JOHNS HOPKINS UNIVERSITY

Looking for ultra-light axion-like particles in the CMB

Vivian Poulin - Johns Hopkins University

In collaboration with
T. Smith (Swarthmore U.), D. Grin (Haverford C.), T. Karwal & M. Kamionkowski (JHU); 1806.10608

Identification of Dark Matter, Brown University, Providence RI
24 July 2018

Introductory Remarks

- I am a cosmologist! I will enter (very) little into particle physics details.

- "axion-like particles"(ALP): our results can be applied to specific axion models, but generally concern any light scalar field with oscillating potential.

- This talk focuses on linear observables, especially CMB.

- Best constraints on the minimal mass of axion (fuzzy) DM is actually coming from non-linear observables due to power suppression below Jeans scale ~ de Broglie wavelength of the ground state of a particle in the potential well.

Hu++ astro-ph/0003365

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- ALP can play many roles in Cosmology: from the inflaton to Dark Energy, including Dark Matter. What if all theses new "dark" sectors were connected to each other?

  review Marsh, Phys.Rept. 643 (2016)

- It could explain why accelerated expansion is happening now. Within a specific realization of the axiverse: 1/100 chance to have accelerated expansion today.

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  Karwal&Kamionkowski, PRD94 (2016) no.10, 103523; Hill&Baxter, 1803.07555

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=> SEE TALK BY T. KARWAL ON THURSDAY

what are ultra-light axion like particles?

- We consider generic potential: $V_n(\phi) = \Lambda^4(1-\cos(\phi/f))^n$
- new U(1) global symmetry spontaneously broken at scale f: residual angular degree of freedom with shift symmetry is the axion. Λ the non-perturbative physics scale which leads to the axion mass $m_a \approx \Lambda^2/f$.
- Axion in QCD: originally introduced by Peccei-Quinn as a solution to the strong CP problem. $\Lambda = \Lambda_{QCD}$, f~EW, $m_a \sim 6*10^{-6}$ eV (10^{12}GeV/f), *Peccei&Quinn PRL 38 (1977)*
- In string theory, the "Axiverse": Many axion fields from compactification of extra-dimensions. *Svrcek&Witten hep-th/0605206, Arvanitaki++ 0905.4720*
- Typical mass range interesting for us [10^{-33},10^{-23}].
- Most studies have focused on n = 1. We extend former work to n > 1 as it has many interesting phenomenological consequences and can evade CDM constraints.
Hu++ astro-ph/0003365, Hlozek++ 1410.2896, Hlozek++ 1708.05681

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Background evolution of ALP

Marsh, 1510.07633

- Energy density/pressure of the field: $\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_n(\phi),\ P_\phi = \frac{1}{2}\dot{\phi}^2 - V_n(\phi)$
- The KG equation governs the field dynamics: $\ddot{\phi} + 3H\dot{\phi} + \frac{dV_n(\phi)}{d\phi} = 0$

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- If 3H dominates over V', the field is frozen -> Dark Energy $w \equiv \frac{P_\phi}{\rho_\phi} = -1$
- If it is negligible the field will start oscillating and dilutes with $w = \frac{n-1}{n+1}$

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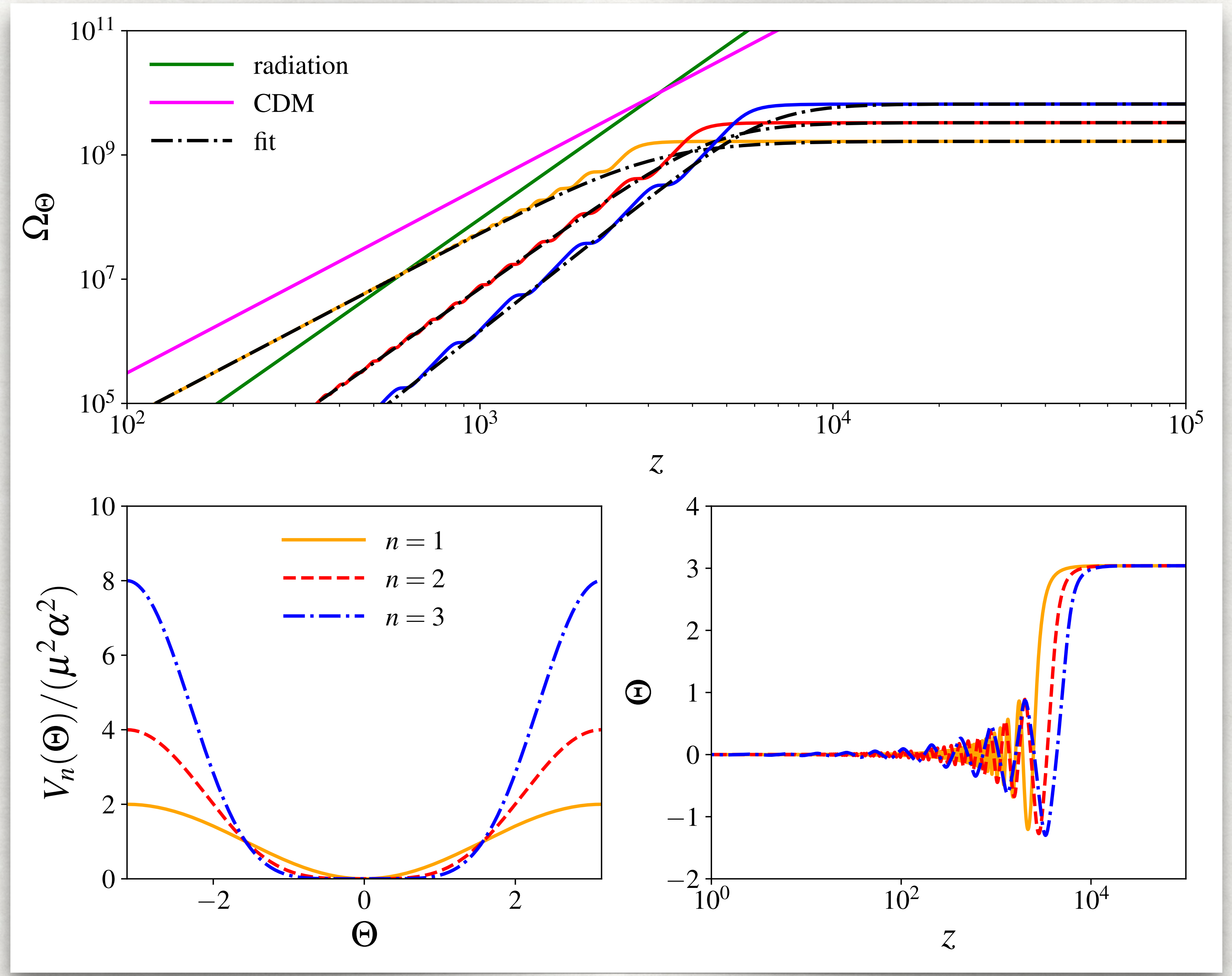
- Problem: solution of KG equations show oscillations that can be difficult to resolve numerically (stiff system) if $\omega >> H/\Gamma$ (the typical scale involved in a Boltzmann code).
- Solution: We develop a parametrization based on time-averaging the KG equation that describes the ALP dynamics as a perfect fluid. 4 parameters: ($\Omega_{alp,o}$, a_c, w_n, c_s^2).
- We are able to map our parametrization to axion model parameters (θ_i, m_a, f, n)

Homogeneous evolution

VP, Smith, Grin, Karwal, Kamionkowski; 1806.10608

$$\Omega_a(z) = \frac{2\Omega_a(z_c)}{[(1+z_c)/(1+z)]^{3(w_n+1)} + 1}$$

$$w_a(z) = \frac{1+w_n}{1+[(1+z)/(1+z_c)]^{3(1+w_n)}} - 1,$$



When is this approximation valid?

VP, Smith, Grin, Karwal, Kamionkowski; 1806.10608

- Our WKB approximation requires oscillation time-scale << Hubble time-scale

- The oscillation time-scale can be obtained from requiring that energy is conserved over several oscillations (no friction).

$$\frac{\varpi}{H} \propto \begin{cases} a^{(5-n)/(1+n)} & a < a_{\rm eq}, \\ a^{6/(1+n)-3/2} & a > a_{\rm eq}, \end{cases}$$

see also Johnson and Kamionkowski, 0805.1748

- This ratio increases with time for n < 5 during radiation domination and for n < 3 for matter domination.

- The condition ω > H holding at all time requires n < 3.

Perturbations of the ALP

VP, Smith, Grin, Karwal, Kamionkowski; 1806.10608

- CMB requires calculation of axion perturbations

$$\ddot{\phi}_1 + 3H\dot{\phi}_1 + \left(\frac{k^2}{a^2} + V''\right)\phi_1 = (\dot{A} + 3\dot{H}_L - k/aB)\dot{\phi}_0 - 2AV'$$

Beltran++ hep-ph/0606107

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- Using the WKB approx.: we derive the sound speed of such ALPs, which controls the growth of density perturbations.

$$c_s^2 \equiv \frac{\langle \delta P_\phi \rangle}{\langle \delta \rho_\phi \rangle} = \frac{2a^2(n-1)\omega^2 + k^2}{2a^2(n+1)\omega^2 + k^2}.$$

- This sound-speed reduces to the known result when n = 1 and generalizes it for any power of n.

