The Cosmic Distance Scale

Lecture 1

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Acknowledgments

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  - Mónica Taormina (CAMK)

Introduction

- Over the next four days, I plan to present an in-depth overview of the Cosmological Distance Ladder
- I organized this mini-course as follows:

[1] Introduction & Motivation

[1] 1st rung: geometric distances

[2] 2nd rung: standard(izable) candles

[3] 3rd rung: into the Hubble Flow

[3] Alternative distance methods

[4] The Hubble Tension

[4] Future prospects

Organization

- Most slides will have citations to papers on the bottom right
- The full list of cited papers is here: NASA ADS link
- Please feel free to stop me and ask questions at any time!

Citations will appear here

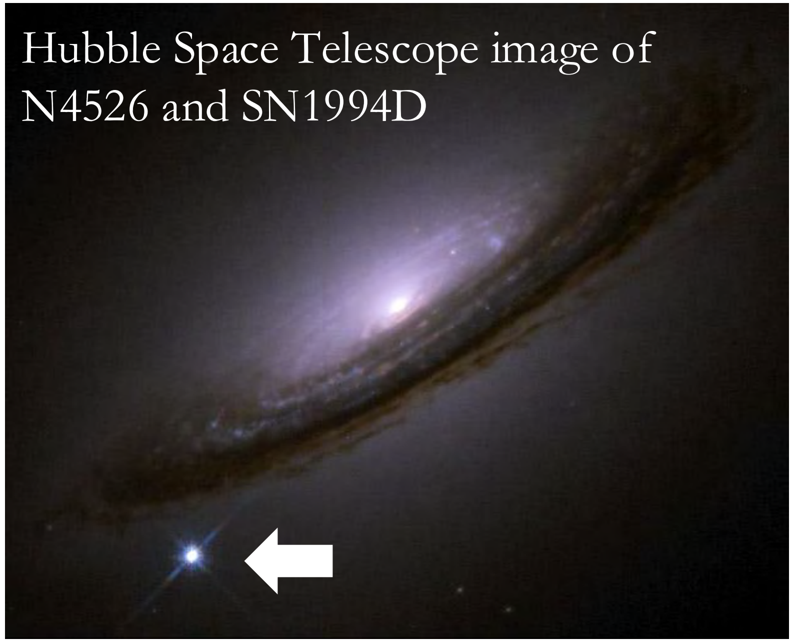
Introduction

- How do we measure cosmological distances?
- What can measurements based on different methods tell us about the cosmological model?
- Let us start by considering two types of “observables” that give strong evidence that we live in an expanding Universe

Evidence for an expanding Universe

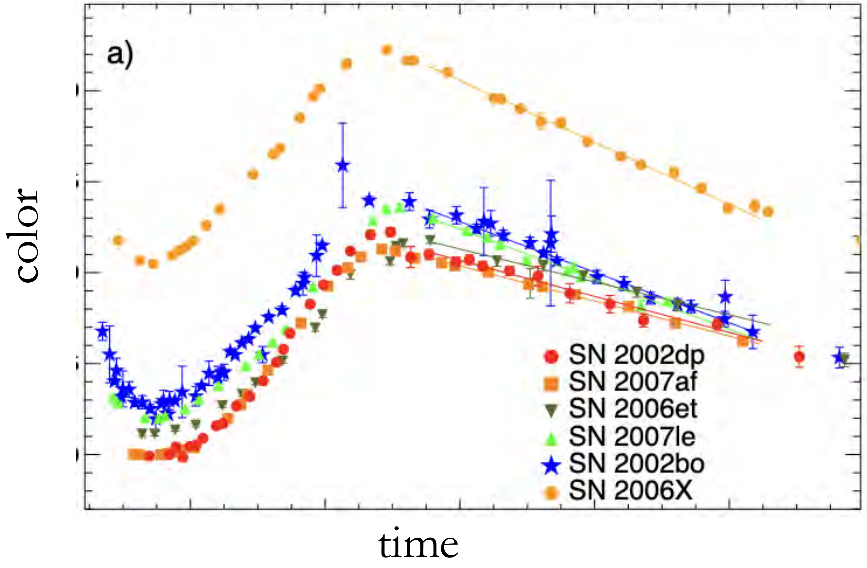
- Suppose you repeatedly image large areas of the sky for several years and discover a set of transients
- Some are fainter than others, but they share many similar characteristics…

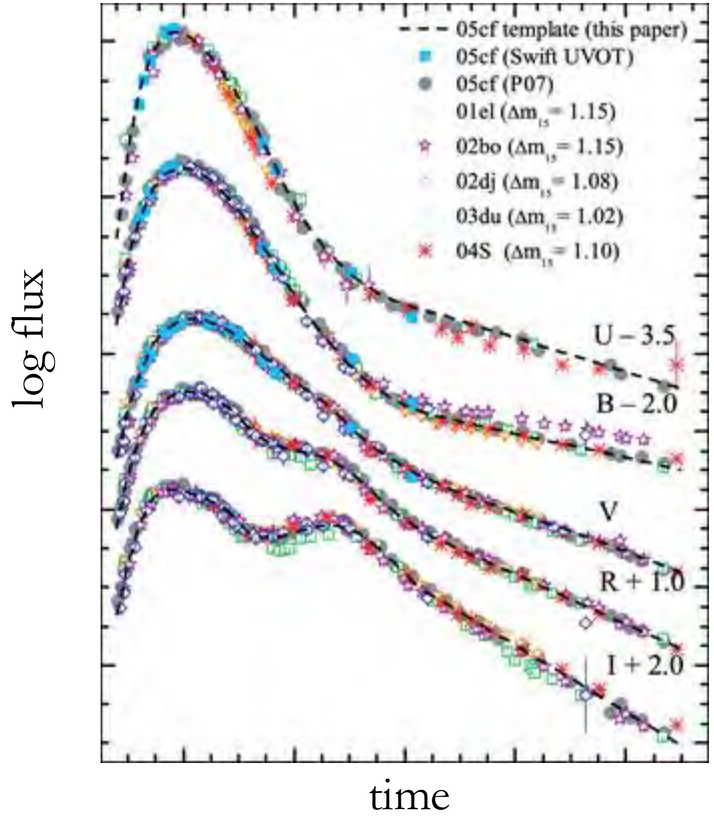

Pan-STARRS telescope, Haleakala, Hawai'i


Hubble Space Telescope image of N4526 and SN1994D

Evidence for an expanding Universe

- This set of transients shows a rapid rise over ~2 weeks, followed by a slower decline; similar color evolution
- Could these be the same type of object, seen at different distances?

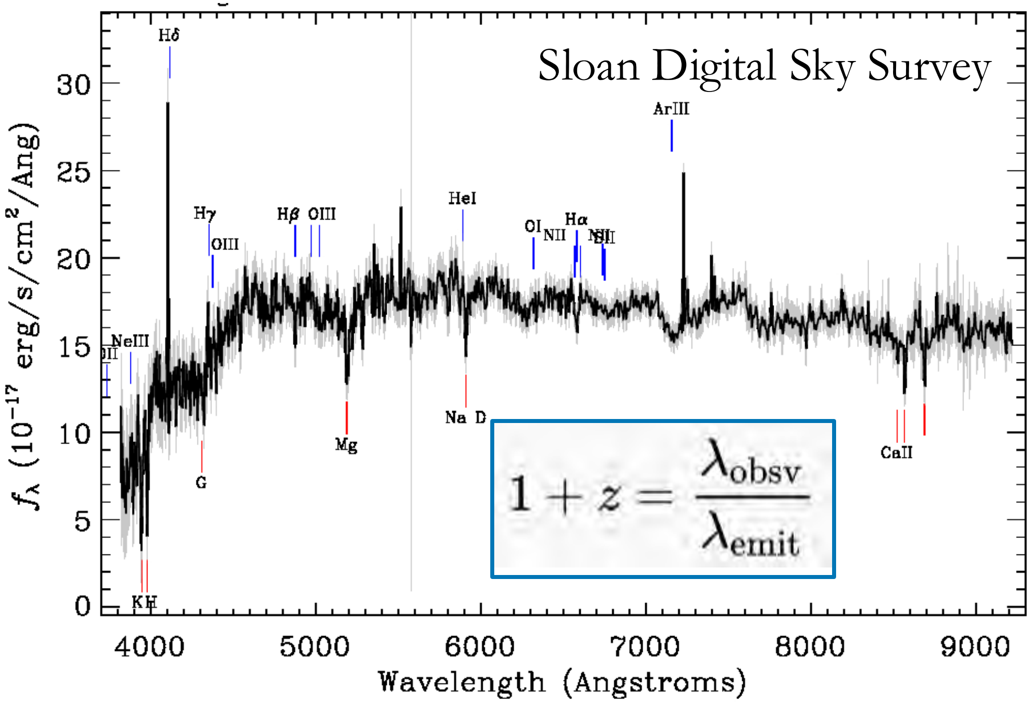




Wang+ (2009); Forster+ (2013)

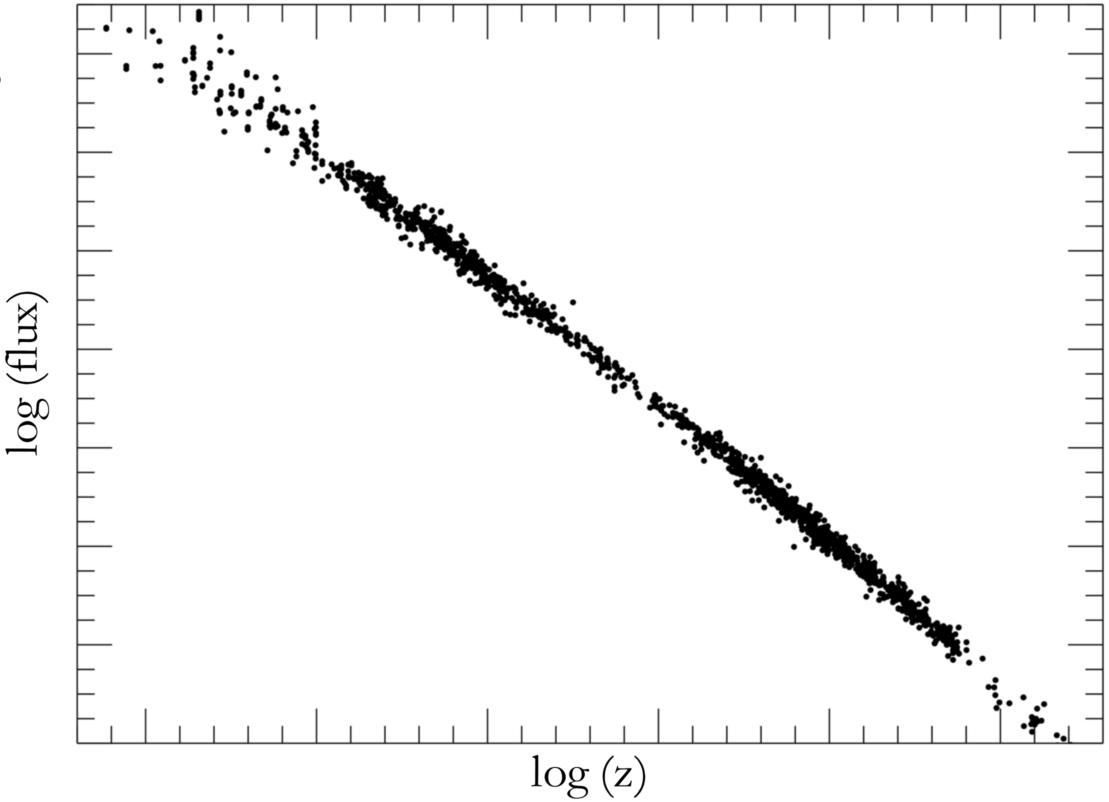
Evidence for an expanding Universe

- Take spectra of the hosts of these transients and you'll notice similar features, although at different wavelengths and consistently shifted to the red of laboratory values…



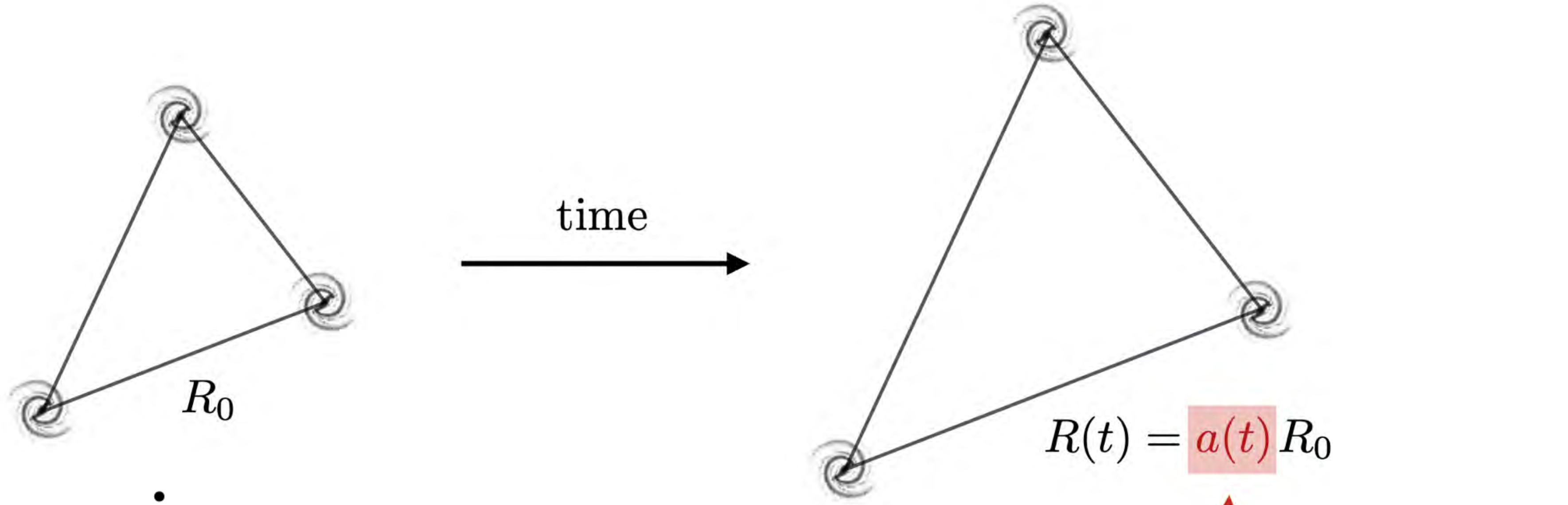
Evidence for an expanding Universe

- Repeat 1700 times, carefully cross-calibrating images and spectra from multiple telescopes (Brout+2022; Scolnic+2022)…
- Fainter transients appear in hosts that have larger values of z
- Very tight correlation between log (flux) and log (z)
  - Across 10^5 range in flux
  - Slope ~2 (inverse sq law!)
  - Scatter $\lesssim$ 9% in log(flux)



Evidence for an expanding Universe

- Under General Relativity, this correlation can be interpreted as being due to the expansion of space

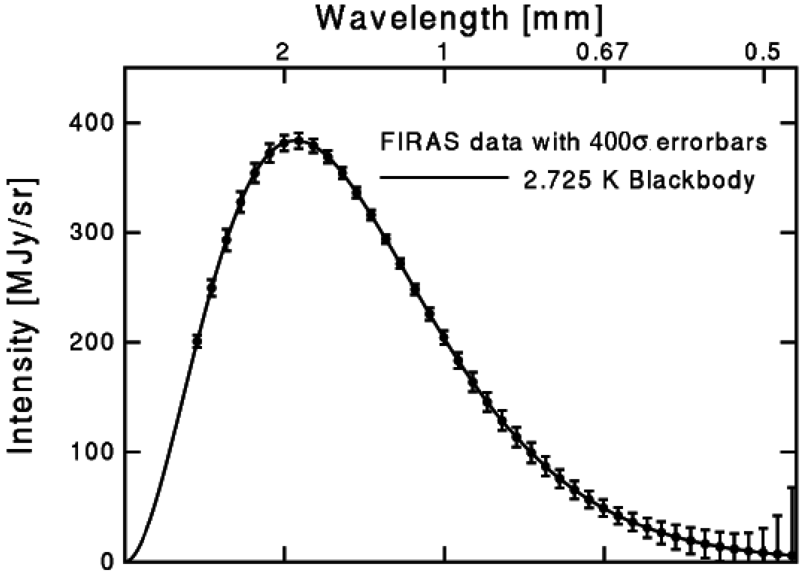


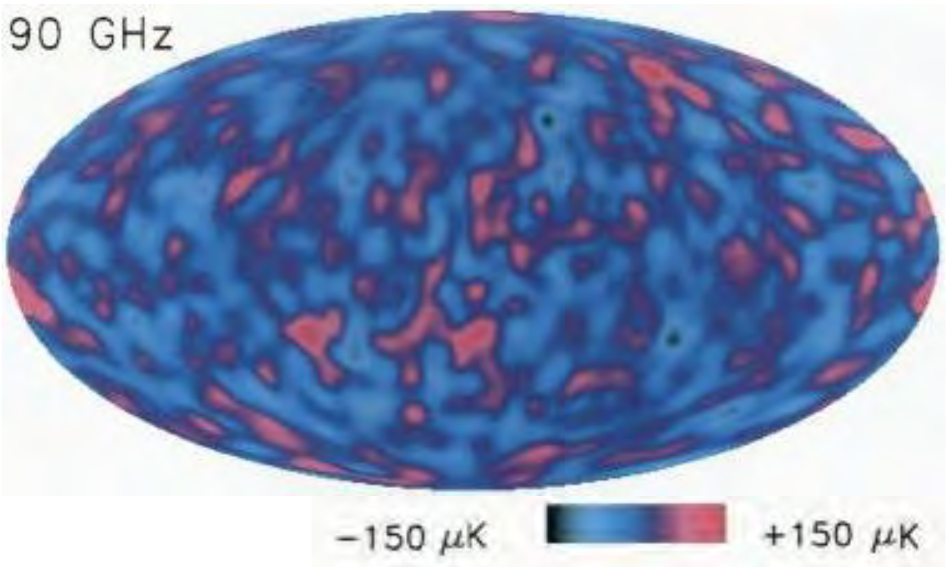
$$cz \equiv \dot{R} = \frac{\dot{a}}{a} R \equiv \mathrm{H}_0 R$$

Credit: Dr. D. Baumann

Evidence for an expanding Universe

- If the Universe is undergoing expansion, a(t) must have been smaller in the past → hotter/denser conditions
- Detect very smooth blackbody radiation from those early times: the Cosmic Microwave Background (CMB)





Mather+ (1994); Bennet+ (1994)

Evidence for an expanding Universe

- So, two very different types of observations show conclusive evidence of an expanding Universe
- Those transients are, of course, the well-known "Type Ia" supernovae (SNe Ia)
- SNe Ia are an excellent example of standard*izable* candles (more on that later)
- The very small amplitude of temperature fluctuations in the CMB tells us the Universe was very homogeneous and isotropic at early times

The Friedmann Equations

- The expansion of a homogeneous and isotropic Universe can be described by a Friedmann-Lemaître-Robertson-Walker cosmology, using parameters that describe:
  - Expansion rate, or Hubble constant:
    - a: scale factor (today = 1; Big Bang = 0)

$$H = \frac{\dot{a}}{a}$$

  - Global geometry (open, flat or closed)
  - Composition of the Universe
    - Density of atomic & dark matter, photons, neutrinos, etc.
- These parameters are related via the Friedmann equations, a solution of Einstein's General Relativity field equations

The Friedmann Equations

- These equations allow us to calculate the value of the Hubble parameter for any z, relative to the present value (H_0)

$$\frac{H^2(z)}{H_0^2} = \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_\phi(1+z)^{3(1+w)}$$

$$H = \frac{\dot{a}}{a}$$

$$\Omega_m(z) \equiv \frac{\rho_m(z)}{\rho_{\rm crit}(z)}$$

$$\rho_{\rm crit} = \frac{3H_0^2}{8\pi G}$$

$$(1+z) \equiv a^{-1}$$

$\wedge_m$: matter (baryonic+dark)

$\wedge_r$: relativistic species

$\wedge_k$: curvature

$\wedge_\Phi$: fluid

The Friedmann Equations

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$$\frac{H^2(z)}{H_0^2} = \Omega_m(1+z)^3 + \Omega_r(1+z)^4 + \Omega_k(1+z)^2 + \Omega_\phi\,(1+z)^{3(1+w)}$$

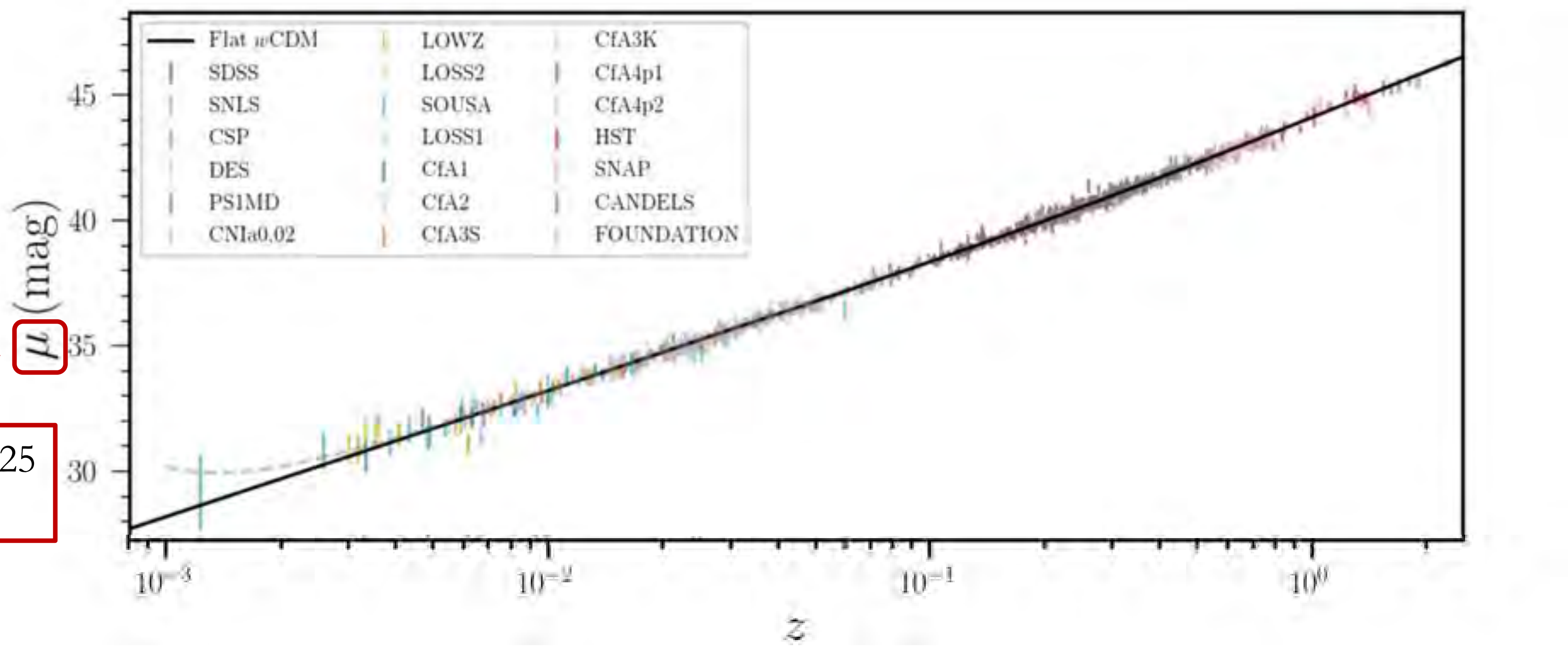
- Equation of state parameter: $P = w\rangle c^2$
- If w=-1, then we have a fluid with time-independent density, known as "dark energy" or the "cosmological constant": Ω_Λ

Cosmological probes

- In order to measure the parameters in the Friedmann equation, we need to probe the expansion history of the Universe at different redshifts
- We can do this with standardizable candles such as SNe Ia
- The power spectrum of CMB anisotropies also yields critical constraints on certain parameters or combination of parameters
- As we will see, it is critical to use multiple "cosmological probes" to cross-check results and break degeneracies

Hubble diagram of Type Ia SNe

- Using only the relative fluxes (magnitudes) of SNe Ia, we can trace the expansion history and detect the effect of dark energy



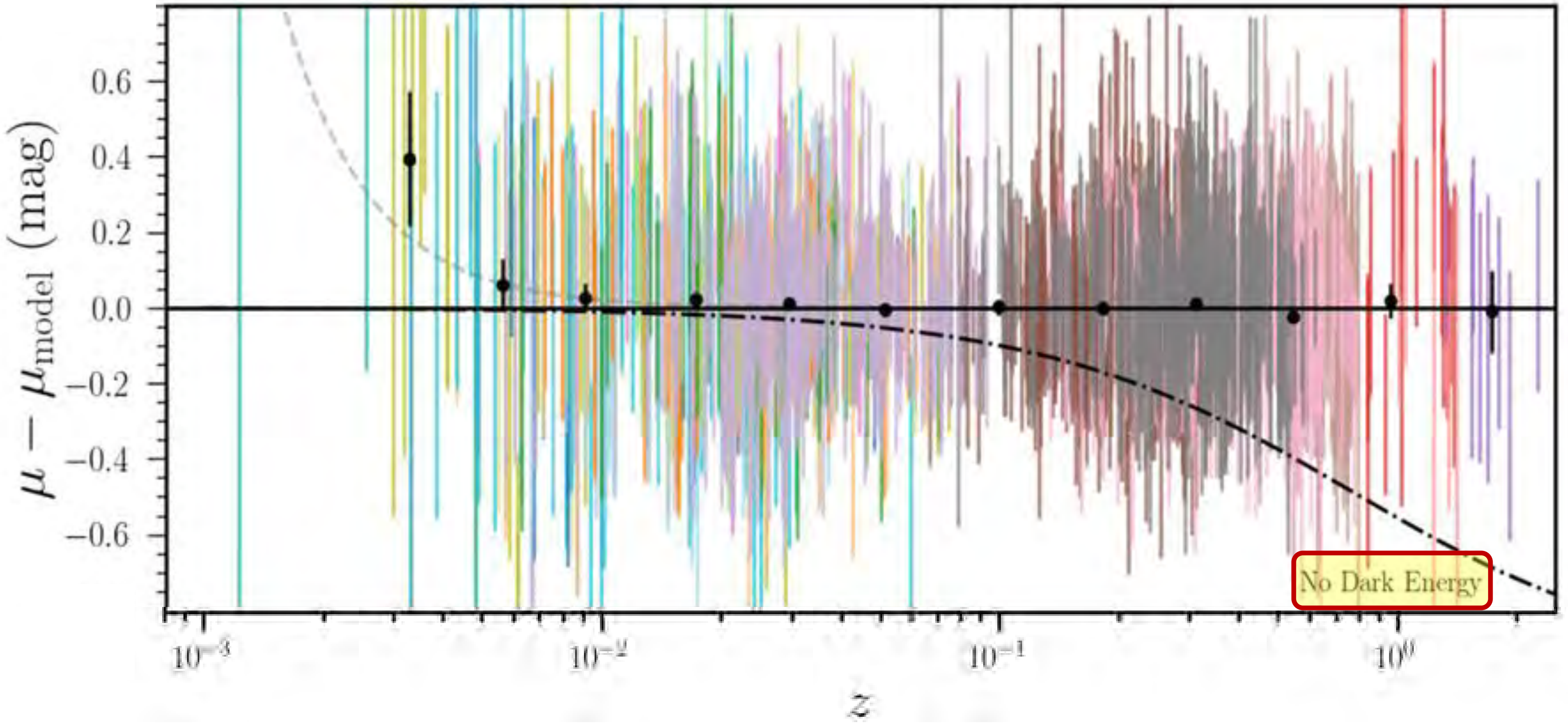
$\mu = 5 \log D\ (\mathrm{Mpc}) + 25$

$\mu = m - M$

Brout+(2022)

Hubble diagram of Type Ia SNe

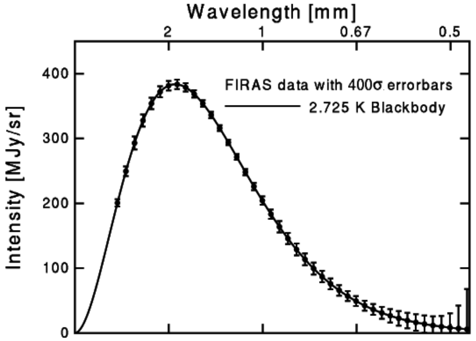
- Using only the relative fluxes (magnitudes) of SNe Ia, we can trace the expansion history and detect the effect of dark energy

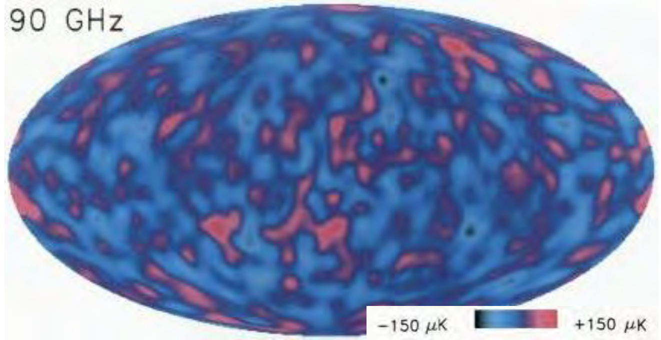


Brout+(2022)

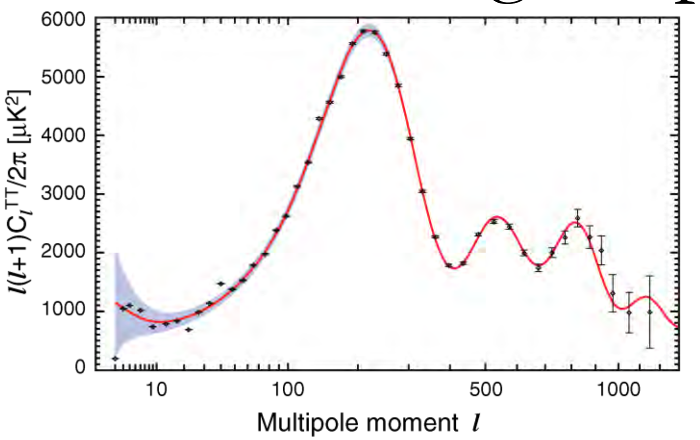
From the CMB to cosmological parameters

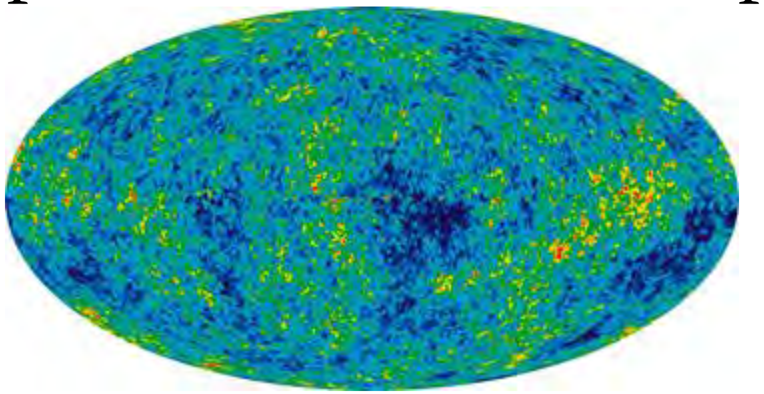
- 1994: COBE → CMB blackbody & detection of anisotropy





- 2002: WMAP → angular power spectrum of T anisotropies

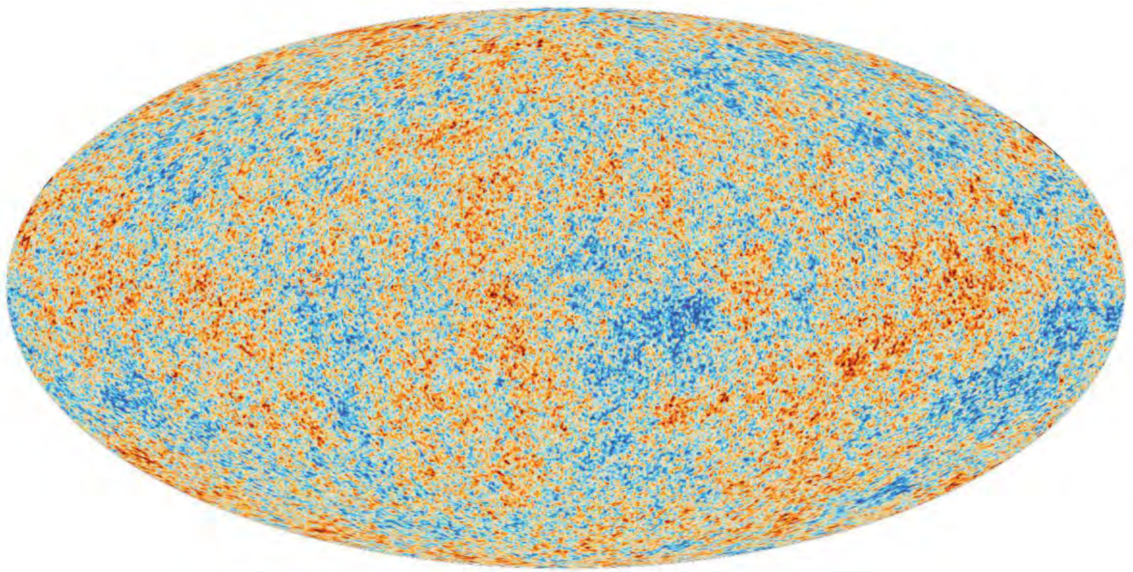


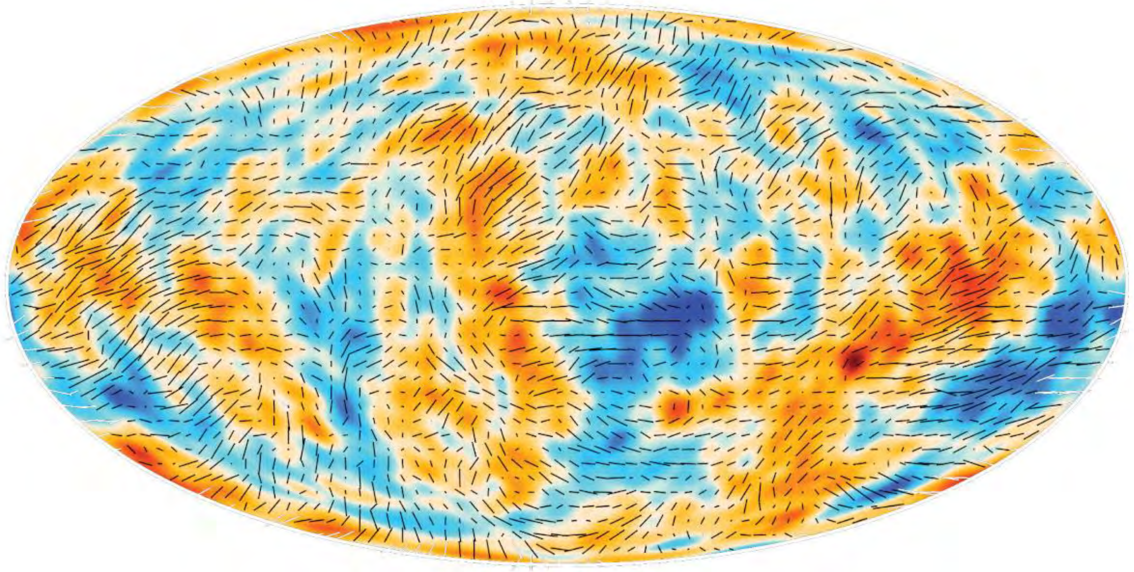


Mather+ (1994); Bennet+ (1994)
Jarosik+ (2011); Larson+ (2011)

From the CMB to cosmological parameters

- 2013: Planck → angular power spectrum of T anisotropies & polarization

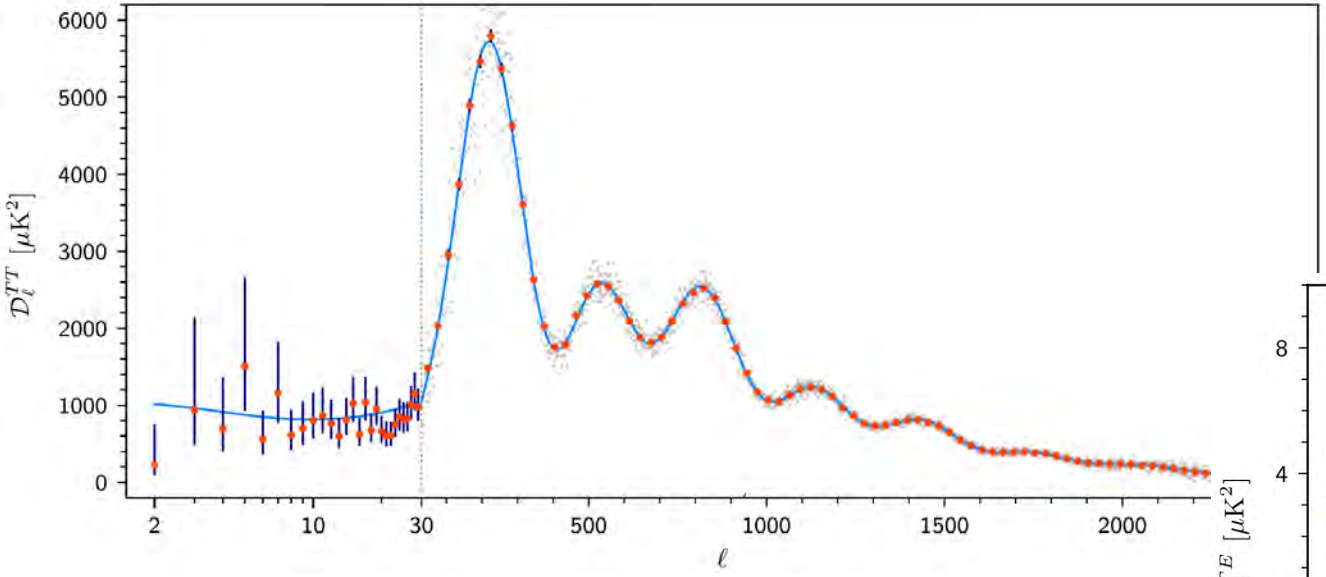


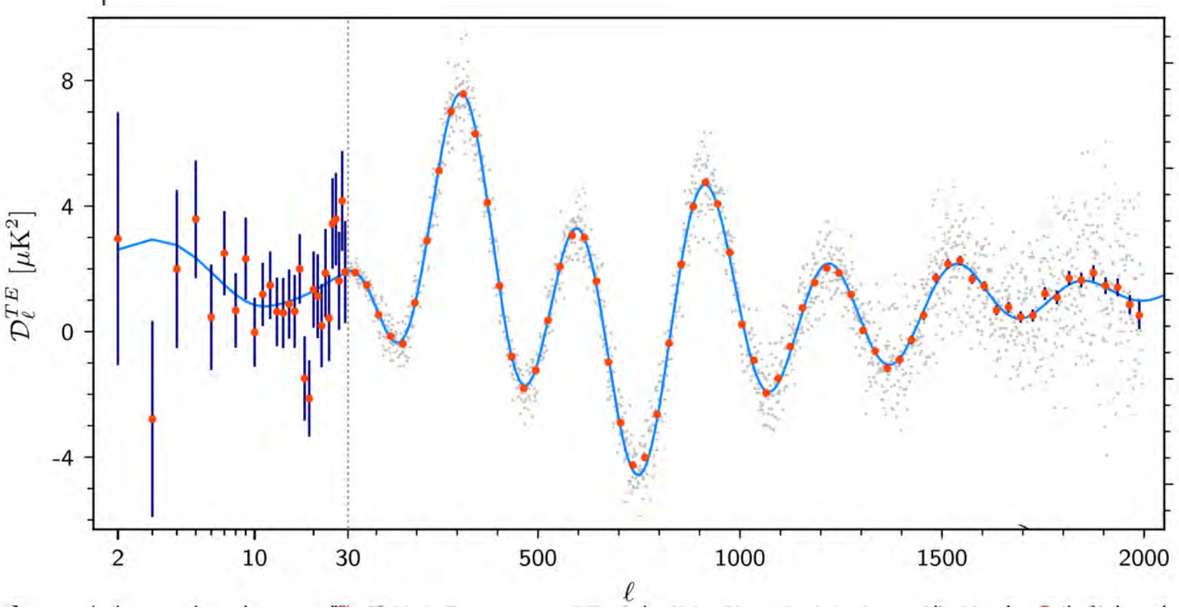


Planck collaboration (2020)

From the CMB to cosmological parameters

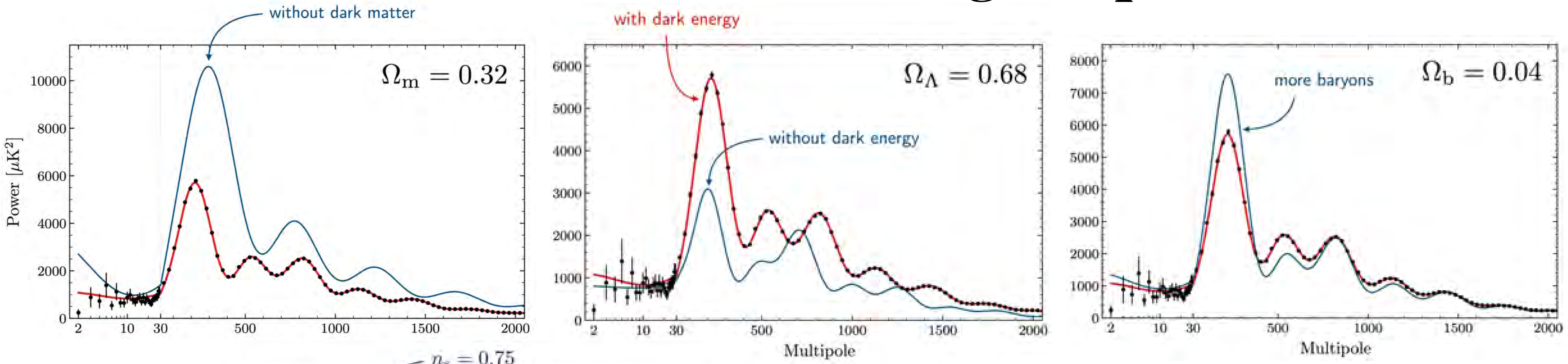
- 2013: Planck → angular power spectrum of T anisotropies & polarization

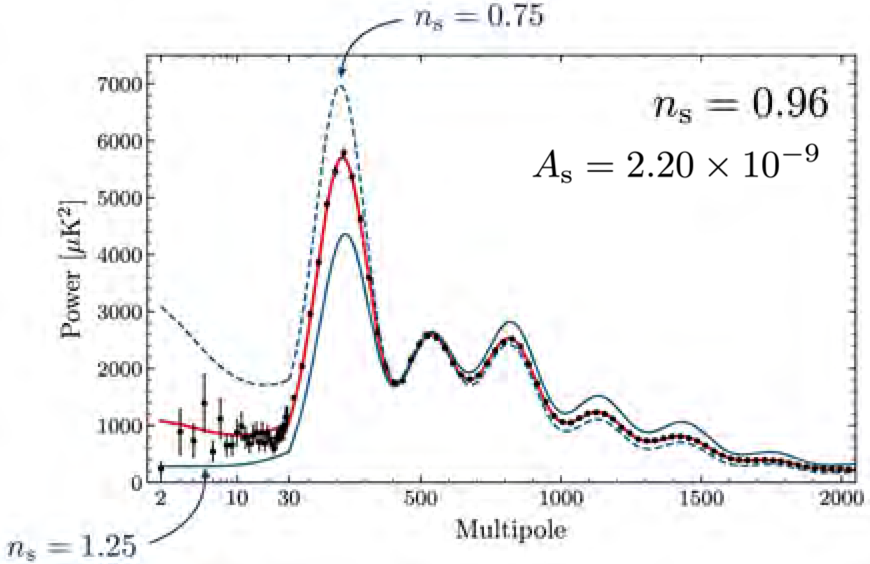


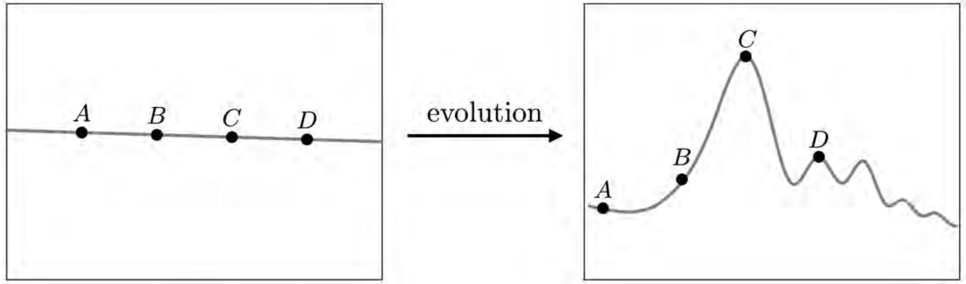


Planck collaboration (2020)

From the CMB to cosmological parameters







$$A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$

Amplitude

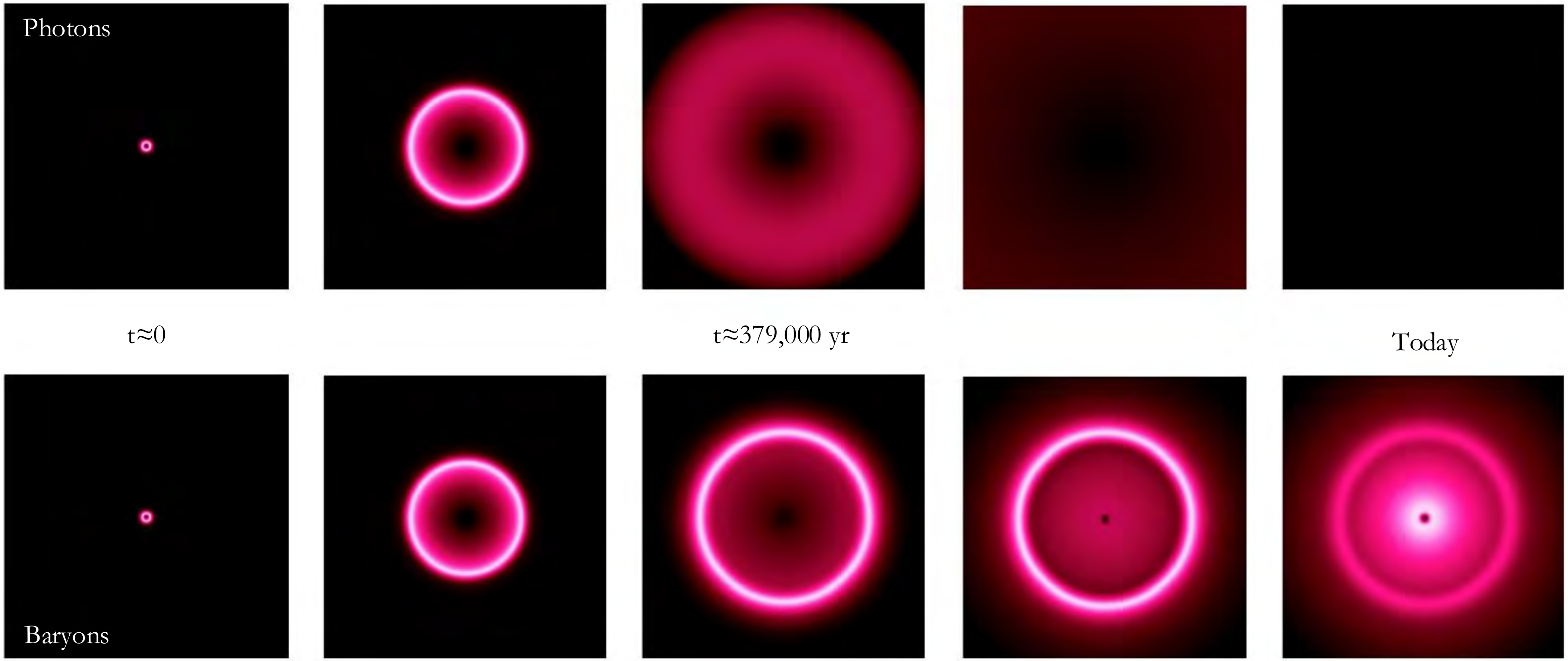
scale-dependence

Credit: Dr. D. Baumann

Baryon Acoustic Oscillations

- For the first 379,000 years after the Big Bang, the Universe was filled with a photon-baryon plasma that was reacting to the growing dark matter inhomogeneities
- This left a detectable "imprint" in the distribution of matter that can be used to trace the expansion history
- Independently predicted by Peebles & Yu (1970) and by Sunyaev & Zel'dovich (1970)
- Detected by Cole+(2005) and by Eisenstein+(2005)

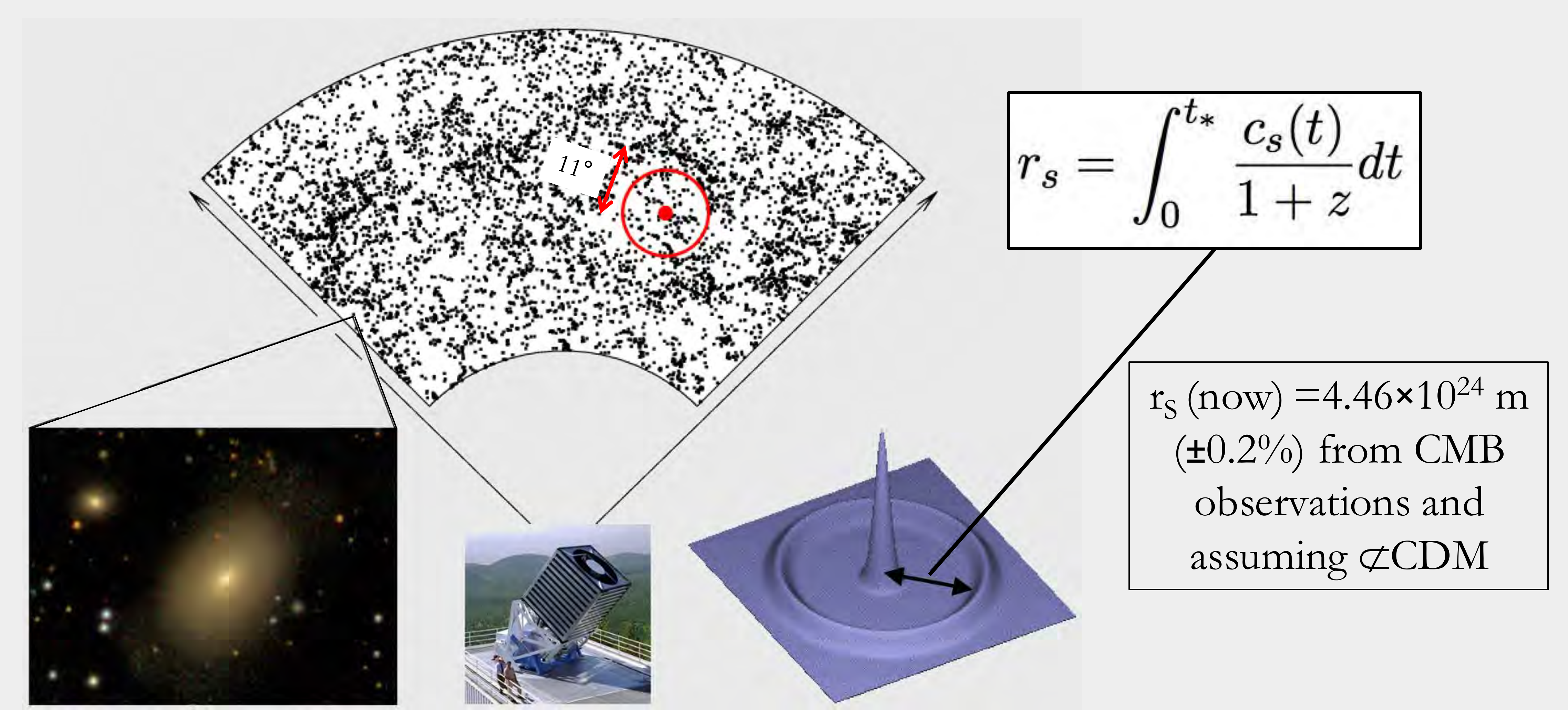
Baryon Acoustic Oscillations



Primordial sound waves in baryon-photon plasma, frozen as density waves at recombination

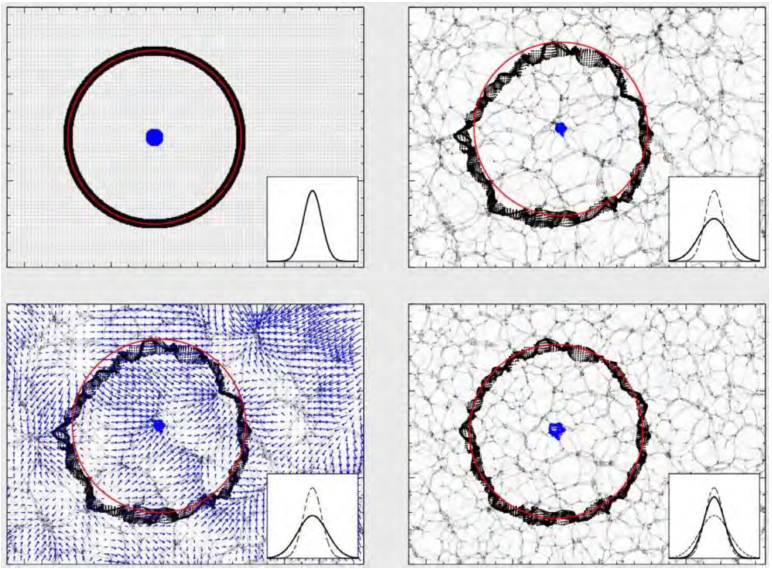
Credit: Dr. M. White

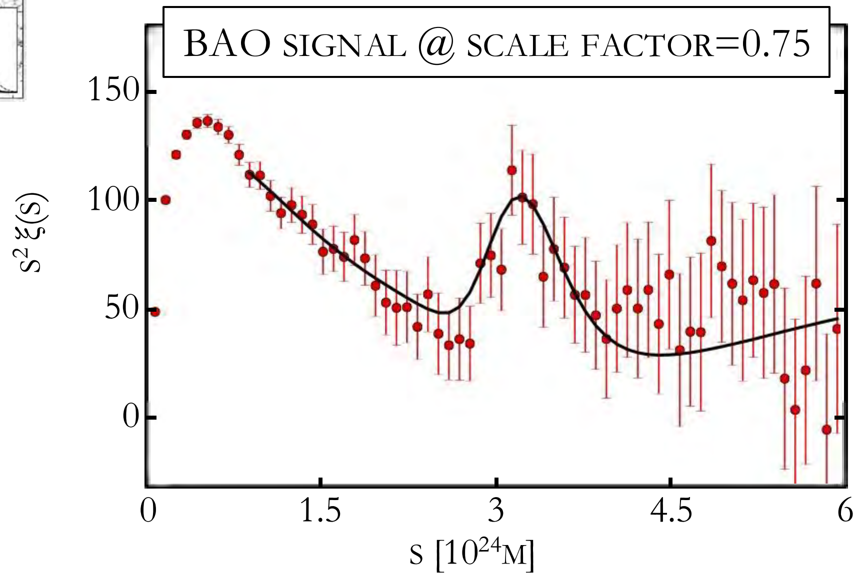
Baryon Acoustic Oscillations

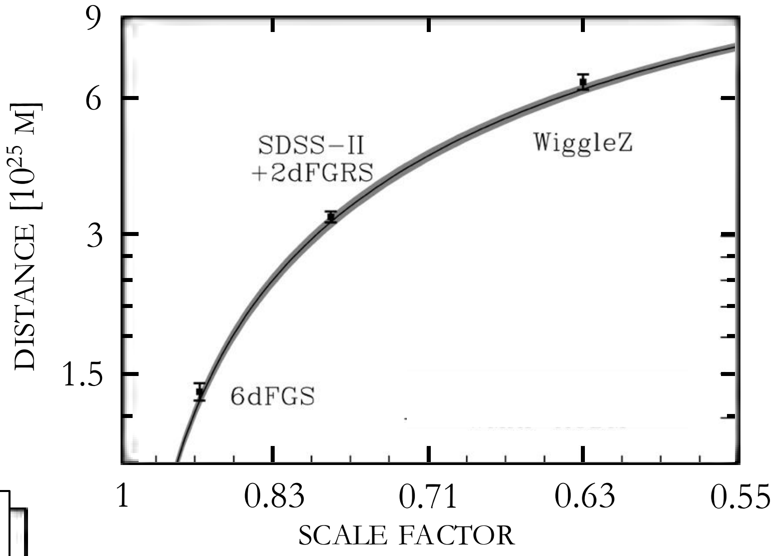


Credit: Dr. D. Eisenstein and SDSS collaboration

The BAO peak as a "standard ruler"

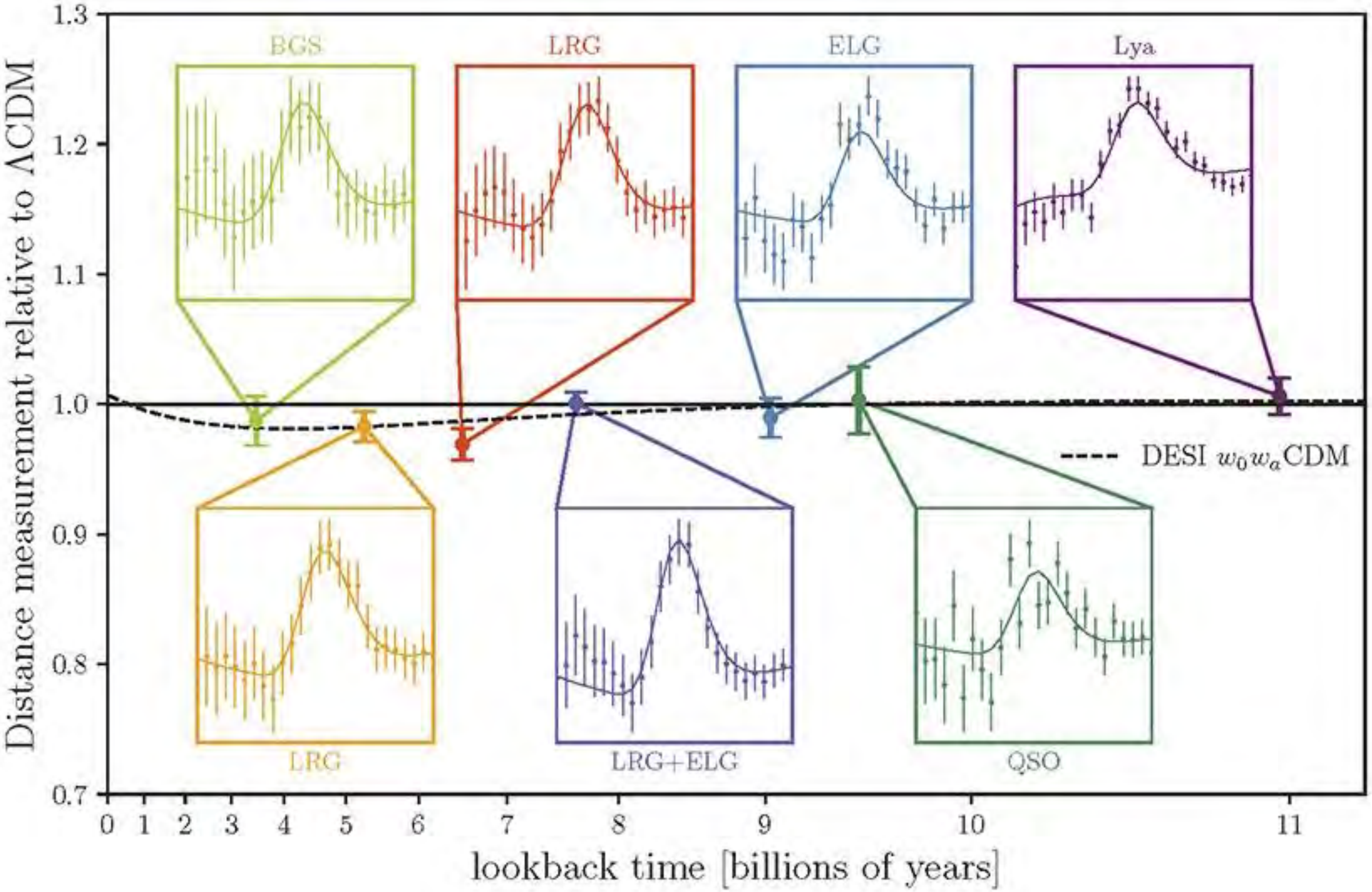






Padmanabhan+ (2012); Weinberg+ (2013)

The BAO peak as a "standard ruler"

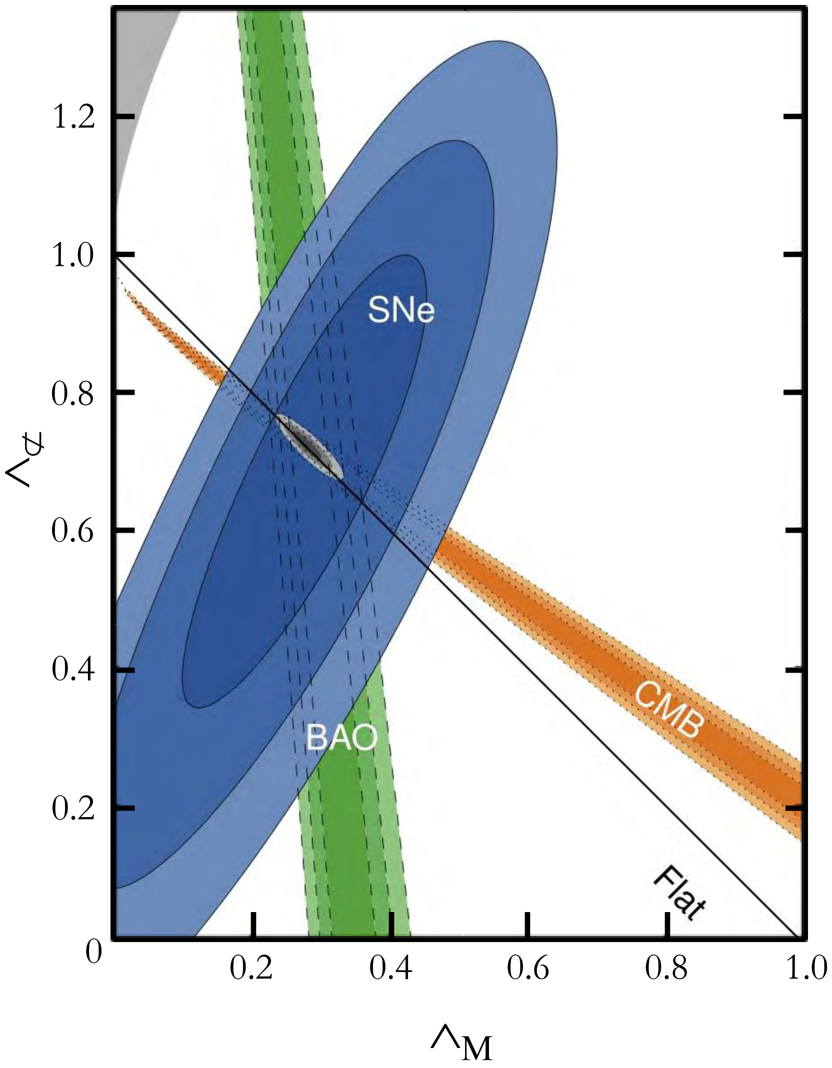


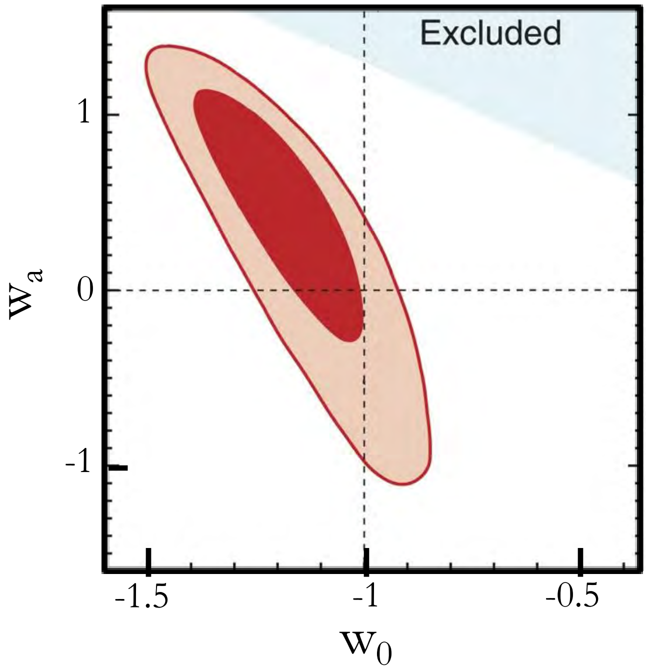
DESI Collaboration (2024)

Breaking the degeneracies

- Some of the cosmological parameters derived from the CMB can only be known up to a factor of $h^2 = (H_0/100\ \mathrm{km/s/Mpc})^2$
- Likewise, SNe Ia are mostly sensitive to $\Omega_\Lambda - \Omega_m$
- BAO are mostly sensitive to Ω_m
- Need to combine these probes to break degeneracies
- And… an independent determination of H_0 provides a robust test of the cosmological model (more on this later)

Combining Cosmological Probes circa 2012





$$w = P/\rho c^2$$

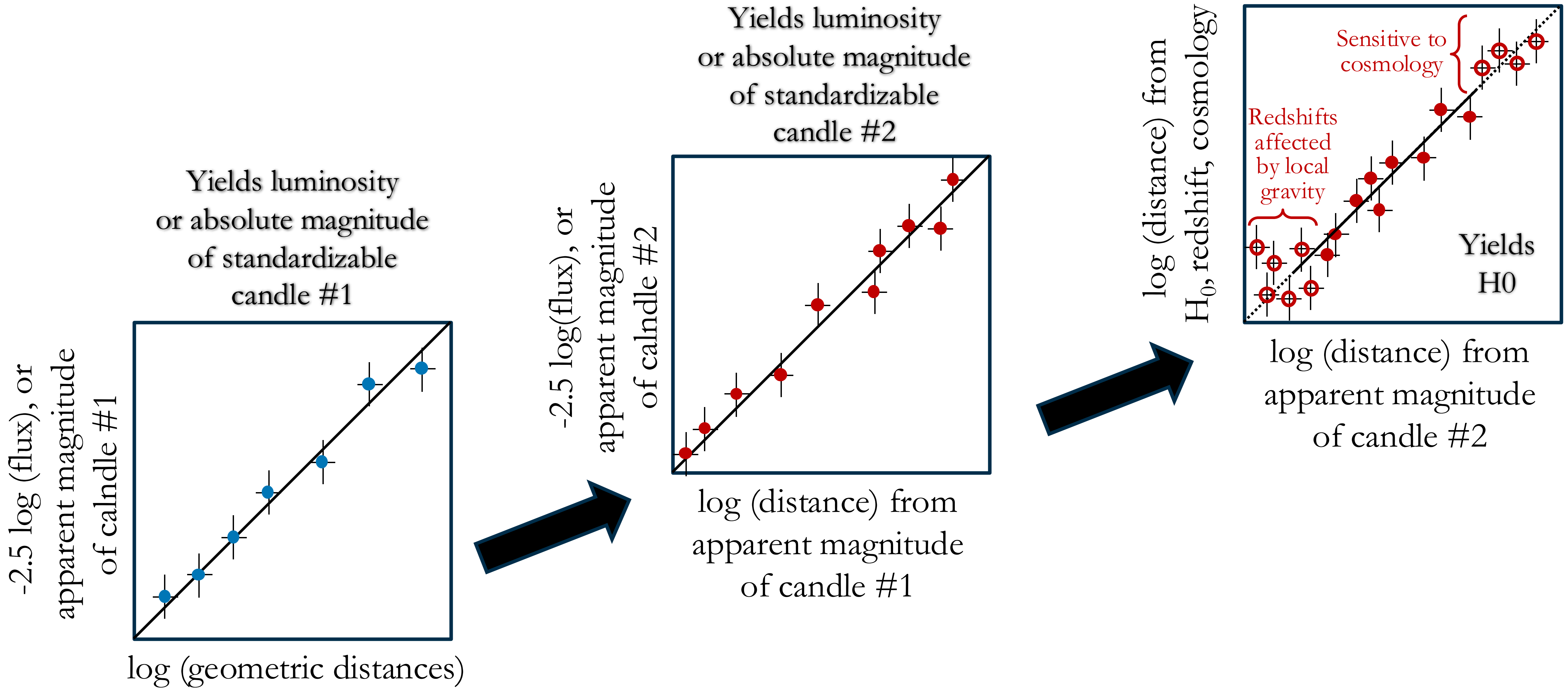
$$w(a)=w_0+w_a(1\text{-}a)$$

Suzuki+ (2012)

The Cosmological Distance Ladder

- In order to measure H_0 locally, we need to construct a distance ladder
- This is because we cannot use a single method across the entire range of distances we need to cover
- Start with geometric methods (nearby) and then rely on the inverse-square law applied to standard*izable* “candles”

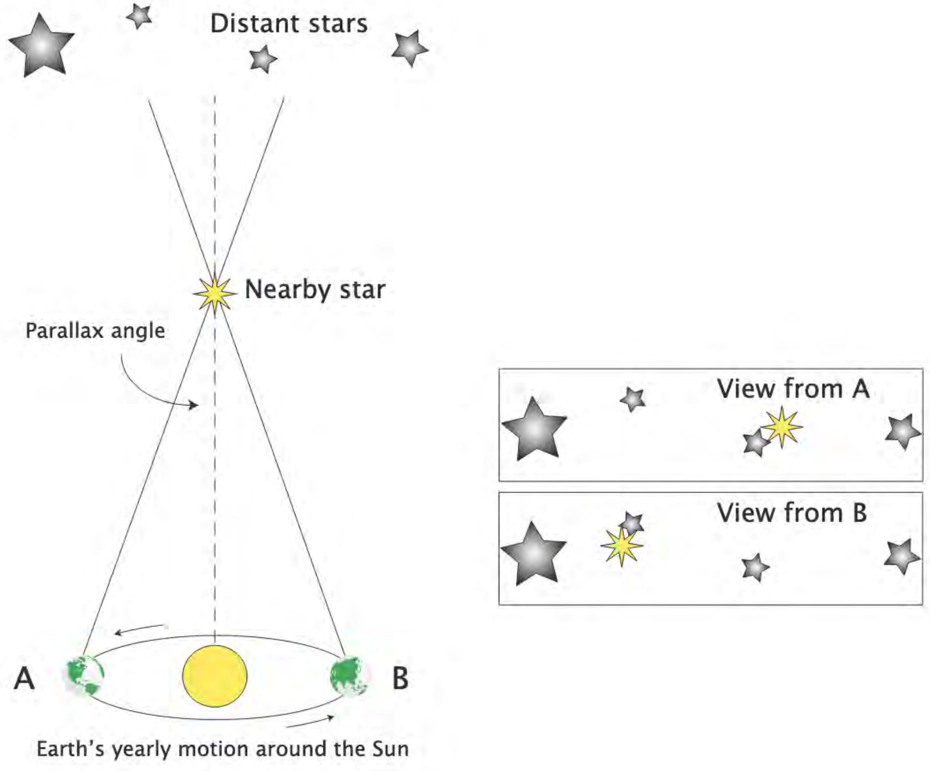
The Cosmological Distance Ladder



Based on Riess, Macri+ (2016)

Parallax

- The "gold standard" of primary distance indicators
- Parallax angle π [in milli-arcsec] =1/distance [in kiloparsec]
- Requires astrometric measurements with extremely high precision and accuracy
- Best done from space: *Hipparcos*, *Gaia* (ESA missions); *Hubble*
- Can be done globally, or locally with suitable reference stars



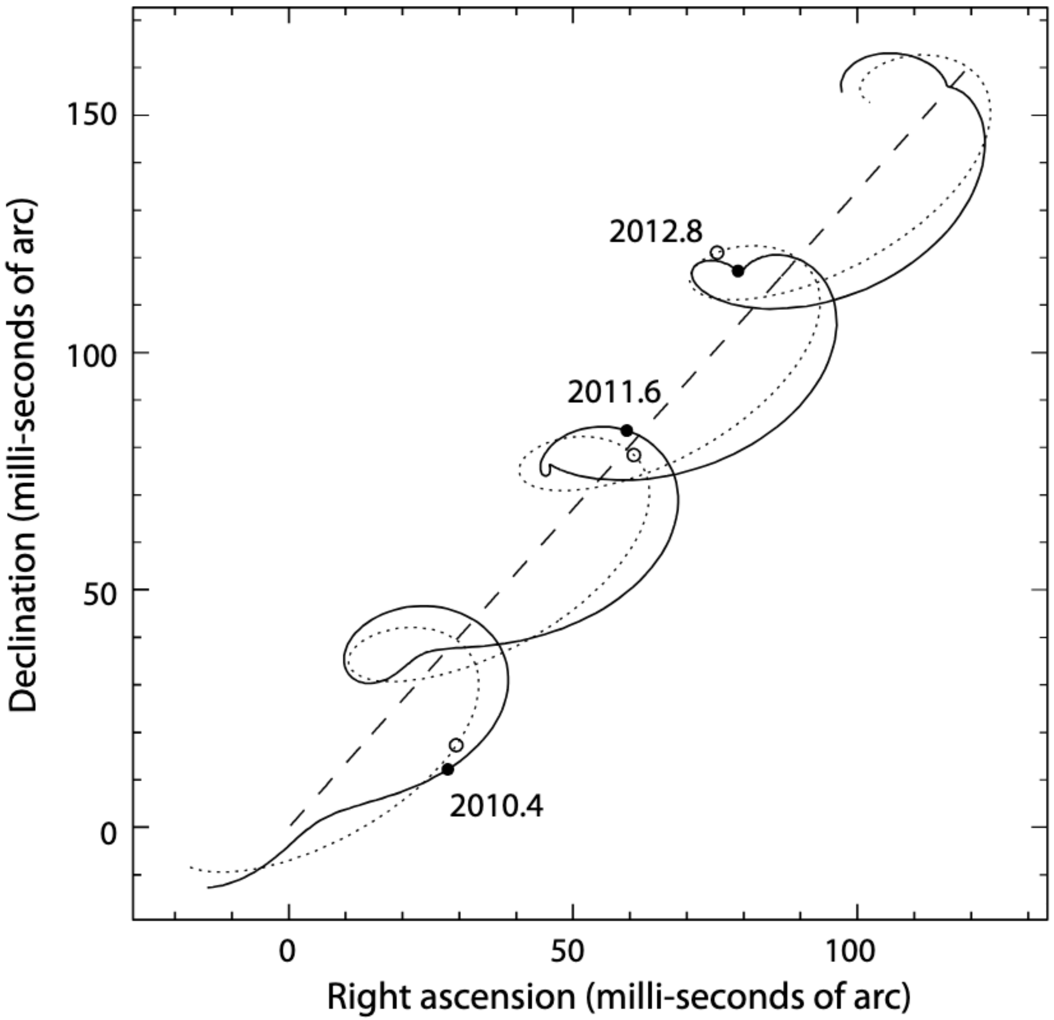
Perryman (2012)

Parallax complications

- Measurements must span at least a few months (or years)

- Must also measure the stellar *proper motion*, due to the spatial velocities of stars wrt Sun

