Interacting Dark Energy

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☛ - Coupled cosmologies: the landscape
- Coupled cosmologies and cosmological tensions
- Constraints from redshift space distortions
- Summary and ideas for future work and collaborations

Dark energy- Ω_{dm} coupled models

In the absence of a fundamental symmetry which sets the vacuum energy to zero, it is mandatory to look for an alternative mechanism: dynamical explanation of the accelerated expansion via a cosmic scalar field. *Wetterich; Peebles &Ratra; Wang, Caldwell, Ostriker & Steinhardt*

Cosmic scalar fields may naturally couple to all other fields in nature.
Negligible couplings to matter. *Carroll, PRL'98*
In practice, only to invisibles.

Dark sectors follow same time evolution on time:
cosmic coincidence-why now? problem

$$\nabla_\mu T^\mu_{(dm)\nu} = Q\, u_\nu^{(dm,de)}/a$$ *Kodama & Sasaki, PTPS'84*

$$\nabla_\mu T^\mu_{(de)\nu} = -Q\, u_\nu^{(dm,de)}/a$$ *Gavela et al JCAP'09*

Simplest phenomenological scenarios

$$Q \propto \xi \rho_{\mathrm{de}}$$

He at al PLB'09
Jackson et al PRD'09
Gavela et al JCAP'09

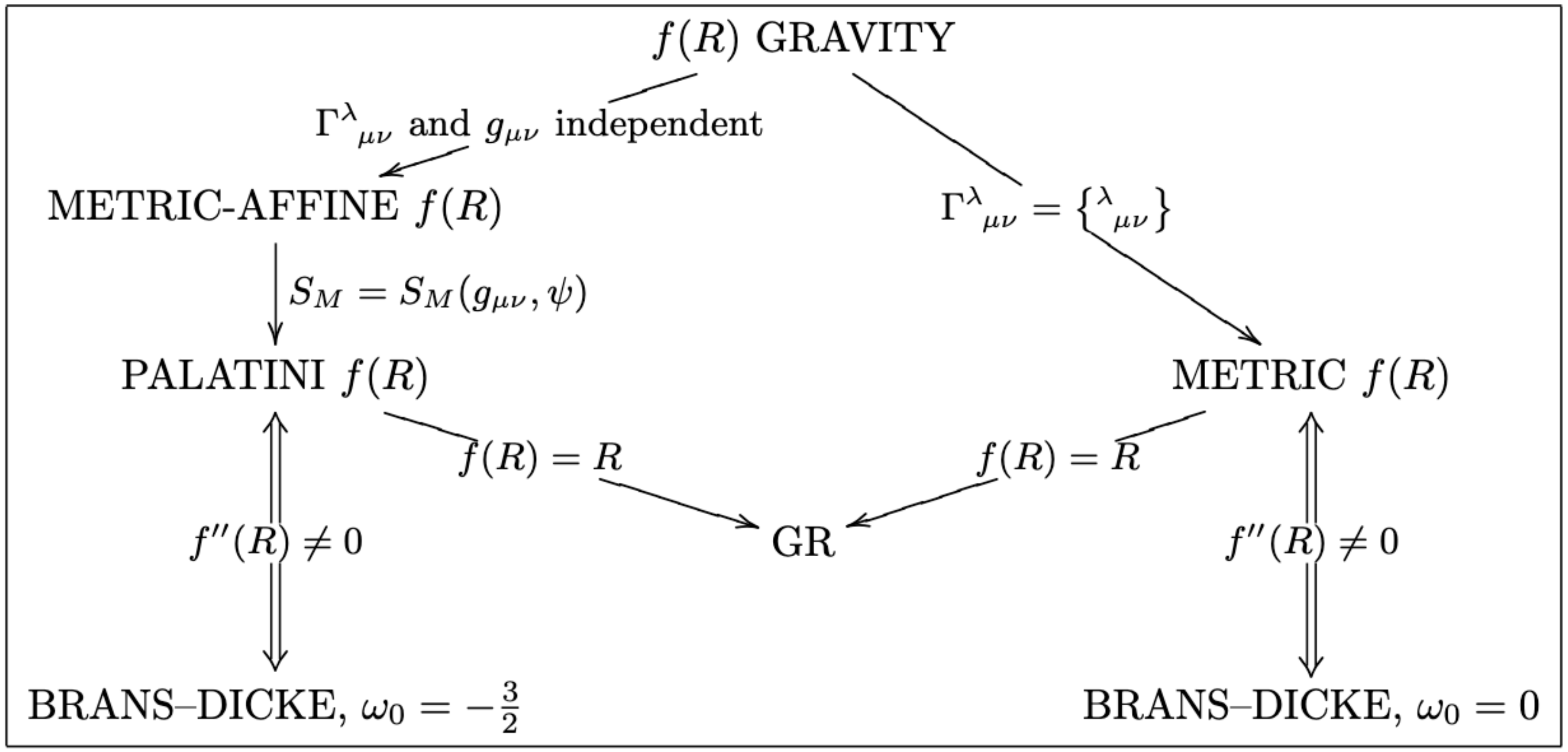
$$Q \propto \xi \rho_{\mathrm{dm}}$$

Damour et al PRL'90, Wetterich AA'95, Amendola PRD'00, Zimdahl et al PLB'01, Farrar &Peebles APJ'04, Das et al PRD'06, Zhang et al PRD'06, Olivares et al PRD'08, Bean et al NJP'08, Koyama et al JCAP'10, Valiviita et al JCAP'08, He at al PLB'09, Jackson et al PRD'09, Gavela et al JCAP'09

Possible field descriptions at classical and quantum levels *Gleyzes et al JCAP'15, Pan et al PRD'20*

Quintessence coupled field models can be written as a scalar-tensor gravity theory. f (R) gravity theories correspond to generalized Brans Dicke (BD) theory with a BD parameter $w_{BD} = 0$ or $w_{BD} = -3/2$.

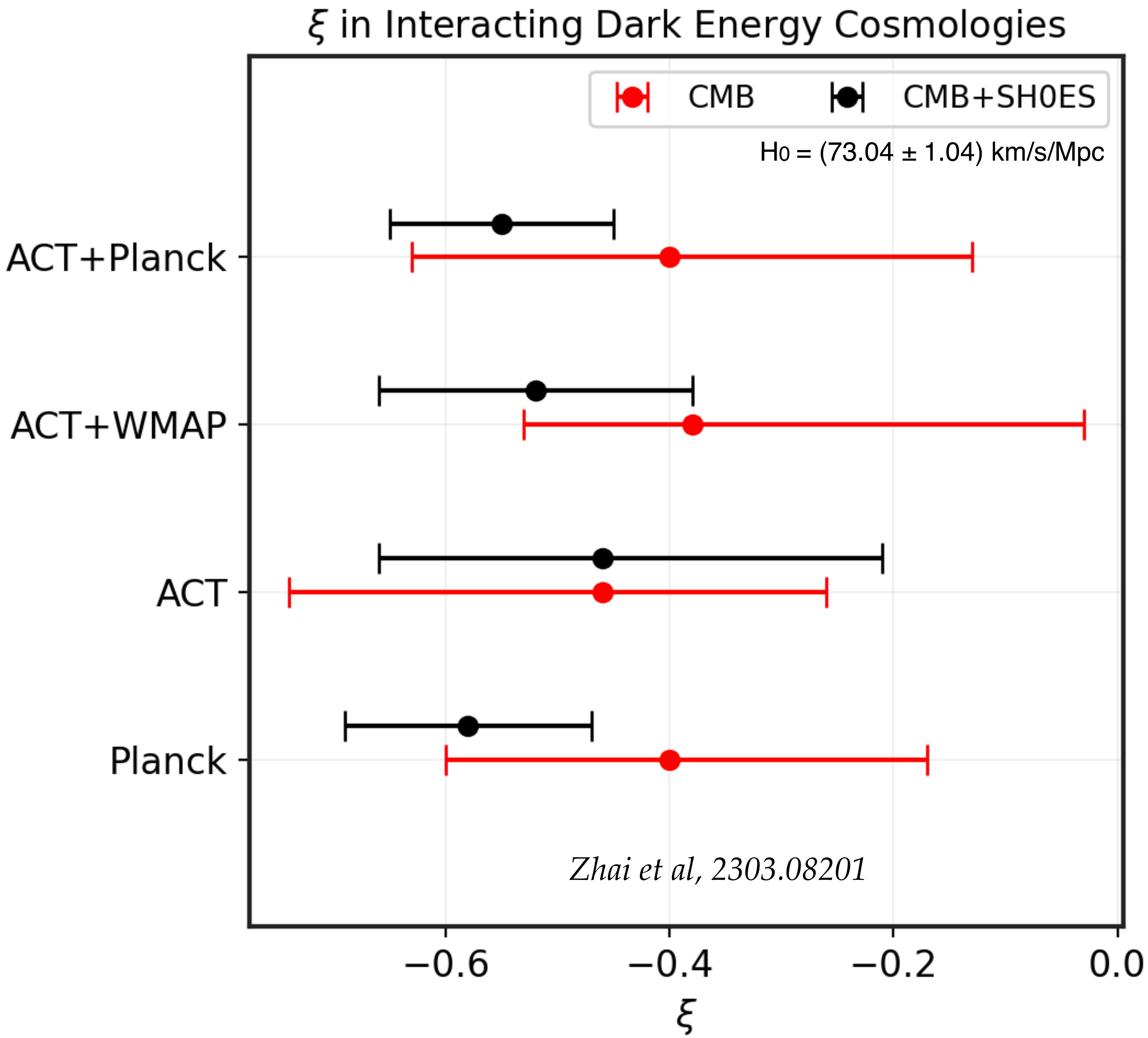
Sotiriou & Faraoni, Rev. Mod. Phys'10



Is there any preference for $\xi \neq 0$?

An interacting dark sector is favoured with 95% CL significance from current CMB data

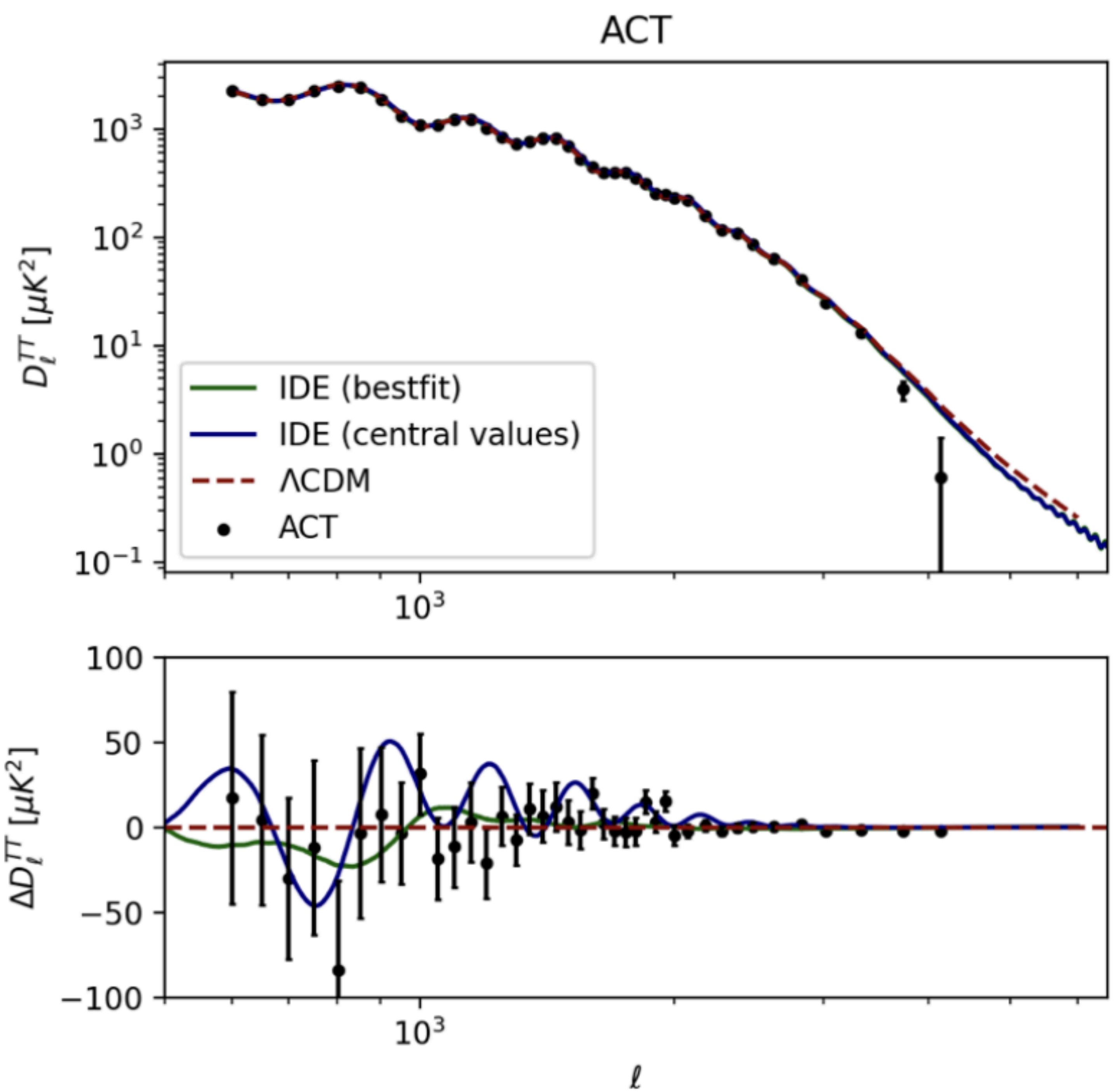
$$Q = 3H\xi\rho_{\rm de}$$



Is there any preference for $\xi \neq 0$?

An interacting dark sector is favoured with a 95% CL significance from current CMB data due to the lower amplitude of high-multipole data

$$Q = 3H\xi\rho_{\rm de}$$



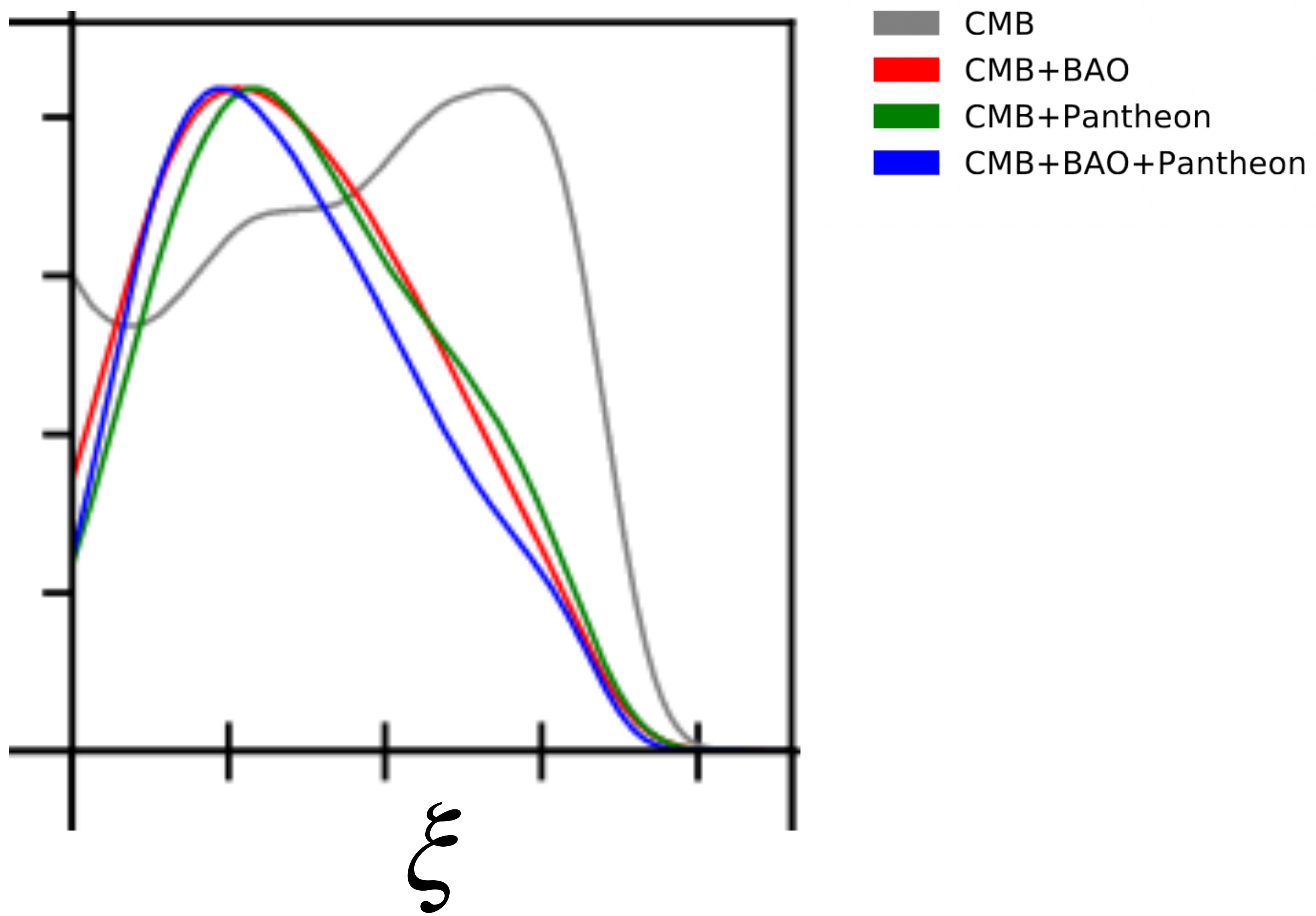
Zhai et al, 2303.08201

Is there any preference for $\xi \neq 0$?

The CMB "preference" dilutes within the simplest ΛCDM after BAO data.

However....

$$Q = 3H\xi\rho_{\rm de} \qquad w > -1$$



Wang et al, 2209.14816

Is there any preference for $\xi \neq 0$?

The CMB "preference" dilutes within the simplest ΛCDM after BAO data.

However, within the wCDM model:

$$Q = 3H\xi\rho_{\rm de} \qquad w > -1$$

Parameters	CMB	CMB+BAO	CMB+Pantheon	CMB+BAO+Pantheon
$\Omega_c h^2$	< 0.083 < 0.115	$0.076^{+0.037+0.046}_{-0.018-0.058}$	$0.074^{+0.038+0.046}_{-0.019-0.057}$	$0.077^{+0.036+0.044}_{-0.016-0.058}$
$\Omega_b h^2$	$0.02236^{+0.00015+0.00029}_{-0.00015-0.00029}$	$0.02239^{+0.00014+0.00029}_{-0.00014-0.00027}$	$0.02234^{+0.00015+0.00029}_{-0.00015-0.00029}$	$0.02238^{+0.00014+0.00028}_{-0.00014-0.00027}$
$100\theta_{MC}$	$1.0448^{+0.0019+0.0050}_{-0.0037-0.0043}$	$1.0438^{+0.0010+0.0043}_{-0.0025-0.0031}$	$1.0438^{+0.0011+0.0043}_{-0.0026-0.0032}$	$1.0437^{+0.0009+0.0043}_{-0.0024-0.0031}$
τ	$0.0544^{+0.0071+0.016}_{-0.0074-0.015}$	$0.0550^{+0.0077+0.017}_{-0.0079-0.015}$	$0.0538^{+0.0074+0.016}_{-0.0075-0.015}$	$0.0547^{+0.0074+0.016}_{-0.0073-0.015}$
n_s	$0.9650^{+0.0042+0.0084}_{-0.0042-0.0084}$	$0.9658^{+0.0042+0.0082}_{-0.0041-0.0084}$	$0.9643^{+0.0043+0.0085}_{-0.0043-0.0082}$	$0.9660^{+0.0040+0.0078}_{-0.0040-0.0079}$
$\ln(10^{10}A_s)$	$3.045^{+0.015+0.031}_{-0.015-0.031}$	$3.045^{+0.016+0.034}_{-0.016-0.032}$	$3.044^{+0.016+0.033}_{-0.015-0.032}$	$3.044^{+0.015+0.033}_{-0.015-0.031}$
w_q	< -0.897 < -0.768	< -0.892 < -0.801	< -0.879 < -0.793	< -0.887 < -0.792
ξ_0	$0.15^{+0.11}_{-0.07}$ < 0.27	$0.119^{+0.054}_{-0.090}$ < 0.242	$0.125^{+0.056+0.13}_{-0.090-0.12}$	$0.115^{+0.047+0.12}_{-0.087-0.12}$
Ω_{m0}	$0.18^{+0.07+0.10}_{-0.12-0.15}$	$0.212^{+0.083+0.11}_{-0.047-0.13}$	$0.210^{+0.084+0.11}_{-0.047-0.13}$	$0.215^{+0.080+0.10}_{-0.038-0.13}$
σ_8	$1.6^{+0.2+2.1}_{-1.0-1.2}$	$1.25^{+0.09+1.1}_{-0.50-0.7}$	$1.27^{+0.09+1.1}_{-0.51-0.6}$	$1.22^{+0.07+1.1}_{-0.46-0.6}$
H_0 [km/s/Mpc]	$69.3^{+3.9+6.2}_{-2.8-6.5}$	$68.4^{+1.3+2.7}_{-1.4-2.5}$	$68.1^{+1.0+2.1}_{-1.0-2.0}$	$68.2^{+0.8+1.6}_{-0.8-1.5}$
S_8	$1.07^{+0.08+0.52}_{-0.27-0.32}$	$0.97^{+0.04+0.35}_{-0.16-0.21}$	$0.99^{+0.04+0.35}_{-0.17-0.21}$	$0.97^{+0.03+0.33}_{-0.15-0.20}$
$r_{\rm drag}$ [Mpc]	$147.04^{+0.30+0.59}_{-0.29-0.58}$	$147.12^{+0.27+0.55}_{-0.27-0.52}$	$147.03^{+0.29+0.58}_{-0.29-0.58}$	$147.15^{+0.26+0.52}_{-0.27-0.54}$

Wang et al, 2209.14816

Is there any preference for $\xi \neq 0$?

The CMB "preference" dilutes within the simplest ΛCDM after BAO data.

