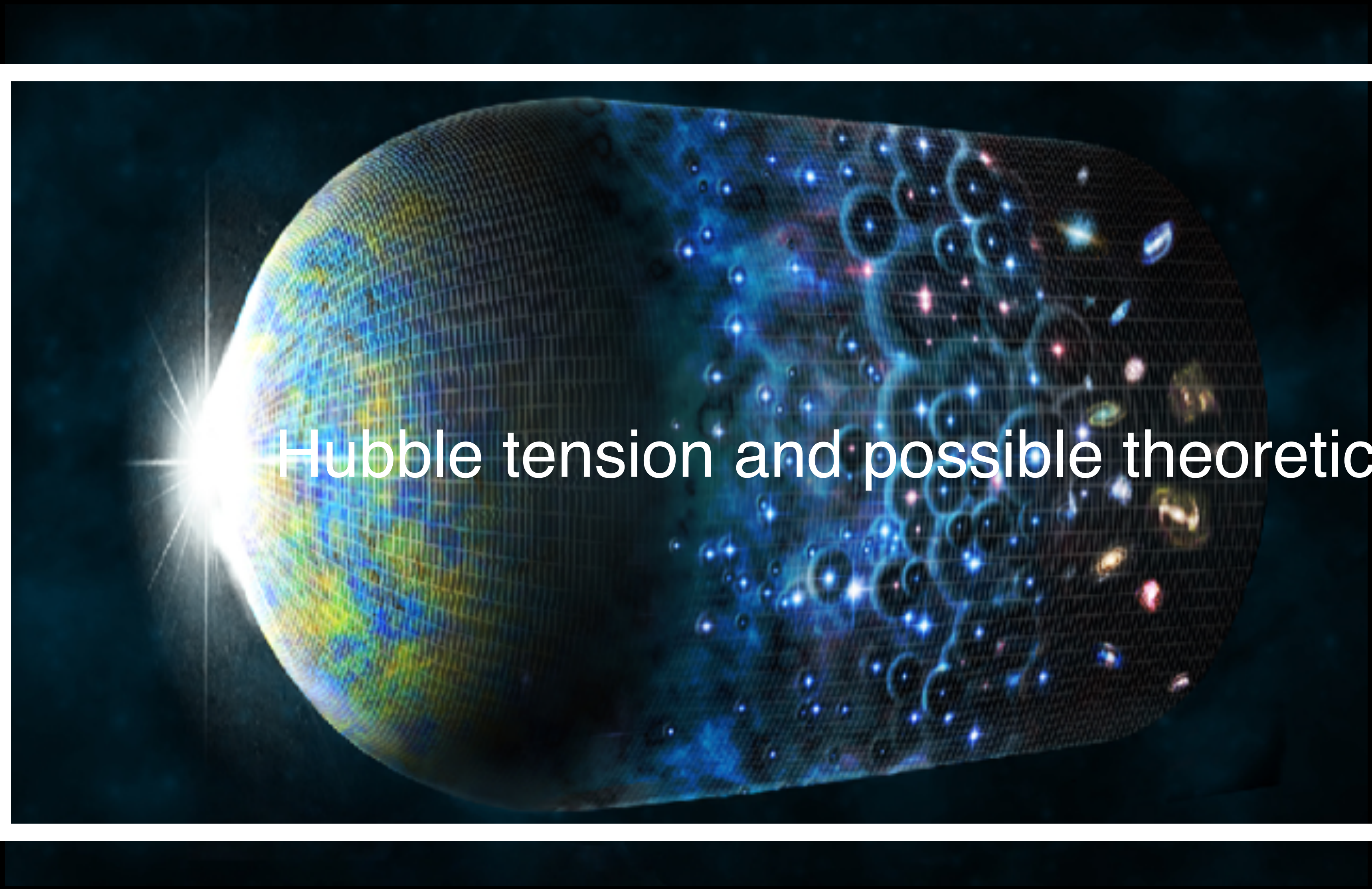
Mainz Universität, 8.02.2023



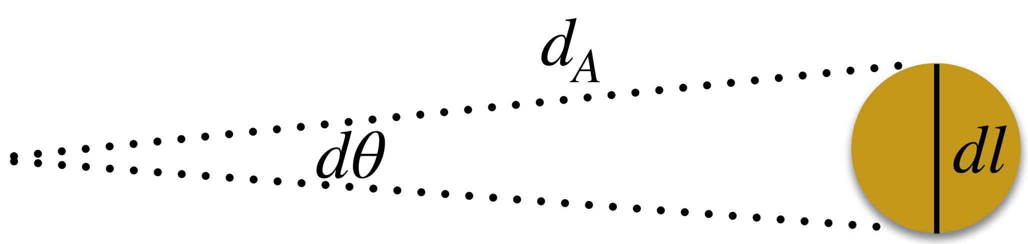
Hubble tension and possible theoretical solutions

J. Lesgourgues

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

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”

Concordance cosmology

1992 - 2016: towards concordance cosmology:

- Cosmic Microwave Background (CMB): maps for
  - temperature,
  - polarisation,
  - gravitational lensing.

- Big Bang Nucleosynthesis (BBN) & primordial elements

- Large Scale Structure of the universe (LSS):
  - Galaxy clustering
  - Cosmic shear (weak lensing)

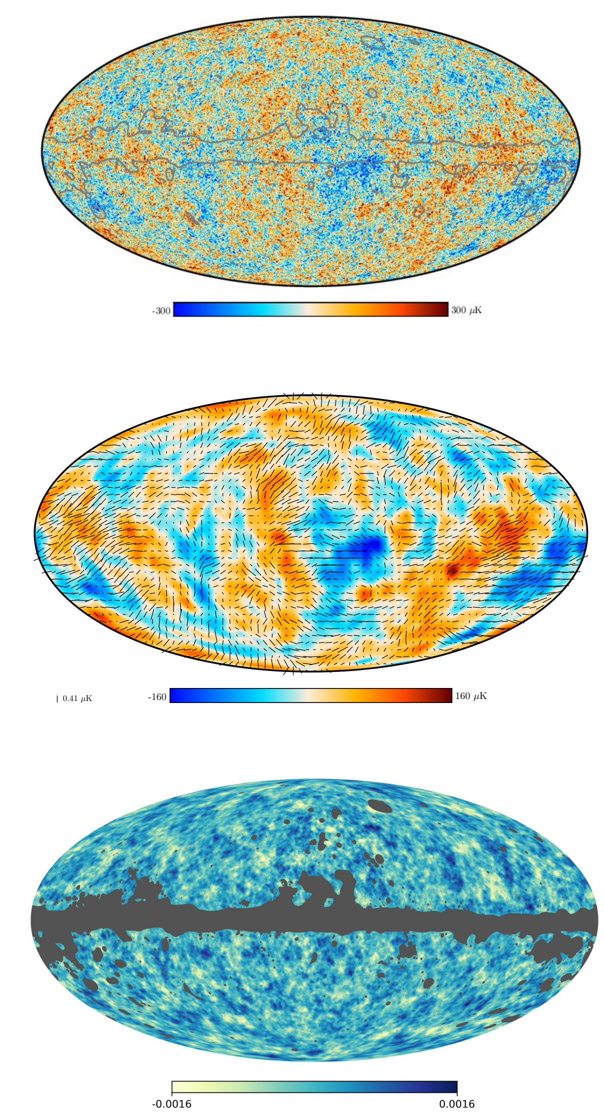
- Cepheids and Supernovae luminosity

…

$\Rightarrow$ ΛCDM concordance model:

  - General Relativity, QED, nuclear physics;
  - inflation, baryons, Cold Dark Matter, cosm. const., photons, neutrinos;
  - 7 free params. (6 after measurement of $T_{\rm CMB}$)

Planck maps



Discordance cosmology

2016 - 2012: towards discordance cosmology?

