Axion Star Explosions and the Reionization History of the Universe

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based on ongoing work with:

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ArXiv:2210.XXXX1
ArXiv:2210.XXXX2

PADUA
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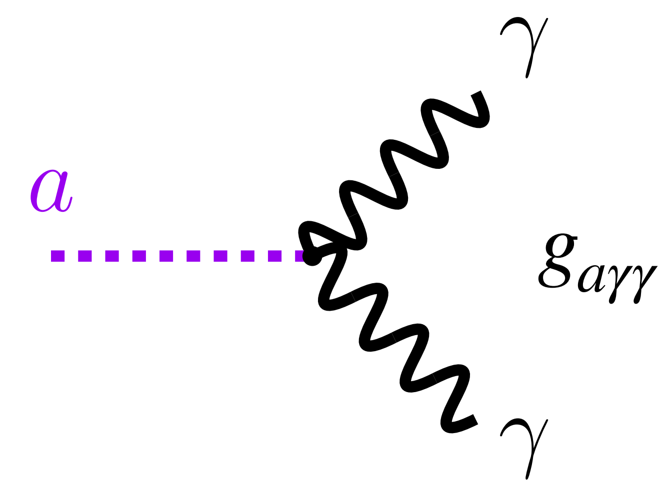
Axion-Photon Interactions

- **Axion-like particles are expected to interact with photons**



- **This means that axions should decay!**

- **In vacuum, the lifetime is really long:** $\tau_a = \dfrac{64\pi}{m_a^3\, g_{a\gamma\gamma}^2} \gg t_U$ **for** $m_a < 1\,\mathrm{eV}$

- **However, finite density effects can dramatically change this picture because:**

  1) the axion field is coherent and there are huge occupation numbers

  2) both axions and photons are bosons

These two properties in principle enable an exponentially fast decay of axions!

Axion-Photon interactions in a medium

- **In a medium, the decay could happen on a much shorter timescale:**

$$\boxed{\Gamma \simeq g_{a\gamma\gamma}\sqrt{\rho_a}}$$

Provided that:

i) the system is dense enough $\Gamma L > 1$

ii) the photons in the medium have an energy precisely of $E_\gamma = m_a/2$

These are direct consequences of solving the Mathieu equation for the EM field. Typically called parametric resonance

Already discussed in: **Abbott & Sikivie 83' and Preskill, Wise & Wilczek 83'**
for more recent refs see e.g. Alonso-Álvarez et al. 1911.07885

- **The question is, which systems are dense enough so that the decay can happen?**

$$\boxed{\textbf{Axion Stars!}}$$

see Levkov, Panin & Tkachev 2004.05179
also e.g.: Arza 1810.03722

In what follows, I will show that these star decays (or explosions) can lead to important cosmological consequences!

Outline

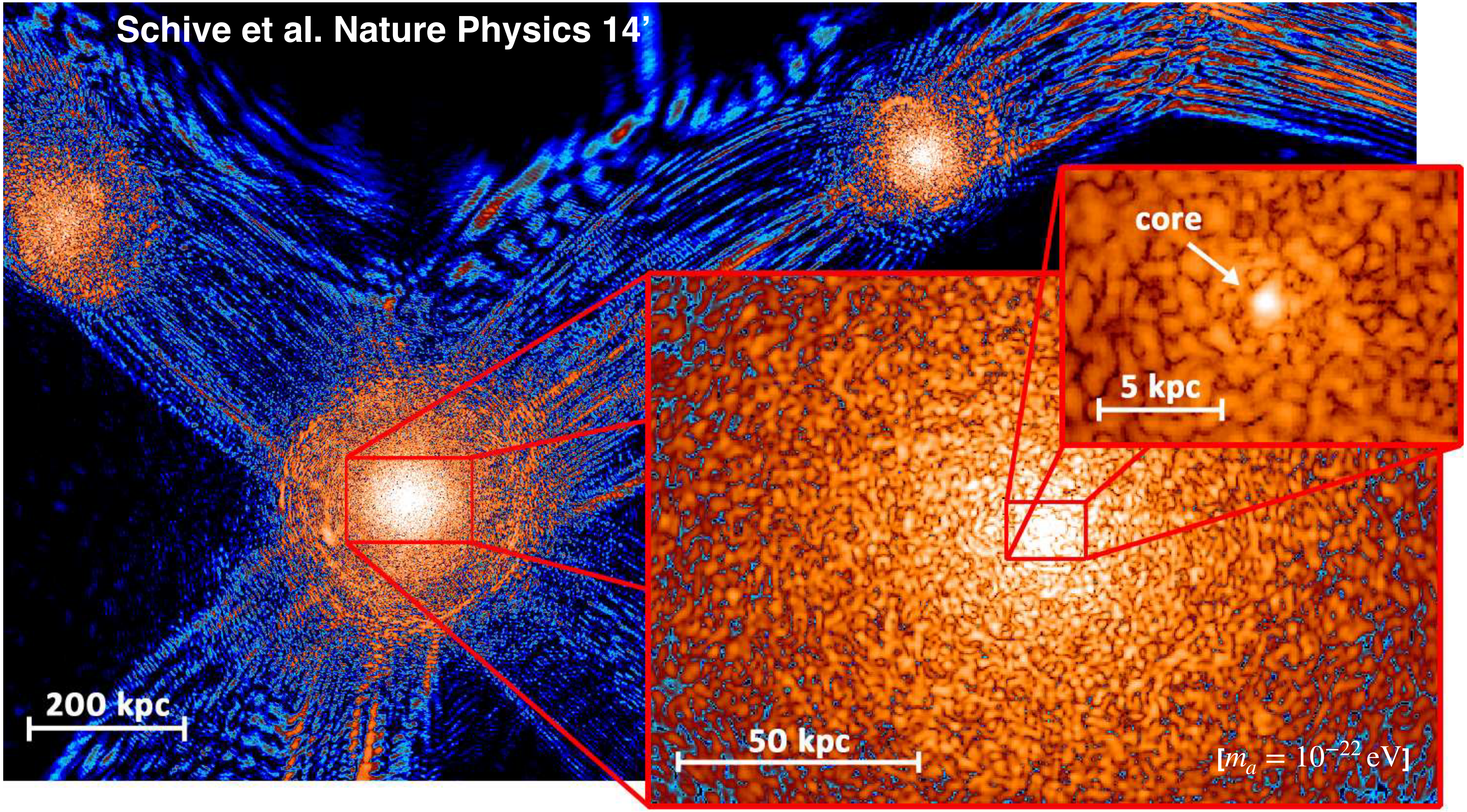
1) Axion Stars

2) Cosmological Implications of Axion Star Decays

3) Summary and Outlook

Axion Stars

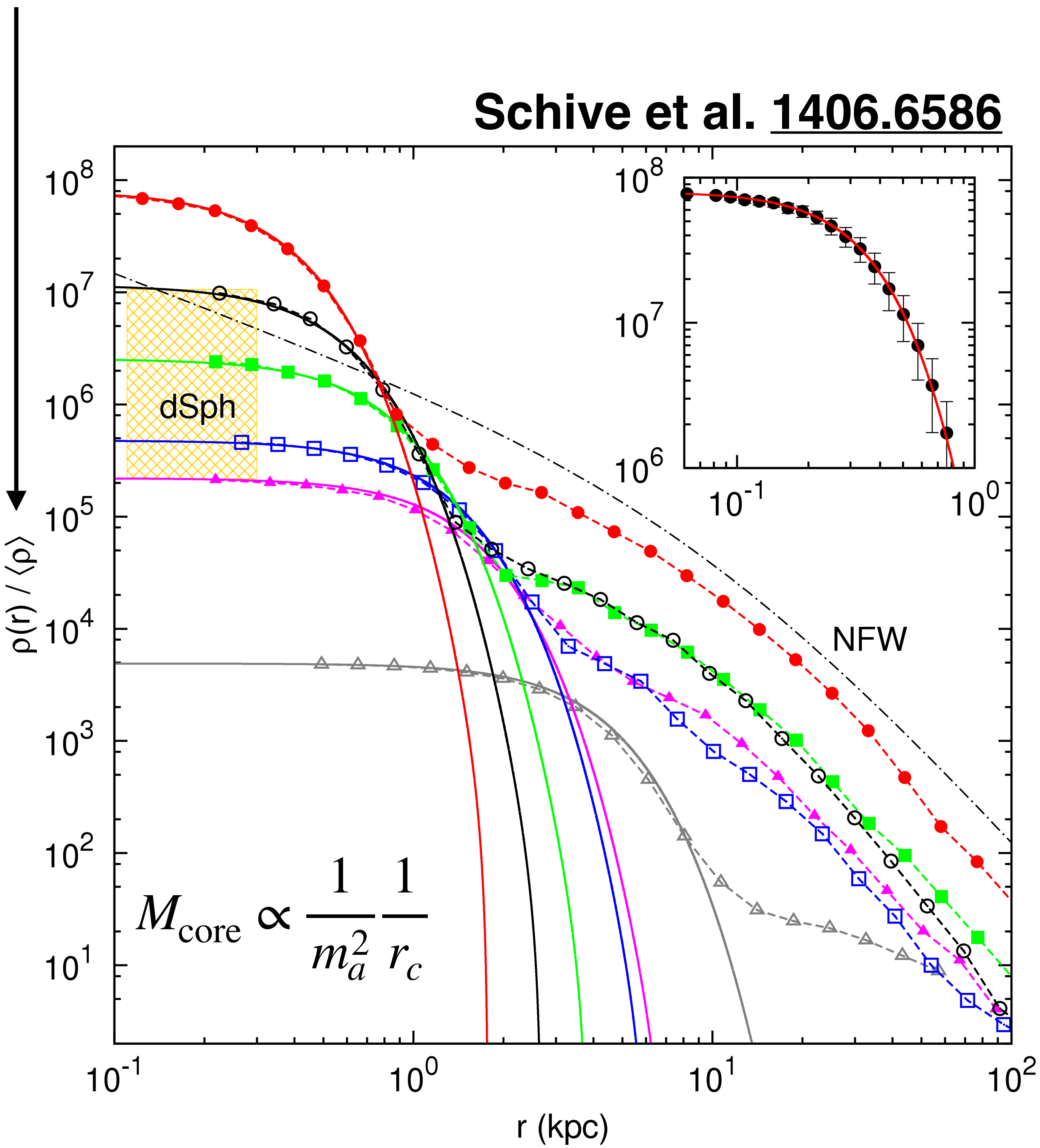
Cosmological simulations of axion-like dark matter have shown that there should be a dense core at the center of each dark matter halo



