Axion-like Particle Dark Matter & Small-scale Structure

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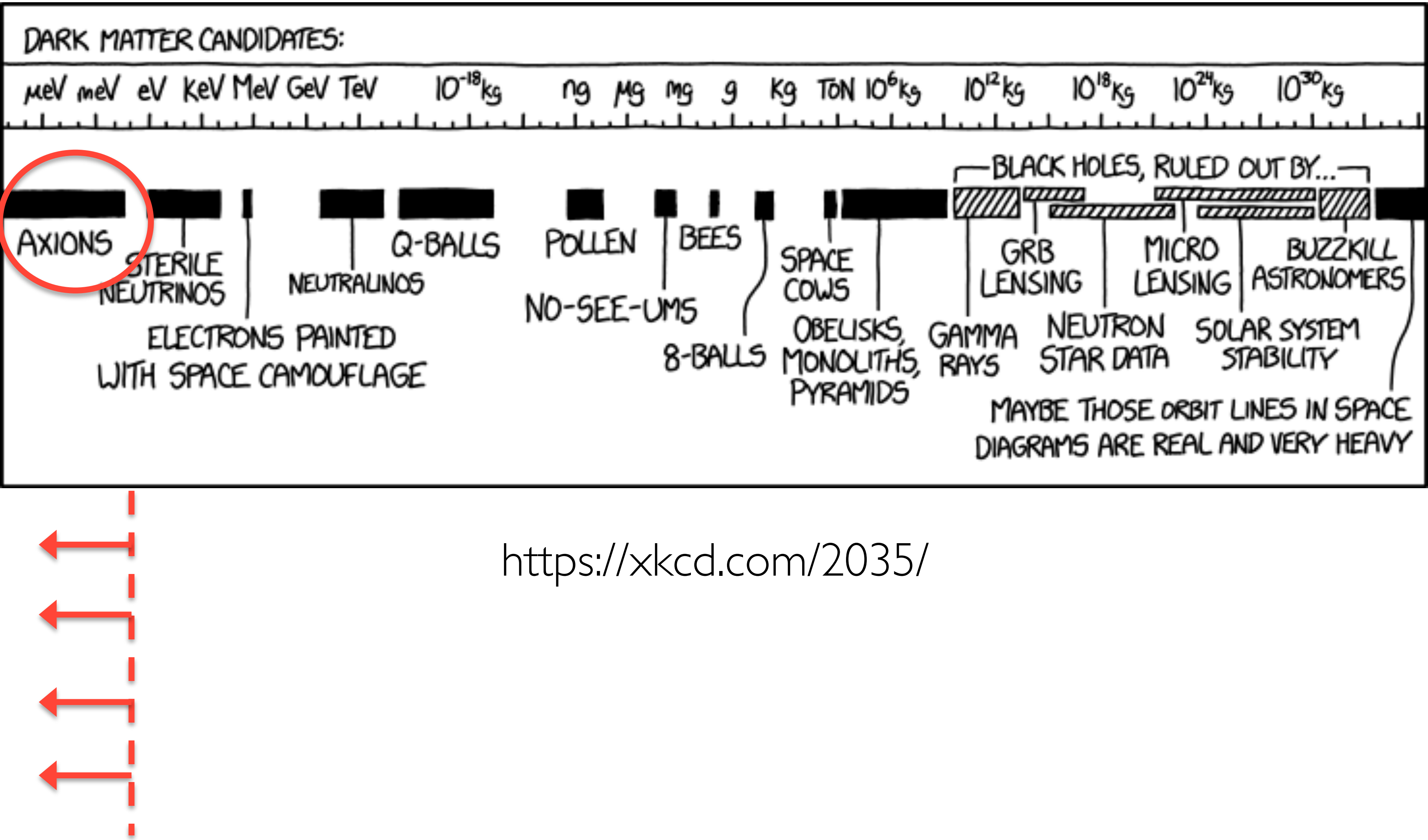
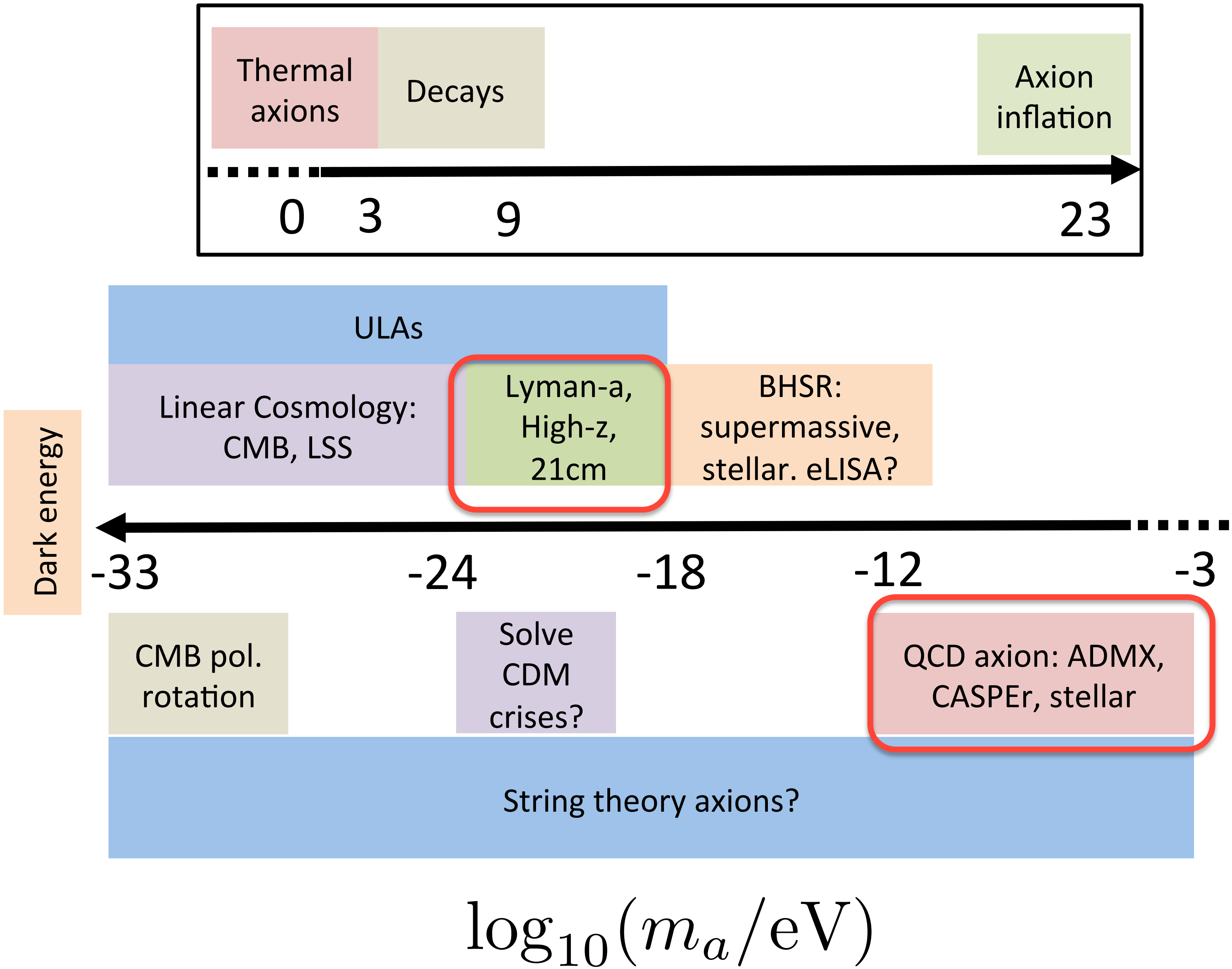
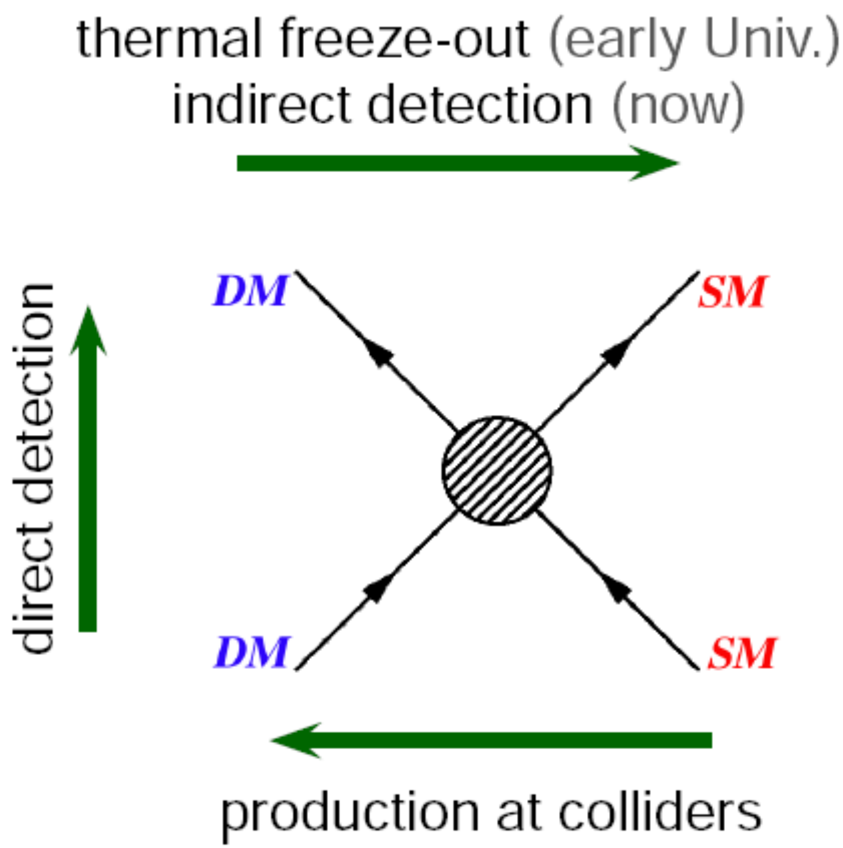


