The SH0ES project and the accelerating Universe

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OUTLINE

- **Introduction**
- How to measure the expansion rate to ~1%
- Cosmological probes of the expansion
- New Physics in the dark sector?
- Next steps

UNITS…

- I've done my best to remove astronomical units from this version of my talk; however, a few might appear…

- $1\ L_\odot \sim 10^{26}$ W, "luminosity"; "flux" → W m^{-2}
- $1\ R_\odot \sim 10^{9}$ m
- $1\ M_\odot \sim 10^{30}$ kg
- 1 Mpc ~ 10^{22} m ~ $3 \cdot 10^{6}$ ly

- "Magnitude" $= -2.5 \log_{10}(\text{flux}) + C$
  - In mag: Vega ≡ 0; Sun ≈ −25; stars in this talk ≈ +25
  - In flux: Vega ≡ 1; Sun ≈ 10^{10}; stars in this talk ≈ 10^{-10}

One hundred years ago…

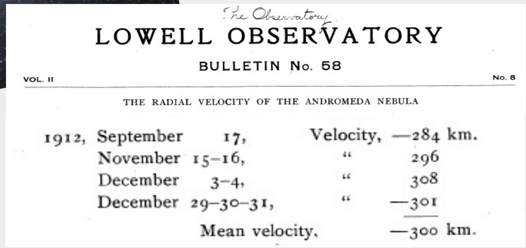
- What was the "consensus view" of the Universe around 1921?

- Age of the Universe (Earth):
  - $\gtrsim$ 1 Gyr from radioactive dating (e.g. Boltwood 1907)

- Size of the Universe
  - The Milky Way is the entire Universe ($D=4\text{-}20\cdot10^{20}$ m)
  - Composed of stars and "nebulae" (elliptical, spiral, etc.)
  - Rotating, but no expansion or contraction
    - Thus, Einstein's Λ in 1917

THE GREAT DISCOVERIES OF 1912

- Vesto Slipher obtains the first spectrum of a "spiral nebula"
  - Andromeda: v=-297±10 km/s (modern value: -300±4 km/s)
- He observes many more nebulae over next few years
- Most velocities are positive (receding) and much larger than the velocities of stars
- What is the reason for these "red shifts"?



The Observatory

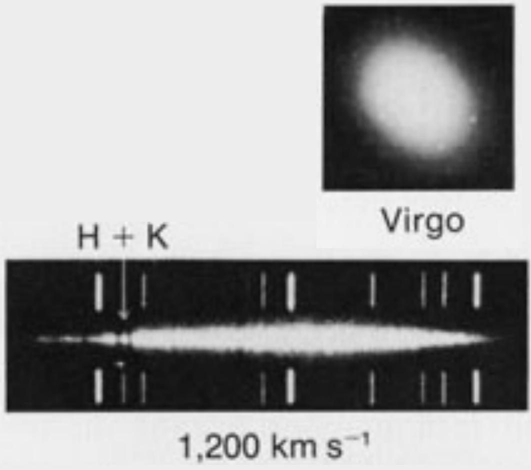
LOWELL OBSERVATORY

BULLETIN No. 58

VOL. II — No. 8

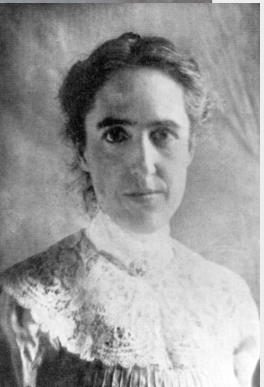
THE RADIAL VELOCITY OF THE ANDROMEDA NEBULA

1912,	September	17,	Velocity,	—284 km.
	November	15–16,	"	296
	December	3–4,	"	308
	December	29–30–31,	"	—301
		Mean velocity,		—300 km.



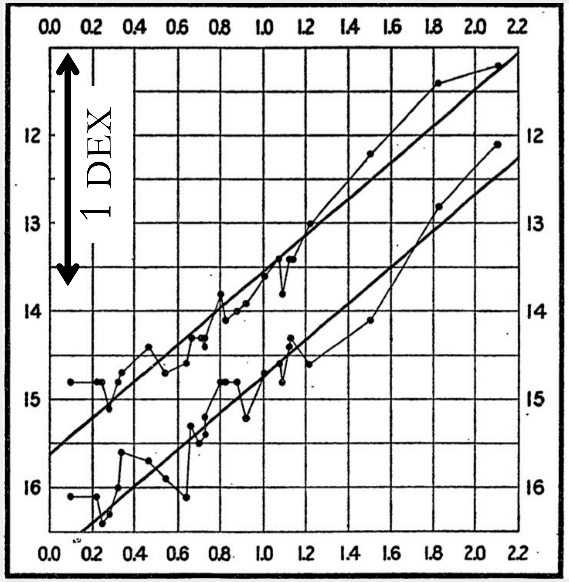
The great discoveries of 1912

- Henrietta Swan Leavitt discovers a relation between the periods and luminosities of "Cepheid variables"
  - Nature of variability was unknown at the time; not binaries…
- Cepheids become a "standard candle": $D^2 = L / 4\pi f$



Leavitt (1912)

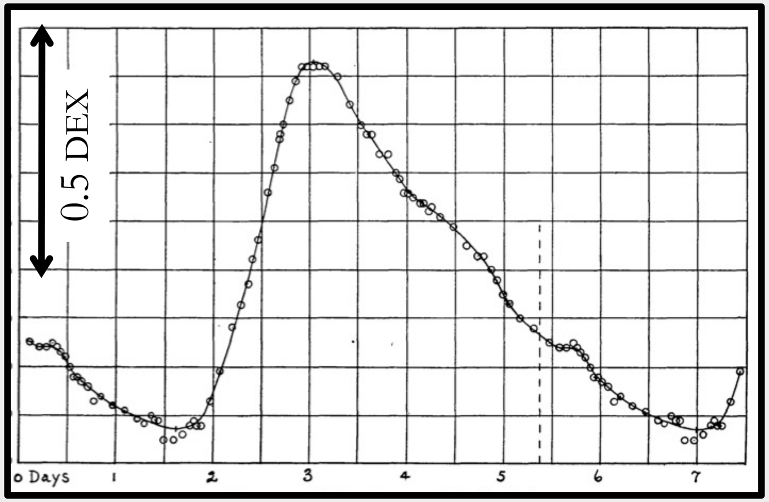
LOG FLUX + C



LOG PERIOD [DAYS]

Stebbins (1908)

LOG FLUX + C

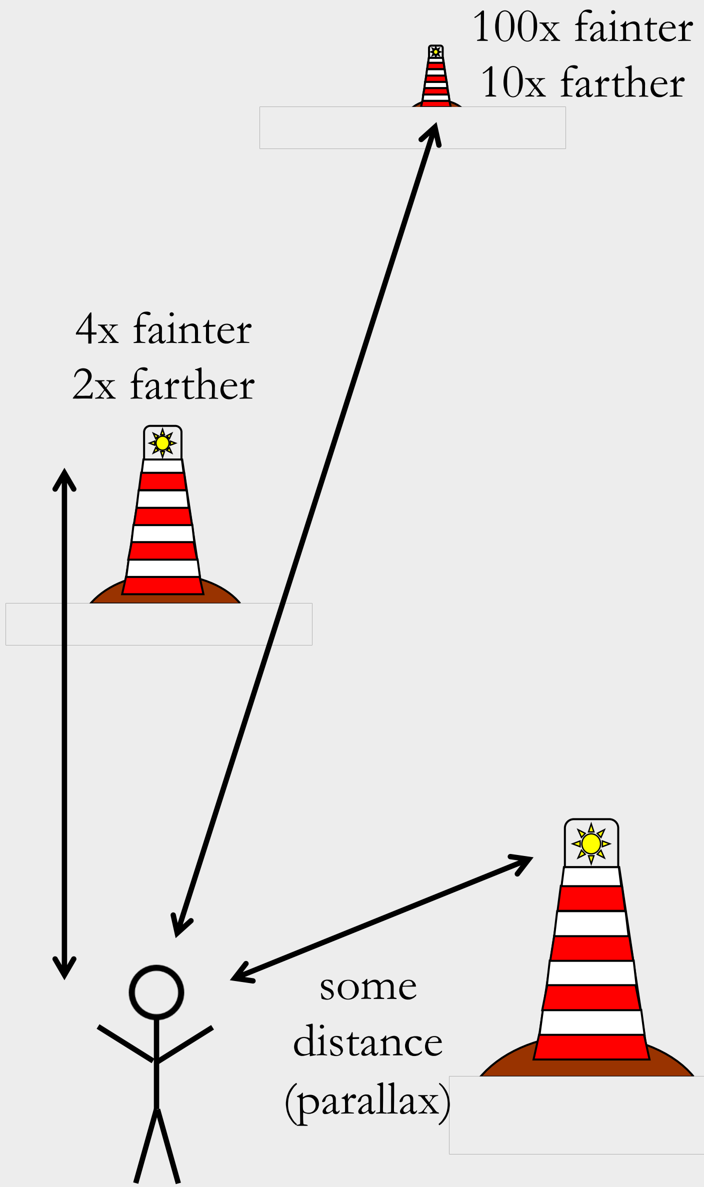


Time [days]

STANDARD CANDLES

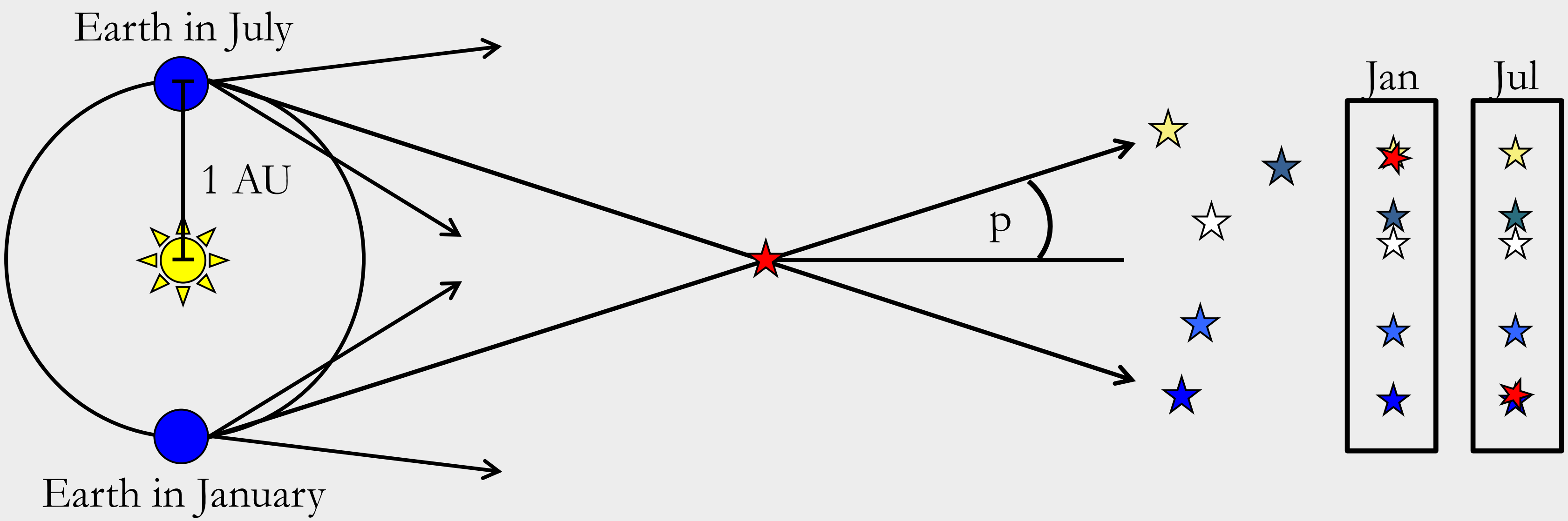
- If we know that members of some class of stars have the same luminosity, then we can use their *relative* fluxes to estimate *relative* distances

- We need to know the *absolute* distance to at least one of these stars, which we can measure via parallax



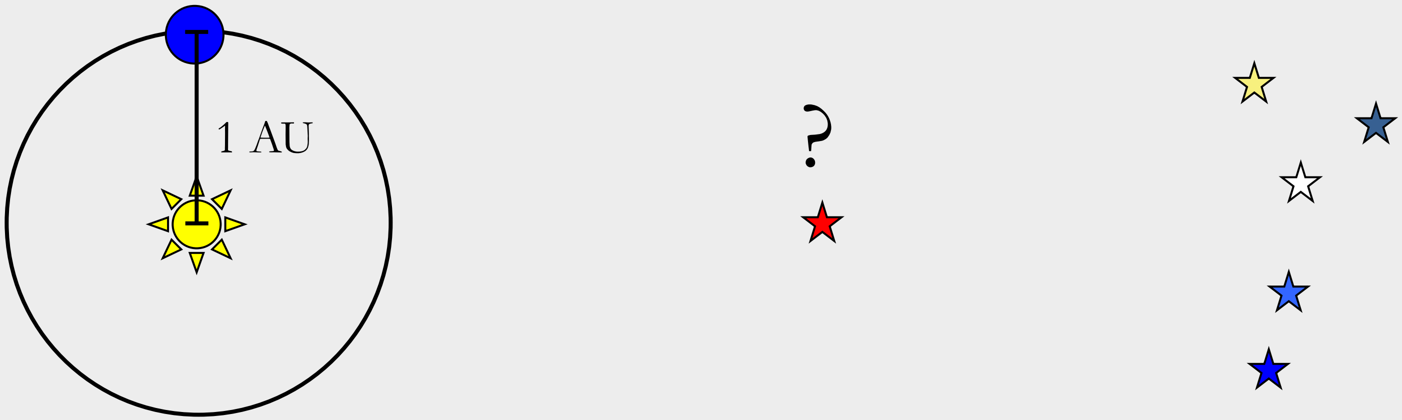
PARALLAX

- In 1838, Friedrich Bessel first measured the distance to a star using a method known as "parallax."



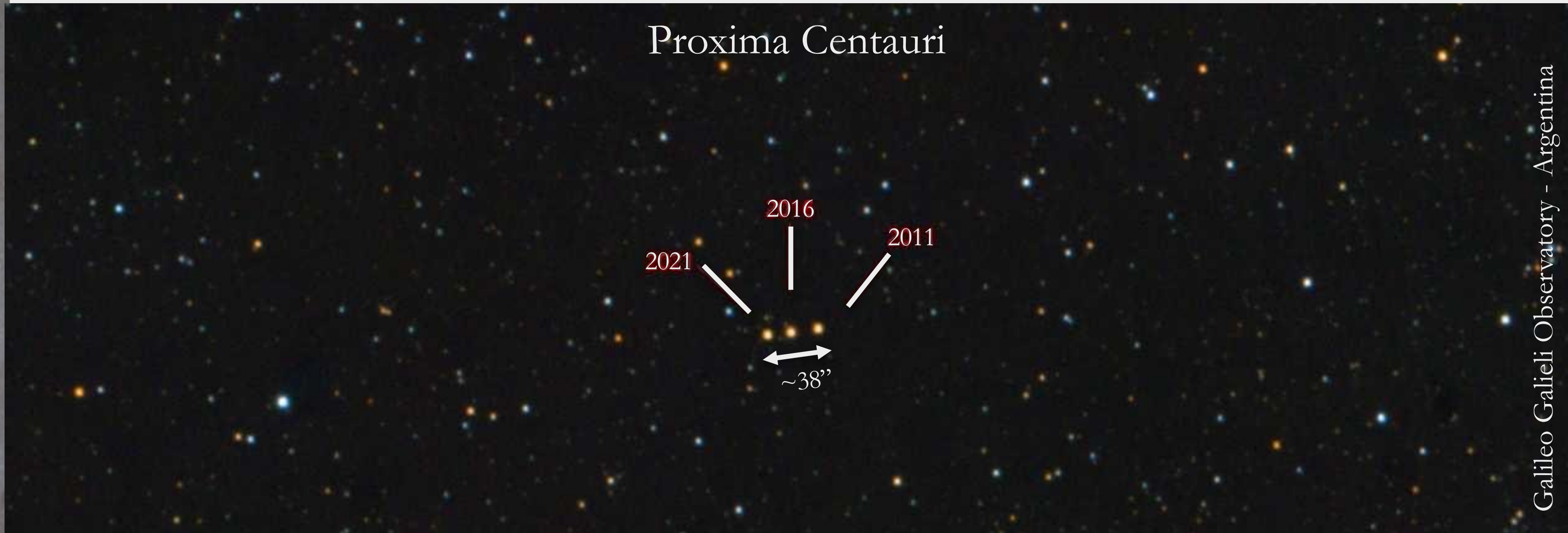
PARALLAX

- Question for the group: how would you identify a star that may be reasonably closer to you than others?



PROPER MOTION

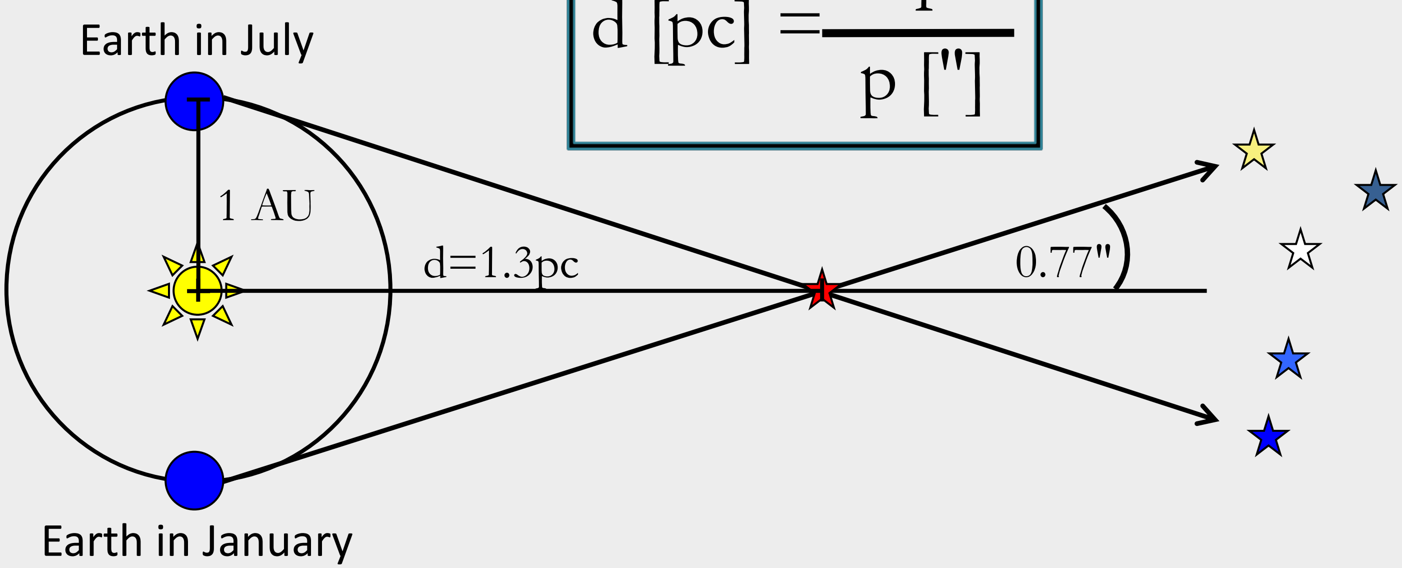
- If stars move at similar speeds through space, then those closer to us will appear to move faster across the sky (*proper motion*)
  - 1 arc-second ["] = 1/3600 deg ~ 5×10^{-6} rad



PARALLAX

- If we can measure:
  - The distance between the Sun and the Earth (1 AU)
  - The angle subtended by the apparent motion of a star
- Then use trigonometry to solve for its distance

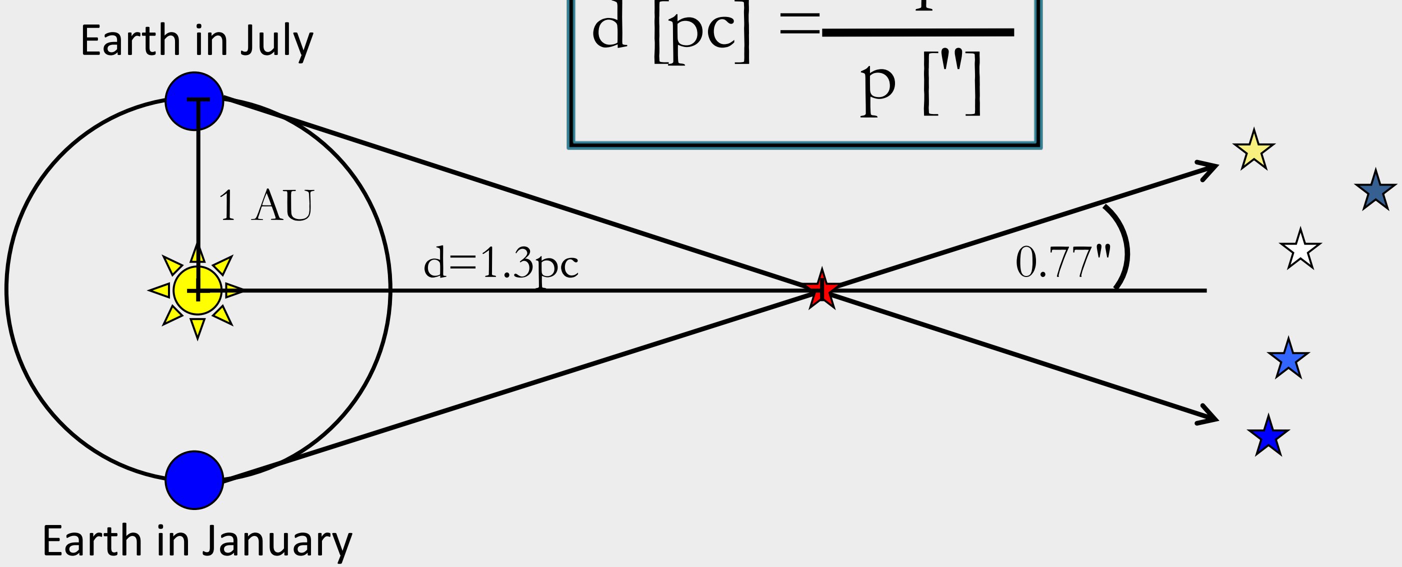
$$\boxed{d\ [pc] = \frac{1}{p\ ['']}}$$



PARALLAX

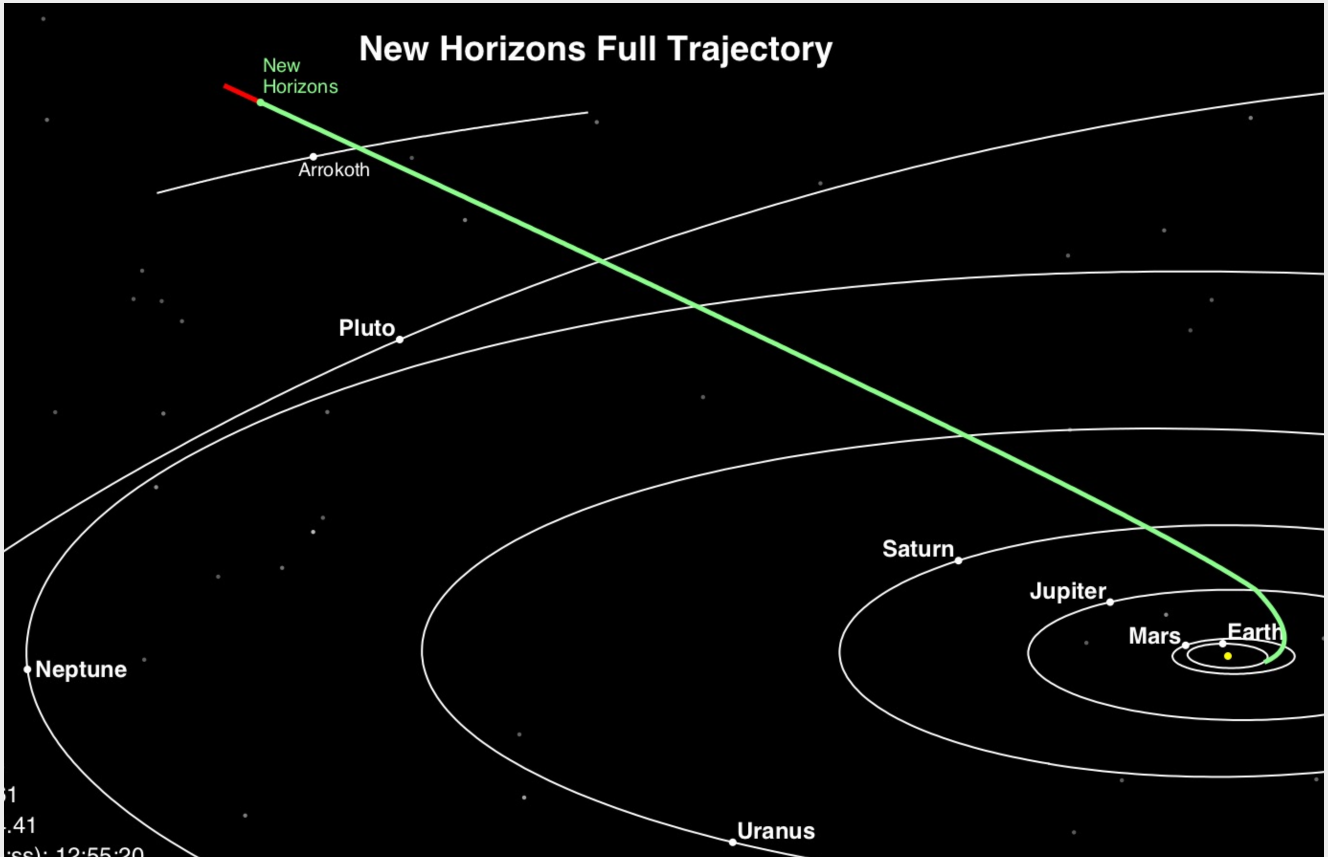
- Why in 1838? Parallax angle is *very* small (~0.04% angular diameter of Moon) and required mechanical devices
- That's ~80× smaller than the resolution of the human eye and about the size the of the "blur" imposed by the Earth's atmosphere on telescopic images

$$\boxed{d\,[\mathrm{pc}] = \frac{1}{p\,['']}}$$



PARALLAX

- The parallax angle grows larger if we measure it using a wider baseline… how about one image from Earth and the other one from New Horizons (45 AU away)?



