INTERACTING DARK SECTOR WITH INTRINSIC ENTROPY COUPLINGS

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Based on ongoing work with:

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- Tristan L. Smith, Swarthmore U.

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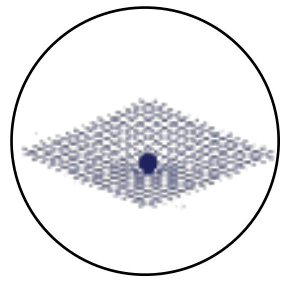
The Standard Model of Cosmology

The Lambda Cold Dark Matter Model

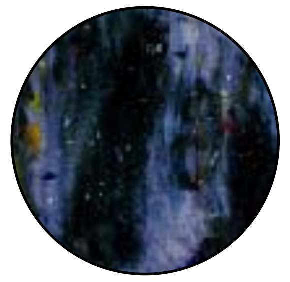
THEORY OF GRAVITY



General Relativity:

$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$

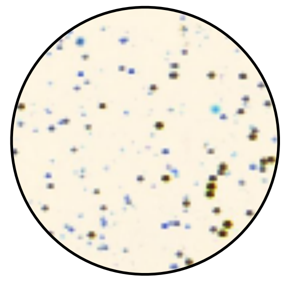
METRIC ANSATZ



FLRW Metric:

$$ds^2 = -dt^2 + a(t)d\vec{x}^2$$

STANDARD MATTER



Baryons, Photons, Neutrinos

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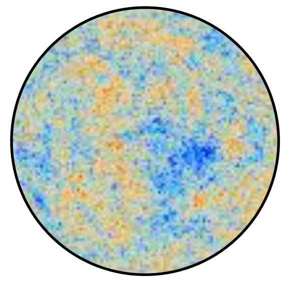
ΛCDM MODEL

INFLATION — INFLATON

Early accelerated expansion produce density fluctuations



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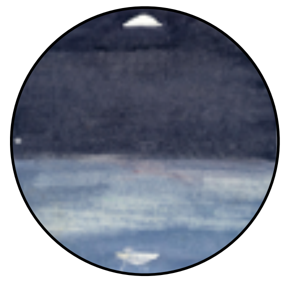
COSMIC STRUCTURE — CDM

Clustering matter component for structure formation

70%

LATE ACCELERATION — Λ

Component to explain current accelerated expansion



Challenges to the ΛCDM Model

The ΛCDM model relies on:

- Inflation but needs firm theoretical grounds: primordial power spectrum of quantum fluctuations (simplest parameterisation in terms of spectral index and amplitude)
- Dark matter being a pressureless fluid of unknown nature/origin and no detection success (new particle(s) in the SM)
- Dark energy being a cosmological constant (Λ) with unknown nature/origin (vaccuum energy, properties of empty space, etc)

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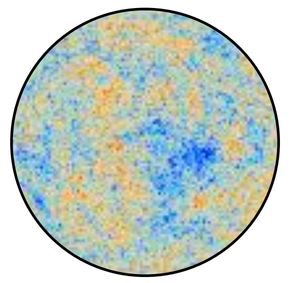

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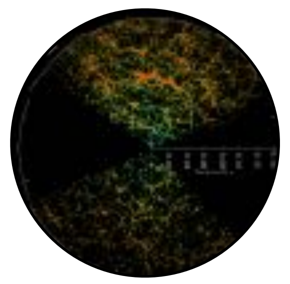

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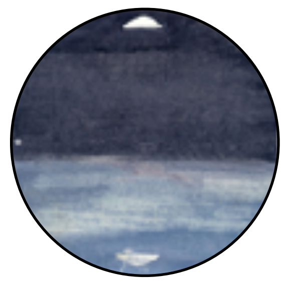

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Cosmic tensions may signal that ΛCDM is incomplete:

- Anomalies in the CMB: lensing, curvature, etc
- The matter clustering S_8 tension
- The Hubble/H_0 expansion rate tension

INFLATION — INFLATON

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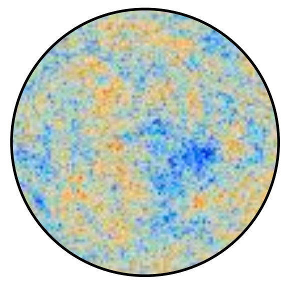

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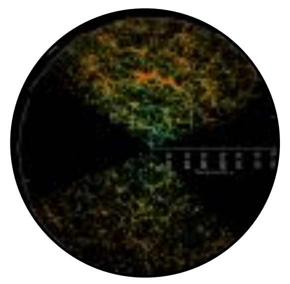

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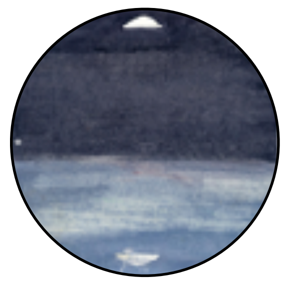
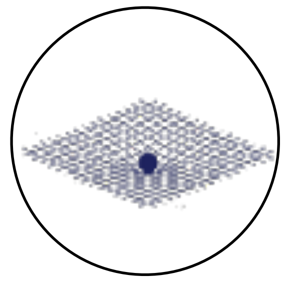


Going Beyond the Standard Model

THEORY OF GRAVITY



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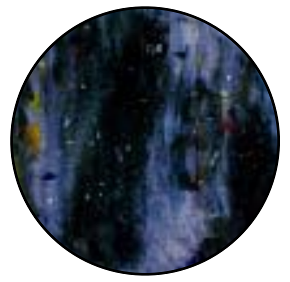

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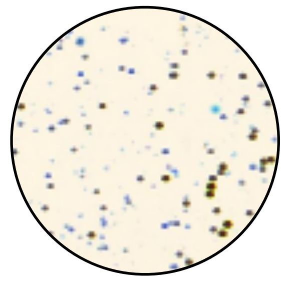

Baryons, Photons, Neutrinos

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ΛCDM MODEL

$$S = \int d^4x \sqrt{-g}\frac{1}{2}R$$

- Challenge geometric assumptions (homogeneity, isotropy and spatial flatness)
- Theories beyond GR (new degrees of freedom)
- Higher invariants, new fields, non-Riemannian geometry, etc
- Physics of the dark sector

Interacting dark sector with intrinsic entropy couplings

Based on: [E. Jensko, E. M. Teixeira, V. Poulin, T.L. Smith: arxiv:25xx.xxxxx]

Interacting dark sector

- Background cosmological couplings between dark matter (DM) and dark energy (DE) can be imposed at the level of the field equations:

- However, these are just phenomenological modifications:

- Prone to instabilities [Valiviita et. al. arxiv:0804.0232]

- Ambiguous definition of cosmological perturbations (e.g., added by hand)

- Couplings often heavily constrained by background observations

- Focus on Lagrangian formulations

$$\dot{\rho}_{\rm DM} + 3H\left(\rho_{\rm DM} + p_{\rm DM}\right) = Q$$
$$\dot{\rho}_{\rm DE} + 3H\left(\rho_{\rm DE} + p_{\rm DE}\right) = -Q$$

$$\delta'_{\rm DM} + 3\mathscr{H}\left(\frac{\delta p_{\rm DM}}{\delta\rho_{\rm DM}} + w_{\rm DM}\right)\delta_{\rm DM} = -\left(1 + w_{\rm DM}\right)\left(\theta_{\rm DM} - 3\Phi'\right) + F(Q, \delta Q)$$
$$\theta'_{\rm DM} + \left[\mathscr{H}(1 - 3w_{\rm DM}) + \frac{w'_{\rm DM}}{1+_{\rm DM}}\right]\theta_{\rm DM} = k^2\left[\Psi + \frac{\delta p_{\rm DM}}{\delta\rho_{\rm DM}}\frac{\delta_{\rm DM}}{1 + w_{\rm DM}} + G(Q, \delta Q)\right]$$

Cosmological fluids

Perfect fluid energy-momentum tensor:

$$T_{\mu\nu} = (\rho + p)u_\mu u_\nu + p g_{\mu\nu}, \quad \nabla^\mu T_{\mu\nu} = 0$$

Key thermodynamic quantities:

- particle number density n
- intrinsic entropy/particle s
- energy density $\rho = \rho(n, s)$
- pressure p
- temperature T
- chemical potential μ

+ four components of the 4-velocity u^μ with $u^\mu u_\mu = -1$

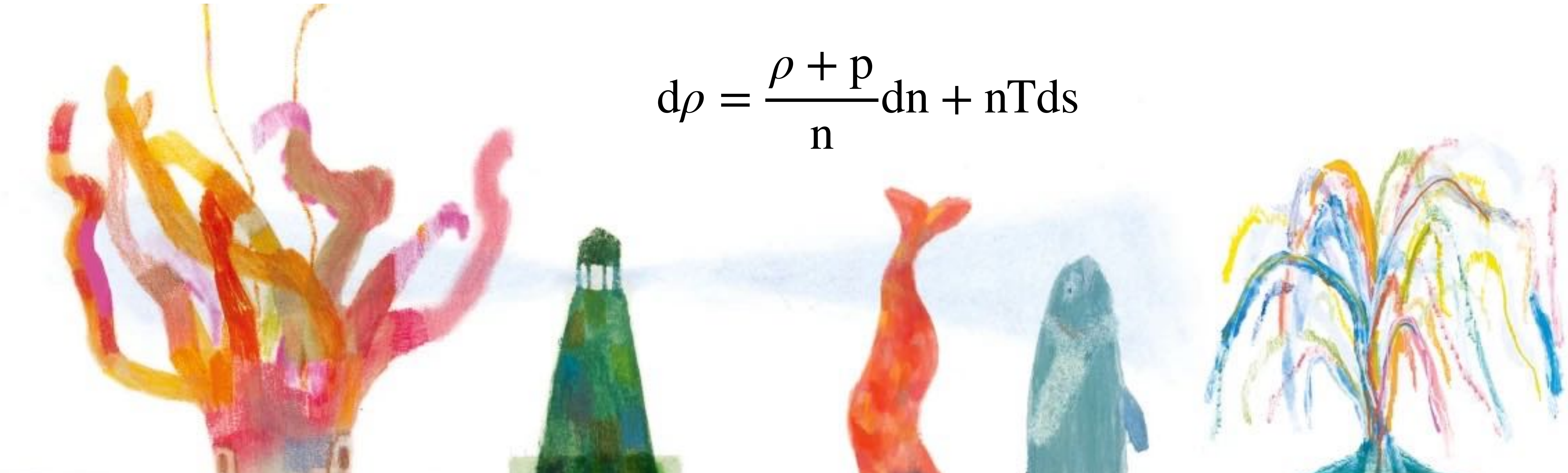
- EoM (continuity & Euler equations) from projections along u_μ and $h_{\mu\nu}$
- Thermodynamic identities

$$p(n, s) = n\left(\frac{\partial\rho}{\partial n}\right)_s - \rho$$

$$T(n, s) = \frac{1}{n}\left(\frac{\partial\rho}{\partial s}\right)_n$$

- Satisfying 1st law of thermodynamics

$$\mathrm{d}\rho = \frac{\rho + \mathrm{p}}{\mathrm{n}}\mathrm{dn} + \mathrm{nTds}$$



Perfect fluid action

- Model DM as a perfect fluid through action with variables $g_{\mu\nu}, n^\mu, s$ with Lagrange multipliers φ, θ - define the fluid's internal structure and and conservation laws covariantly

$$S_{\text{Brown}} = \int \sqrt{-g}\left[-\rho(n,s) + n^\mu(\varphi_{,\mu} + s\theta_{,\mu})\right] d^4x$$

constraints

[J. D. Brown, Class. Quant. Grav. 10, 1579 (1993), arXiv:gr-qc/9304026]

where we introduced the number flux $n^\mu := nu^\mu$ with $n = \sqrt{n^\mu n_\mu}$

- Variations give perfect fluid $T_{\mu\nu}$ with conservation equation $\nabla^\mu T_{\mu\nu} = 0$

- Additional constraints preserving particle number and entropy fluxes

$$\nabla_\mu(nu^\mu) = 0, \quad \nabla_\mu(snu^\mu) = 0 \quad \Longrightarrow \quad u^\mu \nabla_\mu s = 0$$

Cosmological fluids

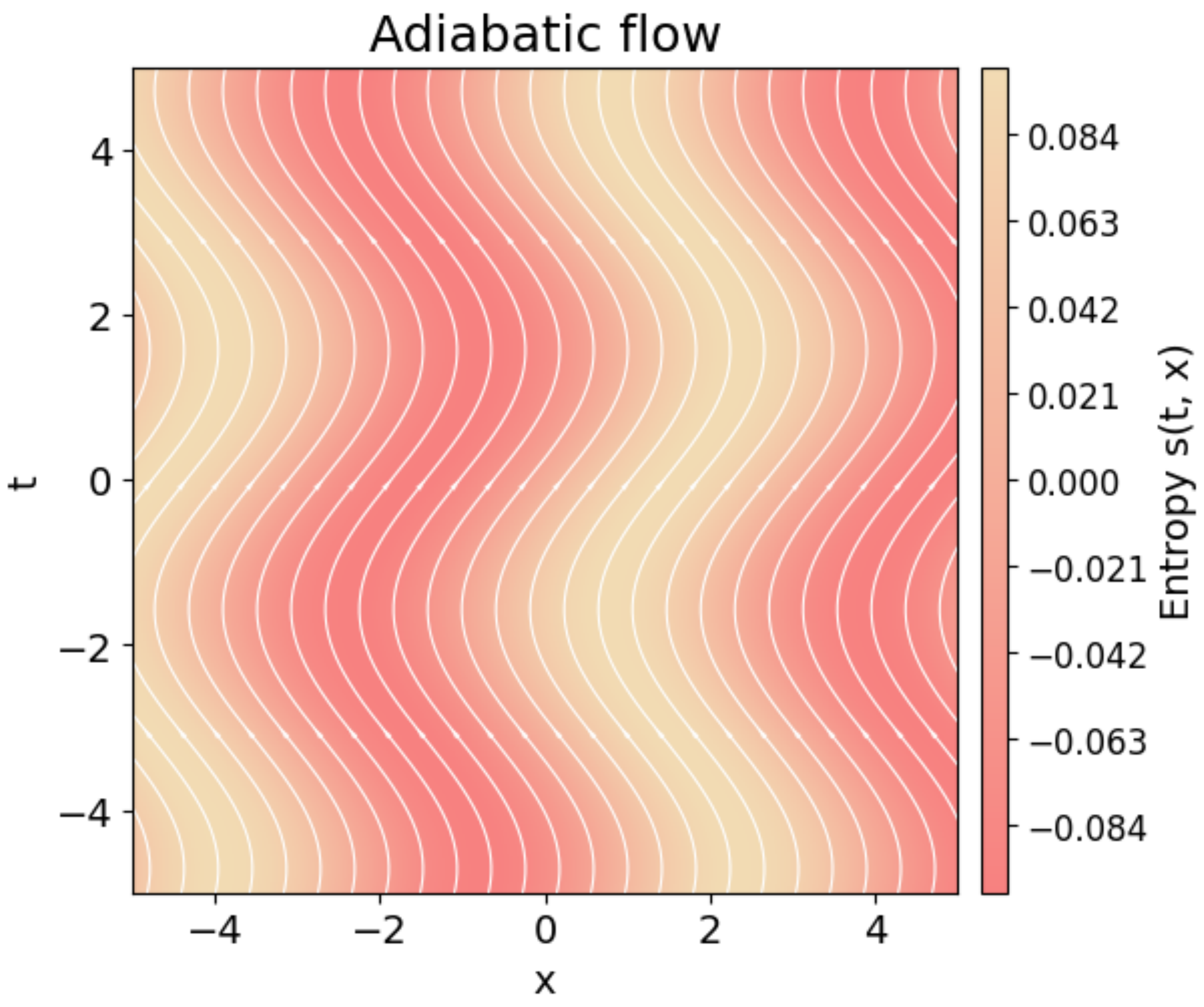
$$\nabla_\mu(nu^\mu) = 0$$
$$\nabla_\mu(nsu^\mu) = 0$$

