Cosmological bounds on ALPs from strings

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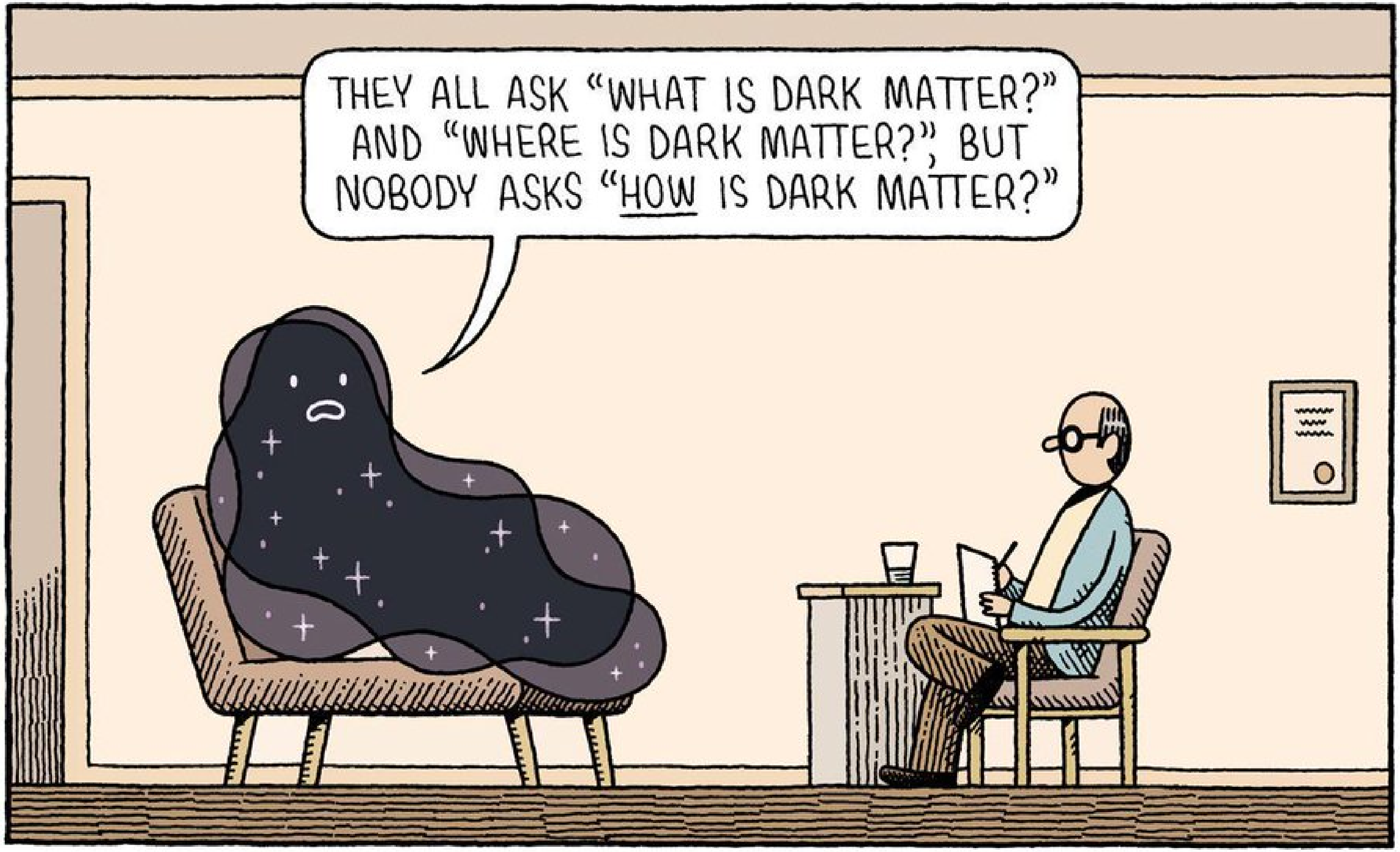


TOM GAULD for NEW SCIENTIST

How is the distribution function of light relics?

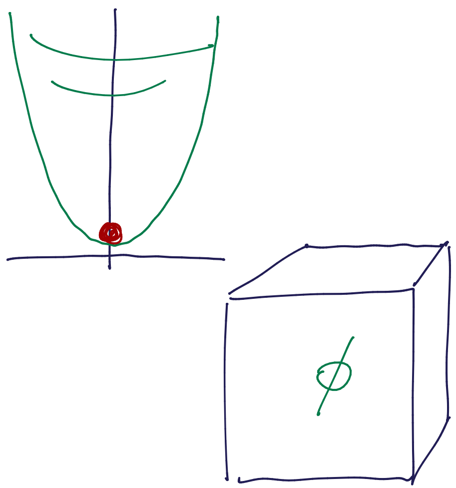
- **What we know: neutrinos.**
  Neutrinos in the Early Universe reach thermal equilibrium before decoupling. Thereafter, they retain a thermal Fermi-Dirac distribution with $T_\nu \simeq (4/11)^{1/3} T_\gamma \simeq$ 2 K today.
  However, small deviations from a Fermi-Dirac distribution do not leave such strong signatures on CMB spectra (Alvey et al 2021).

- **What we wish we knew: axions.**
  Axions, and more generically ALPs, can be produced in many ways. Among those, they may be radiated from a network of cosmic strings. Their distribution function is very non-thermal. Does this very non-termal relic leave a signature on cosmological observables?

