Axion Star Explosions in the Early Universe

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SCIENCE NEWS
Dark Matter
Explosions?
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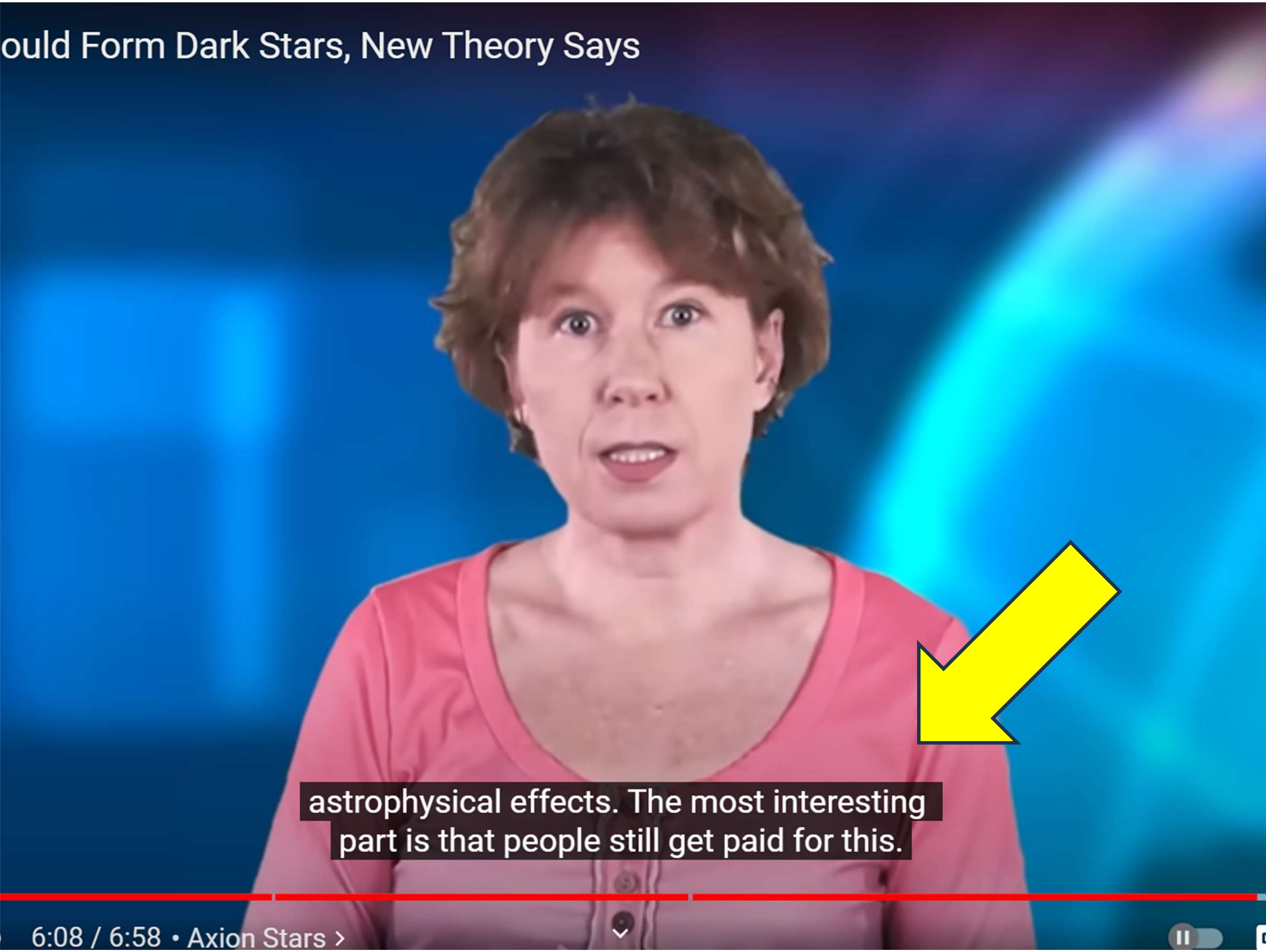
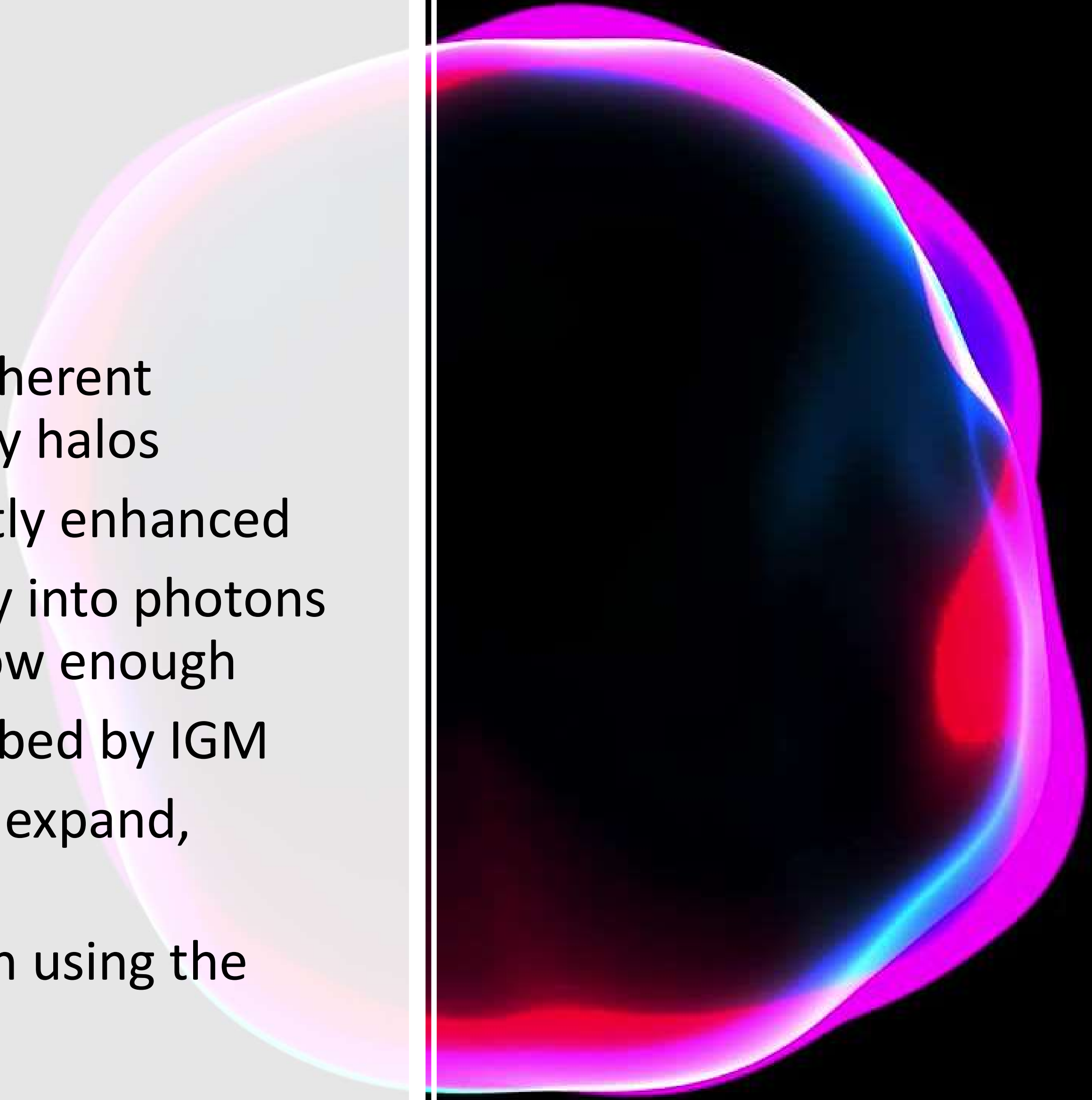


ould Form Dark Stars, New Theory Says

astrophysical effects. The most interesting part is that people still get paid for this.

Here is the Idea…



- Light dark matter forms coherent solitonic cores inside galaxy halos
- Decay to photons resonantly enhanced
- Dense cores partially decay into photons when electron density is low enough
- Low energy photons absorbed by IGM
- Shock bubbles form which expand, ionising the Universe
- We constrain the ionisation using the CMB

Axions

Lagrangian of QCD

Quark kinetic term

$$S = \int d^4x \left[-\frac{1}{4g^2} G^{a,\mu\nu} G^{a}_{\mu\nu} - \frac{\theta}{32\pi^2} G^{a,\mu\nu} \tilde{G}^{a}_{\mu\nu} + \imath \bar{\psi} D_\mu \gamma^\mu \psi + \bar{\psi} \mathrm{M} \psi \right]$$

Gluon kinetic term

Quark masses

?

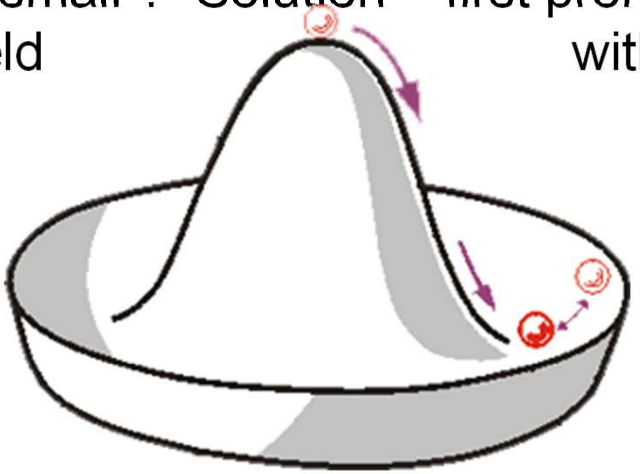
Neutron Dipole Moment and strong CP problem

$$\frac{\theta}{32\pi^2} G^{a,\mu\nu} \tilde{G}^{a}_{\mu\nu}$$

predicts electric dipole moment for neutron d~ 10^{-16} θ' e cm

However, no edm observed down to d~ 10^{-27} e cm

Why is θ' so small ? Solution – first promote θ to expectation value of a field with U(1) symmetry then…



$$m_a^2 \sim \frac{f_\pi^2 m_\pi^2}{f_a^2}$$

This is a prediction for axion models which solve strong CP problem.

Axion like Particles

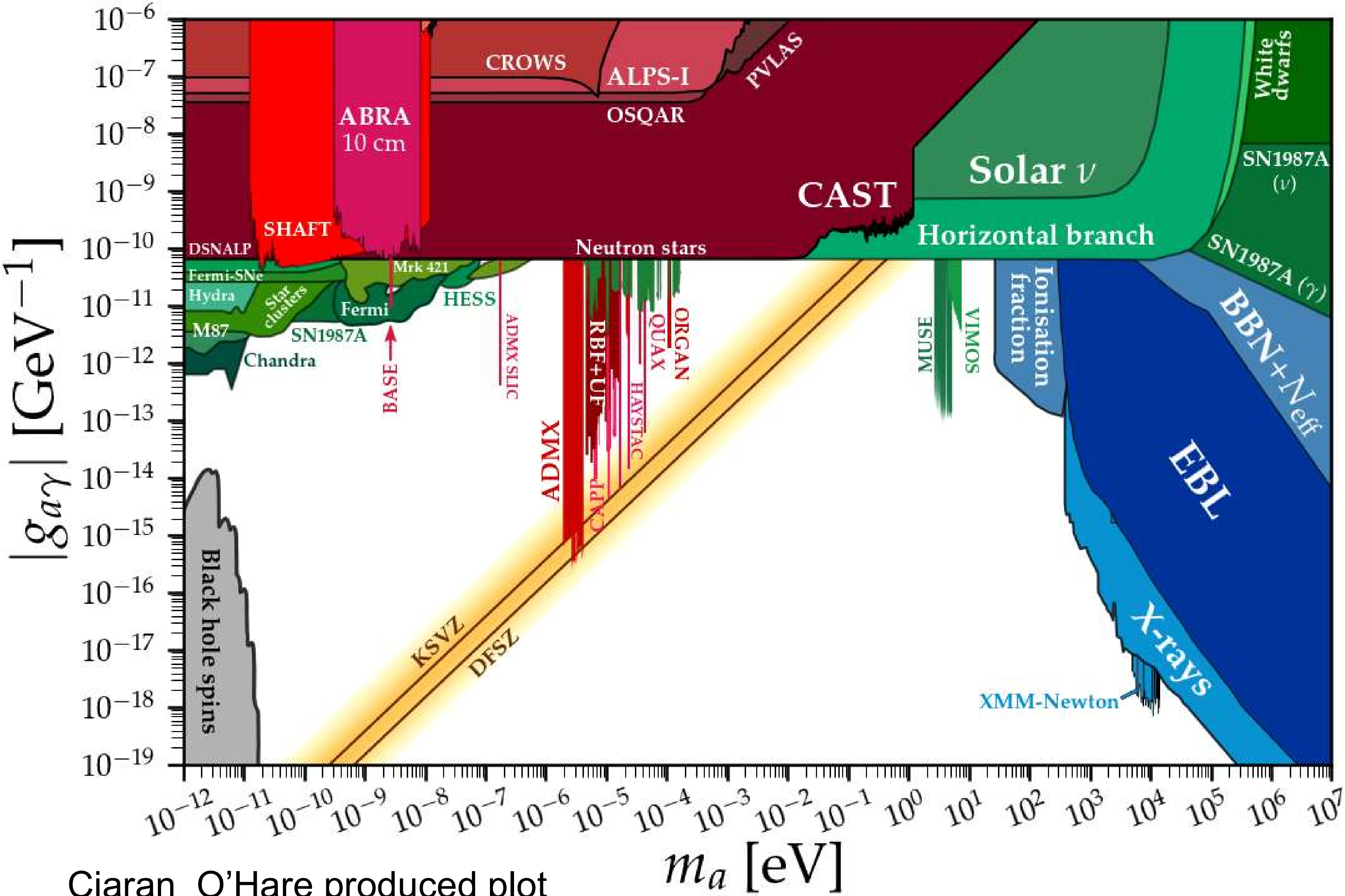
One can simply be agnostic and leave the coupling to photons as a free parameter

