TeV Particle Astrophysics
TeVPA
Valencia 2025

DARK ENERGY AND NEUTRINOS ALONG THE COSMIC EXPANSION HISTORY

Pietro Ghedini [IFIC, CSIC-UV - pietro.ghedini@ific.uv.es]
in collaboration with **Olga Mena** [IFIC, CSIC-UV] and **Rasmi Hajjar Muñoz** [Ohio State University, CCAPP]

CSIC
Consejo Superior de Investigaciones Científicas
Vniversitat de València
IFIC Institut de Física Corpuscular
Excelencia Severo Ochoa

TO DO LIST:

- ❏ INTRODUCTION
- ❏ RECONSTRUCTION FORMALISM
- ❏ METHODOLOGY
- ❏ RESULTS

THE SPANISH COSMOLOGICAL PICTURE

Credits: S. Gariazzo

ΛCDM

Highly successful

BUT

based on two unknowns…

… and

emergence

of *anomalies*

and *tensions*

ΛCDM

4

See also W. Giarè talk later and A. R. Khalife talk tomorrow

ANOMALIES & TENSIONS IN COSMOLOGY • COSMOVERSE •

[CosmoVerse White Paper, 2504.01669]

… and

emergence

of *a*

and

Λ

NEED FOR NEW PHYSICS?

hite Paper, 2504.01669]

... and

emergence

of *anomalies*

and *tensions*

ΛCDM

ANOMALIES & TENSIONS IN COSMOLOGY • COSMOVERSE •

[CosmoVerse White Paper, 2504.01669]

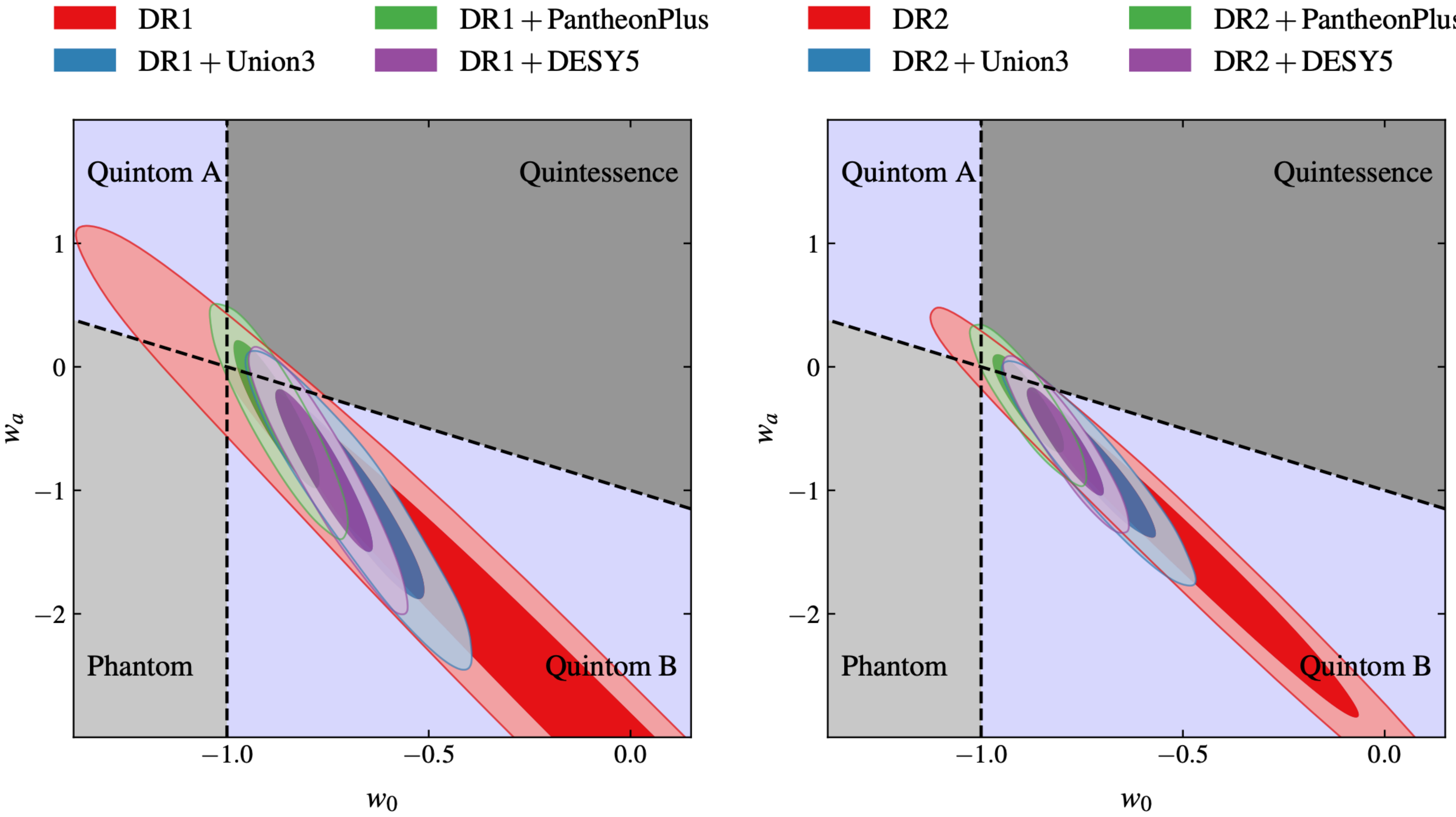
DARK ENERGY SPECTROSCOPIC INSTRUMENT

U.S. Department of Energy Office of Science

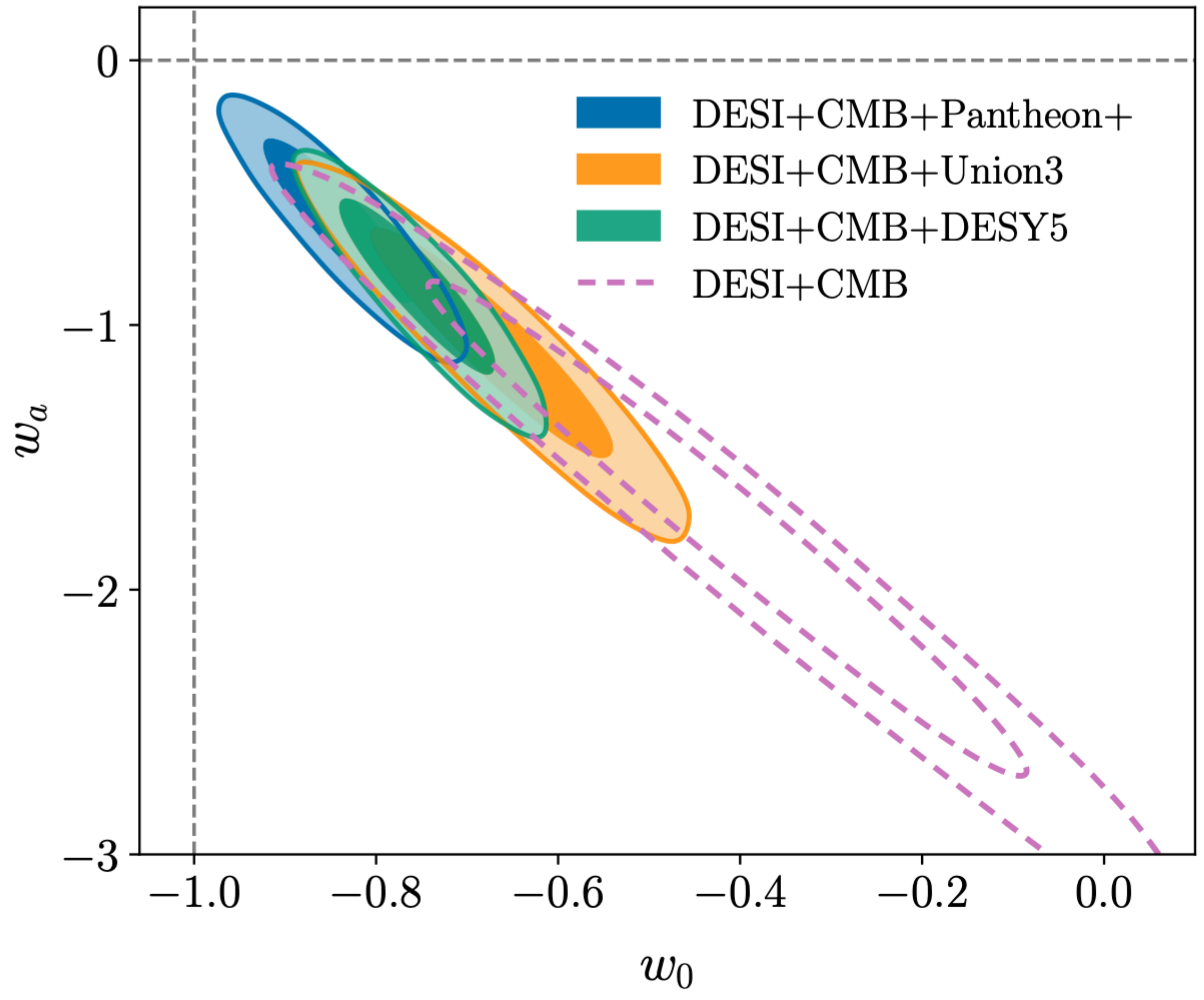
EVIDENCES FOR DYNAMICAL DARK ENERGY

Assuming CPL: $w(a) = w_0 + w_a(1 - a)$

[DESI collaboration, 2504.06118]



[DESI collaboration, 2503.14738]



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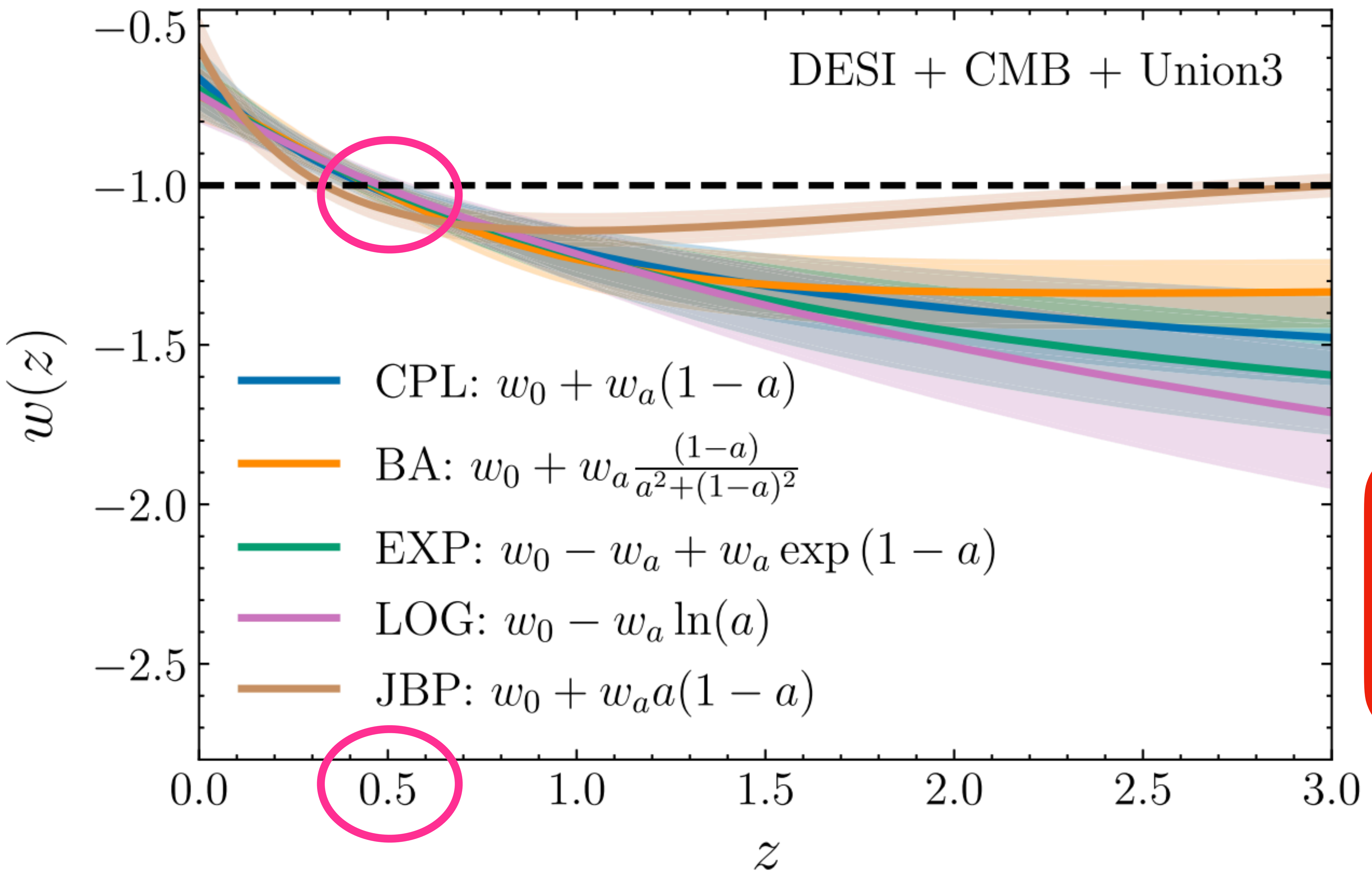