Axion Star Densities

The density profile of these stars is by now well known. These solitons would then represent the densest axion environments in the Universe

Schive et al. 1406.6586



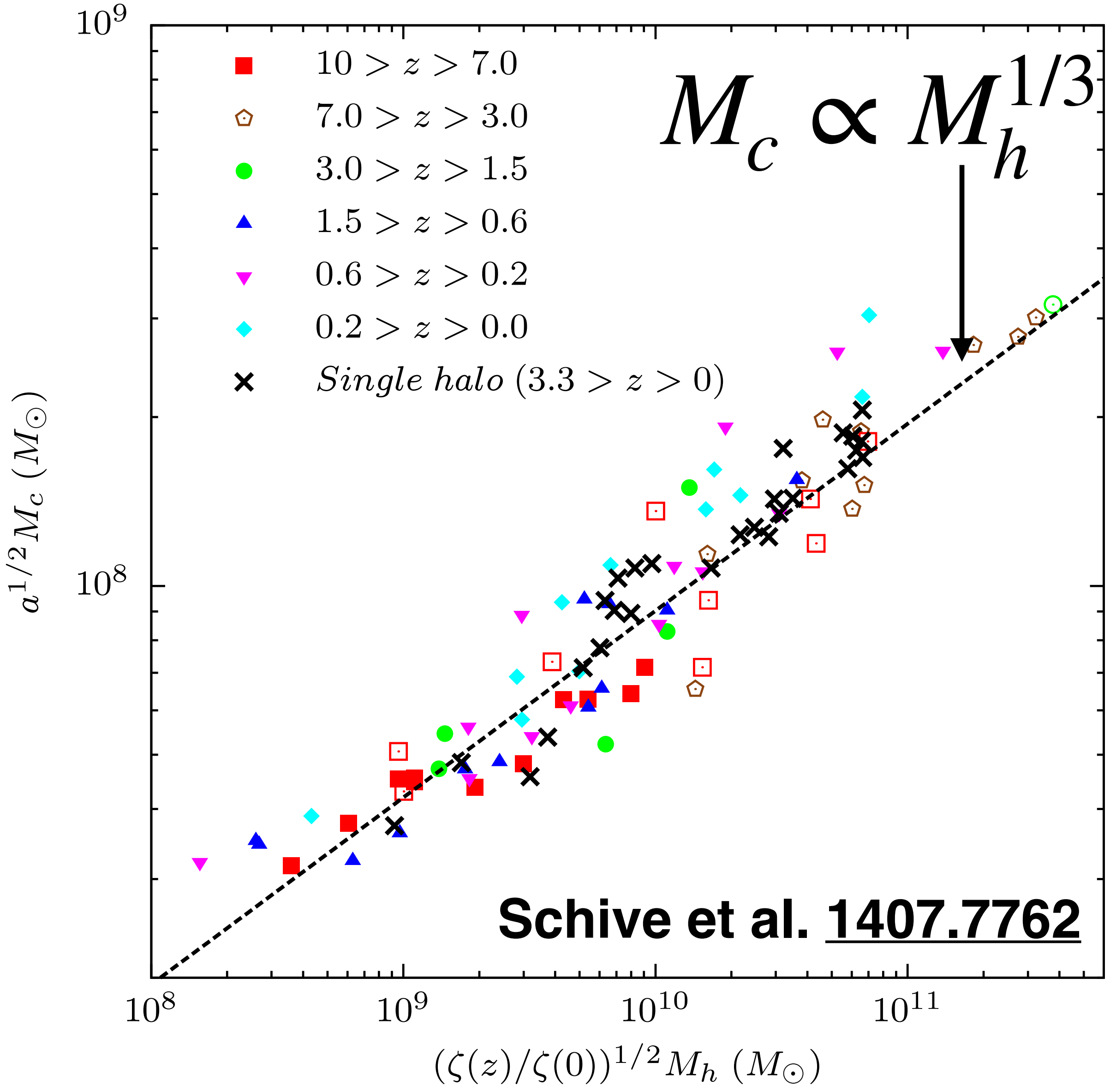
Given these profiles, we can estimate what is the mass that an axion star must have in order to lead to parametric resonance:

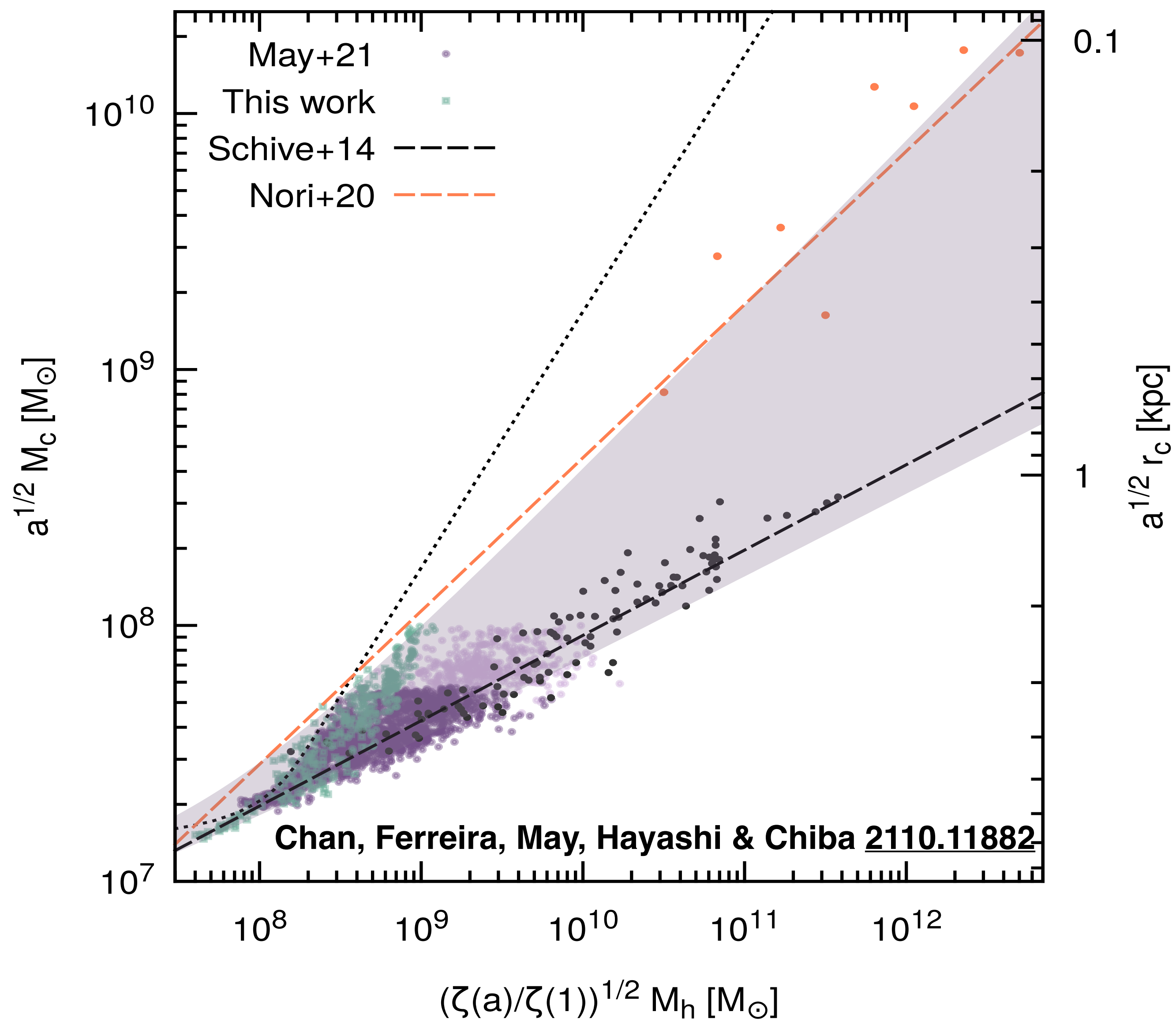
$$M_{\rm decay} \approx 4.4 \times 10^{-4}\, M_\odot \left(\frac{10^{-12}\,{\rm GeV}^{-1}}{g_{a\gamma\gamma}}\right)\left(\frac{10^{-13}\,{\rm eV}}{m_a}\right)$$