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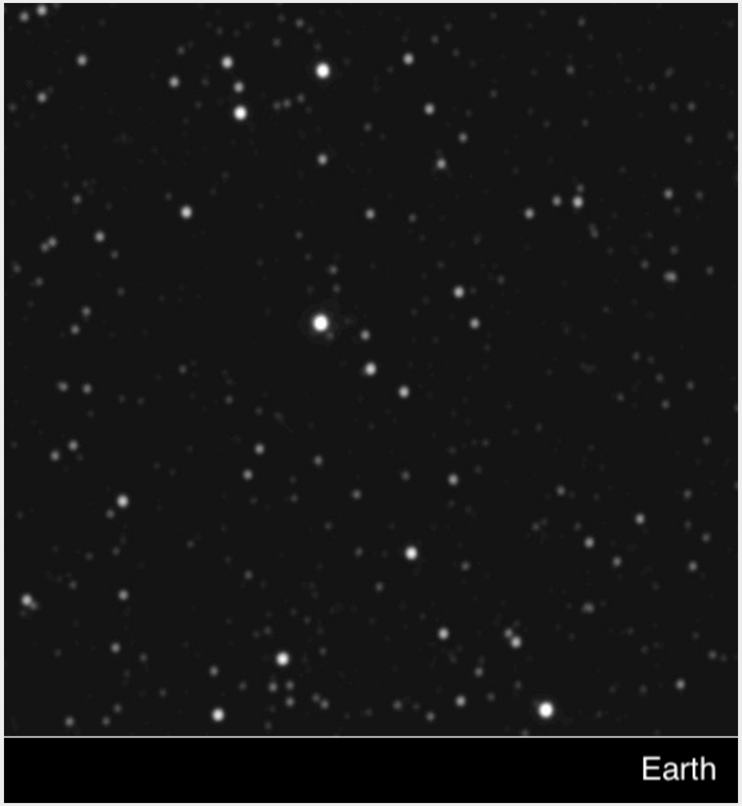
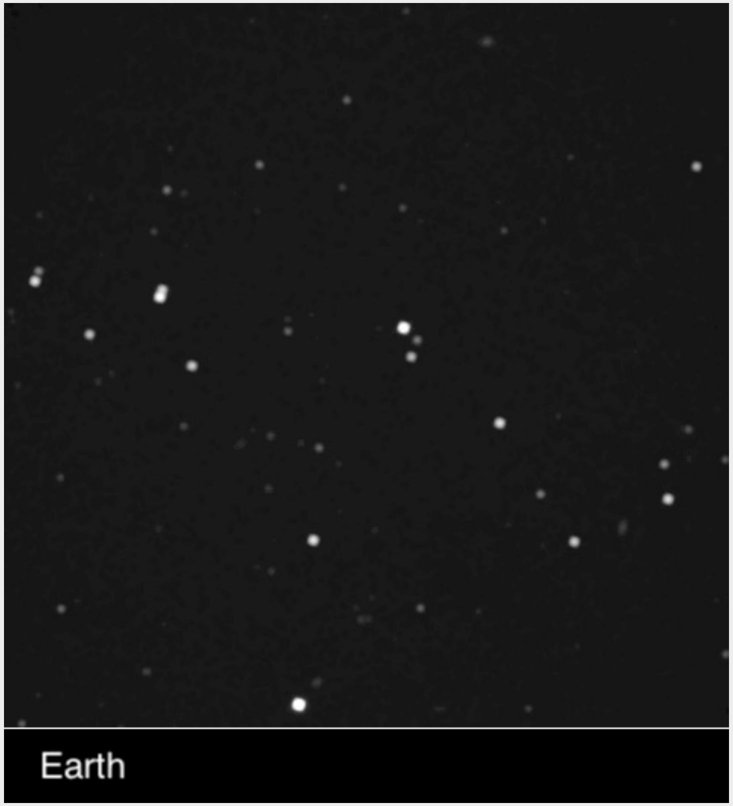
PARALLAX

- Images obtained June 2020: Parallaxes of Proxima Centauri and Wolf 359 are obvious ☺ but still ~2× smaller than what the unaided human eye can see ☹



Proxima Centauri



Wolf 359

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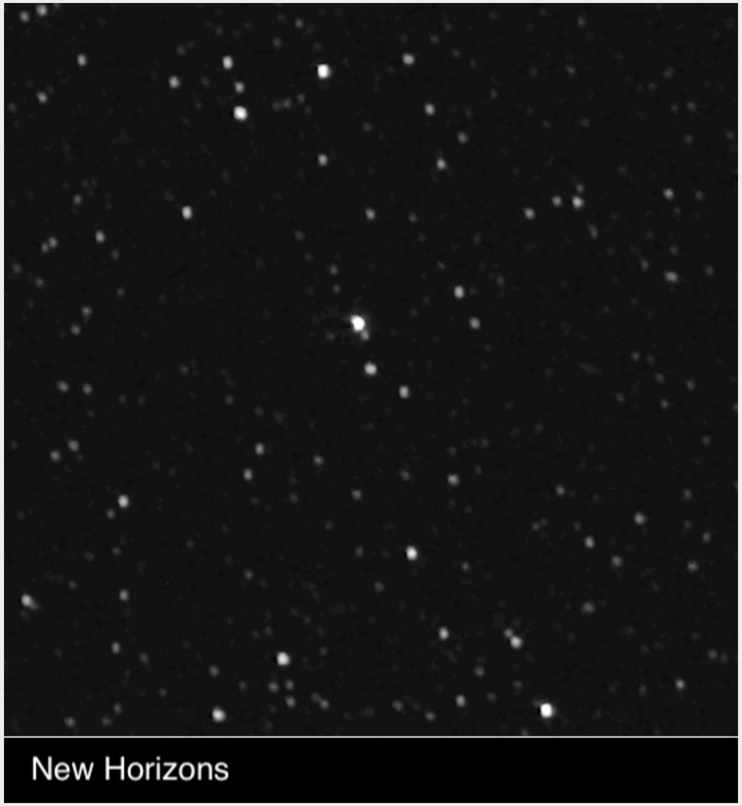
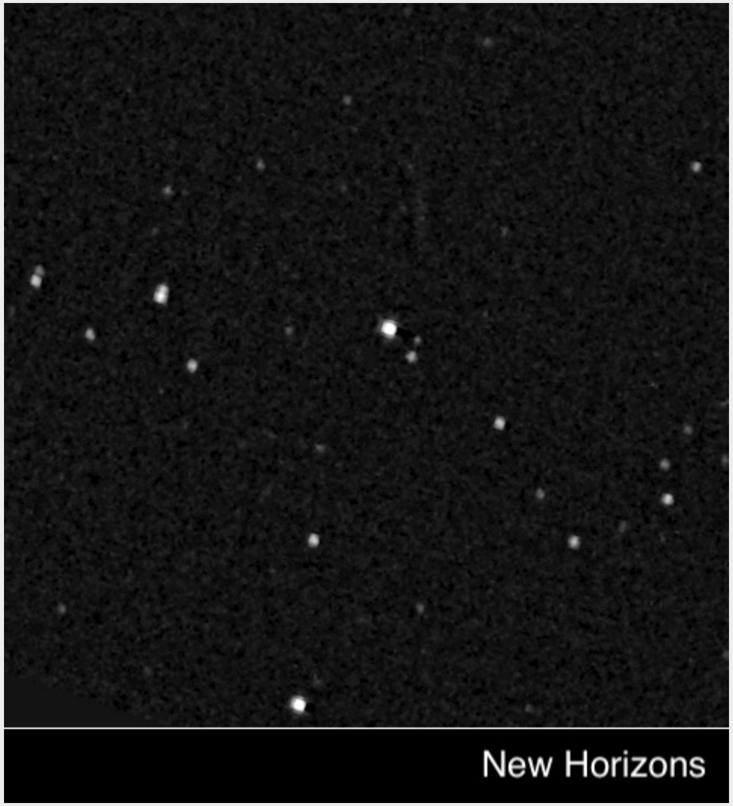


Proxima Centauri



Wolf 359

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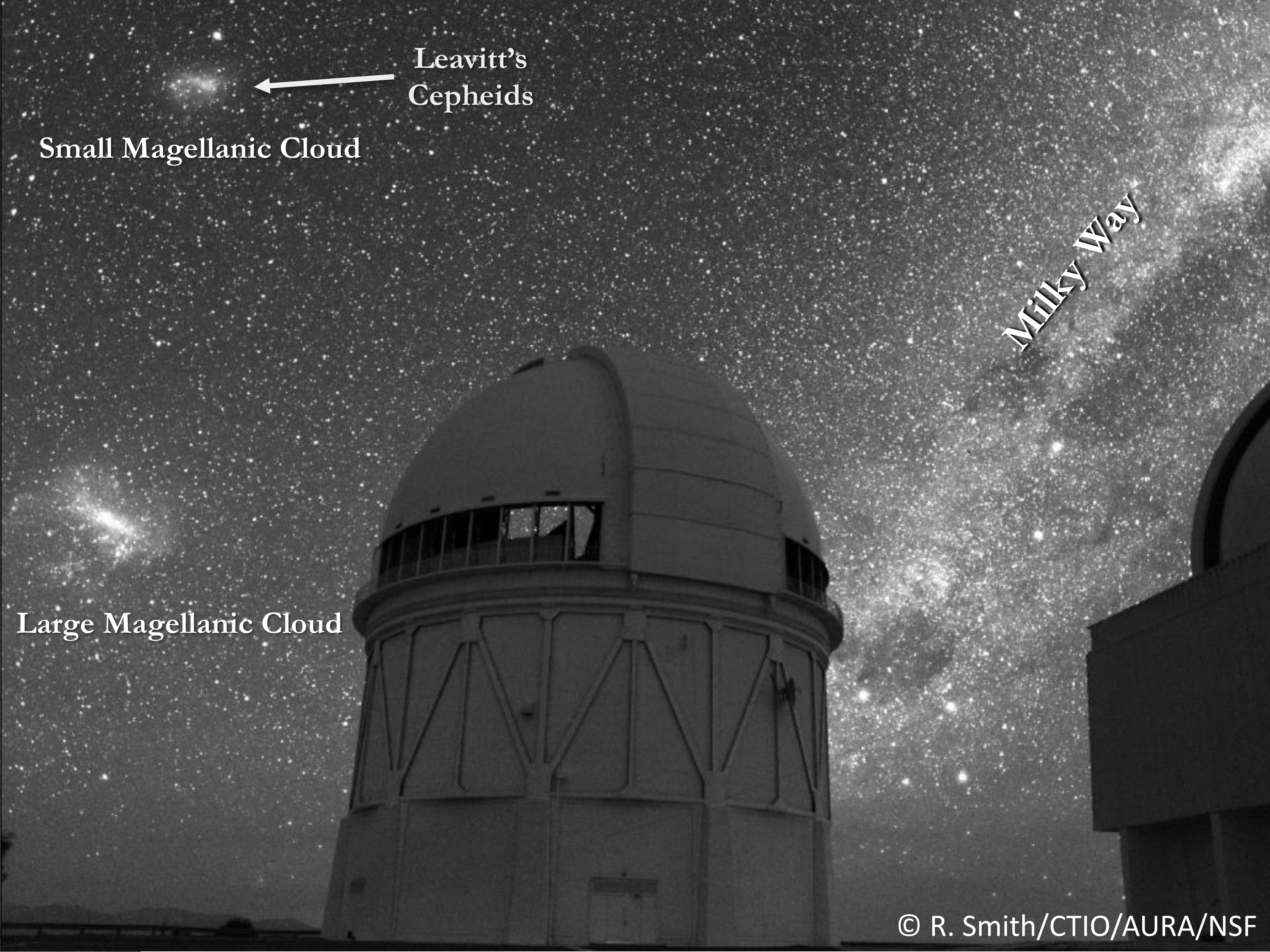
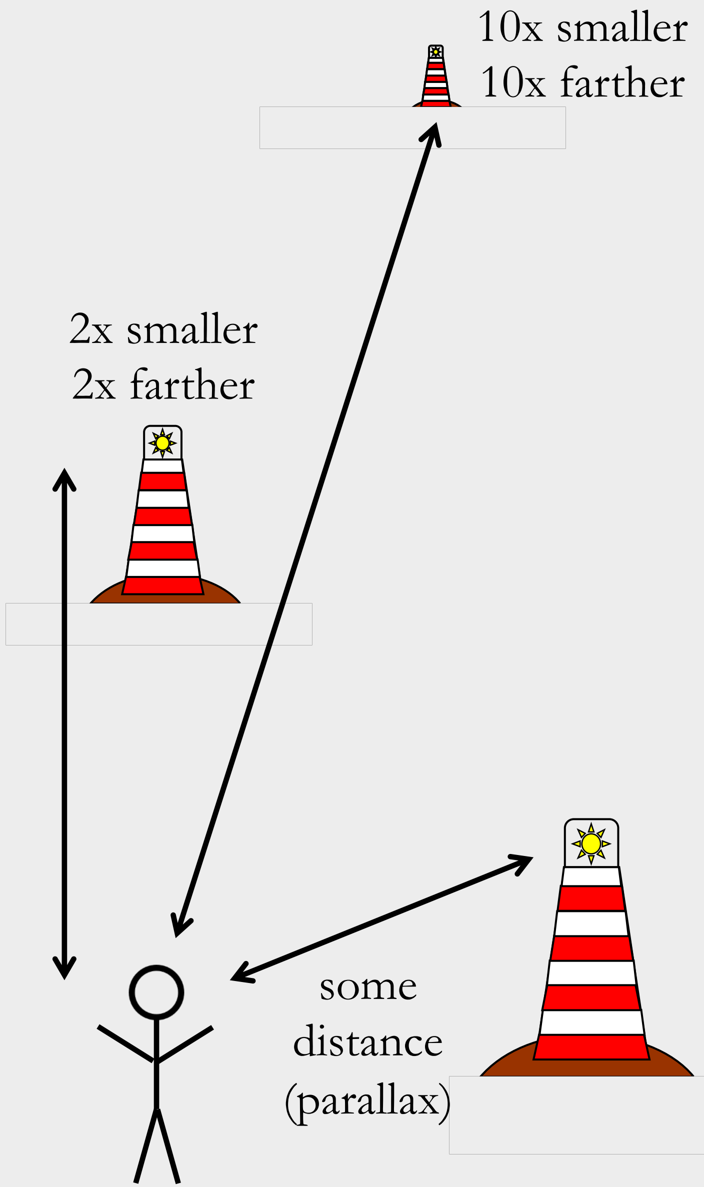

Leavitt's
Cepheids
Small Magellanic Cloud
Large Magellanic Cloud
Milky Way
© R. Smith/CTIO/AURA/NSF

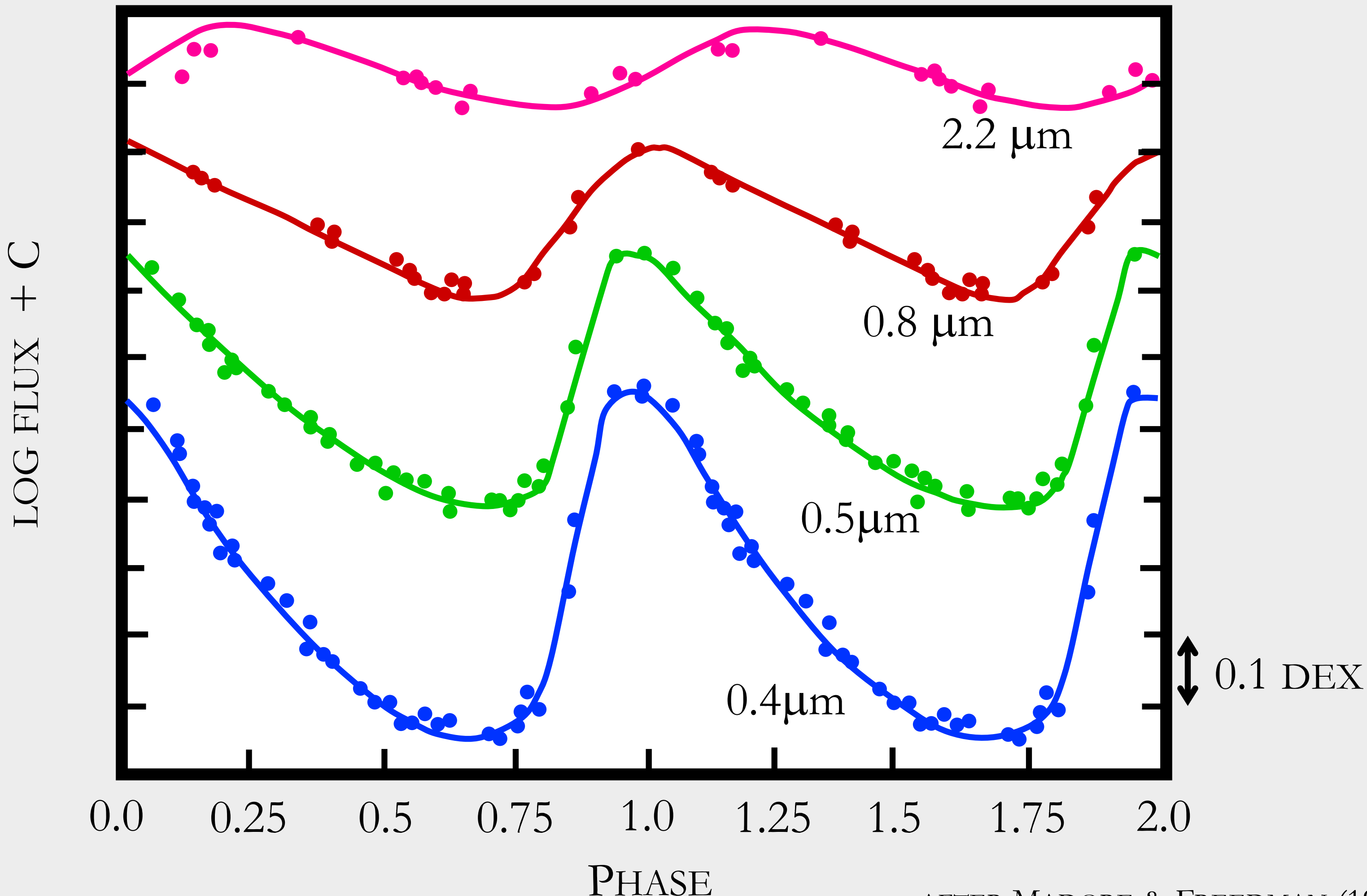
STANDARD CANDLES (AND RULERS!)

