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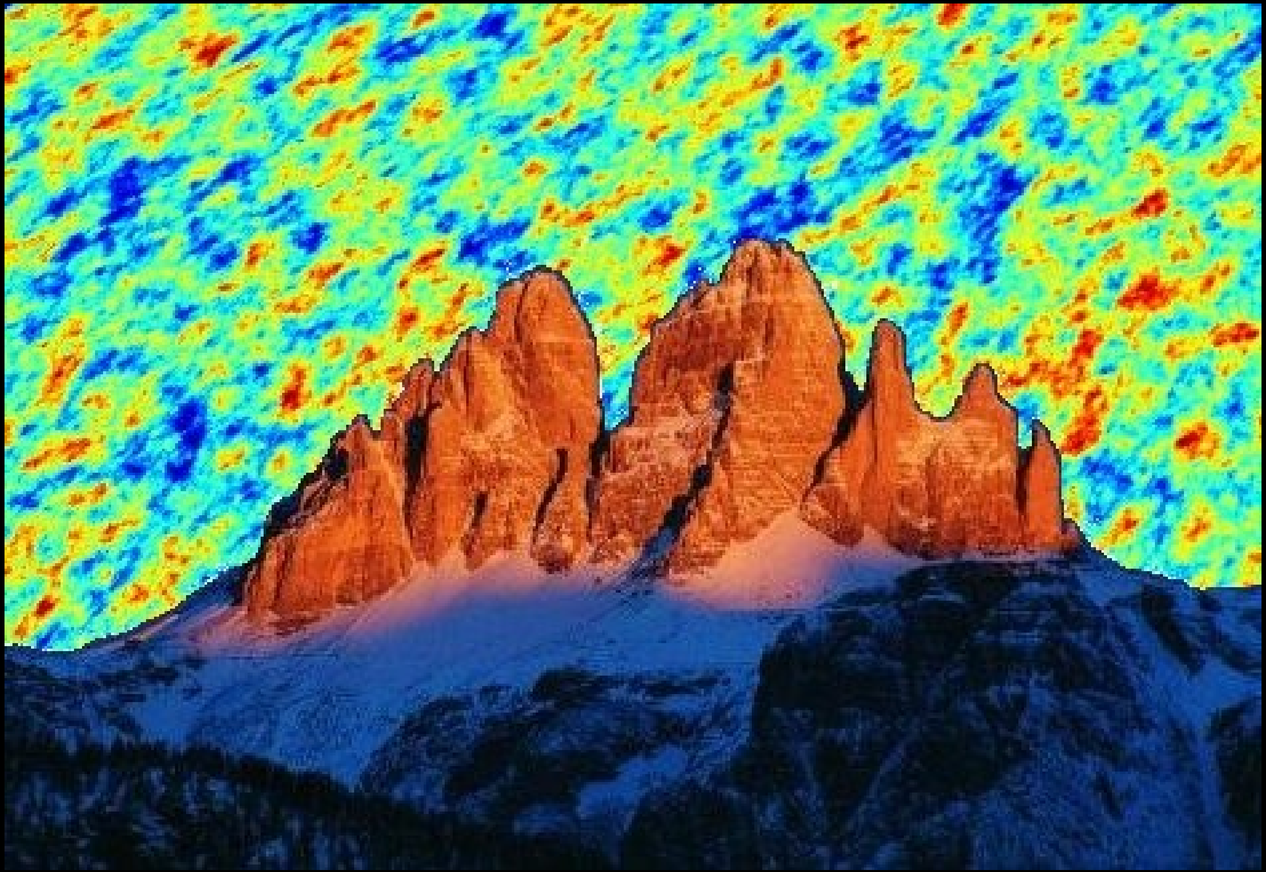
Is there room for ALPs in cosmology?



In collaboration with Javier Redondo, based on ArXiv:1110.2895

Outline

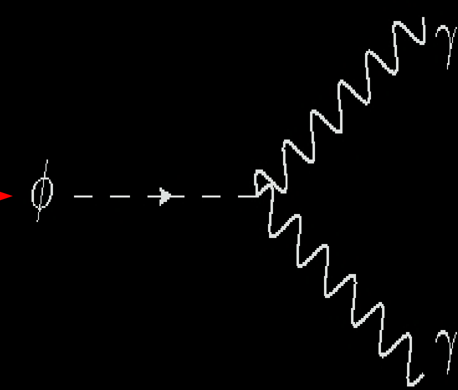
- Introducing the axion-like particles (ALPs)
- Can they be dark matter?
- Have cosmologically unstable ALPs left some traces in cosmological observables?
- New bounds from N_{eff} and *BBN*

Introducing the axion-like particles

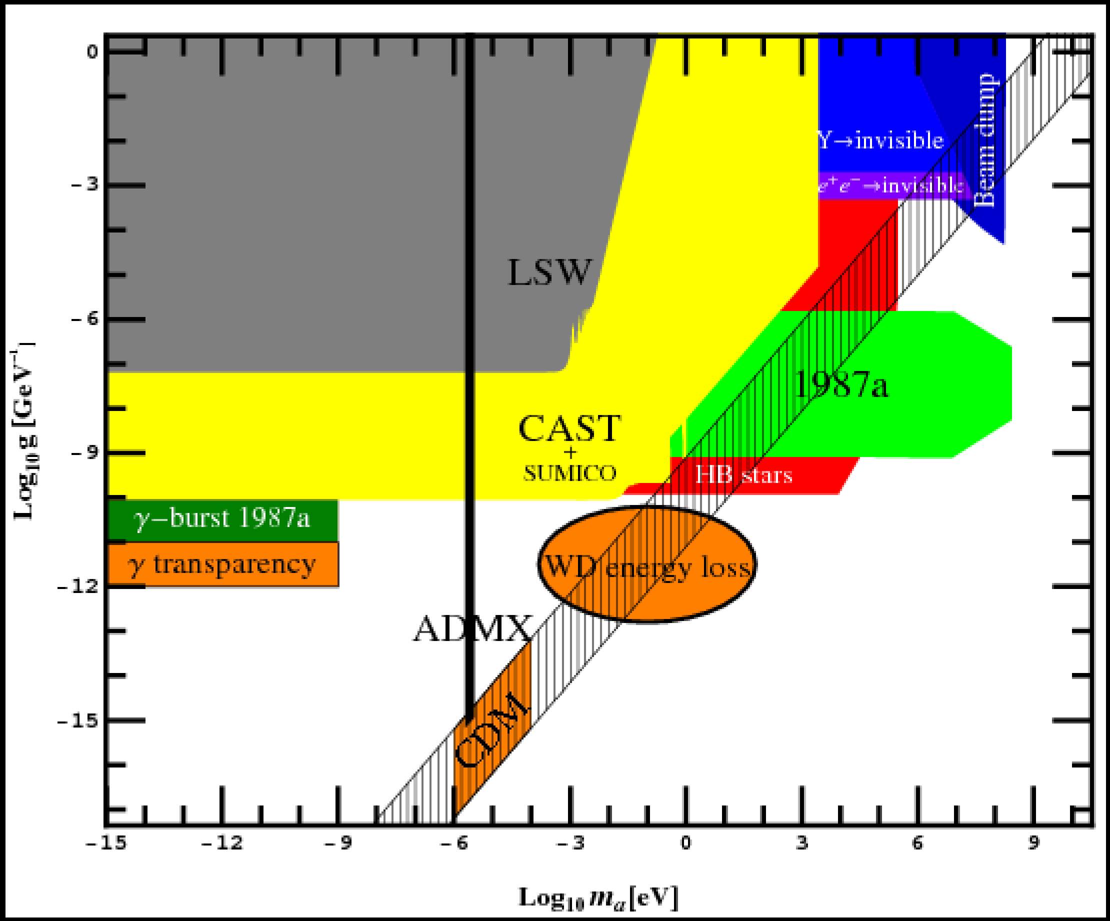
You know what an axion is ('cause I've already explained it to you last semester)... if not, let's discuss later!!

