On the Robustness of the Constancy of the Supernova Absolute Magnitude

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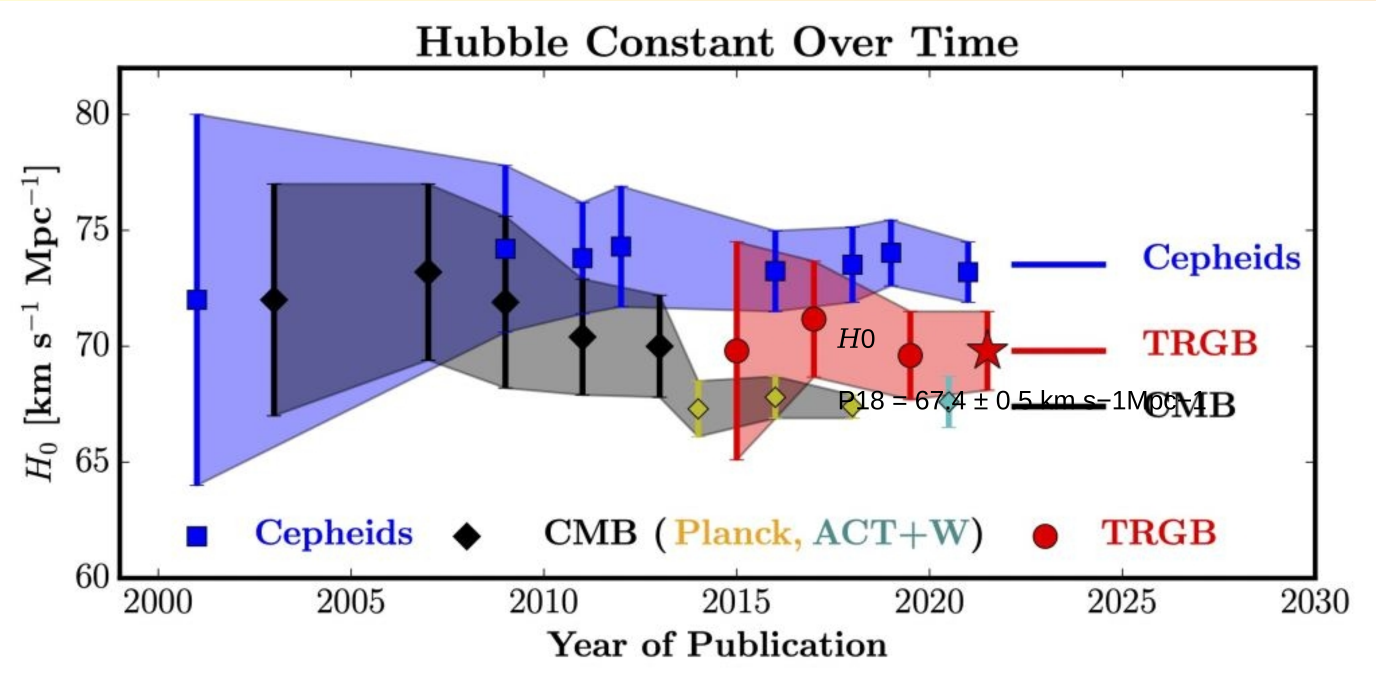
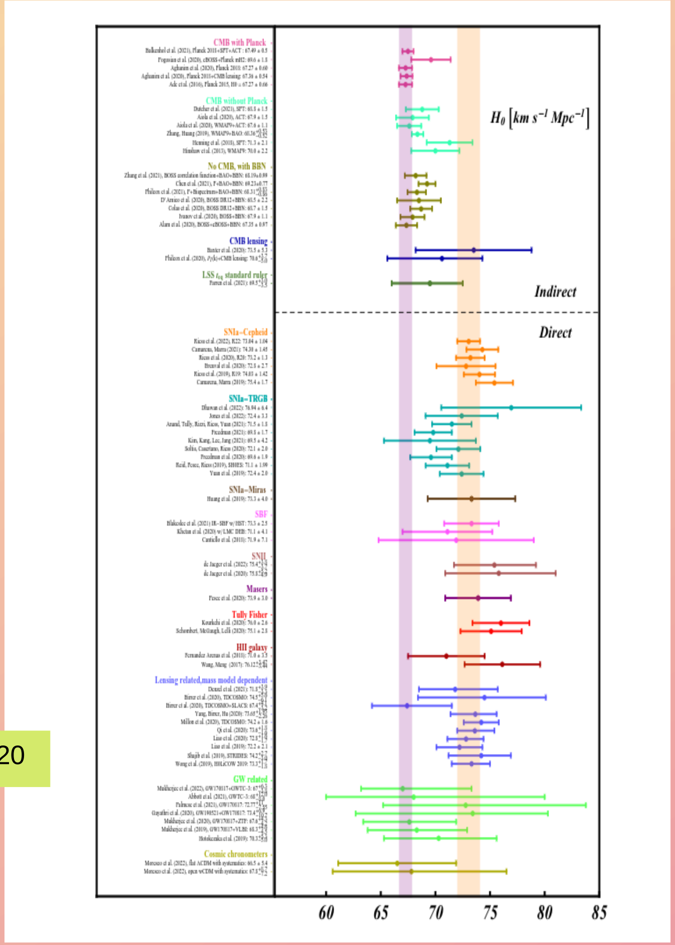
Based on Phys.Dark Univ. 39 (2023) 101160 with D. Benisty, J. Mifsud, J. Levi Said

Tensions in Cosmology – Corfu, 6-13.09.2023

The well-known picture...





H_0^{P18} = 67.4 ± 0.5 km\s\Mpc

Aghanim et al. , Astron. Astrophys. 641, 2020

H_0^{SH0ES} =73.04 ± 1.04 km\s\Mpc

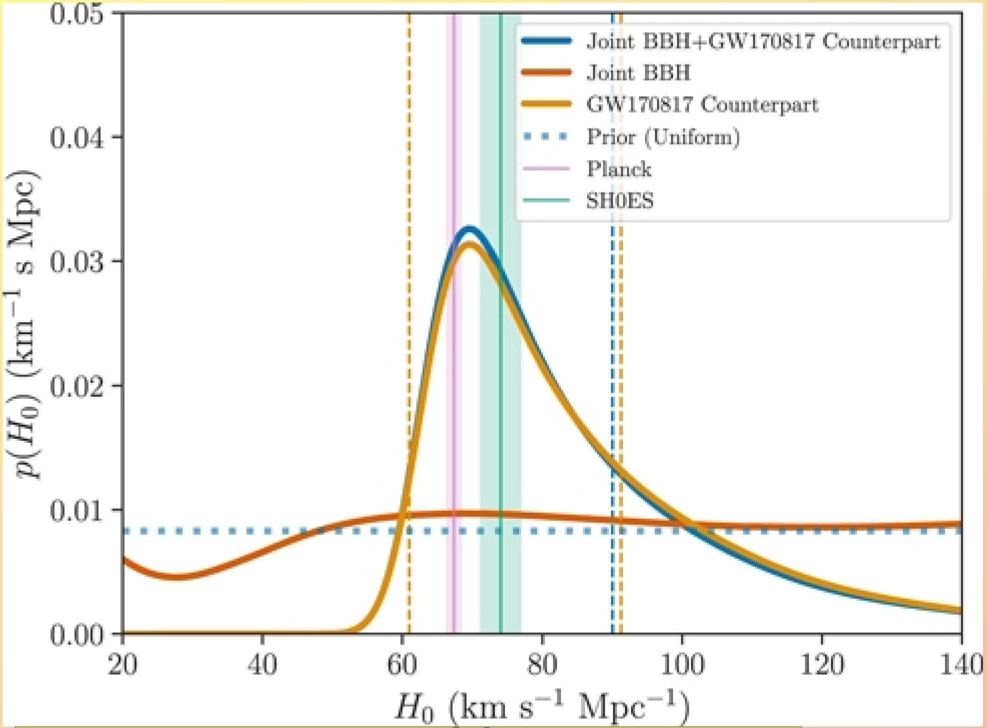
Riess, A. G. et al. ApJL 934 (2022) L7

Wendy Freedman, Nature Astronomy, 1, 0169 (2017), arXiv:2106.15656 (2021)

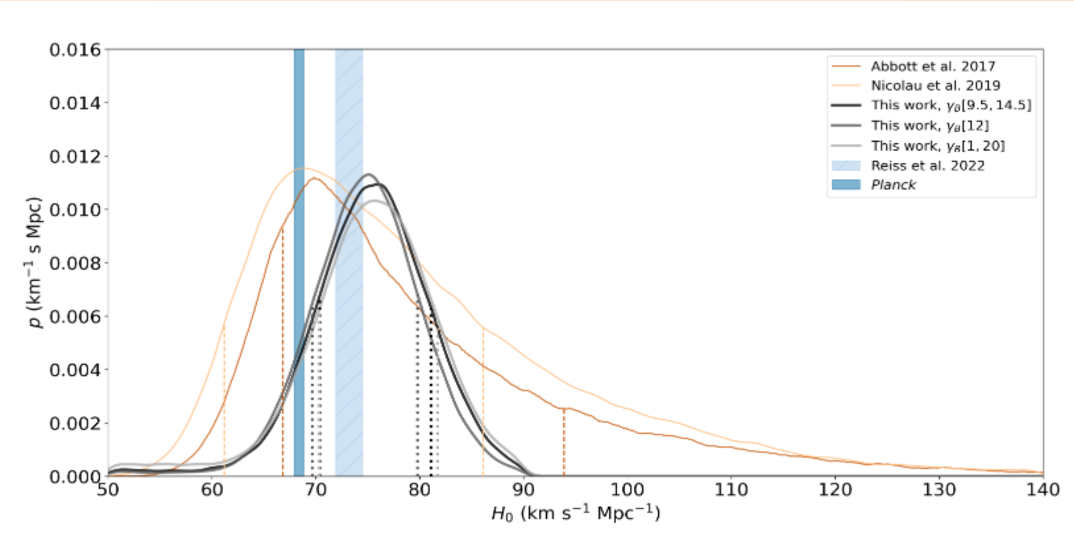
The Hubble tensions is at 5.3σ as of 2023!
But it does not affet only H_0!

