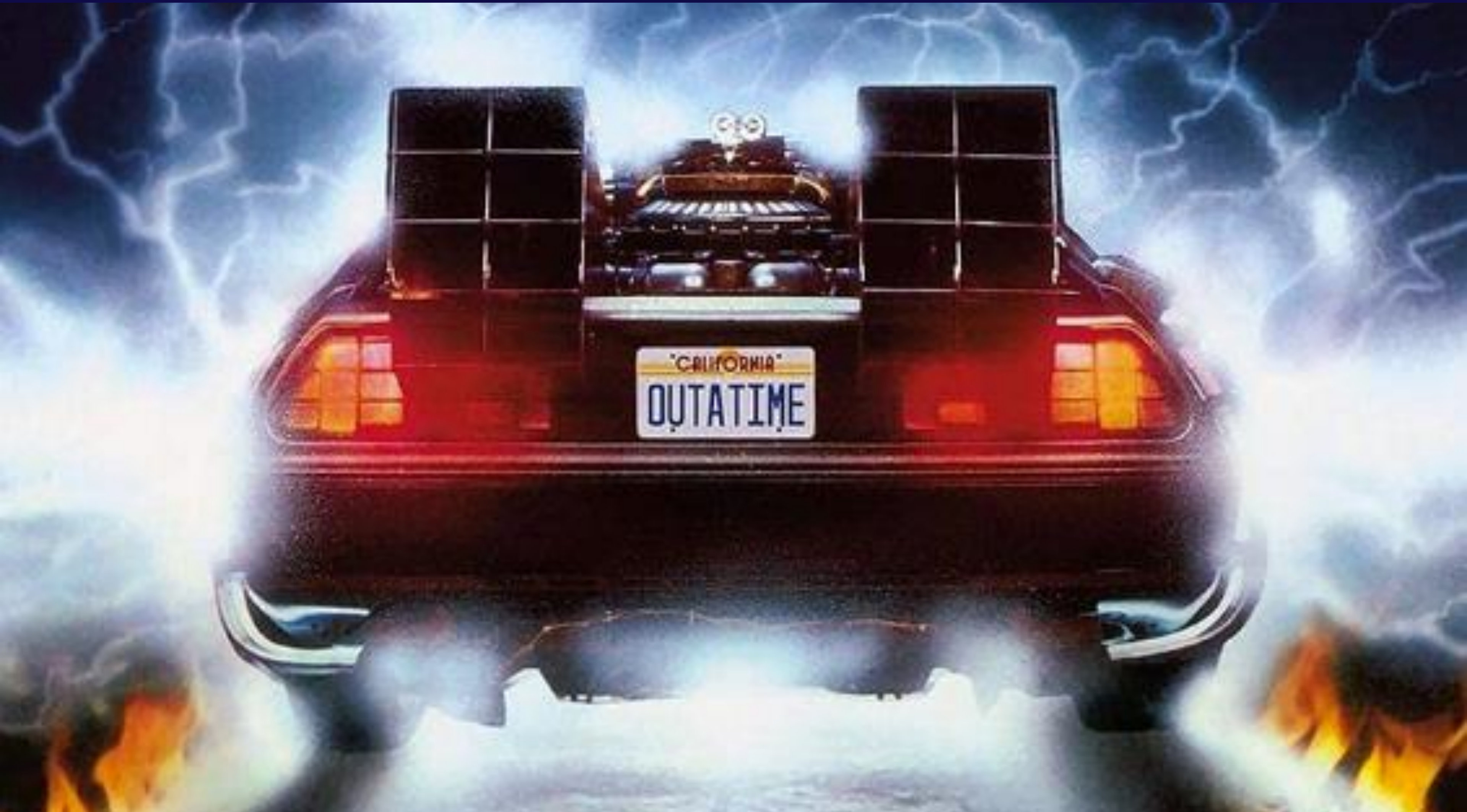
Malcolm Fairbairn

King's College London

Young Theorists Forum 2022



Plan For Today

Some Career advice from a middle aged white man!

Axion star explosions in the Early Universe

- I really don’t want to patronize you!
- Please tell me to shut up if I do.

My career so far...

- UG Birmingham Physics with Astrophysics
- Part III maths at Cambridge
- DPhil. University of Sussex
- Postdoc ULB Brussels
- Postdoc Stockholm
- Postdoc CERN
- Lecturer position at KCL (age 32, 6 years after PhD)
- Senior Lecturer at KCL
- Reader at KCL (got ERC consolidator grant)
- Professor at KCL (age 41)
- Head of Research for Physics
- Head of TPPC Group (age 46)

I earn decent money, top of professor grade 2.

All my PhD students who have left the field earn more money than me (apart from the one who just left)

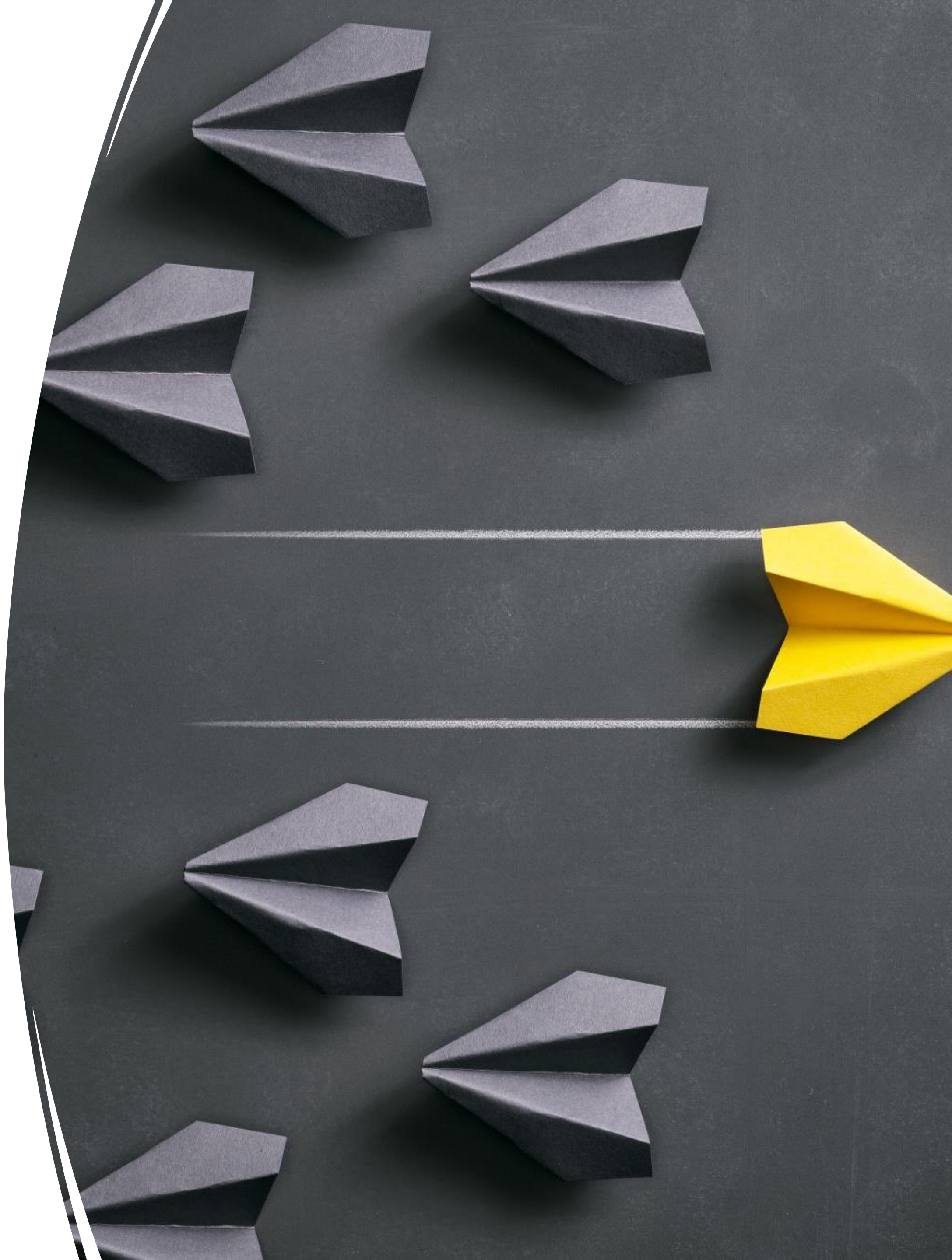
What people are looking for when hiring postdocs…

- Multiple areas of expertise
- Independence
- Context
- Originality
- Impact
- Team player

Not ALL of these are necessary to get a postdoc!

Learn to give good talks

- Make it easy
- Keep technical slides in reserve.
- Narrative structure - storytelling.



Vary your output

- Technical papers which take a long time to write and are detailed and solid ***are valued***
- Ambulance chasing rapid reactions to new results which take a couple of days to write ***are valued***
- You could try to do a bit of both?

Reep Benefits but don’t stagnate

- If you come up with a new original result, try to be the one who gets the impact. (I’m very bad at this)

- At the same time, don’t spend the rest of your career wallowing in the aftermath of your one original result.

Other Advice

- Be nice to people on the way up… (you might see them again on the way down, or on your way up!)
- Ask Questions, even if you are scared it's a stupid question. It's OK to be wrong.
- Don't ask questions **ALL** the time. Don't be ***that*** physicist.

Axion Star Explosions in the Early Universe

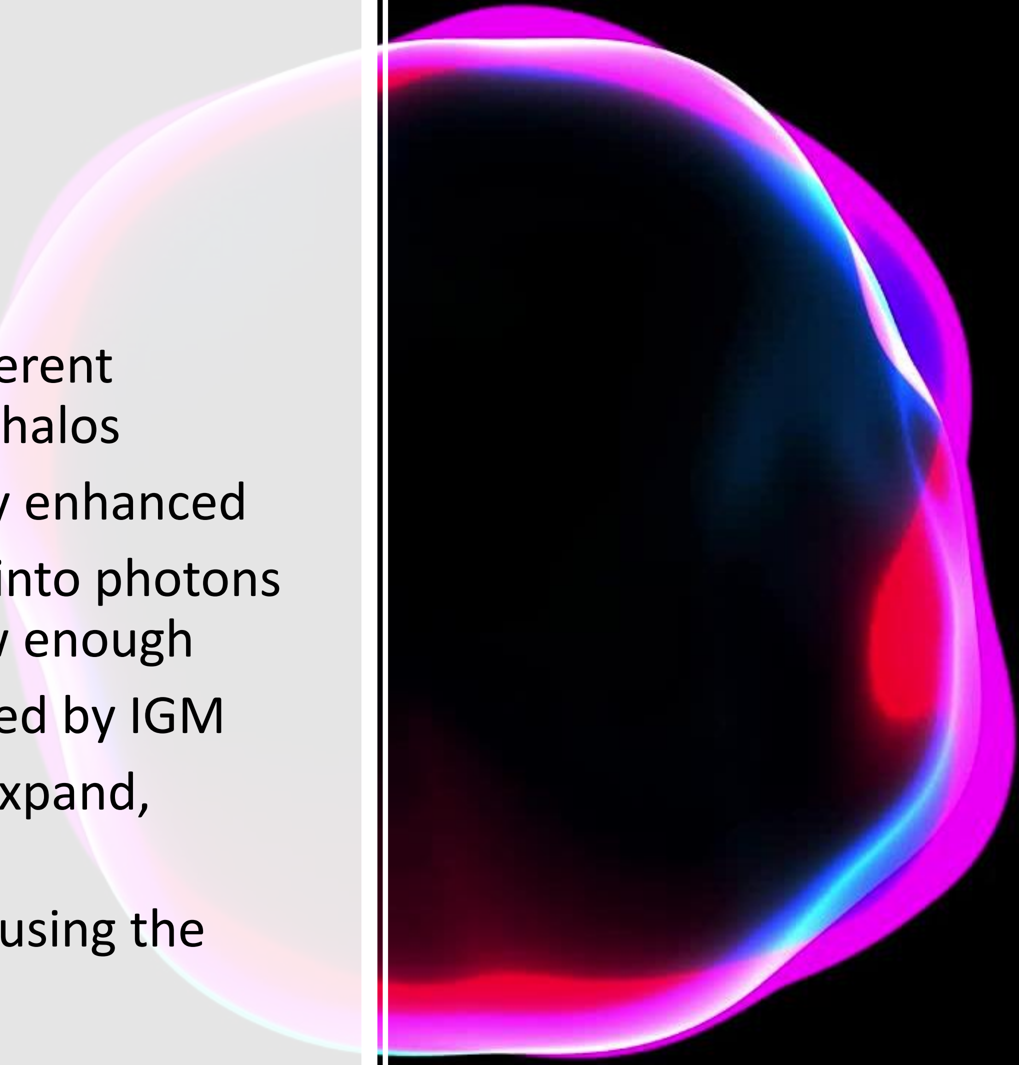
Malcolm Fairbairn

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

?

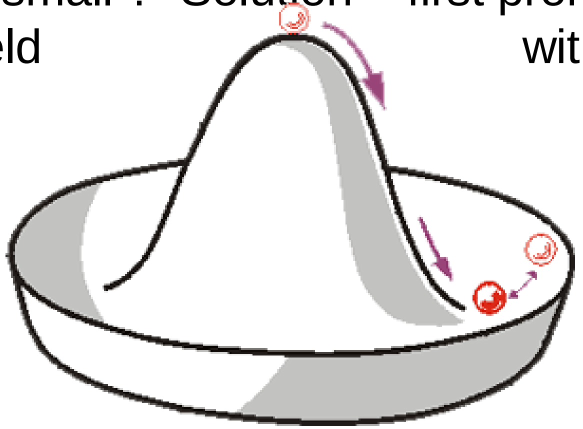
Neutron Dipole Moment and strong CP problem

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

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

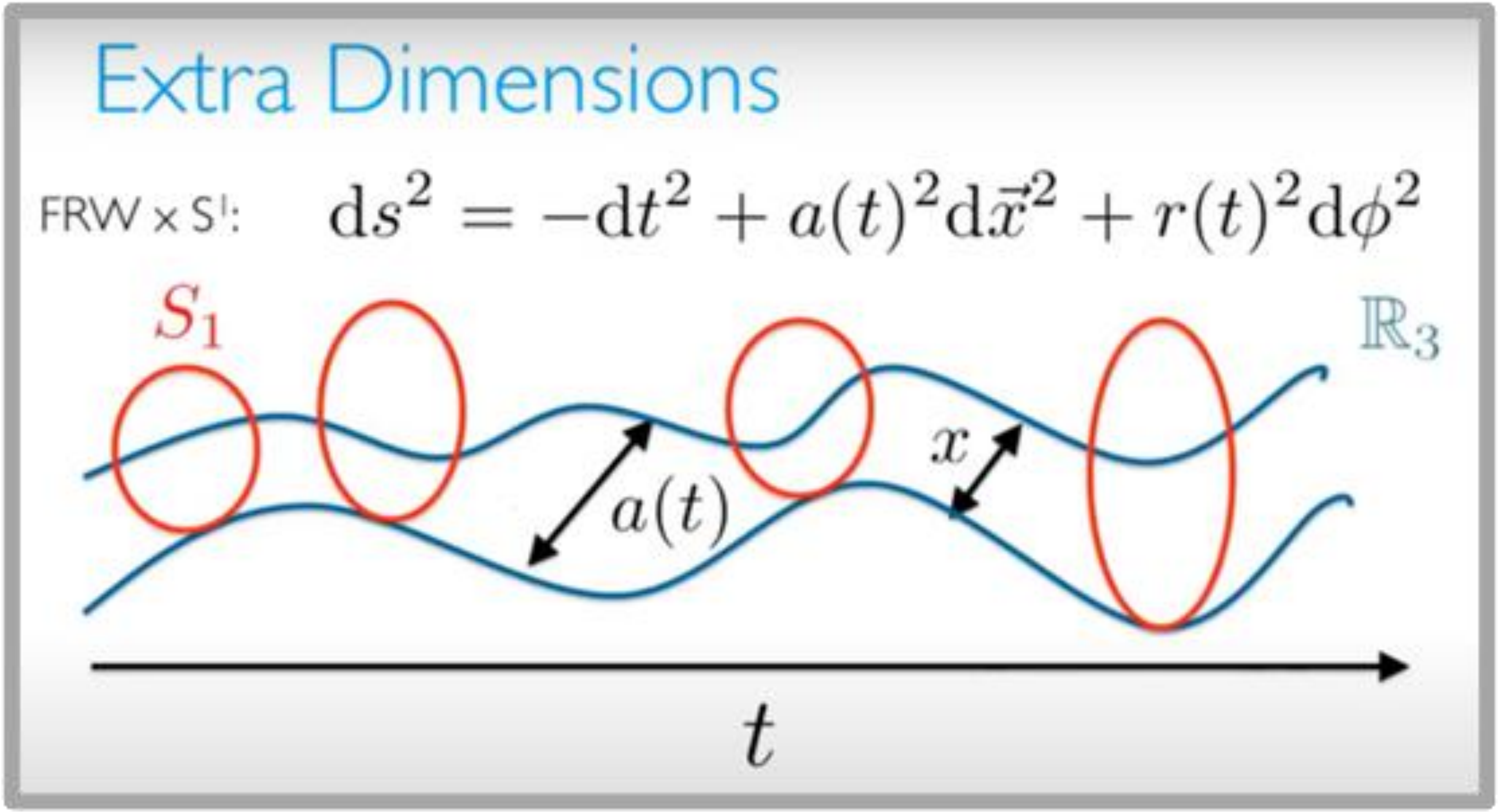
However, no edm observed down to d~ 10^{-27} e cm

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

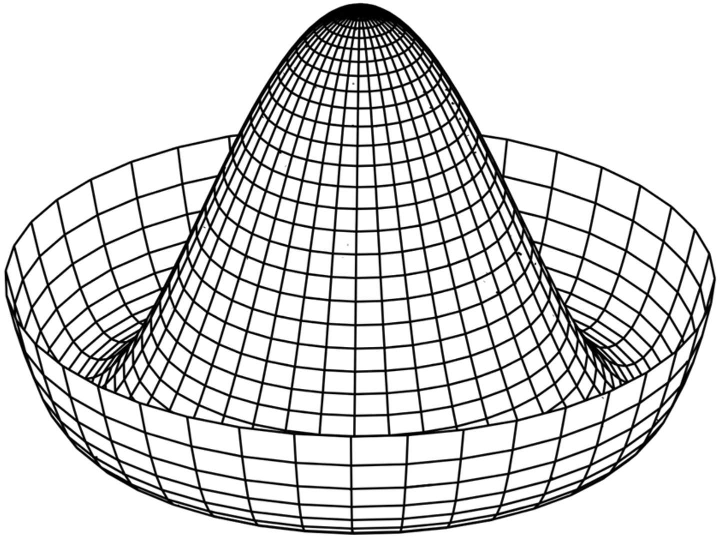
FRW × S¹: $\mathrm{d}s^2 = -\mathrm{d}t^2 + a(t)^2\mathrm{d}\vec{x}^2 + r(t)^2\mathrm{d}\phi^2$

axion like particles also predicted by string theory compactifications.