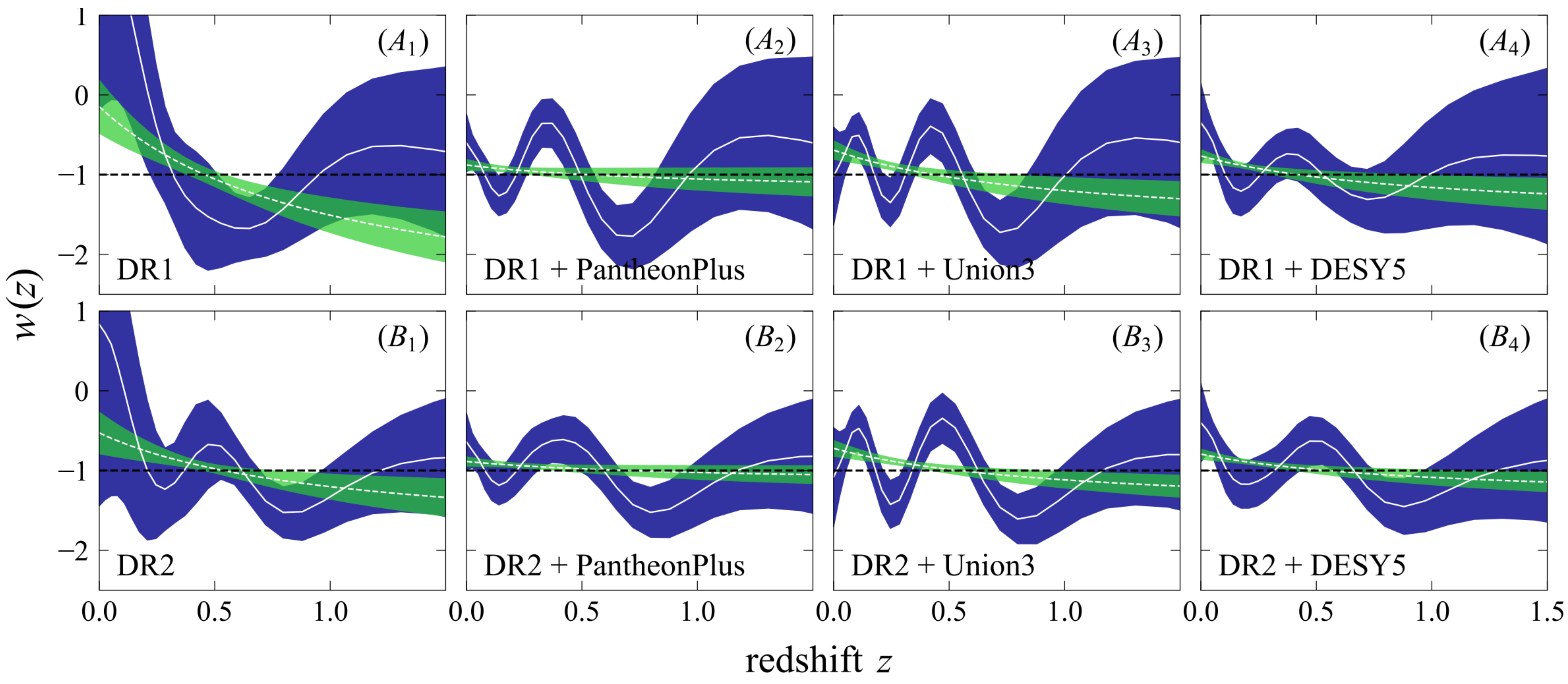
Phantom crossing

[DESI collaboration, 2503.14743]

We conduct an extended analysis of dark energy constraints, in support of the findings of the DESI DR2 cosmology key paper, including DESI data, Planck CMB observations, and three different supernova compilations. Using a broad range of parametric and non-parametric methods, we explore the dark energy phenomenology and find consistent trends across all approaches, in good agreement with the w_0w_aCDM key paper results. Even with the additional flexibility introduced by non-parametric approaches, such as binning and Gaussian Processes, we find that extending ΛCDM to include a two parameter $w(z)$ is sufficient to capture the trends present in the data. Finally, we examine three dark energy classes with distinct dynamics, including quintessence scenarios satisfying $w \geq -1$, to explore what underlying physics can explain such deviations. The current data indicate a clear preference for models that feature a phantom crossing; although alternatives lacking this feature are disfavored, they cannot yet be ruled out. Our analysis confirms that the evidence for dynamical dark energy, particularly at low redshift ($z \lesssim 0.3$), is robust and stable under different modeling choices.

RECONSTRUCTIONS OF w: OSCILLATIONS

[DESI collaboration, 2504.06118]



and many other works:

M. A. Zapata et al., 2507.22292

A. González-Fuentes et al., 2506.11758

S. H. Sheikh et al., 2506.13446

D. A. Kessler et al., 2504.00776

DESI collaboration, 2405.04216

L. A. Escamilla et al., 2404.00181

…

RELATION BETWEEN DE AND ν

Distinguishing between Neutrinos and time-varying Dark Energy through Cosmic Time

Christiane S. Lorenz,[1,*] Erminia Calabrese,[1,2] and David Alonso[1]
[1] *Sub-department of Astrophysics, University of Oxford, Keble Road, Oxford OX1 3RH, UK*
[2] *School of Physics and Astronomy, Cardiff University, The Parade, Cardiff, CF24 3AA, UK*

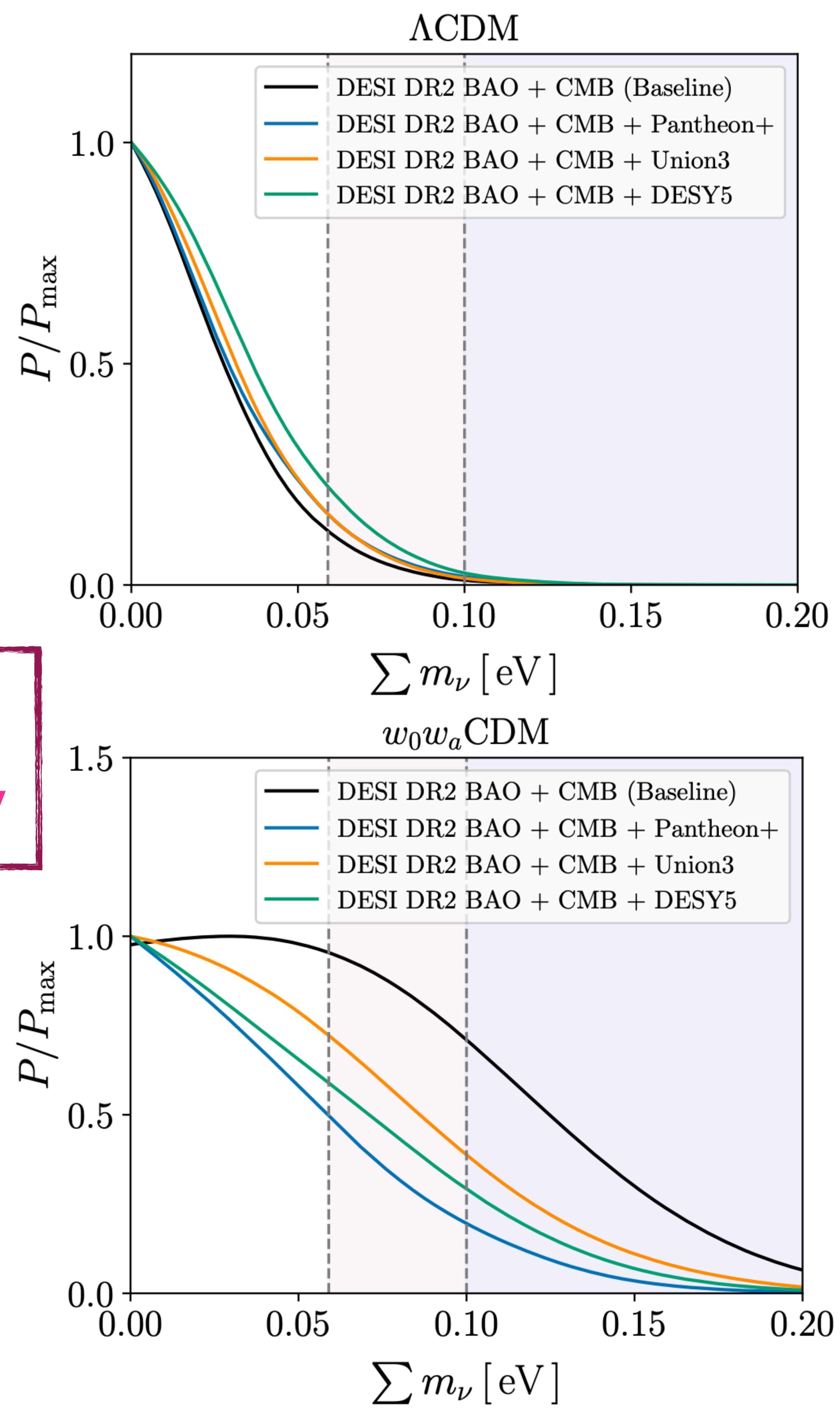
We study the correlations between parameters characterizing neutrino physics and the evolution of dark energy. Using a fluid approach, we show that time-varying dark energy models exhibit degeneracies with the cosmic neutrino background over extended periods of the cosmic history, leading to a degraded estimation of the total mass and number of species of neutrinos. We investigate how to break degeneracies and combine multiple probes across cosmic time to anchor the behaviour of the two components. We use *Planck* CMB data and BAO measurements from the BOSS, SDSS and 6dF surveys to present current limits on the model parameters, and then forecast the future reach from the CMB Stage-4 and DESI experiments. We show that a multi-probe analysis of current data provides only marginal improvement on the determination of the individual parameters and no reduction of the correlations. Future observations will better distinguish the neutrino mass and preserve the current sensitivity to the number of species even in case of a time-varying dark energy component.

[C. S. Lorenz et al., 1706.00730]

[DESI collaboration, 2503.14744]

cluded [42]. A similar conclusion was obtained from the DESI DR1 FS analysis [43] which, furthermore, showed that the $\sum m_\nu$ constraints strongly depend on the assumed dark energy model; a consequence of the well-known degeneracy between $\sum m_\nu$ and the dark energy equation of state [37, 58–66]. The datasets are consistent with an evolving dark energy equation of state, $w = P/\rho$, based on constraints in terms of the CPL parametrization

See talk from R. Choudhury



[DESI collaboration, 2503.14744]

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RECONSTRUCTION METHODS

- ✴ Principal Component Analysis (PCA)

  [L. Zhi-E et al., 1501.02971; …]

- ✴ Gaussian Processes (GP)

  [M.-J. Zhang et al., 1806.02981; F. Avila et al., 2505.24543; …]

- ✴ Weighted Function Regression method

  [A. González-Fuentes et al., 2506.11758; …]

- ✴ Redshift binning

  [J.-X. Li et al., 2506.22953; …]

- ✴ PCHIP reconstruction

  [S. Gariazzo et al., 1412.7405; …]

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…

PCHIP FORMALISM

[Fritsch et al., 1980; S. Gariazzo et al., 1412.7405]

Piecewise Cubic Hermite Interpolating Polynomial

$h_j = a_{j+1} - a_j$ $t = a - a_j$

$$w(a; w_1, w_2, \ldots, w_N) = \frac{(h_j + 2t)(h_j - t)^2}{h_j^3} w_j + \frac{(3h_j - 2t)t^2}{h_j^3} w_{j+1} + \frac{t(h_j - t)^2}{h_j^2} d_j + \frac{(h_j - t)t^2}{h_j^2} d_{j+1}$$