Hubble rate $H_0 = \frac{\dot{a}(t_0)}{a(t_0)} = 100\,h$ km/s/Mpc

- CMB:

Planck 2018: $H_0 = 67.36 \pm 0.54$ km/s/Mpc

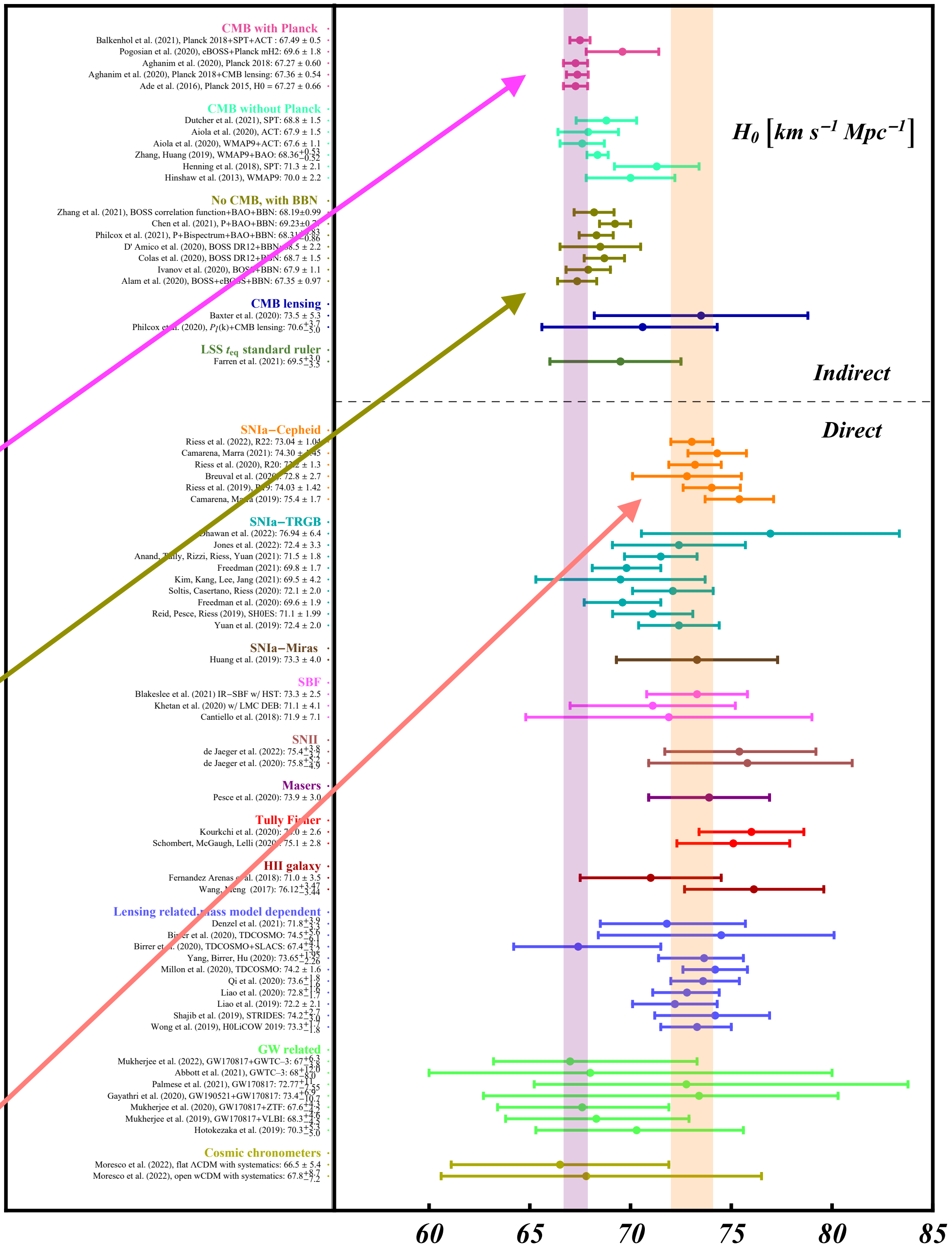
- Baryon Acoustic Oscillations (BAO):

BOSS+eBOSS+BBN: $H_0 = 67.35 \pm 0.97$ km/s/Mpc

$\sim 5\sigma$ tension

- Supernovae + Cepheids:

SH0ES 2022: $H_0 = 73.04 \pm 1.04$ km/s/Mpc



Riess et al. 22

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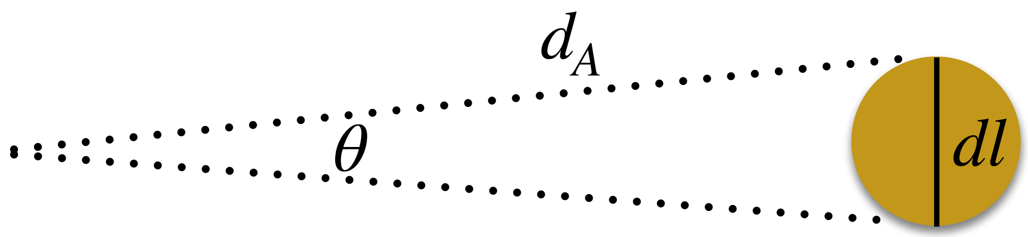

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redshift z = "look-back time"

$\Rightarrow$ Measurement of H_0 by CMB/BAO: sound horizon as standard ruler: $d_A = d_s / \theta_s$

Foundations of the minimal cosmological model

Physics of CMB anisotropies and LSS:

- Einstein equations + Friedmann metric: $3\,H^2 = 8\pi G\,\rho$ and $\delta G_{\mu\nu} = 8\pi G\,\delta T_{\mu\nu}$
- Equations of motion:
  - linearised Boltzmann $\partial_t\, f_i(x^\mu, p^\nu) = C[f_1, f_2, \ldots]$
  - or linearised fluid equations (continuity, Euler)
- Thomson scattering rate ⇒ ionisation fraction ⇒ basic QED, hydrogen atom
- Initial conditions: inflation ⇒ gaussian random field with nearly scale-invariant 2-point correlation function / power spectrum

CLASS, CAMB

2-point correlation function / power spectrum at any later time

⇒ many features, incl. oscillations: $\cos(2\pi d_s/\lambda)$ (acoustic waves before $\gamma - b$ decoupling)

wavelength

sound horizon = distance travelled by sound wave from BB till decoupling

ΛCDM = 6-parameter fit

to ~5000 independent data points

agreement of CMB and BAO with:

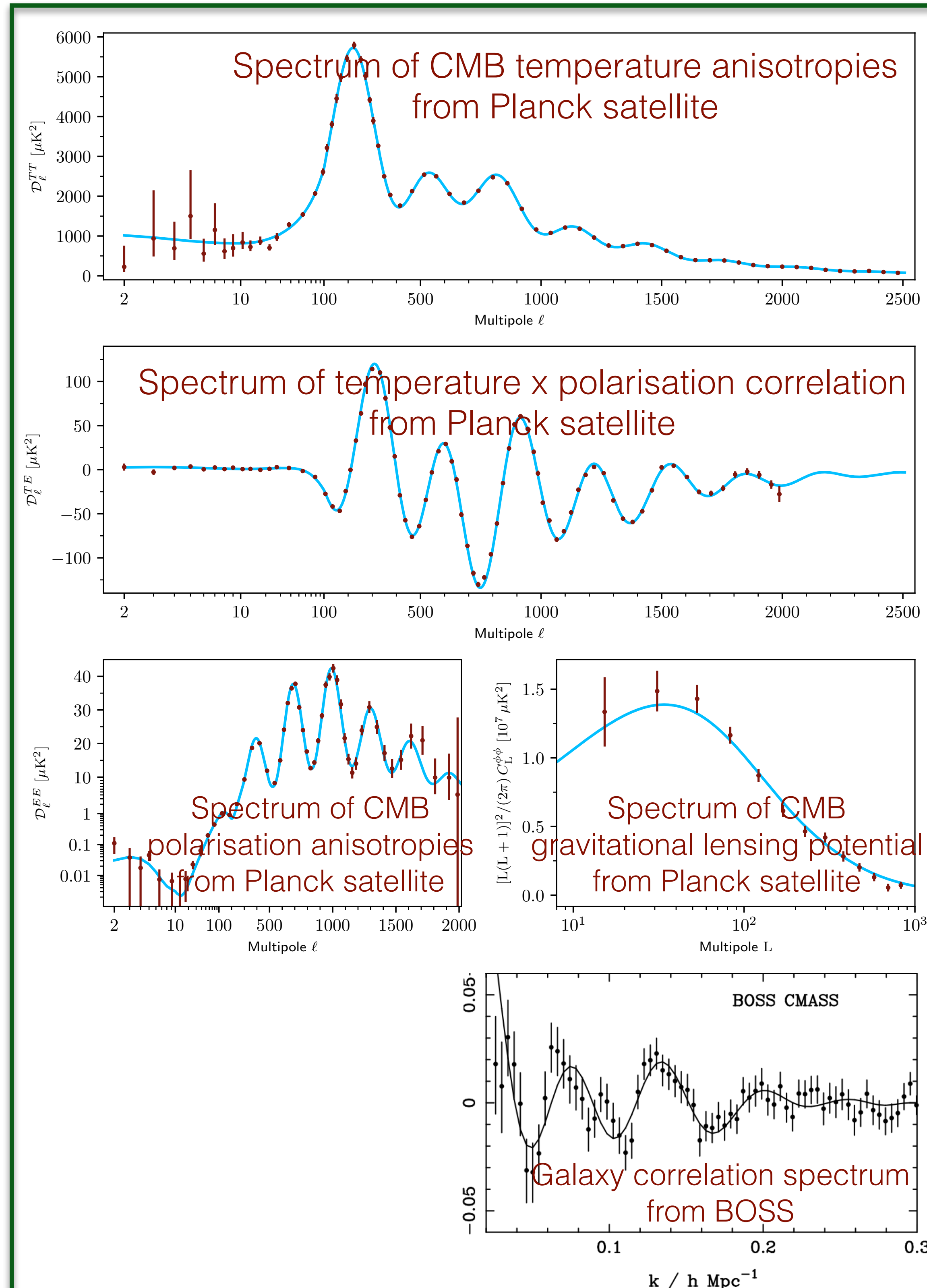
- CMB/BAO with BBN and primordial abundances,
- luminosity of distant SNIa,
- various probes of the Large Scale Structure…

