# Axion Star Explosions and the Reionization History of the Universe

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**based on work with:**

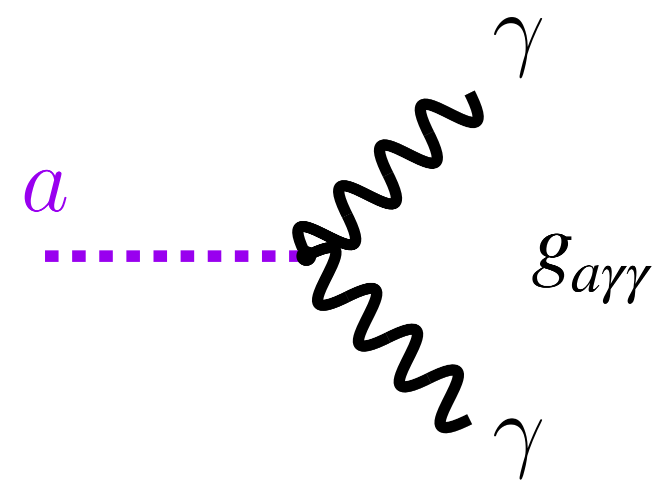
**Diego Blas, Xiaolong Du, Malcolm Fairbairn, Doddy Marsh & Charis Pooni**

**ArXiv:2302.10206**
**ArXiv:2301.09769**

**1st General Meeting of COST Action COSMIC WISPers (CA21106)**
**05-09-2023**

# 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?

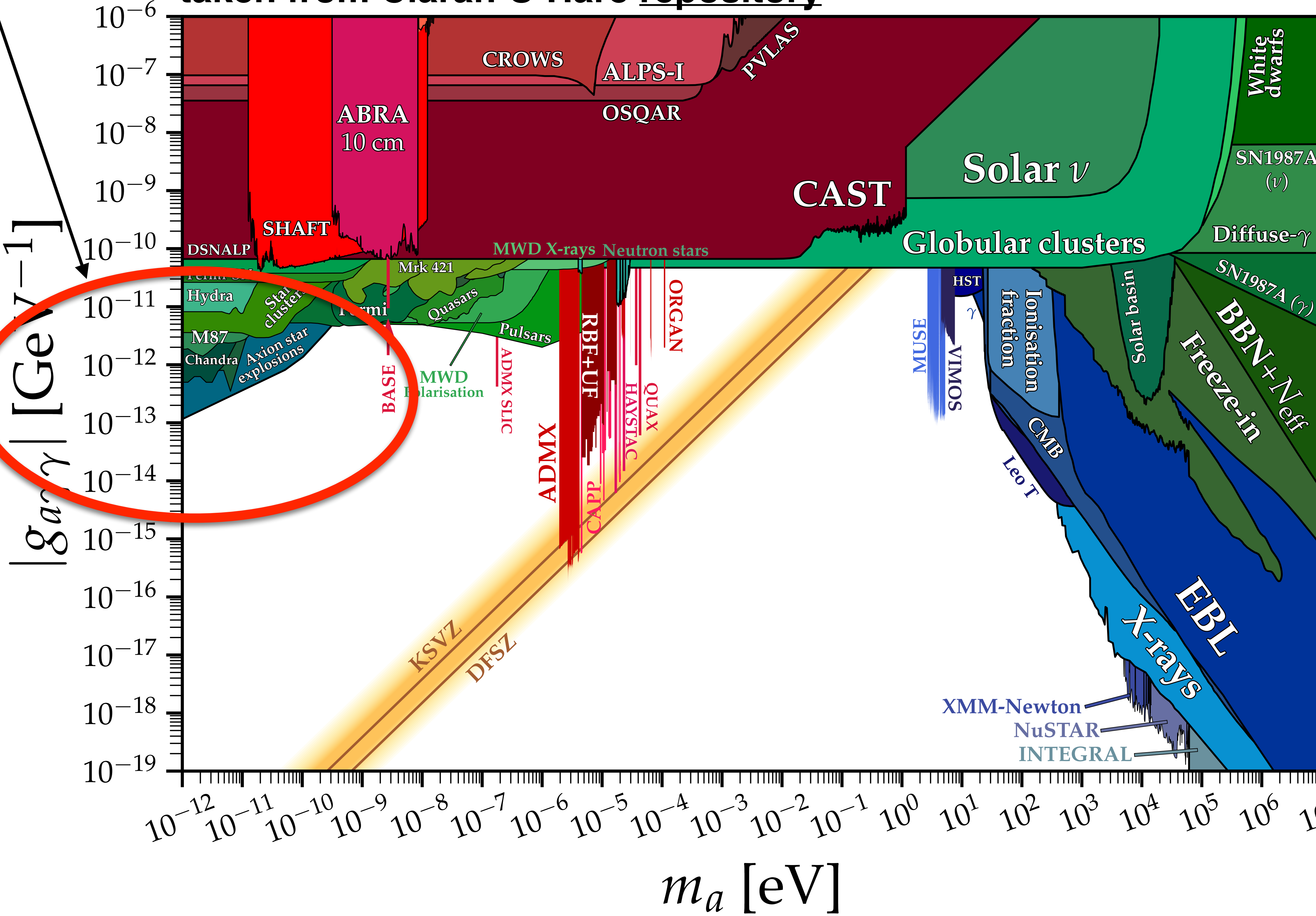
**Axion Stars!**

see Levkov, Panin & Tkachev 2004.05179
Tkachev '87, Arza 1810.03722,
Hertzberg & Schiappacasse 1805.00430
Amin & Mou 2009.11337

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

# Parameter Space of Interest

taken from Ciaran O'Hare repository



# Essence behind the constraints

**Energetically, it is very easy to ionize the Universe:**

It only takes $E = 13.6\,\mathrm{eV}$ to ionize Hydrogen

This is just a fraction of $10^{-8}$ of the rest mass of a proton

And the energy density in Dark Matter is 5 x the baryon one

**Only $f_{\rm DM} \gtrsim 2\times 10^{-9}$ of the DM energy density would in principle be needed to ionize the entire Universe after recombination**

**This is the key behind the constraints on s-wave annihilating WIMPs from CMB observations**

$$\langle \sigma v \rangle \lesssim 3\times 10^{-26}\,\mathrm{cm}^3/\mathrm{s} \times \frac{m_{\rm WIMP}}{10\,\mathrm{GeV}}$$

see e.g. Slatyer 1506.03811
but also McDermott & Witte 1911.05086
Bolliet, Chluba & Battye 2012.07292

**We find that in the region of couplings and masses highlighted above axion stars that decay into photons represent more than $f_{\rm DM} \gtrsim 2\times 10^{-9}$ of the DM energy density and are therefore excluded by Planck!**

# Outline

## 1) Axion Stars

**What are they?**
**Where and when do they form?**
**What are their masses?**
**How many of them do we expect in the Universe?**

## 2) Cosmological Implications of Axion Star Decays

**Heating and reionization**
**Bounds from Planck CMB observations**

## 3) Summary and Outlook

# Axion Stars: What are they?

**Axion stars are the ground state configuration of the non-linear Schrödinger-Poisson equation as relevant for non-relativistic axion-like dark matter particles:**

$$i\partial_t \Psi = -\frac{\nabla^2 \Psi}{2m_a} + m_a \phi \Psi \qquad \nabla^2 \phi = 4\pi G \rho \qquad \text{with } \rho = m_a |\Psi|^2$$

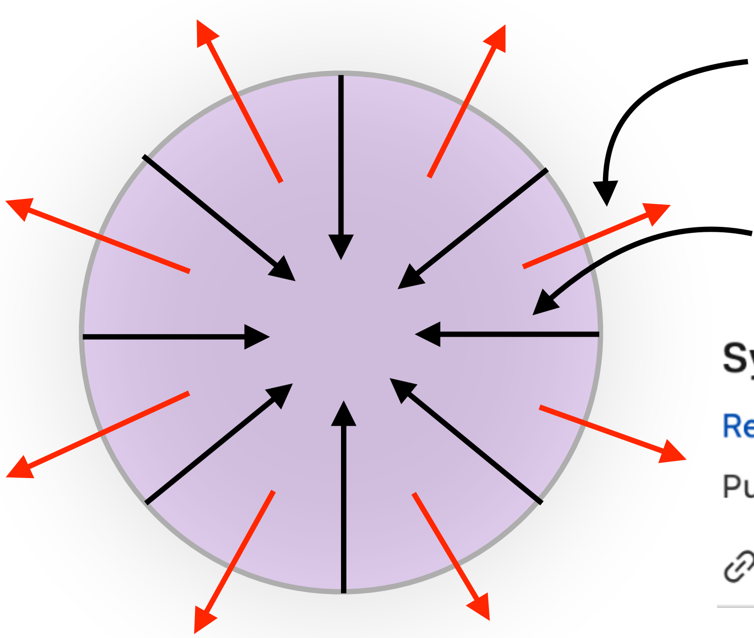
**Axion-like particles can have a macroscopic de-Broglie wavelength:**

$$\boxed{\lambda_{\rm dB} = \frac{2\pi}{mv} \simeq 1\,{\rm kpc} \times \frac{10^{-22}\,{\rm eV}}{m_a} \times \frac{100\,{\rm km/s}}{v}}$$

**Hu, Barkana & Gruzinov astro-ph/0003365**

**This changes the dynamics of the scalar field on scales $L < \lambda_{\rm dB}$ and allows to support self gravitating system by generating a "quantum pressure". These objects are called axion stars.**

**Axion Star:**




Systems of selfgravitating particles in general relativity and the concept of an equation of state #1

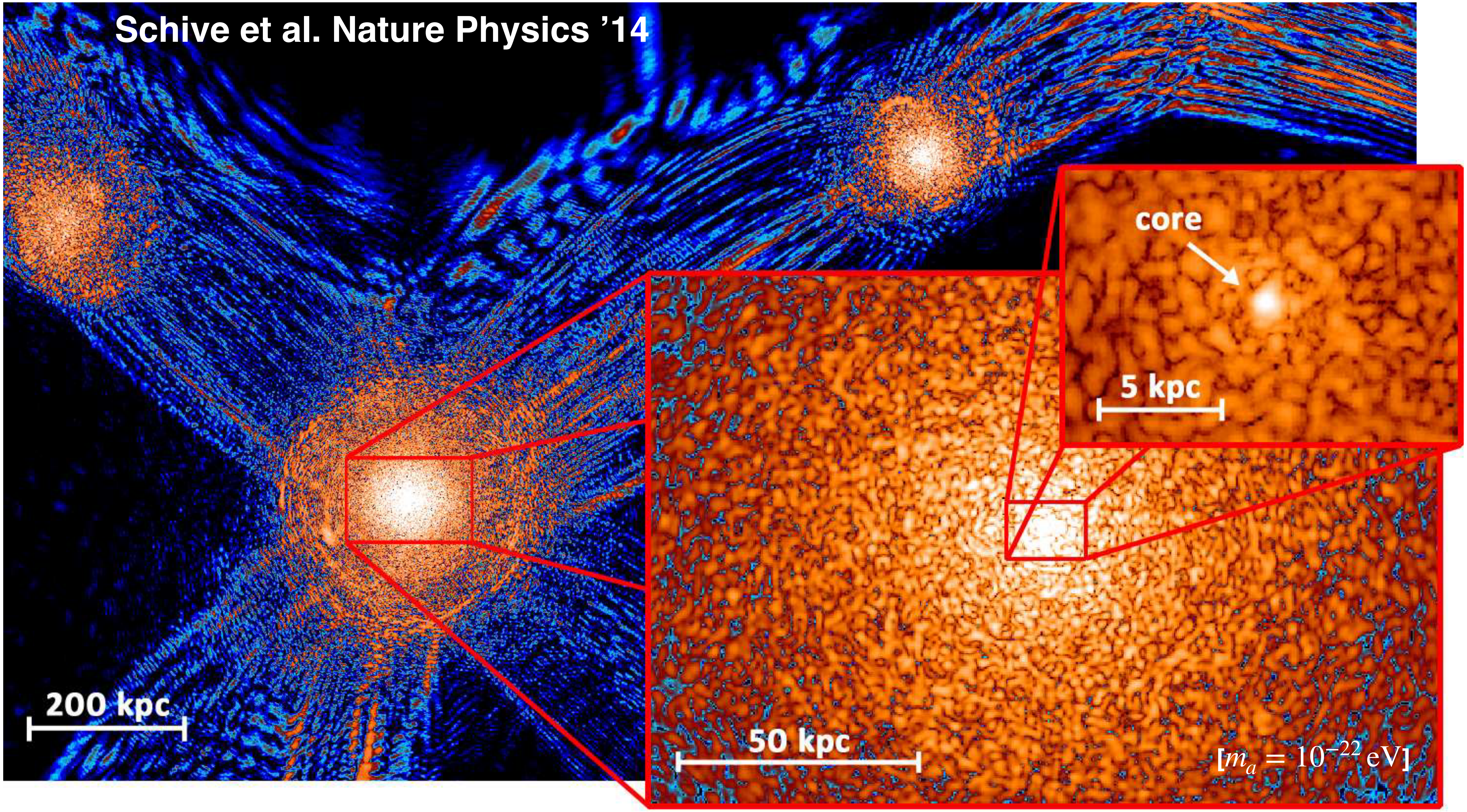
Remo Ruffini (Princeton U. and Princeton, Inst. Advanced Study), Silvano Bonazzola (Rome U.) (Feb, 1969)

