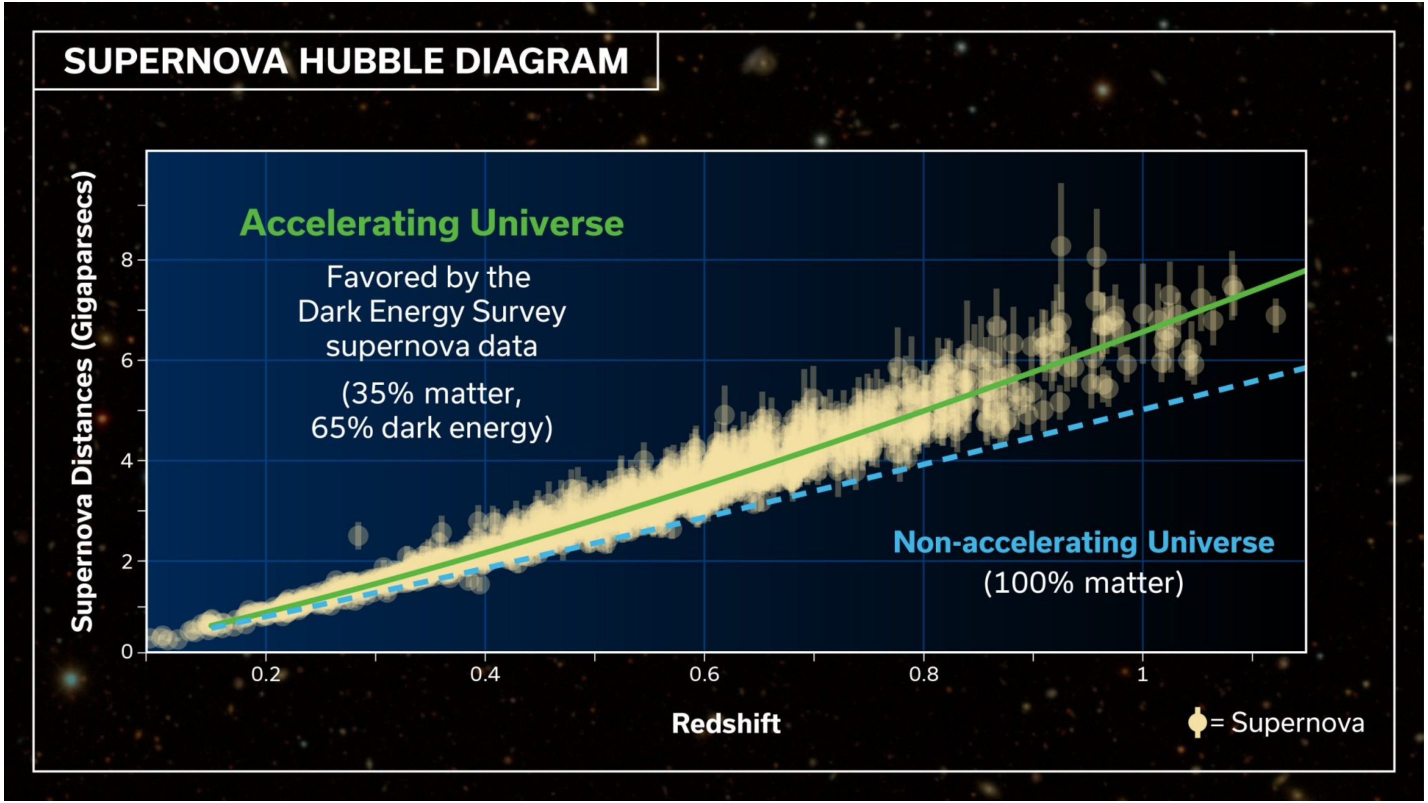
Standard Candles
and the Cosmic distance ladder [Part 1]

Dan Scolnic [Prof. at Duke University]
Galileo Galilei Institute, July 6 2026



Lecture Part 1 (theory/measurements-systematics):

GitHub repos for reproducible SN cosmology and H0 ladders

Selected examples, grouped by use case

Core SN cosmology / H0

PantheonPlusSH0ES.github.io
github.com/PantheonPlusSH0ES/PantheonPlusSH0ES.github.io
Papers, release links, and documentation for Pantheon+SH0ES.

des-science/DES-SN5YR
github.com/des-science/DES-SN5YR
DES-SN5YR / Dovekie cosmology products, simulations, and covariance inputs.

LSSTDESC/sn_lc2cosmo_tutorials
github.com/LSSTDESC/sn_lc2cosmo_tutorials
Tutorial pipeline from light curves to bias correction and cosmology fitting.

Likelihood frameworks / samplers

CobayaSampler/sn_data
github.com/CobayaSampler/sn_data
SN datasets used with Cobaya, including Pantheon, JLA, Union3, and Pantheon+ links.

cosmosis-standard-library
github.com/cosmosis-developers/cosmosis-standard-library
CosmoSIS likelihood modules, including Pantheon+ / SH0ES-style components.

Distance ladder / distance network

StefCas789/H0DN
github.com/StefCas789/H0DN
H0 Distance Network code spanning anchors, Cepheids, TRGB, Miras, JAGB, SNe, TF, and FP.

JiaxiWu1018/CATS-H0
github.com/JiaxiWu1018/CATS-H0
Inputs for the CATS TRGB H0 analysis, including detection settings and standardization choices.

jjensen-uvu/sbf_distances_2021
github.com/jjensen-uvu/sbf_distances_2021
SBF distance tables and calibration material, including TRGB/JWST-related updates.

syeduddin/h0csp
github.com/syeduddin/h0csp
Carnegie Supernova Project H0 analysis with Cepheid-, TRGB-, and SBF-calibrated SNe Ia.

Other / specialized / reanalysis

chvogl/h0-no-rungs-spectral-data
github.com/chvogl/h0-no-rungs-spectral-data
Data products for an SN II spectral-modeling route to H0, useful as a ladder-free comparison.

Motivation:

1. We have a great standard model of cosmology.

2. If you poke it at, no good answers, and now tensions.

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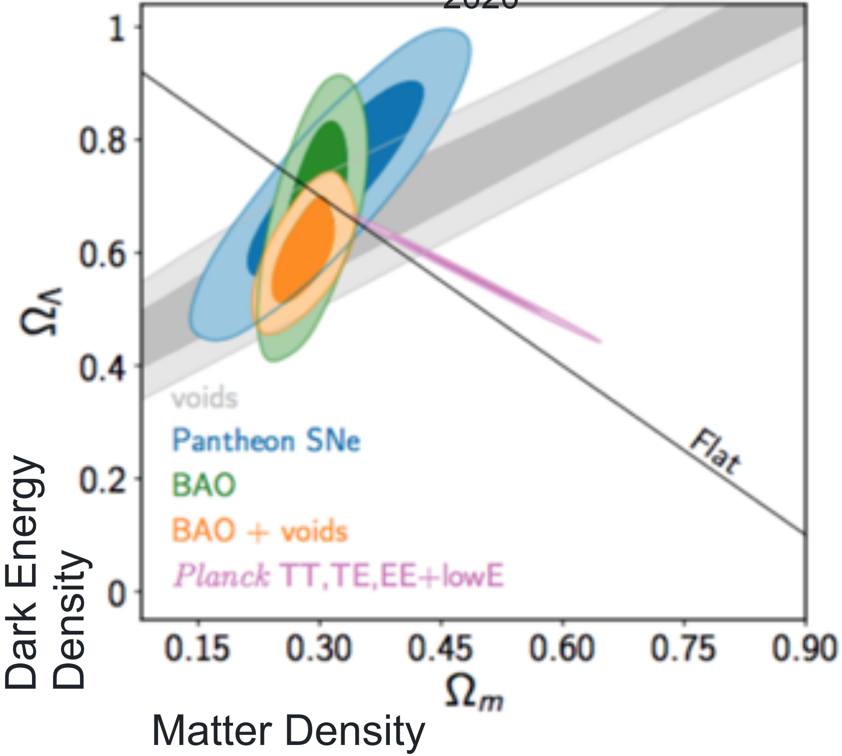
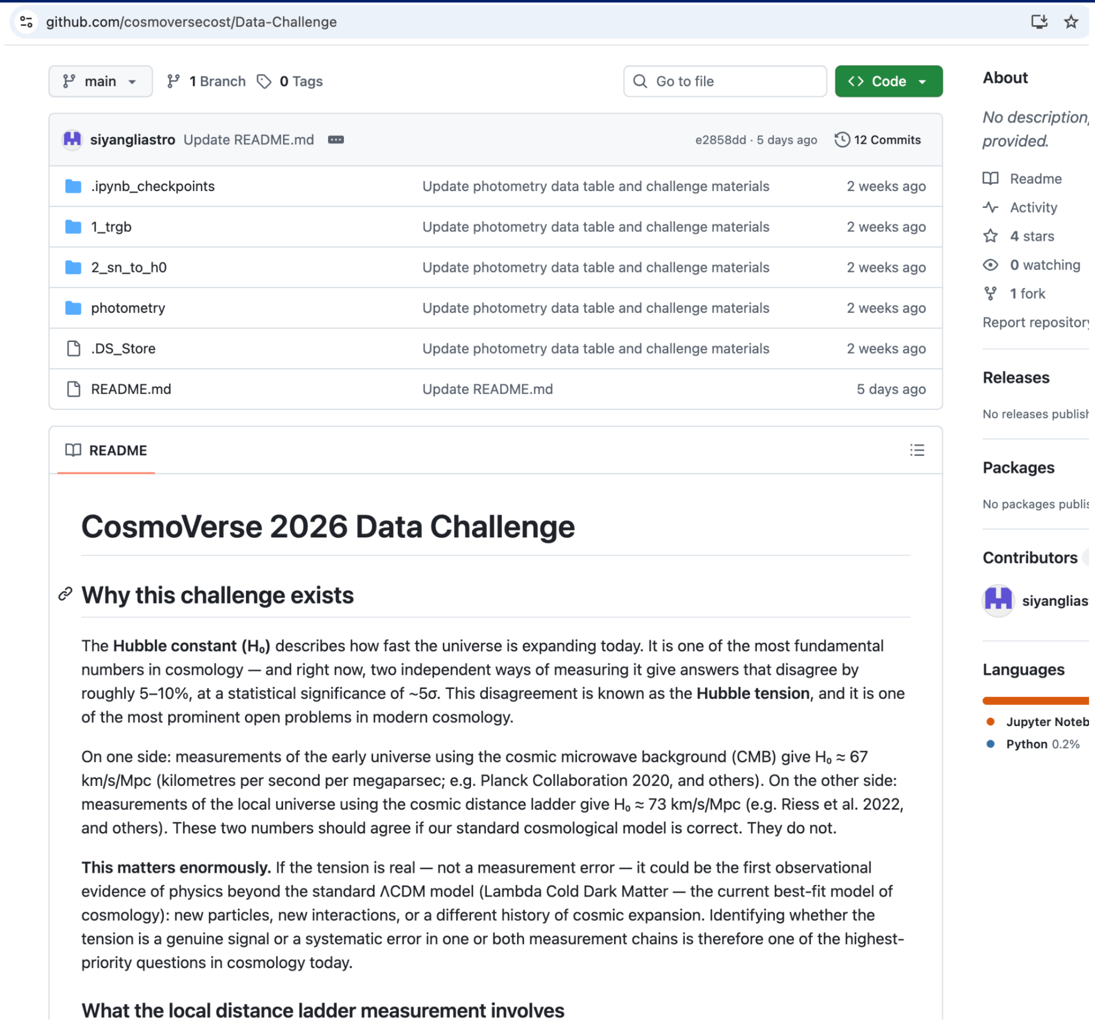
3. The Hubble Tension has been around for >10 years, well poked. Evolving dark energy signal around for ~1.5 years, needs more poking.

Fig. from Nadathur et al. 2020



Very new CosmoVerse 2026 Data Challenge (measuring TRGB, but great for distance ladder). Let's grab it!!

https://github.com/cosmoversecost/Data-Challenge



Roadmap: from photons to w or H_0

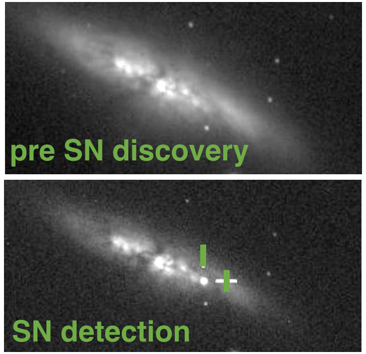
Main idea:

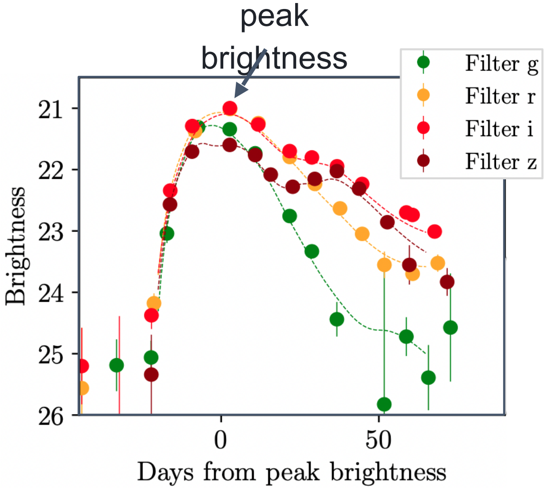
"Standardizable Candles" can be used to make relative measurements (w, q0, Omega_M) or absolute measurements (H0).

For absolute measurements, the candles need to be calibrated. For relative measurements, they don't.

How do we measure stuff?