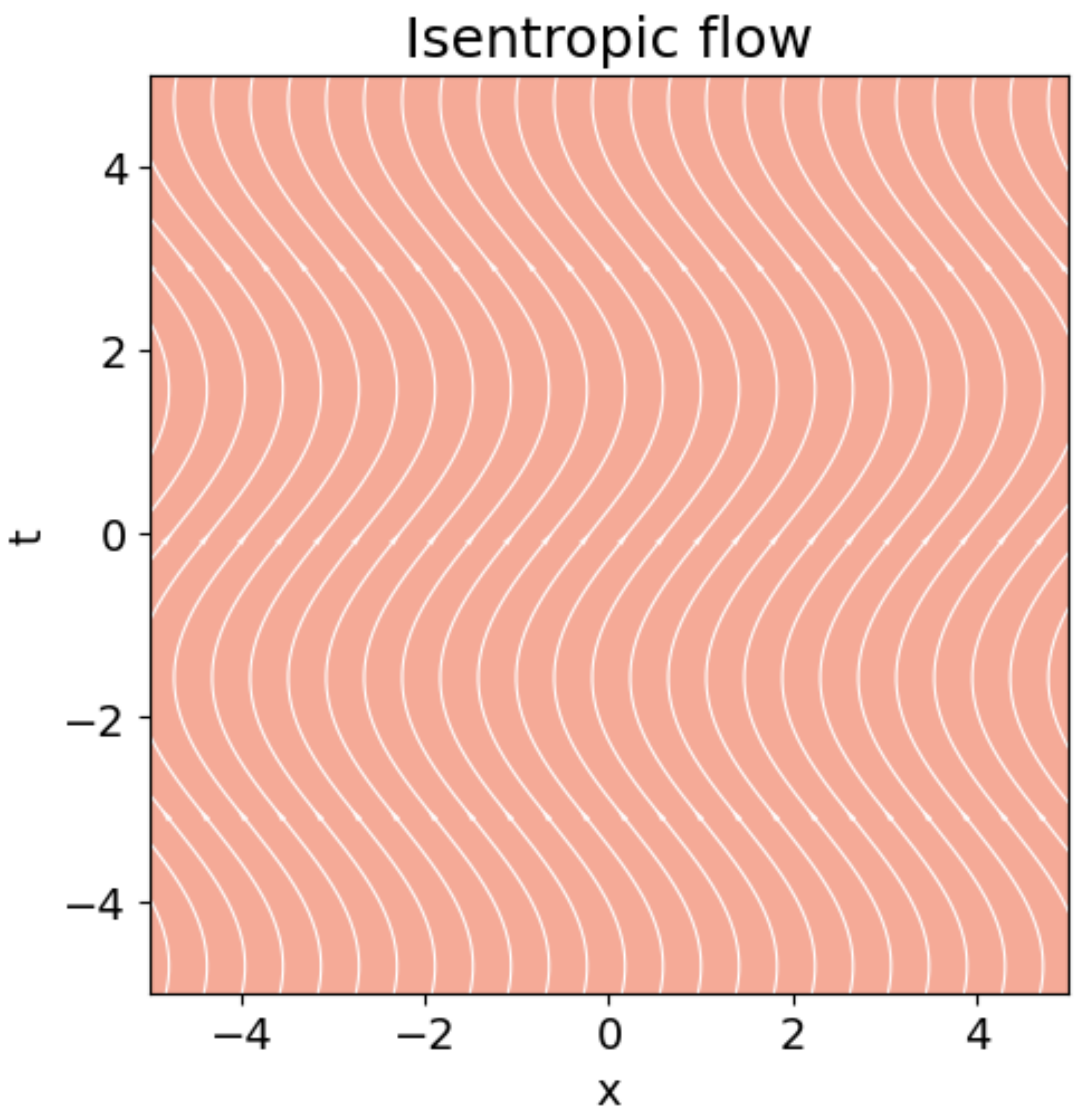
- Conservation of particle number and entropy along fluid flow lines
- Taken together these imply the entropy per particle is constant along fluid flow

adiabatic: $u^\mu \nabla_\mu s = 0$ $\nRightarrow$ isentropic: $\nabla_\mu s = 0$

General fluid condition: uniform entropy per particle s along the fluid flow (no shocks or heat conduction):

$$\rho = \rho(n, s)$$





Usual assumption in cosmology: the entropy per particle s is itself time and spatially uniform (irrotational flow):

$$\rho = \rho(n)$$

Perfect fluid dark matter in FLRW

Traditional CDM	General perfect fluid DM	"Entropic" CDM
Barotropic and isentropic ($\nabla_\mu s = 0$)	Non-barotropic and adiabatic ($u^\mu \nabla_\mu s = 0$)	Barotropic and adiabatic ($u^\mu \nabla_\mu s = 0$)
$\rho(n) = nm$	$\rho(n, s)$ arbitrary	$\rho(n, s) = nm\gamma(s)$
$p = 0$	$p \neq 0$	$p = 0$
$c_s^2 = 0$	$c_s^2 \neq 0$	$c_s^2 = 0$
$\Gamma = 0$	$\Gamma \neq 0$	$\Gamma = 0$
$\bar{s} = 0$	$\bar{s} =$ constant	$\bar{s} =$ constant
$\delta s = 0$	$\delta s = \delta s(x, y, z)$	$\delta s = \delta s(x, y, z)$
$T = 0$	$T \neq 0$	$T = m\gamma'(s)$

$$\boxed{\delta p = c_a^2 \delta\rho + \Gamma}$$

with non-adiabatic pressure perturbation

$$\boxed{\Gamma = \left.\frac{\partial p}{\partial s}\right|_\rho \delta s}$$

- intrinsic ~ fluctuations in fluid's internal entropy ($\Gamma = 0 \not\Rightarrow \delta s = 0$)

- relative ~ relative density isocurvature perturbations

Dark sector interactions

- Interactions in the dark sector accomplished through non-minimally coupled scalar fields ϕ

$$S_{\rm tot} = \int \sqrt{-g}\, f(n, s, \phi, \ldots)\, \mathrm{d}^4x + S_{\rm Brown} + S_\phi + S_{\rm SM}$$

Interactions

Many different choices of interacting terms in the literature:

- Algebraic ("coupled quintessence"): $f(n, \phi)$ [Boehmer et al., arxiv:1501.06540]
- Derivative ("momentum coupling"): $f(n) n^\mu \partial_\mu \phi$ [Boehmer et al., arxiv:1502.04030]
- General with $Y = \partial_\mu \phi \partial^\mu \phi$ and $Z = u^\mu \partial_\mu \phi$: $f(n, \phi, Y, Z)$ [Pourtsidou et al., arxiv:1307.0458]

Type-1: $Y + V(\phi) + e^{\alpha(\phi)}$ Type-2: $Y + V(\phi) + nh(Z)$ Type-3: $Y + V(\phi) + \gamma(Z) + f(n)$

E.g. Type-3 models is pure momentum-transfer up to linear order - background unchanged

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- General with $Y = \partial_\mu \phi \partial^\mu \phi$ and $Z = u^\mu \partial_\mu \phi$: $f(n, \phi, Y, Z)$

All past studies neglect the role of entropy in couplings $f(n, s, \phi, \partial\phi)$ by assuming $\partial_\mu s = 0$

Type-1: $Y + V(\phi) + e^{\alpha(\phi)}$ Type-2: $Y + V(\phi) + nh(Z)$ Type-3: $Y + V(\phi) + \gamma(Z) + f(n)$

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Entropy couplings in the dark sector

- Couple the intrinsinc entropy of dark matter s in $\rho_c(n_c, s) = m_c n_c \gamma(s)$ to the dark energy scalar ϕ - excite the otherwise hidden degrees of freedom associated with the entropy perturbations in barotropic fluids

- For this we consider pure entropy-scalar interactions:

$$\mathscr{L}_{\text{alg}} = g(\phi, s)$$

$$\mathscr{L}_{\text{der}} = h(\nabla_\mu \phi, \nabla_\mu s)$$

$$\mathscr{L}_{\text{int}}(\phi, s, \nabla_\mu \phi, \nabla_\mu s, \dots)$$

- Later distinguish into algebraic and first-order derivative model

- Generally derived from an interaction action

$$S_{\text{int}} = -\int \sqrt{-g}\, f(s, \phi, \mathcal{S})\, \mathrm{d}^4 x \quad \text{with} \quad \mathcal{S} := \nabla^\mu \phi \nabla_\mu s$$

Equations of motion

- Modified Einstein field equations

$$G_{\mu\nu} = \kappa\left(T_{\mu\nu} + T^{\phi}_{\mu\nu} + T^{(\mathrm{int})}_{\mu\nu}\right)$$

with interaction EM tensor (with heat-fluxes $q_\mu = u^\nu h^\lambda_\mu T_{\nu\lambda}$):

$$T^{(\mathrm{int})}_{\mu\nu} = -g_{\mu\nu} f + 2\frac{\partial f}{\partial \mathcal{S}} \nabla_{(\mu}\phi\nabla_{\nu)}s$$

- Total effective dark energy tensor $\tilde{T}^{(\phi)}_{\mu\nu} := T^{(\phi)}_{\mu\nu} + T^{(\mathrm{int})}_{\mu\nu}$ with coupling current

$$J_\nu := \nabla^\mu \tilde{T}^{(\phi)}_{\mu\nu} = \nabla_\mu\left(f_{,\mathcal{S}}\nabla^\mu\phi\right)\nabla_\nu s - f_{,s}\nabla_\nu s$$

which acts only in the perpendicular direction $u^\nu J_\nu = 0$ (from $u^\nu\nabla_\nu s = 0$)

Pure “momentum” transfer (up to linear order) - preserve background dynamics

Cosmology

- Conformal Newtonian gauge at linear order: $\mathrm{d}s^2 = -a(\tau)^2(1+2\Phi)\mathrm{d}\tau^2 + a^2(1-2\Psi)(\mathrm{d}x^2+\mathrm{d}y^2+\mathrm{d}z^2)$

- Entropy conservation $u^\mu \nabla_\mu s = 0$ to linear order

constant

Background $\bar{s} = s_0$

Perturbations $\delta s = \delta s(x, y, z)$

frozen-in

- Trivial background modification with effective potential $\hat{V}(\bar{\phi}) = V(\bar{\phi}) + f(\bar{\phi}, s_0, 0)$

$$\bar{\rho}_{\mathrm{DE}} = \frac{1}{2a^2}\bar{\phi}'^2 + \hat{V}(\bar{\phi})\,, \qquad \bar{p}_{\mathrm{DE}} = \frac{1}{2a^2}\bar{\phi}'^2 - \hat{V}(\bar{\phi})$$

- Uncoupled dark sector in the background - perturbative effects only

$\bar{\rho}_I' + 3\mathscr{H}(\bar{p}_I + \bar{\rho}_I) = 0 \quad \Longrightarrow \quad$ indistinguishable from uncoupled quintessence or ΛCDM

Cosmological perturbations

- Split interaction term and take $p_c = \delta p_c = 0$ for simplicity

$$f(\phi, s, \nabla_\mu \phi \nabla^\mu s) = g(\phi, s) + h(\nabla_\mu \phi \nabla^\mu s)$$

Algebraic

Derivative

- Unchanged continuity equation but modified Euler equation with scale-dependent source

$$\delta_c' + \theta_c - 3\Psi' = 0$$

$$\theta_c' + \theta_c \mathscr{H} - k^2 \Psi = -k^2 Q_s \delta s(k)\,, \quad \text{with} \quad Q_s := \frac{\bar{g}_{,s} - h_0 \hat{V}_{,\bar{\phi}}}{\bar{\rho}_c}$$

- In the quasi-static limit ($k \gg \mathscr{H}$) this becomes:

$$\delta_c'' + \mathscr{H}\delta_c' - 4\pi G a^2 \left[\bar{\rho}_c \delta_c + \Delta\rho_s(k,a)\delta s\right] \simeq k^2 Q_s(a) \delta s$$

- The coupling appears as “fifth-force” $Q_s(a)$ and “effective density source” contribution $\Delta\rho_s(k,a)$

Observational signatures

$$f(\phi, s, \mathcal{S}) = h_0 \mathcal{S} = h_0 \nabla_\mu \phi \nabla^\mu s$$
$$\delta s(k) = \mathcal{A}\,(k/k_s)^n$$

Pure derivative interaction with scale invariant entropy perturbations with standard DE exponential potential

- In the QS limit algebraic and derivative couplings reduce to similar effective source

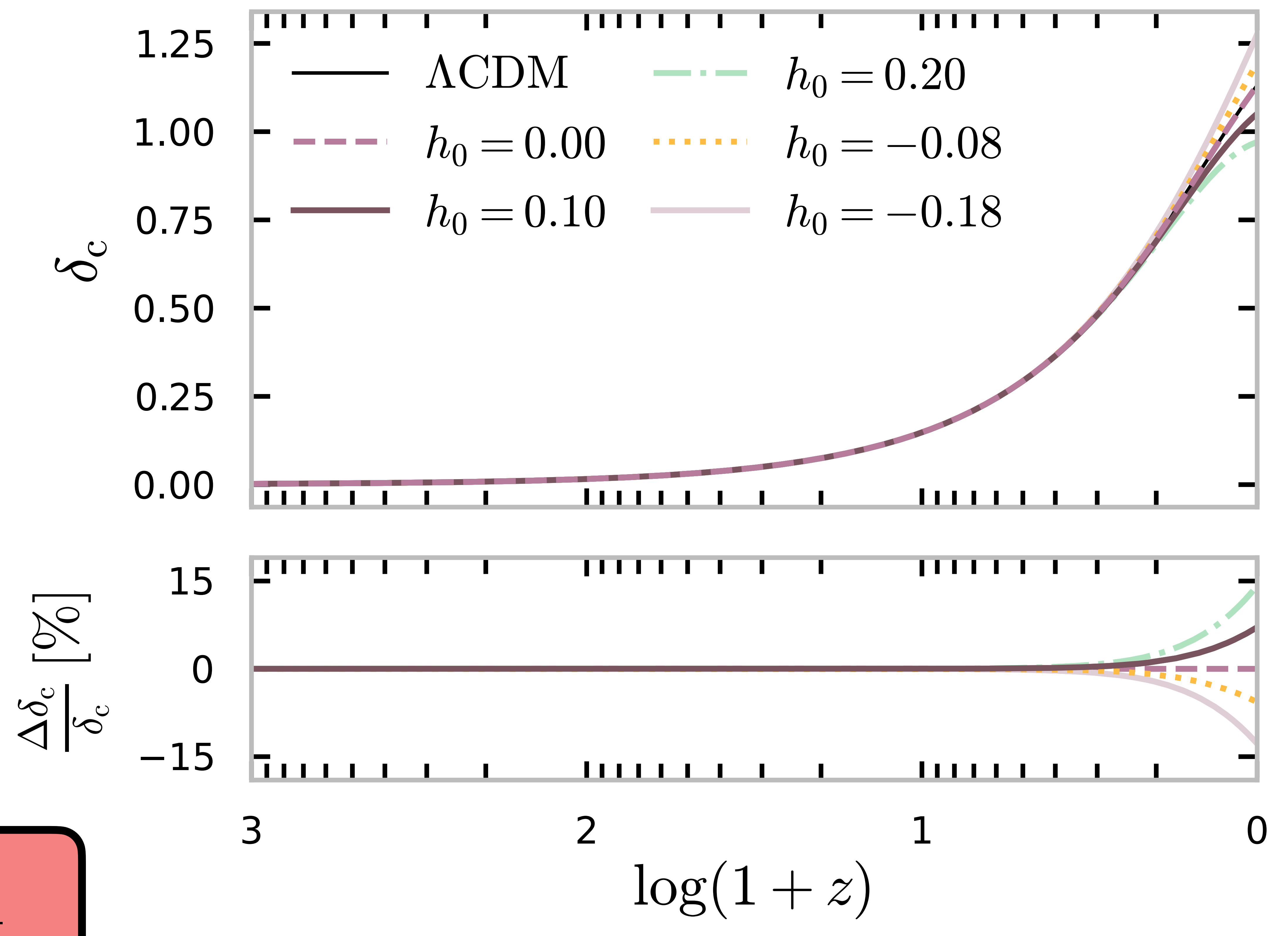
$$k^2\Psi \propto -a^2(\delta\rho_m + \delta\rho_{\rm DE})$$
$$k^2(\Psi' + \mathcal{H}\Psi) \propto a^2(\theta_m + \theta_{\rm DE})$$

- Modification in $\theta_{\rm DE} = -k^2(h_0\delta s + \delta\phi)/\phi'$

- If $n \neq 0$ need to tame large effects of the coupling at small scales

$$Q_s^{\rm der}(a) = -\frac{h_0}{\bar{\rho}_c}\hat{V}_{,\bar{\phi}}$$

$$\Delta\rho_s^{\rm der}(k,a) = -\frac{k^2 h_0}{k^2 + a^2 m_{\rm eff}^2}\hat{V}_{,\bar{\phi}}$$



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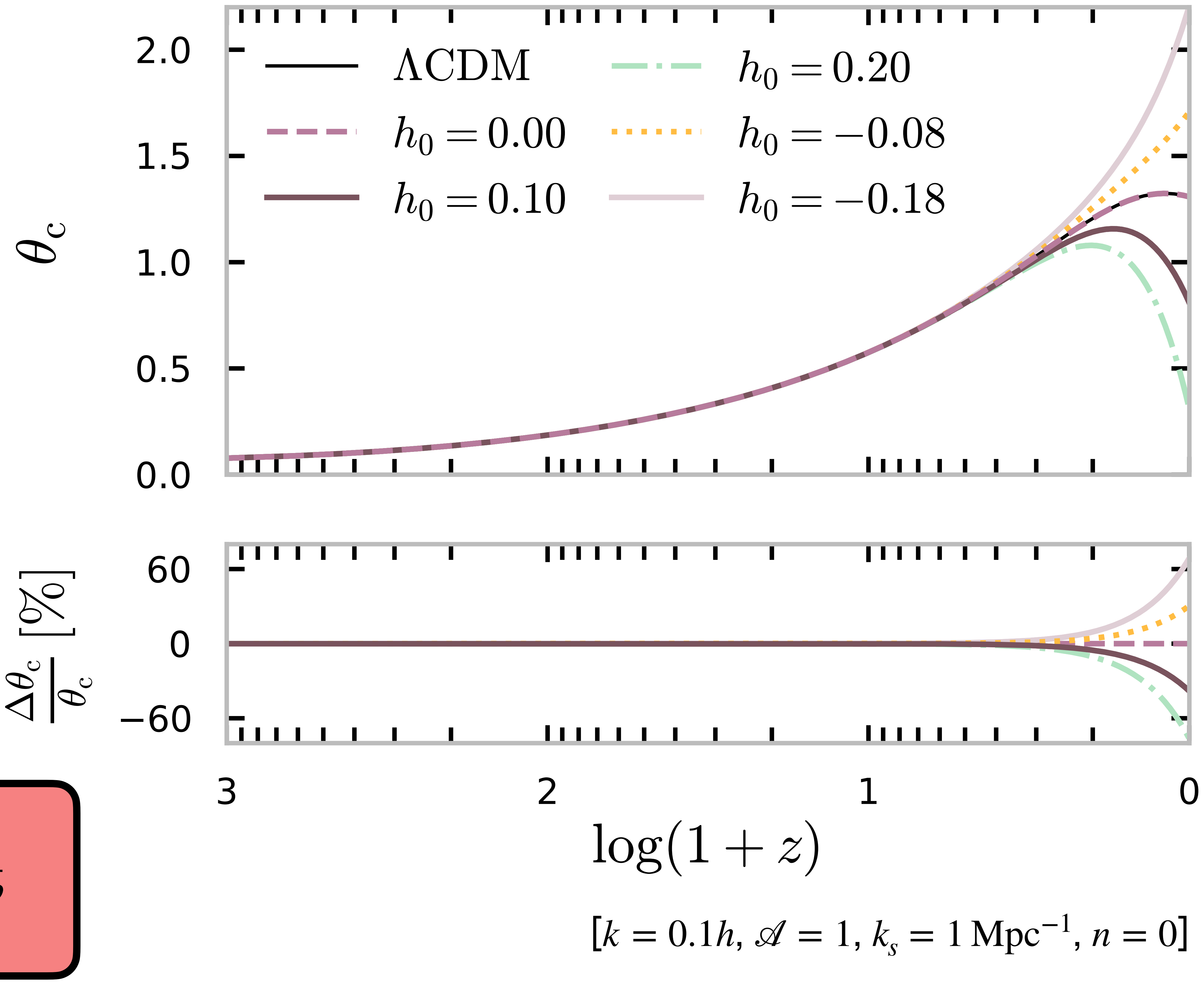

