AST 1430

Cosmology

Week Index	Dates	Topics
Week 1	Jan 11, 13	logistics, introduction, basic observations
Week 2	Jan 18, 20	Basic GR, RW metric, Distances, coordinates, Friedmann equations, cosmological models
Week 3	Jan 25, 27	Consistency with observations, Early Hot Universe, BBN
Week 4	Feb 1, 3	Inflation, Perturbations & Structure pre-recombination
Week 5	Feb 8, 10	CMB: basics, polarization, secondaries
Week 6	Feb 15 (2h)	Early-Universe Presentations
Reading Week – No Class		
Week 7	Mar 1, 3	Post-recombination growth of structure, formation of dark matter halos, halo mass function
Week 8	Mar 8, 10	The relation between dark matter halos and galaxies
Week 9	Mar 15, 17	Probing the cosmic density field / clustering
Week 10	Mar 22, 24	Late Universe Presentations; lcosmological observations: BAO, supernovae, weak lensing, etc.
Week 11	Mar 29, 31	H0 controversy: how fast exactly is the Universe expanding today?
Week 12	Apr 5	Review

Keith

Jo

asst1

asst2

asst3

The H_0 controversy

H_0

- Hubble's law: foundation of modern cosmology

$$v = H_0\, D$$

- H_0 is one of the most fundamental cosmological parameters, the expansion rate today

$$H_0 = \frac{\dot{a}}{a}$$

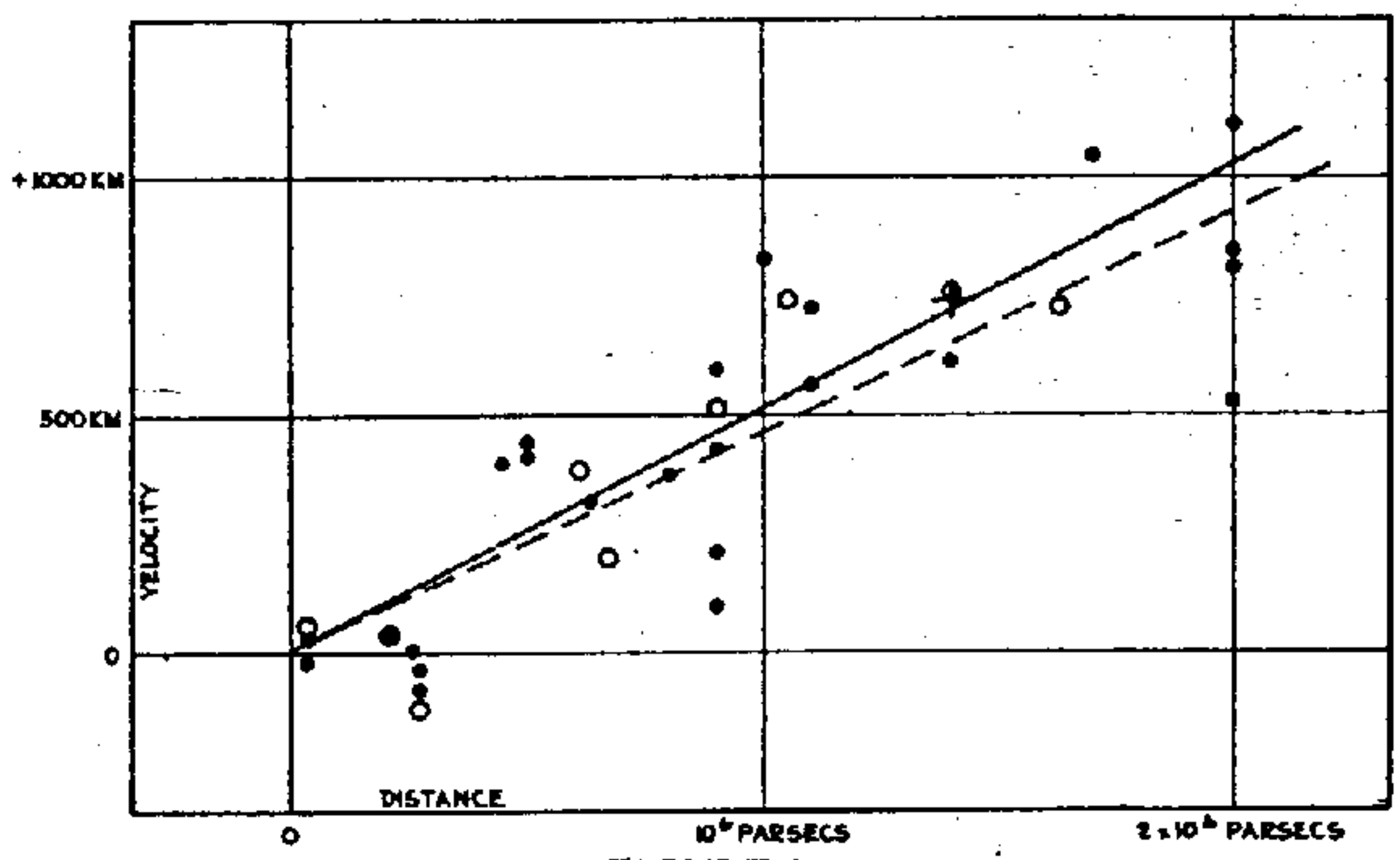


FIGURE 1

Hubble (1929)

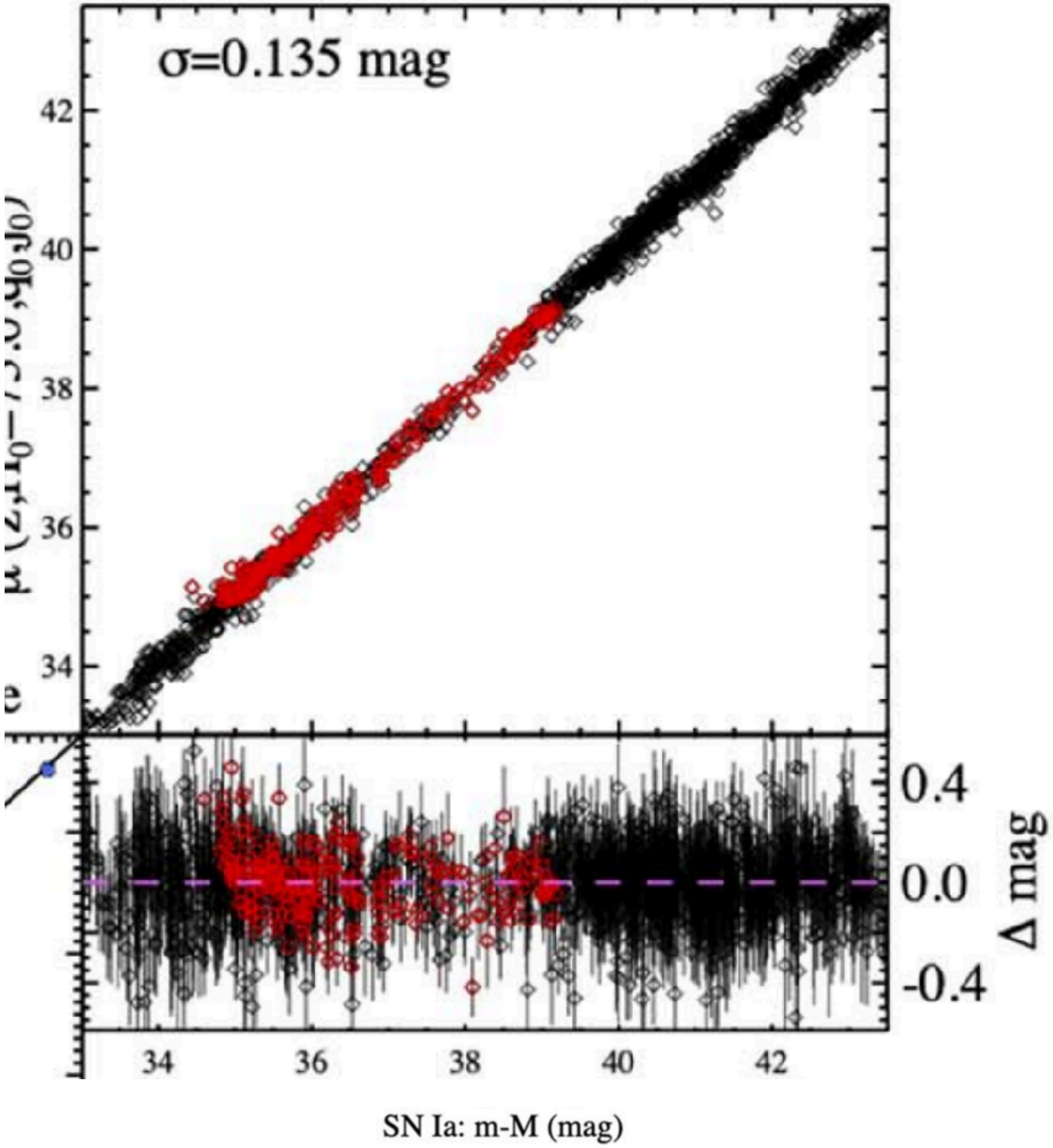
- Expansion rate at all other times is a function of H_0 and the density parameters

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

Outline

- Measuring H_0 locally using the distance ladder
- Measuring H_0 using CMB + BAO
- Measuring H_0 cosmologically using the inverse distance ladder
- Alternative ways of measuring H_0
- Theoretical implications of the H_0 discrepancy

Measuring H_0 locally

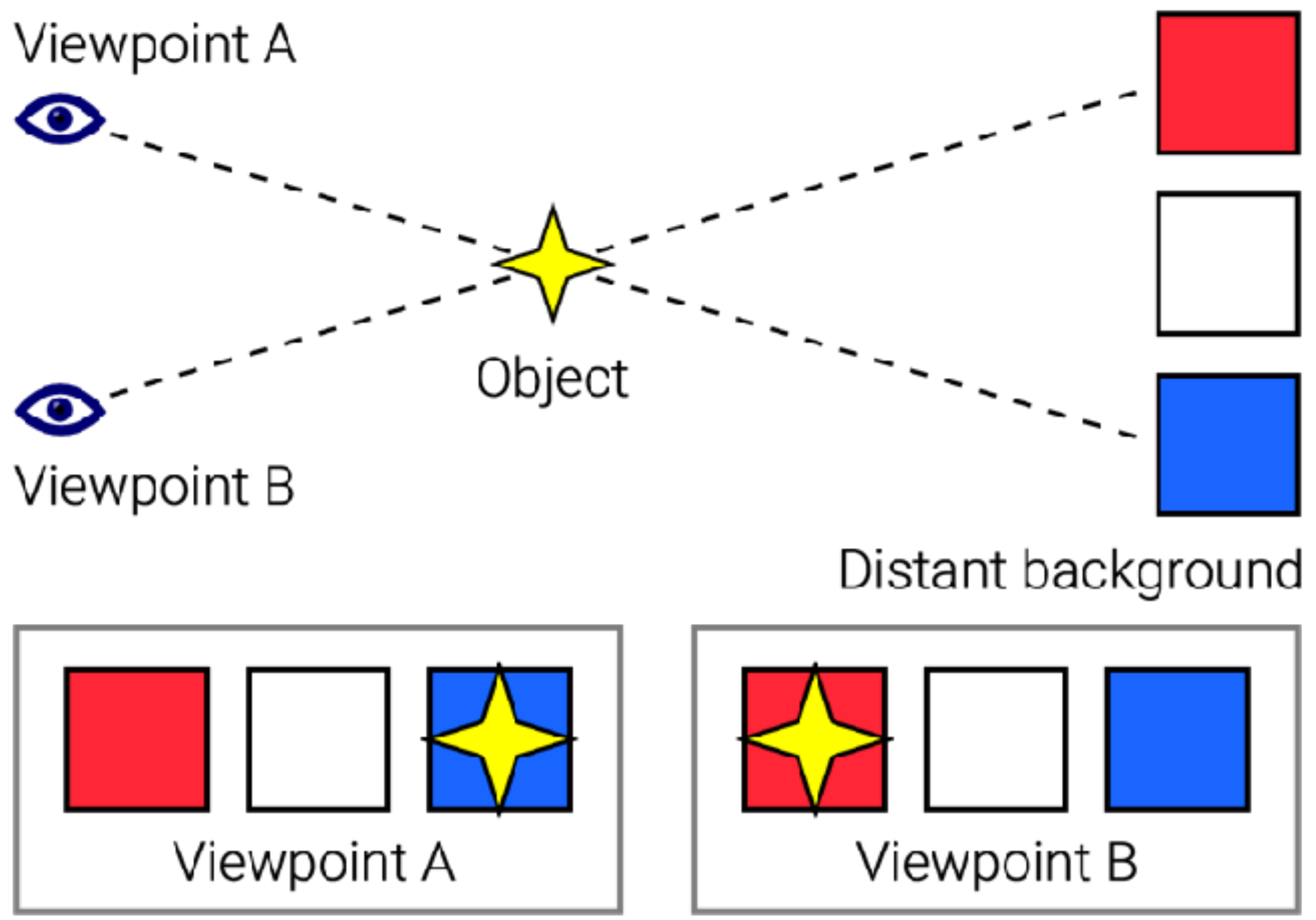


Measuring H_0 locally using the distance ladder

- Measuring H0 locally is “easy”:
  - Measure distances to galaxies
  - Measure velocities to galaxies
  - Measure slope of velocity vs. distance
- Main problem is that measuring absolute distances is difficult
- Measuring velocities is easy using redshifts, but same complication as RSD: Hubble law velocity =/= total velocity
  - Small effect at large distances, can be alleviated further using reconstruction of the density field

