

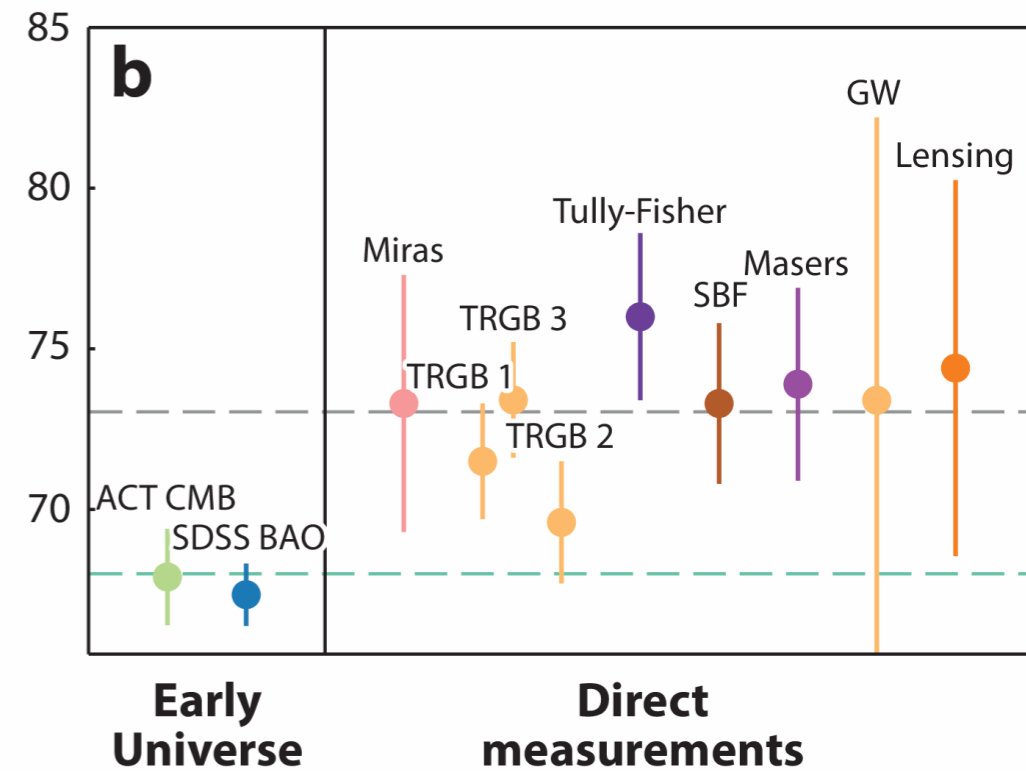
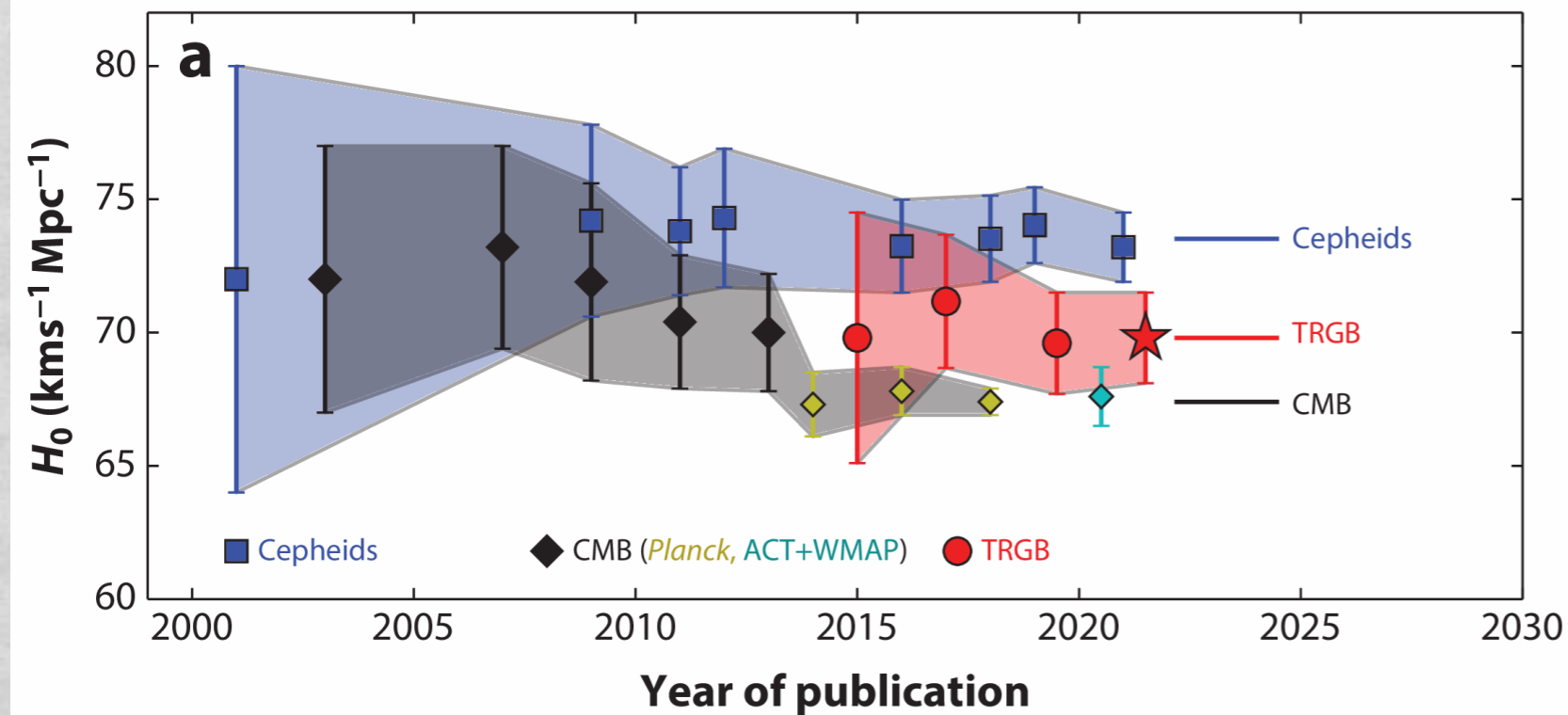
THE HUBBLE TENSION

PHYS 76000

THE HUBBLE TENSION

- Around 2013, people started to notice that measurements of the Hubble parameter at $z=0$ becoming increasingly in disagreement.
- This wasn't a huge shock since there have been disagreement over the Hubble parameter since Hubble's paper.
- However, in this case it seemed that different approaches were giving different values.

Hubble constant over time



Verde L, et al. 2024

Annu. Rev. Astron. Astrophys. 62:287–331

- We see that methods using Cepheids give values around 72 km/s/Mpc .
- While methods using the CMB find 68 km/s/Mpc .
- Also direct measurements of velocity versus distance generally give the higher value, while methods that are using the baryon acoustic oscillations give the lower value.

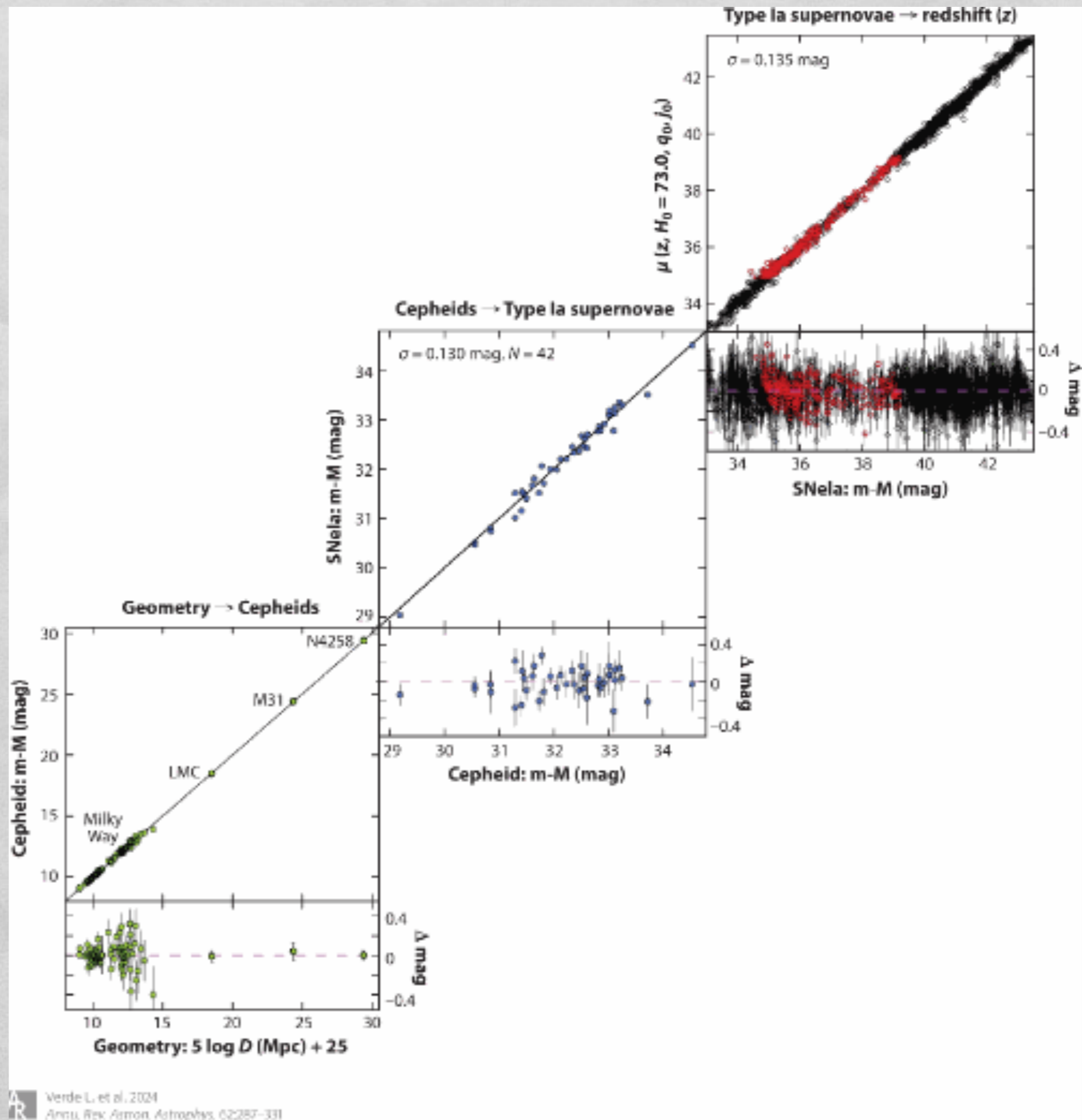
THE HUBBLE TENSION

- This has motivated a great deal of research to understand if there are any errors in these measurements.
 - A Tale of Many H_0 , ARA&A, Vol 62, 2024
- And what changes to the standard Λ CDM model might be needed if the measurements are correct.
 - The Hubble Tension and Early Dark Energy, ARA&A, Vol 73, 2023

DIRECT MEASUREMENTS

- The most direct way to measure the Hubble parameter is to simply do what Hubble did and measure the velocity of and distance to many galaxies.
- But as we've discussed before, distances are hard to measure in astronomy, so can we convince ourselves that direct measurements of the Hubble parameter do not have an error in them.

