And Then Everything Exploded: Exploring the Hubble Tension

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From CMB to H0

- The CMB is very well-mapped, leading to an H0 prediction with within-one-percent uncertainty: $H_0 = 67.36 \pm 0.54\ \mathrm{km\,s^{-1}Mpc^{-1}}$ (Planck 2018)
- Any CMB-derived parameters of the "now" are heavily model-dependent

The Distance Ladder

- Main idea: connect standard candles spanning different z ranges together and "step along" through calibration (like rungs on a ladder)
- Can be CMB-free, but requires extensive observational data in many channels from different sources, depends on the source models

Up the Ladder: Cepheids+Supernovae

- Rung I: Calibrating Cepheids (variable stars with a period-luminocity dependence)
- Rung II: Calibrating Type Ia SNe (supernovae with fixed absolute magnitude) from Cepheids by co-observing them in galaxies
- Rung III: Inferring distance from distant Type Ia SNe
- Completely CMB-free but heavily reliant on correctly estimating absolute magnitudes

Down the Ladder

- Calibrate the farthest SNe from Baryon Acoustic Oscillations (BAO) / strong lensing time delay / etc., use them to map the distances down to small z
- Independent from local calibration uncertainties, but of course heavily dependent on the calibrating source model and possibly CMB
- If everything is fine, going either up or down the ladder should yield the same result