Axions and Axion-like particles

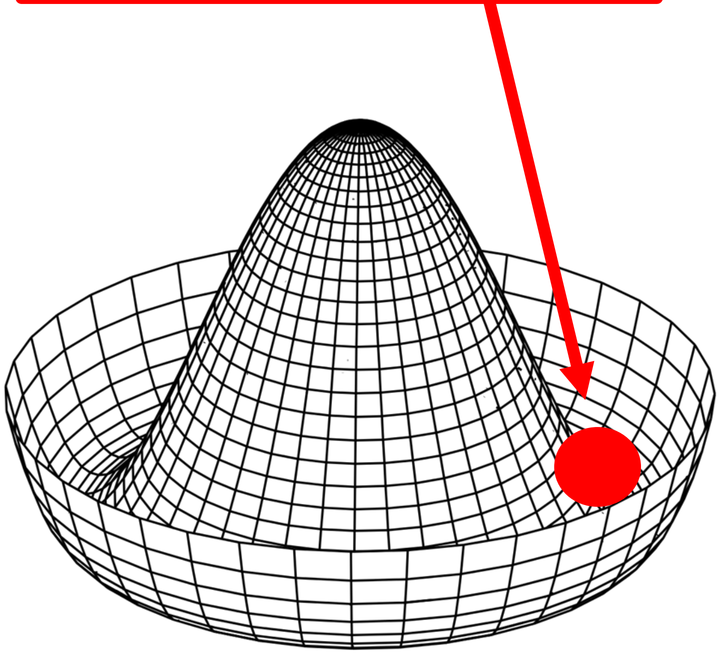
Peccei-Quinn Like Field

- U(1) degenerate minimum
- symmetry breaks
- vacuum chooses random direction



$$V(\varphi) = \frac{\lambda}{4!}\left(|\varphi|^2 - \frac{f_a^2}{2}\right)^2$$

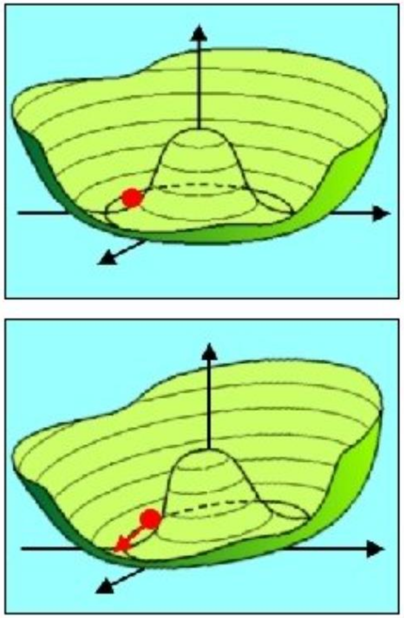
If **before** inflation, same random direction spread out over observable Universe.



- U(1) degenerate minimum
- symmetry breaks
- vacuum chooses random direction

$$V(\varphi) = \frac{\lambda}{4!}\left(|\varphi|^2 - \frac{f_a^2}{2}\right)^2$$

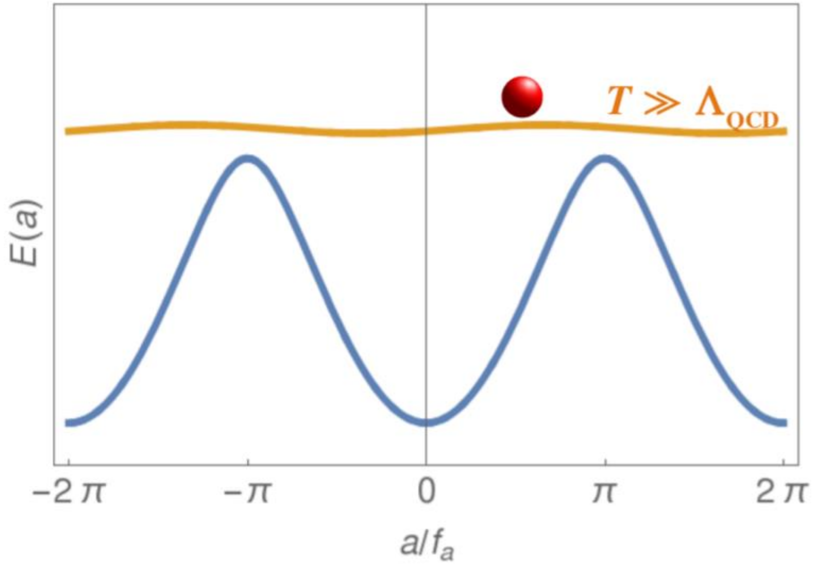
Axion gets a Mass at some later Stage



$$\begin{aligned}\rho &= \frac{1}{2}\dot{\phi}^2 + V(\phi)\\ P &= \frac{1}{2}\dot{\phi}^2 - V(\phi)\end{aligned}$$

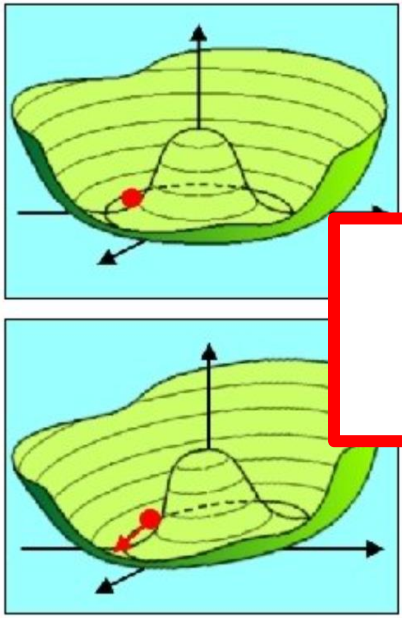
$$w = \frac{P}{\rho} = \frac{\dot{\phi}^2 - 2V}{\dot{\phi}^2 + 2V}$$

$$\ddot{a} + 3H(T)\dot{a} + m_a^2(T)\,a = 0$$



$$\langle w \rangle = \frac{\int_0^{t=2\pi/m} \left\{\cos^2(mt') - \sin^2(mt')\right\} dt'}{\int_0^{t=2\pi/m} dt''} = \left[\frac{m\sin(2mt)}{4\pi}\right]_0^{t=2\pi/m} = 0$$

Axion gets a Mass at some later Stage



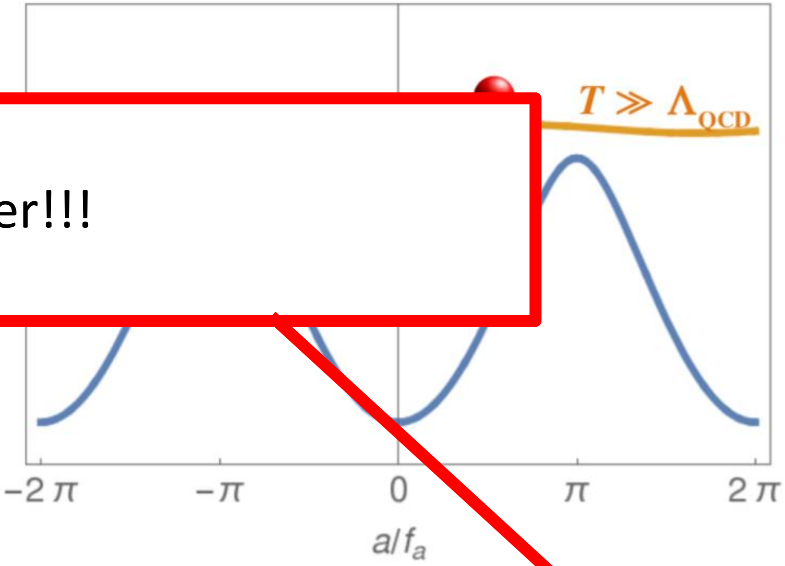
$$\rho \;=\; \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$1$$

i.e. matter!!!

$$w = \frac{\;}{\rho} = \frac{\dot{\phi} \;\; 2V}{\dot{\phi}^2 + 2V}$$

$$\ddot{a} + 3H(T)\dot{a} + m_a^2(T)\,a = 0$$



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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

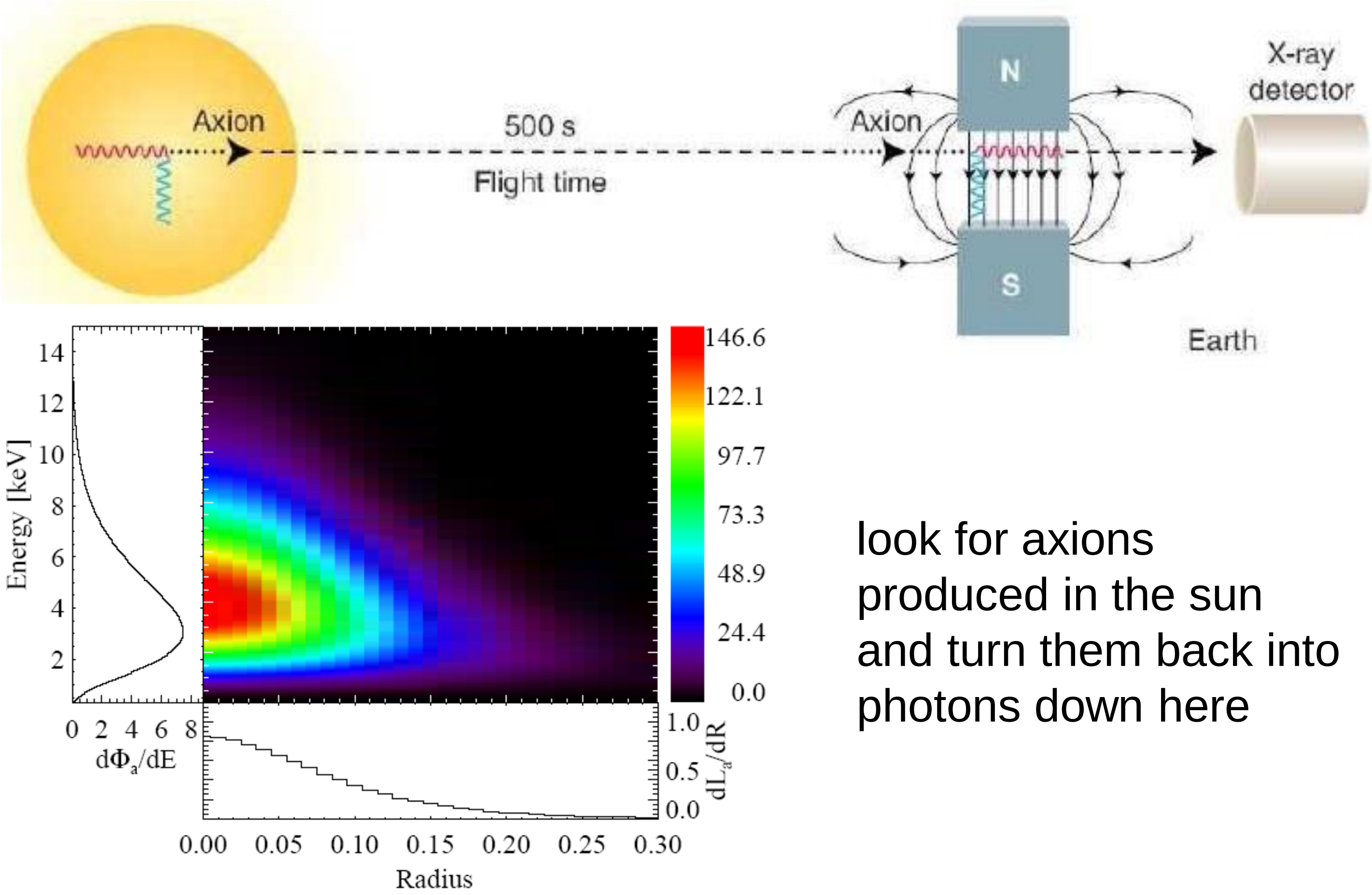
$$\mathcal{M} \equiv \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_\parallel & \Delta_M \\ 0 & \Delta_M & \Delta_m \end{pmatrix}$$

