# Axion Star Explosions and the Reionization History of the Universe

**Miguel Escudero Abenza**
miguel.escudero@cern.ch

**based on work with:**

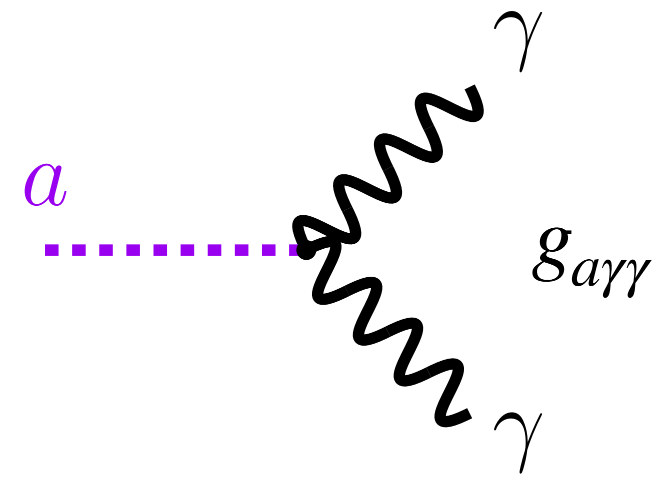
**Diego Blas, Xiaolong Du, Malcolm Fairbairn, Doddy Marsh & Charis Pooni**

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

**Axions ++**
**Annecy**
**27-09-2023**

# 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:** $$\tau_a = \frac{64\pi}{m_a^3\, g_{a\gamma\gamma}^2} \gg t_U \quad \textbf{for } m_a < 1\,\mathrm{eV}$$

- **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:

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

**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?

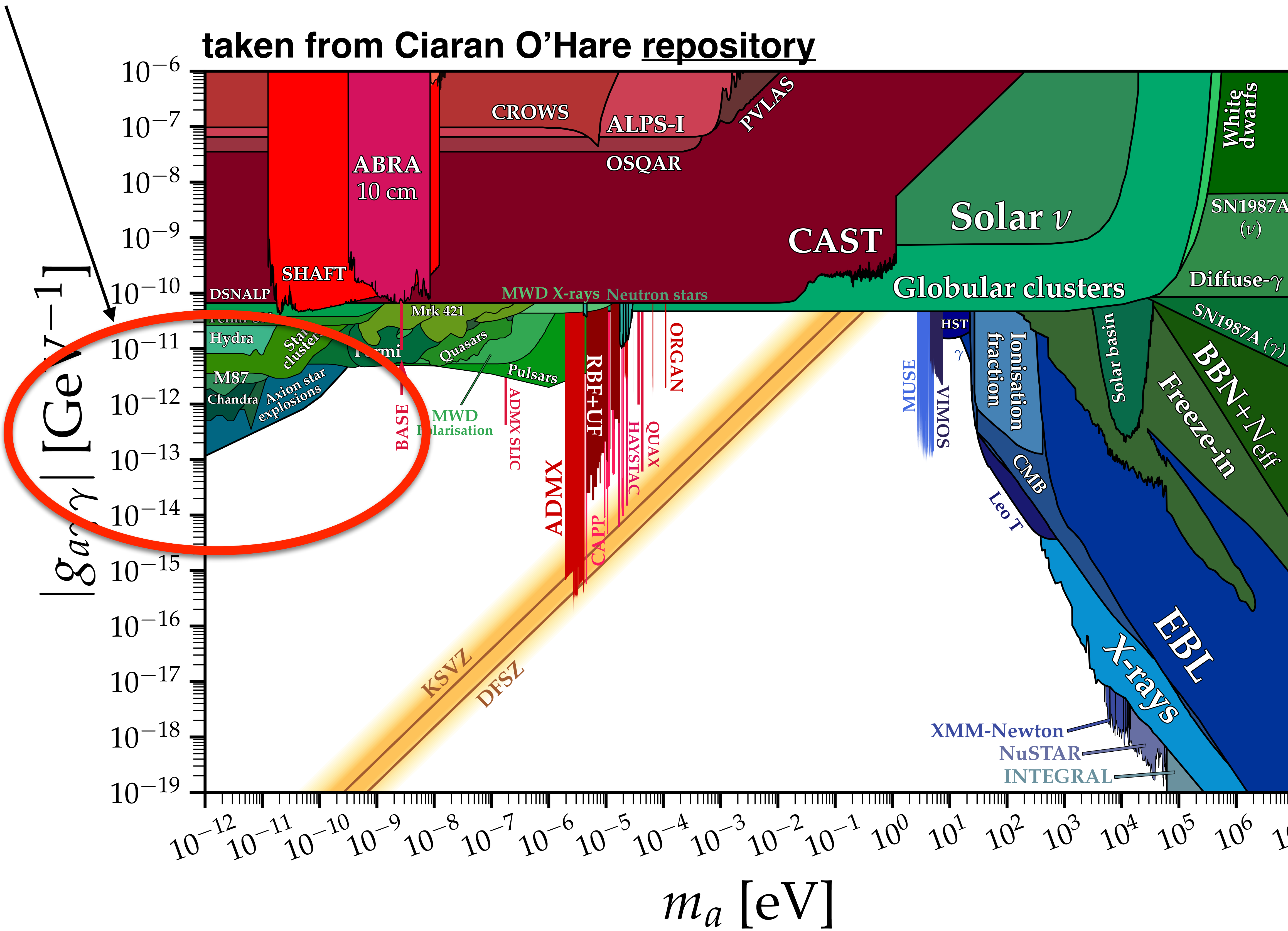
**Axion Stars!**

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



# Outline

**1) Axion Stars**

**2) Cosmological Implications of Axion Star Decays**

**3) Summary and Outlook**

# Axion Stars: What are they?

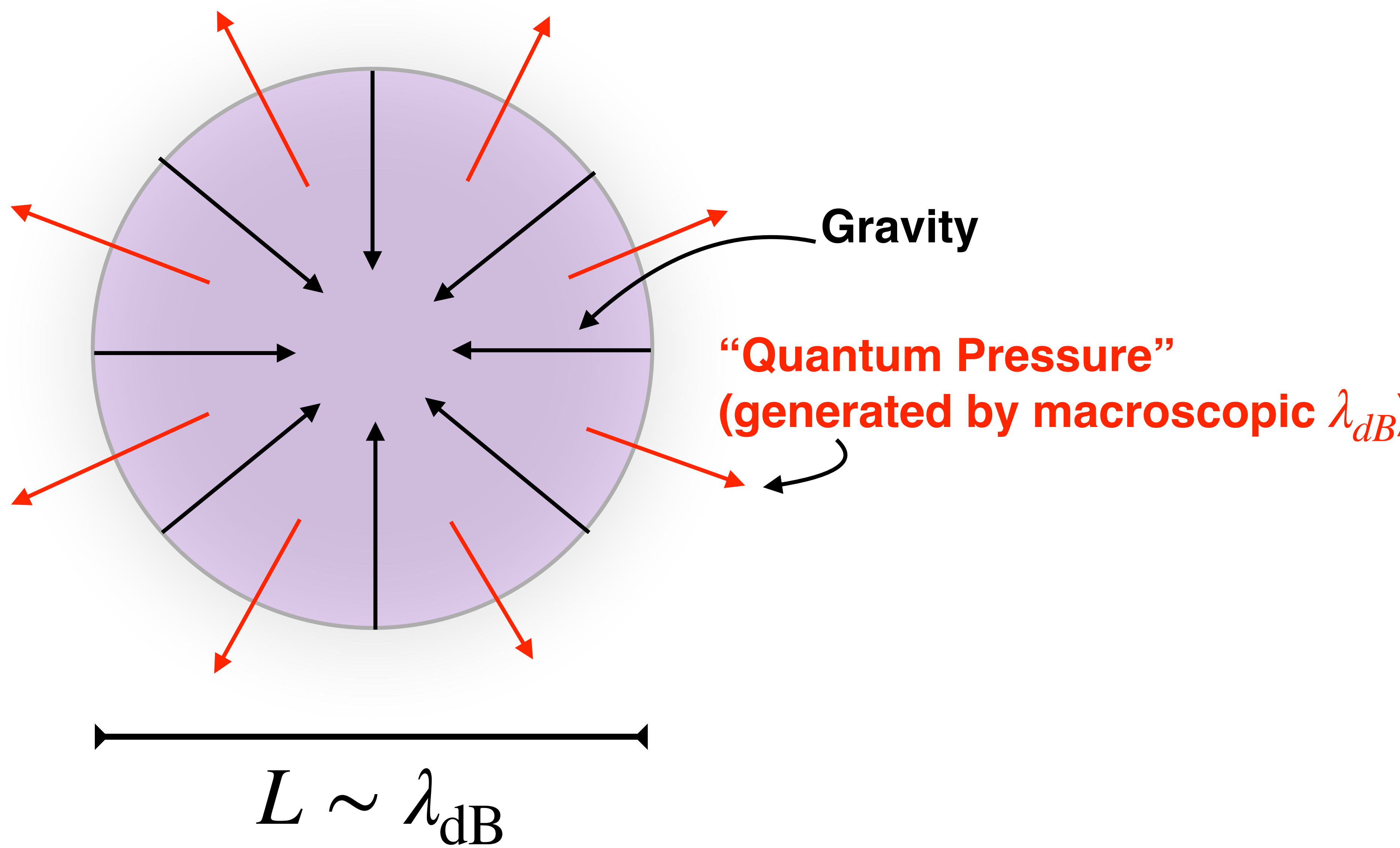
Systems of selfgravitating particles in general relativity and the concept of an equation of state #1