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{g_{a\gamma\gamma}}{4}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

creates mixing/interactions between photons and axions

laboratory CAST bound

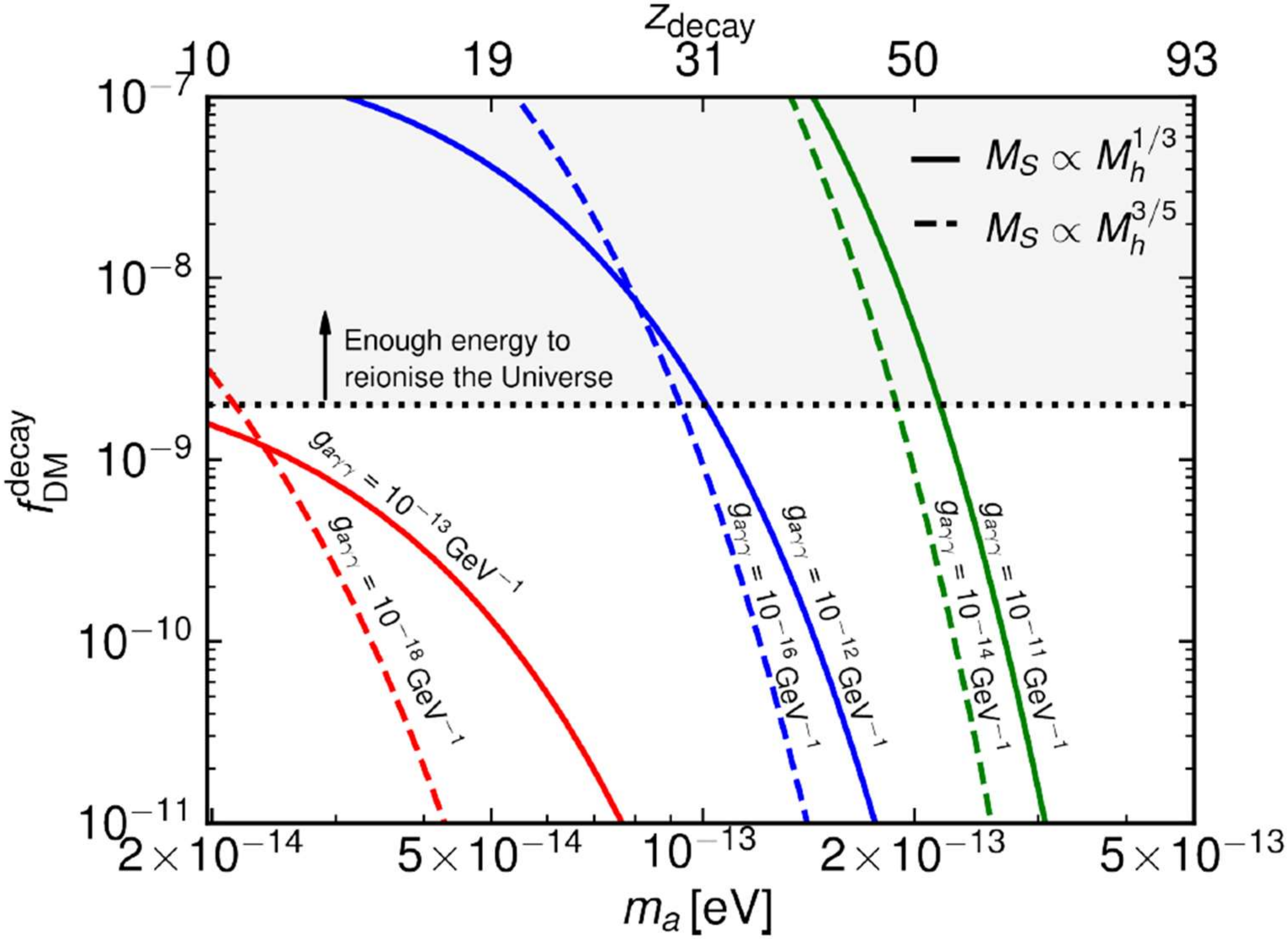
$$g_{a\gamma\gamma} < \ 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1} \ \text{ for } \ m_a \ < \ 0.02\,\mathrm{eV}$$



Ciaran O'Hare produced plot

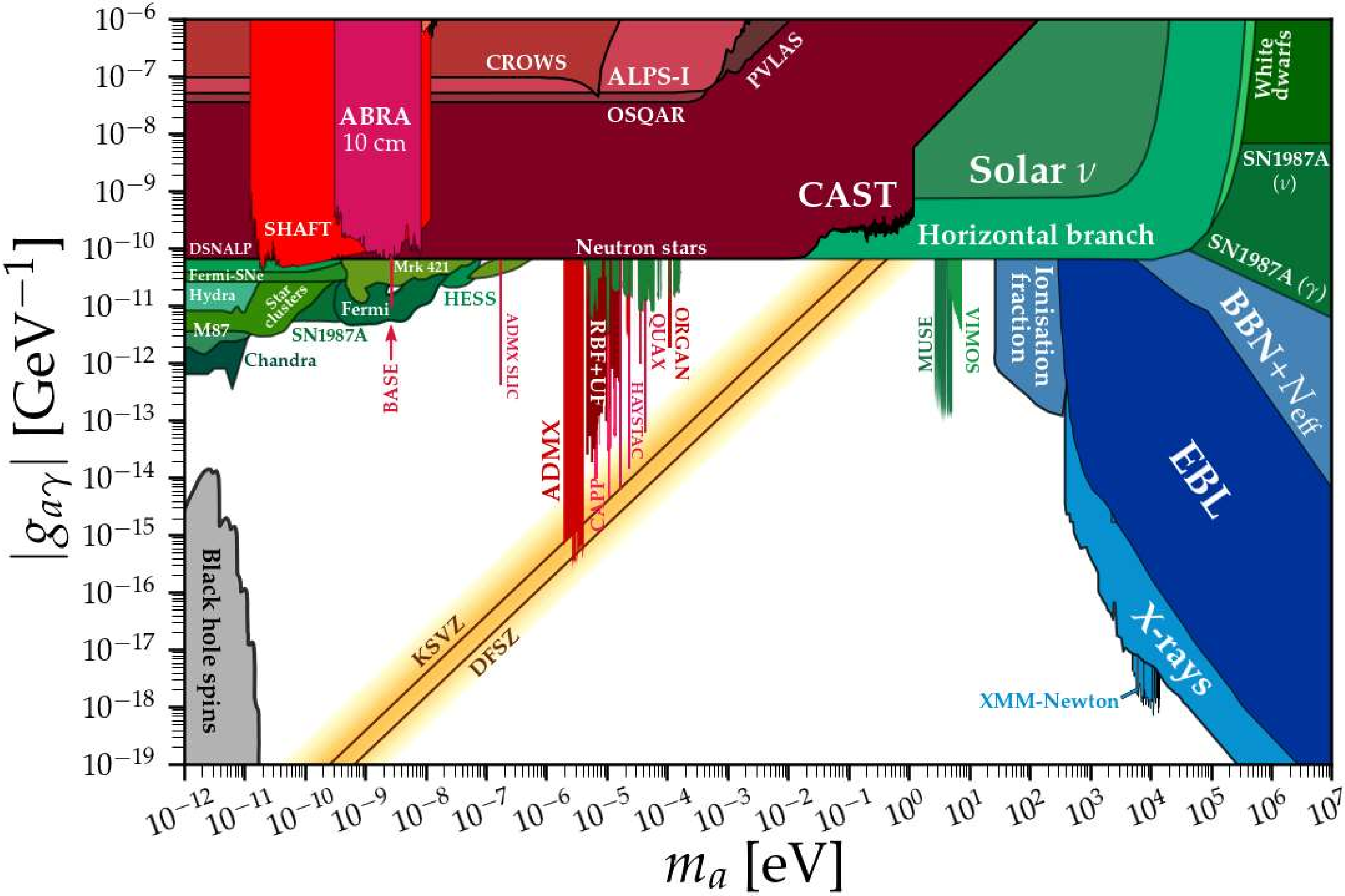
Axions can also decay! Only a small fraction would ionise the Universe

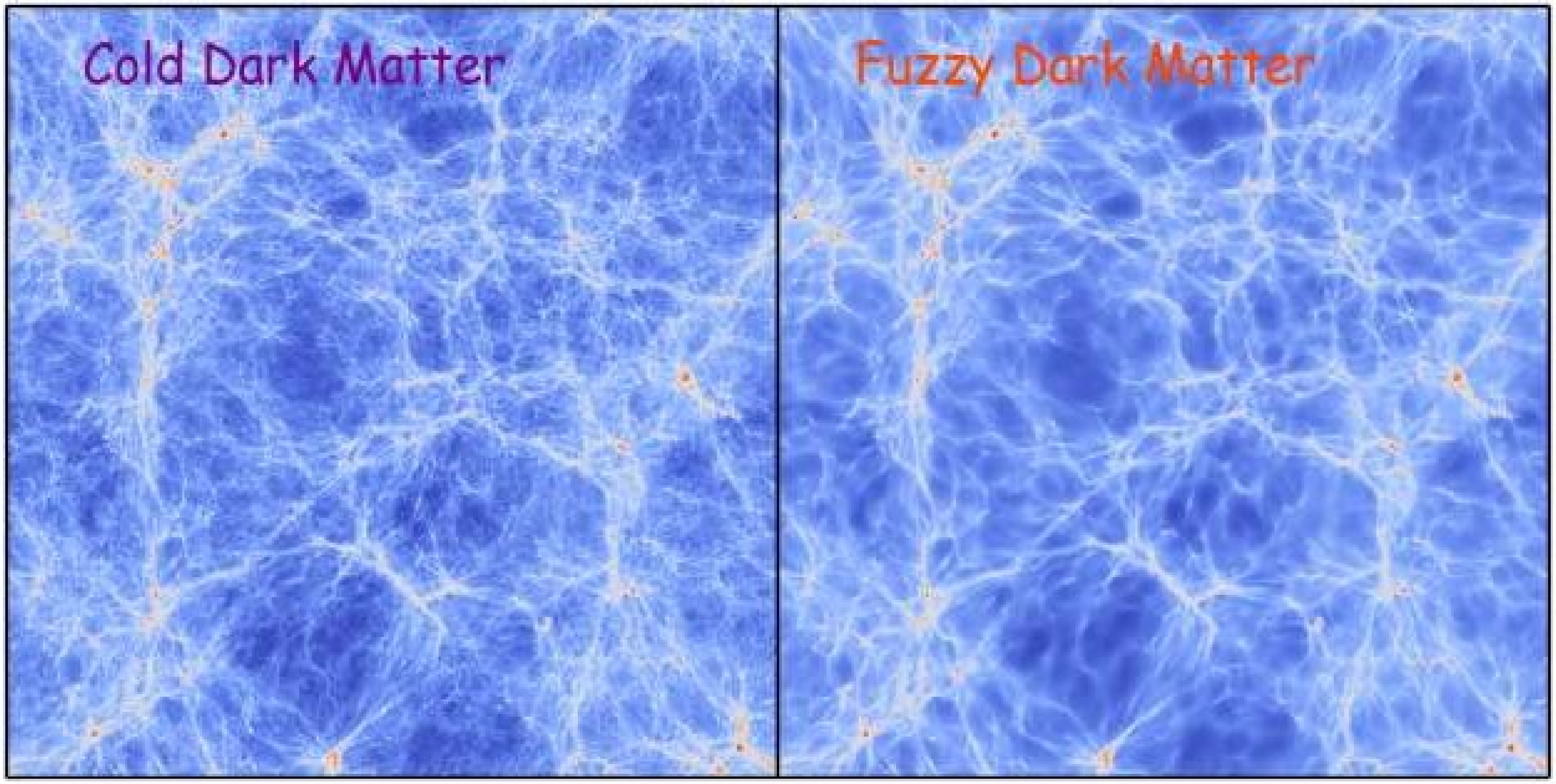
$$\Gamma(a \to \gamma\gamma) = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$



CAST bound means decay time much larger than age of Universe though!

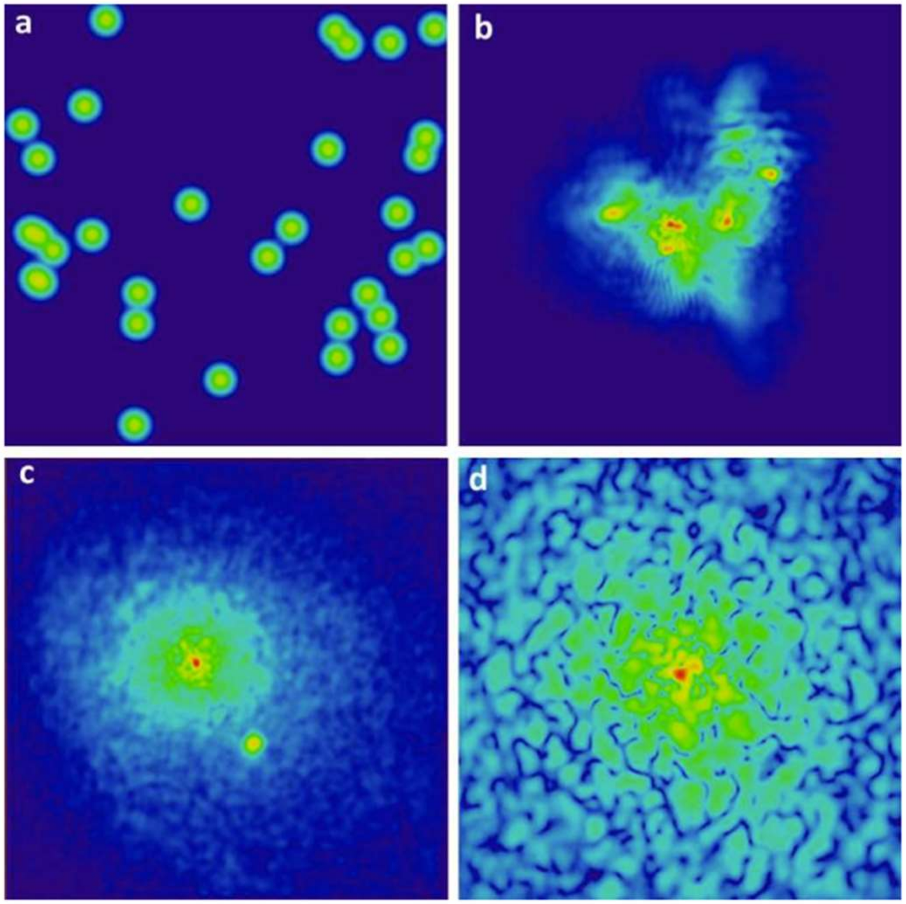
$$g_{a\gamma\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1} \;\; \text{for} \;\; m_a < 0.02\,\mathrm{eV}$$