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

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

CAST: cern-axion-solar-telescope

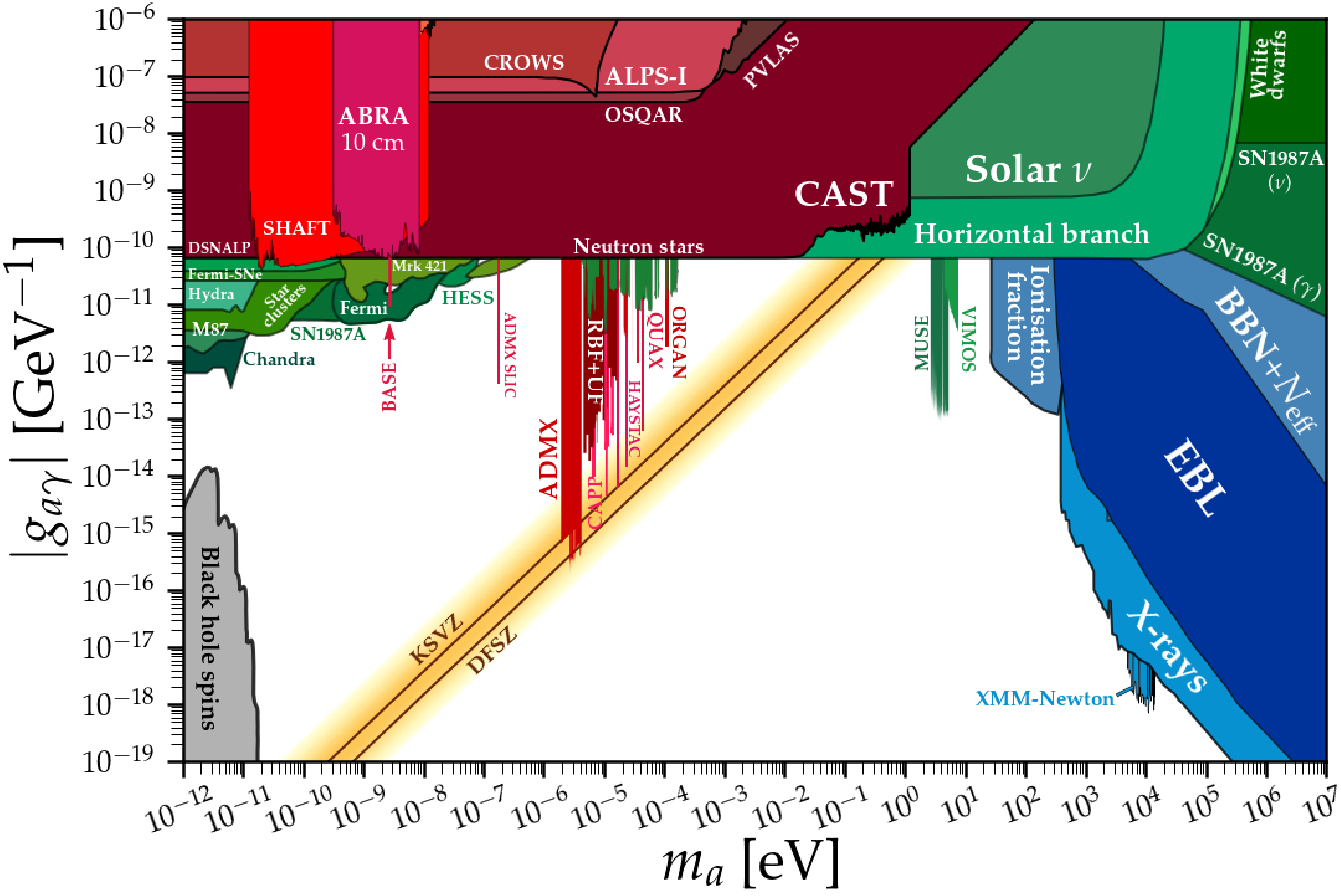
Search for Solar axions



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

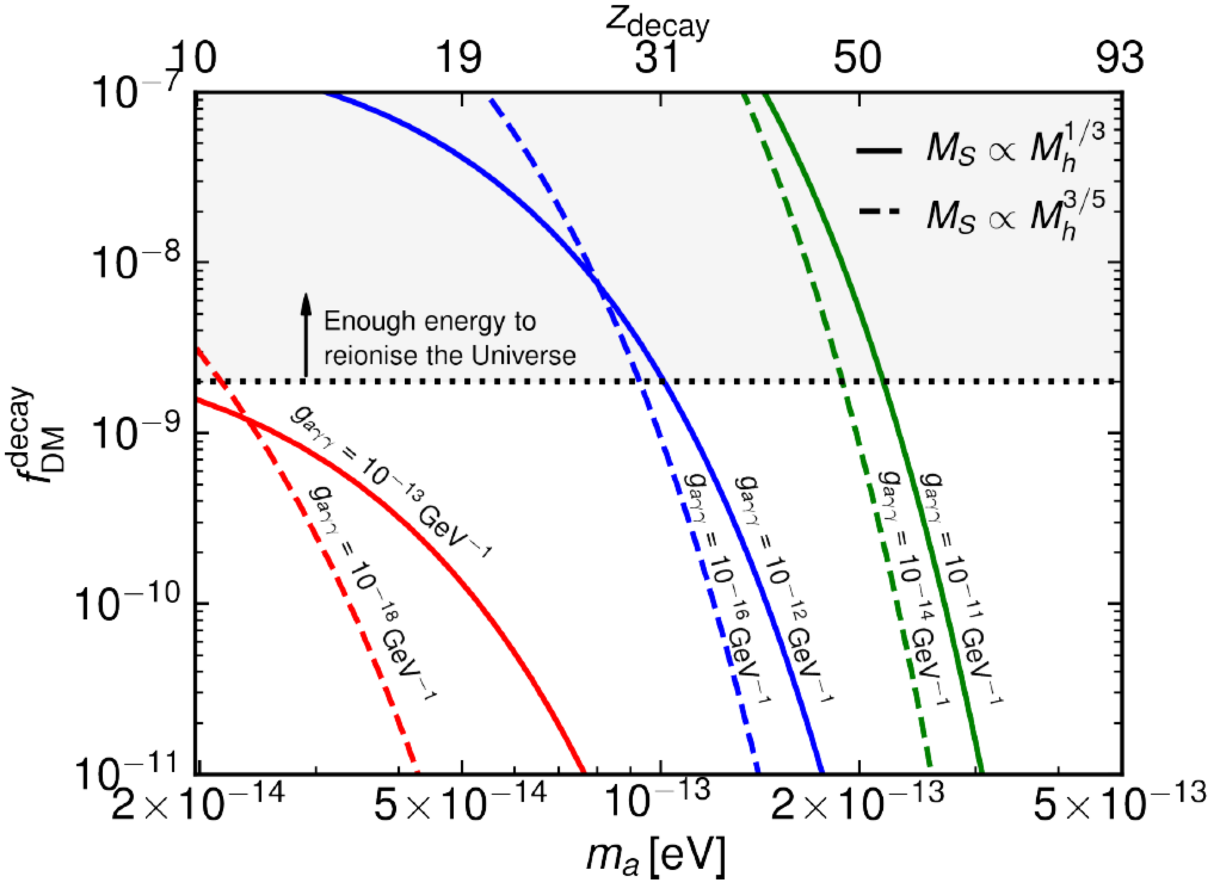
laboratory CAST bound

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



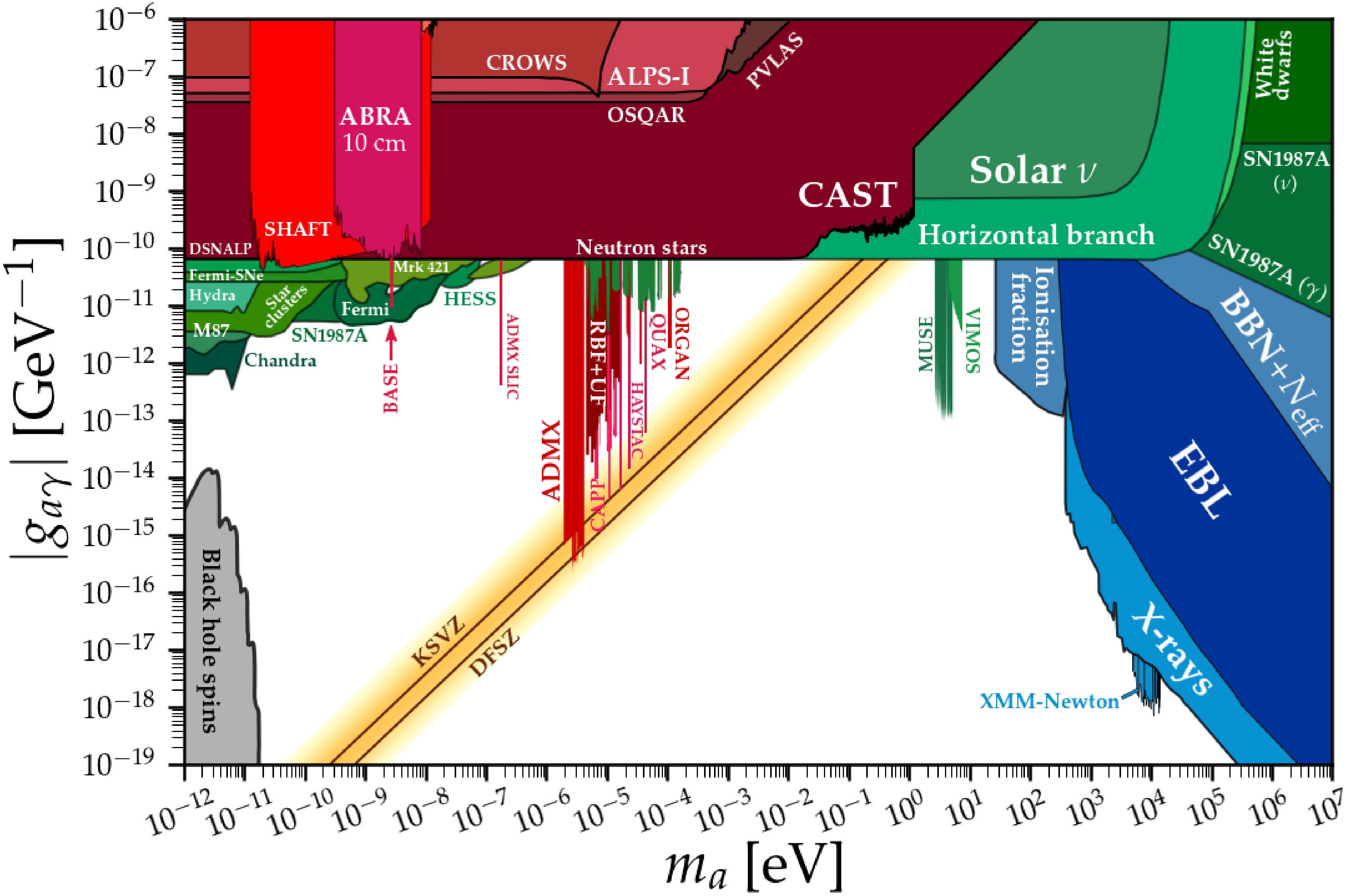
Axions can also decay! Only a small fraction would ionise the Universe

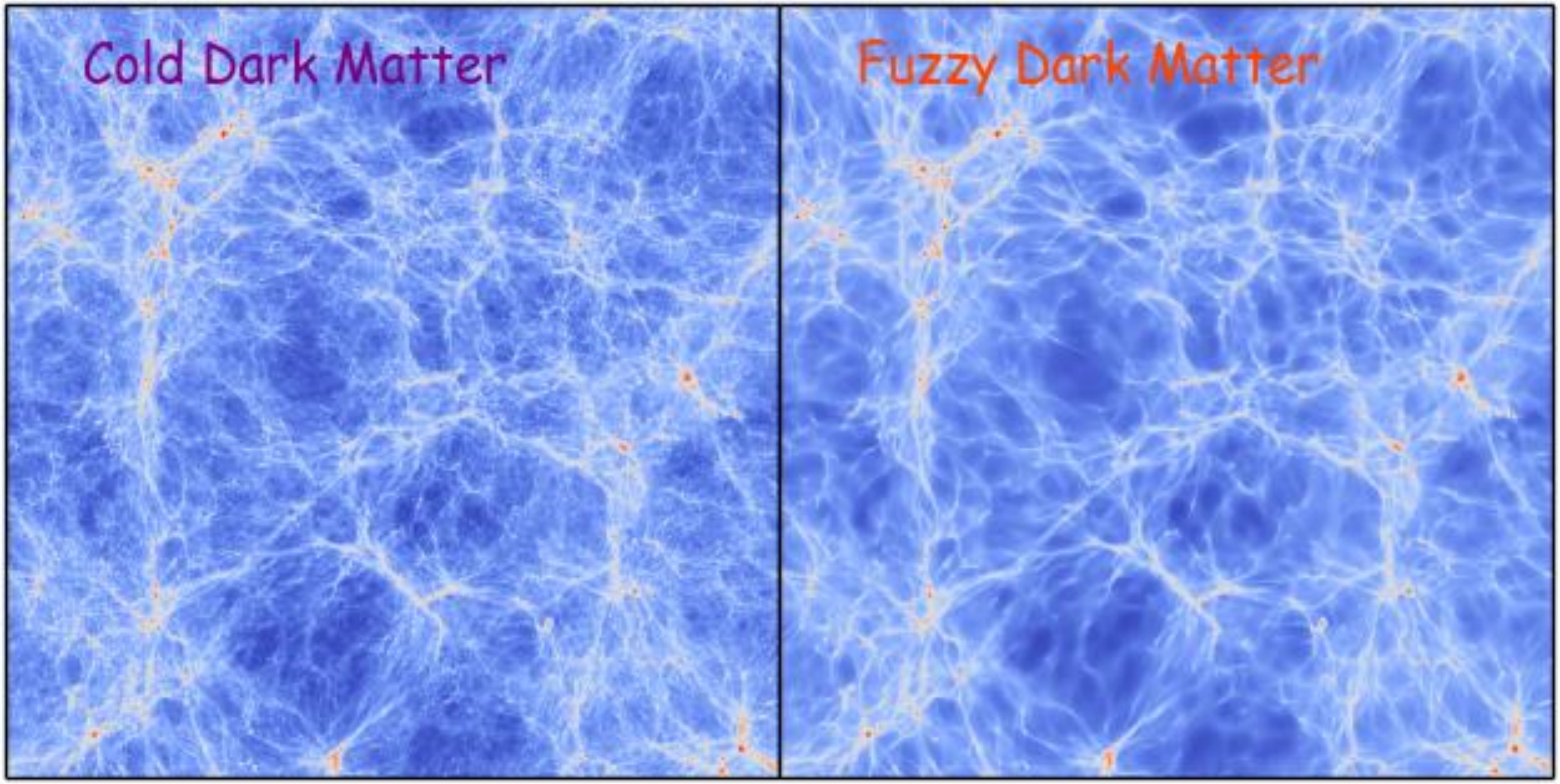
$$\Gamma(a \to \gamma\gamma) = \frac{g_{a\gamma\gamma}^2 m_a^3}{64\pi}$$



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

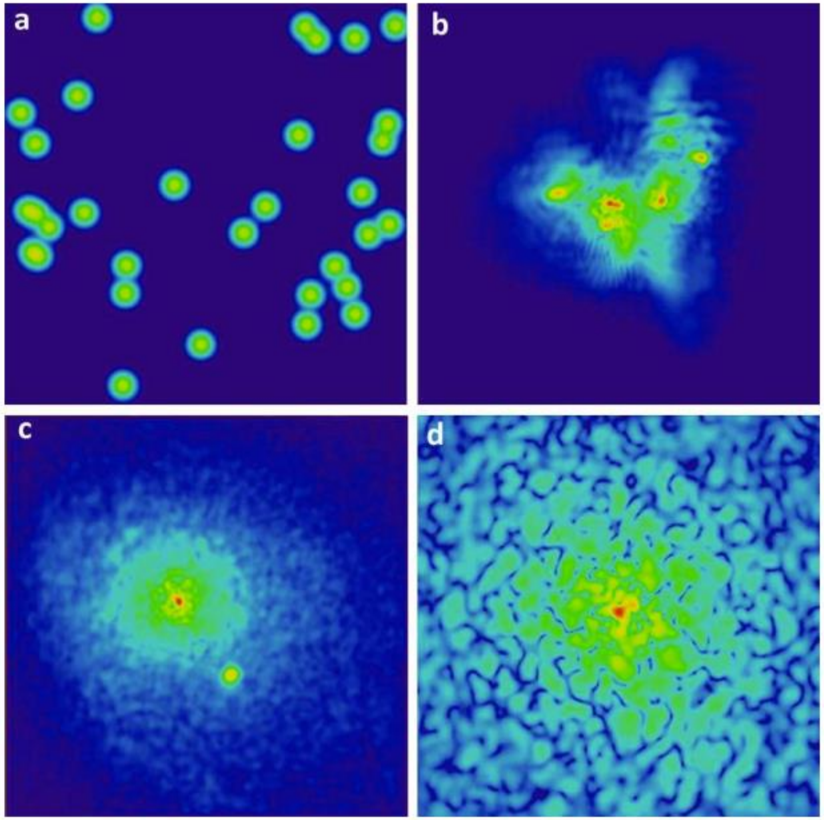
$$g_{a\gamma\gamma} < \ 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1} \ \ \text{for} \ \ m_a \ < \ 0.02\,\mathrm{eV}$$

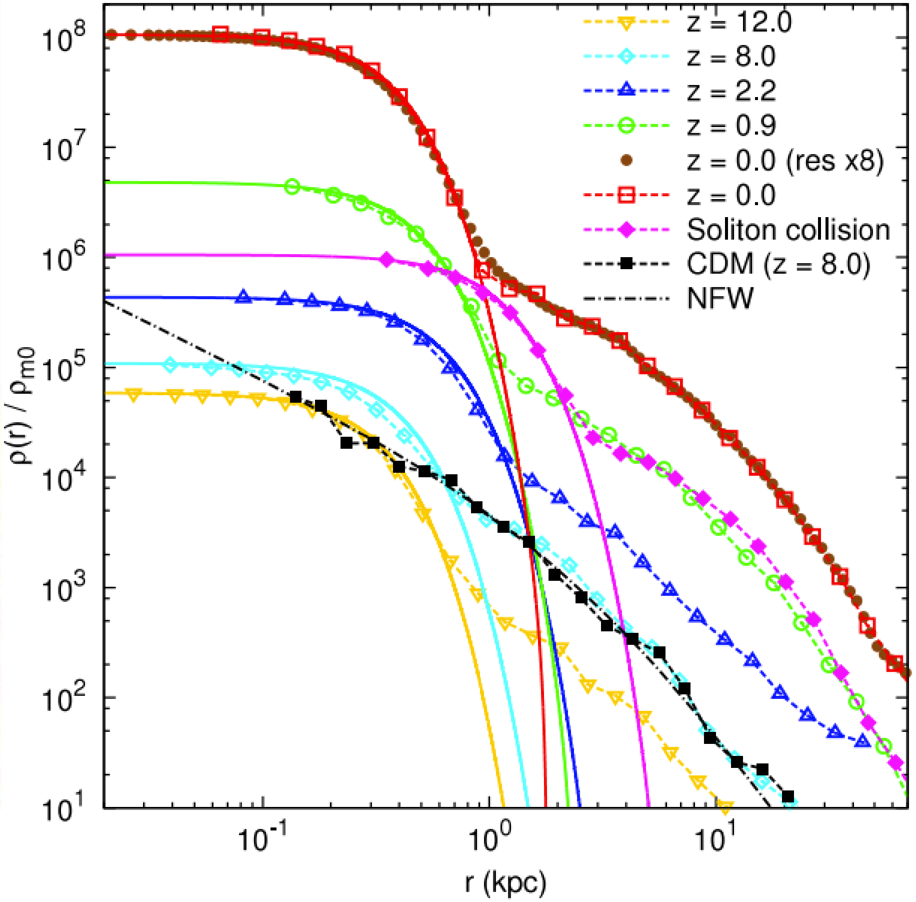




$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2ma^2}\nabla^2\psi + \frac{m\Phi}{a}\psi$$