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- The adiabatic sound speed c_a^2 is derived from w'.

- We can use the GDM formalism to calculate perturbation dynamics.

Hu astro-ph/9801234

- We assume adiabatic initial perturbations. Conservative! IC modes to be included.

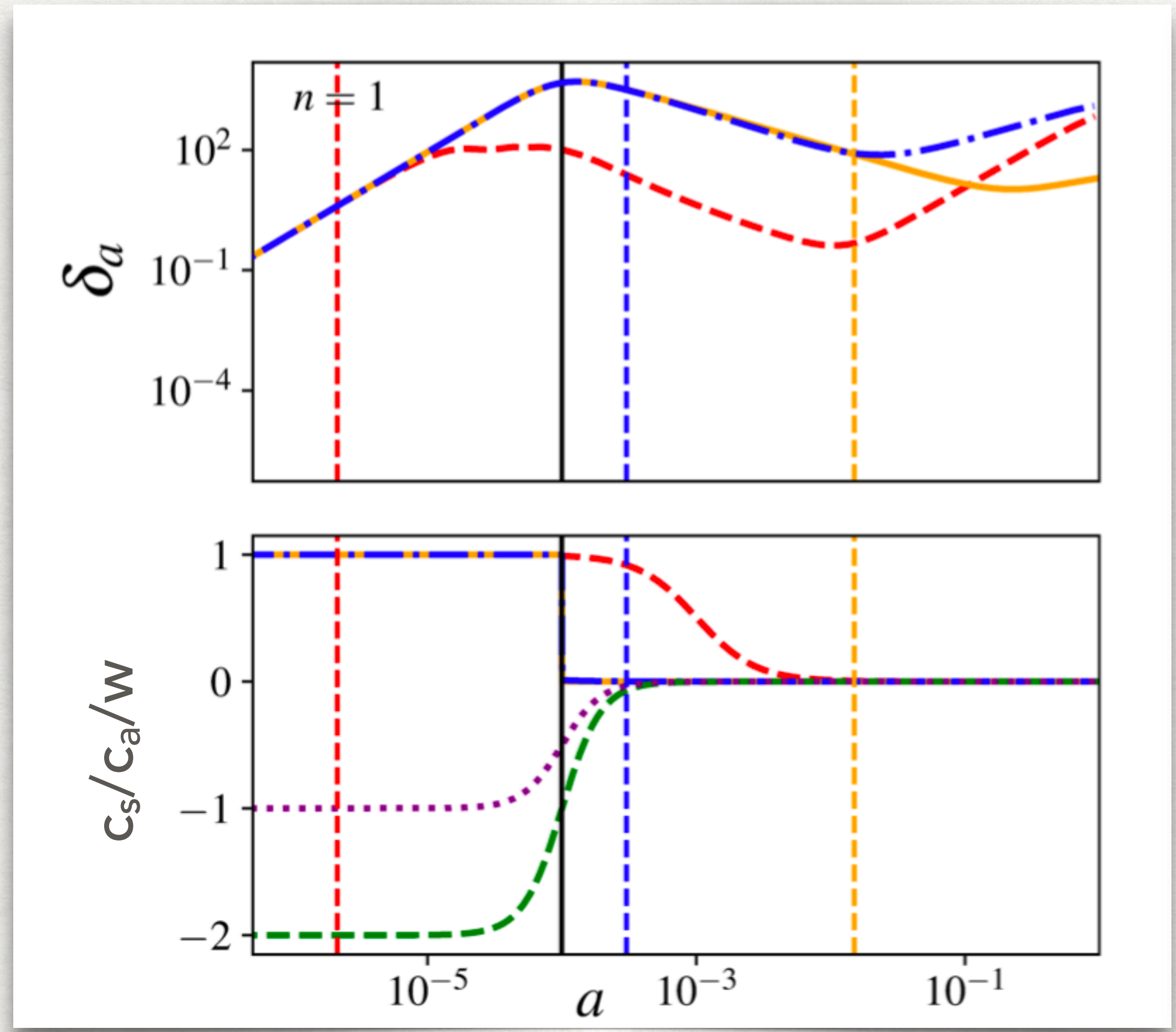
Beltran++ hep-ph/0606107

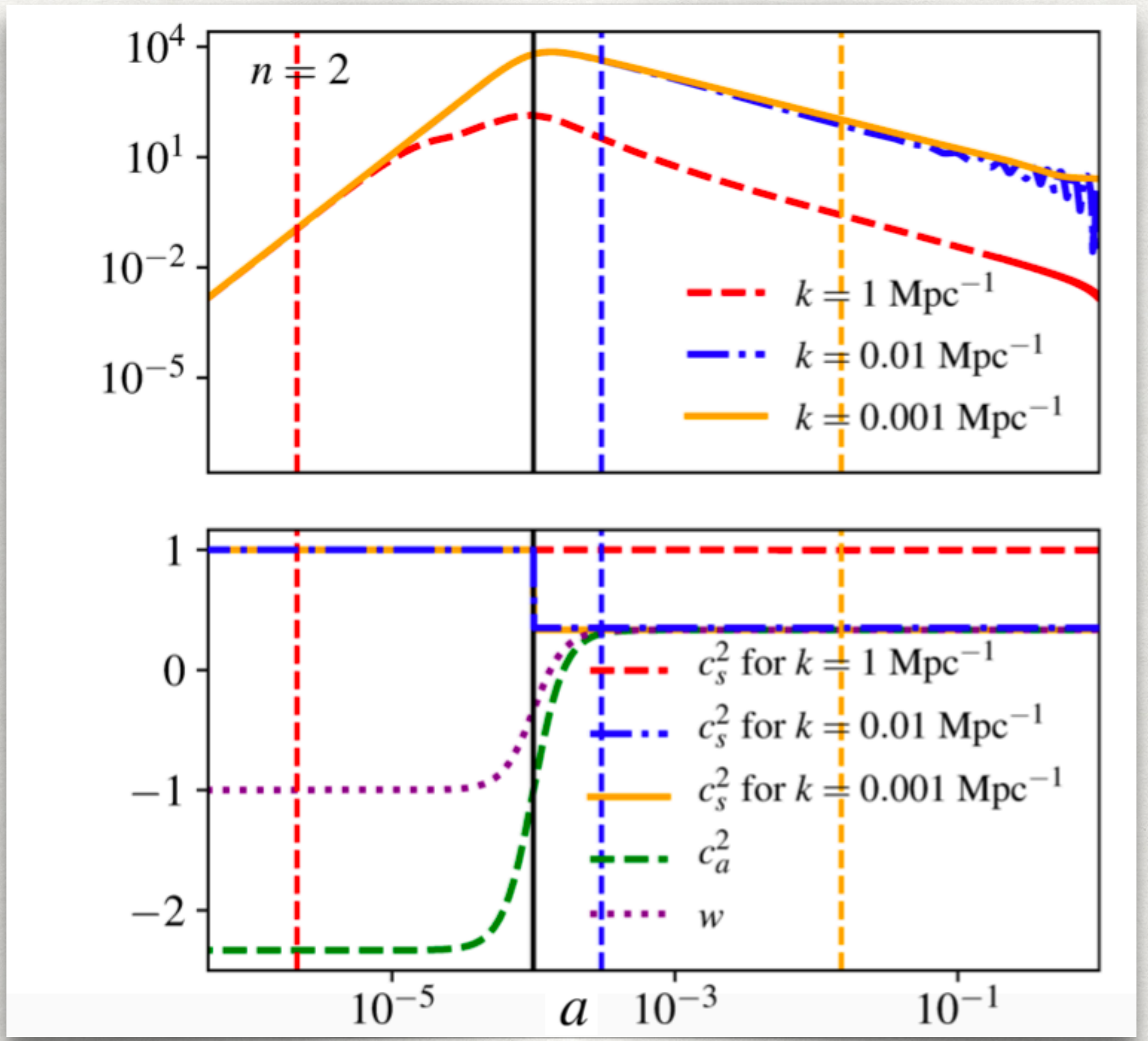
Density perturbations for ac = 0.001

VP, Smith, Grin, Karwal, Kamionkowski; 1806.10608

<u>3 scales in the problem:</u>

- a_c (w = -1 to w_n): identical for each k
- a_k, Hubble horizon crossing and a_s (cs = 1 to w): different for each k





n=3 similar to n=2; slightly different oscillation frequency (3/2).