Published in: *Phys.Rev.* 187 (1969) 1767-1783

DOI cite claim reference search 860 citations

# Axion Stars: Where do they form?

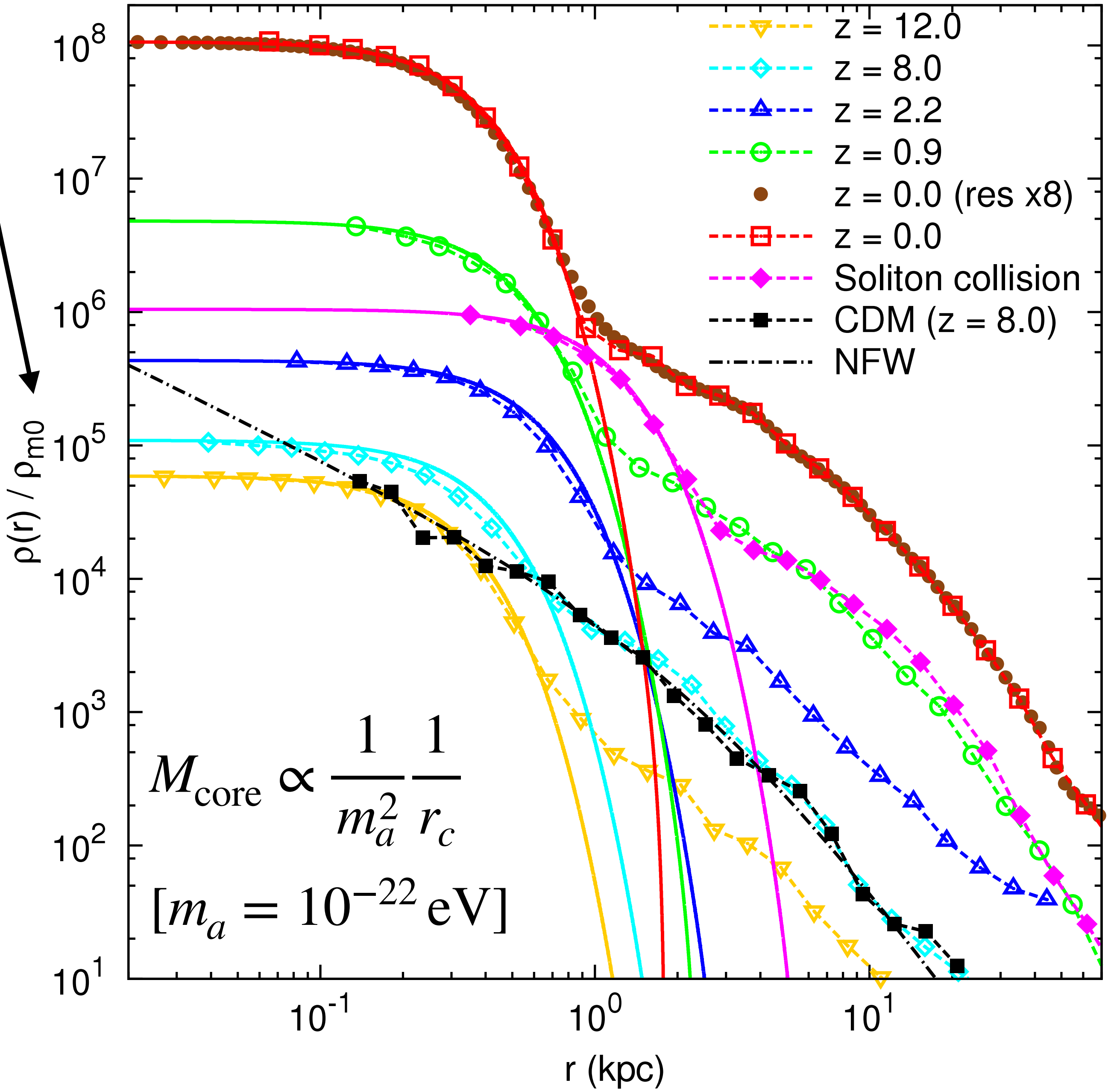
**Cosmological simulations of axion-like dark matter have demonstrated that a dense core forms at the center of every dark matter halo**



# 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 1407.7762**




**Occupation numbers are huge:**

$$\boxed{\mathcal{N} \sim n/p^3 \sim 10^{60}}$$

# Axion Star Decay: Parametric Resonance

**The classical equations of motion for the EM field in an axion background are:**

$$\frac{dA_\pm}{dt^2} + \left(k^2 \pm g_{a\gamma\gamma} k \frac{d\phi}{dt}\right) A_\pm = 0$$

**see e.g. Alonso-Álvarez et al. 1911.07885**

**for $k = m_a/2$ :** $\quad A \sim e^{\Gamma t}$ **which means exponential growth!**

**provided that:**

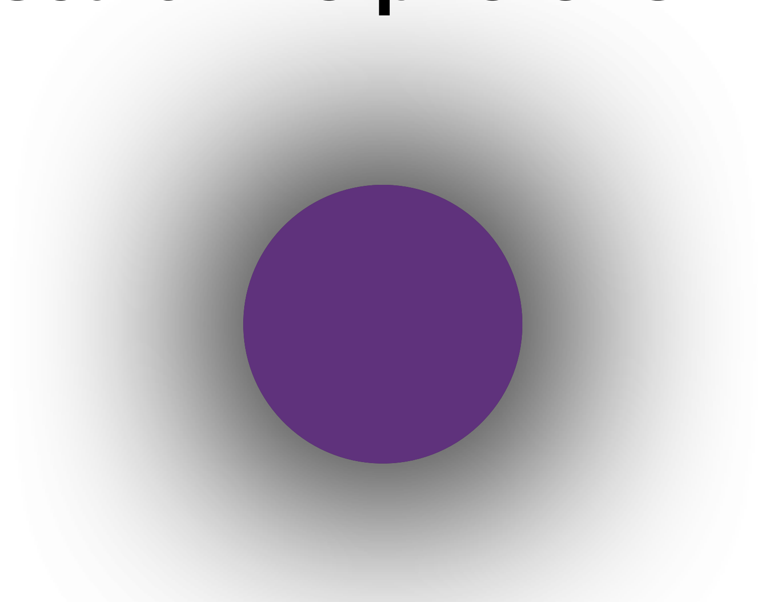
$$\Gamma \times L \simeq g_{a\gamma\gamma}\sqrt{\rho_a} \times L > 1$$

**There will be an exponential decay**

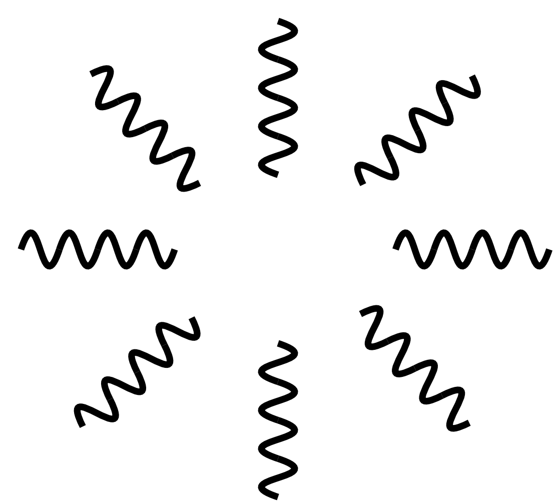
$$\boxed{M_{\rm decay} \approx 10^{-4}\, M_\odot \left(\frac{10^{-11}\,{\rm GeV}^{-1}}{g_{a\gamma\gamma}}\right)\left(\frac{10^{-13}\,{\rm eV}}{m_a}\right)}$$

**This is however not only analytical. Sophisticated numerical simulations do show that for $M_S > M_{\rm decay}$ the axion star decays on a very short timescale into photons with $E_\gamma = m_a/2$**