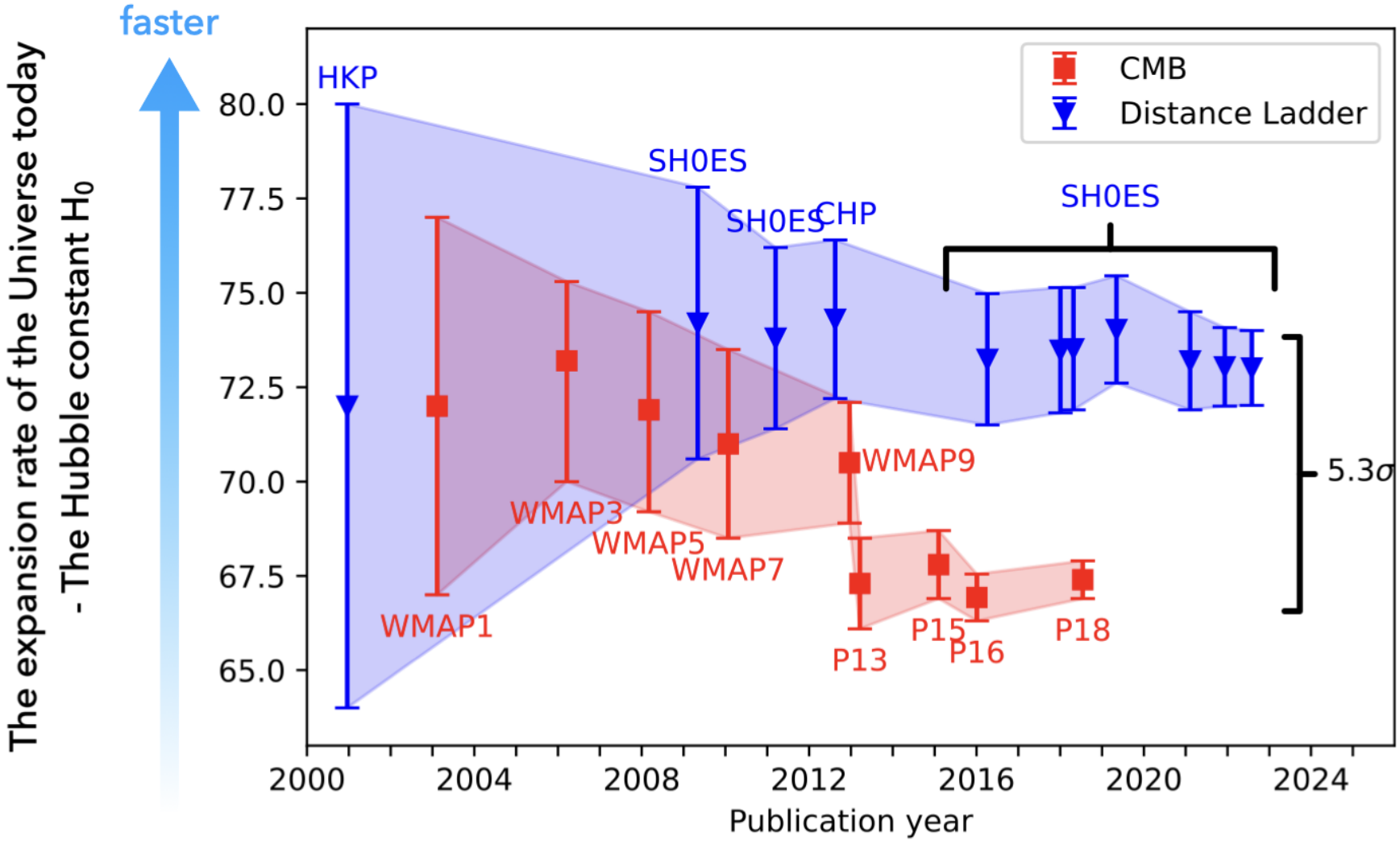


Figure: sourced from The Association of Universities for Research in Astronomy (AURA) website

Datasets

1. Combining CMB data from the Planck-2018 (TT cross-correlation map, $\ell_{max} = 1000$) and SPT-3G (TE and EE maps + lensing) surveys to mitigate some internal oddities of the Planck dataset
2. Large Scale Structure (LSS) information from a perturbational treatment of the BOSS DR12 full-sky survey with additional BAO data and local $S_8 (= \sigma_8 \sqrt{\Omega_m / 0.3})$ measurements
3. The Pantheon sample of 1048 Type Ia supernovae

Friedmann's Equations

- $H^2 = (\frac{\dot{a}}{a})^2 = \frac{8\pi G}{3}\rho$
- $\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p)$
- $\rho = \rho_m + \rho_{rad} + \rho_{DE}$
- $\rho_i \propto a^{-3(1+w_i)}, w_i = \frac{p_i}{\rho_i}$

PDE

1. If we assume the SN ladder is correct, we have to modify cosmology
2. The easiest way to do so is to change the Dark Energy equation of state (all we know about it is that it's close to -1).
3. Phantom-crossing Dark Energy (PDE), a phenomenological late-time (dynamic at small z) modification
4. PDE energy density has a minimum at a_m:
   $\rho_{\rm PDE}(a) = \rho_0[1 + \alpha(a - a_m)^2 + \beta(a - a_m)^3]$
5. The PDE equation of state is $w_{\rm PDE}(a) = -1 - \frac{a[2\alpha(a-a_m)+3\beta(a-a_m)^2]}{3[1+\alpha(a-a_m)^2+\beta(a-a_m)^3]}$
6. a_m, α and β are free parameters to be determined from data