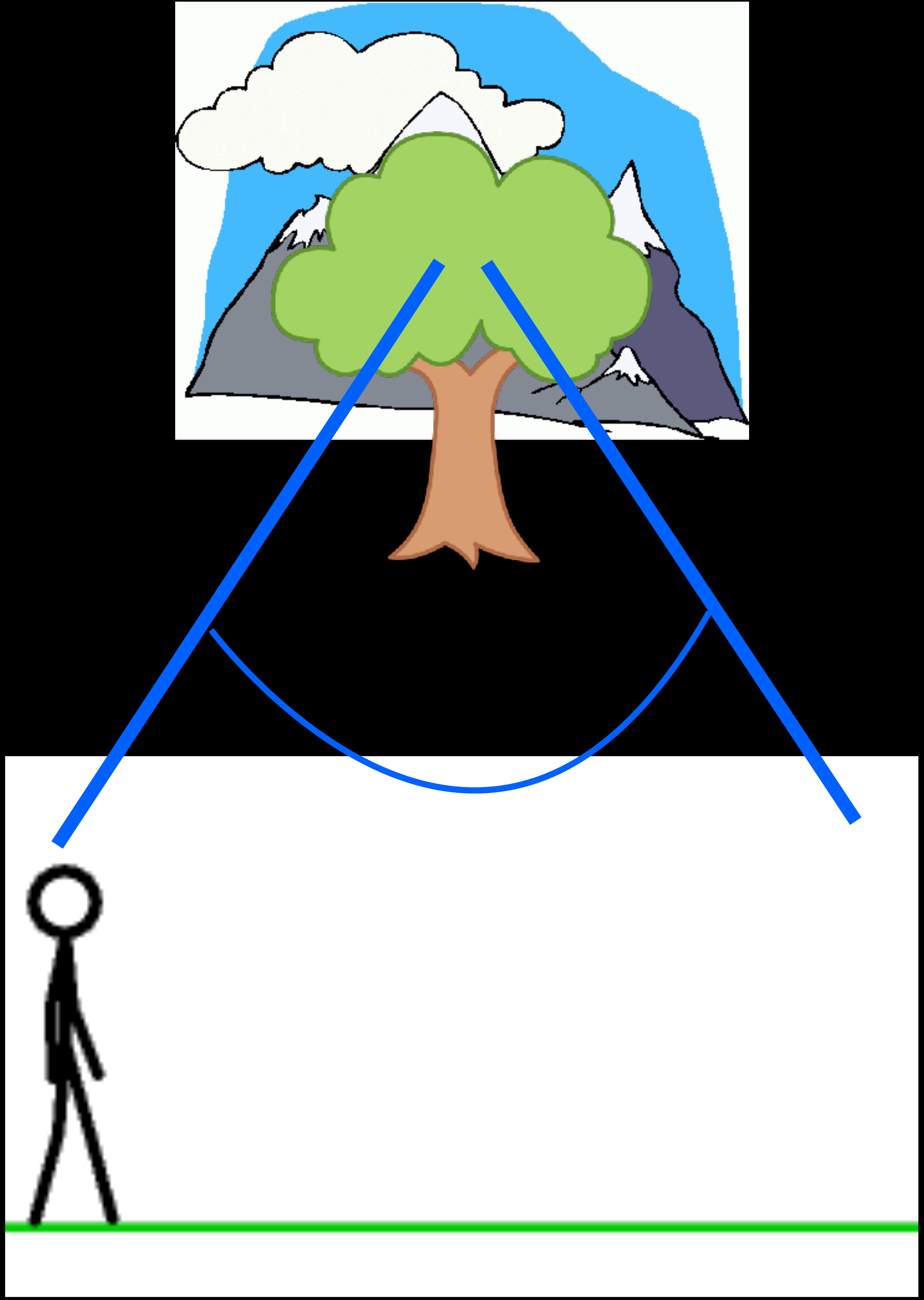
Measuring distances

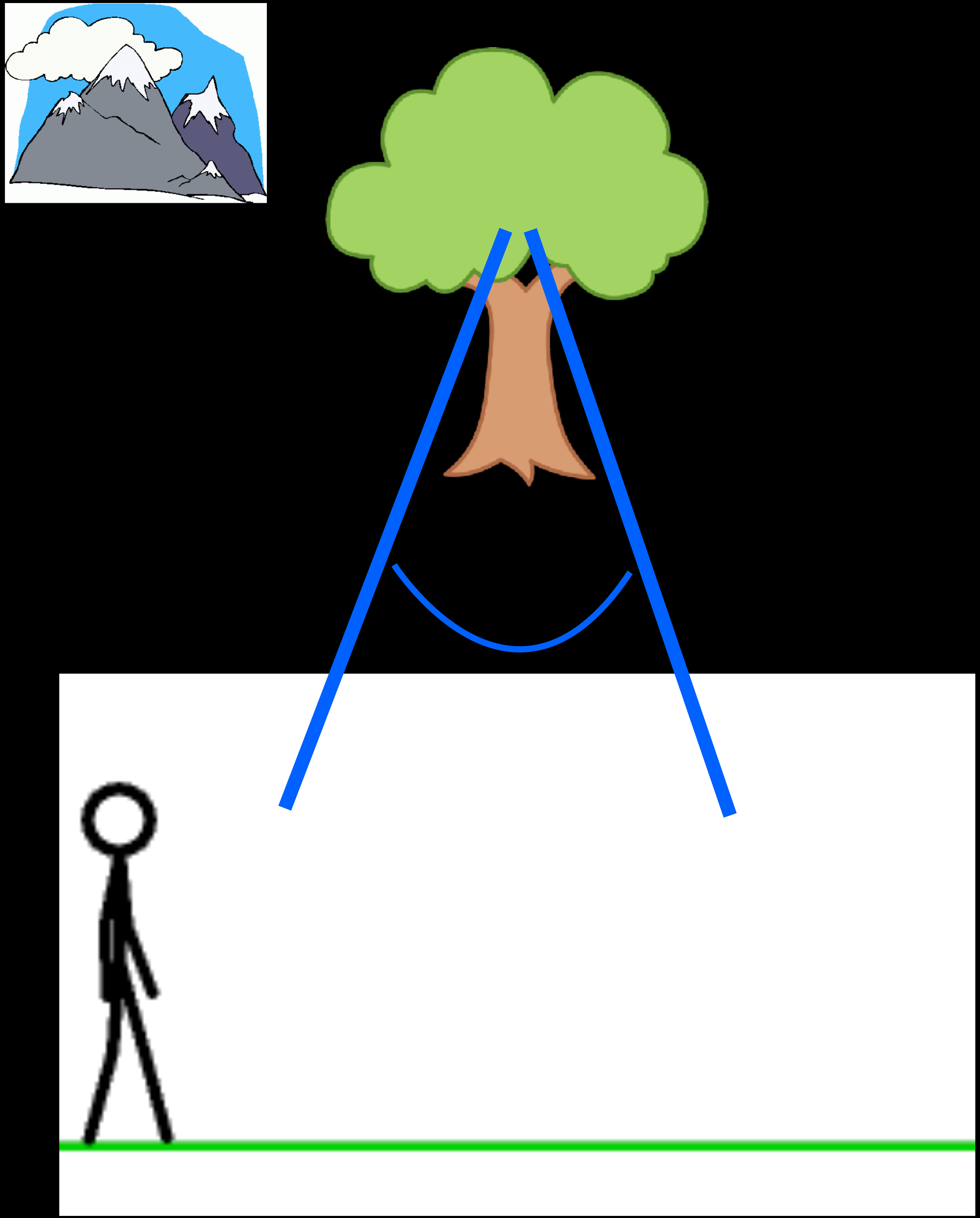
The gold standard: geometric parallaxes

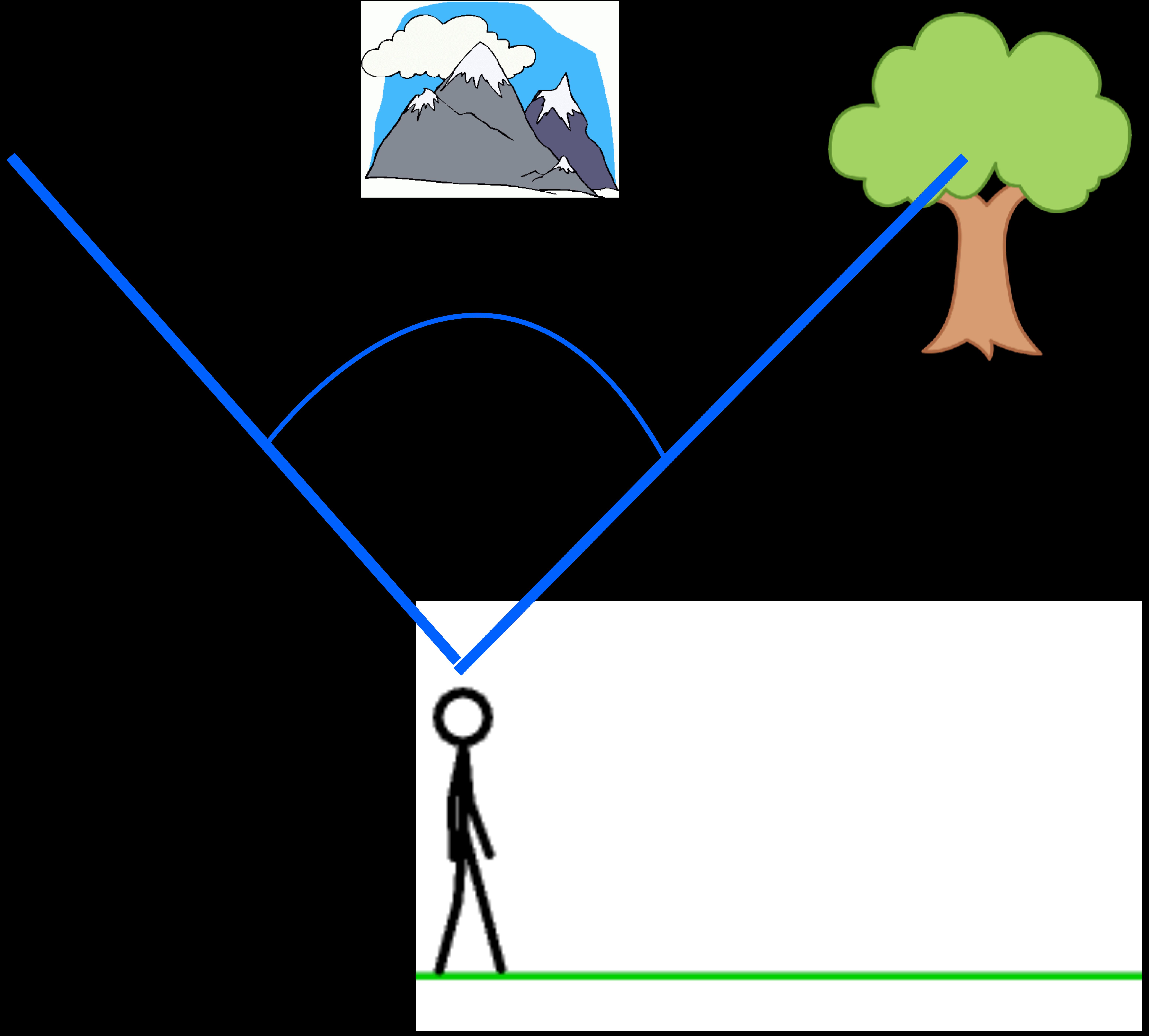


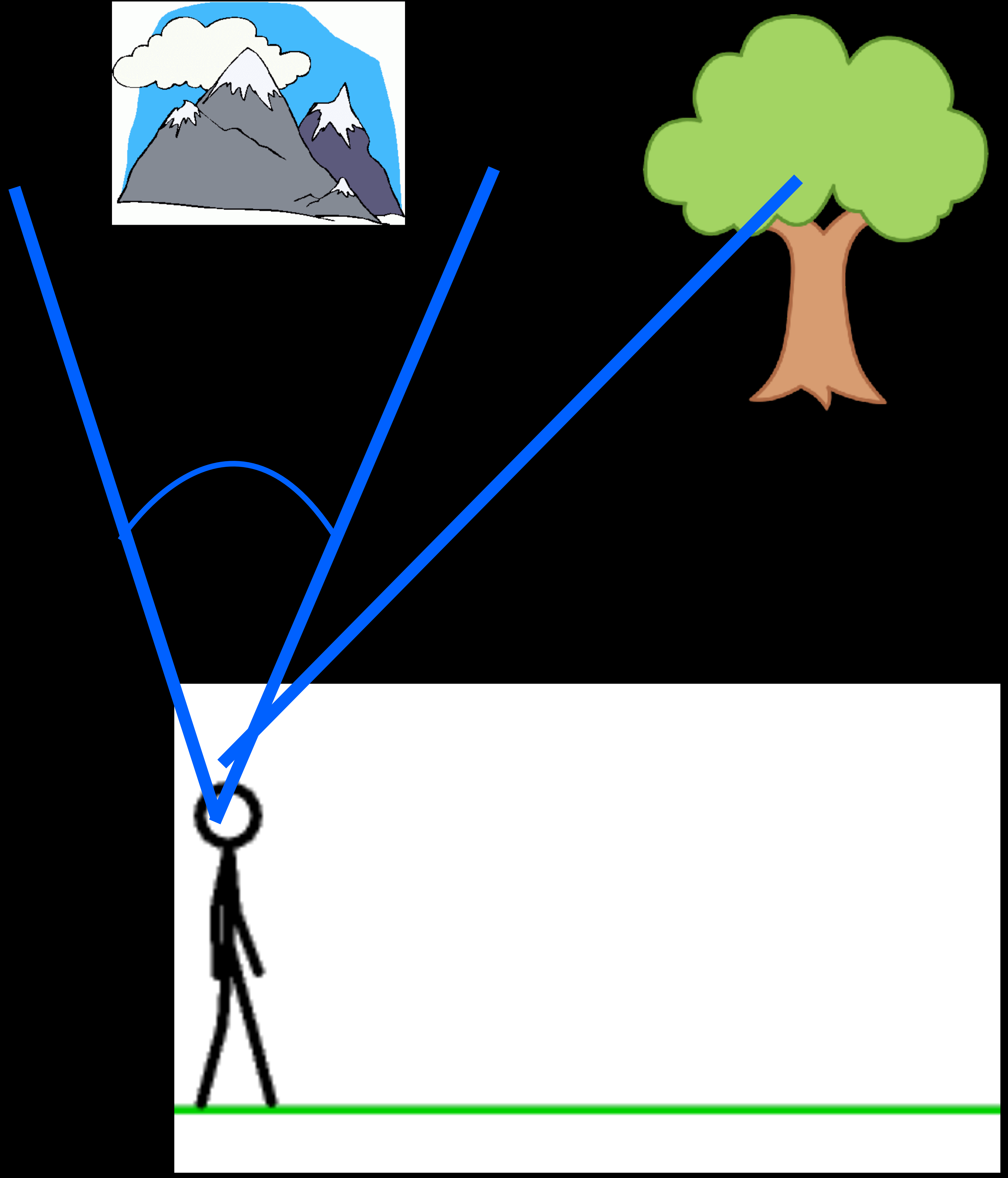
JustinWick at English Wikipedia

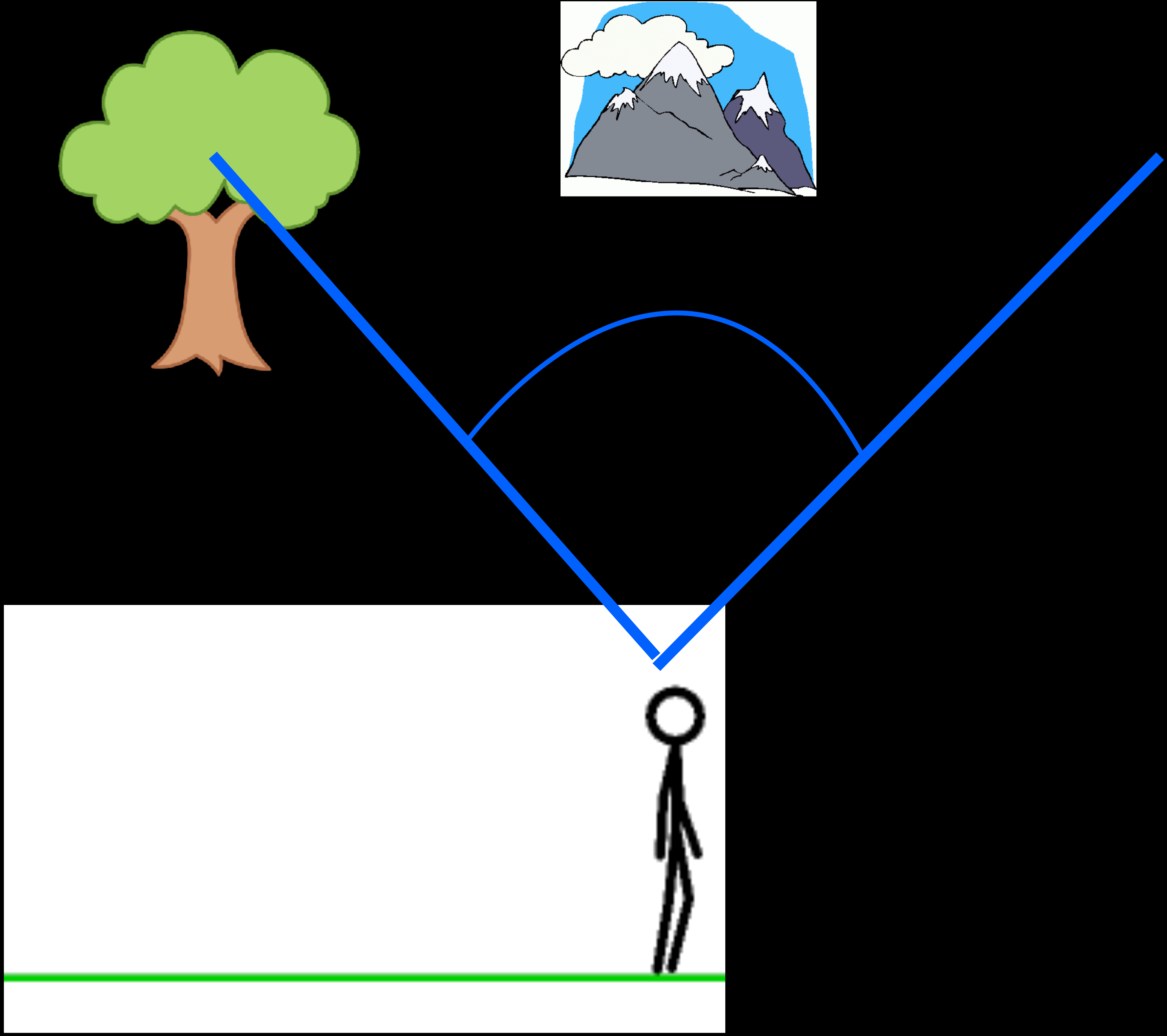
- Essentially the only way to directly measure distances in astronomy is as parallaxes
- 1 arcsecond parallax = 1 kpc
- State-of-the-art: *Gaia* satellite, parallax uncertainty ~ 10 μas
  —> 10% distance to 10 kpc
  —> not cosmological at all!
- Thus, we need to build a distance ladder that starts with parallaxes to calibrate secondary distance methods