**Levkov, Panin & Tkachev 2004.05179**
**Amin & Mou 2009.11337**



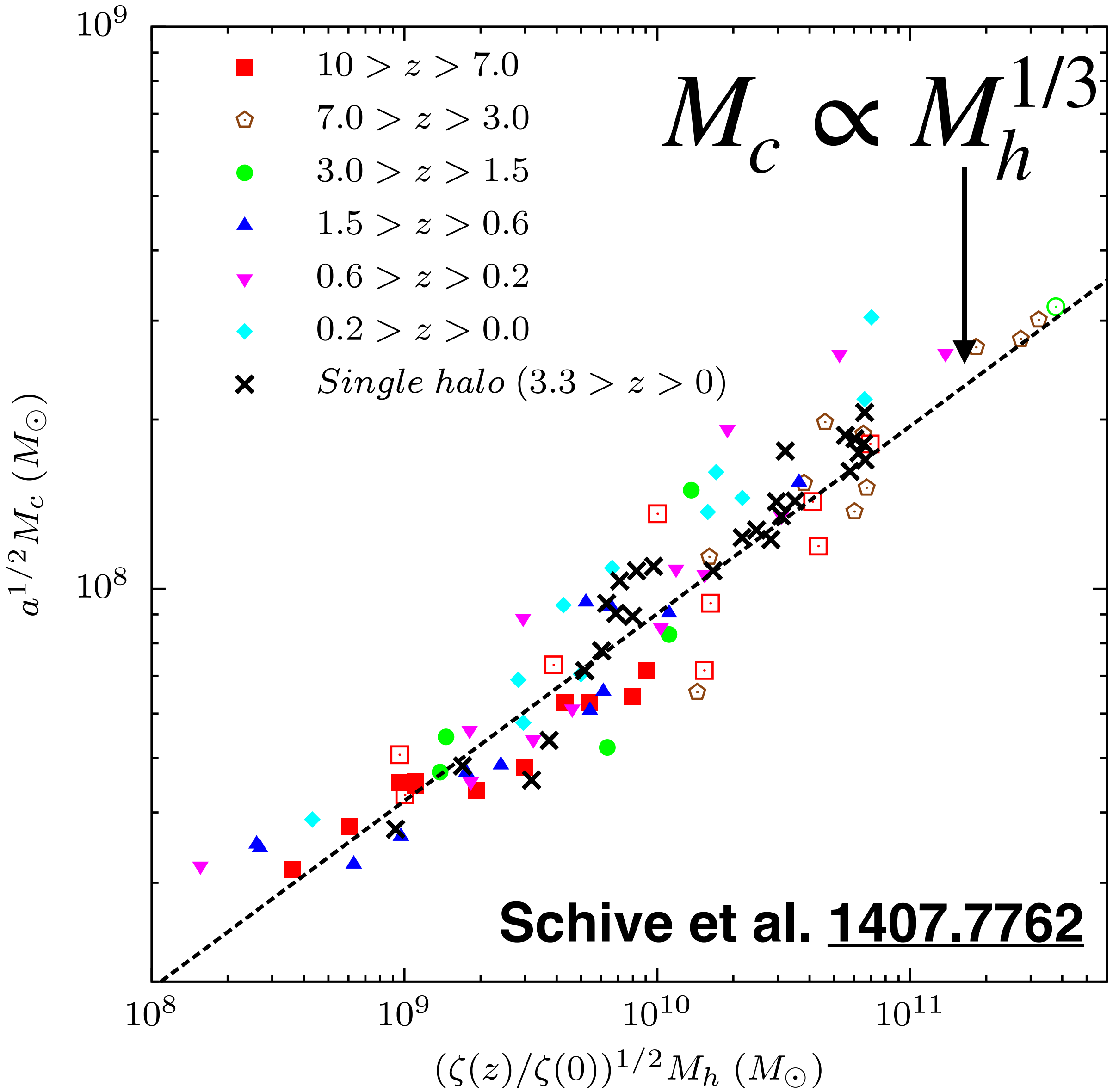
$\tau \sim \mathcal{O}(\text{day})$

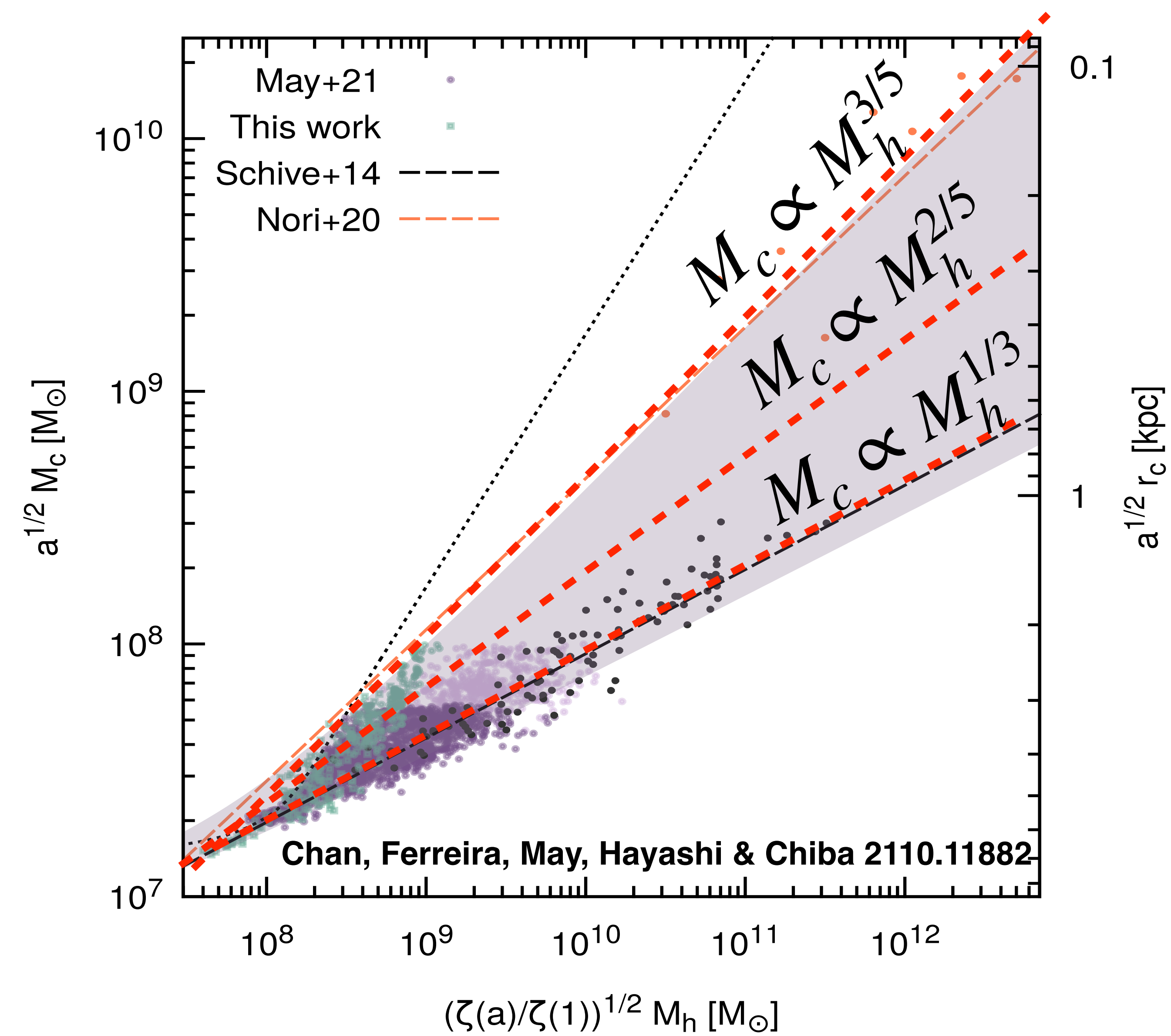


$$\boxed{E = M_s - M_{\rm decay}}$$

# 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**
**see also Zagorac, Kendall, Padmanabhan, Easther 2212.09349**

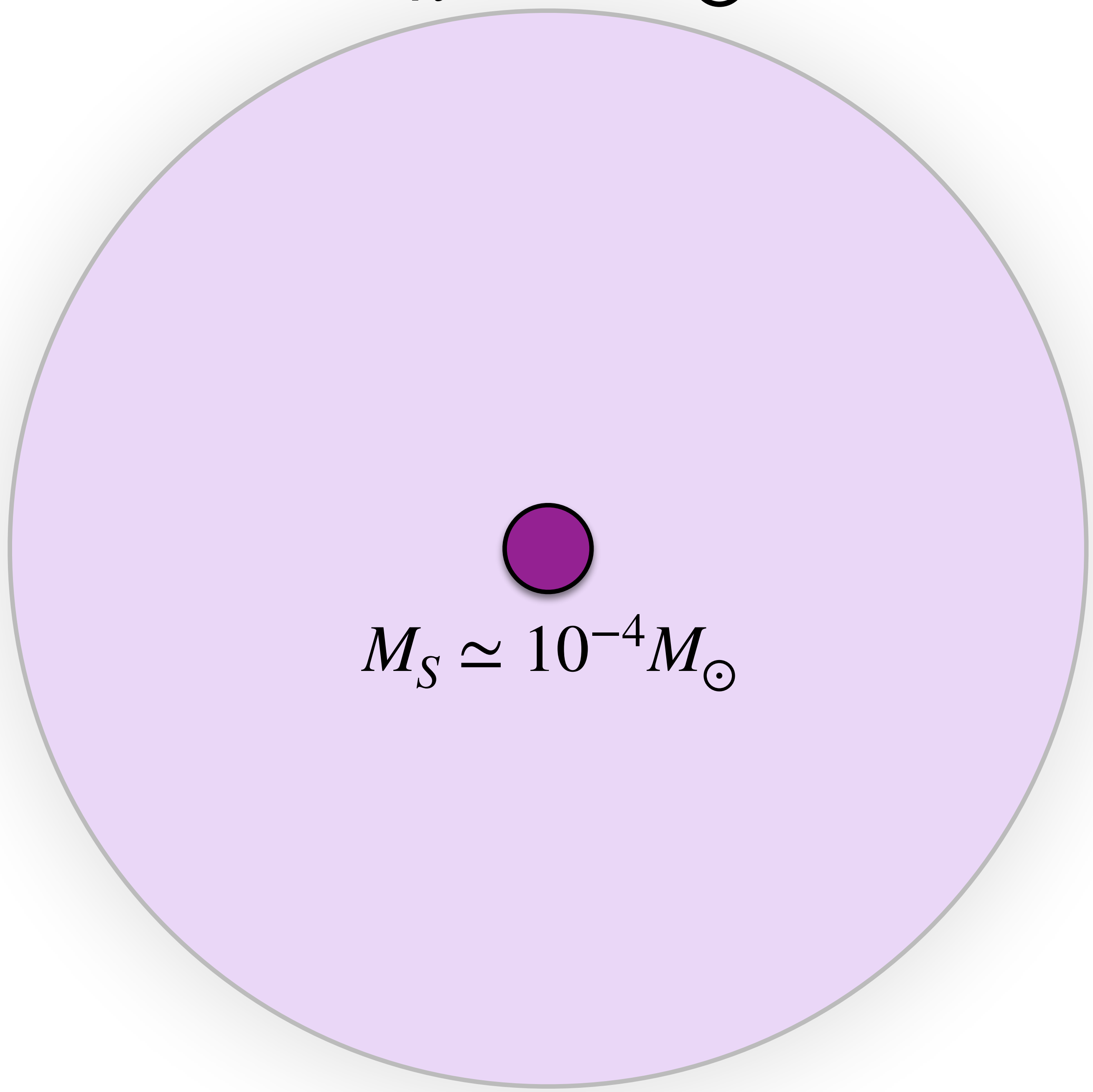
# Core-Halo Mass Relation Implication

**Schive Relation:**

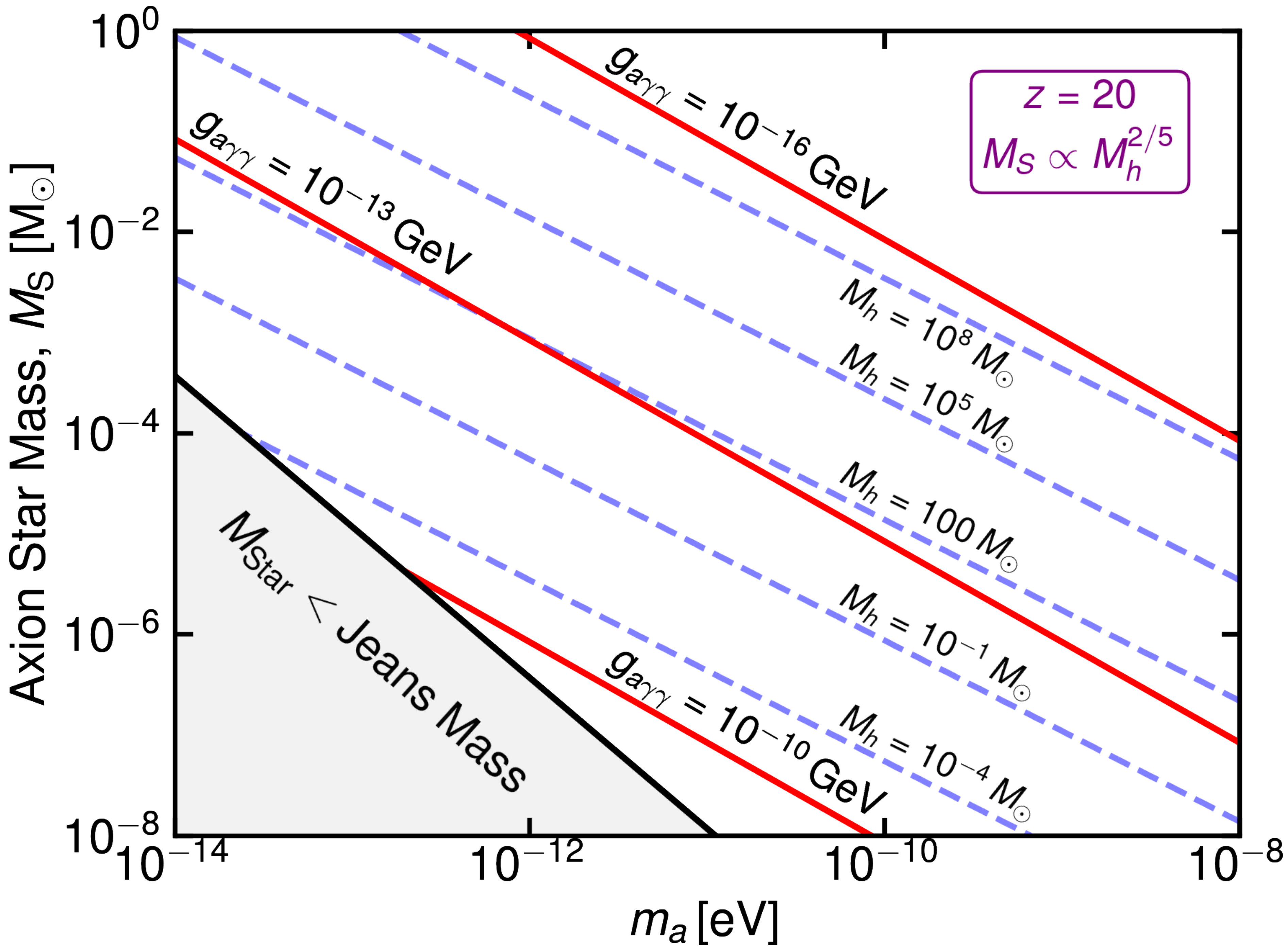
$[m_a = 10^{-13}\,\mathrm{eV}]$

$[z = 20]$

$$M_h \simeq M_\odot$$



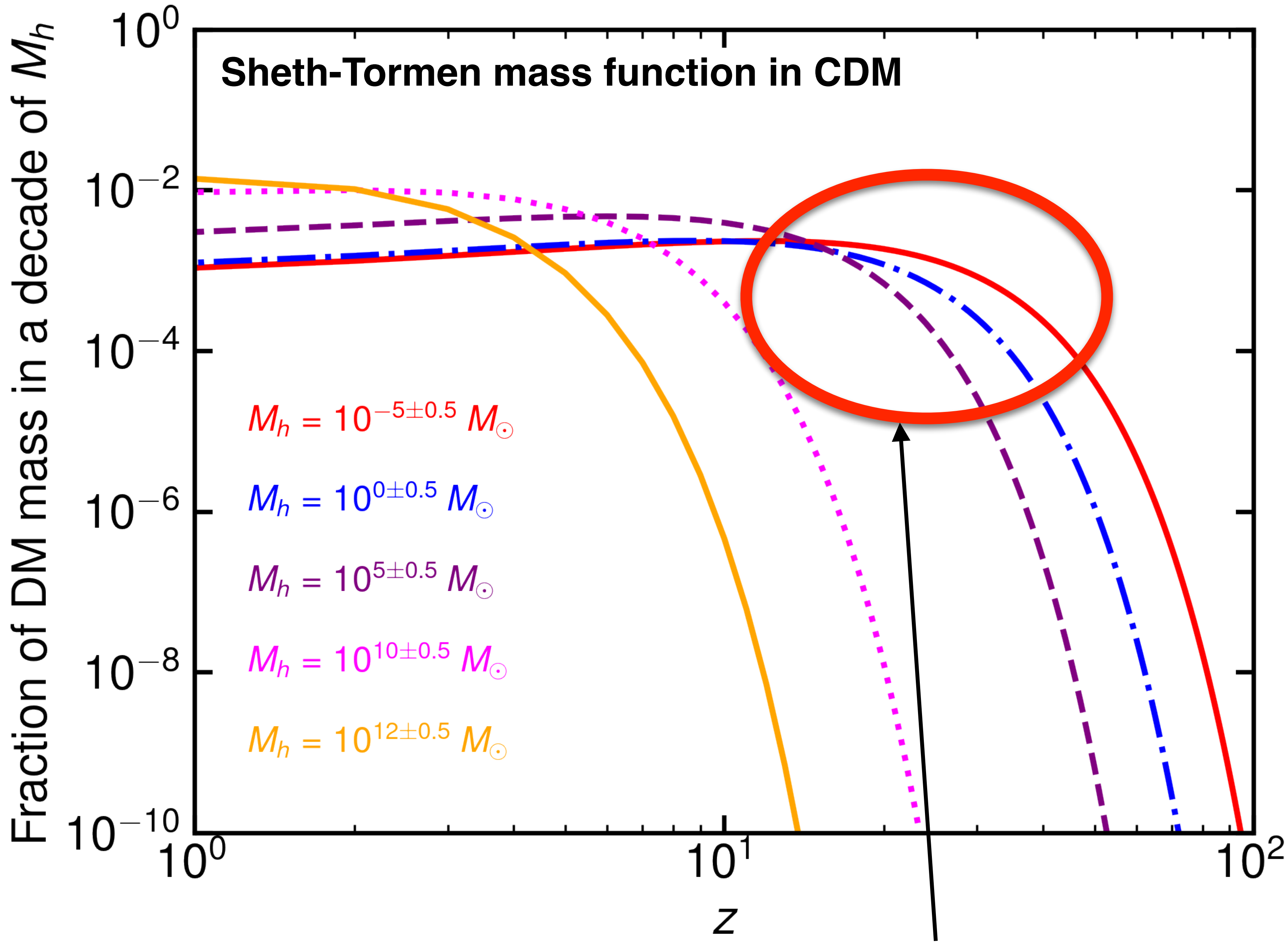
