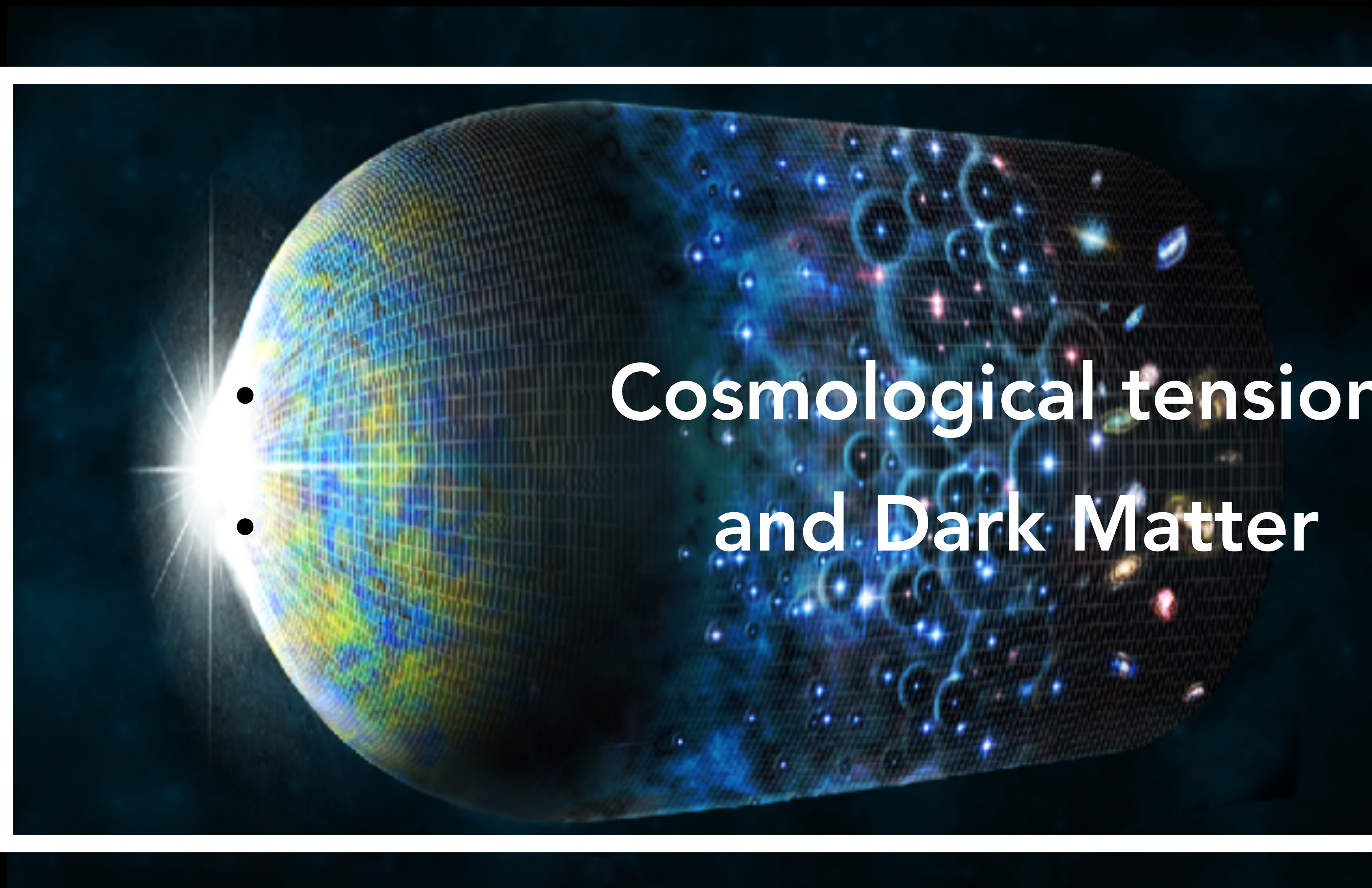
News from the dark, LAPTh Annecy, 24.11.2021



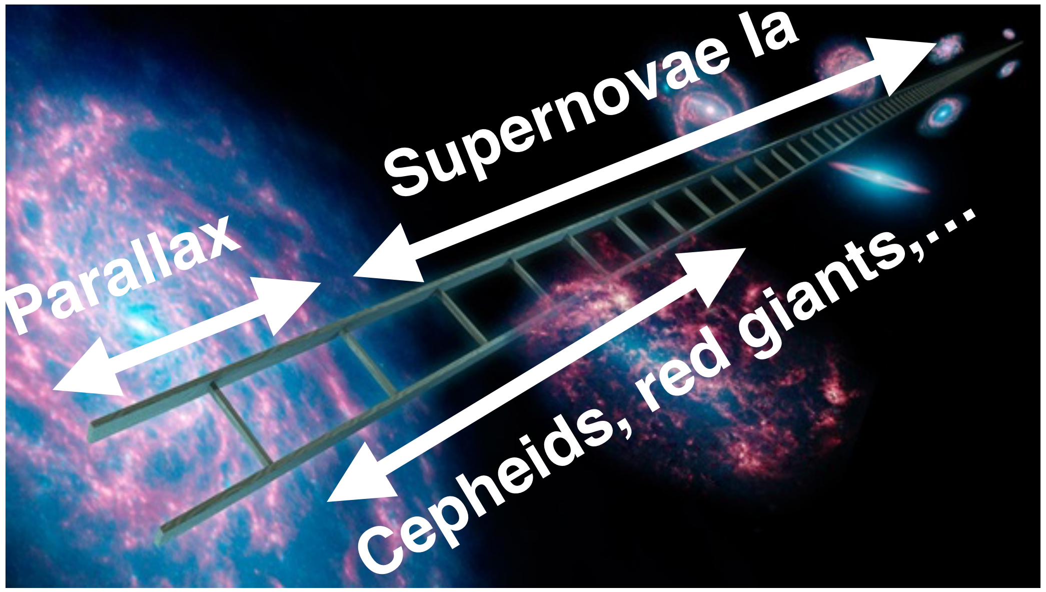
Cosmological tensions and Dark Matter

Involving Maria Archidiacono, Niklas Becker, Thejs Brinckmann, Manuel Buen-Abad, Stefan Heimersheim, Deanna Hooper, Misha Ivanov, Andrea Perez-Sanchez, Matteo Lucca, Nils Schöneberg, Sam Witte, + more senior collaborators…

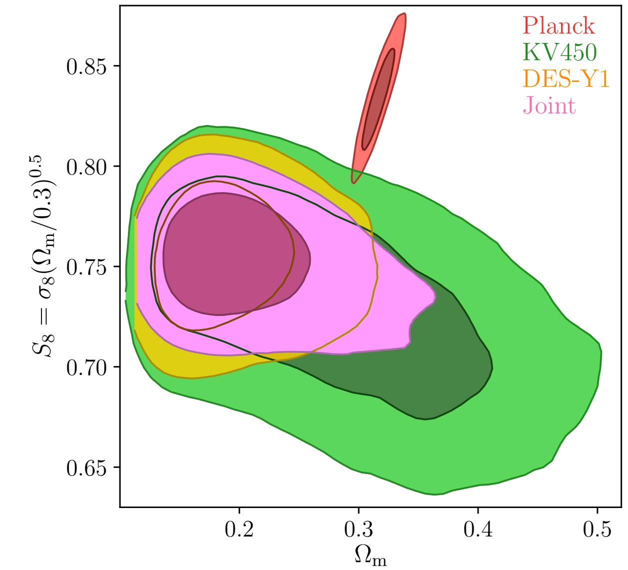
J. Lesgourgues

Institut für Theoretische Teilchenphysik und Kosmologie (TTK), RWTH Aachen University