Nodes : $w_i = w(a_i)$

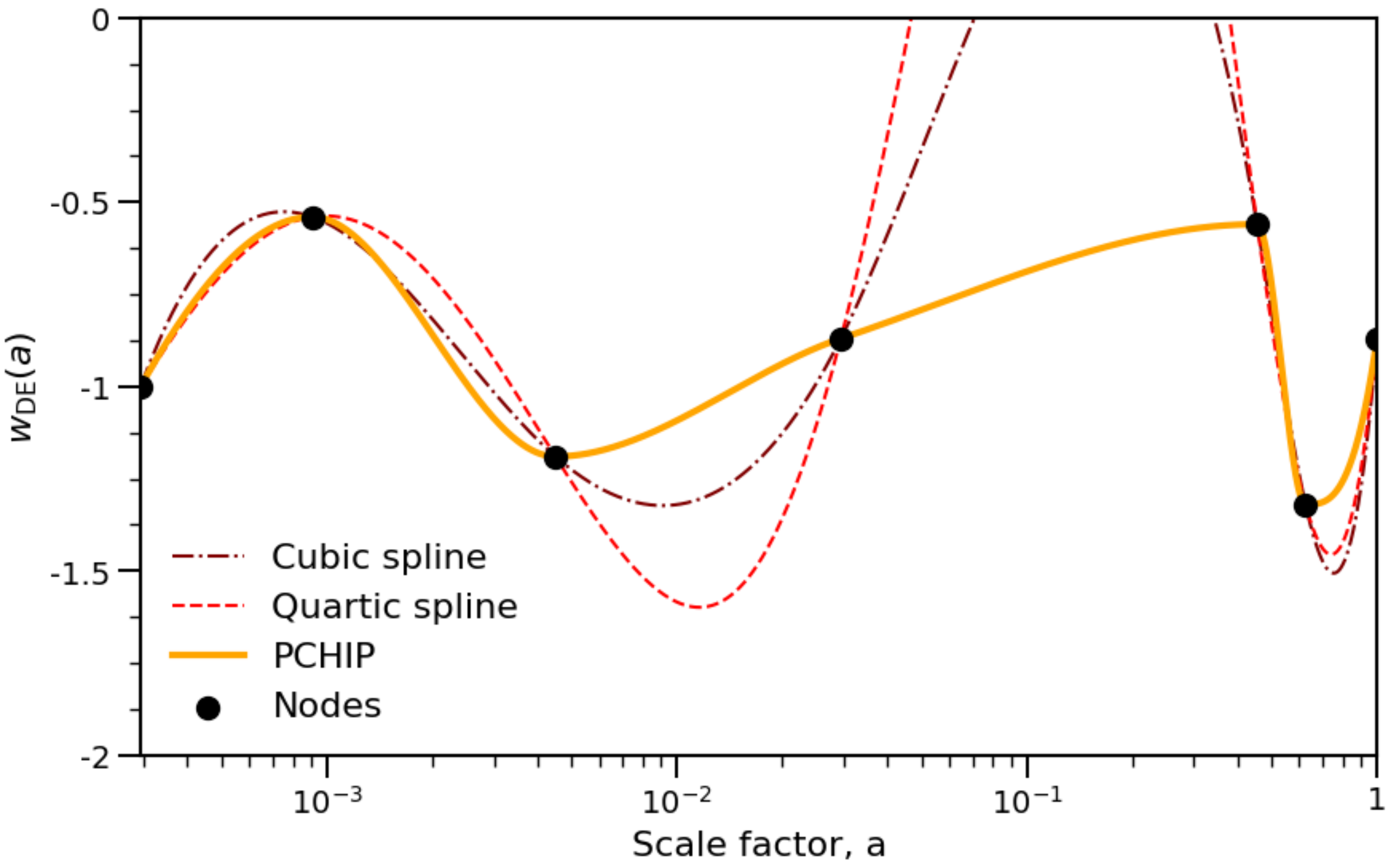
Point of interpolation

PCHIP FORMALISM

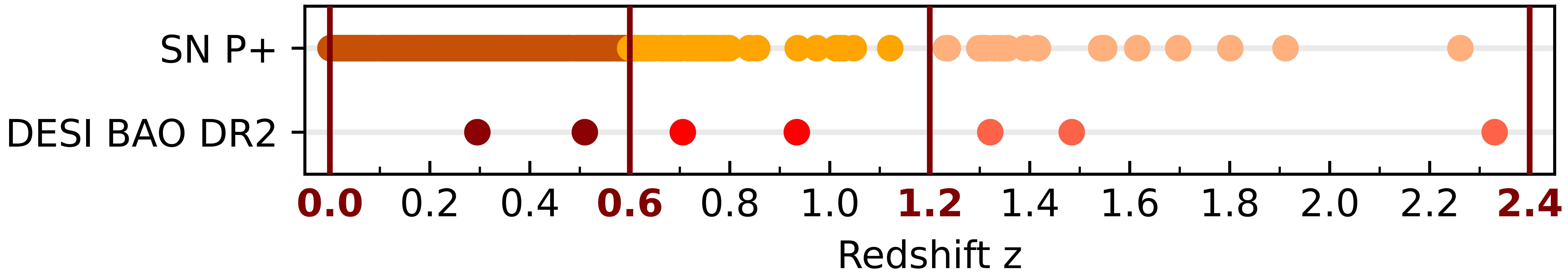
[Fritsch et al., 1980; S. Gariazzo et al., 1412.7405]

Piecewise **C**ubic **H**ermite **I**nterpolating **P**olynomial

- Preserves the shape of the interpolated data points
- Removes spurious oscillations due to interpolation



PCHIP: NODE CHOICE



	Redshift z	Scale factor a	
Today →	0.0	1.0	
	0.6	0.625	
	1.2	≈ 0.45	
	2.4	≈ 0.29	
	1100	$\approx 9 \times 10^{-4}$	← Recombination
Matter-radiation equality →	3400	$\approx 3 \times 10^{-4}$	
	10^{14}	$\approx 10^{-14}$	← Initial point of **CLASS**

$$1 + z = \frac{1}{a}$$

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METHODOLOGY: DE & ν

2 different conditions for dark energy

Case	Model	$w_{\mathrm{DE},i}$ prior
1	$\sum m_\nu^{\mathrm{NO}}$ + Non−phantom	
2	$\sum m_\nu^{\mathrm{free}}$ + Non−phantom	$\mathcal{U}[-1.0, 0.0]$
3	$\sum m_\nu^{\mathrm{PCHIP}}$ + Non−phantom	
1	$\sum m_\nu^{\mathrm{NO}}$ + Phantom	
2	$\sum m_\nu^{\mathrm{free}}$ + Phantom	$\mathcal{U}[-2.0, 0.0]$
3	$\sum m_\nu^{\mathrm{PCHIP}}$ + Phantom	

NOTE:

Phantom: we allow $w < -1$

We always fix

$$w_{\mathrm{ini}} = w_{\mathrm{mre}} = -1$$

METHODOLOGY: DE & ν

2 different conditions for dark energy

Case	Model	$\sum m_\nu$ prior	$w_{\mathrm{DE},i}$ prior
1	$\sum m_\nu^{\mathrm{NO}}$ + Non−phantom	Fixed 0.06 eV	
2	$\sum m_\nu^{\mathrm{free}}$ + Non−phantom	$\mathcal{U}[0.0, 3.0]$ [eV]	$\mathcal{U}[-1.0, 0.0]$
3	$\sum m_\nu^{\mathrm{PCHIP}}$ + Non−phantom	$\sum m_{\nu,i} \in \mathcal{U}[0.0, 3.0]$ [eV]	
1	$\sum m_\nu^{\mathrm{NO}}$ + Phantom	Fixed 0.06 eV	
2	$\sum m_\nu^{\mathrm{free}}$ + Phantom	$\mathcal{U}[0.0, 3.0]$ [eV]	$\mathcal{U}[-2.0, 0.0]$
3	$\sum m_\nu^{\mathrm{PCHIP}}$ + Phantom	$\sum m_{\nu,\mathrm{i}} \in \mathcal{U}[0.0, 3.0]$ [eV]	

NOTE:

We always fix

$$w_{\mathrm{ini}} = w_{\mathrm{mre}} = -1$$

3 different conditions for neutrinos

NOTE:

We fix

$$\sum m_{\mathrm{ini}} = \sum m_{\mathrm{mre}}$$

ATTENTION

CASE 3 : $\sum m_\nu$ reconstructed

Phenomenological approach

[G. B. Zhao et al., 0611227; C. S. Lorenx et al. 2102.13618]

ATTENTION

CASE 3 : $\sum m_\nu$ reconstructed

Phenomenological approach

[G. B. Zhao et al., 0611227; C. S. Lorenx et al. 2102.13618]

MaVaN models; coupling to (**ultra-**) **light DM**; …

[U. Franca et al., 0908.0534; O. Avsajanishvili, 2502.13097; G.-Y. Huang et al., 2205.08431; …]

ATTENTION

Ma …

[U. F …]

METHODOLOGY: COSMOLOGICAL INFERENCE

- Modified version of **CLASS** as Boltzmann solver
  [D. Blas et al., 1104.2933]

- **Cobaya** for the MCMC analysis
  [J. Torrado et al., 2005.05290]

- Sampled parameters

$\{100\theta_s, \omega_c, \omega_b, \tau_{reio}, n_s, \log(10^{10}A_s)\}$ ΛCDM **+**

$\{w_0, w_{0.6}, w_{1.2}, w_{2.4}, w_{rec}\}$, for CASE 1

CASE 1 + $\{\sum m_\nu\}$, for CASE 2

CASE 1 + $\{\sum m_0, \sum m_{0.6}, \sum m_{1.2}, \sum m_{2.4}, \sum m_{rec}, \sum m_{ini}\}$, for CASE 3

METHODOLOGY: DATA

- **CMB** measurements from **Planck18**

  [N. Aghanim et al., 1907.12875; N. Aghanim et al., 1807.06205]

- **Lensing** from **ACT DR6** and **Planck18**

  [T. Louis et al., 2503.14452; F. J. Qu et al., 2304.05202; N. Aghanim et al., 1807.06210]

  } **CMB**

- **BAO** measurements from **DESI DR2**

  [M. Abdul Karim et al., 2503.14738]

- **Supernovae** from **Pantheon+** → **SN**

  [D. Brout et al., 2202.04072]

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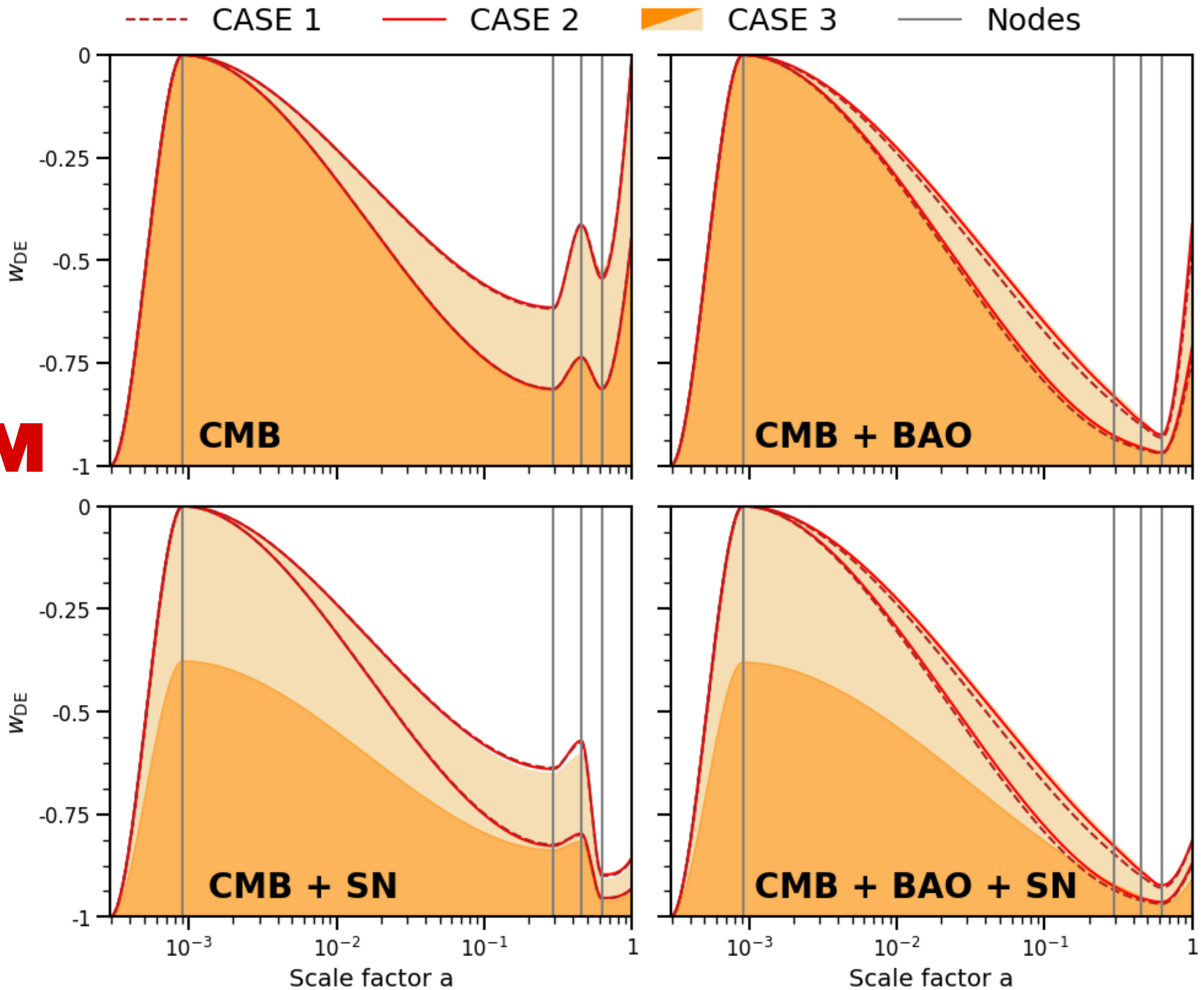
RESULTS: NON - PHANTOM