- Direct Distance Ladder
- Use geometry to get distances to and calibrate Cepheids.
- Use Cepheids to get distances to and calibrate supernova.
- Use supernova to measure the Hubble parameter.



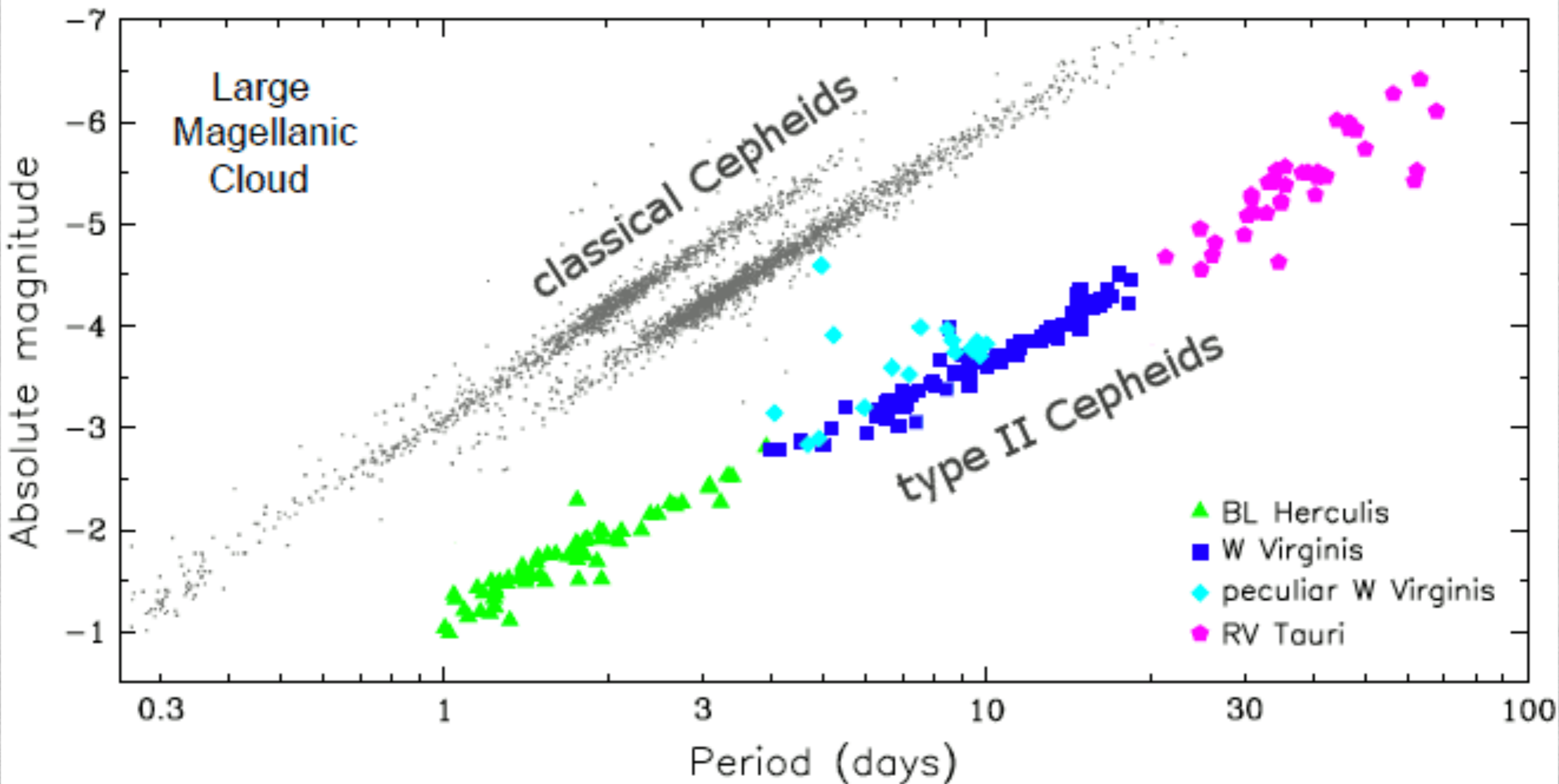
CEPHEIDS

- First Rung:
 - 83 Cepheids in the Milky Way with distances from parallax.
 - 669 Cepheids in NGC 4258 a galaxy whose distance is well measured from water masers orbiting the central black hole. Masers allow one to measure velocities and the angular extent of the rotation which yields a distance from Keplerian orbits.
 - 70 Cepheids in the LMC, whose distance is measured with eclipsing binaries. The eclipse measures the size of the stars, which when combined with the observed brightness and calibrated surface brightness leads to a distance.

CEPHEIDS

- 2nd Rung:
 - The distances to Cepheids can be used to calibrate the period-luminosity relation of these stars. We now think Cepheid distances are accurate to 1%.
 - Supernova that occur in nearby galaxies can then be given a distance using Cepheids in the galaxies where they occur.
 - Unfortunately there are only 42 of these, and given the supernova rate of one in 100 years, we won't increase this number any time soon.

- You can see Cepheids follow a pretty tight relationship in period versus luminosity.
- This has gotten much tighter with the understanding that there are different types of Cepheids.



CEPHEIDS

- 3rd Rung:
- Finally with the calibrated supernova one can measure the distances to further away supernova and make a measurement of the luminosity distance at different redshifts.

$$D_L(z) = \frac{1}{H_0} (1+z) \int_0^z \frac{dz'}{E(z')}$$

- Using machine learning to get the best calibration of the supernova gives:

$$H_0 = 73.29 \pm 0.85 \text{ (stat)} \pm 0.3 \text{ (sys)} \text{ km/s/Mpc}$$

2 RUNG LADDER

- But what if we are totally missing something about supernova?
- We can try to do measurement only using Cepheids, thus not going out very far in z .
- This 2 rung ladder gives:

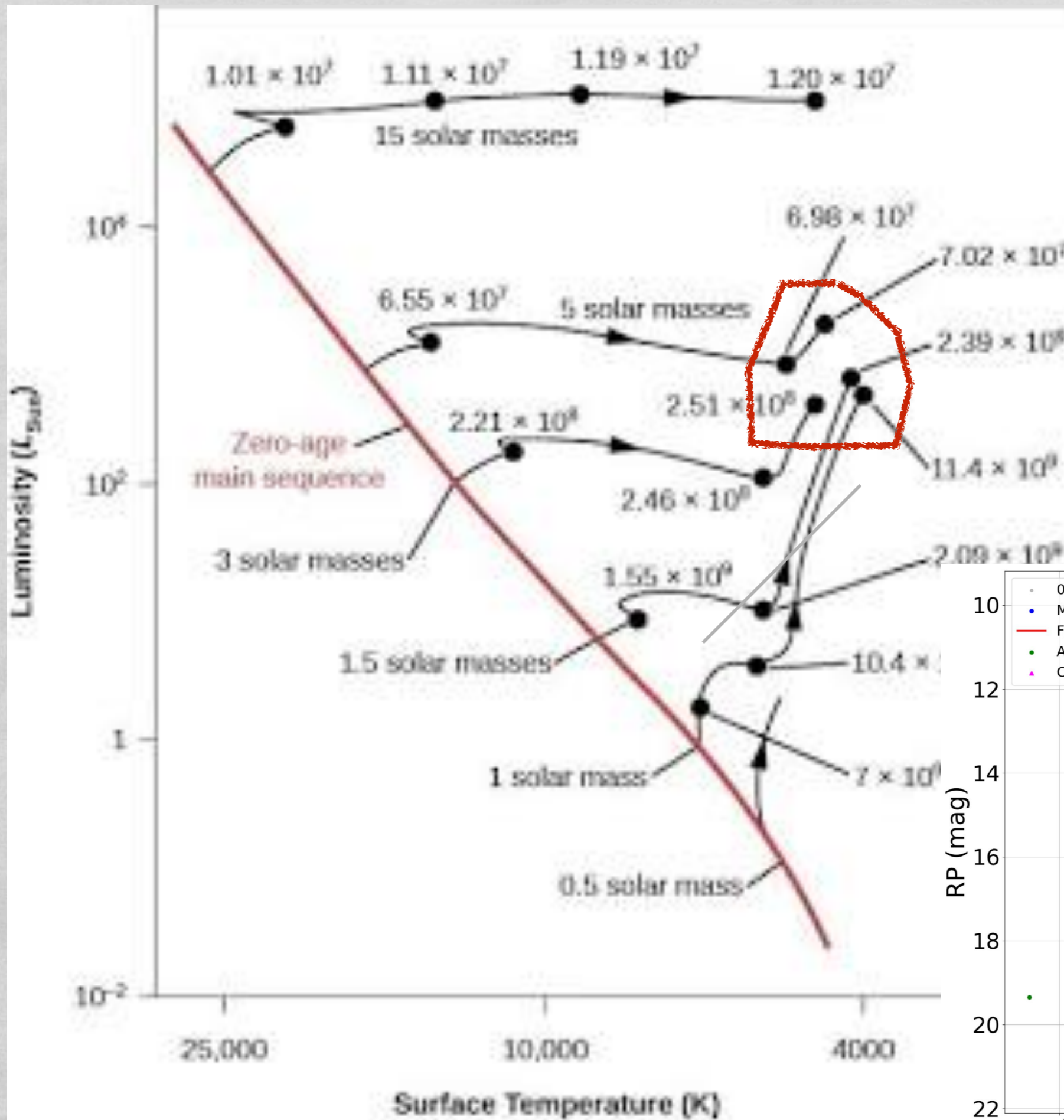
$$H_0 = 73.1 \pm 2.6 \text{ km/s/Mpc}$$

ALTERNATIVE DISTANCE INDICATORS

- Okay, so what if there is something wrong with Cepheids?
- We can try to use a different standard candle.
 - Tip of the Red Giant Branch (TRGB).
 - Tip of the asymptotic red giant branch
 - Mira variable stars.
 - Supernova Type II
 - Masers