- Note also that (in this crude analogy) the <u>angular size</u> of the lighthouses can also be used as a distance indicator (assuming they were all built to the same specs)
- We refer to such techniques as "standard rulers"



"LIGHT CURVE" OF A CEPHEID

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



AFTER MADORE & FREEDMAN (1991)

"Light curve" of a Cepheid

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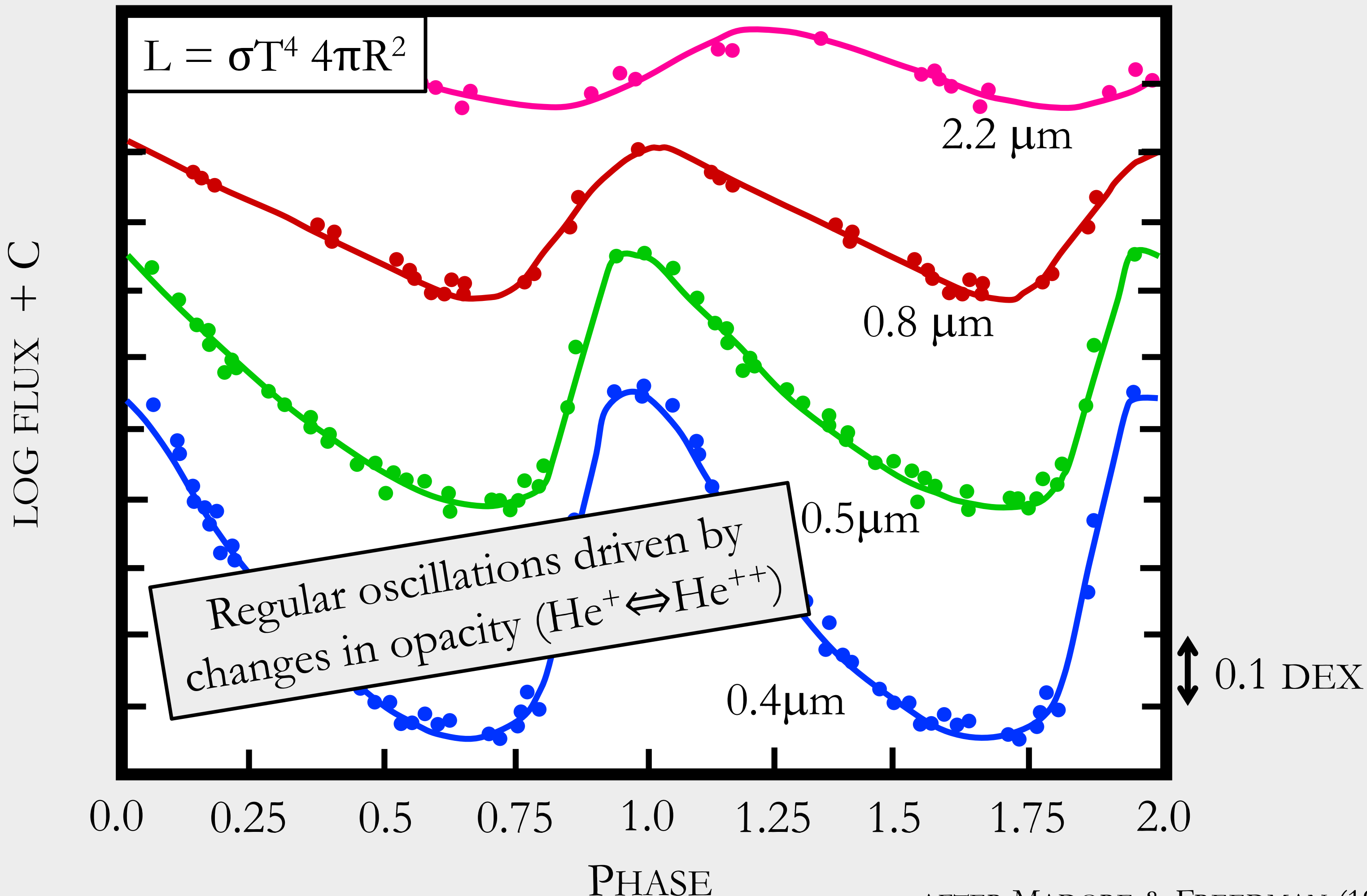
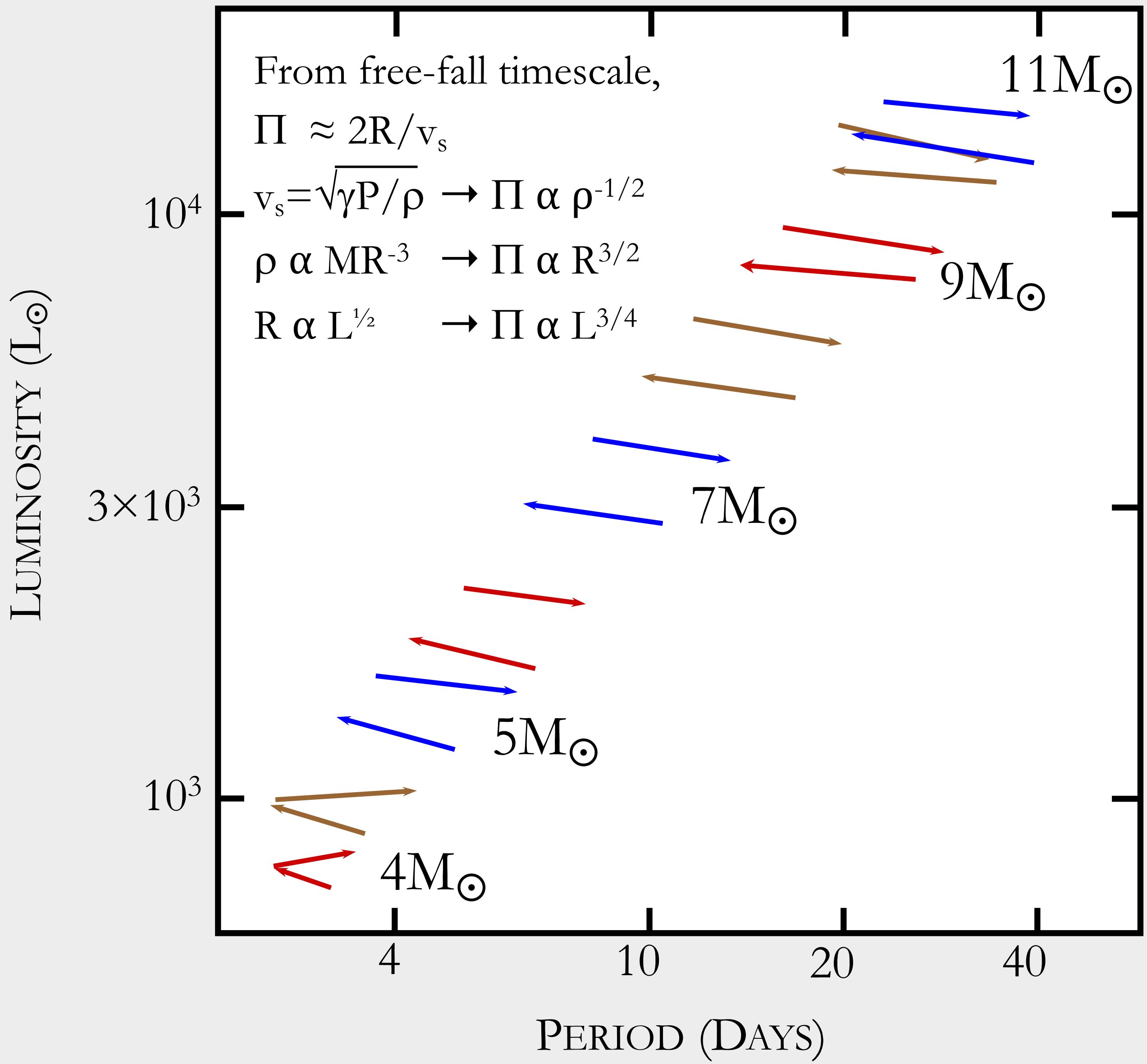


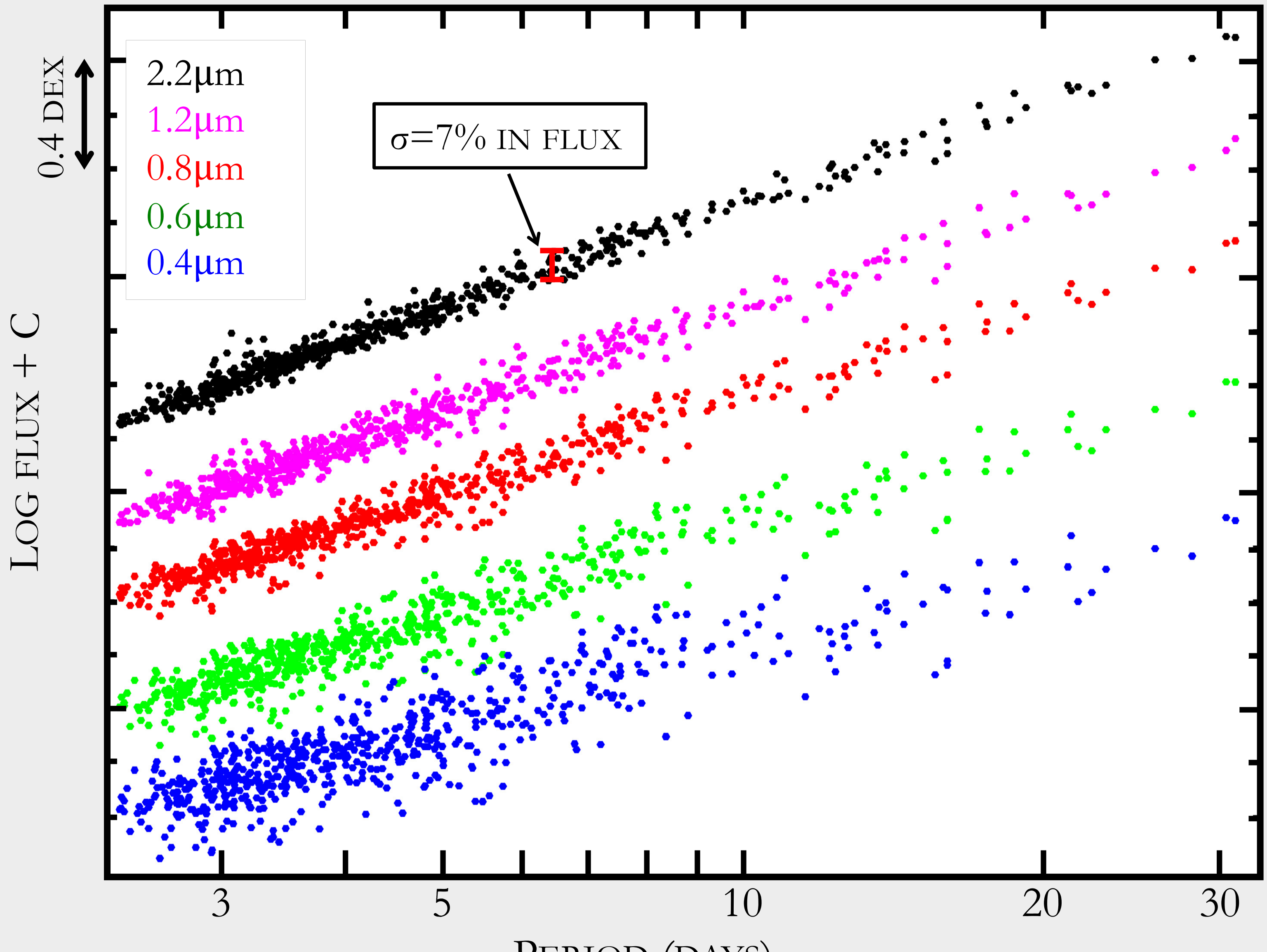
After Madore & Freedman (1991)

Theoretical P-L Relation



Alibert+ (1999)

"Leavitt law" in the LMC

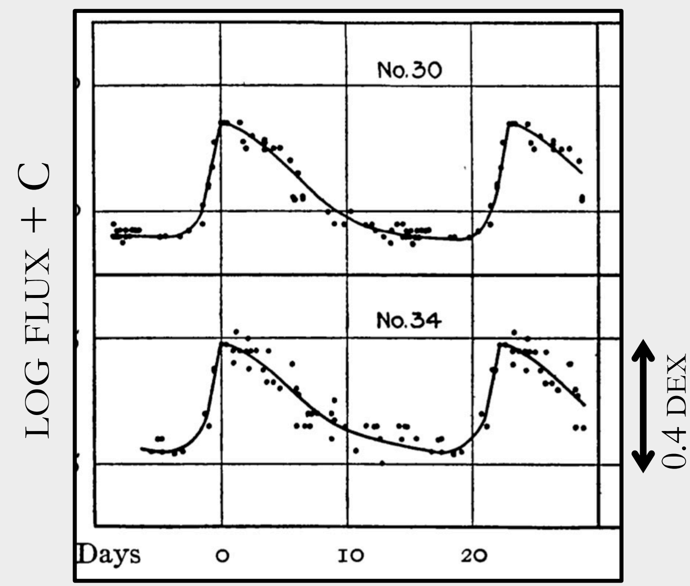


Udalski+ (1999); Macri+ (2015)

1925: Hubble & Cepheids

- Edwin Hubble discovers Cepheids within "spiral nebulae"
  - These nebulae are ~10× farther than the Magellanic Clouds
- The Universe becomes much larger… and full of "galaxies"!

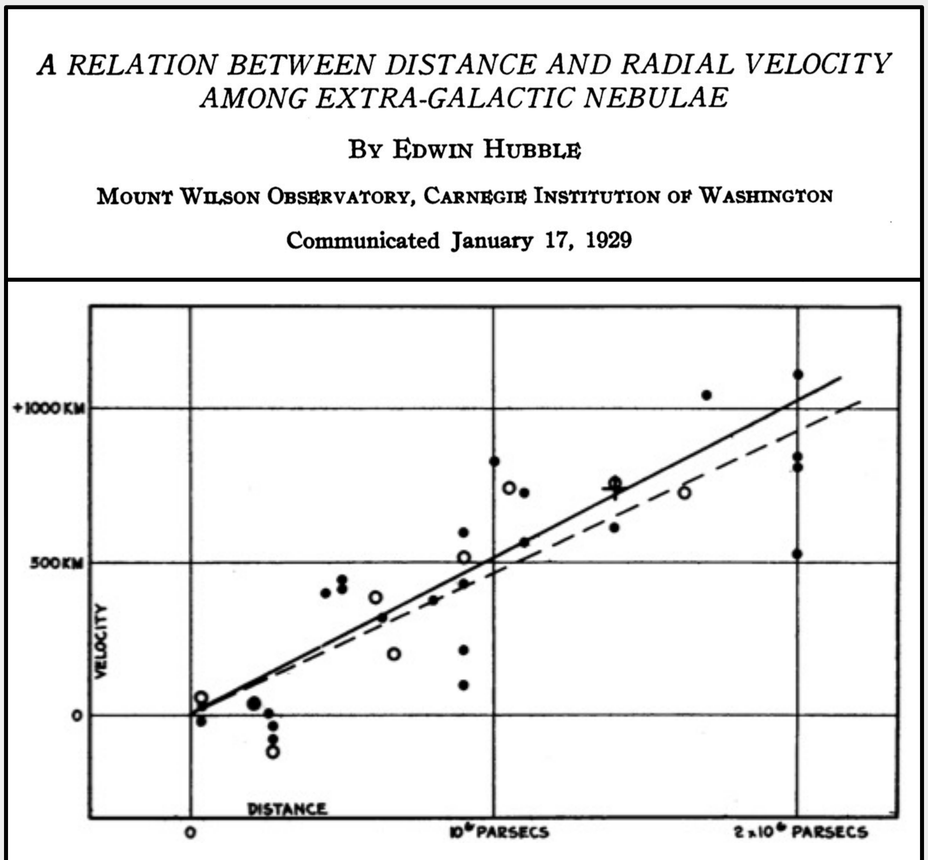
Light curves of Cepheids in Messier 33



1924-1929: An Expanding Universe

- Lundmark (1924), Lemaître (1927) and Hubble (1929) find relations between the distances to "nebulae" and Slipher's velocities: evidence for an expanding Universe

Velocities (from Slipher)

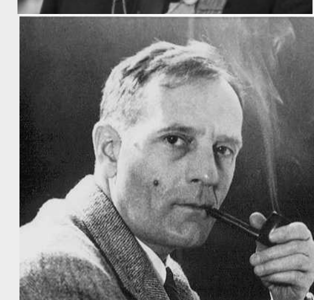

A RELATION BETWEEN DISTANCE AND RADIAL VELOCITY AMONG EXTRA-GALACTIC NEBULAE

By Edwin Hubble

Mount Wilson Observatory, Carnegie Institution of Washington

Communicated January 17, 1929

Distances (from Hubble)



1924-1929: An Expanding Universe

- We now refer to this relation as the "Hubble-Lemaître Law":

$$\boxed{V = H_0 D}$$

- Note that the "Hubble constant", H_0, has units of s^{-1}, so the age of the Universe is

$$\boxed{t_0 \approx 1/H_0}$$

- Hubble (1929): $t_0 \sim 2$ Gyr "±10%" [not quite…]

H_0 & Cosmology

- 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)

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

  - 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 equation, a solution of Einstein's General Relativity field equations

H_0 & COSMOLOGY

- These parameters are related via the Friedmann equation, a solution of Einstein's General Relativity field equations:

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

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

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

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

- Ω_m: matter (baryonic+dark)
- Ω_k: curvature
- Ω_r: relativistic species
- Ω_Φ: dark energy

H_0 & Cosmology

- These parameters are related via the Friedmann equation, a solution of Einstein's general relativity field equations:

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

$$\boxed{H = \frac{\dot{a}}{a}} \qquad \boxed{\Omega_m(z) \equiv \frac{\rho_m(z)}{\rho_{\mathrm{crit}}(z)}} \rightarrow \boxed{\rho_{\mathrm{crit}} = \frac{3H_0^2}{8\pi G}} \qquad \boxed{(1+z) \equiv a^{-1}}$$

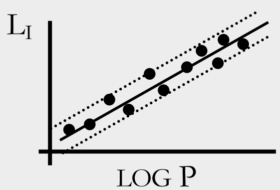
- Ω_m: matter (baryonic+dark)
- Ω_r: relativistic species
- Ω_k: curvature
- Ω_Φ: dark energy (Ω_Λ)
- z = v/c
- w: equation of state parameter of dark energy, $\boxed{P = w\rho c^2}$
- if w = -1, then dark energy becomes the "cosmological constant" Λ

OUTLINE

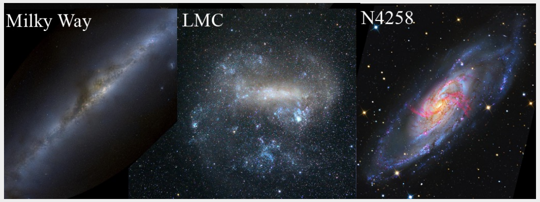
- ✓ Introduction
- ➢ **How to measure the Hubble constant to ~1%**
- Cosmological probes of the expansion
- New Physics in the dark sector?
- Next steps

Steps to the Hubble constant

$$\boxed{H_0 = v/d}$$



"Anchor" galaxies



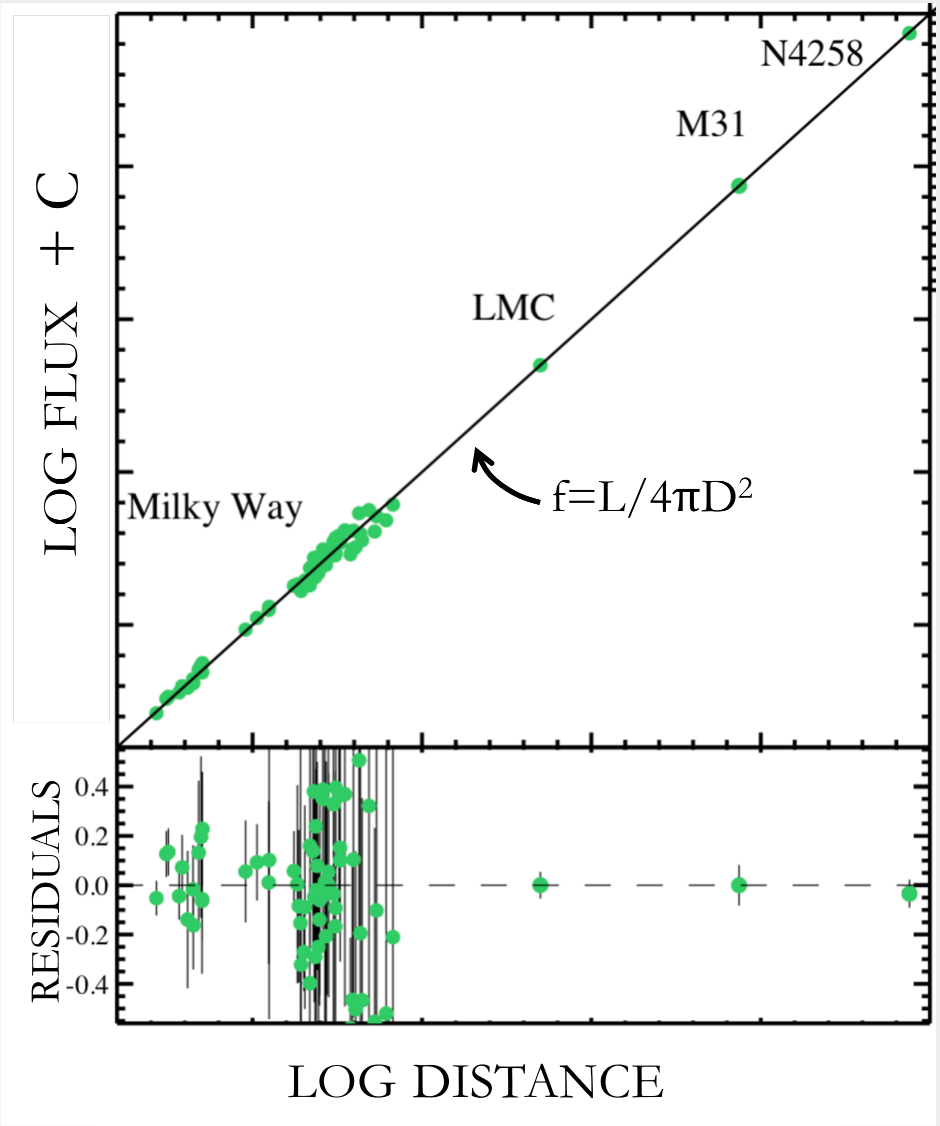
Well-characterized Cepheid samples

Accurate & precise distances

Cepheid Luminosities

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

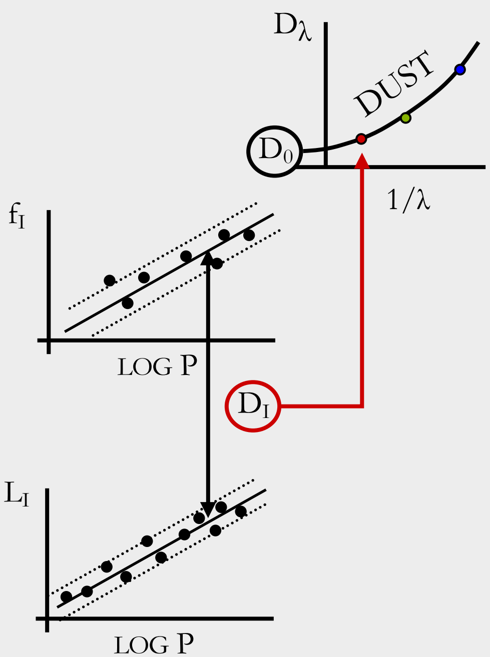
Cepheid Luminosities



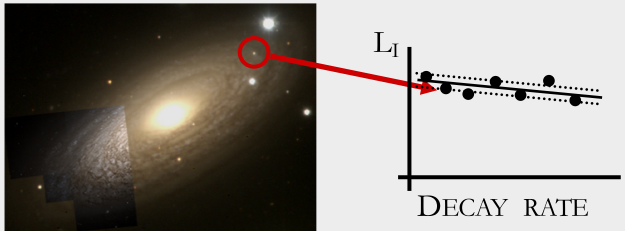
Based on Riess, Macri+ (2016)

Steps to the Hubble constant

$H_0 = V/D$



SN host galaxies
($D<10^{24}$ m)



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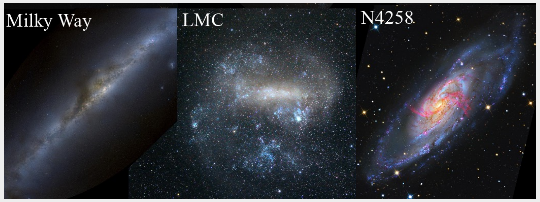
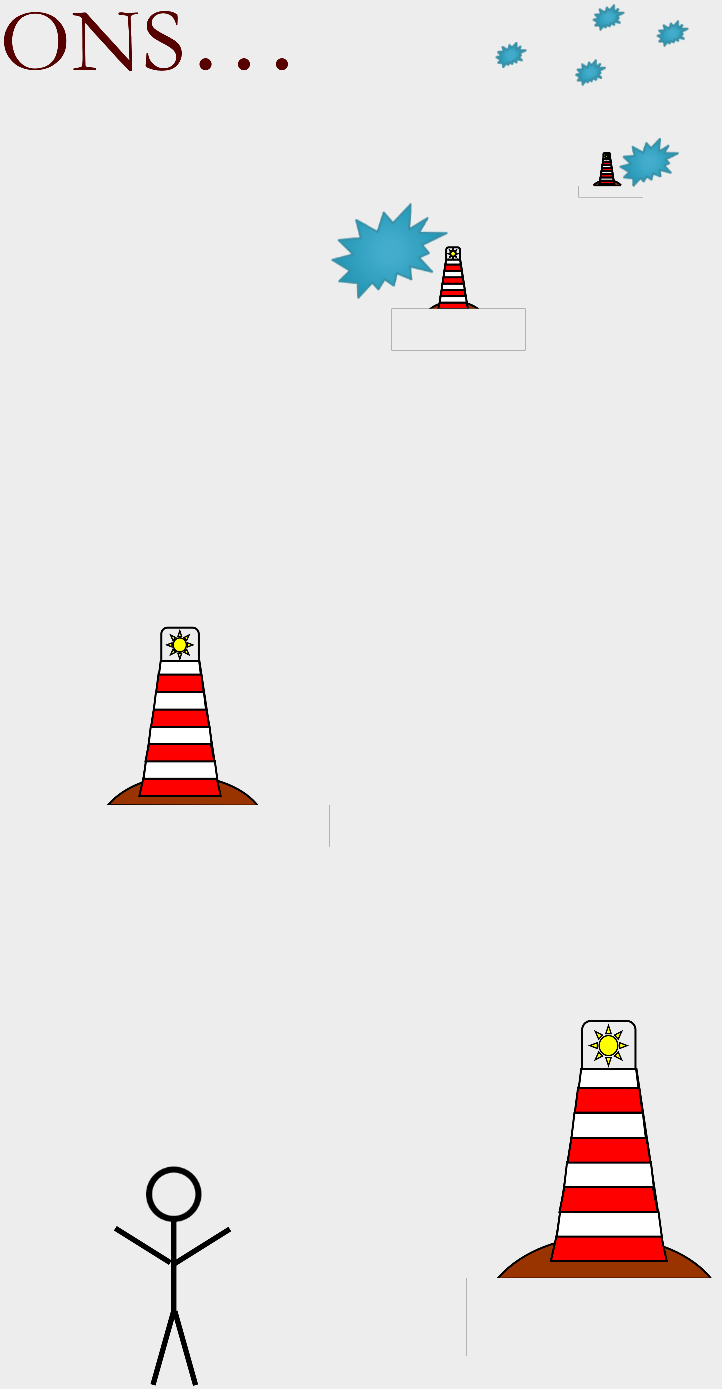