H_0 and S_8 tensions



Local current expansion rate H_0 from distance ladder



Matter fluctuation amplitude S_8 from weak lensing

4 to 5σ

Repeated 2 to 3σ

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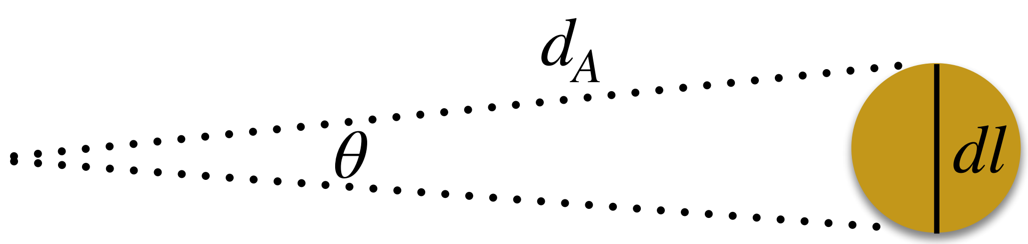
Distances in cosmology

Angular diameter distance $d_A \equiv \frac{dl}{d\theta}$



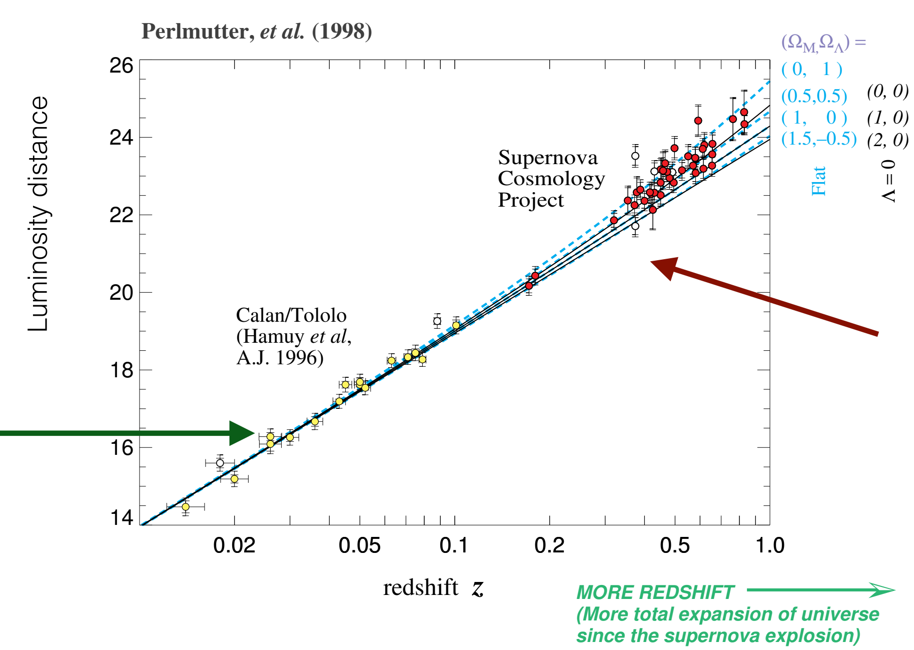
Standard ruler

Luminosity distance $d_L \equiv \sqrt{\frac{L}{4\pi l}}$

Standard candle

Relation between distances and redshift $d_L = a(t_0)\,(1+z_e)\,f_k\left(\int_0^{z_e} \frac{c\,dz}{a(t_0)H(z)}\right) = (1+z_e)^2 d_A$

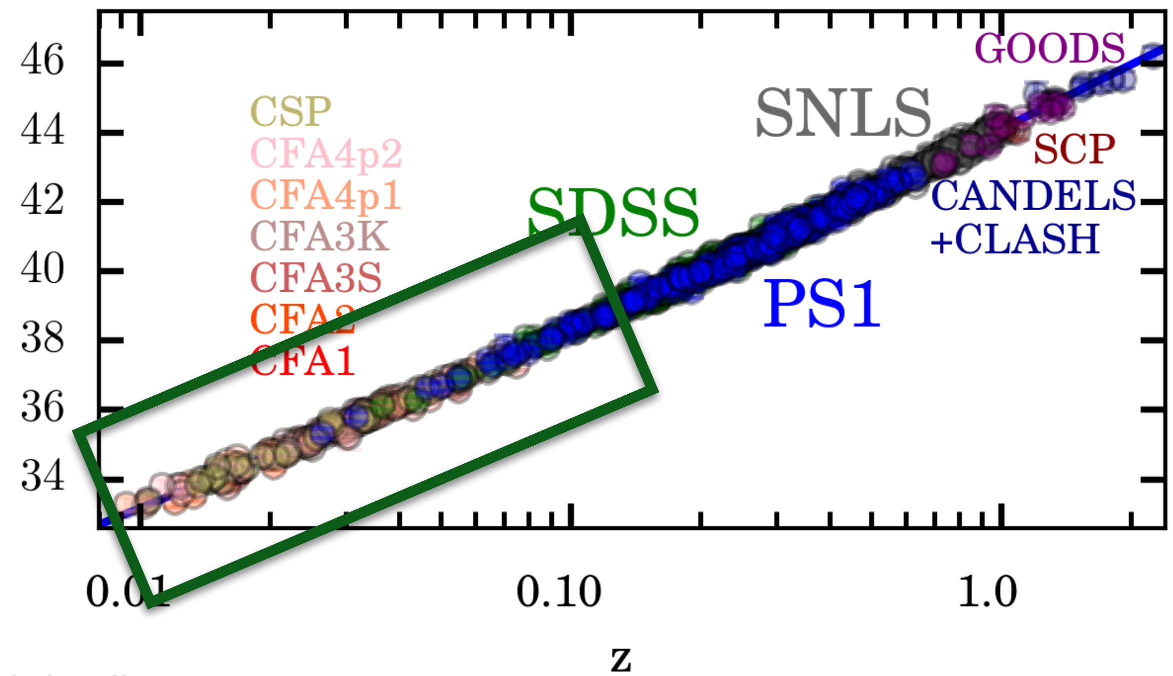
redshift z = “look-back time”



First derivative $\Rightarrow H_0$

Second derivative $\Rightarrow \Omega_k, \Omega_\Lambda$

H_0 from cepheids and supernovae :