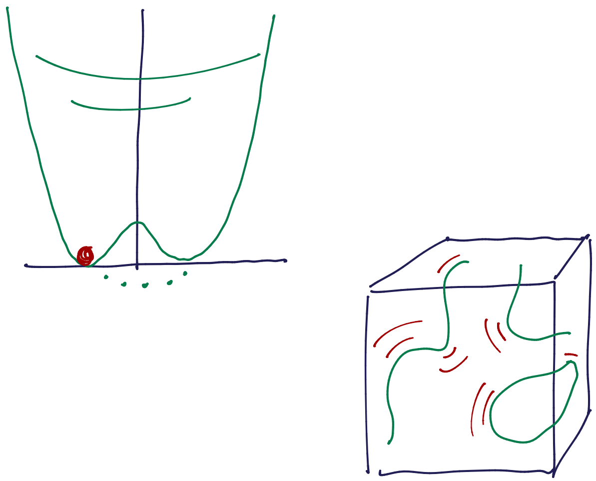
ALPs from strings: formation

$H \leq f_a = T_{U(1)_{SSB}}$ $\qquad$ $H \leq m_a$ $\qquad$ time

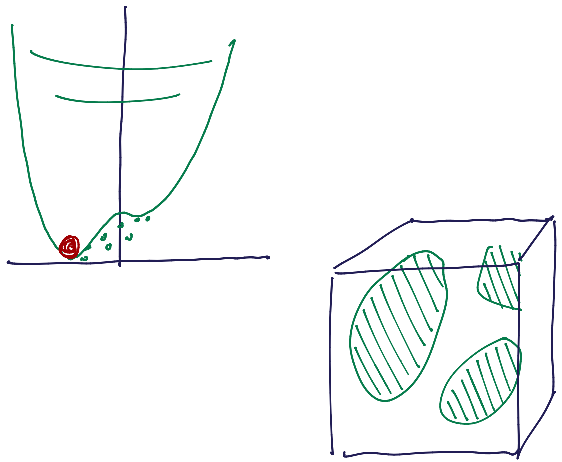
REHEATING



Before **SSB**:
no strings



After **SSB**:
in the **scaling regime**
ALPs are radiated from strings

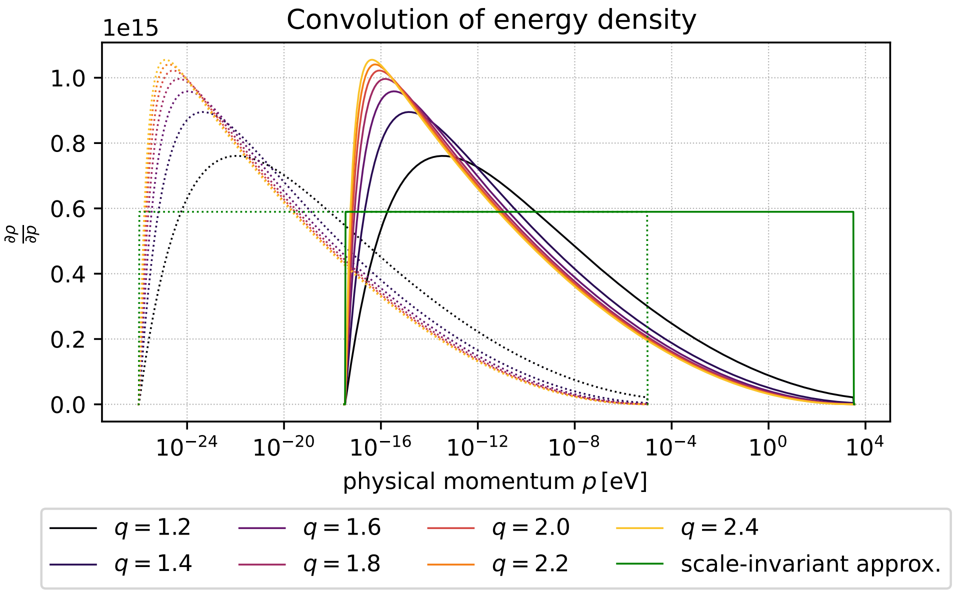


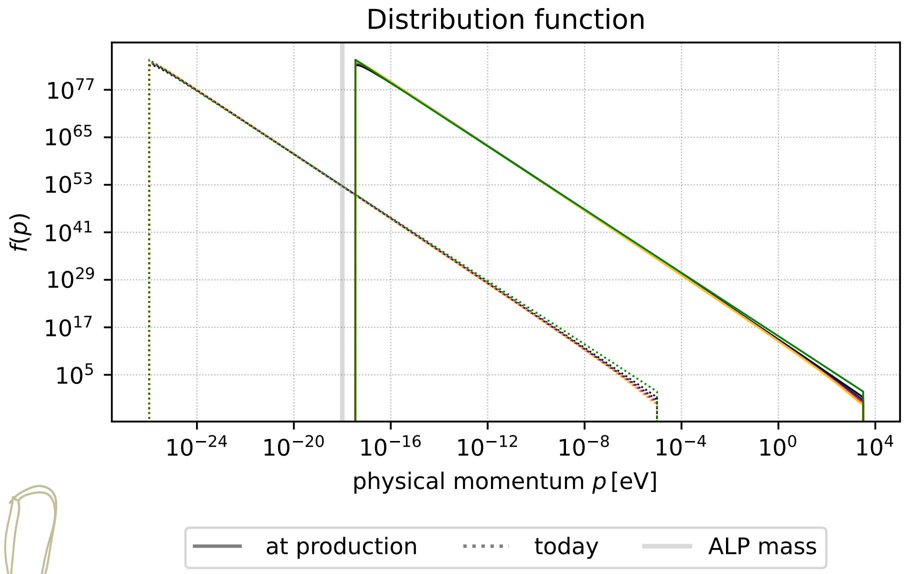
After the **tilt of the potential**:
Strings + domain walls

ALPs from strings: distribution function

$$f(p, m_a, f_a) = \frac{4}{\pi^2} \frac{\xi_\star(m_a, f_a)\mu_\star(m_a, f_a) m_a^2}{p^3\sqrt{p^2 + m_a^2}} \left[1 + \mathcal{O}\left(\log\left(f_a/m_a\right), p^{q_a - 1}\right)\right] \overset{m_a \ll p \ll f_a,\, q_a \to 1}{\propto} \frac{1}{p^4},$$

