Tensions in cosmology (from the perspective of Type Ia Supernovae)

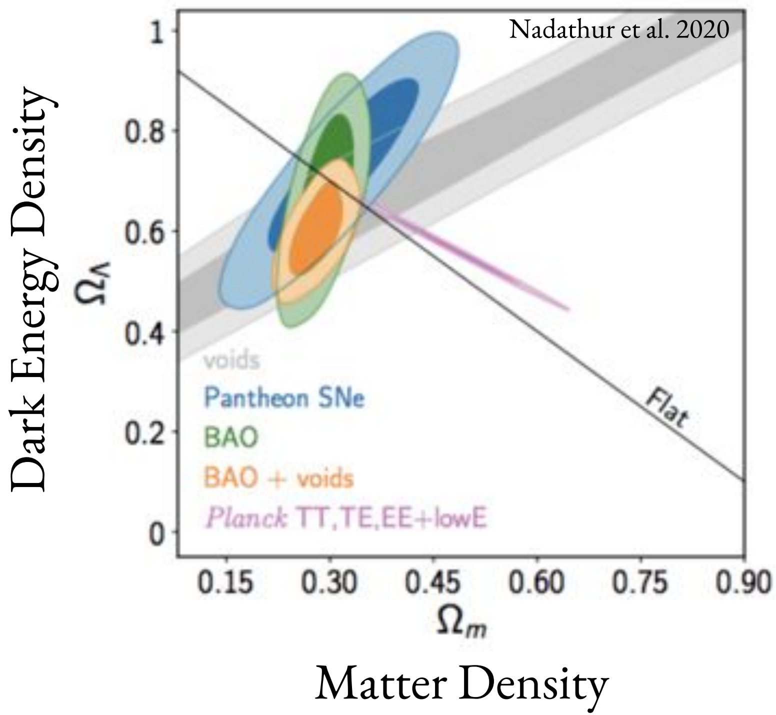
Dillon Brout

Boston University

SSI, August 13th, 2024

Cosmology has this great success story.

<u>ΛCDM 'concordance cosmology'</u>



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What is the cause of cosmic acceleration/dark energy?

- Is it the vacuum energy (cosmological constant) or is it something else?
- Is dark energy evolving?
- Is it in fact isotropic and homogeneous?

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The Cosmological Constant problem

- Why is the observed cosmological constant 120 orders of magnitude smaller than theoretical expectation?
  The largest discrepancy in all of science.

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Does ΛCDM stand up to the test?

- Hubble Constant *Crisis*
  The 'end-to-end' test doesn't pass.
- Also the S8 tensions/curiosity?

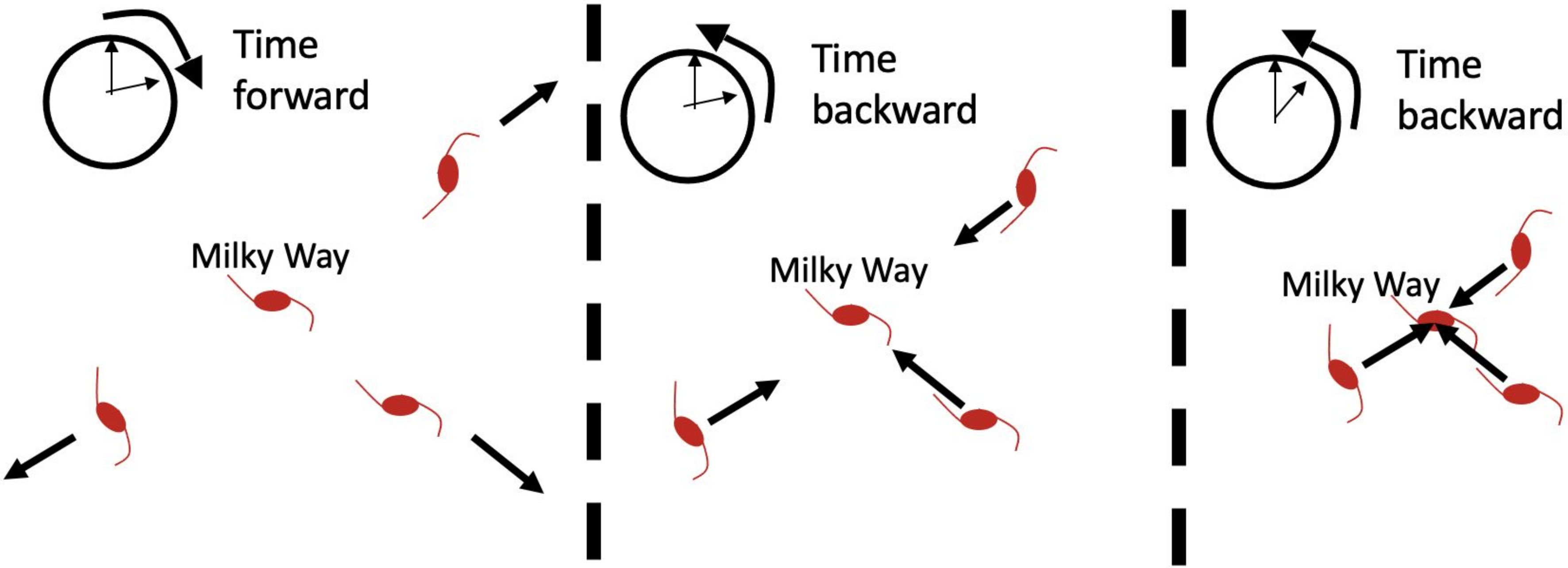
Expansion History

Today I will focus on two big issues:

Part I: The Hubble Constant (H0)

Part II: The Cosmological Constant (**Λ**), and potentially evolving/thawing dark energy.

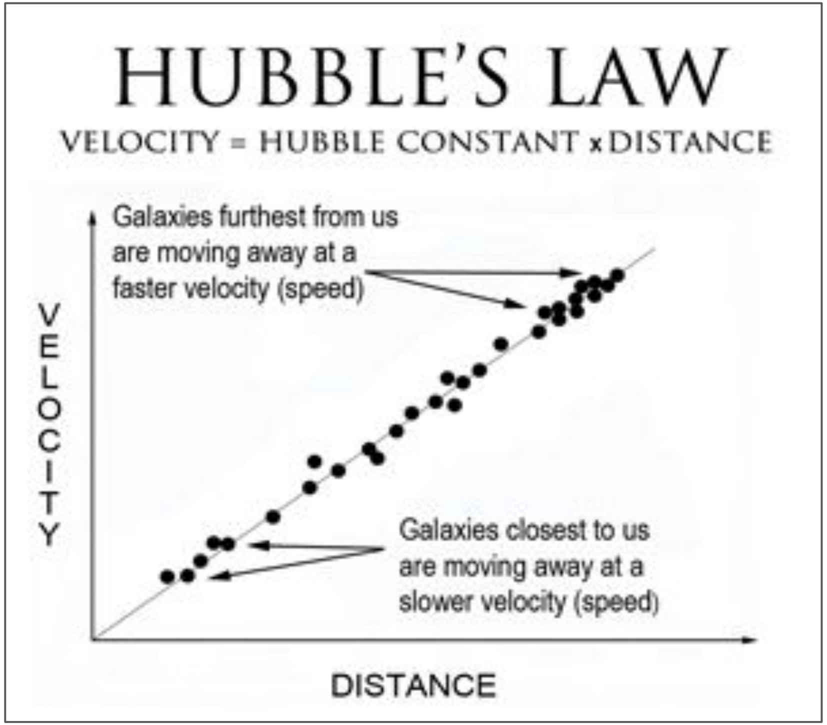
Nearby/Today's expansion rate of the universe H0 (linear regime)



Hubble constant, H_0, gives the present expansion rate.

The Cosmic Distance Ladder Method Tells us the Current Expansion Rate

$$v = H0*d$$



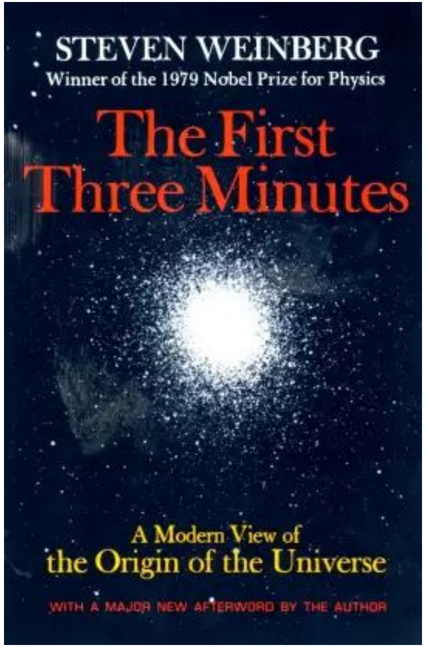
Credit:
astrobites

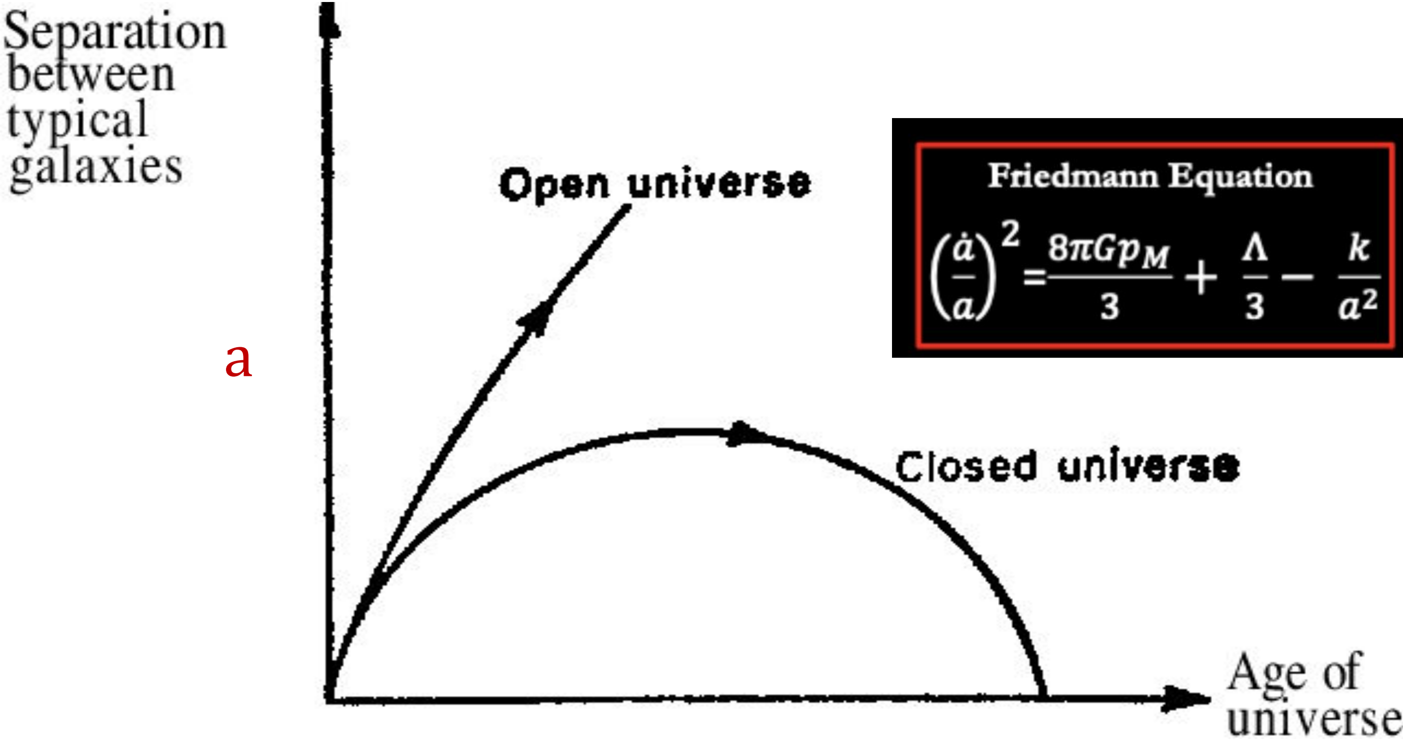
H0 has units $\mathrm{km\ s^{-1}\ Mpc^{-1}}$
or
1/seconds

→ *1/H0 is a remarkably good approximation for the age of the universe.*

You need to know physical distances!

Measuring distances in cosmology is hard
But fundamental for several reasons





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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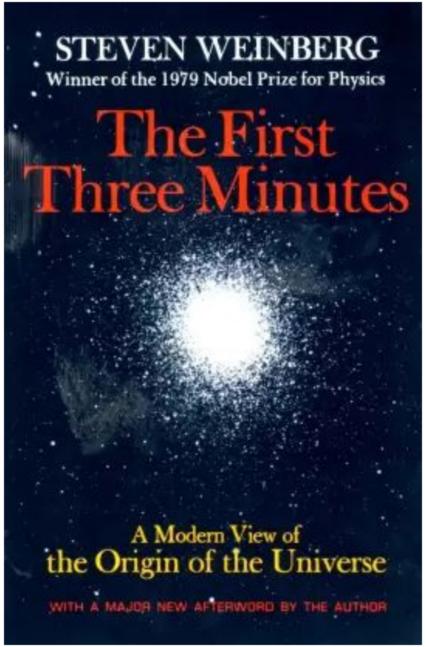
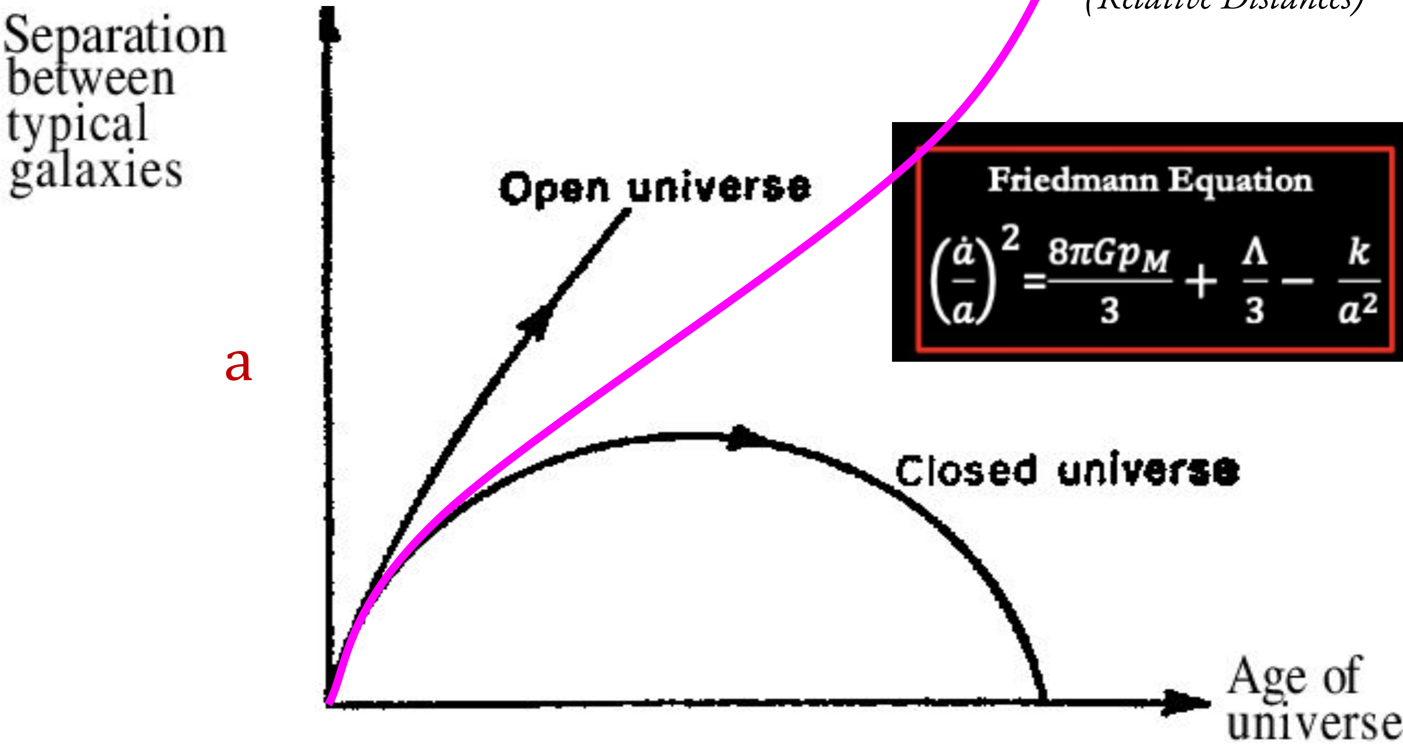




In summary, measuring both **a** and **H0** tells us about

The fundamental composition of the universe

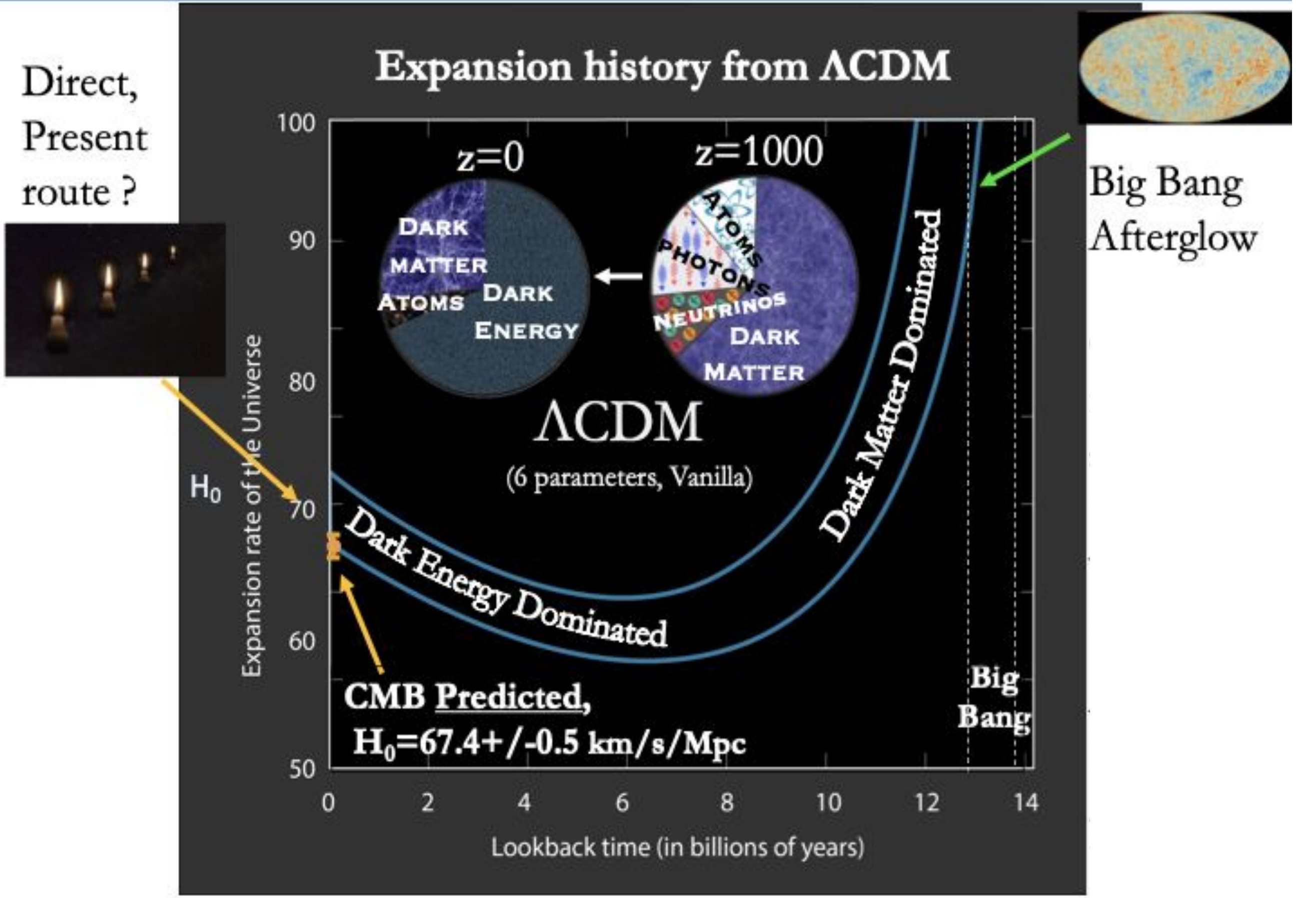
- Matter (and dark matter) Density,
- The Cosmological constant/Dark Energy,
- Curvature (lesser extent but true),

The age of the universe,

The fate of the universe,

And more

The ultimate end to end test of LCDM is to Predict and Measure H0



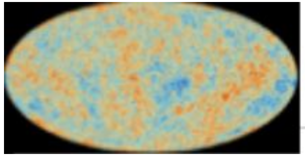
And ensuring end-to-end consistency is very important!