CASE 1 : $\sum m_\nu = 0.06$ eV

CASE 2 : $\sum m_\nu$ free

CASE 3 : $\sum m_\nu$ reconstructed



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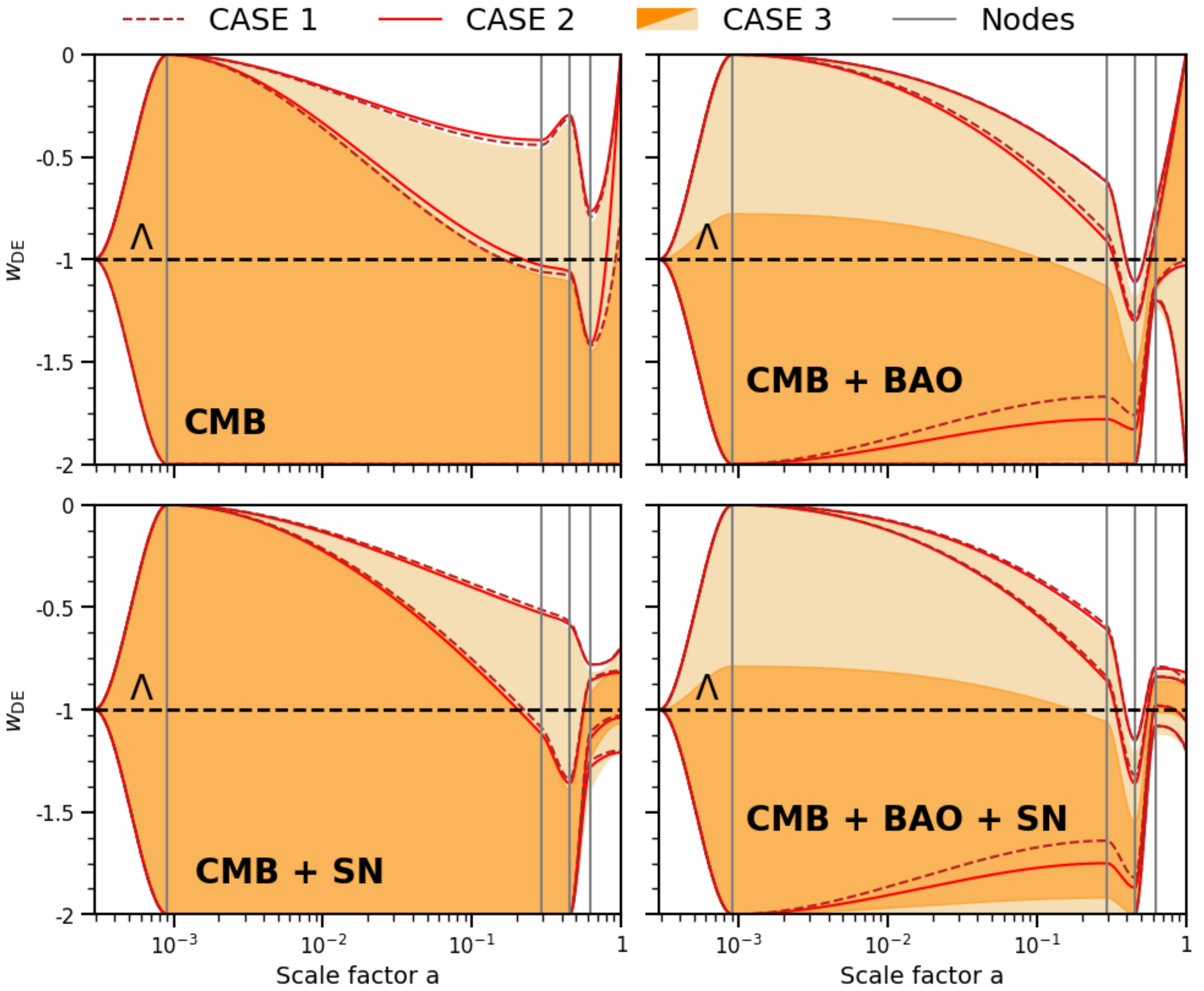

RESULTS: $\sum m_\nu$ [eV]

$$\text{CASE 1}: \sum m_\nu = 0.06 \text{ eV}$$

$$\text{CASE 2}: \sum m_\nu \text{ free}$$

95 % C.L.	CMB	CMB + BAO	CMB + SN	CMB + BAO + SN
NP	< 0.2022 eV	< 0.0531 eV	< 0.138 eV	< 0.0546 eV
P	< 0.2643 eV	< 0.1632 eV	< 0.2673 eV	< 0.1626 eV

RESULTS: $\sum m_\nu$ [eV]

$$\text{CASE 1}: \sum m_\nu = 0.06 \text{ eV}$$

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NP	< 0.2022 eV	< 0.0531 eV	< 0.138 eV	< 0.0546 eV
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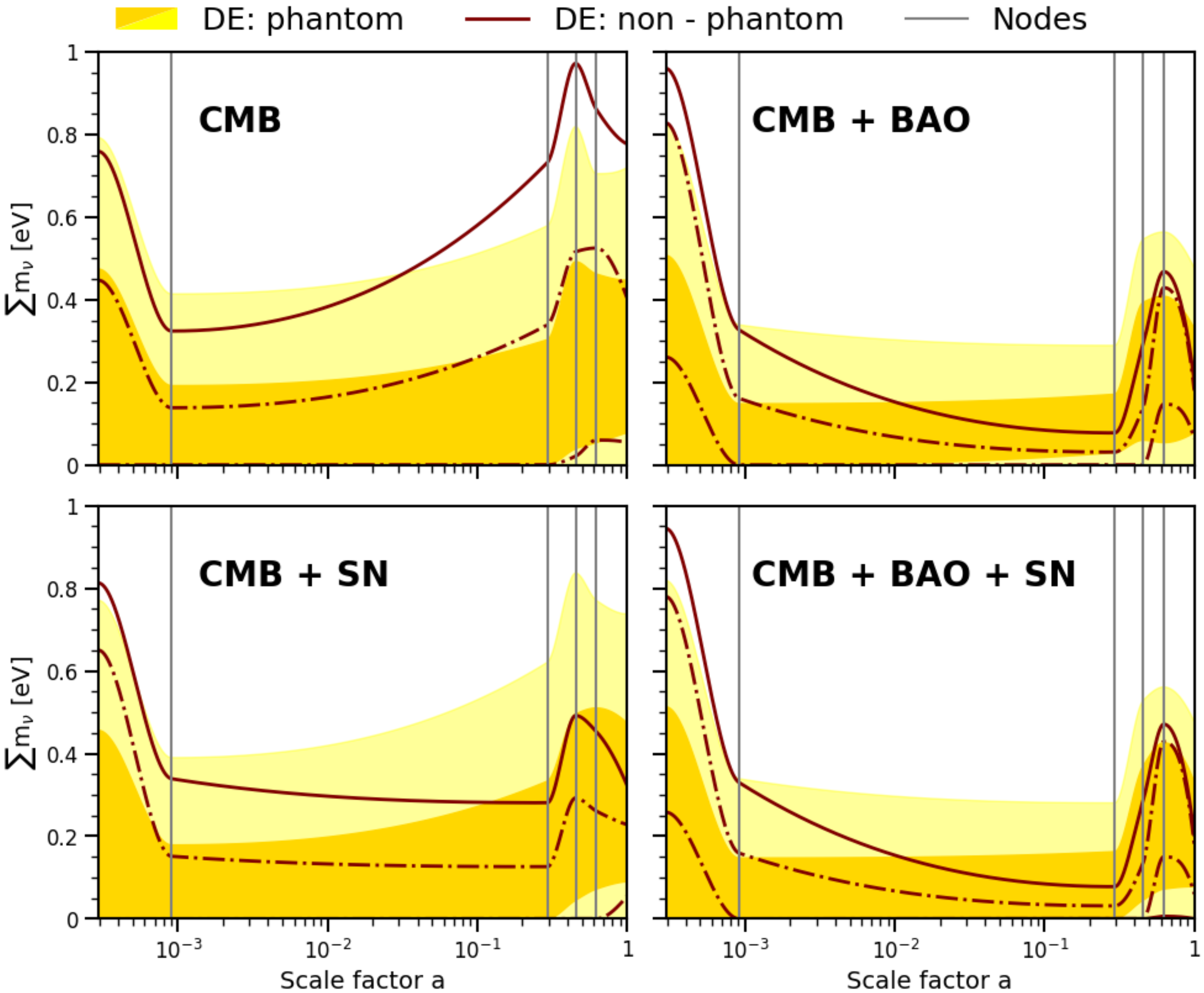
Bounds get relaxed going from **NP** to **P**

[S. Vagnozzi et al., 1801.08553]

RESULTS: $\sum m_\nu$ RECONSTRUCTED



CONCLUSIONS

- ☑ We find **oscillations** in the reconstructed $w_{\rm DE}$
- ☑ **BAO** data drive the strongest bounds on $w_{\rm DE}$ and $\sum m_\nu$
- ☑ Bounds on $\sum m_\nu$ get relaxed once phantom crossing is allowed

THANK YOU FOR PAYING ATTENTION TO OUR HUMAN!

QUESTIONS?

BACK UP SLIDES

PCHIP FORMALISM: PRESCRIPTION

$h_j = x_{j+1} - x_j$ $\qquad t = x - x_j$ $\qquad$ [Fritsch et al., 1980; S. Gariazzo et al., 1412.7405]

$$f(x; y_1, ..., y_N) = \frac{(h_j + 2t)(h_j - t)^2}{h_j^3} y_j + \frac{(3h_j - 2t)t^2}{h_j^3} y_{j+1} + \frac{t(h_j - t)^2}{h_j^2} d_j + \frac{t^2(h_j - t)}{h_j^2} d_{j+1}$$

$$\delta_j = \frac{y_{j+1} - y_j}{x_{j+1} - x_j}$$

- if $\delta_{j-1} \times \delta_j < 0 \rightarrow d_j = 0$;
- if $\delta_{j-1} \times \delta_j > 0$:

$$\frac{\omega_1 + \omega_2}{d_j} = \frac{\omega_1}{\delta_{j-1}} + \frac{\omega_2}{\delta_j}$$

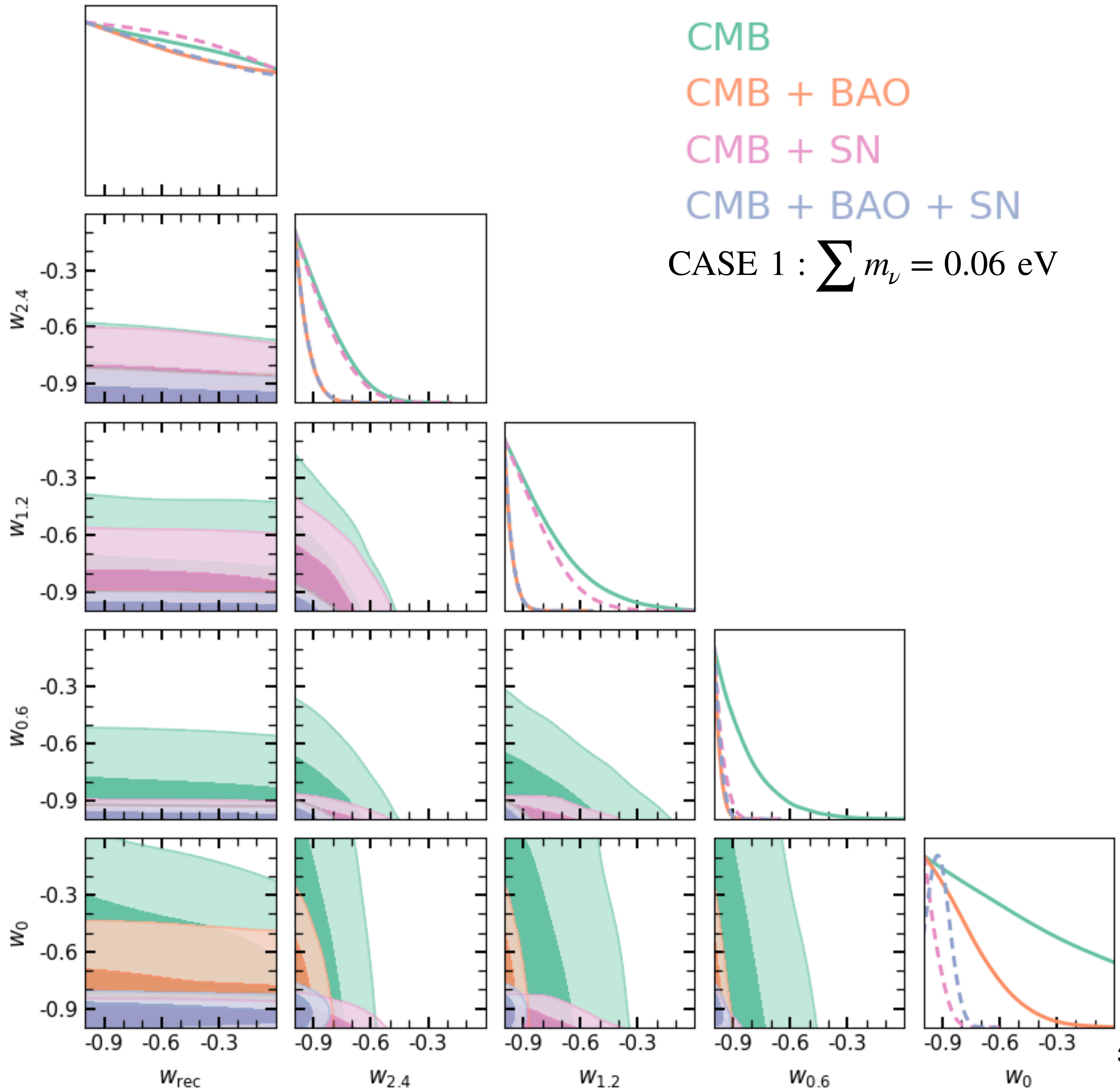
$\omega_1 = 2h_j + h_{j+1}$ $\qquad$ $\omega_2 = h_j + 2h_{j+1}$