Gorghetto et al. 2021





ALPs from strings: thermal history

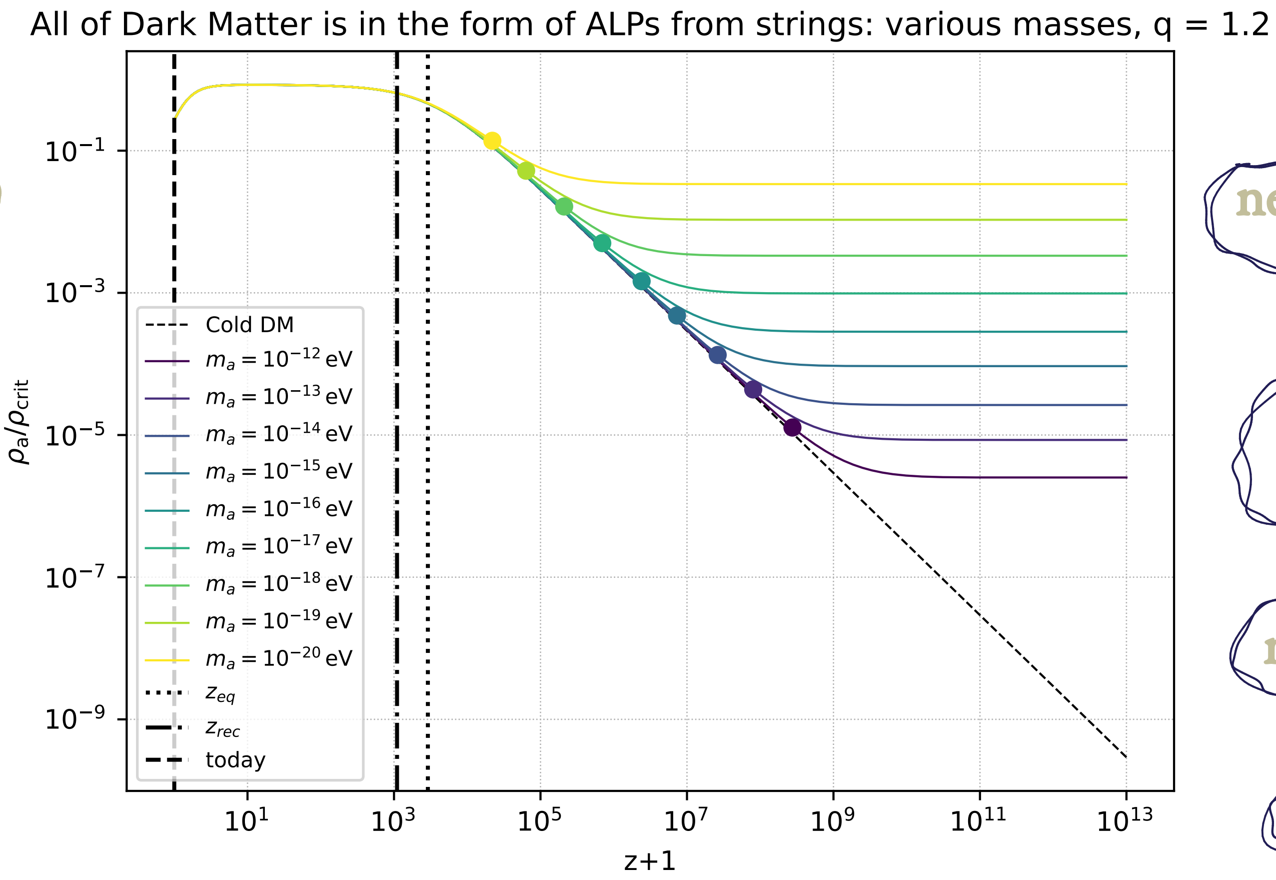
smaller m_a

network persits longer

ALPs radiated until recently

less redshifted

hotter ALPs



larger m_a

network destroyed sooner

ALPs radiated long time ago

more redshifted

colder ALPs

Effects + CLASS Implementation

background

perturbations

$$f(q) = f_0(aq)(1+\Psi(q))$$

$$\rho_a, P_a \sim \int \left(\sqrt{q^2+m^2}\right)^{A_1} (q^2)^{A_2} f_0(aq) dq$$

$$w_a = P_a/\rho_a \qquad A_1, A_2 \in \mathbb{Z}$$

$$H^2 = \frac{8\pi G}{3} a^2(\rho_a + \rho_{\rm else})$$

$$\frac{1}{\rho_a}\frac{\mathrm{d}\rho_a}{\mathrm{d}\,\log a} = -3(1+w_a(a))$$

Effects + CLASS Implementation

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$$\delta, \theta, \delta P, \sigma \sim \int \left(\sqrt{q^2 + m^2}\right)^{A_1} (q^2)^{A_2} f_0(aq) \Psi(q) dq$$

$$A_1, A_2 \in \mathbb{Z} \qquad \Psi = \sum_\ell \Psi_\ell P_\ell$$

$$\vec{\Psi} = (\Psi_0, \Psi_1, \Psi_2, ..)$$

$$\dot{\vec{\Psi}} = A\vec{\Psi} + B$$

Effects + CLASS Implementation

background

$$\rho_a, P_a \sim \sum \left(\sqrt{q_i^2 + m^2/a^2}\right)^{A_1} ({q_i}^2)^{A_2} w_i$$

Just once in the code

Accurate enough quadrature strategy

$$H^2 = \frac{8\pi G}{3} a^2 (\rho_a + \rho_{\rm else})$$

$$\frac{1}{\rho_a}\frac{\mathrm{d}\rho_a}{\mathrm{d}\,\log a} = -3(1 + w_a(a))$$

perturbations

$$\delta, \theta, \delta P, \sigma \sim \sum \left(\sqrt{{q_i}^2 + m^2/a^2}\right)^{A_1} ({q_i}^2)^{A_2} w_i \Psi(q_i)$$