# Core-Halo Mass Relation Implication




**Parameter Space:** $M_S \sim [10^{-7} - 10^{-2}]\, M_\odot$ $\quad M_h \sim [10^{-7} - 10^{5}]\, M_\odot$

# When do Axion Stars form?

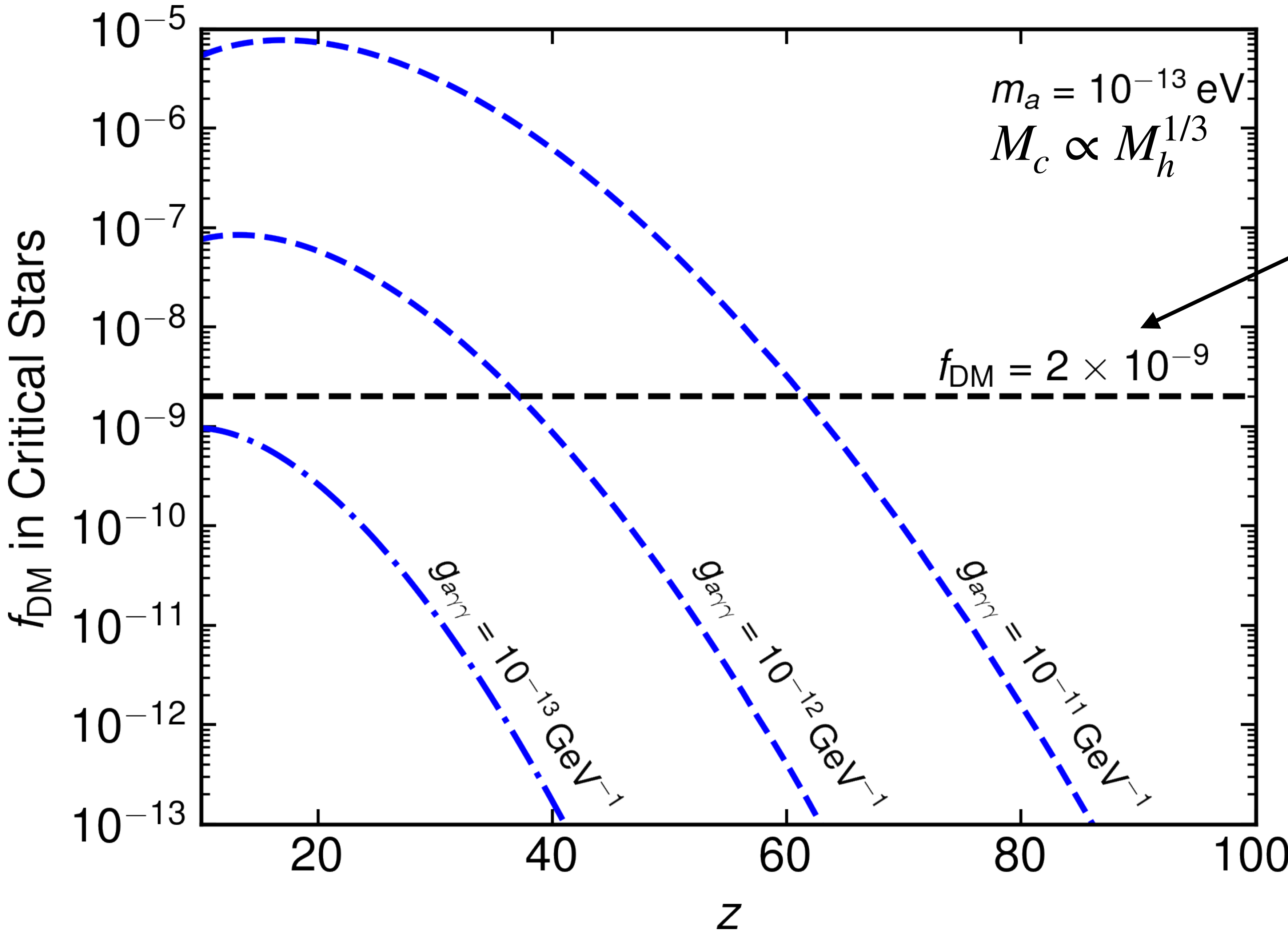
**Axion Stars form as soon as the halos that host them form. This happens hierarchically as in Cold Dark Matter cosmologies**




**Large number of Axion Stars form at redshifts:** $20 \lesssim z \lesssim 50$

# Axion Star Abundances

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



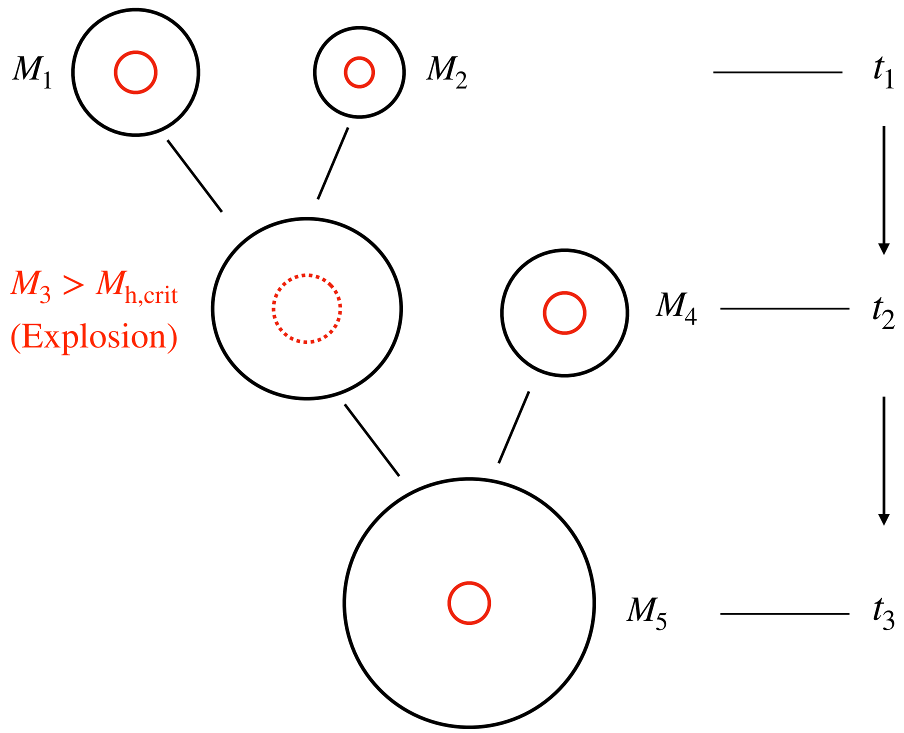

**This amount of Dark Matter transformed into heat could fully reionize the Universe!**

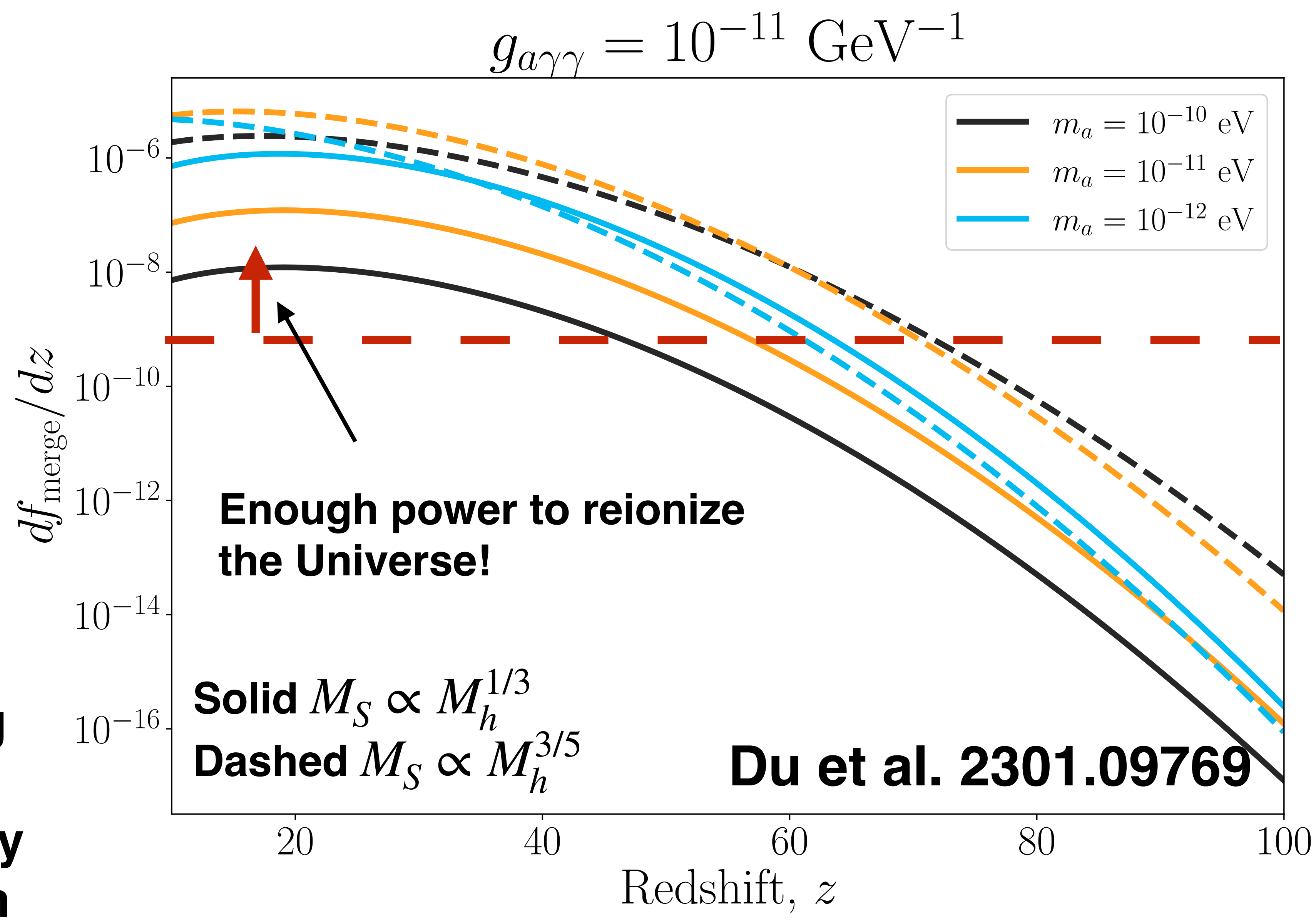
$\rho_{\rm ion} \sim 13.6\,{\rm eV} n_b \sim 10^{-9}\,\rho_{\rm DM}$