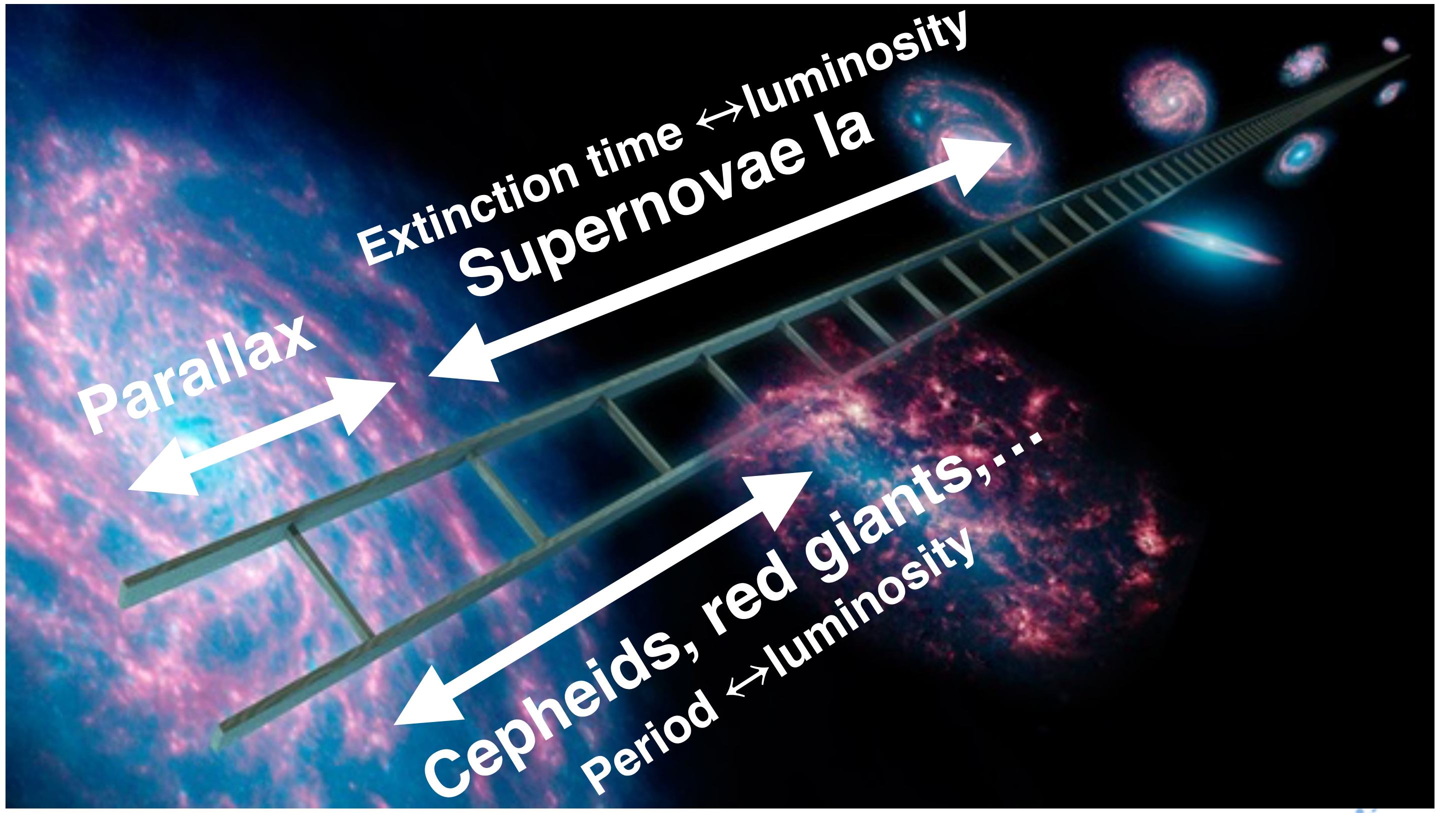


Luminosity distance

SH0ES: large H_0 ~ 73 km/s/Mpc ⇐

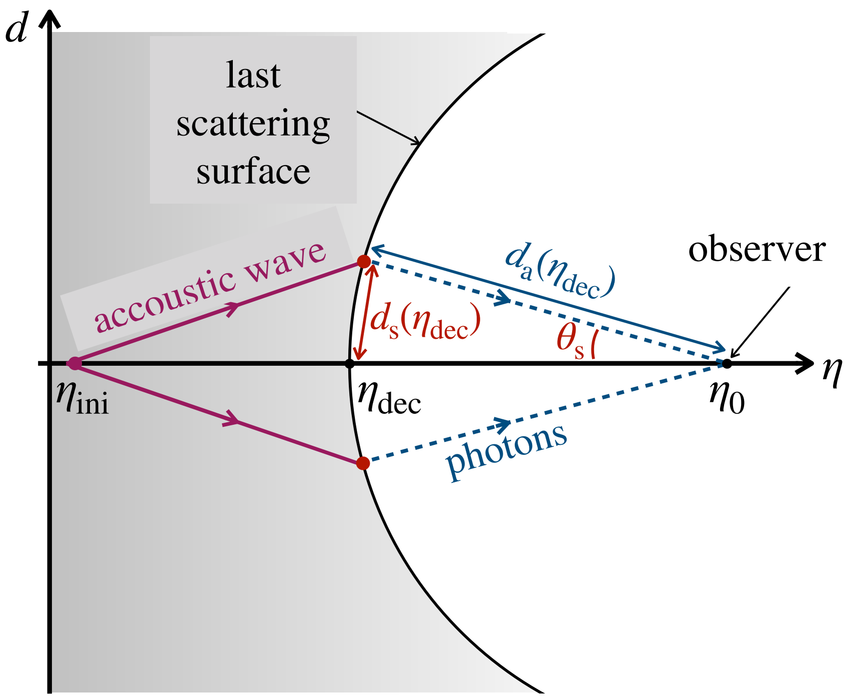
Riess et al. 2021

Use standard candles and "distance ladder":



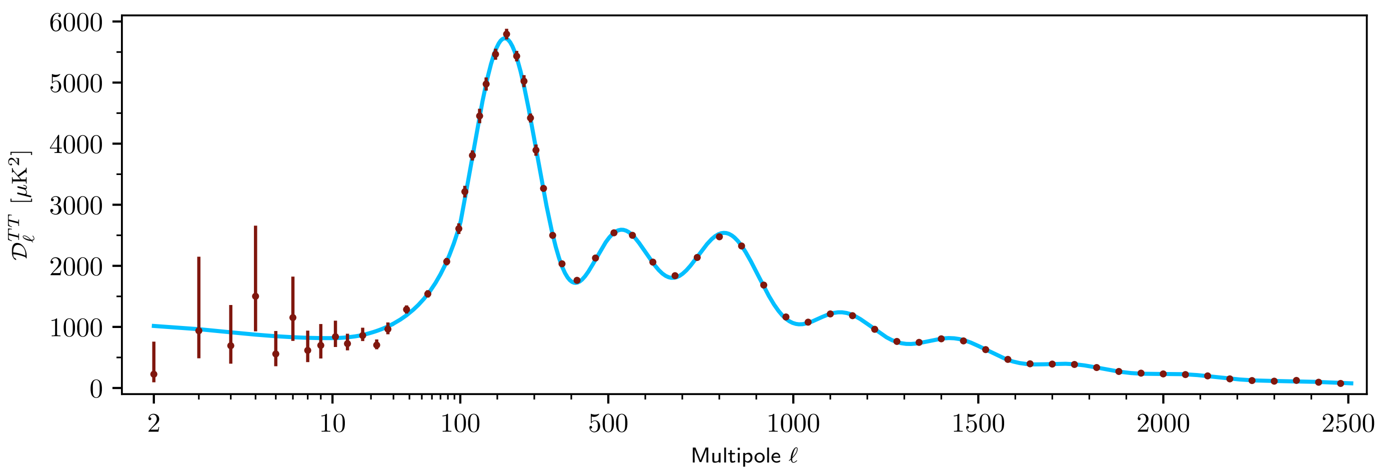
"Early" probes of Hubble rate (CMB, Baryon Acoustic Oscillations)

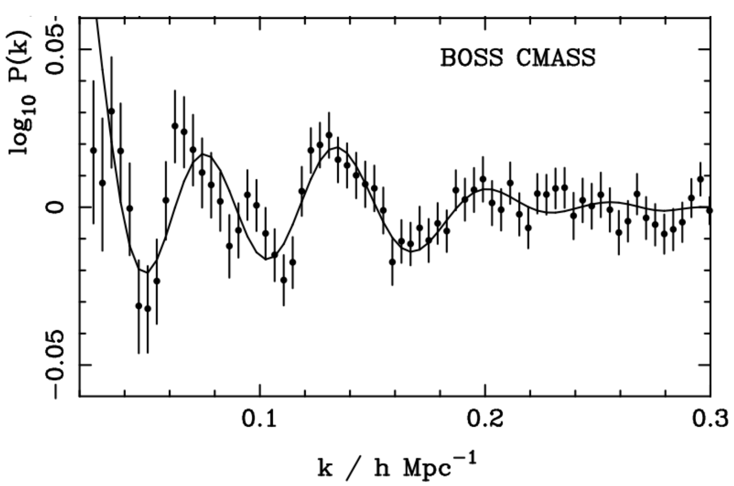
H_0 from sound horizon = standard ruler:



$$\theta(z) = \frac{\int_{z_D}^{\infty} c_s(\omega_b, \tilde{z}) H(\tilde{z})^{-1} d\tilde{z}}{\int_0^z H(\tilde{z})^{-1} d\tilde{z}}$$