Anyway, all that you need to know today is that an **axion-like particle (ALP)** is a pseudoscalar with a two-photon coupling (like the axion indeed)

$$\mathcal{L}_\phi^{\rm eff} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 + \phi\frac{g}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}$$



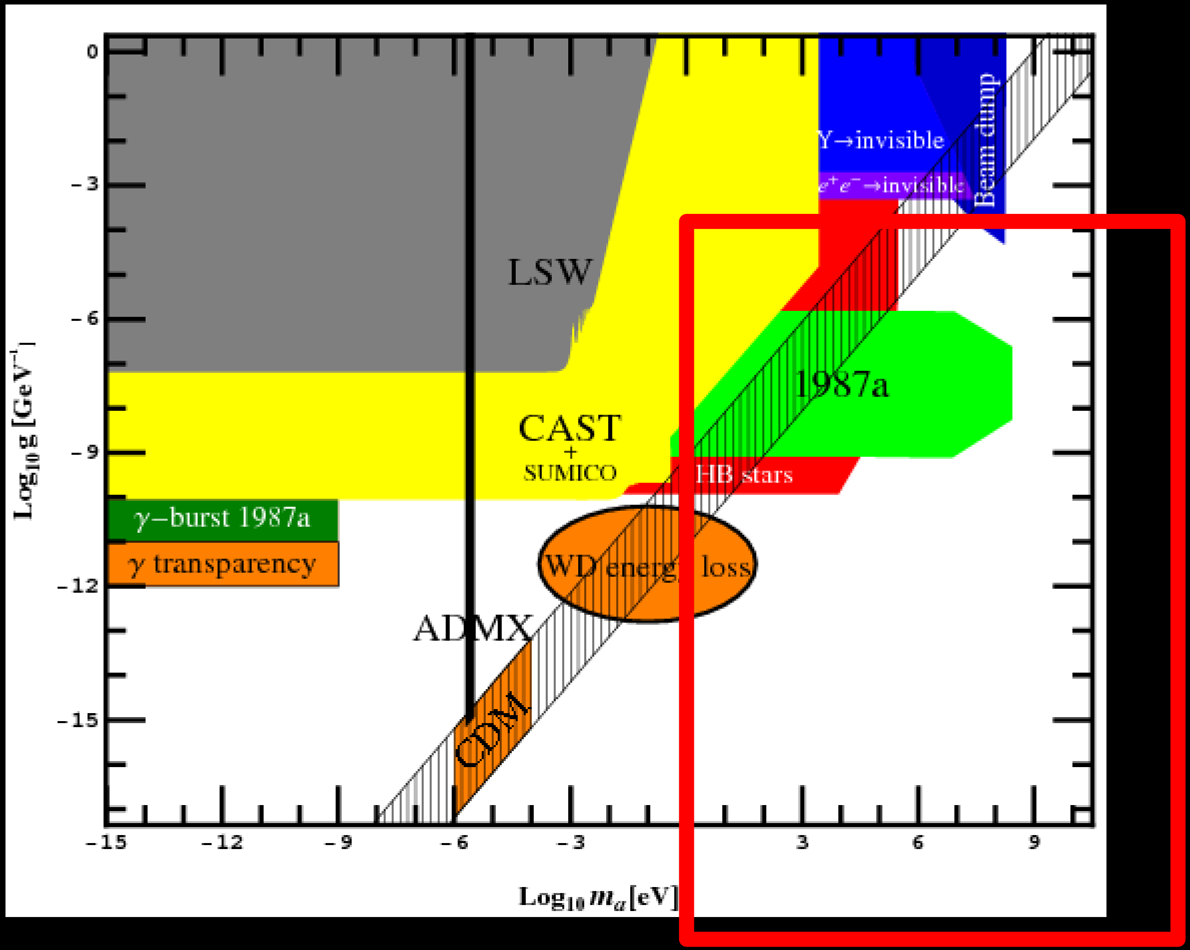
Introducing the axion-like particles



[Jaeckel, Ringwald (2010)]

People is looking for these ALPs exploiting this two-photon coupling.

Introducing the axion-like-particles

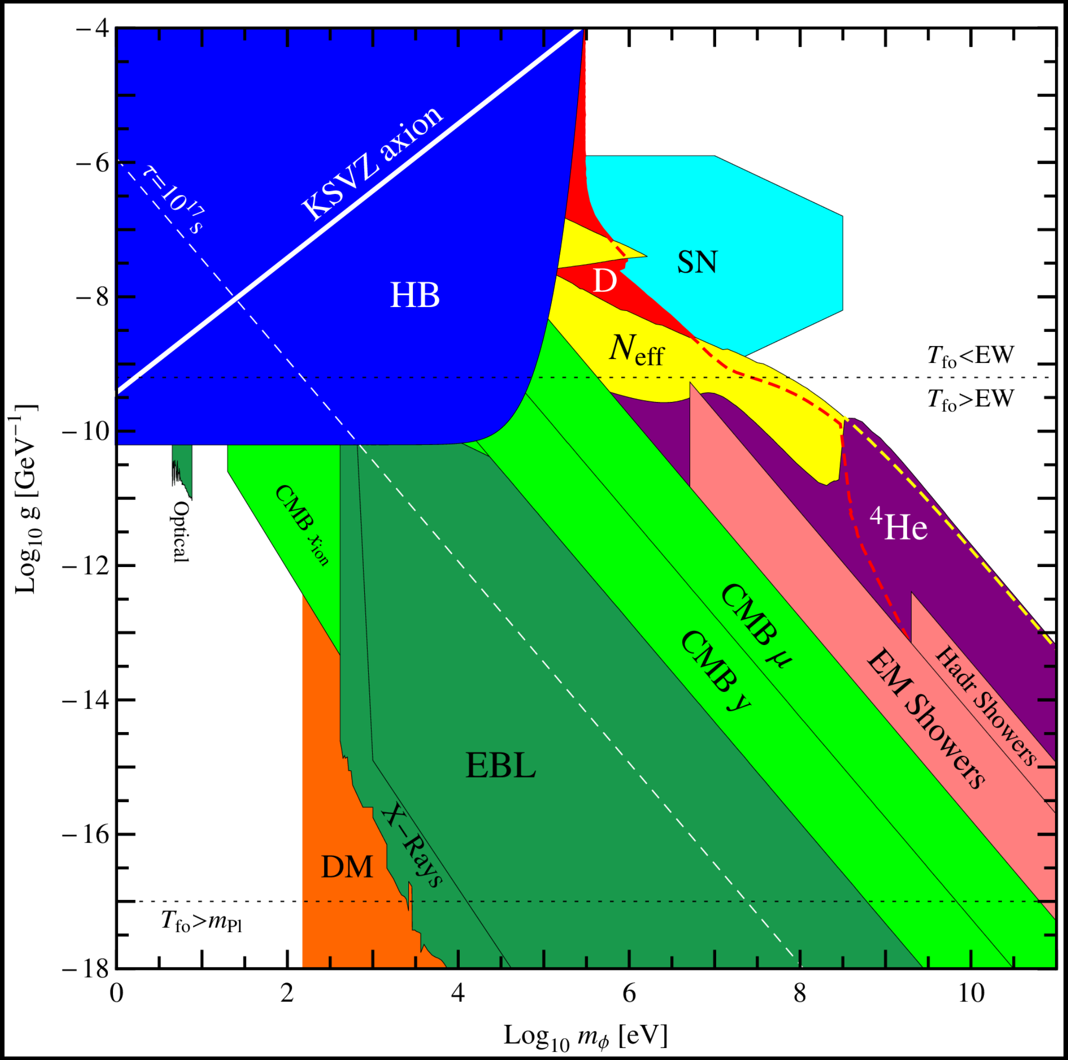


[Jaeckel, Ringwald (2010)]

People is looking for these ALPs exploiting this two-photon coupling.