Over and over again

Fast enough quadrature strategy

$$\dot{\vec{\Psi}} = A\vec{\Psi} + B$$

Effects + CLASS Implementation

background

perturbations

Accurate enough quadrature strategy

Fast enough quadrature strategy

Gaussian quadrature
using $f_0(q)$ as the weight function

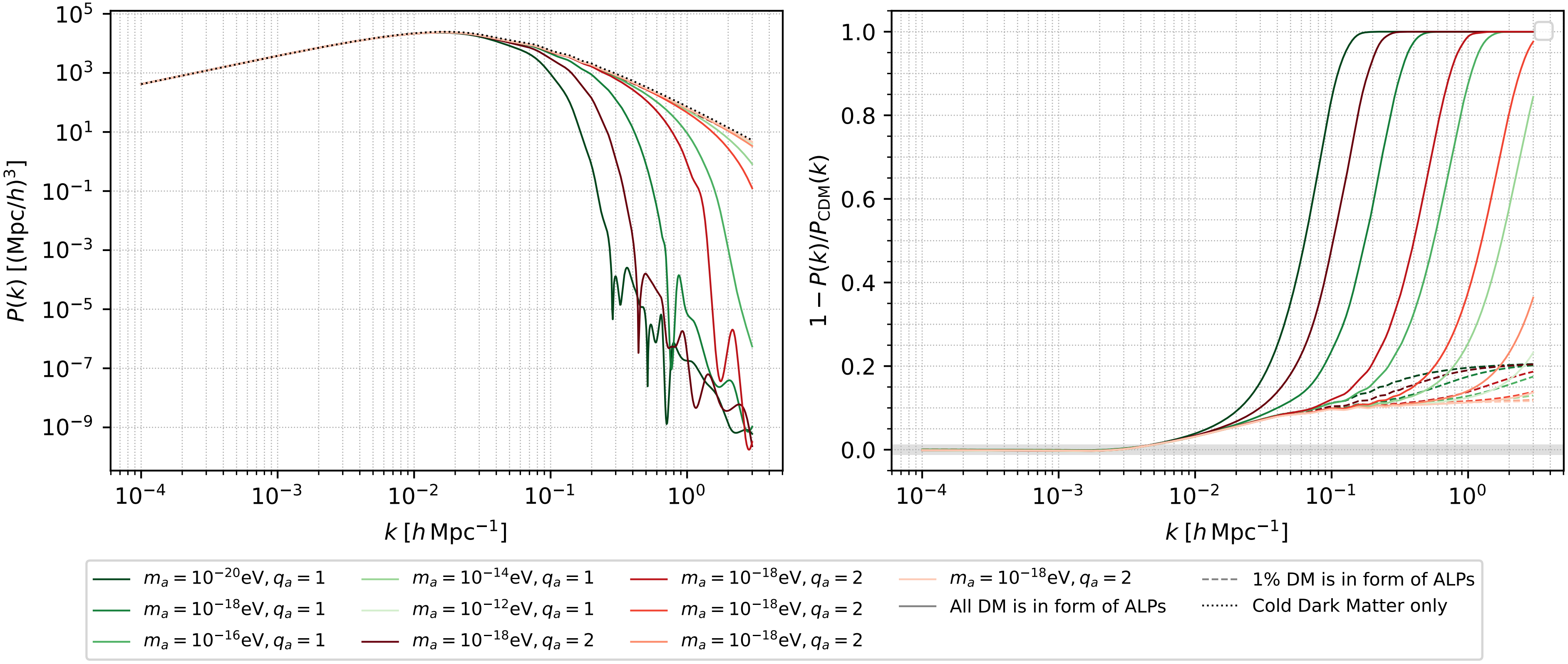
O(20) nodes are enough for O(20) orders of magnitude in momentum

Fukuda et al. 2005

Results

C_ℓ : ALPS are almost indistinguishable w.r.t CDM
P(k) : ALPS damp the power at small scales!

ALP species and three massive neutrinos: matter power spectrum



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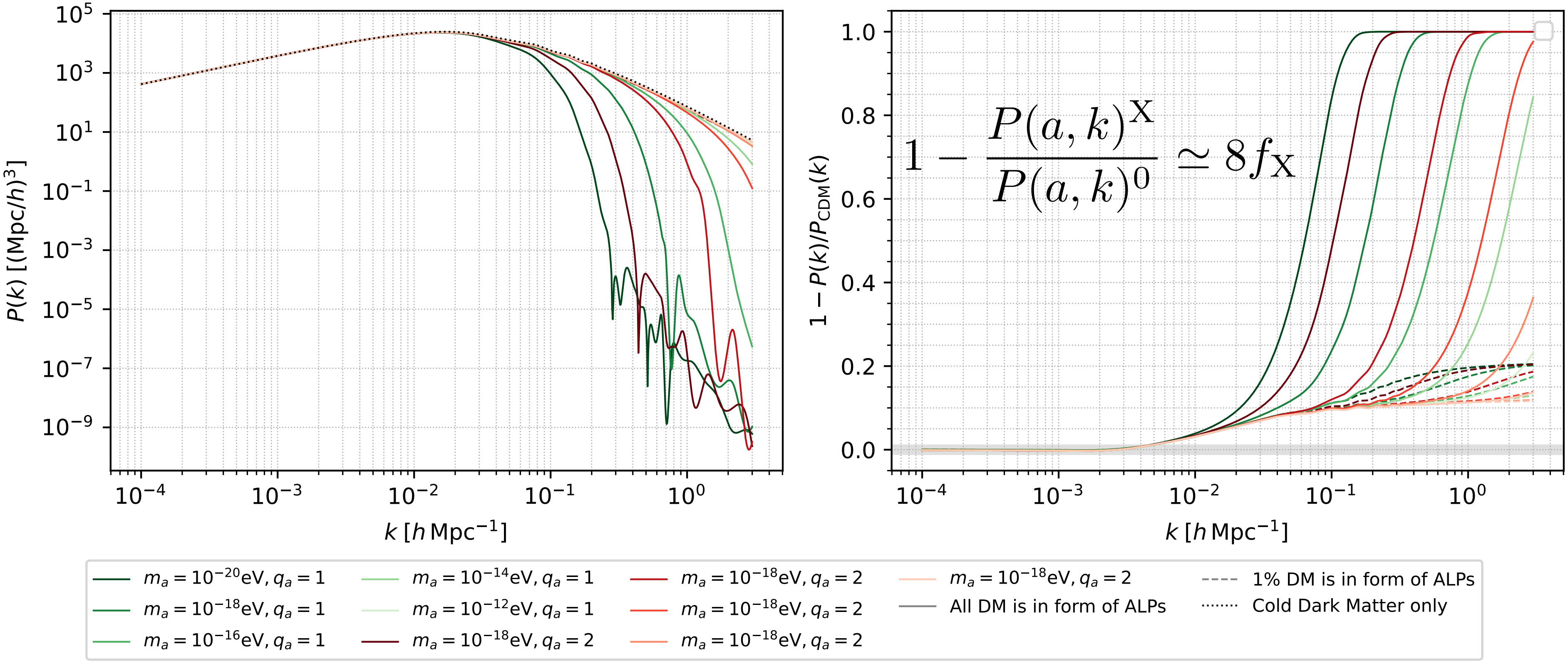
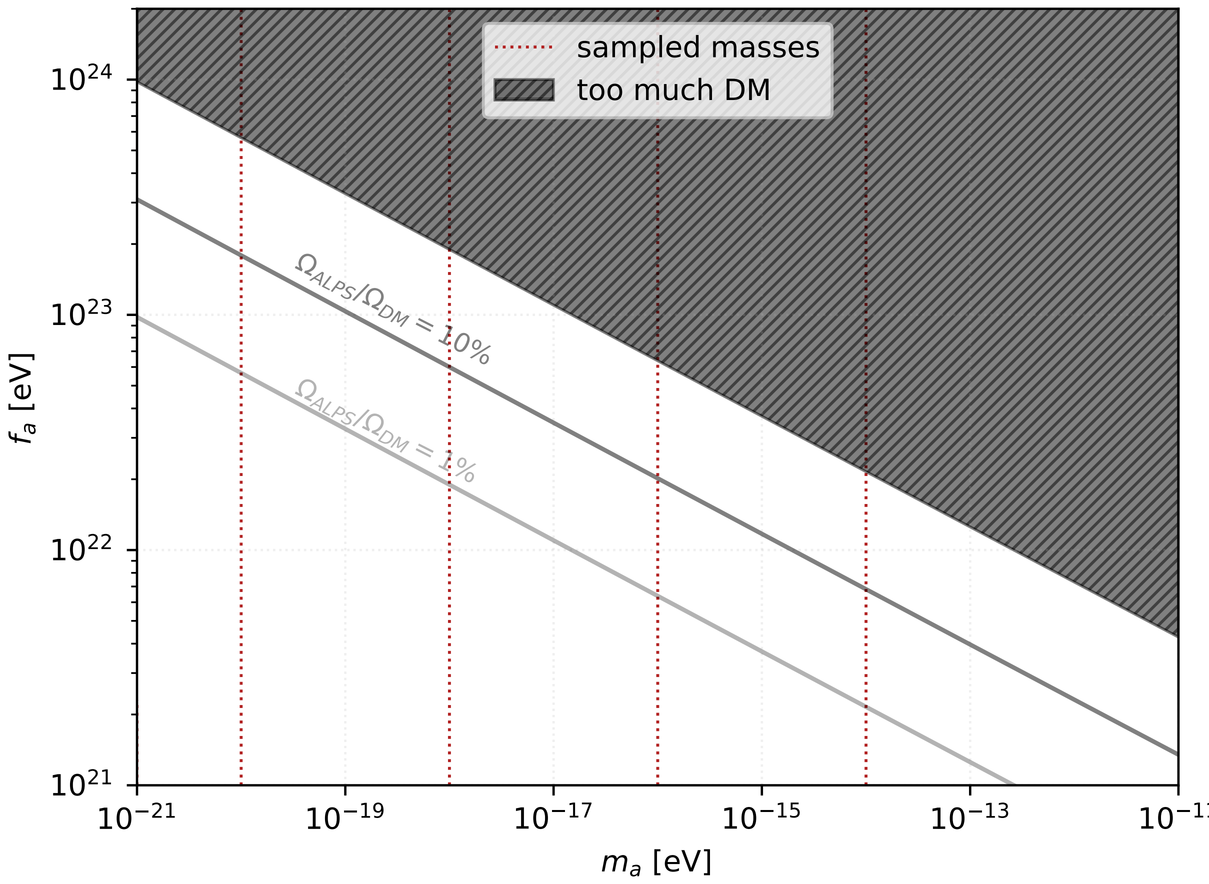