Well-characterized Cepheid samples

Accurate & precise distances

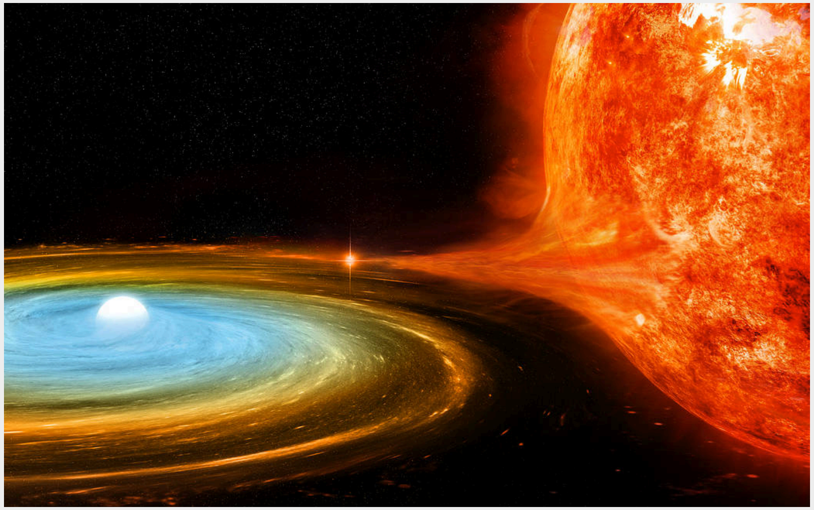
COMPLICATIONS…

- As the ocean "expands", all islands are moving randomly at small speeds
- These "peculiar motions" become irrelevant at larger distances → measure the expansion rate using the farthest islands
- Lighthouses become too dim to be useful, but (thankfully!) nuclear explosions go off in some of the islands…

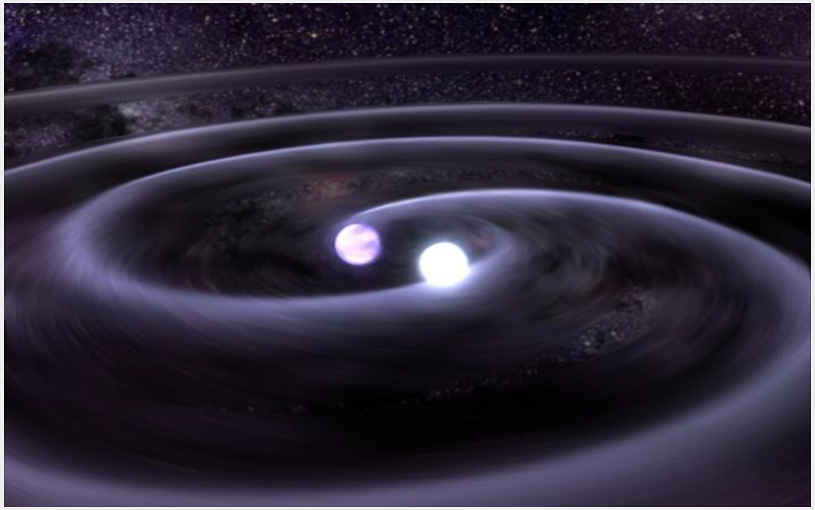


White Dwarf Supernovae

- Earth-sized degenerate C/O stellar core reaches $\sim 1.4 M_\odot$
  - Nature of "donor" unknown (merger of 2 white dwarfs, companion star)
  - $T_{max} > 5 \times 10^9$ K $\rightarrow$ nuclear statistical equilibrium $\rightarrow \sim 0.4\ M_\odot\ ^{56}Ni$
- Excellent secondary distance indicator (single SN $\rightarrow \pm 7\%$)
  - 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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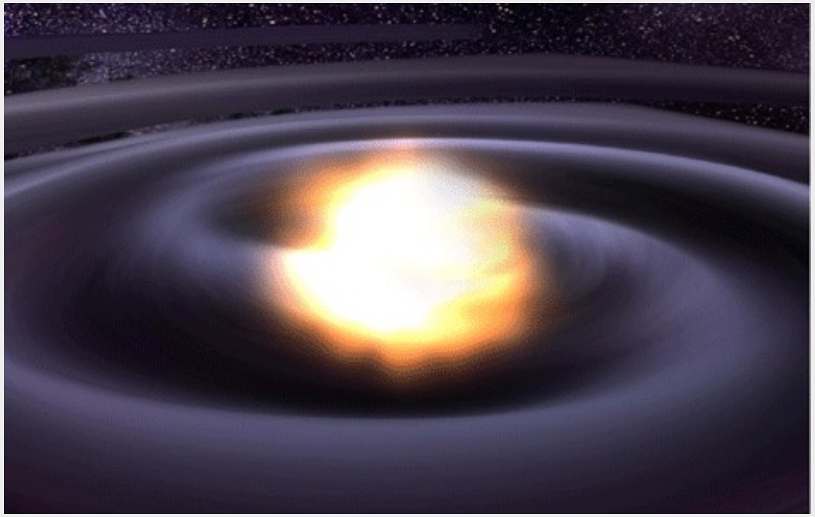
ESA/C. Carreau



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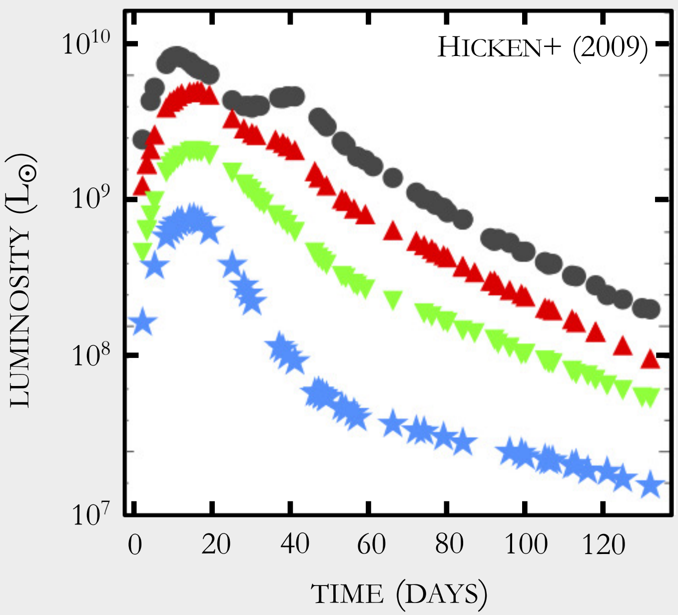

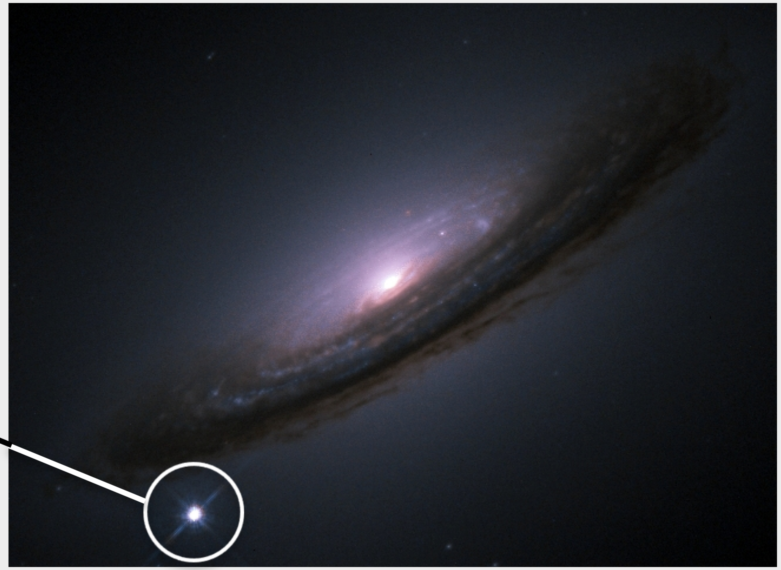

NASA/ESA/High-Z Supernova Search Team

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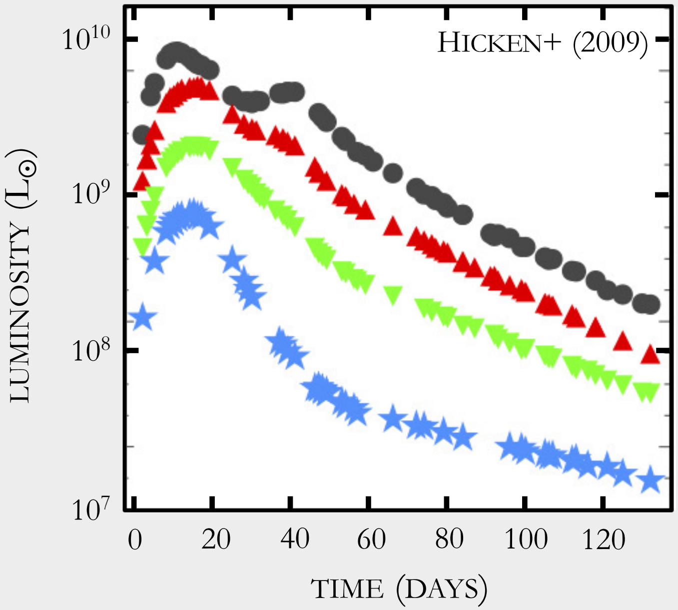
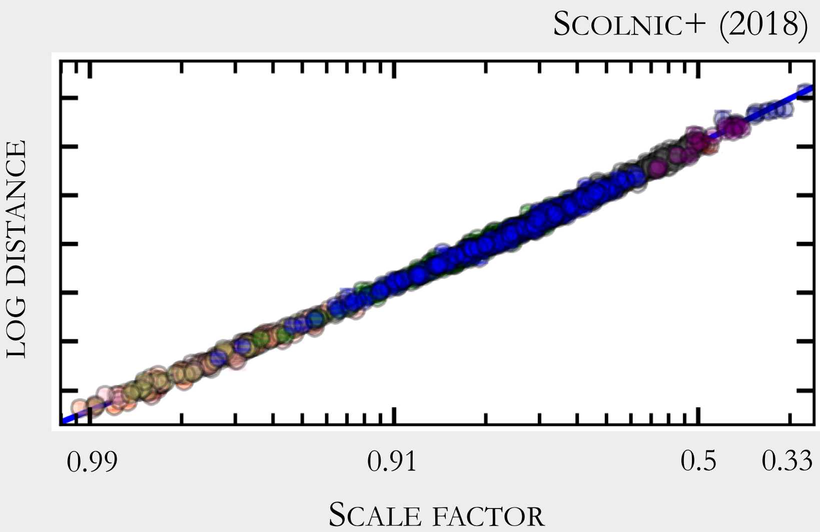
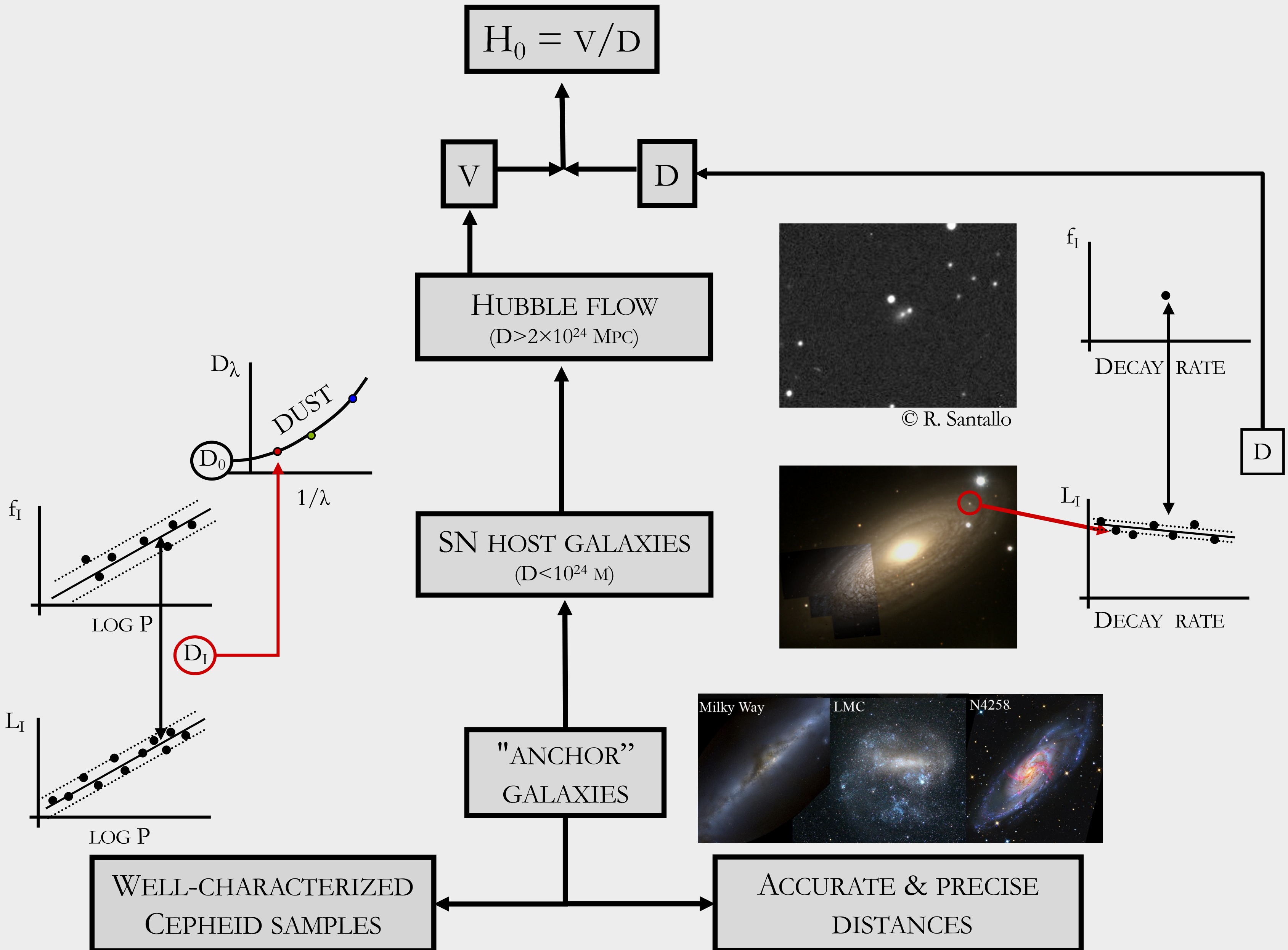




Steps to the Hubble constant



The SH$_0$ES project

- Started in 2005 by Riess, Macri & collaborators to reduce uncertainty in H_0 (10% at the time) by using:
  - Only geometric distance indicators
    - Milky Way (π's): HST+*Hipparcos* (Benedict+2007; v. Leeuwen+2007)
    - NGC 4258 (masers): D=7.54 Mpc ±3% (Humphreys+ 2008)
  - Only modern & ideal SNe Ia (N = 2 → 6)
    - Photoelectric or CCD photometry; low reddening; observed pre-max
  - Single telescope (HST) & cameras, focusing on near-infrared (less affected by interstellar dust & variations in chem abundance)
    - Optical: second & third-gen cameras
    - Near-infrared: first-gen camera
- Results: $\sigma(H_0)$=4.8% (Riess, Macri+ 2009)

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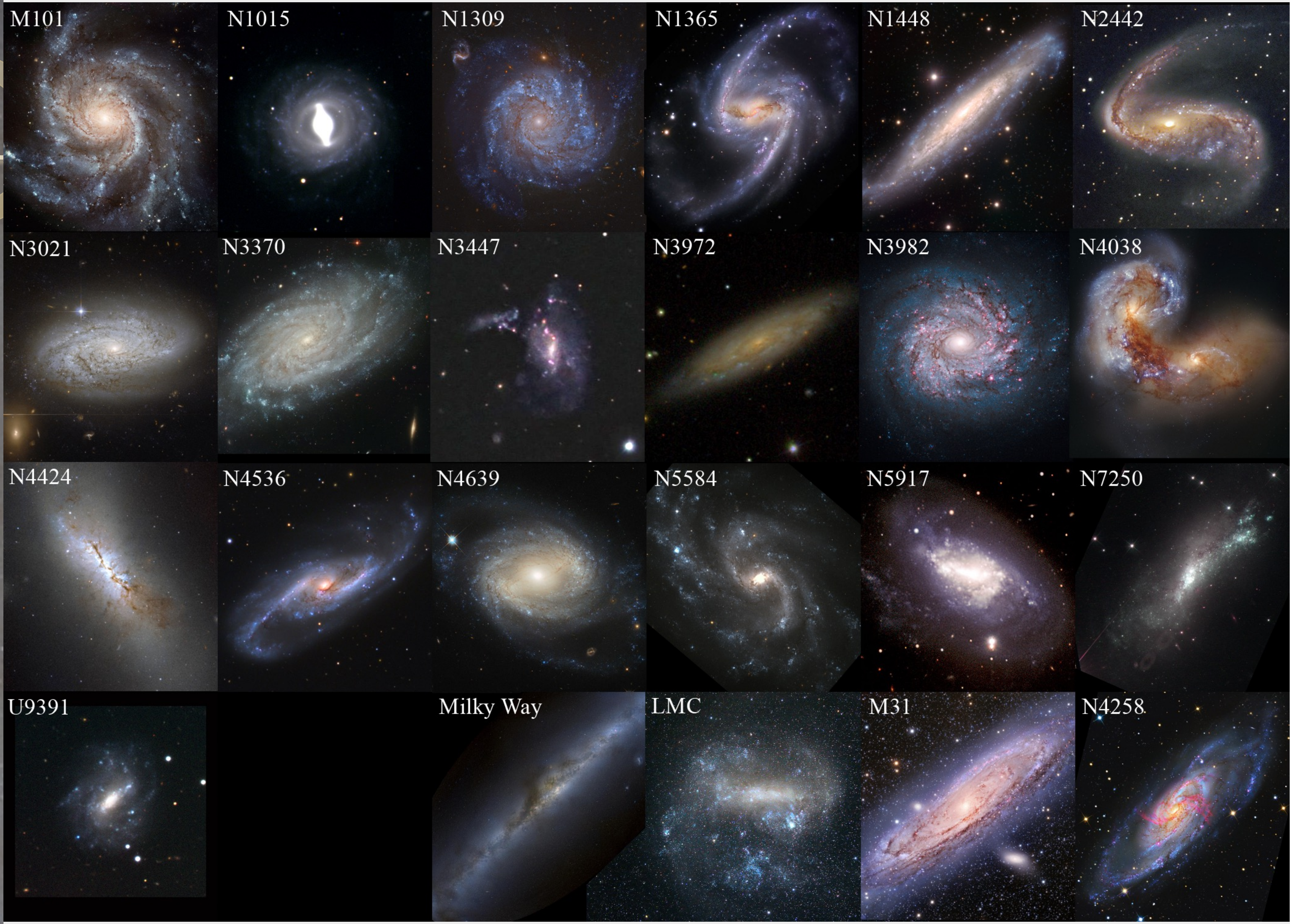
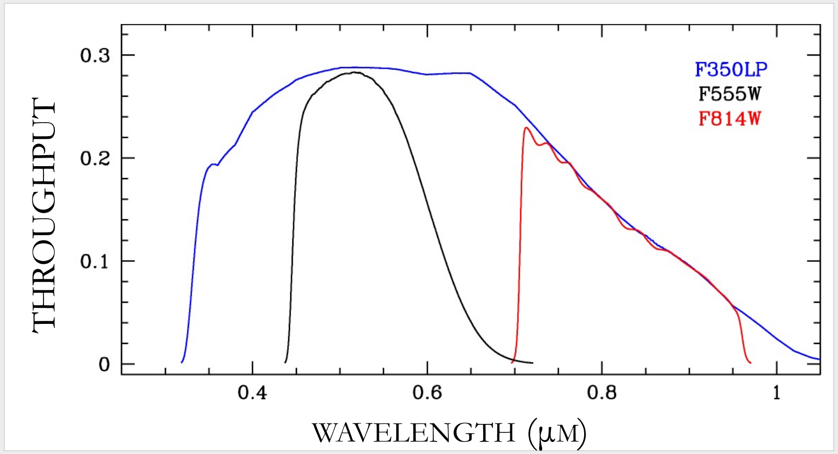
    - Milky Way (π's): HST/FGS+*Hipparcos* → HST/WFC3 (Riess+2014)
    - LMC (eclipsing binaries): D=50 kpc ±2.2% (Pietrzynski+ 2013)
    - NGC 4258 (masers): D=7.54 Mpc ±2.6% (Humphreys+ 2013)
  - Only modern & ideal SNe Ia (N = 2 → 6, 8, 19)
    - Photoelectric or CCD photometry; low reddening; observed pre-max
  - Single telescope (HST) & cameras, focusing on near-infrared (less affected by interstellar dust & variations in chem abundance)
    - Optical: → third- & fourth-gen cameras
    - Near-infrared: → second-gen camera
- Results: $\sigma(H_0)$=4.8, 3.3, 2.4% (Riess, Macri+ 2009, 11, 16)

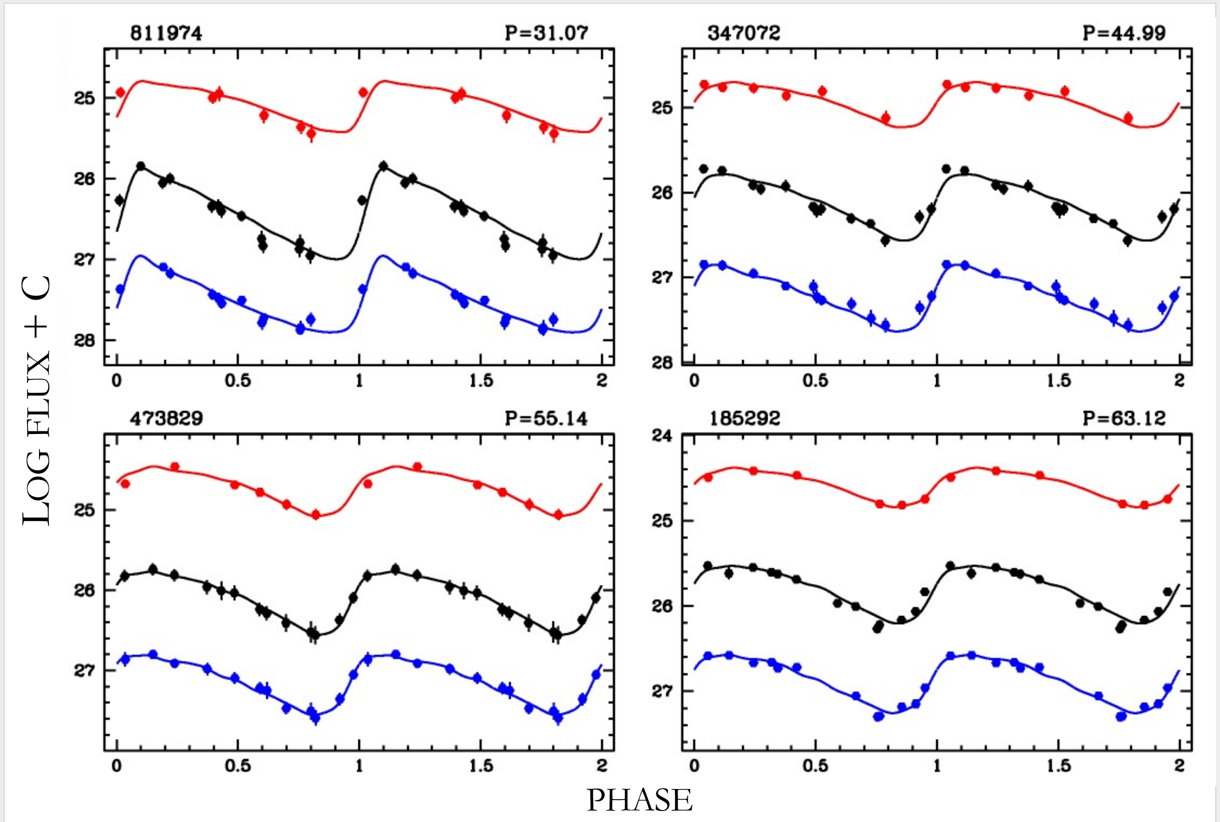
SH0ES ANCHORS & SN HOST GALAXIES



RIESS, MACRI, HOFFMANN+ (2016)

