The H_0 tension and non-minimal couplings to gravity

Matteo Braglia

APC, Paris

06/30/2020

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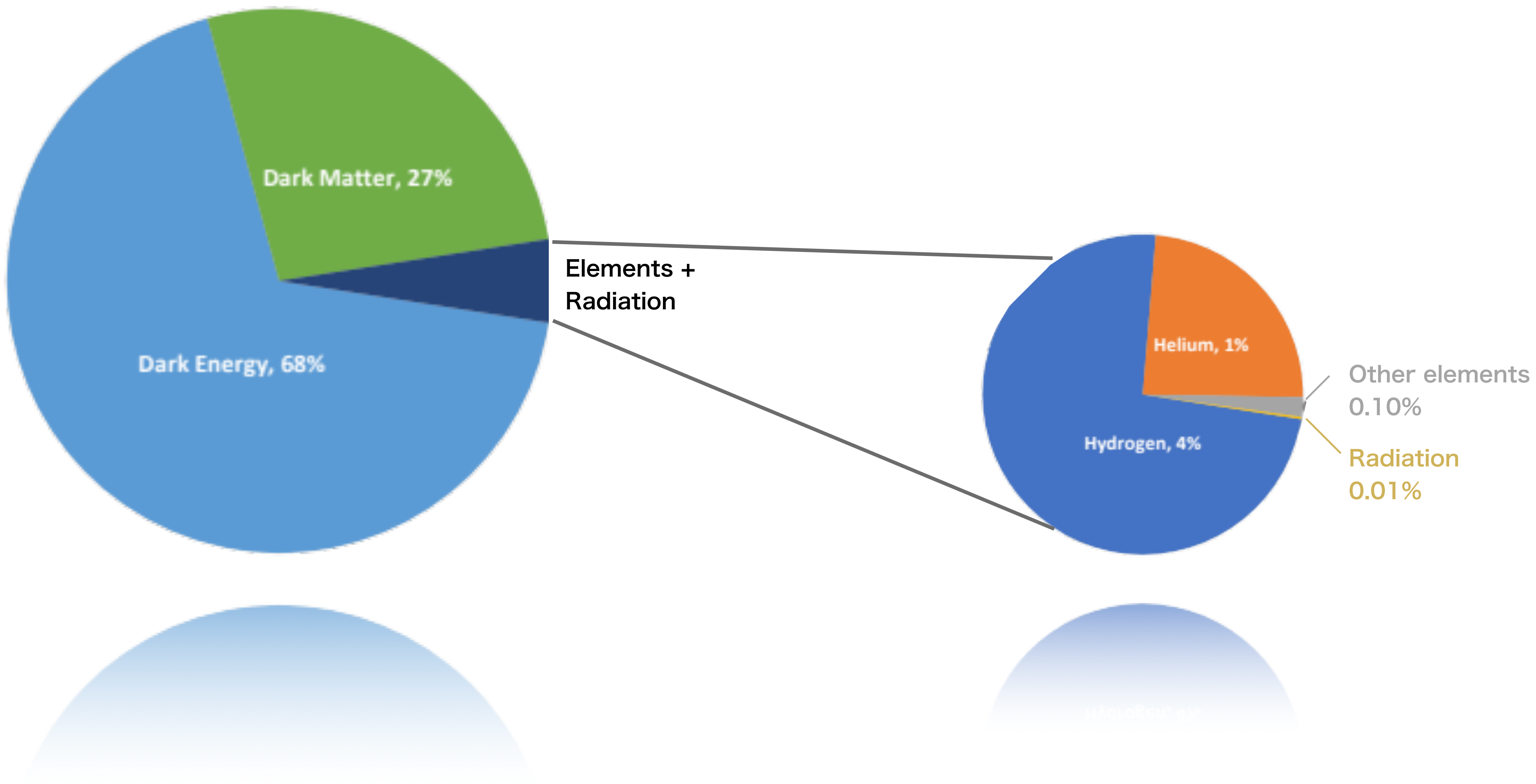
Based on

- 1906.10218 Rossi, Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà
- 2004.11161 MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti
- 2004.14349 Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà

The ΛCDM Standard Model



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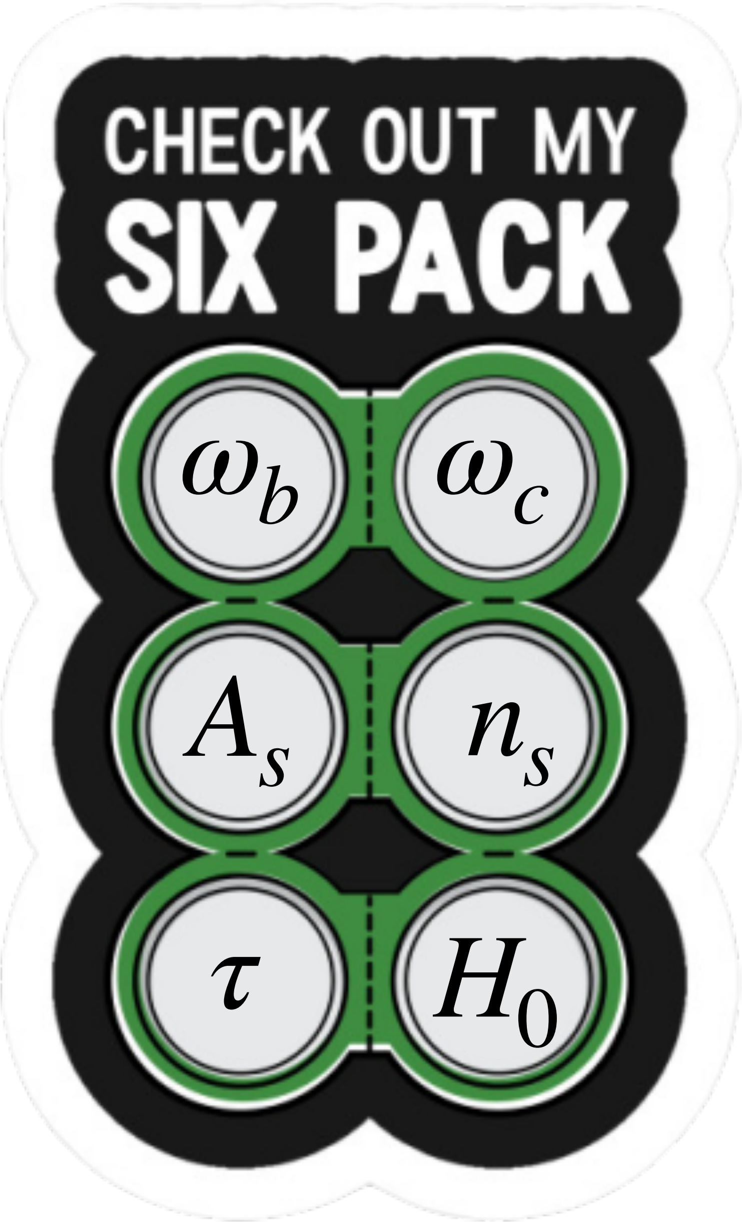

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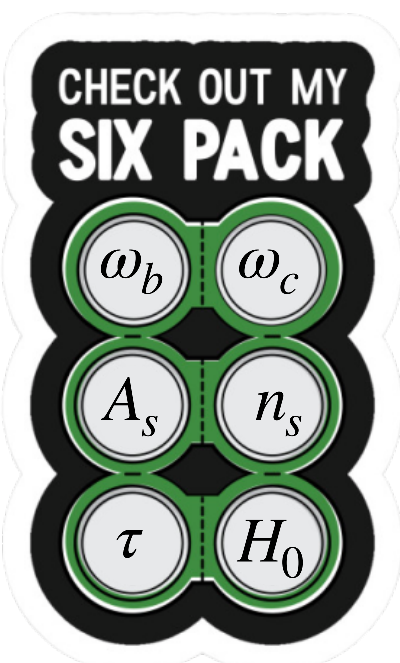
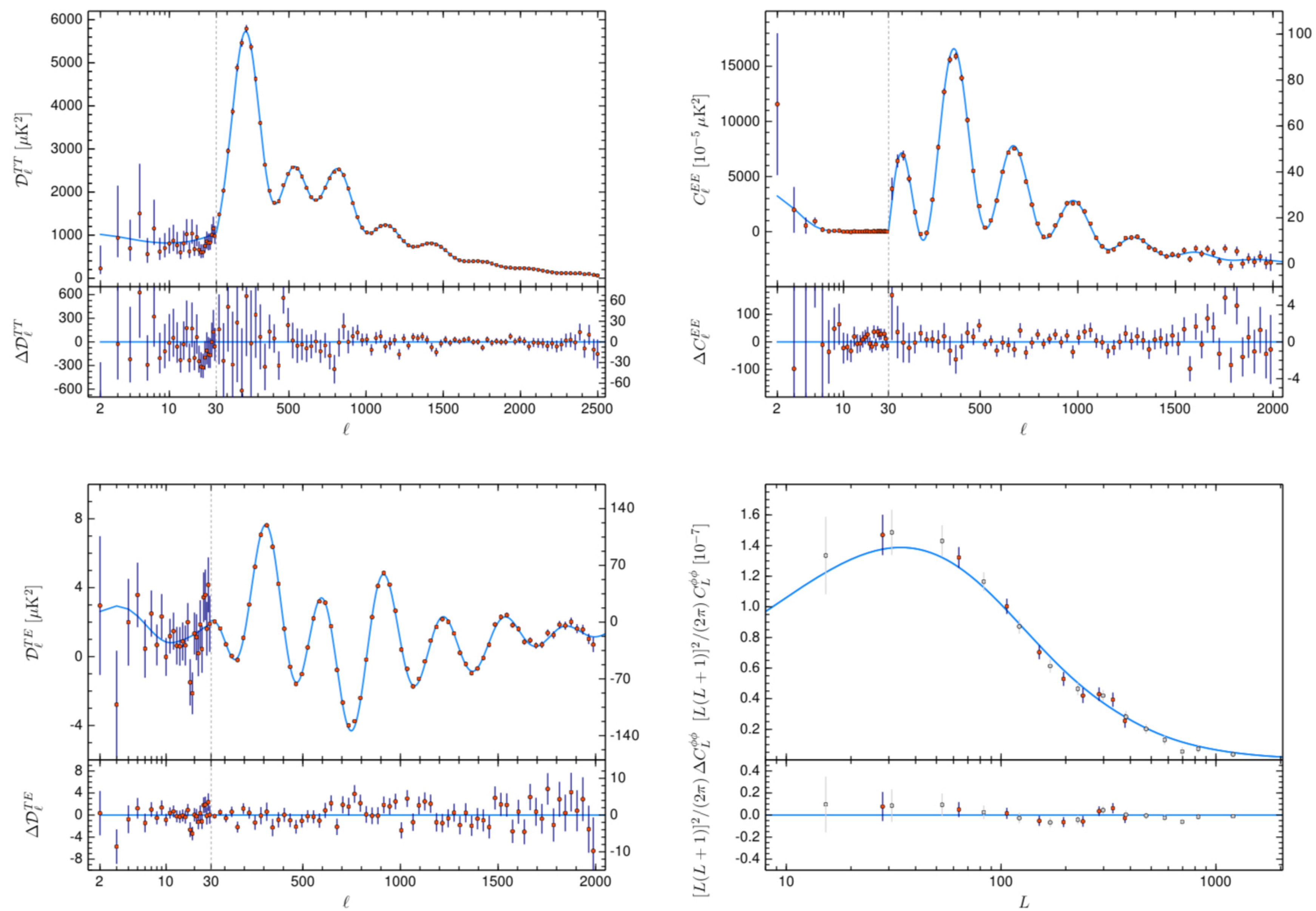
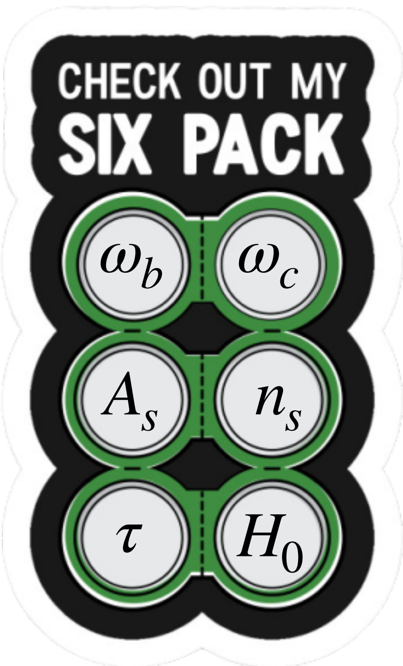
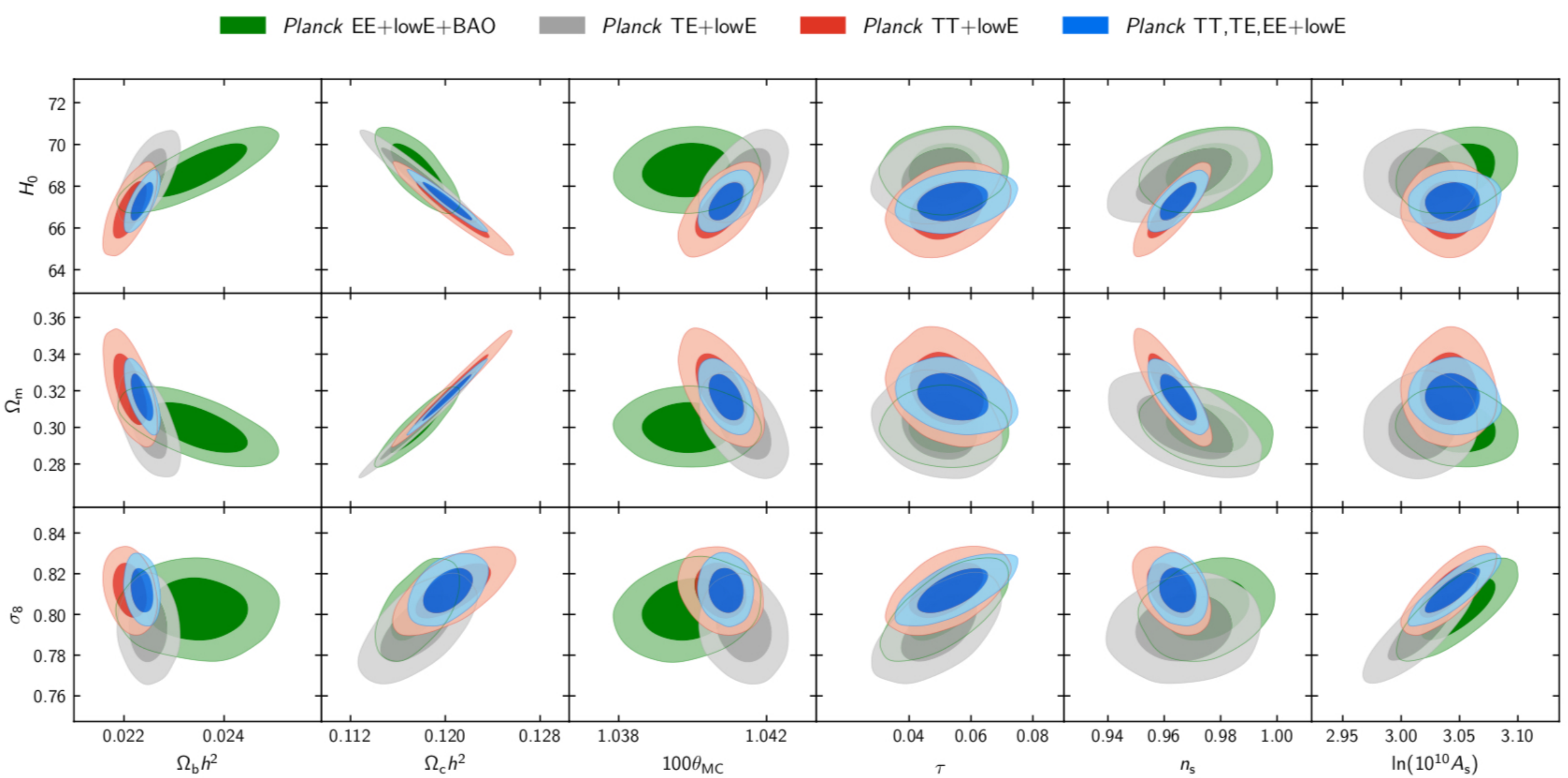




Planck 2018 results. VI. Cosmological parameters

The ΛCDM Standard Model



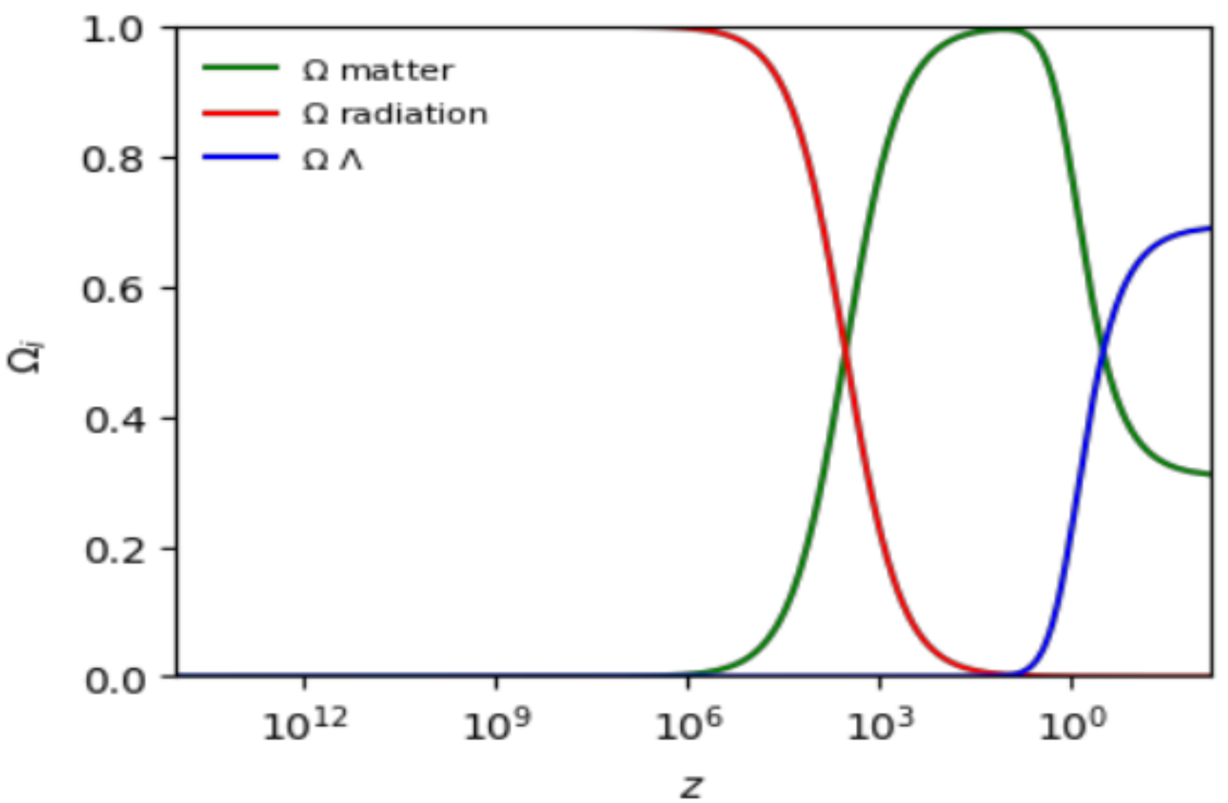


Planck 2018 results. VI. Cosmological parameters

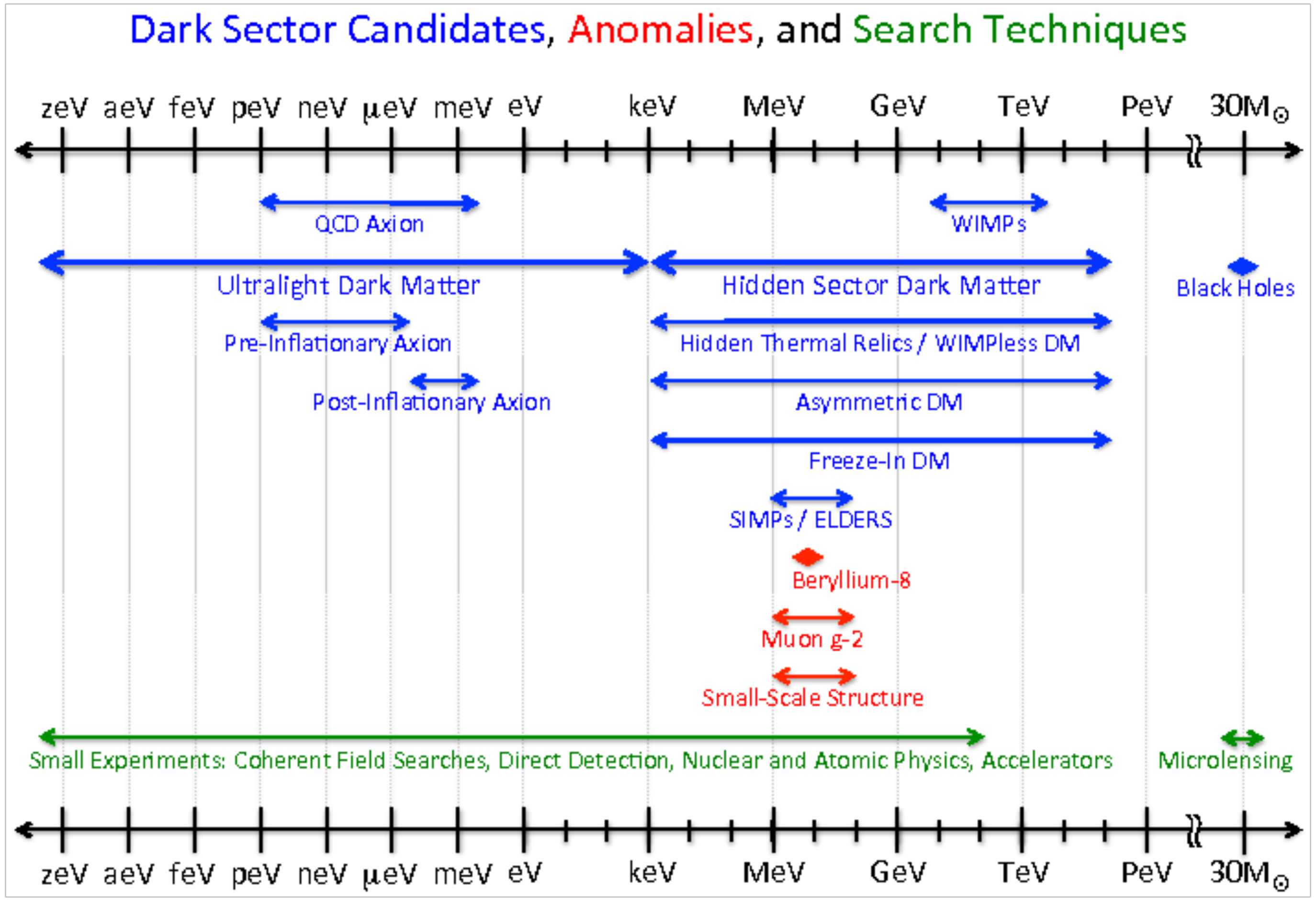

That's all Folks!

ΛCDM problems: the dark sector

Dark Energy

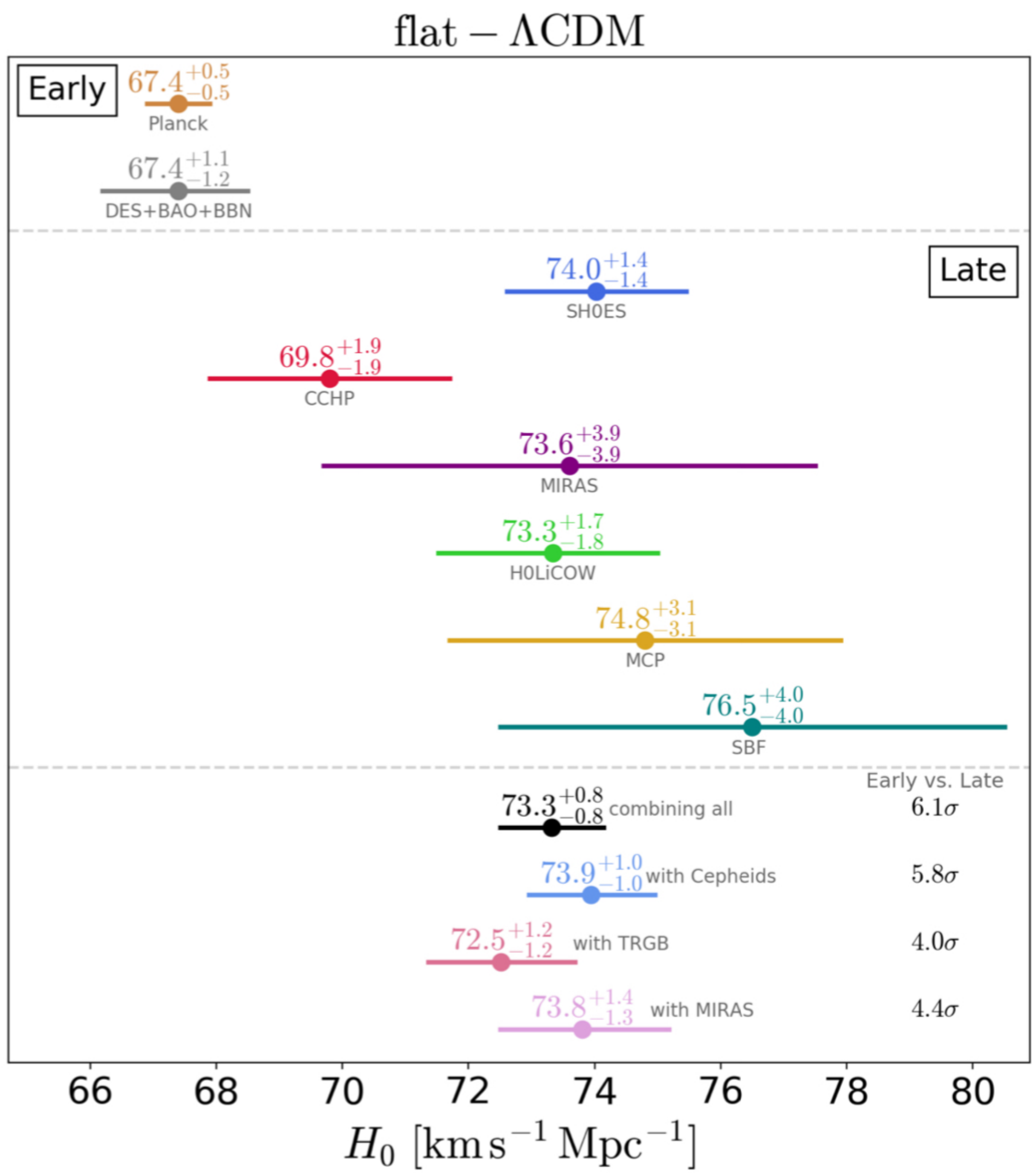


Dark Matter



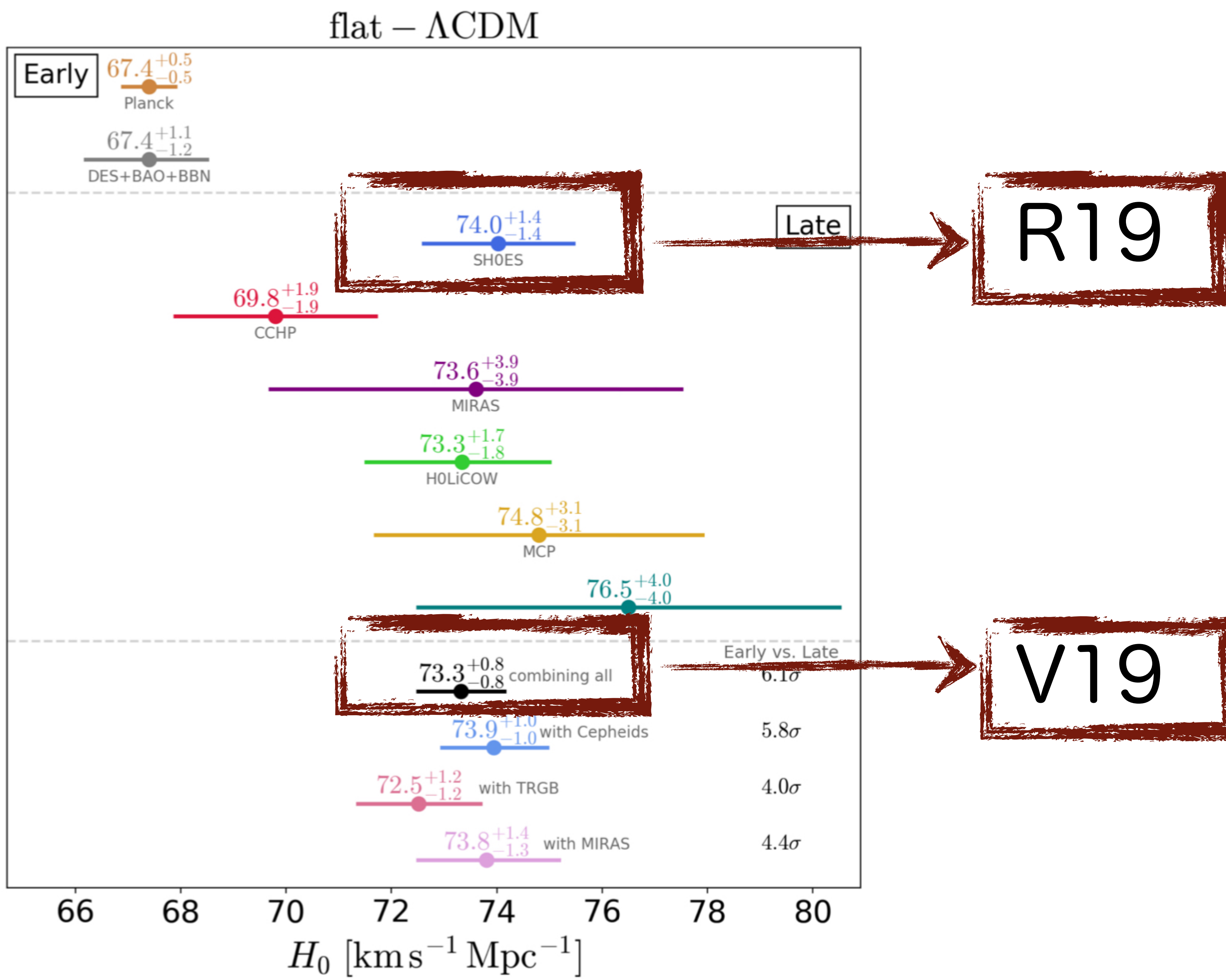
US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report

ΛCDM problems: the H_0 tension



Verde, Treu & Riess 2019

ΛCDM problems: the H_0 tension



Verde, Treu & Riess 2019

Outline

- Why consider prerecombination solutions
- Brief review of existing solutions (extra radiation, Early Dark Energy etc)
- Non-minimal coupling and the H_0 tension
- Degeneracies with neutrino sector
- Complementary tests of modified gravity

H_0 tension or r_s tension?

The H_0 tension is usually rephrased into a tension on the comoving size of the sound horizon at baryon drag

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

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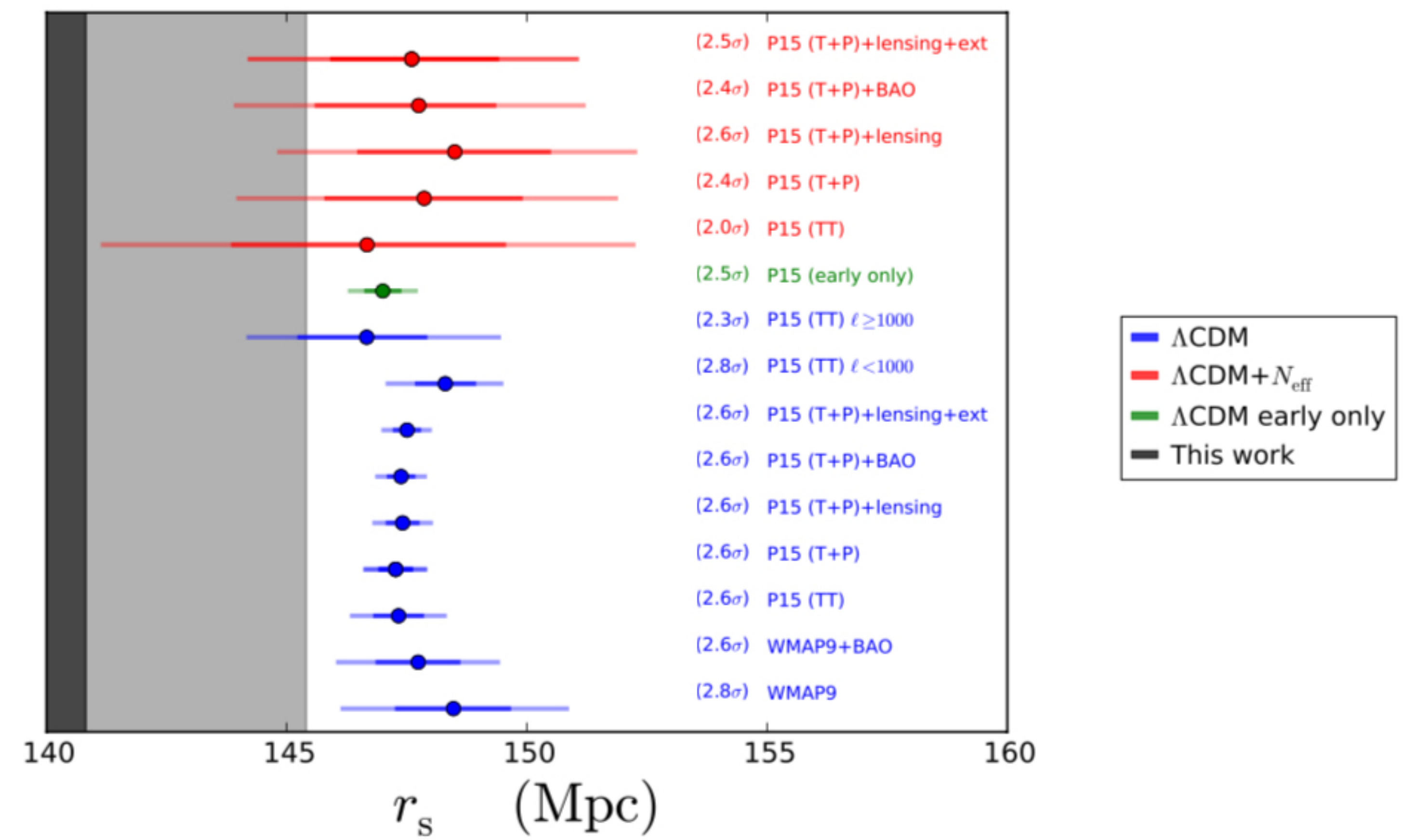

Bernal, Verde, Riess 2016

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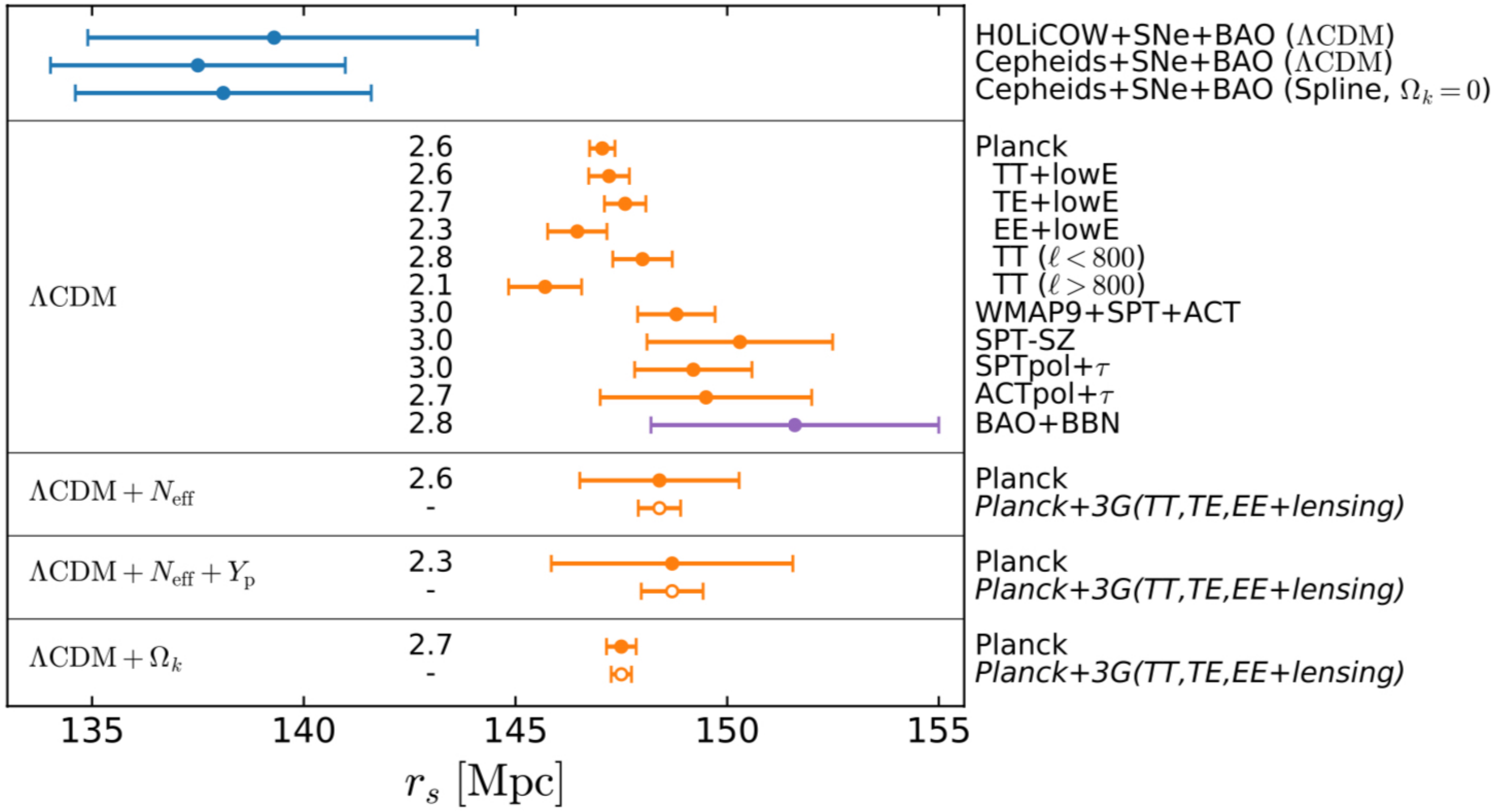

Aylor et al 2019

H_0 tension or r_s tension?

1. Determine ω_b and ω_m and compute r_s

H_0 tension or r_s tension?

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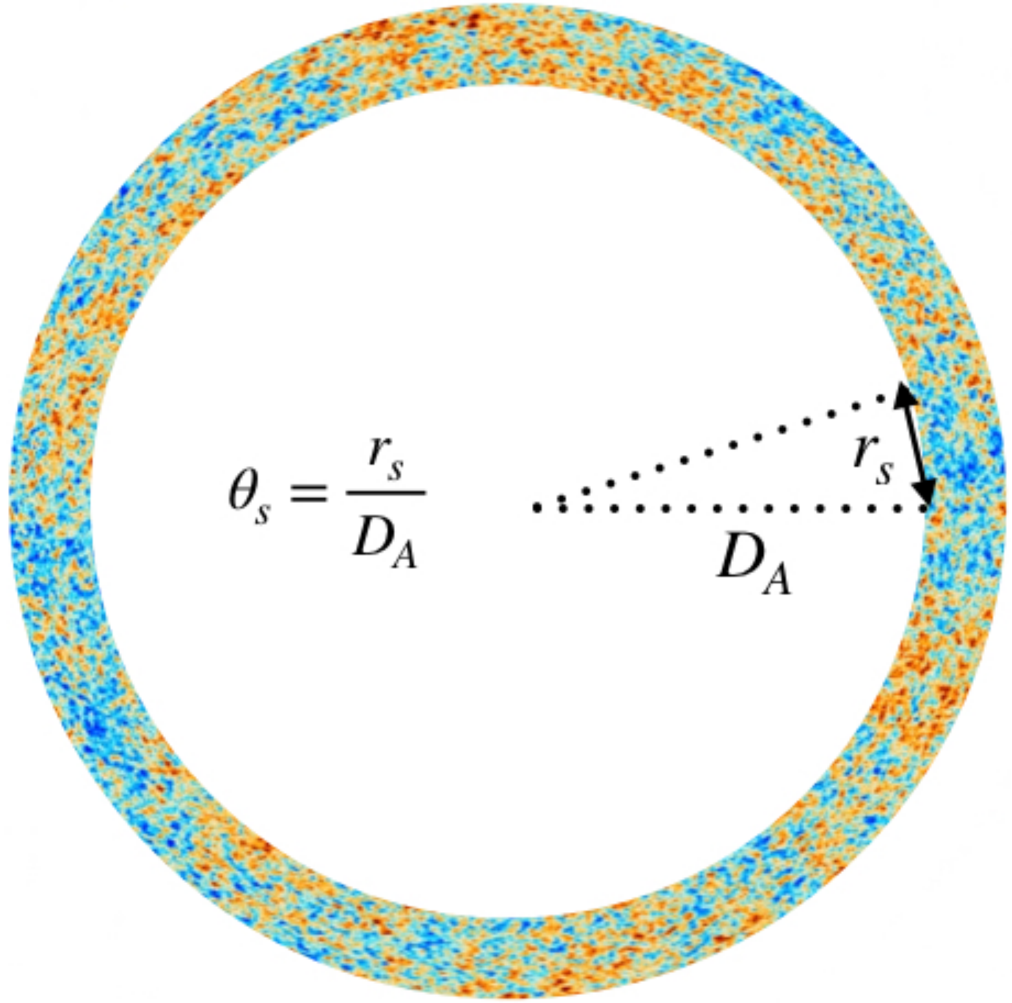
Boost and suppression of odd and even peaks

Potential envelope

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

H_0 tension or r_s tension?

