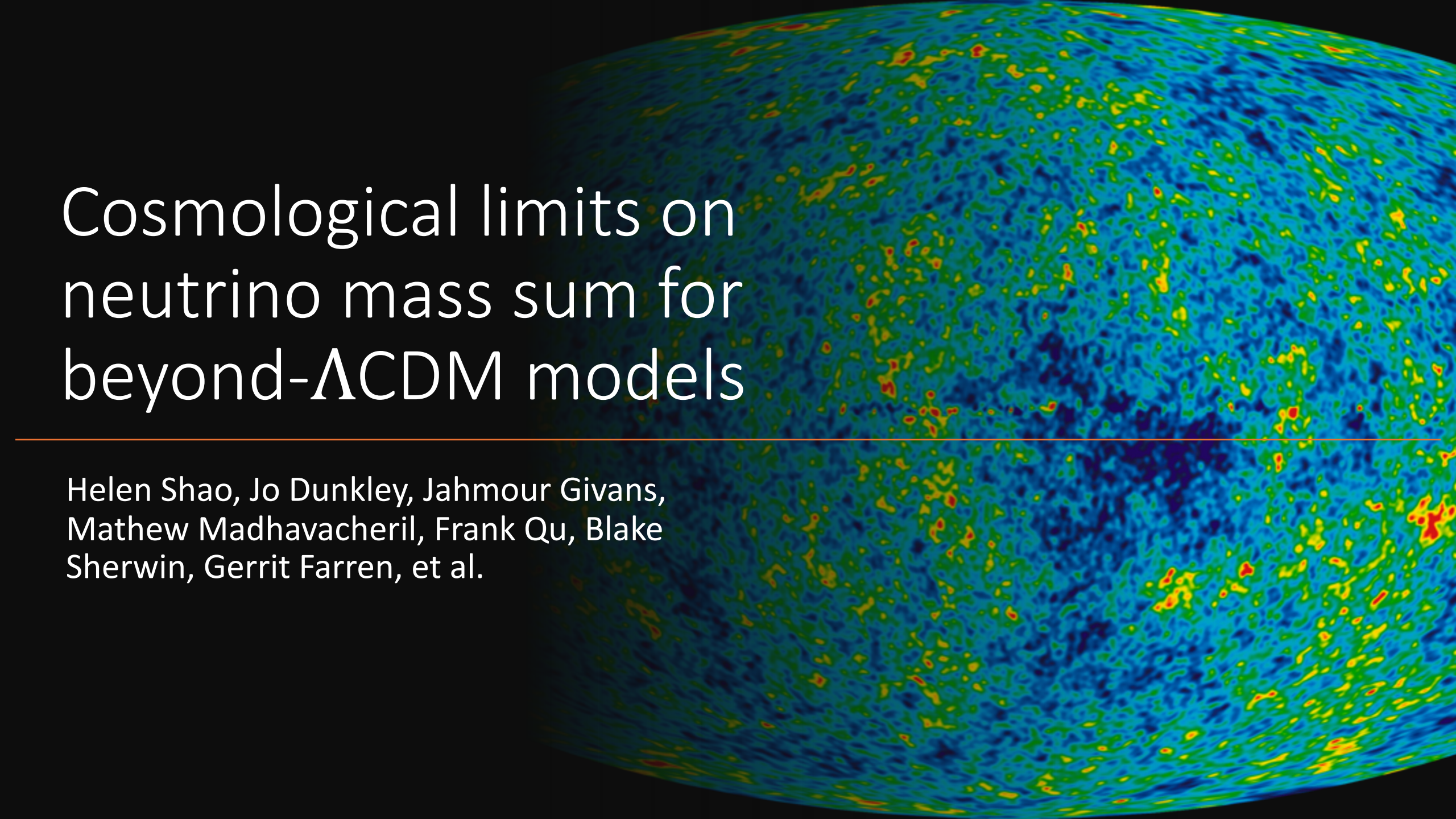
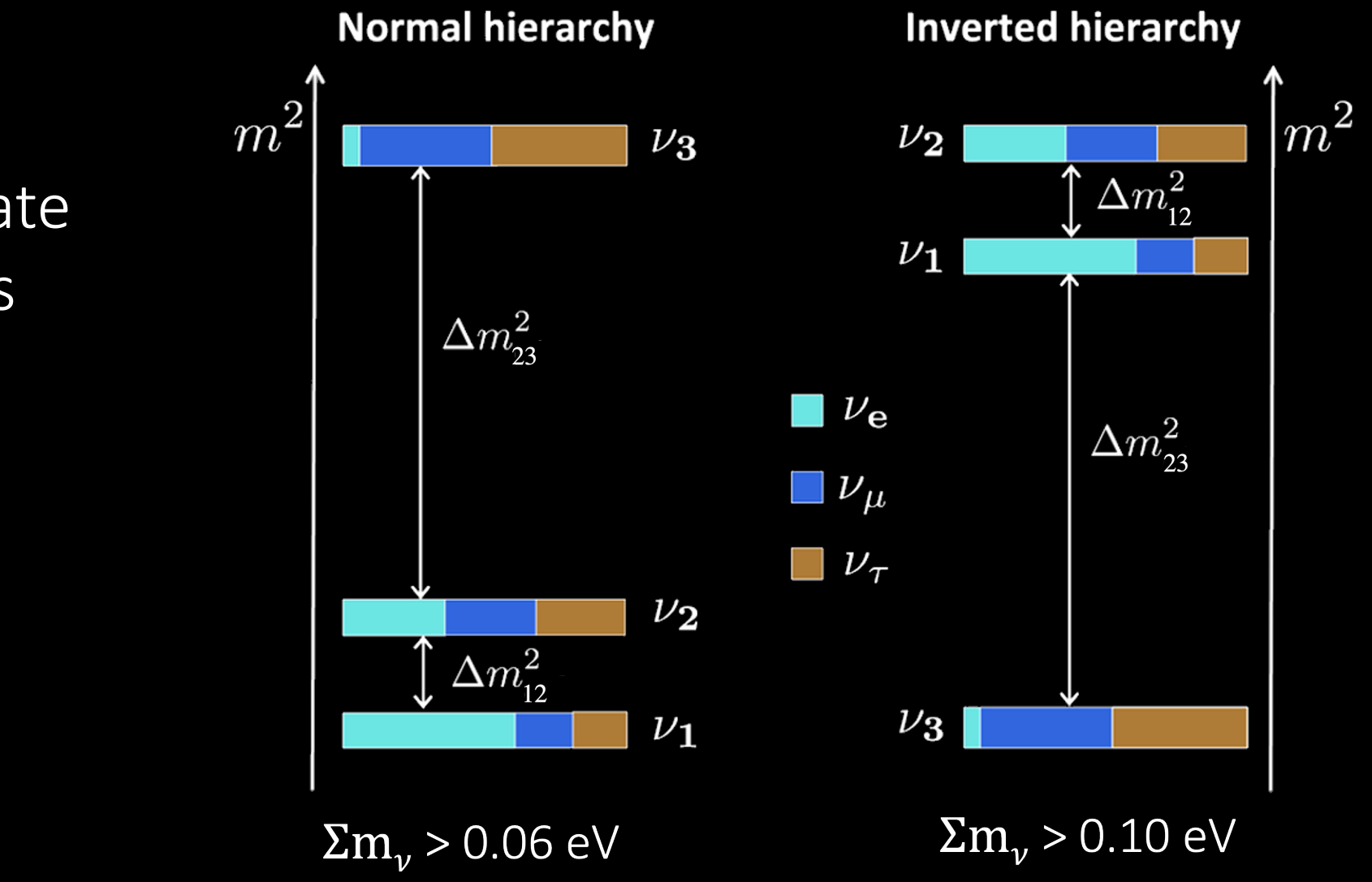
Cosmological limits on neutrino mass sum for beyond-ΛCDM models

Helen Shao, Jo Dunkley, Jahmour Givans, Mathew Madhavacheril, Frank Qu, Blake Sherwin, Gerrit Farren, et al.



Neutrino Mass

- Neutrinos oscillate between masses



$\Sigma m_\nu > 0.06$ eV

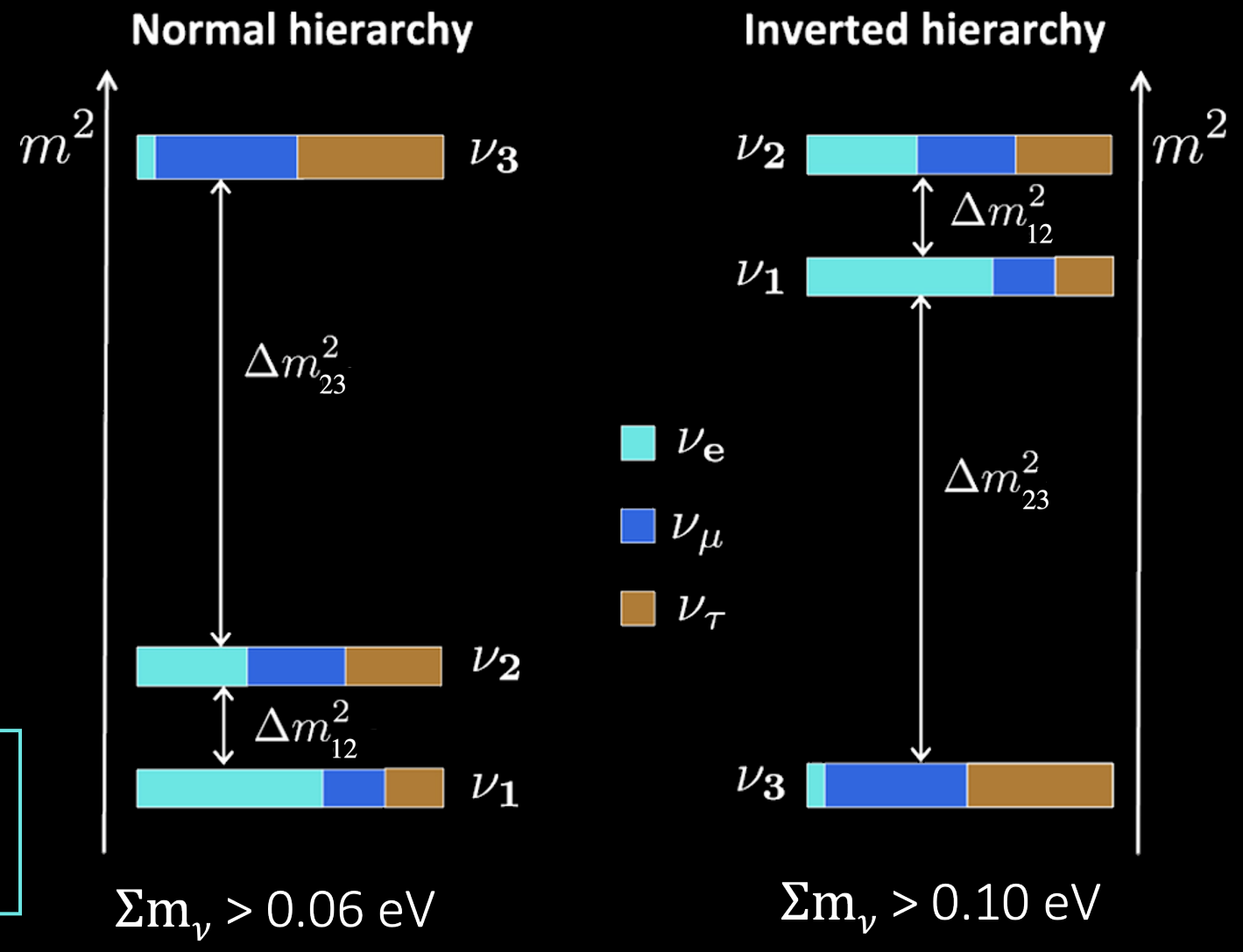
$\Sigma m_\nu > 0.10$ eV

Neutrino Mass

- Neutrinos oscillate between masses
- Direct detection experiments (KATRIN): $m_\beta < 0.8$ eV (Acker 2021, 90%)