The New York Times

symmetry

dimensions of particle physics

The 9 percent difference



Measuring the distance to the CMB (D_{cmb})

$$D_{cmb} = s/\theta$$

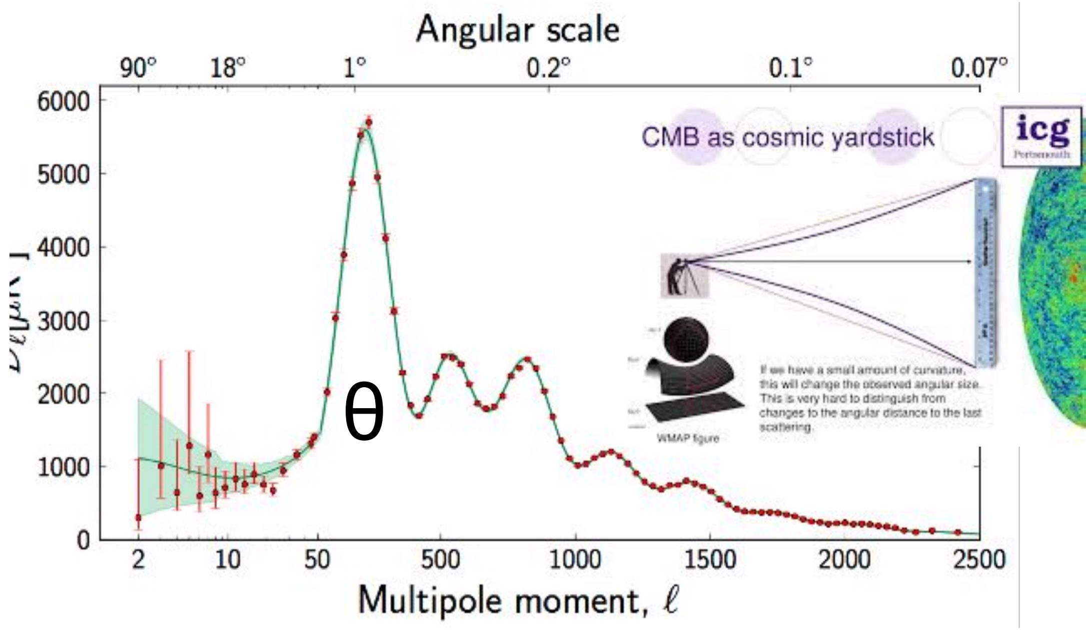
where s is the physical size and θ is angular size of sound horizon

The physical size s

$$s = \int_0^{t_{rec}} c_s\,(1+z)dt = \int_{z_{rec}}^{\infty} \frac{c_s\,dz}{H(z)}$$

Standard ruler

- Depends on
  - Epoch of recombination
  - Expansion of universe
  - Baryon-to-photon ratio (through c_s)

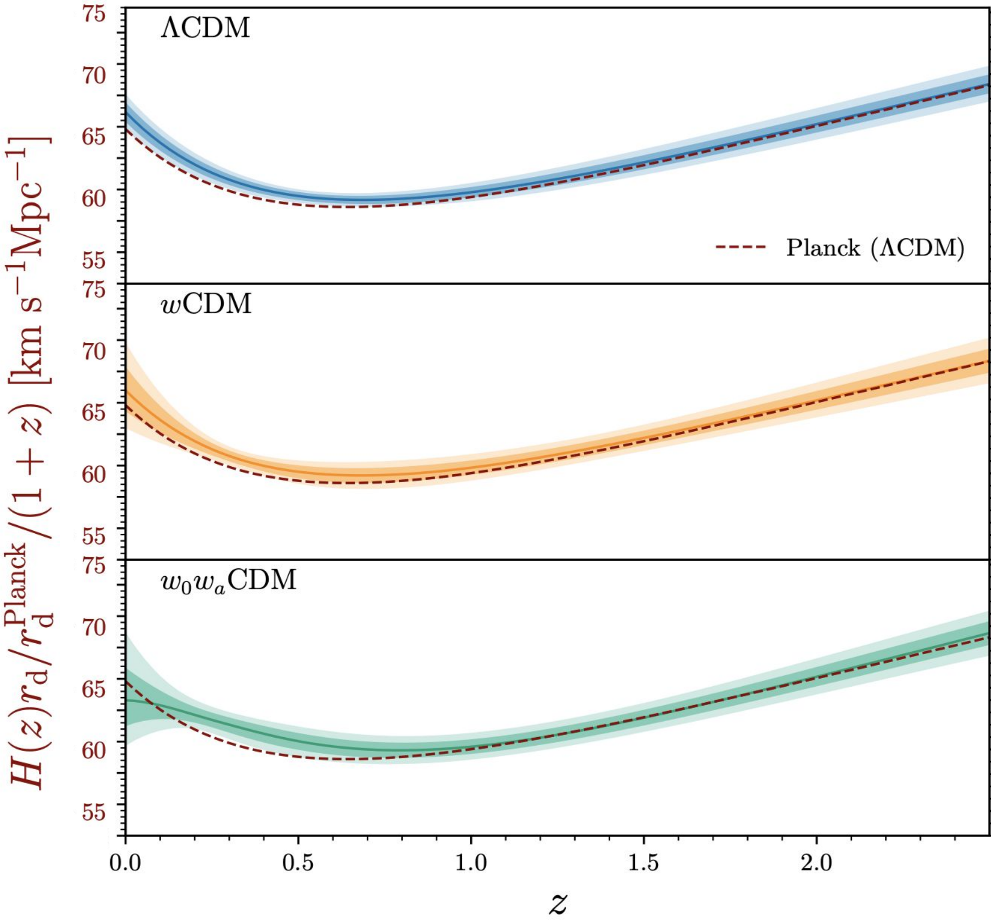


Predicting H0 From CMB/Planck Requires the assumption of a cosmological model

The black dashed line is anchored at z=1100.

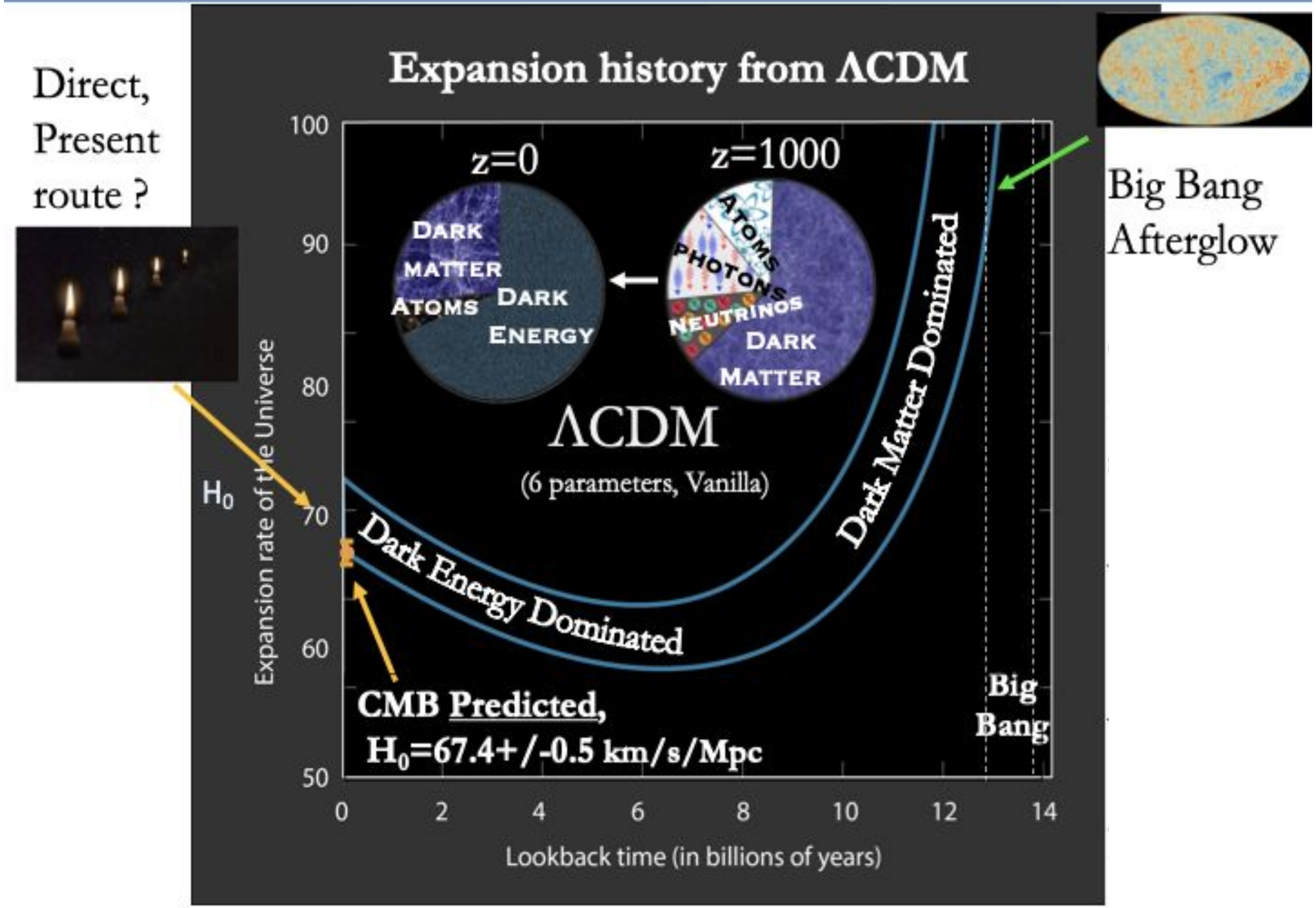
H0 is defined at z=0

Constraints on the expansion history can come from Planck alone, but you can also combine with other probes of expansion history to constrain the shape of the curve. (see Camileri et al 2024)

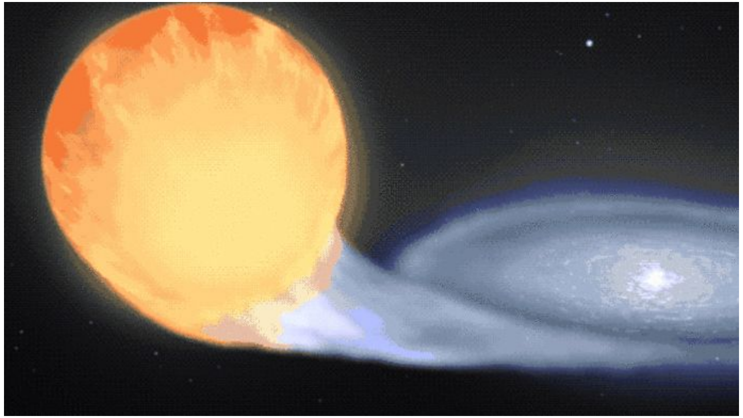


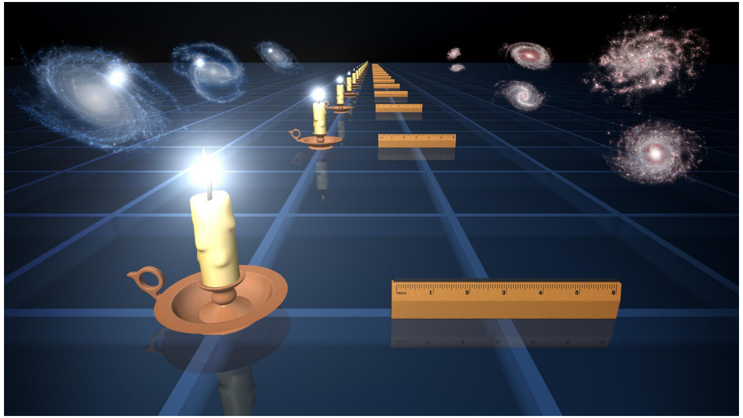
DESI Collaboration 2024

The ultimate end to end test of LCDM is to Predict and Measure H0

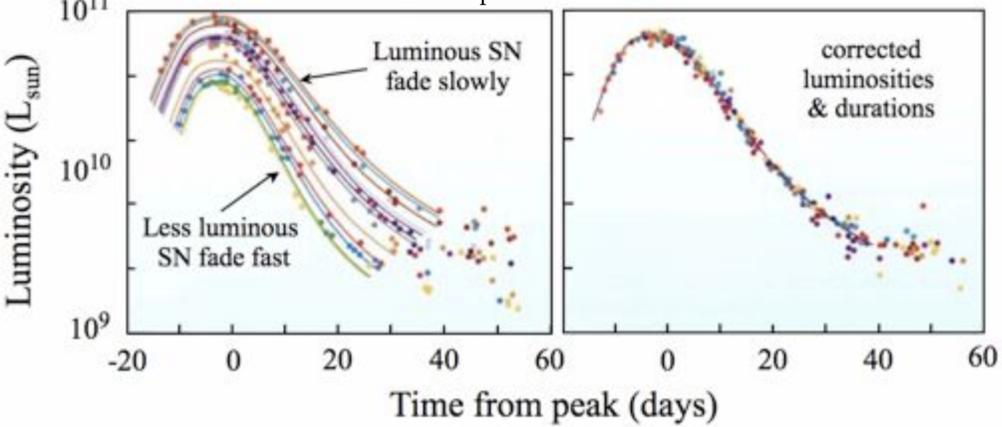


Supernovae Ia (SNe Ia) can be seen across the universe and are standard*izable* candles.





“Phillips relation” - 1993



- Correct (10%) for a stretch-luminosity relation (Ni56) and <u>a color-luminosity relation (i.e. dust)</u>.
- The ratio of the *intrinsic* to *apparent* luminosity provides the luminosity-distance (d_L) of the supernova.

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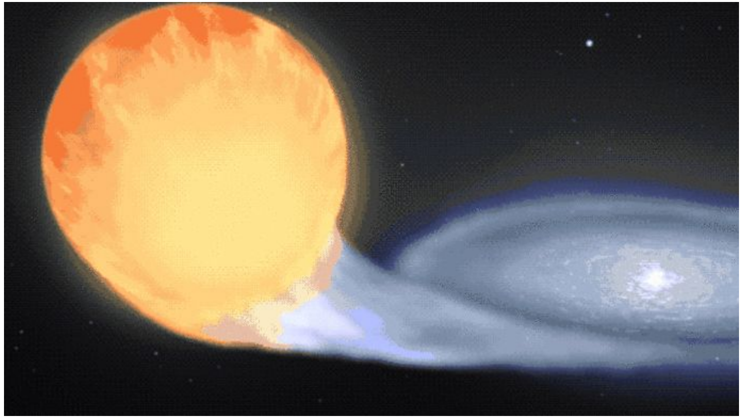

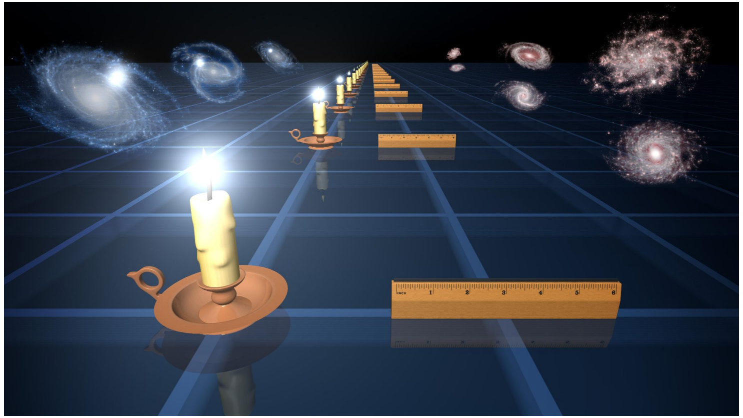

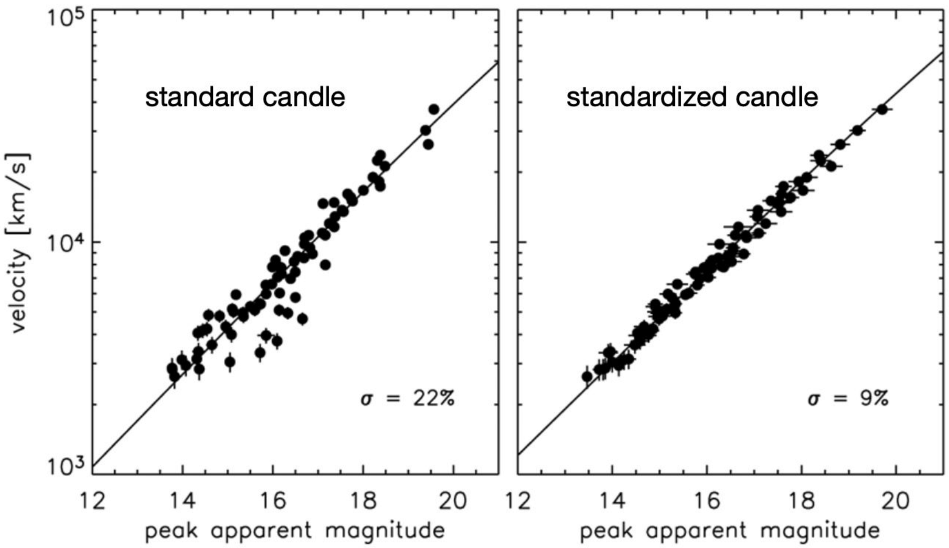

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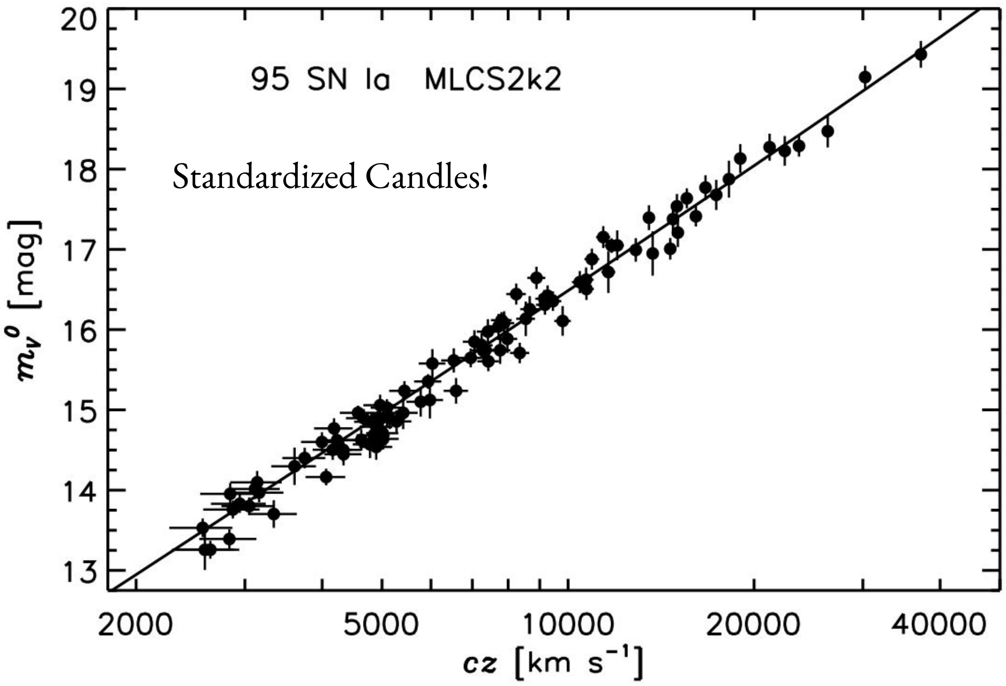
The straightforward answer to SNIa Evolution

Jha, Riess, Kirshner 2007



How do we know?

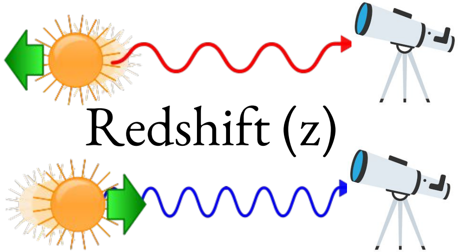
SNIa in the smooth `Hubble Flow' are the key.

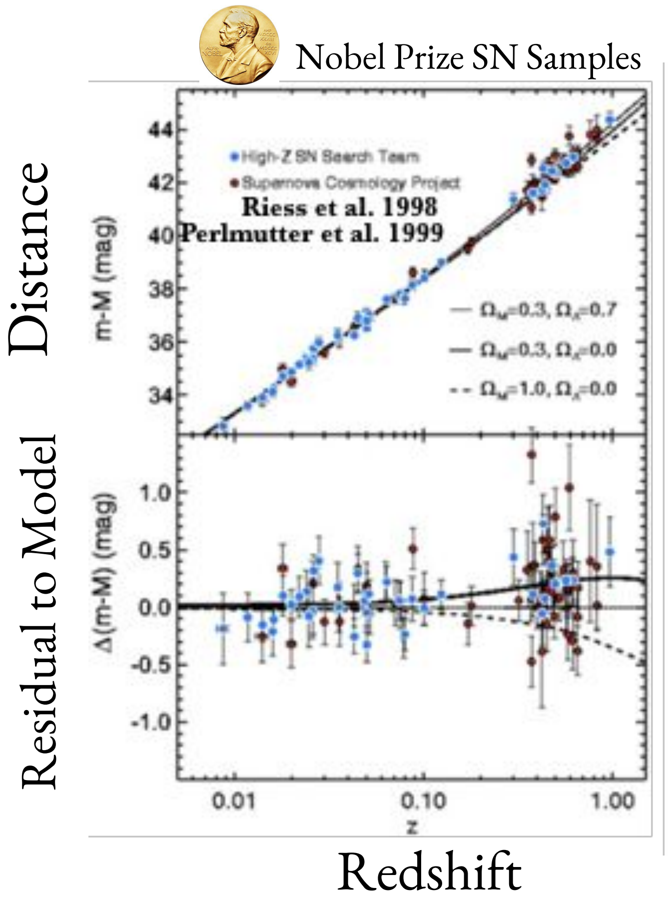
e.g. for 0.02<z<0.1, z_obs ~ z_cosmological

We can compute relative distances with negligible dependence on cosmological parameters… (there is no H0 in this plot)

<u>This Hubble Flow sample spans the full range of SNIa light curve parameters, host types</u> (ages, masses etc).

The Standard Model of Cosmology (ΛCDM)





Combine luminosity distance with host galaxy redshift (z) to place on the Hubble Diagram and compare to cosmological models. Reveals an accelerating universe.