However....

$$Q = 3H\xi\rho_{\rm de} \qquad w < -1$$

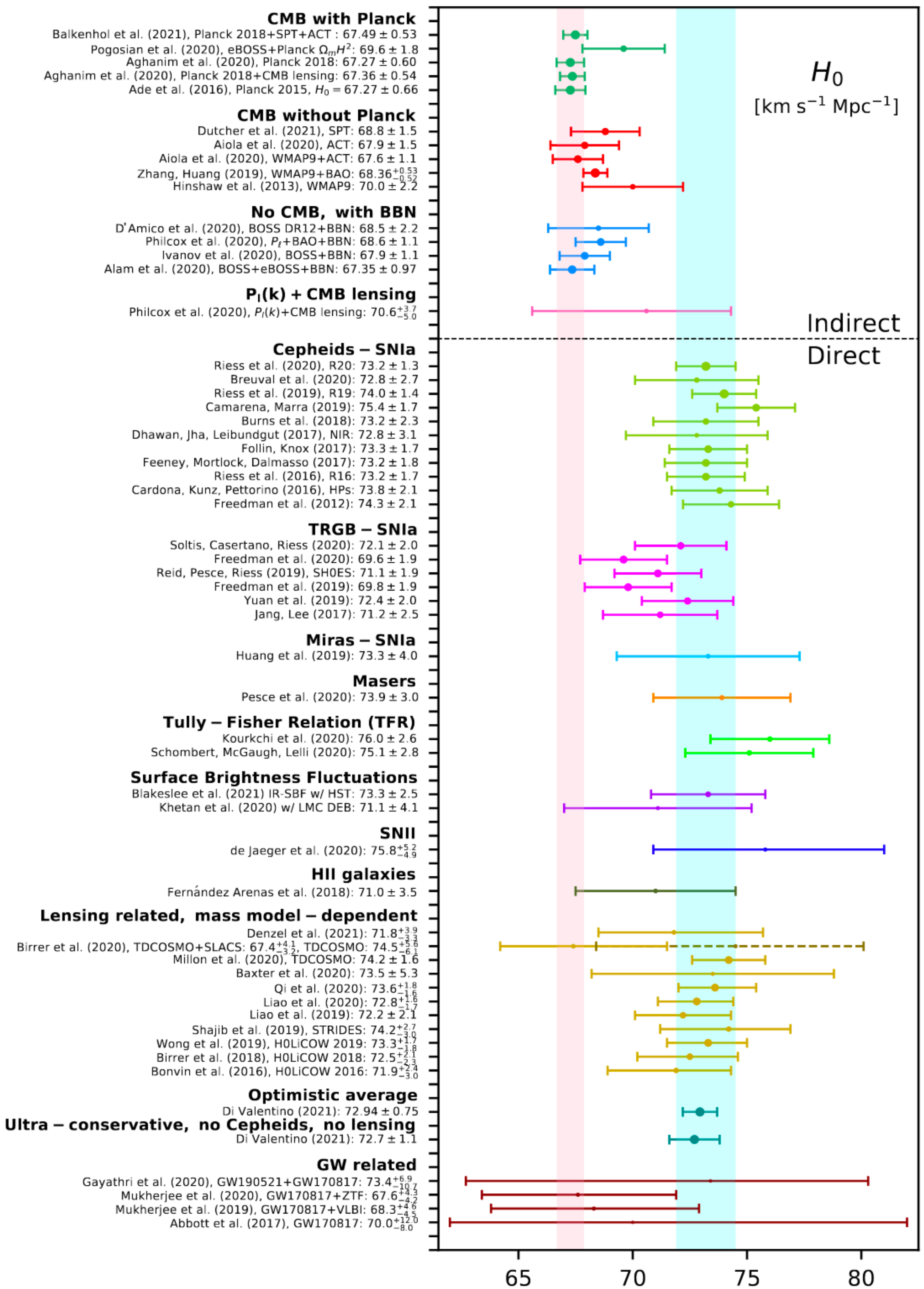
Parameters	CMB	CMB+BAO	CMB+Pantheon	CMB+BAO+Pantheon
$\Omega_c h^2$	$0.134^{+0.007+0.017}_{-0.013-0.015}$	$0.1352^{+0.0099+0.014}_{-0.0098-0.014}$	$0.135^{+0.009+0.015}_{-0.011-0.014}$	$0.1350^{+0.0098+0.014}_{-0.0098-0.014}$
$\Omega_b h^2$	$0.02239^{+0.00015+0.00030}_{-0.00015-0.00030}$	$0.02239^{+0.00014+0.00028}_{-0.00014-0.00028}$	$0.02236^{+0.00015+0.00029}_{-0.00015-0.00029}$	$0.02239^{+0.00014+0.00028}_{-0.00014-0.00027}$
$100\theta_{MC}$	$1.04018^{+0.00065+0.0011}_{-0.00054-0.0011}$	$1.04013^{+0.00055+0.0010}_{-0.00055-0.0010}$	$1.04010^{+0.00055+0.00098}_{-0.00055-0.00099}$	$1.04015^{+0.00054+0.00099}_{-0.00055-0.00099}$
τ	$0.0540^{+0.0074+0.015}_{-0.0074-0.015}$	$0.0548^{+0.0073+0.016}_{-0.0079-0.015}$	$0.0543^{+0.0075+0.016}_{-0.0075-0.015}$	$0.0549^{+0.0075+0.016}_{-0.0075-0.015}$
n_s	$0.9652^{+0.0043+0.0086}_{-0.0044-0.0086}$	$0.9657^{+0.0042+0.0081}_{-0.0042-0.0082}$	$0.9647^{+0.0043+0.0086}_{-0.0044-0.0084}$	$0.9659^{+0.0040+0.0078}_{-0.0040-0.0077}$
$\ln(10^{10}A_s)$	$3.043^{+0.015+0.029}_{-0.015-0.031}$	$3.045^{+0.015+0.032}_{-0.016-0.030}$	$3.045^{+0.015+0.032}_{-0.015-0.031}$	$3.045^{+0.015+0.032}_{-0.015-0.031}$
w_p	$-1.58^{+0.21+0.49}_{-0.34-0.44}$	$-1.094^{+0.070}_{-0.040}$ > -1.193	$-1.087^{+0.049+0.085}_{-0.041-0.076}$	$-1.080^{+0.047+0.079}_{-0.038-0.072}$
ξ_0	> -0.051 > -0.090	$-0.052^{+0.046}_{-0.023}$ > -0.100	$-0.051^{+0.047}_{-0.021}$ > -0.101	$-0.052^{+0.044}_{-0.025}$ > -0.101
Ω_{m0}	$0.226^{+0.031+0.11}_{-0.072-0.09}$	$0.336^{+0.025+0.044}_{-0.025-0.042}$	$0.339^{+0.024+0.041}_{-0.024-0.040}$	$0.339^{+0.023+0.037}_{-0.023-0.036}$
σ_8	$0.886^{+0.086+0.15}_{-0.089-0.16}$	$0.760^{+0.038+0.074}_{-0.047-0.070}$	$0.761^{+0.035+0.068}_{-0.046-0.064}$	$0.756^{+0.034+0.067}_{-0.046-0.063}$
H_0 [km/s/Mpc]	85^{+13+16}_{-7-17}	$68.7^{+1.1+2.7}_{-1.5-2.5}$	$68.3^{+1.0+2.0}_{-1.0-1.9}$	$68.32^{+0.77+1.6}_{-0.78-1.5}$
S_8	$0.756^{+0.034+0.064}_{-0.034-0.063}$	$0.802^{+0.020+0.036}_{-0.020-0.036}$	$0.807^{+0.021+0.040}_{-0.021-0.039}$	$0.802^{+0.019+0.036}_{-0.019-0.035}$
$r_{\rm drag}$ [Mpc]	$147.08^{+0.29+0.57}_{-0.29-0.58}$	$147.11^{+0.27+0.54}_{-0.28-0.54}$	$147.05^{+0.29+0.58}_{-0.29-0.56}$	$147.14^{+0.27+0.52]}_{-0.27-0.52}$

Wang et al, 2209.14816

A phantom interacting dark energy cosmology is also favoured!

- Coupled cosmologies: the landscape
- ☛ Coupled cosmologies and cosmological tensions
- Constraints from redshift space distortions
- Summary and ideas for future work and collaborations

The Hubble constant tension



$$H_0 = 67.27 \pm 0.60 \text{ km/s/Mpc}$$

Planck Coll. A&A'20

$$4\sigma - 6\sigma$$

$$H_0 = 73.17 \pm 0.86 \text{ km/s/Mpc}$$

Breuval, Riess et al APJ'24

OPEN ACCESS
IOP Publishing — Classical and Quantum Gravity

Class. Quantum Grav. **38** (2021) 153001 (110pp) https://doi.org/10.1088/1361-6382/ac086d

Topical Review

In the realm of the Hubble tension—a review of solutions*

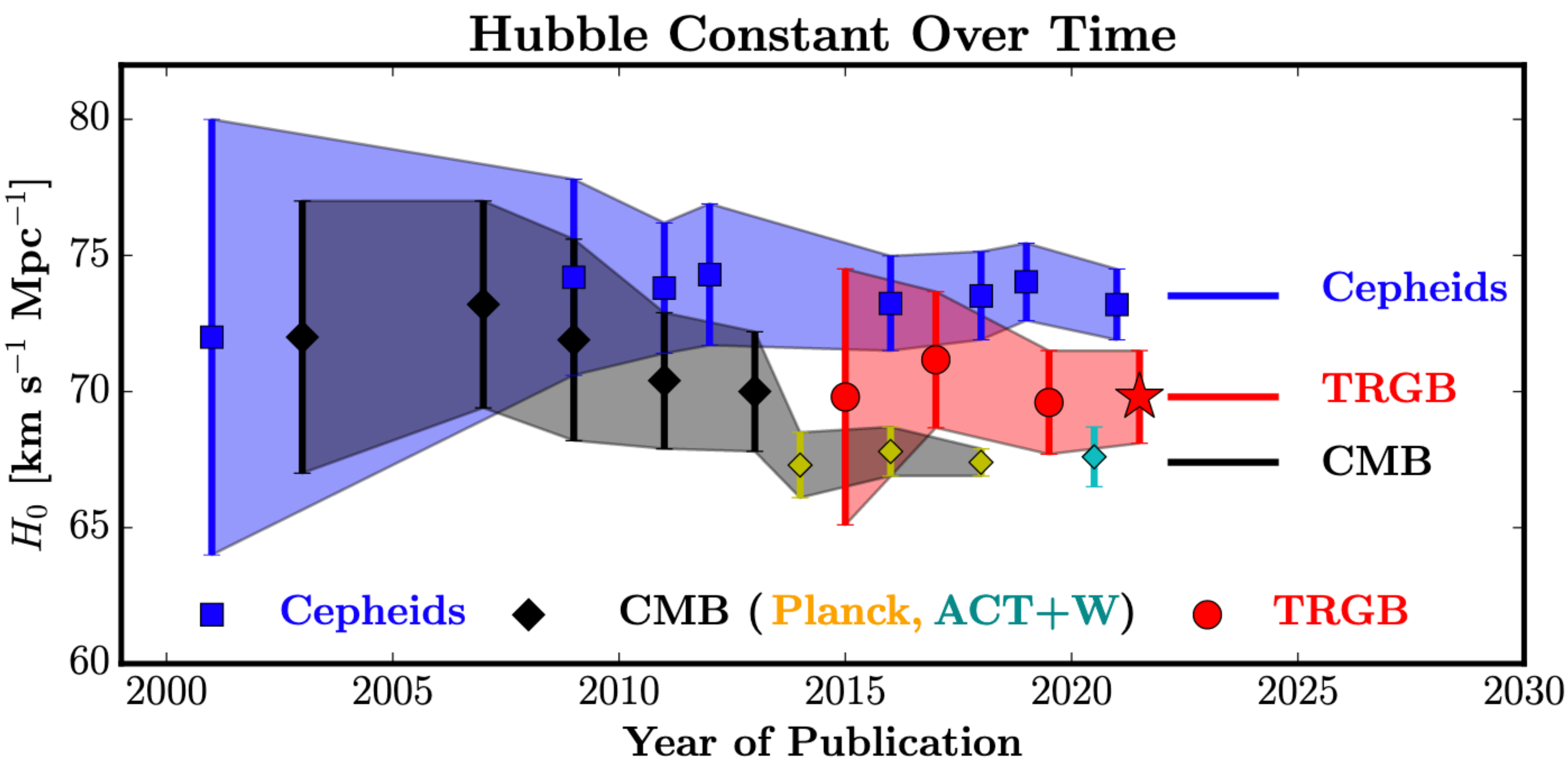
Eleonora Di Valentino[1,], Olga Mena[2], Supriya Pan[3], Luca Visinelli[4], Weiqiang Yang[5], Alessandro Melchiorri[6], David F Mota[7], Adam G Riess[8,9] and Joseph Silk[8,10,11]**

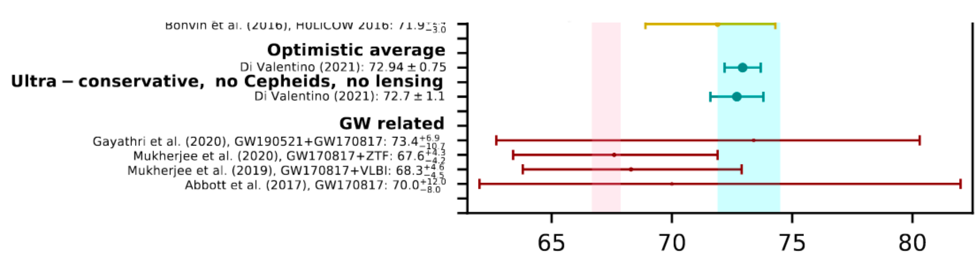
Di Valentino et al Class.Quant.Grav'21

See also Schöneberg et al Phys.Rept.'22

The Hubble constant tension

W. Freedman, APJ'21





Di Valentino et al Class.Quant.Grav'21

See also Schöneberg et al Phys.Rept.'22

From A. Riess

Hubble Tension in Perspective: Why Compelling?

1. **Comes from Best Tools, Best Measurements**
   - "Gold Standard" tools: CMB, Parallax, SN Ia, Cepheids
     (New measures less tested/have additional model dependencies)
   - Best Data Sources: HST, JWST, Gaia, Planck, all public

2. **At >5σ, Highly Significant**
   - With significance steadily growing

3. **Lasted Ten Years**
   - Field finds problems quickly (months) if data public
     Recent Examples: BICEP, OPERA, Oumuamua

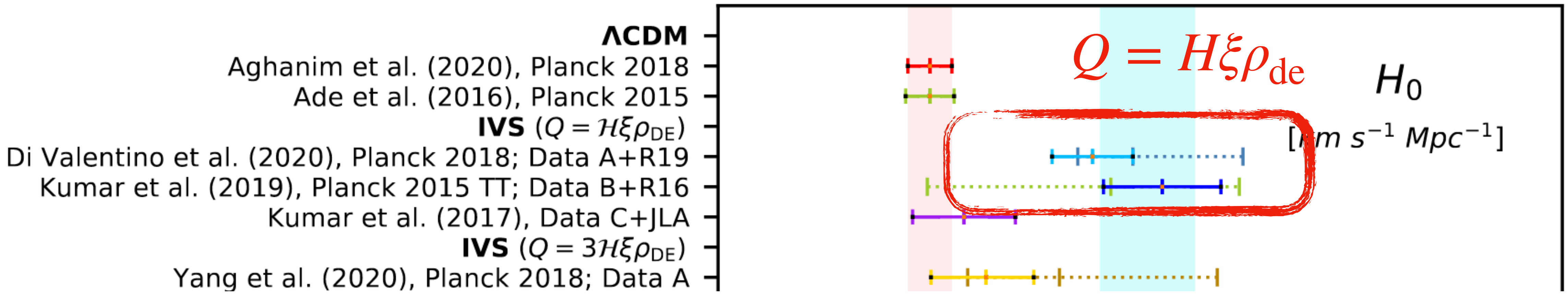
4. **The Model, ΛCDM, shallow physics roots**
   - Phenomenological, lacking physics roots (Dark Matter, Dark Energy, etc). It would be surprising if its exact too

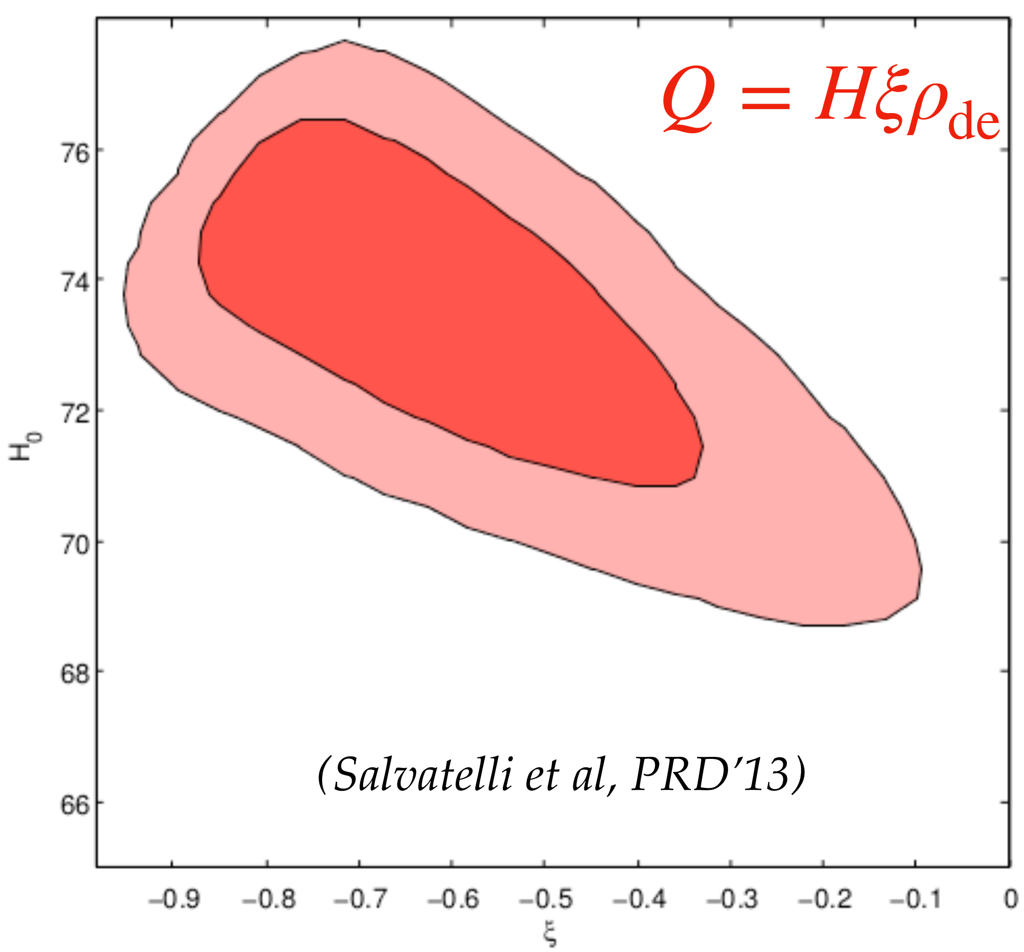
Interacting dark energy and the Hubble constant tension

Di Valentino, Melchiorri and Mena PRD'17

Coupled cosmologies predict a mismatch between high and low redhsift H_0 measurements.

One of the most simplest scenarios is able to alleviate the issue





(Salvatelli et al, PRD'13)

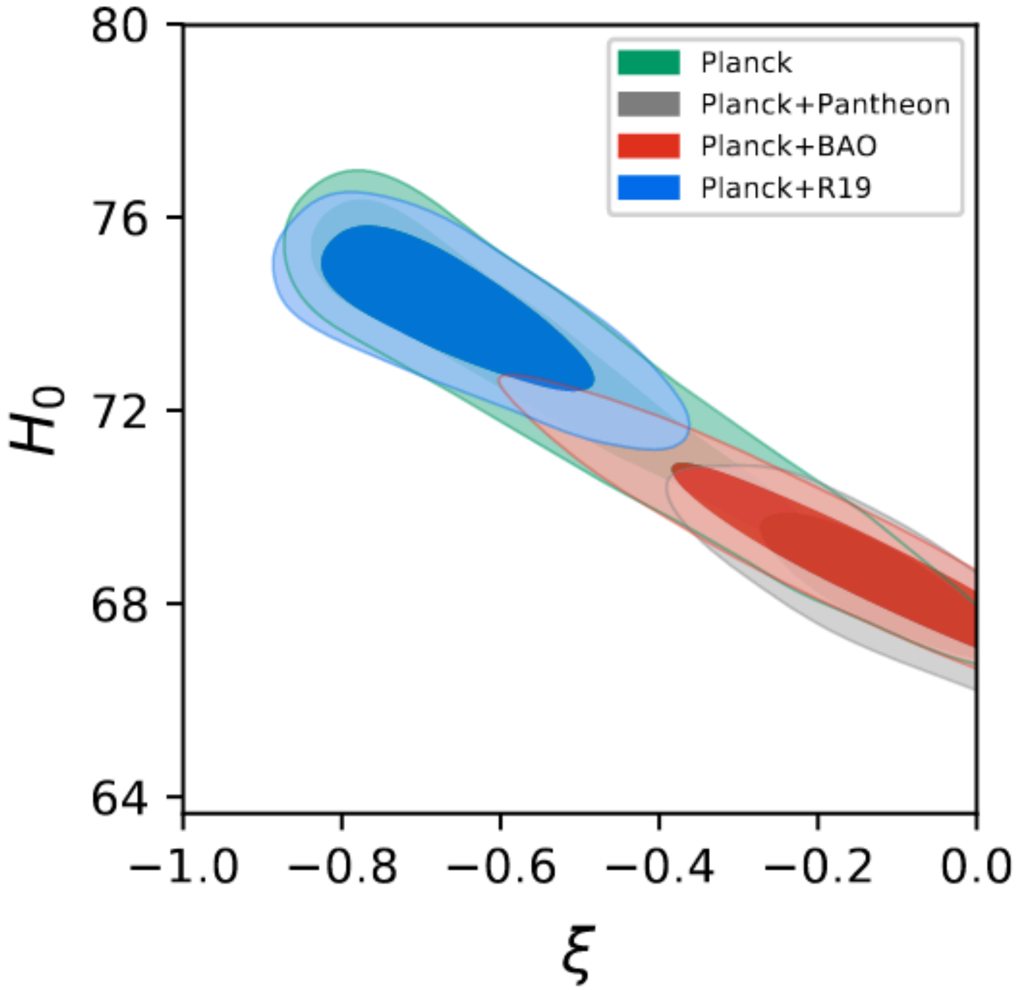
R16 $H_0 = 73.20 \pm 1.74$ km/s/Mpc

R19 $H_0 = 74.03 \pm 1.42$ km/s/Mpc

Interacting dark energy and the Hubble constant tension

Strong degeneracy between ξ and H_0!