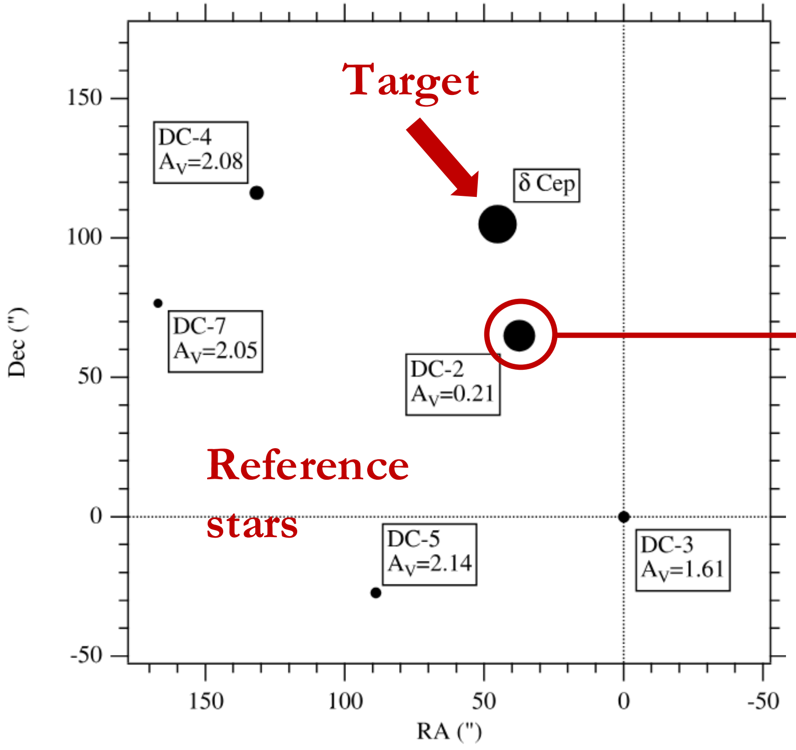
- Many stars of interest will have companions…

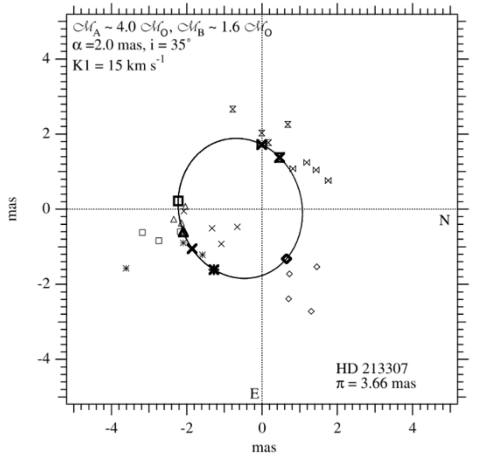


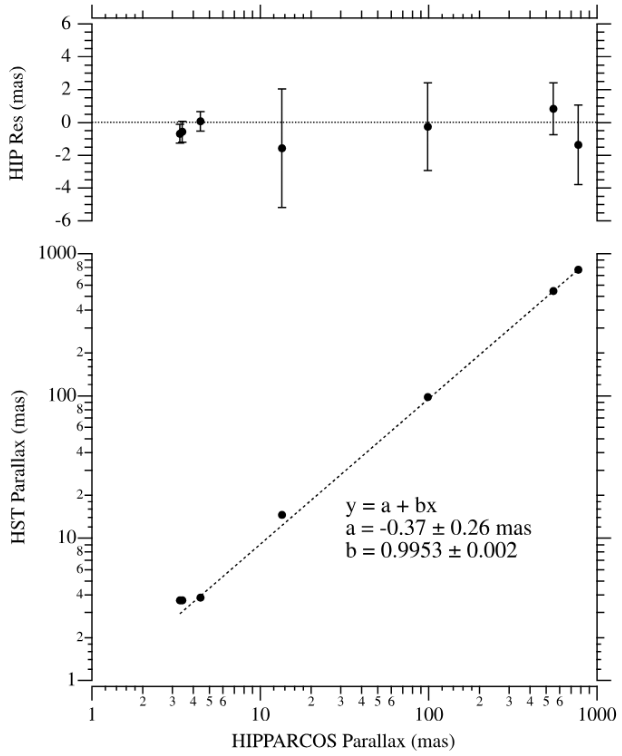
Perryman (2012)

Parallaxes with HST/FGS

- The first high S/N parallaxes useful for the distance scale were obtained using the Fine Guidance Sensors (FGS) on Hubble







Benedict+ (2002)

Parallaxes with HST/FGS

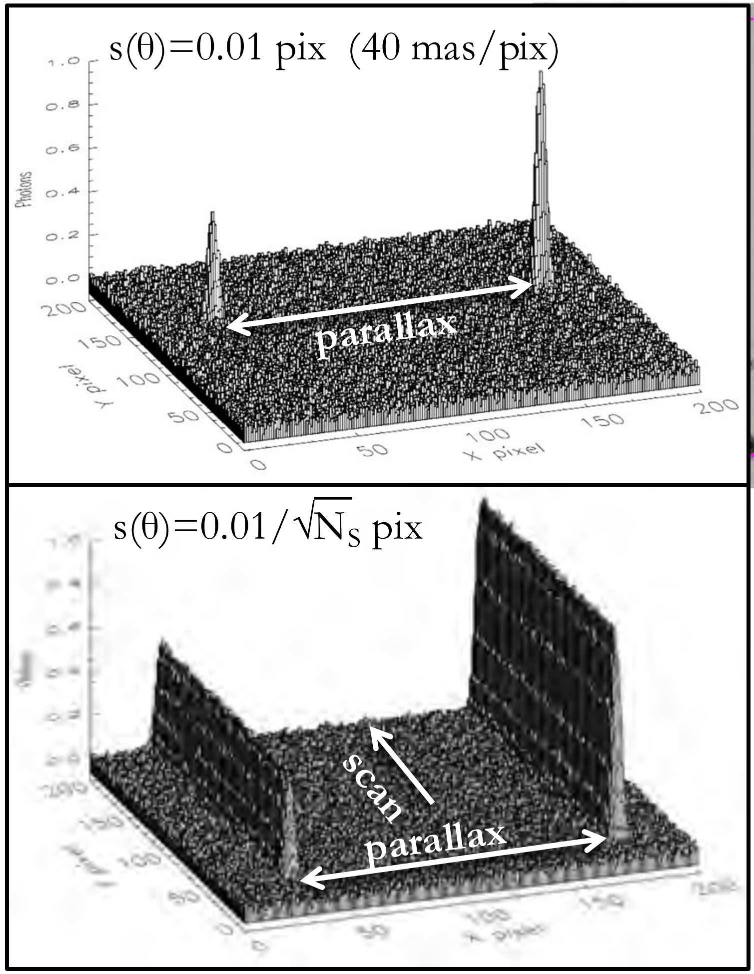
- The first high S/N parallaxes useful for the distance scale were obtained using the Fine Guidance Sensors (FGS) on Hubble

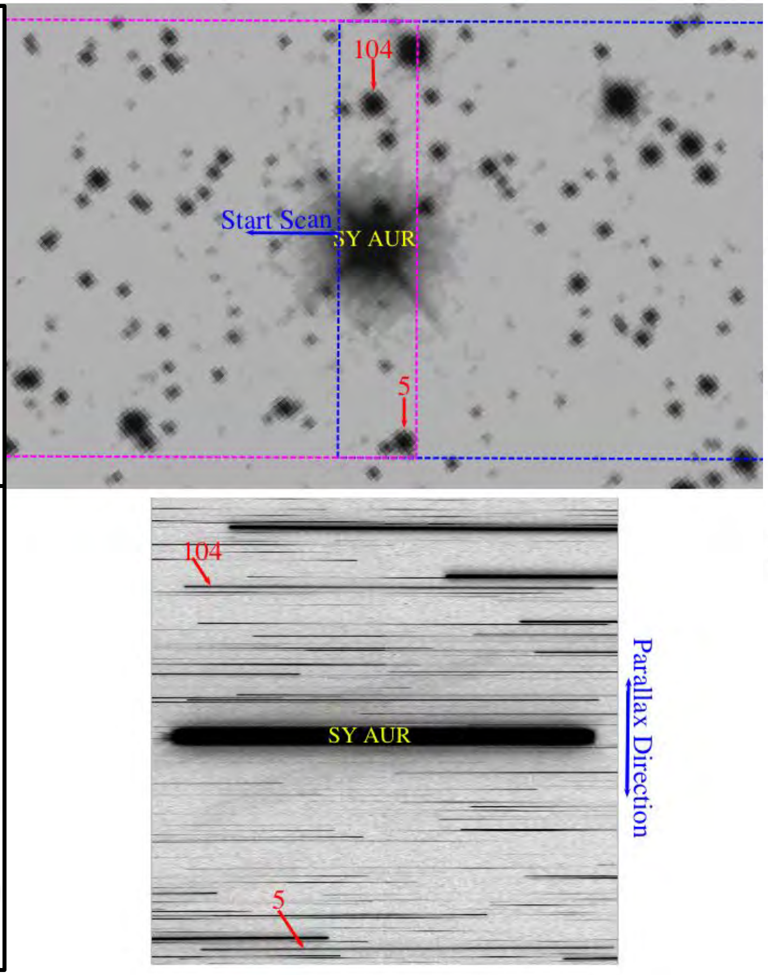
- Unfortunately, FGS could only measure parallaxes to ±0.2 mas, limiting its reach to D~500 pc (π=2 mas so S/N~10)

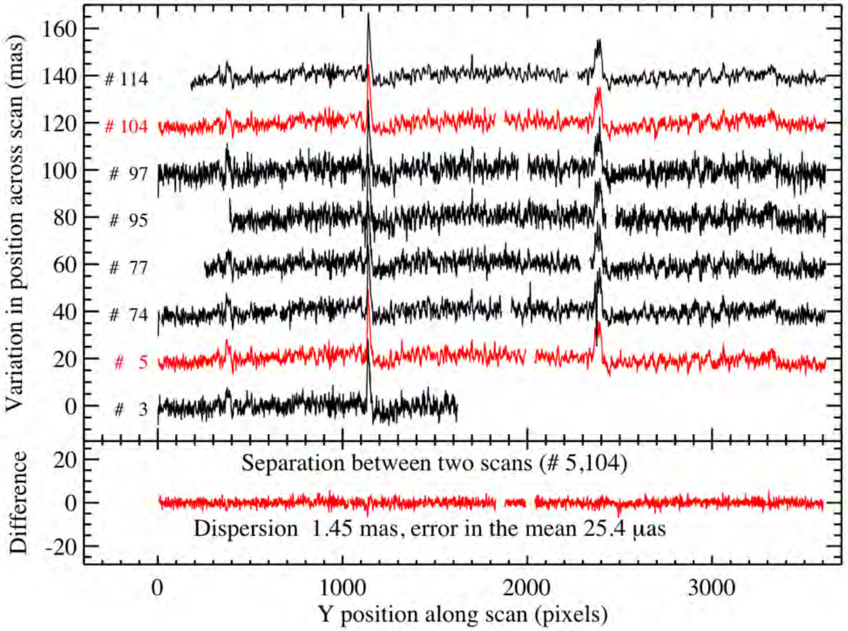
- The development of a spatial scanning technique on Hubble, using the WFC3 camera, increased its reach 7×, to D~3.5 kpc

Benedict+ (2002)

Parallaxes with HST/WFC3 scanning







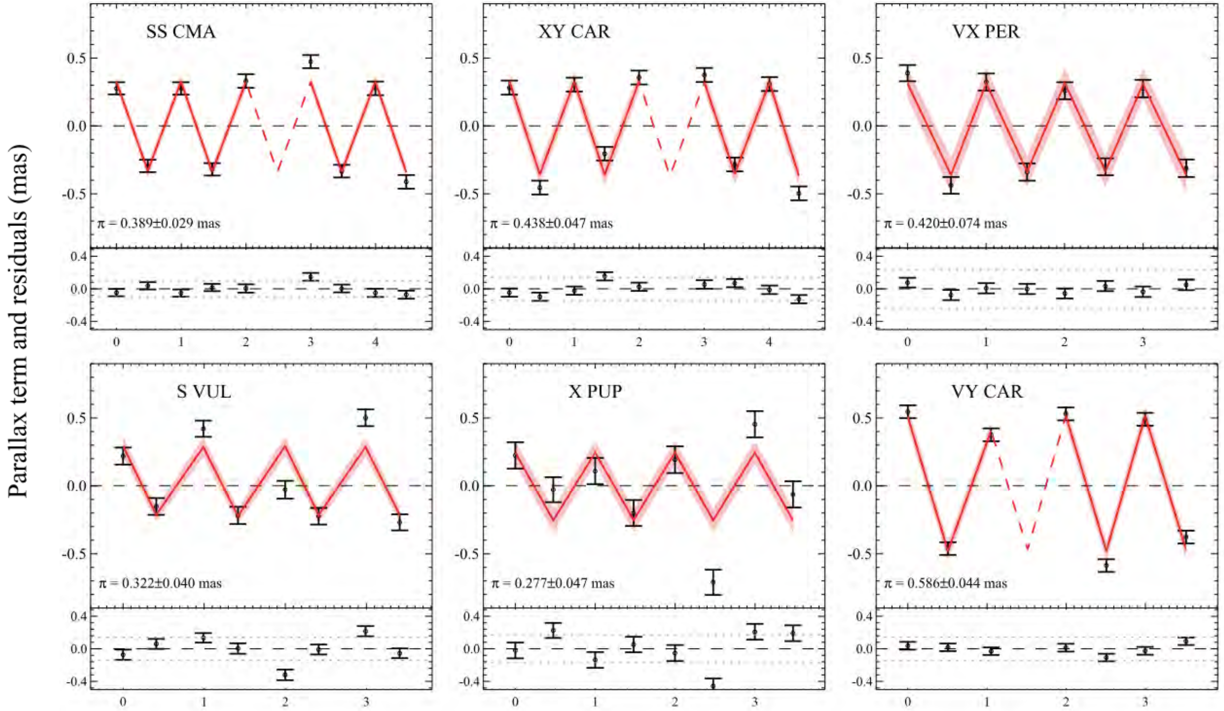
Jitter between lines is *coherent*, subtracted in line separations

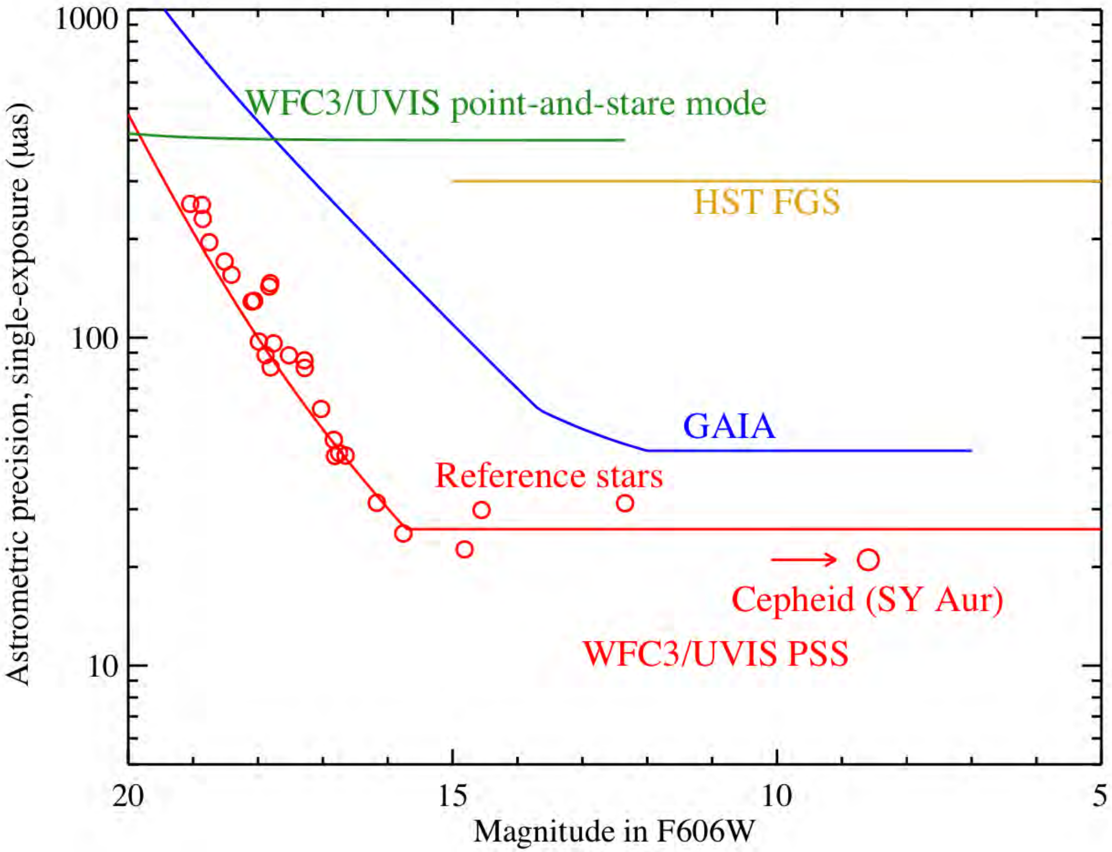
Astrometric precision of 30-80 µas

Riess+ (2014)

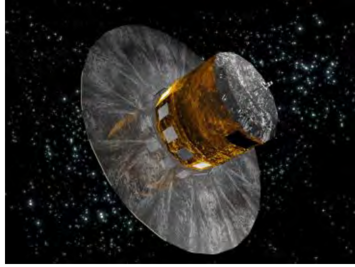
Parallaxes with HST/WFC3 scanning

- These observations also yielded homogeneous photometry of the targets (more on that later)



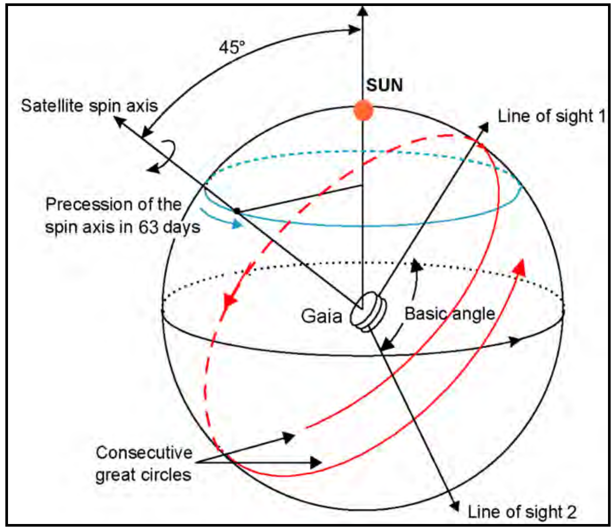


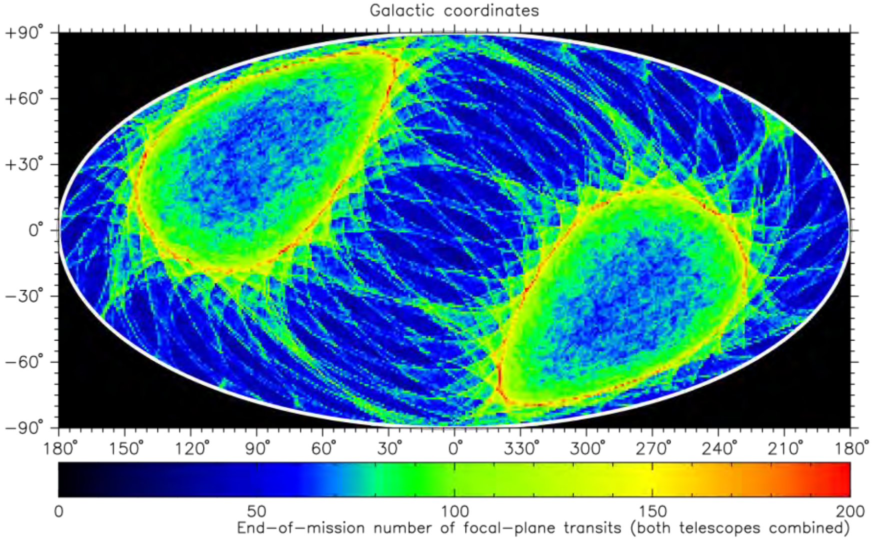
Riess+ (2014, 2018)

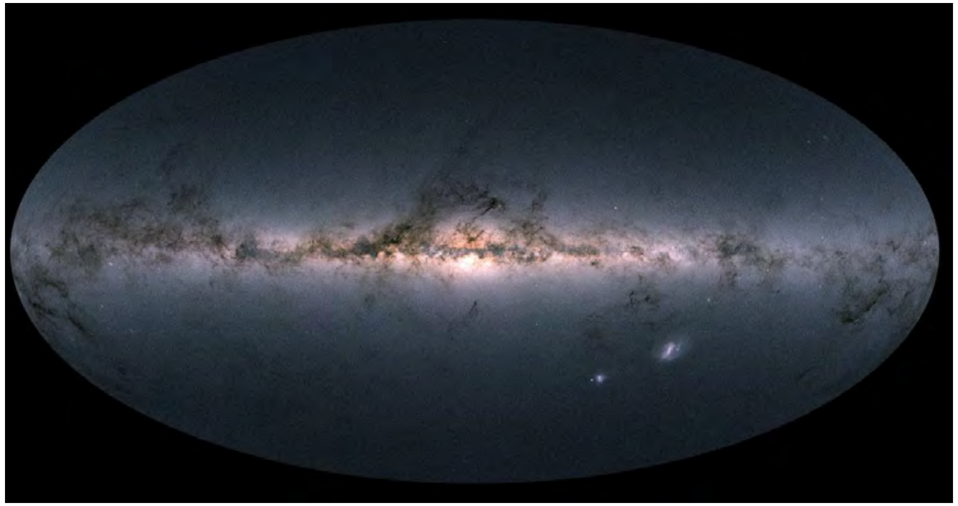


Parallaxes with *Gaia*

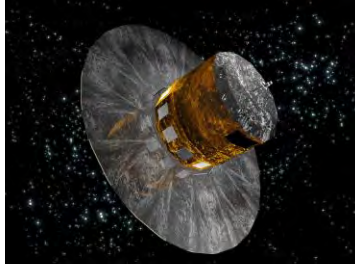
- ESA mission, observing entire sky from L2 since July 2014
- 4 observations in 6h, repeated ~14 times per year
- ~2×10^{9} sources to V~21 mag; ~3×10^{5} for distance scale
- Parallaxes out to D~100 kpc; photometry and spectroscopy





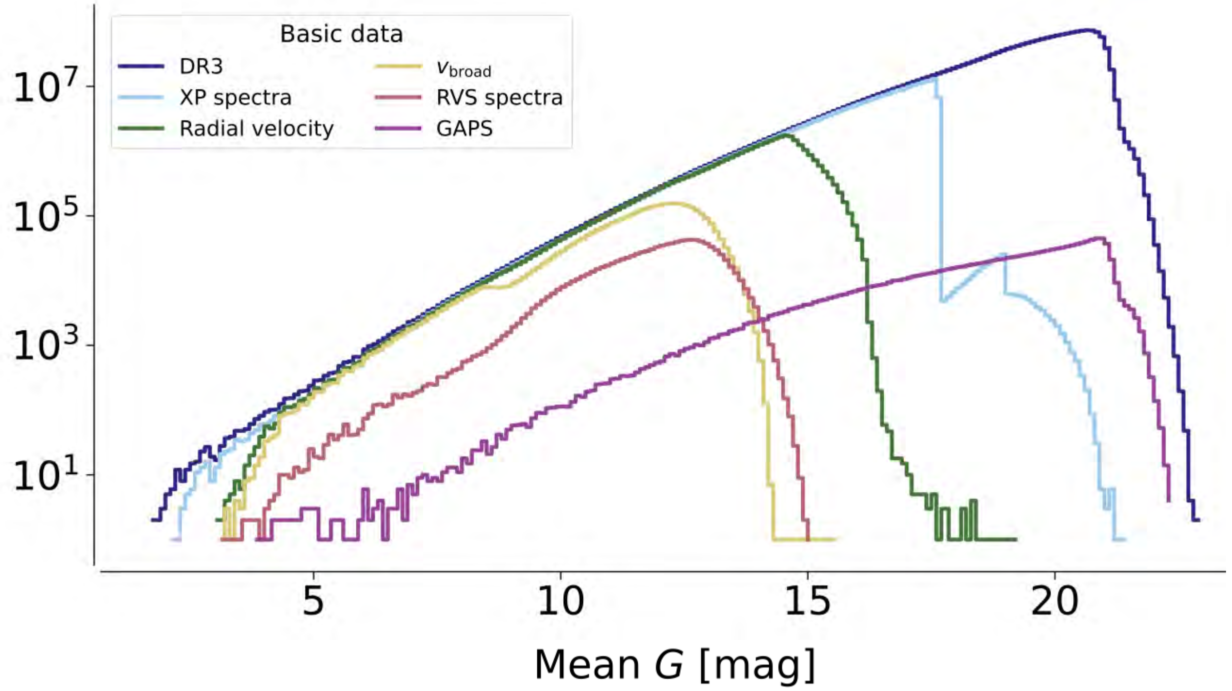


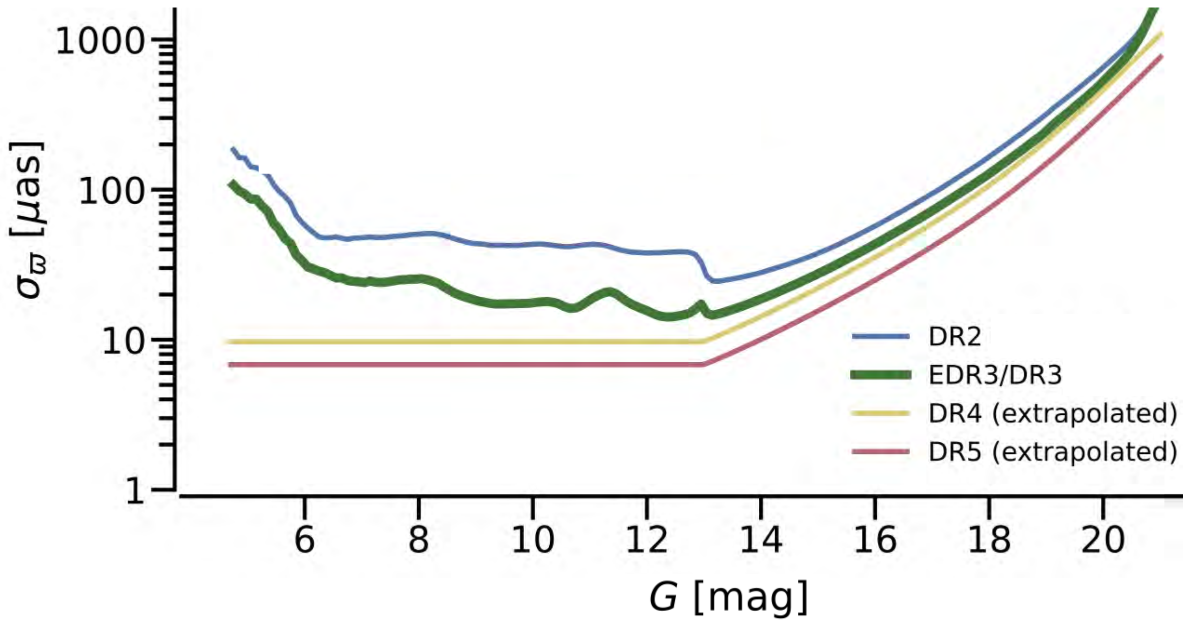
Credit: Dr. G. Clementini



Parallaxes with *Gaia*

- Data Release 3 in June 2022; Data Release 4 mid-2026
- Final Data Release no earlier than Dec 2030





Gaia Collaboration (2023)

Beyond Parallaxes

- As great as *Gaia* is, it can only measure parallaxes for stars within the Milky Way (and its satellites)
    - Limitations / complications due to large amounts of interstellar dust along the line of sight in certain directions within the Milky Way
    - Low S/N parallaxes for individual stars in MW satellites

- Need other geometrical methods to go beyond D~100 kpc with accuracy and precision

The Surface Brightness – Temperature relation

- Based on Stefan-Boltzmann Law, and the definitions of luminosity, angular diameter, and bolometric magnitude

$$L = 4\pi R^2 \sigma T_e^4$$

$$\log L \propto 2 \log R + 4 \log T_e$$

- R=radius ; T_e=effective temperature; L=luminosity

Barnes & Evans (1976)

The Surface Brightness – Temperature relation

- Based on Stefan-Boltzmann Law, and the definitions of luminosity, angular diameter, and bolometric magnitude

$$L = 4\pi R^2 \sigma T_e^4$$

$$\log L \propto 2 \log R + 4 \log T_e$$

$$M = -2.5 \log L + C$$

$$M \propto -5 \log R - 10 \log T_e$$

- R=radius ; T_e=effective temperature; L=luminosity

Barnes & Evans (1976)

The Surface Brightness – Temperature relation

- Based on Stefan-Boltzmann Law, and the definitions of luminosity, angular diameter, and bolometric magnitude

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$$\log T_\mathrm{e} \propto -0.1M - 0.5 \log R$$

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$$\log T_{\rm e} \propto -0.1M - 0.5 \log R$$

$$m - M \propto 5 \log D$$
$$M \propto m - 5 \log D$$
$$\log T_{\rm e} \propto -0.1m + 0.5 \log D - 0.5 \log R$$

- R=radius ; T_e=effective temperature; L=luminosity
- D=distance

Barnes & Evans (1976)

The Surface Brightness – Temperature relation

- Based on Stefan-Boltzmann Law, and the definitions of luminosity, angular diameter, and bolometric magnitude

$$L = 4\pi R^2 \sigma T_\mathrm{e}^4$$
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$$m - M \propto 5\log D$$
$$M \propto m - 5\log D$$
$$\log T_\mathrm{e} \propto -0.1m + 0.5\log D - 0.5\log R$$
$$\phi = 2R/D$$
$$\log \phi \propto \log R - \log D$$
$$\log T_\mathrm{e} \propto -0.1m - 0.5\log \phi$$

- R=radius ; T_e=effective temperature; L=luminosity
- D=distance ; ϕ = angular diameter

Barnes & Evans (1976)

The Surface Brightness – Temperature relation

- Based on Stefan-Boltzmann Law, and the definitions of luminosity, angular diameter, and bolometric magnitude

$$\log T_{\rm e} \propto -0.1m - 0.5 \log \phi$$

$$m = V + BC$$

$$\boxed{\log T_{\rm e} \propto -0.1(V + BC) - 0.5 \log \phi}$$

Barnes & Evans (1976)

The Surface Brightness – Temperature relation

- Based on Stefan-Boltzmann Law, and the definitions of luminosity, angular diameter, and bolometric magnitude

$$\log T_{\rm e} \propto -0.1m - 0.5\log\phi$$

$$m = V + BC$$

$$\boxed{\log T_{\rm e} \propto -0.1(V + BC) - 0.5\log\phi}$$

- Initial calibration using the Sun, to arrive at:

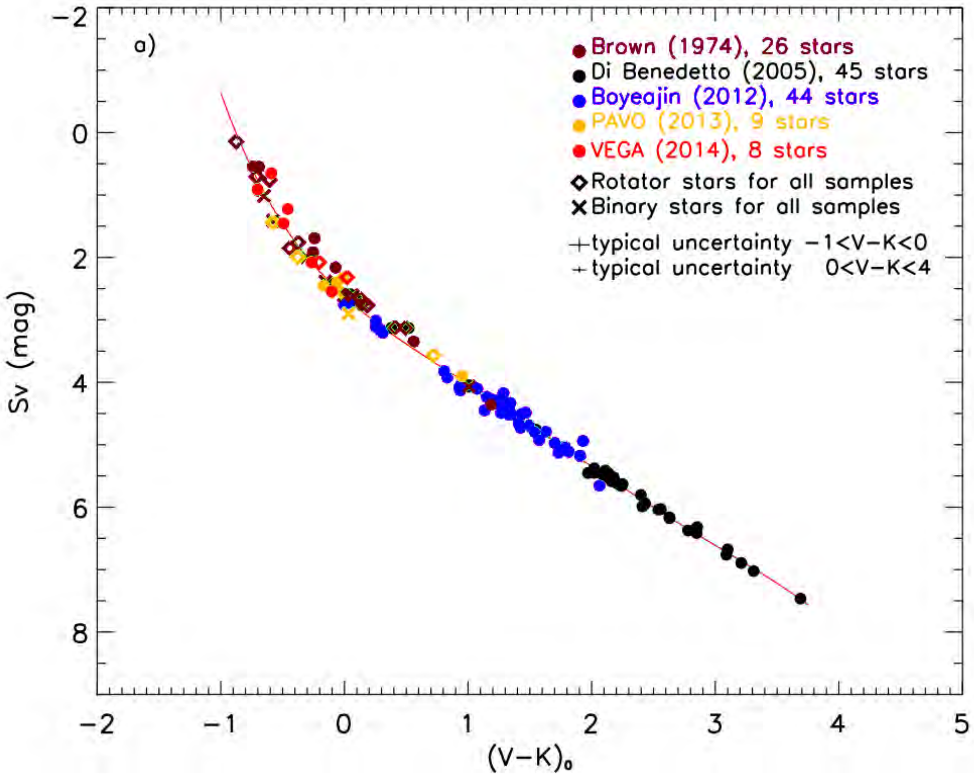
$$\boxed{\log T_{\rm e} = 4.2207 - 0.1(V + BC) - 0.5\log\phi}$$

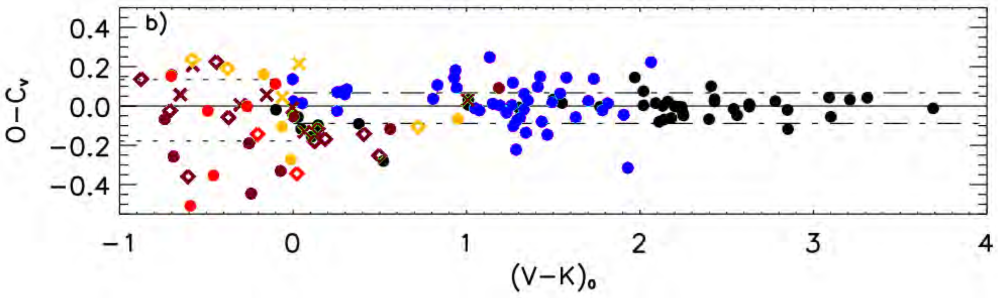
- T_e=effective temperature; V=apparent V-band magnitude; BC = bolometric correction; ϕ = angular diameter

Barnes & Evans (1976)

The Surface Brightness – Color relation

- Use angular diameters based on interferometric measurements and lunar occultations; replace temperature with (V-K) color





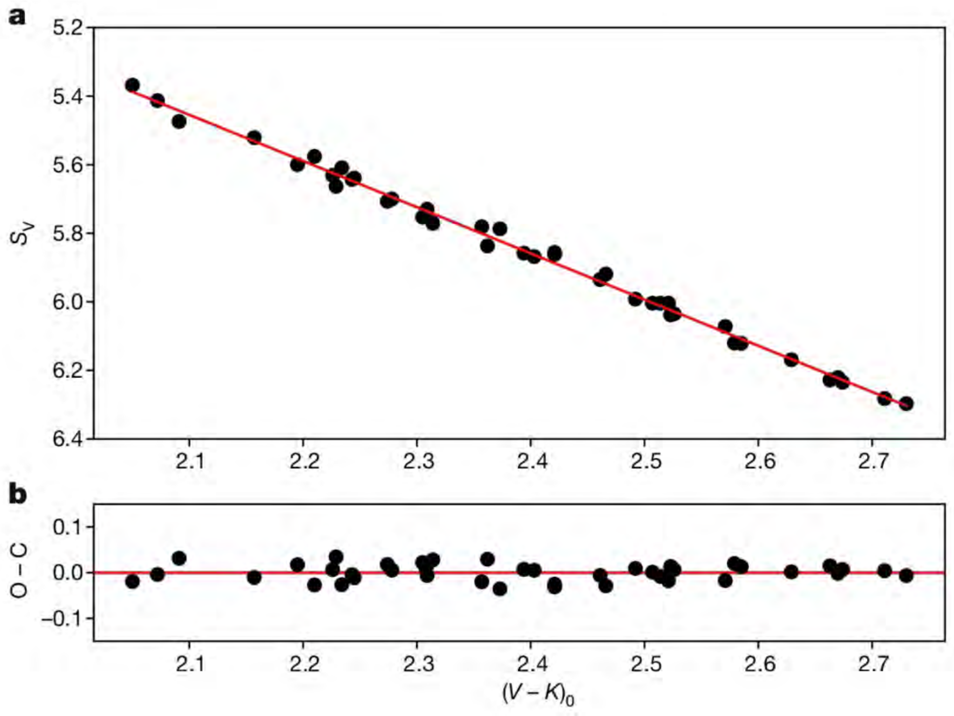
$$S_V = V + 5 \log \phi$$

Large scatter for hot stars, but promising for cooler ones (V-K>2)

Challouf+(2014)

The Surface Brightness – Color relation

- Measure angular diameter of 41 nearby core-He fusing giants to determine a 0.8% calibration of the SBCR



Pietrzyński+ (2019)

The Surface Brightness – Color relation

$$\log T_{\rm e} = 4.2207 - 0.1(V + BC) - 0.5 \log \phi$$

- We can use the SBCR to predict angular diameters, based on observed V magnitudes and V-K colors
- If we have an independent method to estimate linear diameters, then we can determine the distance to the stars
- Detached Eclipsing Binaries (DEBs) are ideal systems for this

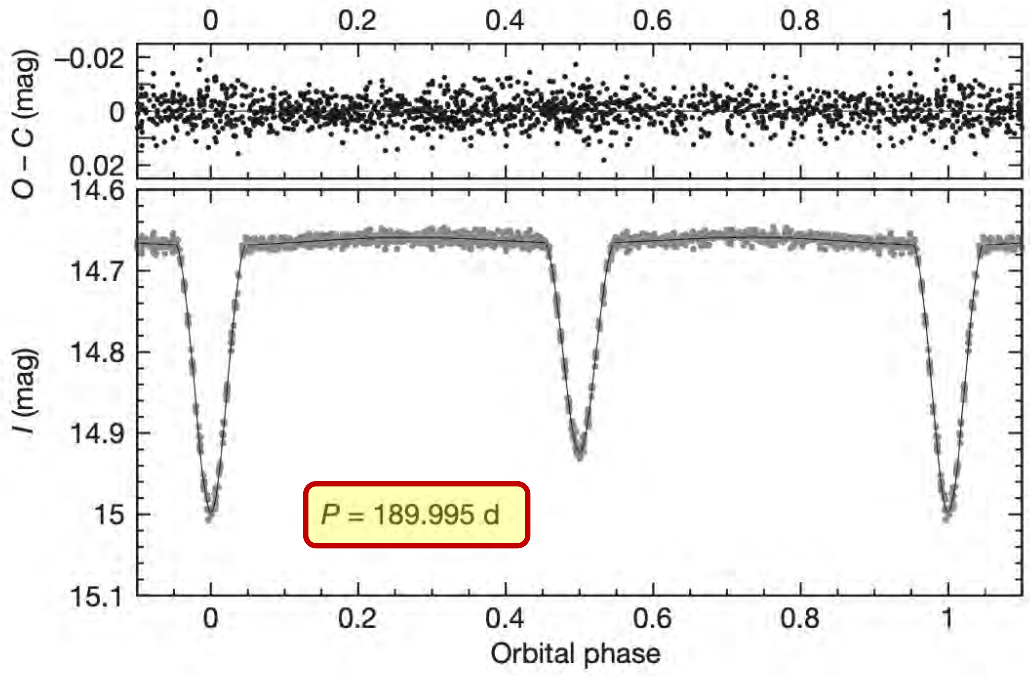
The Surface Brightness – Color relation

$$S_V = V + 5 \log \phi = f(V\text{-}K)$$

- We can use the SBCR to predict angular diameters, based on observed V magnitudes and V-K colors
- If we have an independent method to estimate linear diameters, then we can determine the distance to the stars
- Detached Eclipsing Binaries (DEBs) are ideal systems for this

Detached Eclipsing Binaries as Distance Indicators

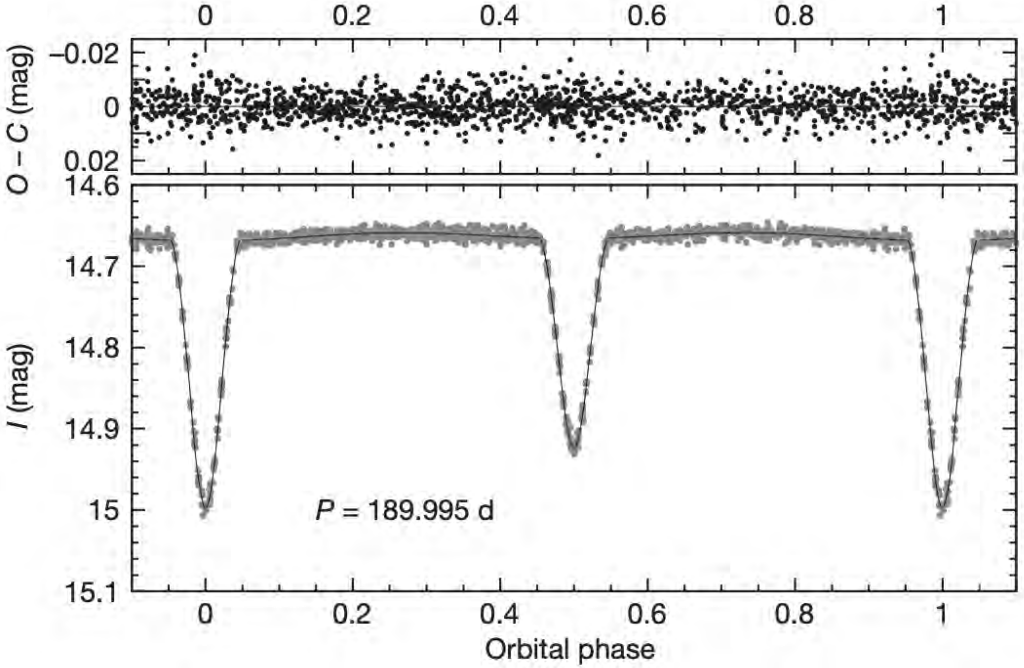
- Optical Gravitational Lensing Experiment: 25+ years of observations of Magellanic Clouds (among other targets)
- Discover suitable binaries composed of red giants

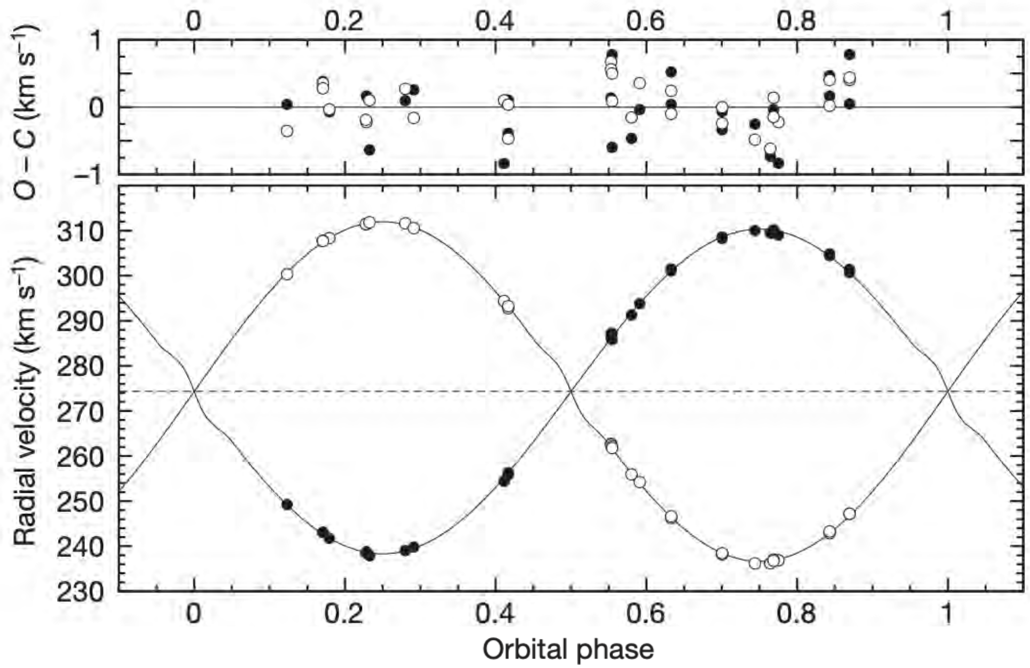


Pietrzyński+ (2013)

Detached Eclipsing Binaries as Distance Indicators

- Optical Gravitational Lensing Experiment: 25+ years of observations of Magellanic Clouds (among other targets)
- Follow-up spectroscopy: T_e, orbital velocities

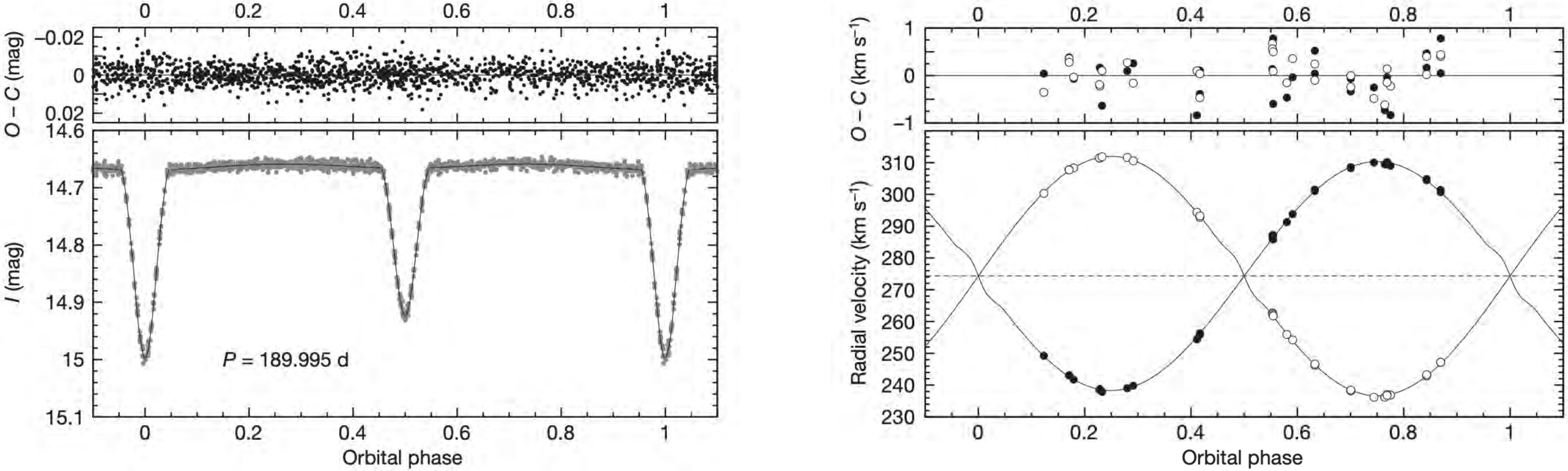




Pietrzyński+ (2013)

Detached Eclipsing Binaries as Distance Indicators

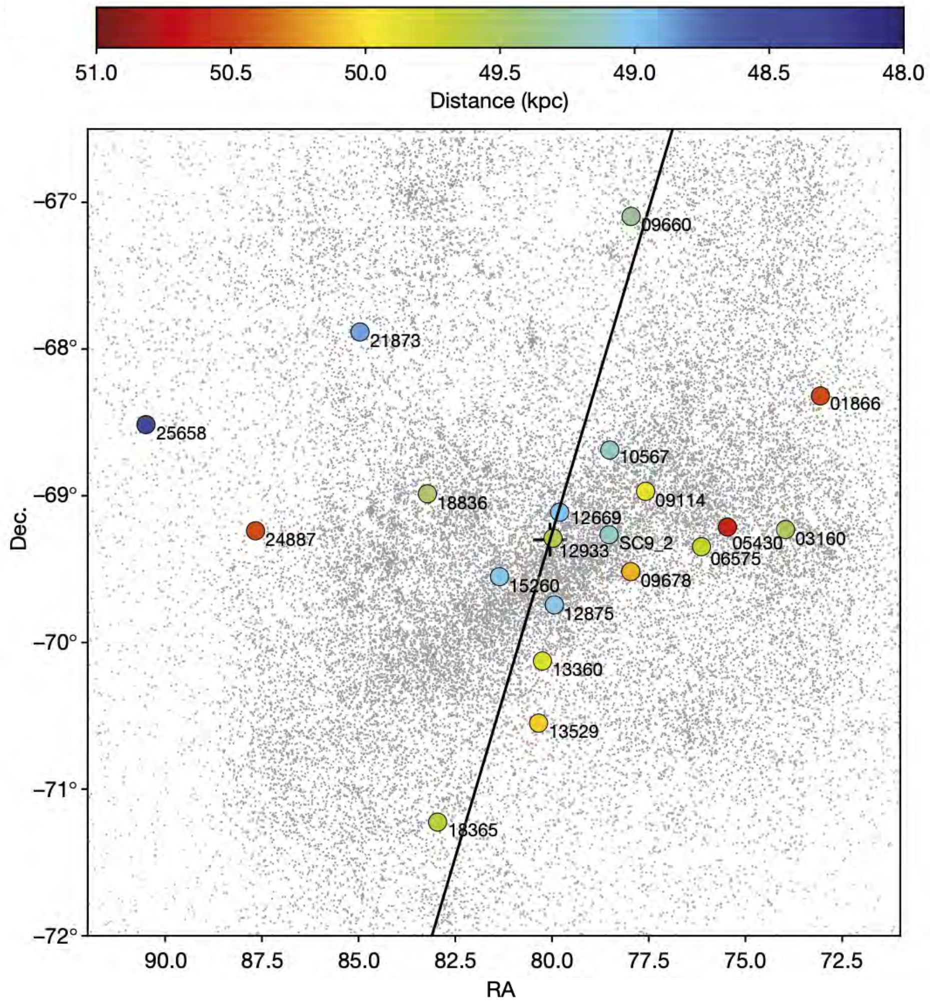
- Light curves yield stellar radii in units of orbital separation
- Orbital velocities from spectra yield size of orbit in km
- Combine to get radii in km and solve for distance



Pietrzyński+ (2013)

Detached Eclipsing Binaries as Distance Indicators

- A method so precise that it can map the depth of the LMC!
- D=49.59±0.09(stat)±0.54(sys) kpc
  (total uncertainty of 1.1%)
- Even for the elongated SMC, D=62.44±0.47(stat)±0.81(sys) kpc
  (total uncertainty of 1.5%)



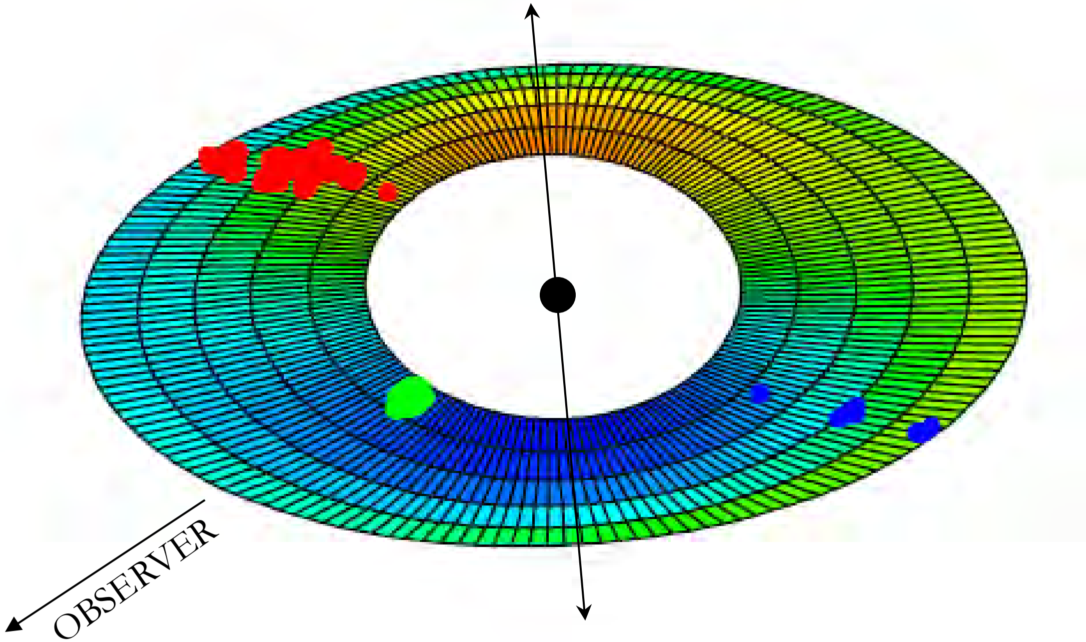
Pietrzyński+ (2019); Graczyk+ (2020)

Beyond the Magellanic Clouds: Masers

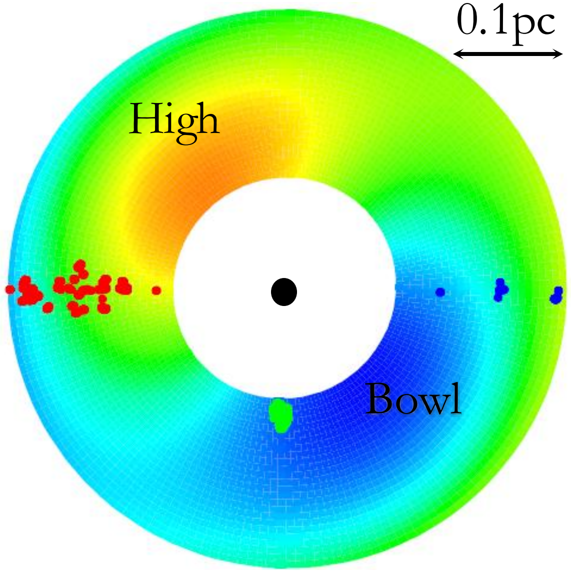
- The next generation of extremely large telescopes may allow us to extend this technique further into the Local Group (M31, M33)
- For now, if we want to go farther, we need another technique…

- Water masers in accretion disks of central massive black holes can also be used to determine geometric distances
- Requires Very Long Baseline Array observations over many years
- Best case: NGC 4258 (Messier 106), only ~7 Mpc away

Masers in NGC 4258 (Messier 106)

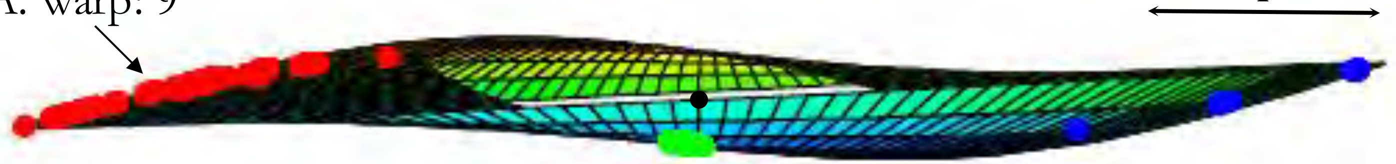


Top View



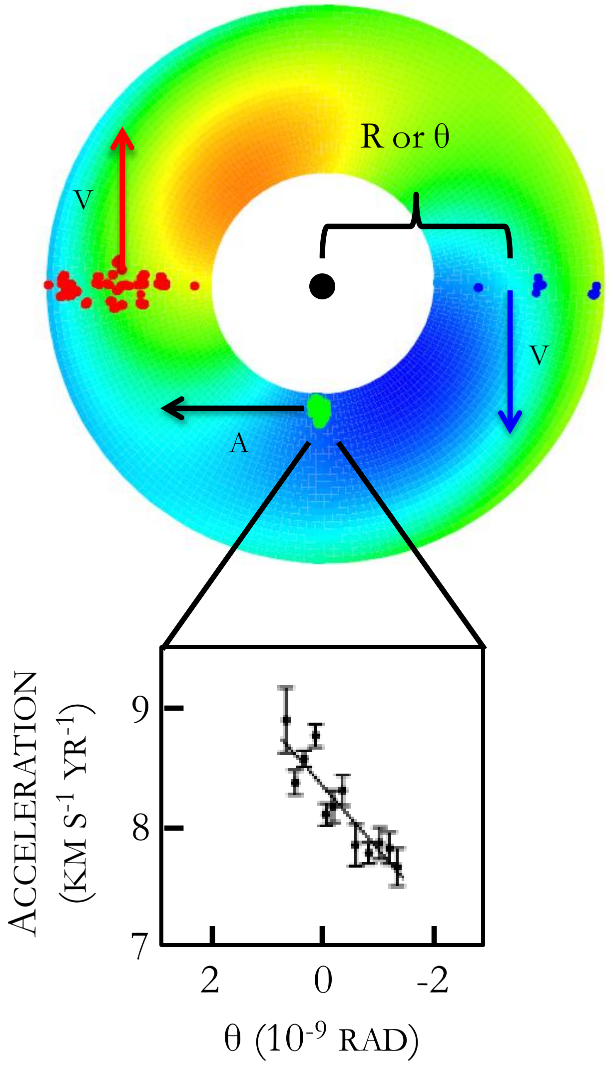
Incl. warp: 8°
P.A. warp: 9°

Observer's View



Diagrams by Liz Humphreys

Masers in NGC 4258 (Messier 106)



Angular diameter distance

- Velocities from tangential masers
- Accelerations from masers in front
- θ from radio map

- $A=V^2/R$
- $R=D\ \theta$

$D=V^2/A\theta$

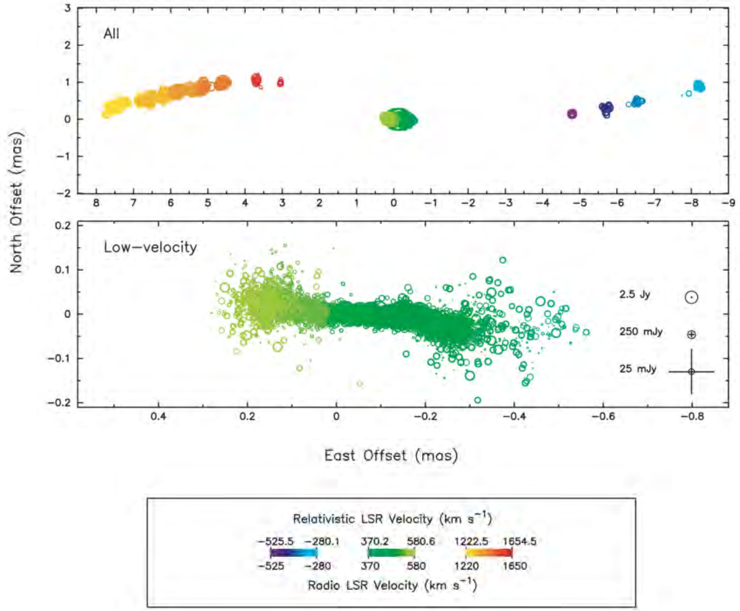
- D=7.58 Mpc ± 1.5%
- Mass= 3.98×10^7 ± 1.0% $M_\odot$

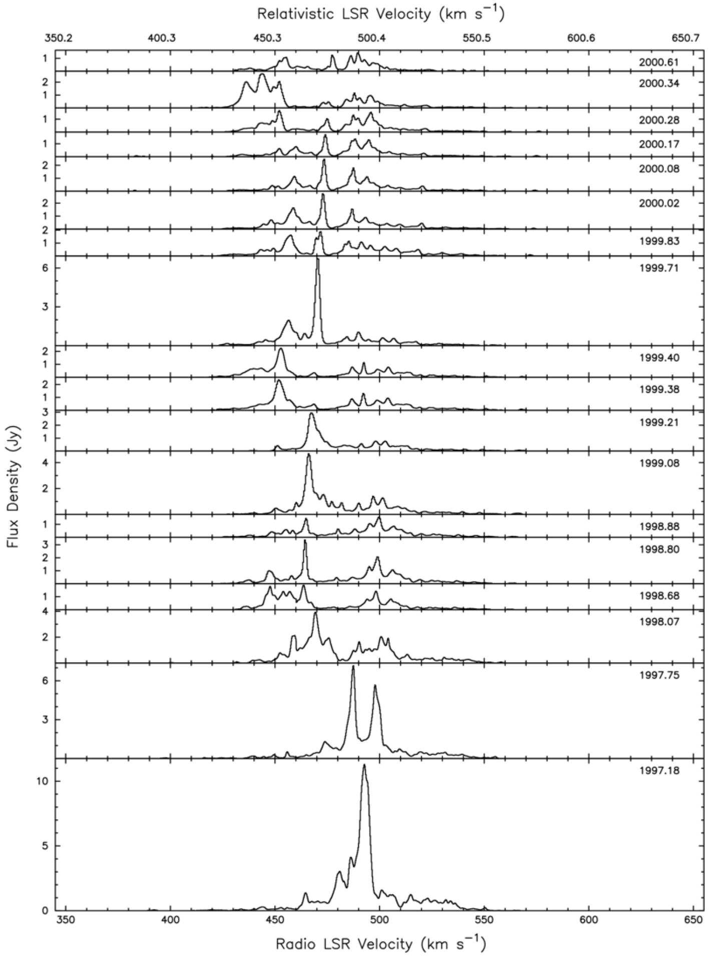
(Reid+2019)

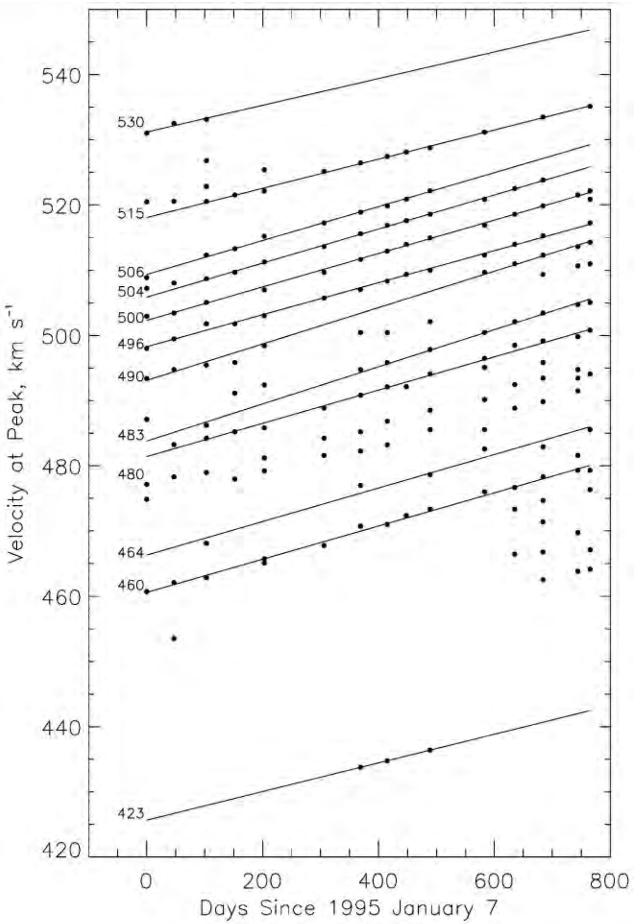
Herrnstein+ (1999); Argon+ (2007); Humphreys+ (2013); Reid+ (2019)

Masers in NGC 4258 (Messier 106)

- The accelerations are measured by following spectral features from individual masers







Bragg+ (2000); Argon+ (2007)

Summary – Lecture 1

- Strong evidence for an expanding Universe
- Strong evidence for a homogeneous and isotropic Universe
- Under FRLW metric, H(z) sensitive to cosmological parameters
- End-to-end check of cosmology: local and inverse distance ladders
- Three-rung local distance ladder: geometry, flux, flux
- The first rung: parallaxes, detached eclipsing binaries, masers

The Cosmic Distance Scale

Lecture 2

Lucas Macri

NSF NOIRLab

Escola JPB Cosmo 2024

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- Casey Papovich (Texas A&M)
- Adam Riess (JHU/STScI)
- Dan Scolnic (Duke Univ.)
- Sherry Suyu (TUM/MPA)
- Mónica Taormina (CAMK)

Recap – Lecture 1

- Strong evidence for an expanding Universe
- Strong evidence for a homogeneous and isotropic Universe
- Under FRLW metric, H(z) sensitive to cosmological parameters
- End-to-end check of cosmology: local and inverse distance ladders
- Three-rung local distance ladder: geometry, flux, flux
- The first rung: parallaxes, detached eclipsing binaries, masers

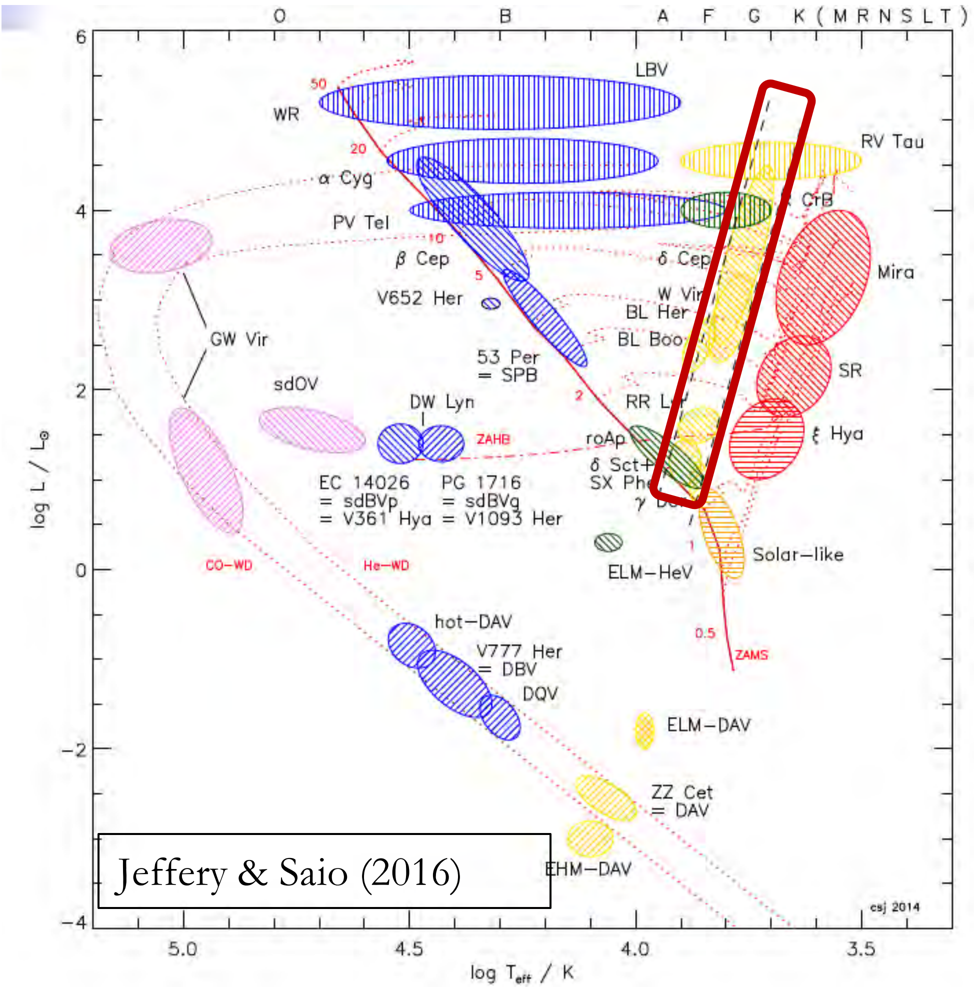
Second Rung: from geometry to flux

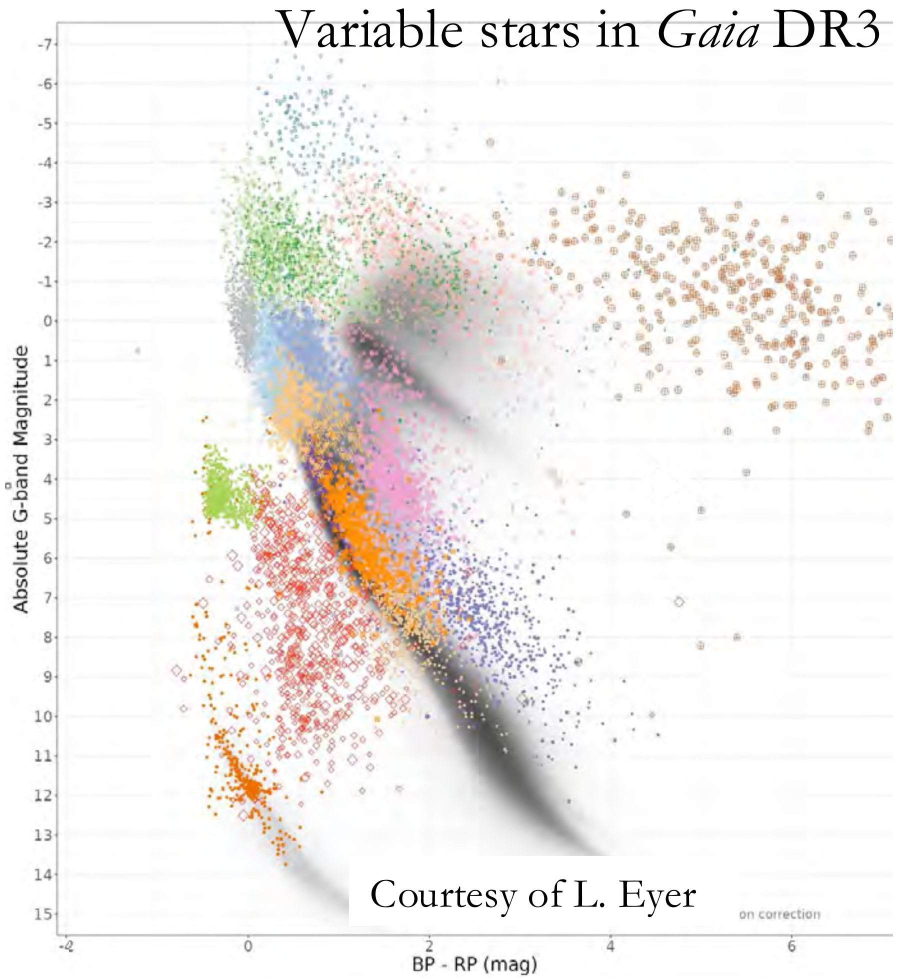
- At some point, we can't measure parallaxes, proper motions, angular diameters, or obtain spectra / radial velocities…
- Requires move from geometry to flux and reliance on the inverse-square law
- Need to develop standard or standard*izable* "candles"
- Use distance-independent property (e.g., temperature) to predict a distance-dependent one (e.g., luminosity) → D^2=L/f
- We may also be able to use standard "rulers" or "sirens" (more on that later…)

Standard candles in the Color-Magnitude Diagram

- Some types of variable stars may be useful standard candles
  - Regular magnitude changes → relatively easy to identify and classify
  - Period of variability → Distance-independent property
- We may also use the luminosity functions of stars in certain phases of evolution
- We may also use specific stellar types if they can be accurately identified
- Use parallaxes / binaries / masers (MW, MCs, NGC 4258) to calibrate their absolute magnitudes or luminosities

Standard candles in the Color-Magnitude Diagram

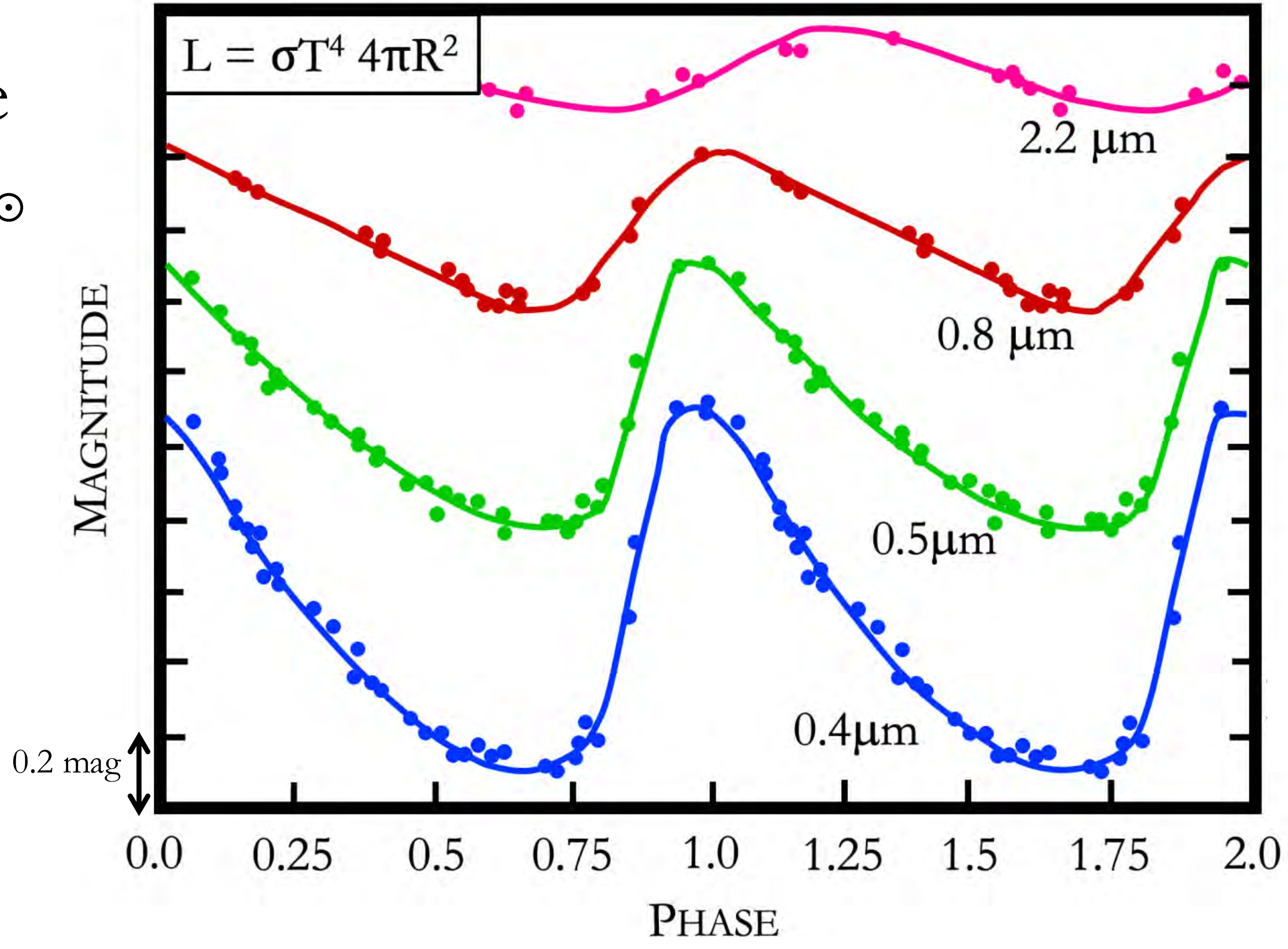




Credit: Dr. G. Clementini

Cepheid variables

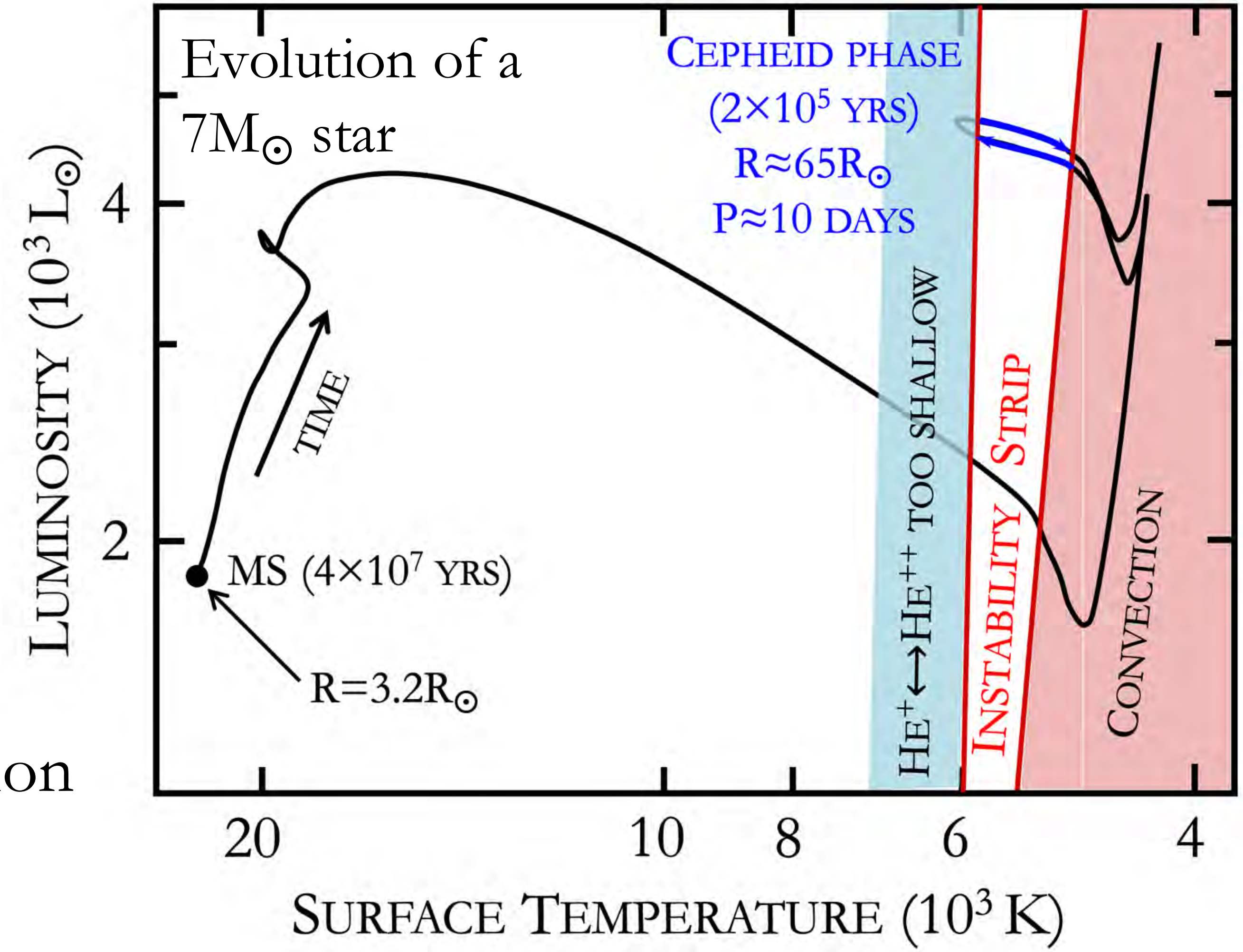
- Brief evolutionary phase for stars with ~4−15 $M_{\odot}$ (1% of lifetime, $10^{3\text{-}5}$ yr)
- Regular pulsations with periods of 2 to 100 days
- Oscillations are driven by changes in opacity ($He^{+} \Leftrightarrow He^{++}$)



