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New standard ingredients in cosmological analyses?

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CosmoForward, IAC, Tenerife Feb 11, 2026

Context

- Inflation: reconstruct the properties of the initial conditions, and look for gravitational waves $f_{\rm NL}$ $n_s, \; r$

- Dark Energy and Gravity: the growth of structure depends sensitively on the expansion history of the Universe, and the nature of gravity $w_0, \; w_a, \; f \propto D'/D$

  Growth equation: $D'' + aH D' = 4\pi G \, \bar{\rho} \, D$

- Dark Matter/neutrinos: how "cold" is cold dark matter ? What is the sum of neutrino masses ? $\sum m_\nu$

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  How should we do inference in this space?
  What to vary, what to keep fixed?

  Growth equation: $D'' + aH\,D' = 4\pi\,G\,\bar\rho\,D$

- Dark Matter/neutrinos: how “cold” is cold dark matter ? What is the sum of neutrino masses ? $\sum m_\nu$

The standard model of cosmology

- (Euclidean) νΛCDM

$$\omega_{\rm c},\ \omega_{\rm b},\ M_\nu,\ h,\ A_s,\ n_s,\ (\Omega_\Lambda)$$

  - not counting astrophysics parameters

- **Assumptions/issues:**
  - Assume *simple inflation* prior (Euclidean; scale-invariant $P_R(k)$; purely adiabatic perturbations)
  - We don't really know what we are parametrizing with ω_c
  - Assume cosmological constant
  - Assume specific neutrino mass ordering

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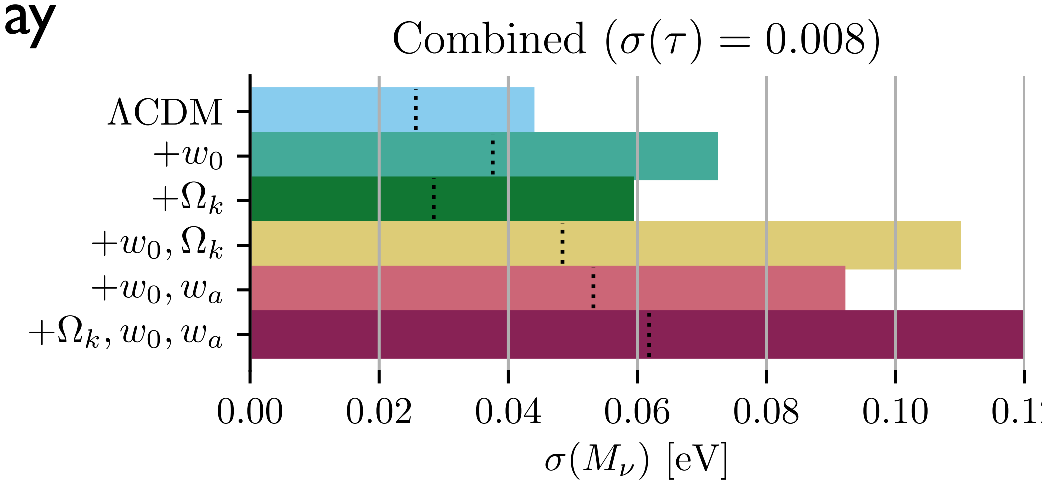
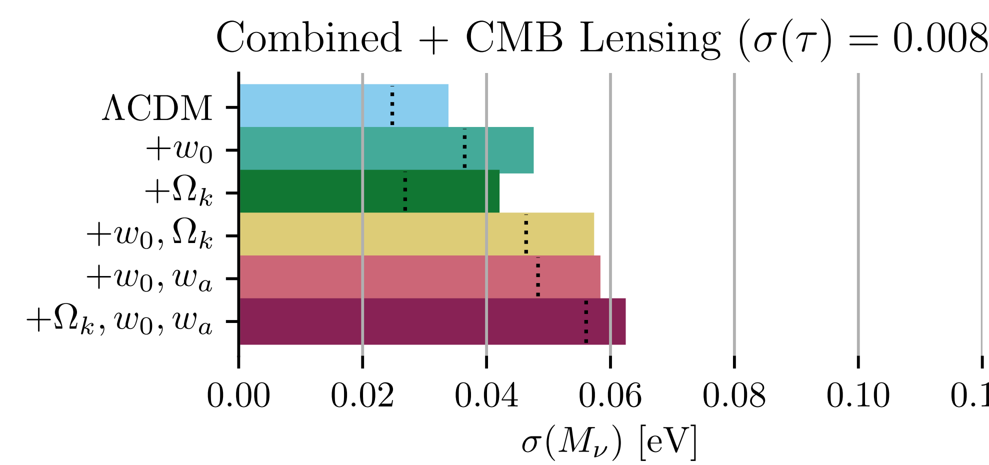
Neutrino masses

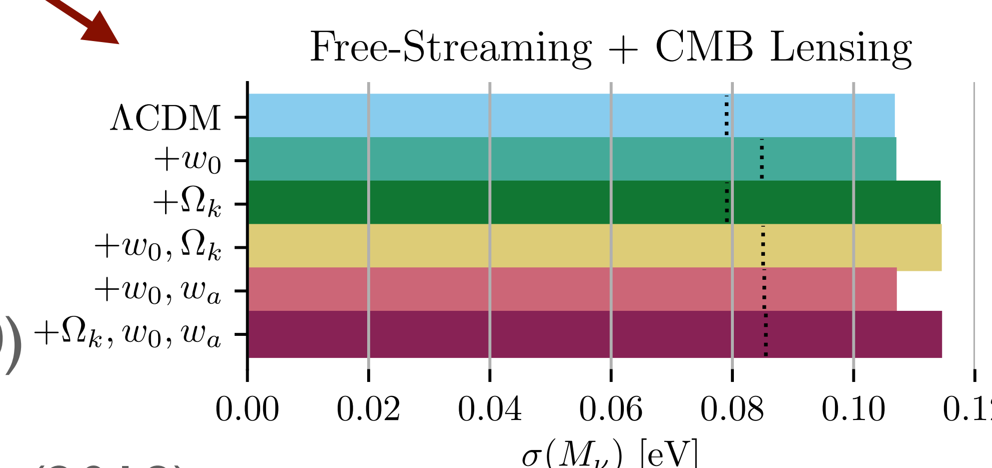
Forecast

Cf. discussion on Monday

- Part of the standard model — but current M_ν constraints sensitive to model extensions
- Model-independent constraints possible using scale-dependent suppression, but these are much weaker and will remain so for some time







Boyle & FS (2020)
Boyle (2018)
Boyle & Komatsu (2018)