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

# Axion Stars Merging Rates

**Once axion stars with $M_S > M_{\rm decay}$ have decayed, the only way of forming stars with $M_S > M_{\rm decay}$ is via merger of two axion stars from major halo mergers. This results in a merger rate.**



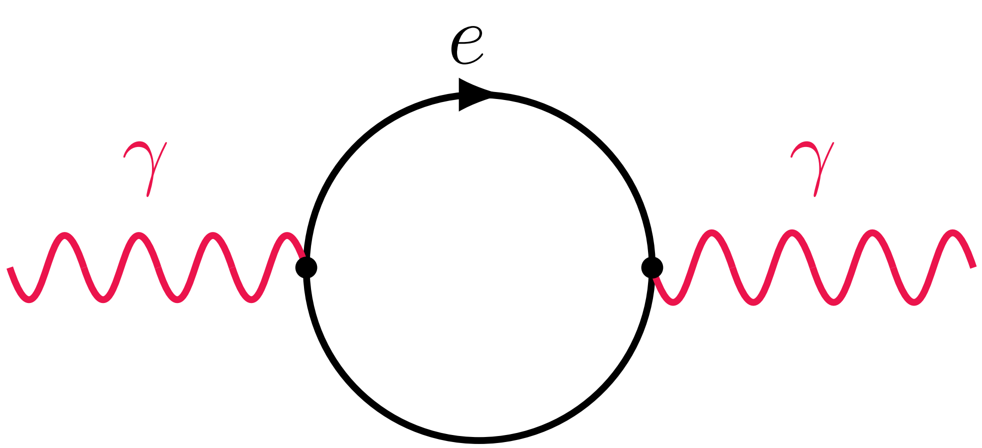




**We have calculated the merging rate using the extended Press-Schechter formalism analytically but also explicitly checking with merger trees**

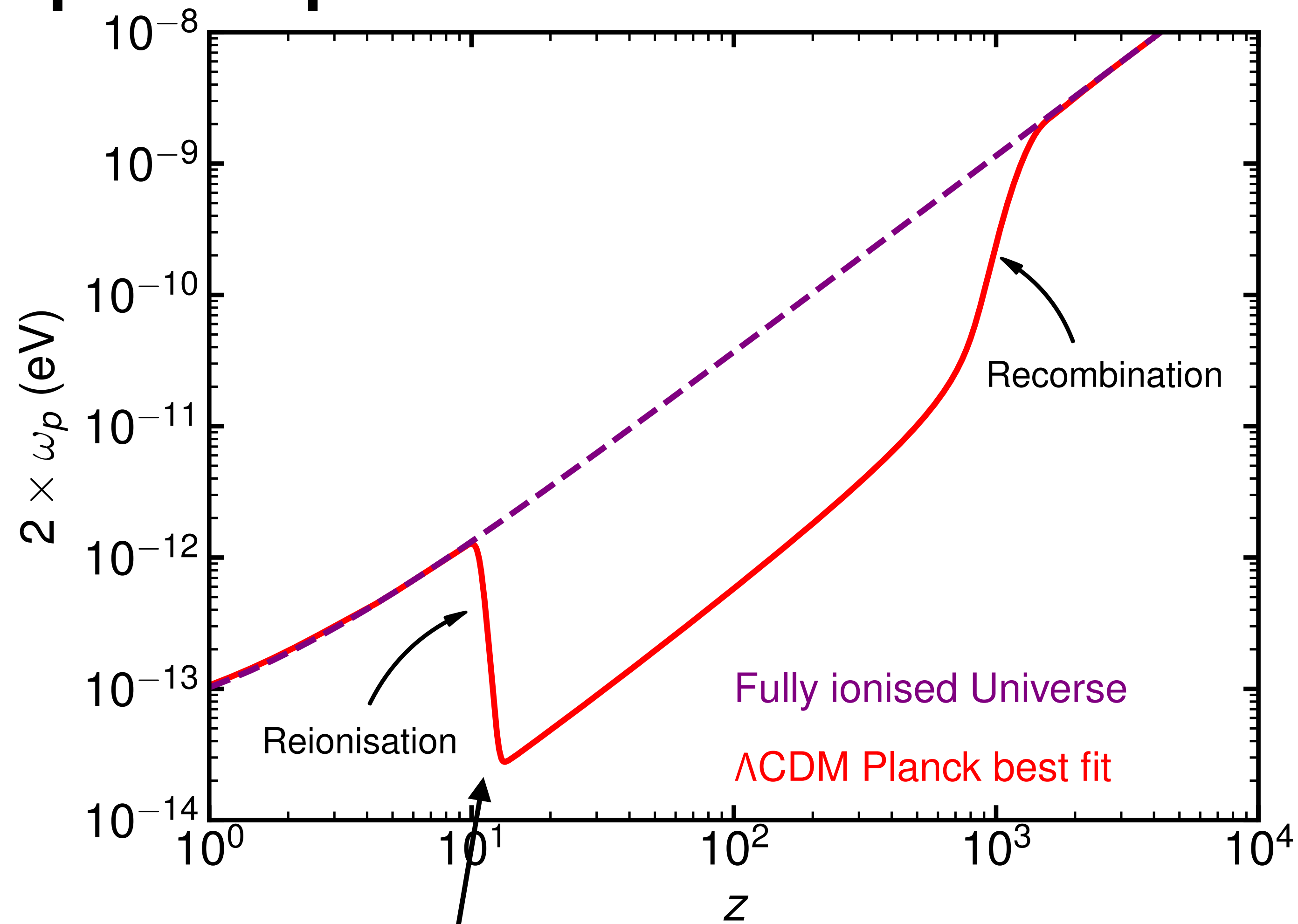
# Can these stars actually decay?

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

**The photon is not massless in the early Universe!**




$$\omega_p \equiv m_\gamma(T) \sim \sqrt{\alpha\, n_e / m_e}$$




**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:** $\boxed{m_a \gtrsim 2 \times 10^{-14}\, \mathrm{eV}}$

# Cosmological Impact

1) Axion Stars of $M > M_{\rm decay}$ will decay into photons of $E_\gamma = m_a/2$ as soon as they are formed provided that $\omega_p < m_a/2$

$[E \gtrsim 10^{-4} M_\odot]$

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 $T_b \sim 1\,\mathrm{eV}$ (which roughly corresponds to $f_{\rm DM}^{\rm decay} \sim 10^{-9}$ ) thanks to collisional ionization processes : $e + H \to e + e + p$

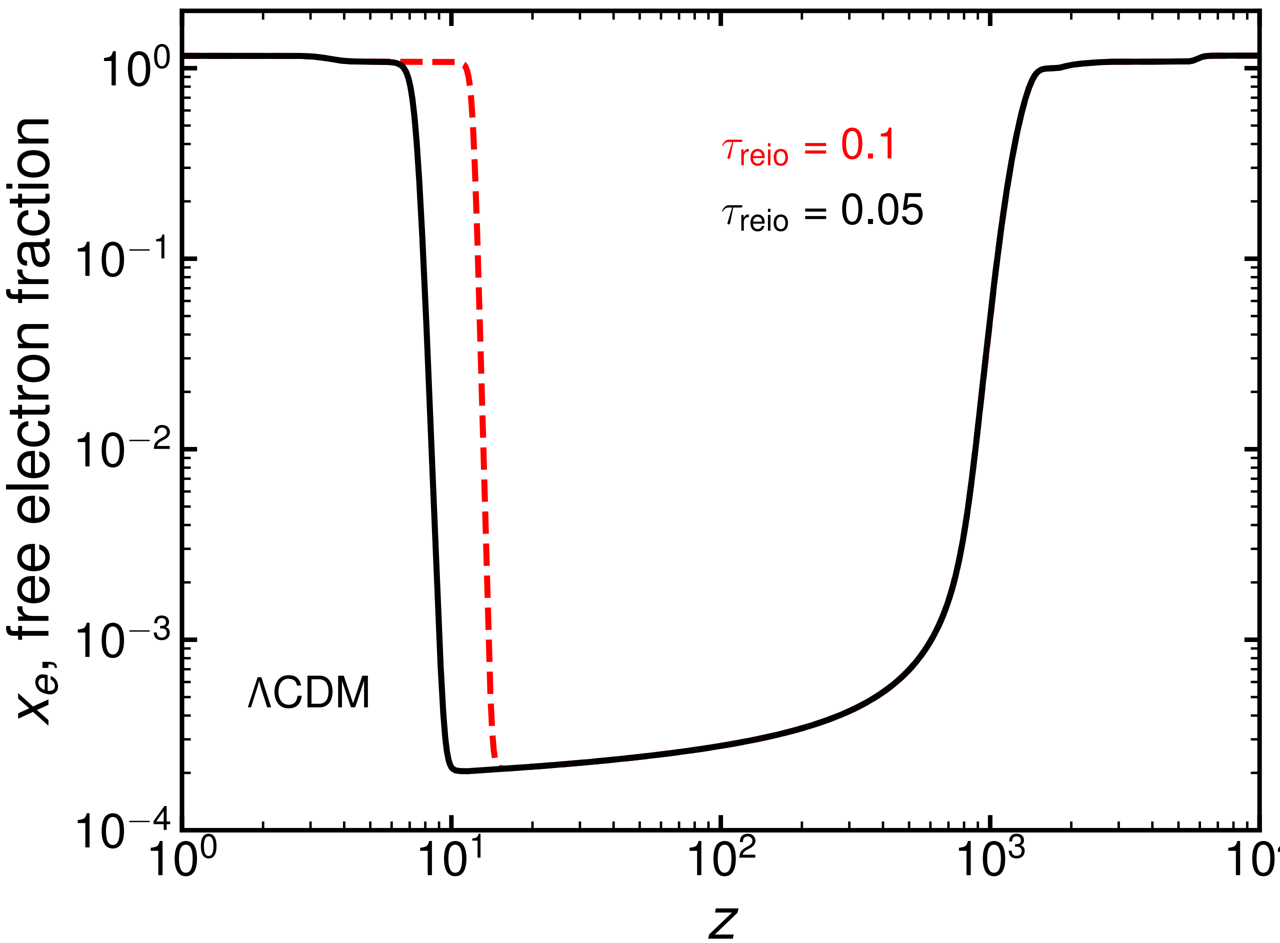
**This allows us to set constrains on $g_{a\gamma\gamma}$ for certain axion-like DM models**