SH$_0$ES HST/WFC3 PHOTOMETRY

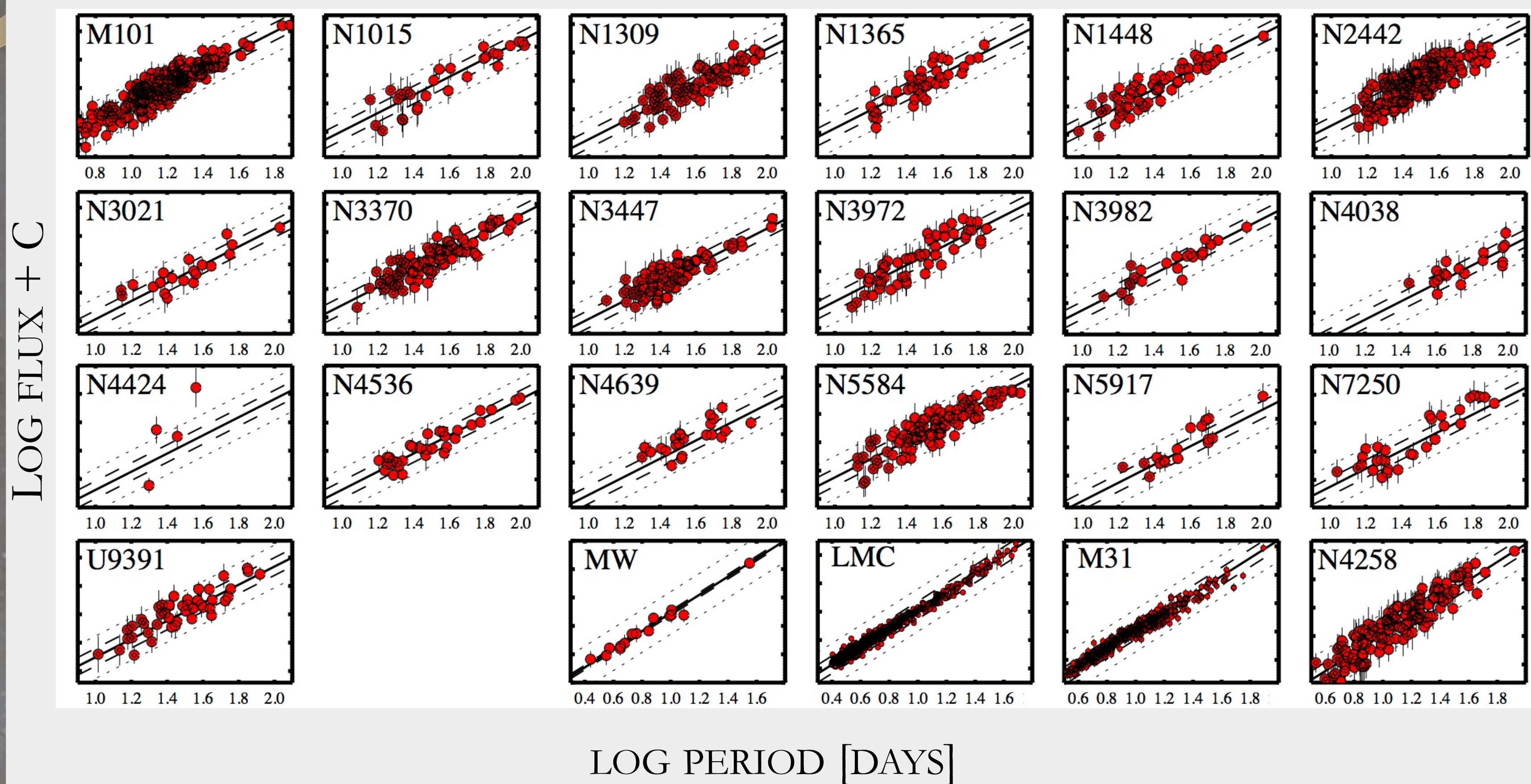




HOFFMANN, MACRI, RIESS+ (2016)

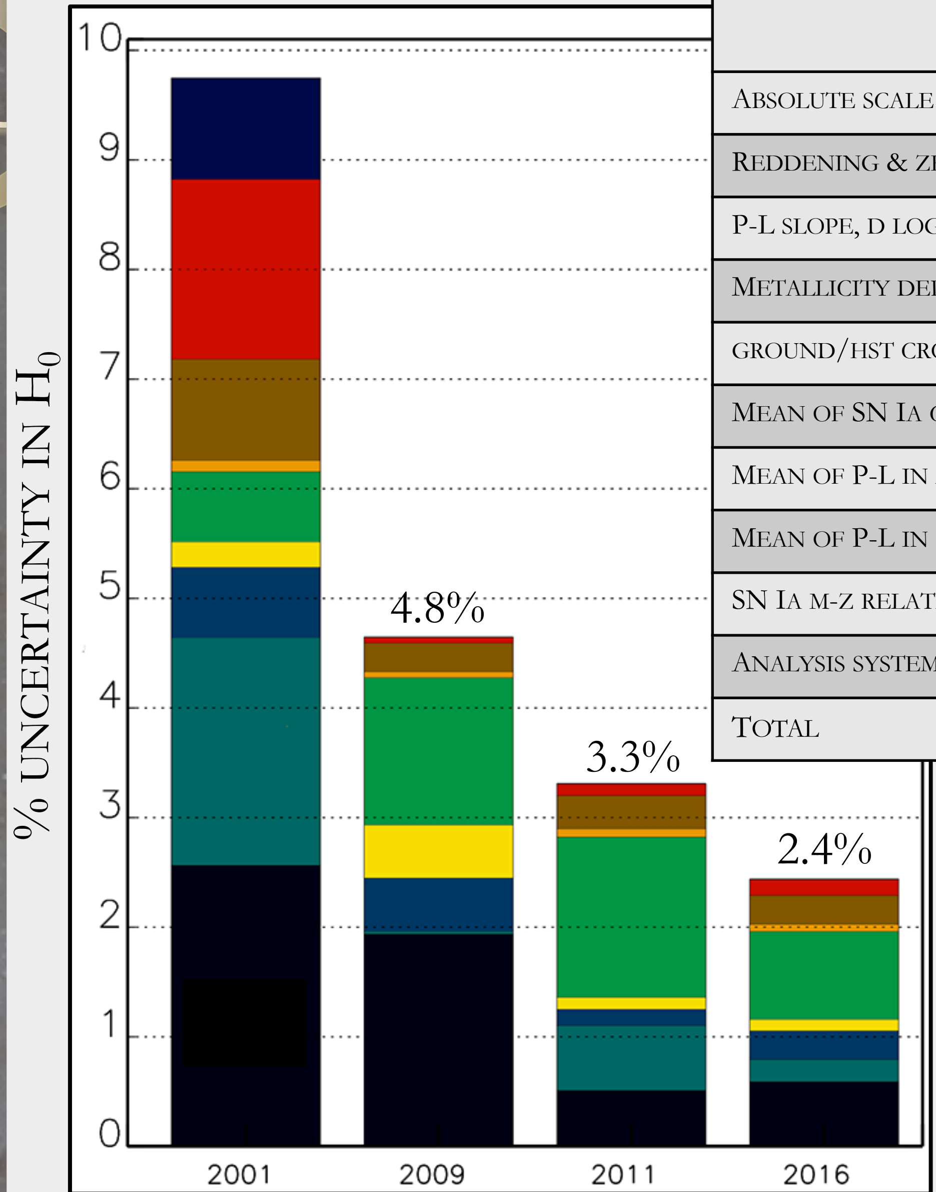
“LEAVITT LAWS” IN SH$_0$ES GALAXIES

2300 Cepheids with homogeneous near-infrared photometry enable a 2.4% determination of H_0



RIESS, MACRI, HOFFMANN+ (2016)

Error budget for H_0



Term	KP	'09	'11	'16
	%			
Absolute scale	5.0	3.0	1.3	1.3
Reddening & zeropoints (anchor-to-hosts)	4.5	0.3	1.4	0.7
P-L slope, d log P (anchor-to-hosts)	4.0	0.5	0.6	0.5
Metallicity dependence (anchor-to-hosts)	3.0	1.1	1.0	0.8
Ground/HST cross-calibration	3.0	--	--	--
Mean of SN Ia calibrators	2.5	2.5	1.9	1.3
Mean of P-L in anchor(s)	2.5	1.5	0.8	0.7
Mean of P-L in SN hosts	1.5	1.5	0.6	0.4
SN Ia m-z relation	1.0	0.5	0.4	0.4
Analysis systematics	??	1.3	1.0	0.9
Total	10	4.8	3.3	2.4

All sources of uncertainty fully propagated using matrix approach

Riess, Macri+ (2009, 2011, 2016)

Perform simultaneous fit to retain interdependence of data and parameters

Measurements

Cepheids in SN hosts

Cepheids in Anchors

SN Ia

Geometric Distance Priors

$$\begin{pmatrix} m^W_{H,1,j} \\ .. \\ m^W_{H,18,j} \\ m^W_{H,j,N4258} - \mu_{0,N4258} \\ m^W_{H,M31,j} \\ m^W_{H,MW,j} - \mu_{\pi,j} \\ m^W_{H,LMC,j} - \mu_{0,LMC} \\ m^0_{B,1} \\ .. \\ m^0_{B,18} \\ 0 \\ 0 \\ 0 \end{pmatrix} =$$

Regression Matrix

$$\begin{pmatrix}
1 & .. & 0 & 0 & 1 & 0 & 0 & \log P^h_{18,1}/0 & 0 & [\mathrm{O/H}]_{18,1} & 0 & \log P^l_{18,1}/0 \\
.. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. & .. \\
0 & .. & 1 & 0 & 1 & 0 & 0 & \log P^h_{18,j}/0 & 0 & [\mathrm{O/H}]_{18,j} & 0 & \log P^l_{18,j}/0 \\
0 & .. & 0 & 1 & 1 & 0 & 0 & \log P^h_{N4258,j}/0 & 0 & [\mathrm{O/H}]_{N4258,j} & 0 & \log P^l_{N4258,j}/0 \\
0 & .. & 0 & 0 & 1 & 0 & 1 & \log P^h_{M31,j}/0 & 0 & [\mathrm{O/H}]_{M31,j} & 0 & \log P^l_{M31,j}/0 \\
0 & .. & 0 & 0 & 1 & 0 & 0 & \log P^h_{MW,j}/0 & 0 & [\mathrm{O/H}]_{MW,j} & 1 & \log P^l_{MW,j}/0 \\
0 & .. & 0 & 0 & 1 & 1 & 0 & \log P^h_{LMC,j}/0 & 0 & [\mathrm{O/H}]_{MW,j} & 1 & \log P^l_{LMC,j}/0 \\
1 & .. & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & .. & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & .. & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & .. & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & .. & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0
\end{pmatrix}$$

Free Parameters

$$* \begin{pmatrix} \mu_{0,1} \\ .. \\ \mu_{0,18} \\ \Delta\mu_{\mathrm{N4258}} \\ M^W_{H,1} \\ \Delta\mu_{\mathrm{LMC}} \\ \mu_{M31} \\ b \\ M^0_B \\ Z_W \\ \Delta\mathrm{zp} \\ b_l \end{pmatrix}$$

Absolute Host Distances

ΔD (N4258)

Cepheid Luminosity

ΔD(LMC)

ΔD(M31)

P-L slope (P>10 days)

SN Ia Luminosity

Metallicity, Cepheid

Zeropoint, LMC

P-L slope (P<10 days)

Error Matrix

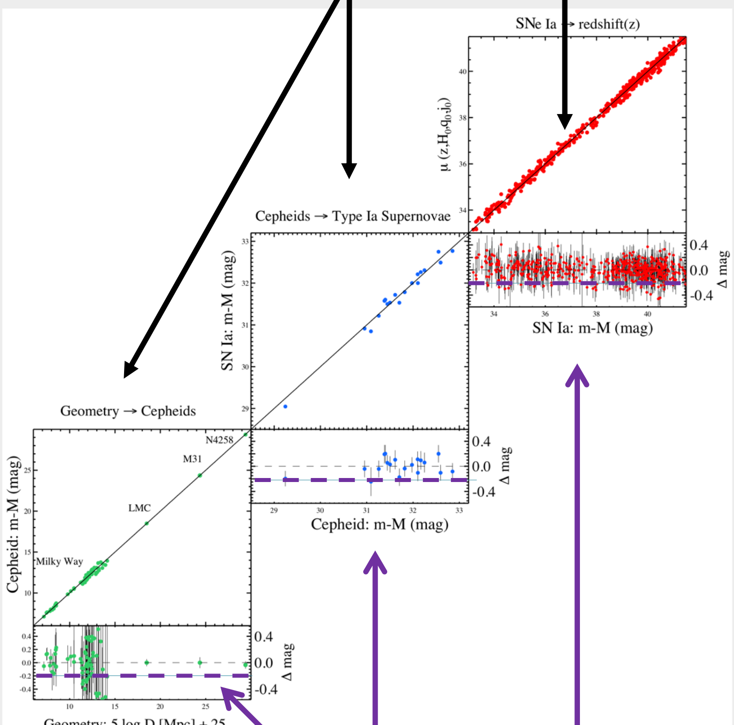
$[\sigma^2_{tot,1,j}, .. \sigma^2_{tot,19,j}, \sigma^2_{tot,N4258,j}, \sigma^2_{tot,M31,j}, \sigma^2_{tot,MW,j} + \sigma^2_{\pi,j}, \sigma^2_{tot,LMC,j}, \sigma^2_{mB,1}, .. \sigma^2_{mB,19}, \sigma^2_{zp}, \sigma^2_{\mu,N4258}, \sigma^2_{\mu,LMC}]$

$$5 \log H_0 = M_B^0 + 5 a_B + 25$$

23 ANALYSIS VARIANTS, PROPAGATE VARIATION TO ERROR

Best Fit:

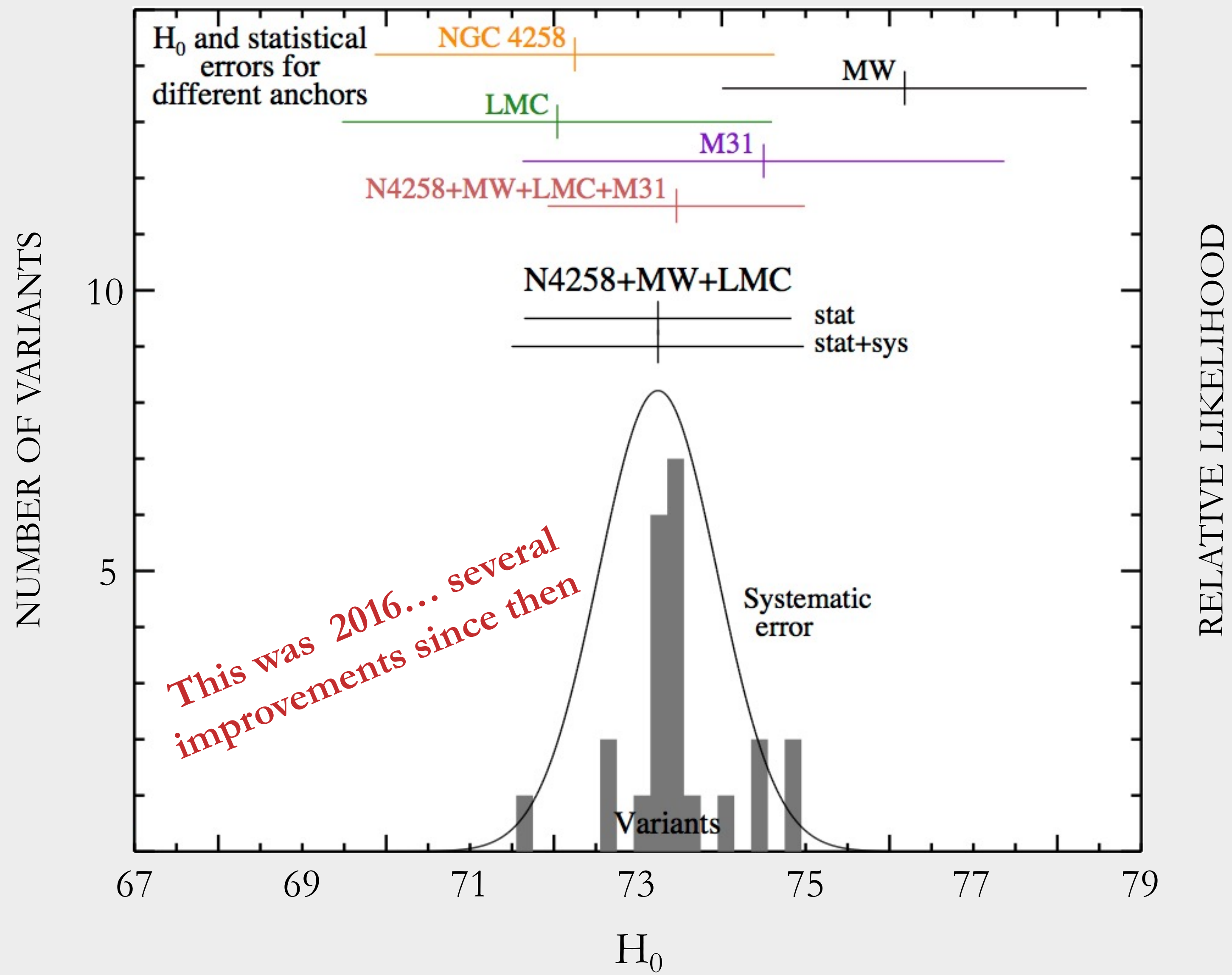
$$5\log H_0 = M_B^0 + 5a_B + 25$$



Planck +ΛCDM
Δ=0.20 mag

Analysis Variants	H_0
Best Fit (2019)	73.5
Reddening Law: LMC-like (R_V=2.5, not 3.3)	73.4
Reddening Law: Bulge-like (N15)	73.9
No Cepheid Outlier Rejection (normally 2%)	73.8
No Correction for Cepheid Extinction	75.2
No Truncation for Incomplete Period Range	74.6
Metallicity Gradient: None (normally fit)	74.0
Period-Luminosity: Single Slope	73.8
Period-Luminosity: Restrict to P>10 days	73.7
Period-Luminosity: Restrict to P<60 days	74.1
Supernovae z>0.01 (normally z>0.023)	73.7
Supernova Fitter: MLCS (normally SALT)	75.4
Supernova Hosts: Spiral (usually all types)	73.6
Supernova Hosts: Locally Star Forming	73.8
Optical Cepheid Data only (no NIR)	72.0

INCLUSION OF "ANALYSIS SYSTEMATICS"



RIESS, MACRI+ (2016)

The SH$_0$ES Project

- Started in 2005 by Riess, Macri & collaborators to reduce uncertainty in H$_0$ (10% at the time) by using:
  - Only geometric distance indicators
    - Milky Way (parallaxes): HST+*Hipparcos* → HST+*Gaia* (Riess+2021)
    - LMC (eclipsing binaries): D=50 kpc ±1.1% (Pietrzynski+ 2019)
    - NGC 4258 (masers): D=7.58 Mpc ±1.5% (Reid, Pesce & Riess 2019)
  - Only modern & ideal SNe Ia (N = 2 → 6, 8, 19)
    - Photoelectric or CCD photometry; low reddening; observed pre-max
  - Single telescope (HST) & cameras, focusing on near-infrared (less affected by interstellar dust & variations in chem abundance)
    - Optical: → third- & fourth-gen cameras
    - Near-infrared → second-gen cameras
- Current uncertainty in SH$_0$ES ladder: 1.8%

OUTLINE

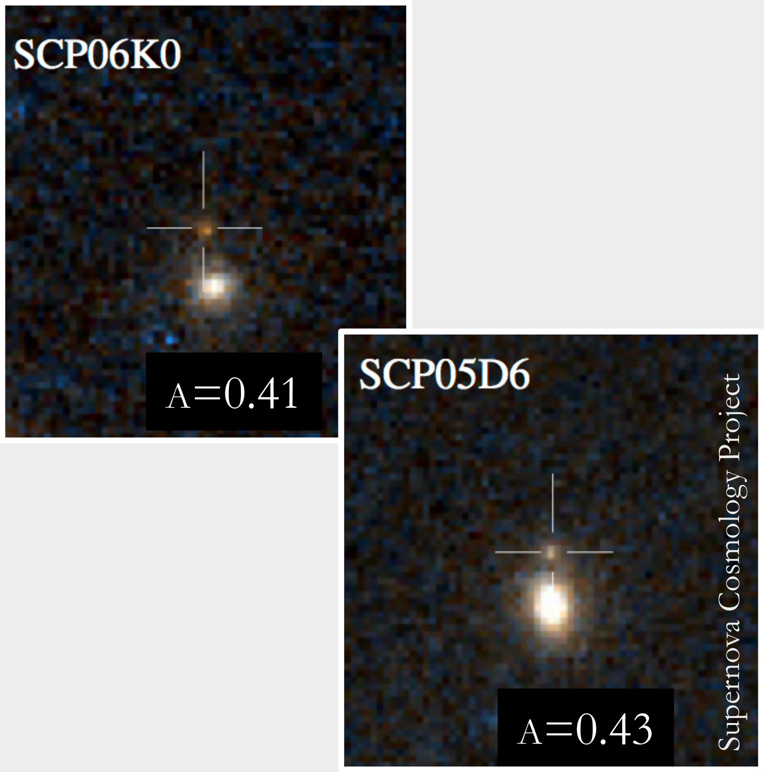
- ✓ Introduction
- ✓ How to measure the Hubble constant to ~1%
- ➢ **Cosmological probes of the expansion**
- New Physics in the dark sector?
- Next steps

Cosmological Probes

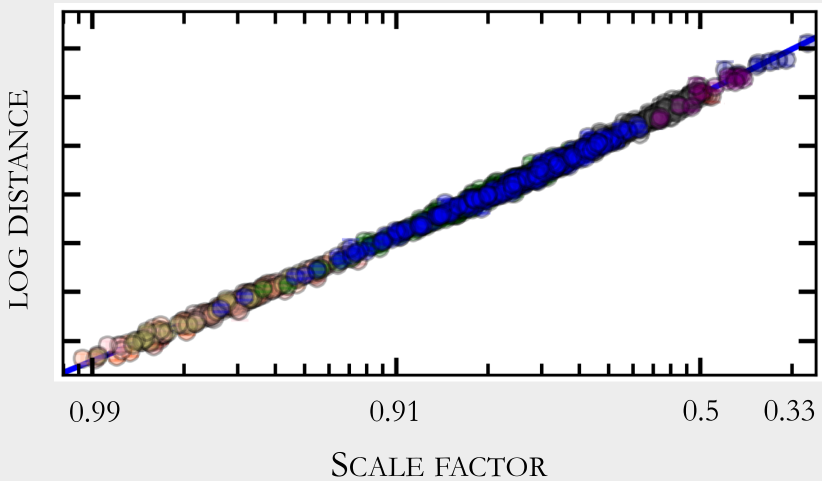
- ✓ Hubble constant
- White-dwarf supernovae
- Cosmic microwave background anisotropies
- Baryon acoustic oscillations
- Others (weak gravitational lensing, clusters of galaxies)
- Each one constrains different cosmological parameters
  → combine as many probes as possible