$\theta(z)$ = scale of the peak in CMB spectrum, or in Baryon Acoustic Oscillations in galaxy spectrum

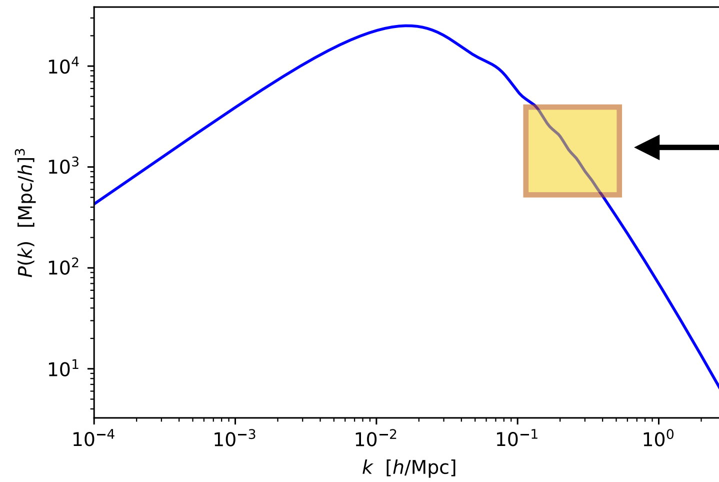




⇒ low H_0 ~68 km/s/Mpc even without CMB, but with BAO (+ Nucleosynthesis)

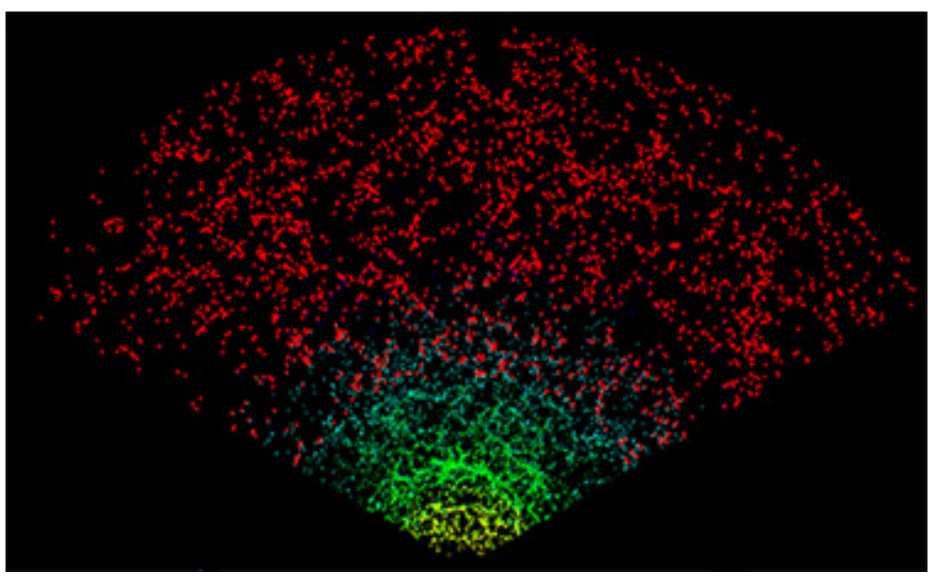
Matter power spectrum

$P(k, z)$ = 2-point correlation function of smoothed matter density field at redshift z, expanded in Fourier space

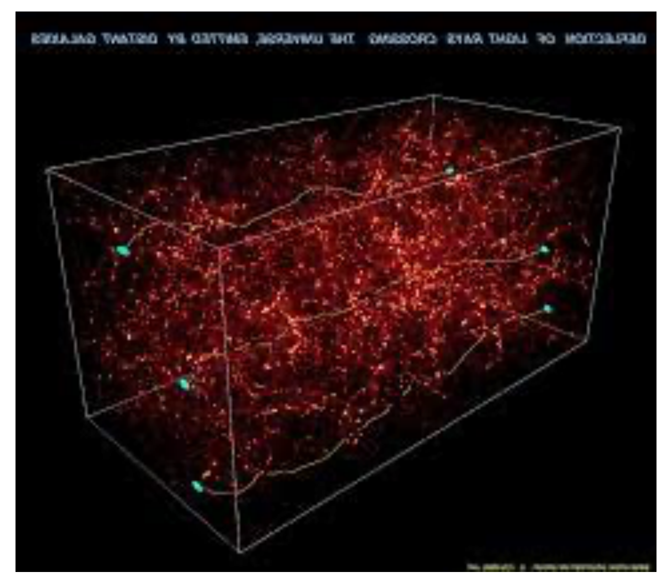


S_8 = amplitude of $P(k, z)$ around $k \sim 0.2\, h/\mathrm{Mpc}$ and $z \sim 0.6$

Galaxy surveys: shape, not amplitude



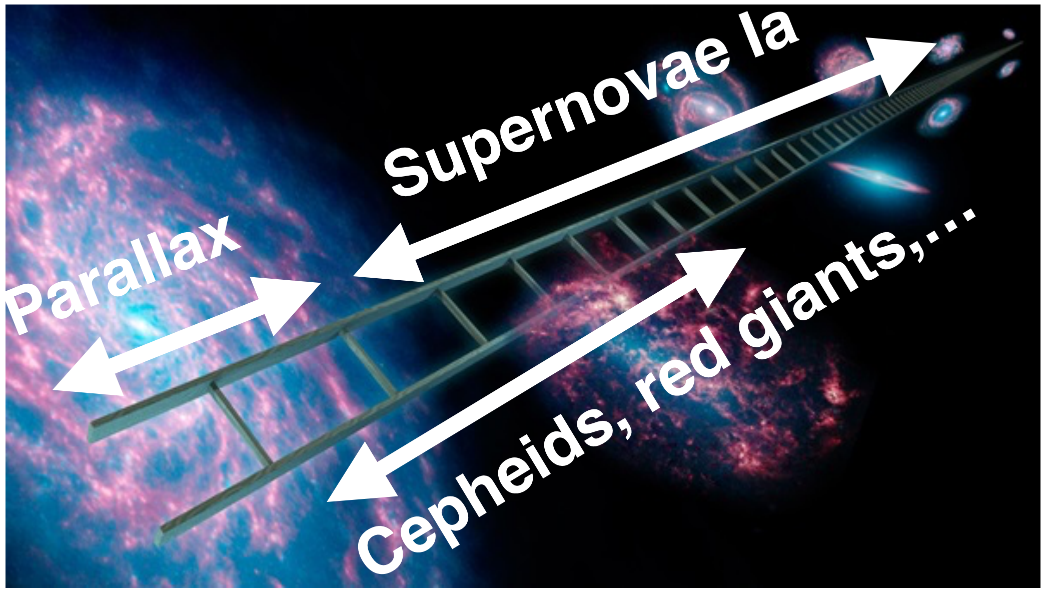
Weak lensing survey: low S8 (also: cluster count)