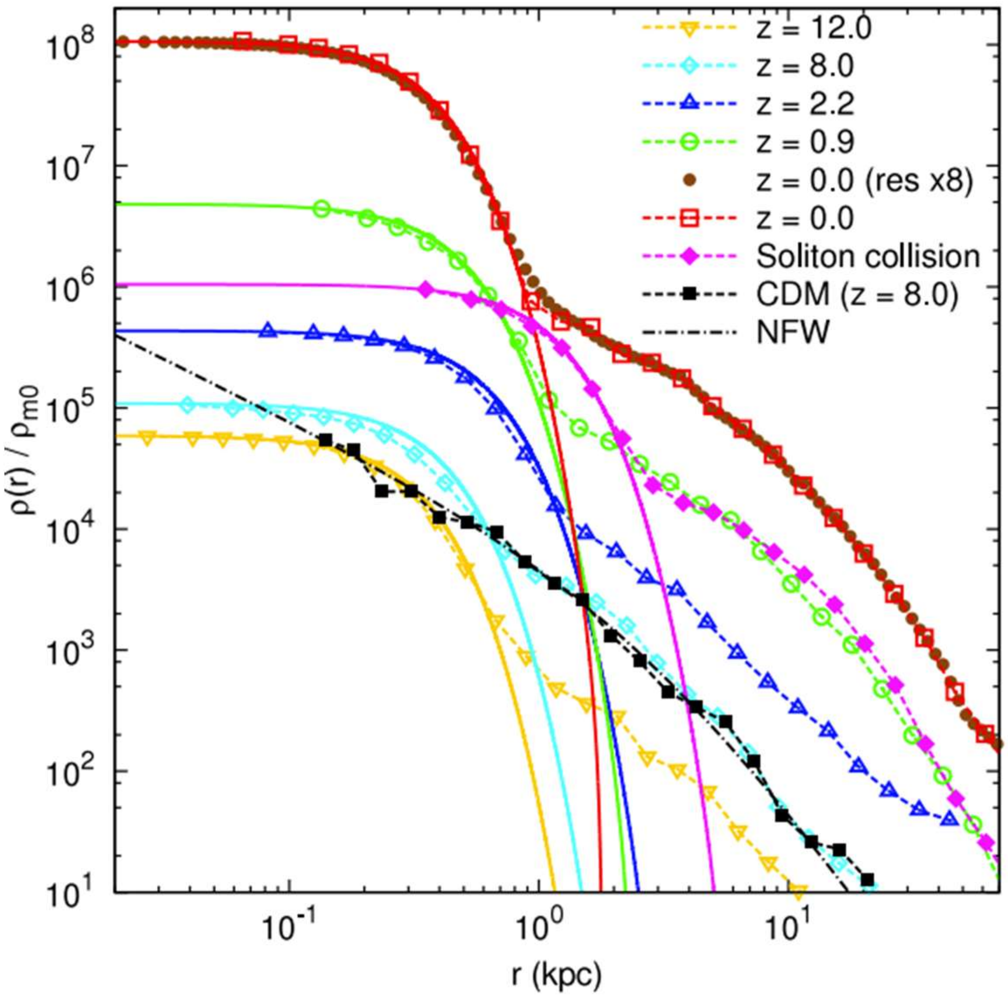




$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2ma^2}\nabla^2\psi + \frac{m\Phi}{a}\psi$$

$$\nabla^2\Phi = 4\pi G m\left(|\psi|^2 - \langle|\psi|^2\rangle\right)$$





$$M_c = \frac{1}{4} a^{-1/2} \left(\frac{\zeta(z)}{\zeta(0)}\right)^{1/6} \left(\frac{M_h}{M_{min,0}}\right)^{1/3} M_{min,0}$$

$$M_{\mathrm{min},0} \sim 4.4 \times 10^{7} \left(mc^2/(10^{-22}\ \mathrm{eV})\right)^{-3/2} \mathrm{M}_\odot$$

$$r_c = 1.6\ m_{22}^{-1} a^{1/2} \left(\frac{\zeta(z)}{\zeta(0)}\right)^{-1/6} \left(\frac{M_h}{10^9\ M_\odot}\right)^{-1/3}\ \mathrm{kpc}$$

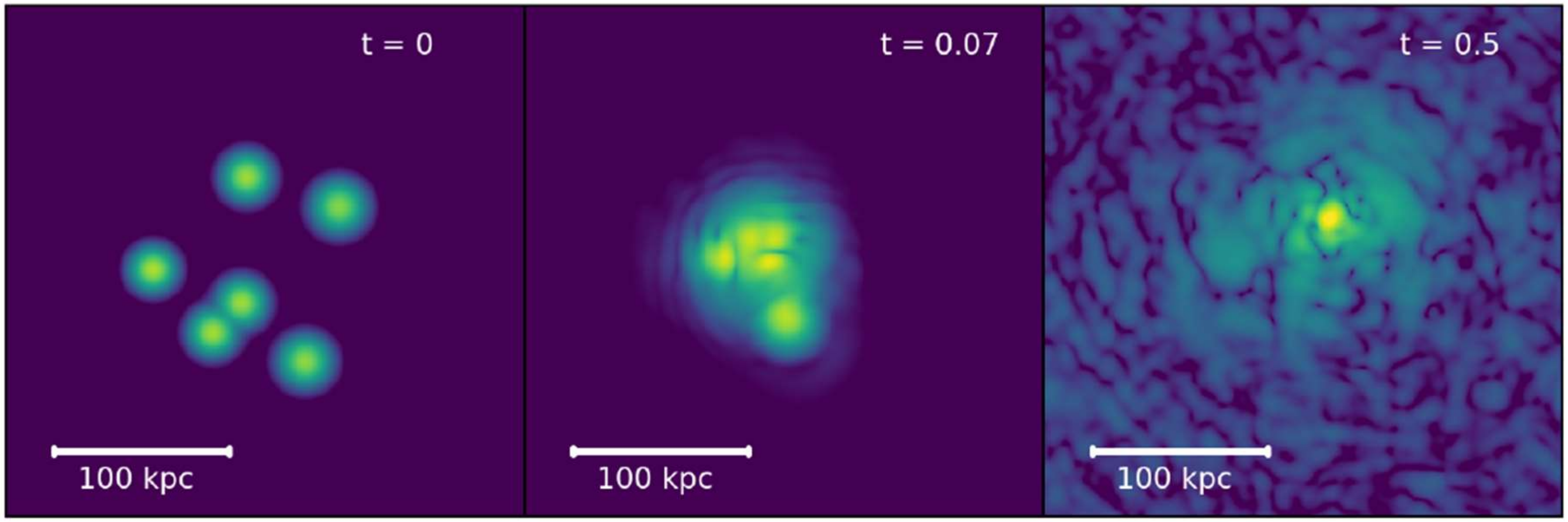
$$\rho(r) = \begin{cases} \rho_{\mathrm{c}} \left[1 + 0.091 \left(\frac{r}{r_{\mathrm{c}}}\right)^2\right]^{-8} & , \text{for } r < r_{\mathrm{t}} \\ \rho_{\mathrm{s}} \left[\frac{r}{r_{\mathrm{s}}}\right]^{-1} \left[1 + \left(\frac{r}{r_{\mathrm{s}}}\right)\right]^{-2} & , \text{for } r \geq r_{\mathrm{t}} \end{cases}$$

Schive et al 2014

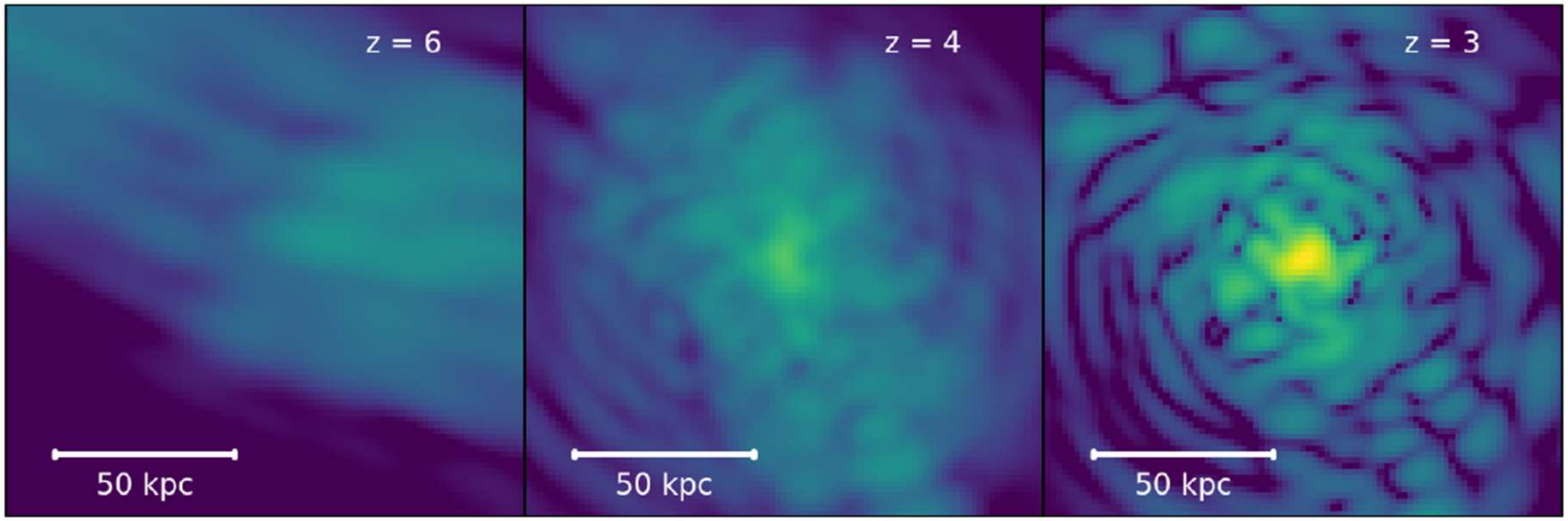
The Diversity of Core–Halo Structure in the Fuzzy Dark Matter Model

Hei Yin Jowett Chan,[1]★ Elisa G. M. Ferreira,[2,3,4] Simon May,[2]★ Kohei Hayashi,[5,6] Masashi Chiba[1]

Coalesence of halos to form bigger halo

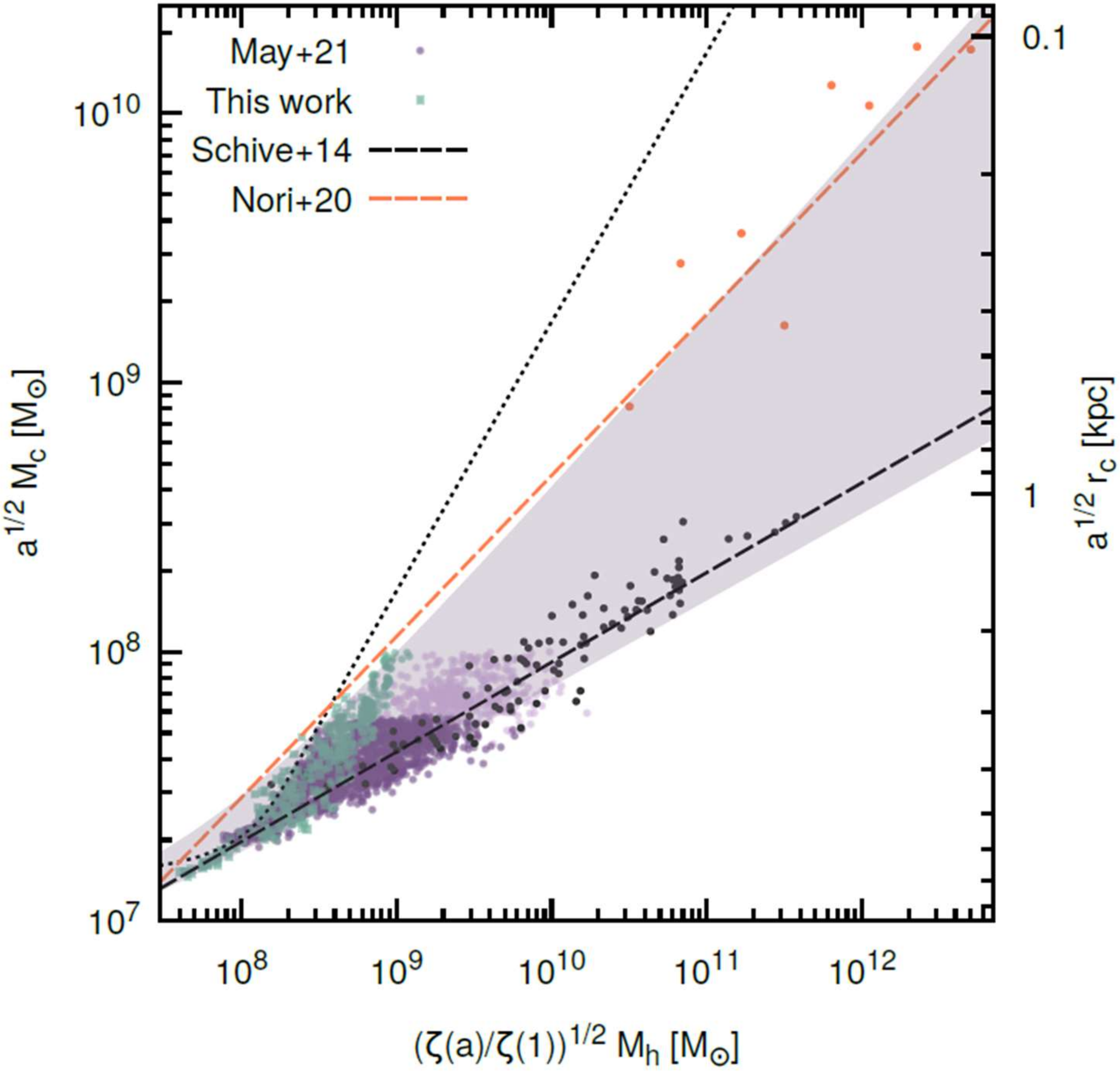


Formation of a single halo from smaller halos



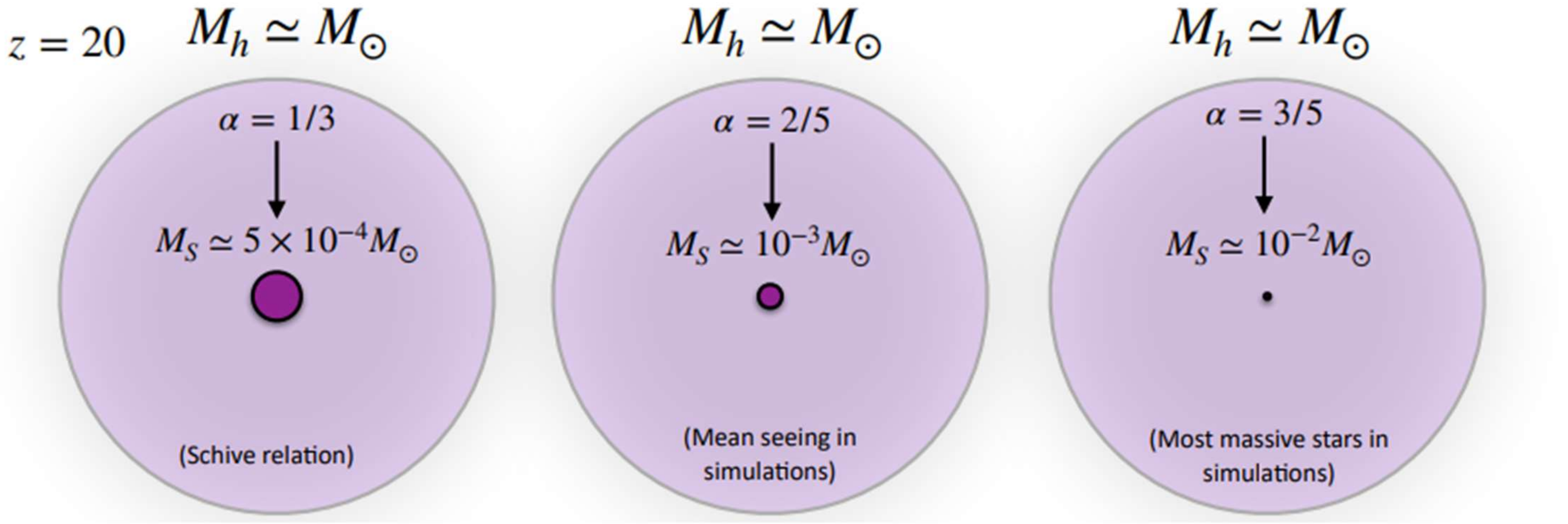
$$M_c = \frac{\sqrt{1+z}}{4}\left[\frac{\zeta(z)^{1/2}}{\zeta(z=0)^{1/2}}\,\frac{M_h}{M_h^{\min}}\right]^{\alpha} M_h^{\min}$$

!