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





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

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

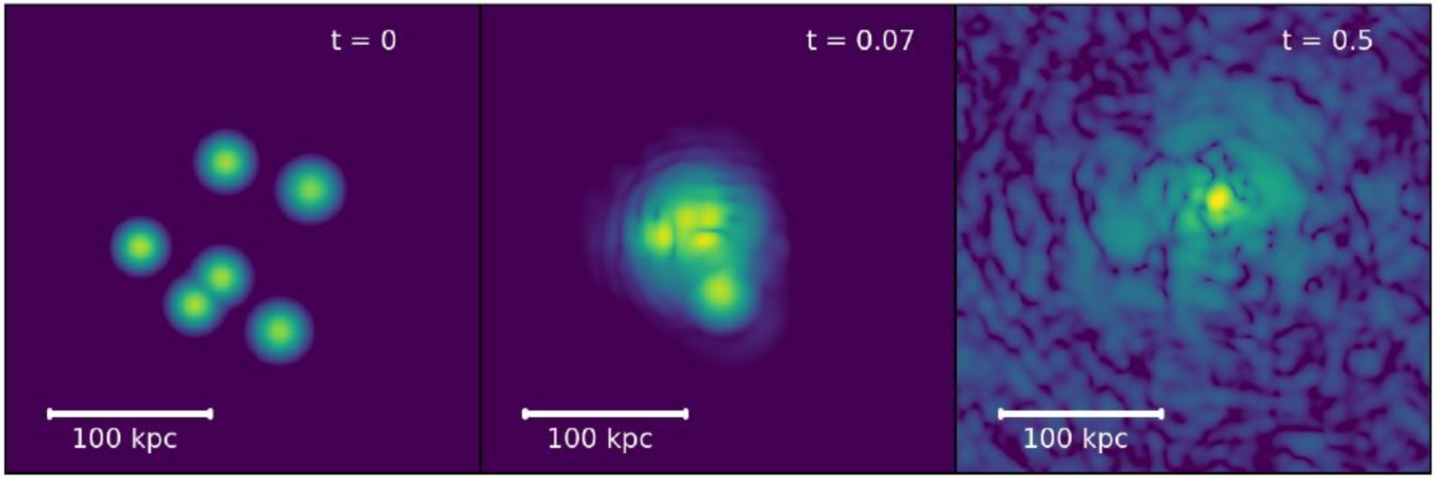
$$r_c = 1.6\ m_{22}^{-1} a^{1/2} \left(\frac{\zeta(z)}{\zeta(0)}\right)^{-1/6} \left(\frac{M_h}{10^9\ M_\odot}\right)^{-1/3}\ \text{kpc}$$

$$\rho(r) = \begin{cases} \rho_c \left[1 + 0.091 \left(\frac{r}{r_c}\right)^2\right]^{-8} & , \text{for } r < r_t \\ \rho_s \left[\frac{r}{r_s}\right]^{-1} \left[1 + \left(\frac{r}{r_s}\right)\right]^{-2} & , \text{for } r \geq r_t \end{cases}$$

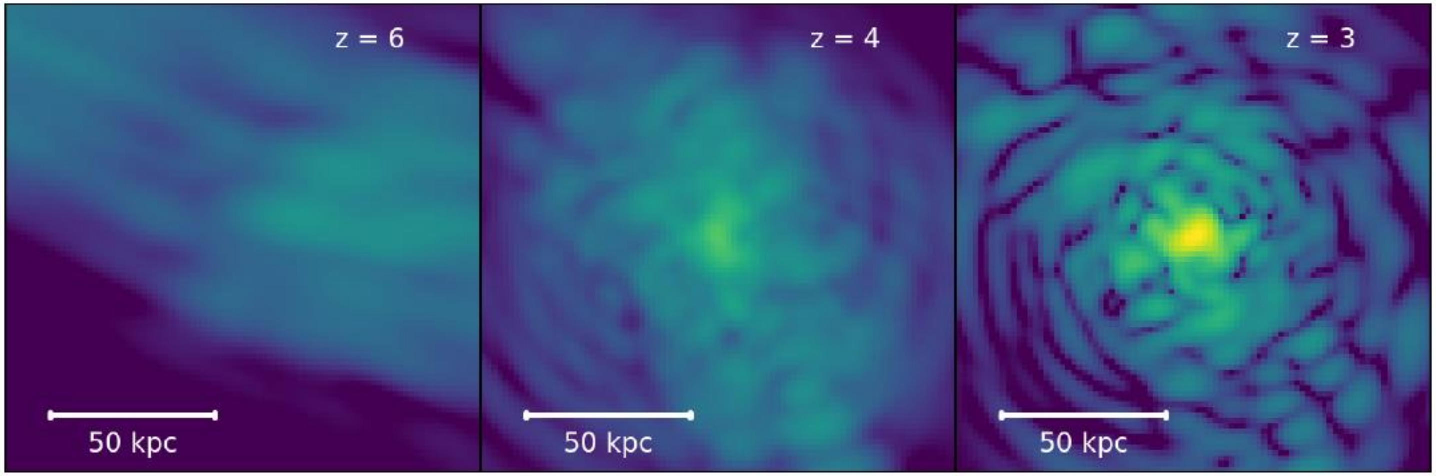
Schive et al 2014

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

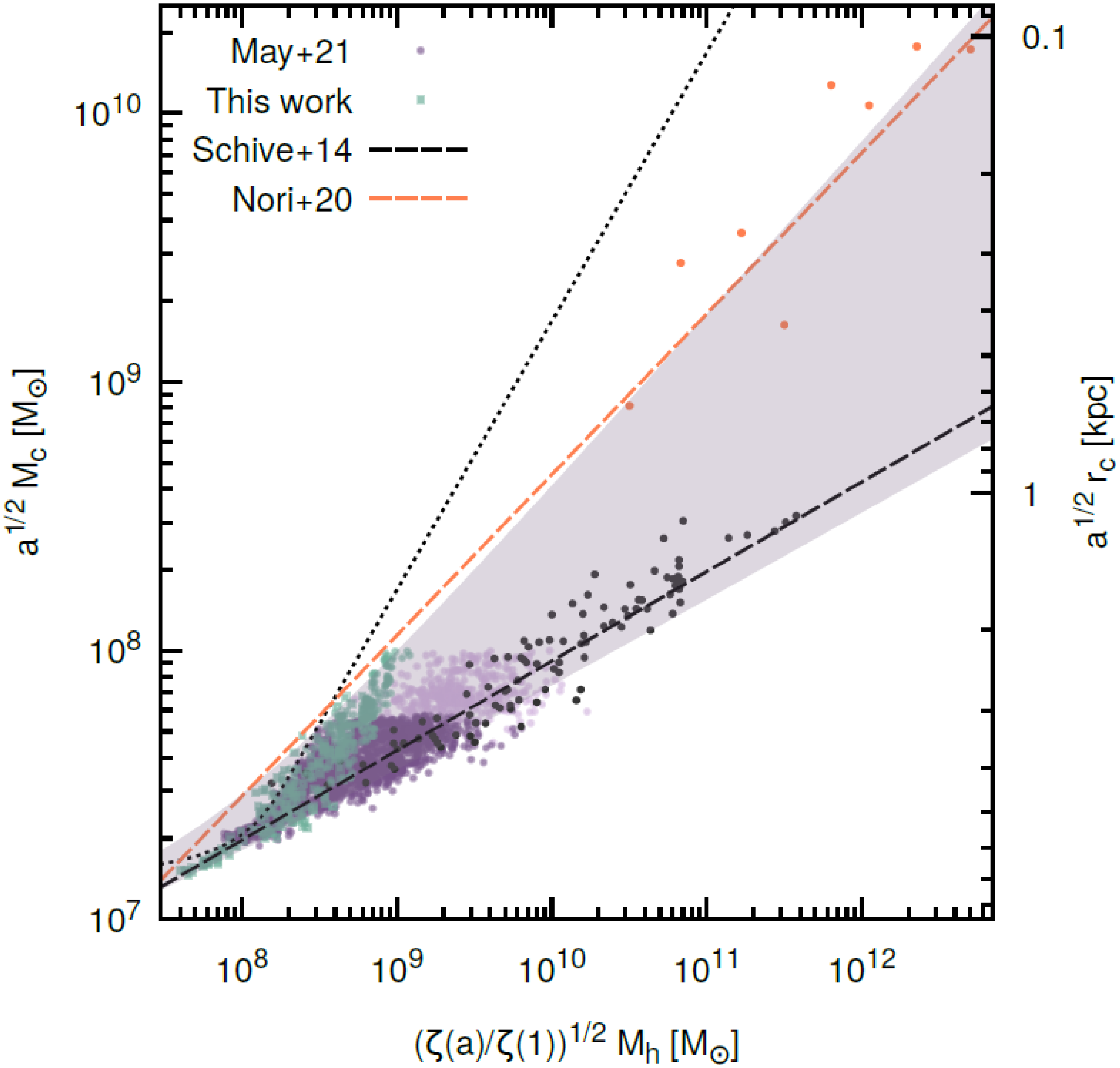
Hei Yin Jowett Chan,[1]★ Elisa G. M. Ferreira,[2,3,4] Simon May,[2]★ Kohei Hayashi,[5,6] Masashi Chiba[1]



Coalesence of halos to form bigger halo



Formation of a single halo from smaller halos



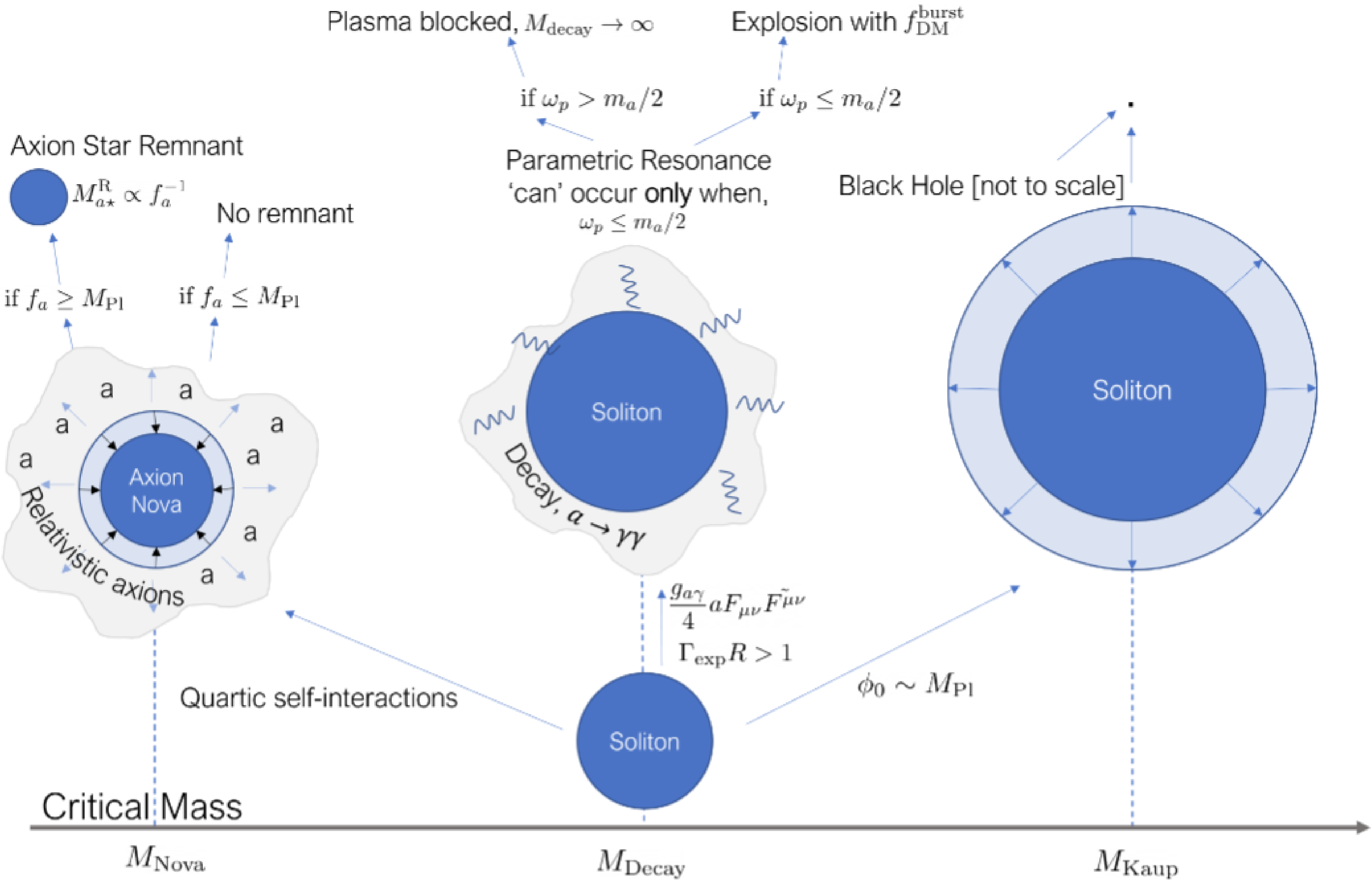
Schive et al found α=1/3

This more recent work finds that α=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!)



Axion Star Remnant

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

No remnant

if $f_a \geq M_{\mathrm{Pl}}$

if $f_a \leq M_{\mathrm{Pl}}$

Relativistic axions

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

Explosion with $f_{\mathrm{DM}}^{\mathrm{burst}}$

if $\omega_p > m_a/2$

if $\omega_p \leq m_a/2$

Parametric Resonance
'can' occur only when,
$\omega_p \leq m_a/2$

Decay, $a \to \gamma\gamma$

$\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F^{\mu\nu}}$

$\Gamma_{\mathrm{exp}} R > 1$

.