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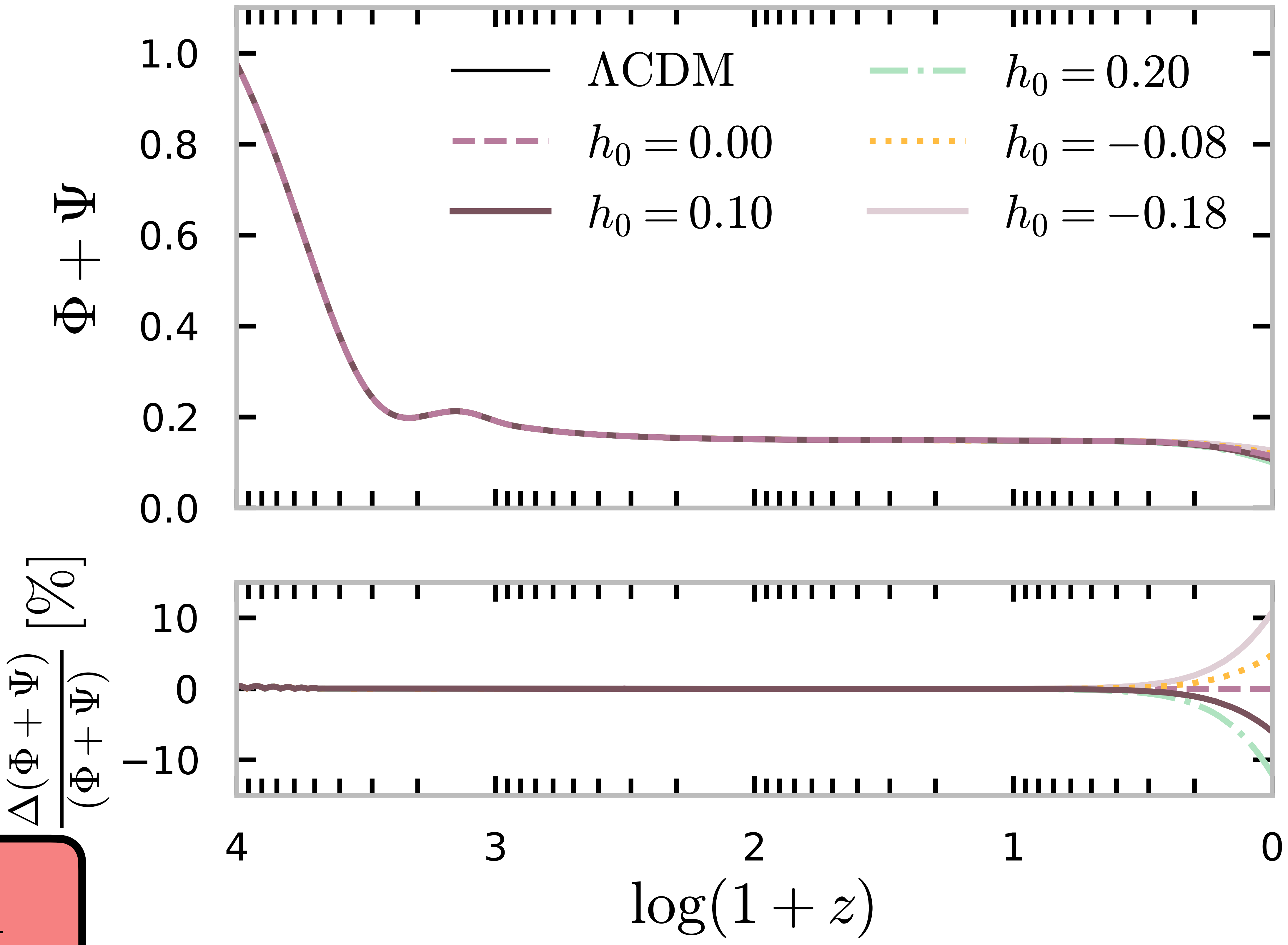

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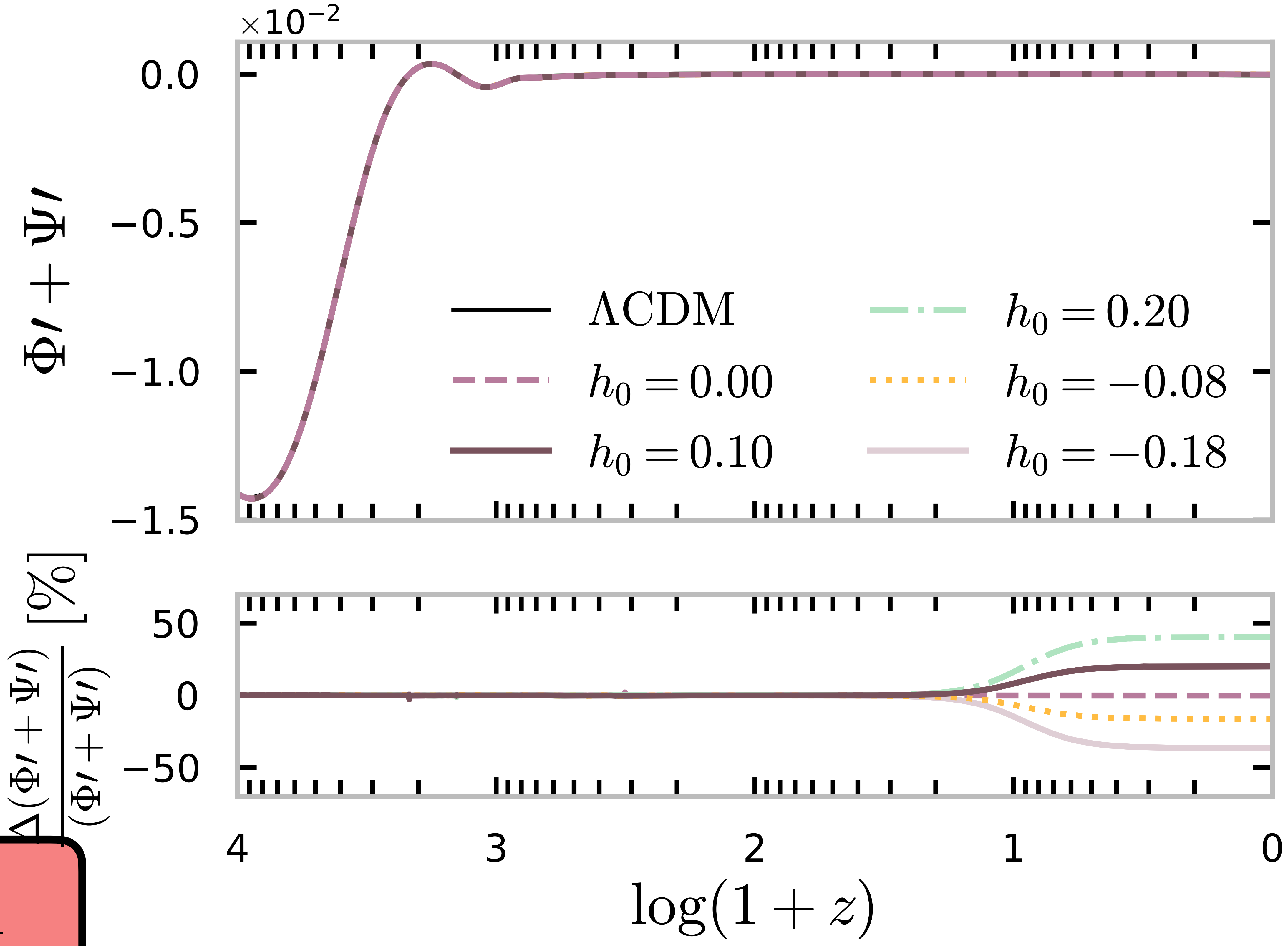

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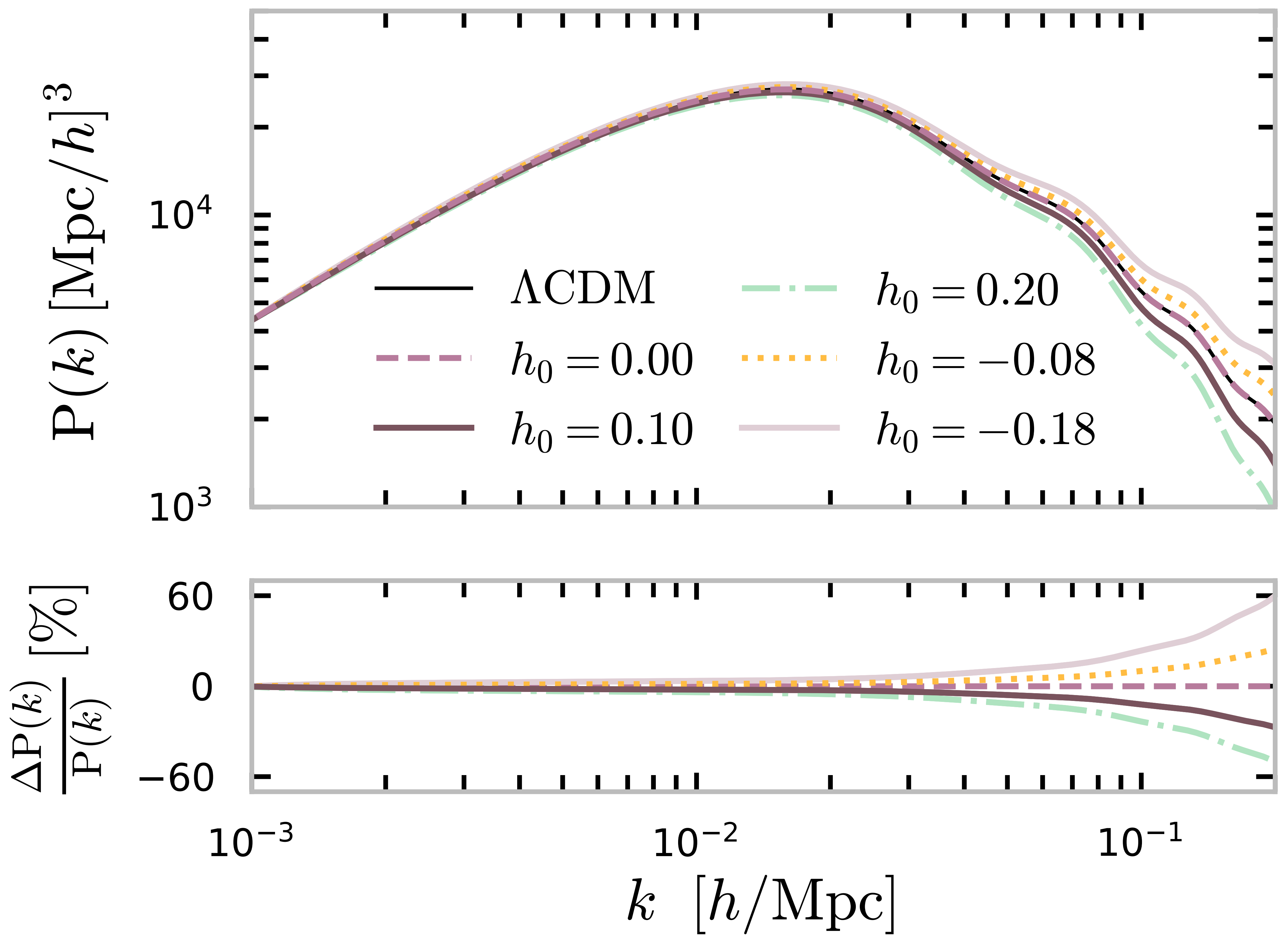
Suppression/enhancement of matter power spectrum on small scales



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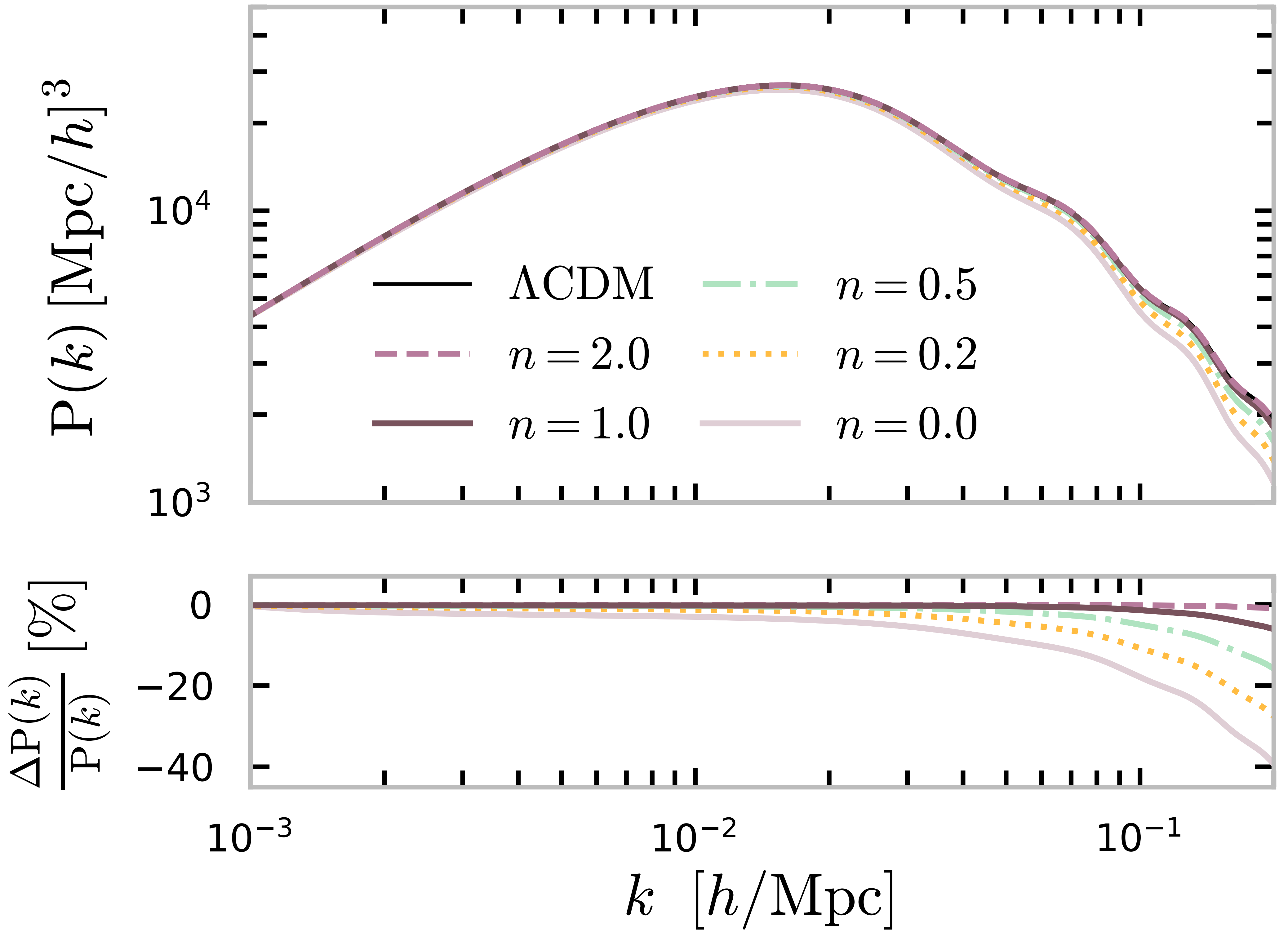