White-dwarf supernovae

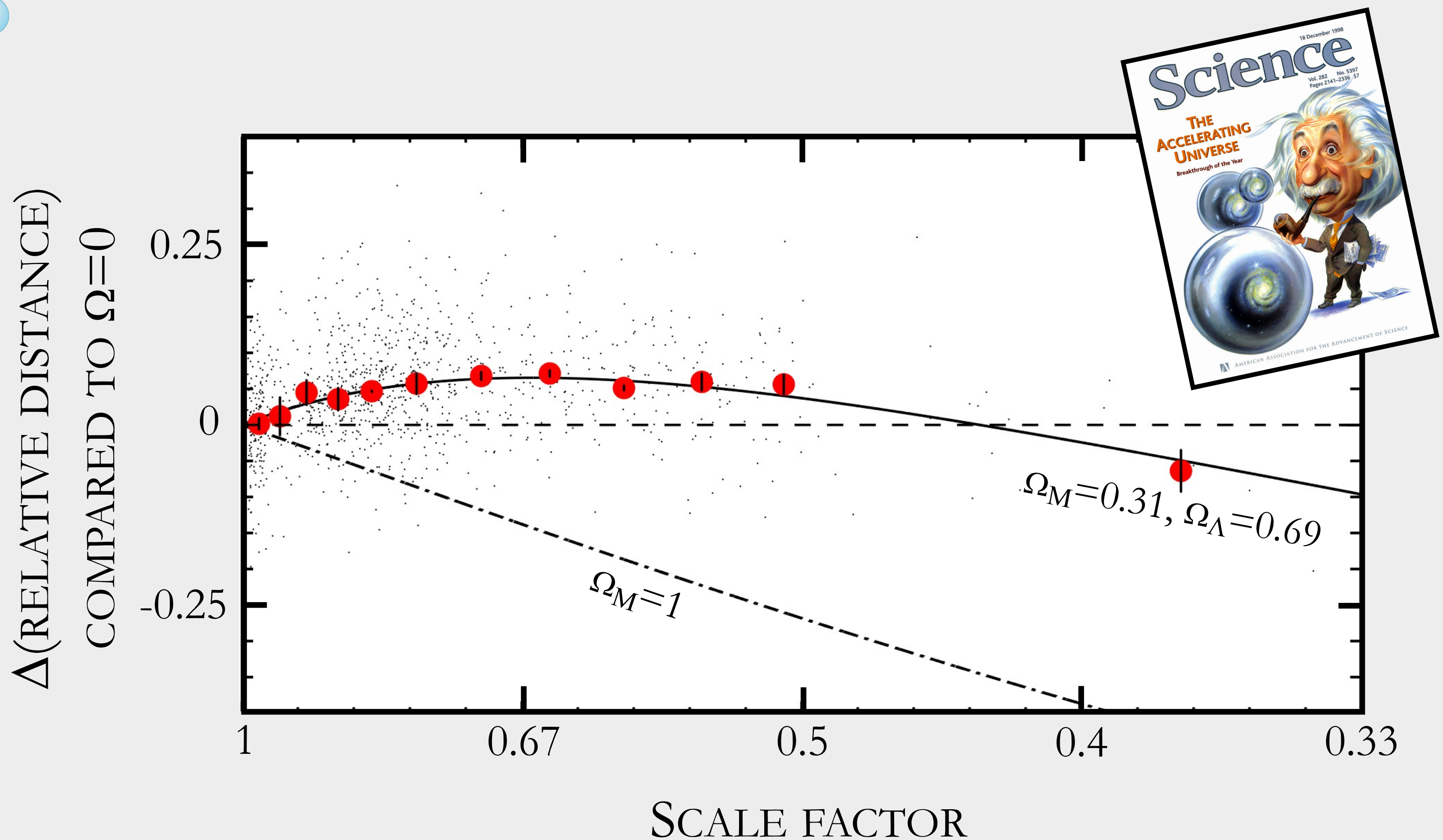
- Peak luminosity of white-dwarf SNe = $3.9\times10^{9}\ L_{\odot}$ (±2.5%)
- Trace expansion of the Universe for ~10 Gyr (75% of its age)
  - Using *Hubble* and the largest ground-based telescopes



Scolnic+ (2018)



SNe Ia: Universe dominated by dark energy & dark matter



Riess+ (1998); Perlmutter+ (1999)

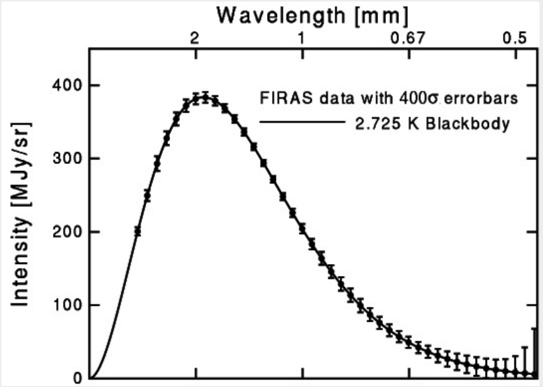
Scolnic+ (2018)

Cosmic Microwave Background

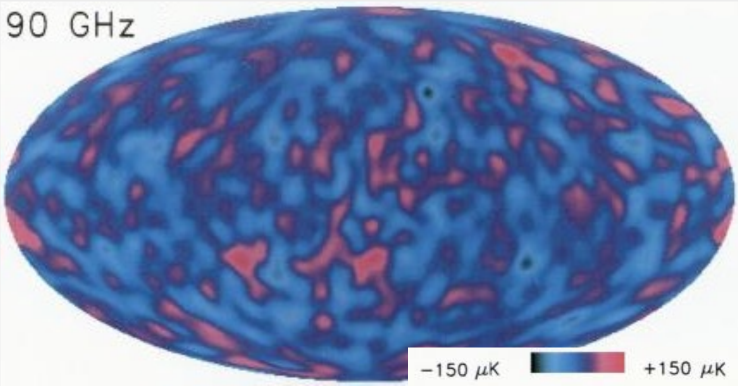
- Primordial gas of Big Bang is completely ionized
  - Coupling of photons & electrons via Compton scattering
- Initial density fluctuations
  - Dark matter begins to collapse
  - Photon-baryon fluid undergoes acoustic oscillations
- ~379,000 yrs later… $e^- + p^+ \rightarrow H + \gamma$
  - Photons decouple and can now travel freely
- Density fluctuations → temperature "anisotropies"
  - Angular power spectrum ↔ cosmological parameters

Cosmic Microwave Background

- 1994: COBE → CMB blackbody & detection of anisotropy

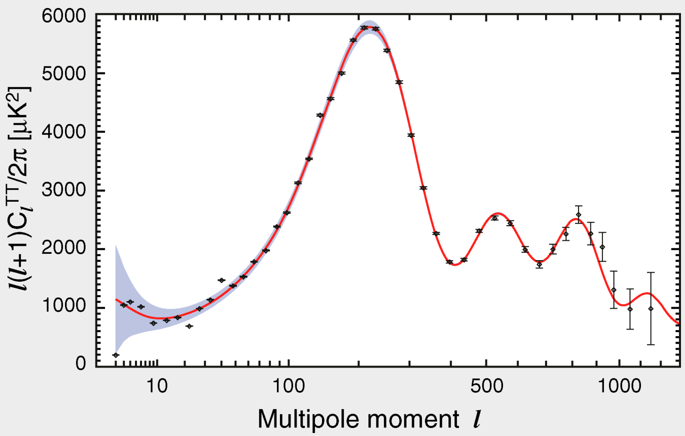


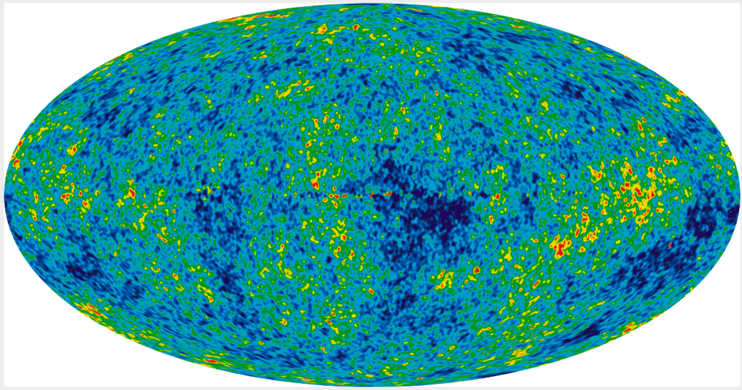
Mather+ (1994)



Bennett+ (1994)

- 2002: WMAP → angular power spectrum of anisotropies

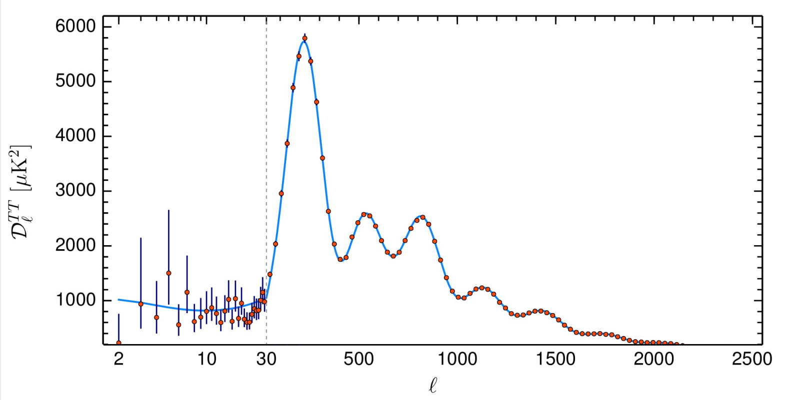


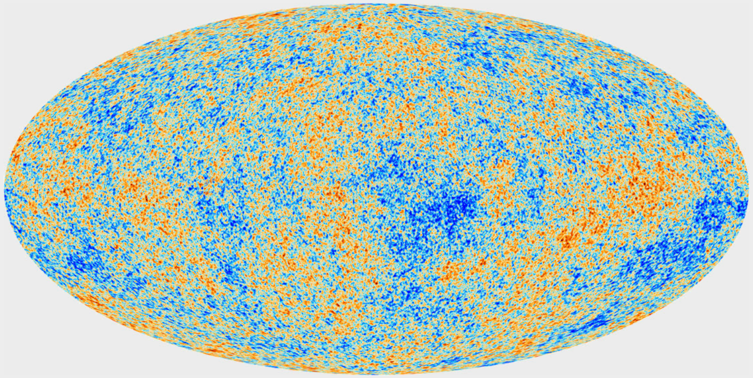


Jarosik+ (2011); Larson+ (2011)

Cosmic Microwave Background

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

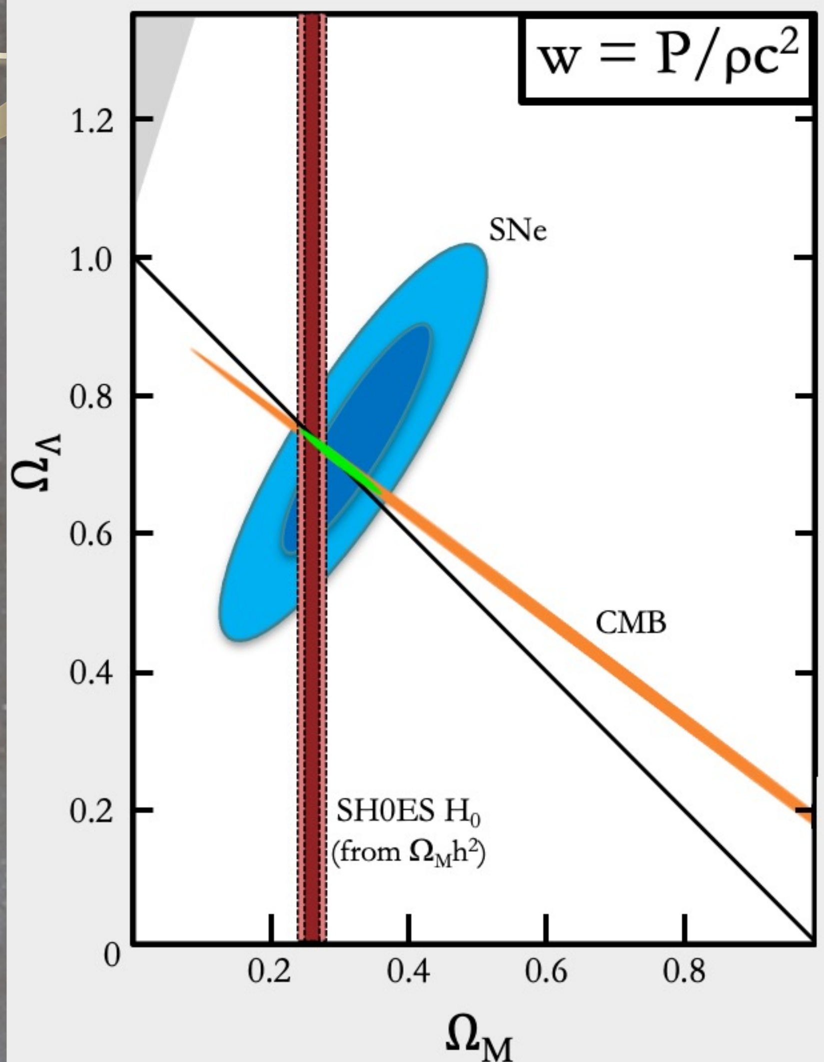




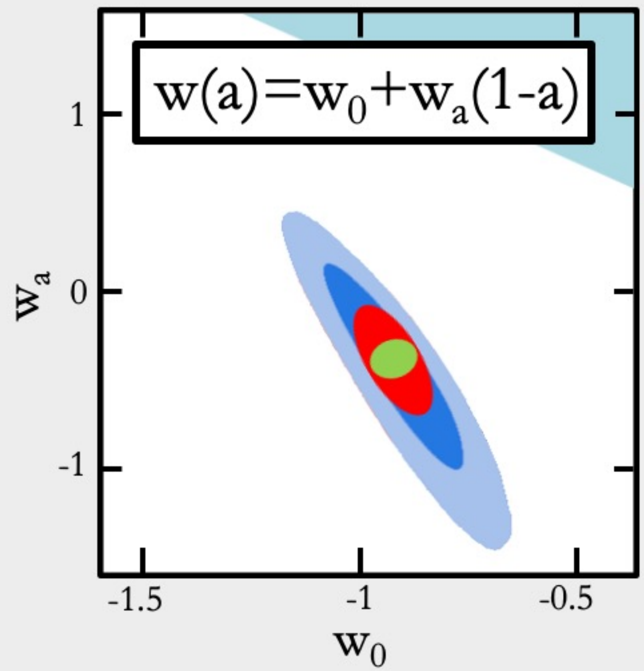
Planck collaboration (2020)

- CMB anisotropies probe many critical cosmological parameters
  - Baryon density ($\times H_0^2$)
  - Dark matter density ($\times H_0^2$)
  - Overall geometry of Universe
  - Time of recombination
  - Dark energy negligible at that time ($a \approx 1/1090$)

Combining the constraints



Planck coll. (2018); Scolnic+ (2018); Riess+ (2019)



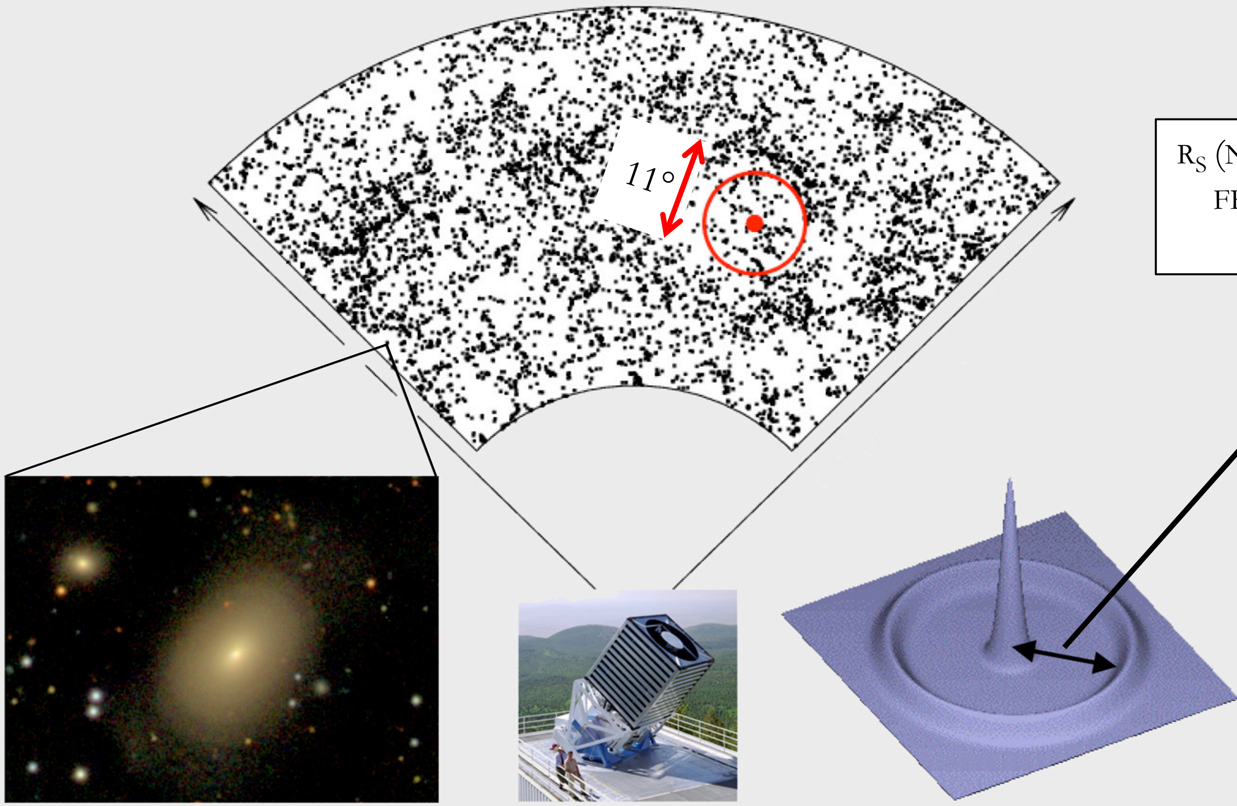
After Cuesta+ (2016)

Coupled with additional priors (such as H_0)

- C16: w_0 ±0.18; w_a ±0.6
- DES: w_0 ±0.08; w_a ±0.3
- LSST: w_0 ±0.05; w_a ±0.1

Baryon acoustic oscillations

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



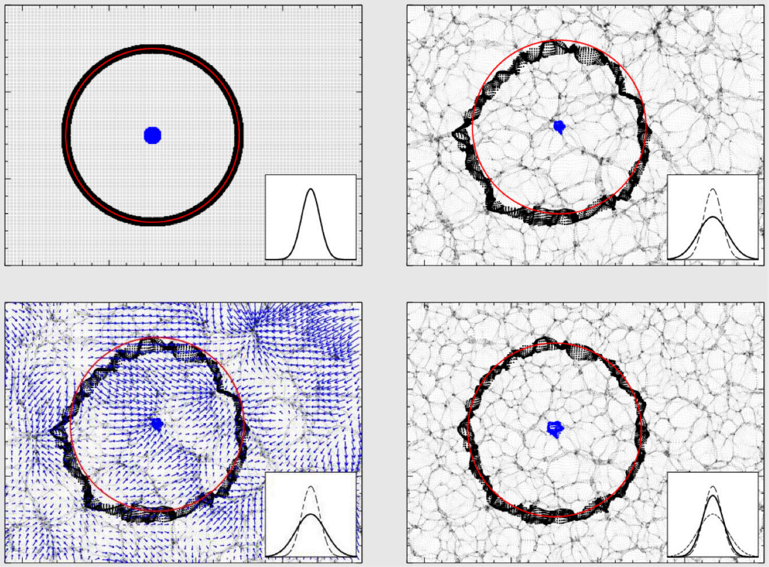
R_S (now) $=4.46\times10^{24}$ m ($\pm0.2\%$) from CMB observations and assuming ΛCDM

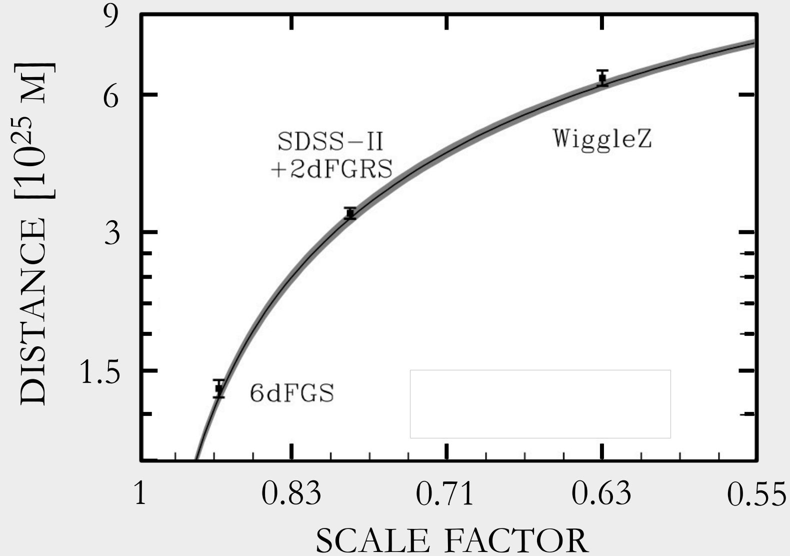
$$r_s = \int_0^{t_*} \frac{c_s(t)}{1+z} dt$$

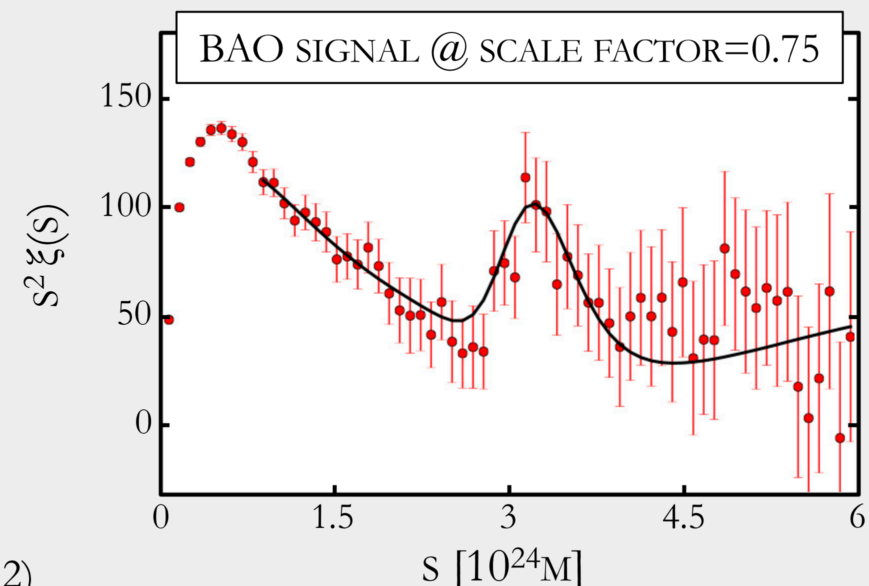
Figure by D. Eisenstein/SDSS

Peebles & Yu (1970); Sunyaev & Zel'dovich (1970)

BAO PEAK AS "STANDARD RULER"