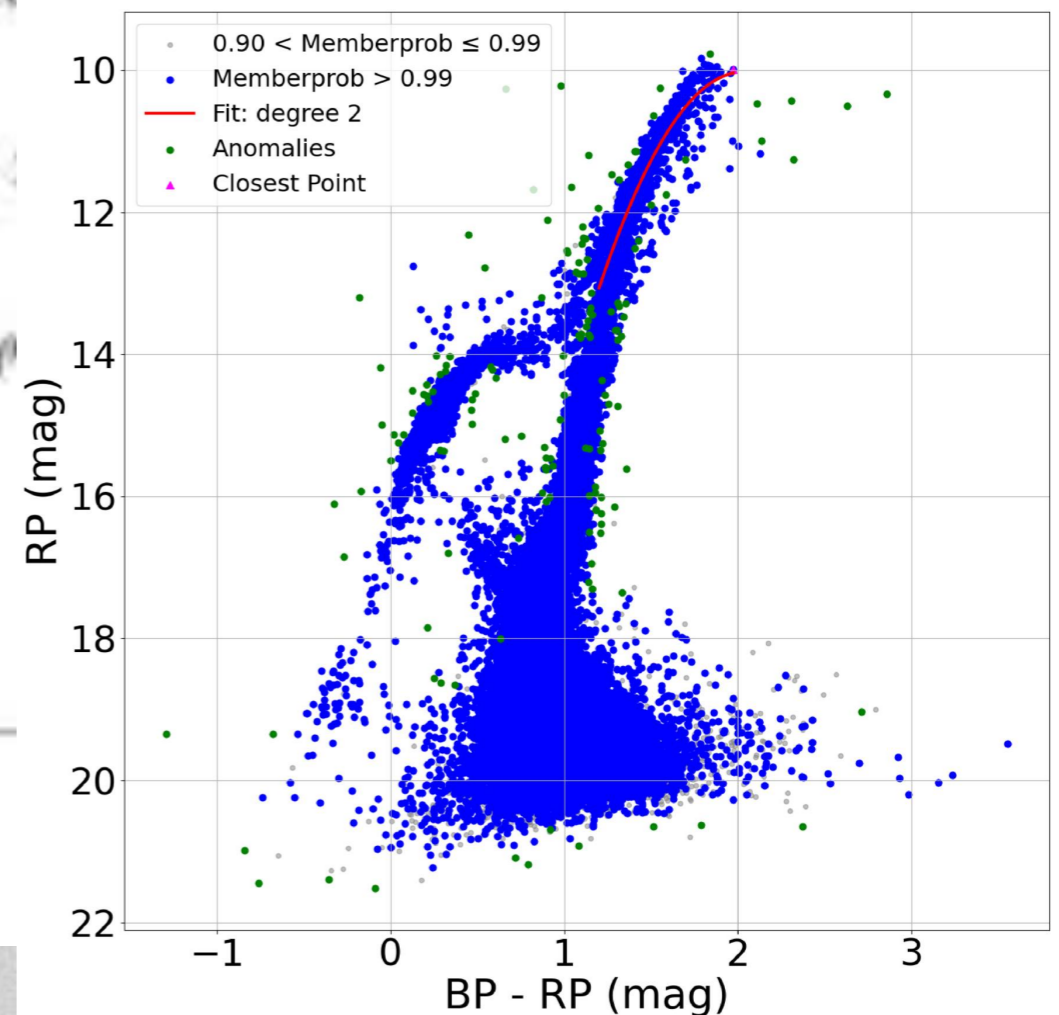
TIP OF THE RED GIANT BRANCH

- A very good standard candle is the tip of the red giant branch.
- Stars at many different ages evolve to about the same luminosity ($M_I \sim -4.0 \pm 0.1$) when they are red giants.
- So we expect the tip of the red giant branch to have this luminosity for most groups of stars.
- However, this is not that bright, so only good out to 20Mpc and depends somewhat on how you fit this limit.



Very close to same luminosity

However, there is some uncertainty in choosing the tip.



TIP OF THE RED GIANT BRANCH

- There are also only 19 supernova in galaxies with distance measured with the tip of the red giant branch. Two groups have measured the Hubble parameter based on this calibration.
- CCHP got $H_0 = 69.8 \pm 0.8(\text{stat}) \pm 1.7(\text{sys}) \text{ km/s/Mpc}$
- and EDD got, $H_0 = 71.5 \pm 1.8 \text{ km/s/Mpc}$
- so maybe a bit lower, but another group reanalyzing the same data (CATS) got $H_0 = 73 \pm 2.0 \text{ km/s/Mpc}$.

ASYMPTOTIC RED GIANTS

- What about other stars that could act as standard candles?
- The red giant branch are He burning stars, carbon burning stars could also be a standard candle. These are the tip of the asymptotic red giants.
- Another possibility is carbon stars. These are carbon burning red giants where carbon has been dredged up from the interior. This makes them easier to identify.
- Neither of these ideas are as yet as accurate as Cepheids or TRGB.

MIRA VARIABLES

- What about other variable stars?
- Most variable stars don't have a tight period-luminosity relationship, the the Mira variable star does in the infrared.
- This allows for a determination of the Hubble parameter without using Cepheids. Unfortunately, there is only one galaxy with a Mira variable and a SNIa. This gives $H_0 = 73.3 \pm 4.0 \text{ km/s/Mpc}$.

SUPERNOVA TYPE II

- What about not using supernova type Ia (SNIa)?
- Core collapse supernova are not expected to be as much standard candles as type Ia. However, if we have distances to them we can still hope to calibrate them and use them as a distance indicator.
- They are not as bright as type Ia, but they are more abundant. Calibrating their distances using both Cepheids and TRGB one gets

$$H_0 = 75.4 \pm 3.8 \text{ km/s/Mpc}$$

MEGA MASERS

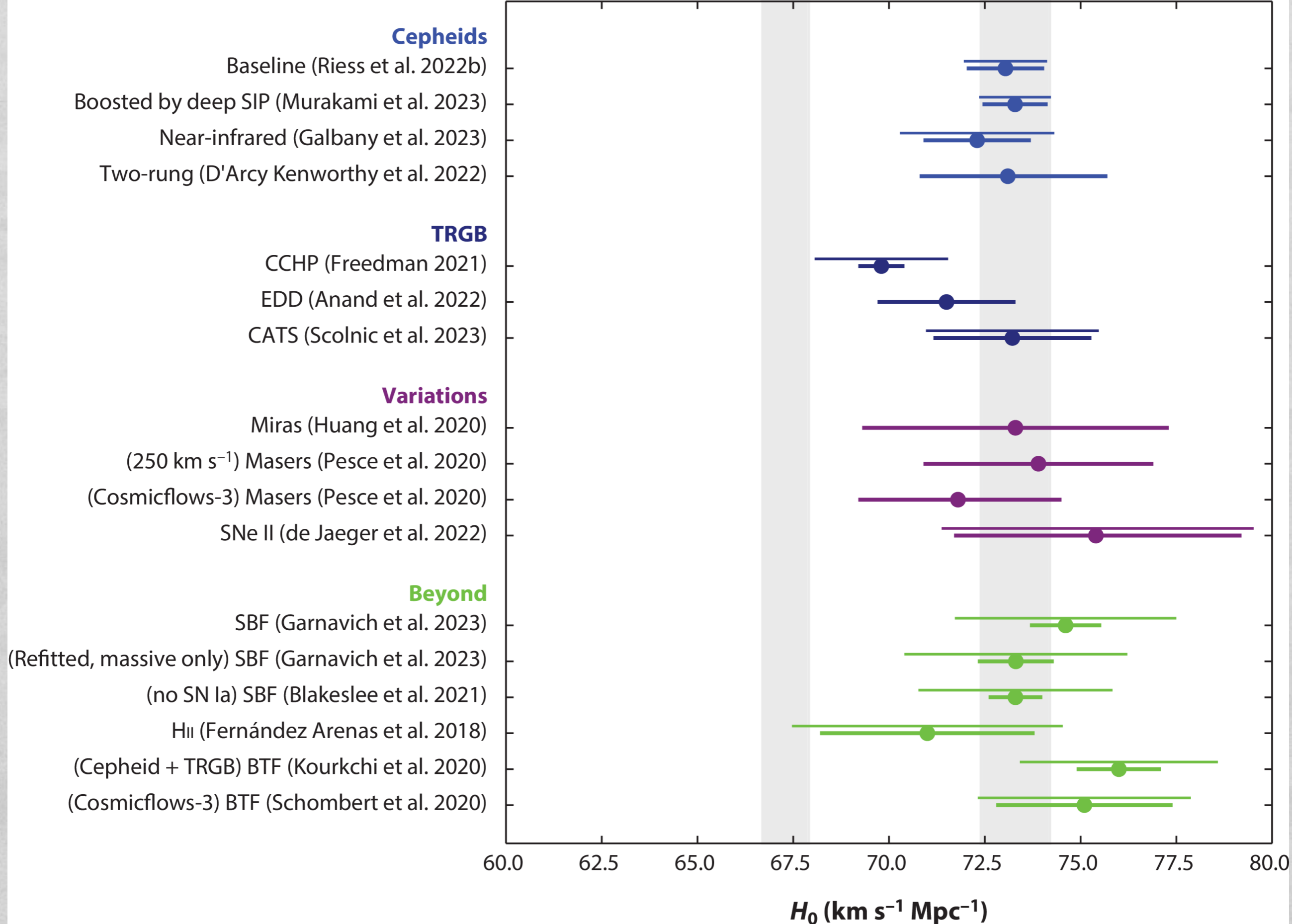
- One can skip the distance ladder entirely by observing masers at Hubble flow distances.
- This is the goal of the MegaMaser Cosmology Project which measured distances to 6 masers out to 130Mpc.
- The main uncertainty are the motions of these galaxies on top of the Hubble flow. Just treating that as a error gives $H_0 = 73.9 \pm 3.0 \text{ km/s/Mpc}$.
- Using a model of the motions of galaxies (CosmicFlows) one can hope to improve on this measurement giving a value of $H_0 = 72.1 \pm 2.7 \text{ km/s/Mpc}$.