Without a Ladder

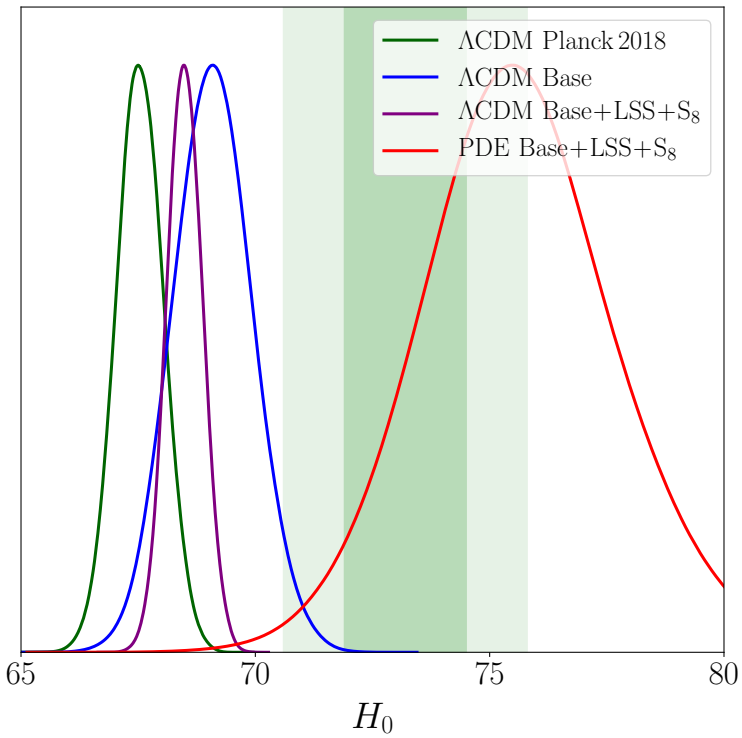
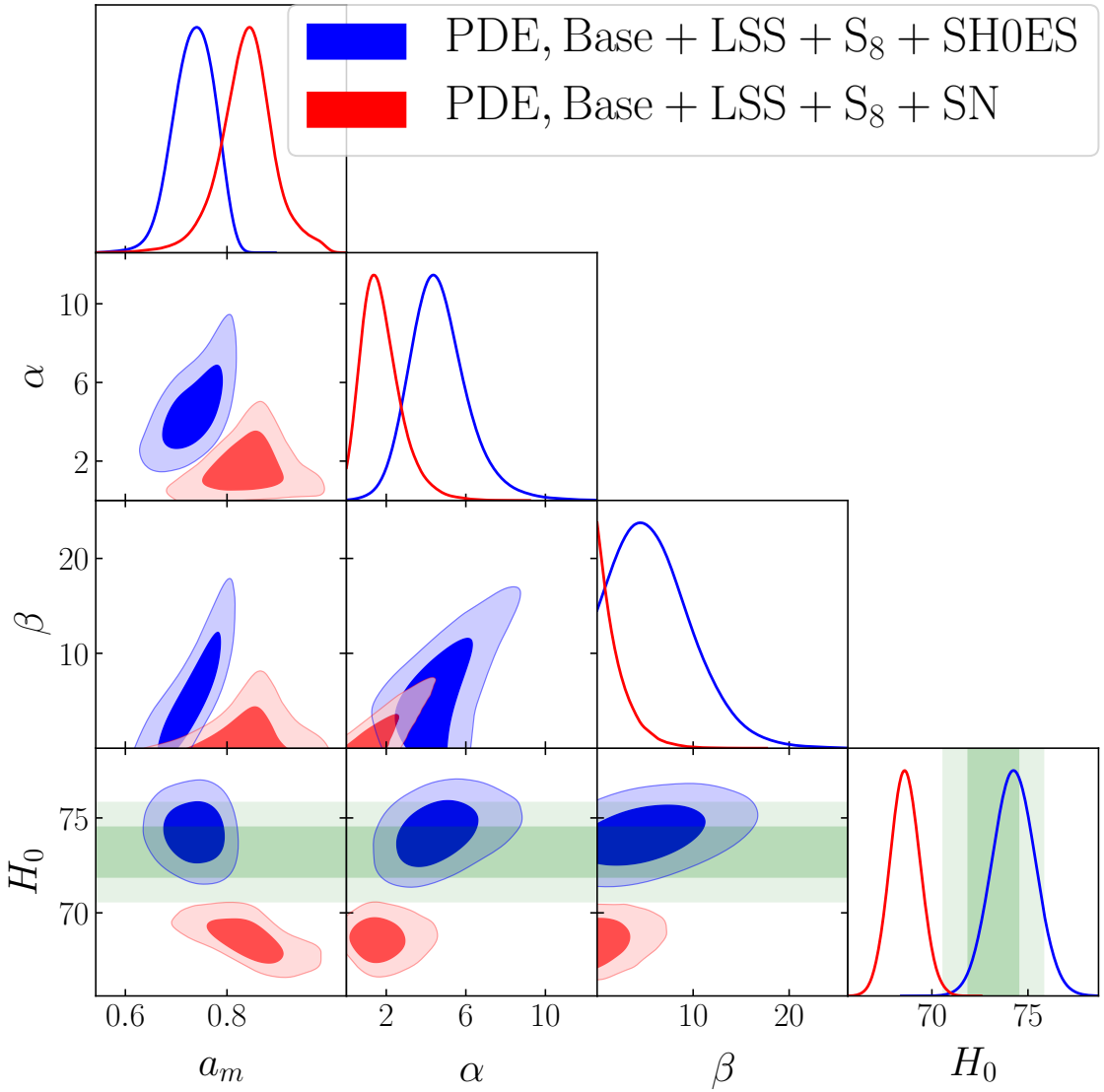