Schive et al found α=1/3

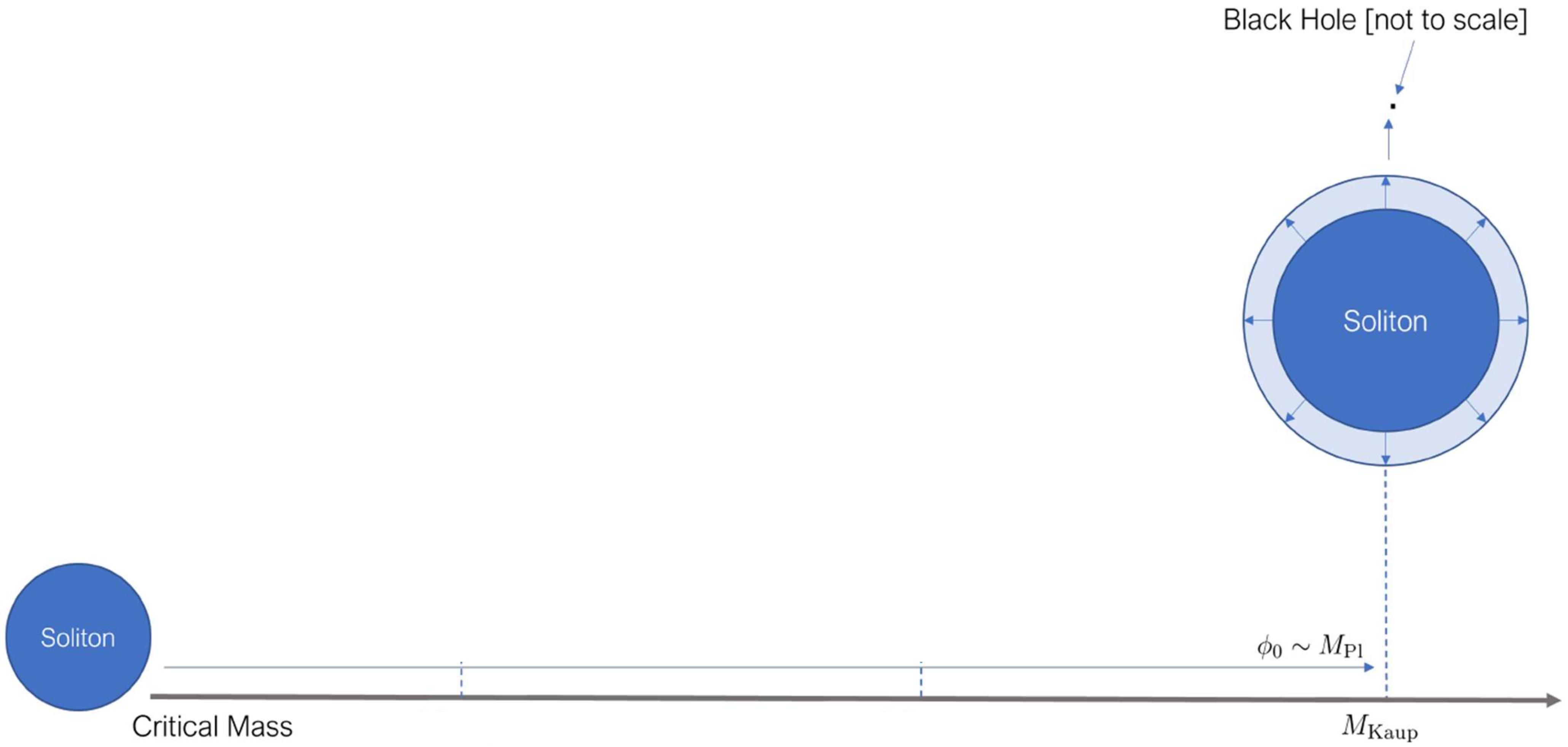
More recent work (Chan, Ferreira, May, Hayashi & Chiba) finds that α=3/5



More massive but smaller cores for bigger values of α

As Theorists, we can contemplate many possible deaths for these dense cores…

Possible fates of dense axion cores (could also just stick around!)



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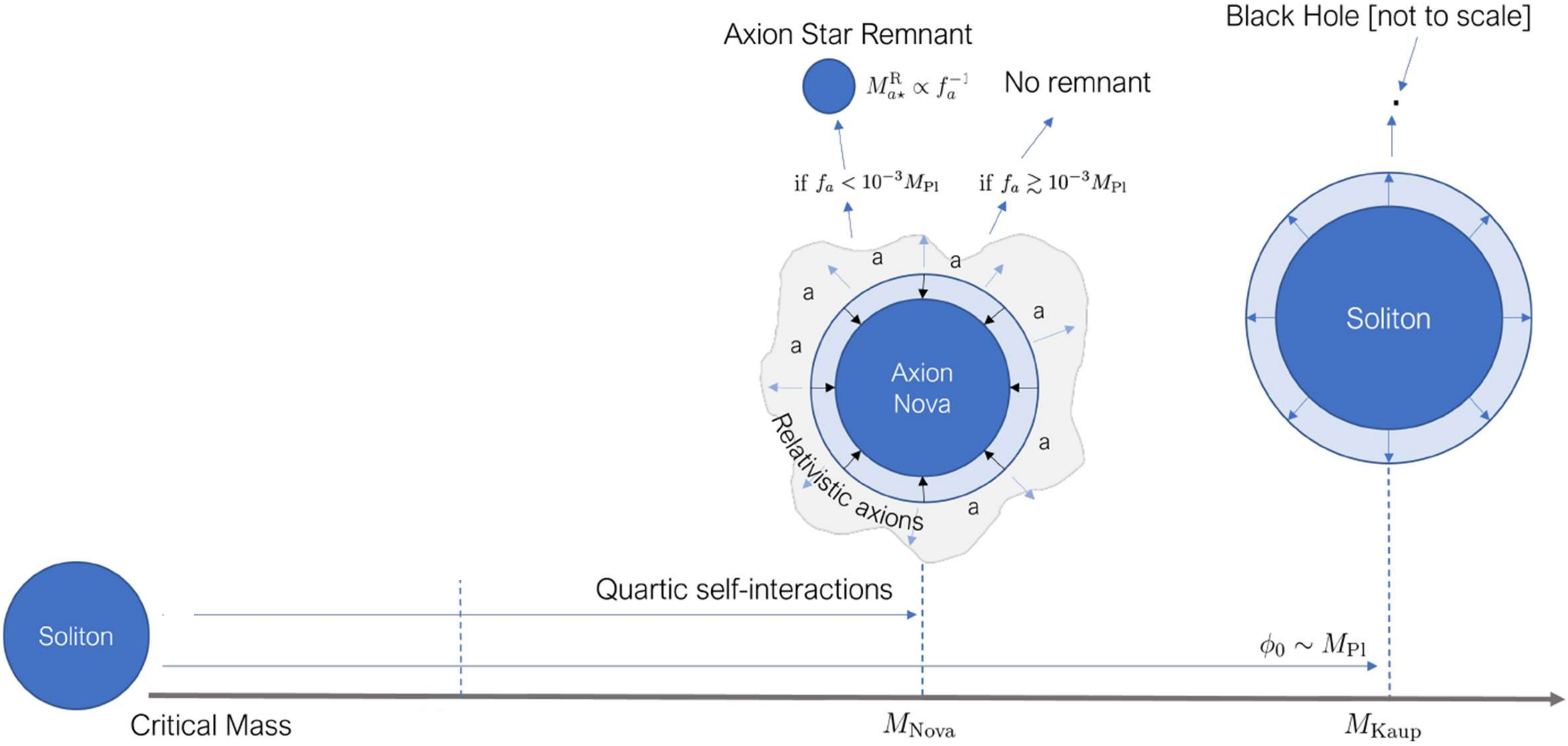

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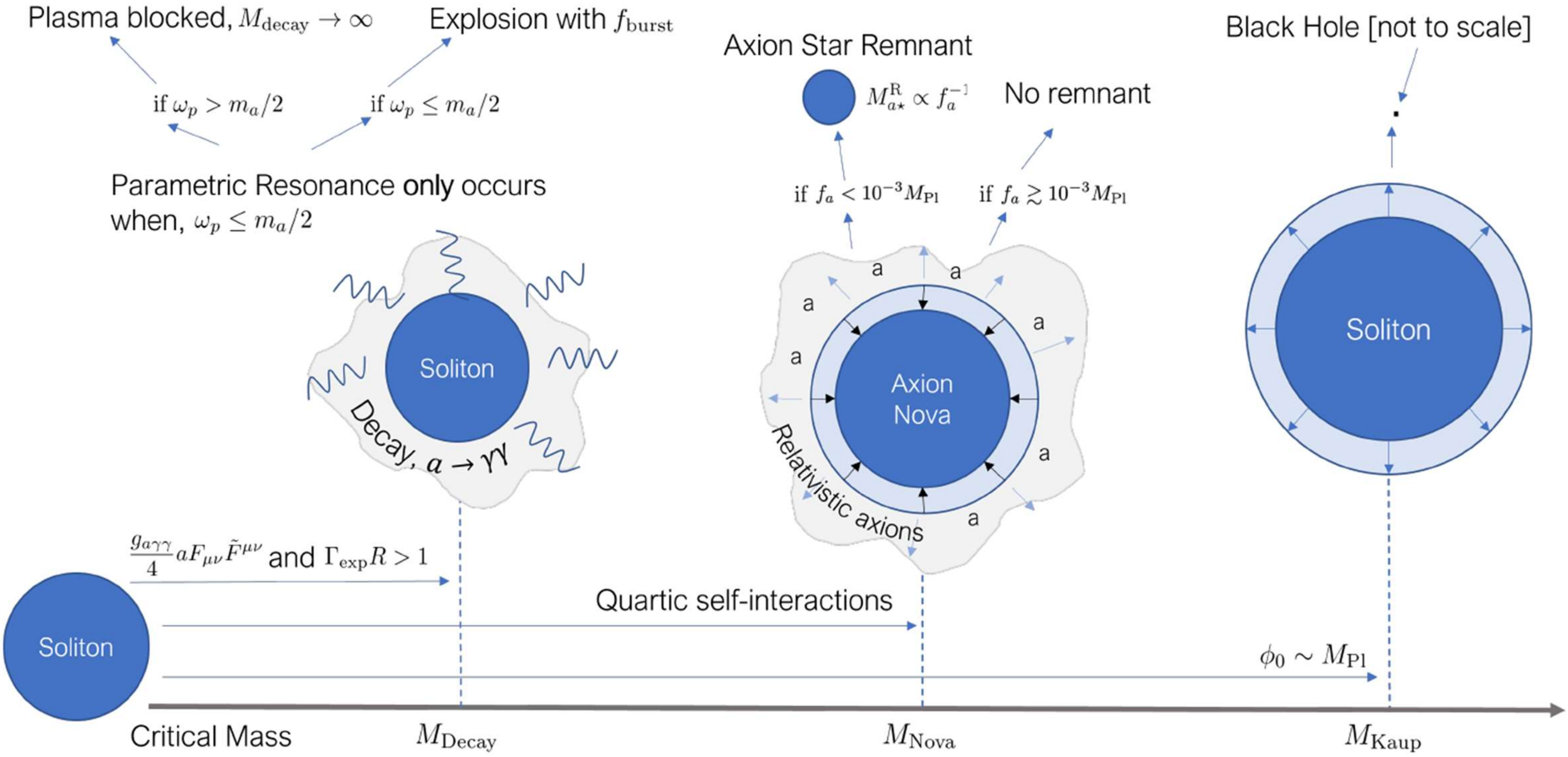


Plasma blocked, $M_{\rm decay} \to \infty$

Explosion with $f_{\rm burst}$

if $\omega_p > m_a/2$

if $\omega_p \leq m_a/2$

Parametric Resonance **only** occurs when, $\omega_p \leq m_a/2$

Axion Star Remnant

$M^{\rm R}_{a\star} \propto f_a^{-1}$

No remnant

if $f_a < 10^{-3} M_{\rm Pl}$

if $f_a \gtrsim 10^{-3} M_{\rm Pl}$

Black Hole [not to scale]

$\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$ and $\Gamma_{\rm exp} R > 1$

Quartic self-interactions

$\phi_0 \sim M_{\rm Pl}$

Critical Mass

$M_{\rm Decay}$

$M_{\rm Nova}$

$M_{\rm Kaup}$

Concentrate on parametric resonance

Stimulated emission exponentially enhances decay

$$\Gamma_{\exp} L \gtrsim 1\,, \qquad \text{where} \qquad \Gamma_{\exp} \equiv g_{a\gamma\gamma}\sqrt{\frac{\rho_a}{2}}$$

Translates into halos with a certain minimum mass

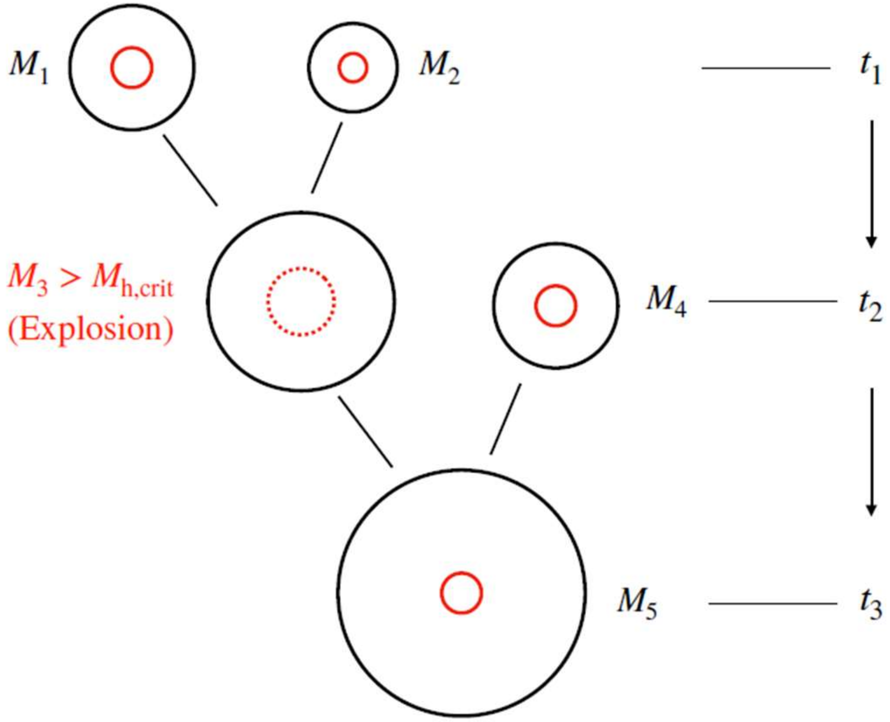
$$M_S^{\text{decay}} \simeq 8.4 \times 10^{-5}\, M_\odot \left(\frac{10^{-11}\,\text{GeV}^{-1}}{g_{a\gamma\gamma}}\right)\left(\frac{10^{-13}\,\text{eV}}{m_a}\right)$$