SURFACE BRIGHTNESS FLUCTUATIONS

- An alternative to using single objects as distance indicators is to use properties of the entire galaxy.
- These methods include Tully-Fisher, fundamental plane and surface brightness fluctuations (SBF).
- SBF is the fluctuation in surface brightness in a galaxy which occurs because of Poisson fluctuations in the number of stars in an area. This depends on the physical size of the region and thus distance.

SURFACE BRIGHTNESS FLUCTUATIONS

- SBF can either be used to replace Cepheids in calibrating the distances to SNIa, giving $H_0 = 73.3 \pm 1.0 \text{ km/s/Mpc}$.
- or as the 3rd rung in the distance ladder replacing the supernova giving $H_0 = 73.3 \pm 0.7(\text{stat.}) \pm 2.4(\text{sys.}) \text{ km/s/Mpc}$



INVERSE DISTANCE LADDER

- Instead of directly measuring the Hubble parameter, we can infer it from measurements of early time processes most importantly the baryon acoustic oscillations before decoupling at $z \sim 1100$.
- This can be referred to as the inverse distance ladder, because we are using a standard ruler to infer H_0 , instead of a standard candle to measure it.
- Once calibrated this standard ruler plays a role similar to the anchors of the distance ladder.

CMB ANISOTROPIES

- A value of the Hubble parameter can be determined from CMB anisotropies using a global fit of all cosmological parameters.
- This is because no single measurement directly measures H_0 , which is degenerate with other parameters.
- However, from multiple measurements these degeneracies are largely broken and for a given cosmological model a value for the Hubble parameter with small error bars can be attained.
- Planck using the full dataset comprising Planck temperature, polarization, and lensing spectra analyzed in the Λ CDM model give $H_0 = 67.36 \pm 0.54 \text{ km/s/Mpc}$.

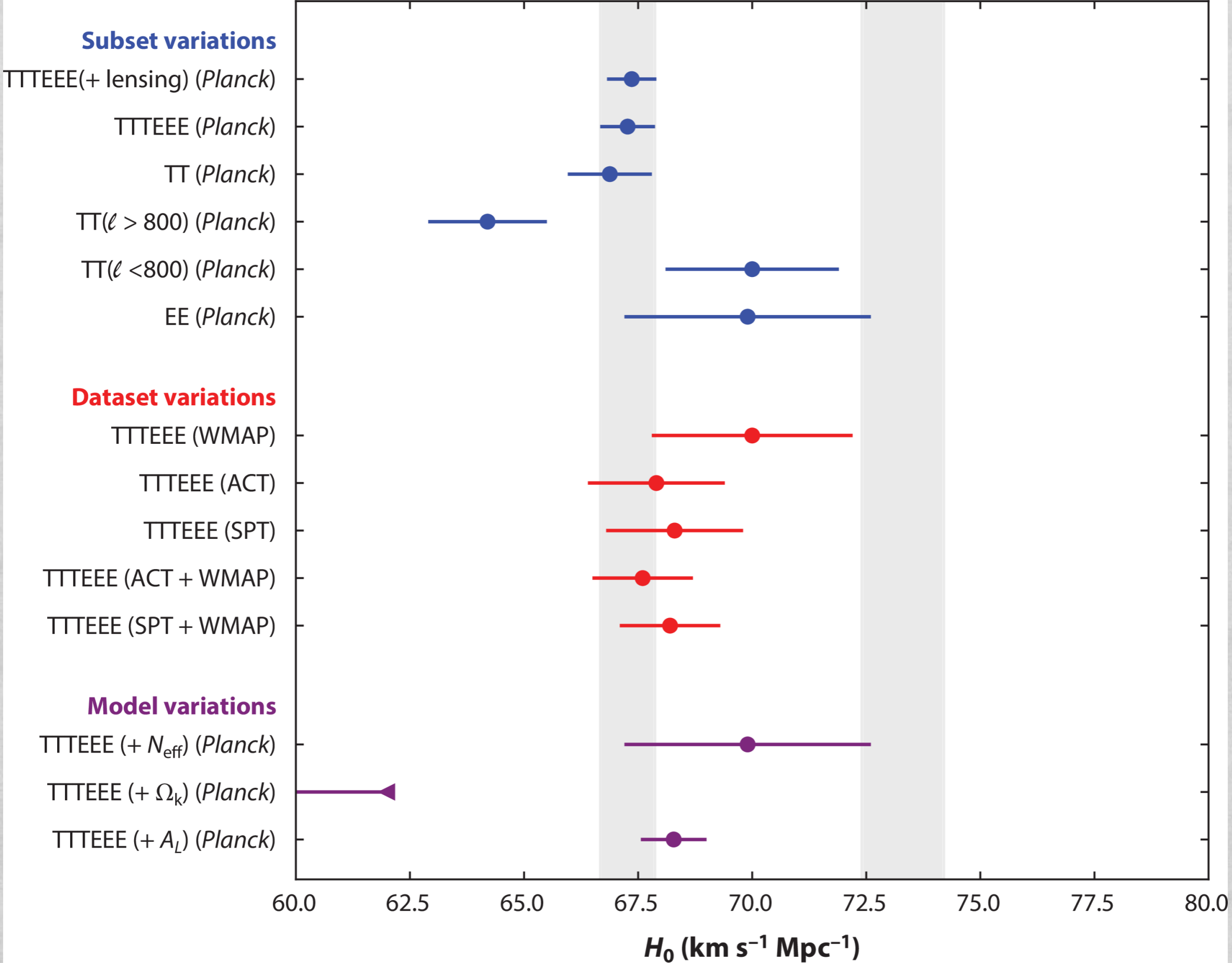
Notice these error bars are half that of the best direct measurement.

MANY FLAVORS

- The previous number is a consensus value for the Hubble parameter, but there are many assumptions that go into it that we would like to check.
- Planck is a single satellite with some known peculiar features.
 - The temperature-temperature (TT) and polarized-polarized (EE) correlations give differing values of H_0 .
 - The $l < 800$ (those probed by WMAP) and $l > 800$ scales give different H_0 , but the $l < 800$ is in excellent agreement with WMAP.
- Ground based CMB telescopes (ACT and SPT) agree with Planck.

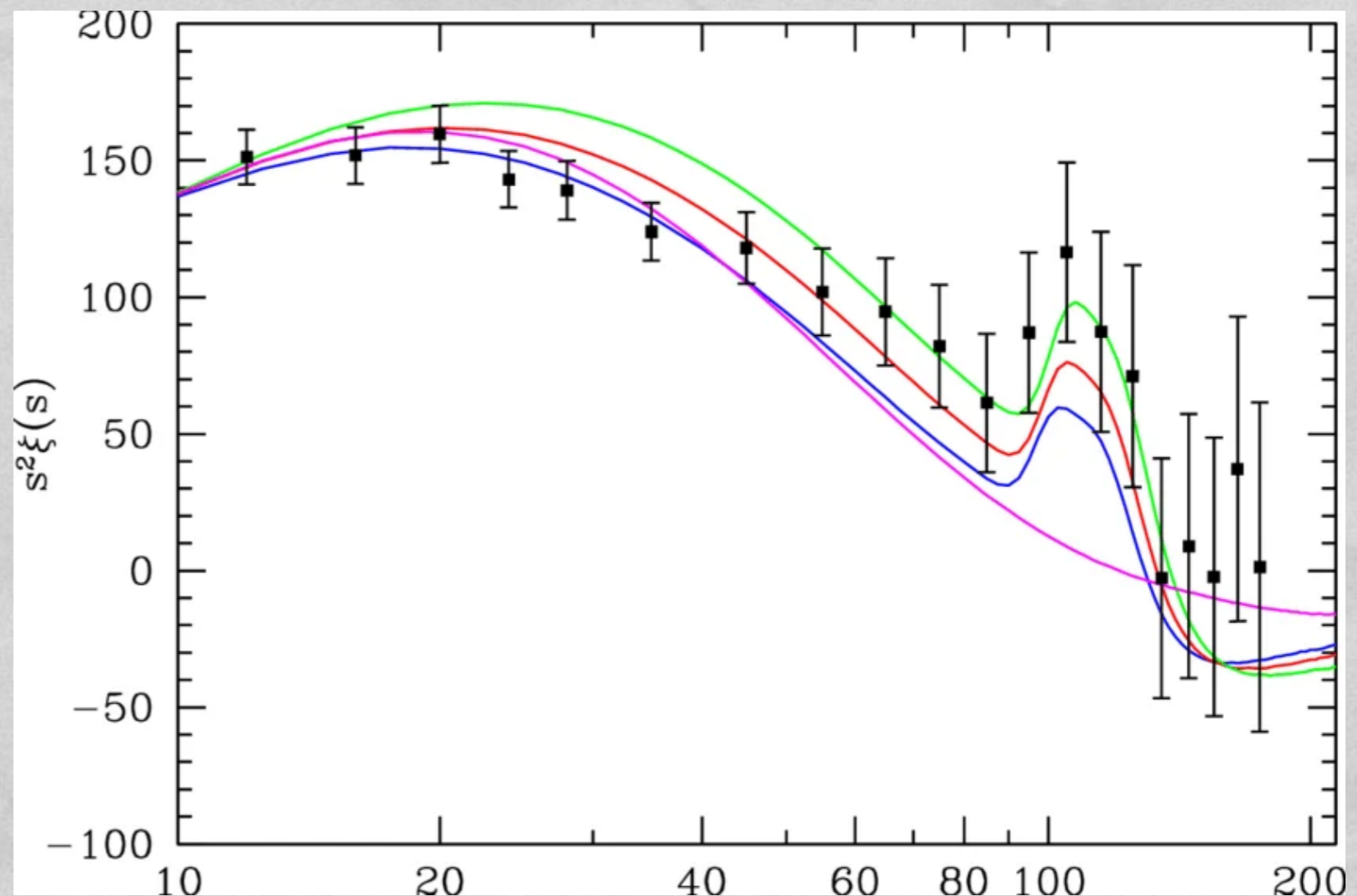
MODEL VARIATIONS

- However, because these constraints are only derived within a full cosmological model, they can be very sensitive to assumptions about the model.
- Allowing the number of neutrino flavors as a free parameter, can increase the Hubble parameter to ~ 70 km/s/Mpc.
- Alternatively, allowing a curvature can decrease the Hubble parameter to less than 62 km/s/Mpc.



