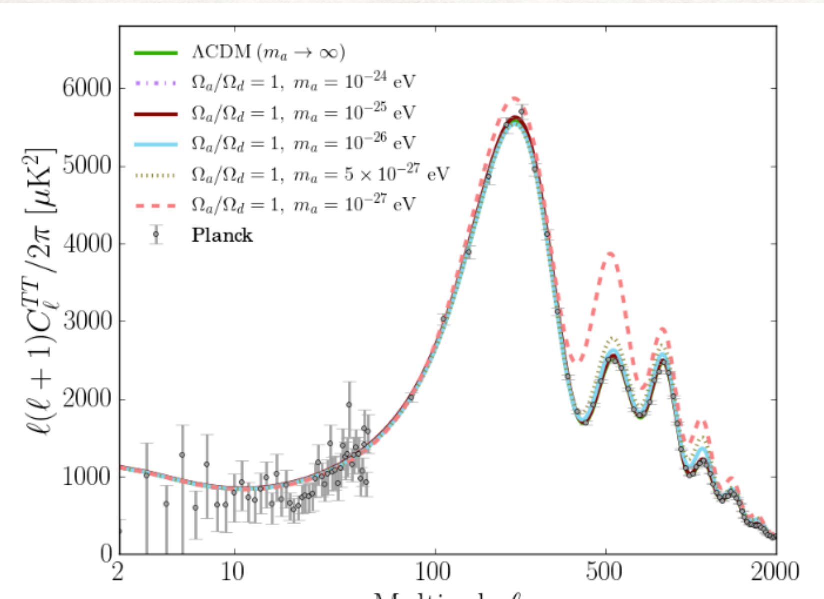
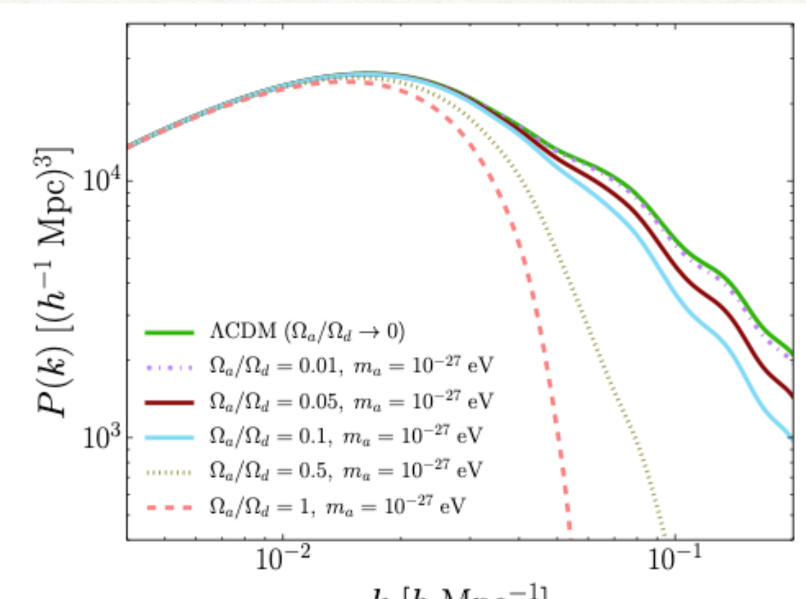
Cosmological signatures of axion-like particles



Hlozek++ 1410.2896



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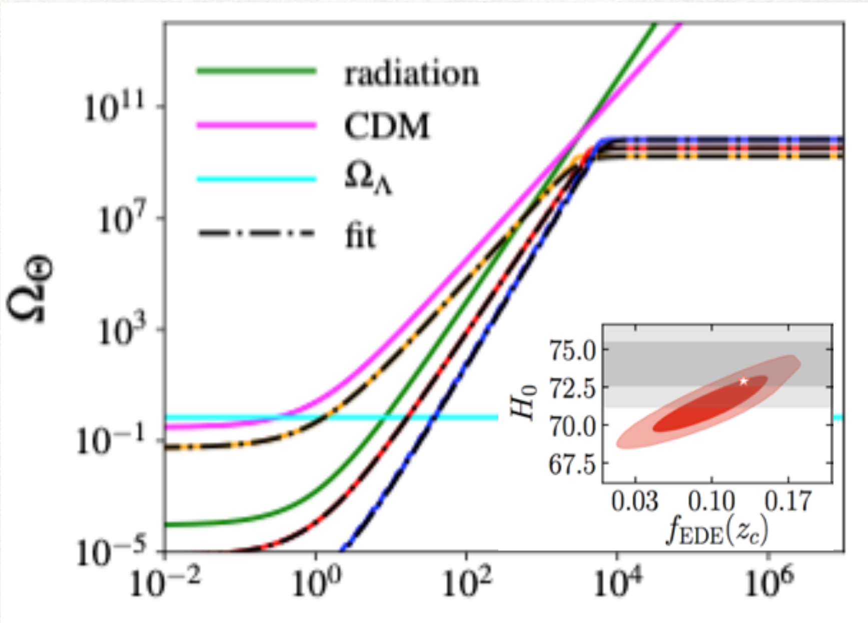

Poulin++ 1806.10608

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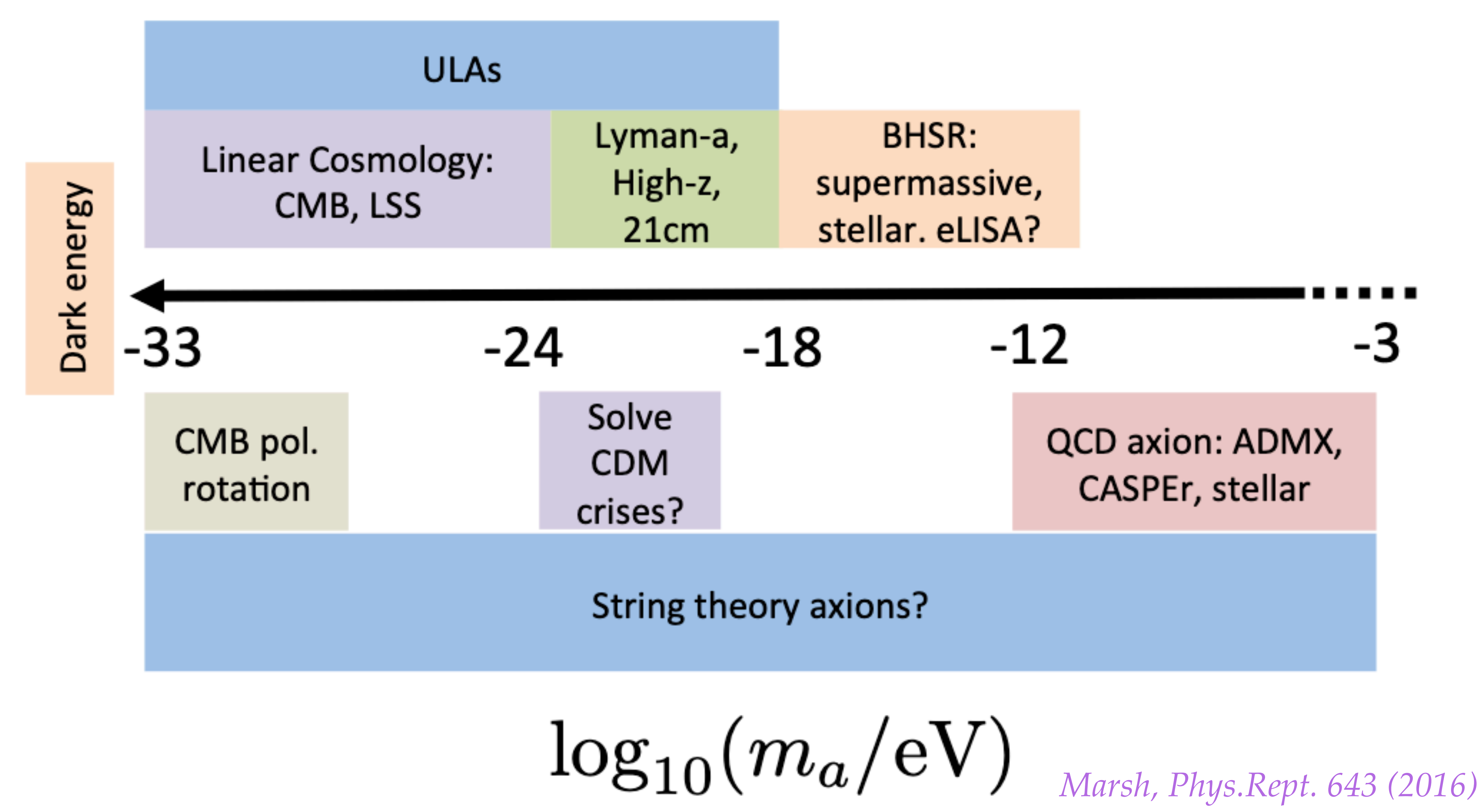
ICTS, "Less travelled path of Dark Matter"
November, 11 2020

The Axion landscape



Marsh, Phys.Rept. 643 (2016)

Theory of cosmological ALP in a nutshell

Marsh, 1510.07633

- Typical mass range interesting for us [10^{-33},10^{-18}]

- Potential has the form: $V(\phi) = \Lambda^4(1 - \cos(\phi/f))$

- f is the spontaneous symmetry breaking scale, Λ the non-perturbative physics scale. Both scales enter the axion mass $m_a \approx \Lambda^2/f$.

- The energy density and pressure of the field are given by:

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_n(\phi),\ \ P_\phi = \frac{1}{2}\dot{\phi}^2 - V_n(\phi)$$

- The KG equation governs the field dynamics $$\ddot{\phi} + 3H\dot{\phi} + \frac{dV_n(\phi)}{d\phi} = 0$$

- In the limit $\phi/f \ll 1$, $V(\phi) = m_a^2\phi^2/2$ such that $\ddot{\phi} + 3H\dot{\phi} + m_a^2\phi = 0$.

- This is exactly solvable in the limit where H is dominated by a single component.

Producing a cosmological population of ALP

$$\Omega_a h^2 = \frac{\rho_a}{\rho_{c,0}} h^2 = F\Omega_{\rm cdm} h^2 \simeq 0.12F$$

Lecture by D.J.E. Marsh

- Thermal population produced from the thermal bath typically from $\pi\pi \to \pi a$. The axion-SM coupling can be arbitrary in the general case.

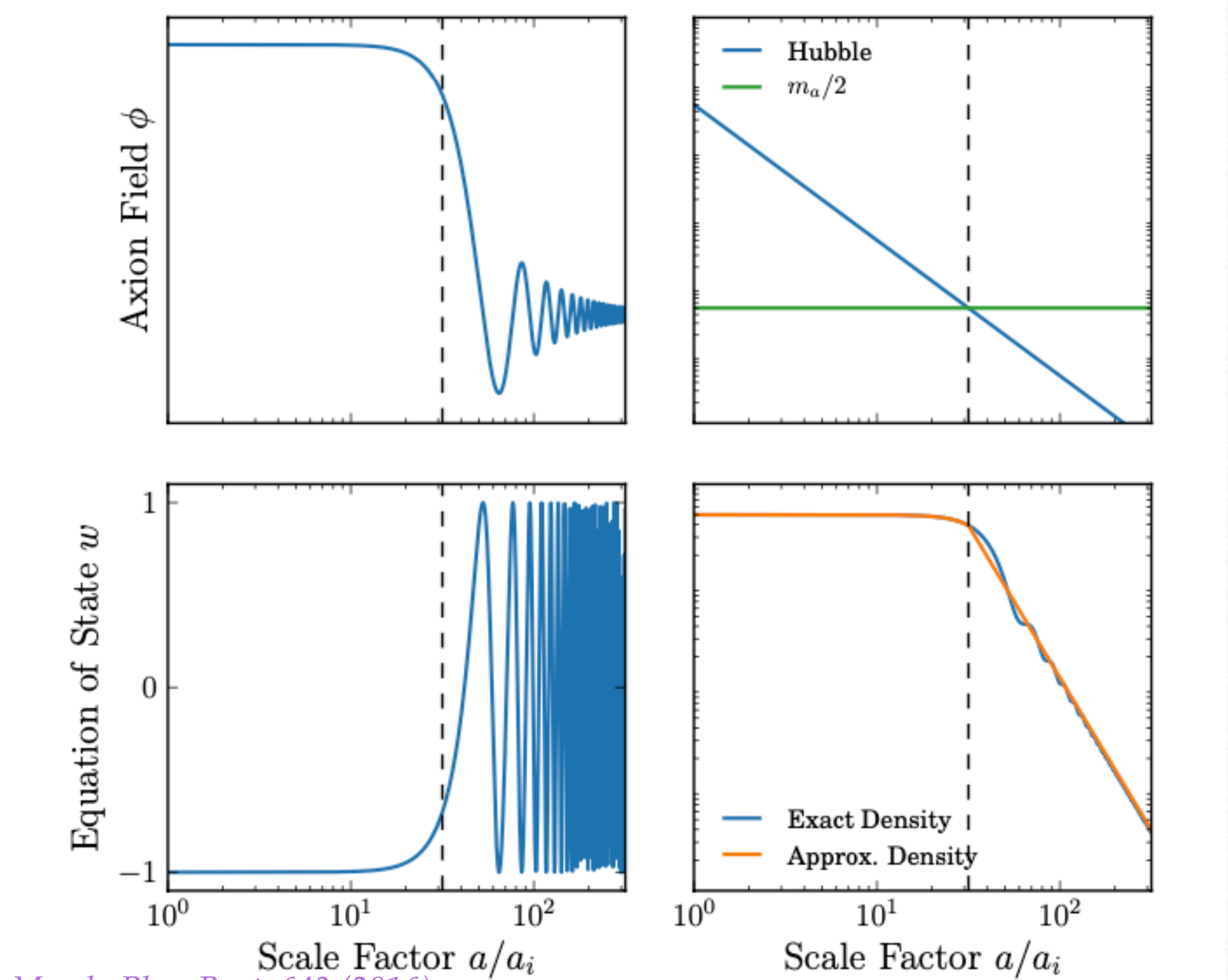
- Production from the decay of a mother particle X with $m_X > m_a$. The axion would contribute to the radiation bath $N_{\rm eff}$ an amount (if X particles dominate energy density):

$$\Delta N_{\rm eff} = \frac{43}{7}\left(\frac{10.75}{g_{\star S}(T_r)}\right)^{1/3} \frac{B_a}{1-B_a}$$

- Production from the decay of topological defects: if $f_a < H_I/2\pi$, Peccei-Quinn symmetry is unbroken during inflation; leads to horizon patches with different ϕ_i and formation of "topological defects". These are unstable and leads to the creation of axion particles.

- The "misalignment mechanism": population from the coherent initial displacement of the axion field $\phi_i \neq 0$. This is the scenario we focus in the remainder of this lecture.