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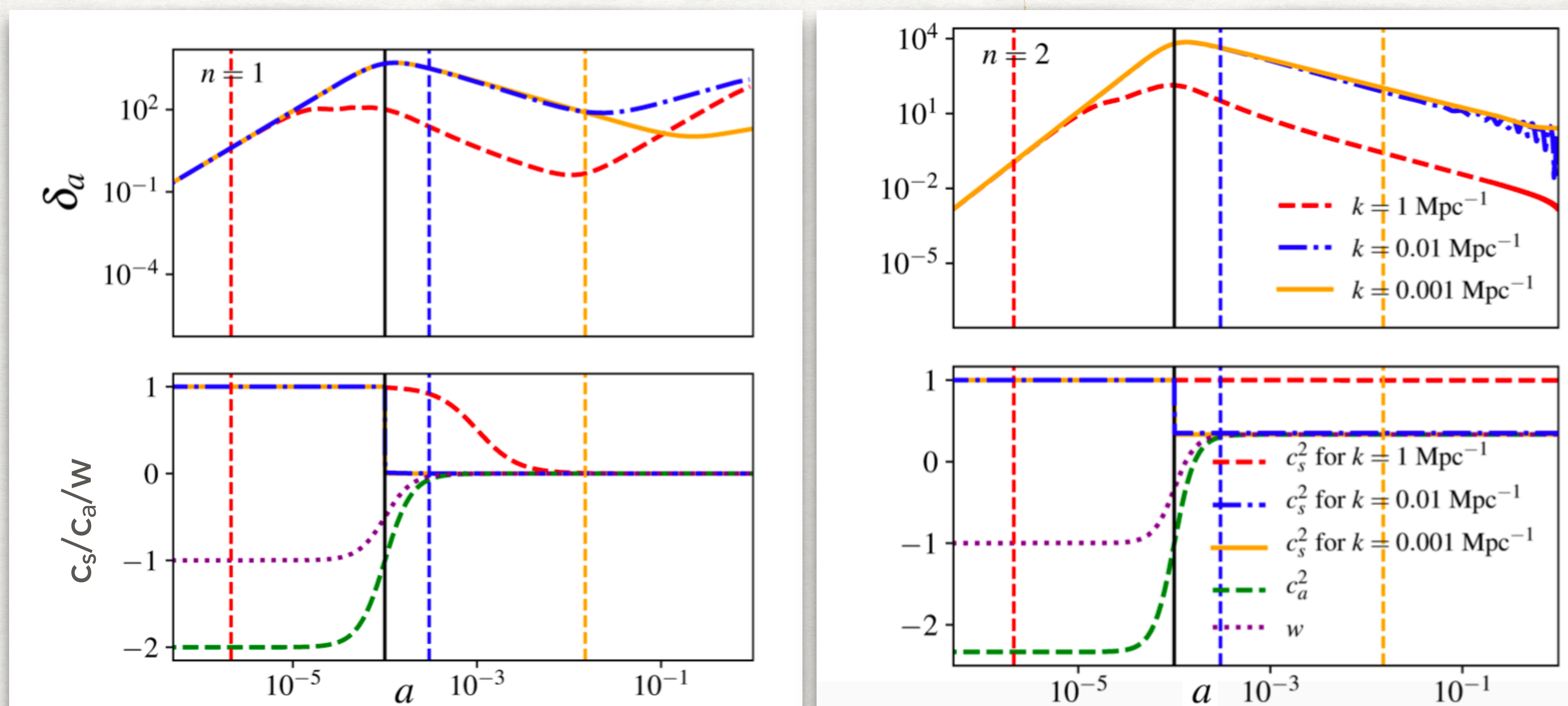

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How can a decoupled species affect the CMB?

See e.g. book by Lesgourgues ++ "neutrino cosmology"

I) affect the background expansion $H(z) = H_0\sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_a(z)}$

- ULA affect the angular scale of sound horizon θ_s and the scale of Silk damping θ_d.
- Both scales cannot kept fixed simultaneously! keeping θ_s fixed lead to a change in θ_d.

II) affect the evolution of perturbations through its impact on gravitational potential wells

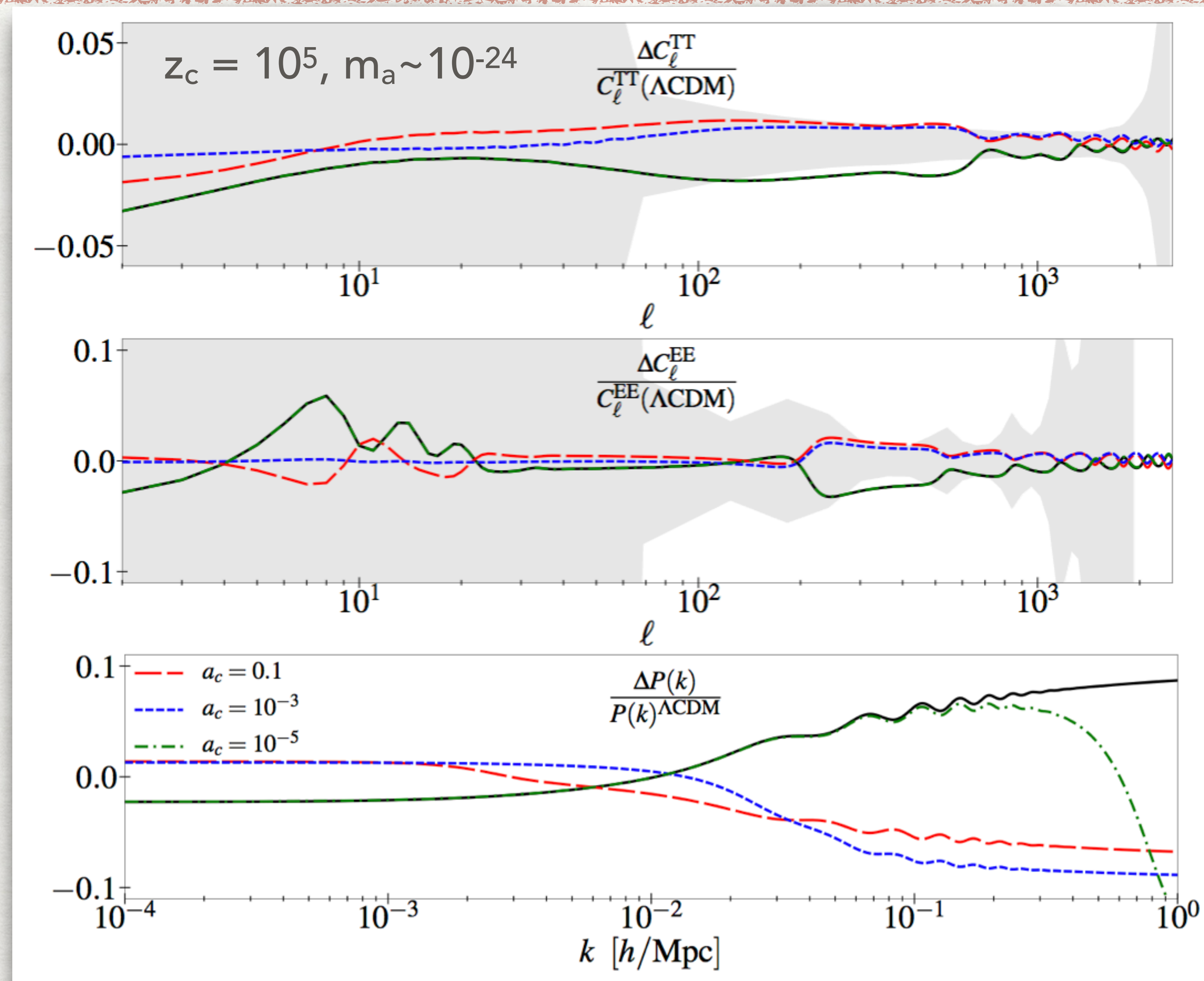
$$C_\ell = \int \frac{dk}{k}\mathcal{P}_\mathcal{R}(k)[\Theta_\ell(\tau_0,k)]^2 \quad \texttt{with} \quad \Theta_\ell(\tau_0,k) = \int_\tau^{\tau_0} d\tau S_T(\tau,k) j_\ell(k(\tau_0-\tau))$$

$$S_T(k,\tau) \equiv \underbrace{g(\Theta_0+\psi)}_{\text{SW}} + \underbrace{(gk^{-2}\theta_B)'}_{\text{Doppler}} + \underbrace{e^{-\kappa}(\phi'+\psi')}_{\text{ISW}} + \text{polarisation}$$

- Leads to ISW effect
- Affect lensing of CMB power spectra

CMB and matter power spectra with ULA

VP, Smith, Grin, Karwal, Kamionkowski; 1806.10608



Fields becomes dynamical at early times: all powers of n lead to distinct imprints!

- n = 1: similar to CDM on CMB scales but power suppression in P(k).
- n = 2 and n = 3: similar but distinguishable from ΔNeff.