Any axion star with a mass above this critical value will explode into photons of $E_\gamma = m_a/2$

Axion Star Masses

The simulations of Schive et al. pointed to the existence of a one-to-one relationship between the mass of the host halo and the axion star:





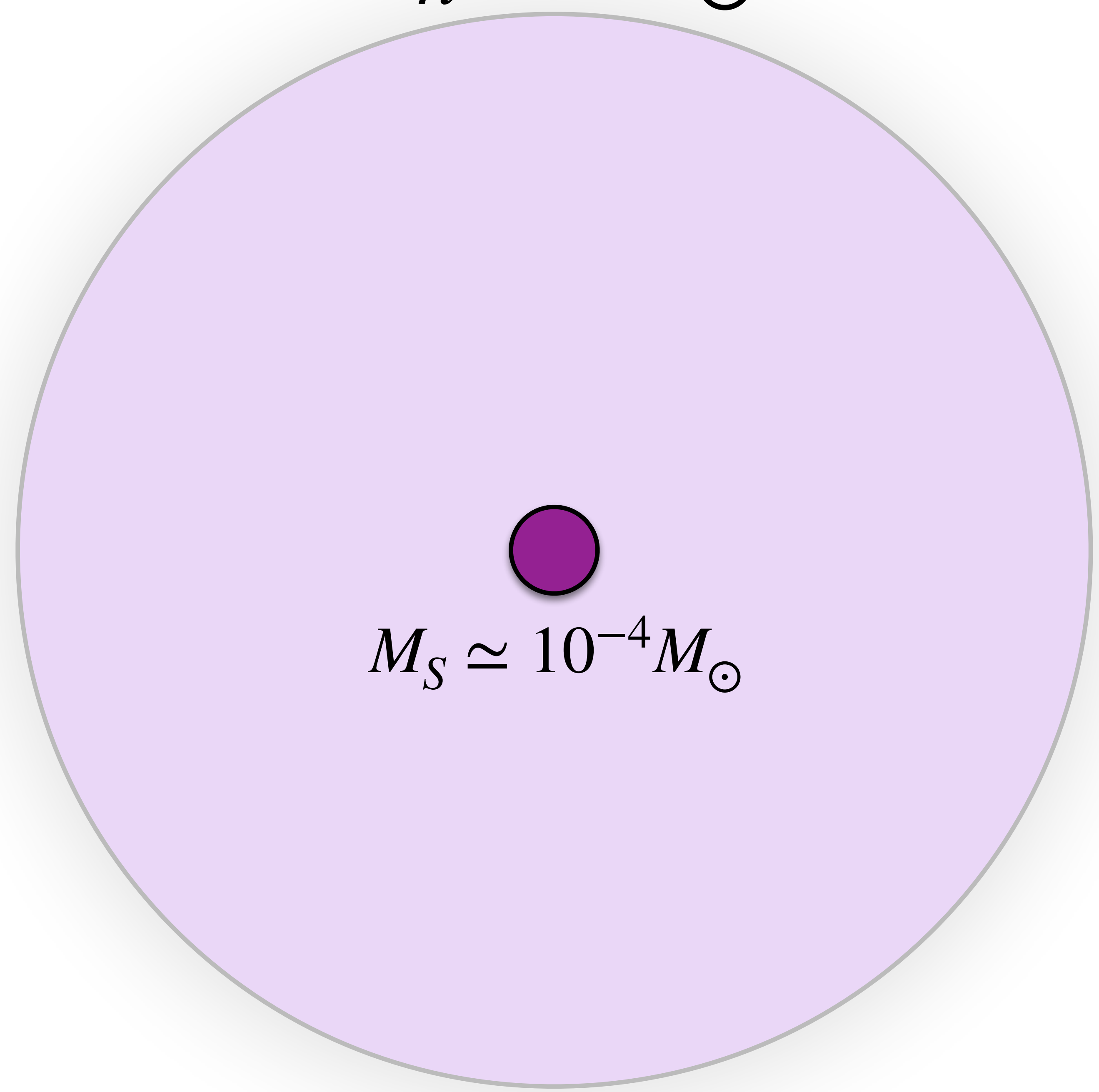
Further investigations seem to no longer support this strict relation but the cores inside halos are still restricted to have $\alpha > 1/3$ in $M_c \propto M_h^\alpha$

Chan, Ferreira, May, Hayashi & Chiba 2110.11882

Core-Halo Mass Relation implication

Schive Relation:

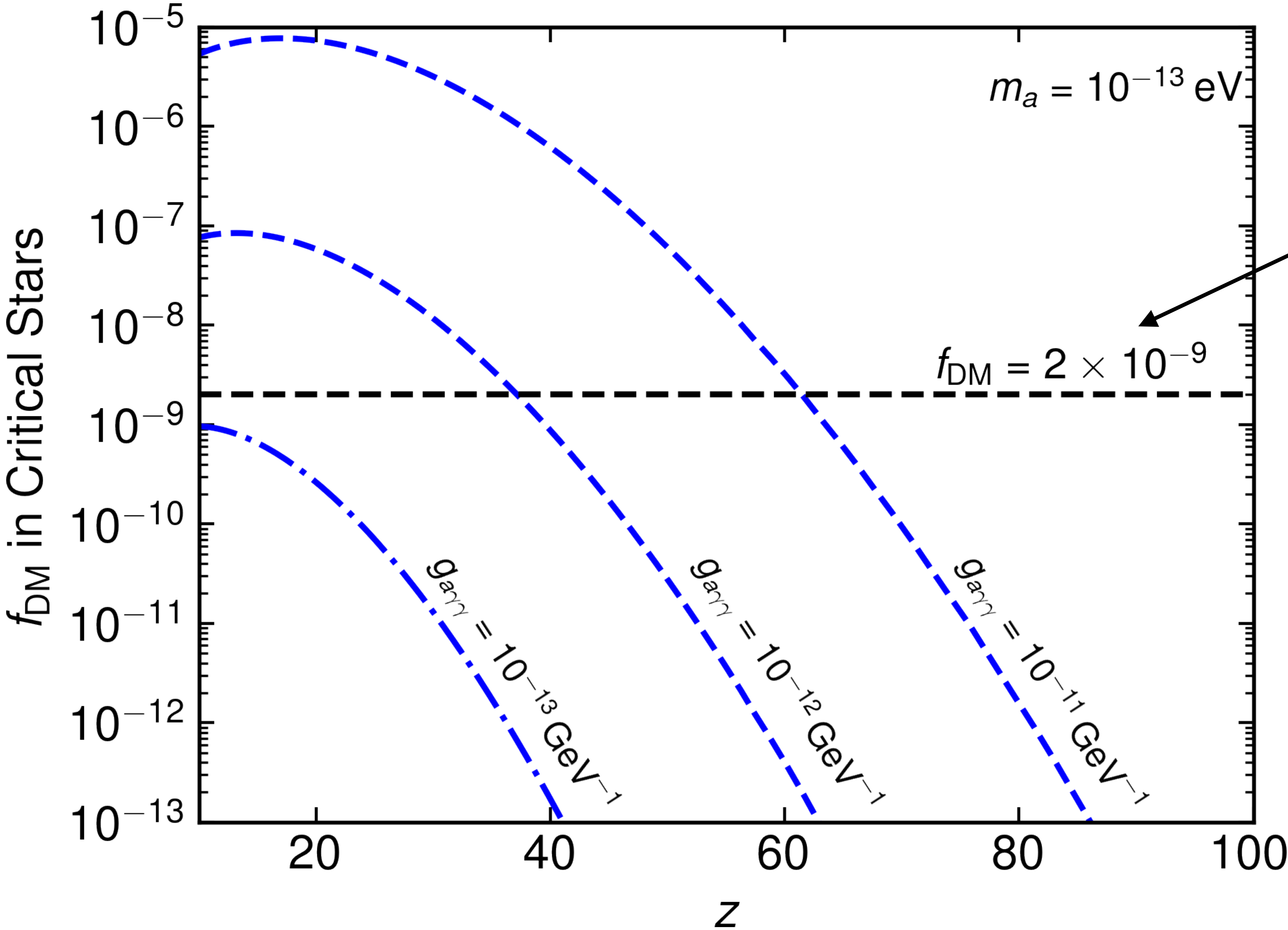
$$M_h \simeq M_\odot$$



Axion Stars Abundances

Hierarchical structure formation will lead to the formation of heavier and heavier dark matter halos and as such of heavier and heavier axion stars.