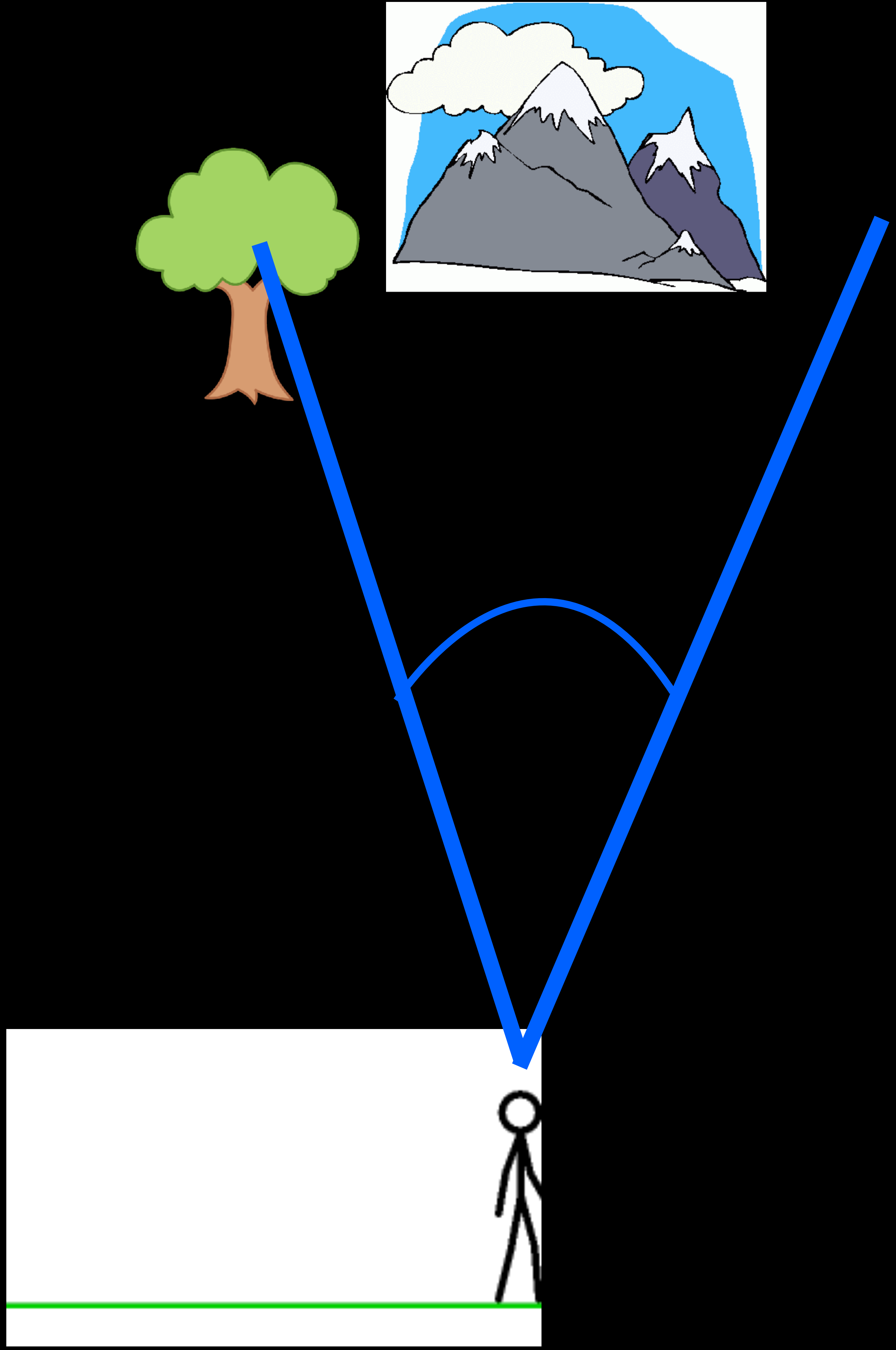


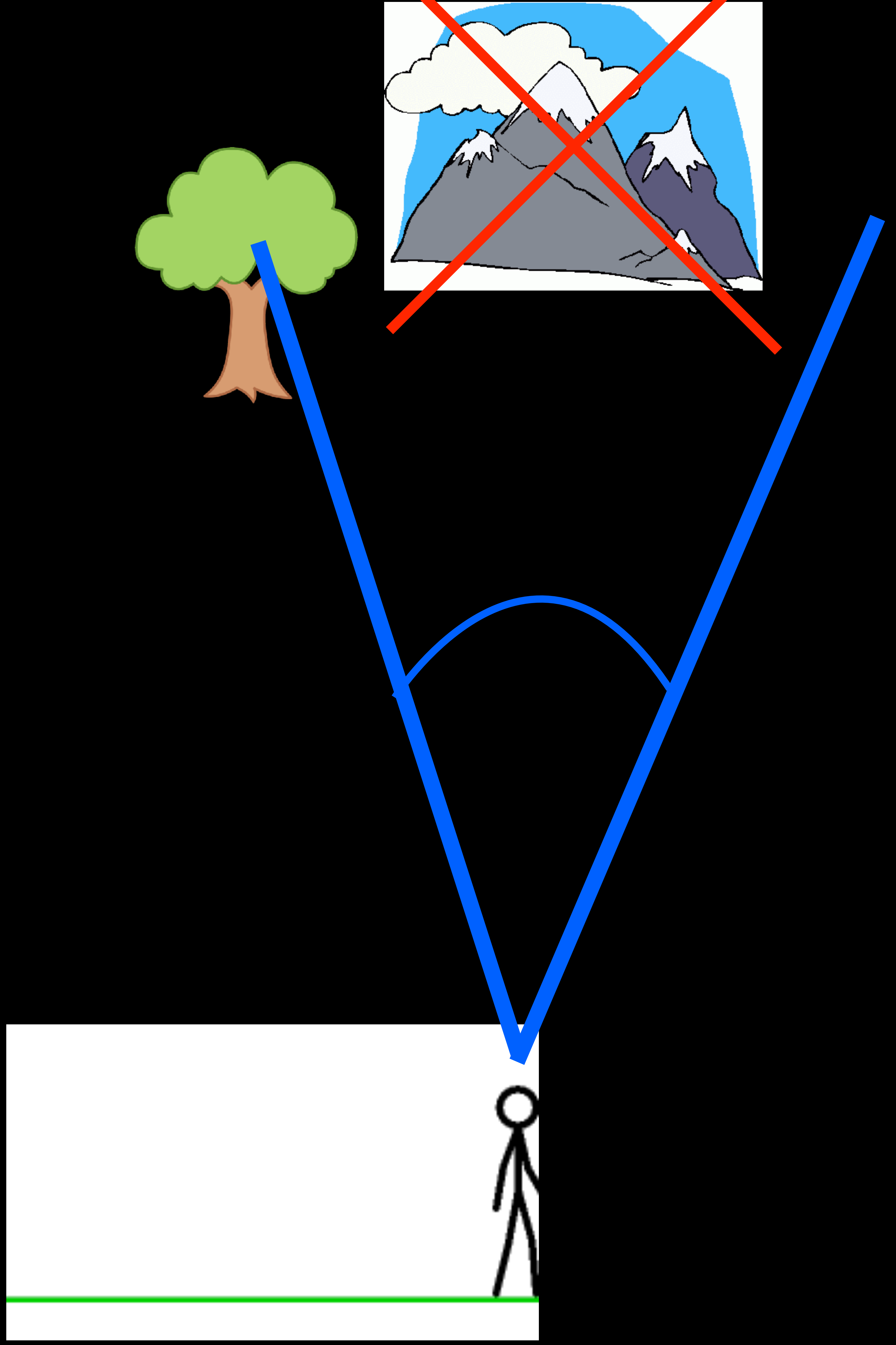


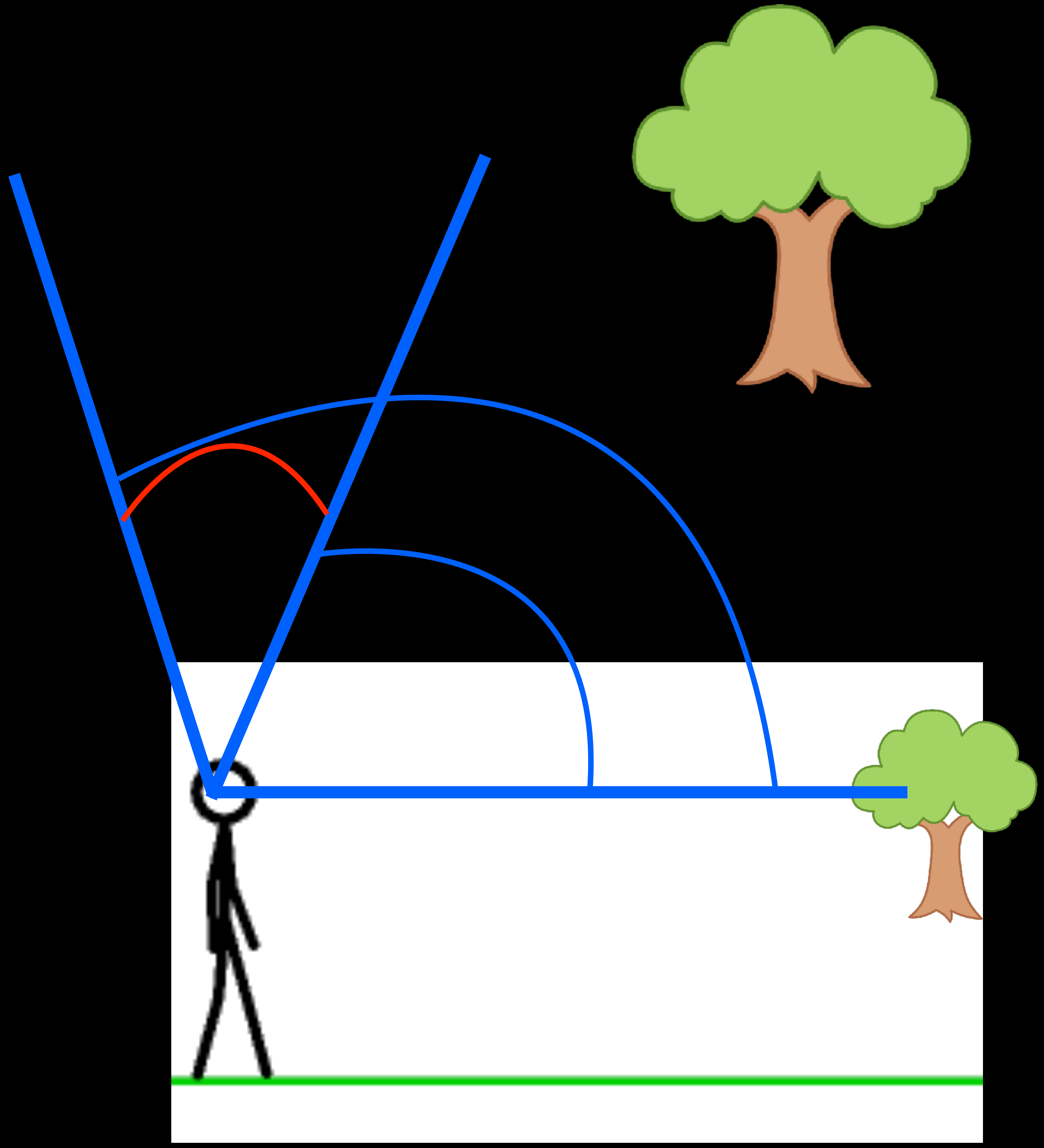






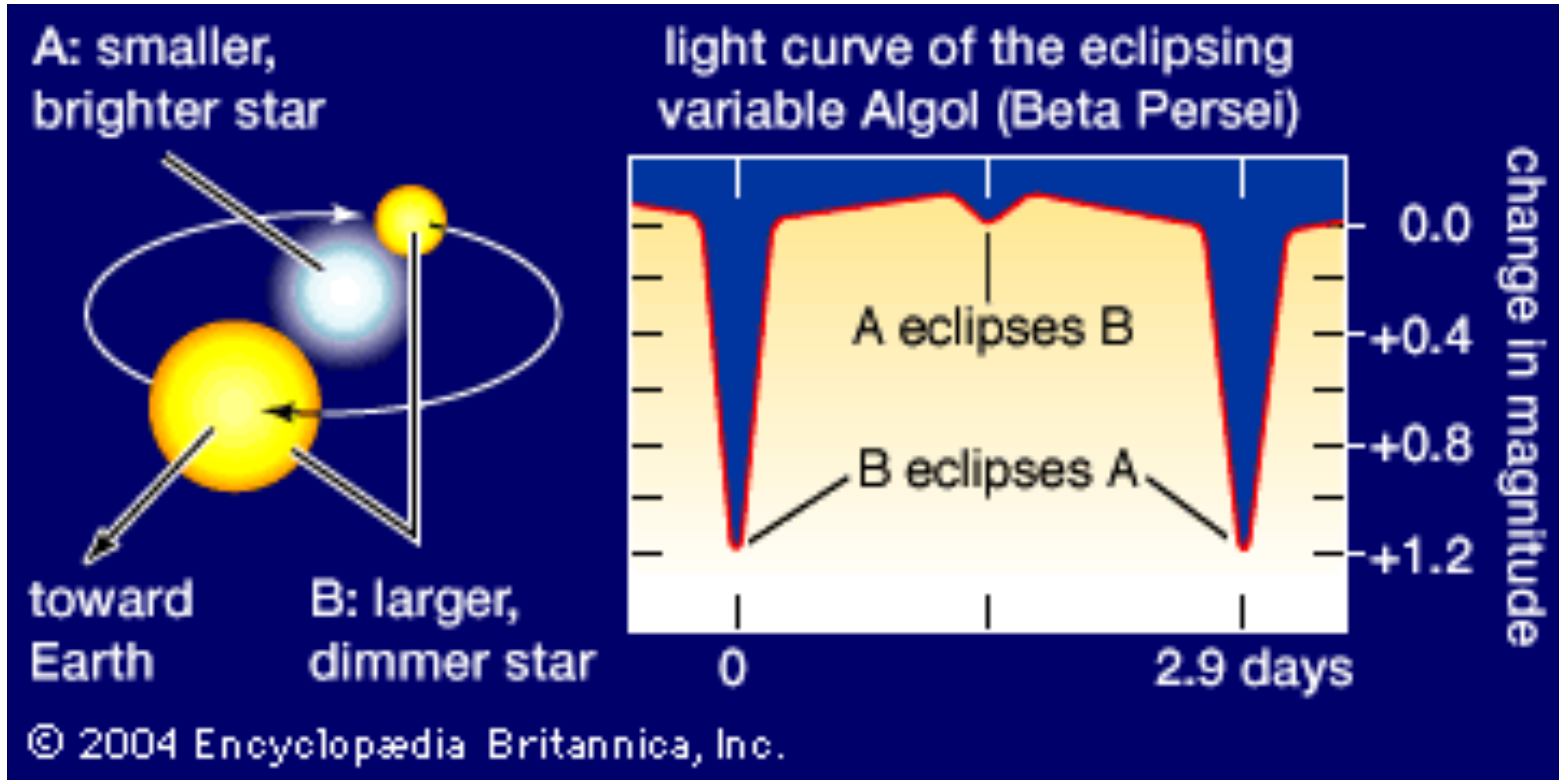






Measuring distances

Also good: eclipsing binaries

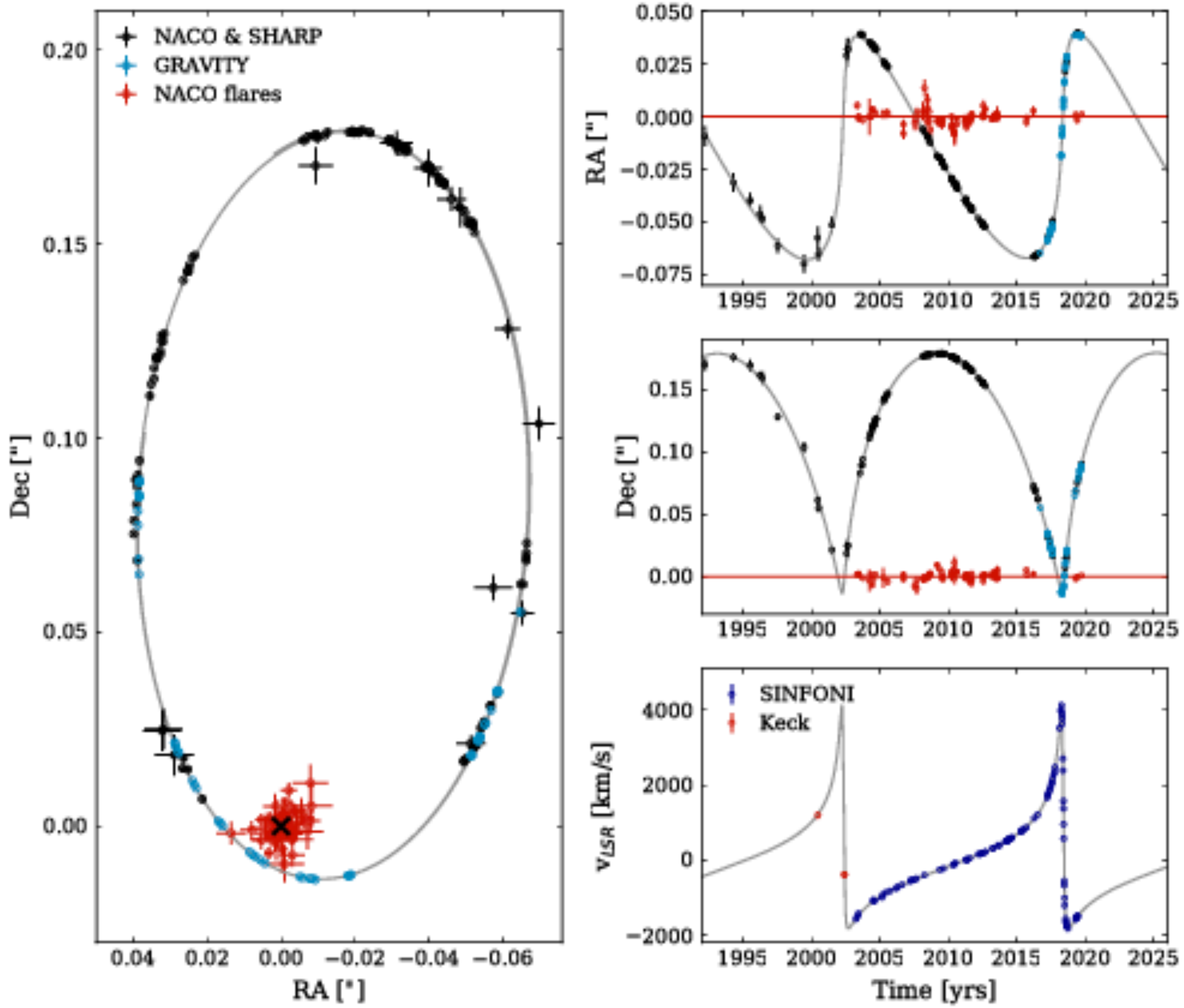


- Surface-brightness vs. color relation determines surface flux
- Combination of radial-velocity and brightness monitoring of the eclipses determines orbit and then radii of stars
- Combine to give the absolute luminosity: $L = 4\pi \, f \, R^2$
- Obtain distance from apparent magnitude
- E.g., distance to the LMC to 1% (Pietrzyński et al. 2019)

Measuring distances

Also good: dynamical distances

- Observe Keplerian orbit in velocity and angular offsets
- Consistency between the two determines distance
- Example, distance to the Milky Way's Galactic centre using the star S2: <1% distance

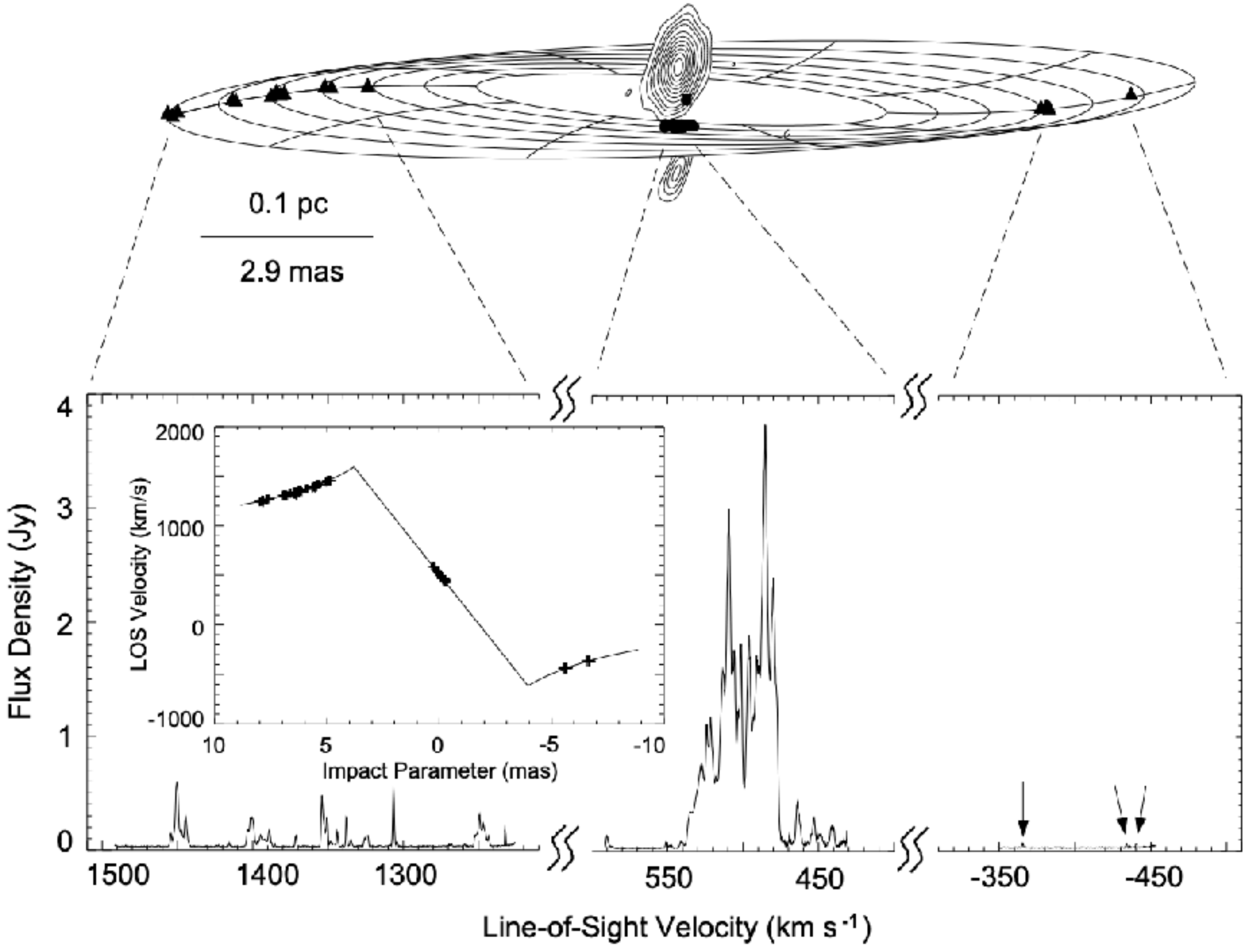


Abuter et al. (2020; GRAVITY)