1. Determine ω_b and ω_m and compute r_s



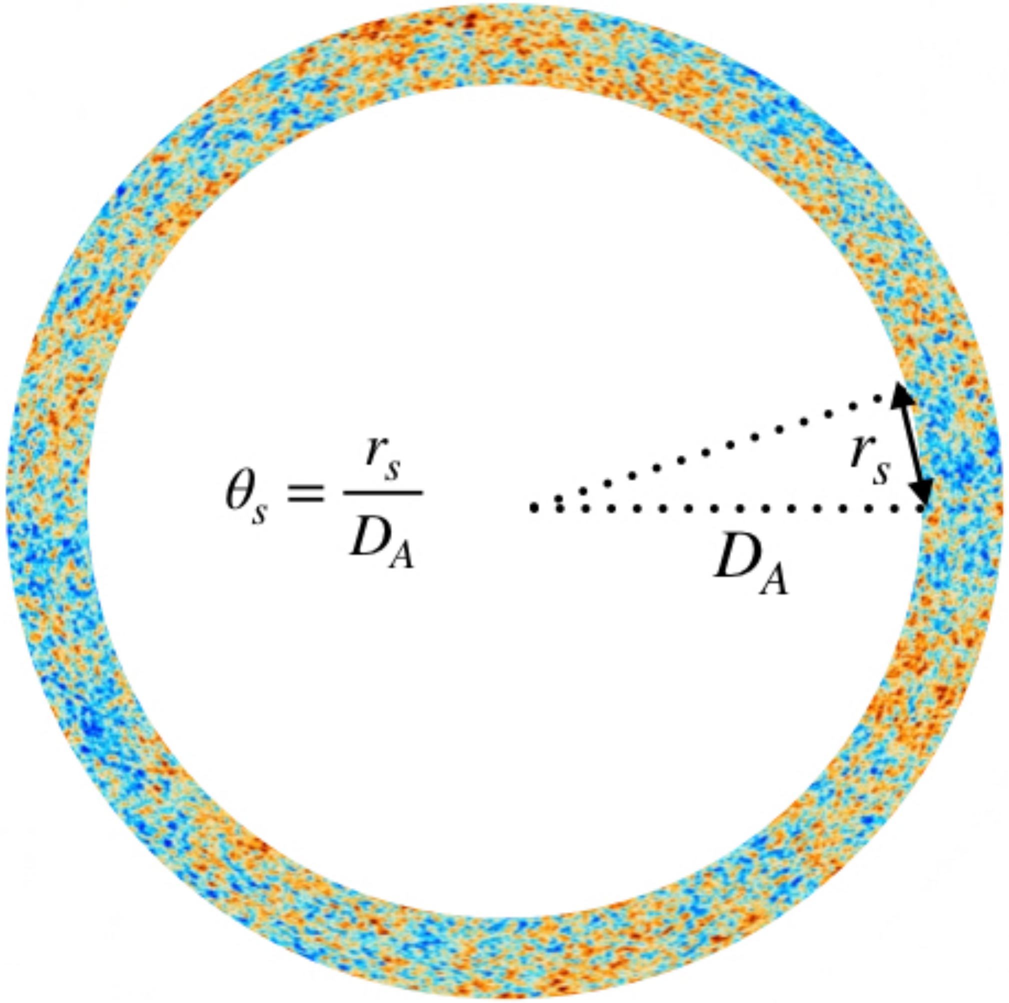
2. Infer $\theta_s \simeq \pi/\Delta\ell$

H_0 tension or r_s tension?

1. Determine ω_b and ω_m and compute r_s

2. Infer $\theta_s \simeq \pi/\Delta\ell$

3. Adjust $H(z)$ in $D_A = \int_0^{z_*} \frac{dz}{H(z)}$ to match $\theta_s$and get H_0



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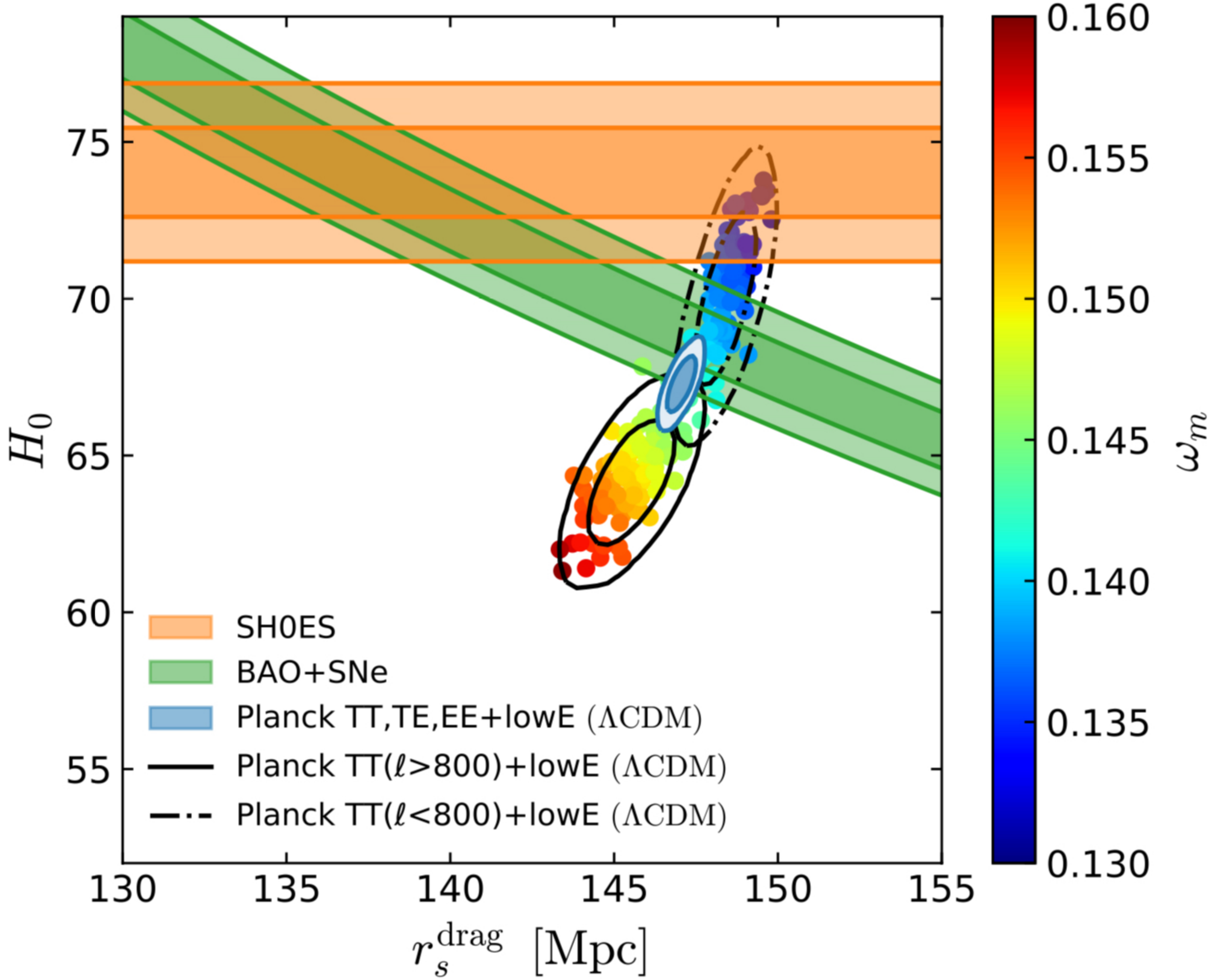

Knox & Millea 2019

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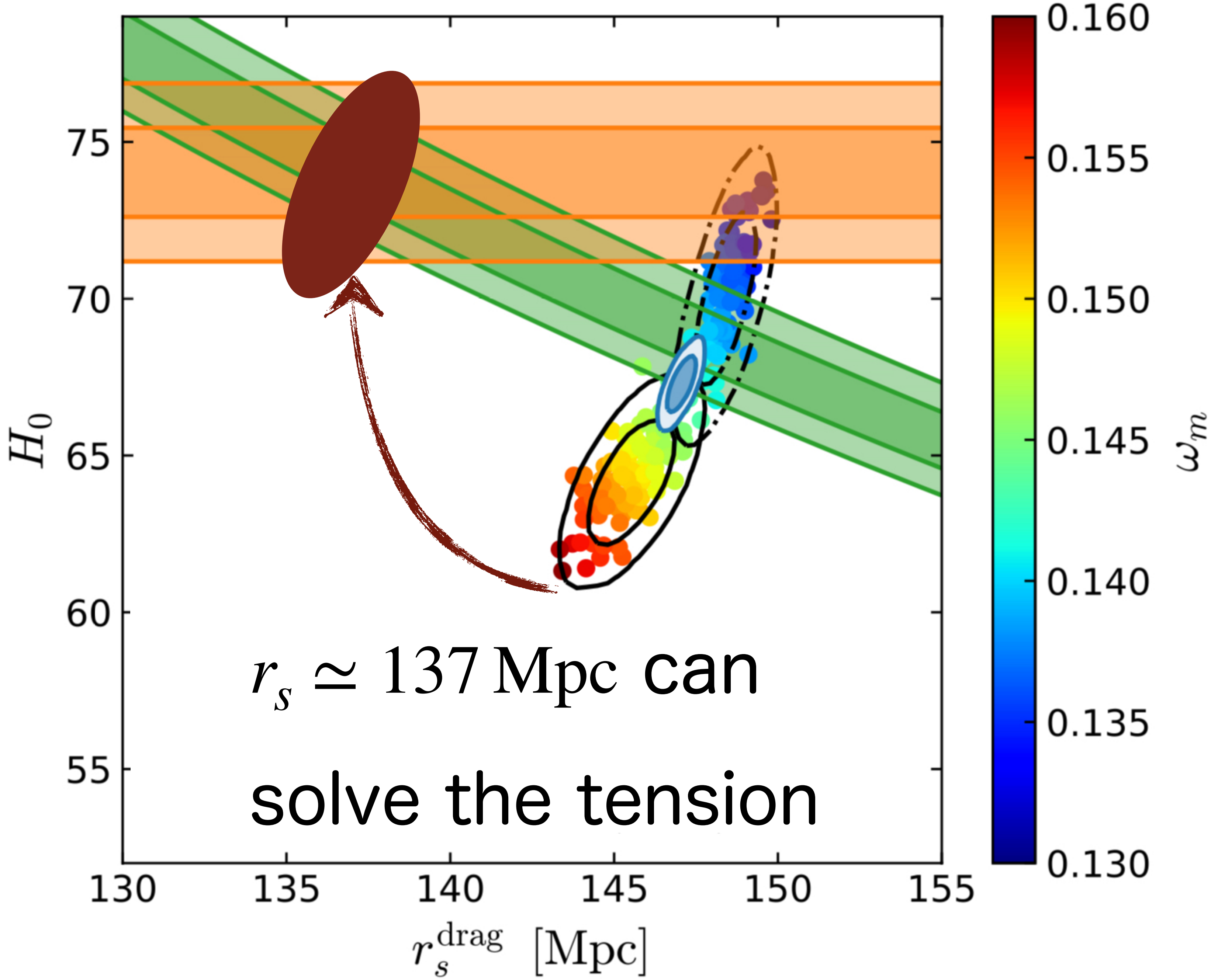

Knox & Millea 2019

"Original" attempts: extra dark radiation

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right]\rho_\gamma$$

Riess et al 2011

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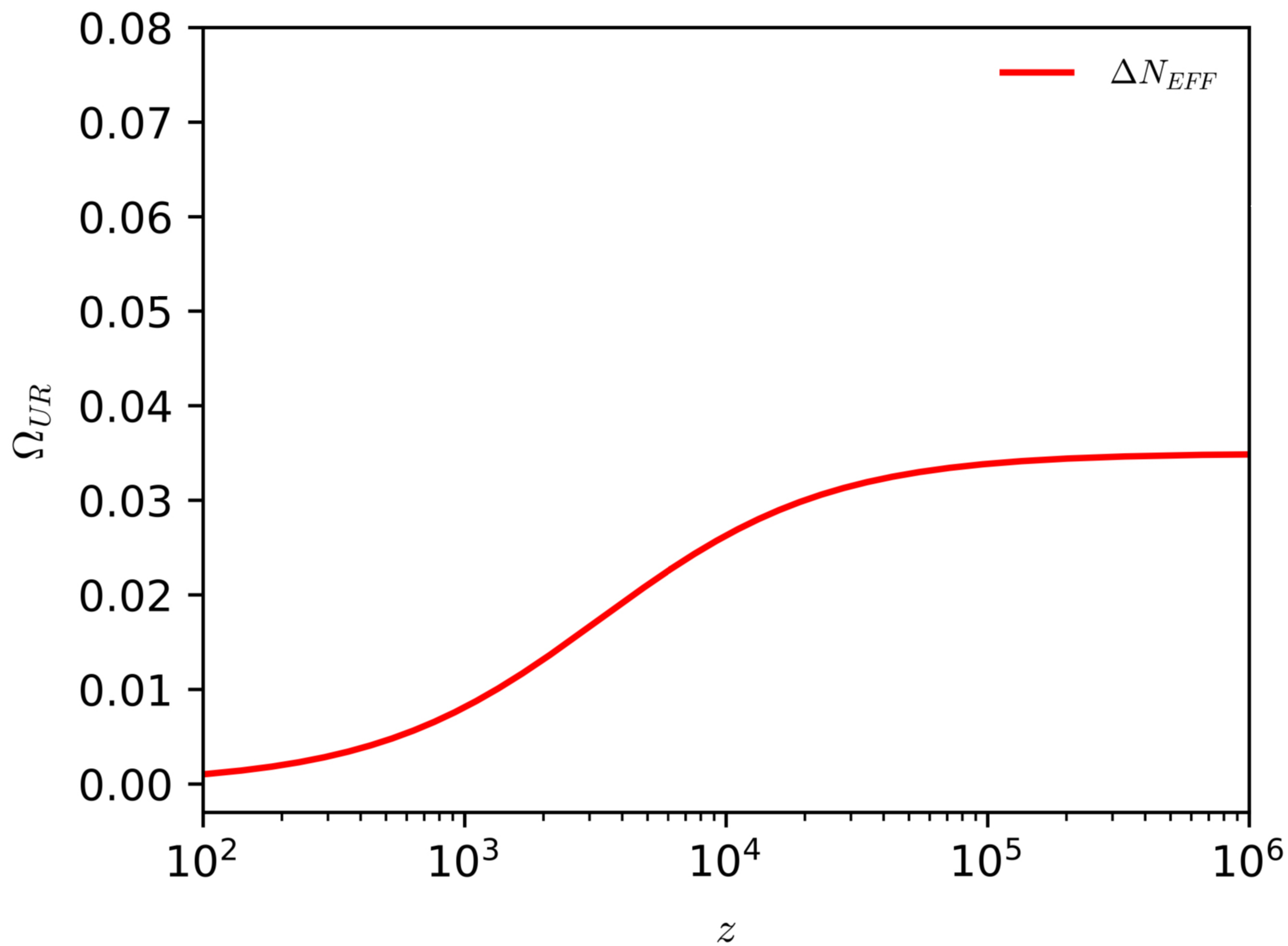

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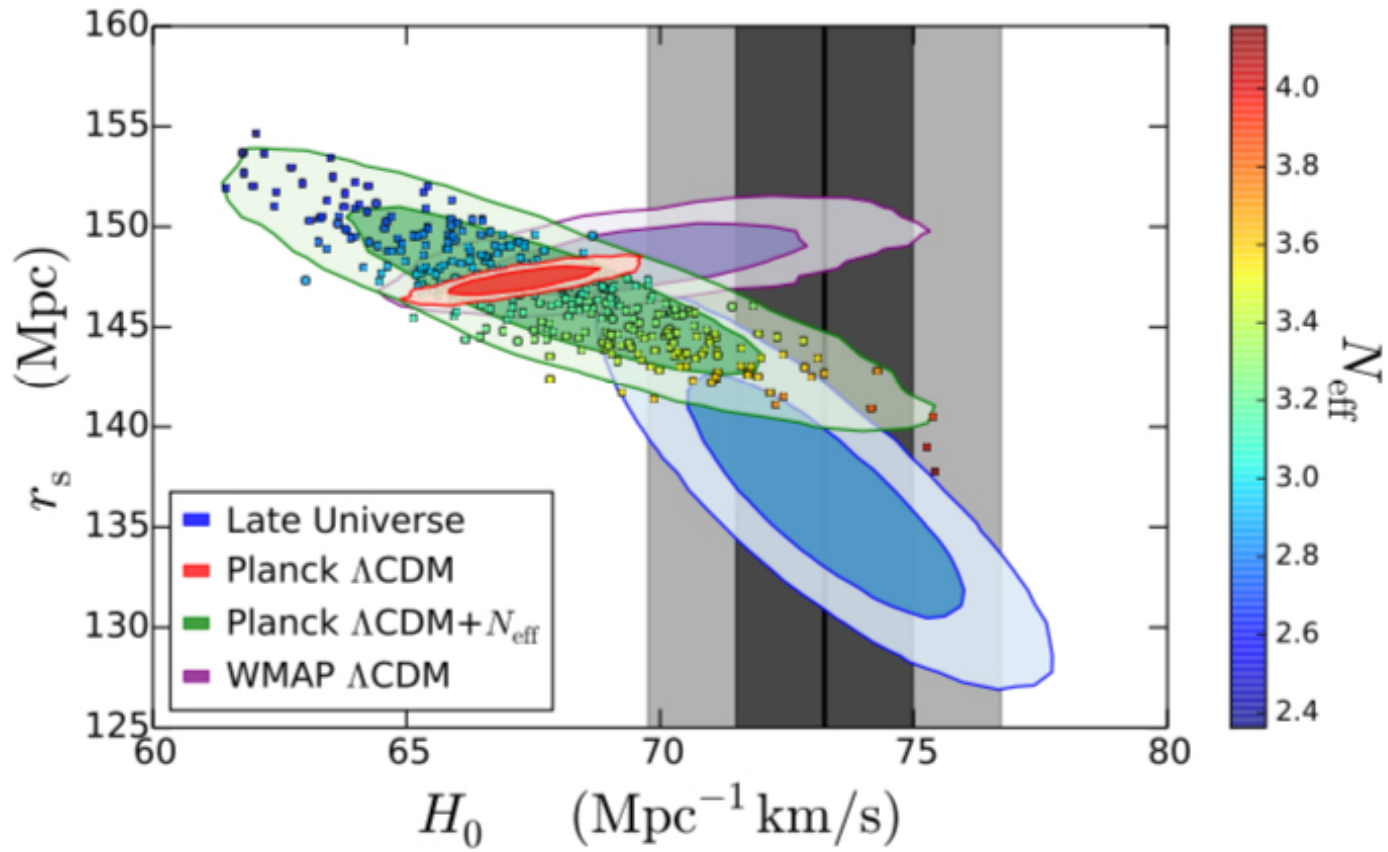

Bernal, Verde, Riess 2016

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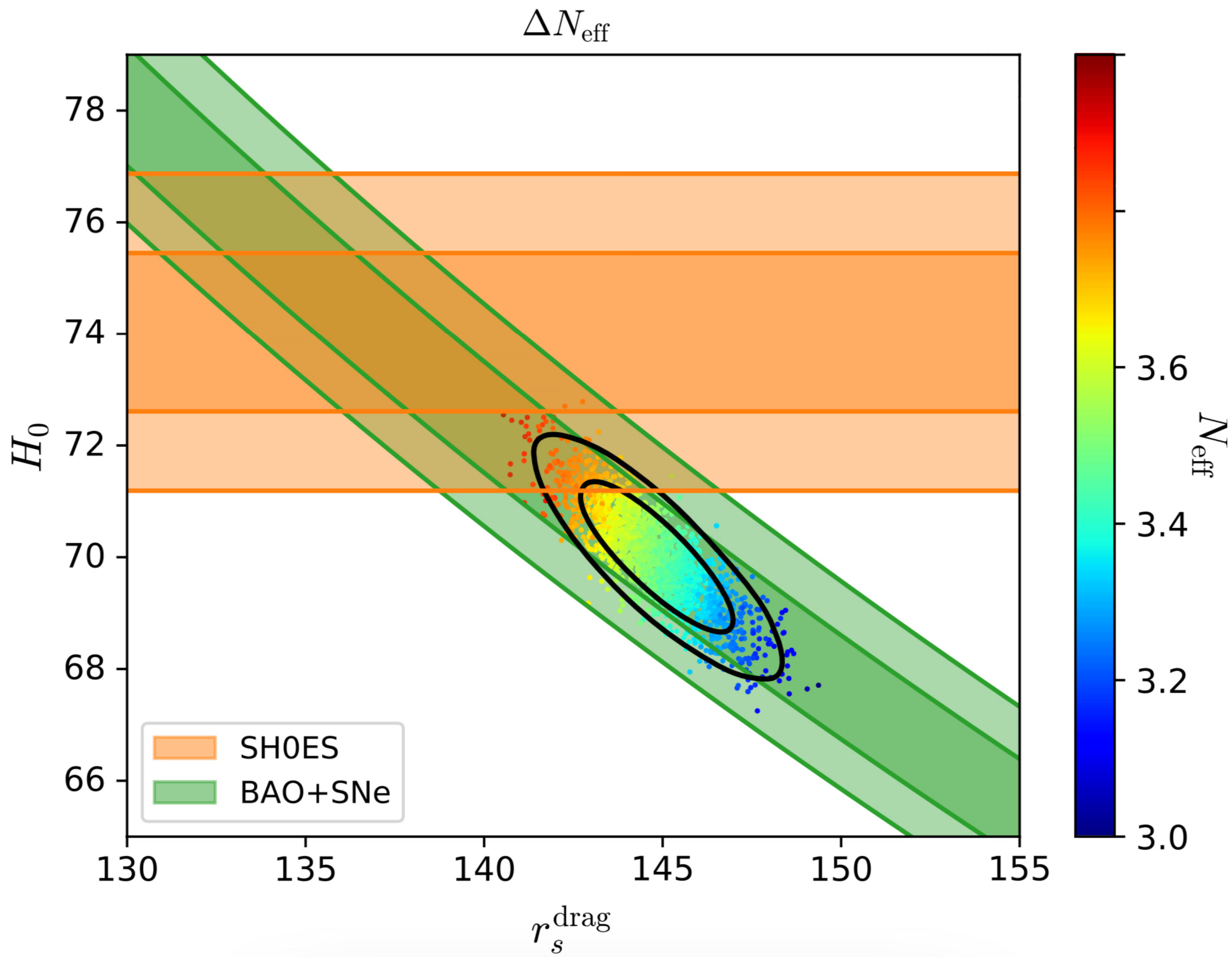
Riess et al 2011

$$H_0 = 70.01 \pm 0.89 \ (68\,\%\ \mathrm{CL})$$

$$N_{\rm eff} = 3.30 \pm 0.14 \ (68\,\%\ \mathrm{CL})$$

MB, Ballardini, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020



“Original” attempts: extra dark radiation

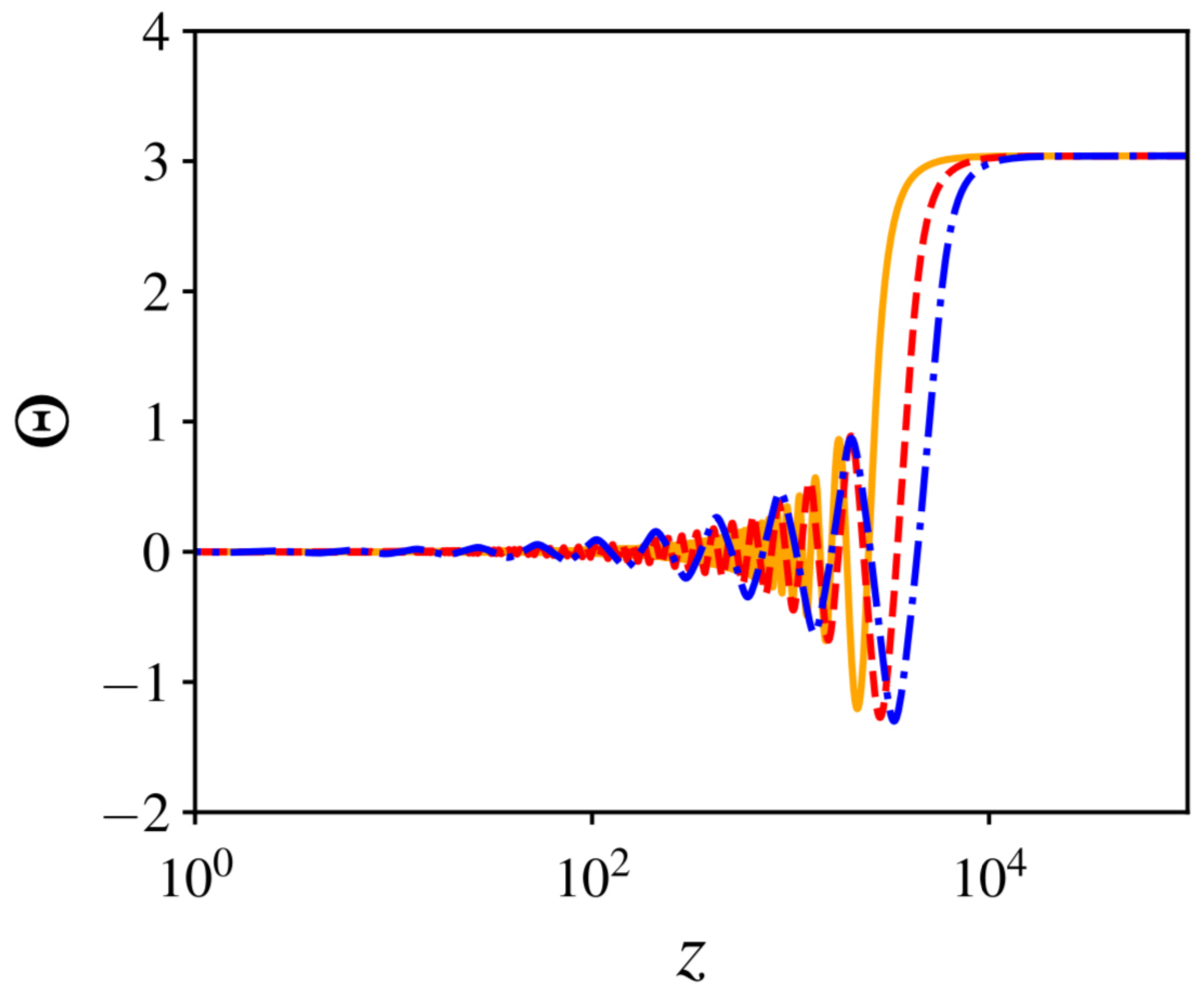
Fit to CMB is worsen!

Planck 2018 results. VI. Cosmological parameters

“Original” attempts: Early Dark Energy

Minimally coupled canonical scalar field with potential $V(\phi)$

$$V(\phi) = m^2 f^2 \left[1 + \cos\left(\frac{\phi}{f}\right)\right]^n$$



Poulin et al 2018, 2019

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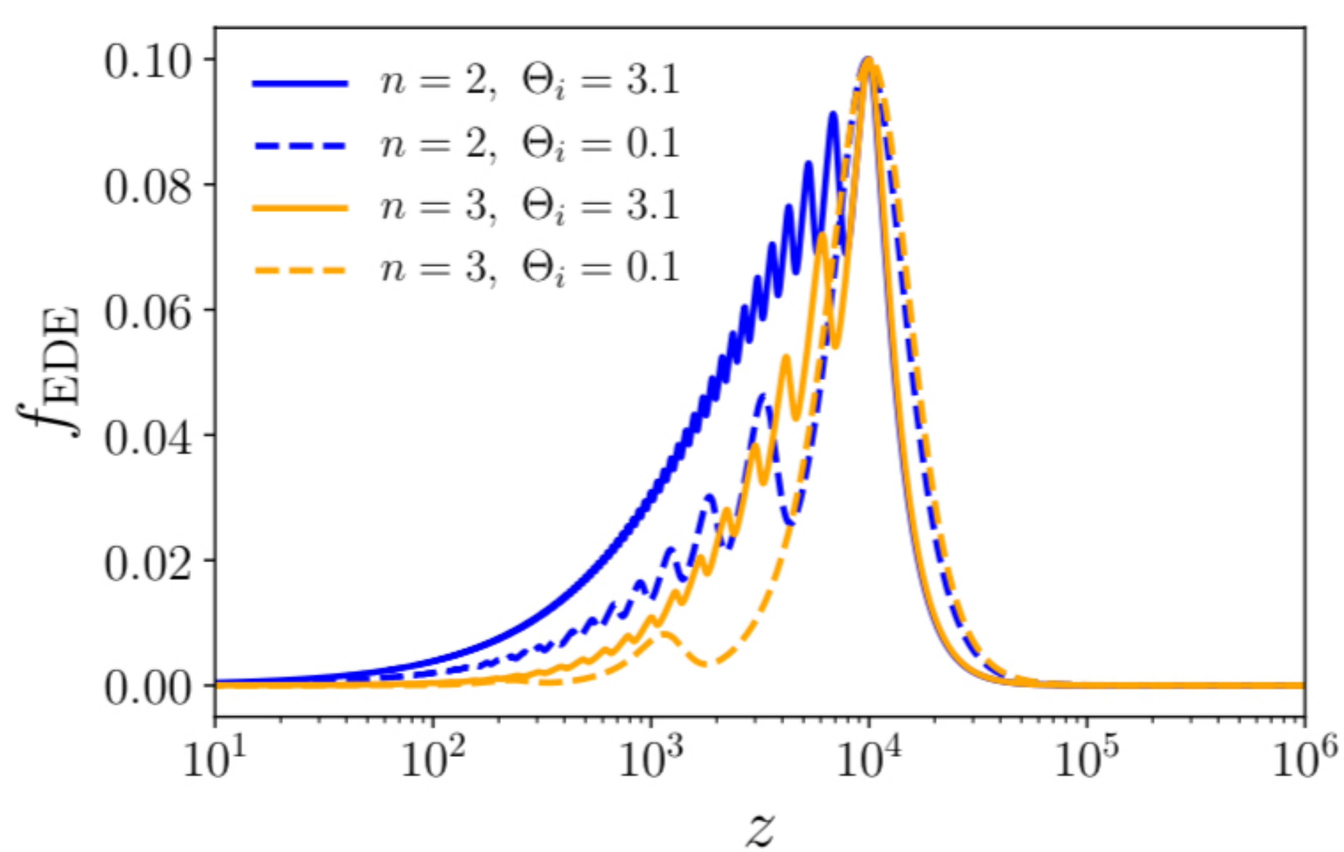

Poulin et al 2018, 2019
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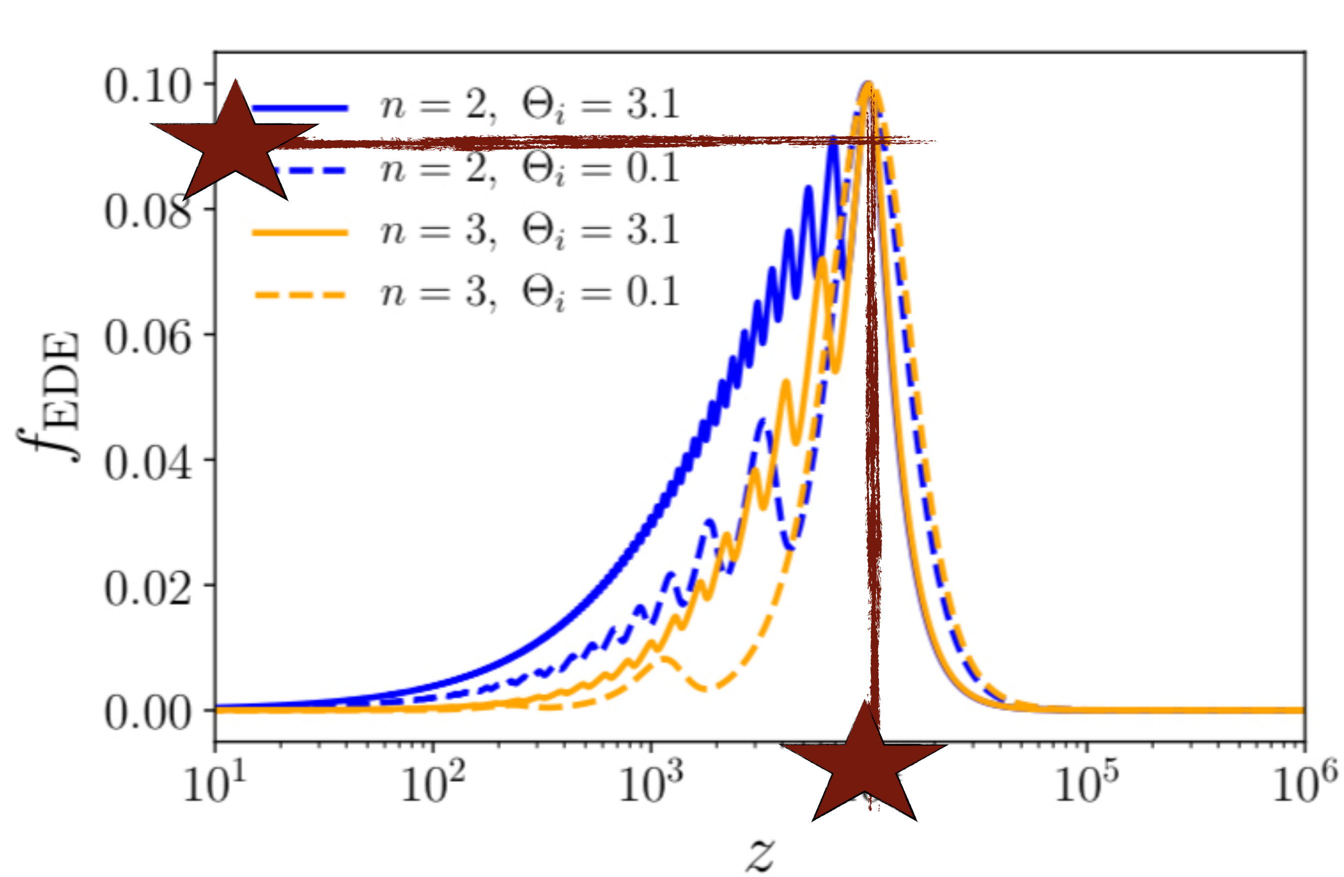

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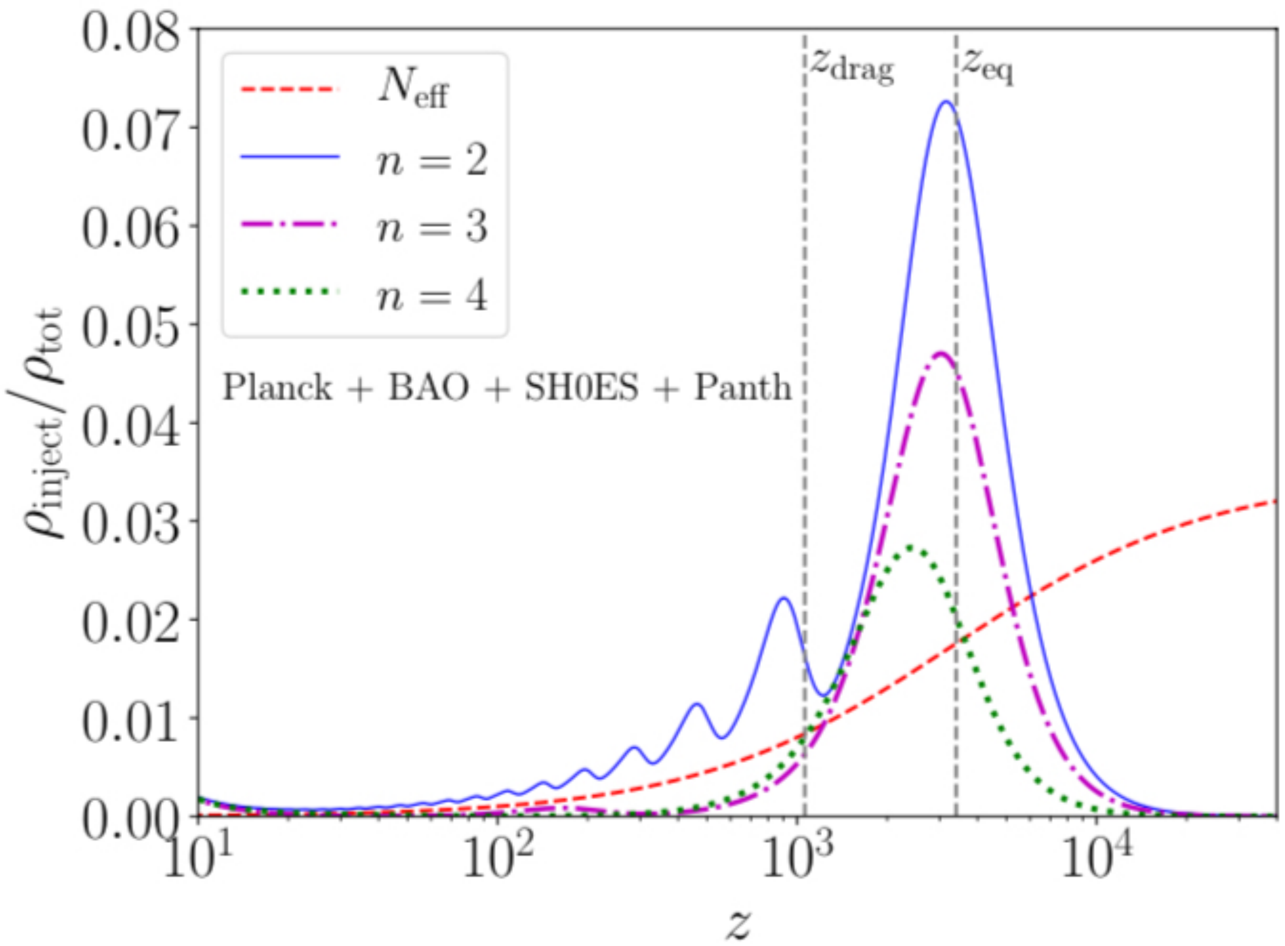

Agrawal et al 2019

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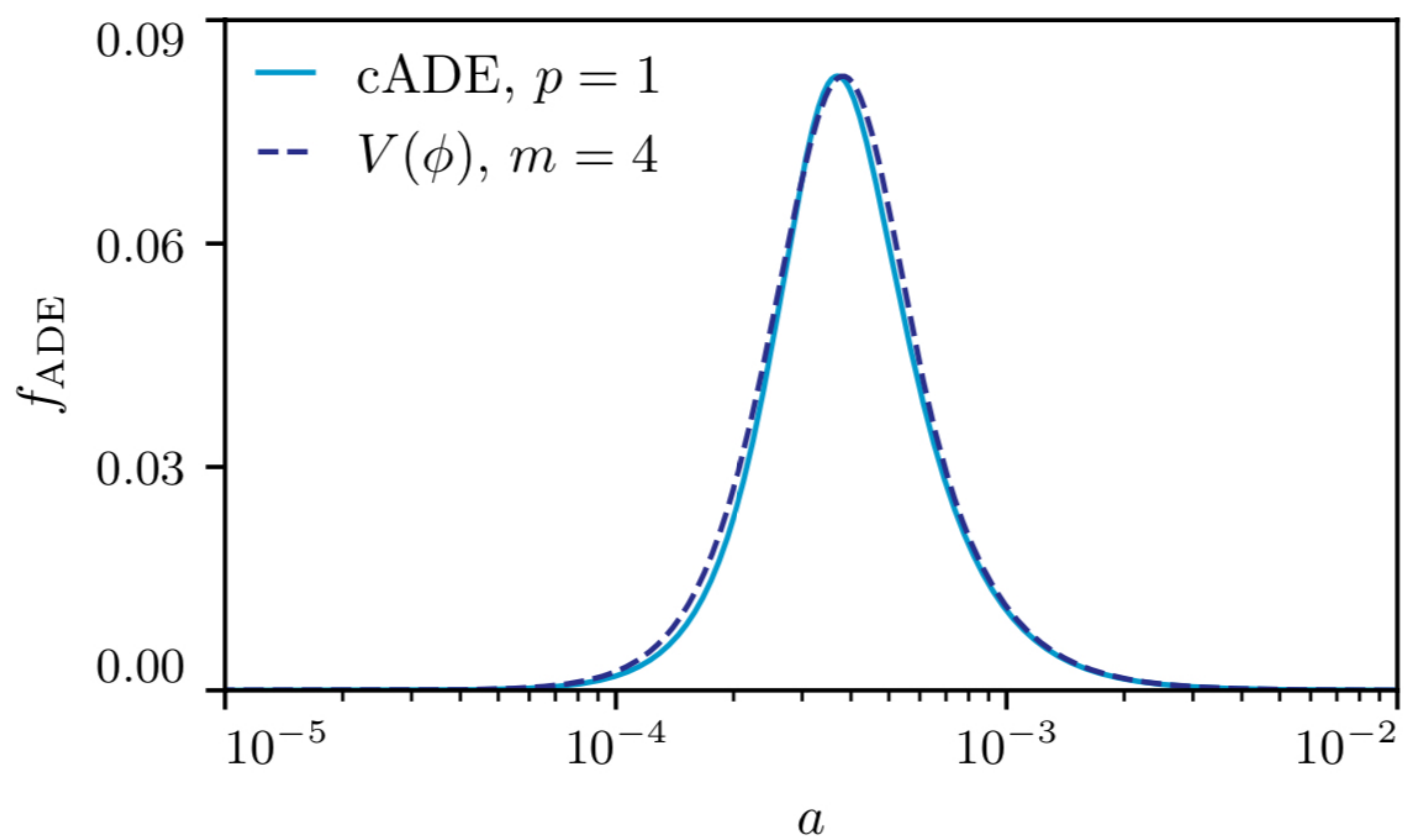