Δm^2_{12}

Δm^2_{23} or Δm^2_{13}

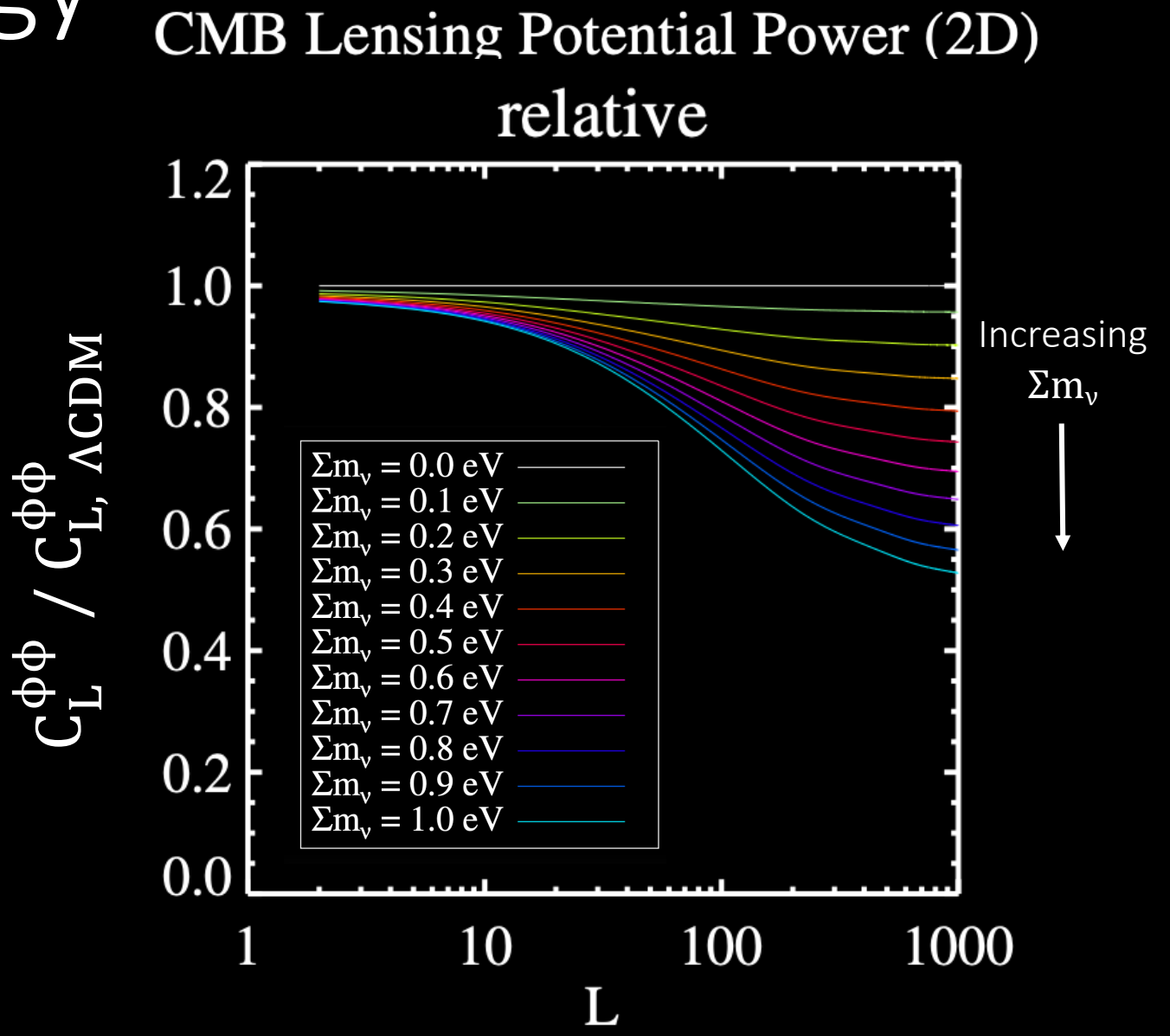


$\Sigma m_\nu > 0.06$ eV

$\Sigma m_\nu > 0.10$ eV

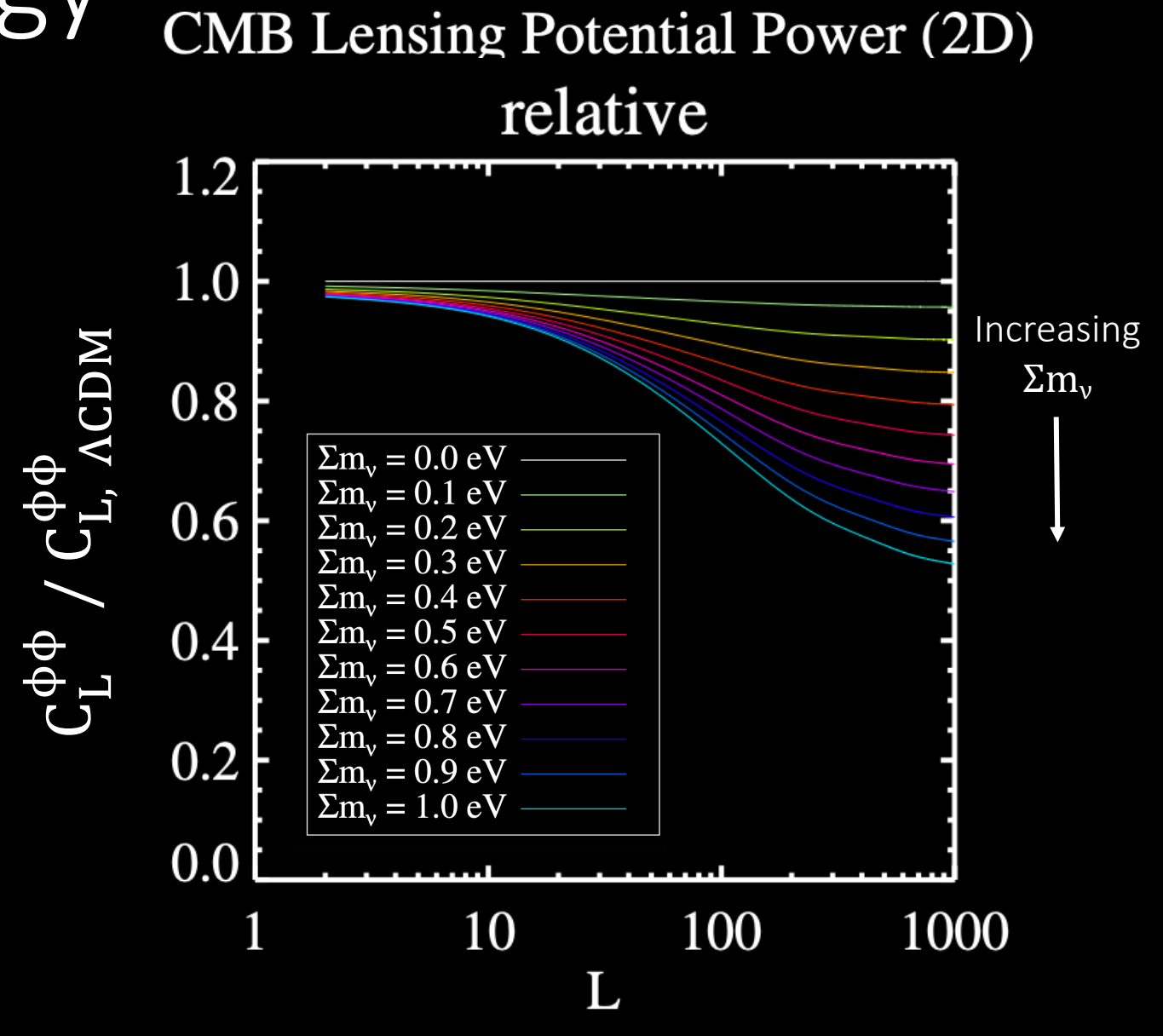
Σm_ν from cosmology

- Neutrino free-streaming → suppression of structure growth on small-scales



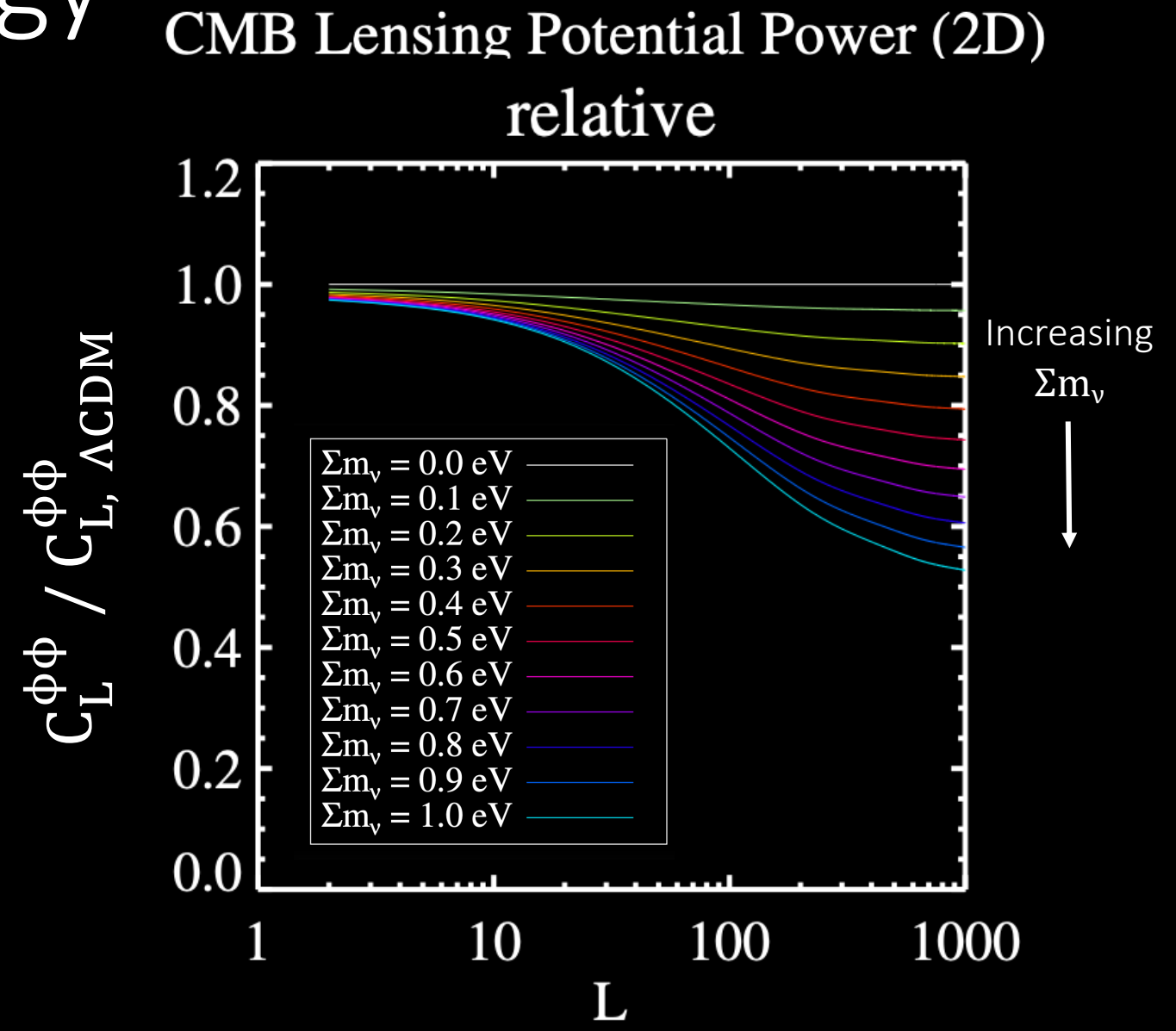
Σm_ν from cosmology

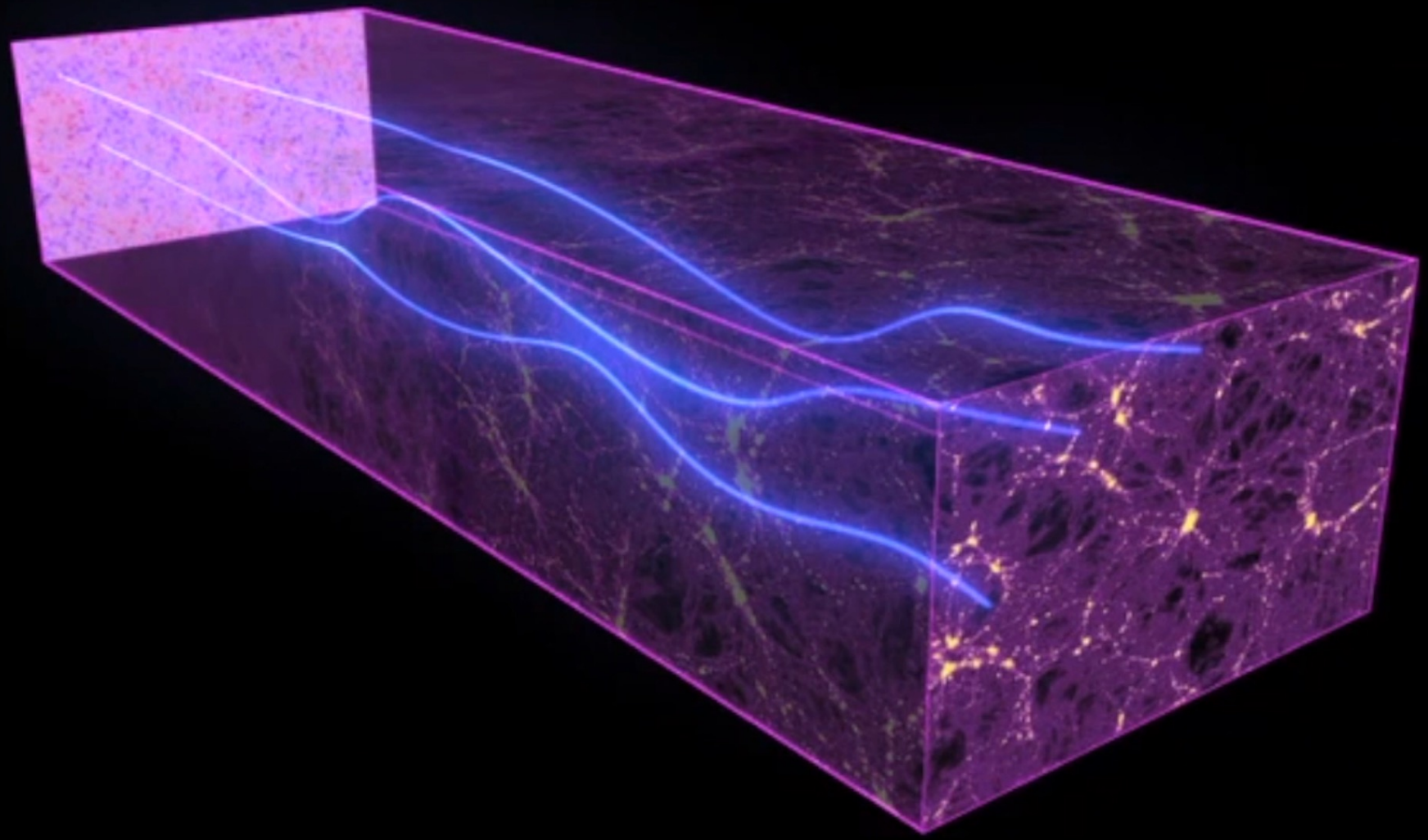
- Neutrino free-streaming → suppression of structure growth on small-scales
- $\Sigma m_\nu < 0.12$ eV (Planck18, 95%), < 0.072 eV (DESI, 95%)

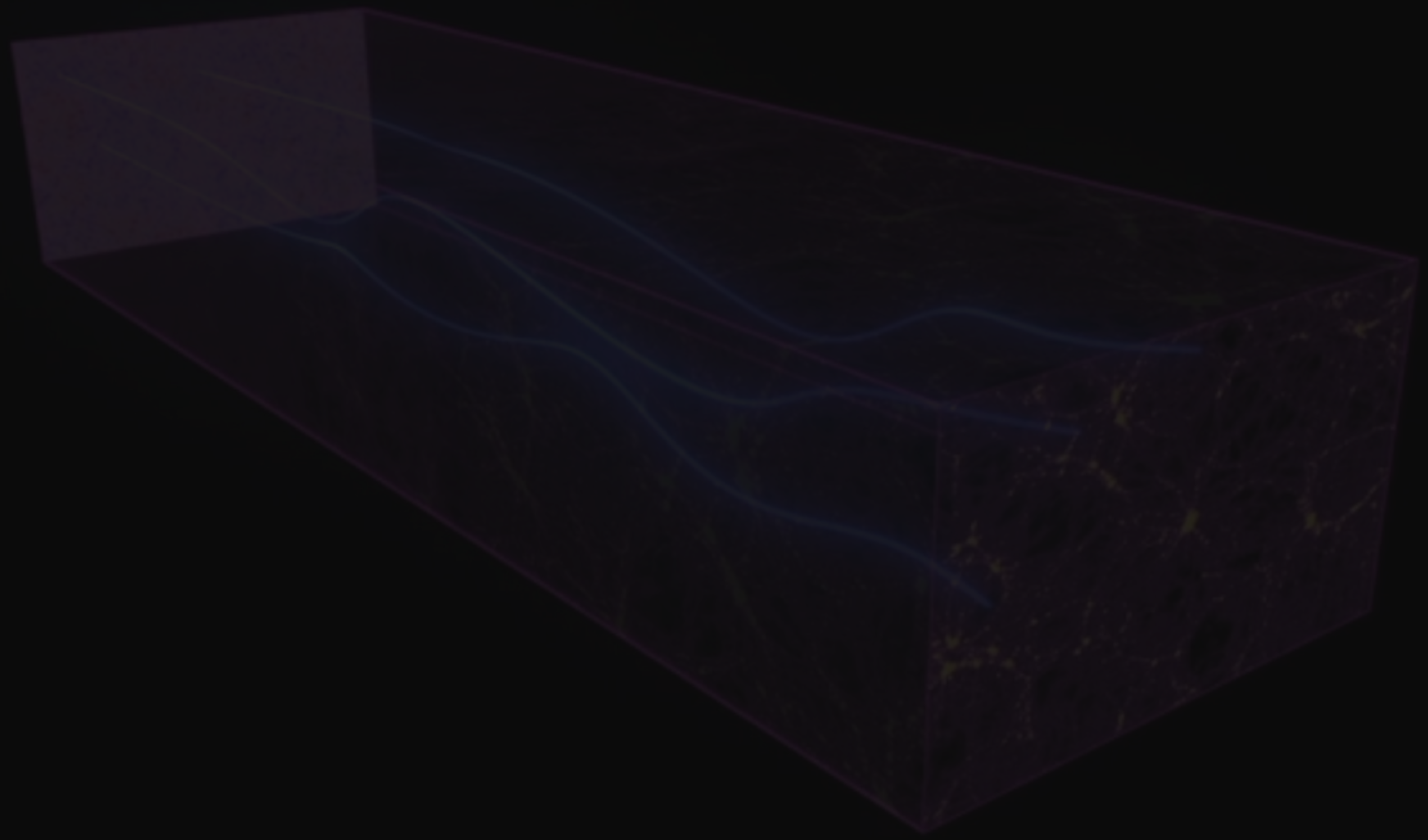


Σm_ν from cosmology

- Neutrino free-streaming → suppression of structure growth on small-scales
- $\Sigma m_\nu < 0.12$ eV (Planck18, 95%), < 0.072 eV (DESI, 95%)
- Question: are Σm_ν bounds robust to cosmologies beyond LCDM?