$[\mathcal{A} = 1, k_s = 1\,\mathrm{Mpc}^{-1}, h_0 = 0.15]$

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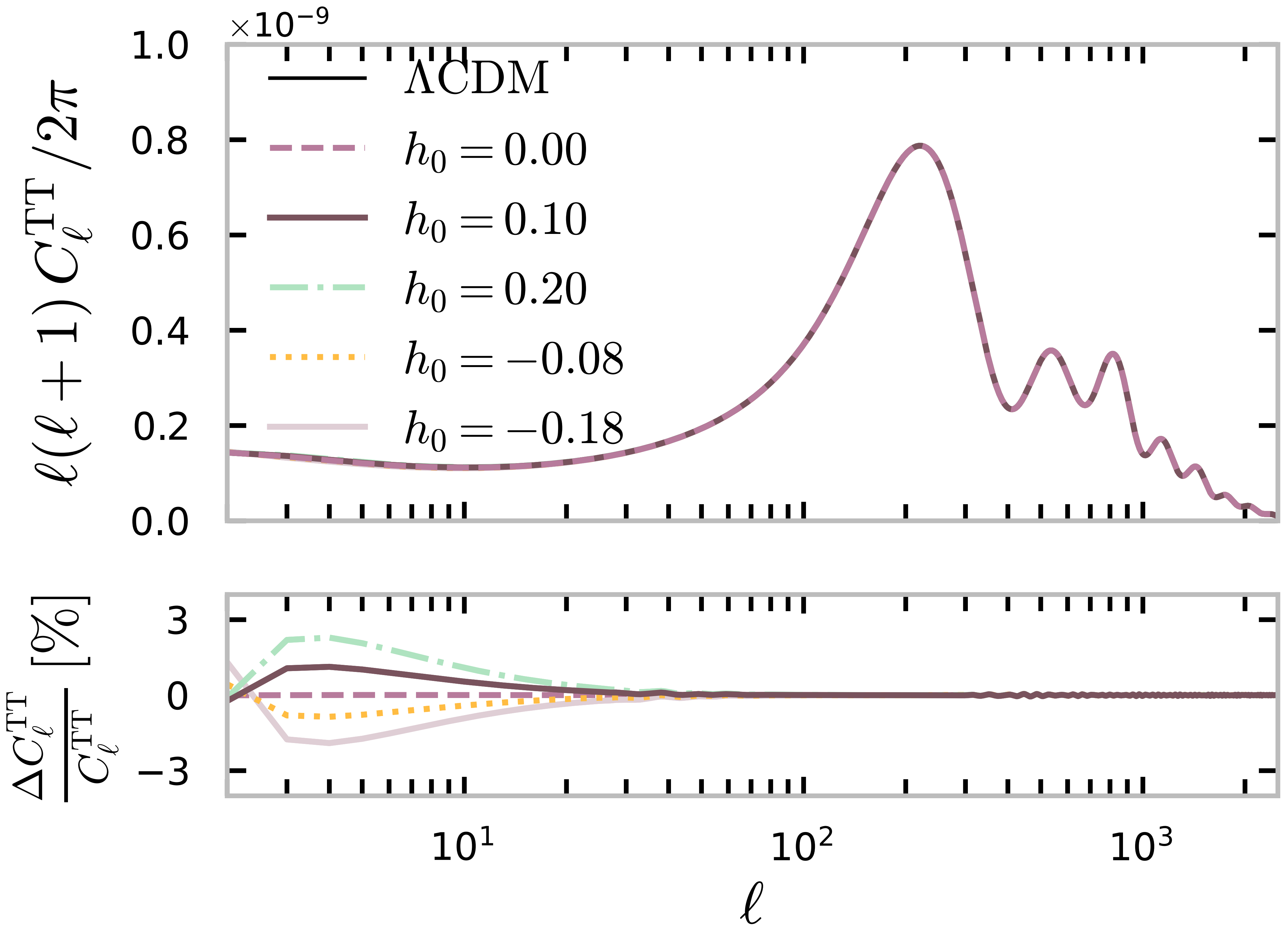
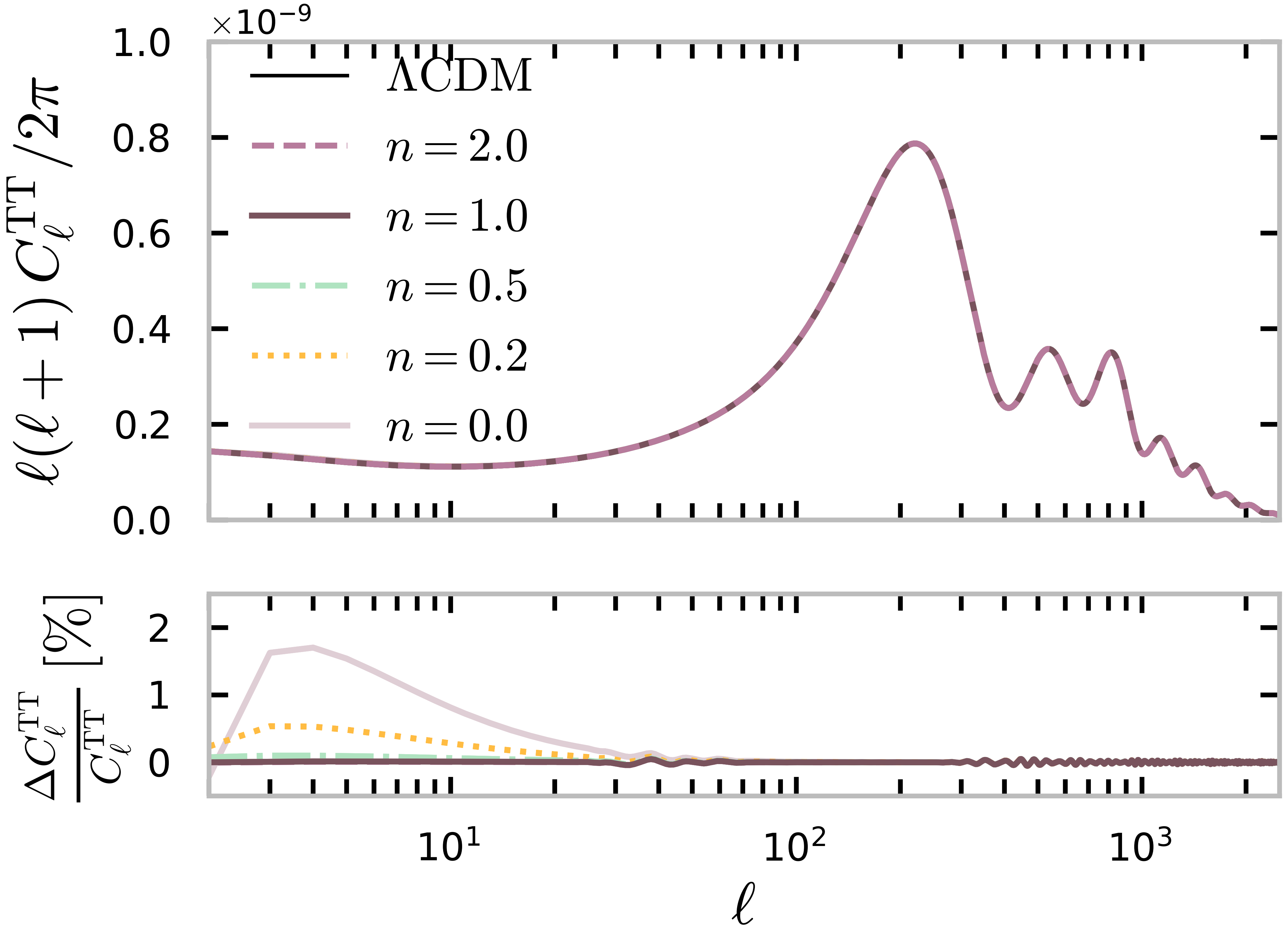
$$\delta s(k) = \mathcal{A} \left(k/k_s\right)^n$$

Tiny ISW changes to CMB temperature spectrum $\mathcal{C}_\ell^{TT}$ at low-ℓ



$[\mathcal{A} = 1, k_s = 1\,\mathrm{Mpc}^{-1}, n = 0]$

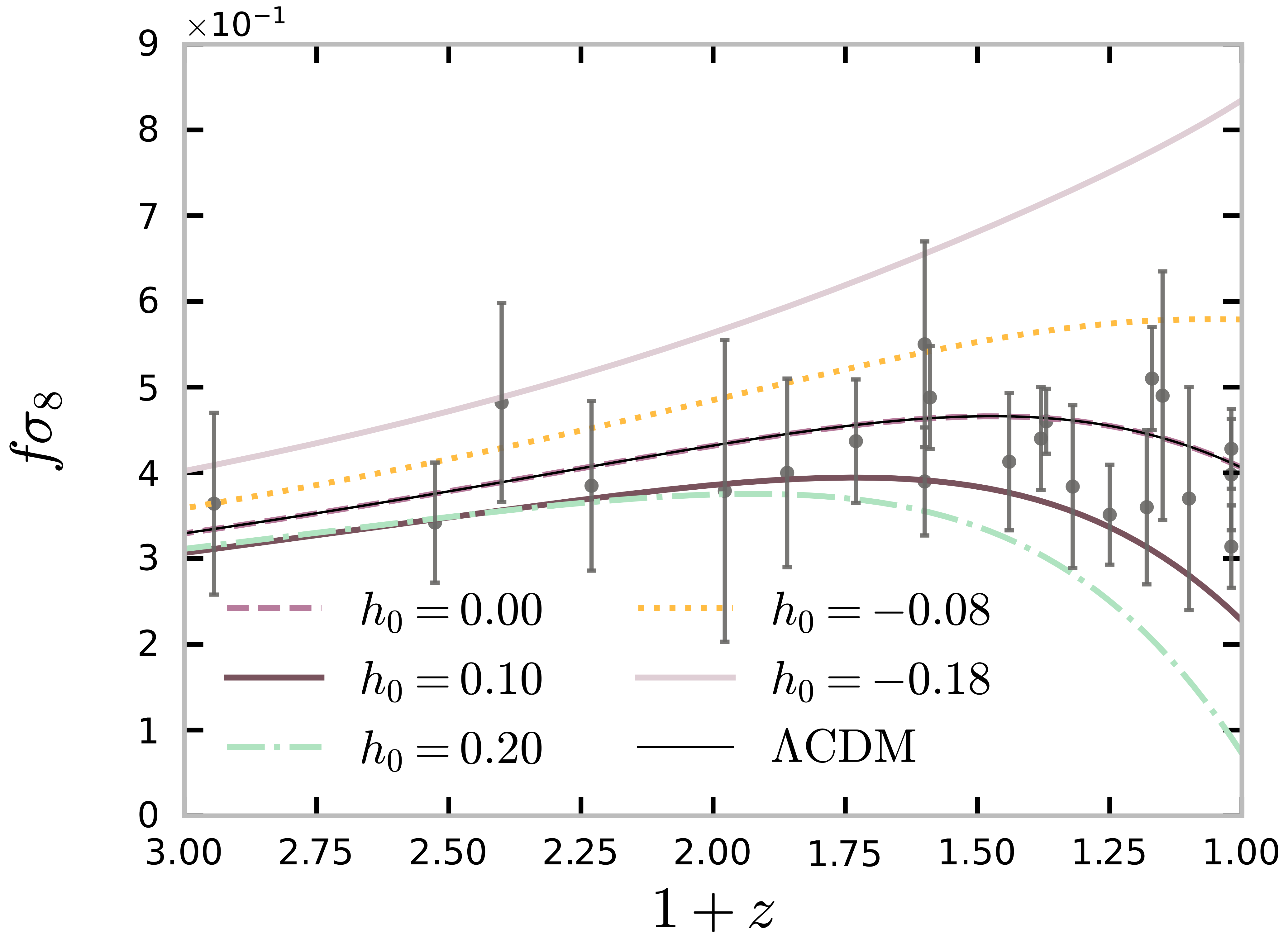


$[\mathcal{A} = 1, k_s = 1\,\mathrm{Mpc}^{-1}, h_0 = 0.15]$

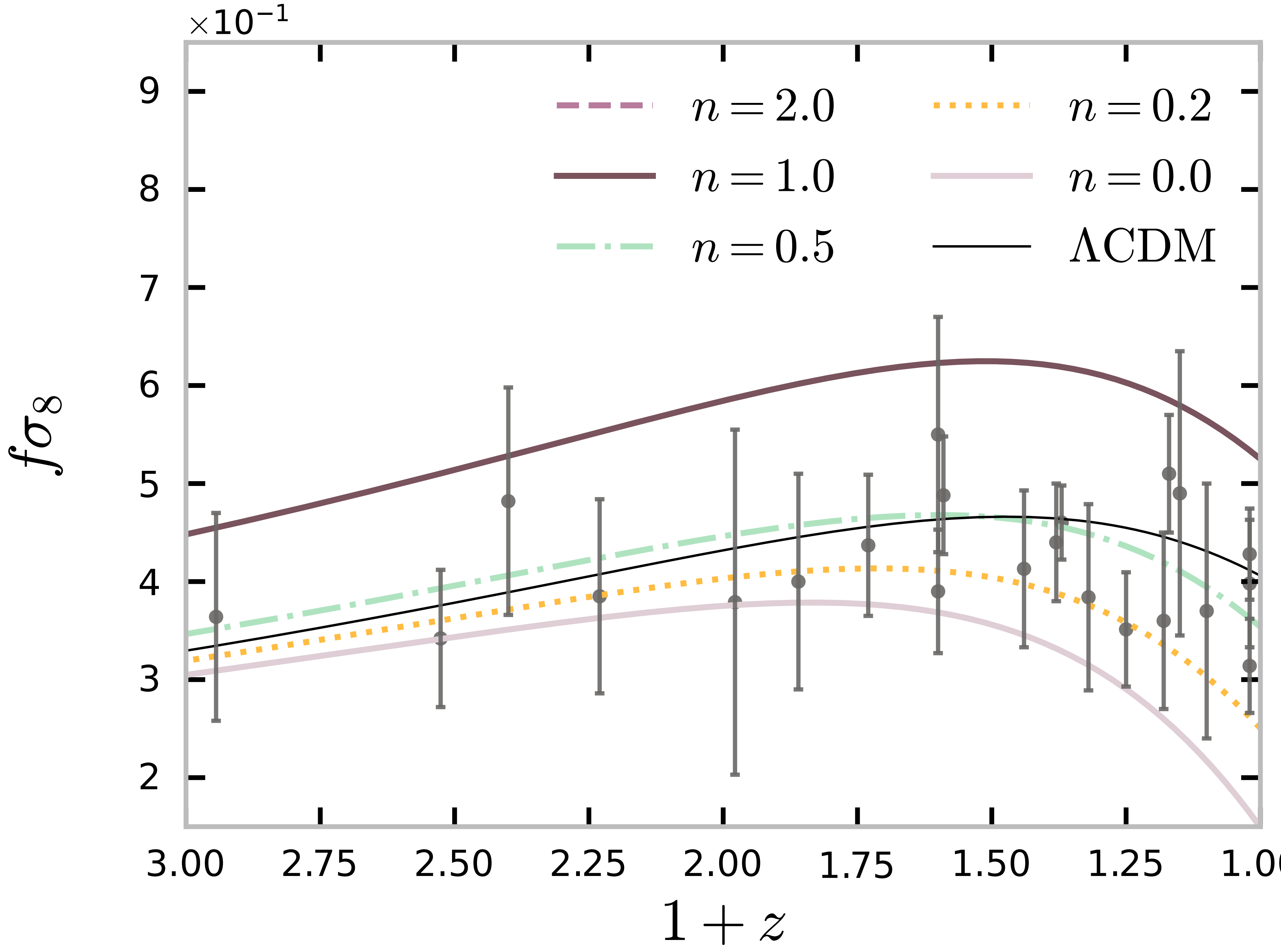
Observational signatures

$$f(\phi, s, \mathcal{S}) = h_0 \mathcal{S} = h_0 \nabla_\mu \phi \nabla^\mu s$$
$$\delta s(k) = \mathscr{A}\,(k/k_s)^n$$

Significant changes to the growth - observational constraints



$[\mathscr{A} = 1, k_s = 1\,\mathrm{Mpc}^{-1}, n = 0]$



$[\mathscr{A} = 1, k_s = 1\,\mathrm{Mpc}^{-1}, h_0 = 0.15]$

Observational signatures

Similar behaviour for algebraic models except for scale-dependent effects

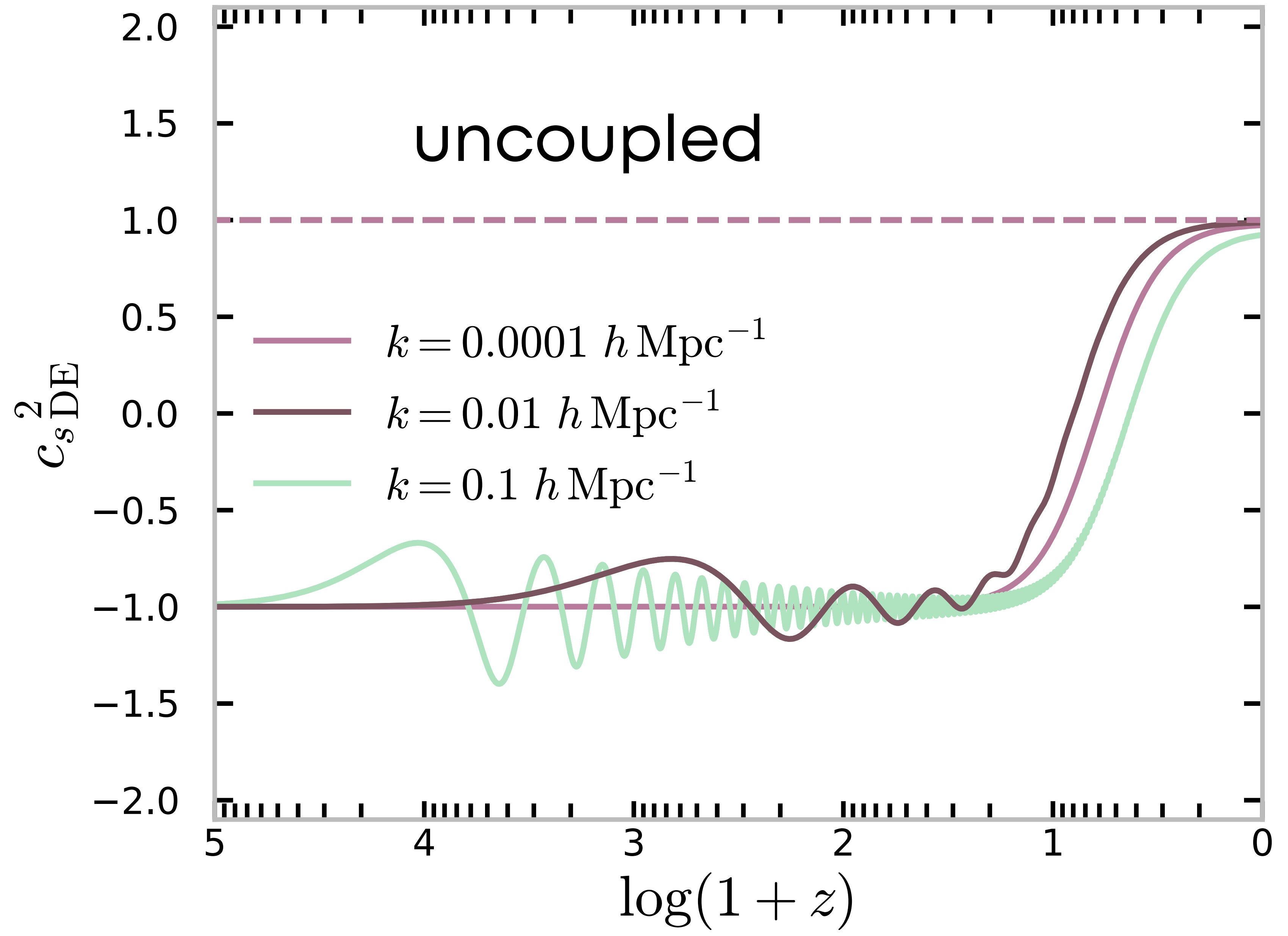
- Different scale-dependance of source term