We personally took care of this part of the parameter space

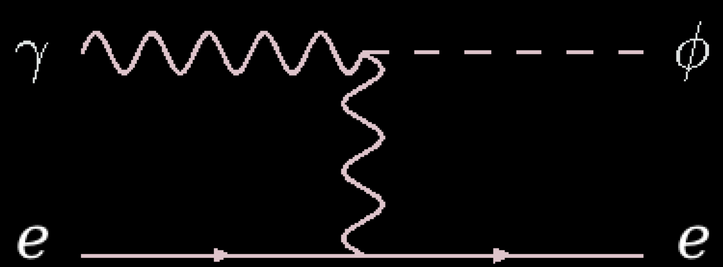
ALPs and cosmology



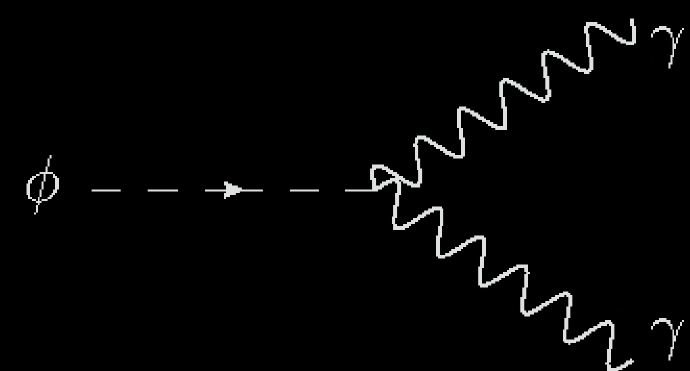
[D.C., Redondo (2011)]

ALPs and cosmology

We have not considered the non-thermal production. Anyway, through the Primakoff process a thermal population is created (if the Universe was hot enough) and later decay (via the two-photon channel)



$$\Gamma_q \simeq \frac{\alpha\, g^2\, \pi^2}{36\zeta(3)} \left(\log\left(\frac{T^2}{m_\gamma^2} \right) + 0.82 \right) n_q$$



$$\Gamma_\gamma = \tau^{-1} = \frac{m_\phi^3 g^2}{64\pi}$$

ALPs and cosmology

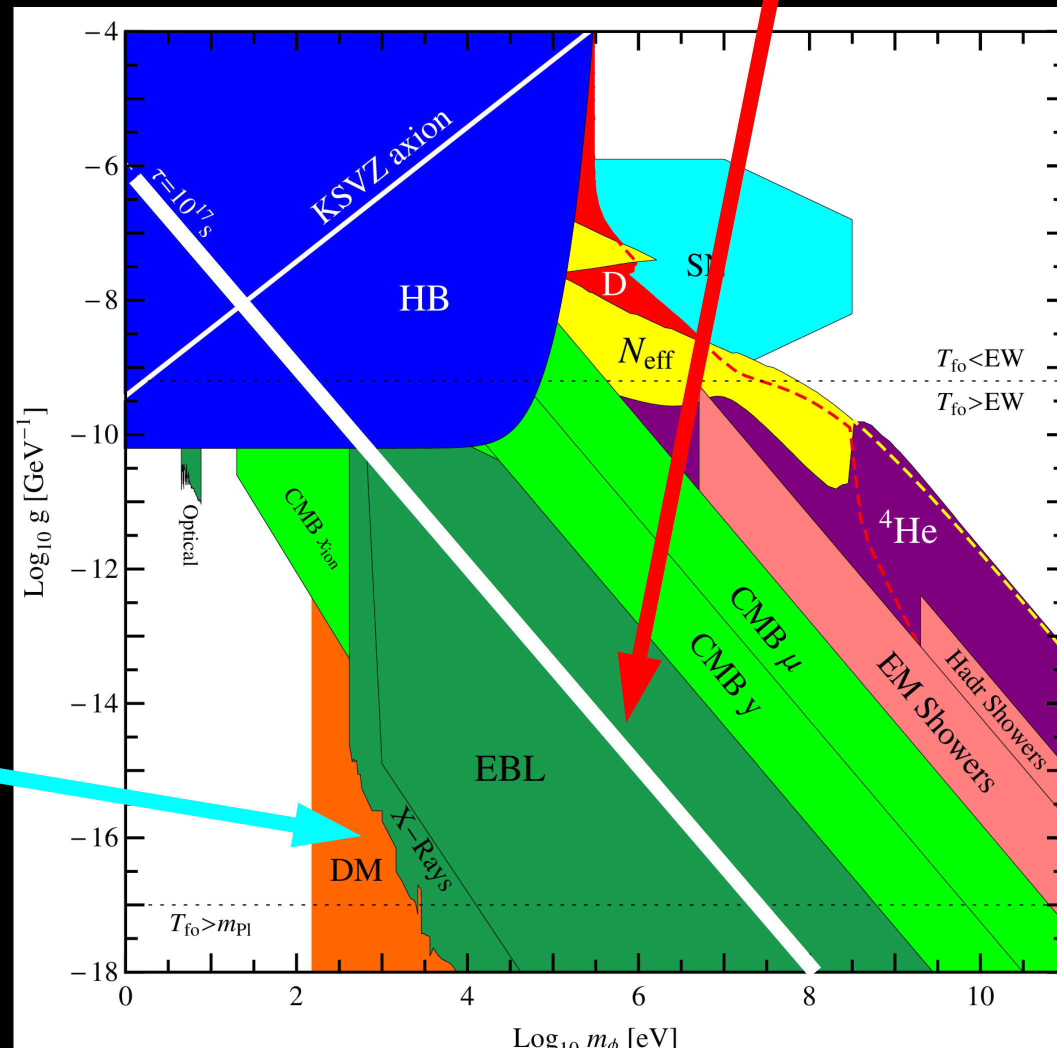
Below this line ALPs are cosmologically stable

The freeze-out temperature of the Primakoff process determines the ALP number density:

$$n_\phi(T) = \frac{n_\gamma(T)}{2}\frac{g_{*S}(T)}{g_{*S}(T_{\rm fo})}$$

In the orange region they provide too much dark matter

$$\frac{m_\phi n_\phi}{\rho_c}h^2 > \Omega_{\rm DM}h^2 = 0.11$$



[D.C., Redondo (2011)]

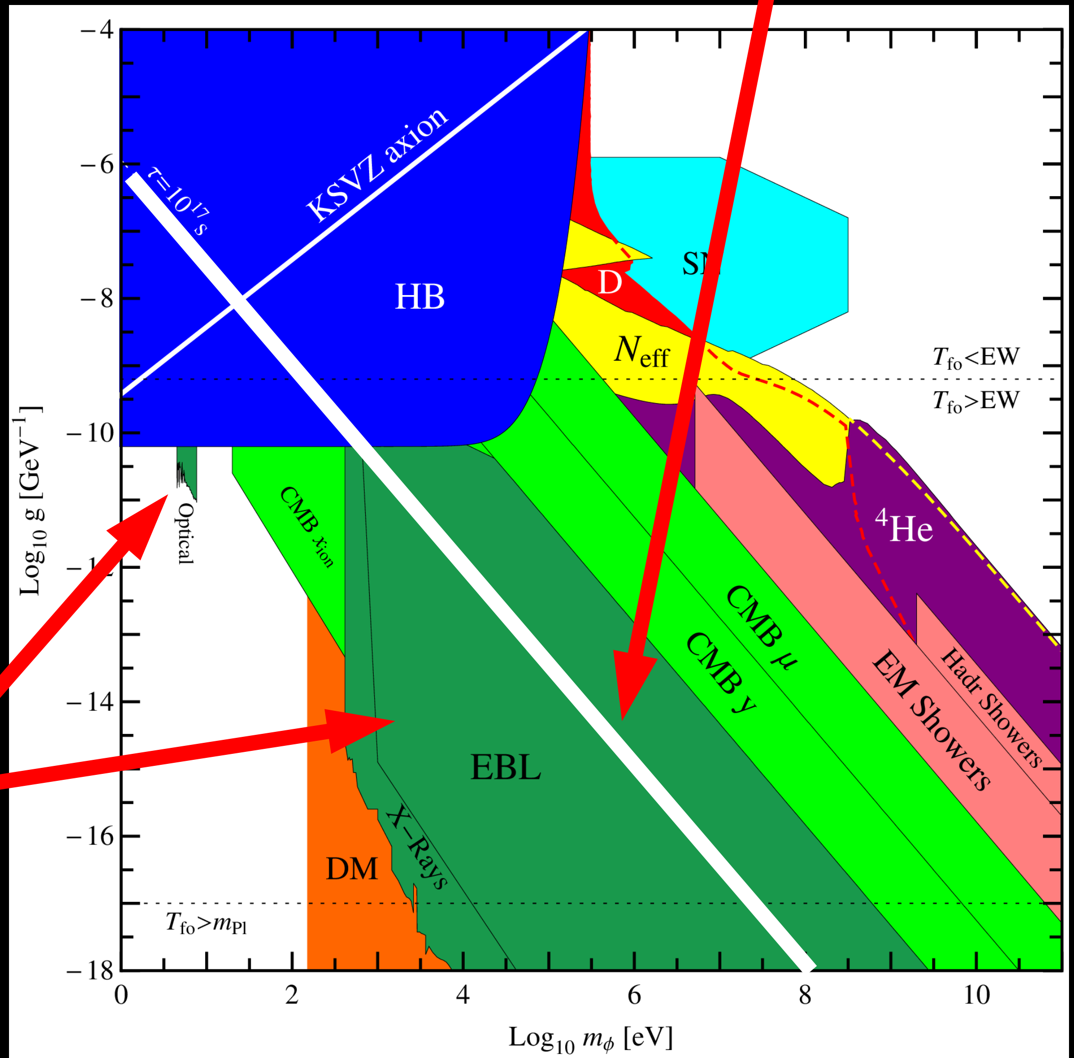
ALPs and cosmology

Below this line ALPs are cosmologically stable

Being unstable, there is also a freezing-in temperature for ALP decay when

$$\frac{\Gamma_\gamma}{H(T)} \simeq 1$$

In the dark green regions, the decay photons are emitted when the universe is transparent to radiation and they should be directly detected