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- Part of the standard model — but current M_ν constraints sensitive to model extensions
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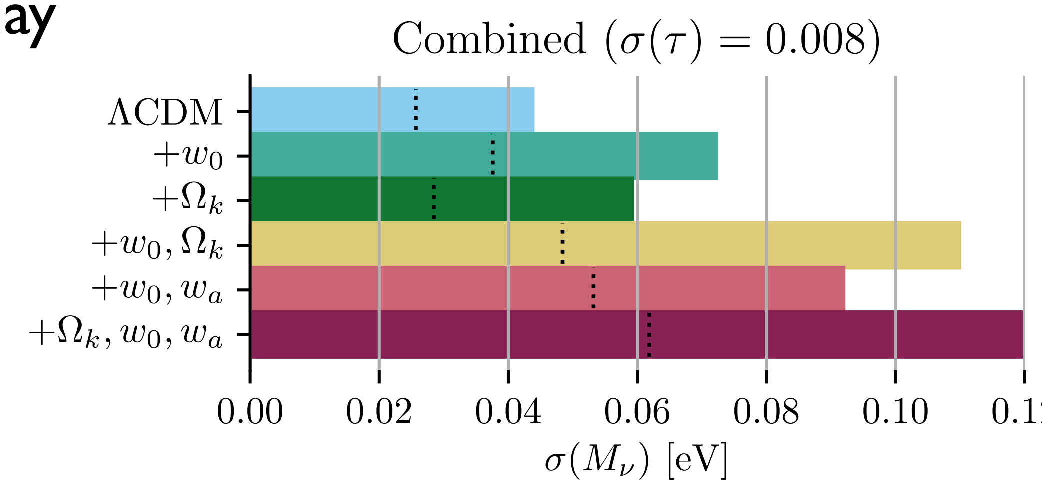
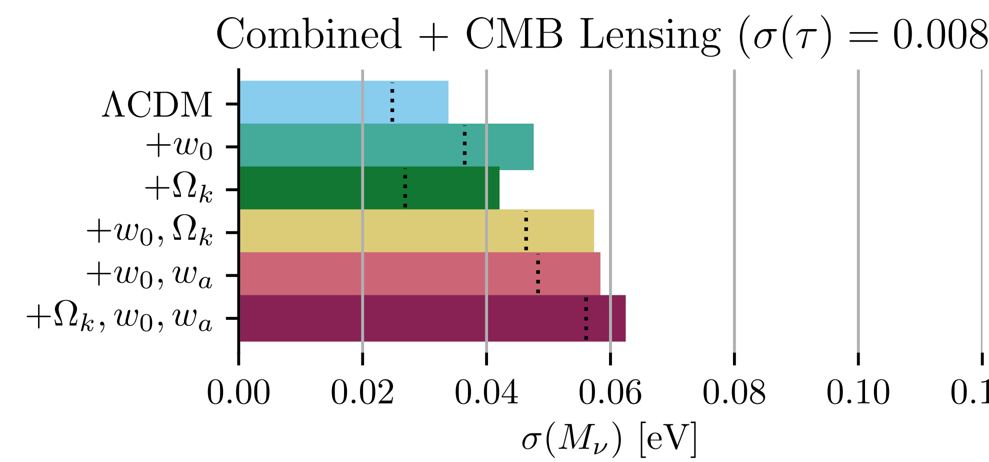
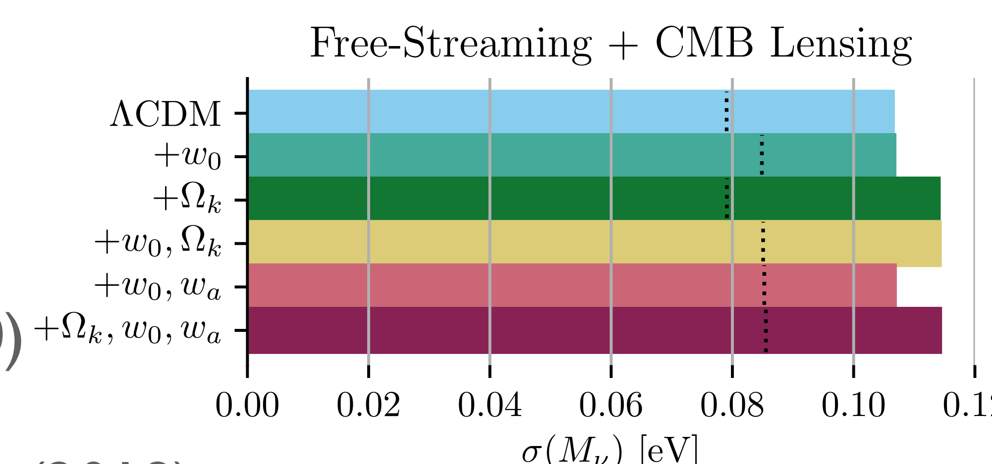
- Sources of constraint depend strongly on details of dataset combination — lots of possibilities for confusion; clear and careful phrasing essential
  - Also prior dependence…







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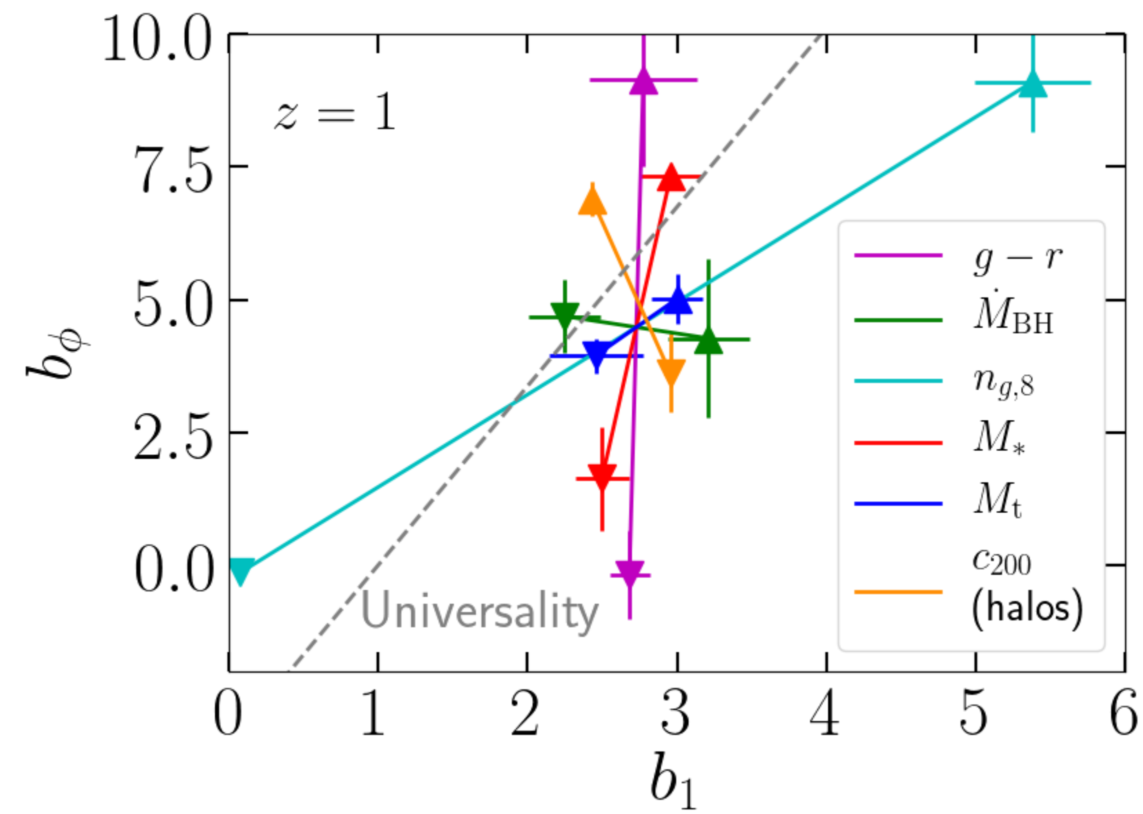
Inflation: CMB