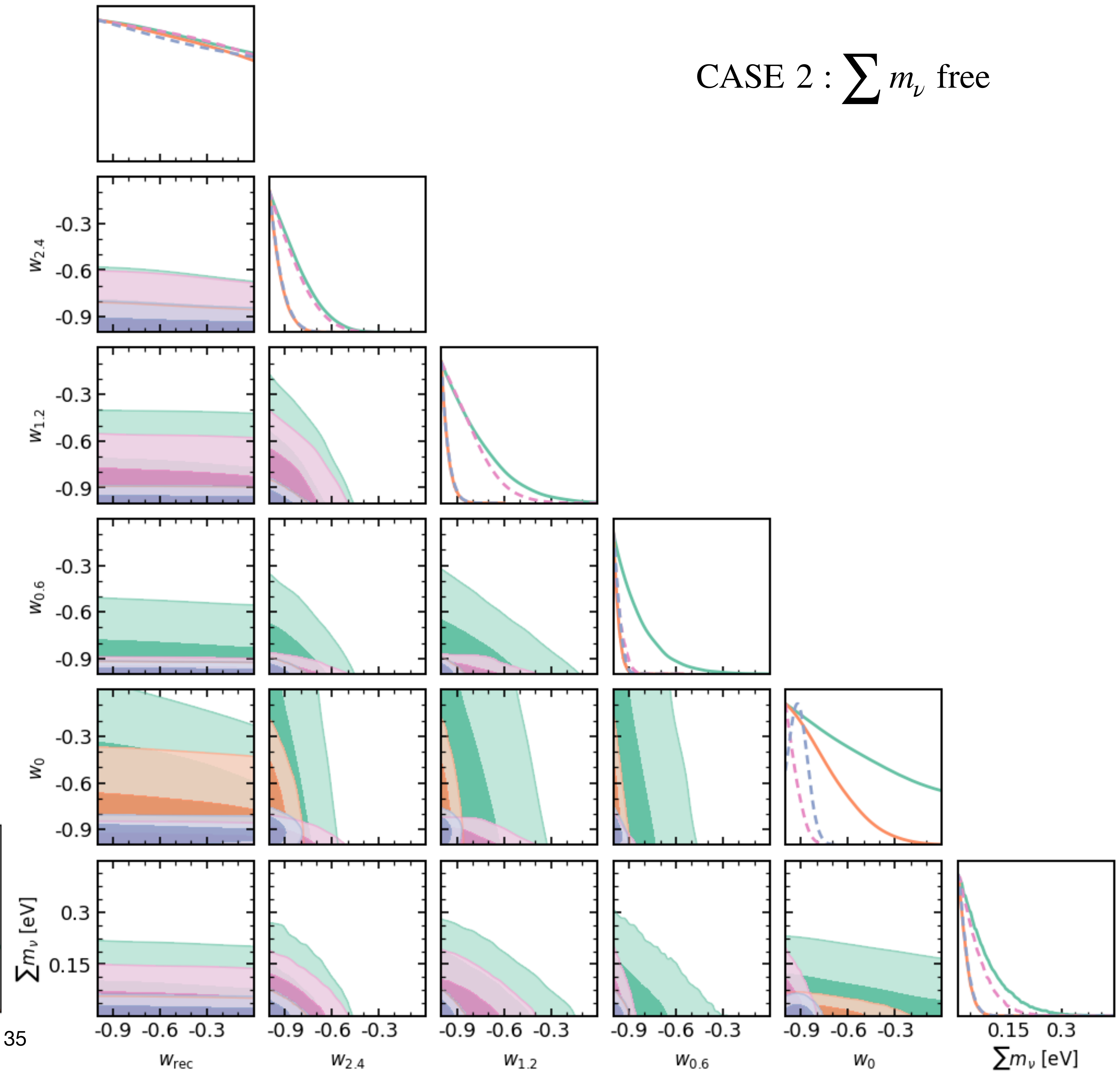
For the first and last $(1 \rightarrow N-1;\ 2 \rightarrow N-2)$ nodes:

$$d(h_1, h_2, \delta_1, \delta_2) = \frac{(2h_1 + h_2)\delta_1 - h_1\delta_2}{h_1 + h_2}$$

- if $\delta_1 \times d(h_1, h_2, \delta_1, \delta_2) < 0 \rightarrow d_1 = 0$;
- if $\delta_1 \times \delta_2 < 0$ & $|d(h_1, h_2, \delta_1, \delta_2)| > 3|\delta_1| \rightarrow d_1 = 3\delta_1$;
- else $d_1 = d(h_1, h_2, \delta_1, \delta_2)$

RESULTS: NON - PHANTOM





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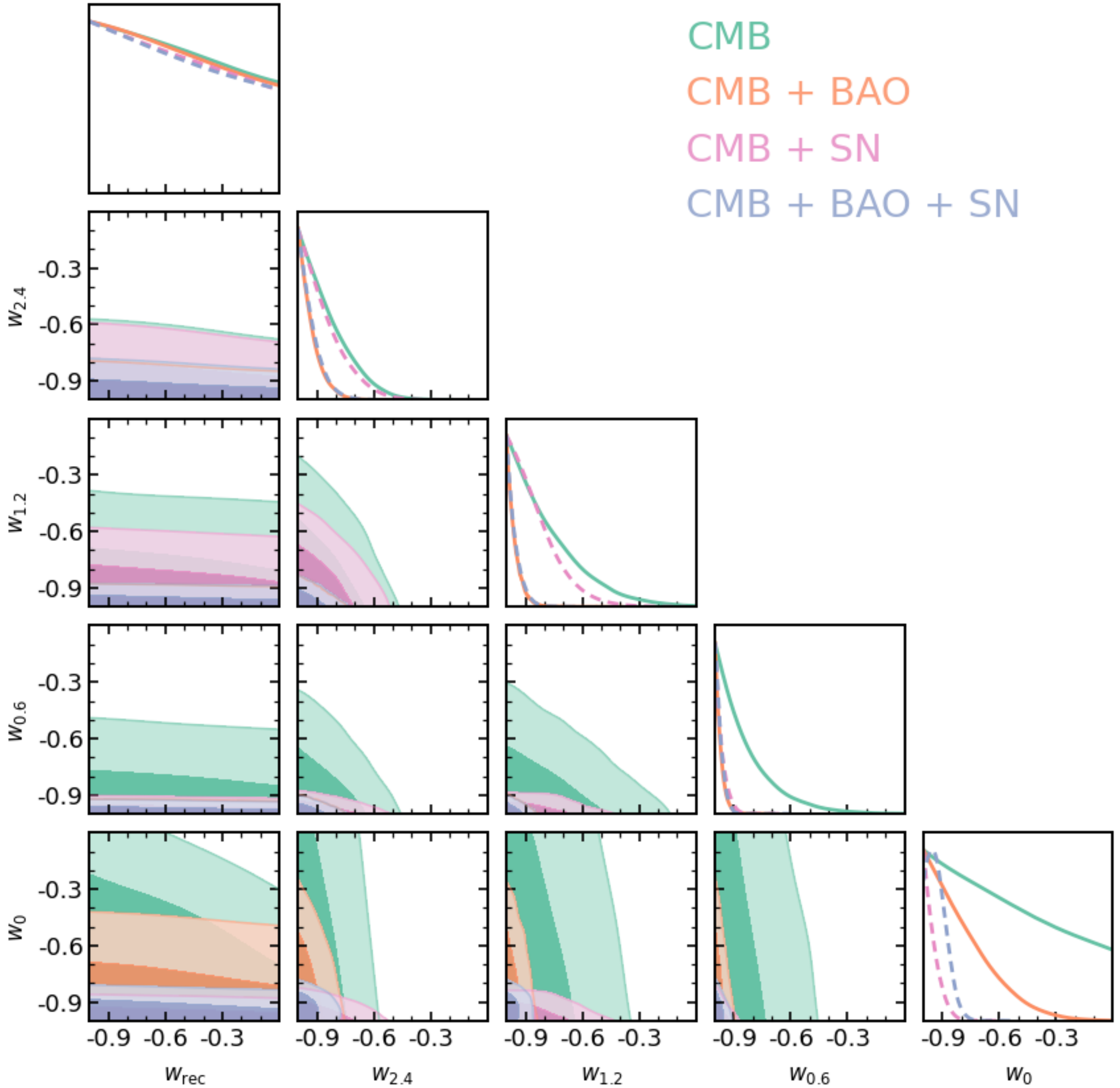
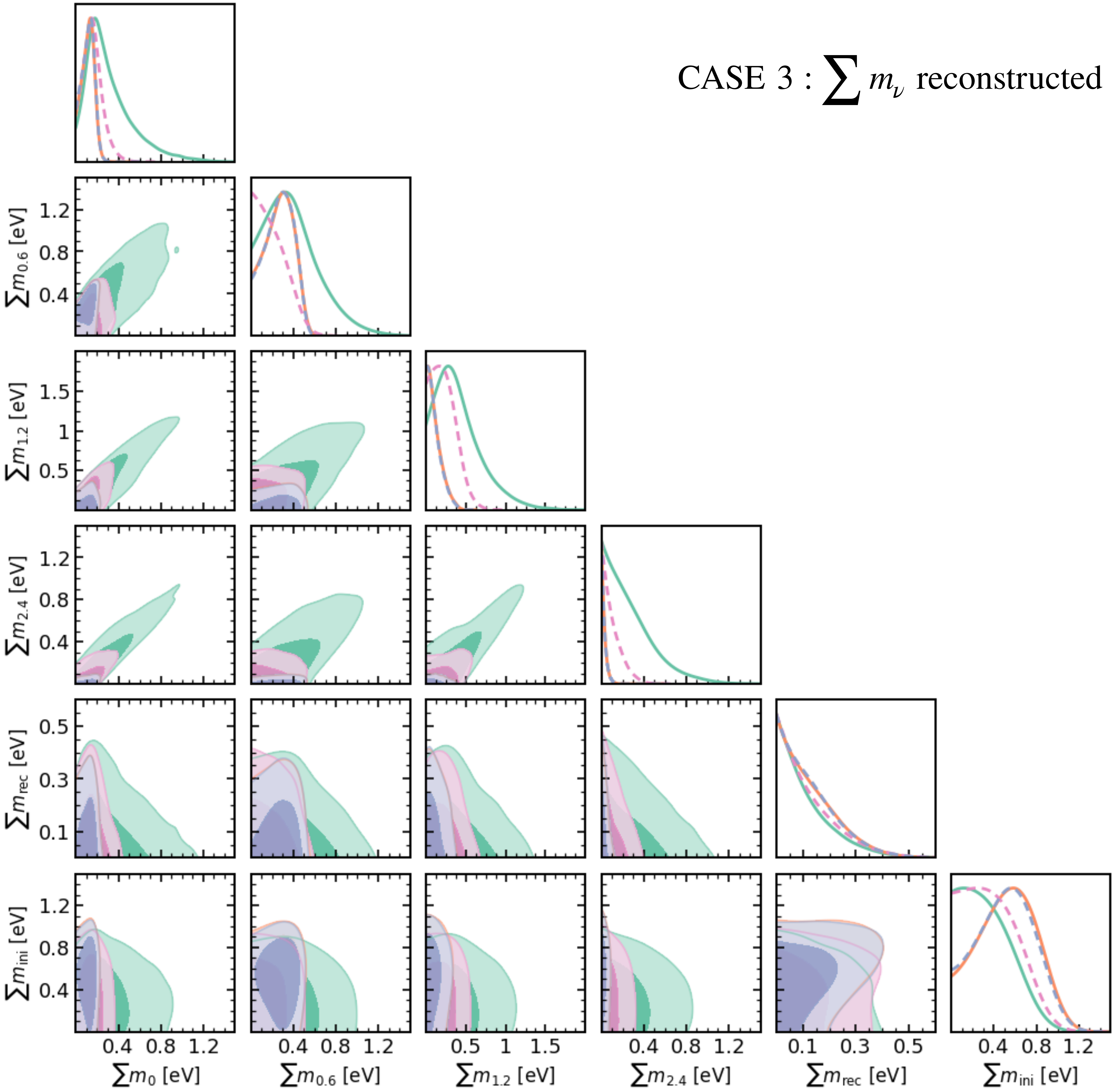


CASE 3 : $\sum m_\nu$ reconstructed



RESULTS:
NON - PHANTOM

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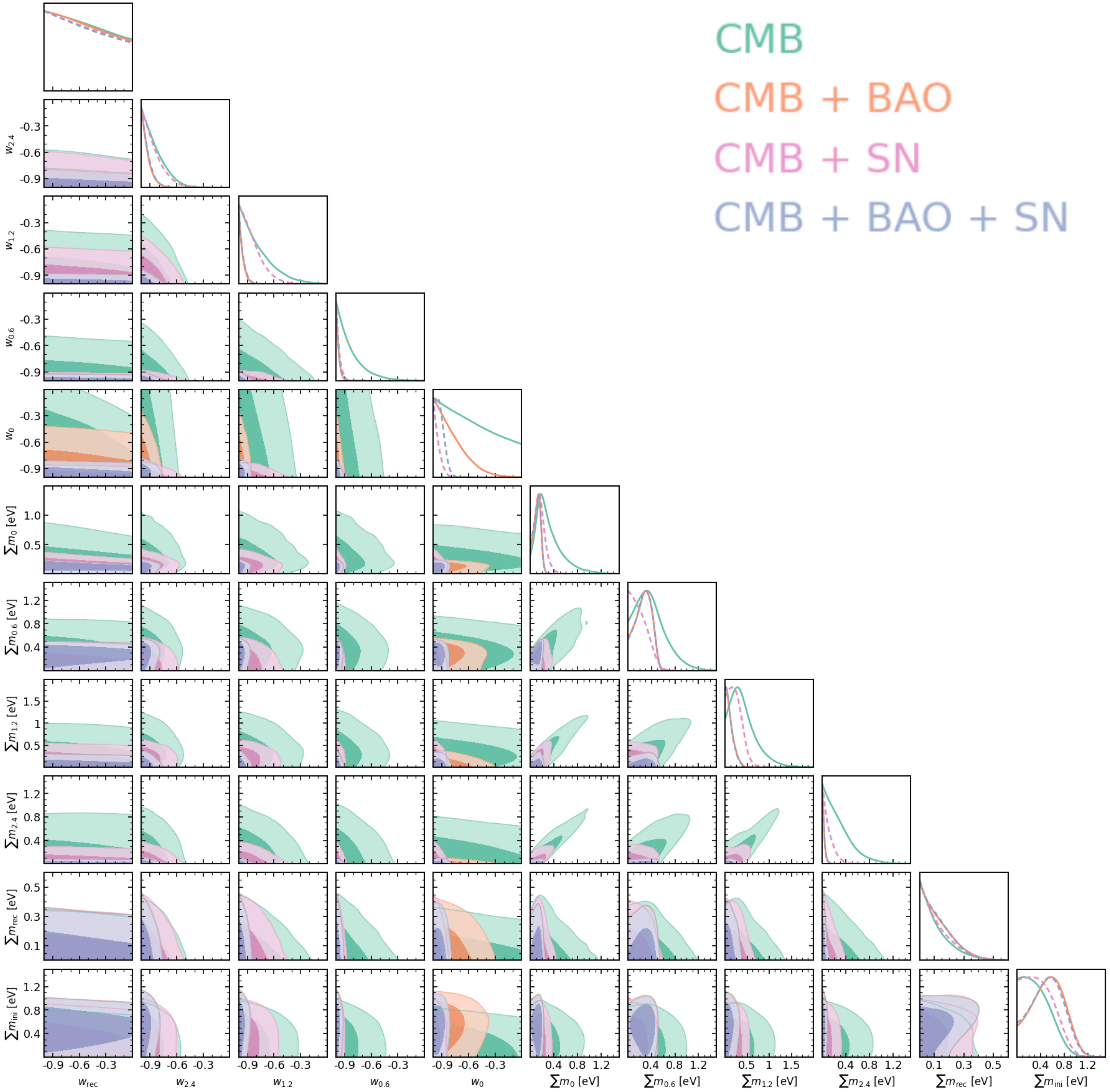