$\xi\Lambda CDM$



Di Valentino et al PDU'20

Dataset	$\xi\Lambda$CDM	ξqCDM	ξpCDM
Planck	0.4σ	1.0σ	0.5σ
Planck+R19	$< 0.1\sigma$	0.4σ	$< 0.1\sigma$
Planck+lensing	0.4σ	1.0σ	2.1σ
Planck+BAO	2.7σ	2.7σ	2.9σ
Planck+Pantheon	3.3σ	3.3σ	3.3σ
All19	2.5σ	2.7σ	2.7σ

Di Valentino et al PRD'20

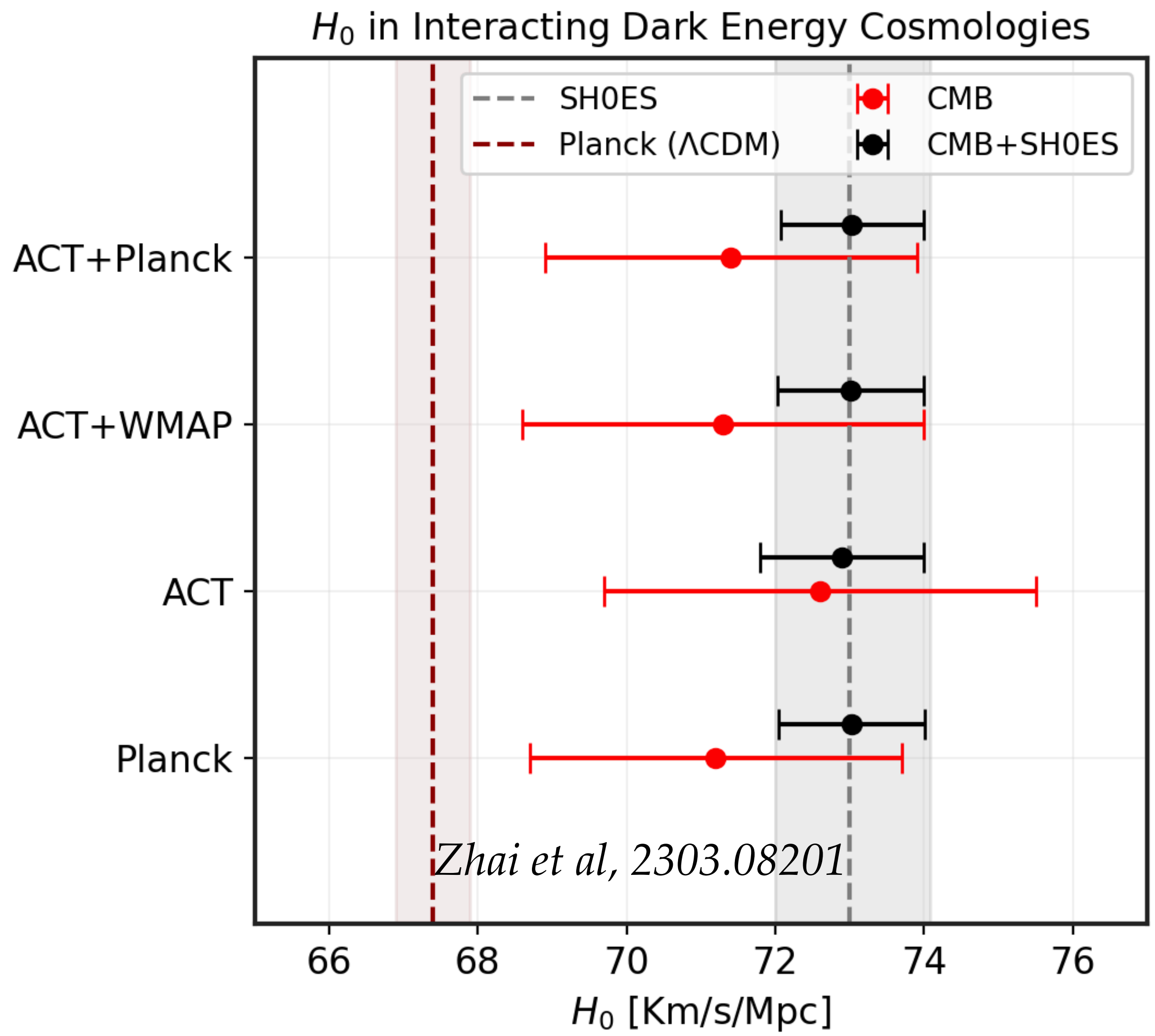
Interacting dark energy and the Hubble constant tension

For all the CMB data sets explored, the mean value of H_0 is much larger, and the significance of the H_0 tension is therefore strongly reduced.

In addition it is led by the shift in the mean value of H_0 and not by the larger size of the errors.

Model-comparison results to negative values of the Bayes factor: tendency from current CMB measurements towards an IDE cosmology.

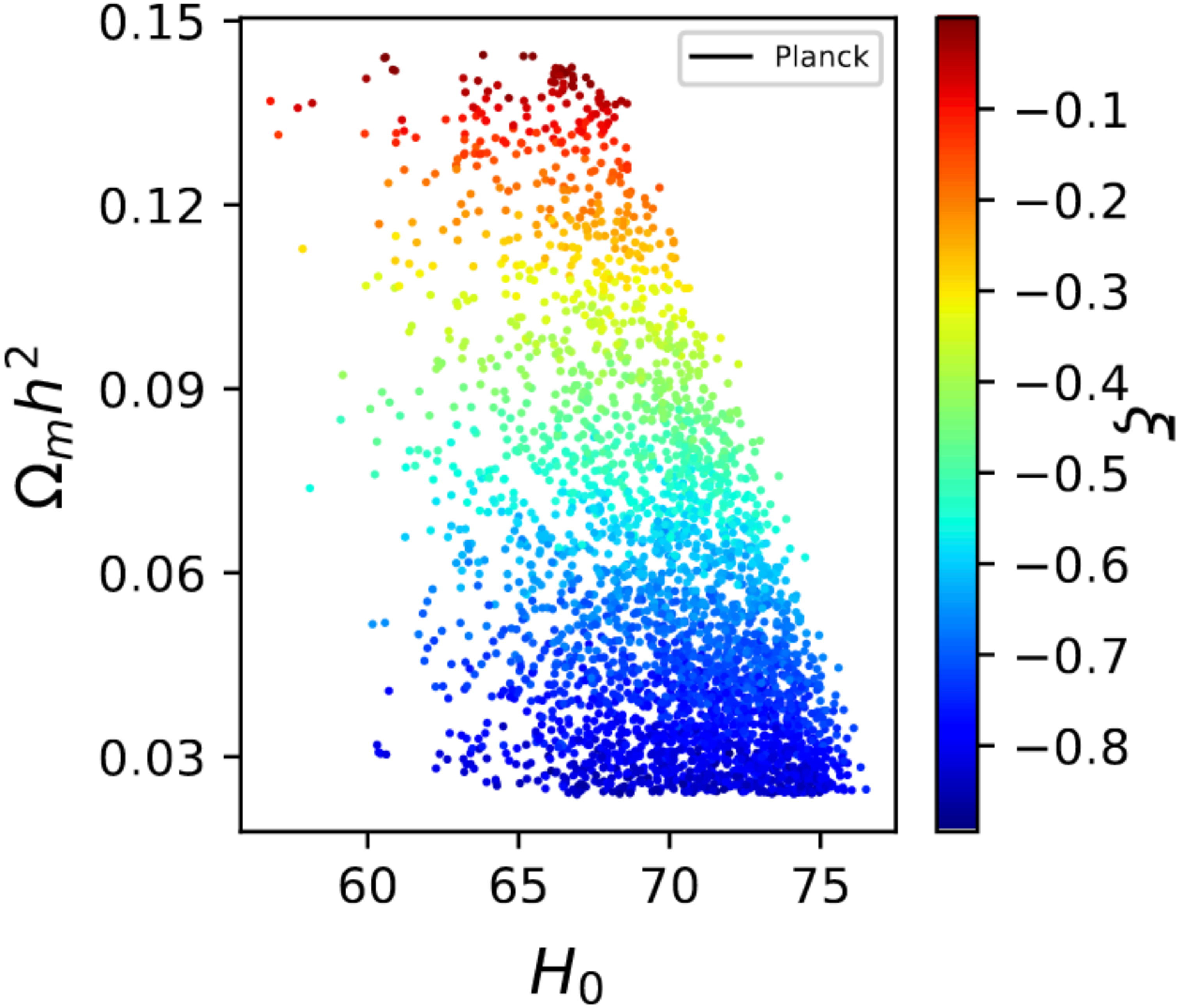
Such a preference could potentially improve with future CMB observations.



Interacting dark energy and the Hubble constant tension

Smaller amount of Ω_m is translated into a larger value of H_0

$$\rho_c = \frac{\rho_c^0}{a^3} + \frac{\rho_x^0}{a^3}\left[\frac{\xi}{3w+\xi}\left(1 - a^{-3w-\xi}\right)\right]$$

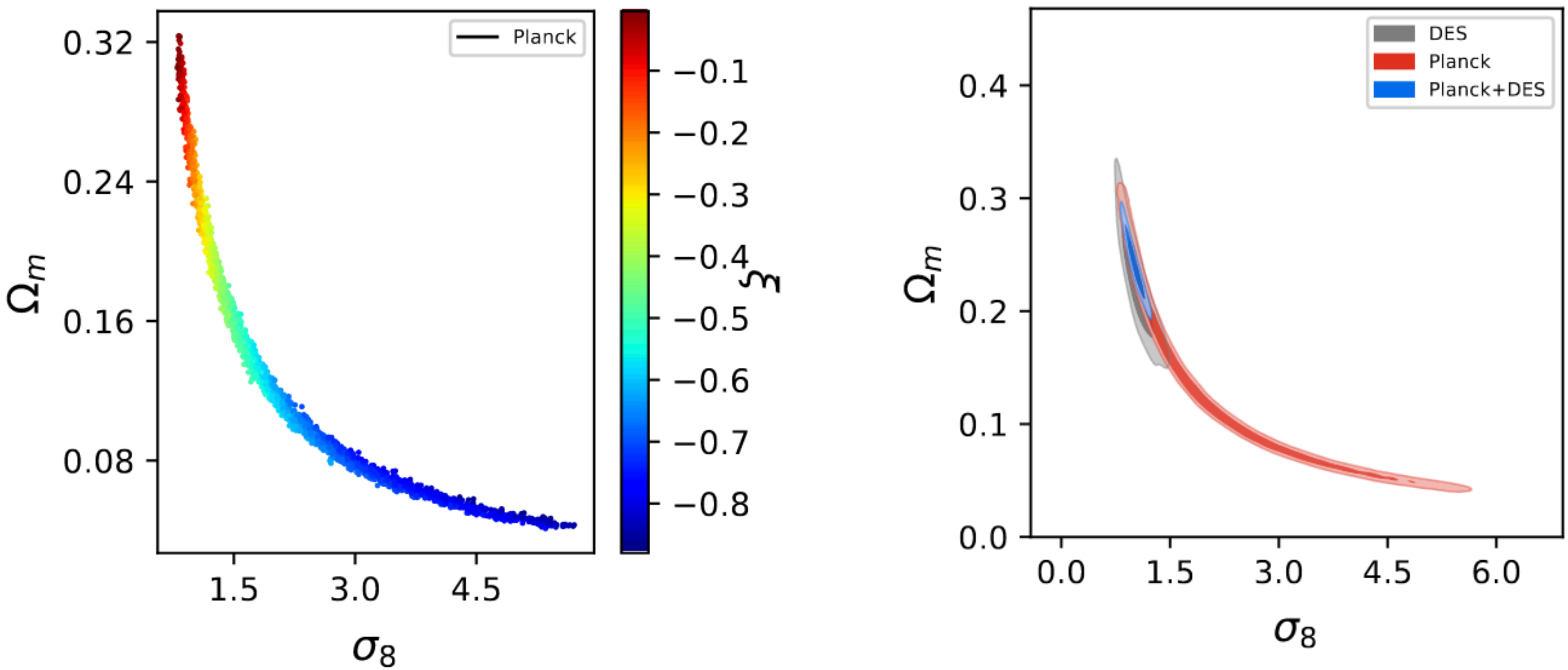


$$Q = H\xi\rho_{\rm de}$$

Interacting dark energy and the Hubble constant tension

Also alleviates other tensions!

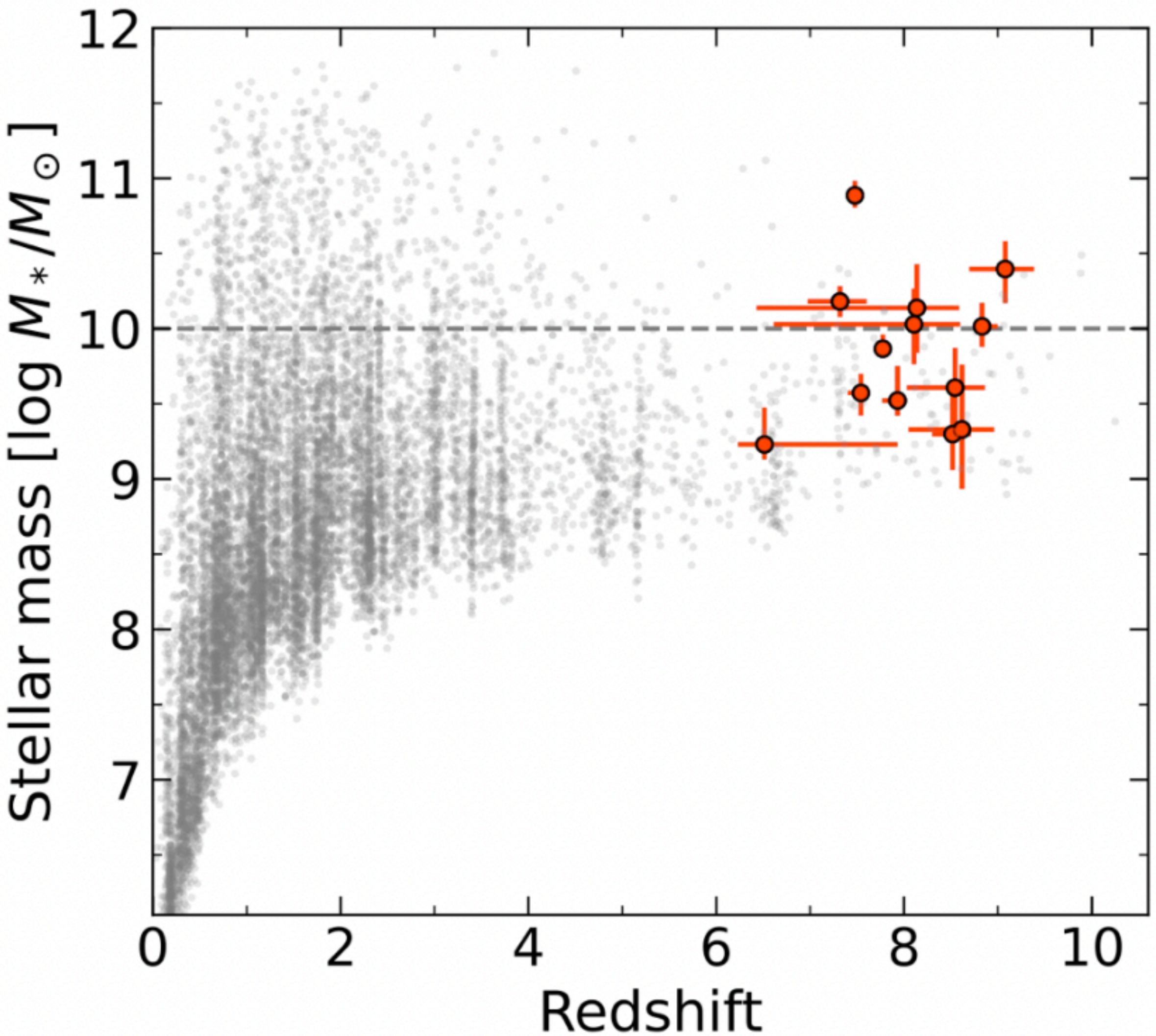
Improved overlap between the Planck and DES allowed regions in $\xi\Lambda CDM$

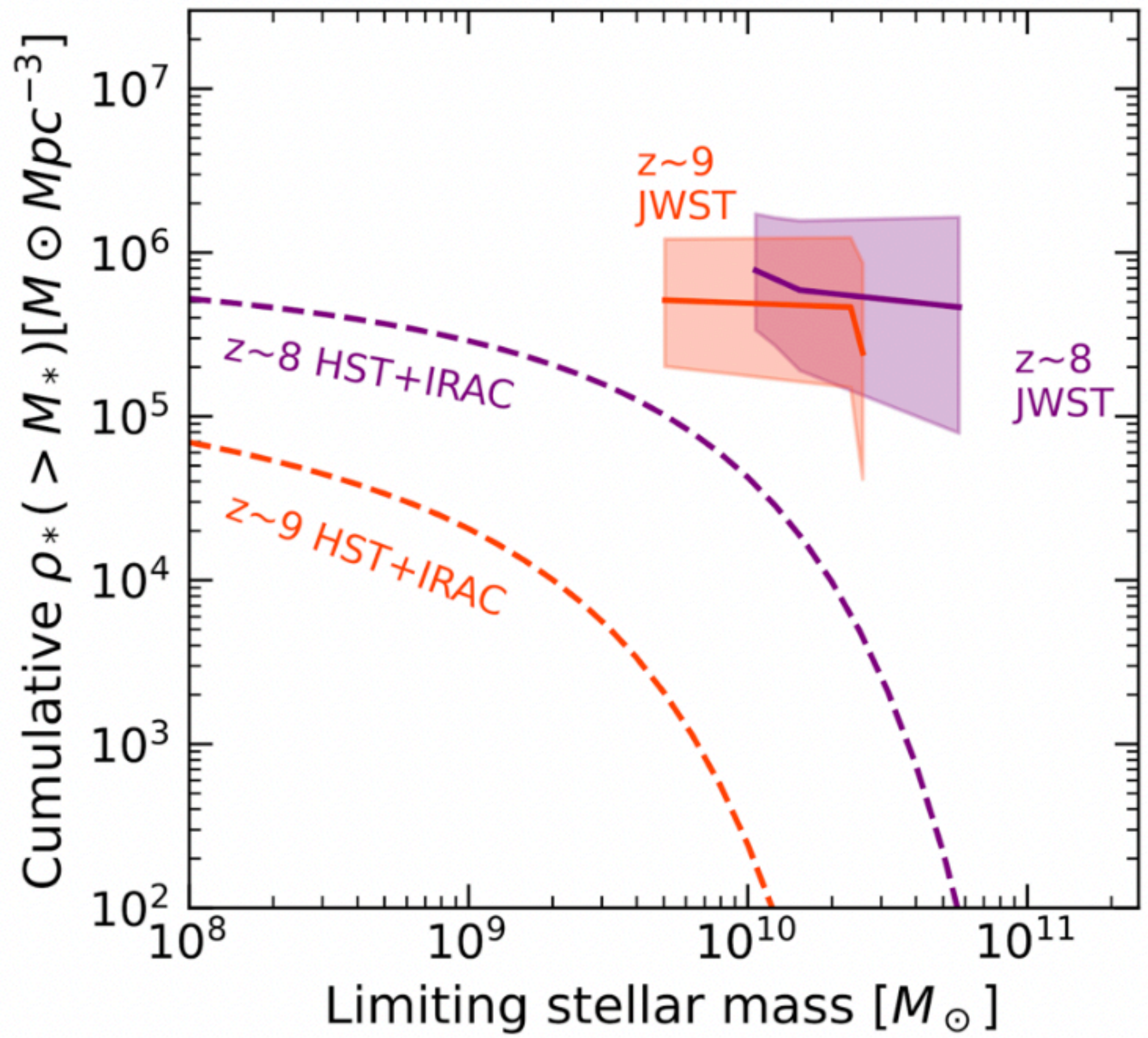


Di Valentino et al PDU'20

Is interacting dark energy the panacea for all tensions?

First James Webb Space Telescope images show that massive galaxy formation began extremely early. The stellar mass density in massive galaxies is much higher than anticipated from previous studies based on rest-frame UV-selected samples: a factor of 10 − 30 at z ~ 8 and more than three orders of magnitude at z ~ 10! Structure formation predicted by the ΛCDM framework must be enhanced!





Labbe et al'22

These results imply that the central regions of massive galaxies began forming very early in processes different from the gradual build-up of the rest of the galaxy population!

Is interacting dark energy the panacea for all tensions?

Has dark energy something to do with this?

Labbe et al'22

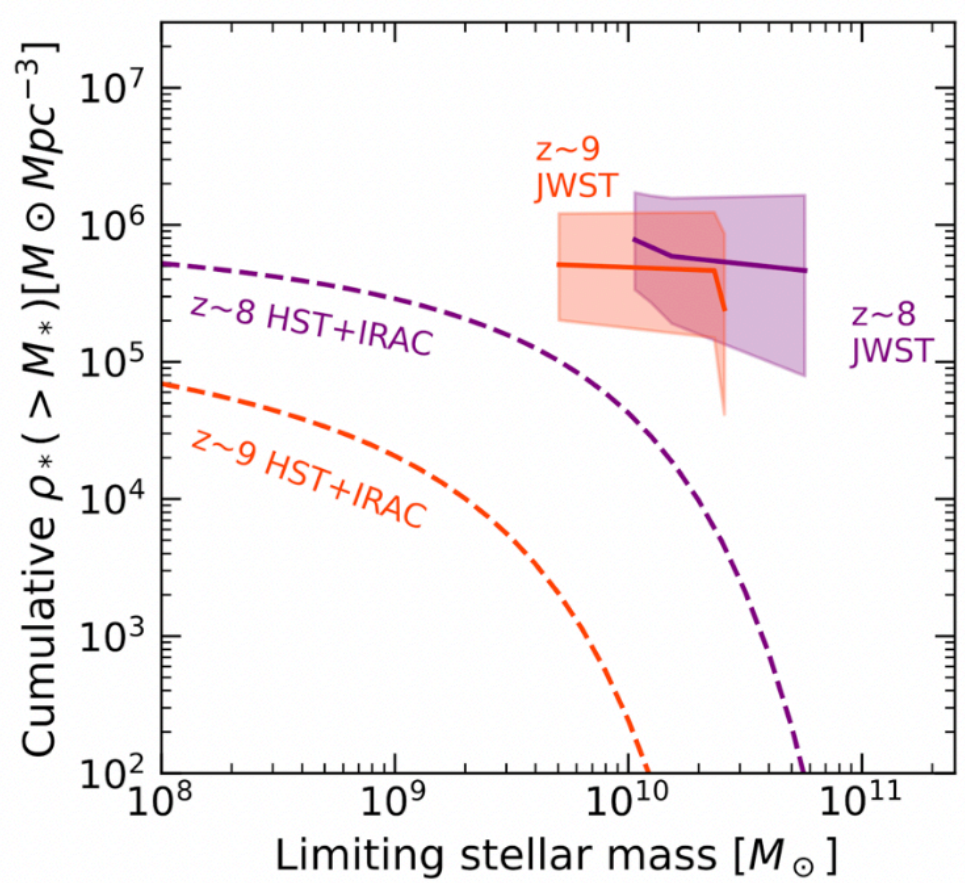
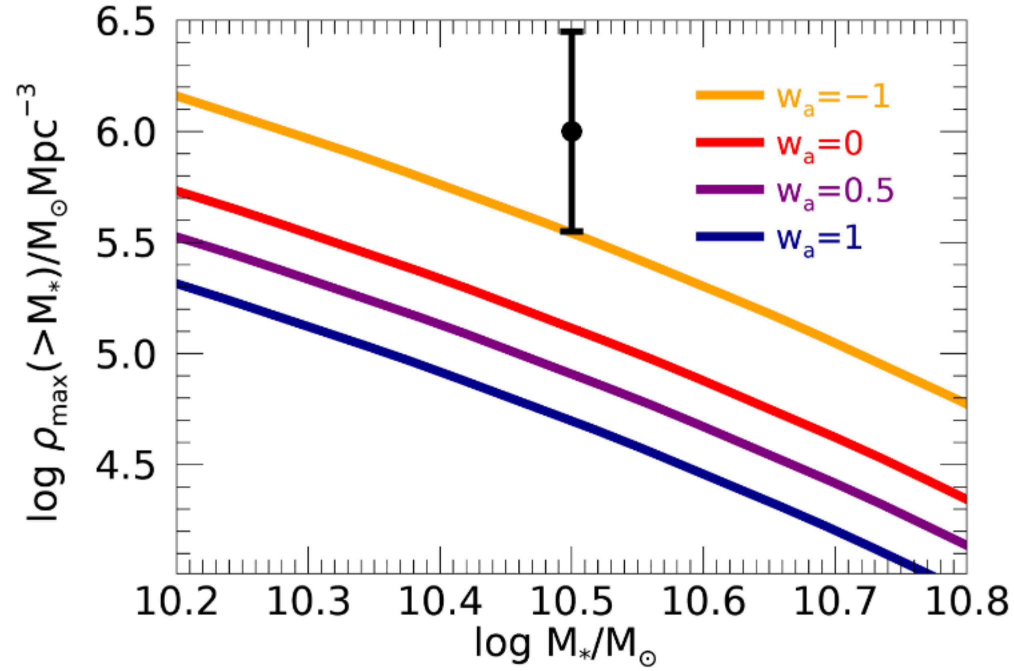
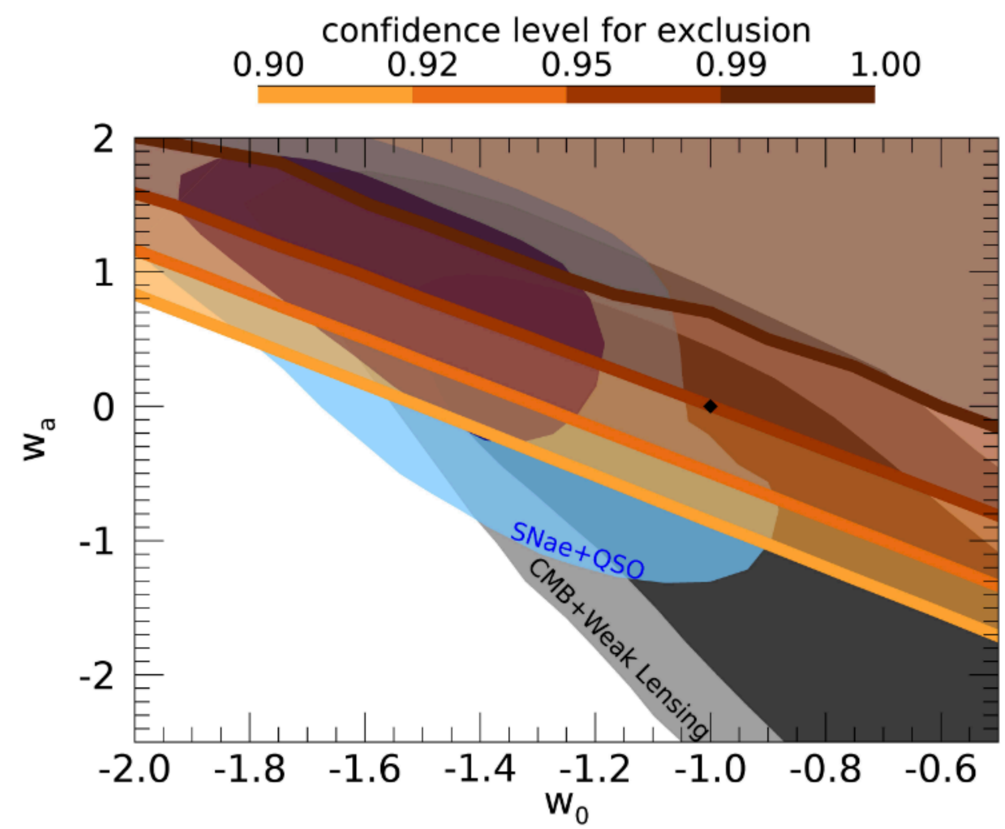


Figure 4: **Cumulative stellar mass density, if the fiducial masses of the *JWST*-selected red galaxies are confirmed.** The solid symbols show the total mass density in two redshift bins, $7 < z < 8.5$ and $8.5 < z < 10$, based on the three most massive galaxies in each bin. Uncertainties reflect Poisson statistics and cosmic variance. The dashed lines are derived from Schechter fits to UV-selected samples.[3] The *JWST*-selected galaxies would greatly exceed the mass densities of massive galaxies that were expected at these redshifts based on previous studies. This indicates that these studies were highly incomplete or that the fiducial masses are overestimated by a large factor.