Using a core-halo mass relation and the HMF we can obtain the energy density in stars that are critical, namely for which $M_S > M_{\rm decay}$



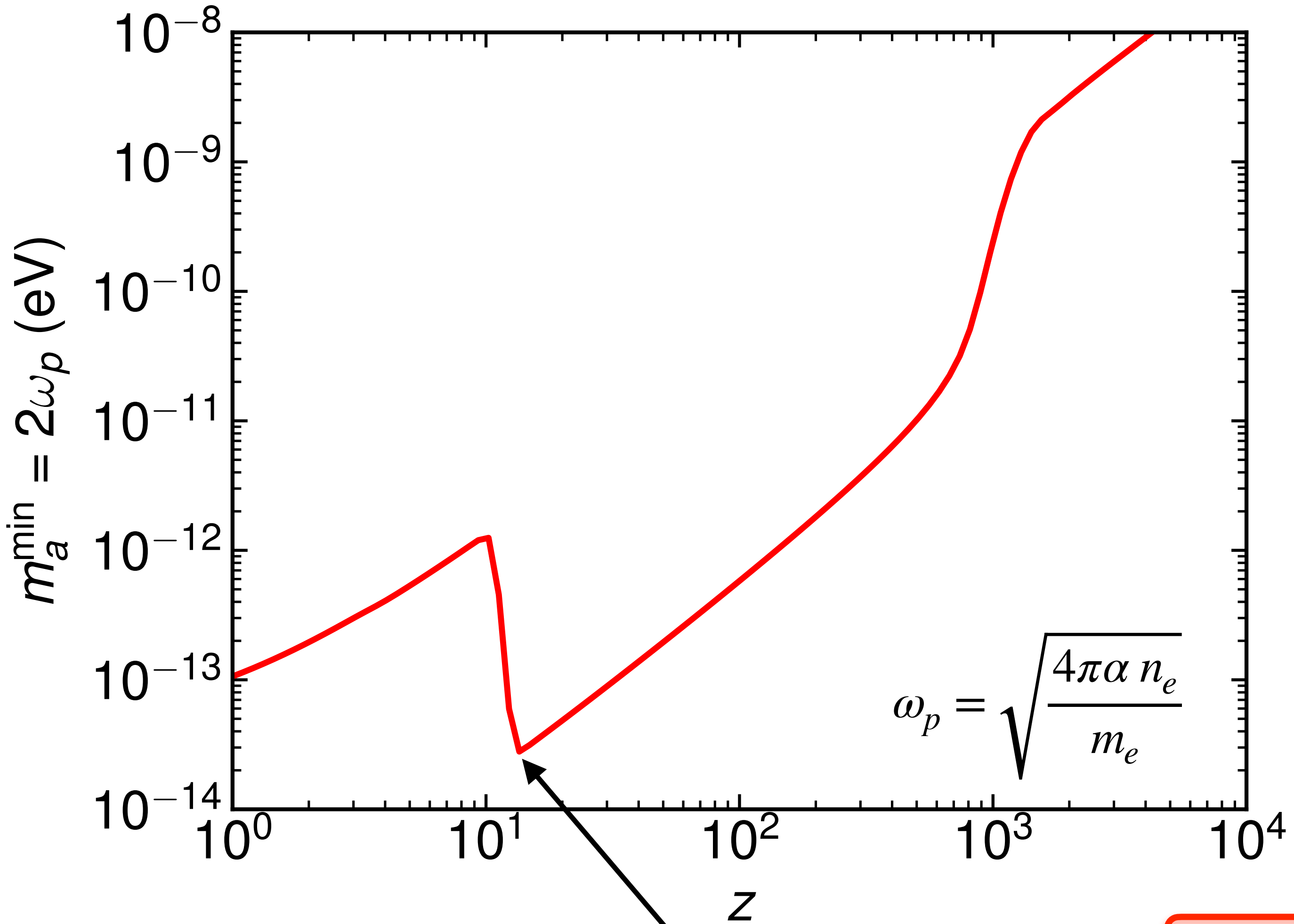
This amount of Dark Matter transformed into heat will fully reionize the Universe!

$$\rho_{\rm ion} \sim 13.6\,{\rm eV} n_b \sim 10^{-9} \rho_{\rm DM}$$

Using the Schive relation, the Sheth-Tormen HMF and accounting for the P(k) suppression from ultralight dark matter at $k > k_J$

Can these stars actually decay?

Importantly, the decay of axion stars into photons can only happen for axions that are 2xheavier than the photon plasma mass in the Universe:



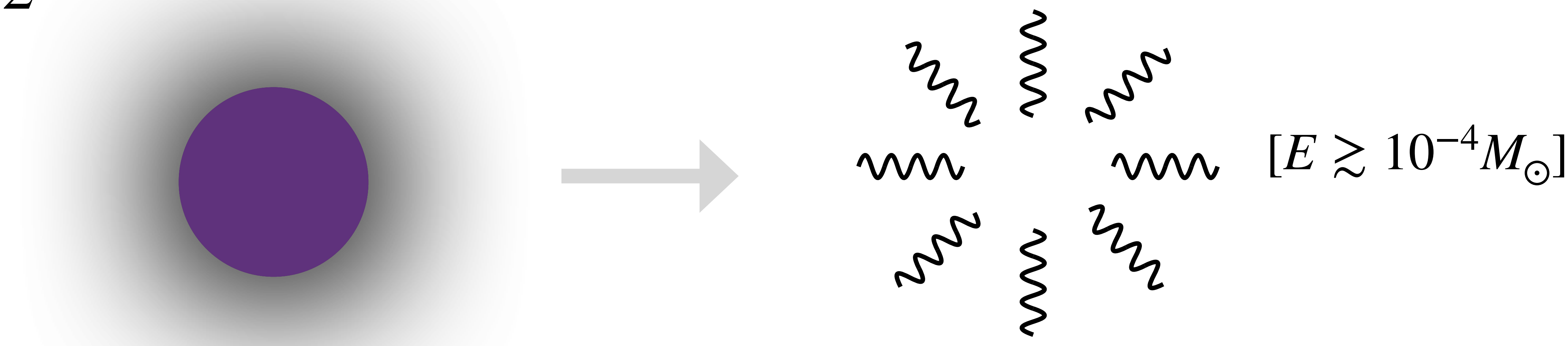
Axion Stars will only be able to decay when: $\boxed{2\omega_p < m_a}$

1) We will expect that in some cases there is a burst of energy that goes into the IGM right when $2\omega_p = m_a$.

2) We will only be interested in: $\boxed{m_a \gtrsim 3 \times 10^{-14}\,\mathrm{eV}}$

Cosmological Impact

1) Axion Stars of $M > M_{\rm decay}$ will decay into photons of $E_\gamma = m_a/2$ once $\omega_p < m_a/2$



2) Once produced, these photons will be quickly absorbed by the plasma due to Bremsstrahlung absorption, see Chluba 1506.06582

3) This will generate a blast of energy and will lead to reionization and heating during the dark ages when these axion stars start to form

This will happen as soon as $T_b \sim 10\,{\rm eV}$ (which roughly corresponds to $f_{\rm DM}^{\rm decay} \sim 10^{-9}$)

This allows us to set constrains on $g_{a\gamma\gamma}$ for certain axion-like DM models

The Procedure in 4 steps

1/4 Calculation of the energy density in critical stars

We do this by:

1) Using a power law Core-Halo mass relation $M_c \propto M_h^\alpha$, $\alpha = 1/3$ for Schive et al.

2) Obtaining the number density of halos via the Sheth-Tormen Halo Mass Function

2/4 Evolution of the injected photons

**The energy of these axion star decays is very large: $M_{\rm decay} \gtrsim 10^{-4}\, M_\odot$.
This means that these explosions will look like a blast of energy in the IGM.
Very similar to a SN remnant!**

We track the radius of these bubbles in the early Universe as typically done with Supernova remnants, see Ostriker and McKee (88') and Witte and Blas [2009.10074]

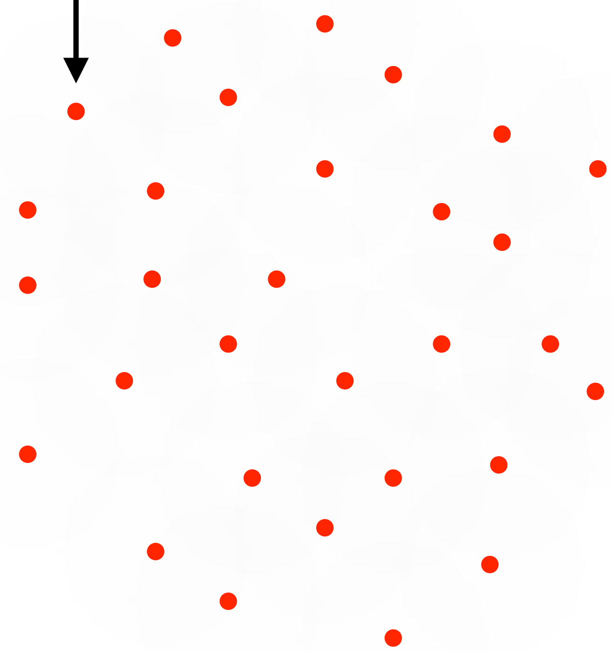
This allows us to calculate the evolution of the free electron fraction by knowing the fractional volume of the Universe in these bubbles.