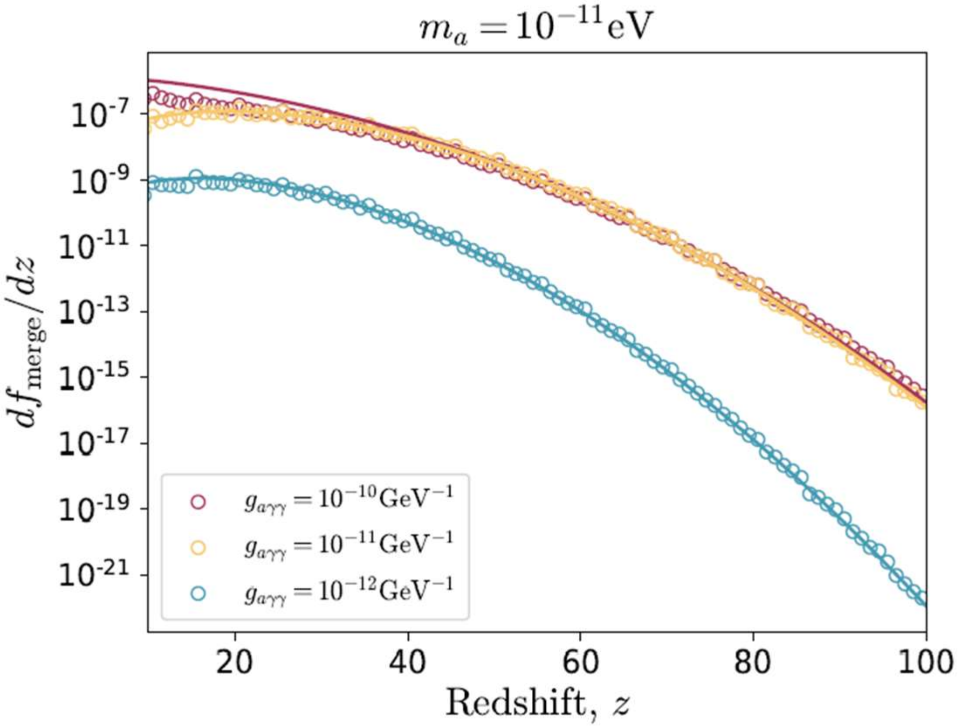
And it doesn’t take long to happen…

$$\tau_S^{\text{decay}} \simeq r_c \simeq \text{day}\left(\frac{8.4 \times 10^{-5} M_\odot}{M_S}\right)\left(\frac{10^{-13}\,\text{eV}}{m_a}\right)^2$$

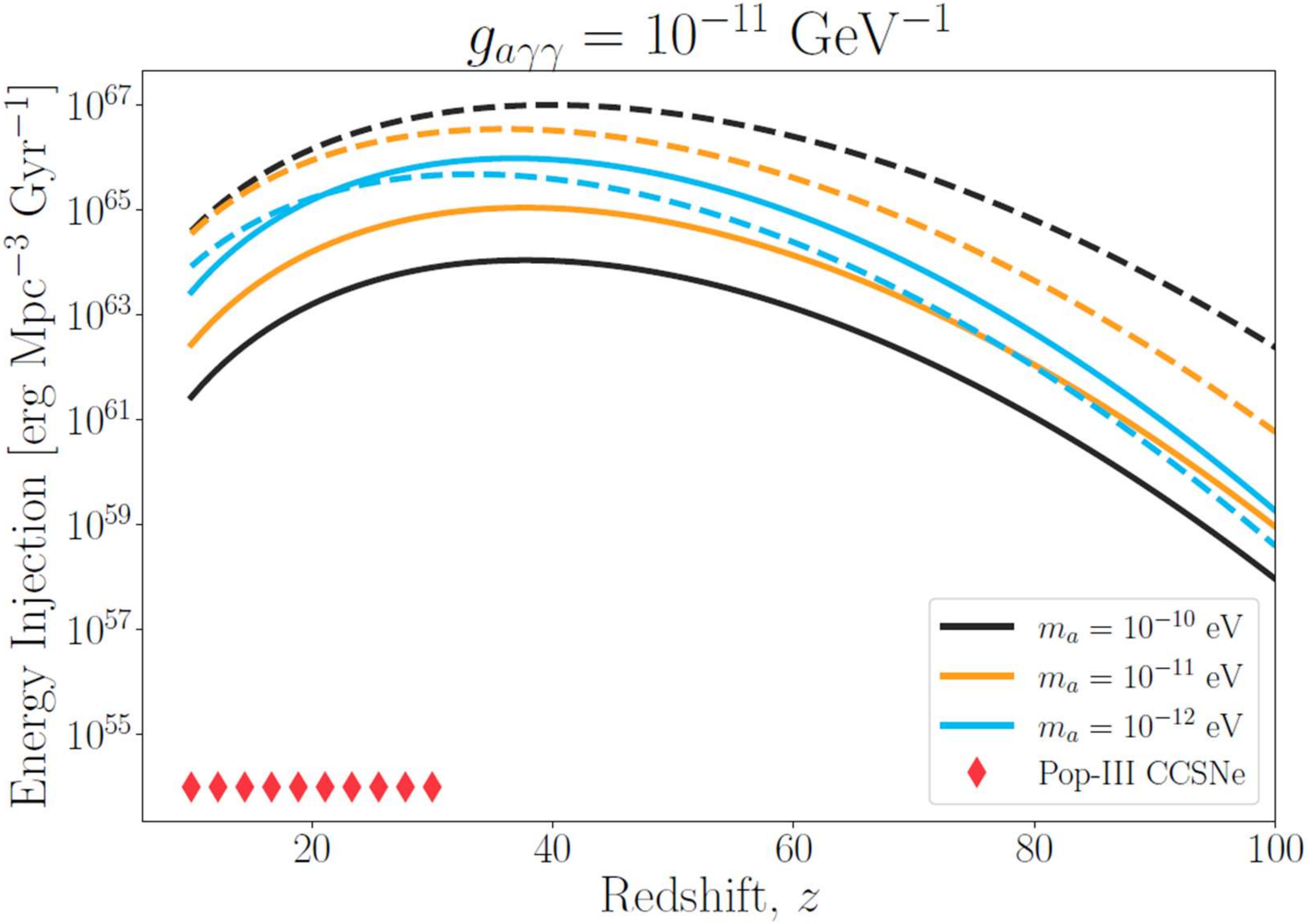
Levkov, Tkachev et al.

Need to track the production and destruction of axion stars through mergers…

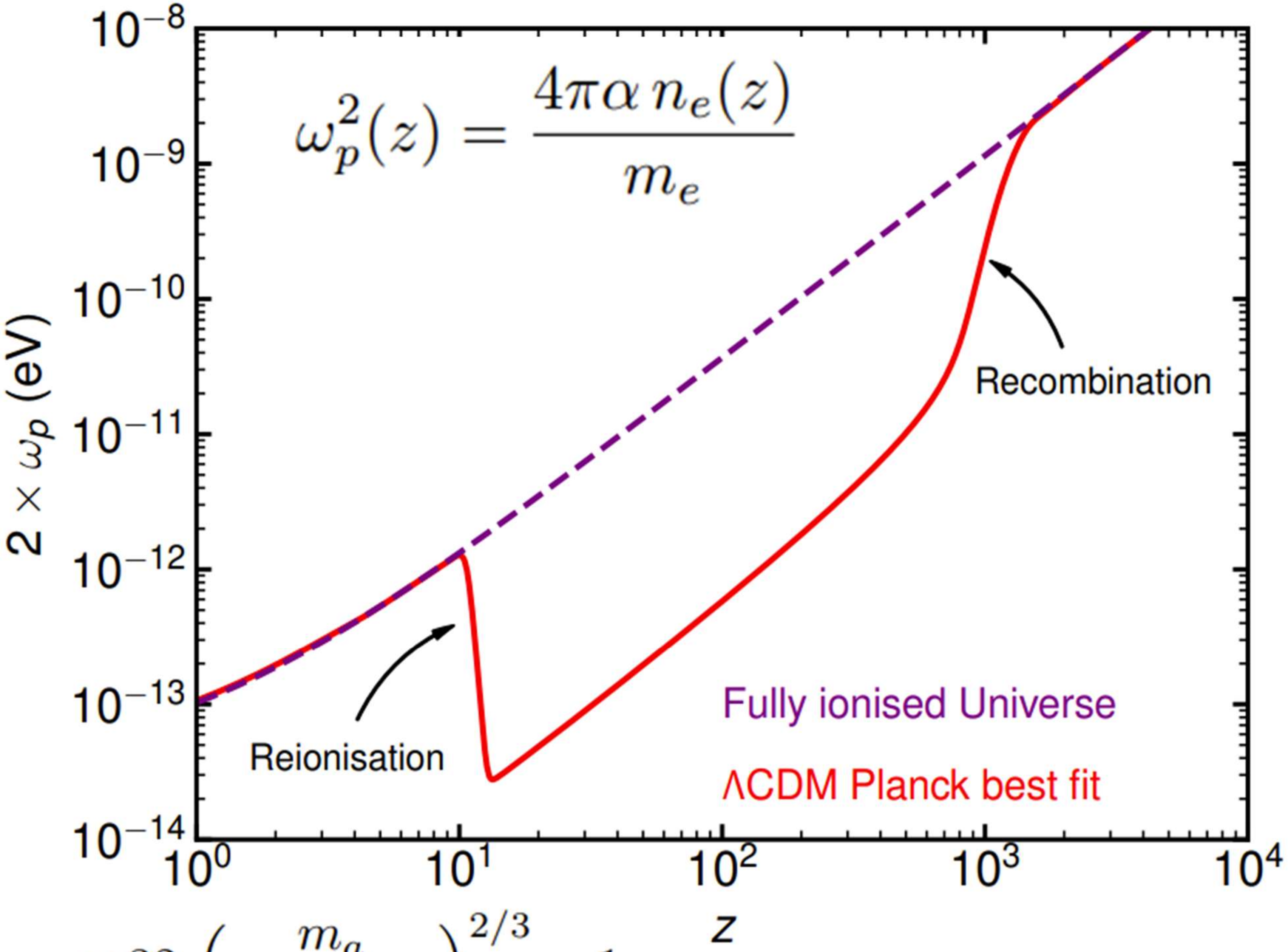




Total energy emitted many orders of magnitude larger than that from Supernovae

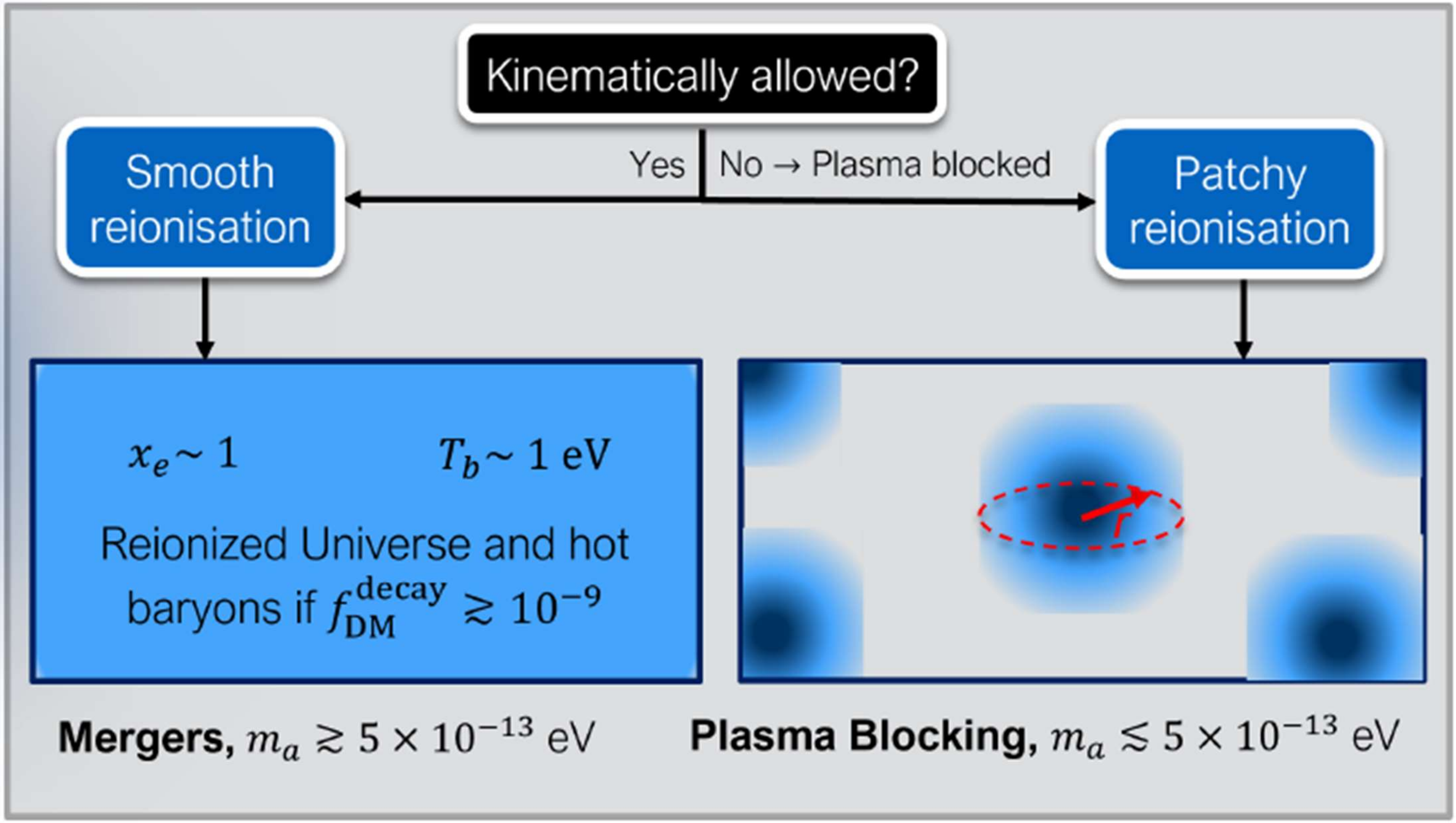


Photon Effective Mass can prevent Decay!



$$z_{\rm decay} \simeq 32 \left(\frac{m_a}{10^{-13}\,{\rm eV}}\right)^{2/3} - 1$$

Different Signatures → Consequence of Plasma Blocking



Kinematically allowed?