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

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

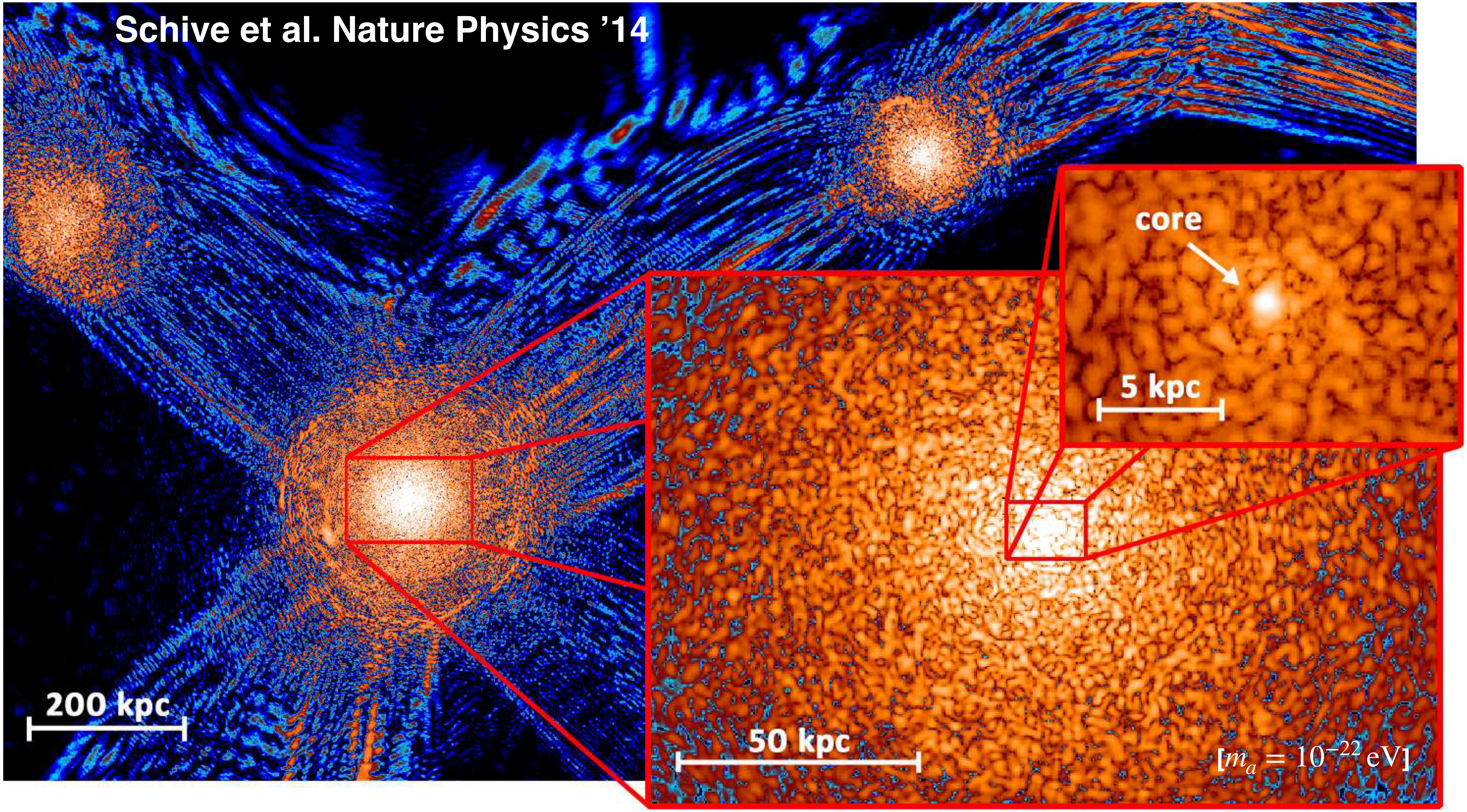


**Axion Star:**



# Axion Stars: Where do they form?

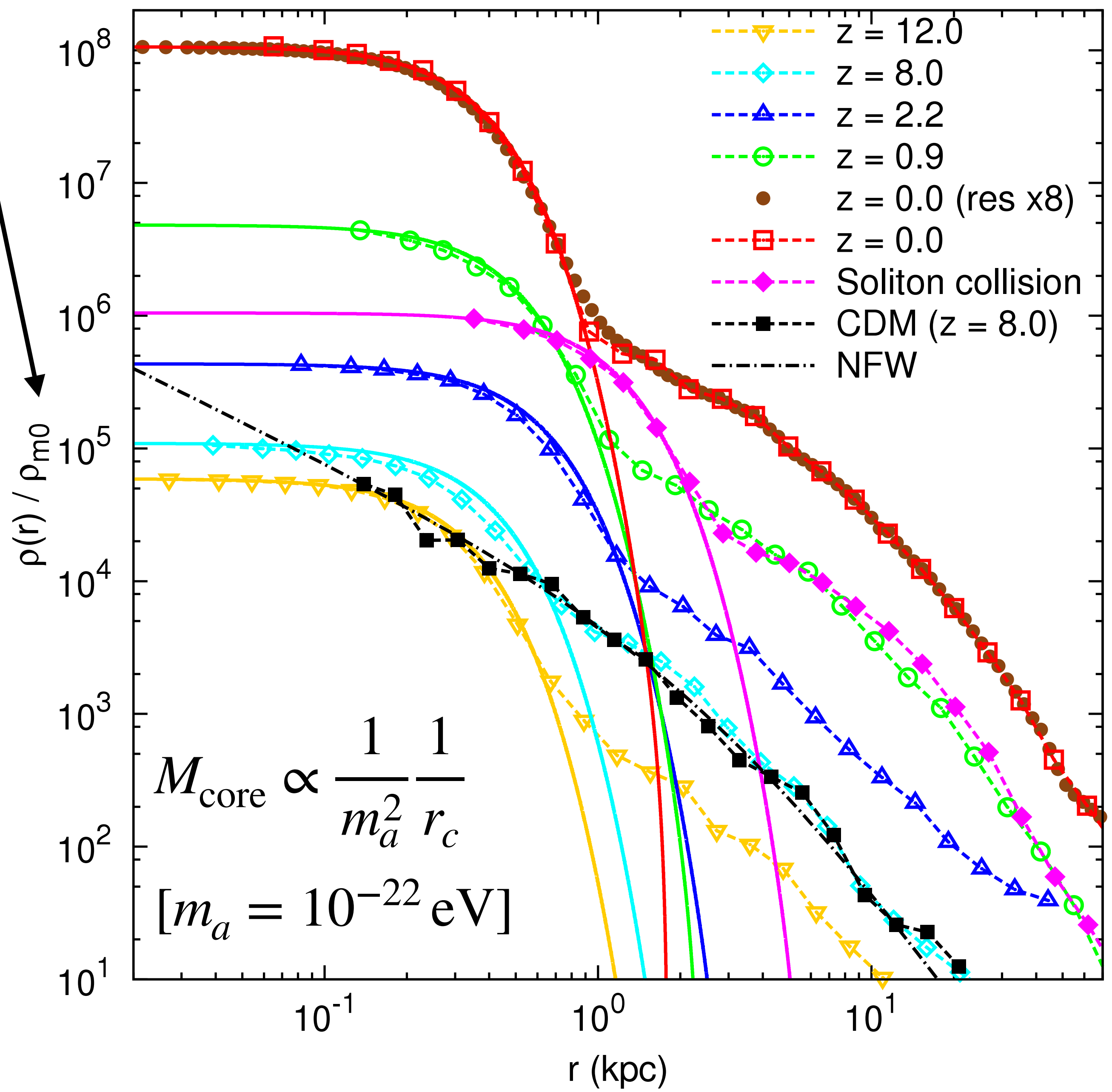
**Cosmological simulations of axion-like dark matter have demonstrated that a dense core forms at the center of every dark matter halo**



# 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:**

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

# 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:**

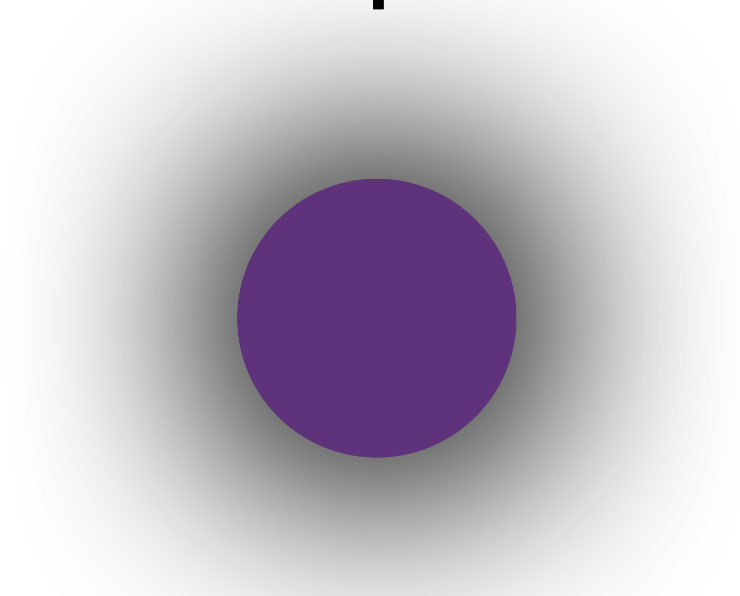
$$\Gamma \times L \simeq g_{a\gamma\gamma}\sqrt{\rho_a} \times L > 1$$

**There will be an exponential decay**

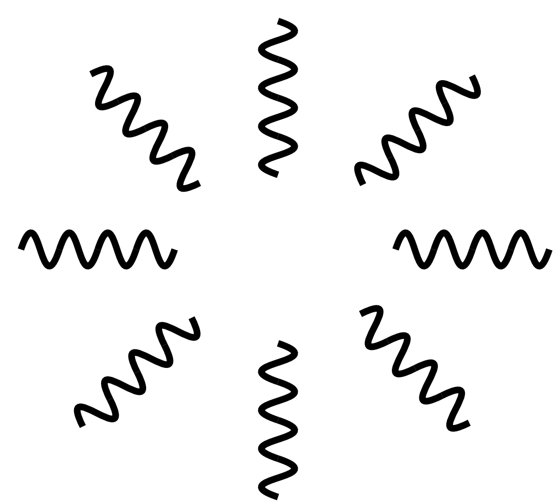
$$M_{\rm decay} \approx 10^{-4}\, M_\odot \left(\frac{10^{-11}\,\mathrm{GeV}^{-1}}{g_{a\gamma\gamma}}\right)\left(\frac{10^{-13}\,\mathrm{eV}}{m_a}\right)$$