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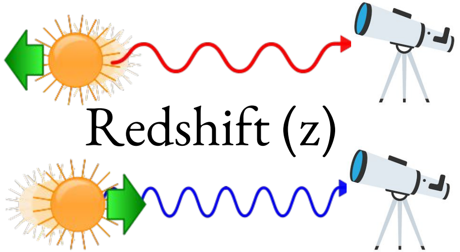

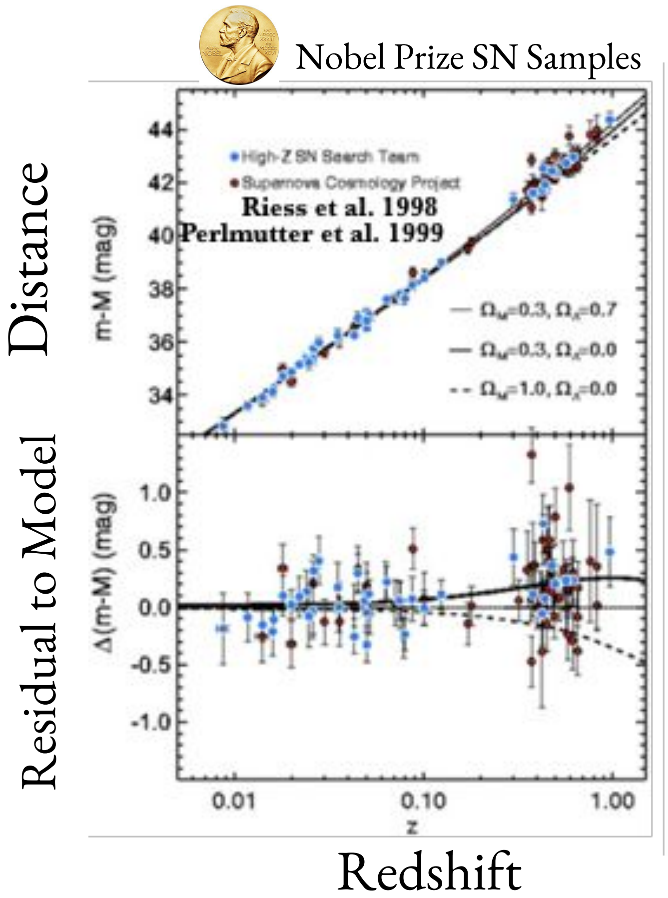

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$$d_L(z) = (1{+}z)\, c \int_0^z \frac{dz'}{H_0\sqrt{\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}}}$$

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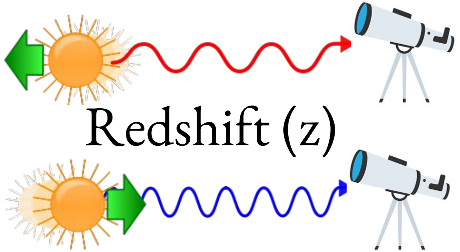

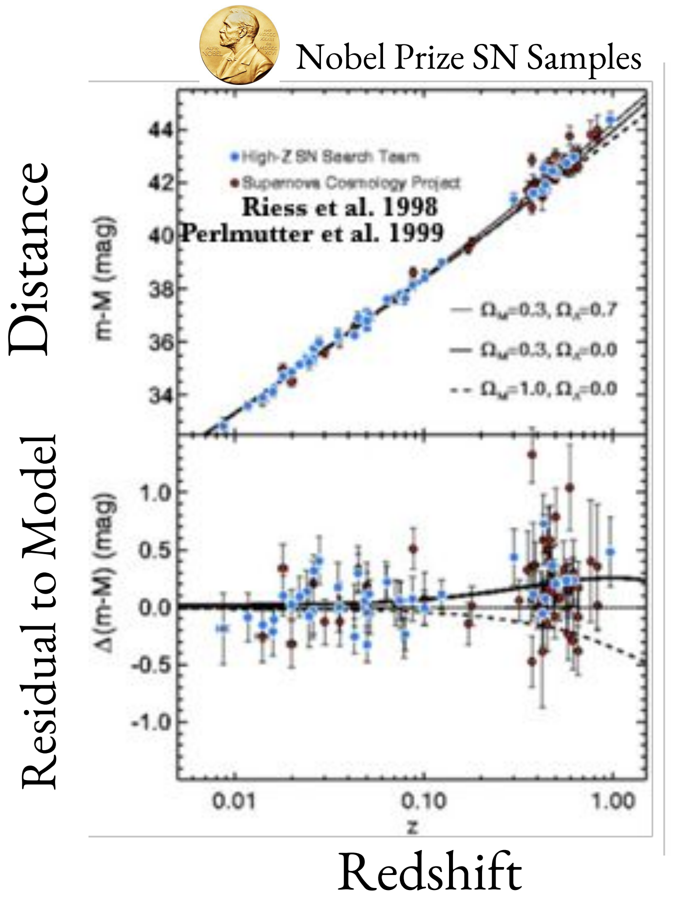

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Matter + Dark Matter — Dark Energy — Equation of State

If w = -1, DE is cosmological constant (constant energy density)

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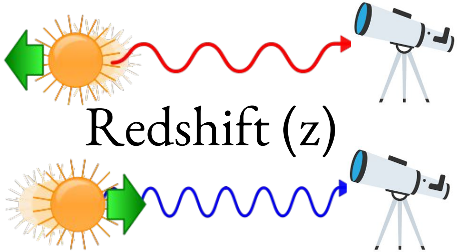
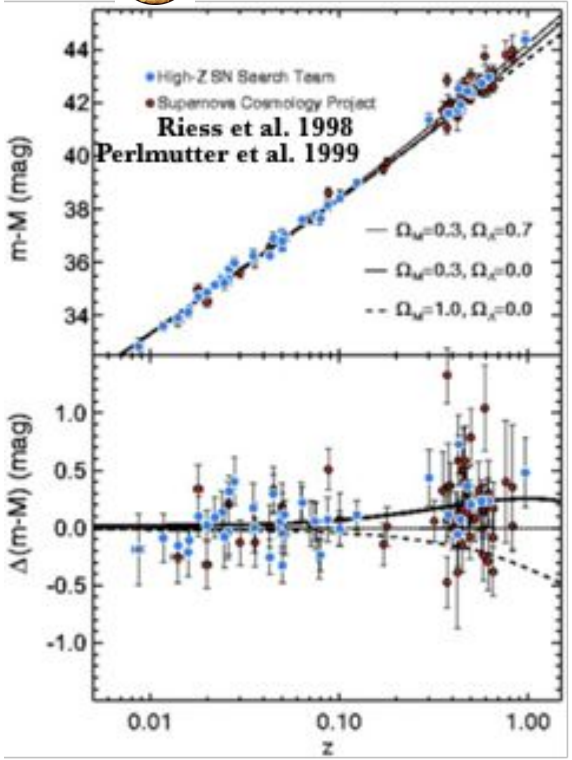


Nobel Prize SN Samples

Distance

Residual to Model



Redshift

Combine luminosity distance with host galaxy redshift (z) to place on the Hubble Diagram and compare to cosmological models. Reveals an accelerating universe.

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Matter + Dark Matter

Dark Energy

Equation of State

If w = -1, DE is cosmological constant (constant energy density)

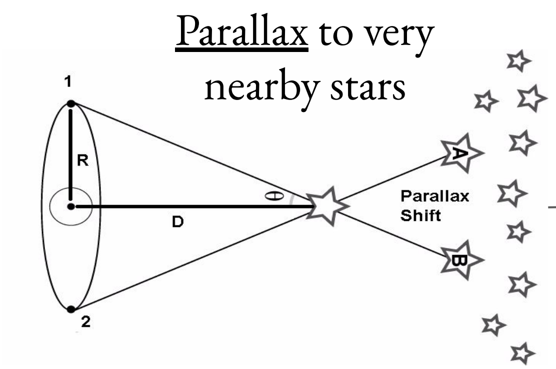
w_a = time varying dark energy

However, Supernova Ia intrinsic luminosity is not known.

Thus far we have only discussed SNeIa as a relative distance indicator.

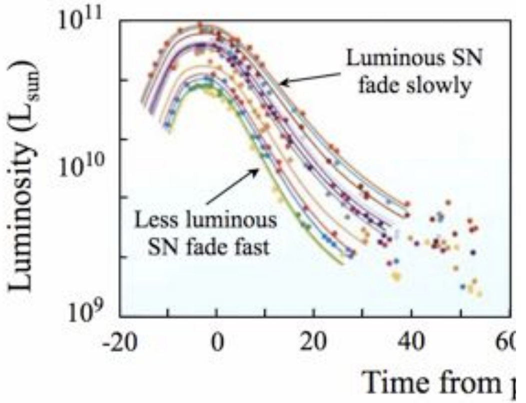
So we are forced to calibrate the SNeIa to a physical distance scale.

Additionally, because SNeIa are rare (1/gal/100y), we have to use an intermediary.



Some other distance indicator that is found ubiquitously

Type Ia Supernovae



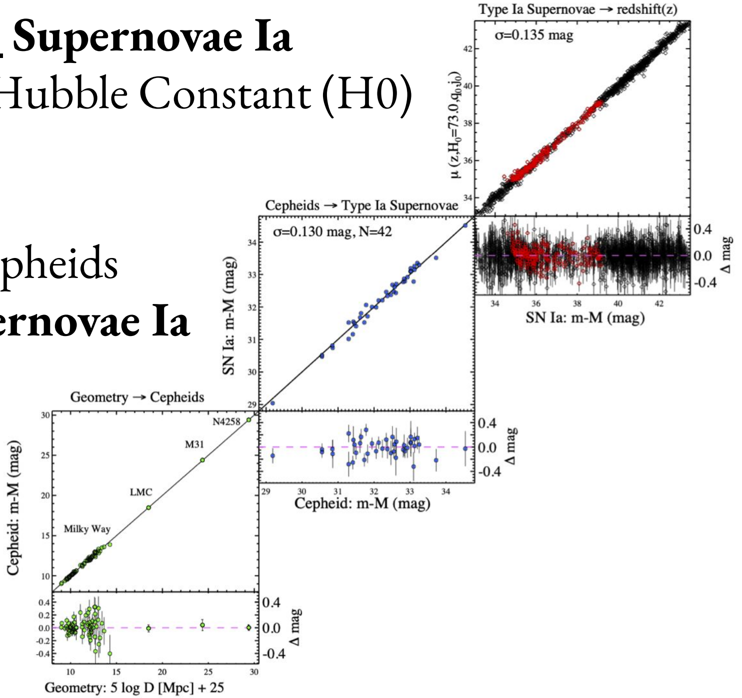
A Direct, Local Measurement of H_0, percent precision w/ HST

The SH0ES Project (since 2005)

<u>3rd:</u> **Supernovae Ia**
→ Hubble Constant (H0)

<u>2nd:</u> Cepheids
→ **Supernovae Ia**

<u>1st:</u> Geometry
→ Cepheids



The Cosmic Distance Ladder Method Tells us the Current Expansion Rate

SH0ES

v = H0*d

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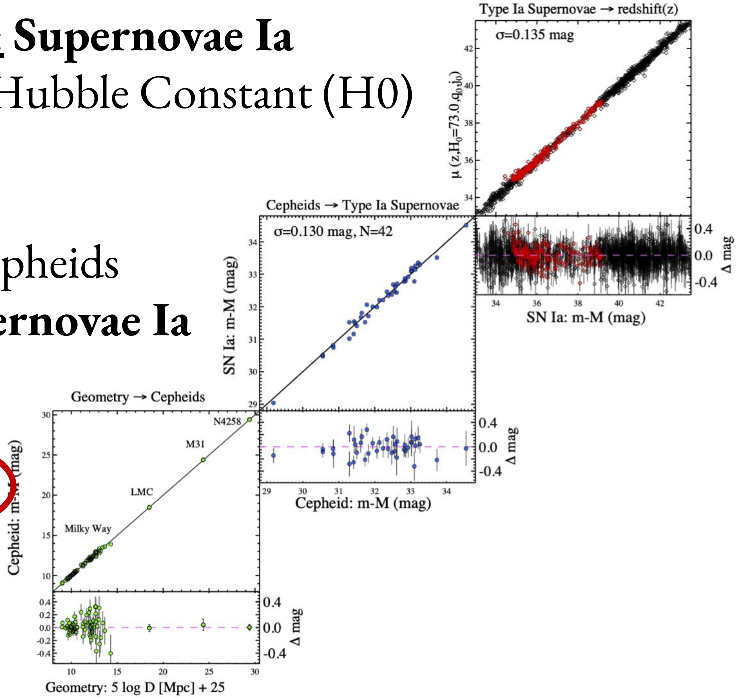
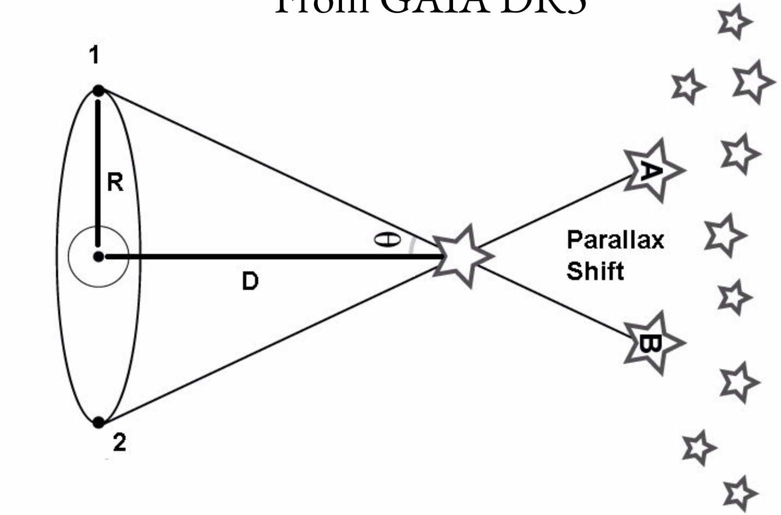


Riess, Yuan, Macri, Scolnic, **Brout**+21

Parallax to very nearby stars
From GAIA DR3



To measure v=H0*d you need absolute distances (not relative)

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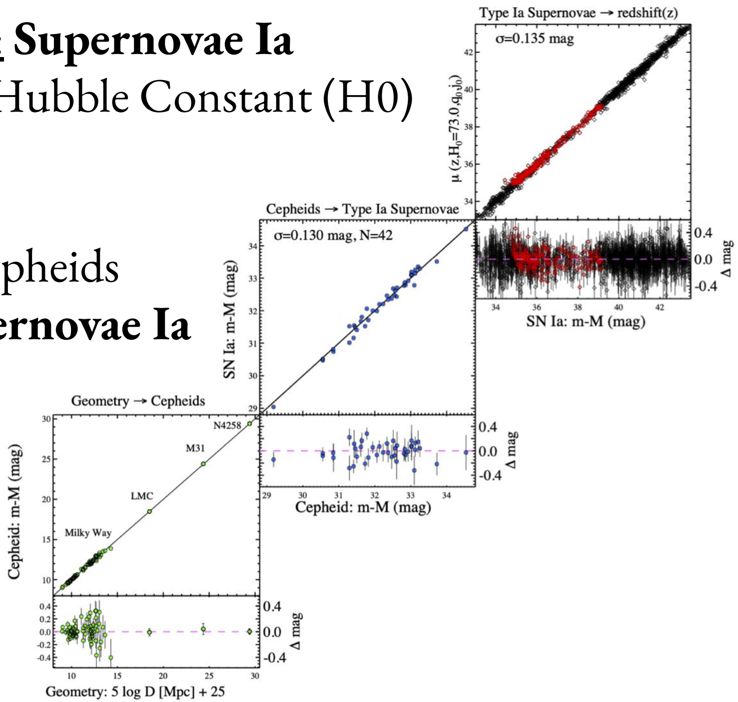
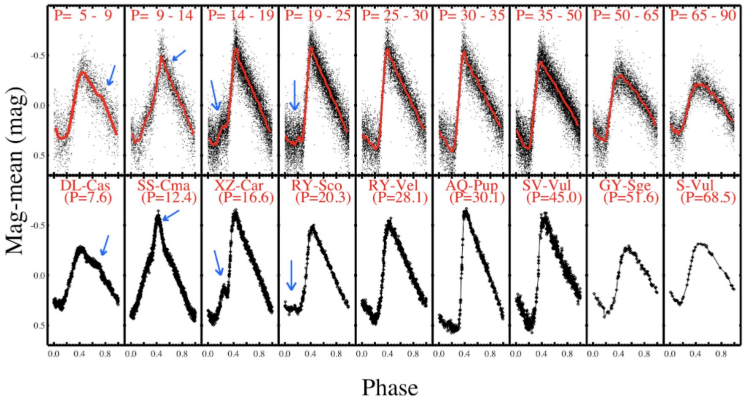


Riess, Yuan, Macri, Scolnic, **Brout**+21

Cepheids exhibit a relation between their period and their luminosity



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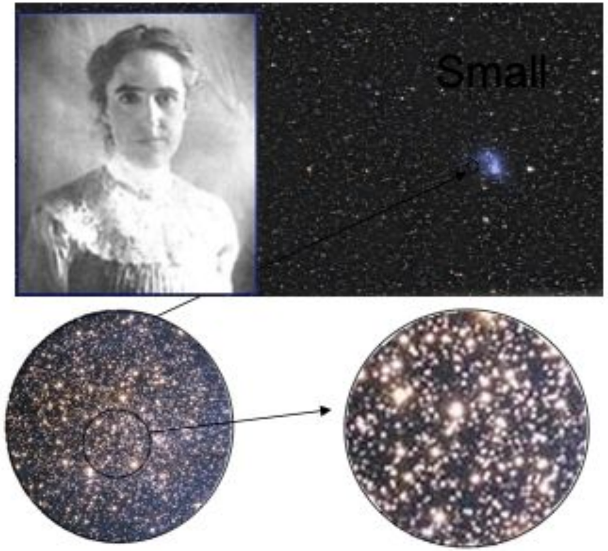
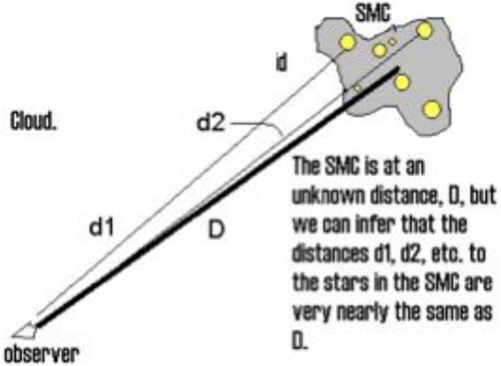
Henrietta Leavitt (1912) Discovers a Cosmic Yardstick

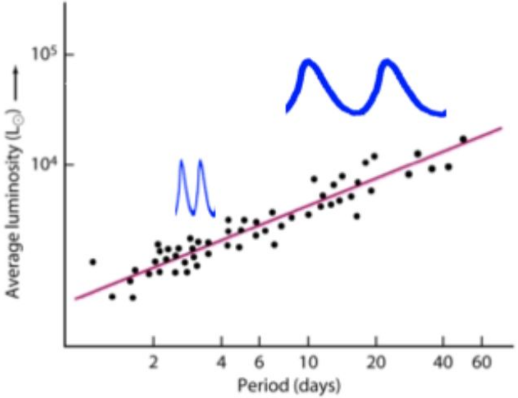




H.L. assumed stars in cloud at same distance→brightness rank=luminosity rank.

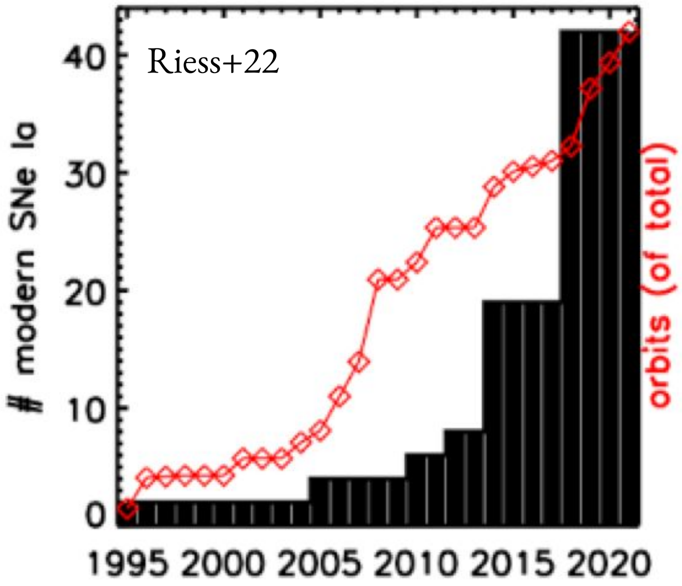
1) Some *of the brightest* SMC stars brightness varied *cyclically* over days, weeks (like the Milky Way star δ Cephei). So called these "Cepheids"

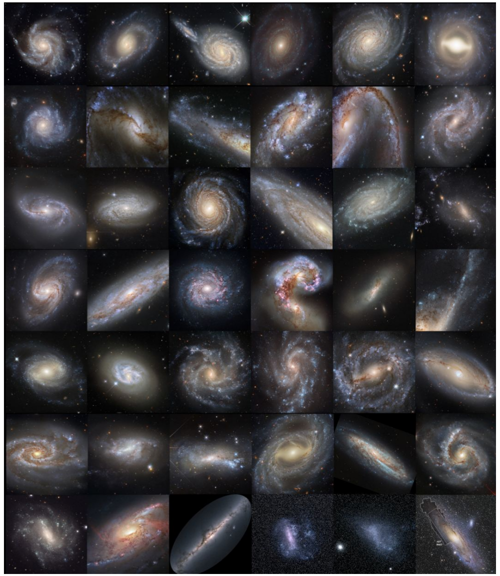
2) Slower they varied (i.e., longer Period), brighter (on average) they appeared. Since all roughly same distance, *luminosity depends on their period*.
Huge discovery!! Cepheid Variables could be used as a cosmic yardstick!