Abdalla et all. JHEAp. 2204 (2022) , Di Valentino et al. CQG, 38 (2021)

The GW contribution just as unclear

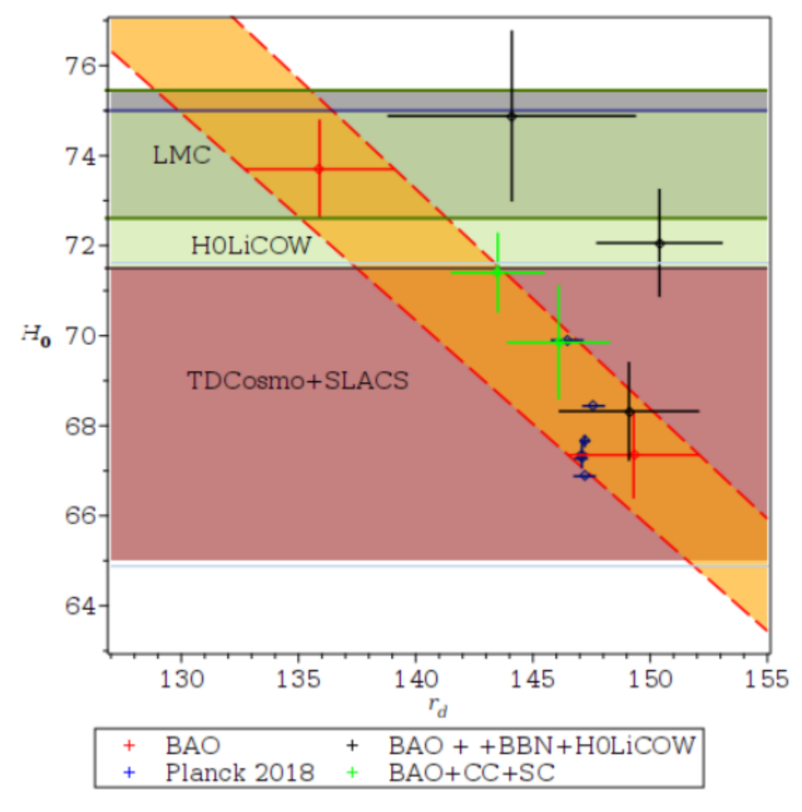


From LIGO:
$H_0=69^{+16}_{-18}$km/s/Mpc
(GW170814+GW170817)
B. P. Abbott et al 2021 ApJ 909 and ApJ 923



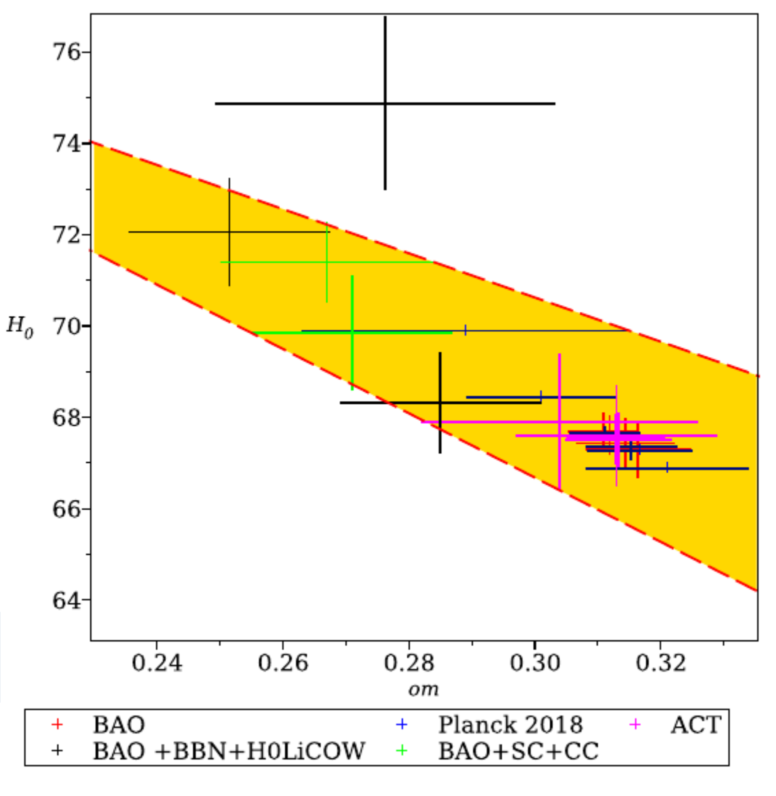
Re-analisis of GW170814,
H_0~75km/s/Mpc
Palmese et al. 2305.19914

Tension in the r_d, H_0 and Ω_m plane



Any solution of the H_0-tension should take into account also r_d and Ω_m

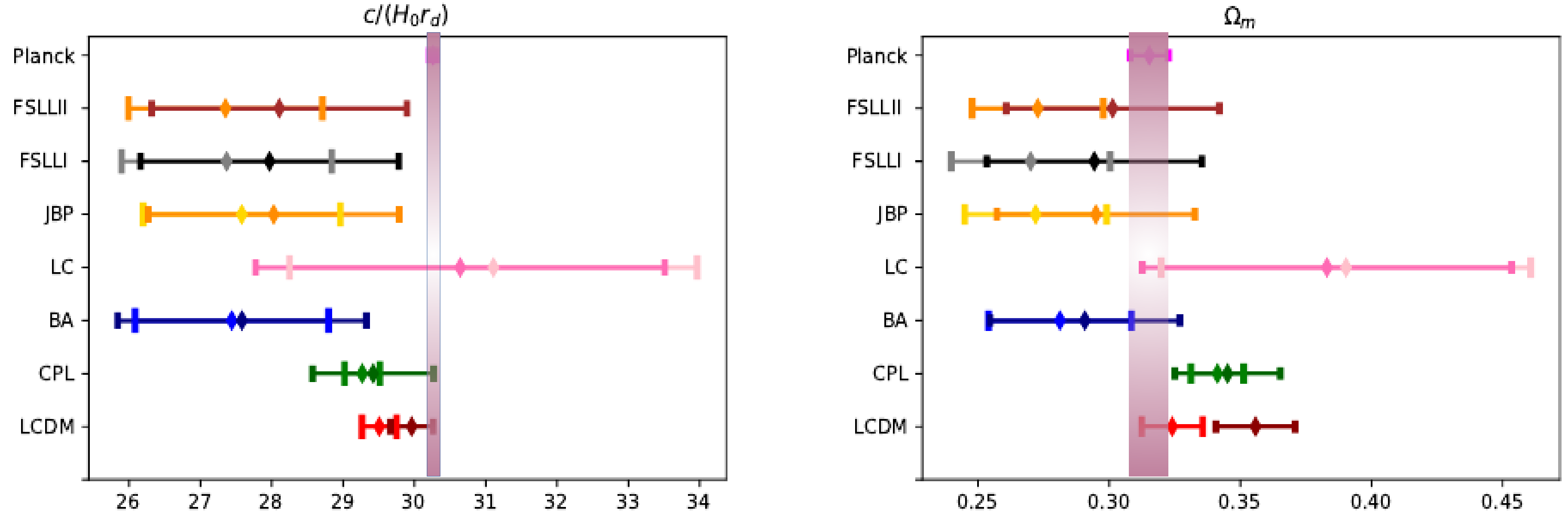
Knox & Millea (2020) PRD 101, 043533



D.S., MG-16 proc

Where + and + are from D.B&D.S. A&A 647, A38 (2021)

Tension in both Ω_m and $c/H_0 r_d$

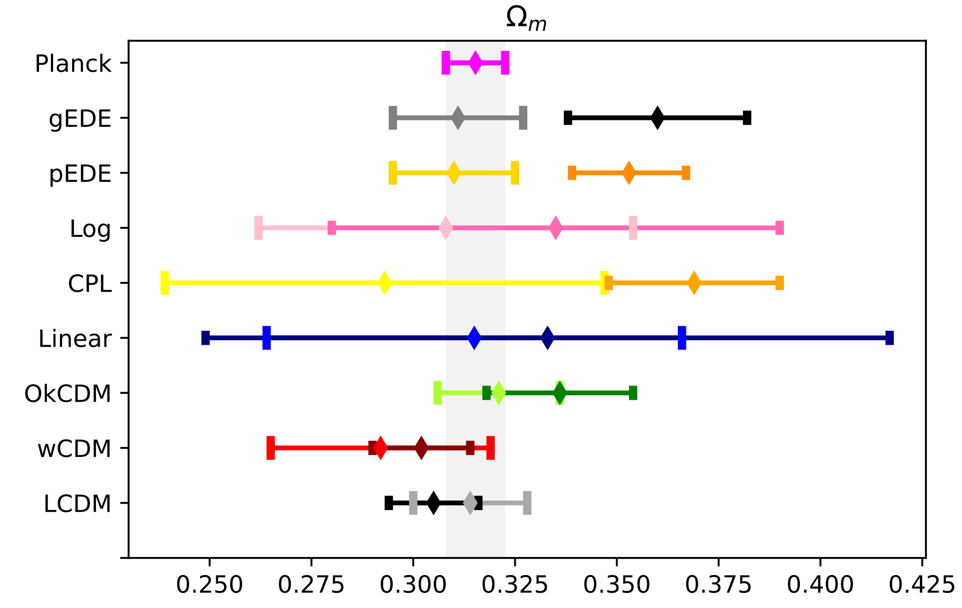


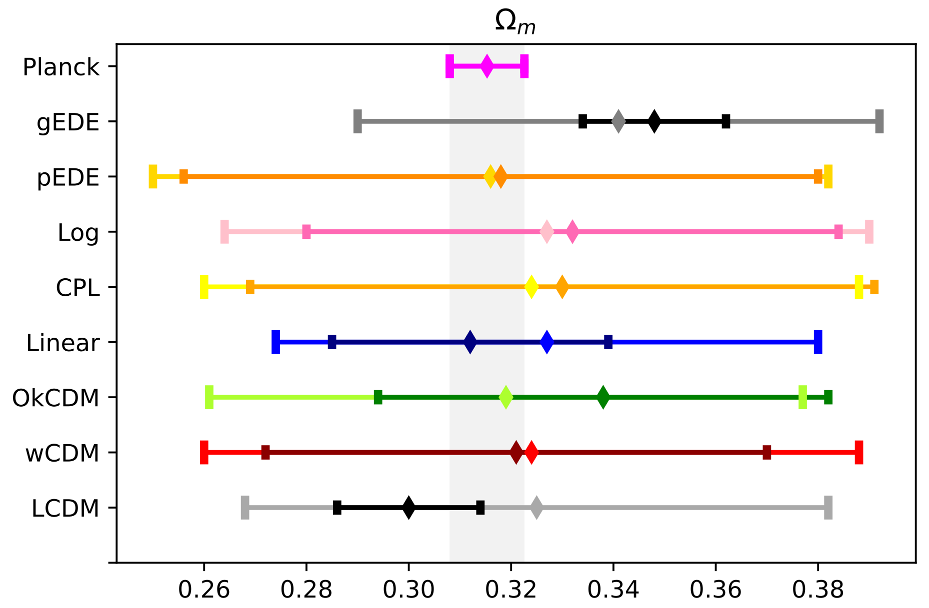
The lighter colors are BAO, the darker ones are the BAO+SN