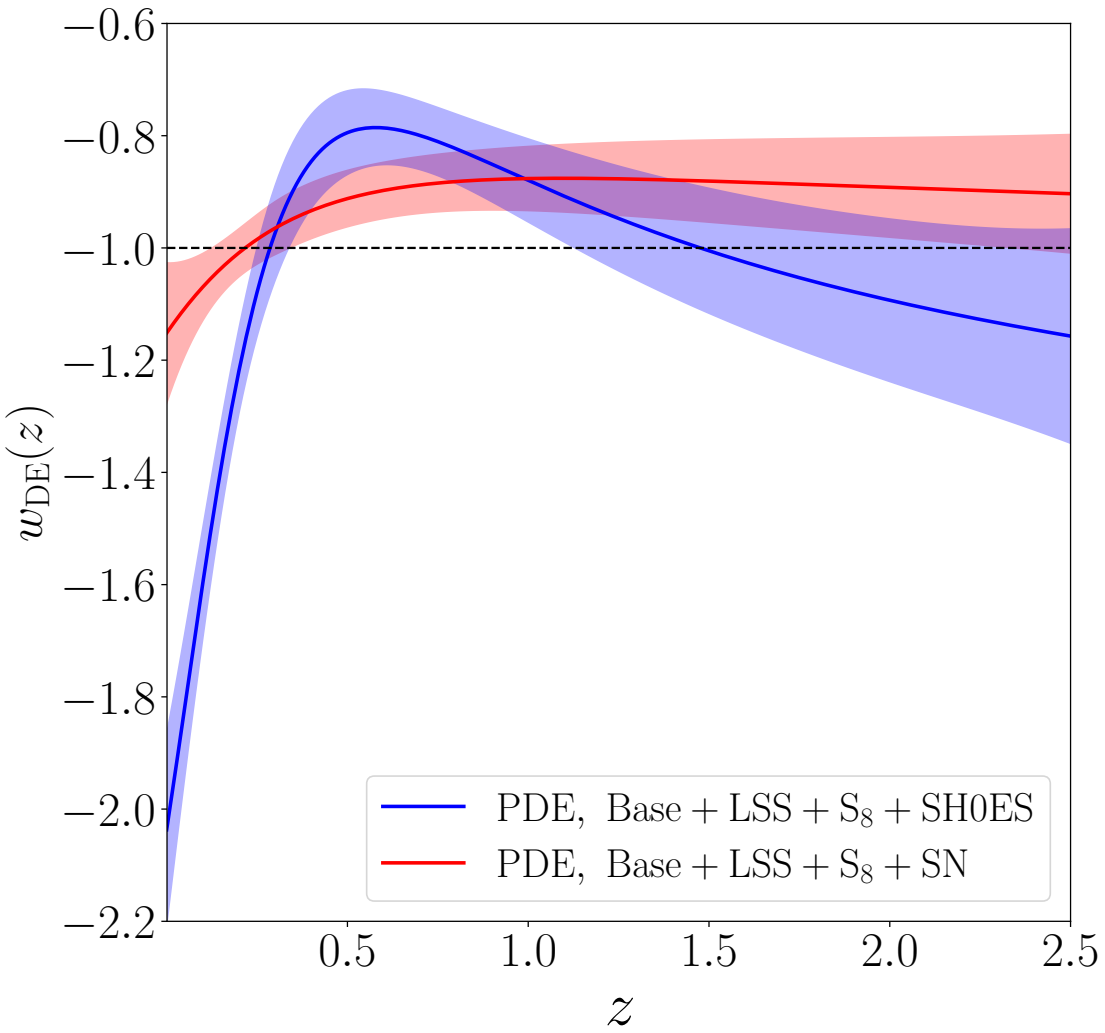
Figure: In PDE CMB+LSS produces a large H0 without any additional priors, yet LCDM is still the preferred model in terms of Bayesian evidence

The Fault in (the Calibration of) Our Stars

- When calibrated from Cepheids, the SN Ia absolute magnitude M_B is -19.226 ± 0.039
- When calibrated from CMB+LSS, the SN Ia absolute magintude in PDE is -19.414 ± 0.018 (essentially the same as in ΛCDM for the same set-up)
- The difference is about 4.5σ
- Some possible causes: z dependence of M_B (due to astrophysical effects or new physics); Unaccounted for dust effects in the Cepheid sample; This is a very hotly debated topic, no conclusions can be drawn for now


