Axion Star Explosions in the Early Universe

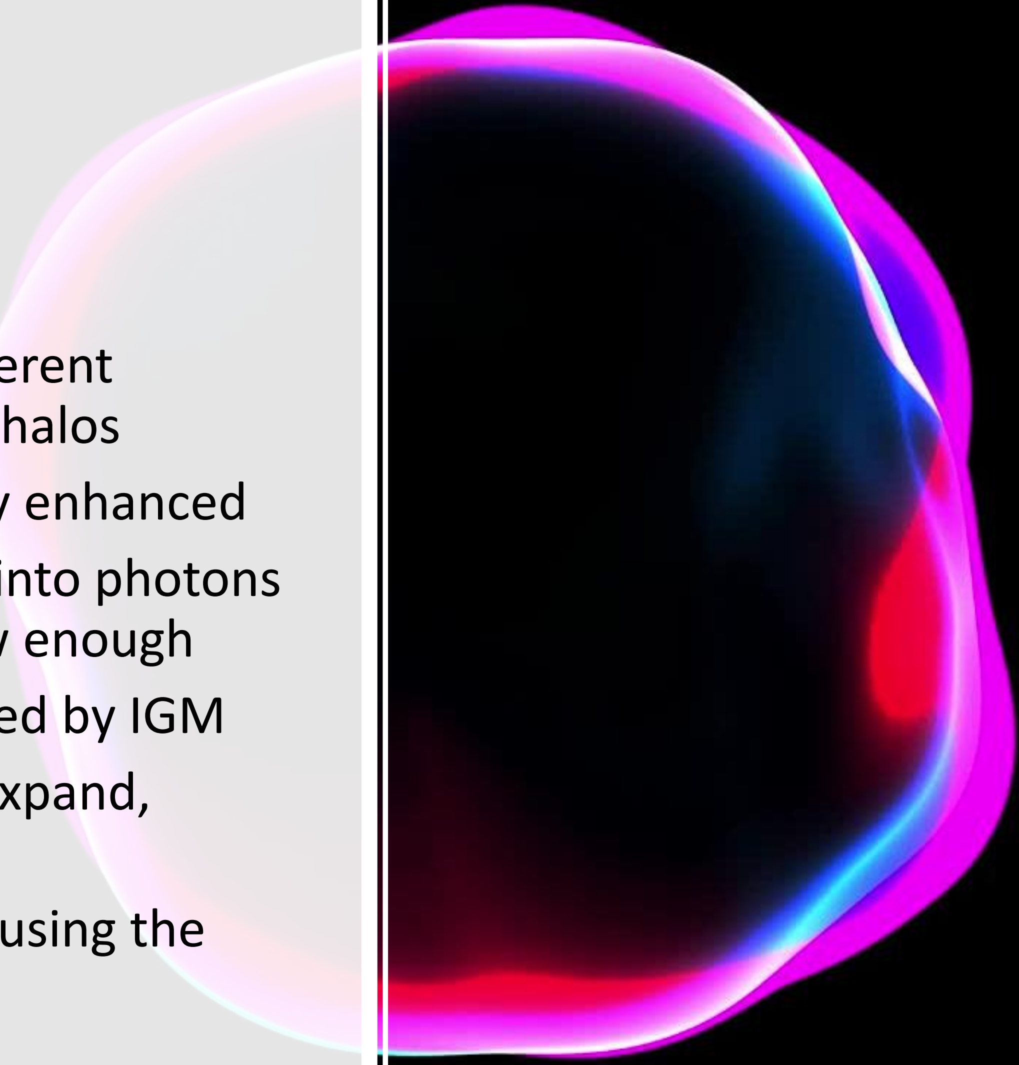
Malcolm Fairbairn

Work done together with

Xiaolong Du, Charis Pooni, Miguel Escudero, Doddy Marsh & Diego Blas

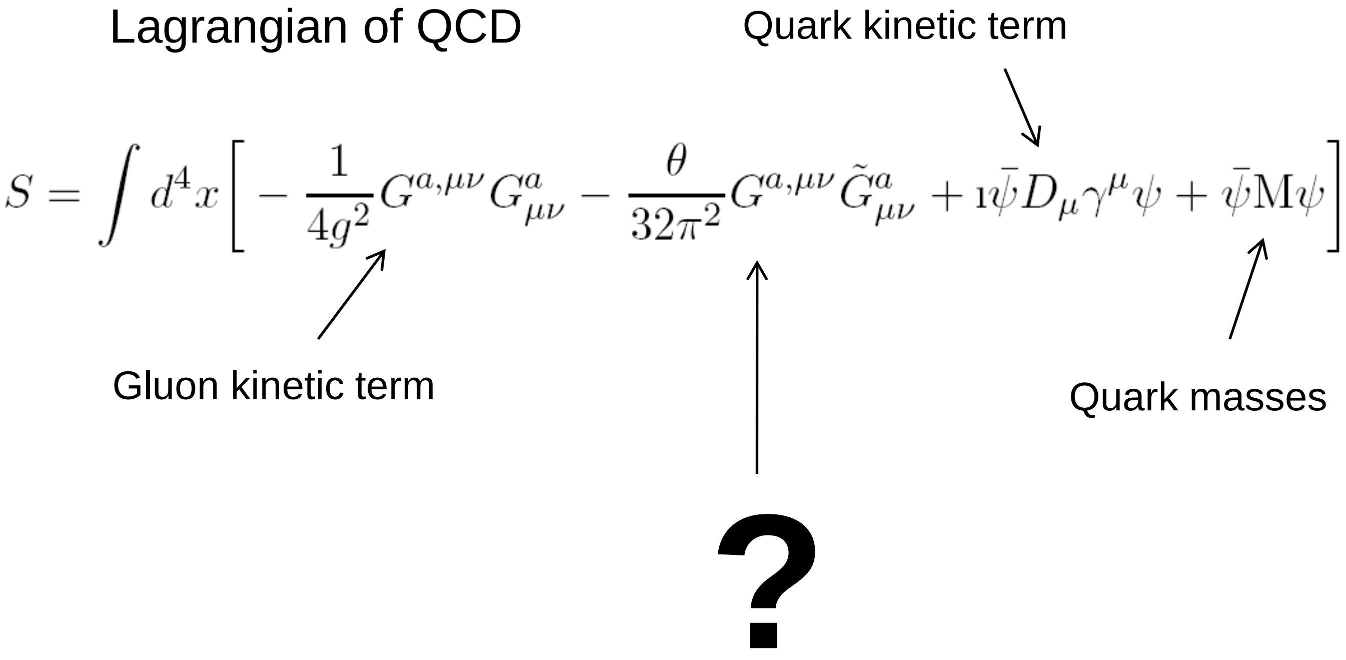
Here is the Idea…

- 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

?

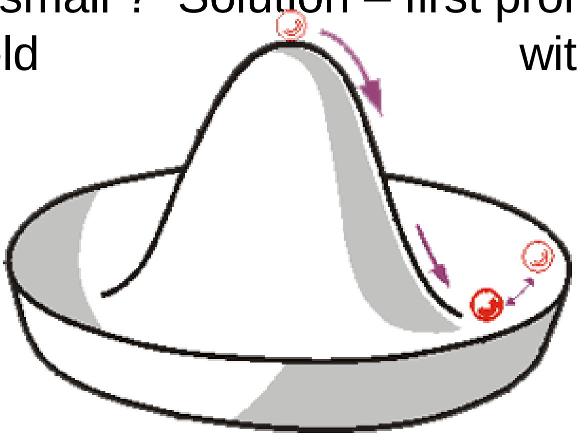
Neutron Dipole Moment and strong CP problem

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

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

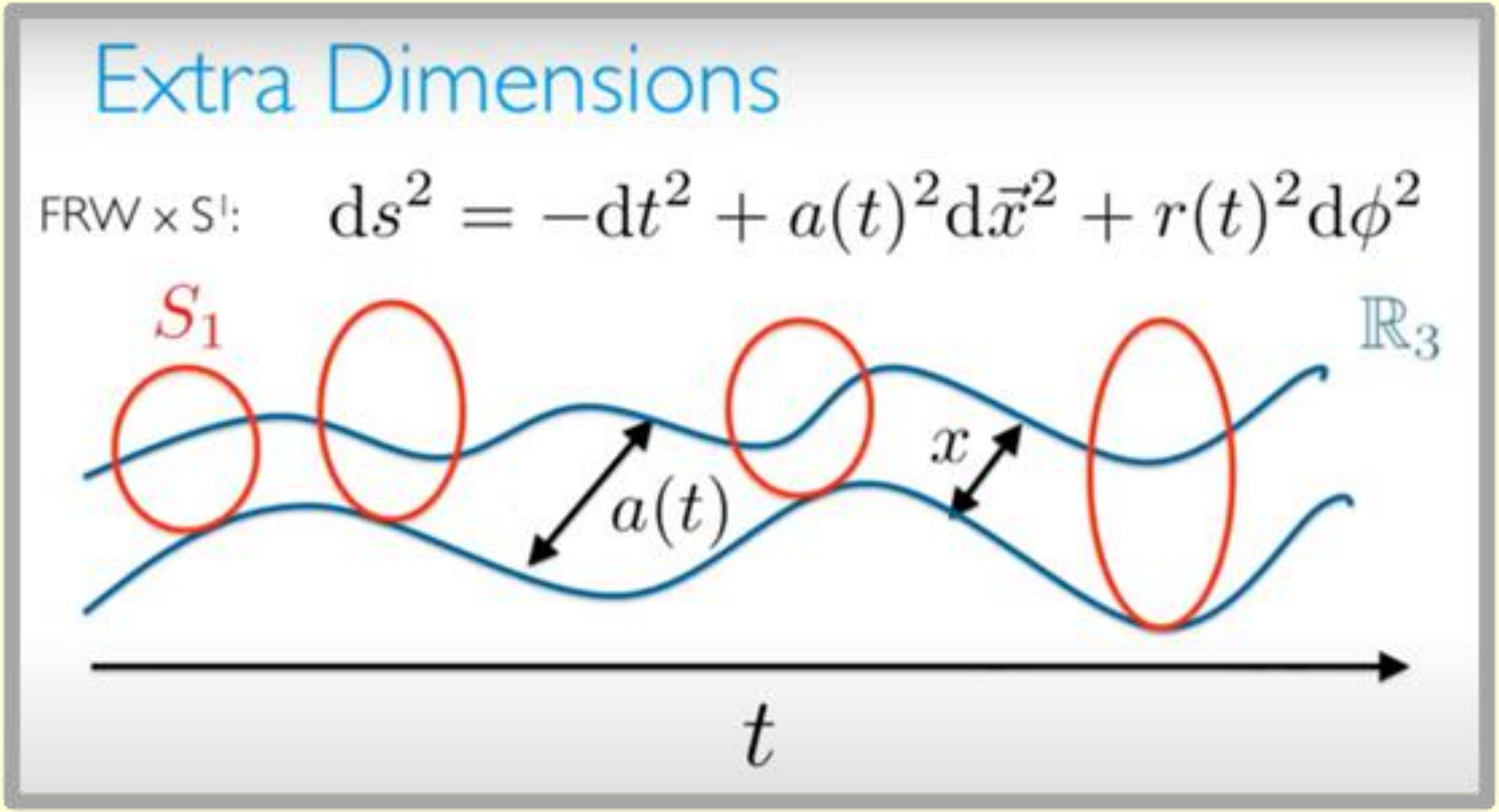
However, no edm observed down to d~ 10^{-27} e cm

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.



Extra Dimensions

FRW × S^1: $ds^2 = -dt^2 + a(t)^2 d\vec{x}^2 + r(t)^2 d\phi^2$

axion like particles also predicted by string theory compactifications.

Coupling to Photons

Usually there is also an induced coupling to photons.

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

Which allows for mixing between photons and axions in magnetic fields….

Linearised wave equation

$$i\partial_z \Psi = -\left(\omega + \mathcal{M}\right)\Psi \qquad ; \qquad \Psi = \begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix}$$

$$\mathcal{M} \equiv \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_\parallel & \Delta_M \\ 0 & \Delta_M & \Delta_m \end{pmatrix}$$

See, e.g. Raffelt and Stodolsky 1987

Mixing Matrix

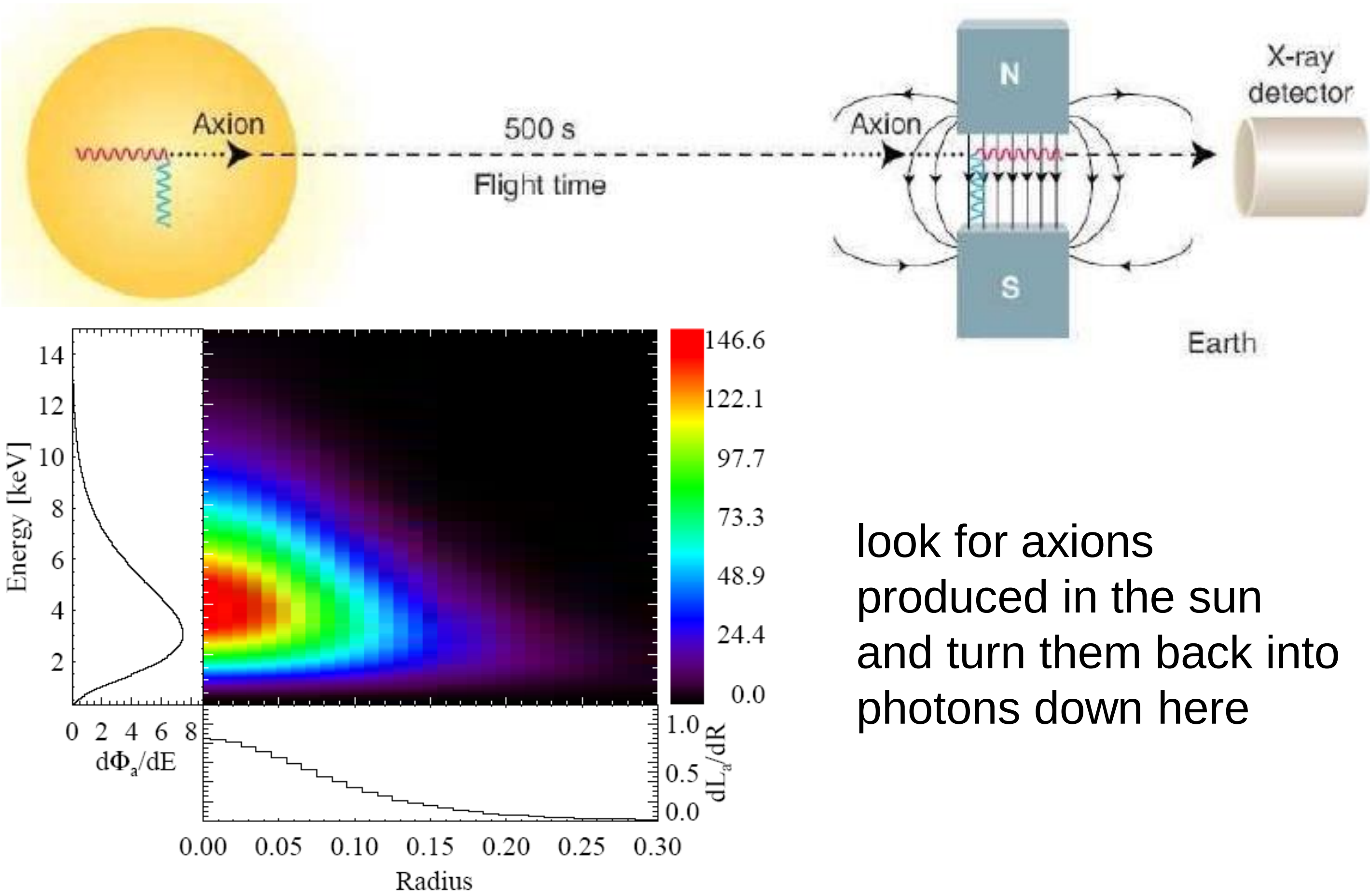
$$\mathcal{M} \equiv \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_\parallel & \Delta_M \\ 0 & \Delta_M & \Delta_m \end{pmatrix}$$

$$\begin{aligned} \Delta_m &= -\frac{m_a^2}{2\omega} \\ \Delta_M &= \frac{B}{2M} \end{aligned}$$

$$\begin{aligned} \Delta_\perp &= \frac{4}{2}\omega\xi\sin^2\Theta + \Delta_p \\ \Delta_\parallel &= \frac{7}{2}\omega\xi\sin^2\Theta + \Delta_p \\ \xi &= \frac{\alpha^2}{180\pi}\left(\frac{B}{m_e^2}\right)^2 \\ \Delta_p &= -\frac{\omega_p^2}{2\omega} \\ \omega_p^2 &= \frac{4\pi\alpha n_e}{m_e} \end{aligned}$$