Lin, Benevento, Hu, Raveri 2019

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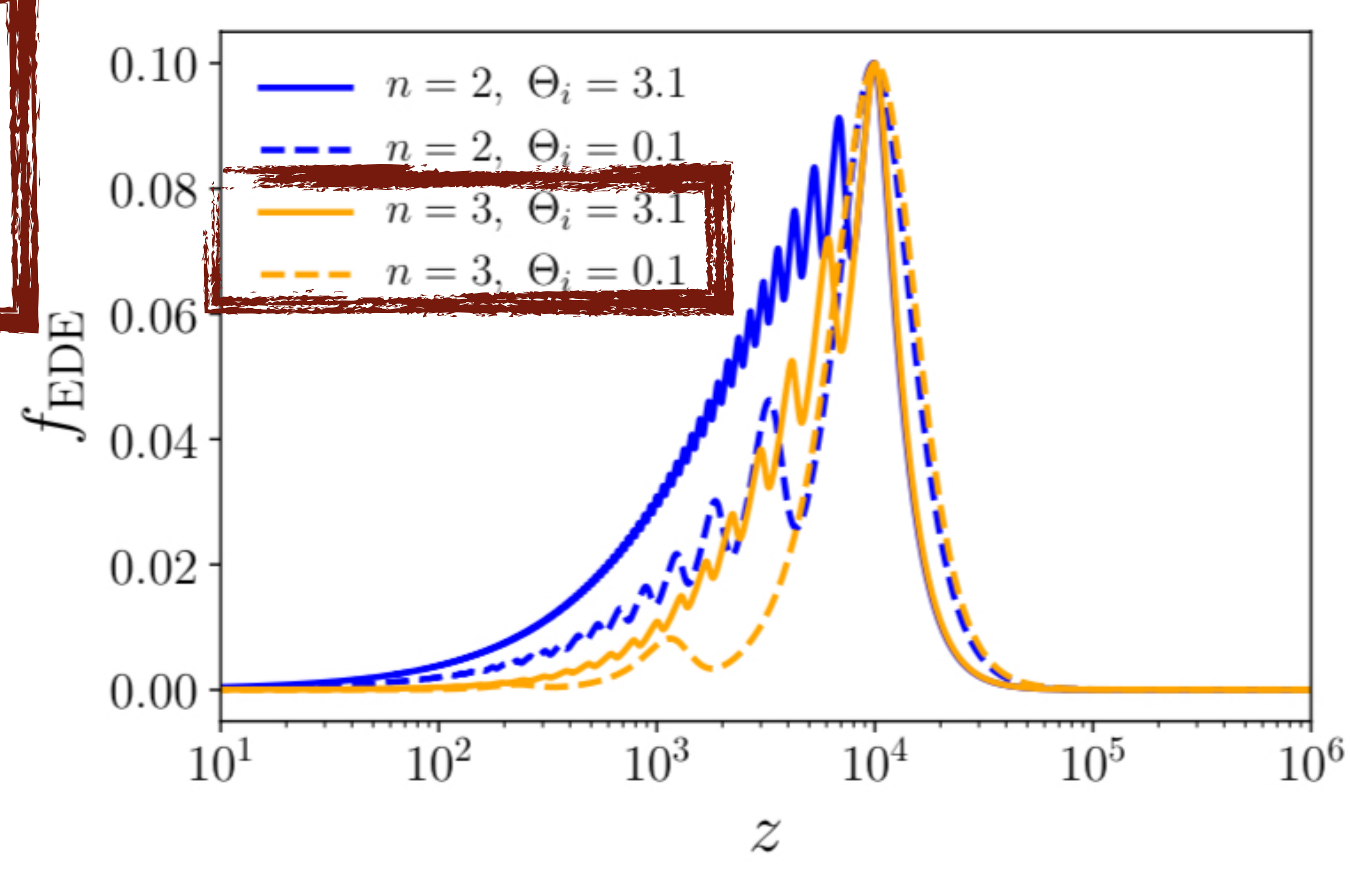

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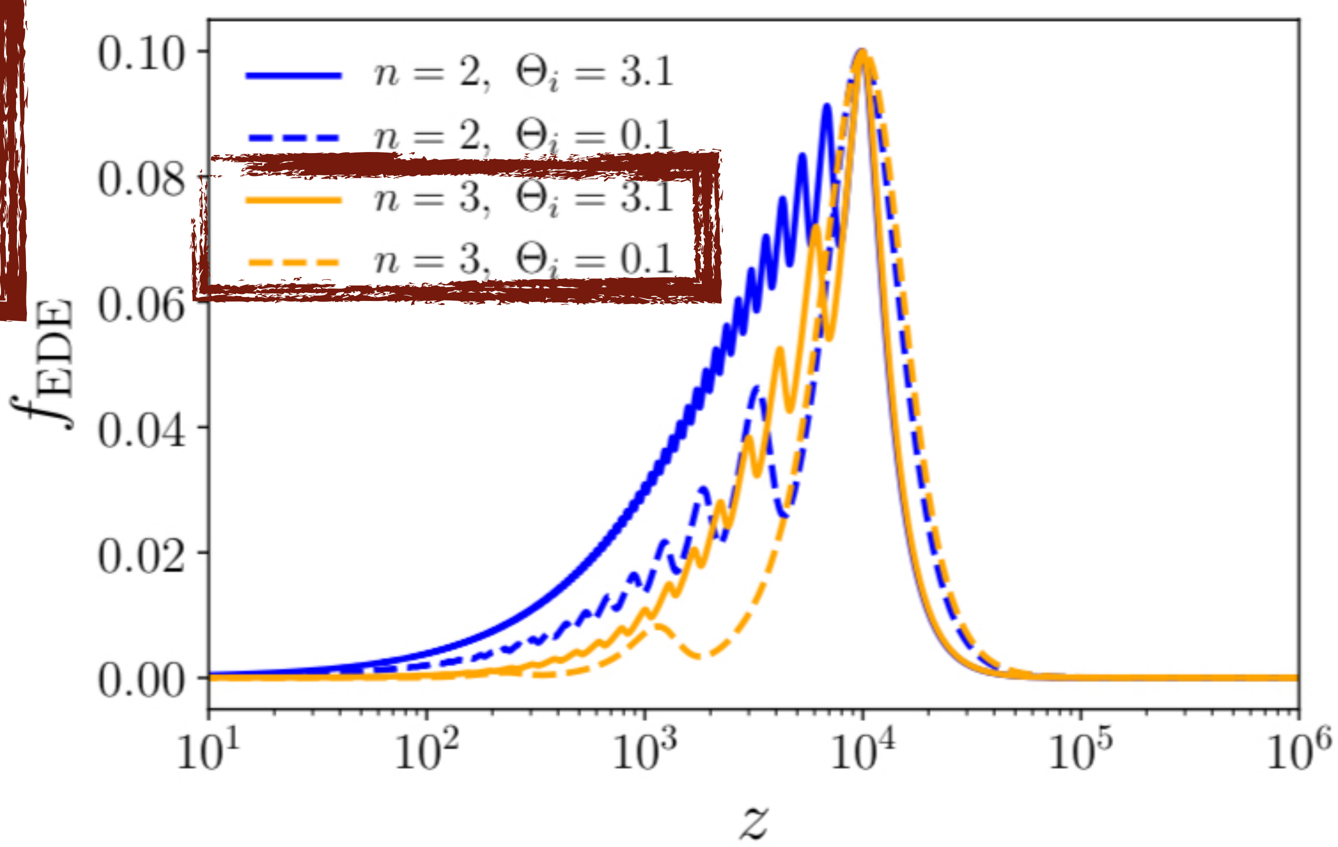
$$= m^2 f^2 \sum_n c_n \cos\left(\frac{n\phi}{f}\right)$$

$$\frac{c_2}{c_1} = -\frac{2}{5},\ \frac{c_3}{c_1} = \frac{1}{15},\ c_{n\geq 4} = 0$$



Unrealistic instanton expansion

Hill et al 2020
Gonzalez et al 2020

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$$V(\phi) = V_0 \frac{\tanh(\phi\sqrt{6\alpha})^{2p}}{[1 + \tanh(\phi\sqrt{6\alpha})]^{2n}}$$

Linder 2015,
García-García et al 2018

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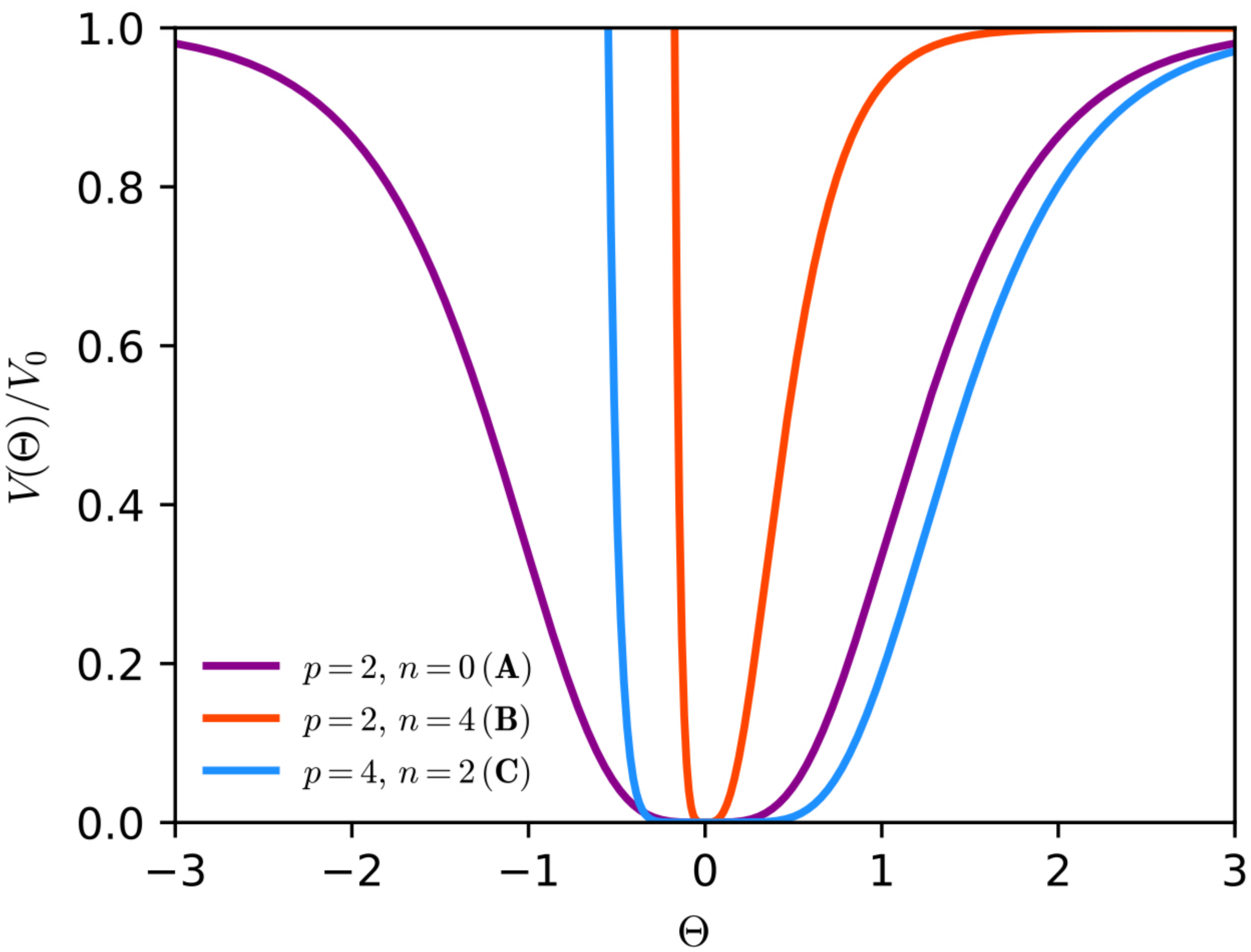
MB, Emond, Finelli, Gumrukcuoglu, Koyama 2020



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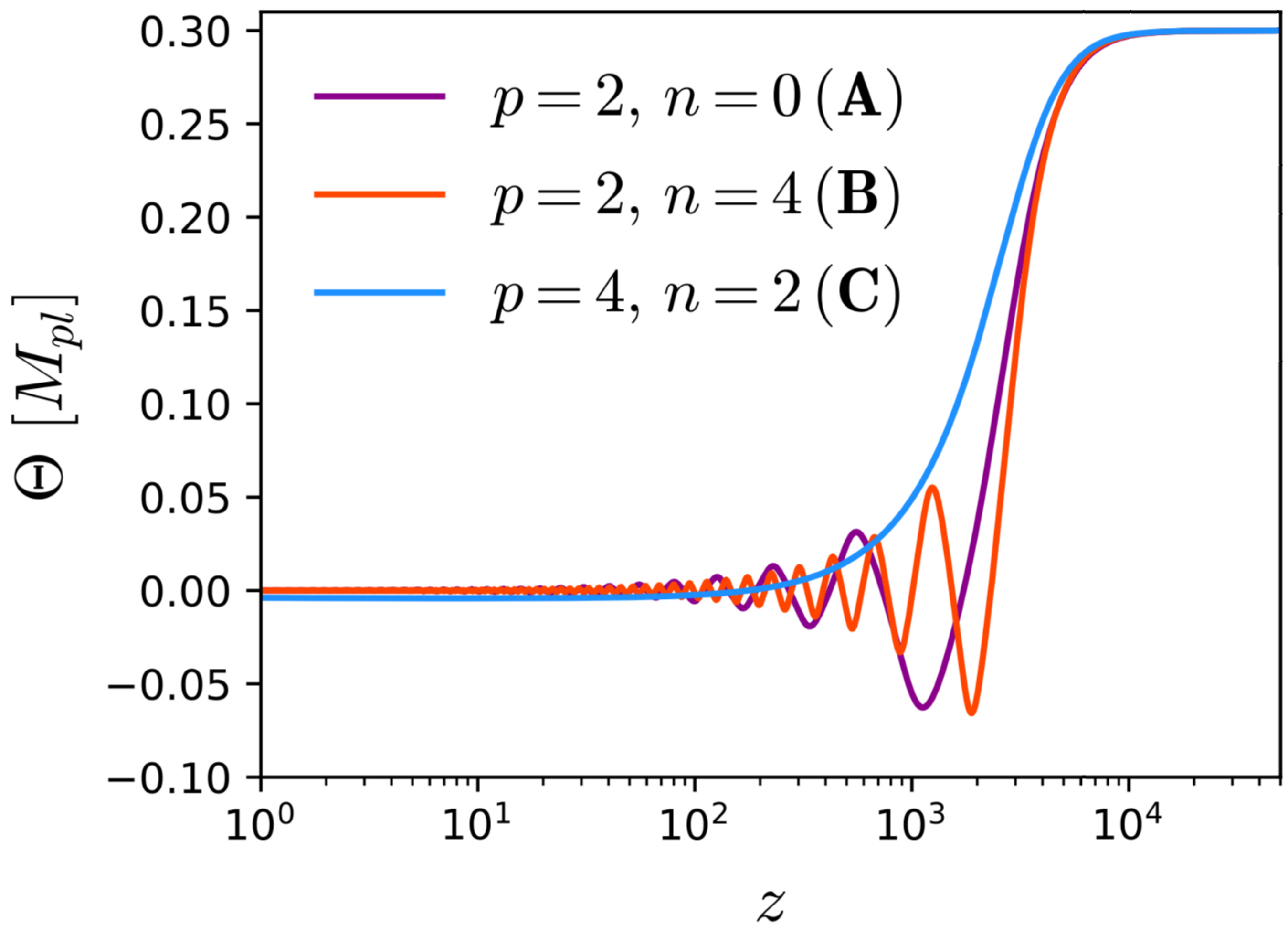

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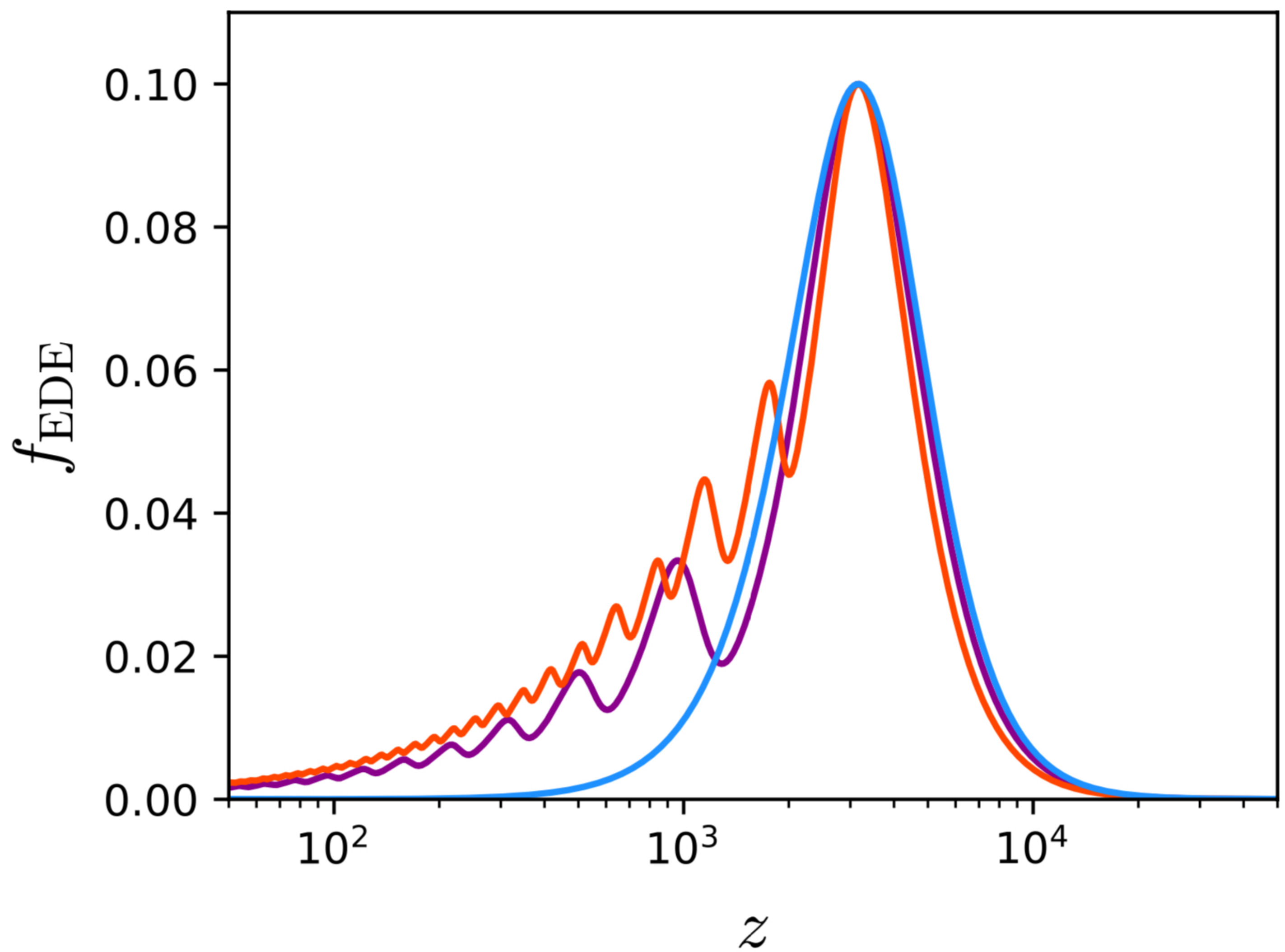

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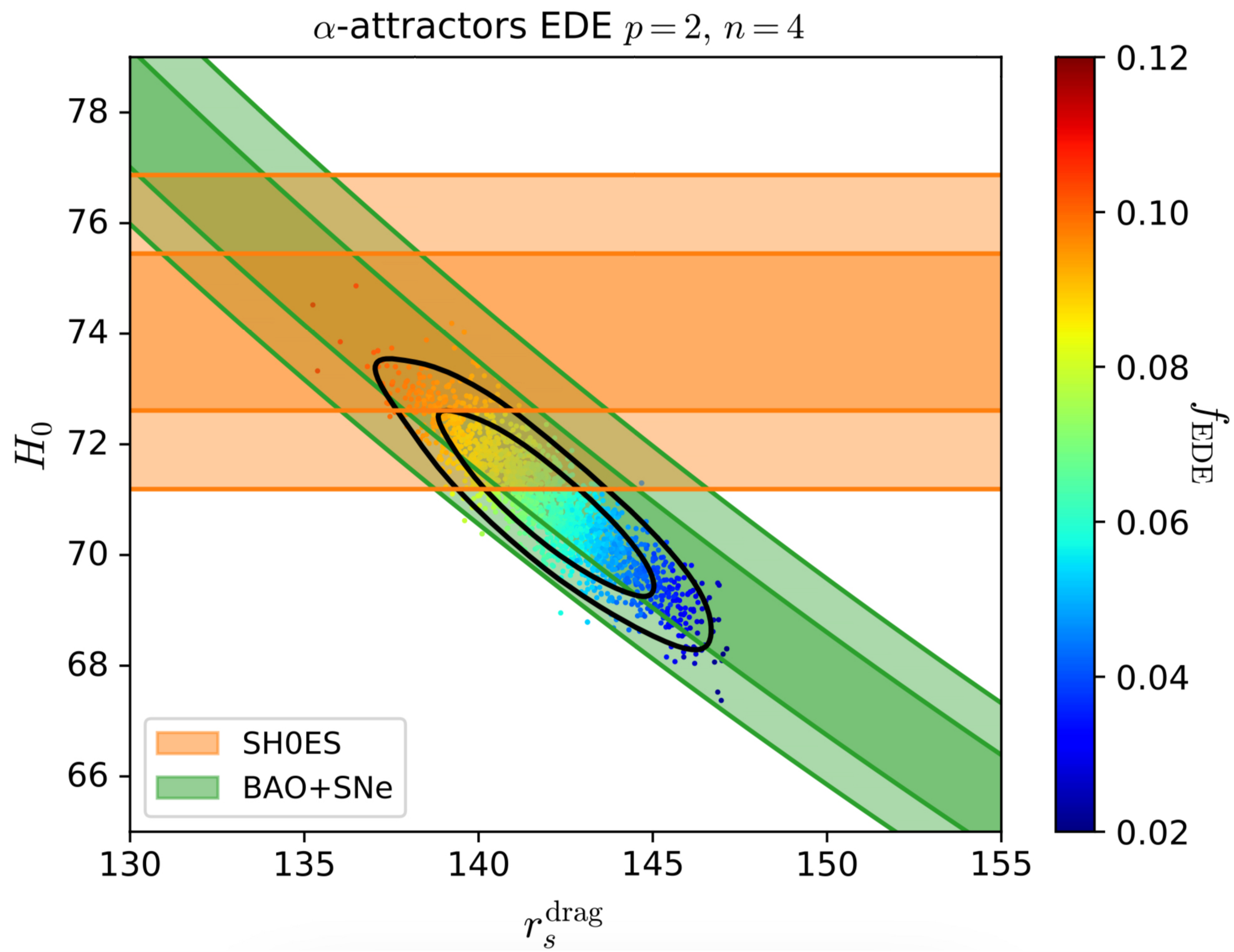


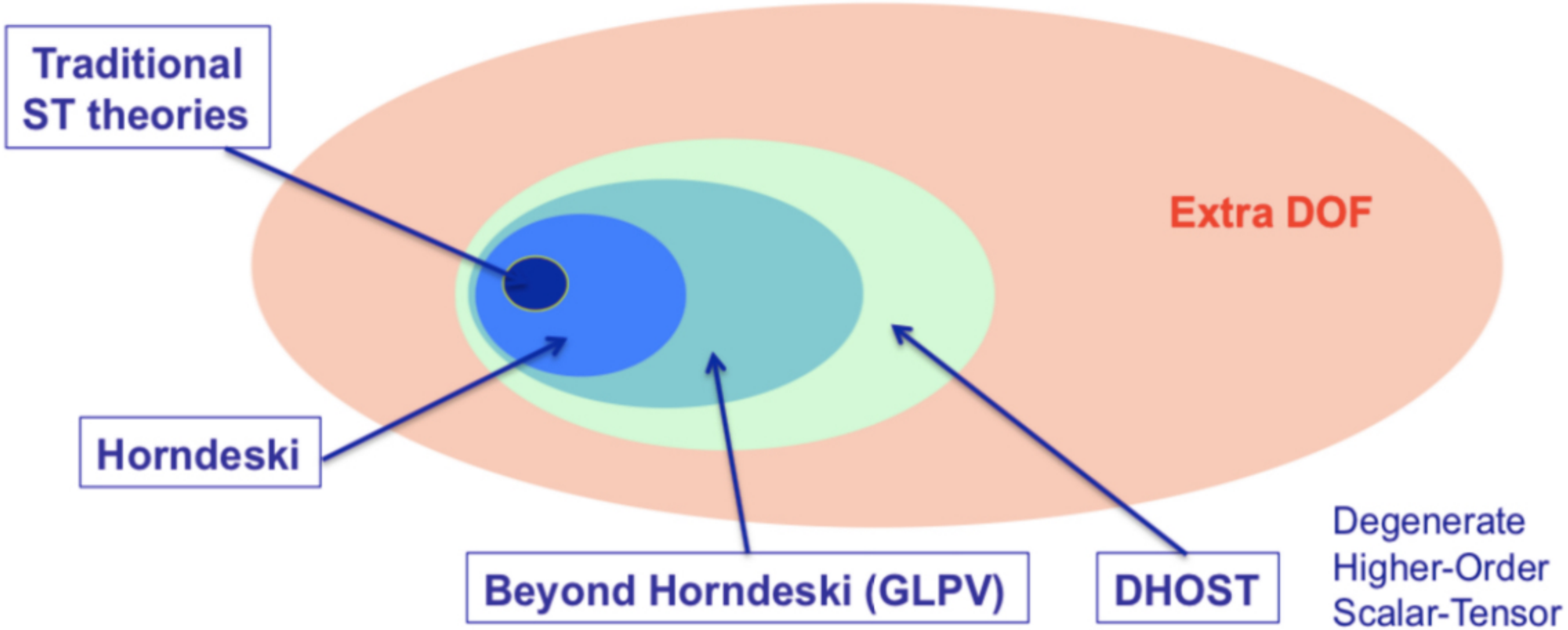
“Original” attempts: Early Dark Energy

EDE only eases the tension if LSS data are included

Dataset	H_0	f_{EDE}	σ_{SH0ES}	σ_{Planck}
Planck + BAO + SN	$69.45^{+0.72}_{-1.8}$	< 0.14 (95% CL)	2.4	1.5
Planck + FS + BAO + SN	$67.72^{+0.42}_{-1.0}$	< 0.07 (95% CL)	4.0	0.4
Planck + BAO + SN + SH0ES	71.3 ± 1.2	$0.104^{+0.034}_{-0.029}$	1.5	3.0
Planck + FS + BAO + SN + SH0ES	$69.2^{+1.1}_{-1.2}$	$0.066^{+0.033}_{-0.036}$	2.6	1.4

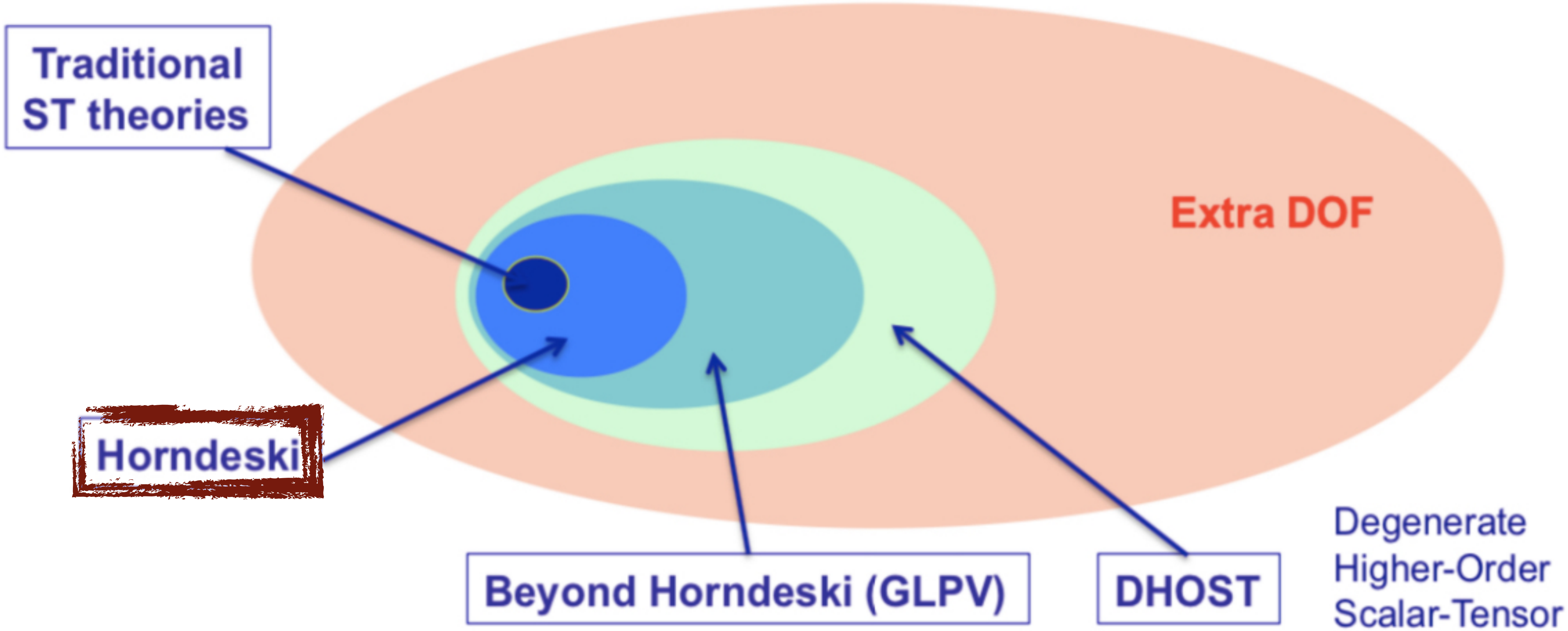
D’Amico, Senatore, Zhang, Zheng 2020,
Hill, McDonough, Toomey, Alexander 2020,
Ivanov et al 2020

Scalar-tensor theories



Langlois 2018

Scalar-tensor theories



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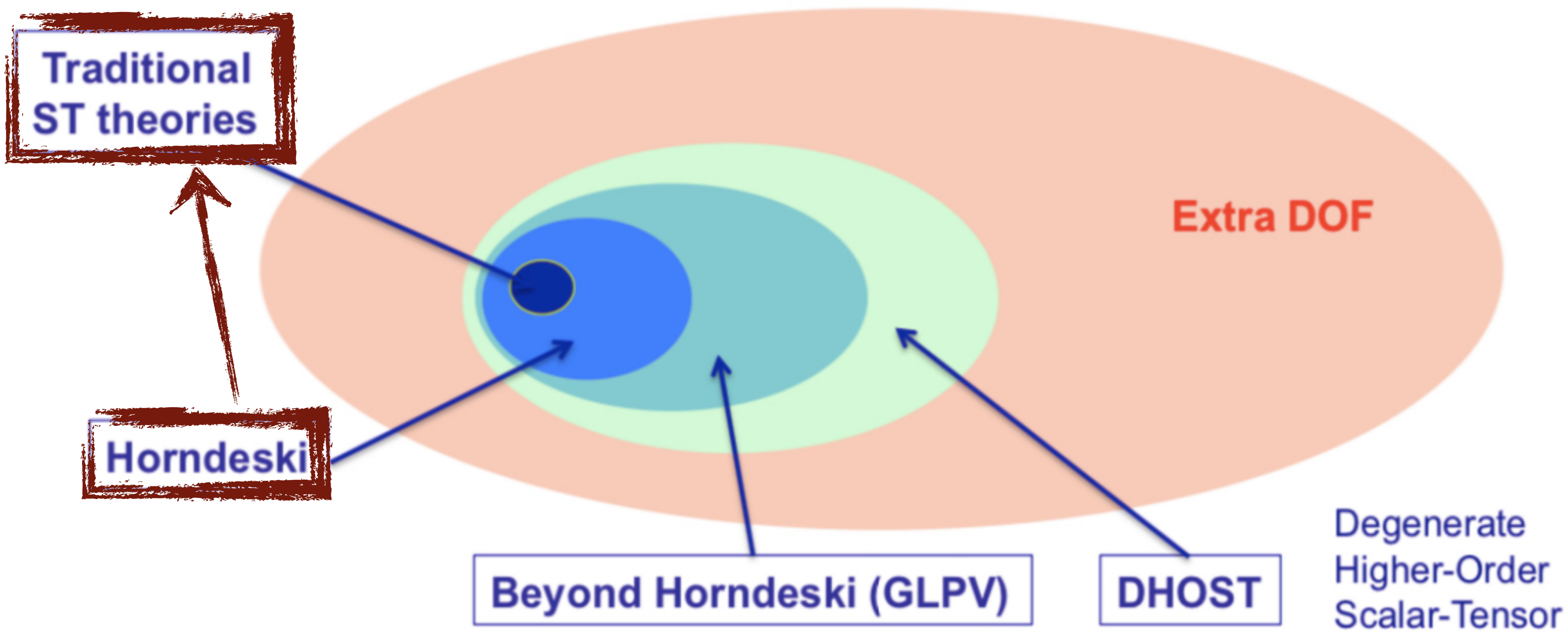
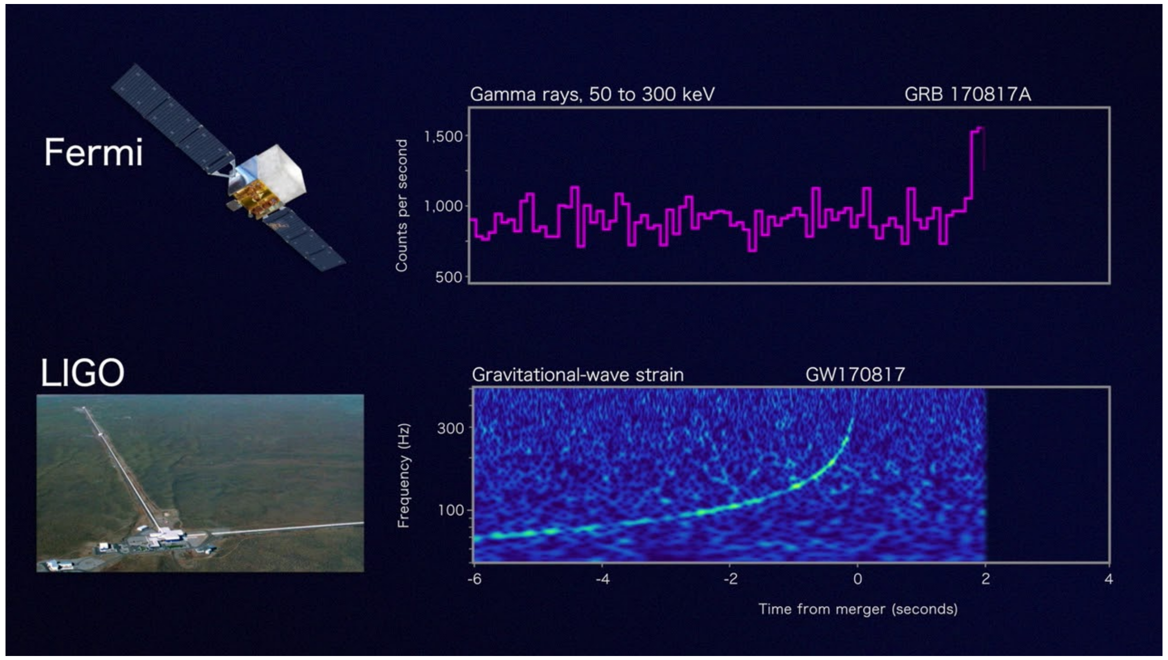


Langlois 2018

Scalar-tensor theories

$$S[g_{\mu\nu},\phi] = \int \mathrm{d}^4x\,\sqrt{-g}\left[\sum_{i=2}^{5}\mathcal{L}_i[g_{\mu\nu},\phi] + \mathcal{L}_{\mathrm{m}}\right]$$

$$\begin{aligned}
\mathcal{L}_2 &= G_2(\phi,\,X)\,,\\
\mathcal{L}_3 &= -G_3(\phi,\,X)\Box\phi\,,\\
\mathcal{L}_4 &= G_4(\phi,\,X)R + G_{4X}(\phi,\,X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right]\\
\mathcal{L}_5 &= G_5(\phi,\,X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}G_{5X}(\phi,\,X)\Big[(\Box\phi)^3\\
&\quad +2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\Big]\,.
\end{aligned}$$



Hordenski 1974
Deffayet, Gao, Steer, Zahariade 2011
Kobayashi, Yamaguchi, Yokoyama 2011

Ezquiaga & Zumalacarregui 2017
Creminelli & Vernizzi 2017
Sakstein & Jain 2017
Baker et al 2017

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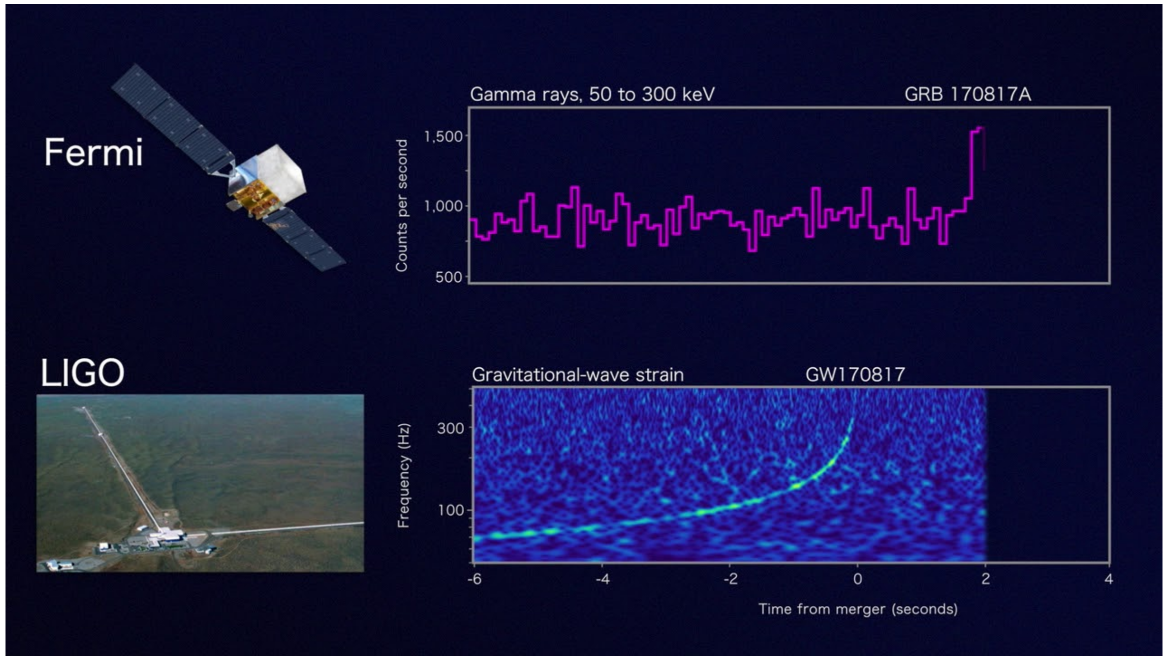

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Sakstein & Jain 2017
Baker et al 2017

Scalar-tensor theories

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [46] Brans-Dicke/$f(R)$ [47, 48] Kinetic Gravity Braiding [50]	quartic/quintic Galileons [13, 14] Fab Four [15] de Sitter Horndeski [49] $G_{\mu\nu}\phi^\mu\phi^\nu$ [51], $f(\phi)$·Gauss-Bonnet [52]
beyond H.	Derivative Conformal (19) [17] Disformal Tuning (21) quadratic DHOST with $A_1 = 0$	quartic/quintic GLPV [18] quadratic DHOST [20] with $A_1 \neq 0$ cubic DHOST [23]
	Viable after GW170817	Non-viable after GW170817

Ezquiaga & Zumalacarregui 2017

H&H: Hubble & Hordenski

$$S[g_{\mu\nu}, \phi] = \int \mathrm{d}^4x\,\sqrt{-g}\left[\sum_{i=2}^{5}\mathcal{L}_i[g_{\mu\nu}, \phi] + \mathcal{L}_\mathrm{m}\right]$$

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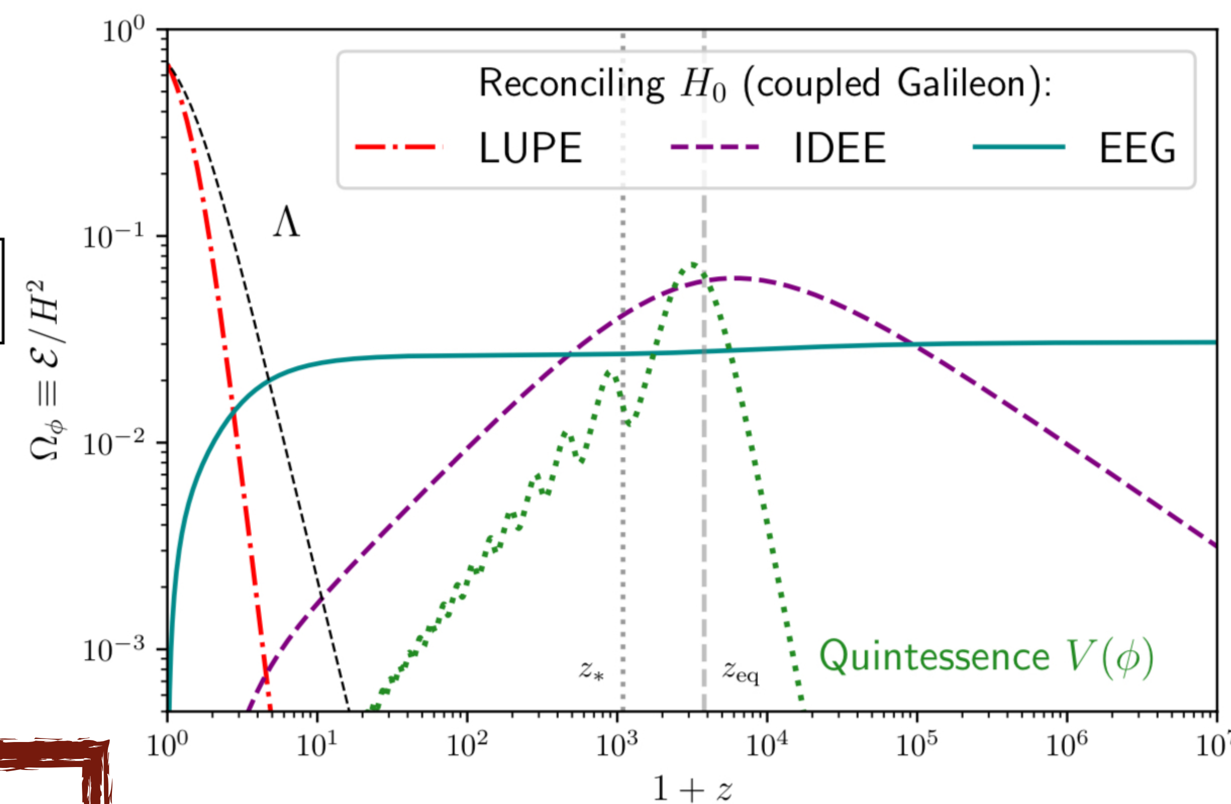


$$\boxed{\mathcal{L}_{G3,C} = \frac{M_P^2}{2}C(\phi)R + 2\frac{c_3}{M^3}X\Box\phi + c_2X - 2\Lambda + \mathcal{L}_\mathrm{m}}$$

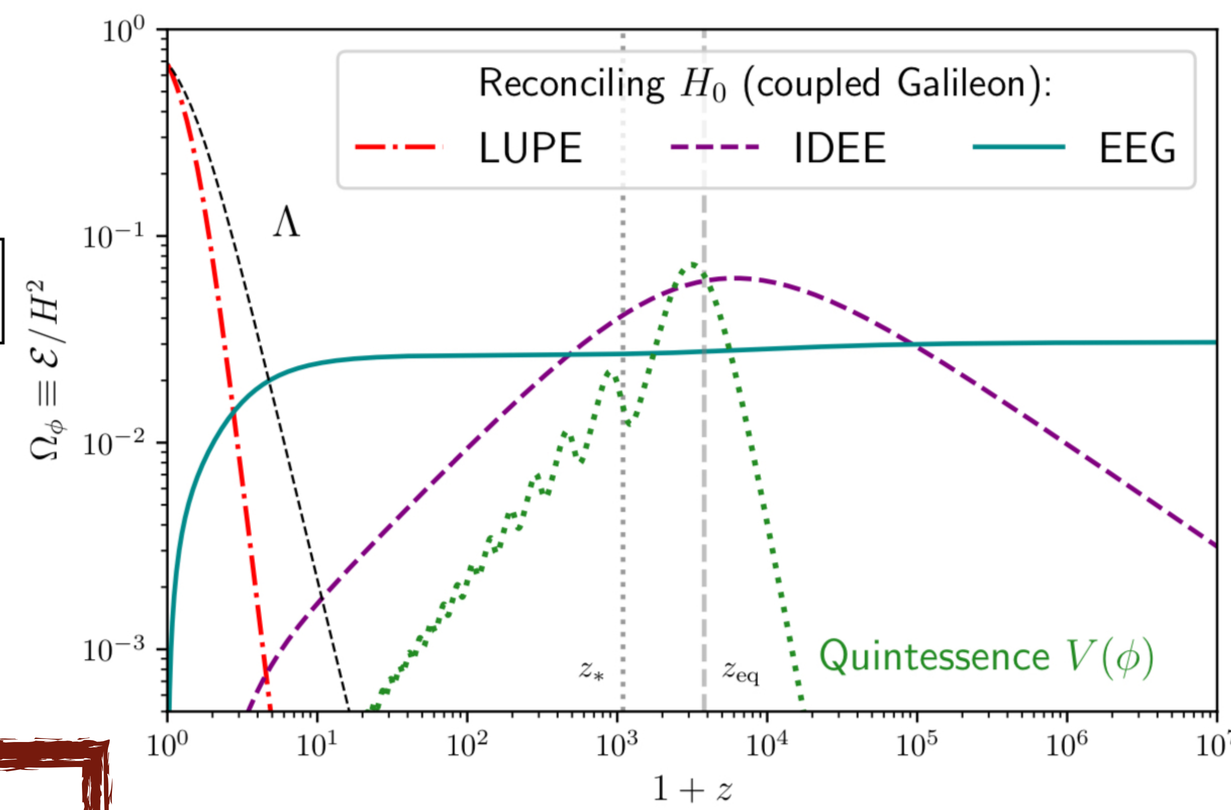
Zumalacarregui 2020

H&H: Hubble & Hordenski

mordial element abundances and gravitational waves. While further model building is required to fully resolve the H_0 problem and satisfy all available observations, these examples show the wealth of possibilities to solve cosmological tensions beyond Einstein's General Relativity.