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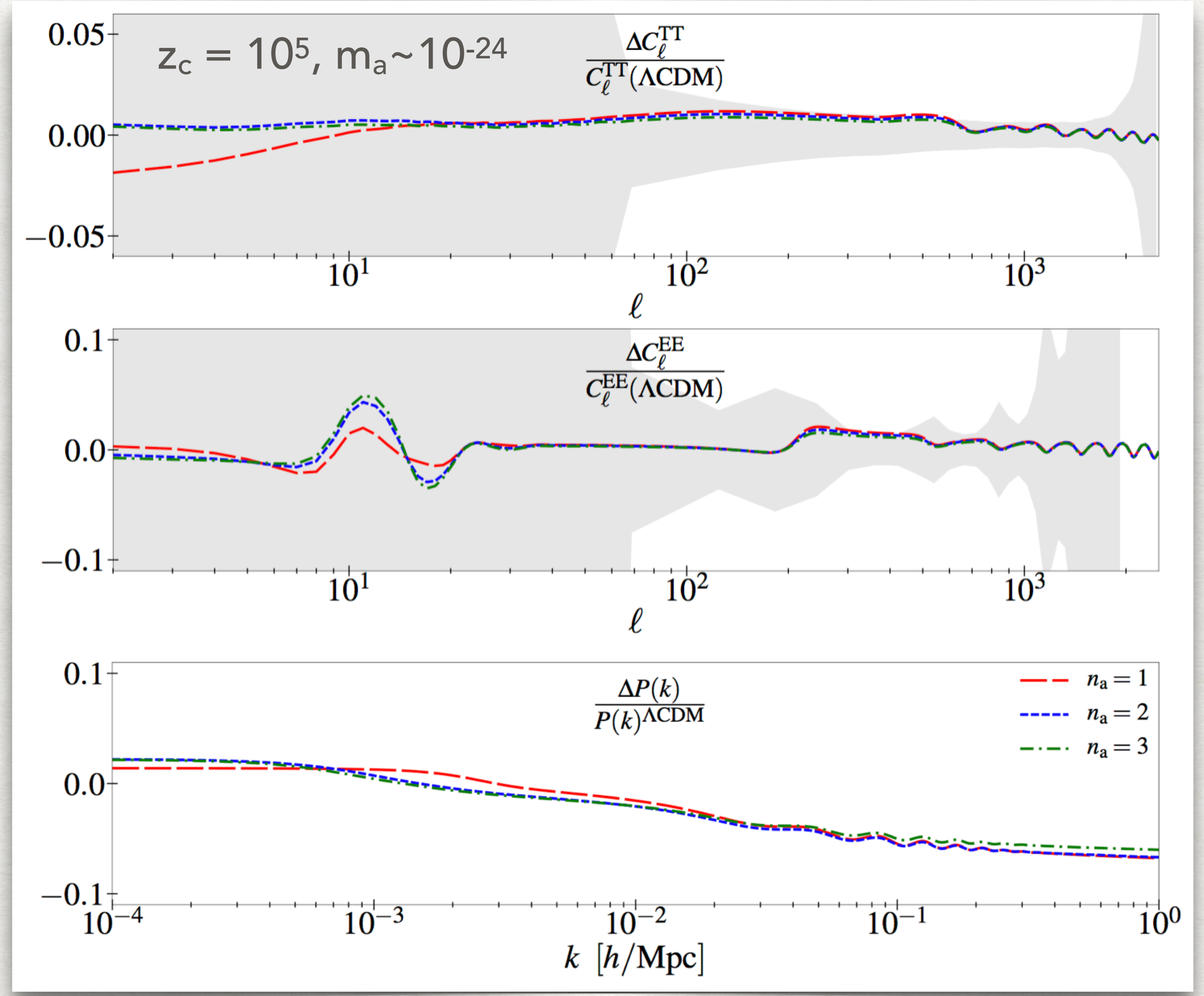
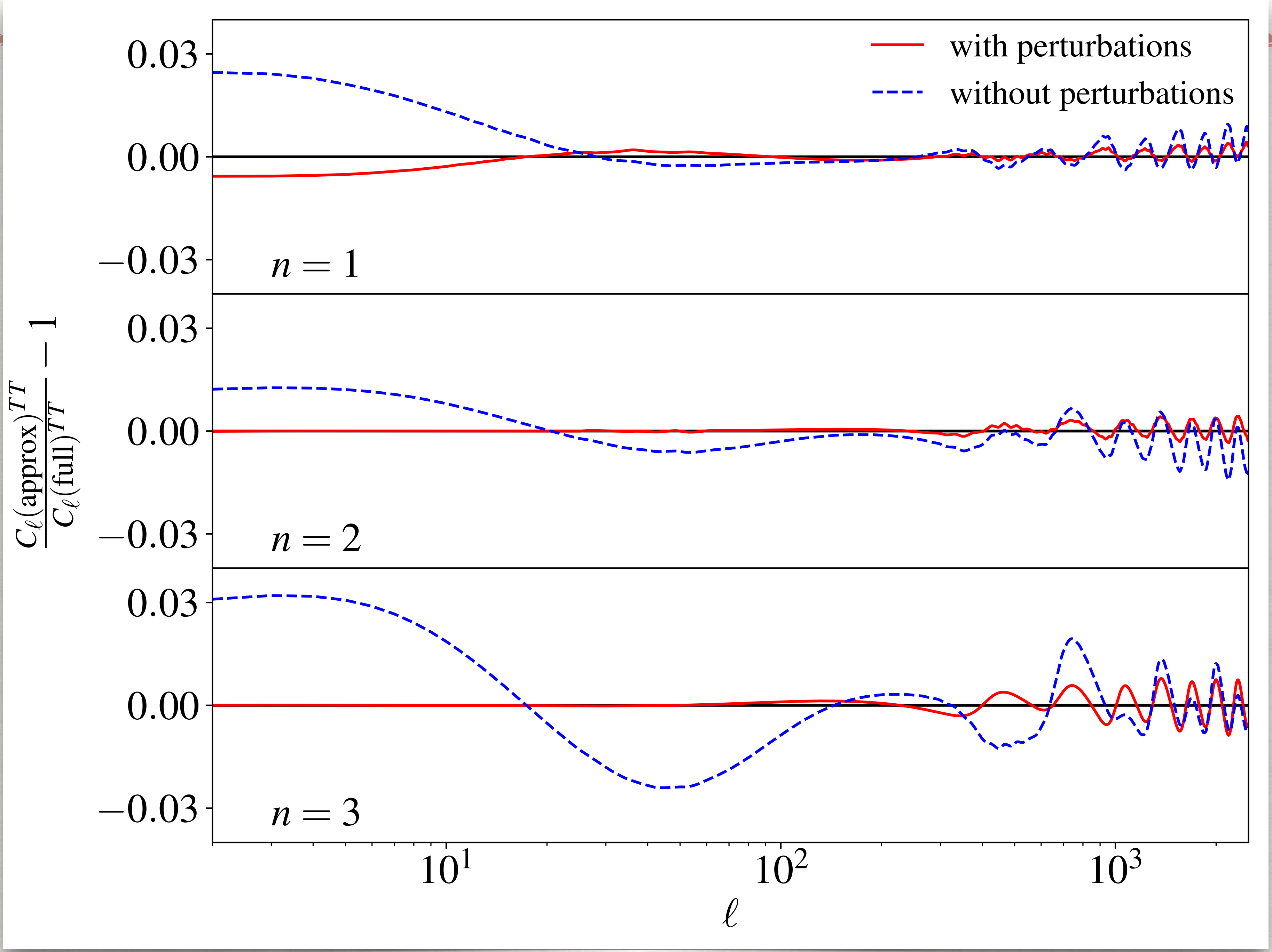


Fields become dynamical at late times: All powers of n have similar signatures

- effects boil down to LISW and decrease of lensing power.

Comparison with full calculation



- Without perturbations, precision is ~3% given Planck constraints. Planck is ~1% precise!
- With perturbations, sub-percent agreement: 1h vs 1sec computation time!