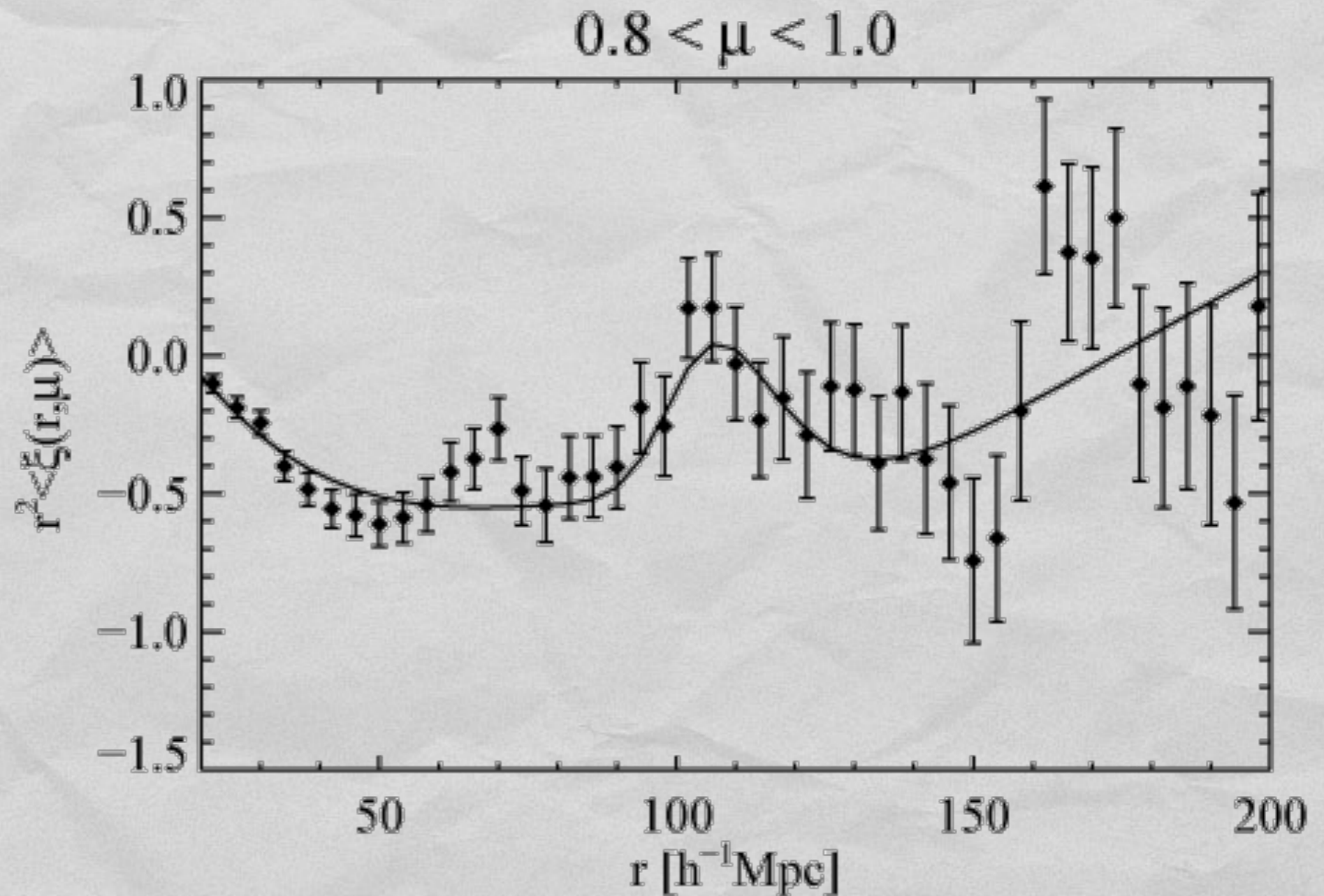
LARGE SCALE CLUSTERING

- The baryon acoustic oscillations can also be seen in galaxy clustering.
- The accuracy of this detection depends on the total volume and density of galaxies.
- In addition a reconstruction method is used to displace the galaxies back in time using the Zedovich approximation.
- This can reach 1% accuracy.



IN LYMAN ALPHA FOREST

- The BAO measured in the Lyman alpha forest, from using BOSS quasars.
- This allows for detection of the BOA scale at much higher redshifts.



UNCALIBRATED BAO

- The BAO signal at redshifts after photon decoupling is the result of two effects.
- The actual size of the sound horizon at photon decoupling, r_d .
- the mapping from co-moving distance to redshift and angle.
- which depends on the integrated expansion history of the universe.

CALIBRATED BAO

- Without calibrating the BAO (knowing r_d) the measurement of the BAO at different redshifts can only be used to measure the expansion history of the universe $E(z)$ and not the Hubble parameter.
- If we can determine the value of the length of the sound horizon, then all measures of the BAO can be used to measure H_0 , but also depend on $E(z)$.
- In a Λ CDM model the sound horizon is given by

$$r_d = \int_{\infty}^{z_d} \frac{c_s(z)}{H(z)} dz \approx \frac{147.05}{Mpc} \left(\frac{\Omega_m h^2}{0.1432} \right)^{-0.23} \left(\frac{N_{eff}}{3.04} \right)^{-0.1} \left(\frac{\Omega_b h^2}{0.1432} \right)^{-0.13}$$

EARLY/LATE TIME PHYSICS

- We can separate the early and late time physics in the BOA measurement, by taking the sound horizon as measured by Planck, $r_d = 147.09 \pm 0.26$.
- And then measuring the proper size of the BOA in galaxy clustering, $hr_d = 100.4 \pm 1.3$ Mpc, which gives a value of $H_0 = 68.28 \pm 0.89$ km/s/Mpc.
- One can use SNIa to measure $E(z)$ and thus make this almost a pure measurement of the Hubble parameter.
- Two groups have done this and gotten $H_0 = 69.71 \pm 1.28$ km/s/Mpc and $H_0 = 67.8 \pm 1.3$ km/s/Mpc

BOA AND BBN

- One can attempt to bypass the CMB entirely by using big bang nucleosynthesis to determine early universe physics and thus the sound horizon.
- BBN constrains $\Omega_b h^2$ and N_{eff} , so it can calibrate the sound horizon assuming Λ CDM (or a given model).
- Combining with BOA gives $H_0 = 67.6 \pm 1.0 \text{ km/s/Mpc}$ without the use of the CMB at all.

BOA + SHAPEFIT

- Galaxy clustering contains much more information than just the BOA.
- There is a turnover at matter-radiation equality, baryonic suppression and growth of structure.
- The large scale shape of the power spectrum is an effective probe of $\Omega_m h^2$ and can be used to determine the hubble parameter by itself.
- The shapefit approach measures the slope of the power spectrum at a given scale around matter-radiation, baryonic suppression and the tilt of the power spectrum. This can be used to measure the Hubble parameter with priors on $\Omega_m h^2$ and n_s .
- Taking $n_s = 0.97$ gives $H_0 = 68.3 \pm 0.7$ km/s/Mpc.