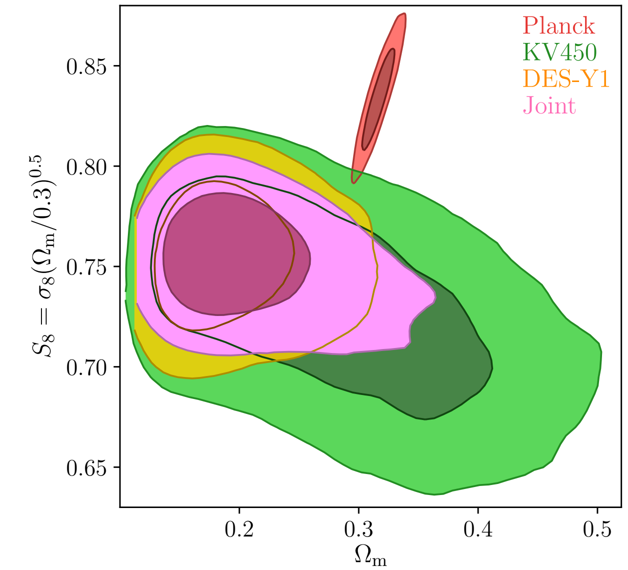


$\Rightarrow$ low $S_8 \sim 0.77$

Indirect: ΛCDM model fitted to Planck $\Rightarrow$ high $S_8 \sim 0.86$

H_0 and S_8 tensions





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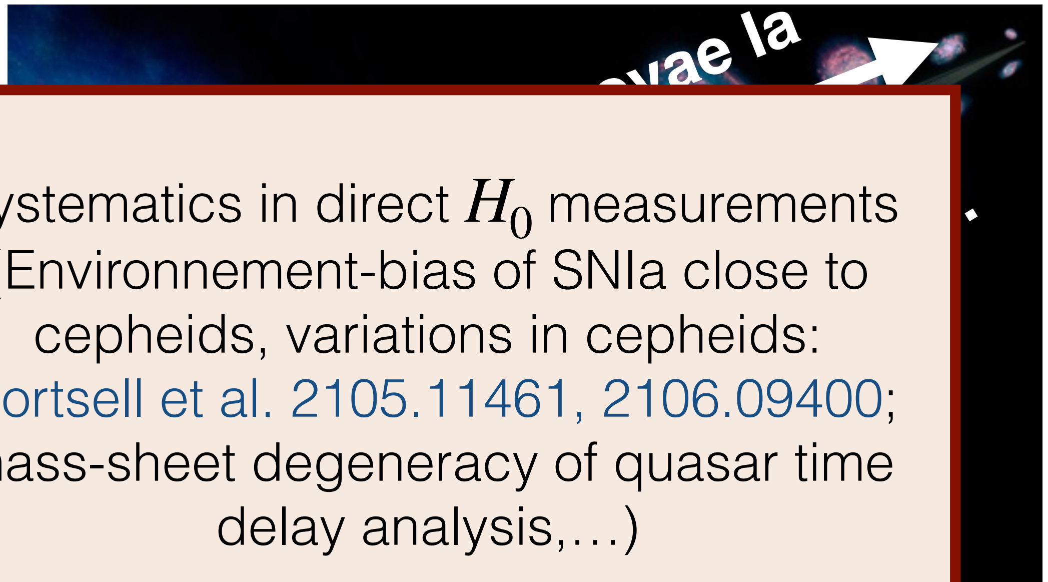

Systematics in direct H_0 measurements (Environnement-bias of SNIa close to cepheids, variations in cepheids: Mortsell et al. 2105.11461, 2106.09400; mass-sheet degeneracy of quasar time delay analysis,…)

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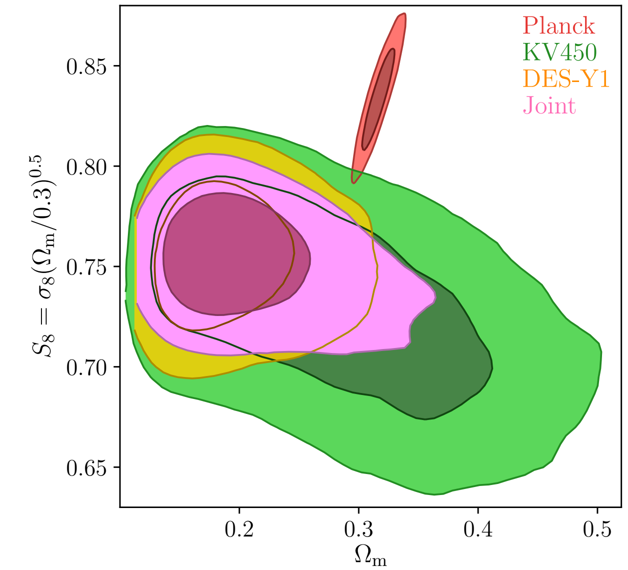

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Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

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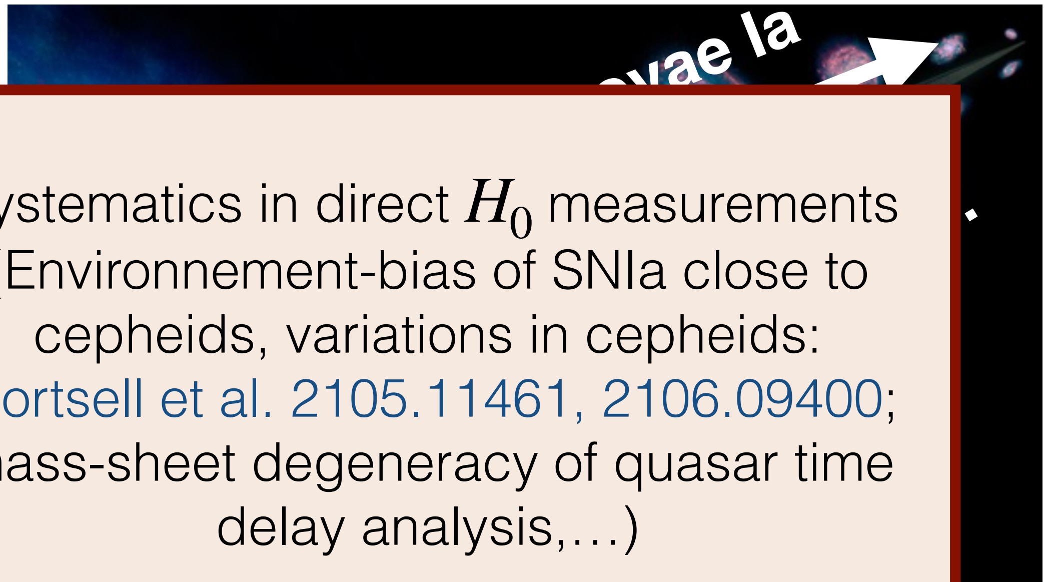

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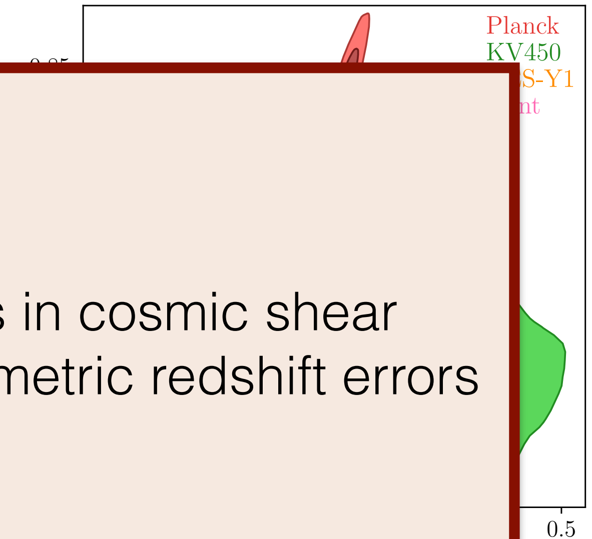