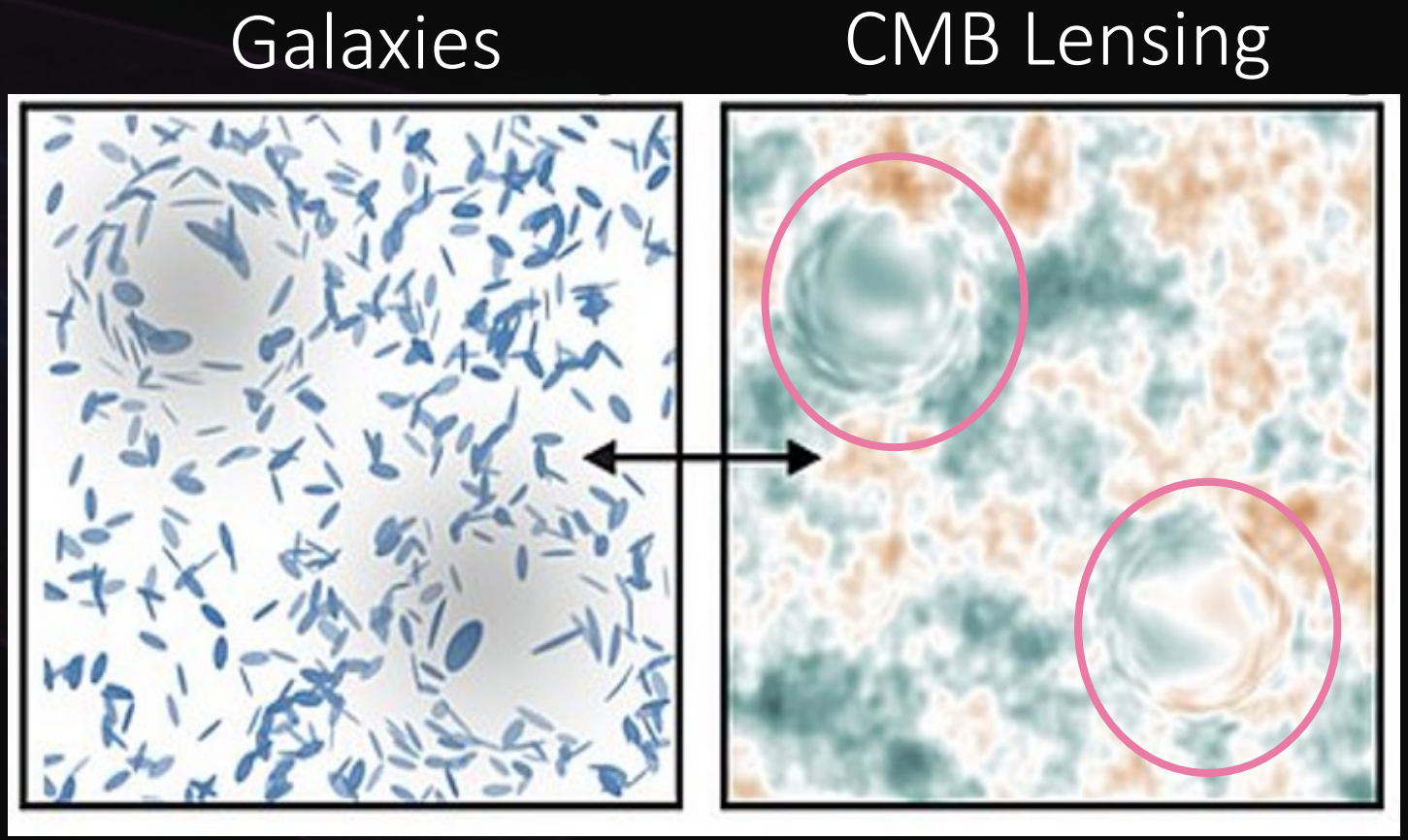






CMB lensing: late universe

Primary CMB: early universe

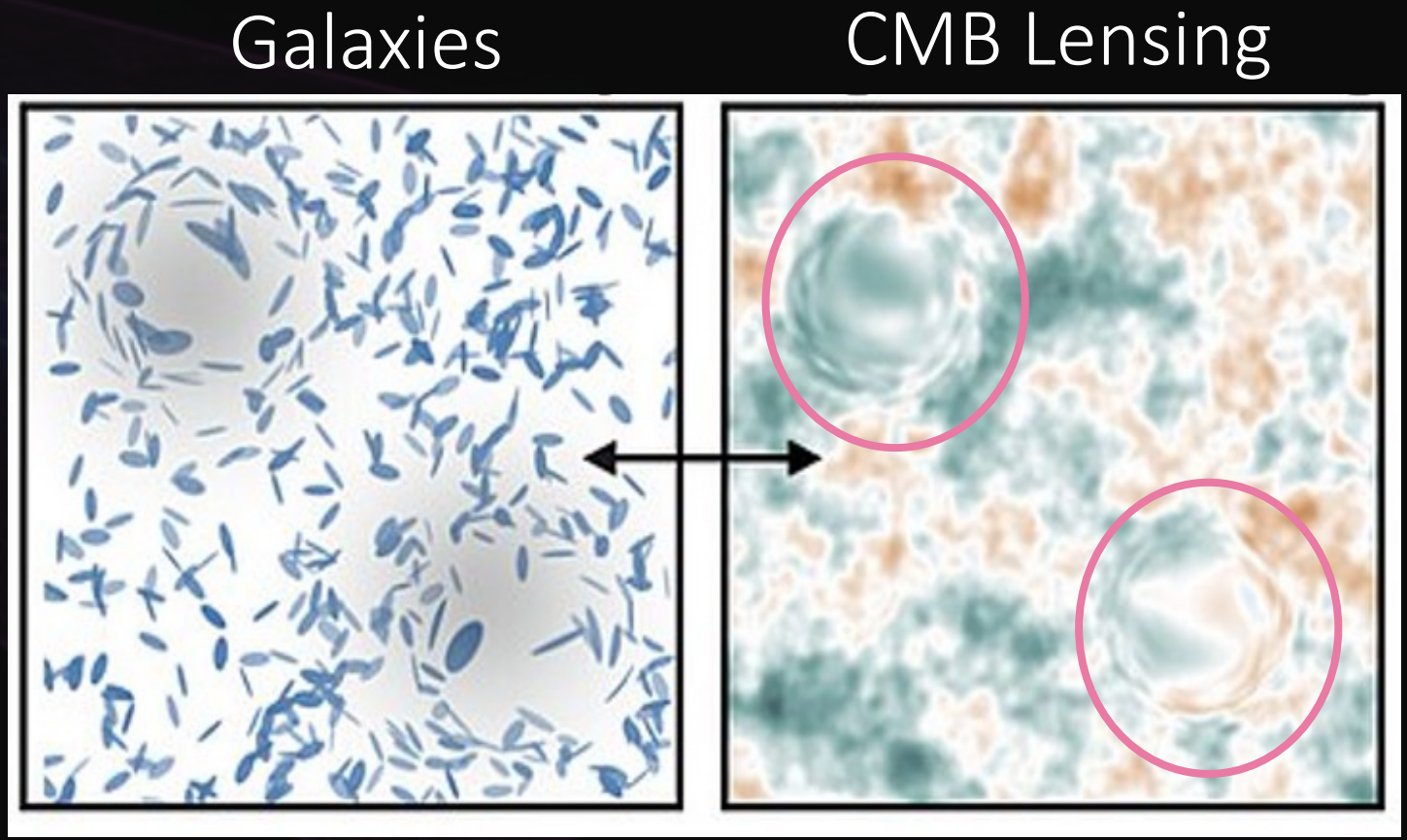


CMB lensing: late universe

Primary CMB: early universe

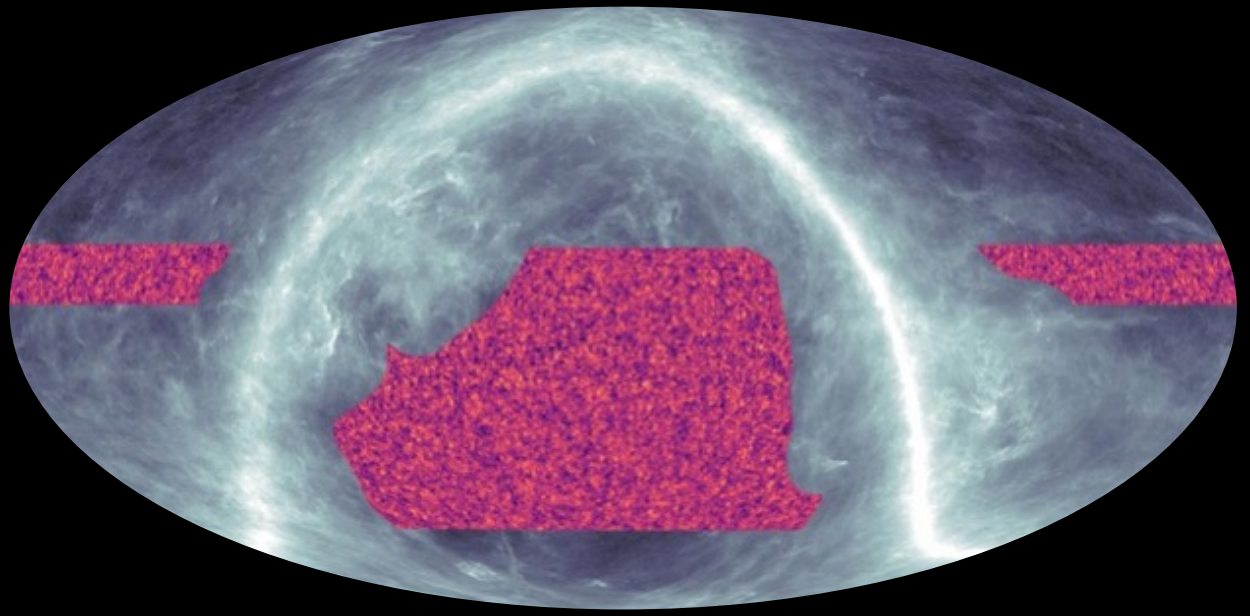
$C_\ell^{\Phi\Phi}$ = lensing power

- **Matter clustering**
- Σm_ν suppresses clustering



Atacama Cosmology Telescope (ACT)

- 5x Planck resolution
- 2007-2022: 46% of sky
- **DR6 lensing**: No A_{Len} (Planck) anomaly



Data & Likelihoods

CMB anisotropies

- High-ℓ: CamSpec TT, TE, EE (Rosenberg et al. 2022)
- low-ℓ: TT (Planck 2018), EE sroll2 (Pagano et al. 2020)

Planck Lensing

Planck PR4 NPIPE (Carron et al. 2022)

$100 \leq L \leq 2048$

ACT Lensing

ACT DR6 (Madhavacheril et al. 2023)

(ACT + Planck Lensing)

$40 \leq L \leq 763$

BAO

6dF (Beutler et al. 2016)

SDSS

- DR7 (Percival et al. 2010)
- BOSS DR12 (Dawson et al. 2013)
- DR16 (Alam et al 2016)

Supernovae

Pantheon+ (Scolnic et al. 2022)

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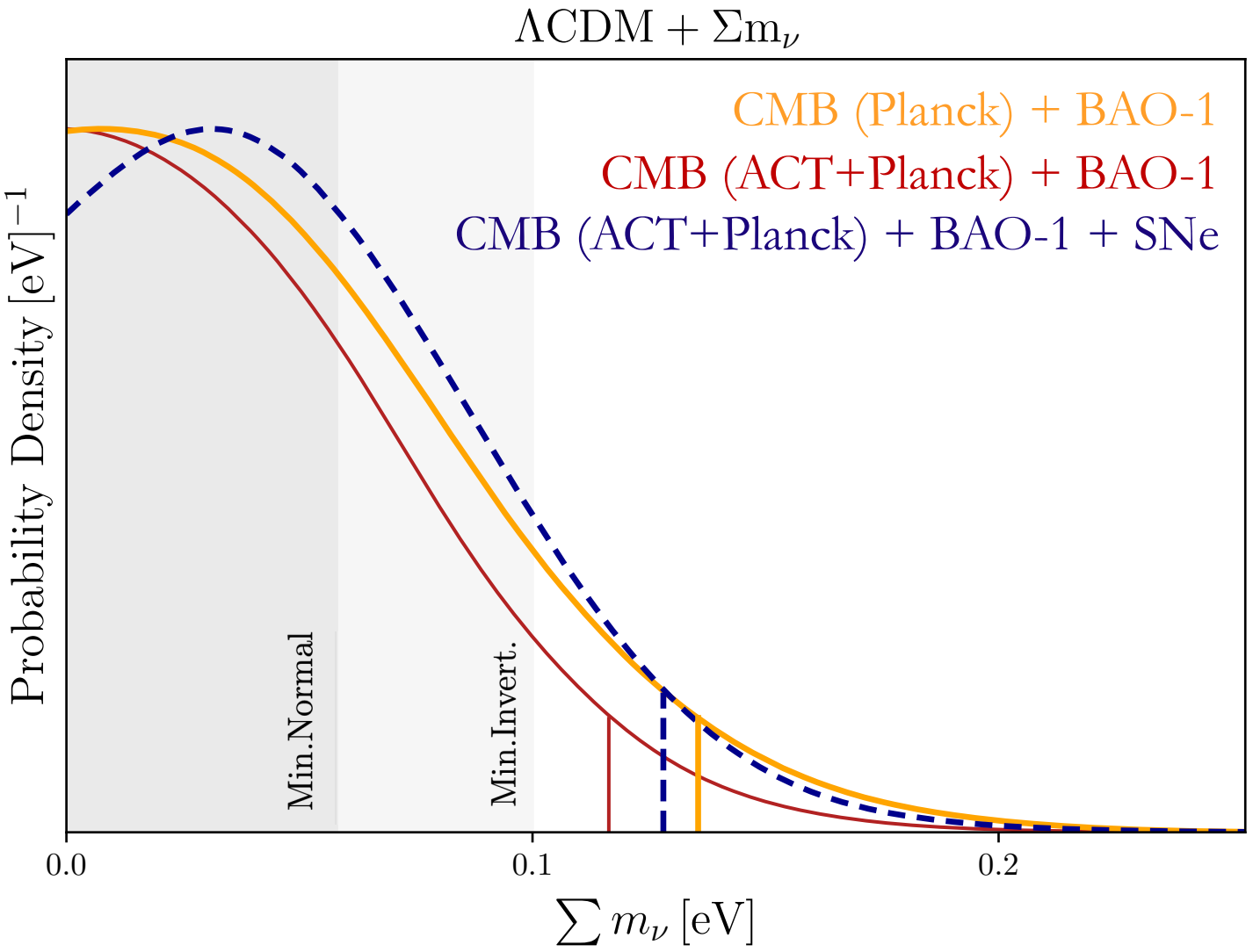
- **DESI** 2024

Supernovae

- **Pantheon+** (Scolnic et al. 2022)

ΛCDM + Σm_ν



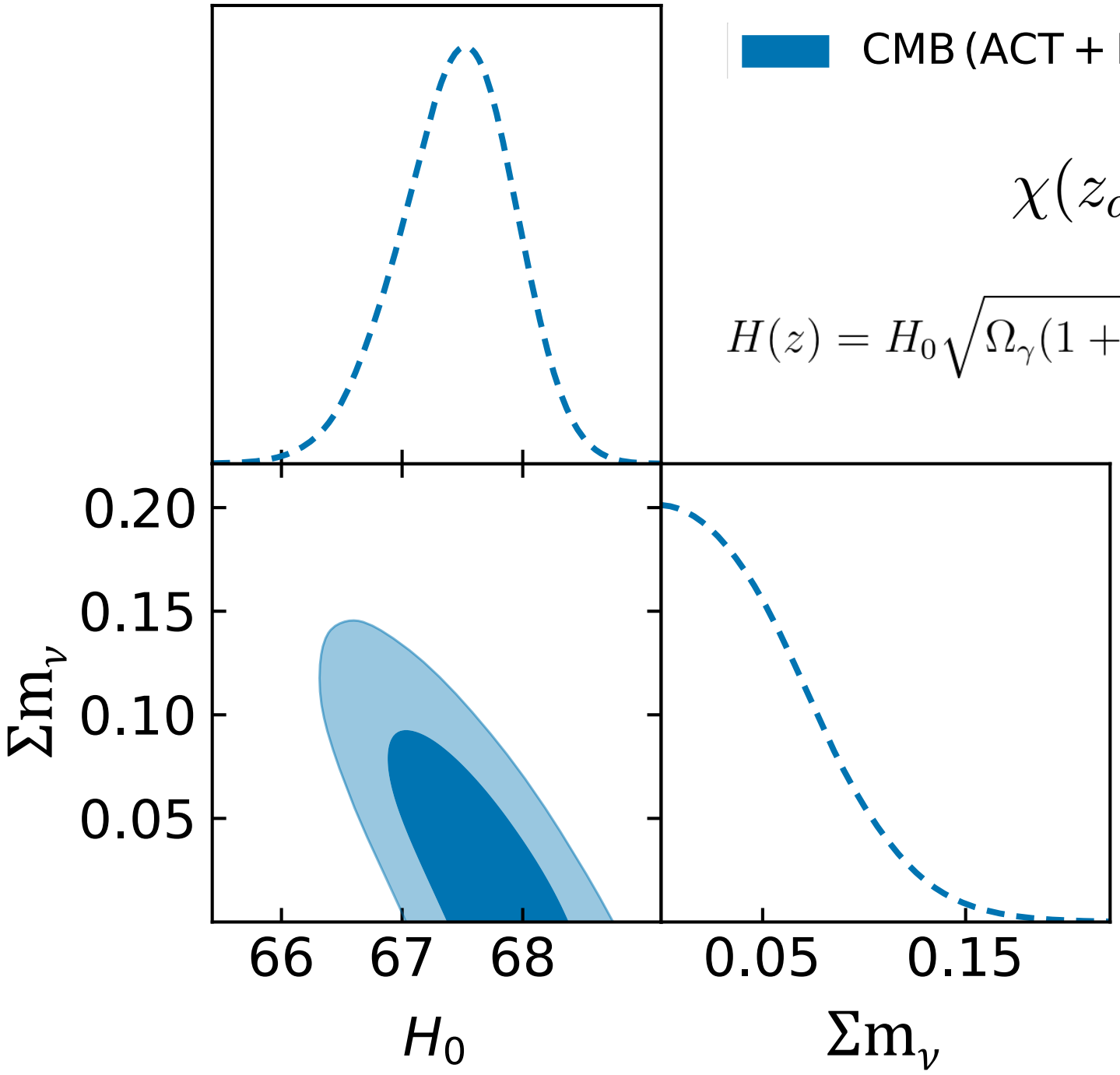
Vertical lines indicate 2σ bounds

Consistent with (Madhavacheril et al., 2023)

$\Sigma m_\nu < 0.135$ eV

$\Sigma m_\nu < 0.121$ eV

$\Sigma m_\nu < 0.129$ eV

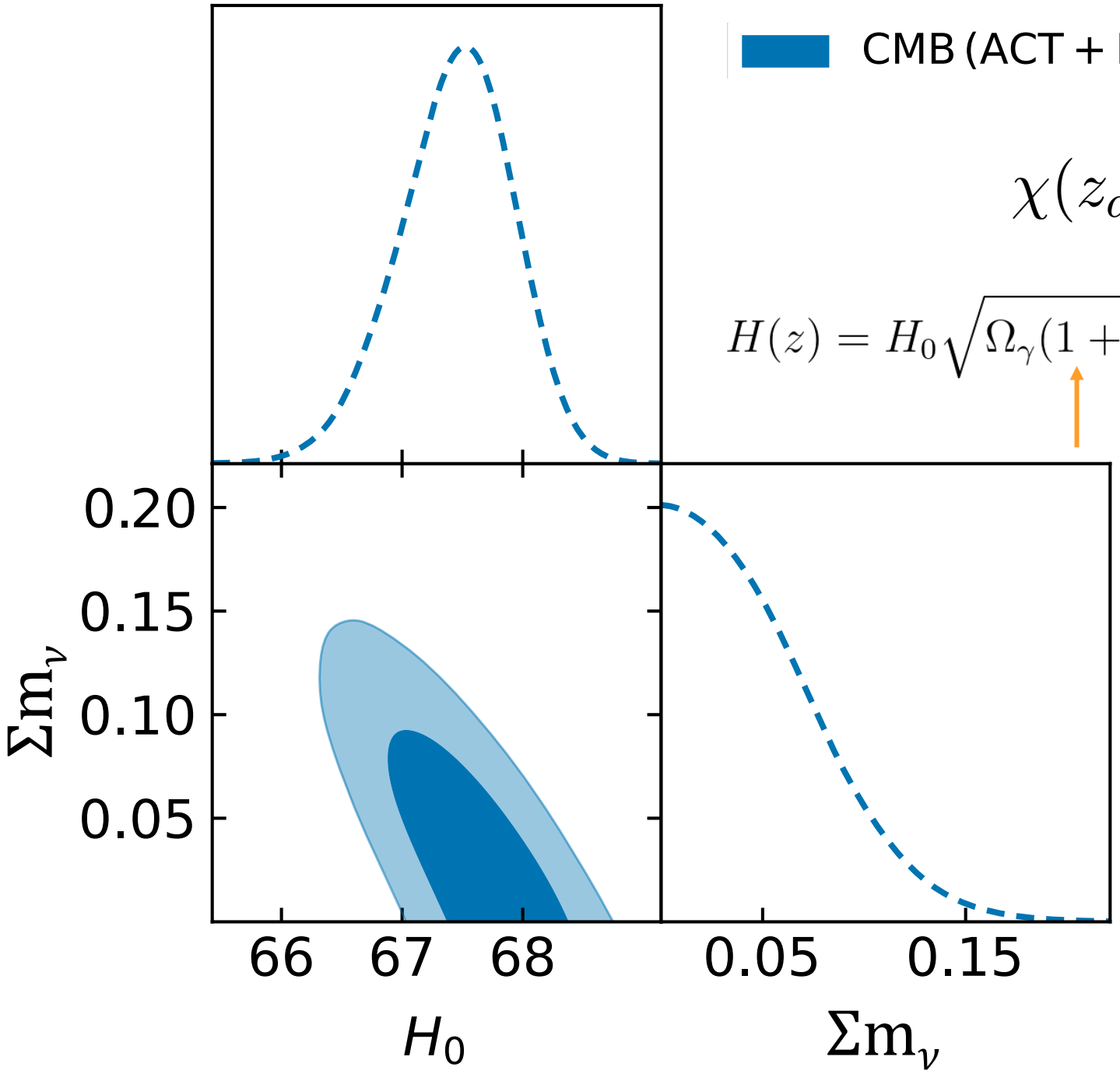


$$\chi(z_{dec}) = \int_0^{z_{dec}} dz/H(z)$$

$$H(z) = H_0\sqrt{\Omega_\gamma(1+z)^4 + (\Omega_m)(1+z)^3 + \Omega_{DE}(z) + \rho_\nu(z)/\rho_{cr,0}}$$