Yes

No → Plasma blocked

Smooth reionisation

Patchy reionisation

$x_e \sim 1$

$T_b \sim 1$ eV

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

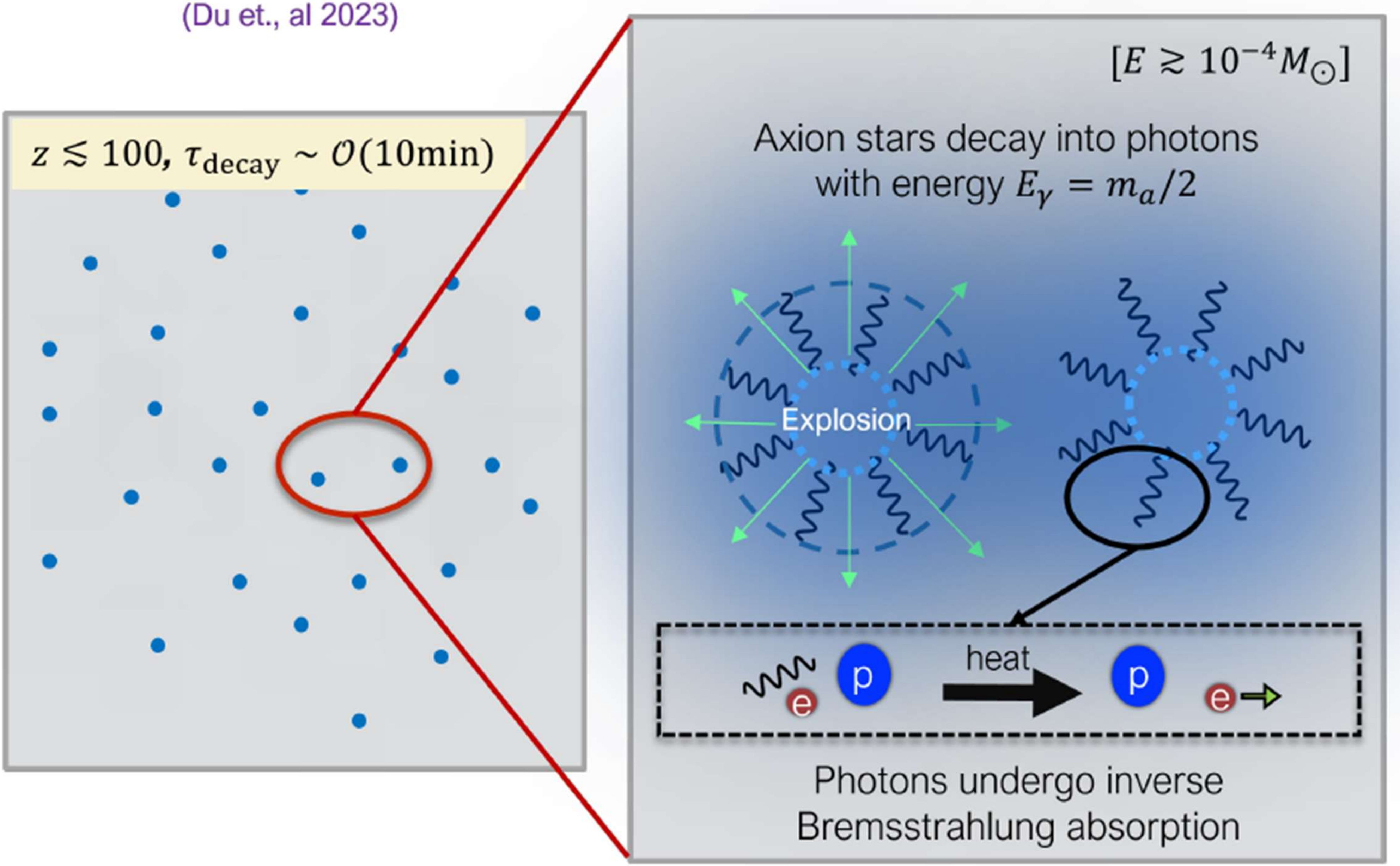
Mergers, $m_a \gtrsim 5 \times 10^{-13}$ eV

Plasma Blocking, $m_a \lesssim 5 \times 10^{-13}$ eV

Energy Density of Critical Solitons

(Du et., al 2023)

Emission of photons into IGM



$z \lesssim 100, \tau_{\text{decay}} \sim \mathcal{O}(10\text{min})$

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

Axion stars decay into photons with energy $E_{\gamma} = m_a/2$

Photons undergo inverse Bremsstrahlung absorption

Absorption of the photons in IGM through inverse Bremsstrahlung

$$\Gamma_{\rm abs} = n_e \sigma_T \frac{\Lambda_{\rm BR}(E_\gamma, z)(1 - e^{-E_\gamma/T_e})}{(E_\gamma/T_e)^3}$$

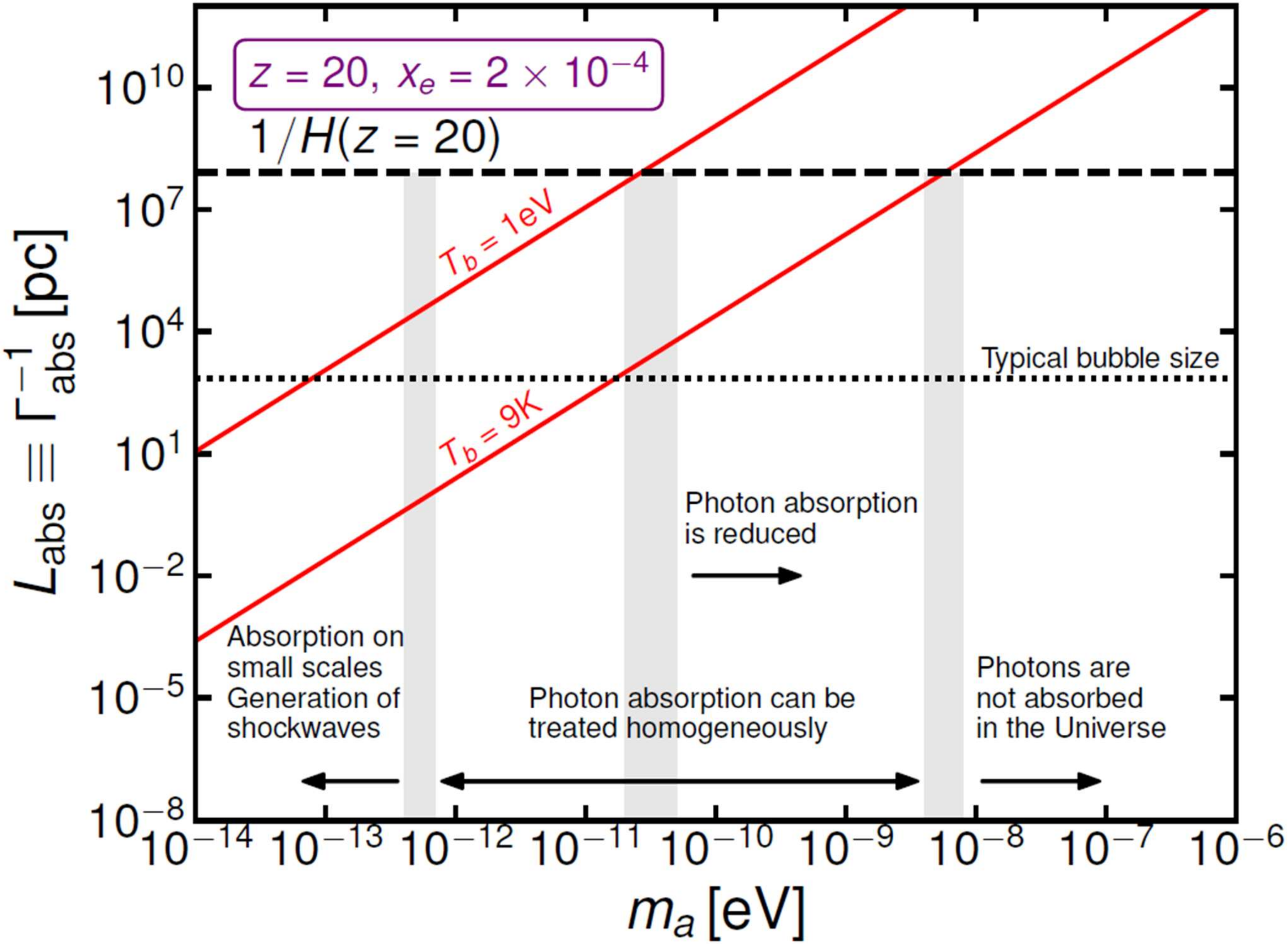
$$\Lambda_{\rm BR}(E_\gamma, z) = g_{\rm BR} \frac{n_p}{m_e^3} \sqrt{\frac{2}{3}} 2\pi^{3/2} \alpha \left(\frac{T_e}{m_e}\right)^{-7/2}$$

$$\Gamma_{\rm abs} \simeq 10^{-22}\,{\rm eV} \left[\frac{x_e}{2 \times 10^{-4}}\right]^2 \left[\frac{10^{-13}\,{\rm eV}}{m_a}\right]^2 \left[\frac{1+z}{21}\right]^4$$

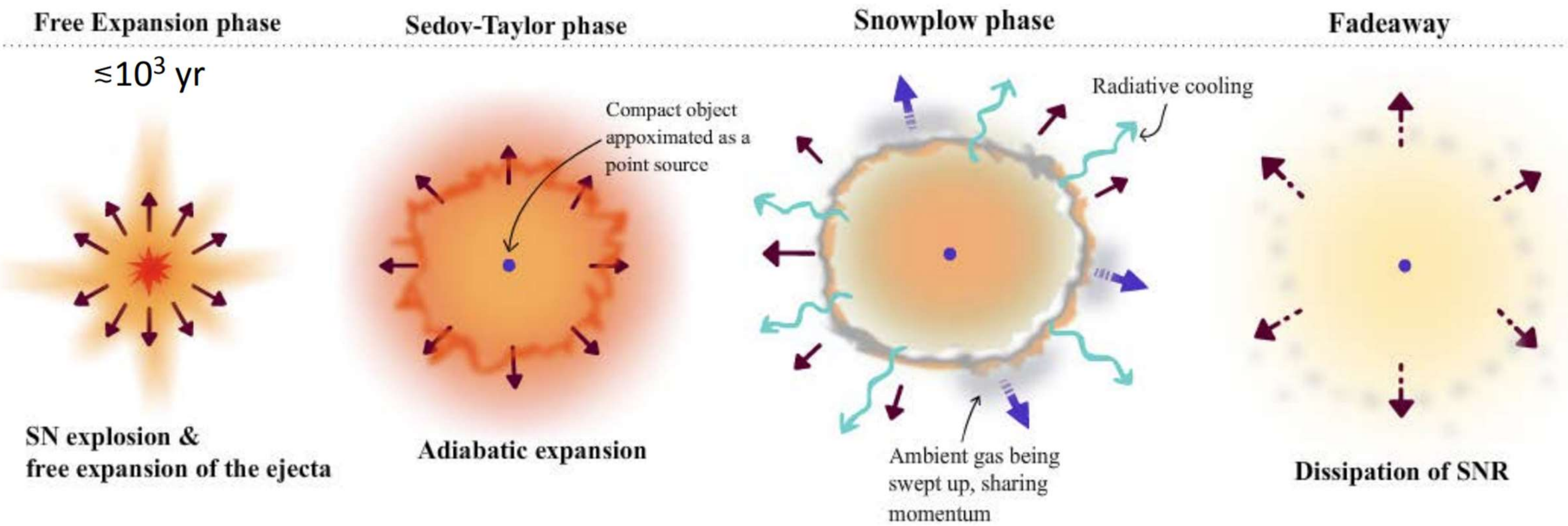
Less than a parsec

Absorption leads to super heated region which subsequently expands

Absorption of the photons in IGM through inverse Bremsstrahlung

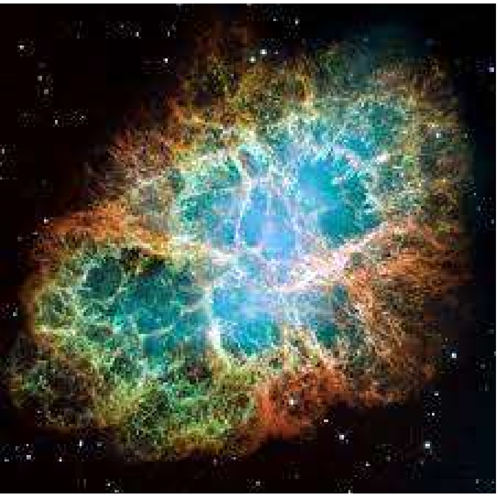
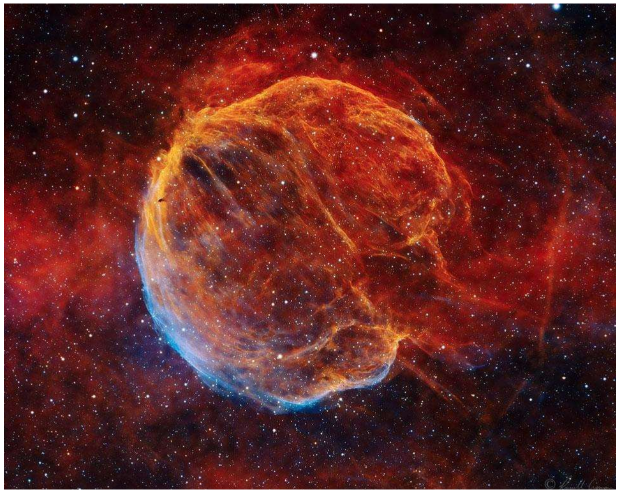
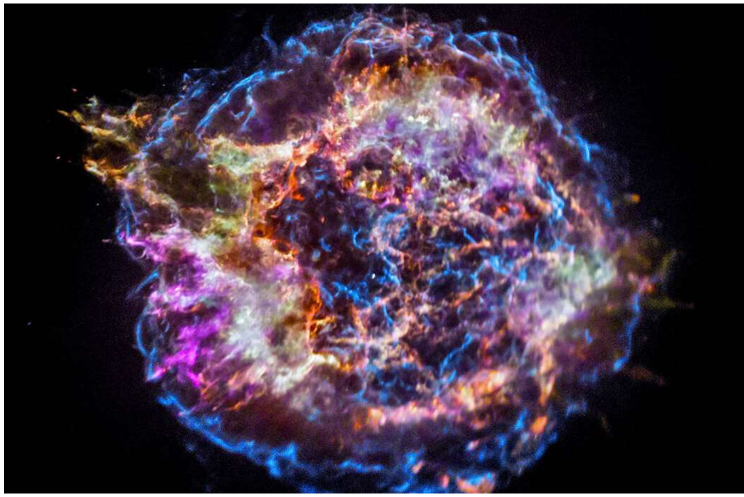


Have to use technology from Supernova Remnant evolution



$\lesssim 10^3$ yr

Picture from Ken Nagamine

Bubble of Hot Gas is created which Expands

Two simultaneous equations to solve.