Preliminary Bounds

$$\Omega_a^{\rm st} \propto \left(\frac{f_a}{10^{14}\,\rm GeV}\right)^2 \left(\frac{m_a}{10^{-18}\,\rm eV}\right)^{1/2}$$

Gorghetto et al. 2021



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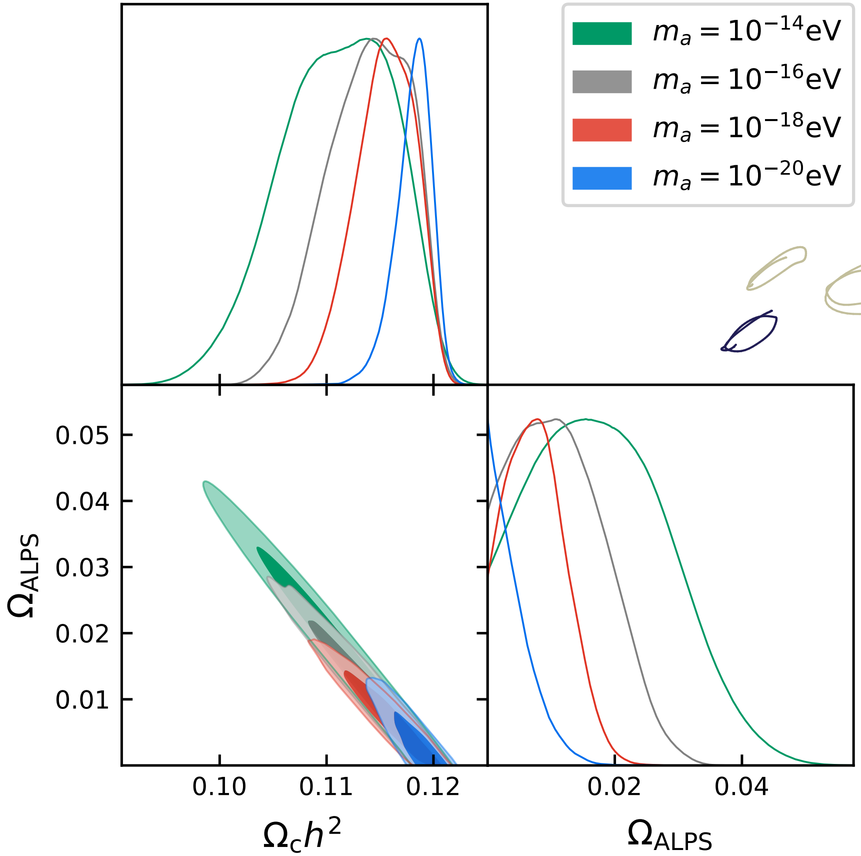