Menci et al'22



Is interacting dark energy the panacea for all tensions?

Structure formation enhanced to that predicted within the ΛCDM framework

IF $Q \propto \rho_{\rm dm}$: the difference with non-interacting cosmologies arise exclusively due to the different background evolution of the quantities H and $\Omega_{\rm dm}$. The growth equation is not modified but the scaling with redshift of $\rho_{\rm dm}$ is different from that of a conserved pressureless fluid. These models are effectively indistinguishable from minimally coupled dark energy models with a w(z) and may or not be able to solve the JWST tension.

$$\delta''_\alpha = -(2-q)\frac{\delta'_\alpha}{a} + \frac{3}{2}\left(\Omega_{\rm dm}\frac{\delta_{\rm dm}}{a^2} + \Omega_{\rm b}\frac{\delta_{\rm b}}{a^2}\right)$$

IF $Q \propto \rho_{\rm de}$: for negative coupling ξ, the Hubble friction term B is suppressed and the A contribution to the source term in enhanced. This implies that the dark matter growth will be larger than in uncoupled models. More generally, this feature is valid for any coupled model in which Q is directly proportional to the dark energy density and $Q/\rho_{\rm de}$ is negative.

Highly promising!

$$\delta''_{\rm dm} = -B\frac{\delta'_{\rm dm}}{a} + \frac{3}{2}\left(A\Omega_{\rm dm}\frac{\delta_{\rm dm}}{a^2} + \Omega_{\rm b}\frac{\delta_{\rm b}}{a^2}\right)$$

$$B = 2 - q + (2-b)\xi\frac{\rho_{\rm de}}{\rho_{\rm dm}}\ ,$$

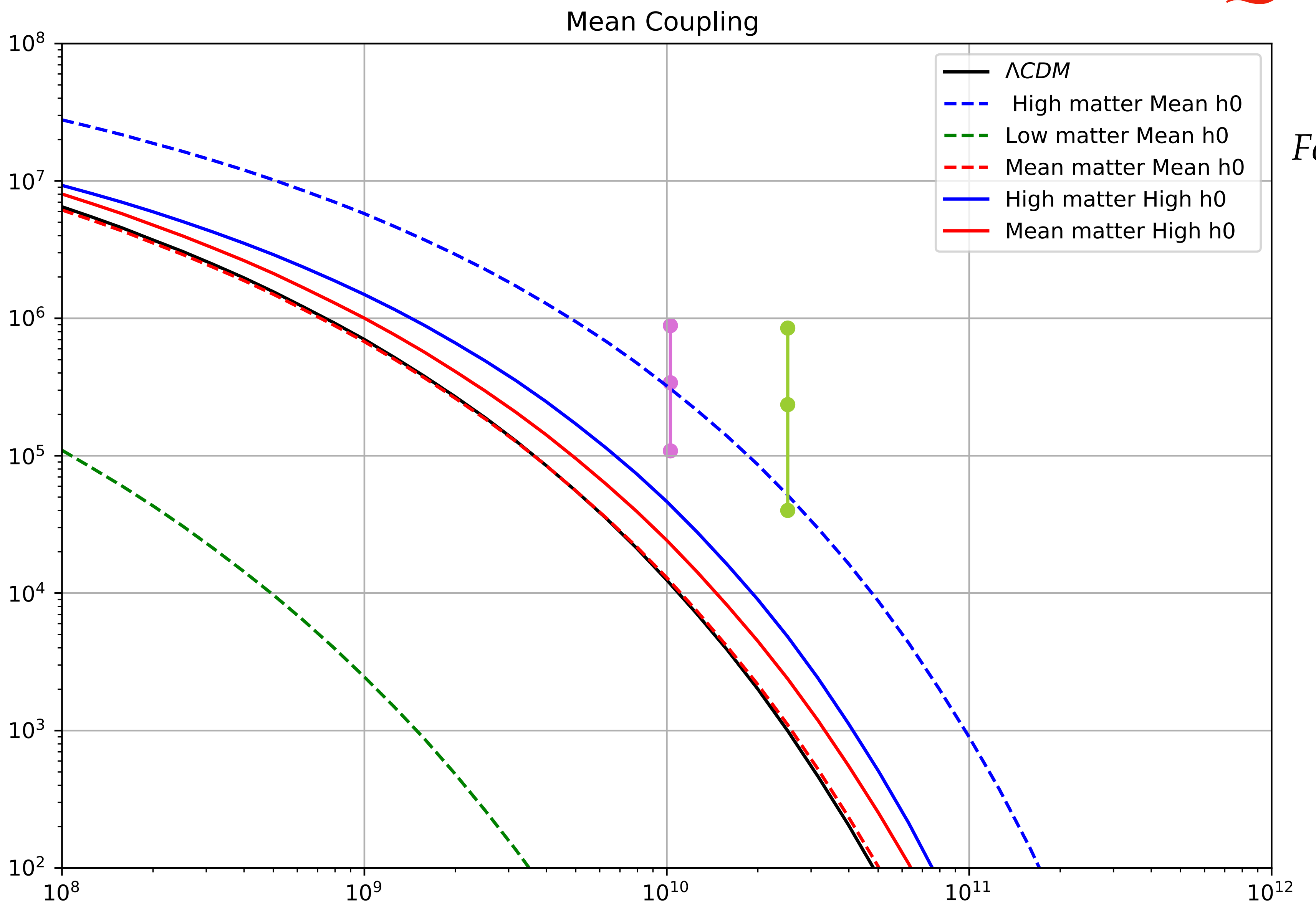
$$A = 1 + \frac{2}{3}\frac{1}{\Omega_{\rm dm}}\frac{\rho_{\rm de}}{\rho_{\rm dm}}\left[-\xi\left(1-q-3w\right) + \xi^2\left(\frac{\rho_{\rm de}}{\rho_{\rm dm}} + 1\right)\right]$$

Honorez et al JCAP'10

Is interacting dark energy the panacea for all tensions?

Structure formation is more enhanced than predicted by the ΛCDM framework!

$$Q = H\xi\rho_{\rm de}$$

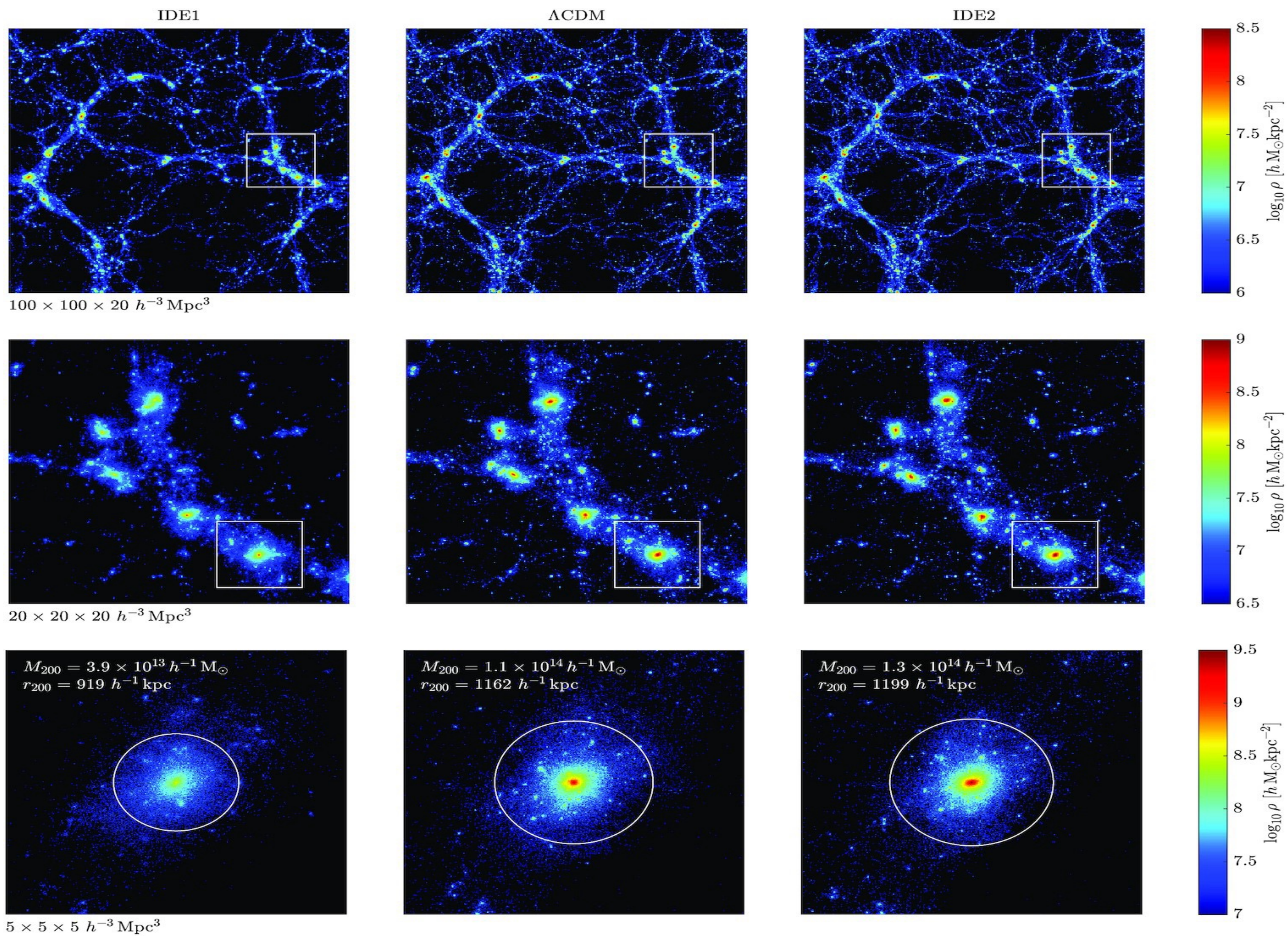


Forconi et al, JCAP'24

Highly promising!

Liu et al, MNRAS'22

Figure 2. Contrasts on the z = 0 cosmic structures in IDE1 (left column), ΛCDM (middle column), and IDE2 (right column) ...

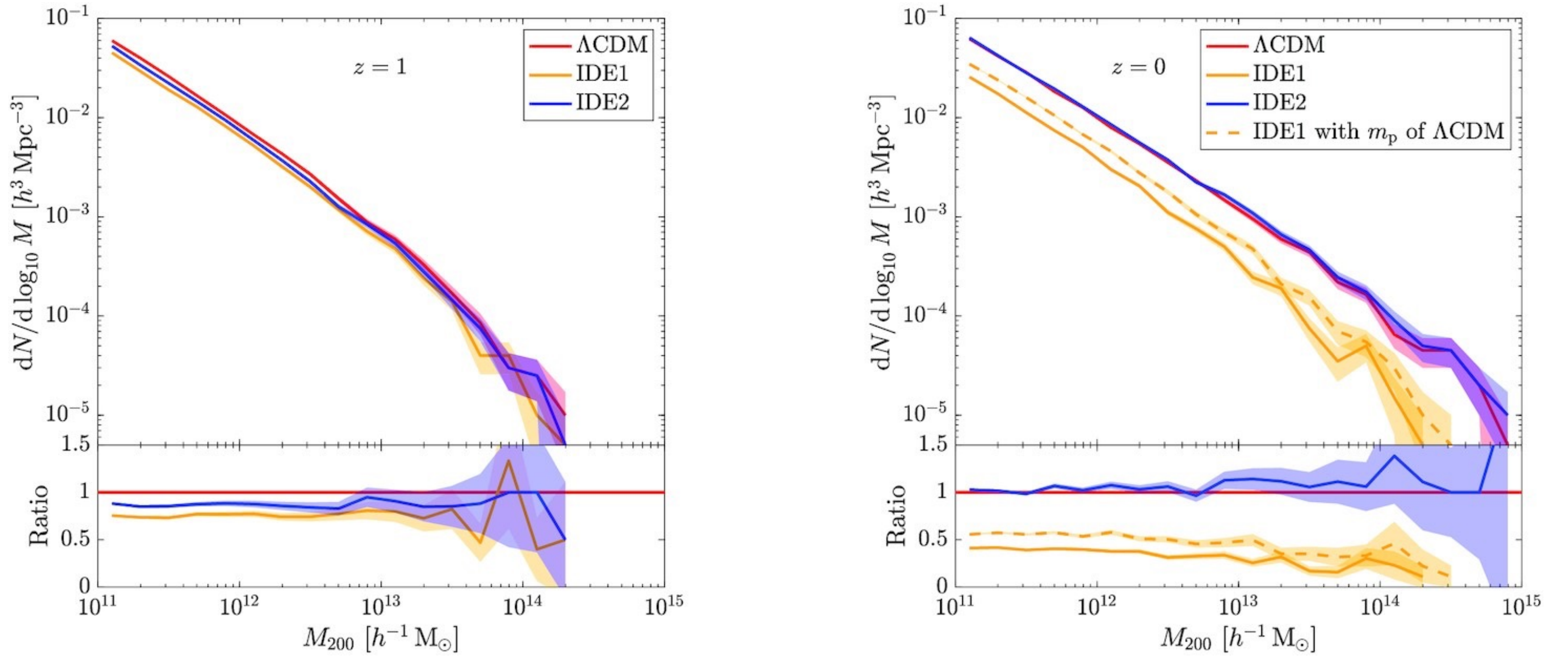


Mon Not R Astron Soc, Volume 511, Issue 2, April 2022, Pages 3076–3088, https://doi.org/10.1093/mnras/stac229

N-body simulations confirm this hypothesis

Liu et al, MNRAS'22

Figure 4. Halo mass functions at z = 1 (left) and z = 0 (right) in ΛCDM (red), IDE1 (yellow solid), and IDE2 (blue) ...



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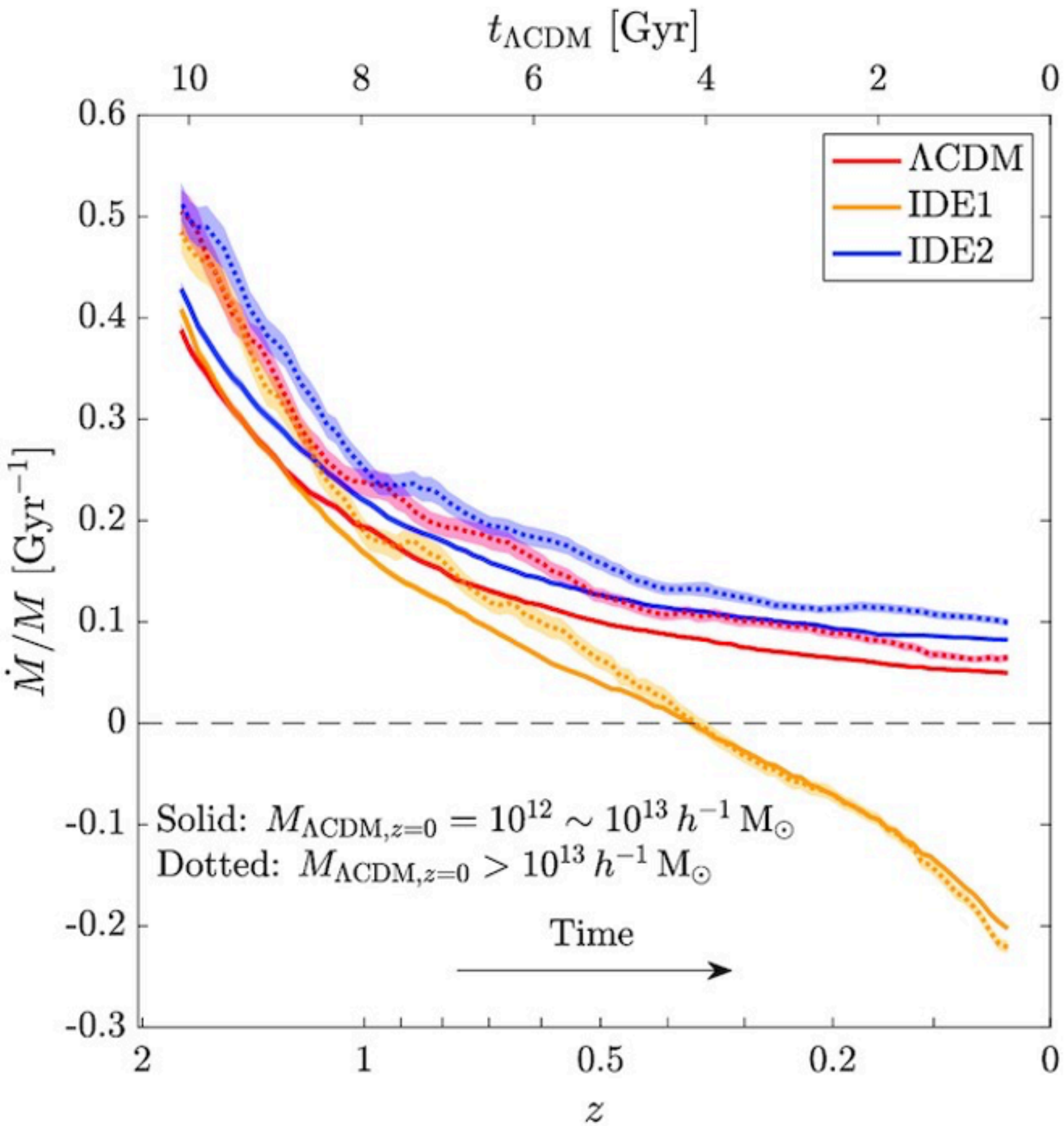
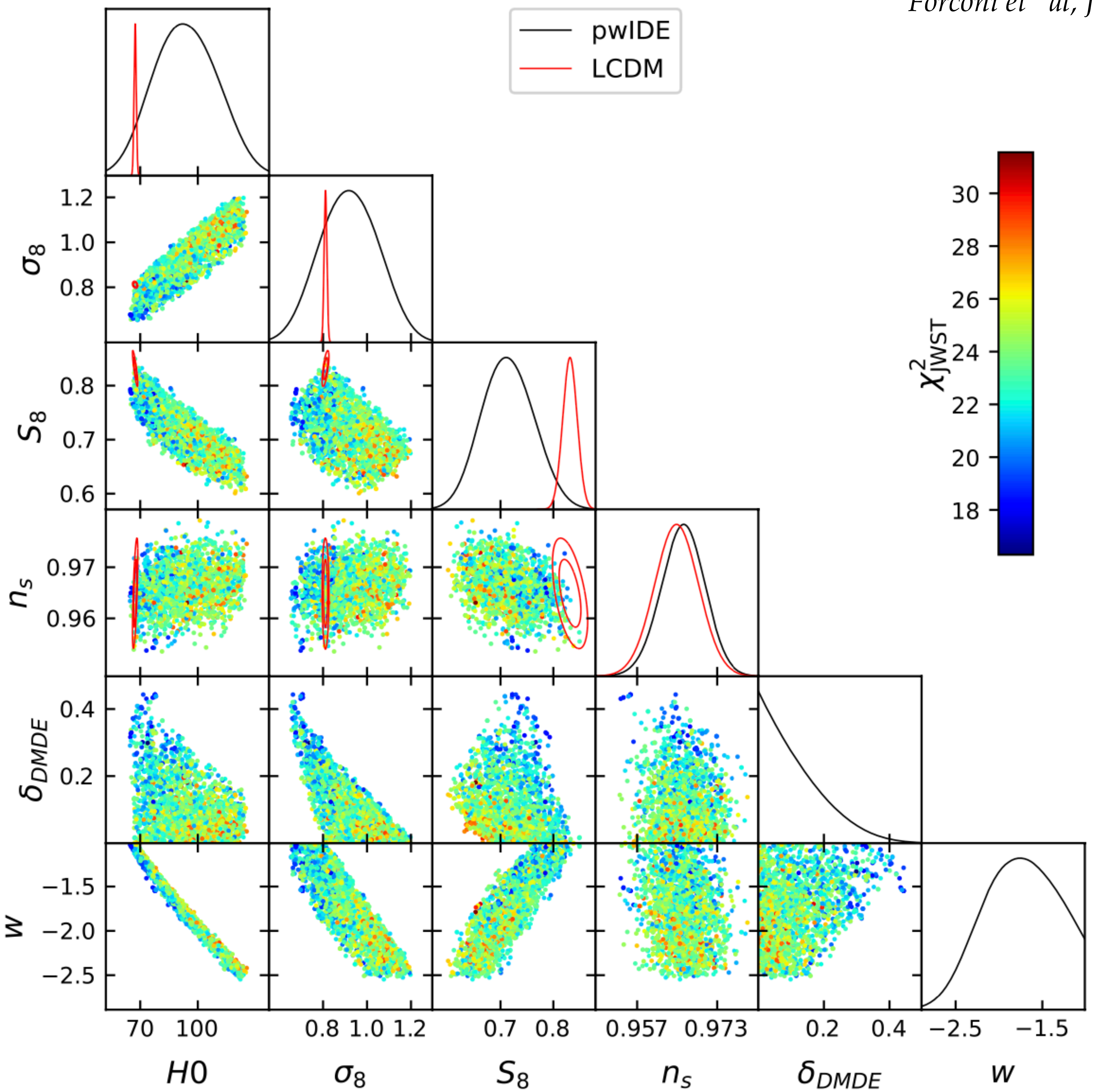
N-body simulations confirm this hypothesis: Halo growth history



Liu et al, MNRAS'22

Forconi et al, JCAP'24



Forconi et al, JCAP'24

Parameter	CMB		JWST-CEERS	CMB+JWST
n_s	0.9663	$z_{\rm low}$	0.963	0.969
		$z_{\rm high}$	0.967	0.969
H_0	103.8	$z_{\rm low}$	67.10	75.62
		$z_{\rm high}$	73.88	75.62
σ_8	1.026	$z_{\rm low}$	0.685	0.760
		$z_{\rm high}$	0.739	0.760
τ	0.05087	$z_{\rm low}$	0.0612	0.0617
		$z_{\rm high}$	0.0644	0.0617
Ω_m	0.139	$z_{\rm low}$	0.396	0.292
		$z_{\rm high}$	0.319	0.292
ξ	0.05235	$z_{\rm low}$	0.374	0.229
		$z_{\rm high}$	0.299	0.229
w	-2.0436	$z_{\rm low}$	-1.149	-1.33
		$z_{\rm high}$	-1.33	-1.33
χ^2	2767	$z_{\rm low}$	10.8	2783.90 (2771 + 12.90)
		$z_{\rm high}$	16.3	2790.15 (2771 + 19.15)

$$\chi^2(\Lambda CDM) \simeq 17$$

- Coupled cosmologies: the landscape
- Coupled cosmologies and cosmological tensions
- ☛ Constraints from redshift space distortions
- Summary and ideas for future work and collaborations

Redshift Space Distortions (Kaiser, 1987)

Hubble's (1929) law states that the recession velocity cz of a galaxy is proportional to its distance $cz = H_0 d$. The recession velocity cz of a galaxy can be measured from the redshift z of its spectrum.
This has been a primary motivation for redshift surveys.