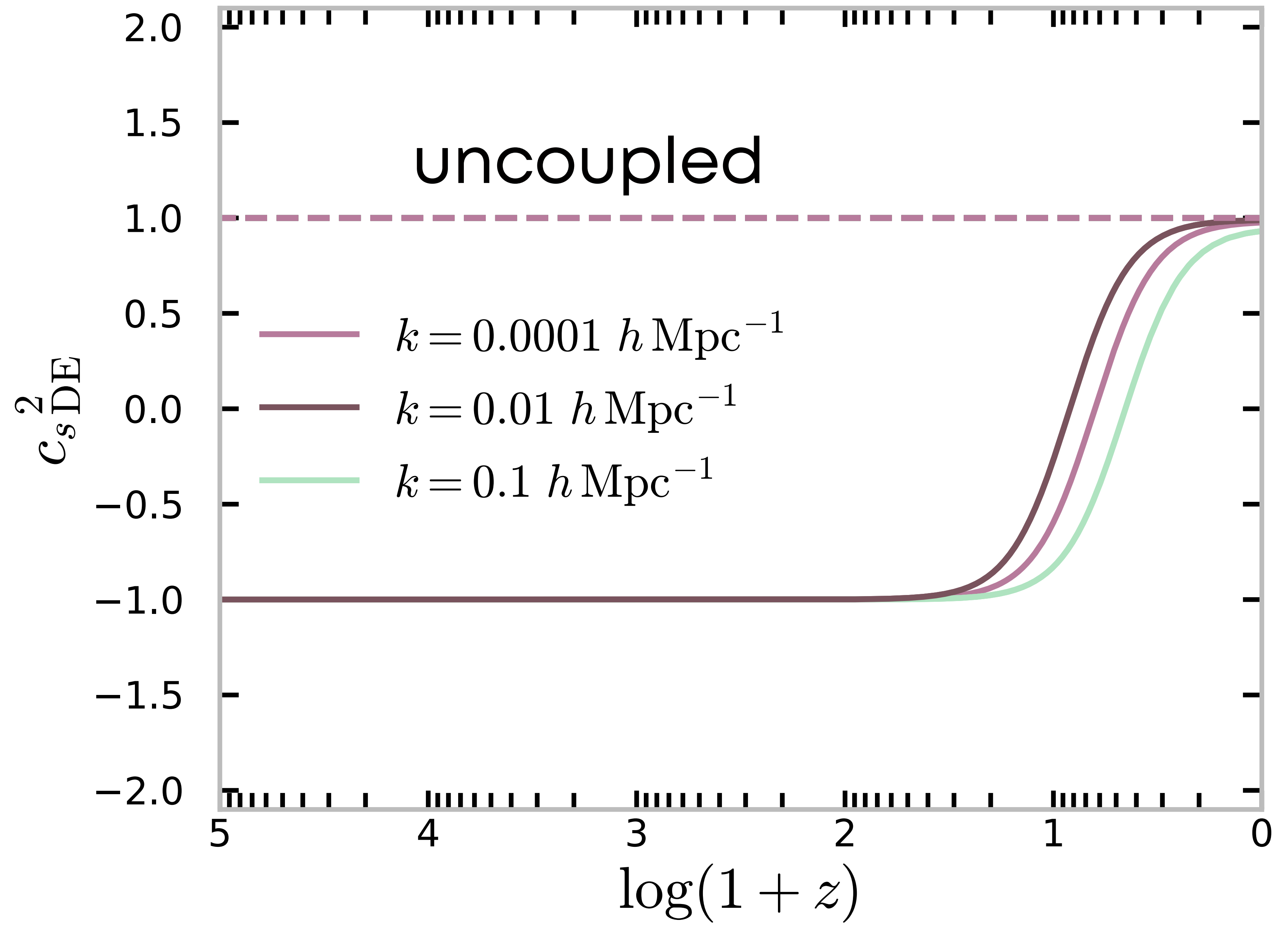
$$\Delta\rho_s^{\mathrm{der}}(k,a) = -\frac{k^2 h_0}{k^2 + a^2 m_{\mathrm{eff}}^2}\hat{V}_{,\bar{\phi}}$$

$$\Delta\rho_s^{\mathrm{alg}}(k,a) = \bar{g}_{,s} - \frac{a^2 \bar{g}_{,s\phi}}{k^2 + a^2 m_{\mathrm{eff}}^2}\hat{V}_{,\bar{\phi}}$$

- Different sound speed in the fluid rest frame ($c_s^2 \neq 1$):

$$c_s^2 := \frac{\delta p}{\delta \rho}\bigg|_{\mathrm{restframe}} = 1 - \frac{2a^2\delta s(h_0\hat{V}_{,\bar{\phi}} - \bar{g}_{,s})}{a^2\delta s(h_0\hat{V}_{,\bar{\phi}} - \bar{g}_{,s}) + \bar{\phi}'(\delta\phi' - \bar{\phi}'\Psi)}$$





Observational signatures

$$\delta\phi'' + 2\mathscr{H}\delta\phi' + (k^2 + a^2\hat{V}_{,\bar{\phi}\bar{\phi}})\delta\phi = -2a^2\Psi\hat{V}_{,\bar{\phi}} + 4\Psi'\bar{\phi}' - \left(a^2\bar{g}_{,s\phi} + k^2h_0\right)\delta s$$

- Different scale-dependance of source term

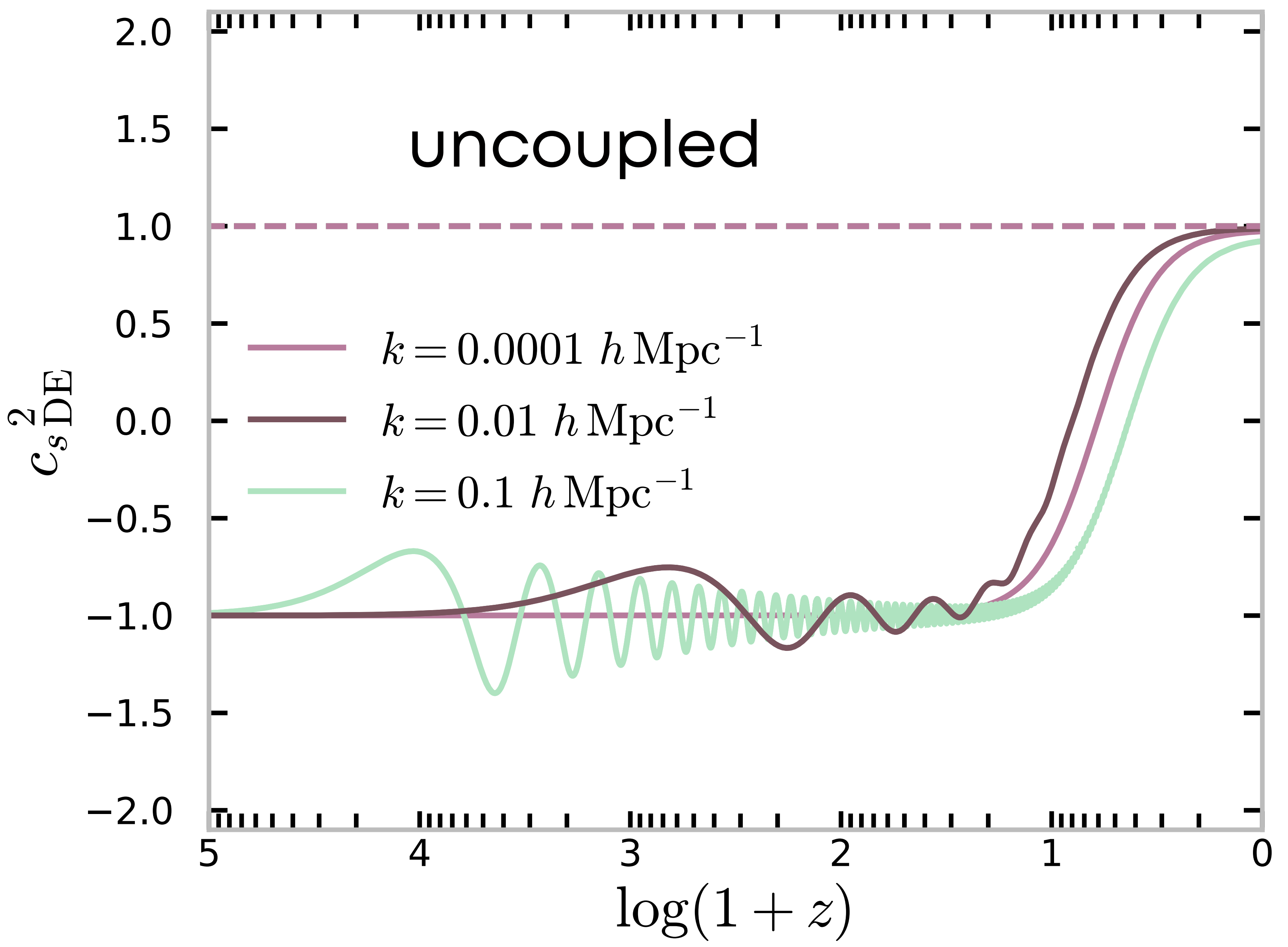
$$\Delta\rho_s^{\mathrm{der}}(k,a) = -\frac{k^2h_0}{k^2 + a^2m_{\mathrm{eff}}^2}\hat{V}_{,\bar{\phi}}$$

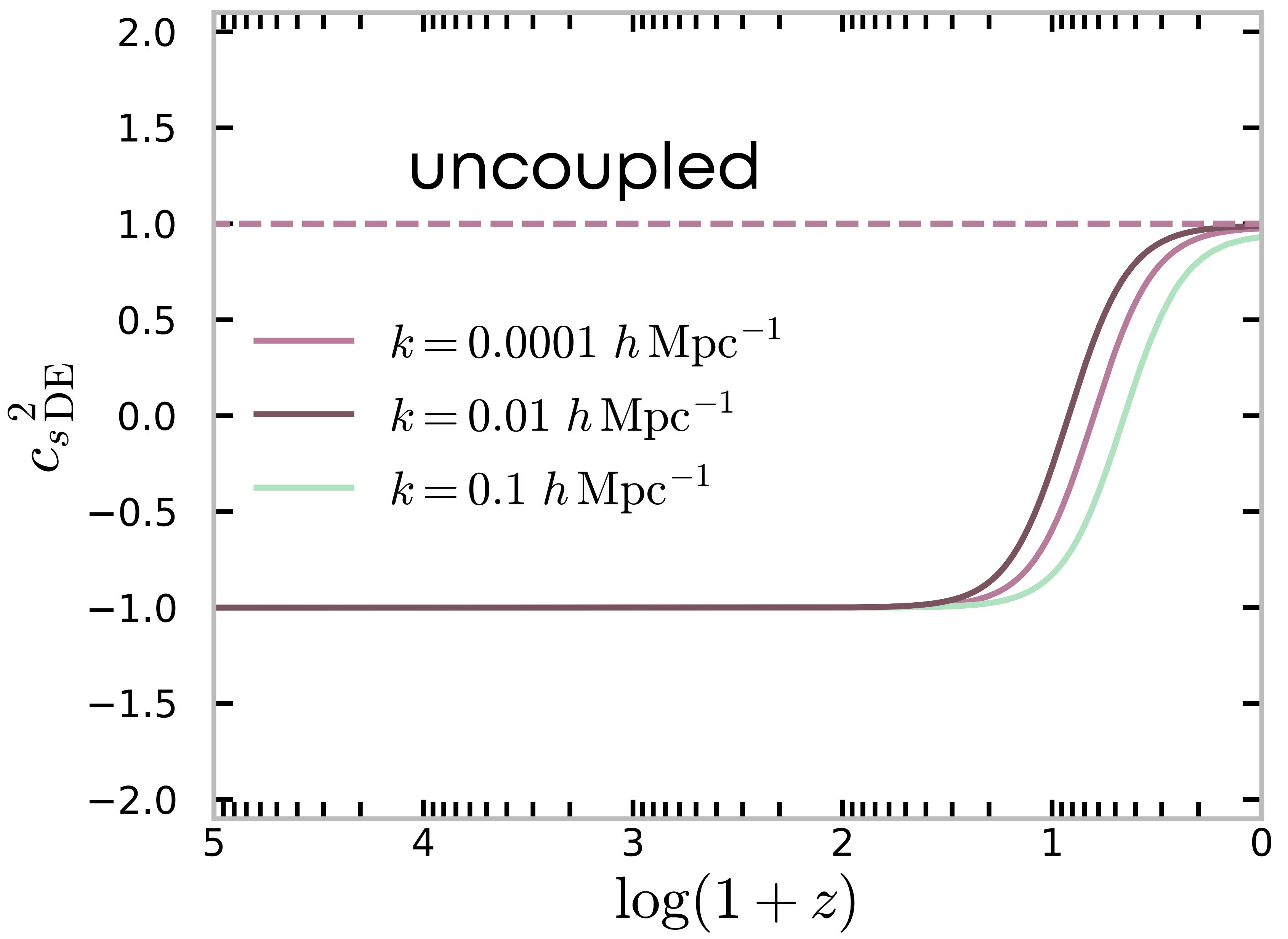
$$\Delta\rho_s^{\mathrm{alg}}(k,a) = \bar{g}_{,s} - \frac{a^2\bar{g}_{,s\phi}}{k^2 + a^2m_{\mathrm{eff}}^2}\hat{V}_{,\bar{\phi}}$$

Oscillations in $\delta\phi$ in the derivative coupling for small scales

- Different sound speed in the fluid rest frame ($c_s^2 \neq 1$):

$$c_s^2 := \left.\frac{\delta p}{\delta\rho}\right|_{\mathrm{restframe}} = 1 - \frac{2a^2\delta s(h_0\hat{V}_{,\bar{\phi}} - \bar{g}_{,s})}{a^2\delta s(h_0\hat{V}_{,\bar{\phi}} - \bar{g}_{,s}) + \bar{\phi}'(\delta\phi' - \bar{\phi}'\Psi)}$$





Summary and Conclusions

Conclusions

- New interacting scenarios from coupling DM intrinsic entropy to DE
- Unchanged background expansion
- No energy transfer (pure-momentum only)
- Scale-dependent suppression/enhancement of matter clustering at late-times

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- Observational constraints on allowed couplings - cosmic tensions
- Explore different primordial power spectrum for $\delta s(k)$ and initial conditions
- Early dark energy/neutrino scenarios
- Key observational signatures: scale-dependent clustering

Thank you for your attention!