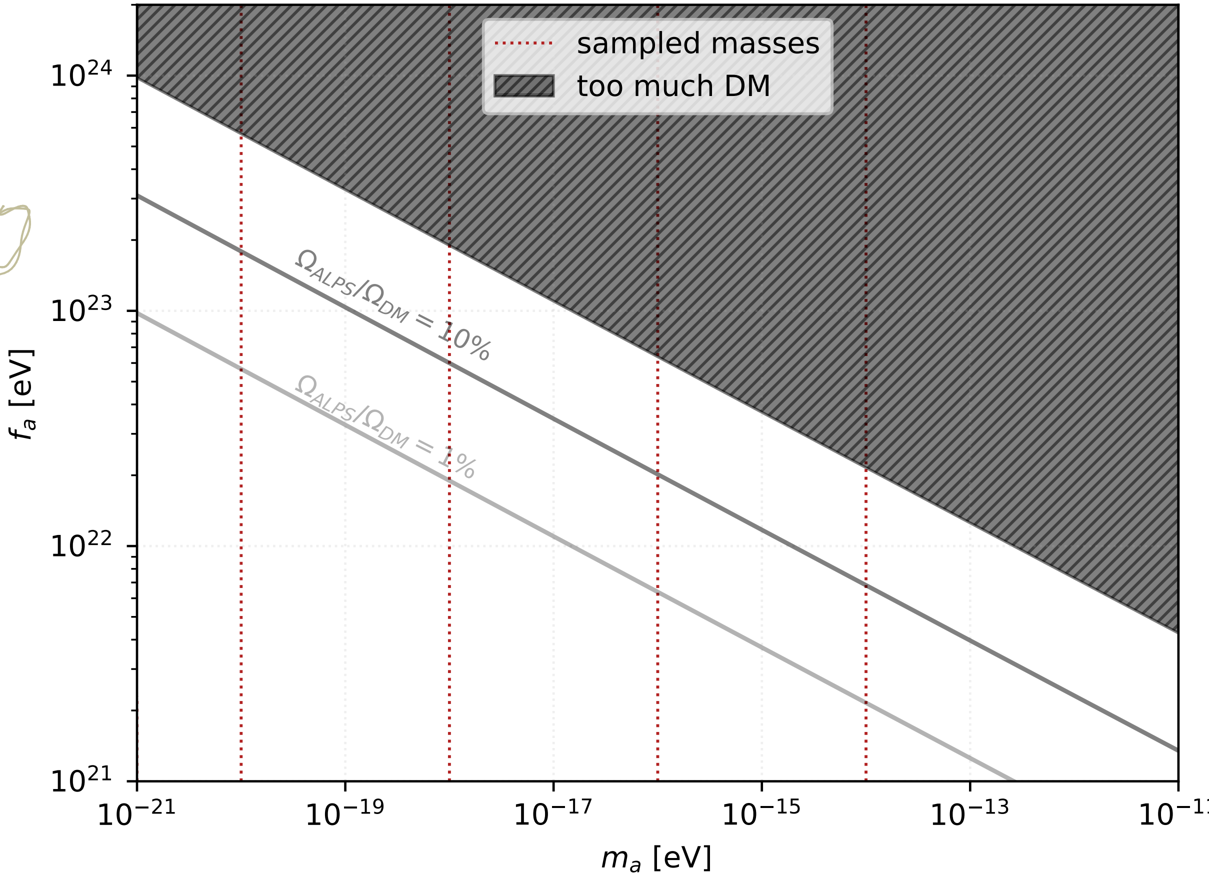

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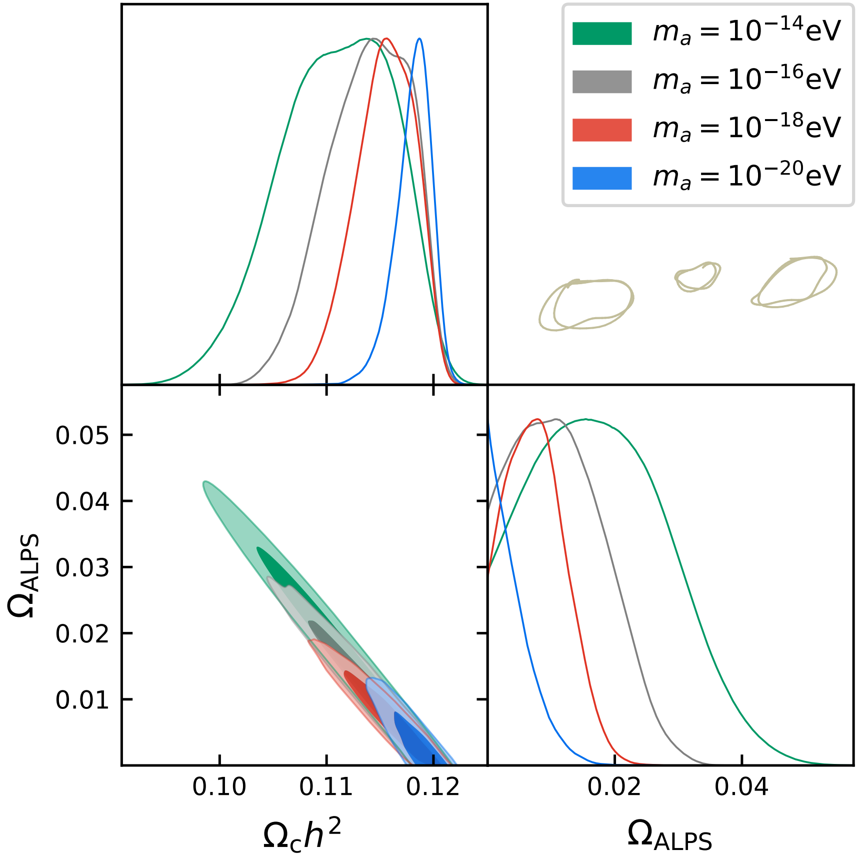
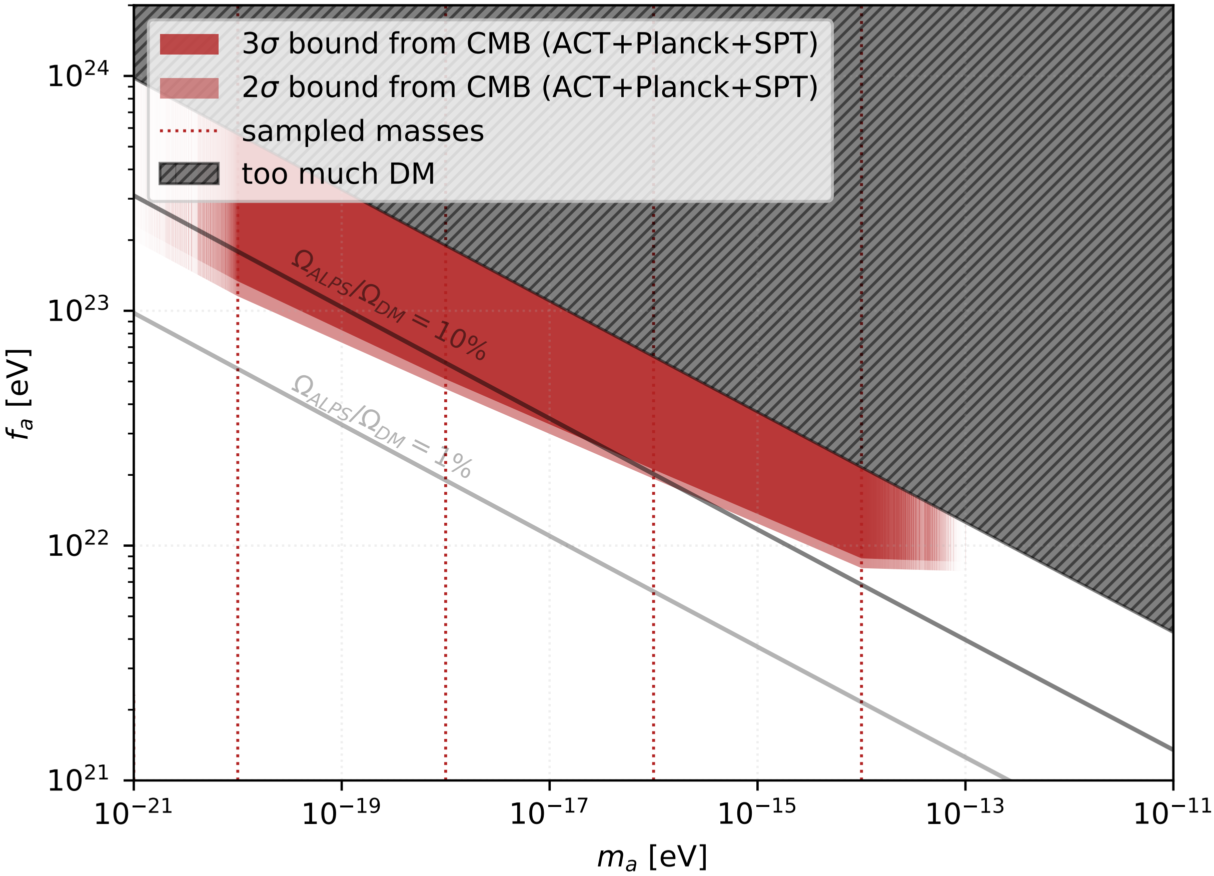