Measuring distances

Also good: dynamical distances

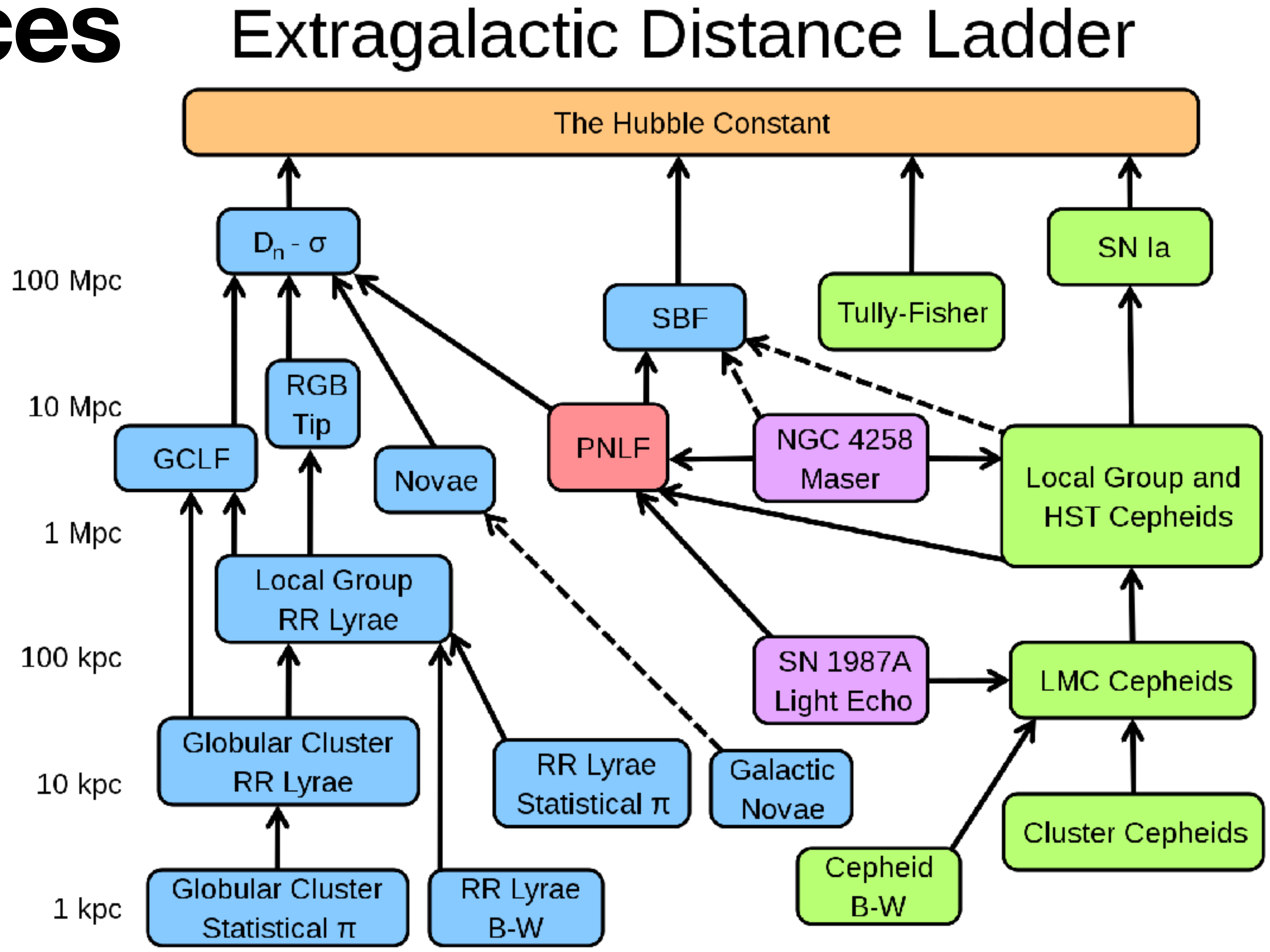
- NGC 4258: galaxy with AGN with maser disk surrounding it
- Maser disk appears to be in Keplerian motion around the AGN (but warped)
- VLBI measures angular offset of masing spots
- Also a 1% distance
- NGC 4258 has a similar metallicity as the Milky Way —> important for calibration of secondary distances



Herrnstein et al. (1999)

Measuring distances

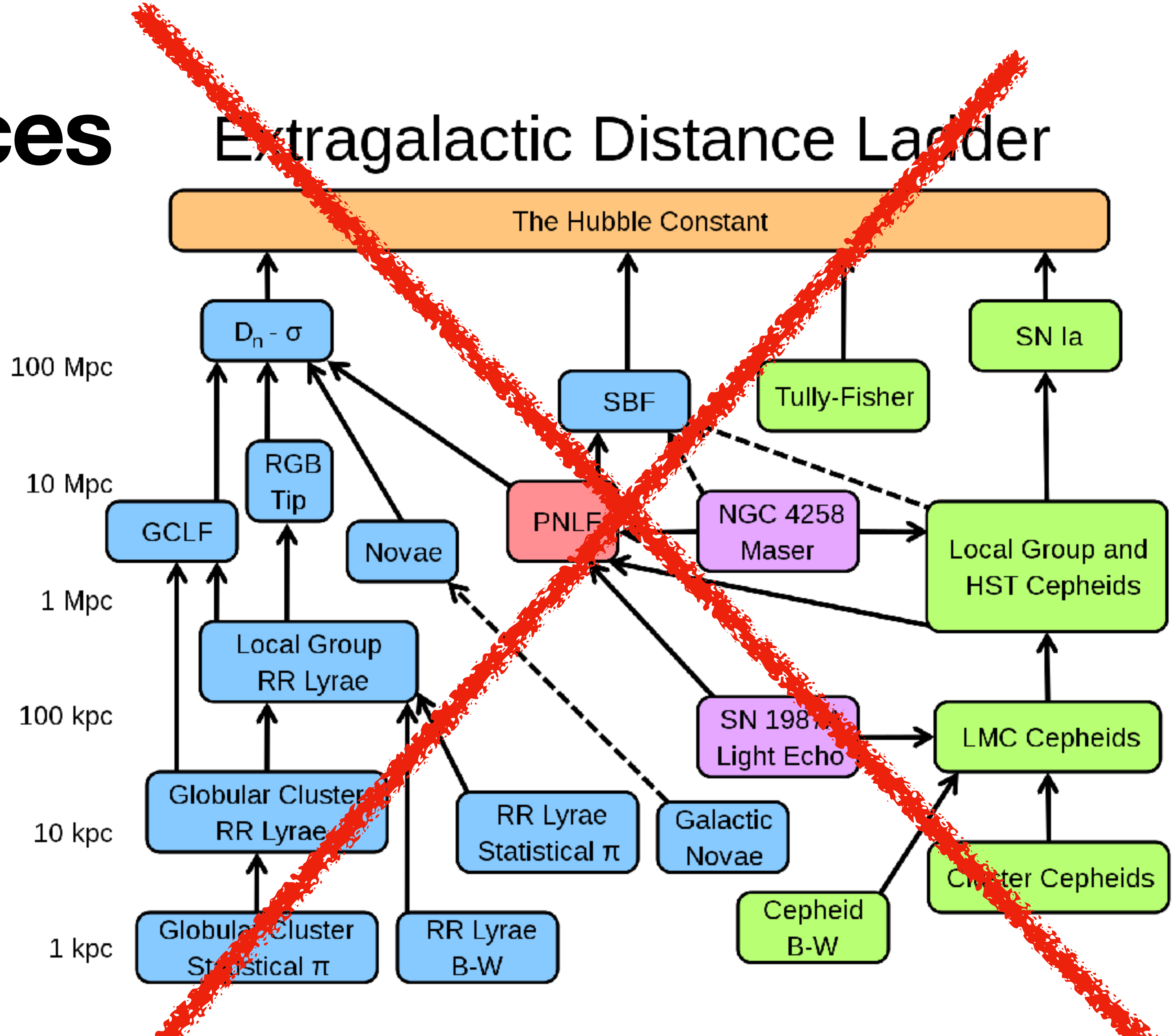
The distance ladder



WilliamKF, TilmannR at Wikipedia

Measuring distances

The distance ladder



WilliamKF, TilmannR at Wikipedia

Measuring distances

The modern distance ladder

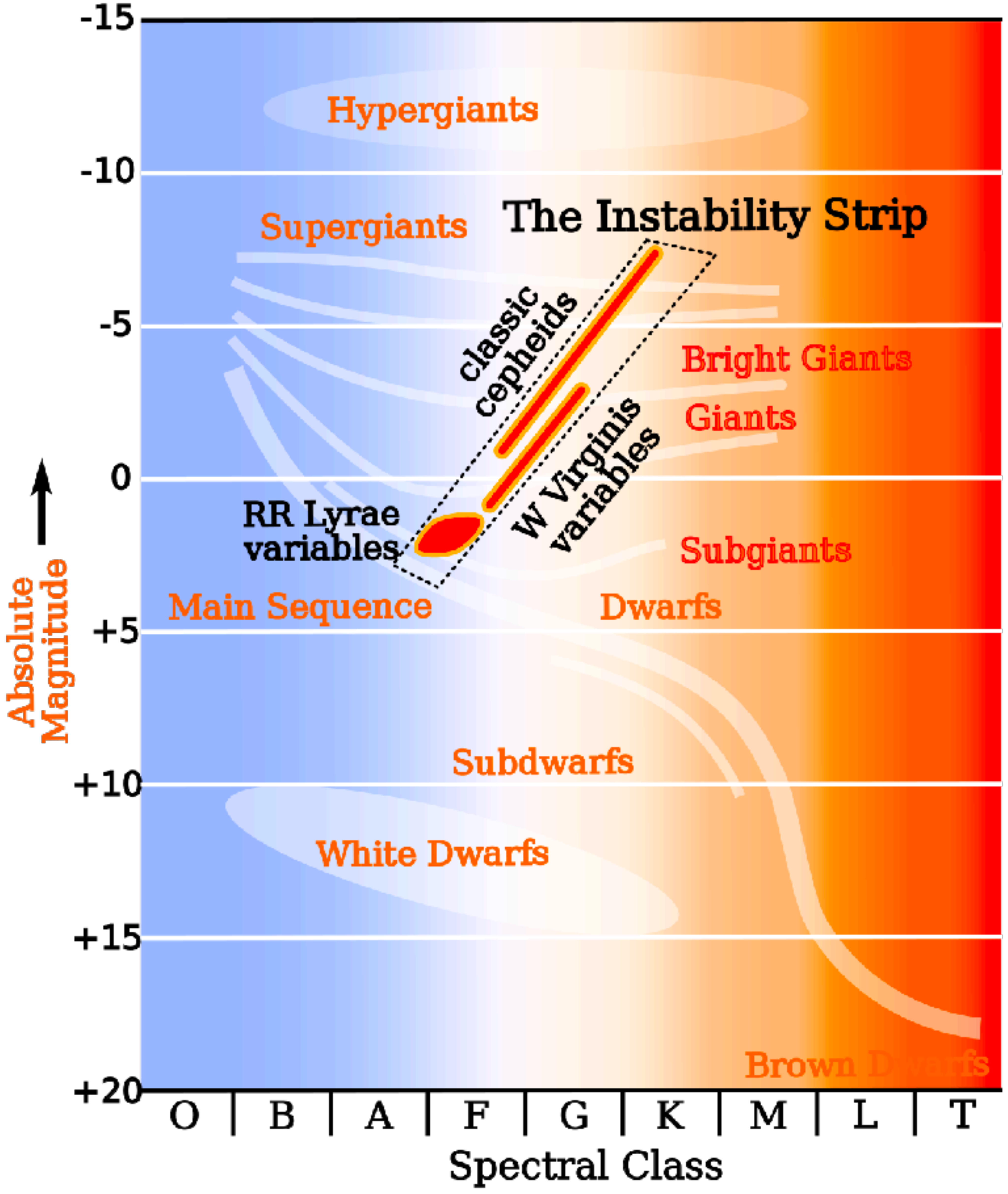
- Primary distances (parallax, eclipsing binaries, dynamical) calibrate the Cepheid period-luminosity relation (incl. metallicity)
- Cepheid distances calibrate supernova Ia distances
- Supernova Ia distances to galaxies in Hubble flow measure H_0

- Main alternative to Cepheids: tip-of-the-red-giant-branch as a standard candle (TRGB)

Measuring distances

Cepheid period-luminosity relation

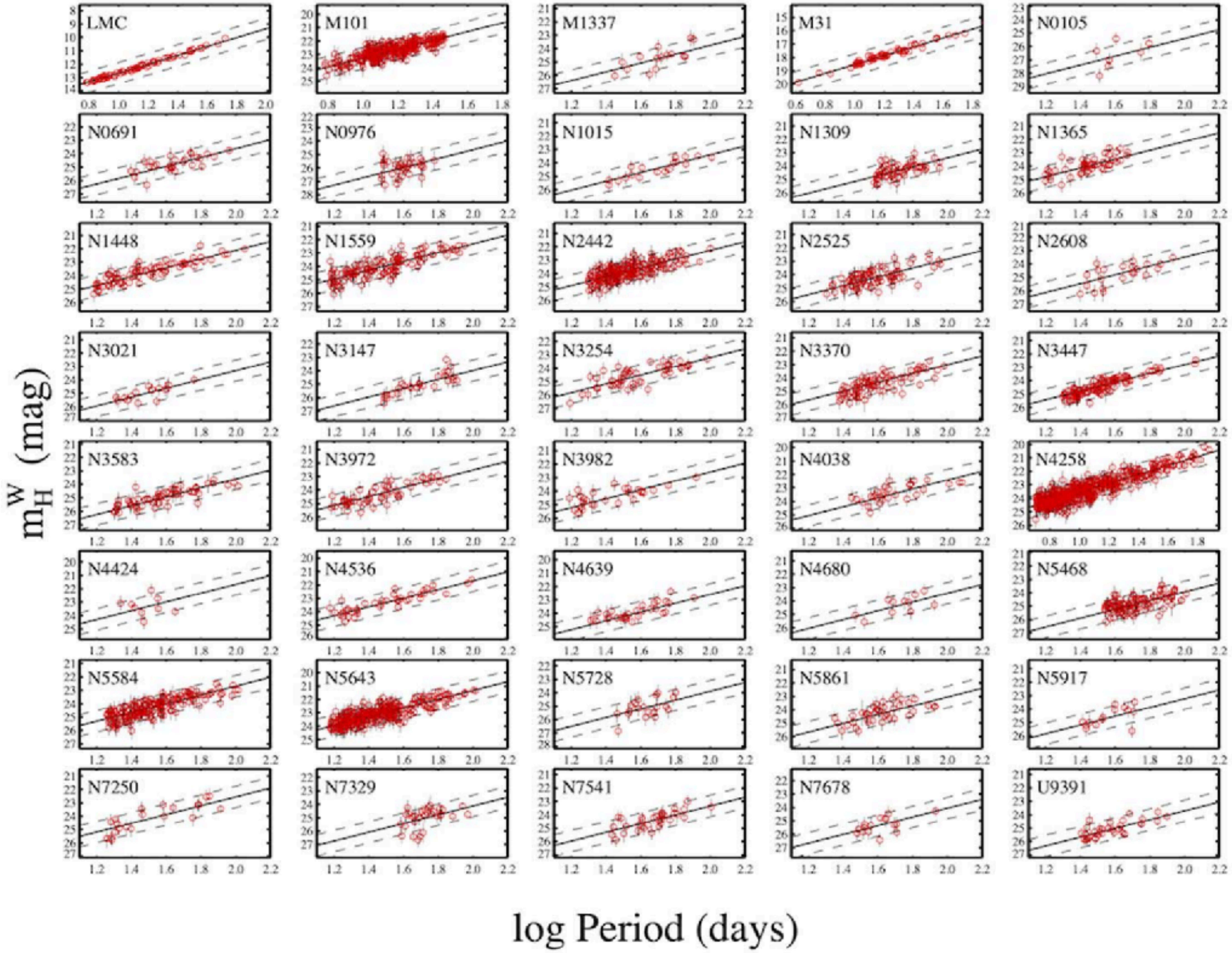
- Some stars execute stable pulsations
- Pulsation period ~ stellar density
- Luminosity ~ stellar density
- So period ~ luminosity
- Cepheids are bright and well-understood variable stars