The relative approach: Find one type of standard candle, standardize, measure versus redshift





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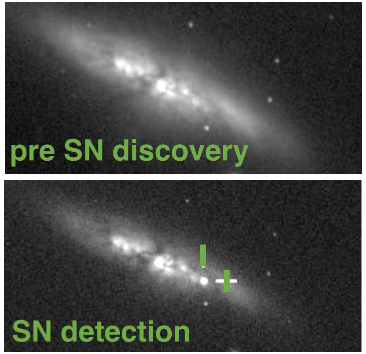

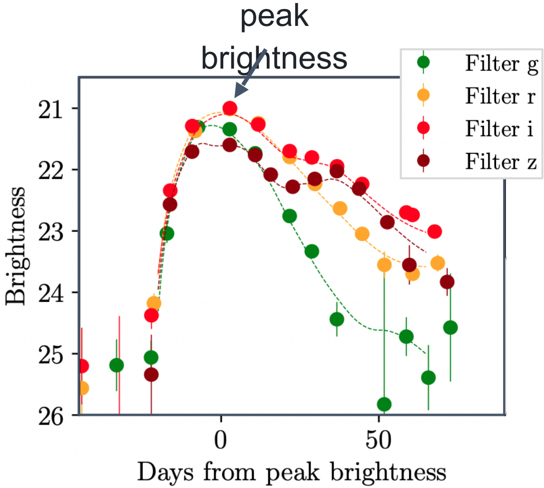

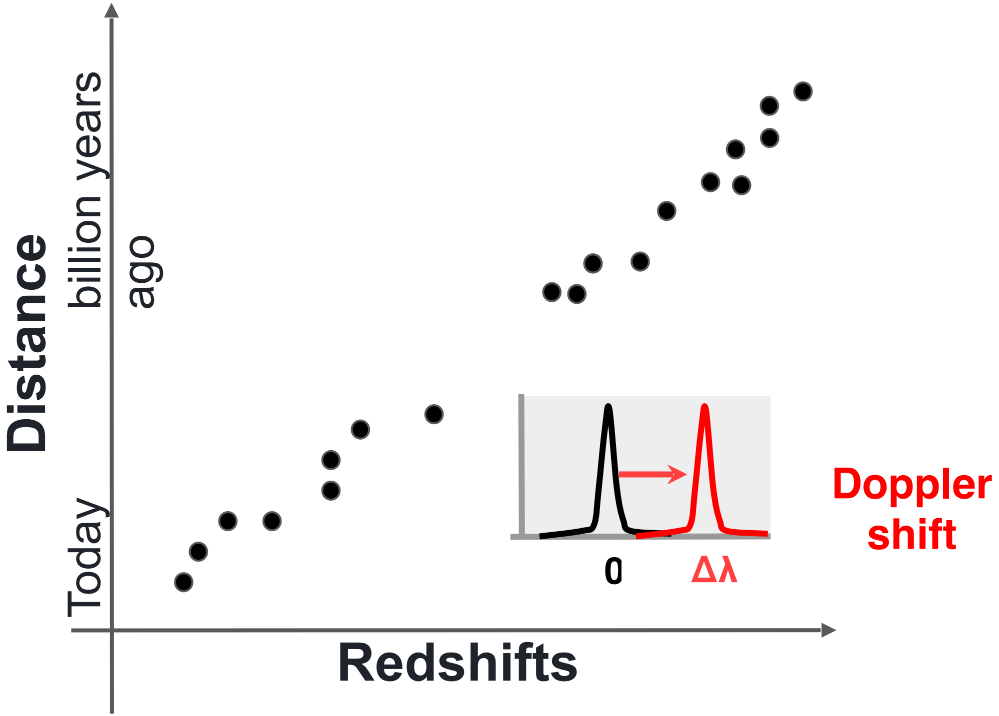

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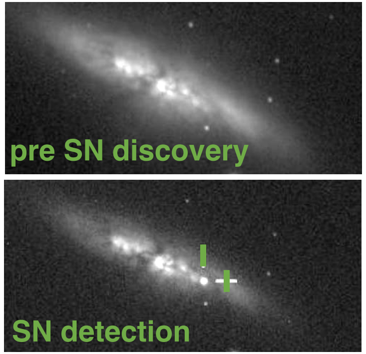

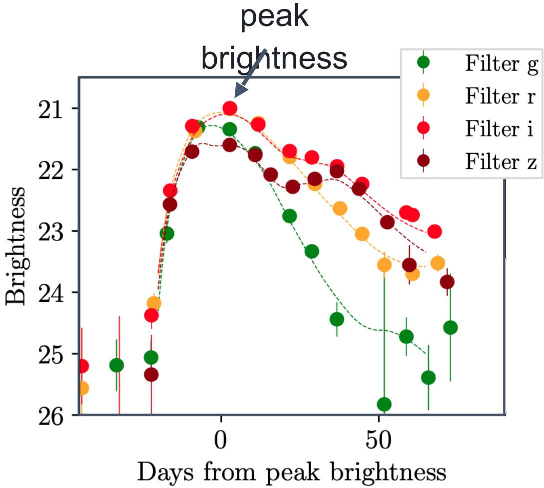

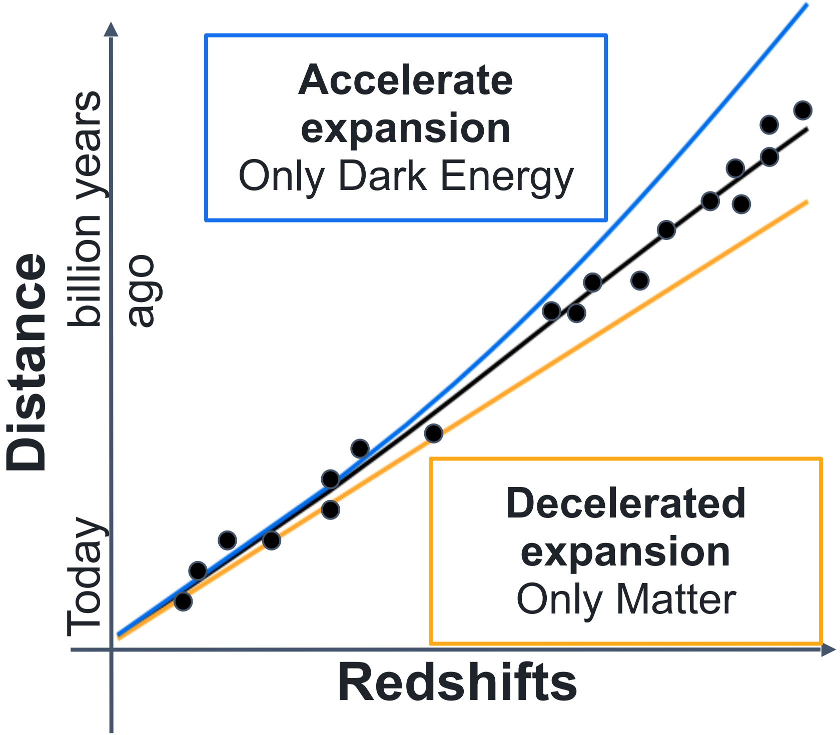

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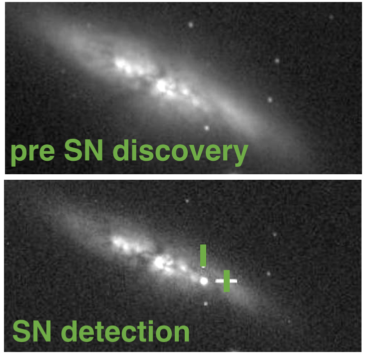
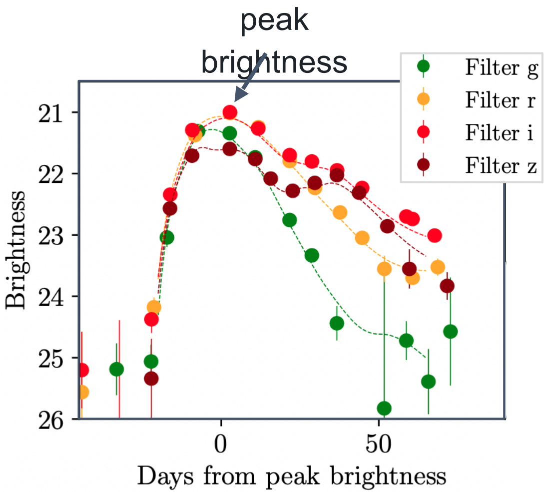
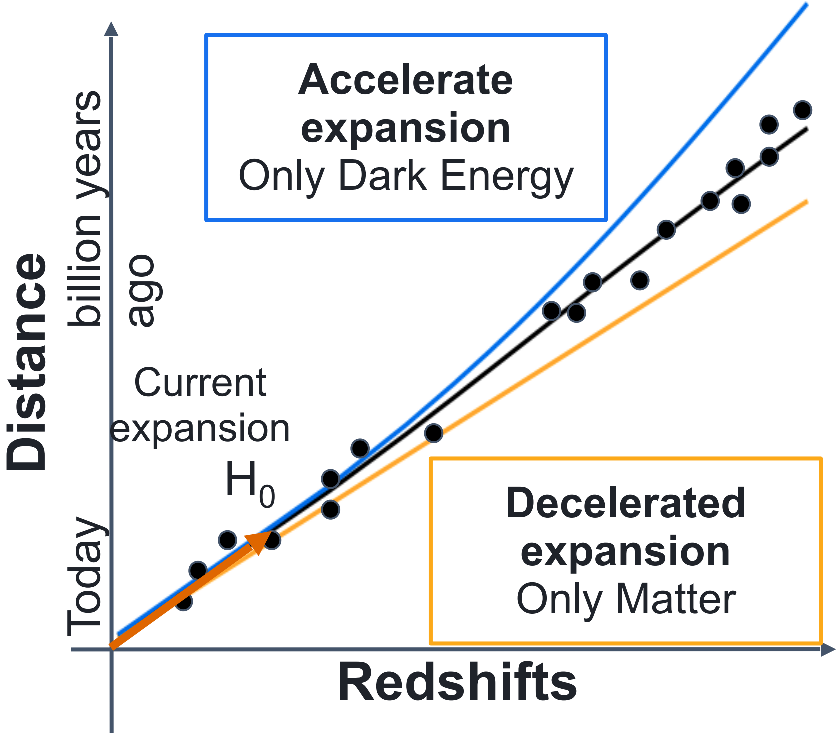
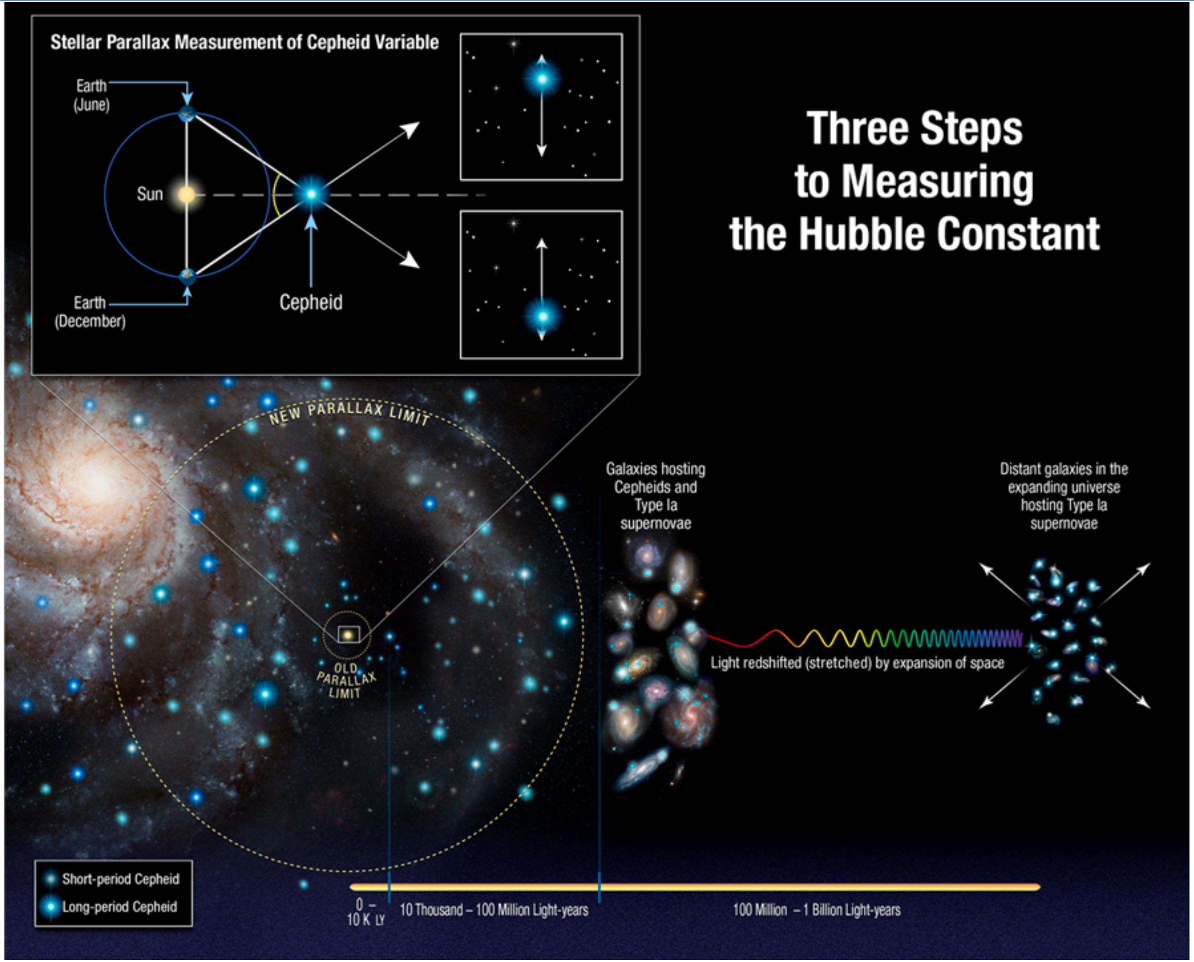






To measure H_0, need to propagate a ‘scale’, from geometry on further



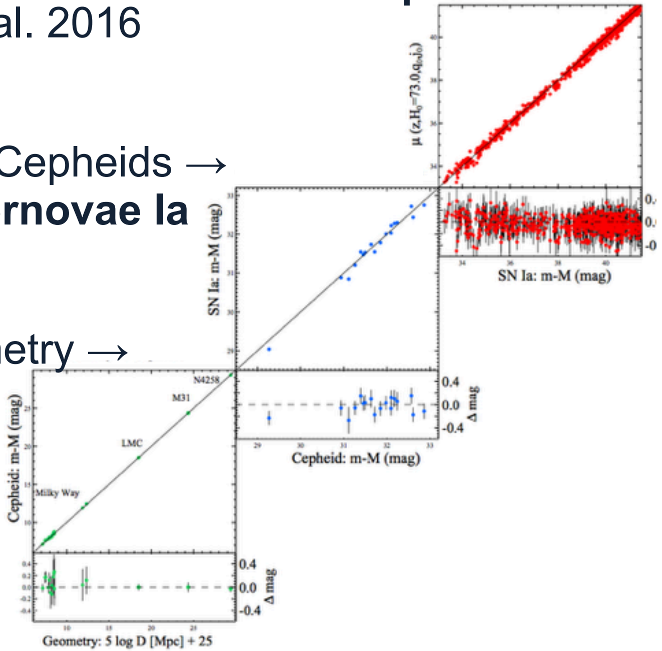
The absolute approach uses geometry and a distance ladder to calibrate the Hubble relation.