Sum Up + Conclusions

Theory:
There are models to produce non thermal Dark Matter, e.g. from cosmic string networks

Phenomenology:
There are codes and tools to precisely characterize a non cold Dark Matter

Data:
There are many CMB and LSS experiments giving more constraining data

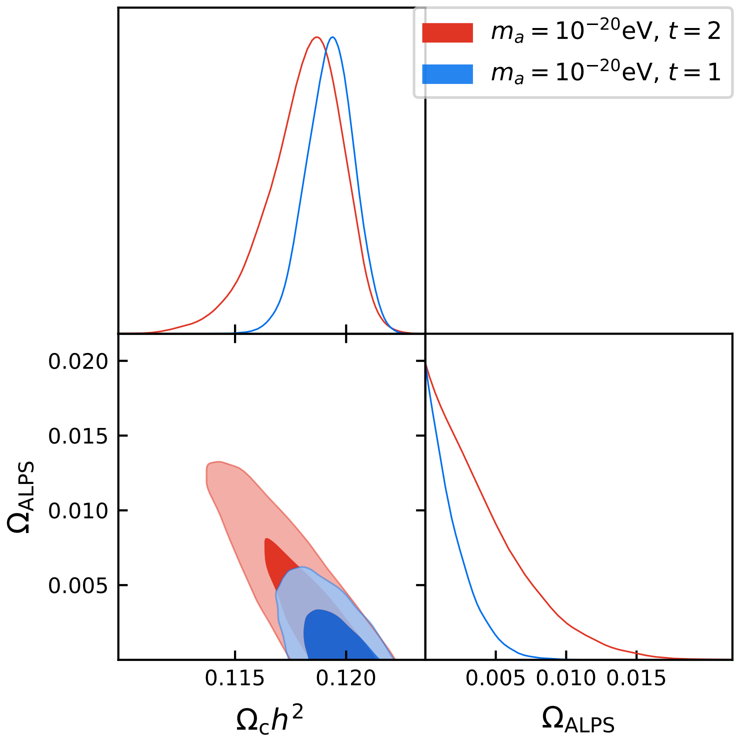
Cosmology (CMB&BAO) can place strong bounds on light relics such as ALPs from strings

(ongoing MCMC runs with most recent CMB and BAO data)