CAST: cern-axion-solar-telescope

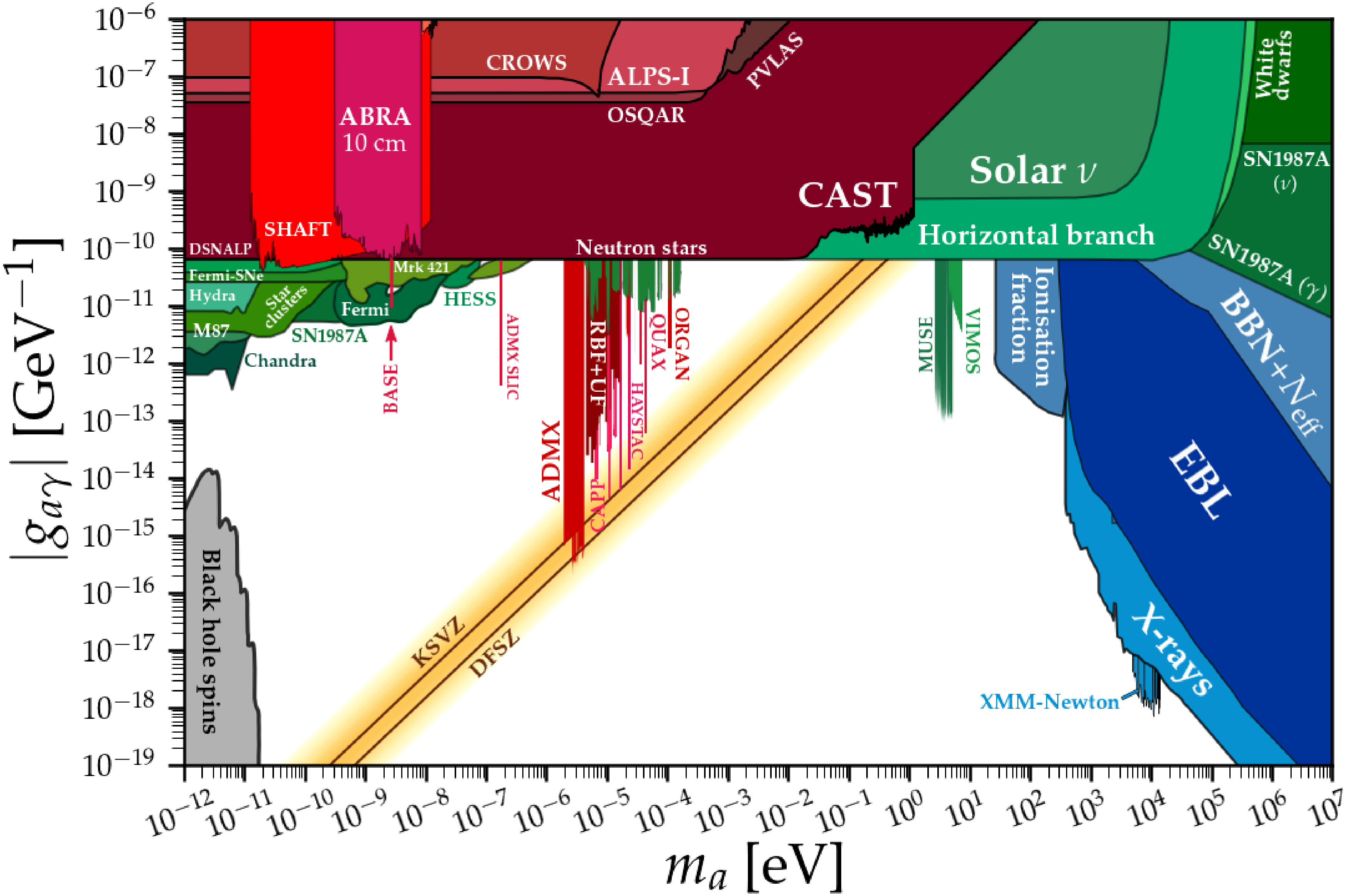
Search for Solar axions



look for axions produced in the sun and turn them back into photons down here

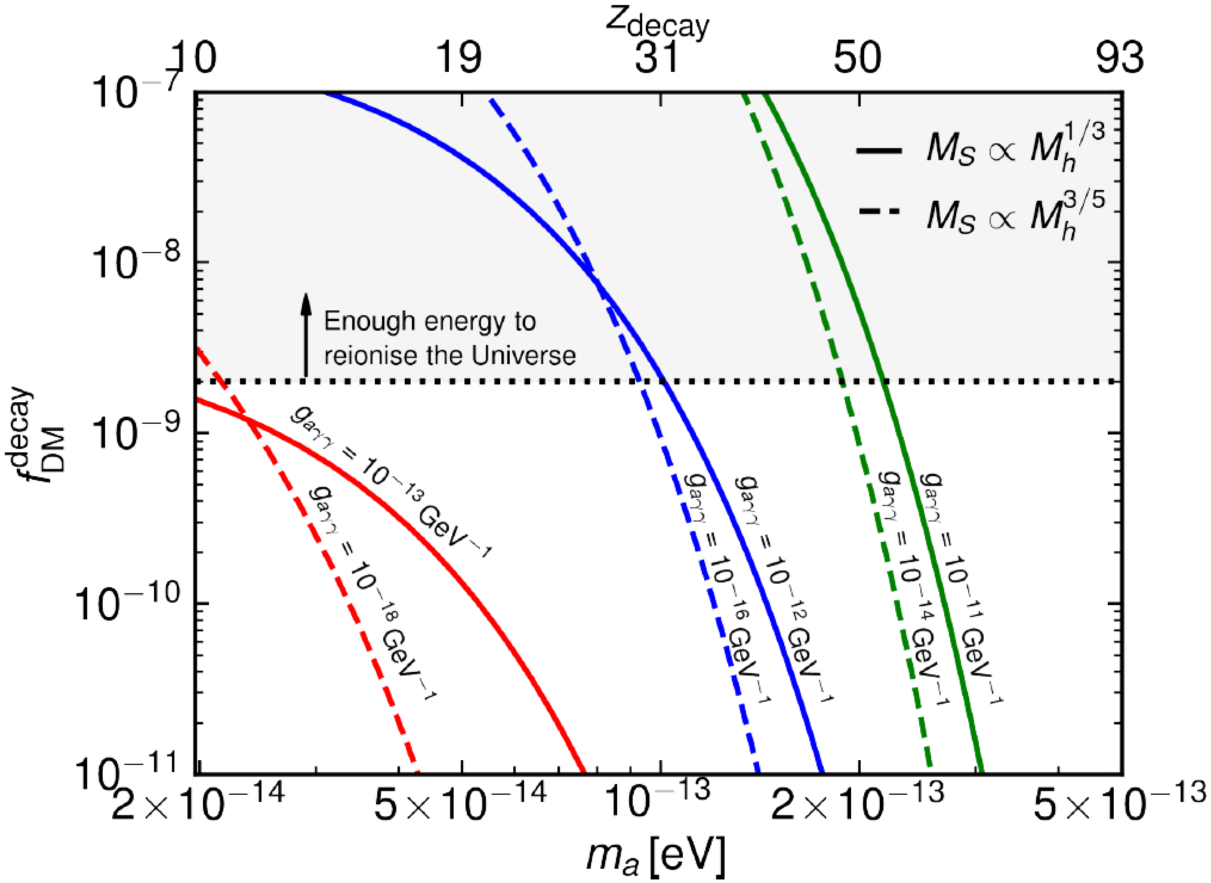
laboratory CAST bound

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



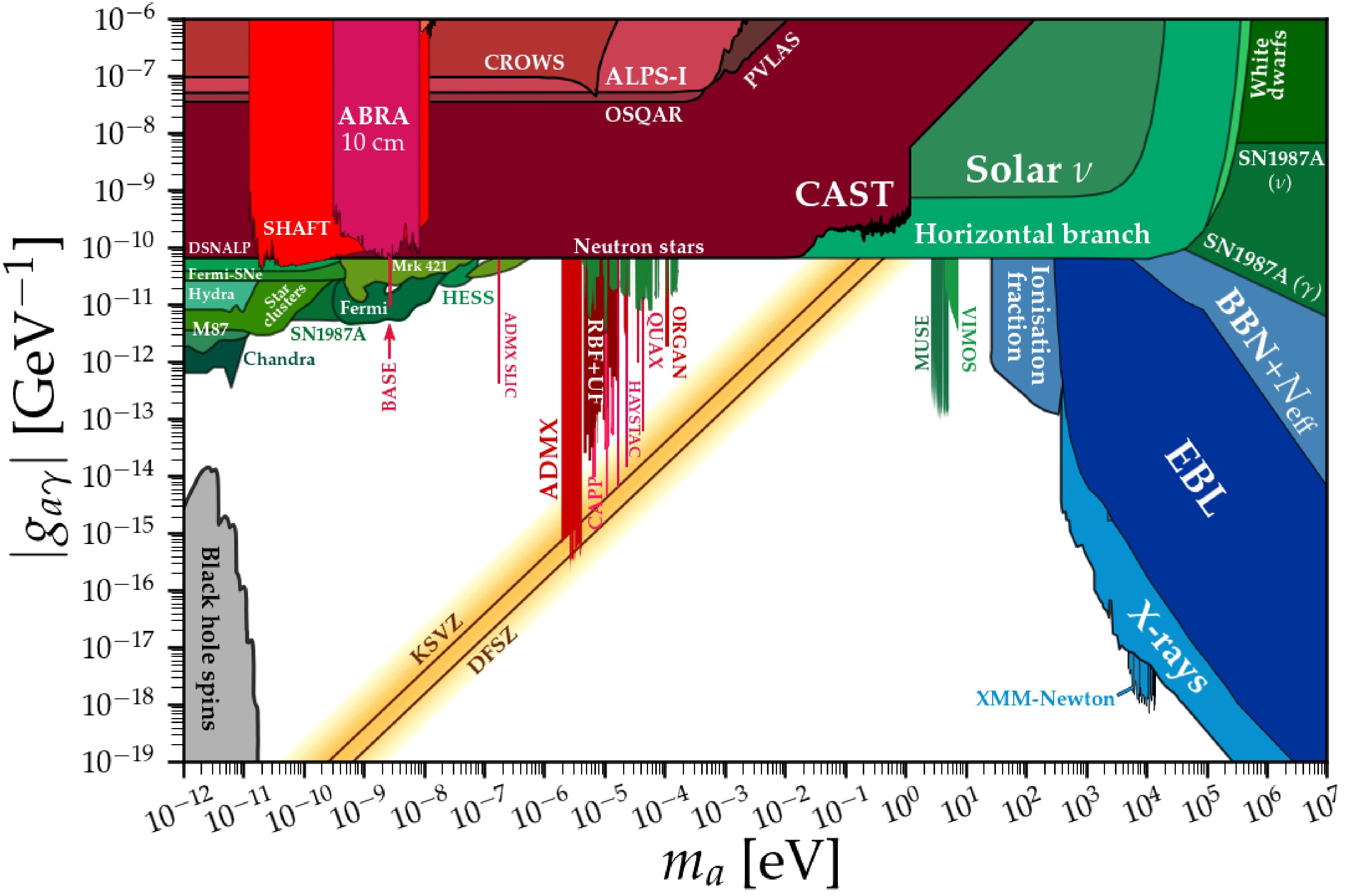
Axions can also decay! Only a small fraction would ionise the Universe