Riess et al. 2016

3rd: **Supernovae Ia** → H0

2nd: Cepheids → **Supernovae Ia**

1st: Geometry → Cepheids



The general approach: calibrate fluxes to make magnitudes, calibrate magnitudes to make standardized magnitudes, convert standardized magnitudes to distance modulus

$$m_X = -2.5 \log_{10}(f_X / f^0_X)$$

$$m_X - M_X = 5 \log_{10}(D_L / 10 \text{ pc}) + K_X + A_X + \ldots$$

$$\mu \equiv m - M = 5 \log_{10}(D_L / \text{Mpc}) + 25$$

The distance modulus μ is logarithmic: 0.01 mag ≈ 0.46% in distance. $\delta D/D = (\ln 10 / 5)\, \delta\mu \approx 0.4605\, \delta\mu$.

legend: $\mathbf{m_X}$ = apparent mag in band X; $\mathbf{f_X}$ = flux, f^0_X = zero-point (reference) flux; $\mathbf{M_X}$ = absolute mag; $\mathbf{D_L}$ = luminosity distance; $\mathbf{K_X}$ = K-correction; $\mathbf{A_X}$ = extinction (dust); **μ** = m−M = distance modulus

How does one calibrate the fluxes though?

$$m_{AB} = -2.5 \log_{10}(f_\nu) - 48.60 \quad [f_\nu \text{ in erg s}^{-1}\text{ cm}^{-2}\text{ Hz}^{-1}]$$

$$m_X^{Vega} = -2.5 \log_{10}\left(\int f_\lambda T_X \lambda \, d\lambda \,/ \int f_\lambda^{Vega} T_X \lambda \, d\lambda \right)$$

$$m_{AB} = m_{Vega} + \Delta_X \,, \quad \Delta_X = -2.5 \log_{10}(f_\nu^{Vega} / 3631 \text{ Jy})$$

A magnitude is only defined once a zero point fixes what "0 mag" means.

AB system: ties the zero point to a fixed spectral flux density — f_ν = 3631 Jy at every frequency. Purely physical; ideal for SEDs, K-corrections, and cross-survey work.

Vega system: ties the zero point to the SED of α Lyrae, so Vega ≈ 0 mag in every classical band by construction. Offsets Δ_X grow toward the infrared.

SDSS, PS1, DES, and LSST report native AB; HST/JWST quote both; 2MASS and older IR data are Vega.

A zero-point error propagates straight down the ladder: $\delta ZP \rightarrow \delta m \rightarrow \delta\mu \rightarrow \delta H_0$.

where: $\mathbf{f_\nu}$**,** $\mathbf{f_\lambda}$ = flux per unit frequency / wavelength; $\mathbf{T_X}$ = filter transmission; **m_(AB), m_(Vega)** = magnitude in each system; $\mathbf{\Delta_X}$ = AB−Vega offset; **α Lyr** = Vega (Jy = jansky)

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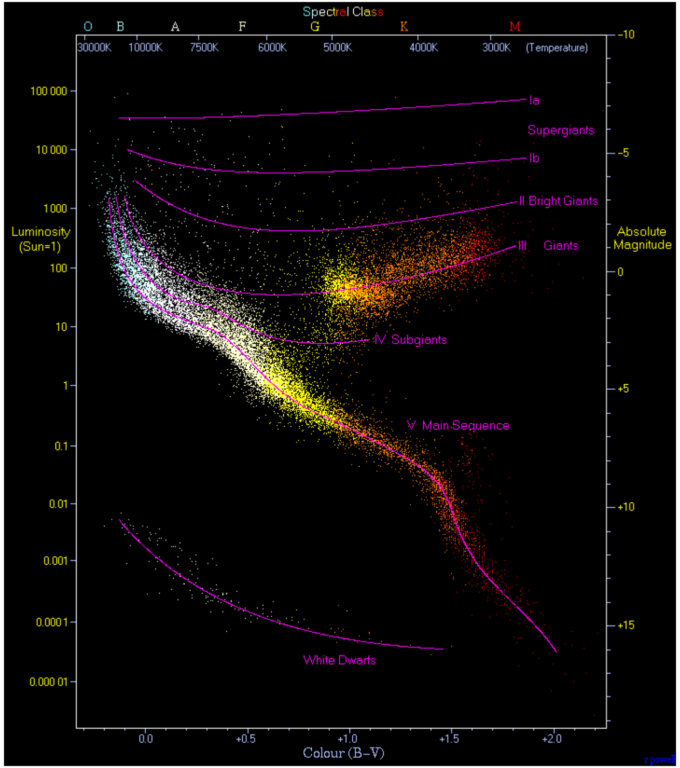

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Standard candles versus standardizable candles

standard candle: $M \approx \text{constant}$

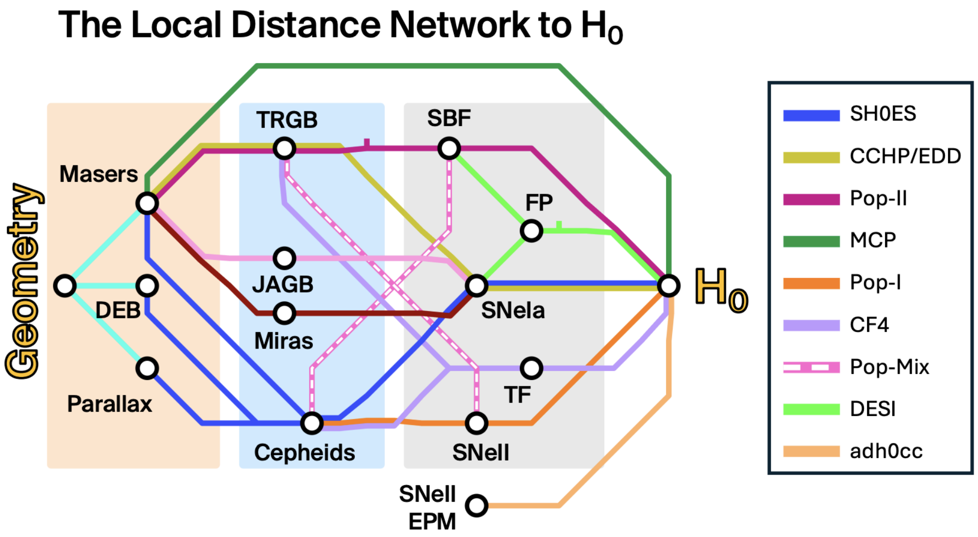
standardizable candle: $M = M_0 + \Sigma_i \beta_i q_i$

distance: $\mu = m - M(q_i) - A - K - \text{bias}$

- Cepheids: luminosity as a function of period, color, metallicity.
- TRGB: nearly fixed I-band luminosity of helium flash, with color correction.
- SNe Ia: peak luminosity corrected by stretch and color.
- SBF/TF/FP: galaxy-level relations calibrated by primary distances.
- Bias can be found from simulations, will be discussed in Lecture 2

where: **M** = absolute mag, M_0 = its zero-point; $\mathbf{q_i}$ = standardization observables (stretch, color, …), β_i = their coefficients; **μ** = distance modulus; **A** = extinction; **K** = K-correction

Which probes are best for which types of measurements?



SNe Ia - very bright, discover them to z~2.5, can standardize to high precision (0.1 mag). Limitation: limited number in very local universe.

TRGB/Cepheids - bright, can standardize to very high precision (0.05 mag), can tie to geometric anchor. Limitation: Can only discover/measure with HST/JWST to z~0.01 (40 Mpc).

Surface Brightness Fluctuations - pretty bright, can standardize to very high precision (0.1 mag), can tie to geometric anchor. Limitation: Need TRGB/Cepheids to tie to geometric anchor, can discover/measure with HST/JWST to z~0.05 (200 Mpc).

So SNe Ia are amazing 'relative probe', need to be part of distance ladder for absolute measurement.

Why Type Ia supernovae are useful

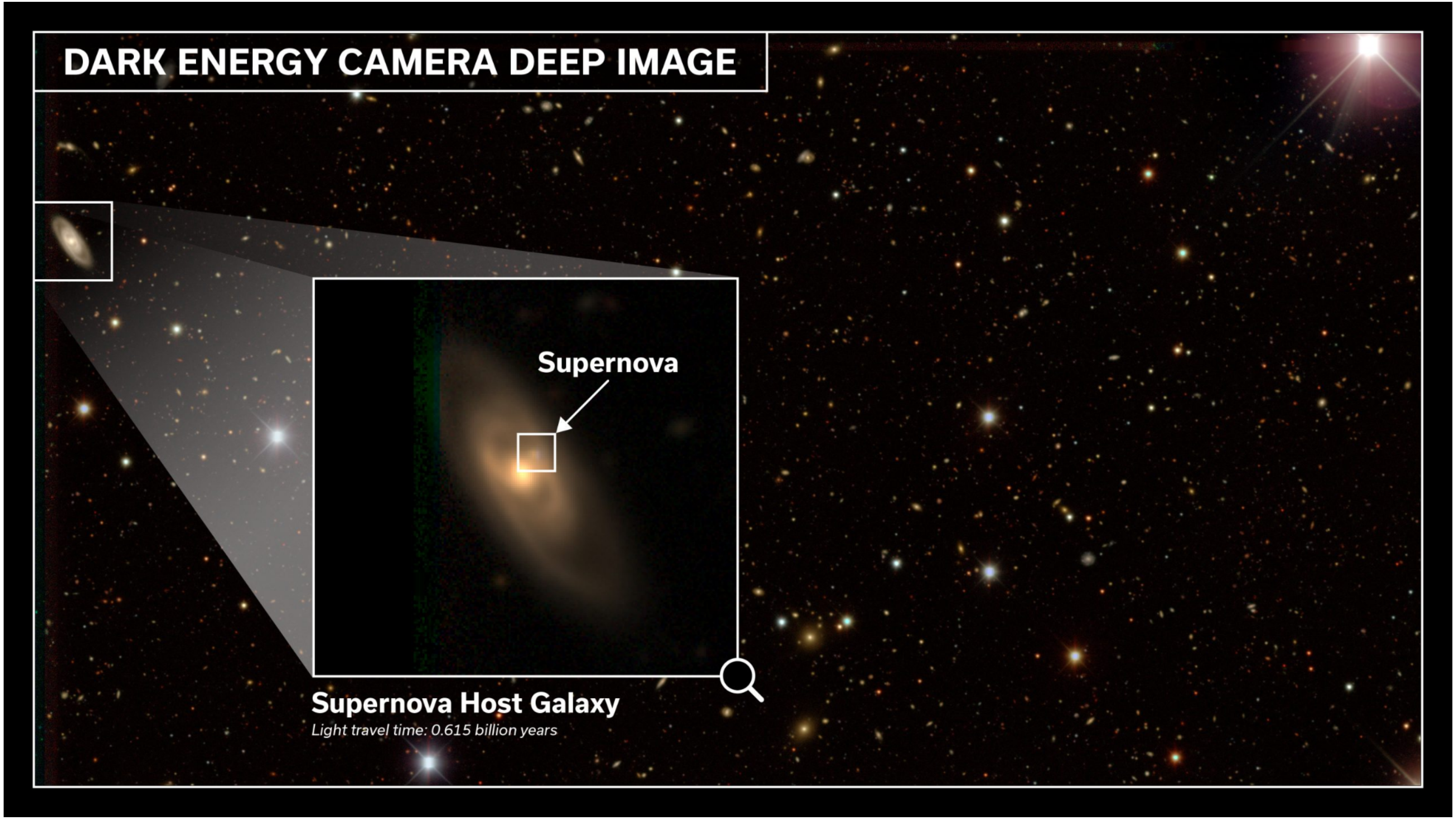
- Thermonuclear explosions of white dwarfs: optical peak $M_B \approx -19.3$ mag.
- Observed in hosts spanning wide stellar populations and dust environments.
- Intrinsic scatter after corrections: roughly 0.10–0.15 mag in modern analyses.
- The measured light curve gives amplitude, shape, color, and time of maximum.

observed data: $\{ f_{b,k}, \sigma_{b,k}, t_k, z, \text{calibration} \}$

fit parameters: $\{ x_0, x_1, c, t_0 \} \rightarrow \{ m_B, x_1, c \}$

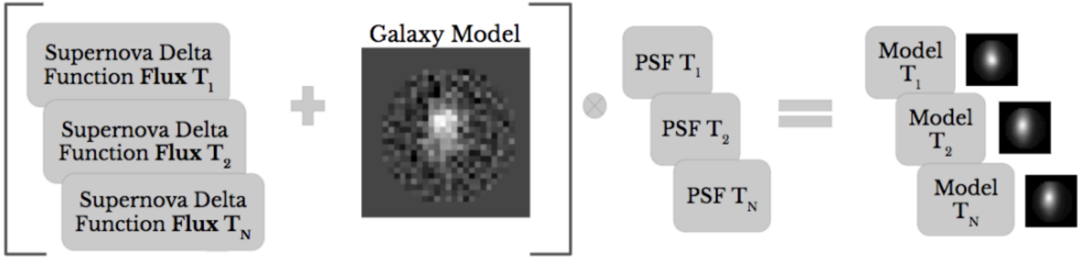
where: f_(b,k), σ_(b,k) = flux & error in band b at epoch k; $\mathbf{t_k}$ = observation time; **z** = redshift; $\mathbf{x_0}$ = amplitude, x_1 = stretch, c = color, t_0 = time of peak; $\mathbf{m_B, M_B}$ = apparent/absolute peak B mag

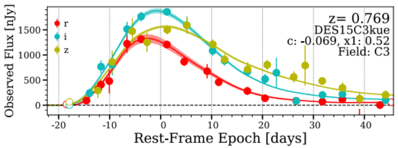
How do we actually extract the supernova flux?