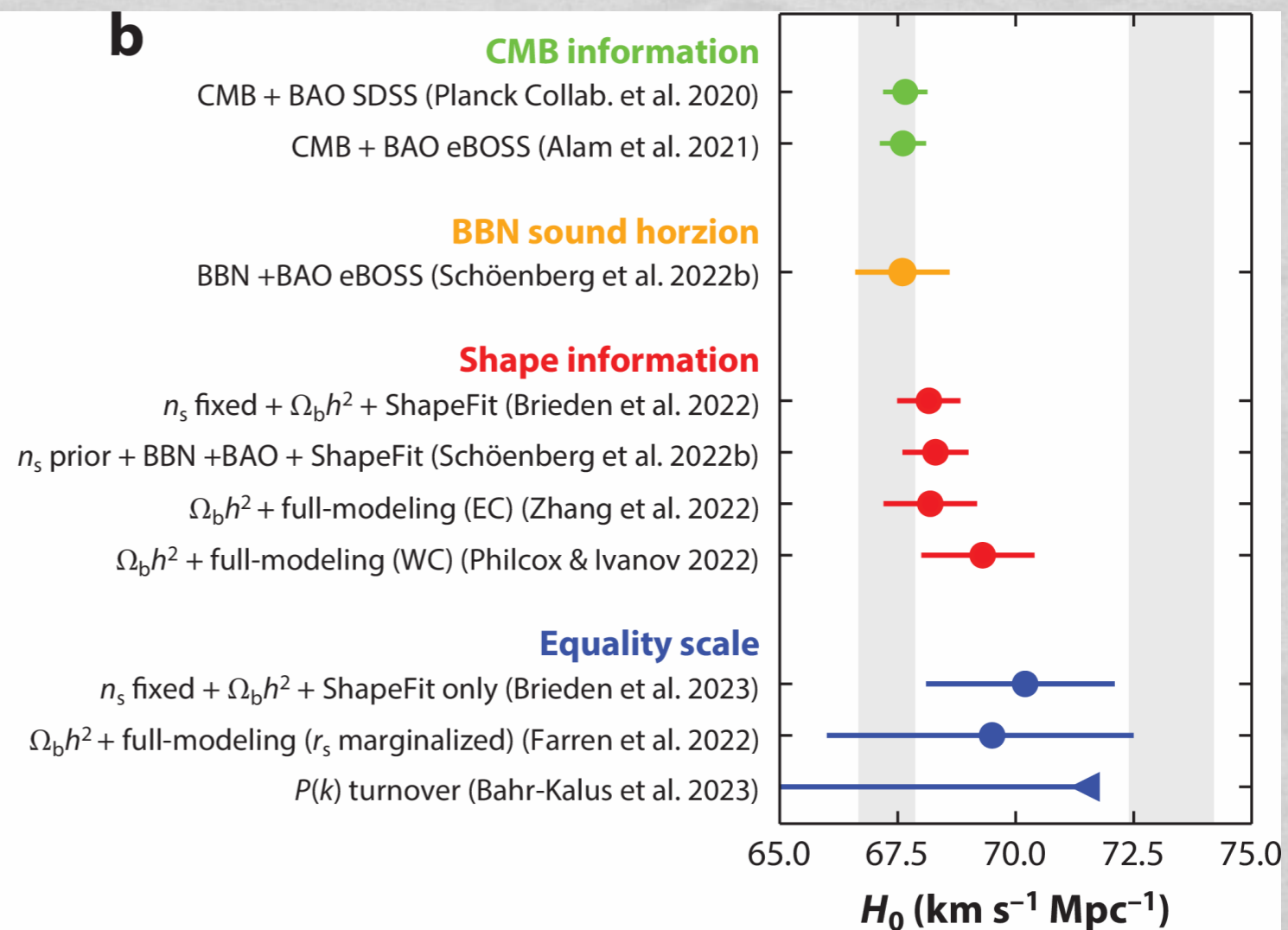
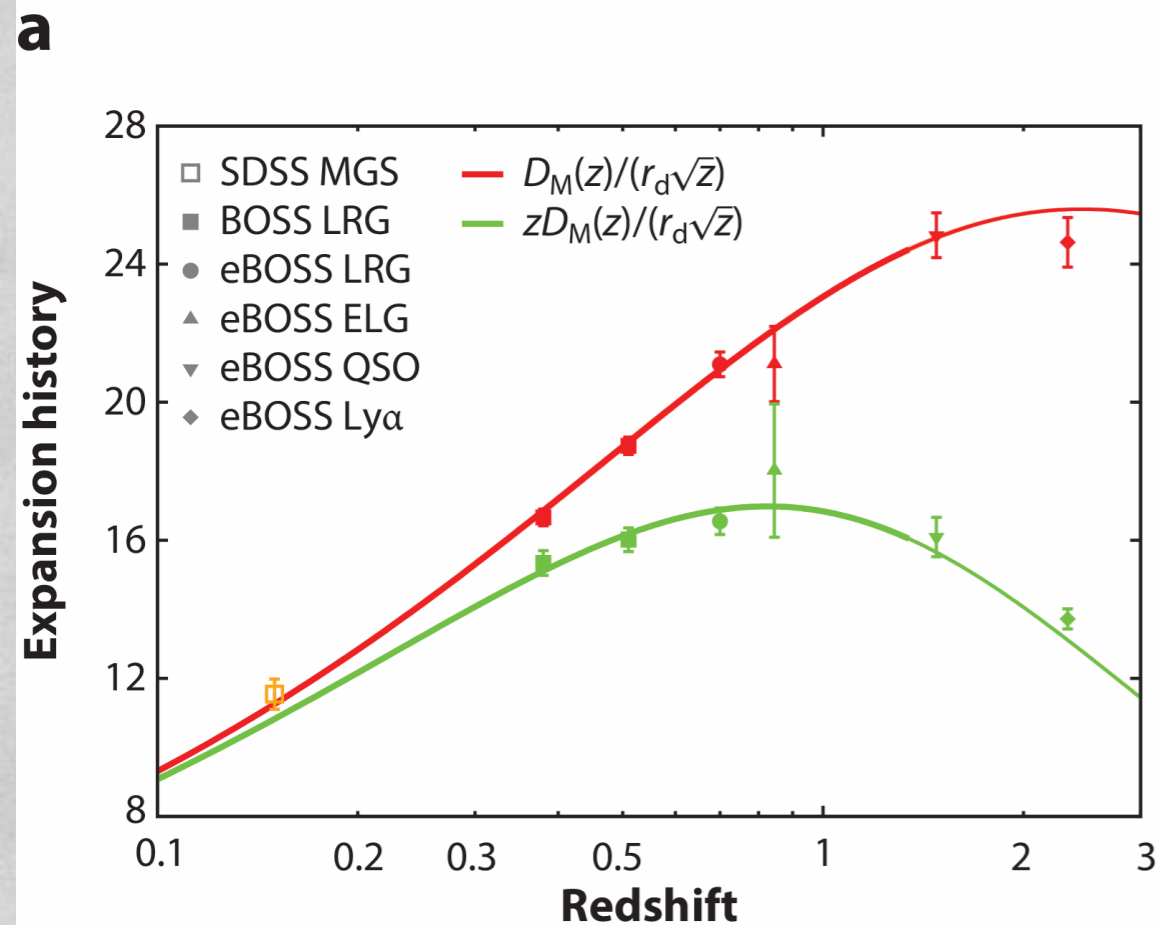
GALAXY POWER SPECTRUM

- One can also model the full power spectrum. This usually still requires a prior on $\Omega_m h^2$ from BBN, but not on n_s .
- This gives a very similar value of the Hubble parameter, $H_0 = 68.19 \pm 0.99$ km/s/Mpc.

SOUND HORIZON INDEPENDENT PROBES

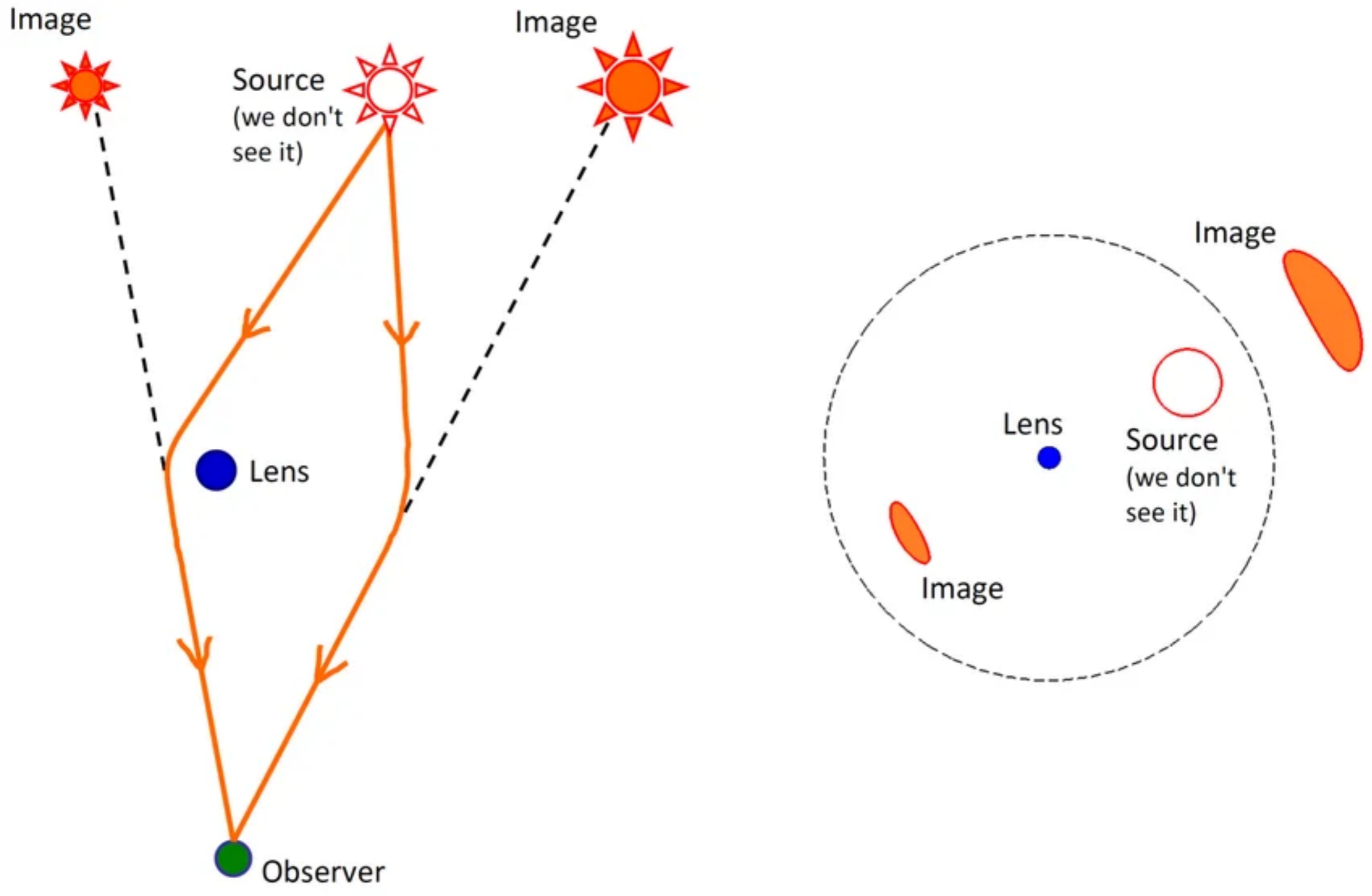
- Instead of calibrating on the sound horizon we can try to use matter-radiation equality which occurs early $z \sim 3300$ instead of $z \sim 1100$.
- Shapefit - combine uncalibrated BAO with shape of $P(k)$, gives $H_0 = 70.2 \pm 2 \text{ km/s/Mpc}$.
- Marginalize over r_d - do the modeling marginalizing over the sound horizon as an unknown, this gives $H_0 = 67.1 \pm 2.9 \text{ km/s/Mpc}$.
- $P(k)$ turnover - one can use the turnover in the matter power spectrum as the standard ruler, thus ignoring the sound horizon completely. This gives $H_0 = 63 \pm 8 \text{ km/s/Mpc}$,

- The left figure shows the shape of the expansion history, $E(z)$, both the transverse BOA (red) and radial BOA (green).
- The lines are not fits to the measurements, but the predicted values from the CMB. We see that the shape of the expansion history is well fit by the best fit parameters from Λ CDM.