SH0ES 2022, First Major Update Since 2016

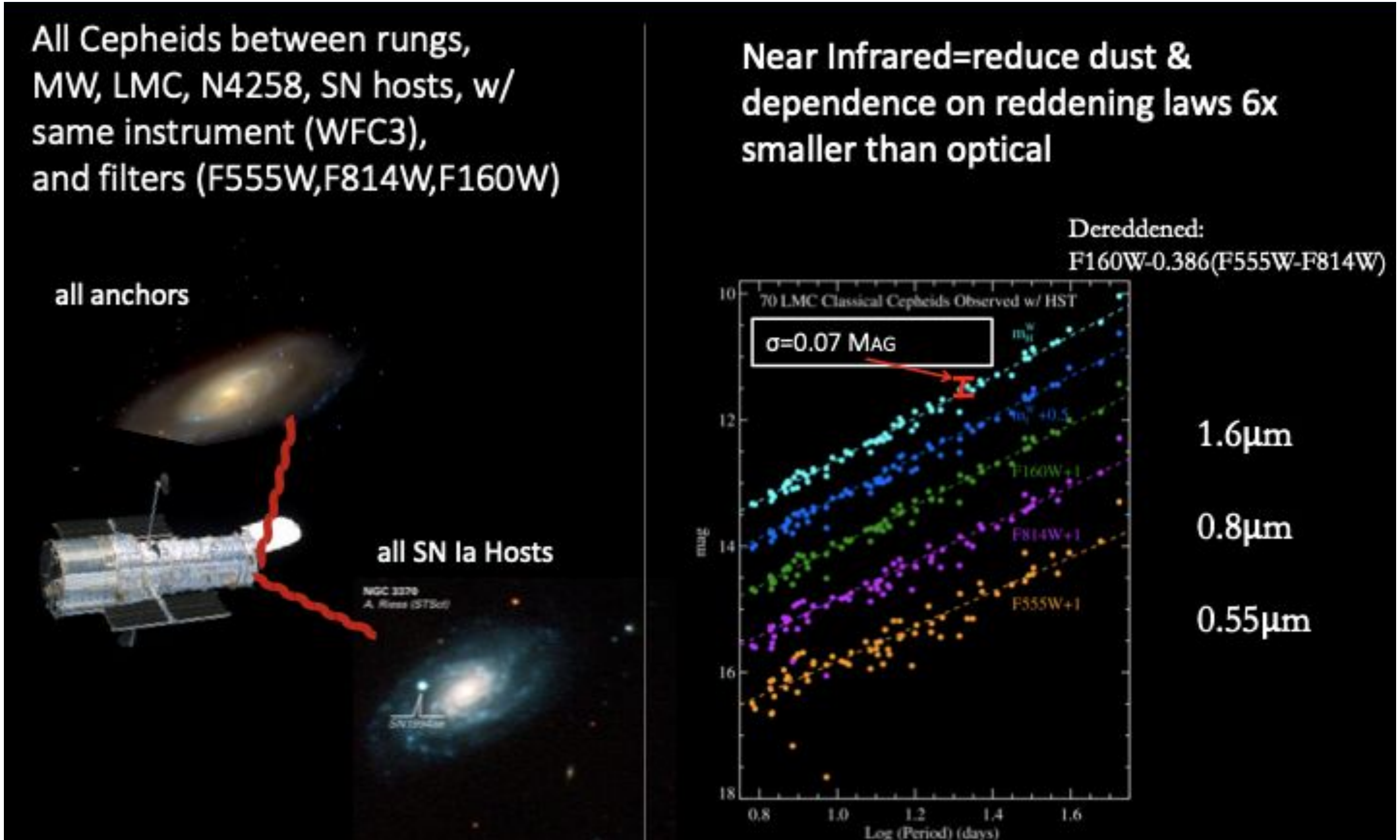
- More than doubles SN calibrators from 19→42 and complete at z<0.01
- Now have an average of 2 photometric systems for each SN that is in a cepheid host (77 light curves in 42 SN in cepheid hosts)
- Cepheid calibrator SNe are analyzed simultaneously with Hubble flow SNe (including systematics)





SH0ES HST Cepheids Have Low Systematics From

Differential Flux Measurements and NIR Dust Insensitivity



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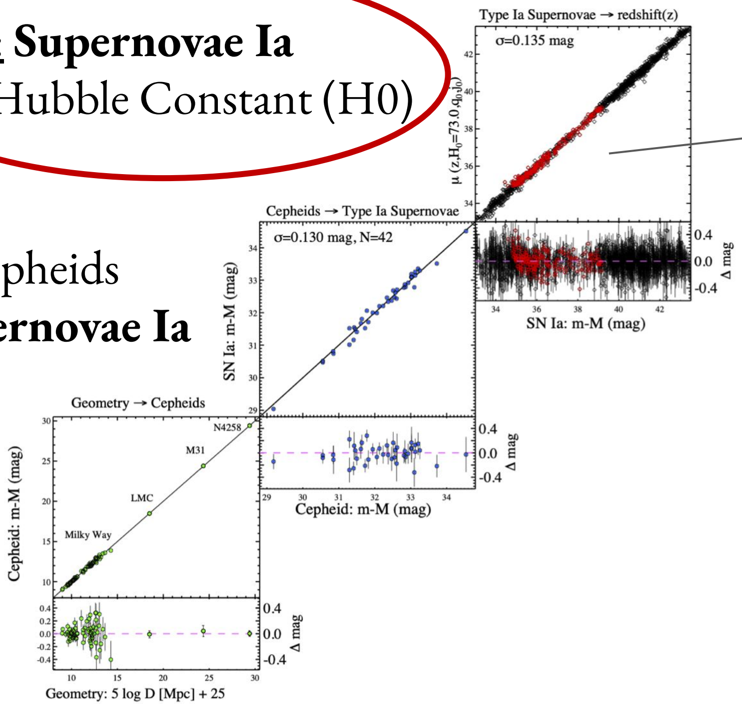


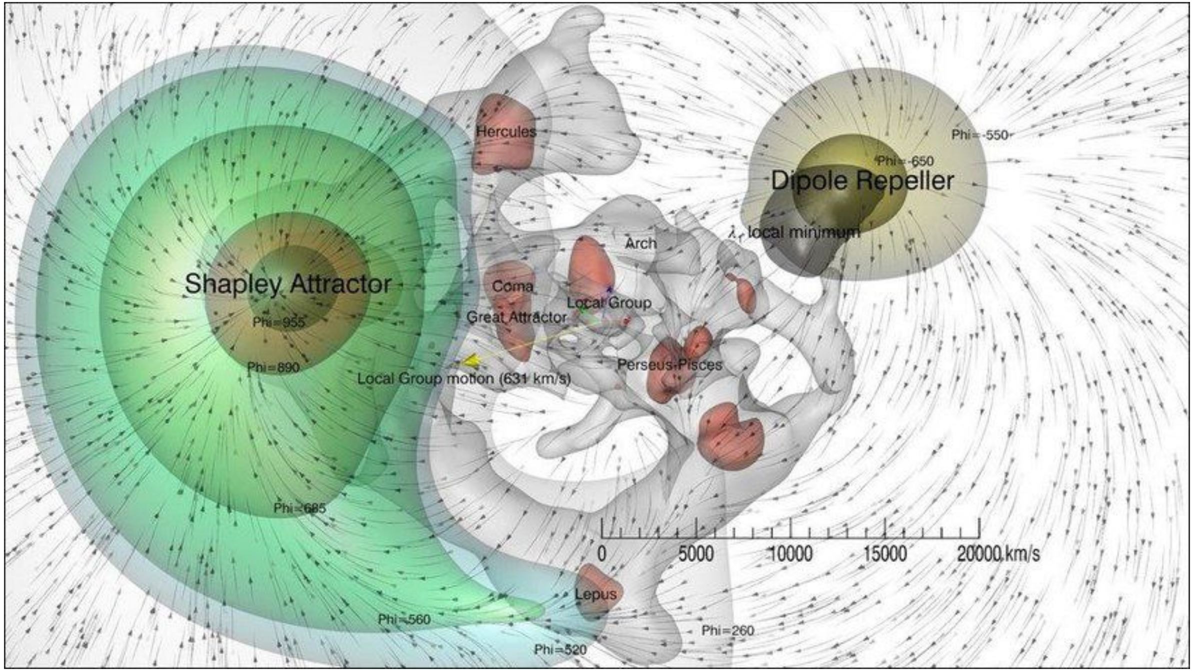
Measure Supernovae out into the "Hubble Flow"

Riess, Yuan, Macri, Scolnic, **Brout**+21

To measure v=H0*d you need absolute distances (not relative)

Side note: Peculiar motions in the local universe make the 2-rung distance ladder imprecise.

Homogeneous and Isotropic rule doesn't hold in very local universe



Credit: Tully ea

Recent work is the marriage of two teams - SH0ES and Pantheon+

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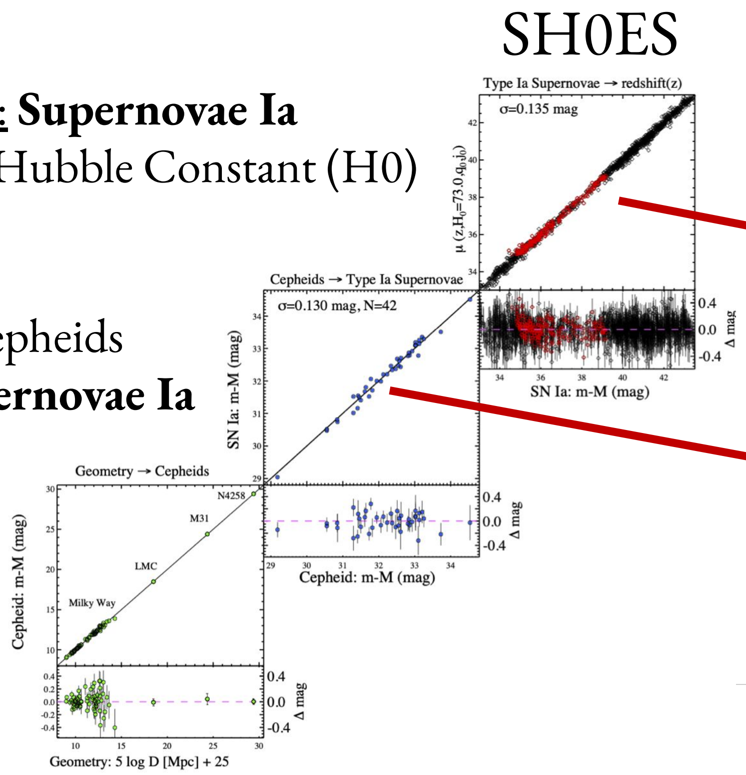

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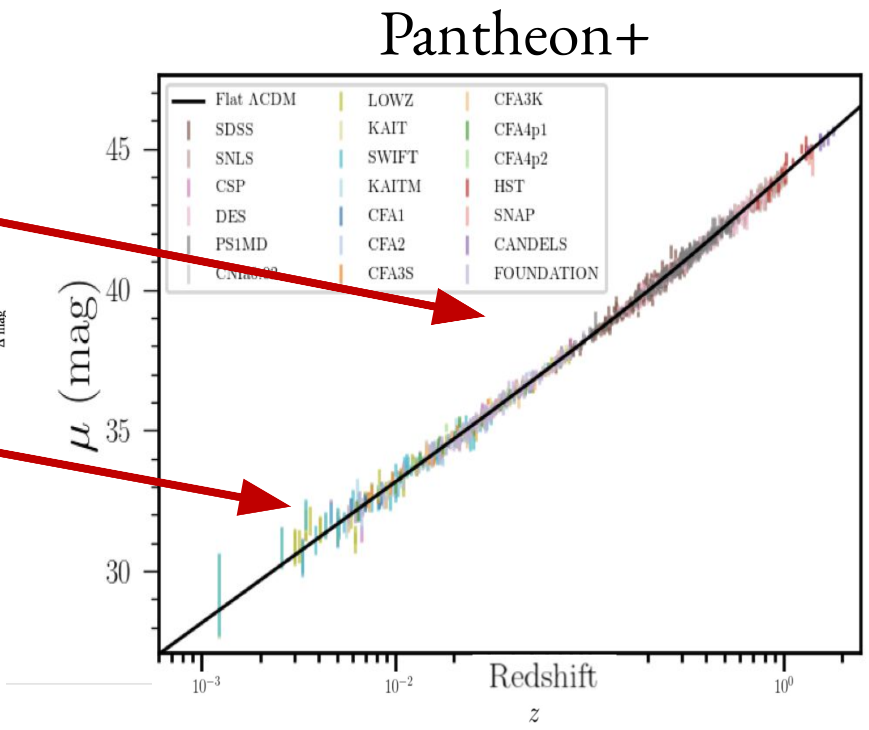
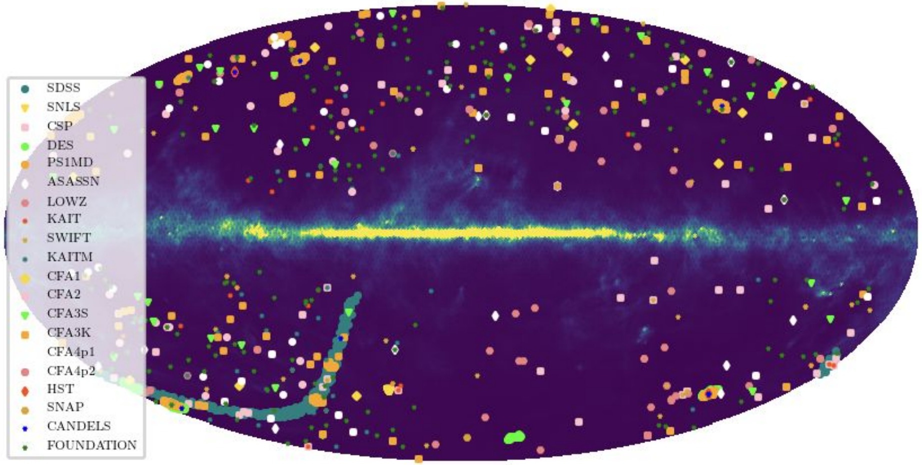


Brout+2022

Pantheon+

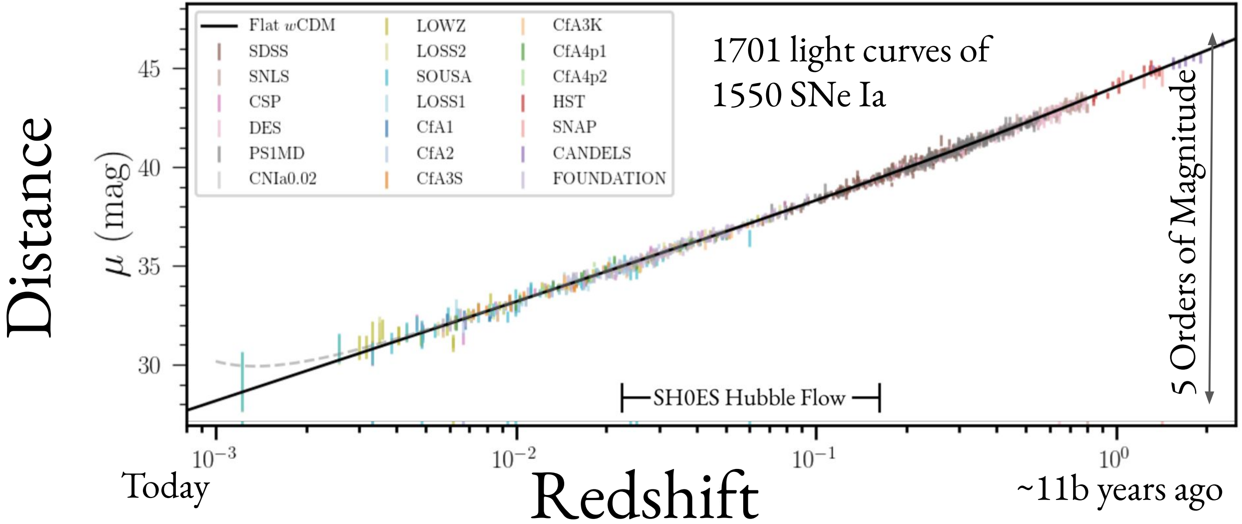
A compilation of the last 30 years of high quality SNe Ia.



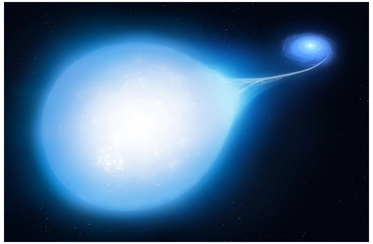
20 Different Photometric Systems (105 filters)

Recalibrated and SNIa model retrained

Numerous light curves from different telescopes of the same SN.

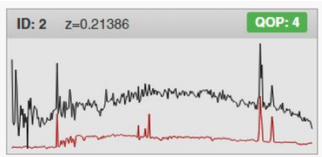


Route to the SNIa Hubble Diagram - Improving at all steps

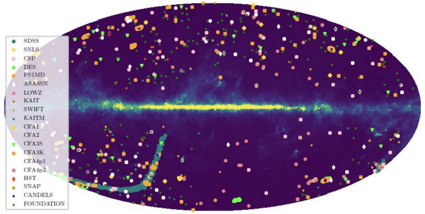


Model SN and host demographics
(**Brout** & Scolnic 2020
Popovic, **Brout** et al. 2021a/b)

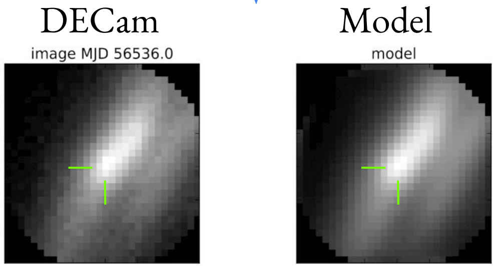
Model Survey strategy, cadence, selection, mismatch
(Kessler, **Brout** et al. 2018)



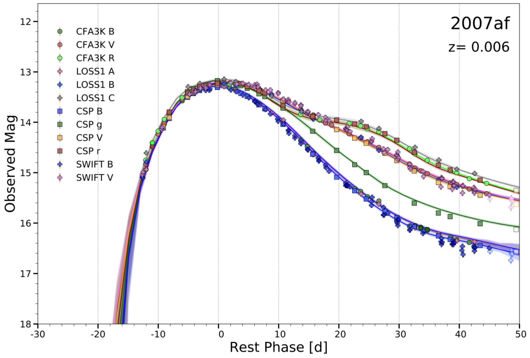
Get redshift and peculiar velocity
(e.g. Carr,...,**Brout**+2021, Peterson,...,**Brout**+2021)



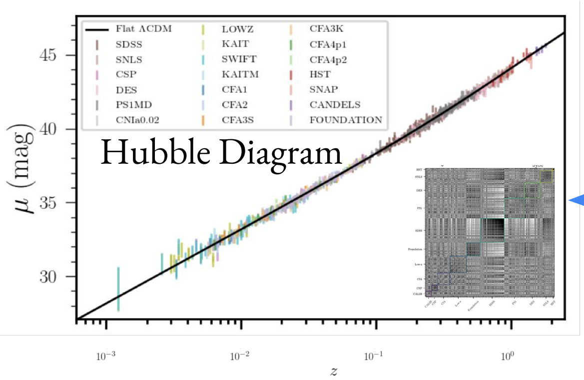
Cross-Calibrate telescopes/instruments/filters
(e.g. **Brout,** Taylor et al 2021)



Forward modeling of SN flux and galaxy model
(e.g. **Brout** et al. 2018a)

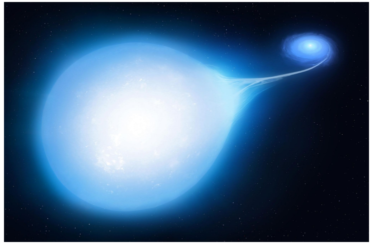


Standardize light curves
(e.g. Scolnic, **Brout** et al. 2022)



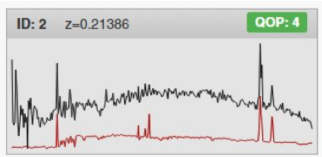
Determine distances and systematic covariance
(e.g. **Brout** et al. 2022)

Route to the SNIa Hubble Diagram - Improving at all steps

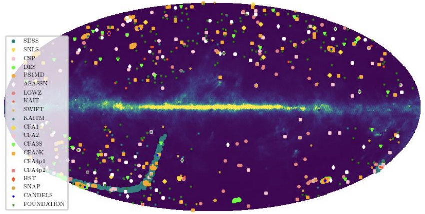


Model SN and host demographics
(**Brout** & Scolnic 2020
Popovic, **Brout** et al. 2021a/b)

Model Survey strategy, cadence, selection, mismatch
(Kessler, **Brout** et al. 2018)



Get redshift and peculiar velocity
(e.g. Carr,...,**Brout**+2021, Peterson,...,**Brout**+2021)



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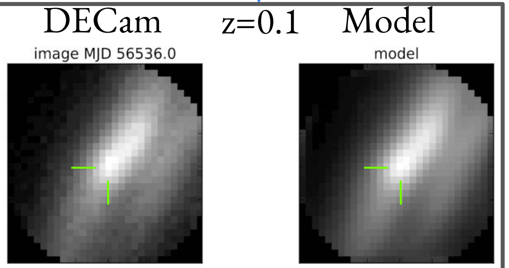

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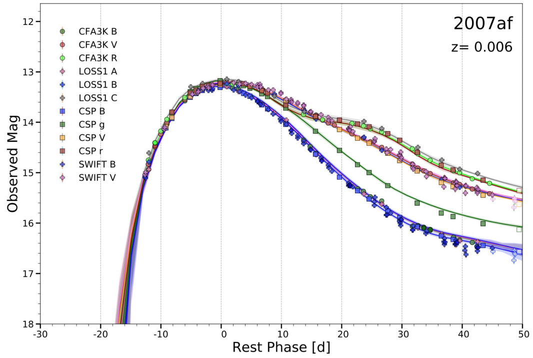
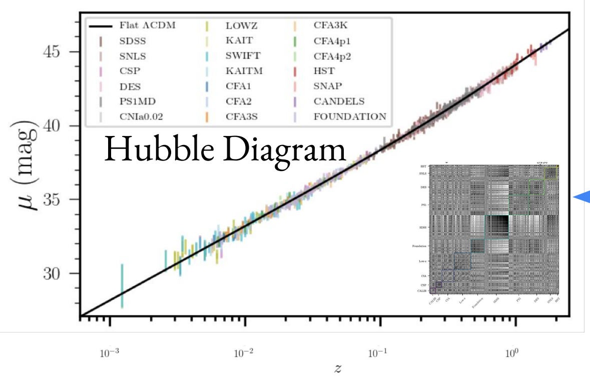


Standardize light curves
(e.g. Scolnic, **Brout** et al. 2022)



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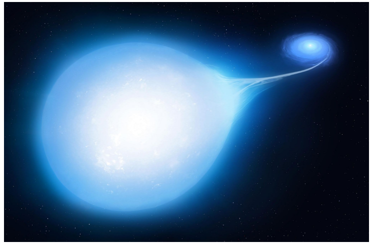

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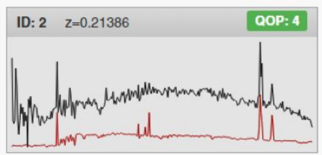

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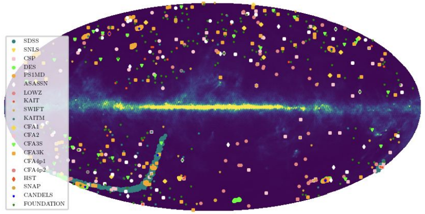

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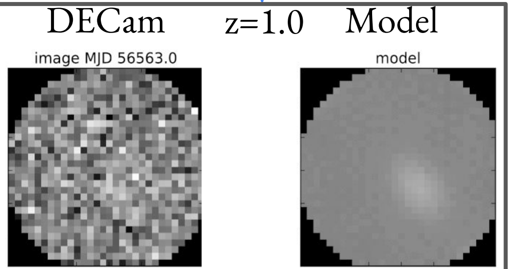

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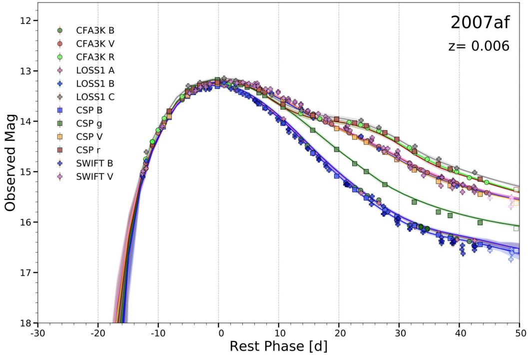
(e.g. **Brout** et al. 2018a)



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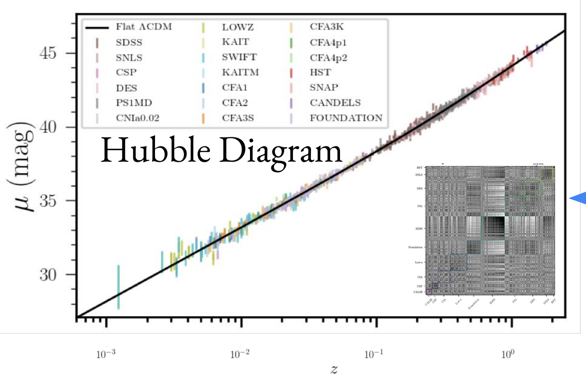


Determine distances and systematic covariance
(e.g. **Brout** et al. 2022)