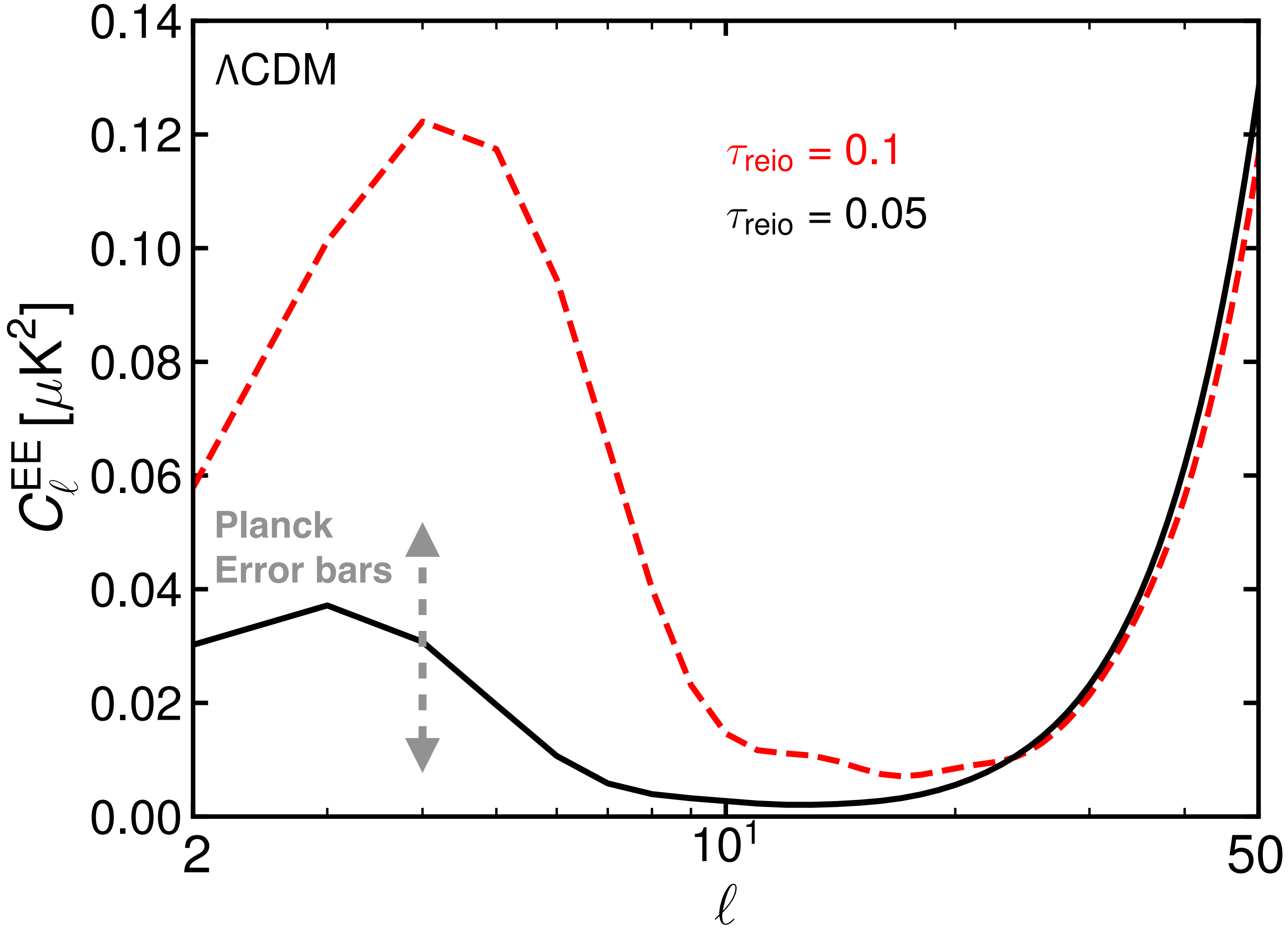
# Planck constraints on reionization

**The CMB is sensitive to the free electron fraction in the Universe:**

**More precisely, to the Thompson optical depth:** $\tau \equiv \int n_e \sigma_T \, dt'$ **Effects:** $C_\ell \propto A_s \times e^{-2\tau_{\rm reio}}$, $C_\ell^{\rm EE}$ at $\ell \lesssim 50$

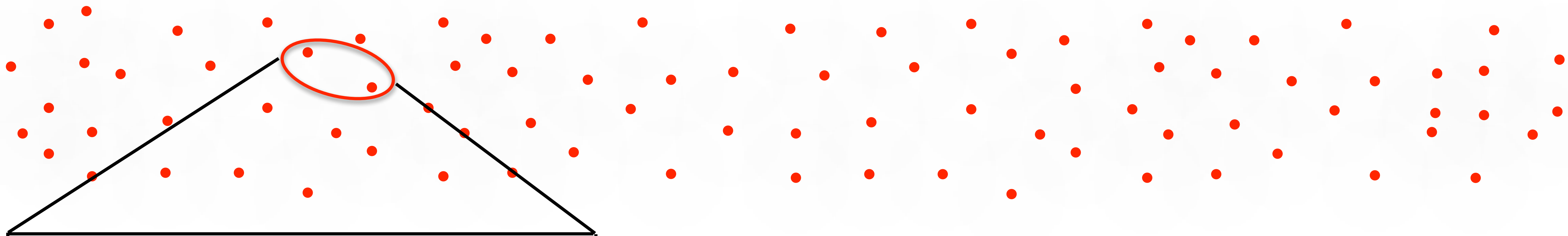
**Planck Collaboration:** $\boxed{\tau = 0.054 \pm 0.007}$ **1605.03507** **1807.06209**