Rursus at Wikipedia

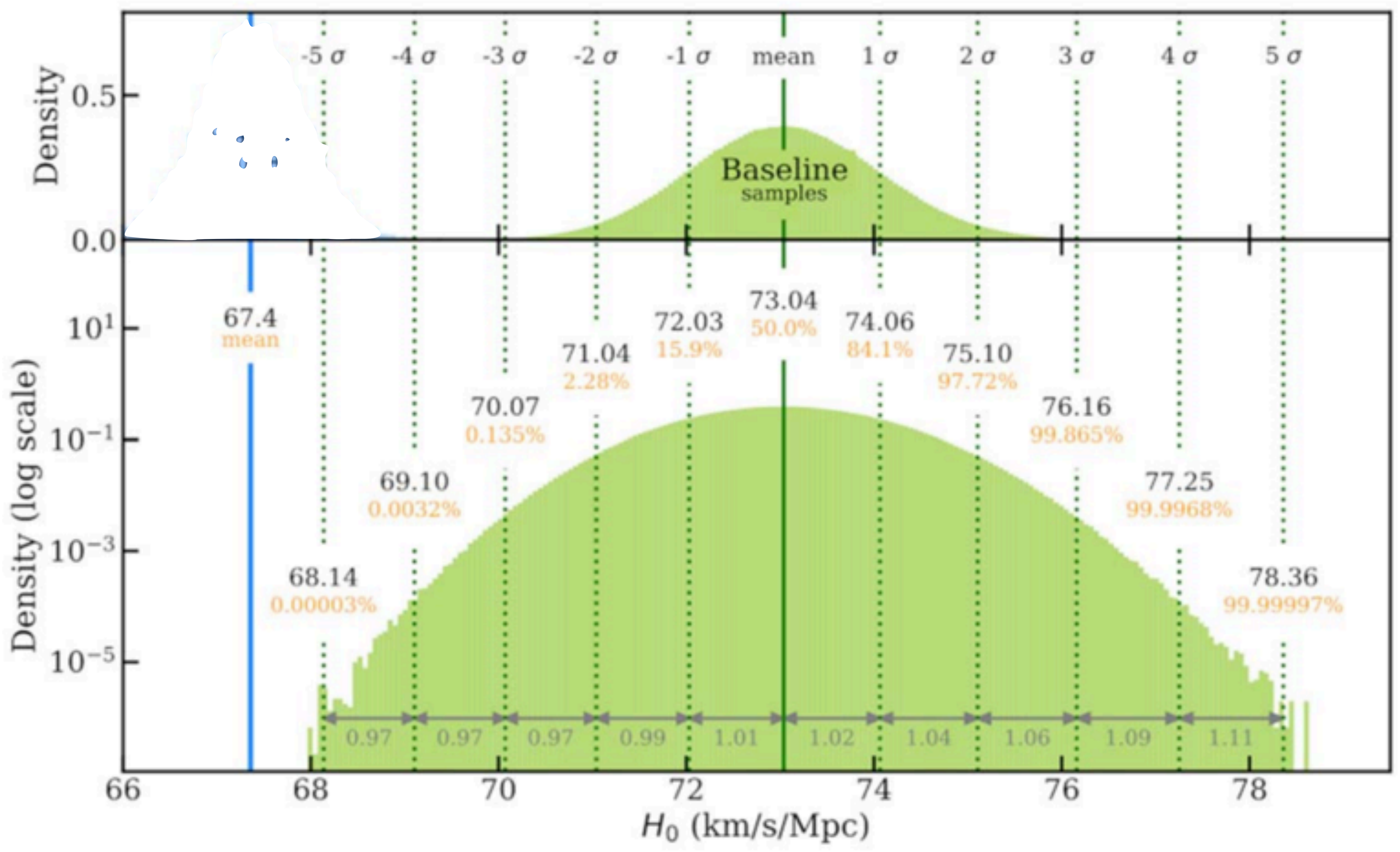
Measuring distances

Cepheid period-luminosity relation

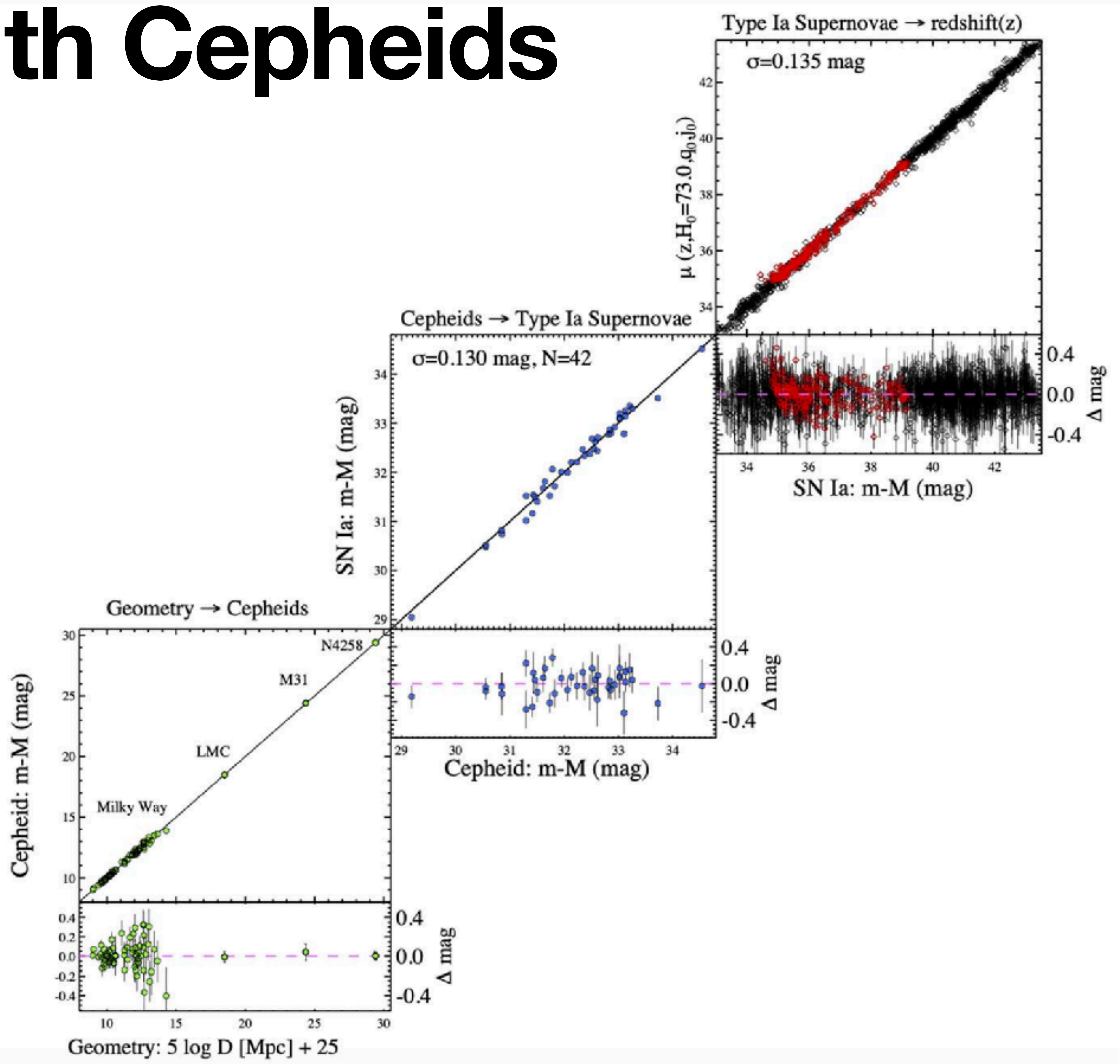


Riess et al. (2022)

Distance ladder with Cepheids



H_0 = 73 +/- 1 km/s/Mpc

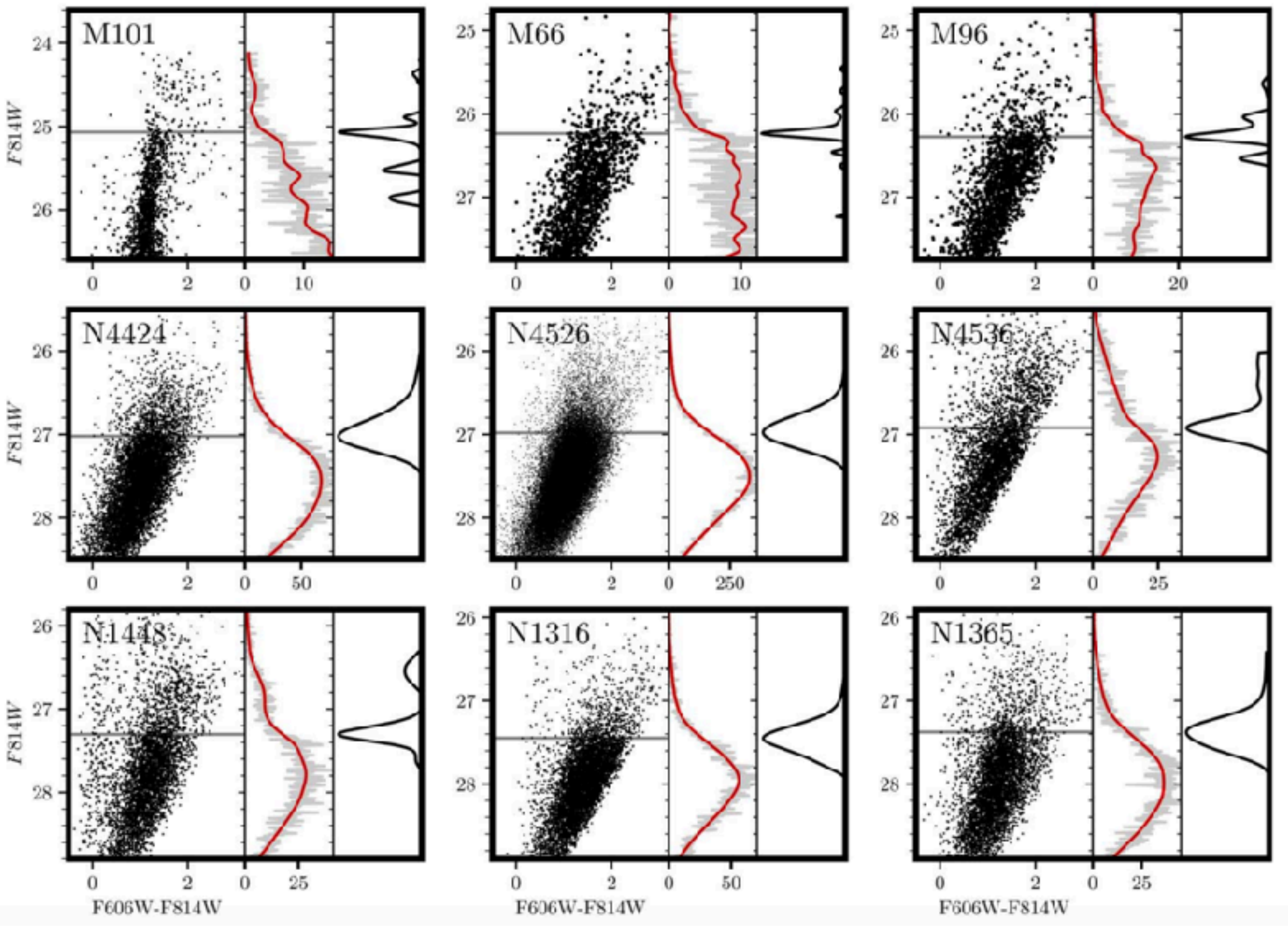


Riess et al. (2022)

Measuring distances

The tip of the red giant branch

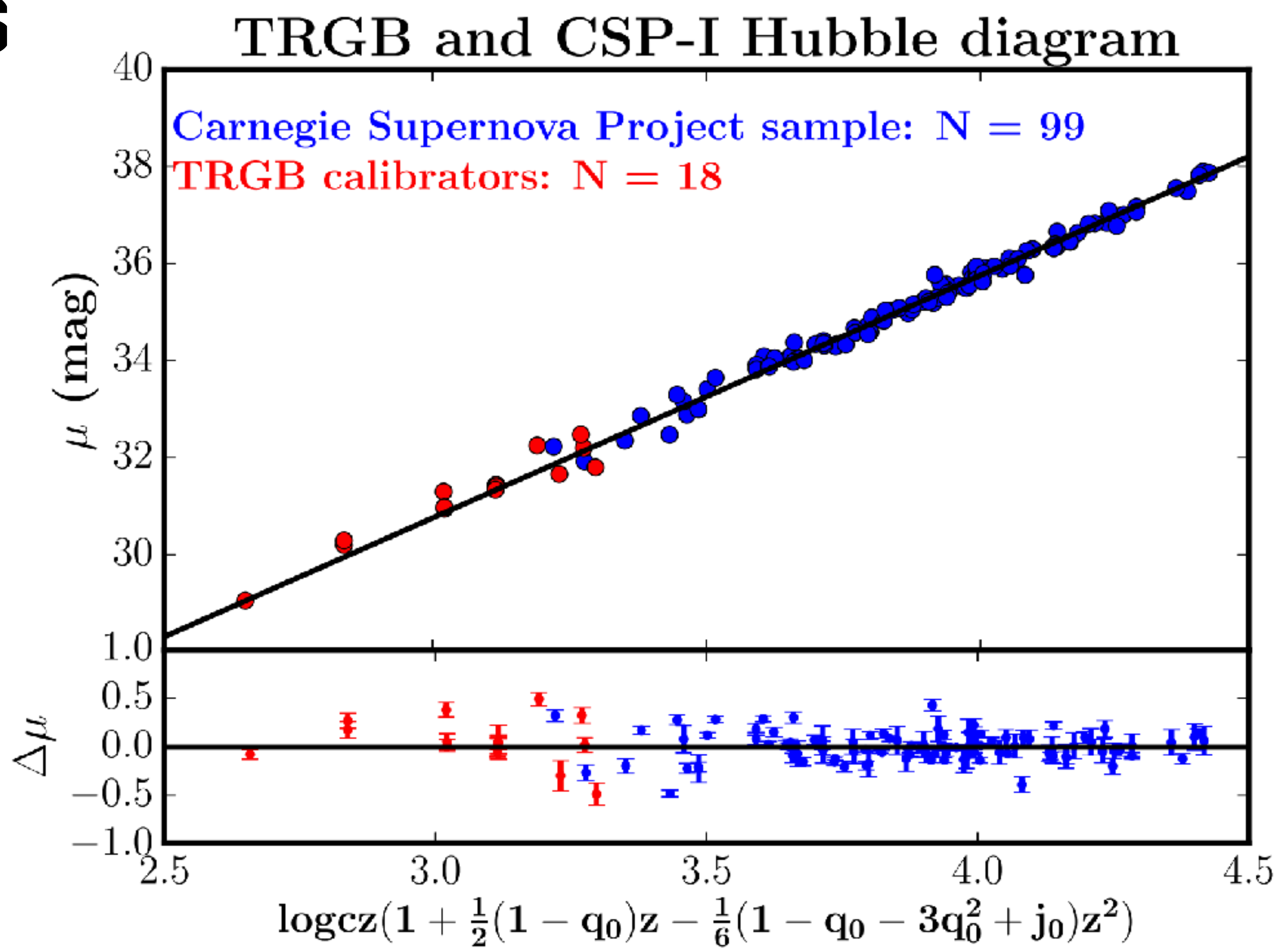
- After exhausting core hydrogen, stars slowly move up on the red giant branch burning hydrogen in shells
- This causes more helium to concentrate in the core, which becomes degenerate, but is not hot enough to fuse helium
- Eventually, the core temperature becomes high enough (~1e8 K) to fuse helium, which starts suddenly in a flash (the helium flash)
- The star then quickly settles into core helium burning at lower luminosity as the core expands and burns helium steadily
- As a process set by degenerate matter deep inside a star, the helium flash is highly regular between different environments (e.g., metallicity has little effect) —> standard candle



Freedman et al. (2019)

Measuring distances

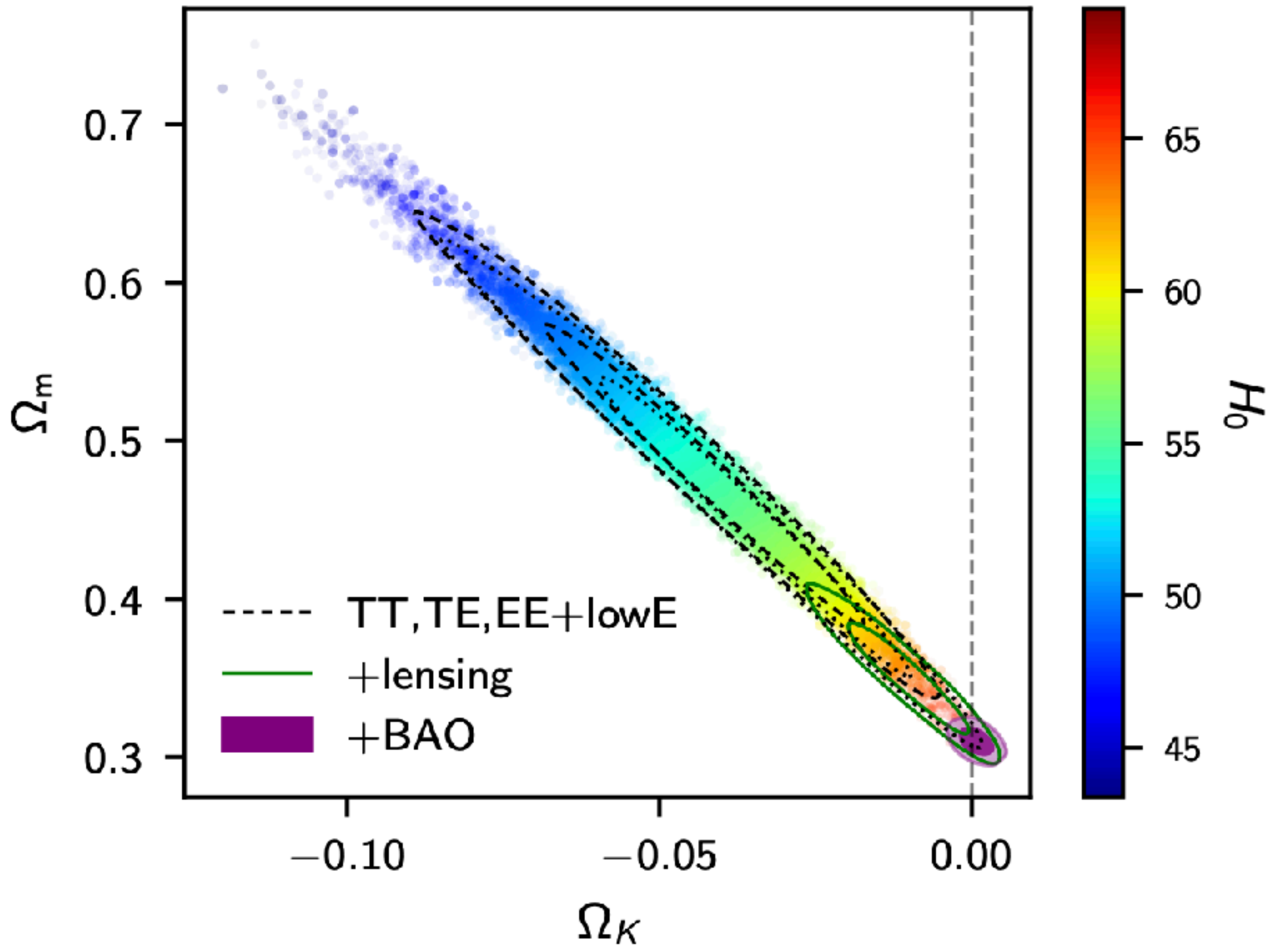
The tip of the red giant branch



H_0 = 70 +/- 2 km/s/Mpc

Freedman et al. (2019)

Measuring H_0 using CMB + BAO



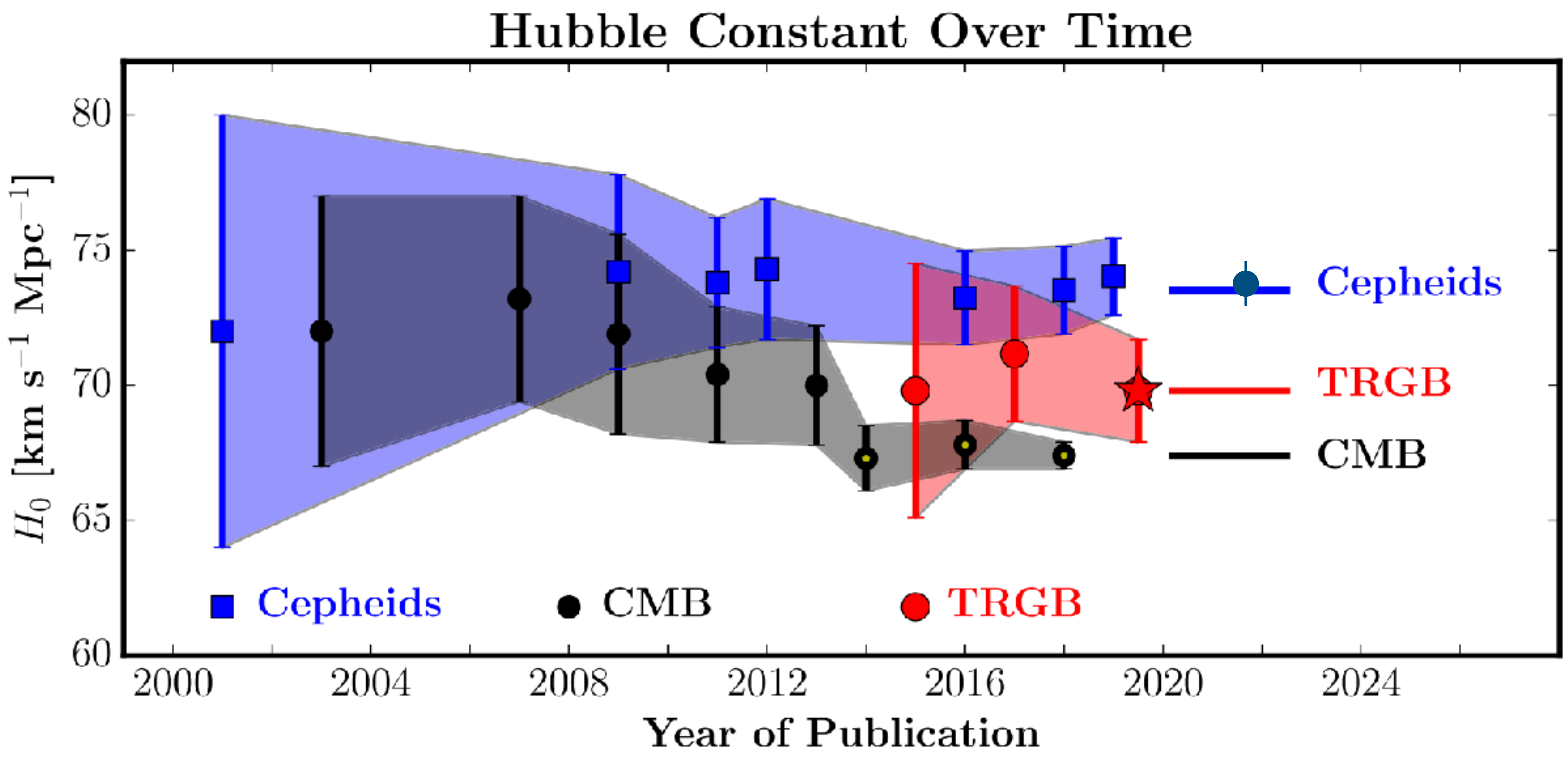
Measuring H_0 using CMB + BAO

- See two weeks ago
- CMB cannot measure H_0 without assuming flatness
- Assuming flat LCDM: $H_0 = 67.7 \pm 0.4$ km/s/Mpc