D.S. Universe 8 (2022)

Tesions in the matter density Ω_m

D.S, D.B., A&A 668, A135 (2022)





3d BAO and BAO+SN

The lighter colors are BAO, the darker ones are the BAO+SN

2d BAO and BAO+SN

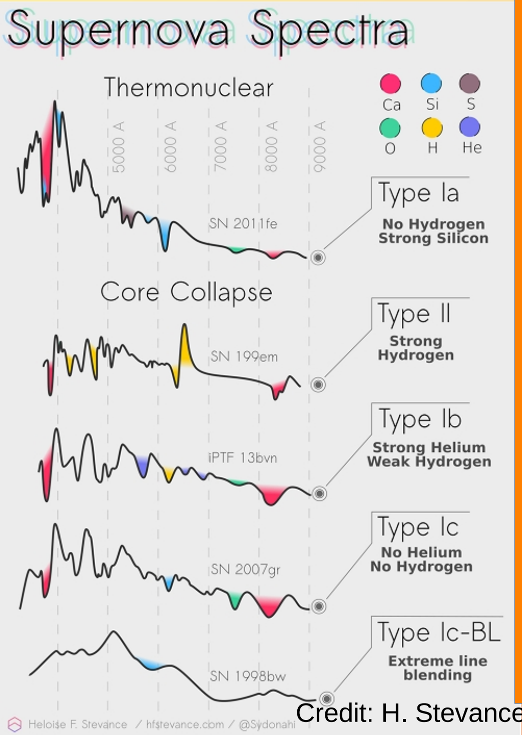
SDSS IV → Ω_m~0.25 - 0.31

Ω_m~0.23 - 0.29 ← **Nunes et al., MNRAS, 497,2, 2020**

So the tension is everywhere!

Welcome to the CosmoVerse!

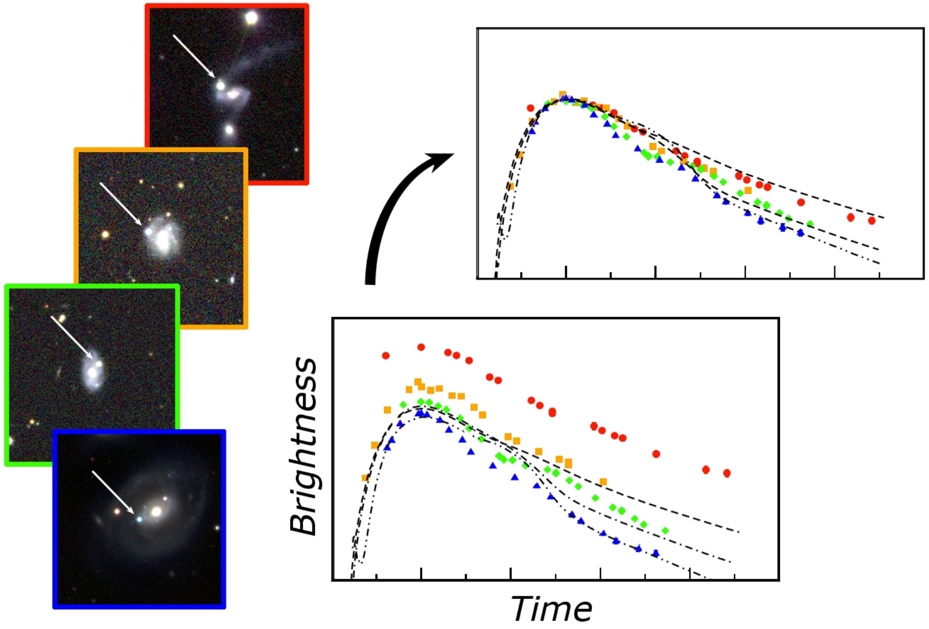
The supernova mechanism



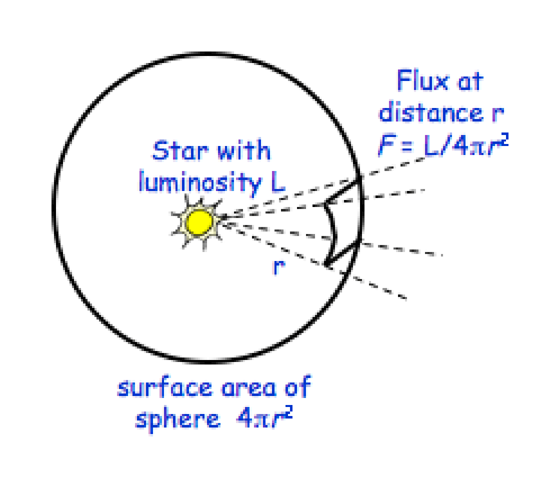
Credit: H. Stevance.

Key moments:
- an explosive disruption of a white dwarf star in a binary system
- primary WD composition C and O
- carbon nuclei begin to fuse rapidly, leading to a runaway nuclear reaction
- characteristic lack of H and excess of Si in the spectra
- stable peak luminosity due to Chandrasekhar limit ($1.4 M_{sol}$)
- broad and smooth LC

Theories that alter Chandrasekhar limit but not the elemental composition?
- magnetized WD
- scalar-tensor theories
- exotic particles
- higher-dimensions



Quantities related to white dwarves



- The flux **F** observed for luminosity **L** at distance **d**

$$F = \frac{L}{4\pi d^2}$$

- The luminosity distance

$$d_L(z) = (1+z)\int_0^z \frac{c\,dz'}{H(z')}$$

- The distance modulus

$$\mu(z) = m_B(z) - M_B\,,$$

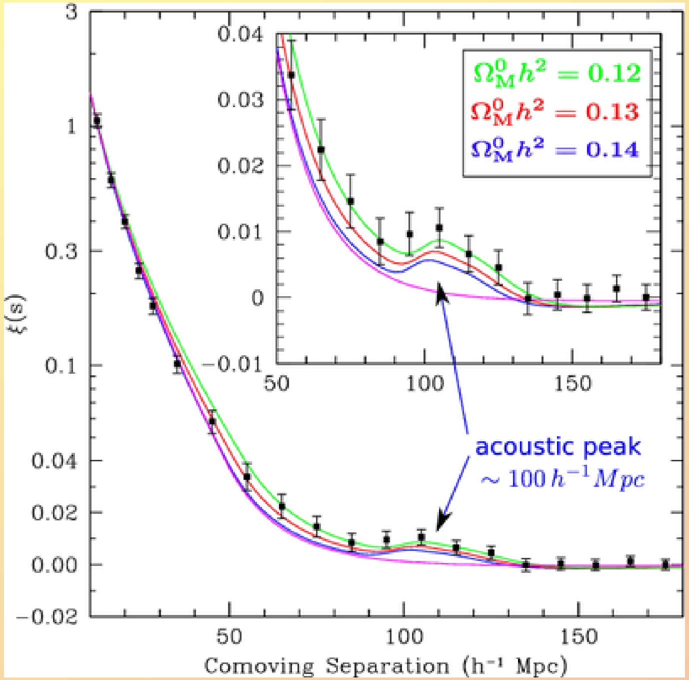
$$m_B(z) = 5\log_{10}\left[\frac{d_L(z)}{1\mathrm{Mpc}}\right] + 25 + M_B$$

- Distance duality relation

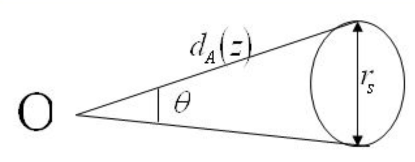
$$d_L = d_A(1+z)^2$$

https://astronomy.swin.edu.au/cosmos/F/Flux

BAO – the „standard ruler“



- Baryonic acoustic oscilations are periodic fluctuations in the density of the visible baryonic matter of the universe.
- Created by the intrerplay of gravity, radiative pressure and the expansion of the universe
- The distance at which plasma waves induced by radiation pressure froze at recombination the sound horizon, r_d (Planck 2018: r_d=147.5 Mpc, z_d=1059, z_*=1100)
- Measured by looking at the large scale structure of matter



$$\Delta z = r_d H(z)/c$$

$$\Delta\theta = \frac{r_d}{(1+z)D_A(z)}$$

$$D_M = \frac{c}{H_0} S_k\left(\int_0^z \frac{dz'}{E(z')}\right)$$

$$D_A = D_M/(1+z)$$

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

$$c_s(z) = \frac{c}{\sqrt{3\left(1 + \frac{3\Omega_b}{4\Omega_\gamma}\frac{1}{1+z}\right)}}$$

Credit: Eisenstein et al., 2005; Cole et al., 2005

Callibrating SN with BAO

- Can we see signs of new physics if we callibrate the SN differently?
- We use the BAO to callibrate the SN by replacing D_L with D_A from BAO.
- The only non-inferrable parameter that remains is the sound horizon r_d
- We use non-parametric methods to check for signs of a non-constant absolute magnitude M_B

$$d_L(z) = (1+z)\int_0^z \frac{c\,dz'}{H(z')}$$

$$\mu_{Ia}(z) = 5\log_{10}[d_L(z)] + 25 + M_B(z)$$

$$M_B = \mu_{Ia} - 5\log_{10}\left[(1+z)^2\left(\frac{D_A}{r_d}\right)_{\mathrm{BAO}} \cdot r_d\right] - 25$$

$$\Delta M_B = \Delta\mu_{Ia} + \frac{5}{\ln 10}\left[\frac{\Delta r_d}{r_d} + \frac{\Delta\left(D_A/r_d\right)_{BAO}}{\left(D_A/r_d\right)_{BAO}}\right]$$