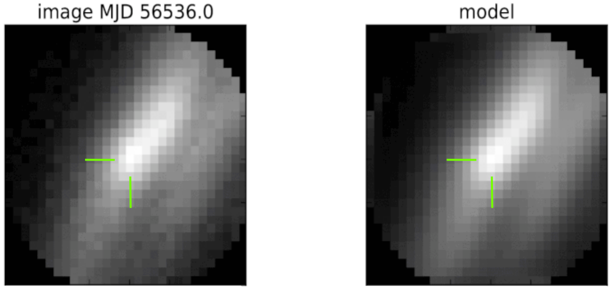


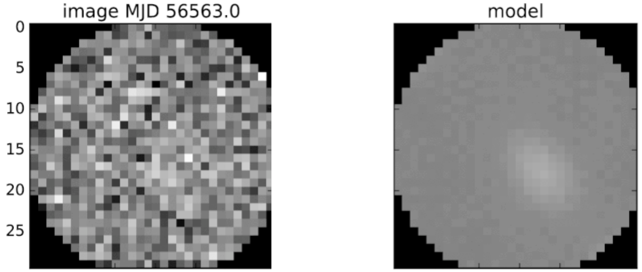
How do we actually extract the supernova flux?

SMP Model Visual Representation



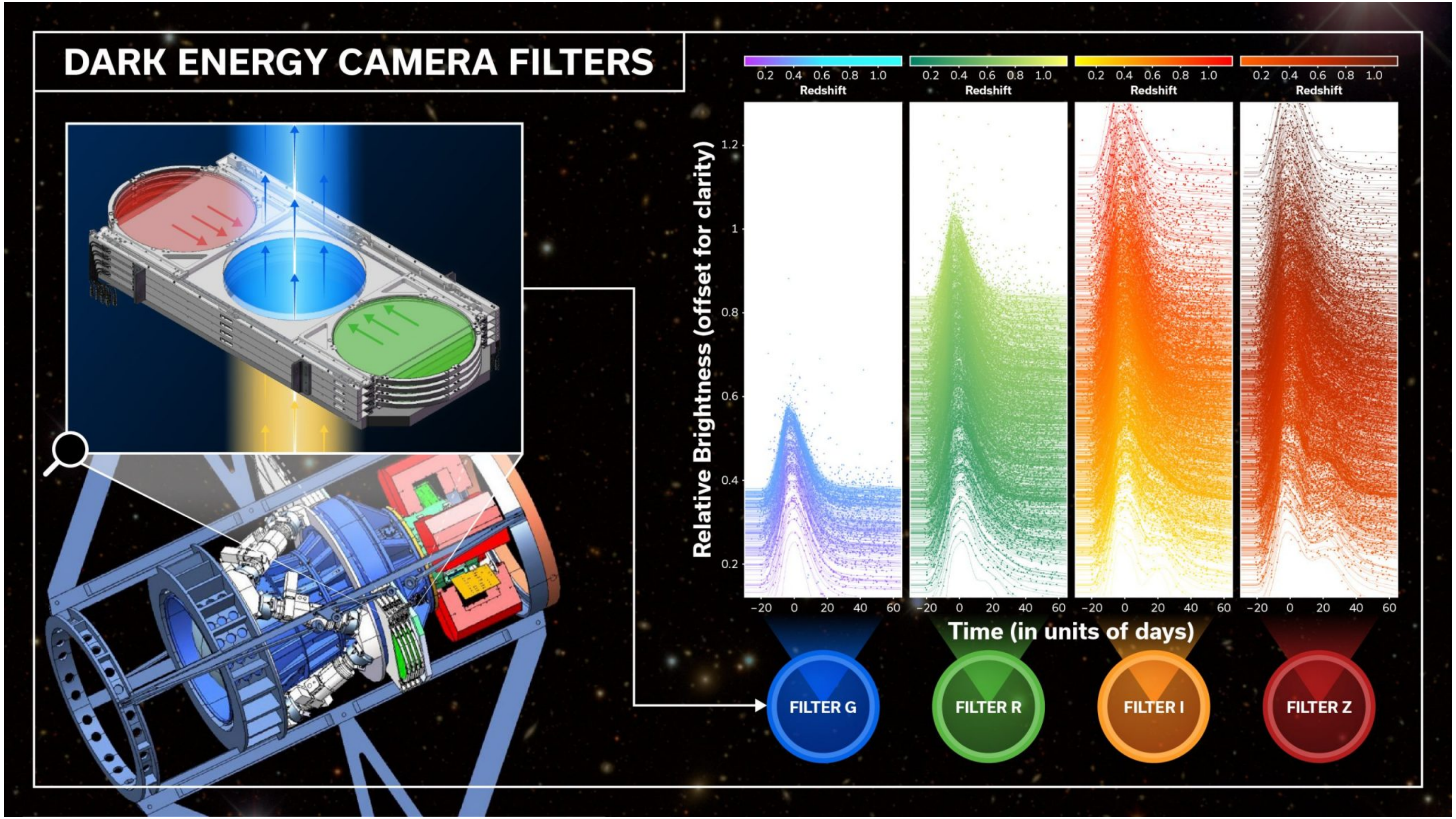




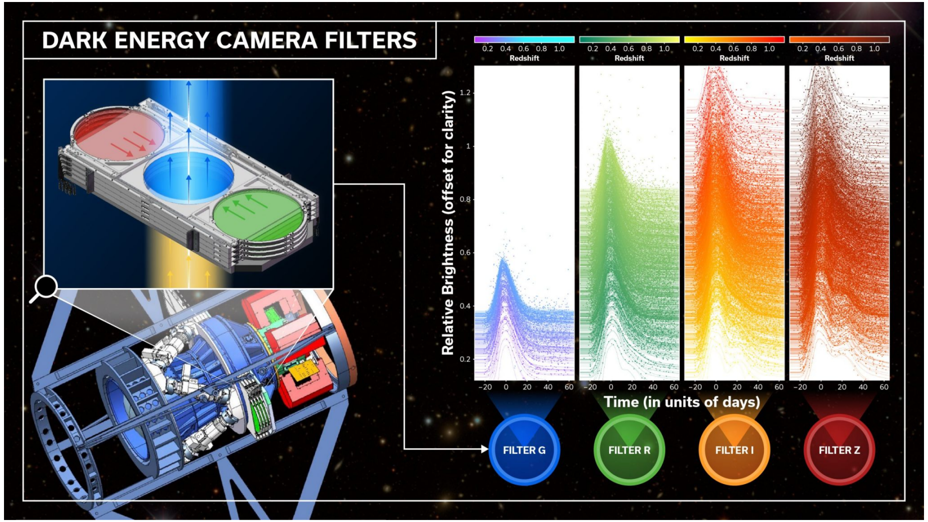


Afterburners for DCR PSF corrections, Chromatic Throughput Corrections, and DCR galaxy effects

We discover and measure the supernovae in multiple filters



And then we do an initial *empirical* standardization



brighter-slower relation: $M_B = M_0 - \alpha x_1$

color correction: $M_B = M_0 - \alpha x_1 + \beta c$

Tripp distance: $\mu = m_B - M_B + \alpha x_1 - \beta c + \ldots$

- x_1 is a stretch/shape parameter; c is color relative to the trained SN model.
- β mixes dust reddening and intrinsic color-luminosity correlations.
- Host correlations enter because SN populations and dust are not universal.
- Use redshift to account for time dilation

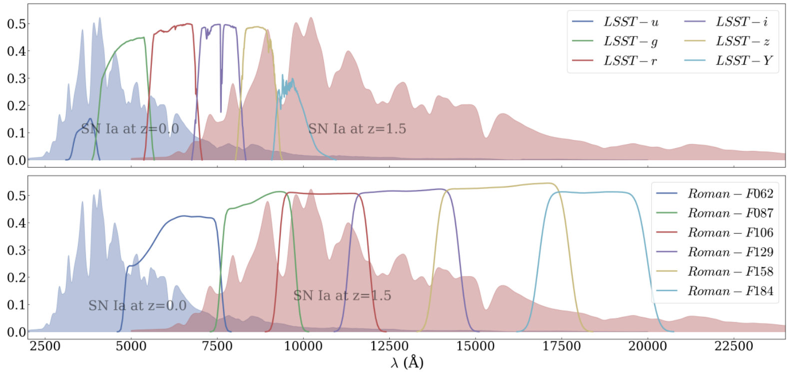
where: $\mathbf{M_B}$ = SN Ia absolute peak mag, M_0 = its zero-point; $\mathbf{x_1}$ = stretch, c = color; **α, β** = stretch- and color-luminosity coefficients; $\mathbf{m_B}$ = apparent peak mag; **μ** = distance modulus

Because the redshift changes, we fit our photometric light curves in spectral space.

$F_{SN}(p, \lambda) = x_0 \, [\, M_0(p,\lambda) + x_1 \, M_1(p,\lambda) + \ldots \,] \exp[c \cdot CL(\lambda)]$

$f_b(t) = \int F_{SN}(p, \lambda) \cdot T_b(\lambda_{obs}) \cdot \lambda \, d\lambda \, / \int T_b(\lambda_{obs}) \cdot \lambda \, d\lambda$

$m_B = -2.5 \log_{10}(x_0) + \text{constant}$



- M_0 (nominal surface), M_1(stretch surface) and CL (color law) are trained using a large SN sample plus calibration model.
- K-corrections are implicit: observed filters sample rest-frame wavelengths via z.
- Light-curve-model training uncertainty is a cosmology systematic.

Output per SN: z, m_B, x_1, c, cov(m_B,x_1,c), selection/bias correction

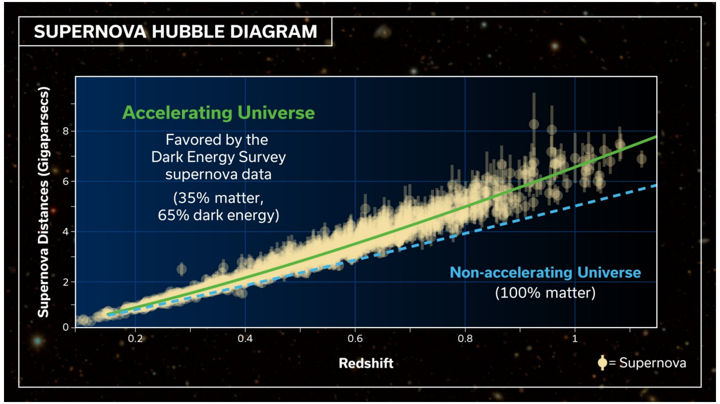
where: F_(SN) = SN spectral flux model; **p** = phase (days from peak), λ = wavelength; $\mathbf{x_0}$ = amplitude, x_1 = stretch, c = color; $\mathbf{M_0, M_1}$ = SALT2 templates; **CL** = color law; $\mathbf{T_b}$ = band-b transmission; $\mathbf{m_B}$ = peak B mag

Finally we obtain a standardized SN Ia distance modulus (with some extra corrections I'll leave for Lecture 2)

$$\mu_i^{obs} = m_{B,i} - M_B + \alpha\, x_{1,i} - \beta\, c_i + \Delta_M(host_i) - \Delta_{bias,i}$$

$$\Delta\mu_i = \mu_i^{obs} - \mu_i^{th}(z_i\, ;\, \theta_{cosmo})$$

$$\chi^2 = \Delta\mu^T\, C^{-1}\, \Delta\mu$$



- α and β are nuisance parameters fitted globally or marginalized.
- Δ_M is often implemented as a host-mass step or continuous host correction.
- Δ_{bias} is obtained from survey simulations: selection, measurement noise, analysis cuts.
- $C = C_{stat} + C_{cal} + C_{model} + C_{bias} + C_{vpec} + C_{scatter} + \ldots$

where: μ^(obs) = observed, μ^(th) = model distance modulus; $\mathbf{m_B}$ = peak mag, M_B = SN Ia absolute mag; $\mathbf{x_1}$ = stretch, c = color; **α, β** = nuisance coefficients; $\mathbf{\Delta_M}$ = host, Δ_(bias) = bias correction; **θ_(cosmo)** = cosmology params; **C** = covariance matrix

Betoule+2014; Brout+2022; Scolnic+2022; DES+2024.