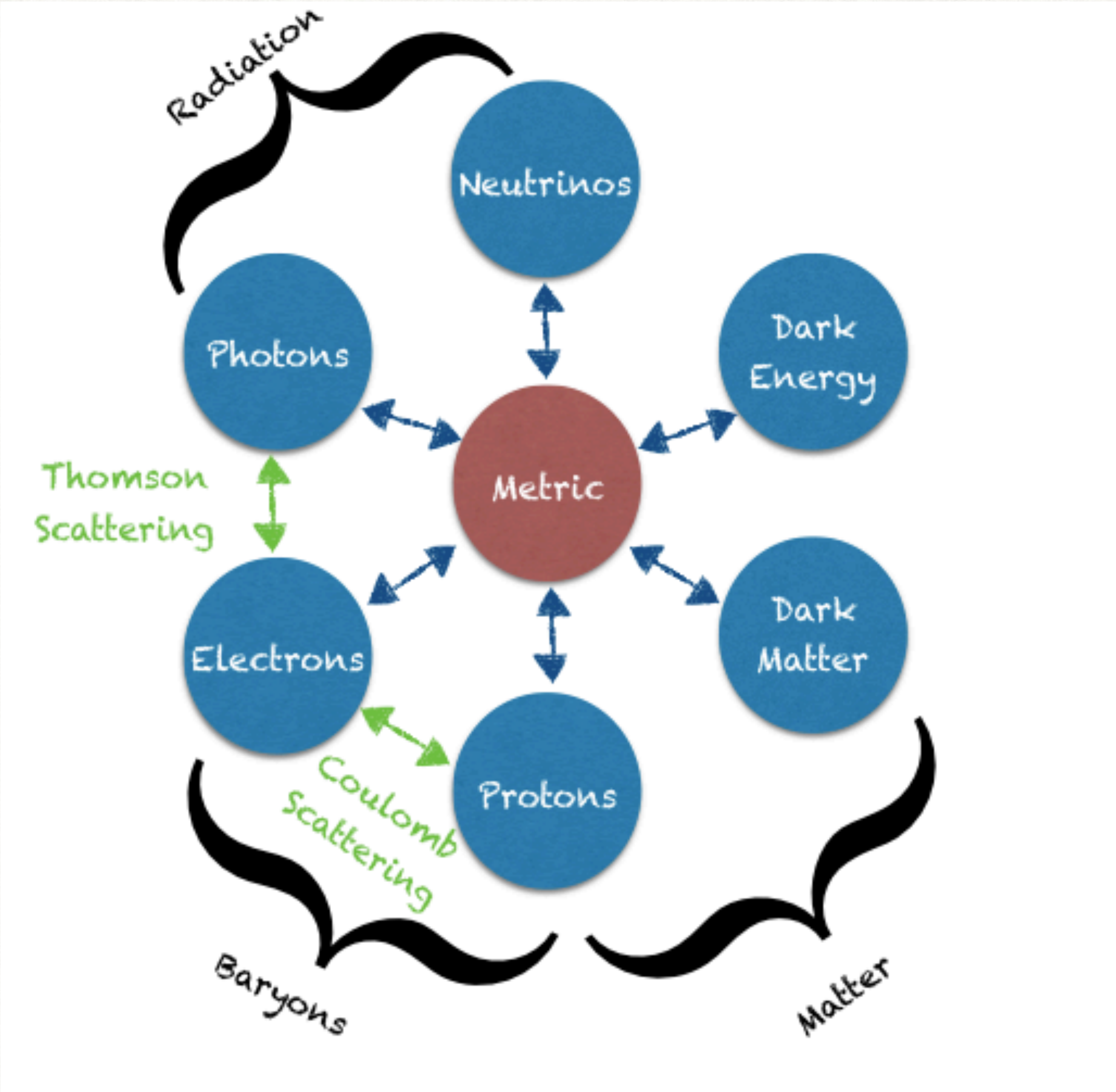
The misalignment mechanism



Marsh, Phys.Rept. 643 (2016)

- $H \gg m_a$: the field is frozen $w \equiv P_\phi/\rho_\phi = -1$ (nb: $\dot{\phi}_i = 0$); $H < m_a$: field ϕ oscillates around 0 and $\rho \propto a^{-3}$.
- Once the fields start oscillating: Virial theorem on the "cycle-average" field $\langle \dot{\phi}/2 \rangle = \langle V_\phi \rangle \Rightarrow \langle w \rangle \simeq 0$
- Cosmological density is estimated as $\rho_{\rm today} \simeq \rho_{\rm osc}(a/a_{\rm osc})^{-3} \simeq (m_a^2\phi_i^2/2)(a/a_{\rm osc})^{-3}$ with $H(a_{\rm osc}) \sim m_a$
- ALP are a good DM candidate if $H(a_{\rm osc}) \sim m_a > H(a_{\rm eq}) \simeq 10^{-28}{\rm eV}$

Cosmological probes are sensitive to ALP perturbations



$$\delta g_{\mu\nu}(\vec{x},t) = 8\pi G \delta T_{\mu_\nu}(\vec{x},t)$$

- Focus on the 4 scalar degrees of freedom $\{\delta_x \equiv \delta\rho_x/\rho_x, \theta_x \equiv k v_x, \delta P_x, \sigma_x\}$

$$\bar{\rho}\,\delta = -\delta T^0_0$$

$$(\bar{\rho}+\bar{P})\,\theta = \sum_i \partial_i \delta T^0_i$$

$$\delta P = \frac{1}{3}\sum_i \delta T^i_i$$

$$(\bar{\rho}+\bar{P})\nabla^2\sigma = -\sum_{i,j}\left(\partial_i\partial_j - \frac{1}{3}\nabla^2\delta_{ij}\right)\delta T^i_j.$$

See e.g. Baumann "cosmology" lectures
Dodelson, "Modern Cosmology"

ULA perturbations

Ma&Bertschinger astro-ph/9506072, Hu astro-ph/9801234

- Let's work in the "newtonian" gauge: $ds^2 = a^2(\tau)\{-(1+2\Psi)d\tau^2 + (1-2\Phi)dx^i dx_i\}$

- From the perturbed KG equations we have: $\delta\phi'' + 2\mathcal{H}\delta\phi' + (k^2 + m_a^2 a^2)\delta\phi = (\Psi' + 3\Phi')\phi' - 2m_a^2 a^2 \phi\Psi$

- And we can use the definition of $T_{\mu\nu}$ to relate $\delta\phi(\vec{x}, t) \equiv \phi(\vec{x}, t) - \bar{\phi}(t)$ to $\{\delta_\phi, \theta_\phi, \delta P_\phi, \sigma_\phi\}$. We obtain:

$$\delta\rho_\phi = a^{-2}(\dot{\phi}\dot{\delta\phi} - \dot{\phi}^2\Psi) + m_a\phi\delta\phi$$

$$\delta p_\phi = \delta\rho_\phi - 2m_a\phi\delta\phi$$

$$(\rho_\phi + p_\phi)\theta_\phi = a^{-2}k^2\dot{\phi}\delta\phi$$

$$\sigma_\phi = 0$$

- Alternatively we can write fluid equations from $\nabla\delta T^\mu_\nu = 0$ as

$$\delta'_\phi = -(1+w_\phi)(\theta\phi - 3\Phi') - 3\mathcal{H}\left(\frac{\delta p_\phi}{\delta\rho_\phi} - w_\phi\right)\delta_\phi$$

$$\theta'_\phi = -\frac{a'}{a}(1-3w_\phi)\theta_\phi - \frac{w'_\phi}{1+w_\phi}\theta_\phi + \frac{\delta p_\phi/\delta\rho_\phi}{1+w_\phi}k^2\delta_\phi + k^2\Psi$$

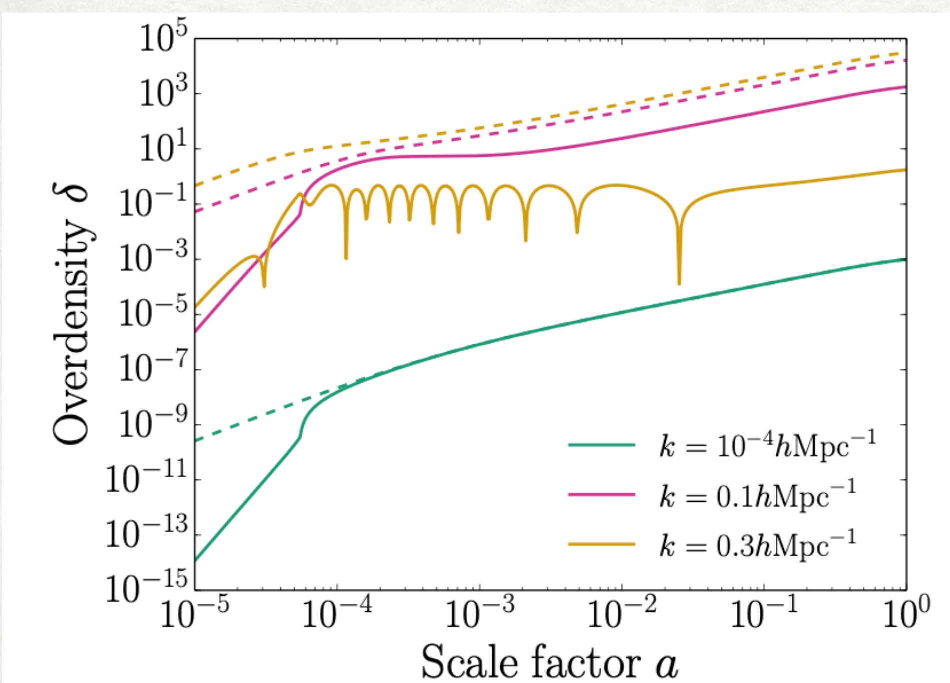
- Key quantities: The equation of state w and the sound-speed $c_s^2 \equiv \dfrac{\delta p_\phi}{\delta\rho_\phi}$.

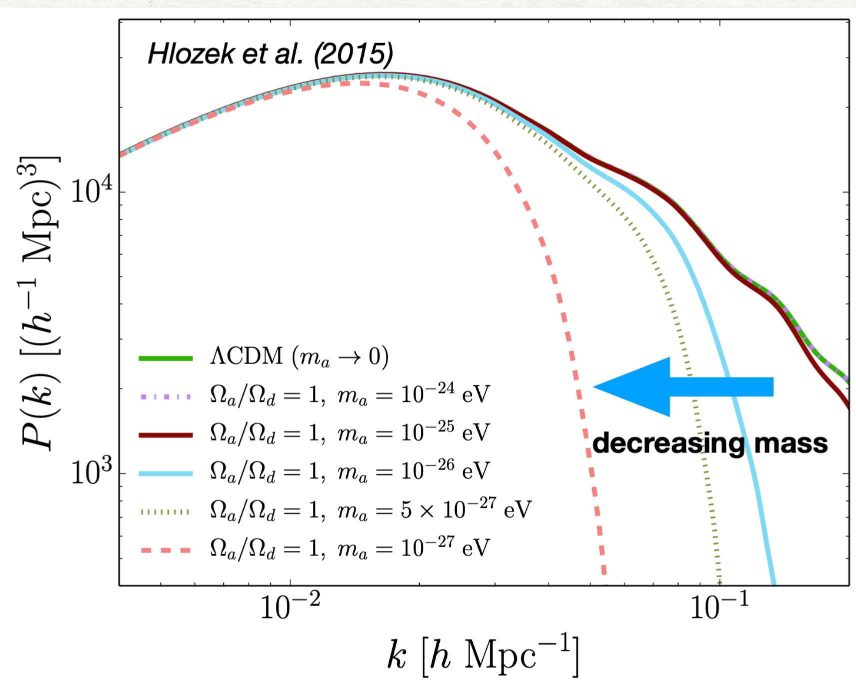
The cycle-average perturbations

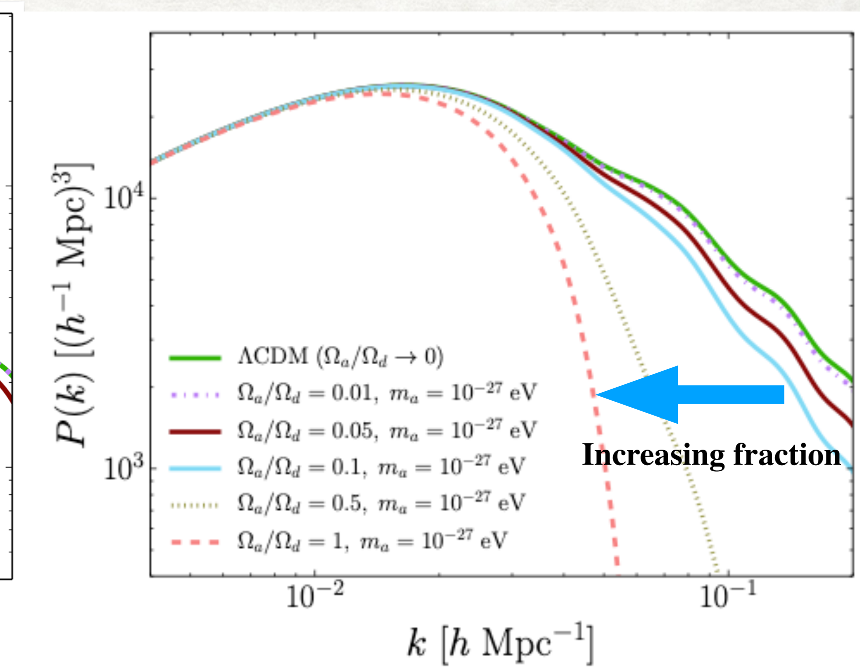
- It is possible to get an approximate expression for the sound speed from the 'cycle-average' $c_{\rm eff}^2 \equiv \langle \delta P_\phi \rangle / \langle \delta \rho_\phi \rangle$
- Famous result: $c_{\rm eff}^2 = \dfrac{k^2/4m_a^2a^2}{1+k^2/4m_a^2a^2}$. There is a power suppression on scales $k^2 \gg 4a^2m_a^2$.