Black Hole [not to scale]

Quartic self-interactions

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

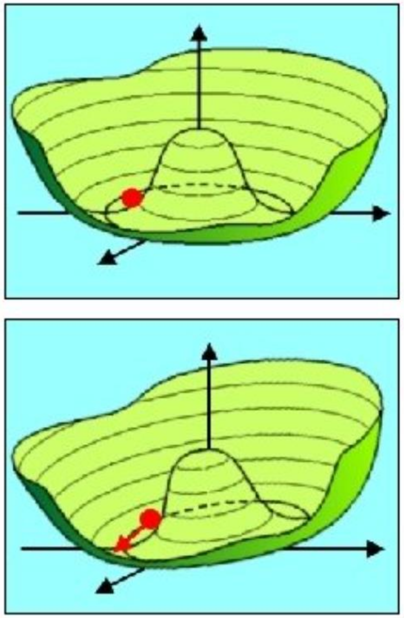
Critical Mass

M_{Nova}

M_{Decay}

M_{Kaup}

Axion gets a Mass at some later Stage

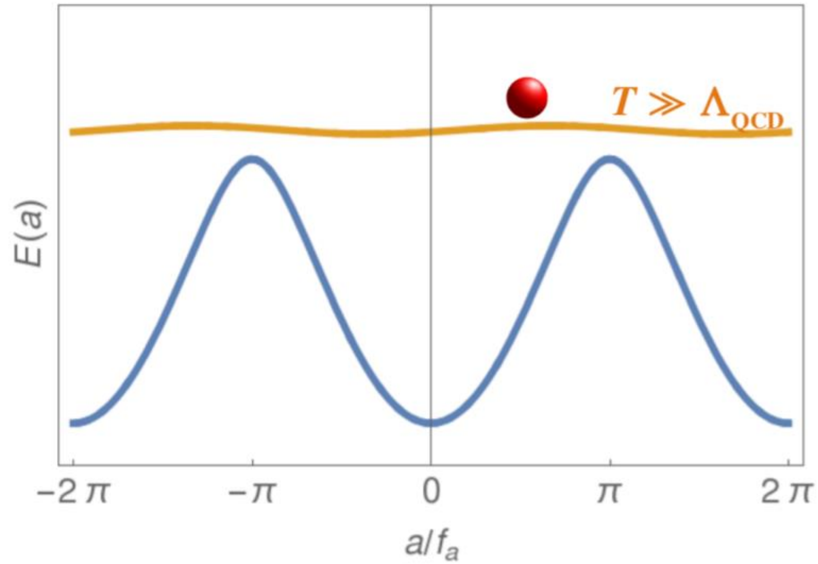


$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$P = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$w = \frac{P}{\rho} = \frac{\dot{\phi}^2 - 2V}{\dot{\phi}^2 + 2V}$$

$$\ddot{a} + 3H(T)\dot{a} + m_a^2(T)\, a = 0$$



$$\langle w \rangle = \frac{\int_0^{t=2\pi/m} \left\{\cos^2(mt') - \sin^2(mt')\right\} dt'}{\int_0^{t=2\pi/m} dt''} = \left[\frac{m \sin(2mt)}{4\pi}\right]_0^{t=2\pi/m} = 0$$

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

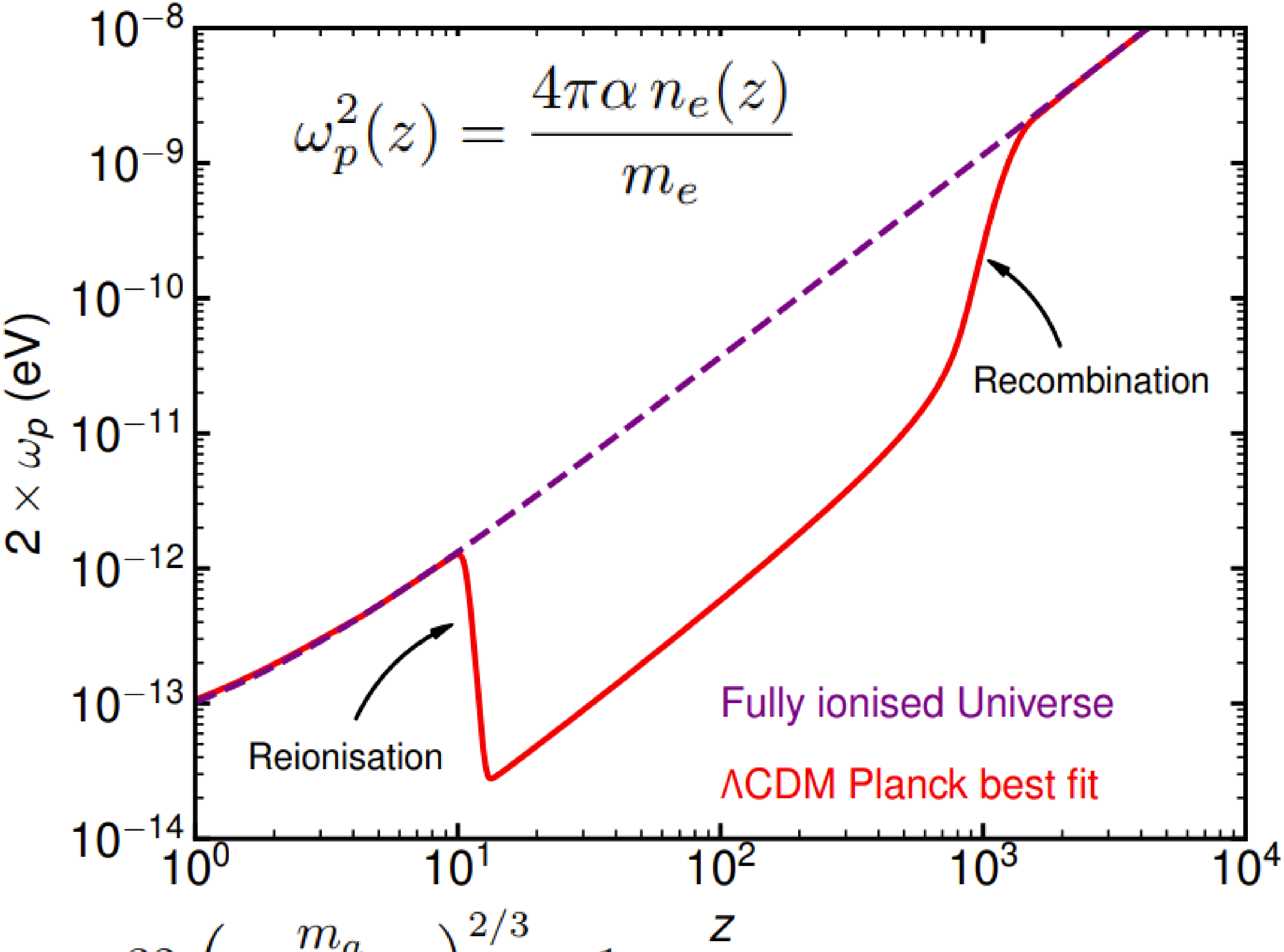
$$M_S^{\rm decay} \simeq 8.4 \times 10^{-5}\, M_\odot \left(\frac{10^{-11}\,{\rm GeV}^{-1}}{g_{a\gamma\gamma}} \right) \left(\frac{10^{-13}\,{\rm eV}}{m_a} \right)$$

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!



$$\omega_p^2(z) = \frac{4\pi\alpha\, n_e(z)}{m_e}$$

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

Absorption of the photons in IGM through inverse Bremsstrahlung

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

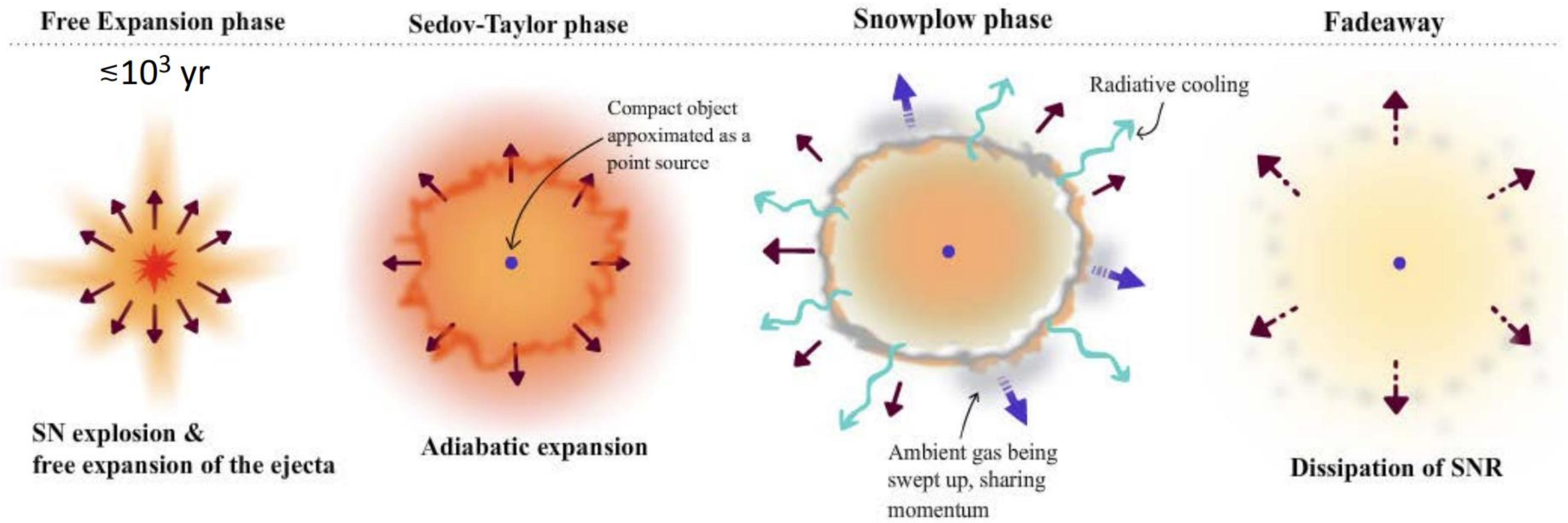
$$\Lambda_{\rm BR}(E_\gamma, z) = g_{\rm BR} \frac{n_p}{m_e^3} \sqrt{\frac{2}{3}} 2\pi^{3/2} \alpha \left(\frac{T_e}{m_e}\right)^{-7/2}$$

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

Less than a parsec

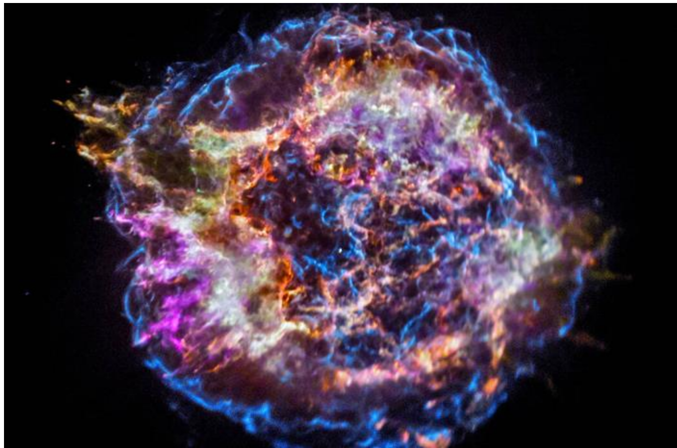
Absorption leads to super heated region which subsequently expands

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.

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

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

Evolution of Luminosity which drives Pressure

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

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

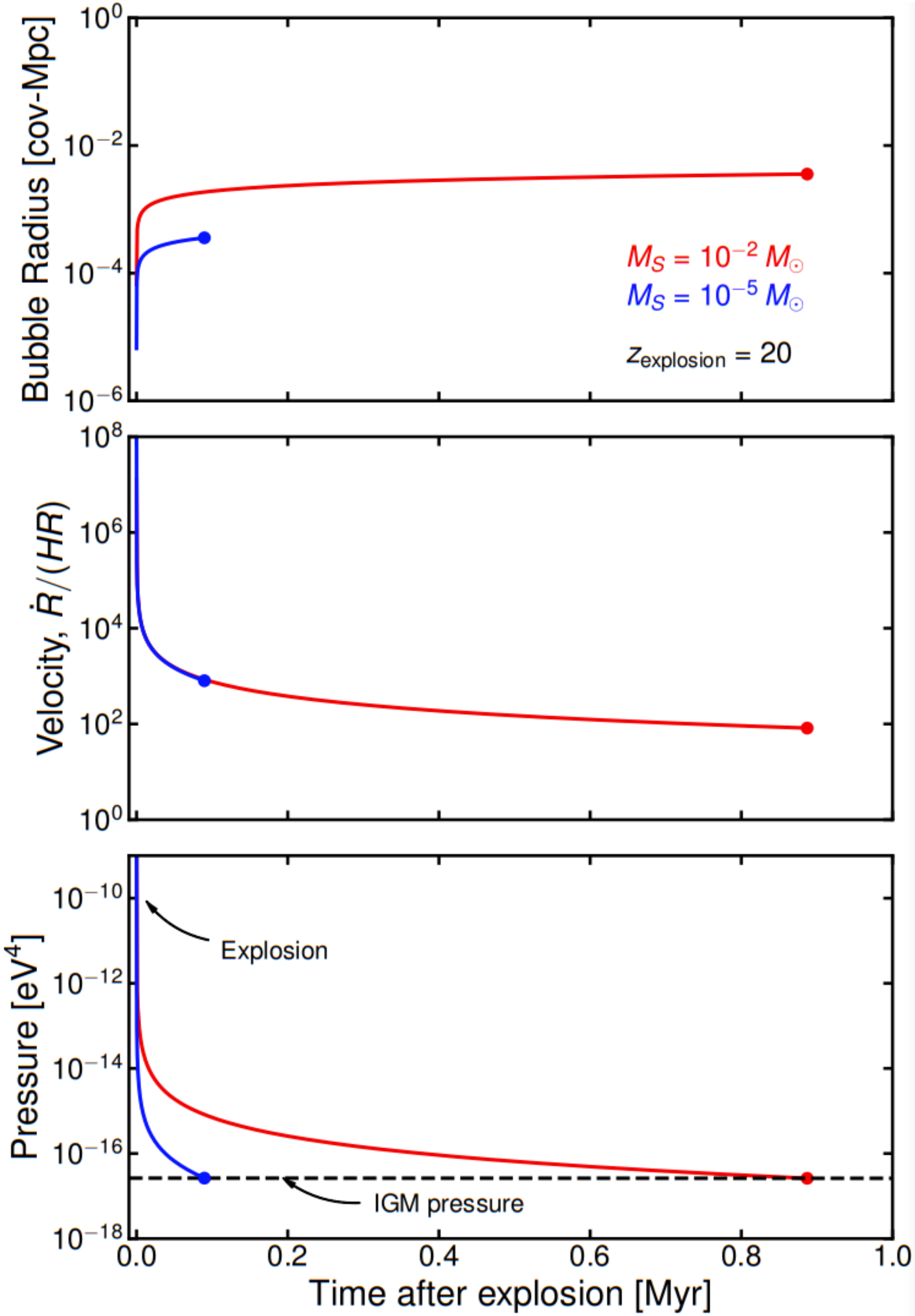
This switches off fairly quickly!

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

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

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

Evolution of Bubble Size, velocity and pressure



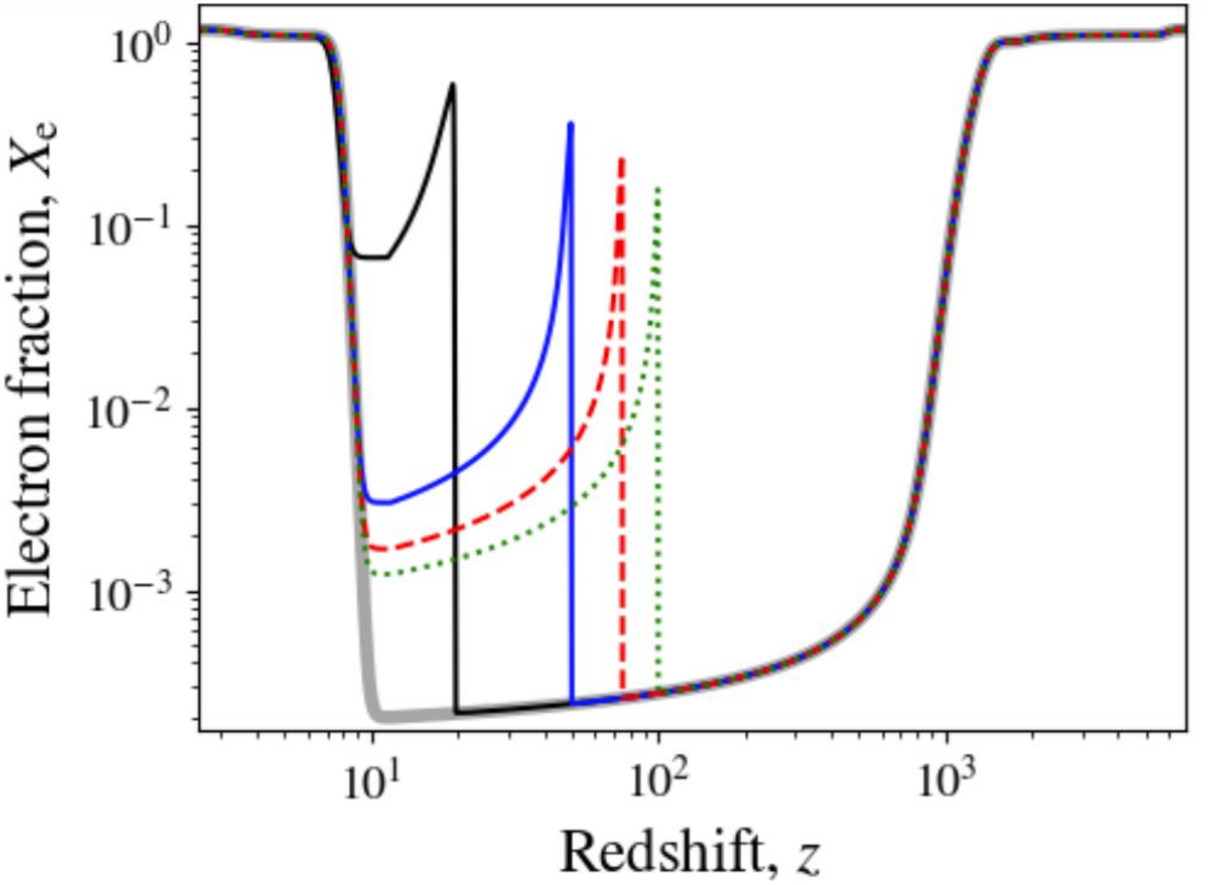
We end evolution when internal pressure is equal to IGM pressure!