**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**



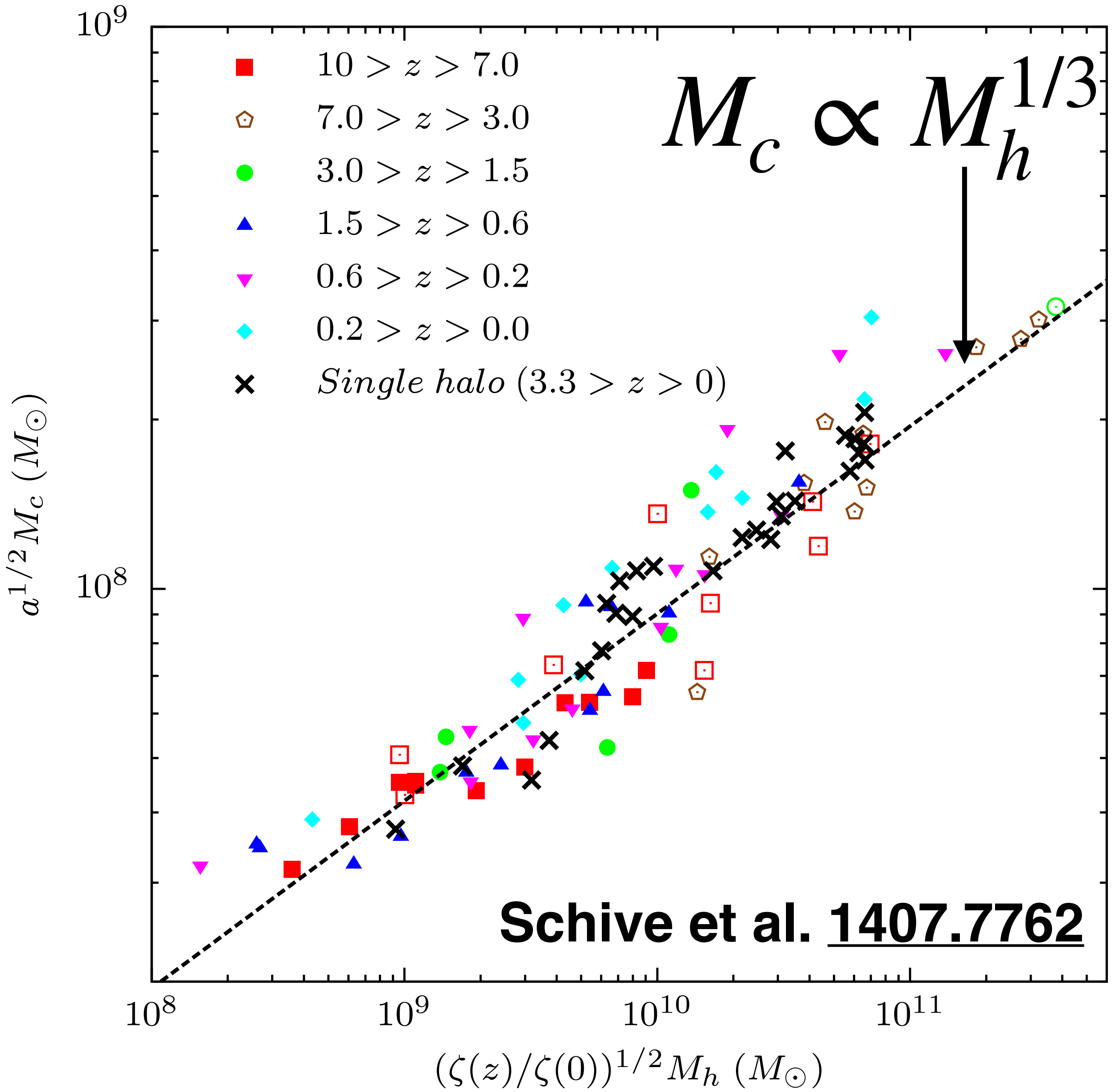
$\tau \sim \mathcal{O}(\mathrm{day})$

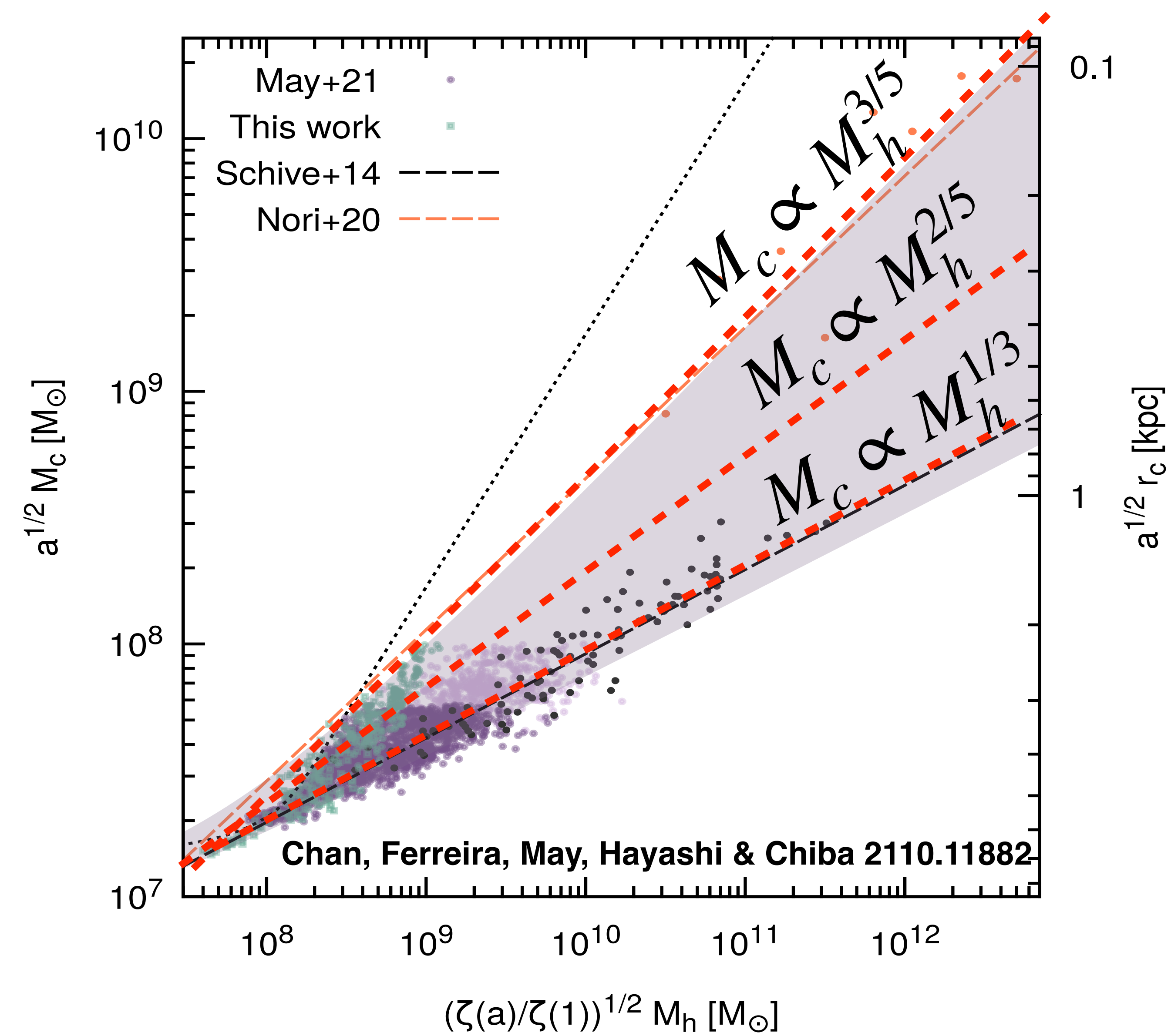


$$E = M_s - M_{\rm decay}$$

# 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 $M_c \propto M_h^\alpha$**

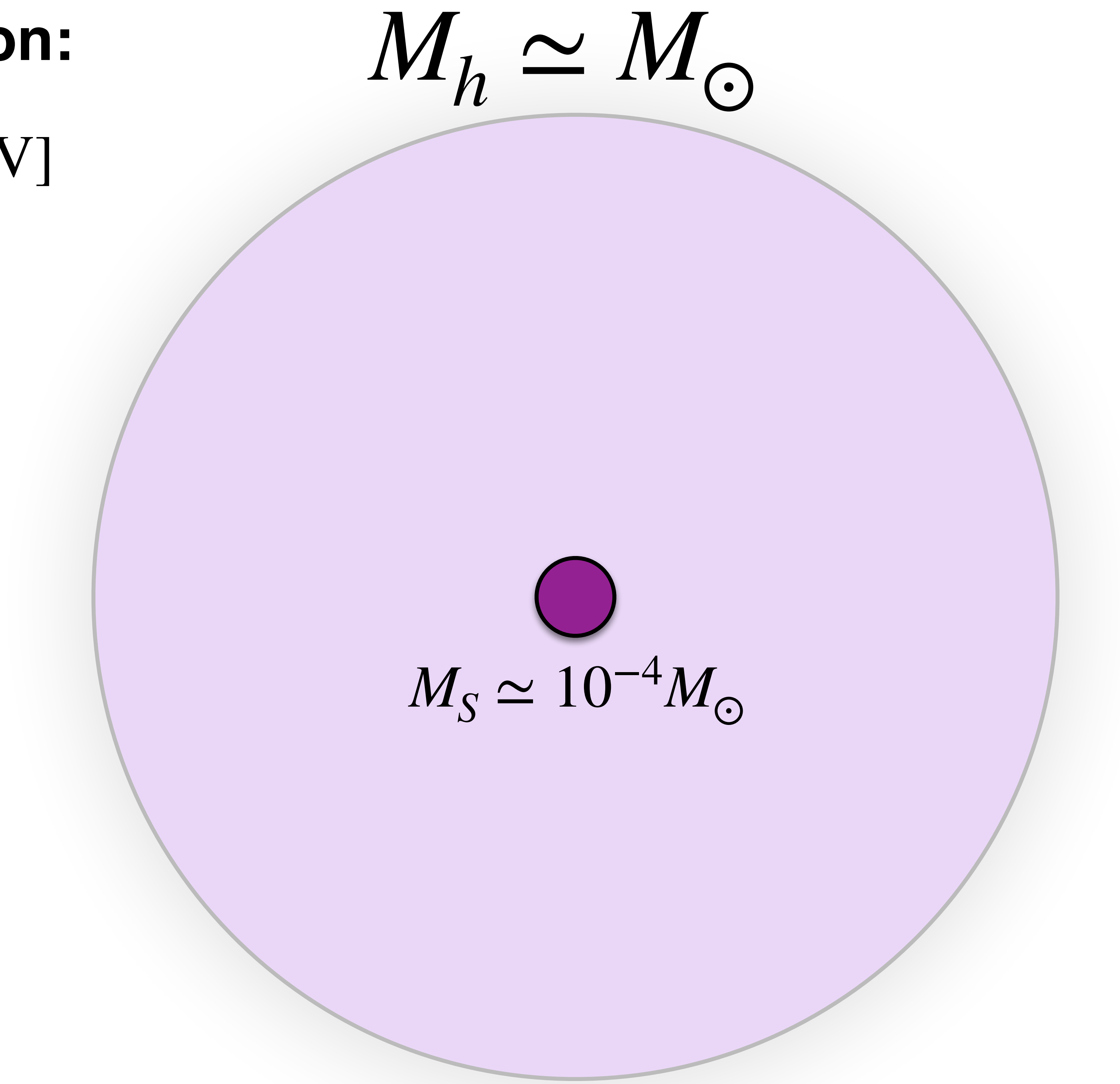
**Chan, Ferreira, May, Hayashi & Chiba 2110.11882**
**see also Zagorac, Kendall, Padmanabhan, Easther 2212.09349**