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

$$c_s(z) = \frac{c}{\sqrt{3\left(1+\frac{3\Omega_b}{4\Omega_\gamma}\frac{1}{1+z}\right)}}$$

Planck 2018:

r_d=147.5 Mpc,
H_0=67.4±0.5km/s/Mpc

SH0ES 2023:

r_d=136.3 Mpc,
H_0=73.04±1.04 km/s/Mpc

The Gaussian process

- GP reconstructs the dataset as part of a stochastic process in which each element is part of a multivariant normal distribution
- Defined via mean function μ(z) and a kernel function $k(z, z_1)$
- GP utilizes a Bayesian approach to optimize its kernel hyperparameter (σ_f and l) controlling the smoothness and the over-all profile of the reconstruction

- Model independent **up to the choice of the kernel**
- Tested in numerical cosmological studies
- Huge advantage: naturally includes the errors

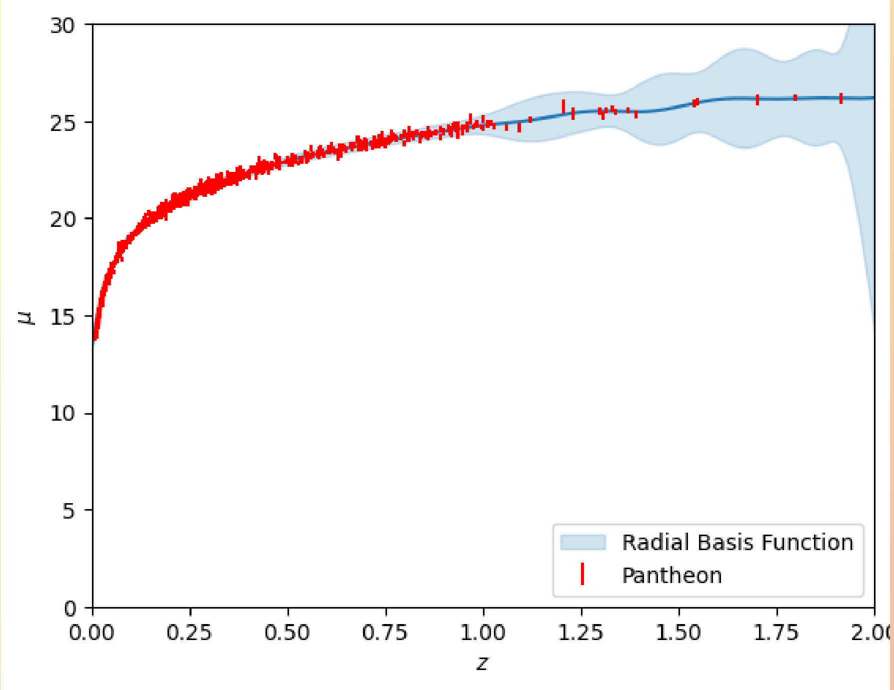
Radial Basis function kernel (RB)

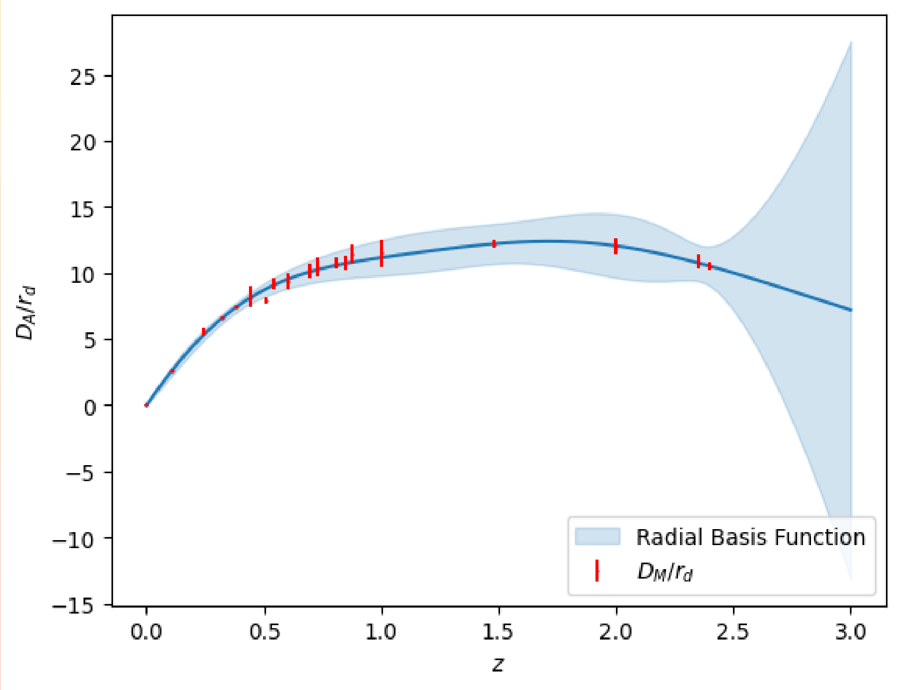
$$k(z, \tilde{z}) = \sigma_f^2 \exp\left(-\frac{(z-\tilde{z})^2}{2l^2}\right)$$

Rational Quadratic kernel (RQ)

$$k(z, \tilde{z}) = \frac{\sigma_f^2}{(1+|z-z'|^2/2\alpha l^2)^\alpha}$$

The GP predictions:

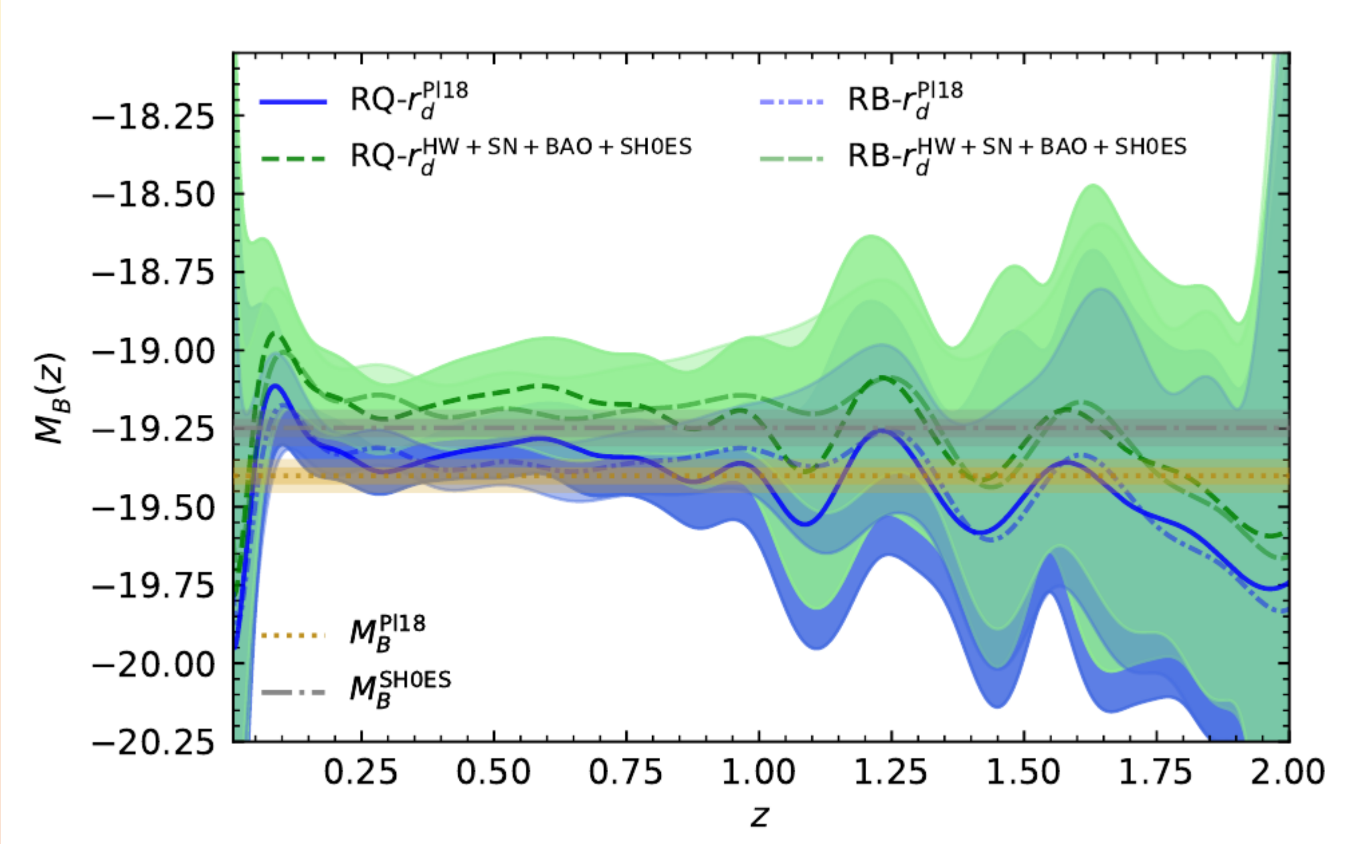




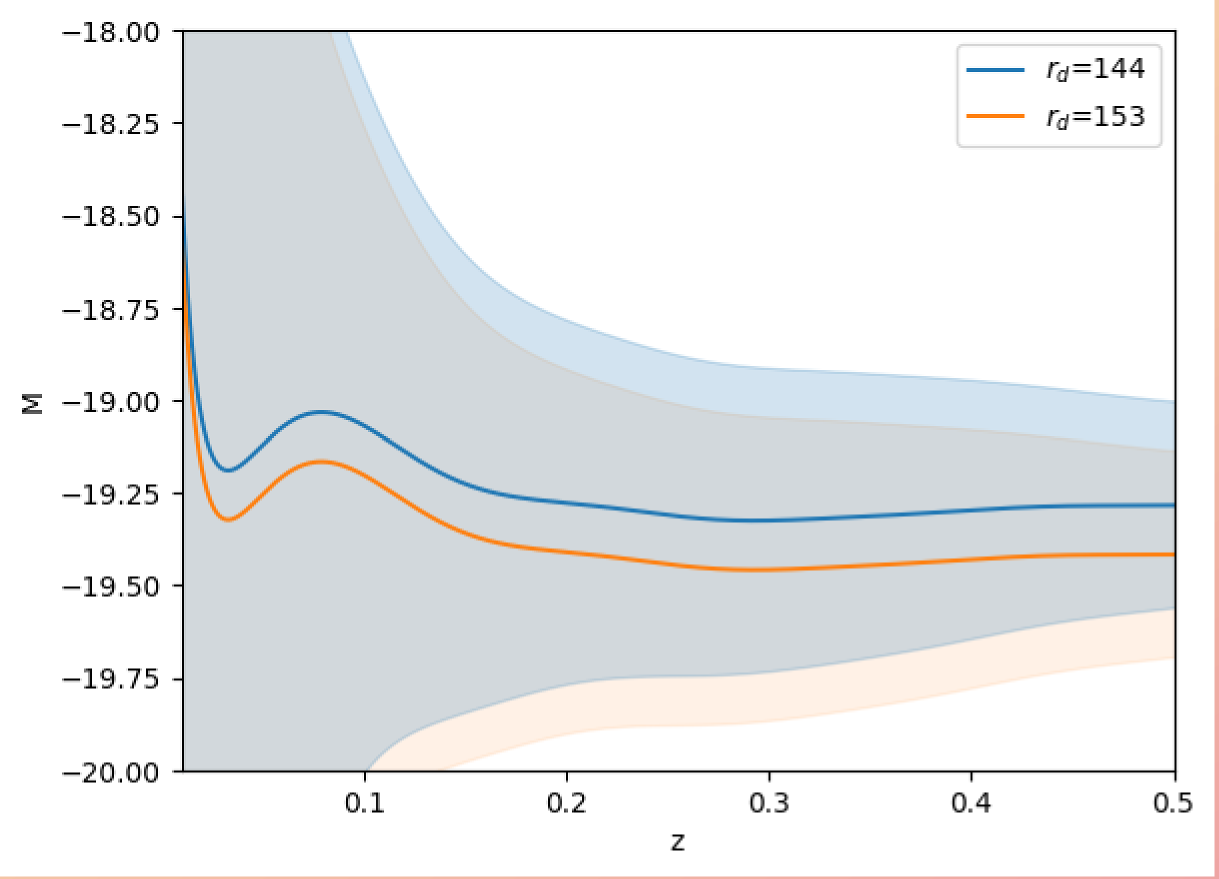
We use them to estimate M_B

The final reconstruction

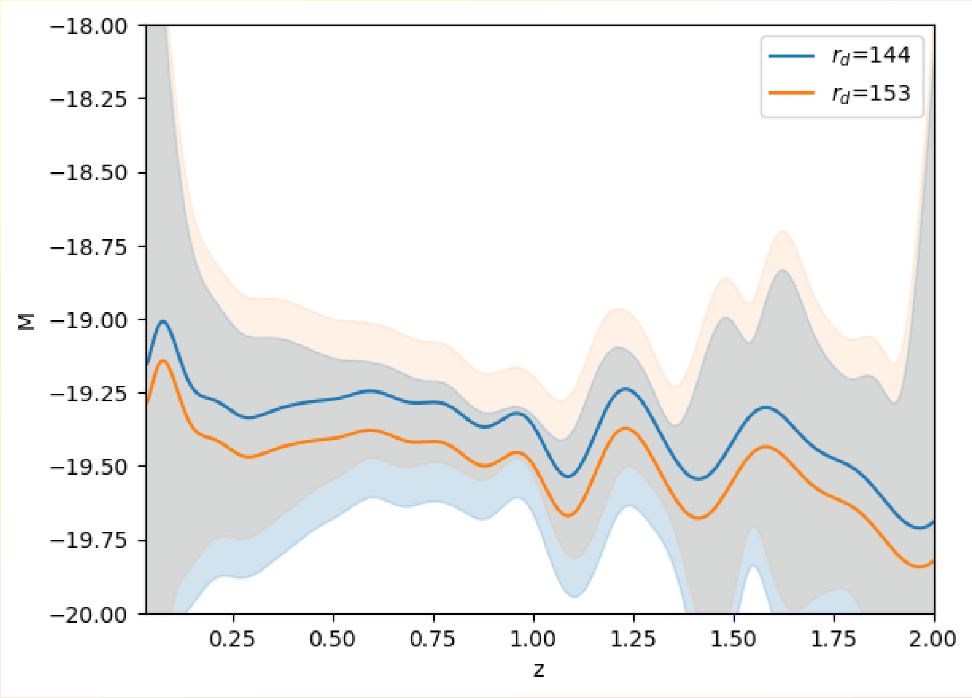
- At z=0 we have numeric singularity due to $D_A(z=0)=0$
- At large z we have big fluctuations due to GP becoming less certain where fewer points are
- We see a hint for a jump around z~0.01-0.15
- The behavior for the two r_d is similar

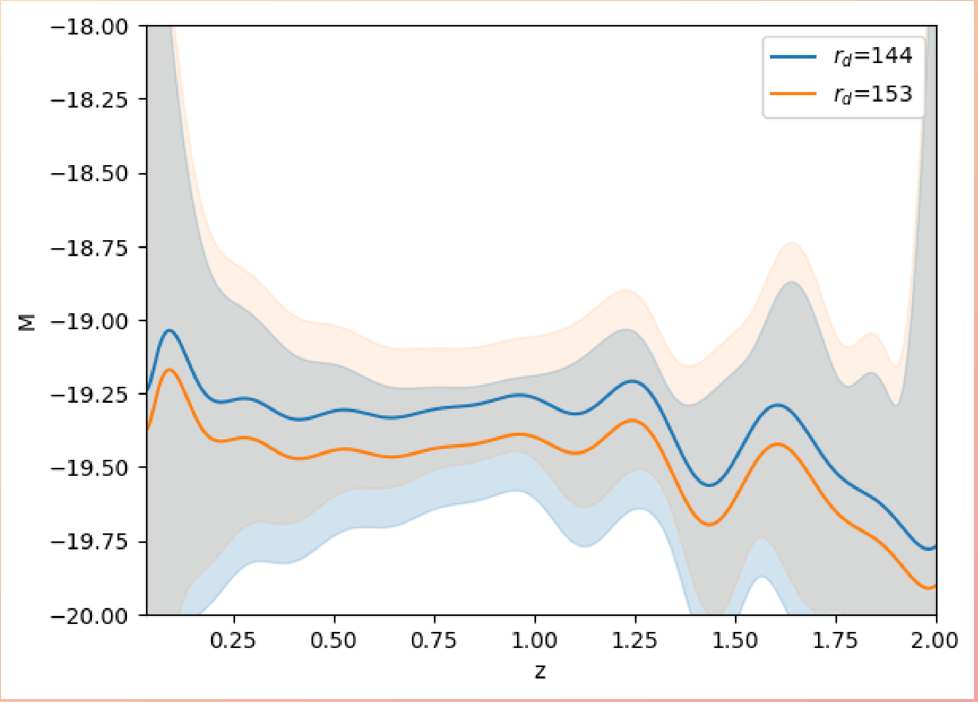


If we zoom in at the origin:



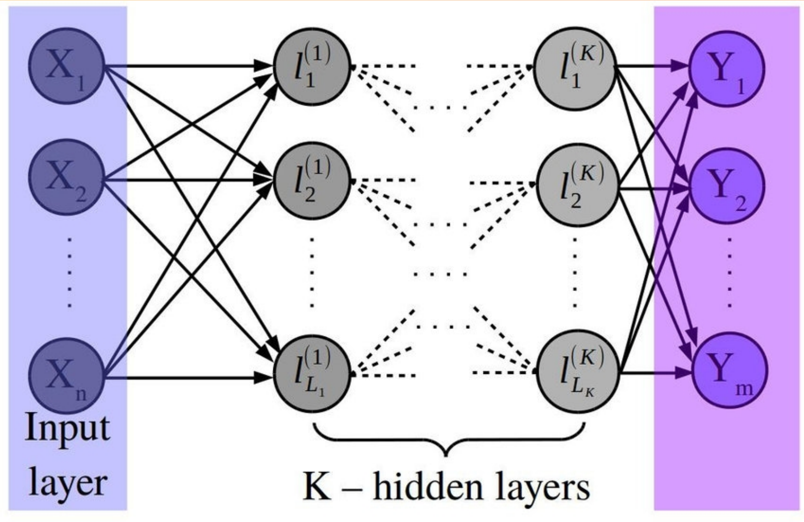
Or in the full range for the two kernels we used





The ANN

- ANN: Input and outptut layers connected to hidden layers with certain weights and certain activation function
- Our input is z and the output are mu and D_A/r_d
- Huge number of hyperparameters optimized during learning
- We use mock data with the same redshift distribution and number of points.
- To optimize the ANN, we compare the generated from SN $\mu_{Ia}(z)$ and their errors $\sigma_{Ia}(z)$ with the dataset trough the risk
- We use L2 loss function