[D.C., Redondo (2011)]

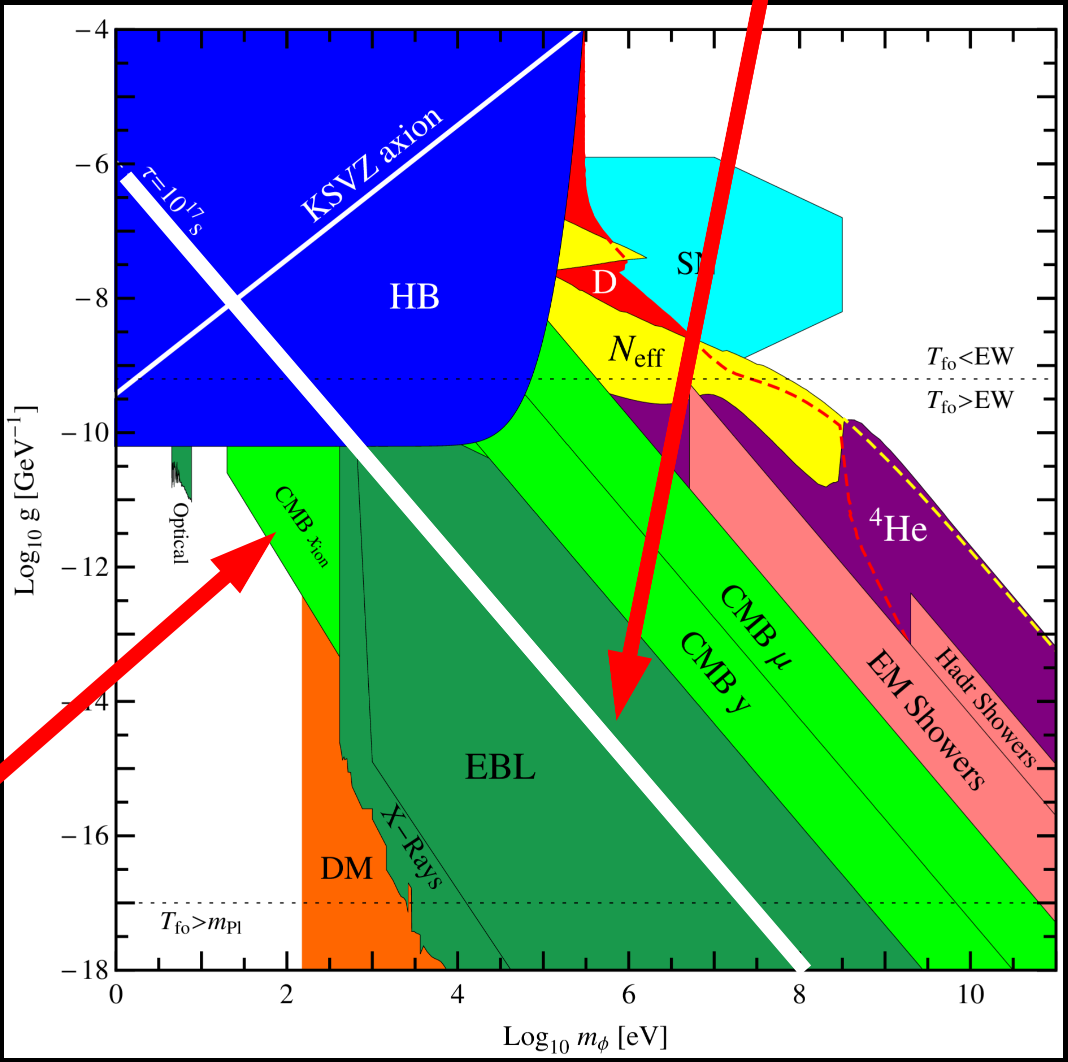
ALPs and cosmology

Being unstable, there is also a freezing-in temperature for ALP decay when

$$\frac{\Gamma_\gamma}{H(T)} \simeq 1$$

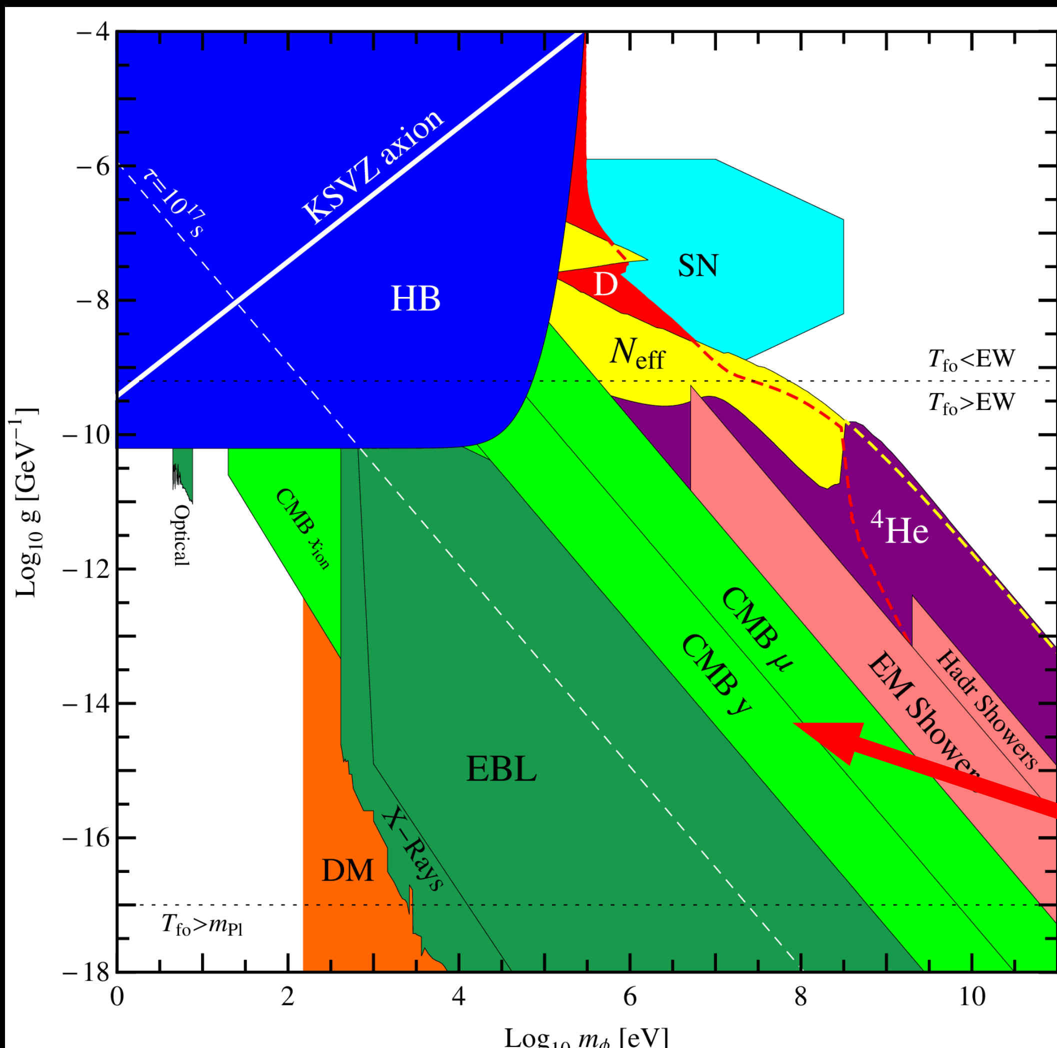
In this light green region, the decay photons have energy E>13.6 eV and are enough to ionize too many atoms during the dark age.