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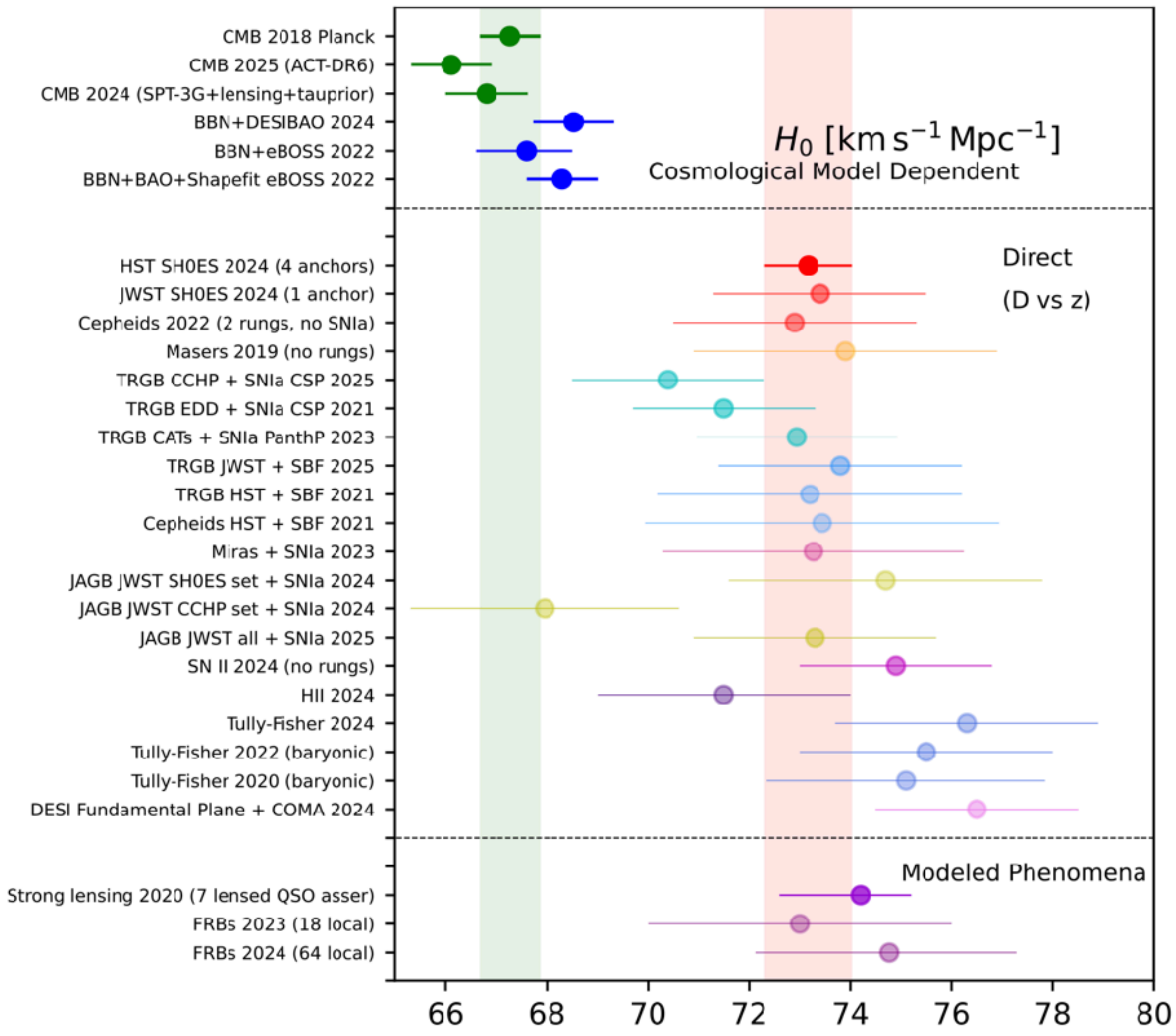
The Hubble Tension

Unreconcilable values for H_0 from the CMB and from direct local distance ladder measurements

- ~5σ tension between Planck 2018 and SH0ES:
  - CMB (Planck): $H_0 = 67.27 \pm 0.60$ km/s/Mpc
  - SNe (R22): $H_0 = 73.04 \pm 1.04$ km/s/Mpc
- The CMB data assumes the ΛCDM model
- DESI BAO (+BBN+CMB): $H_0 = 68.45 \pm 0.47$ km/s/Mpc [DESI Collaboration DR2 2025: arXiv:2503.14738]
- Compilation of early vs late time data that disagree
- Could signal differences in the expansion history (nature of the dark sector)

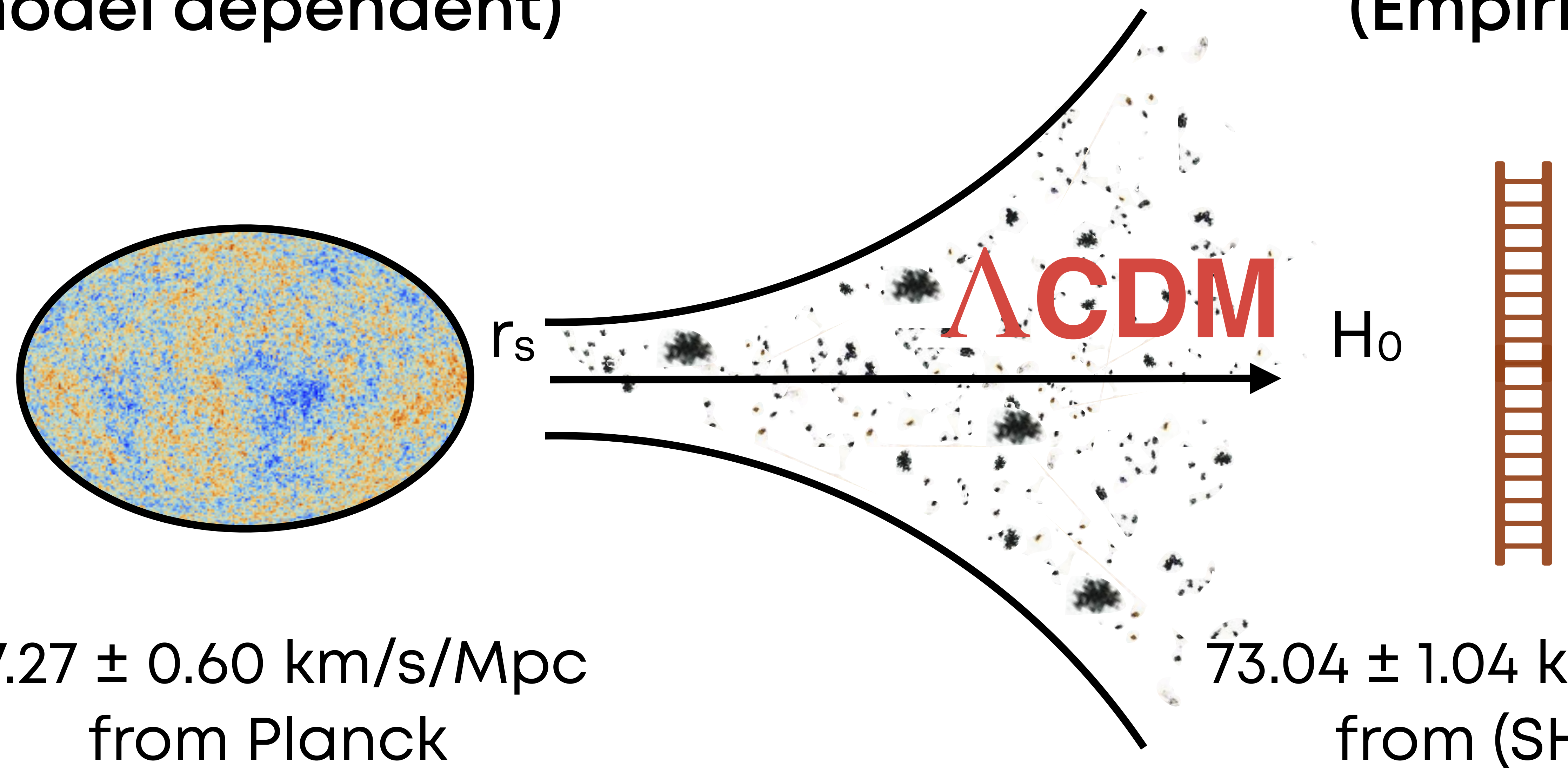


[Cosmoverse white paper arxiv:2504.01669]

Cosmological Tensions

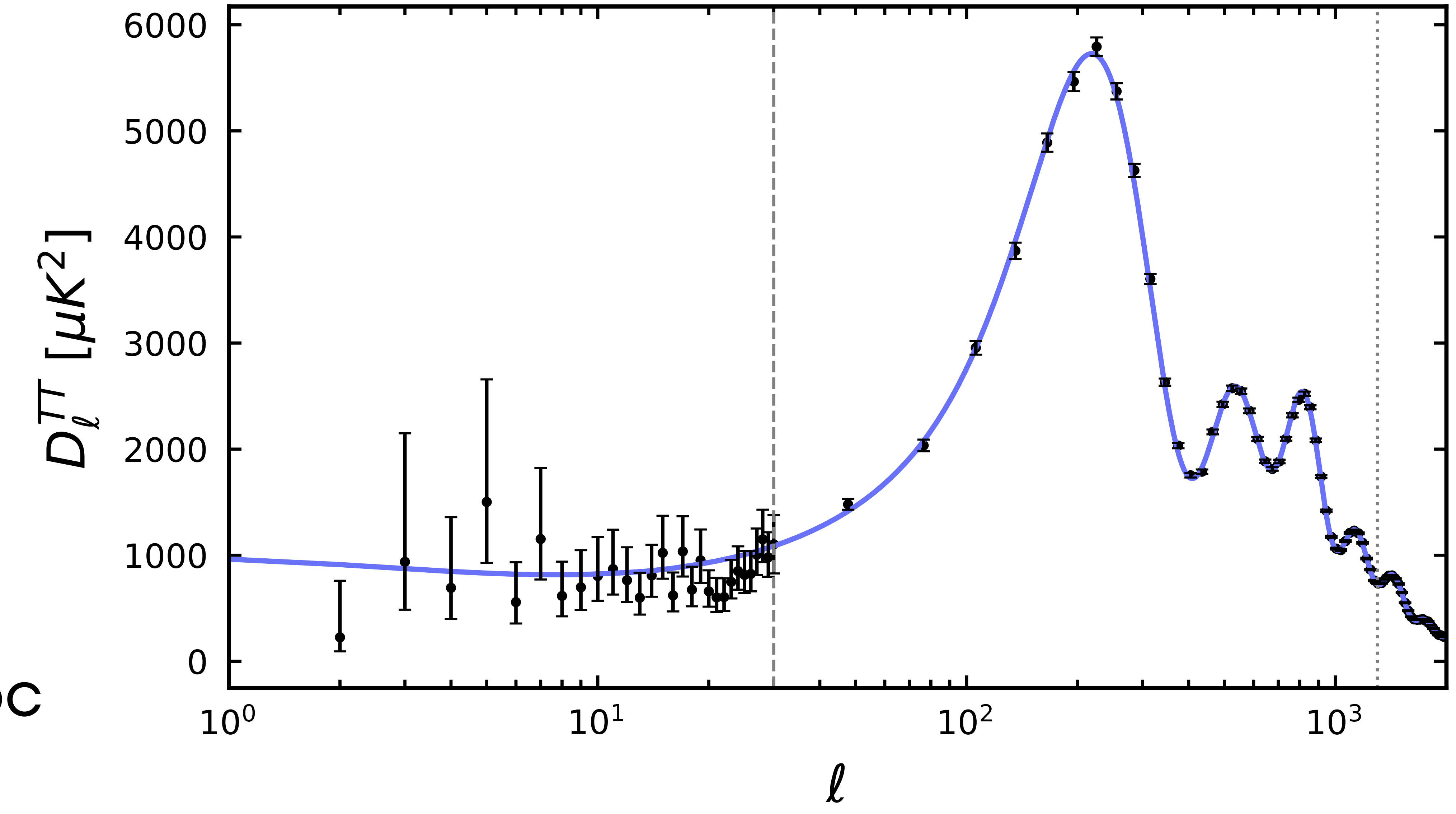
CMB
(model dependent)

Local
(Empirical)



67.27 ± 0.60 km/s/Mpc
from Planck

73.04 ± 1.04 km/s/Mpc
from (SH0ES)

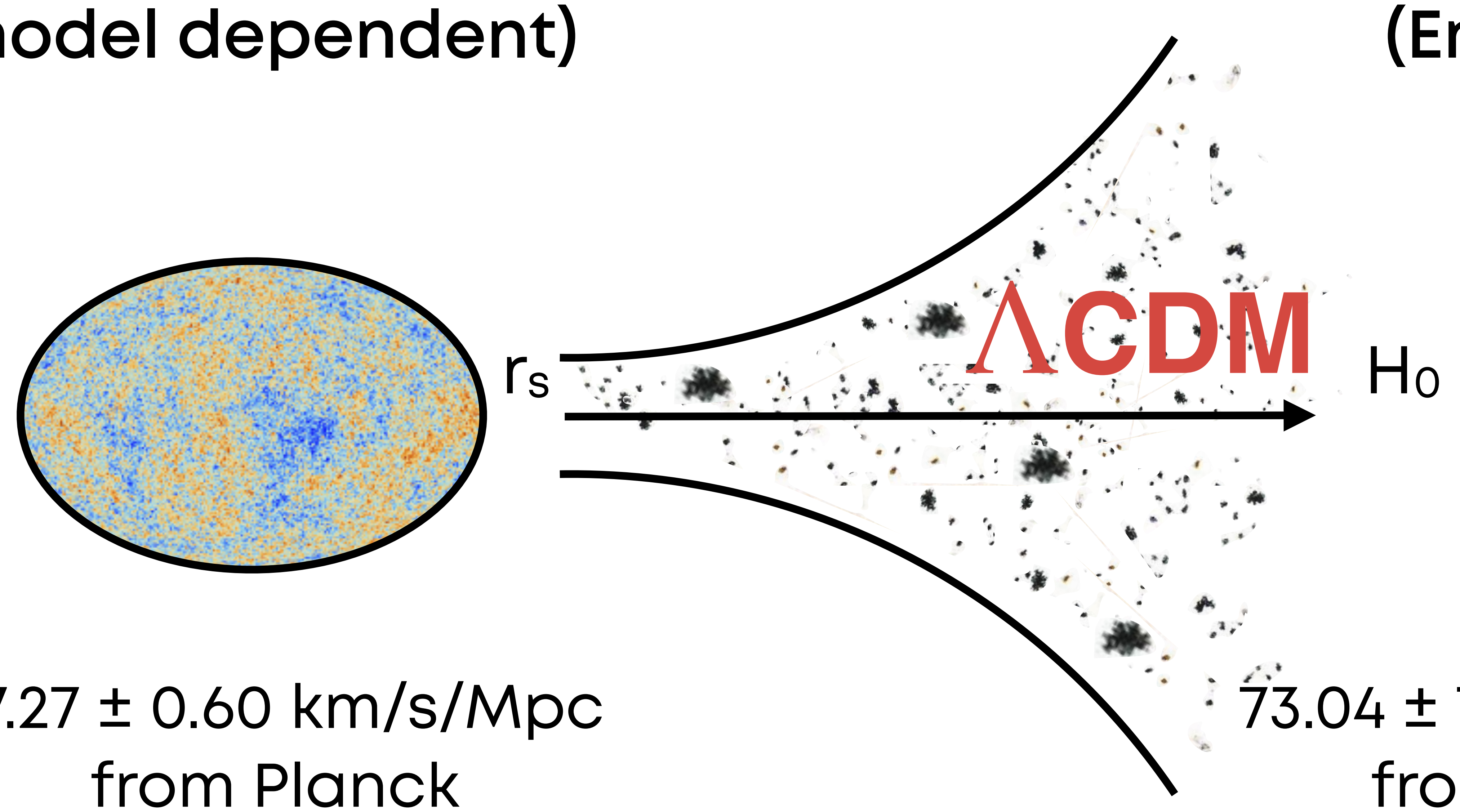


[Aghanim et al.: Astron.Astrophys. 641 (2020) A6]

Cosmological Tensions

CMB
(model dependent)

Local
(Empirical)