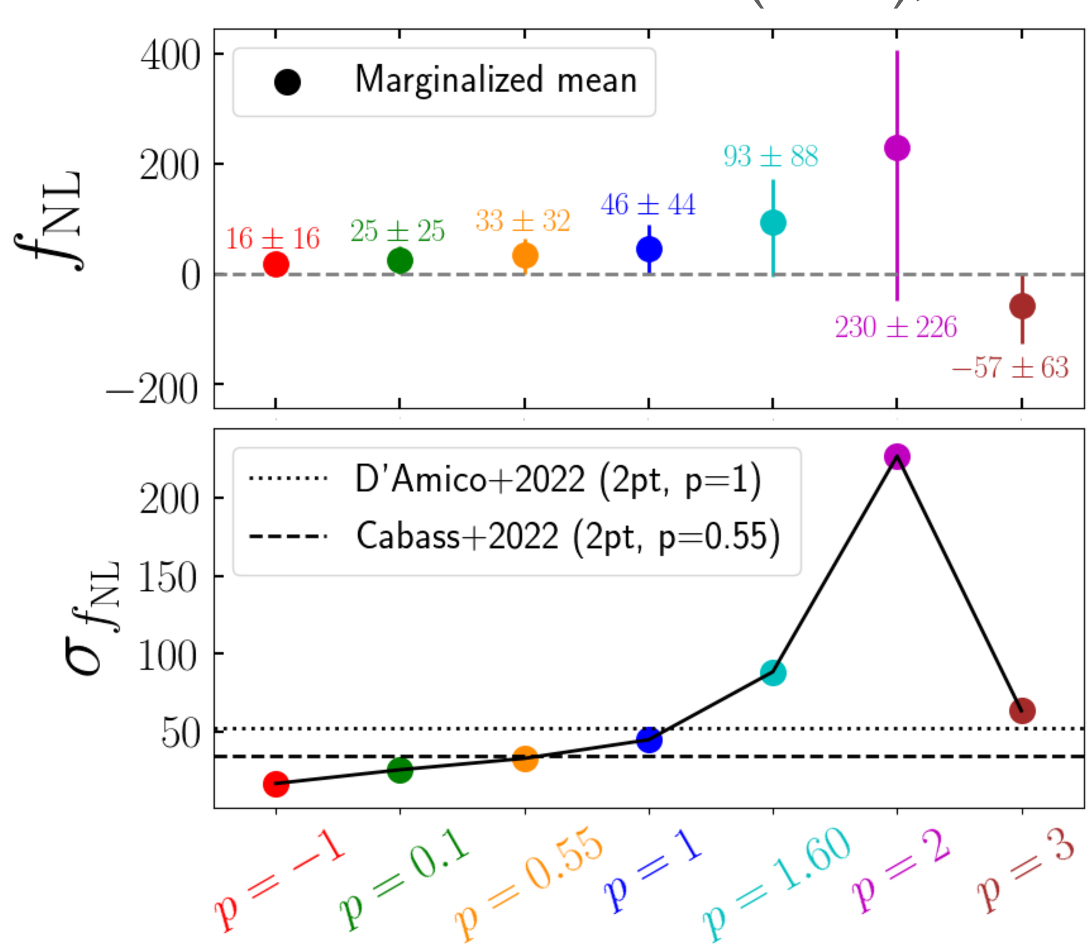
- We need to assume some form of prior in model space
- Luckily, inflation scenarios *largely* divide into two classes *(Braglia)*:
  - Single dominant d.o.f.: r potentially detectable; $f_{NL}^{loc}=0$
  - > 1 light d.o.f. which mix: $r \sim 0$; f_{NL}^{loc} detectable
- Fine to ignore f_{NL} in n_s-r constraints
- CMB: template correlations in PNG searches need to be considered
  - cf. f_{NL}^{ortho} in EFT of single-field inflation
  - quasi-single-field / collider signatures

Inflation: LSS

- Current f_{NL}^{loc} constraints from LSS (scale-dependent bias) fix ΛCDM parameters and b_ϕ , where the data constrain only $b_\phi * f_{NL}^{loc}$
  - This really is no longer ok…
- Of these, b_ϕ is the more difficult problem; we need informative priors to obtain constraints on f_{NL}^{loc}
  - Issue also in kSZ, measuring momentum of ionized gas (biased)
  - More work needed!



Barreira, Krause (2023)
Barreira (2022), …

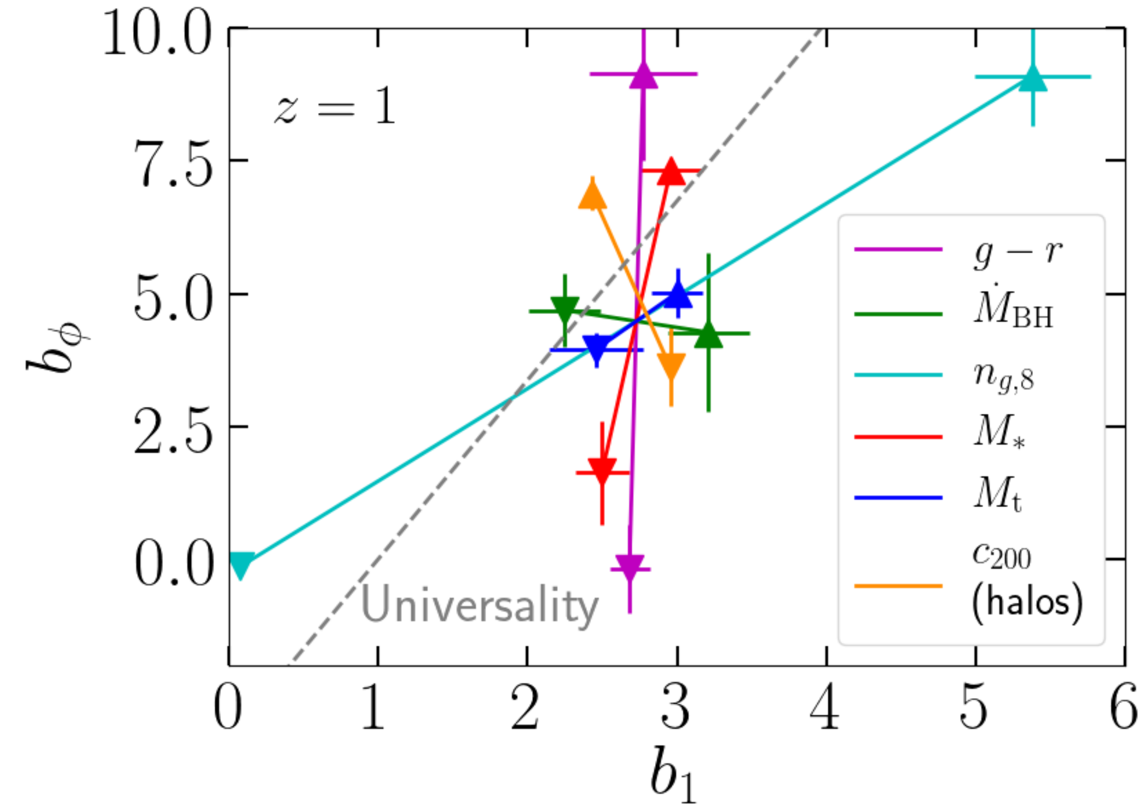


Inflation: LSS

- Moreover, f_{NL}^{loc} signature *exactly degenerate* with g_{NL}^{loc} and compensated isocurvature modes