Below this line ALPs are cosmologically stable



[D.C., Redondo (2011)]

ALPs and cosmology

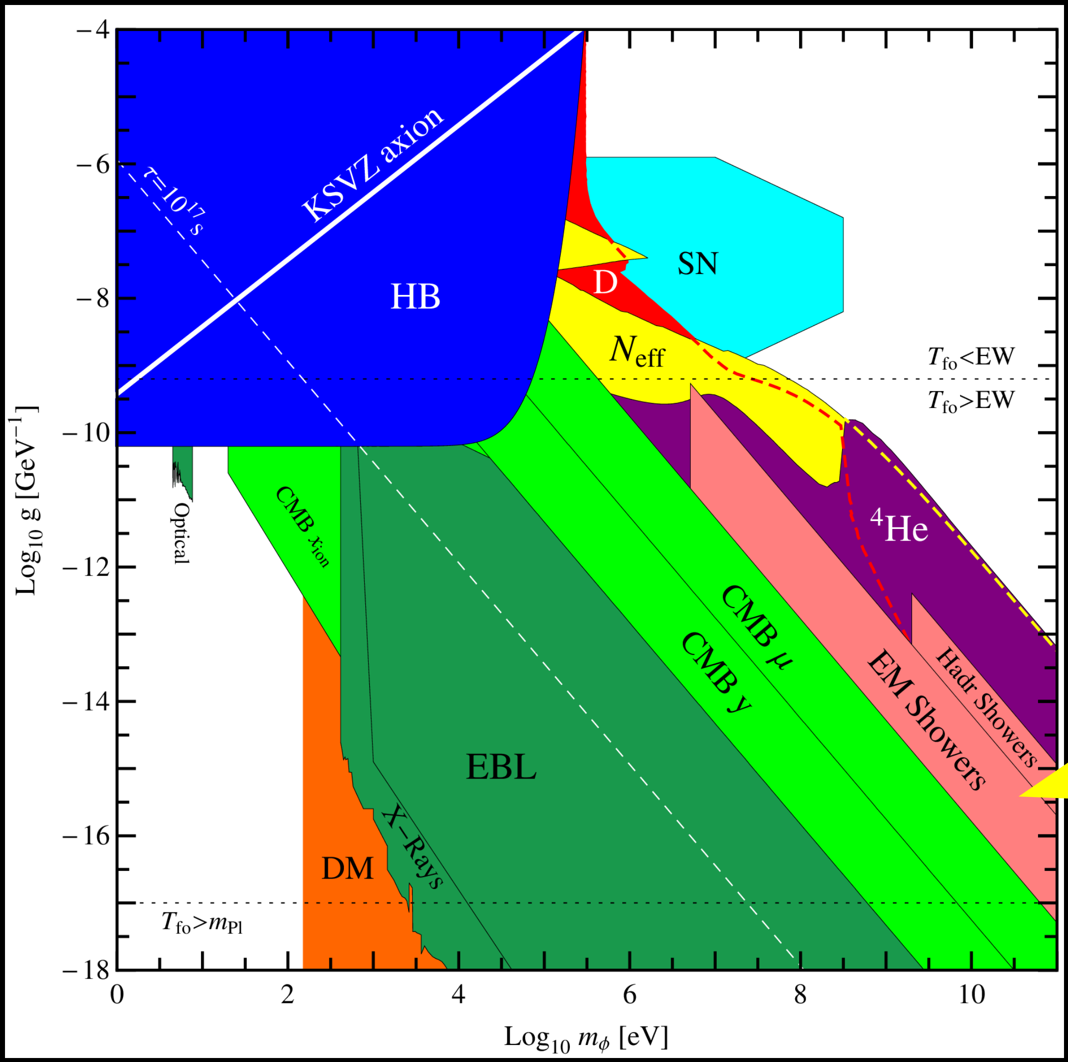


[D.C., Redondo (2011)]

In these two light green bands, ALPs decay before matter-radiation decoupling (i.e. CMB release) but late enough to have the distortions of the CMB spectrum, caused by the decay photons, not erased by the electron-photon interactions:

CMB spectrum would be not a black-body one

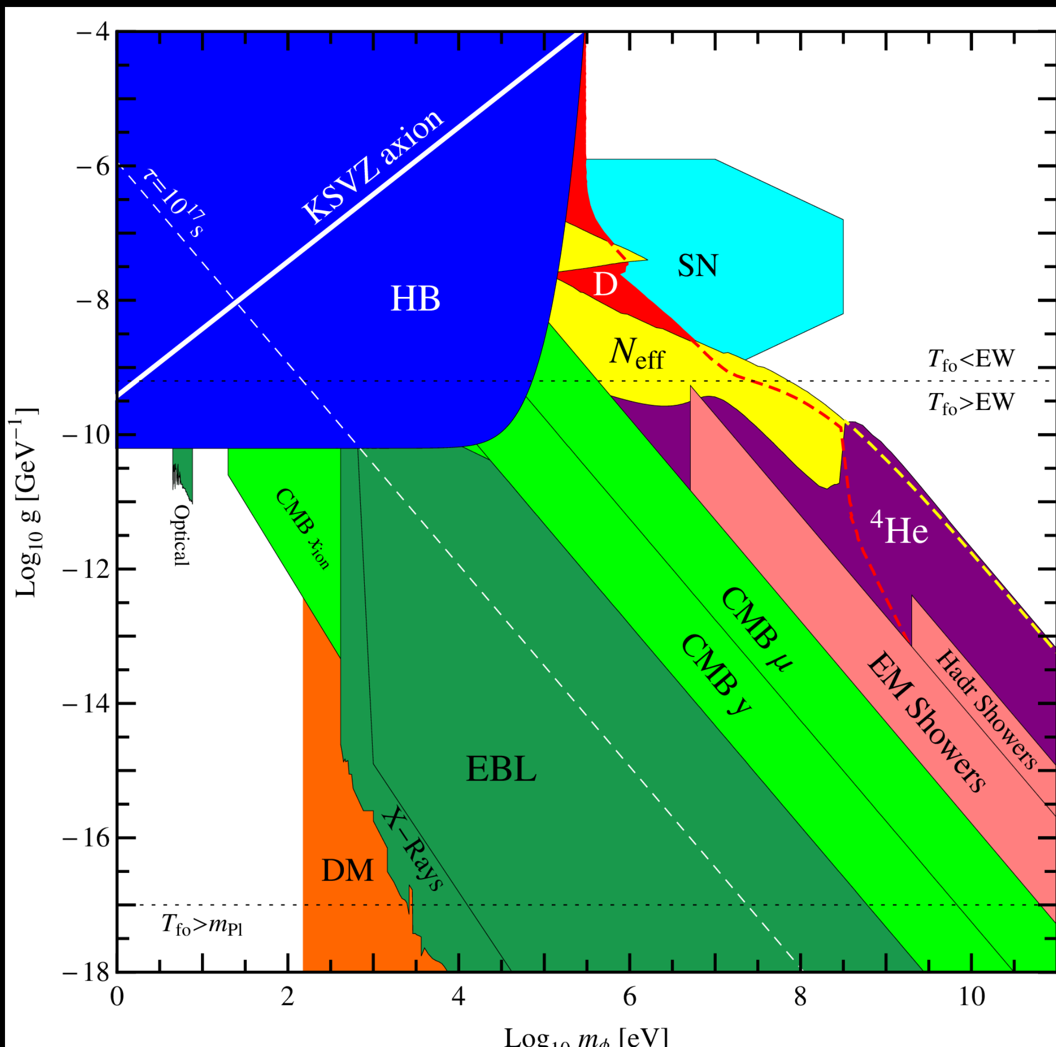
ALPs and cosmology



[D.C., Redondo (2011)]

The final direct effect of decay photons is in these two pink regions:
Here the decay photons are energetic enough to initiate electromagnetic and hadronic showers that dissociate the nuclei formed in BBN

ALPs and cosmology



[D.C., Redondo (2011)]

In the regions coloured as

the effect of the decay photons is subtle and related to the entropy increase it produces.

It needs a bit more detailed explanation.

Entropy release

The decay of ALPs would produce some entropy which is shared among the species in thermal equilibrium with photons.