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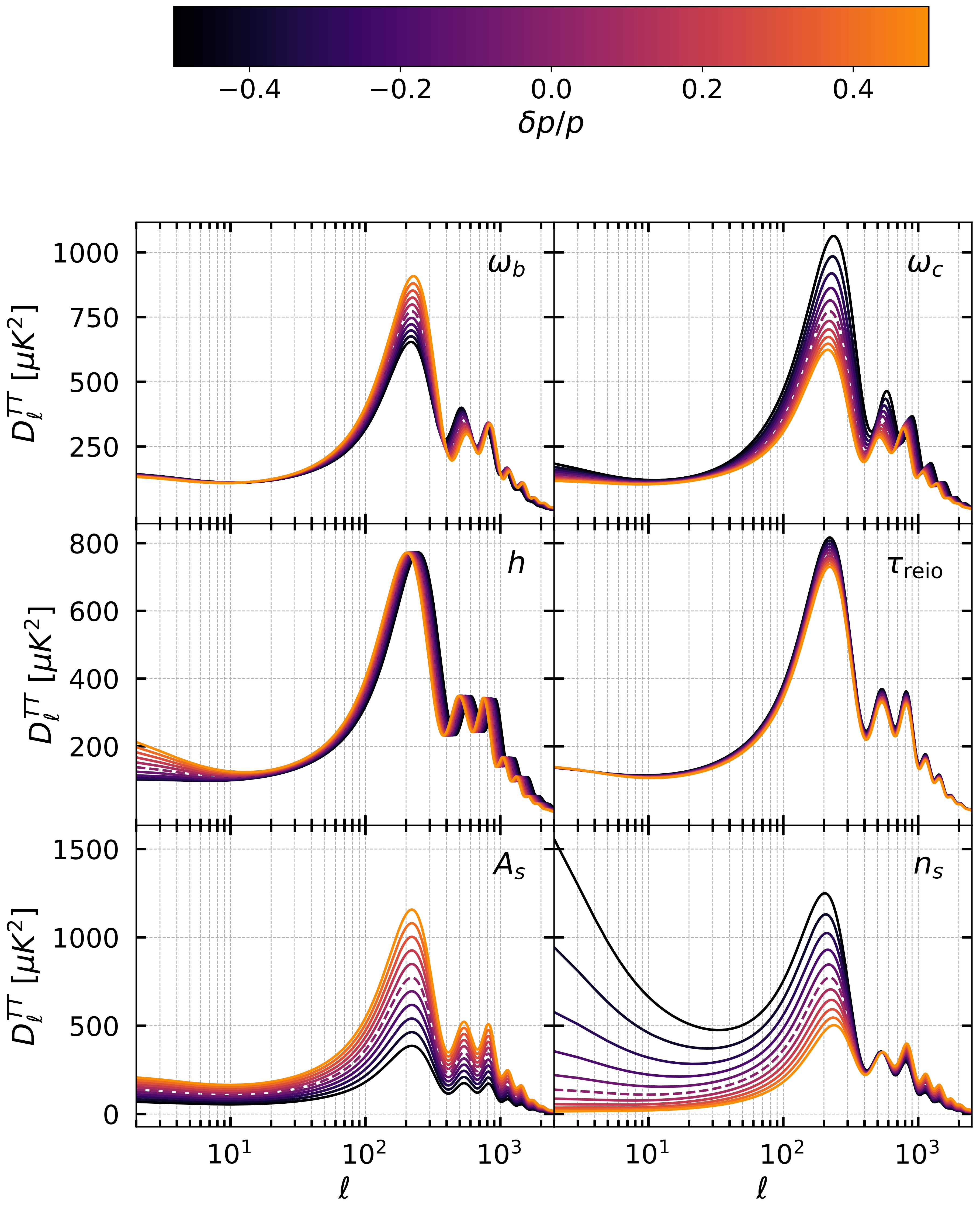
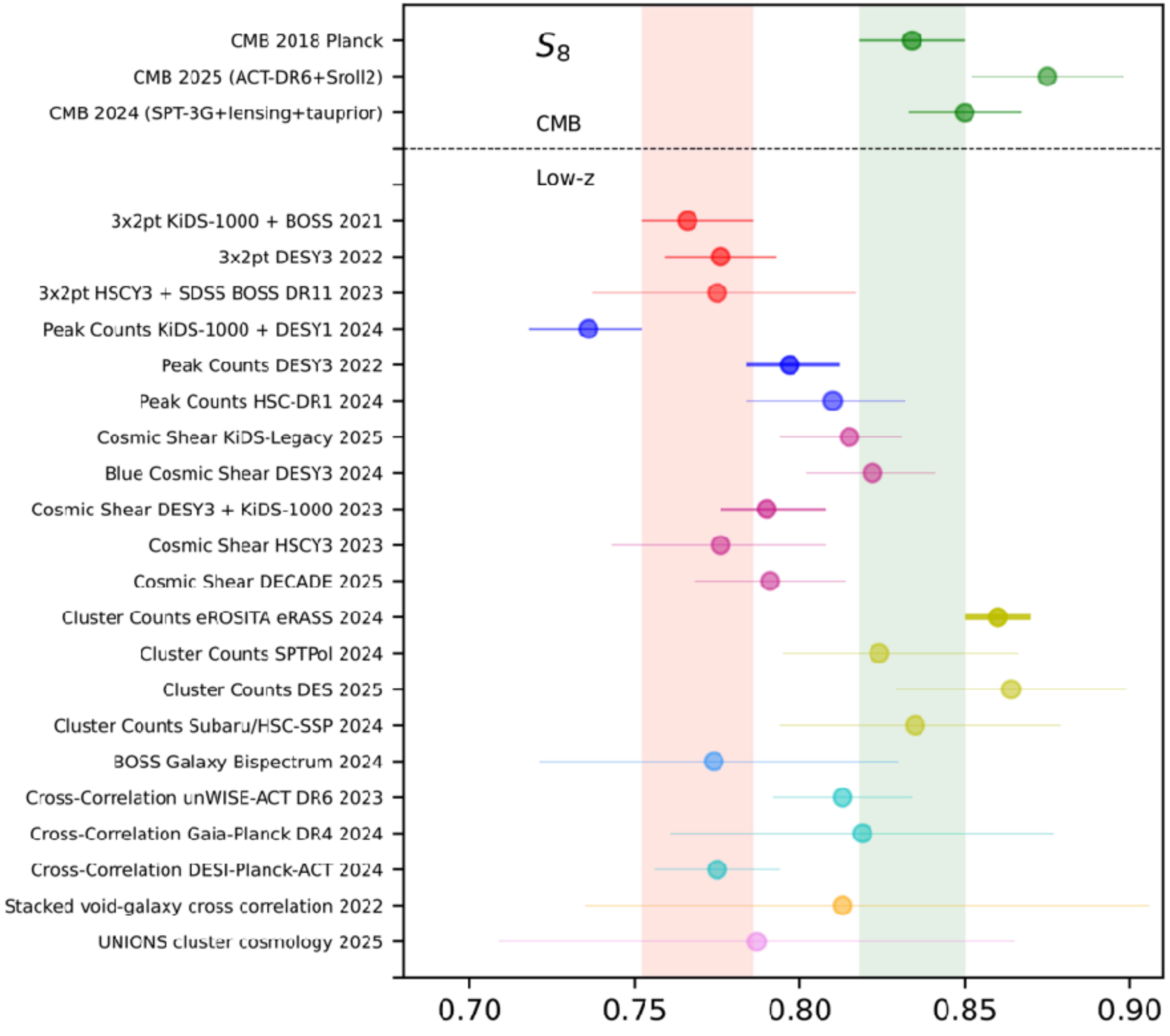


The S_8 Tension

Discrepancy between CMB data and lensing surveys on combined quantity $S_8 = \sigma_8\sqrt{\Omega_m/0.3}$

- $\sim 3\sigma$ tension between Planck 2018 CMB data and KiDS-1000 combination of Cosmic Shear and Galaxy Clustering:
  - CMB (Planck 2018): $S_8 = 0.832 \pm 0.013$
  - Cosmic Shear (DES-Y3): $S_8 = 0.759^{+0.025}_{-0.023}$
- eRosita (eRASS1): $S_8 = 0.86 \pm 0.01$ [Ghirardini et al. 2024]
- Kids-Legacy ($S_8 = 0.815^{+0.016}_{-0.021}$) find possible resolution with Planck but not for the other measurements (improved redshift distribution estimation and calibration, as well as new survey area and improved image reduction)
- Could signal changes in clustering of matter (nature of CDM)

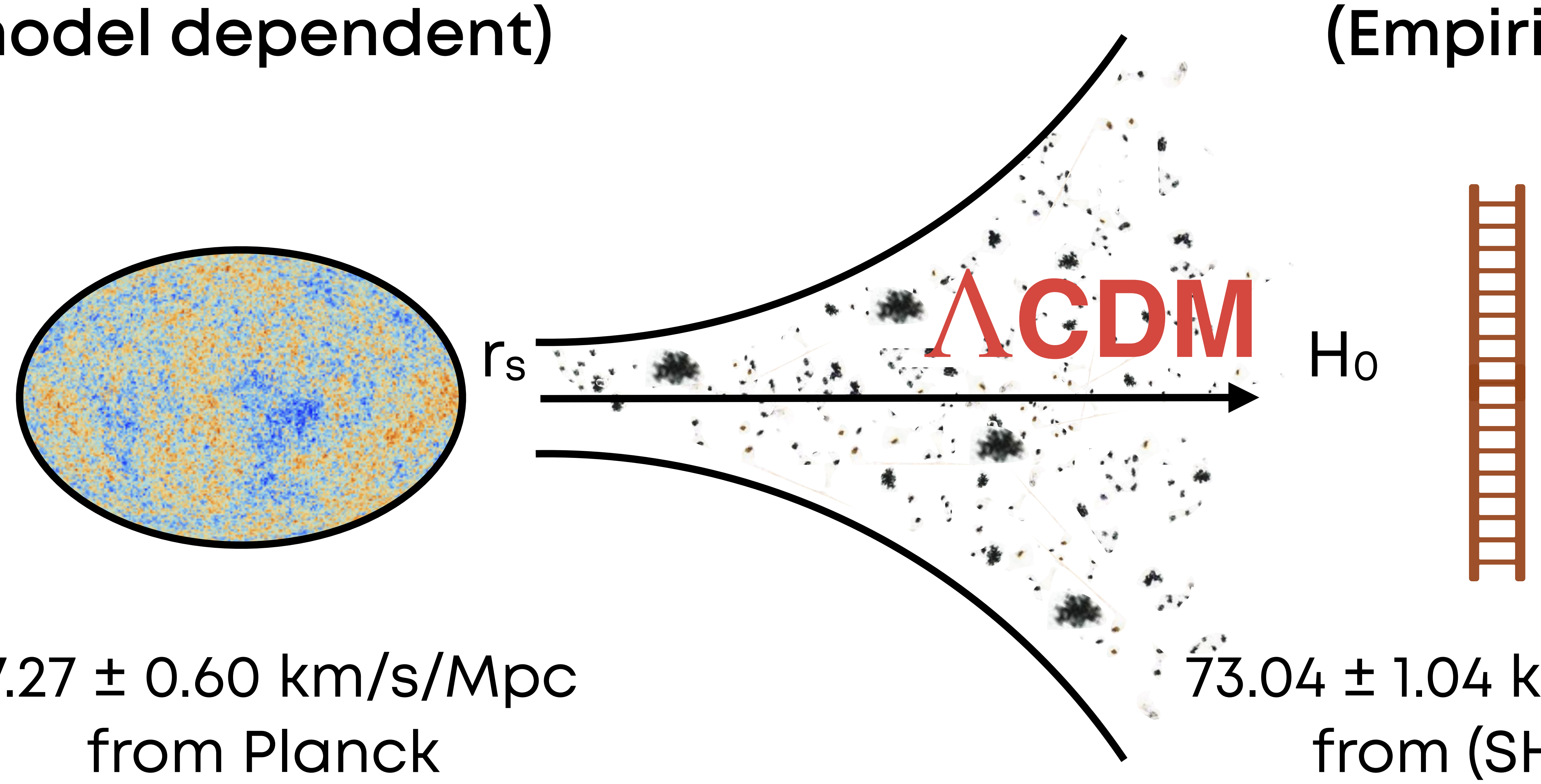


[Cosmoverse white paper arxiv:2504.01669]

Cosmological Tensions

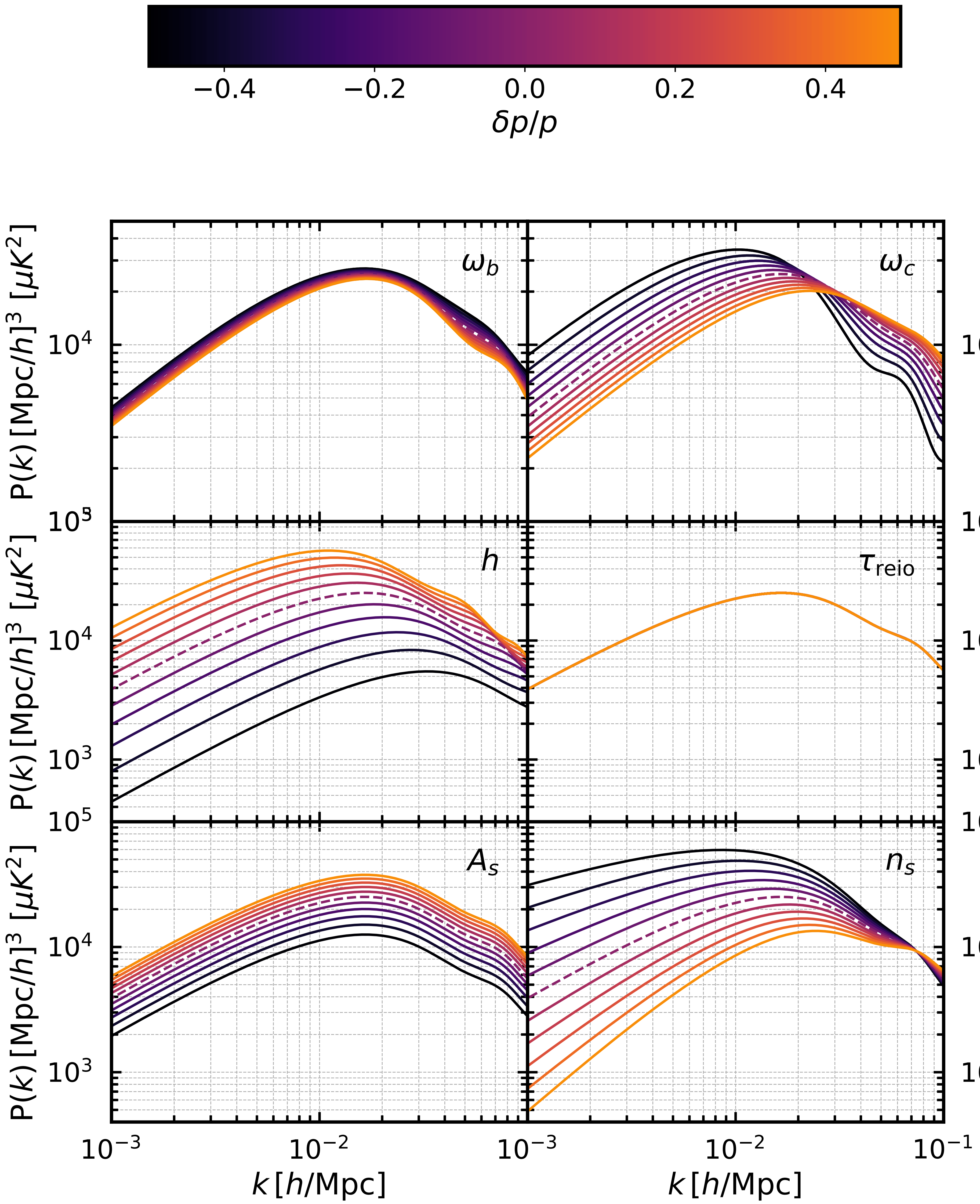
CMB
(model dependent)

Local
(Empirical)



67.27 ± 0.60 km/s/Mpc
from Planck

73.04 ± 1.04 km/s/Mpc
from (SH0ES)



Conformal Transformation

- Simplest way to relate two geometries
- Rescaling of the metric that preserves angles
- Functiona
present in
- Map non-
plus a scalar field ϕ minimally coupled to the geometry
- Preserve the structure of Scalar-Tensor theories of the Jordan-Brans-Dicke form, such as $f(R)$

$$\bar{g}_{\mu\nu} = C(\phi) g_{\mu\nu}$$

[Jordan: Z. Phys. 157 (1959), 112;
Brans and Dicke: Phys. Rev. 124 (1961), 925]

Disformal Transformation

- Distortion of both angles and lengths related with the gradient of ϕ
- The most general covariant effective metric
etric and a
equations
- an is
preserved under disformal transformations
- Many cosmological applications

$$\bar{g}_{\mu\nu} = C(\phi) g_{\mu\nu} + D(\phi) \partial^\mu \phi \partial_\mu \phi$$

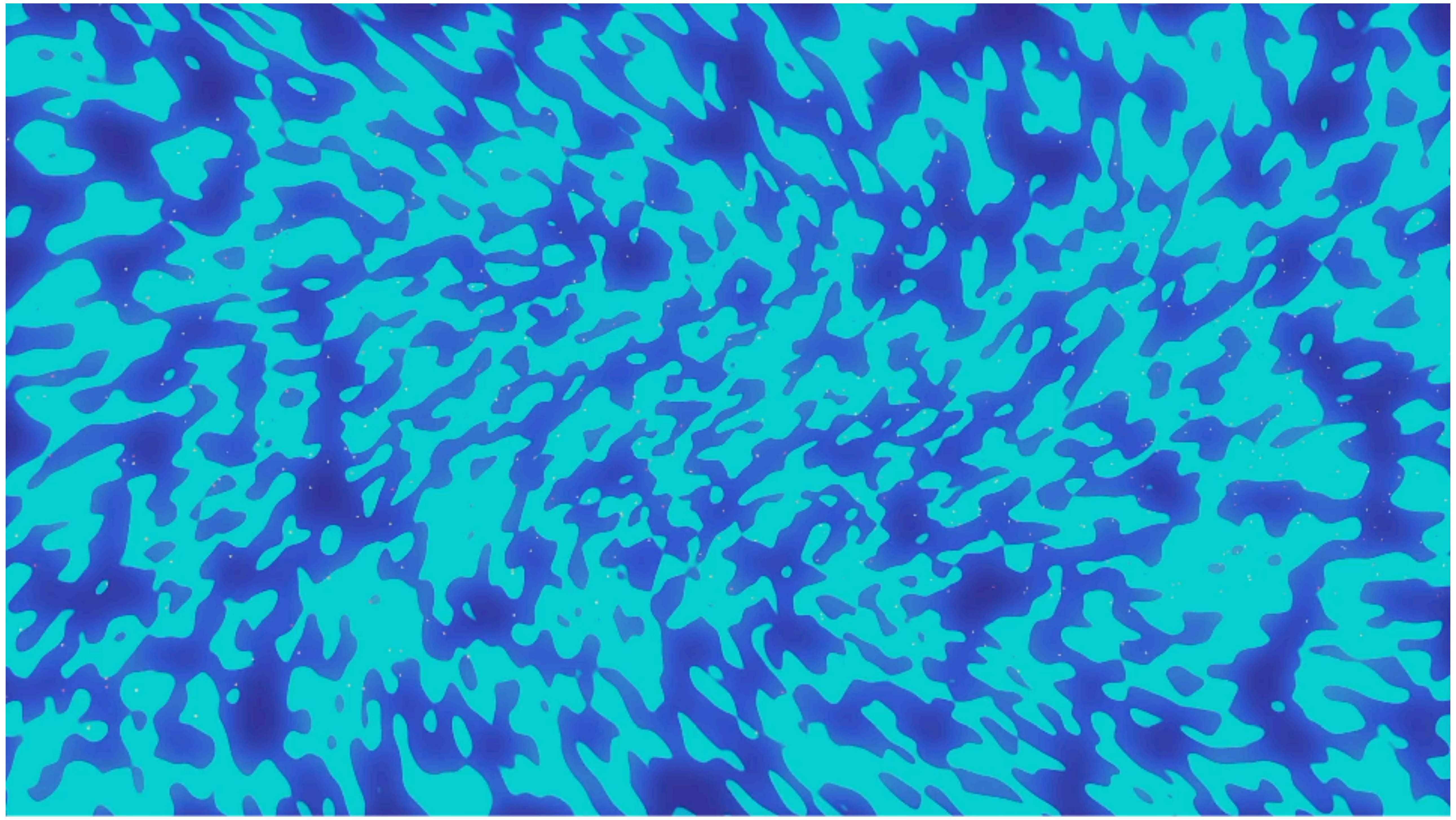
[Bettoni and Liberati: Phys. Rev. D88 (2013) 084020}]