  Desjacques, Ferraro, LoVerde, Smith, …
  Barreira, Cabass, FS, …

- Both expected in general for multifield inflation



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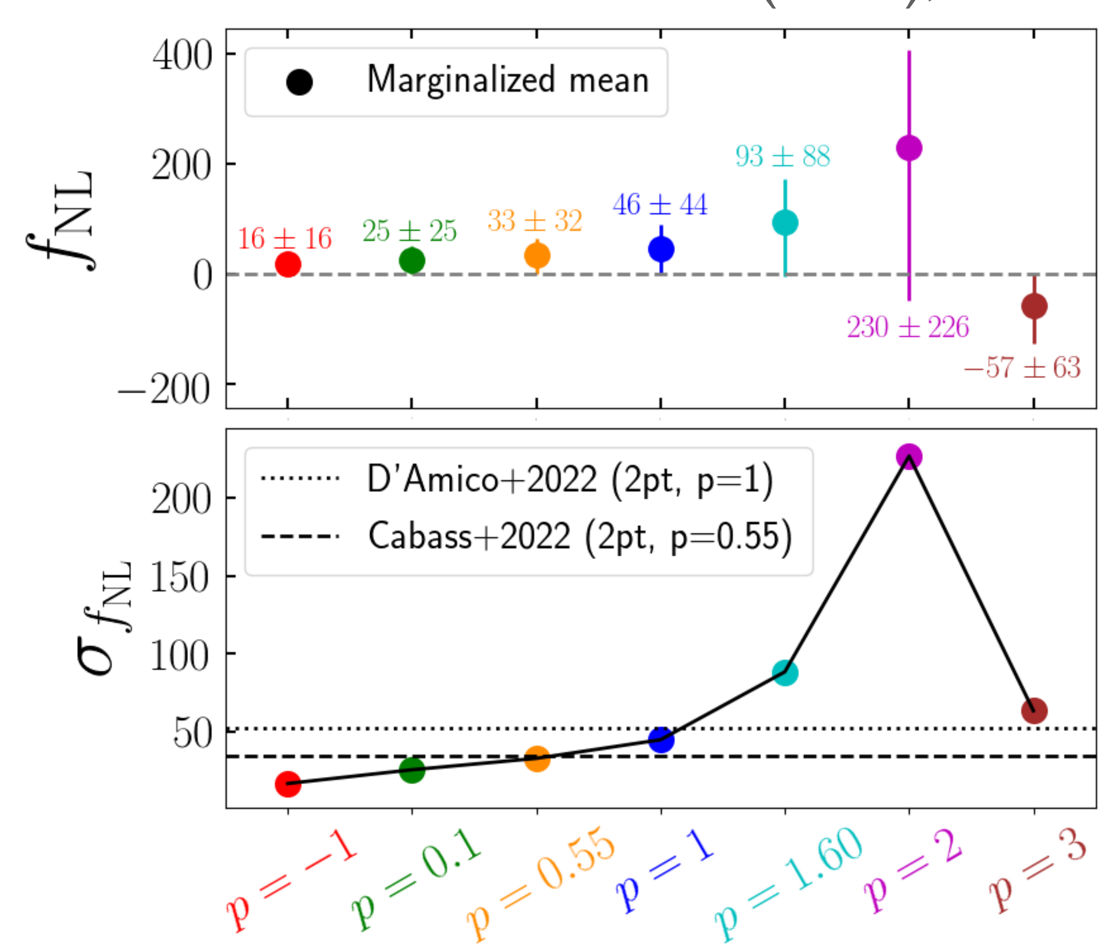
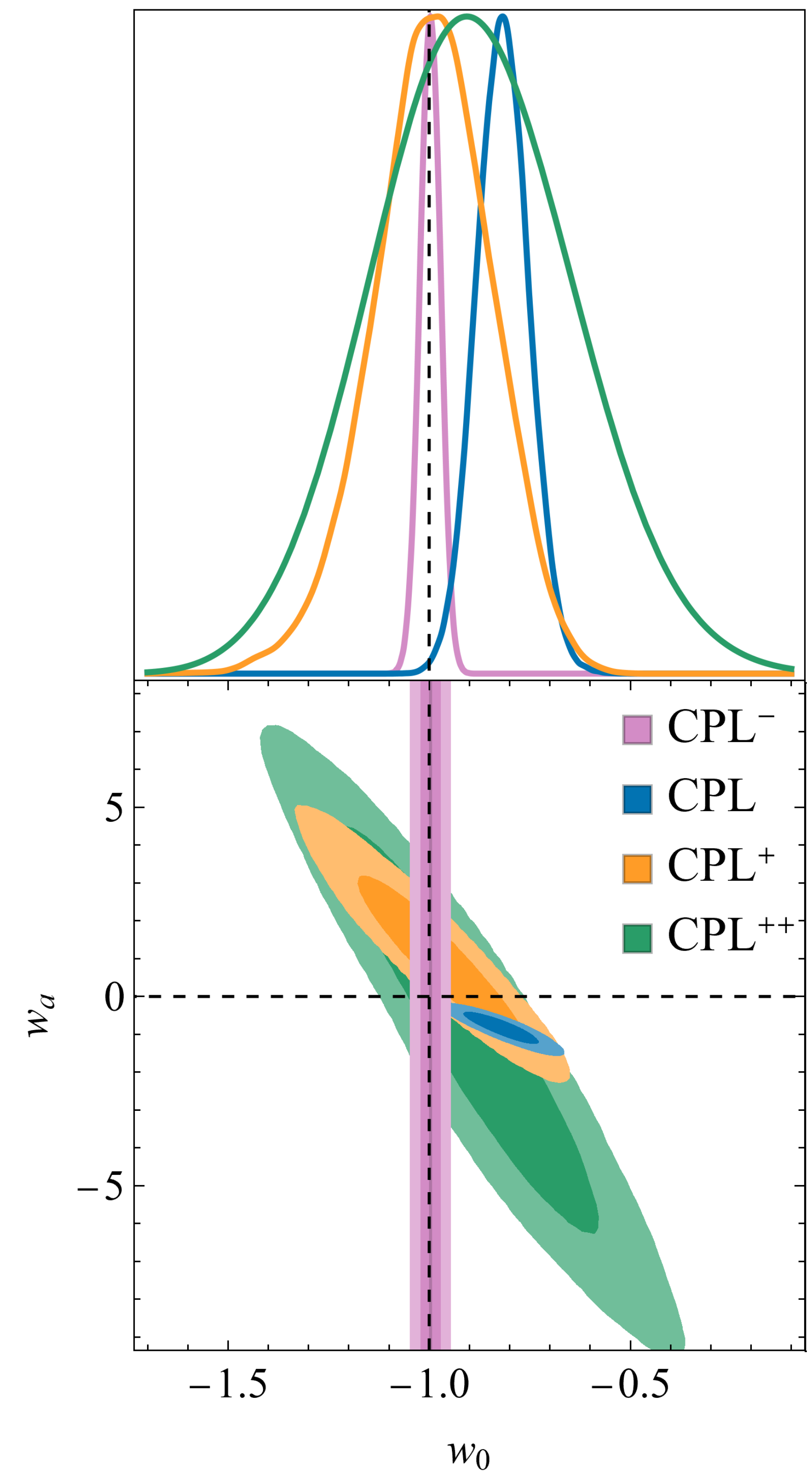


Dark Energy

- How to parametrize dark energy beyond Λ?
  - Consider concrete models
  - Parametrize equation of state
- Both have issues:
  - Simple quintessence models possibly too restrictive —> *Baker*; see below
  - Parametrization like w_0, w_a can only be trusted over limited redshift interval

On w_0-w_a

- Parametrization like w_0, w_a can only be trusted over limited redshift interval
- Best constraints on DE from $d_A(z)$
  - $w_0 \sim d_A''$; $w_a \sim d_A'''$ (!)
  - If $w_a \sim 1$, expect $w_{aa} \sim 1$ as well, but almost all analyses fix it to 0…



$$w_{\mathrm{DE}}(a) = w_0 + w_a(1-a) + w_b(1-a)^2 + w_c(1-a)^3$$

Nesseris, Akrami, Starkman (2025)

FS (2017)

Dark Energy *can* cross phantom divide

- If observations indicate w goes below -1, have we ruled out "ordinary" dark energy?
  - Canonical scalar field: yes

$$X \equiv -\frac{1}{2}(\partial_\mu \phi)^2$$

$$p(\phi) = X + V(\phi) \quad \Rightarrow \quad w = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}/2 + V(\phi)}$$

- Not true in general: could have equation of state that *varies around* w=-1

- *Monodromic k-essence:*

$$p(\phi, X) = \tilde{V}(\phi)\left[-X/M^4 + (X/M^4)^2\right]$$

$$\tilde{V}(\phi) = C\left(\frac{\phi}{\phi_0}\right)^{-\alpha}\left[1 - A\sin(\nu H_0 \phi + \delta)\right].$$