Parameter(s)	$\Omega_b h^2$	$\Omega_c h^2$	$100\theta_{MC}$	H_0	n_s	$\ln(10^{10}A_s)$
Base ΛCDM	0.02237 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.54	0.9649 ± 0.0042	3.044 ± 0.014
r	0.02237 ± 0.00014	0.1199 ± 0.0012	1.04092 ± 0.00031	67.40 ± 0.54	0.9659 ± 0.0041	3.044 ± 0.014
$dn_s/d\ln k$	0.02240 ± 0.00015	0.1200 ± 0.0012	1.04092 ± 0.00031	67.36 ± 0.53	0.9641 ± 0.0044	3.047 ± 0.015
$dn_s/d\ln k, r$	0.02243 ± 0.00015	0.1199 ± 0.0012	1.04093 ± 0.00030	67.44 ± 0.54	0.9647 ± 0.0044	3.049 ± 0.015
$d^2n_s/d\ln k^2, dn_s/d\ln k$.	0.02237 ± 0.00016	0.1202 ± 0.0012	1.04090 ± 0.00030	67.28 ± 0.56	0.9625 ± 0.0048	3.049 ± 0.015
N_{eff}	0.02224 ± 0.00022	0.1179 ± 0.0028	1.04116 ± 0.00043	66.3 ± 1.4	0.9589 ± 0.0084	3.036 ± 0.017
$N_{eff}, dn_s/d\ln k$	0.02216 ± 0.00022	0.1157 ± 0.0032	1.04144 ± 0.00048	65.2 ± 1.6	0.950 ± 0.011	3.034 ± 0.017
Σm_ν	0.02236 ± 0.00015	0.1201 ± 0.0013	1.04088 ± 0.00032	$67.1^{+1.2}_{-0.67}$	0.9647 ± 0.0043	3.046 ± 0.015
$\Sigma m_\nu, N_{eff}$	0.02221 ± 0.00022	$0.1179^{+0.0027}_{-0.0030}$	1.04116 ± 0.00044	$65.9^{+1.8}_{-1.6}$	0.9582 ± 0.0086	3.037 ± 0.017
$m^{eff}_{\nu,\,sterile}, N_{eff}$	$0.02242^{+0.00014}_{-0.00016}$	$0.1200^{+0.0032}_{-0.0020}$	$1.04074^{+0.00033}_{-0.00029}$	$67.11^{+0.63}_{-0.79}$	$0.9652^{+0.0045}_{-0.0056}$	$3.050^{+0.014}_{-0.016}$
α_{-1}	0.02238 ± 0.00015	0.1201 ± 0.0015	1.04087 ± 0.00043	67.30 ± 0.67	0.9645 ± 0.0061	3.045 ± 0.014
w_0	0.02243 ± 0.00015	0.1193 ± 0.0012	1.04099 ± 0.00031	. . .	0.9666 ± 0.0041	3.038 ± 0.014
Ω_K	0.02249 ± 0.00016	0.1185 ± 0.0015	1.04107 ± 0.00032	$63.6^{+2.1}_{-2.3}$	0.9688 ± 0.0047	$3.030^{+0.017}_{-0.015}$
Y_P	0.02230 ± 0.00020	0.1201 ± 0.0012	1.04067 ± 0.00055	67.19 ± 0.63	0.9621 ± 0.0070	3.042 ± 0.016
Y_P, N_{eff}	0.02224 ± 0.00022	$0.1171^{+0.0042}_{-0.0049}$	1.0415 ± 0.0012	$66.0^{+1.7}_{-1.9}$	0.9589 ± 0.0085	3.036 ± 0.018
A_L	0.02251 ± 0.00017	0.1182 ± 0.0015	1.04110 ± 0.00032	68.16 ± 0.70	0.9696 ± 0.0048	$3.029^{+0.018}_{-0.016}$

Planck 2018 VI (2020)

The H_0 tension



Freedman et al. (2019)

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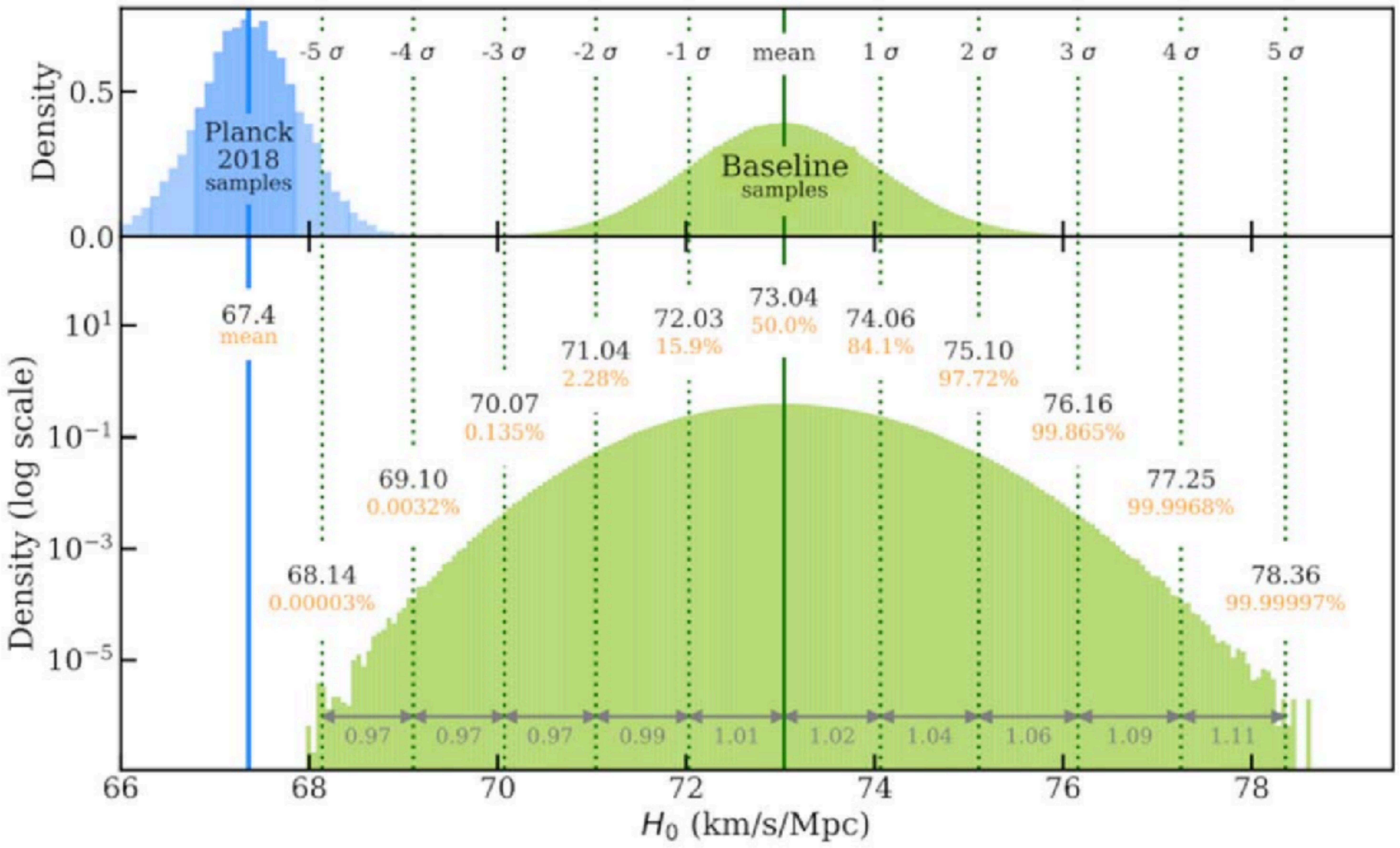
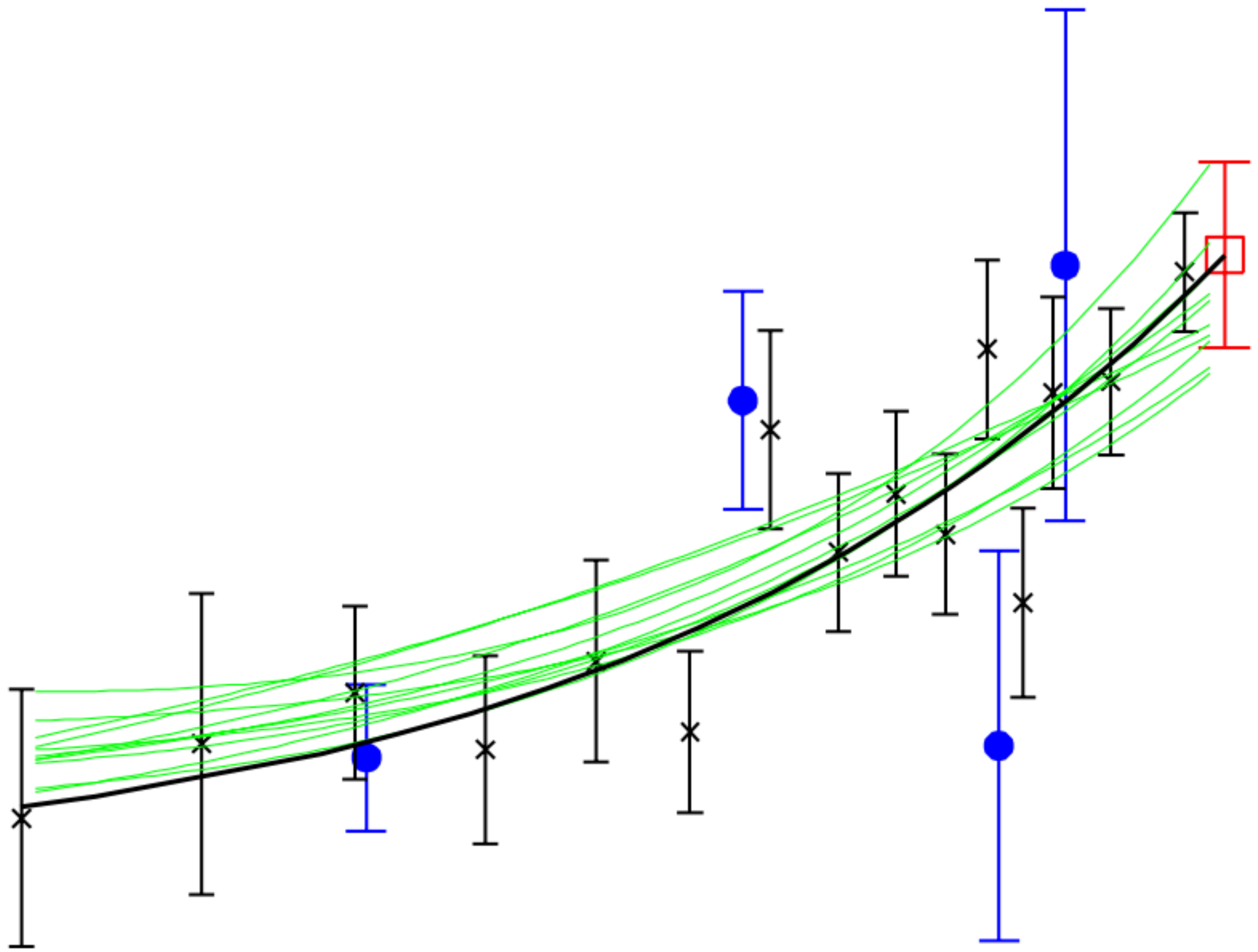


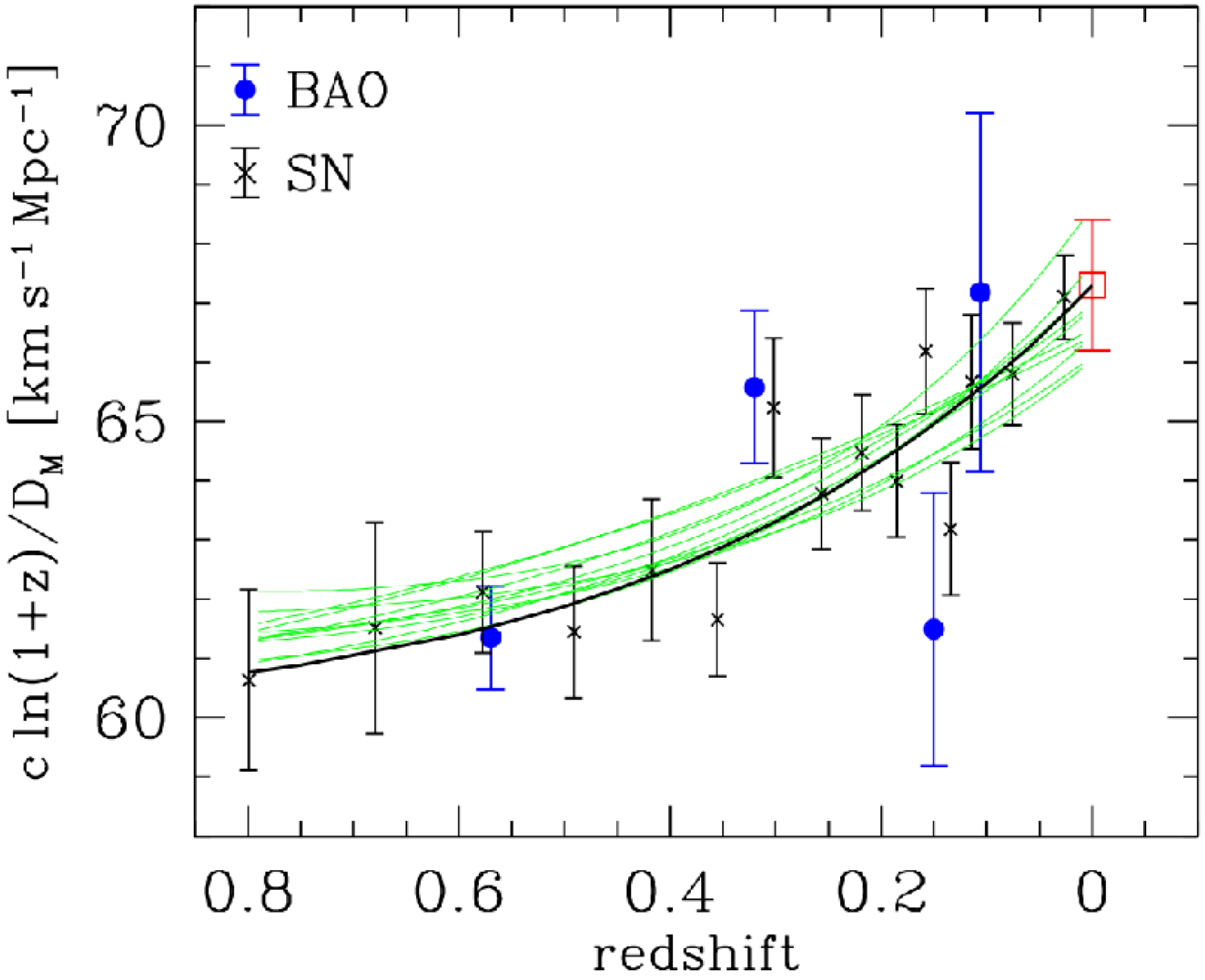
Riess et al. (2022)

Measuring H_0 cosmologically using the inverse distance ladder



Measuring H_0 cosmologically using the inverse distance ladder

- Inverse distance ladder:
  - CMB calibrates r_d, the sound horizon at decoupling
  - BAO measurements determine Hubble function $H(z)/r_d$ and co-moving angular diameter distance $D_M(z)/r_d$ at the median redshift of a survey
    —> + CMB provides absolute distances
  - SNe Ia provide relative distance measurements from z ~ 0 to z ~ 2
    —> + BAO calibrates absolute distances
  - Extrapolation to z = 0 provides H_0
- Extrapolation to z=0 depends on cosmological model, but only weakly



Aubourg et al. (2015)