# Core-Halo Mass Relation Implication

**Schive Relation:**

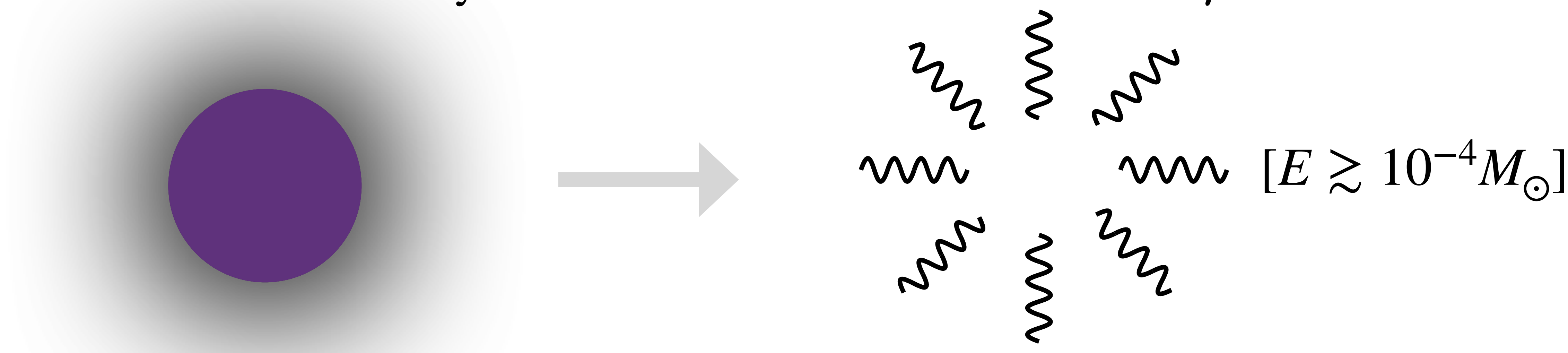
$[m_a = 10^{-13}\,\mathrm{eV}]$

$[z = 20]$



# The Physics in 3 steps:

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




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


**3) This will make the temperature of the baryons rise and lead to reionization during the dark ages when these stars start to form**

**This will happen through collisional ionizations as soon as $T_b \sim 1\,{\rm eV}$ (which roughly corresponds to $f_{\rm DM}^{\rm decay} \sim 10^{-9}$ )**

$$eH \to eep$$

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

# The Procedure in 3 steps:

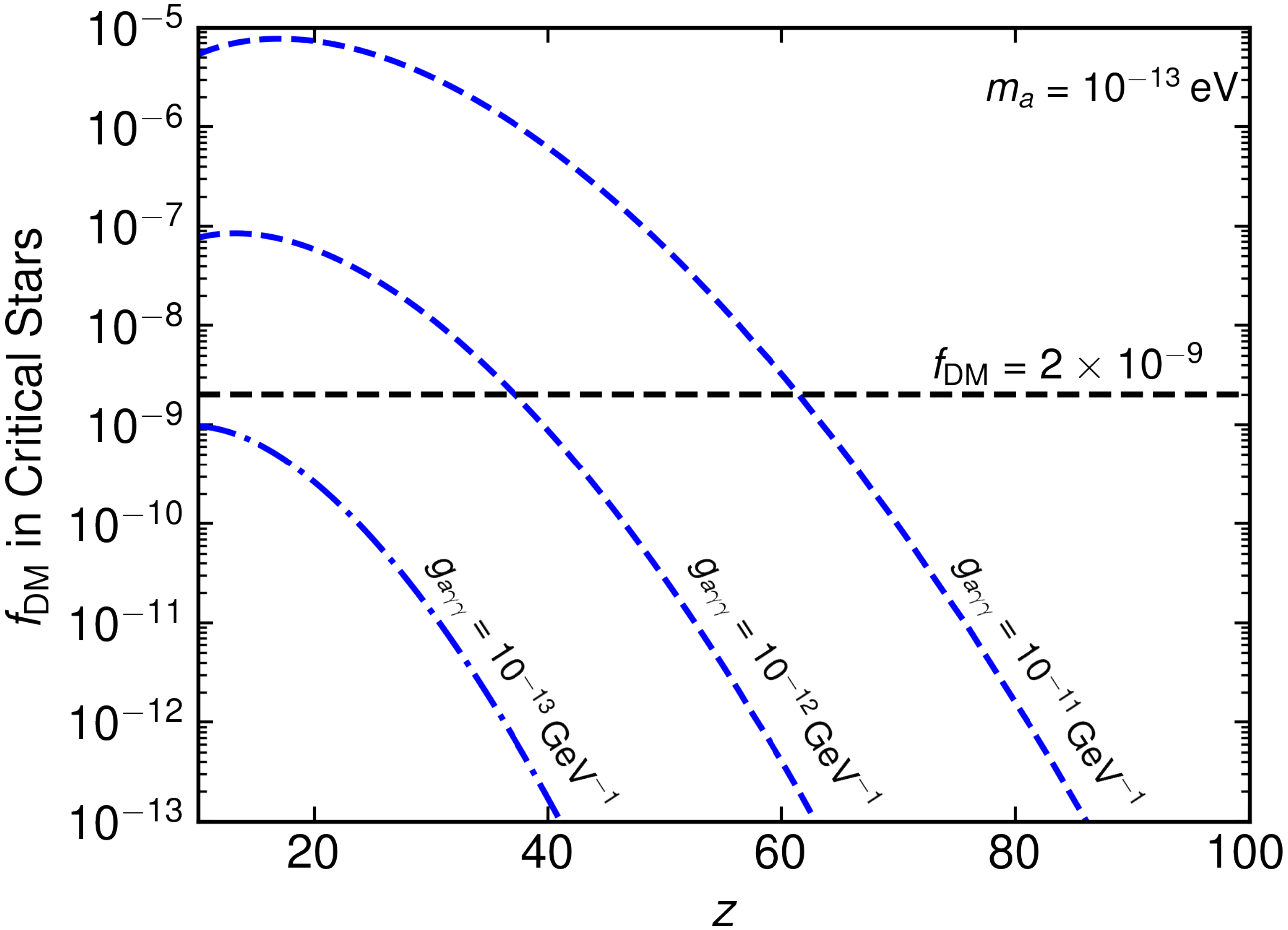
**We need to calculate the energy density in stars that can decay into photons and then track the evolution of the free electron fraction.**