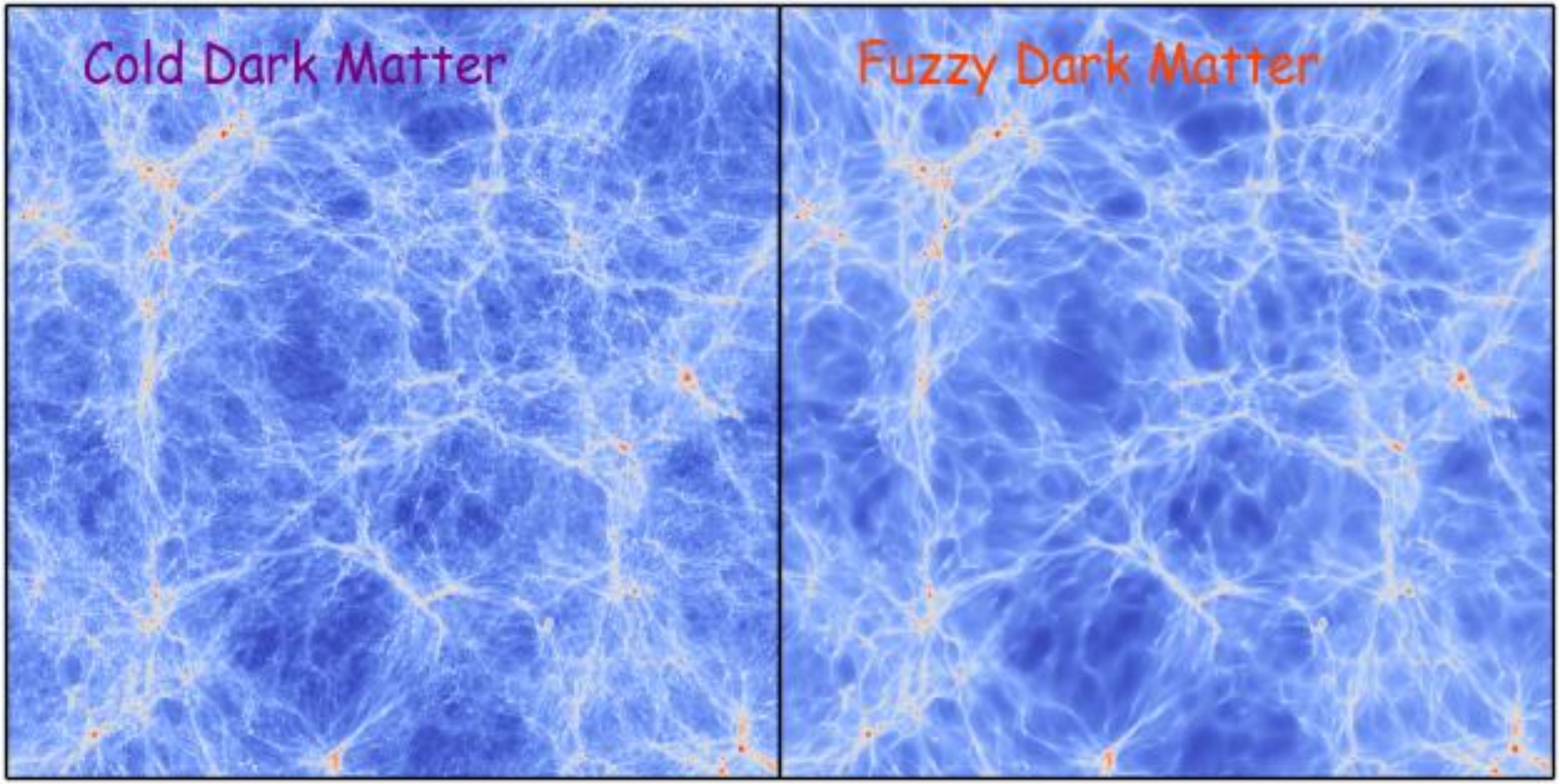
$$\Gamma(a \to \gamma\gamma) = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$



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

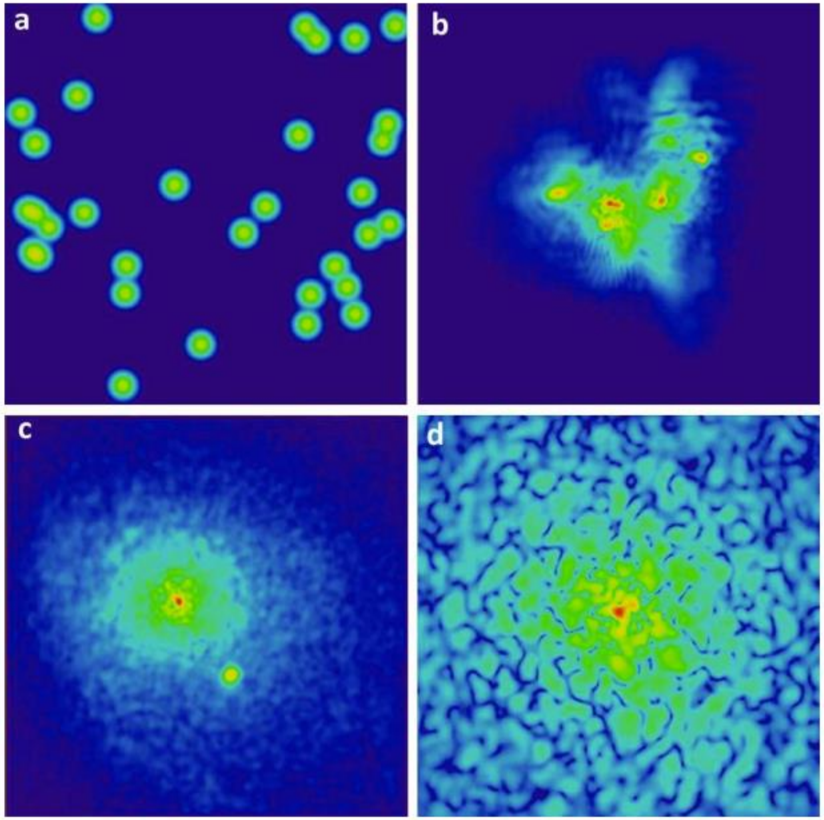
$$g_{a\gamma\gamma} < \ 0.66 \ \times \ 10^{-10}\,\mathrm{GeV}^{-1} \ \ \text{for} \ \ m_a \ < \ 0.02\,\mathrm{eV}$$

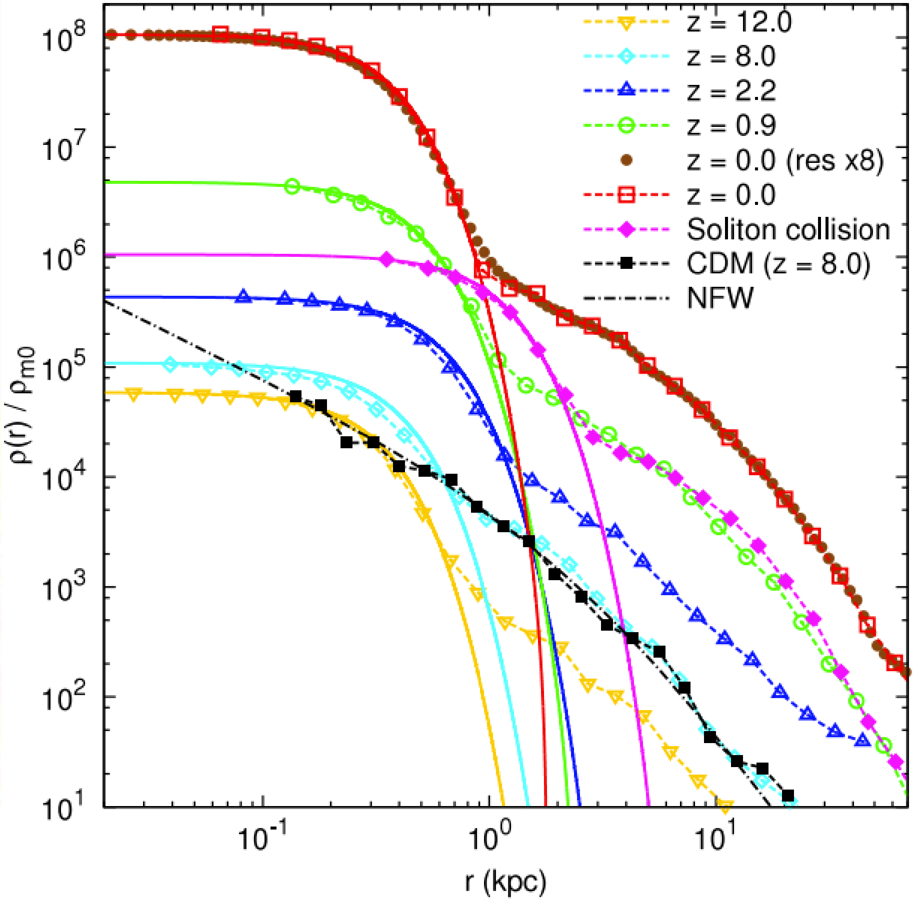




$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2ma^2}\nabla^2\psi + \frac{m\Phi}{a}\psi$$

$$\nabla^2\Phi = 4\pi Gm(|\psi|^2 - \langle|\psi|^2\rangle)$$





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

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

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

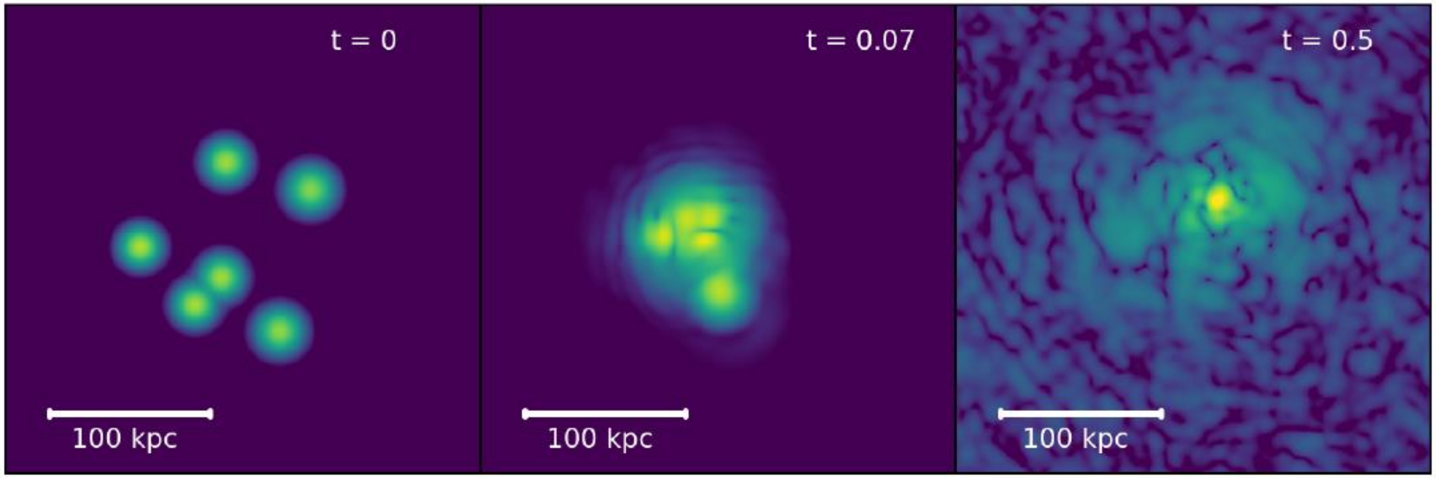
$$\rho(r) = \begin{cases} \rho_\mathrm{c} \left[1 + 0.091 \left(\frac{r}{r_\mathrm{c}}\right)^2\right]^{-8} & , \text{for } r < r_\mathrm{t} \\ \rho_\mathrm{s} \left[\frac{r}{r_\mathrm{s}}\right]^{-1} \left[1 + \left(\frac{r}{r_\mathrm{s}}\right)\right]^{-2} & , \text{for } r \geq r_\mathrm{t} \end{cases}$$

Schive et al 2014

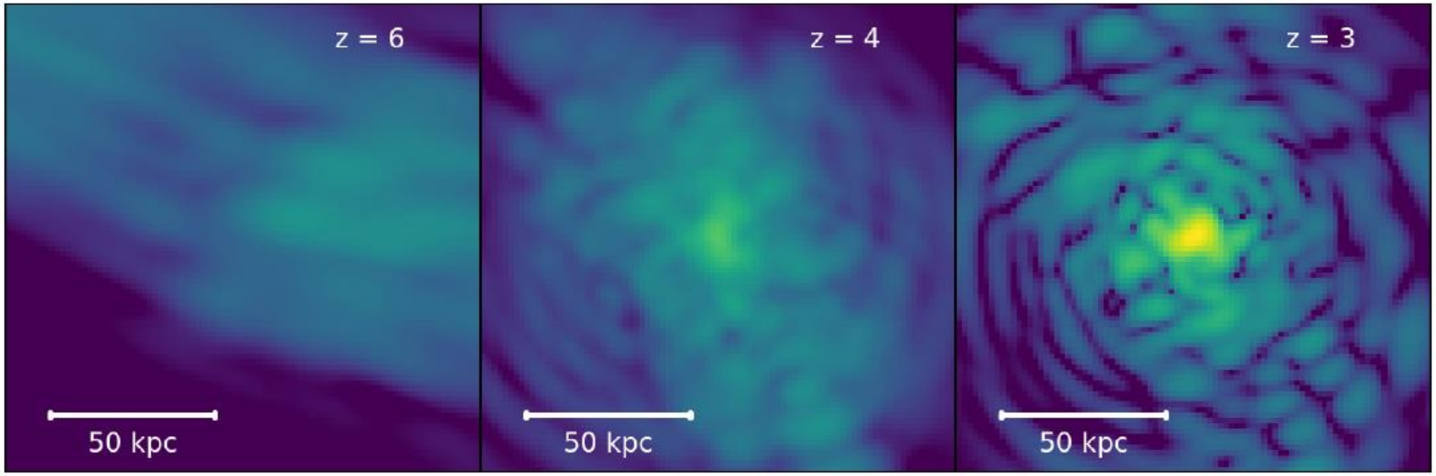
The Diversity of Core–Halo Structure in the Fuzzy Dark Matter Model

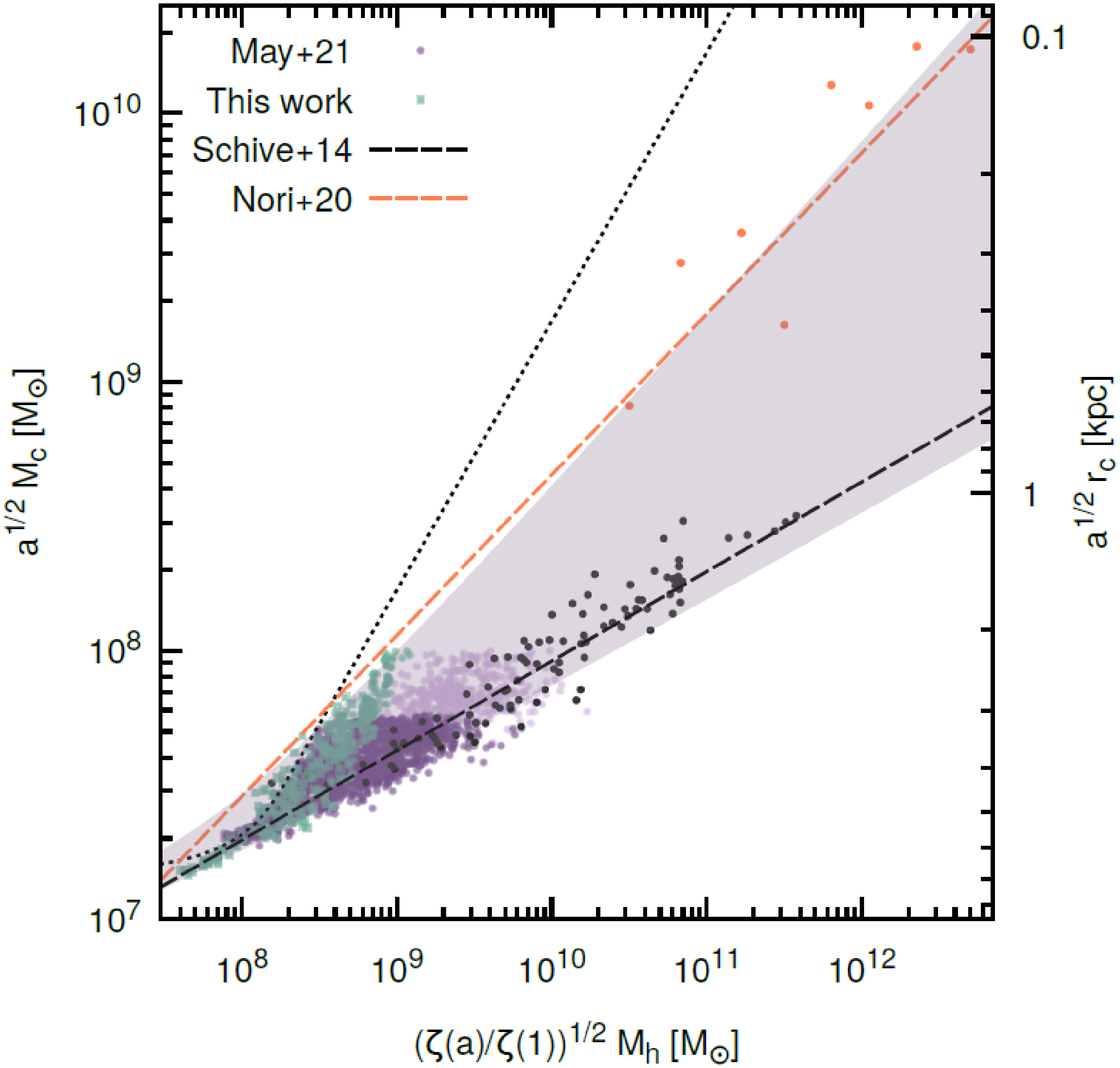
Hei Yin Jowett Chan,[1]★ Elisa G. M. Ferreira,[2,3,4] Simon May,[2]★ Kohei Hayashi,[5,6] Masashi Chiba[1]