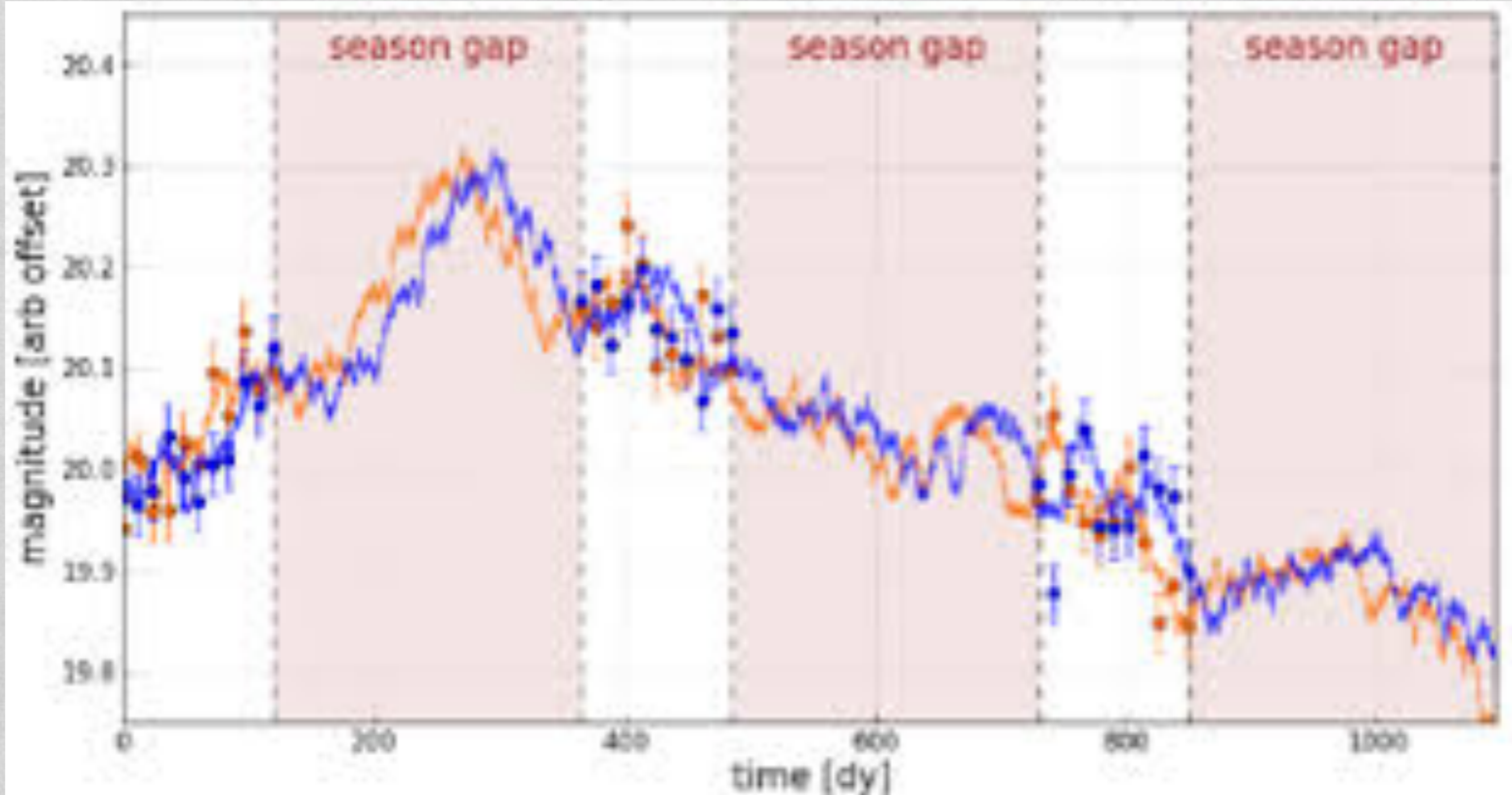


LENSING TIME DELAYS

- A completely separate estimate of the Hubble parameter can be arrived at from measuring time delays in gravitational lenses.
- When gravity bends the path of light, it also makes that light travel a different distance. If we have multiple images of one source, then some time varying signal will be seen in the images at different times.
- This is a direct measure of the Hubble parameter because it depends on distance.



Total path lengths are different, so signal will arrive at different times. This is a physics length so depends on H_0^{-1} .



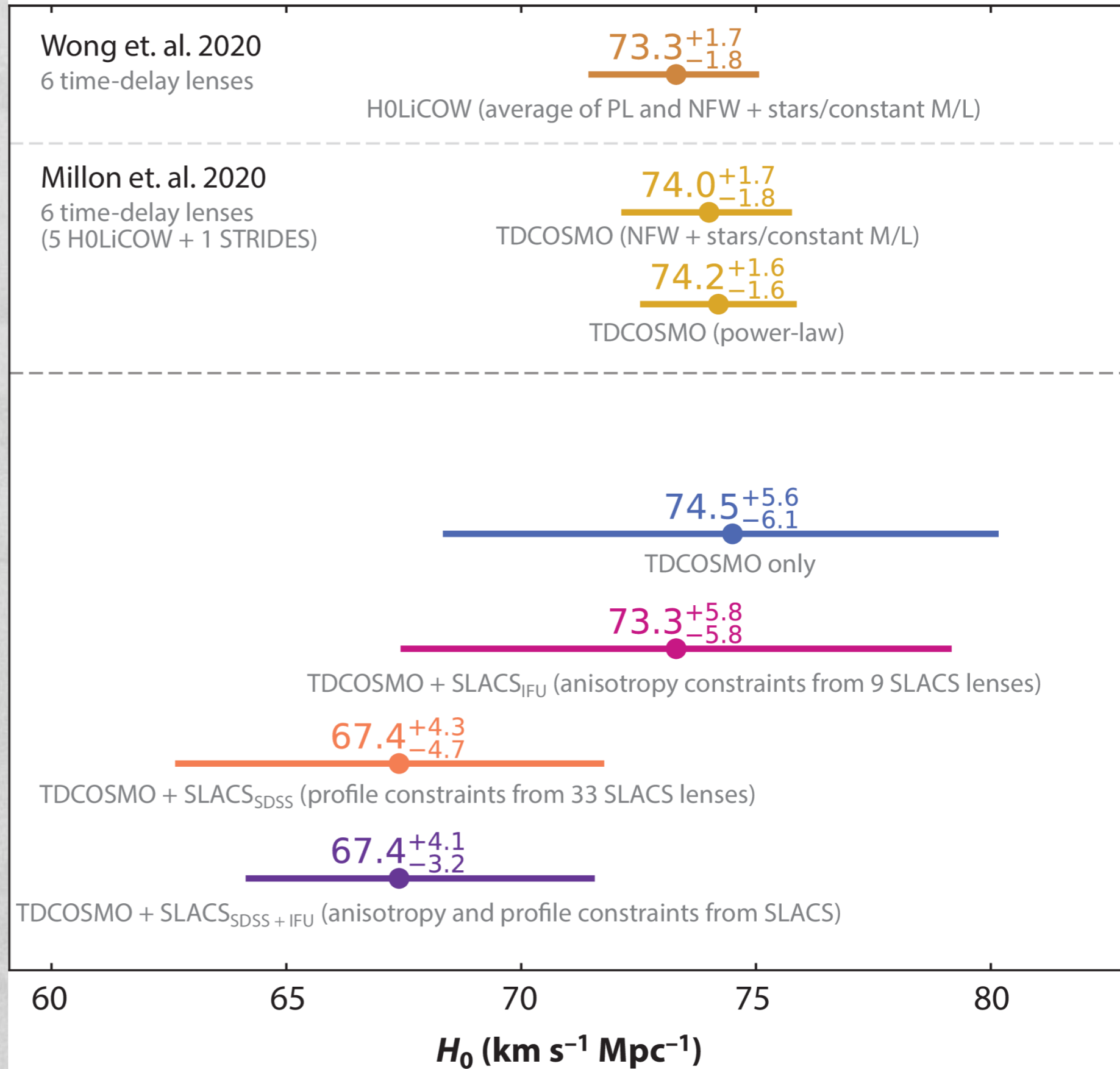
Since quasars flux varies with time, we can hope to see multiple images that vary in sync. Unfortunately, there is also micro-lensing of each image that makes this more difficult.

TIME DELAYS

- The greatest uncertainty in this modeling is the lensing potential, which must be reconstructed from the image positions.
- A simple mass model gives relatively strong constraints on the Hubble value, $H_0 = 74 \pm 2 \text{ km/s/Mpc}$.
- A more flexible mass model increases the error bars, $H_0 = 74.5 \pm 6 \text{ km/s/Mpc}$.

H_0 measurements in flat Λ CDM performed blindly

- Time delay measurements give values of H_0 , similar to that found using direct measurements.
- But the results strongly depend on the mass model, and different assumptions about the lensing potential can give H_0 consistent with the lower values.



STANDARD SIRENS

- Another independent measurement is to use gravitational wave detections of merging compact objects with electromagnetic counterparts.
- The inspiral of the compact objects can be used to determine the luminosity distance. However, without an electromagnetic counterpart we don't have a redshift.
- This was first done for GW170817 giving $H_0 = 70 \pm 10 \text{ km/s/Mpc}$.
- Further observations reduce this error and give various mean values between 68 and 75. While the errors are relatively large, it should be stressed that this measurement is completely independent of any quantities we have discussed before and more detections will follow.