Explosion and Reionization Process

Critical Axion stars

Explosion

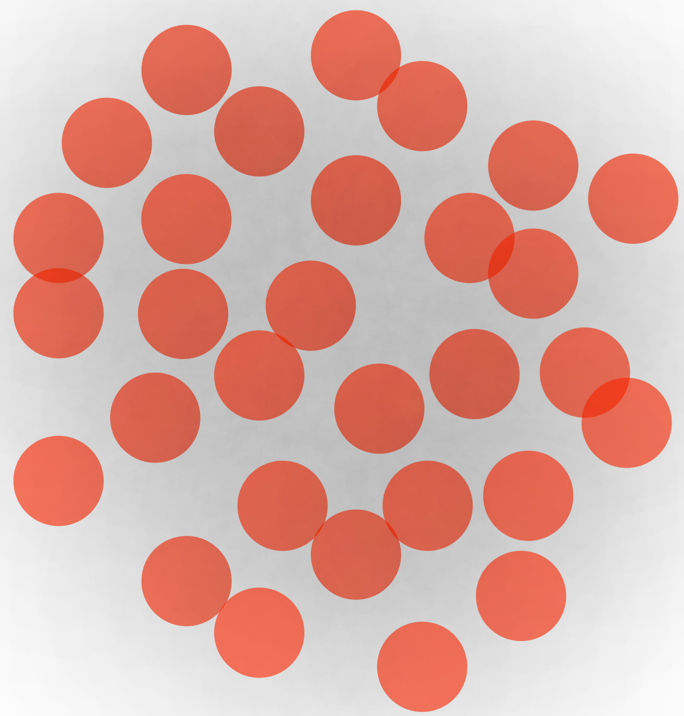
$\omega_p(z) = m_a/2$



$z \lesssim 100$

$\tau_{\rm decay} \sim \mathcal{O}(10\,{\rm min})$

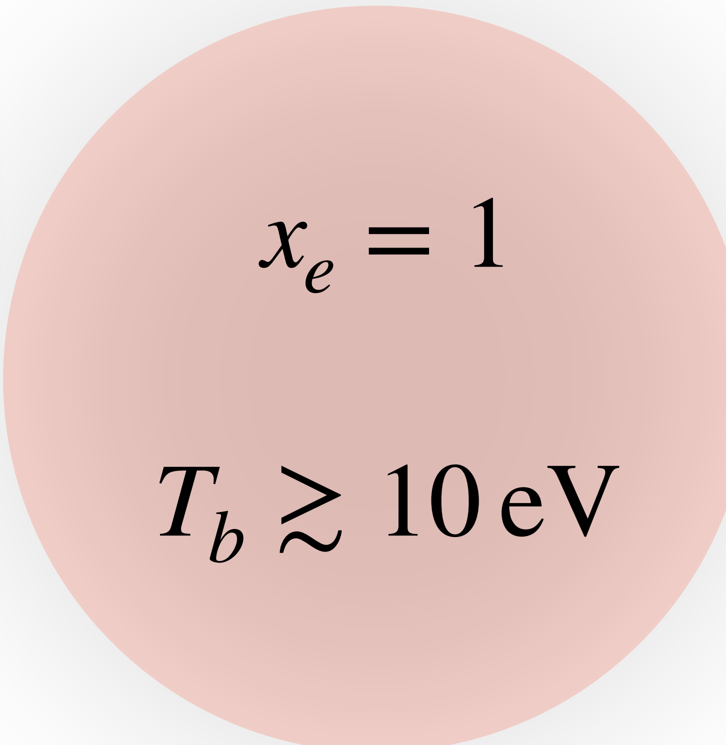
Expansion and Ionization



Sedov-Taylor expansion

$\tau_{\rm coalescence} \ll t_U$

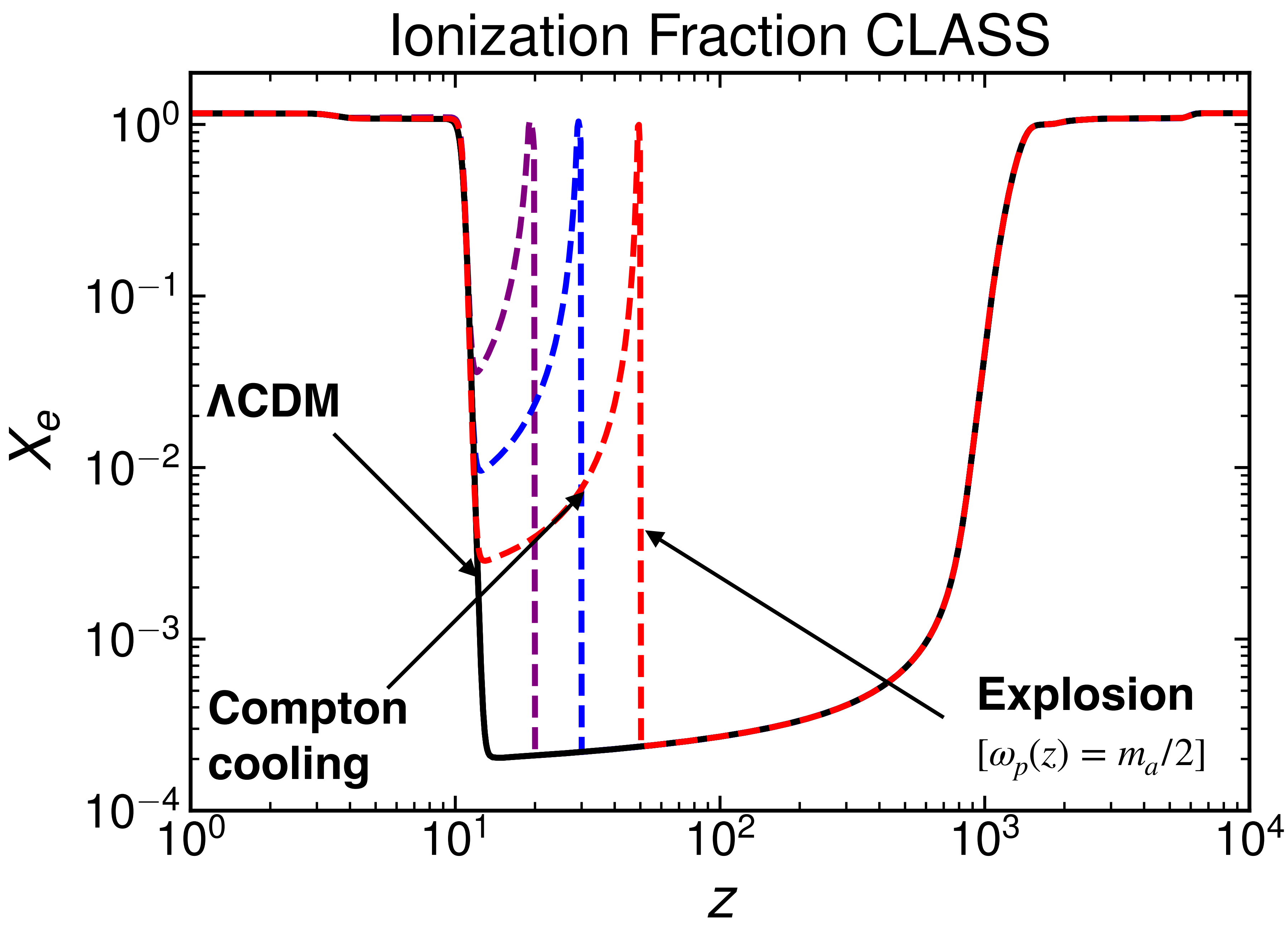
Final State after coalescence



Reionized Universe and hot baryons if
$f_{\rm DM}^{\rm decay} \gtrsim 10^{-9}$

The Procedure in 4 steps

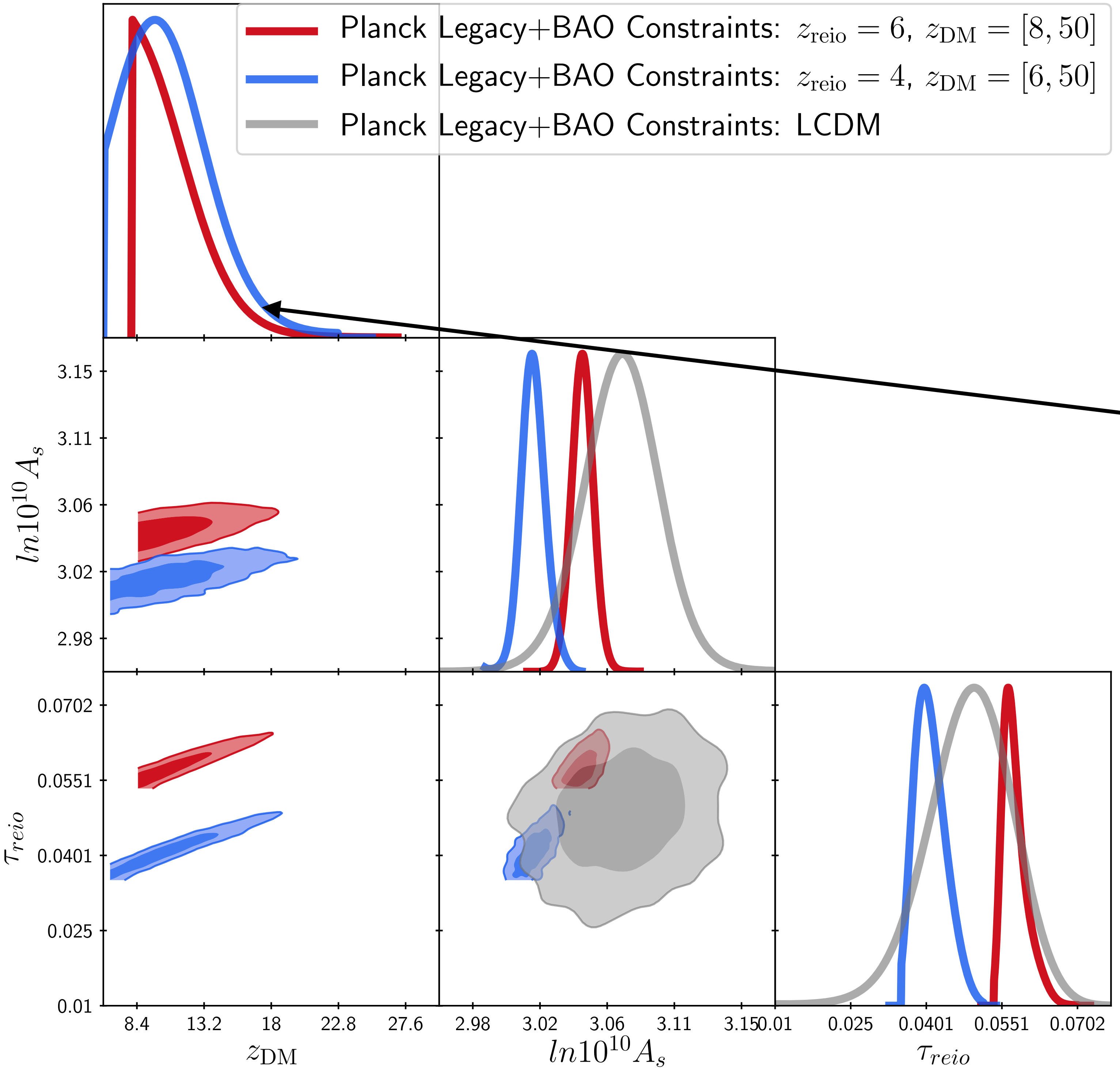