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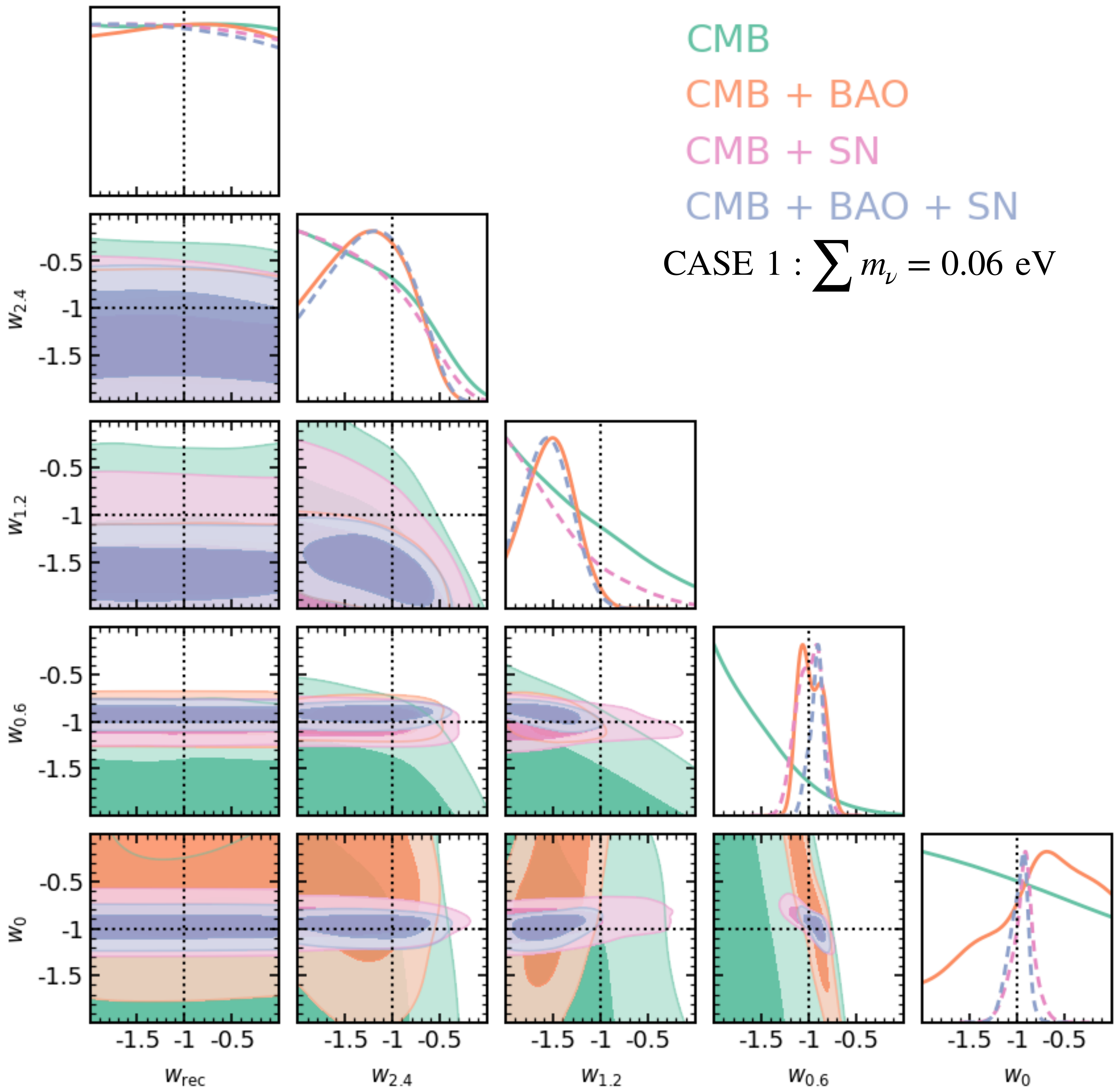

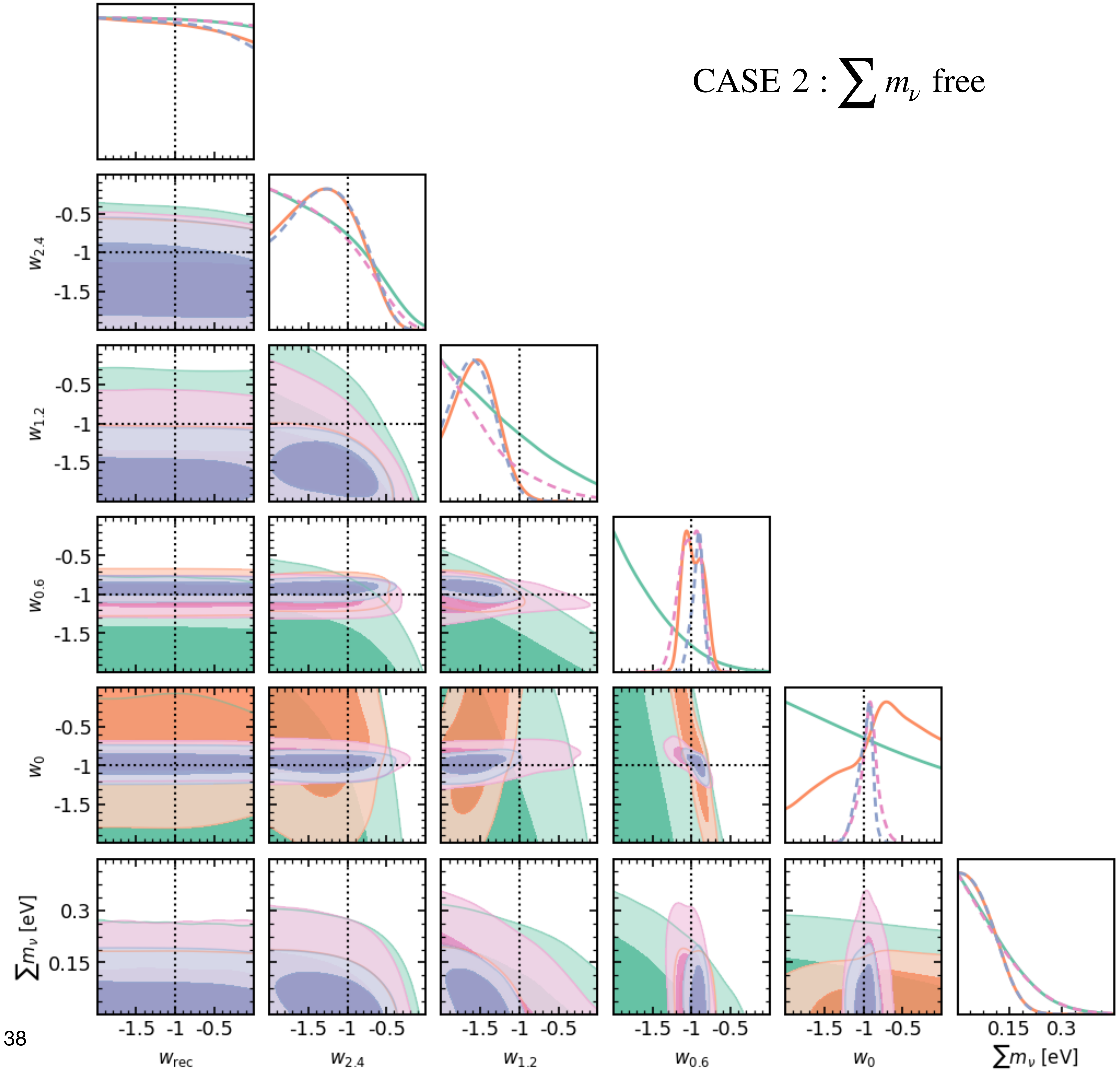

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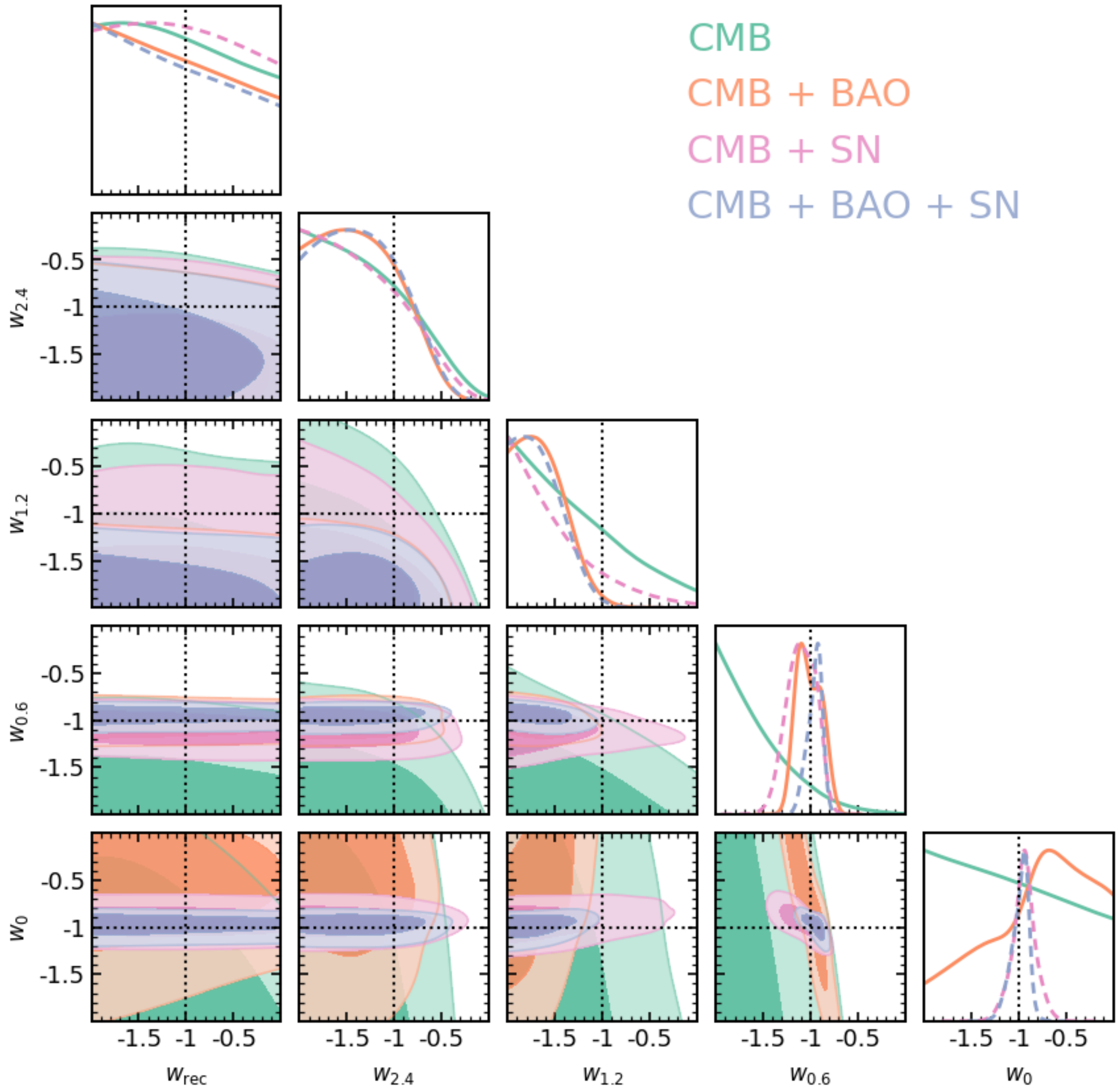