Based on Madore & Freedman (1991)

Cepheid variables

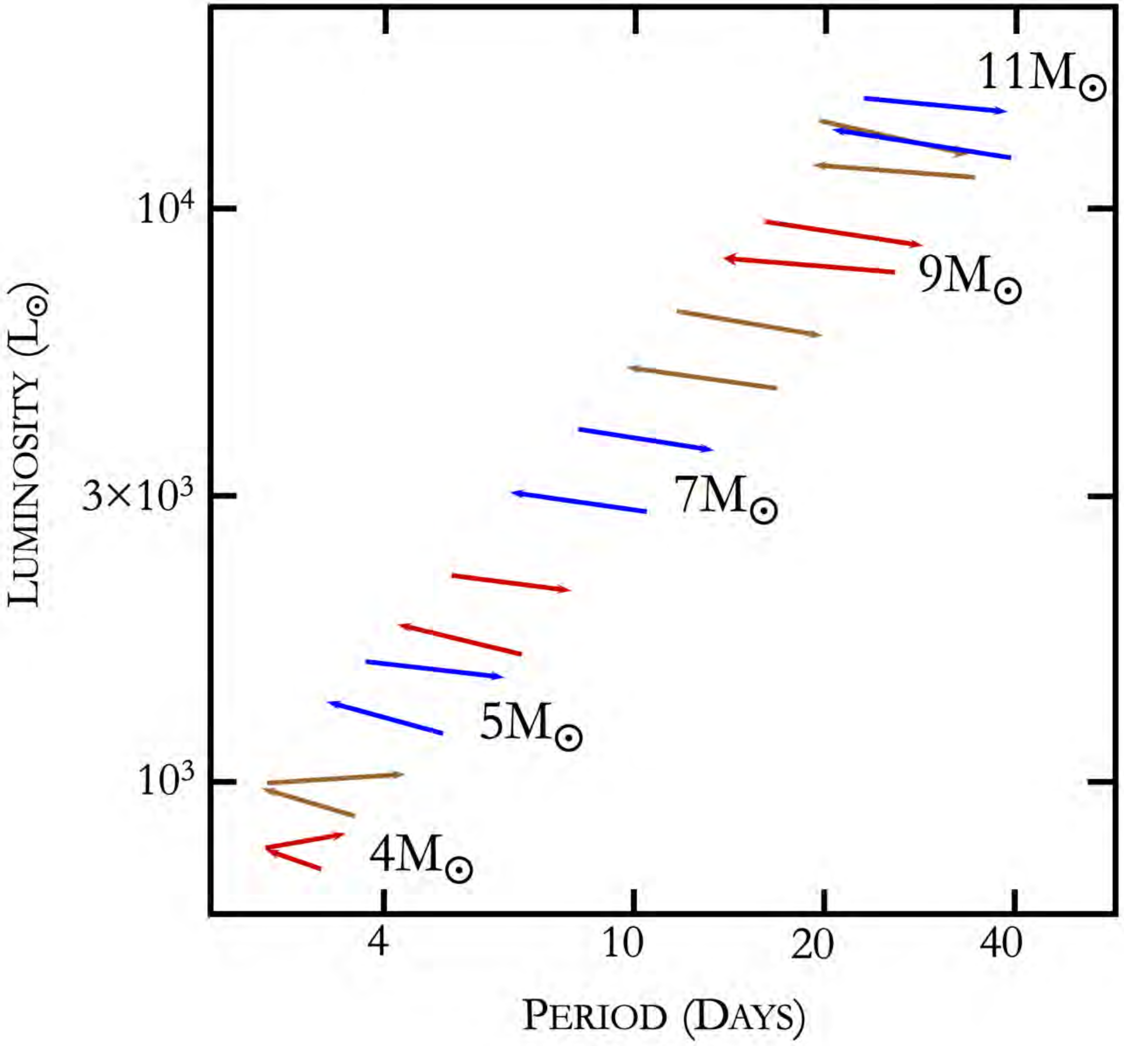
- Cepheids follow a "loop" in the CMD as the mean molecular weight of their core changes due to He fusion
- As the radius of a Cepheid changes, so does its density and thus its period of pulsation (Period α $\varrho^{-1/2}$)



Fiorentino+(2002), Pietrinferni+(2004)

Cepheid variables

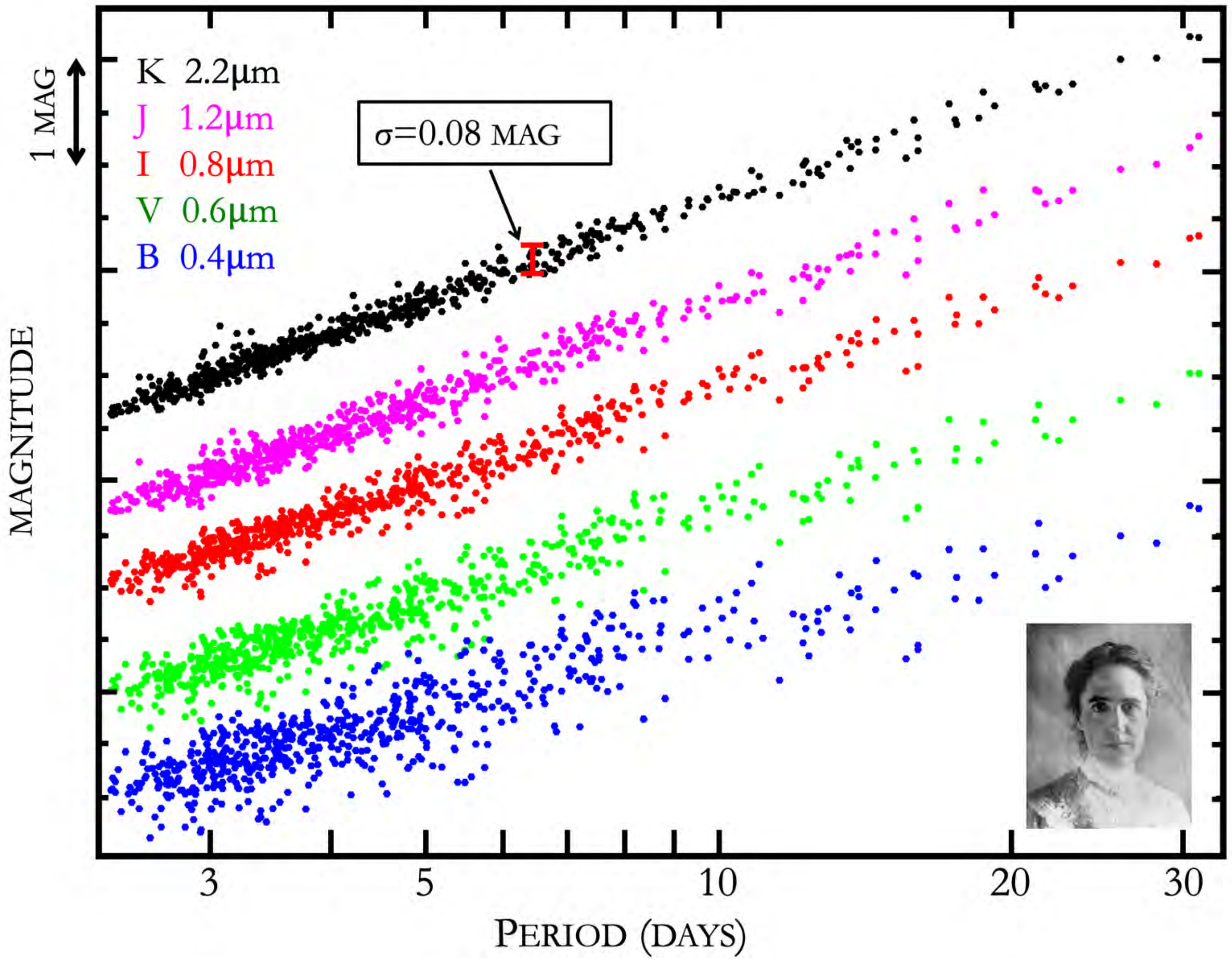
- Calculate period of pulsation and luminosity during the "loop" for a series of masses…
- This is the theoretical version of the Period-Luminosity relation



Alibert+ (1999)

Cepheid variables

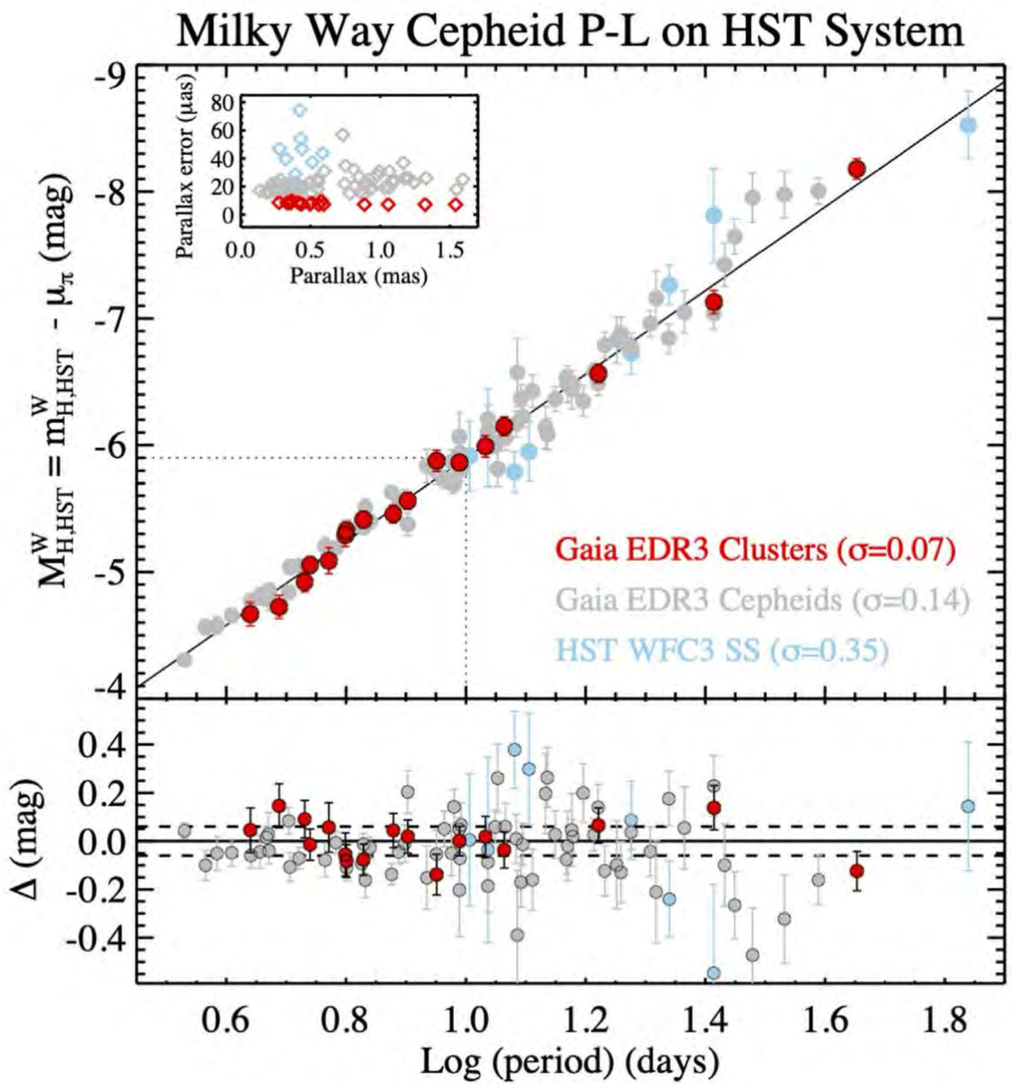
- Here are the observed Cepheid P-L relations (PLRs) or "Leavitt Laws" in the LMC
- Cepheids are easiest to discover and phase at optical wavelengths
- They yield PLRs with the lowest dispersion at near-infrared wavelengths



Udalski+ (1999); Macri+(2015)

Cepheid variables in the Milky Way

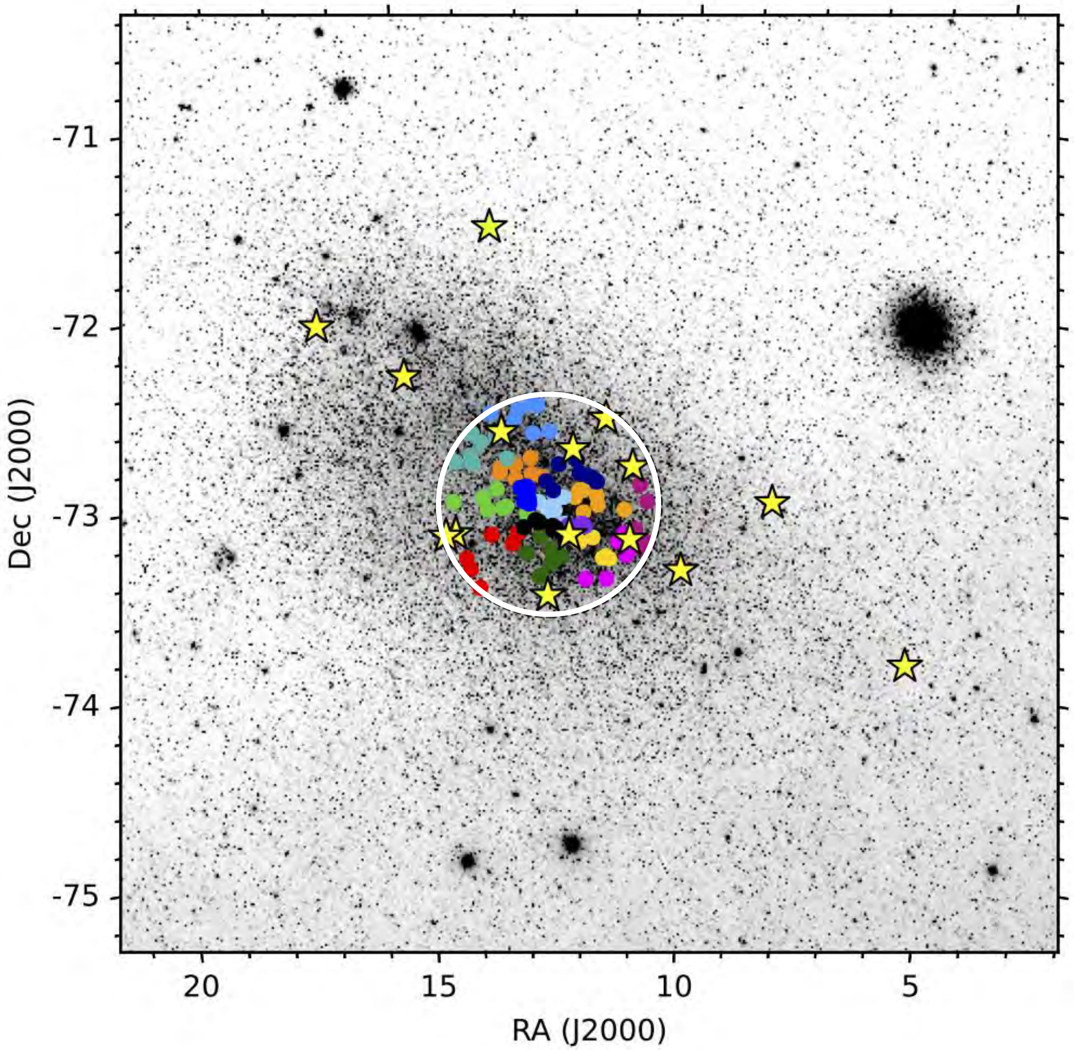
- The calibration of the PLR in the Milky Way relies on parallaxes, since each star is at a different distance
- Currently based on *HST* scanning and *Gaia* parallaxes
- The Cepheids have magnitudes measured with *HST* (critical to avoid systematic uncertainties in zeropoints)



Riess+ (2022b)

Cepheid variables in the Magellanic Clouds

- The calibration of the PLR in the Magellanic Clouds relies on distances based on DEBs
- The Cepheids have magnitudes measured with *HST* (critical to avoid systematic uncertainties in zeropoints)
- This required the use of a new technique to slew Hubble farther than normally possible



Breuval+ (2024)

Cepheid variables in the Magellanic Clouds

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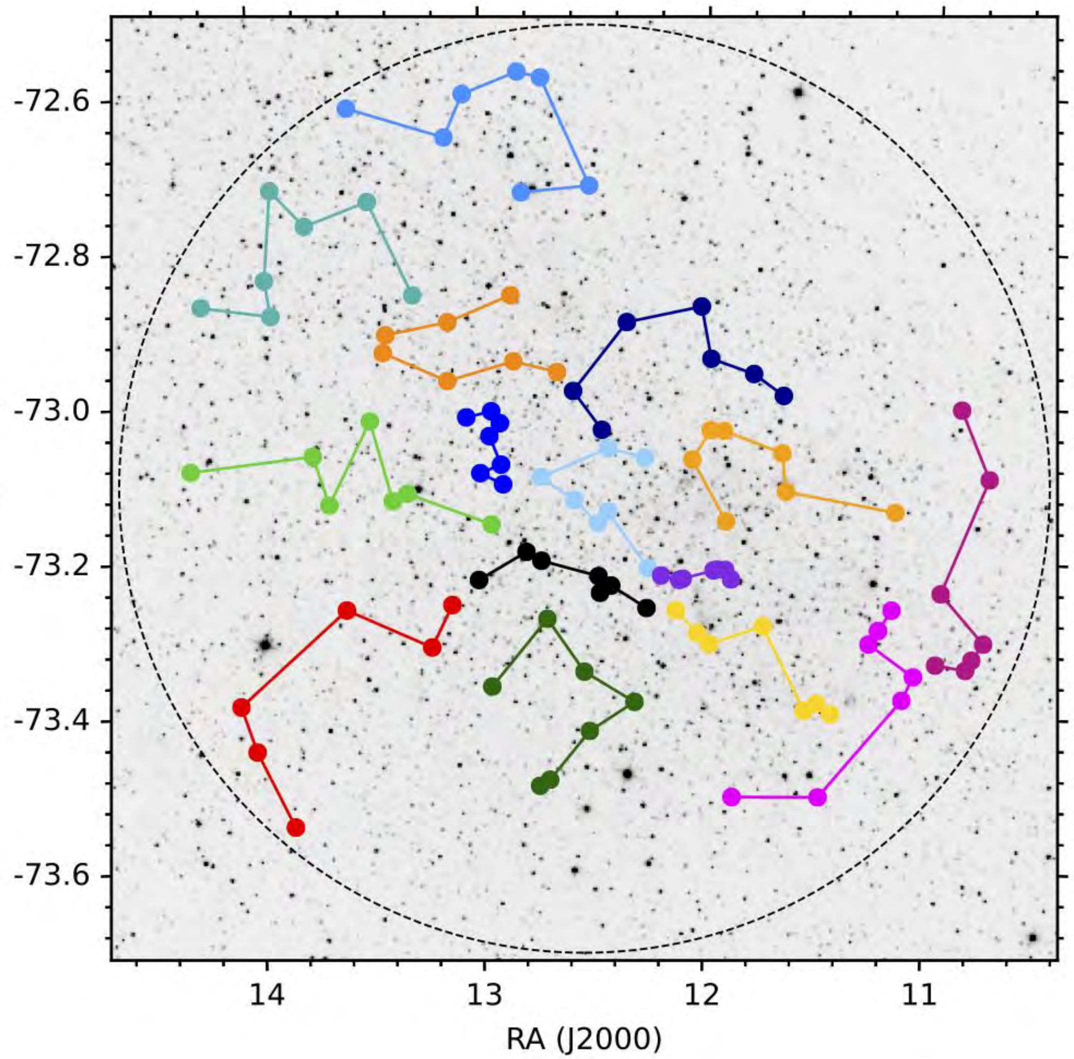
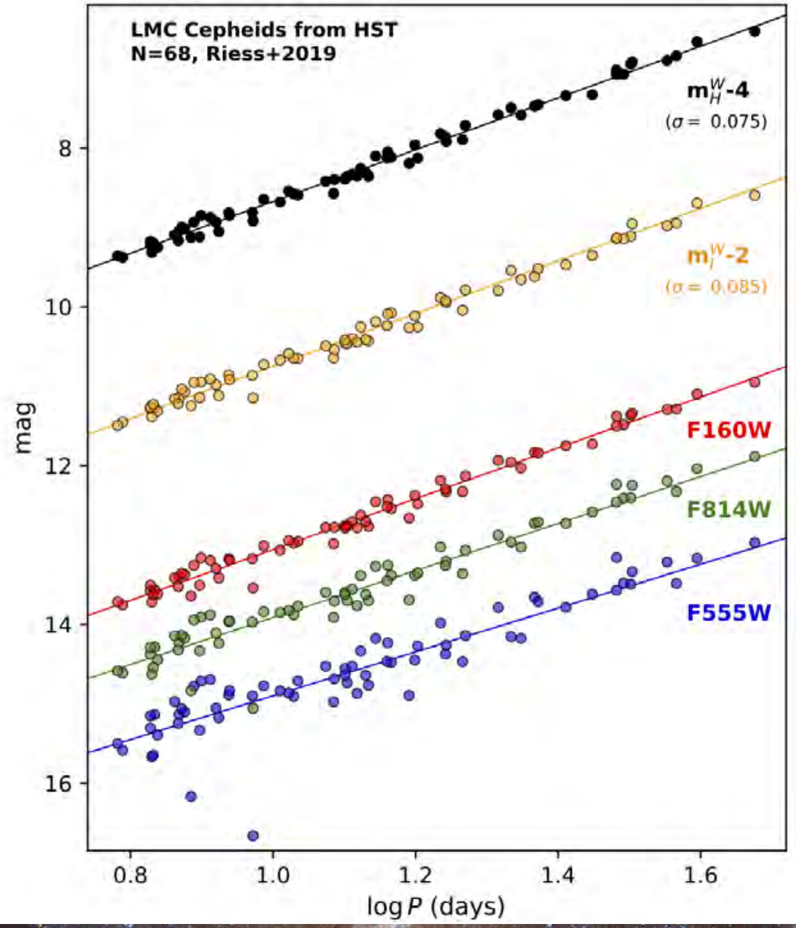
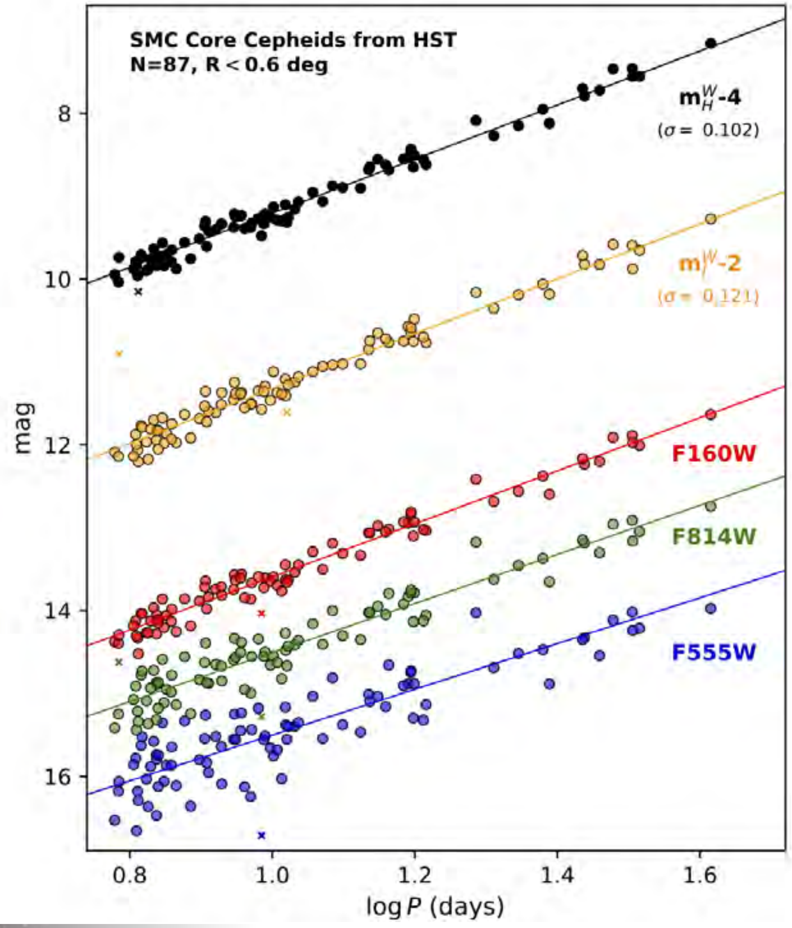


Breuval+ (2024)

Cepheid variables in the Magellanic Clouds

- LMC & SMC PLRs based on *HST* photometry





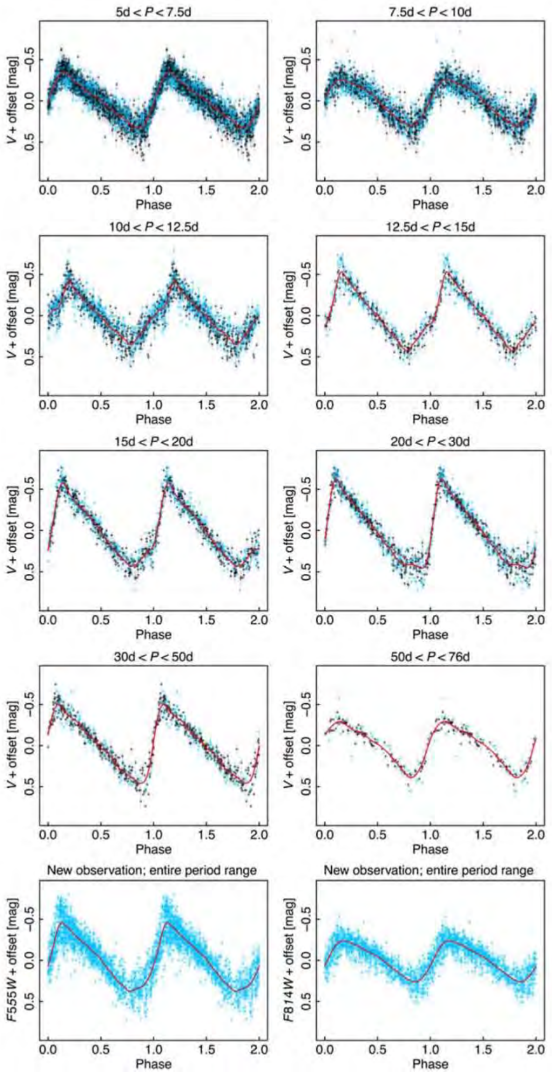
Riess+ (2019); Breuval+ (2024)

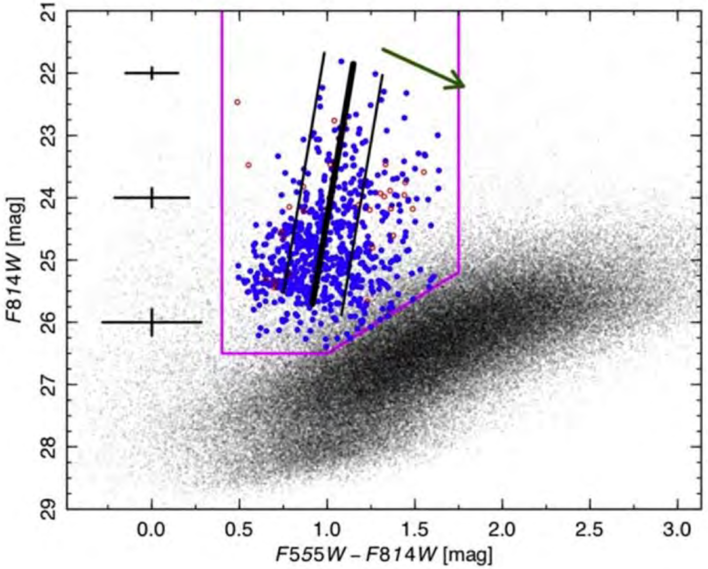
Cepheid variables in NGC 4258

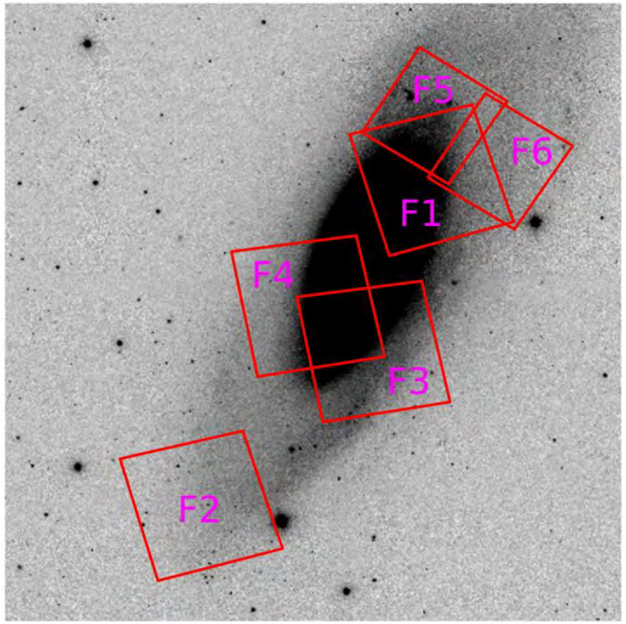
- The calibration of the PLR in NGC4258 relies on the maser-based distance
- Multiple surveys (ground and *HST*) discovered the variables
- The Cepheids have magnitudes measured with *HST* (critical to avoid systematic uncertainties in zeropoints)

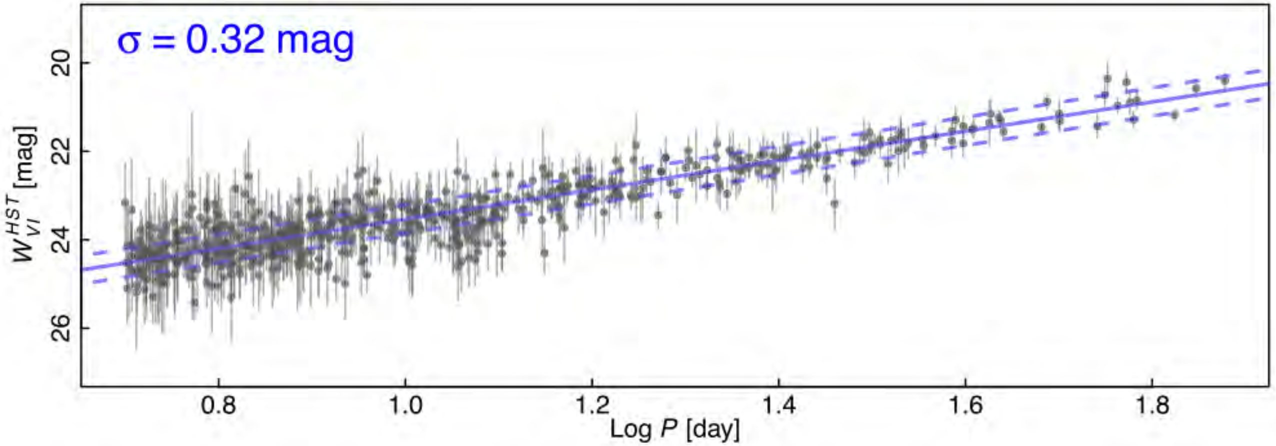
Hoffmann+(2016)

Cepheid variables in NGC 4258







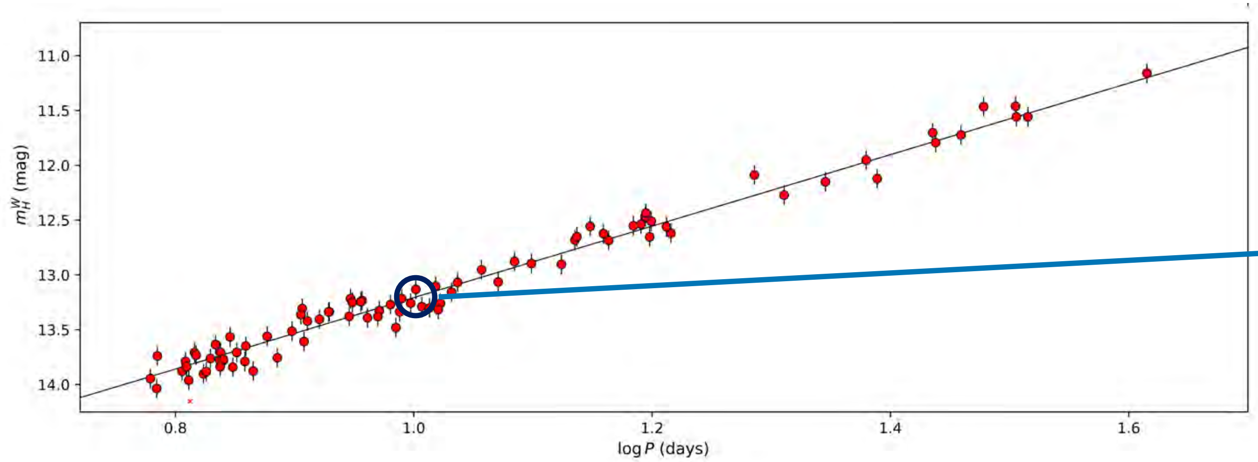


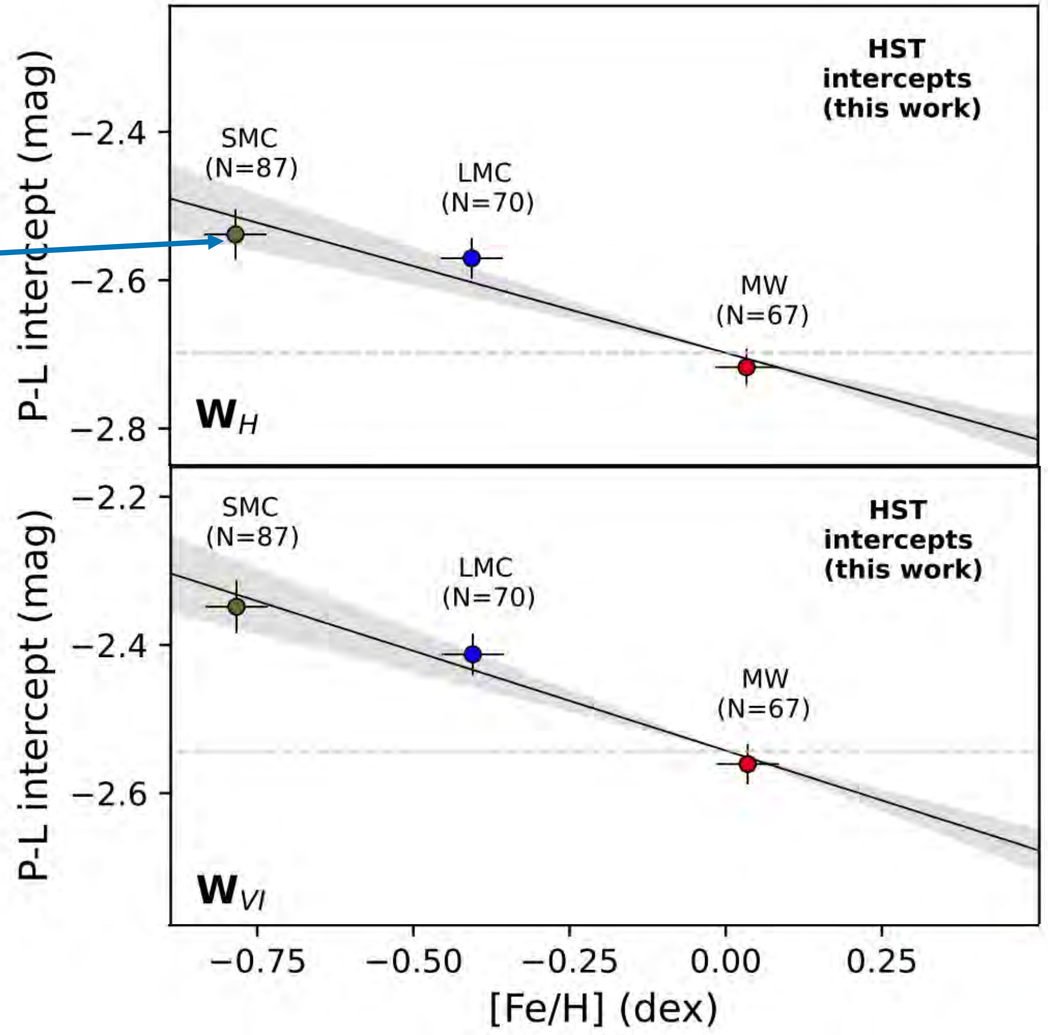
Yuan+ (2022)

Metallicity Dependence of Cepheid PLRs

- Theoretical pulsation models indicate that the luminosity of a Cepheid of a given period will depend on its abundances
- This “metallicity dependence” can be empirically measured by comparing the intercepts of the PLRs in the Milky Way and the Magellanic Clouds (and NGC 4258) since their Cepheids span a fairly large range in abundance

Metallicity Dependence of Cepheid PLRs



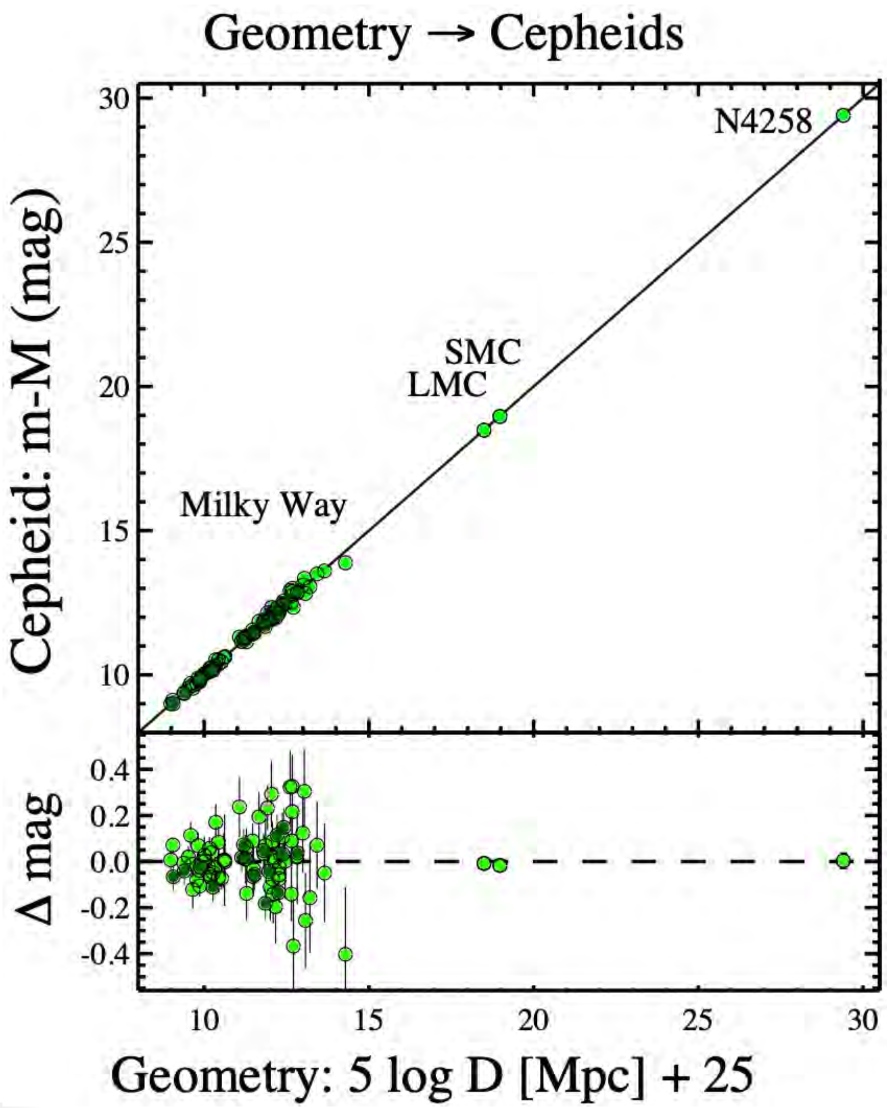


- Most recent determinations:
  γ_{VI}=-0.264±0.058 mag/dex
  γ_H =-0.234±0.052 mag/dex

Breuval+ (2024)

Cepheid calibration for the “first rung”

- Putting it all together, here’s the state-of-the-art calibration of the Cepheid PLR using geometric distance indicators

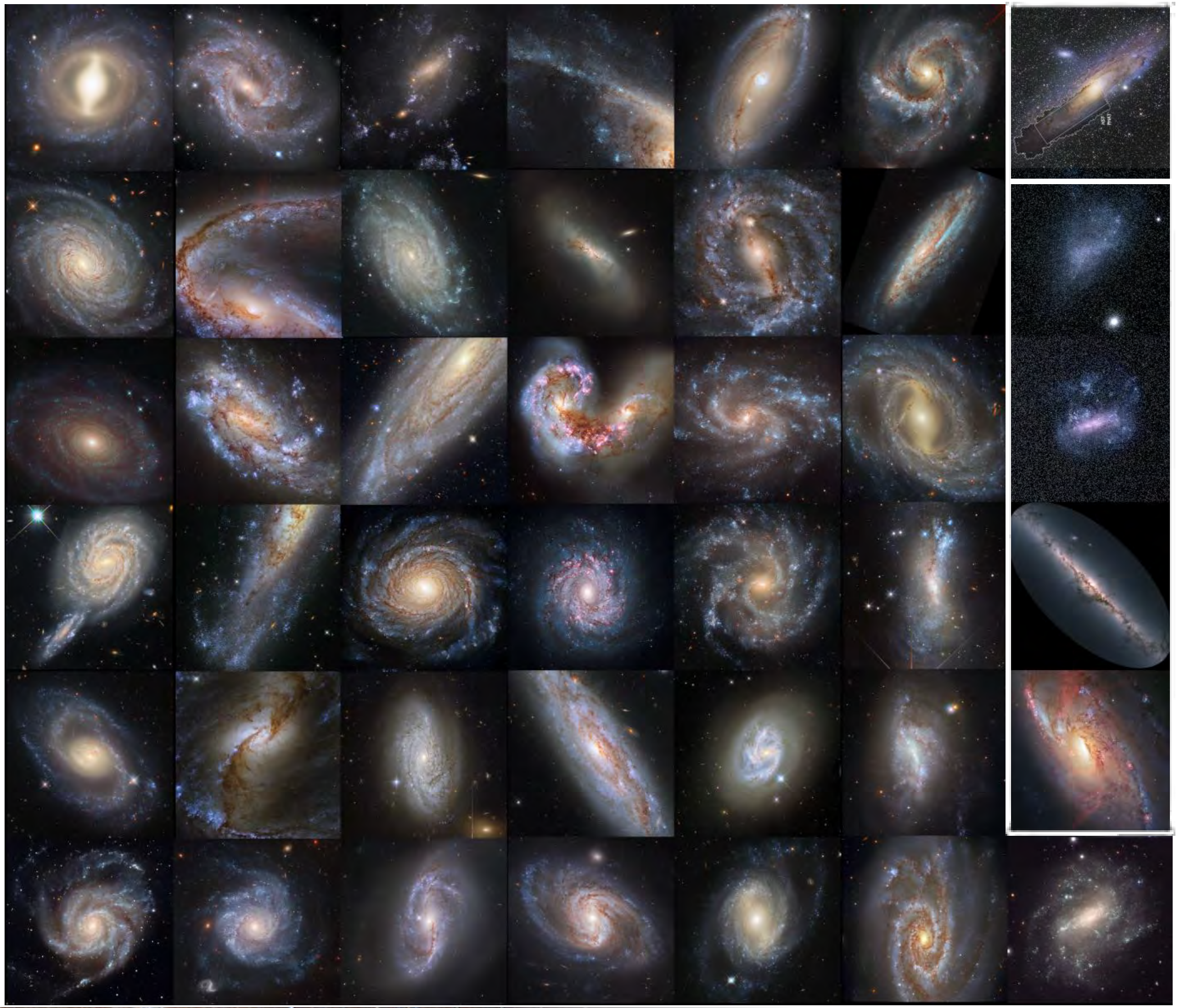


Based on Riess+ (2022a)

Cepheid variables in the "second rung"

- Now that we have a precise and accurate geometric calibration of the Cepheid PLR based on four "first rung" galaxies, we can apply it to galaxies of interest
- The SH0ES program (PI: A. Riess) has used *Hubble* since 2006 to discover >3,000 Cepheids in 37 galaxies out to D=50 Mpc
- All Cepheids are imaged with the same telescope and cameras, negating what used to be a large source of uncertainty
- Thorough "artificial star" simulations to correct for expected photometric biases

Cepheid variables in SH0ES sample



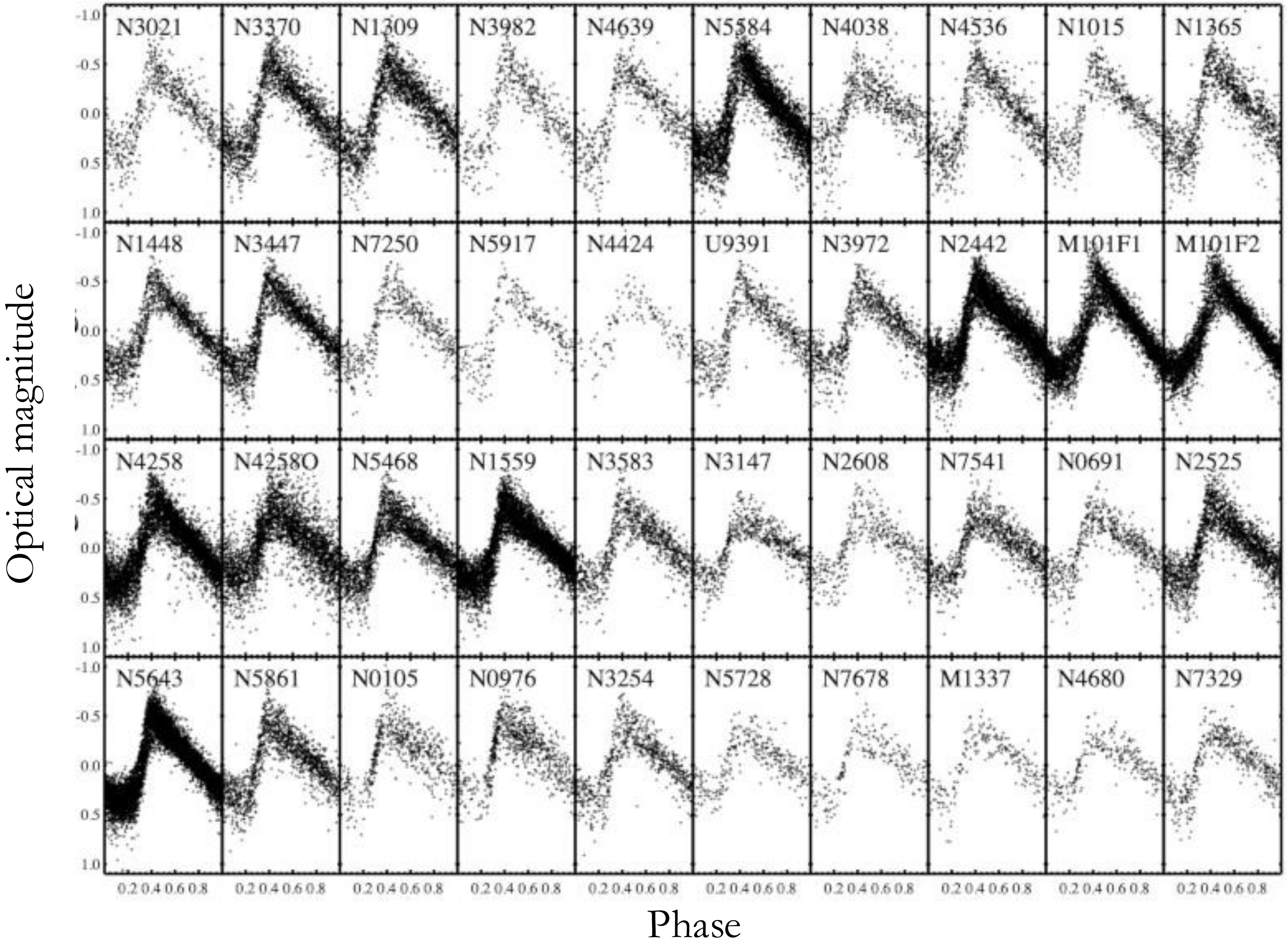
"Second rung"
Targets

Supporting
role (M31)

"First rung"
Calibrators

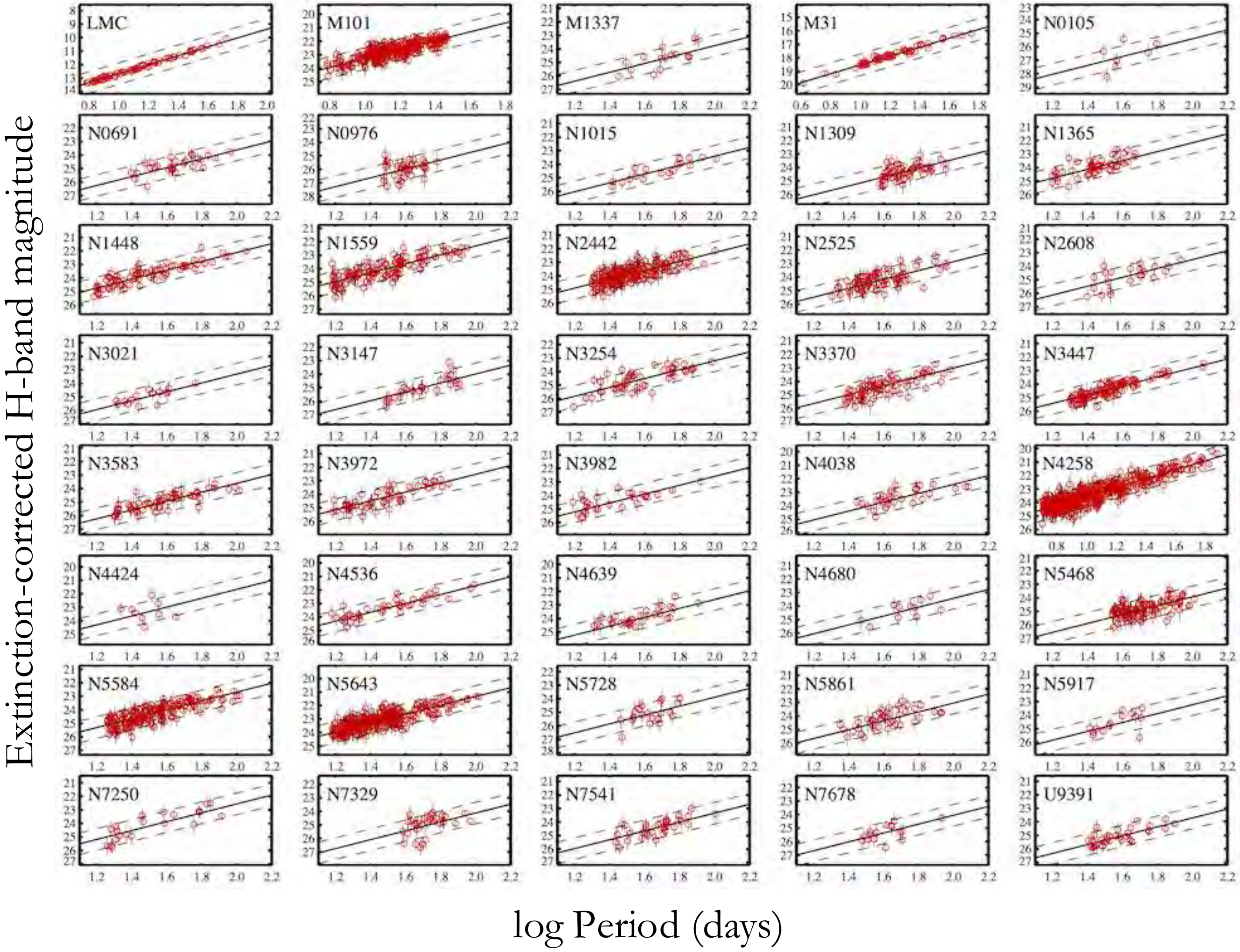
Riess+ (2022a)

Cepheid variables in SH0ES sample



Riess+ (2022a)

Cepheid variables in SH0ES sample

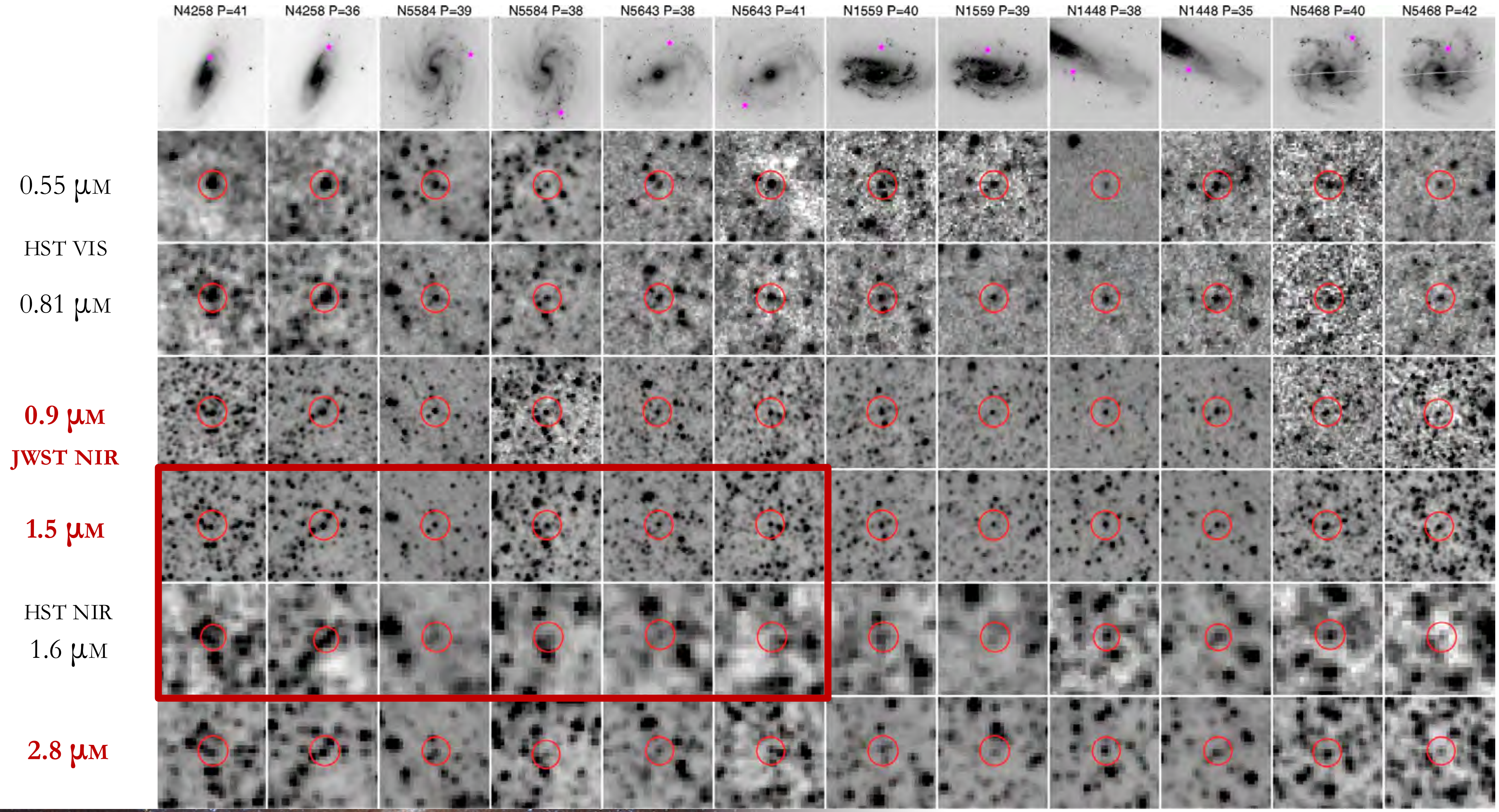


Riess+ (2022a)

Cepheid variables with *JWST*

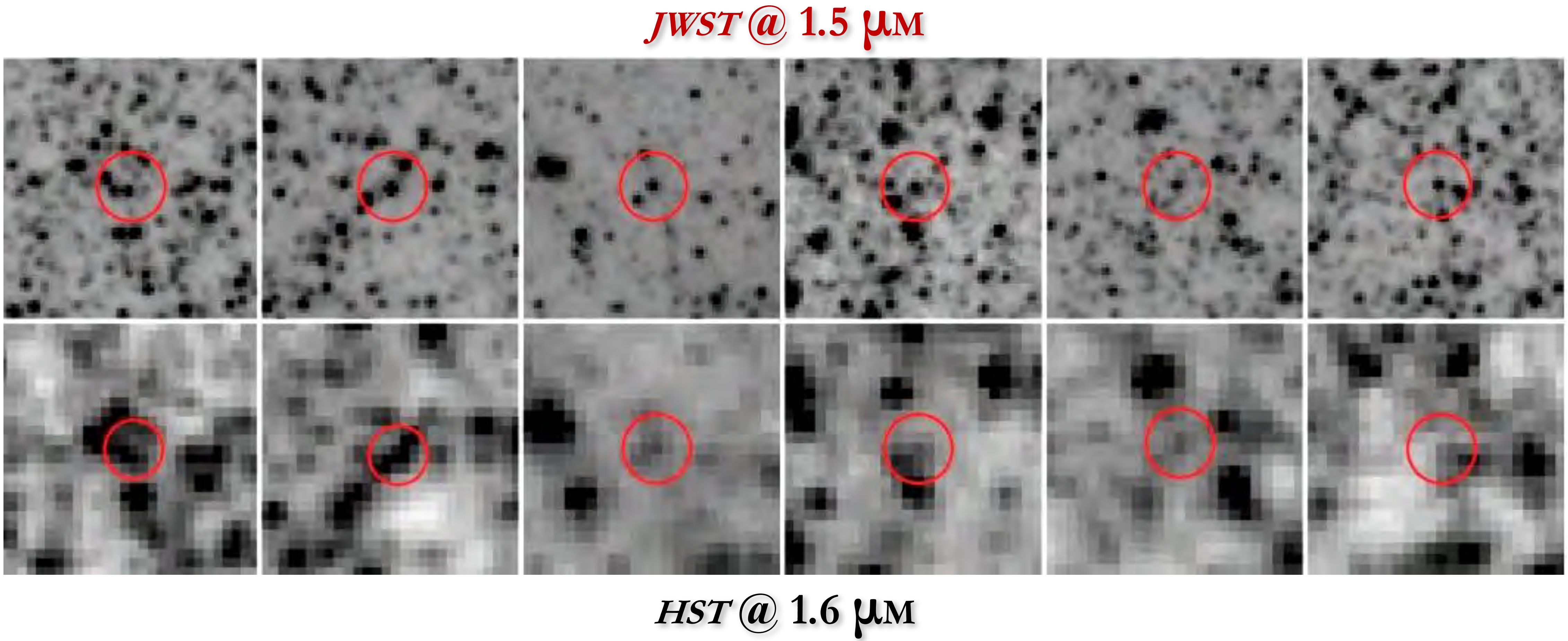
- Recent observations with *JWST* in excellent agreement with *HST* – proving photometric biases were properly corrected
- Given the superior resolution of *JWST*, the resulting PLRs have much narrower dispersion than their *HST* counterparts
- *JWST* sample (N=14 galaxies) still relatively small compared to *HST* (N=37) so it cannot yet deliver a competitive value of H_0

Cepheid variables with *JWST*



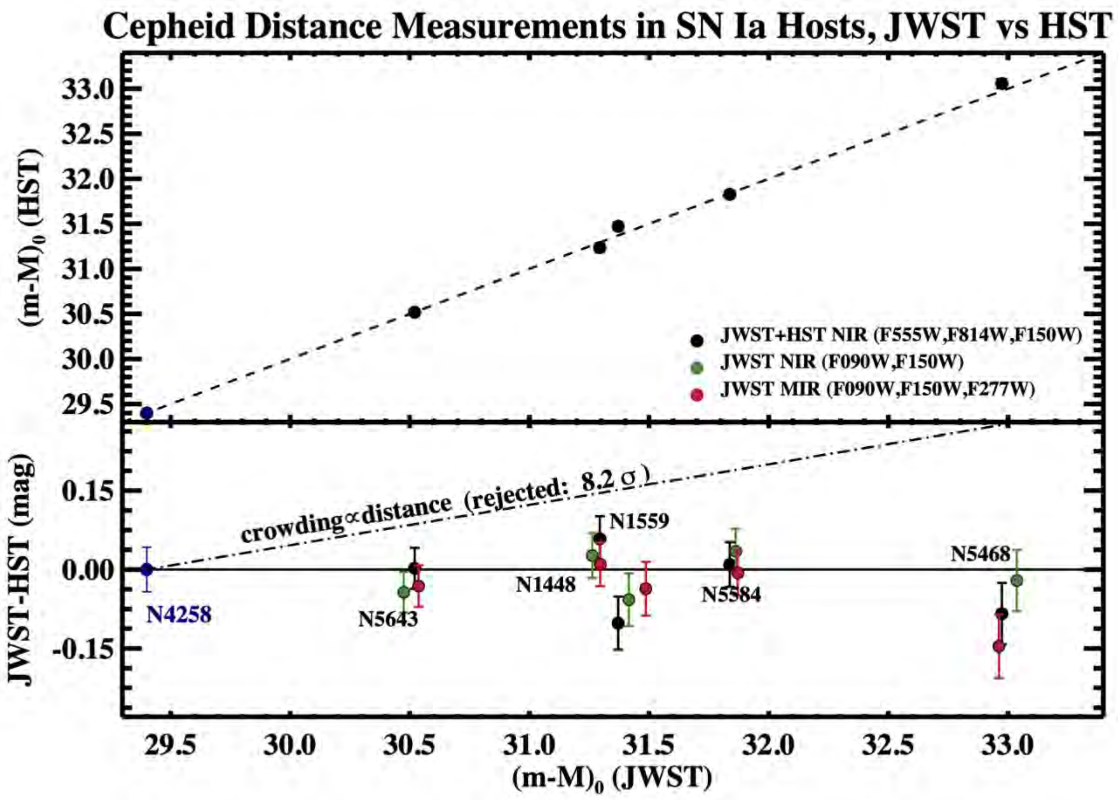
Riess+ (2024a)

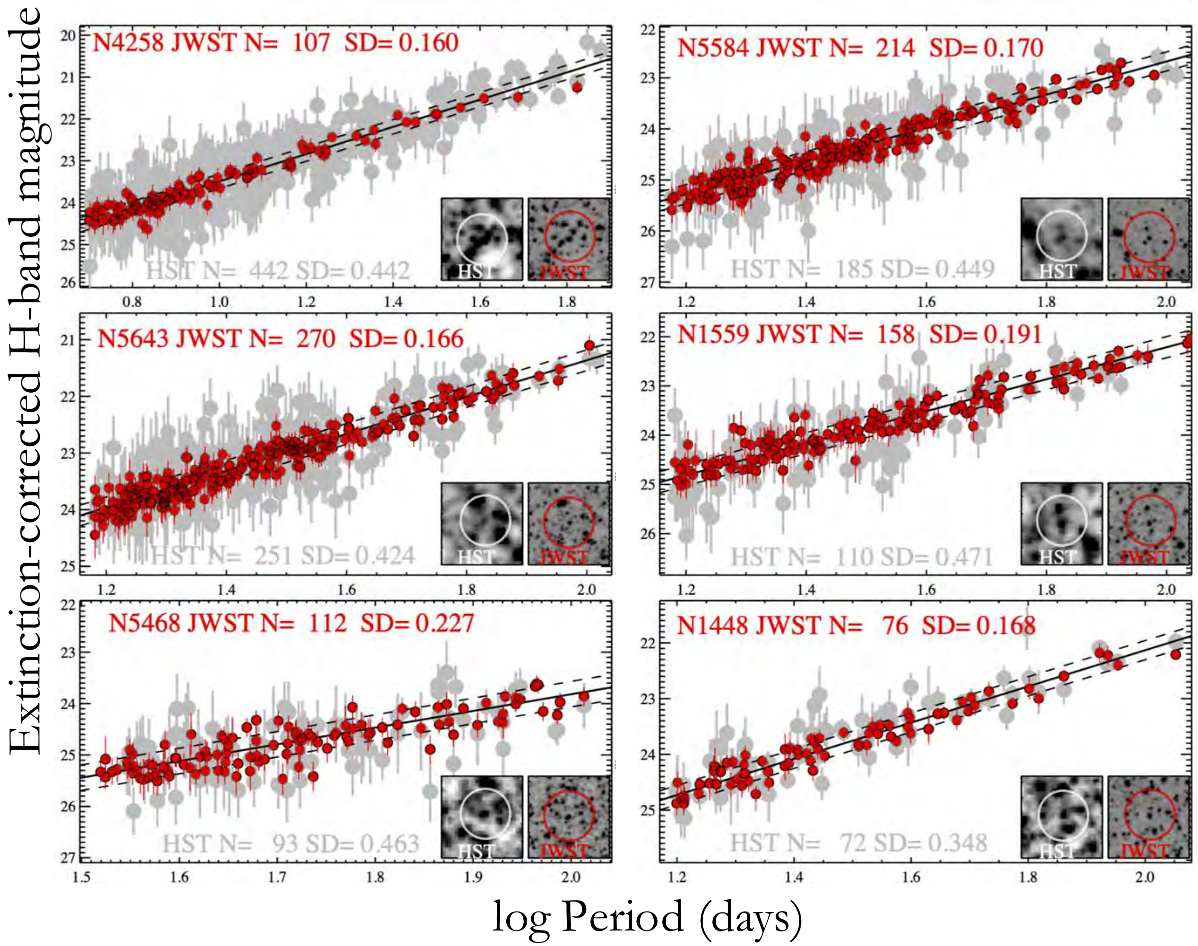
Cepheid variables with *JWST*



Riess+ (2024a)

Cepheid variables with *JWST*





Riess+ (2024a)

Low-mass stars as distance indicators

- Low-mass stars (0.5-2.5 $M_\odot$) can also serve as distance indicators during certain phases of their evolution
- We can use luminosity functions (LFs) as well as PLRs
- LFs: Tip of the Red Giant Branch (TRGB)
  LFs: J-band Asymptotic Giant Branch (JAGB)
- PLRs: Mira variables
  PLRs: RR Lyrae variables

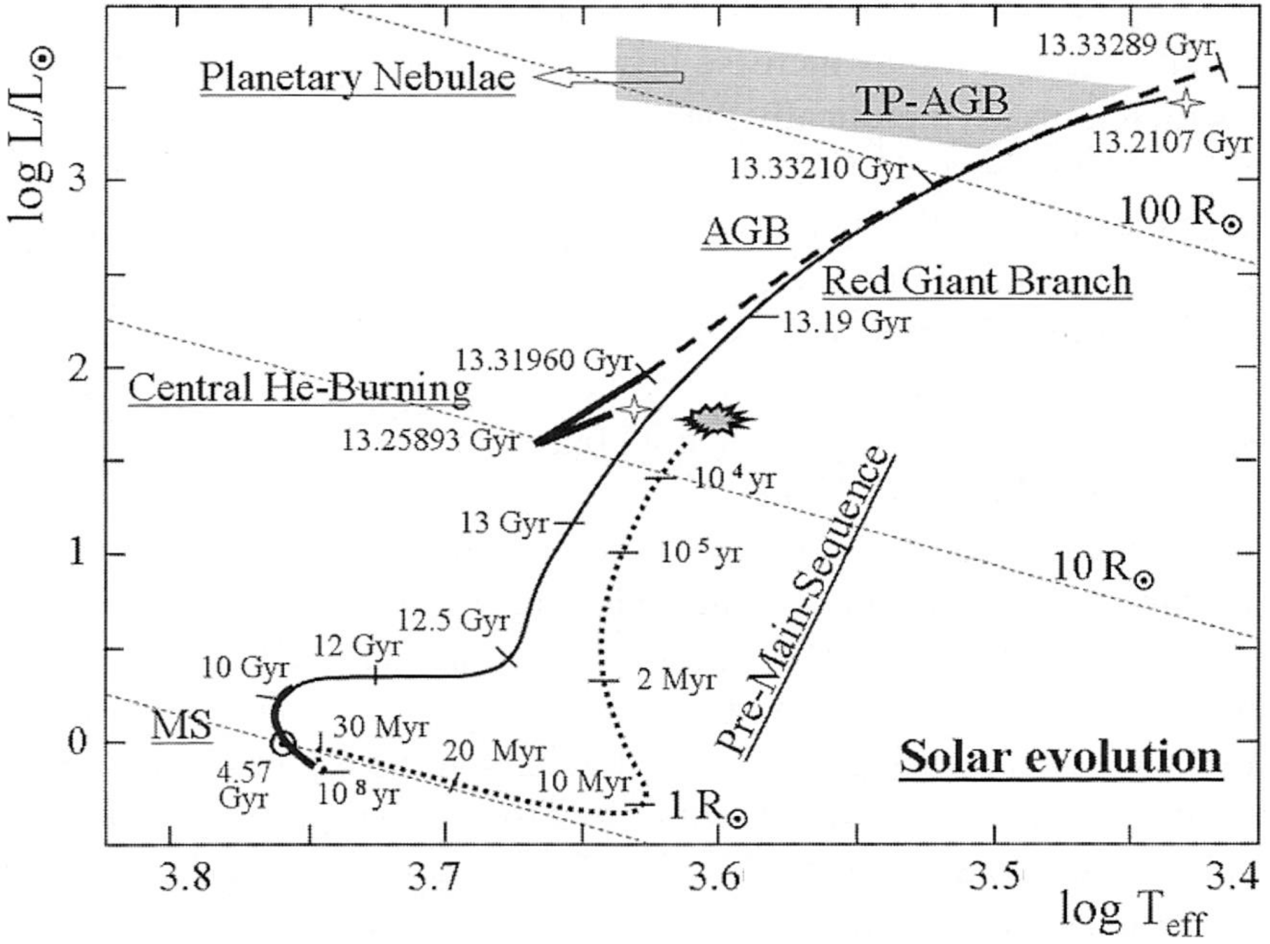
Evolution of low-mass stars (0.5-2.5 $M_\odot$)

- Main sequence (H core fusion)
- Red giant branch (H shell fusion)
- Tip of RGB (He flash, ignition of He core fusion)
- Horizontal branch (He core, H shell fusion): RR Lyrae
- Asymptotic giant branch (He & H shell fusion): JAGB, Miras
- White dwarfs: Supernovae Ia

Credit: Dr. R.-P. Kudritzki

Tip of the Red Giant Branch

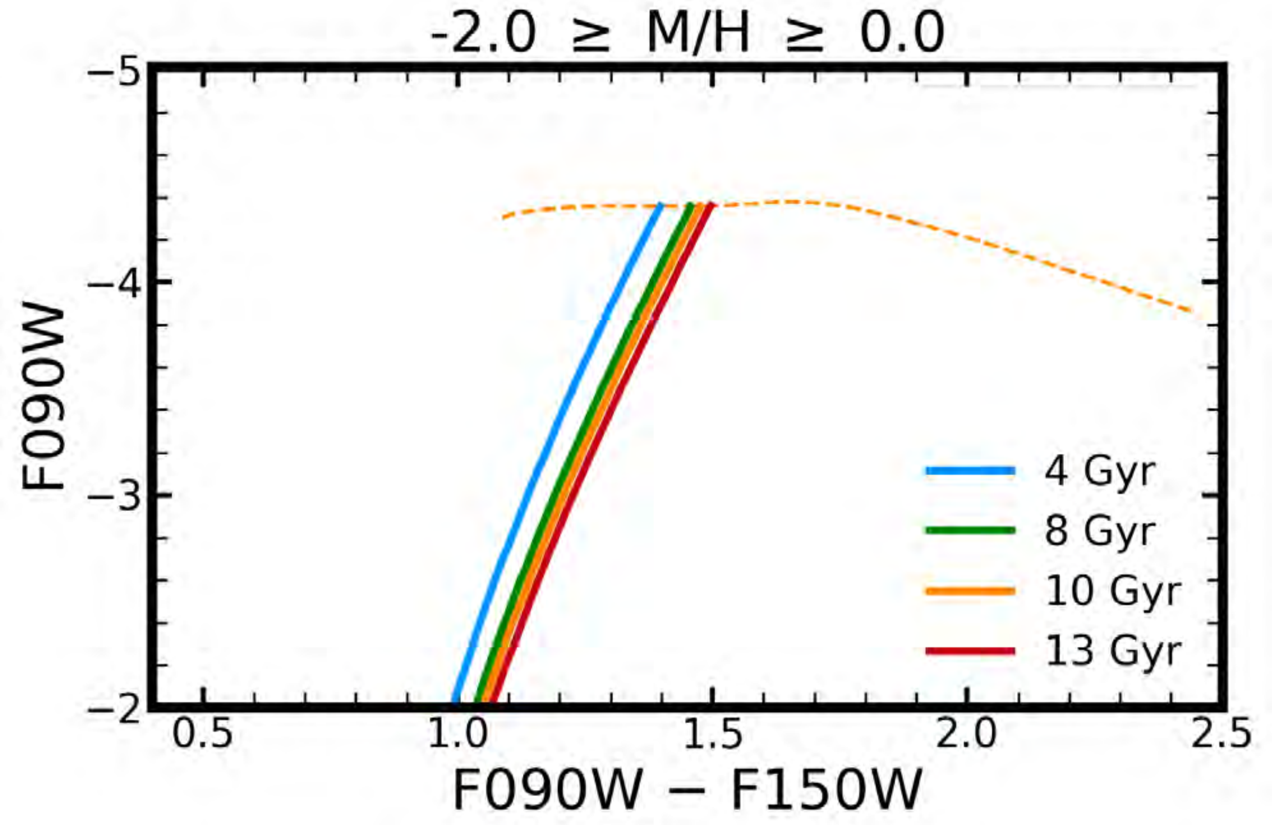
- All low-mass stars ignite their degenerate He cores at ~the same luminosity
- The feature can be detected in a well-populated CMD (Frogel+1983, Lee+1993)
- The luminosity depends on stellar abundance and age of population



Maeder (2009)