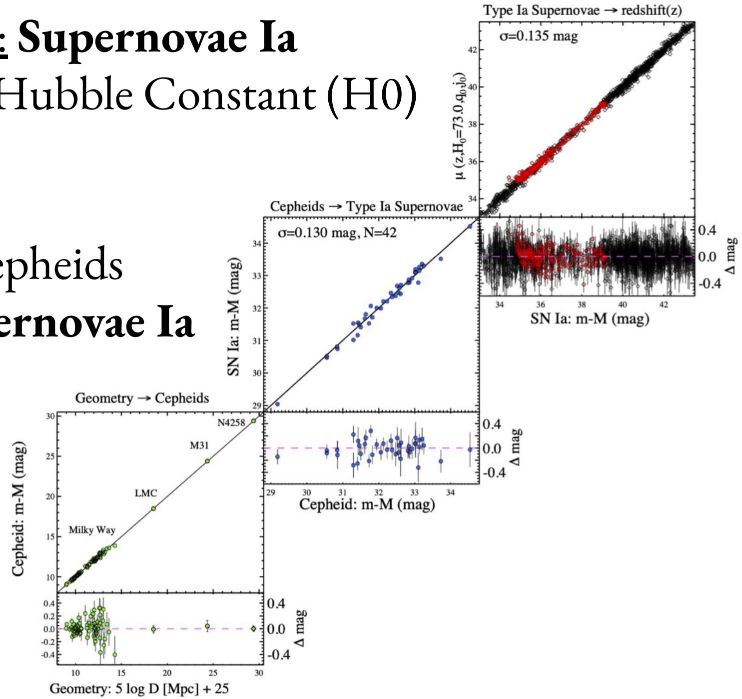
Recent work is the marriage of two teams - SH0ES and Pantheon+

SH0ES

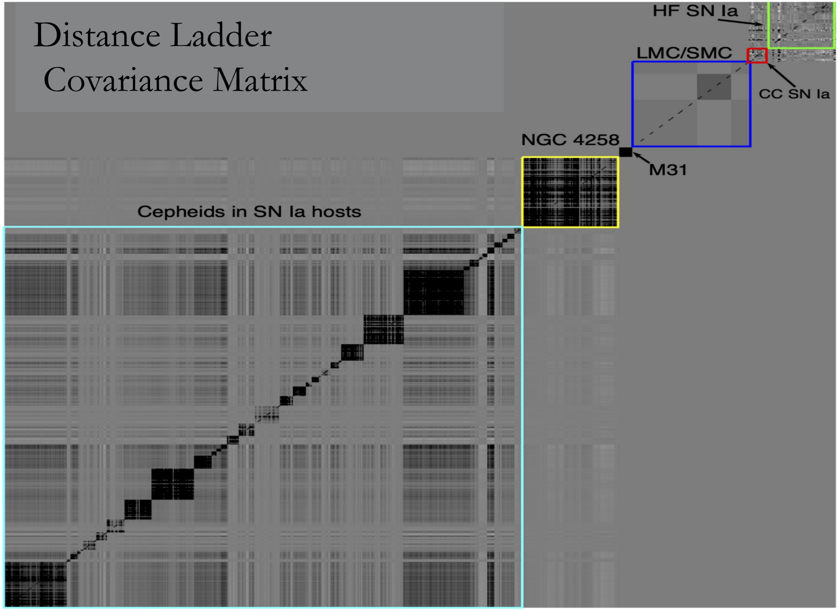
3rd: **Supernovae Ia**
→ Hubble Constant (H0)

2nd: Cepheids
→ **Supernovae Ia**

1st: Geometry
→ Cepheids

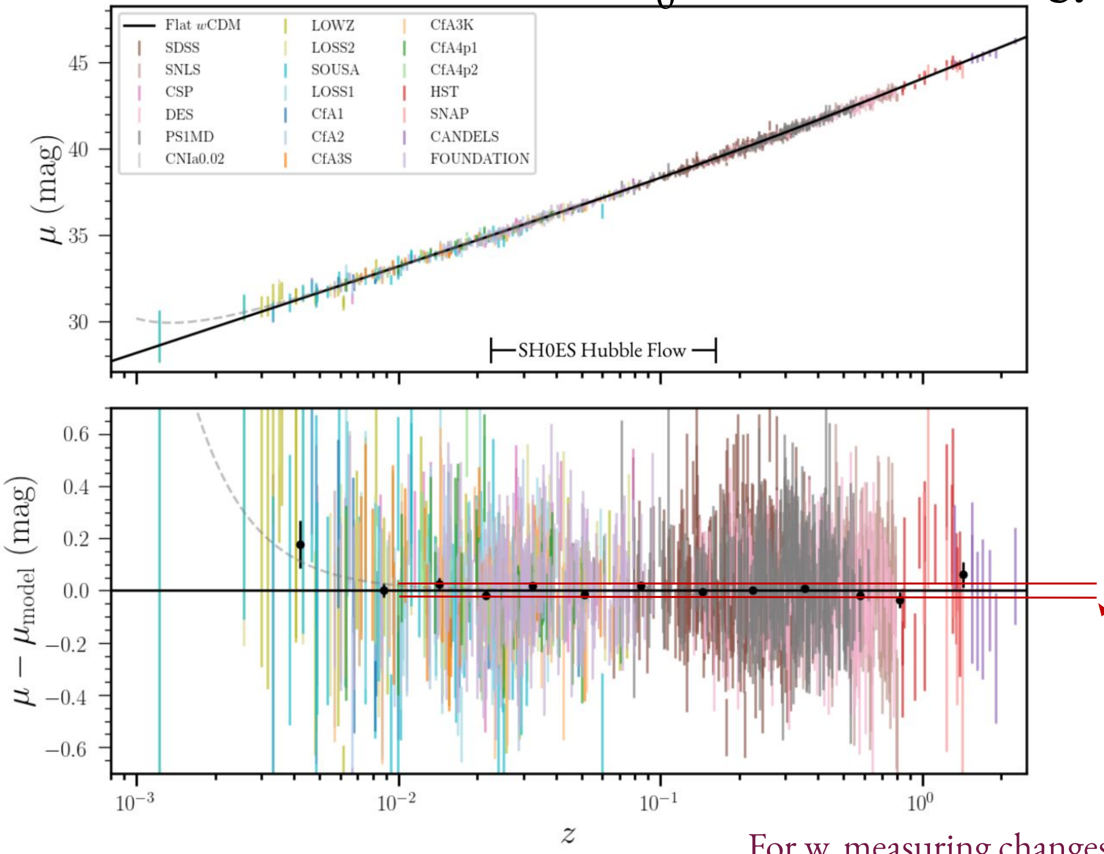


Riess, ..., **Brout**+21



Accounts for covariant systematics
between rungs!

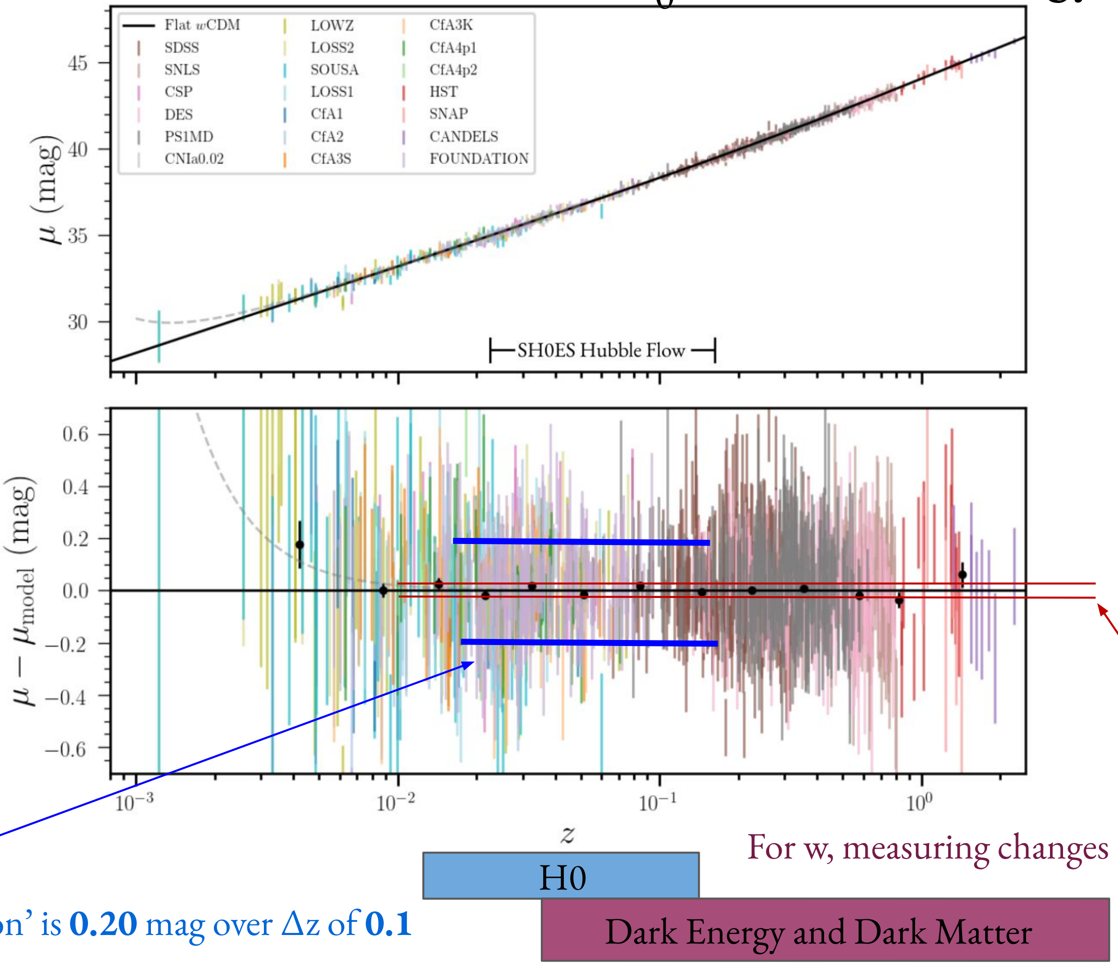
SNe Ia are used for Hubble Constant H_0 and Dark Energy w



For w, measuring changes of **0.02** mag over Δz of **1.0**

Dark Energy and Dark Matter

SNe Ia are used for Hubble Constant H_0 and Dark Energy w



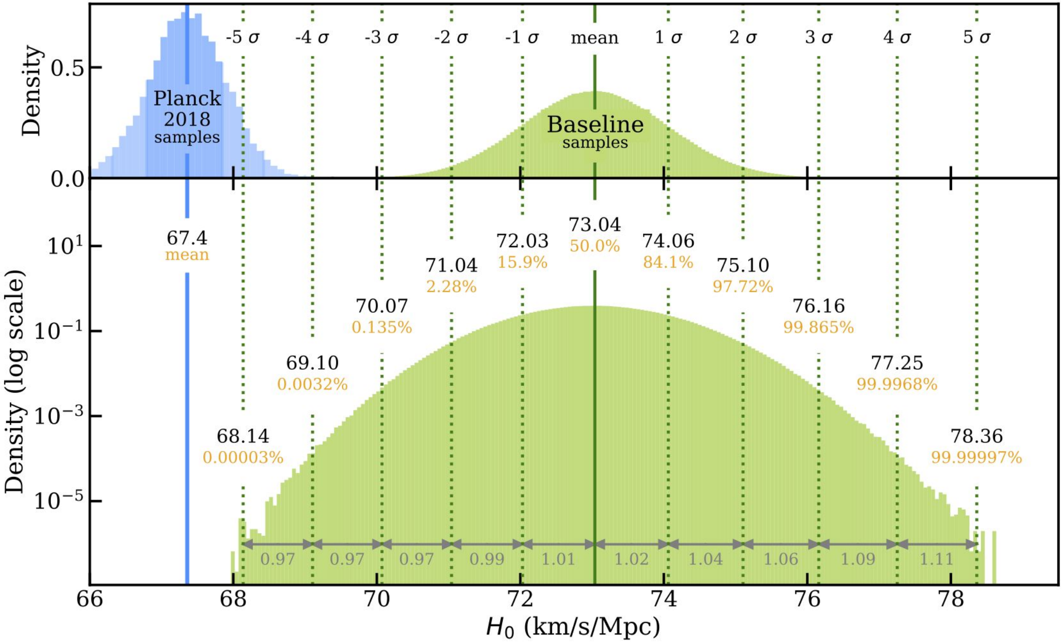
For w, measuring changes of **0.02** mag over Δz of **1.0**

For H_0, the 'Hubble tension' is **0.20** mag over Δz of **0.1**

SH0ES reaches 5sigma

+ΛCDM
Planck 67+-0.5

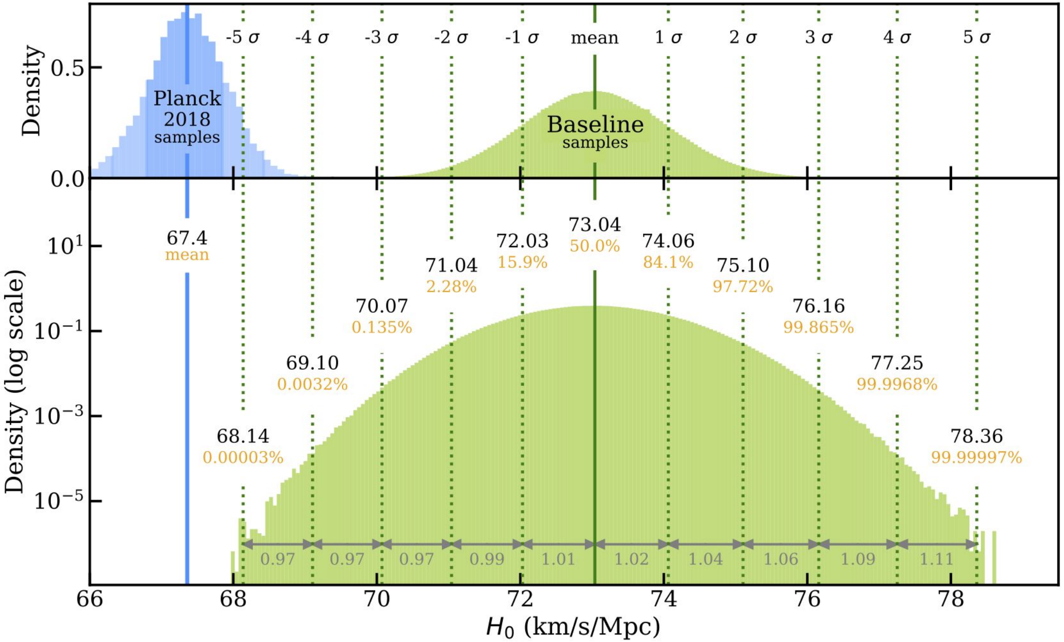
SH0ES 73+-1



Riess, Yuan, Macri, Scolnic, **Brout**+21

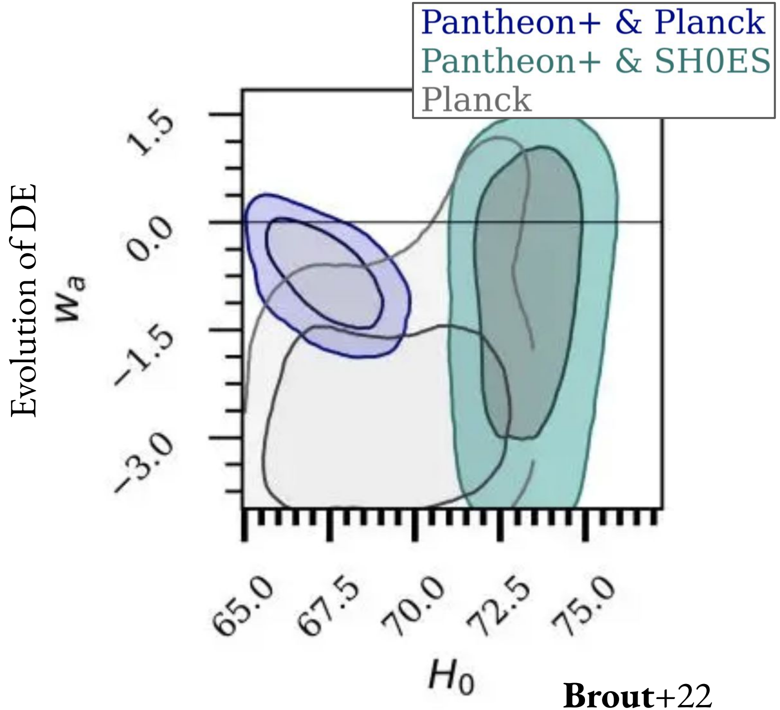
SH0ES reaches 5sigma

+ΛCDM
Planck 67+-0.5 SH0ES 73+-1



Riess, Yuan, Macri, Scolnic, **Brout**+21

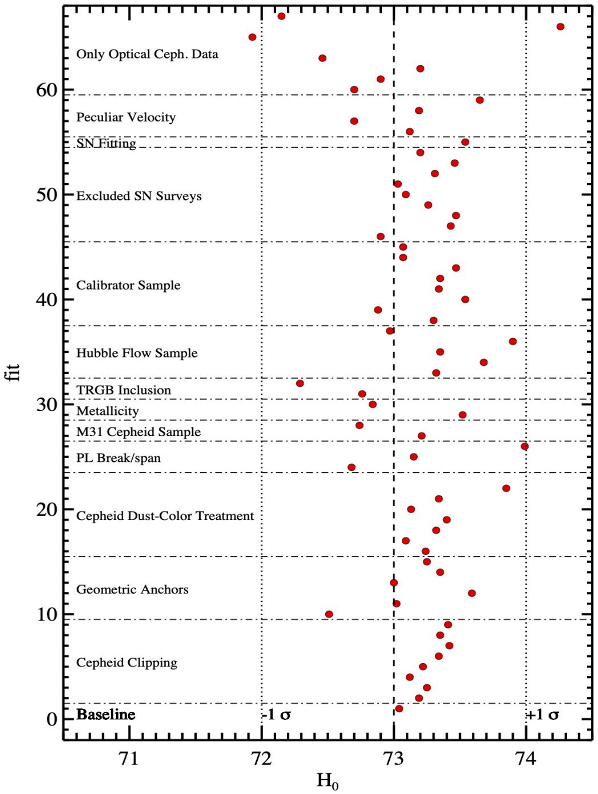
Pantheon+ beyond ΛCDM



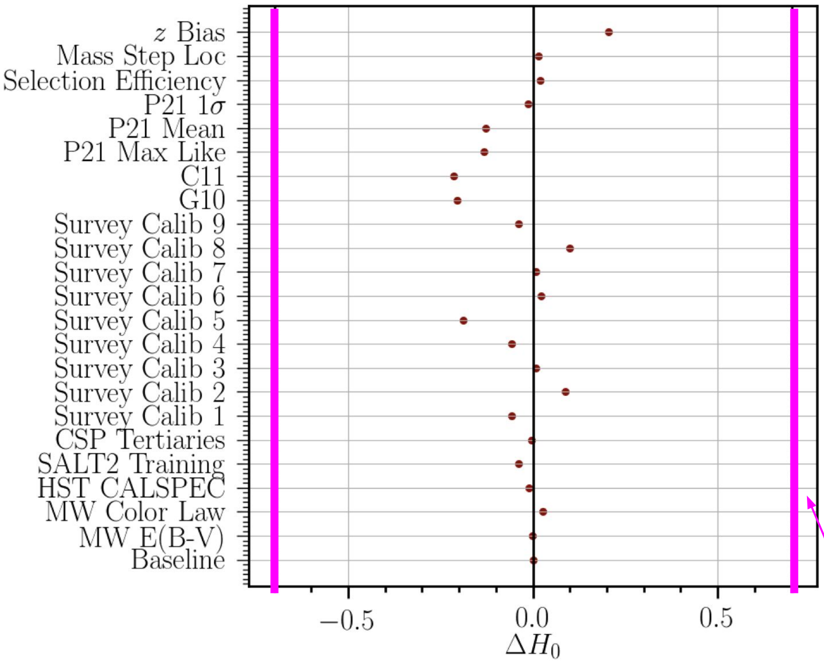
Brout+22

We looked at everything that the community has raised over last 5 years.

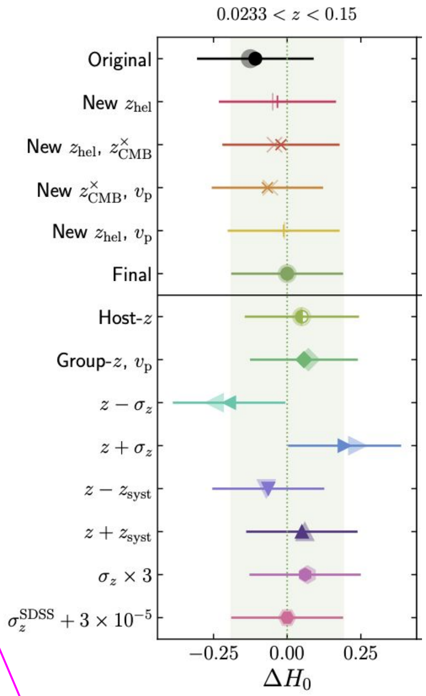
70+ SH0ES Analysis Variants (Riess+22)



SN H0 Systematics (**Brout**+22)



Redshifts (Carr+22)

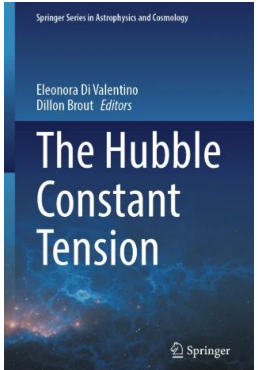


Reported SN uncertainty on H0

Bottom line: it's very hard to get below 72.5 without throwing out data or adding new tensions…

We (and the community) have done many cross-checks by using novel/independent samples.

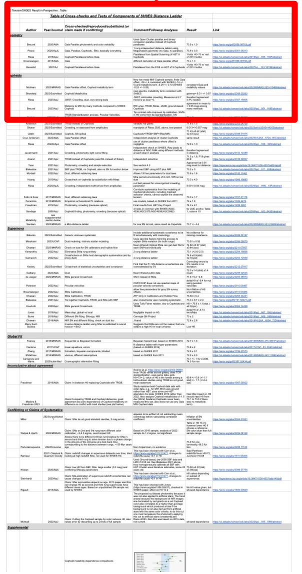
I have compiled a database of recent papers addressing systematics.