PDE, Base + LSS + S_8 + SH0ES
PDE, Base + LSS + S_8 + SN
α
β
H_0
a_m
α
β
H_0

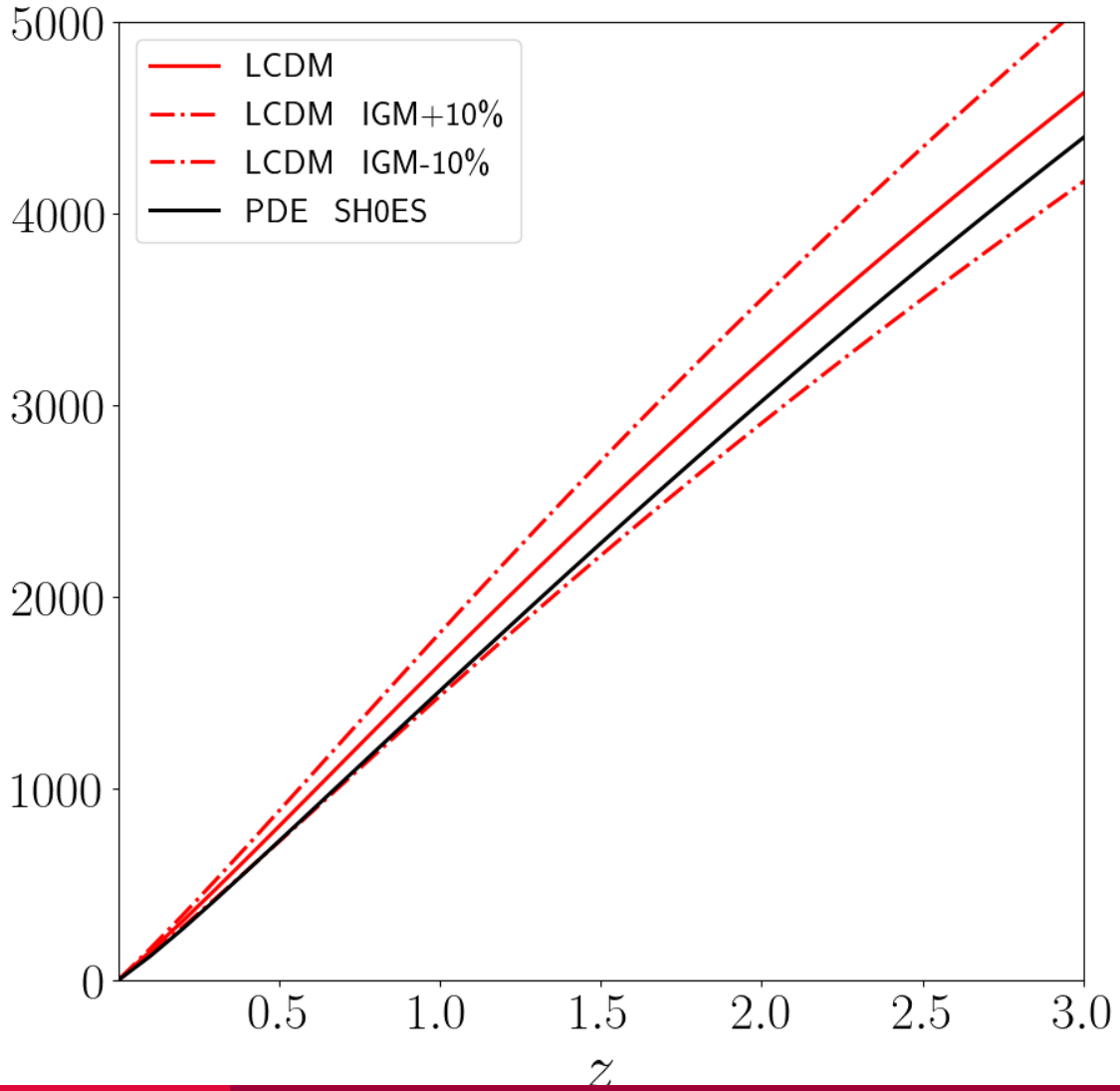
(the part where everything explodes. hypothetically)