Tip of the Red Giant Branch

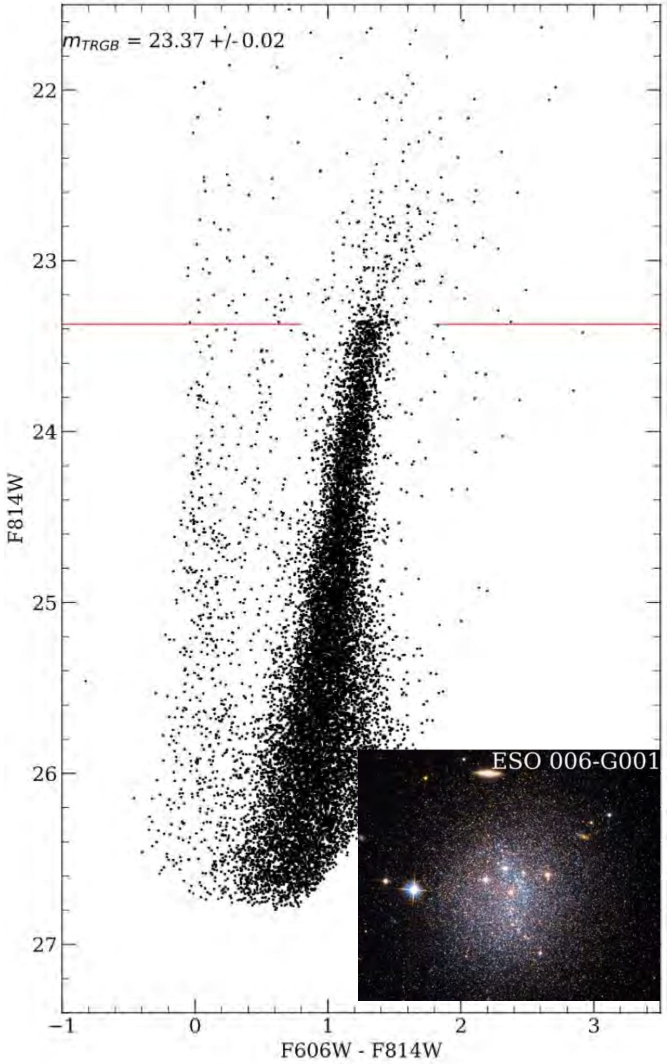
- Stellar evolutionary models tell us that the TRGB dependence on age and abundance is smallest for magnitudes measured close to 0.8μm (I-band)
- At this wavelengths, the TRGB should appear as a horizontal feature in the CMD



Anand+ (2024a)

Tip of the Red Giant Branch

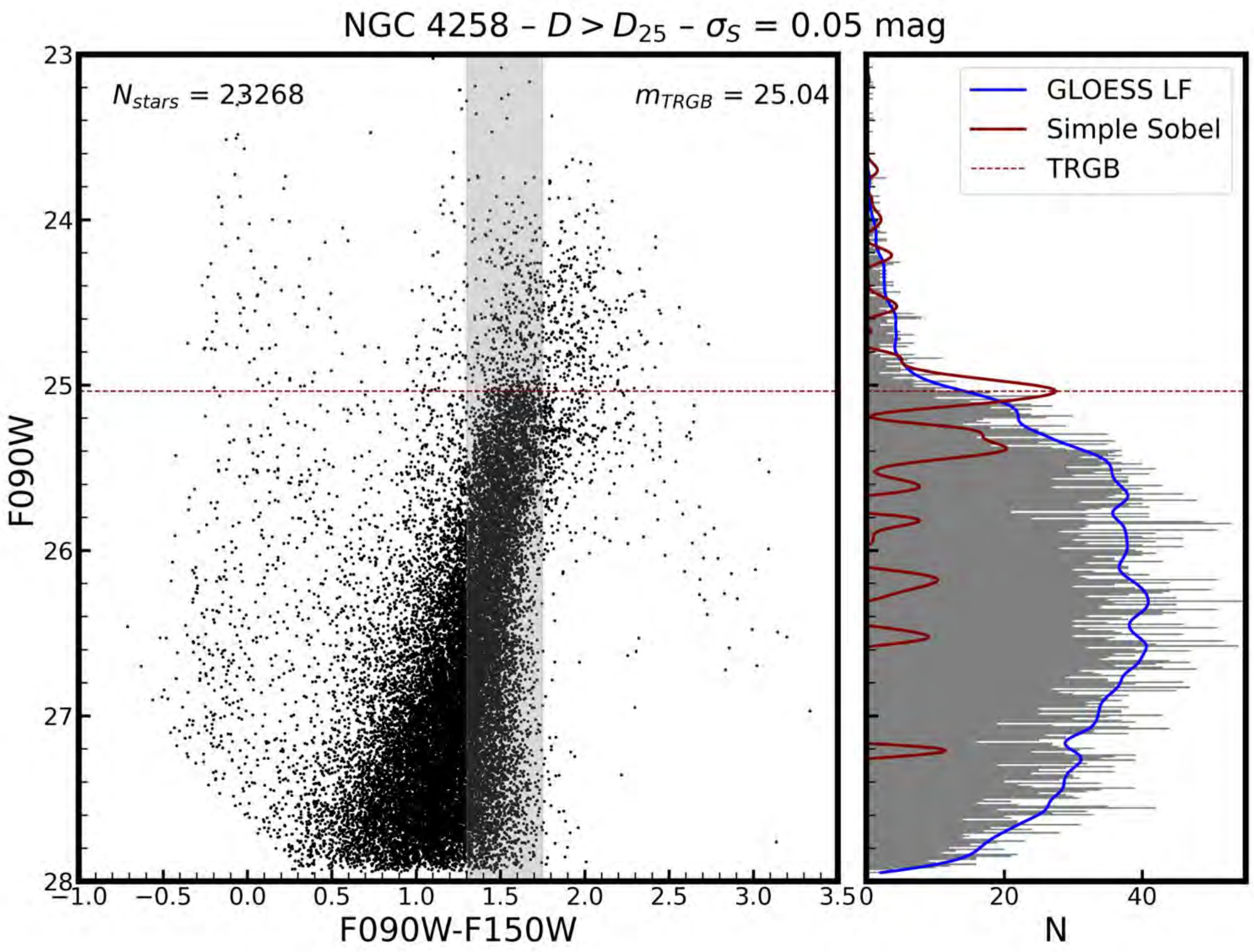
- Stellar evolutionary models tell us that the TRGB dependence on age and abundance is smallest for magnitudes measured close to 0.8μm (I-band)
- Detection of this feature in the RGB LF requires a well-populated CMD
- Contamination by AGB stars can be minimized by observing regions without much recent star formation



Anand+ (2021)

Tip of the Red Giant Branch

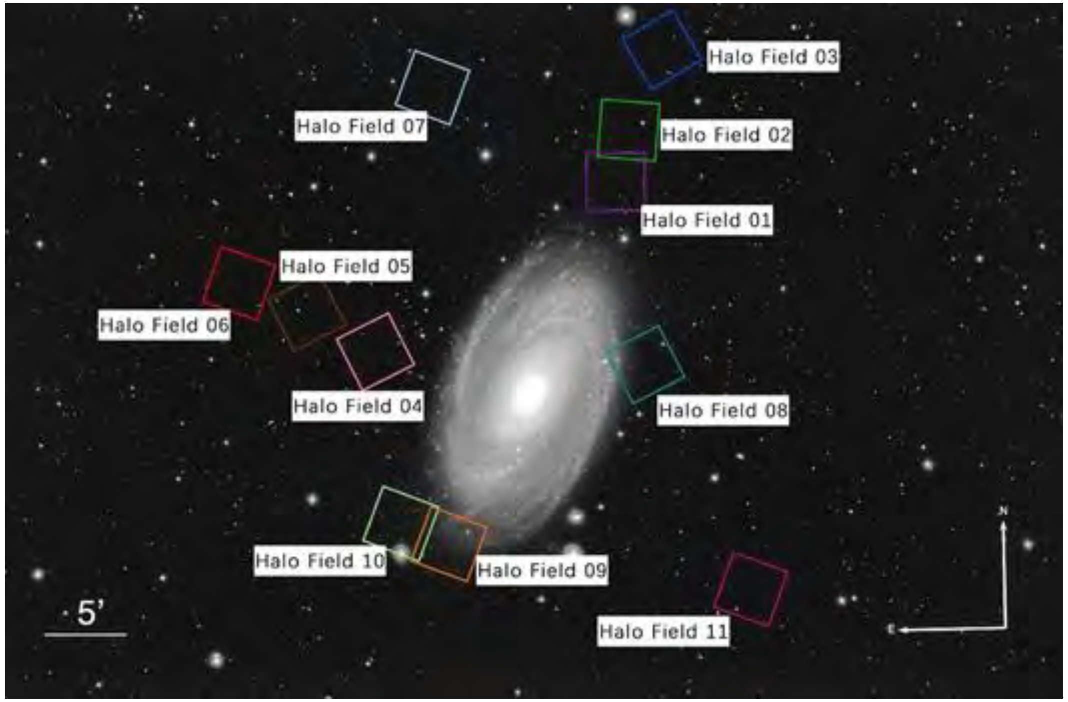
- Absolute calibration of the TRGB using *JWST* observations of halo fields within NGC4258, coupled to the maser distance
- Also possible in Milky Way and LMC, with some complications (parallaxes, dust)

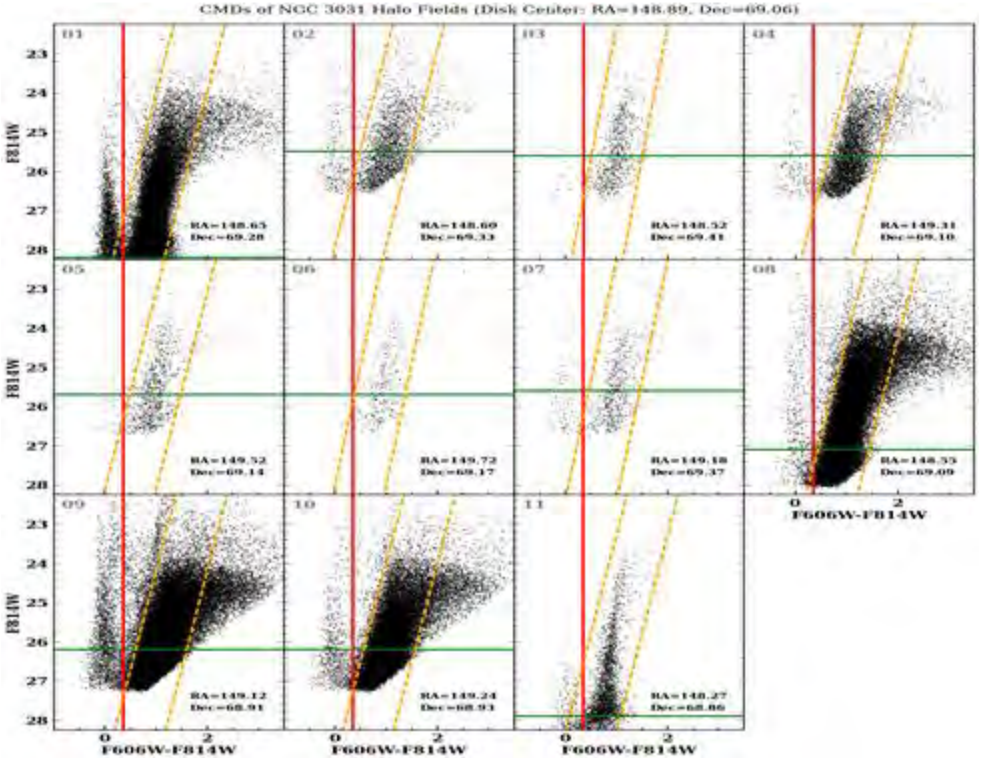


Anand+ (2024a)

Tip of the Red Giant Branch

- Recent development: tip detection is affected by contrast with RGB
- Study based on 50 halo fields across 10 galaxies using various metrics

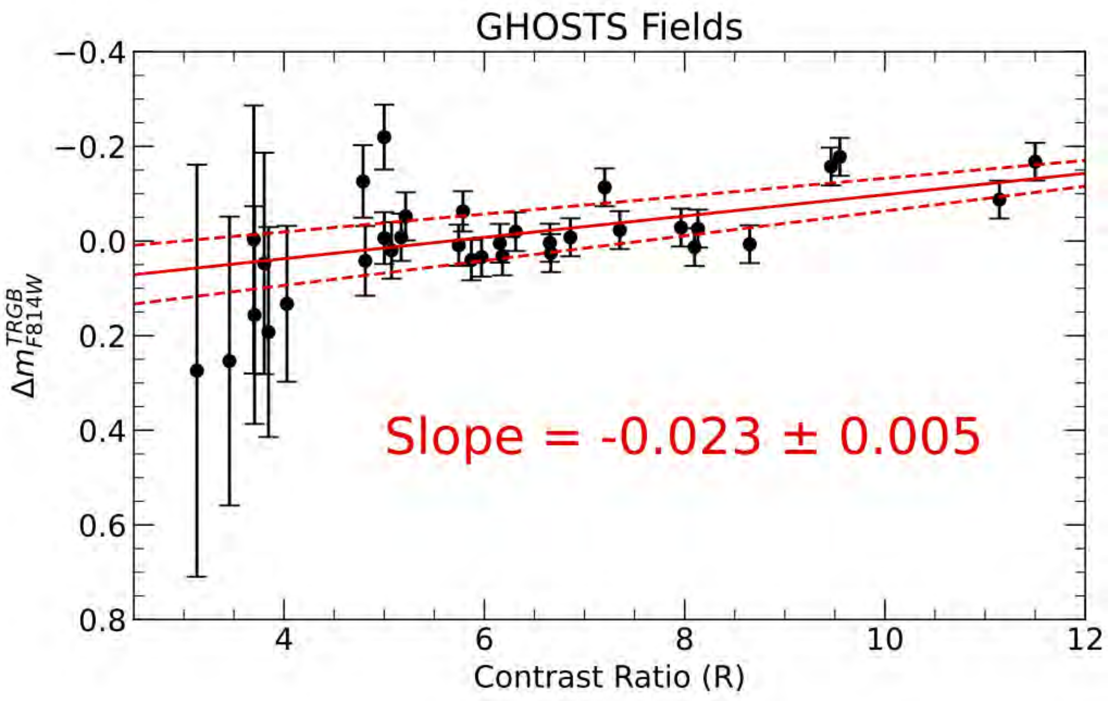


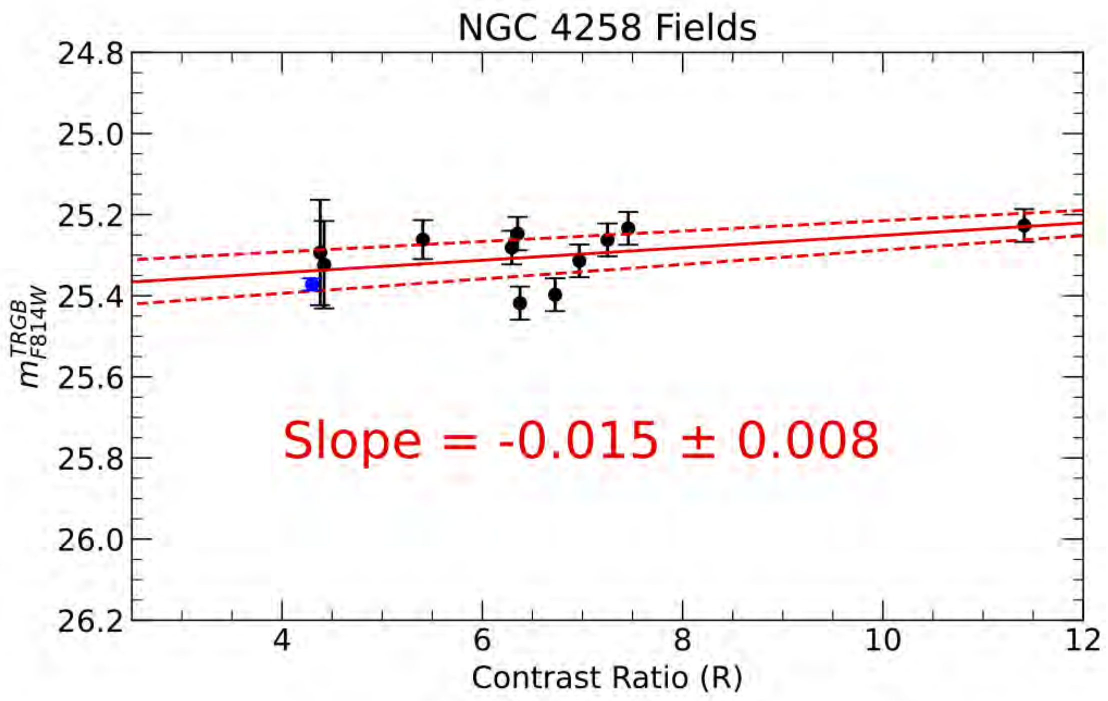


Wu+ (2023); Scolnic+ (2023)

Tip of the Red Giant Branch

- Likely caused by further weighting of tip measurements (Anderson+24)
- Tip-contrast relation also seen in NGC 4258 fields

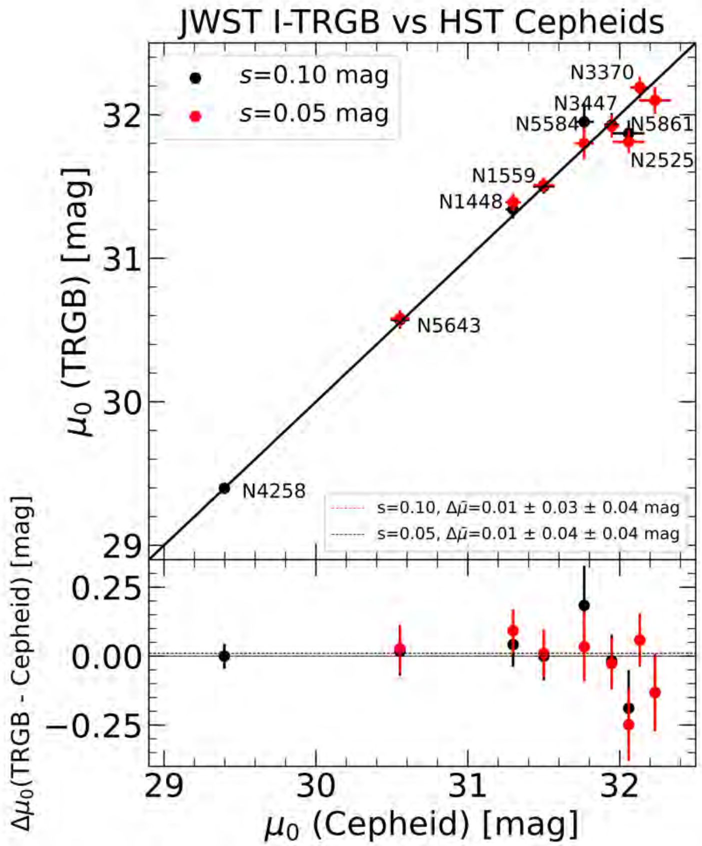


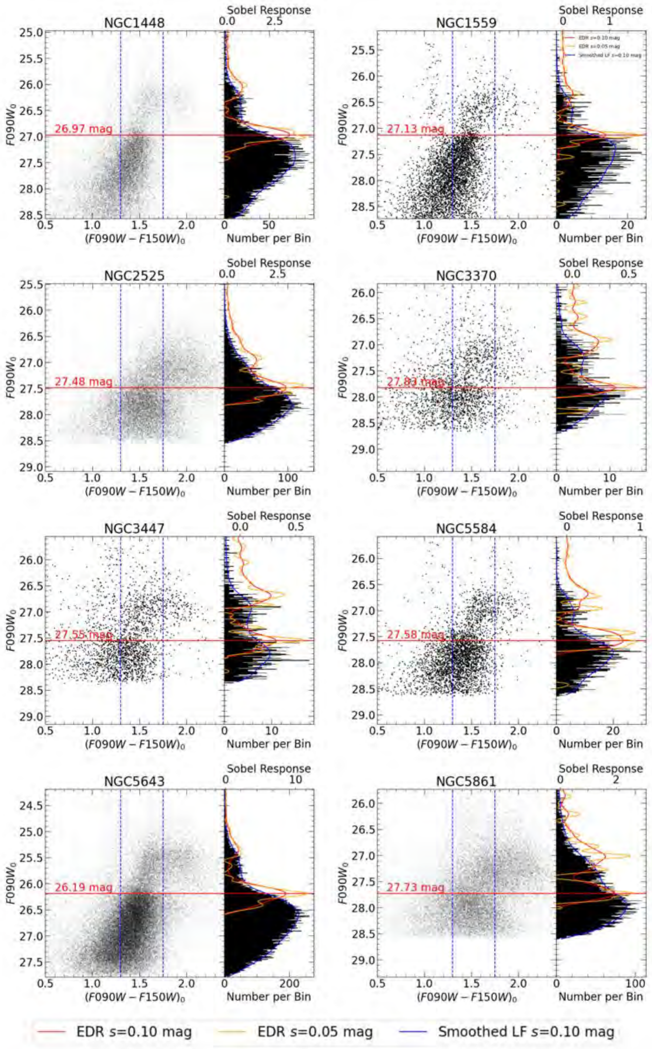


Wu+ (2023); Scolnic+ (2023); Li+ (2023)

Tip of the Red Giant Branch

- TRGB in halo fields of Cepheid-bearing galaxies shows great agreement between the two methods
- Important check because TRGB can also be used in galaxies without Cepheids (but need to ensure consistency)

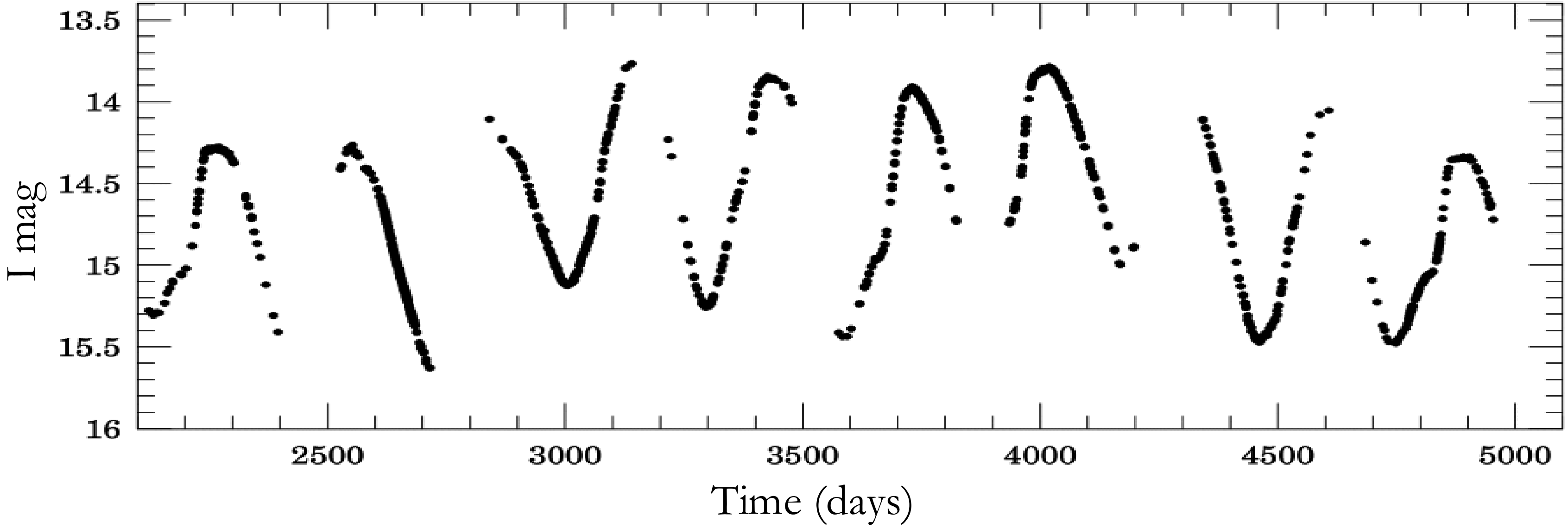




Li+ (2024a)

Miras

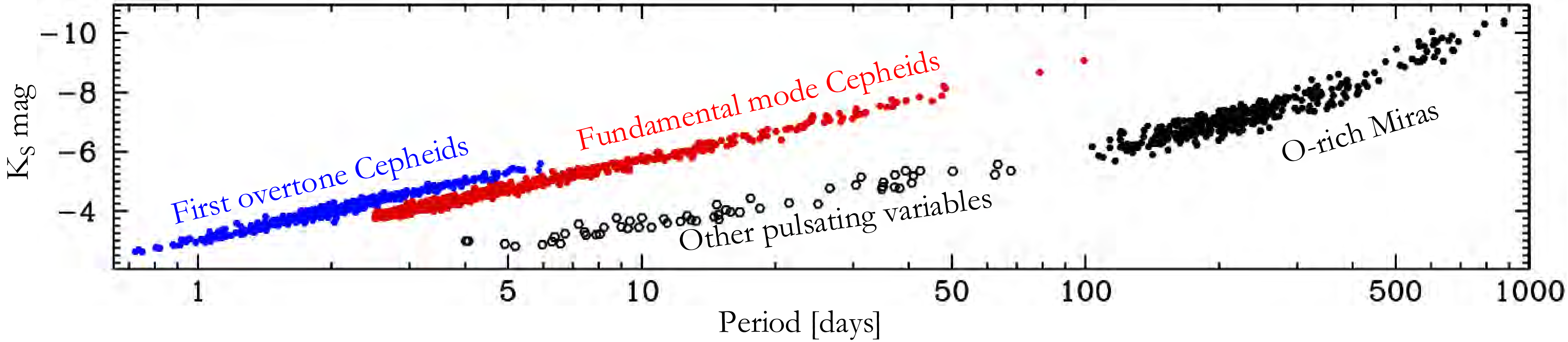
- Miras originate from stars with 0.5-4$M_{\odot}$ → plentiful in all galaxies
- Miras occur during the Asymptotic Giant Branch phase and have long-period, large-amplitude pulsations → relatively easy to detect (but require long observing campaigns)



Soszynski+ (2009)

Miras

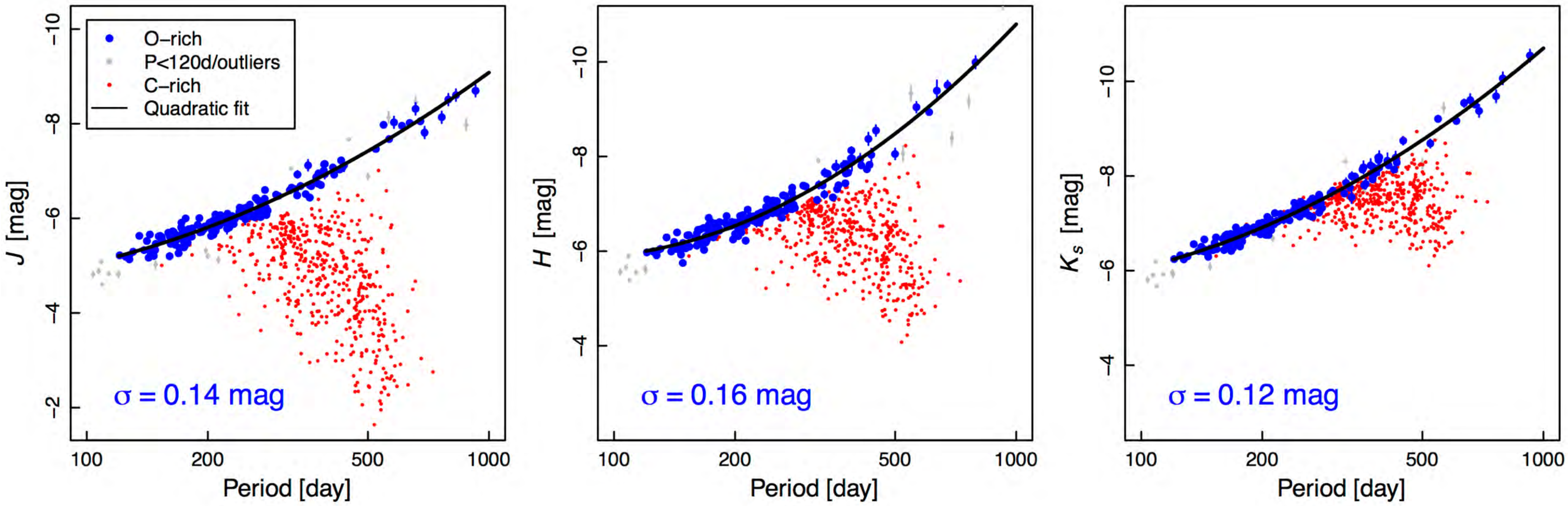
- Carefully-selected subsets of Miras (with Oxygen-rich atmospheres instead of Carbon-rich ones) are good distance indicators
- O-rich Miras have near-infrared luminosities comparable to or exceeding Cepheids → detectable at large distances



Macri+ (2015); Bhardwaj +(2017); Yuan+ (2017a)

Miras

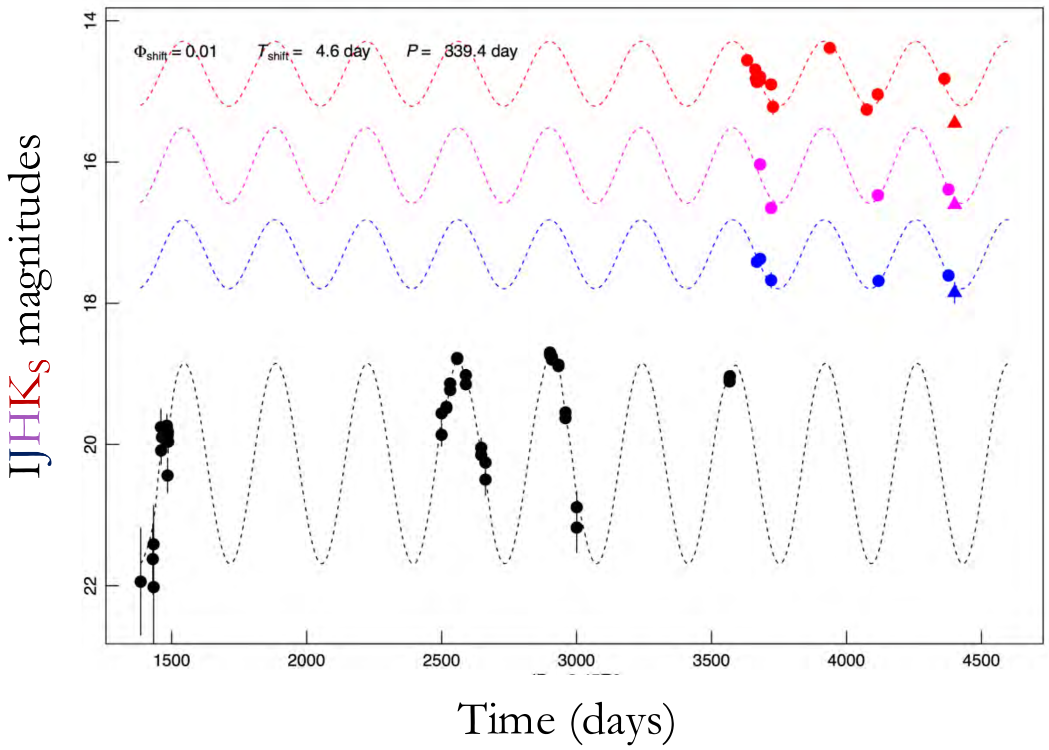
- Absolute calibration of O-rich Mira PLRs in the LMC with DEBs
- Note C-rich Miras do not follow a useful PLR

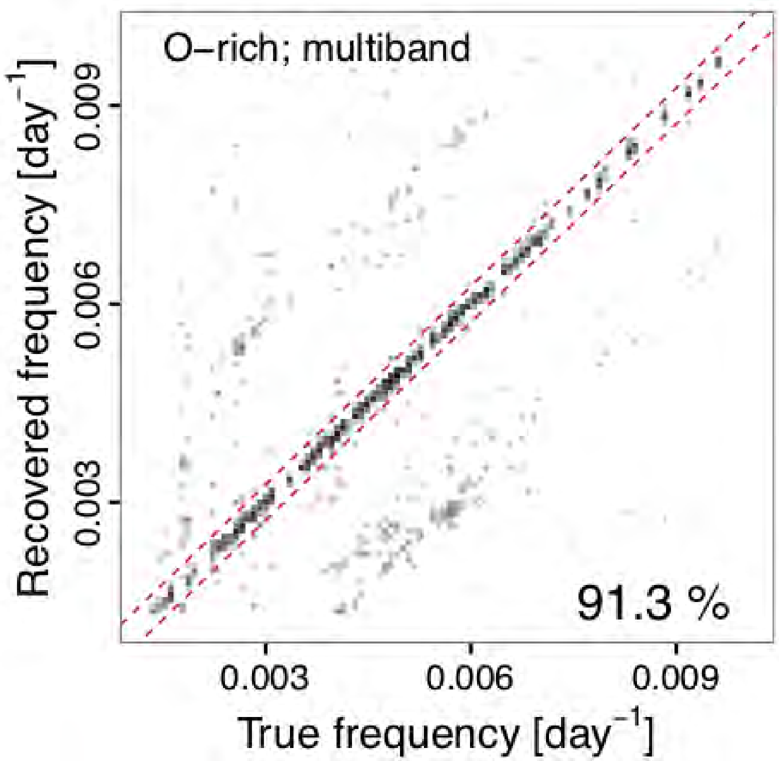


Yuan+ (2017a)

Miras

- Search for Miras in a target galaxy (M33) using ML for classification
- Simulations show good period recovery even with sparse light curves

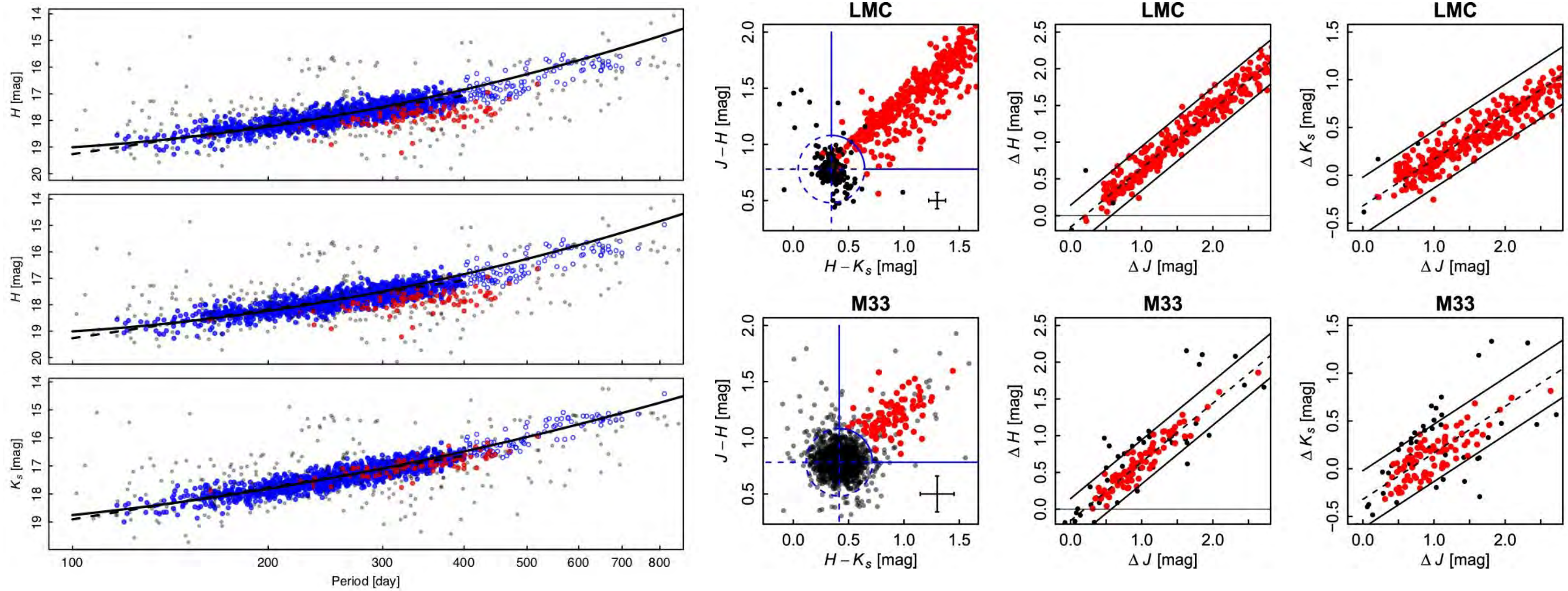




Yuan+ (2018)

Miras

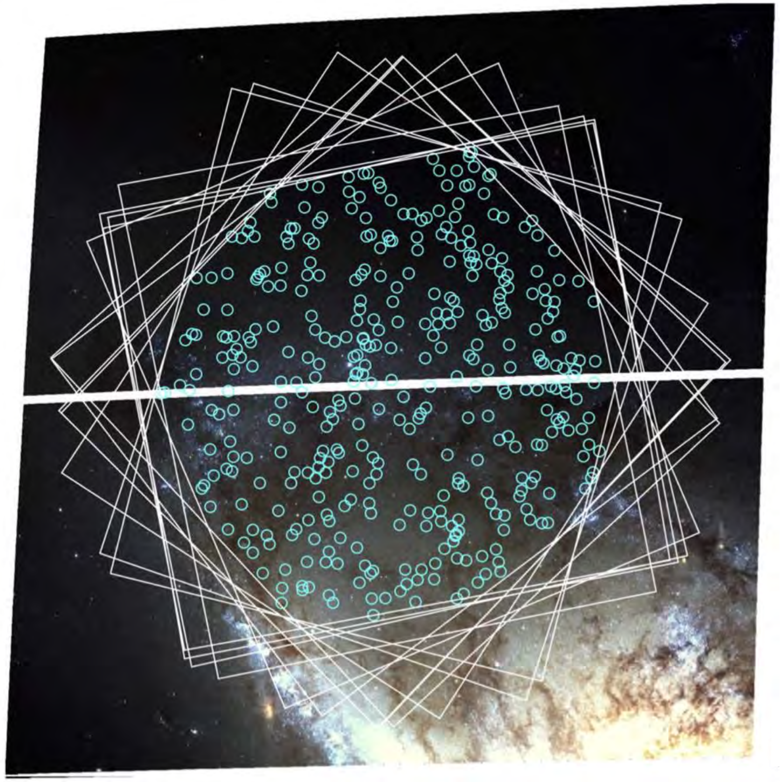
- O- and C-rich Miras separate fairly well in color-color space
- P>400d excluded due to evolutionary effects ("hot bottom burning")

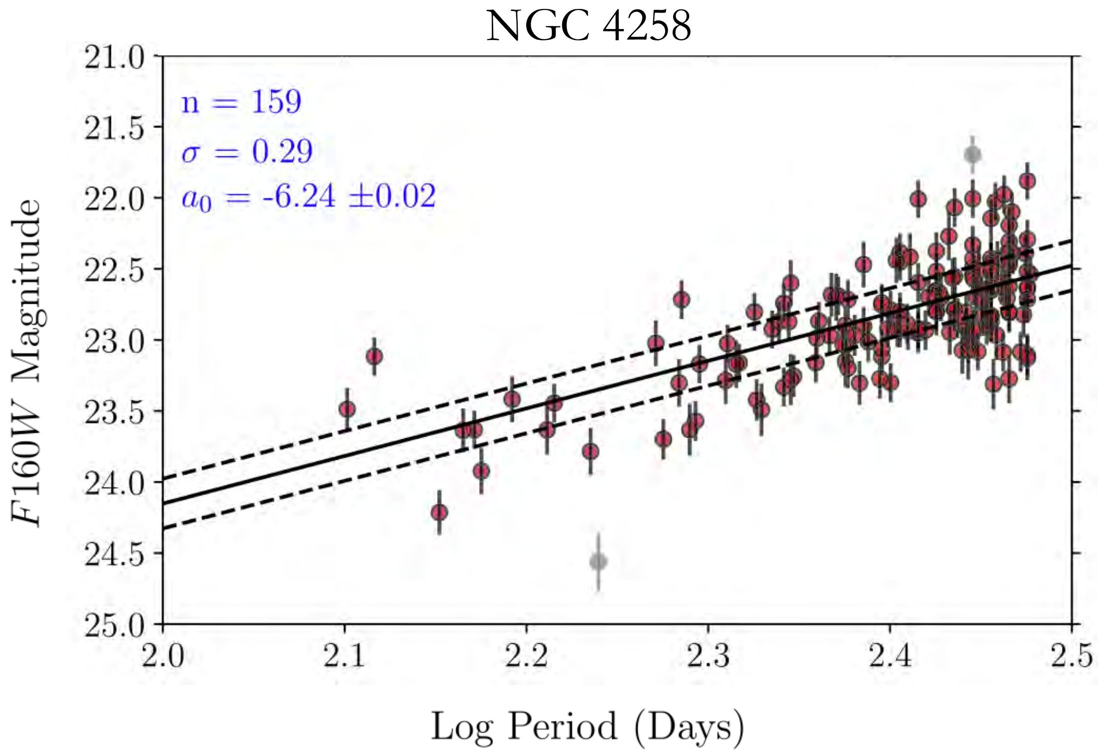


Yuan+ (2018)

Miras

- Related to the SH0ES project, Huang et al. have obtained Mira PLRs in the anchor NGC 4258 and in two "second rung" galaxies





Huang+ (2018, 2020)

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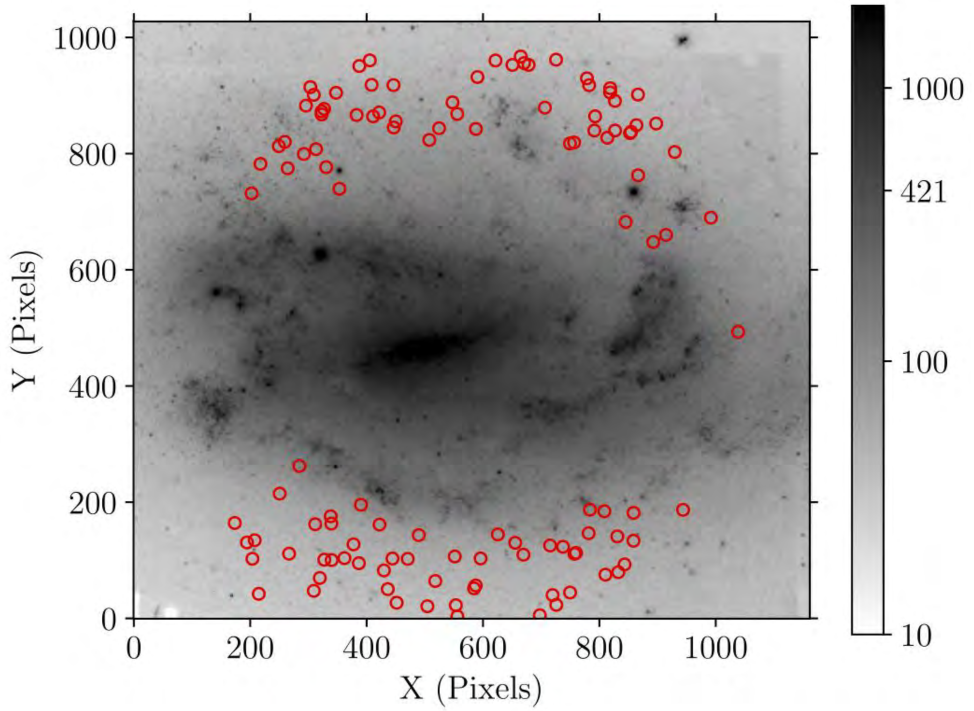

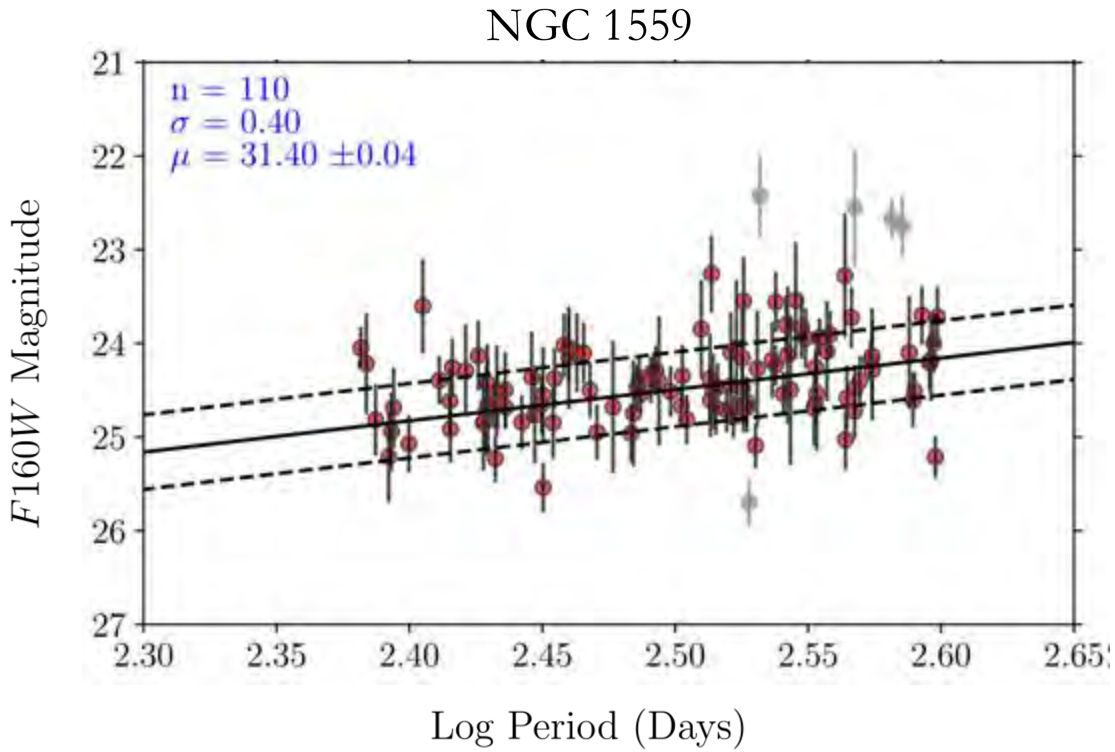

Huang+ (2020)

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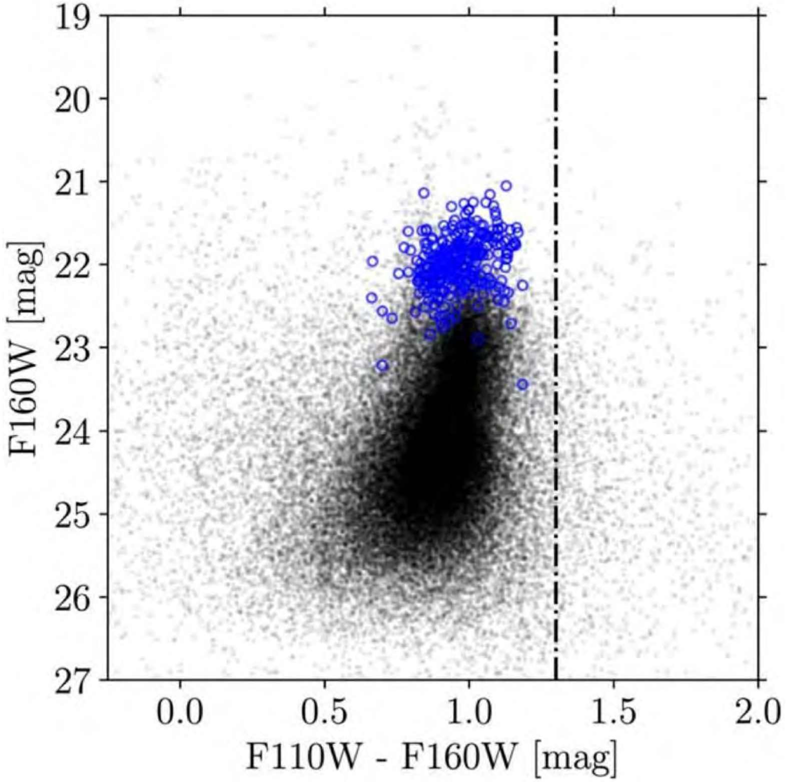
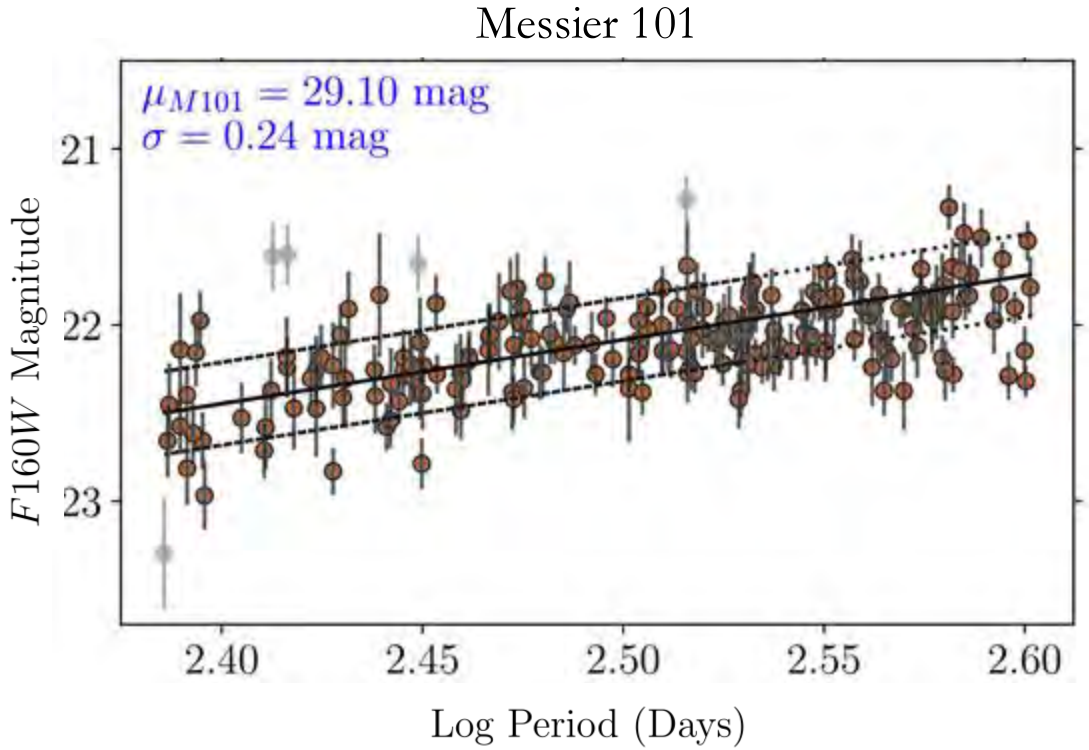
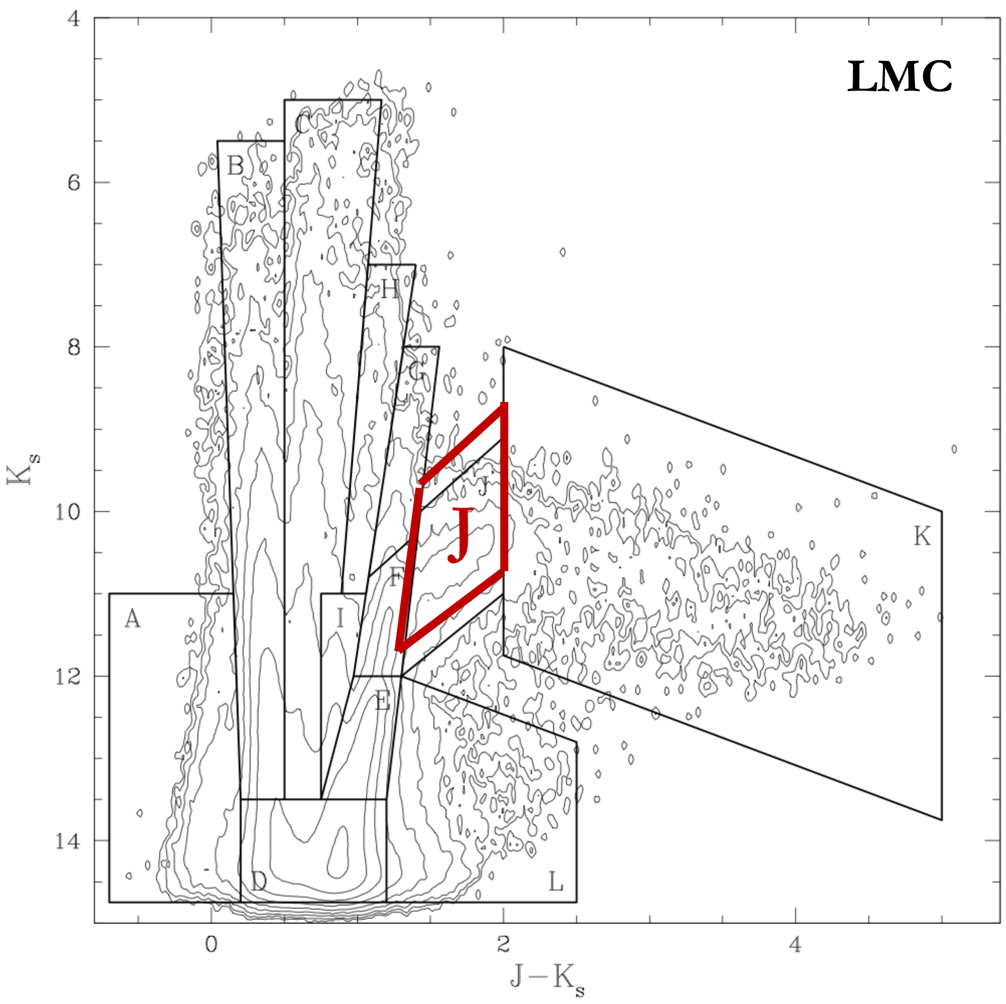




Huang+ (2024)

JAGB

- The potential of Carbon-rich thermally-pulsating AGB stars as a standard candle was first recognized in the mid-1980s (Richer+1985; Cook+1986)
- Nikolaev & Weinberg (2000) used 2MASS photometry of the LMC to advocate for the "J" region of the CMD



Nikolaev & Weinberg (2000)

JAGB

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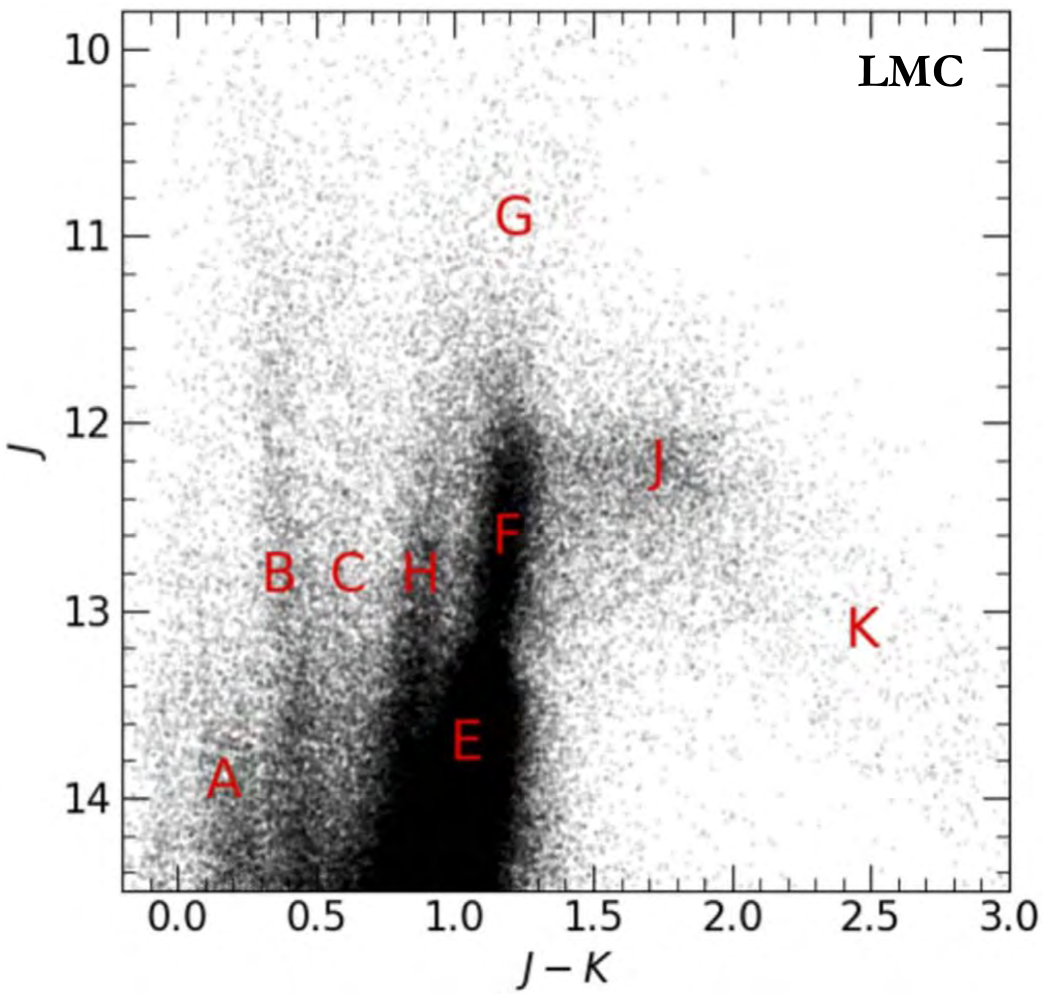
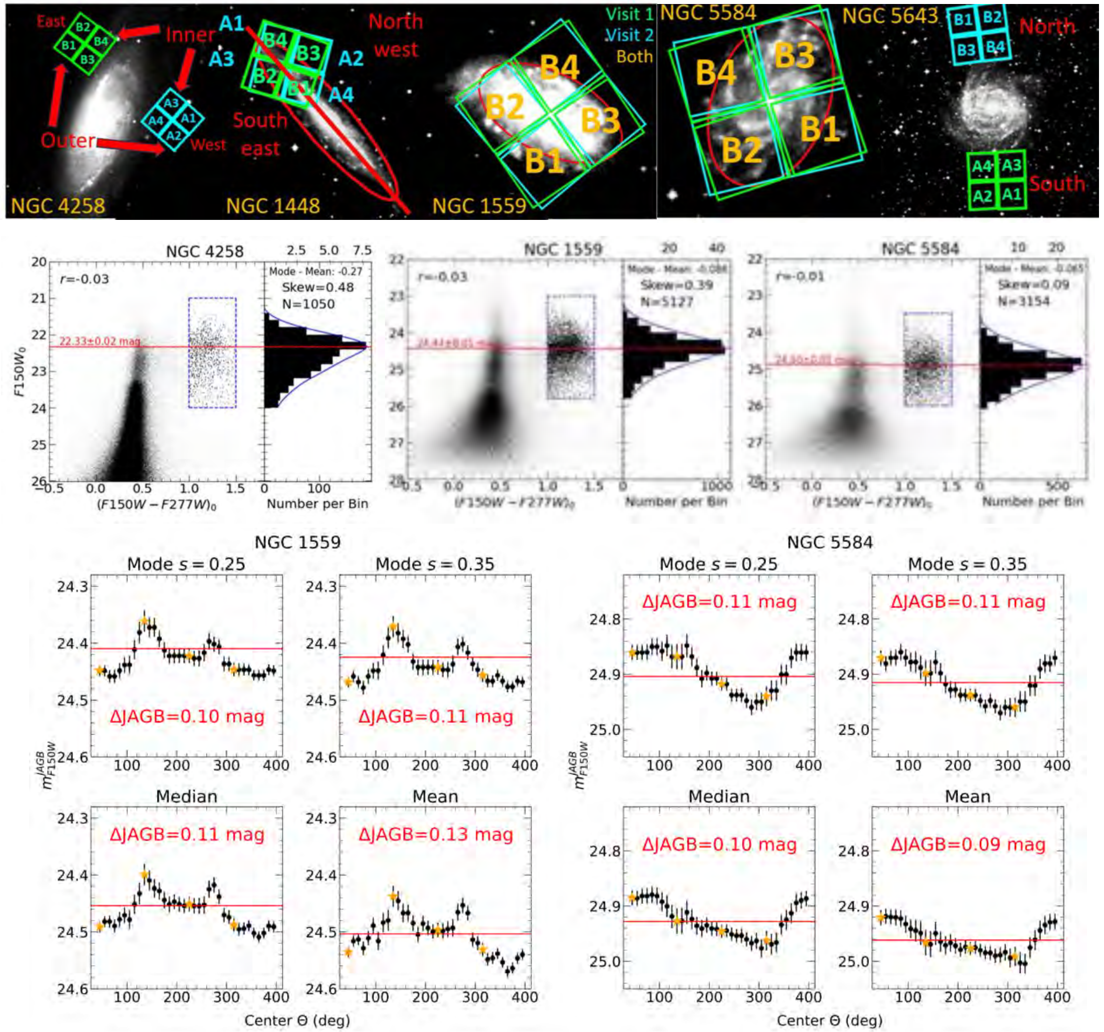


Li+ (2024b) based on Macri+ (2015)

JAGB

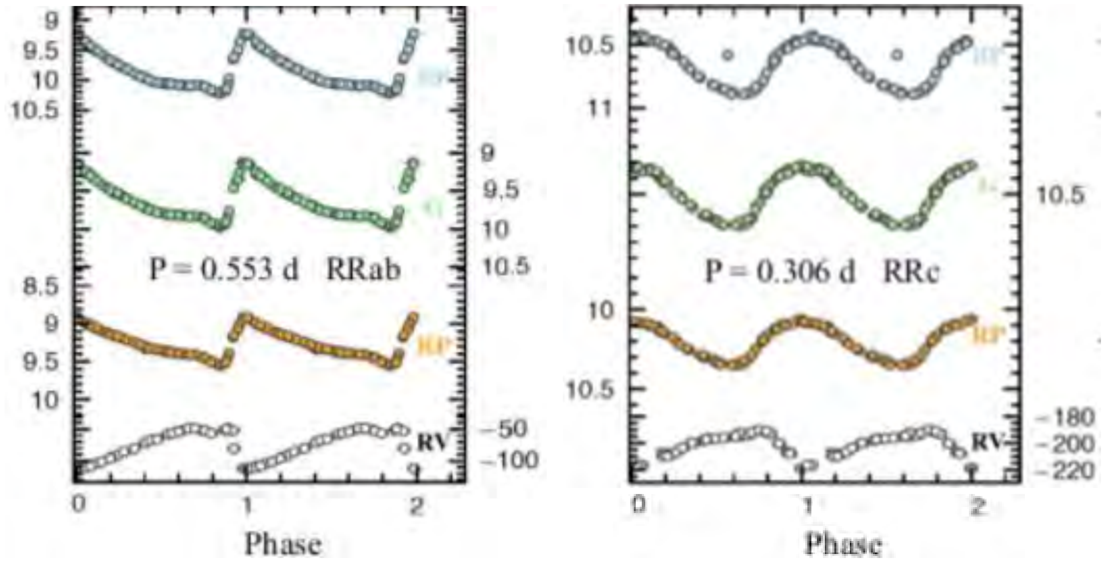
- Calibrations in the I & J bands (Battinelli & Demers 2005; Freedman & Madore 2020)
- Application to "second rung" galaxies (Lee+ 2024a, Li+ 2024b)
- Li+(2024b) calibrated in N4258 and found large variations in JAGB magnitude depending on technique and galaxy region



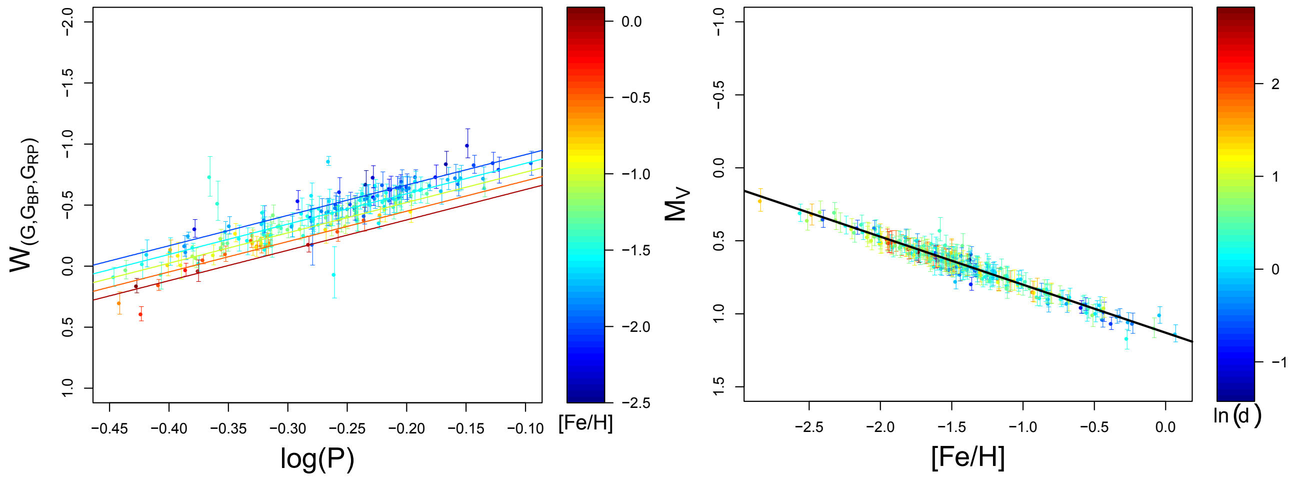
Li+ (2024b)

RR Lyrae

- RR Lyrae variables are old (10-13 Gyr), low-mass, metal-poor, He core fusing stars
- Large-amplitude pulsations driven by the same He^{++} mechanism as Cepheids
- They also follow a Period-Luminosity relation with a strong metallicity dependence



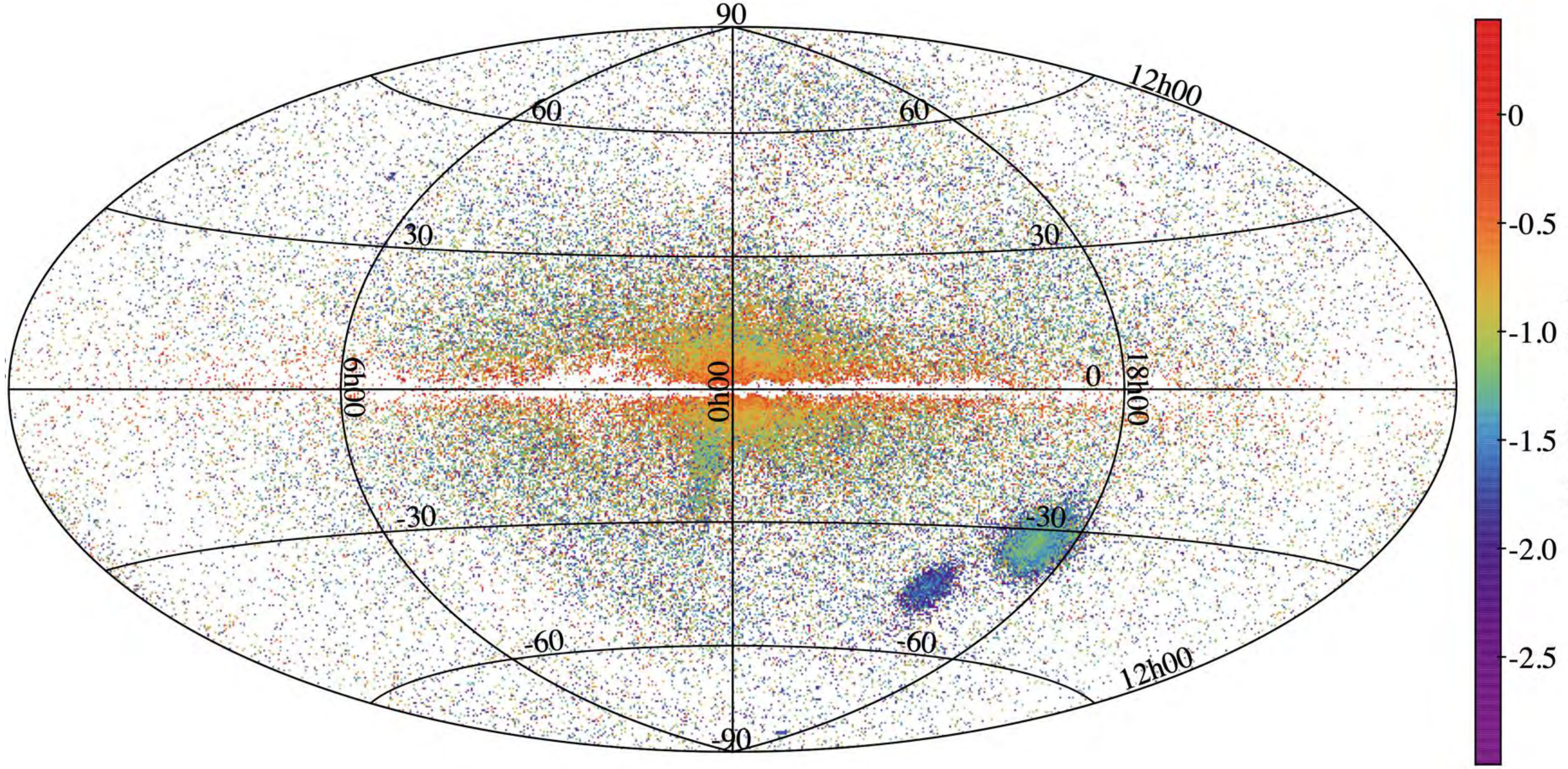
ESA/Gaia/DPAC



Garofalo+ (2022)

RR Lyrae

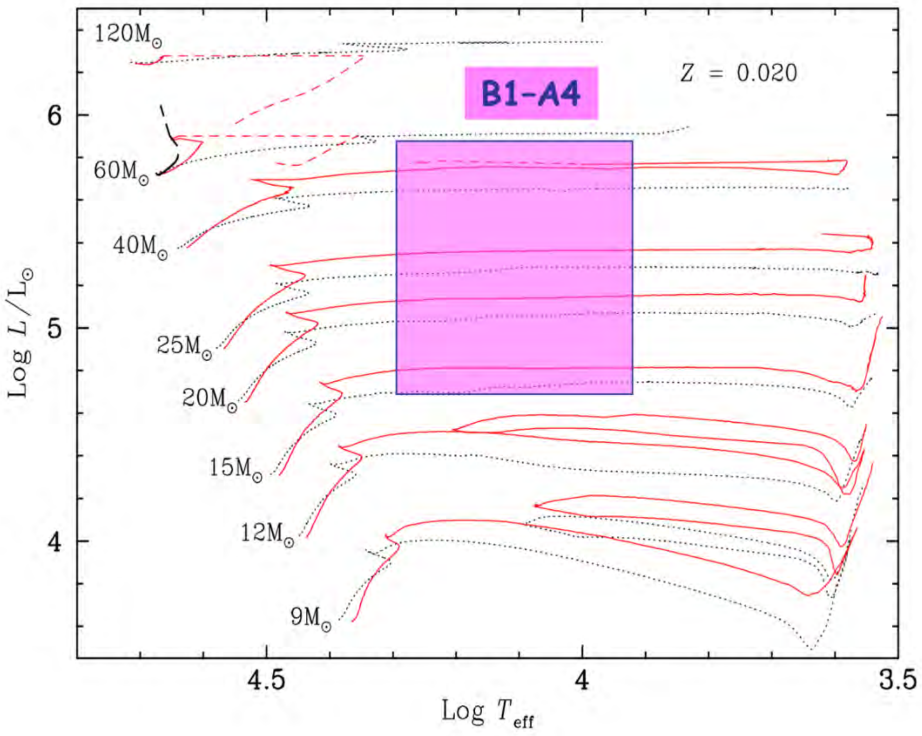
- While RR Lyrae are too faint to be useful at large distances (for now), they are excellent tracers of halo substructure within the Milky Way



ESA/Gaia/DPAC

Flux-weighted Gravity – Luminosity Relation

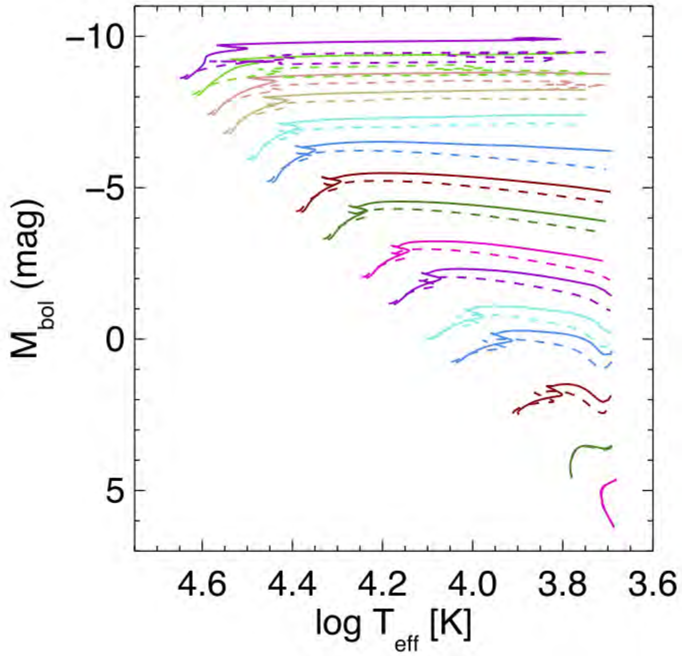
- Blue supergiants (15-40 $M_\odot$) undergo evolution at constant mass and luminosity for $\sim 10^4$ years after the main sequence
- They are also the most luminous stars at visible wavelengths ($10^{5\text{-}6}$ $L_\odot$)
- Ideal to determine abundances, extinction laws, and distances
- You can see one tonight!

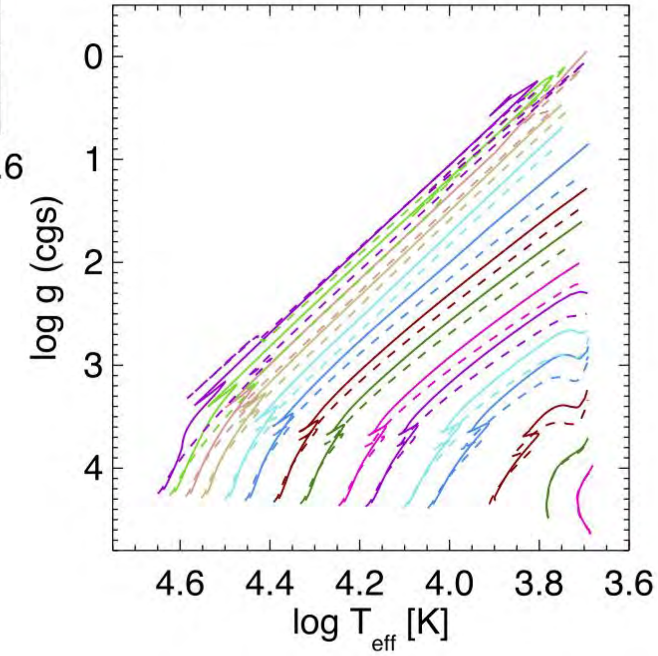


Credit: Dr. R-P. Kudritzki

Flux-weighted Gravity – Luminosity Relation

- If stellar evolution proceeds at constant mass and luminosity, then g_F = surface gravity/T^4 ("flux-weighted gravity") must also be a constant
- Since luminosity ∝ M^x, we can derive a relation between absolute magnitude and g_F
- g_F is distance-independent, so we have the ingredients for a distance indicator





Kudritzki+ (2003, 2020)

Flux-weighted Gravity – Luminosity Relation

$L, M \sim const.$

$M \sim g \times R^2 \sim L \times (g/T^4) = const.$

const.