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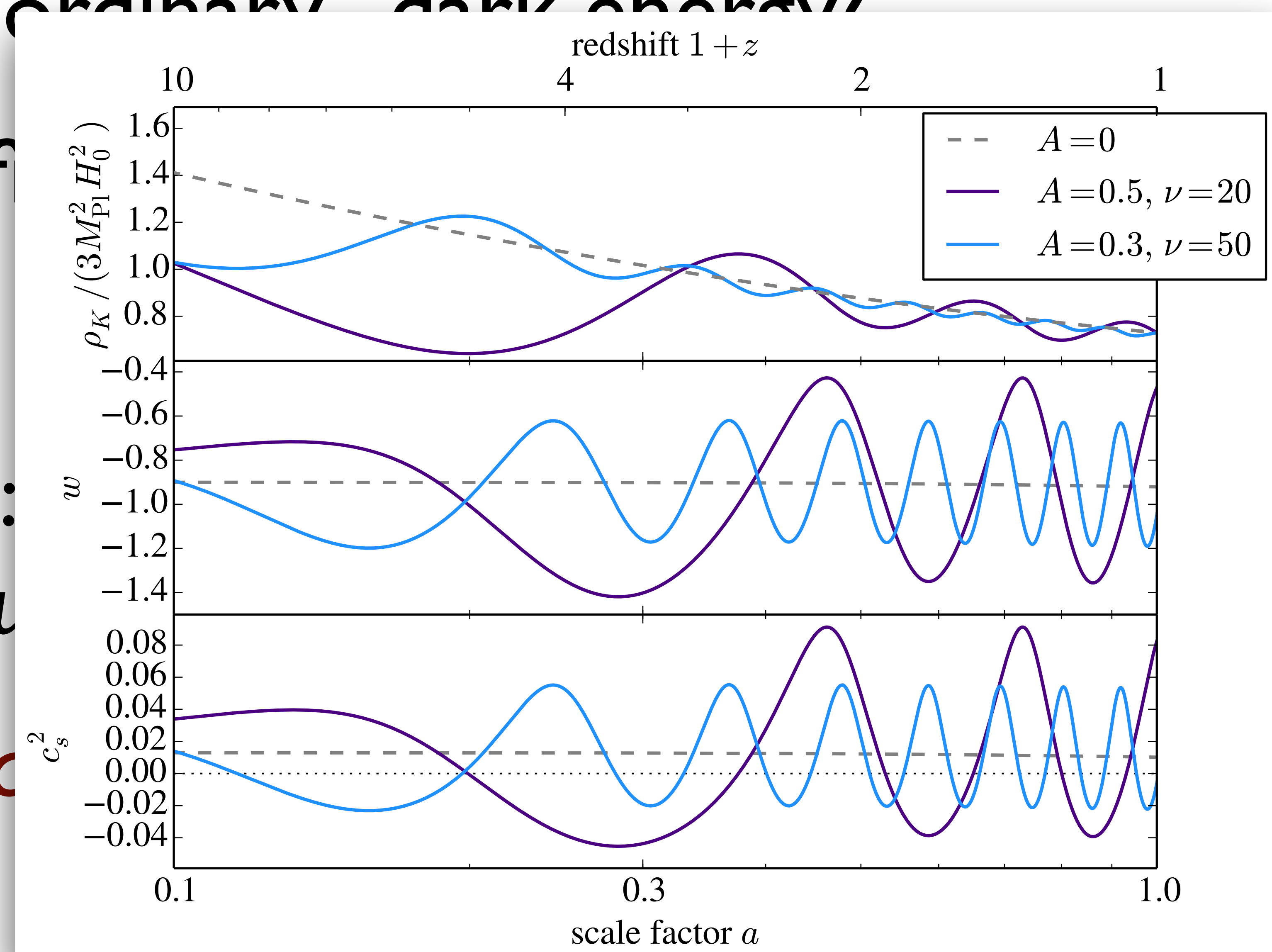

Dark Energy *can* cross phantom divide

- Fine at the background level, but DE perturbations suffer tachyonic instabilities if $c_s^2 < 0$
- k-essence case naturally has $c_s^2 \ll 1$; in fact, $c_s^2 \sim (1+w)$ in $1+w \to 0$ limit, leading to tachyonic instabilities as $1+w < 0$
- These can be dealt with consistently if
  - Higher-derivative contributions are present:

$$\ddot{\delta\phi} \sim -c_s^2 k^2 \delta\phi + \frac{k^4}{\bar{M}^2}\delta\phi + \ldots$$

e.g., from

$$\Delta\mathcal{L}_{\mathrm{DE,h.deriv.}} = -\frac{\bar{M}^2}{2}\left[\Box\phi + 3H(\phi)\right]^2$$

  - c_s^2 stays infinitesimally below 0
- Lowers cutoff of the theory, but not ruled out.

Creminelli, D'Amico, Noreña, Vernizzi (2009)

Dark Energy *can* cross phantom divide

- An example viable model (due to Marco Celoria):

$$
\begin{aligned}
p(\phi, X) &= \frac{\bar{M}^4}{2}(2X-1)^2 - F(\phi) + G(\phi)(2X+1) \\
F(\phi) &= V_0\left[1 - \tilde{A}\sin(\tilde{\nu}H_0\phi)\right] \\
G(\phi) &= V_0\tilde{A}\tilde{\nu}H_0\cos(\tilde{\nu}H_0\phi).
\end{aligned}
$$

- Oscillations with amplitude Δw ~ 0.1 around w = -1 easily possible while satisfying constraints on instabilities and having cutoff > eV scale.

Goldstein, Celoria, FS (2025)

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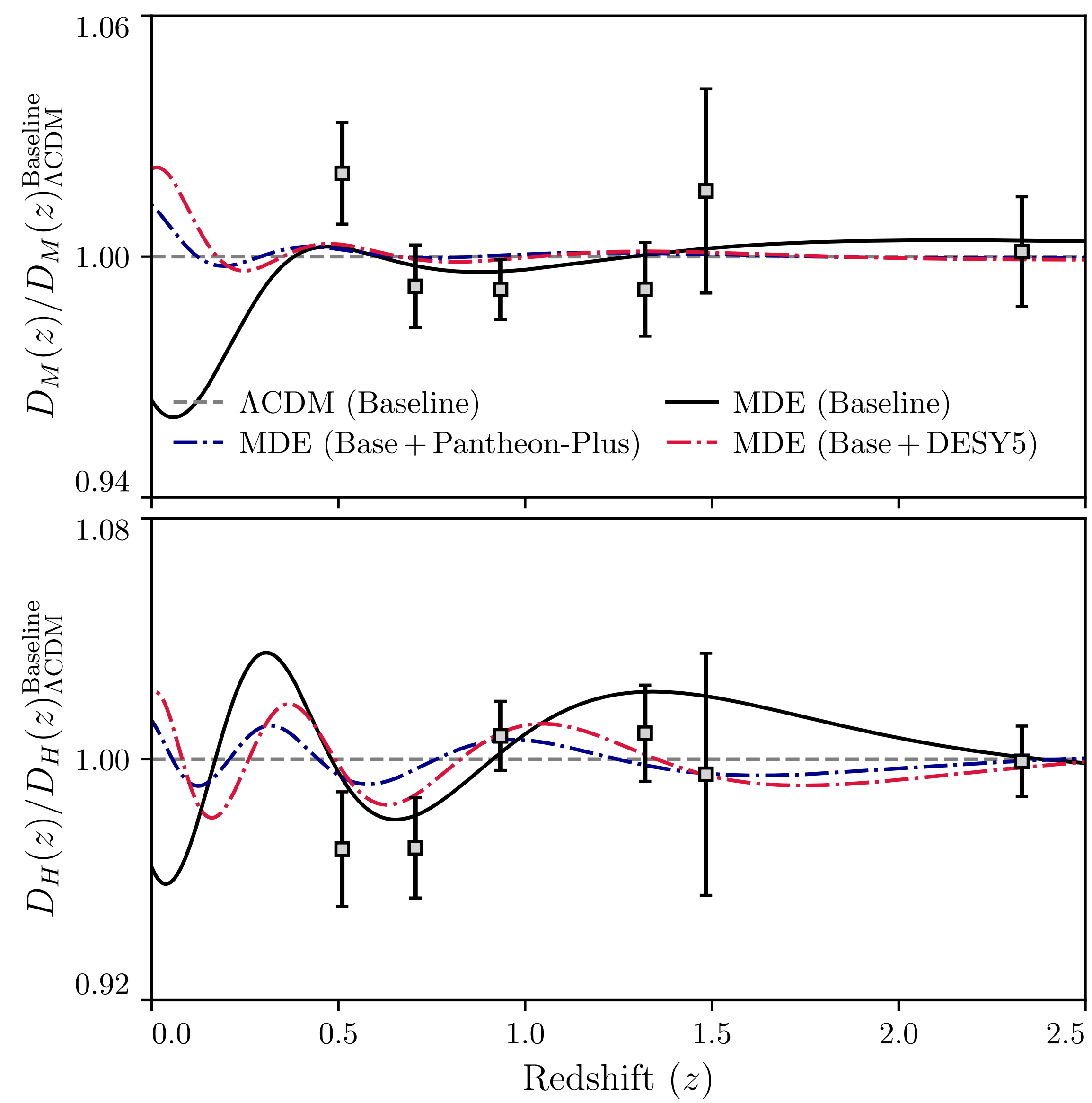
Monodromic k-essence and DESI