CMB (+ BAO) probe directly:

$d_s \Leftarrow$
- density ratio of baryon/photons,
- density ratio of non-relativistic/relativistic matter,

$\theta_s \Leftarrow$
- angular scale of the sound horizon,
- 2 params. for primordial spectrum,
- optical depth to reionization

Indirectly: $\Rightarrow H_0 \equiv \dfrac{\dot{a}(t_0)}{a(t_0)} \sim 67\ \mathrm{km/s/Mpc}$



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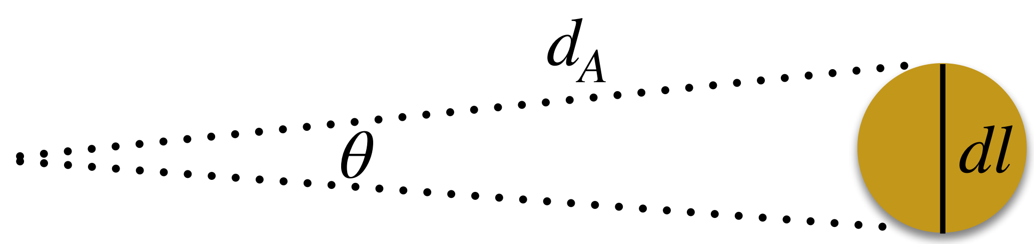


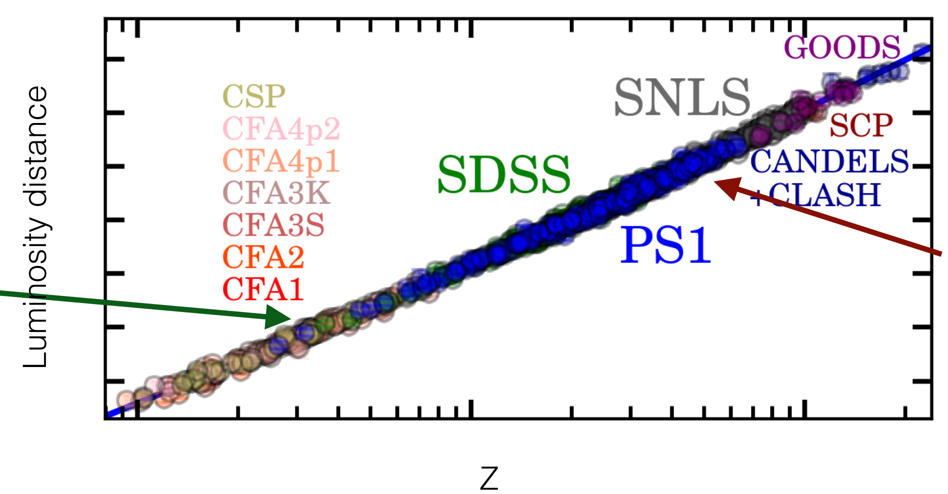
Standard ruler

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

Standard candle

$\Rightarrow$ Measurement of H_0 by cepheids + SNIa: d_L vs. Redshift ! $d_L(z) = (1+z)\int_0^z \frac{d\tilde{z}}{H(\tilde{z})}$

nearby SNIa:
first derivative $\Rightarrow H_0$



remote SNIa:
second derivative $\Rightarrow \Omega_k, \Omega_\Lambda$

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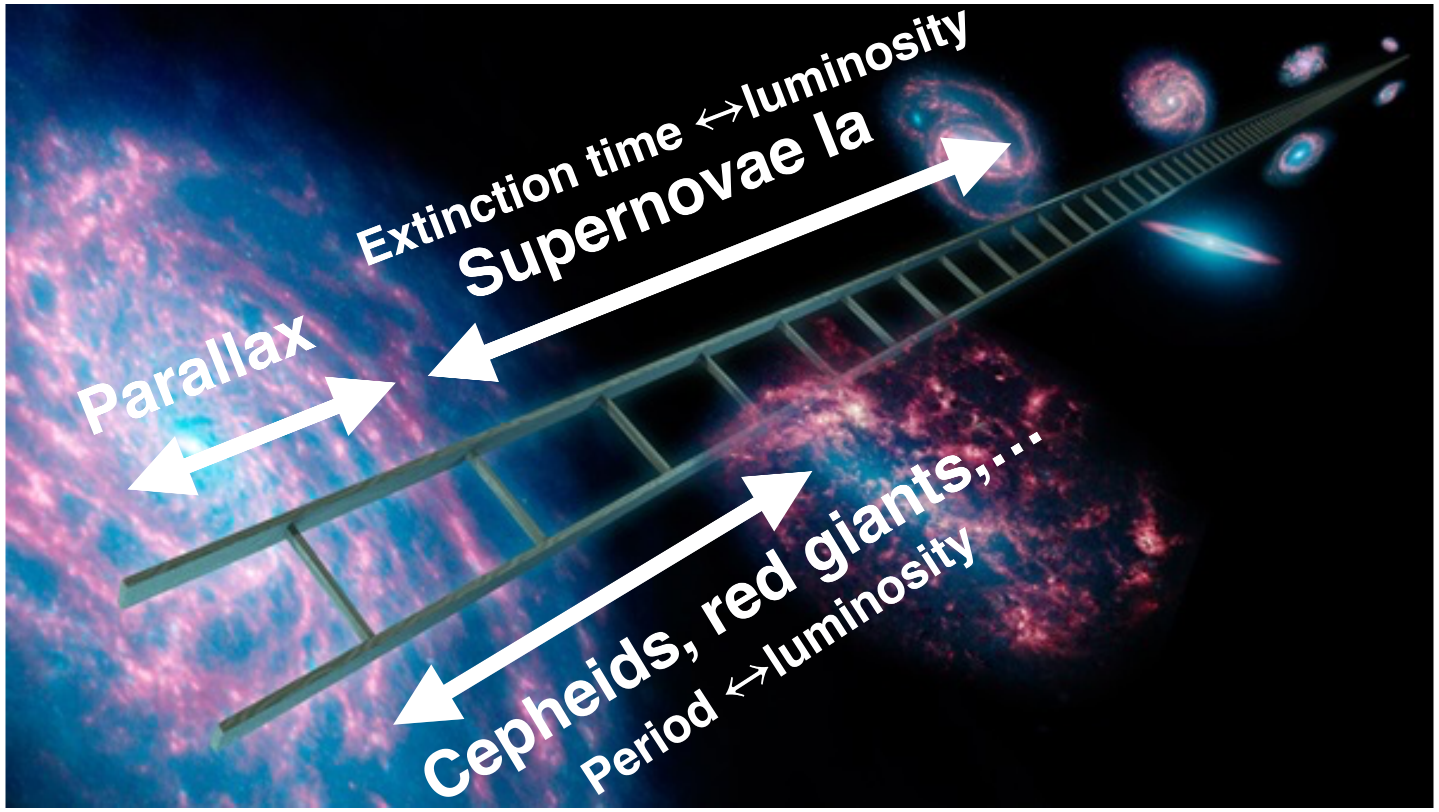
Direct measurement of Hubble rate from standard candles