See Hu astro-ph/9801234, Hlozek++ 1410.2896, VP++ 1806.10608

- On small scales the equation for δ_a (+Poisson equation) becomes: $\ddot{\delta}_a + 2H\dot{\delta}_a + (k^2c_{\rm eff}^2/a^2 - 4\pi G\rho_a)\delta_a = 0$
- Axion jeans scale: $k_j = (16\pi G a \rho_{a,0})^{1/4} m_a^{1/2} \simeq 70 a^{1/4} \left(\dfrac{\Omega_a h^2}{0.12}\right)^{1/4} \left(\dfrac{m_a}{10^{-22}{\rm eV}}\right)^{1/2} {\rm Mpc}^{-1}$







The Halo Mass Function

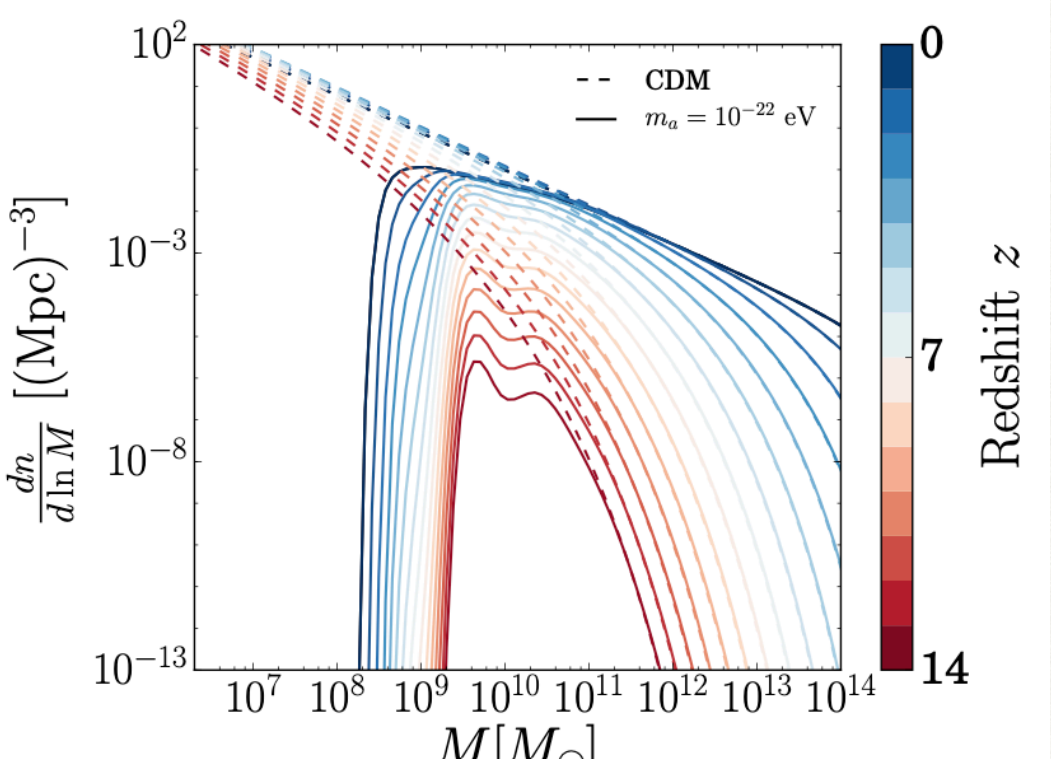
- The number of halos in the ULA DM scenario is reduced: connection to the missing satellites problem?

$$\frac{dn}{d\ln M} = -\frac{1}{2}\frac{\rho_m}{M} f(\nu)\frac{d\ln\sigma^2}{d\ln M} \qquad f(\nu) = A\sqrt{\frac{2}{\pi}}\sqrt{q}\nu(1+(\sqrt{q}\nu)^{-2p})\exp\left[-\frac{q\nu^2}{2}\right] \qquad \nu \equiv \frac{\delta_{\rm crit}}{\sigma}$$

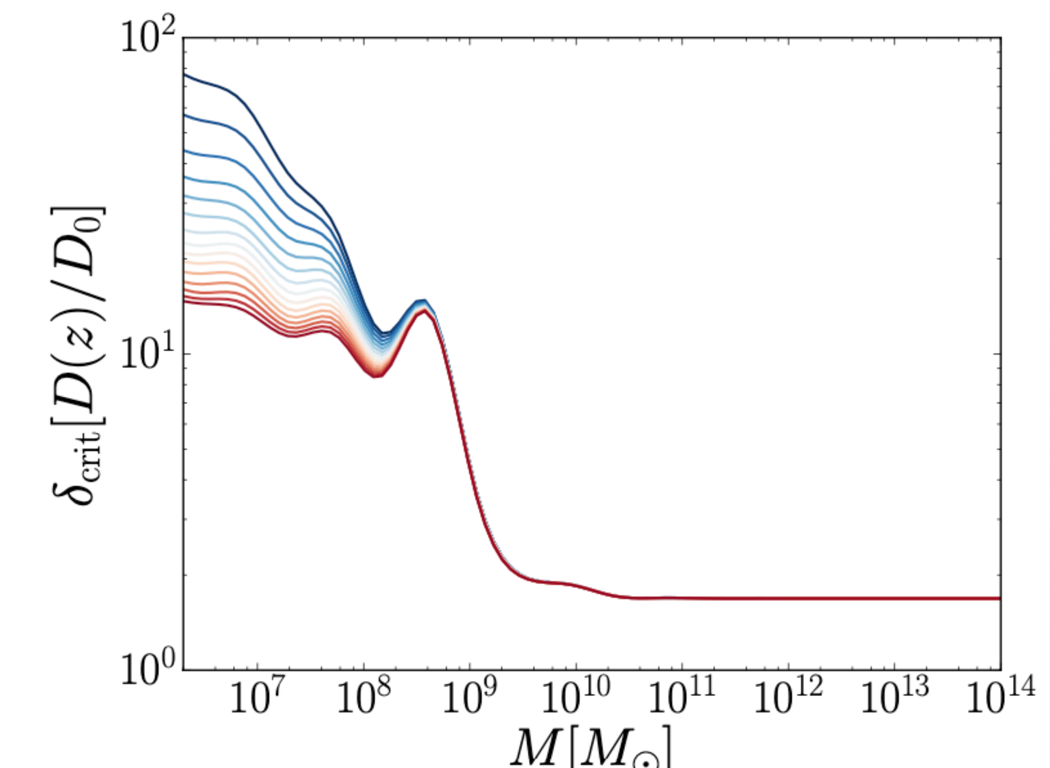
(From CDM simulation)

Press-Schechter ApJ 1974, Sheth&Tormen astro-ph/9901122

- The scale-dependent growth can be incorporated via a scale-dependent collapse threshold $\delta_{\rm crit}(M,z) = 1.686\mathcal{G}(M,z)$



Bozek++ 1409.3544



Bozek++ 1409.3544

See also recent update Kulkarni&Ostriker 2011.02116

- This impacts also the reionization of the universe by the first stars and the UV luminosity function, 21cm….

The ULA halo density profile

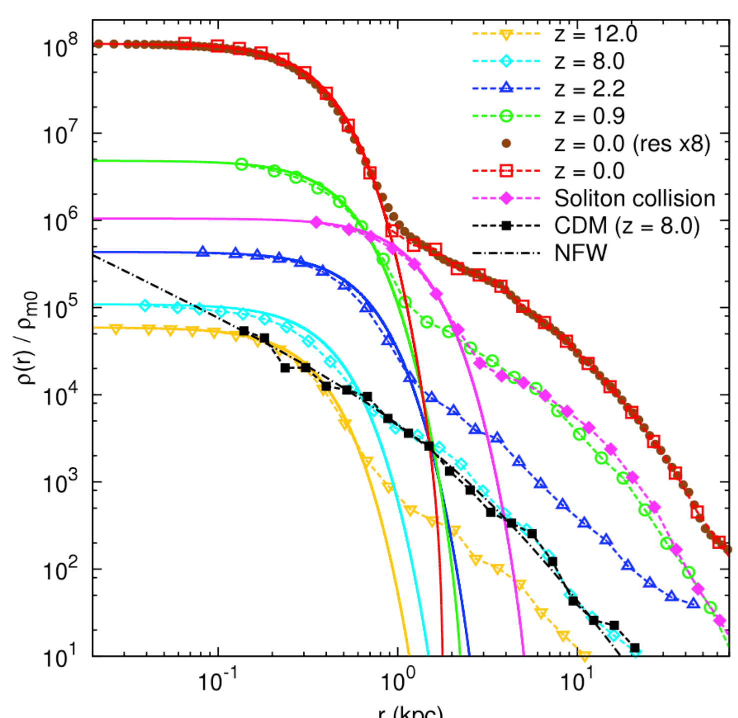
- The wave-like nature of the ULA shows up on scale $\lambda_{\rm dB} = 1/mv \simeq 10^{-2}\left(\frac{m_a}{10^{-22}\ {\rm eV}}\right)^{-1}\left(\frac{v}{100\ {\rm km/s}}\right)^{-1}$ kpc
- Density profile comes from solving the 'Schrödinger-Poisson' equation $\left[i\frac{\partial}{\partial\tau}+\frac{\nabla^2}{2}-aV\right]\psi=0$ $\psi=\mathcal{X}(r)e^{-i\gamma t}$ $\rho=\mathcal{X}^2$
- A 'soliton' forms (stationary wave of constant energy)

$$\rho(r)=\Theta(r_\epsilon-r)\rho_{\rm sol}(r)+\Theta(r-r_\epsilon)\rho_{\rm NFW}(r)$$

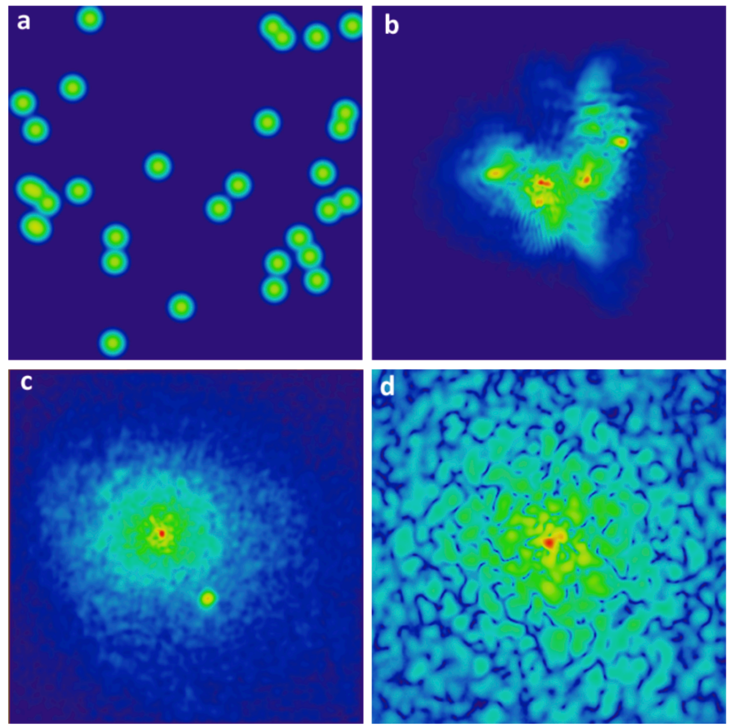
$$\rho_{\rm sol}(r)=\frac{\rho_{\rm sol}(0)}{(1+(r/r_{\rm sol})^2)^8}$$

$$r_{\rm sol}=22\left(\frac{\rho_{\rm sol}(0)}{\rho_{\rm crit}}\right)^{-1/4}\left(\frac{m_a}{10^{-22}\ {\rm eV}}\right)^{-1/2}\ {\rm kpc}$$

$r_{\rm sol}\sim r_{\rm dB}\sim r_J$



$m_a = 8\times10^{-23}$ eV

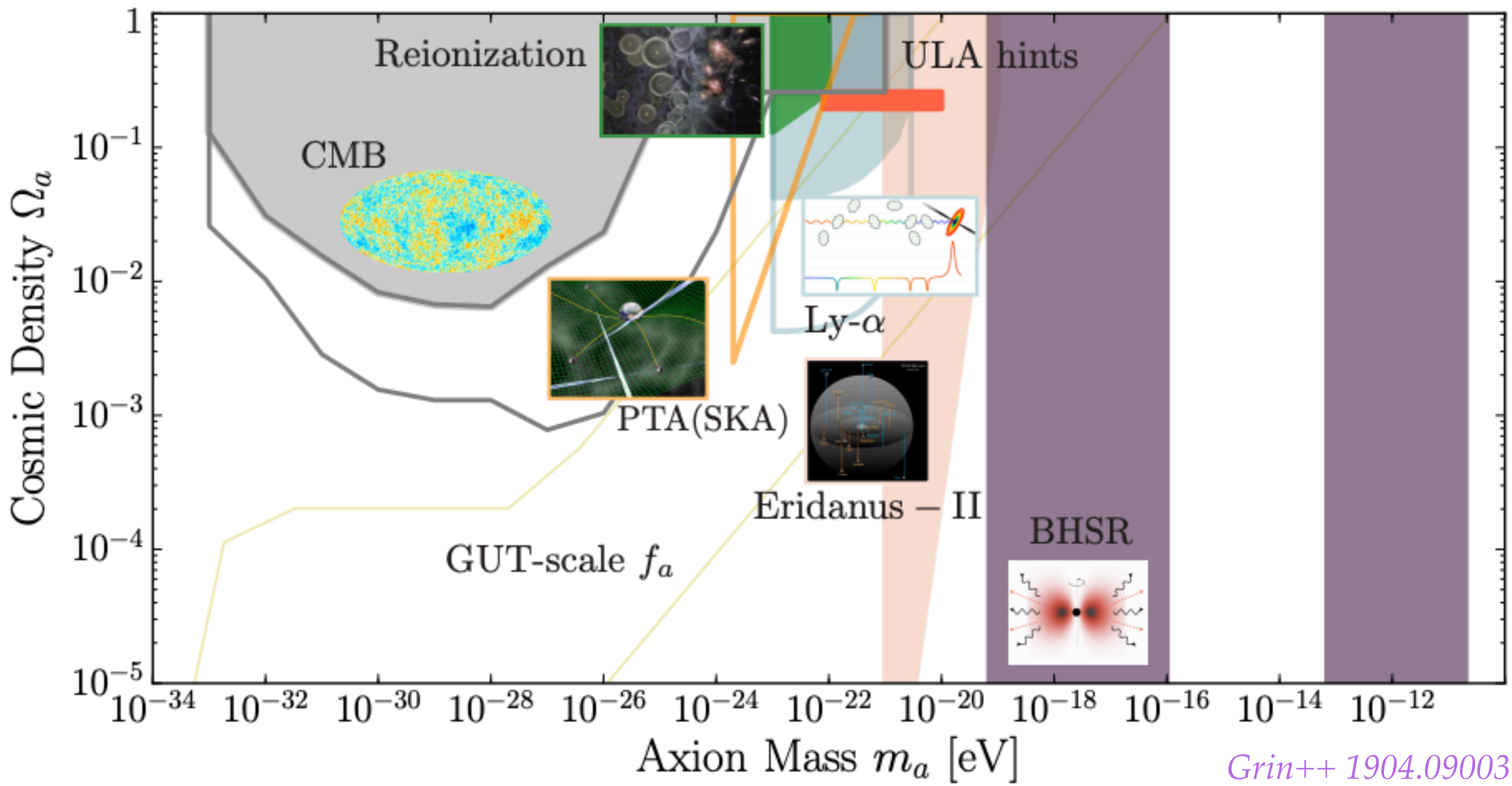


Schive++ 1407.7762

- ULA might solve the 'core-cusp' problem of CDM for $m_a \lesssim 10^{-22}$ eV! *Marsch & Pop, 1502.03456*

Bounds on the ALP mass & fraction

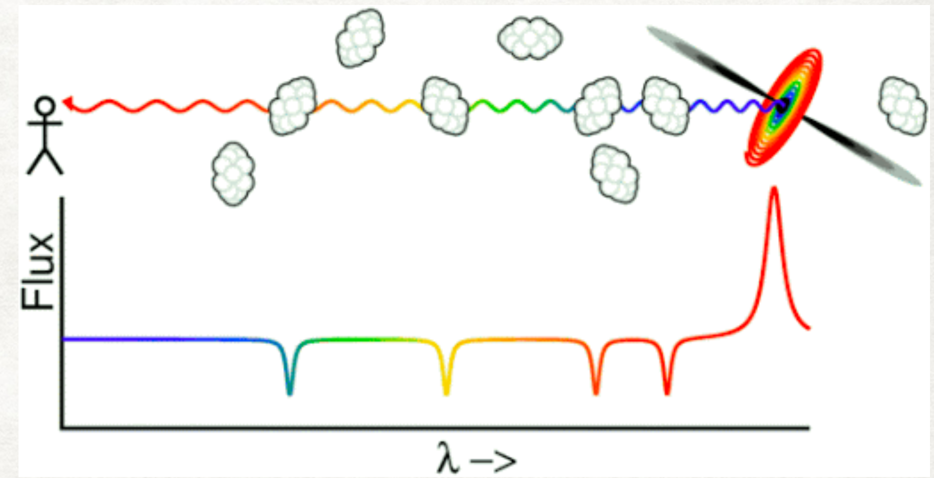
- There exists various ways of putting bounds on the ALP mass from large-scale structure observations: e.g. galaxy clustering and weak lensing power spectrum, Ly-α power spectrum, sub halos number count and more!