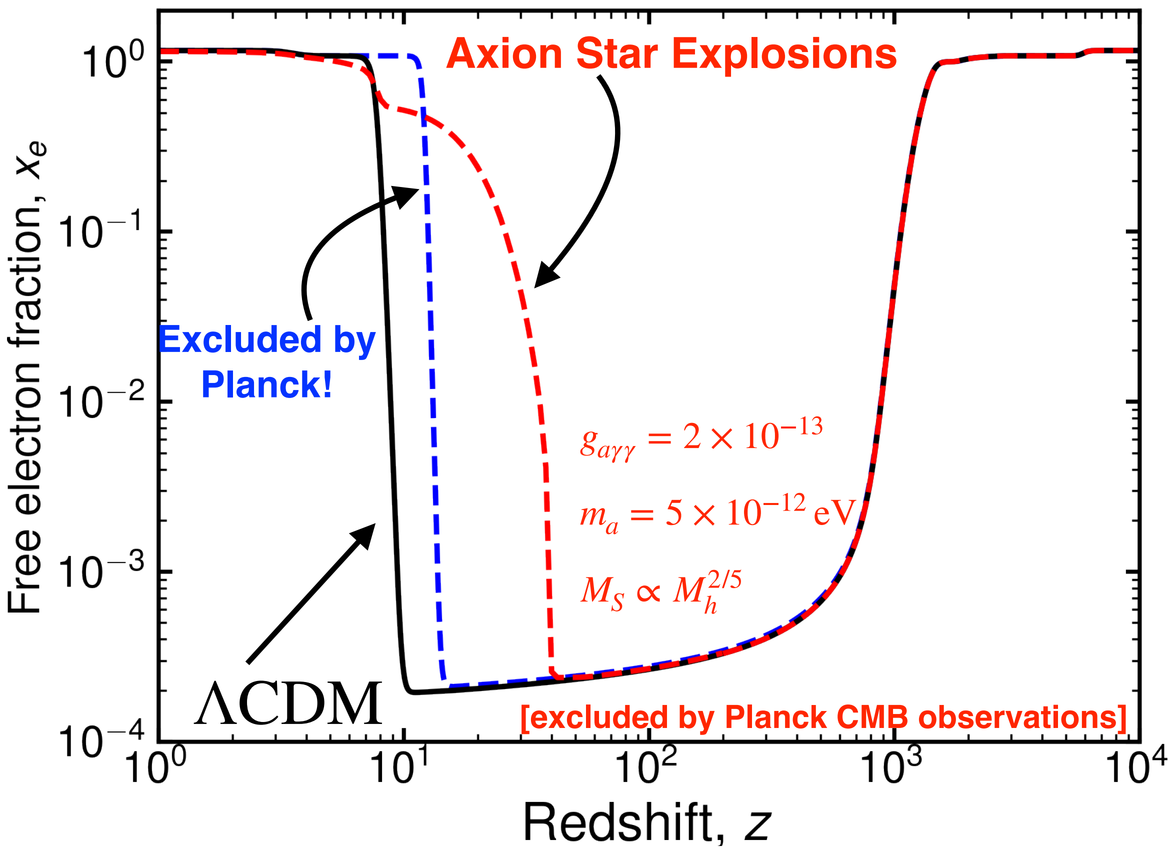
**We do this by:**

**1) Using the a given Core-Halo mass relation** $M_c \propto M_h^{\alpha}$, $\alpha \in 1/3 - 3/5$

**2) Obtaining the number density of halos via the Sheth-Tormen Halo Mass Function and also calculating the axion star merging rate using the extended Press-Schechter formalism**

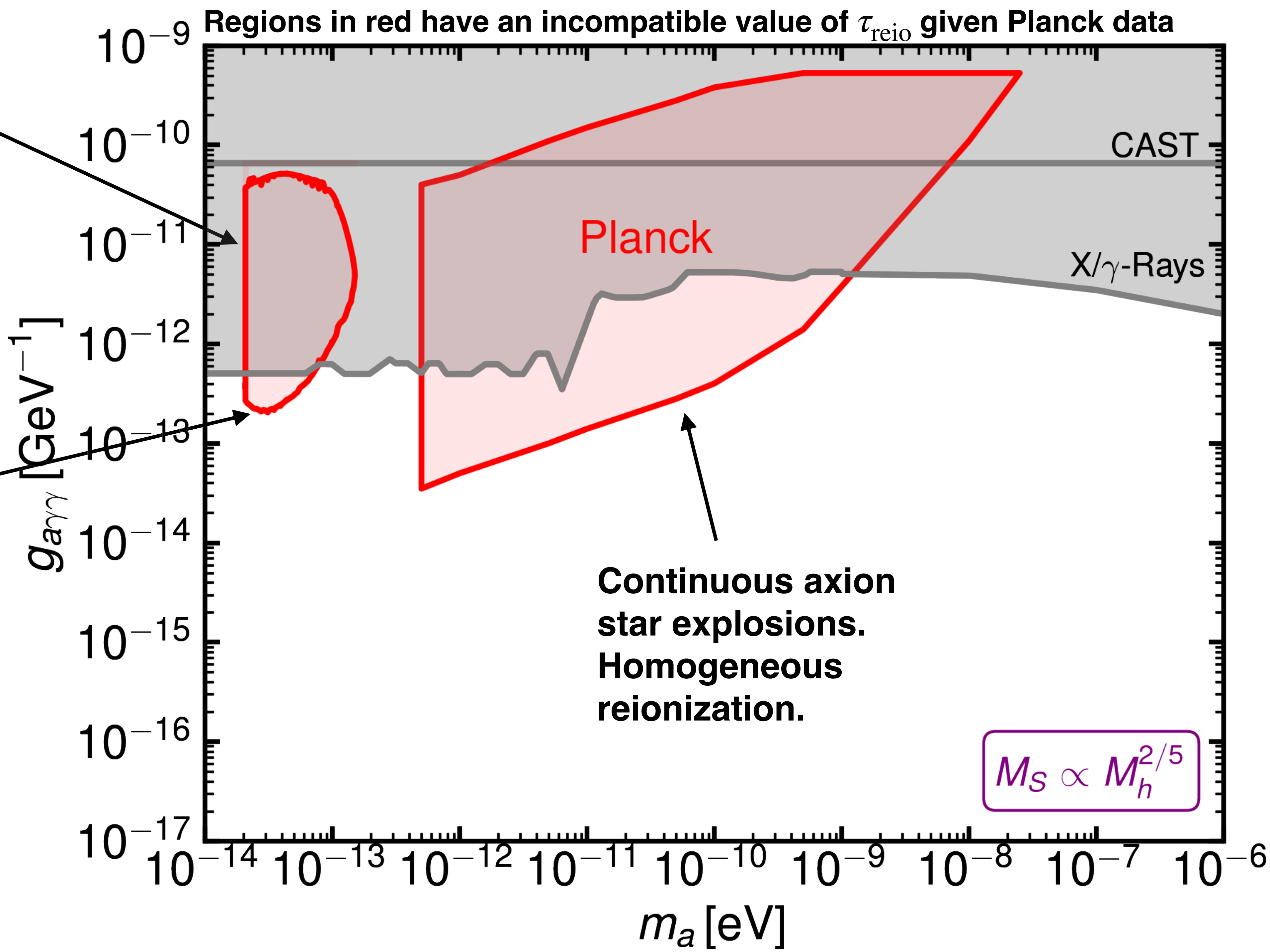
**3) We then solve the temperature evolution equations to find the reionization history of the Universe and contrast it against Planck CMB observations on** $\tau_{\rm reio}$