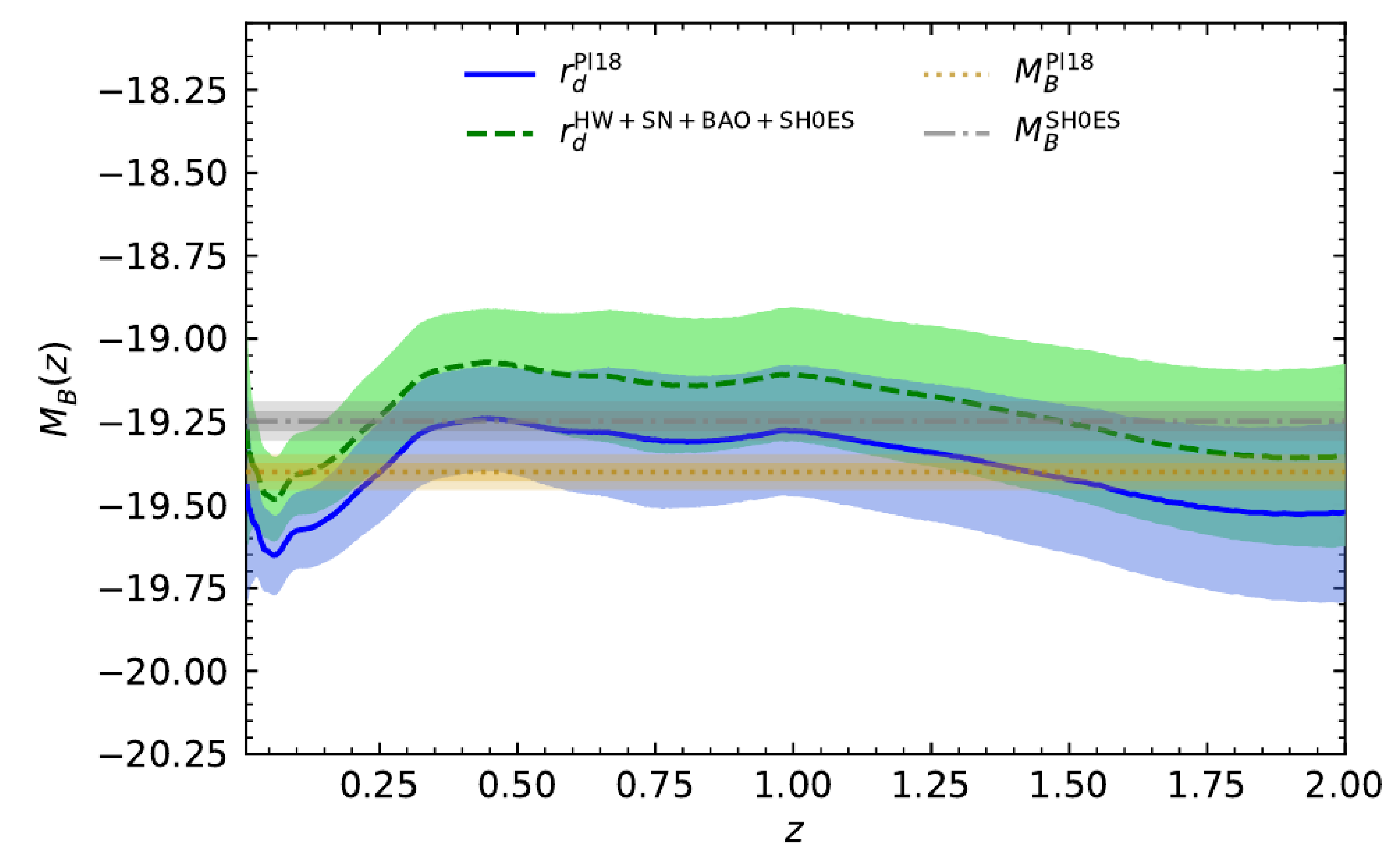


$$\text{risk} = \sum_{i=1}^{N} \text{bias}_i^2 + \sum_{i=1}^{N} \text{variance}_i$$
$$= \sum_{i=1}^{N} \left[\mu_{Ia}(z_i) - \bar{\mu}_{Ia}(z_i)\right]^2 + \sum_{i=1}^{N} \sigma_{Ia}^2\left(\mu_{Ia}(z_i)\right)$$

$$L2 = \frac{1}{N}\sum_{1}^{N}(H_{obs}(z_i) - H_{pred}(z_i))^2$$

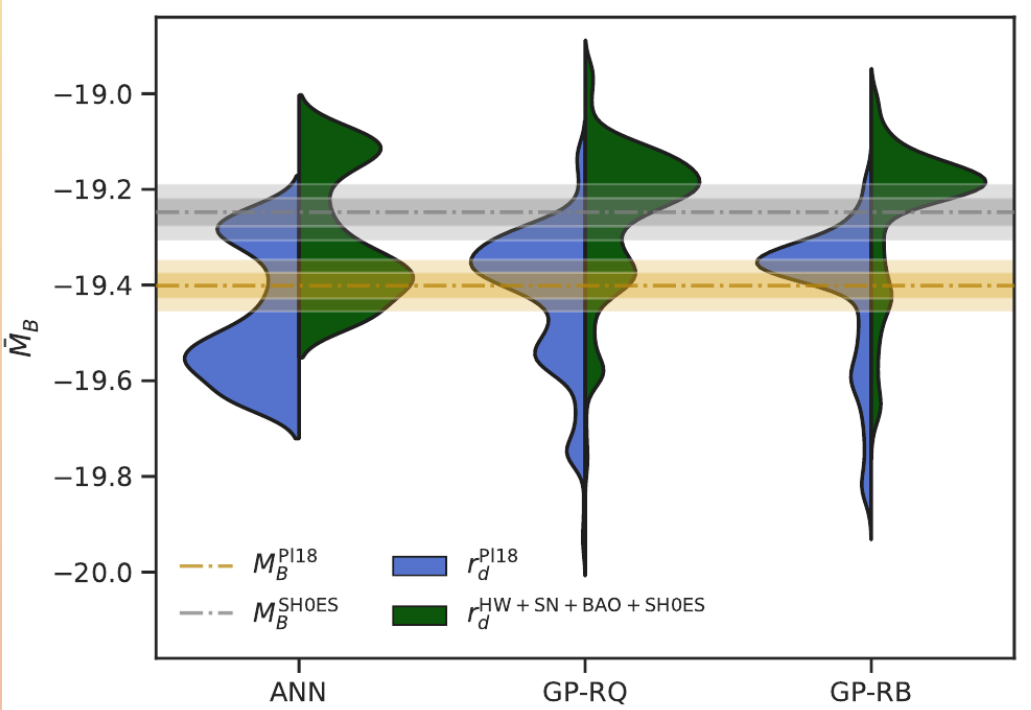
The ANN reconstruction

- Much cleaner than the GP
- Still we see the jump around z~0.5-0.15
- There are hints of decrease of M_B for higher z



The combined plots

- Not a single Gaussian but a multi-peak distributions or notable tails
- The mean value differs for the different NP methods.
- The mean values are close to the expected from Planck and SH0ES only if one assumes a single Gaussian, otherwise.
- Camarena & Mara get M_B=-19.23±0.4 (Phys. Rev. Research 2, 013028 (2020), 1906.11814).



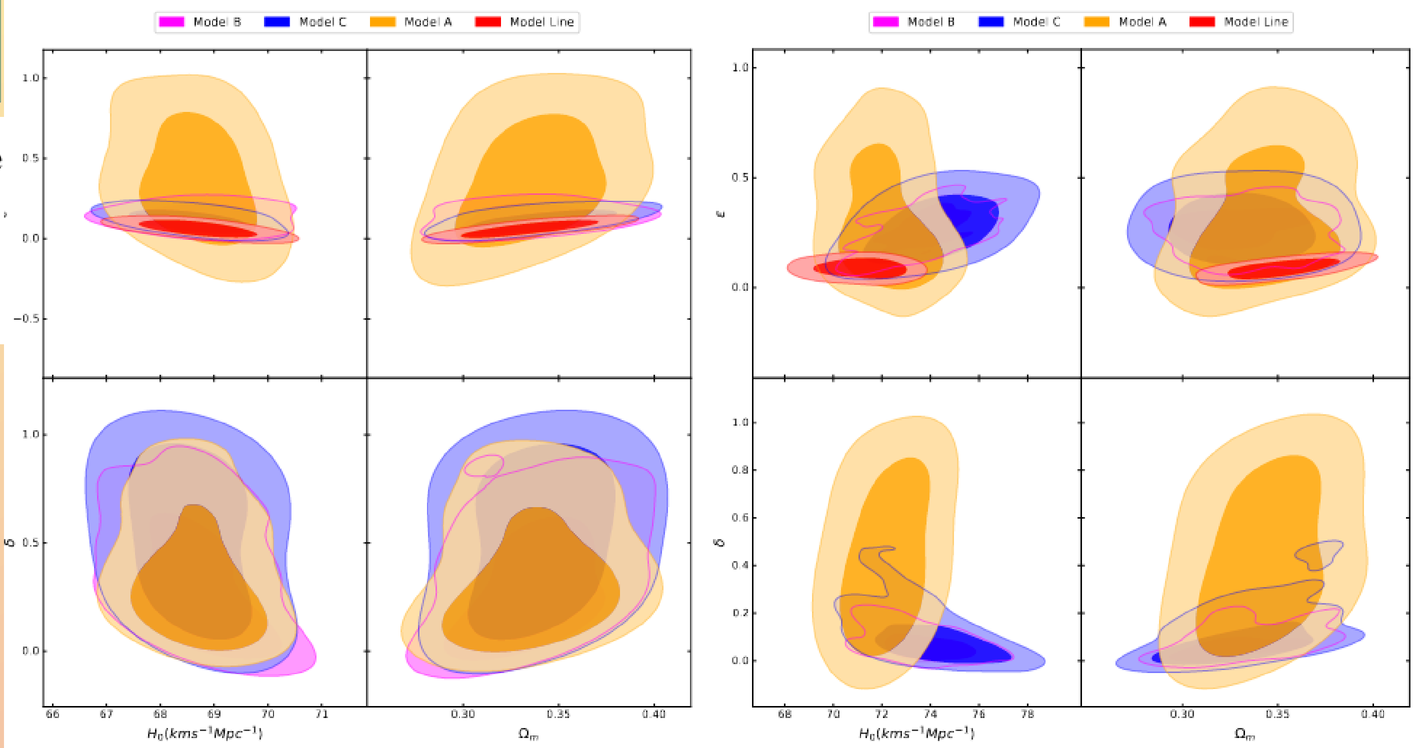
Technique	$r_{d,fit}^{Pl18}$	$r_{d,fit}^{HW+SN+BAO+SH0ES}$	$r_{d,full}^{Pl18}$	$r_{d,full}^{HW+SN+BAO+SH0ES}$
ANN	-19.58 ± 0.11 and -19.26 ± 0.04	-19.1 ± 0.04 and -19.42 ± 0.11	-19.38 ± 0.20	-19.22 ± 0.20
GP-RQ	-19.35 ± 0.03	-19.18 ± 0.03	-19.42 ± 0.35	-19.25 ± 0.39
GP-RB	-19.35 ± 0.07	-19.18 ± 0.07	-19.42 ± 0.29	-19.25 ± 0.33

What if we assume $M_B(z)$?