- 3 free parameters (FS 2017 model) in addition to Ω_{de}, potential tilt α <=> mean w:
  - amplitude, frequency, phase of oscillations
- Exclude all observables sensitive to perturbations here



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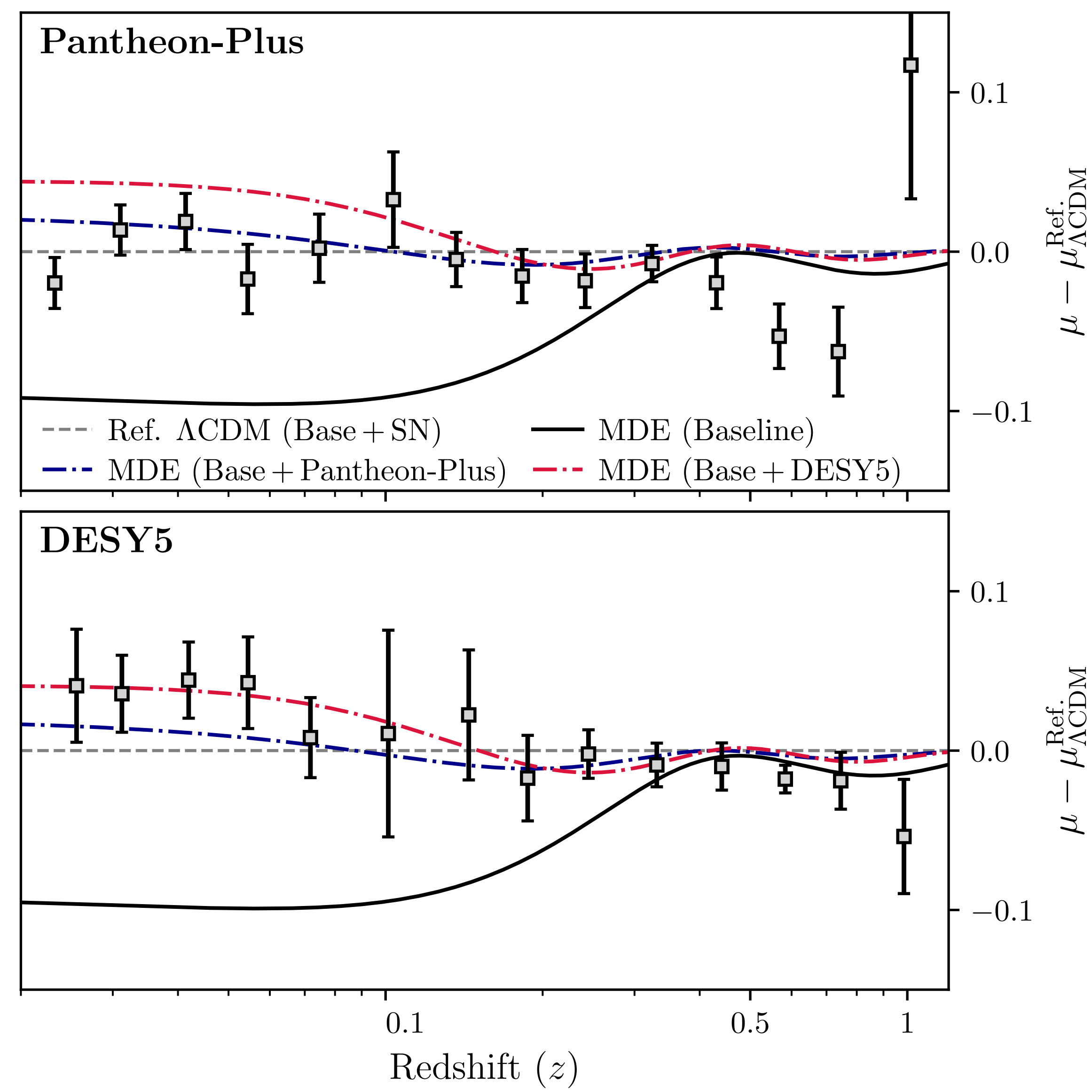

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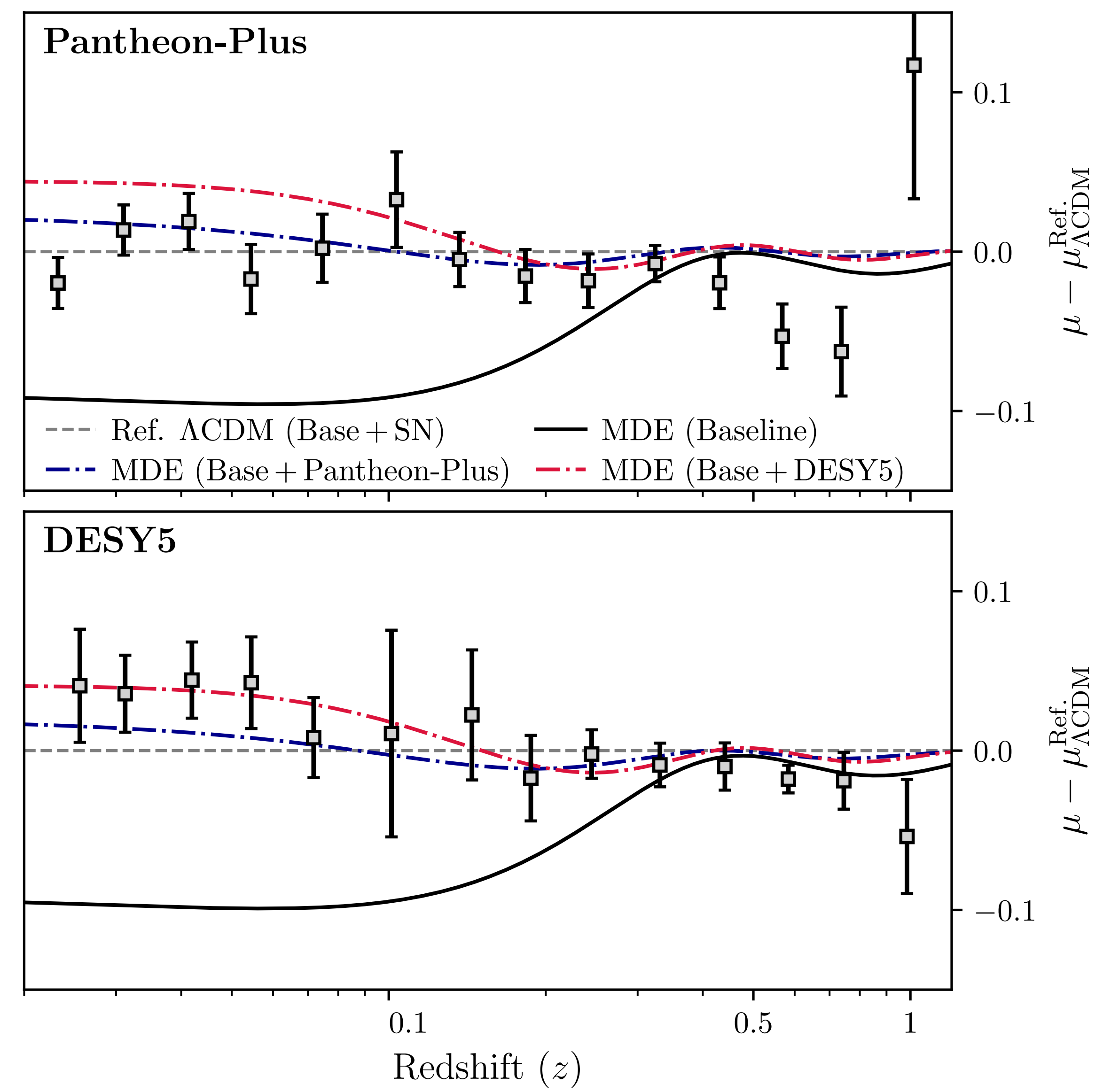
- Exclude all observables sensitive to perturbations here
- Similar fit quality to DESI BAO + SN as w_0, w_a
- Mean w consistent with -1 (motivated by theory as well); then, only 1 more free parameter than w_0, w_a !