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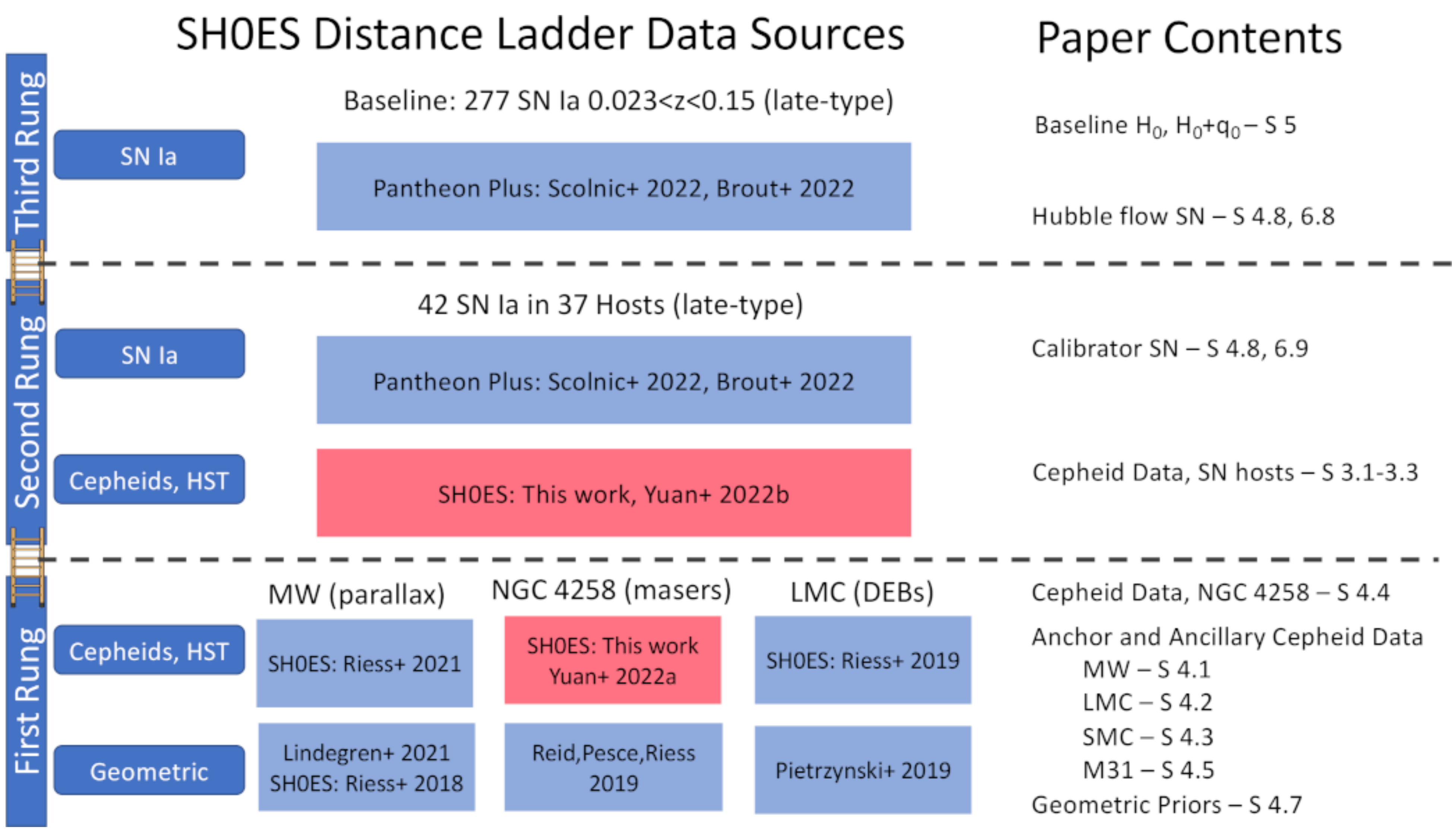
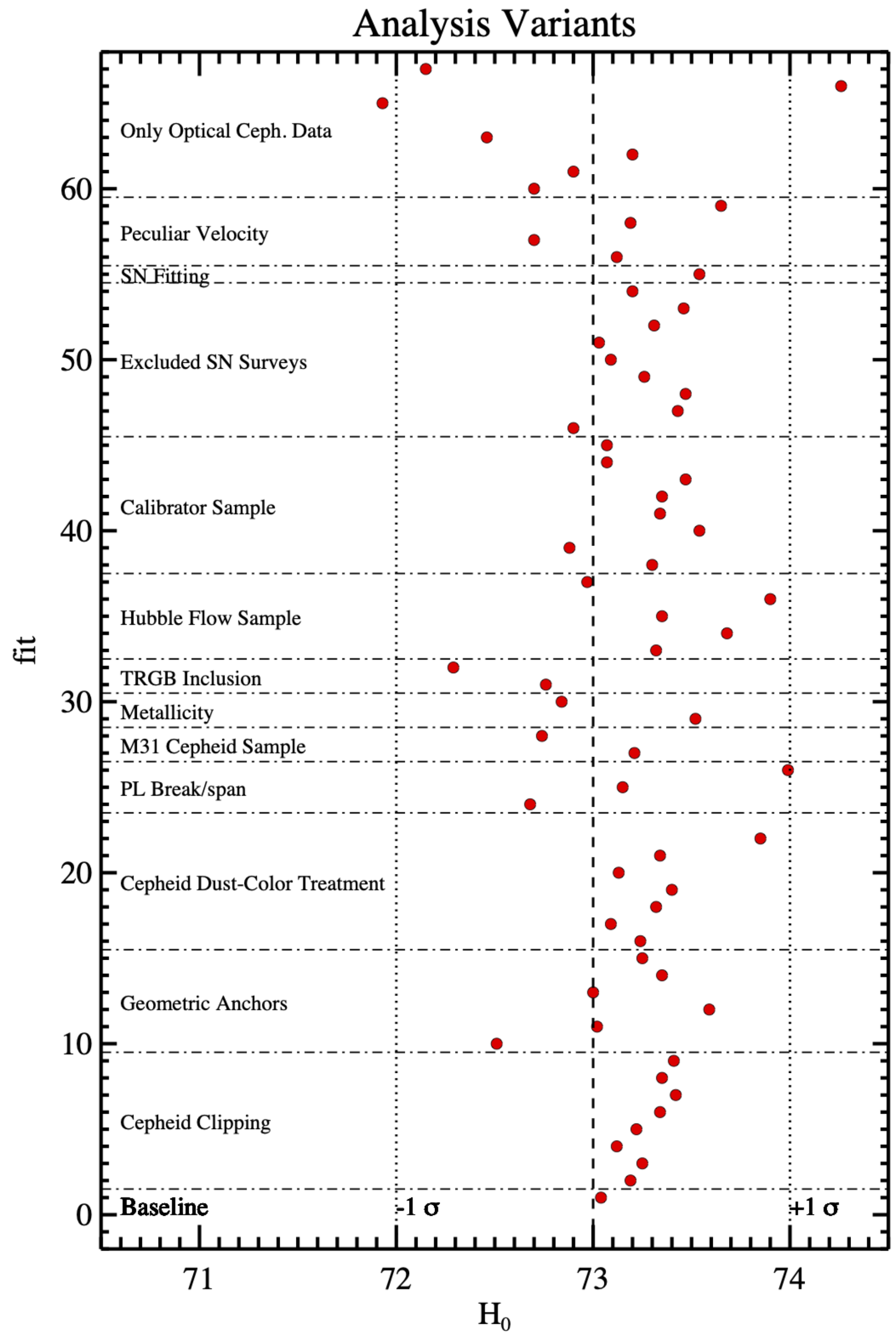


Direct measurement of Hubble rate from standard candles

Systematics in direct H_0 measurements?
Environnement-bias of SNIa close to cepheids,
variations in cepheids:
Mortsell et al. 2105.11461, 2106.09400,…



Riess et al. 22

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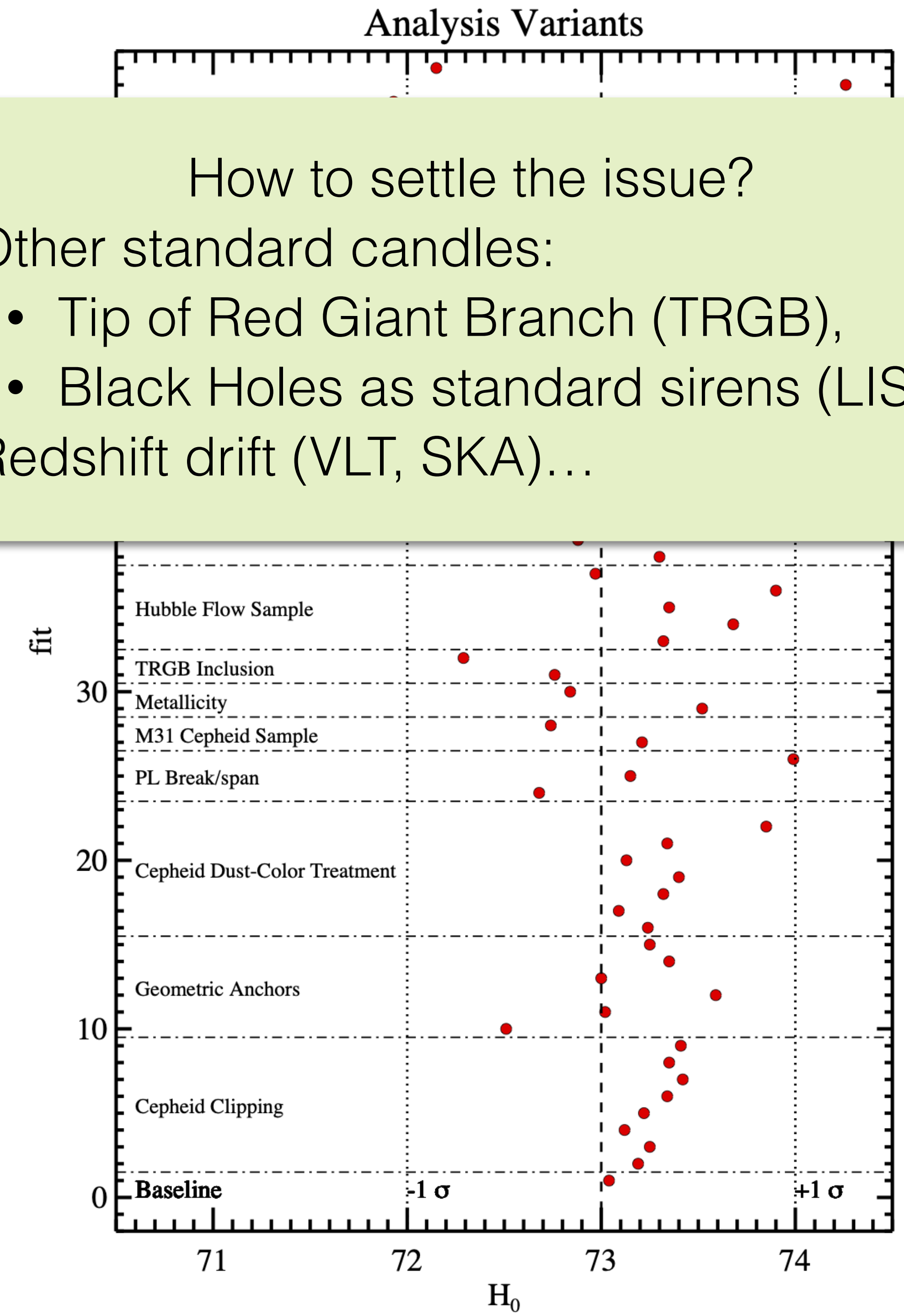
How to settle the issue?