Up the Ladder: Fast Radio Bursts

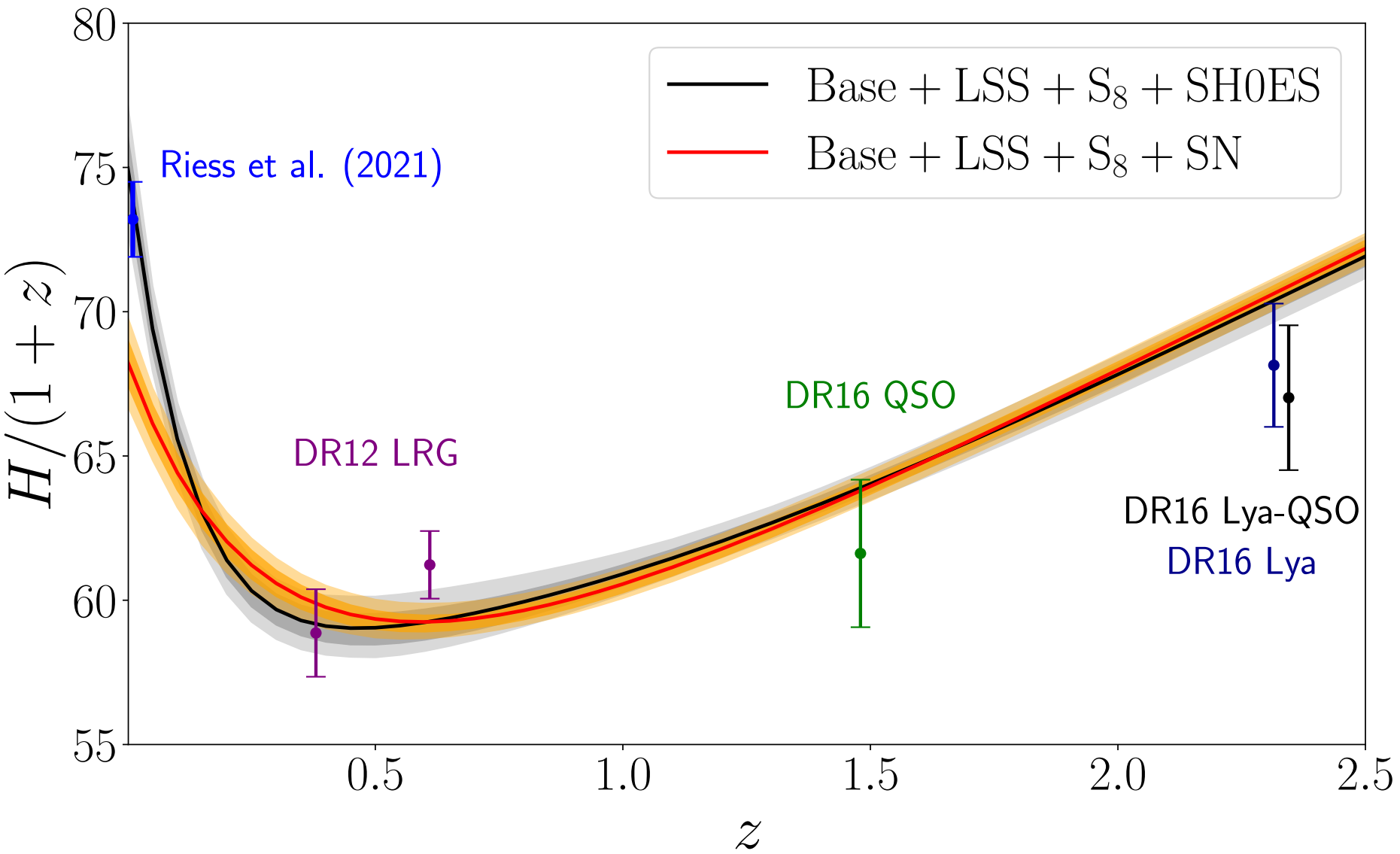
1. An example of a rapidly developing alternative expansion history tracer
2. Rapid bursts of radiowaves of uncertain origin, distance traced via measuring the dispersion due to the electron background in the intergalactic medium (IGM)
3. Issues: large uncertainties in extracting the IGM contribution; Poor understanding of the IGM electron distribution
4. Accuracy nowhere close to SNIa for now

Up the Ladder: Fast Radio Bursts



Conclusions

- Late-time modifications cannot explain the M_{SN} discrepancy
- Some extreme solutions emerging (very-late-time (last 100 My) G_N shifts, sign-switching Λ, etc.), but suffer from lack of physical explanations
- It's very important to look at the whole $H(z)$ history, not just at H_0
- Better understanding of high-z SNe is needed
- Finding a non-SN ladder of comparable accuracy is crucial
- A unified framework for comparing different models and datasets is needed


Base + LSS + S_8 + SH0ES
Base + LSS + S_8 + SN
Riess et al. (2021)
DR12 LRG
DR16 QSO
DR16 Lya-QSO
DR16 Lya
$H/(1+z)$
z
80
75
70
65
60
55
0.5
1.0
1.5
2.0
2.5