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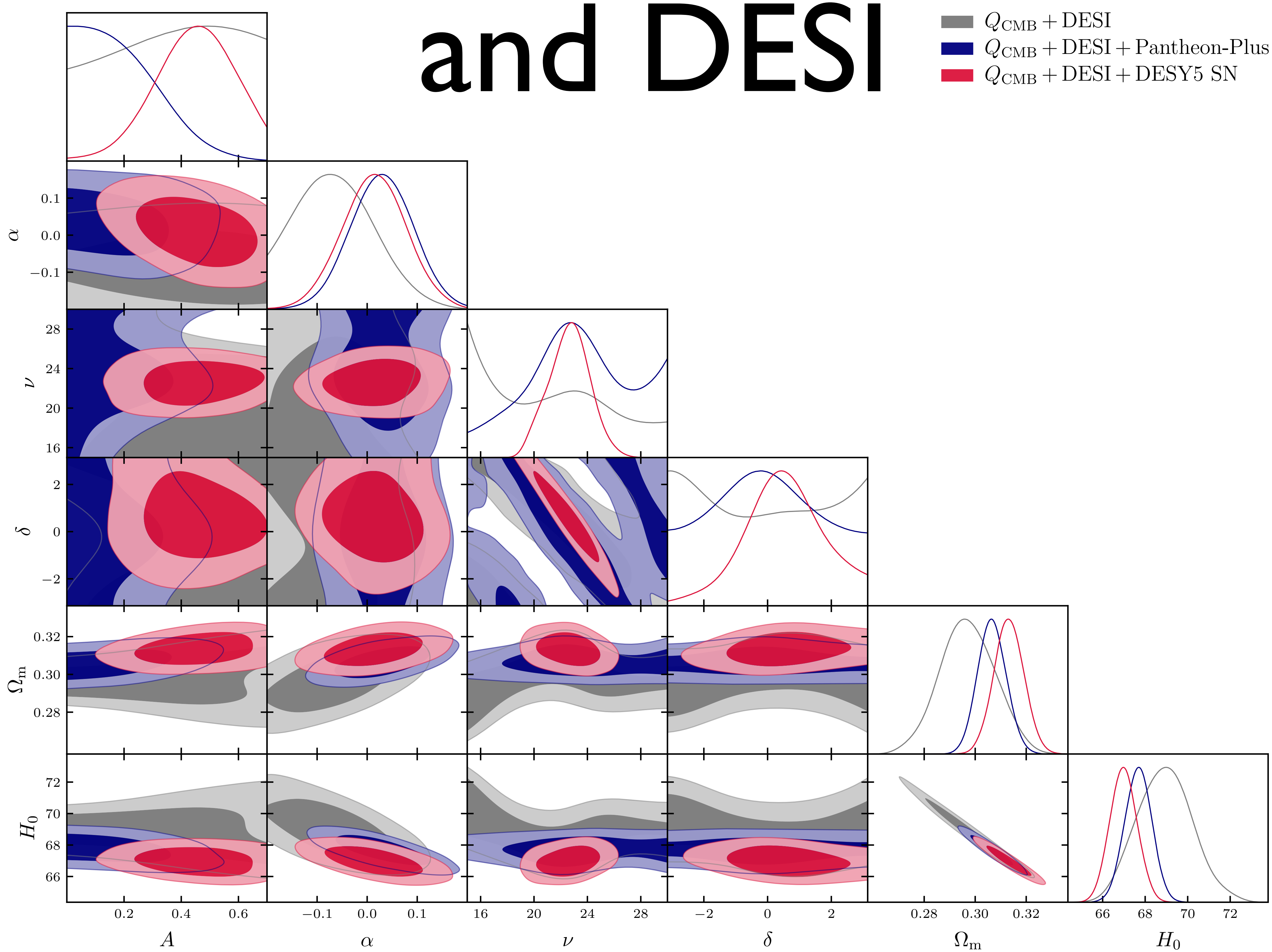

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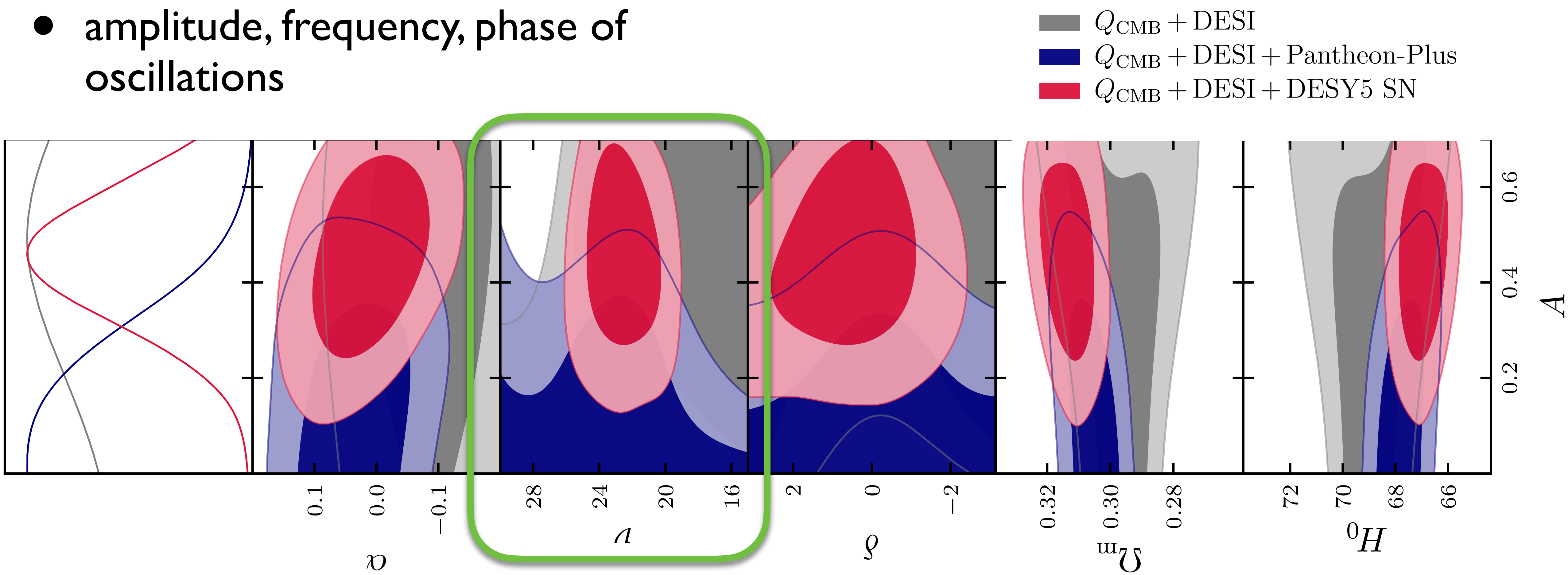