Injection of energy heats up baryons

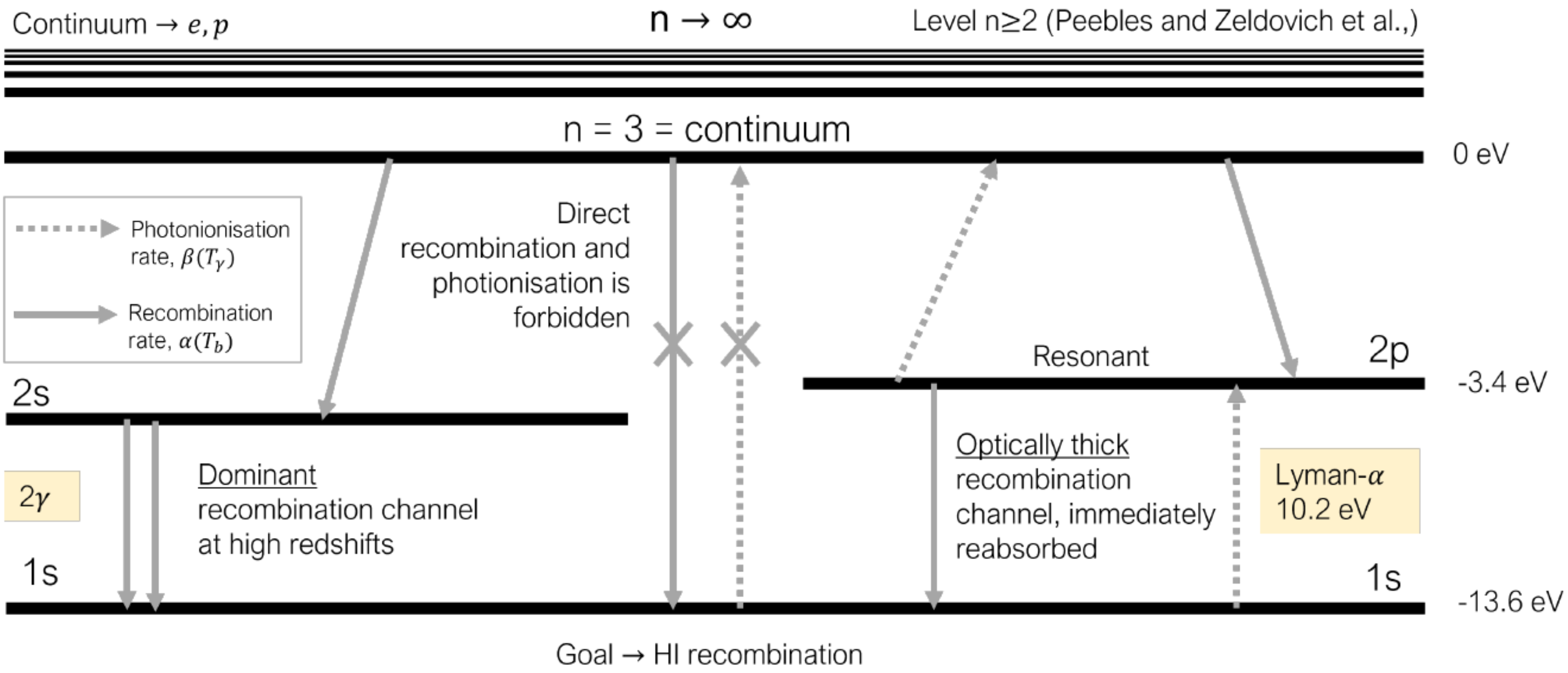
$$\frac{\mathrm{d}T_{\mathrm{b}}}{\mathrm{d}z}(1+z) = \underbrace{2T_{\mathrm{b}}}_{\text{Adiabatic cooling}} + \underbrace{\gamma_{\mathrm{op}}(T_{\mathrm{b}} - T_{\gamma})}_{\text{Compton cooling}} + \underbrace{\frac{2}{3}\frac{1}{N_{\mathrm{H}}(1+f_{\mathrm{He}}+X_{\mathrm{e}})}\left.\frac{\mathrm{d}E}{\mathrm{d}z}\right|_{\mathrm{dep}}}_{\text{Additional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

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

The burst of radiation changes the ionisation of the Universe



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



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

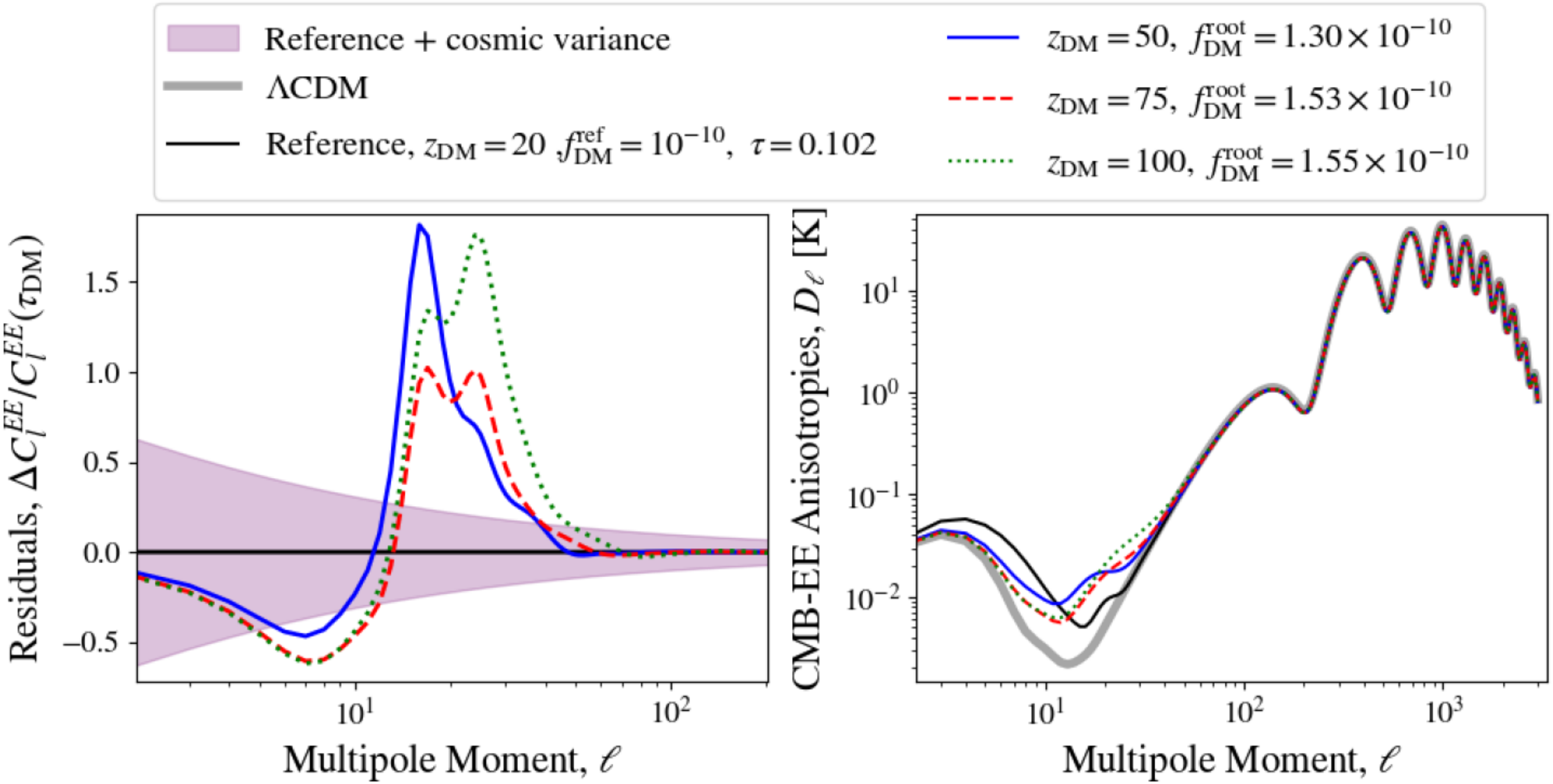
$$\frac{\mathrm{d}X_{\mathrm{p}}}{\mathrm{d}t} = \mathcal{C}_{\mathrm{H}} \left(\beta_{\mathrm{H}}(T_\gamma)(1 - X_{\mathrm{p}}) \mathrm{e}^{\frac{-\epsilon_{\mathrm{H},2s1s}}{T_\gamma}} - X_{\mathrm{e}} X_{\mathrm{p}} N_{\mathrm{H}} \alpha_{\mathrm{H}}^{(2)}(T_b) + \left.\frac{\mathrm{d}X_{\mathrm{p}}}{\mathrm{d}t}\right|_{\mathrm{coll}}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

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

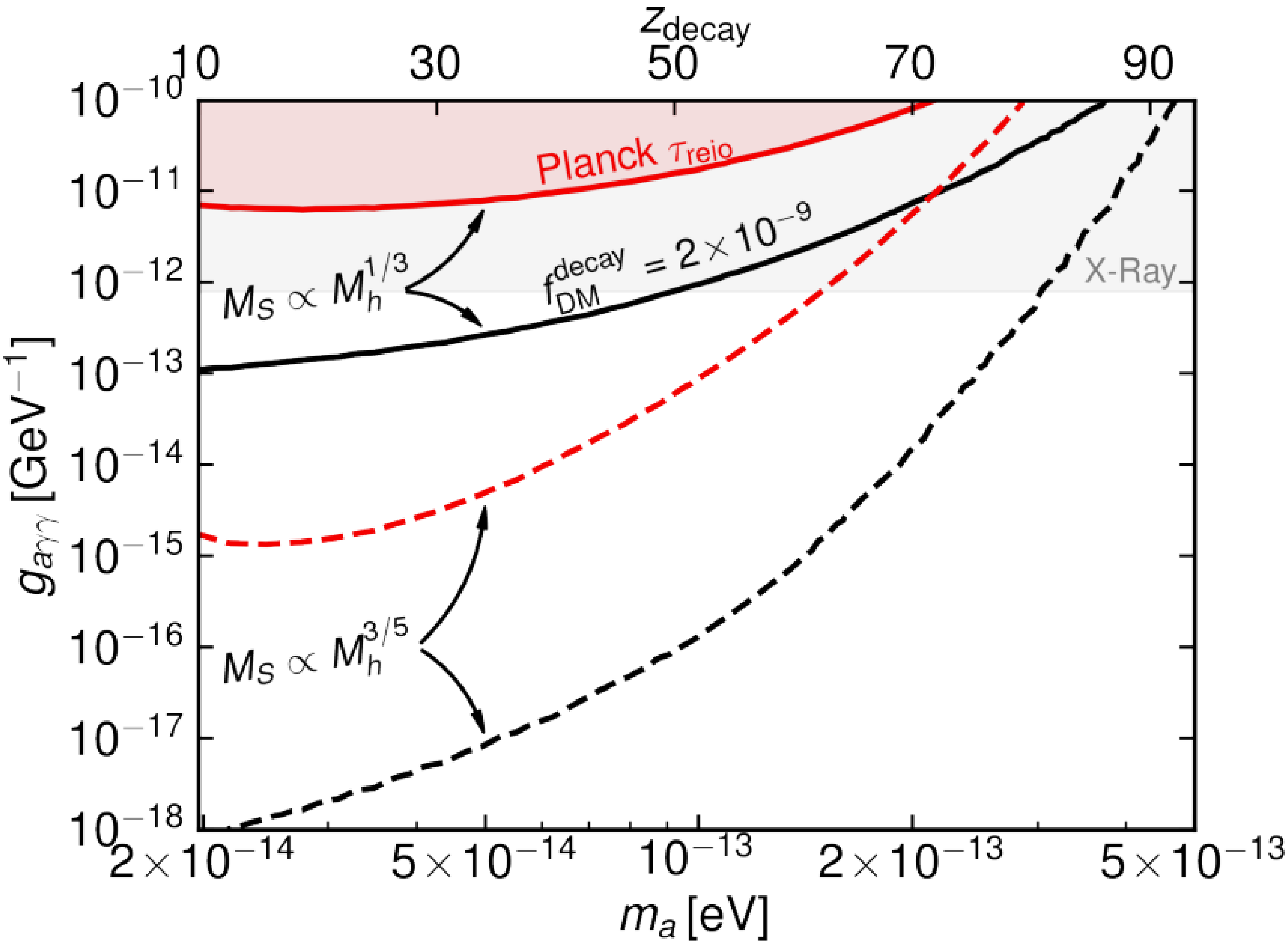
Net result depends on the following factors:-

- 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?

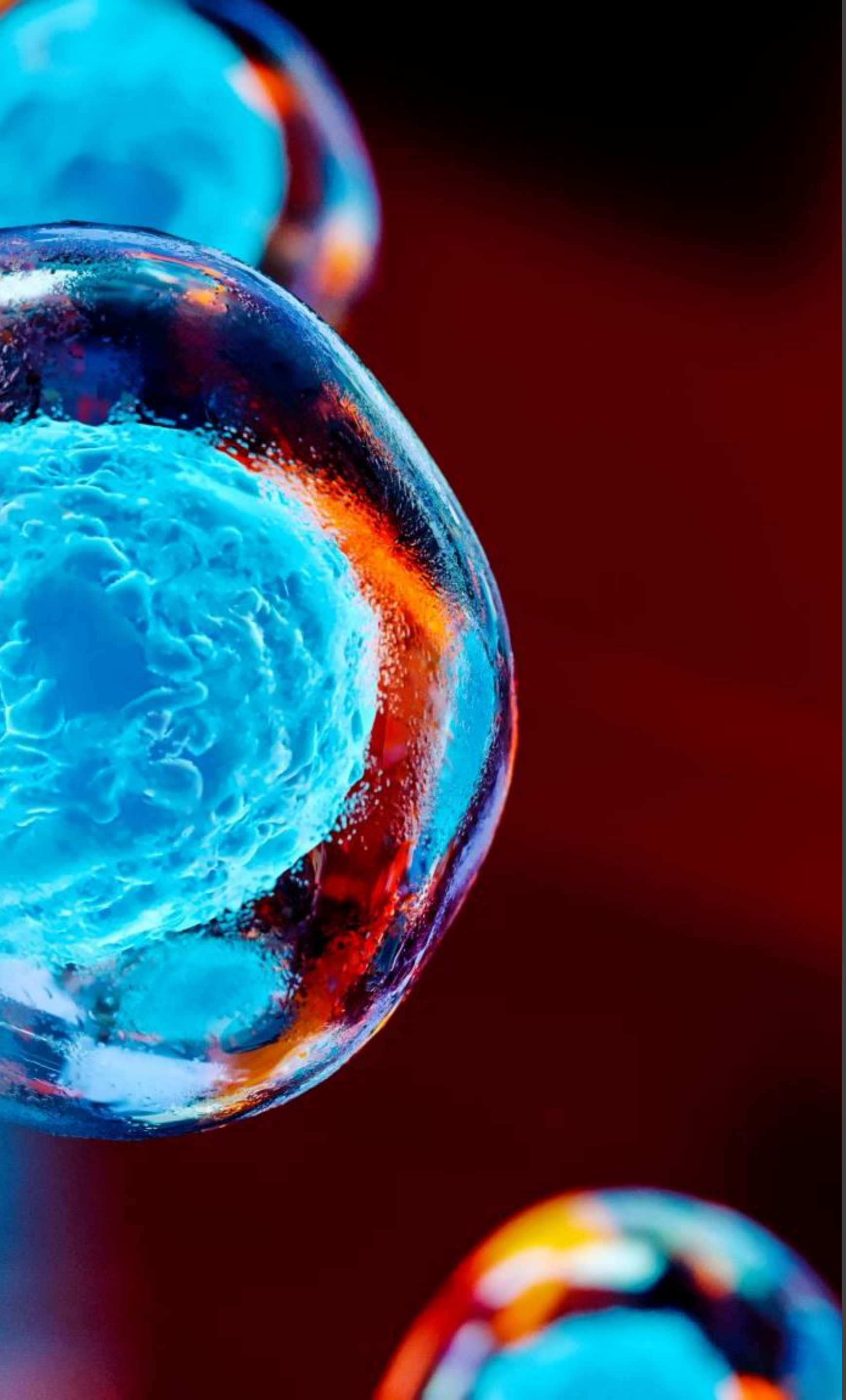
Need to look at the effect on the CMB and compare to Planck.