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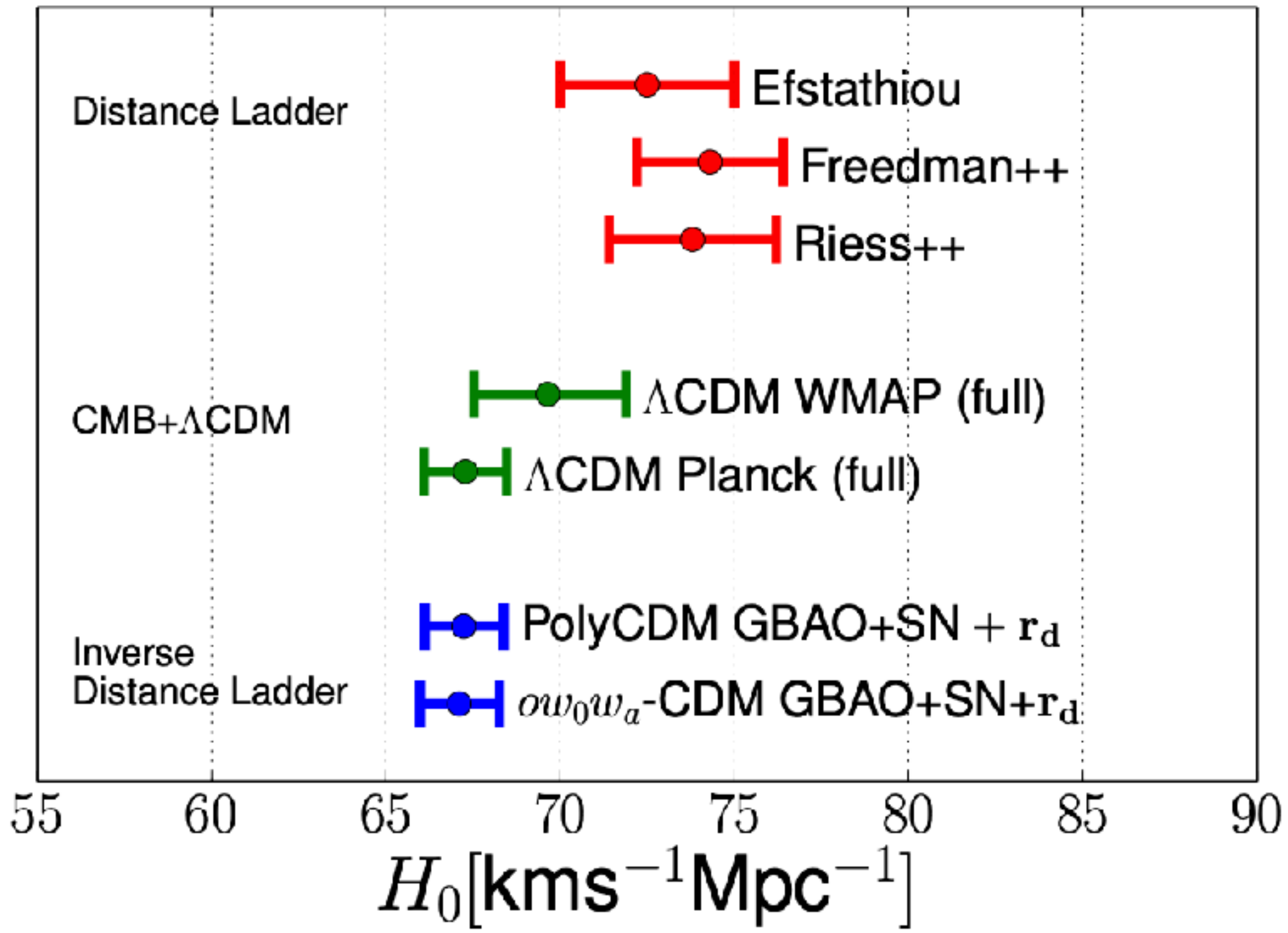
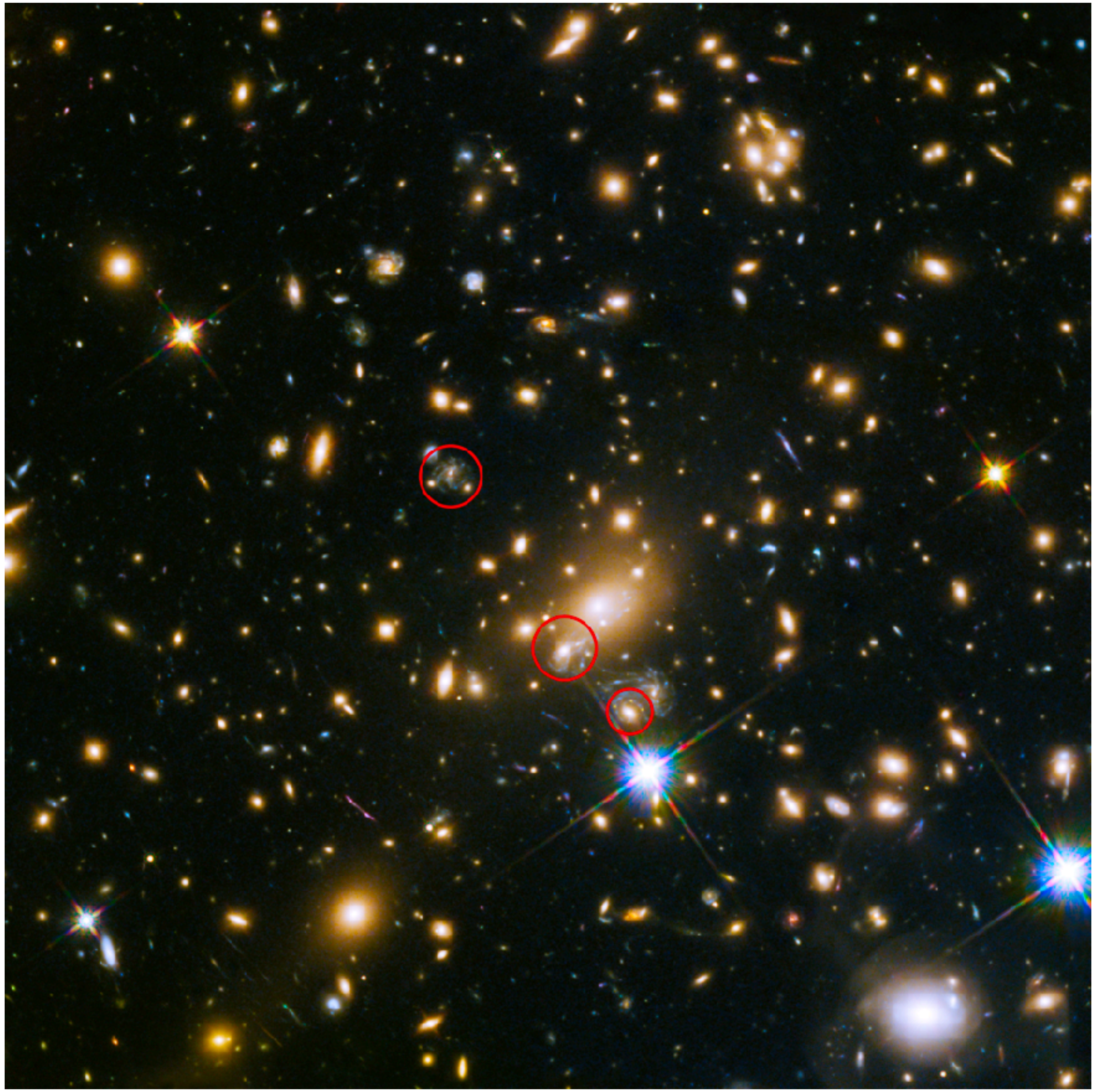


Aubourg et al. (2015)

Alternative ways of measuring H_0



Alternative ways of measuring H_0

Gravitational lensing

- Strong gravitational lensing is sensitive to:
    - Lensing potential $$\psi(\boldsymbol{\theta}) = \frac{D_{\rm LS}}{D_{\rm S}\, D_{\rm L}} \frac{2}{c^2} \int {\rm d}z\, \Phi(D_{\rm L}\boldsymbol{\theta}, z)$$
    - Deflections $$\hat{\boldsymbol{\alpha}} = 2 \int {\rm d}s\, \nabla_\perp \left(\frac{\Phi}{c^2}\right)$$
    - Distortions and magnifications $$\mathcal{A}_{ij} = \frac{\partial \beta_i}{\partial \theta_j} = \delta_{ij} - \frac{\partial \alpha_i}{\partial \theta_j}$$
- Deflections, distortions, and magnifications are *dimensionless quantities* —> measure dimensionless aspects of the mass distribution (so no H_0!)
- Time delay between different images is dimensionful!

Alternative ways of measuring H_0

Gravitational lensing

- Time delay between different images is the sum of the geometric time delay and the Shapiro delay

$$\Delta t_{\mathrm{lensing}} = \frac{1+z_{\mathrm{L}}}{c} \frac{D_{\mathrm{L}}\, D_{\mathrm{S}}}{D_{\mathrm{LS}}} \left[\frac{1}{2} |\boldsymbol{\theta} - \boldsymbol{\beta}|^2 - \psi(\boldsymbol{\theta}) \right]$$
$$= \frac{D_{\Delta t}}{c}\, \tau(\boldsymbol{\theta}; \boldsymbol{\beta})\,,$$

- With

$$D_{\Delta t} = (1+z_{\mathrm{L}}) \frac{D_{\mathrm{L}}\, D_{\mathrm{S}}}{D_{\mathrm{LS}}}$$

  where all the distances are angular diameter distances and $\boldsymbol{\tau}$ is the Fermat potential

- $D_{\Delta t} \propto H_0$, with only a weak dependence on the assumed cosmological model

Alternative ways of measuring H_0

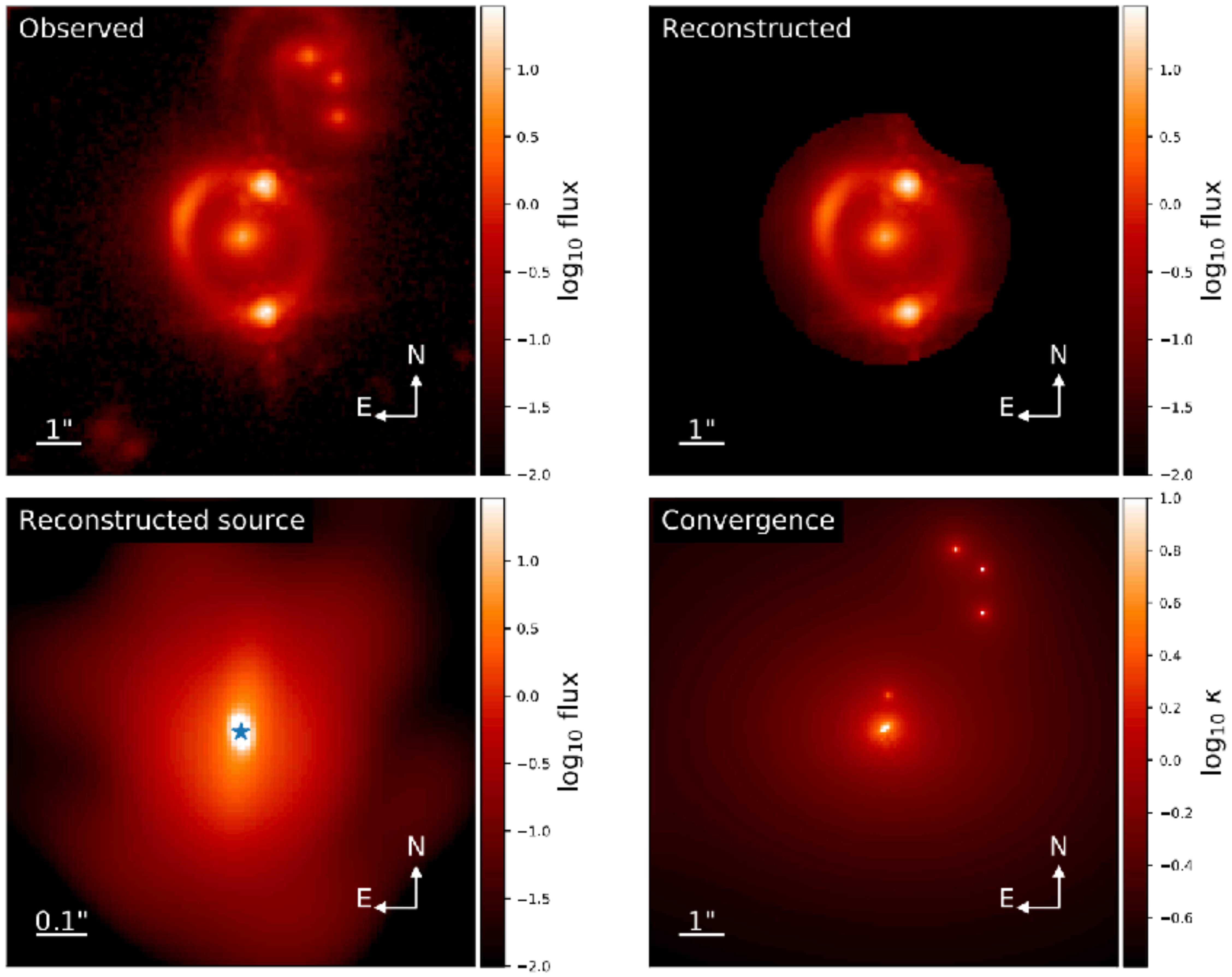
Gravitational lensing

- Time delay cosmography:
  - Determine time delays of lensed images using a variable background source (originally supernova, Refsdal 1964; now generally quasars)
  - Measurements of deflection angles (arcs) and/or relative magnifications fix the dimensionless Fermat potential τ
  - Observed time delays then provide a measurement of H_0
  - No need for distance calibration!

Alternative ways of measuring H_0

Gravitational lensing - some results

- Current: H_0 = 73.3 +/- 1.7 km/s/Mpc (Wong et al. 2020)
    - So agrees with Cepheid measurement



Birrer et al. (2019)

Alternative ways of measuring H_0

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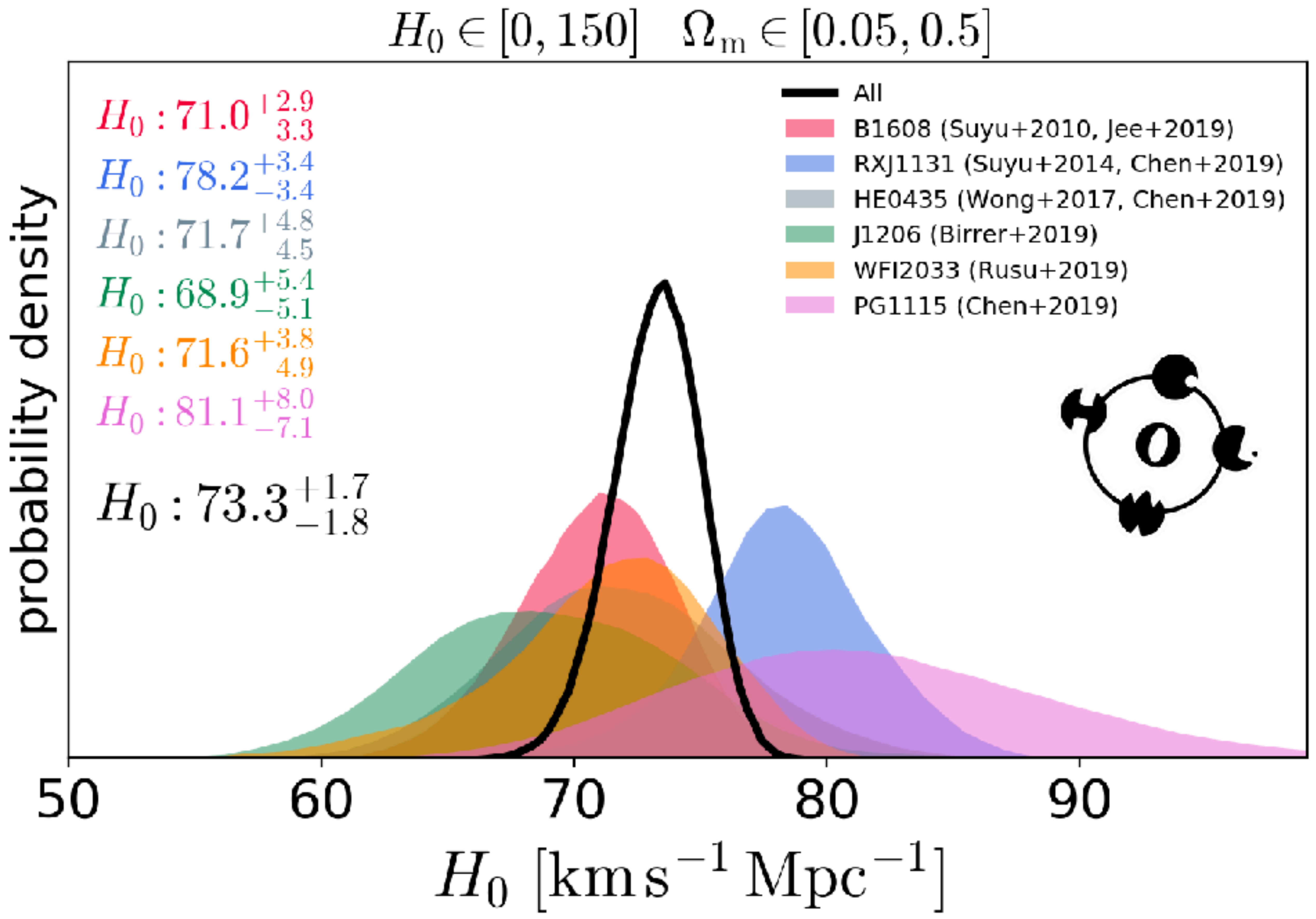
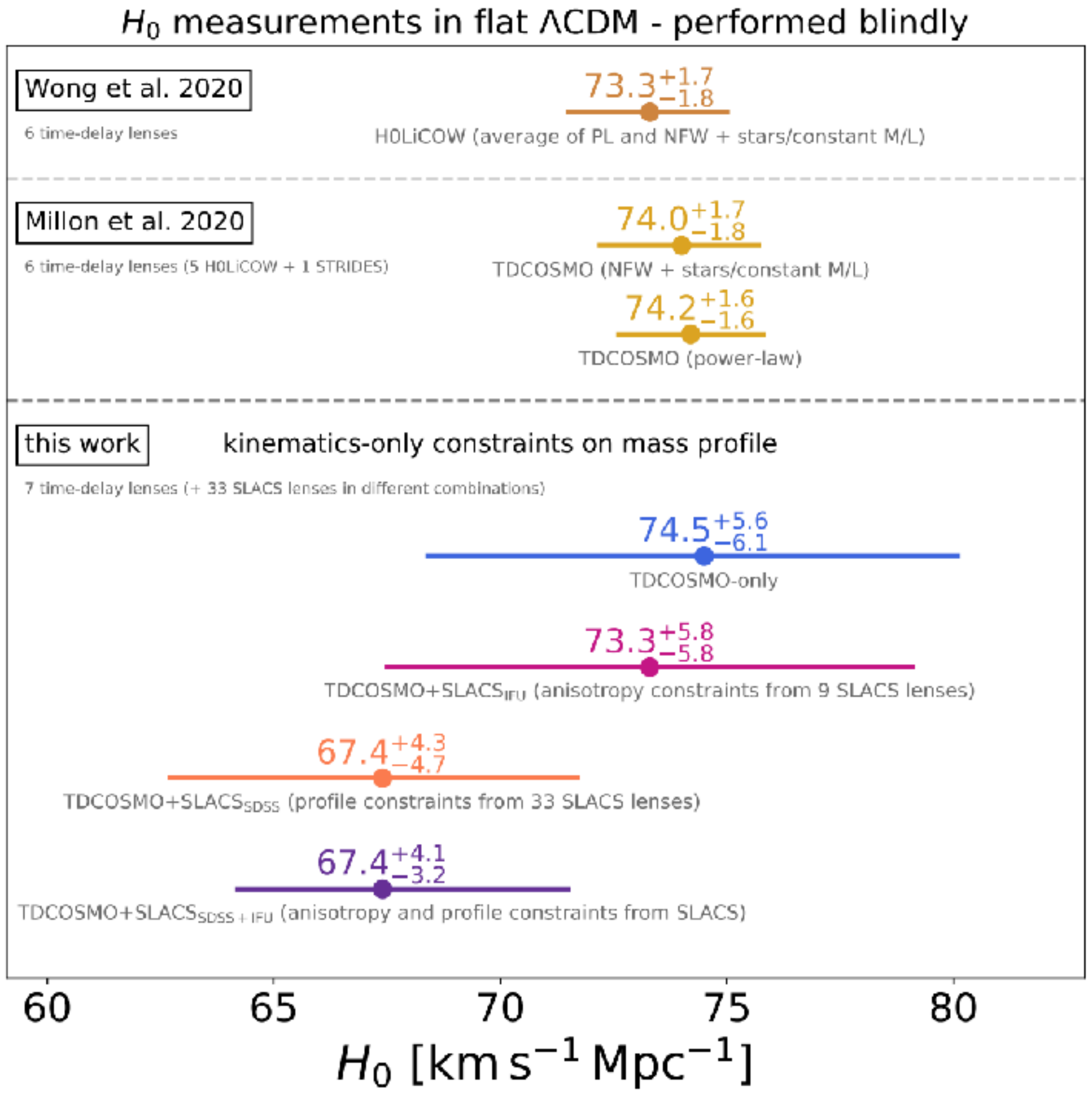