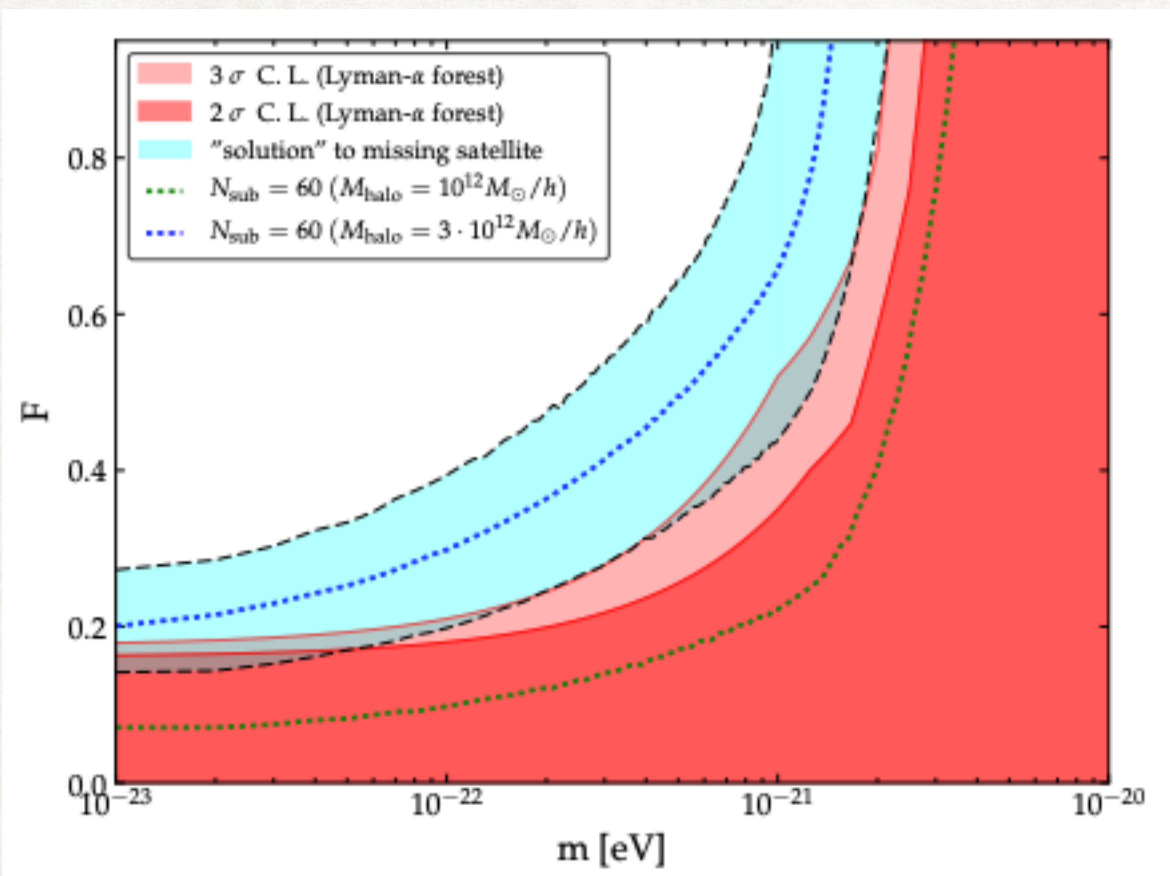


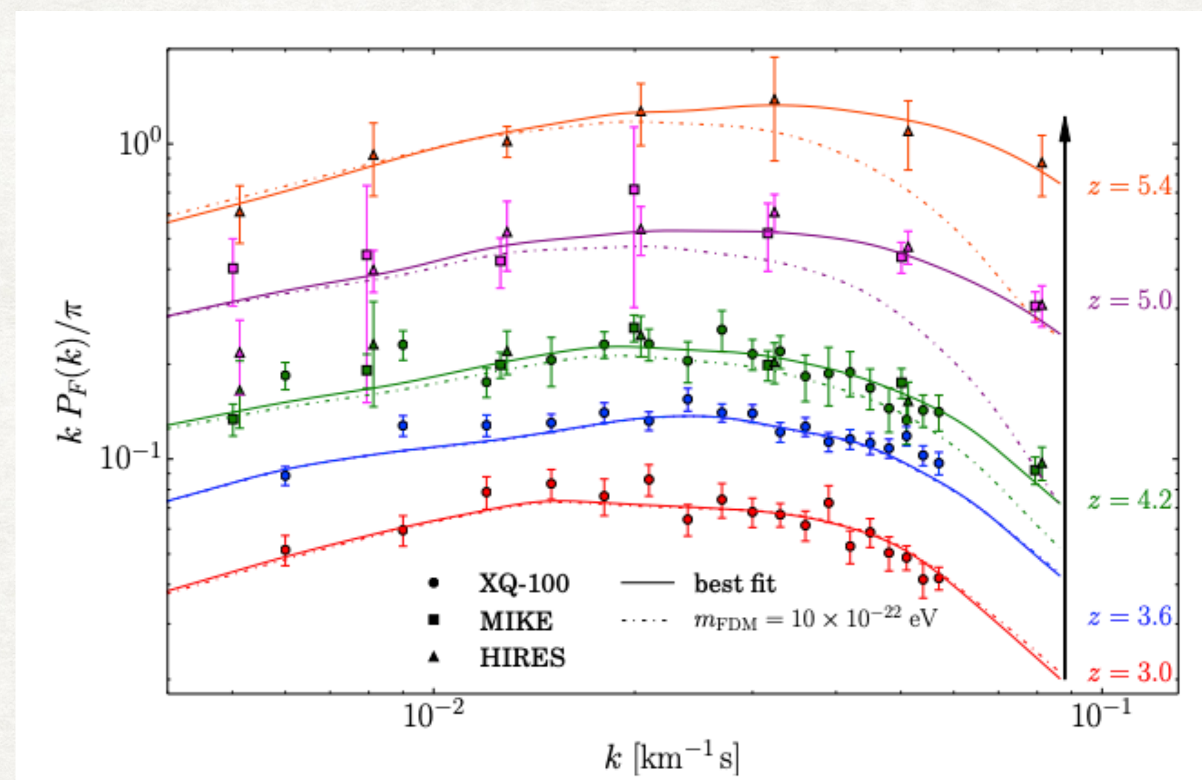
Grin++ 1904.09003

The Ly-α bound

- Absorption of the QSOs light by neutral hydrogen leads to the lyman-α forest.
- Measures properties (T and density) of the IGM at z ~ 3-6.
- This provides strong constraint on the ULA mass and density (some uncertainty on the IGM temperature history).







Irsic++ 1703.04683

Most stringent bounds from Lyα to date: $m_a > 2 \times 10^{-20}$ eV *Rogers&Peiris 2007.12705*

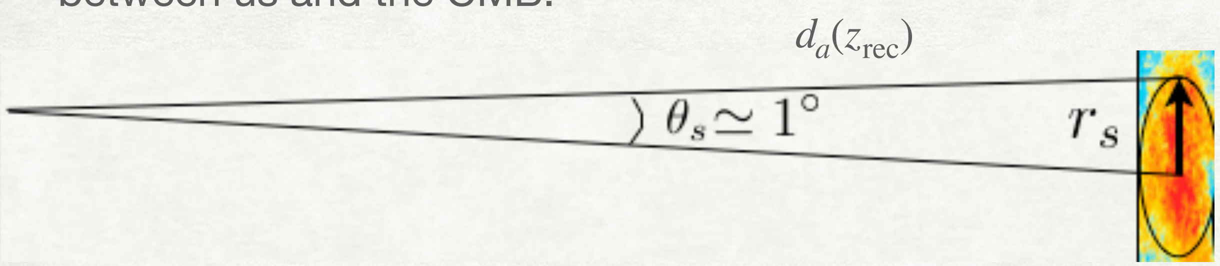
Constraints from the CMB

- The CMB does not provide the best constraints on the ALP mass, but is able to probe small fraction of ultra-light ALP
- CMB probes linear scales and therefore $10^{-33}\ \mathrm{eV} \lesssim m_a \lesssim 10^{-24}\ \mathrm{eV}$
- Field becoming dynamical before $z_{\rm rec} \sim 1000$: affect (mostly) the time-evolution of potential well (integrated sachs-wolfe effect)

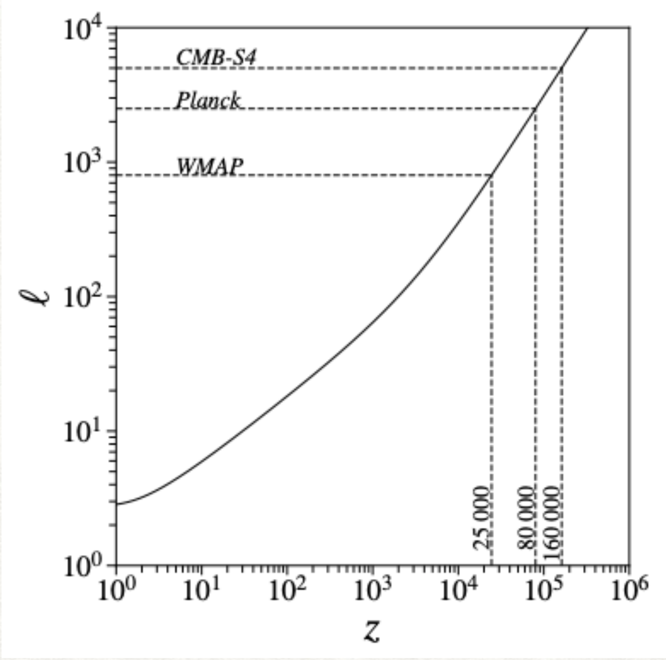
$$C_\ell^{TT} \simeq C_\ell^{\rm SW} + C_\ell^{\rm doppler} + C_\ell^{\rm ISW}$$

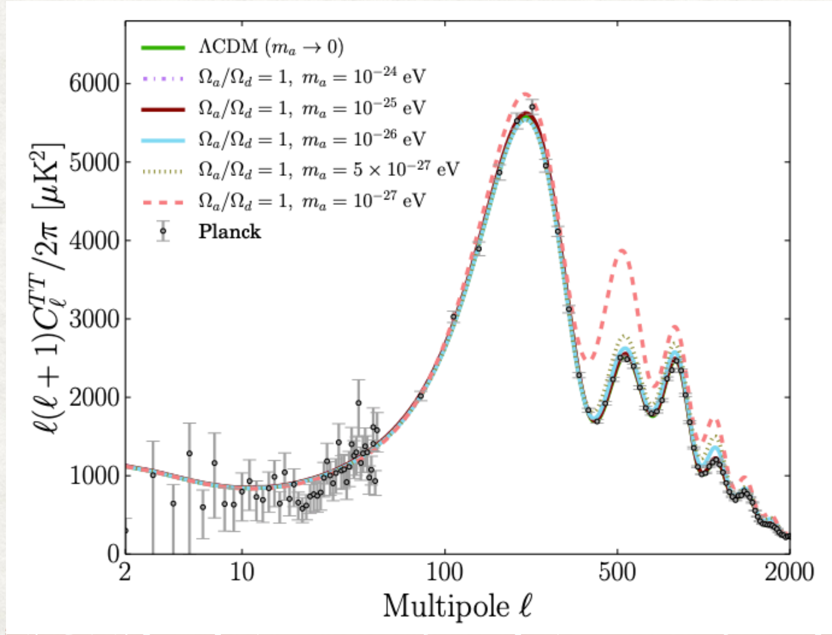
$$C_\ell^{(\rm ISW)} = \frac{2}{\pi}\int \frac{dk}{k} k^3 \left[\int_{\eta_*}^{\eta_0} d\eta (\dot\Psi - \dot\Phi) j_\ell(k(\eta_0 - \eta))\right]^2$$

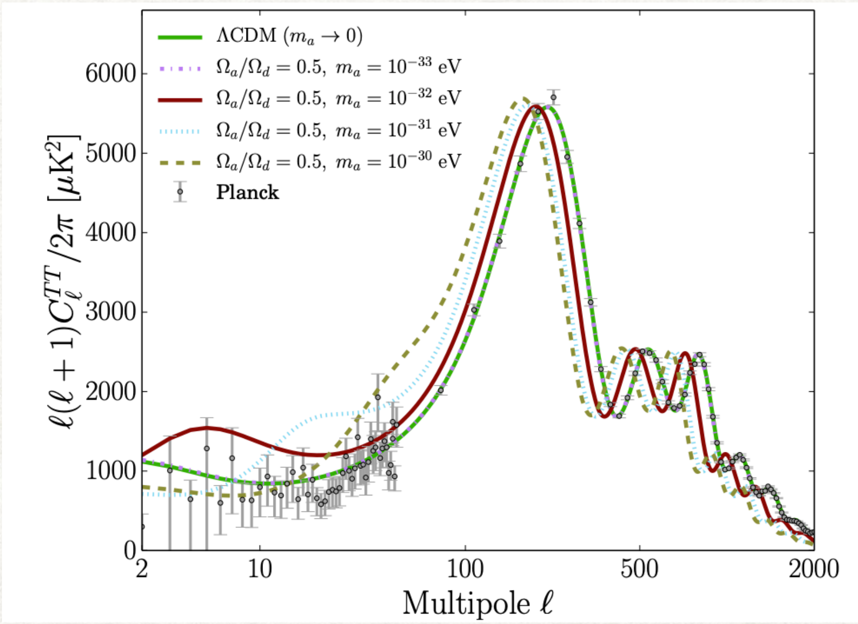
- Field becoming dynamical after $z_{\rm rec} \sim 1000$: affect (mostly) the angular-diameter distance between us and the CMB.