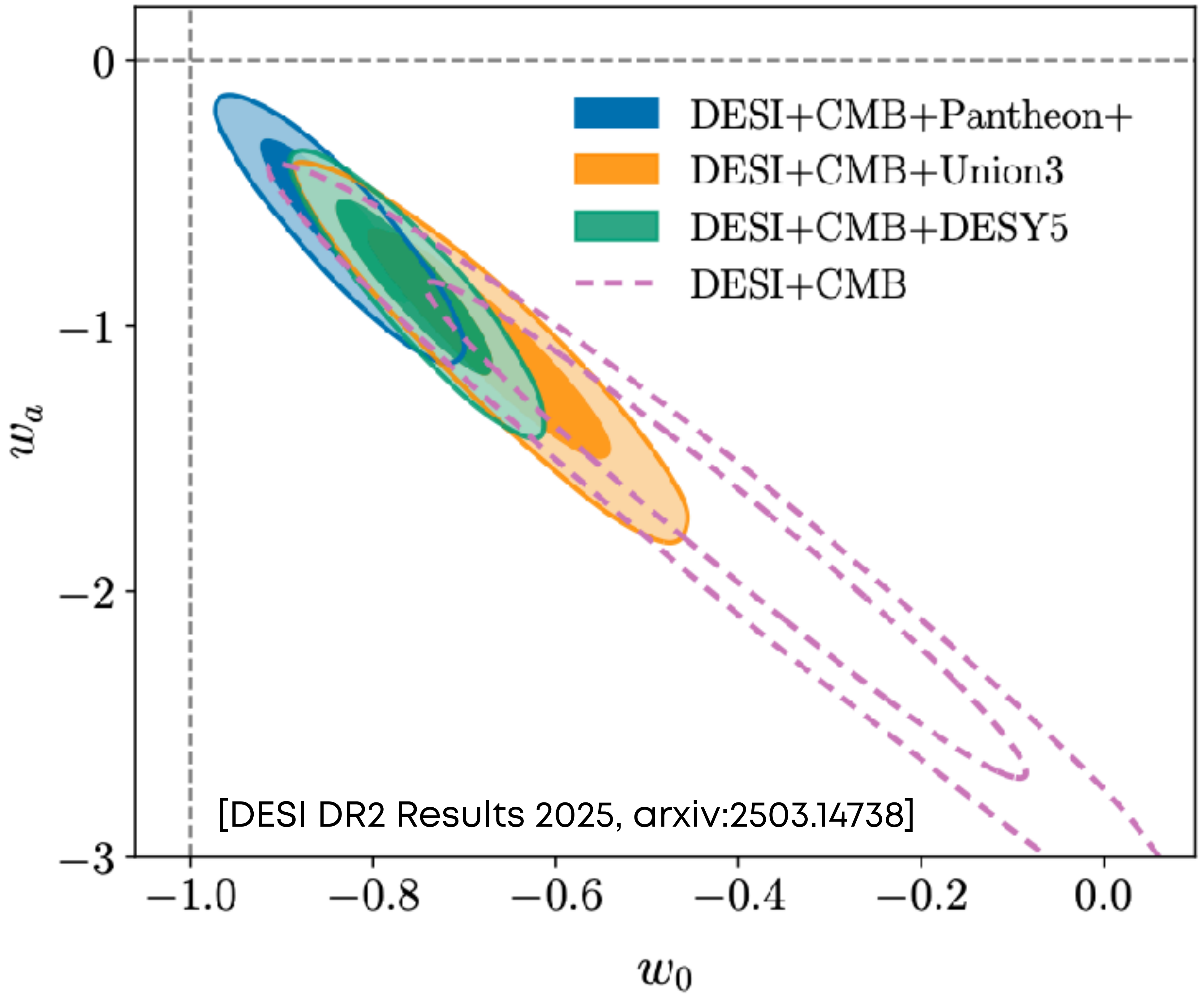
Non-Universal Coupling in the Dark Sector

Extensions to ΛCDM

Hints of dynamical DE in DESI BAO (baryonic accoustic oscillations) data when combined with CMB and SN data

$$\begin{cases} \dot{\rho}_{\mathrm{DE}} + 3H\rho_{\mathrm{DE}}(1 + w_{\mathrm{DE}}) = 0, \\ w_{\mathrm{DE}} = w_0 + w_a(1 - a) \end{cases}$$





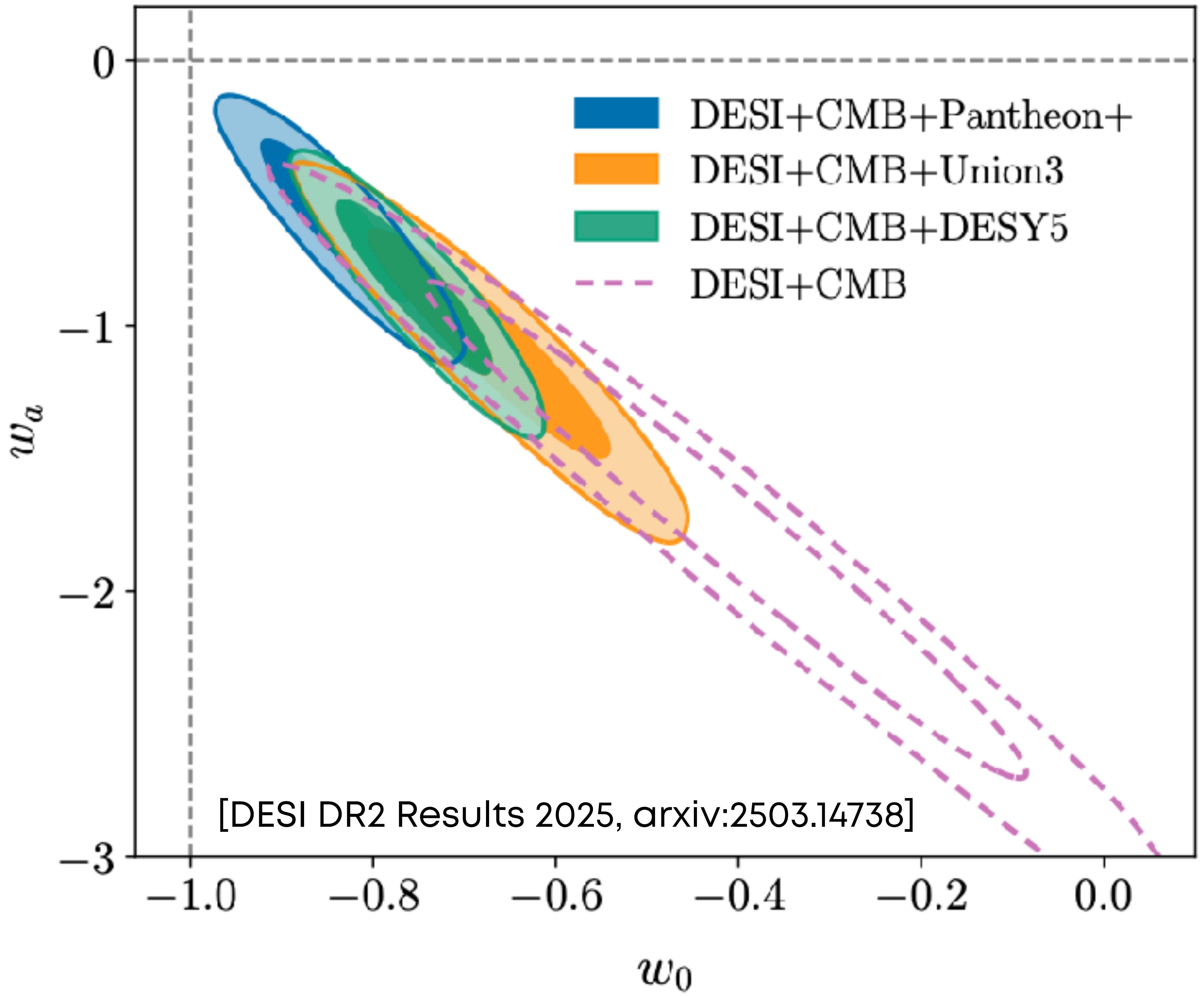
[DESI DR2 Results 2025, arxiv:2503.14738]

Extensions to ΛCDM

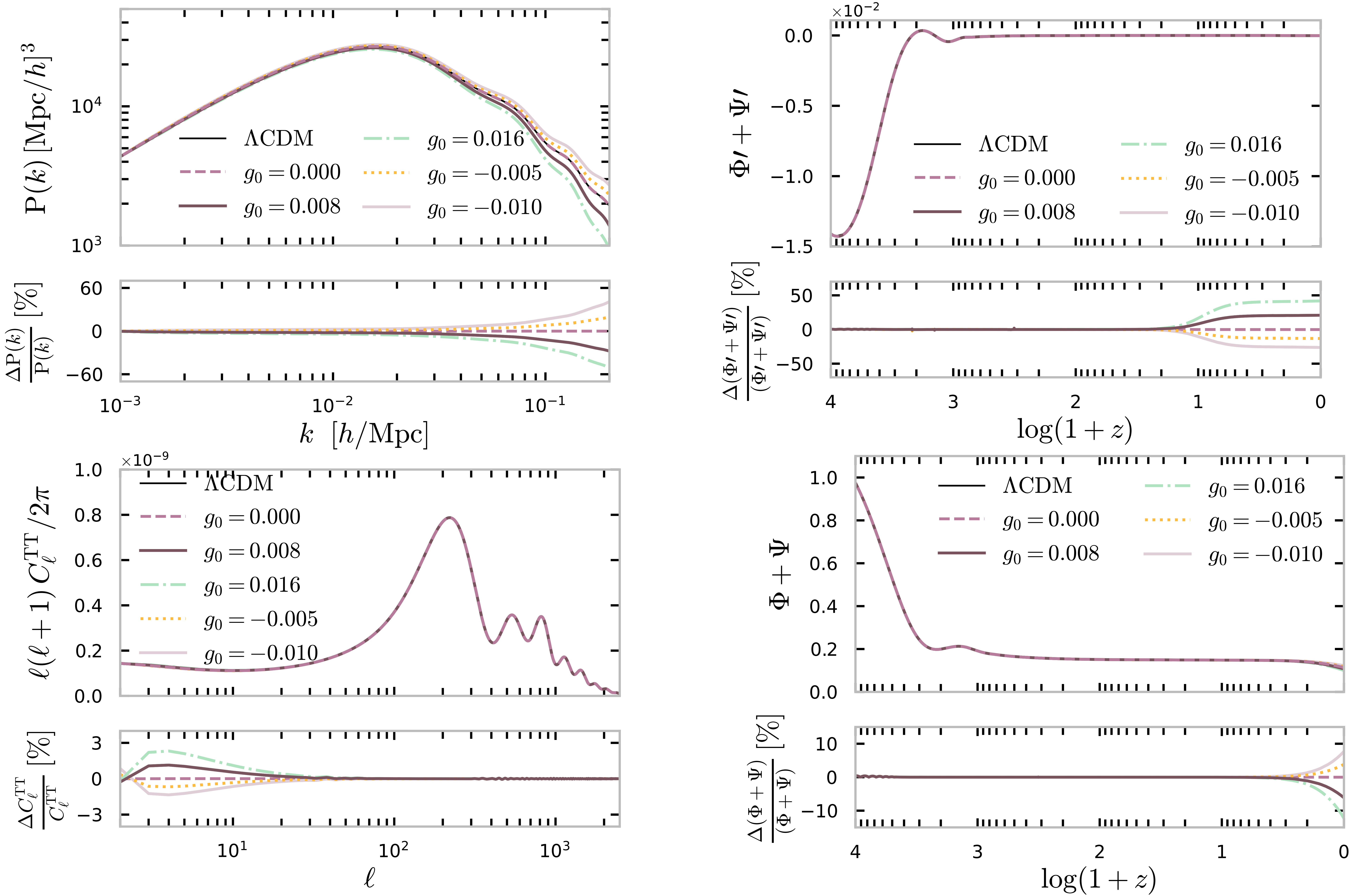
The observational tensions hint at missing ingredients or need for completely new physics

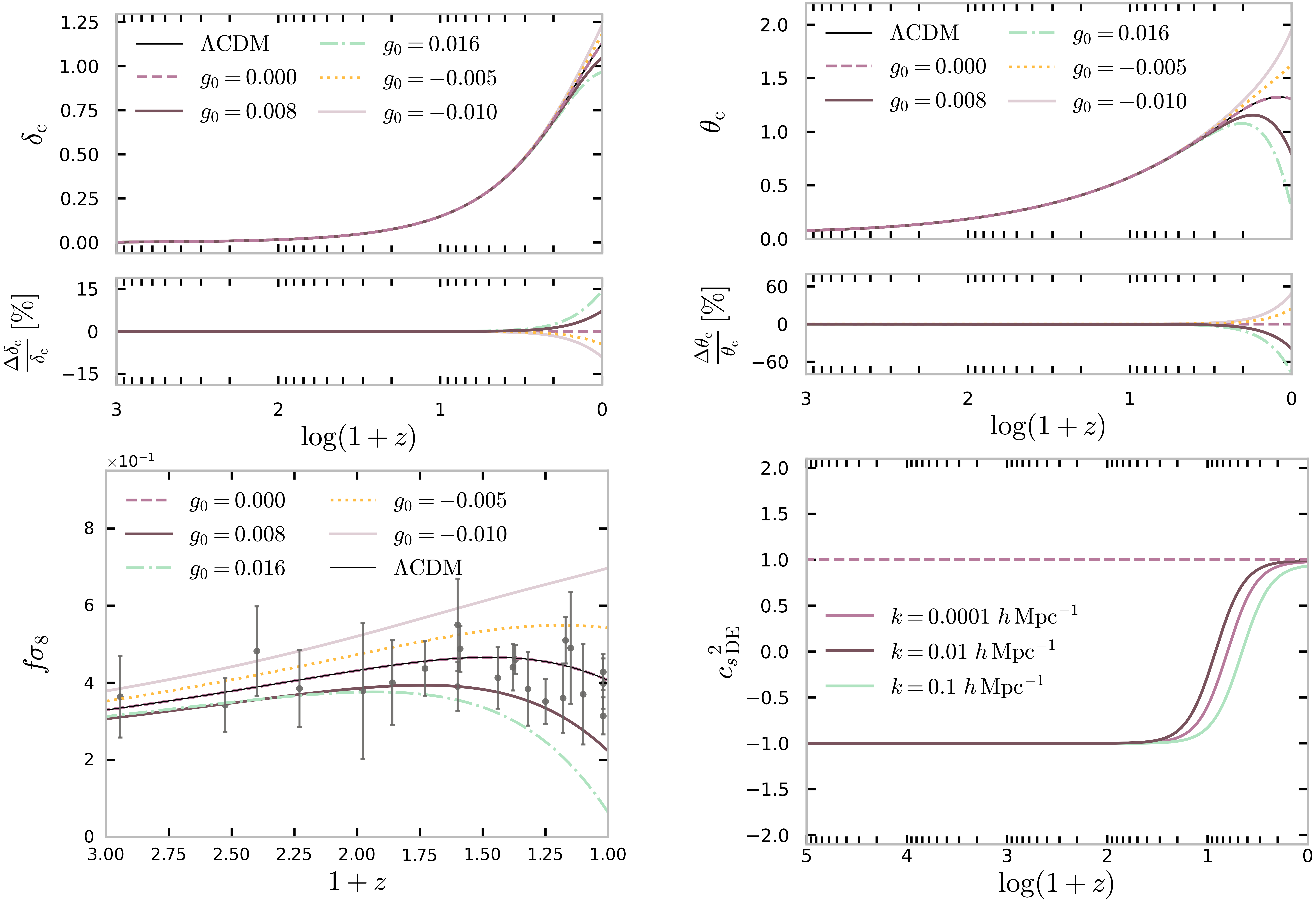
- "Quintessence" (ϕ) - dynamical scalar field that evolves in space and time, as opposed to Λ
- More physically motivated than a parametric fluid
- No fundamental principle/observational constraints which forbid interactions between the dark species
- Modified predictions for the evolution of the dark sector could naturally address the cosmic tensions

$$\begin{cases} \dot{\rho}_\phi + 3H\rho_\phi(1+w_\phi) = 0, \\ \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi), \quad p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi) \end{cases}$$



[DESI DR2 Results 2025, arxiv:2503.14738]


$P(k)$ [Mpc/h]^3
$\frac{\Delta P(k)}{P(k)}$ [%]
k [h/Mpc]
ΛCDM
$g_0 = 0.000$
$g_0 = 0.008$
$g_0 = 0.016$
$g_0 = -0.005$
$g_0 = -0.010$
$\Phi\prime + \Psi\prime$
$\frac{\Delta(\Phi\prime+\Psi\prime)}{(\Phi\prime+\Psi\prime)}$ [%]
$\log(1+z)$
$\ell(\ell+1)\,C_\ell^{TT}/2\pi$
$\frac{\Delta C_\ell^{TT}}{C_\ell^{TT}}$ [%]
ℓ
$\Phi + \Psi$
$\frac{\Delta(\Phi+\Psi)}{(\Phi+\Psi)}$ [%]


ΛCDM
$g_0 = 0.000$
$g_0 = 0.008$
$g_0 = 0.016$
$g_0 = -0.005$
$g_0 = -0.010$
δ_c
$\frac{\Delta\delta_c}{\delta_c}$ [%]
θ_c
$\frac{\Delta\theta_c}{\theta_c}$ [%]
$\log(1+z)$
$\times 10^{-1}$
$f\sigma_8$
$1+z$
$c^2_{s\,\mathrm{DE}}$
$k = 0.0001\ h\,\mathrm{Mpc}^{-1}$
$k = 0.01\ h\,\mathrm{Mpc}^{-1}$
$k = 0.1\ h\,\mathrm{Mpc}^{-1}$