Coalesence of halos to form bigger halo



Formation of a single halo from smaller halos





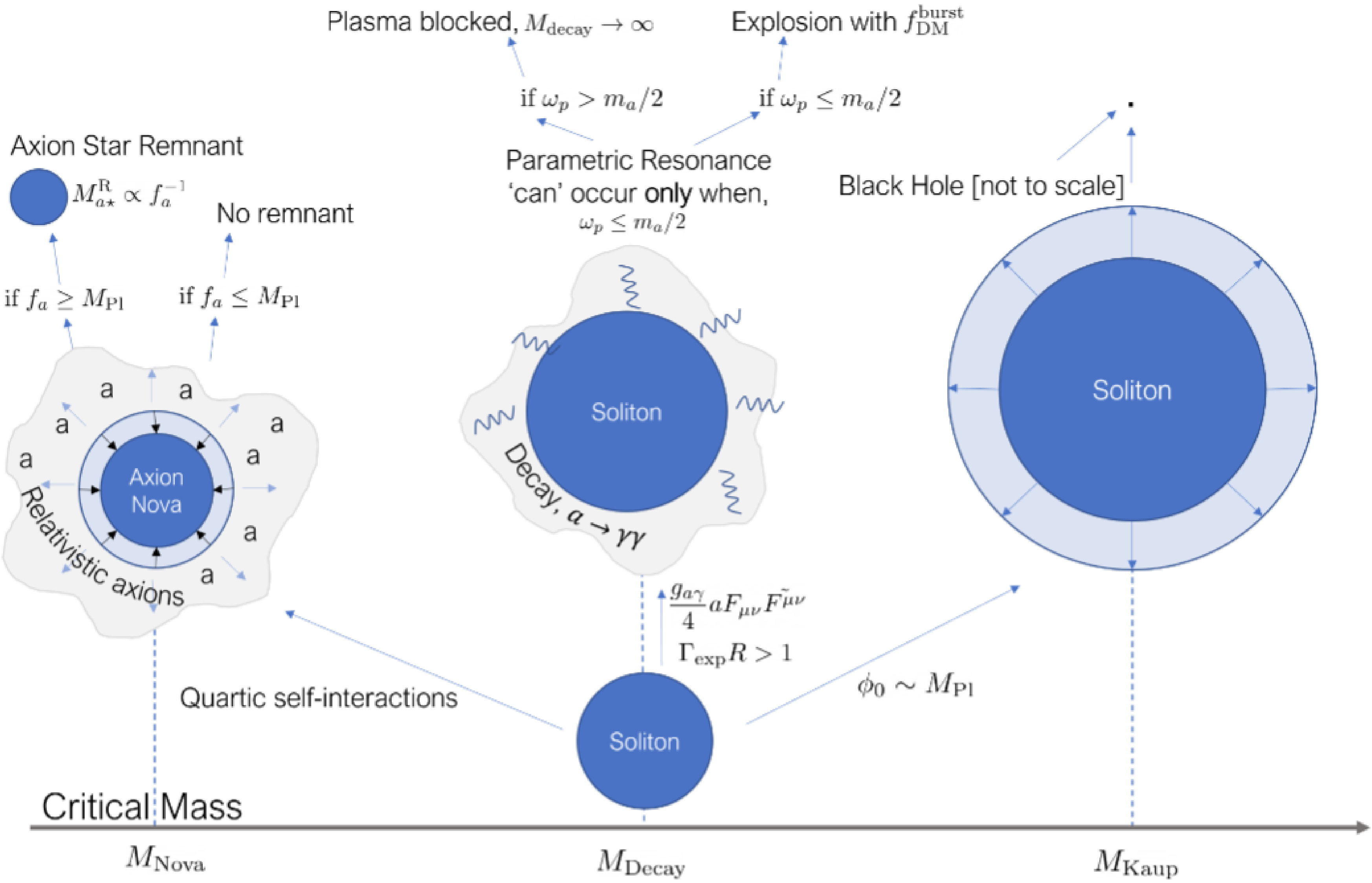
Schive et al found $\alpha=1/3$

This more recent work finds that $\alpha=3/5$

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

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

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



Concentrate on parametric resonance

Stimulated emission exponentially enhances decay

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

Translates into halos with a certain minimum mass

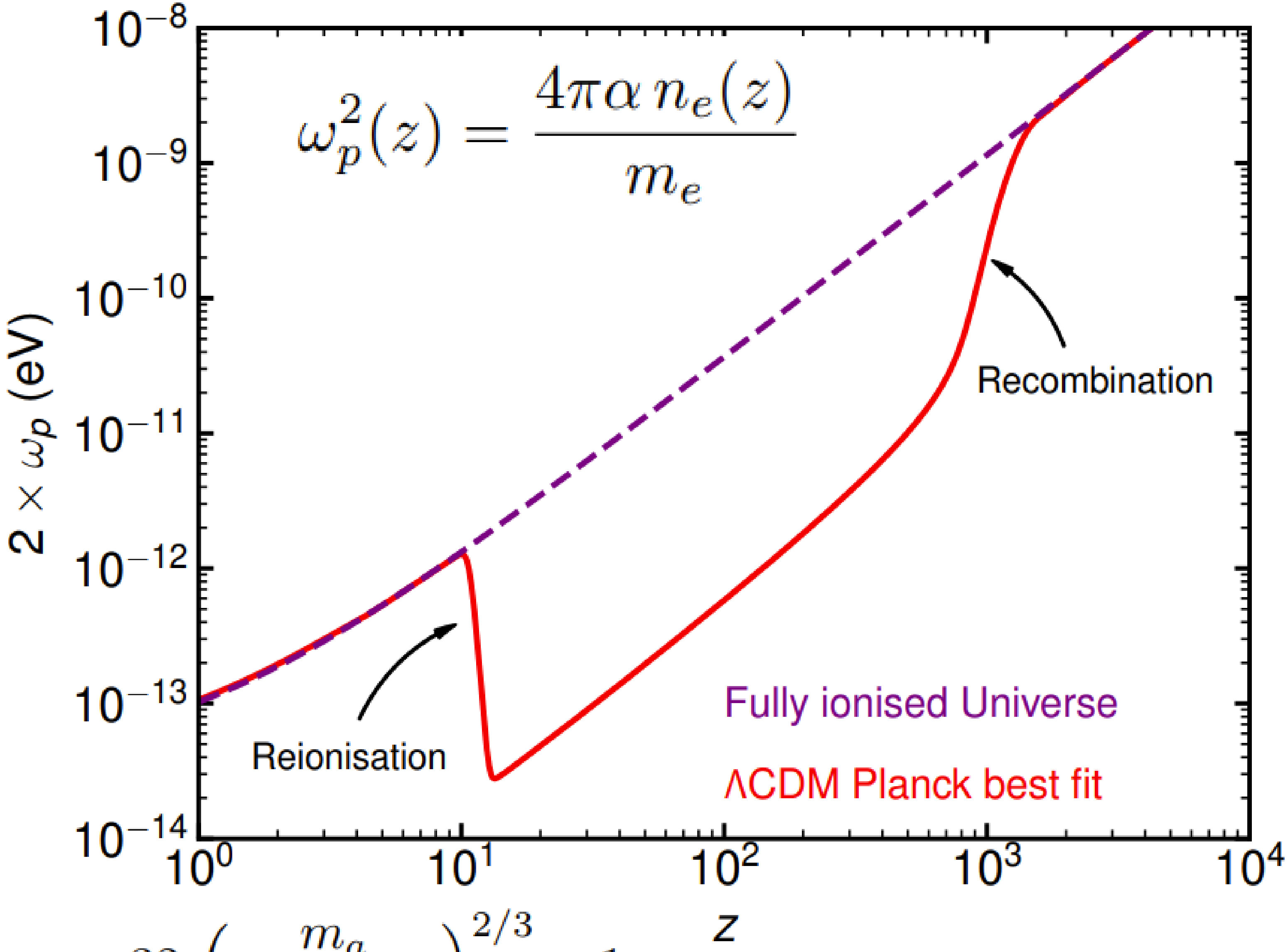
$$M_S^{\rm decay} \simeq 8.4\times 10^{-5}\, M_\odot \left(\frac{10^{-11}\,{\rm GeV}^{-1}}{g_{a\gamma\gamma}}\right)\left(\frac{10^{-13}\,{\rm eV}}{m_a}\right)$$

And it doesn’t take long to happen…

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

Levkov, Tkachev et al.

Photon Effective Mass can prevent Decay!



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

Absorption of the photons in IGM through inverse Bremsstrahlung

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

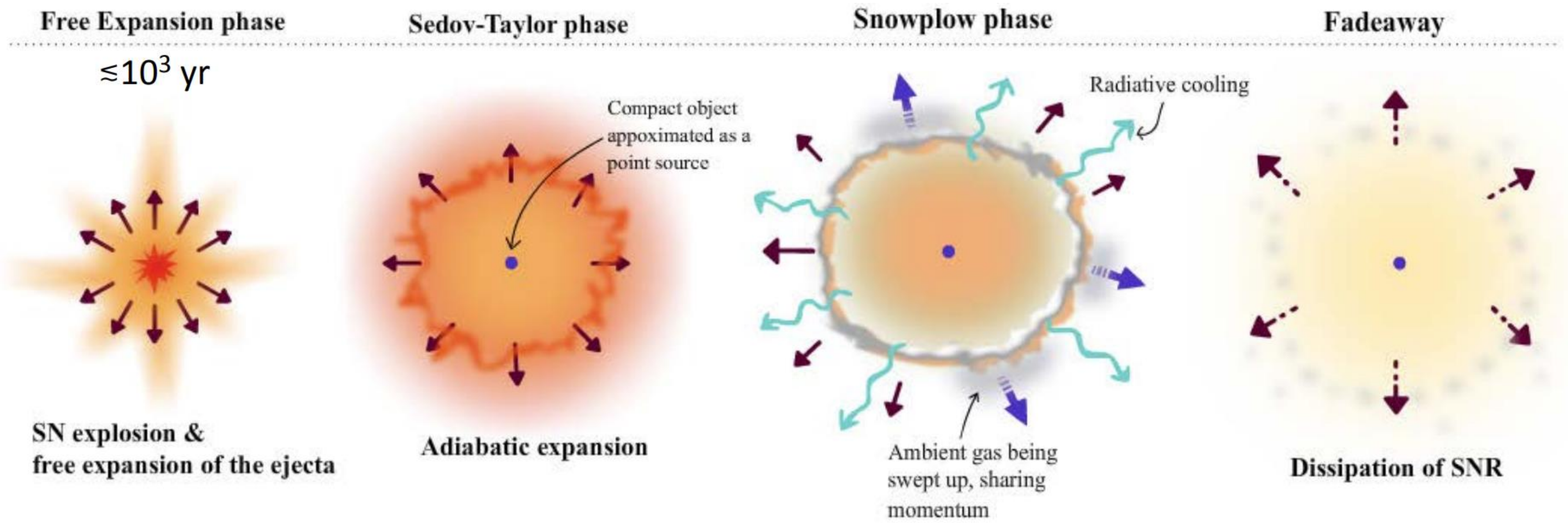
$$\Lambda_{\rm BR}(E_\gamma, z) = g_{\rm BR} \frac{n_p}{m_e^3} \sqrt{\frac{2}{3}} 2\pi^{3/2} \alpha \left(\frac{T_e}{m_e}\right)^{-7/2}$$

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

Less than a parsec

Absorption leads to super heated region which subsequently expands

Have to use technology from Supernova Remnant evolution



Picture from Ken Nagamine

Bubble of Hot Gas is created which Expands

Two simultaneous equations to solve.