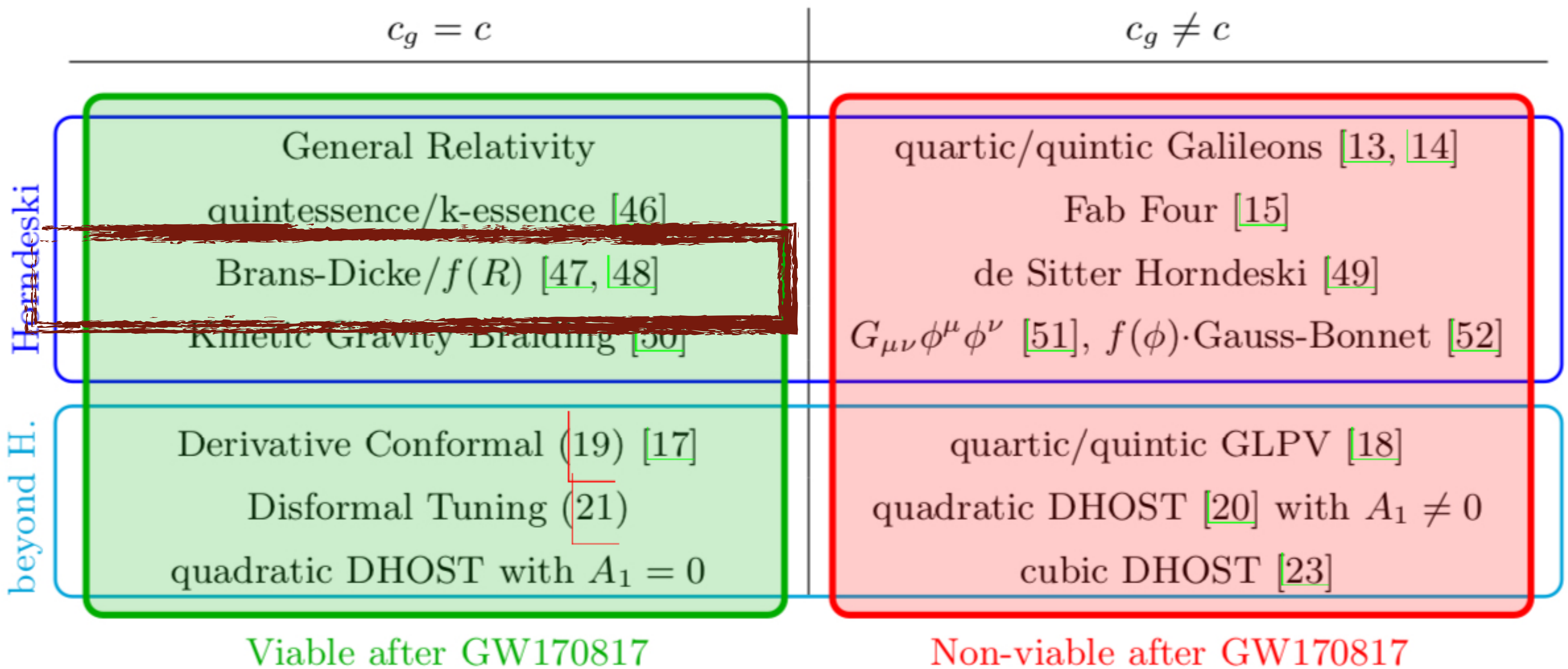
$$\begin{aligned}
\mathcal{L}_2 &= G_2(\phi,\, X)\,, \\
\mathcal{L}_3 &= -G_3(\phi,\, X)\Box\phi\,, \\
\mathcal{L}_4 &= G_4(\phi,\, X)R + G_{4X}(\cancel{\phi,}\, X)\left[(\Box\phi)^2 - \phi_{;\mu\nu}\phi^{;\mu\nu}\right] \\
\mathcal{L}_5 &= G_5(\cancel{\phi,}\, X)G_{\mu\nu}\phi^{;\mu\nu} - \frac{1}{6}\cancel{G_{5X}}(\phi,\, X)\Big[(\Box\phi)^3 \\
&\quad +2\phi_{;\mu}{}^{\nu}\phi_{;\nu}{}^{\alpha}\phi_{;\alpha}{}^{\mu} - 3\phi_{;\mu\nu}\phi^{;\mu\nu}\Box\phi\Big]\,.
\end{aligned}$$

$$\boxed{\mathcal{L}_{G3,C} = \frac{M_P^2}{2}C(\phi)R + 2\frac{c_3}{M^3}X\Box\phi + c_2X - 2\Lambda + \mathcal{L}_{\rm m}}$$



Zumalacarregui 2020

Non-minimally coupled scalar field



$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{F(\sigma)}{2}R + \frac{(\partial\sigma)^2}{2} - \Lambda + \mathcal{L}_m\right]$$

Non-minimally coupled scalar field

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{F(\sigma)}{2}R + \frac{(\partial\sigma)^2}{2} - \Lambda + \mathcal{L}_m\right]$$

$$F(\sigma) = N_{pl}^2 + \xi\sigma^2$$

Massless Quintessence: $N_{pl} = M_{pl},\ \xi = 0$

Jordan-Brans-Dicke (JBD): $N_{pl} = 0$

Conformal coupling (CC): $\xi = -\frac{1}{6}$

Laboratory constraints

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{F(\sigma)}{2}R + \frac{(\partial\sigma)^2}{2} - \Lambda + \mathcal{L}_m\right]$$

Cosmological Newton constant

$$G_N \equiv \frac{1}{8\pi F}$$

Laboratory constraints

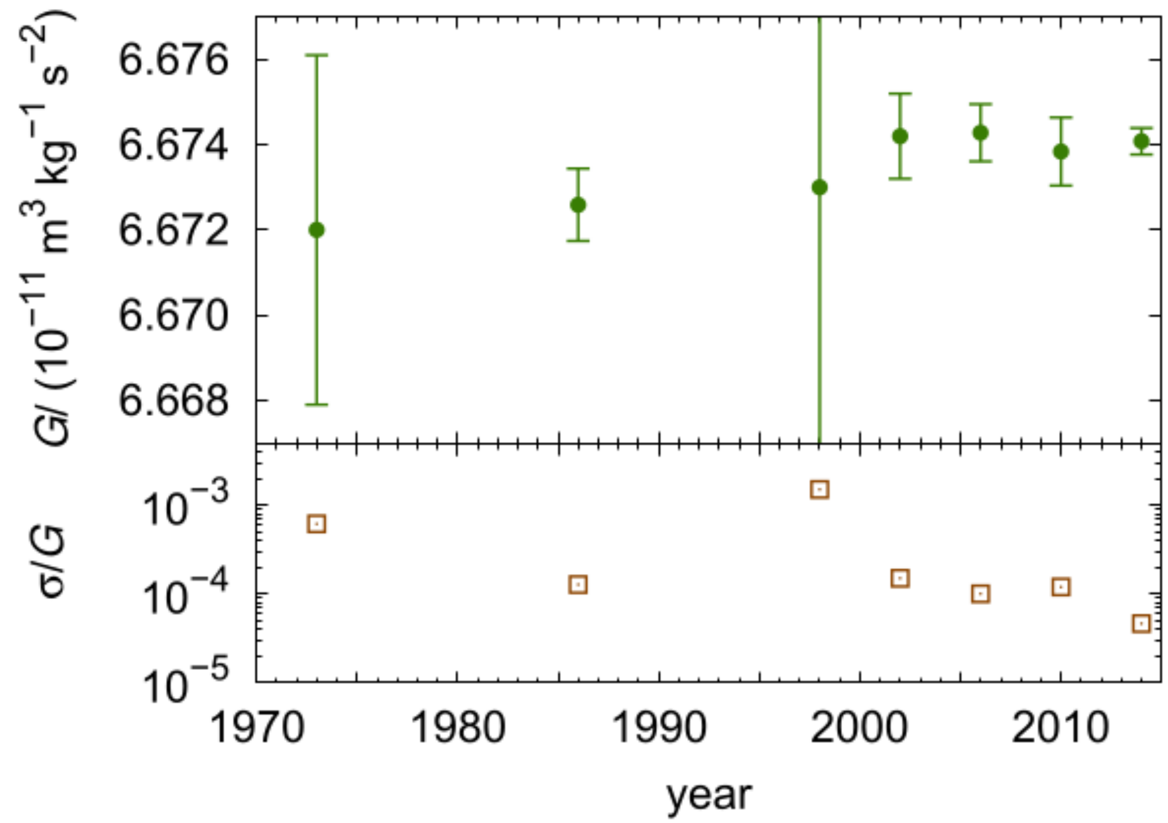
$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{F(\sigma)}{2}R + \frac{(\partial\sigma)^2}{2} - \Lambda + \mathcal{L}_m\right]$$

Cosmological Newton constant

$$G_N \equiv \frac{1}{8\pi F}$$

Effective Newton constant

$$G_{eff} \equiv \frac{1}{8\pi F}\frac{2F + 4F_\sigma^2}{2F + 3F_\sigma^2}$$



Rothleitner & Schlamminger 2017

Solar System constraints

$$ds^2 = -(1 + 2\epsilon - 2\beta_{PN}\epsilon^2)dt^2 + (1 - 2\gamma_{PN}\epsilon)d\mathbf{x}^2$$

$$\gamma_{\rm PN} = 1 - \frac{F_{,\sigma}^2}{F + 2F_{,\sigma}^2}$$

$$\beta_{\rm PN} = 1 + \frac{F F_{,\sigma}}{8F + 12F_{,\sigma}^2}\frac{\mathrm{d}\gamma_{\rm PN}}{\mathrm{d}\sigma}$$

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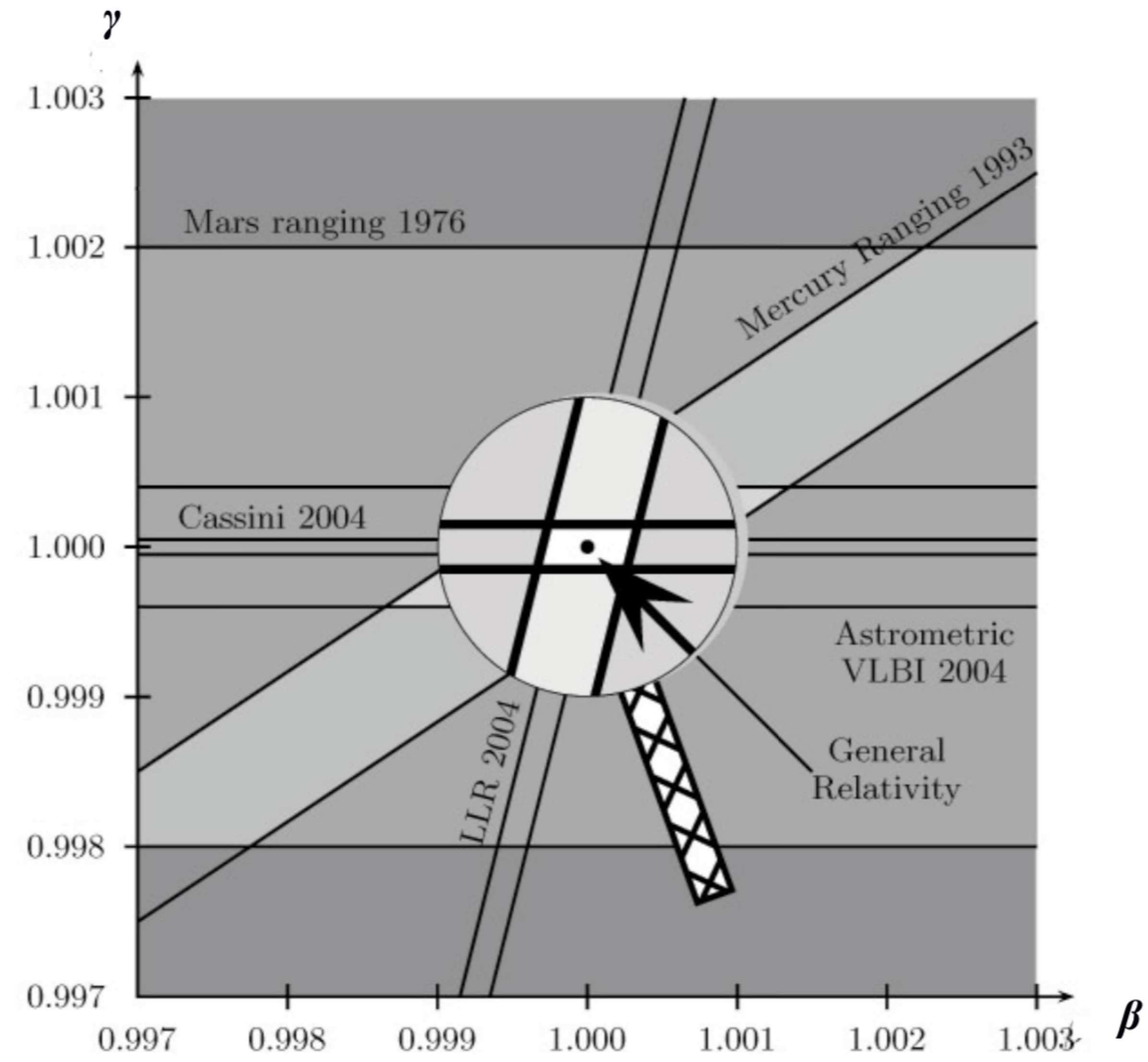

Turyshev et al 2006

Solar System constraints

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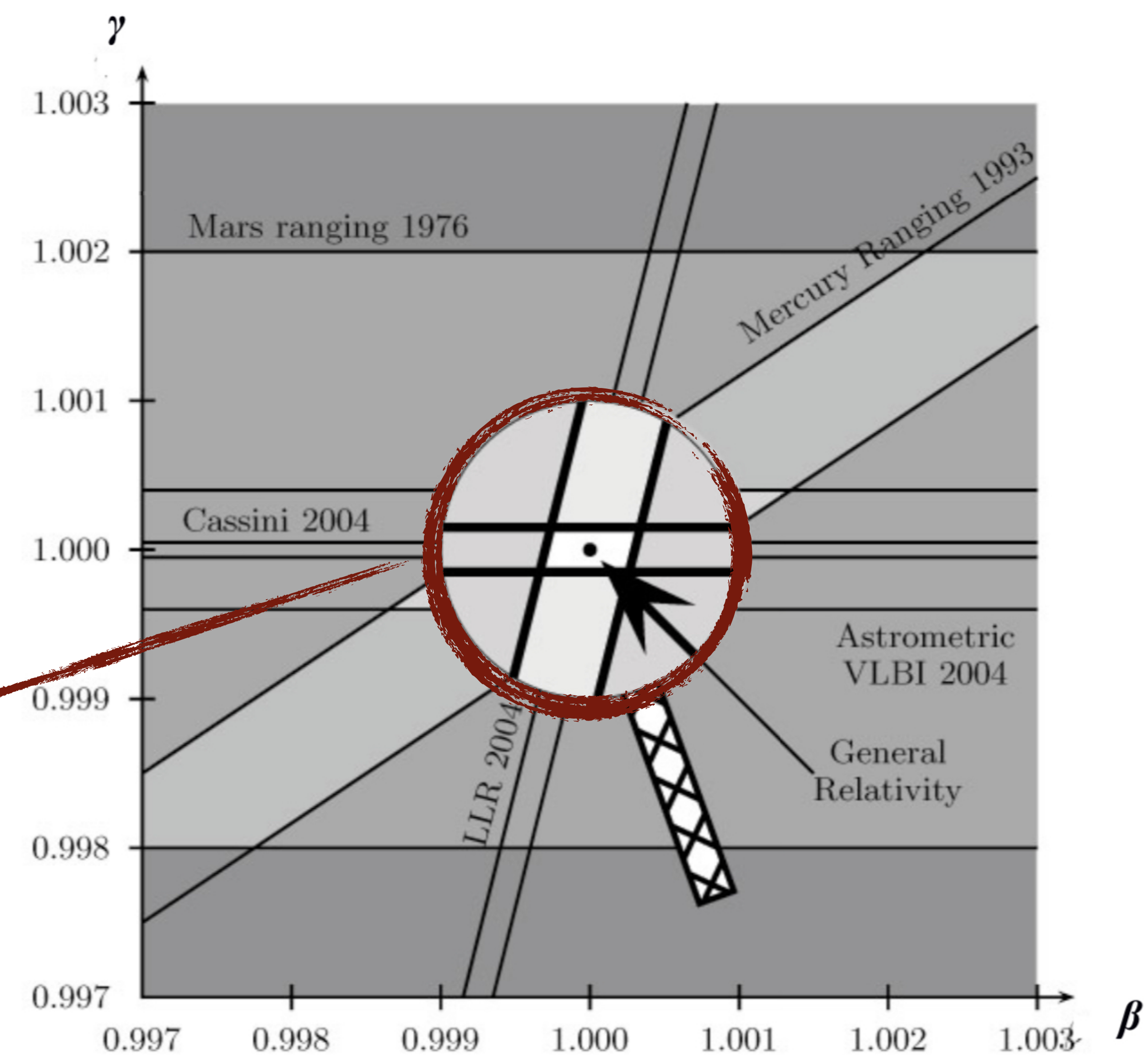
Deviation of $\mathcal{O}\left(10^{-5}\right)$



Turyshev et al 2006

Stability conditions

Scalar perturbations

$$F\left(F+3F_{\sigma}^{2}\right)>0$$

Positive kinetic term in the Einstein frame

Tensor perturbations

$$F>0$$

Positive Newton constant

See e.g. Gannouji, Polarski, Ranquet, Starobinsky 2006

Non-minimal coupling and H_0 tension

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{F(\sigma)}{2}R + \frac{(\partial\sigma)^2}{2} - \Lambda + \mathcal{L}_m\right]$$

$$F(\sigma) = N_{pl}^2 + \xi\sigma^2$$

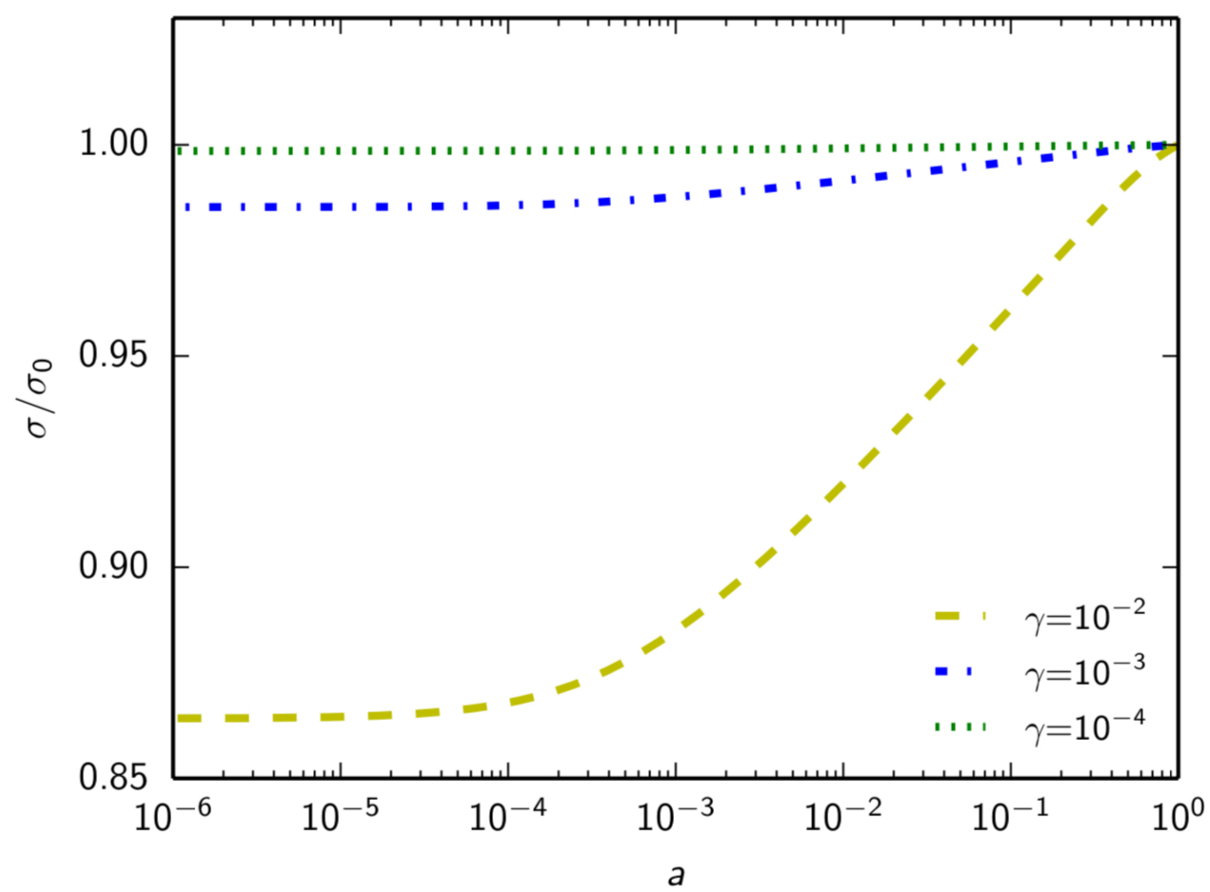
$$r_s^d = \int_{z_d}^{\infty} \frac{dz}{H(z)} c_s(z)$$

$$\frac{\Delta H}{H} \sim \frac{1}{F} - 1$$

Increase or decrease depending on whether $F < 1$ or $F > 1$

Jordan-Brans-Dicke

$$\boxed{F(\sigma) = \xi\sigma^2}$$



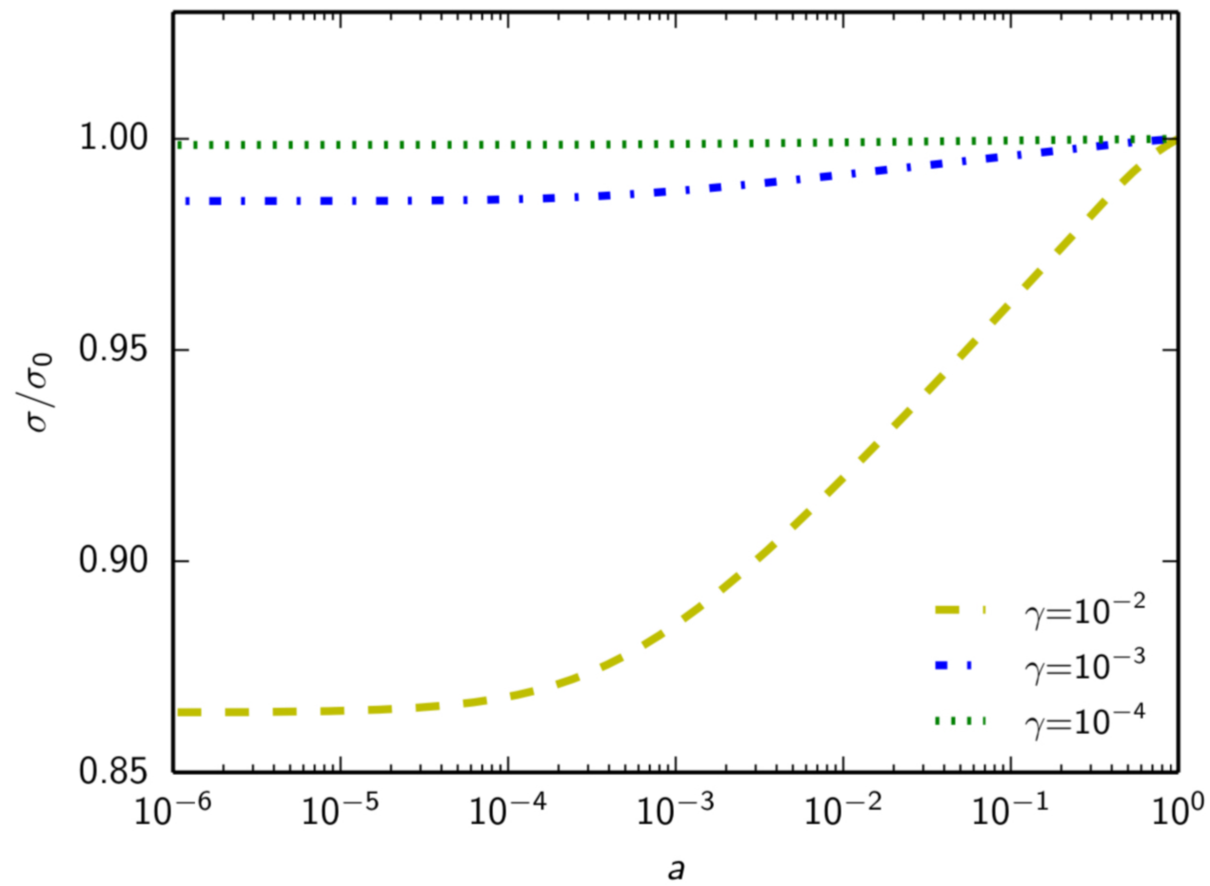
Umiltà, Ballardini, Finelli, Paoletti 2015
Ballardini, Finelli, Paoletti, Umiltà 2016

Jordan-Brans-Dicke

$$\boxed{F(\sigma) = \xi\sigma^2}$$

Fix G_{eff} to G today and get σ_0

then use a shooting algorithm to find σ_i



Umiltà, Ballardini, Finelli, Paoletti 2015

Ballardini, Finelli, Paoletti, Umiltà 2016

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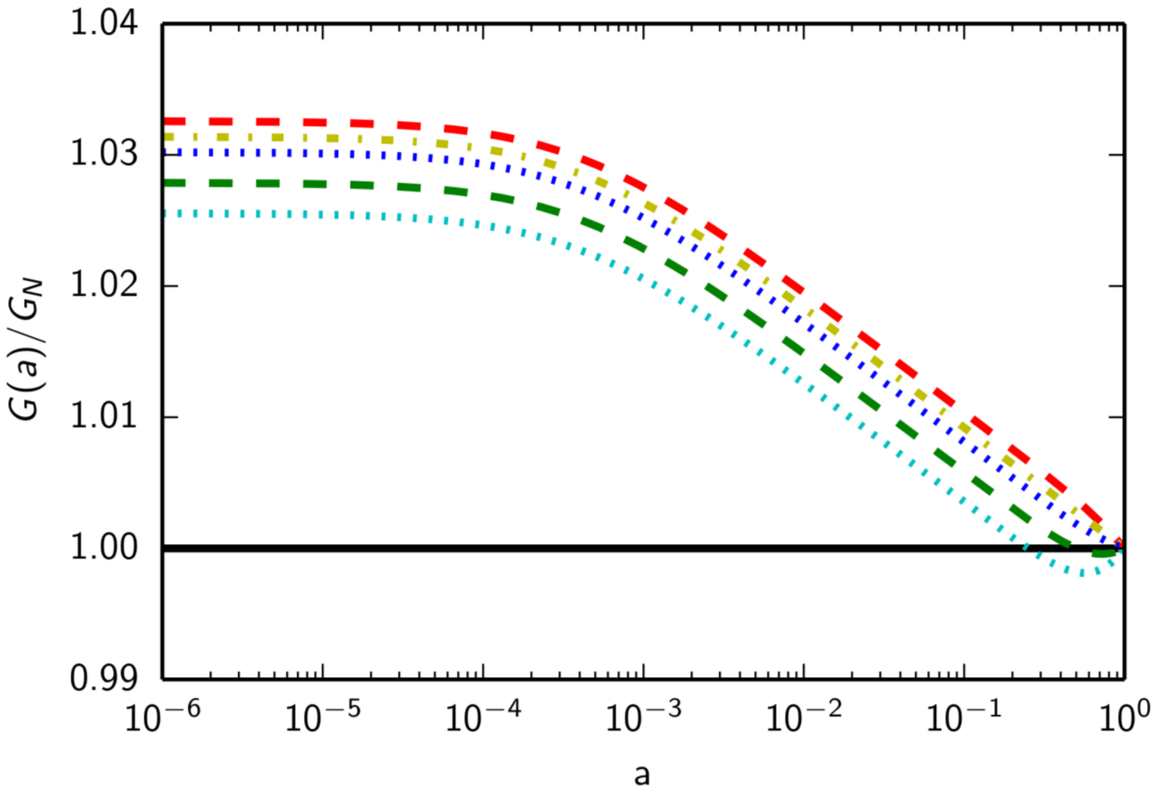

Umiltà, Ballardini, Finelli, Paoletti 2015
Ballardini, Finelli, Paoletti, Umiltà 2016

Jordan-Brans-Dicke

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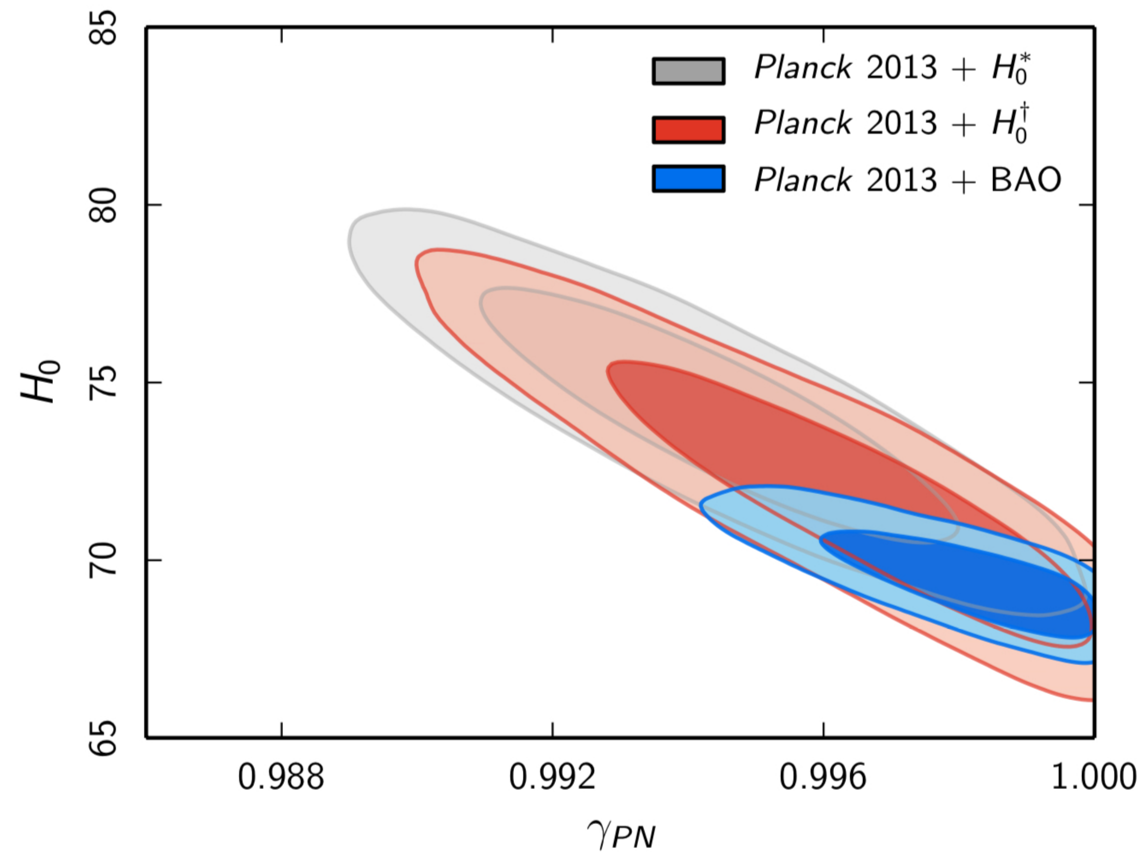
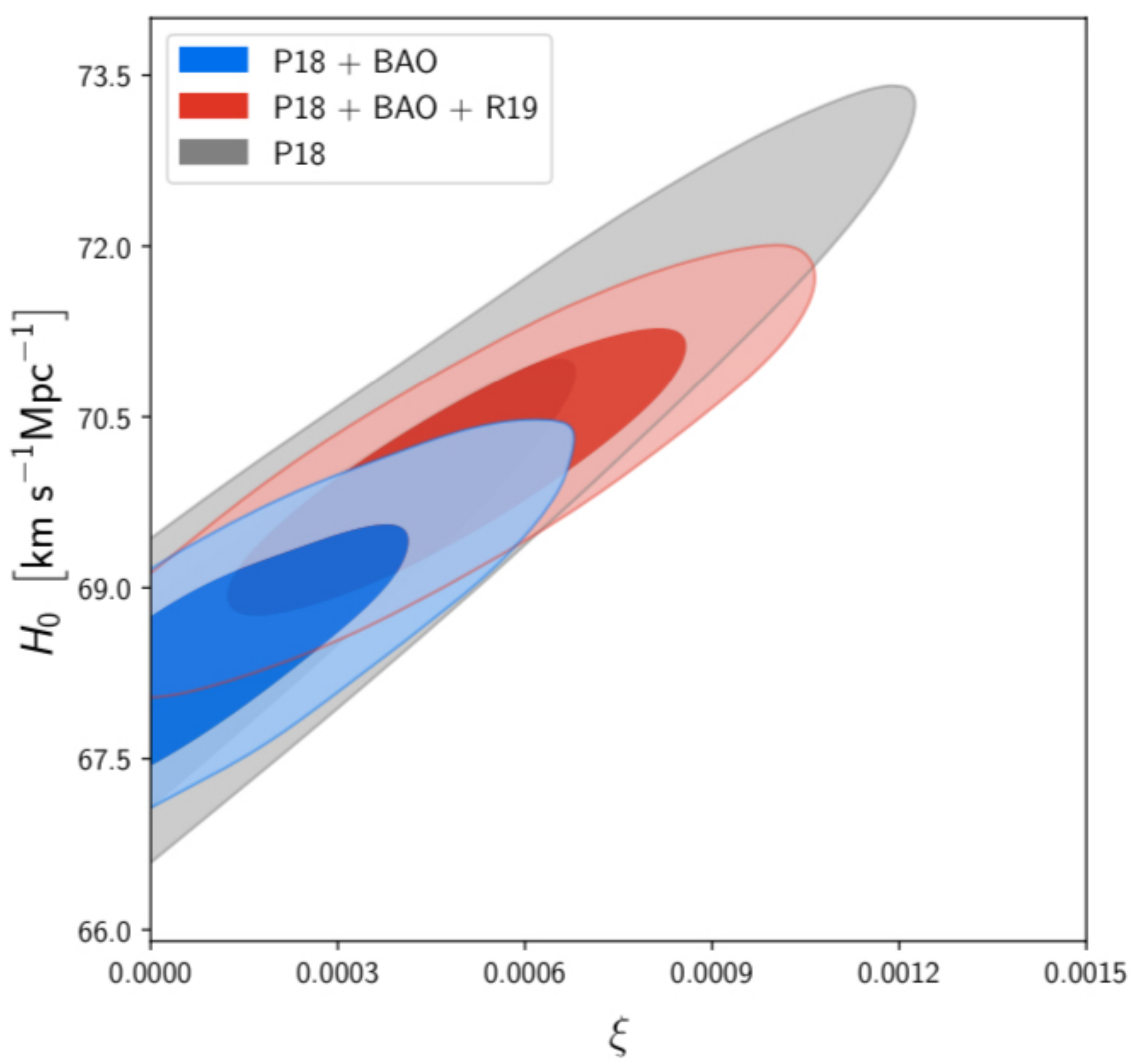


Umiltà, Ballardini, Finelli, Paoletti 2015
Ballardini, Finelli, Paoletti, Umiltà 2016