H0 Tension/SH0ES Result in Perspective : Table

Table of Cross-checks and Tests of Components of SH0ES Distance Ladder

Author	Year/Journal	Cross-checked/reproduced/substituted (or claim made if conflicting)	Comment/Followup Analyses	Result	Link
Geometry					
Breuval	2020/A&A	Gaia Parallax photometric and color variability	Uses Open Cluster parallax and binary companion parallax instead of Cepheid parallaxes	73.0 ± 1.9	https://arxiv.org/pdf/2006.08763.pdf
Pesce	2020/ApJL	Gaia, Parallax, Cepheids , SNe, basically everything	1 rung independent distance ladder using Megamasers geometry (no Gaia, no parallax).	73.9 ± 3.0	https://arxiv.org/abs/2001.09213
Riess	2018/ApJ	Cepheid Parallaxes before Gaia	Parallaxes from Spatial Scanning of HST 8 Cepheids	Yields H0=75 w/ rest of 2016 ladder	https://ui.adsabs.harvard.edu/abs/2018ApJ...855..136R/abstract
Groenewegen	2018/A&A	Gaia	different derivation of Gaia parallax offset	76 ± 1.3	https://arxiv.org/pdf/1808.05796.pdf
Benedict	2007/AJ	Cepheid Parallaxes before Gaia	Parallaxes from the FGS on HST of 9 Cepheids	Yields H0=76 w/ rest of 2016 ladder	https://ui.adsabs.harvard.edu/abs/2007AJ....133.1810B/abstract
Cepheids					
Molinaro	2023/MNRAS	Gaia Parallax offset, Cepheid metallicity term	New low metal MW Cepheid sample, finds Gaia offset, -22+/- 4 consistent with SH0ES (-14 +/- 5) and metallicity term -0.29 +/- 0.10 (SH0ES -0.22 +/- 0.05)	consistent Gaia and metallicity values	https://ui.adsabs.harvard.edu/abs/2023MNRAS.520.4154M/abstract
Bhardwaj	2023/Submitted	Cepheid Metallicities	new spectra, metallicity term consistent with SH0ES	gamma=-0.31 +/- 0.07	https://arxiv.org/abs/2309.03263
Riess	2023/ApJ	JWST: Crowding, dust, very strong tests	JWST, eliminates crowding. Measures at 2.7 microns so dust ~0.	Excellent agreement in PL relation	https://arxiv.org/abs/2307.15806
Breuval	2023/ApJ	Distance to M33 by many methods compared to SH0ES Cepheid	RR Lyrae, TRGB, Miras, JAGB, ground-based Cepheids	agreement in mean to < 0.05 mag among many methods	https://ui.adsabs.harvard.edu/abs/2023ApJ...951..118B/abstract
		TRGB Standardization process. Peculiar Velocities.	Tip contrast ratio improves tip calibration. Shifts in H0 come from tip standardization, SN		



https://djbrout.github.io/SH0ESrefs.html

The Tension is Hard to Avoid: Not Exclusive to one method/dataset…

Measurements that depend on physical scales set in the early universe

CMB (Planck)

CMB (No Planck)

No CMB, with BBN

CMB Lensing

Direct Measurements of H0 determined locally

Parallax+Cepheids+SNIa

Replace Cepheids with TRGB

Replace Cepheids with Miras

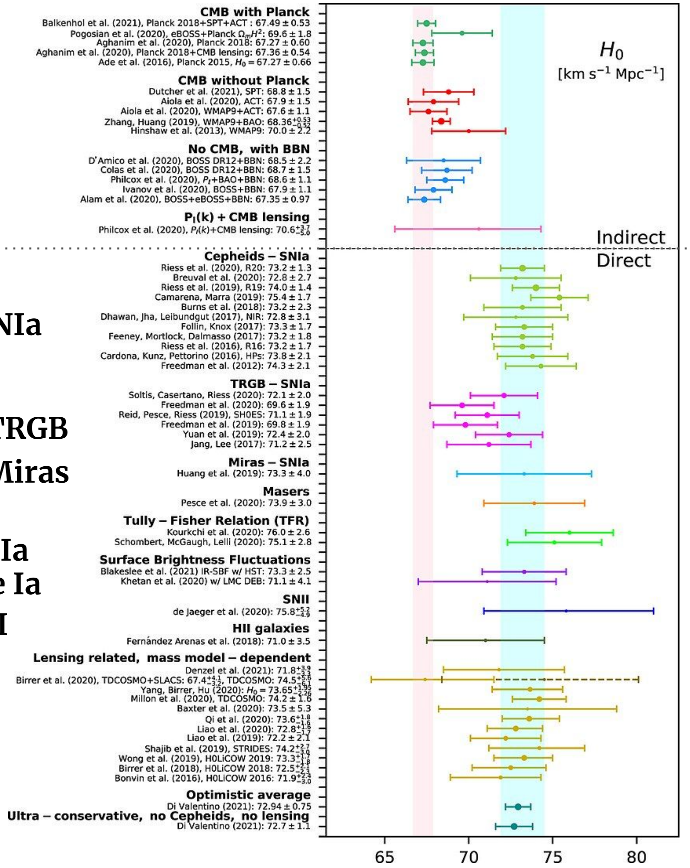
Masers Only!

Tully-Fisher Relation → Different SNe Ia

Surface Brightness Fluctuations → Different SNe Ia

Replace SNIa with SNII

Strong Lensing

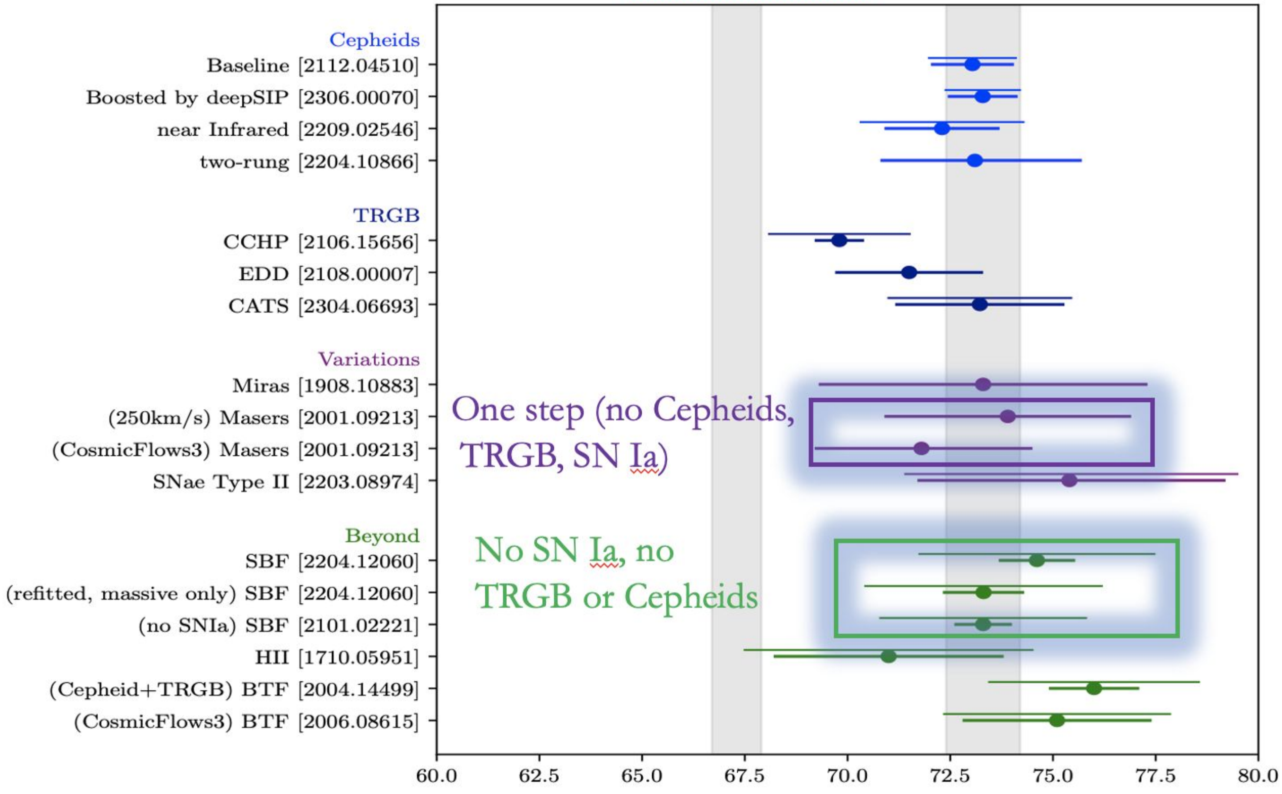


Credit: Eleonora DiValentino (co-editor on H0 book)

Do H_0 measurements that use TRGB agree with SH0ES?

Yes.

Verde, Schonenberg, Gil-Marin, ARAA 2023

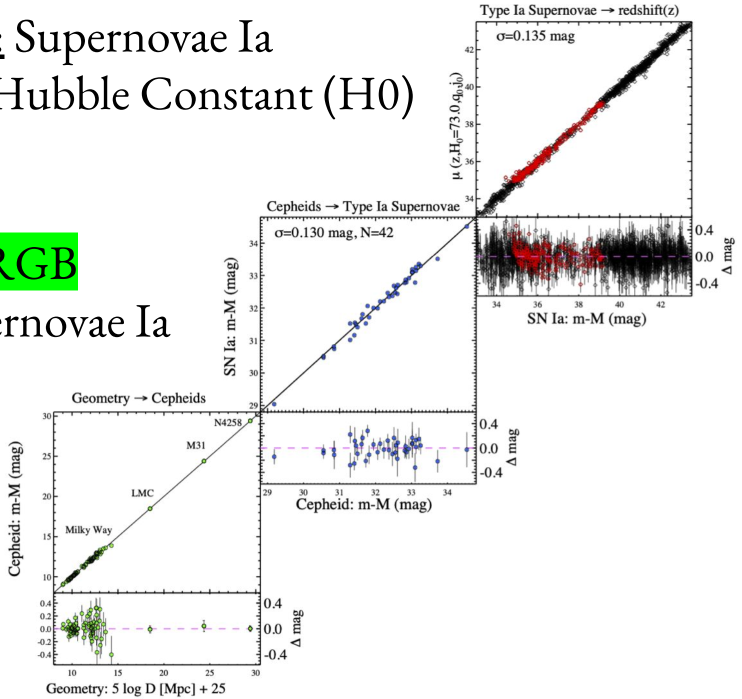


Tip of the Red Giant Branch from Freedman et al. 2019 acheives

3rd: Supernovae Ia
→ Hubble Constant (H0)

2nd: TRGB
→ Supernovae Ia

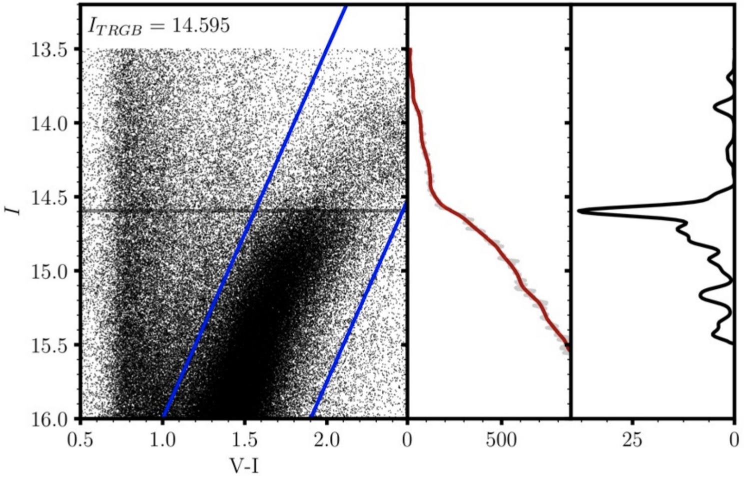
1st: Geometry
→ Cepheids



BUT REMEMBER CONSISTENCY ACROSS THE RUNGS IS KEY!

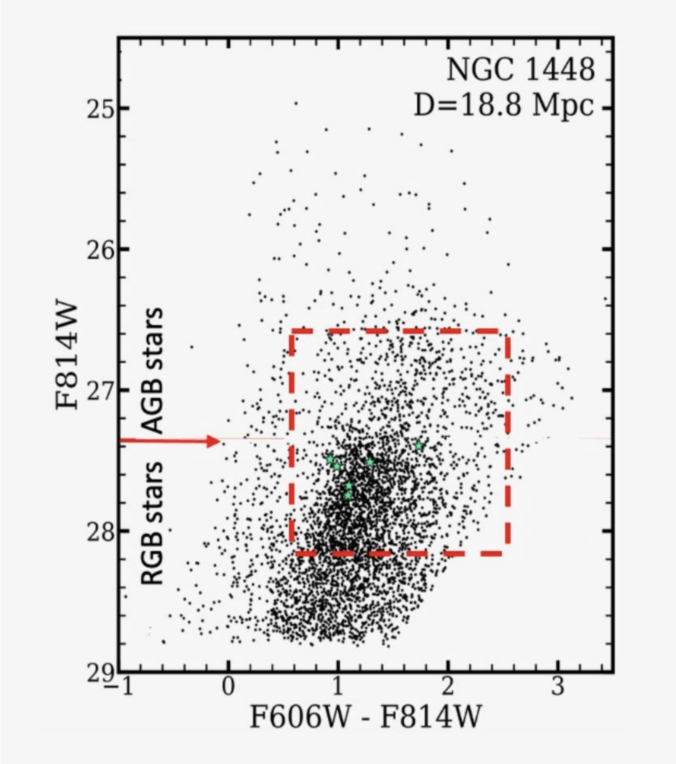
TRGB measurements are difficult to replicate across rungs

First Rung (LMC)



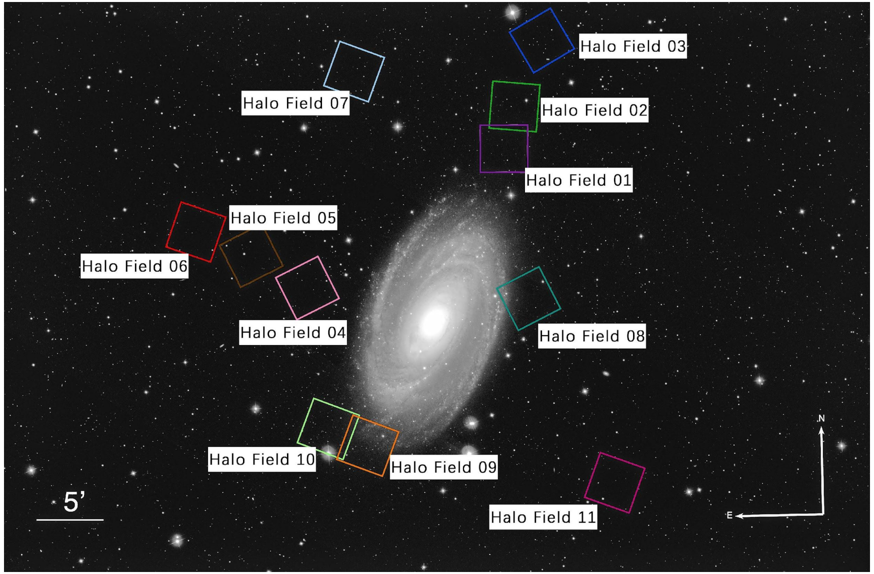
At High SNR this isnt too hard...

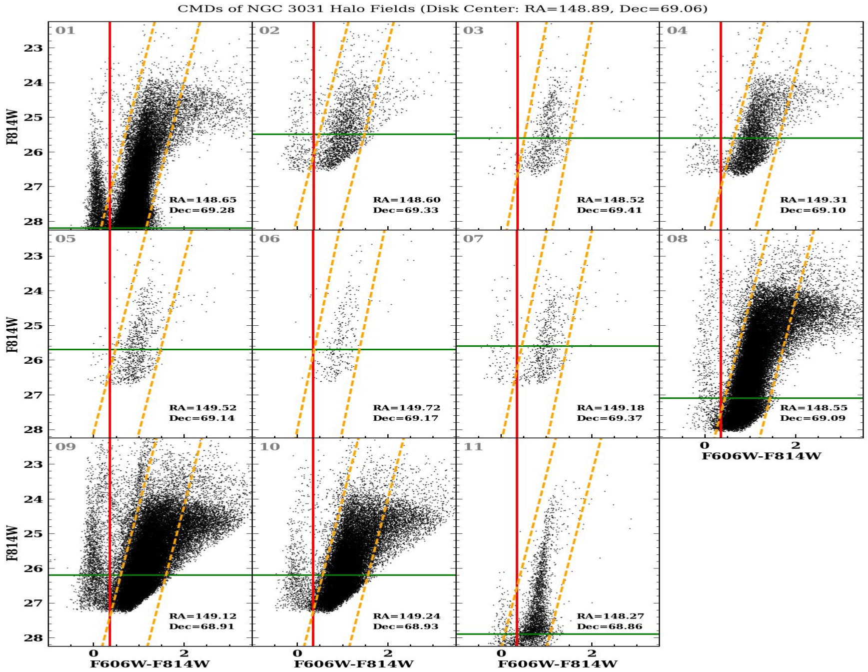
Second Rung (NGC1448)



But at lower SNR measuring a noisy tip is hard!

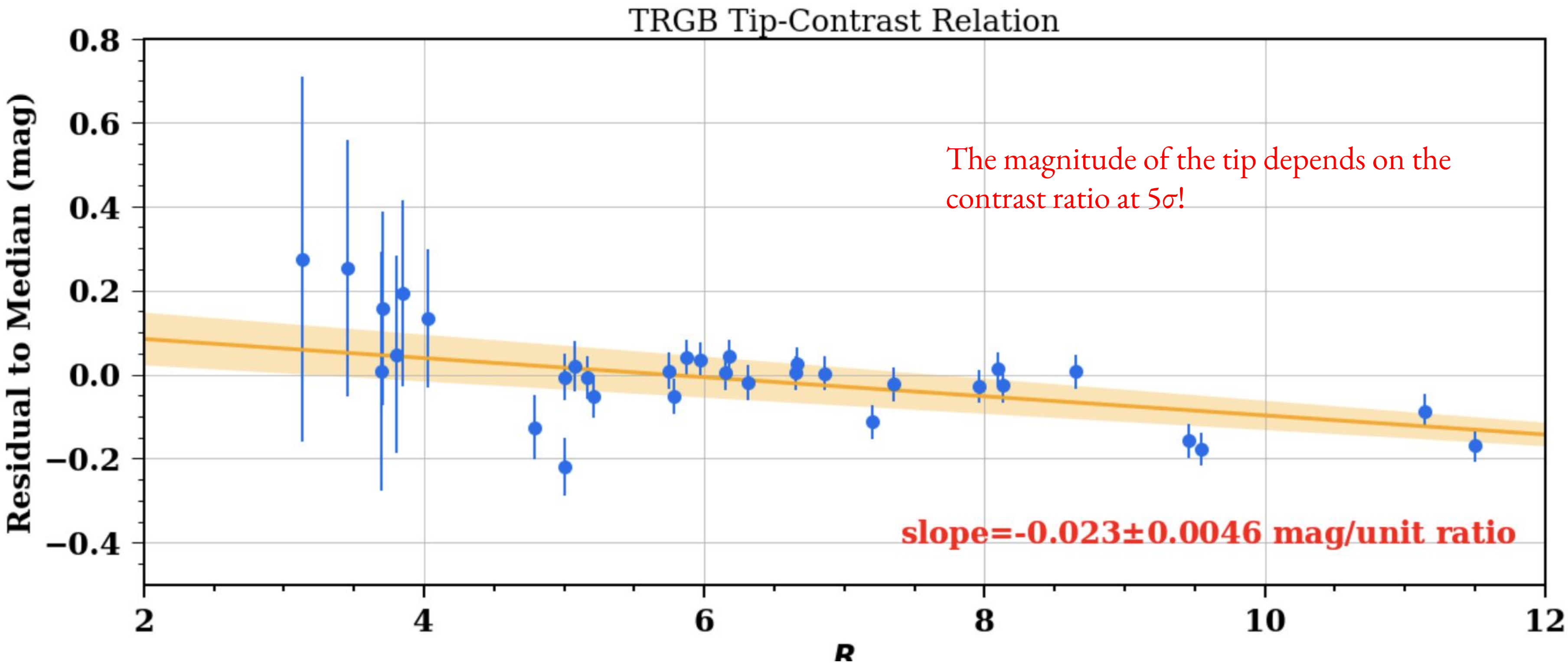
Do H_0 measurements that use TRGB agree with SH0ES?





'CATS' Team. Wu et al. 2023

CATS found TRGB *standardizable* candle, empirical, 5σ relation between tip magnitude and contrast, 'TCR' relation



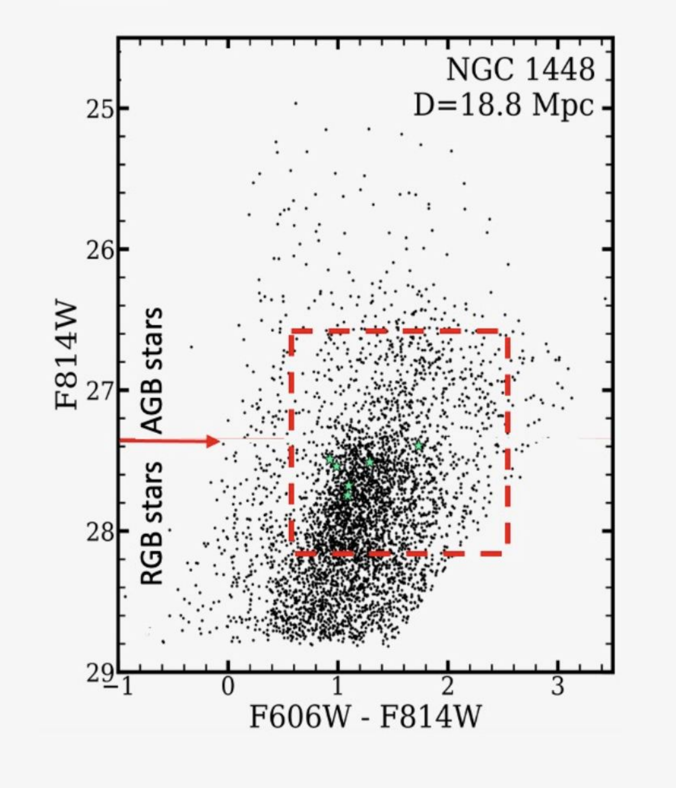
Where does SH0ES - CCHP difference come from? More on SN side.