- Other standard candles:
  - Tip of Red Giant Branch (TRGB),
  - Black Holes as standard sirens (LISA, ET)
- Redshift drift (VLT, SKA)…



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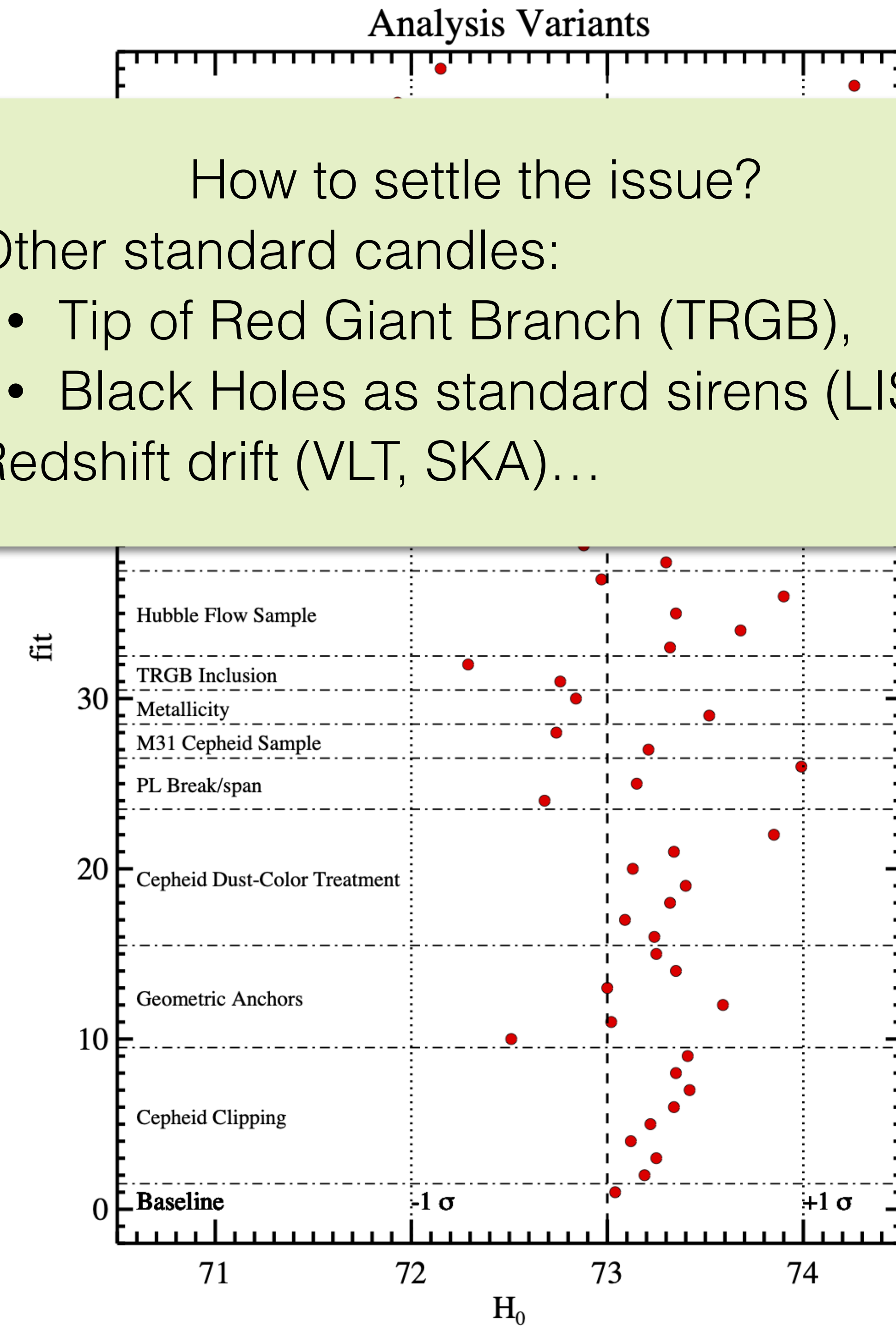

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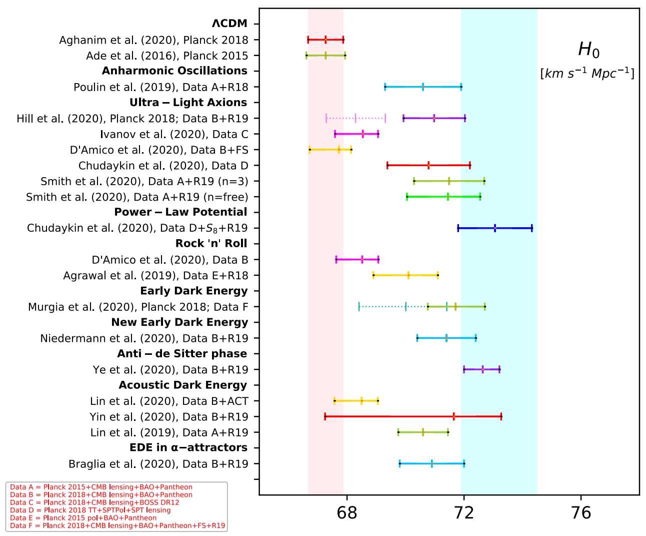
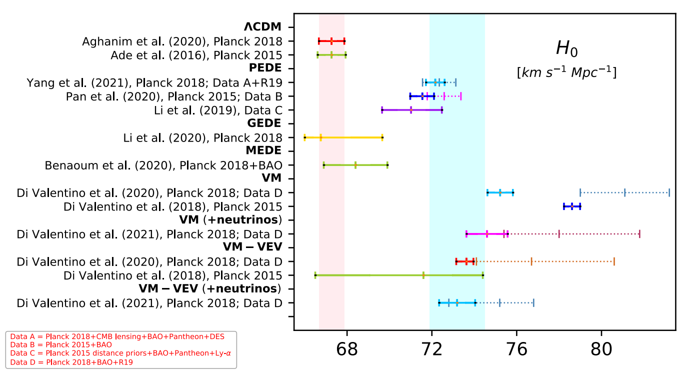
Systematics in CMB?
Unknown foregrounds, insufficient instrument modelling…

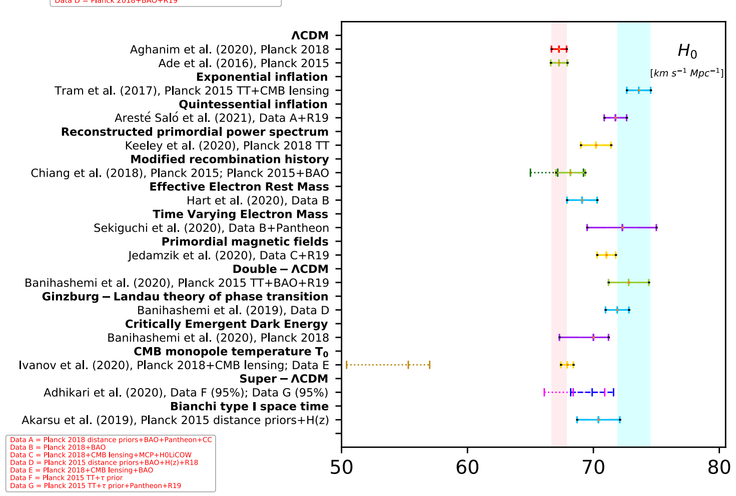
Small deviations from ΛCDM with new ingredients
(DM, DE, MG, magnetic fields, etc.),
or large-scale deviation from Friedmann model