$$\Sigma m_\nu < 0.121 \text{ eV}$$

$$H_0 = 67.45 \pm 0.48$$



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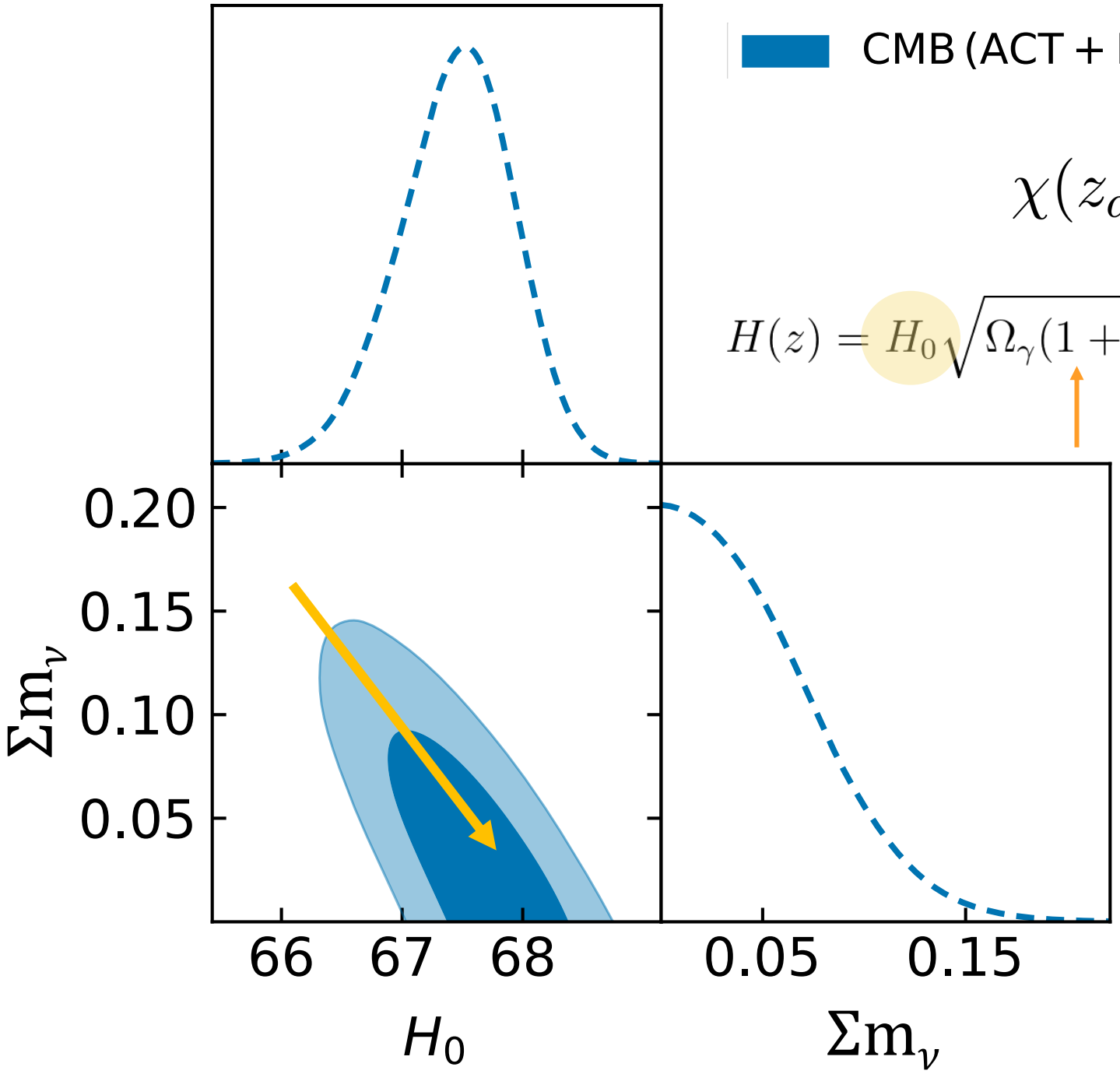

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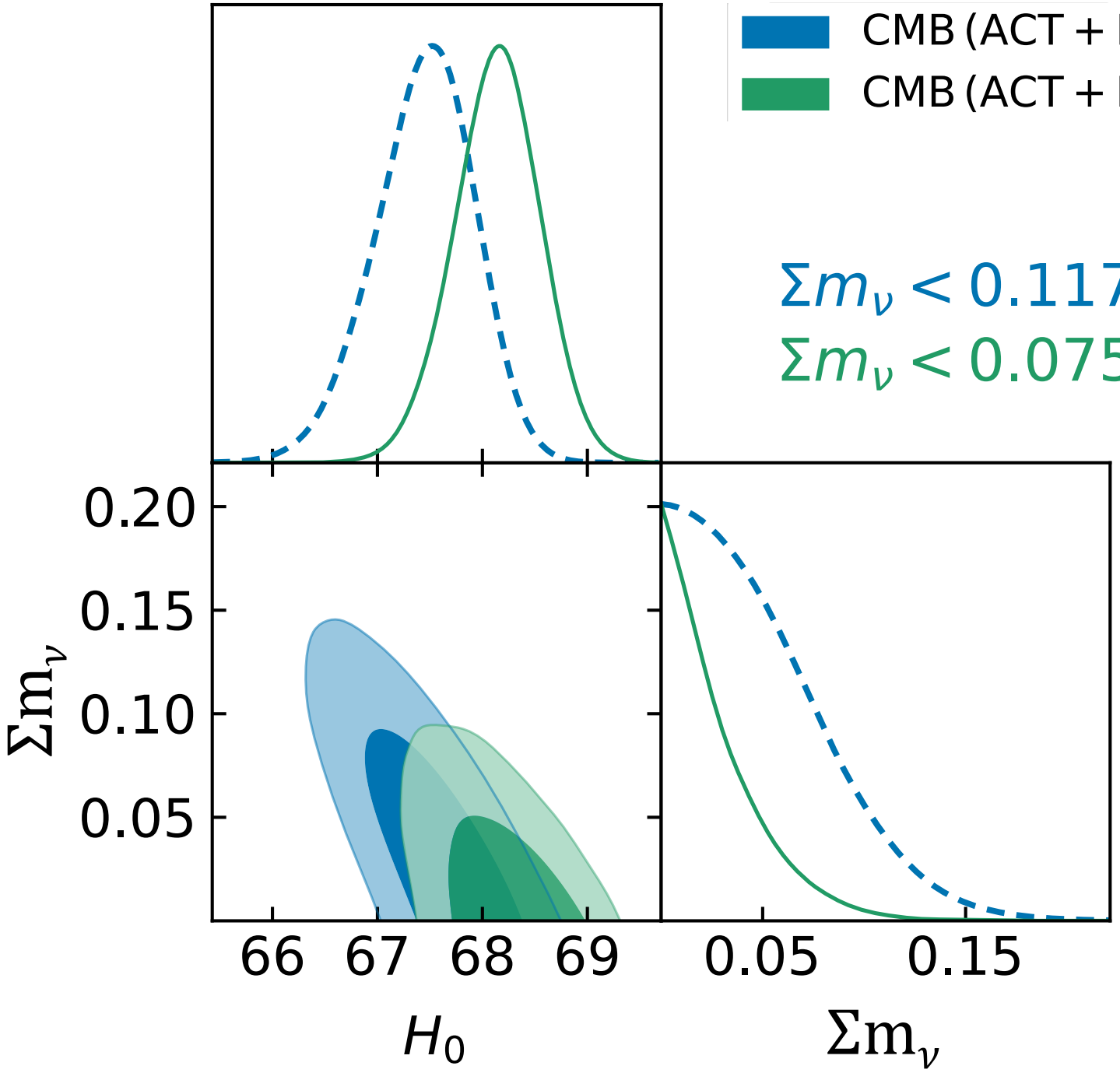
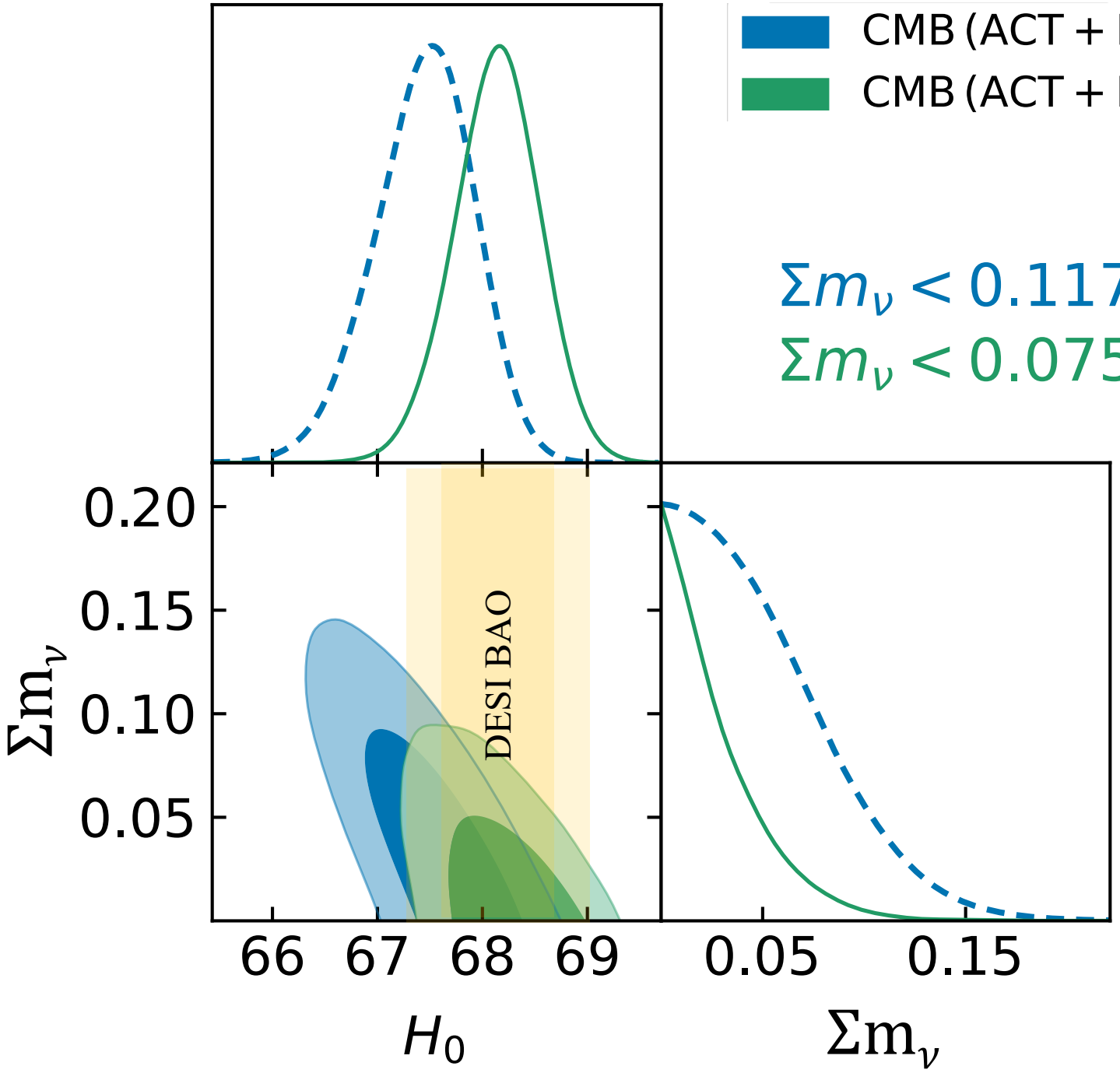


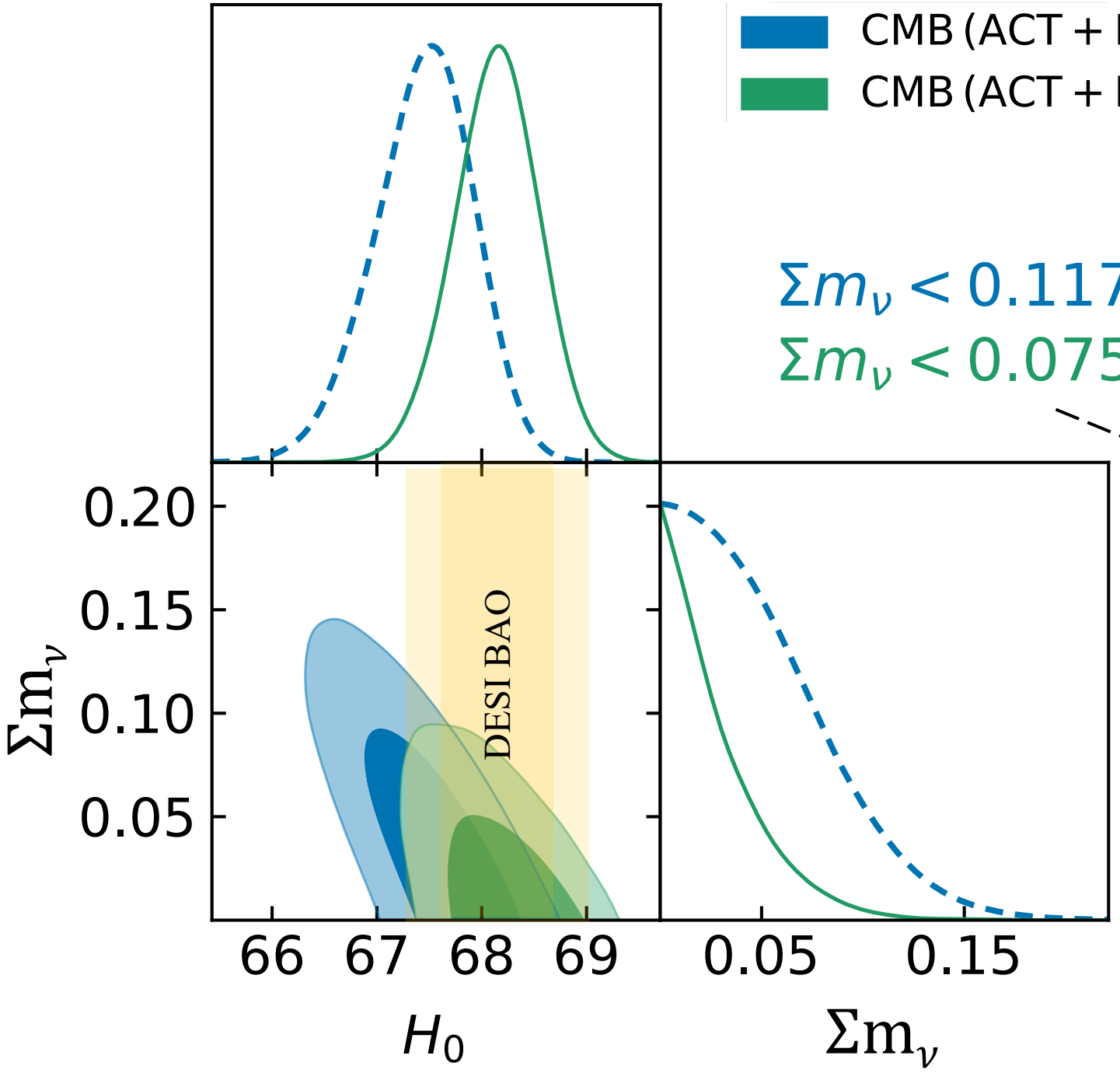
$\Sigma m_\nu < 0.117\,\mathrm{eV}$ $H_0 = 67.45 \pm 0.48$

$\Sigma m_\nu < 0.075\,\mathrm{eV}$ $H_0 = 68.14 \pm 0.41$



$\Sigma m_\nu < 0.117$ eV $\quad H_0 = 67.45 \pm 0.48$

$\Sigma m_\nu < 0.075$ eV $\quad H_0 = 68.14 \pm 0.41$



$\Sigma m_\nu < 0.117$ eV $\quad H_0 = 67.45 \pm 0.48$

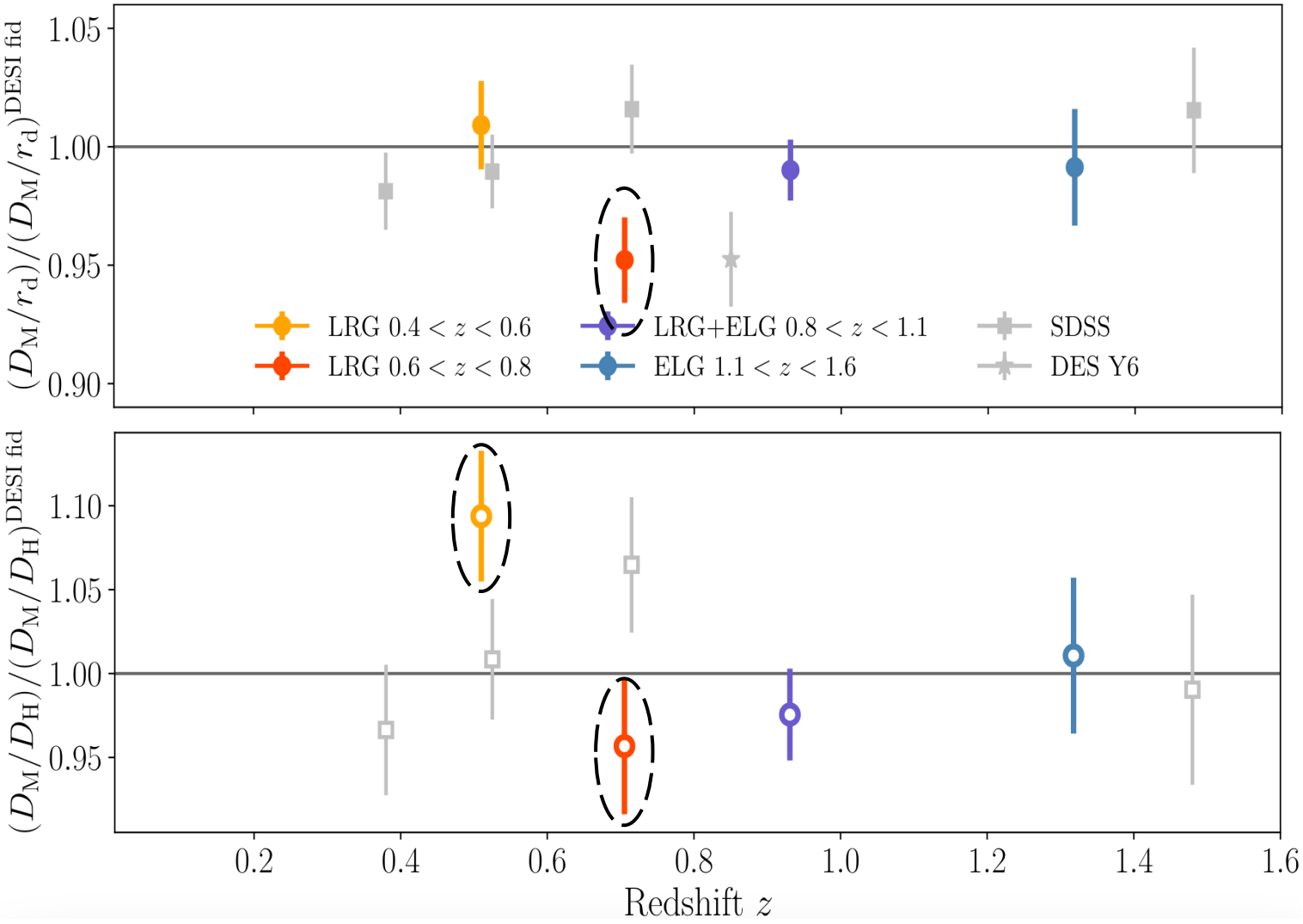
$\Sigma m_\nu < 0.075$ eV $\quad H_0 = 68.14 \pm 0.41$

Excludes Inverted Hierarchy (?)