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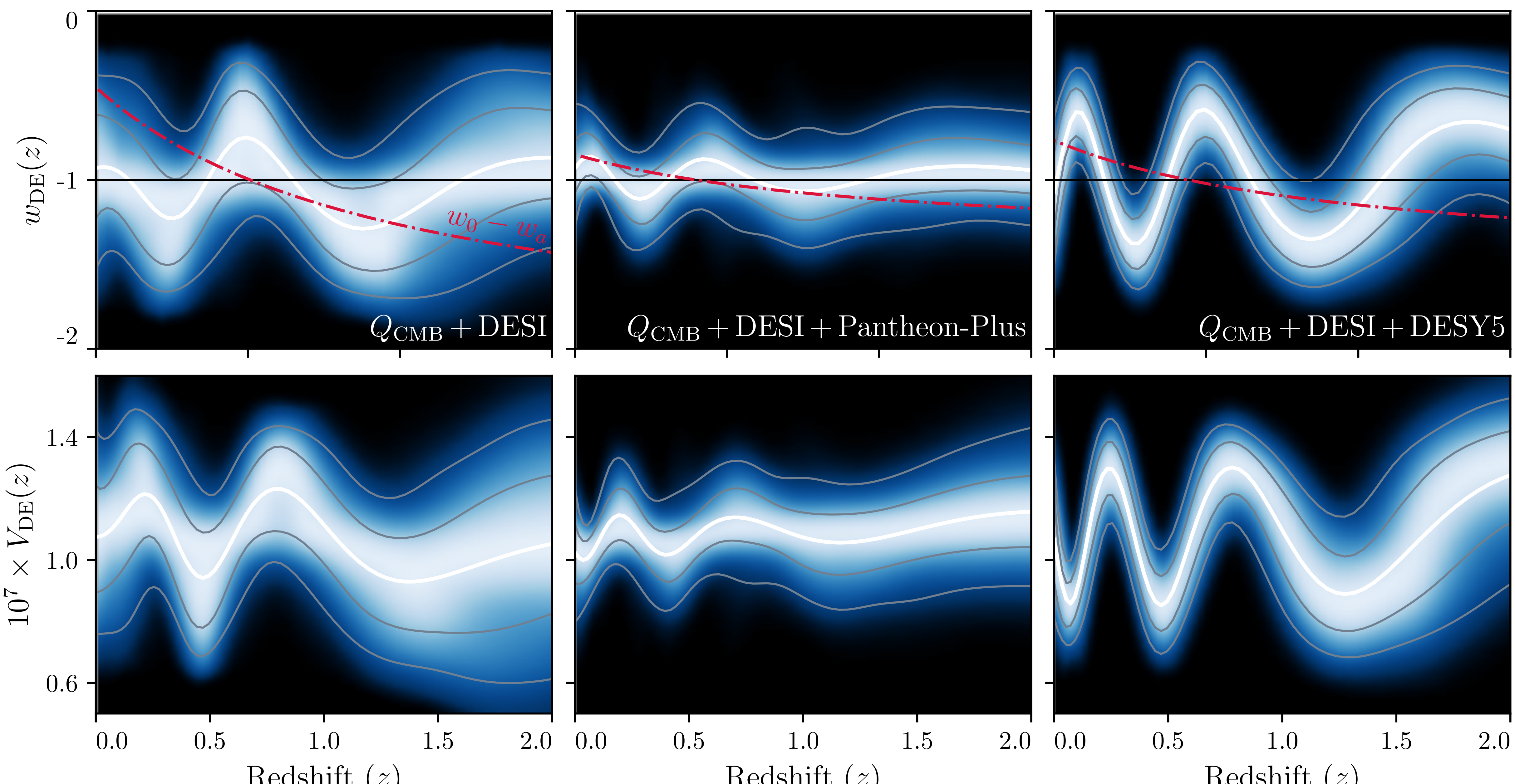
Monodromic k-essence and DESI

- Reconstruction of w(z) and k-essence "potential"



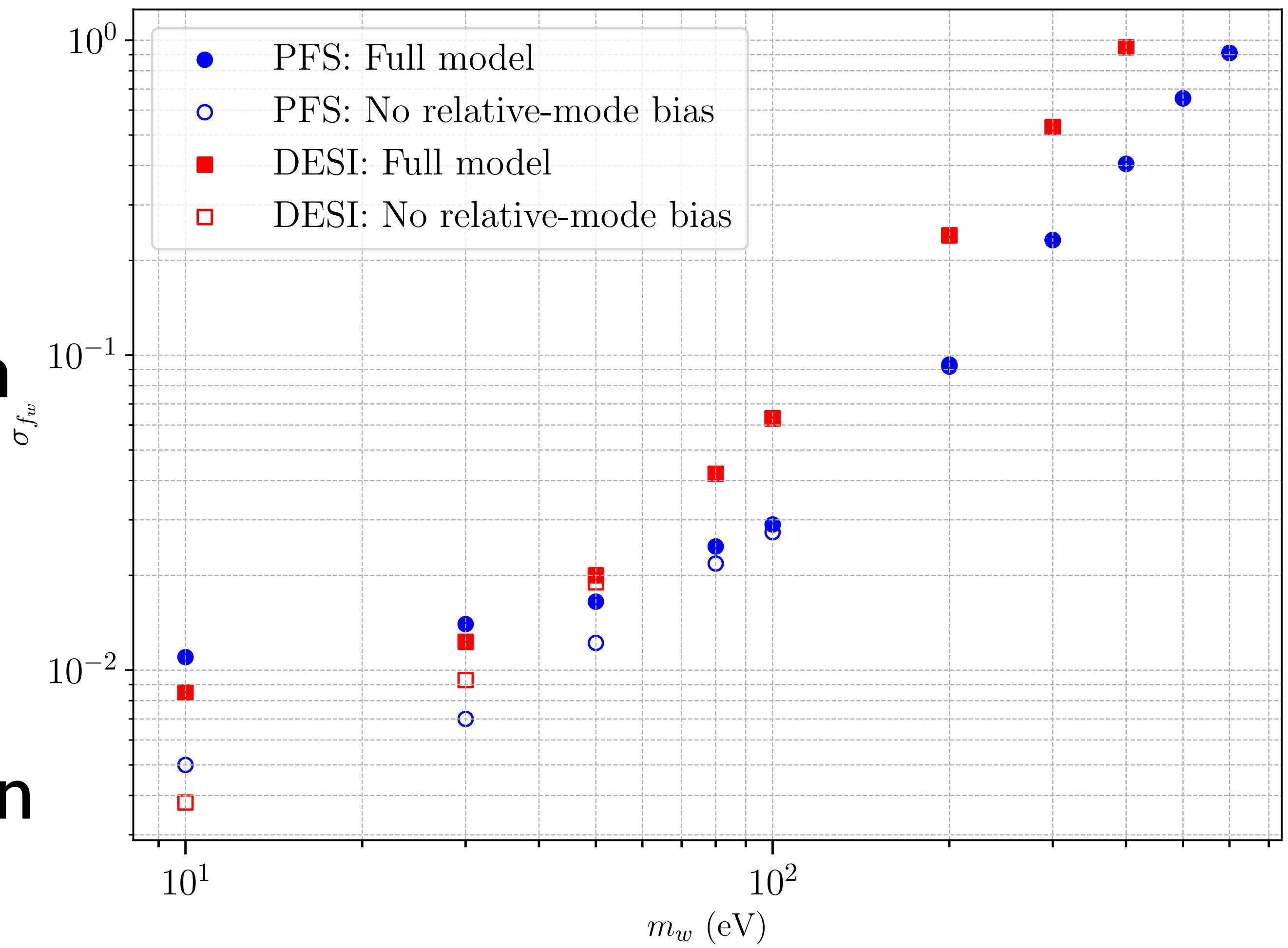
Dark matter and relics

- Light relic searches are well motivated *(Gerbino, Lattanzi)* — these could also have finite mass
- Smooth transition to warm DM, but *allow for CDM component*
- Current constraints on non-CDM (WDM, FDM, SIDM) usually assume 100% non-CDM
  - PBH searches on the other hand constrain f_{PBH}…
- Should we allow for CDM component when constraining the temperature and/or interactions of DM? —> *Mixed DM*

Mixed dark matter

- Interesting effects in LSS — scale-dependent feature at some k_{fs} with amplitude controlled by $f_{\mathrm{relic/WDM}}$
  - Discovery window depending on z and number density of surveys
- Relative density & velocity modes from early universe — need to be taken into account in bias expansion but also have unique signatures
- EFTofLSS and galaxy bias expansion become nontrivial — two complementary approaches pursued

Forecast



Verdiani, Castorina, Salvioni, Sefusatti (2025)
Celik, FS (2025)

Summary… $\omega_{\rm c},\ \omega_{\rm b},\ M_\nu,\ h,\ A_s,\ n_s,\ (\Omega_\Lambda)$

- … of my two cents on current constraint analyses:
  - Need to assume some *inflation* prior
  - Neutrino mass constraints are complicated, dataset- and prior-dependent—do not lend themselves to catchy summaries
  - Issues with w_0-w_a ; use pivot redshift at least, and consider models with more interesting phenomenology
  - Opening up dark matter constraints beyond the 100% single component