3/4 Track the free electron density and baryon temperature after injection



Planck 2018 constraints: $\tau(15{,}30) < 0.023$ $\quad d\tau = n_e \sigma_T d\ell$

The Procedure in 4 steps

4/4 We used CLASS and performed a Planck Legacy data analysis constraining these injections

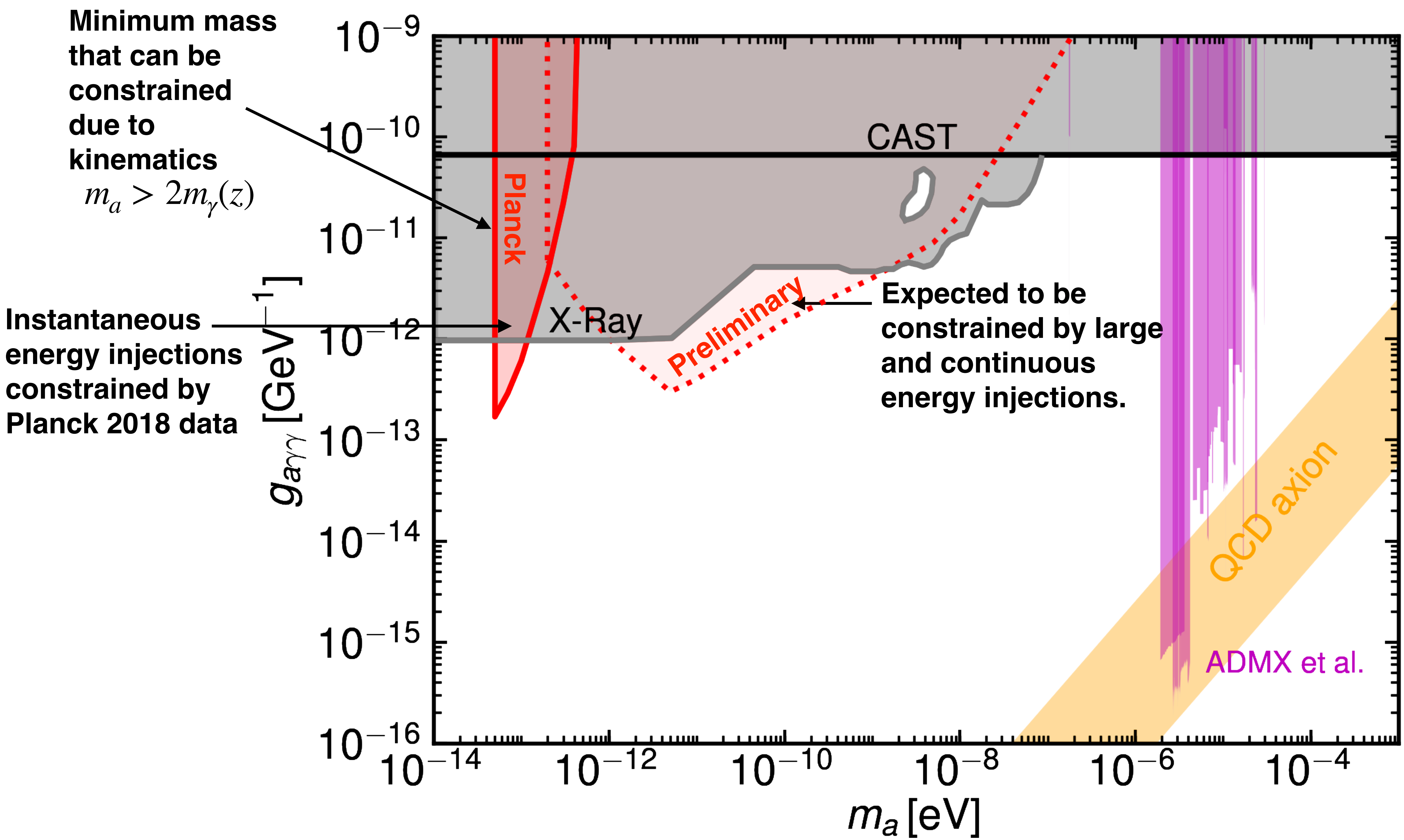


Planck bounds the redshift of an instantaneous injection of energy that leads to $x_e \sim 1$ to be:

$$\boxed{z_{\rm decay} < 16}$$

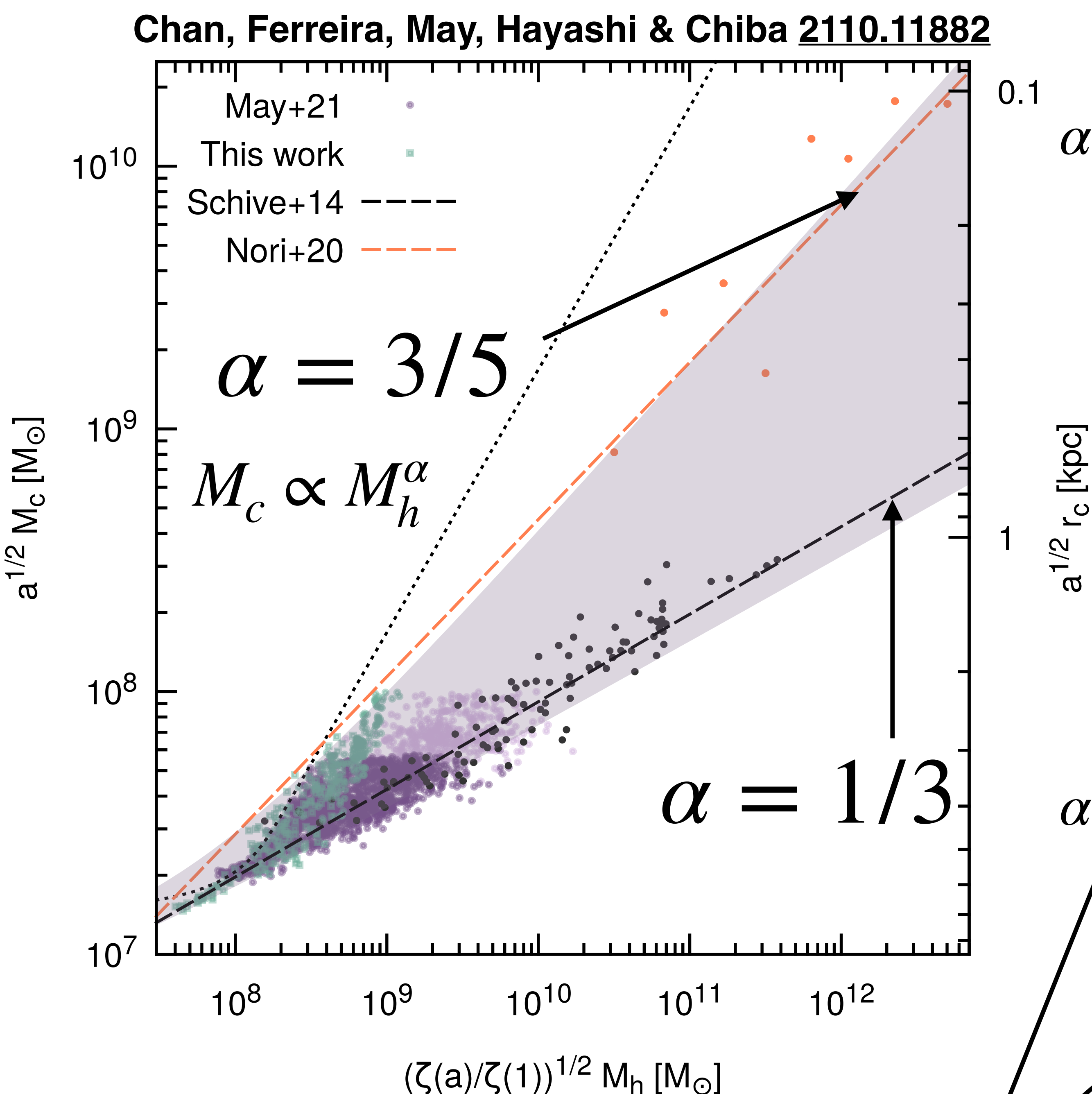
(mainly driven by lowEE data)