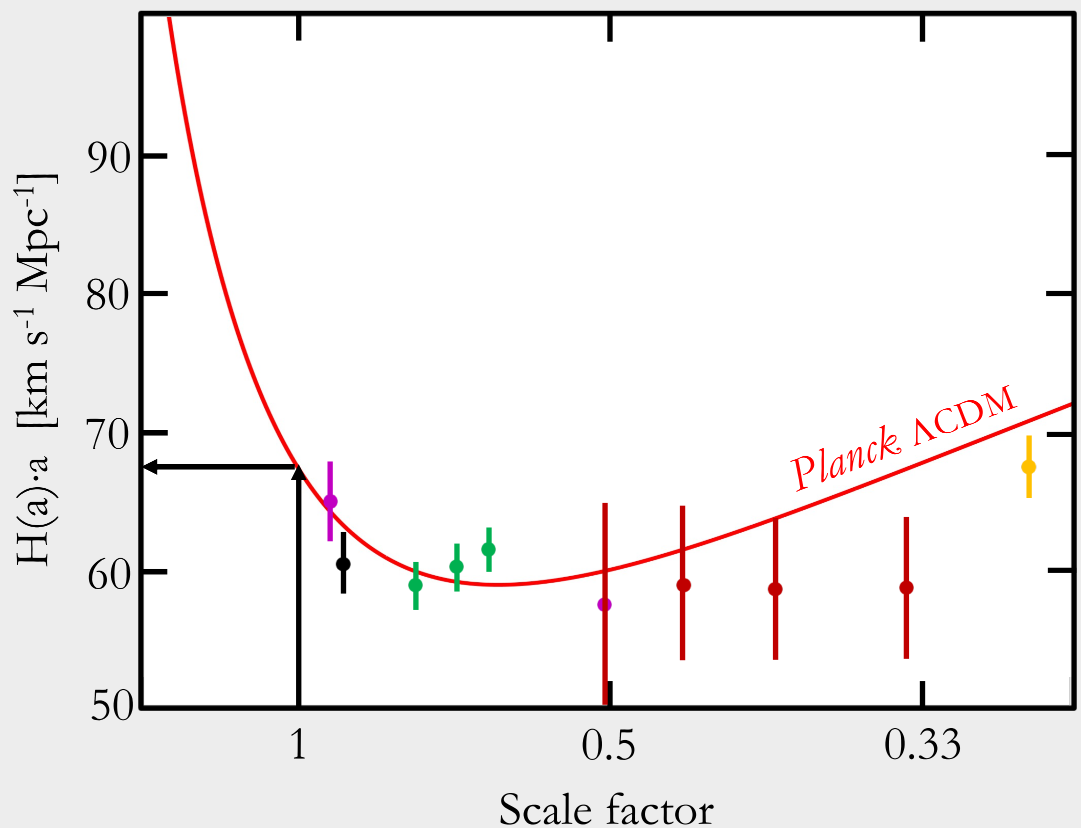


PADMANABHAN+ (2012)

WEINBERG+ (2012)

H(A) VIA BAO

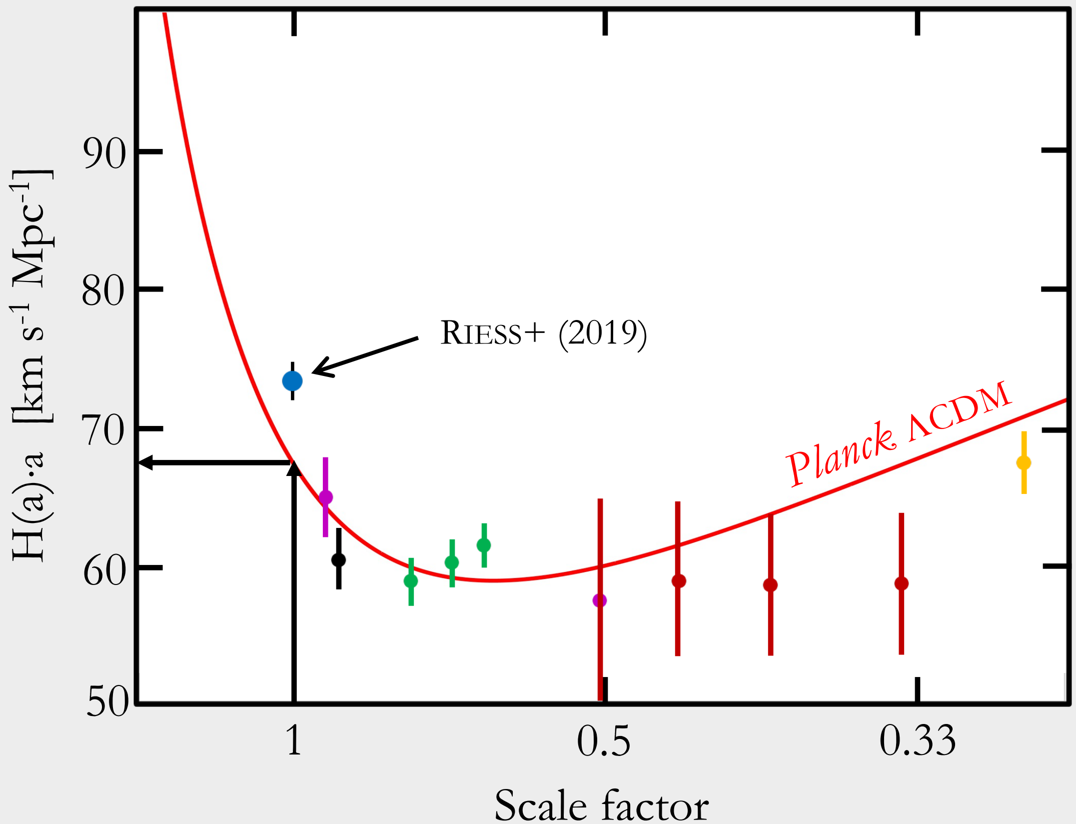
- BAO (calibrated via CMB) can map H(a)
- Can be used to <u>predict</u> H_0 for an *assumed* cosmology



BEUTLER+ (2011); ROSS+ (2015); ALAM+ (2016); BAUTISTA+ (2017); ZHAO+ (2018)

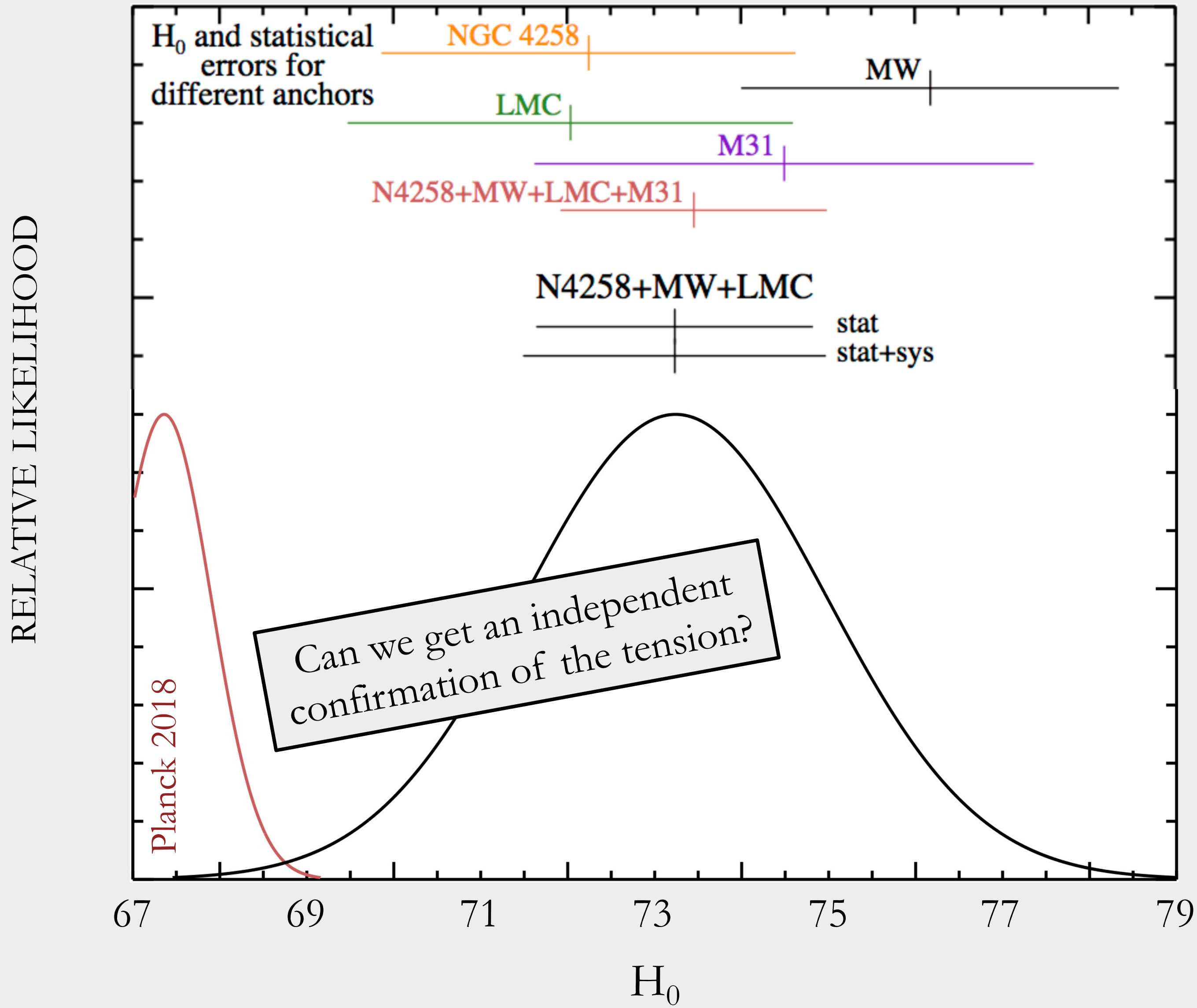
H(a) via BAO

- Compare <u>predicted</u> H_0 for an *assumed* cosmology against local measurement (Cepheids + Supernovae)
- Difference: systematic error(s) or "New Physics"?



Beutler+ (2011); Ross+ (2015); Alam+ (2016); Bautista+ (2017); Zhao+ (2018)

THE "HUBBLE TENSION" CIRCA 2018

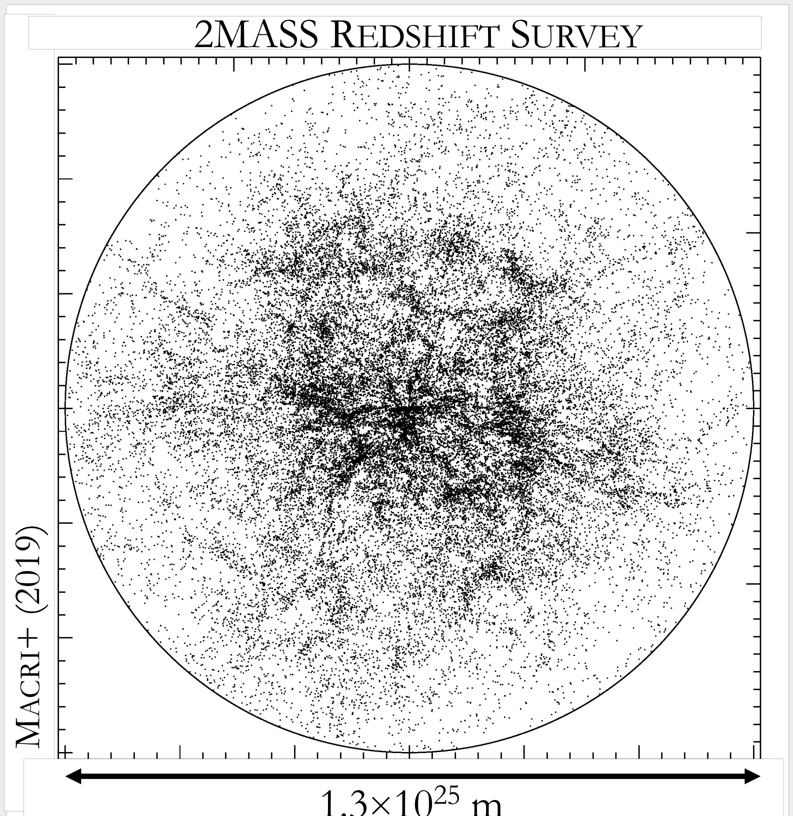


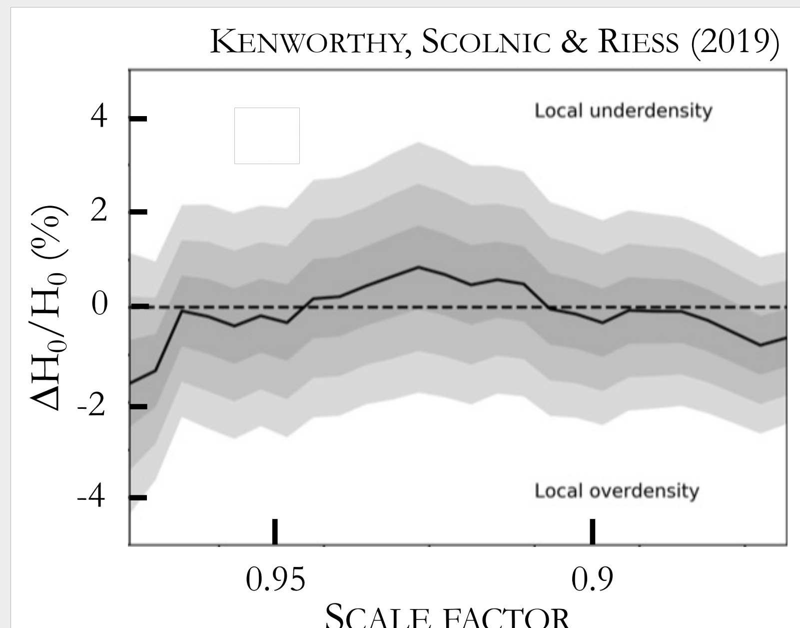
PLANCK COLLABORATION (2018)

RIESS, MACRI, HOFFMANN+ (2016)

Do we live in an underdensity?

- Our measurements already correct for density variations based on all-sky galaxy redshift surveys
- Theory predicts $\Delta H_0/H_0<0.4\%$ (discrepancy is 9%)
- $>10^3$ supernovae empirically constrain $\Delta H_0/H_0<0.6\%$





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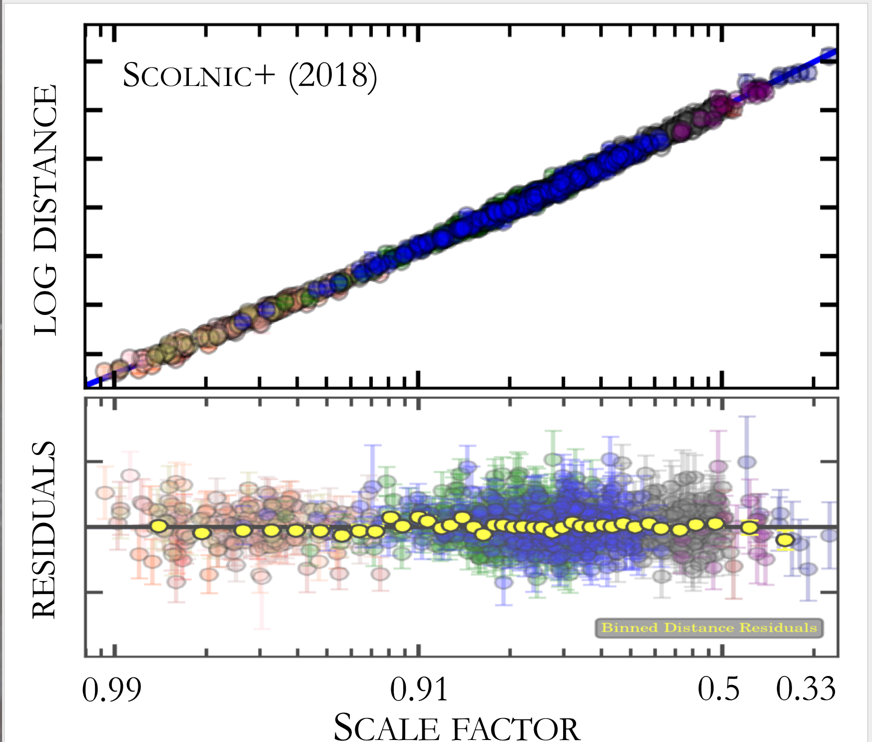
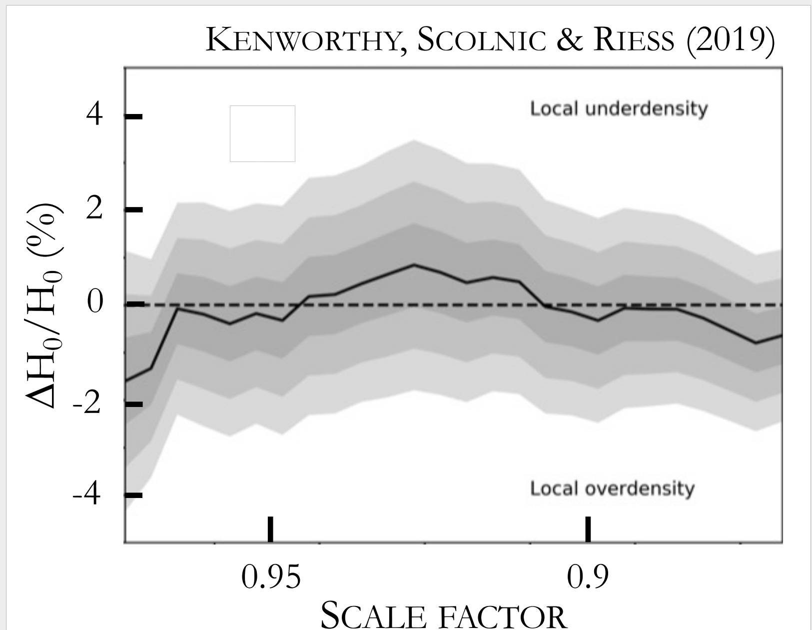
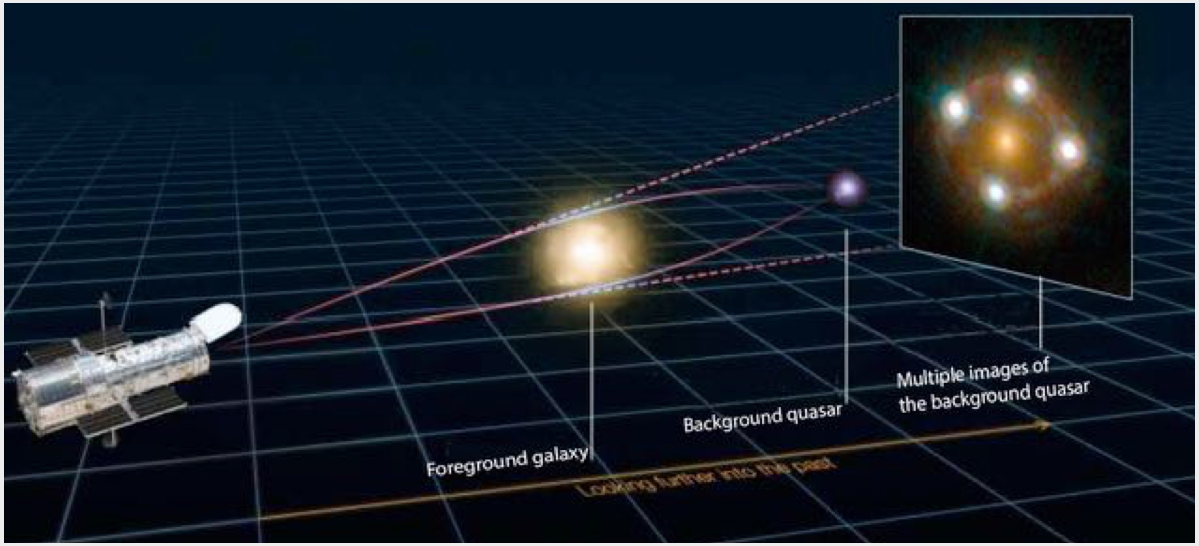




H_0 FROM GRAVITY

- "Time delay cosmography"
  - Photons from a distant (variable) quasar travel paths of different length through a gravity well along the line of sight



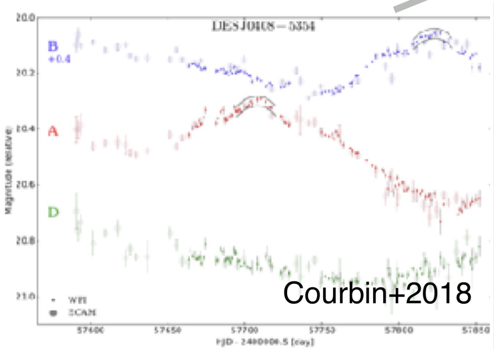
$$D_{\Delta t} \propto \frac{D_{\mathrm{d}} D_{\mathrm{s}}}{D_{\mathrm{ds}}} \propto \frac{\Delta t}{\delta \Psi} \propto \frac{1}{H_0}$$

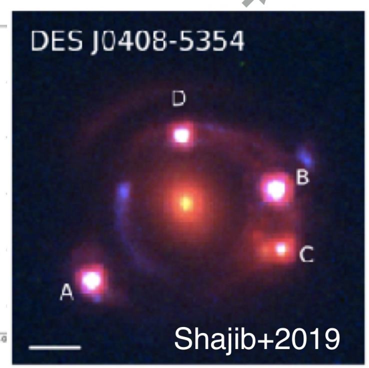
MATERIAL COURTESY OF ANOWAR SHAJIB (UCLA) AND MARTIN MILLON (EPFL)

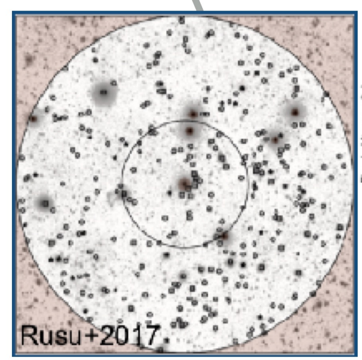
Time-delay cosmography

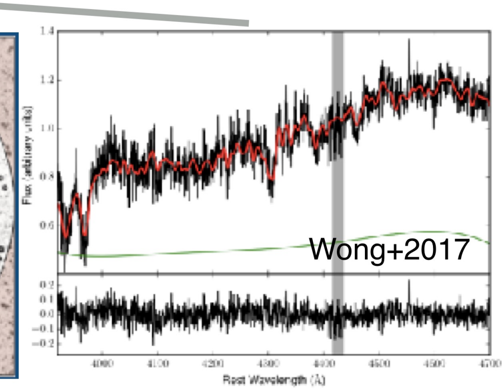
- Requires substantial amount of careful observations from ground and space, with detailed modelling

$$D_{\Delta t} = \frac{c\Delta t}{\Delta \Psi}(1 - \kappa_{\rm ext})$$







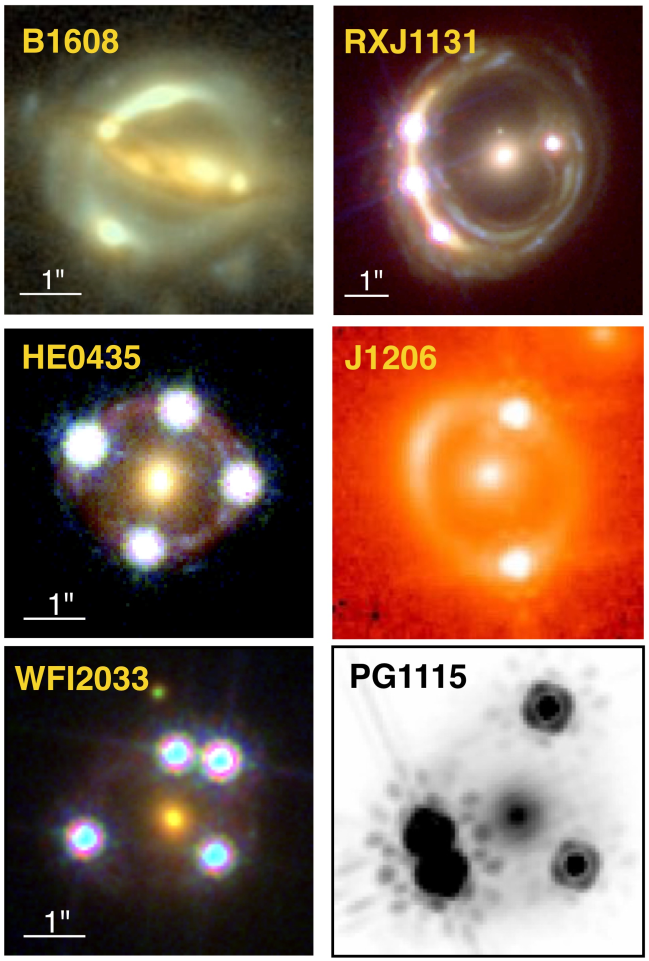


- Time delay measurement
- High resolution imaging of the lens
- Estimate of line-of-sight effects
- Kinematics