We tested known models for the nuisance parameter

$$\delta M_B(z) = \begin{cases} \epsilon z & \text{Model Line} \\ \epsilon\left[(1+z)^\delta - 1\right] & \text{Model A} \\ \epsilon z^\delta & \text{Model B} \\ \epsilon\left[\ln(1+z)\right]^\delta & \text{Model C}\ . \end{cases}$$

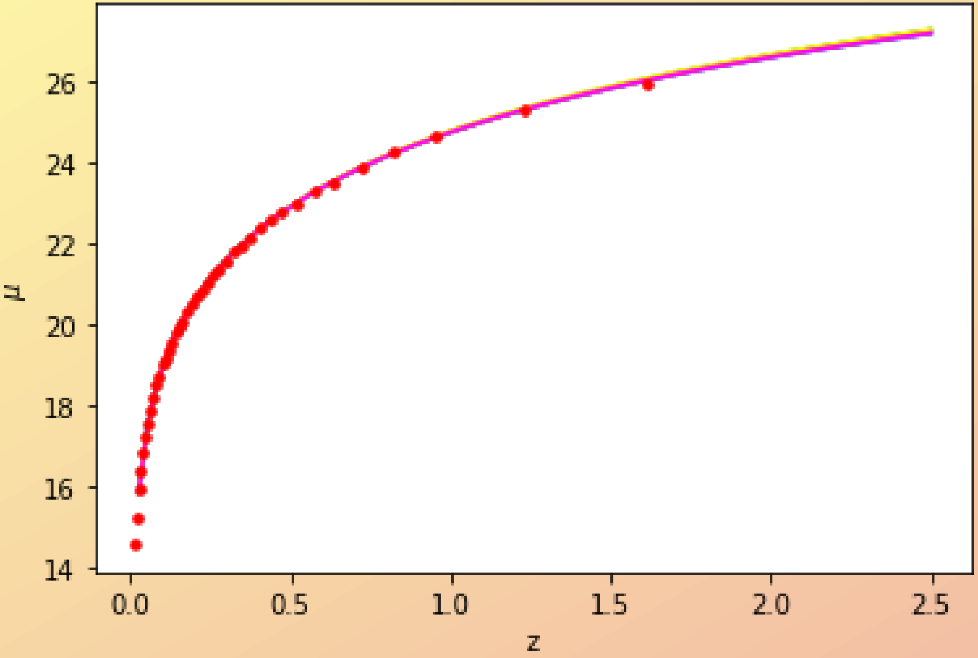
- More parameters lead to bigger contours but not necessairly better fits!
- The statistical measures (AIC, BIC, DIC and BF) do not prefer strongly any of the tested non-constant model significantly.

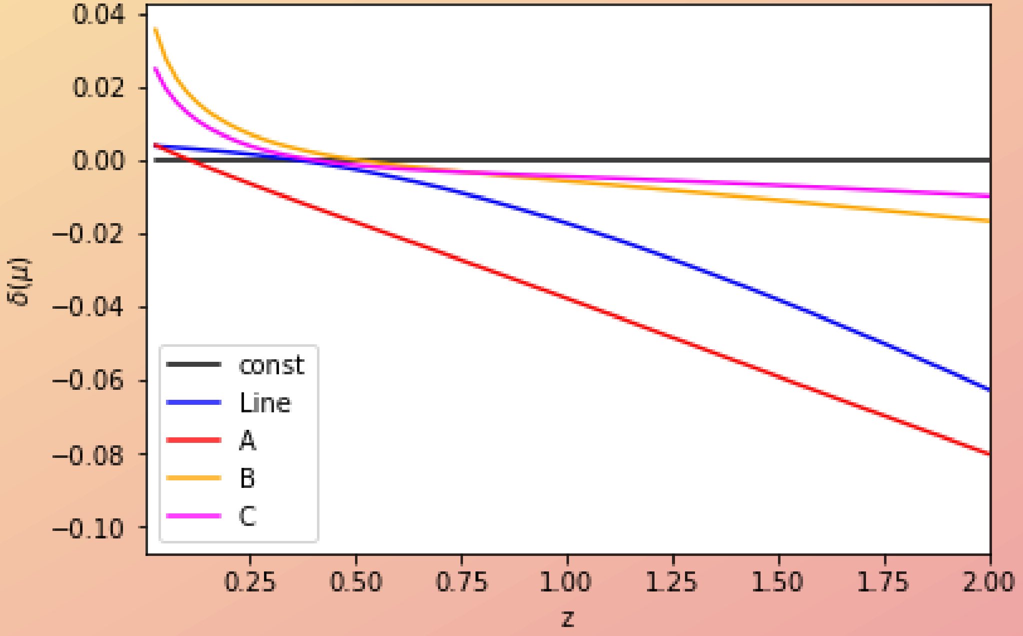


With color correction in the MCMC

$$\mu_{obs} = m_B^* - (M_B - \alpha X_1 + \beta C),$$

The fits from the models are indistinguishable





The deviations are too small
to be caught with this errors

If we check the standard statistical measures

$r_d^{Pl18} = 147.09 \pm 0.26$ Mpc							
Model	AIC	ΔAIC	BIC	ΔBIC	DIC	ΔDIC	log(BF)
$\epsilon = 0$	84.9		99.7		63.7		
Line	87.5	-2.6	103.4	-3.7	63.4	0.29	1.5
A	90.2	-5.3	107.1	-7.4	63.1	0.65	0.4
B	90.1	-5.2	107.0	-7.4	62.9	0.72	0.9
C	89.9	-5.1	106.9	-7.2	62.9	0.85	0.4
$r_d^{HW+SN+BAO+SH0ES} = 136.1 \pm 2.7$ Mpc							

$r_d^{HW+SN+BAO+SH0ES} = 136.1 \pm 2.7$ Mpc							
$\epsilon = 0$	85.2		100.0		64.1		
Line	87.9	-2.8	103.9	-3.9	64.0	0.04	1.3
A	90.3	-5.1	107.2	-7.2	63.2	0.9	-1.4
B	89.8	-4.6	106.7	-6.7	62.7	1.4	-3.4
C	90.4	-5.2	107.3	-7.3	63.3	0.8	-2.3
$\Omega_b = 0.0224 \pm 0.0001$							
$\epsilon = 0$	85.1		99.9		63.9		
Line	87.8	-2.7	103.7	-3.8	63.8	0.1	2.9
A	90.6	-5.5	107.5	-7.6	63.5	0.4	1.0
B	90.3	-5.1	107.1	-7.2	63.1	0.8	1.6
C	90.4	-5.3	107.4	-7.5	63.4	0.6	1.6

$$\text{AIC} = -2\ln(\mathcal{L}_{\max}) + 2k + \frac{2k(k+1)}{N_{\text{tot}} - k - 1}$$

$$\text{BIC} = -2\ln(\mathcal{L}_{\max}) + k\log(N_{\text{tot}})$$

$$\text{DIC} = 2\overline{(D(\theta))} - D(\bar{\theta}),$$

$$B_{ij} = \frac{p(d|M_i)}{p(d|M_j)},$$

We see that there is no strong preference for any model for DIC and BF

The Distance Duality Relation

- The distance duality relation or the Etherington’s reciprocity theorem
- It should hold for any metric theories of gravity
- I.e. for all theories where the photon number is conserved and photons travel along null geodesics.
- The validity of DDR has been studied and confirmed using different astronomical sources in pioneer works
- In more recent works, there are some evidences for mild deviations, especially for models with spatial curvature

$$d_L = d_A(1+z)^2$$

- Examples of models in which it may not hold:
- Curvature of the universe
- DDE
- Gravitational lensing
- Dust extinction
- Modified gravity
- Inhomogenities and clustering

Conclusions and open questions

Conclusions:

- **The constancy of M_B is at level of 1σ.**
- The MCMC do not prefer any of the tested non-constant model significantly.
- **We exchange the tension in H_0-r_d with a tension in the M_B-r_d plane (fixing M_B fixes H_0)**
- **The observed distribution cannot be described as a single Gaussian**
- **Multiple peaks and tails observed**

Is it possible that there is a nuissance parameter contribution M(z) of unknown form?
If so why is this effect so weak?
We see two trends – one for very small z and one for high z
What are the physical origin of the small z jump?
New WD physics, higher Chandrasekhar mass, unknown propagation effect?
What about the high z?

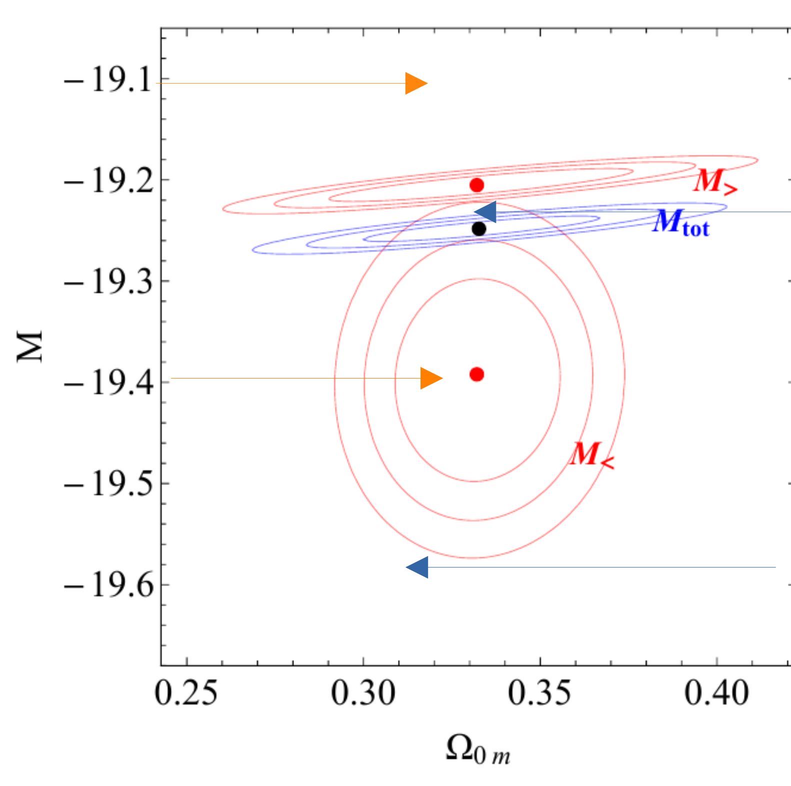
What is the context of our work?