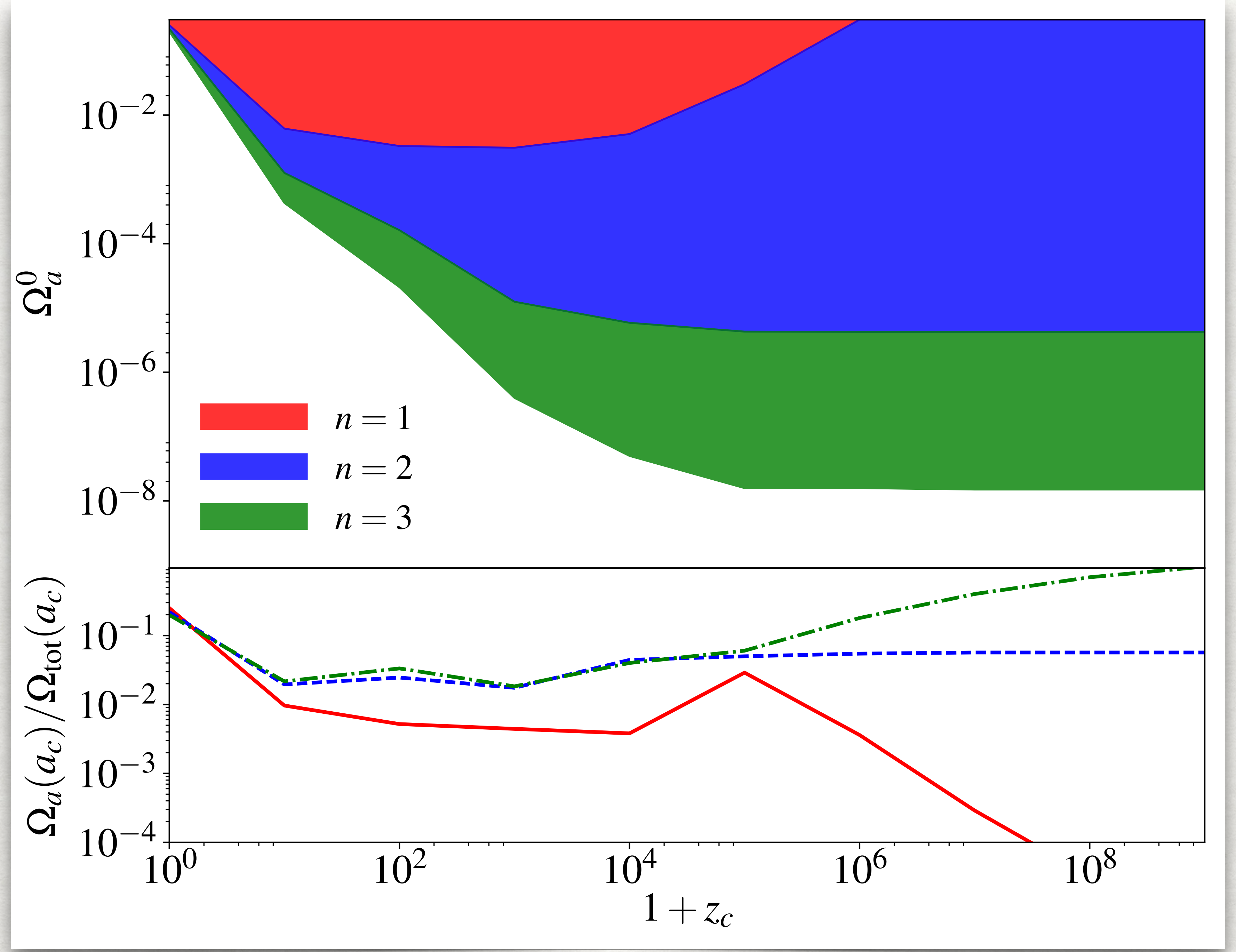
Current CMB constraints

see also Hlozek et al.; 1410.2896

VP, Smith, Grin, Karwal, Kamionkowski; 1806.10608

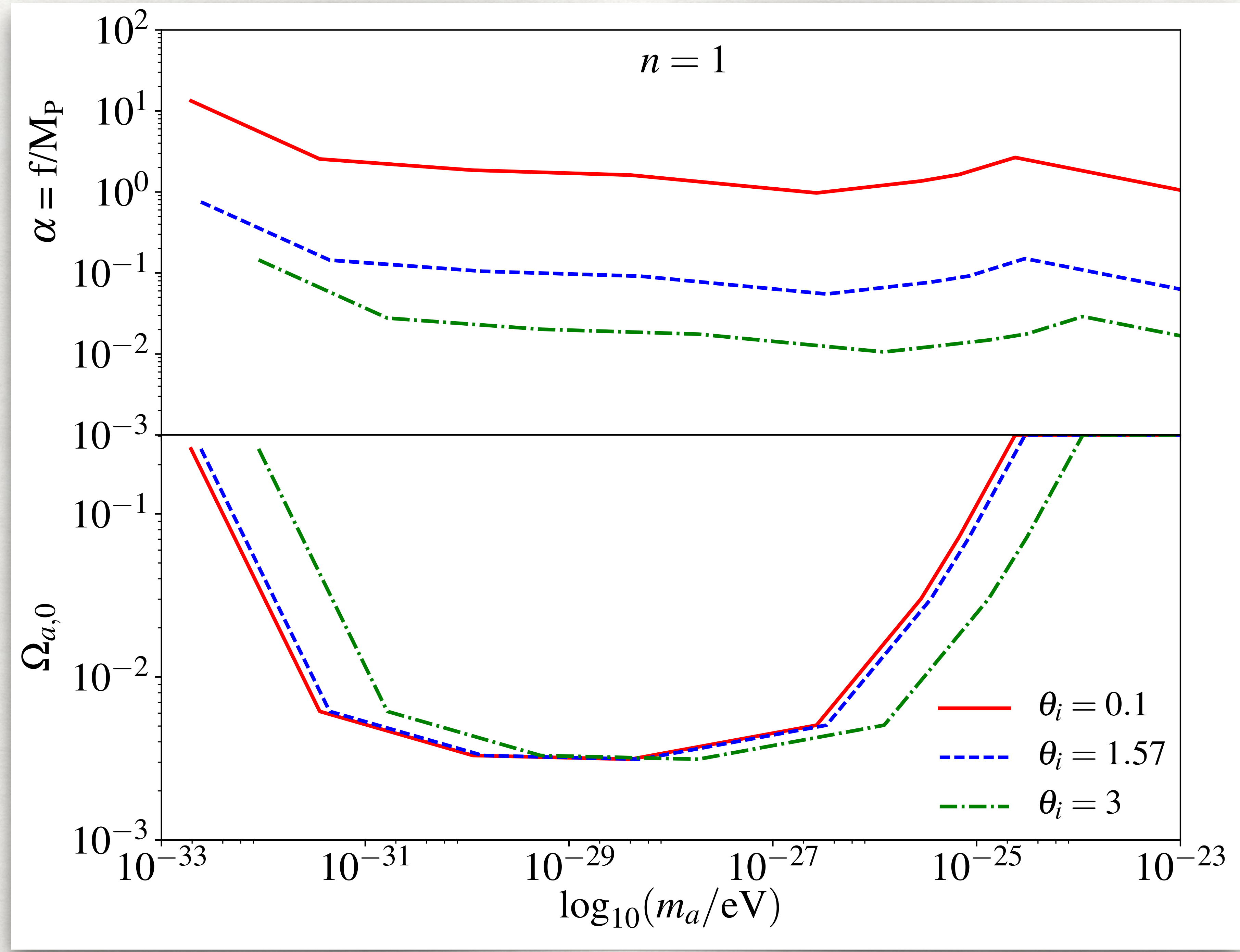
all constraints relaxed:
ALP is the DE

n=1 constraints relaxed:
ALP is the DM



Example 1: Constraining axion parameters

VP, Smith, Grin, Karwal, Kamionkowski; 1806.10608



Isocurvature modes would improve the constraints

Example 2: Solving the EDGES tension

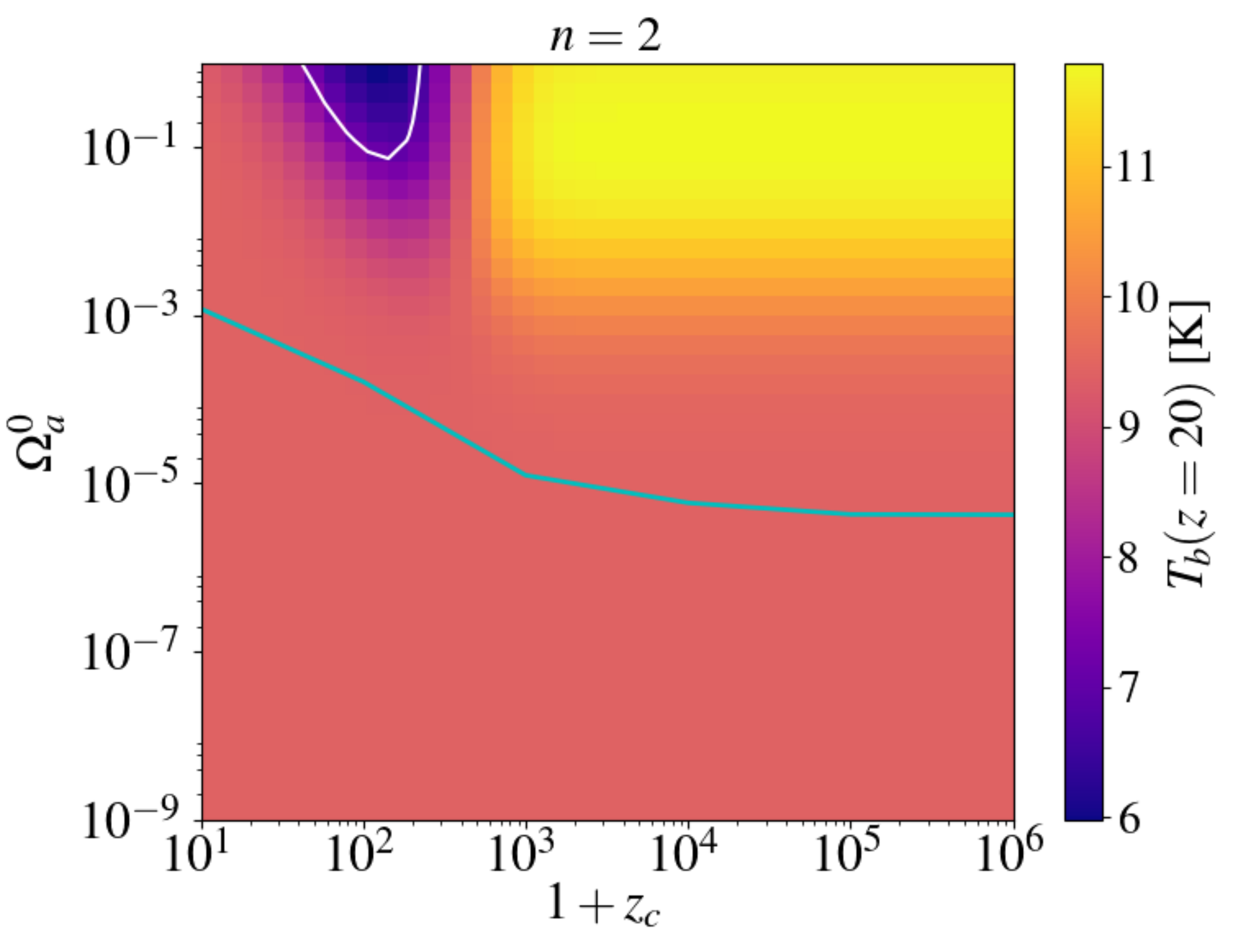
- EDGES can be explained by decreasing the baryon temperature: Tb(z~20) = 7K (99%CL)