https://xkcd.com/2035/

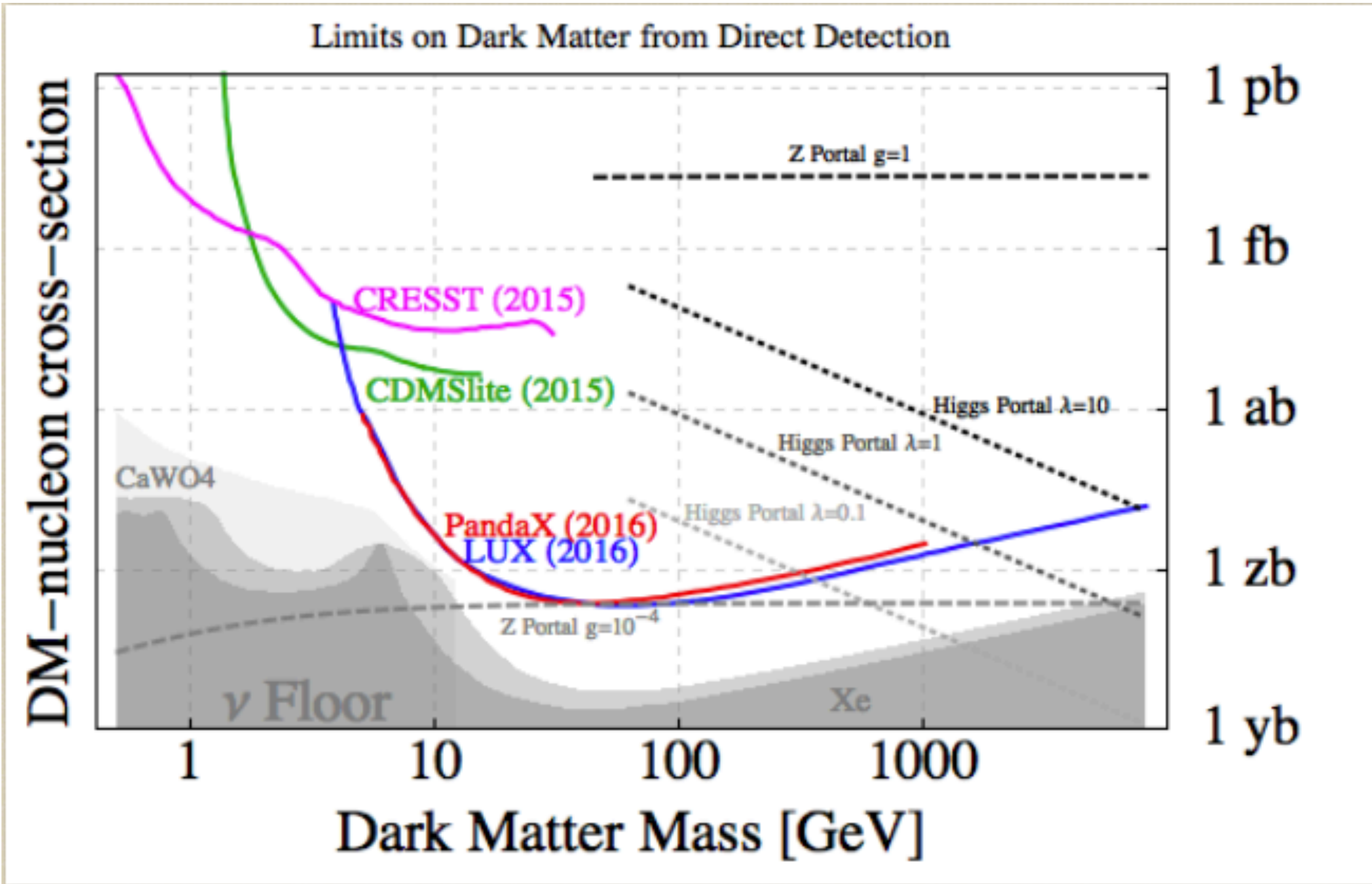

Thermal axions
Decays
Axion inflation
0
3
9
23
ULAs
Linear Cosmology: CMB, LSS
Lyman-a, High-z, 21cm
BHSR: supermassive, stellar. eLISA?
Dark energy
-33
-24
-18
-12
-3
CMB pol. rotation
Solve CDM crises?
QCD axion: ADMX, CASPEr, stellar