Jordan-Brans-Dicke: latest data



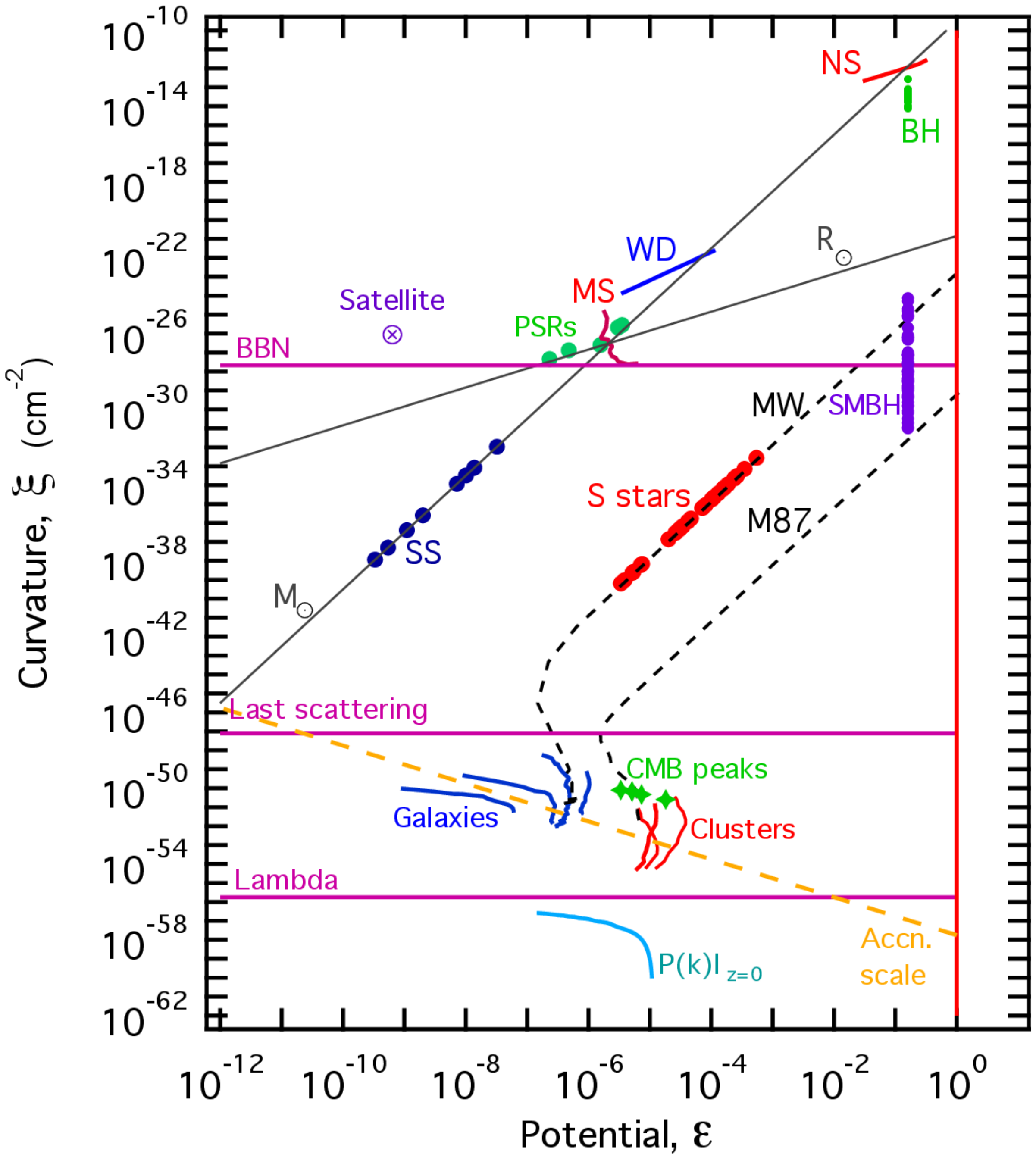
Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà 2020

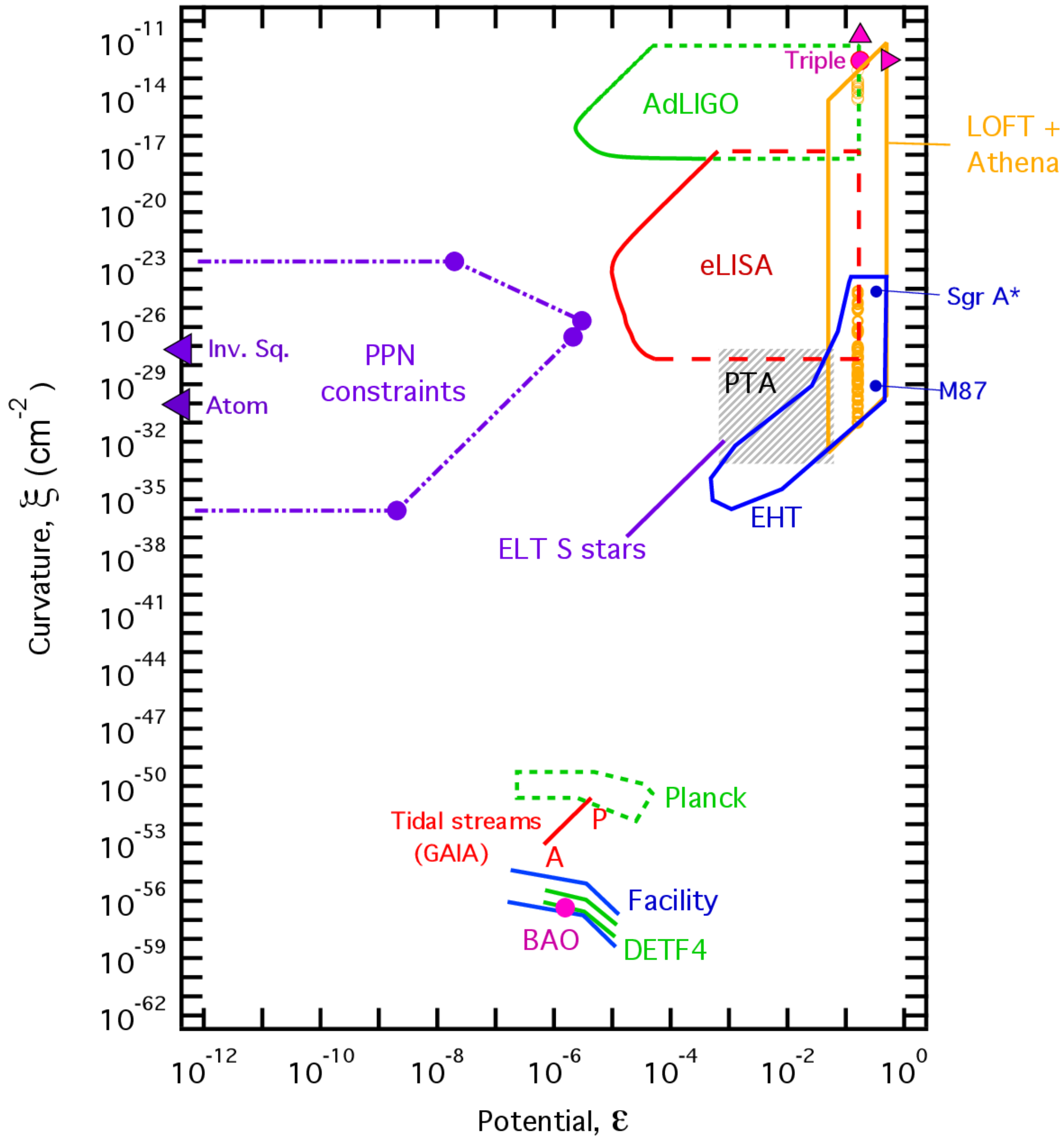
Jordan-Brans-Dicke: latest data

	P18	P18 + BAO	P18 + BAO + R19
ω_b	$0.02244^{+0.00014}_{-0.00016}$	0.02239 ± 0.00013	0.02246 ± 0.00013
ω_c	0.1198 ± 0.0012	0.1201 ± 0.0011	0.1200 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}]	$69.6^{+0.8}_{-1.7}$ (2.7σ)	$68.78^{+0.53}_{-0.78}$ (3.5σ)	70.06 ± 0.81 (2.4σ)
τ	$0.0551^{+0.0065}_{-0.0078}$	$0.0545^{+0.0063}_{-0.0071}$	$0.0554^{+0.0064}_{-0.0073}$
$\ln(10^{10} A_s)$	$3.047^{+0.014}_{-0.015}$	3.046 ± 0.013	3.049 ± 0.013
n_s	$0.9680^{+0.0044}_{-0.0052}$	0.9662 ± 0.0038	0.9688 ± 0.0037
ζ_{IG}	< 0.0039 (95% CL)	< 0.0022 (95% CL)	$0.00202^{+0.00090}_{-0.00100}$
ξ	< 0.00098 (95% CL)	< 0.00055 (95% CL)	$0.00051^{+0.00043}_{-0.00046}$ (95% CL)
γ_{PN}	> 0.9961 (95% CL)	> 0.9978 (95% CL)	$0.9980^{+0.0010}_{-0.0009}$
$\delta G_N/G_N$ (z=0)	> -0.029 (95% CL)	> -0.016 (95% CL)	-0.0149 ± 0.0068
$10^{13}\dot{G}_N/G_N$ (z=0) [yr^{-1}]	> -1.16 (95% CL)	> -0.66 (95% CL)	-0.61 ± 0.28
G_N/G (z=0)	> 0.9981 (95% CL)	> 0.9989 (95% CL)	$0.99899^{+0.00050}_{-0.00045}$
Ω_m	$0.2940^{+0.0150}_{-0.0095}$	$0.3013^{+0.0072}_{-0.0062}$	0.2903 ± 0.0068
σ_8	$0.8347^{+0.0074}_{-0.0130}$	$0.8308^{+0.0067}_{-0.0096}$	0.840 ± 0.010
r_s [Mpc]	$146.37^{+0.79}_{-0.40}$	$146.63^{+0.55}_{-0.34}$	$146.03^{+0.67}_{-0.59}$
$\Delta\chi^2$	0.2	0.2	-3.1

Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà 2020

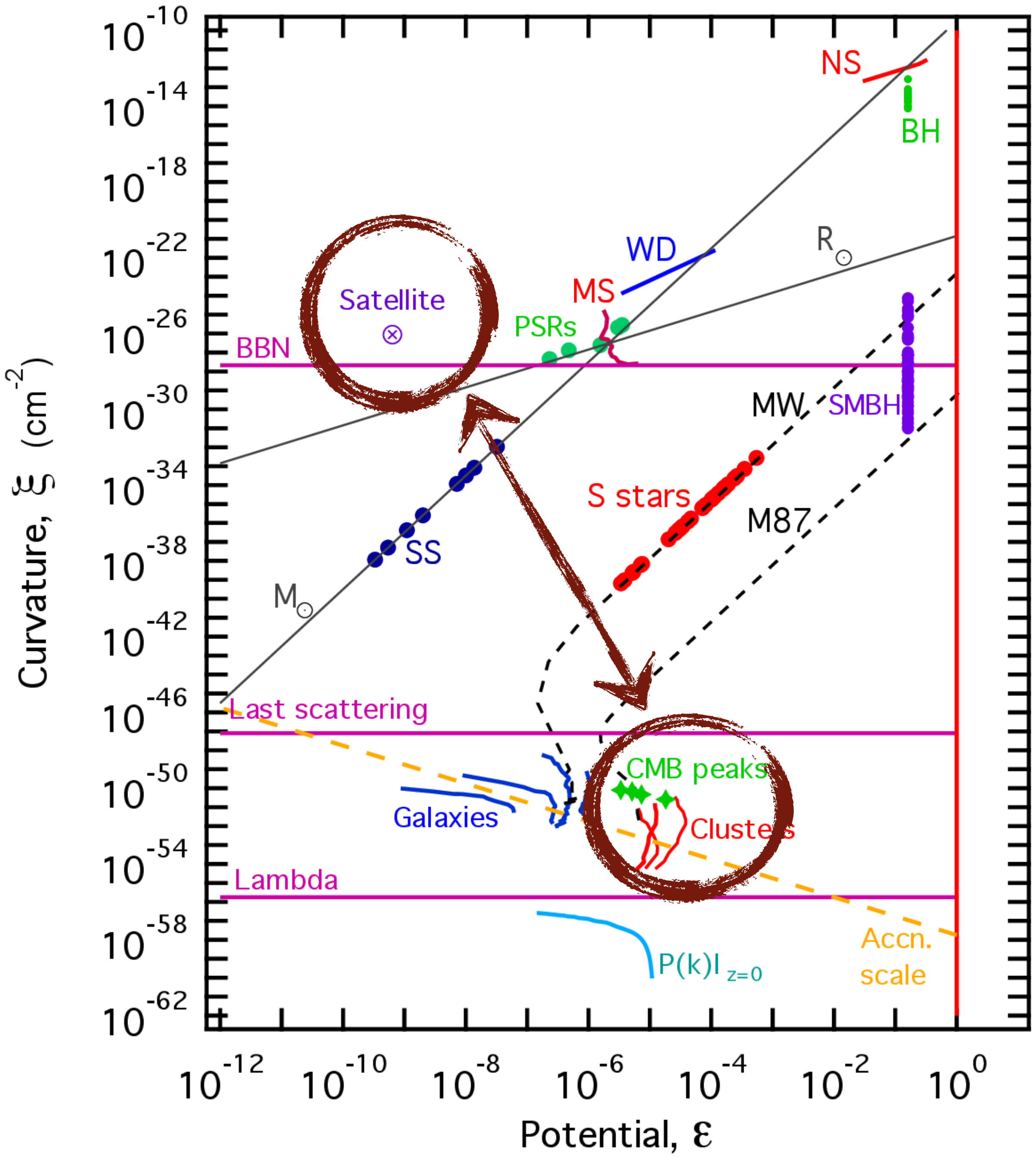
Jordan-Brans-Dicke: latest data

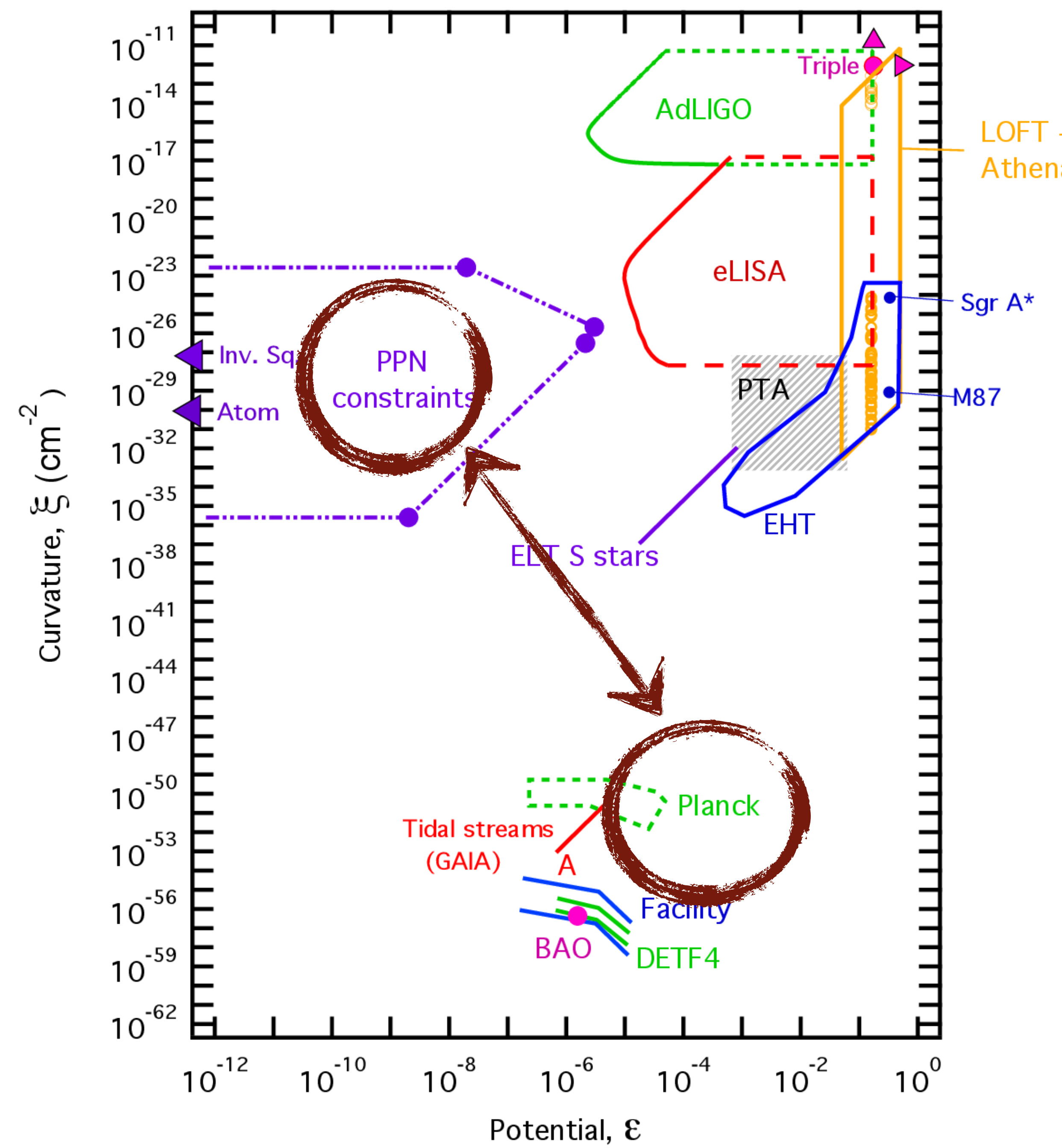




Baker, Psaltis & Skordis 2014

Jordan-Brans-Dicke: latest data





Baker, Psaltis & Skordis 2014

Jordan-Brans-Dicke: other works

	Baseline		Baseline+H_0	
Parameter	GR-ΛCDM	BD-ΛCDM	GR-ΛCDM	BD-ΛCDM
H_0 (km/s/Mpc)	$68.20^{+0.41}_{-0.40}$	$68.86^{+1.15}_{-1.24}$	$68.57^{+0.36}_{-0.42}$	$70.83^{+0.92}_{-0.95}$
ω_b	$0.02227^{+0.00019}_{-0.00018}$	$0.02251^{+0.00026}_{-0.00027}$	0.02238 ± 0.00019	$0.02275^{+0.00024}_{-0.00026}$
ω_{cdm}	$0.11763^{+0.00090}_{-0.00092}$	$0.11598^{+0.00159}_{-0.00152}$	$0.11699^{+0.00092}_{-0.00083}$	$0.11574^{+0.00164}_{-0.00158}$
τ	$0.050^{+0.004}_{-0.008}$	$0.052^{+0.006}_{-0.008}$	$0.051^{+0.005}_{-0.008}$	$0.053^{+0.006}_{-0.008}$
n_s	$0.9683^{+0.0039}_{-0.0038}$	$0.9775^{+0.0084}_{-0.0086}$	$0.9703^{+0.0038}_{-0.0036}$	$0.9873^{+0.0076}_{-0.0075}$
σ_8	$0.797^{+0.005}_{-0.006}$	0.785 ± 0.013	$0.796^{+0.006}_{-0.007}$	0.789 ± 0.013
r_s (Mpc)	$147.83^{+0.29}_{-0.30}$	$145.89^{+2.26}_{-2.49}$	147.88 ± 0.31	$142.46^{+1.84}_{-1.86}$
ϵ_{BD}	-	$-0.00184^{+0.00140}_{-0.00142}$	-	$-0.00199^{+0.00142}_{-0.00147}$
φ_{ini}	-	$0.974^{+0.027}_{-0.031}$	-	$0.932^{+0.022}_{-0.023}$
$\varphi(0)$	-	$0.960^{+0.032}_{-0.037}$	-	$0.918^{+0.027}_{-0.029}$
$w_{\rm eff}(0)$	-	$-0.983^{+0.015}_{-0.014}$	-	$-0.966^{+0.012}_{-0.011}$
$\dot{G}(0)/G(0)(10^{-13}yr^{-1})$	-	$2.022^{+1.585}_{-1.518}$	-	$2.256^{+1.658}_{-1.621}$
χ^2_{min}	2271.98	2271.82	2285.50	2276.04
$2\ln B$	-	-2.26	-	+4.92
ΔDIC	-	-0.54	-	+4.90

Sola, Gomez-Valent, de Cruz Perez, Moreno-Pulido 2019-2020

Jordan-Brans-Dicke: other works

	Baseline		Baseline+H_0	
Parameter	GR-ΛCDM	BD-ΛCDM	GR-ΛCDM	BD-ΛCDM
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τ	$0.050^{+0.004}_{-0.008}$	$0.052^{+0.006}_{-0.008}$	$0.051^{+0.005}_{-0.008}$	$0.053^{+0.006}_{-0.008}$
n_s	$0.9683^{+0.0039}_{-0.0038}$	$0.9775^{+0.0084}_{-0.0086}$	$0.9703^{+0.0038}_{-0.0036}$	$0.9873^{+0.0076}_{-0.0075}$
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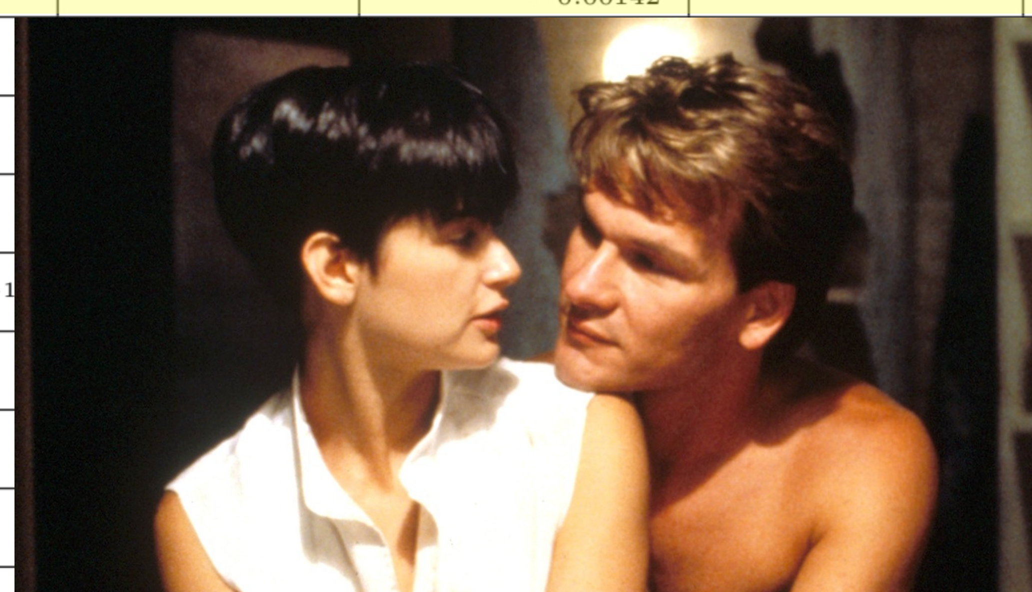


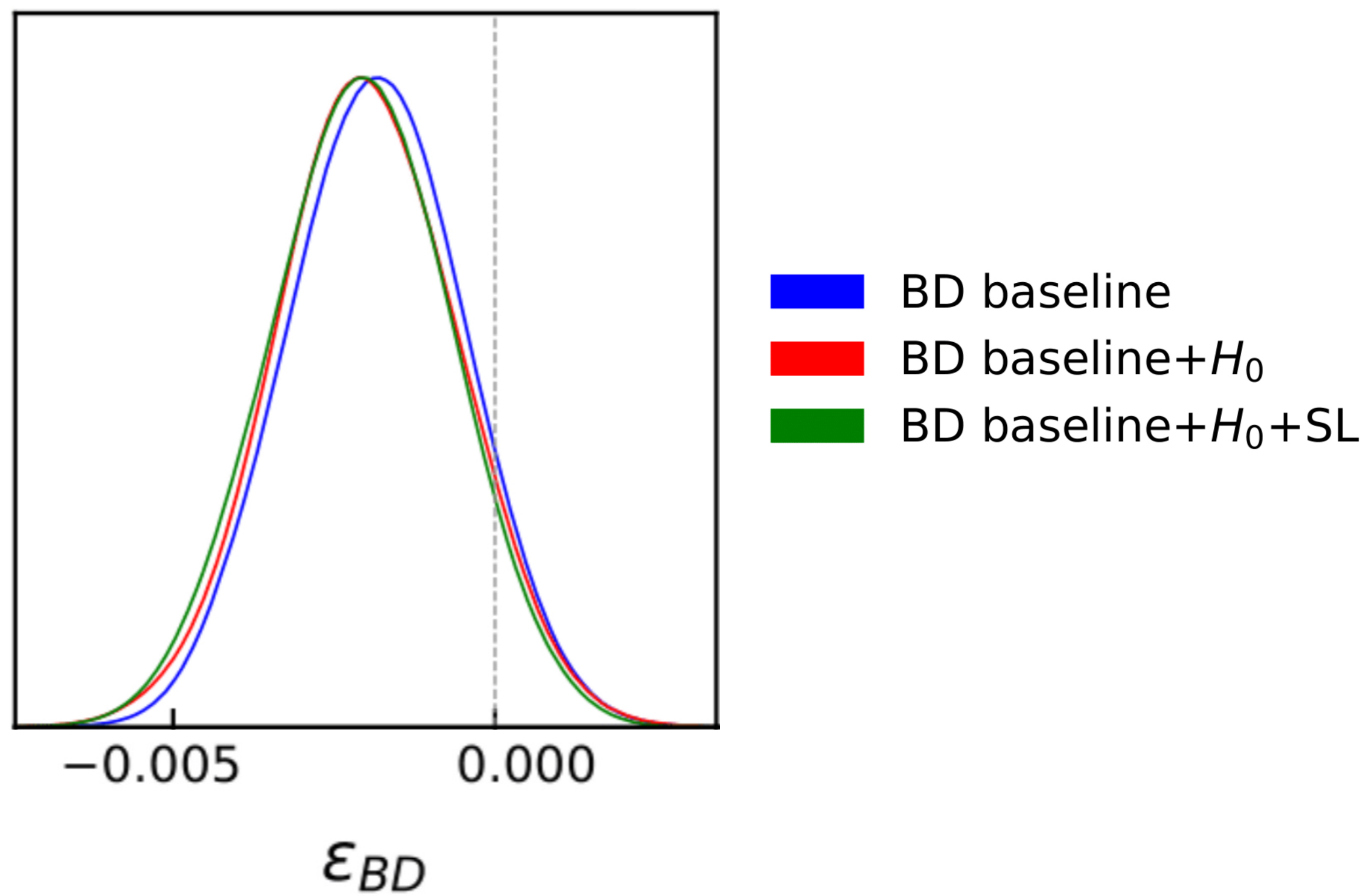
Sola, Gomez-Valent, de Cruz Perez, Moreno-Pulido 2019-2020

Jordan-Brans-Dicke: other works

$$\xi < -\frac{1}{6}$$

$$\downarrow$$

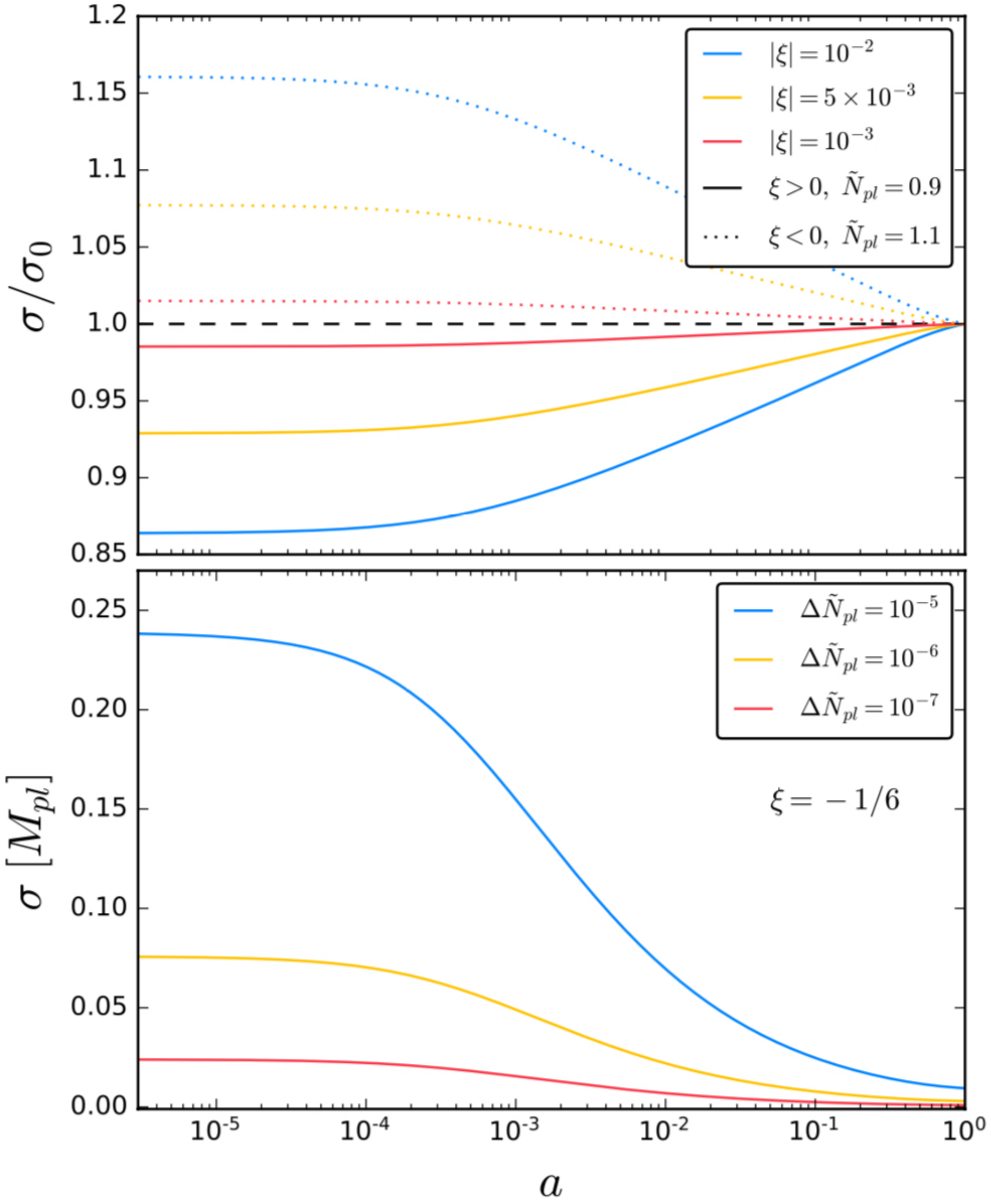
$$\epsilon_{BD} = 4\xi < -\frac{2}{3}$$



Sola, Gomez-Valent, de Cruz Perez, Moreno-Pulido 2019-2020

NMC and H_0 tension

$$\boxed{F(\sigma) = N_{pl}^2 + \xi\sigma^2}$$



Rossi, Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà 2019

NMC and H_0 tension

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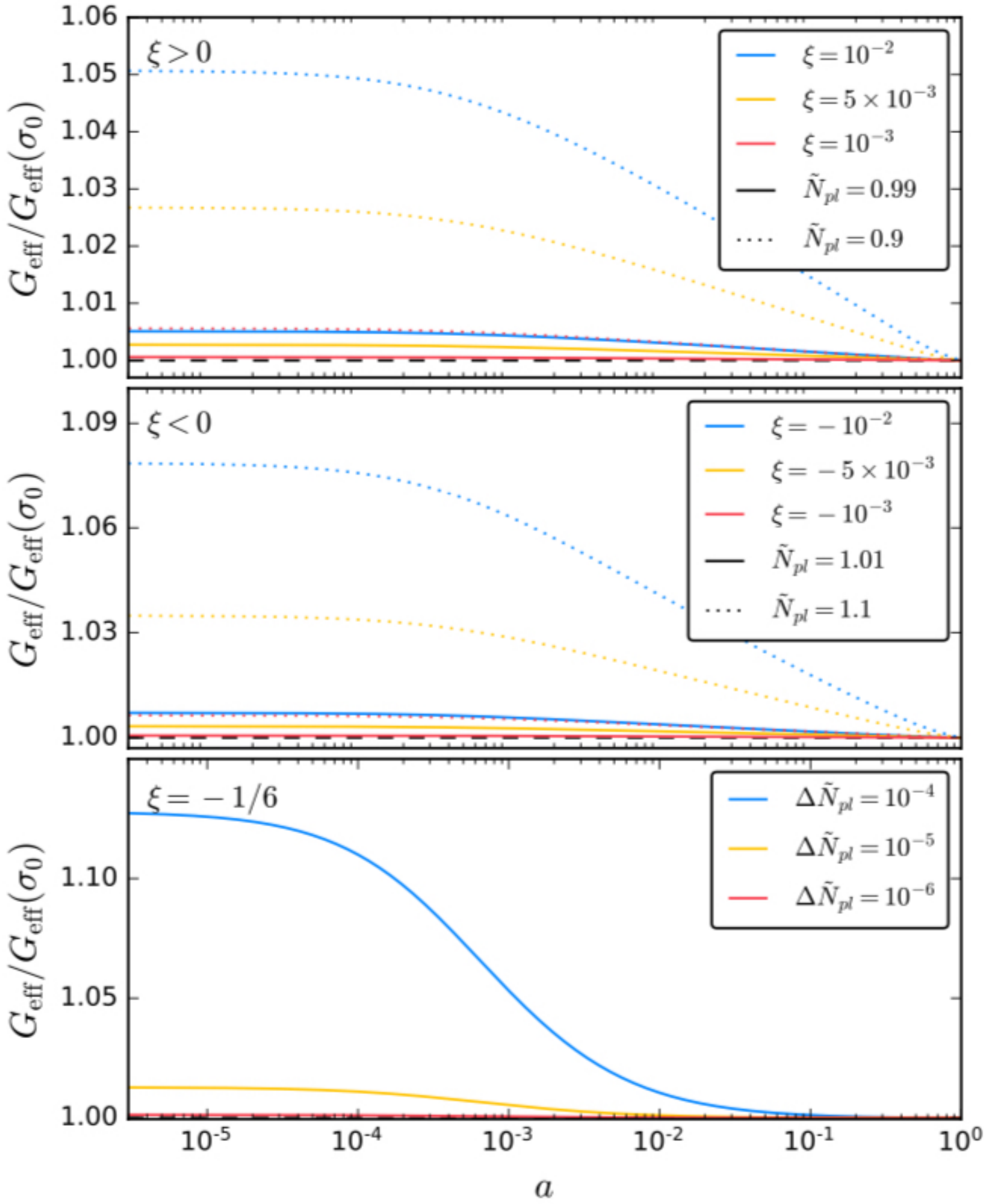

Rossi, Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà 2019

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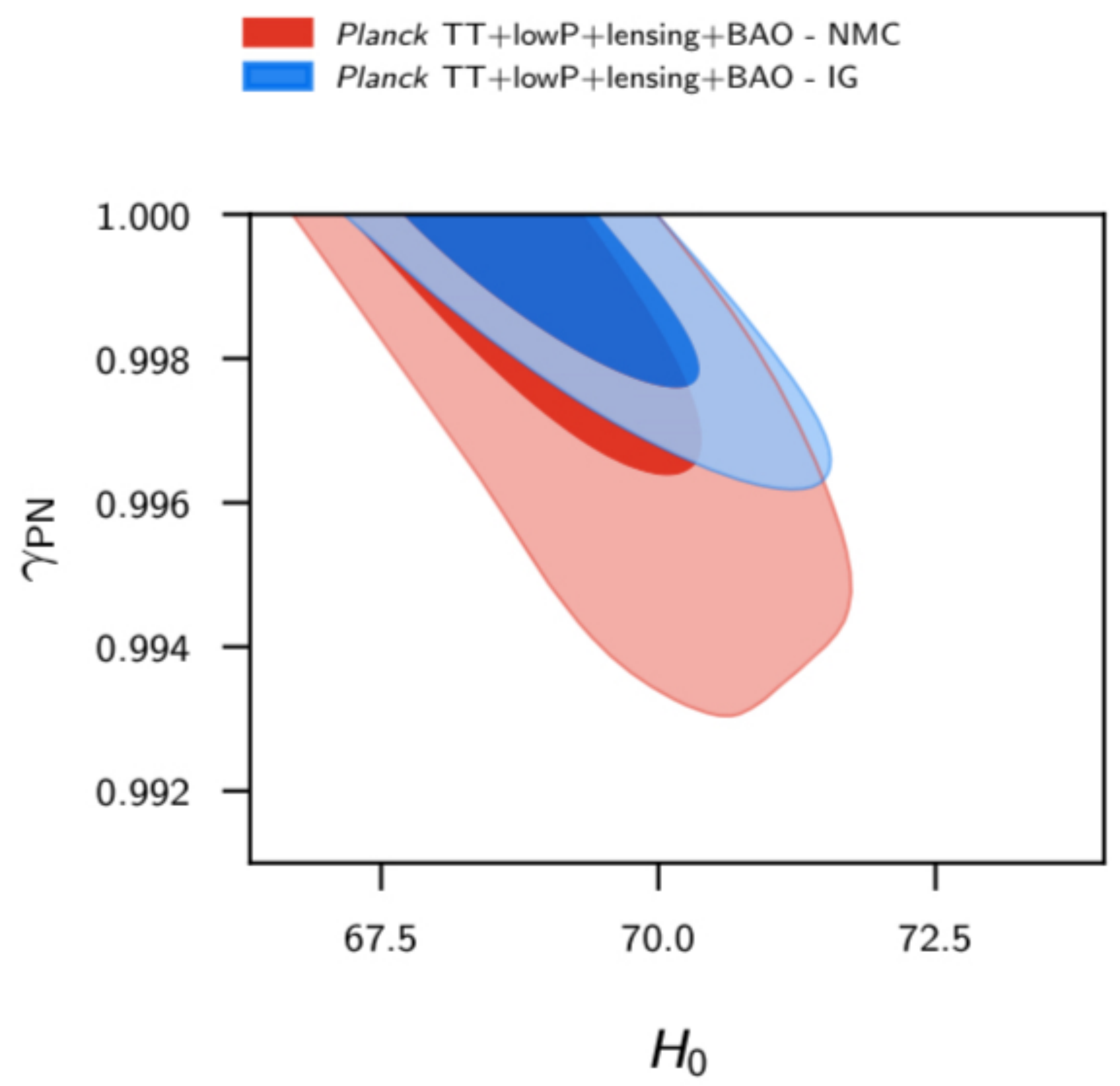
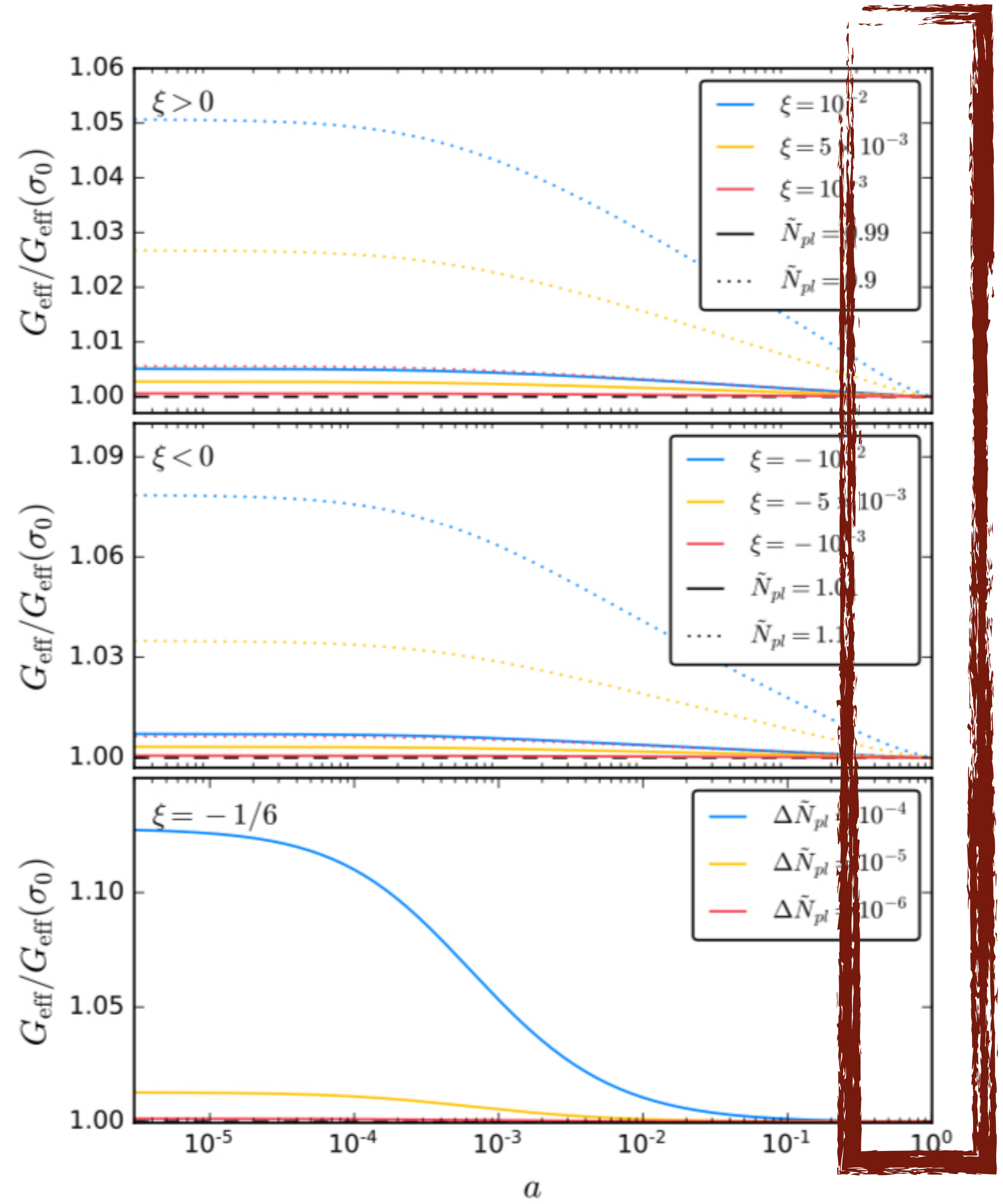


Rossi, Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà 2019

NMC and H_0 tension

$$\boxed{F(\sigma) = N_{pl}^2 + \xi\sigma^2}$$

G_{eff} fixed to G today to get σ_i



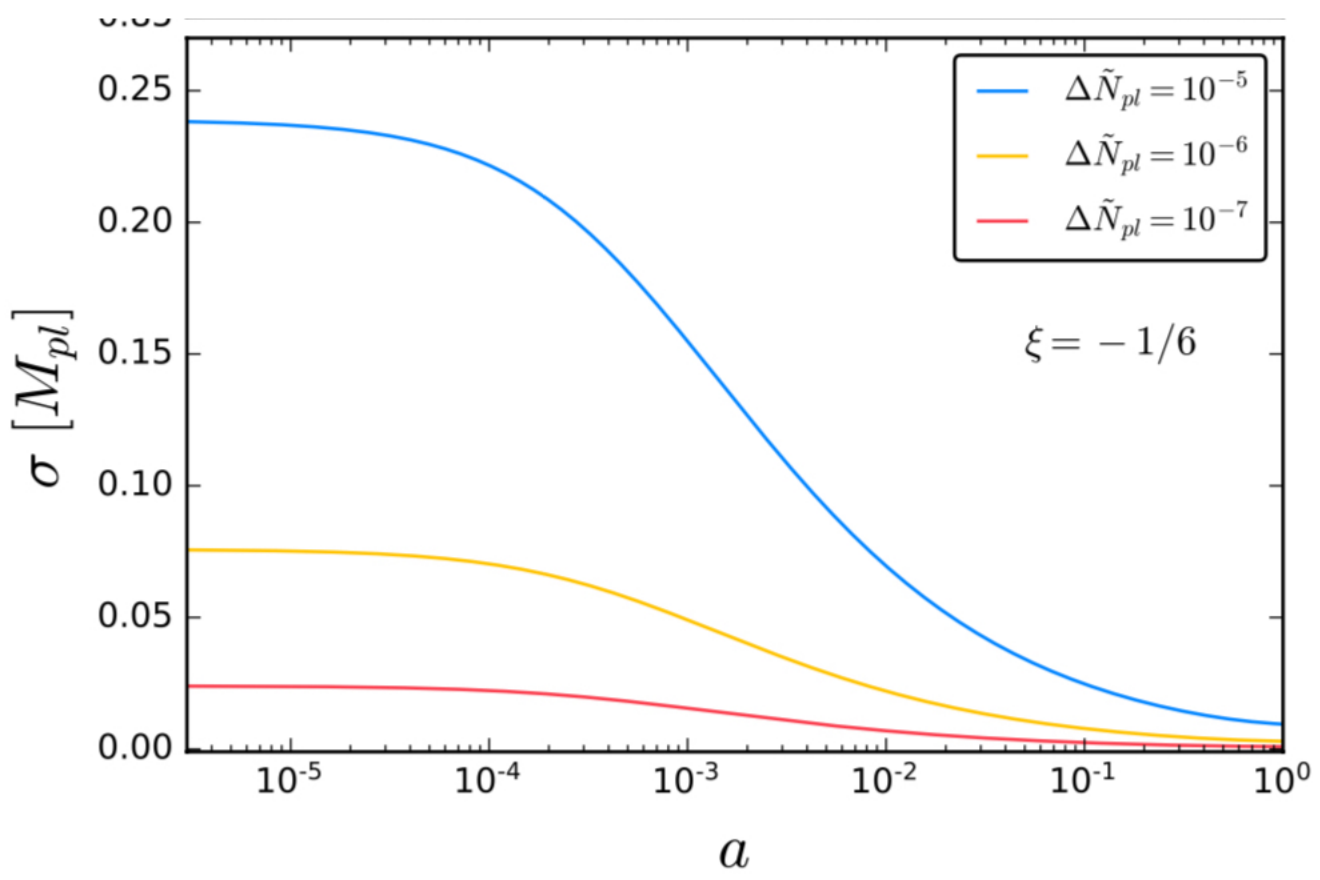
Rossi, Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà 2019

NMC and H_0 tension

$$\boxed{F(\sigma) = N_{pl}^2 + \xi\sigma^2}$$

G_{eff} fixed to G today to get σ_i

σ decreases for $\xi < 0$, do we really need this?