How we construct our covariance matrix from systematics

$$\sigma^2_{stat} \approx \sigma^2_{mB} + \alpha^2\sigma^2_{x1} + \beta^2\sigma^2_{c} + 2\alpha C_{mx} - 2\beta C_{mc} - 2\alpha\beta C_{xc} + \sigma^2_{int} + \sigma^2_{vpec}$$

$$C_{ij} = C^{stat}_{ij} + \Sigma_k (\partial\mu_i/\partial s_k)(\partial\mu_j/\partial s_k)\, \sigma^2(s_k)$$

$$-2 \ln L = \Delta\mu^T C^{-1} \Delta\mu + \ln |C| + \text{const}$$

- Correlated calibration shifts can move many SNe coherently.
- Peculiar velocities dominate at very low redshift.
- Intrinsic scatter models alter β, bias corrections, and errors.
- Good analyses validate end-to-end on simulations before unblinding.

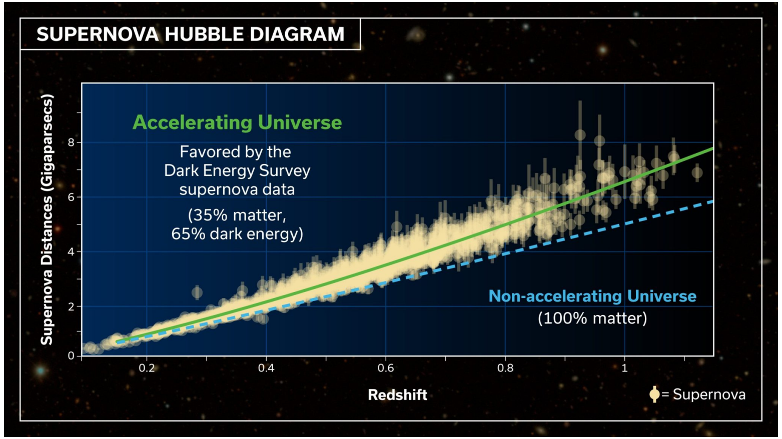
where: **L** = likelihood; **C** = covariance (C^(stat) statistical part), C_(ij) = its elements; $\mathbf{s_k}$ = systematic parameter, $\sigma(s_k)$ = its uncertainty; **σ_(int)** = intrinsic scatter, σ_(vpec) = peculiar-velocity term; **C_(mx), C_(mc), C_(xc)** = covariances among m_B, x_1, c

From redshift to luminosity distance

$$D_L(z) = (1+z) \cdot D_M(z)$$

$$D_M = (c/H_0)\, S_k \left[\int_0^z dz' / E(z') \right]$$

$$E(z) = H(z)/H_0$$



flat $w_0 w_a$CDM:

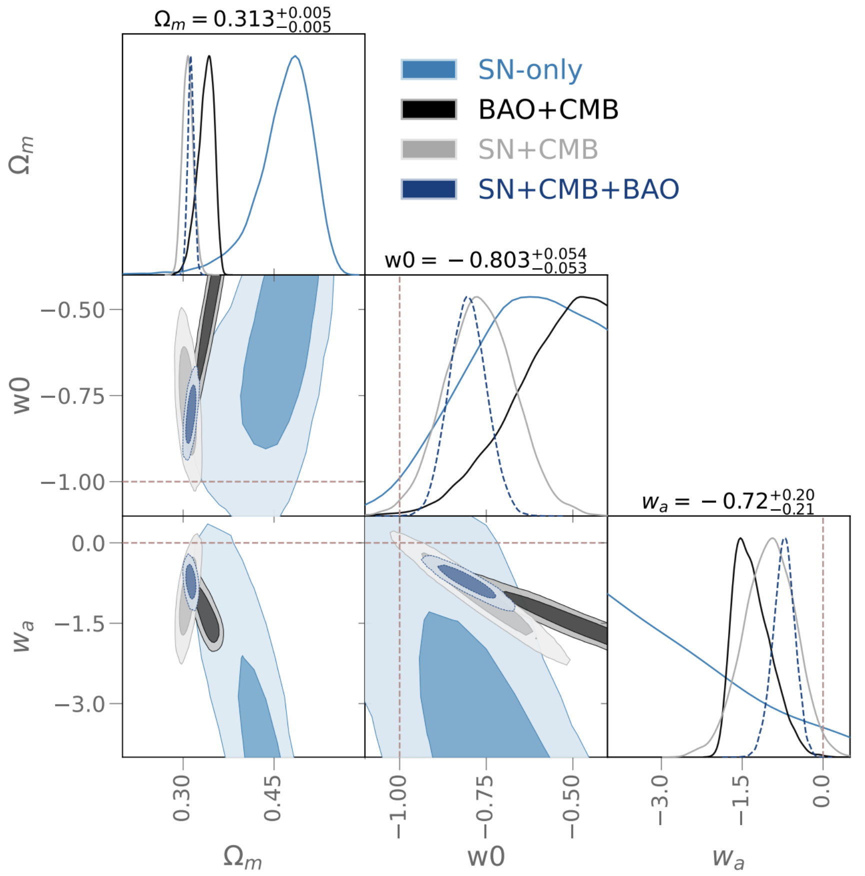
$$E^2(z)=\Omega_M(1+z)^3 + (1-\Omega_M)(1+z)^{3(1+w0+wa)} \exp[-3w_a\, z/(1+z)]$$

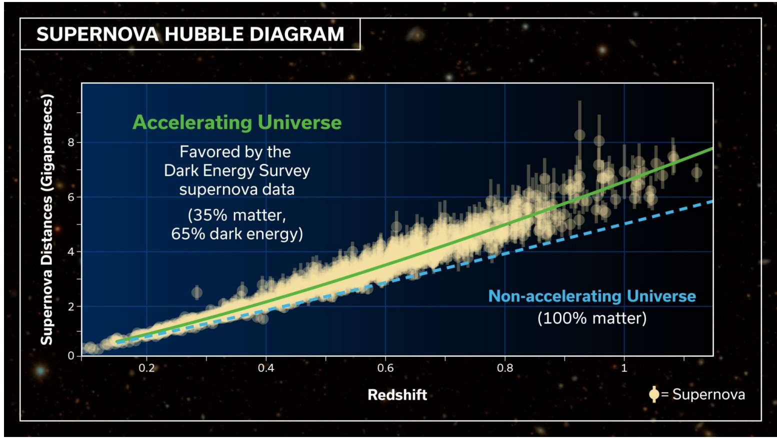
where: $\mathbf{D_L}$ = luminosity, D_M = comoving (transverse) distance; **c** = speed of light; $\mathbf{H_0}$ = Hubble constant, H(z) = Hubble parameter, E = H/H_0; $\mathbf{S_k}$ = curvature function; $\mathbf{\Omega_M}$ = matter density; $\mathbf{w_0}$, $\mathbf{w_a}$ = dark-energy equation-of-state (CPL) params

- SN-only likelihood usually fits M_B/H_0 as one intercept-like nuisance parameter.
- Add Cepheid/TRGB/etc. distances to break the M_B–H_0 degeneracy.
- Add BAO/CMB to break matter-density/dark-energy degeneracies.

Hogg 1999 distance measures; Pantheon+ Brout+2022.

Finally, we fit the model to the Hubble diagram

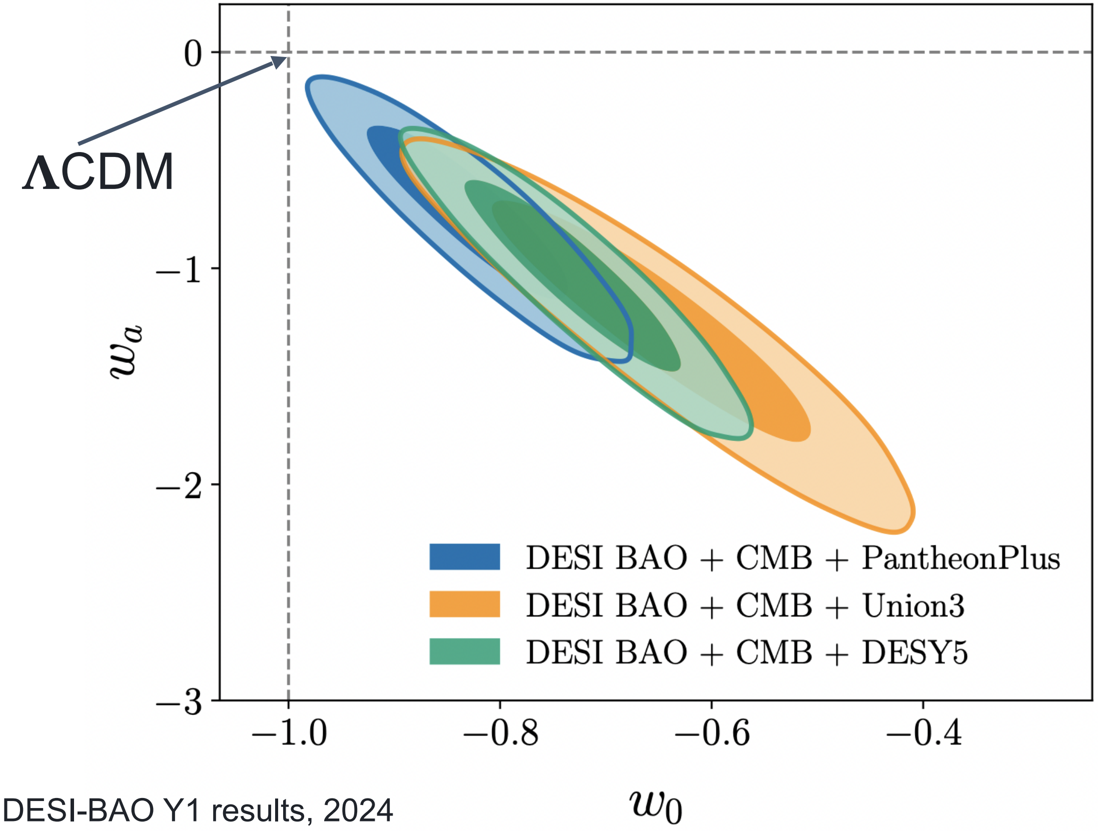




This can be done for several different parameterizations, for different combinations of probes.

	Ω_m	H_0	Ω_k	w_0	w_a	χ^2	$\log \mathcal{Z}$
DES-Dovekie (SN-only)							
Flat-ΛCDM	0.330 ± 0.015	-	-	-	-	1640.3	-822.5
ΛCDM	0.279 ± 0.057	-	0.14 ± 0.15	-	-	1639.5	-822.5
Flat-wCDM	$0.263^{+0.064}_{-0.078}$	-	-	$-0.838^{+0.130}_{-0.142}$	-	1639.0	-823.8
Flat-w_0w_aCDM	$0.473^{+0.035}_{-0.050}$	-	-	$-0.497^{+0.348}_{-0.267}$	$-7.46^{+3.60}_{-4.48}$	1634.2	-823.4
DES-Dovekie + CMB							
Flat-ΛCDM	0.317 ± 0.005	67.29 ± 0.34	-	-	-	2224.1	-1144.4
ΛCDM	0.335 ± 0.012	65.04 ± 1.24	$-0.0063 \pm +0.0037$	-	-	2219.9	-1145.4
Flat-wCDM	0.322 ± 0.008	66.70 ± 0.71	-	-0.978 ± 0.024	-	2223.1	-1147.7
Flat-w_0w_aCDM	0.308 ± 0.009	68.11 ± 0.89	-	-0.769 ± 0.100	-0.98 ± 0.48	2219.5	-1147.0
DES-Dovekie + BAO							
Flat-ΛCDM	0.306 ± 0.008	-	-	-	-	1654.5	-833.2
ΛCDM	0.293 ± 0.011	-	$0.054^{+0.033}_{-0.036}$	-	-	1652.4	-833.3
Flat-wCDM	0.297 ± 0.008	-	-	$-0.909^{+0.035}_{-0.037}$	-	1648.6	-833.5
Flat-w_0w_aCDM	$0.313^{+0.013}_{-0.016}$	-	-	$-0.843^{+0.071}_{-0.065}$	-0.53 ± 0.44	1647.2	-834.3
DES-Dovekie + CMB + BAO							
Flat-ΛCDM	0.304 ± 0.003	68.14 ± 0.23	-	-	-	2244.0	-1155.6
ΛCDM	0.305 ± 0.003	68.57 ± 0.30	0.0026 ± 0.0011	-	-	2238.4	-1156.7
Flat-wCDM	0.305 ± 0.005	68.02 ± 0.53	-	-0.995 ± 0.019	-	2244.5	-1159.6
Flat-w_0w_aCDM	0.313 ± 0.005	67.47 ± 0.55	-	-0.803 ± 0.054	-0.72 ± 0.21	2230.5	-1153.9

Most exciting has been hint of evolving dark energy at 3 sigma (will save more of this for Lecture 2)