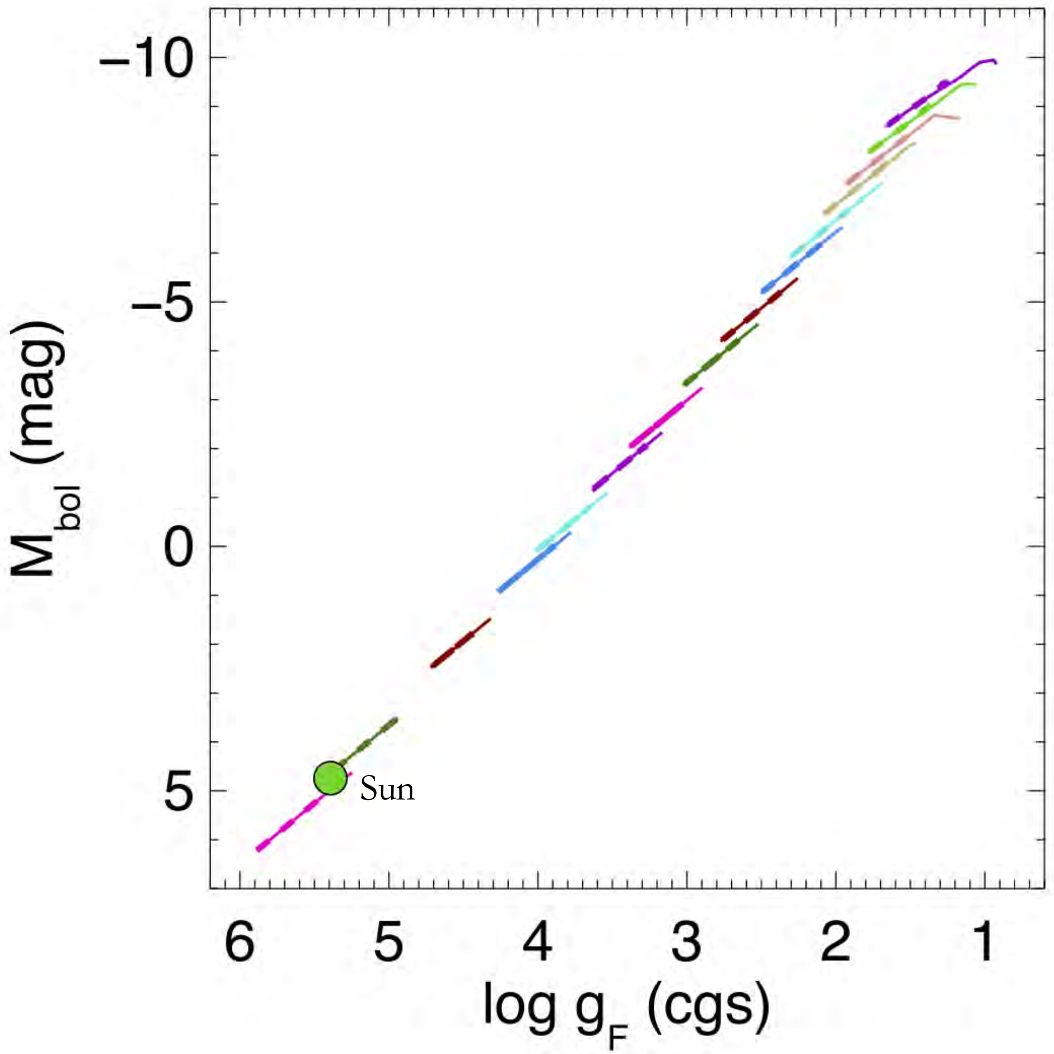
with $L \sim M^x \sim L^x (g/T^4)^x$, $x \sim 3$

$\rightarrow L^{1-x} \sim (g/T^4)^x$

or with $M_{bol} \sim -2.5 \log L$

$M_{bol} = a \log(g/T^4) + b$ FGLR

$a = 2.5\, x/(1-x) \sim 3.75$

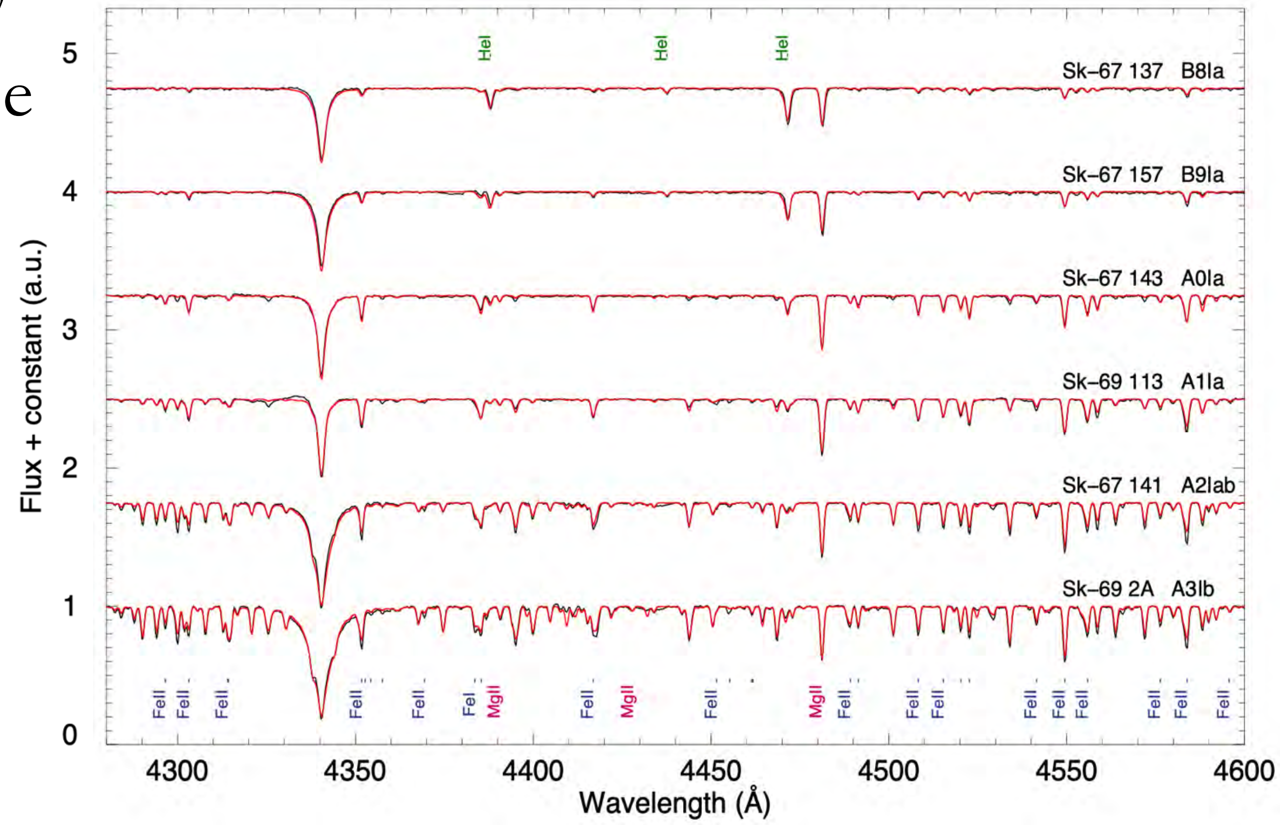


Credit: Dr. R-P. Kudritzki; Kudritzki+ (2020)

Flux-weighted Gravity – Luminosity Relation

- Requires high S/N spectroscopy to determine accurate and precise stellar parameters

- Nevertheless, one of the few ways we have to obtain critical measurements beyond the Milky Way and MCs



Urbaneja+ (2017)

Flux-weighted Gravity – Luminosity Relation

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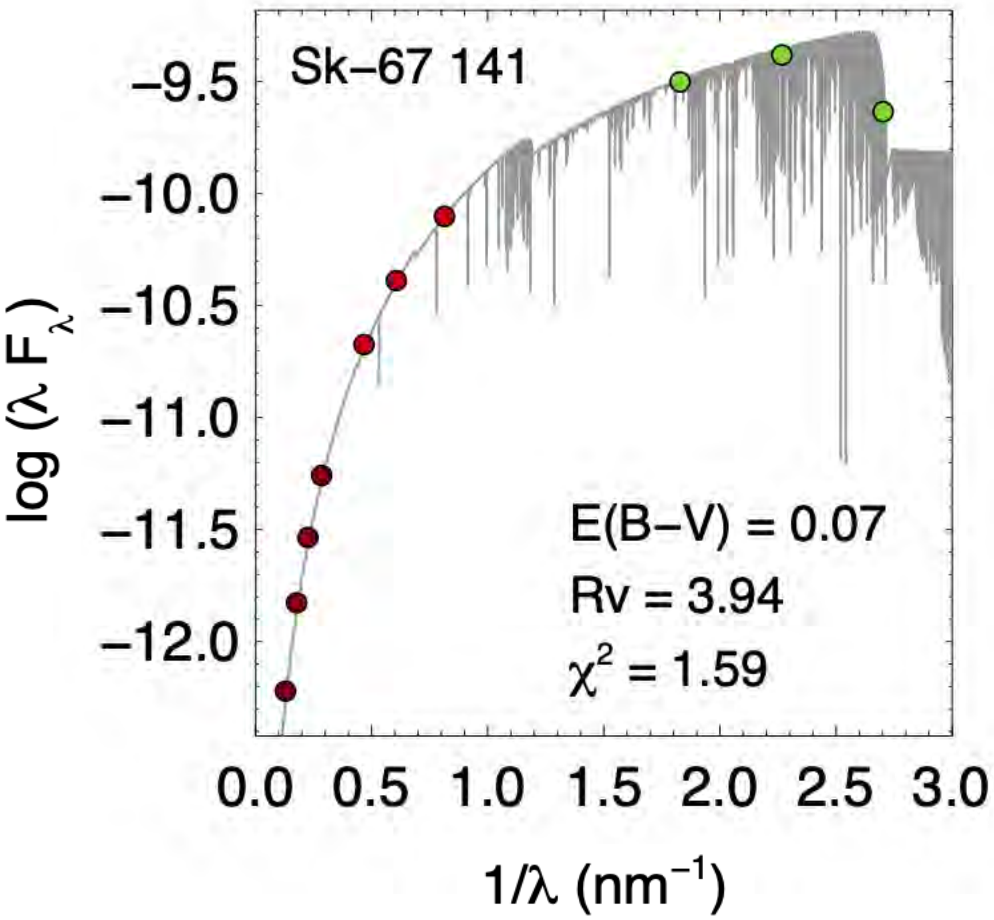
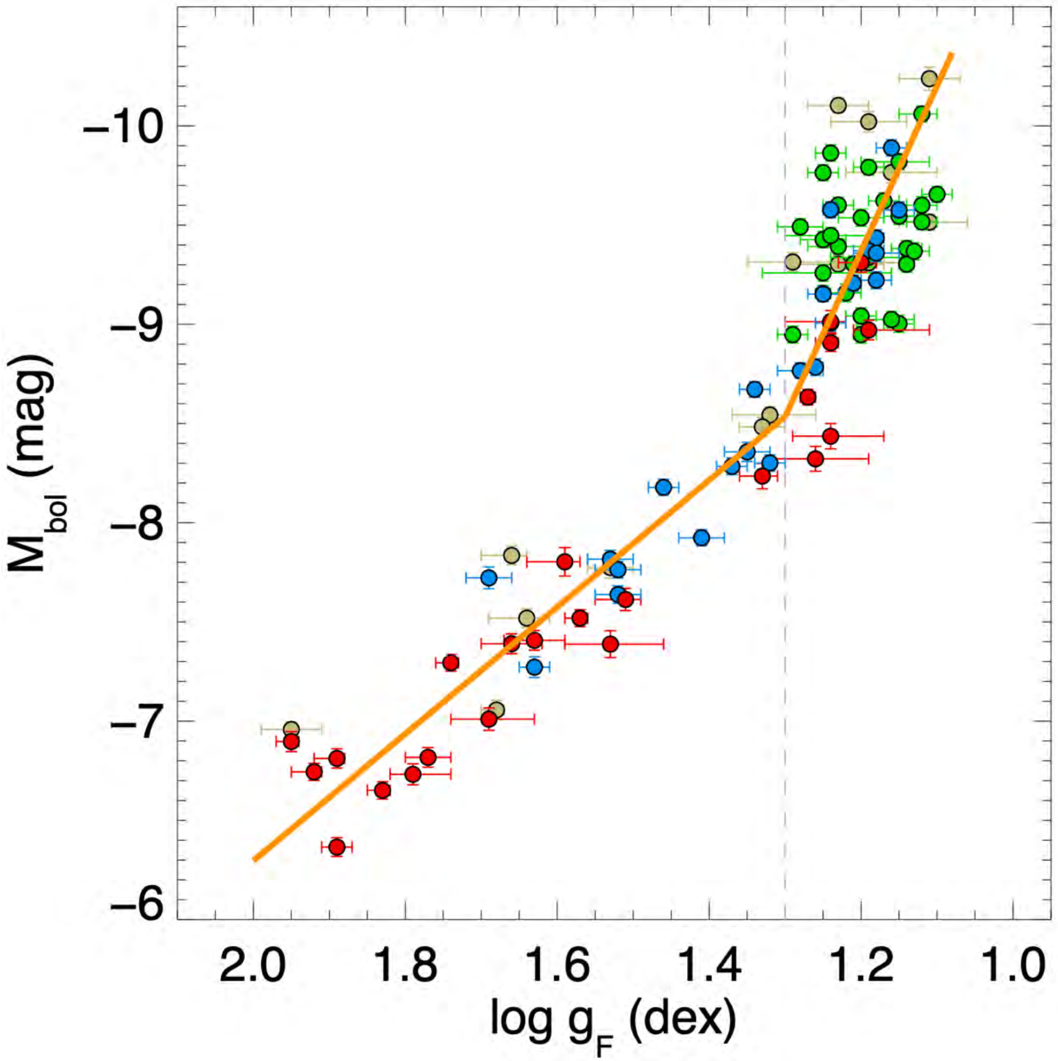


Urbaneja+ (2017)

Flux-weighted Gravity – Luminosity Relation

- Absolute calibration in Large Magellanic Cloud, based on observations of 90 blue supergiants

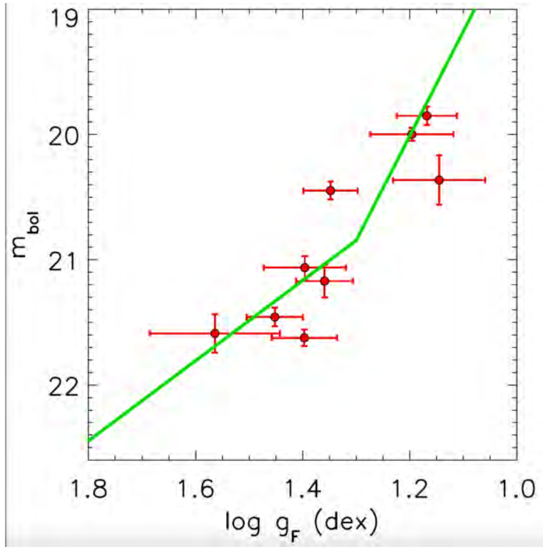
- Distance from eclipsing binaries as discussed yesterday

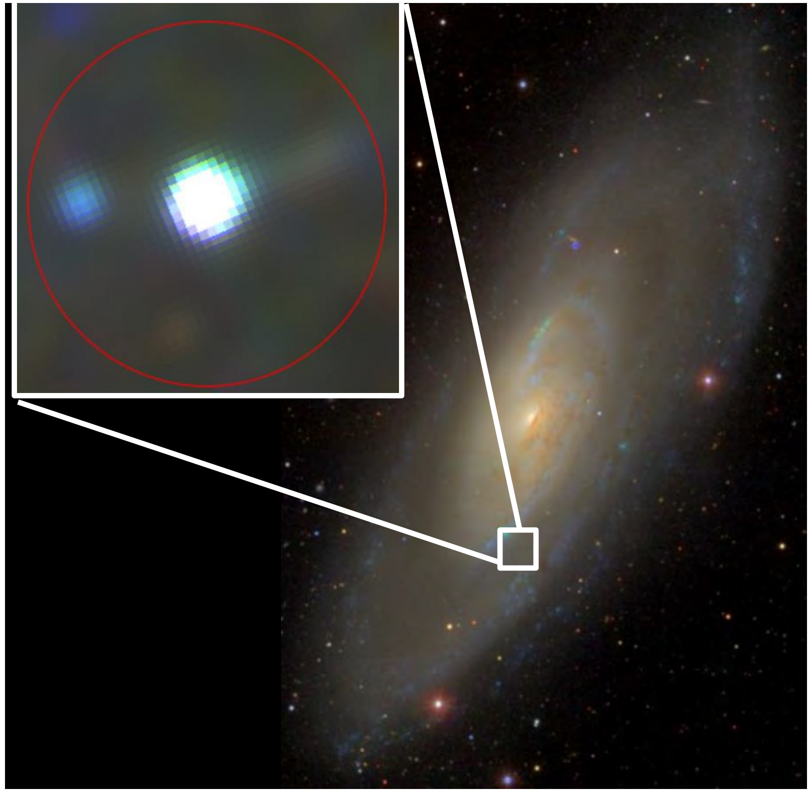


Urbaneja+ (2017)

Flux-weighted Gravity – Luminosity Relation

- Check FLGR distance to NGC 4258 against maser-based one
- *HST* and *JWST* photometry + Keck spectroscopy
- D (Mpc) = 7.52±5.3% vs 7.58±1.5%
  (Kudritzki+, A&A, submitted)

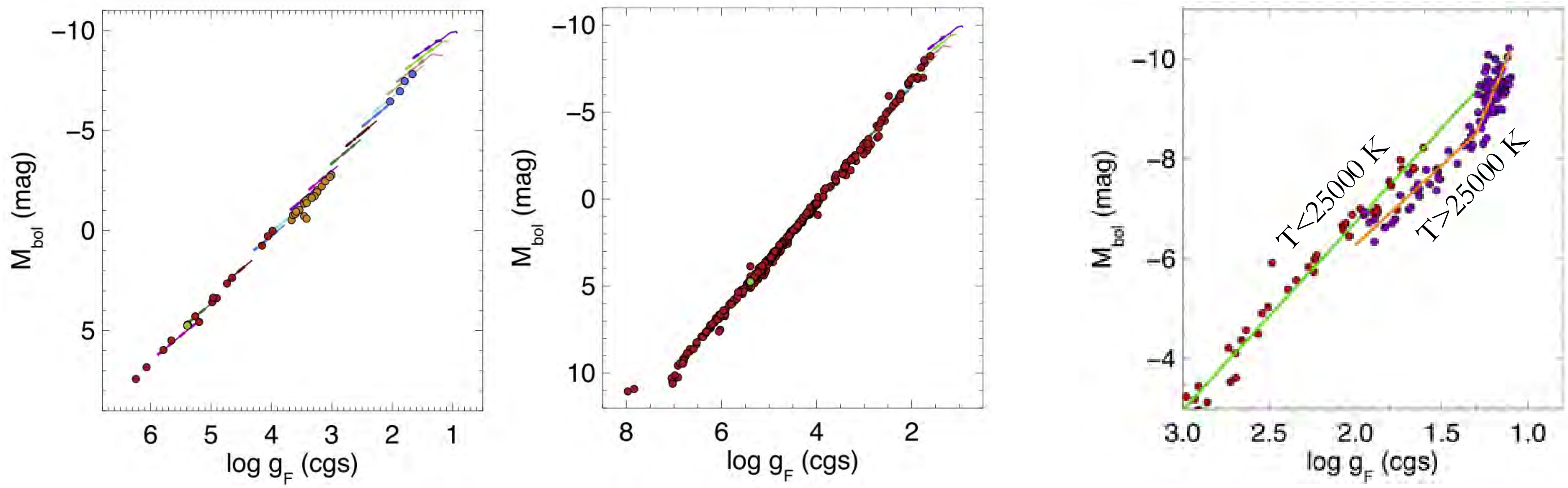




Credit: Dr. R-P. Kudritzki

Flux-weighted Gravity – Luminosity Relation

- In fact, a single FGLR applies to all stars in the main sequence! (except for the most massive, where mass loss is important)
- Stellar evolutionary models verified against *Gaia* benchmark sample and detached eclipsing binaries in Milky Way and LMC



Kudritzki+ (2020)

Summary

- Cepheid variables are the "gold standard" for the second rung of the distance ladder – recent *JWST* observations validate *HST* results
- Critical to develop additional standardizable candles with equally robust calibration uncertainties and systematics. Bonus points if they can be found in non-Cepheid bearing galaxies!
- TRGB is another great distance indicator – cannot reach as far, but expands "second rung" galaxies beyond face-on spirals
- Other techniques are potentially useful, but need additional studies for more robust calibrations (Miras, JAGB) or require significant telescope time for spectroscopy (FGLR)

The Cosmic Distance Scale

Lecture 3

Lucas Macri

NSF NOIRLab

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- I want to thank the following colleagues, who generously contributed material for these presentations:

- Gagandeep Anand (STScI)
- John Blakeslee (NOIRLab)
- Dillon Brout (Boston Univ.)
- Gisella Clementini (INAF)
- Mario Diaz (UT-RGV)
- Joe Jensen (Utah Valley Univ.)
- Rolf-Peter Kudritzki (MIAPbP/UH)
- Casey Papovich (Texas A&M)
- Adam Riess (JHU/STScI)
- Dan Scolnic (Duke Univ.)
- Sherry Suyu (TUM/MPA)
- Mónica Taormina (CAMK)

Recap of Lecture 2

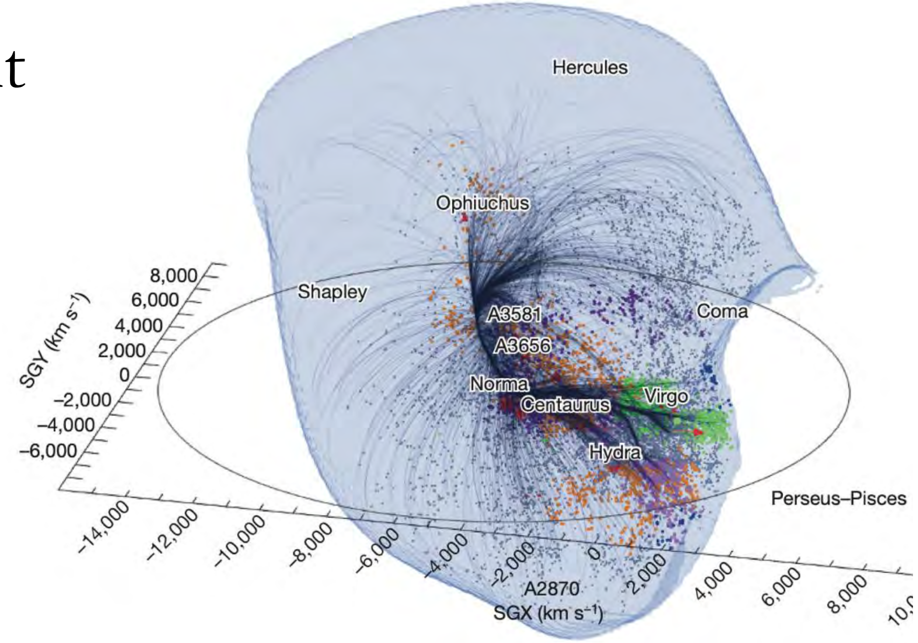
- Cepheid variables are the "gold standard" for the second rung of the distance ladder – recent *JWST* observations validate *HST* results
- Critical to develop additional standardizable candles with equally robust calibration uncertainties and systematics. Bonus points if they happen in non-Cepheid bearing galaxies!
- TRGB is another great distance indicator – cannot reach as far, but expands "second rung" sample beyond face-on spirals
- Other techniques are potentially useful, but require additional studies for robust calibrations (Miras, JAGB)

Third Rung: Into the Hubble Flow

- We have standardizable candles (Cepheids, TRGB, etc.) calibrated via geometric distances (parallaxes, binaries, masers)
- Even with *JWST*, we cannot detect these candles beyond D~100 Mpc
- We cannot measure H_0=cz/D accurately if cz's are affected by gravity!
- Need to calibrate another set of techniques to reach the Hubble Flow

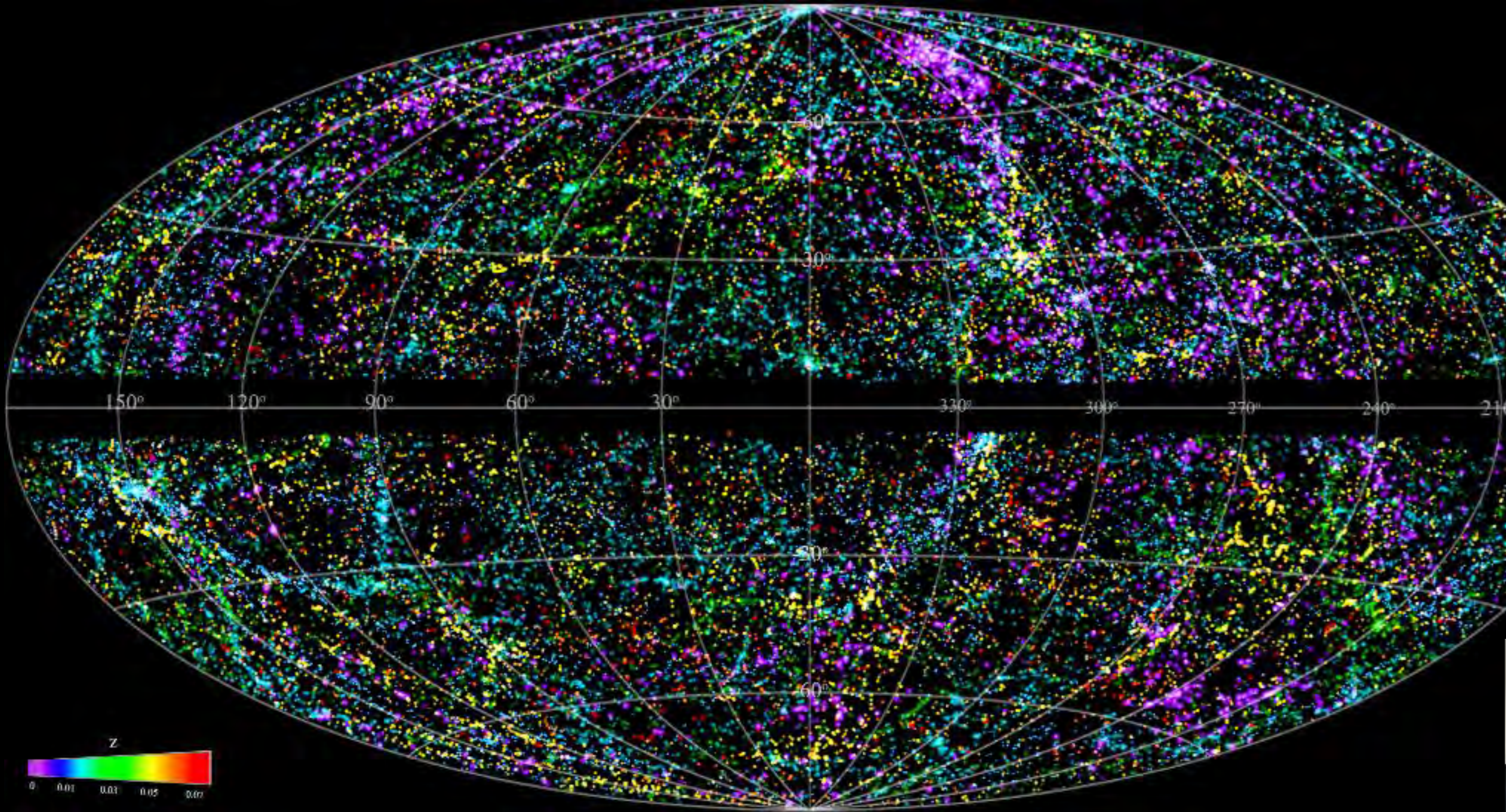
Large-Scale Structure & Peculiar Velocities

- Since the mid-1980s, galaxy redshift surveys have revealed the large-scale structure of the Universe: groups, clusters, walls, superclusters…
- The gravitational attraction of these objects introduces a non-cosmological component to the redshift: "peculiar velocities"
- Since these velocities can be ~300 km/s, we must seek galaxies with $cz > 10^4$ km/s to ensure H_0 is unbiased
  → too far away for Cepheids



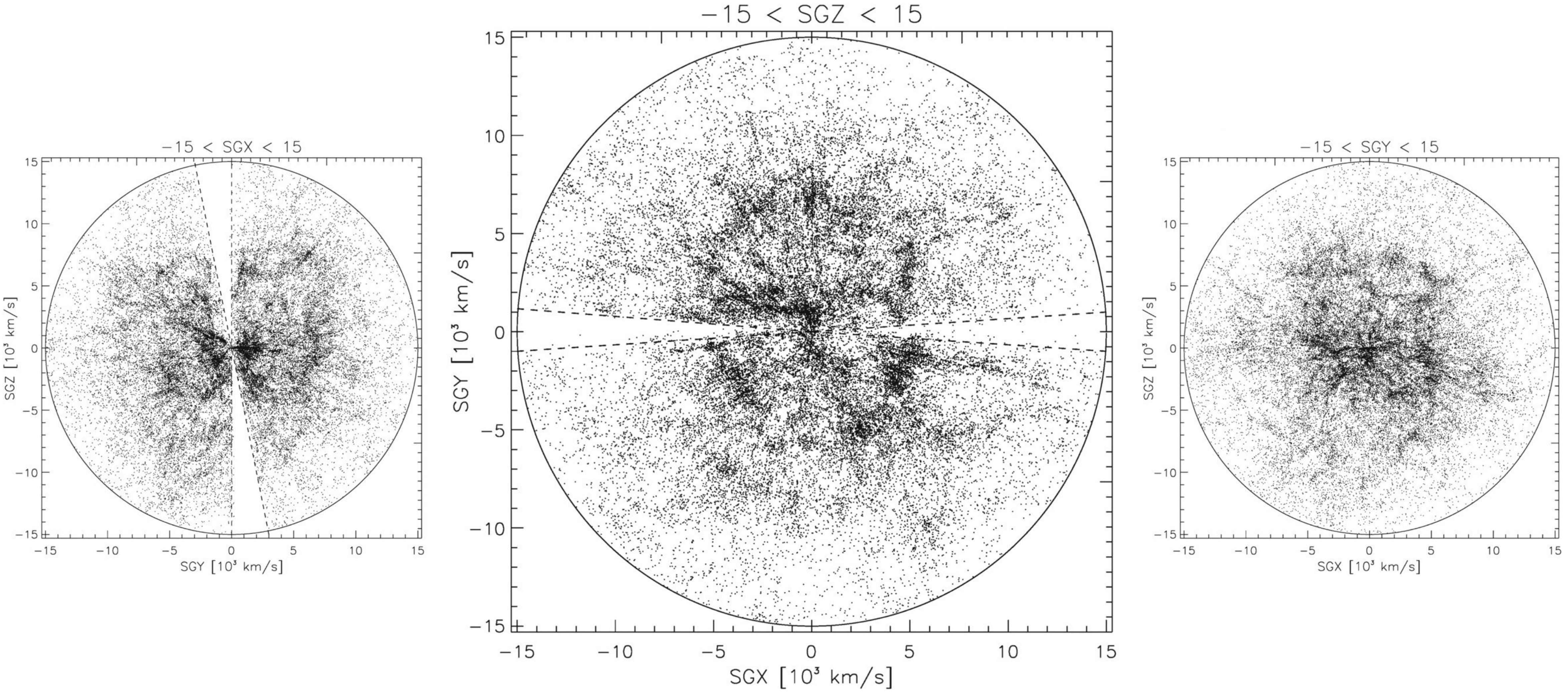
Tully+ (2014)

Large-Scale Structure & Peculiar Velocities



Huchra, Macri+ (2012); Macri+ (2019)

Large-Scale Structure & Peculiar Velocities

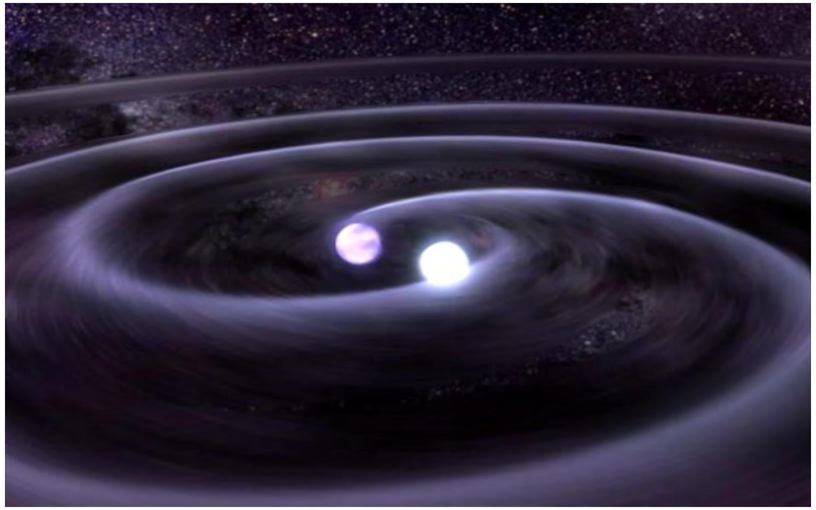


Huchra, Macri+ (2012); Macri+ (2019)

Type Ia supernovae

- Earth-sized degenerate C/O stellar core reaches ~1.4$M_\odot$
    - Nature of “donor” unknown (merger of 2 white dwarfs, companion star)
    - $T_{max} > 5\times10^9$ K → nuclear statistical equilibrium → ~0.4 $M_\odot$ ^{56}Ni
- Excellent secondary distance indicator (single SN → ±7%)
    - Based on empirically-determined corrections to light curve

NASA/CXC/Texas Tech/T. Maccarone; NASA/CXC/M. Weiss



NASA/GSFC/T. Strohmayer NASA/CXC/D. Berry

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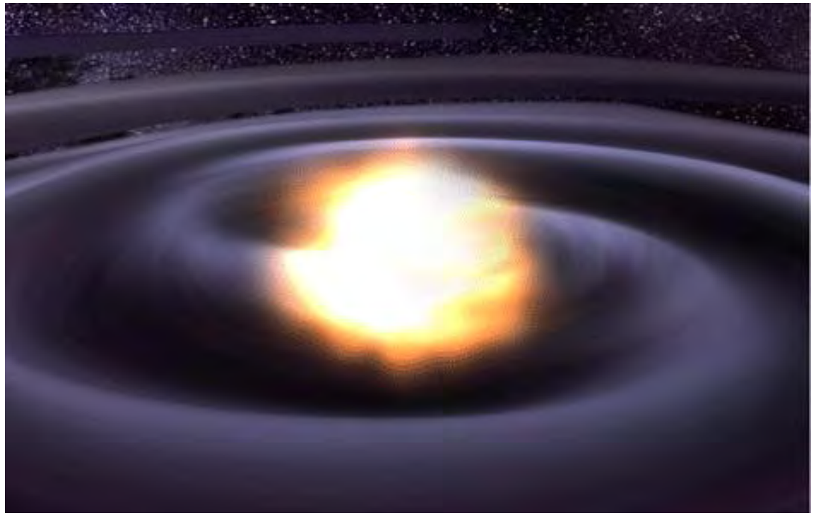
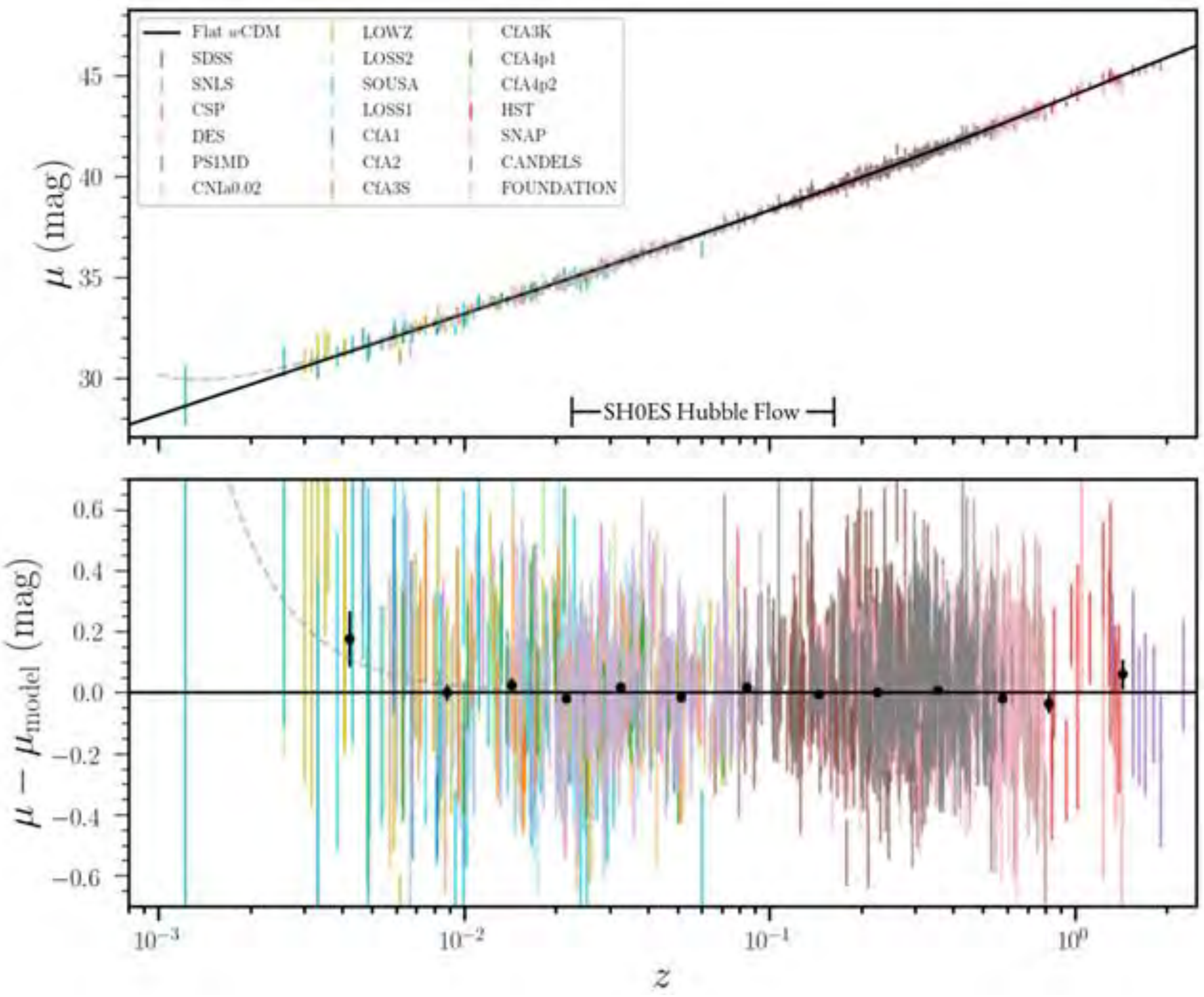
ESA/C. Carreau



NASA/GSFC/T. Strohmayer
NASA/CXC/D. Berry

Type Ia supernovae: Pantheon+

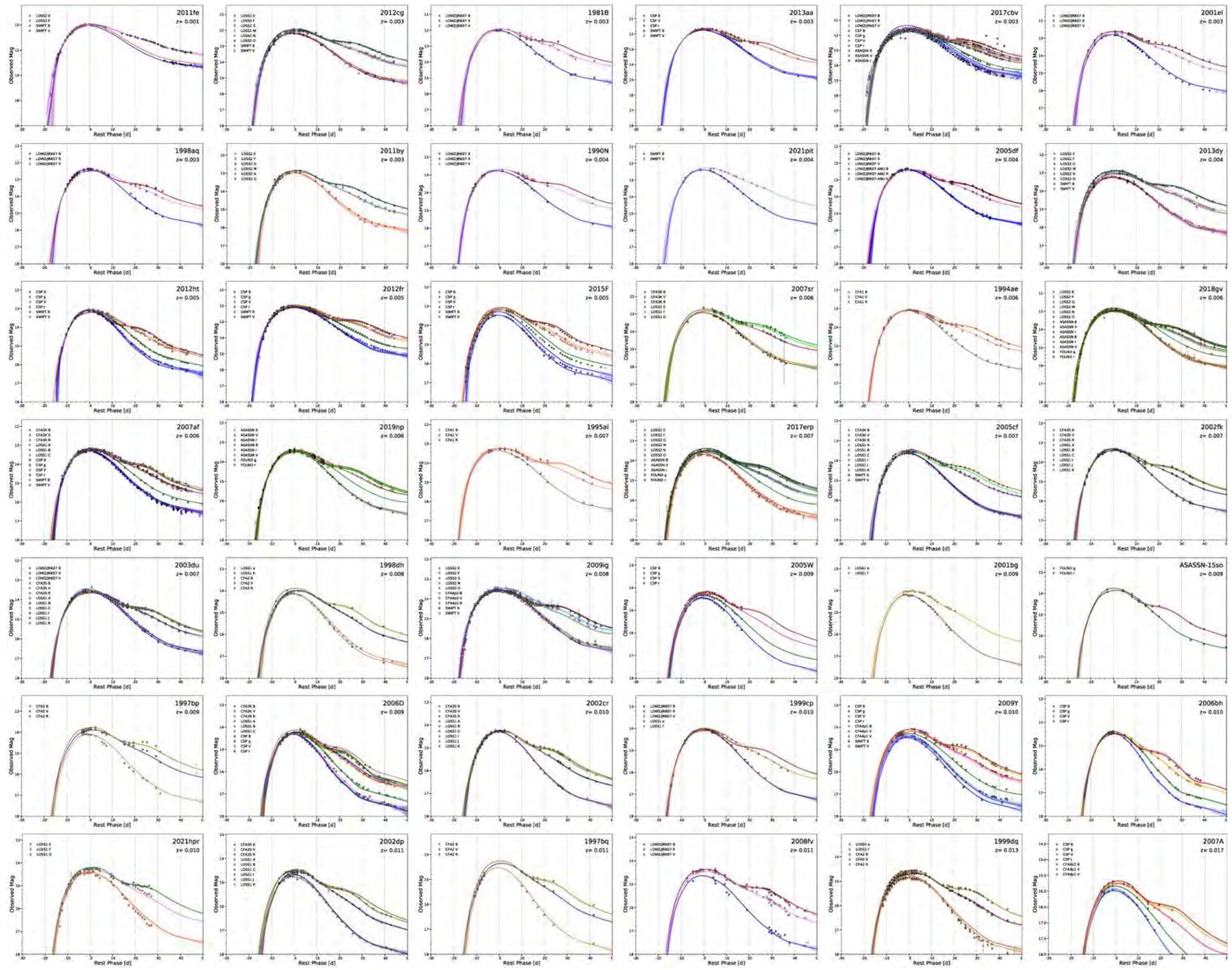
- The full Pantheon+ sample has ~1,550 SNeIa
- All calibrated to the same reference system and with corrections due to light curve shape, dust, …
- ~280 of these are in the redshift range best suited for measuring H_0



Brout+ (2022); Scolnic+ (2022)

Type Ia supernovae: Pantheon+

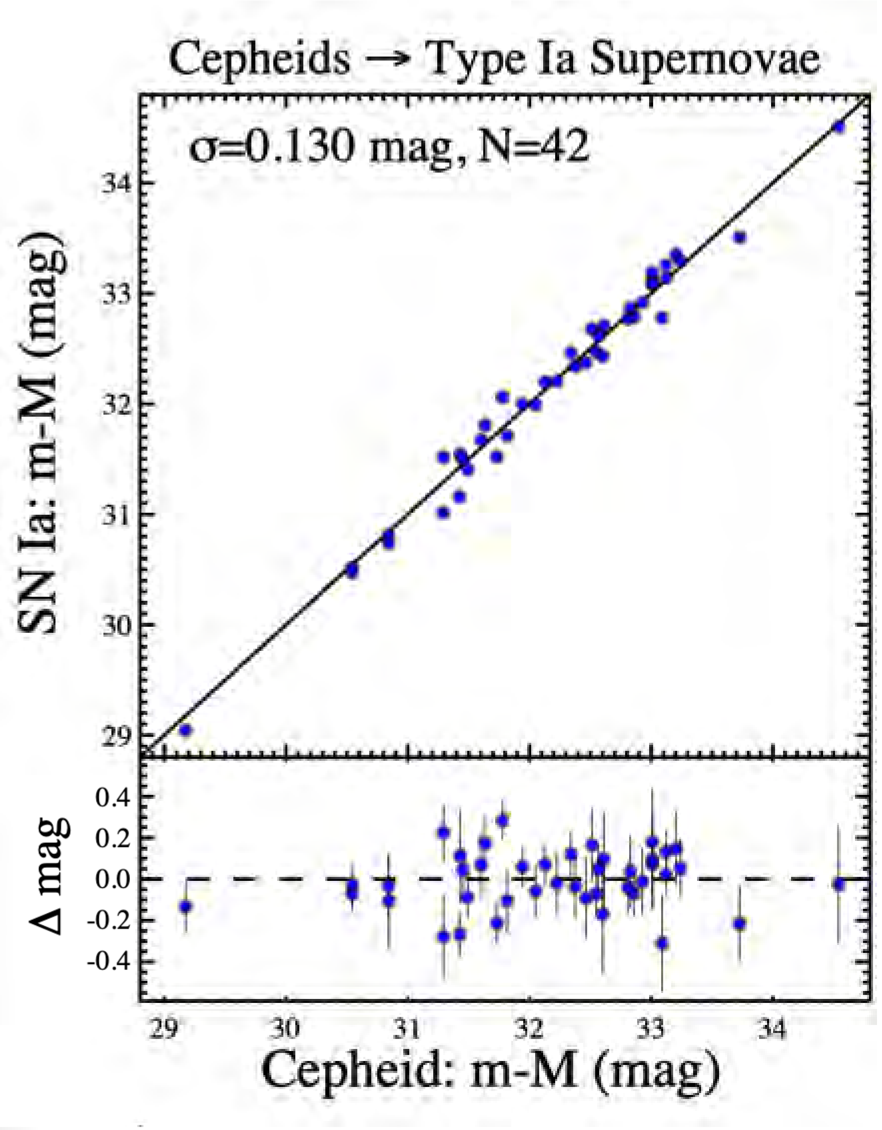
- These are the SNe Ia from Pantheon+ that occurred in Cepheid-bearing galaxies
- N=42 in 37 hosts with 7 < D [Mpc] < 50



Brout+ (2022); Scolnic+ (2022)

SNe Ia calibration for the "second rung"

- Here's the state-of-the-art calibration of SNe Ia luminosity using Cepheid-based distances
- There's another ~15 SNe Ia that could be calibrated using TRGB

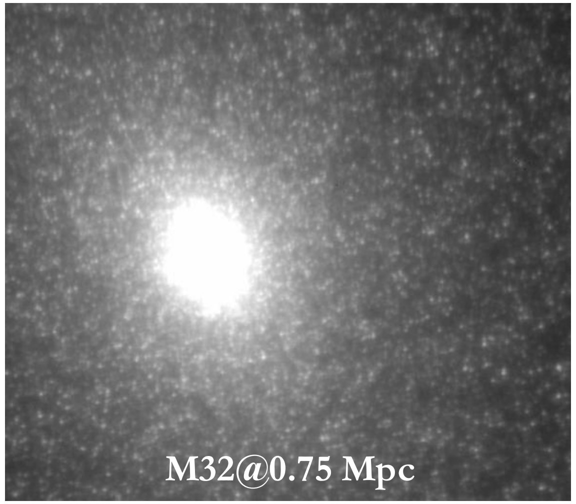


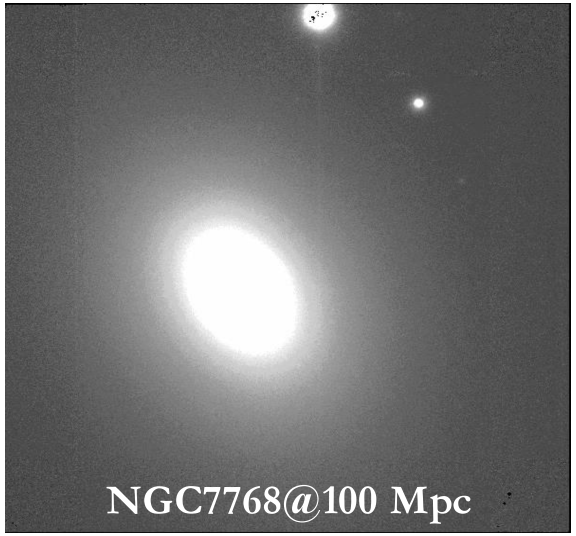
Riess+(2022a)

Surface brightness fluctuations

Tonry & Schneider (1988)

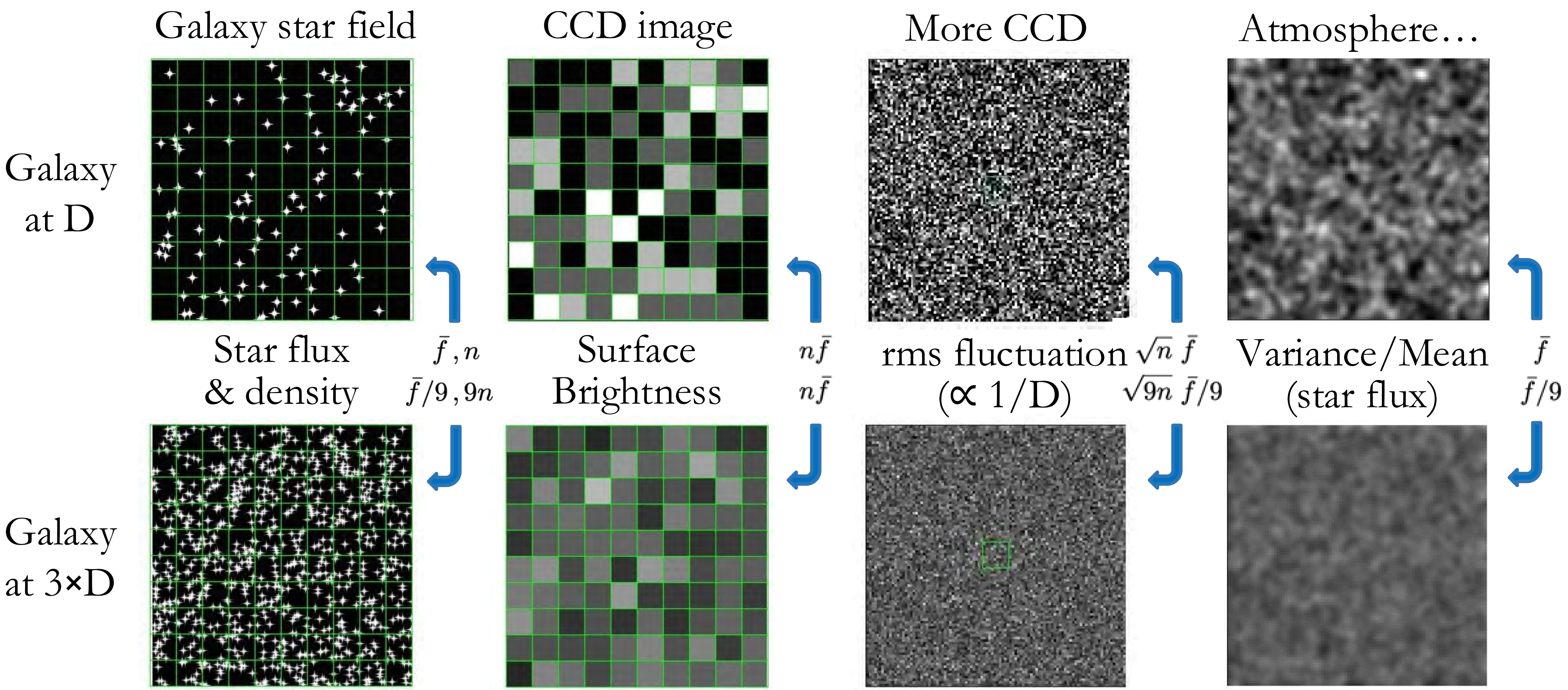
- "A relatively direct technique [which] relies on measuring the luminosity fluctuations that arise from the counting statistics of the stars contributing the flux in each pixel of a high-signal-to-noise CCD image of a galaxy"
- "The amplitude of these fluctuations is inversely proportional to the distance of the galaxy"





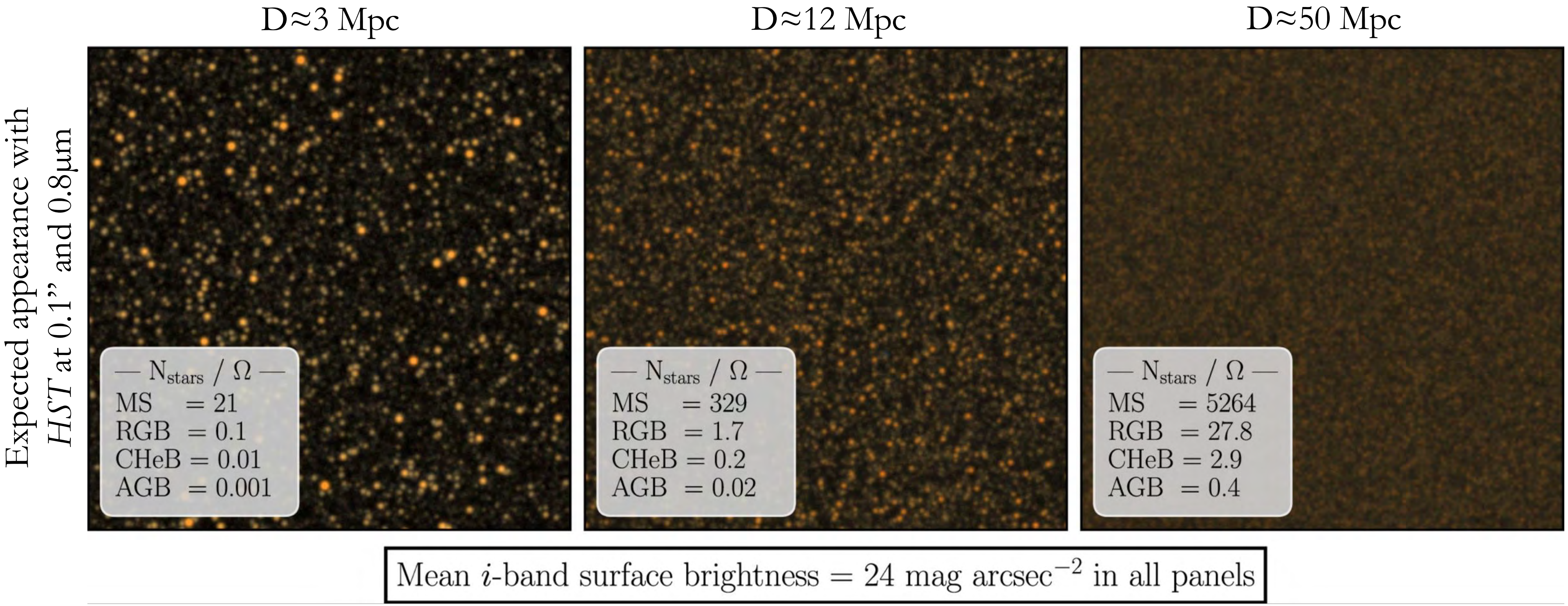
Credit: Drs. J. Blakeslee & J. Jensen

Surface brightness fluctuations



Credit: Drs. J. Blakeslee & J. Jensen

Surface brightness fluctuations



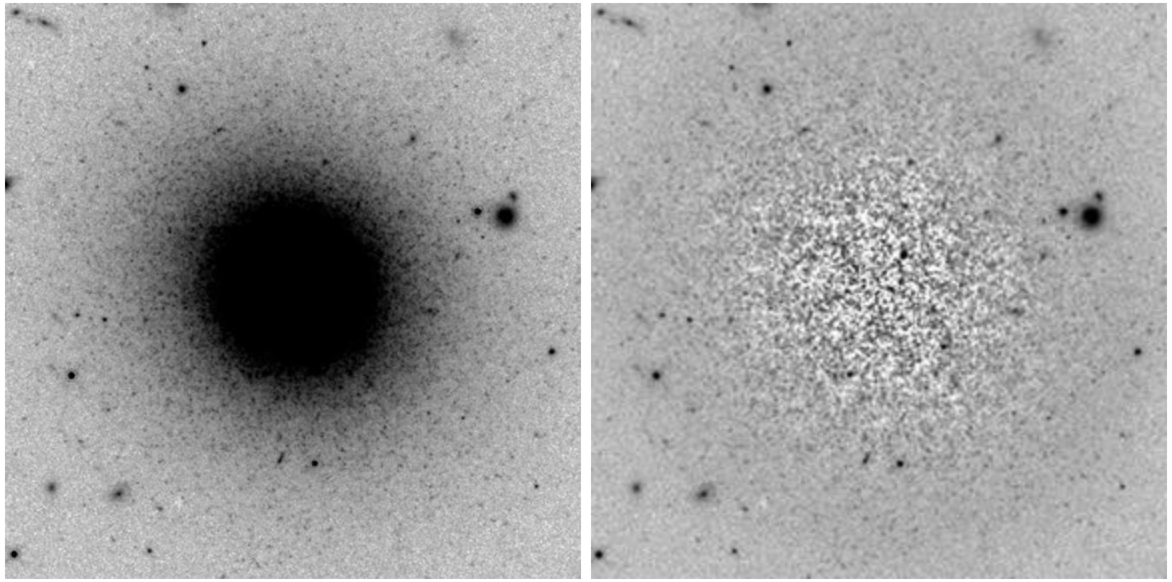
Choose appropriate old, metal-rich populations, to minimize influence of young MS stars and intermediate-age AGB stars.

$$\overline{f} = \frac{\Sigma_i n_i f_i^2}{\Sigma_i n_i f_i} \equiv \frac{\overline{L}}{4\pi d^2}$$

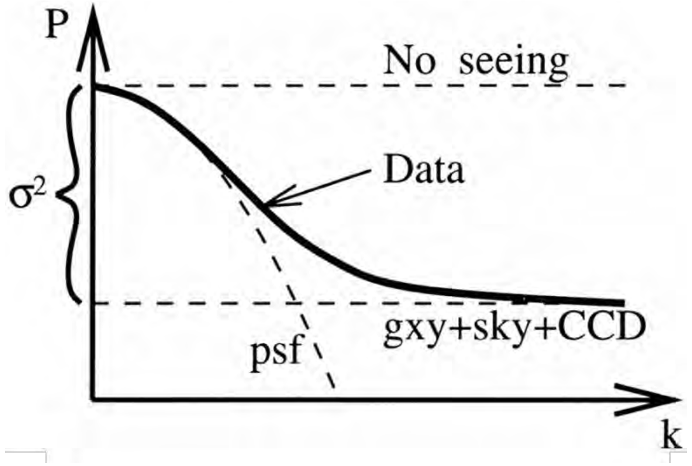
Figure from Greco+ (2021)
Credit: Drs. J. Blakeslee & J. Jensen

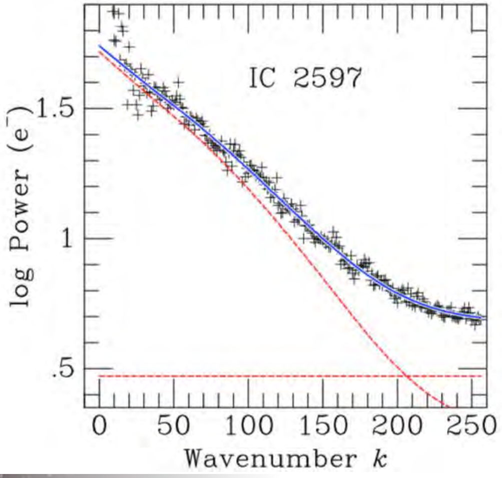
Surface brightness fluctuations

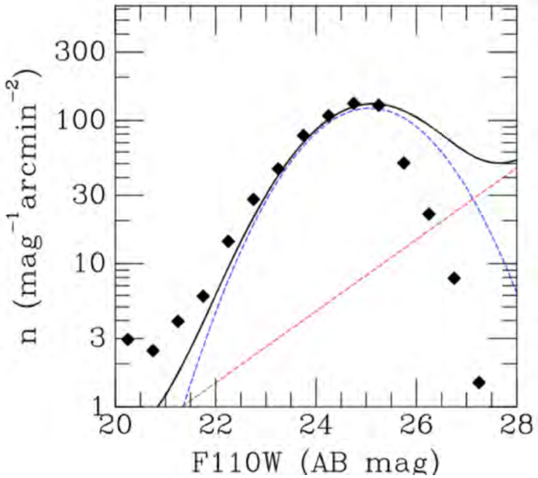
- Definition of "SBF magnitude"
- Subtract galaxy model
- Account for globular clusters



$$P(k) = P_0\,E(k) + P_1$$
$$m = -2.5\log(P_0 - P_r) + m_{zpt}$$





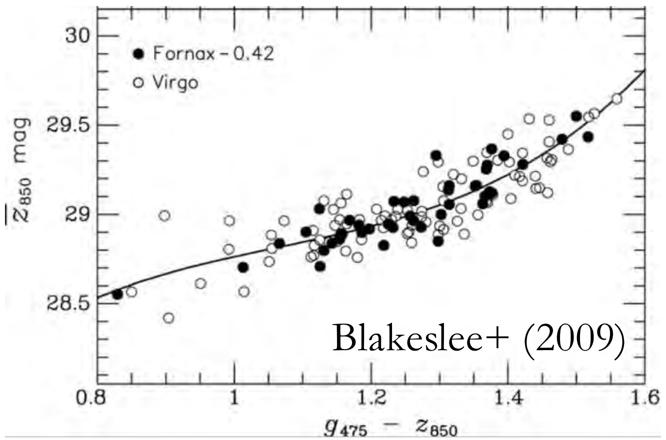


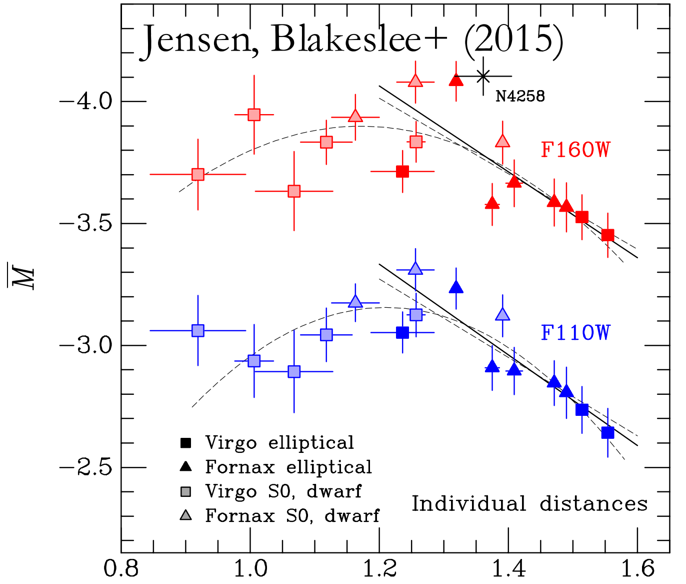
Credit: Drs. J. Blakeslee & J. Jensen

Surface brightness fluctuations

- Empirical SBF calibration has intrinsic scatter of 0.06 mag (*z*), 0.08 mag (*J*), 0.11 mag (*H*)
- Correct for stellar population age and metallicity variations with optical (or sometimes IR) color measurements

- SBF currently calibrated with Cepheid distances to Virgo & Fornax clusters through the LMC
- Ongoing work to replace with TRGB distances to build a pure "Pop II" distance ladder

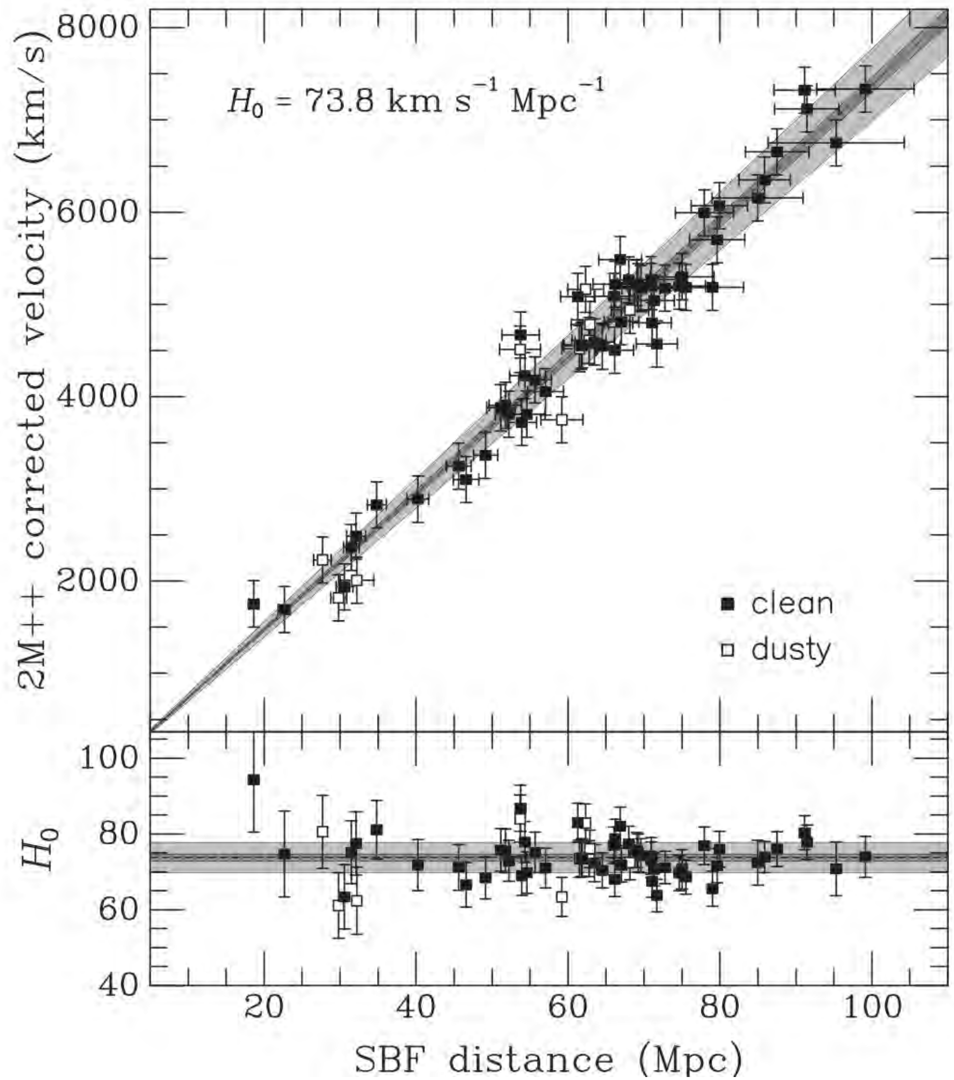




Credit: Drs. J. Blakeslee & J. Jensen

Surface brightness fluctuations

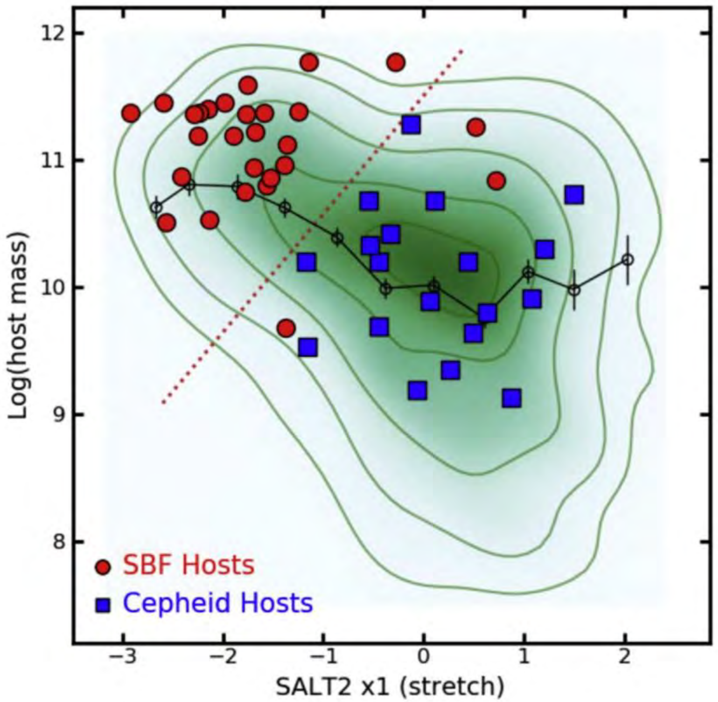
- Hubble diagram based on SBF distances obtained with *HST* in the near-infrared
- SBF zeropoint calibrated using Cepheid distances to Virgo & Fornax clusters through the LMC (Jensen+ 2021)
- Velocities corrected using the flow field derived from 2MRS and other catalogs (Carrick+ 2015)

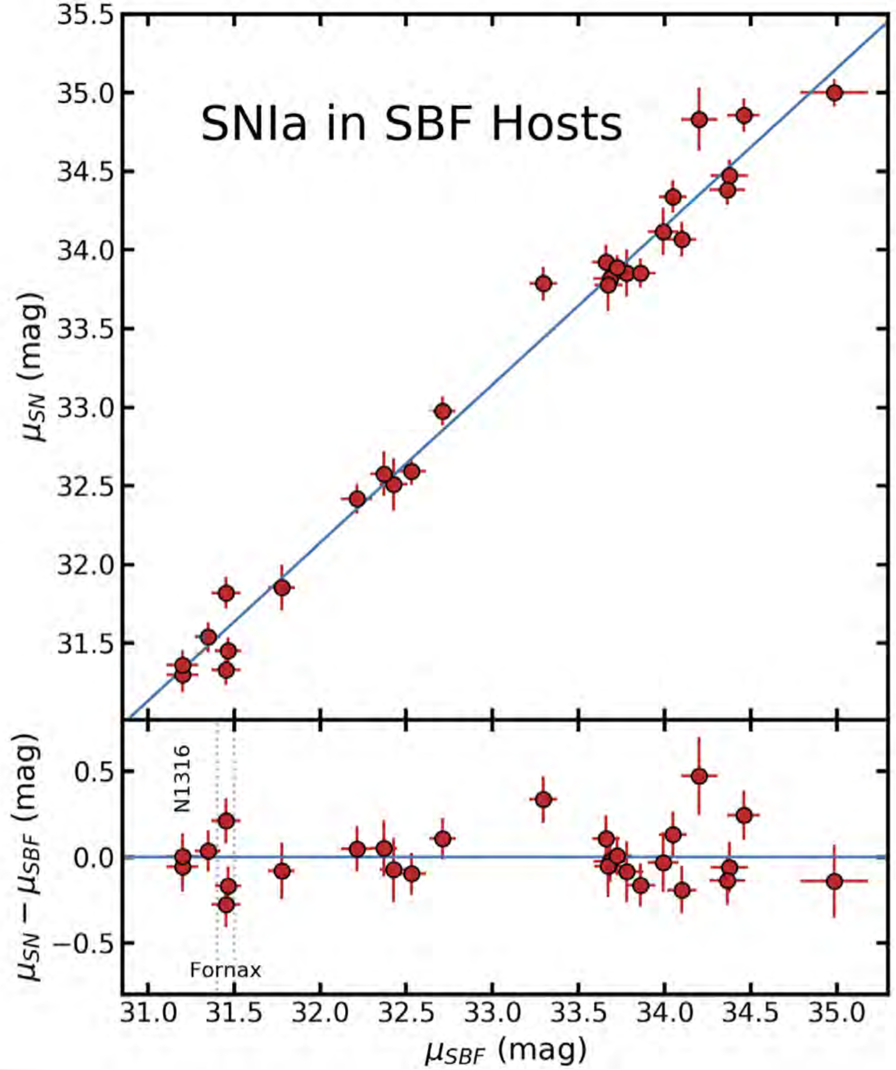


Blakeslee+ (2021)

Surface brightness fluctuations

- SBF can also calibrate SNeIa in elliptical galaxies out to D~100 Mpc, complementing the Cepheid-based sample





Garnavich+ (2023)

TRGB & SBF with *JWST*

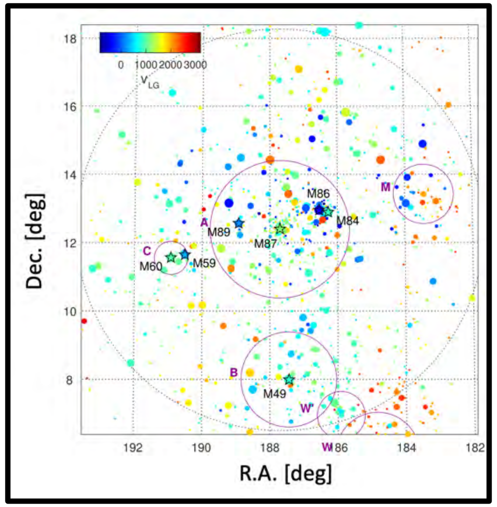
Core of NGC 1380 (Fornax cluster)

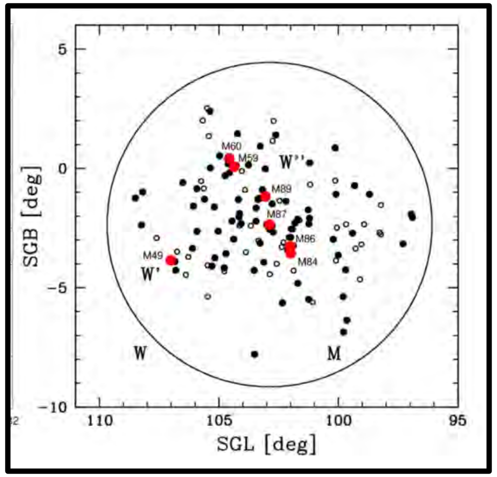
Halo field for TRGB

Anand+ (2024b,c)

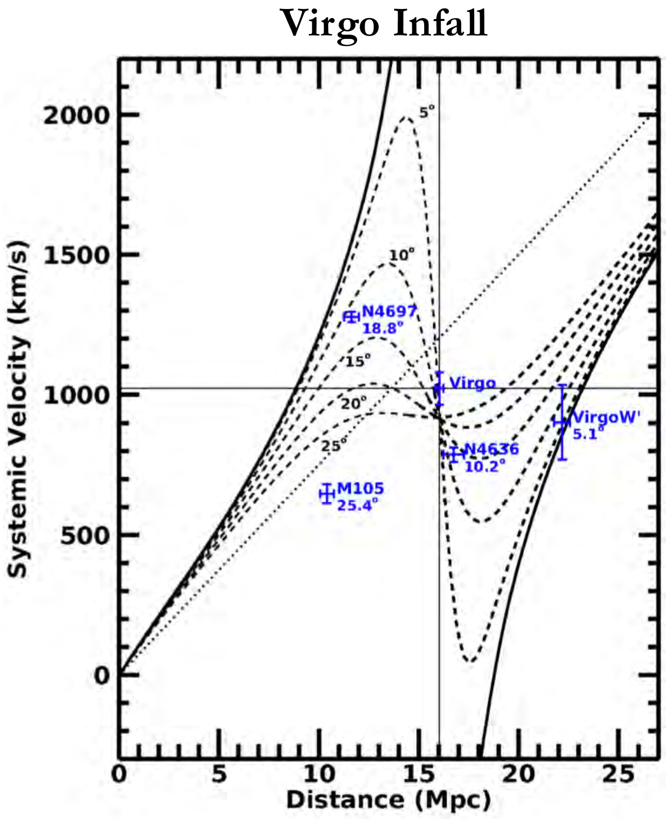
TRGB & SBF with *JWST*

- Observations of 13 galaxies in Fornax+Virgo clusters
- Approved *JWST* Cycle 3 program with ~40 SBF targets in Coma
- Plans for future observations into Hubble Flow and SNeIa hosts





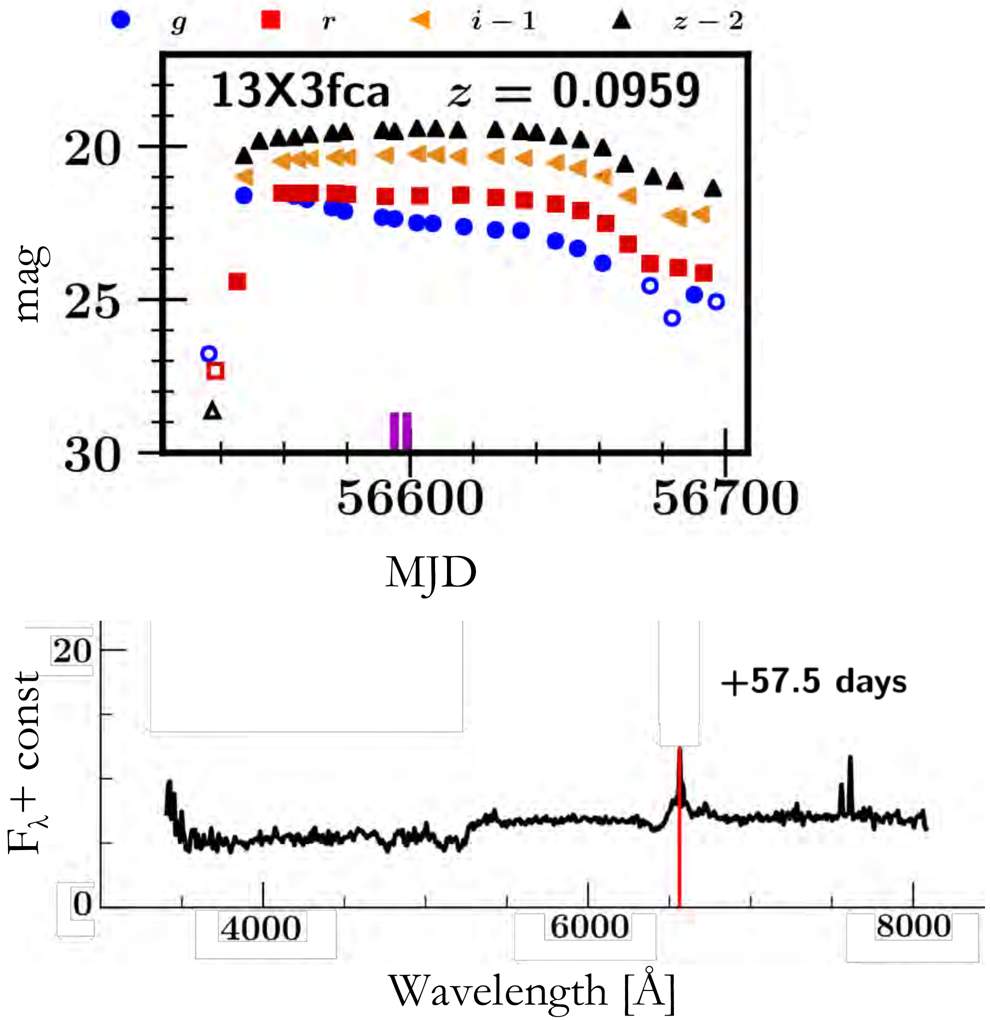
Anand+ (2024b)