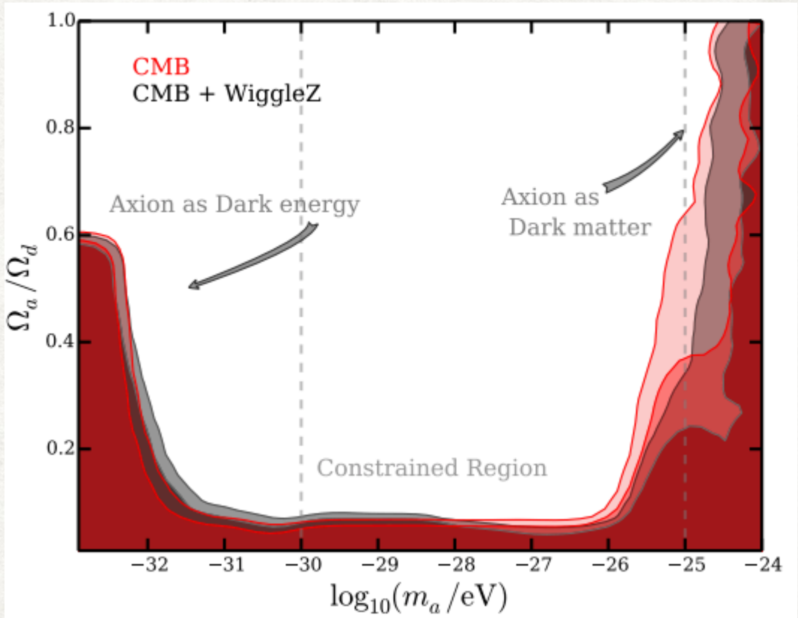


$$d_a(z_{\rm rec}) = \frac{1}{1+z_{\rm rec}}\int_0^{z_{\rm rec}} \frac{dz}{H(z)}$$









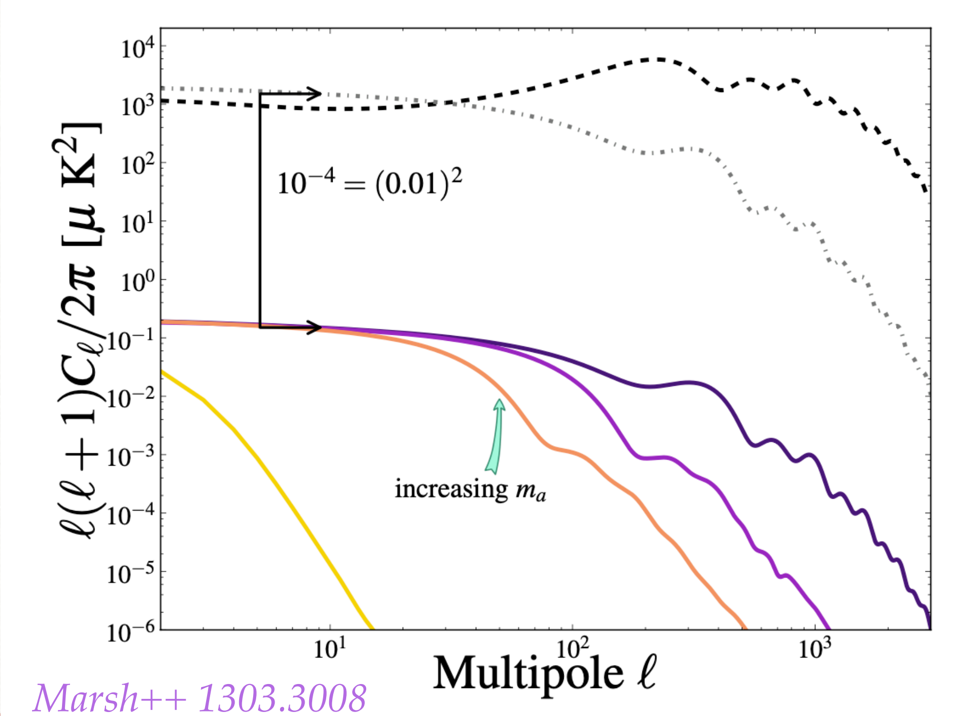
Initial conditions and iso-curvature

e.g. Langlois C. R. Physique 4 (2003) 953–959, Hlozek++ 1708.05681

- Initial condition (i.e. condition right after inflation) are decomposed between one adiabatic mode and a number of iso-curvature modes.
- The adiabatic mode verifies $\delta(n_i/n_j) = 0$ which can be shown to give $\delta_i = \frac{3}{4}(1+w_i)\delta_\gamma$. For a frozen axion $w'_a \simeq -1 \Rightarrow \delta_a \simeq 0$.

(Nb: in practice numerical code do not start at $\tau = 0$ and include a small correction valid for $k\tau \ll 1$).

- 'iso-curvature' modes: variations in the particle number ratios at constant total density perturbation (i.e. curvature) $S_{i,j} = \frac{\delta n_i}{n_i} - \frac{\delta n_j}{n_j}$
- In the case $f_a > H_I/2\pi$: the axion exists as a massless field during inflation and develop perturbations $\delta\phi = \frac{H_I}{2\pi} \equiv M_{\rm pl}\sqrt{\frac{A_s r_T}{8}}$
- $r_T \equiv A_T/A_s$ is the tensor-to-scalar ratio, it is bounded $r < 0.06$ (95%C.L., Bicep+Planck) which implies $H_I/2\pi \lesssim 10^{13}\mathrm{GeV}$



Marsh++ 1303.3008

- This translates into a spectrum of fluctuations for the axion

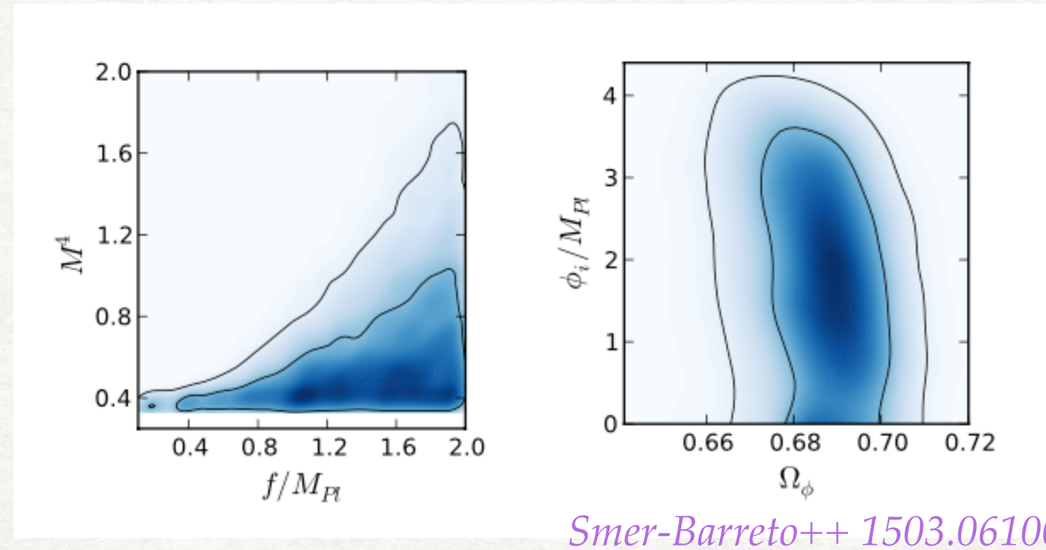
$$P_{\delta_a}(k) = A_I\left(\frac{k}{k_0}\right)^{n_{\rm iso}-1} \quad \text{with } A_I = \frac{H_i^2}{\pi^2\bar{\phi}_i^{\,2}}$$

- Hence the detection of a non-zero r implies the existence of a non-zero A_I. Current constraints: $A_I/A_{\rm ad} < 0.038/F^2$ (95% Planck)
- Detecting r would constrain ALP as DM! Alternatively detecting ALP iso-curvature would constrain the energy scale of inflation.

e.g. Visinelli++ 1403.4594

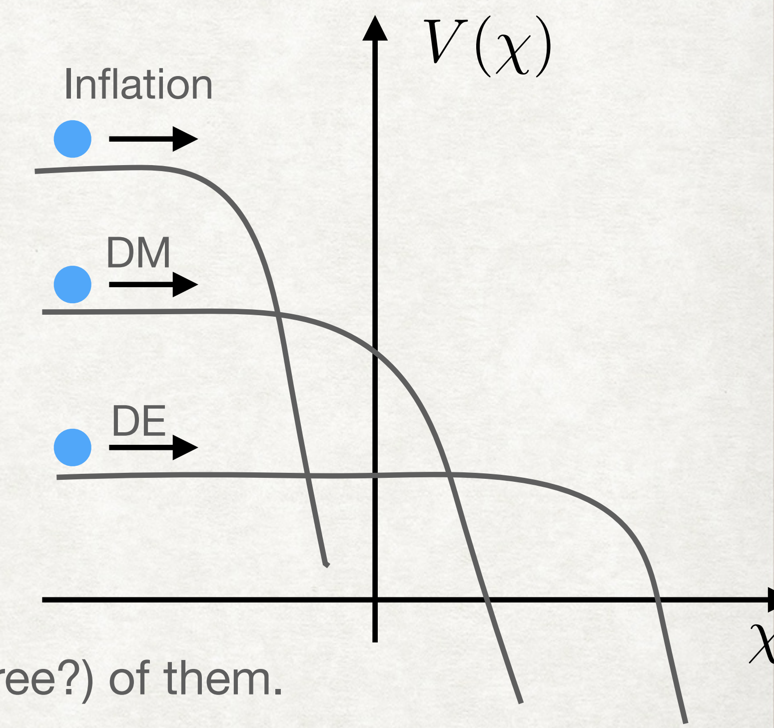
ALP as a dark energy candidate

- ALP with masses $m_a \sim 10^{-33}$ eV are frozen by Hubble friction until today and therefore viable DE candidate.
- Assume $V = M^4(1+\cos(\phi/f))$, energy density set by ϕ_i.
- Degeneracy between M^4 and f from requirement $H_0 \gtrsim m_a$



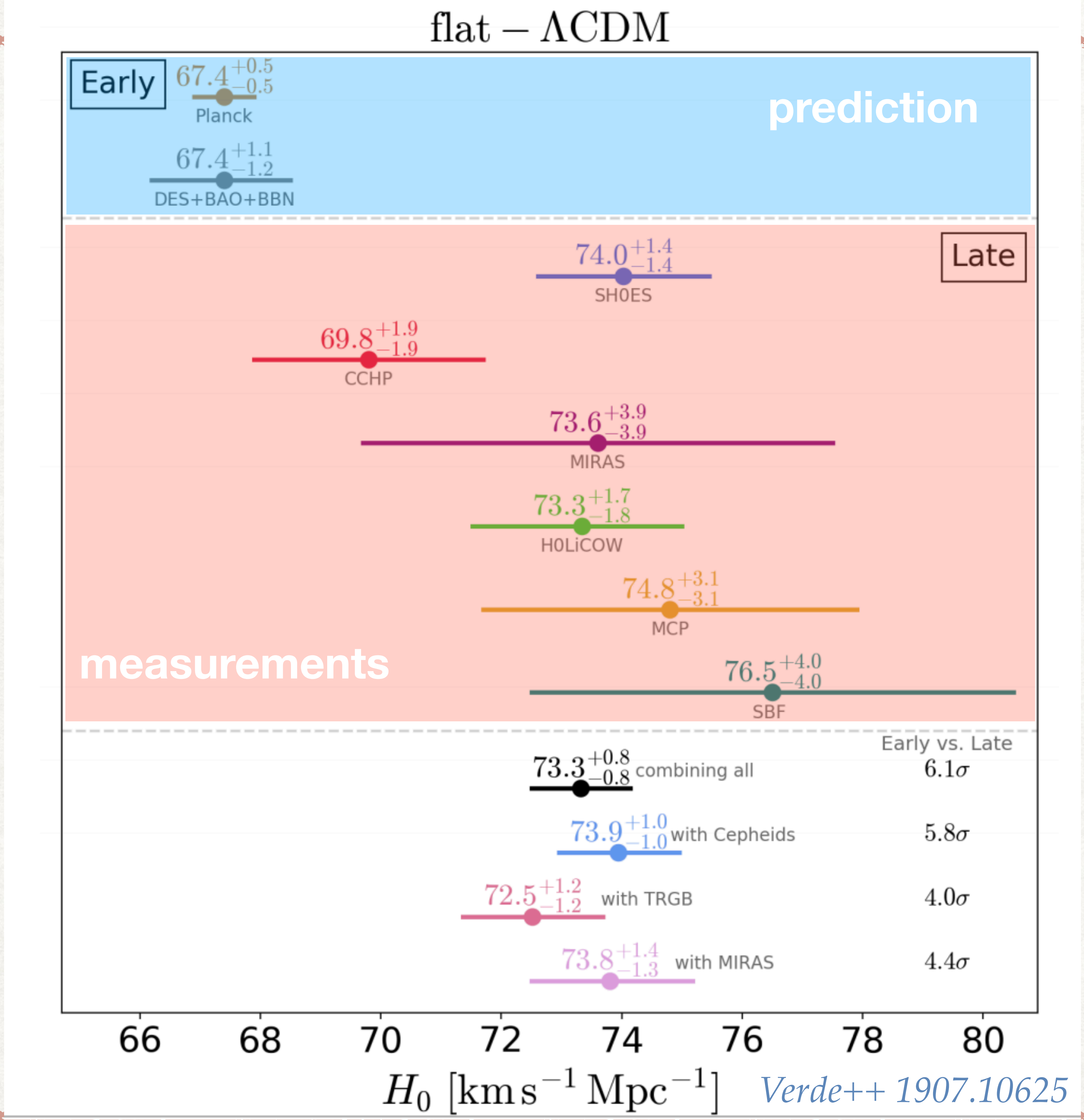
Smer-Barreto++ 1503.06100

- However, this model does not explain why the accelerated expansion occurs now, or in other words why $\Omega_{\rm m} \sim \Omega_{\rm DE}$.
- One possible paradox: the `axiverse' many ALP fields which had impact at various epochs.



- First field could be the inflation: `natural inflation' similar to $m^2\phi^2$ inflation: testable prediction $r > 0.01$ for next generation CMB experiment
- Another field could be Dark Matter (not the same! Otherwise inflation never ends).
- Another field could be Dark Energy. In Kamionkowski++1409.0549 : 1/100 chance.
- What if there were more of such era to be discovered? We already have seen two (three?) of them.

The H_0 tension now reaches $4-6\sigma$



Verde++ 1907.10625

How does CMB data measure H_0?