DESI 2024

0.6 < z < 0.8 LRG

~ 3σ discrepancy between DESI and SDSS results



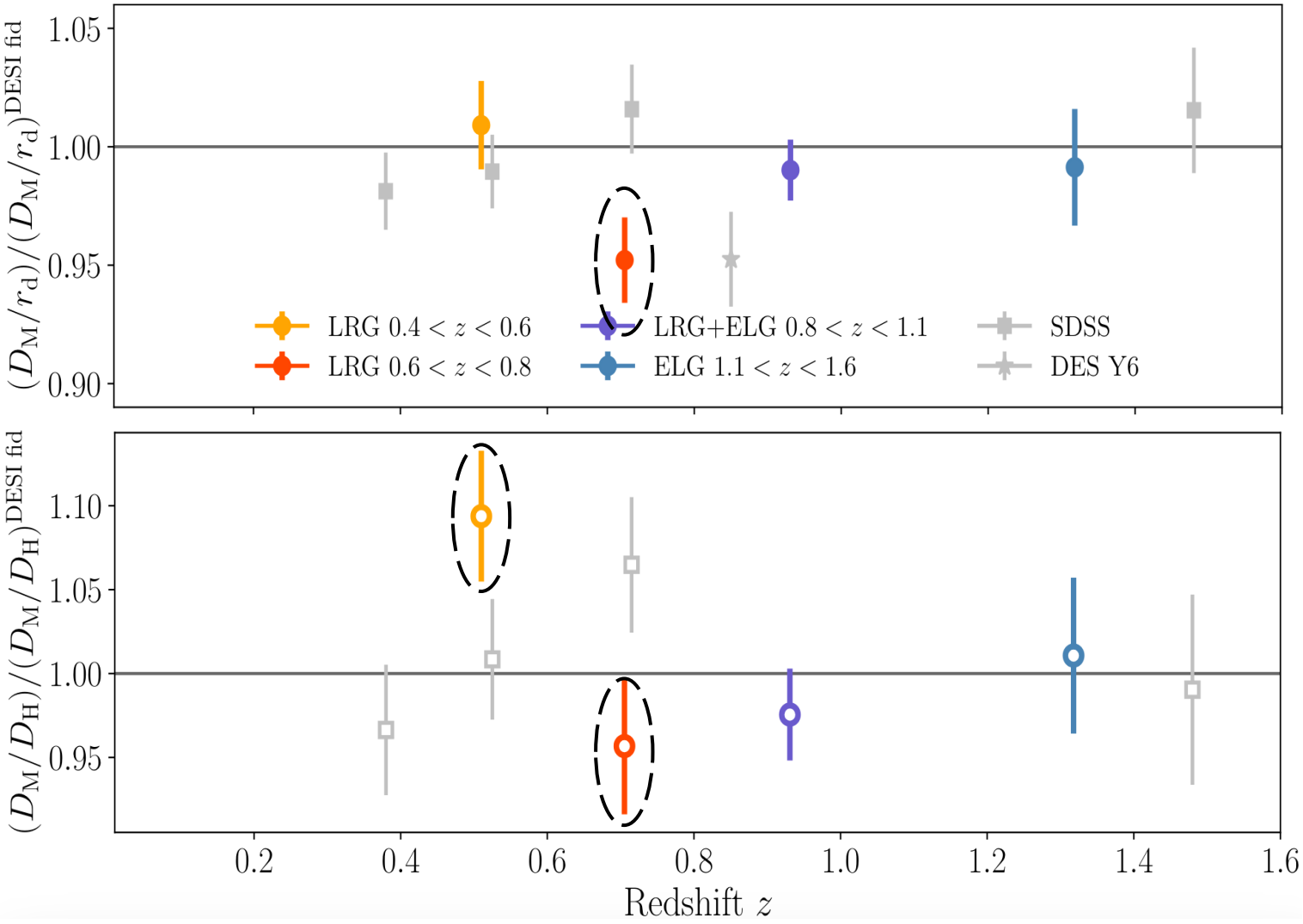
[DESI, 2024]

BAO-2 Dataset

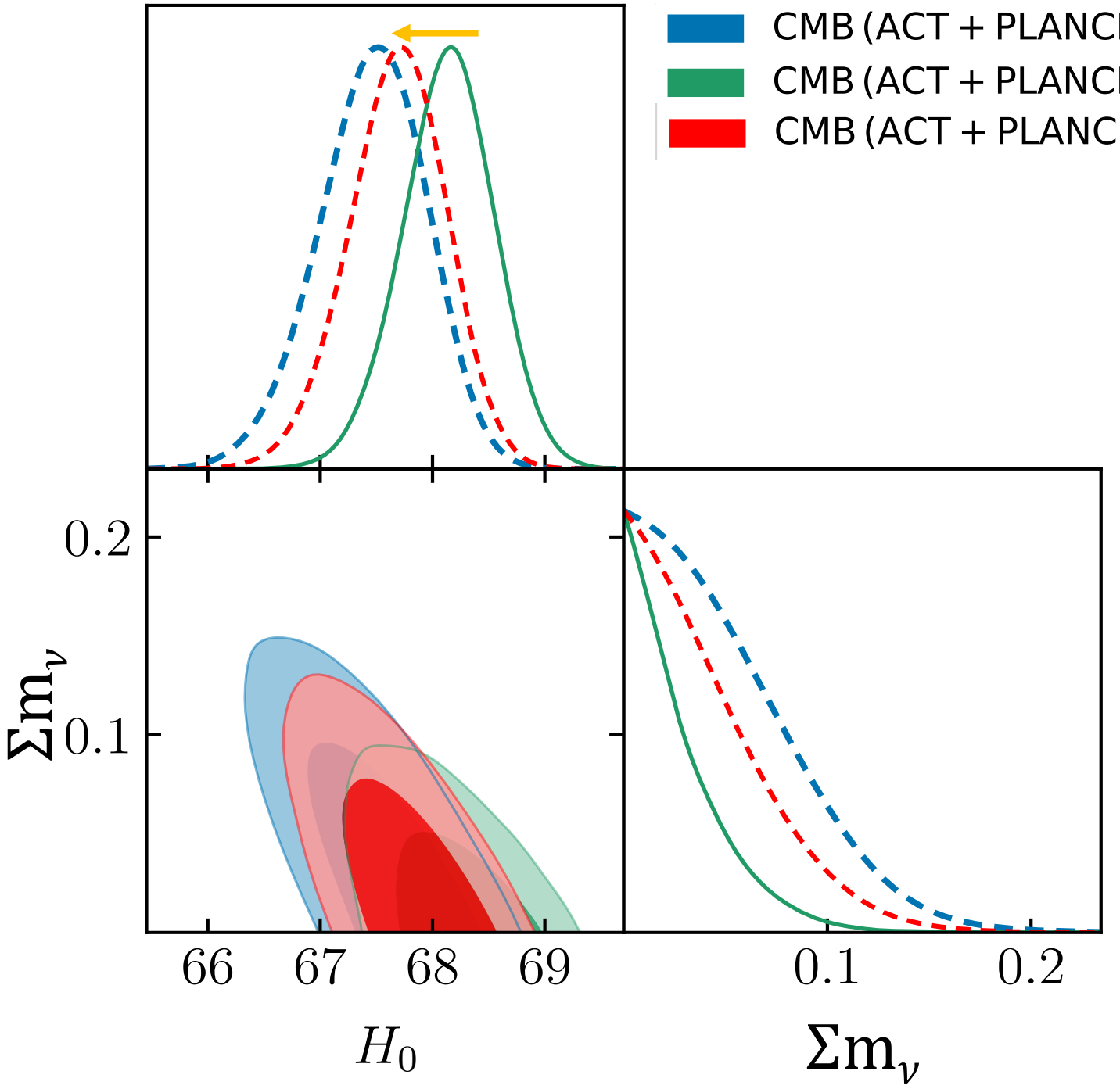
(1) SDSS: z=0.15, 0.38, **0.51** (larger effective volume), **0.6<z<0.8** (3σ deviation)

(2) DESI: LRGs & ELGs in 0.8 < z < 1.1, ELGs and QSOs at higher z

(3) Combined DESI+SDSS for Lyα BAO



[DESI, 2024]