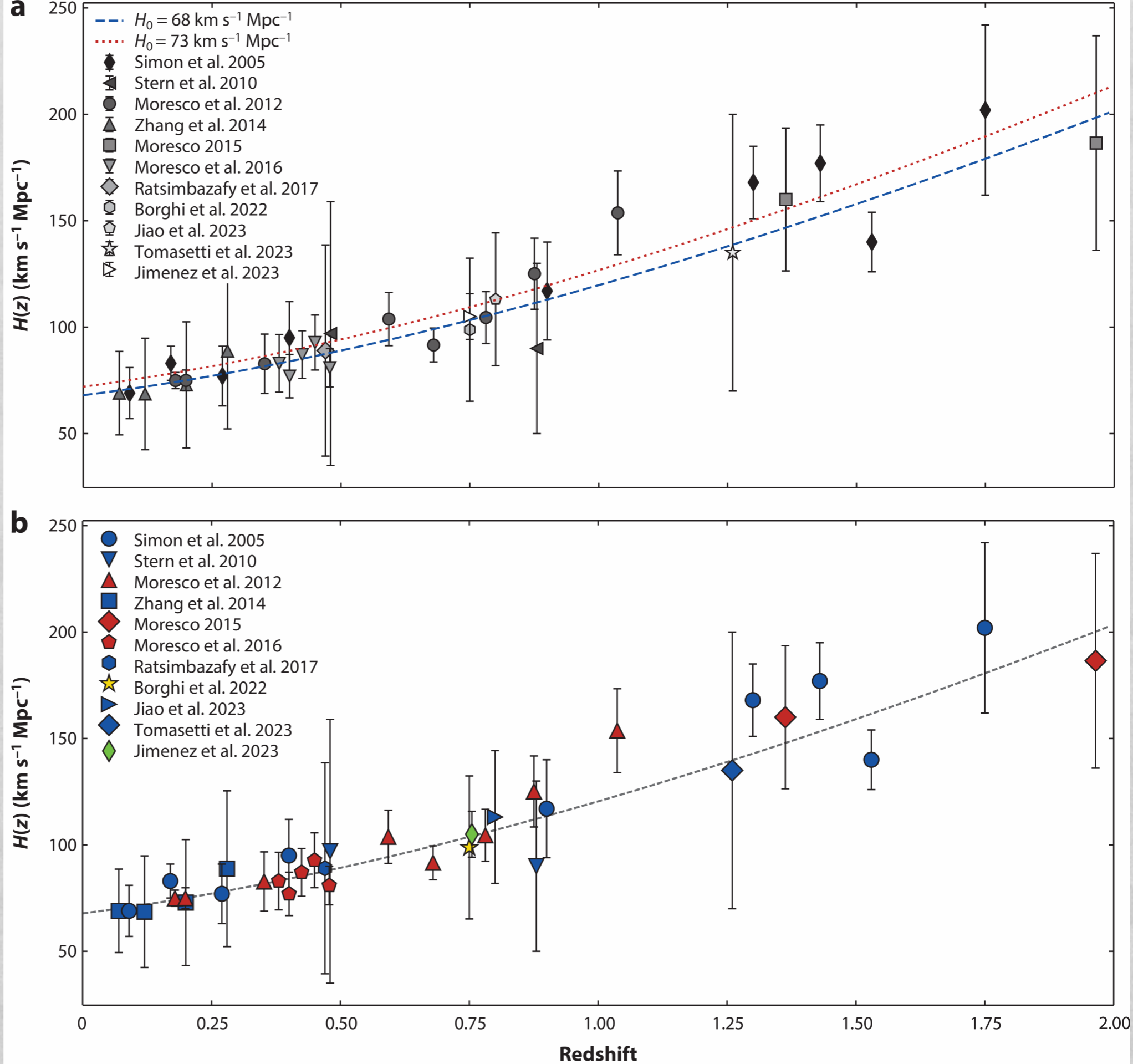
CHRONOMETERS

- The Hubble parameter $H(z)$ can be written as a function of the differential time evolution of the Universe as a function of redshift:

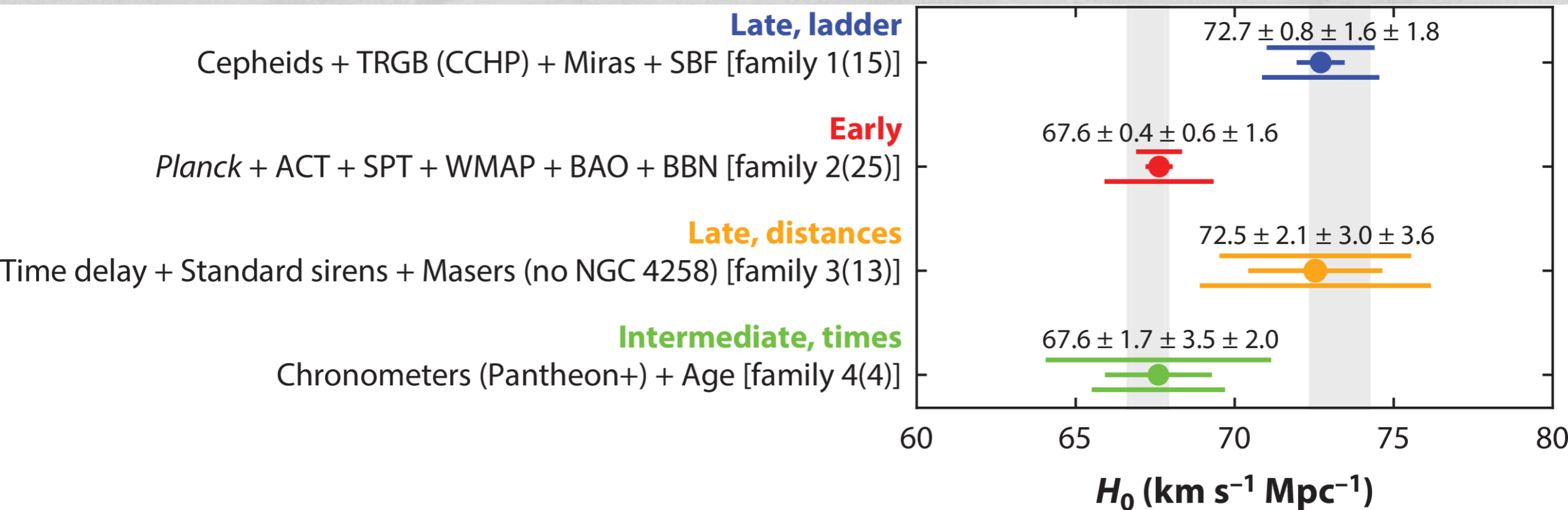
$$H(z) = -(1+z)^{-1} \left(\frac{dt}{dz} \right)^{-1}$$

- So if we have something that can measure differential time we can use that to determine the Hubble parameter.
- To date the best ‘clock’ has been massive passively evolving elliptical galaxies, as long as one can obtain spectra over a long enough spectral range.

This gives a best fit of $H_0 = 66.7 \pm 5.3 \text{ km/s/Mpc}$



In summary different methods of measuring the Hubble parameter give different results that are not consistent, something must be wrong. Unfortunately, there is no clarity as to exactly what it is.



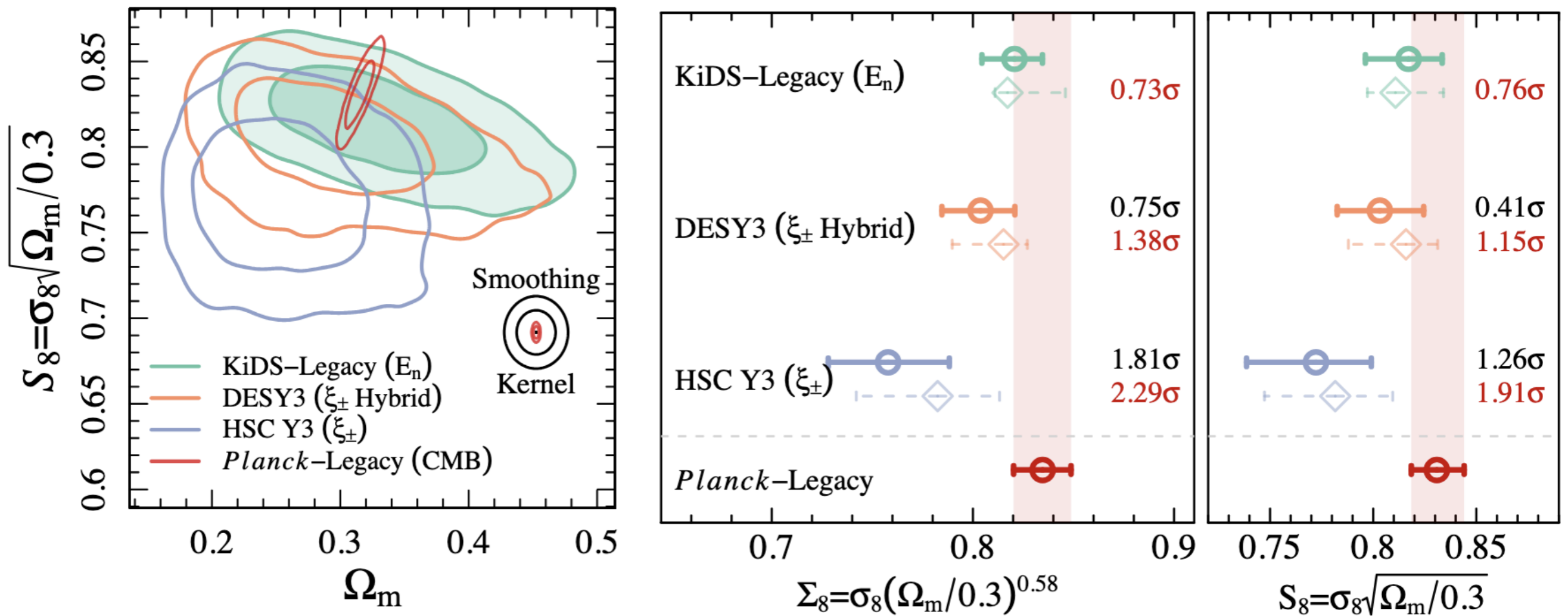
SOLUTIONS

1. There is an error in the distance measurements, maybe in the anchors.
2. We live in a local void, or lately the universe has speed up, dark energy is not a cosmological constant.
3. Modifications to the early universe so that the sound horizon is off by 7%, usually done by adding a bit of dark energy that lasts only a short time.

σ_8/S_8 TENSION

- Another tension that is not as robust is a tension in the normalization of the perturbation spectrum.
- We usually call this σ_8 which is the amplitude of fluctuations on scales of $8/h$ Mpc.
- However, with weak lensing measurements there is a dependance on Ω_m which can be scaled out so they often report $S_8 = \sigma_8 (\Omega_m/0.3)$.
- Either way there is a tension between this measurement at early times from the CMB and today from weak lensing.

σ_8/S_8 TENSION



The tension is only 1-2 sigma, so not really significant. The reason it has gotten so much attention is that it is also an early/late time tension, so a solution that fixes the Hubble tension will look better if it also fixes this tension (and worse if it makes it worse).