Wong et al. (2020)

Alternative ways of measuring H_0

Gravitational lensing - some results

- Current: H_0 = 73.3 +/- 1.7 km/s/Mpc (Wong et al. 2020)
    - So agrees with Cepheid measurement
- But affected by the *mass-sheet degeneracy*:
    - $$\psi(\boldsymbol{\theta}) \to \frac{\lambda}{2}|\boldsymbol{\theta}|^2 + \boldsymbol{\beta}' \cdot \boldsymbol{\theta} + \frac{1}{2}|\boldsymbol{\beta}|^2 - \frac{1}{2(1-\lambda)}|\boldsymbol{\beta} + \boldsymbol{\beta}'|^2 + (1-\lambda)\,\psi(\boldsymbol{\theta})$$
    - Does not affect deflections or relative magnifications, but multiplies H_0 by (1-λ)



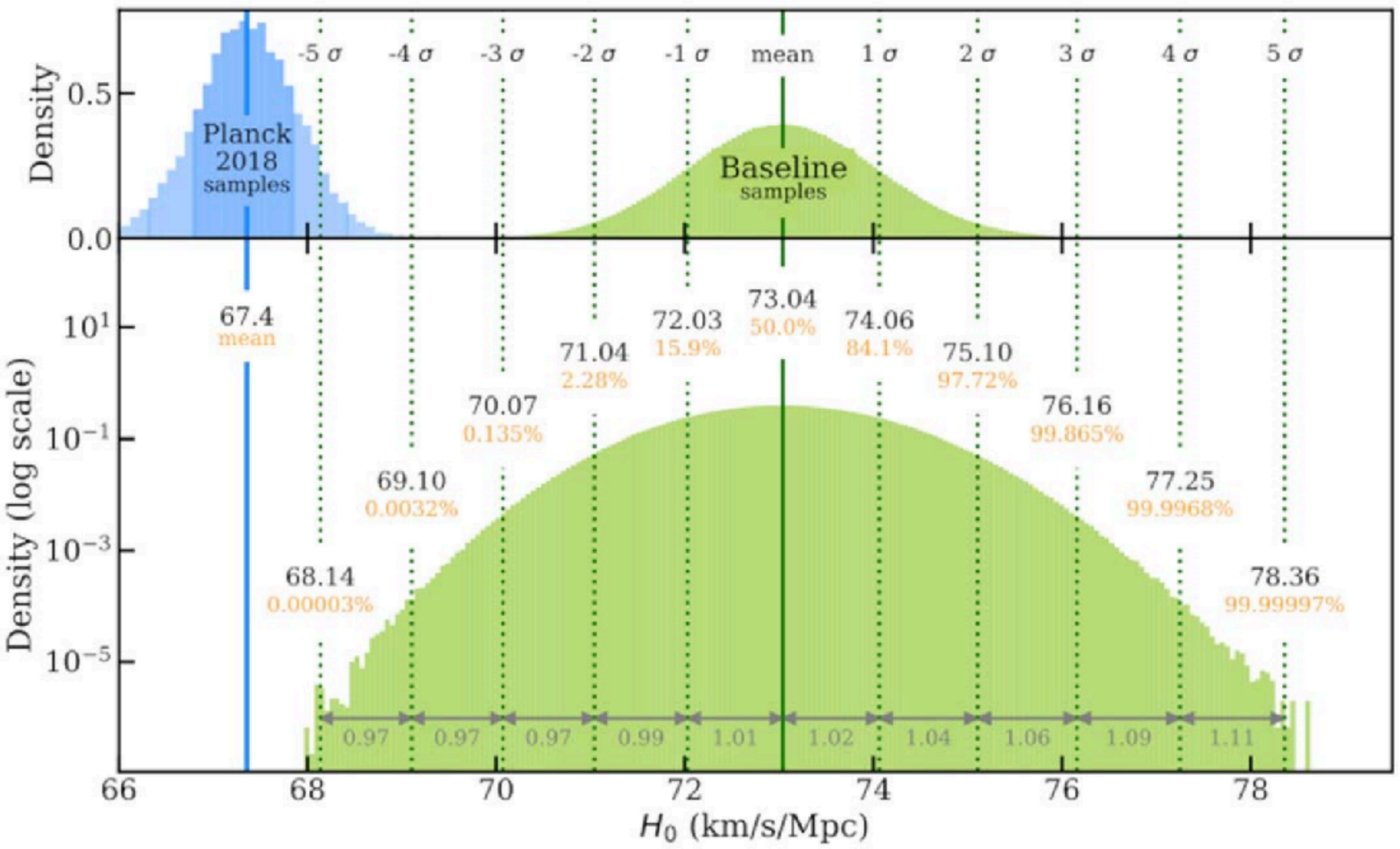
Birrer et al. (2020)

Alternative ways of measuring H_0

Gravitational waves

- Gravitational waves from the merger of binary neutron stars (NS) allow measurements of the amplitude and the time scale of frequency changes
- These depend on NS masses in the same way and otherwise the only unobservable is the (luminosity) distance —> gravitational waves from binary NS are standard candles (Schutz 1986)
- EM counterpart allows redshift to be determined (e.g., GW 170817) —> H_0
- Abbott et al. (2017) with GW170817: H_0 = 70 +/- 10 km/s/Mpc
- Will need *many* more sources to become a competitive measurement

Theoretical implications of the H_0 discrepancy



Theoretical implications of the H_0 discrepancy

- Inhomogeneities from structure growth change locally observed value of H_0
—> tiny effect over the large volume observed by the SN Ia

- Inverse distance ladder demonstrates that late-time solutions are difficult to make work: even very general cosmological models used in inverse distance ladder give low H_0

- Both simple flat-LCDM Planck and the inverse distance ladder depend on the sound horizon r_d at decoupling
—> changing this could alleviate the H_0 tension

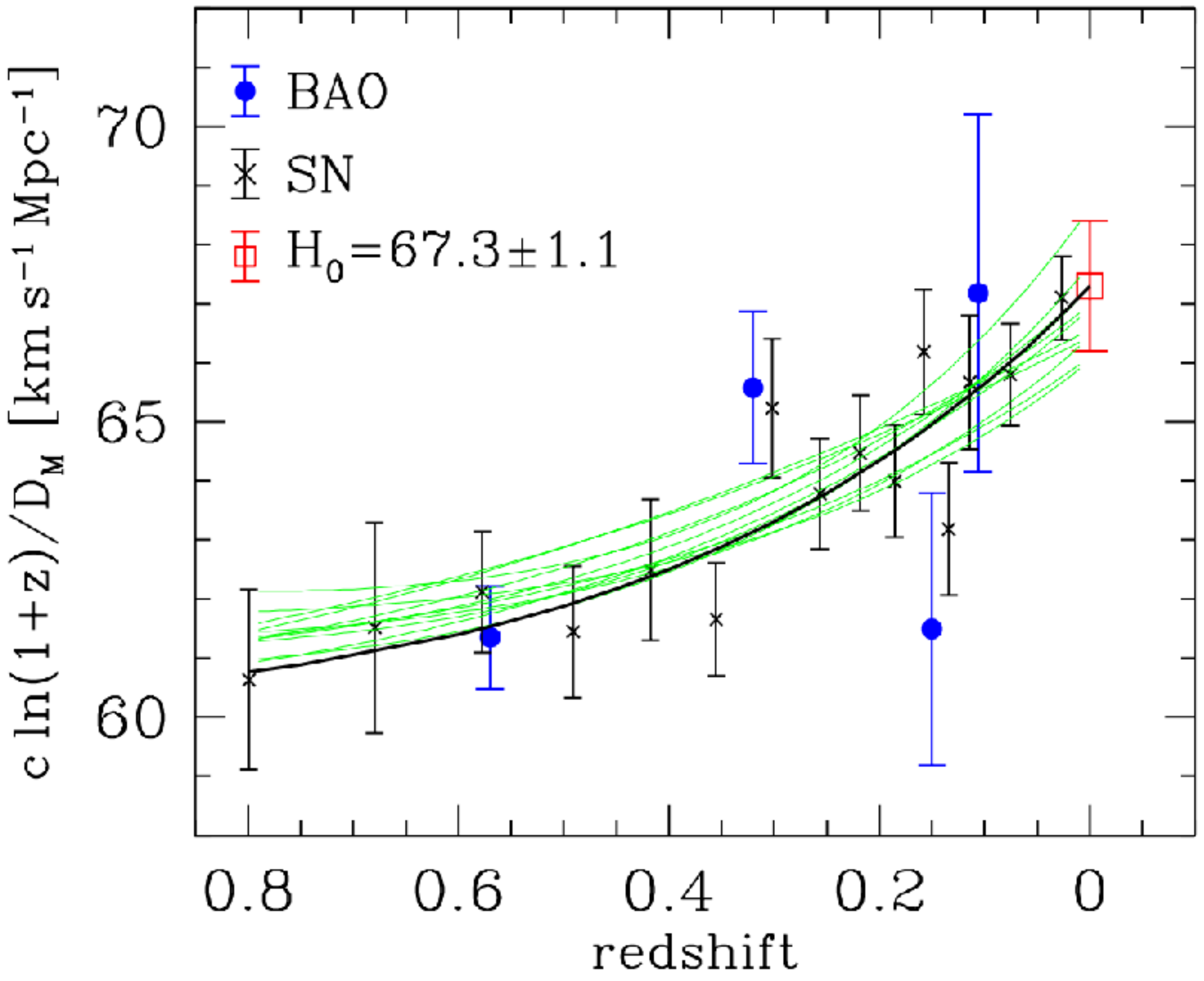
- Changing the sound horizon requires some non-standard physics *before recombination*

Changing the sound horizon

- The sound horizon at decoupling is given by

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz$$

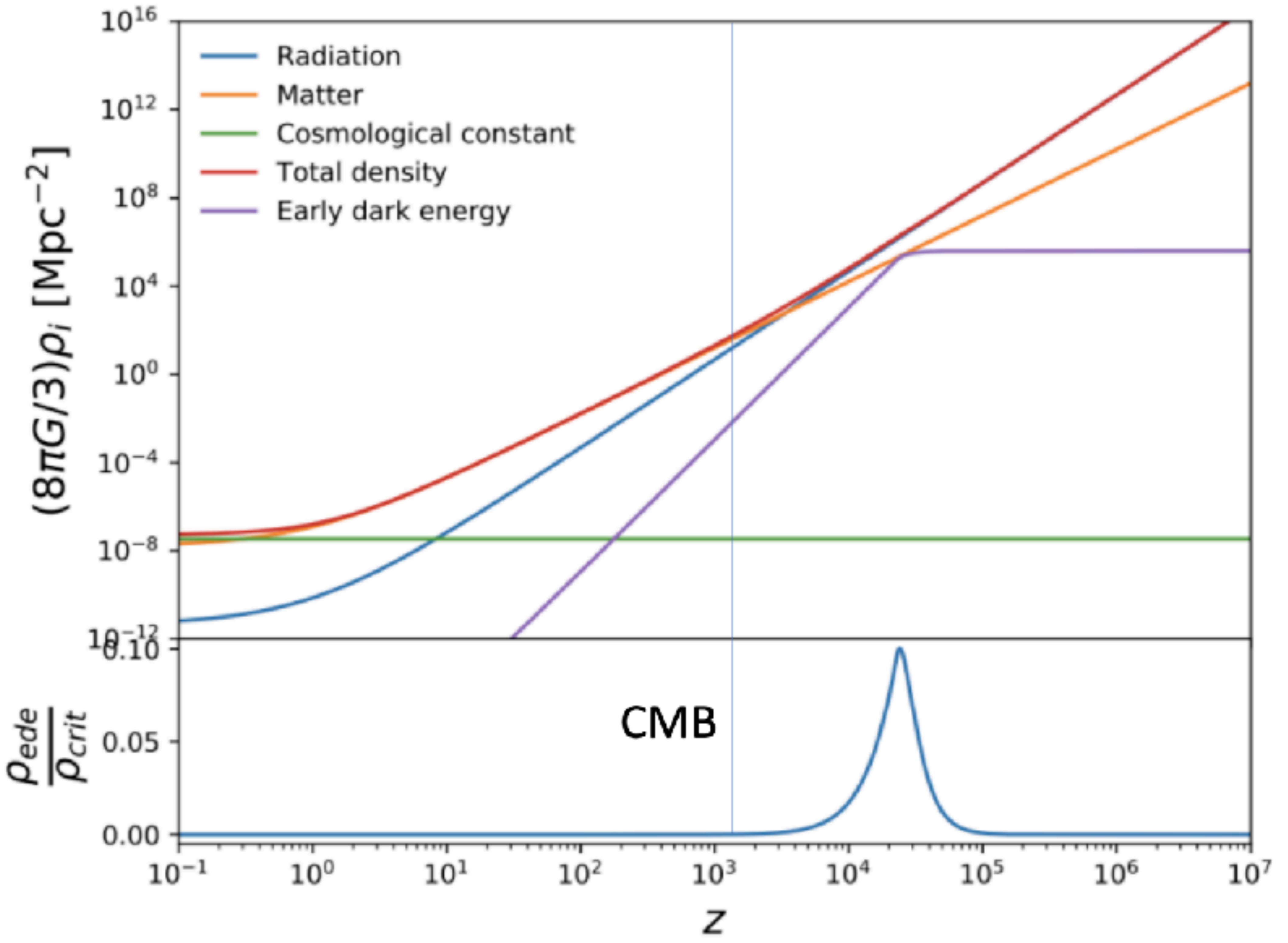
- Alleviating the inverse distance ladder requires
  - Smaller D_M
  - BAO measures DM/r_d —> smaller r_d
  - So H(z) must have been higher pre-decoupling than in the standard scenario



Aubourg et al. (2015)

Early dark energy

- One way to raise H(z) before decoupling is to posit an epoch of dark energy that is important before decoupling
- Has to decay, because otherwise would drive exponential inflation!
- This is like inflation, which is driven by a similar field (e.g., slow-roll inflation)
- Other current models for changing r_d don't seem to be able to fit all the data (e.g., changing the effective number of neutrino species, interacting neutrinos…)



Kamionkowski & Riess (2022)

Conclusion

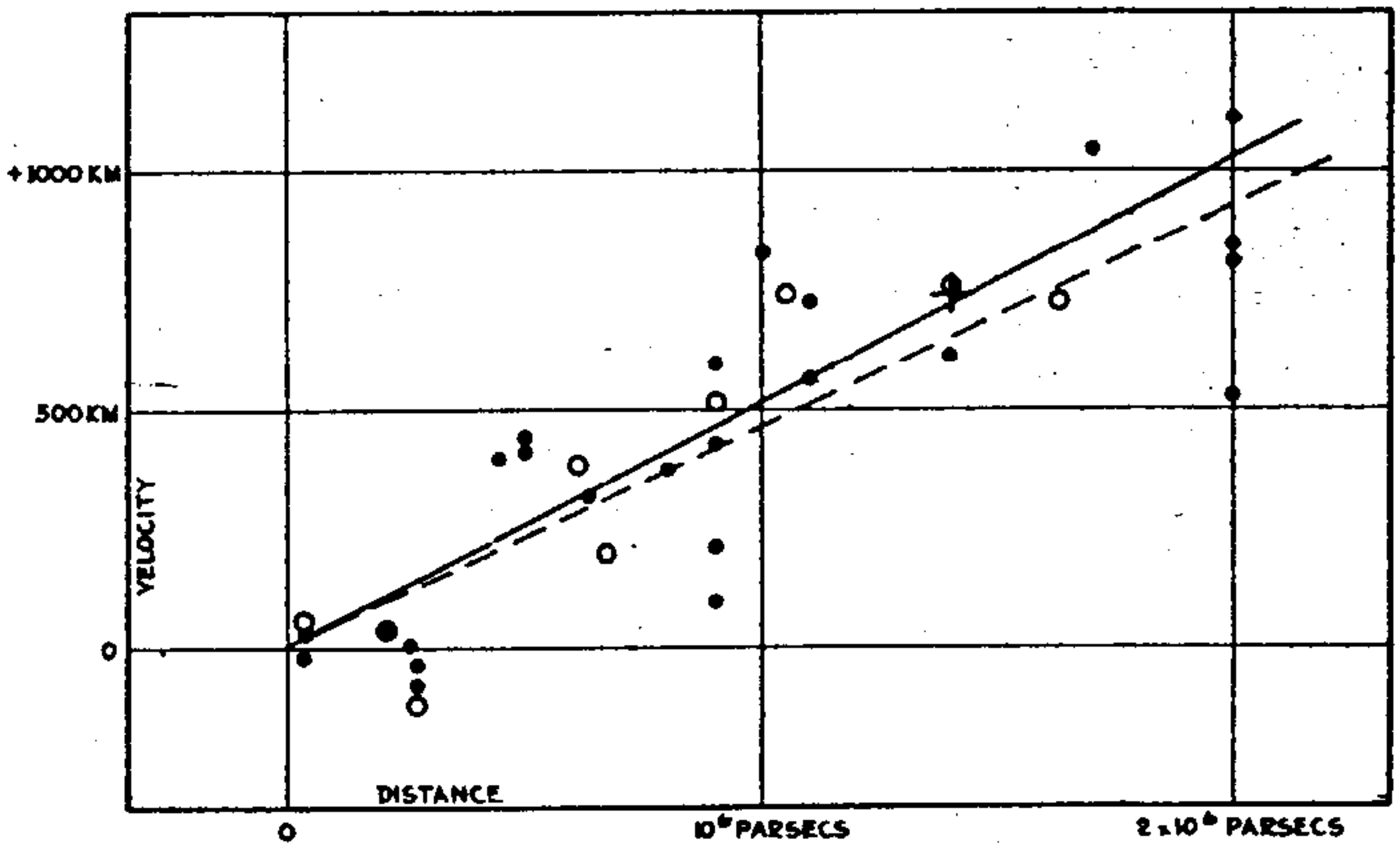


FIGURE 1

Conclusion

- 5σ discrepancy between H_0 from Planck/inverse-distance-ladder and that from Cepheids+SNIa (local)
- No other method has the precision and accuracy currently to show that the local measurement is in error
- Possible that there is a systematic that is unaccounted for in the Cepheid+SNIa analysis, but data-driven analysis that is quite robust
- Few good theoretical models for the discrepancy exist, with early dark energy being the leading contender, but no compelling physical model that has other unique implications exists
- Most optimistically: the H_0 discrepancy might be the indication of the nature of dark energy —> perhaps different epochs of ‘inflation’ are related through a single model???