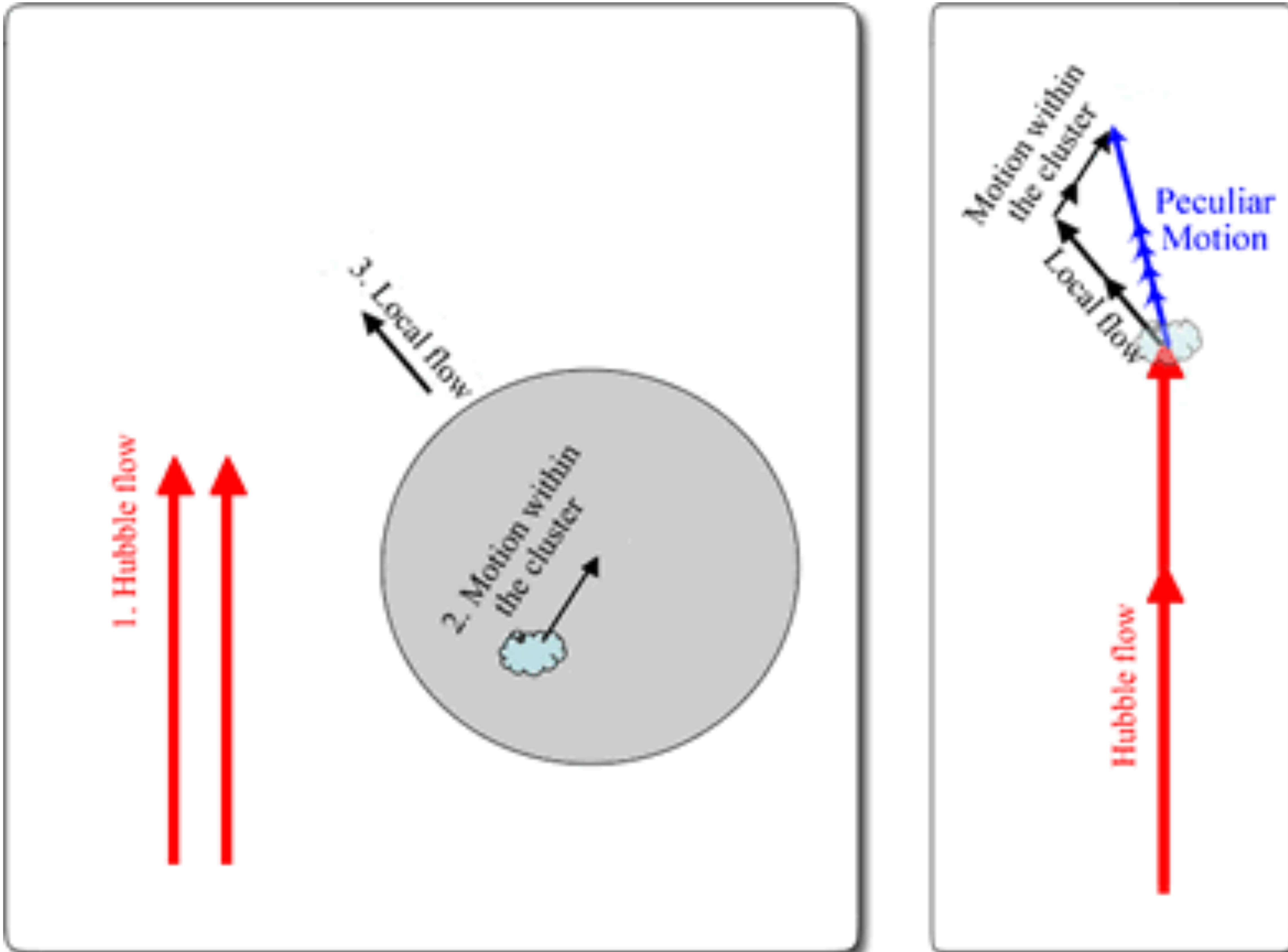
Hubble's law is not perfect, however!

Galaxies have peculiar velocities v relative to the general Hubble expansion: it is necessary in general to distinguish between a galaxy's redshift distance $s \equiv cz$ and its true distance $r \equiv H_0 d$.

The redshift distance s of a galaxy differs from the true distance r by its peculiar velocity along the line of sight:

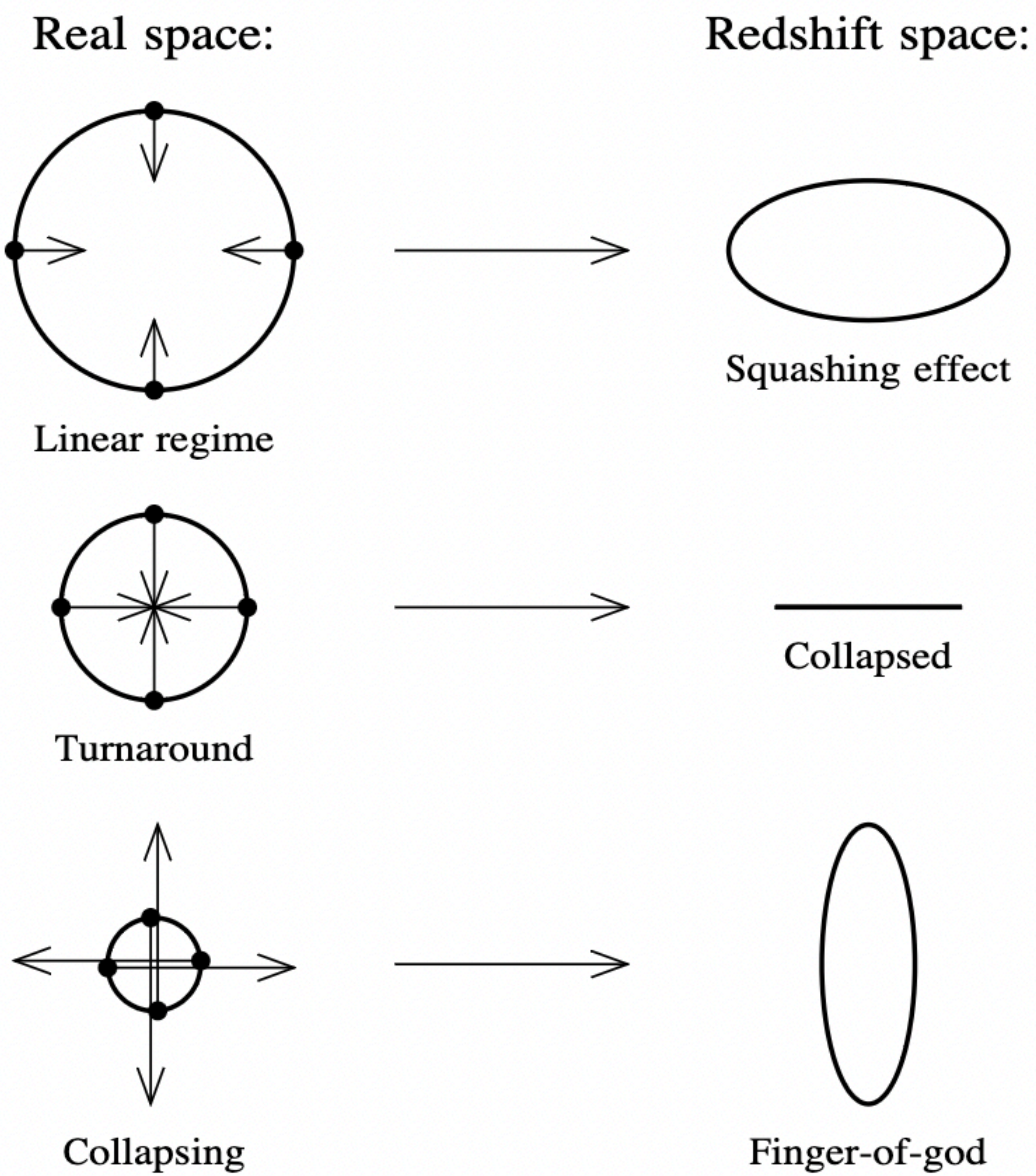
$s = r + v$

The peculiar velocities of galaxies thus cause them to appear displaced along the line of sight in redshift space. These displacements lead to redshift distortions in the pattern of clustering of galaxies in redshift space.



1. Hubble flow
3. Local flow
2. Motion within the cluster
Motion within the cluster
Peculiar Motion
Local flow
Hubble flow

Redshift Space Distortions (Kaiser, 1987)



Although such distortions complicate the interpretation of redshift maps as positional maps, they have the tremendous advantage of bearing information about the dynamics of galaxies.

In particular, the amplitude of distortions on large scales yields a measure of the linear redshift distortion, which is related to the growth of structure, modified in coupled dark matter-dark energy models!

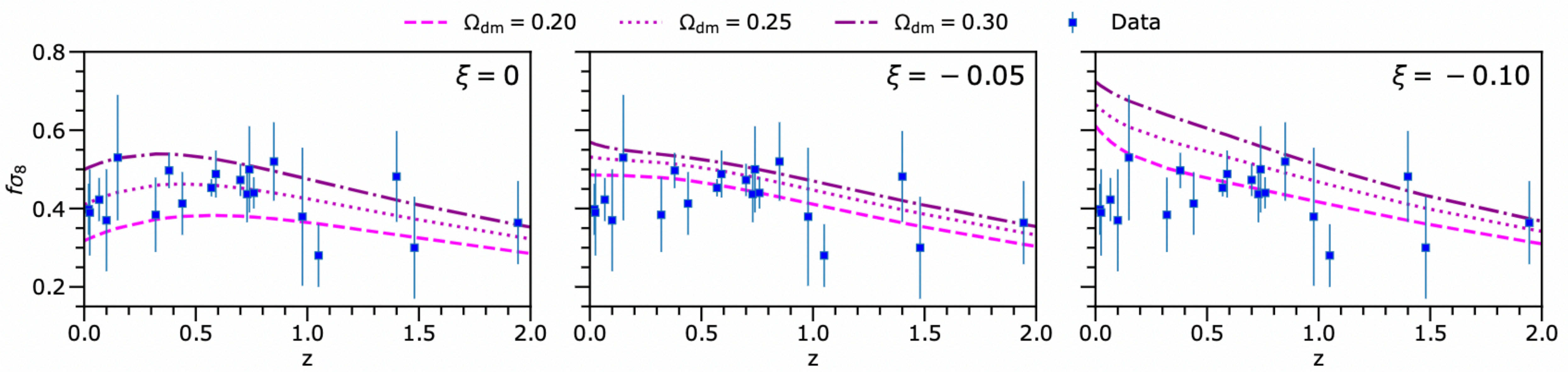
$$P_{gal}(k) = P_m(b^2 + f\mu^2)^2$$

$$f \equiv \frac{d\ln\delta(a)}{d\ln a} \qquad f \equiv \Omega_{\mathrm{m}}(a)^\gamma$$

$$\gamma \simeq 0.55$$

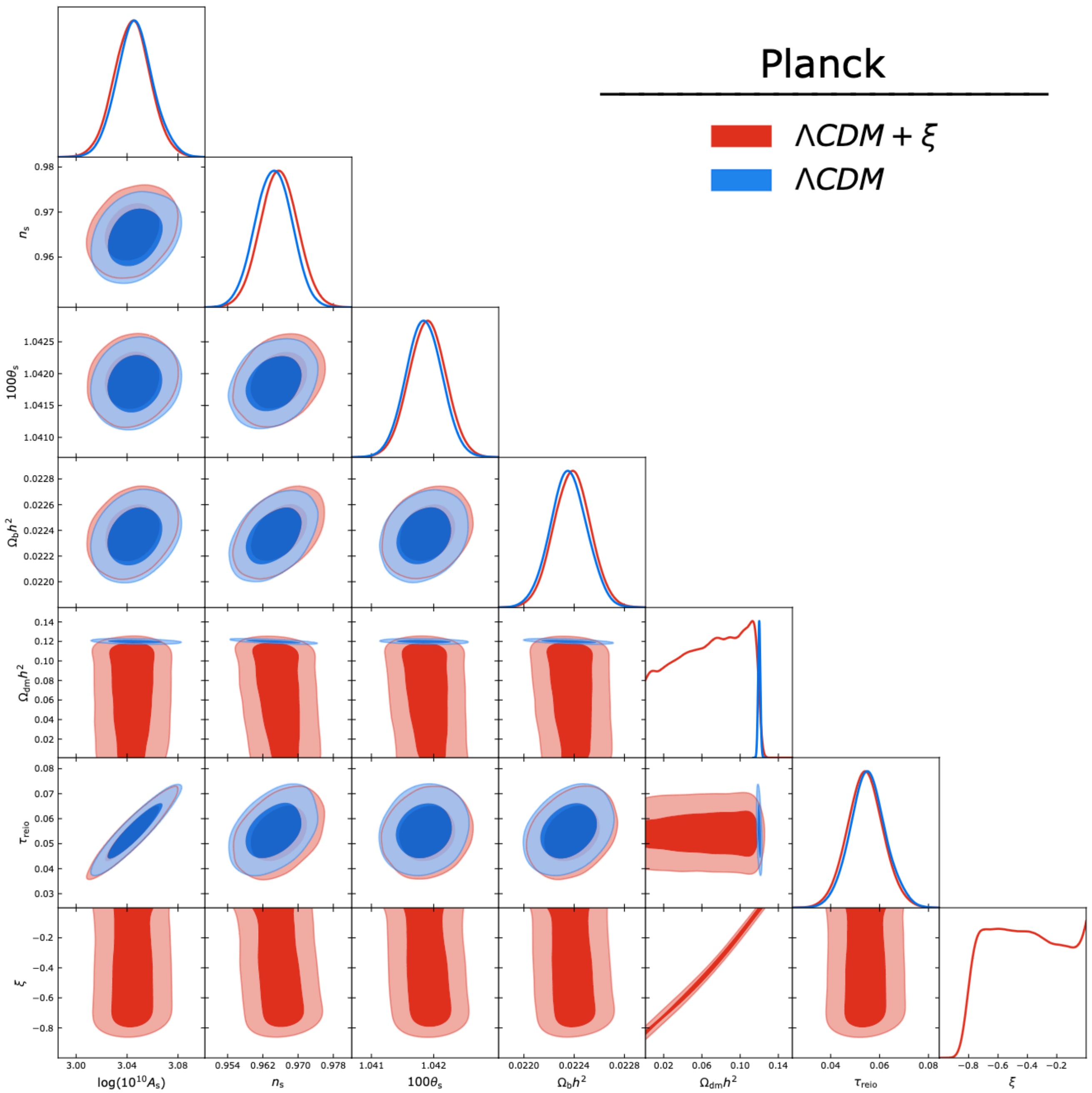
$$f \equiv \frac{d\ln\delta_{\rm dm}}{d\ln a} = \frac{\delta'_{\rm dm}}{\delta_{\rm dm}}a \qquad \sigma_R^2 = \frac{1}{2\pi^2}\int_0^\infty P(k,z)W_R^2(k)dk$$

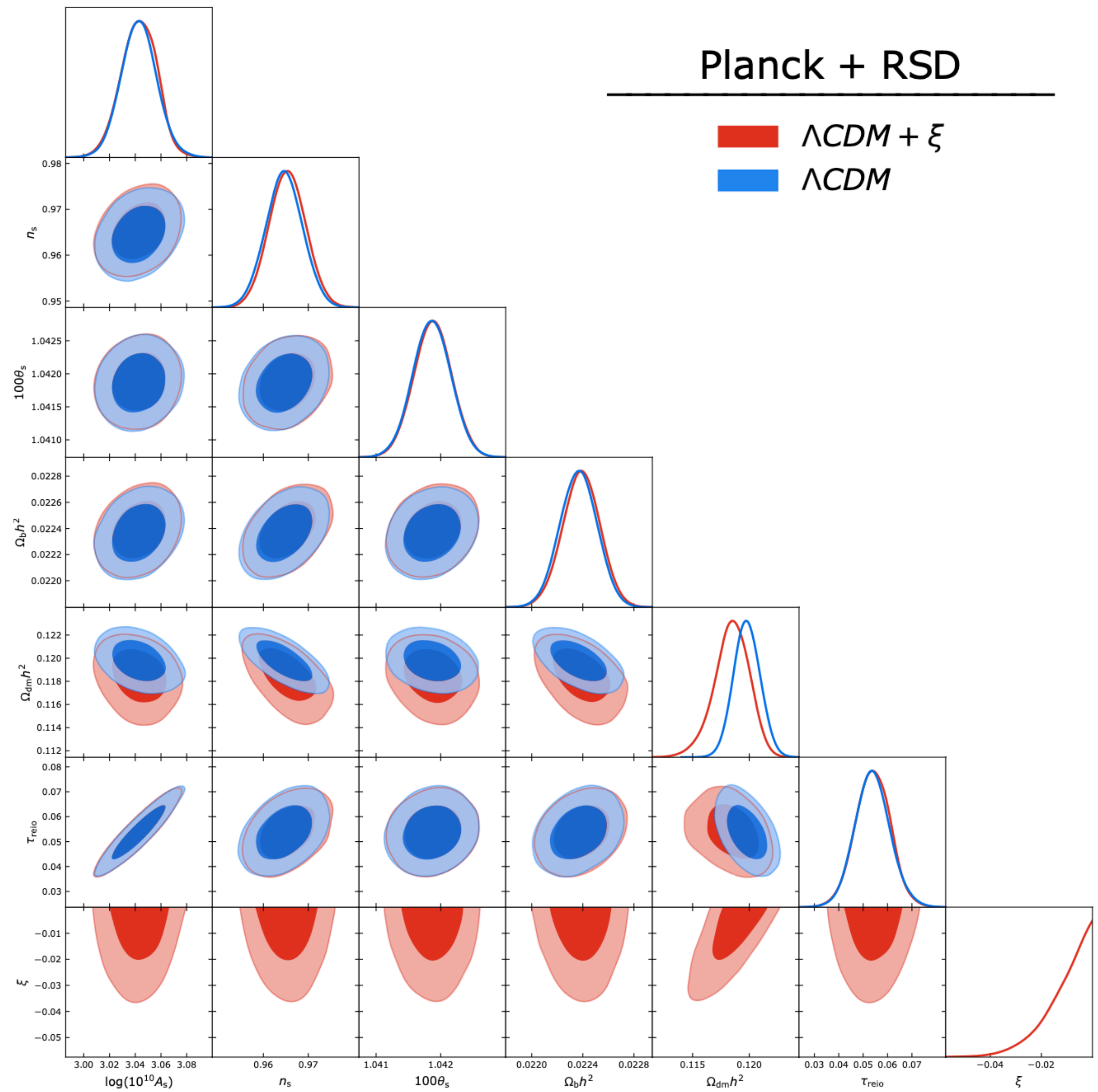
Survey	z	$f\sigma_8$	**Reference**	**Cosmological tracer**
SnIa + IRAS	0.02	0.398 ± 0.065	[132]	SNIa + galaxies
6dFGS	0.025	0.39 ± 0.11	[133]	void
6dFGS	0.067	0.423 ± 0.055	[134]	galaxies
SDSS-veloc	0.10	0.37 ± 0.13	[135]	DR7 galaxies
SDSS-IV	0.15	0.53 ± 0.16	[136]	eBOSS DR16 MGS
BOSS-LOWZ	0.32	0.384 ± 0.095	[137]	DR10, DR11
SDSS-IV	0.38	0.497 ± 0.045	[136]	eBOSS DR16 galaxies
WiggleZ	0.44	0.413 ± 0.080	[138]	LRG & bright emission-line galaxies
CMASS-BOSS	0.57	0.453 ± 0.022	[139]	DR12 voids + galaxies
SDSS-CMASS	0.59	0.488 ± 0.060	[140]	DR12
SDSS-IV	0.70	0.473 ± 0.041	[136]	eBOSS DR16 LRG
WiggleZ	0.73	0.437 ± 0.072	[138]	bright emission-line galaxies
SDSS-IV	0.74	0.50 ± 0.11	[141]	eBOSS DR16 voids
VIPERS v7	0.76	0.440 ± 0.040	[142]	galaxies
SDSS-IV	0.85	0.52 ± 0.10	[141]	eBOSS DR16 voids
SDSS-IV	0.978	0.379 ± 0.176	[143]	eBOSS DR14 quasars
VIPERS v7	1.05	0.280 ± 0.080	[142]	galaxies
FastSound	1.40	0.482 ± 0.116	[144]	ELG
SDSS-IV	1.48	0.30 ± 0.13	[141]	eBOSS DR16 voids
SDSS-IV	1.944	0.364 ± 0.106	[143]	eBOSS DR14 quasars



Ghedini et al, PDU'24

Ghedini et al, PDU'24





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Tendency from ALL current CMB measurements favouring an IDE cosmology.

IDE cosmologies are able to alleviate the Hubble constant tension.
A phantom closed universe also solves the issue.

Simplest model compromised by RSD observations. Other models still allowed though!