DESI-BAO Y1 results, 2024

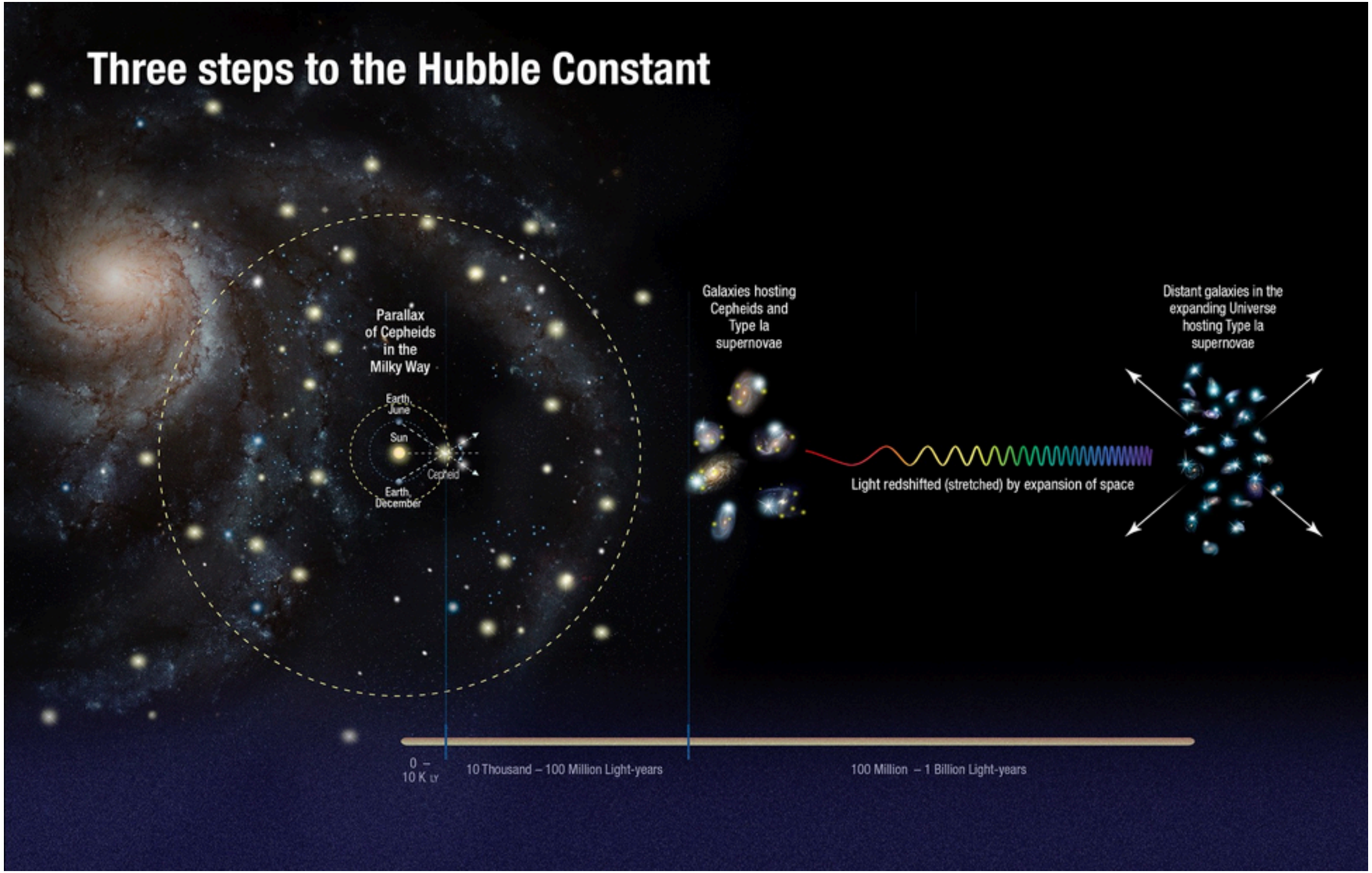
Roadmap: from photons to w or H_0

Main idea:

"Standardizable Candles" can be used to make relative measurements (w, q0, Omega_M) or **absolute measurements (H0)**.

For absolute measurements, the candles need to be calibrated. For relative measurements, they don't.

Roadmap: from photons to w or H_0



H_0 from SNe: calibrate M_B and measure a_B

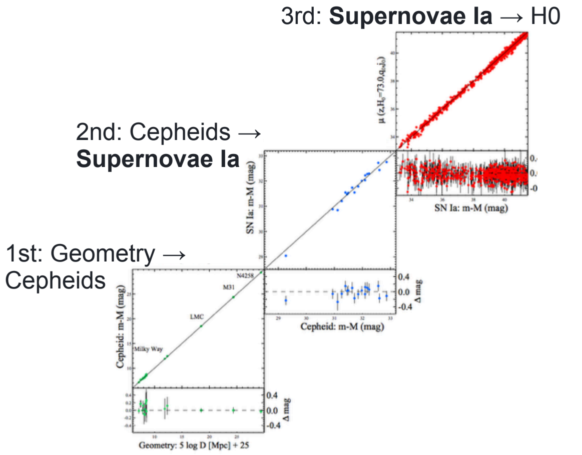
$$m_B^0 = m_B + \alpha x_1 - \beta c + \Delta_M - \Delta_{bias}$$

calibrators: $M_B = m_B^0 - \mu_{anchor}$

Hubble flow: $a_B \equiv \log_{10}(cz) - 0.2\, m_B^0$ + small cosmographic terms

$$\log_{10} H_0 = (M_B + 5a_B + 25) / 5$$

$$H_0 = 10^{(MB + 5aB + 25)/5}$$



- Fainter M_B → larger H_0 (brighter M_B → smaller H_0), for the same Hubble-flow intercept.
- 0.01 mag in M_B corresponds to about 0.46% in H_0.
- This is why distance-ladder work is calibration-limited.

where: $\mathbf{m_B^0}$ = standardized apparent mag; **α, β** = nuisance coeffs, x_1 = stretch, c = color; $\mathbf{\Delta_M}$ = host, Δ_(bias) = bias corrections; $\mathbf{M_B}$ = SN Ia absolute mag; **μ_(anchor)** = anchor distance modulus; $\mathbf{a_B}$ = Hubble-flow intercept; $\mathbf{H_0}$ = Hubble constant

Riess+2022; Pantheon+SH0ES; Betoule+2014 for intercept formalism.

Distance ladder as one simultaneous fit

$$\chi^2_{total} = \chi^2_{anchor} + \chi^2_{Cepheid} + \chi^2_{SNcal} + \chi^2_{SNflow}$$

parameters = { H_0, M_B, M_H^W, b_W, Z_W, μ_{hosts}, α, β, Δ_M, … }

data vector = { parallaxes, DEB μ_{LMC}, maser μ_{4258}, Cepheid m_H^W, SN m_B,x_1,c,z }

- Host distances μ_{hosts} are nuisance parameters that connect Cepheids/TRGB to SNe.
- SN nuisance parameters and survey covariances connect calibrators to the Hubble flow.
- Covariance matters because the same zeropoint can affect anchors, Cepheids, and SN photometry.

where: χ^2 per rung (anchor/Cepheid/SN-cal/SN-flow); $\mathbf{M_H^W}$ = Cepheid Wesenheit absolute mag, b_W = P–L slope, Z_W = metallicity coeff; **μ_(hosts)** = host distance moduli; **μ_(LMC), μ_(4258)** = LMC and NGC 4258 anchor distances; **α, β** = SN nuisance params

Riess+2022; Pantheon+SH0ES data release.

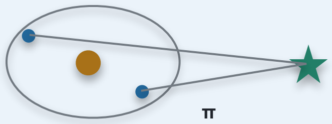
Rung 0: geometric anchors set the absolute distance scale

Parallax, DEBs, and megamasers calibrate the ladder before any standard candle is used.

Parallax

Earth's 1 AU orbit makes nearby stars shift against background sources.

$d(\text{pc}) = 1 / \pi(\text{arcsec})$



- MW Cepheid anchor
- Gaia zero point, crowding
- Precision falls as π shrinks

Detached eclipsing binaries

Eclipses + radial velocities give binary geometry, radii, and temperatures.

$D = R / \theta \quad \mu = m - M$

eclipse + velocity curves

- LMC anchor for Cepheids
- Extinction, limb darkening
- Surface-brightness/color relation

H_2O megamasers

VLBI maps a rotating nuclear disk; velocities and accelerations give a radius.

$D = r/\theta = v^2/(a\theta)$

angular disk + v + a

- NGC 4258 anchor
- Disk warp and geometry
- Velocities + acceleration drifts

Anchor shifts propagate directly: $\delta H_0/H_0 \approx -\delta D\_anchor/D\_anchor$

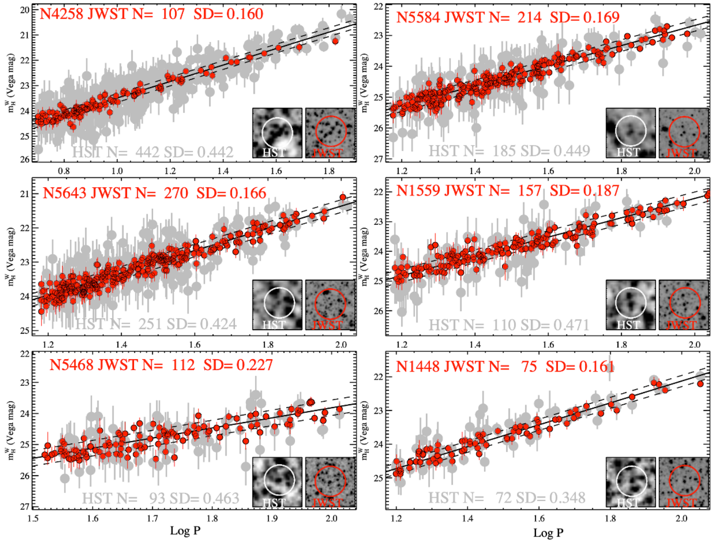
Different geometries mean different systematics, which is why anchor agreement is powerful.

Rung 1+2: Cepheids, the classical primary rung

$$m^{W}_{H,i,j} = \mu_j + M_H^{W} + b_W (\log P_{i,j} - 1) + Z_W [O/H]_{i,j}$$

Wesenheit magnitude: $m_H^{W} = m_H - R\,(V - I)$

μ_{SN} host $\leftarrow$ fit Cepheids in same host galaxy as SN Ia

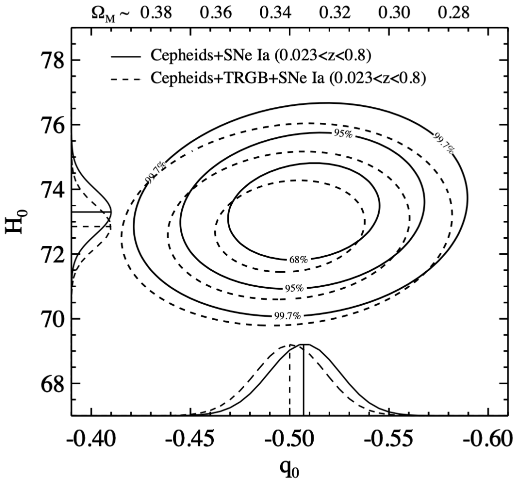


- Advantages: bright, high precision, same instruments/filters can connect anchors and SN hosts.
- Systematics: crowding/blending, metallicity, dust law, period cuts, PL nonlinearity, Gaia parallax zeropoint.
- Young-star indicator: Cepheid hosts can differ from early-type SN hosts.

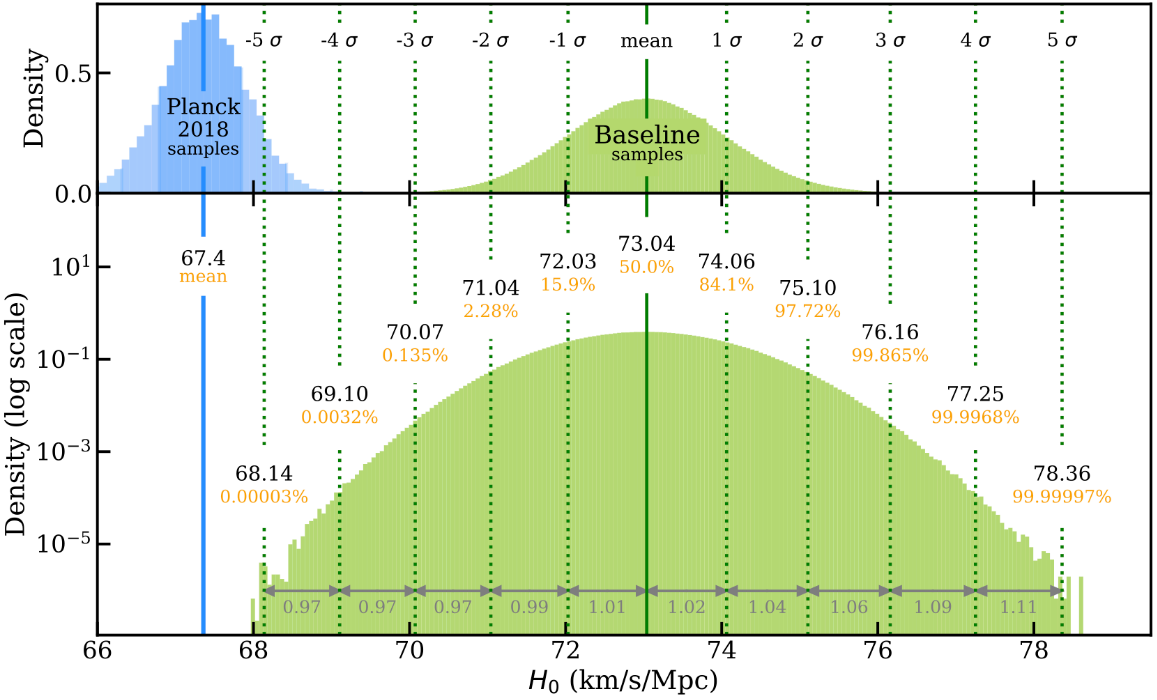
where: $\mathbf{m_H^{W}}$ = Wesenheit apparent, M_H^{W} = absolute H mag; $\boldsymbol{\mu_j}$ = host distance modulus; $\mathbf{b_W}$ = P–L (Leavitt) slope, P = period; $\mathbf{Z_W}$ = metallicity coeff, [O/H] = metallicity; **R** = reddening ratio, (V−I) = color

Riess+2022; Breuval+2022; SH0ES.