Driving pressure inside bubble

Self gravity of expanding shell

$$\ddot{R} = \frac{8\pi G\, p}{\Omega_b H^2 R} - \frac{3}{R}(\dot{R} - HR)^2 - \frac{\Omega_m H^2 R}{2} - \frac{GM}{R^2}$$

Drag pressure to accelerate medium

Self gravity of entire halo

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

Evolution of Luminosity which drives Pressure

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

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

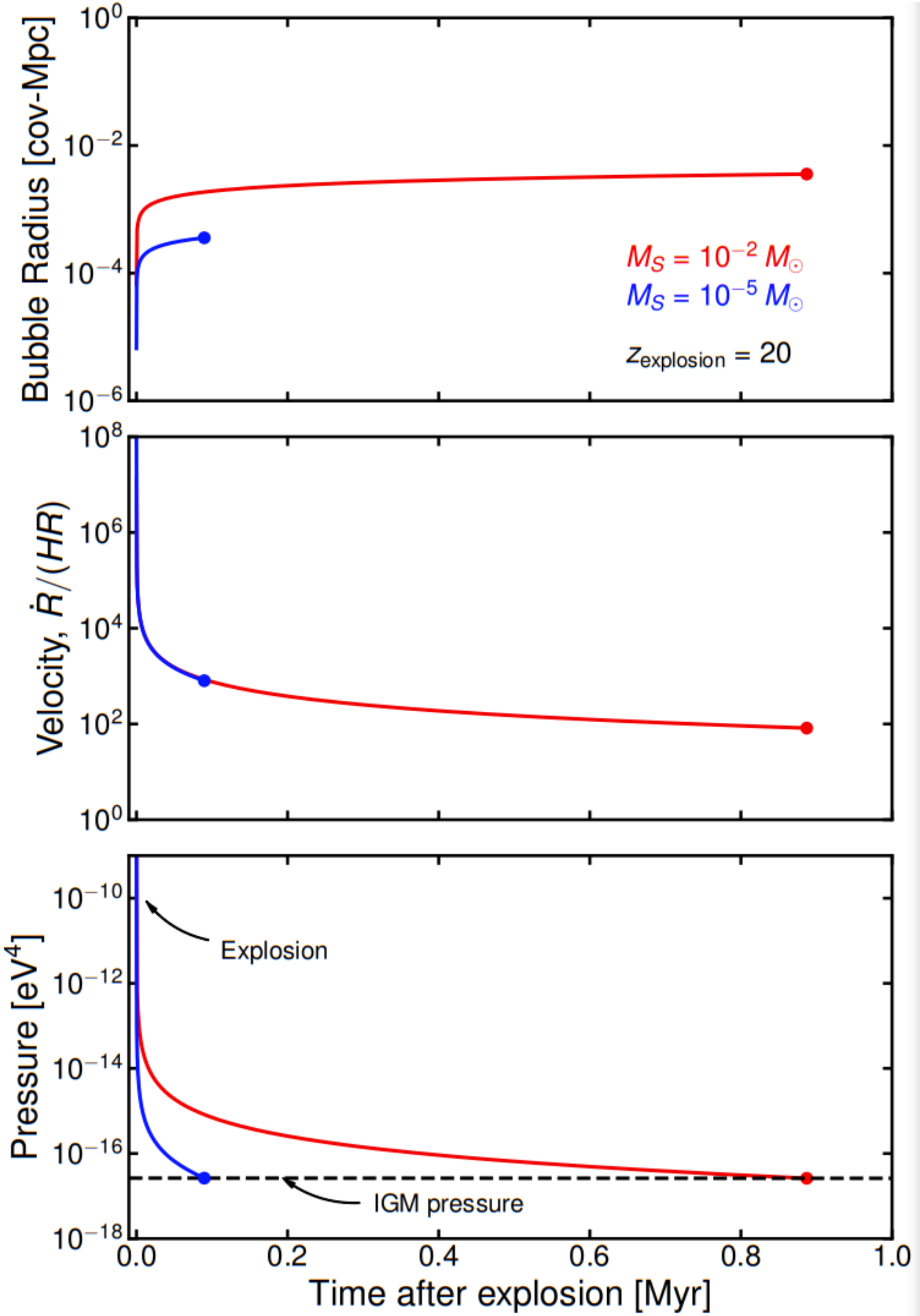
This switches off fairly quickly!

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

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

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

Evolution of Bubble Size, velocity and pressure



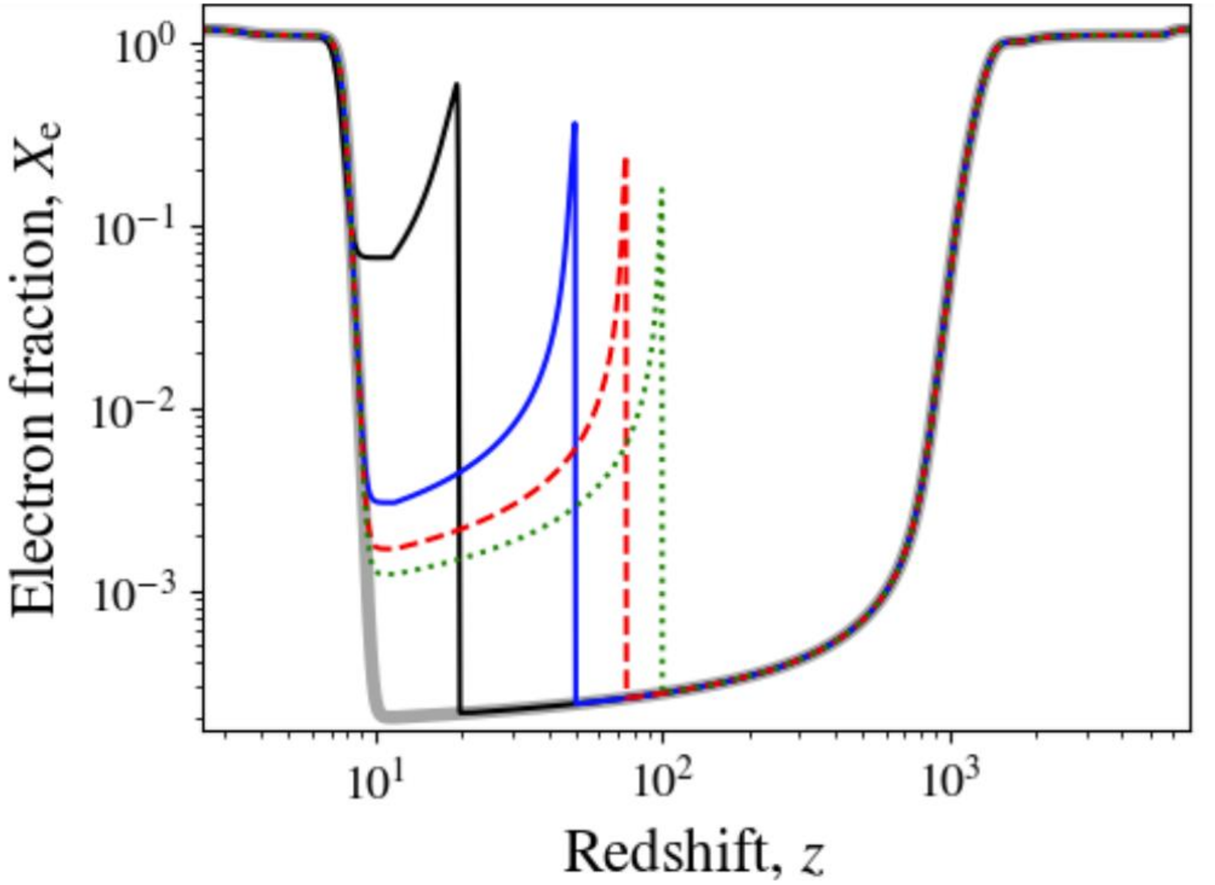
We end evolution when internal pressure is equal to IGM pressure!

Injection of energy heats up baryons

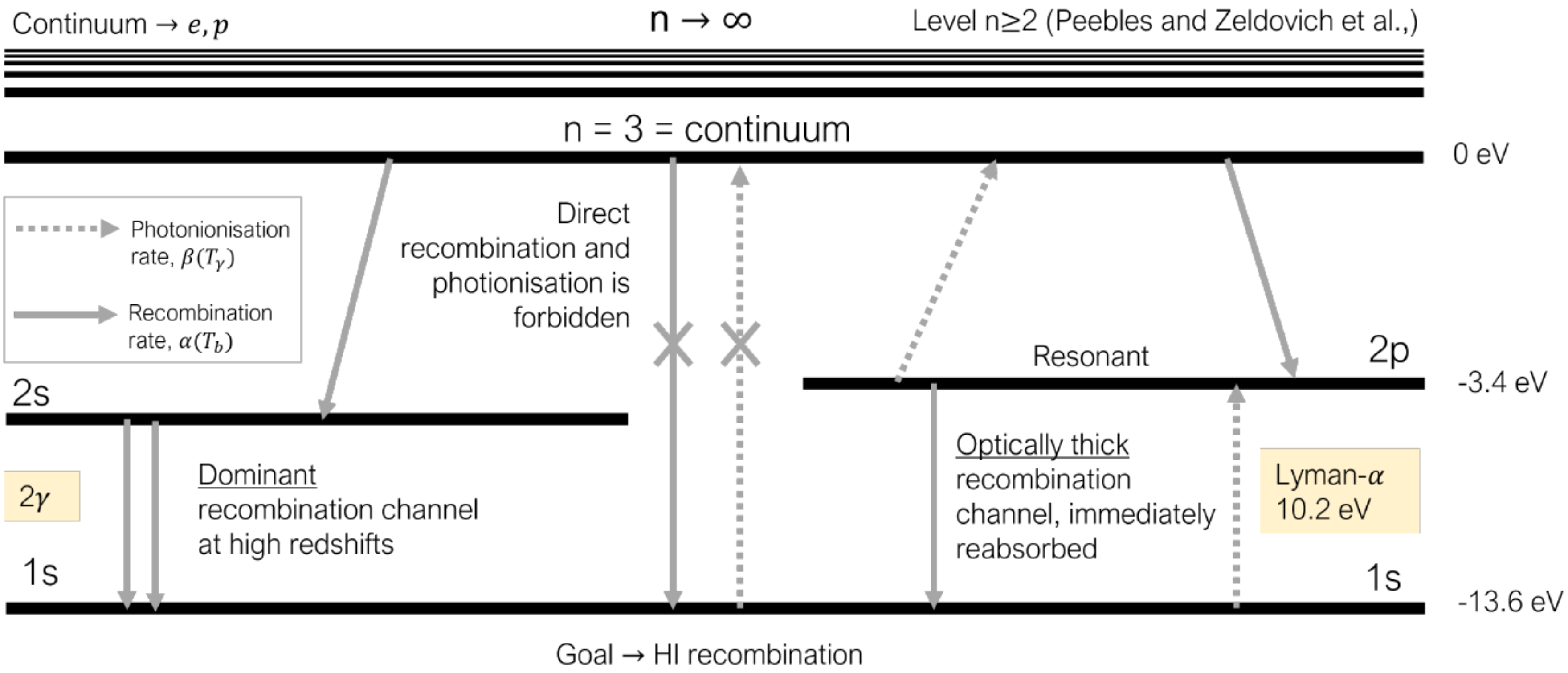
$$\frac{\mathrm{d}T_\mathrm{b}}{\mathrm{d}z}(1+z) = \underbrace{2T_\mathrm{b}}_{\text{Adiabatic cooling}} + \underbrace{\gamma_\mathrm{op}(T_\mathrm{b}-T_\gamma)}_{\text{Compton cooling}} + \underbrace{\frac{2}{3}\frac{1}{N_\mathrm{H}(1+f_\mathrm{He}+X_\mathrm{e})}\left.\frac{\mathrm{d}E}{\mathrm{d}z}\right|_\mathrm{dep}}_{\text{Additional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

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

The burst of radiation changes the ionisation of the Universe



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

1s

<u>Dominant</u> recombination channel at high redshifts

<u>Optically thick</u> recombination channel, immediately reabsorbed

Lyman-α 10.2 eV

1s

-13.6 eV

Goal → HI recombination

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

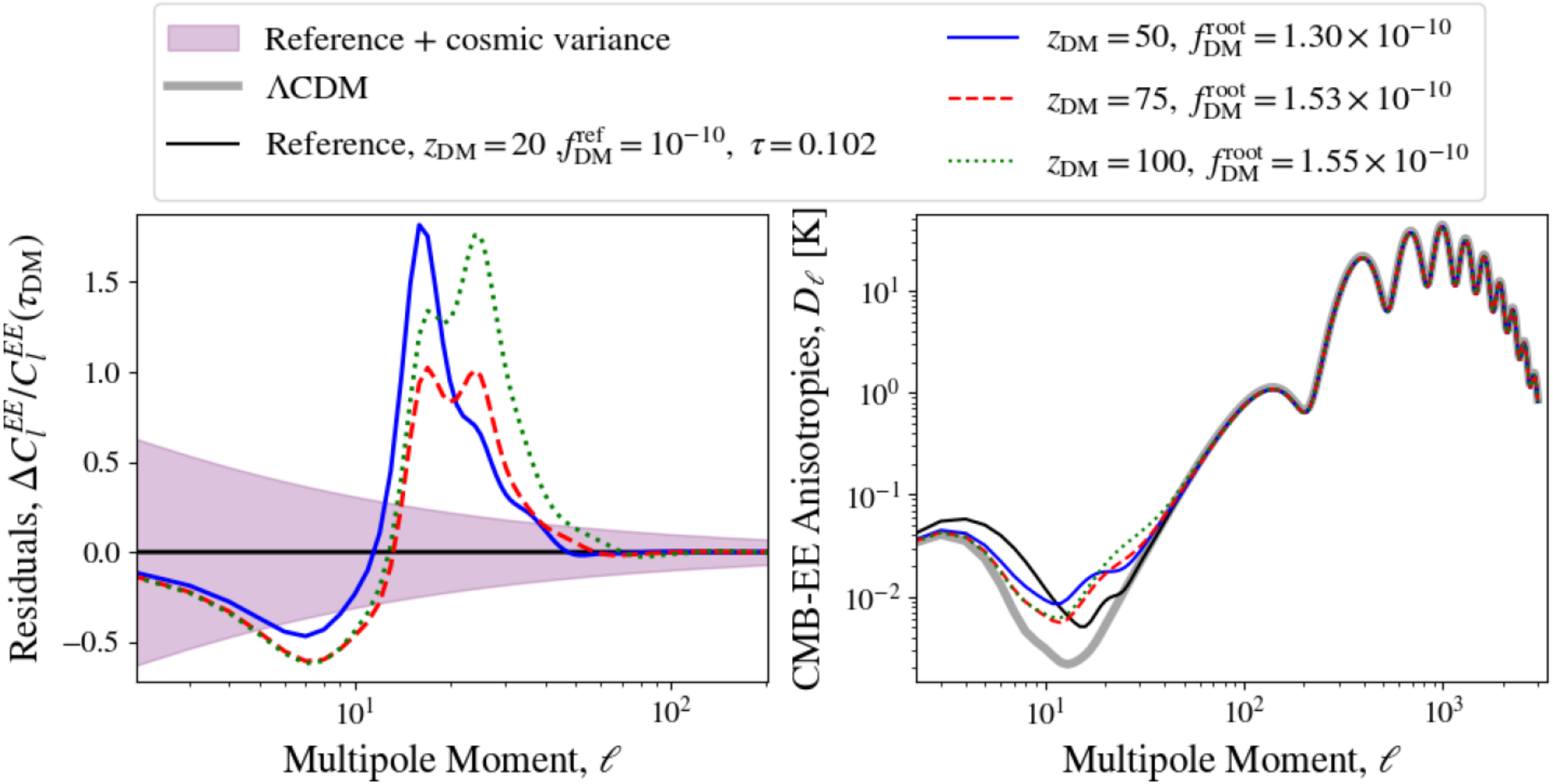
$$\frac{\mathrm{d}X_\mathrm{p}}{\mathrm{d}t} = \mathcal{C}_\mathrm{H}\left(\beta_\mathrm{H}(T_\gamma)(1-X_\mathrm{p})\mathrm{e}^{\frac{-\epsilon_{\mathrm{H},2s1s}}{T_\gamma}} - X_\mathrm{e}X_\mathrm{p}N_\mathrm{H}\alpha^{(2)}_\mathrm{H}(T_b) + \left.\frac{\mathrm{d}X_\mathrm{p}}{\mathrm{d}t}\right|_\mathrm{coll}\right)$$