Credit: Drs. J. Blakeslee & J. Jensen

Core-collapse supernovae

- Among core-collapse supernovae, those belonging to "Type II" (with hydrogen lines in spectra) can be used as distance indicators
- Progenitors have been detected!
- Two techniques: SCM (Hamuy & Pinto 2002) is more accurate but requires spectroscopy, while PCM (de Jaeger+ 2015) is purely photometric



Adapted from de Jaeger+ (2020)

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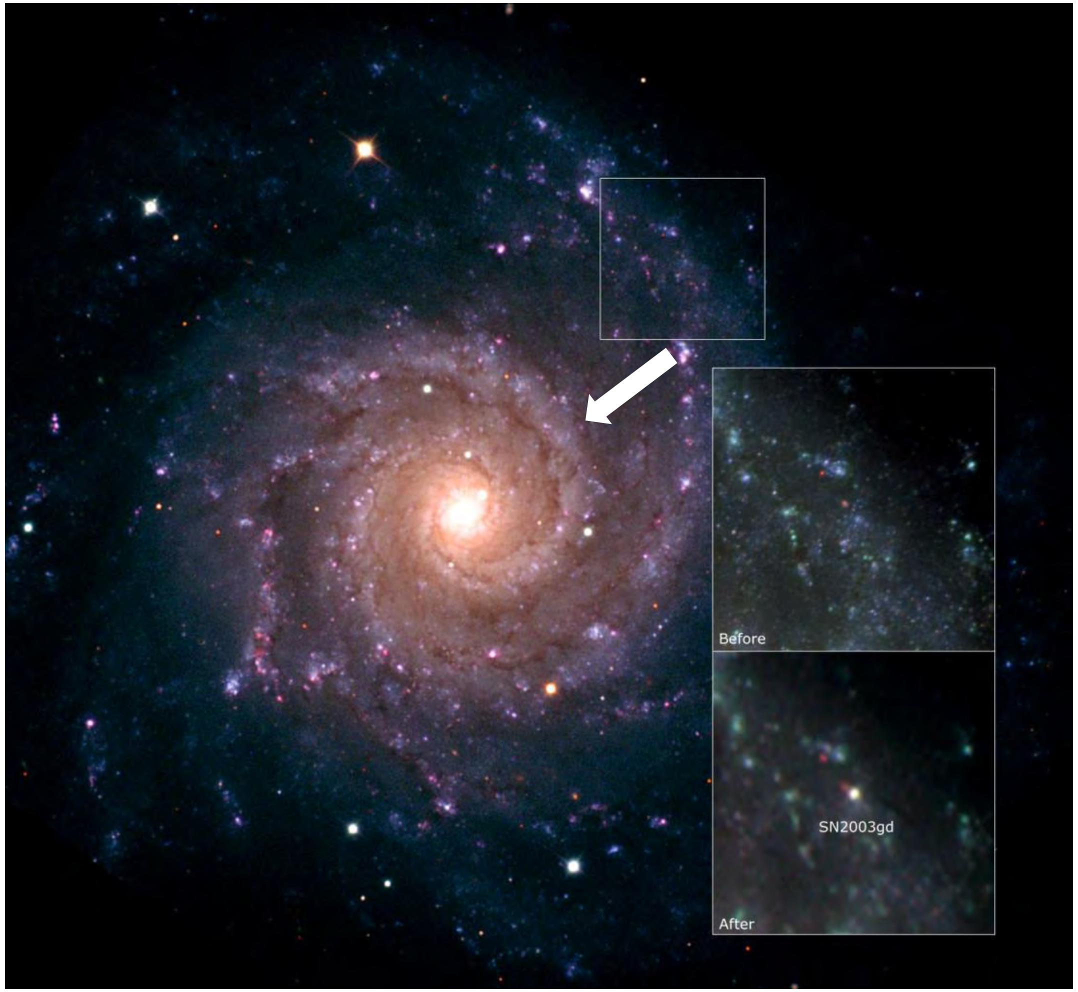

Smartt+ (2004)

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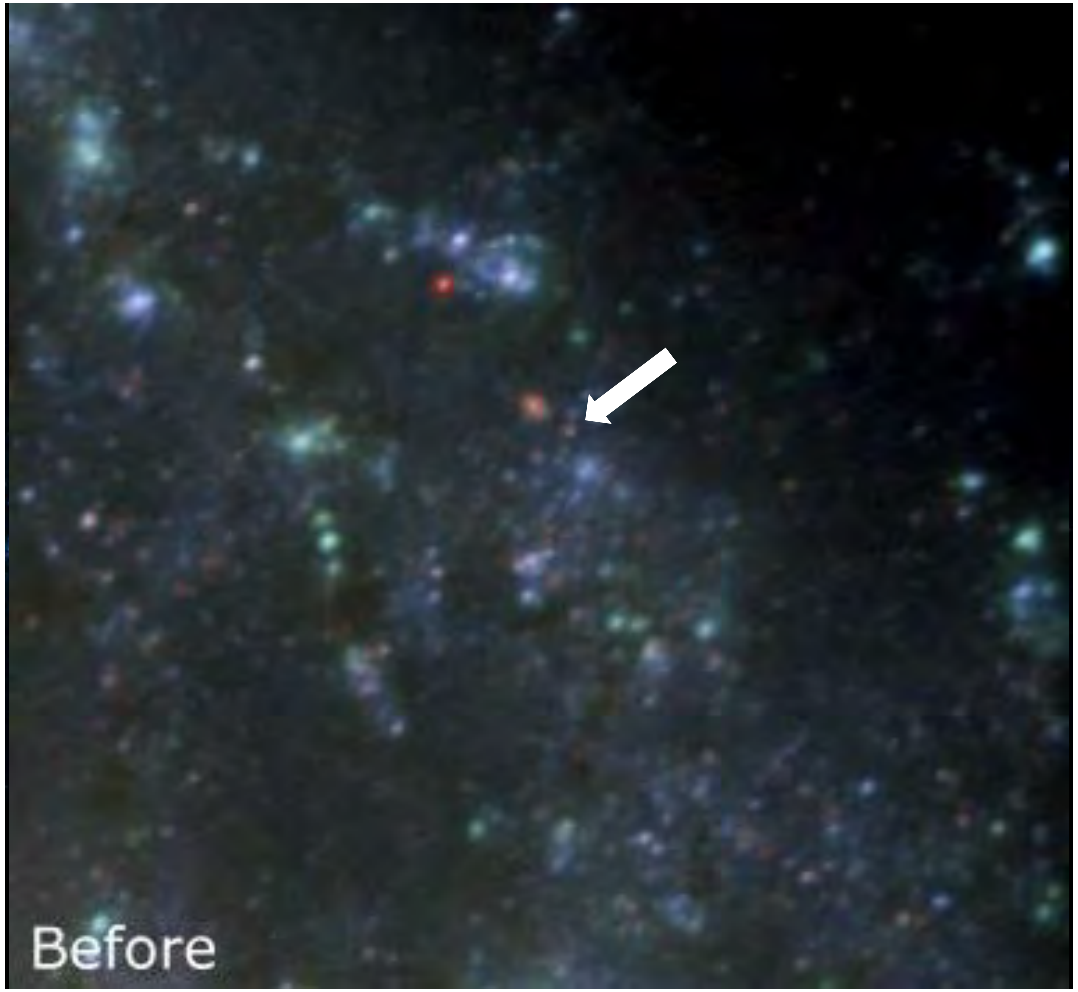

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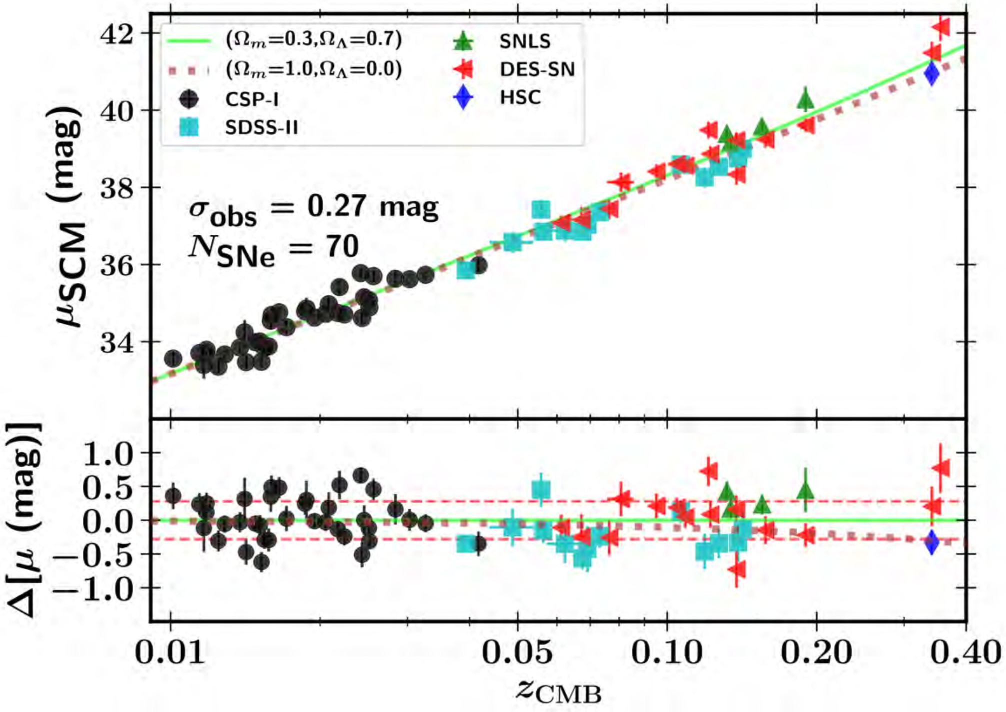
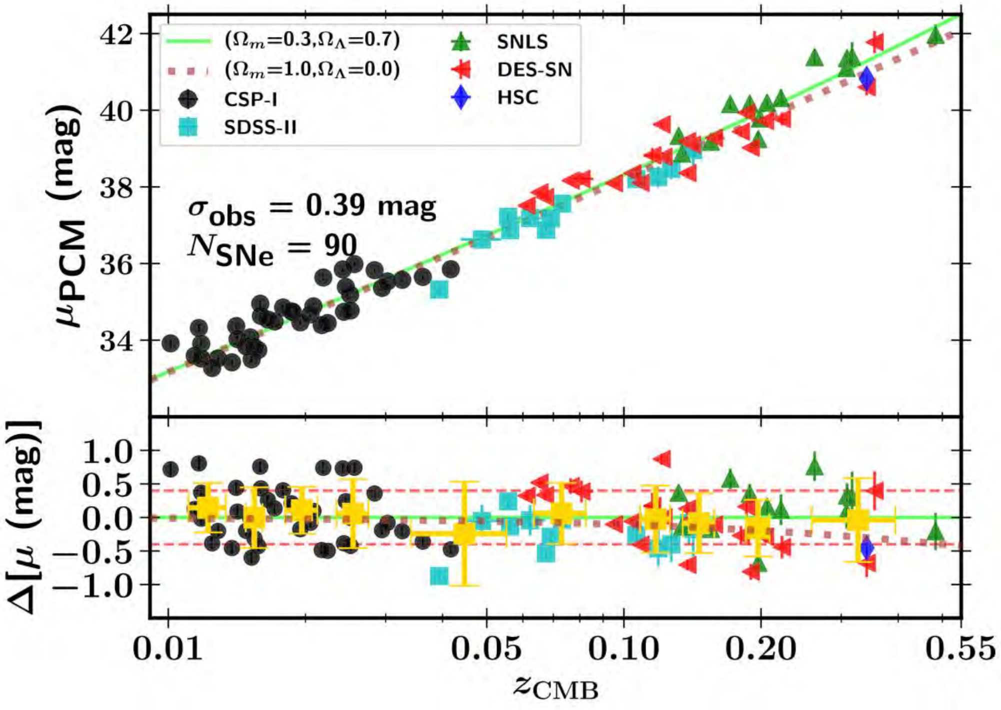
Smartt+ (2004)

Core-collapse supernovae

- Hubble diagrams from Type II SNe based on the two techniques
- There should be great progress once LSST starts!





de Jaeger+ (2020)

Virial theorem in Spirals and Ellipticals

- The rotational velocity *v* and velocity dispersion σ in spirals/ellipticals, following the virial theorem, is given by the mass M confined within a given radius – the disk scale length R_0 or the half-light radius R_{eff}:

$$v_{\rm rot}^2 = \alpha_s G \frac{M(R_0)}{R_0} \qquad \sigma^2 = \alpha_e G \frac{M(R_{\rm eff})}{R_{\rm eff}}$$

- The radial surface brightness distributions follow an exponential disk or a de Vaucoulers (1941) profile:

$$I(r) = I_0 e^{-\frac{r}{R_0}} \qquad I(r) = I_{\rm eff} e^{-7.67\left(\left(\frac{r}{R_{\rm eff}}\right)^{1/4}-1\right)}$$

Credit: Dr. R-P. Kudritzki

Virial theorem in Spirals and Ellipticals

- Integrate surface brightness profile to obtain luminosity: $L = 2\pi \int_0^\infty I(r) r dr$

$$L = 2\pi R_0^2 I_0 \qquad\qquad L = 7.22\pi R_{\mathrm{eff}}^2 I_{\mathrm{eff}}$$

- Substitute R_0 and R_{eff} by their definitions from the previous slide and move the *v* or σ term to the left-hand side, assuming constant M/L

$$L = 2\pi I_0 \alpha_s^2 G^2 \frac{M^2}{v_{\mathrm{rot}}^4} \qquad\qquad L = 2\pi I_{\mathrm{eff}} \alpha_e^2 G^2 \frac{M^2}{\sigma^4}$$

$$v_{\mathrm{rot}}^4 = 2\pi I_0 \alpha_s^2 G^2 \left(\frac{M}{L}\right)^2 L \qquad\qquad \sigma^4 = 7.22\pi I_{\mathrm{eff}} \alpha_e^2 G^2 \left(\frac{M}{L}\right)^2 L$$

Credit: Dr. R-P. Kudritzki

Virial theorem in Spirals and Ellipticals

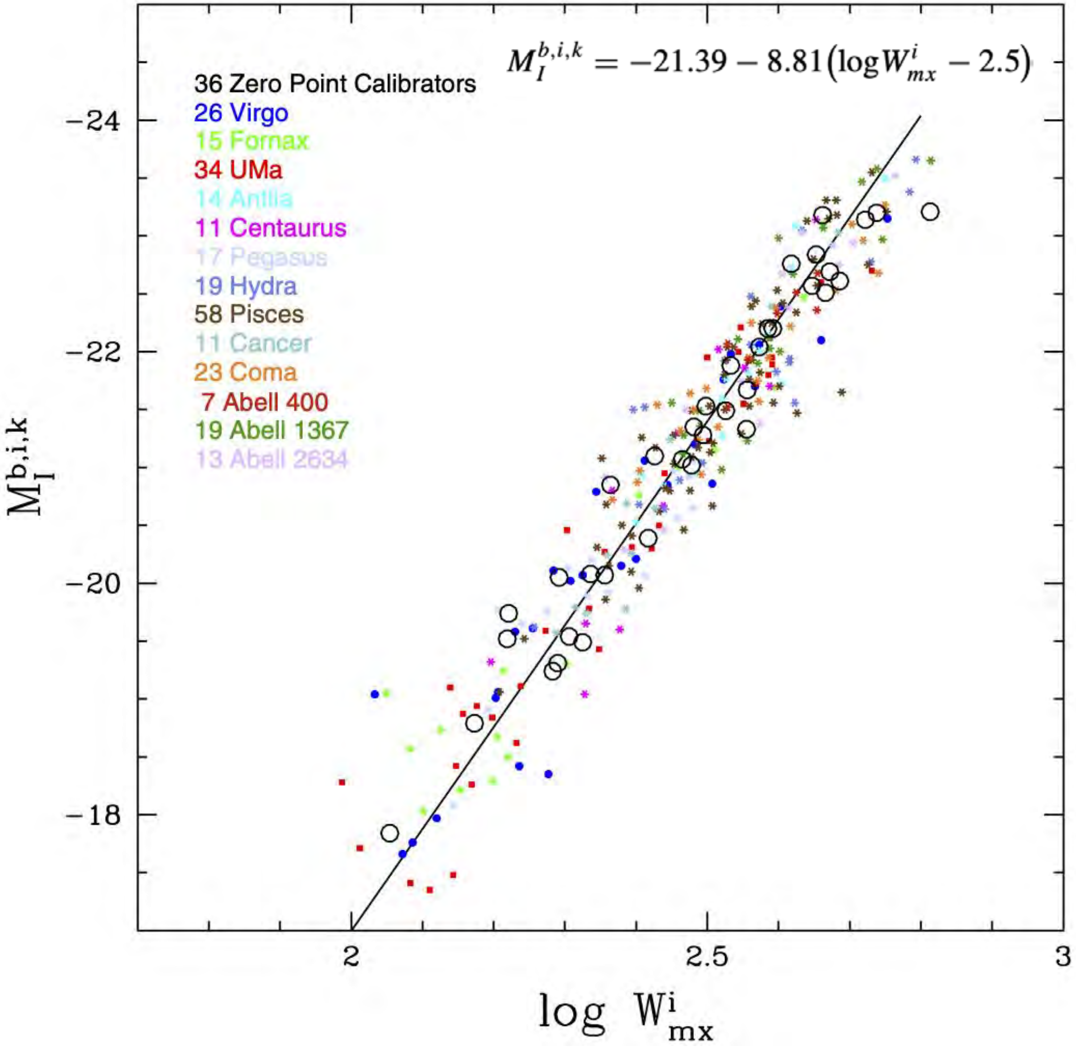
- Recast into absolute magnitudes with M = -2.5 log L to arrive at

$$M = n \log(v_{\rm rot}) + C_{TF}$$

$$M = n \log(\sigma) + C_{FJ}$$

with n ~ –10

- These relations were derived by Tully & Fisher (1977) and by Faber & Jackson (1976), respectively.



Tully+ (2012)

Virial theorem in Spirals and Ellipticals

- The Faber-Jackson relation is now understood to be a projection of the Fundamental Plane relation (Djorgovski & Davis 1987), due to a dependence of M/L on absolute magnitude:

$$\log(\sigma) = \alpha \log(R_{\rm eff}) + \beta \log\langle I \rangle_{\rm eff}$$

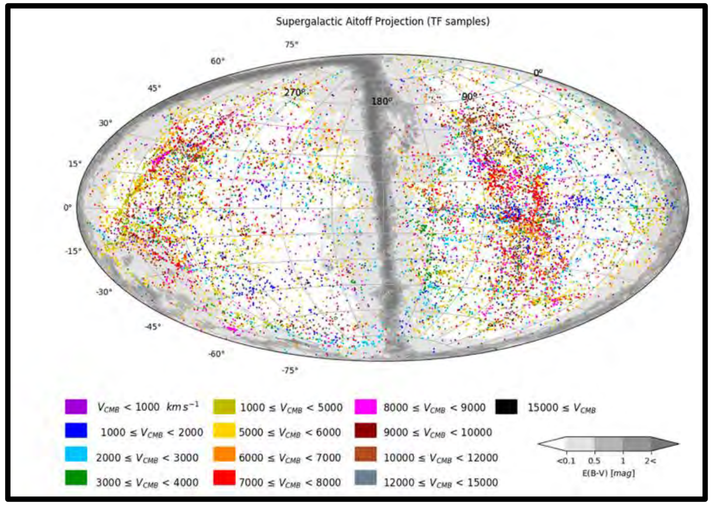
- Likewise, the Tully-Fisher relation has been recast using baryonic mass instead of absolute magnitude, to take into account the contributions from gas in addition to those from stars (Kourkchi+ 2022):

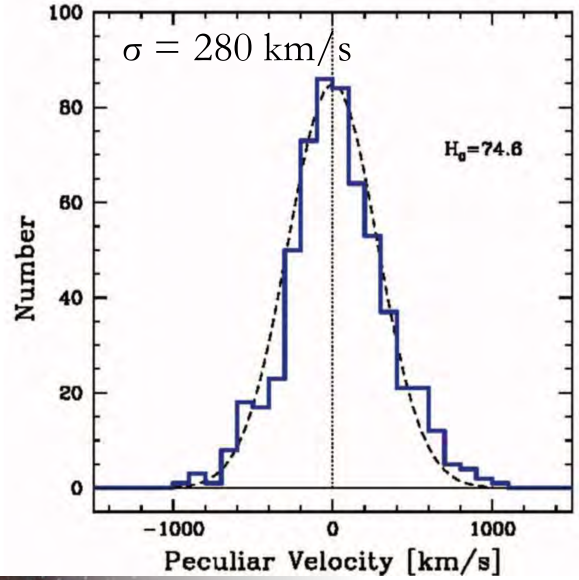
$$\log M_{\rm b} = \alpha + \beta(\log W^{i}_{\rm mx} - 2.5)$$
$$M_{\rm b} = K_{\rm g} M_{\rm HI} + \gamma^{*}_{\lambda} L_{\lambda}$$

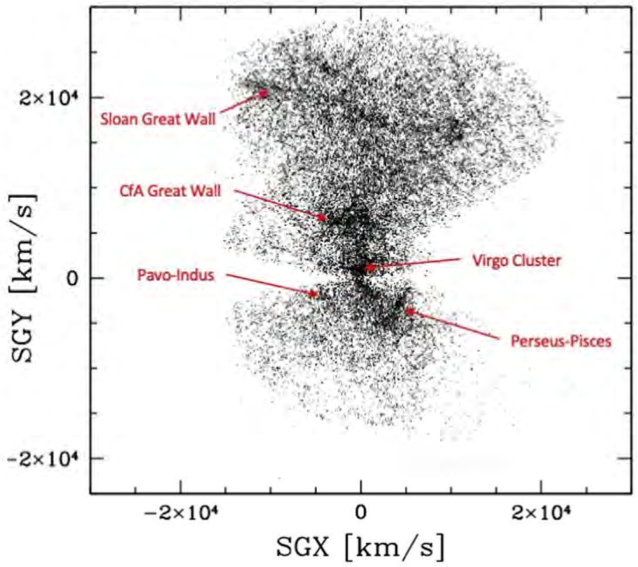
CosmicFlows 4

- Largest homogenized collection of galaxy distances based primarily on Baryonic Tully-Fisher & Fundamental Plane, with important samples based on TRGB, SBF, SNe Ia, etc., plus redshifts

- N=55,877 galaxies gathered into 38,065 groups to map structures & large-scale flows



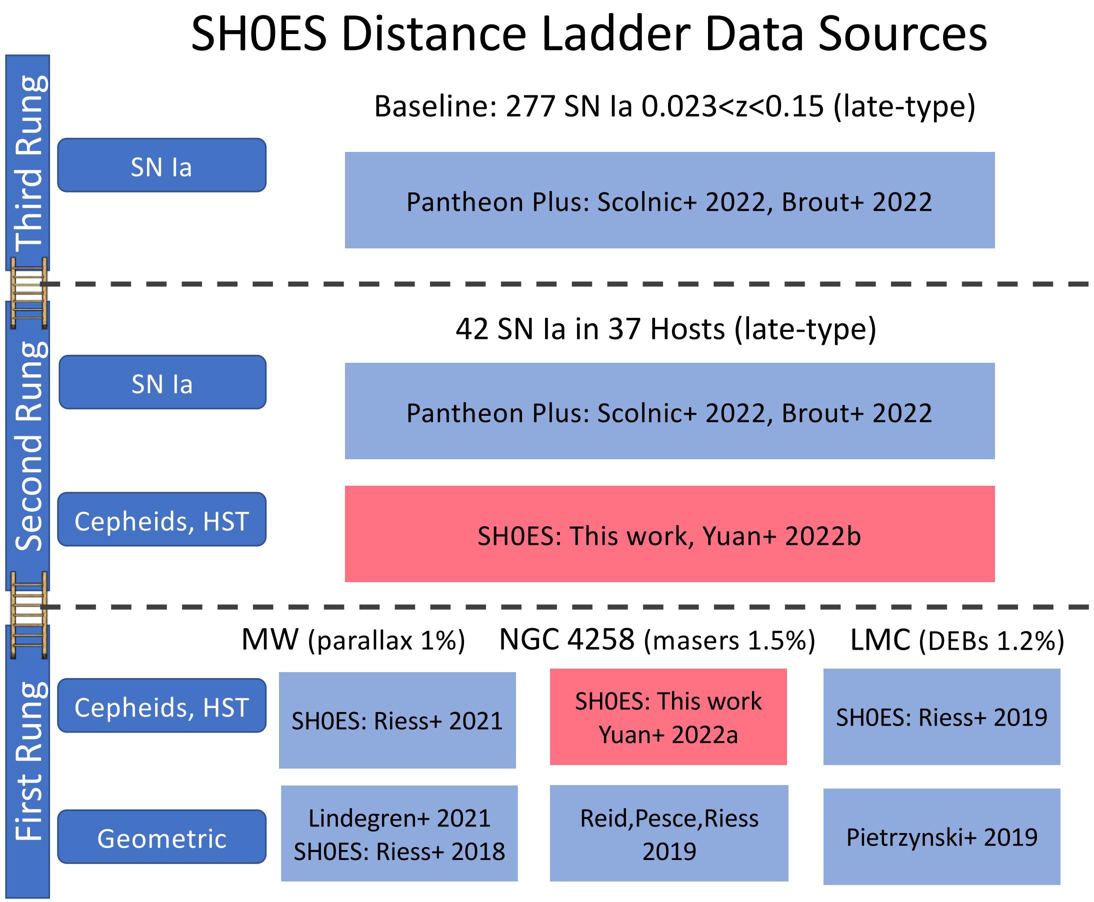




Tully+ (2023)

Putting it all together: SH0ES

- SH0ES project: started in 2005 by Riess, Macri and collaborators
- Geometric calibration of Cepheids, Cepheid calibration of SNeIa, SNeIa in Hubble Flow → H_0
- 18 competed proposals in *HST* Cycles 11-29, ~1,000 orbits
- 2022: complete sample of SNeIa in Cepheid-bearing hosts with z<0.01



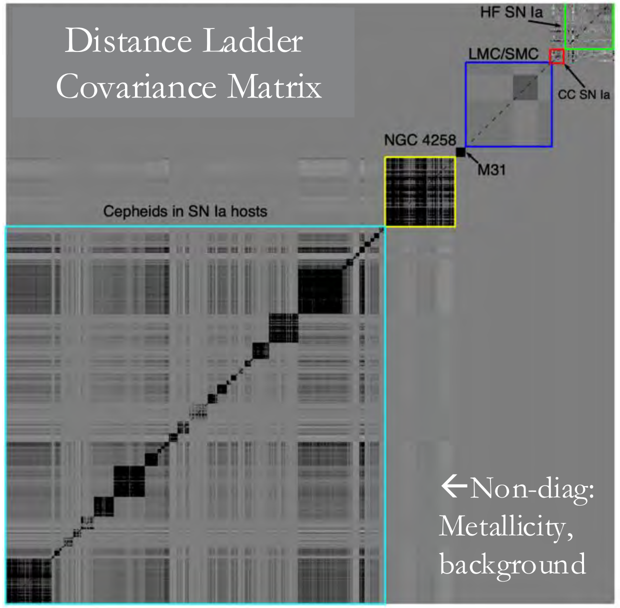
Riess+ (2022a)

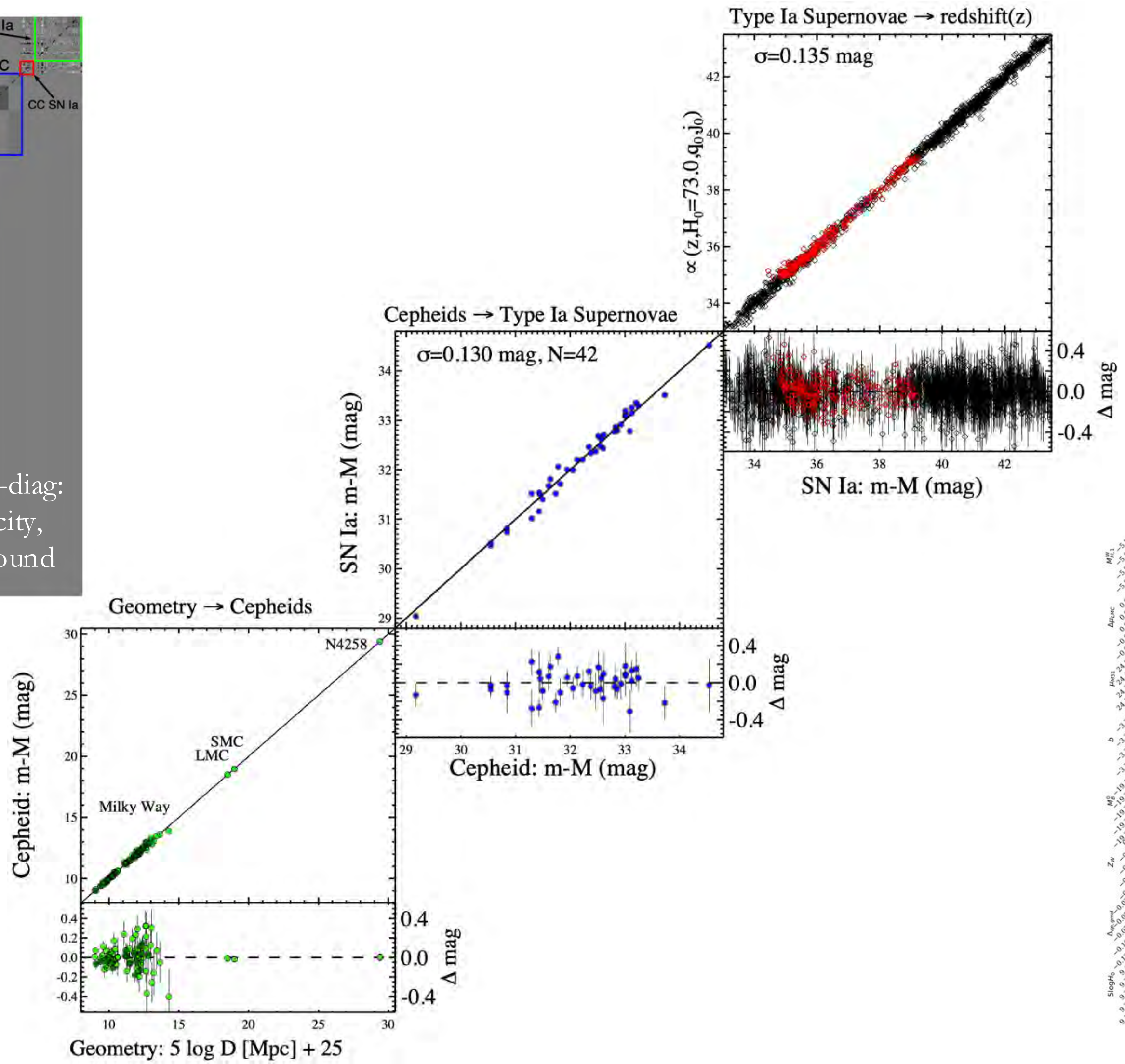
The SH0ES Project

- All Cepheid photometry on *HST* system to negate systematic effects; extensive artificial star simulations to characterize photometric bias
- Combine *H* band (1.6μm) with *V*-*I* colors (0.55, 0.8μm) to correct for effects of dust and temperature in Cepheid P-L relation
- All SN photometry (Pantheon+) on same system and fully corrected

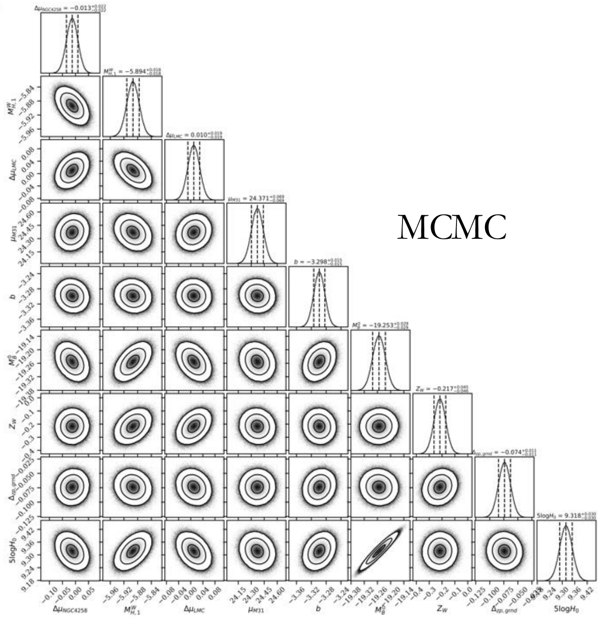
- Joint analysis of all photometry using matrix-based approach
- Enables study of many "variants" (different anchors, different dust laws, different Cepheid P-L relations, etc.) → carry into error budget
- Take into account non-diagonal covariance for error budget

The SH0ES Project





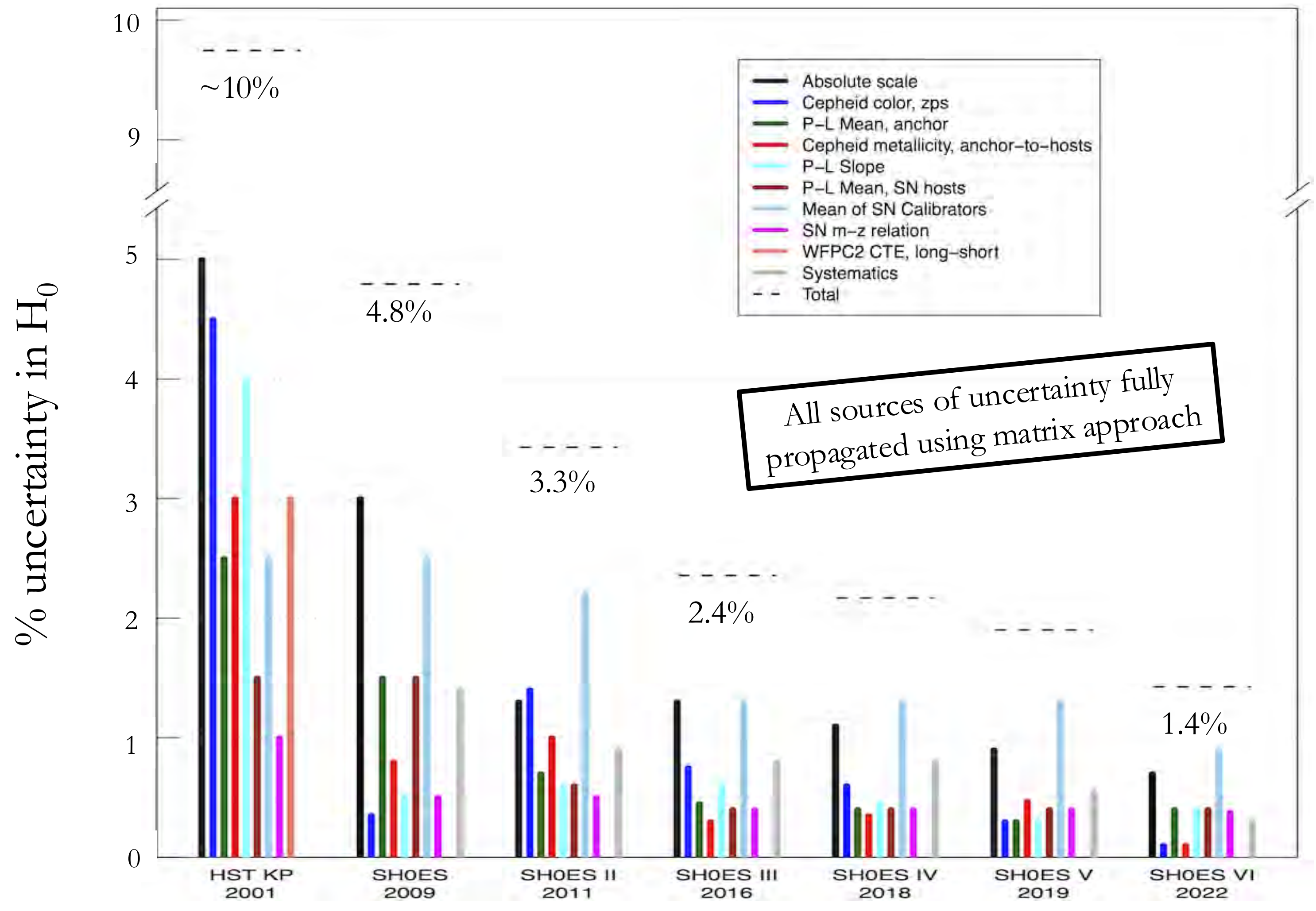
5 free parameters: Cepheid P-L zeropoint, slope, metallicity; SNeIa luminosity, $5\log H_0$



MCMC

Riess+ (2022a)

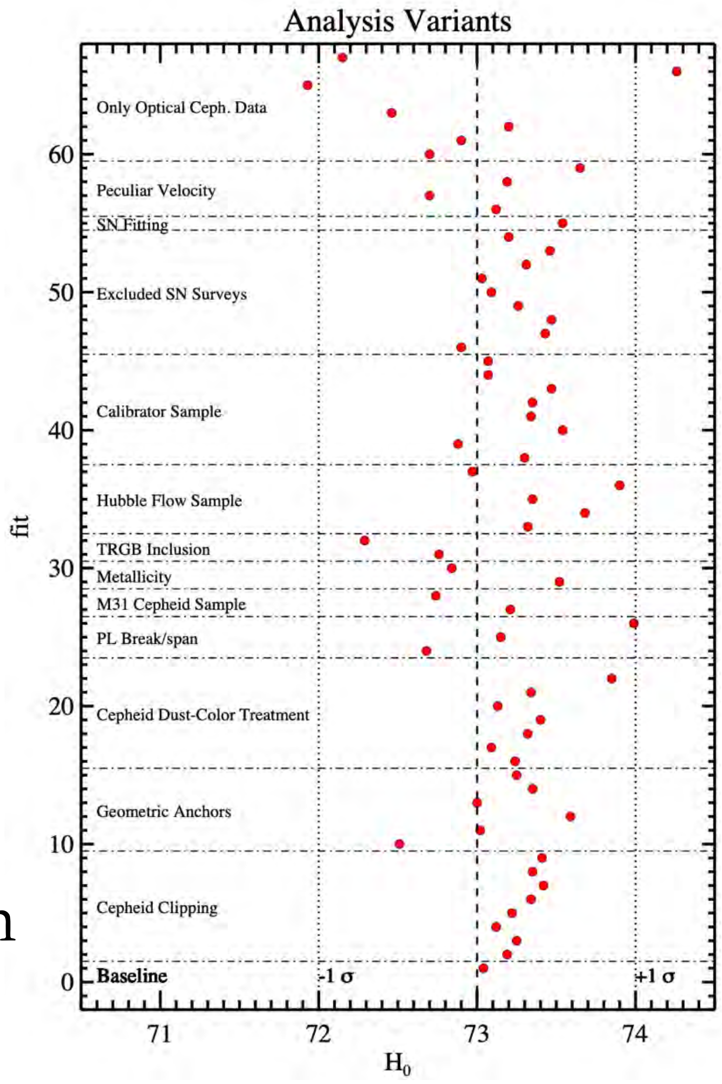
The SH0ES Project



Riess+ (2022a)

The SH0ES Project

- Analysis variants: 12 categories, 67 variants, bifurcations, extensions, etc
- Bottom line: hard to get below 72.5, above 73.5
- Propagate dispersion as extra systematic

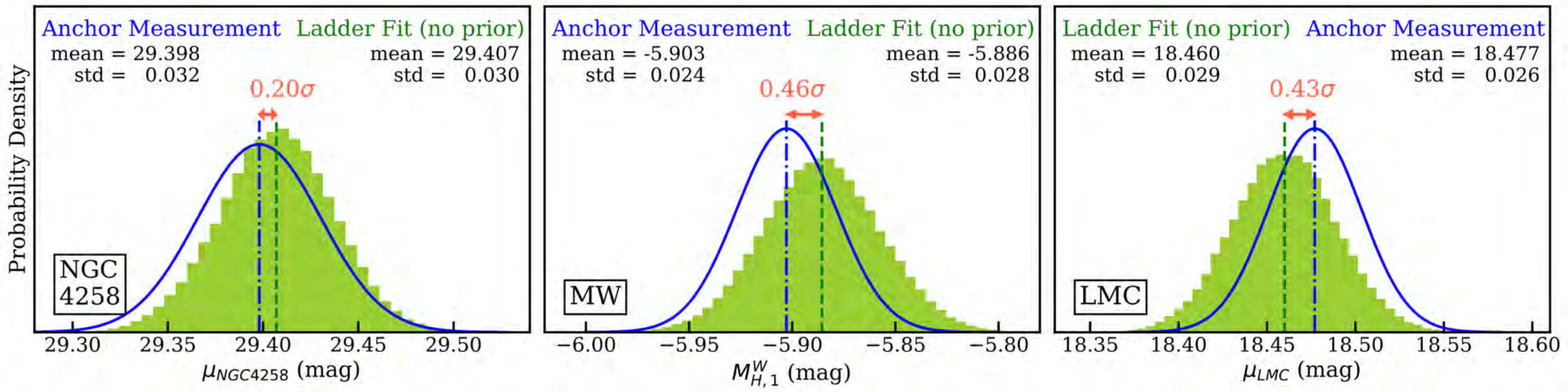


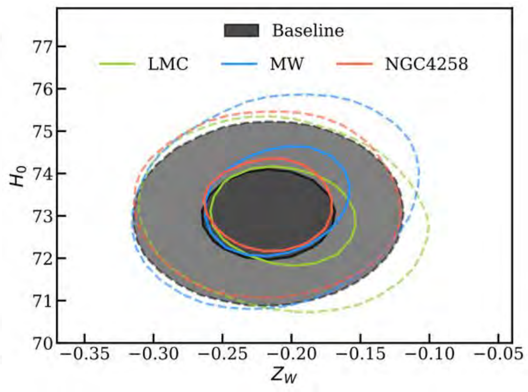
- Optical Cepheid data only (72.7)
- Different pec. vel map or none (73.1,72.7)
- SN scatter ind. wave+mass step (73.5)
- No pre-2000 SNe (73.2)
- closest half hosts (73.1)
- most crowded half (73.4)
- least crowded half (73.3)
- Skip "local hole" z>0.06 (73.4)
- All host types (73.3)
- include TRGB (consistent) jointly (72.5)
- No metallicity term (73.5)
- Break in PL at P=10 days (72.7)
- No dust correction (74.8)
- Individual host dust law (73.9)
- Free param dust law (73.3)
- Low R_V=2.5 dust law (73.2)
- Two of three anchors (73.0,73.4,73.2)
- No outlier rejection (73.4)

Riess+ (2022a)

The SH0ES Project

- Baseline fit: H_0=73.04±1.04, km/s/Mpc, including systematics
- Recent addition of SMC as 4th anchor yields 73.17±0.86 (Breuval+ 2024)
- All anchors internally consistent, with Cepheid metallicity dependence





Riess+ (2022a)

Recent results from *JWST*

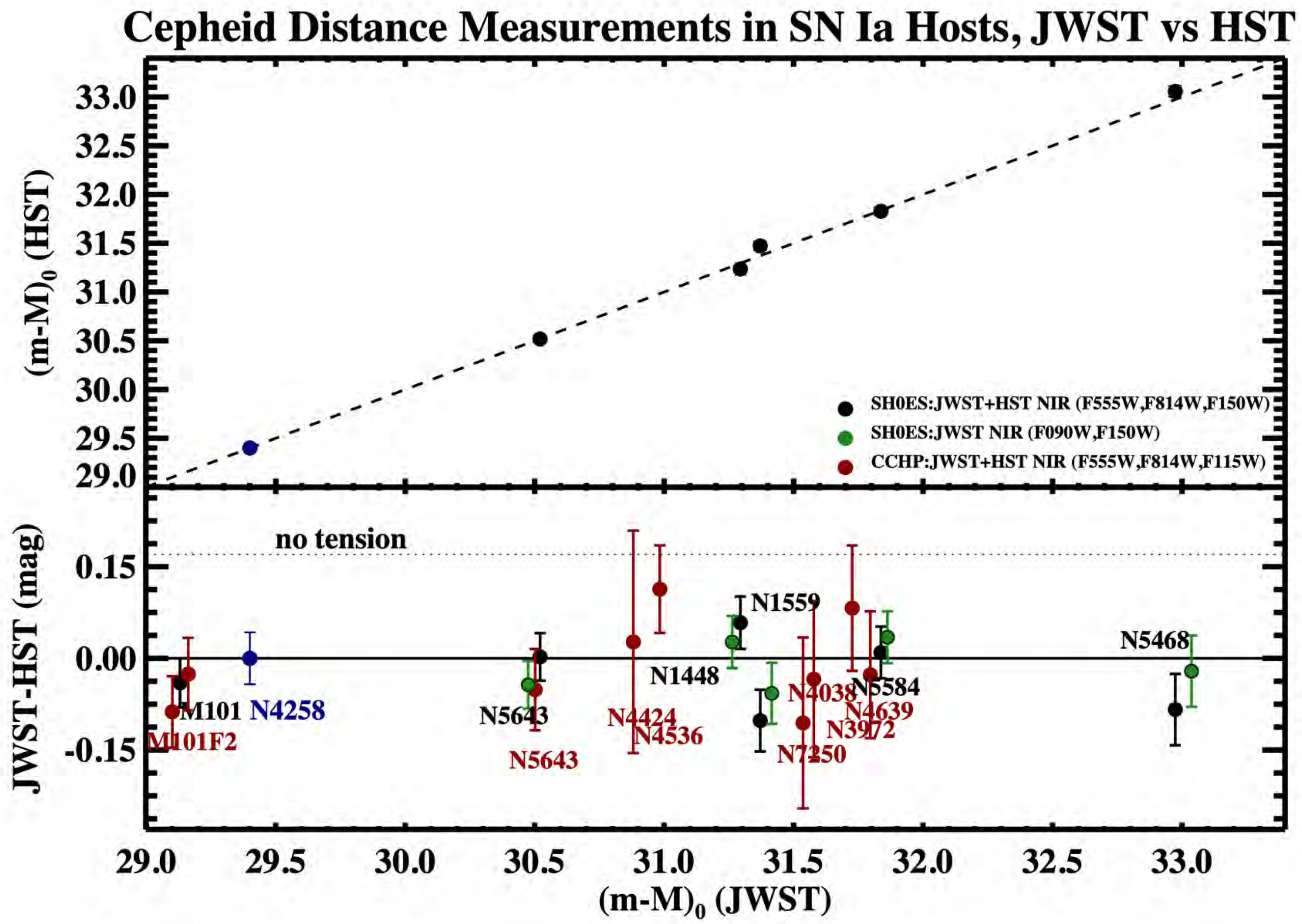
- *JWST* imaged 15 SH0ES galaxies (19 SNe) in Cycle 1 [CCHP, SH0ES]
- Cycle 2 program [SH0ES] observed 5 more galaxies (7 SNe)
- 2 additional SH0ES galaxies imaged by other programs in Cycles 1 & 2

- Cepheids, TRGB & JAGB measurements available for most of these (Riess+23; Riess+24a; Li+24a,b; Anand+24a; Lee+24; Freedman+24)

- Riess+24b carried out a detailed comparison of distances to each galaxy obtained by each method with *JWST* and *HST* (adds *I* TRGB, Miras) all anchored to NGC 4258 (no *JWST* observations of MW, MCs yet)

Recent results from *JWST*

- Comparison of *JWST* Cepheid distances to *HST* ones shows excellent agreement and no distance-dependent bias
- Larger errors for CCHP distances because of their choice of filteres



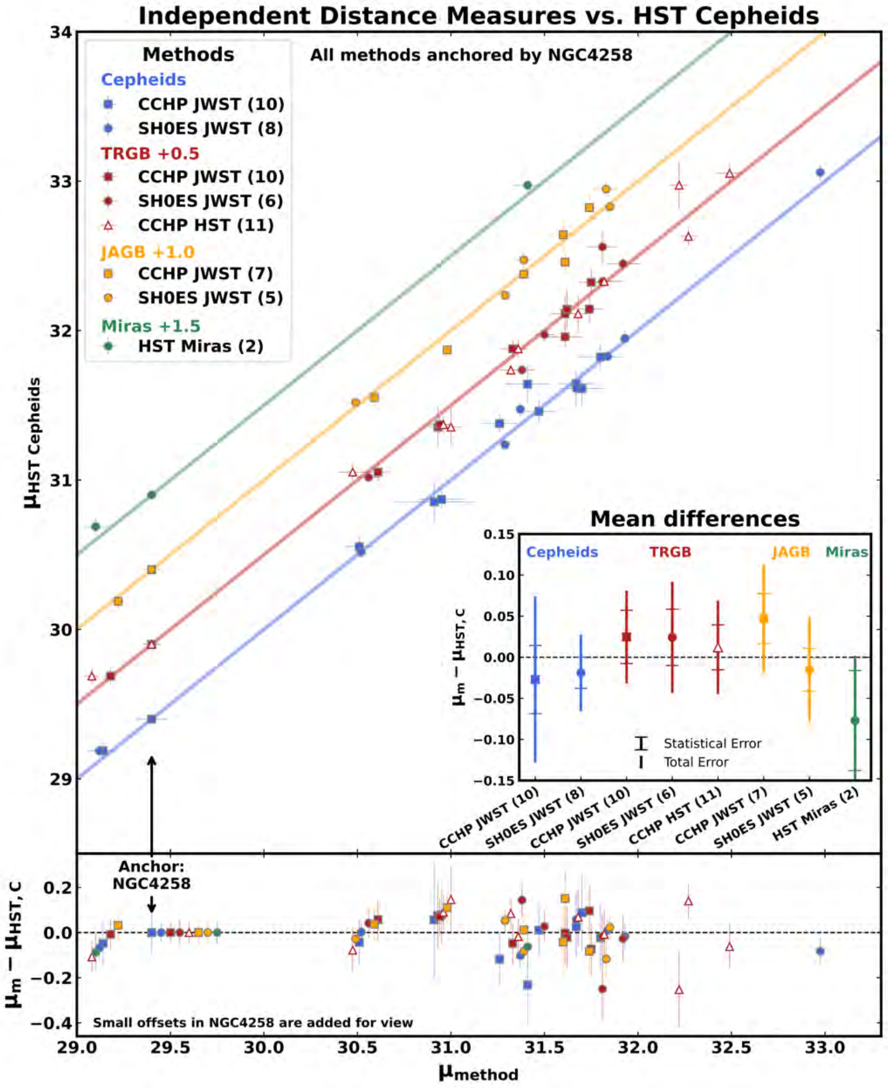
Credit: Dr. A. Riess

Recent results from *JWST*

All methods agree at 1σ

Sample	Team	$\mu_{JWST} - \mu_{HST}$ [mag]	σ
HST Cepheids vs. *JWST* Cepheids			
10 Hosts[a]	CCHP	−0.027	0.10
8 Hosts ($D \leq 25$ Mpc)	SH0ES	−0.02	0.03
14 Unique Hosts	Both	−0.02	0.03
HST Cepheids vs. *JWST* JAGB			
7 Hosts (mode)	CCHP	0.047	0.066
5 Hosts	SH0ES	-0.015	0.064
HST Cepheids vs. *JWST* NIR-TRGB			
10 Hosts	CCHP	0.032	0.056
HST Cepheids vs. *JWST* I-TRGB			
6 Hosts ($D \leq 25$ Mpc)	SH0ES	0.02	0.067
HST Cepheids vs. I-TRGB			
11 Hosts	CCHP	0.01	0.057
HST Cepheids vs. *HST* Miras			
2 Hosts		−0.08	0.078

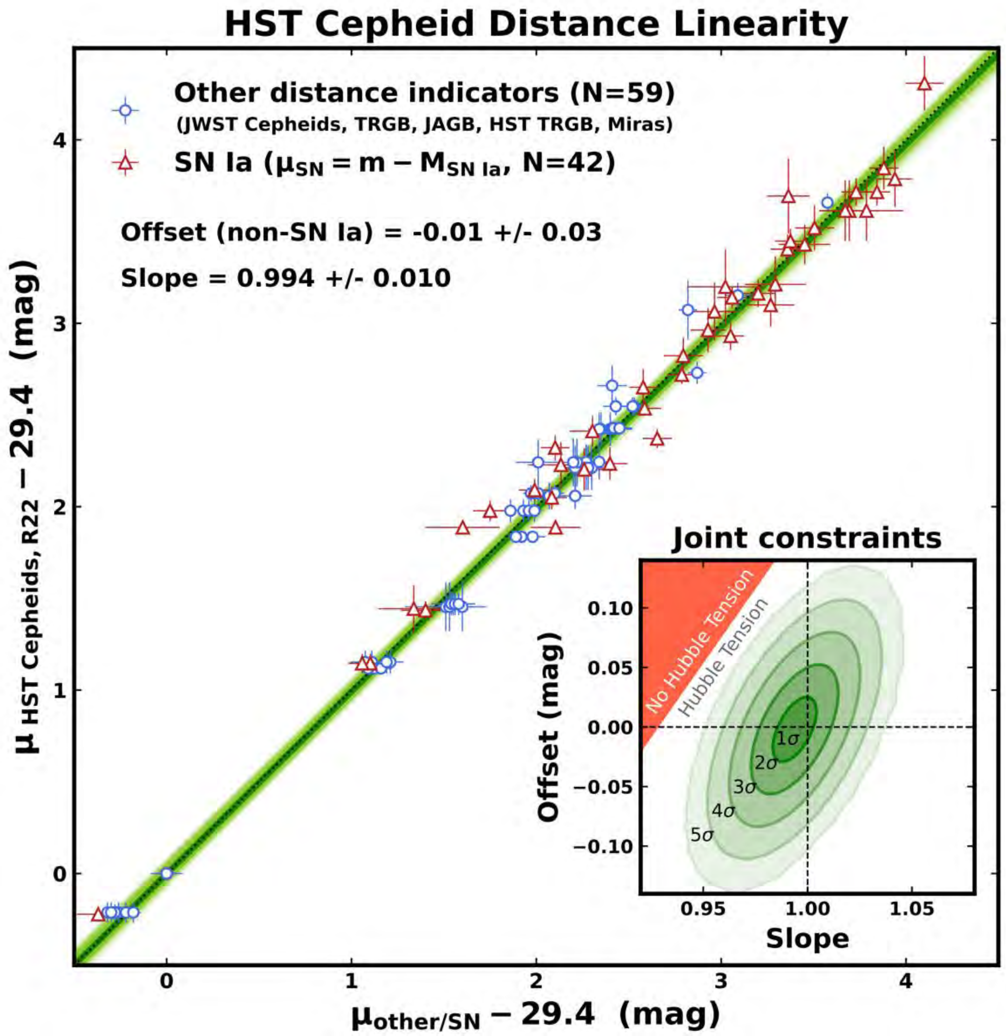
NOTE—(*): SH0ES $D \leq 25$ Mpc sample includes NGC 4038, M101 and NGC 3447 and excludes NGC 5468 as discussed in text. CCHP distances from F24 Table 2 and including uncertainties in F24 Table 5.



Riess+ (2024b)

Recent results from *JWST*

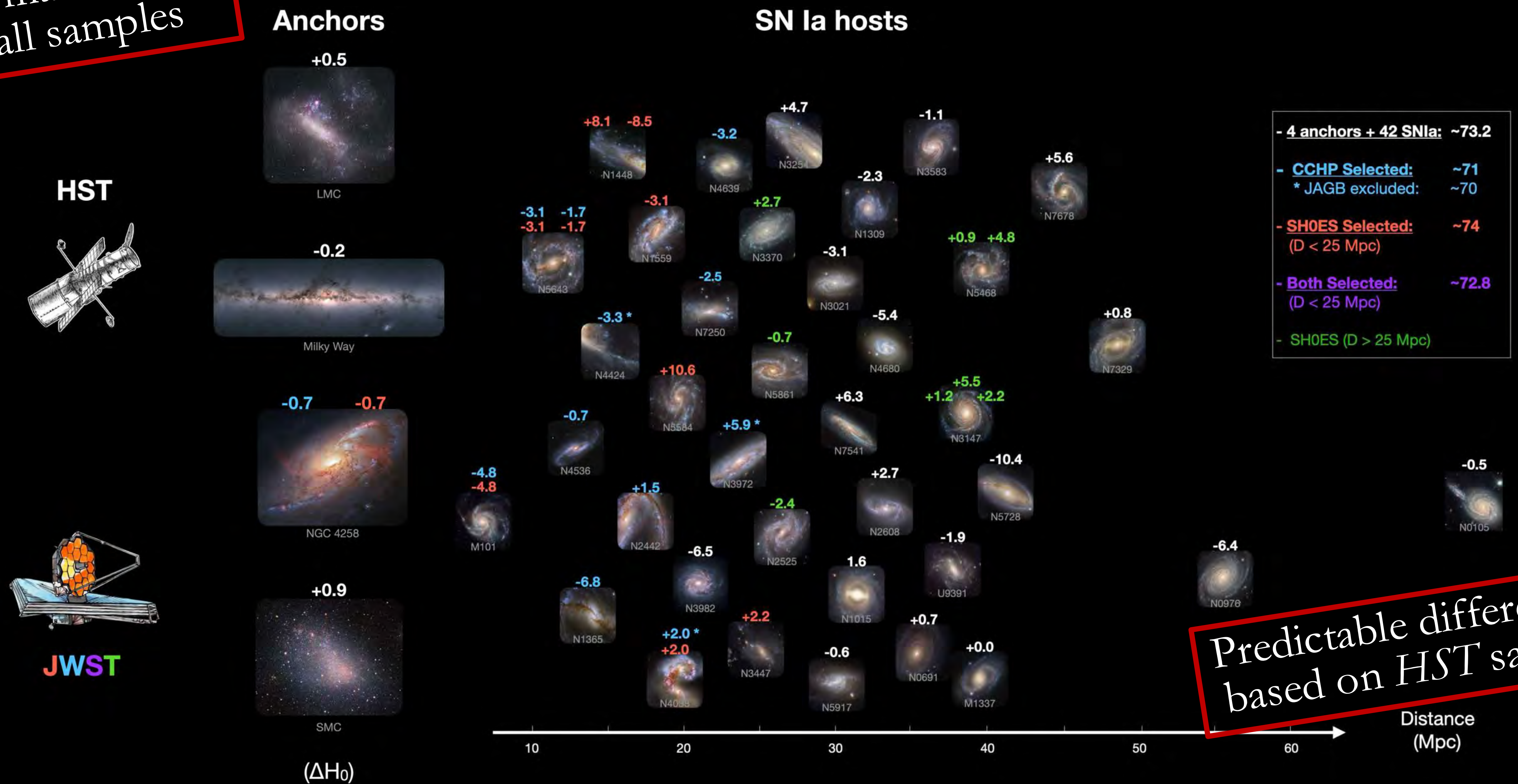
- Stringest test to date of *HST* Cepheid distance linearity: 59 comparisons against all other available methods, anchored to N4258
- If there's such excellent agreement, what's the reason for $\Delta H_0=2.5$ in Freedman+(2024)?
- Sample variance!



Riess+ (2024b)

Recent results from *JWST*

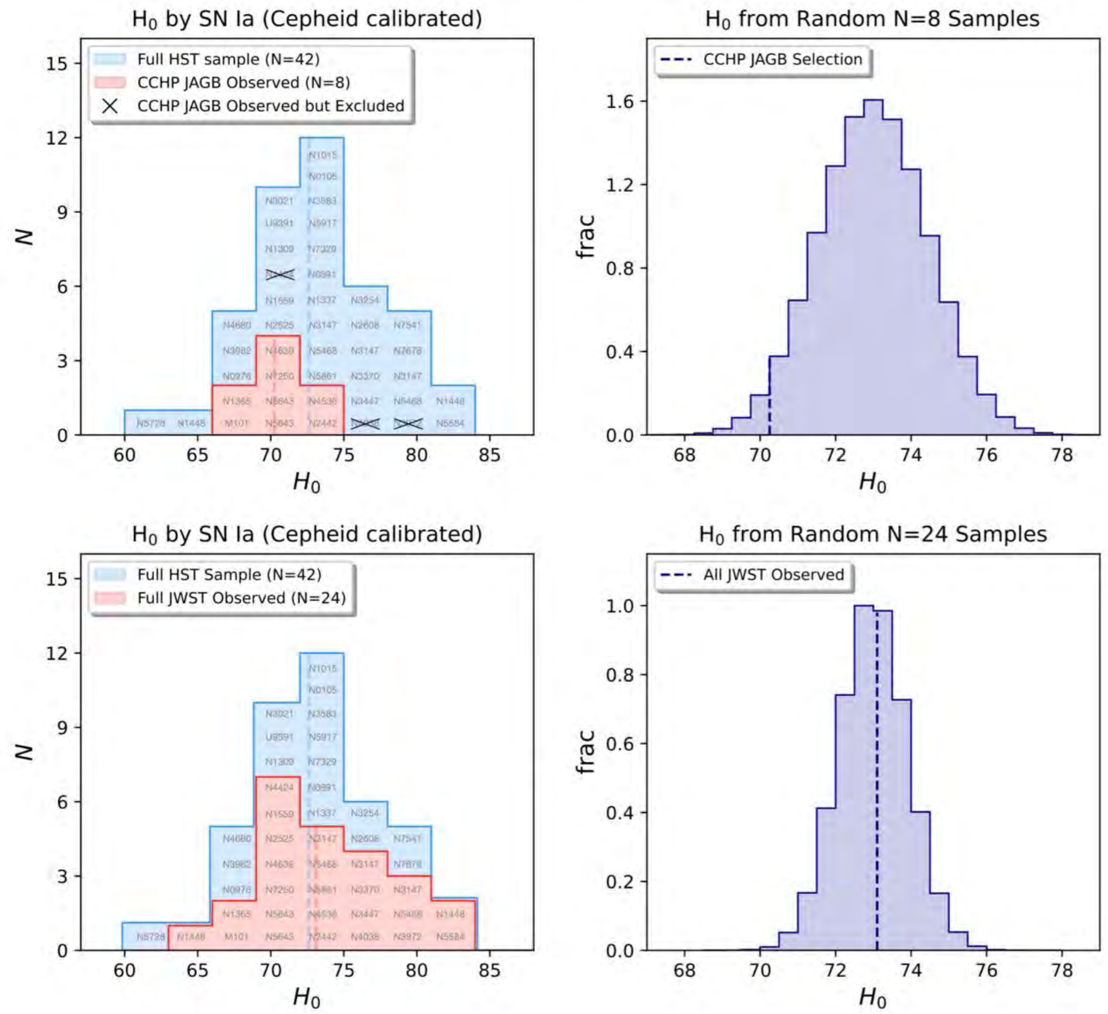
Choice of specific SNe matters for small samples

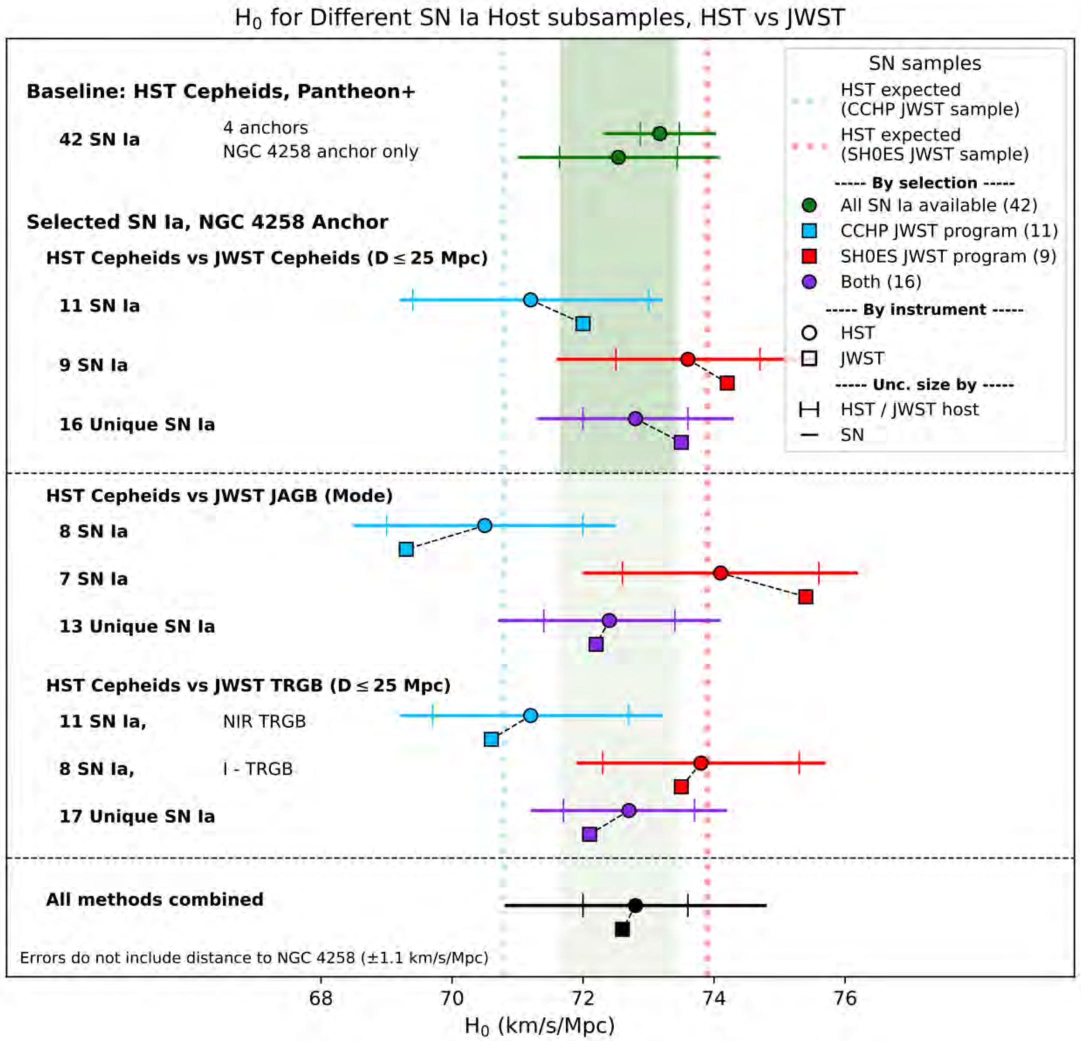


Predictable differences based on *HST* sample

Riess+ (2024b)

Recent results from *JWST*





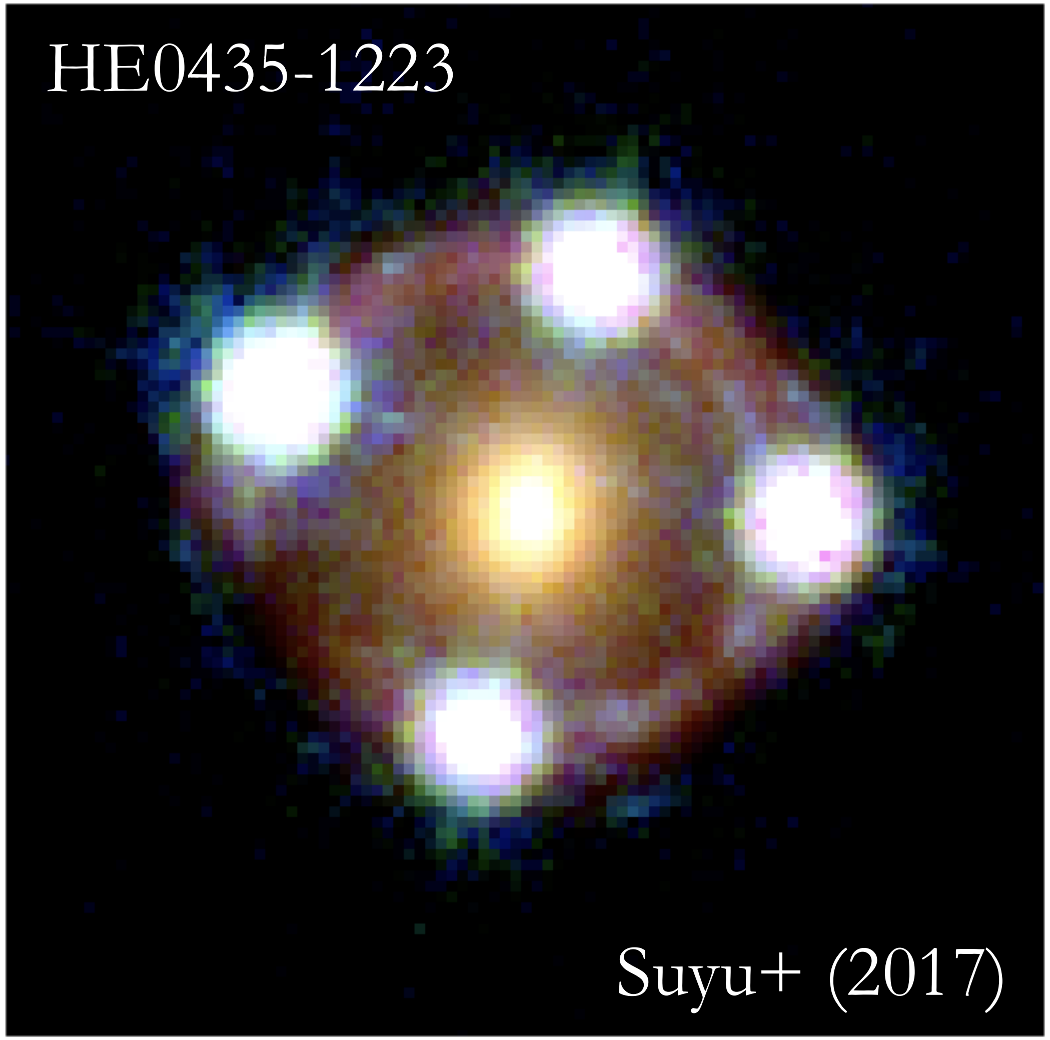
Riess+ (2024b)

Recent results from *JWST*

- Bottom line: *JWST* samples are still too small to yield competitive H_0
- Nevertheless, they provide an extremely important cross-check and validation of the larger *HST* sample, which it clearly passes
- H_0 from currently available *JWST* sample (N=17 SNe): 72.6±2.0; expected value for same galaxies with *HST*: 72.8 (full sample: 73.2±0.9)
- CMB analogy: South Pole Telescope observations of ~3,000 sq deg yielded much larger H_0 values than *Planck* – but they agreed extremely well on the same patches of the sky
- Sample variance again! No reason to discard more robust *Planck* results, but still a critical consistency check

H_0 from gravitational lensing

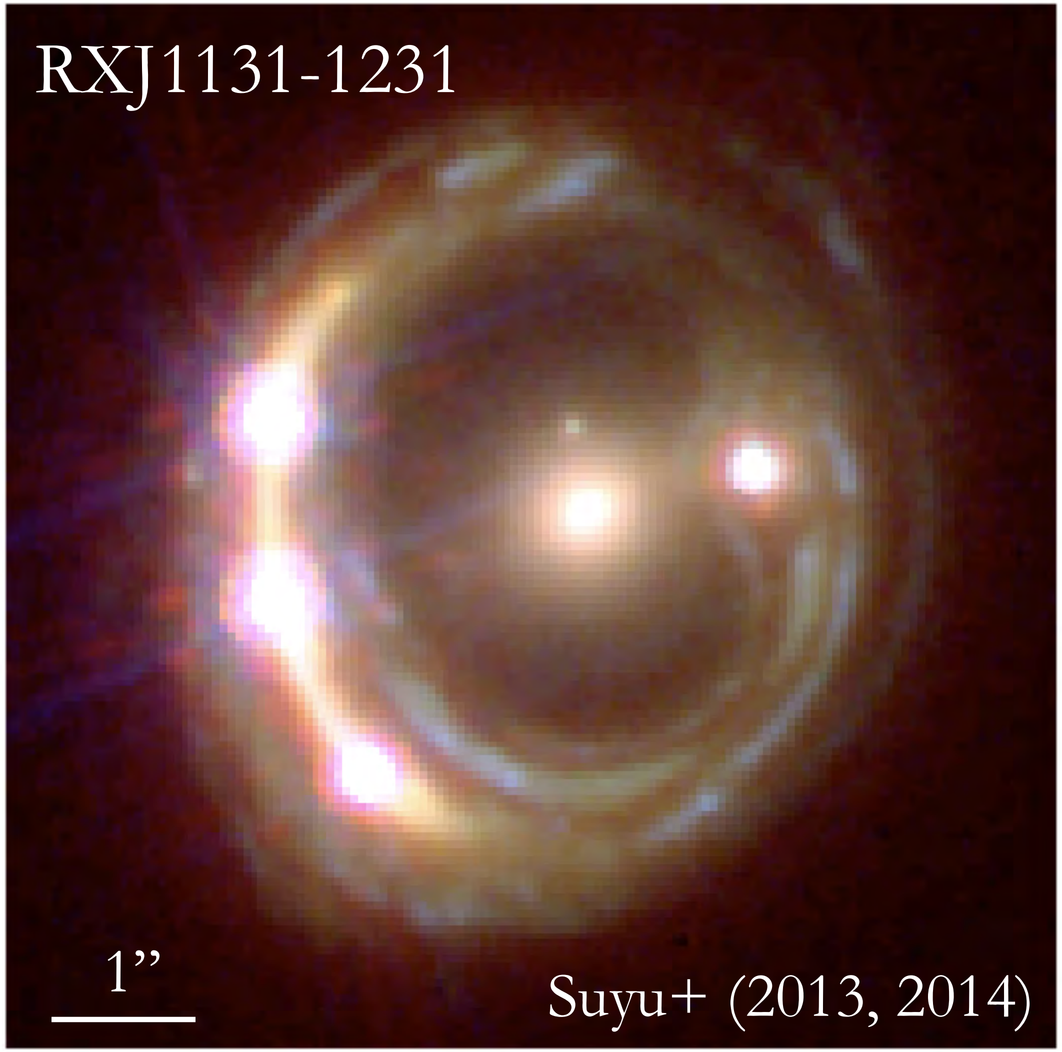
- Method first proposed by Refsdal (1964)
- Lensing of a quasar by a galaxy along the line of sight yields multiple images with different light travel times
- Relies on variability of quasar emission, as material is accreted onto supermassive black hole



Credit: Dr. S. Suyu

H_0 from gravitational lensing

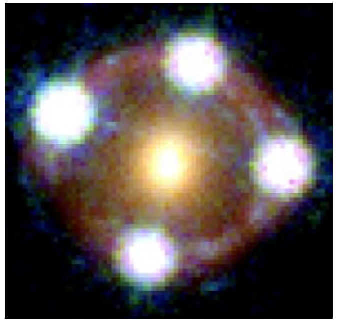
- Time delay: $t = \frac{1}{c} \boxed{D_{\Delta t}} \, \phi_{\text{lens}}$
- Time delay distance: $D_{\Delta t} \propto \frac{1}{H_0}$
- To measure H_0, one needs:
  (1) Time delays
  (2) Lens mass model (ϕ_{lens})
  (3) Mass along the line of sight