Rossi, Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà 2019

NMC and H_0 tension

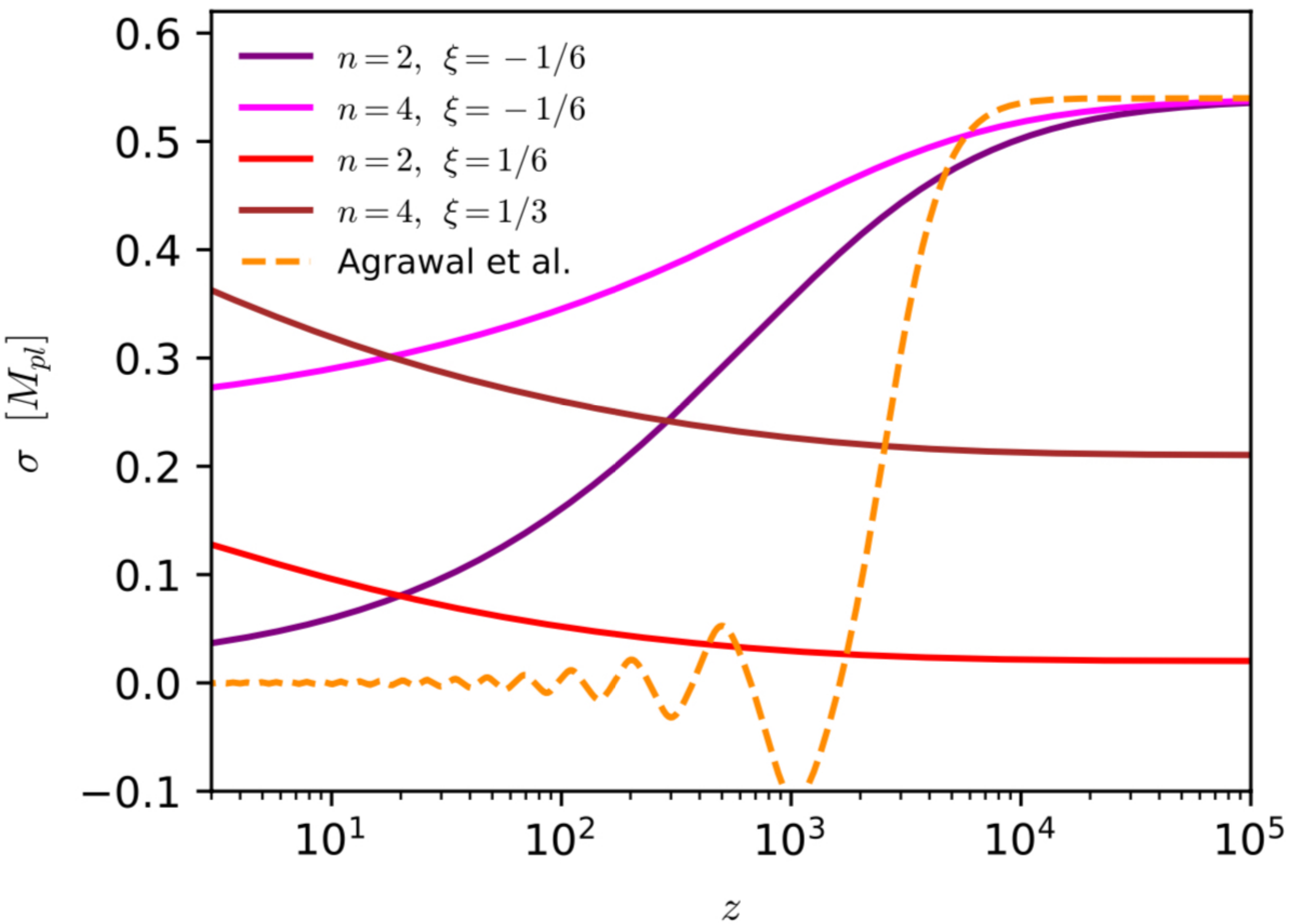
$$F(\sigma) = N_{pl}^2 + \xi\sigma^2 \longrightarrow \boxed{F(\sigma) = M_{pl}^2 + \xi\sigma^2}$$

MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

NMC and H_0 tension

$$F(\sigma) = M_{pl}^2 + \xi\sigma^2$$

σ decreases/increases for $\xi < 0/\xi > 0$ and naturally starts to thaw around matter-radiation equality



MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

NMC and H_0 tension

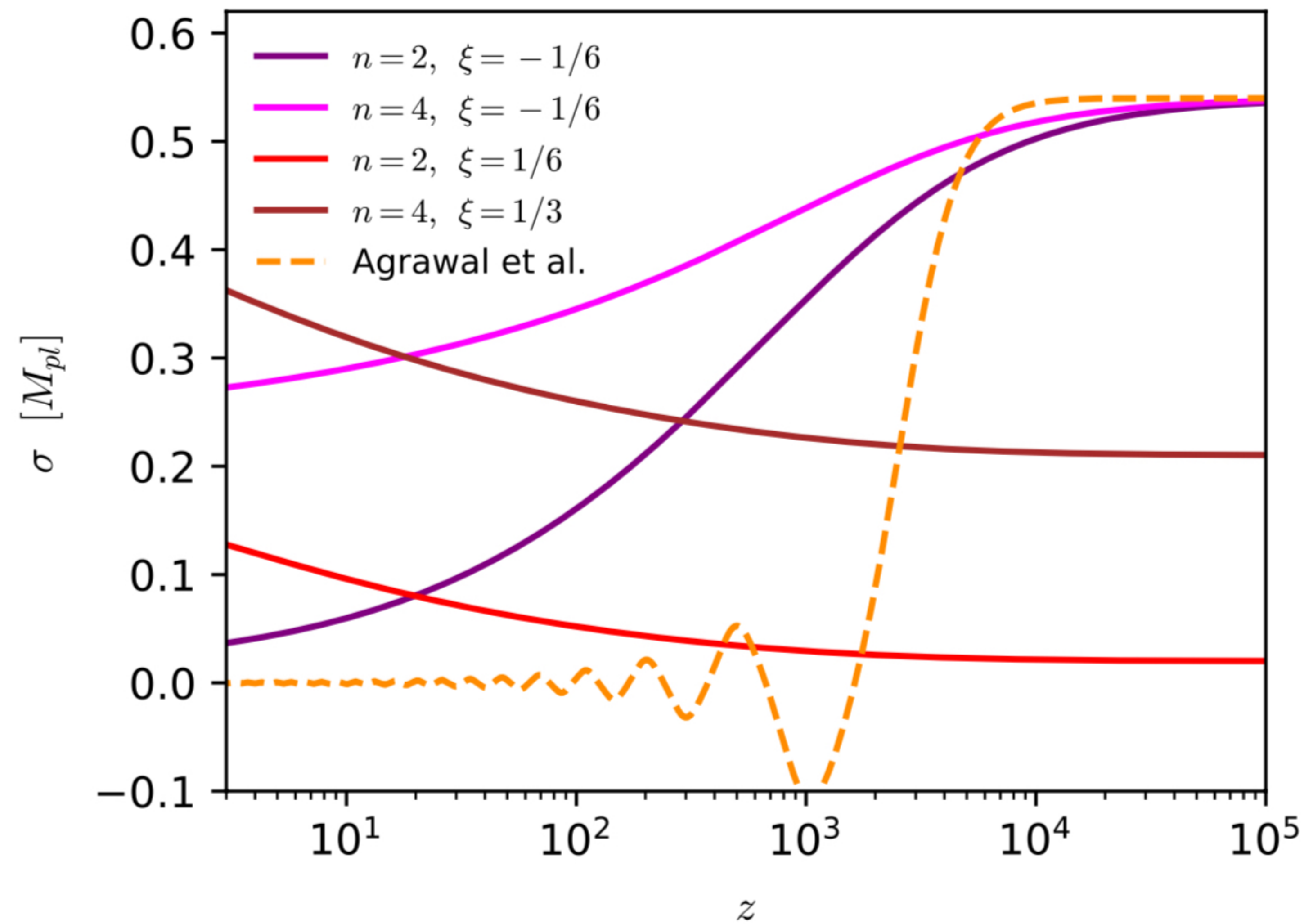
$$\boxed{F(\sigma) = M_{pl}^2 + \xi\sigma^2}$$

σ decreases/increases for $\xi < 0 / \xi > 0$

and naturally starts to thaw around

matter-radiation equality

$$\ddot{\sigma} + 3H\dot{\sigma} = \frac{F_{,\sigma}}{2F + 3F_{,\sigma}^2}\Big[\rho - 3p + 4\Lambda - (1 + 3F_{,\sigma\sigma})\dot{\sigma}^2\Big]\,,$$



MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

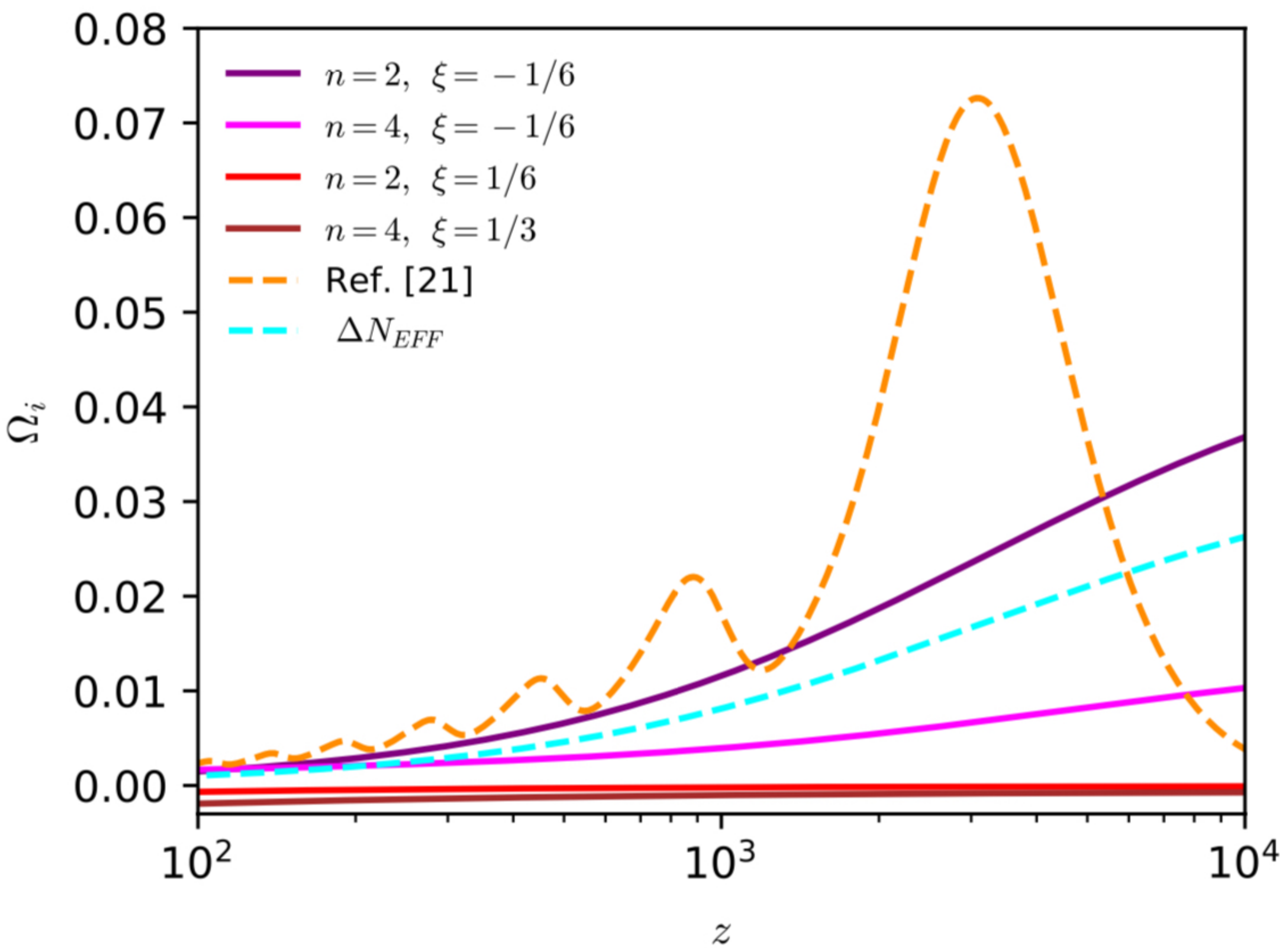
NMC and H_0 tension

$$\boxed{F(\sigma) = M_{pl}^2 + \xi\sigma^2}$$

σ decreases/increases for $\xi < 0/\xi > 0$

and naturally starts to thaw around matter-radiation equality

$$\ddot{\sigma} + 3H\dot{\sigma} = \frac{F_{,\sigma}}{2F + 3F_{,\sigma}^2}\Big[\rho - 3p + 4\Lambda - (1 + 3F_{,\sigma\sigma})\dot{\sigma}^2\Big],$$

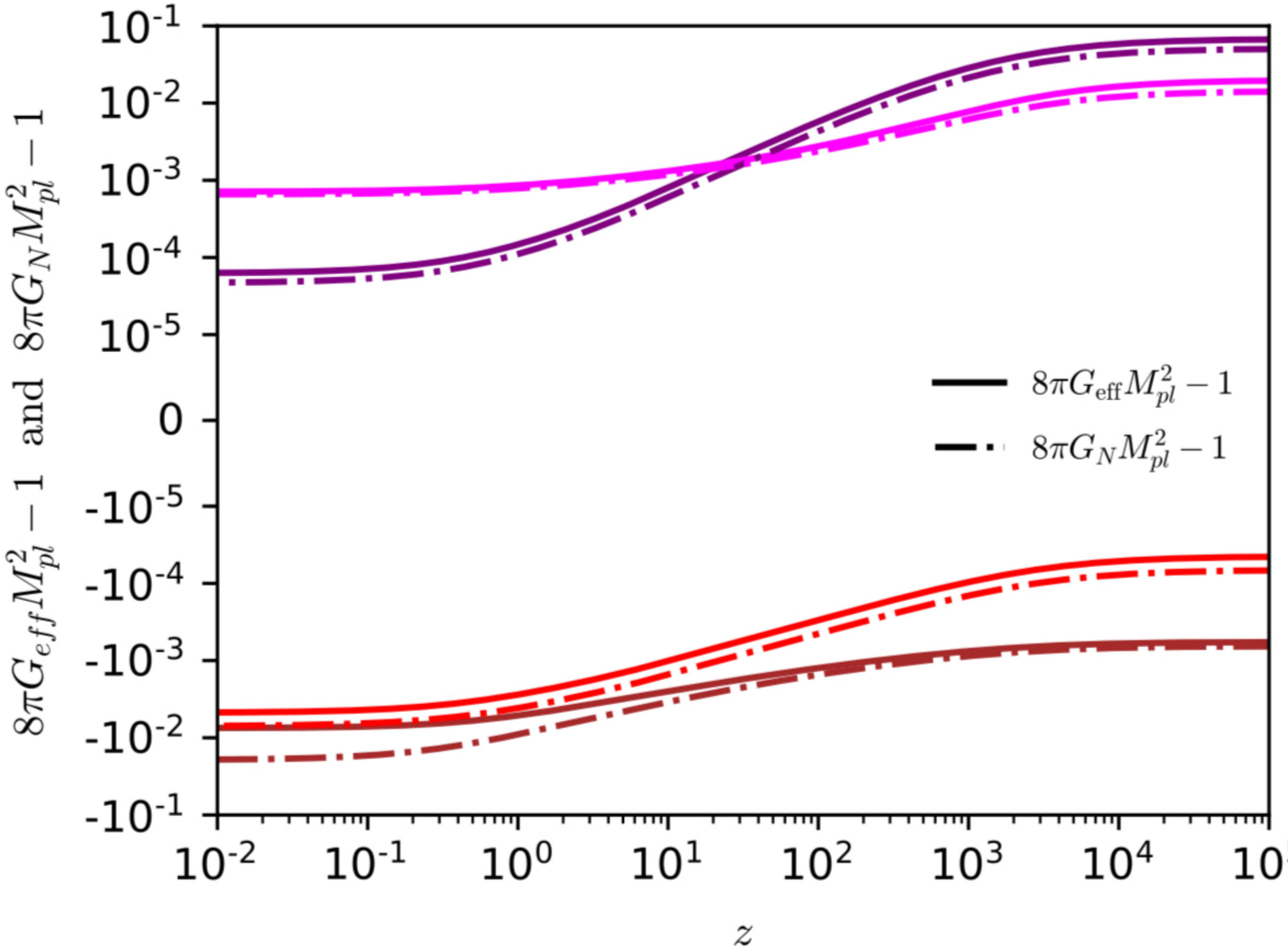


MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

NMC and H_0 tension

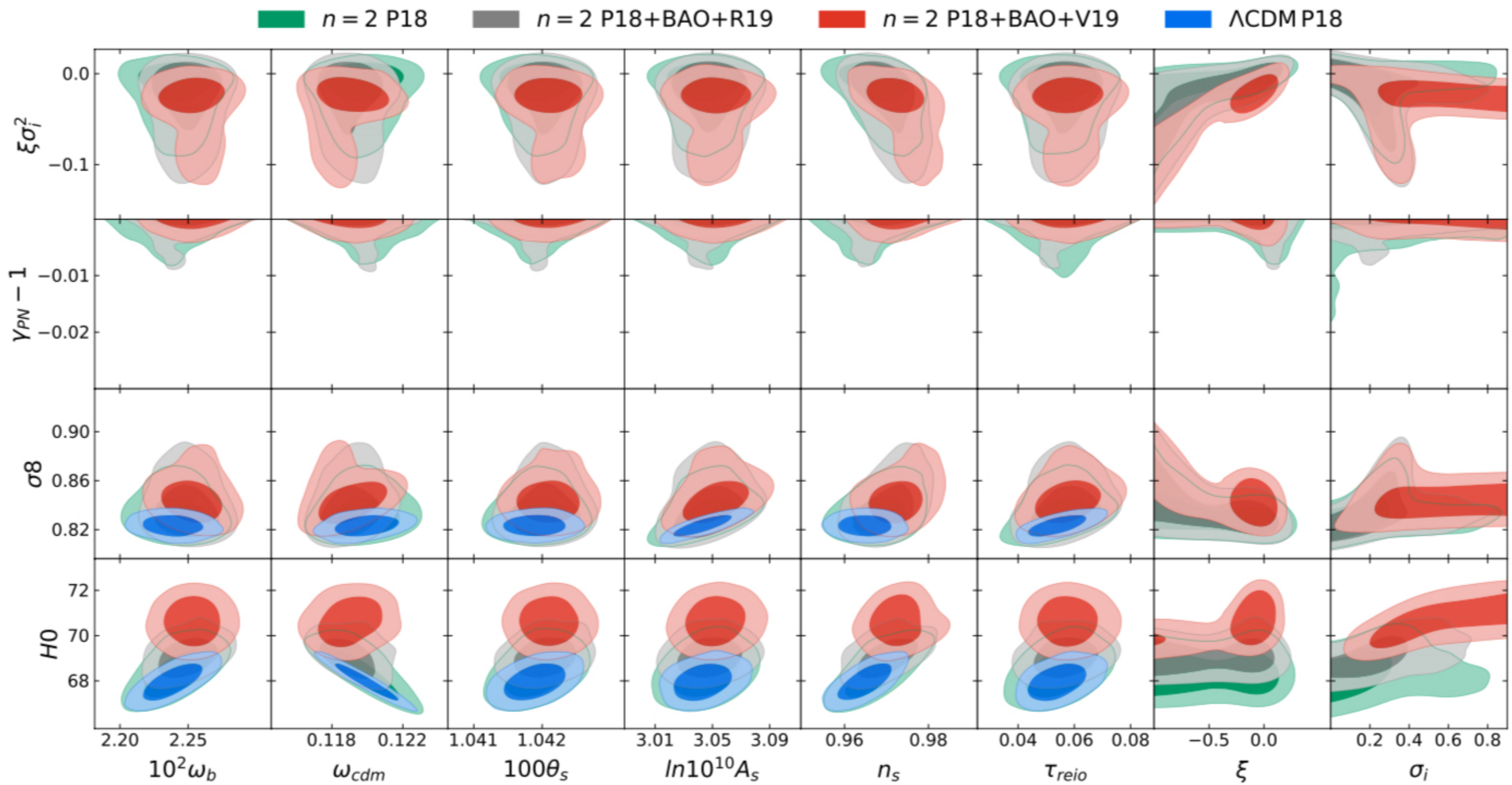
$$\boxed{F(\sigma) = M_{pl}^2 + \xi\sigma^2}$$

G always decreases, but approaches 1 for $\xi < 0$ and departs from 1 for $\xi > 0$



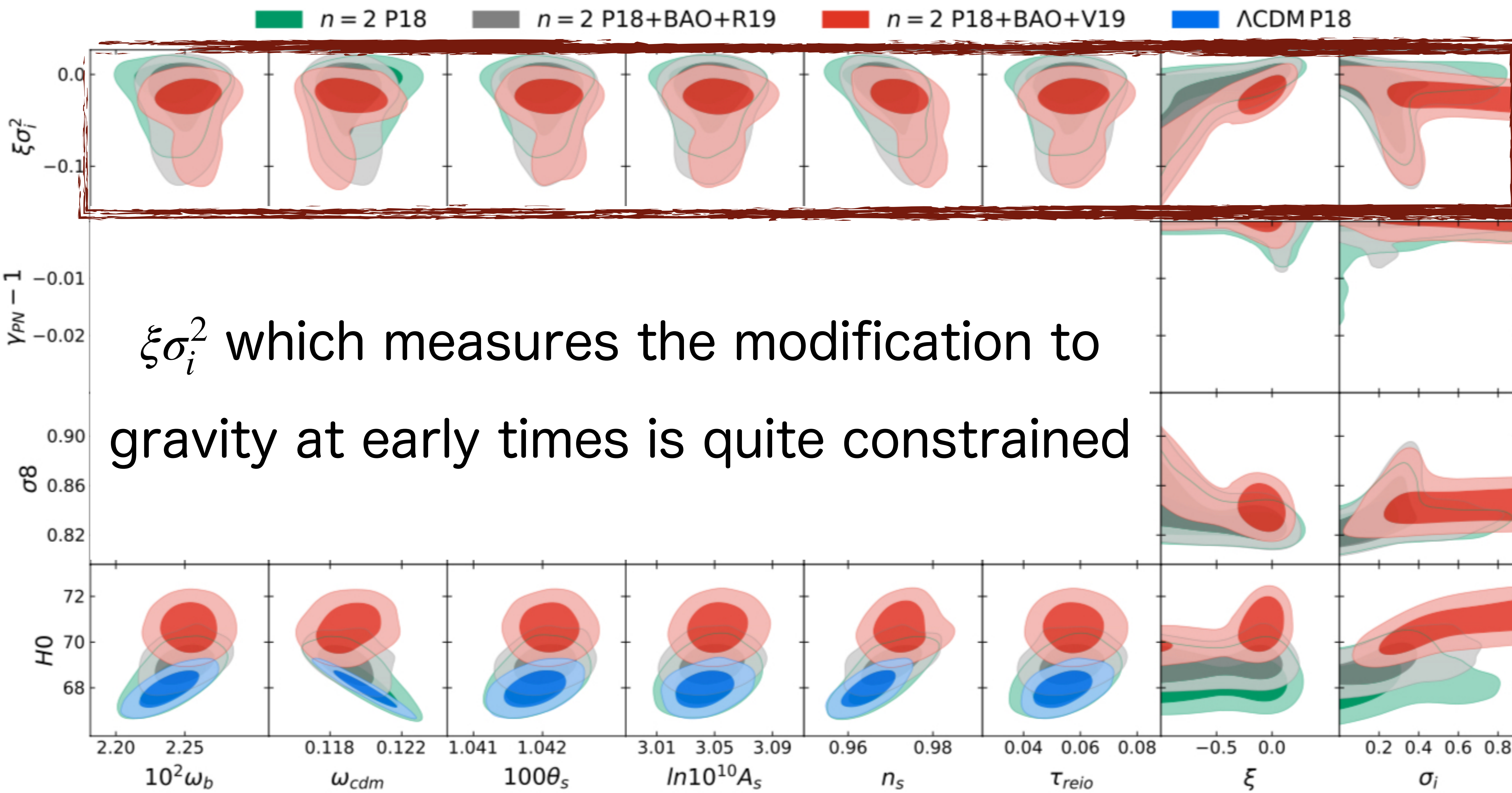
MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

NMC and H_0 tension



MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

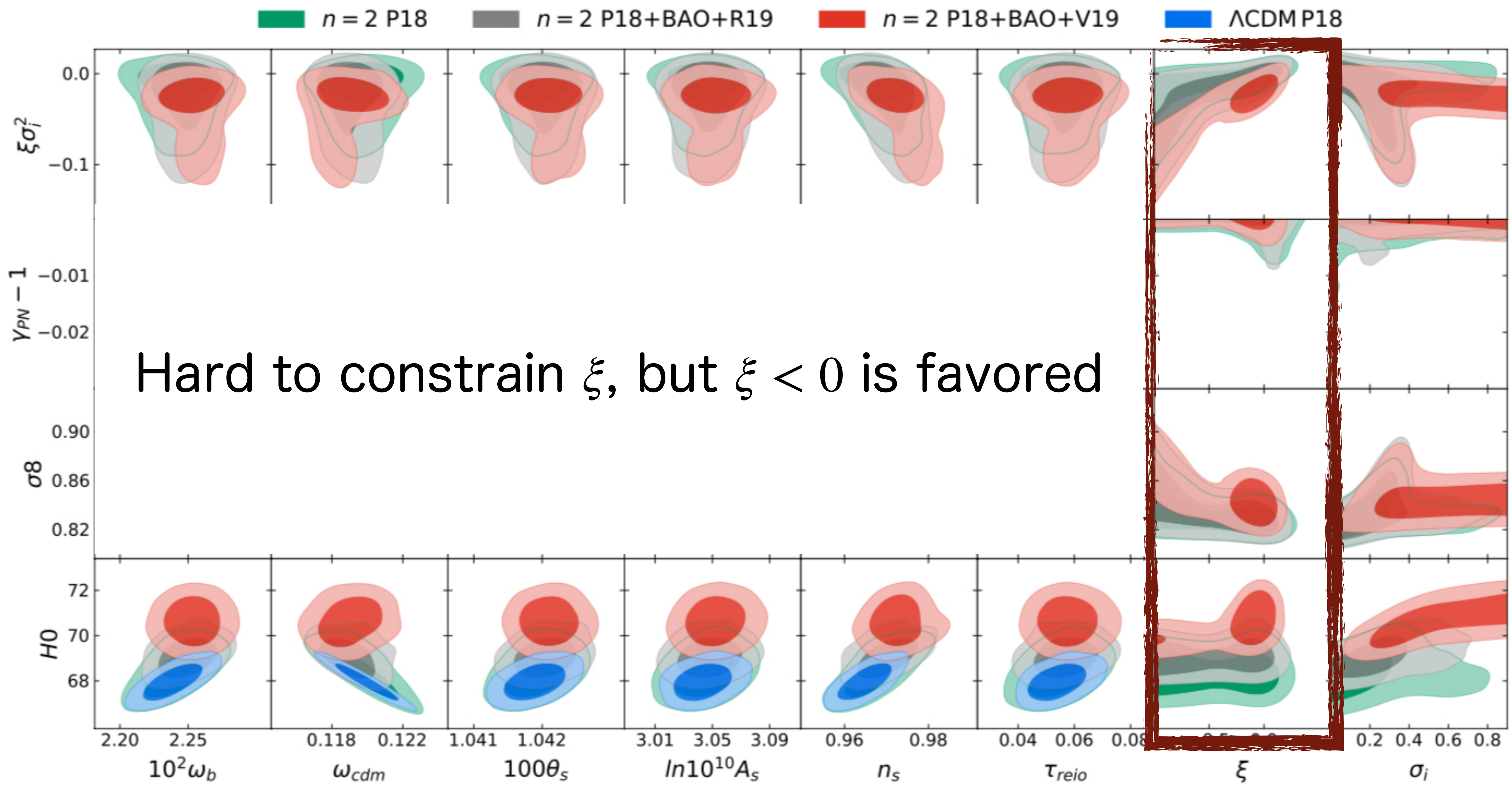
NMC and H_0 tension



$\xi\sigma_i^2$ which measures the modification to gravity at early times is quite constrained

MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

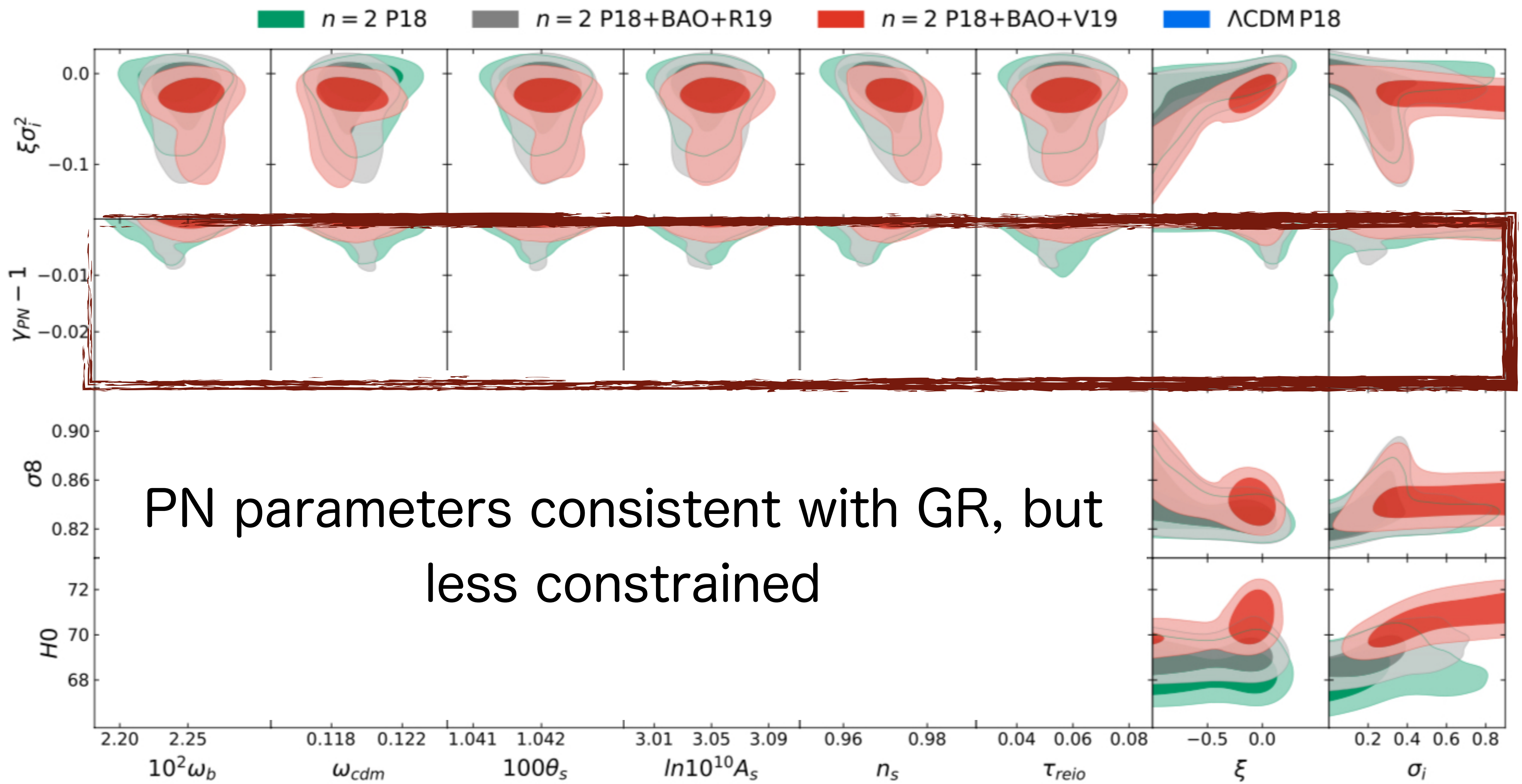
NMC and H_0 tension



Hard to constrain ξ, but $\xi < 0$ is favored

MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

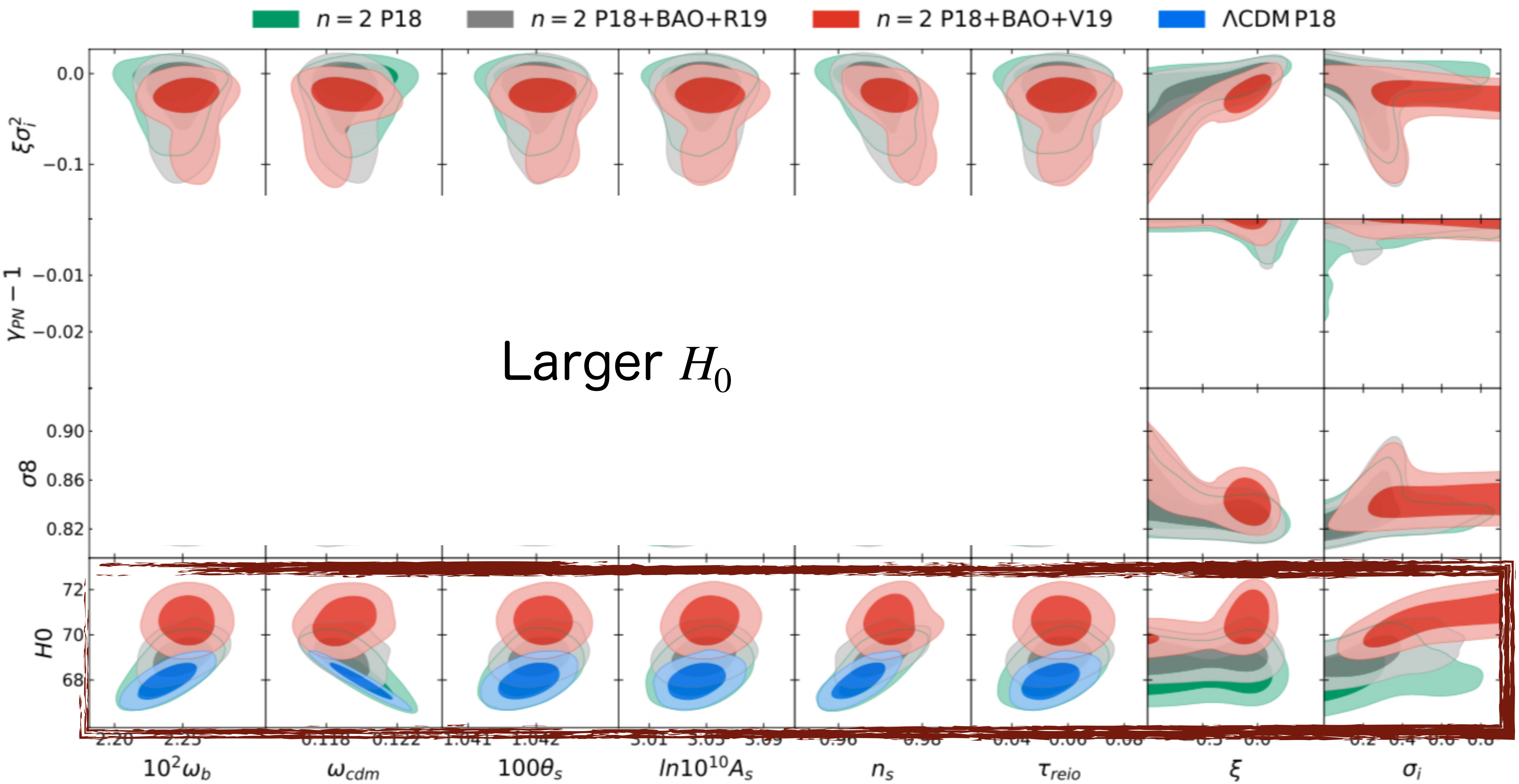
NMC and H_0 tension



PN parameters consistent with GR, but less constrained

MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

NMC and H_0 tension



MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

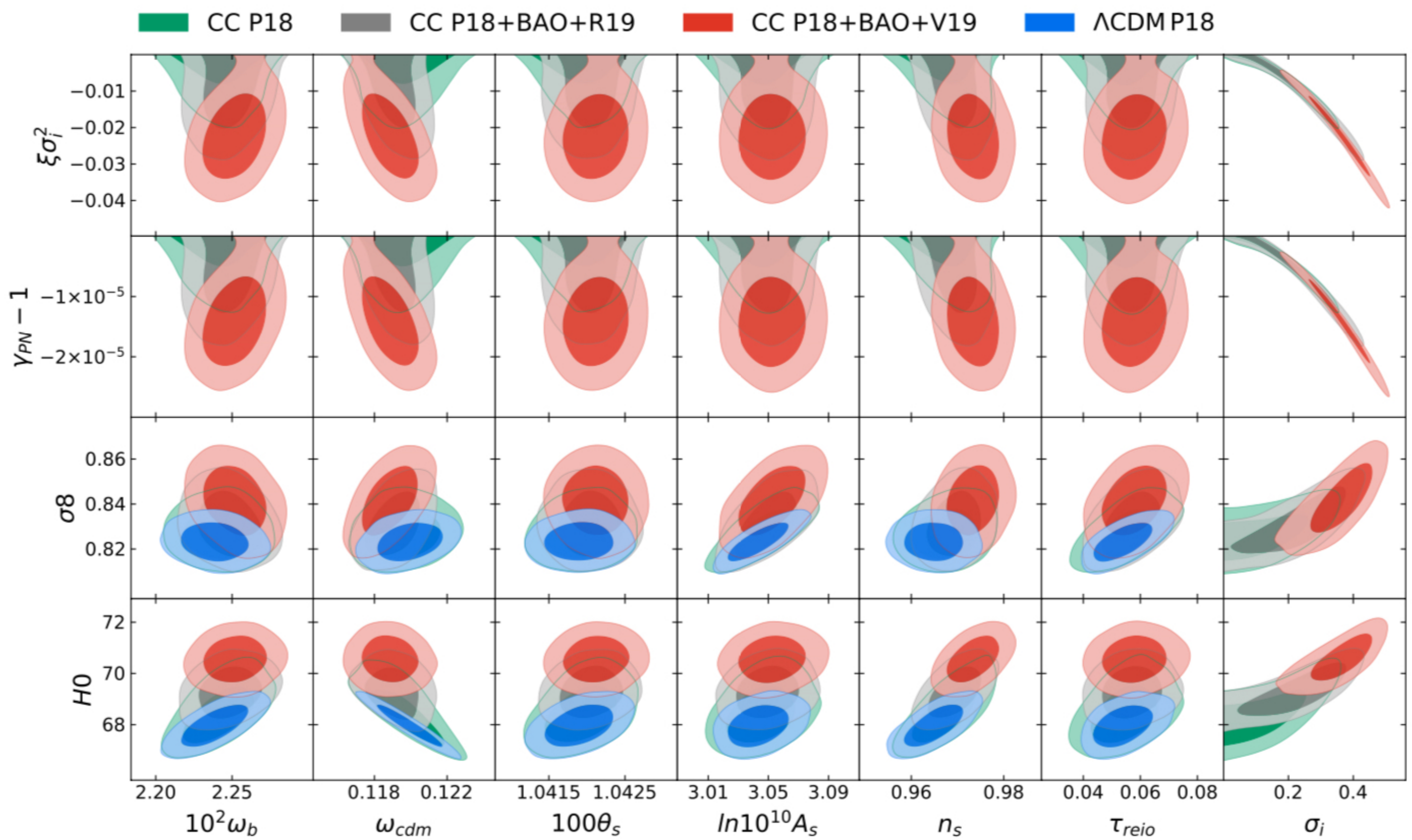
CC and H_0 tension

One parameter (σ_i) extension to ΛCDM

$$F(\sigma) = M_{pl}^2 - \frac{1}{6}\sigma^2$$

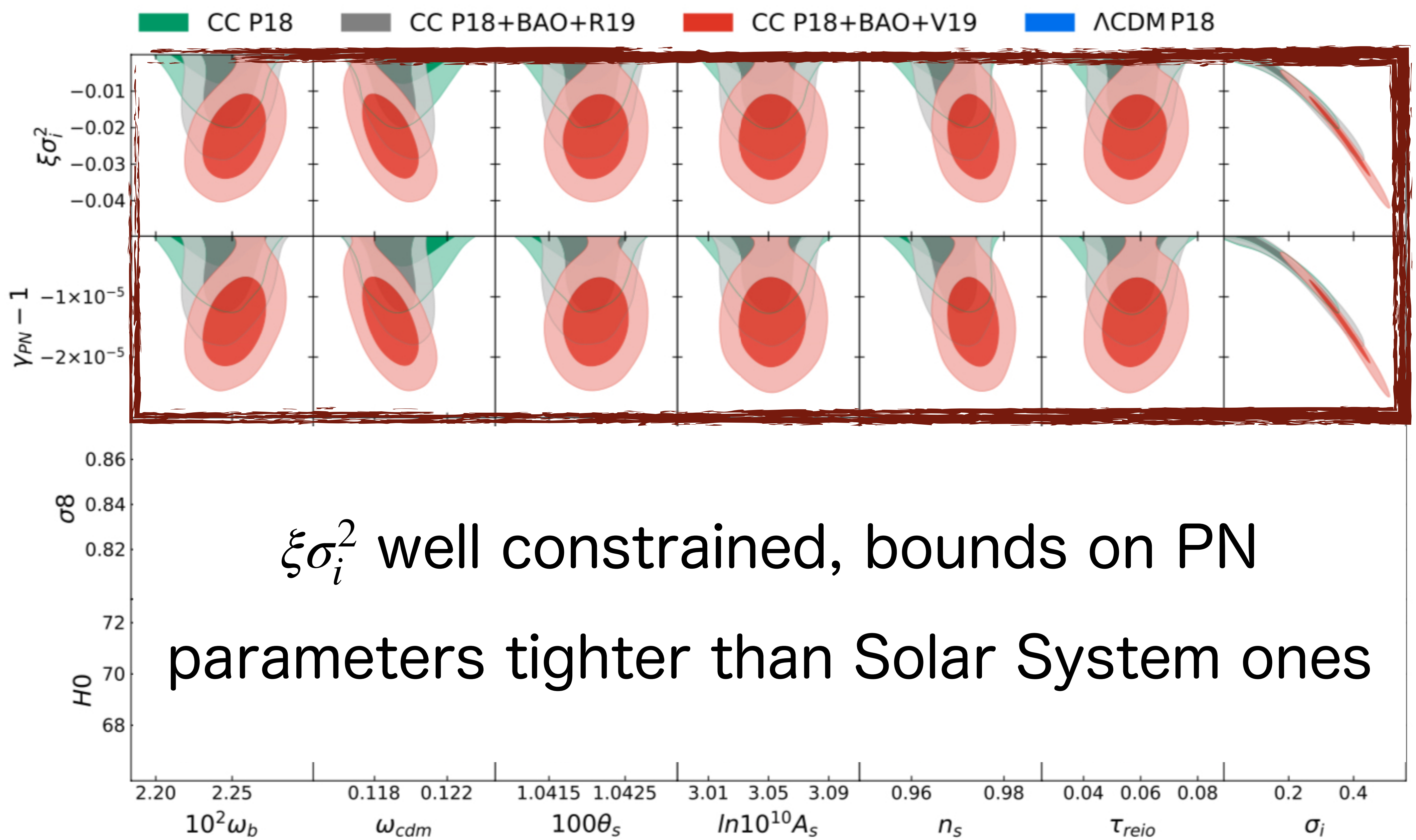
MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