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

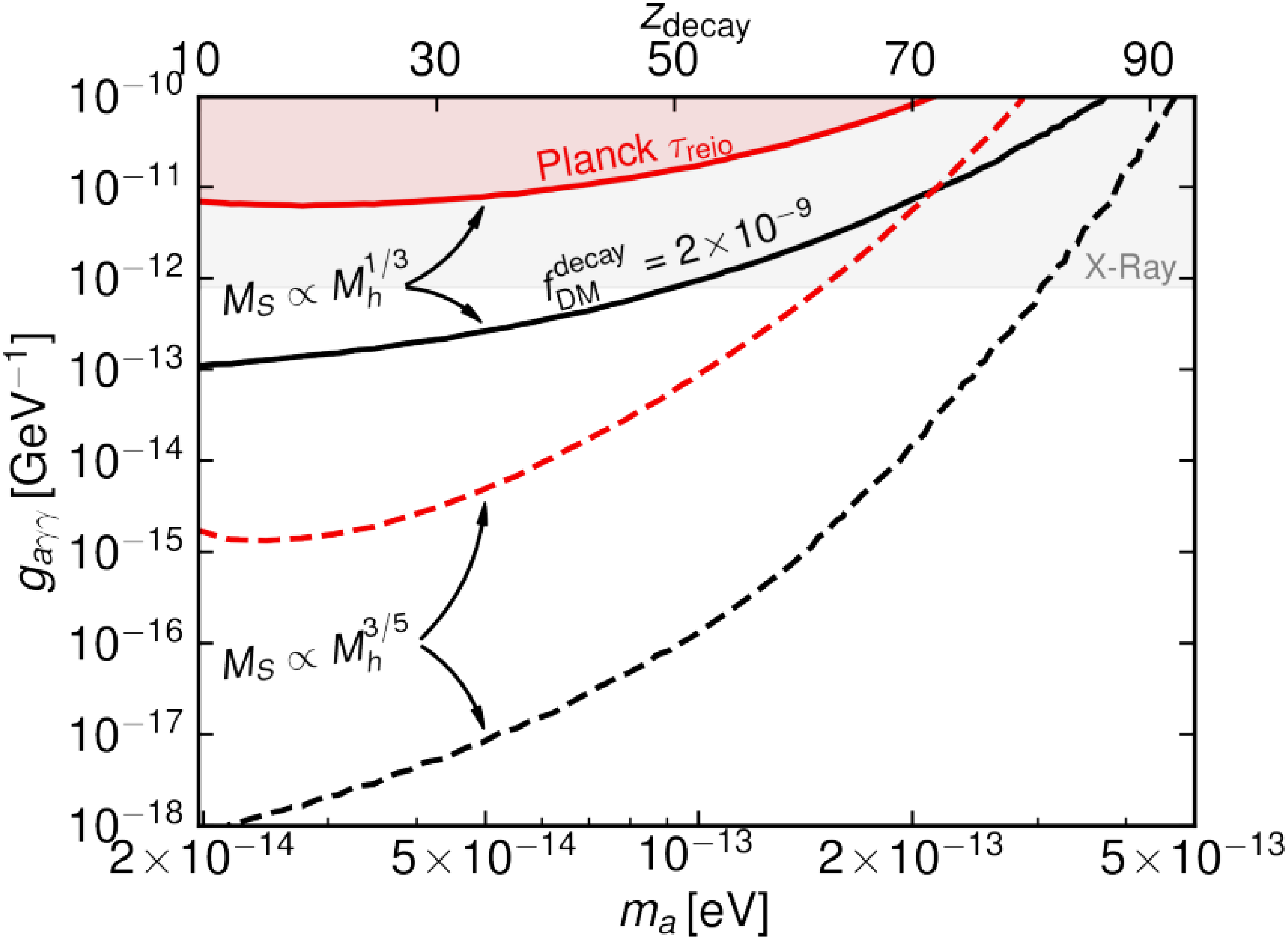
Net result depends on the following factors:-

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

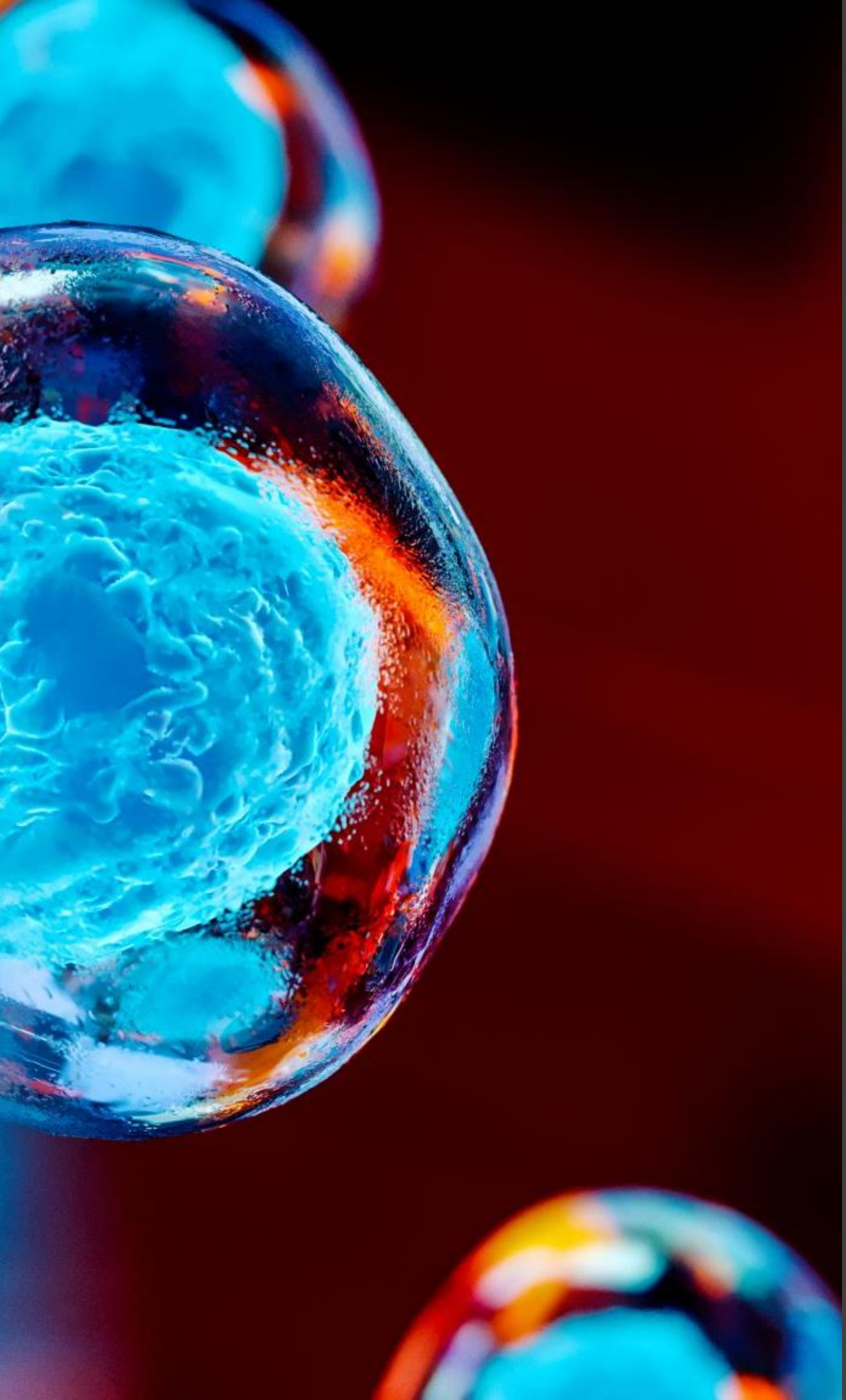
Need to look at the effect on the CMB and compare to Planck.



Parameter space we are sensitive to



PROVISIONAL



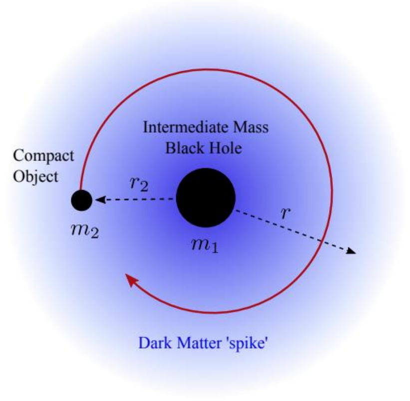
Conclusions

- 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 may be competitive with other constraints

SETTING CONSTRAINTS ON DARK MATTER WITH OJ 287

arXiv 2207.10021 Malcolm Fairbairn
(with John Ellis and **Ahmad Alackhar**)

DARK MATTER AROUND BLACK HOLES

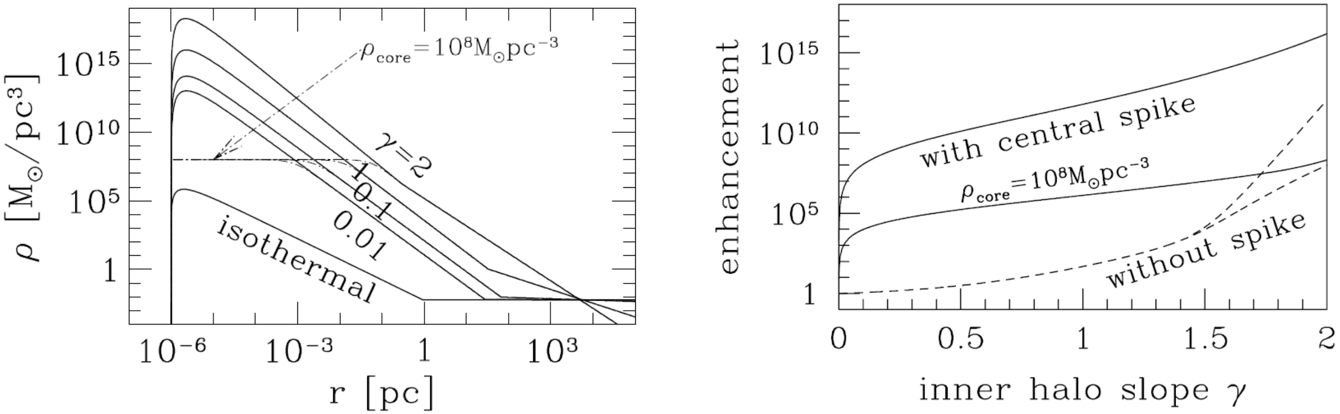


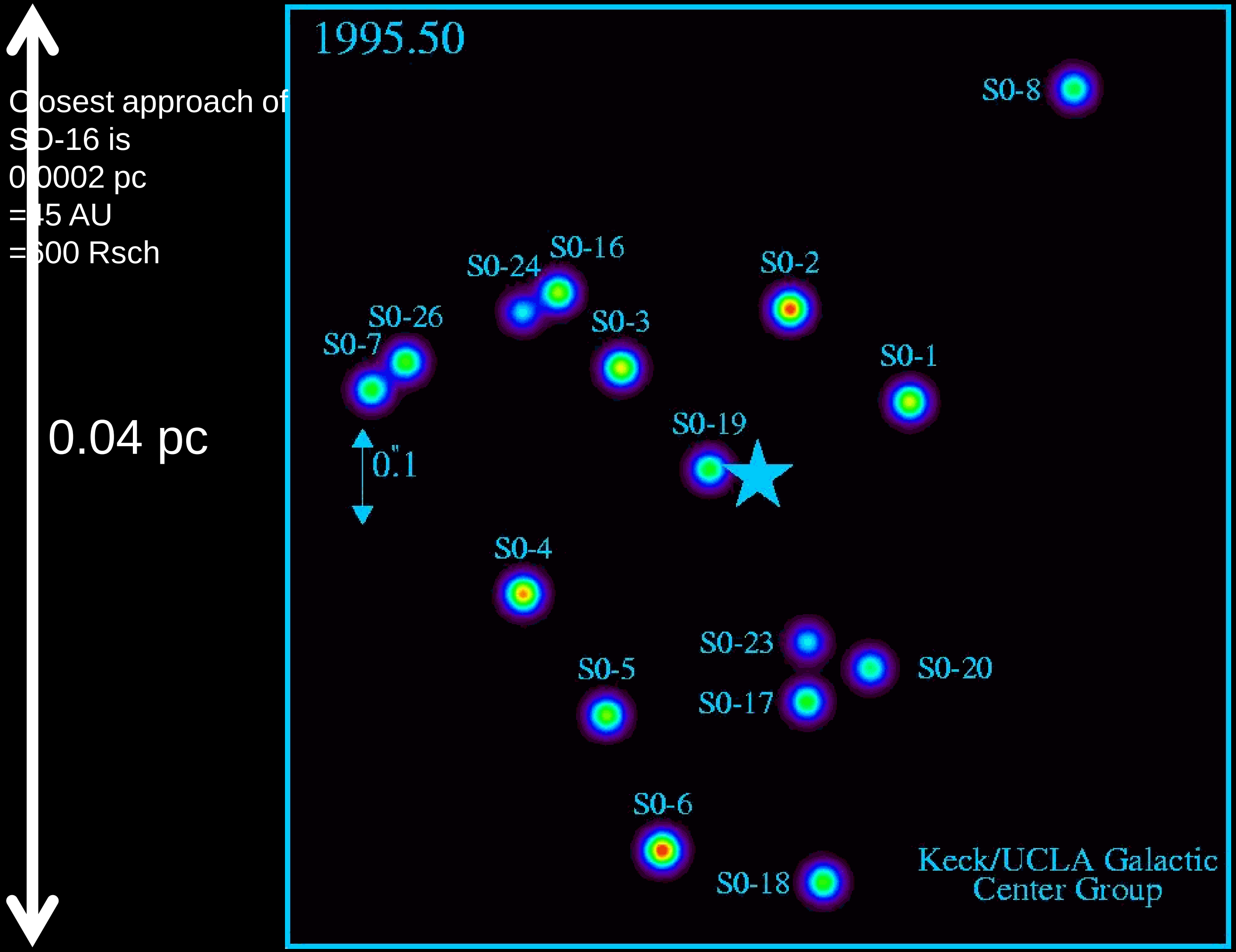
Kavanagh et al. 2021

- DM overdensity around a BH may significantly alter the dynamics of BH's merger with another compact object
- The strong gravitational potential of a BH is theorised to lead to a significant increase in the concentration of DM in the central region
- Creation of a "spike" in the dark matter density- Gondolo & Silk 1999
- OJ287: accurate timing of outbursts constraints DM distribution

Dark Matter spike at Centre of Galaxy?