Two limit situations:

- LT Equilibrium

$$\frac{g_{*S}(T_f)}{g_{*S}(T_i)} = \frac{2+7/2}{2+7/2+1} = \frac{11}{13}$$

- ALP domination

$$\frac{S_f}{S_i} \propto \frac{m_\phi n_\phi(T_\mathrm{d})}{\sqrt{m_\mathrm{Pl}\Gamma_\gamma}}$$

[Kolb & Turner (1990)]

Bound from $N_{\rm eff} = \frac{\rho_\nu(T_\nu)}{\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma(T_\gamma)}$

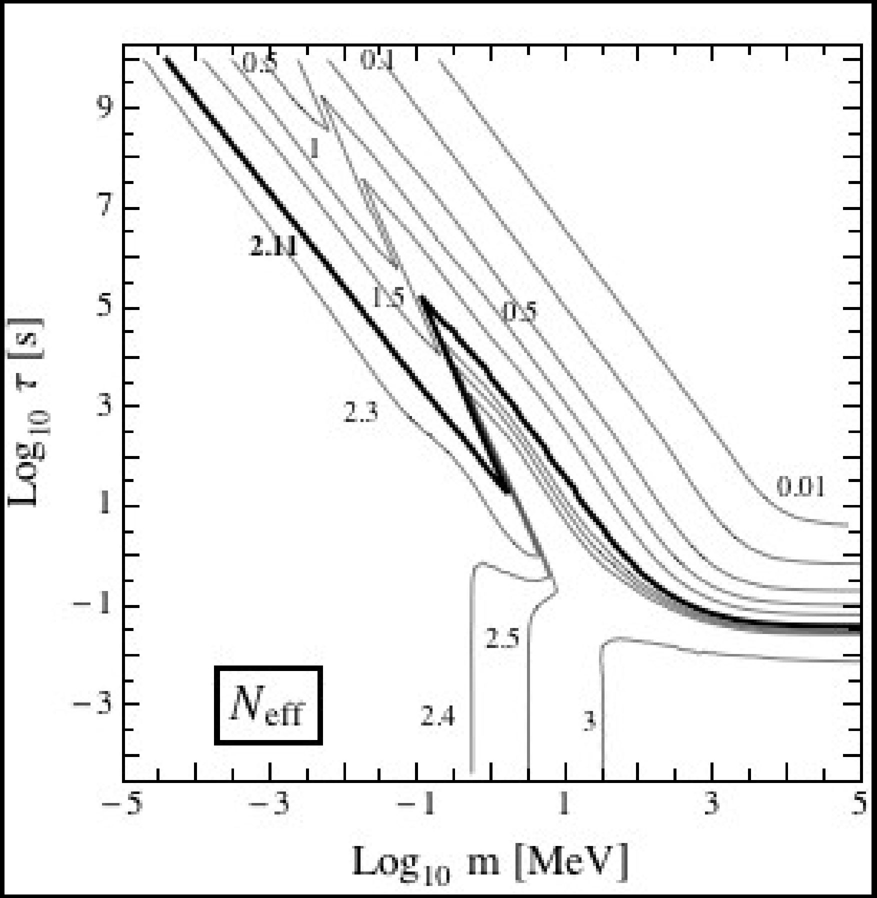
Using WMAP7, 7th release by SDSS and H_0 from HST

$$N_{\rm eff} > \begin{cases} 2.70 & \text{at } 68\% \text{ C.L.} \\ 2.39 & \text{at } 95\% \text{ C.L.} \\ 2.11 & \text{at } 99\% \text{ C.L.} \end{cases}$$

[D.C., Hannestad, Raffelt & Redondo (2010)]

Bound from $N_{\rm eff} = \dfrac{\rho_\nu(T_\nu)}{\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma(T_\gamma)}$

Increasing lifetime

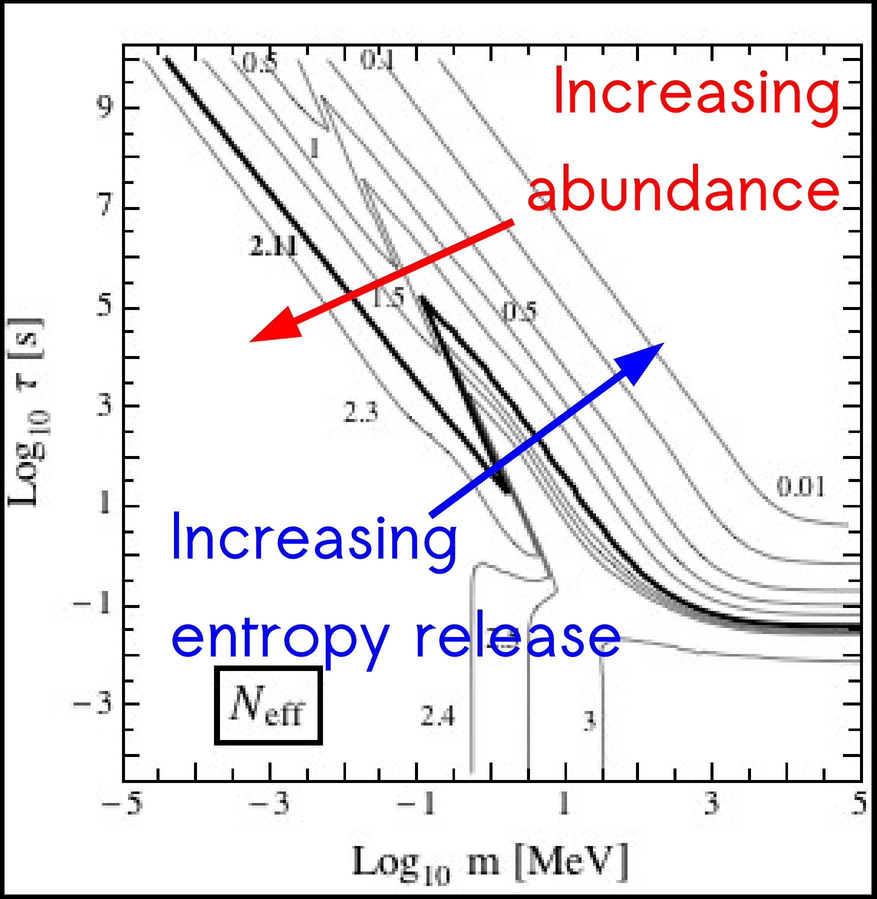


Increasing mass

[D.C. & Redondo (2011)]

Bound from $N_{\rm eff} = \dfrac{\rho_\nu(T_\nu)}{\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma(T_\gamma)}$

Increasing lifetime

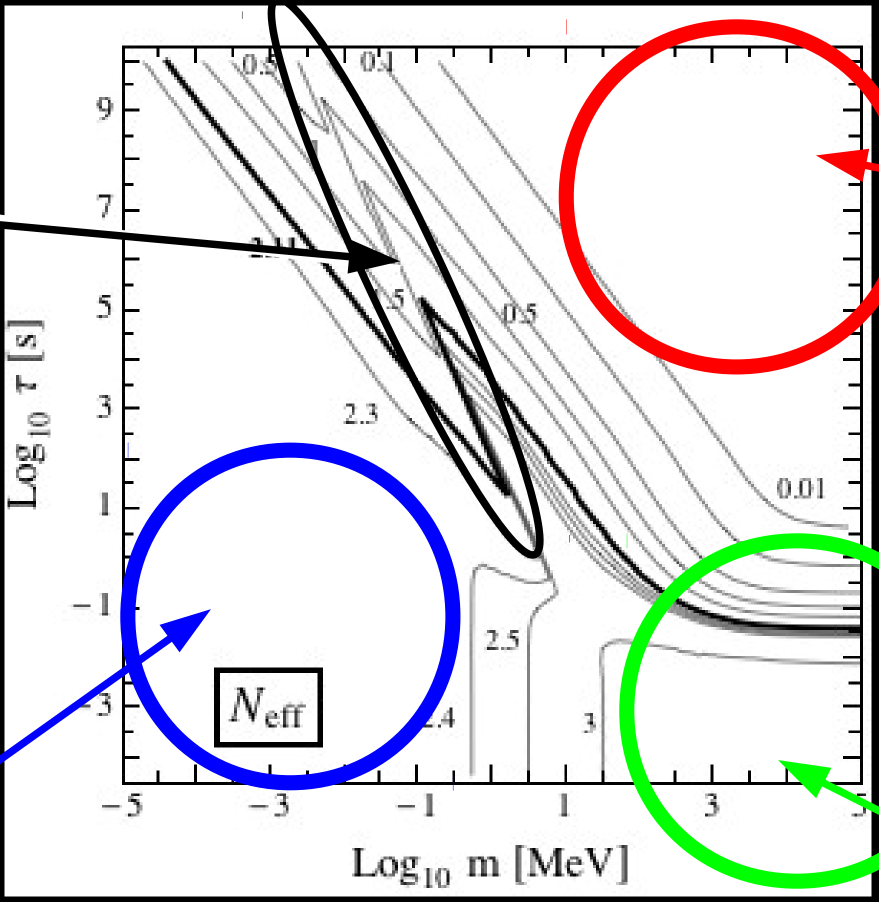


Increasing mass

[D.C. & Redondo (2011)]

Bound from $N_{\rm eff} = \frac{\rho_\nu(T_\nu)}{\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma(T_\gamma)}$

ALPs decoupling at QCD ph.tr.