Parameter space we are sensitive to

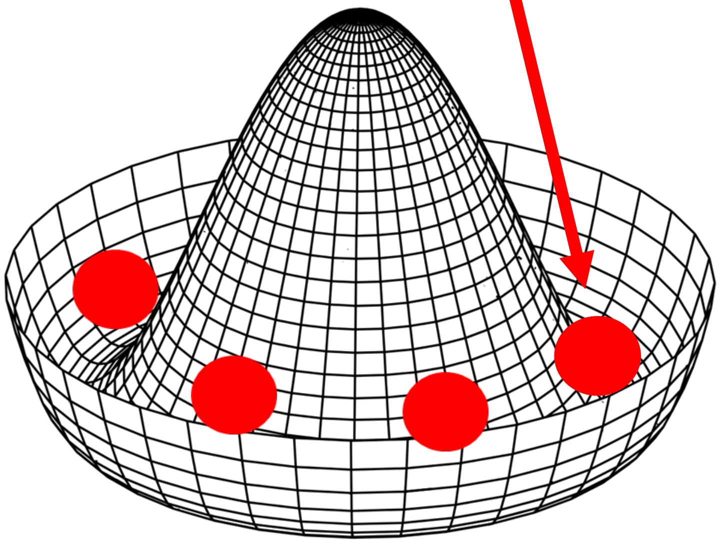


PROVISIONAL



Conclusions

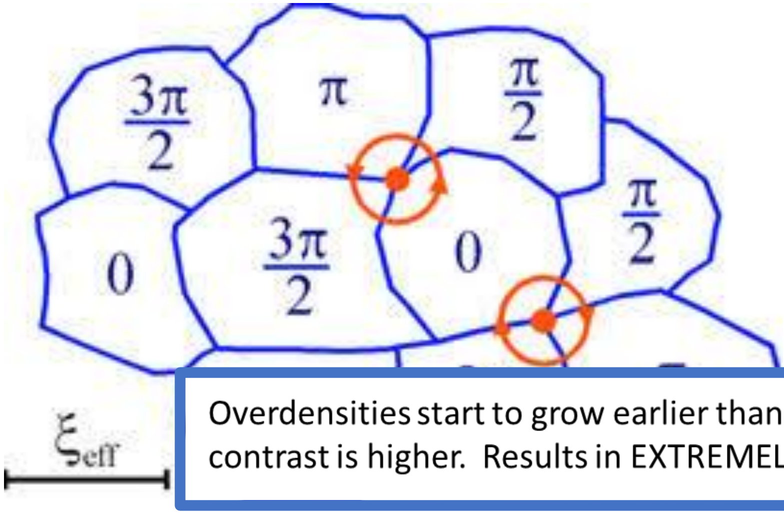
- Fuzzy Dark Matter leads to solitonic cores in dark matter halos
- Axion decay into photons is enhanced in dense regions
- Solitons decay and ionise the Universe
- CMB puts constraints on this region of parameter space which may be competitive with other constraints



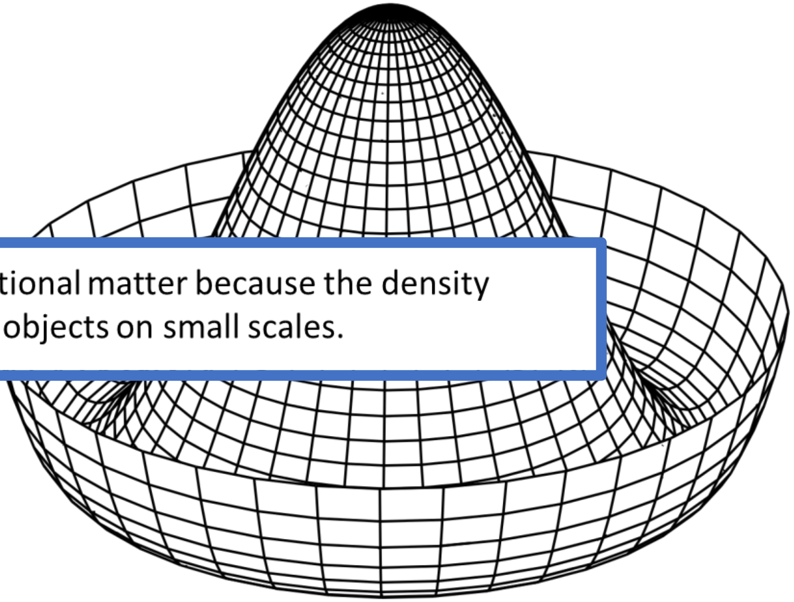
If **after** inflation, different values in different regions of the Universe.

- U(1) degenerate minimum
- symmetry breaks
- vacuum chooses random direction

$$V(\varphi) = \frac{\lambda}{4!}\left(|\varphi|^2 - \frac{f_a^2}{2}\right)^2$$



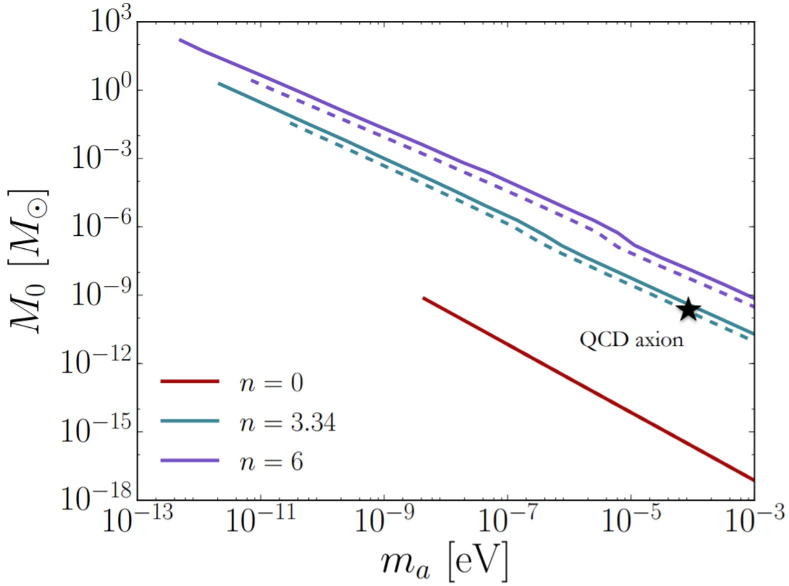
Overdensities start to grow earlier than conventional matter because the density contrast is higher. Results in EXTREMELY dense objects on small scales.



Kibble Mechanism

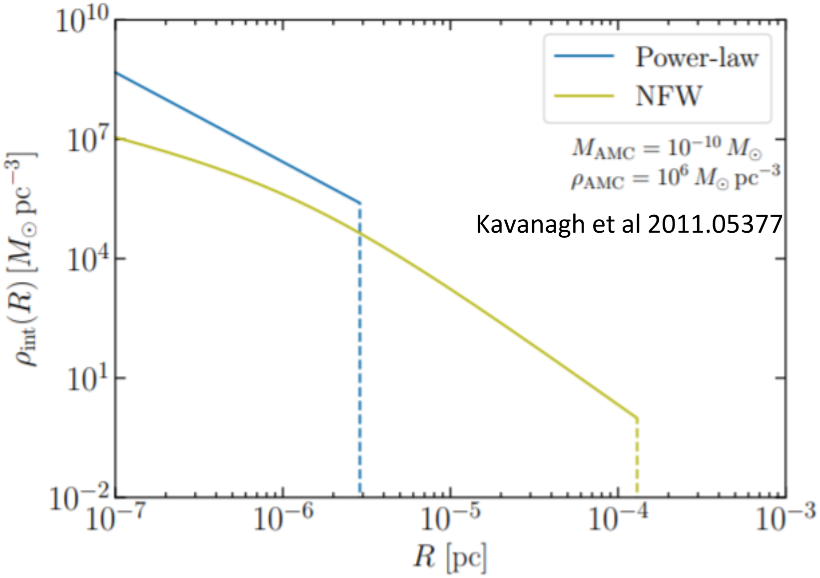
Characteristics of the resulting "miniclusters"

Moment at which they form depends on temperature dependence of mass.



$$M_0 = \bar{\rho}_a \frac{4}{3}\pi \left(\frac{\pi}{a(T_0)H(T_0)} \right)^3$$

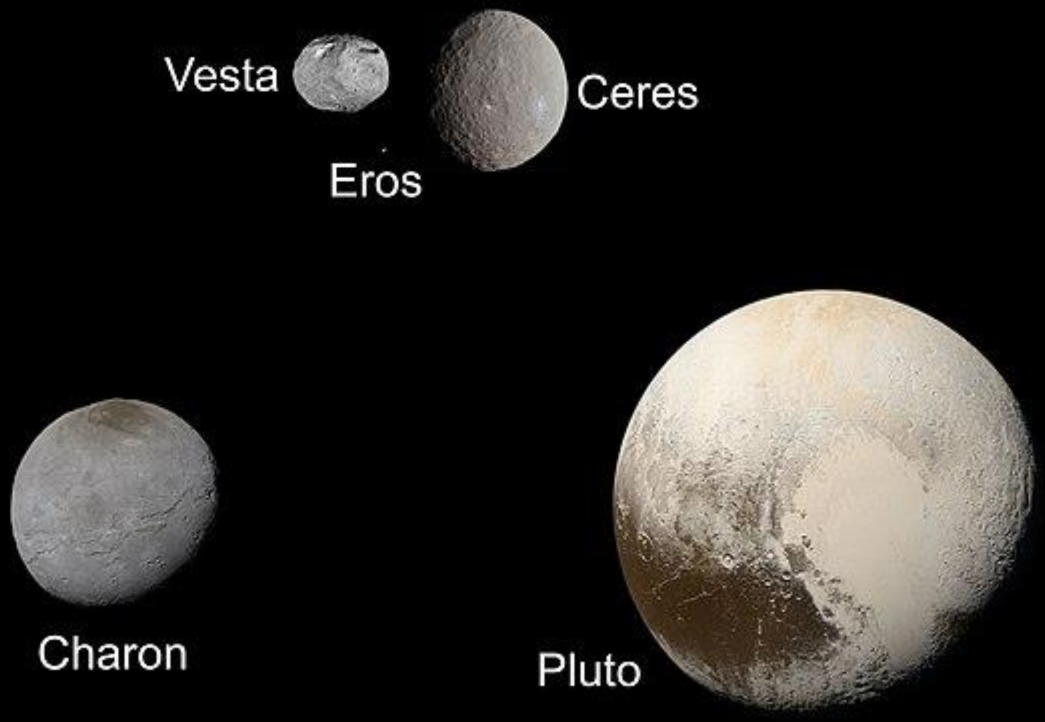
Collapse to form (very) dense small objects



Kavanagh et al 2011.05377

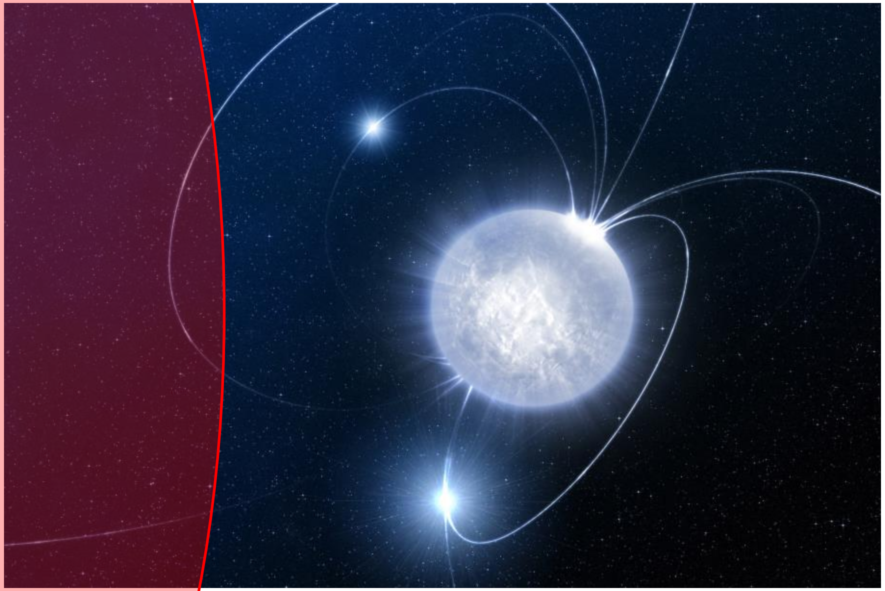
For example, for QCD axion R~ 1 AU, M~10^{-10}Msun

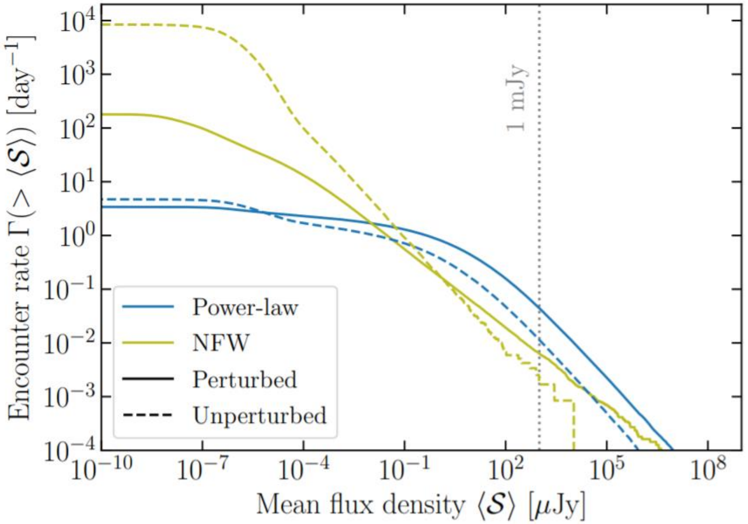
Results in dense haloes with the mass of a small asteroid (invisible asteroid)

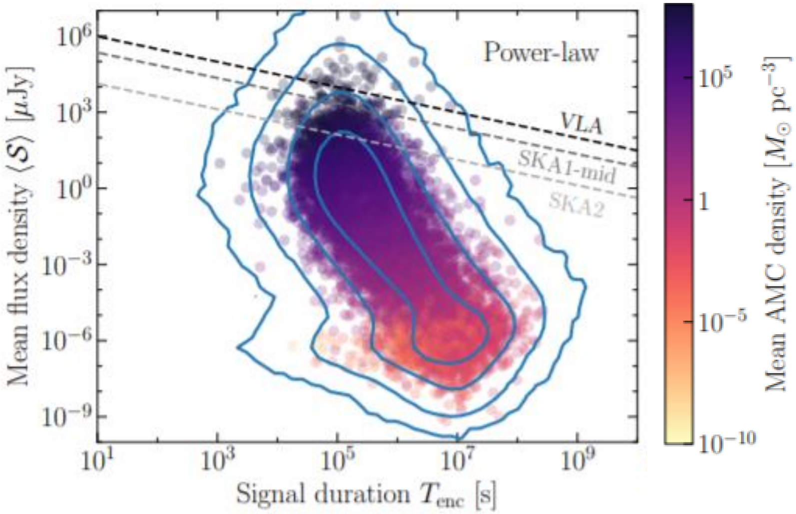


What are the Astrophysical Windows on this scenario?