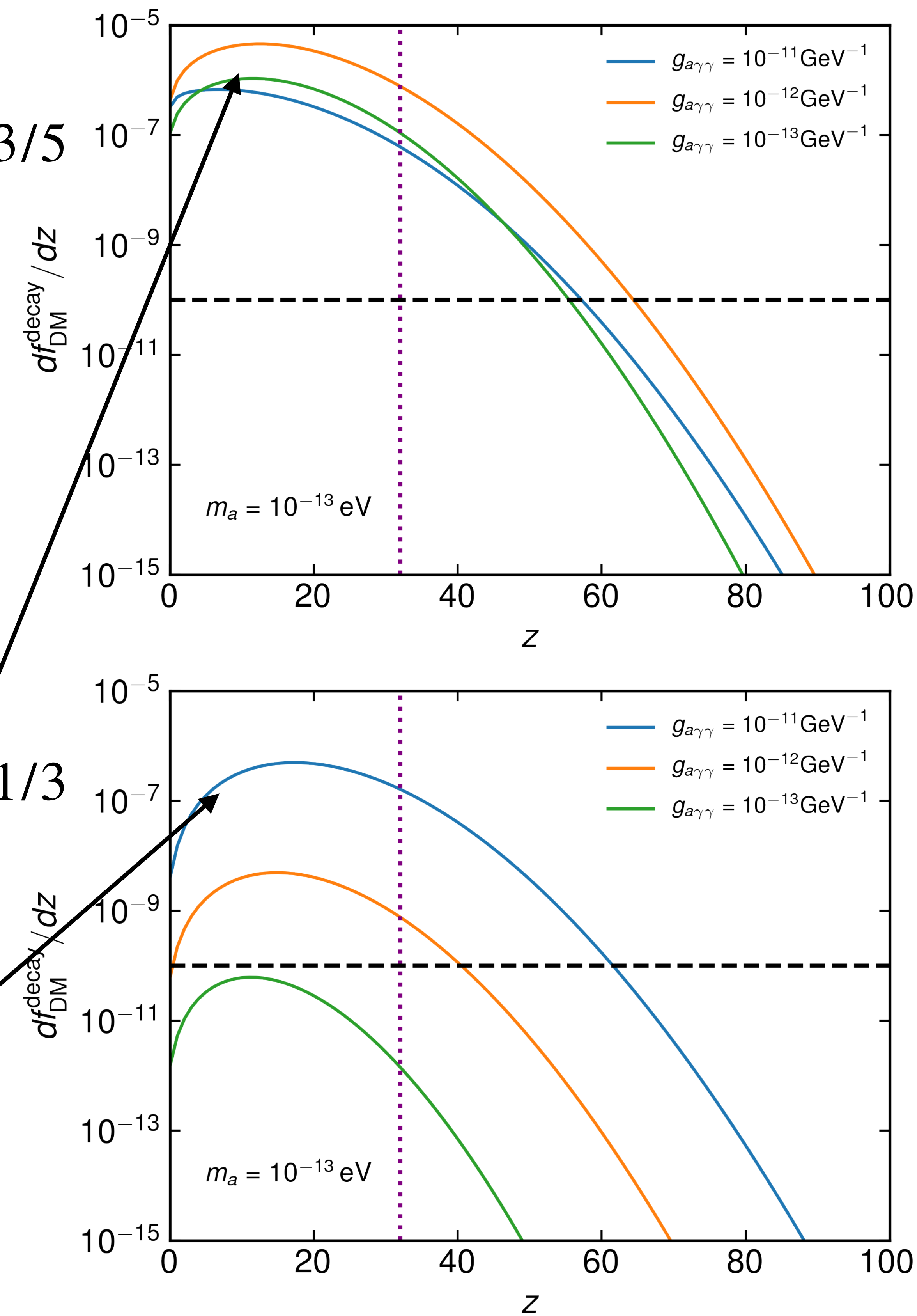
Resulting Constraints



However, there is strong sensitivity to the slope of the Core-Halo mass relation

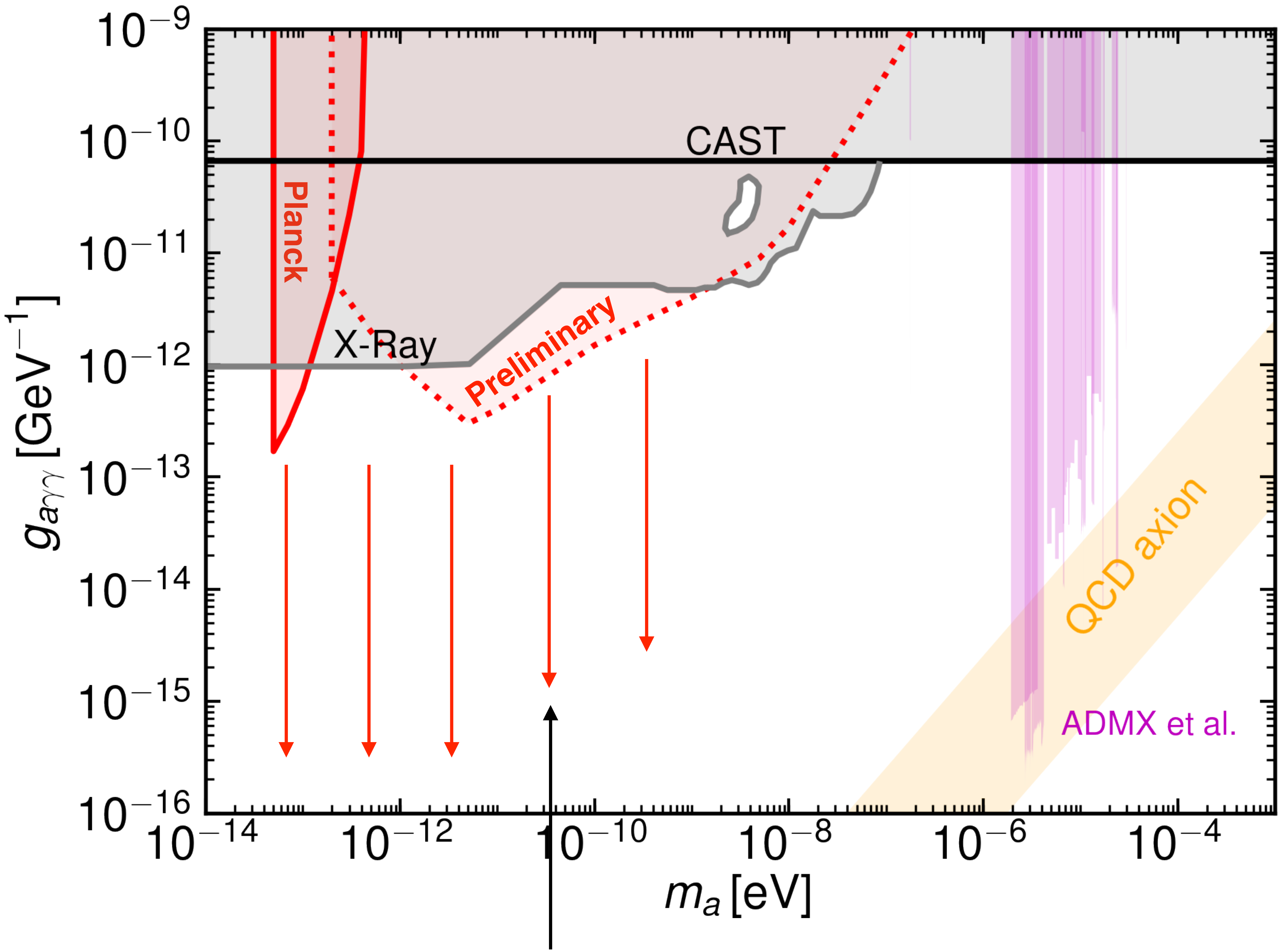
Core-Halo Mass relation sensitivity





Different Core-Halo Mass relations can lead to huge changes in what $f_{\rm DM}^{\rm decay}$ is