- The 'sound horizon' r_s, a standard ruler in the sky: distance travelled by sound wave until recombination.
- Planck measures θ_s and, given a model, can extract r_s.
- H_0 appears *only* in the angular diameter distance d_A.

$$\theta_s \equiv \frac{r_s(z_*)}{d_A(z_*)} = \frac{\int_\infty^{z_*} dz\ c_s(z)/\sqrt{\rho_{\rm tot}(z)}}{\int_0^{z_*} dz/\sqrt{\rho_{\rm tot}(z)}}$$

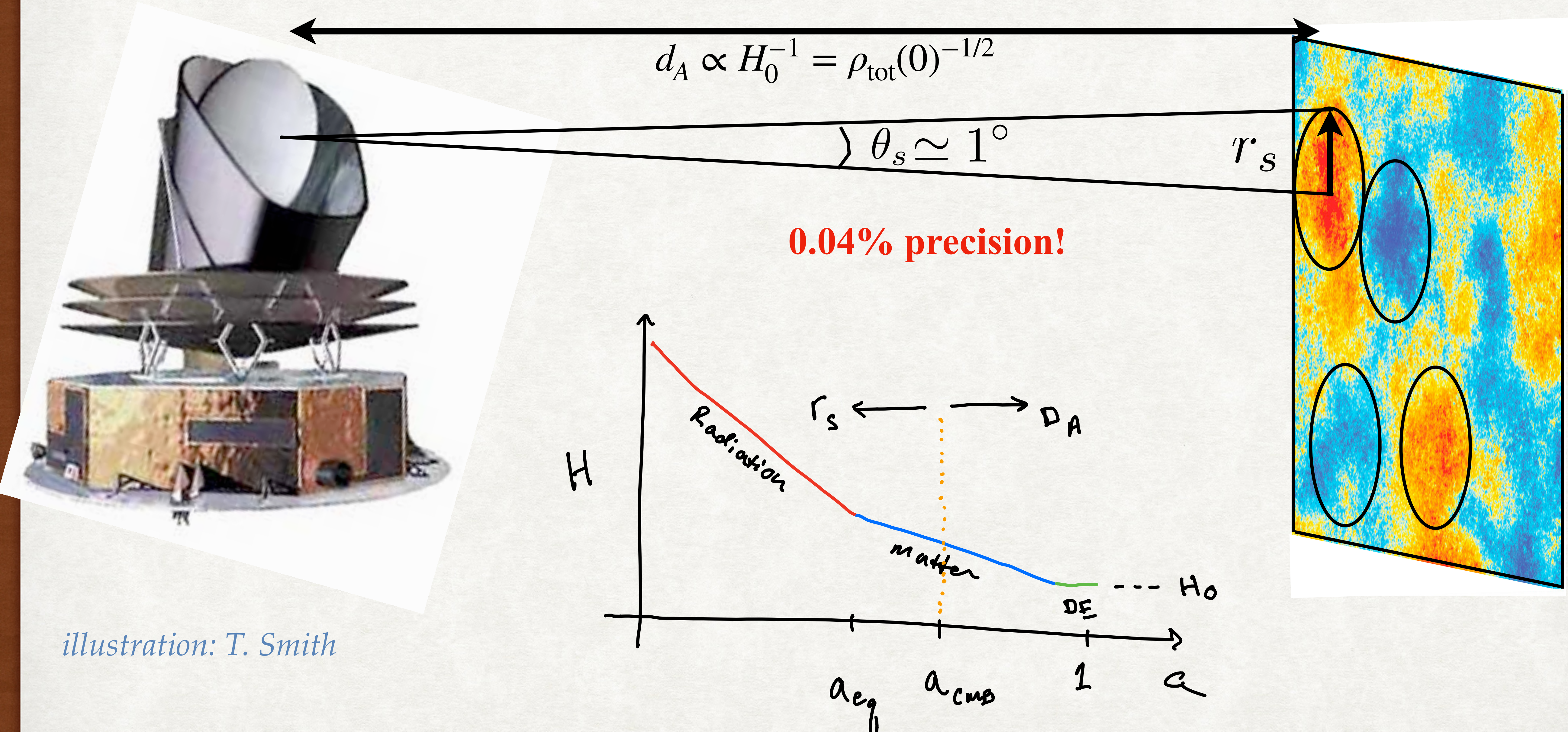


illustration: T. Smith

Geometrical degeneracy in Planck!

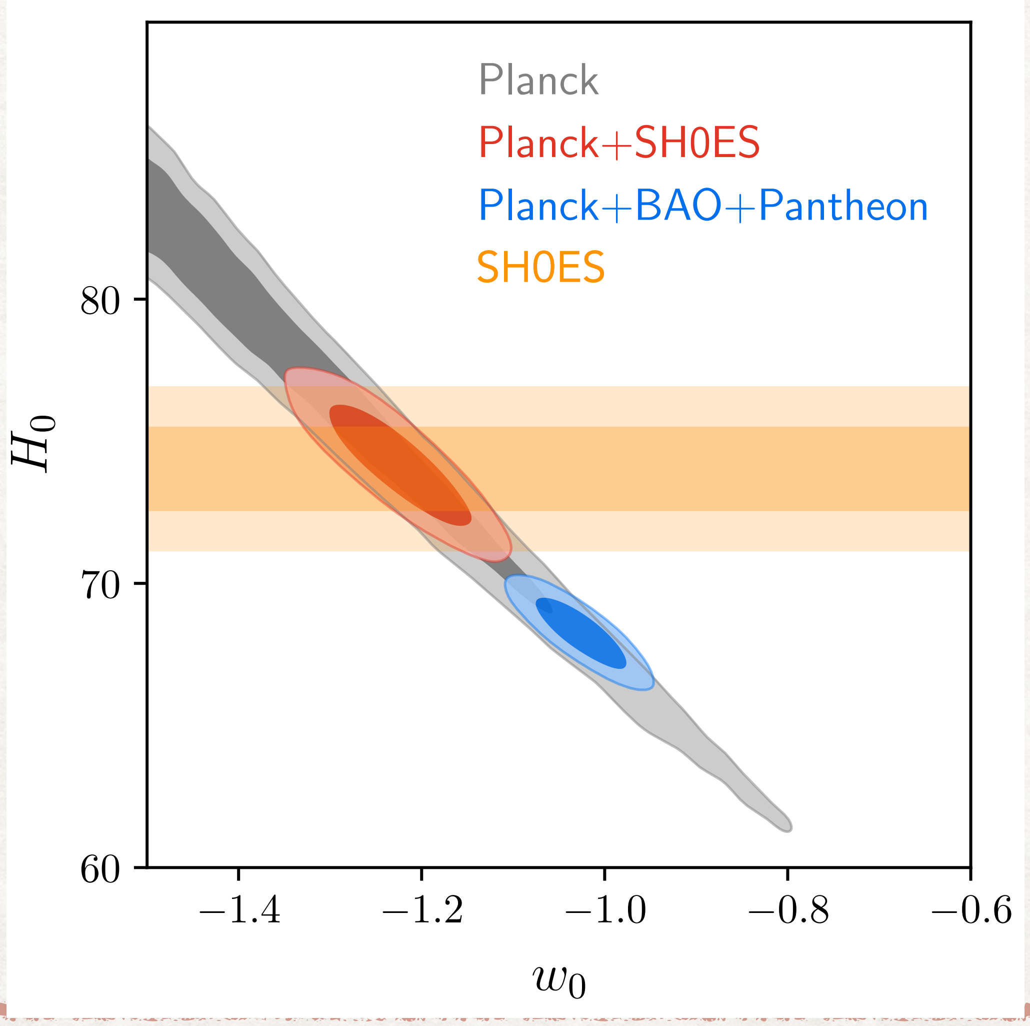
- A higher H_0 can be compensated by a lower $H(z>0)$ such as to keep $d_A(z_*)$ fixed

$$d_A(z_*) = \frac{1}{1+z_*}\int_0^{z_*} \frac{dz}{100\sqrt{\omega_{\rm M}(1+z)^3 + \Omega_{\rm DE}(z)h^2}}$$

- 'phantom dark energy' w < -1, DE phase transition, DE-DM interaction, decaying/annihilating DM, and many more…

[http://arxiv/insert_your_favorite_ model_here.com]

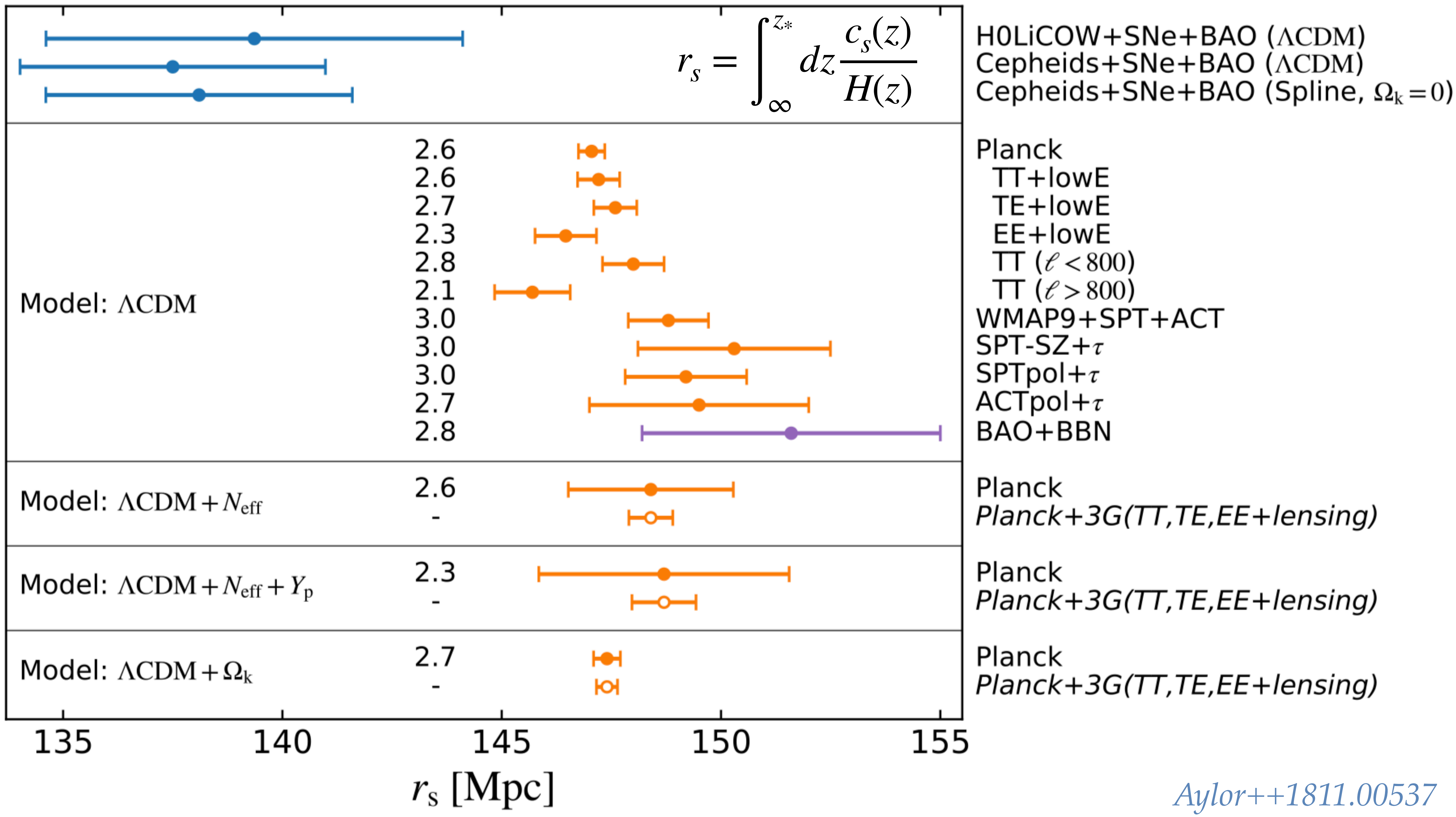
- Planck can easily accommodate a higher H_0: problem with BAO and Pantheon



H_0 tension or r_s tension?

One can deduce the co-moving sound horizon r_s from H_0 and BAO

r_s from CMB needs to decrease by ~ 10 Mpc



Aylor++1811.00537

A sketch of the physics at play

- Could the CMB be closer to us than ΛCDM tells us? This is what a higher H_0 suggests.
- Therefore, could spot in the CMB be smaller? This is what new physics must achieve.