Pantheon+SH0ES simultaneously fit for H0 and q0, didn't change H0 much



H_0=73.30 +/- 1.04=

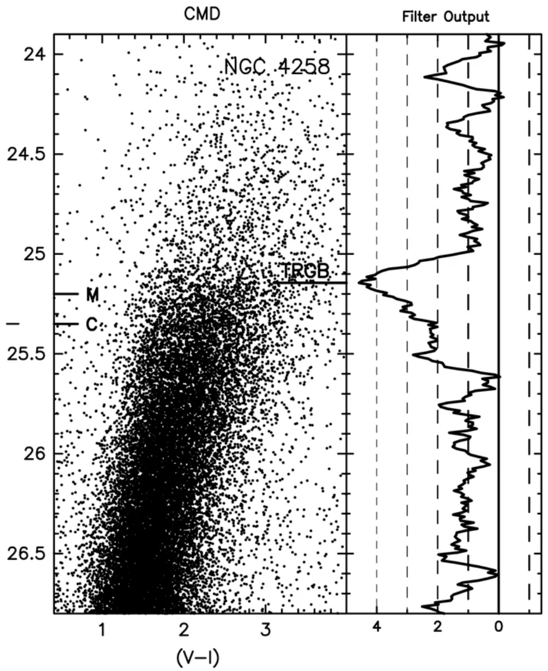


Rung 1+2: TRGB, a Population II primary rung

$$\mu_j = m^{TRGB}_{I,j} - M^{TRGB}_{I} - A_{I,j} - C[(V-I)_j - (V-I)_0]$$

edge detector: $E(m) \approx \Phi(m+\sigma_m) - \Phi(m-\sigma_m)$

calibrators: TRGB in SN hosts → M_B(SN Ia)



- Advantages: old stars, low dust in halos, independent of Cepheid young-population effects.
- Systematics: edge detection, population/color corrections, AGB contamination, halo selection, crowding, zero point.
- JWST improves reach and crowding but adds calibration/filter transformations.

where: m_(TRGB) = tip apparent (I) mag, M_(TRGB) = absolute; **A** = extinction; **C** = color-correction slope, $(V-I)_0$ = reference color; **E(m)** = edge response, Φ = Gaussian kernel, σ_m = photometric error; $\mathbf{M_B}$ = SN Ia absolute mag

Freedman+2019; Freedman+2024; Scolnic+2023 CATS.

Rung 1+2: JAGB and Miras: infrared alternatives

Miras: $M_\lambda = a_\lambda\,[\log P - \log P_0] + b_\lambda + c_\lambda\,[\text{color}] + \ldots$

JAGB: $\mu = m_J^{JAGB} - M_J^{JAGB} - A_J -$ population terms

Infrared advantage: $A_\lambda \downarrow$, crowding/stellar-population modeling $\uparrow$

- Miras: long-period AGB variables; useful in older populations and infrared surveys.
- JAGB: carbon-rich AGB stars with a narrow near-IR luminosity range.
- Current role: cross-check Cepheids/TRGB and potentially increase the number of SN calibrator hosts.

where: $\mathbf{M_\lambda}$ = absolute mag at band λ; **P** = period, P_0 = reference period; $\mathbf{a_\lambda, b_\lambda, c_\lambda}$ = P–L fit coefficients; $\mathbf{m_J, M_J}$ = JAGB apparent/absolute J mag; $\mathbf{A_\lambda, A_J}$ = extinction; **μ** = distance modulus

Miras: Huang 2024; JAGB/TRGB: Freedman+2024.

Galaxy-scale candles and rulers used in the ladder

SBF: $\bar{m} = \bar{M}(\text{population, color}) + \mu$

Tully–Fisher: $M = a\,[\log W - 2.5] + b + \gamma\ \text{color} + \ldots$

Fundamental Plane: $\log R_e = a \log \sigma + b \log \langle I \rangle_e + c$

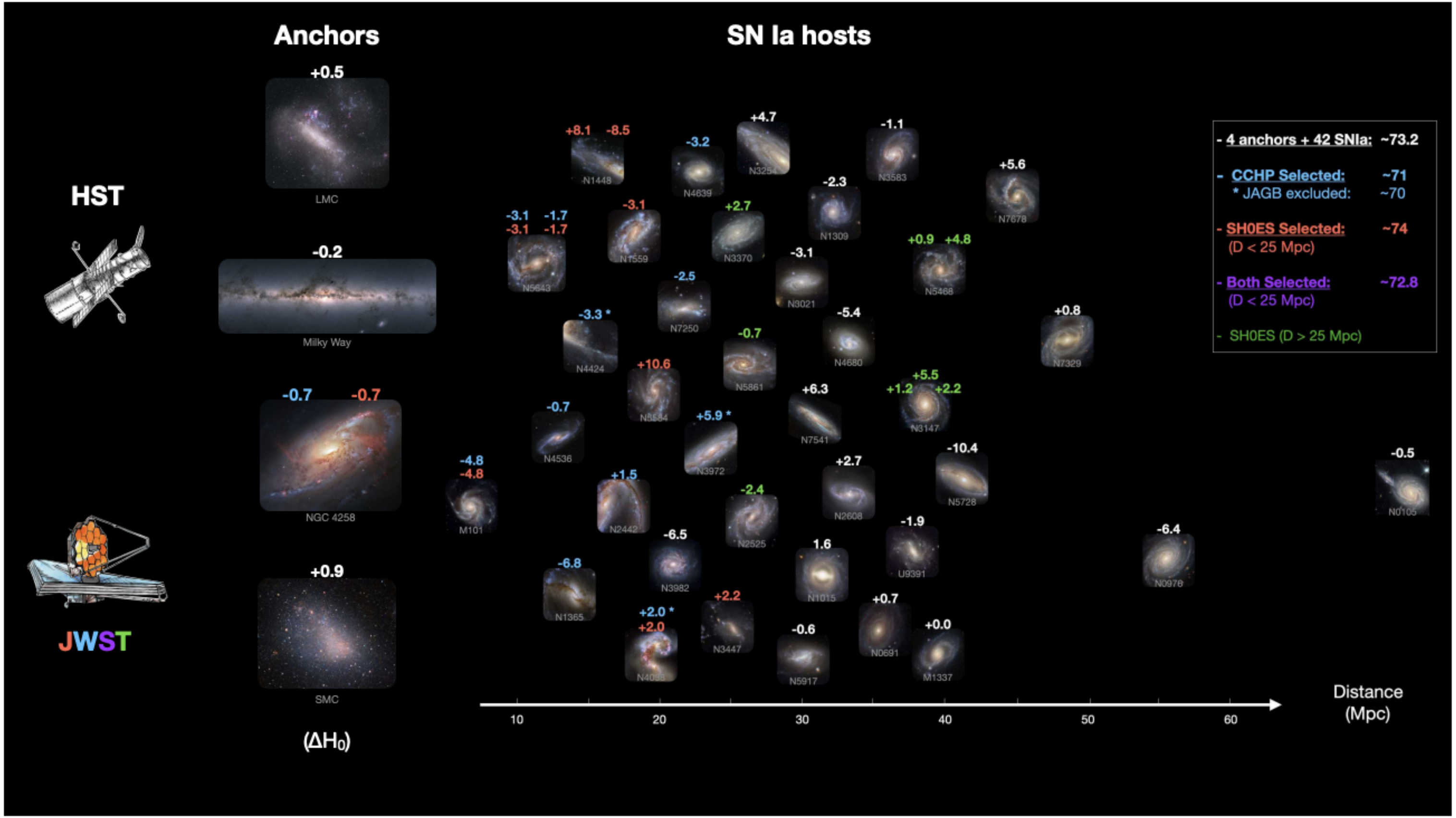
SN II SCM: $M = m - \mu = a \log(v_{ph}) + b\ \text{color} + c$

- SBF works best in smooth early-type galaxies and can reach farther than TRGB for some samples.
- TF/FP use whole-galaxy dynamics/structure; large samples help average peculiar velocities.
- SN II distances are physically different from SN Ia and are an emerging independent check.

where: SBF $\bar{m}$, $\bar{M}$ = apparent/absolute fluctuation mag; **W** = H I line width (TF); **R_e** = effective radius, σ = velocity dispersion, $\langle I \rangle_e$ = mean surface brightness (FP); **v_(ph)** = SN II photospheric velocity; **a, b, c, γ** = fit coefficients

SBF: Blakeslee+2021; Garnavich+2022; TF: Boubel+2024, Scolnic+2024.

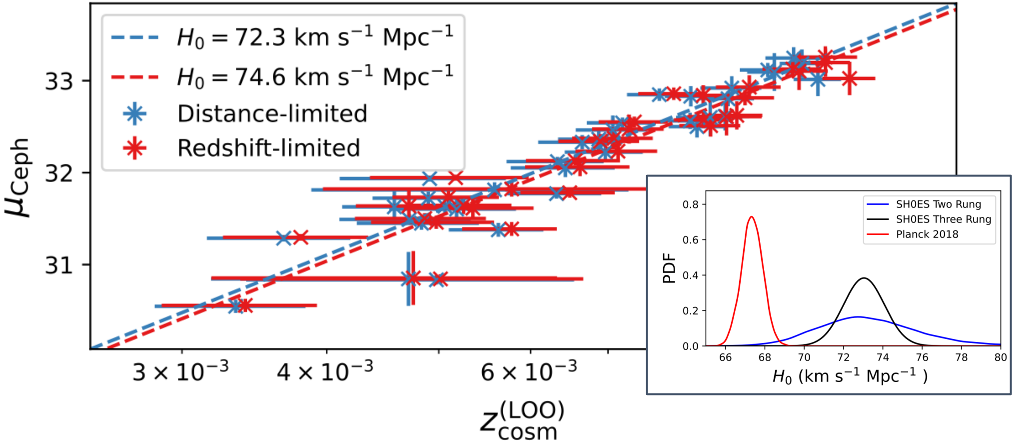
Different anchors offer independent path to H0; the more SN hosts, the better precision (and usually accuracy)



Why do we need a 3rd rung? To get into the Hubble Flow

2-Rung Distance Ladder
(*Kenworthy ea*) arXiv:2204.10866

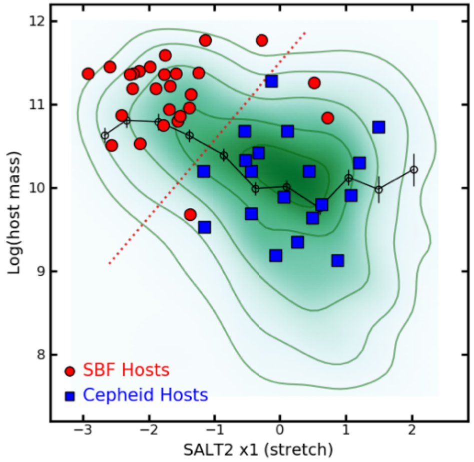
$$H_0 = 73.1^{+2.6}_{-2.3}$$



Geometry→Cepheids
Dominated by peculiar velocities and Cepheid host-z selection

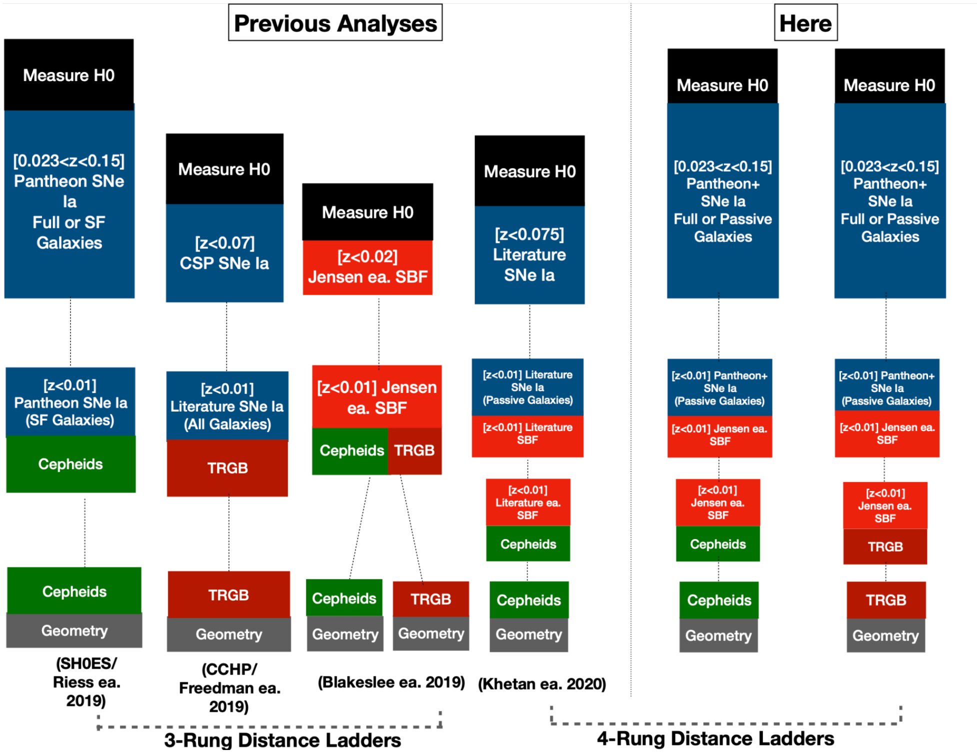
4-Rung Distance Ladder
(*Garnavich ea*) arXiv:2204.12060

$$H_0 = 74.6 \pm 0.9(\text{stat}) \pm 2.7(\text{syst})$$



Geometry→Cepheids or TRGB→SBF→Pantheon+ SNeIa

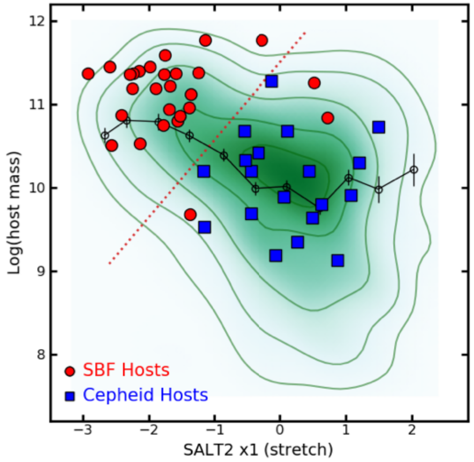
Do more rungs help? Yes and no, can use different populations, but add complexity.