ALP domination

LTE

ν still coupled

[D.C. & Redondo (2011)]

Bounds from BBN

Small mass ALPs ($m_\phi < 2m_\pi$) have two effects on BBN:

Before the decay they increase the energy budget of the universe respect to the standard cosmology → faster expansion (earlier freezing-out of the reactions, so for example higher n_n/n_{p^+})

Bounds from BBN

Small mass ALPs ($m_\phi < 2m_\pi$) have two effects on BBN:

Decaying they dilute the baryons → measured elemental abundance requires the baryon to photon ratio to be

$$\eta_{\rm BBN} \simeq 5.1 - 6.5 \times 10^{-10}$$

CMB measurement is $\eta_{\rm CMB} = 6.23 \times 10^{-10}$

Thus, if ALPs decay before CMB release would mean that before the decay η was

$$\eta_{\rm ALP} = \frac{S_f}{S_i}\eta_{\rm CMB}$$

Bounds from BBN

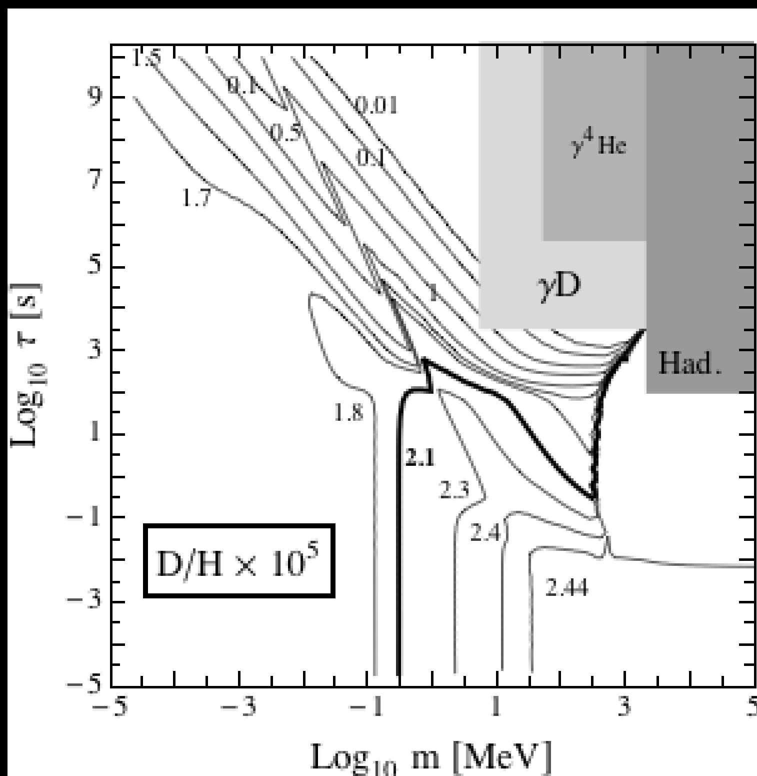
Large mass ALPs produces cascades which direcly dissociate nuclei. Above the threshold $m_\phi > 2m_\pi$ pions can be radiatively produced from the decay. Through the reactions

$$\pi^+ n \to \pi^0 p^+ \ , \ \pi^- p^+ \to \pi^0 n$$

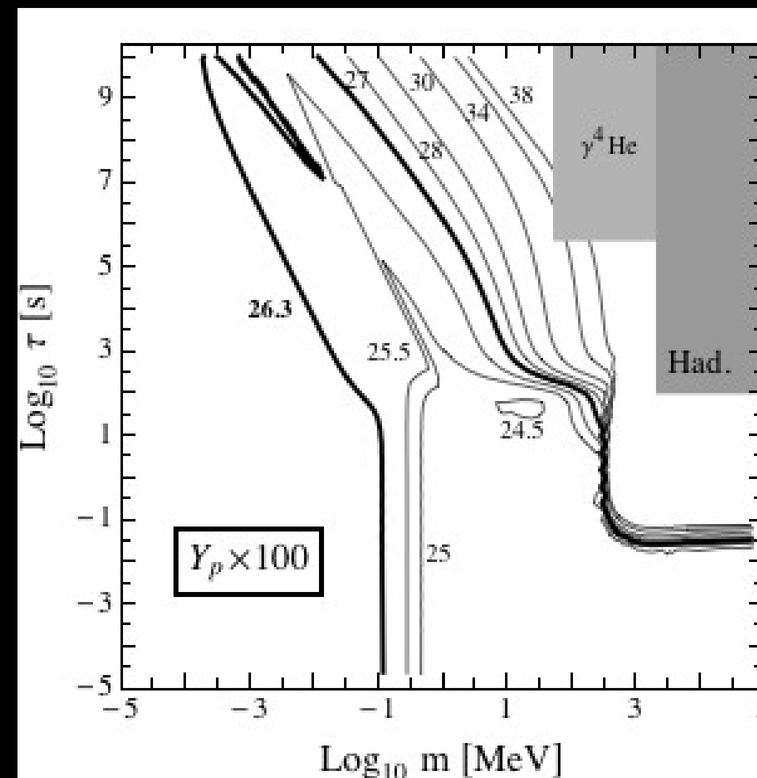
they can enhance the ratio n_n/n_{p+} (even to O(1)!!!!)

This translates into overproduction of He.

Bounds from BBN



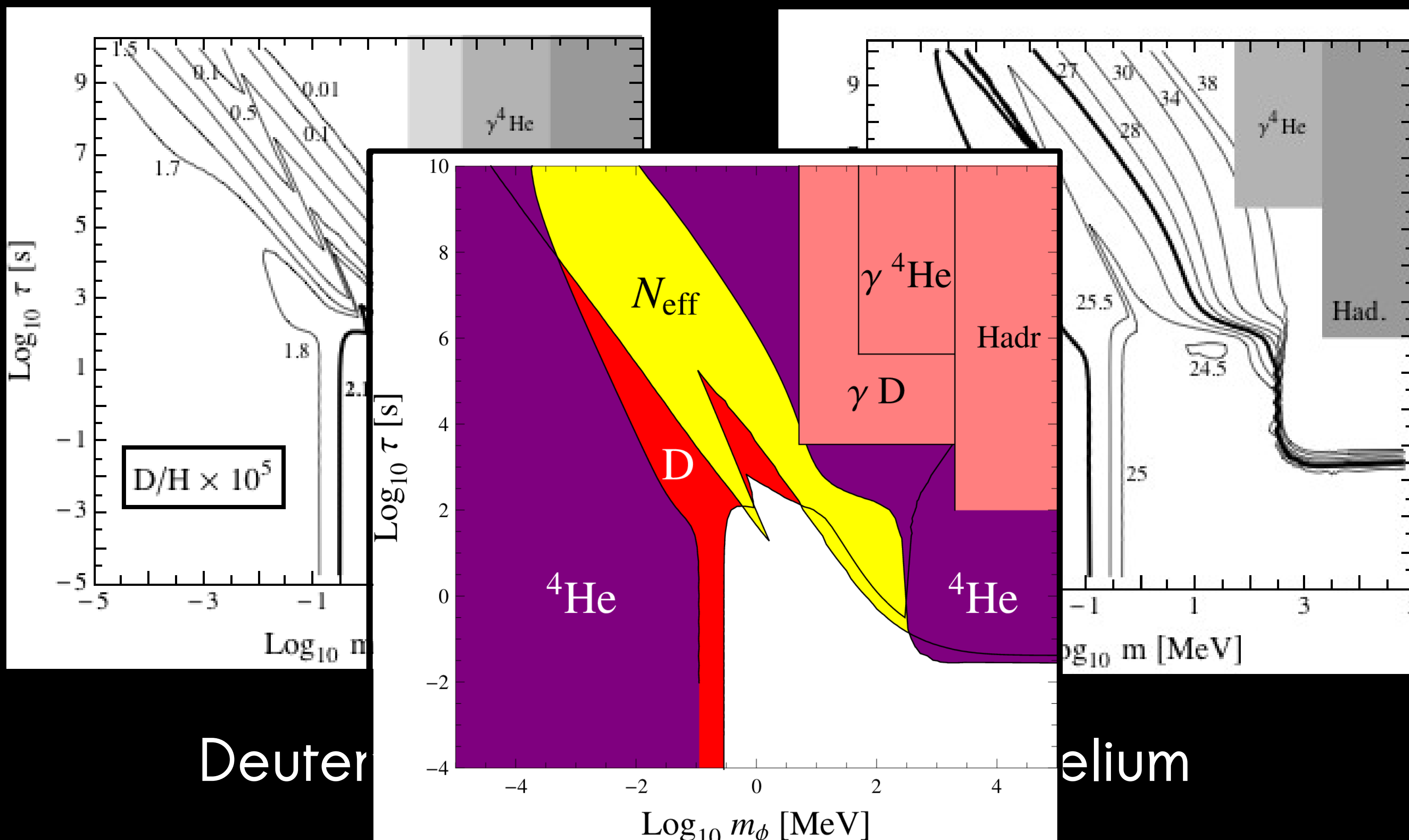
Deuterium



Helium

[D.C. & Redondo (2011)]