Adiabatic contraction of dark matter during formation of black hole leads to spike at centre of galaxy (Gondolo+Silk ‘99)

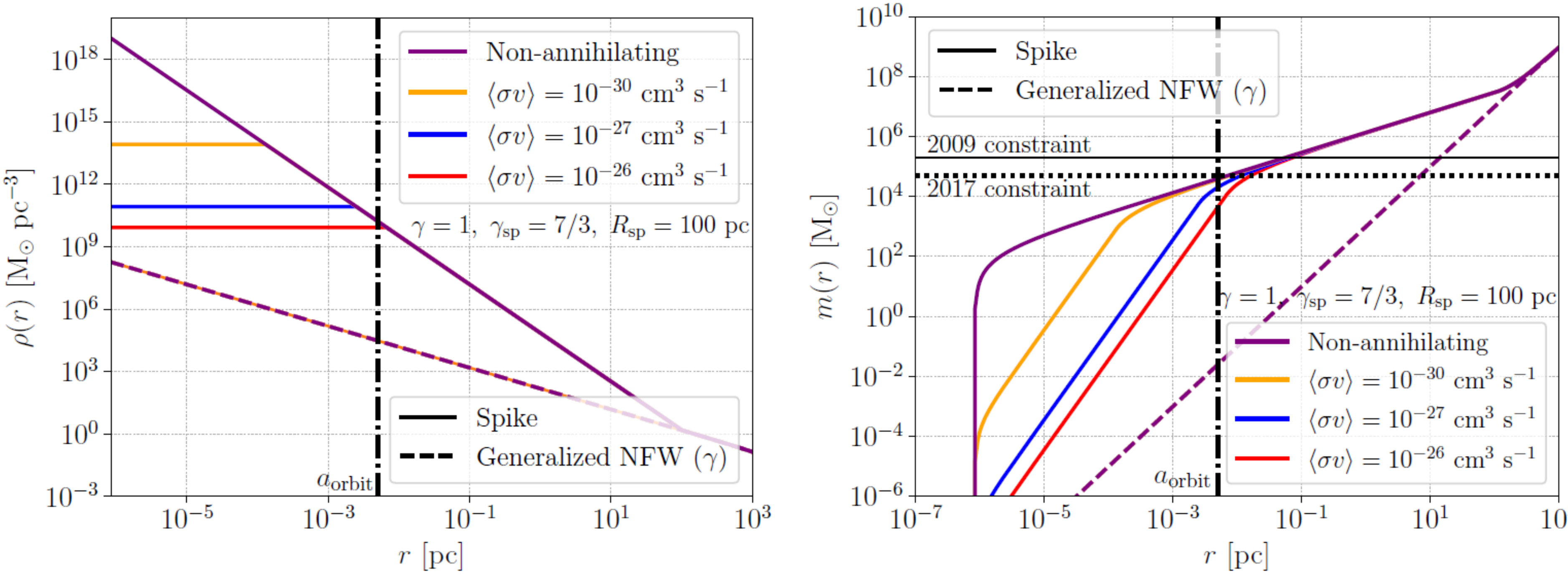




Closest approach of
S0-16 is
0.0002 pc
=45 AU
=600 Rsch

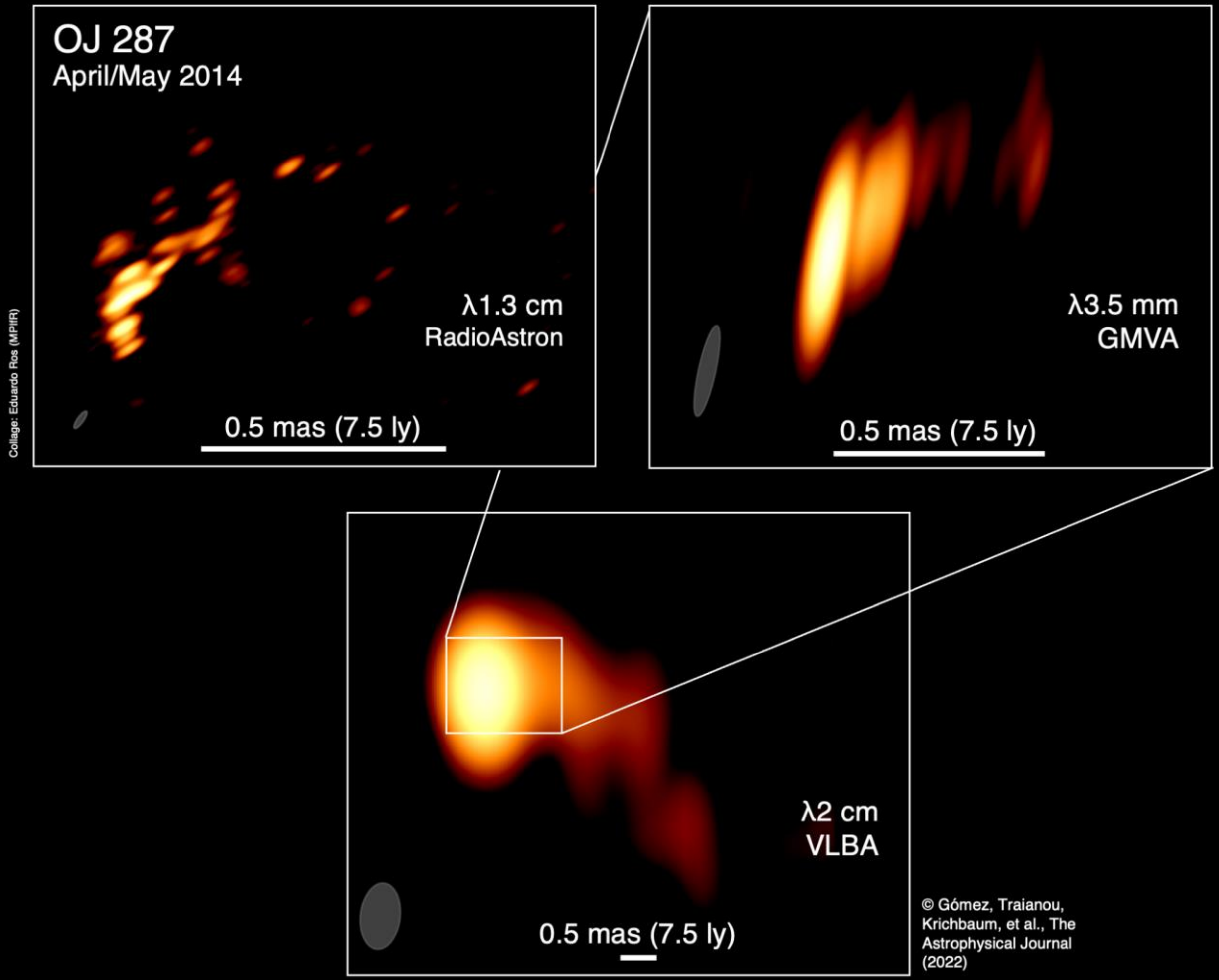
0.04 pc

Constraints from Sag A*

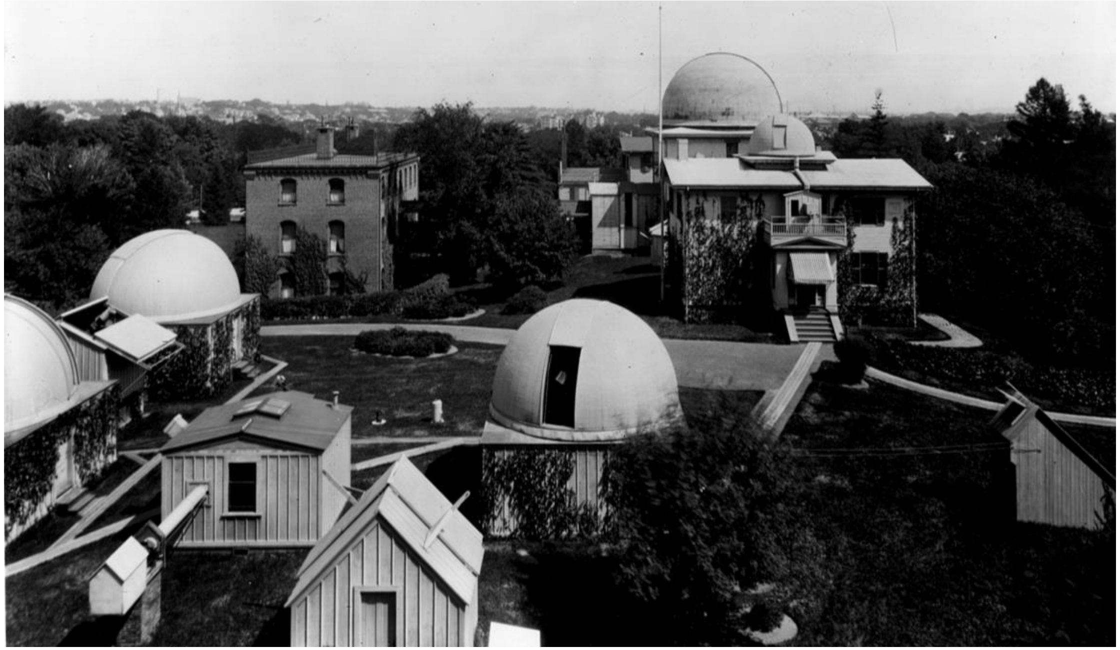


Lacroix 1801.01308

OJ287 is a BL-Lac object



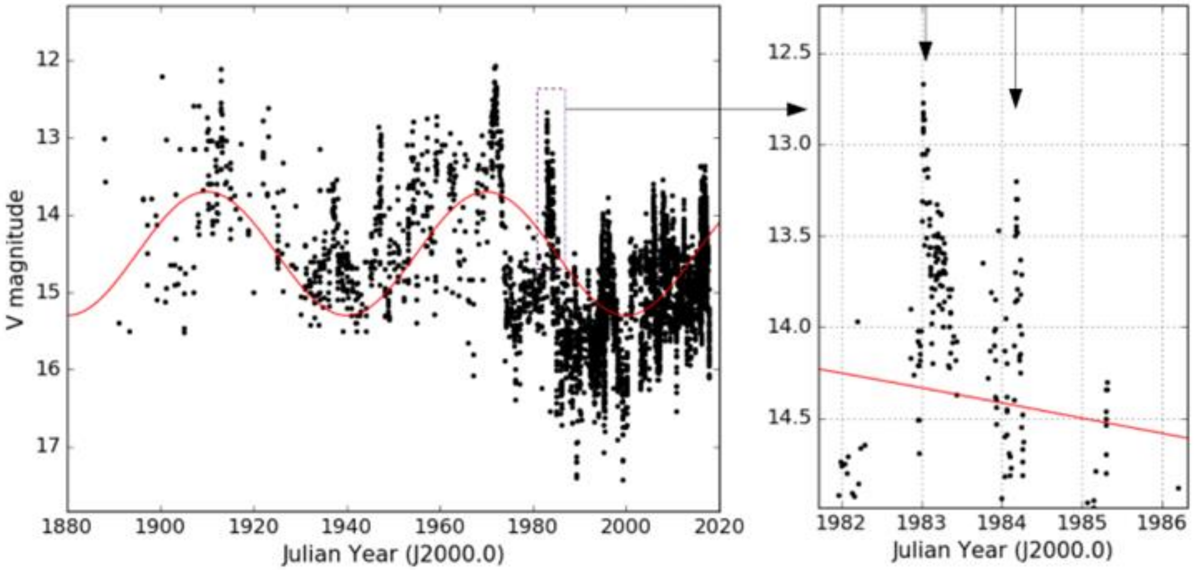
© Gómez, Traianou, Krichbaum, et al., The Astrophysical Journal (2022)



Outbursts of OJ287 discovered back to 1891 on photographic plates.