CC and H_0 tension



MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

CC and H_0 tension

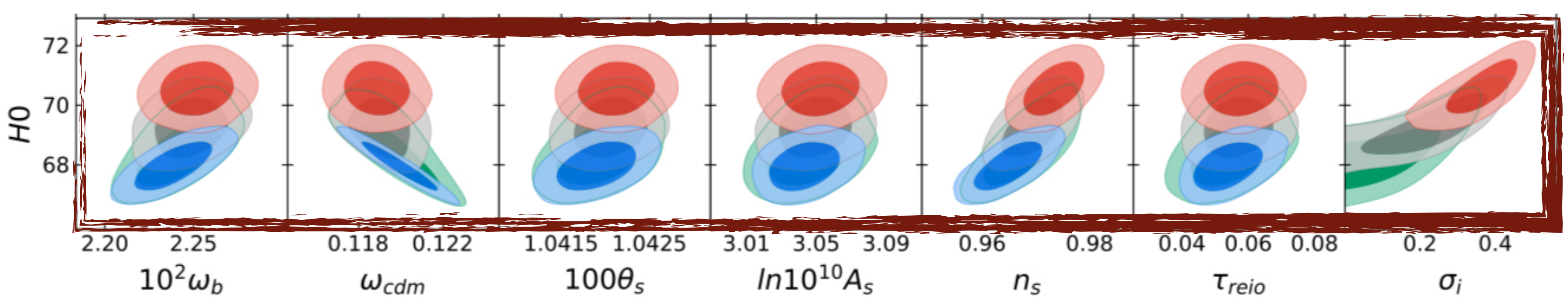


$\xi\sigma_i^2$ well constrained, bounds on PN parameters tighter than Solar System ones

MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

CC and H_0 tension

What about H_0?



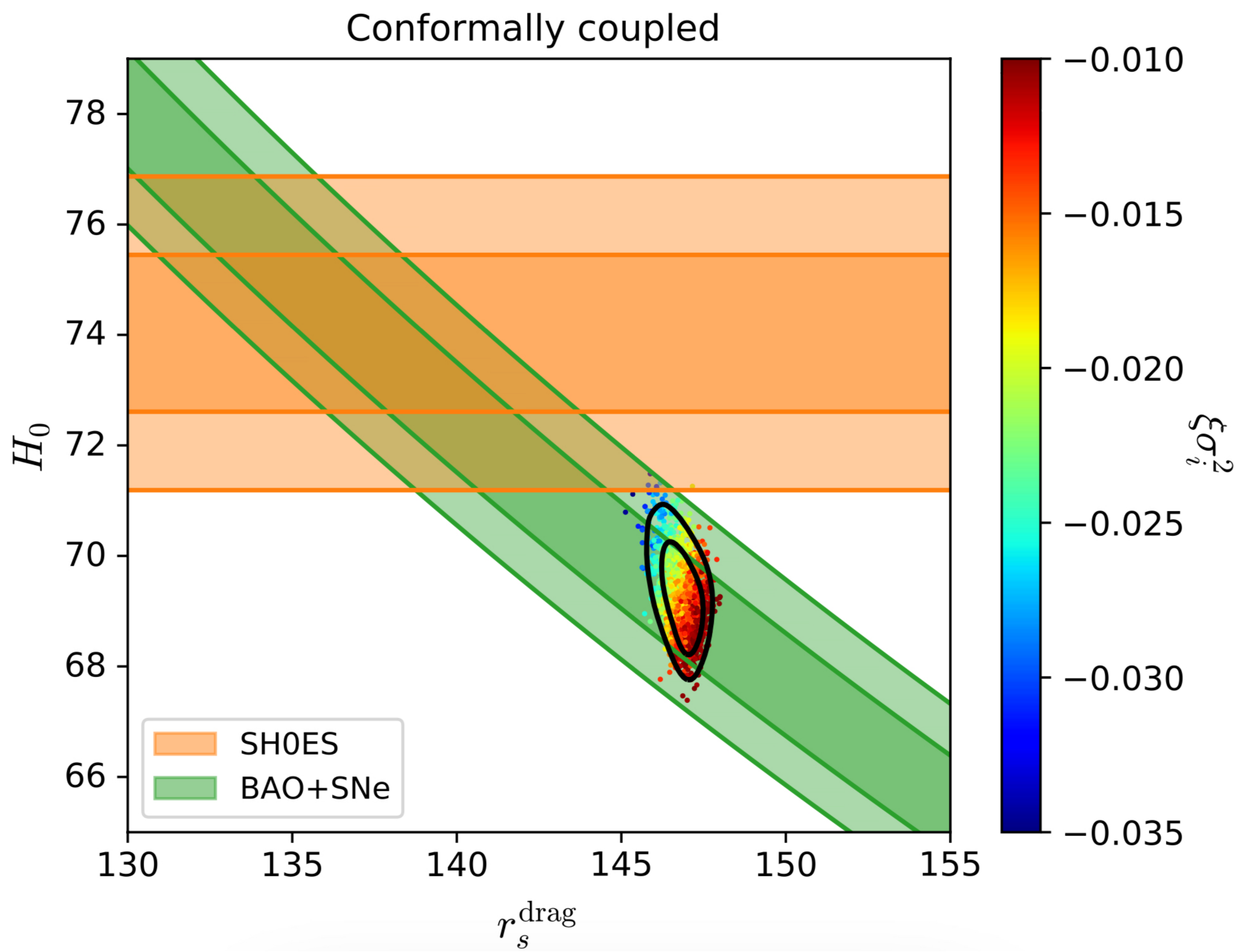
MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

CC and H_0 tension

CC	P18	P18 + BAO + R19	P18 + BAO + V19
$10^2\omega_{\rm b}$	2.242 ± 0.015	2.248 ± 0.014	2.252 ± 0.013
$\omega_{\rm c}$	0.1197 ± 0.0012	0.11910 ± 0.00099	0.1188 ± 0.0010
$100 * \theta_s$	1.04194 ± 0.00030	1.04205 ± 0.00028	1.042 ± 0.00028
$\tau_{\rm reio}$	0.0547 ± 0.0077	0.0570 ± 0.0071	0.05803 ± 0.0075
$\ln\left(10^{10} A_{\rm s}\right)$	3.046 ± 0.015	3.049 ± 0.014	3.053 ± 0.015
$n_{\rm s}$	0.9675 ± 0.0046	0.9695 ± 0.0038	0.9734 ± 0.0037
σ_i [M$_{\rm pl}$]	$0.1312^{+0.039}_{-0.13}$	$0.224^{+0.13}_{-0.081}$	$0.3585^{+0.078}_{-0.047}$
H_0 [km s^{-1}Mpc^{-1}]	$68.47^{+0.58}_{-0.86}$	$69.29^{+0.59}_{-0.72}$	70.56 ± 0.6
σ_8	$0.8272^{+0.0063}_{-0.0081}$	$0.8313^{+0.0079}_{-0.011}$	0.841 ± 0.010
r_s [Mpc]	$146.97^{+0.33}_{-0.29}$	$146.83^{+0.48}_{-0.34}$	146.4 ± 0.45
$\xi\sigma_i^2$ [$M_{\rm pl}^2$]	> -0.0150	> -0.0234	$-0.022^{+0.016}_{-0.015}$
σ_0 [M$_{\rm pl}$]	$0.004017^{+0.0012}_{-0.004}$	$0.006841^{+0.004}_{-0.0025}$	$0.01102^{+0.0024}_{-0.0015}$
$\gamma_{\rm PN} - 1$	$> -0.95 \cdot 10^{-5}$	$> -1.5 \cdot 10^{-5}$	$\left(-1.4^{+1.0}_{-0.9}\right) \cdot 10^{-5}$
$\beta_{\rm PN} - 1$	$\left(0.23^{+0.61}_{-0.34}\right) \cdot 10^{-6}$	$\left(0.53^{+0.75}_{-0.61}\right) \cdot 10^{-6}$	$\left(1.16^{+0.78}_{-0.84}\right) \cdot 10^{-6}$
$\Delta\chi^2$	$+0.42$	-5.0	-13.64

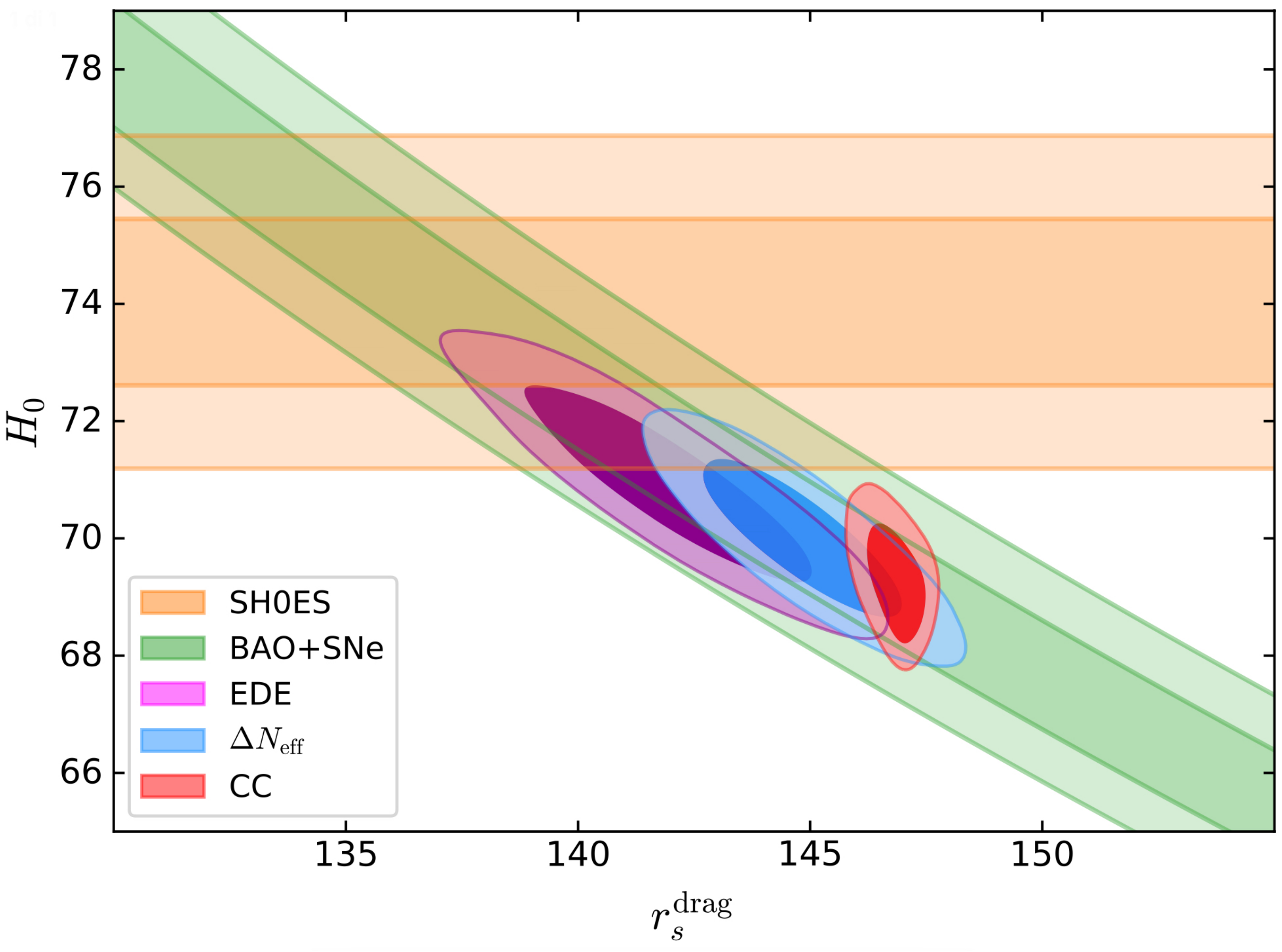
MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

CC and H_0 tension



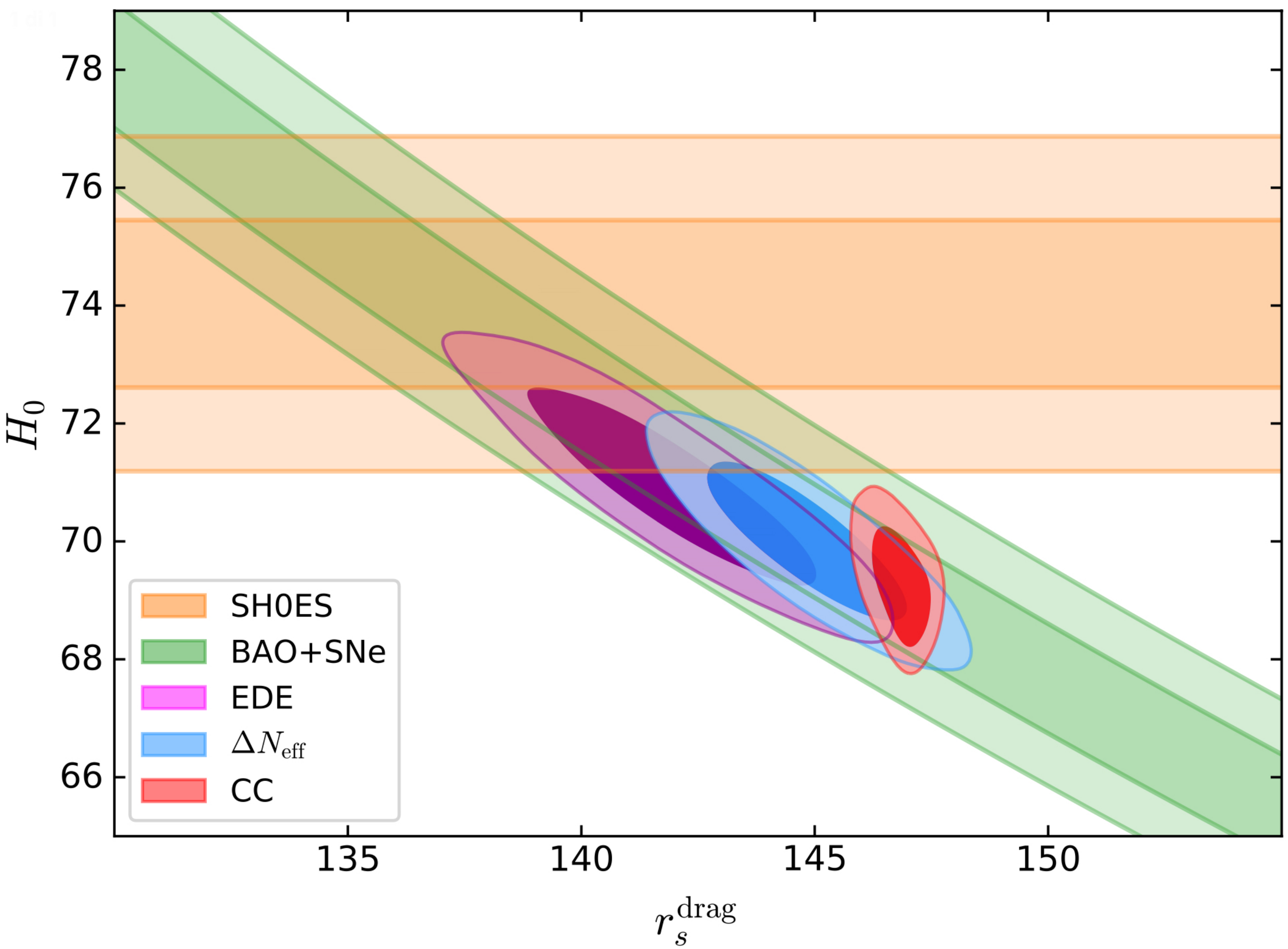
MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

CC and H_0 tension



MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

CC and H_0 tension



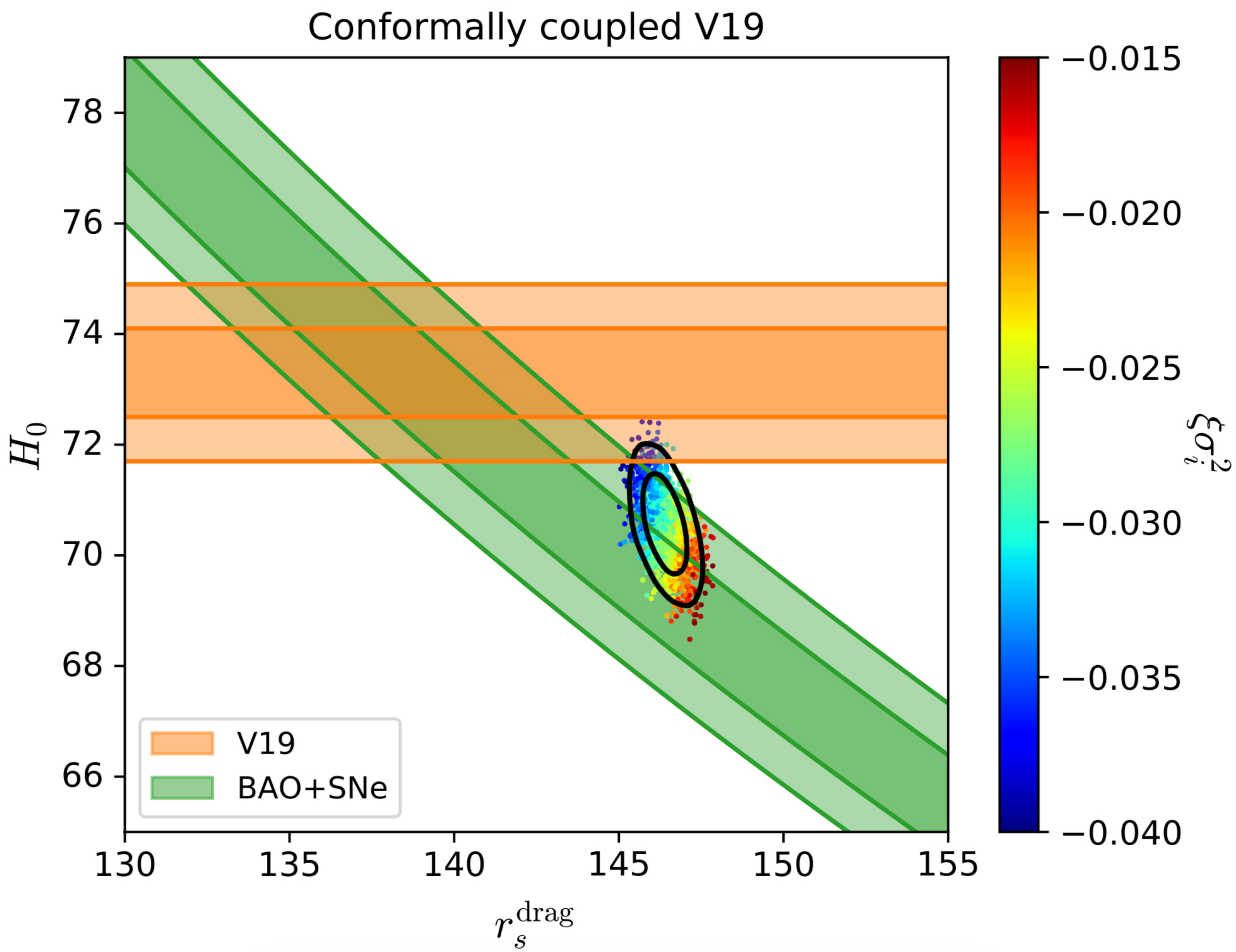
$$\Delta\chi^2_{\rm CC} = -5$$

$$\Delta\chi^2_{\rm N_{eff}} = -2.8$$

In contrast with
Ballesteros, Notari, Rompineve 2020

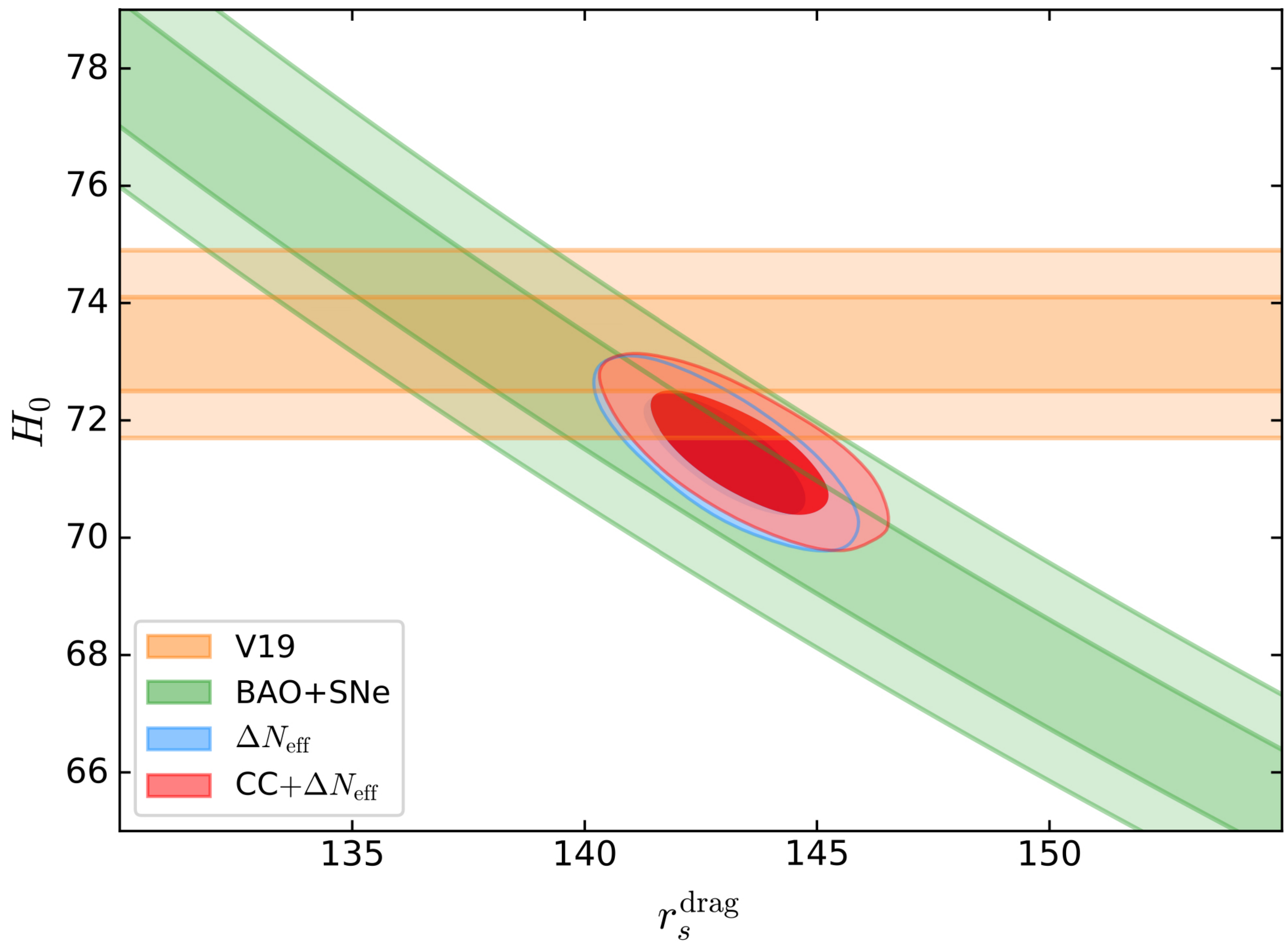
MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

CC and H_0 tension



MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

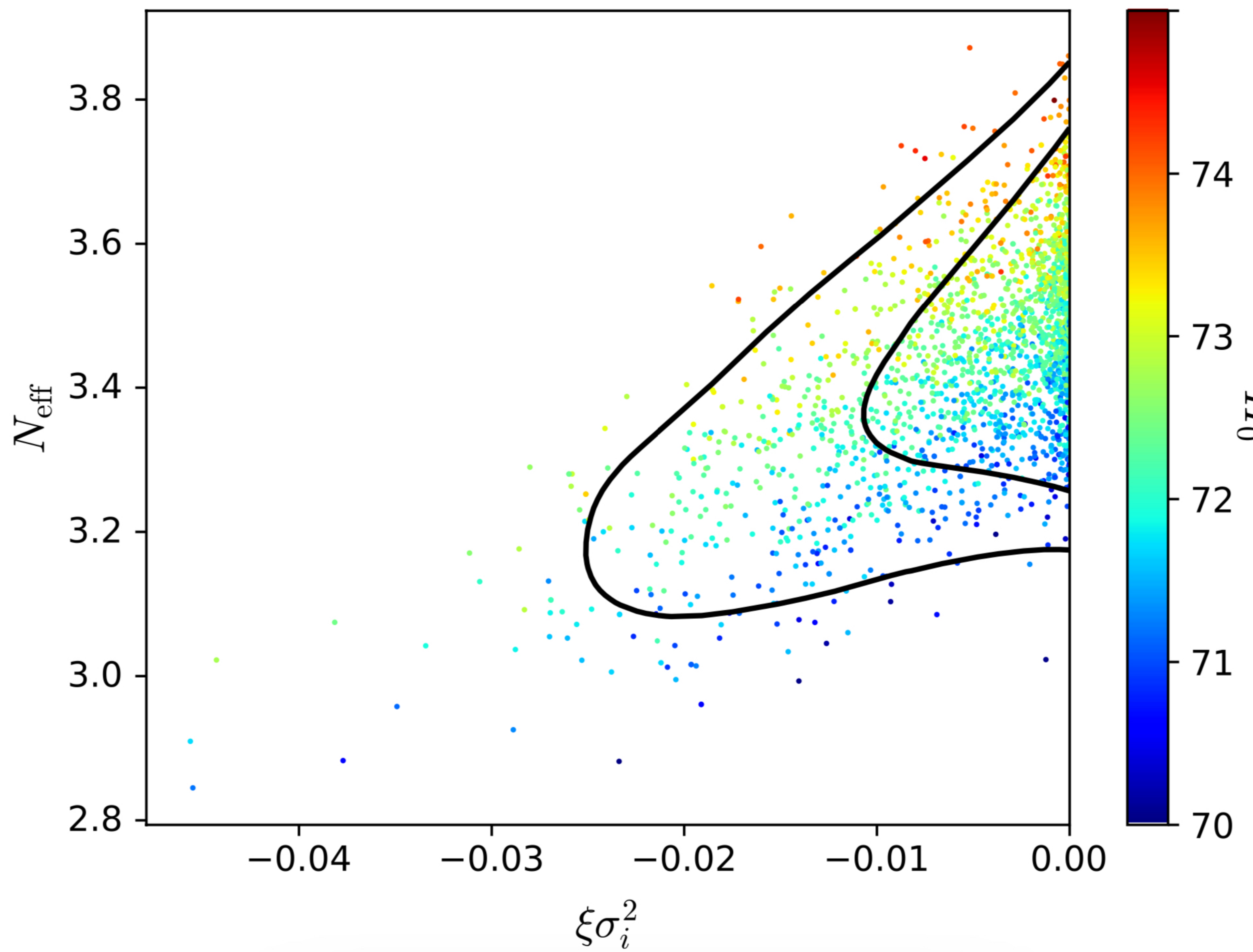
CC + $\Delta N_{\rm eff}$ and H_0 tension



MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

CC + $\Delta N_{\rm eff}$ and H_0 tension

Little degeneracy between extra radiation and modified gravity



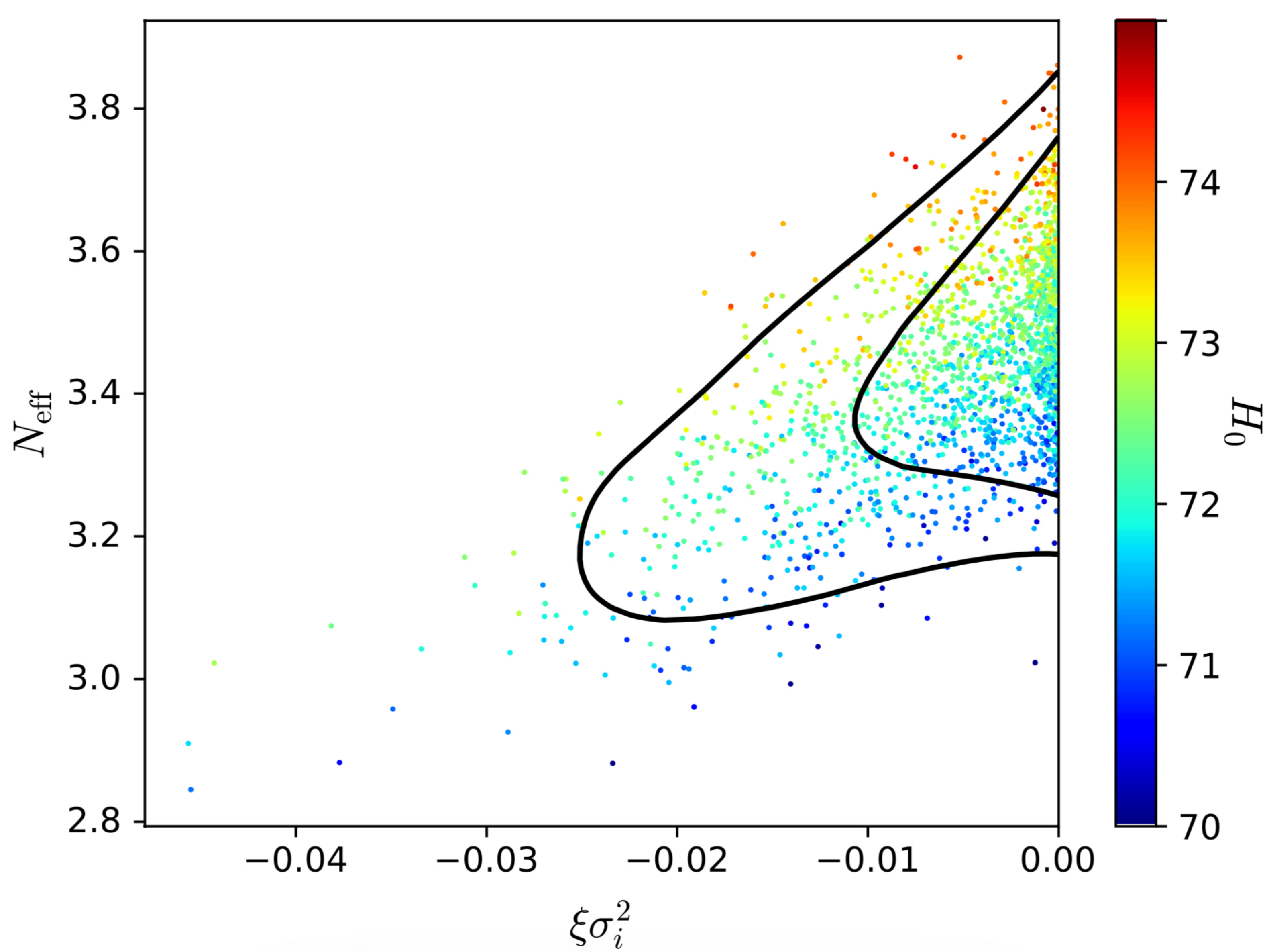
MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

CC + ΔN_{eff} and H_0 tension

Little degeneracy between extra radiation and modified gravity

$$\Delta\chi^2_{\mathrm{N_{eff}}} = -14.54$$

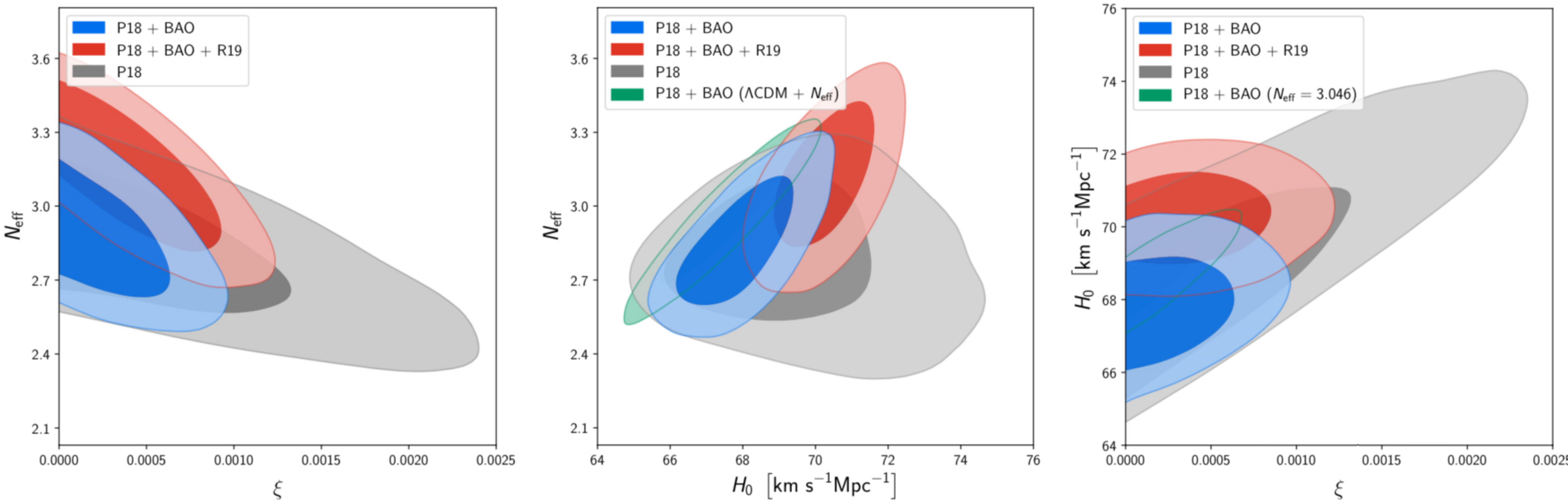
$$\Delta\chi^2_{\mathrm{CC+N_{eff}}} = -20.48$$