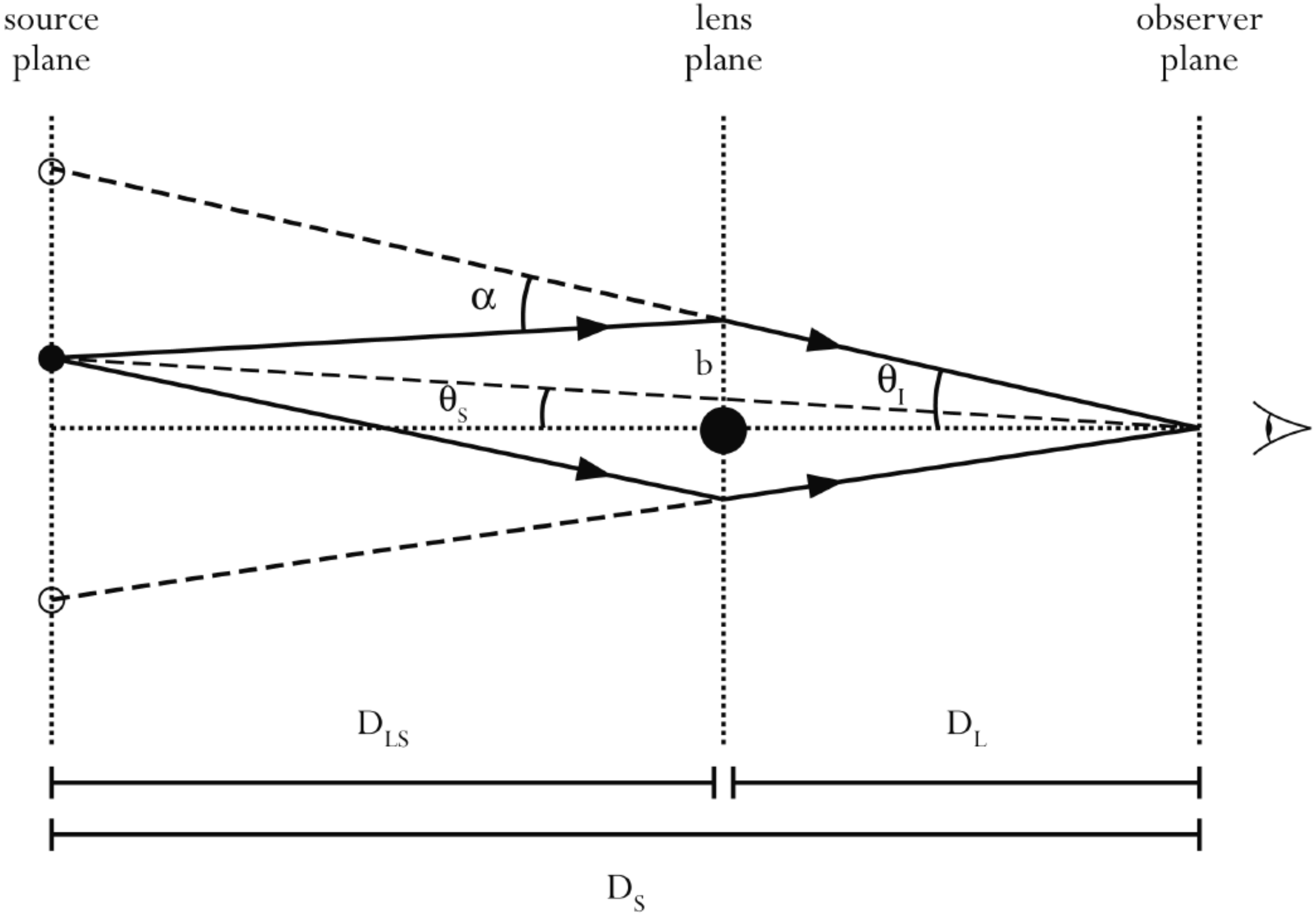
Encounters with Neutron Stars

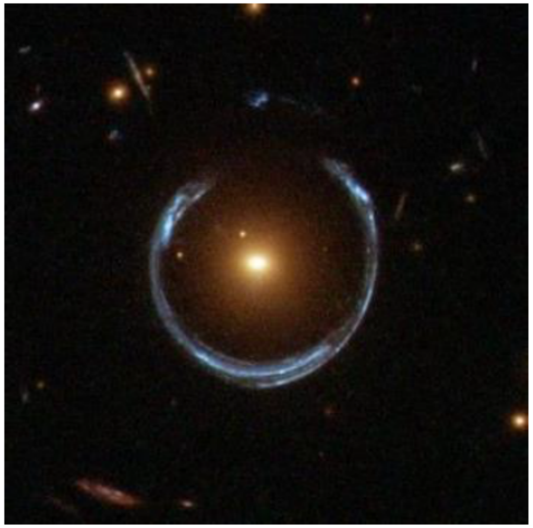




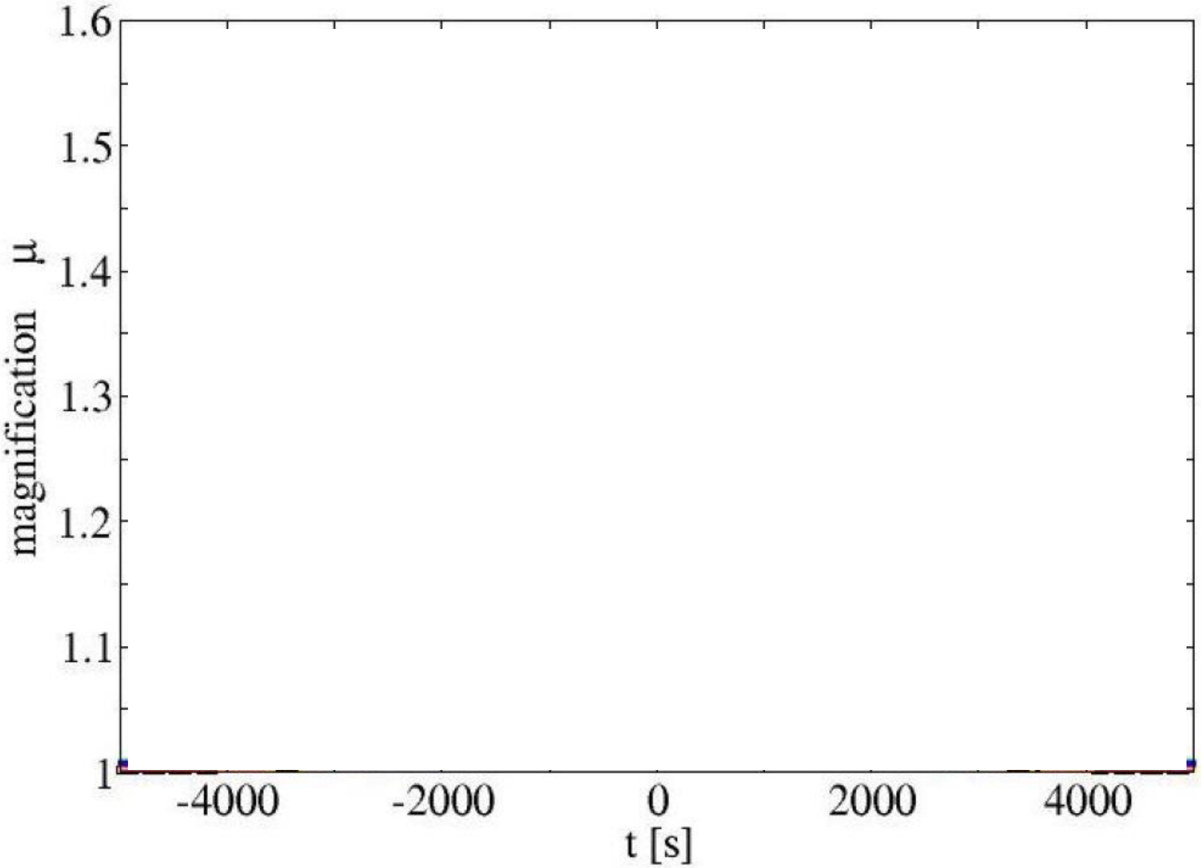


Gravitational Lensing





$$R_{\mathrm{E}}(x, M) = 2\left[GMx(1-x)d_s\right]^{1/2}$$


1.6
1.5
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1.2
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magnification μ
-4000
-2000
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2000
4000
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Subaru Telescope Mauna Kea Hawaii

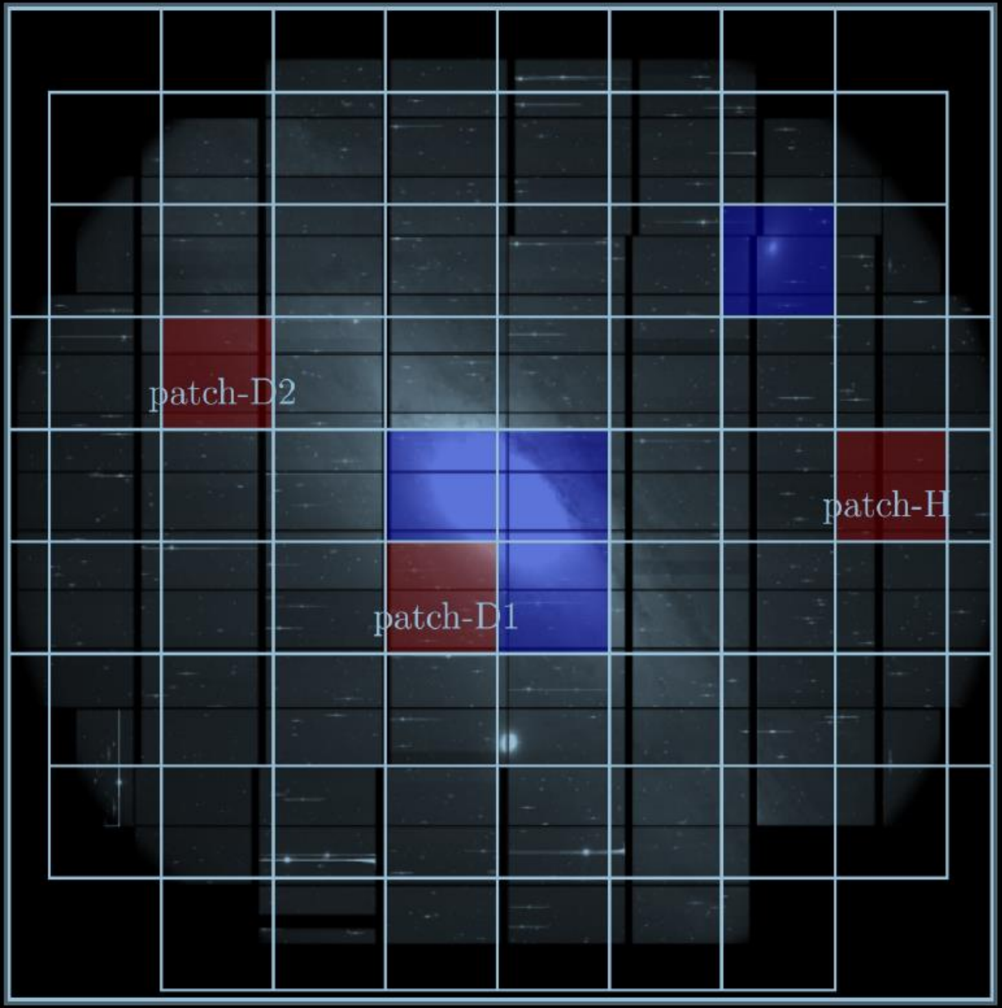
Subaru Hyper Suprime Cam (HSC)

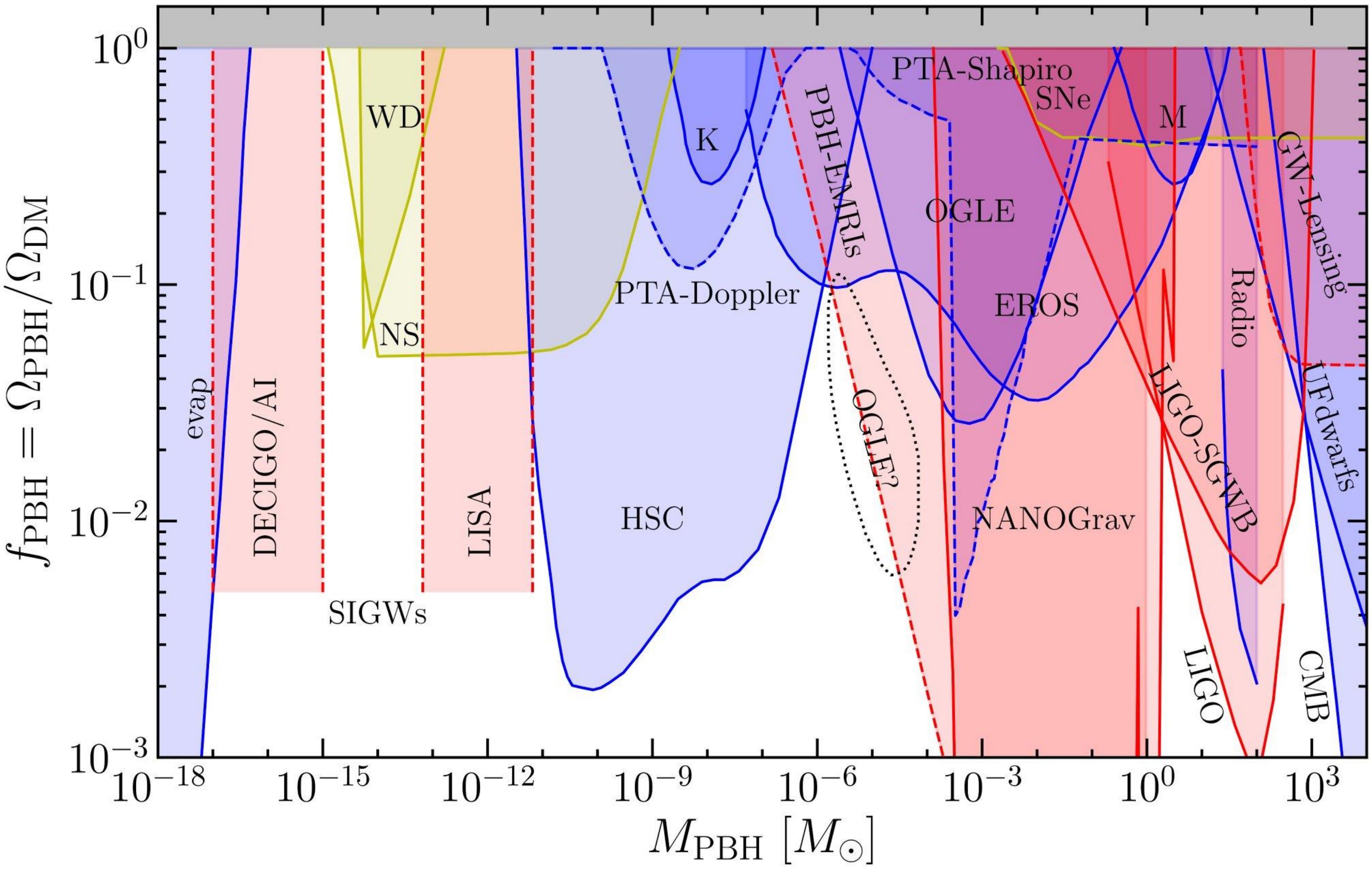
1.5 degree coverage on sky, can cover whole of Andromeda Galaxy (M31)

Blue patches excluded due to too many objects

D1 representative of inner disk
D2 outer disk
H halo

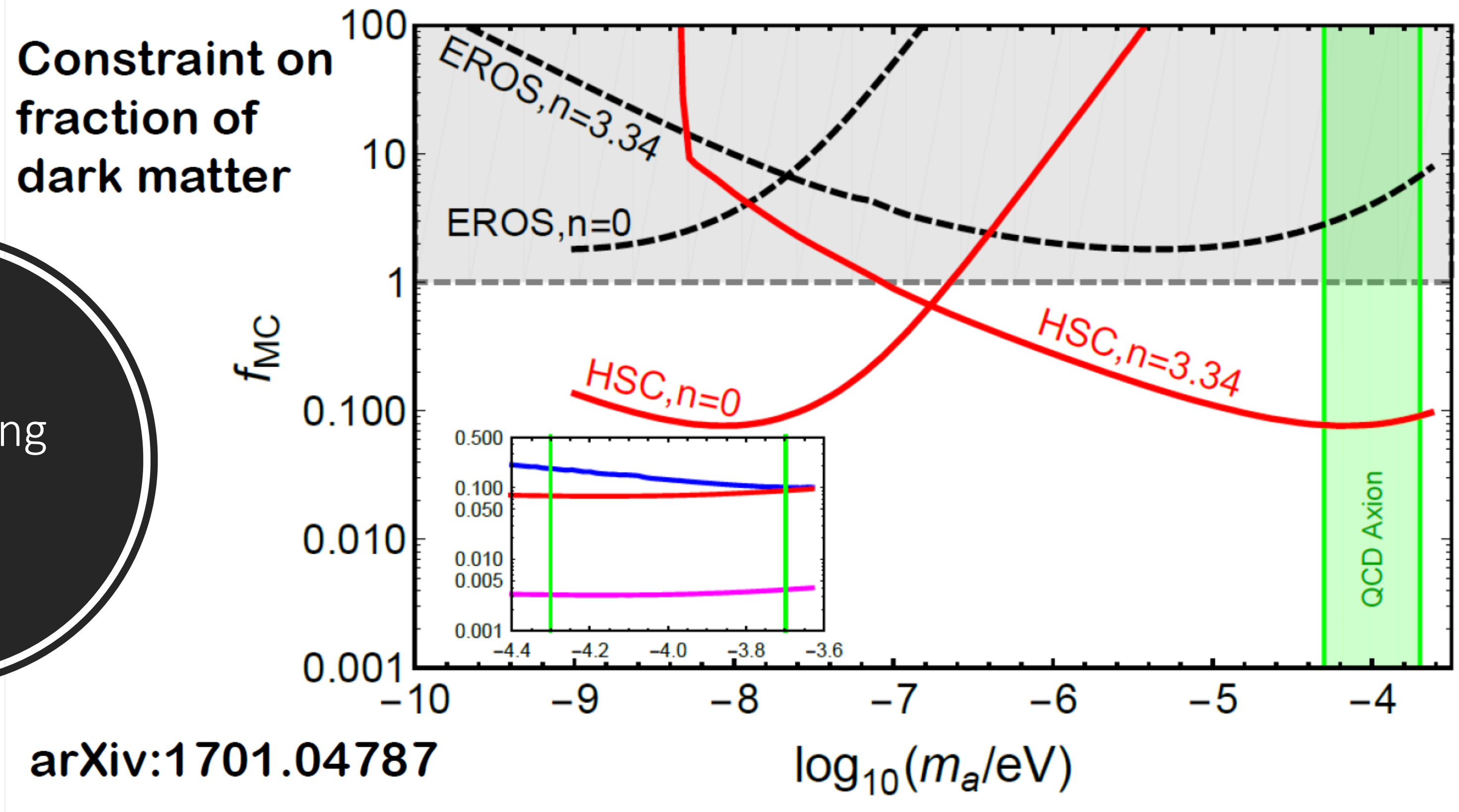
Niikura et al, 1701.02151





PBH
constraints
from HSC

Our Lensing Results



Caveats:-

- Finite size of sources will reduce this constraint (Fujikura et al 2109.04283)
- Also other uncertainties mentioned earlier