Perivolaropoulos and Skara - series of models with a jump at d~20-50Mpc (Universe 2022 and MNRAS 2023)

Ashall et al., **SNe Ia from star-forming galaxies have a mean M_B = −19.20 ± 0.05 mag, while SNe Ia from passive galaxies -- M_B = −18.57 ± 0.24 mag**, MNRAS, 2016

Evslin, „Calibrating Effective Ia Supernova Magnitudes using the Distance Duality Relation“, Phys.Dark Univ. 14 (2016) **„statistically insignificant downward shift M(2.34)-M(0.32)=-0.08±0.15„**

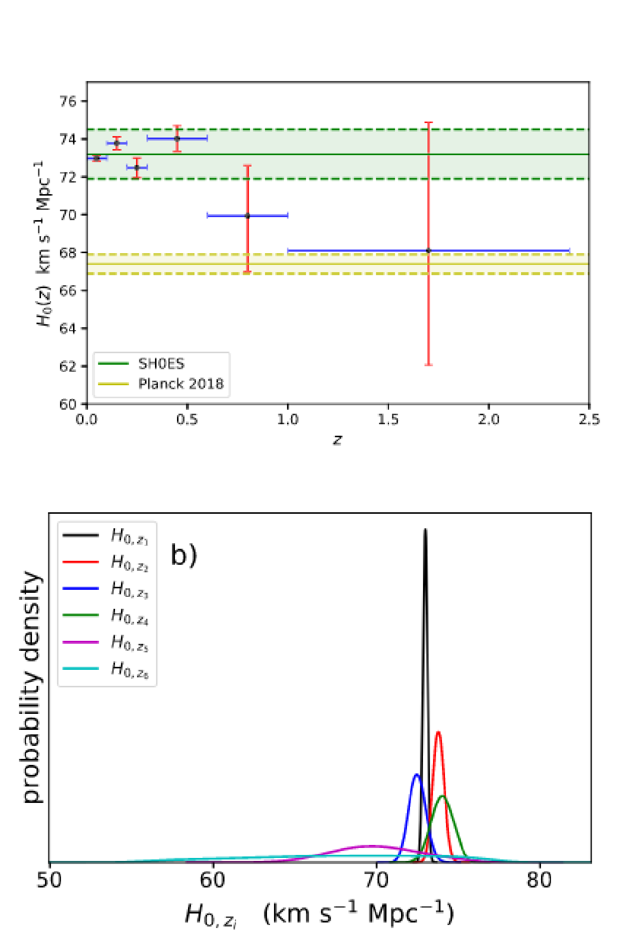
Alestas et al., „A w − M phantom transition at z_t < 0.1 as a resolution of the Hubble tension“, Phys. Rev. D 103 (2021)
Alestas et al., „Late-transition vs smooth H(z) deformation models for the resolution of the Hubble crisis“ Phys.Rev.D 105 (2022) **The LMT model includes a sharp transition in the SnIa absolute magnitude M**



Leandros Perivolaropoulos, Foteini Skara,
Mon.Not.Roy.Astron.Soc. 520 (2023) 4, 5110-5125

Furthermore...

- „Evidence of a decreasing trend for the Hubble constant“, XD Jia et al., A&A 674, A45 (2023) (5.6σ)
- „On the Hubble Constant Tension in the SNe Ia Pantheon Sample“ – M. Dainotti et al., ApJ, 912, 150 (2021) – Decreasing H_0 as $g(z) \sim H_0/(1+z)^\alpha$
- „A rapid transition of Geff at zt ~0.01 as a possible solution of the Hubble and growth tensios“, Marra and Perivolaropoulos, Phys. Rev. D 104, 021303 (2021)
- „Intrinsic tension in the supernova sector of the local Hubble constant measurement and its implications“, Wojtak & Hjorth, MNRAS 2022
- „A Cosmological Underdensity Does Not Solve the Hubble Tension“, Castello et al, JCAP07(2022)

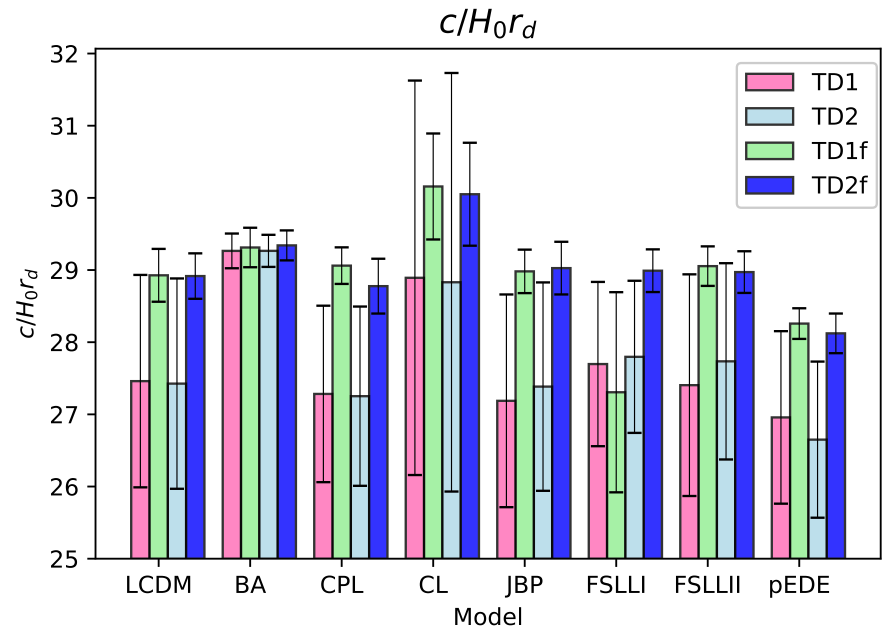


Other perspectives

- LIV

$$E^2 = p^2c^2\left[1 - s_\pm\left(\frac{E}{\xi_n E_{QG}}\right)^n\right]$$

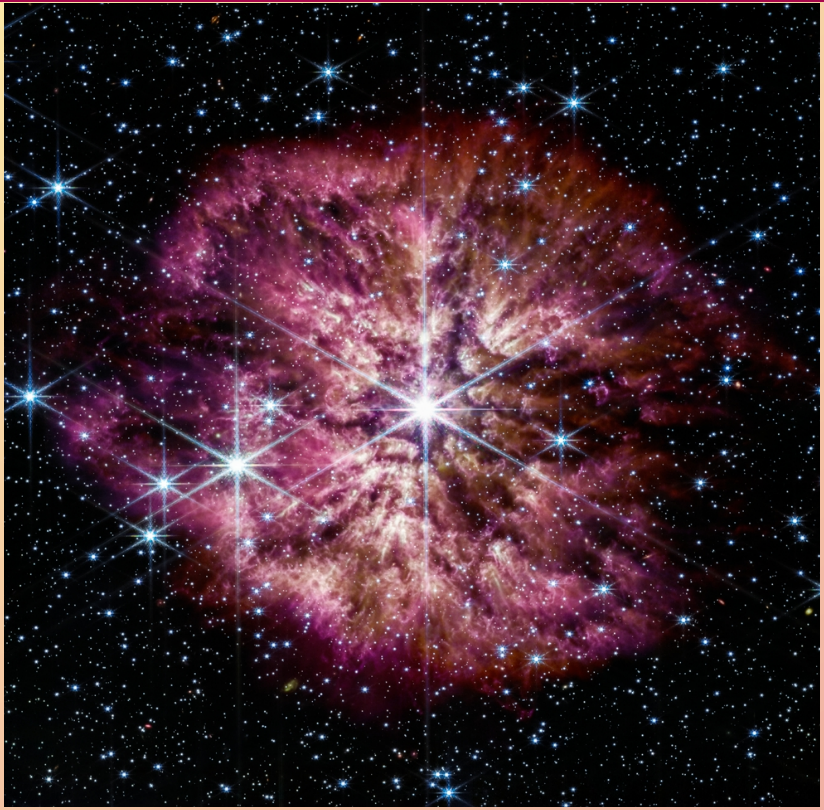
$$t_{LIV} = \int_0^z [1+\frac{E}{E_{QG}}(1+z')]\frac{dz'}{H(z')}$$



- Two different time-delay datasets producing significant effect in the c/H0rd parameter constraints
- Can this dataset be used for cosmology?
- Can this be a sign of the tension?
- To be continued soon with more effects on cosmology

D.S., Class.Quant.Grav. 40 (2023)

Thank you for your attention!



Credits: NASA, ESA, CSA, STScI, Webb ERO Production Team

Supported by grant KP-06-N 38/11

The DE models

Model	$\Omega_{DE}(z) = \Omega_\Lambda \times$	$w(z)$
CPL	$\exp\left[\int_0^z \frac{3(1+w(z'))dz'}{1+z'}\right]$	$w_0 + w_a \frac{z}{z+1}$
BA	$(1+z)^{3(1+w_0)}(1+z^2)^{\frac{3w_1}{2}}$	$w_0 + z\frac{1+z}{1+z^2}w_1$
LC	$(1+z)^{(3(1-2w_0+3wa))}e^{\frac{9(w_0-wa)z}{(1+z))}}$	$\frac{(-z+z_c)w_0+z(1+z_c)w_c}{(1+z)z_c}$
JPB	$(1+z)^{3(1+w_0)}e^{\frac{3w_1z^2}{2(1+z)^2}}$	$w_0 + w_1\frac{z}{(1+z)^2}$
FSLLI	$(1+z)^{3(1+w_0)}e^{\frac{3w_1}{2}\arctan(z)}(1+z^2)^{\frac{3w_1}{4}}(1+z)^{-\frac{3}{2}w_1}$	$w_0 + w_1\frac{z}{1+z^2}$
FSLLII	$(1+z)^{3(1+w_0)}e^{-\frac{3w_1}{2}\arctan(z)}(1+z^2)^{\frac{3w_1}{4}}(1+z)^{+\frac{3}{2}w_1}$	$w_0 + w_1\frac{z^2}{1+z^2}$
PEDE	$\frac{1-\tanh(\bar{\Delta}\log_{10}(\frac{1+z}{1+z_t}))}{1+\tanh(\bar{\Delta}\log_{10}(1+z_t)}$	$-\frac{(1+\tanh[\log_{10}(1+z)])}{3\ln 10}-1$