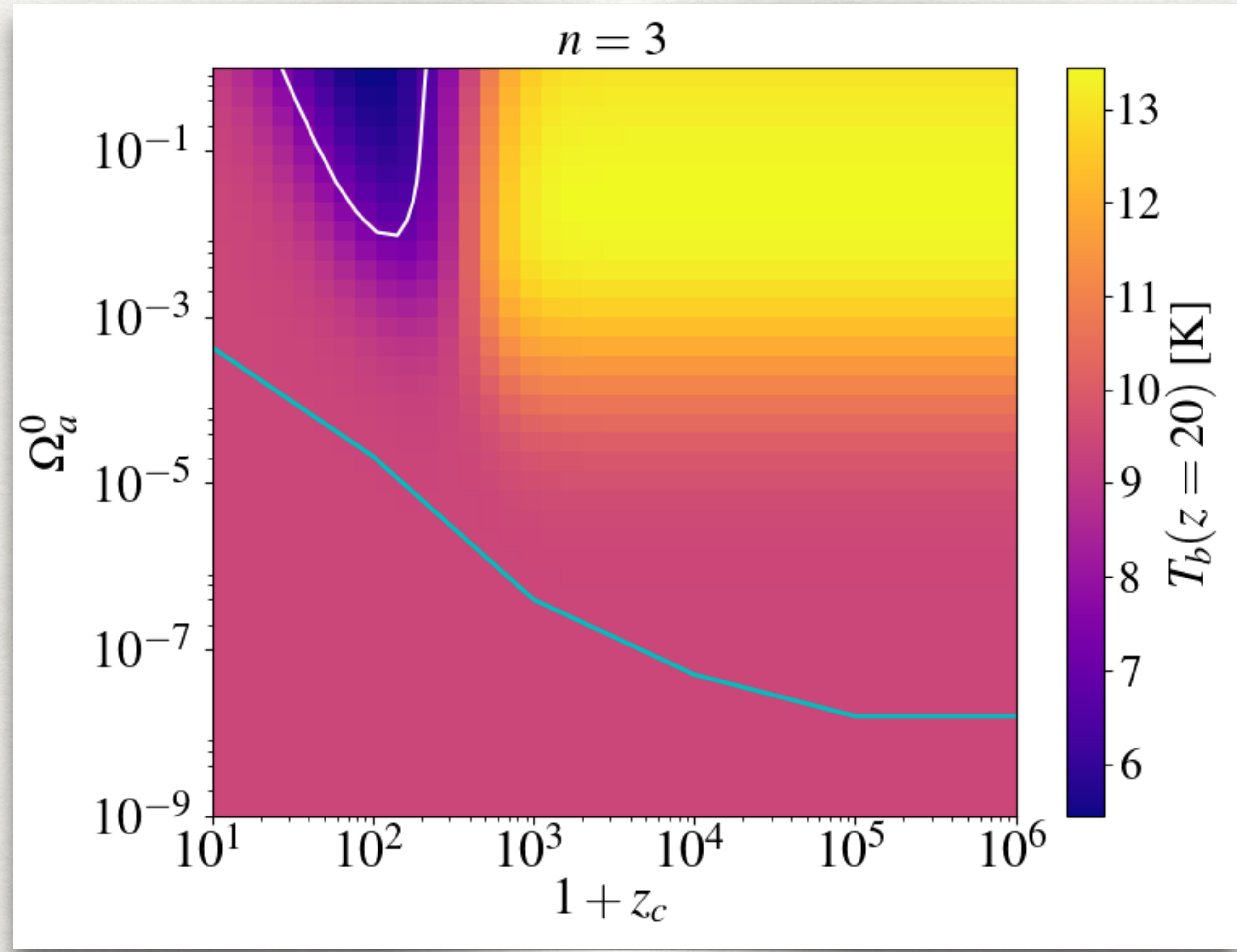
  Bowman++, nature25792, Barkana, nature25791

- if H >> $\Gamma_{compton}$ at high redshift, early adiabatic cooling can achieve this.

  Hill&Baxter, 1803.07555

- This suggested solution is strongly constrained by the CMB!

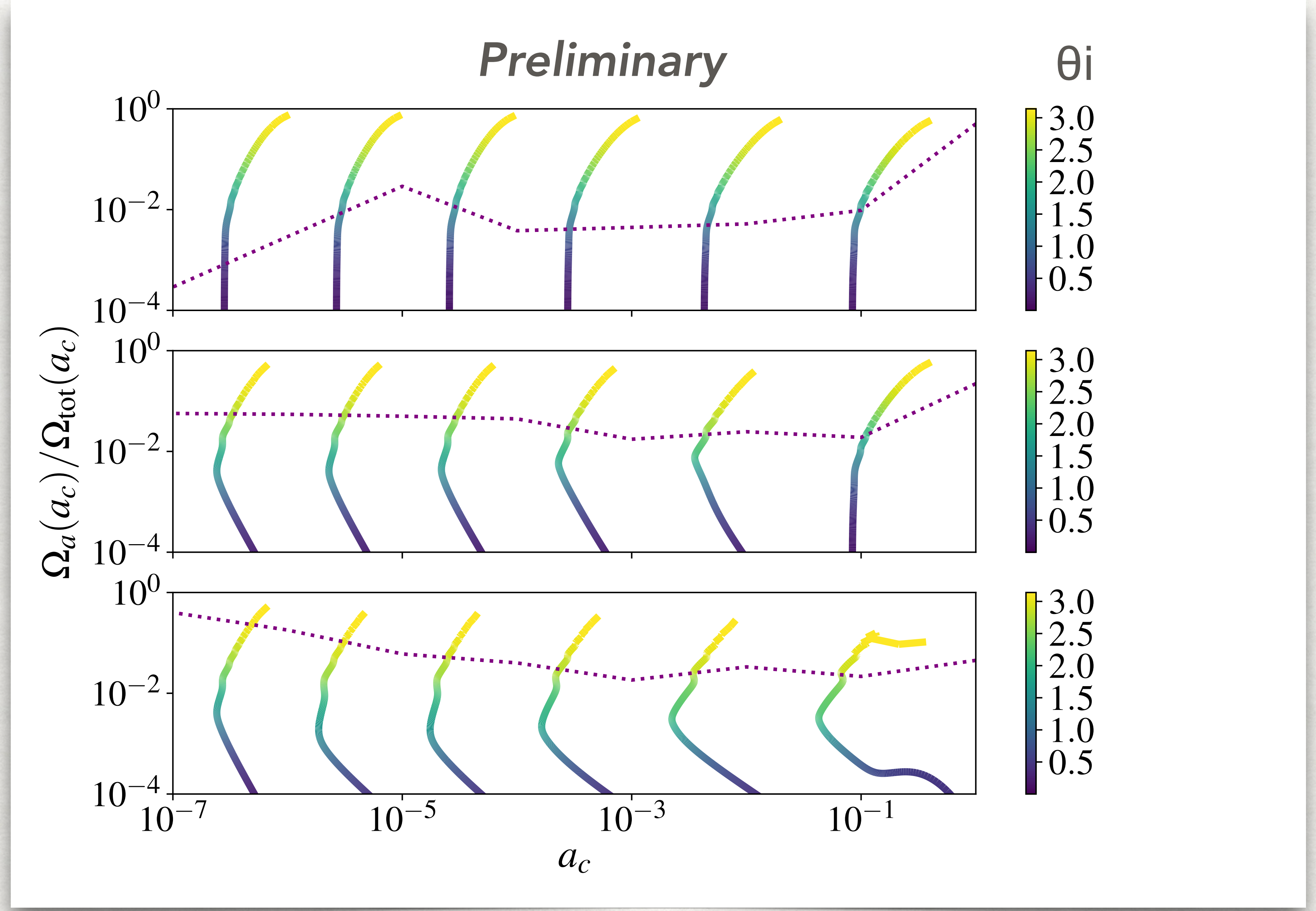




Example 3: Constraining the Axiverse

Smith, VP, Grin, Marsch, Hlozek, Kamionkowski; in prep.