$\Sigma m_\nu < 0.121$ eV

$\Sigma m_\nu < 0.075$ eV

$\Sigma m_\nu < 0.104$ eV

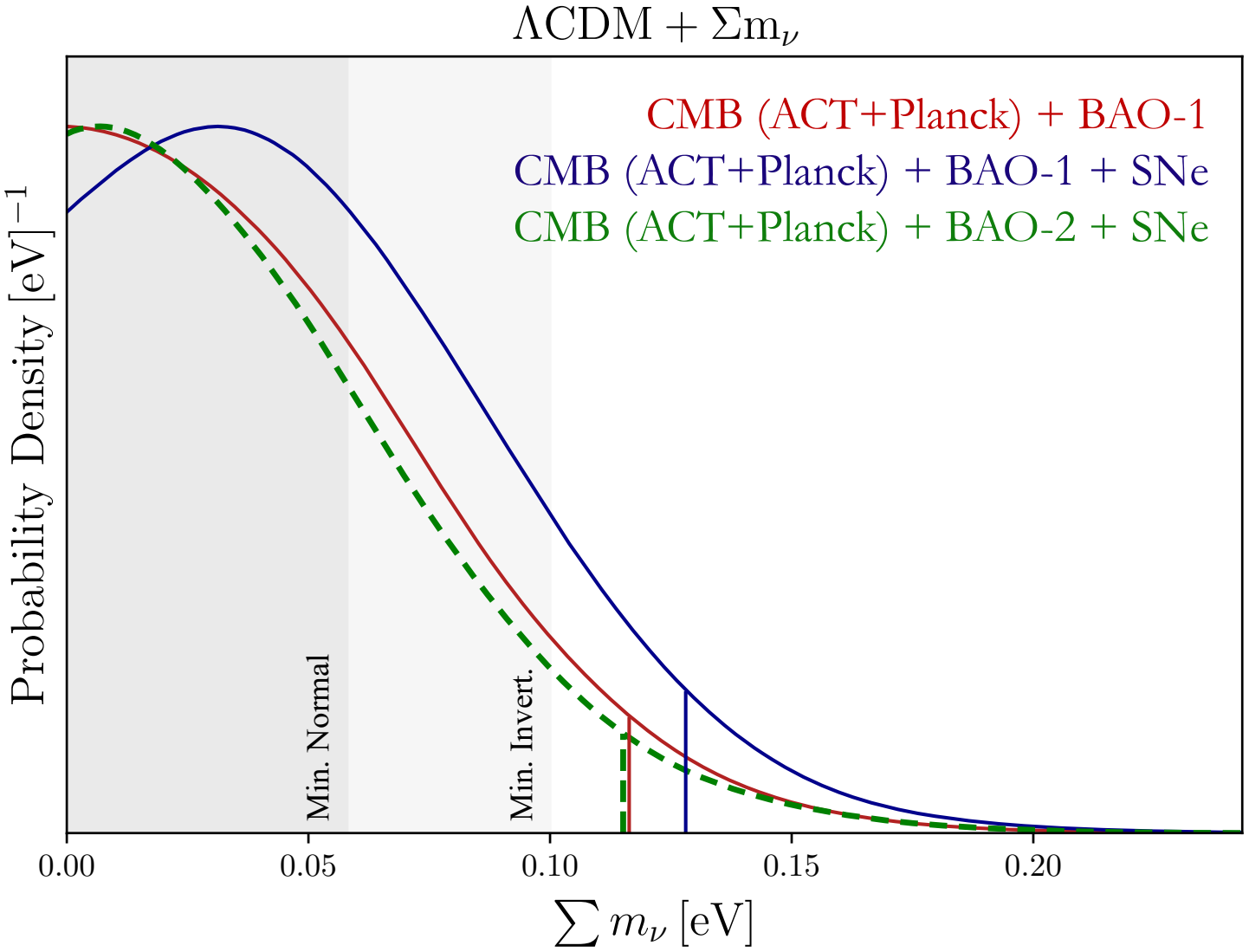
$H_0 = 67.45 \pm 0.48$

$H_0 = 68.14 \pm 0.41$

$H_0 = 67.77 \pm 0.44$

ΛCDM + Σm_ν

See also: **Allali & Notari, 2024**
arXiv: 2406.14554



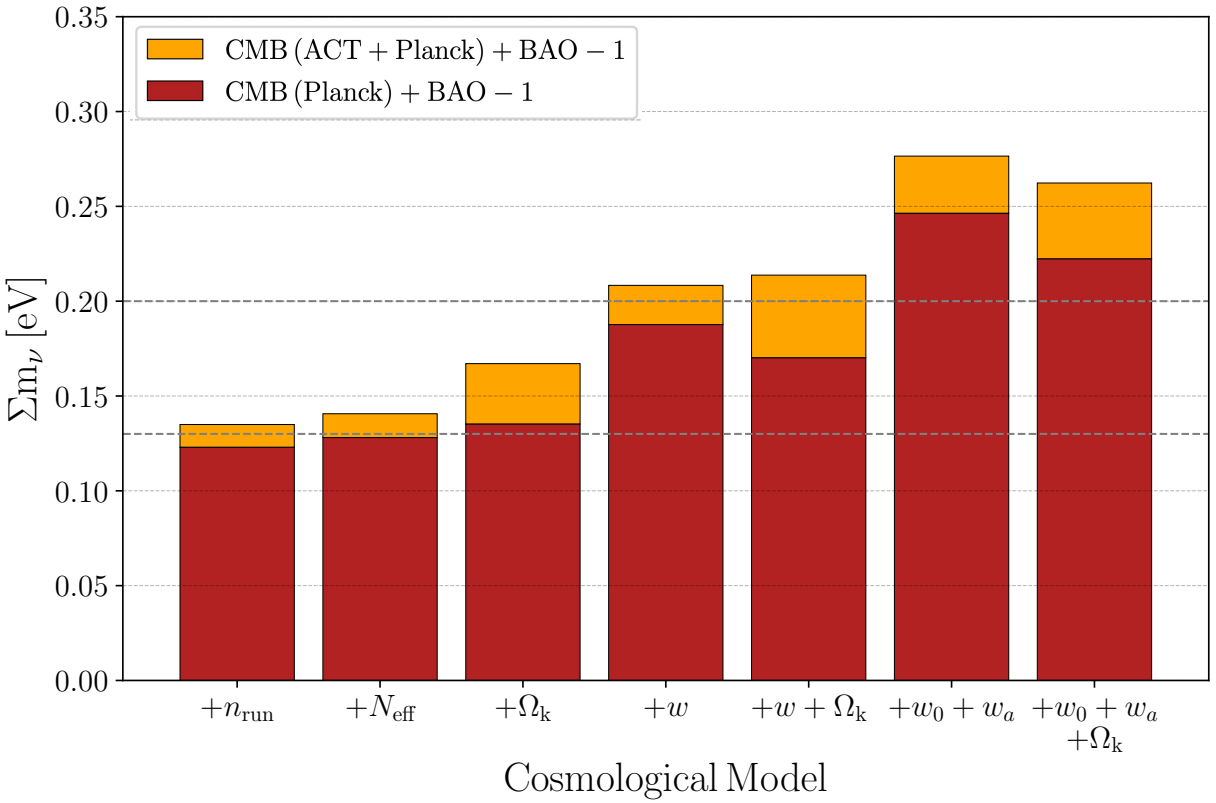
Vertical lines indicate
2σ bounds

$\Sigma m_\nu < 0.121$ eV

$\Sigma m_\nu < 0.129$ eV

$\Sigma m_\nu < 0.116$ eV

Σm_ν Bounds in Extended Cosmologies

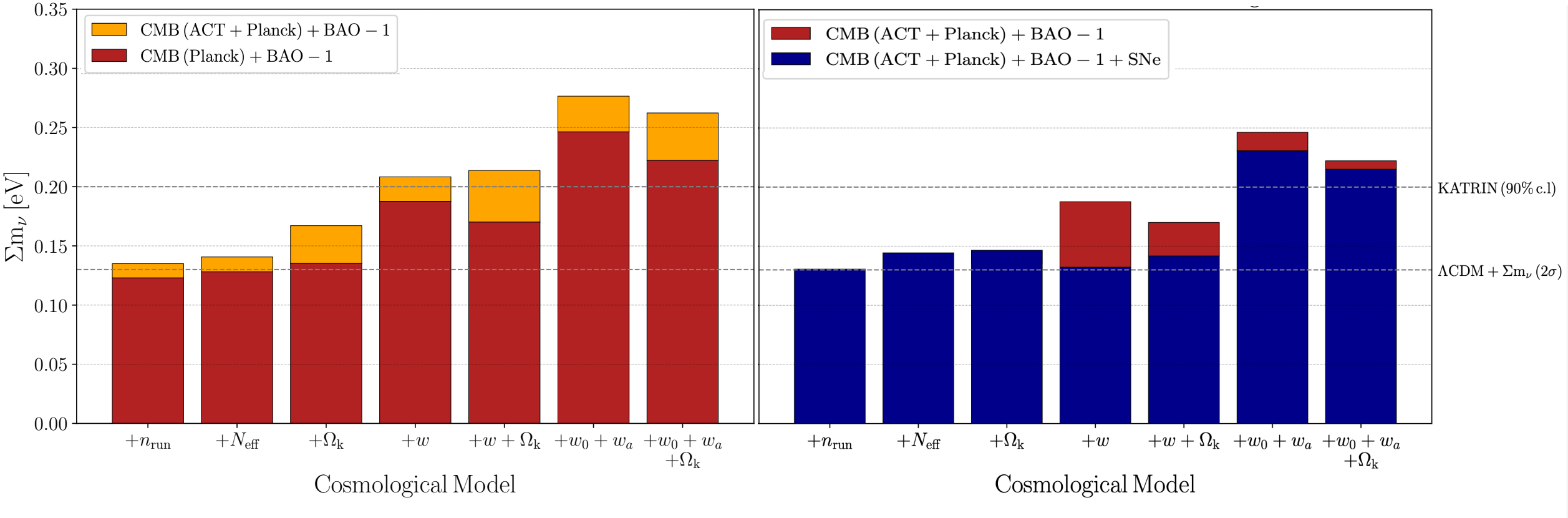


"CMB" – CMB temperature and polarization anisotropies

"Planck" – Planck PR4 lensing

"ACT + Planck" – Planck PR4 + ACT DR6 lensing

Σm_ν Bounds in Extended Cosmologies



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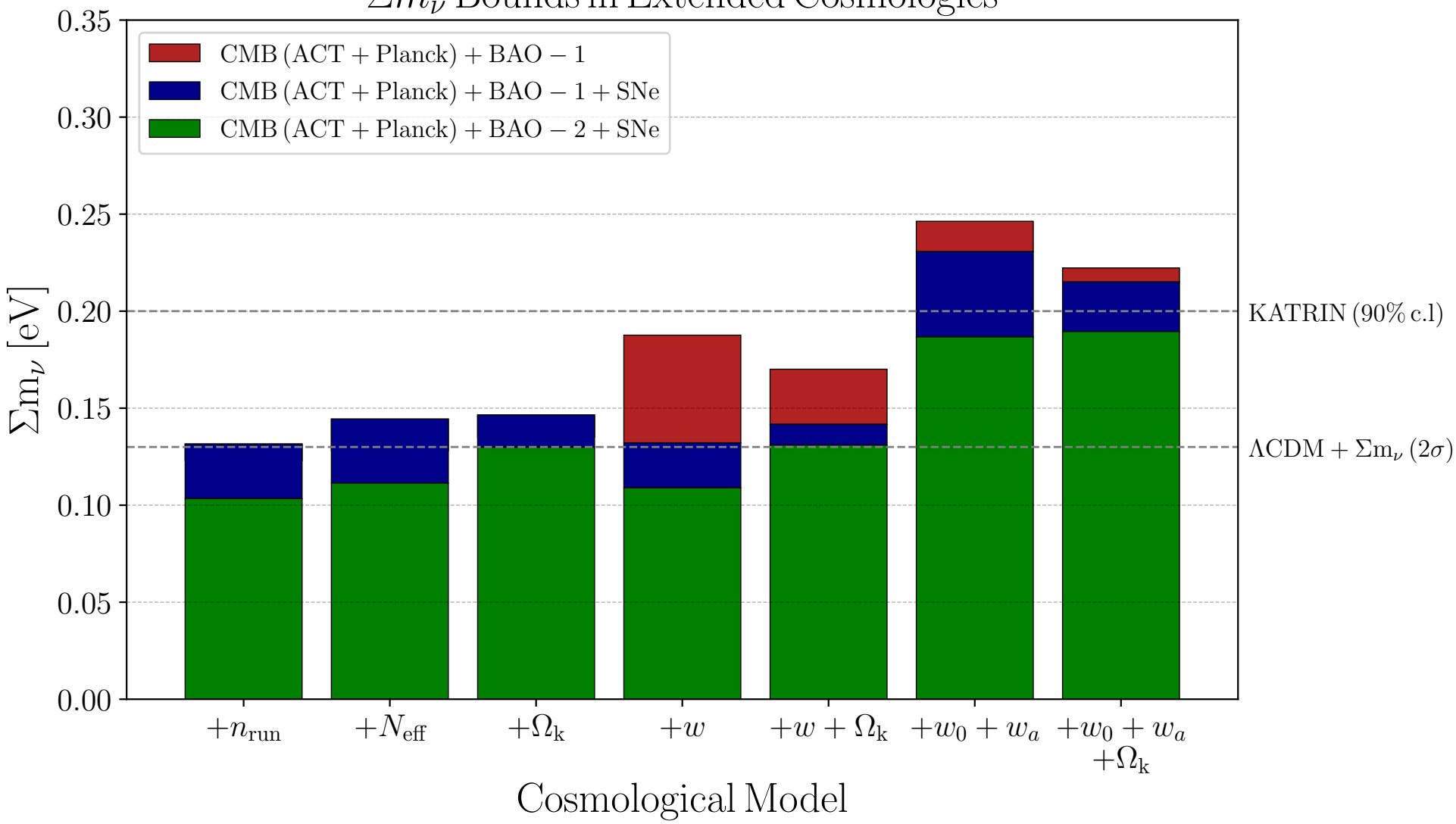
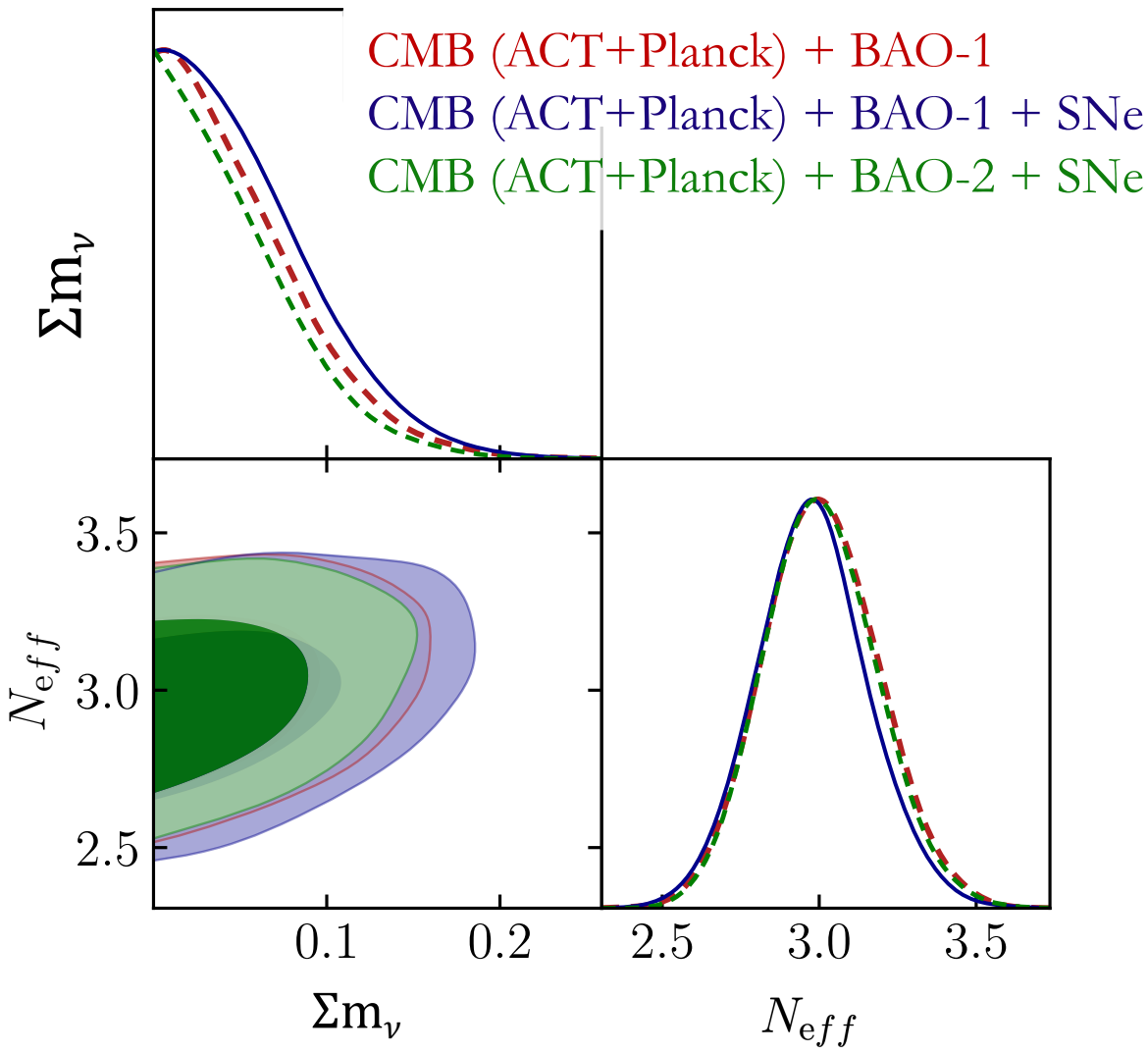


"CMB" – CMB temperature and polarization anisotropies

"BAO-1" – SDSS only

"BAO-2" – SDSS + DESI

ΛCDM + $N_{\rm eff}$ + Σm_ν



Number of effective relativistic species

Radiation energy density

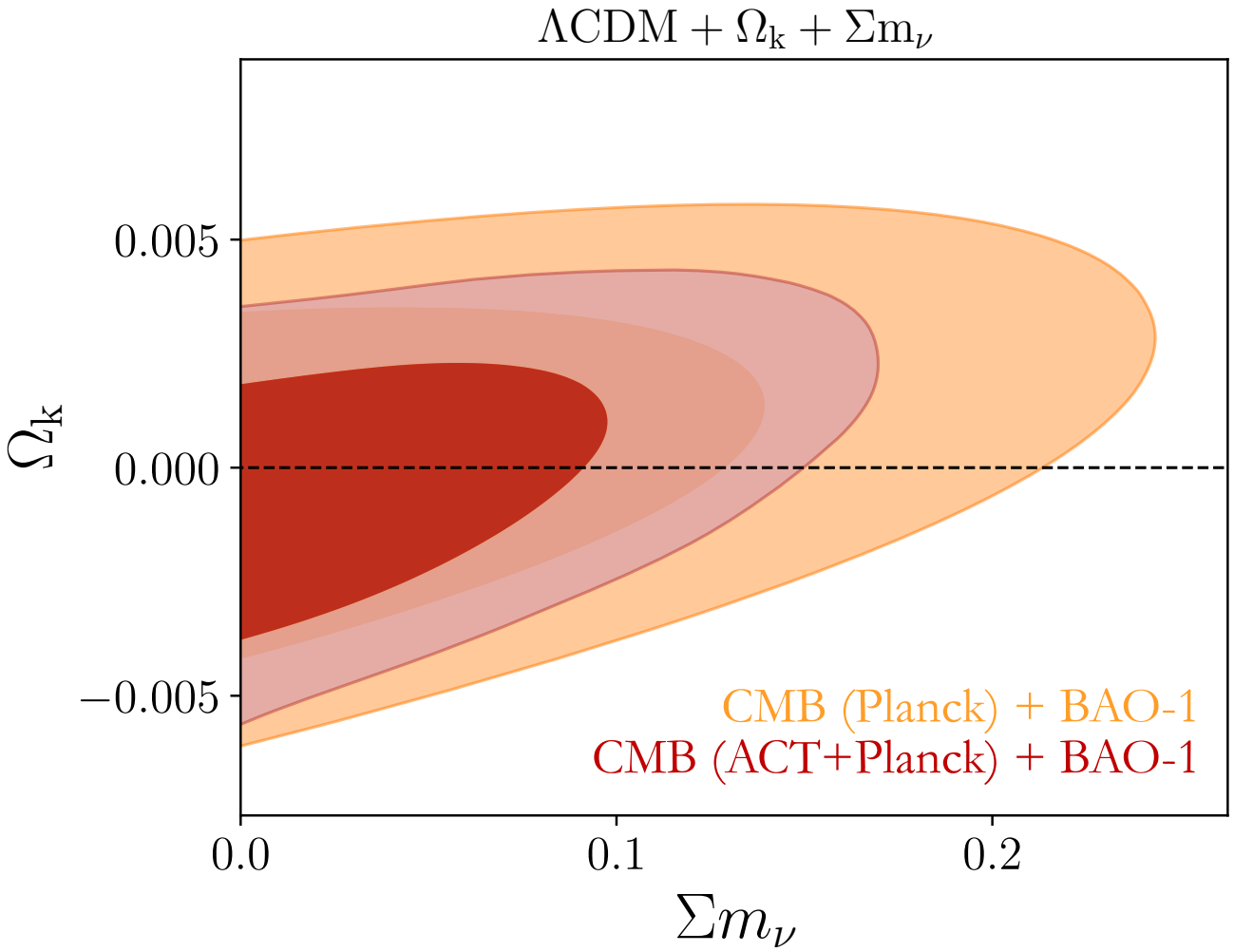
$$\rho_{\gamma+\nu} = \rho_\gamma \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]$$

$\Sigma m_\nu < 0.14$ eV

$\Sigma m_\nu < 0.13$ eV

$\Sigma m_\nu < 0.12$ eV

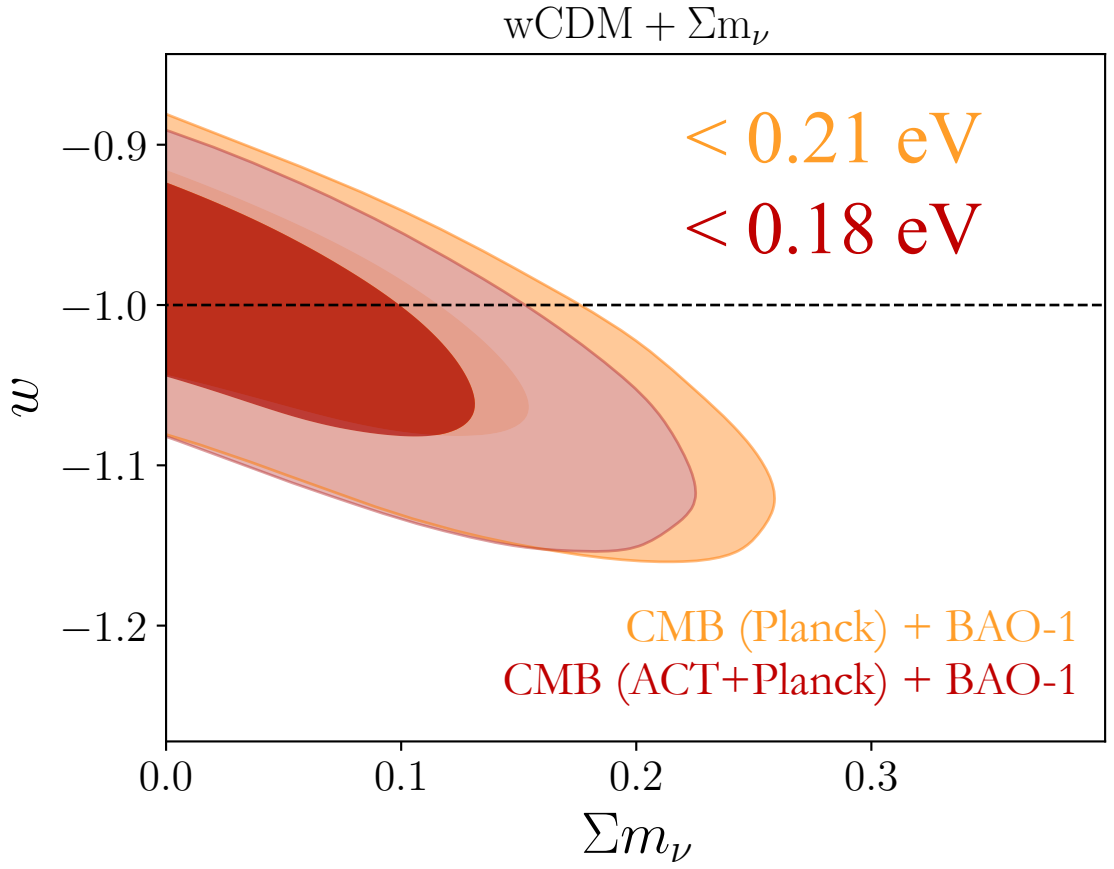
ΛCDM + Ω_k + Σm_ν



Dataset	$\sum m_\nu$ (95% c.l)
CMB (Planck) + BAO-1	< 0.17 eV
CMB (Planck) + BAO-1 + SNe	< 0.13 eV
CMB (ACT+Planck) + BAO-1	< 0.13 eV
CMB (ACT+Planck) + BAO-1+ SNe	< 0.14 eV
CMB (ACT+Planck) + BAO-2 + SNe	< 0.13 eV

wCDM + Σm_ν

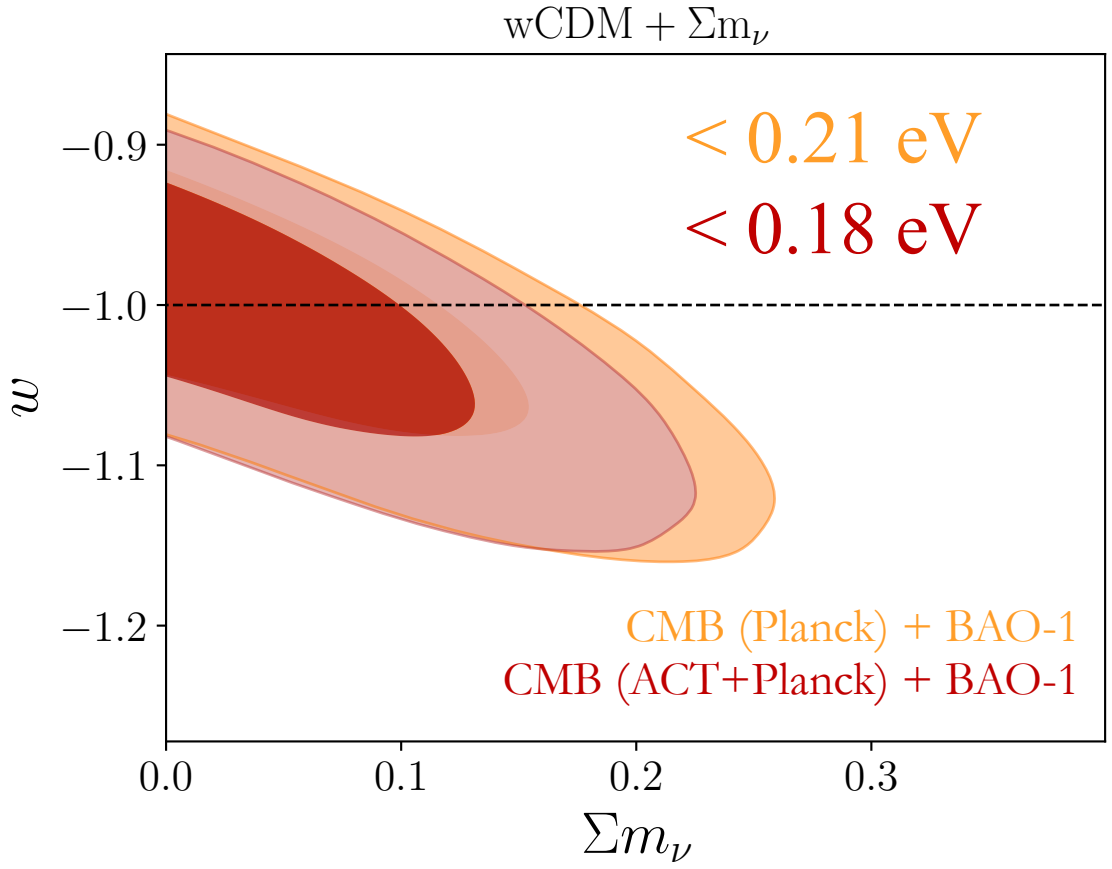
$$\rho_{\mathrm{DE}}(z) = \mathrm{w} * p(z)$$