$$\ddot{R} = \overbrace{\frac{8\pi G\, p}{\Omega_b H^2 R}}^{\text{Driving pressure inside bubble}} - \underbrace{\frac{3}{R}(\dot{R} - HR)^2}_{\text{Drag pressure to accelerate medium}} - \overbrace{\frac{\Omega_m H^2 R}{2}}^{\text{Self gravity of expanding shell}} - \underbrace{\frac{GM}{R^2}}_{\text{Self gravity of entire halo}}$$

$$\dot{p} = \frac{L_{\text{tot}}}{2\pi R^3} - \frac{5\dot{R}p}{R}$$

Evolution of Luminosity which drives Pressure

$$\dot{p} = \frac{L_{\rm tot}}{2\pi R^3} - \frac{5\dot{R}p}{R}$$

$$L_{\rm tot} = L_{\rm Explosion} - L_{\rm Compton} - L_{\rm Ionisation}$$

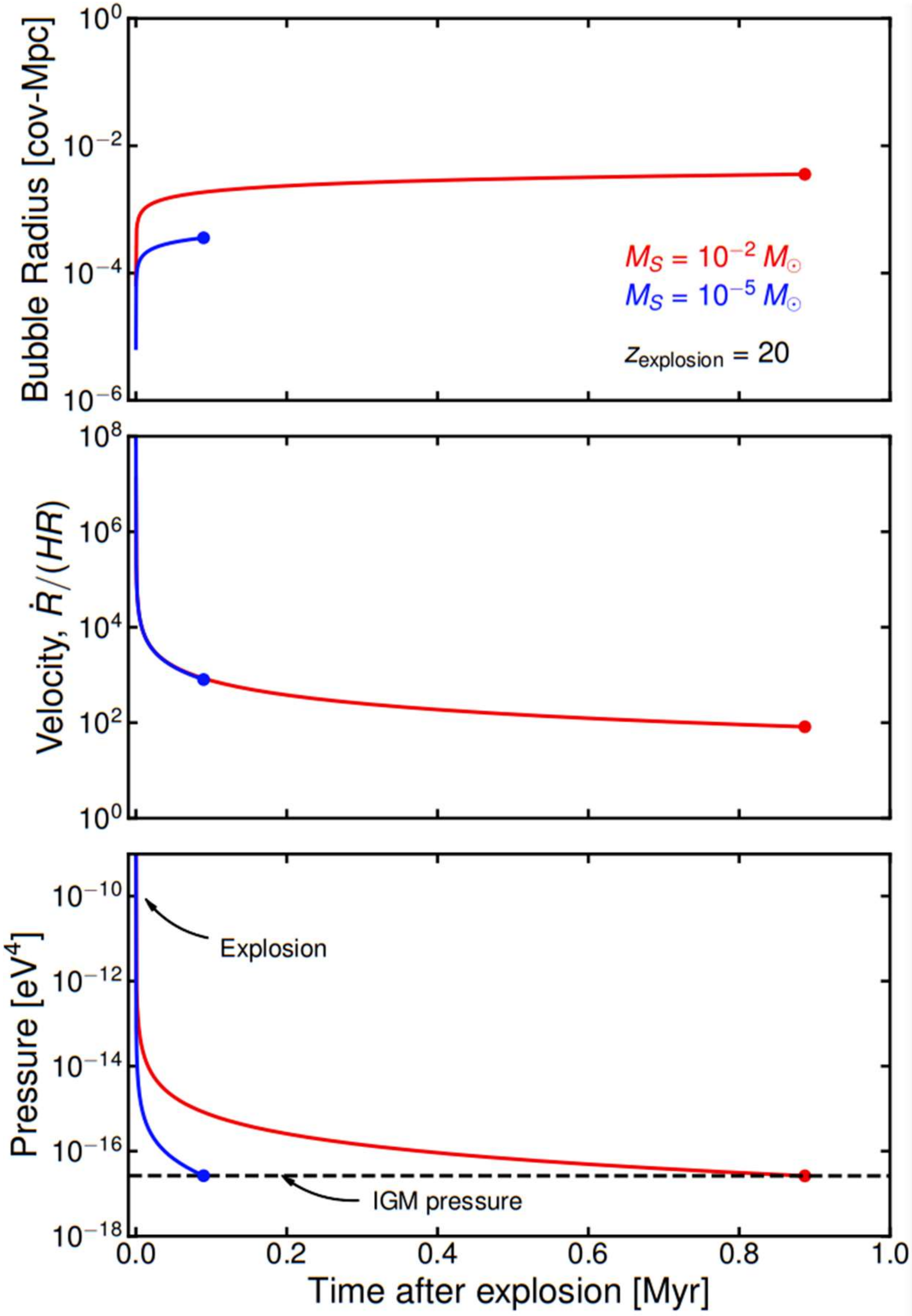
This switches off fairly quickly!

$$L_{\rm Compton} = \frac{2\pi^3}{45}\frac{\sigma_T}{m_e} T_\gamma^4 \, p R^3$$

$$L_{\rm Ionisation} = f_m \, n_b \, I_H 4\pi^2 R^2 (\dot{R} - HR)$$

$f_m << 1$ is fraction of baryonic mass kept inside bubble

Evolution of Bubble Size, velocity and pressure



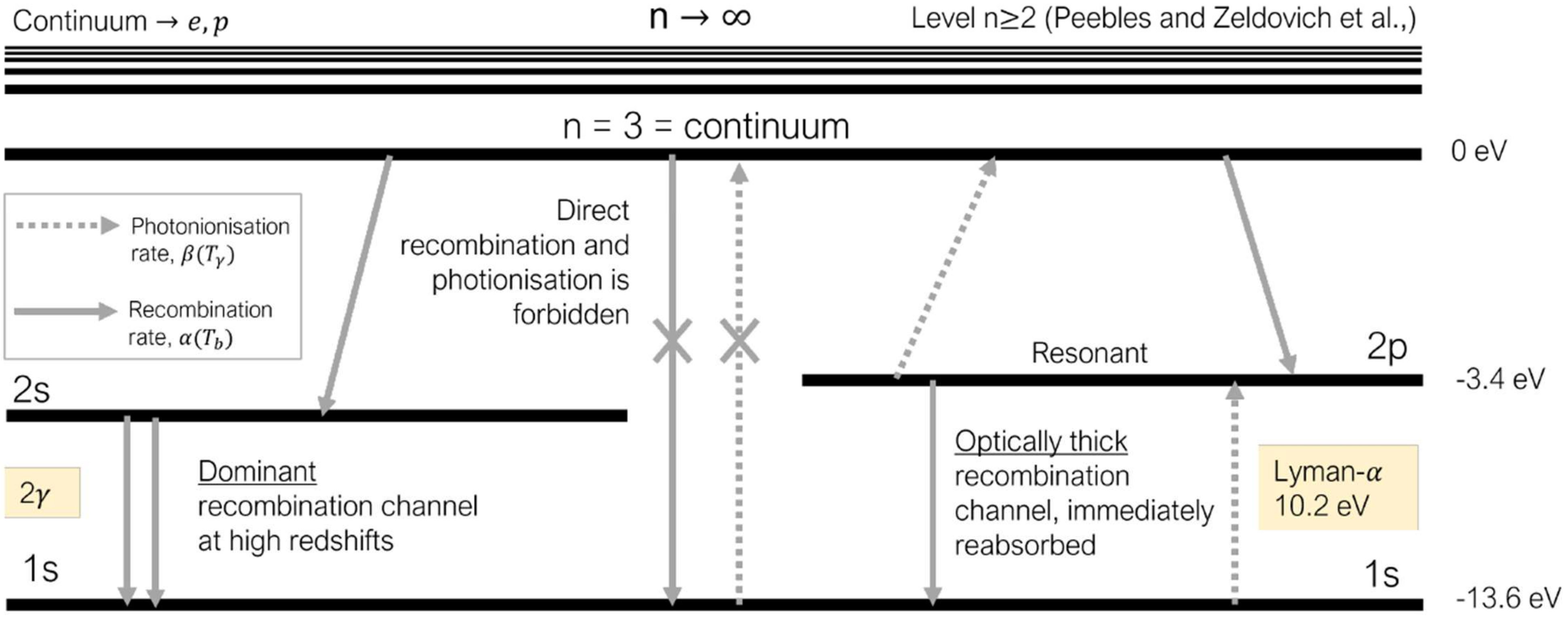
We end evolution when internal pressure is equal to IGM pressure!

Injection of energy heats up baryons

$$\frac{\mathrm{d}T_{\mathrm{b}}}{\mathrm{d}z}(1+z) = \underbrace{2T_{\mathrm{b}}}_{\text{Adiabatic cooling}} + \underbrace{\gamma_{\mathrm{op}}(T_{\mathrm{b}} - T_{\gamma})}_{\text{Compton cooling}} + \underbrace{\frac{2}{3}\frac{1}{N_{\mathrm{H}}(1+f_{\mathrm{He}}+X_{\mathrm{e}})}\frac{\mathrm{d}E}{\mathrm{d}z}\bigg|_{\mathrm{dep}}}_{\text{Additional heating}}$$

$$\frac{dT_b}{dt}\bigg|_{a\gamma\gamma} = \frac{2}{3}\frac{1}{N_{\mathrm{H}}(1+f_{\mathrm{He}}+X_{\mathrm{e}})} f_{\mathrm{DM}}^{\mathrm{burst}} \rho_{\mathrm{DM}} \delta(t - t_{\mathrm{DM}})$$

We use a three level model for hydrogen and also include Helium



Continuum → e, p

n → ∞

Level n≥2 (Peebles and Zeldovich et al.,)

n = 3 = continuum

0 eV

Photonionisation rate, $\beta(T_\gamma)$

Recombination rate, $\alpha(T_b)$

Direct recombination and photionisation is forbidden

Resonant

2p

-3.4 eV

2s

2γ

Dominant recombination channel at high redshifts

Optically thick recombination channel, immediately reabsorbed

Lyman-α 10.2 eV

1s

1s

-13.6 eV

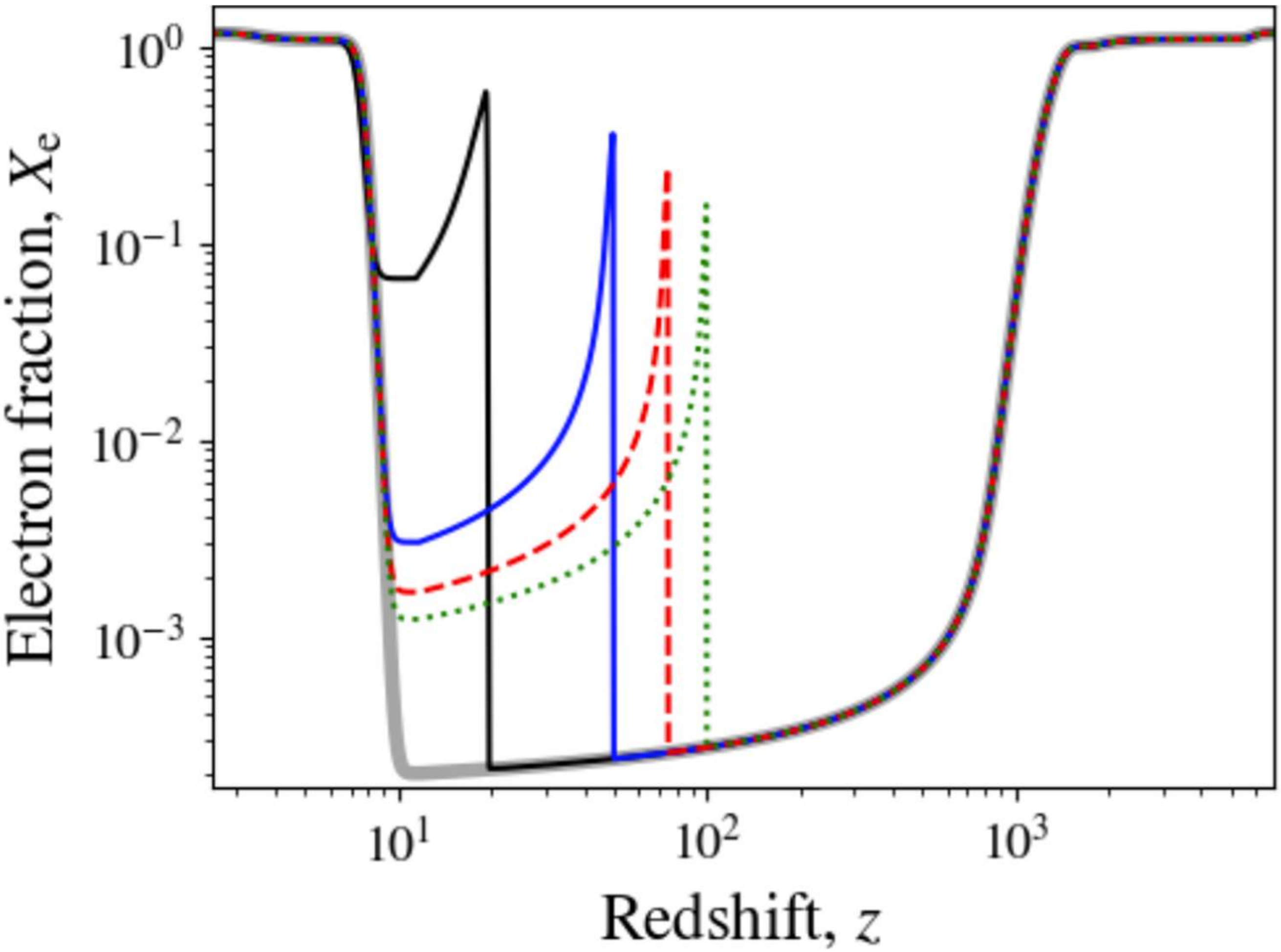
Goal → HI recombination

$$X_\mathrm{e}(z) = X_\mathrm{HeI}(z) + X_\mathrm{p}(z)$$

$$\frac{\mathrm{d}X_\mathrm{p}}{\mathrm{d}t} = \mathcal{C}_\mathrm{H}\left(\beta_\mathrm{H}(T_\gamma)(1-X_\mathrm{p})\mathrm{e}^{\frac{-\epsilon_{\mathrm{H},2s1s}}{T_\gamma}} - X_\mathrm{e}X_\mathrm{p}N_\mathrm{H}\alpha_\mathrm{H}^{(2)}(T_b) + \left.\frac{\mathrm{d}X_\mathrm{p}}{\mathrm{d}t}\right|_\mathrm{coll}\right)$$

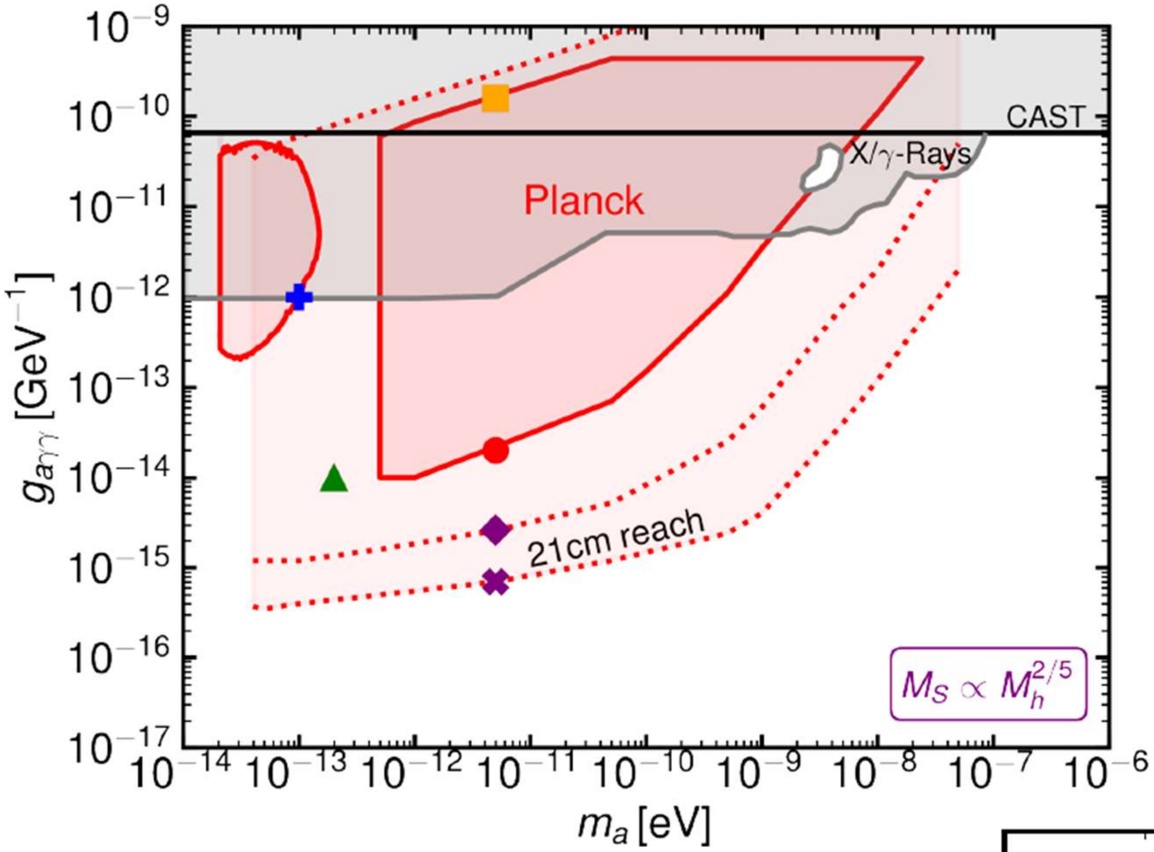
$$\frac{\mathrm{d}X_\mathrm{HeII}}{\mathrm{d}t} = \mathcal{C}_\mathrm{He}\left((f_\mathrm{He} - X_\mathrm{HeII})\beta_\mathrm{He}(T_\gamma)\mathrm{e}^{\frac{-\epsilon_{\mathrm{He},2s1s}}{T_\gamma}} - X_\mathrm{HeII}^2 N_\mathrm{H}\alpha_\mathrm{HeII}^{(2)}(T_b) + \left.\frac{\mathrm{d}X_\mathrm{HeII}}{\mathrm{d}t}\right|_\mathrm{coll}\right)$$