Material courtesy of Anowar Shajib (UCLA) and Martin Millon (EPFL)

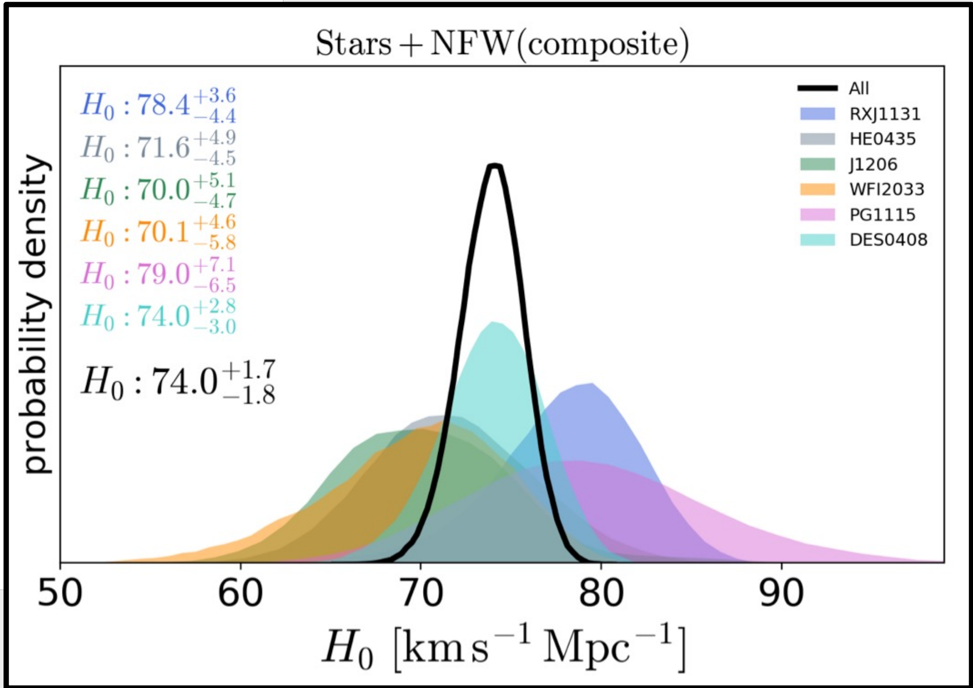
Time-delay cosmography

- Yields completely independent (and blinded!) results



Suyu+2010, 2014; Wong+2017; Birrer+2019; Chen+2019; Rusu+2019; Shajib+2020

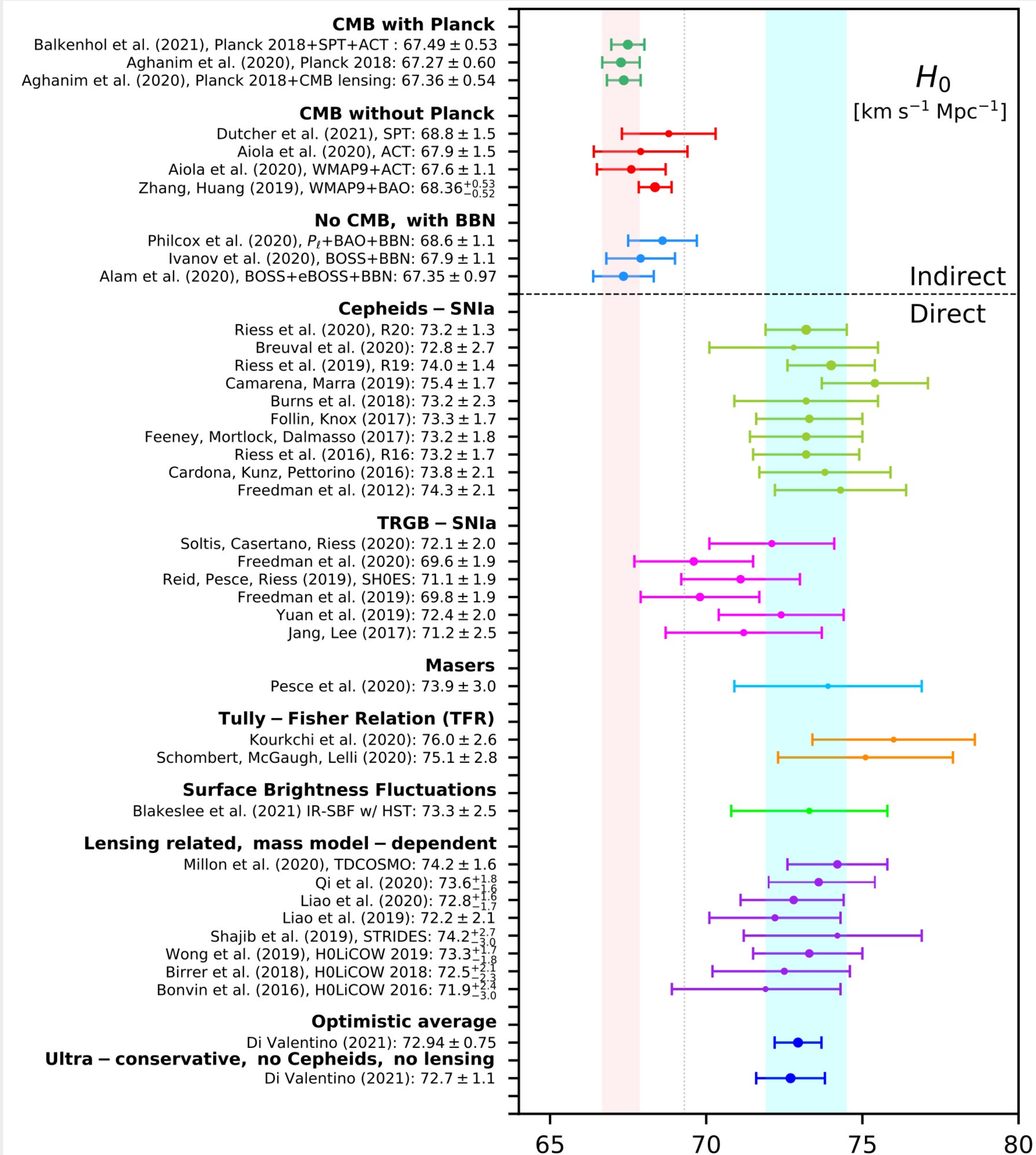
Millon+2020, arXiv:1912.08027



RECENT ESTIMATES OF H_0

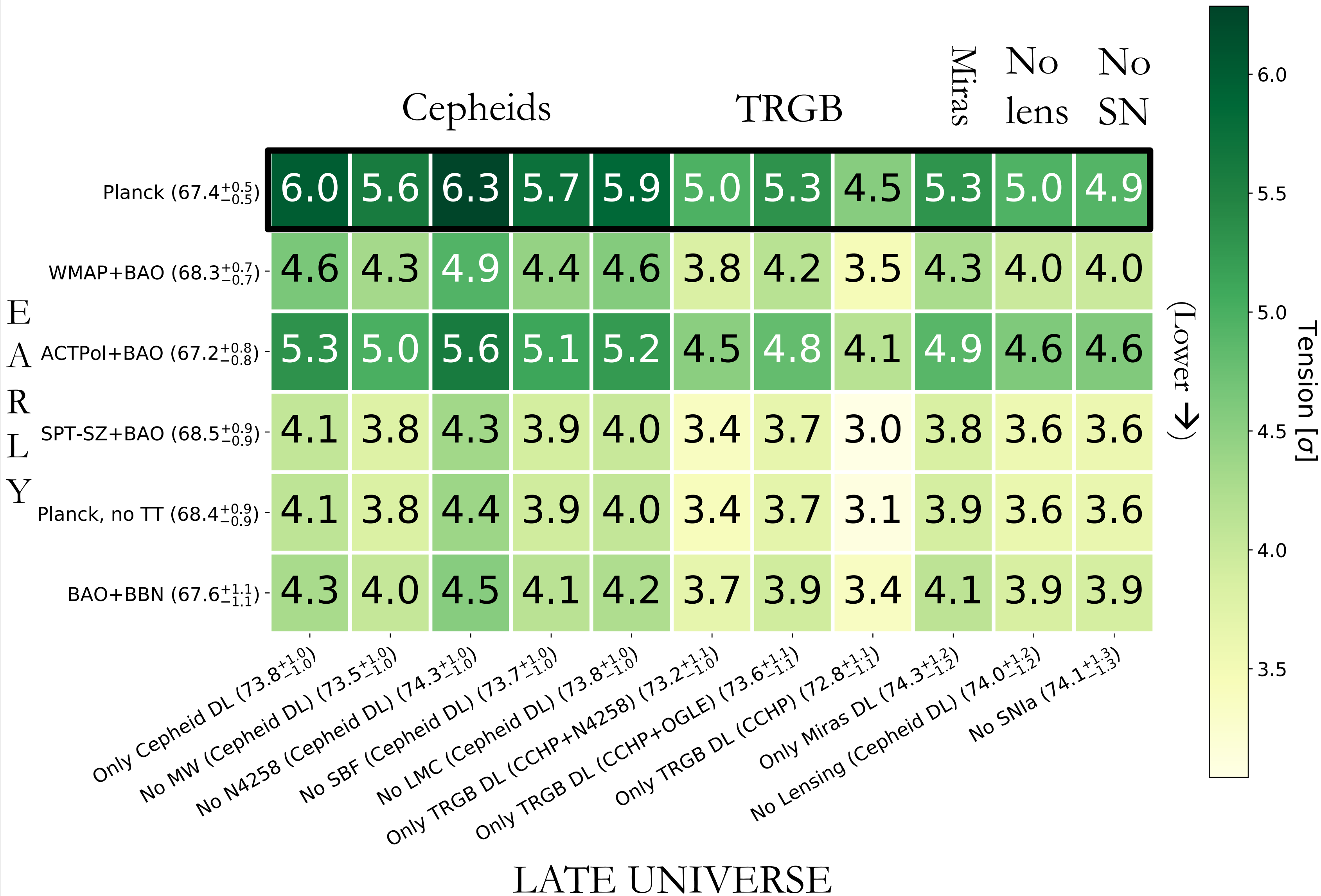
- Gravitational time-delays (H0LICOW+STRIDES)
  - 7 lenses, blinded analysis: $H_0 = 74.0 \pm 1.8$ km s^{-1} Mpc^{-1} (Millon+2020, arXiv:1912.08027)
- Maser-based distances in the Hubble Flow (MCP)
  - 5 hosts beyond N4258: $H_0 = 73.9 \pm 3.0$ km s^{-1} Mpc^{-1} (Pesce+2020, arXiv:2001.09213)
- Tip of the Red Giant Branch
  - *Gaia* parallax, ω Cen: $H_0 = 72.0 \pm 2.0$ km s^{-1} Mpc^{-1} (Soltis+, arXiv:2012.09196)
  - LMC + HST/OGLE: $H_0 = 72.4 \pm 1.9$ km s^{-1} Mpc^{-1} (Yuan+2019, arXiv:1908.00993)
- Miras
  - $H_0 = 73.3 \pm 4.0$ km s^{-1} Mpc^{-1} (Huang+2020, arXiv:1908.10883)

Recent high-precision H_0 measurements



DiValentino (2021), arXiv:2103.01183

SIGNIFICANCE OF THE DISCREPANCY



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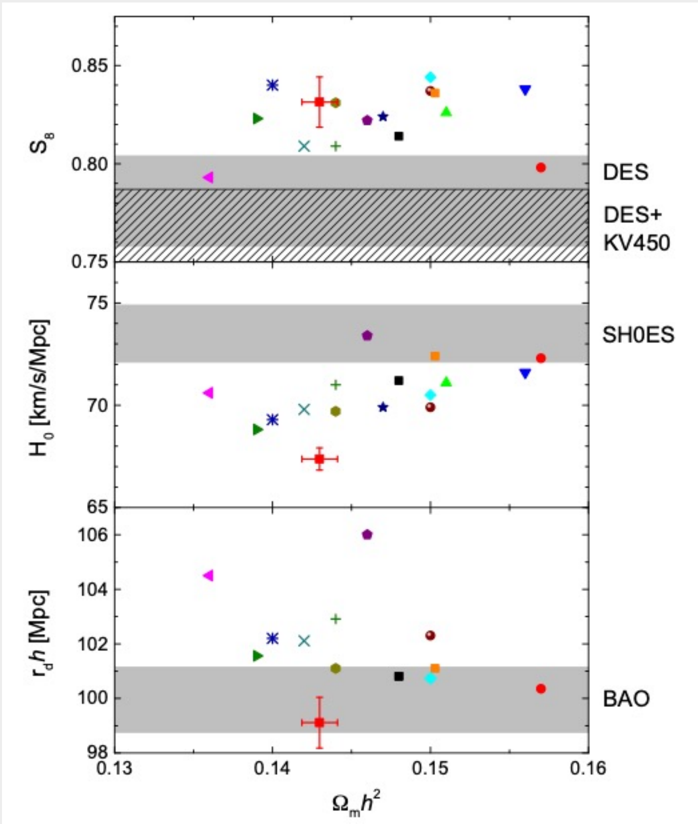
- ➢ **New Physics in the dark sector?**
- Next steps

NEW PHYSICS IN DARK SECTOR?

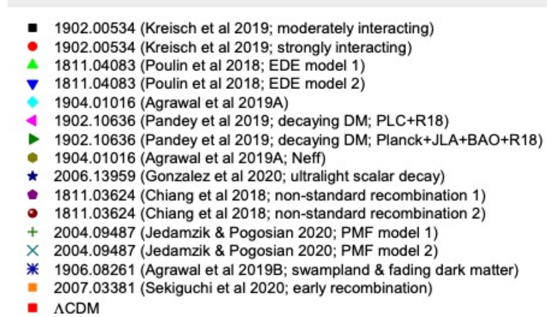
Reviews: Di Valentino+, 2103.01183; Jedamzik, Pogosian & Zhao, 2010.04158



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

<u>Better</u>: strong neutrino interactions, early dark energy, evolving e^- mass, early recombination, primordial B fields

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



SLIDE COURTESY OF A. RIESS

<u>“The Hubble Hunter’s Guide”, Knox and Millea, 2019</u> “Most Likely”:
Increase Expansion Rate Pre-recombination reduce sound horizon by 5-8%
<u>Mechanisms:</u> Early dark energy or sterile (and/or self-interacting) neutrinos
<u>Claims: not worse</u> fit to CMB, should produce new CMB features for next stage

New Physics in Dark Sector?

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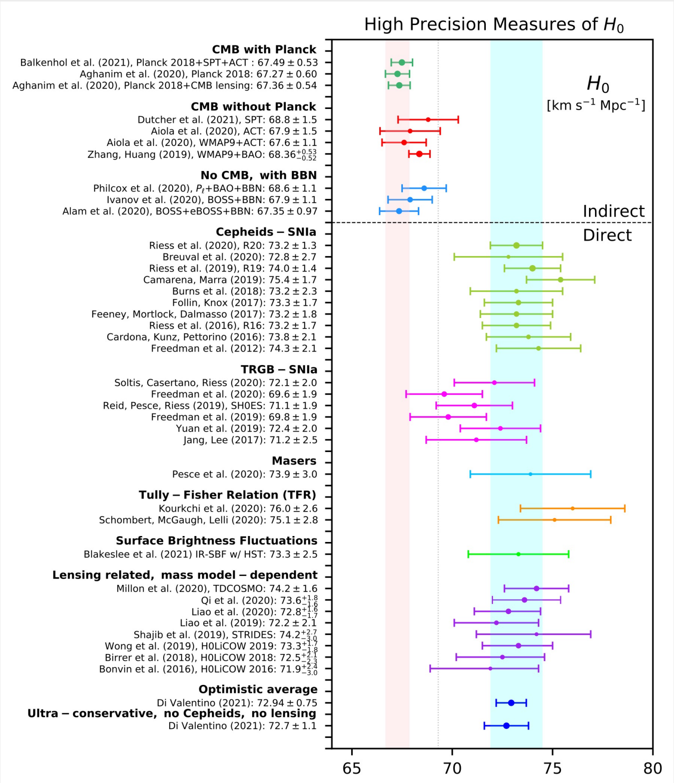

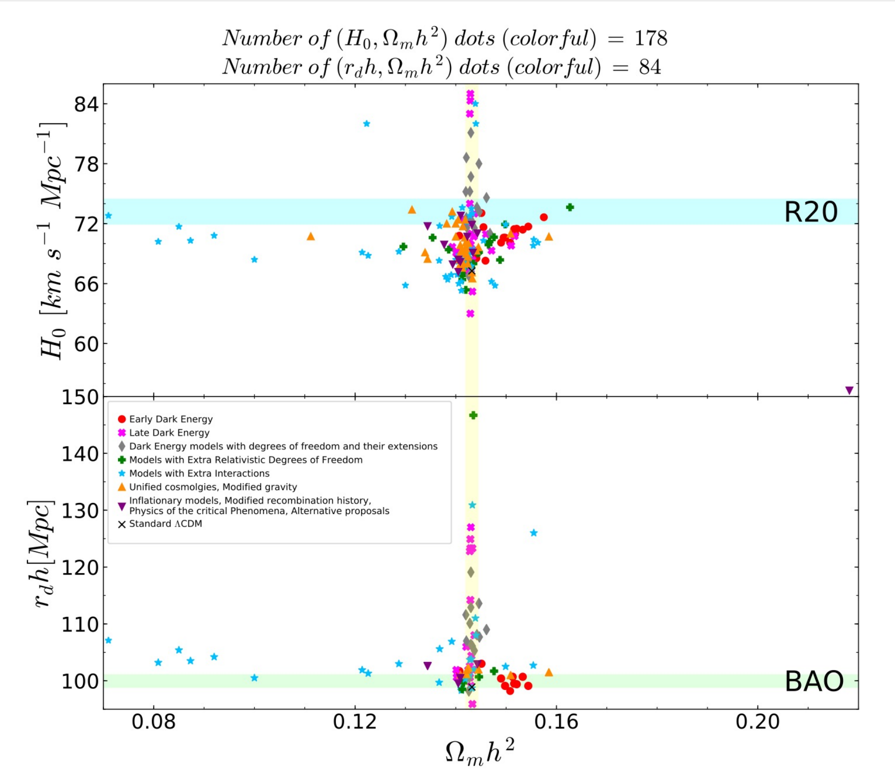

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Specific hypotheses needed

- Present data provides formidable challenge!
  - "It's New Physics"—constrained precise H(z) data, CMB
  - "It's Systematics"—many measures, many independent rungs, duplicate measurements, Copernican principle
  - IMHO: Data too good for non-specific claims or nit-picking; there is a "signal" that demands specific, testable explanation

- Reasons for optimism:
  - New data: LIGO, DESI, *Roman*, *Rubin*, Euclid, JWST, Simons, S4
  - New clues: Early-vs-late σ_8, CMB high-l, BBN?
  - Big Playground: ΛCDM is 95% dark, quantum gravity

Slide courtesy of A. Riess

Outline

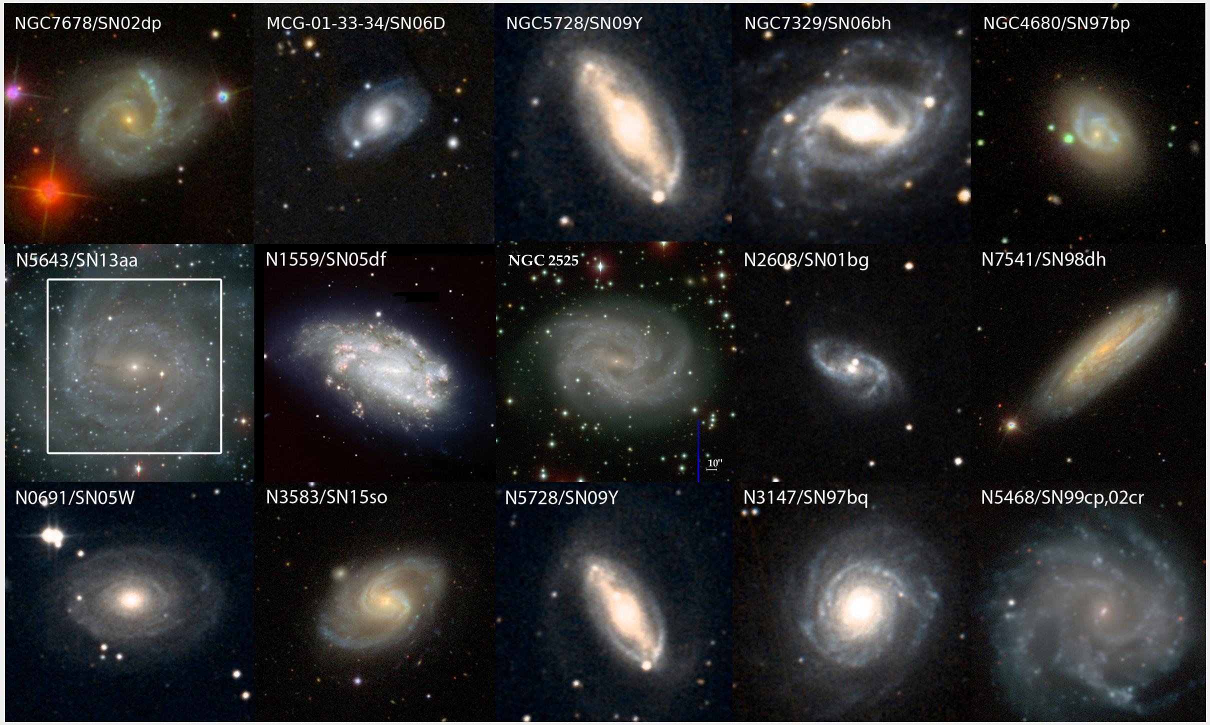
- ✓ Introduction
- ✓ How to measure the Hubble constant to ~1%
- ✓ Cosmological probes of the expansion
- ✓ New Physics in the dark sector?
- ➢ **Next steps**

H_0 TO ~1.4%

- HST + *Gaia* parallaxes to Milky Way Cepheids
  - "Spatial scanning" technique: D = 0.5 → 4 kpc
- HST photometry for all observations
  - Milky Way and Large Magellanic Cloud
- 1% distance to LMC (eclipsing binaries)
  - N=8 → 20, improved absolute calibration of technique
- Cepheid distances to more hosts of SNe Ia
  - Ongoing HST observations: N = 19 → 40
- Improved understanding of Cepheid systematics
  - Detailed chemical abundances of Magellanic Cloud Cepheids

Ongoing Hubble observations

- Cepheid searches in 20 additional hosts of SNe Ia
  - Some hosted 2 SNe -> N=40
- Mira search in nearest 4 of those hosts
  - Consistency check of Cepheid Distance Scale



SUMMARY

- SH_0ES project: calibration of modern, high-quality SNe Ia using Cepheids in the near-infrared
  - $H_0=73.2\pm1.3$ km s^{-1} Mpc^{-1} ; $\sigma(H_0)= 10\% \rightarrow 1.8\%$
  - 4.2σ discrepancy wrt ΛCDM $\rightarrow$ New Physics in dark sector?
- Goal: $\sigma(H_0)=1.4\%$ later this year
  - *HST*+*Gaia* parallaxes to Milky Way Cepheids
  - 40 Cepheid distances to nearby SNe Ia
- The discrepancy is quite robust (4-6σ), regardless of the combination of cosmological probes used