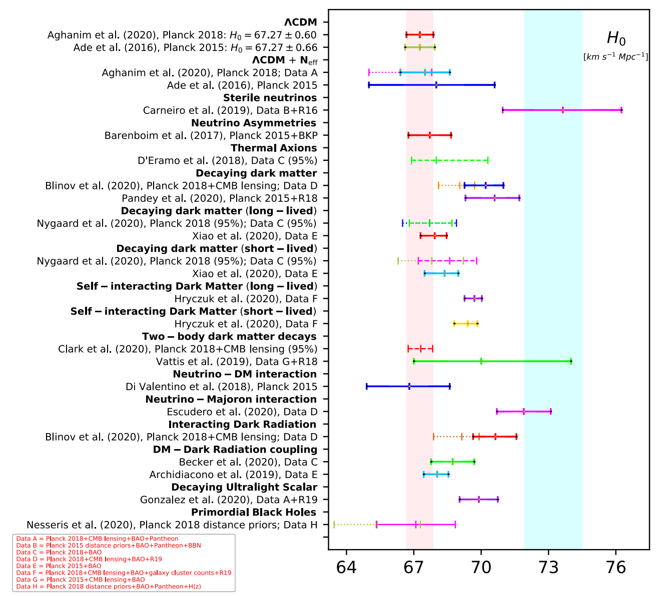
Solving the H_0 tension with extended cosmological models: exhaustive review

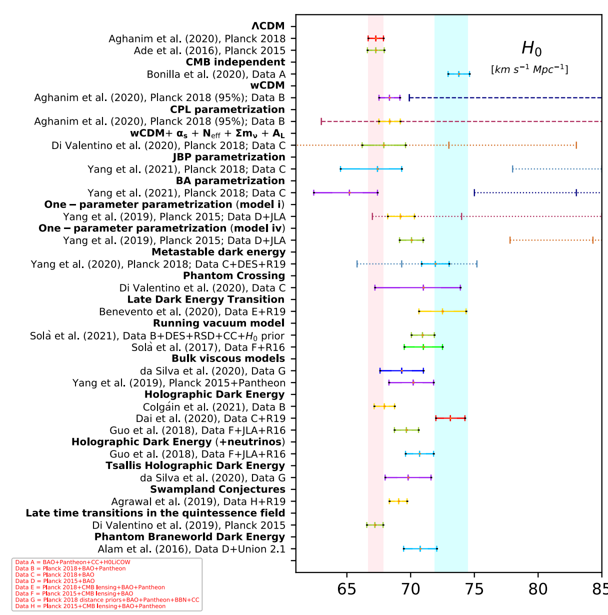
De Valentino et al. 2103.01183

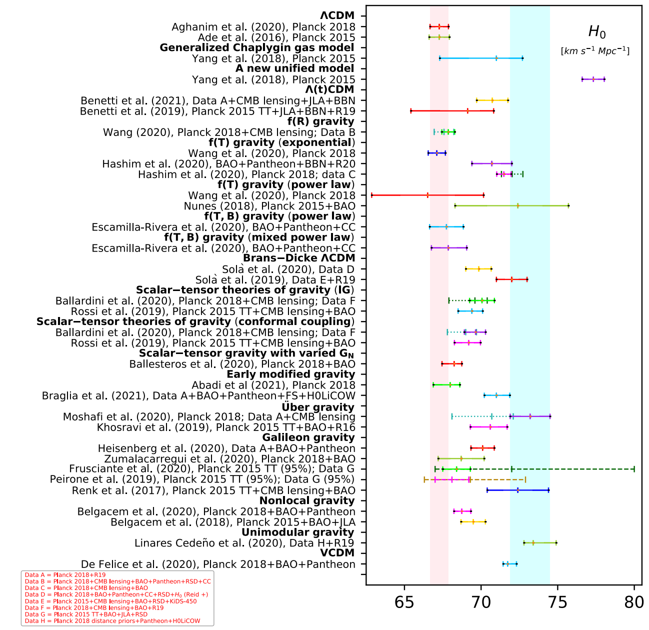


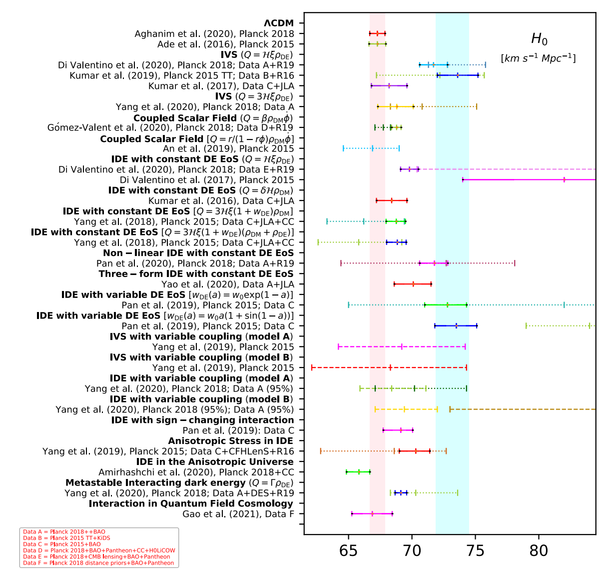


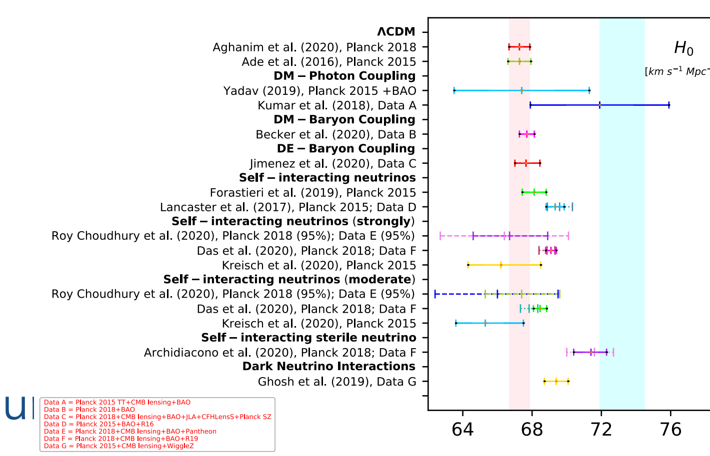












Solving the H_0 tension with extended comsological models: fair comparison

Schöneberg, Abellan, Pérez, JL, Witte, Poulin, Lesgourgues, 2107.10291, *Phys. Rep. 984 (2022) 1-55*

- Selection of 19 “representative models” (see later)
- Three metrics to quantify the (resolution of the) tension

Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	X	0.00	0.00	X	X
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	X	-6.10	-4.10	X	X
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	X	-9.57	-7.57	✓	✓ (3)
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	X	-8.83	-4.83	X	X
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	X	-8.92	-4.92	X	X
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	X	-4.98	1.02	X	X
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓ (2)
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	X	-11.42	-9.42	✓	✓ (3)
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓ (1)
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓ (1)
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓ (2)
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓ (2)
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓ (2)
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	X	-4.94	-0.94	X	X
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	X	X
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	X	-0.45	1.55	X	X
DM $\to$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	X	-0.19	3.81	X	X
DM $\to$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	X	-0.53	3.47	X	X

Table 1: Test of the models based on dataset $\mathcal{D}_{\rm baseline}$ (Planck 2018 + BAO + Pantheon), using the direct measurement of M_b by SH0ES for the quantification of the tension (3rd column) or the computation of the AIC (5th column). Eight models pass at least one of these three tests at the 3σ level.

How to concile larger Hubble rate with observed θ_S ?

- **sound horizon angle** as seen by BAO or CMB must be preserved:

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

redshift z = "look-back time"

Sound horizon =
integral over sound speed
from early universe till decoupling

Angular diameter distance =
integral over inverse Hubble rate
from observation till today

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- Global rescaling of $H(z)$?

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- Global rescaling of $H(z)$?

Forbidden: at early time, related to density of photons, fixed by $T_{CMB} = 2.7255\,\mathrm{K}$, and to density of neutrinos, fixed by $N_\nu = 3$

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Late time solutions

- **sound horizon angle** as seen by BAO or CMB:

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Sound horizon =
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First idea: keep early cosmology unchanged; alter only *late* evolution $H(z)$ to get a large H_0 today

⇒ "Late time solutions".

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First idea: keep early cosmology unchanged; alter only *late* evolution $H(z)$ to get a large H_0 today

⇒ "Late time solutions".