The burst of radiation changes the ionisation of the Universe

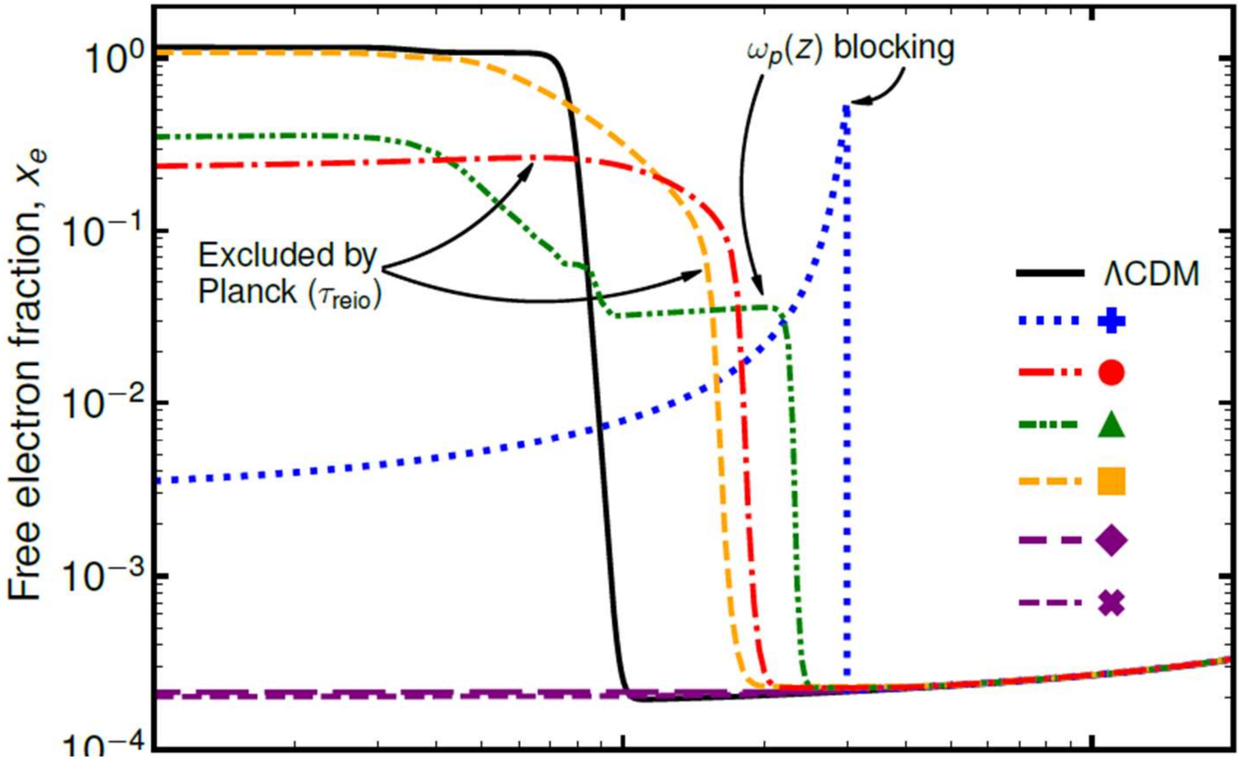


Net result depends on following factors:-

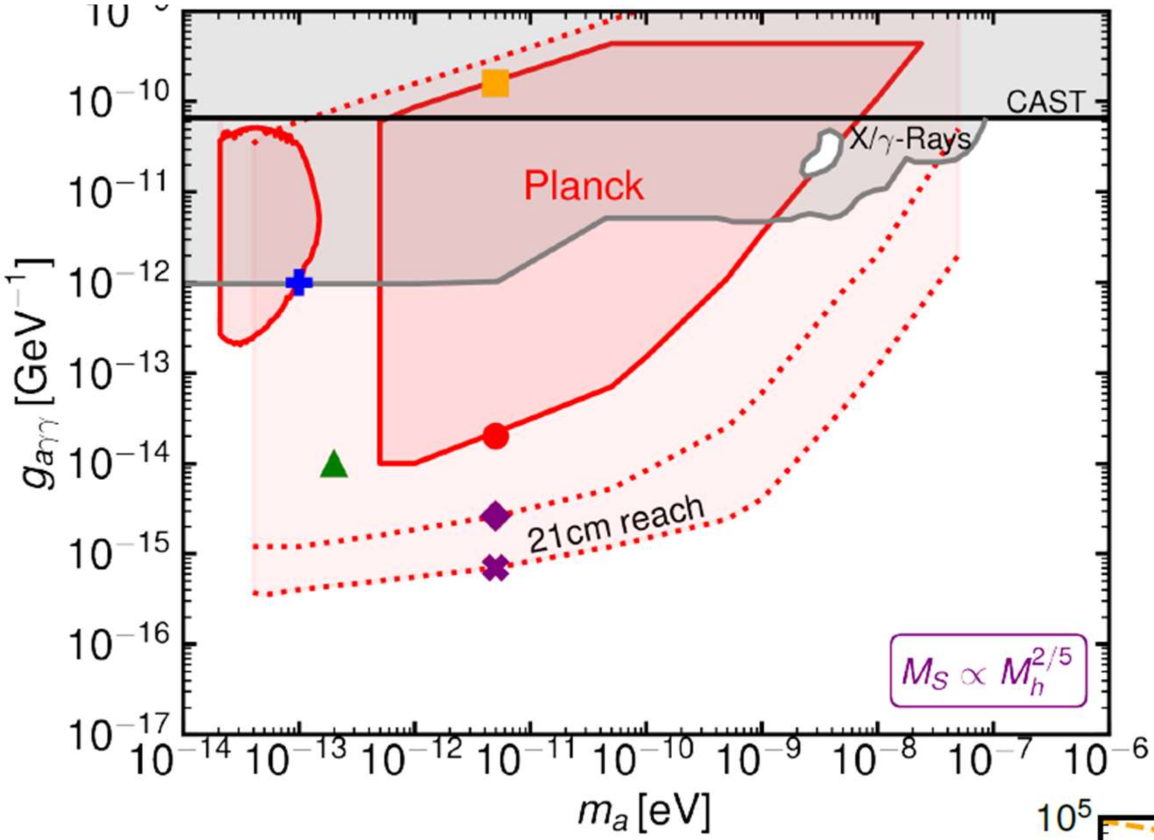
- How many solitons exist above critical mass when $m_a = \omega_p$?
- How many solitons above critical mass form later?
- How much energy is dumped into the Universe?
- How much ionisation takes place?
- Do the bubbles Coalesce?

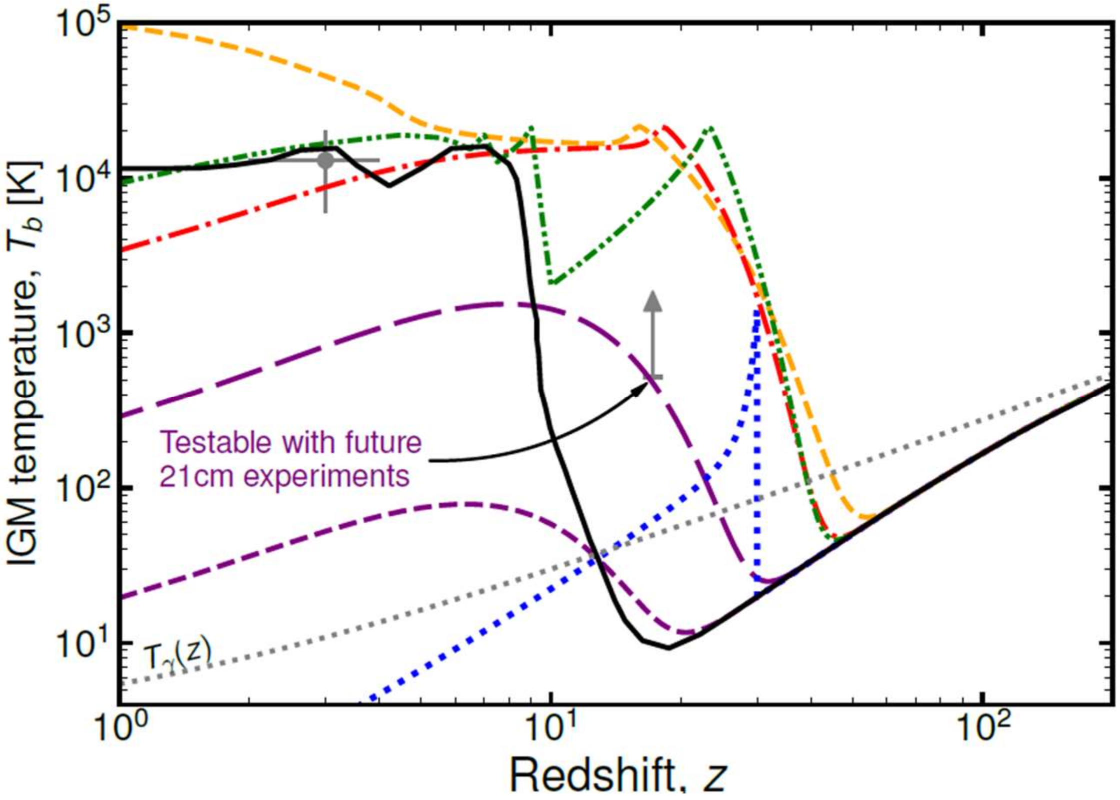


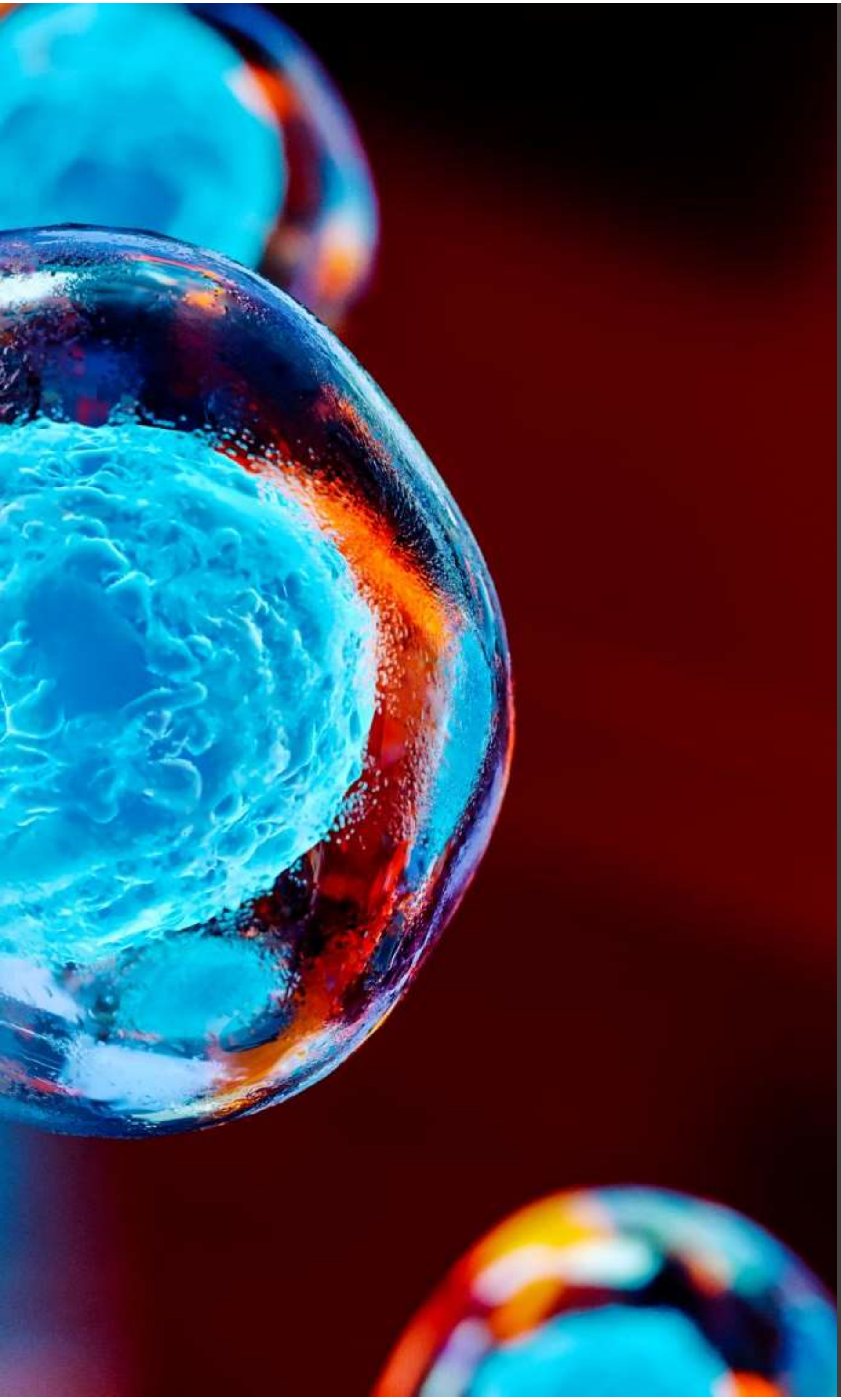
Constraints from the Opacity of the CMB



Constraints from future 21cm observations







Conclusions

- Fuzzy Dark Matter leads to solitonic cores in dark matter halos
- Axion decay into photons is enhanced in dense regions
- Solitons decay and ionise the Universe
- CMB puts constraints on this region of parameter space which beats other tests