- In Kamionkowski++ PRL 113 (2014) 061301: 24 axion fields, 2 per decades of mass. It is claimed 1/100 chance that one of them is DE today.
- CMB is sensitive to 6 of them! Probability that none of them is excluded $\Pi_i \theta_{i,\max}/\pi$



n=1 p = $1/10^{100}$

n=2 p = $1/10^{12}$

n=3 p = $1/10^{3}$

Conclusions

- The CMB can probe decoupled species even if they represent small fractions of the total density (typically few percent). This can lead to strong constraints on scalar fields with axion-like potentials.

- We have developed a parametrization based on the WKB approximation that describes ALP as a perfect fluid for generic (an-)harmonic potential, including the effect of perturbations (essential for precision cosmology).

- We can translate our CMB constraints on axion parameters and apply them to axiverse scenarios or early-dark-energy solution to cosmological tensions (e.g. EDGES).

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Thank you!

Back up

Marsh, 1510.07633

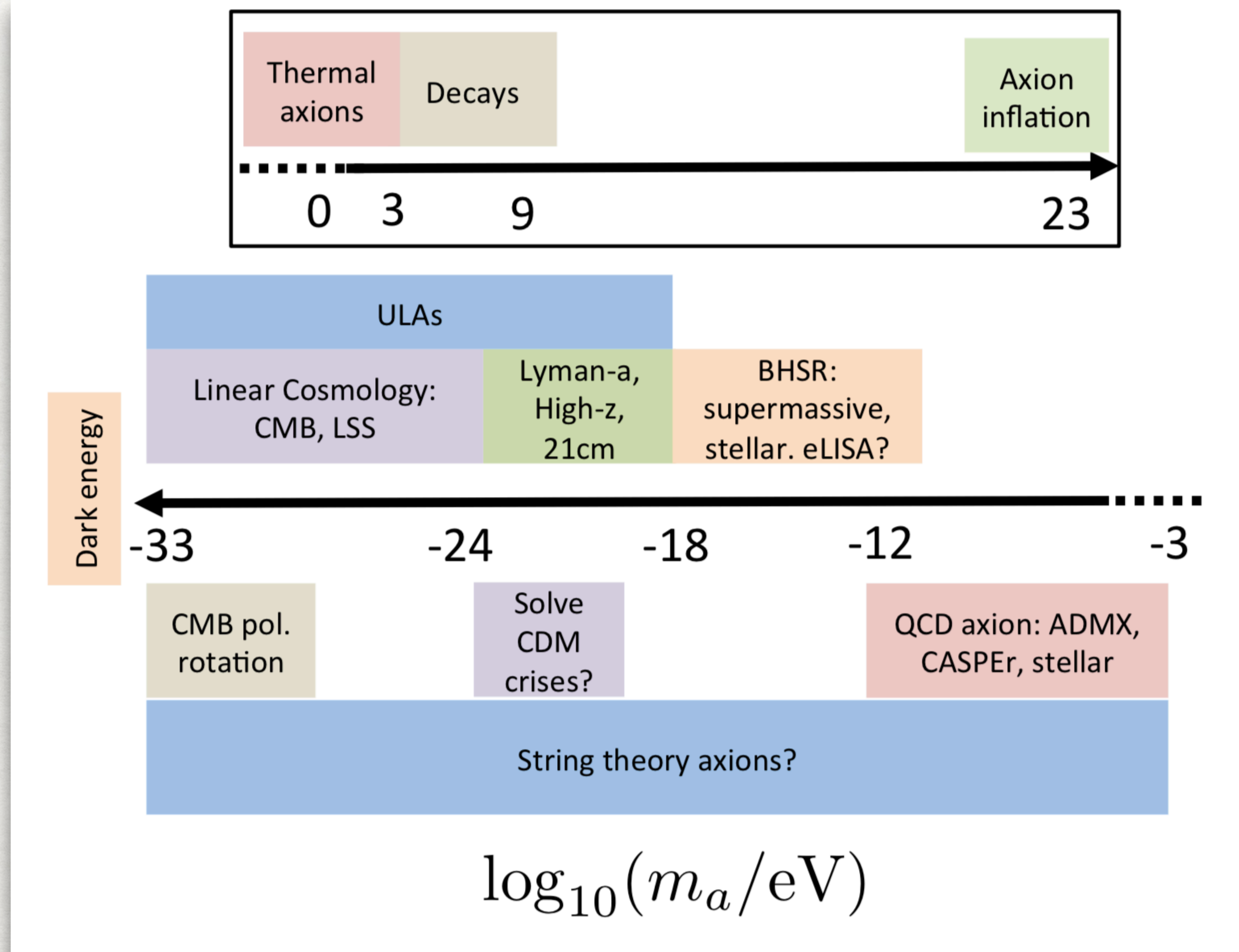
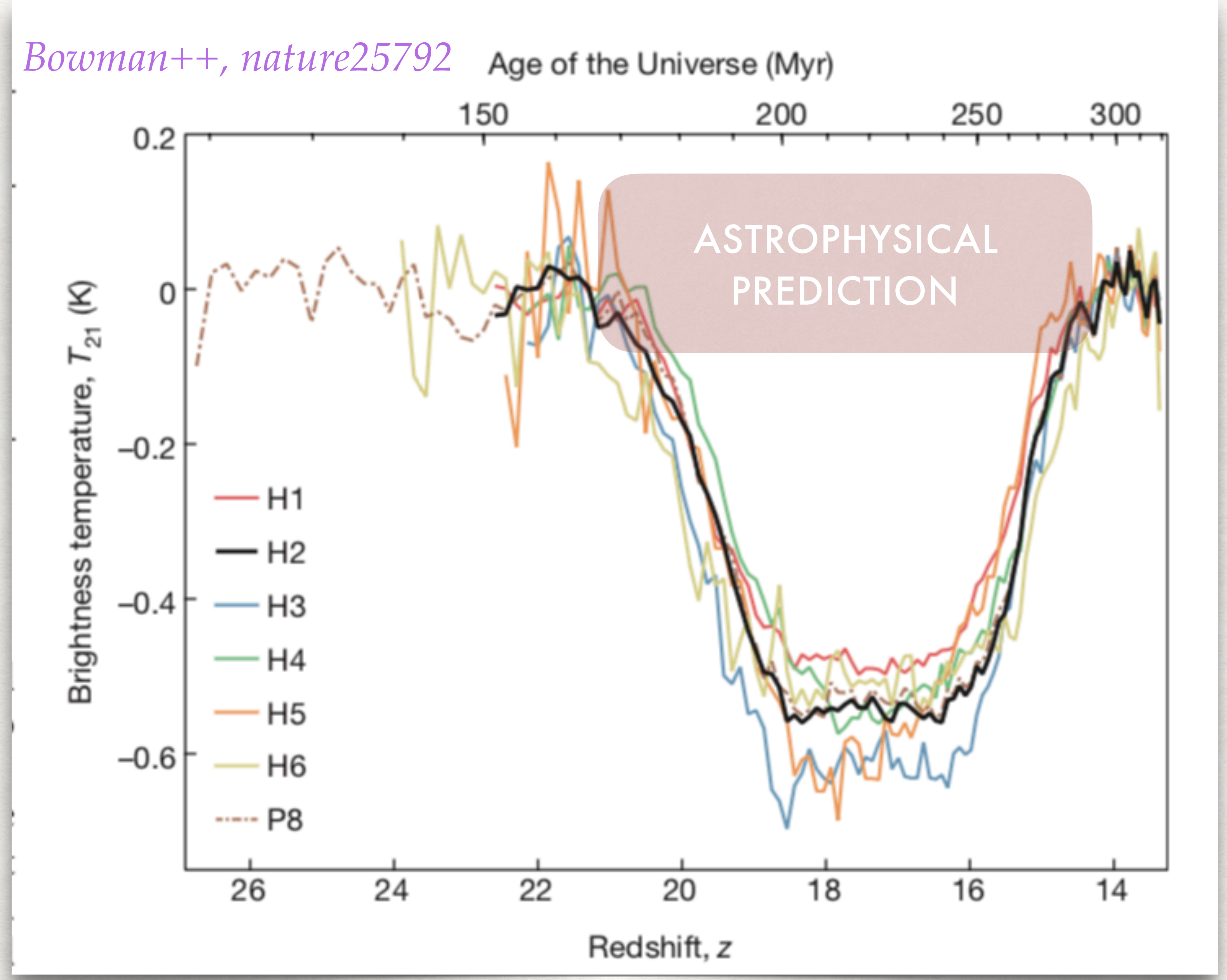


Figure 1: Summary of constraints and probes of axion cosmology.