Larger growth of structure in EDE/IDE cosmologies may provide a compelling solution to early massive galaxy formation from JWST first results.


ngiyabonga
danke
謝謝
spas
teşekkür ederim
Баярлалаа
mersi
kia ora
barka
welalin
tack
mahalo
спасибо
faafetai lava
vinaka
спасибі
blagodaram
dank je
misaotra
matondo
paldies
grazzi
kiitos
dankie
nanni
nandri
dhanyavad
thank you
gracias
хвала
asante
manana
mauruuru
köszönöm
aciú
dankon
akun
obrigada
tenki
murakoze
bedankt
bayarlalaa
gràçie
hvala
enkosi
djiere dieuf
tau
mochchakkeram
дякую
mamnun
dziękuję
chnorakaloutioun
gratias ago
gràcies
sulpáy
go raibh maith agat
chokrane
sobodi
děkuji
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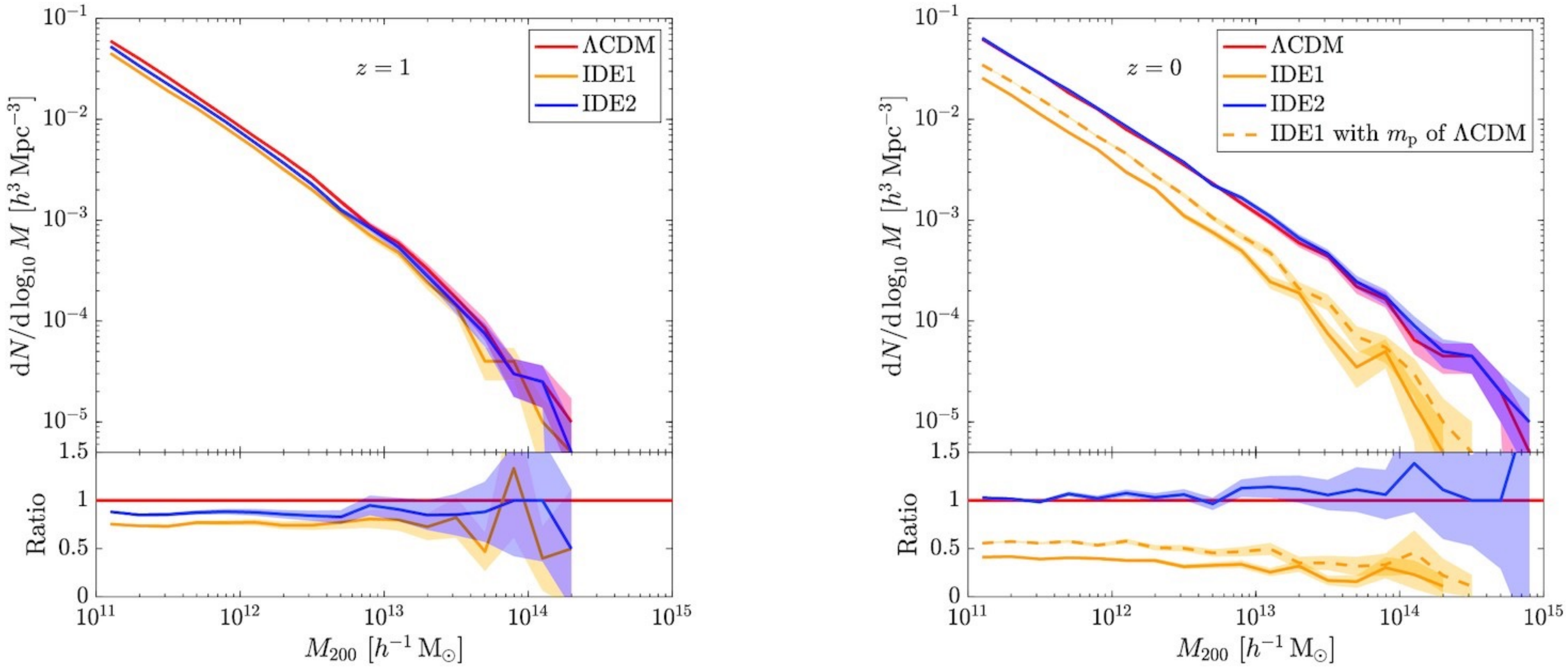
taiku
sukriya
kop khun krap
obrigado
mèsi
didi madloba
najis tuke
ありがとう
tanemirt
grazie
arigatô
takk
dakujem
trugarez
kam sah hamnida
rahmat
terima kasih
rahmet
diolch
dhanyavadagalu
shukriya
mercé
мерси
তোমাকে ধন্যবাদ
감사합니다
xièxie
ευχαριστώ
merci

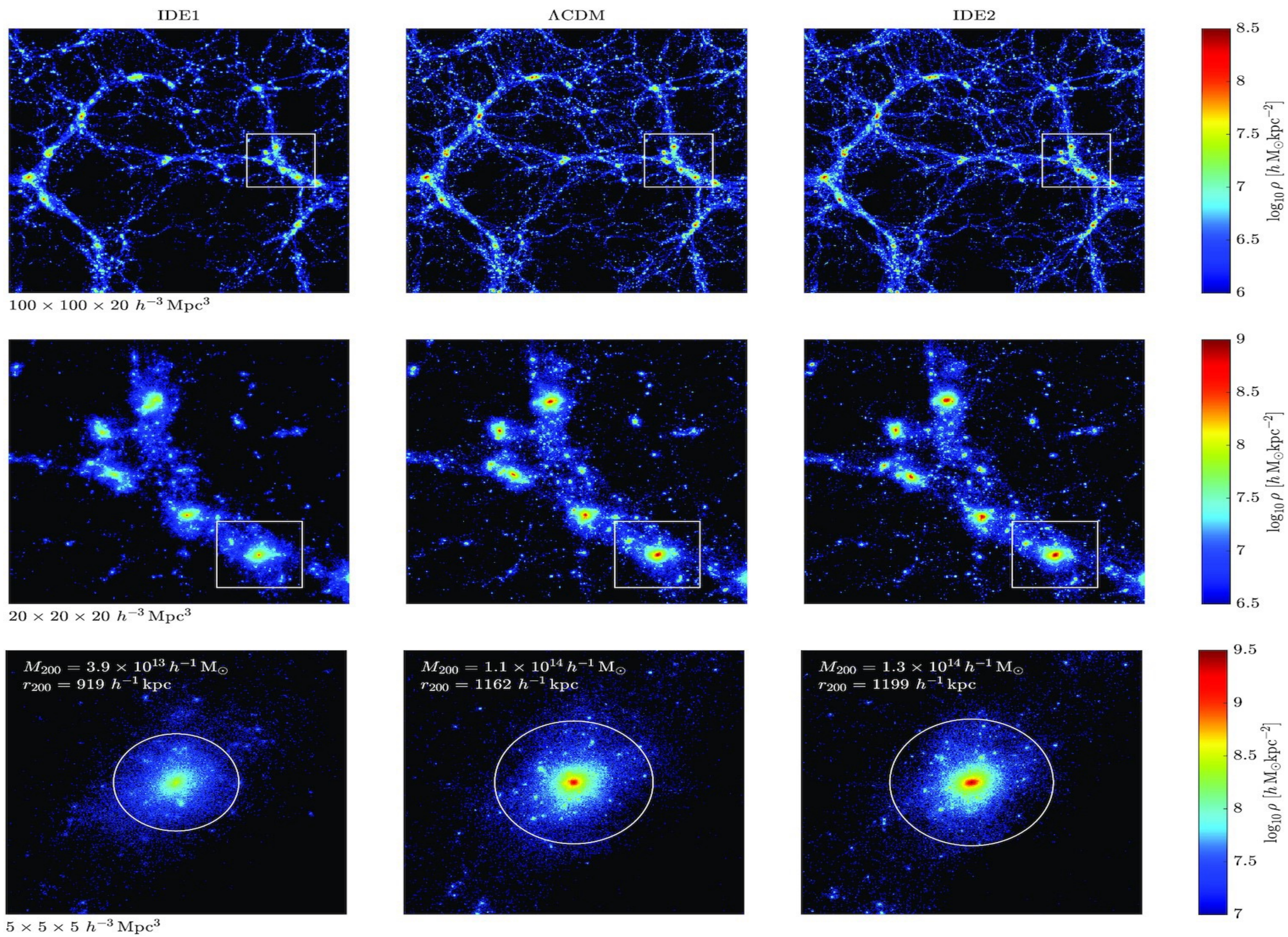
Backup material

Figure 4. Halo mass functions at z = 1 (left) and z = 0 (right) in ΛCDM (red), IDE1 (yellow solid), and IDE2 (blue) ...



Mon Not R Astron Soc, Volume 511, Issue 2, April 2022, Pages 3076–3088, https://doi.org/10.1093/mnras/stac229

Figure 2. Contrasts on the z = 0 cosmic structures in IDE1 (left column), ΛCDM (middle column), and IDE2 (right column) ...



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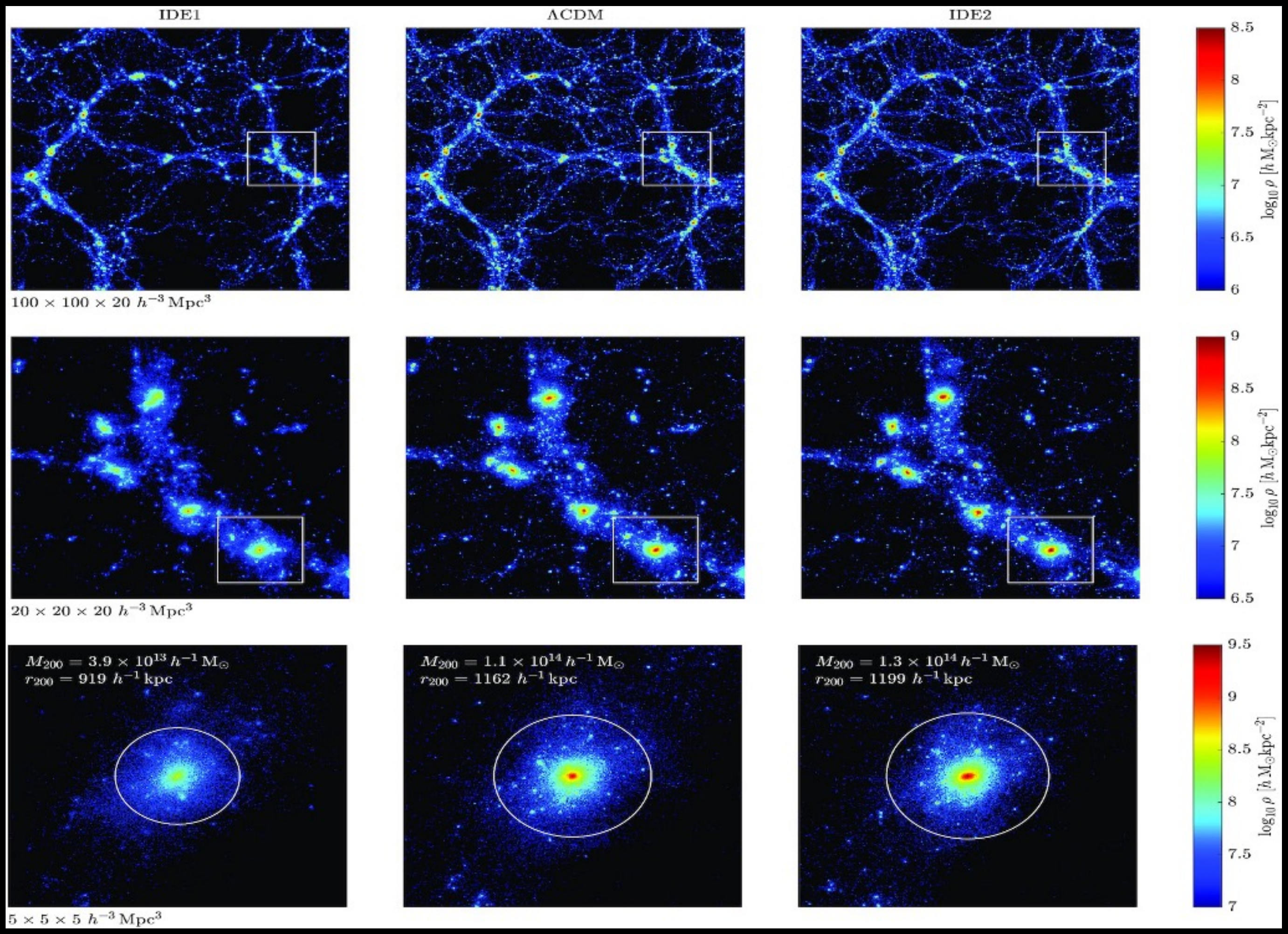

IDE1
ΛCDM
IDE2
$100 \times 100 \times 20\ h^{-3}\,\mathrm{Mpc}^3$
$20 \times 20 \times 20\ h^{-3}\,\mathrm{Mpc}^3$
$5 \times 5 \times 5\ h^{-3}\,\mathrm{Mpc}^3$
$M_{200} = 3.9 \times 10^{13}\,h^{-1}\,\mathrm{M}_\odot$
$r_{200} = 919\ h^{-1}\,\mathrm{kpc}$
$M_{200} = 1.1 \times 10^{14}\,h^{-1}\,\mathrm{M}_\odot$
$r_{200} = 1162\ h^{-1}\,\mathrm{kpc}$
$M_{200} = 1.3 \times 10^{14}\,h^{-1}\,\mathrm{M}_\odot$
$r_{200} = 1199\ h^{-1}\,\mathrm{kpc}$
$\log_{10}\rho\ [h\,\mathrm{M}_\odot\mathrm{kpc}^{-2}]$
8.5
8
7.5
7
6.5
6
9
8.5
8
7.5
7
6.5
9.5
9
8.5
8
7.5
7

Simplest phenomenological scenarios

$$Q = \Sigma \rho_{\rm dm}$$

Damour et al PRL'90, Wetterich AA'95, Amendola PRD'00, Zimdahl et al PLB'01, Farrar &Peebles APJ'04, Das et al PRD'06, Zhang et al PRD'06, Olivares et al PRD'08, Bean et al NJP'08, Koyama et al JCAP'10, Valiviita et al JCAP'08, He at al PLB'09, Jackson et al PRD'09, Gavela et al JCAP'09

$$Q = \Sigma \rho_{\rm de}$$

He at al PLB'09, Jackson et al PRD'09, Gavela et al JCAP'09

$$Q = \Sigma_1 \rho_{\rm dm} + \Sigma_2 \rho_{\rm de}$$

$$Q = \Sigma_1 \rho_{\rm dm} + \Sigma_2 \rho_{\rm de} + \Sigma_3 \rho'_{\rm dm} + \Sigma_4 \rho'_{\rm de}$$

Pan et al, MNRAS'18

$$Q = \Sigma \left(\frac{\rho_{\rm dm} \rho_{\rm de}}{\rho_{\rm dm} + \rho_{\rm de}} \right)$$

Zang et al JCAP'06, Li et al PRD'14, Hu et al A&A'16, Bouhmadi–Lopez et al PDU'16, Feng et al JCAP'16, Yang et al PRD'18 Yang et al PRD'19, Pan et al PRD'20

$$\Sigma \propto H$$

Valiviita et al JCAP'08, He at al PLB'09, Jackson et al PRD'09, Gavela et al JCAP'09

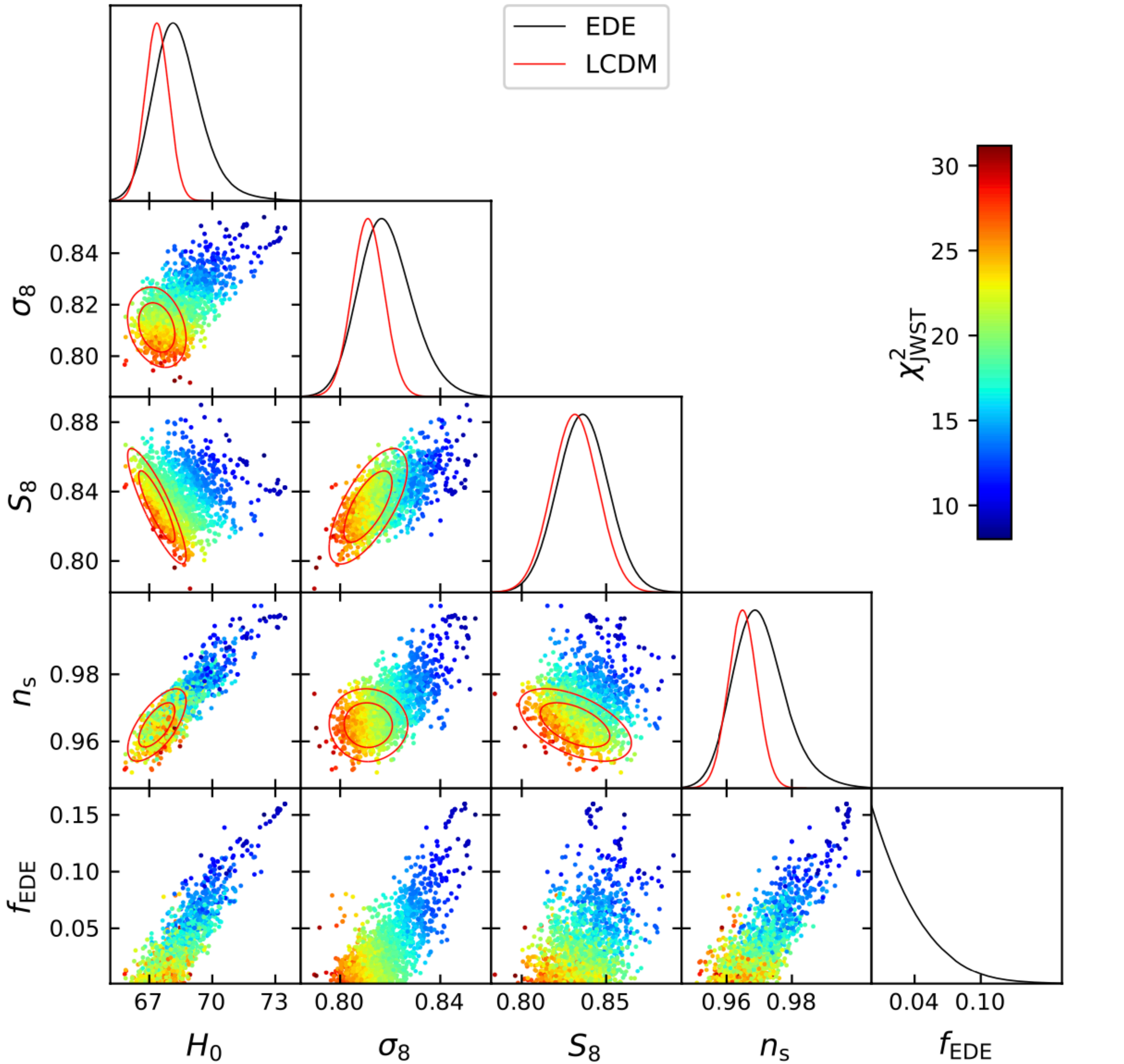
$$\Sigma \propto H_0$$

Valiviita et al JCAP'08, Majerotto et al, MNRAS'10

$$\Sigma \propto (1 + w)$$

Model stable for any choice of w *Yang et al JCAP'18*

Forconi et al, JCAP'24



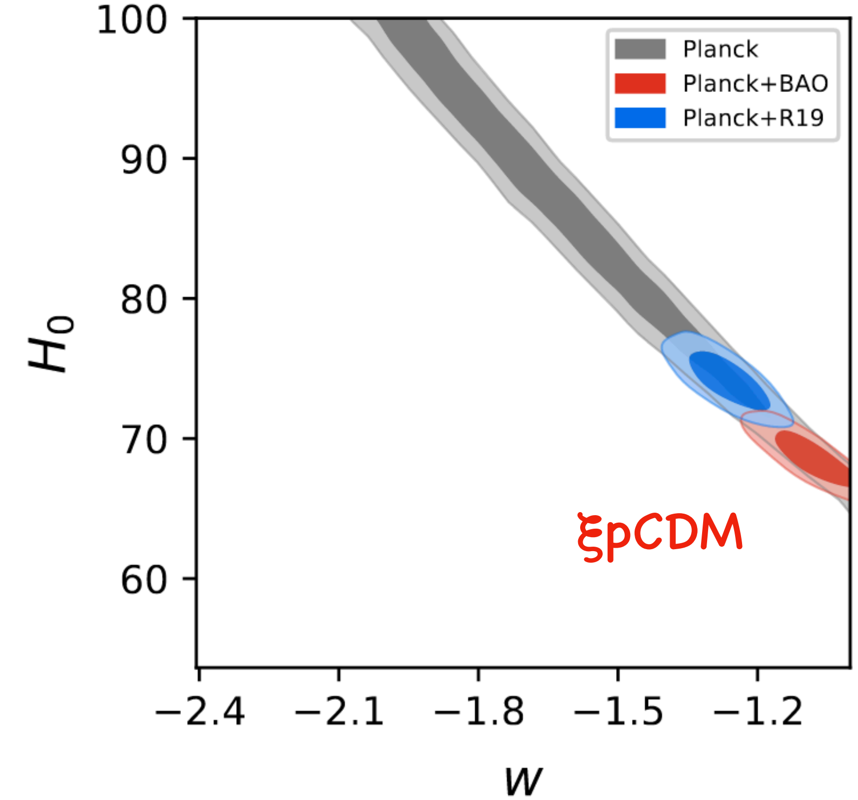
Forconi et al, JCAP'24

Parameter	CMB		JWST-CEERS	CMB+JWST
n_s	0.981	$z_{\rm low}$	0.997	0.981
		$z_{\rm high}$	0.997	0.981
H_0	69.45	$z_{\rm low}$	72.60	69.45
		$z_{\rm high}$	72.60	69.45
σ_8	0.8273	$z_{\rm low}$	0.854	0.8273
		$z_{\rm high}$	0.854	0.8273
τ	0.0575	$z_{\rm low}$	0.0497	0.05753
		$z_{\rm high}$	0.0497	0.05753
Ω_m	0.307	$z_{\rm low}$	0.304	0.307
		$z_{\rm high}$	0.304	0.307
$f_{\rm EDE}$	0.0628	$z_{\rm low}$	0.151	0.0628
		$z_{\rm high}$	0.151	0.0628
χ^2	2772	$z_{\rm low}$	5.75	$2782.76\ (2772+10.76)$
		$z_{\rm high}$	7.99	$2787.34\ (2772+15.34)$

$$\chi^2(\Lambda CDM) \simeq 17$$

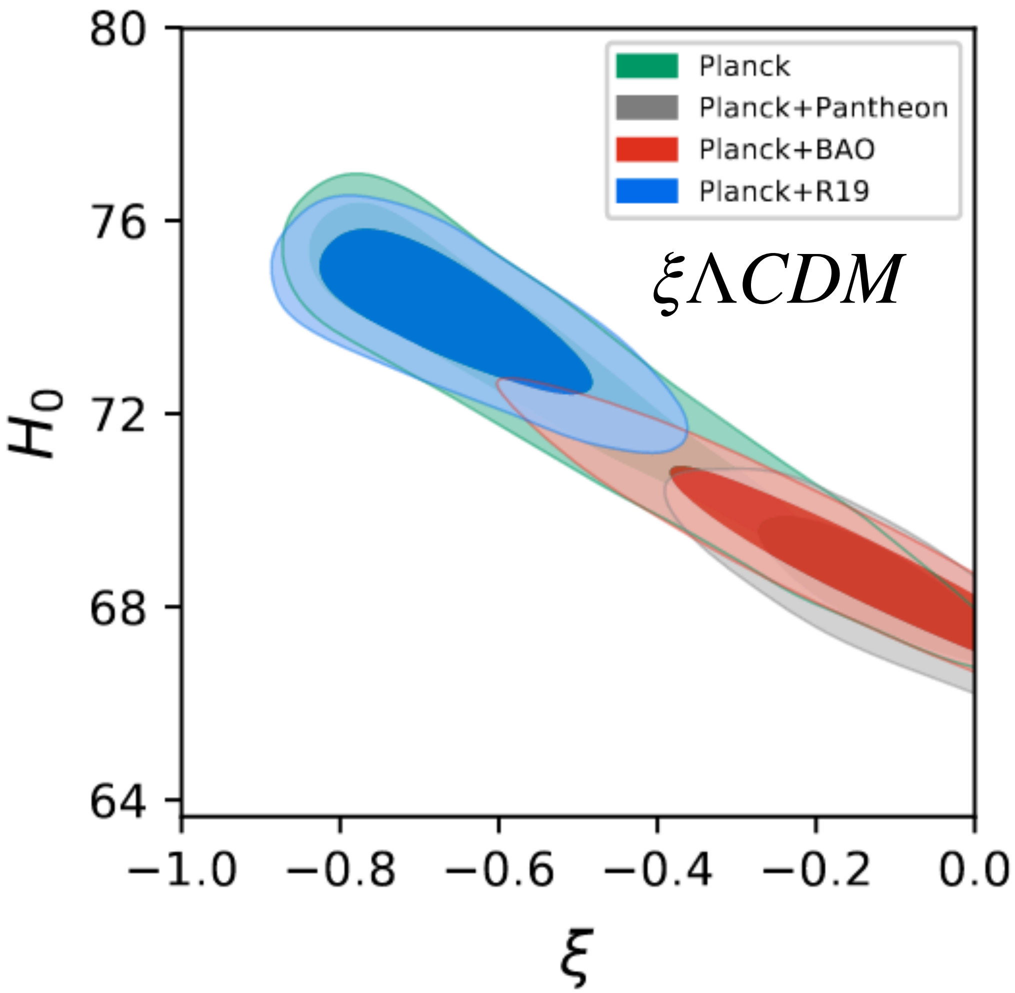
Interacting dark energy and the Hubble constant tension

When we allow the DE EoS w to change, we the $H_0 - w$ degeneracy strongly dominates over the $H_0 - \xi$ one. The H_0 tension is more efficiently solved in the coupled phantom ξpCDM model than in the coupled quintessence ξqCDM model due to the phantom character of the DE rather than due to the presence of the DM-DE interaction.