4-Rung Distance Ladder

(*Garnavich ea*) arXiv:2204.12060

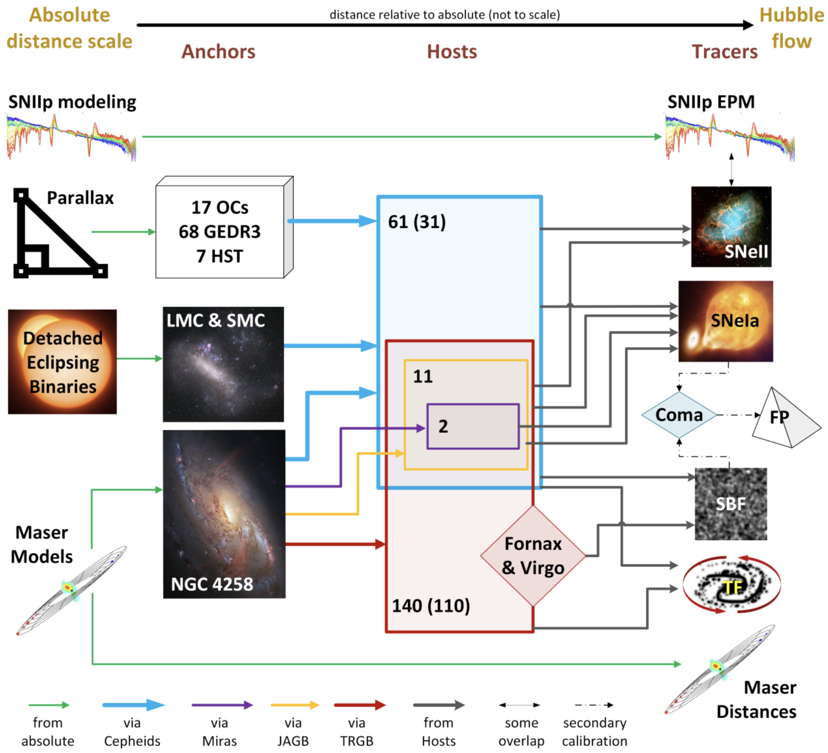
$$H_0 = 74.6 \pm 0.9(\text{stat}) \pm 2.7(\text{syst})$$



Geometry→Cepheids or TRGB→SBF→Pantheon+ SNeIa

Baseline network: what goes into the consensus H_0

Baseline uses Cepheids + TRGB host distances, SNe Ia + SBF + megamasers as tracers.



Headline result

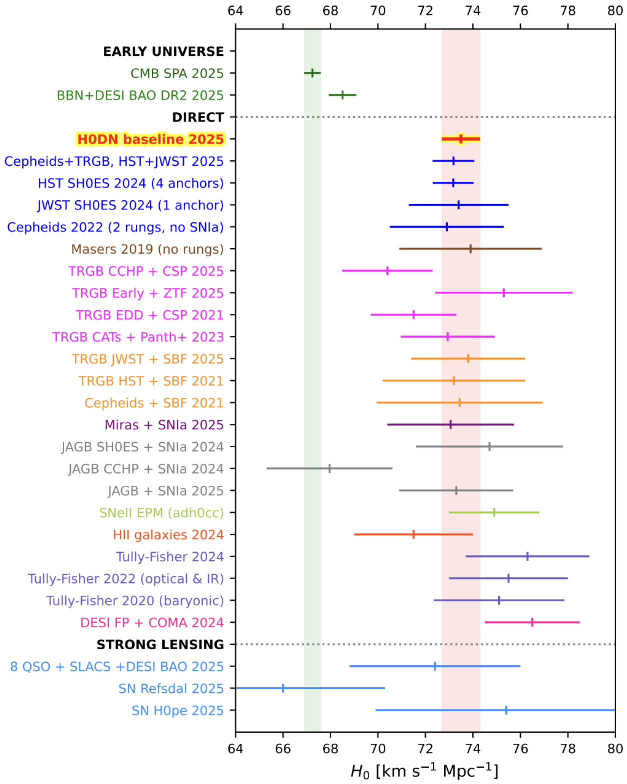
H_0 = 73.50 ± 0.81 km s^{-1} Mpc^{-1}
relative precision ≈ 1.1%
early-Universe ΛCDM comparison: 67.24 ± 0.35
tension quoted in paper: 7.1σ

where: $\mathbf{H_0}$ = Hubble constant (km s^{-1} Mpc^{-1}); **±** = 1σ; **ΛCDM** = standard cosmological model; **7.1σ** = tension significance

Source: H0DN Collaboration, A&A 708, A166 (2026), figures reproduced from the public A&A/ePrint PDF. Fig. 3; Eq. 1

Baseline network: what goes into the consensus H_0

Baseline uses Cepheids + TRGB host distances, SNe Ia + SBF + megamasers as tracers.



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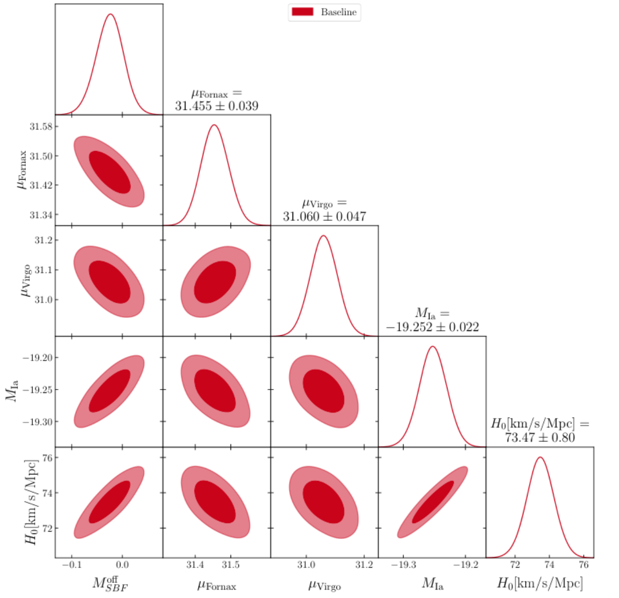
Source: H0DN Collaboration, A&A 708, A166 (2026), figures reproduced from the public A&A/ePrint PDF. Fig. 3; Eq. 1

The result is limited by correlated parameters

Corner plots are useful for teaching what the ladder is actually solving for.



orner plot for the baseline solution illustrating the corre
H_0, the calibration of SNe Ia and SBF, and the dista
nd Virgo, which contribute to the SBF calibration. The p
the naming convention of Appendix B.3.1. Deviation
tically calculated result are due to the numerical precisi
gth chain.

Fit machinery

Example parameter block:

$\theta = \{H_0, M_{Ia}, M_{SBF}, \mu_{Virgo}, \mu_{Fornax}, \ldots\}$

Linear-Gaussian solution:

$\hat{\theta} = (A^T C^{-1} A)^{-1} A^T C^{-1} y$

$\mathrm{Cov}(\hat{\theta}) = (A^T C^{-1} A)^{-1}$

where: **θ** = fit parameters, θ̂ = best-fit estimate; **A** = design matrix, C = covariance, y = data vector; $\mathbf{M_{Ia}}$, $\mathbf{M_{SBF}}$ = SN Ia/SBF abs mag; **μ_(Virgo), μ_(Fornax)** = cluster distances

M_{Ia} anti-correlates with H_0: a brighter calibrated SN absolute magnitude implies a larger inferred H_0.

Cluster distances matter because they calibrate galaxy-based tracers such as SBF.

Source: H0DN Collaboration, A&A 708, A166 (2026), figures reproduced from the public A&A/ePrint PDF. Fig. 6

Takeaways from the 2026 H0DN consensus view

The clean modern language is a covariance-weighted distance network, not isolated ladders.
SNe Ia remain the highest-precision bridge to the smooth Hubble flow.
Cepheids, TRGB, anchors, and galaxy-based tracers are cross-checks as much as inputs.
Systematics are best exposed by leave-one-out variants, instrument variants, redshift-window variants, and independent path splits.
For a summer-school project: reproduce one rung, then add covariance terms one by one and watch H_0 move.

Exercise bridge

Minimal network exercise:
1. Fit a_B from Hubble-flow SNe
2. Fit M_{Ia} from calibrated hosts
3. Combine: $\log_{10}H_0 = (M_B + 5a_B + 25)/5$
4. Add shared-anchor covariance C_{anchor}

where: $\mathbf{M_B}$ = SN Ia absolute mag; $\mathbf{a_B}$ = Hubble-flow intercept; **C_(anchor)** = shared-anchor covariance; $\mathbf{H_0}$ = Hubble constant

Source: H0DN Collaboration, A&A 708, A166 (2026), figures reproduced from the public A&A/ePrint PDF.

What the Hubble tension is, and is not

Early Universe: CMB + ΛCDM → $H_0 \approx 67\text{–}68$

Late Universe: geometry + candles + Hubble flow → $H_0 \approx 69\text{–}77+$

Difference in μ equivalent: $\Delta\mu = 5 \log_{10}(H_0,\text{high} / H_0,\text{low})$

73.0 vs 67.4 → $\Delta\mu \approx 0.17$ mag

- Not a single-object anomaly: it is a coherent distance-scale comparison.
- Not directly solved by changing SN cosmology alone: H_0 needs an absolute anchor.
- New physics explanations generally modify early expansion, recombination, or late-time distances.
- Astrophysical explanations need to produce coherent ~0.1–0.2 mag shifts without failing cross-checks.

where: $\mathbf{H_0}$ = Hubble constant (km s^{-1} Mpc^{-1}); **Δμ** = distance-modulus difference equivalent to the low-vs-high H_0 gap

Riess+2022; Planck 2018; ACT DR6 2025; Freedman+2024.

Summary: the five equations to remember

1. $\mu = m - M = 5\log_{10}(D_L/\mathrm{Mpc})+25$

2. $\mu_{SN} = m_B - M_B + \alpha x_1 - \beta c + \Delta_{host} - \Delta_{bias}$

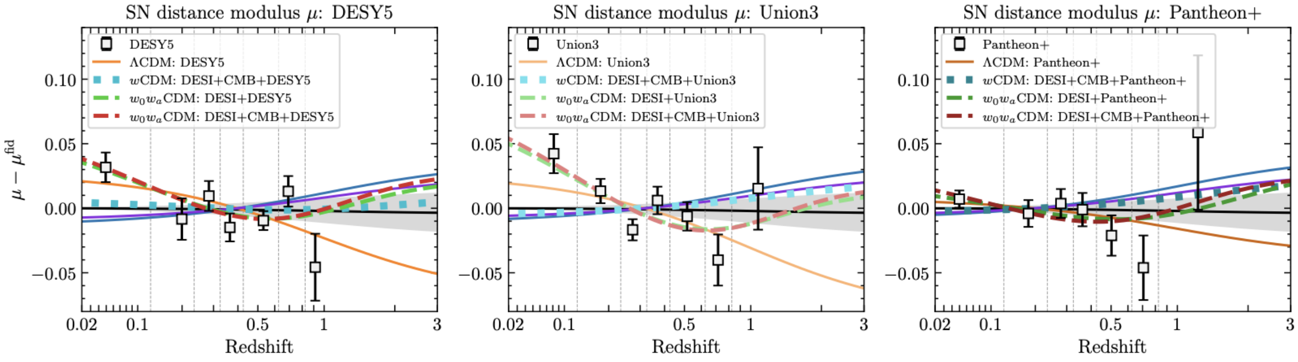
3. $D_L(z) = (1+z)(c/H_0)\, S_k[\int dz'/E(z')]$

4. $m_H{}^W = \mu + M_H{}^W + b(\log P - 1) + Z[O/H]$

5. $\log_{10}H_0 = (M_B + 5a_B + 25)/5$

where: **μ** = distance modulus, D_L = luminosity distance; **m_B/M_B** = SN Ia apparent/absolute mag, α/β = nuisance coeffs, x_1 = stretch, c = color; **a_B** = Hubble-flow intercept; **$m_H{}^W/M_H{}^W$** = Cepheid Wesenheit mags, b = P–L slope, Z = metallicity coeff, P = period

So far I have discussed two ‘tensions’, unfortunately the Evolving Dark Energy signal makes Hubble Tension bigger!



Model/Dataset	$\Omega_{\rm m}$	H_0 [km s^{-1} Mpc^{-1}]
$\boldsymbol{w_0w_a}$**CDM+**$\boldsymbol{\sum m_\nu}$		
DESI BAO+CMB	0.353 ± 0.022	$63.7^{+1.7}_{-2.2}$
DESI BAO+CMB+Pantheon+	0.3109 ± 0.0057	67.54 ± 0.59
DESI BAO+CMB+Union3	0.3269 ± 0.0088	65.96 ± 0.84
DESI BAO+CMB+DESY5	0.3188 ± 0.0058	66.75 ± 0.56

Get ready for part 2 on Wednesday!

Selected references for students

- SN standardization/cosmology: Betoule et al. 2014; Scolnic et al. 2022; Brout et al. 2022; Abbott et al. 2024; Vincenzi et al. 2024.
- Cepheid distance ladder: Riess et al. 2022; SH0ES/Pantheon+ public release.
- TRGB/JAGB: Freedman et al. 2019; Scolnic et al. 2023 CATS; Freedman et al. 2024/2025.
- Miras: Huang 2024 “The Mira Distance Ladder.”
- SBF and TF: Blakeslee et al. 2021; Garnavich et al. 2022; Boubel et al. 2024; Scolnic et al. 2024.
- Early-Universe comparison: Planck Collaboration 2020; ACT DR6 2025.