ACT Lensing rejects larger Σm_ν values

wCDM + Σm_ν

$$\rho_{DE}(z) = w * p(z)$$



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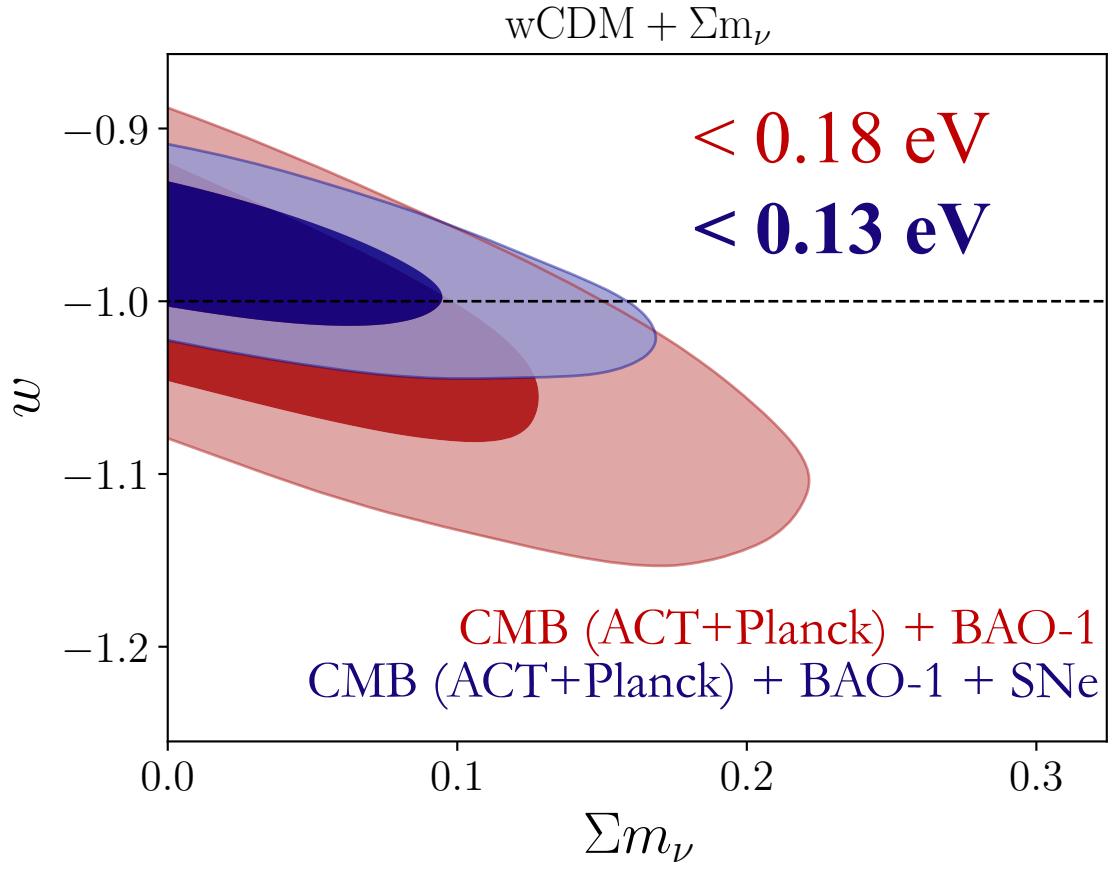
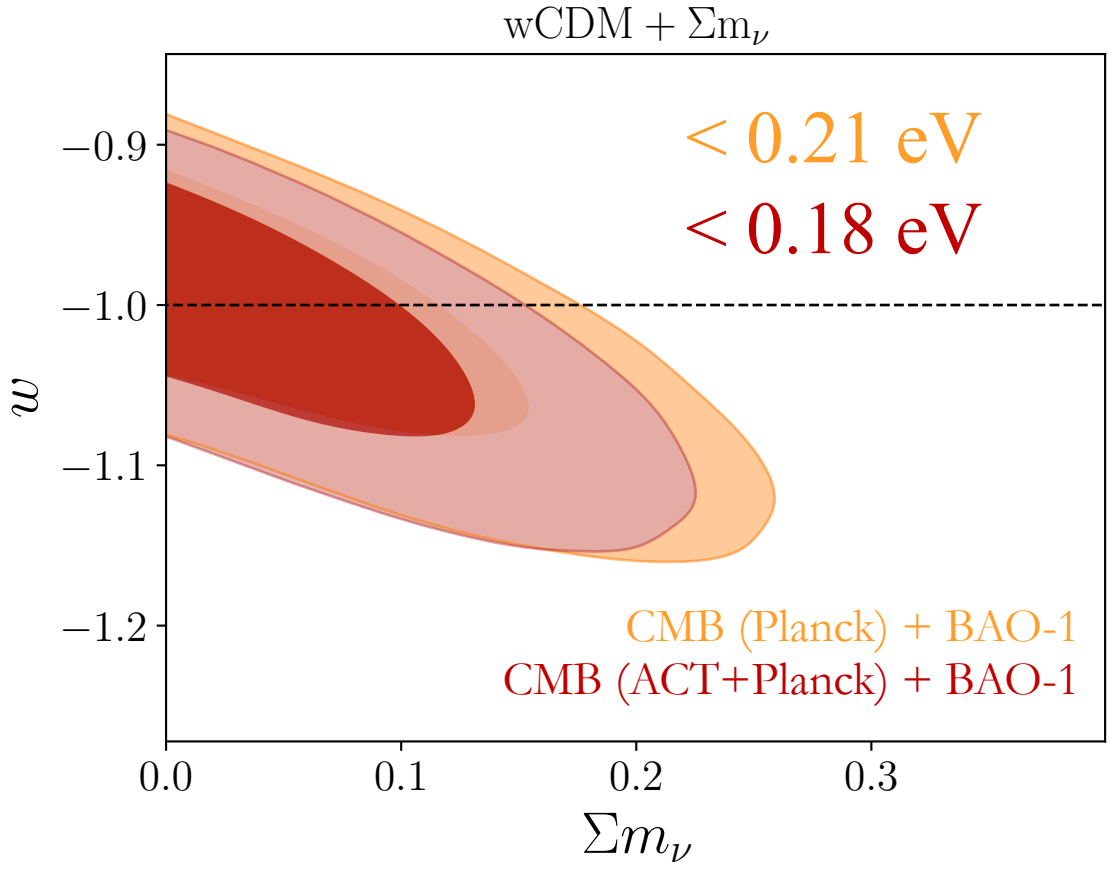


SNe data significantly reduces degeneracy

wCDM + Σm_ν

$$\rho_{DE}(z) = w * p(z)$$



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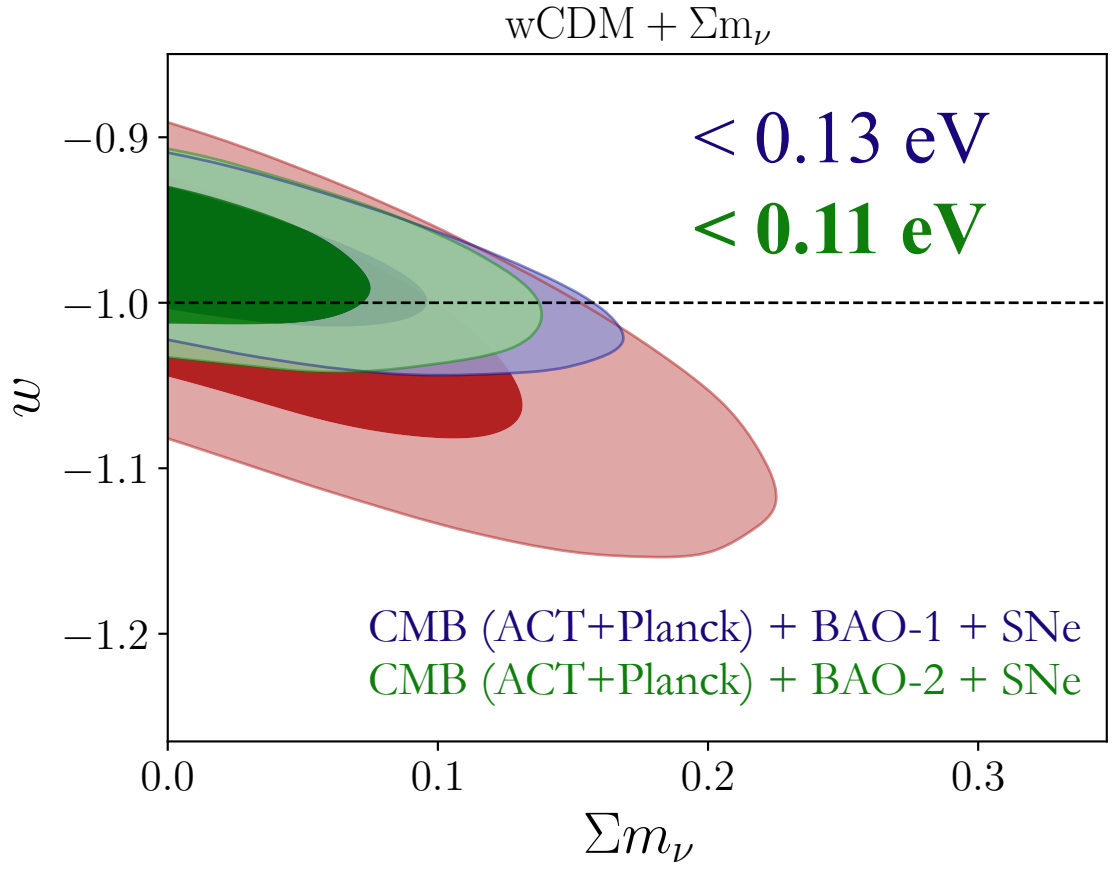
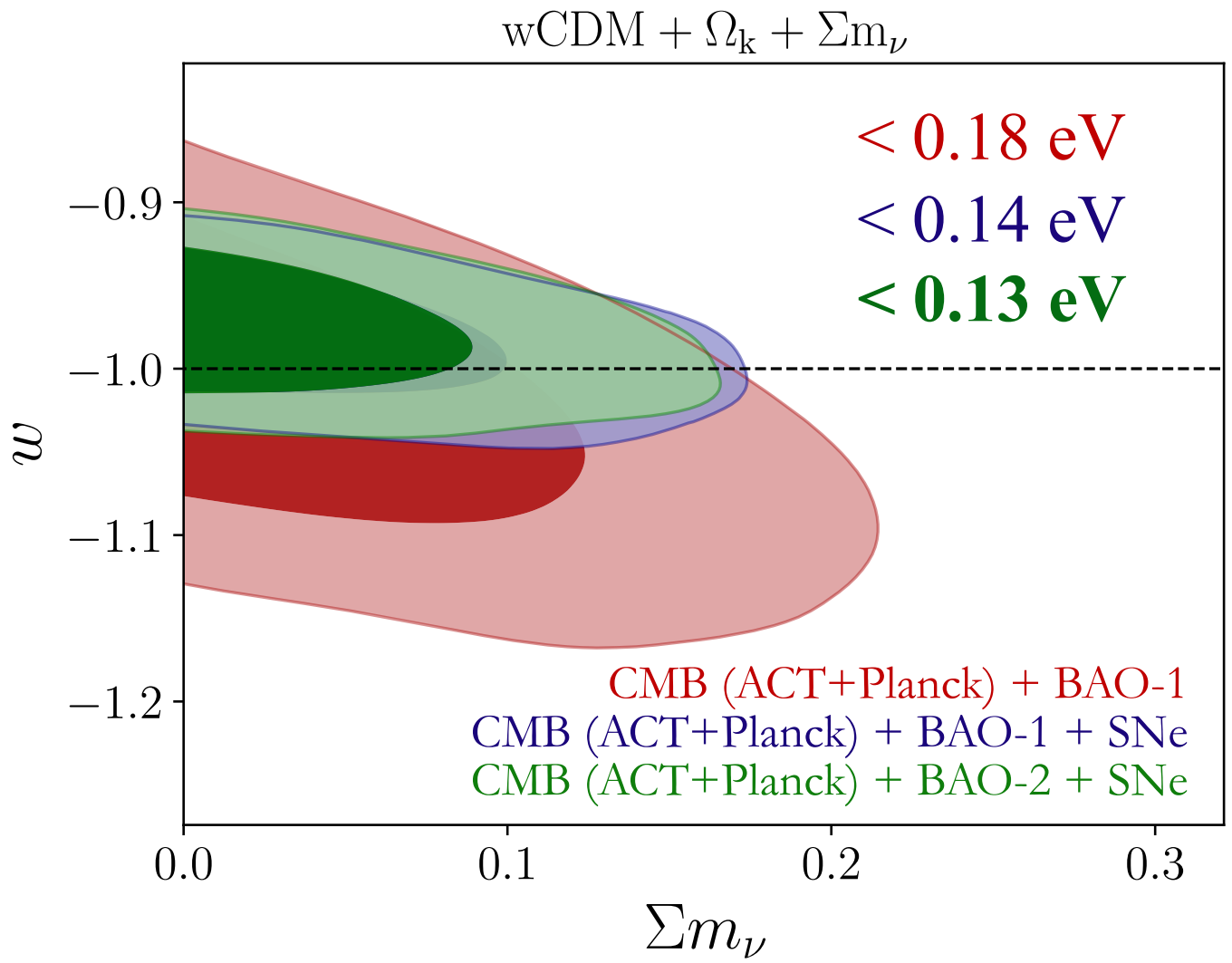


