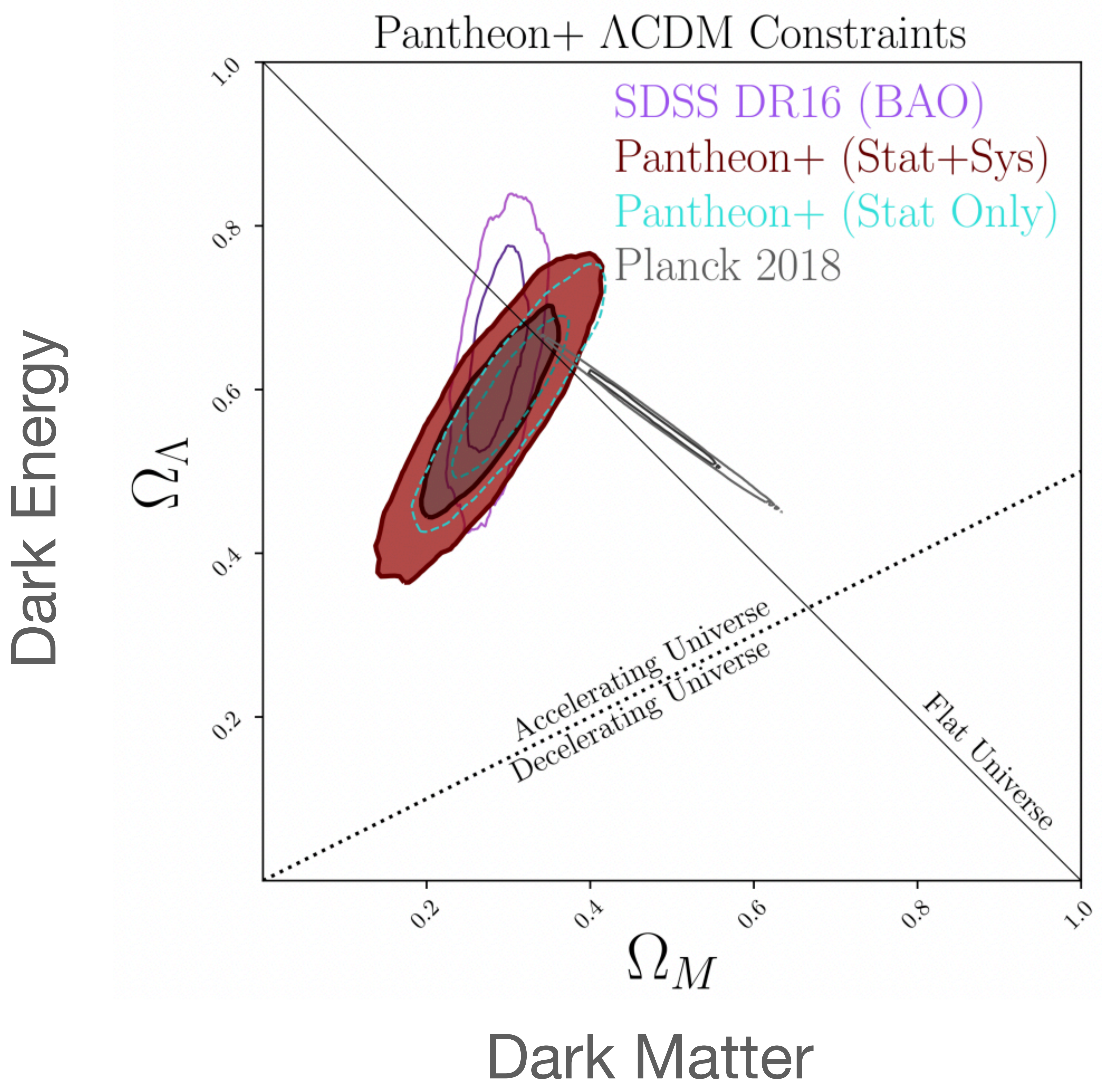


Brout+22, incl. Jones

The Local Distance Ladder
SNe Ia

- SNe Ia are formed by detonation of a Carbon/ Oxygen white dwarf, but progenitor system unclear
- SN Ia are empirically standardizable
- Led to discovery of the accelerating universe
- Also used to constrain dark energy equation of state, *w*, to understand its nature
- Used to measure the distance versus redshift relation -> H_0 measurement