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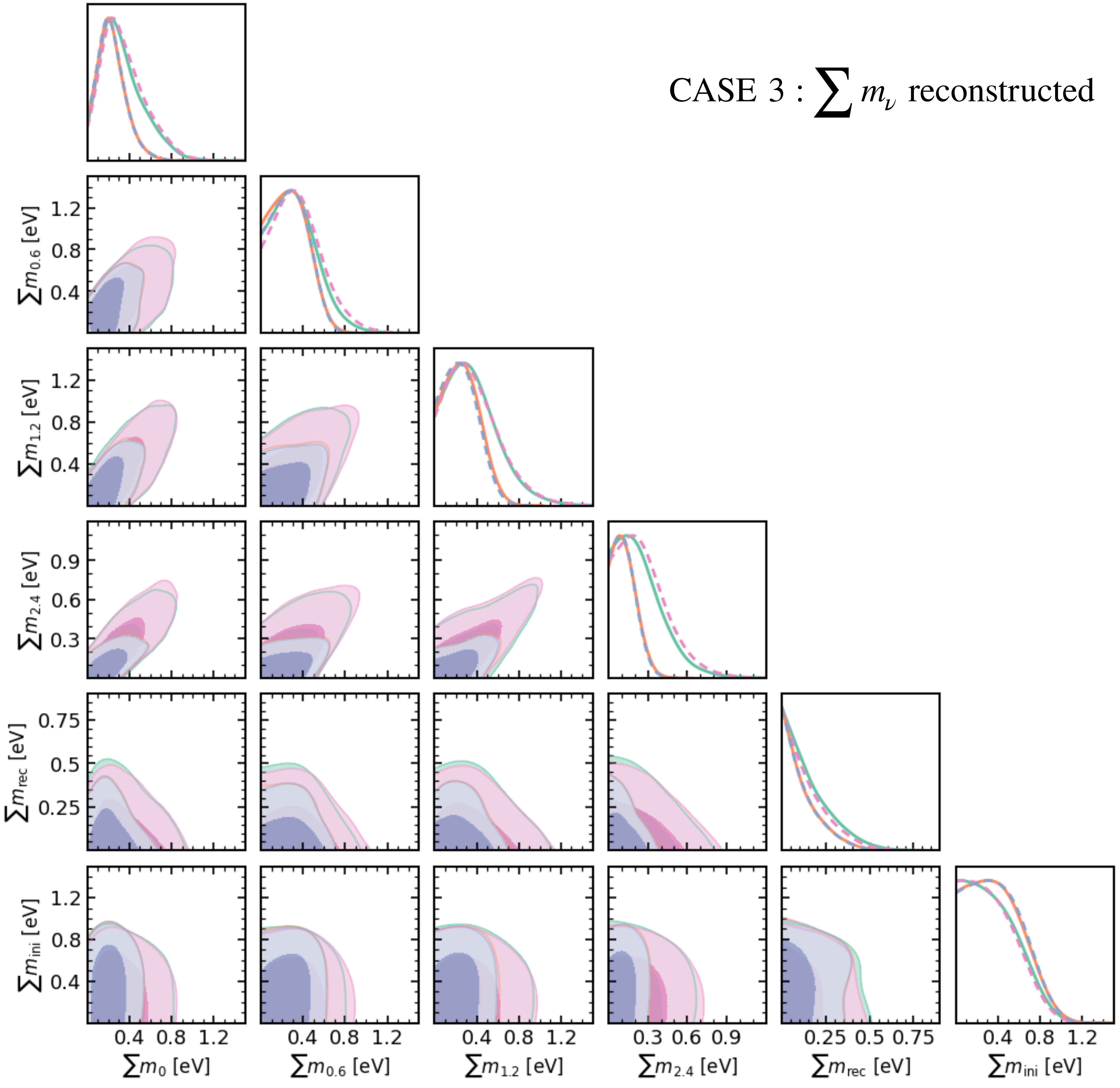

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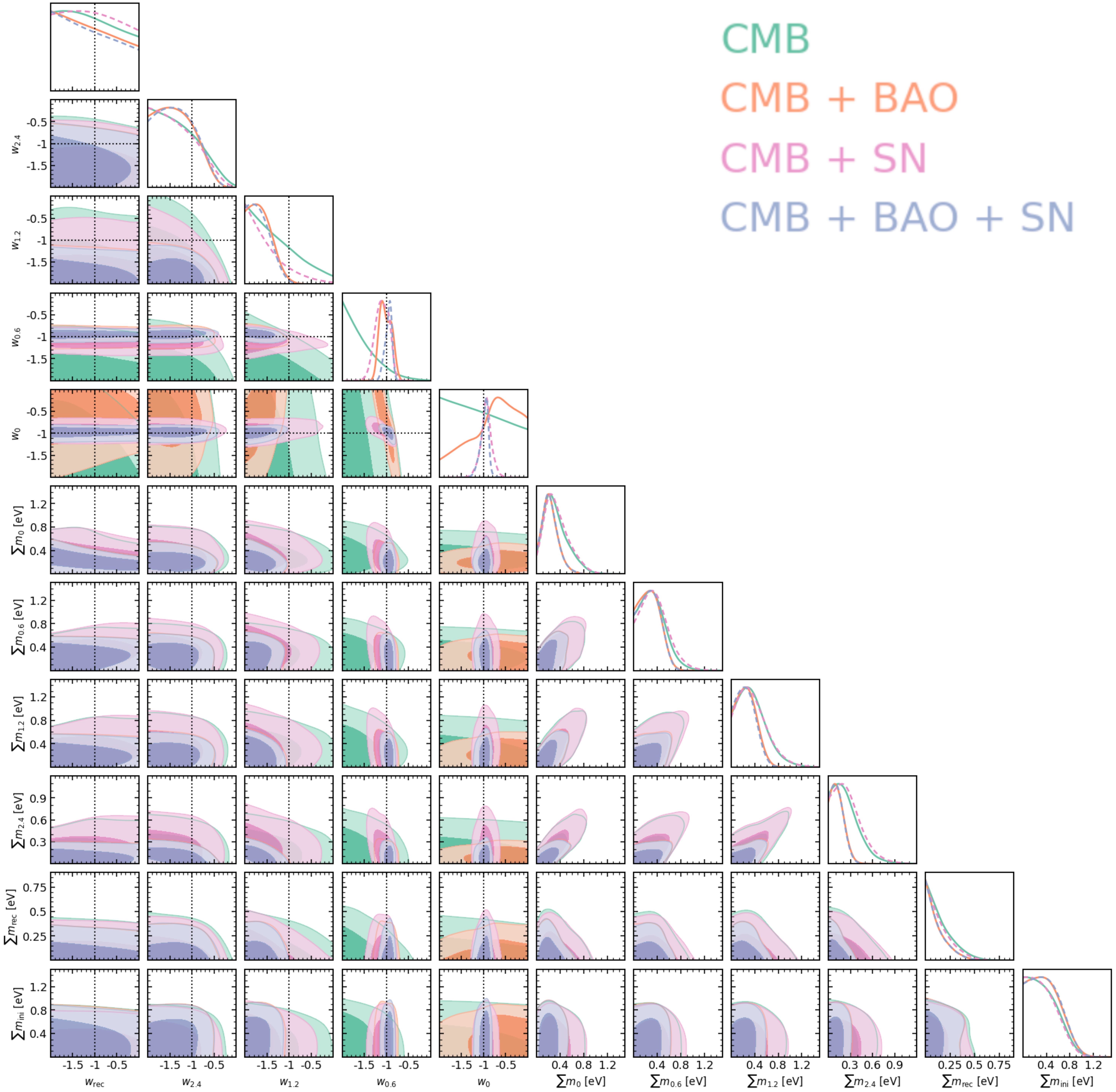


RESULTS: 95% C. L.

CASE 1 : $\sum m_\nu = 0.06$ eV

	CMB	CMB P	CMB+BAO	CMB+BAO P	CMB+SN	CMB+SN P	CMB+BAO+SN	CMB+BAO+SN P
$w_{\rm rec}$	—	—	—	—	—	—	—	—
$w_{2.4}$	< -0.618	< -0.417	< -0.847	< -0.619	< -0.637	< -0.513	< -0.846	< -0.598
$w_{1.2}$	< -0.412	< -0.295	< -0.902	< -1.11	< -0.576	< -0.572	< -0.901	< -1.15
$w_{0.6}$	< -0.538	< -0.765	< -0.932	$-0.97^{+0.23}_{-0.22}$	< -0.900	$-1.00^{+0.22}_{-0.25}$	< -0.929	$-0.92^{+0.13}_{-0.16}$
w_0	—	—	< -0.458	—	< -0.858	$-0.93^{+0.24}_{-0.27}$	< -0.817	$-0.98^{+0.17}_{-0.22}$

CASE 2 : $\sum m_\nu$ free

	CMB	CMB P	CMB+BAO	CMB+BAO P	CMB+SN	CMB+SN P	CMB+BAO+SN	CMB+BAO+SN P
$w_{\rm rec}$	—	—	—	—	—	—	—	—
$w_{2.4}$	< -0.615	< -0.441	< -0.831	< -0.623	< -0.640	< -0.531	< -0.827	< -0.609
$w_{1.2}$	< -0.414	< -0.310	< -0.894	< -1.11	< -0.571	< -0.586	< -0.890	< -1.15
$w_{0.6}$	< -0.545	< -0.791	< -0.925	$-0.98^{+0.24}_{-0.22}$	< -0.897	$-1.02^{+0.24}_{-0.26}$	< -0.923	$-0.93^{+0.13}_{-0.15}$
w_0	—	—	< -0.413	—	< -0.855	$-0.94^{+0.24}_{-0.27}$	< -0.814	$-0.98^{+0.16}_{-0.21}$
$\sum m_\nu$ [eV]	< 0.2022	< 0.2643	< 0.0531	< 0.1632	< 0.138	< 0.2673	< 0.0546	< 0.1626

RESULTS: 95% C. L.

CASE 3 : $\sum m_\nu$ reconstructed

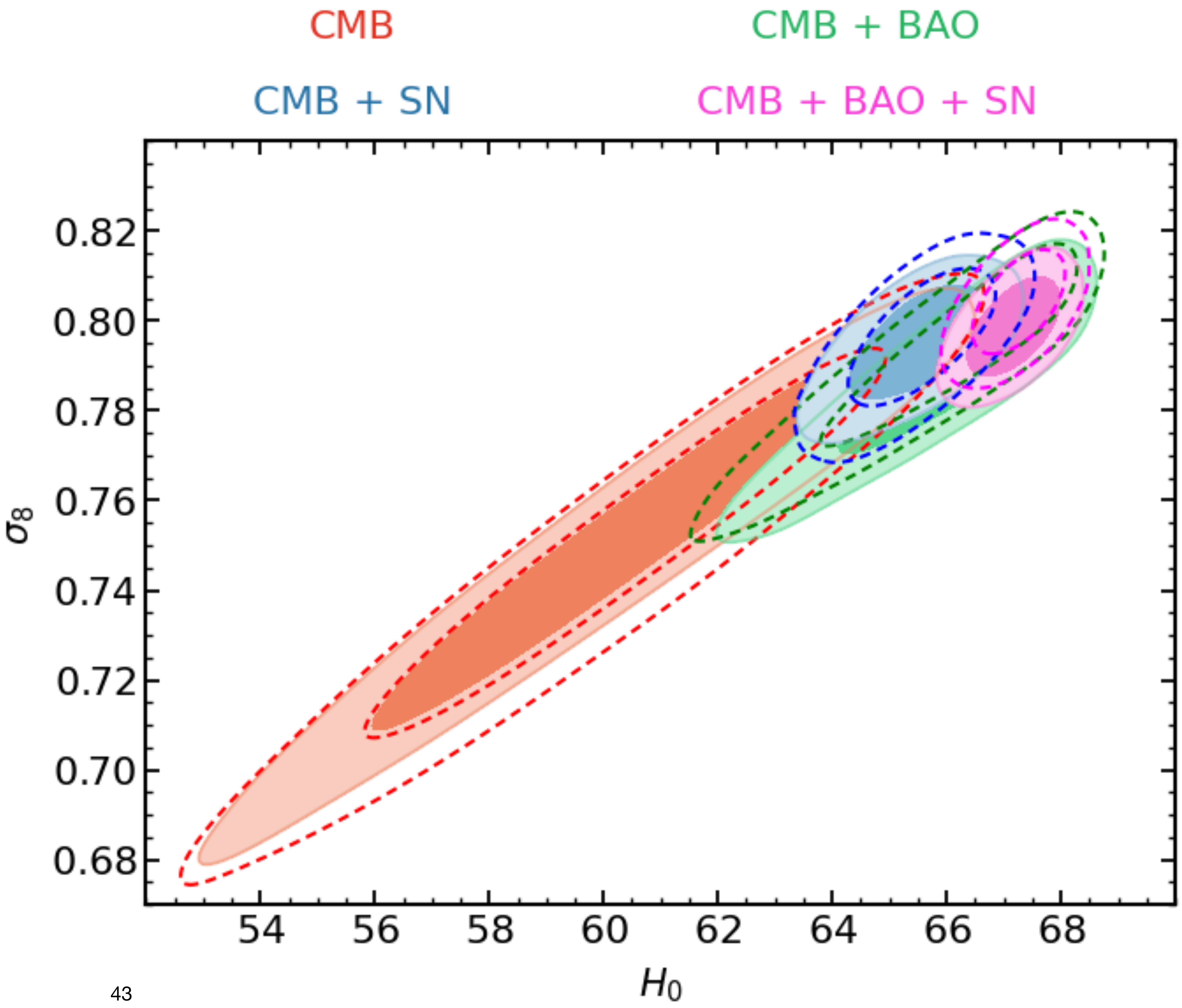
	CMB	CMB P	CMB+BAO	CMB+BAO P	CMB+SN	CMB+SN P	CMB+BAO+SN	CMB+BAO+SN P
w_{rec}	—	—	—	—	—	—	—	—
$w_{2.4}$	< -0.621	< -0.465	< -0.822	< -0.654	< -0.651	< -0.538	< -0.818	< -0.638
$w_{1.2}$	< -0.422	< -0.338	< -0.886	< -1.19	< -0.605	< -0.615	< -0.883	< -1.22
$w_{0.6}$	< -0.524	< -0.824	< -0.927	$-1.01^{+0.25}_{-0.23}$	< -0.909	$-1.10^{+0.28}_{-0.29}$	< -0.931	$-0.95^{+0.13}_{-0.17}$
w_0	—	—	< -0.464	—	< -0.870	$-0.94^{+0.26}_{-0.27}$	< -0.835	$-0.98^{+0.15}_{-0.21}$
Σm_0	< 0.776	< 0.719	< 0.203	< 0.478	< 0.323	< 0.737	< 0.203	< 0.477
$\Sigma m_{0.6}$	< 0.860	< 0.705	$0.27^{+0.20}_{-0.27}$	< 0.565	< 0.454	< 0.771	$0.27^{+0.20}_{-0.26}$	< 0.561
$\Sigma m_{1.2}$	< 0.971	< 0.818	< 0.292	< 0.547	< 0.493	< 0.837	< 0.286	< 0.527
$\Sigma m_{2.4}$	< 0.732	< 0.578	< 0.0774	< 0.289	< 0.281	< 0.622	< 0.0777	< 0.280
Σm_{rec}	< 0.323	< 0.415	< 0.328	< 0.339	< 0.338	< 0.391	< 0.329	< 0.338
Σm_{end}	< 0.759	< 0.792	< 0.959	< 0.823	< 0.812	< 0.771	< 0.946	< 0.820

WHAT ABOUT THE TENSIONS?