# Resulting Constraints

**Minimum mass that can be constrained due to kinematics**
$m_a > 2m_\gamma(z)$

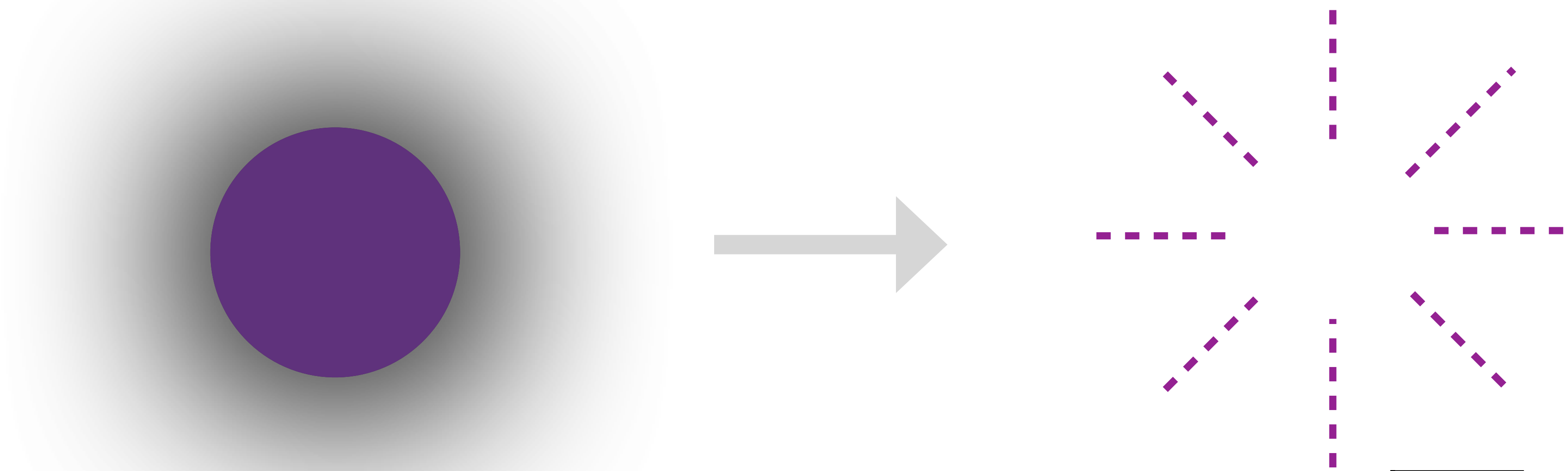



**Energy injections absorbed on very small scales. Patchy reionization.**

**Continuous axion star explosions. Homogeneous reionization.**

# 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:** $M_{\rm Nova} = 12.4\, M_{\rm Pl}/\sqrt{|\lambda|}$ **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

**Constraining axion star explosions into axions is more difficult, but see:** Fox, Weiner & Xiao 2302.00685

# 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

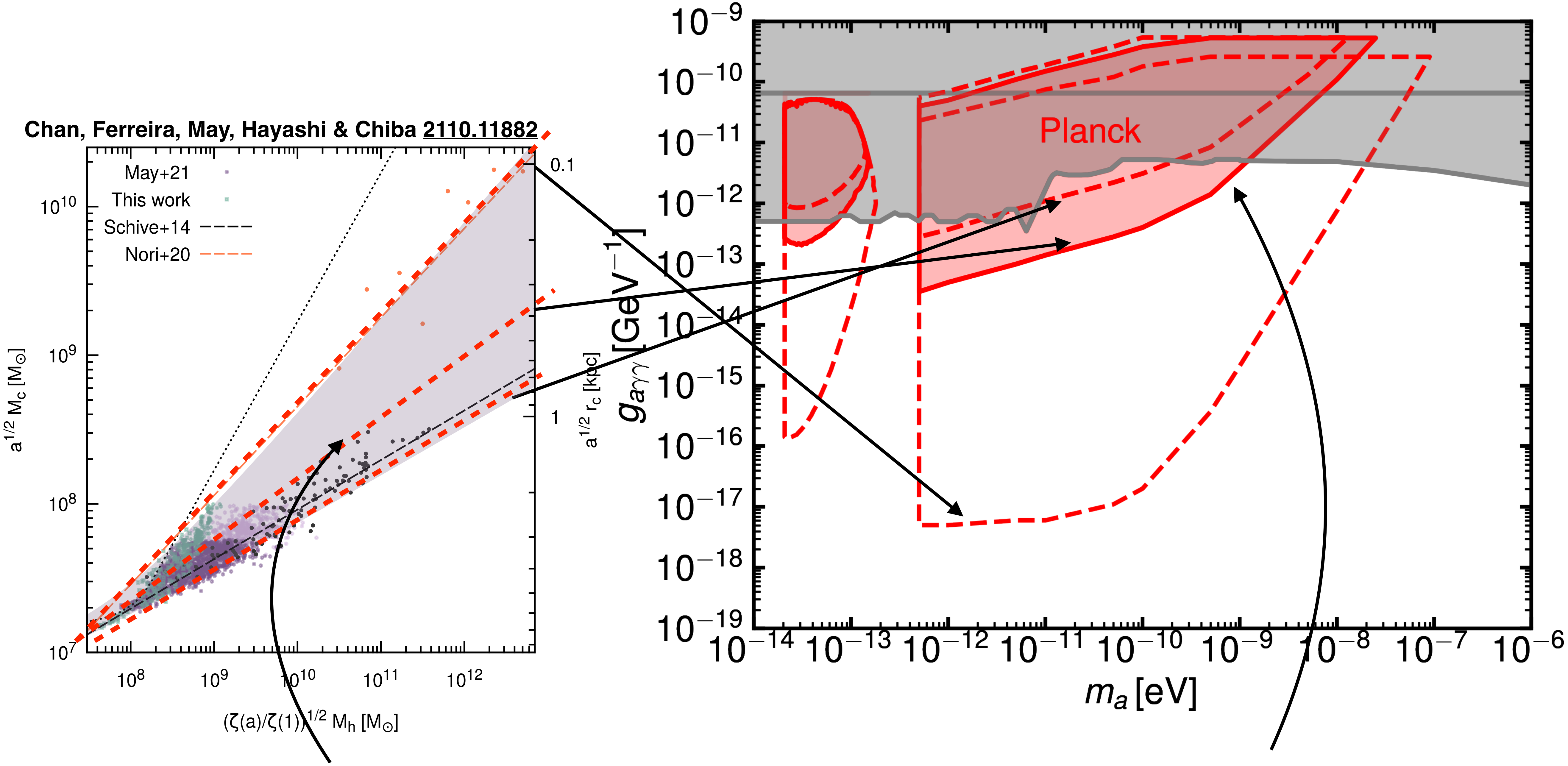
- **These axion stars can be dense enough to decay into photons due to parametric resonance**