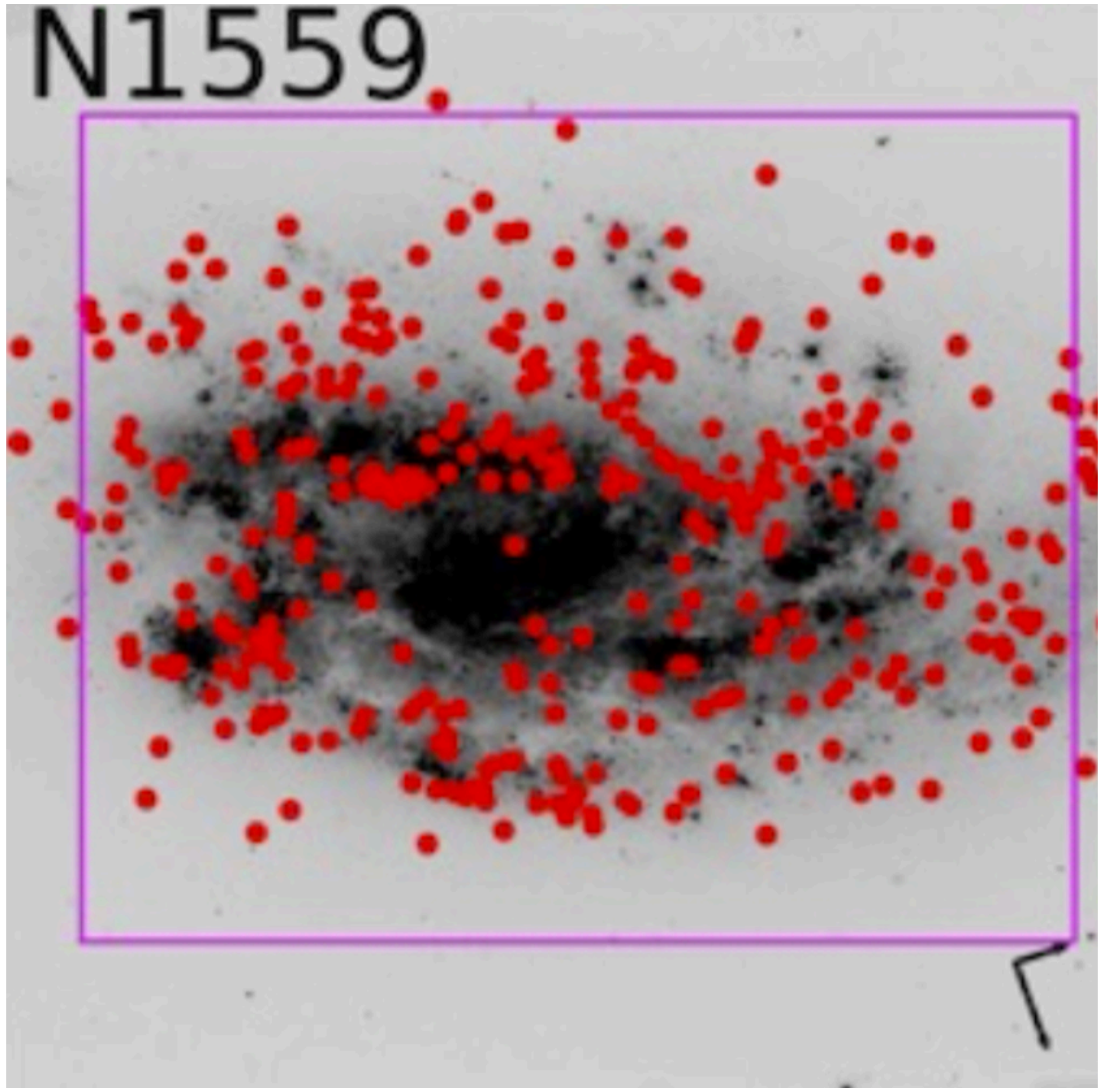


Brout+22, incl. Jones

Improving the Measurement of H_0
2. Cepheid Distances

Example Galaxy
Discovery

- Discovery: power law-spaced F350LP images allow identification of variable sources with a range of periods



Improving the Measurement of H_0

2. Cepheid Distances

- Discovery: power law-spaced F350LP images allow identification of variable sources with a range of periods