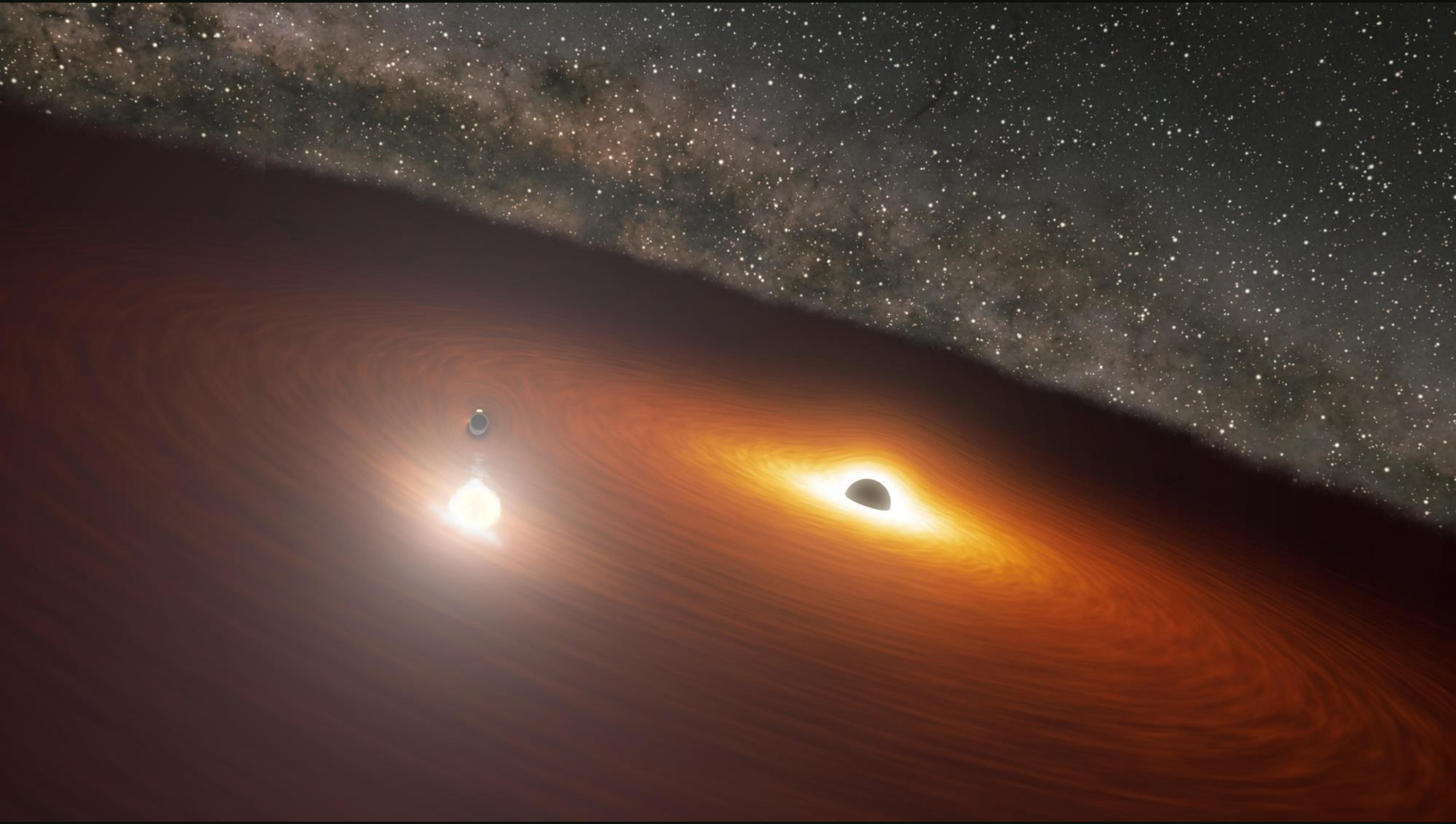
Harvard College Observatory 1899

OJ 287

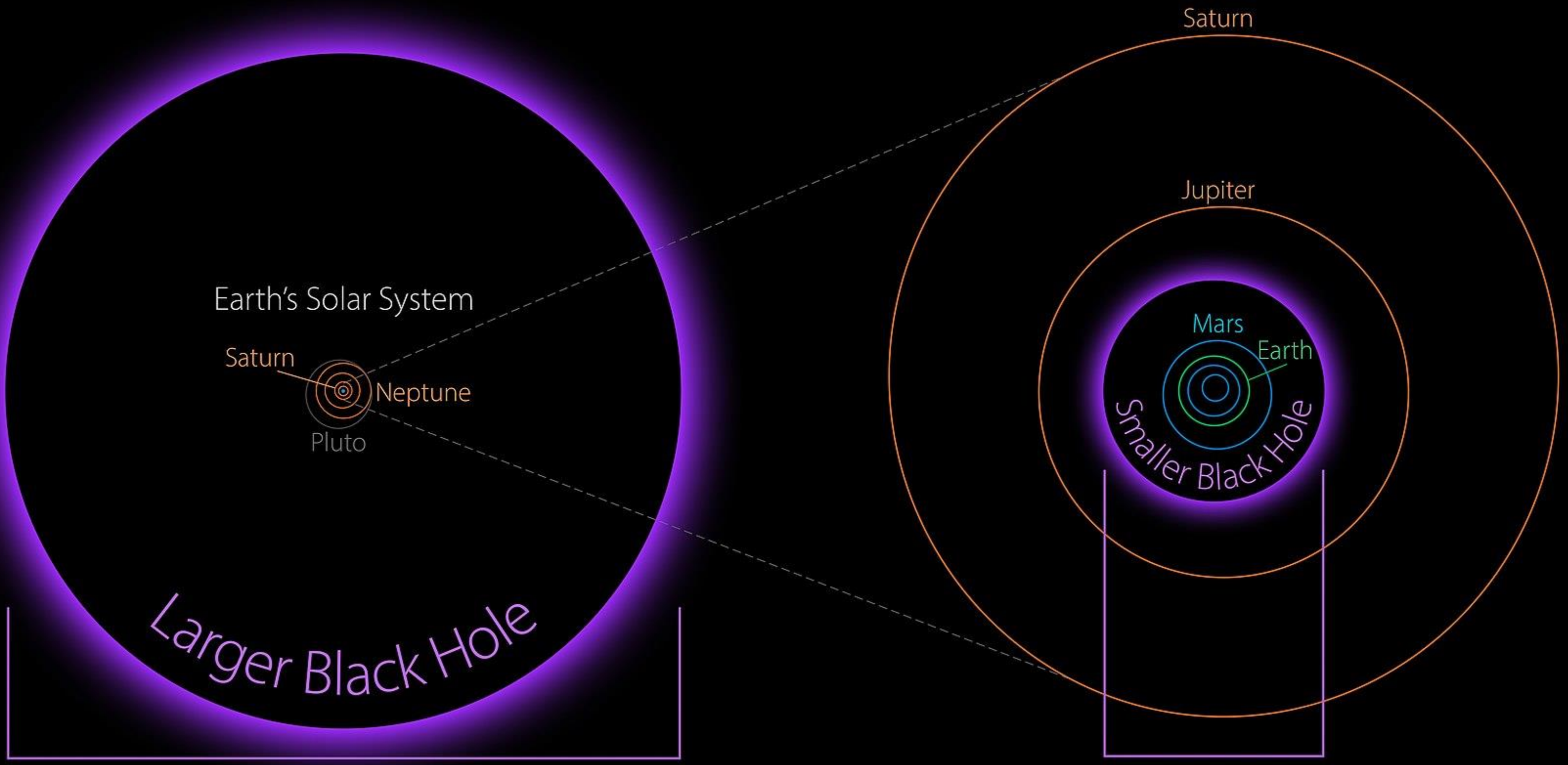


- BL Lac object (z=0.306)- one of the most extensively-monitored blazars
- variations with timescales of ~ 60 and $\sim$ **12 years**
- A feasible model of OJ 287 must at least explain and predict:

advance of pericenter ***orbital period timescale***



Galaxy OJ 287's Central Black Holes Compared to Earth's Solar System



Diameter = 720 AU (67 billion miles)
~9x the size of Pluto's orbit

Diameter = 6 AU (560 million miles)
~the size of the asteroid belt

1 AU (Astronomical Unit) = Distance from Earth to Sun

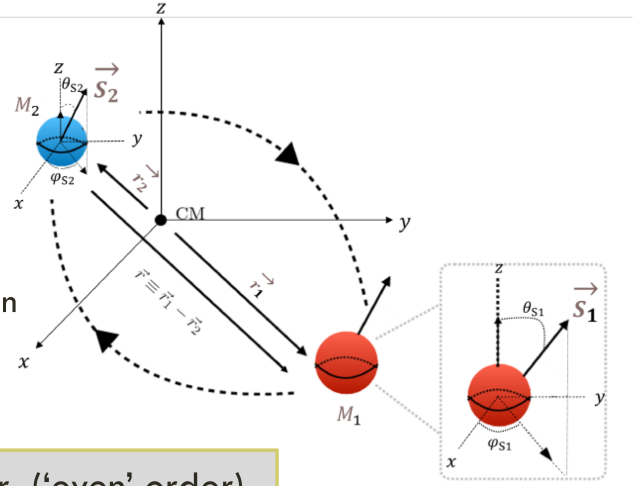
DETERMINING THE RELATIVISTIC BBH ORBIT

$\epsilon \sim (v/c)^2 \sim GM/rc^2$

EOM:

PN numerical integration scheme:

- Relative two-body COM motion
- Precessional dynamics of primary BH spin



$$\ddot{\mathbf{x}} \equiv \frac{d^2\mathbf{x}}{dt^2} = \ddot{\mathbf{x}}_0 + \ddot{\mathbf{x}}_{1\mathrm{PN}} + \ddot{\mathbf{x}}_{2\mathrm{PN}} + \ddot{\mathbf{x}}_{3\mathrm{PN}}$$

Conservative sector ('even' order)

$$+ \ddot{\mathbf{x}}_{2.5\mathrm{PN}} + \ddot{\mathbf{x}}_{3.5\mathrm{PN}} + \ddot{\mathbf{x}}_{4\mathrm{PN(tail)}} + \ddot{\mathbf{x}}_{4.5\mathrm{PN}}$$

Dissipative radiative sector ('odd' order terms)

$$+ \ddot{\mathbf{x}}_{\mathrm{SO}} + \ddot{\mathbf{x}}_{\mathrm{SS}} + \ddot{\mathbf{x}}_{\mathrm{Q}} + \ddot{\mathbf{x}}_{4\mathrm{PN(SO-RR)}}$$

Spin-related contributions

$$\frac{d\mathbf{s}_1}{dt} = \left(\boldsymbol{\Omega}_{\mathrm{SO}} + \boldsymbol{\Omega}_{\mathrm{SS}} + \boldsymbol{\Omega}_{\mathrm{Q}}\right) \times \mathbf{s}_1,$$

$$\mathbf{S}_i = \frac{Gm_i^2\chi_i}{c}\mathbf{s}_i$$

Spitzer Observations of the Predicted Eddington Flare from Blazar OJ 287

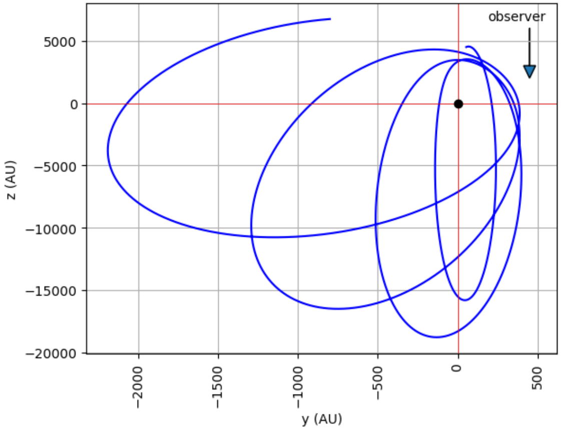
Seppo Laine, Lankeswar Dey, Mauri Valtonen, A. Gopakumar, Stanislaw Zola, S. Komossa, Mark Kidger, Pauli Pihajoki, Jose L. Gómez, Daniel Caton, Stefano Ciprini, Marek Drozdz, Kosmas Gazeas, Vira Godunova, Shirin Haque, Felix Hildebrandt, Rene Hudec, Helen Jermak, Albert K.H. Kong, Harry Lehto, Alexios Liakos, Katsura Matsumoto, Markus Mugrauer, Tapio Pursimo, Daniel E. Reichart, Andrii Simon, Michal Siwak, Eda Sonbas

Binary black hole (BH) central engine description for the unique blazar OJ 287 predicted that the next secondary BH impact-induced bremsstrahlung flare should peak on 2019 July 31. This prediction was based on detailed general relativistic modeling of the secondary BH trajectory around the primary BH and its accretion disk. The expected flare was termed the Eddington flare to commemorate the centennial celebrations of now-famous solar eclipse observations to test general relativity by Sir Arthur Eddington. We analyze the multi-epoch Spitzer observations of the expected flare between 2019 July 31 and 2019 September 6, as well as baseline observations during 2019 February-March. Observed Spitzer flux density variations during the predicted outburst time display a strong similarity with the observed optical pericenter flare from OJ 287 during 2007 September. The predicted flare appears comparable to the 2007 flare after subtracting the expected higher base-level Spitzer flux densities at 3.55 and 4.49 μm compared to the optical R-band. Comparing the 2019 and 2007 outburst lightcurves and the previously calculated predictions, we find that the Eddington flare arrived within 4 hours of the predicted time. Our Spitzer observations are well consistent with the presence of a nano-Hertz gravitational wave emitting spinning massive binary BH that inspirals along a general relativistic eccentric orbit in OJ 287. These multi-epoch Spitzer observations provide a parametric constraint on the celebrated BH no-hair theorem.

ORBIT SOLUTION

Convergent trial orbit
$\chi^2 \approx 0.259$

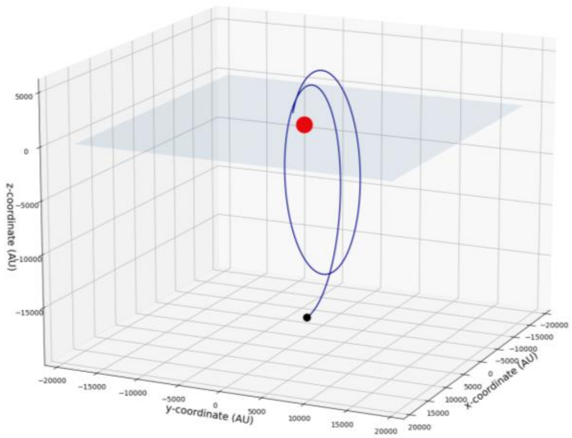
Parameter	Value	Unit
M_1	1.8329×10^{10}	$M_\odot$
M_2	1.5038×10^{8}	$M_\odot$
e_0 (e_{init})	0.732 (0.694)	
γ	1.310	
χ_1	0.389	
a	12648.086	
ω_0	28.938	deg
θ_{S1}	170.320	deg
ψ_{S1}	108.692	deg

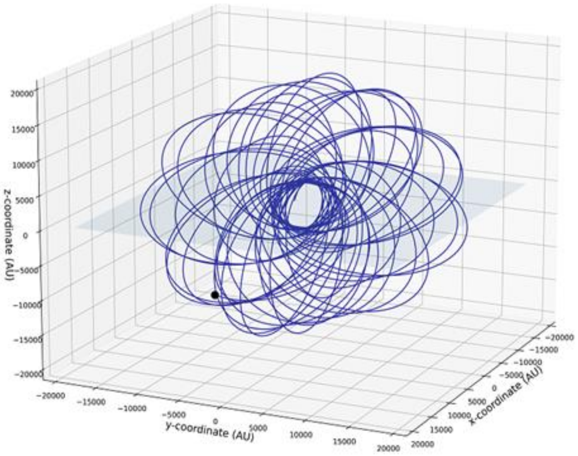


Projection on y-z plane

- Precession of the pericenter
- Precession of the orbital plane
- Gravitational radiation

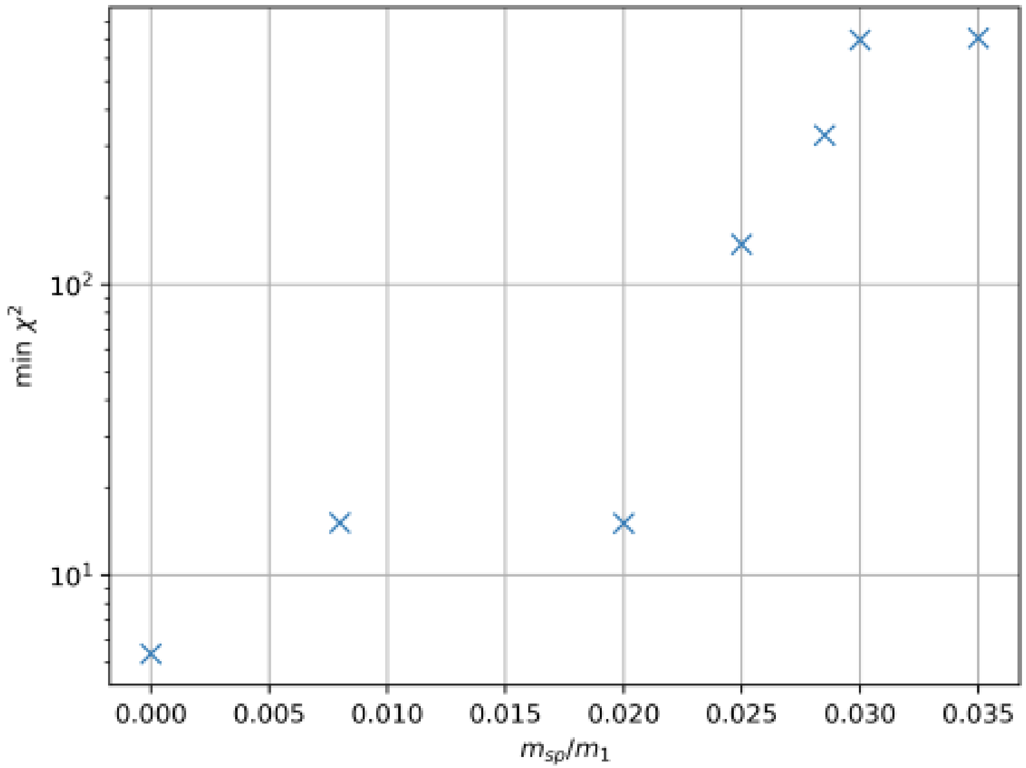
ICs





RESULTS

Total mass of spike cannot be more than around 3% of mass of primary.



CONCLUSIONS

OJ287 is a remarkable, extreme object

Its highly relativistic nature makes it very sensitive to initial conditions and the presence of any spike

We predict that we can rule out any spike with mass greater than 3% of the black hole within the orbit of the secondary