Term	ΔCCHP
	(km/s/Mpc)
SN Related	
1. Include SN 2021pit,2021rhu,2007on	0.6
2. No TRGB detected in N5584,N3021,N1309,N3370	0.0
3. Peculiar Flows (Pantheon+)	0.4
4. Hubble Flow Surveys (Pantheon+)	1.1
SN subtotal	**2.0**
TRGB Related	
5. Fiducial TRGB Calibration/Tip-Contrast Relation	1.4
Total	**3.4**

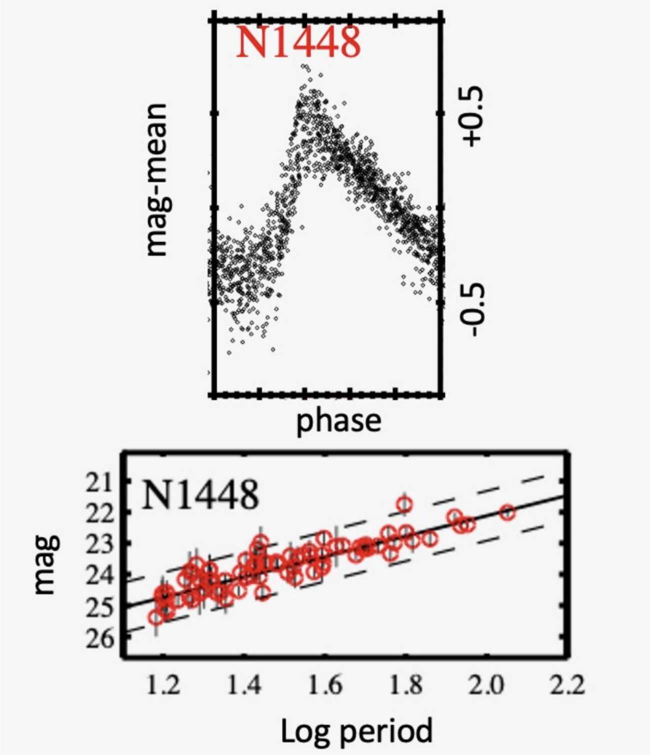
Inconsistency in survey calibration from 2nd to 3rd rungs

Comparison of TRGB and Cepheids in same 2nd rung galaxy

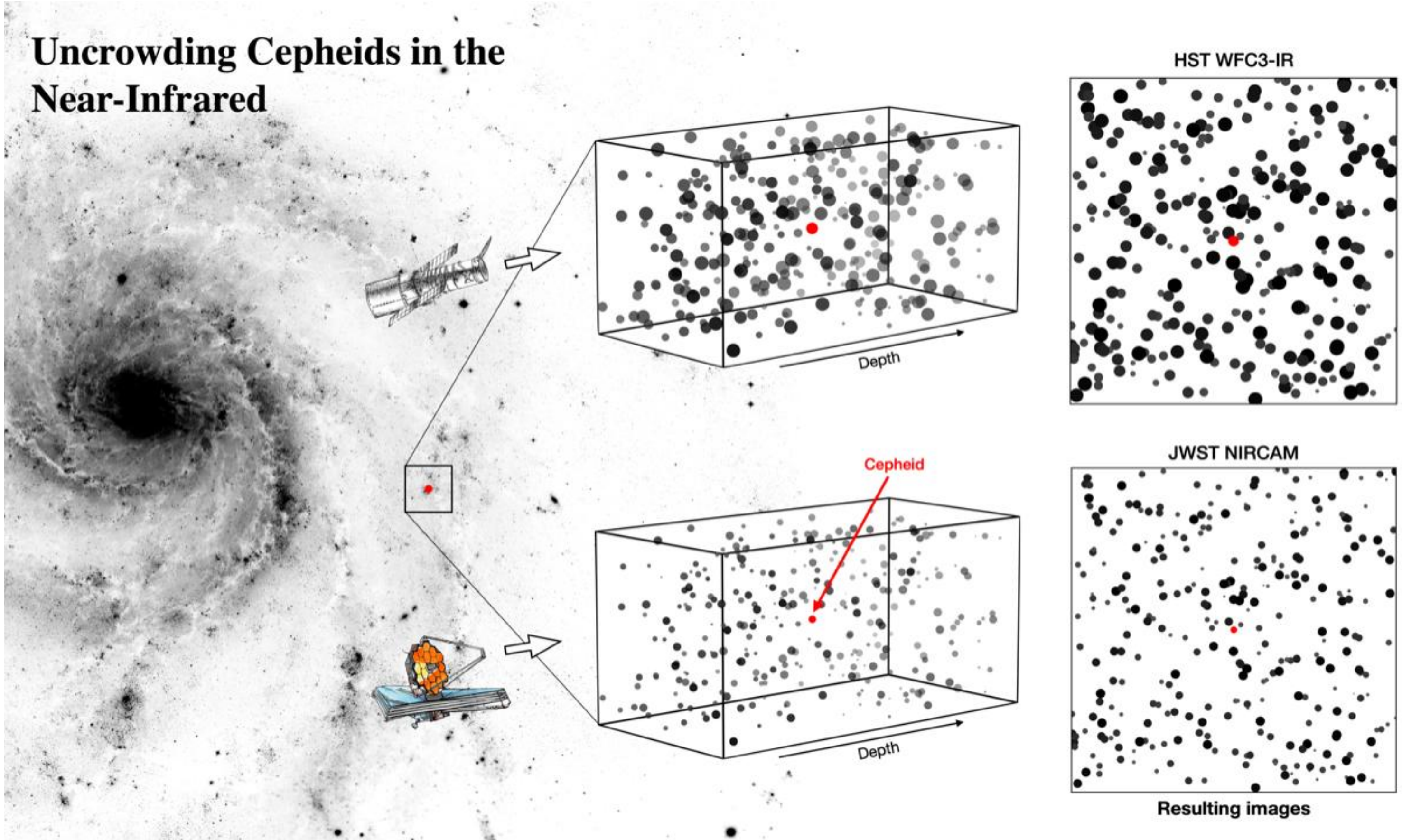
TRGB Second Rung (NGC1448)



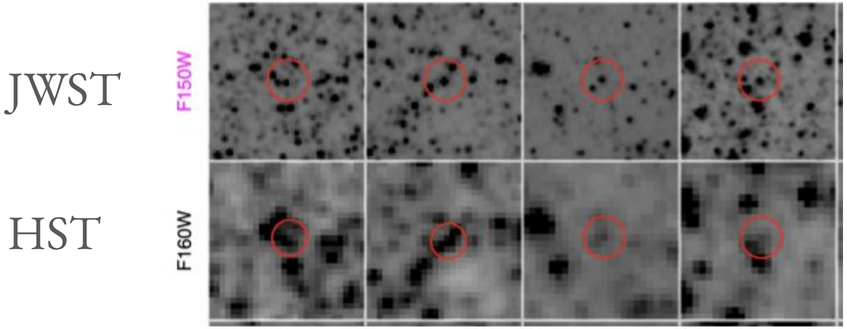
Cepheids Second Rung (NGC1448)

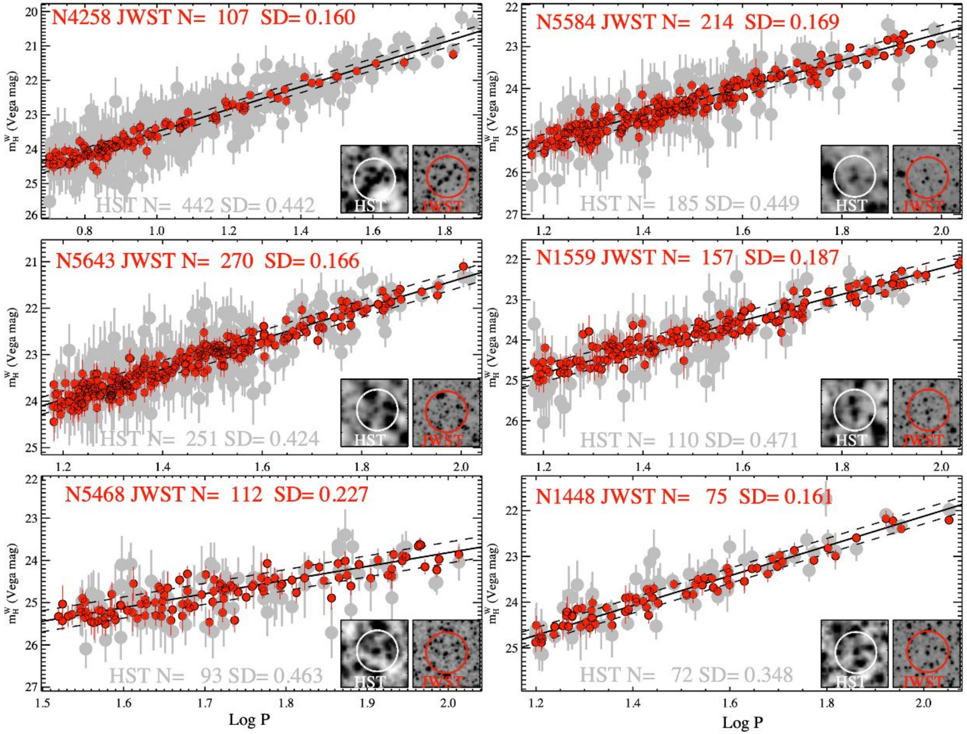


What JWST can do? Systematic checks of HST Cepheid measurements.



Is Cepheid Crowding an Issue?





JWST scatter 2.5 times less than HST at 1.5 microns, excellent agreement of intercepts

Riess et al. 2024

arXiv:2307.15806, arXiv: 2401.04773

Rules out distance-dependent HST crowding error needed to solve tension at 8.3sigma.

Important Public Service Announcement About JWST Results

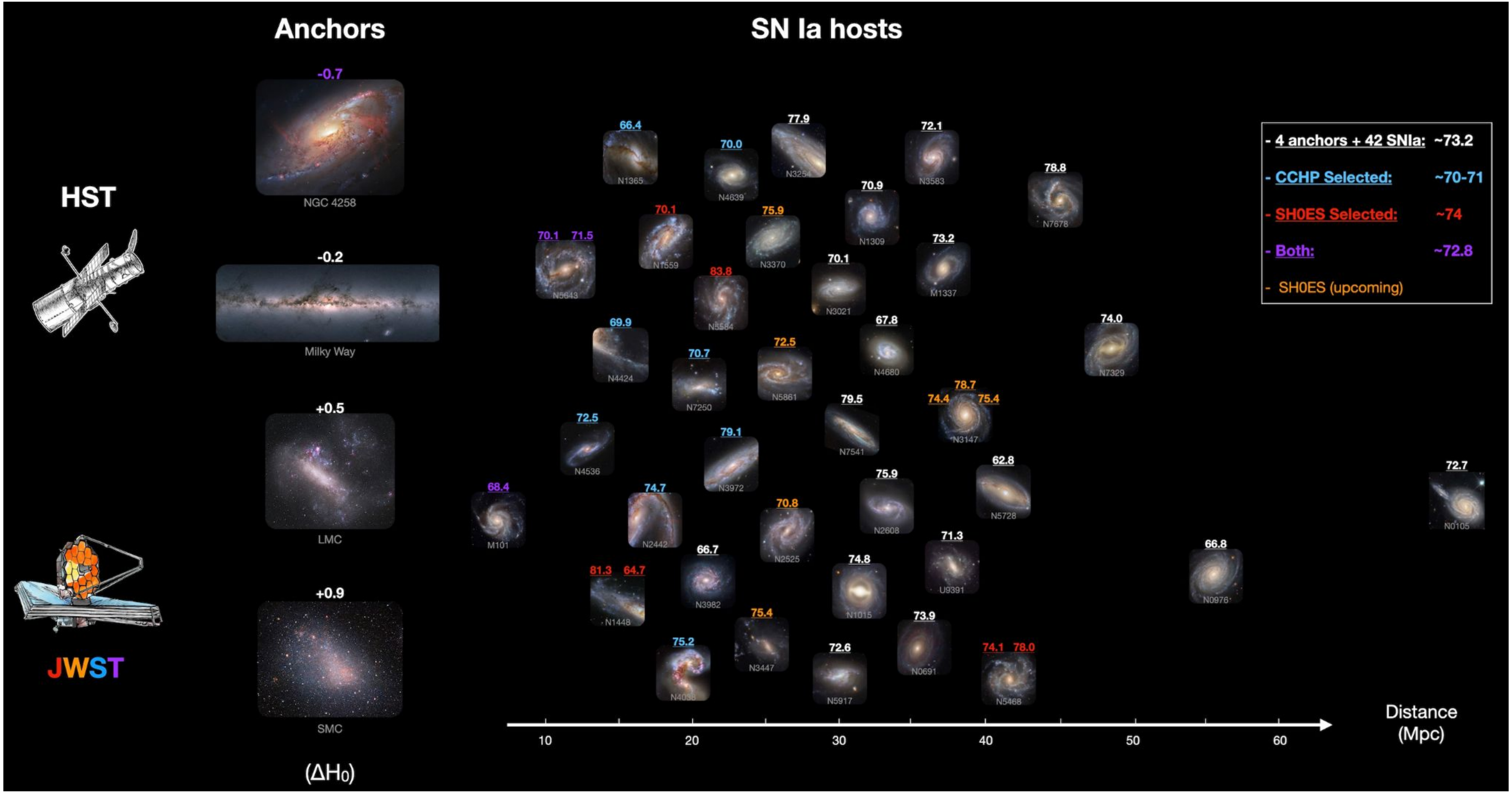
JWST is still in the realm of systematic checks.

Programs do not have enough data to make compelling independent measurements of H0.

If neglect SN scatter, programs with one anchor, small SN sample+luck → spuriously low/high H_0.

We must be patient for fair samples…

JWST has one anchor and small SN samples. Not yet ready for H0 Primetime...



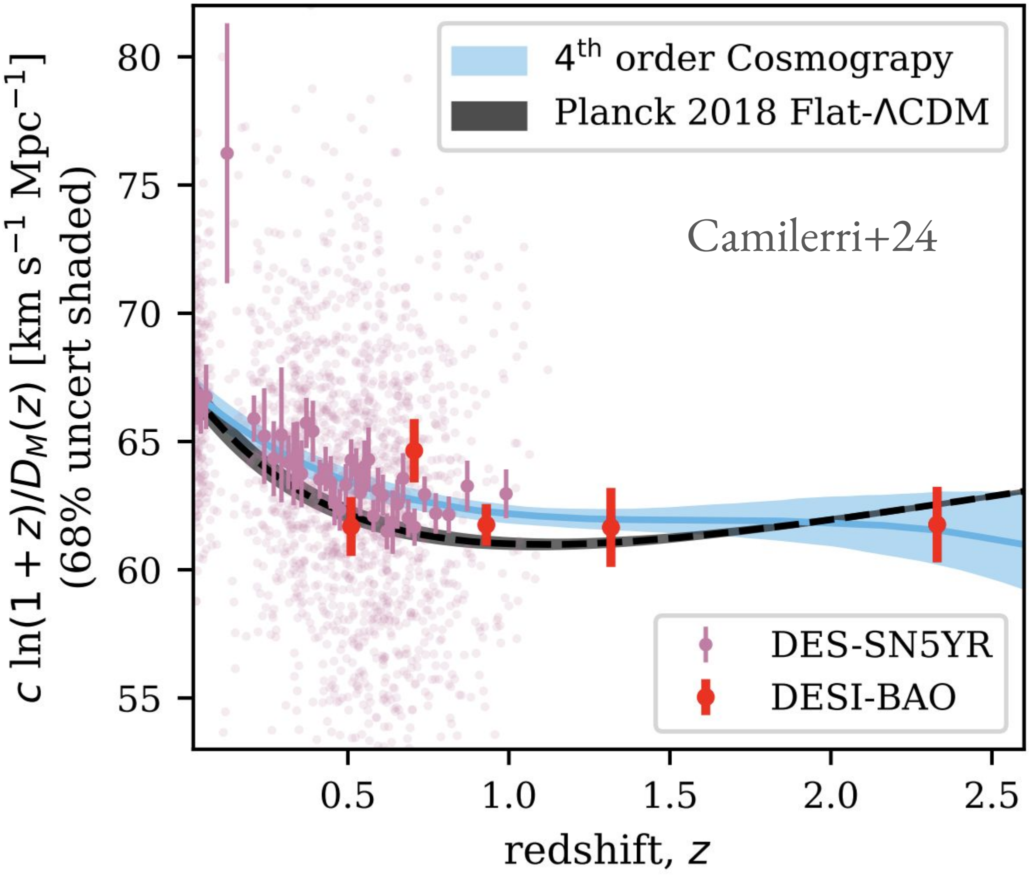
SNe dont allow for any late time expansion history to solve H0.

Instead of calibrating SN distances with ladder…

Combine SNe with BAO *(and the early universe constraint on sound horizon from CMB)*

$$H_0 = 67.19^{+0.66}_{-0.64}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

Strong constraints on late-time physics causing H0 tension. Leads us to examine physics models that can change sound horizon (early universe).



In summary, if real, where should we be looking?

- *Wu & Huterer 17, Dhawan, **Brout**+20, Benevento, Hu,+20, **Brout**+22* suggest that late universe physics (e.g. decaying dark matter, evolving dark energy, or local voids/fluctuations) are strongly constrained by SNe and unlikely.

- Inverse distance ladder measurements giving low H0 also push us to consider models that modify early time physics affecting the sound horizon (though there is some evidence from Philcox+23 that this may not be early enough).

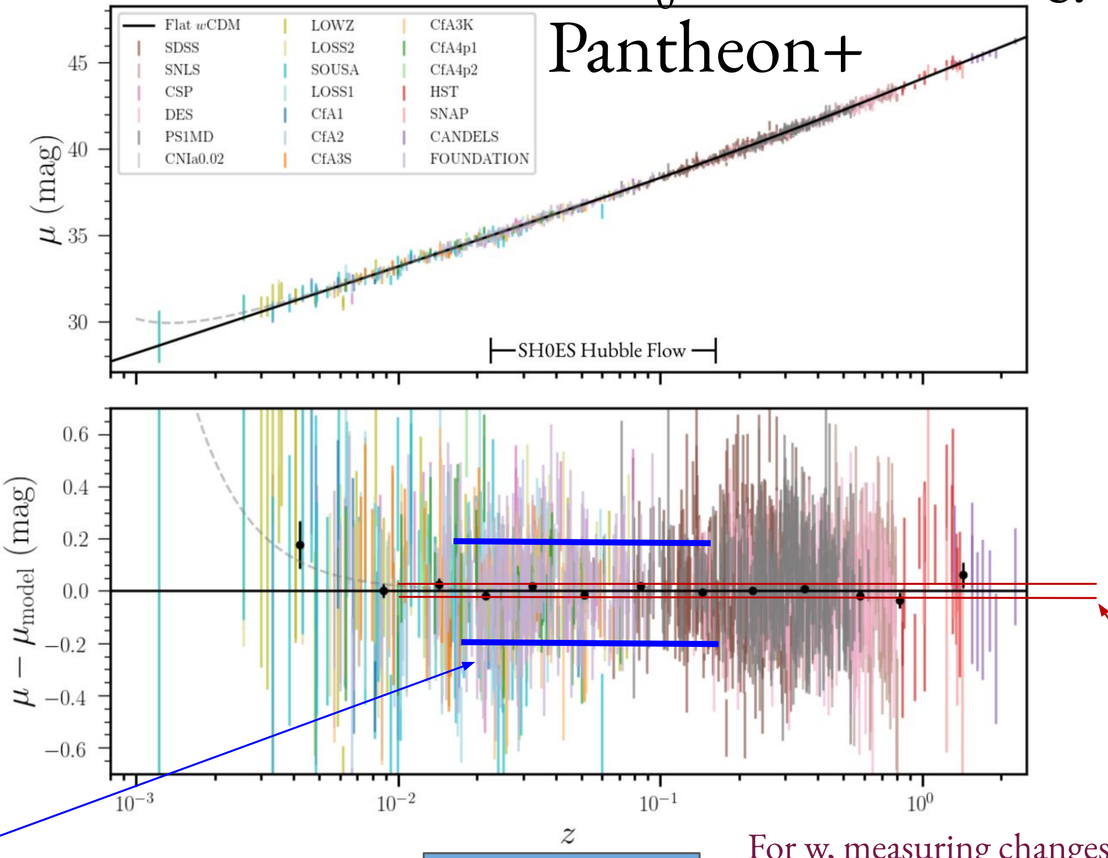
- But, intriguing significant claims of "Early Dark Energy" in *Simon+22, Hill+20, Poulin+19, Agrawal+19, Lin+19, Smith+19* that must be scrutinized.

Today I will focus on two big issues:

Part I: The Hubble Constant (H0)

Part II: The Cosmological Constant (**Λ**), and potentially evolving/thawing dark energy.

SNe Ia are used for Hubble Constant H_0 and Dark Energy w



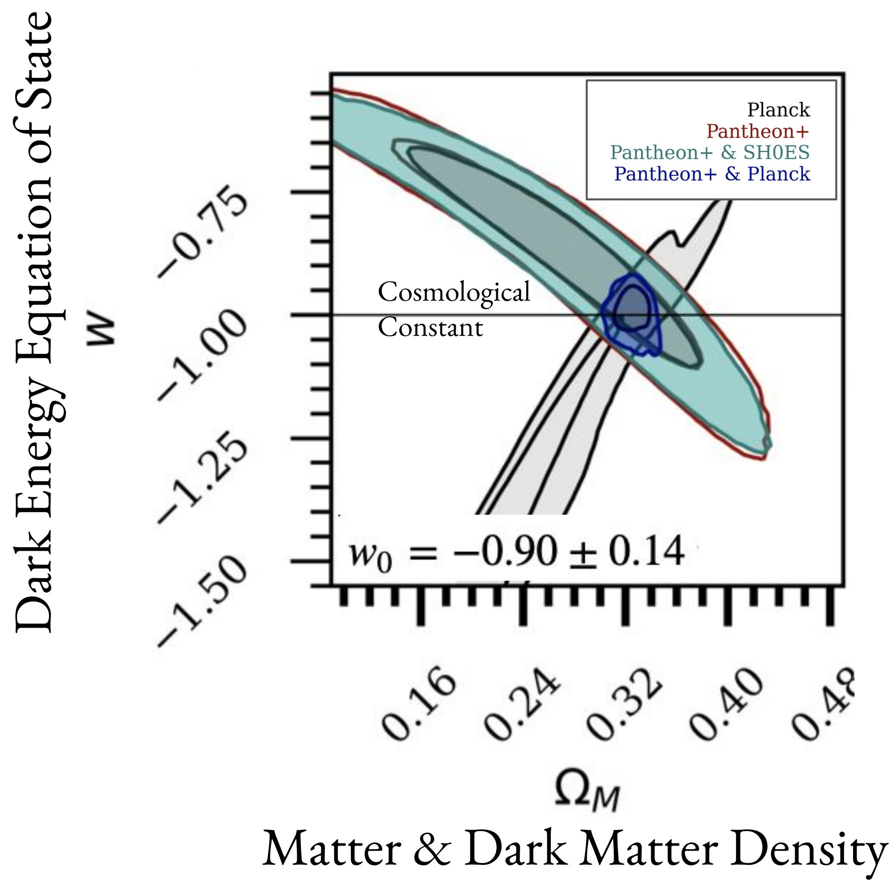
For w, measuring changes of **0.02** mag over Δz of **2.0**

H0

Dark Energy and Dark Matter

For H_0, the `Hubble tension' is **0.20** mag over Δz of **0.1**

Pantheon+ has measured cosmology and pushed on the error floor

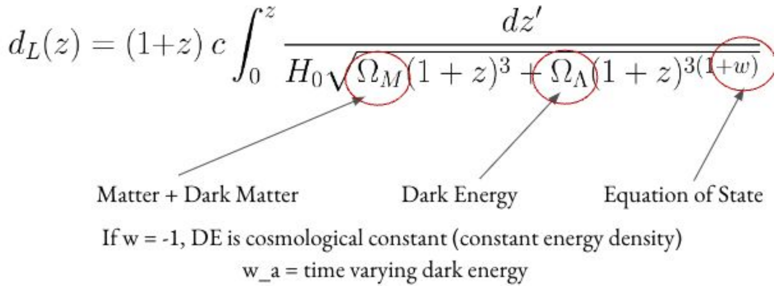


- Incorporates over 115 sources of systematic uncertainty *and not dominated by systematics!*

- Figure of merit 2x better than Pantheon (2018)

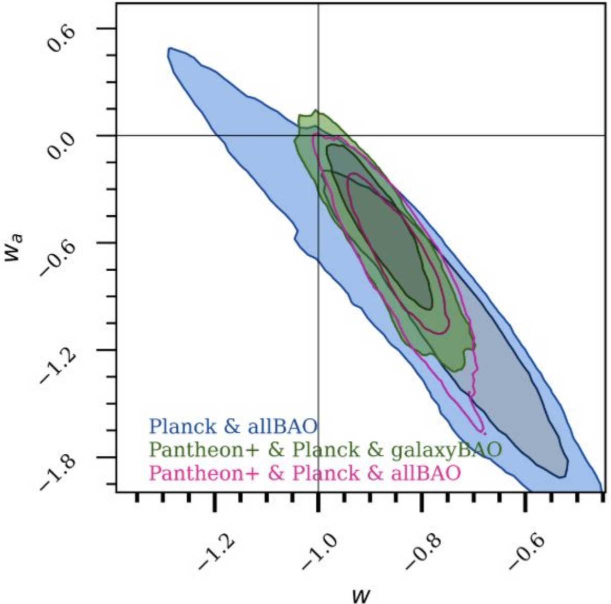
- Consistent with cosmological constant when examining wCDM (including with CMB).