Excluded by combination of BAO, Supernovae, H(z) data

"Shifted decoupling solutions"

- **sound horizon angle** as seen by BAO or CMB:

$$\theta(z) = \frac{\int_{z_D}^{\infty} c_s(\omega_\mathrm{b}, \tilde{z}) H(\tilde{z})^{-1} d\tilde{z}}{\int_0^z H(\tilde{z})^{-1} d\tilde{z}} \overset{\Lambda\mathrm{CDM}}{=} \frac{\displaystyle\int_{z_\mathrm{D}(\omega_b, \Omega_\mathrm{m} h^2)}^{\infty} \frac{c_s(\omega_b; \tilde{z}) d\tilde{z}}{\left[(1+\tilde{z})^3 + \frac{1.68\omega_\gamma}{\Omega_\mathrm{m} h^2}(1+\tilde{z})^4\right]^{1/2}}}{\displaystyle\int_0^z \frac{d\tilde{z}}{\left[\frac{1-\Omega_\mathrm{m}}{\Omega_\mathrm{m}} + (1+\tilde{z})^3\right]^{1/2}}}$$

"Shifted decoupling solutions"

- **sound horizon angle** as seen by BAO or CMB:

$$\theta(z) = \frac{\int_{z_D}^{\infty} c_s(\omega_\mathrm{b}, \tilde{z}) H(\tilde{z})^{-1} d\tilde{z}}{\int_0^z H(\tilde{z})^{-1} d\tilde{z}} \overset{\Lambda\mathrm{CDM}}{=} \frac{\displaystyle\int_{z_\mathrm{D}(\omega_b, \Omega_\mathrm{m} h^2)}^{\infty} \frac{c_s(\omega_b; \tilde{z}) d\tilde{z}}{\left[(1+\tilde{z})^3 + \frac{1.68\omega_\gamma}{\Omega_\mathrm{m} h^2}(1+\tilde{z})^4\right]^{1/2}}}{\displaystyle\int_0^z \frac{d\tilde{z}}{\left[\frac{1-\Omega_\mathrm{m}}{\Omega_\mathrm{m}} + (1+\tilde{z})^3\right]^{1/2}}}$$

Second idea: preserve overall background evolution of ΛCDM, but anticipate the time of photon decoupling (*increase* z_D) and simultaneously of radiation-matter equality with larger h:

⇒ "Shifted decoupling" solutions

"Shifted decoupling solutions"

•

$\theta($

Issue: *recombination of protons + electrons* and *decoupling of photons* = accurately modelled processes; atom hydrogen model, fundamental constants (fine-structure constant, electron mass, Thomson scattering cross-section…) -> definite prediction for T_D and z_D

- First way: string theory / runaway-dilaton-inspired models with running of the constants: slightly different α or m_e at z~1000 and z~1 Hart & Chluba 2020
  (e.g. $m_e \searrow$ by 0.5%: works very well) golden medal

- Second way: large inhomogeneities on very small scales (e.g. from primordial magnetic fields) -> inhomogeneous recombination, average recombination time decreased without changing the background model bronze medal Jedamzik & Pogosian 2020

Second idea: preserve overall background evolution of ΛCDM, but anticipate the time of photon decoupling (*increase* z_D) and compensate numerator with larger h:

⇒ "Shifted decoupling" solutions

"Early time solutions"

- **sound horizon angle** as seen by BAO or CMB:

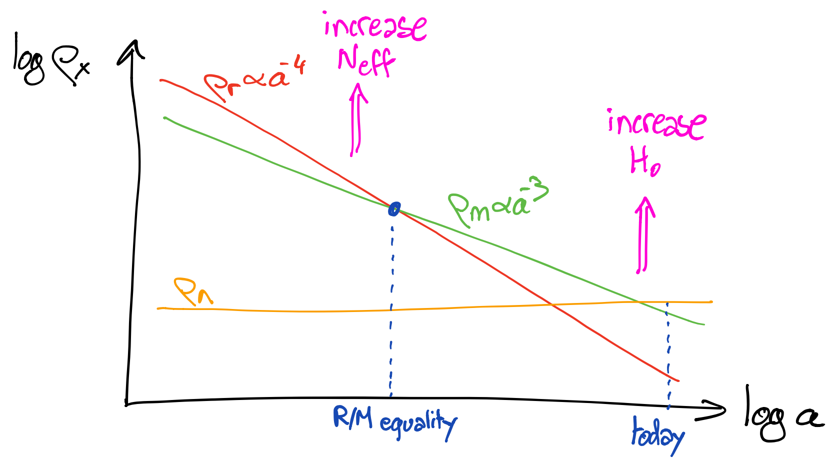
$$\theta(z) = \frac{\int_{z_D}^{\infty} c_s(\omega_\mathrm{b}, \tilde{z}) H(\tilde{z})^{-1} d\tilde{z}}{\int_0^z H(\tilde{z})^{-1} d\tilde{z}} \overset{\Lambda\mathrm{CDM}}{=} \frac{\int_{z_\mathrm{D}(\omega_b, \Omega_\mathrm{m} h^2)}^{\infty} \frac{c_s(\omega_b; \tilde{z}) d\tilde{z}}{\left[(1+\tilde{z})^3 + \frac{1.68\omega_\gamma}{\Omega_\mathrm{m} h^2}(1+\tilde{z})^4 + \ldots\right]^{1/2}}}{\int_0^z \frac{d\tilde{z}}{\left[\frac{1-\Omega_\mathrm{m}}{\Omega_\mathrm{m}} + (1+\tilde{z})^3\right]^{1/2}}}$$

Third idea: additional contribution to $H(z)$ in denominator (*enhanced radiation* or *something similar*) and compensate with larger h:

⇒ "Early time solutions"

"Early time solutions"

Third idea: rescale all densities equally and enhance $H(z)$ to get a large H_0 today
⇒ "Early time solutions"

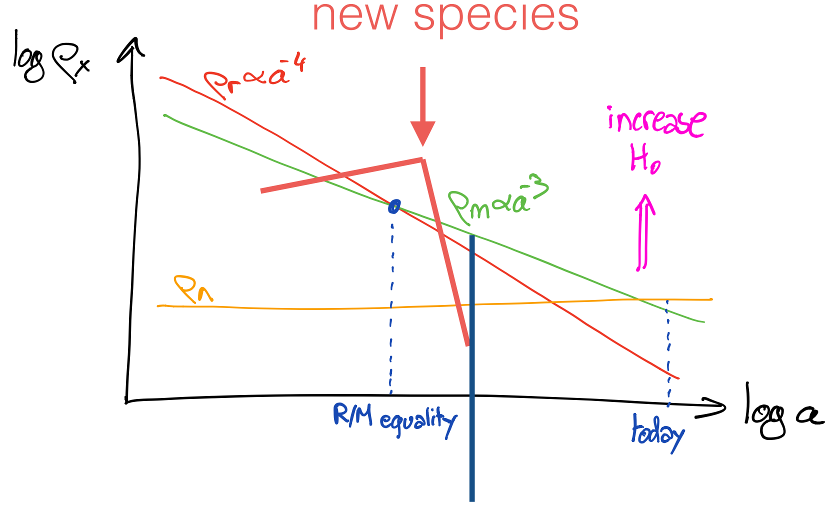


- Need to increase the relic density of relativistic species around the times relevant for the CMB: effectively, like "adding extra neutrino-like species" (effective neutrino number N_{eff}). Would need approximately 0.5 to 1 more…
- Issues:
  - incompatible with Nucleosynthesis and primordial element abundances: extra relics to be produced between "Nucleosynthesis times" and "CMB times"
  - Incompatible with CMB spectrum shape (scale of the peaks, enhanced Silk damping…) and matter power spectrum amplitude/shape, at least if extra relics are decoupled and free-streaming…
  - Baseline dataset: $N_{\mathrm{eff}} = 3.1557 \pm 0.0677$ $(68\,\%\,CL)$. Simple "ΛCDM+N_{eff}" model fails!

"Early time solutions"

Third idea: rescale all densities equally and enhance $H(z)$ to get a large H_0 today

⇒ "Early time solutions"



- Need to increase the expansion rate only around recombination with new particle, scalar field… escape early BBN constraint and late Silk damping constraint

- Possibly play with other effects on perturbations to cure CMB spectrum issues (additional ingredients to increase DR clustering before recombination and/or decrease DM clustering after recombination)

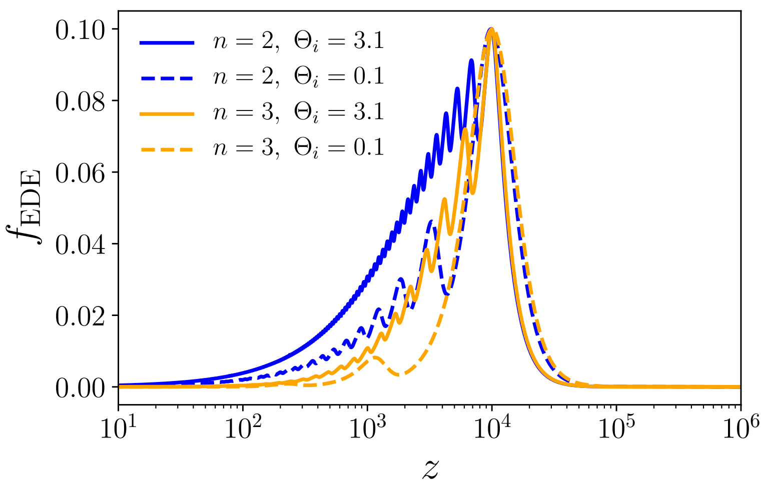
"Early time solutions"