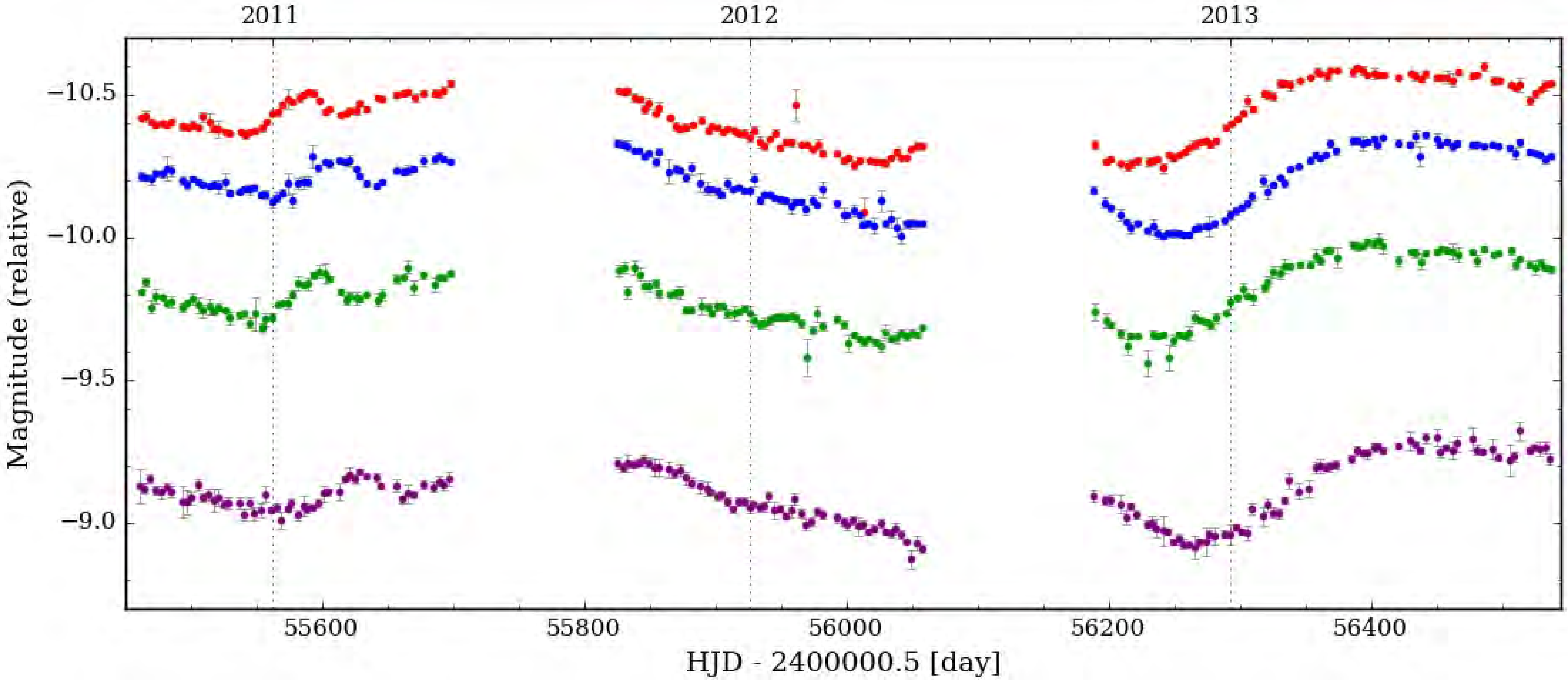


Credit: Dr. S. Suyu

H_0 from gravitational lensing

- COSMOGRAIL collaboration: monitor gravitational lenses over multiple years to determine time delays to ~1-2%

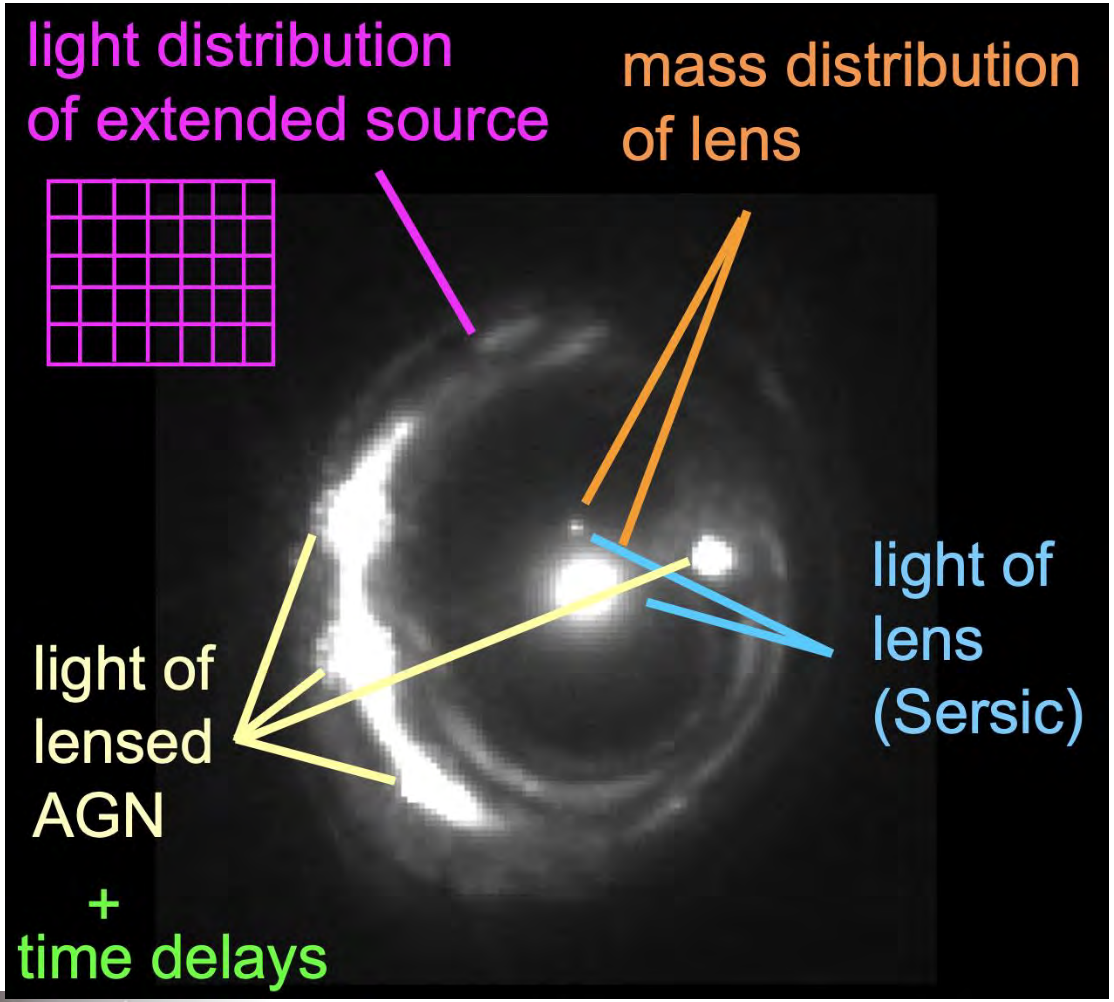




Credit: Dr. V. Bonvin

H_0 from gravitational lensing

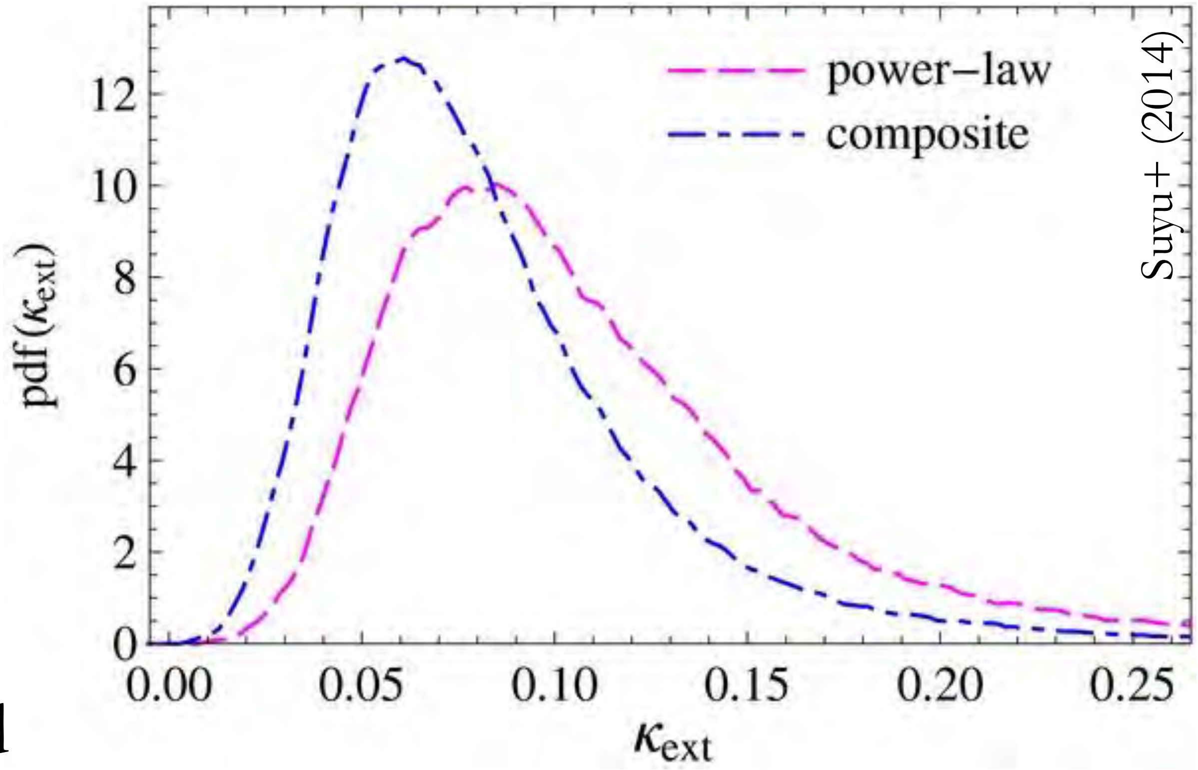
- Lens mass modeling has moved beyond simply using the AGN positions and now uses the extended images of the host
- This greatly increases the number of constraints that can be placed on the lens model



Credit: Dr. S. Suyu

H_0 from gravitational lensing

- External mass can bias $\Delta t \rightarrow H_0$ (dominant source of uncertainty)
- Lens models only account for external shear, γ
- Quantify line-of-sight effects with external convergence in lens plane, κ_{ext} (Suyu+ 2010, 2013)
- κ_{ext}: statistical correction calibrated to simulations using galaxy number counts (Suyu+ 2010; Fassnacht+ 2011; Greene+ 2013; Rusu+ 2017)

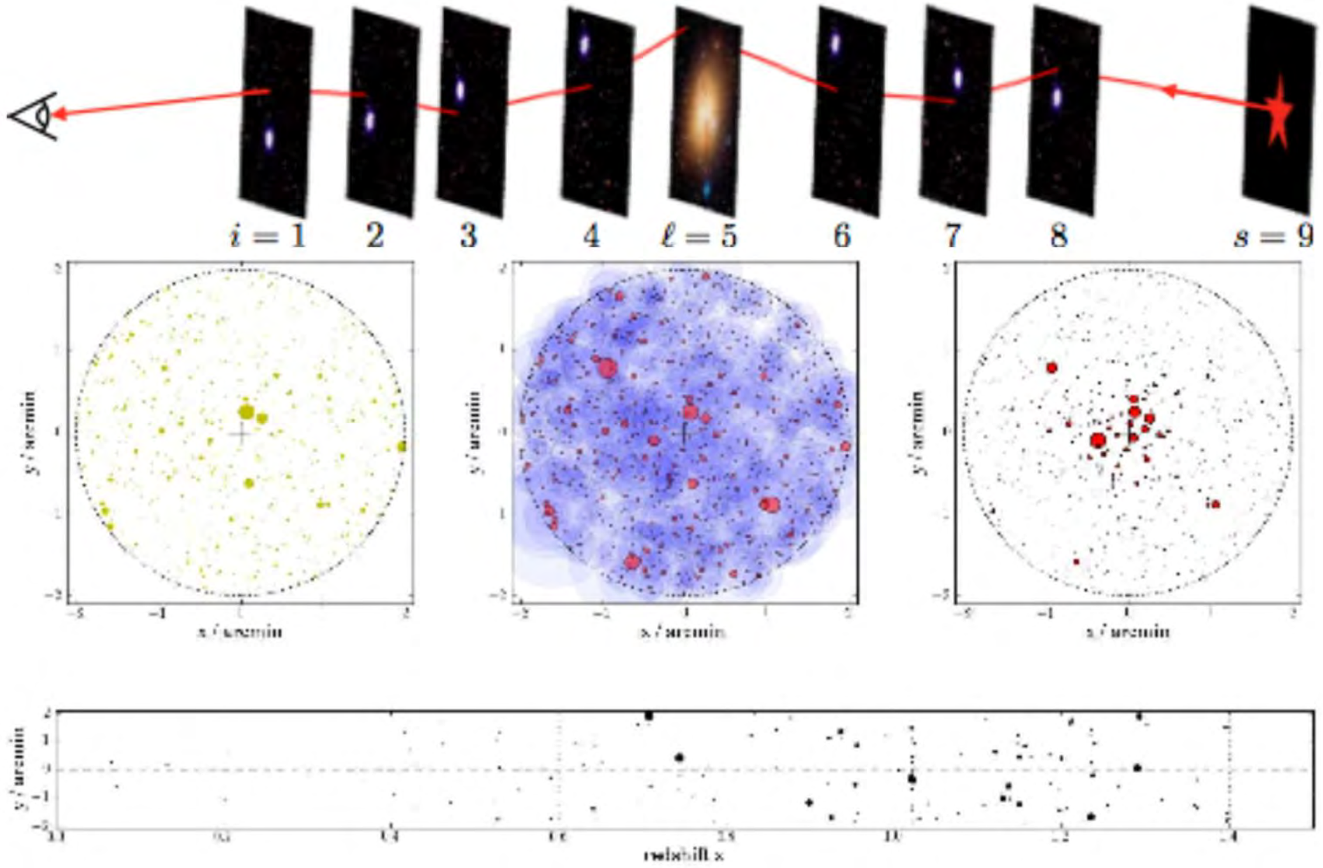


Suyu+ (2014)

Credit: Dr. S. Suyu

H_0 from gravitational lensing

- Some perturbers are more important than others: multi-plane formalism

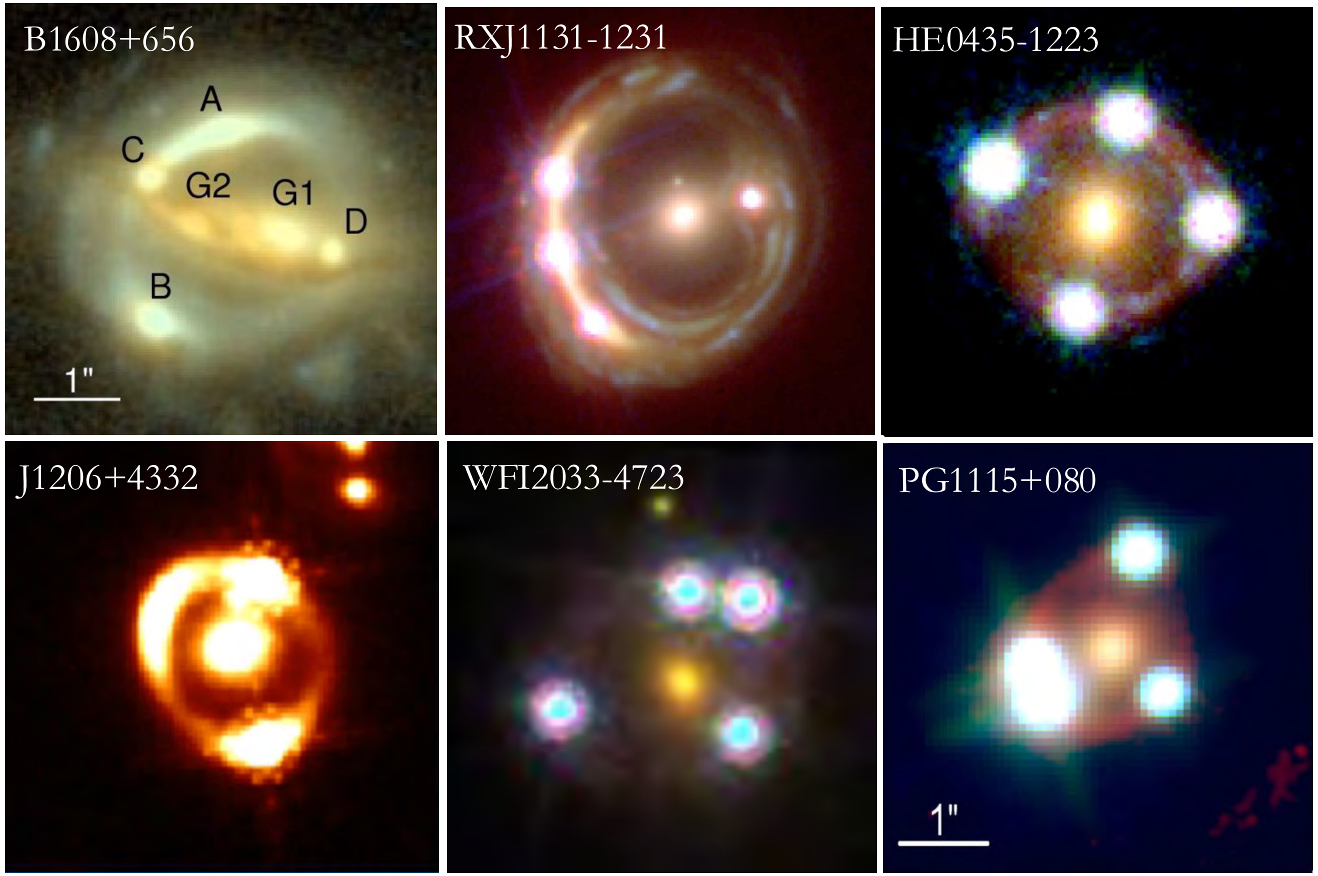


Mcully+ (2014); Collett+ (2013)

Credit: Dr. A. Agnello

H_0 from gravitational lensing

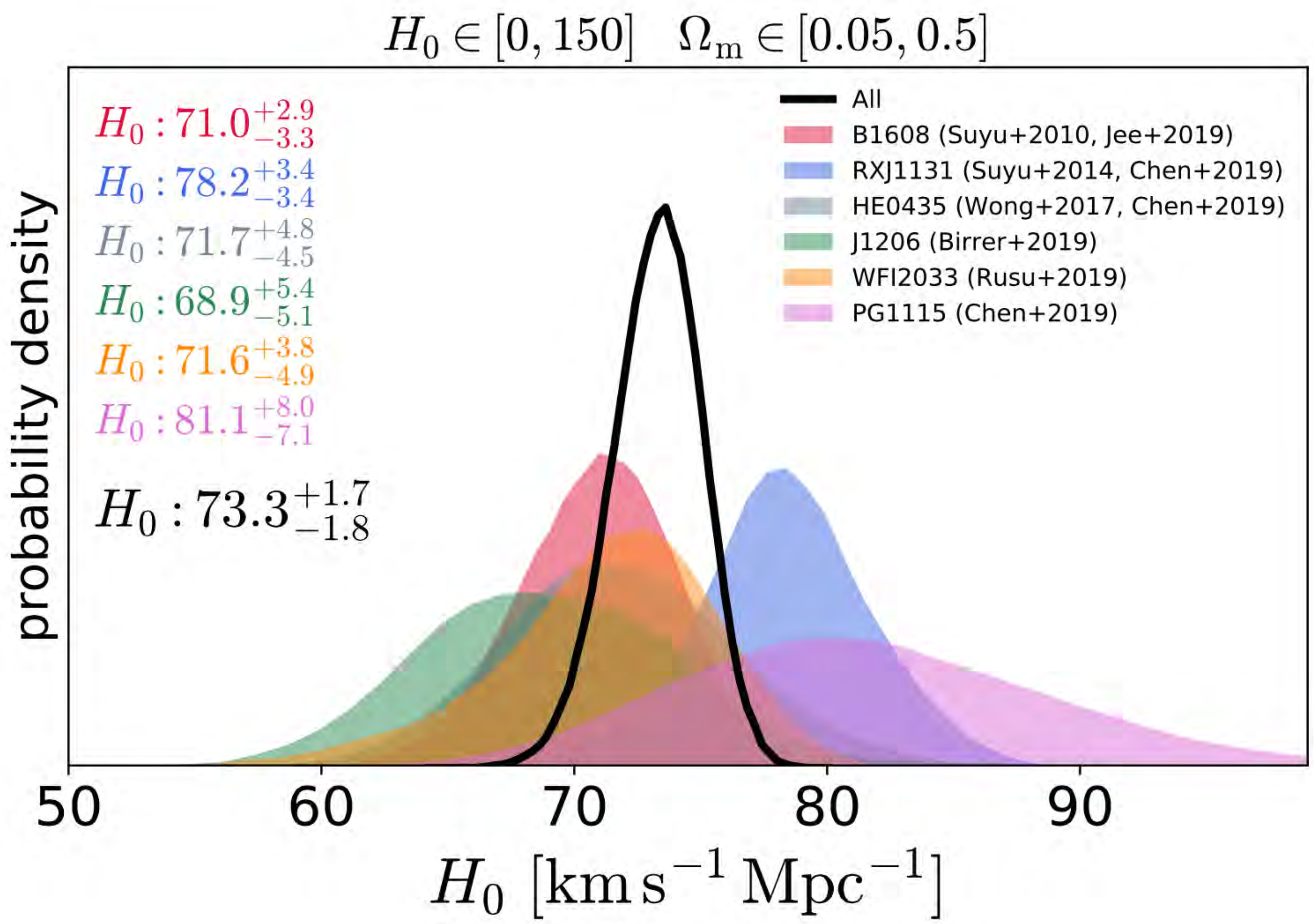
- H0LiCOW collaboration analyzed 6 lenses with blinded methods
- Well-motivated mass models: galaxies are described by power law/stars and NFW profiles



Credit: Dr. S. Suyu

H_0 from gravitational lensing

- H0LiCOW collaboration analyzed 6 lenses with blinded methods
- Well-motivated mass models: galaxies are described by power law/stars and NFW profiles
- H_0=73.3±1.8 assuming flat ΛCDM



Wong+ (2020)

Credit: Dr. S. Suyu

H_0 from gravitational lensing

No assumption on the radial mass density profile of the lens galaxy

Galaxies are described by power law/stars+NFW mass profile

$73.3^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1}

H0LiCOW

$74.0^{+1.7}_{-1.8}$ km s^{-1} Mpc^{-1}

TDCOSMO (NFW + stars/constant M/L)

$74.2^{+1.6}_{-1.6}$ km s^{-1} Mpc^{-1}

TDCOSMO (power-law)

Assuming SLACS lenses and TDCOSMO lenses share the same anisotropy property

$73.3^{+5.8}_{-5.8}$ km s^{-1} Mpc^{-1}

TDCOSMO+SLACS$_{IFU}$ (anisotropy constraints from 9 SLACS lenses)

Assuming SLACS lenses and TDCOSMO lenses share the same anisotropy and radial mass density property

$67.4^{+4.1}_{-3.2}$ km s^{-1} Mpc^{-1}

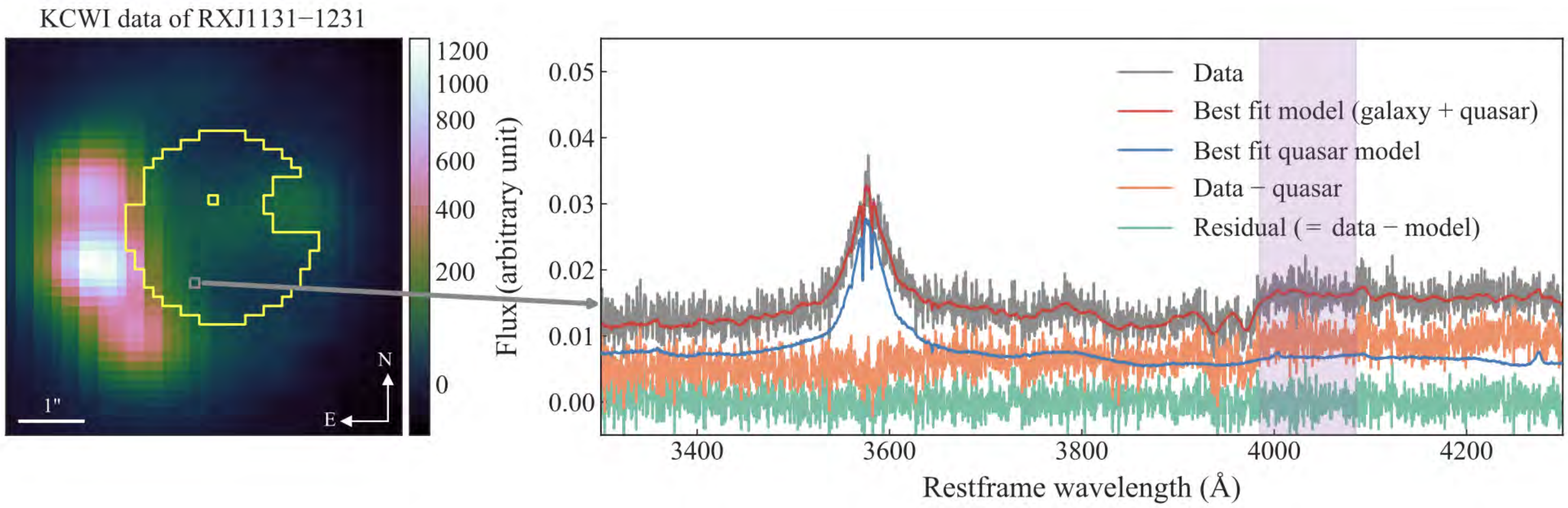
TDCOSMO+SLACS$_{SDSS+IFU}$ (anisotropy and profile constraints from SLACS)

Birrer et al. 2020
Millon et al. 2020
Shajib et al. 2020
Wong et al. 2020
Chen et al. 2019

Credit: Dr. G. C-F Chen

H_0 from gravitational lensing

- Moving forward, spatially-resolved stellar kinematics are key to break model degeneracies and constrain D_{lens}

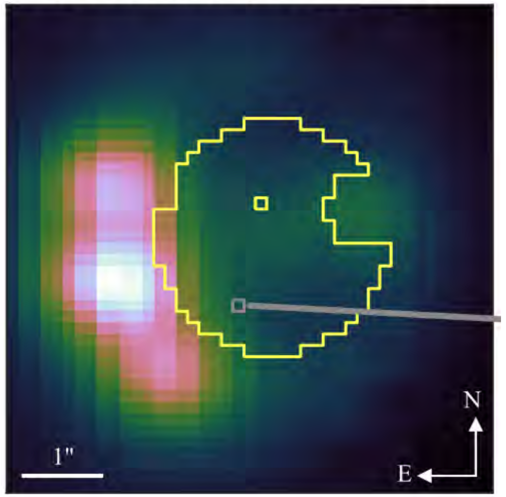


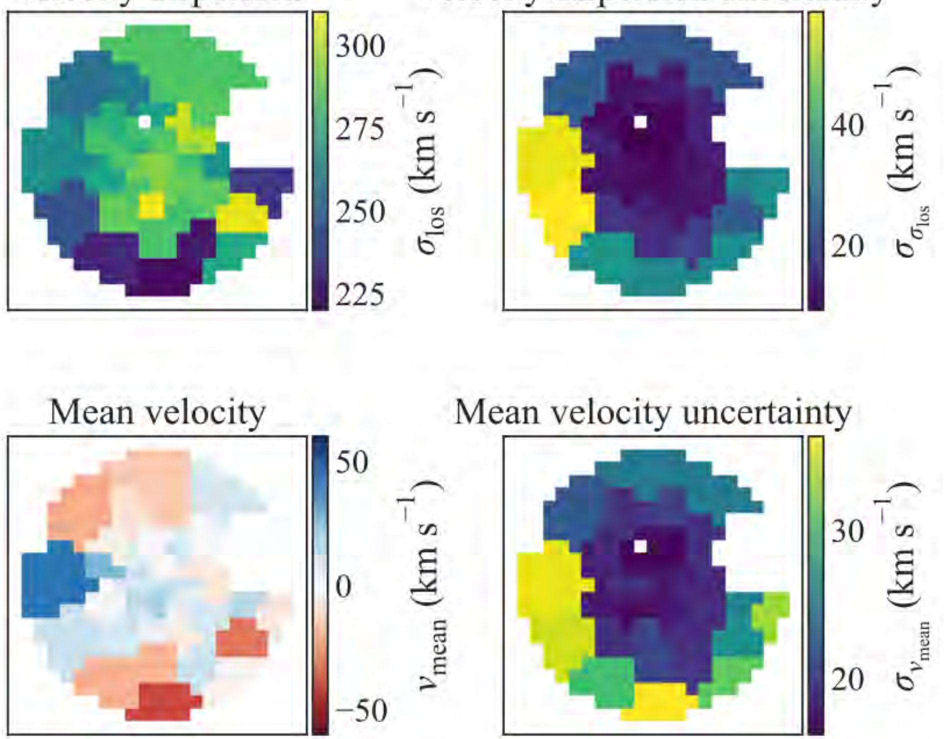
Shajib+ (2023)

Credit: Dr. S. Suyu

H_0 from gravitational lensing

- Moving forward, spatially-resolved stellar kinematics are key to break model degeneracies and constrain D_{lens}
- H_0=77±7 using flexible mass models





Shajib+ (2023)

Credit: Dr. S. Suyu

Summary

- Cepheids, TRGB, etc. cannot reach into the Hubble flow, needed to minimize impact of peculiar velocities
- Use them to calibrate another set of "standard candles" with much greater reach: SNe Ia, Surface Brightness Fluctuations are best; core-collapse supernovae, virial theorem applications have larger σ
- Current best approach: Cepheids + SNe Ia as implemented by SH0ES with HST; JWST gives critical cross-check but not competitive yet
- Gravitational lensing offers a completely independent approach; need to improve mass models to break degeneracies

The Cosmic Distance Scale

Lecture 4

Lucas Macri

NSF NOIRLab

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- I want to thank the following colleagues, who generously contributed material for these presentations:

- Gagandeep Anand (STScI)
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- Gisella Clementini (INAF)
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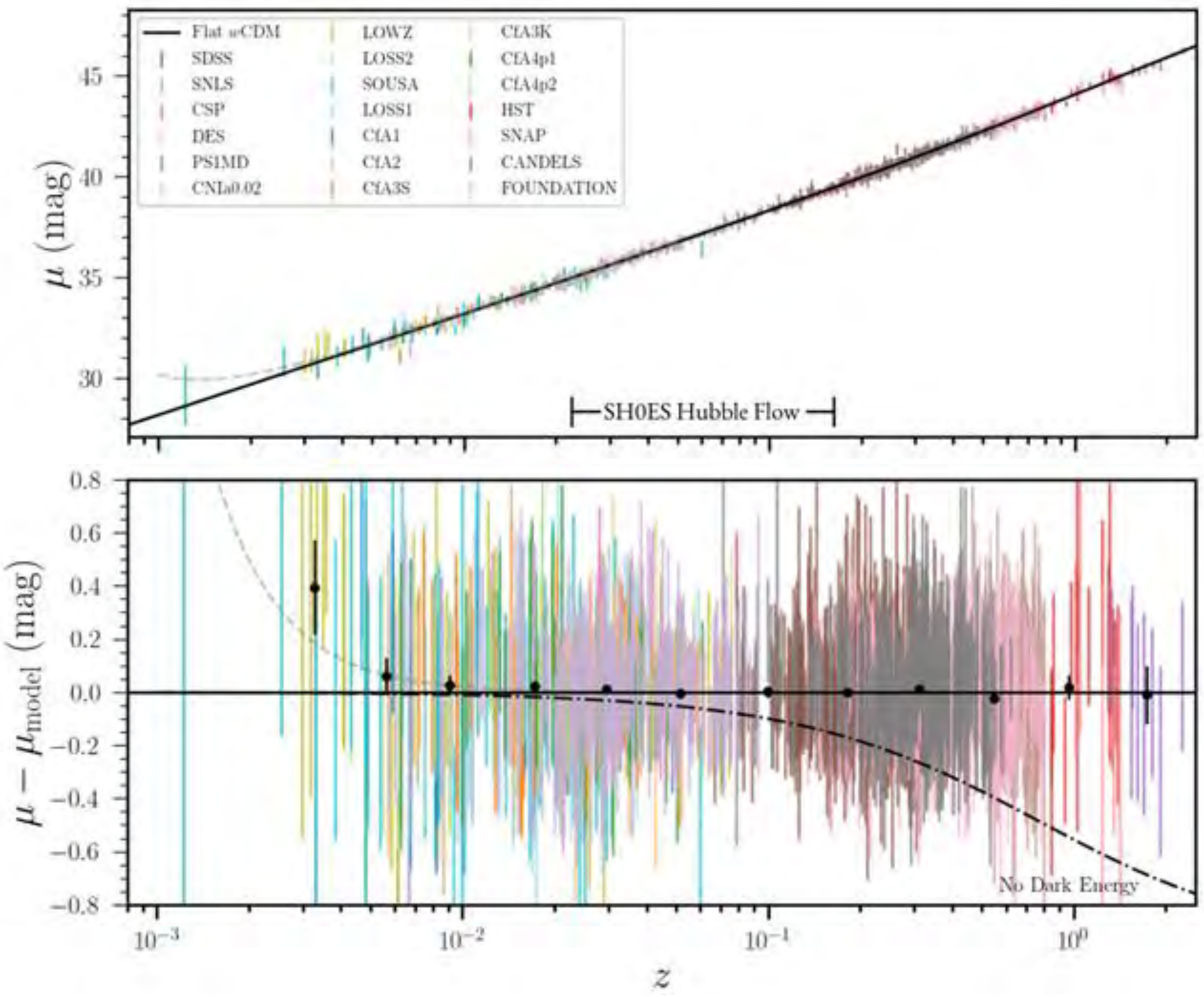
- Rolf-Peter Kudritzki (MIAPbP/UH)
- Casey Papovich (Texas A&M)
- Adam Riess (JHU/STScI)
- Dan Scolnic (Duke Univ.)
- Sherry Suyu (TUM/MPA)
- Mónica Taormina (CAMK)

Recap of Lecture 3

- Cepheids, TRGB, etc. cannot reach into the Hubble flow, needed to minimize impact of peculiar velocities
- Use them to calibrate another set of “standard candles” with much greater reach: SNe Ia, Surface Brightness Fluctuations are best; core-collapse supernovae, virial theorem applications have larger σ
- Current best approach: Cepheids + SNe Ia as implemented by SH0ES with *HST*; *JWST* gives critical cross-check but not competitive yet
- Gravitational lensing offers a completely independent approach; need to improve mass models to break degeneracies

Type Ia supernovae: Pantheon+

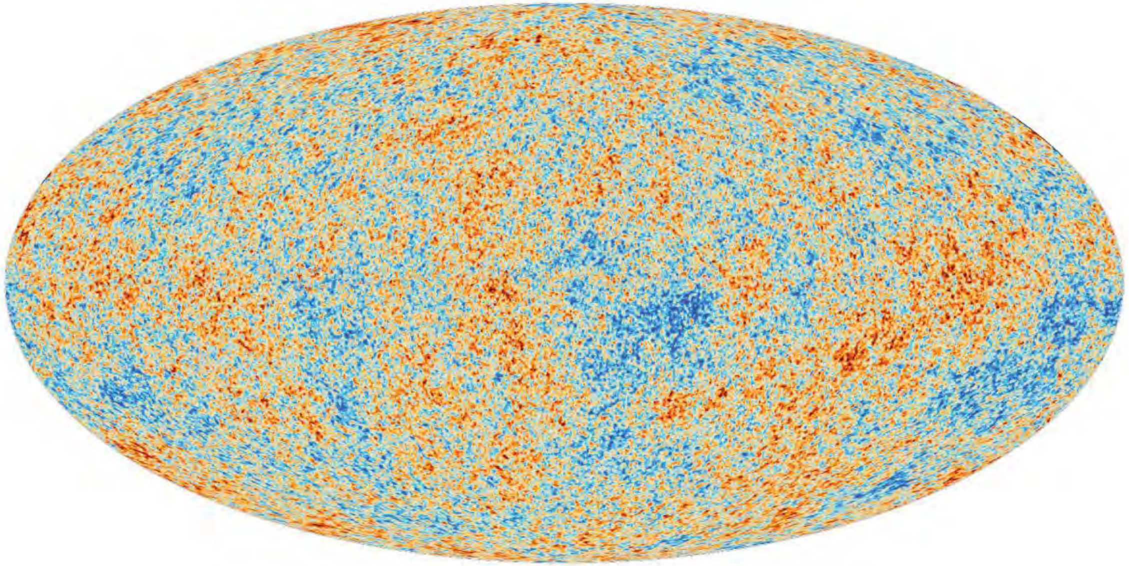
- The full Pantheon+ sample has ~1,550 SNeIa
- All calibrated to the same reference system and with corrections due to light curve shape, dust, …
- Ω_Λ=0.666 ±0.018 for flat ΛCDM

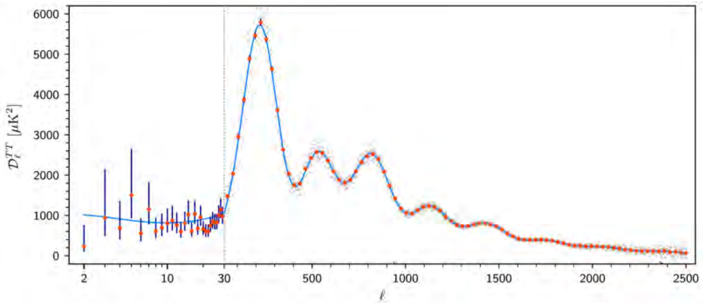


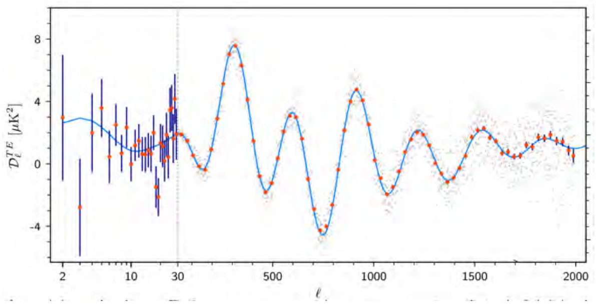
Brout+ (2022); Scolnic+ (2022)

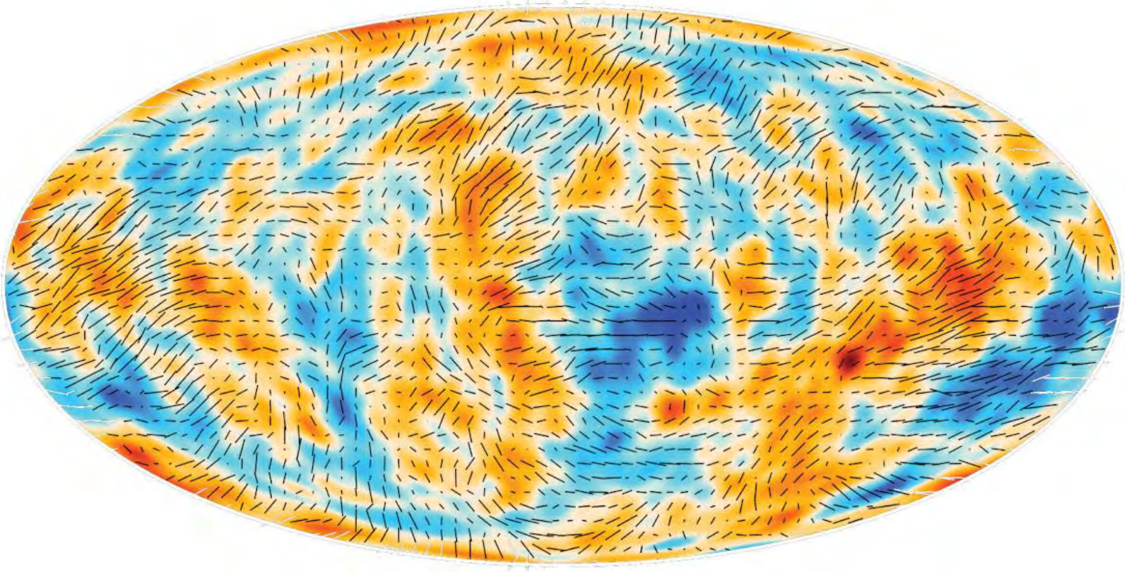
From the CMB to cosmological parameters

- 2013: *Planck* → angular power spectrum of T anisotropies & polarization



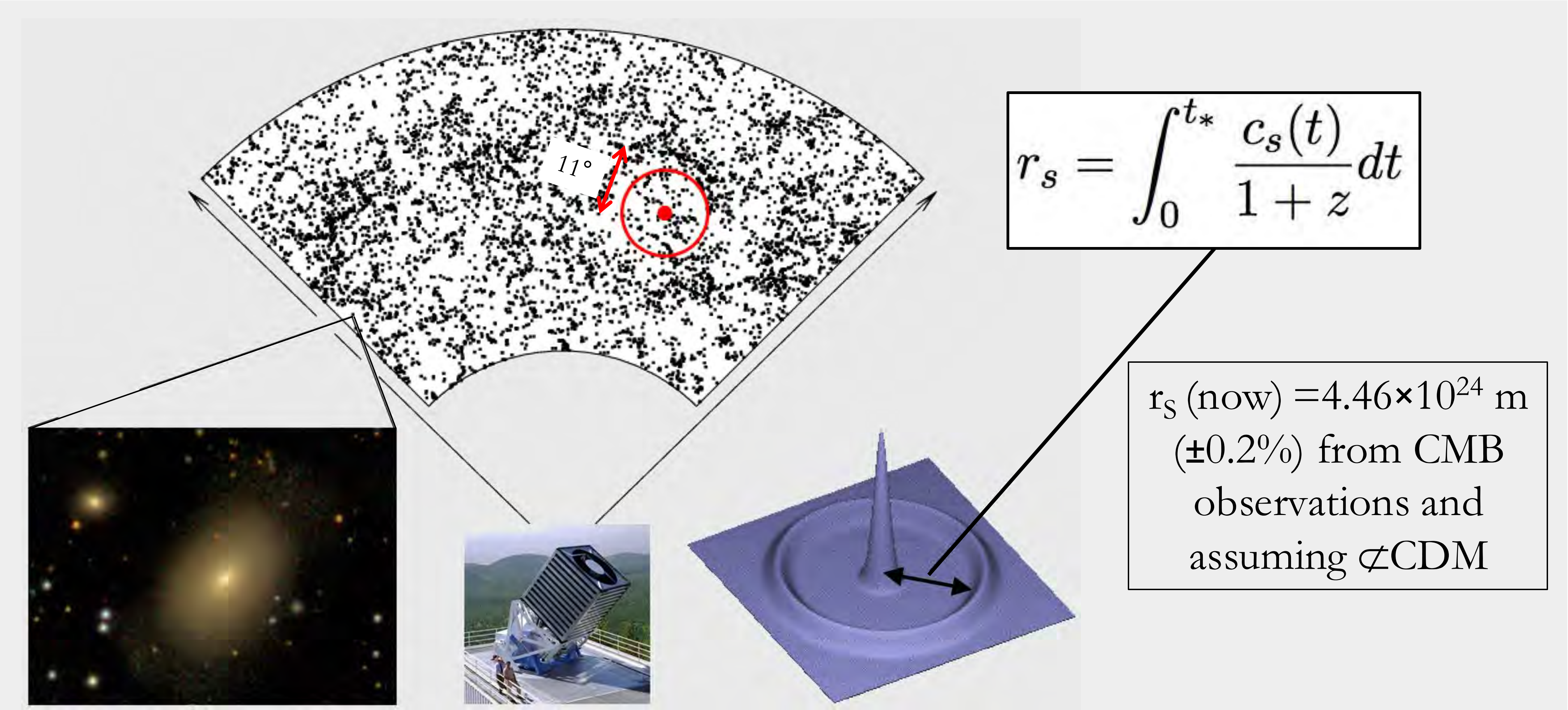






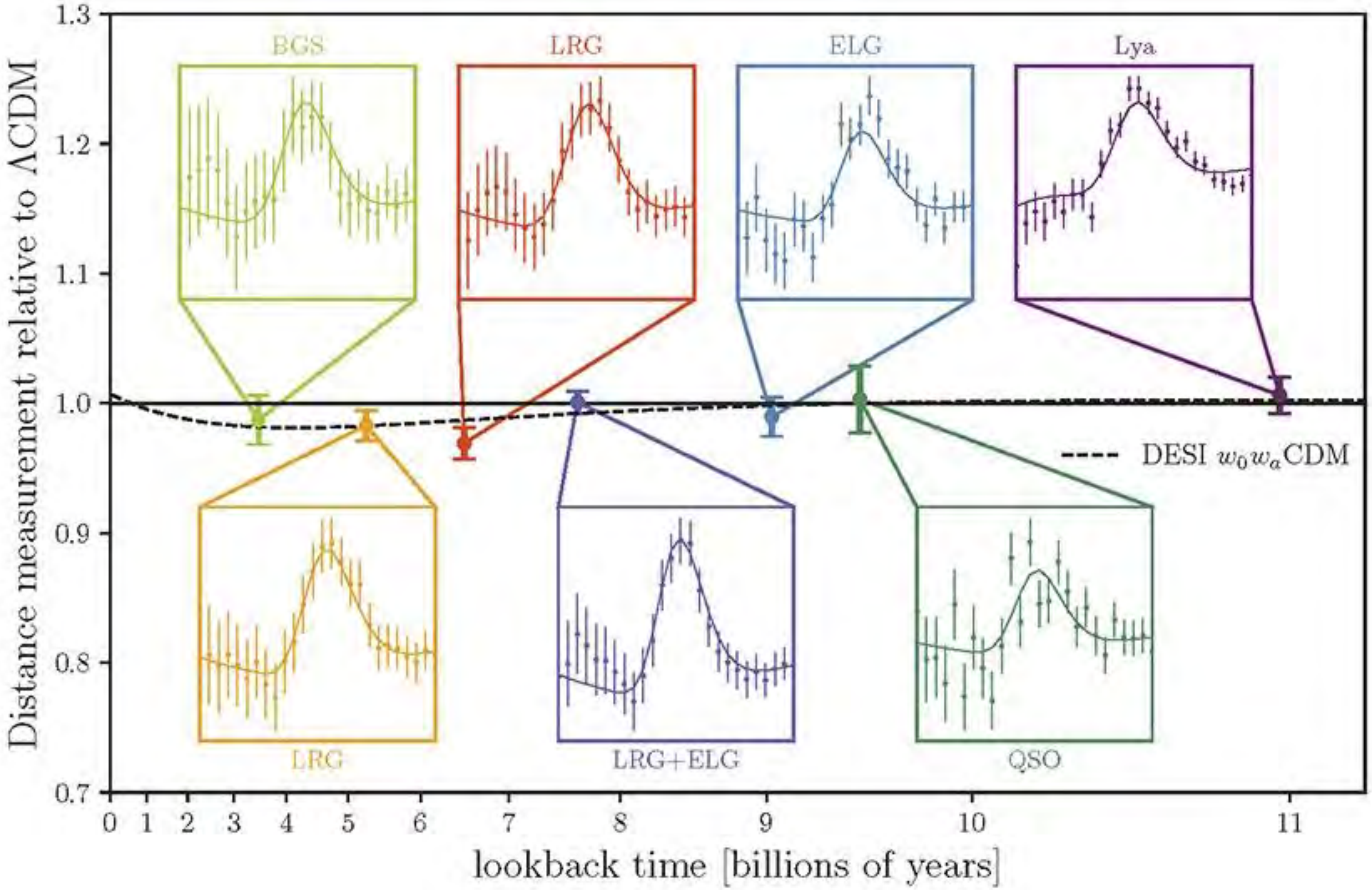
Planck collaboration (2020)

Baryon Acoustic Oscillations



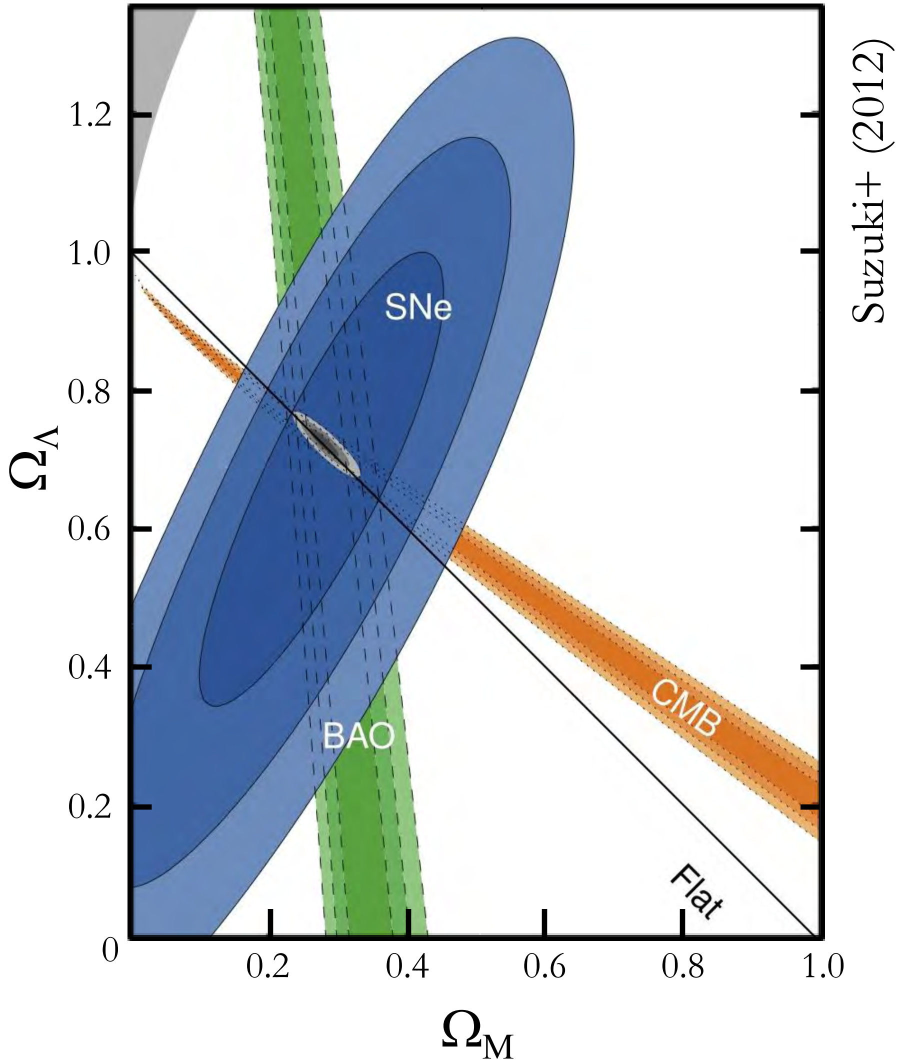
Credit: Dr. Dan Eisenstein and SDSS collaboration

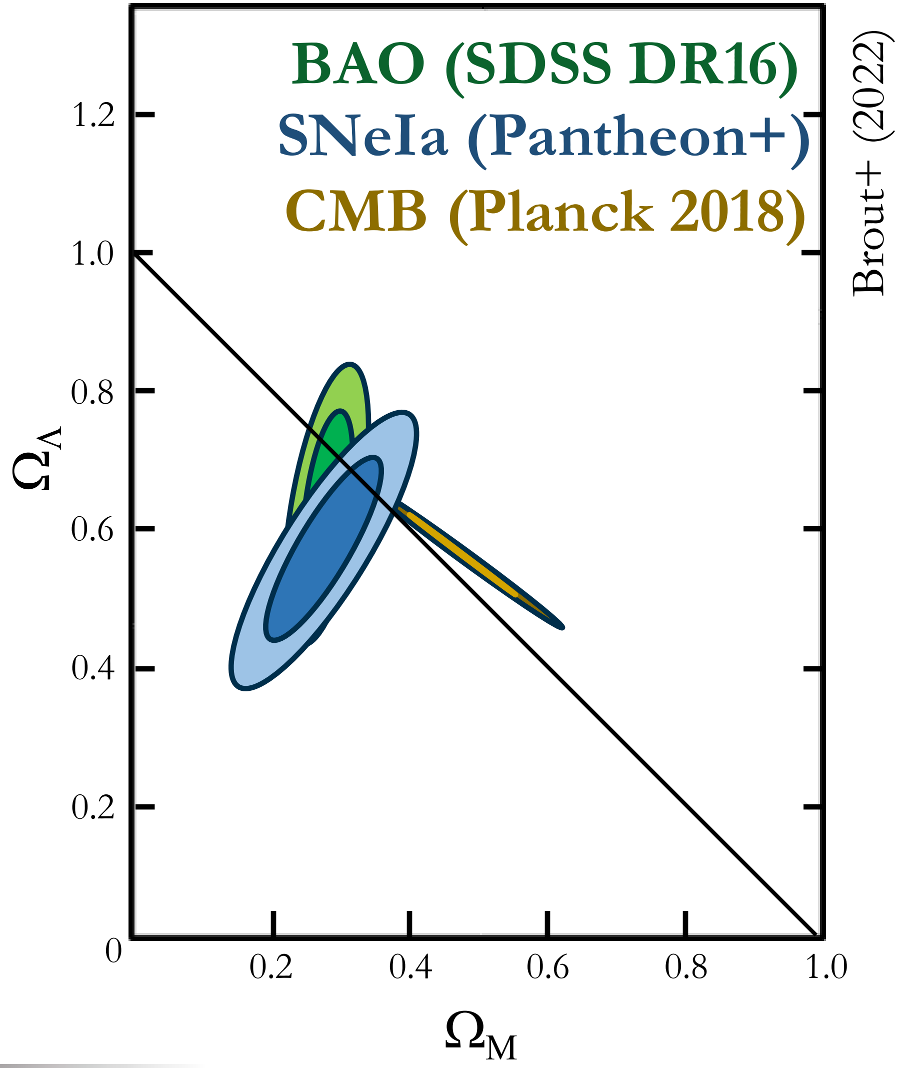
The BAO peak as a "standard ruler"



DESI Collaboration (2024)

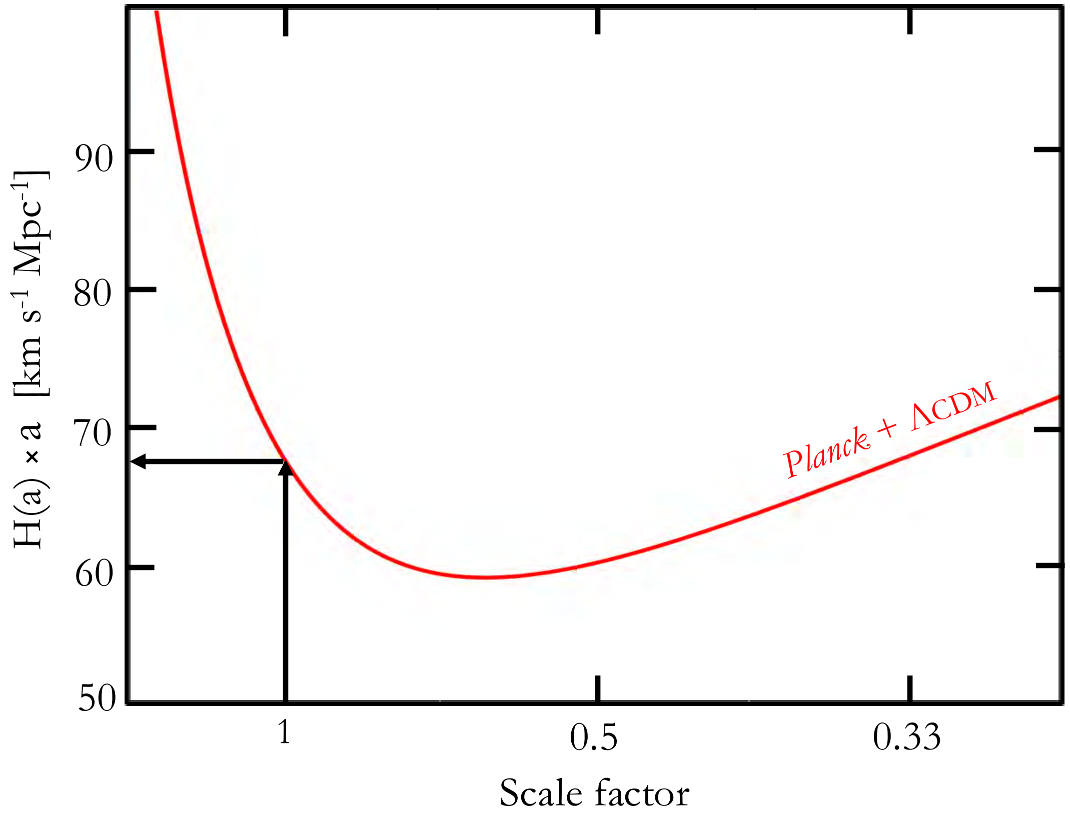
Combining the constraints: 10 years later



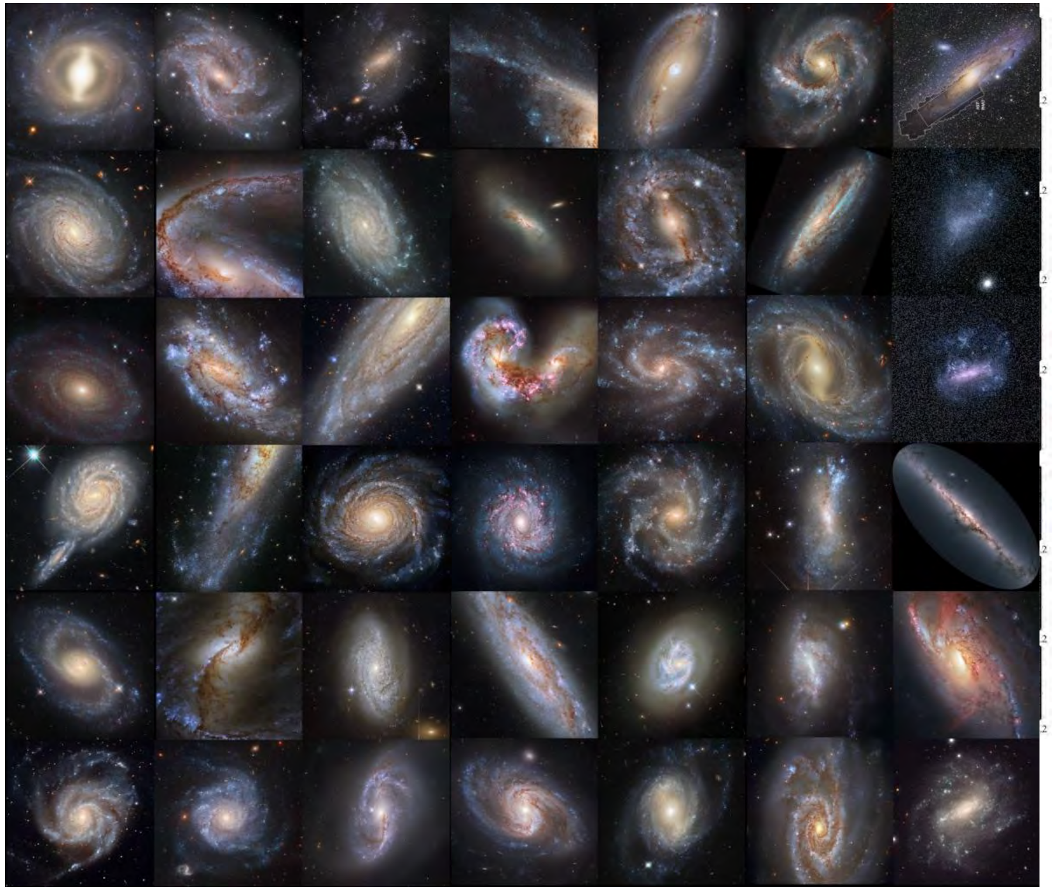


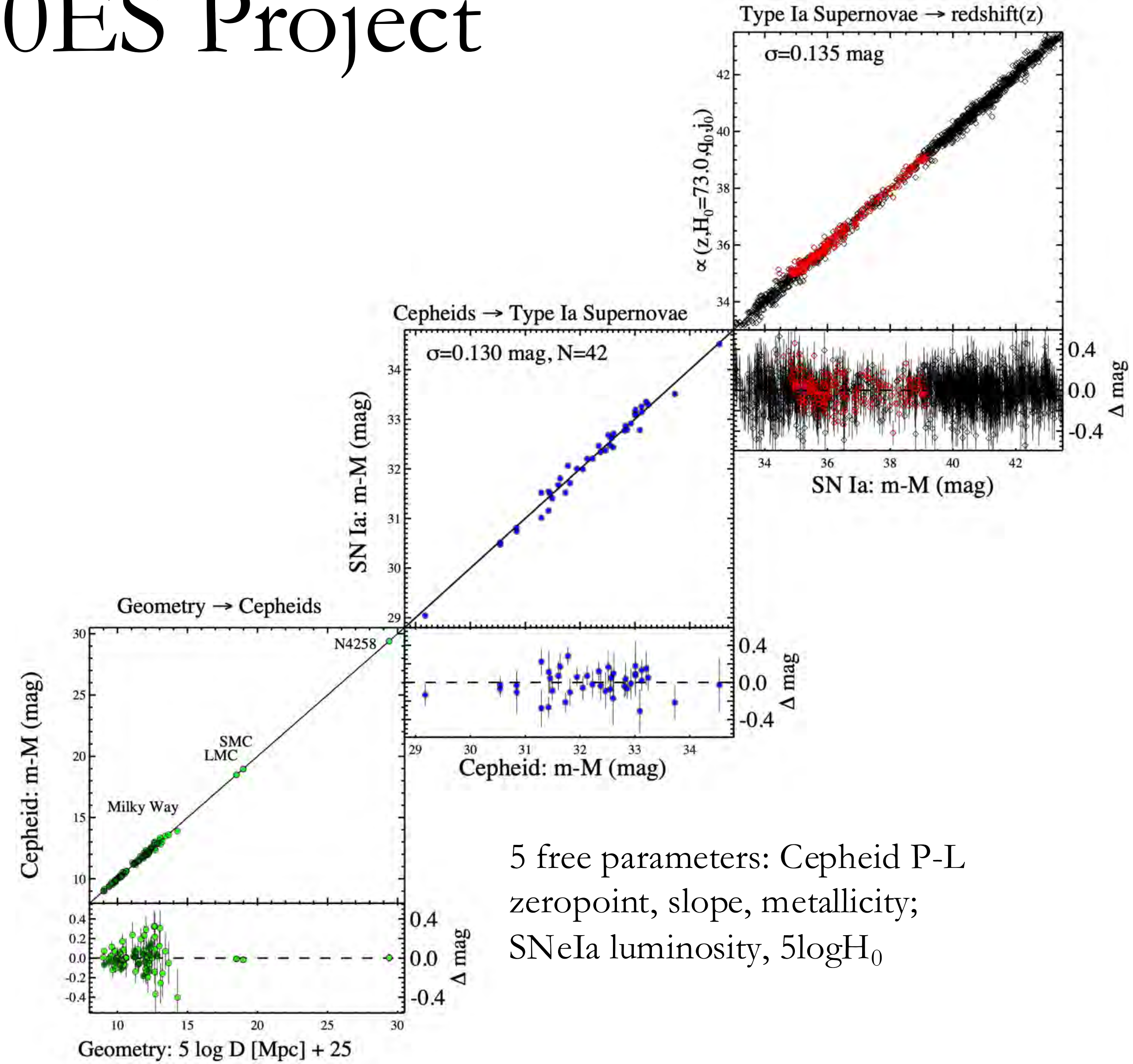
The BAO peak as a "standard ruler"

- BAO, calibrated via CMB, can map H(a) through an "inverse distance ladder"
- Can be used to predict H_0 for an *assumed* cosmology
- Compare with actual local measurements for an "end-to-end" test of the cosmological model



The SH0ES Project





5 free parameters: Cepheid P-L zeropoint, slope, metallicity; SNeIa luminosity, $5\log H_0$

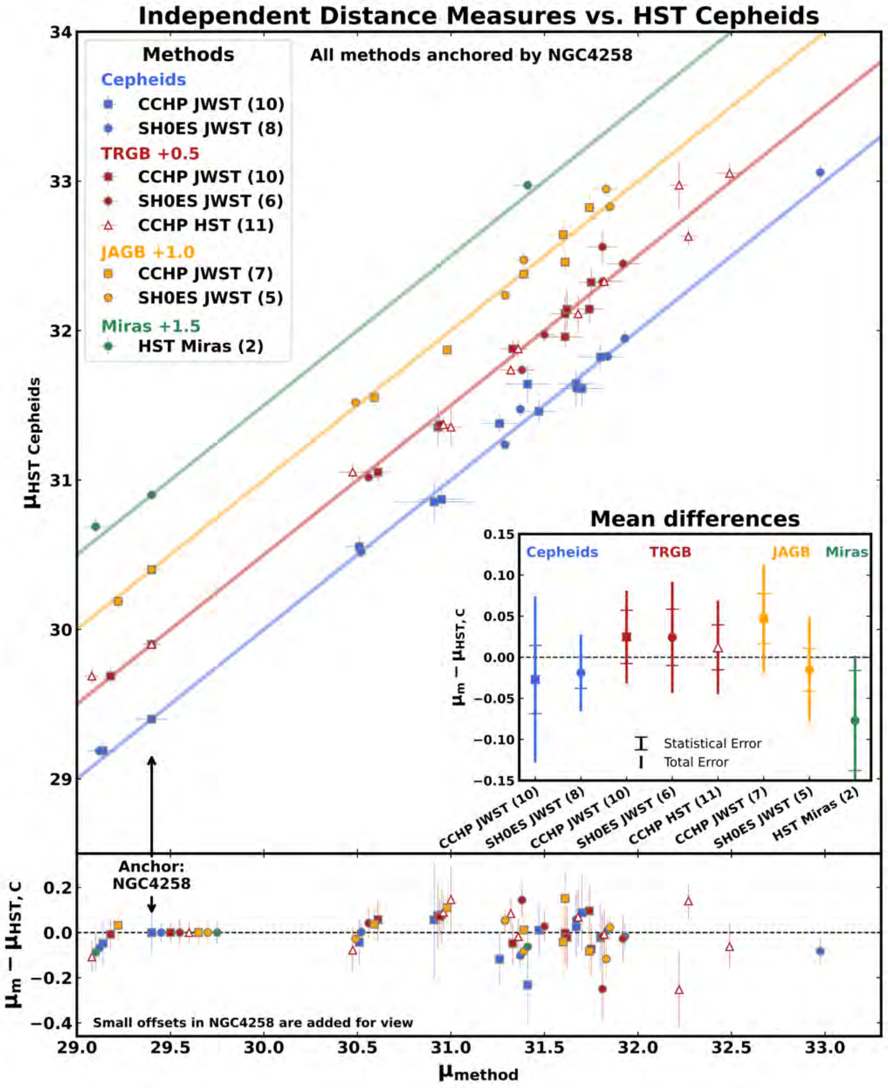
Riess+ (2022a)

Recent results from *JWST*

All methods agree at 1σ

Sample	Team	$\mu_{JWST} - \mu_{HST}$ [mag]	σ
HST Cepheids vs. *JWST* Cepheids			
10 Hosts[a]	CCHP	−0.027	0.10
8 Hosts ($D \leq 25$ Mpc)	SH0ES	−0.02	0.03
14 Unique Hosts	Both	−0.02	0.03
HST Cepheids vs. *JWST* JAGB			
7 Hosts (mode)	CCHP	0.047	0.066
5 Hosts	SH0ES	-0.015	0.064
HST Cepheids vs. *JWST* NIR-TRGB			
10 Hosts	CCHP	0.032	0.056
HST Cepheids vs. *JWST* I-TRGB			
6 Hosts ($D \leq 25$ Mpc)	SH0ES	0.02	0.067
HST Cepheids vs. I-TRGB			
11 Hosts	CCHP	0.01	0.057
HST Cepheids vs. *HST* Miras			
2 Hosts		−0.08	0.078

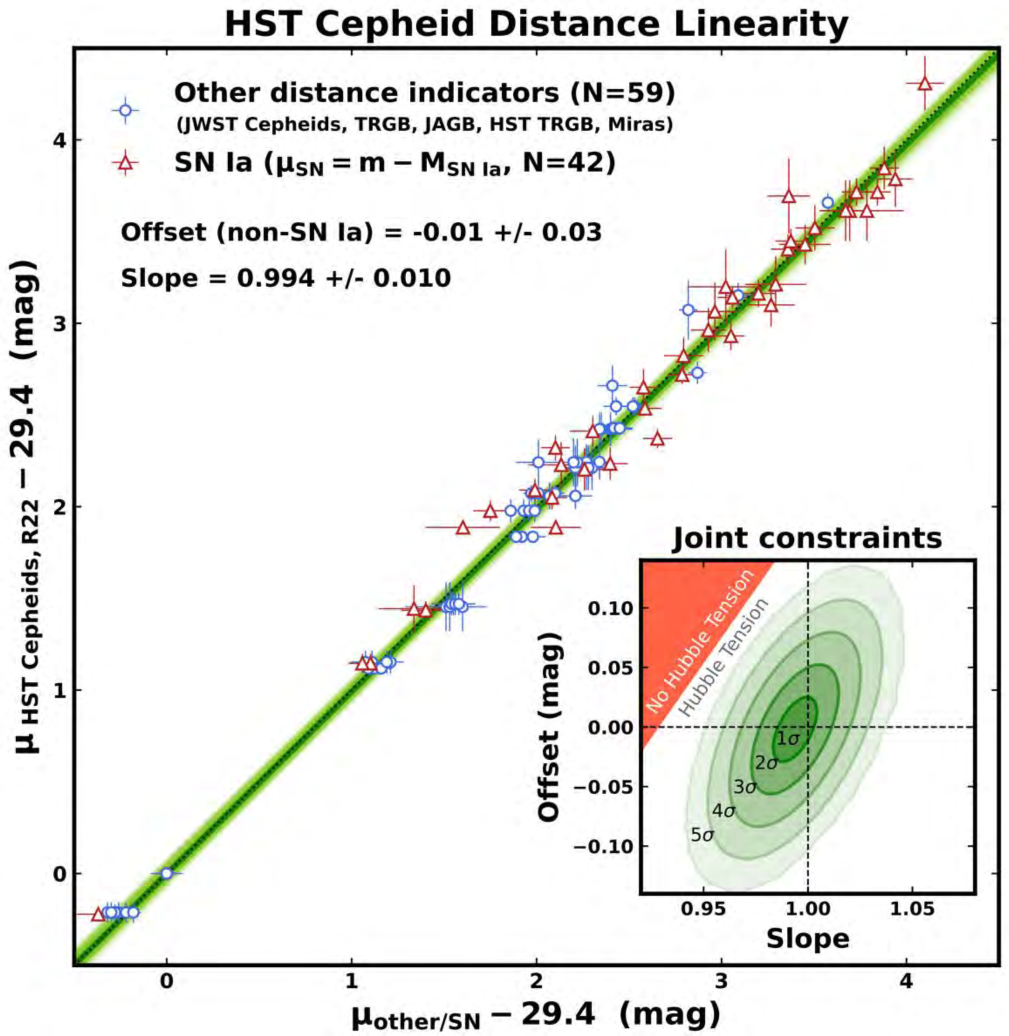
NOTE—(*): SH0ES $D \leq 25$ Mpc sample includes NGC 4038, M101 and NGC 3447 and excludes NGC 5468 as discussed in text. CCHP distances from F24 Table 2 and including uncertainties in F24 Table 5.



Riess+ (2024b)

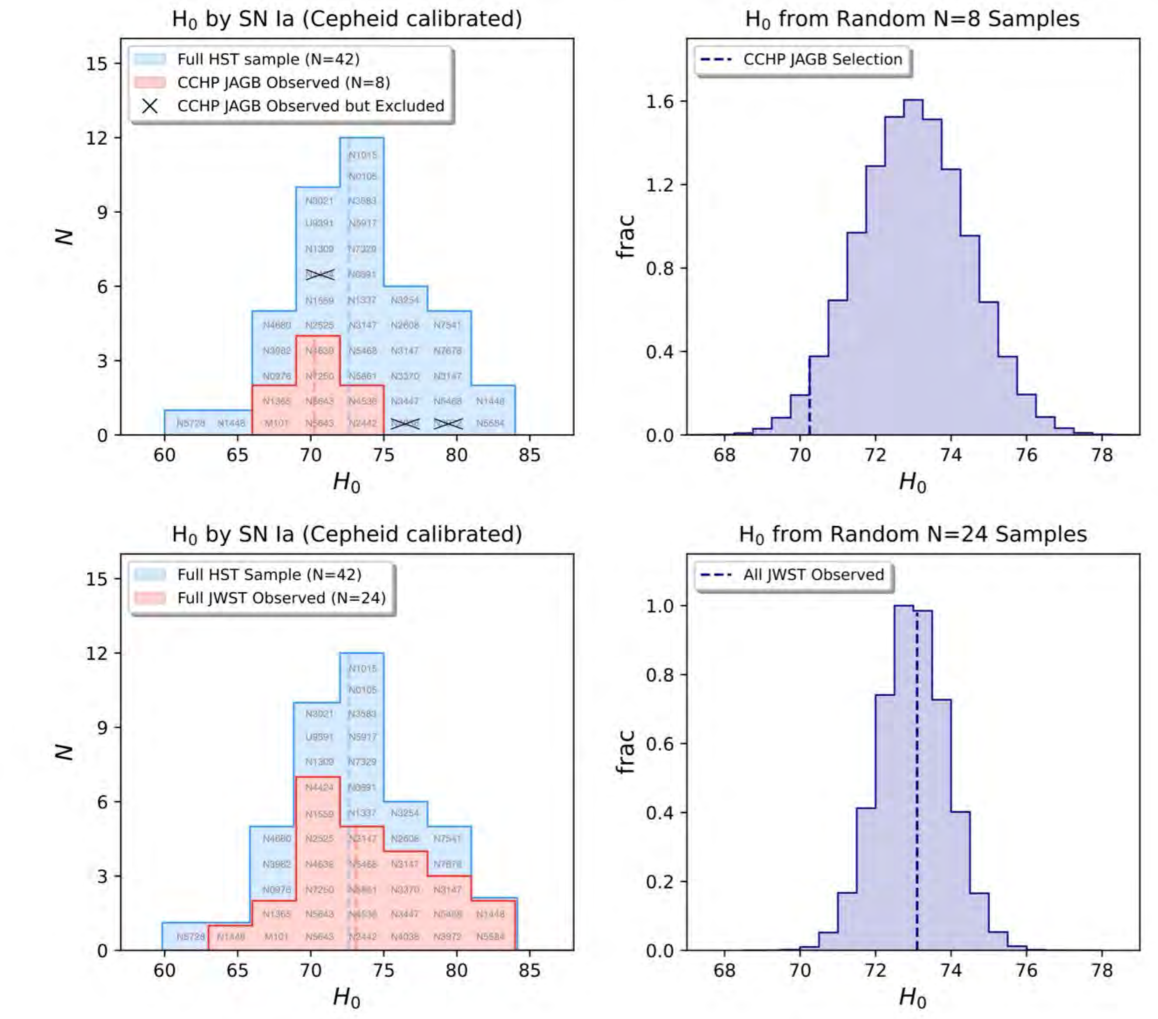
Recent results from *JWST*

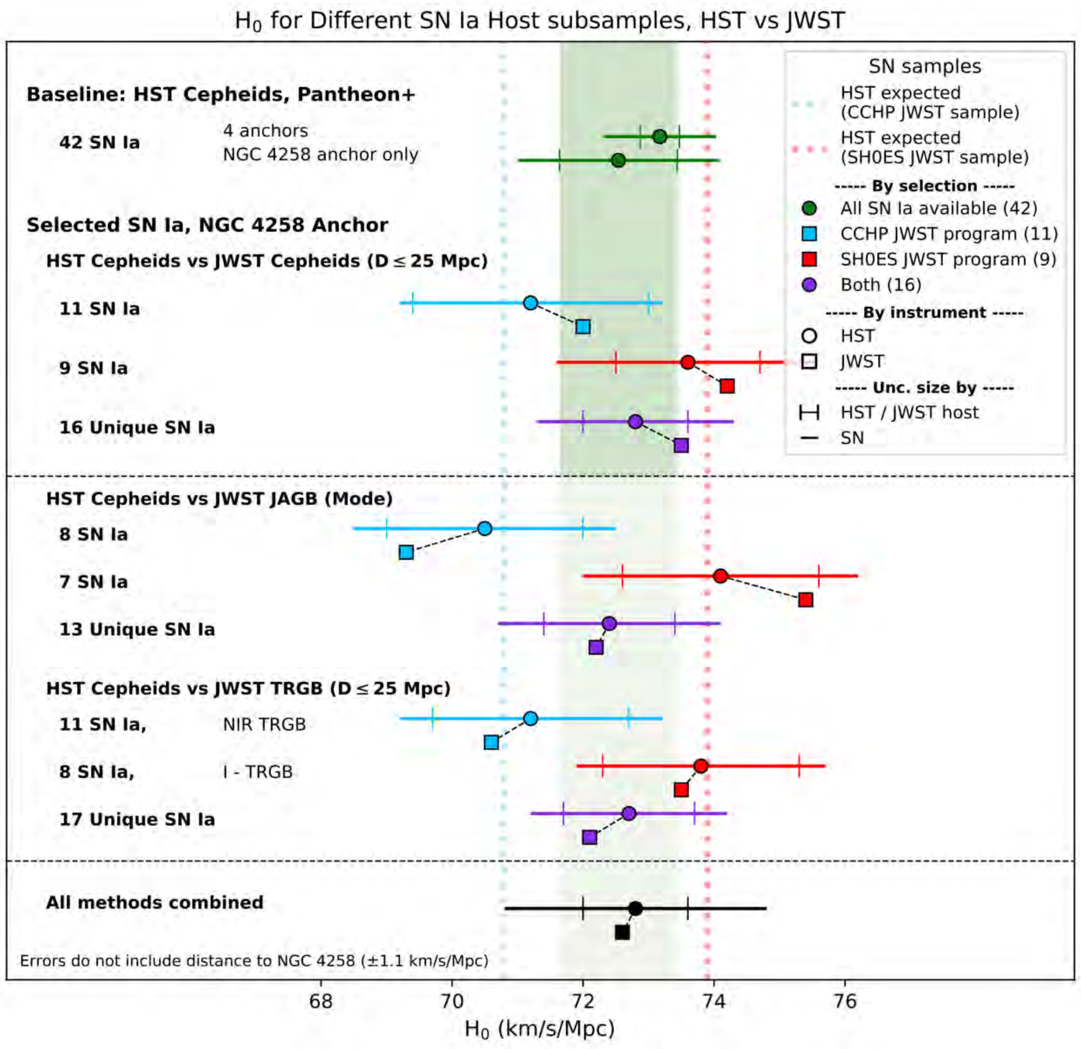
- Stringest test to date of *HST* Cepheid distance linearity: 59 comparisons against all other available methods, anchored to N4258
- If there's such excellent agreement, what's the reason for $\Delta H_0=2.5$ in Freedman+(2024)?
- Sample variance!