- Data and likelihoods available publicly and now widely used.



2.3 Sigma Significance of Evolving/Thawing Dark Energy (w_a) When combining with CMB and SDSS Baryon Acoustic Oscillations (galaxy and quasar).

Flat-w_0w_aCDM	$\left[\Omega_M(1+z)^3 + (1-\Omega_M)(1+z)^{3(1+w_0+w_a)}e^{-3w_a z/(1+z)}\right]^{1/2}$

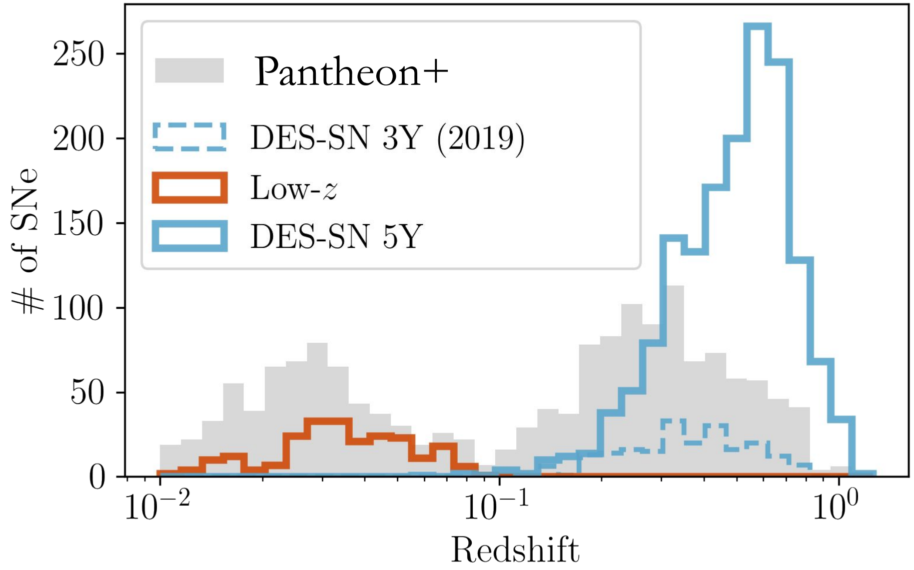


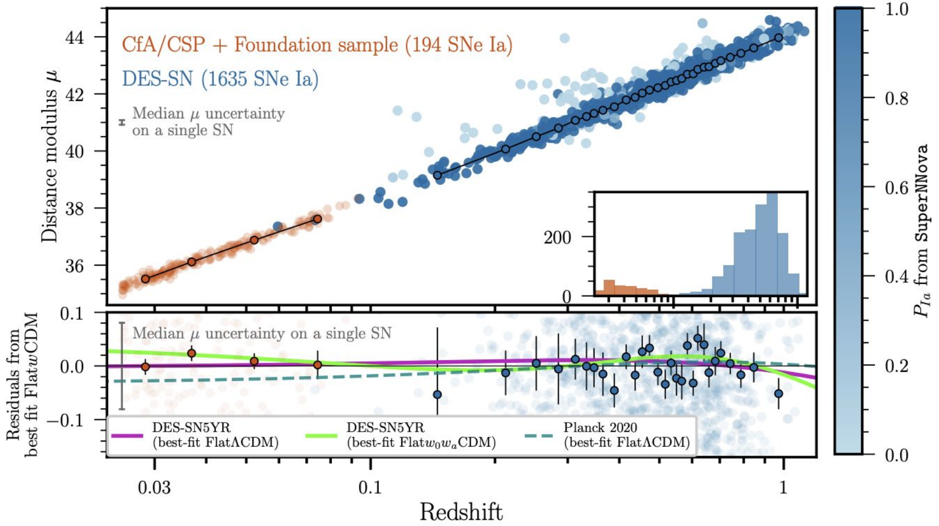
Brout+22

The Dark Energy Survey Supernova Sample is independent high-z sample, can check dark energy signal..

~1600 "Photometrically-classified" Type Ia SNe

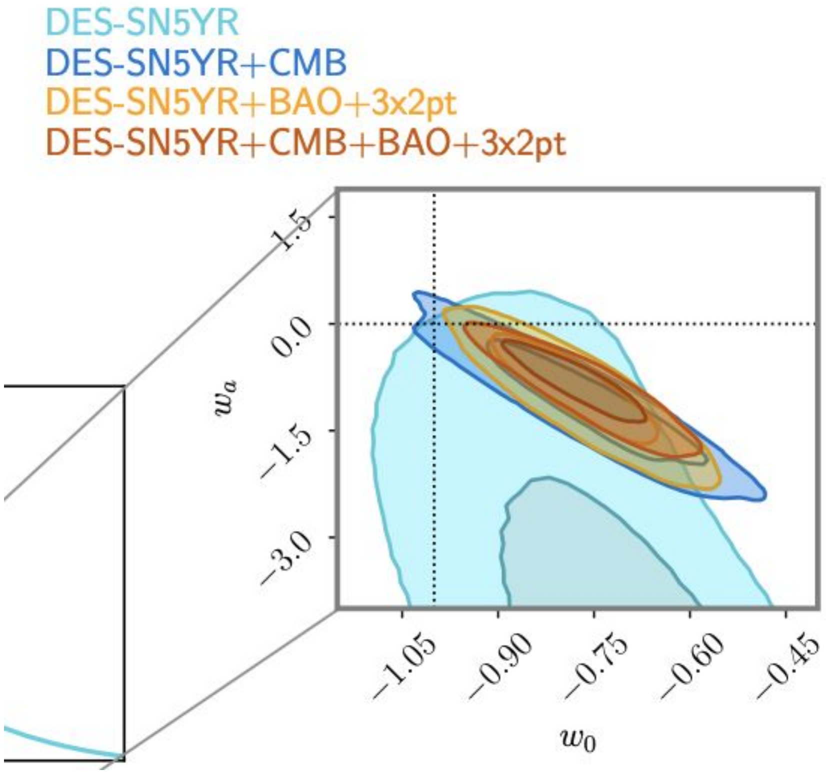
Vincenzi et al. (2024),





Contains 80% of all high-redshift SNe ever discovered.

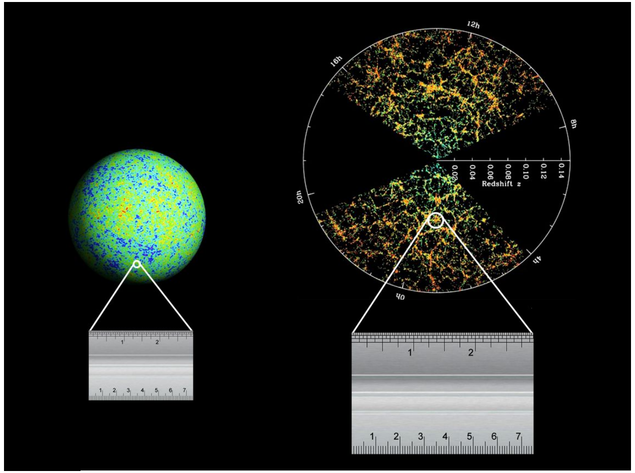
2.5 Sigma w_a when combining the DES supernovae with CMB, SDSS BAO, and DES Weak Lensing.

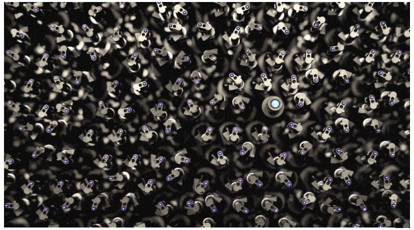


DES Collaboration 2024

DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

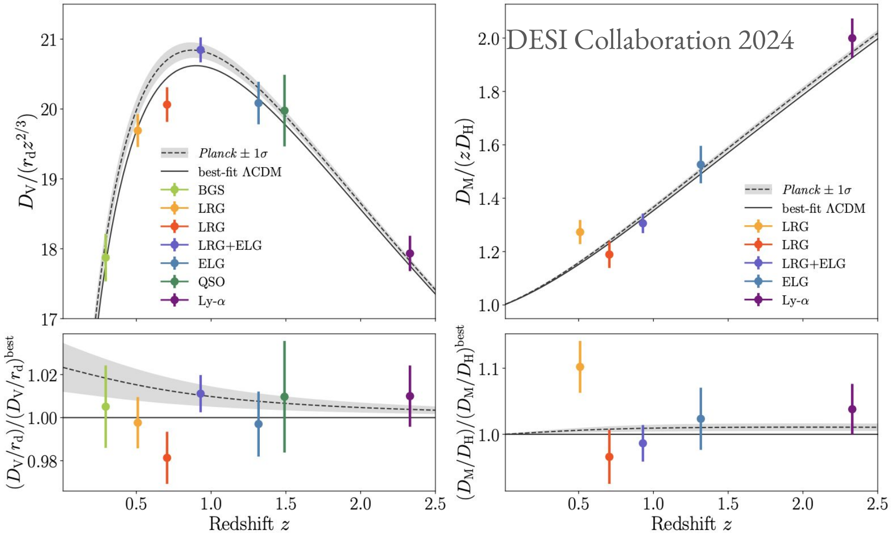




Next-gen BAO measurement.

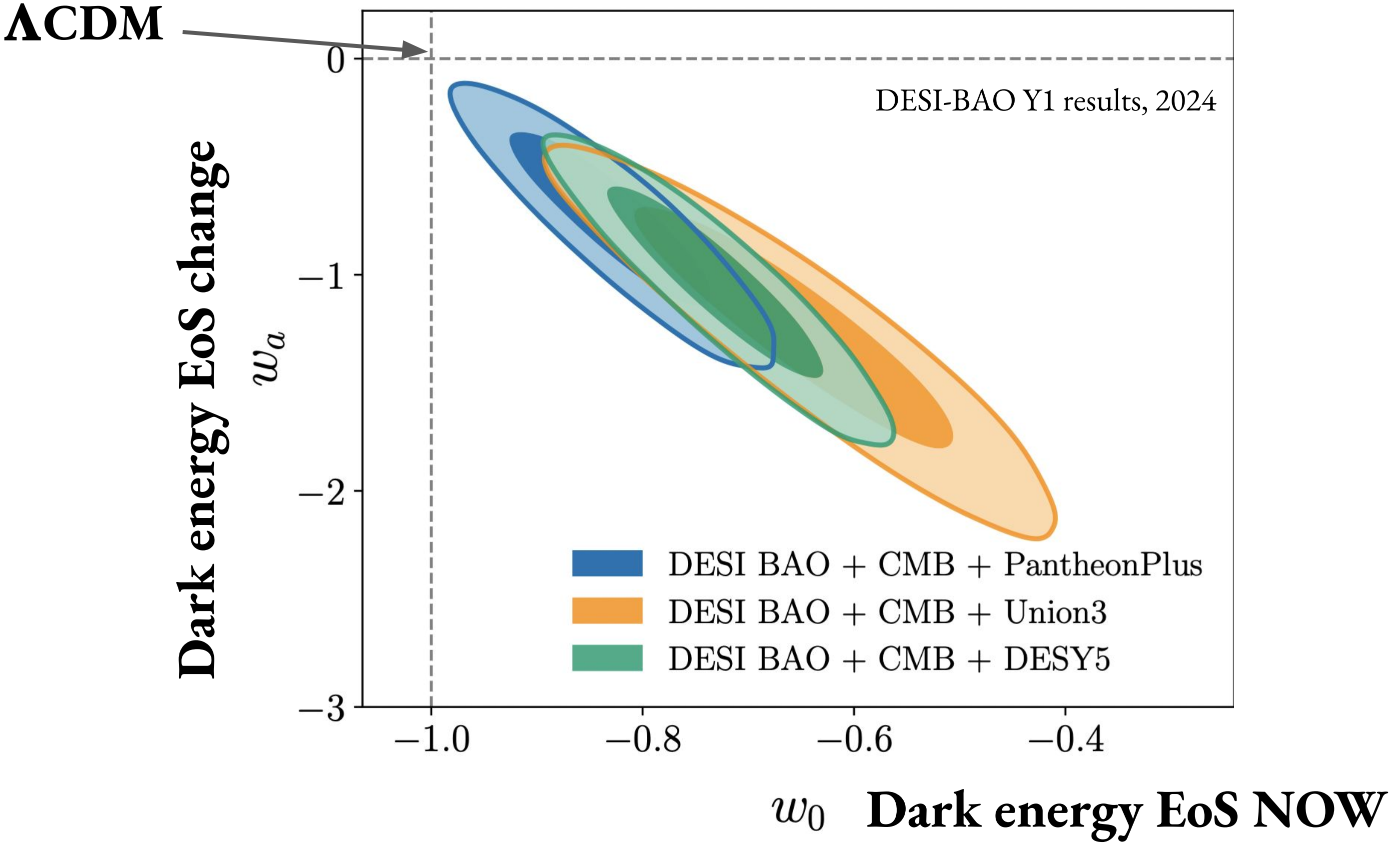
Doubled the 20-year SDSS dataset in a single year (>5million galaxies).

7 Galaxy samples at different redshifts provide measurements of angular diameter distance.

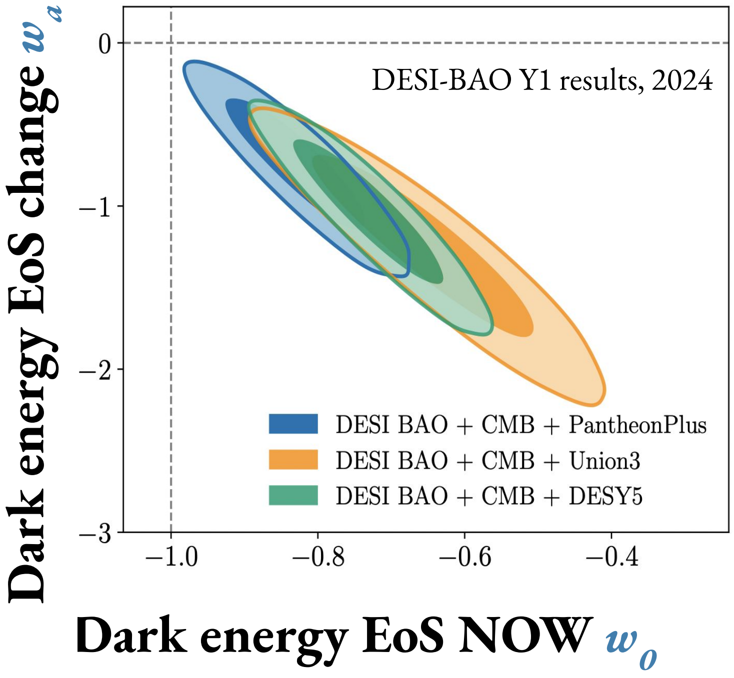


DESI Collaboration 2024

With DES, even stronger signal (2.5-3.9sigma) in same direction, showing here combination with DESI BAO Y1



SN Complementary Datasets and Analyses



	Spectroscopic SN Ia sample	Photometric SN Ia sample
Simulation-based method	**Pantheon+**	**DES-5YR**
Bayesian Hierarchical method ("UNITY")	**Union3**	

Other similarities/differences:
- Similar low-z samples, but DES-5y has smaller subset
- DES-5yr ~independent high-z sample
- Union3 more lax on quality cuts (particularly high-z)
- Union3 data not public

DESI-BAO Y1 results,, 2024

Summary of Evidence for "Evolving Dark Energy"

We have

Two high redshift SNIa datasets: Pantheon+ and DES

Two completely different SNIa analysis pipelines: Pantheon+ (Forward Model) and Union3 (BHM)

Two independent BAO datasets: SDSS and DESI

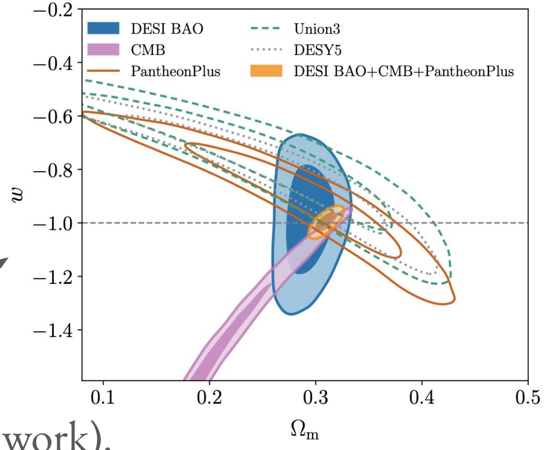
If we exclude any single probe (SN, BAO, CMB), the significance persists.

→ I.e. the preference is not coming from any single probe.

<u>Caveats</u>:

The intersection of SN, BAO, and Planck in wCDM is still w=-1

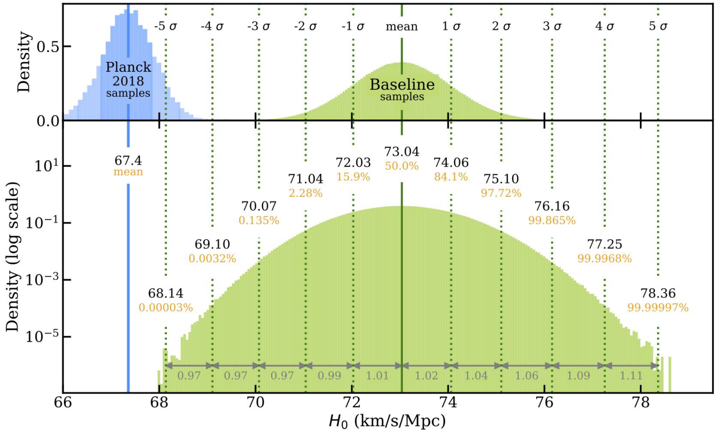
We still need to swap low redshift SN datasets to truly confirm (ongoing work).

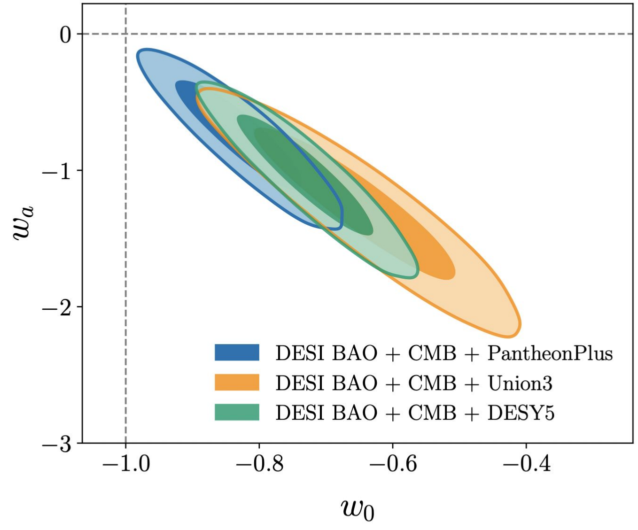


DESI Collaboration 2024

Final thoughts:

- The distance ladder remains extremely robust, fully publicly available, and well tested by the community.
- Strong supernova constraints on expansion history largely rule out late-time exotic physics to explain the hubble tension.
- Numerous recent experiments when combined are giving hints of a model of dark energy that could be more complicated than LCDM.
- If this is the case, all bets are off for H0…





Thank you

BU Cosmology

Institutional Contact: dbrout@bu.edu

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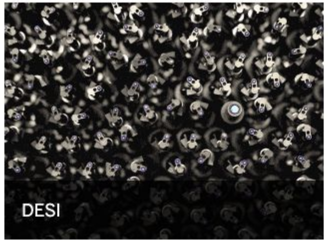
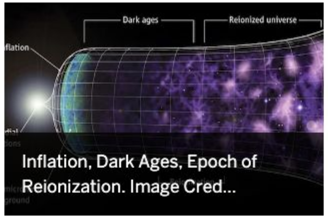
Research Areas and Telescopes

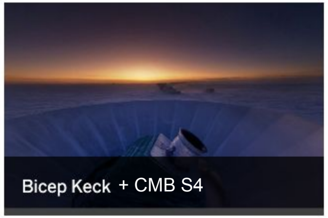

DESI

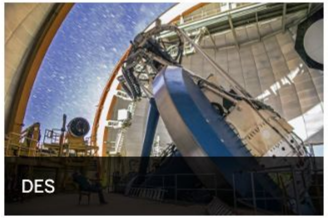
LSST


NASA Roman



Inflation, Dark Ages, Epoch of Reionization. Image Cred...


Bicep Keck + CMB S4


DES

Faculty


Steve Ahlen
Professor Emeritus


Elizabeth Blanton
Professor


Tereasa Brainerd
Professor


Dillon Brout
Assistant Professor


Emily Cunningham
Assistant Professor
(ETA Fall 2025)


Kirit Karkare
Assistant Professor
(ETA January 2025)


Hongwan Liu
Assistant Professor


Siddharth Mishra Sharma
Assistant Professor
(ETA July 2025)


Martin Schmaltz
Professor