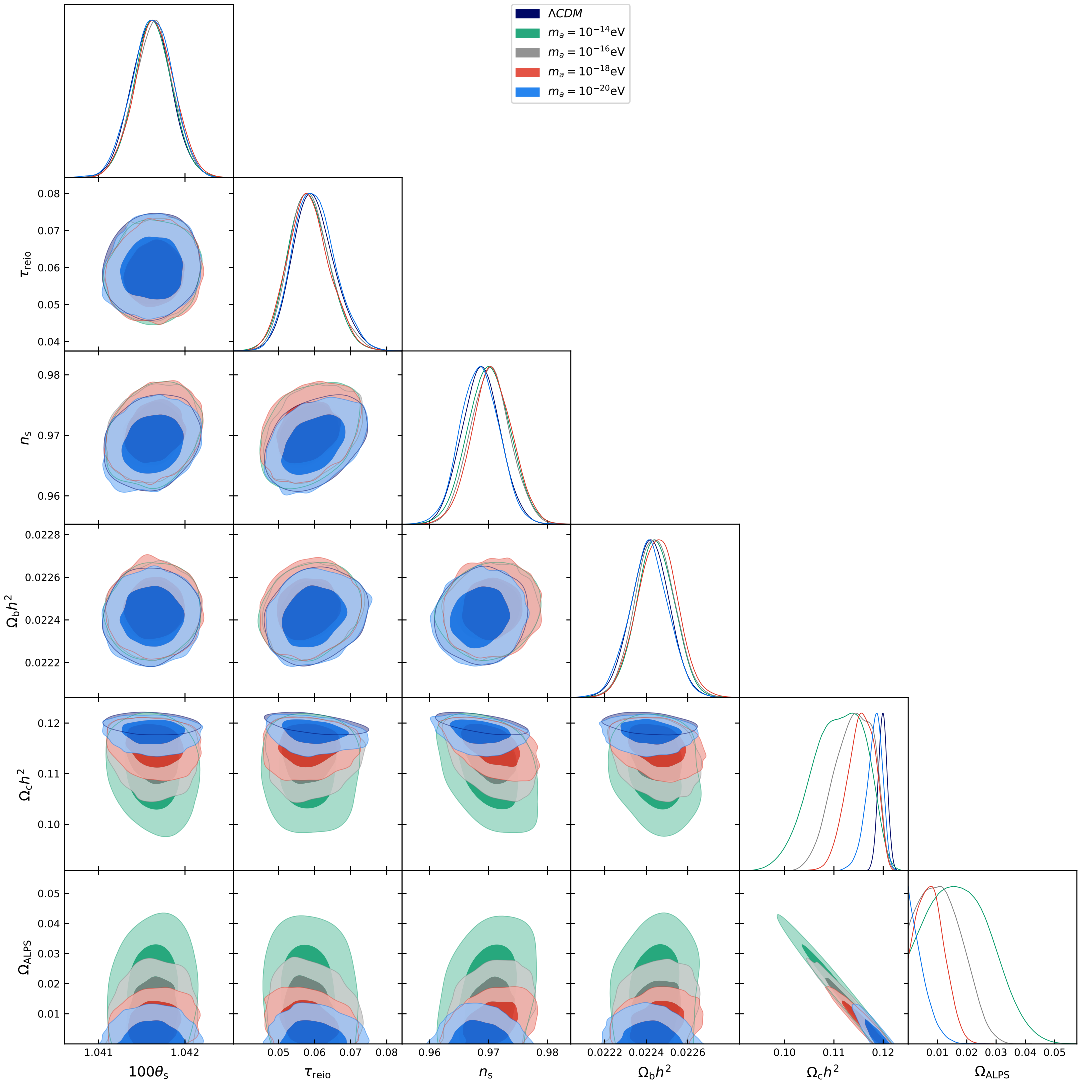
The matter power spectrum is the best observable to do so

ALPs with $m_a \in (10^{-20}, 10^{-16})$ eV are less than 10% of Dark Matter

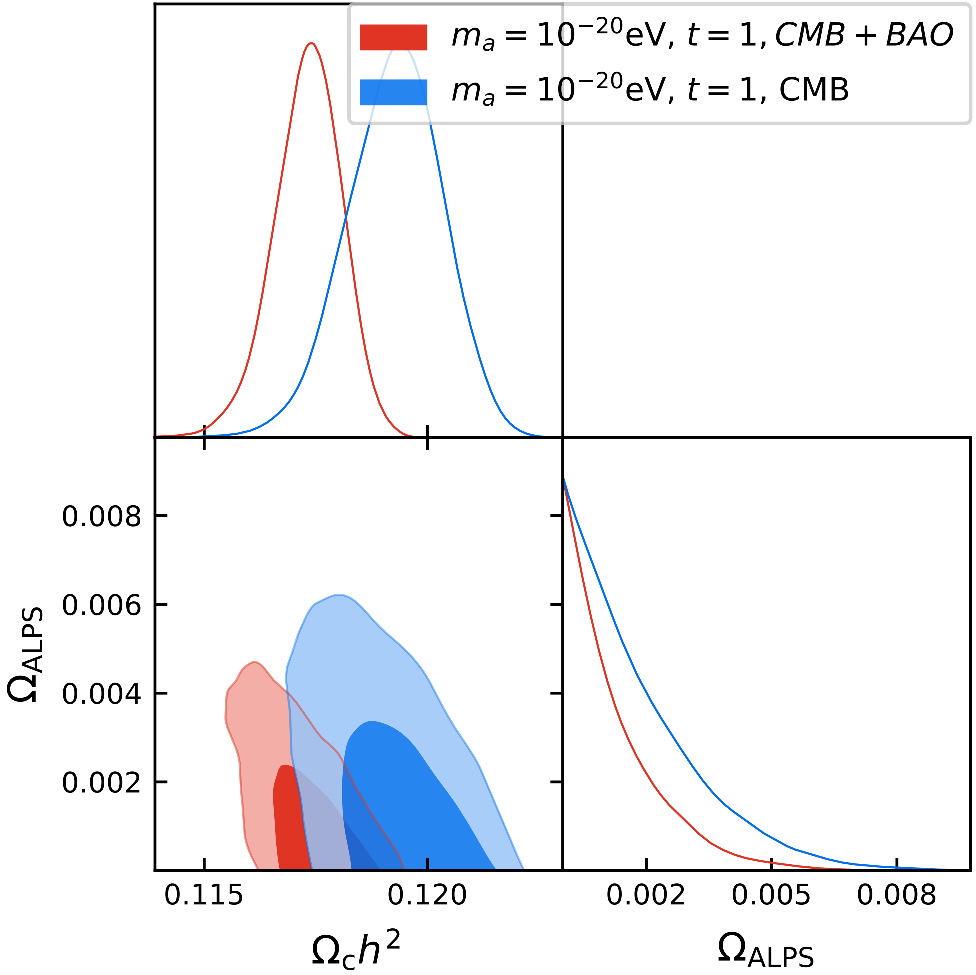
Backup



$m_a = 10^{-20}$eV, $t = 2$
$m_a = 10^{-20}$eV, $t = 1$
0.020
0.015
0.010
0.005
$\Omega_{\rm ALPS}$
0.115
0.120
$\Omega_c h^2$
0.005 0.010 0.015
$\Omega_{\rm ALPS}$



ΛCDM
$m_a = 10^{-14}$eV
$m_a = 10^{-16}$eV
$m_a = 10^{-18}$eV
$m_a = 10^{-20}$eV
$100\theta_s$
τ_{reio}
n_s
$\Omega_b h^2$
$\Omega_c h^2$
Ω_{ALPS}


$m_a = 10^{-20}$eV, $t = 1$, $CMB + BAO$
$m_a = 10^{-20}$eV, $t = 1$, CMB
0.008
0.006
0.004
0.002
$\Omega_{\rm ALPS}$
0.115
0.120
$\Omega_c h^2$
0.002
0.005
0.008
$\Omega_{\rm ALPS}$