Phantom IDE

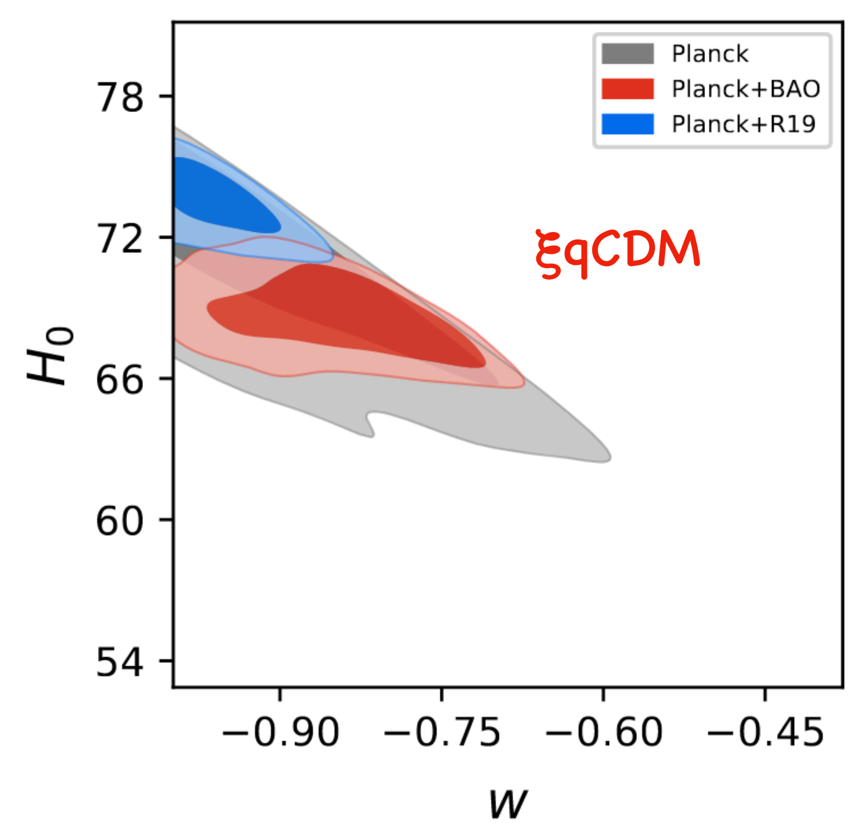
ξ < 0 w > −1



Di Valentino et al PDU'20

Quintessence IDE

ξ < 0 w > −1



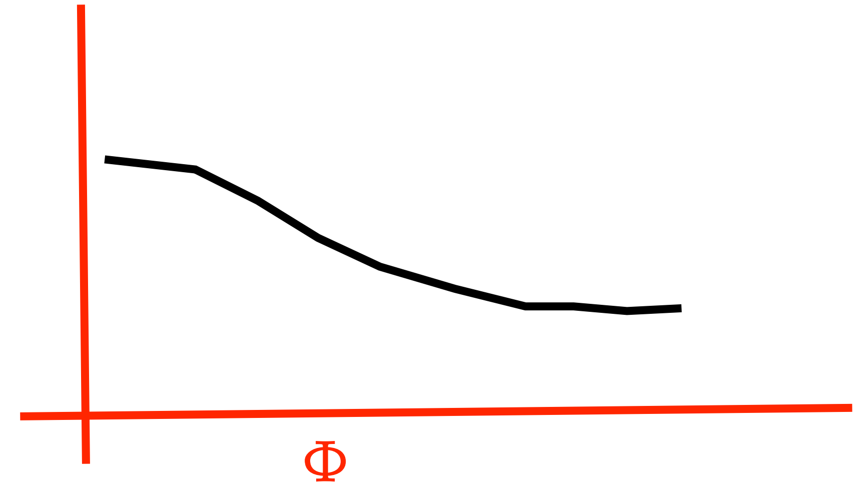
Di Valentino et al PRD'20

Dynamical dark energy

Wetterich; Peebles &Ratra; Wang, Caldwell, Ostriker & Steinhardt

"Quintessence-Cosmon" slowly rolling scalar field

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\nabla\phi)^2 + V(\phi)$$



Fine tuned: Minimum of the potential? $m_\Phi \approx 10^{-33}$ eV?

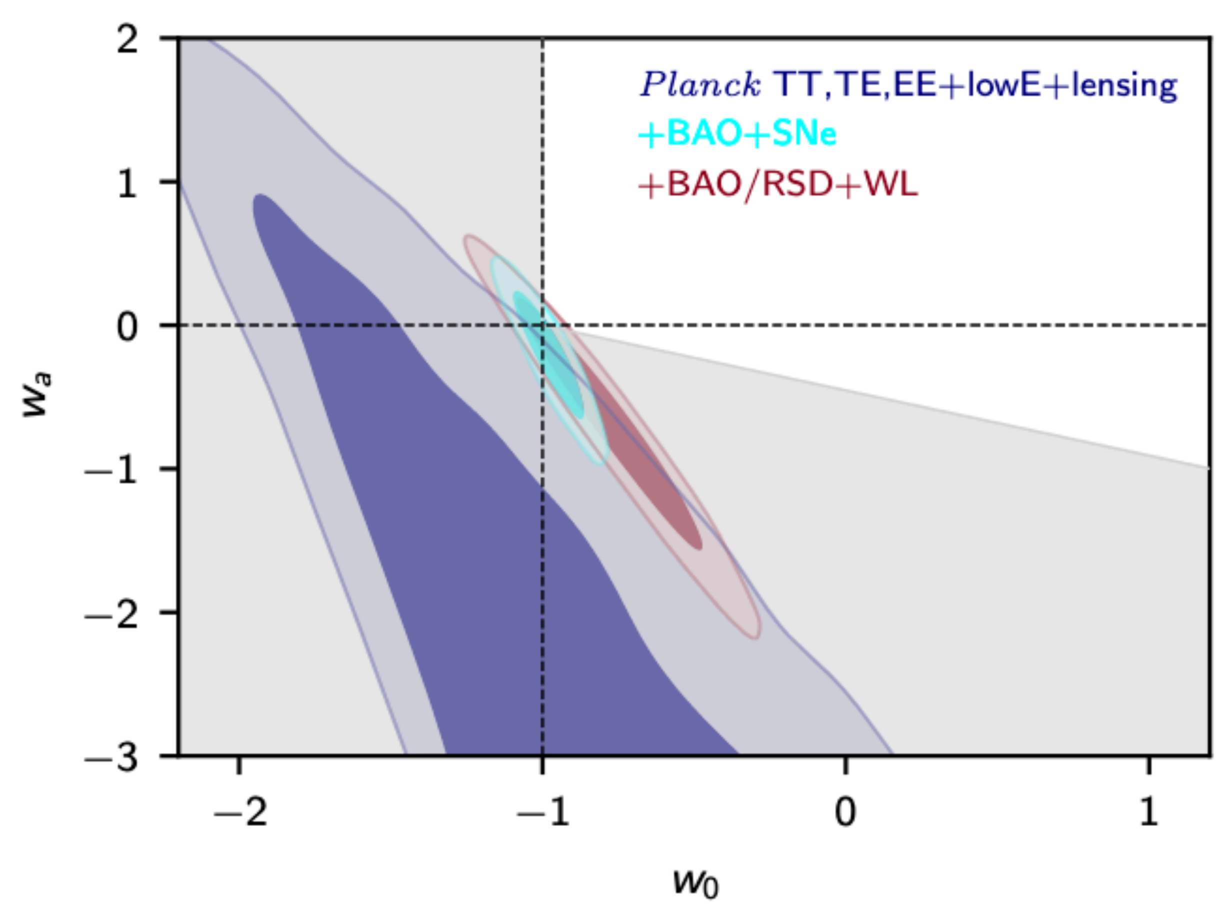
In practice:

$$w(a) = w_0 + w_a(1-a)$$

Chevallier&Polarski'01, Linder'03

Parameter	*Planck*+SNe+BAO	*Planck*+BAO/RSD+WL
w_0	-0.957 ± 0.080	-0.76 ± 0.20
w_a	$-0.29^{+0.32}_{-0.26}$	$-0.72^{+0.62}_{-0.54}$
H_0 [km s^{-1}Mpc^{-1}]	68.31 ± 0.82	66.3 ± 1.8
σ_8	0.820 ± 0.011	$0.800^{+0.015}_{-0.017}$
S_8	0.829 ± 0.011	0.832 ± 0.013
$\Delta\chi^2$	-1.4	-1.4

Planck coll. A&A'20



Simplest phenomenological scenarios

$$Q = \Sigma \rho_{\rm dm}$$

$$Q = \Sigma \rho_{\rm de}$$

$$Q = \Sigma_1 \rho_{\rm dm} + \Sigma_2 \rho_{\rm de}$$

$$Q = \Sigma \left(\frac{\rho_{\rm dm} \rho_{\rm de}}{\rho_{\rm dm} + \rho_{\rm de}} \right)$$

Possible field descriptions at classical and quantum levels

Gleyzes et al JCAP'15, Pan et al PRD'20

Quintessence coupled field models can be written as a scalar-tensor gravity theory. f (R) gravity theories correspond to generalized Brans Dicke (BD) theory with a BD parameter w_{BD} = 0 or = −3/2.

Sotiriou & Faraoni, Rev. Mod. Phys'10

Einstein frame contains a new scalar field, being the energy momentum exchange proportional to its 4-velocity

De Felice & Tsujikawa, Living Rev.Rel.'10

$$S_E = \int d^4x \sqrt{-\tilde{g}} \left[\frac{1}{2\kappa^2} \tilde{R} - \frac{1}{2} \tilde{g}^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) \right] + \int d^4x \mathcal{L}_M (F^{-1}(\phi) \tilde{g}_{\mu\nu}, \Psi_M) ,$$

$$\tilde{\nabla}_\mu \tilde{T}^{\mu(\phi)}_\nu = -Q\tilde{T}\tilde{\nabla}_\nu \phi \qquad \tilde{\nabla}_\mu \tilde{T}^{\mu(M)}_\nu = Q\tilde{T}\tilde{\nabla}_\nu \phi$$

Dark energy- Ω_{dm} coupled models

Cosmic scalar fields may naturally couple to all other fields in nature.

In practice, only to invisibles   Negligible couplings to matter *Carroll, PRL'98*

Dark sectors follow same time evolution on time:

cosmic coincidence-why now? problem

$$\nabla_\mu T^\mu_{(dm)\nu} = Q\, u_\nu^{(dm,de)}/a$$

Kodama & Sasaki, PTPS'84

$$\nabla_\mu T^\mu_{(de)\nu} = -Q\, u_\nu^{(dm,de)}/a$$

Non-adiabatic early-time (large-scale) instabilities, due to Q in the dark energy pressure perturbation.

Valiviita et al JCAP'08, He at al PLB'09,Jackson et al PRD'09, Gavela et al JCAP'09, Chongchitnan PRD'09

An easy recipe to avoid them is to force the doom factor

$$d \equiv \frac{Q}{3\mathcal{H}\rho_e(1+w)}$$

$$\delta''_{\rm de} \simeq 3\,\mathbf{d}\,(\hat{c}^2_{s\,\rm de}+b)\left(\frac{\delta'_{\rm de}}{a} + 3b\frac{\delta_{\rm de}}{a^2}\frac{(\hat{c}^2_{s\,\rm de}-w)}{\hat{c}^2_{s\,\rm de}+b} + \frac{3(1+w)}{a^2}\delta[\,\mathbf{d}\,]\right) + \ldots$$

to be negative.

Gavela et al JCAP'09

Einstein frame contains a new scalar field being the energy momentum exchange proportional to its 4-velocity

$$S=\frac{1}{2\kappa^2}\int \mathrm{d}^4x\sqrt{-g}\,f(R)+\int \mathrm{d}^4x\mathcal{L}_M(g_{\mu\nu},\Psi_M)\,;$$

$$\tilde{g}_{\mu\nu}=\Omega^2\,g_{\mu\nu}\,; \qquad \Omega^2=F \qquad \kappa\phi\equiv\sqrt{3/2}\,\ln F\,.$$

$$S_E=\int \mathrm{d}^4x\sqrt{-\tilde{g}}\left[\frac{1}{2\kappa^2}\tilde{R}-\frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi-V(\phi)\right]+\int \mathrm{d}^4x\mathcal{L}_M(F^{-1}(\phi)\tilde{g}_{\mu\nu},\Psi_M)\,,$$

$$V(\phi)=\frac{U}{F^2}=\frac{FR-f}{2\kappa^2F^2}$$

$$\tilde{\nabla}_\mu\tilde{T}^{\mu(\phi)}_\nu=-Q\tilde{T}\tilde{\nabla}_\nu\phi\,, \qquad \tilde{\nabla}_\mu\tilde{T}^{\mu(M)}_\nu=Q\tilde{T}\tilde{\nabla}_\nu\phi$$

Dark energy- Ω_{dm} coupled models

$$Q_\nu = Q u_\nu^{(\mathrm{de})}/a \ \text{DEvel}$$

$$\propto \rho_{dm} u_\nu^{de}$$

Damour et al PRL'90, Wetterich AA'95, Amendola PRD'00, Zimdahl et al PLB'01, Farrar &Peebles APJ'04, Das et al PRD'06, Zhang et al PRD'06, Olivares et al PRD'08, Bean et al NJP'08, Koyama et al JCAP'10.

$$\Delta_\mu T^\mu_{(\mathrm{dm})\nu} = Q_\nu$$

$$\Delta_\mu T^\mu_{(\mathrm{de})\nu} = -Q_\nu$$

$$\propto \rho_{de} u_\nu^{de}$$

Honorez et al, AIP C.P'10, JCAP'10

$$Q_\nu = Q u_\nu^{(\mathrm{dm})}/a \ \text{DMvel}$$

$$\propto \rho_{dm} u_\nu^{dm}$$

Valiviita et al JCAP'08, He at al PLB'09, Jackson et al PRD'09, Gavela et al JCAP'09, Koyama et al JCAP'10

$$\propto \rho_{de} u_\nu^{dm}$$

He at al PLB'09, Jackson et al PRD'09, Gavela et al JCAP'09.

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$$\Delta_\mu T^\mu_{(\mathrm{dm})\nu} = Q_\nu$$

$$\Delta_\mu T^\mu_{(\mathrm{de})\nu} = - Q_\nu$$

$$\propto \rho_{de} u_\nu^{de}$$

Honorez et al AIP C.P'10, JCAP'10

$$Q_\nu = Q u_\nu^{(\mathrm{dm})}/a \ \mathrm{DMvel}$$

$$\propto \rho_{dm} u_\nu^{dm}$$

Valiviita et al JCAP'08, He at al PLB'09, Jackson et al PRD'09, Gavela et al JCAP'09, Koyama et al JCAP'10

$$\propto \rho_{de} u_\nu^{dm}$$

He at al PLB'09, Jackson et al PRD'09, Gavela et al JCAP'09.

Dark energy- Ω_{dm} coupled models

$$\Delta_\mu T^\mu_{(\mathrm{dm})\nu} = Q_\nu$$

$$\Delta_\mu T^\mu_{(\mathrm{de})\nu} = -Q_\nu$$

$$Q_\nu = Q u_\nu^{(\mathrm{de})}/a \ \mathrm{DEvel}$$

Modified gravity & coupled quintessence models

$$Q_\nu = Q u_\nu^{(\mathrm{dm})}/a \ \mathrm{DMvel}$$

In DEvel models (b=0) there is no momentum transfer to the dark energy frame: momentum must be conserved in the dark matter frame. This implies a fractional increase in the dark matter peculiar velocity equal and opposite to the fractional change in energy density due to the presence of a coupling.

This effect can be interpreted as an extra source of acceleration for the dark matter fluid, that will appear clearly in the dark matter velocity perturbation equation:

$$\dot{\theta}_{\mathrm{dm}} = -\mathcal{H}\theta_{\mathrm{dm}} + (1-b)\frac{Q}{\rho_{\mathrm{dm}}}(\theta_{\mathrm{de}} - \theta_{\mathrm{dm}}) + k^2\Psi$$

$$\dot{\theta}_{\mathrm{de}} = -\mathcal{H}\left(1 - 3\hat{c}^2_{s\,\mathrm{de}} - \frac{\hat{c}^2_{s\,\mathrm{de}} + b}{1+w}\frac{Q}{\mathcal{H}\rho_{\mathrm{de}}}\right)\theta_{\mathrm{de}} + \frac{k^2}{1+w}\hat{c}^2_{s\,\mathrm{de}}\delta_{\mathrm{de}} + k^2\Psi - b\frac{Q}{\rho_{\mathrm{de}}}\frac{\theta_{\mathrm{dm}}}{1+w}$$

In DMvel models (b=1) both momentum and energy density are transferred from the dark matter system to the dark energy one, and therefore the dark matter peculiar velocity field does not have this apparent force.

Dark energy- Ω_{dm} coupled models

Warning!

$$Q_\nu = Q u_\nu^{(\mathrm{de})}/a \ \mathrm{DEvel}$$

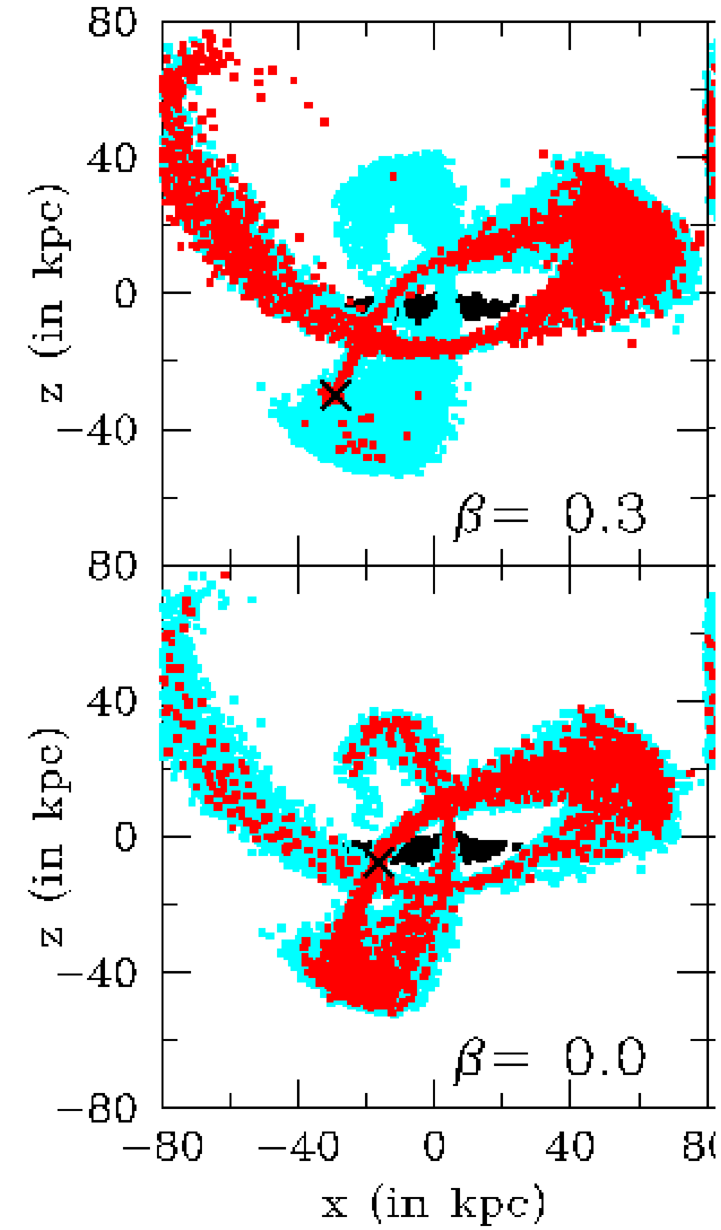
Modified gravity models

$$\propto \rho_{dm} u_\nu^{de}$$

$$\beta \rho_{dm} \nabla_\nu \phi / M_p$$

$$G_{DM} = G_{baryons}(1 + 2\beta^2)$$

$$|\beta| < 0.22$$

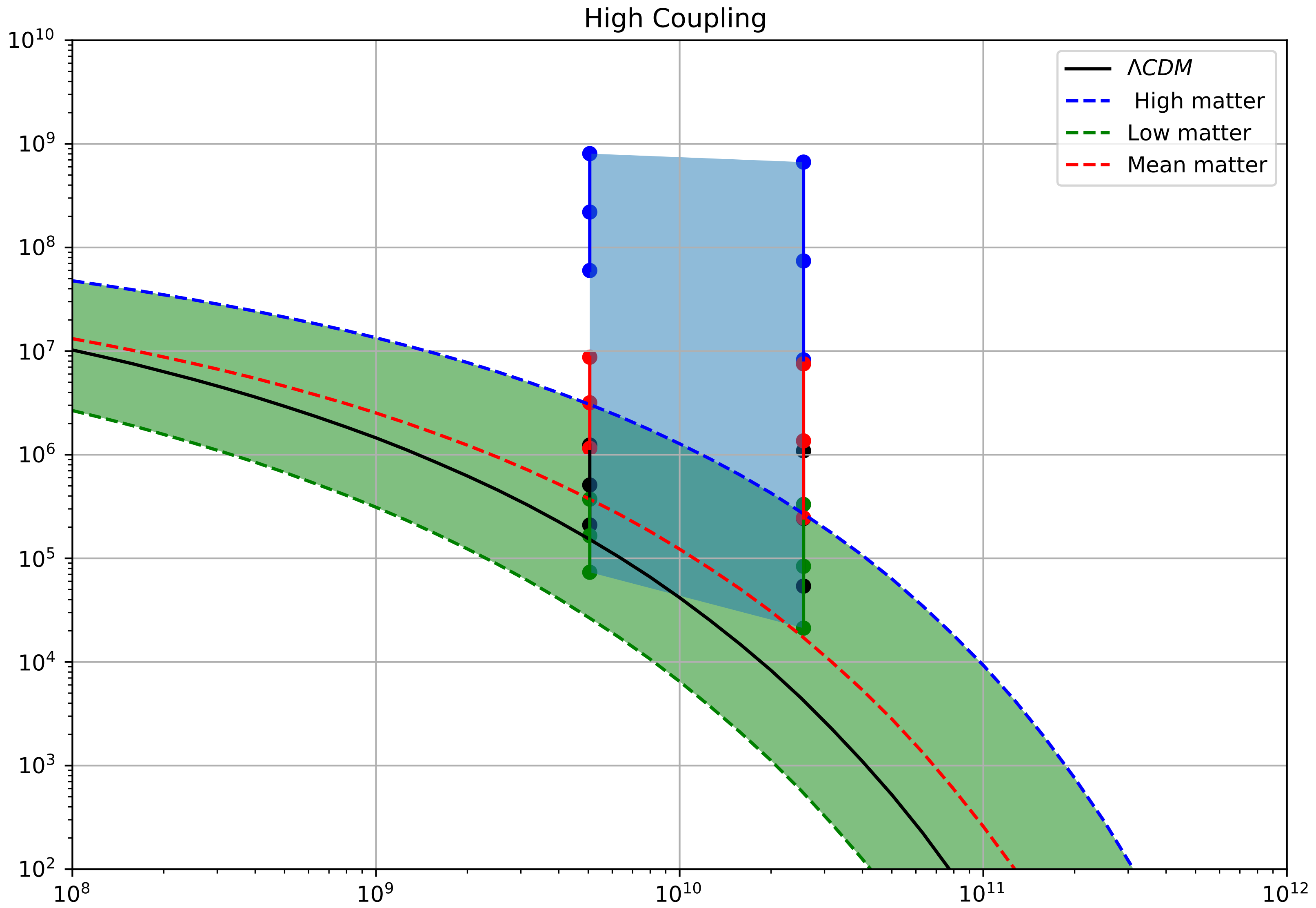


Kesden& Kamionkowski, PRL&PRD'06

Is interacting dark energy the panacea for all tensions?