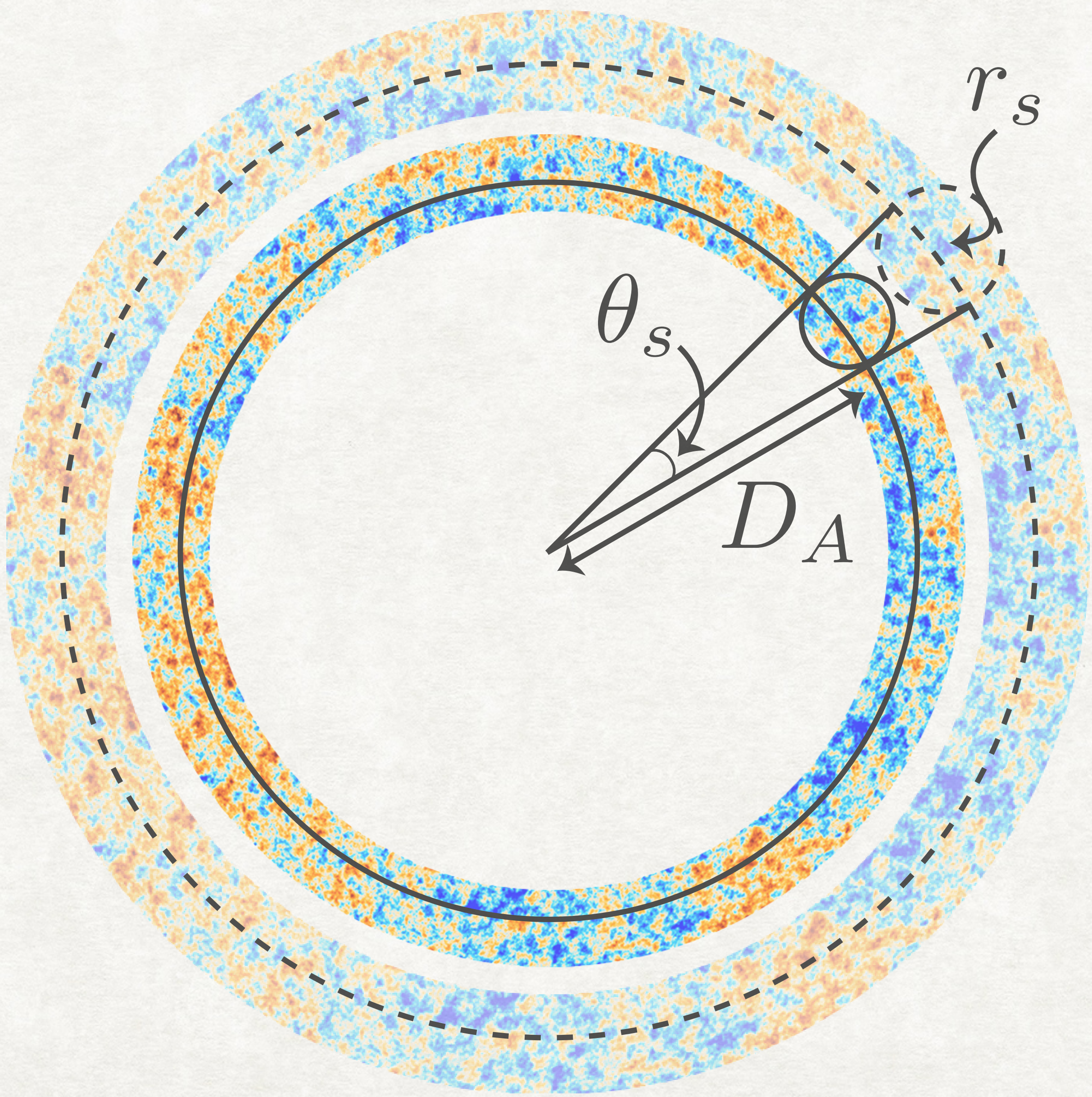


illustration: T. Smith

Early-time resolution to the H_0 tension

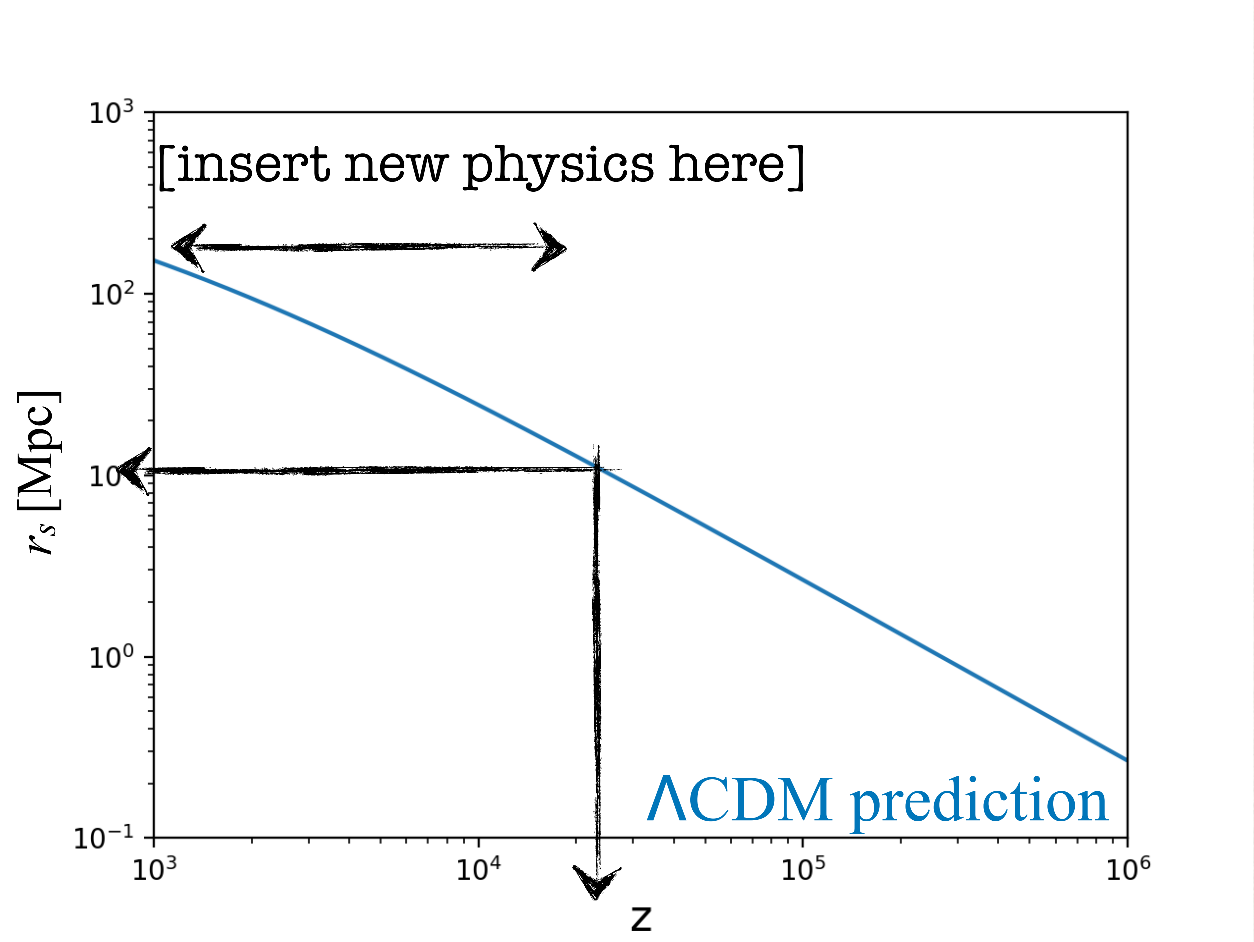
affect z_*: modified recombination physics?

affect c_s: DM-photon scattering? DM-b scattering?

$$r_s = \int_{\infty}^{z_*} dz \frac{c_s(z)}{\sqrt{\rho_{\rm tot}(z)}}$$

increase $\rho(z)$: Neff? Early Dark Energy? Modified Gravity?

- r_s does not reach 10Mpc before ~ 25000 in ΛCDM



GOAL: decreasing r_s by 10Mpc while keeping r_s/r_d and r_s/r_{eq} fixed

See the `Hubble Hunter's guide' Knox&Millea 1908.03663

Scalar field and Early Dark Energy

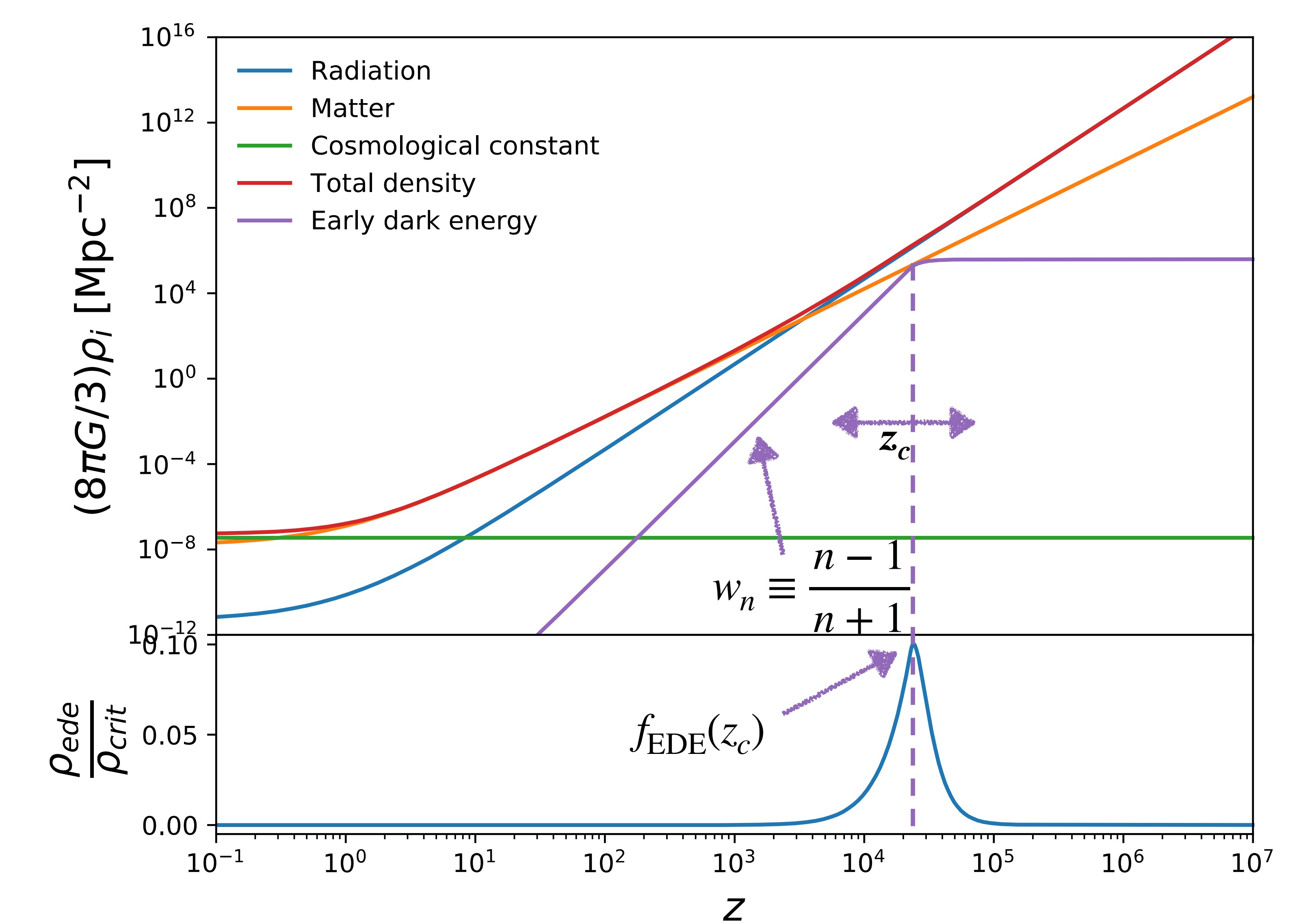
- Initially slowly-rolling field (due to Hubble friction) that later dilutes faster than matter

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV_n(\phi)}{d\phi} = 0 \qquad \rho_\phi = \frac{1}{2}\dot{\phi}^2 + V_n(\phi),\ P_\phi = \frac{1}{2}\dot{\phi}^2 - V_n(\phi)$$

- Oscillating (toy) potential:

$$V(\phi) \propto (1 - \cos(\phi < f))^n \xrightarrow[\phi \ll f]{} \left(\frac{\phi}{f}\right)^{2n}$$

VP++ 1806.10608 & 1811.04083
Smith, VP ++ 1908.06995



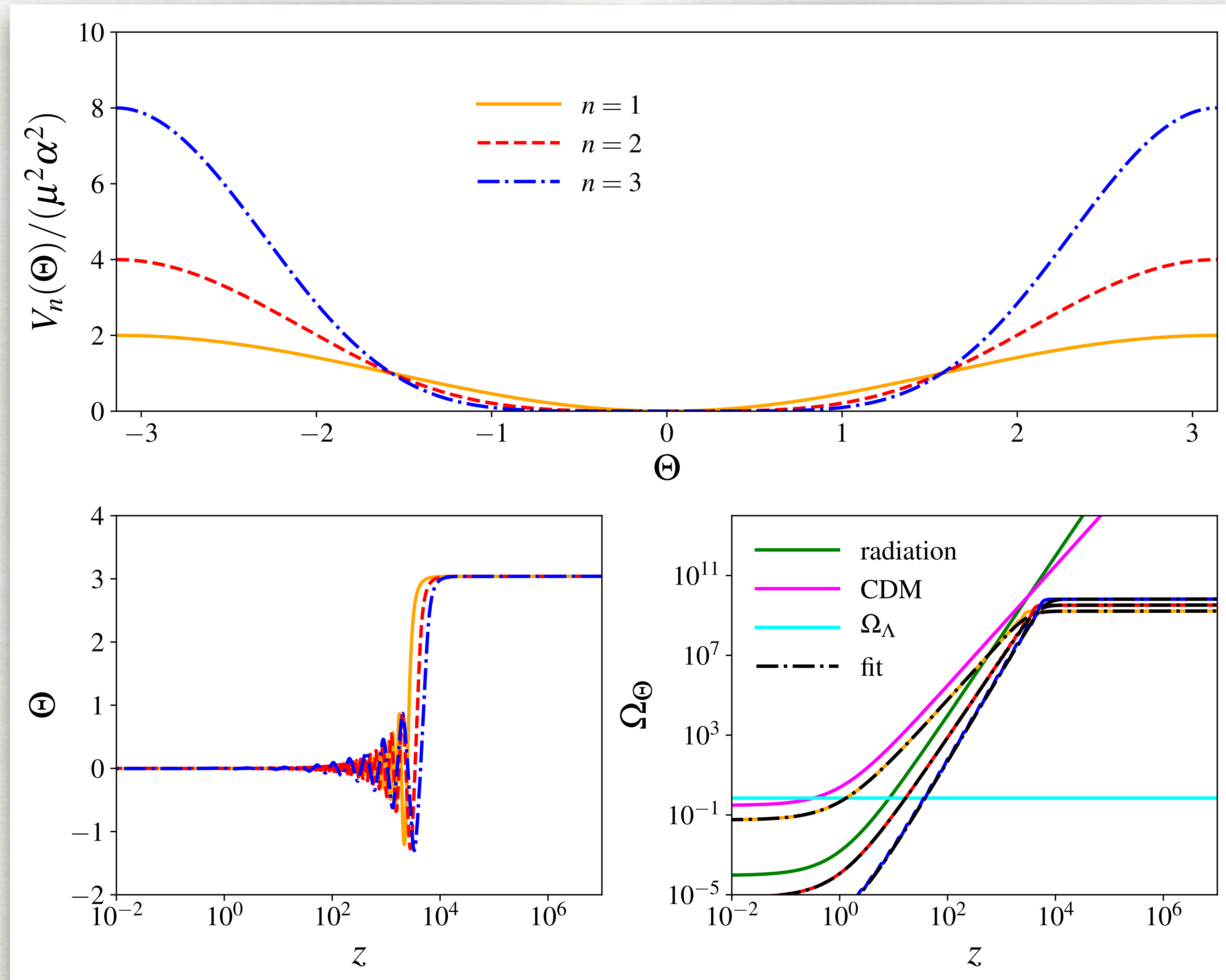
plot by T. Karwal

- Specified by $f_{\rm EDE}(z_c),\ z_c,\ w(n),\ c_s^2(k,\tau)$

$$\begin{cases} z > z_c \Rightarrow w_n = 1 \\ z < z_c \Rightarrow w_n = (n-1)/(n+1) \end{cases}$$

$n = 1$: matter, $n = 2$: radiation, etc.