1. use a scalar field to enhance $\rho_{\rm tot}(z)$ and $H(z)$ for a short while around CMB decoupling time. Escapes Nucleosynthesis and CMB problems of Dark Radiation. silver medal

- Various Early Dark Energy models (= scalar field with a given potential) work well: 3 Silver medals (and consistent with Nucleosynthesis bounds) [Kamionkowsi et al.,…]

Enhancement of $\rho_{\rm tot}(z)$ for various potentials ⇒

(1st or 2nd order phase transition)



- Models are very *ad hoc*… attempts to connect it with particle physics: axion models, Xenon 1T anomaly (Poulin et al.) or sterile/active neutrino mass via inverse see-saw (Niedermann and Sloth)

- Exists in "modified gravity" version, e.g. with [Braglia et al. 2021]:

$$S=\int d^4x\sqrt{-g}\left[(M_{\rm pl}^2+\xi\sigma^2)\frac{R}{2}-\frac{g^{\mu\nu}}{2}\partial_\mu\sigma\partial_\nu\sigma-\Lambda-\frac{\lambda\sigma^4}{4}\right]+S_{\rm m}.$$

- Still predictive models: future CMB polarisation observations

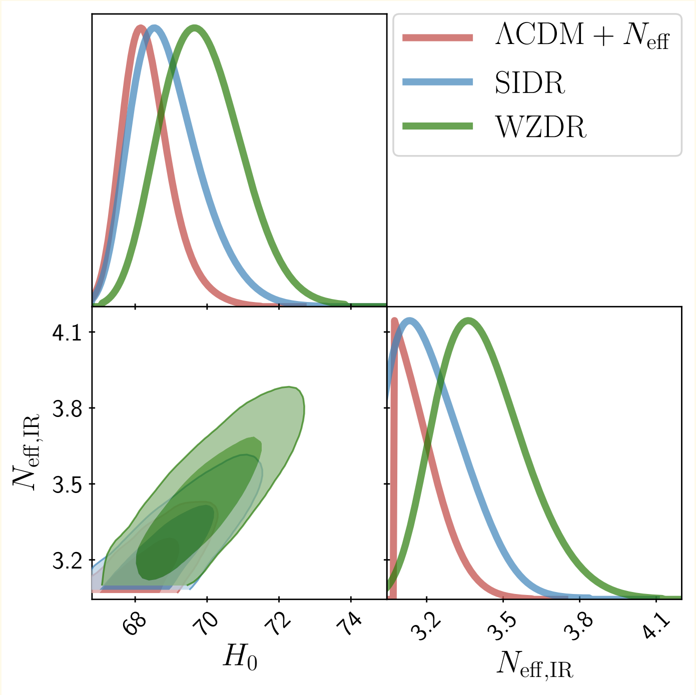
"Early time solutions"

Save ΛCDM+$N_{\rm eff}$ with new physics in dark sector (non-standard interactions, decays, etc.) changing the clustering properties and/or sound speed of Dark Radiation and/or Dark Matter…

2. self-interacting Dark Radiation to slow-down the particle velocity and change their clustering properties: bronze medal (provided that it gets populated after Nucleosynthesis).

Aloni, Berlin, Joseph, Schmaltz & Weiner 2111.00014; Schöneberg & Abellan 2206.11276 transform this into a silver medal; similarities with previous "sterile neutrinos with secrete interactions" of Archidiacono, Hannestad et al.

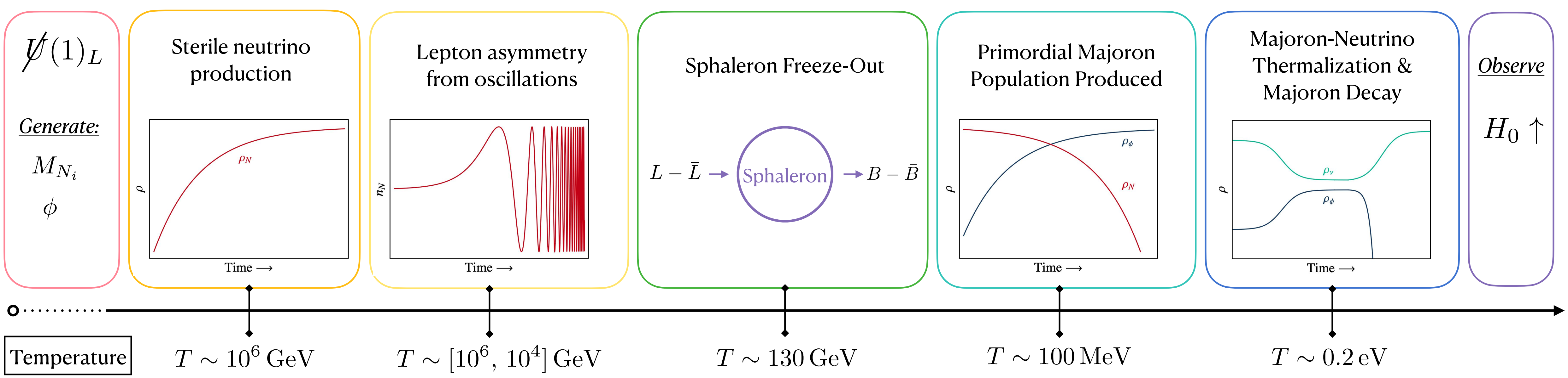
- Wess-Zumino Dark Radiation (WZDR) model of 2111.00014 :
  - Interaction between massless relic fermions (DM and DR) mediated by eV-mass scalar ($eV \sim M_{\rm SUSY}^2/M_{\rm Pl}$)
  - At T~1eV, scalar becomes non-relativistic, entropy release boosts $N_{\rm eff}$ from ~3.3 to ~ 3.5 (precise value depends on $T_{\rm dark}$)
  - Transition leaves imprint in CMB spectrum that compensates for increase of $(N_{\rm eff}, H_0)$



"Early time solutions"

3. particular realisation of a Majoron scenario of Escudero & Witte 1909.04044, 2004.01470, 2103.03249: Silver medal (and consistent with BBN bound)

- O(eV)-mass Majoron ϕ = pseudo-Goldstone of spontaneously broken $U(1)_L$
- small Yukawa-like couplings to active neutrinos
- $T \sim m_\phi$: interactions between majoron and active neutrinos (inverse neutrino decay):
  - Majoron thermalize and contribute to $N_{\rm eff}$,
  - active neutrinos do not free-stream
- $T \sim m_\phi/3$: Majoron decays into active neutrinos, which free-stream



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Conclusions

- In terms of model-building, need to pay a high price, but reassuring that we cannot fit anything…
- Hope that one or more tension solved by systematics! Will know with better data and also new techniques: Tip of the Red Giants Branch (TRGB), redshift drifts (SKA, ELT), GWs as standard sirens (LISA, ET…)

If tension do not arise from systematics:

- Previous models: predictions for next-generation CMB/LSS: SO, CMB S4, Euclid, Rubin… (e.g. EDE, Majoron, shifted recombination…)
- Chance to learn about new particle physics, tests it in laboratory? (e.g. DM interactions, Majoron)
- Revisit models beyond Friedmann? Large-scale inhomogeneity?

Introductory material

Solving the H_0 tension with extended comsological models: fair comparison

Schöneberg, Abellan, Pérez, JL, Witte, Poulin, Lesgourgues, 2107.10291

- Selection of 19 “representative models” (see later)
- Data sets:
  - Baseline: *Planck 2018 (incl. lensing) + BAO + Pantheon + SH0ES* treated as measurement of intrinsic magnitude M_B
  - Additional tests with *Planck -> BAO+BBN* or *WMAP+ACT*, and with *RSD, CC, BAO-Lya*
- Three metrics to quantify the (resolution of the) tension:

1. *When considering a data set D that does not include SH0ES, what is the residual level of tension between the posterior on M_B inferred using D and the SH0ES measurement?*

$$\frac{\bar{x}_{\mathcal{D}} - \bar{x}_{\mathrm{SH0ES}}}{(\sigma^2_{\mathcal{D}} + \sigma^2_{\mathrm{SH0ES}})^{1/2}} \qquad \textit{where} \quad x \equiv M_B$$

2. *How does the addition of the SH0ES measurement to the data set D impact the fit within a particular model M?*

$$\Delta\chi^2 = \chi^2_{\mathrm{min},\mathcal{D}+\mathrm{SH0ES}} - \chi^2_{\mathrm{min},\mathcal{D}} - \chi^2_{\mathrm{min,SH0ES}}$$

3. *When the data set D includes the SH0ES data on M_B, does the fit within a particular model M significantly improve upon that of ΛCDM?*

$$\Delta\mathrm{AIC} = \chi^2_{\mathrm{min},\mathcal{M}} - \chi^2_{\mathrm{min},\Lambda\mathrm{CDM}} + 2(N_{\mathcal{M}} - N_{\Lambda\mathrm{CDM}})$$

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