Systematics in cosmic shear surveys: Photometric redshift errors

Matter fluctuation amplitude S_8 from weak lensing

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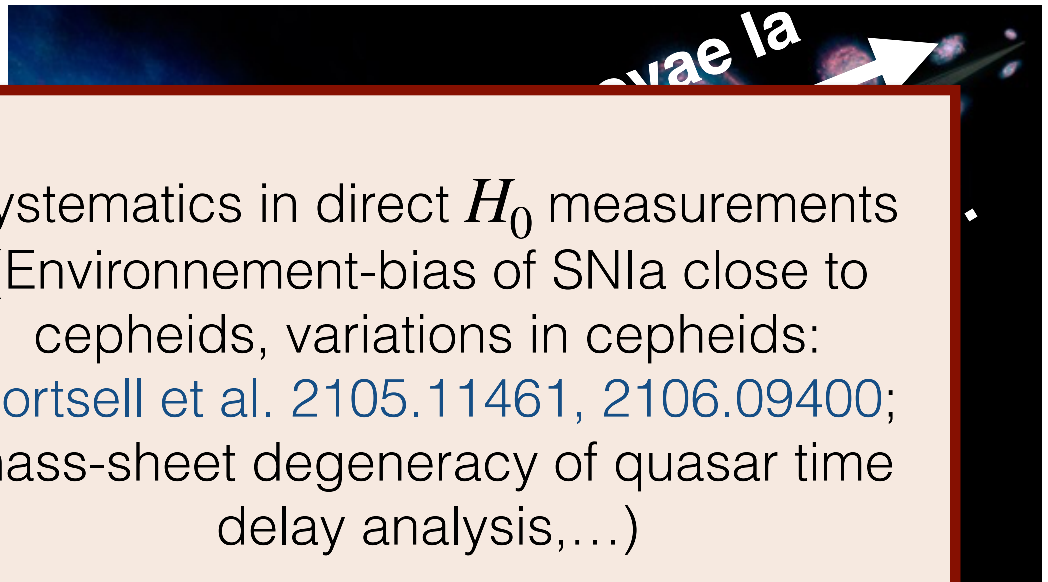

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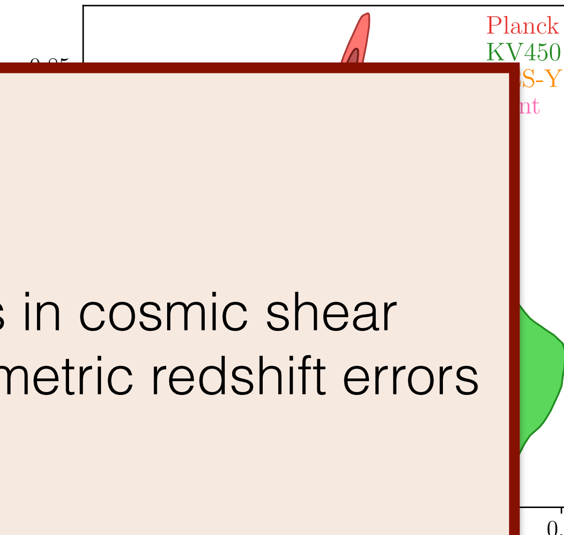

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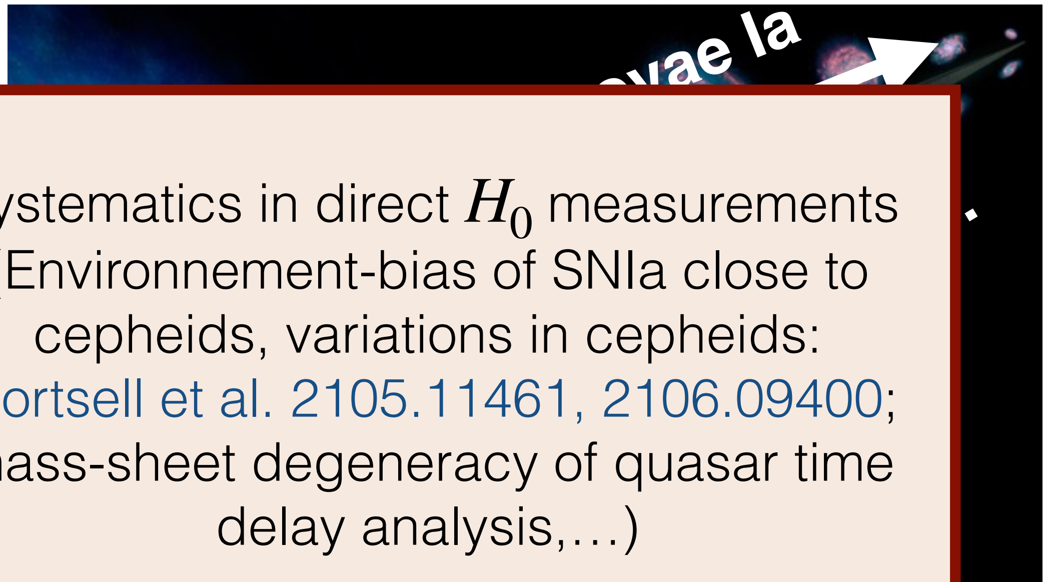
Systematics in CMB (Unknown foregrounds, insufficient instrument modelling)

H_0 and S_8 tensions



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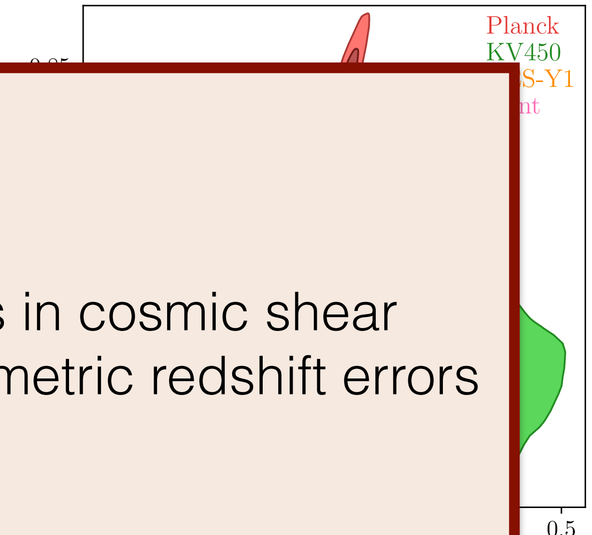


Systematics in cosmic shear surveys: Photometric redshift errors

Matter fluctuation amplitude S_8 from weak lensing

Small deviations from LCDM with new ingredients (DM, DE, MG, magnetic fields, etc.), or large-scale deviation from Friedmann model

Systematics in CMB (Unknown foregrounds, insufficient instrument modelling)

Solving the S_8 tension alone

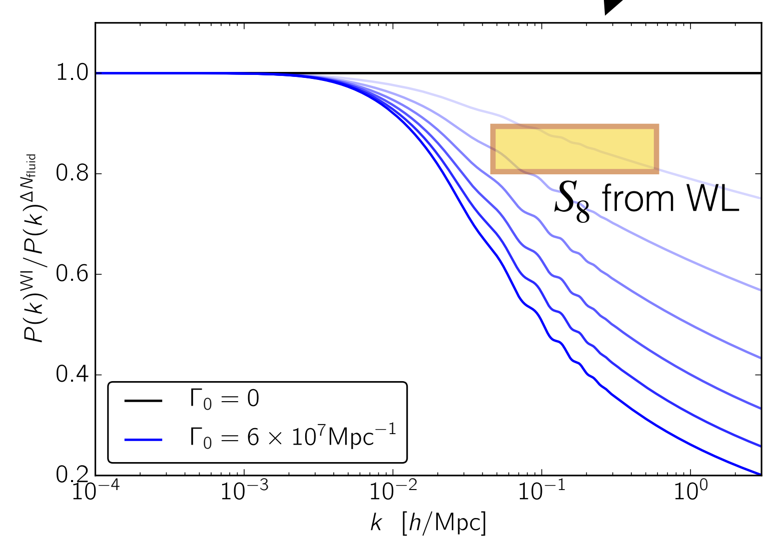
Does not work:

- Standard neutrino mass $\sum m_\nu$ ~0.2 eV (z_{NR} close to z_{dec} -> early ISW; not enough CMB lensing)
- pure Warm Dark Matter (exponential cut-off conflicting Lyman-α observations)
- Simplest decaying DM models (decay between z~1000 and z~1 into electromagnetic components: strong energy injection bounds; into neutrinos / dark radiation -> late ISW) (Chudaykin et al. 1602.08121, Poulin et al. 1606.02073, DES 2011.04606, …)

DM-related

Works well:

- Many Modified Gravity (MG) models (e.g. f(R))
- Feebly interacting DM (with relativistic particles: photons or DR; collisional damping) (Buen-Abad et al. 1708.09406; Becker et al. 2010.04074)
- Cold + Warm DM (small fraction of ~keV DM) (Boyarsky et al. 0812.0010)
- Long-lived CDM decaying into massless + massive but lighter particle; possible connection with Xenon-1T (Abellan et al. 2008.09615)
- Cannibal DM (inelastic scattering 3→2 causing slow transition from radiation-like to matter-like (Heimersheim et al. 2008.08486)
- Connection with small-scale CDM crisis…
- Testable with Lyman-α (should avoid exponential cut-off)



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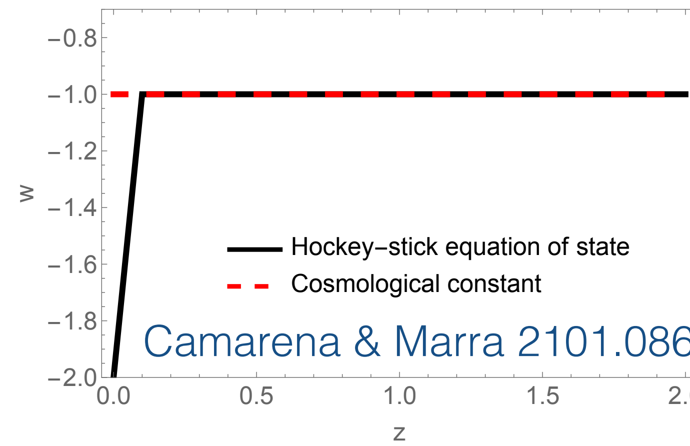
Solving the H_0 tension alone

Does not work:

- Change in late cosmological evolution to get a smaller H0 with the same angular distance $d_A = (\dots) \int_0^{z_{\rm obs}} dz/H(z)$ …

  $\Rightarrow$ too constrained by BAO + Supernovae data



- Increase $N_{\rm eff}$ to change sound horizon r_s and angular distance d_A by same amount, and make sound angular scale $\theta = r_s/d_A$ compatible with larger H_0

  $\Rightarrow$ CMB forbids to increase $(N_{\rm eff}, H_0)$ too much: (enhanced Silk damping, acoustic peak shift from neutrino drag) and BBN + Helium abundance require $N_{\rm eff} < 0.3$

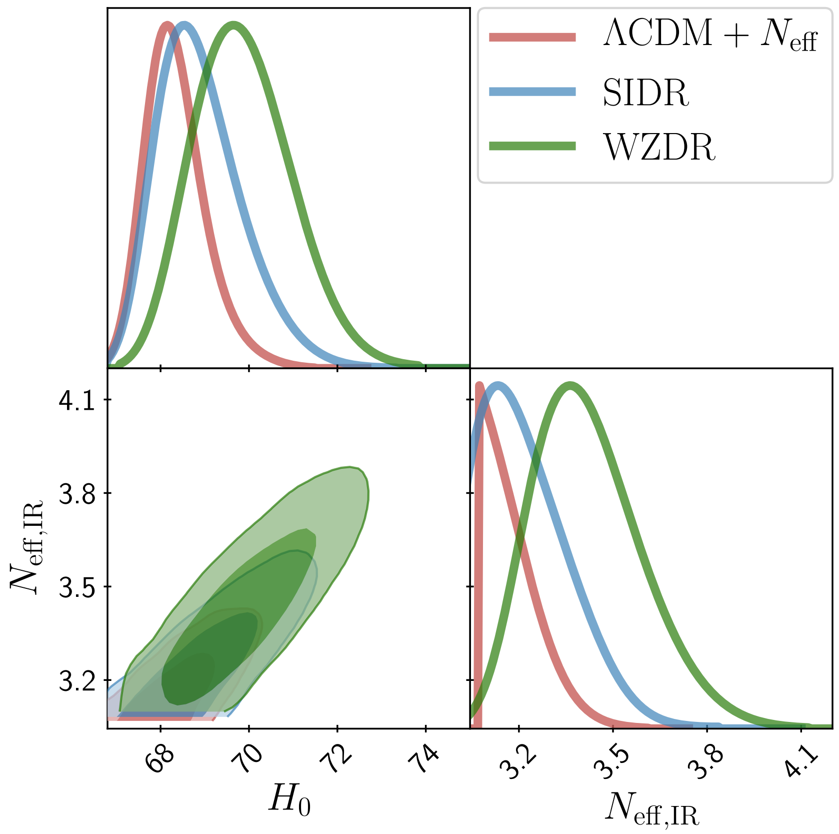
Works better:

1. Increase $N_{\rm eff}$ after BBN and compensate with new ingredients in the Dark Sector
2. Get the same with a scalar field dominating just before recombination (Early Dark Energy)
3. Shift the time of recombination (variation of fundamental constants, inhomogeneous recombination from e.g. small-scale primordial magnetic fields)

Solving the H_0 tension alone

Increasing $N_{\rm eff}$:

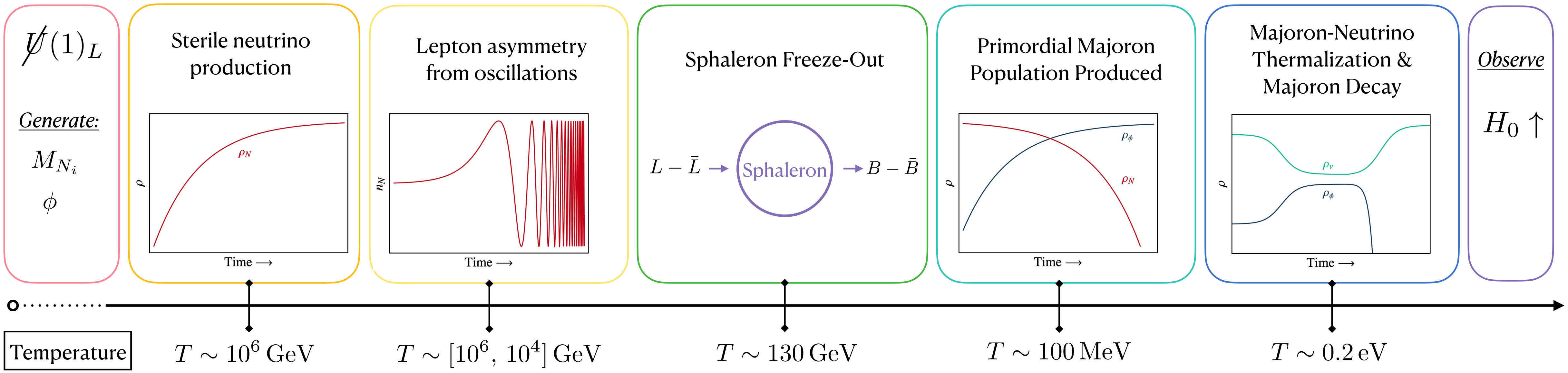
- Self-interacting Dark Radiation works better than free-streaming massless relics (no baryon drag, no offset of CMB peaks)
- $N_{\rm eff}$ should increase between BBN and CMB times (entropy release)
- Wess-Zumino Dark Radiation (WZDR) model of Aloni, Berlin, Joseph, Schmaltz & Weiner 2111.00014 :
  - Interaction between massless relic fermions mediated by eV-mass scalar ($eV \sim M_{\rm SUSY}^2/M_{\rm Pl}$)
  - At T~1eV, scalar becomes non-relativistic, entropy release boosts $N_{\rm eff}$ from ~3.3 to ~ 3.5 (precise value depends on $T_{\rm dark}$)
  - Transition leaves imprint in CMB spectrum that compensates for increase of $(N_{\rm eff}, H_0)$



Solving the H_0 tension alone

Majoron scenario of Escudero & Witte 1909.04044, 2004.01470, 2103.03249:

- O(eV)-mass Majoron ϕ = pseudo-Goldstone of spontaneously broken $U(1)_L$
- small Yukawa-like couplings to active neutrinos
- $T \sim \phi$: interactions between majoron and active neutrinos (inverse neutrino decay):
  - Majoron thermalize and contribute to $N_{\rm eff}$,
  - active neutrinos do not free-stream
- $T < \phi$: Majoron decays into active neutrinos, which free-stream



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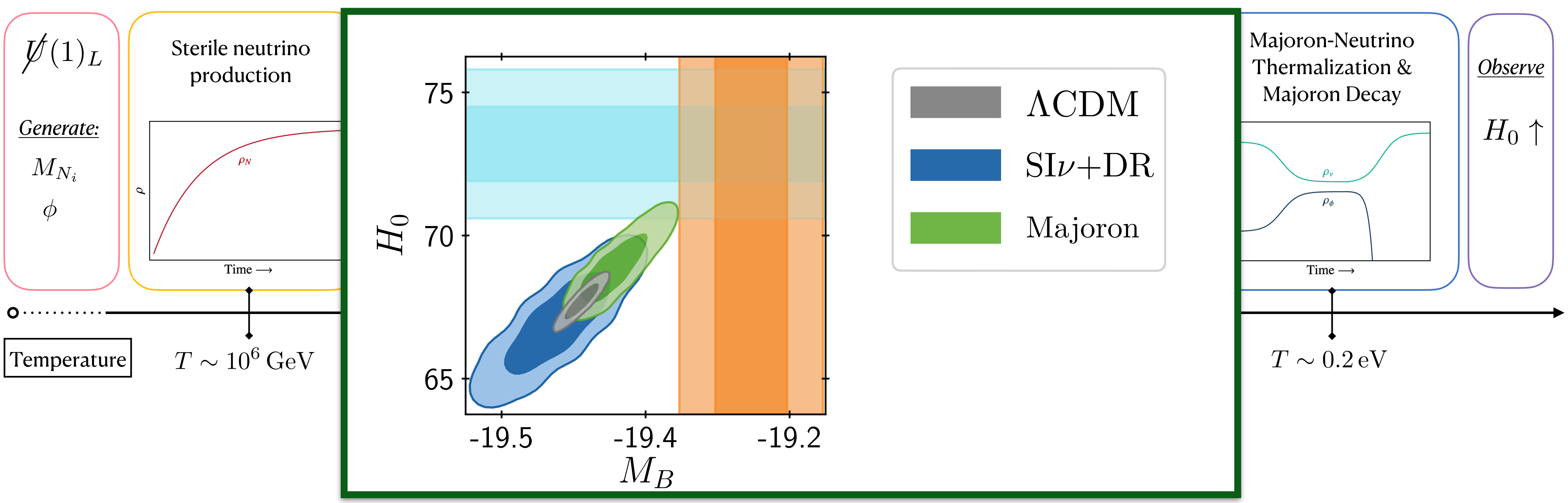
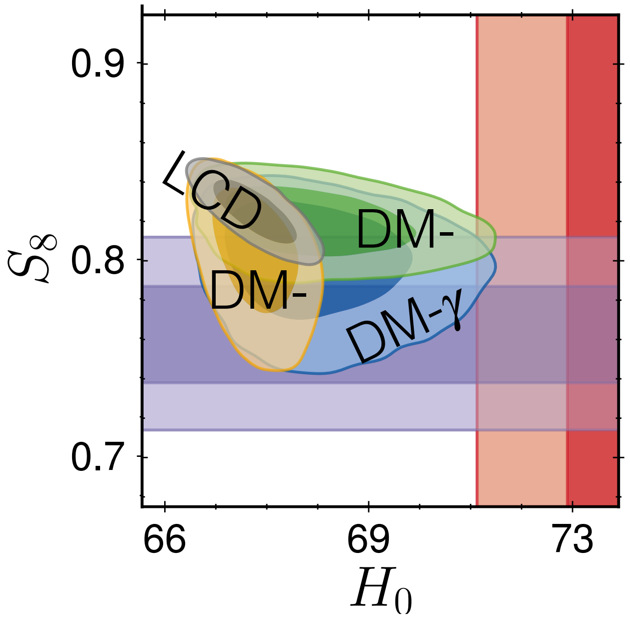


Solving both tensions?

Currently, no known and studied models convincingly solving both tensions!

- Most models ease one tension at expense of making other worse… few exceptions, e.g.:

- DM interacting with DR *and* photons works better (Becker et al. 2010.04074)
  E.g. DM may interact with dark photon, mixed with visible photon…



- Try Majoron of Escudero et al. + sizeable active neutrino mass?

- Try Interacting Dark radiation model of Aloni et al. + DR-DM interactions of Buen-Abad et al. ?

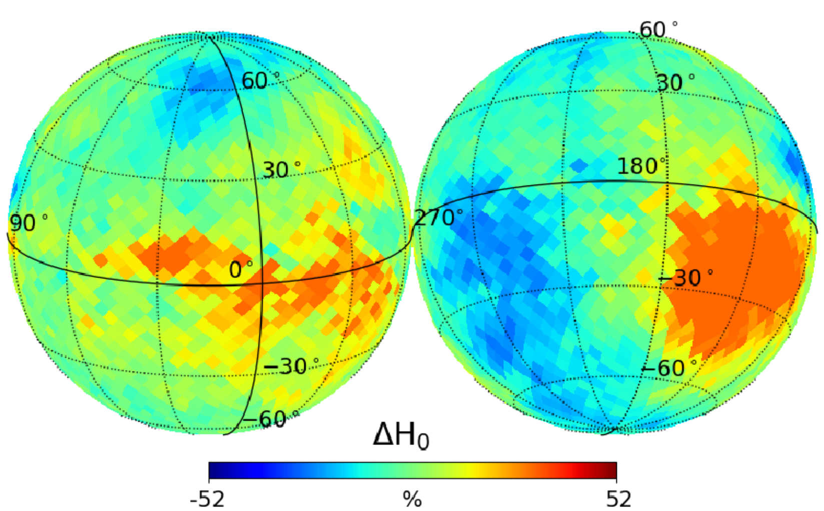
Conclusions

Hope that one or more tension solved by systematics!

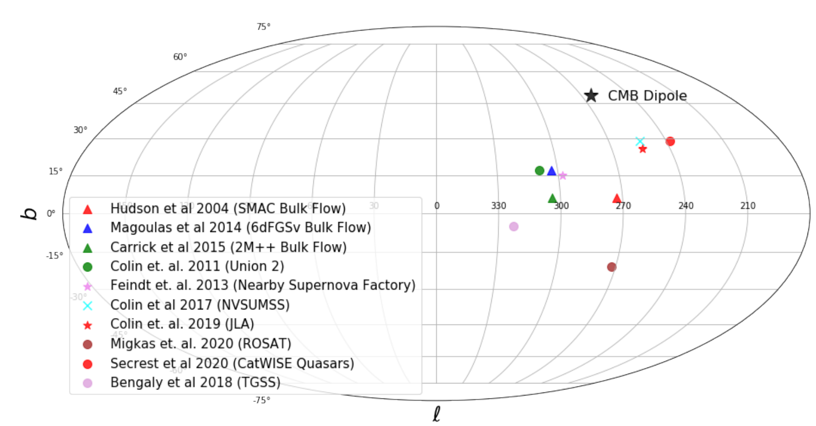
Reassuring that we cannot fit anything? …

If tensions do not settle with systematics:

- Previous models: predictions for next-generation CMB/LSS (e.g. EDE, Majoron, shifted recombination, WZDR…)
- Chance to learn about new particle physics, tests it in laboratory? (e.g. DM interactions, Majoron)
- Revisit models beyond Friedmann? Large-scale inhomogeneity?



Fosalba & Gaztanaga 2011.00910



Kinematic dipole / CMB dipole mismatch

Secrest et al. 2009.14826; 2105.09790, 2106.03119