Homogeneous evolution

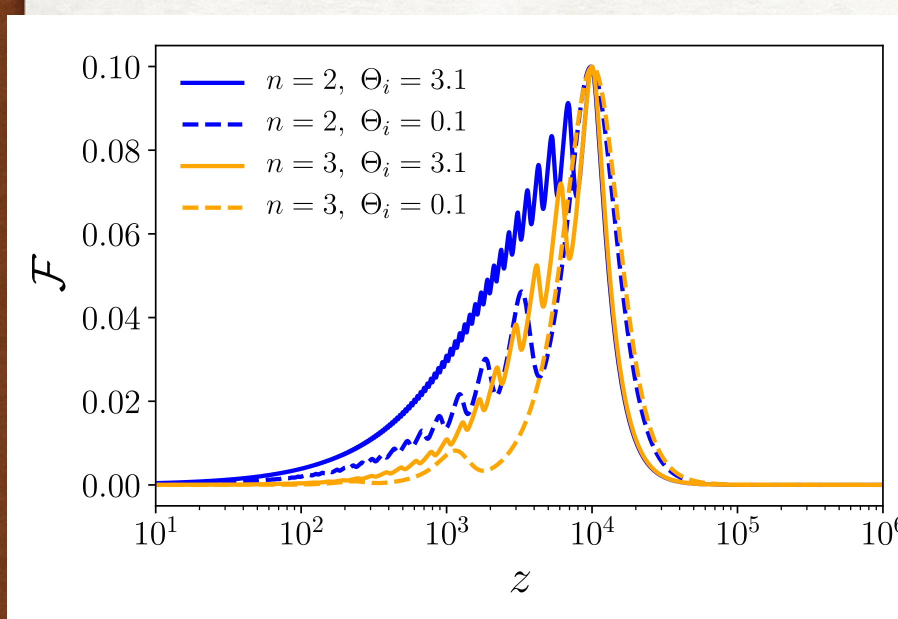


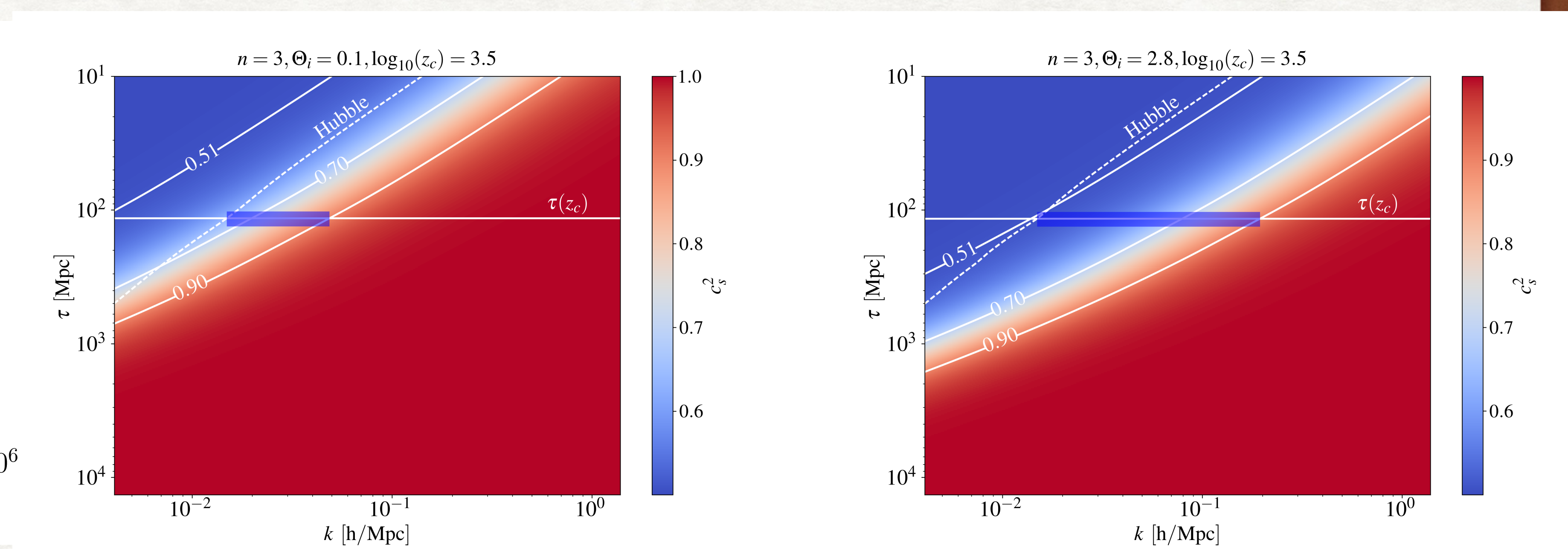
VP++ 1806.10608

Effective sound speed

- Θ_i affects the oscillation frequency $\varpi(a)$ and asymmetry of the energy injection as well as the range of modes having $c_s^2 \to 1$

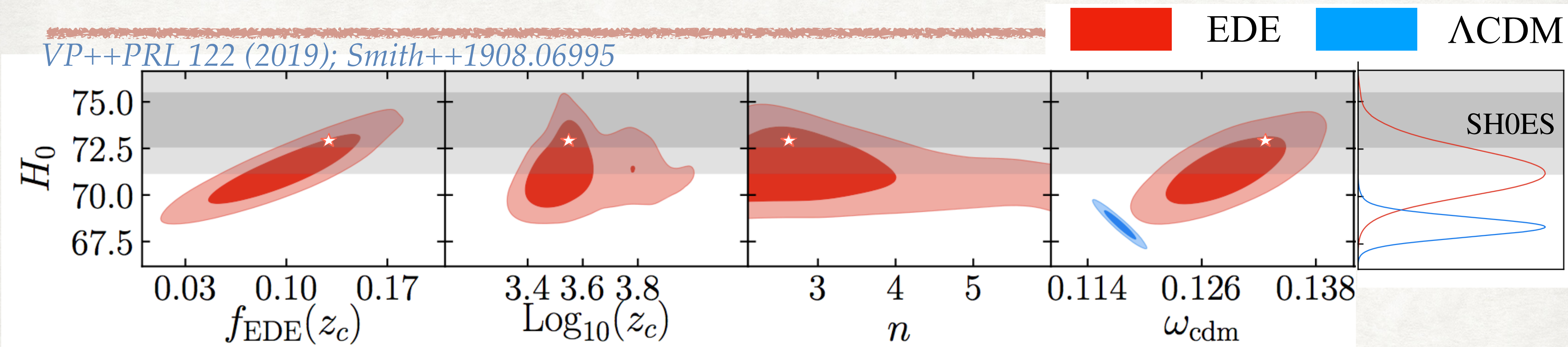
$$c_s^2 = \frac{2a^2(n-1)\varpi^2(a) + k^2}{2a^2(n+1)\varpi^2(a) + k^2} \qquad \varpi(a) \simeq 3H(z_c)\frac{\sqrt{\pi}\Gamma(\frac{1+n}{2n})}{\Gamma\left(1+\frac{1}{2n}\right)}2^{-(1+n)/2}\frac{\Theta_{\rm osc}^{n-1}(a)}{\sqrt{|E_{n,\Theta\Theta}(\Theta_i)|}}$$





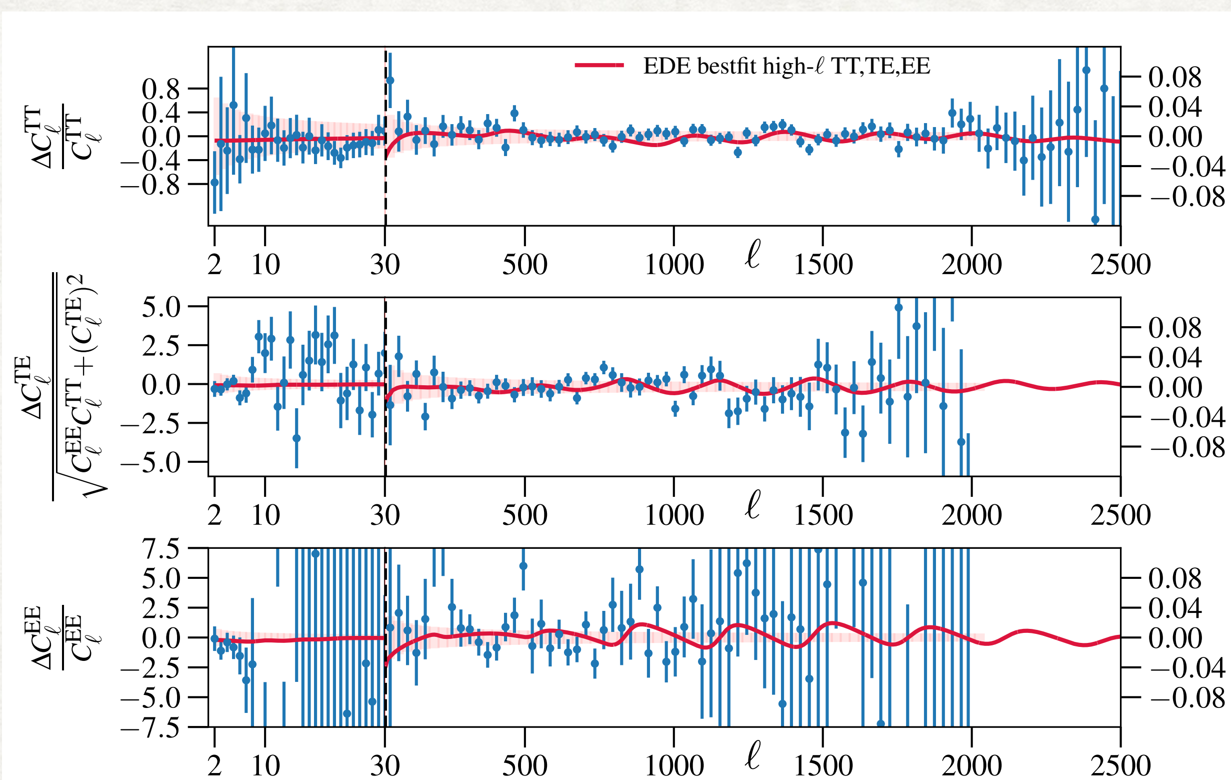
EDE Can Resolve The Hubble Tension

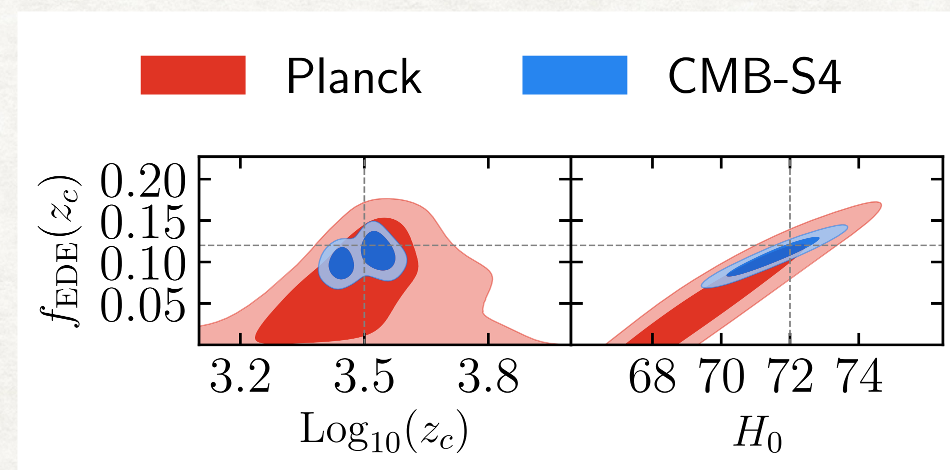
VP++PRL 122 (2019); Smith++1908.06995



- Planck high-ℓ TT,TE, EE+lowTEB+lensing+BAO+Pantheon+SH0ES 19

$f(z_c) = 0.10\ (0.13) \pm 0.03$ $\quad \mathrm{Log}_{10}(z_c) = 3.56\ (3.53)^{+0.05}_{-0.1}$ $\quad H_0 = 71.5\ (72.8) \pm 1.2\ \mathrm{km/s/Mpc}$



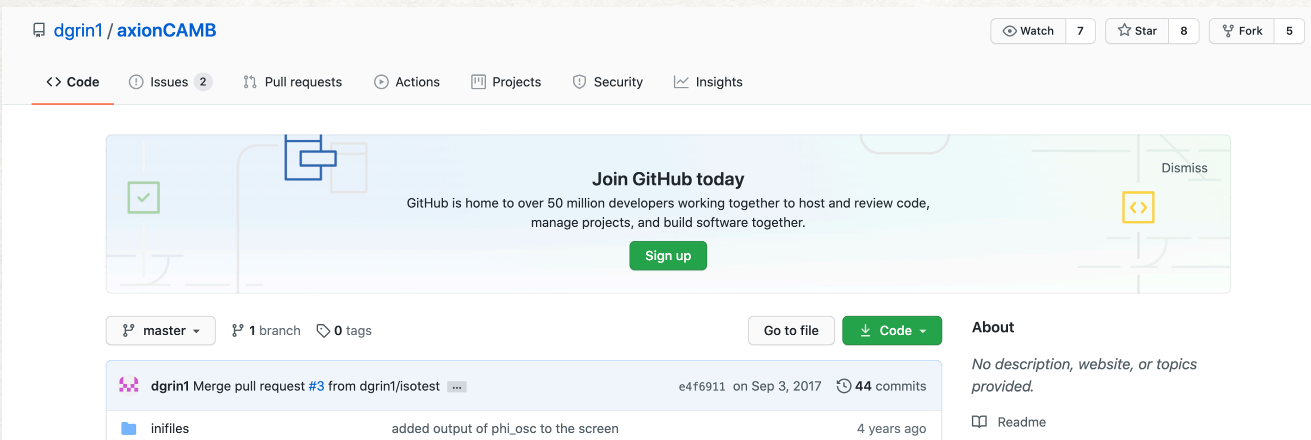


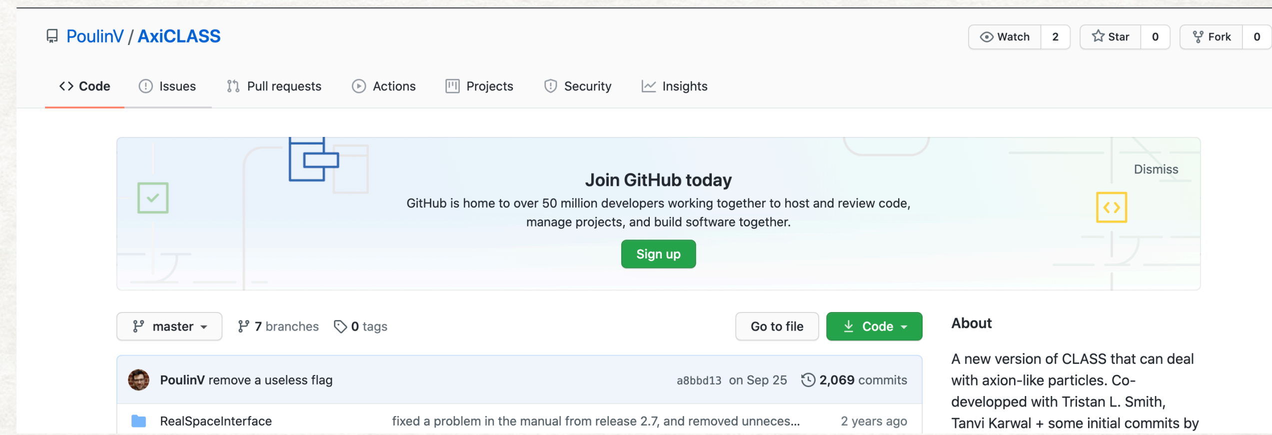
Smith ++ 1908.06995

- CMB-S4 will certainly detect (exclude) $f_{\rm EDE}(z_{\rm eq}) \sim 10\,\%$.

Exercices!

- Numerical codes are public!





- axionCAMB *Hlozek++ 1708.05681*
- axiCLASS *VP++ 1806.10608 & 1811.04083*
  Smith, VP ++ 1908.06995

- You can study the impact of axion dark matter produced via the 'misalignment mechanism' on CMB and LSS

- Try to reproduce some of the figures from this lecture.

Conclusions

- 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?
- As a DM candidate: It could explain the ‘small-scale crisis’ of CDM.
- As a DE candidate: It could explain the old and new cosmological constant problem.
- As an inflaton candidate: r detectable by next generation experiment.
- As an Early Dark Energy candidate: it could relax the H0 tension.
- CMB & matter power spectrum, Ly-a forest, small-scale structure of DM: many ways to test the ALP signatures. Have we already discovered it?