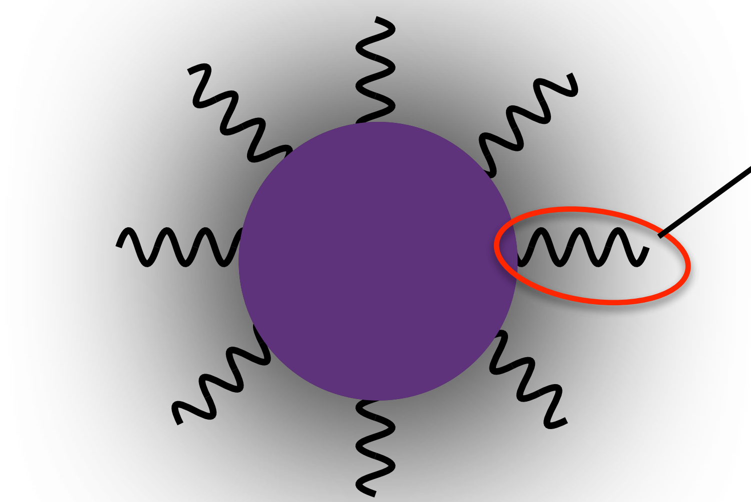



# Summary

**Critical Axion stars** **formed by mergers and hierarchical structure formation** $z \lesssim 50$



**Axion Star Explosion into photons**

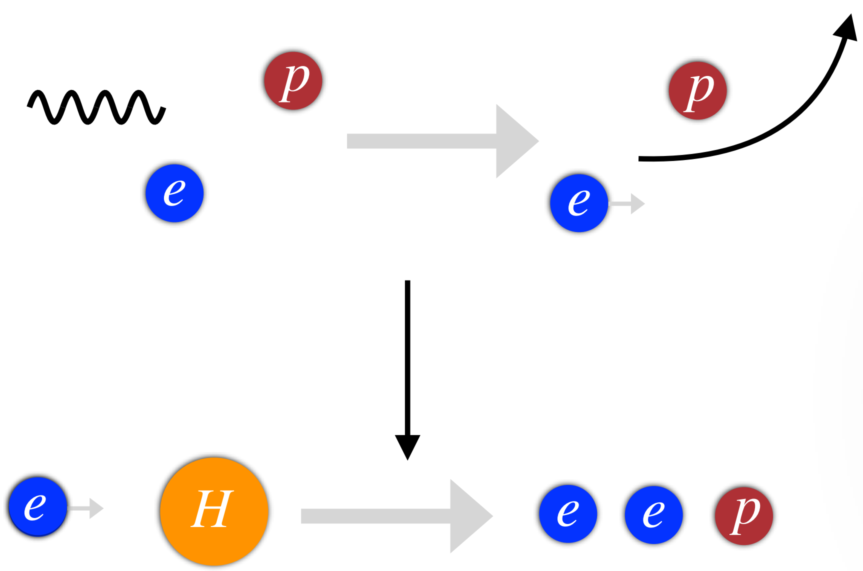


$$E_\gamma = m_a/2$$

$$\tau_{\rm decay} \sim \mathcal{O}(\text{day})$$

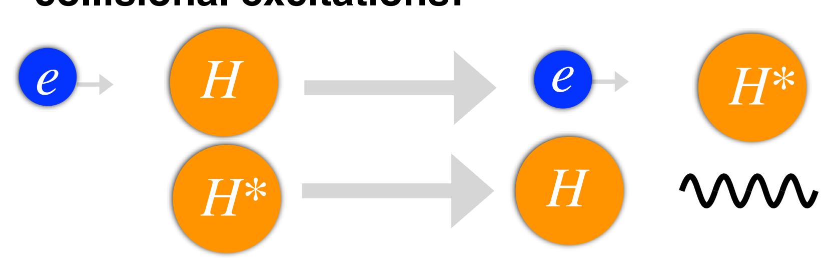
$$E \sim 10^{-4}\,M_\odot$$

**Photons absorbed into heat**




**collisional ionizations cause reionization once** $T_b \gtrsim \text{eV}$

**One should consider also cooling due to collisional excitations:**

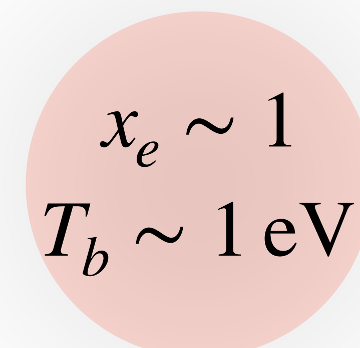



**Photon absorption Length**

**Large (L > kpc):**

$m_a > 5 \times 10^{-13}\,\text{eV}$

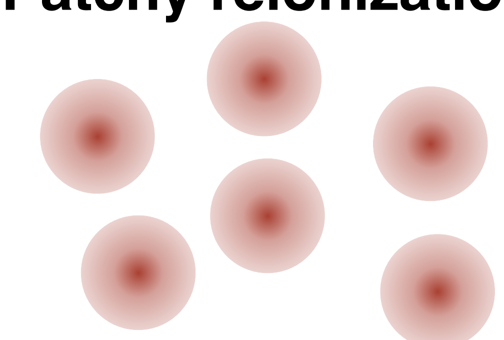
**Smooth reionizaiton**




**Short (L < kpc):**

$m_a < 5 \times 10^{-13}\,\text{eV}$

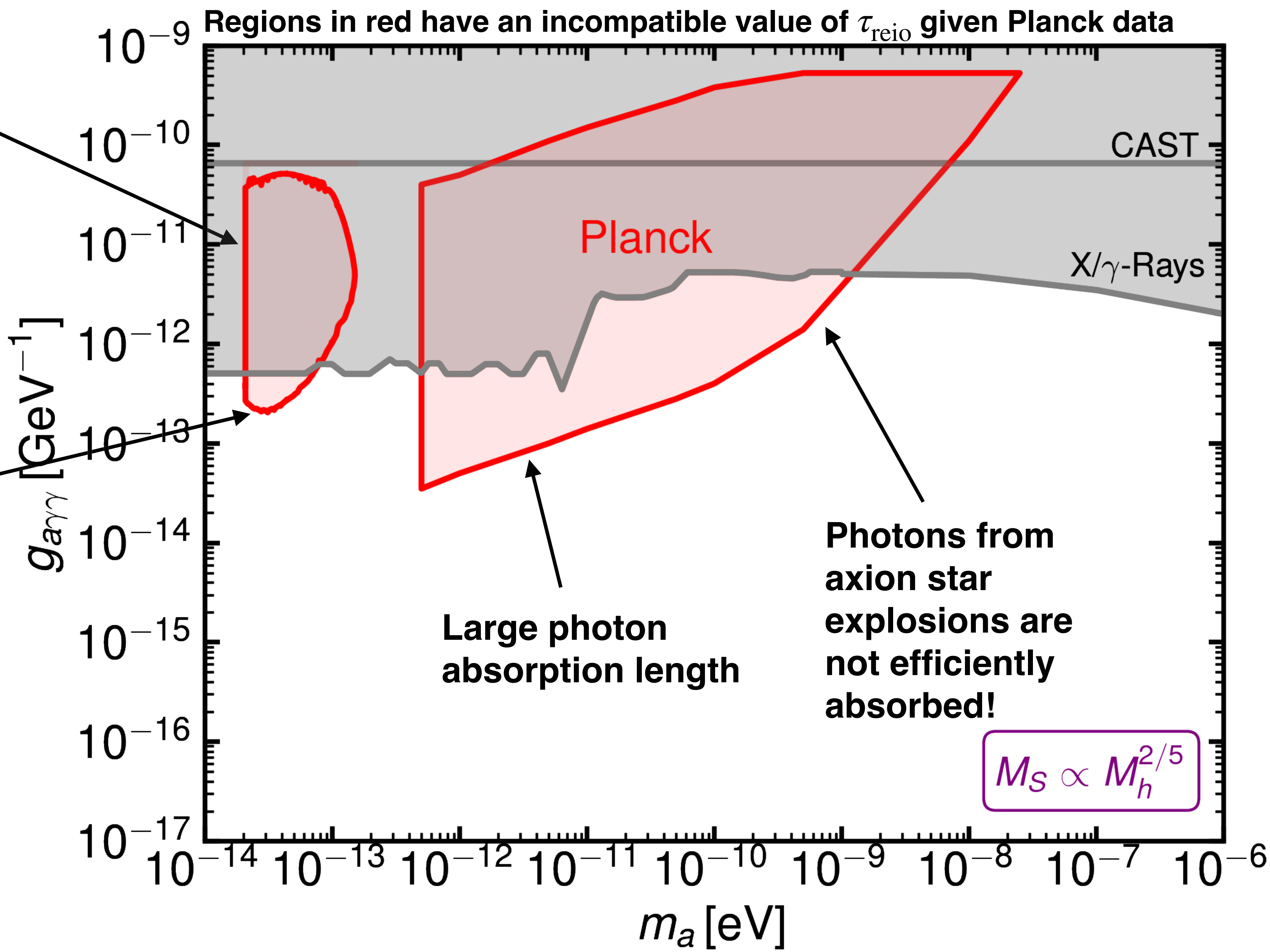
**Patchy reionization**



# Resulting Constraints

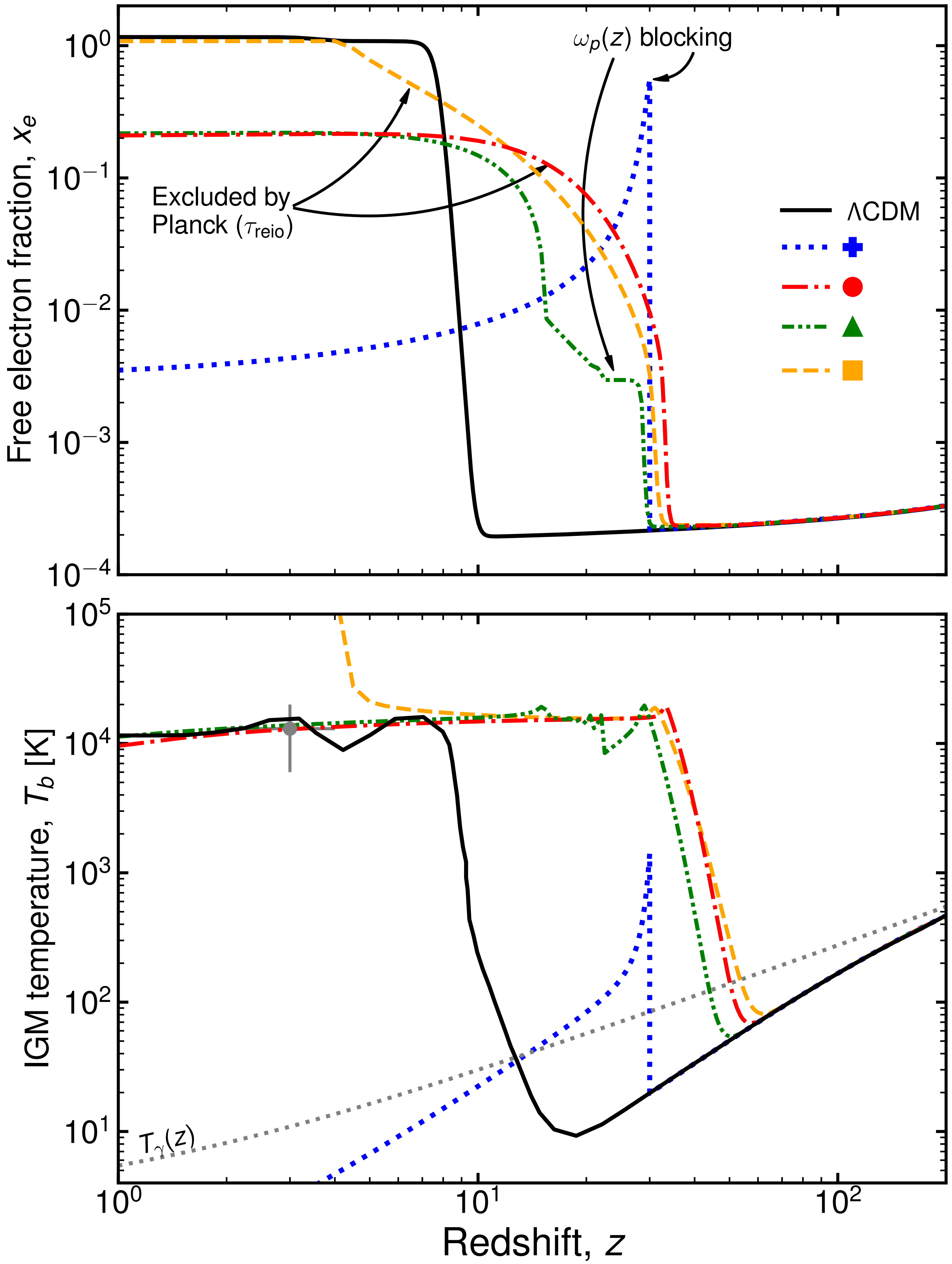
**Minimum mass that can be constrained due to kinematics**

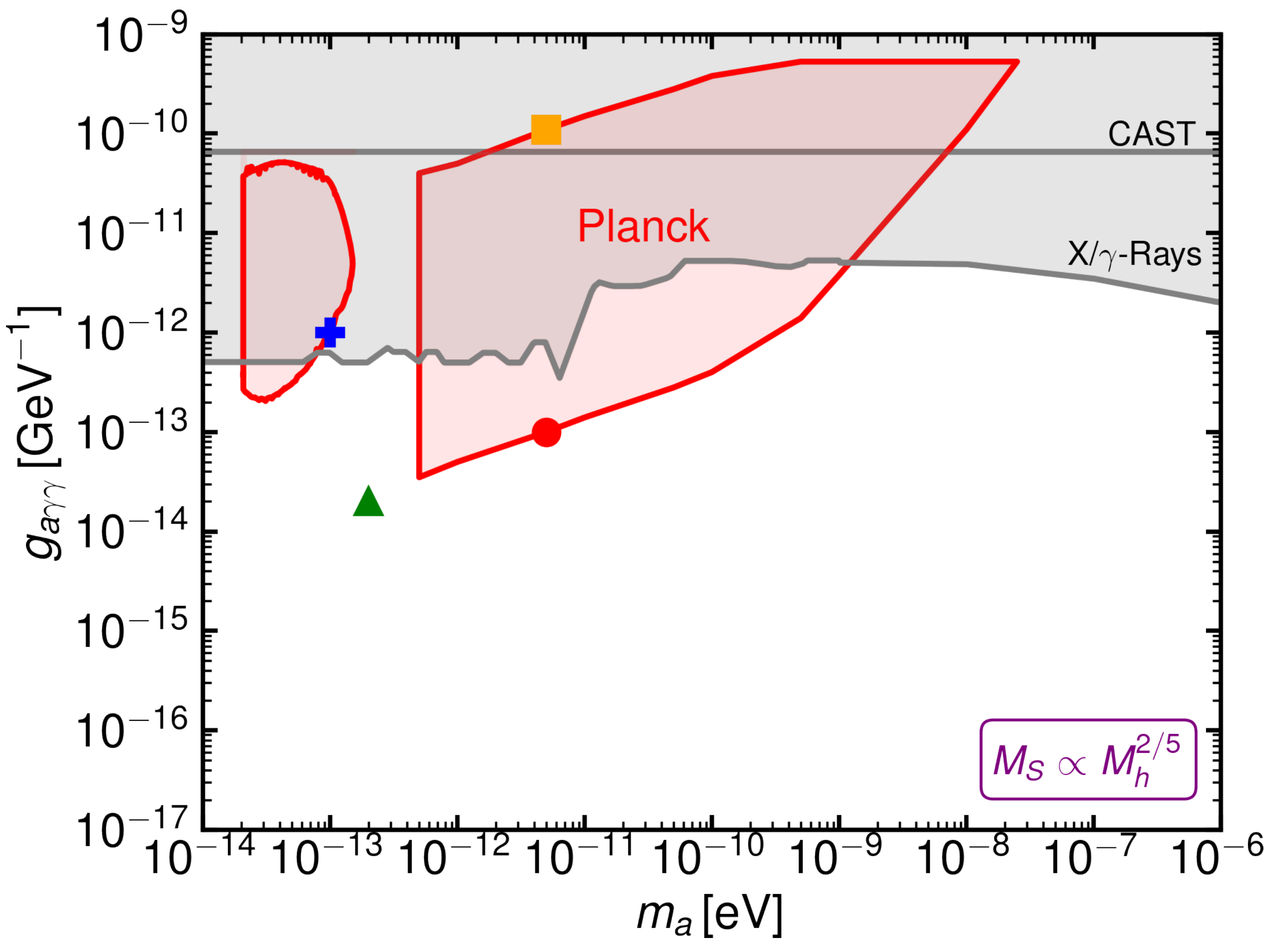
$m_a > 2m_\gamma(z)$




**Energy injections absorbed on very small scales**

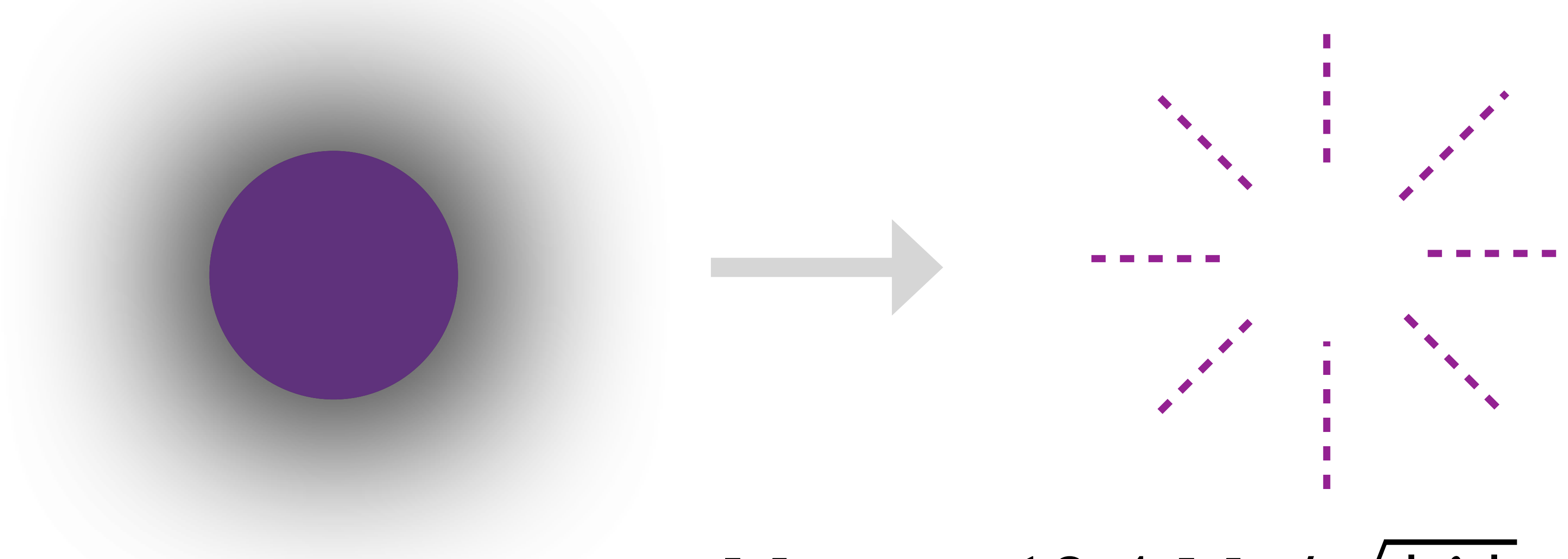
# Effects on xe and Tb



# 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 Bosenova**



**see Levkov, Panin & Tkachev [1609.03611] also Eby et al. [1512.01709] [1608.06911]**

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

**Axions with a cosine potential imply:**

$$\frac{M_{\rm decay}(a \to \gamma\gamma)}{M_{\rm Nova}(3a \to a)} = 600\, \frac{g_{a\gamma\gamma}}{\alpha/(2\pi f_a)} \frac{\sqrt{-\lambda}}{m_a/f_a}$$

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

**see e.g.:** **Farina, Pappadopulo, Rompineve & Tesi 1611.09855**
**Sokolov & Ringwald, 2205.02605**
**di Luzio, Gavela, Quilez & Ringwald 2102.00012 & 2102.01082**