Riess+ (2024b)

Recent results from *JWST*





Riess+ (2024b)

The BAO peak as a "standard ruler"

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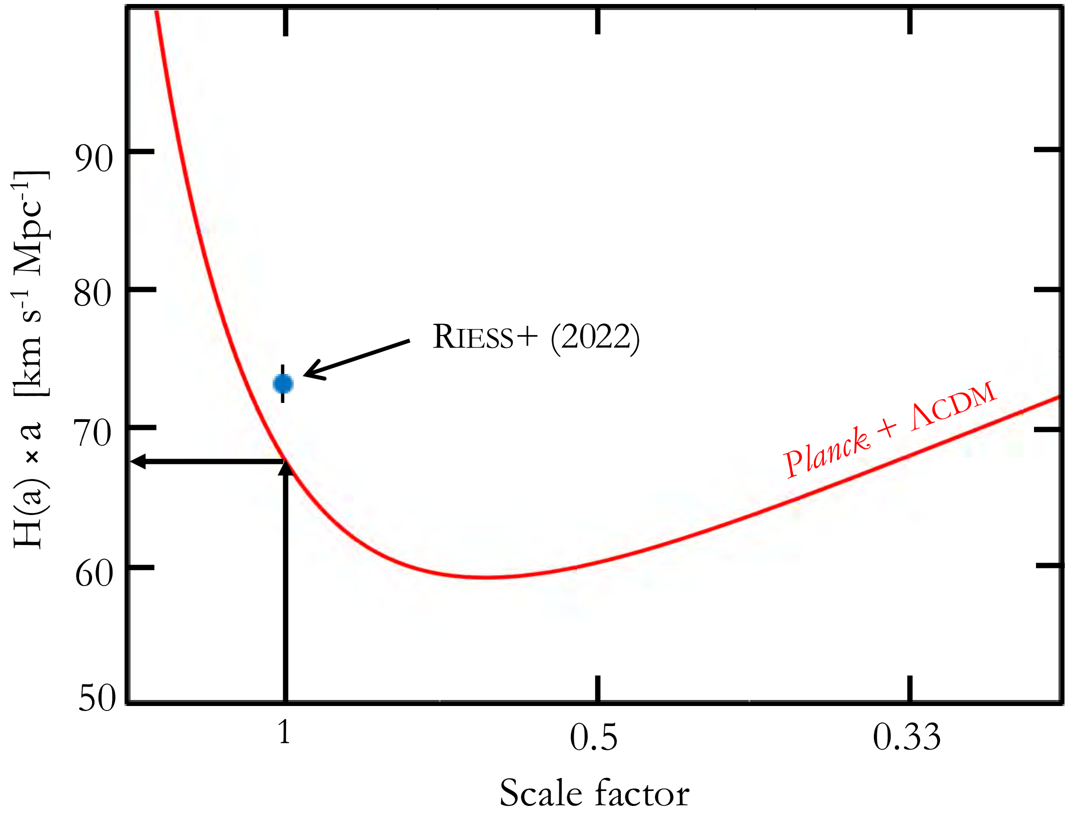


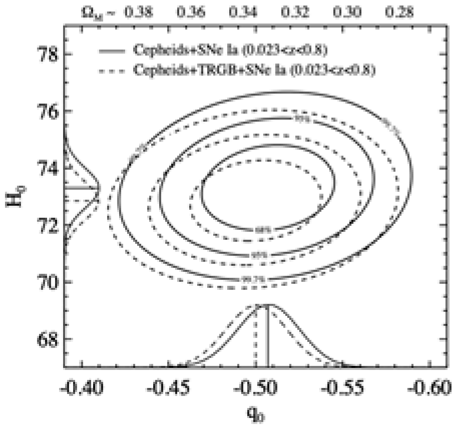
The SH0ES Project

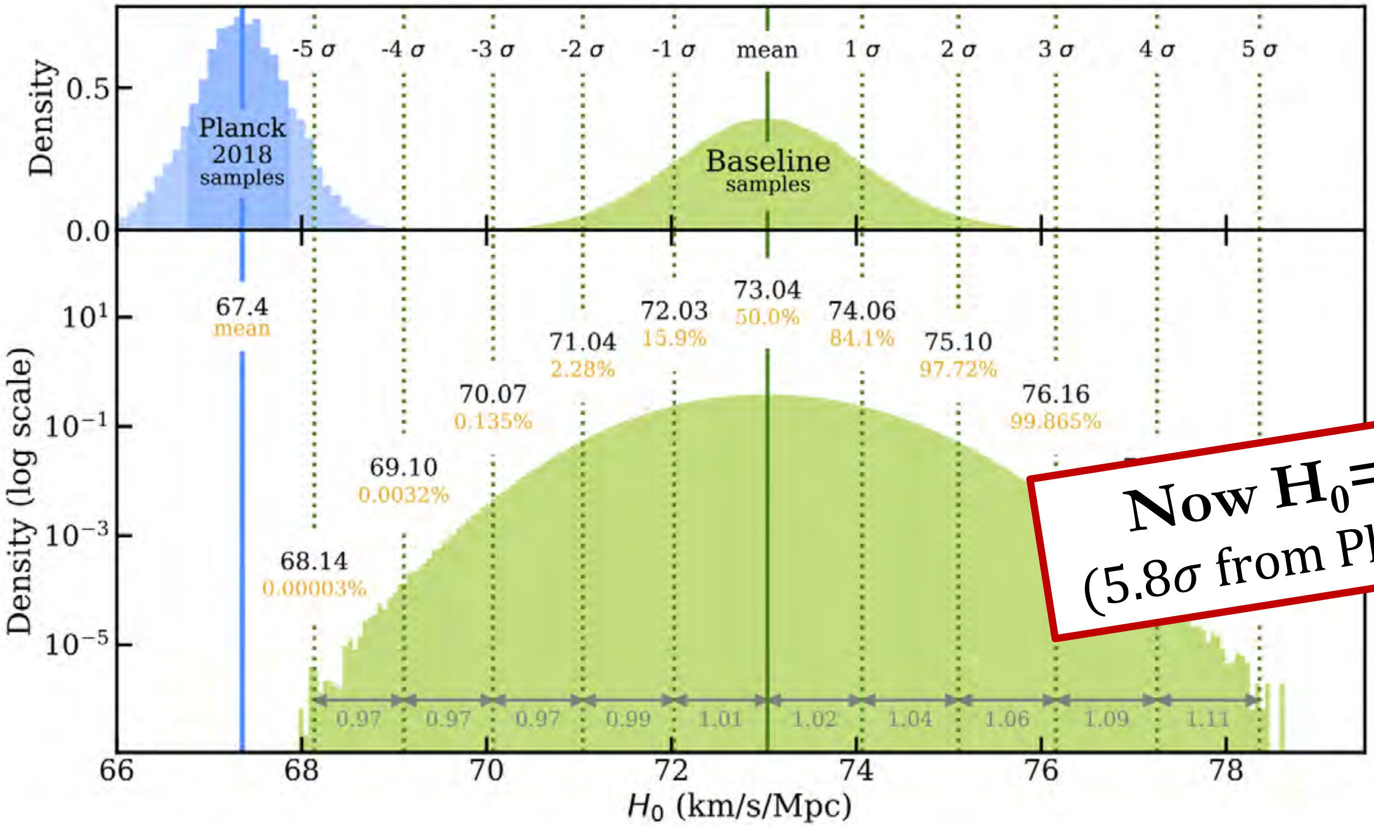
Baseline Fit: **H_0=73.04±1.04**, km s^{-1} Mpc^{-1}, with systematics

5.0σ from Planck + ΛCDM

X^2_υ=1.03,
N=3500

Can also constrain q_0



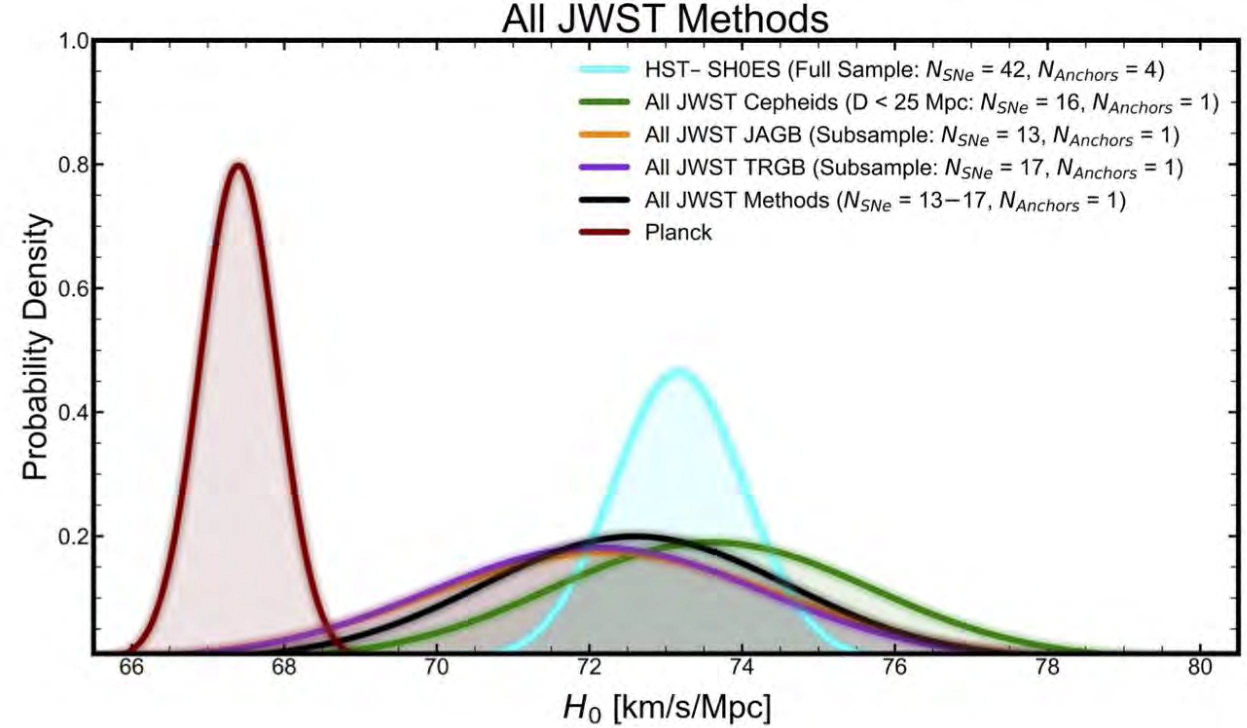


Now H_0=73.17±0.86
(5.8σ from Planck + ΛCDM)

Riess+ (2022); Breuval+ (2024)

The Hubble Tension

- As we discussed yesterday, the different methods used for the local distance scale are in excellent agreement when properly calibrated
- JWST samples too small to be competitive, but critical cross-check



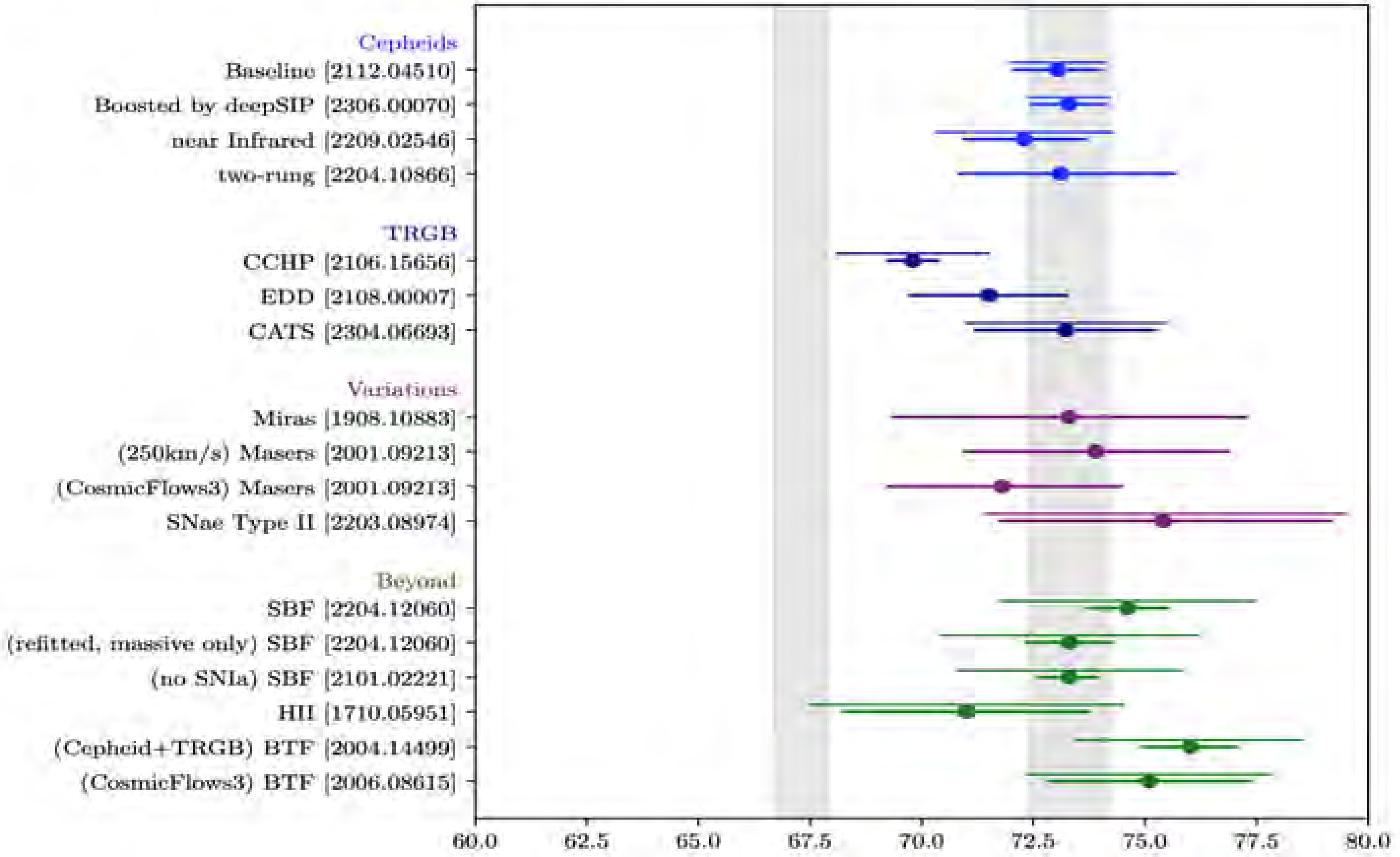
Riess+ (2024b)

The Hubble Tension: is it systematics?

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

The Hubble Tension

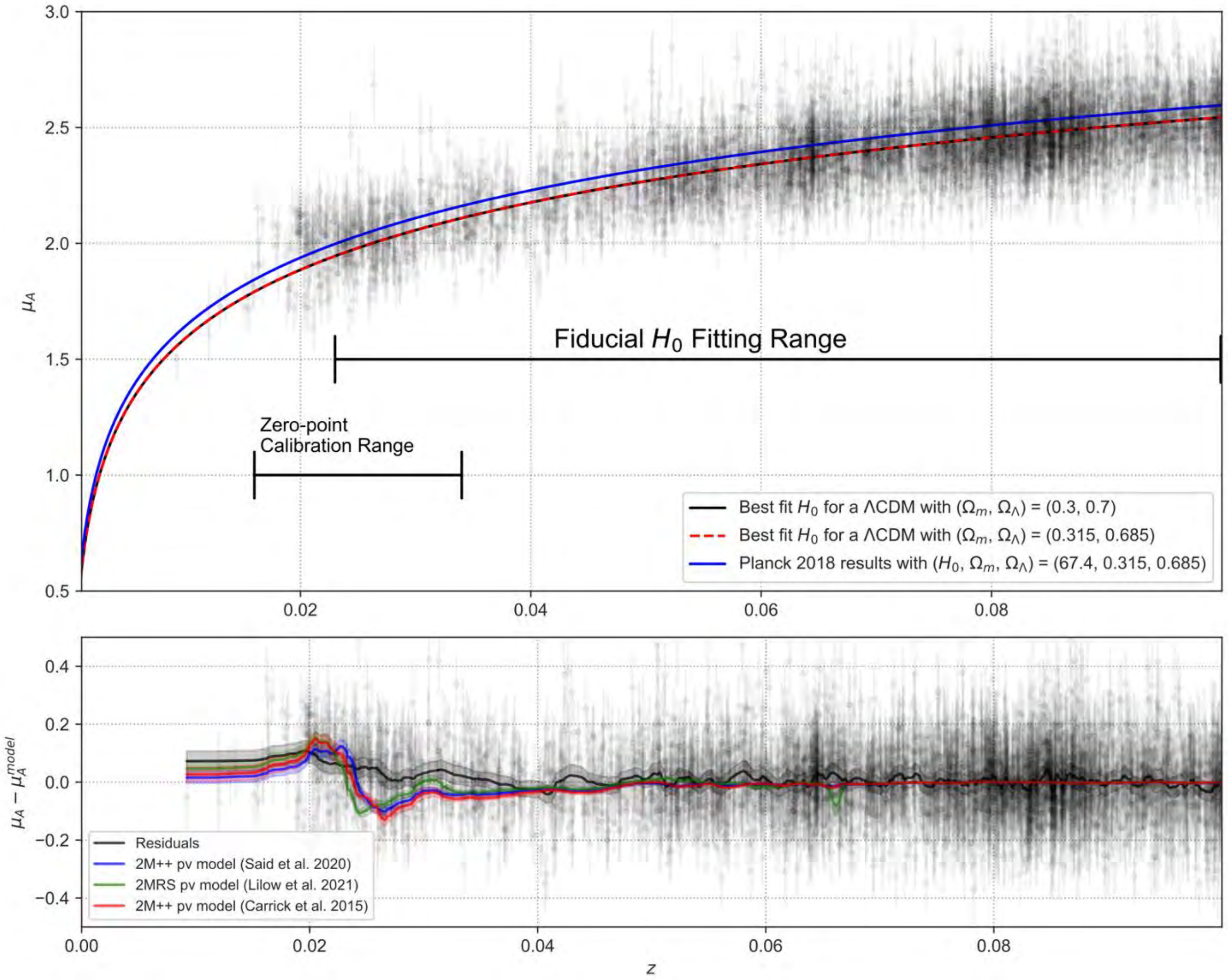
- Redundancy for every part of the ladder



Credit: Dr. Dan Scolnic

Just posted: A fresh look at the Coma distance

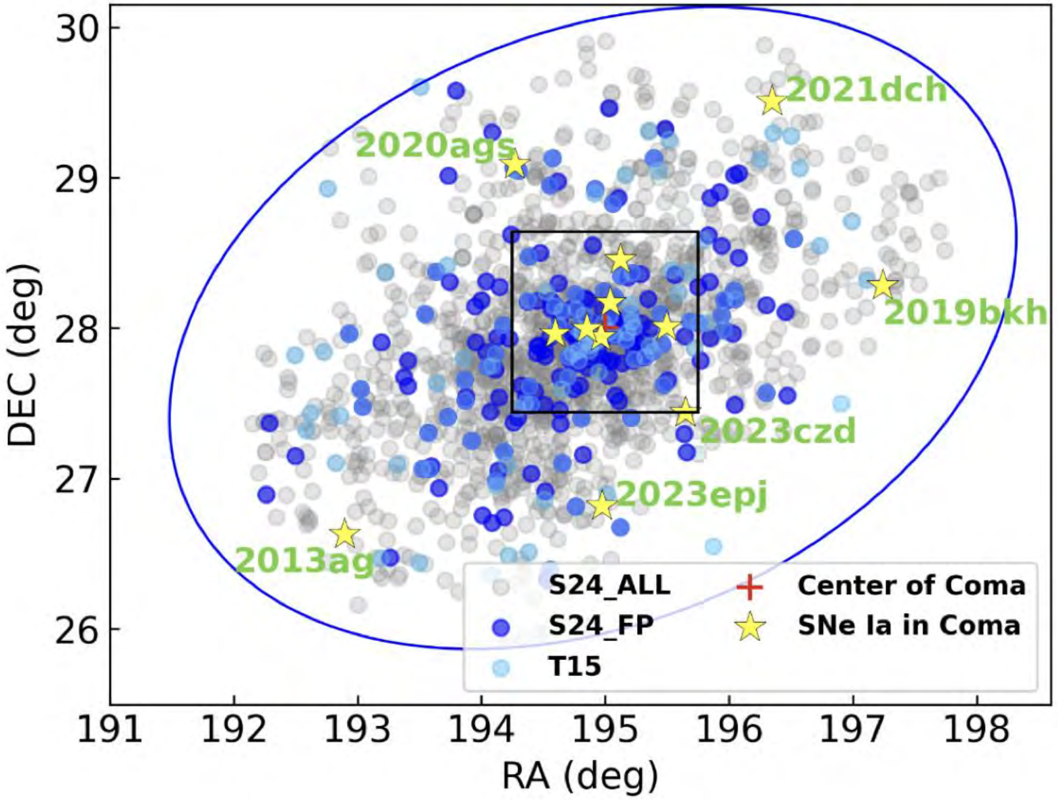
- DESI redshifts and distances (Fundamental-Plane) to 4,191 galaxies in Hubble Flow, plus 226 galaxies in the Coma Cluster (Said+ 2024)
- They find H_0=76.05 ±0.35 (st) ±0.49 (sy FP) ±4.86 (FP zp); H_0=(76.05±1.3)×(99.1 Mpc/ D_{Coma})



Said+ (2024)

Just posted: A fresh look at the Coma distance

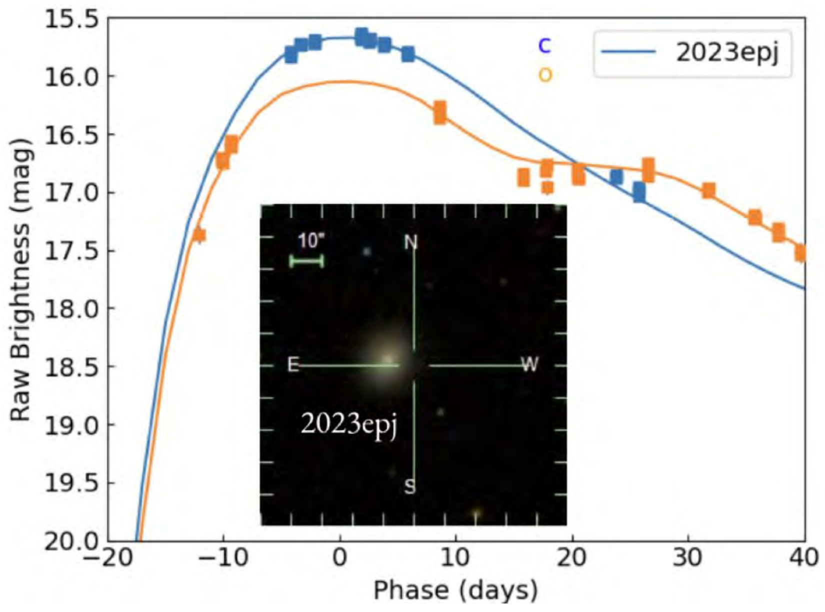
- Uncertainty in the DESI FP H_0 measurement dominated by absolute calibration of the SBF distance to Coma using Cepheids in Virgo & Fornax (Blakeslee+ 2021; Jensen+ 2021)
- Scolnic+ (2024): use Cepheids and SNe Ia to get the distance to Coma

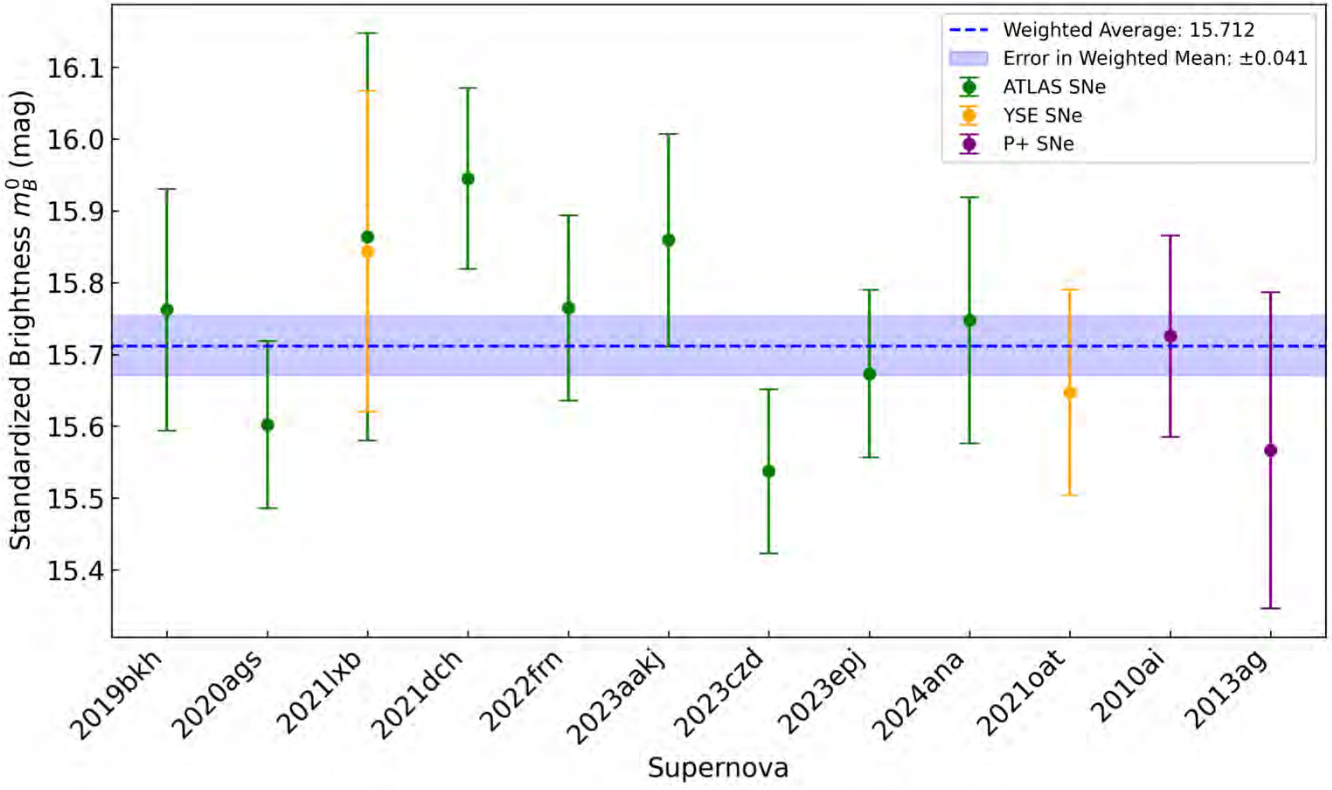


Scolnic+ (2024)

Just posted: A fresh look at the Coma distance

- 12 modern SNeIa identified in Coma, σ=0.12 mag; in line with Pantheon+ observed scatter in Hubble Flow





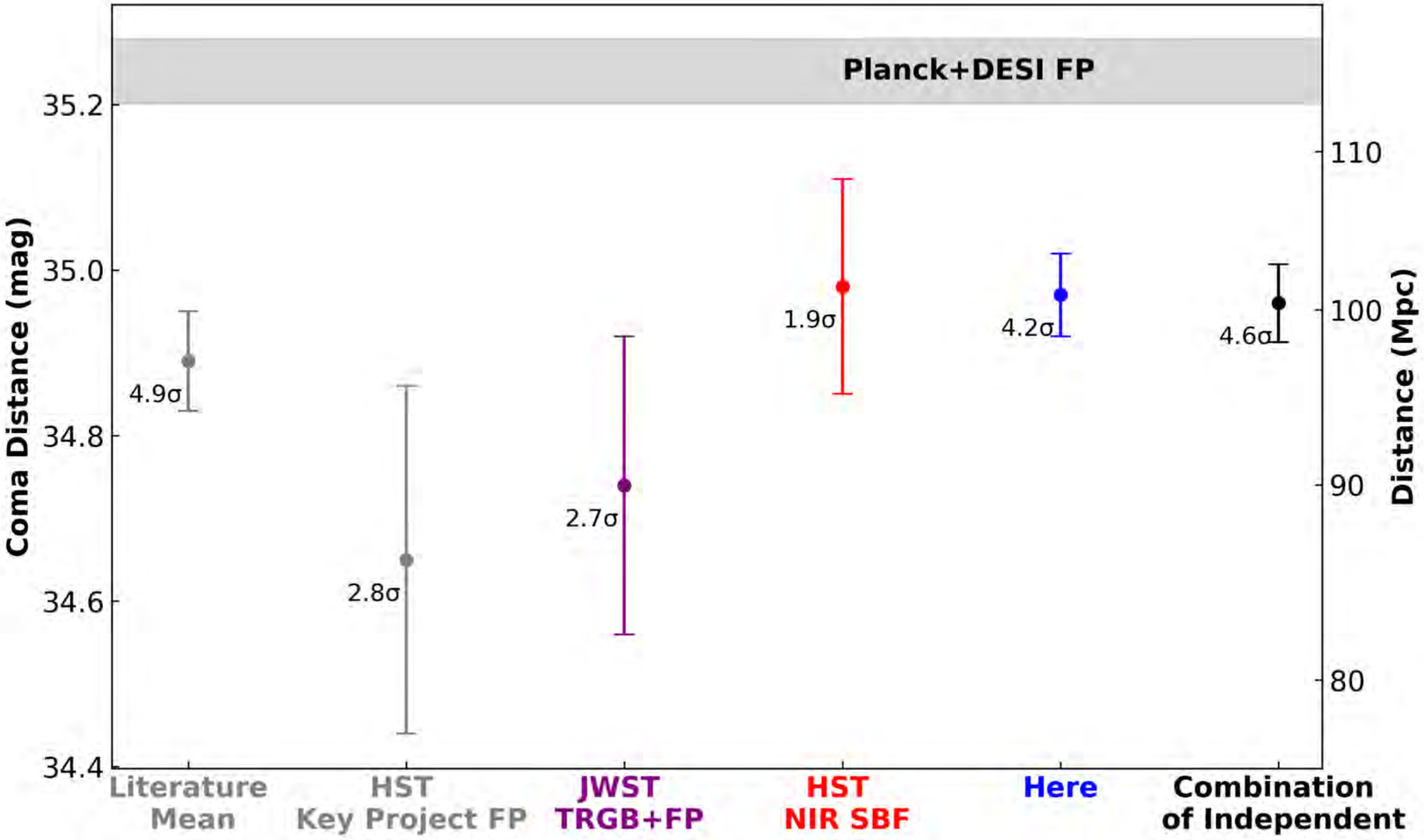
Scolnic+ (2024)

Just posted: A fresh look at the Coma distance

- Yields D(Coma)=98.5±2.2 Mpc and DESI FP H_0=76.5±2.2 km/s/Mpc

- *Planck* calibration of DESI FP yields a Coma distance that is ~13% too large

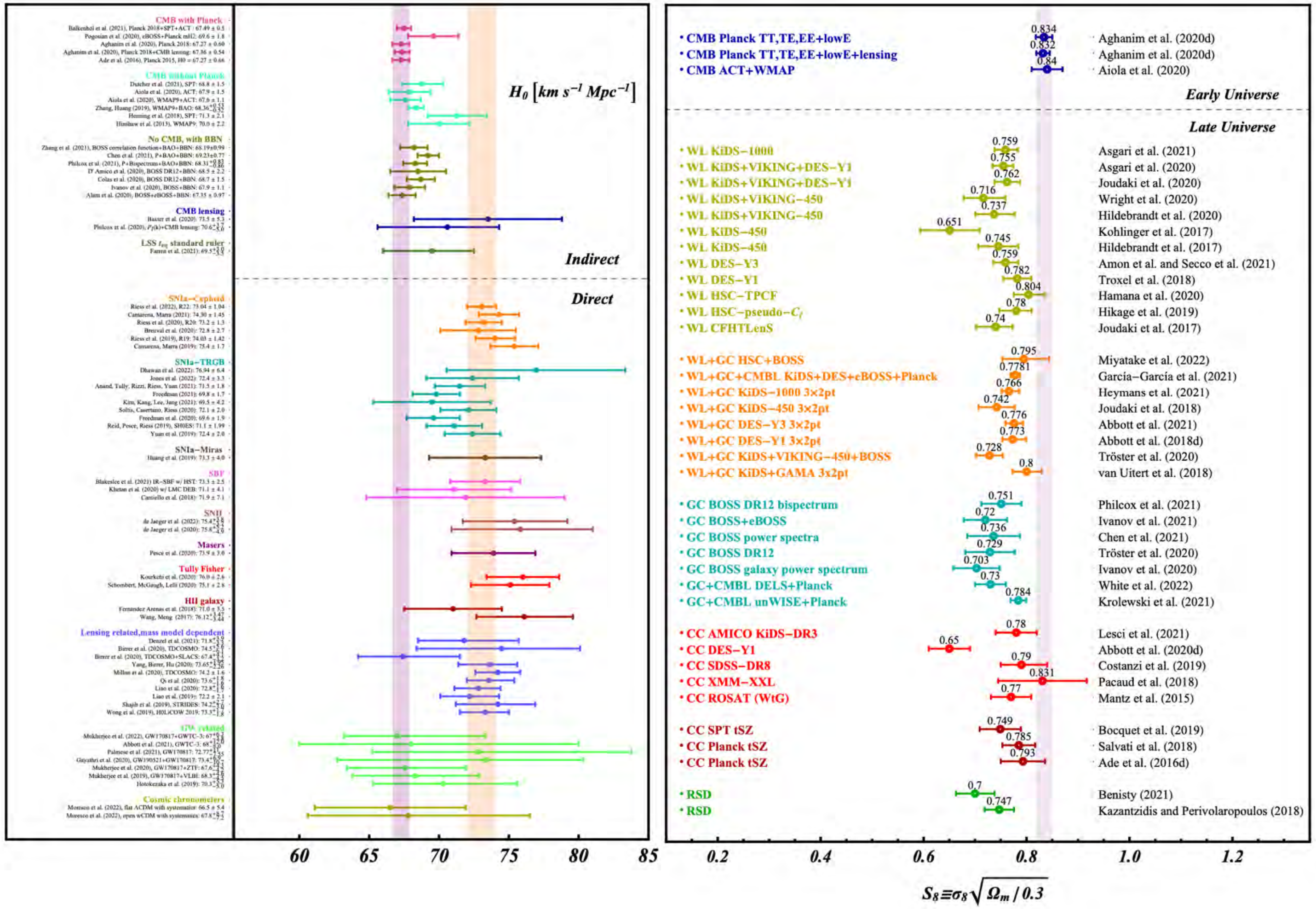
- Another manifestation of the Hubble Tension



Scolnic+ (2024)

The Hubble Tension

- A tale of two tensions?
- Why are there no local H_0 values below the *Planck* value?
- Di Valentino+ (2022): *"does not appear to depend on the use of any one method, team or source"*



di Valentino+ (2022)

New Physics in the Dark Sector?

Reviews: Schöneberg+ (2022); Di Valentino+ (2021)

"H_0 Olympics"

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

- Not so good: decaying dark matter, w<-1, Swampland
- Better: early dark energy, sterile and/or self-interacting ν's, evolving e⁻ mass, primordial B fields, early recombination
- Best: <your idea here>

Credit: Dr. A. Riess

New Physics in the Dark Sector?

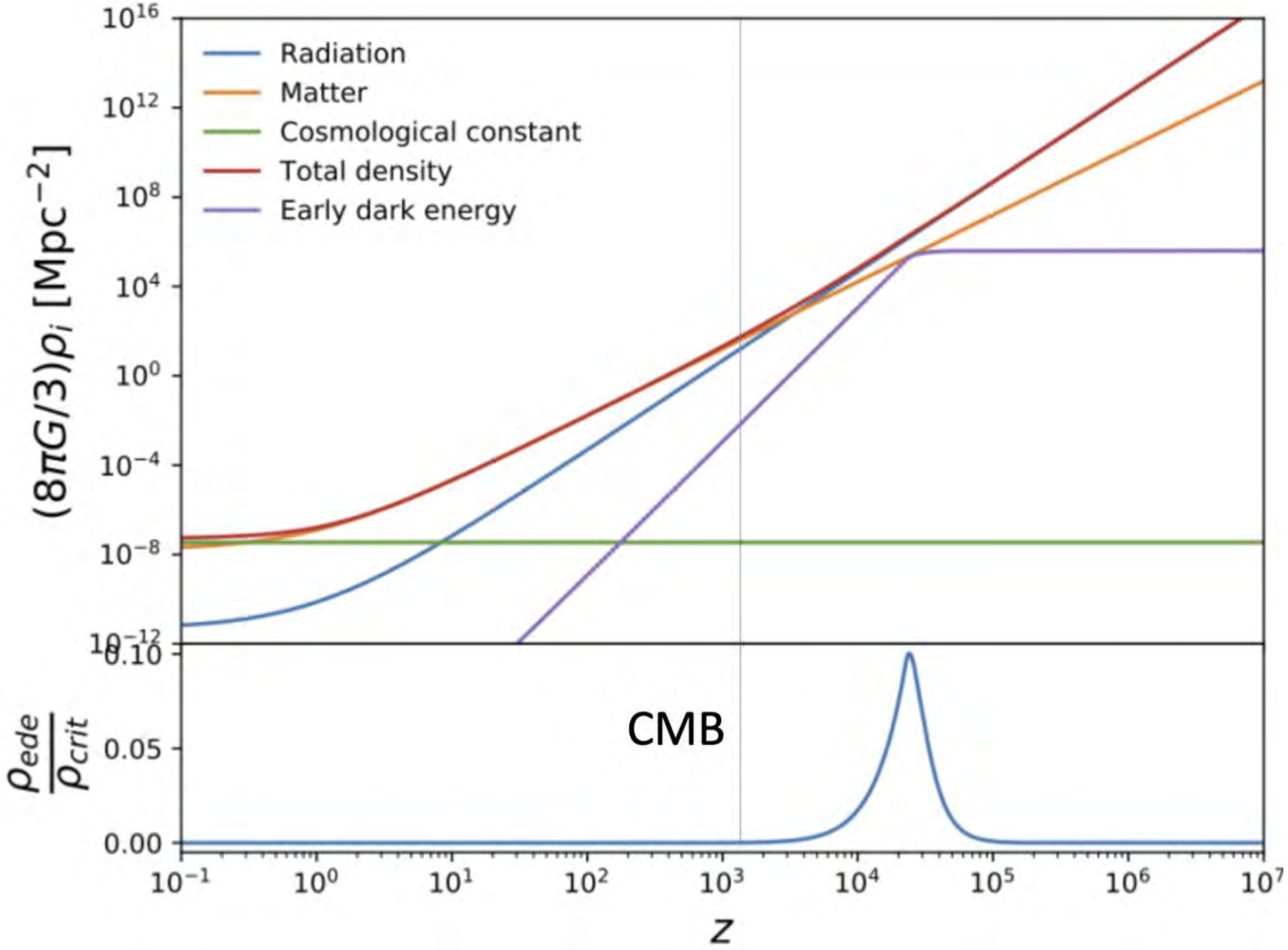
"Hubble Constant Hunter's Guide" (Knox and Millea, 2020)

- "Most Likely": Increased expansion rate pre-recombination reduces sound horizon by 5-8%
- Mechanisms: Early dark energy or sterile (and/or self-interacting) neutrinos
- Claims: not worse fit to CMB, should produce new CMB features for next stage

Credit: Dr. A. Riess

Early Dark Energy?

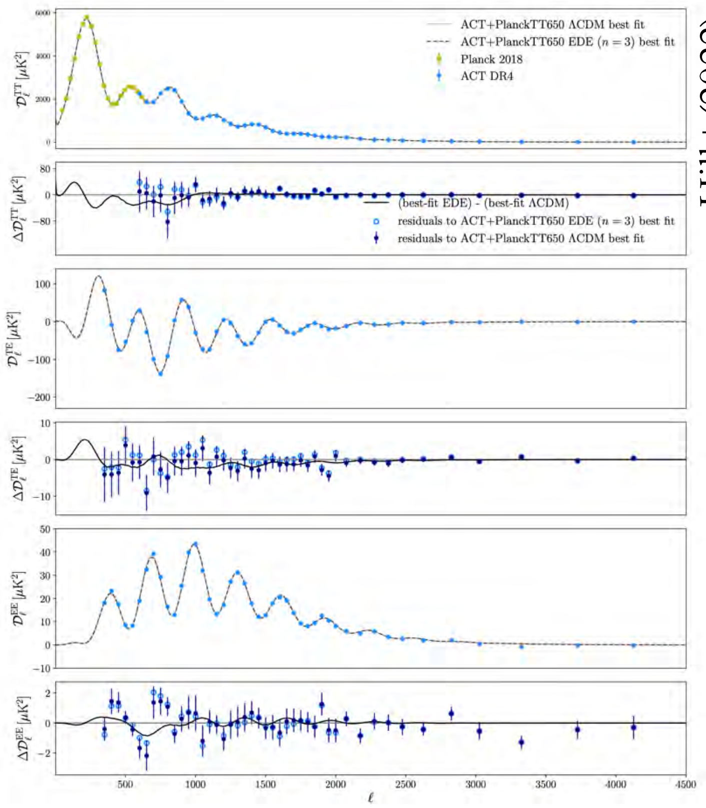
- Decays and contributes ~10% briefly before recombination
- Energy density later decays faster than radiation, leaving late evolution of Universe unchanged



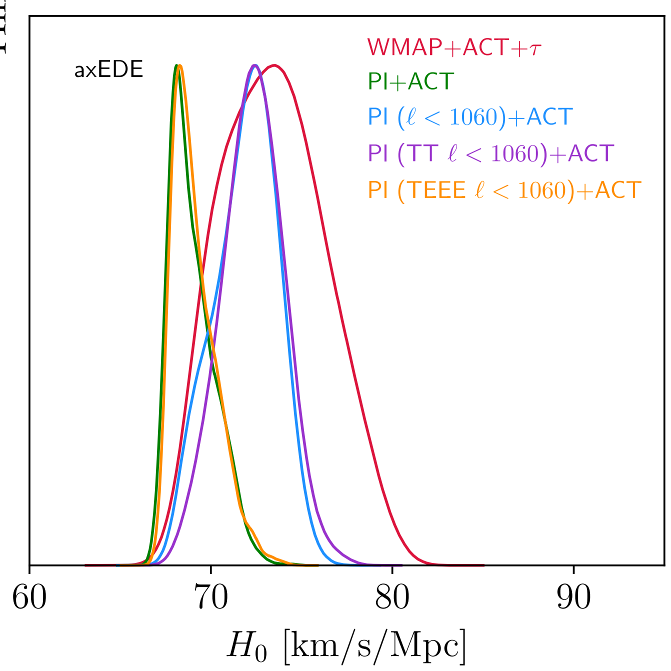
Kamionkowski & Riess (2023)

Early Dark Energy?

- Hill+ (2022): 3σ detection of EDE in ACT+Planck+BAO
- Poulin+ (2021): "More accurate TT at ℓ≳ 2500 and EE at 300<ℓ<500 will play a crucial role in differentiating EDE models"
- CMB S4 delayed… ☹

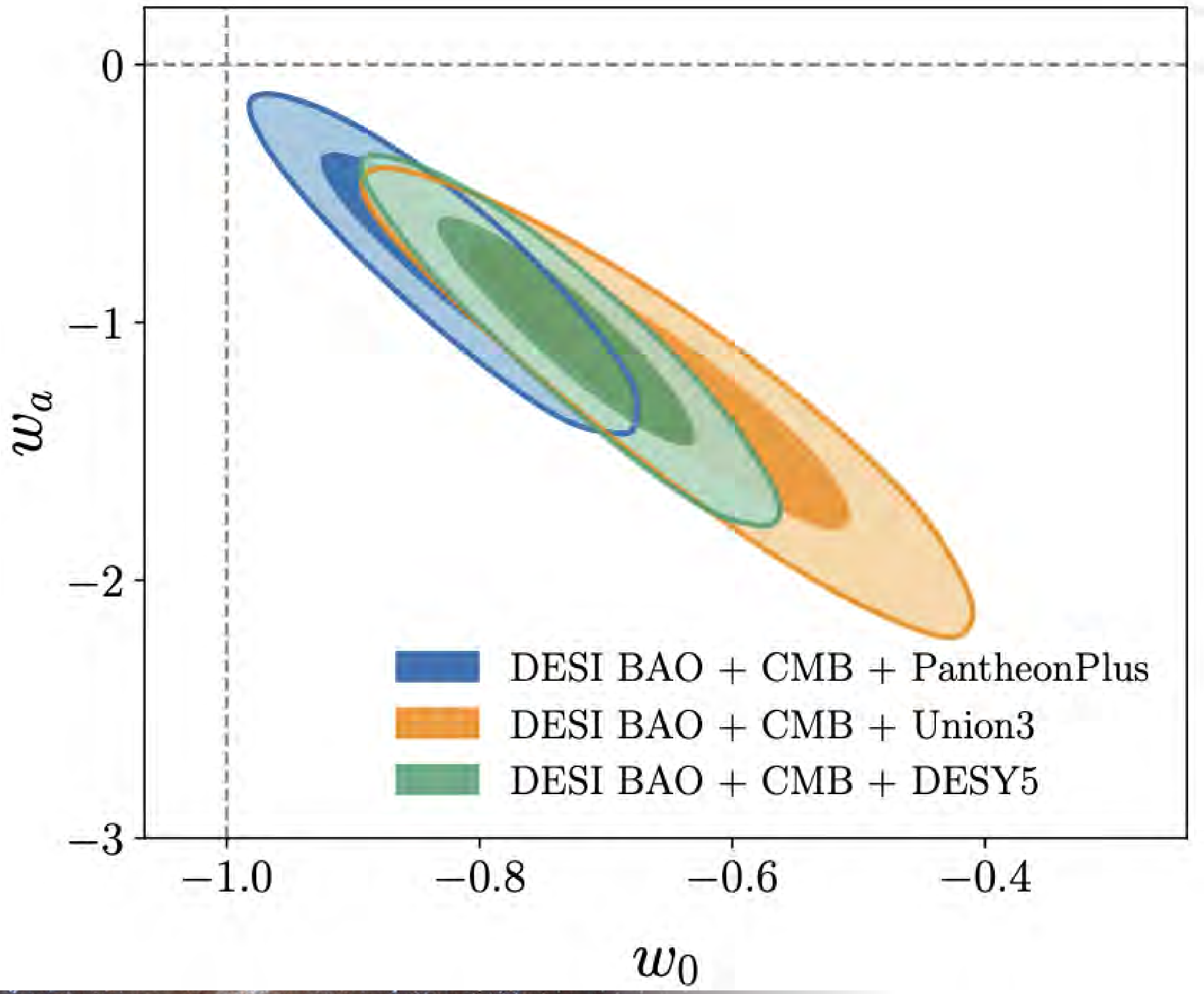


Hill+(2022)



Poulin, Smith & Bartlett (2021)

Time-evolving dark energy?



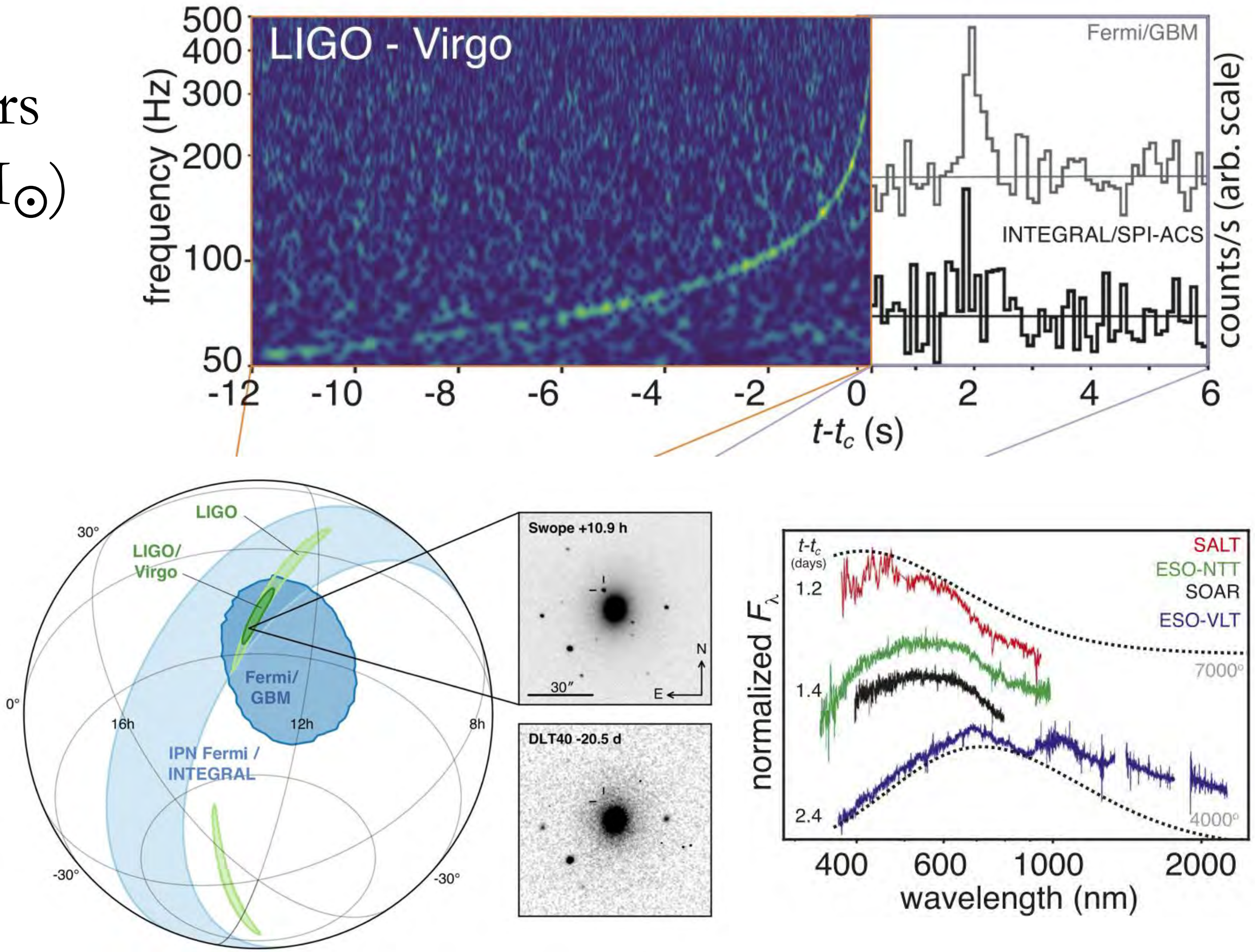
DESI Collaboration (2024)

Coming soon: H_0 from gravitational waves?

- The mergers of neutron stars or stellar-mass black holes generate gravitational waves that are detectable by LIGO/Virgo/Kagra
- The amplitude of these gravitational waves can be used to infer the distance to the binary (Schutz+ 1986)
- If there’s an electromagnetic counterpart, then the redshift of the host galaxy can be easily obtained
- Otherwise, rely on statistical analysis of galaxy redshifts within the GW localization area

Example: GW170817

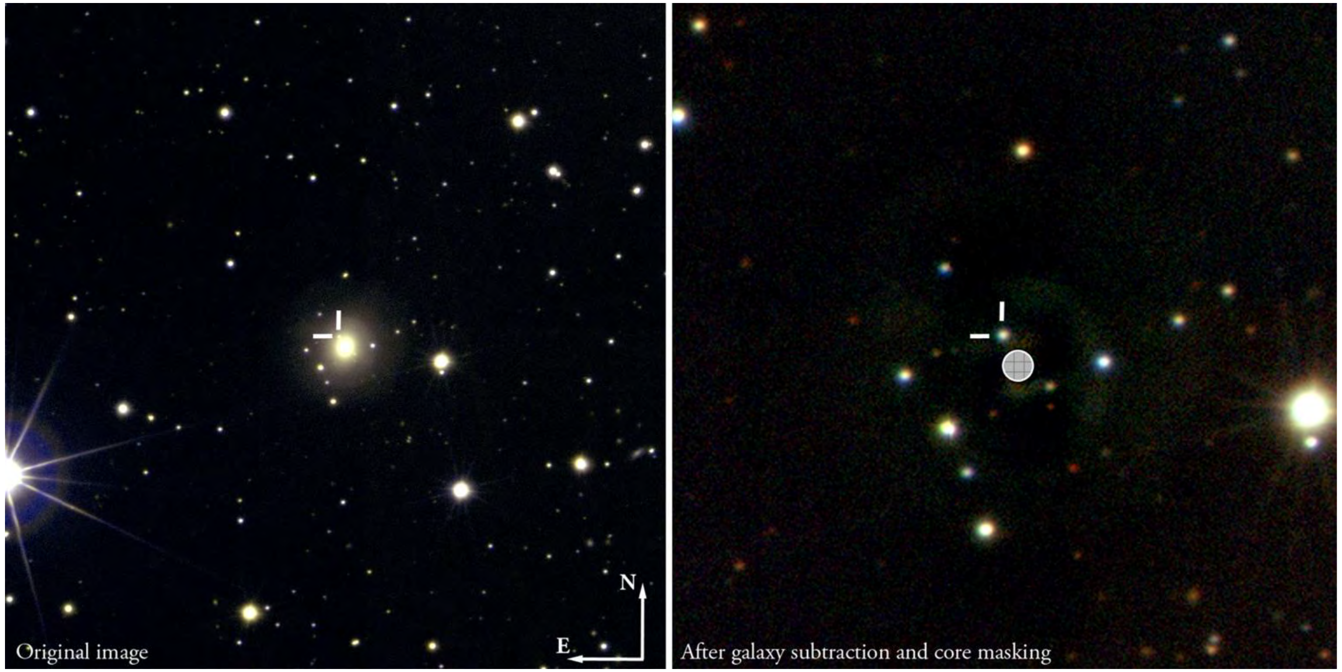
- Merger of two neutron stars (0.86-1.36 and 1.36-2.26 $M_\odot$)
- Localized to 28 sq deg (90% probability)
- Coincident GRB
- EM counterpart identified within 11h: "kilonova" in NGC 4993 (D~40 Mpc) including observations from T80-S (Diaz+ 2017)

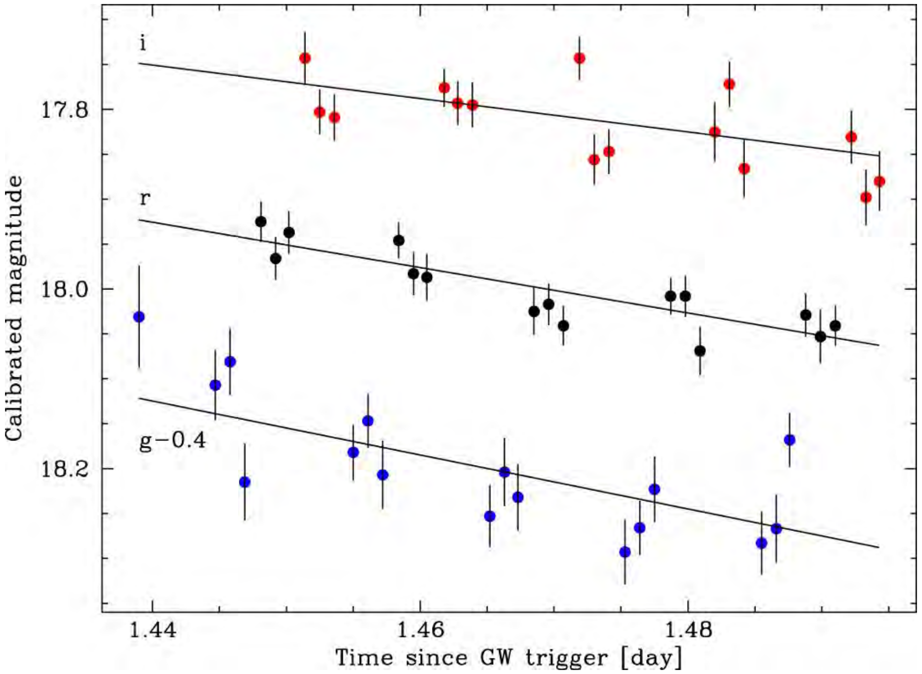


Abbott+ (2017a)

Example: GW170817

- Only one night of observations with T80-S, but still detected rapid decline of the light curves

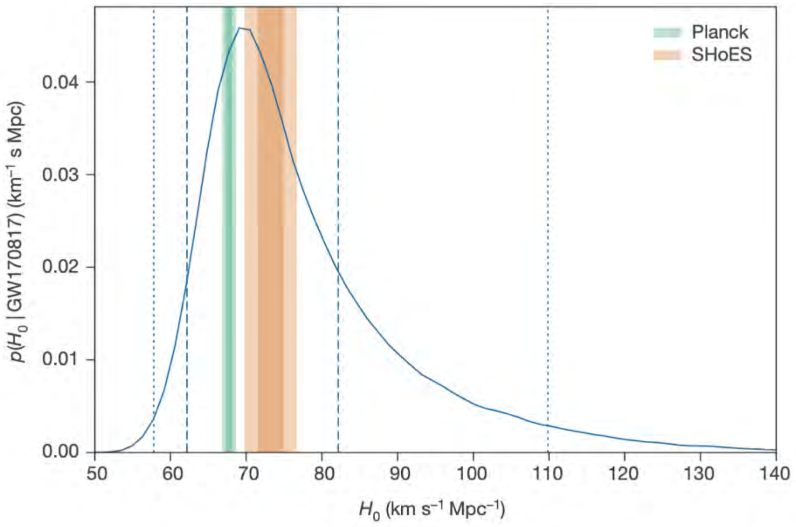


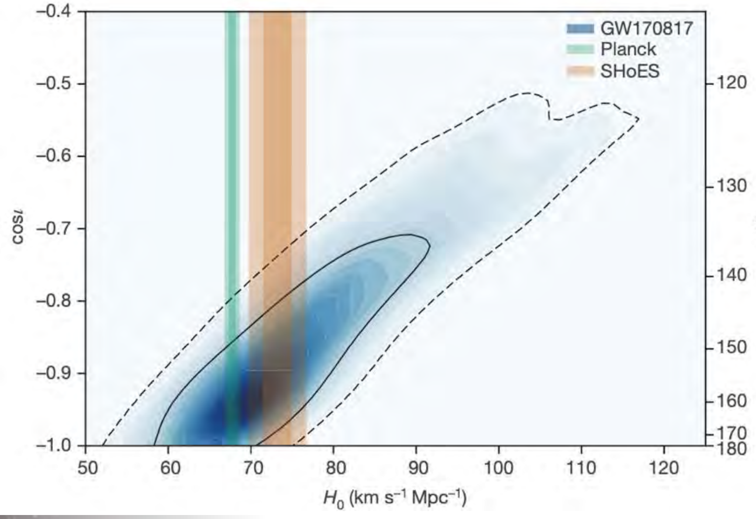


Diaz+ (2017)

Example: GW170817

- Given the close proximity of GW170817, its redshift is significantly affected by peculiar velocities
- Furthermore, degeneracy between derived H_0 and inclination angle of binary
- Nevertheless, a promising start… need a lot more of these!

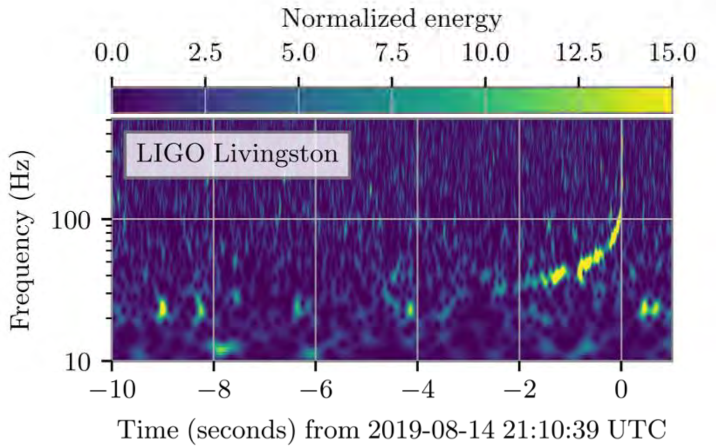


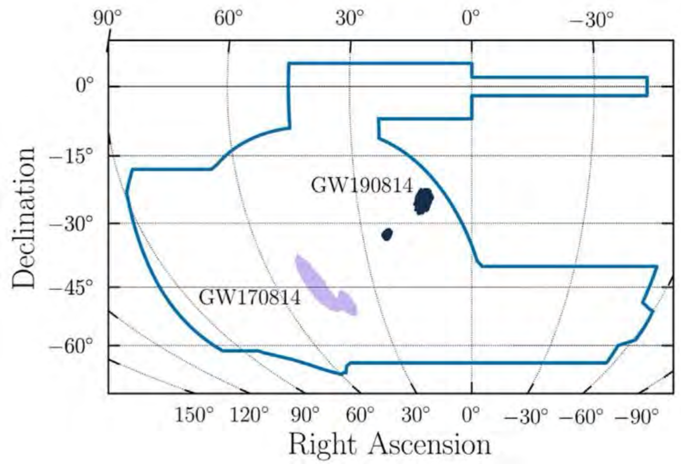


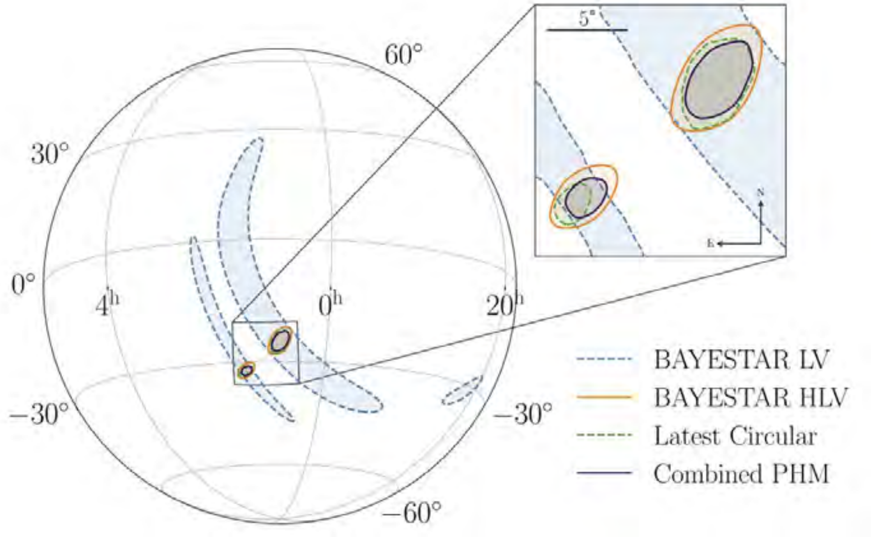
Abbott+ (2017b)

Example: GW190814

- Merger of 23 $M_\odot$ BH + 2.6 $M_\odot$ compact object
- Localized to 18.5 sq deg (90% probability)
- Extensive search for EM counterpart unsuccessful but it was somewhere within the DES footprint…



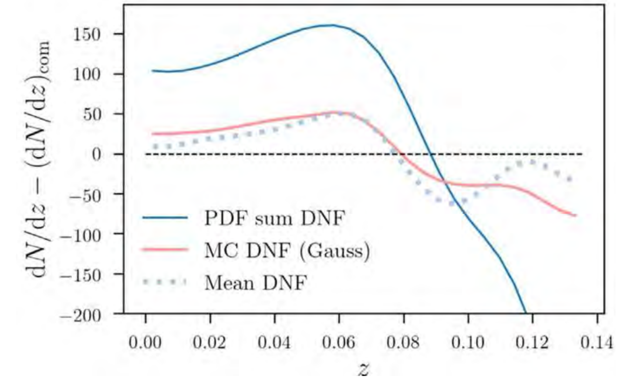


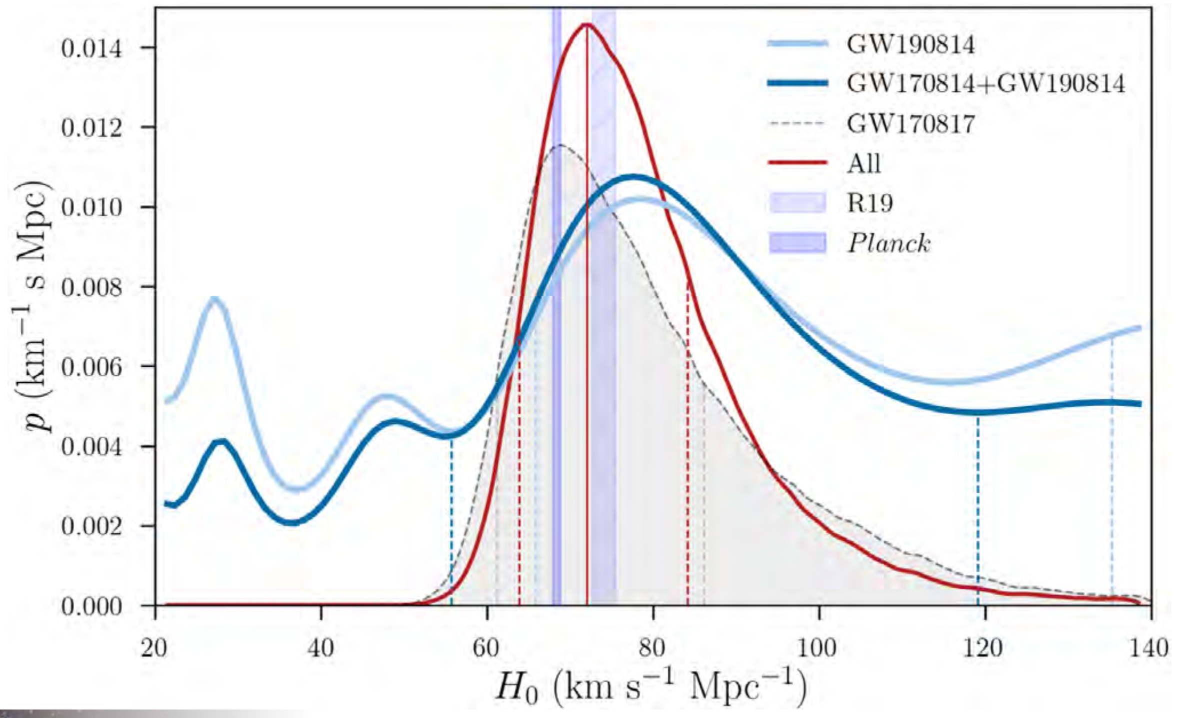


Abbott+ (2020); Palmese+ (2020)

Example: GW190814

- Identify 2,684 DES galaxies within 90% localization area
- Obtain redshift distribution (mostly photo-z's)
- Combine with GW distance to obtain H_0 distribution
- Include two other "standard sirens" to obtain $H_0=72^{+12}_{-8}$

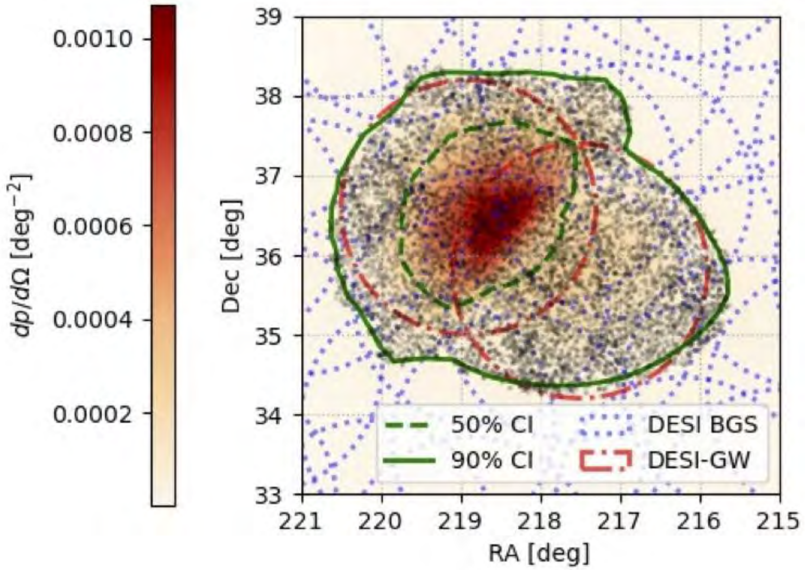


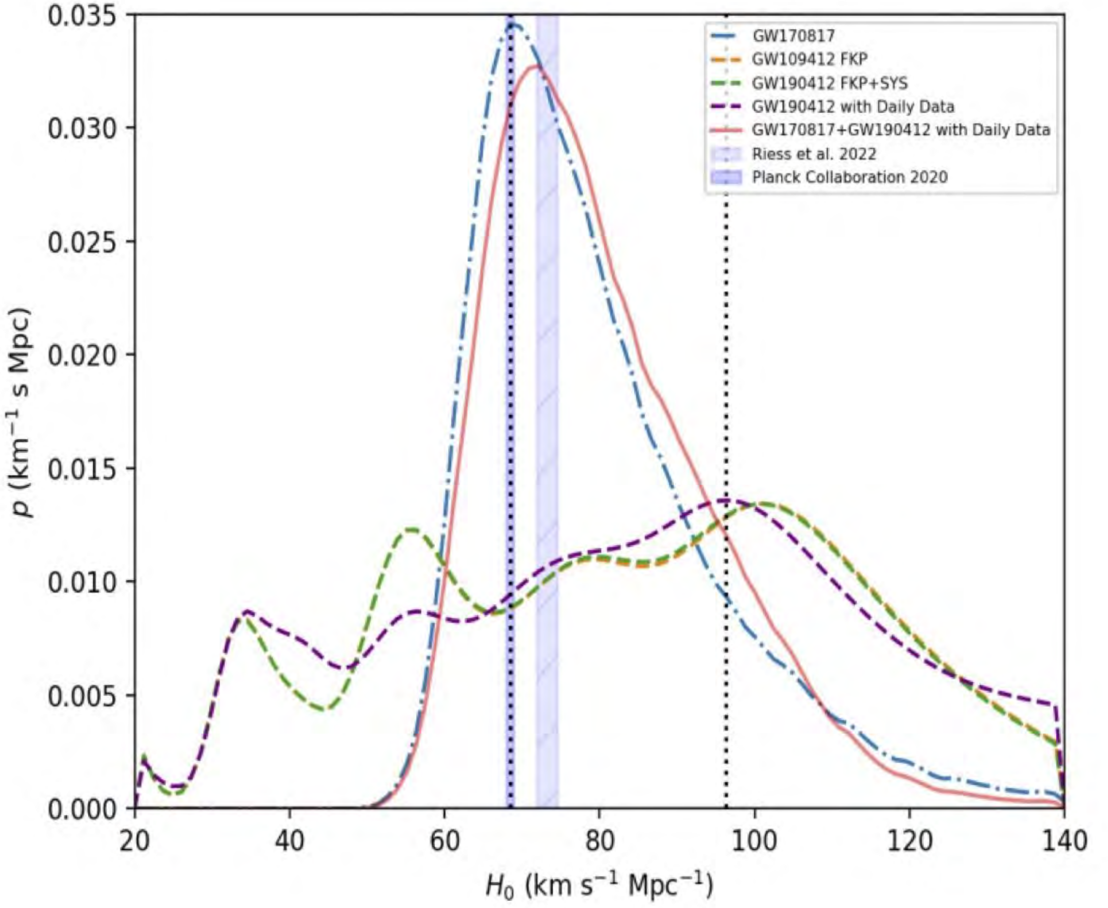


Palmese+ (2020)

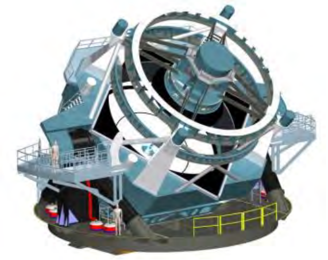
Example: GW190412

- DESI redshifts are now starting to be used for this application
- Recent analysis of GW190412: $H_0 = 85^{+29}_{-34}$; $H_0 = 78^{+18}_{-9}$ (combined)





Ballard+ (2023)



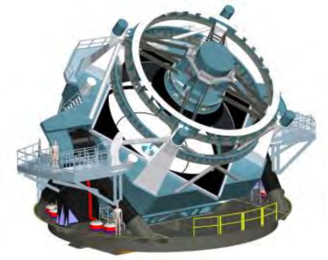
The future: Rubin/LSST and *Roman*

- The Vera C. Rubin Observatory Legacy Survey of Space and Time will survey ~18,000 sq deg in 6 filters (*ugrizY*) every night for 10 years

- 8.4-m telescope and 2.3 Gpix camera; survey starts ~Sep-Dec 2025

- Single-visit 5σ depth g ~24.5, r ~24.0, i ~23.4; coadded g,r ~26.9, i ~26.4

- Rubin/LSST will detect >10^5 Miras in ~200 galaxies with D<15 Mpc and ~10^6 SNeIa with $0.05 < z < 1.1$



The future: Rubin/LSST and *Roman*

- The *Nancy Grace Roman* Space Telescope:
- 2.4-m aperture with 300 Mpix near-infrared camera (100× larger field of view than WFC3 on *Hubble*)
- 5-year nominal mission (+5 year extended?) beginning in 2027
- 1-hr point source 5σ depth YJH~27.5; K_s~25.6
- *Roman* will detect ~15,000 SNe Ia with 0.3 < z < 3.0
- It could be used to efficiently follow up Rubin/LSST Miras

Summary

- Robust determinations of the local value of the Hubble constant provide a critical “end-to-end” test of the cosmological model when compared against predictions based on observations of early Universe
- CMB+BAO predict H_0=67.4±0.5 under the assumption of ΛCDM
- *HST* Cepheids+SNe Ia measure H_0=73.17±0.86; solid *JWST* check
- What is the source of this “Hubble Tension”? Early Dark Energy? Time-varying dark energy? Something else?
- Exciting prospects from DESI, *JWST*, GWs, Rubin/LSST, *Roman*!