- P-L relation: periods measured from F350LP images, amplitudes from NIR

Example Galaxy
Cepheid Periods

Improving the Measurement of H_0

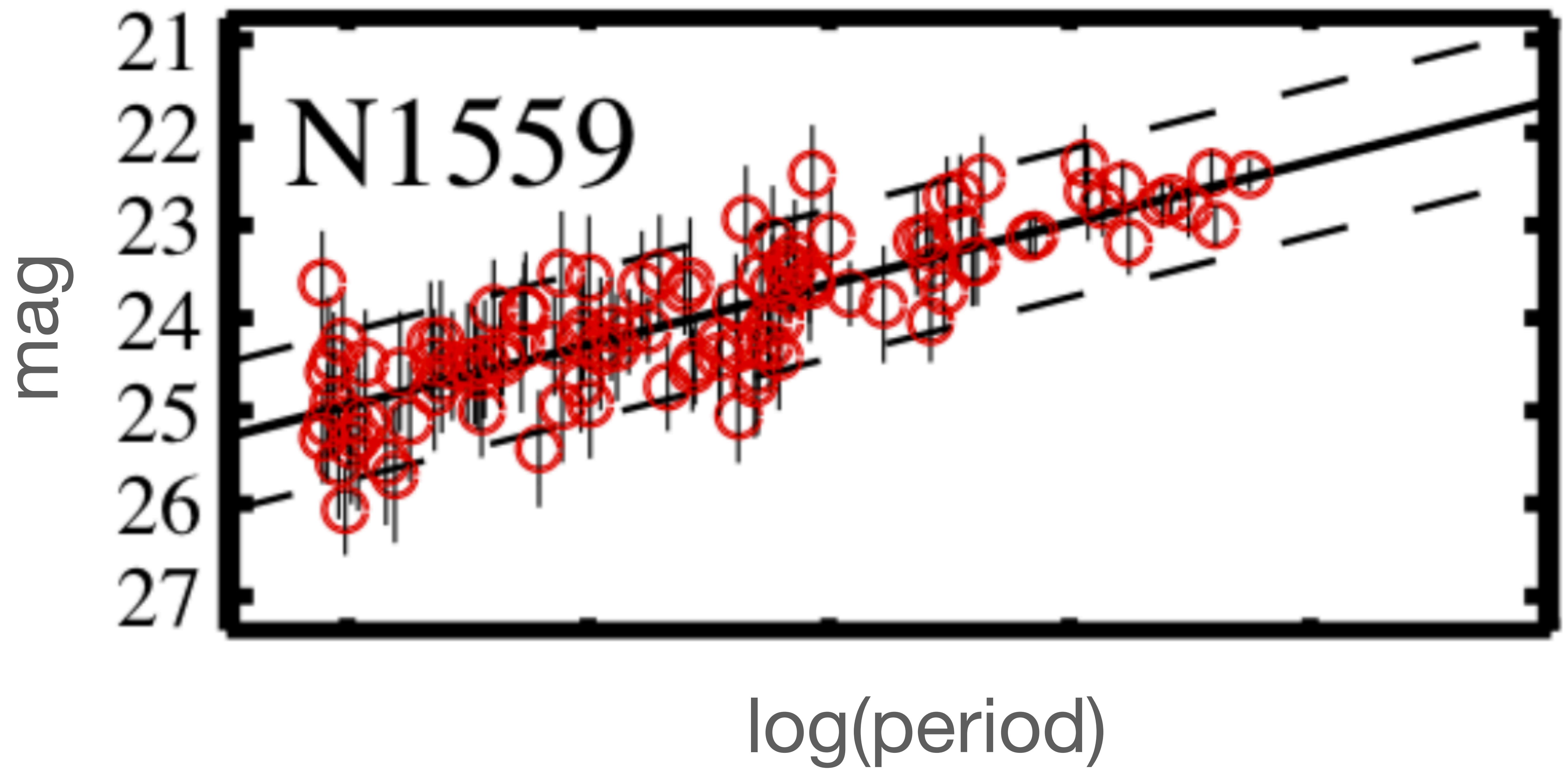
2. Cepheid Distances

- Discovery: power law-spaced F350LP images allow identification of variable sources with a range of periods