DESI data rejects larger Σm_ν

wCDM + Ω_k + Σm_ν

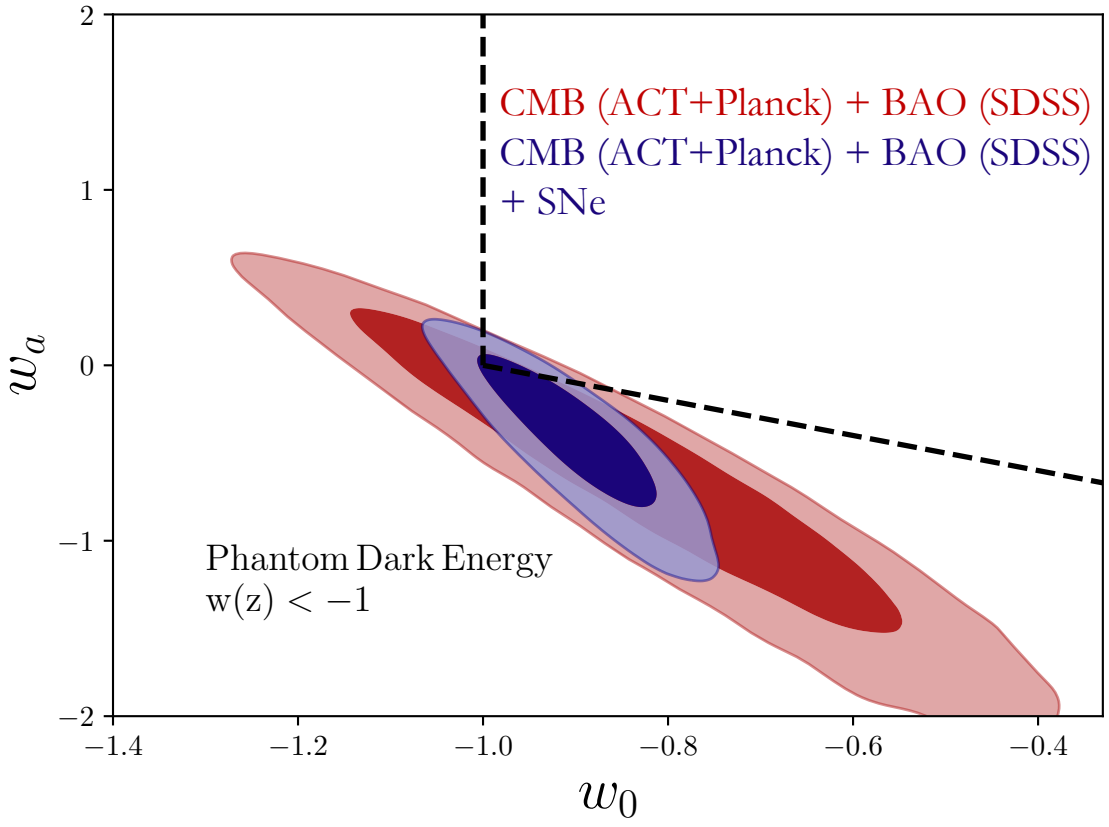


Adding curvature to previous model marginally weakens Σm_ν bounds

$w_0 w_a$CDM + Σm_ν

CPL Parameterization

$$w(z) = w_0 + w_a(1-a) = w_0 + w_a \frac{z}{1+z}$$



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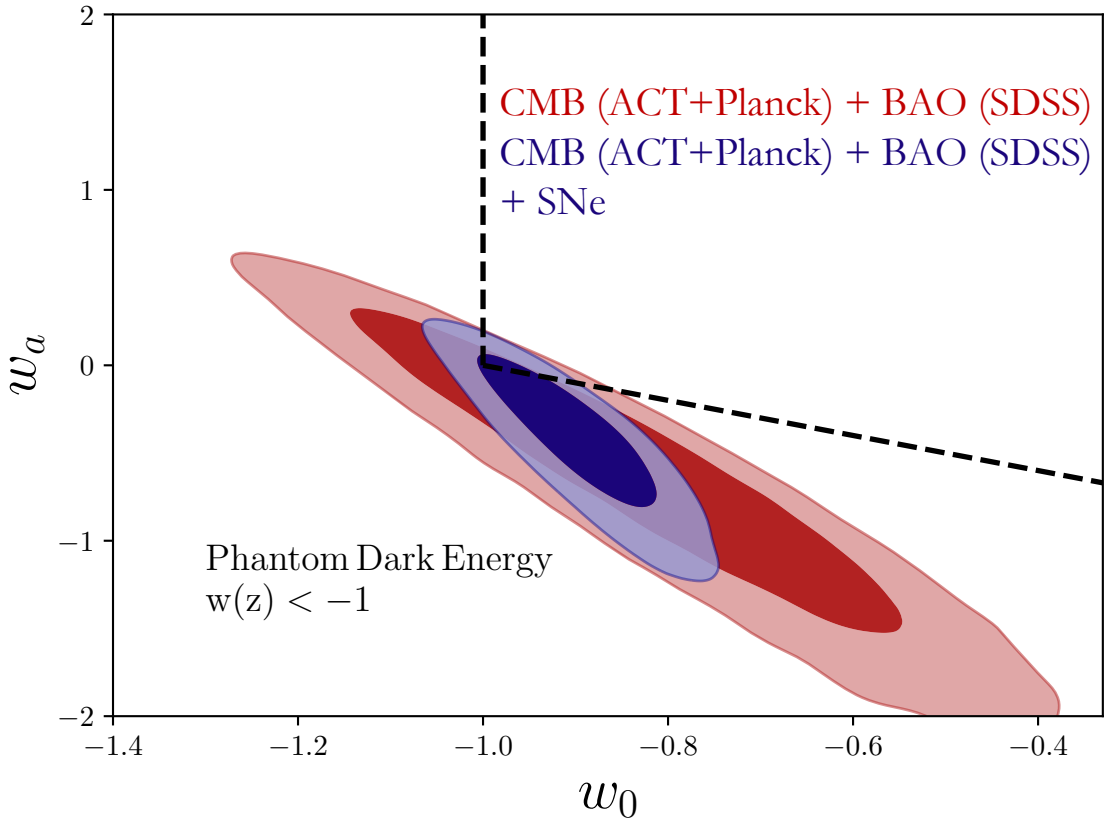

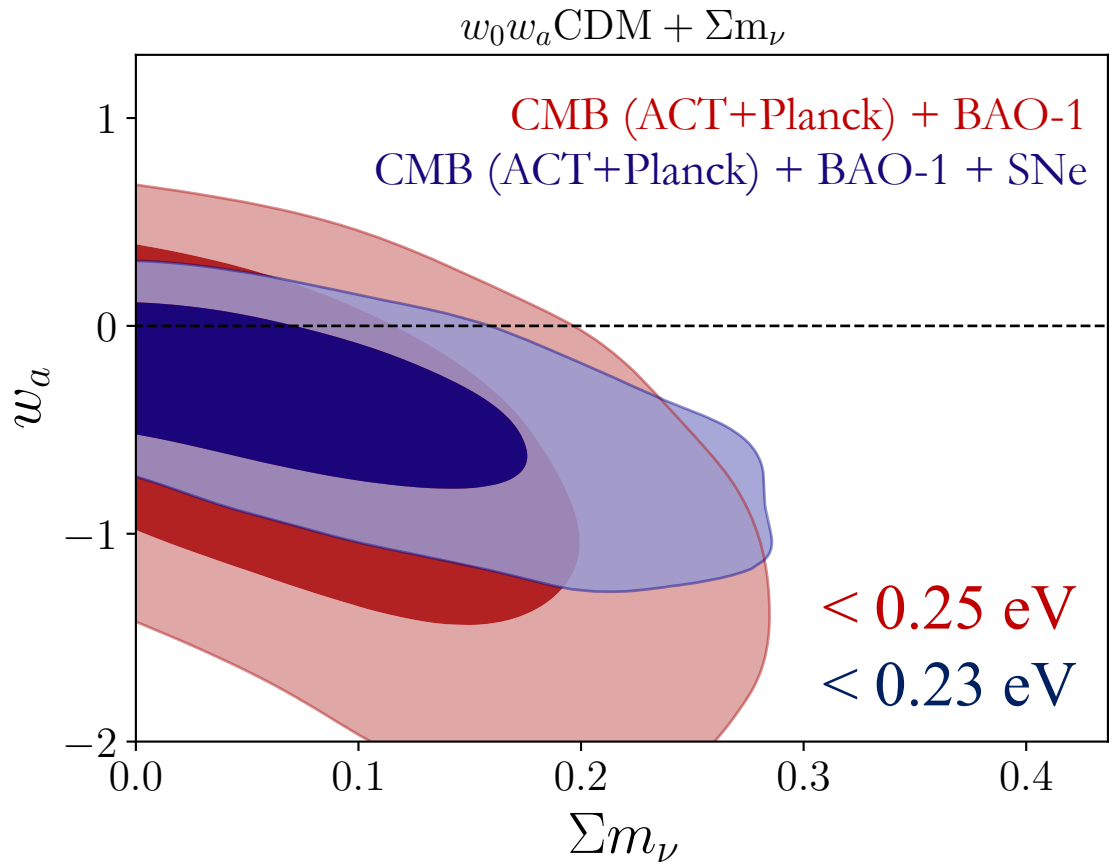

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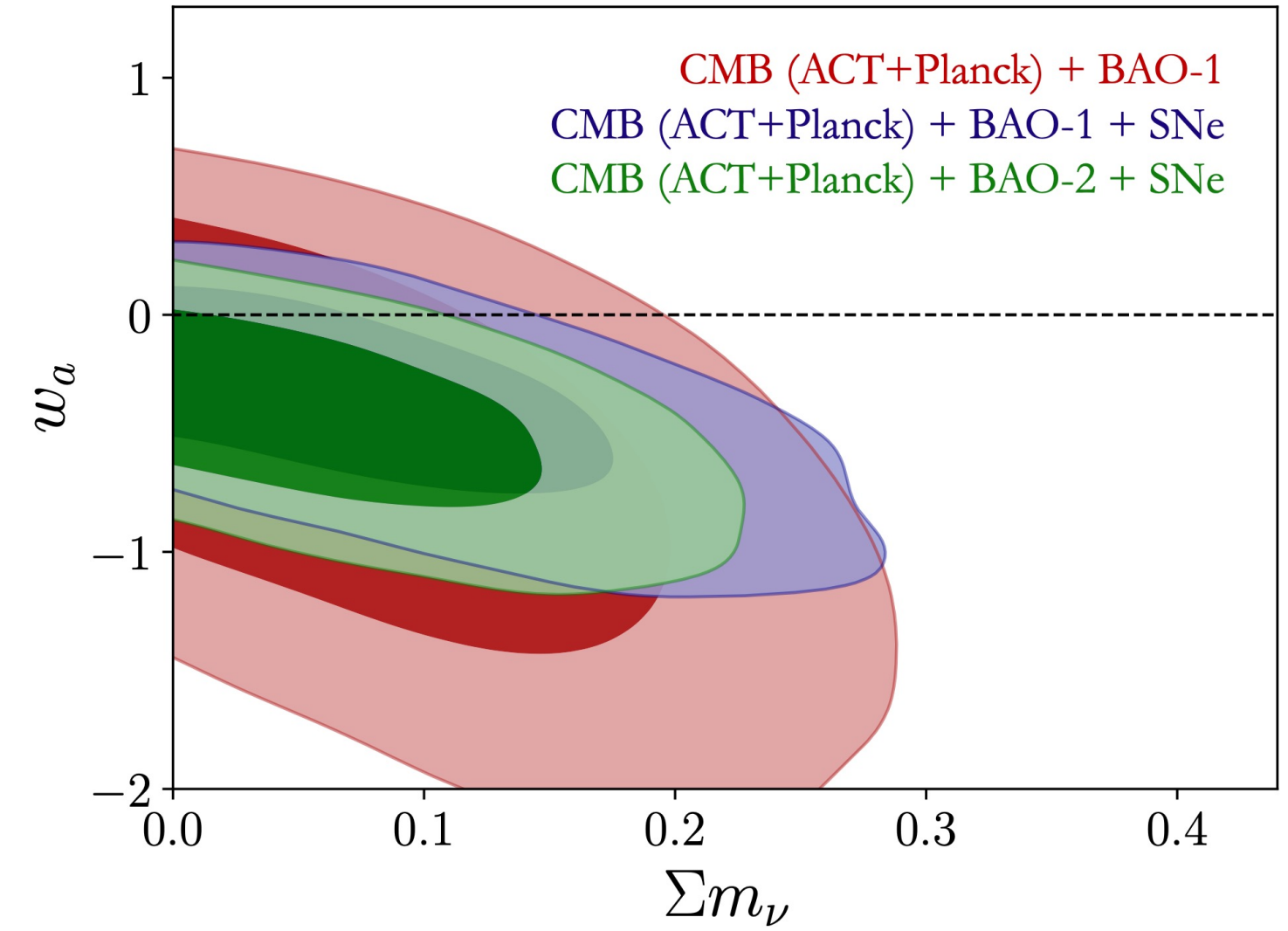
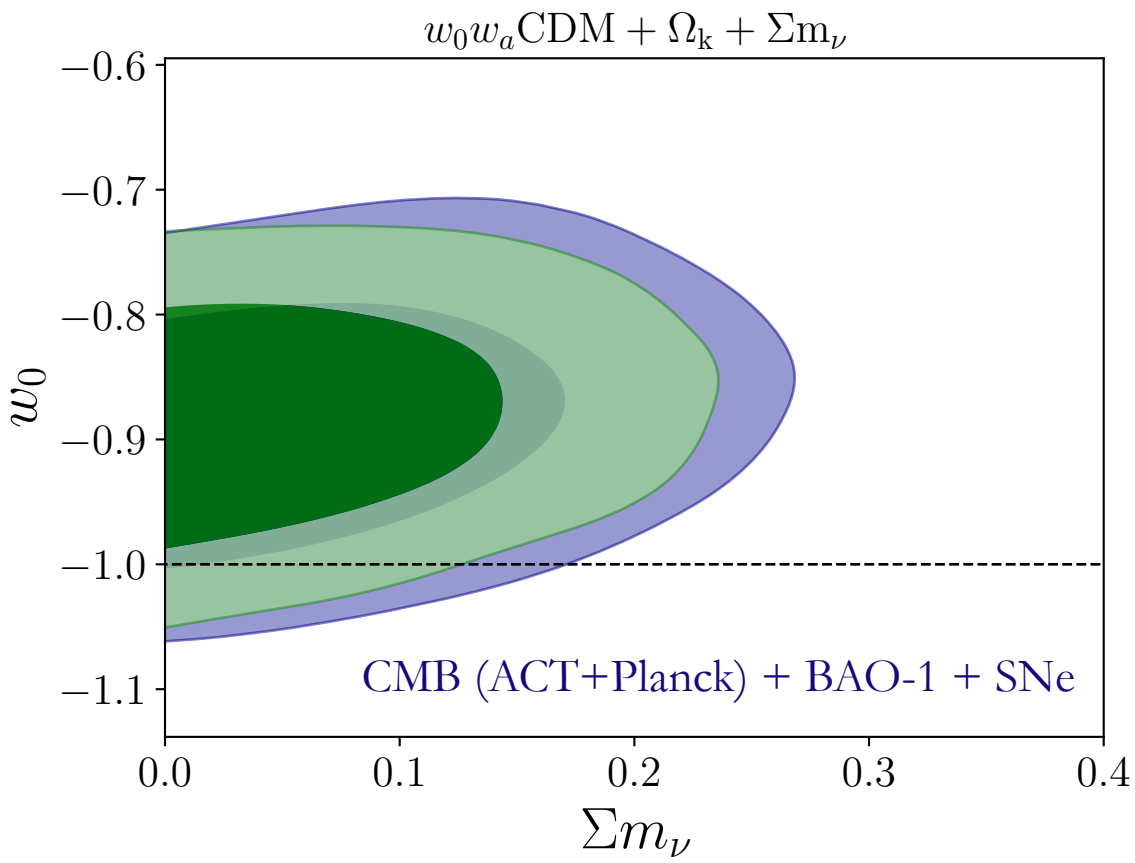
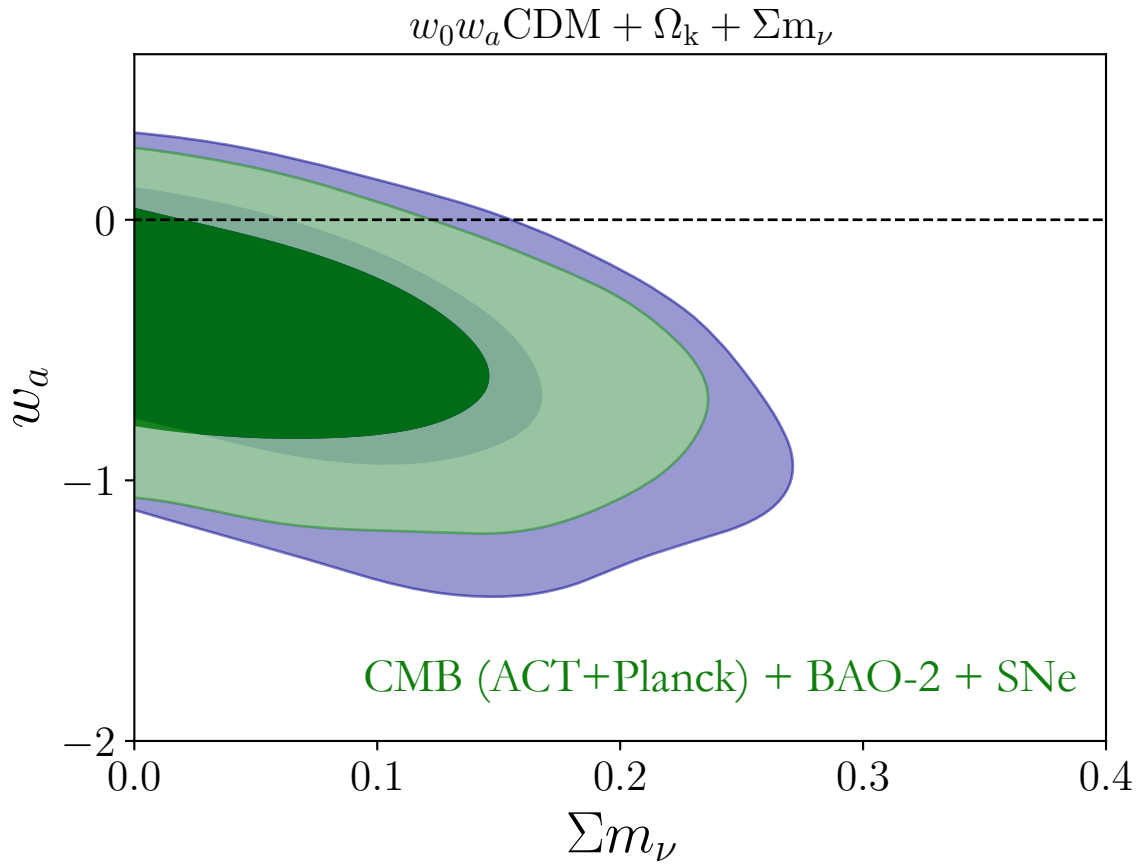


< 0.23 eV

< 0.19 eV

$w_0 w_a$CDM + Ω_k + Σm_ν





< 0.23 eV $\rightarrow$ < 0.19 eV

Conclusions

- Σm_ν bound remains robust to:
  - Dark energy (w)
  - Phantom DE
  - Time-dependent DE $w(z; w_0, w_a)$
  - Curvature

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  - Dark energy (w)
  - Phantom DE
  - Time-dependent DE $w(z; w_0, w_a)$
  - Curvature
- Degeneracies reduced with ACT & Pantheon+ (SNe)

Conclusions

- Σm_ν bound remains robust to:
  - Dark energy (w)
  - Phantom DE
  - Time-dependent DE $w(z; w_0, w_a)$
  - Curvature
- Degeneracies reduced with ACT & Pantheon+ (SNe)
- DESI+SDSS: Inverted hierarchy still viable in ΛCDM

Conclusions

- Σm_ν bound remains robust to:
  - Dark energy (w)
  - Phantom DE
  - Time-dependent DE $w(z; w_0, w_a)$
  - Curvature
- Degeneracies reduced with ACT & Pantheon+ (SNe)
- DESI+SDSS: Inverted hierarchy still viable in ΛCDM
- Future: DESI full-shape, Euclid, SO, LiteBIRD, …