NON-PHANTOM

CASE 1 : $\sum m_\nu = 0.06$ eV

CASE 2 : $\sum m_\nu$ free

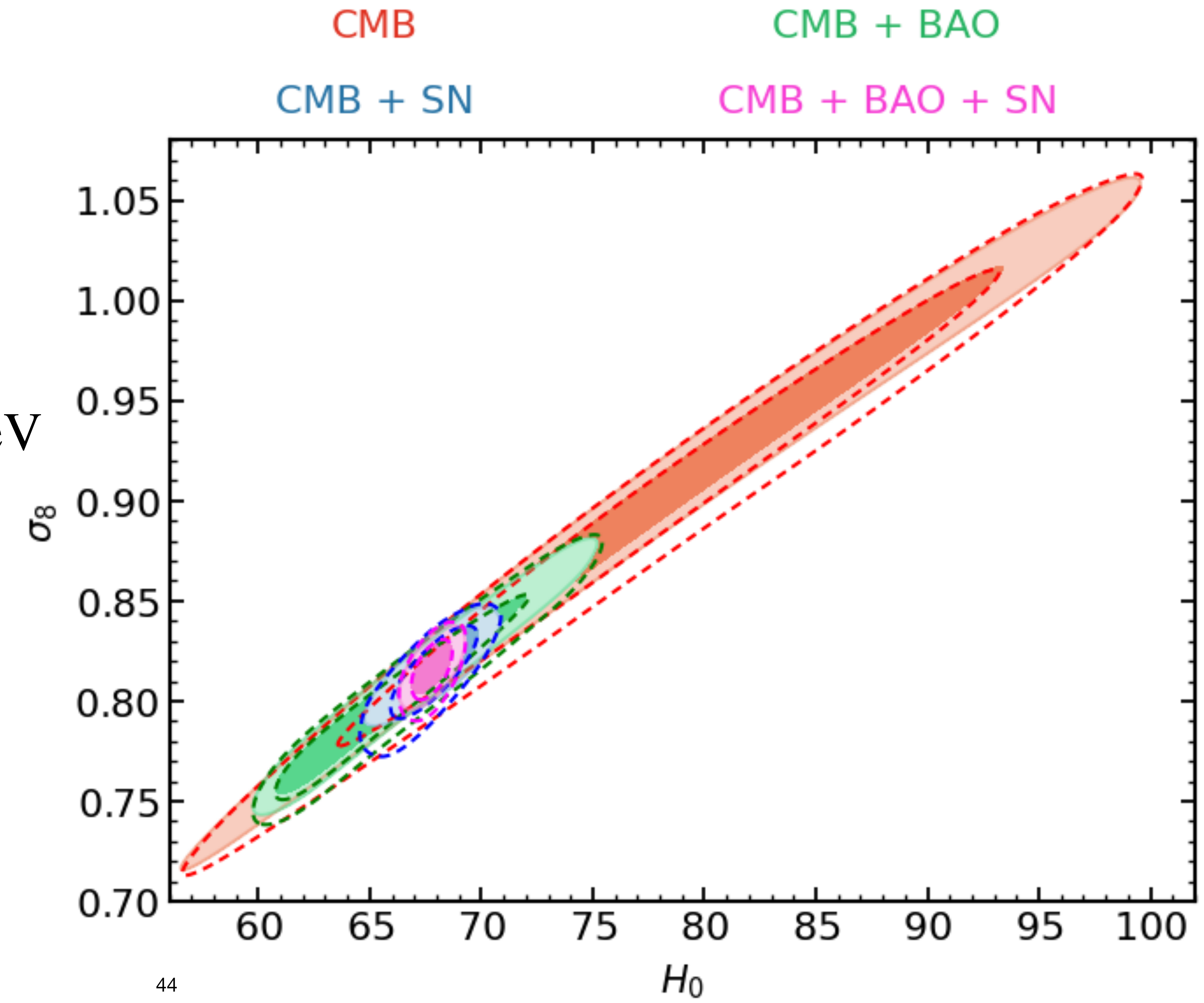


WHAT ABOUT THE TENSIONS?

PHANTOM

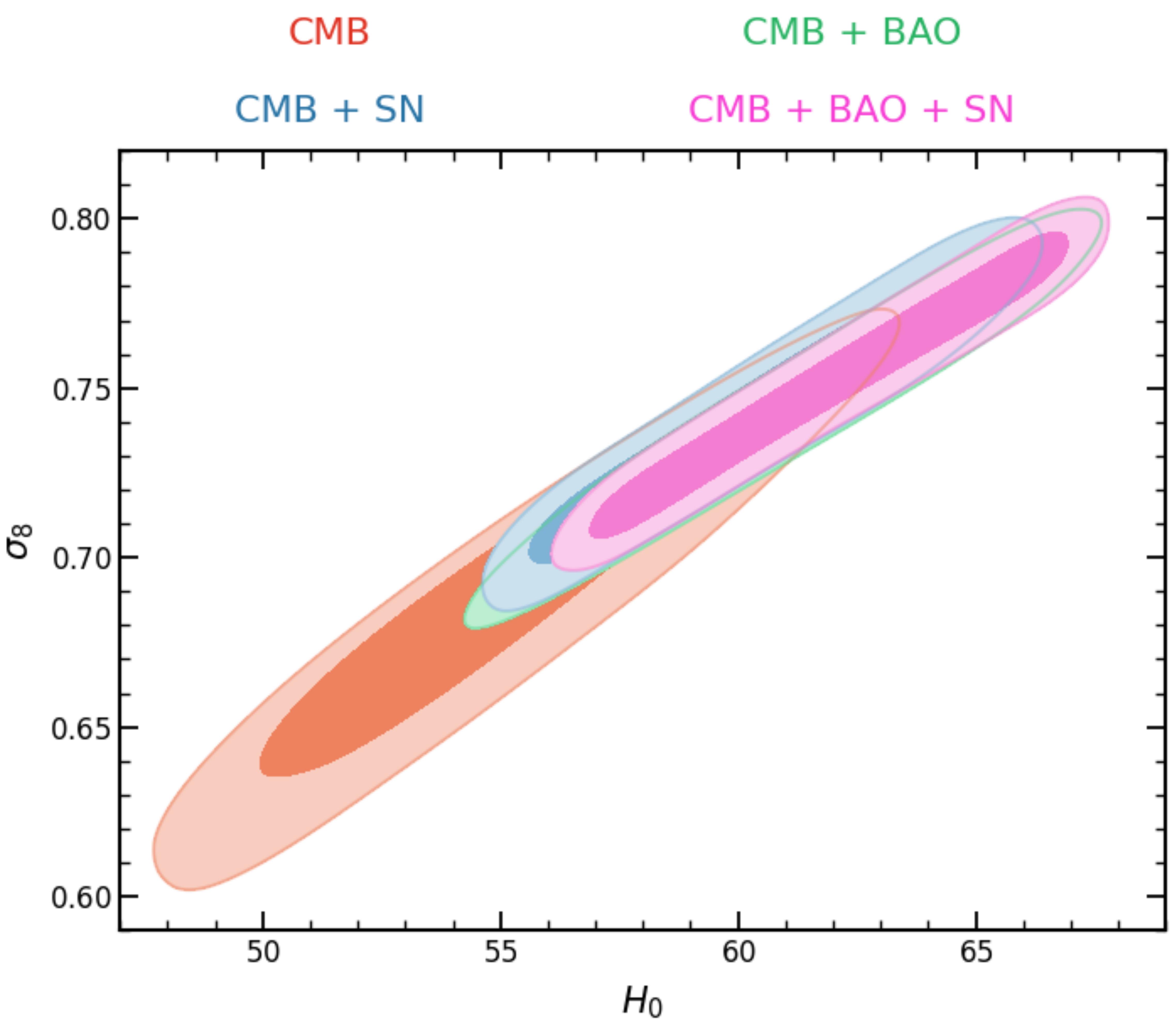
CASE 1 : $\sum m_\nu = 0.06$ eV

CASE 2 : $\sum m_\nu$ free

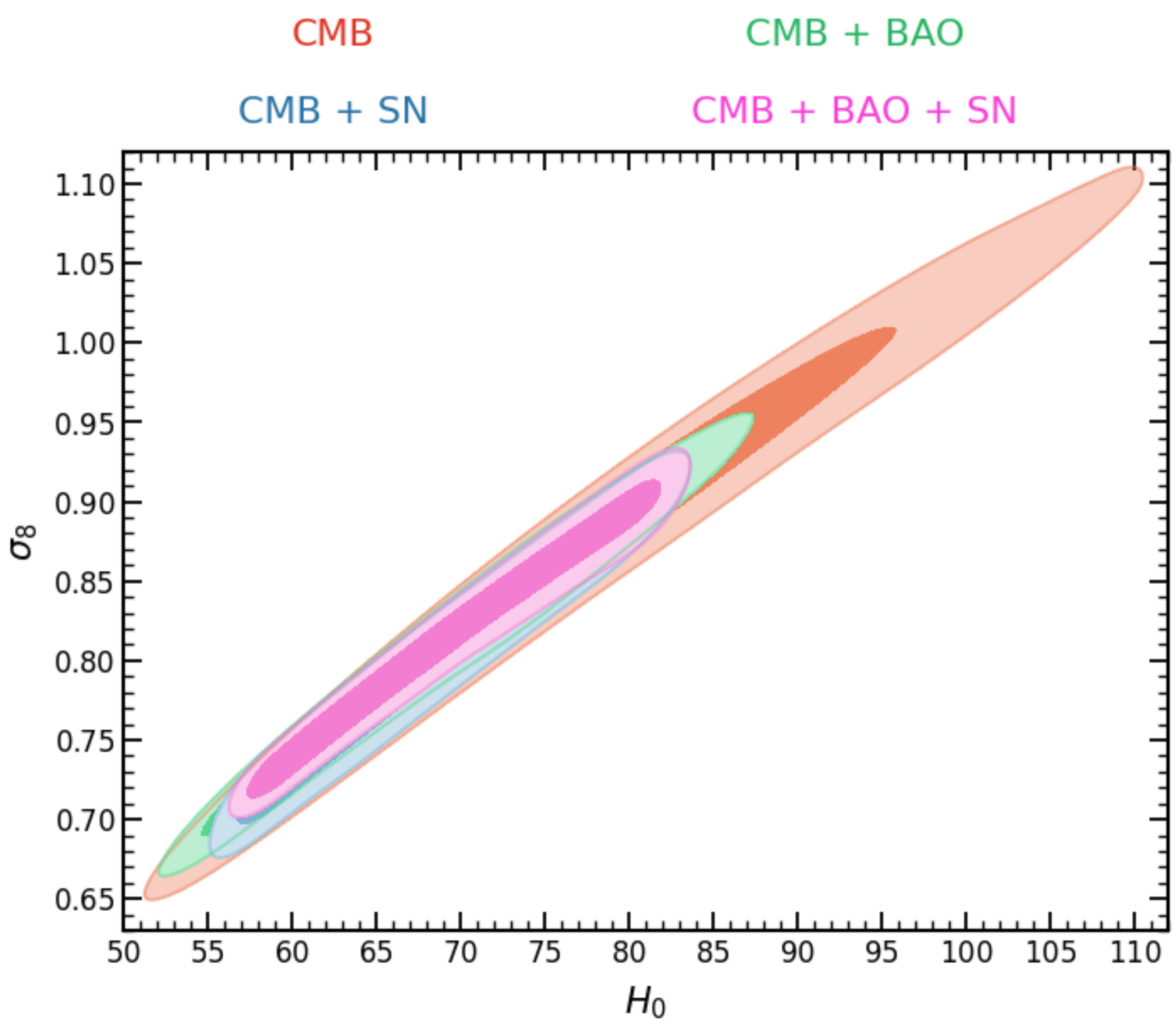


WHAT ABOUT THE TENSIONS?

CASE 3 : $\sum m_\nu$ reconstructed



NON-PHANTOM



PHANTOM