EDGES measurement

- EDGES is a broadband antenna (50-100 MHz) located in Western Australia
- The signal is much more (x2.5) in absorption than one expects.



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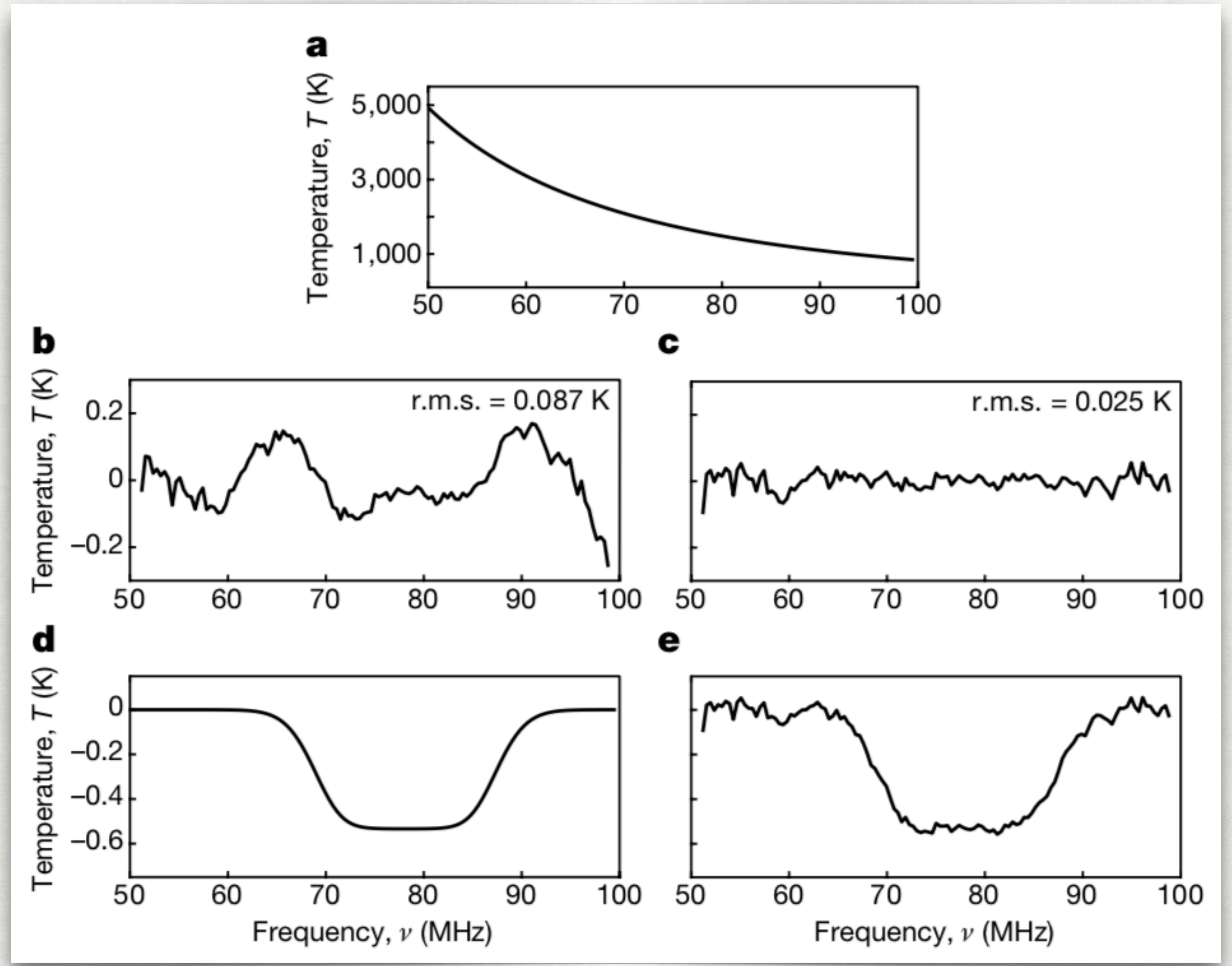
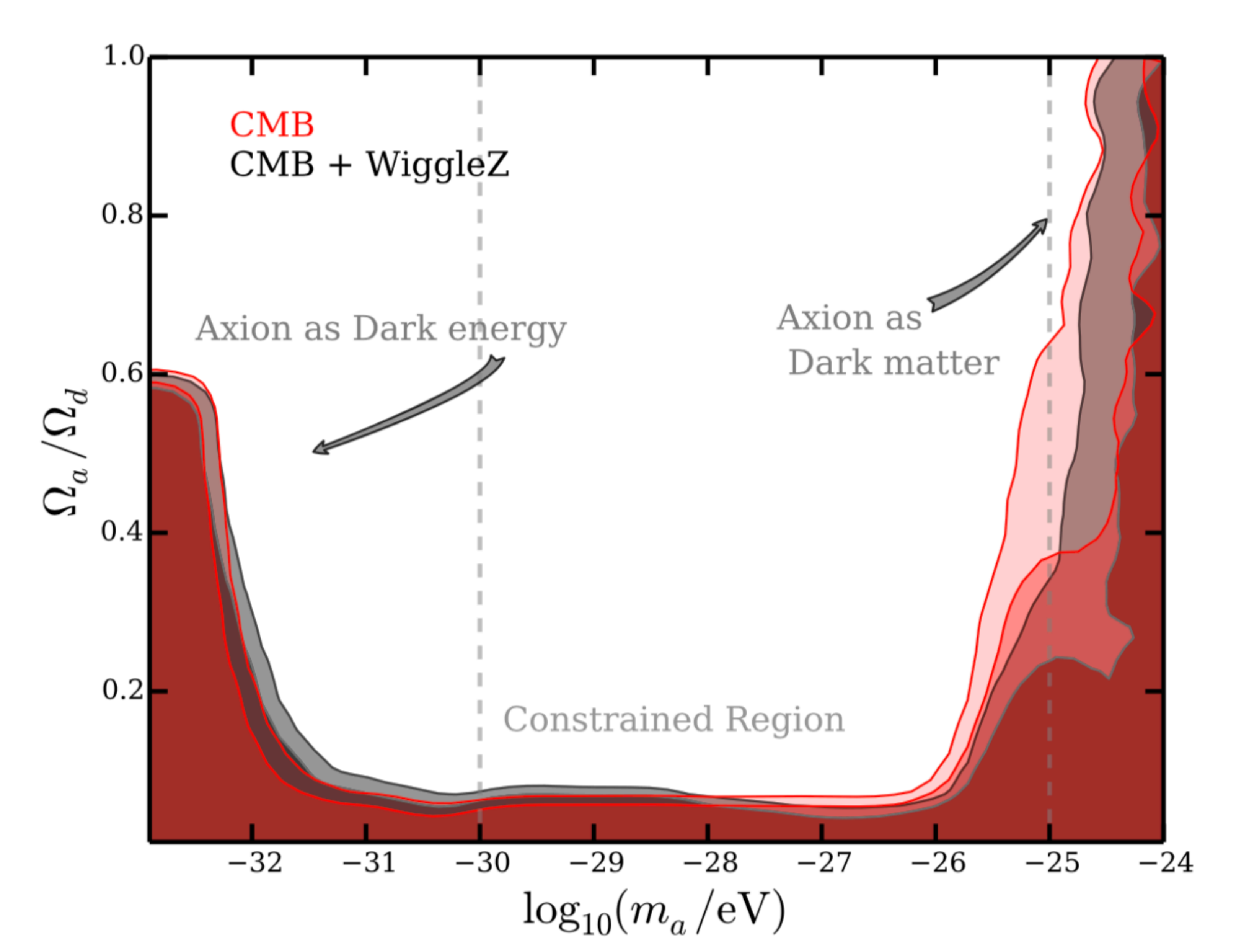


Comparison with axionCAMB

Our results for n=1 are in very good agreement with former studies.



Hlozek et al.; 1410.2896

The "why now?" problem

- Acceleration of the universe expansion can come from vacuum energy domination, which has a constant energy density.
- Other known species have a dropping energy density: when vacuum energy starts to dominate it will keep dominating! Universe would be totally different, most likely no intelligent life. Why did it start today?
- anthropic idea: many vacuum (string landscape~10^{120}), only the one where life occurs are realized.
- Griest, PRD66 (2002) 123501: accelerated expansion is associated with the energy density of a slowly-rolling scalar field. If there is a spectrum of such fields, one could dominate the energy density today, while others might have dominated in the past.
- In Kamionkowski++ PRL 113 (2014) 061301: 24 axion fields, 2 per decades of mass. It is claimed 1/100 chance that one of them is DE today.