MB, Ballardini, Emond, Finelli, Gumrukcuoglu, Koyama, Paoletti 2020

JBD & Neutrino physics

JBD + $N_{\rm eff}$



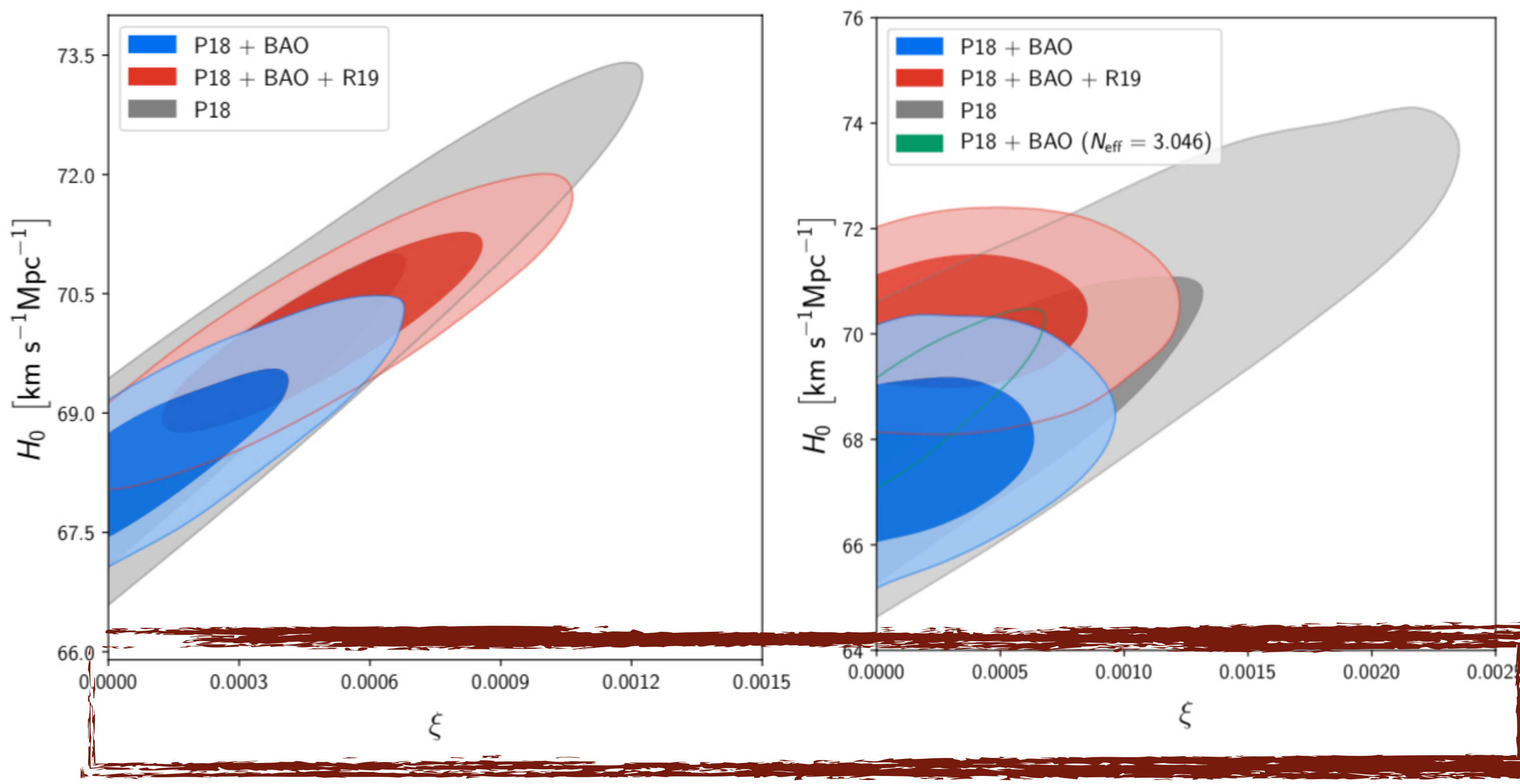
Constraints on ξ are relaxed

Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà 2020

JBD & Neutrino physics

JBD

JBD + N_{eff}

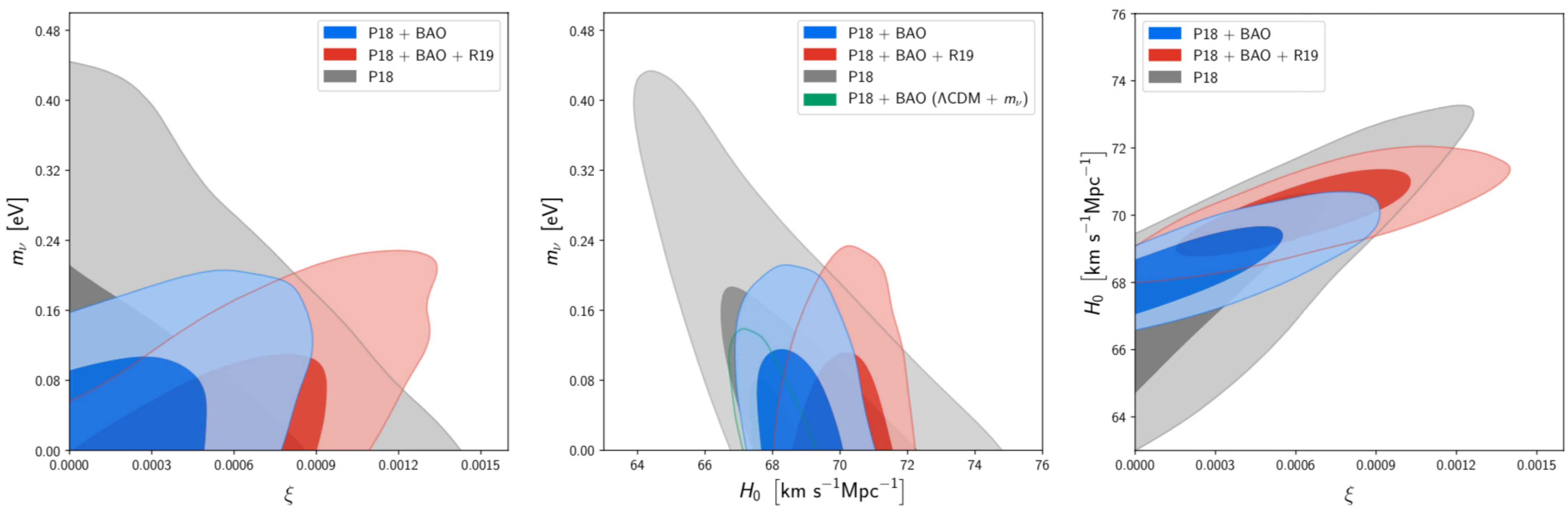


Constraints on ξ are relaxed

Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà 2020

JBD & Neutrino physics

JBD + $N_{\rm eff}$ $+m_\nu$

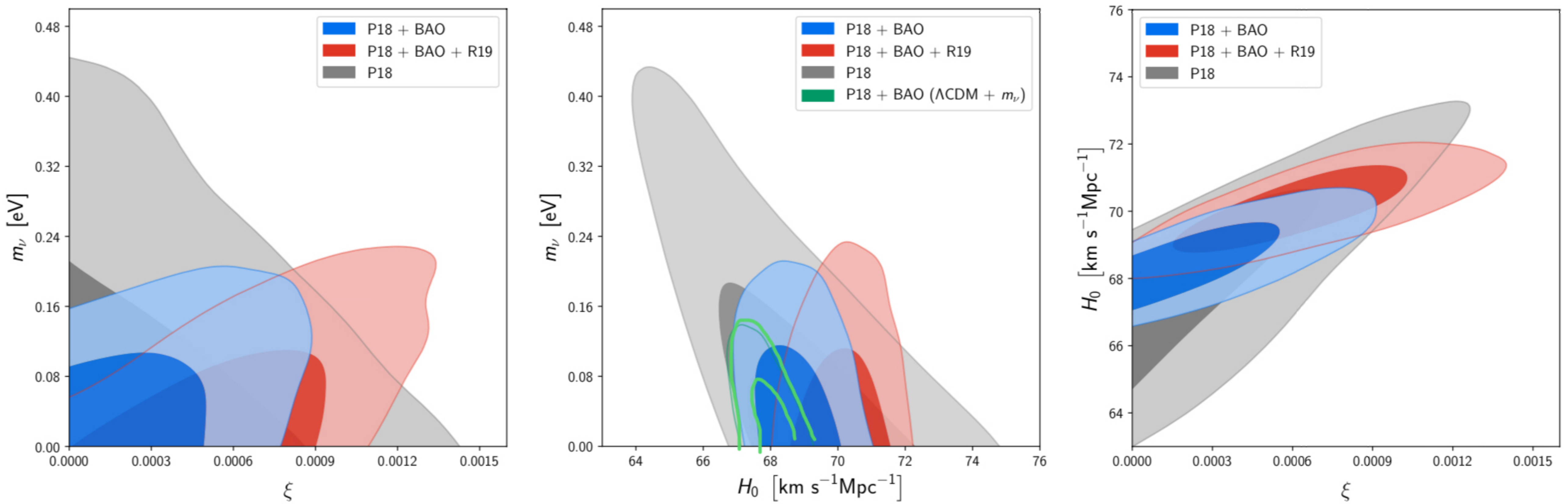


Constraints on ξ and m_ν are relaxed

Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà 2020

JBD & Neutrino physics

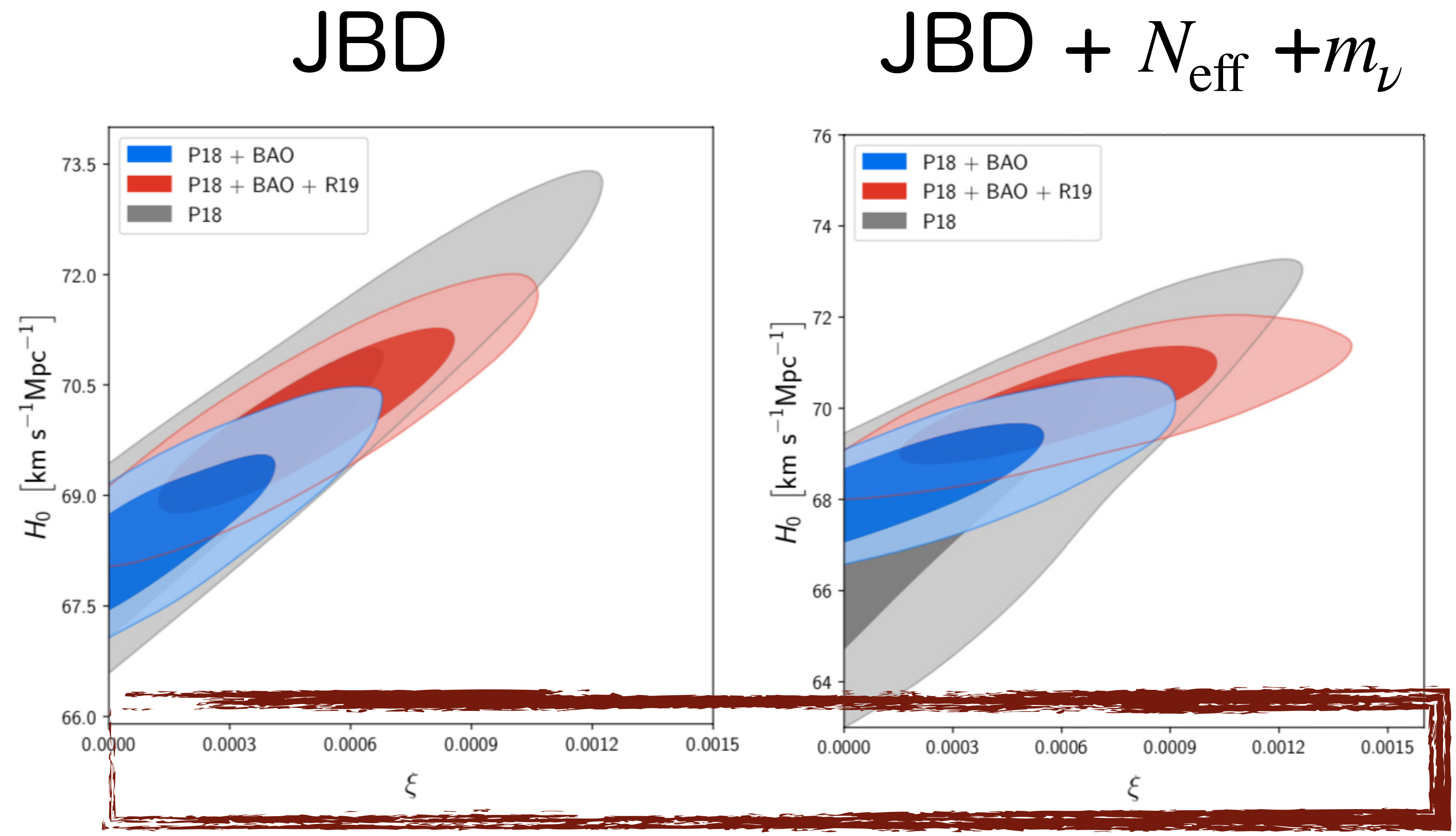
JBD + N_{eff} + m_ν



Constraints on ξ and m_ν are relaxed

Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà 2020

JBD & Neutrino physics



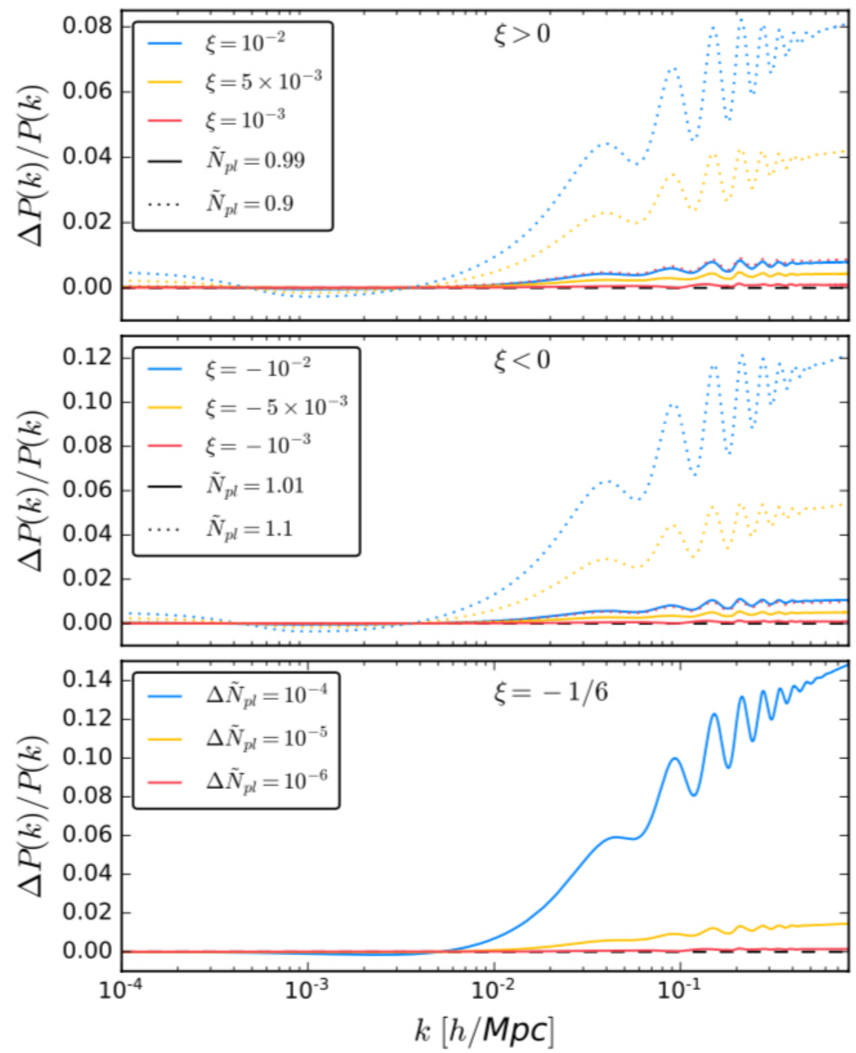
Constraints on ξ and m_ν are relaxed

Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà 2020

Constraining NMC: where to look

- Full shape of the power spectrum

D'Amico, Senatore, Zhang, Zheng 2020, Hill, McDonough, Toomey, Alexander 2020, Ivanov et al 2020



Rossi, Ballardini, MB, Finelli, Paoletti, Starobinsky, Umiltà 2019

Constraining NMC: where to look

- Full shape of the power spectrum
  D'Amico, Senatore, Zhang, Zheng 2020,
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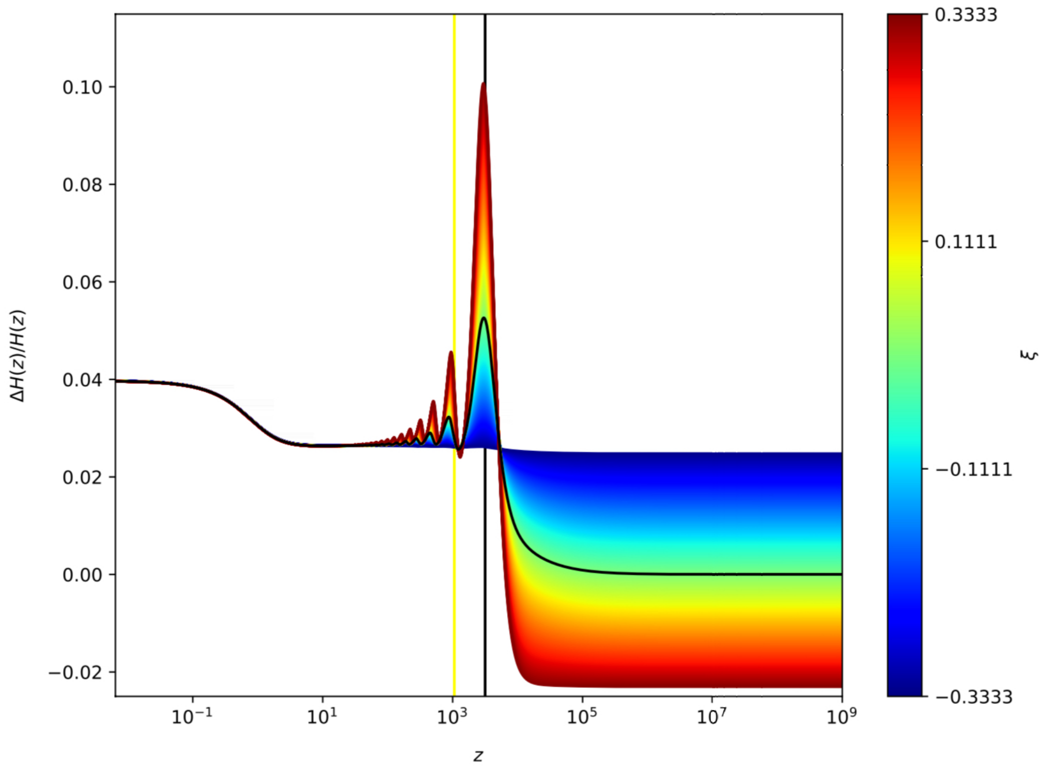
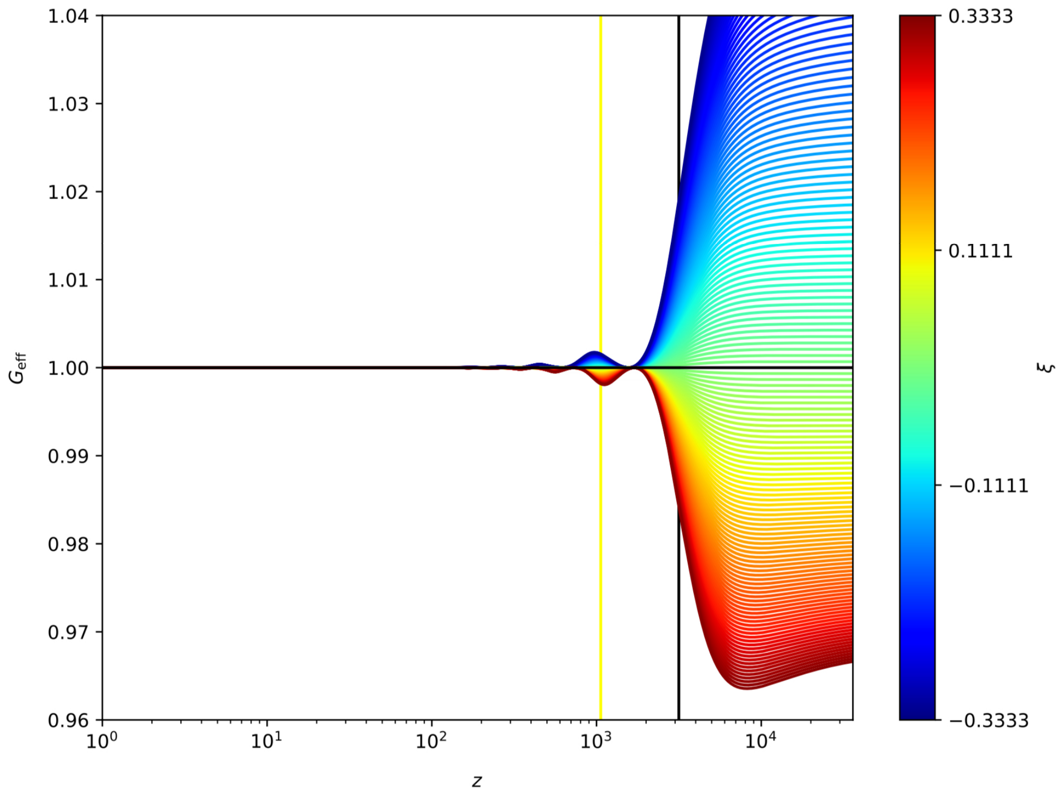




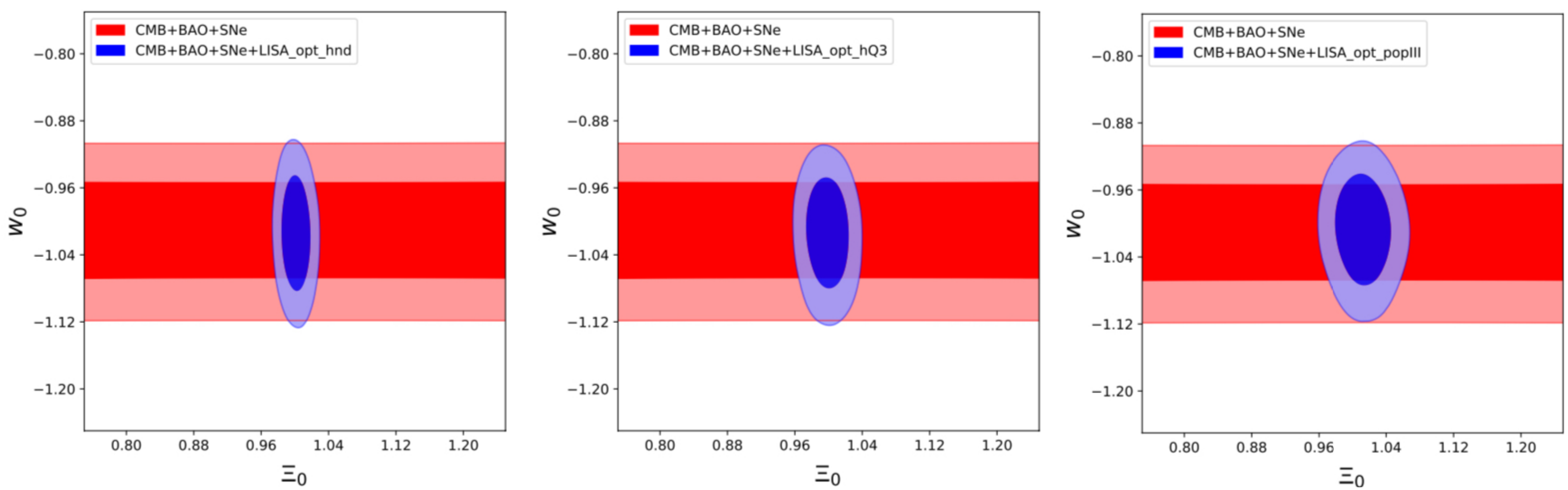
In preparation

Constraining NMC: where to look

- Standard sirens

Caprini & Tamanini 2016

Belgacem et al 2019



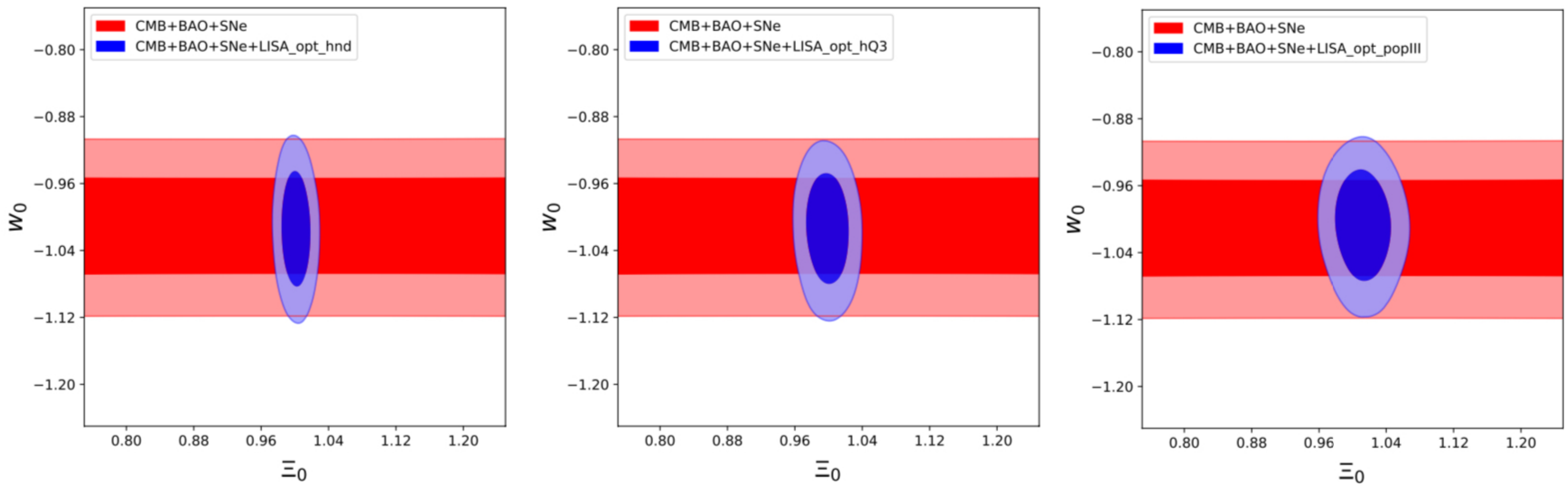
$$w_{DE}(a) = w_0 + w_a(1-a)$$

$$\Xi(z) \equiv \frac{d_L^{\rm gw}(z)}{d_L^{\rm em}(z)} = \Xi_0 + \frac{1-\Xi_0}{(1+z)^n}$$

Constraining NMC: where to look

- Standard sirens
  Caprini & Tamanini 2016

Belgacem et al 2019



Power to constrain JBD

Hard to constrain NMC models that ease the H_0 tension

Constraining NMC: where to look

- Standard sirens
  Caprini & Tamanini 2016

- Scalar gravitational wave effect
  Koyama today

Power to constrain JBD

Hard to constrain NMC models that ease the H_0 tension

Constraining NMC: where to look

- Standard sirens

Caprini & Tamanini 2016

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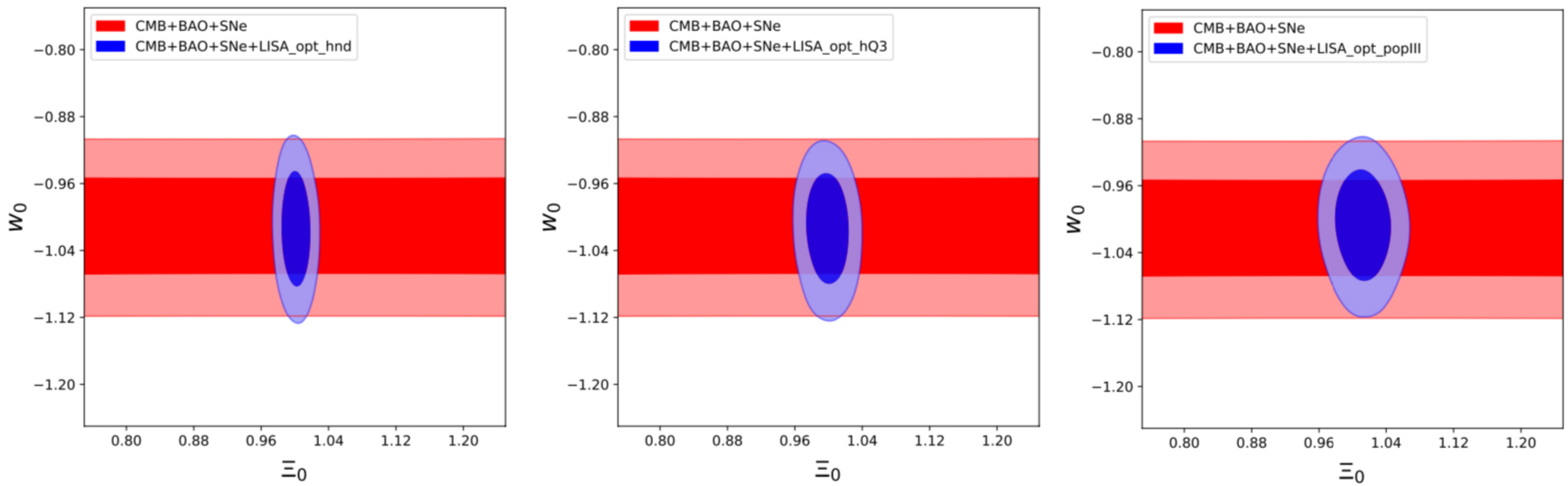

Power to constrain JBD

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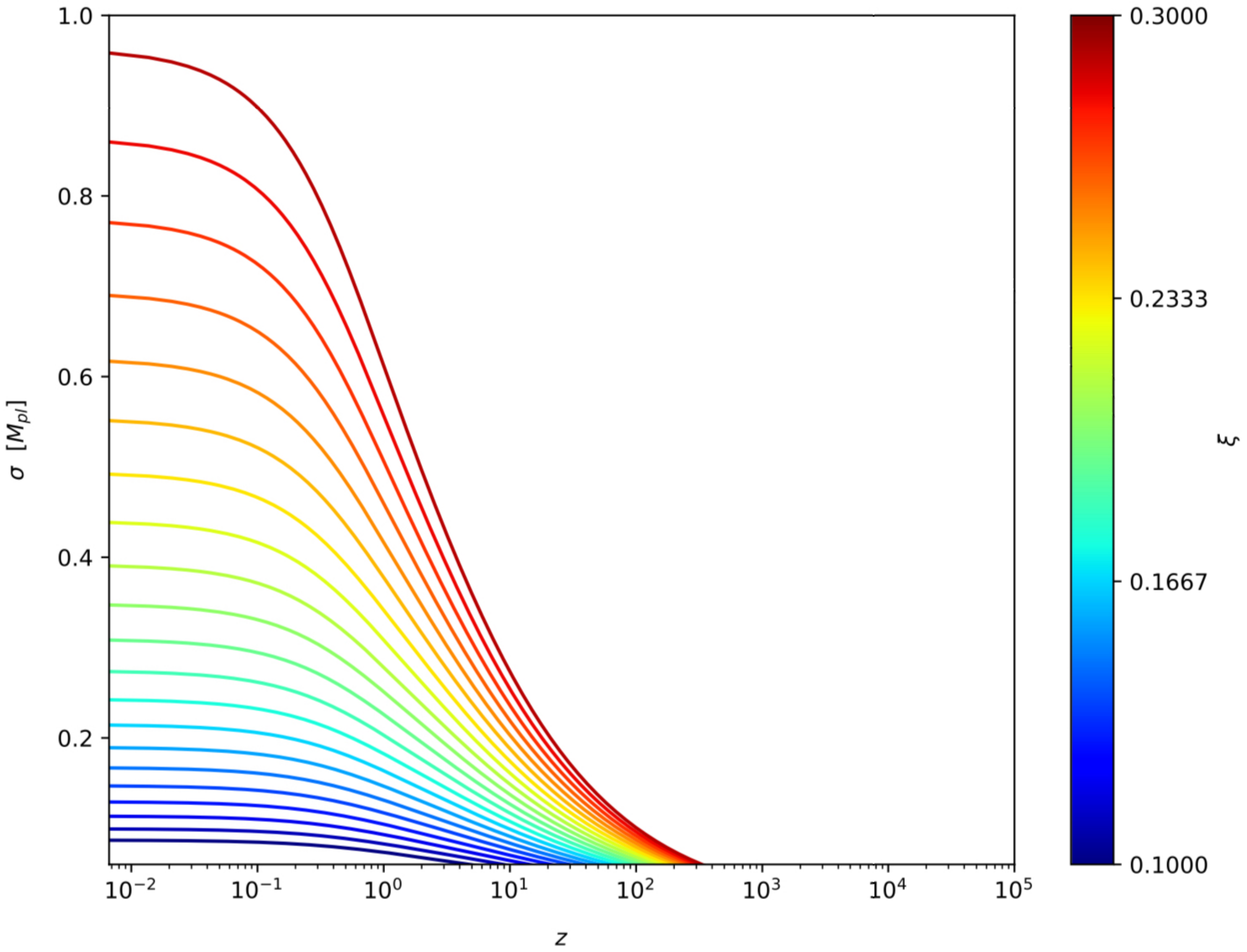
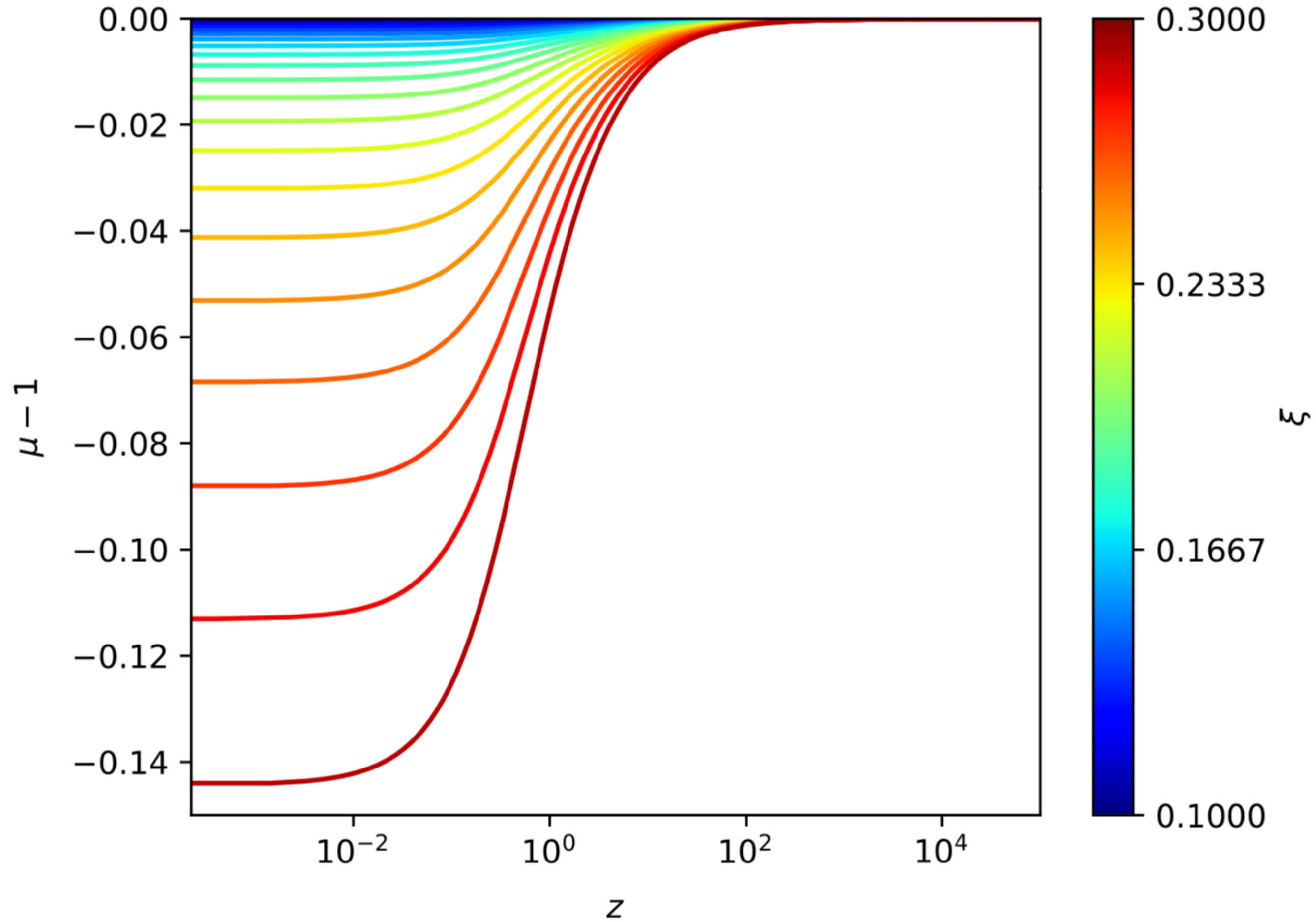
Constraining NMC: where to look

- Standard sirens



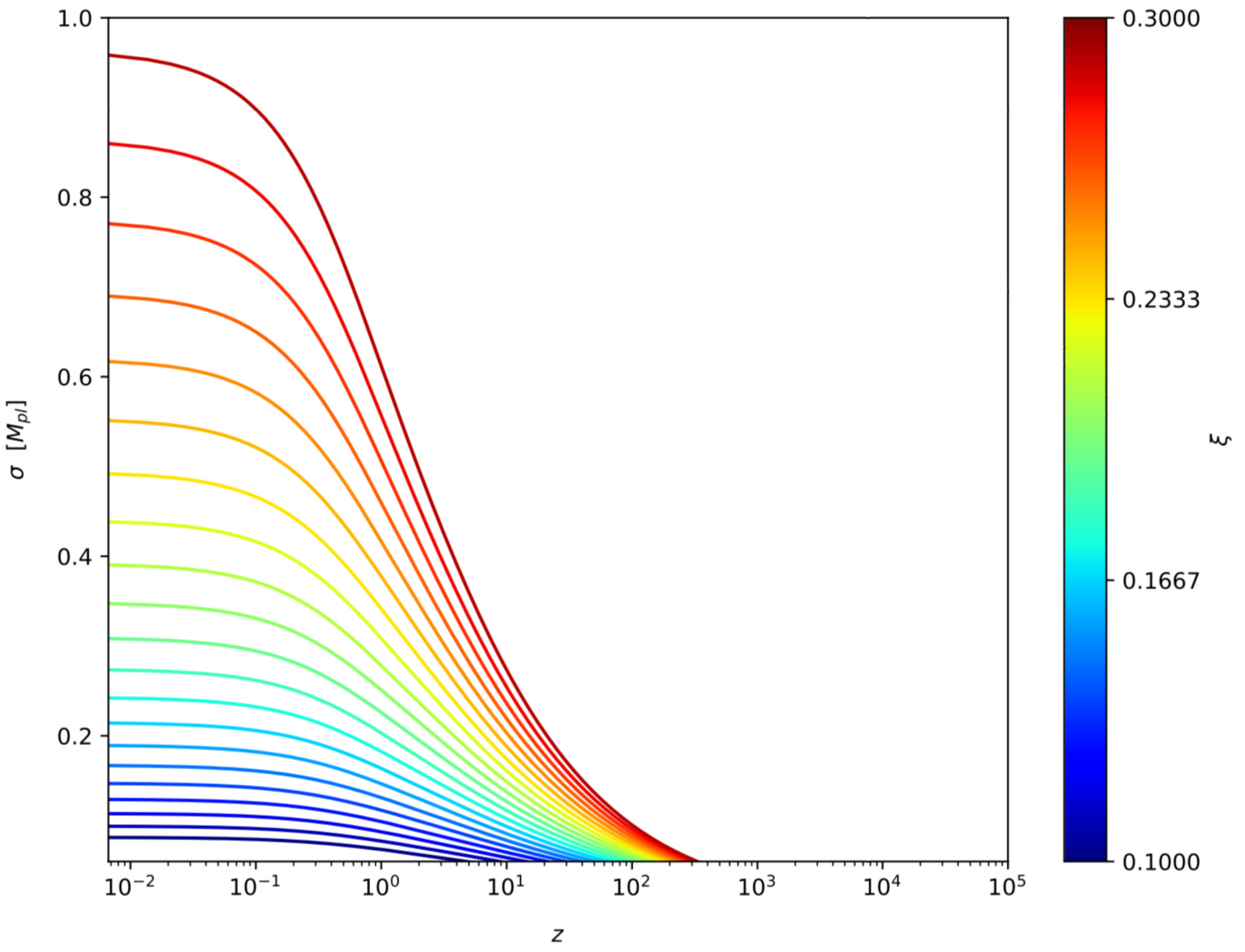


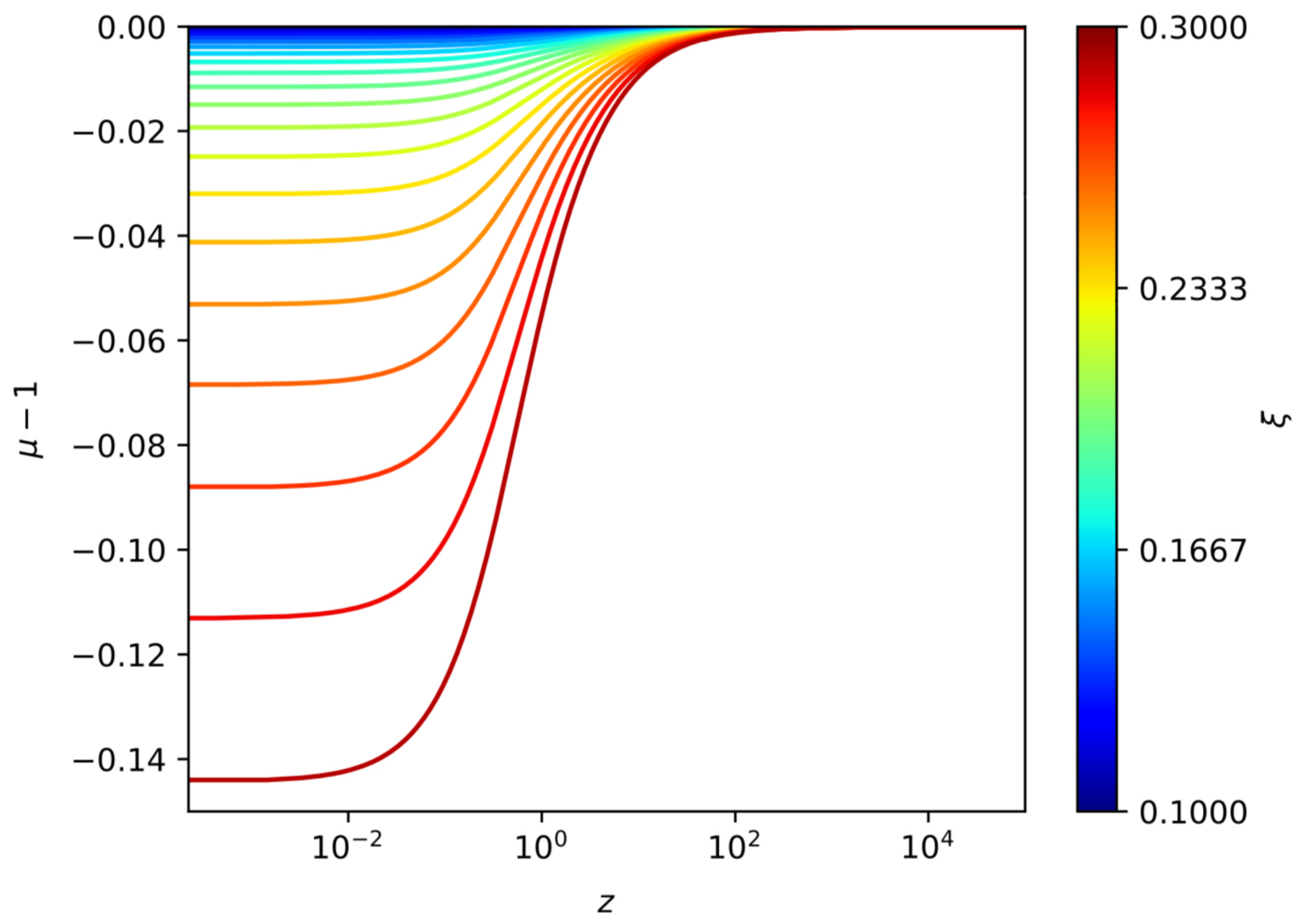
Power to constrain NMC models with late time modifications to gravity

Constraining NMC: where to look

- N-body simulations

  Winther, Koyama, Manera, Wright, Zhao 2017





In preparation

Conclusions

- Modifications to gravity offer a natural framework to address the H_0 tension which is worth exploring extensively
- A non-minimal coupling to gravity, though not as effective as EDE models, can ease the tension without the need of fine tuning. Again, this triggers model building in this direction
- Future experiments that aim at testing gravity can further constrain these models