Structure formation is more enhanced than predicted by the ΛCDM framework!

$$Q = H\xi\rho_{\rm de}$$



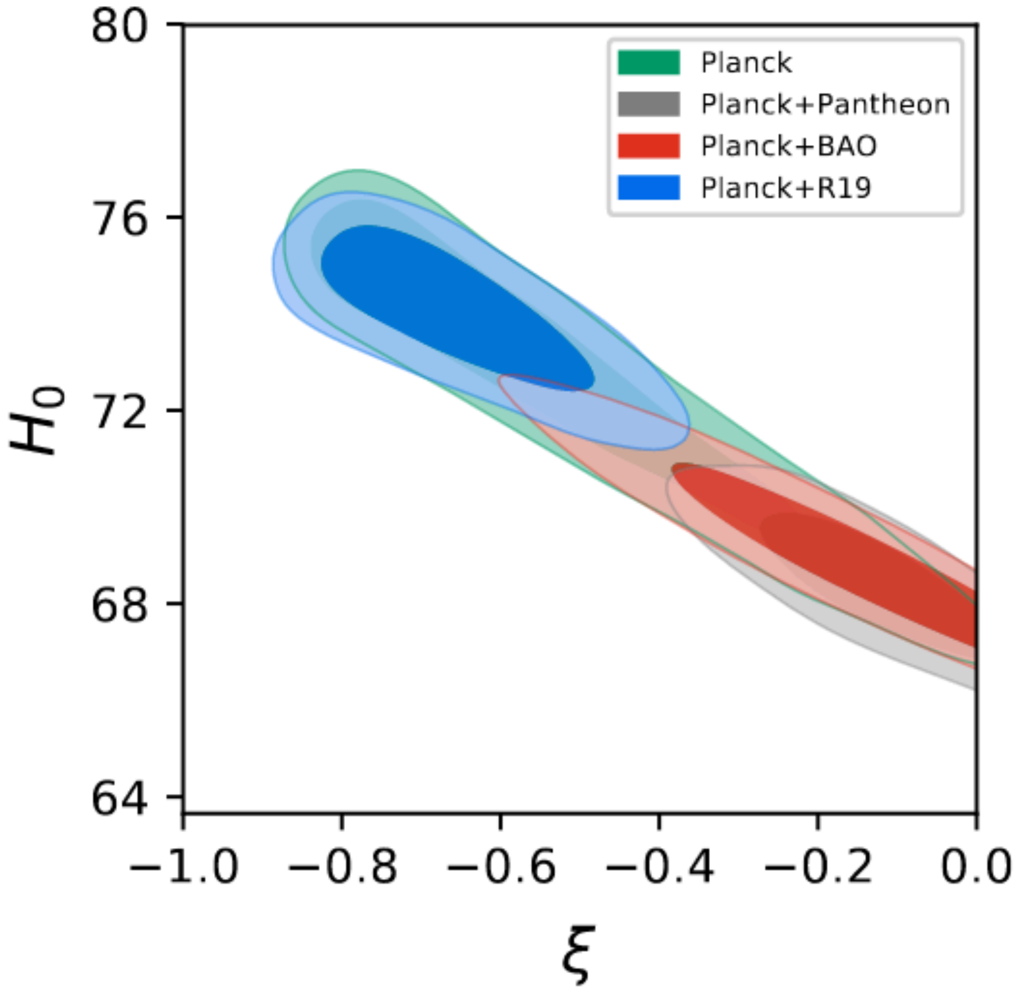
Highly promising!

Kaushik et al, in preparation

Interacting dark energy and the Hubble constant tension

Strong degeneracy between ξ and H_0!

$\xi\Lambda CDM$



Di Valentino et al PDU'20

Dataset	$\xi\Lambda$CDM	ξqCDM	ξpCDM
Planck	0.4σ	1.0σ	0.5σ
Planck+R19	$< 0.1\sigma$	0.4σ	$< 0.1\sigma$
Planck+lensing	0.4σ	1.0σ	2.1σ
Planck+BAO	2.7σ	2.7σ	2.9σ
Planck+Pantheon	3.3σ	3.3σ	3.3σ
All19	2.5σ	2.7σ	2.7σ

Di Valentino et al PRD'20

One loop corrections to the simplest picture:
Interacting scenarios with a dynamical w and/or coupling

(Yang et al PRD'19, Wang et al 2209.14816)

$$\xi(a) = \xi_0 + \xi_a\,(1-a)$$

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However…

$$Q = 3H\xi \left(\frac{\rho_{dm}\rho_{de}}{\rho_{dm} + \rho_{de}} \right) \qquad w > -1$$

Parameters	CMB	CMB+BAO	CMB+Pantheon	CMB+BAO+Pantheon
$\Omega_c h^2$	$0.1153^{+0.0053+0.0072}_{-0.0026-0.0090}$	$0.1129^{+0.0057+0.0074}_{-0.0028-0.0090}$	$0.1130^{+0.0056+0.0079}_{-0.0033-0.0090}$	$0.1125^{+0.0054+0.0074}_{-0.0031-0.0084}$
$\Omega_b h^2$	$0.02236^{+0.00015+0.00030}_{-0.00015-0.00029}$	$0.02244^{+0.00015+0.00027}_{-0.00014-0.00028}$	$0.02240^{+0.00014+0.00029}_{-0.00014-0.00029}$	$0.02244^{+0.00014+0.00027}_{-0.00014-0.00027}$
$100\theta_{MC}$	$1.04117^{+0.00036+0.00080}_{-0.00042-0.00073}$	$1.04139^{+0.00035+0.00078}_{-0.00040-0.00070}$	$1.04134^{+0.00037+0.00078}_{-0.00041-0.00075}$	$1.04140^{+0.00037+0.00075}_{-0.00037-0.00070}$
τ	$0.0538^{+0.0074+0.016}_{-0.0074-0.016}$	$0.0554^{+0.0074+0.016}_{-0.0075-0.014}$	$0.0543^{+0.0078+0.016}_{-0.0076-0.016}$	$0.0550^{+0.0073+0.016}_{-0.0083-0.015}$
n_s	$0.9650^{+0.0043+0.0087}_{-0.0043-0.0085}$	$0.9680^{+0.0039+0.0081}_{-0.0040-0.0075}$	$0.9664^{+0.0043+0.0084}_{-0.0043-0.0084}$	$0.9678^{+0.0038+0.0077}_{-0.0038-0.0076}$
$\ln(10^{10}A_s)$	$3.044^{+0.016+0.031}_{-0.015-0.032}$	$3.044^{+0.015+0.032}_{-0.015-0.030}$	$3.043^{+0.016+0.032}_{-0.016-0.032}$	$3.044^{+0.016+0.033}_{-0.017-0.031}$
w_q	< -0.894 < -0.759	< -0.955 < -0.908	< -0.972 < -0.939	< -0.973 < -0.944
ξ_0	< 0.097 < 0.203	< 0.121 < 0.238	< 0.137 < 0.244	< 0.136 < 0.239
Ω_{m0}	$0.327^{+0.022+0.066}_{-0.033-0.058}$	$0.301^{+0.017+0.027}_{-0.012-0.030}$	$0.299^{+0.016+0.027}_{-0.013-0.031}$	$0.296^{+0.015+0.024}_{-0.011-0.026}$
σ_8	$0.809^{+0.031+0.061}_{-0.028-0.066}$	$0.826^{+0.018+0.050}_{-0.027-0.044}$	$0.834^{+0.017+0.046}_{-0.027-0.042}$	$0.832^{+0.017+0.045}_{-0.027-0.040}$
H_0 [km/s/Mpc]	$65.2^{+2.9+4.1}_{-1.5-5.1}$	$67.30^{+0.99+1.7}_{-0.76-1.8}$	$67.45^{+0.84+1.5}_{-0.75-1.6}$	$67.72^{+0.63+1.2}_{-0.61-1.2}$
S_8	$0.842^{+0.018+0.034}_{-0.017-0.033}$	$0.826^{+0.014+0.027}_{-0.014-0.027}$	$0.833^{+0.016+0.032}_{-0.016-0.030}$	$0.826^{+0.013+0.027}_{-0.013-0.026}$
r_{drag} [Mpc]	$147.06^{+0.29+0.58}_{-0.30-0.58}$	$147.28^{+0.27+0.51}_{-0.26-0.53}$	$147.15^{+0.28+0.55}_{-0.29-0.56}$	$147.26^{+0.25+0.50}_{-0.25-0.50}$

(Wang et al, 2209.14816)

A phantom interacting dark energy cosmology is also (mildly) favoured

Nevertheless it can be model-dependent. Very rich phenomenology!

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Parameters	CMB	CMB+BAO	CMB+Pantheon	CMB+BAO+Pantheon
$\Omega_c h^2$	$0.137^{+0.007+0.032}_{-0.018-0.022}$	$0.136^{+0.006+0.025}_{-0.016-0.019}$	$0.136^{+0.006+0.027}_{-0.016-0.019}$	$0.135^{+0.005+0.024}_{-0.014-0.018}$
$\Omega_b h^2$	$0.02238^{+0.00014+0.00028}_{-0.00014-0.00029}$	$0.02236^{+0.00014+0.00029}_{-0.00014-0.00029}$	$0.02234^{+0.00015+0.00029}_{-0.00015-0.00029}$	$0.02237^{+0.00014+0.00028}_{-0.00014-0.00027}$
$100\theta_{MC}$	$1.0400^{+0.0010+0.0014}_{-0.0005-0.0017}$	$1.04008^{+0.00084+0.0012}_{-0.00050-0.0015}$	$1.04003^{+0.00087+0.0013}_{-0.00050-0.0015}$	$1.04016^{+0.00080+0.0012}_{-0.00046-0.0014}$
τ	$0.0544^{+0.0078+0.016}_{-0.0076-0.015}$	$0.0552^{+0.0075+0.015}_{-0.0075-0.015}$	$0.0548^{+0.0074+0.016}_{-0.0084-0.015}$	$0.0555^{+0.0077+0.016}_{-0.0077-0.015}$
n_s	$0.9645^{+0.0044+0.0086}_{-0.0044-0.0083}$	$0.9644^{+0.0043+0.0082}_{-0.0041-0.0081}$	$0.9636^{+0.0043+0.0083}_{-0.0044-0.0085}$	$0.9649^{+0.0039+0.0078}_{-0.0039-0.0077}$
$\ln(10^{10}A_s)$	$3.045^{+0.015+0.032}_{-0.015-0.032}$	$3.046^{+0.016+0.032}_{-0.015-0.031}$	$3.047^{+0.016+0.033}_{-0.017-0.031}$	$3.047^{+0.016+0.032}_{-0.016-0.031}$
w_p	$-1.67^{+0.16+0.52}_{-0.33-0.41}$	$-1.111^{+0.089}_{-0.044}$ > -1.237	$-1.095^{+0.070}_{-0.035}$ > -1.20	$-1.084^{+0.064}_{-0.032}$ > -1.18
ξ_0	> -0.368 > -0.766	> -0.309 > -0.619	> -0.306 > -0.657	> -0.277 > -0.591
Ω_{m0}	$0.216^{+0.026+0.11}_{-0.064-0.08}$	$0.334^{+0.020+0.061}_{-0.036-0.052}$	$0.342^{+0.018+0.064}_{-0.037-0.050}$	$0.337^{+0.015+0.056}_{-0.033-0.044}$
σ_8	$0.92^{+0.10+0.15}_{-0.07-0.16}$	$0.774^{+0.052+0.078}_{-0.032-0.092}$	$0.769^{+0.053+0.070}_{-0.025-0.090}$	$0.771^{+0.050+0.067}_{-0.024-0.084}$
H_0 [km/s/Mpc]	88^{+12+14}_{-6-18}	$69.0^{+1.2+2.8}_{-1.5-2.7}$	$68.3^{+1.0+2.0}_{-1.0-2.0}$	$68.37^{+0.78+1.6}_{-0.85-1.5}$
S_8	$0.764^{+0.024+0.060}_{-0.035-0.053}$	$0.814^{+0.019+0.033}_{-0.015-0.036}$	$0.819^{+0.020+0.037}_{-0.017-0.038}$	$0.816^{+0.019+0.033}_{-0.014-0.036}$
$r_{\rm drag}$ [Mpc]	$147.04^{+0.30+0.59}_{-0.32-0.57}$	$147.07^{+0.28+0.53}_{-0.28-0.54}$	$147.00^{+0.29+0.56}_{-0.29-0.57}$	$147.10^{+0.26+0.51}_{-0.26-0.52}$

(Wang et al, 2209.14816)

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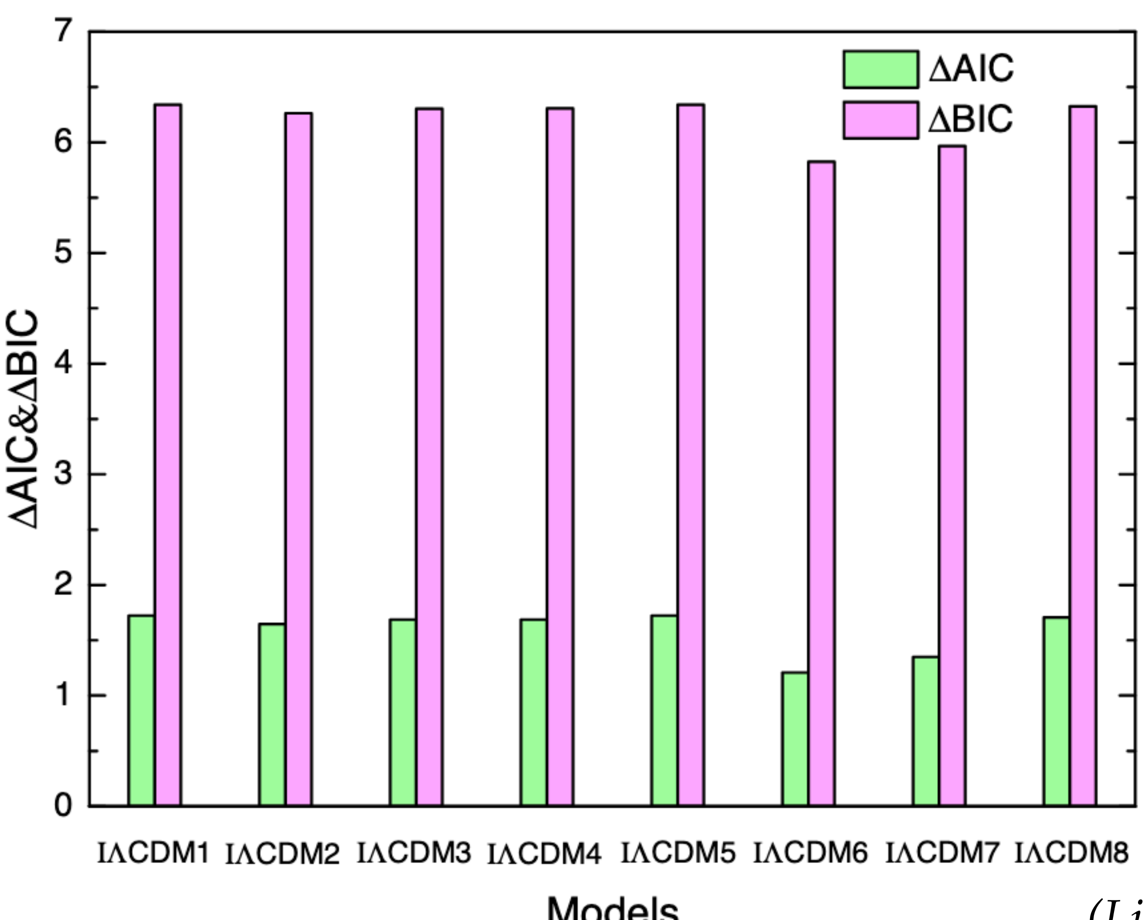
Nevertheless it can be model-dependent. Very rich phenomenology!

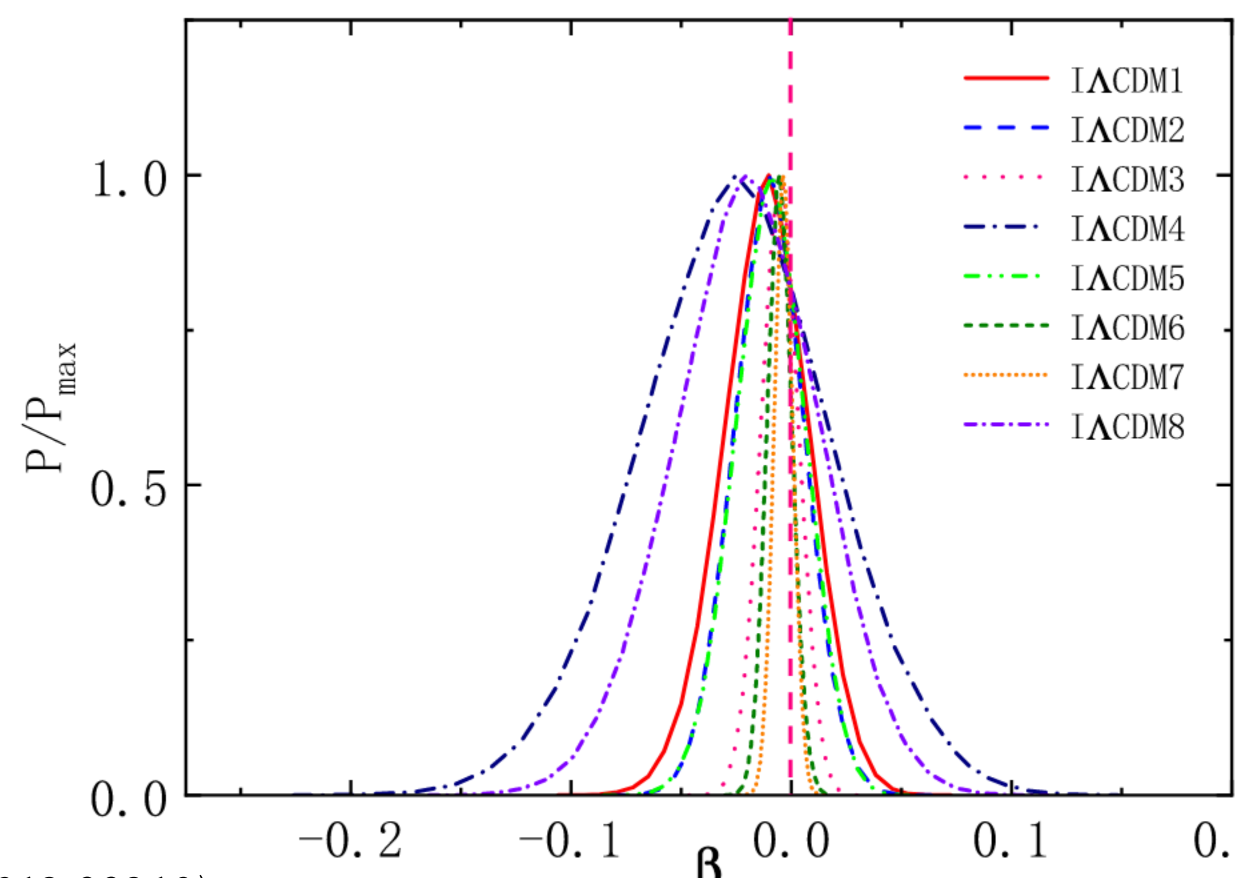
Is there any preference for a particular coupled model?

$$Q_1 = H_0\beta\rho_{de} \quad Q_2 = H_0\beta\rho_{dm} \quad Q_3 = H_0\beta(\rho_{dm}+\rho_{de}) \quad Q_4 = H_0\beta\left(\frac{\rho_{dm}\rho_{de}}{\rho_{dm}+\rho_{de}}\right)$$

$$Q_5 = H\beta\rho_{de} \quad Q_6 = H\beta\rho_{dm} \quad Q_7 = H\beta(\rho_{dm}+\rho_{de}) \quad Q_8 = H\beta\left(\frac{\rho_{dm}\rho_{de}}{\rho_{dm}+\rho_{de}}\right)$$

Non-interacting case





(Li et al 1812.00319)

Einstein frame contains a new scalar field being the energy momentum exchange proportional to its 4-velocity

$$S = \frac{1}{2\kappa^2}\int \mathrm{d}^4x\sqrt{-g}\, f(R) + \int \mathrm{d}^4x\mathcal{L}_M(g_{\mu\nu}, \Psi_M)\,;$$

$$\tilde{g}_{\mu\nu} = \Omega^2\, g_{\mu\nu}\,; \qquad \Omega^2 = F \qquad \kappa\phi \equiv \sqrt{3/2}\,\ln F\,.$$

$$S_E = \int \mathrm{d}^4x\sqrt{-\tilde{g}}\left[\frac{1}{2\kappa^2}\tilde{R} - \frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right] + \int \mathrm{d}^4x\mathcal{L}_M(F^{-1}(\phi)\tilde{g}_{\mu\nu}, \Psi_M)\,,$$

$$V(\phi) = \frac{U}{F^2} = \frac{FR - f}{2\kappa^2 F^2}$$

$$\tilde{\nabla}_\mu \tilde{T}^{\mu(\phi)}_\nu = -Q\tilde{T}\tilde{\nabla}_\nu\phi\,, \qquad \tilde{\nabla}_\mu \tilde{T}^{\mu(M)}_\nu = Q\tilde{T}\tilde{\nabla}_\nu\phi$$