- **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**

- ***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

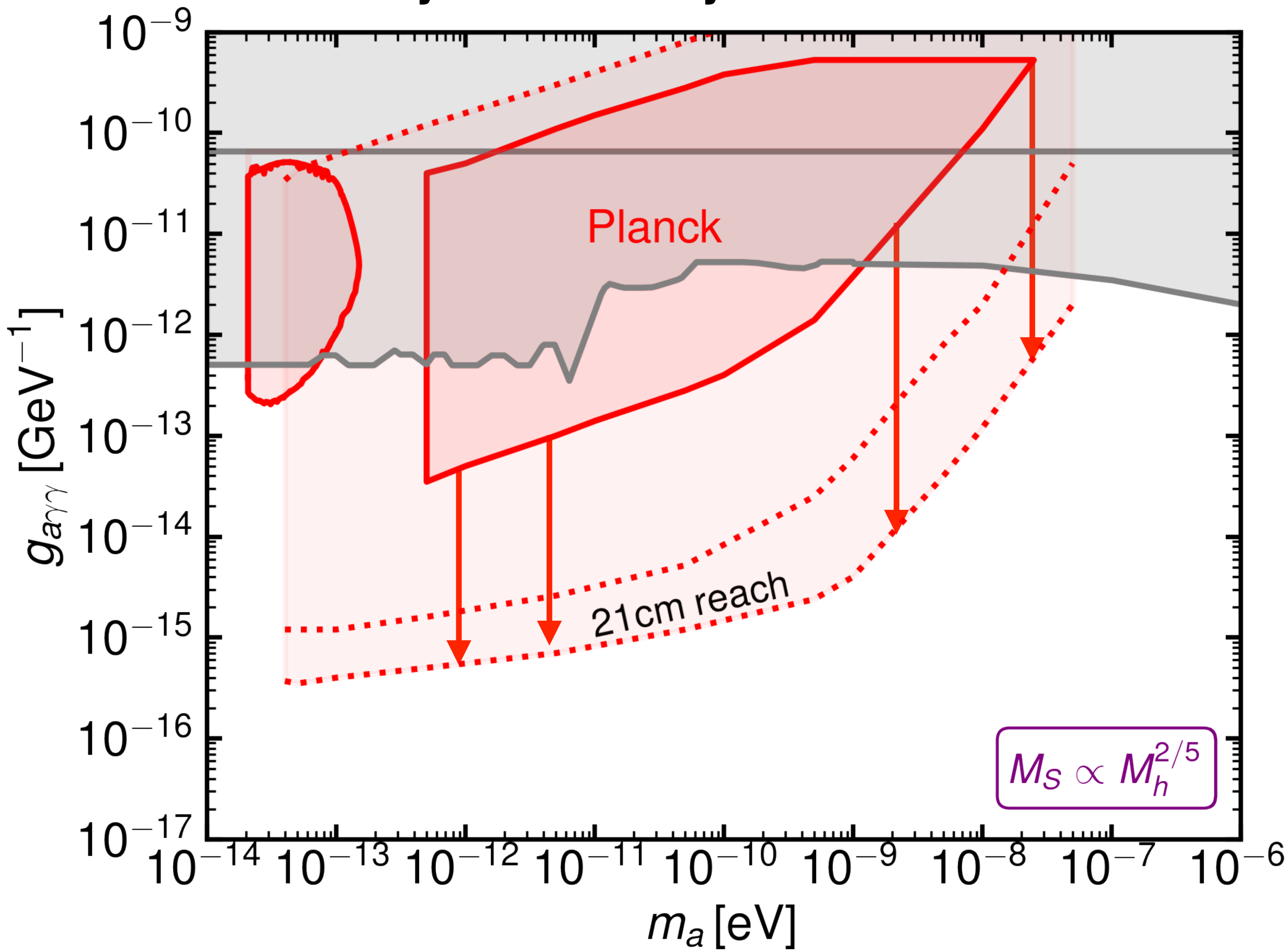
**Our constraints are strongly dependent upon what is the mass of an axion star in a given halo. This is an open issue and further numerical analyses are required in order to draw definite statements.**




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

# Outlook: 21 cm Cosmology

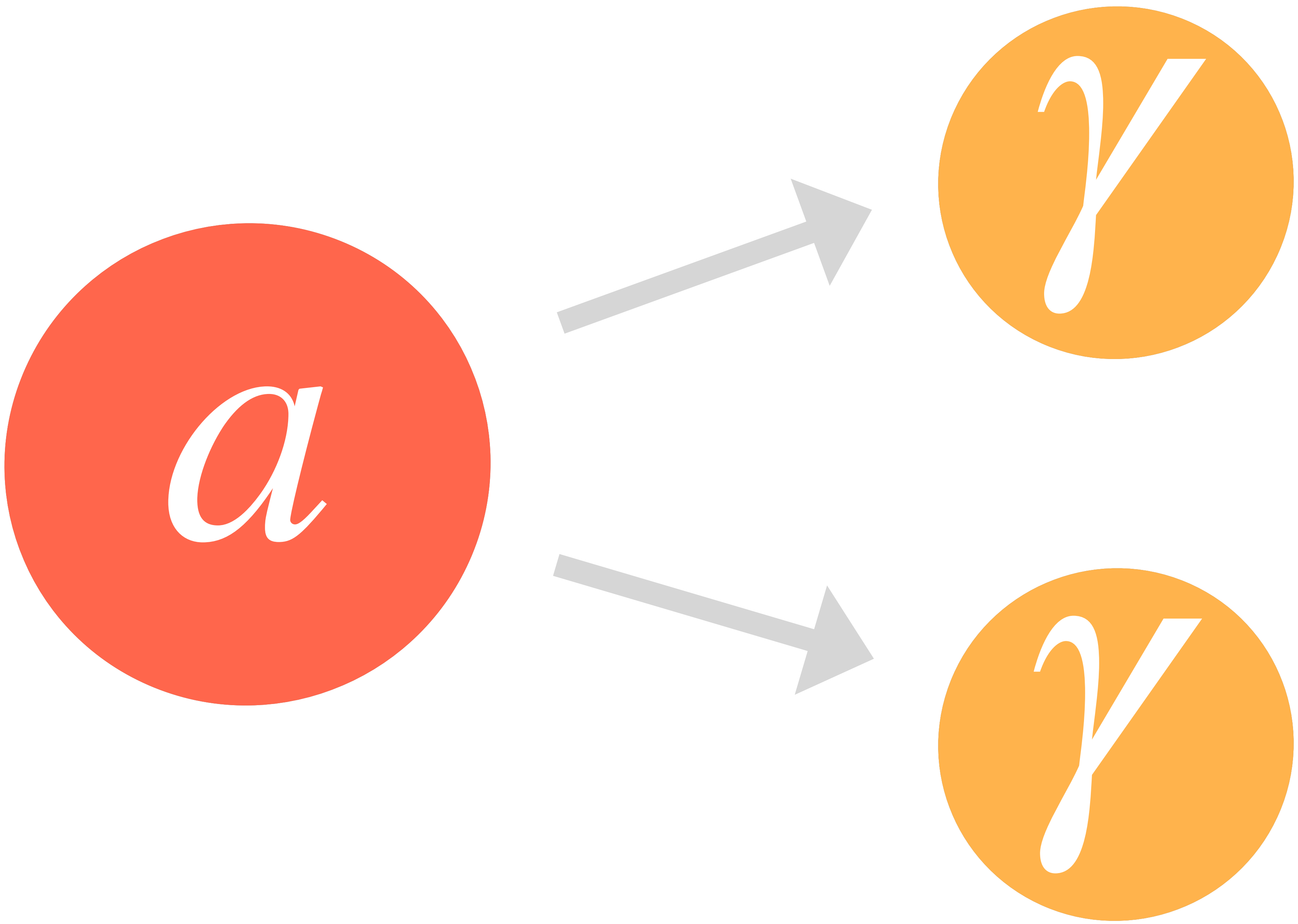
**The next generation of experiments targeting the 21 cm line of neutral Hydrogen are expected to test couplings that are orders of magnitude smaller than those currently excluded by Planck**




**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




miguel.escudero@cern.ch