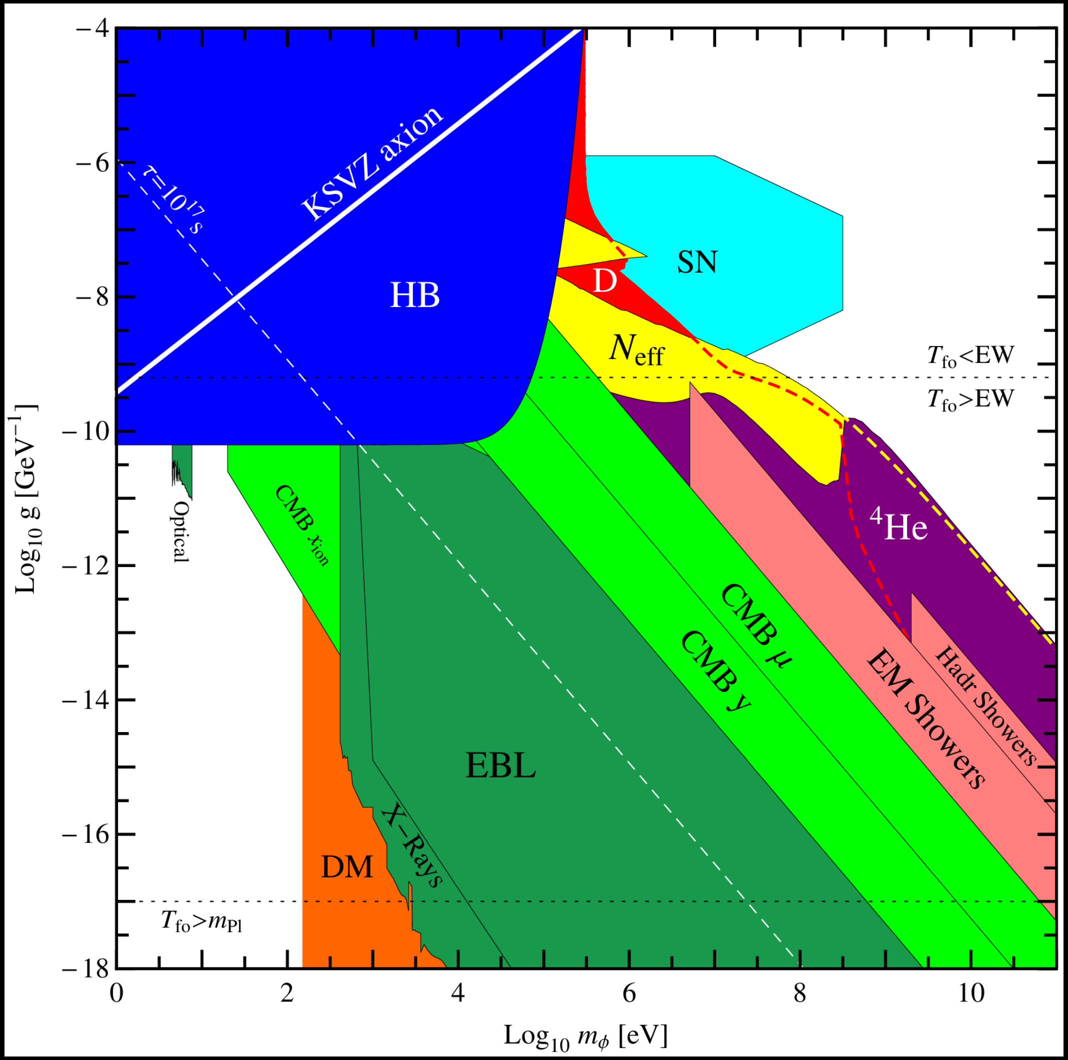
Bounds from BBN



Deuter … elium

[D.C. & Redondo (2011)]

Is there room for ALPs in cosmology?



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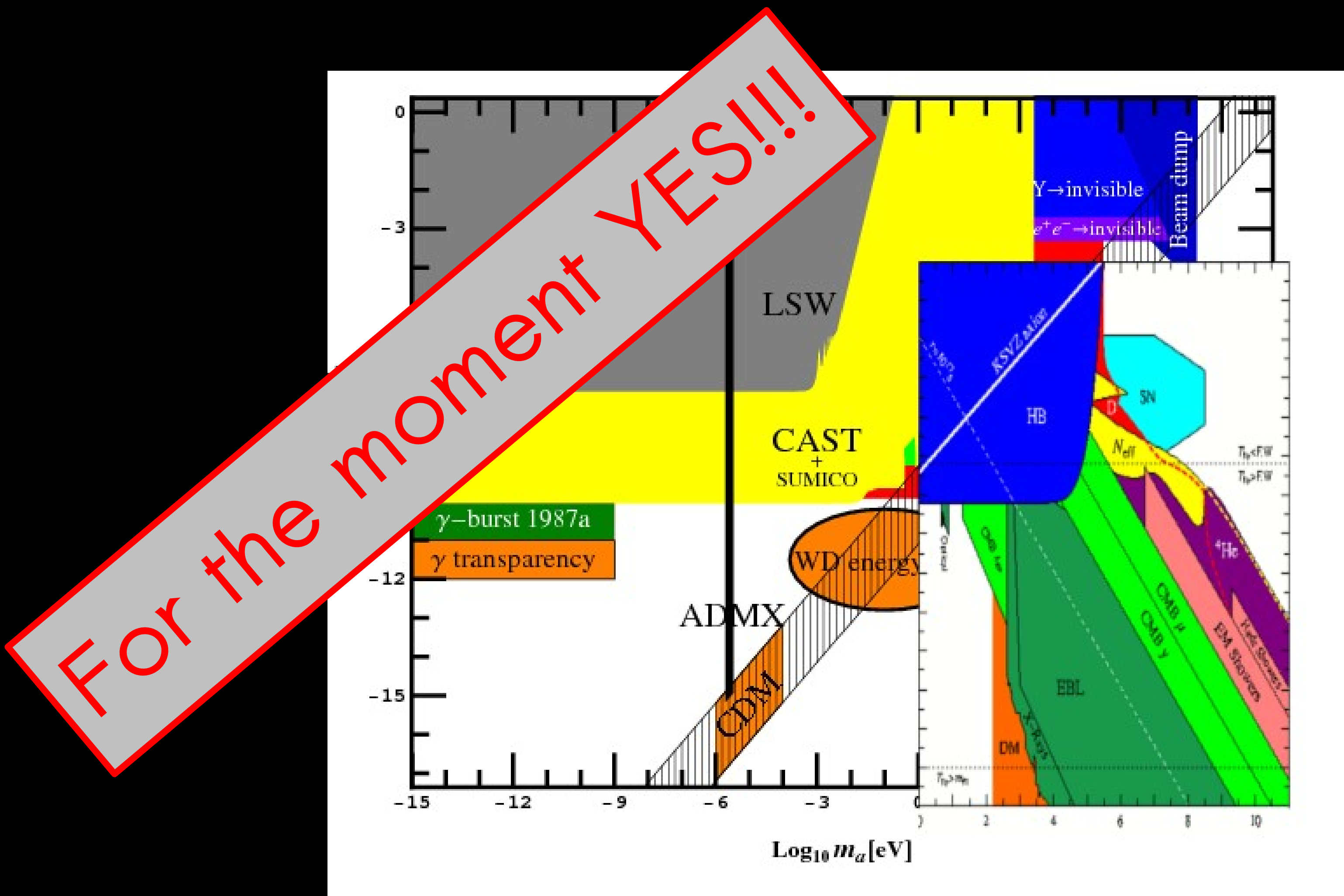

Summary

- Cosmologically stable ALPs can be constrained by DM density.
- The decay products of unstable ALPs would leave some traces in the history of the universe
- Cosmological bounds from CMB and telescope searches
- New cosmological bounds from N_{eff} and *BBN*