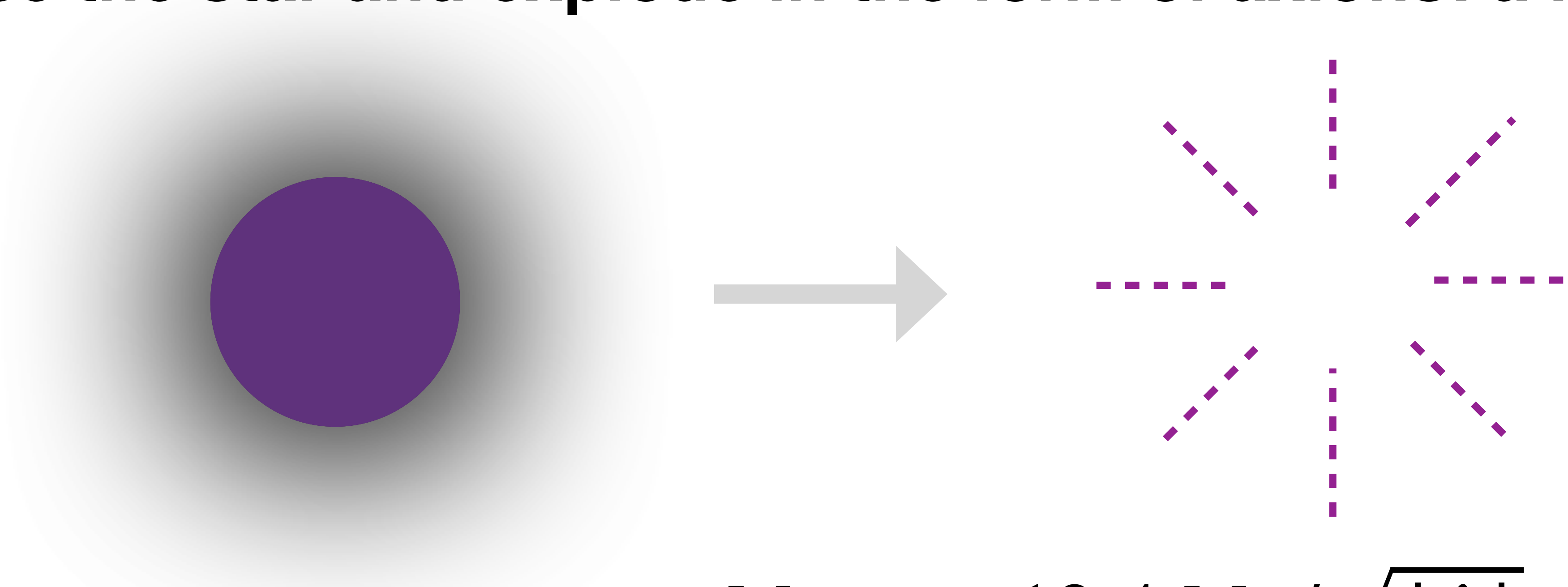
Resulting Constraints



However, there is strong sensitivity to the slope of the Core-Halo mass relation

Caveat: Quartic Coupling

Self-interactions can be important in the very dense environment of an axion star. For attractive self-interactions, the effect is to collapse the star and explode in the form of axions: a Nova



see Levkov, Panin & Tkachev [1609.03611]

This happens at a mass: $M_{\rm Nova} = 12.4\, M_{\rm Pl}/\sqrt{|\lambda|}$ **for** $\lambda < 0$

Axions with a cosine potential imply:

$$\frac{M_{\rm crit}}{M_{\rm Nova}} = 330\, \frac{g_{a\gamma\gamma}}{\alpha/(2\pi f_a)} \frac{\sqrt{-\lambda}}{m_a/f_a}$$

This means that our bounds will only apply for scenarios with suppressed quartic interactions or with with enhanced $g_{a\gamma\gamma}$ couplings

see e.g. talk by Ringwald on Monday

Summary and Conclusions

- **There should be a large number of axion stars in the Universe and they represent a non-negligible contribution of the energy density in dark matter**

  We will provide the machinery to calculate it

- **These axion stars can be dense enough to decay into photons due to parametric resonance**

- **These axion stars are formed during the dark ages and their decays into photons can lead to heating and reionization which is strongly constrained by Planck**

- ***Note that these constraints only apply to axion-like particles with enhanced $g_{a\gamma\gamma}$ couplings or reduced quartic couplings**

Ongoing Work and Outlook

Ongoing:

— Finalizing the phenomenological analysis and refining the constraints from continuous photon emission

— We are exploring what happens for other core-halo mass relations: We expect only stronger constraints! Our derived constraints in this sense are very conservative

— We are investigating the effect of diversity in the core-halo mass relation using merger trees [Xiaolong Du]

Outlook:

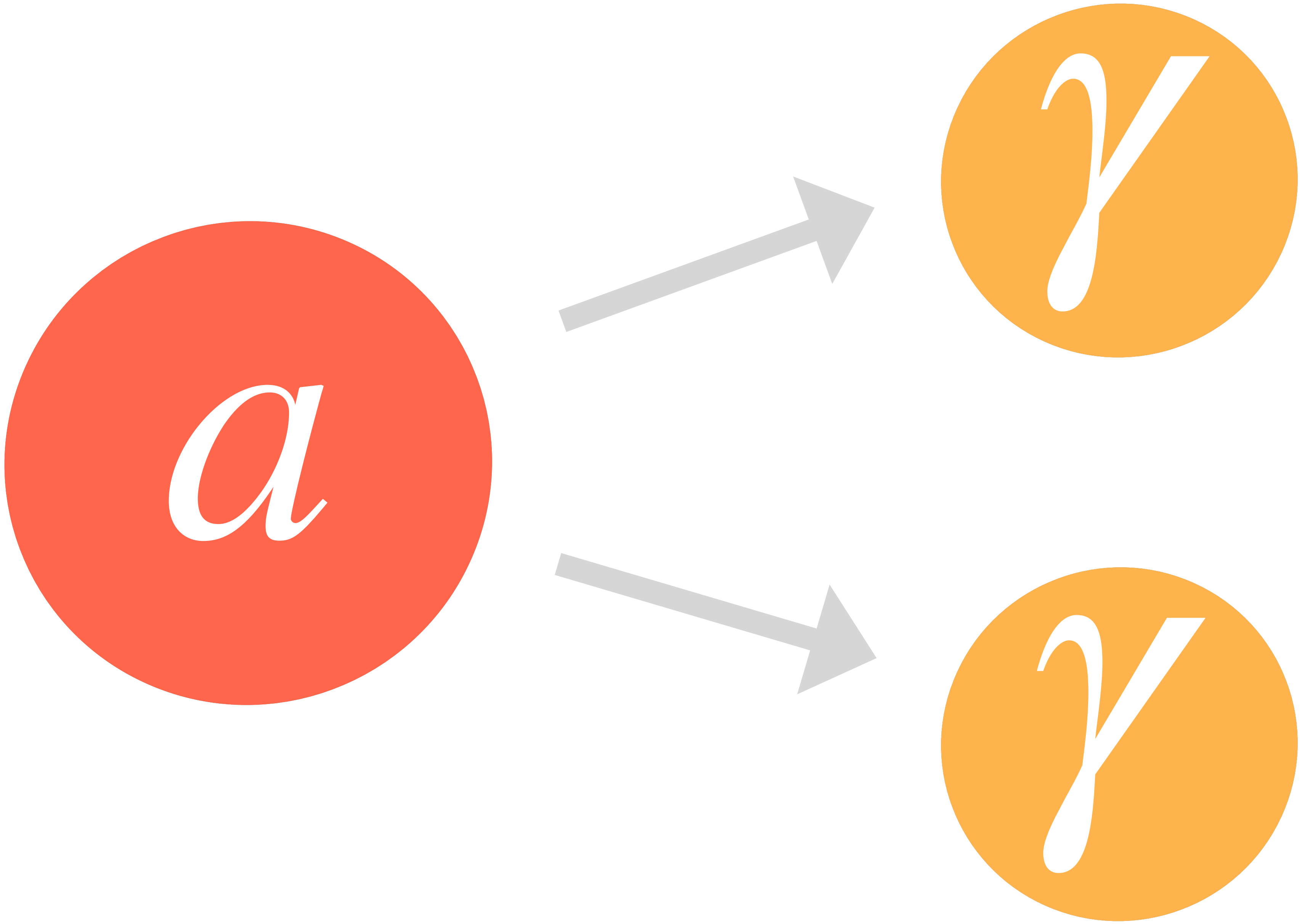
Our formalism allows to calculate the distribution of axion stars in the Universe. It would be interesting to study the case of Axion Star explosions into relativistic axions:

Axion star explosions generate axions with energies $E \lesssim 9\, m_a$ and a well defined spectrum, see Levkov, Panin & Tkachev [1609.03611]

These would make a contribution to the Comic Axion Background which could open new detection possibilities, see Dror, Murayama & Rodd [2101.09287]

Time for Questions and Comments

Thank you for your attention!



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