# Summary and Conclusions

- **In ALP cosmologies 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 provide the machinery to calculate it**

  https://github.com/Xiaolong-Du/Merger_Rate_of_Axion_Stars

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

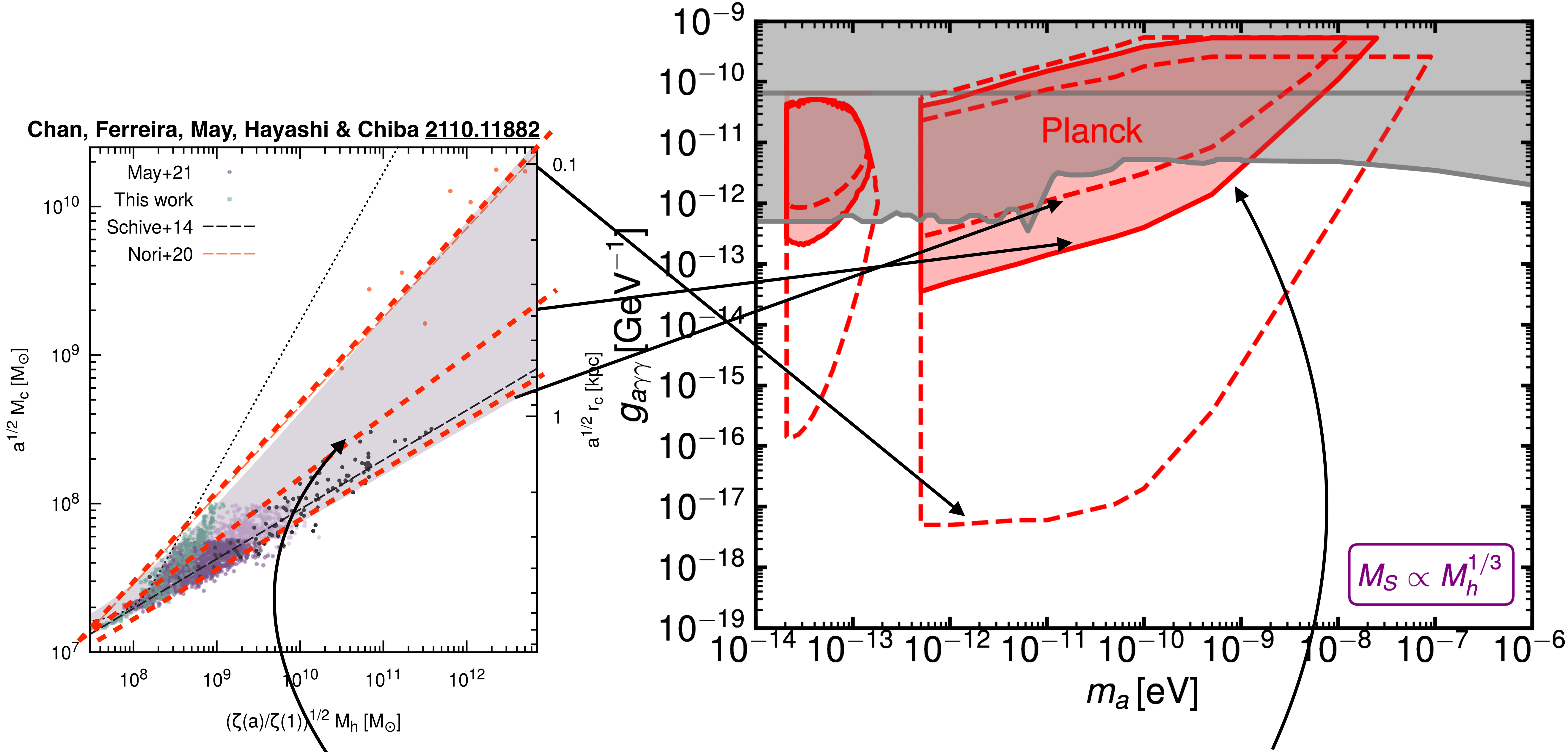
- **These axion stars are formed during the dark ages and their decays into radio photons can lead to heating and subsequent reionization which is strongly constrained by Planck CMB observations as long as $f_{\rm DM} \gtrsim 10^{-9}$ of the DM is converted into heat**

  **The underlying source of the bounds is the very same as for annihilating WIMP DM and heavy decaying DM**

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

# Outlook: Core-Halo Mass Relation

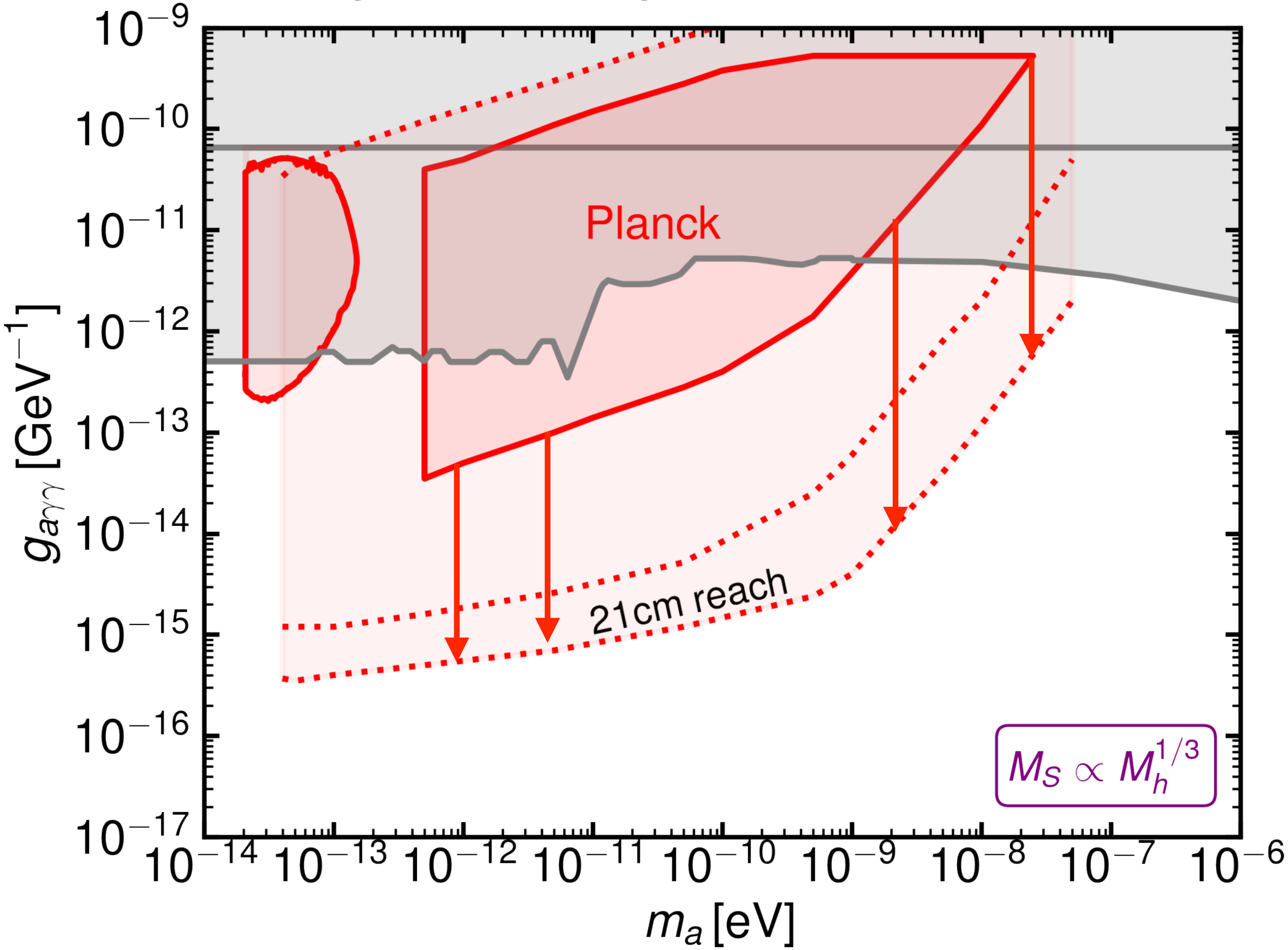
**Our constraints are strongly dependent upon what is the mass of an axion star on a given halo. This is an open issue and further numerical analyses are required in order to draw definite statements.**




**However, we have studied the effect of diversity and find that the middle case is the one realizing it better!**

# Outlook: 21 cm Cosmology

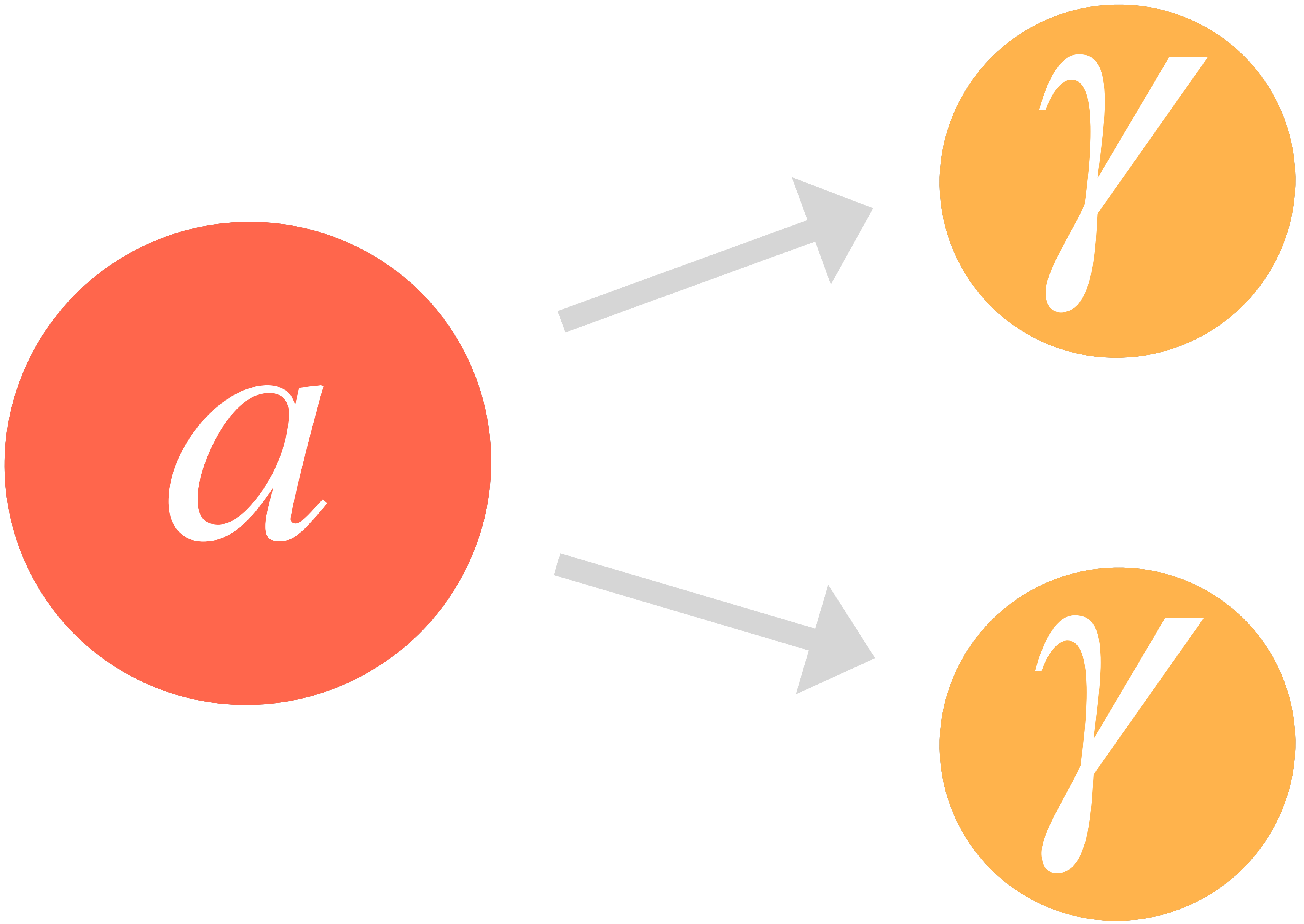
**The next generation of experiments targeting the 21 cm line of neutral Hydrogen are expected to test couplings that are two orders of magnitude smaller than those currently excluded by Planck**




**The reason is simply because 21cm measurements are directly sensitive to the thermal state of the IGM gas!**

# Thank You

## Questions, Comments and Criticism are most welcome

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