- P-L relation: periods measured from F350LP images, amplitudes from NIR

- NIR crowding correction: 100 artificial stars planted and recovered per Cepheid variable to estimate the background noise near the star

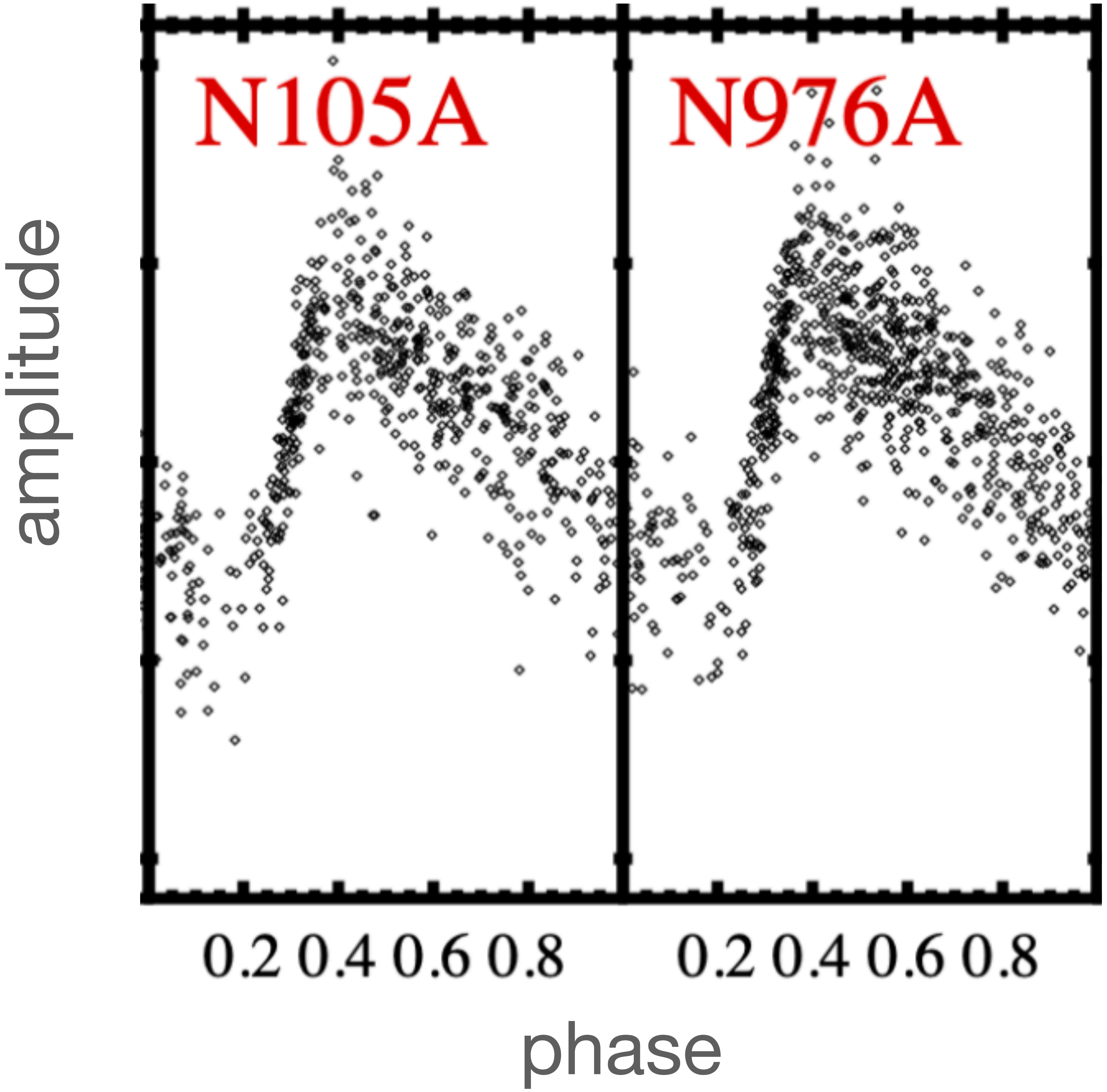
Example Galaxy
P-L Relation



Improving the Measurement of H_0

2. Cepheid Distances

~70 Mpc Galaxies



Improving the Measurement of H_0

2. Cepheid Distances

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