String theory axions?
$\log_{10}(m_a/\mathrm{eV})$

On Axions and WIMPs



$$Z_\mu \bar{\psi} \gamma^\mu \psi$$

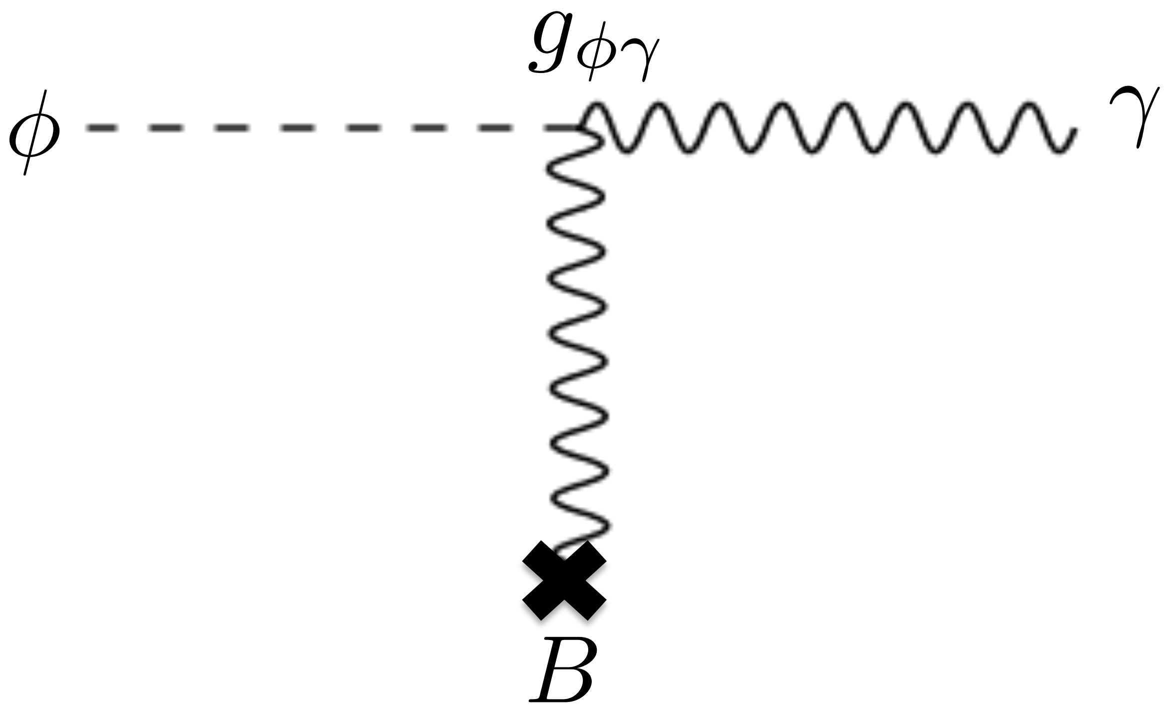
On Axions and WIMPs



Predicted interaction strength for WIMPs has already been excluded. Soon experiments will hit the "neutrino floor".

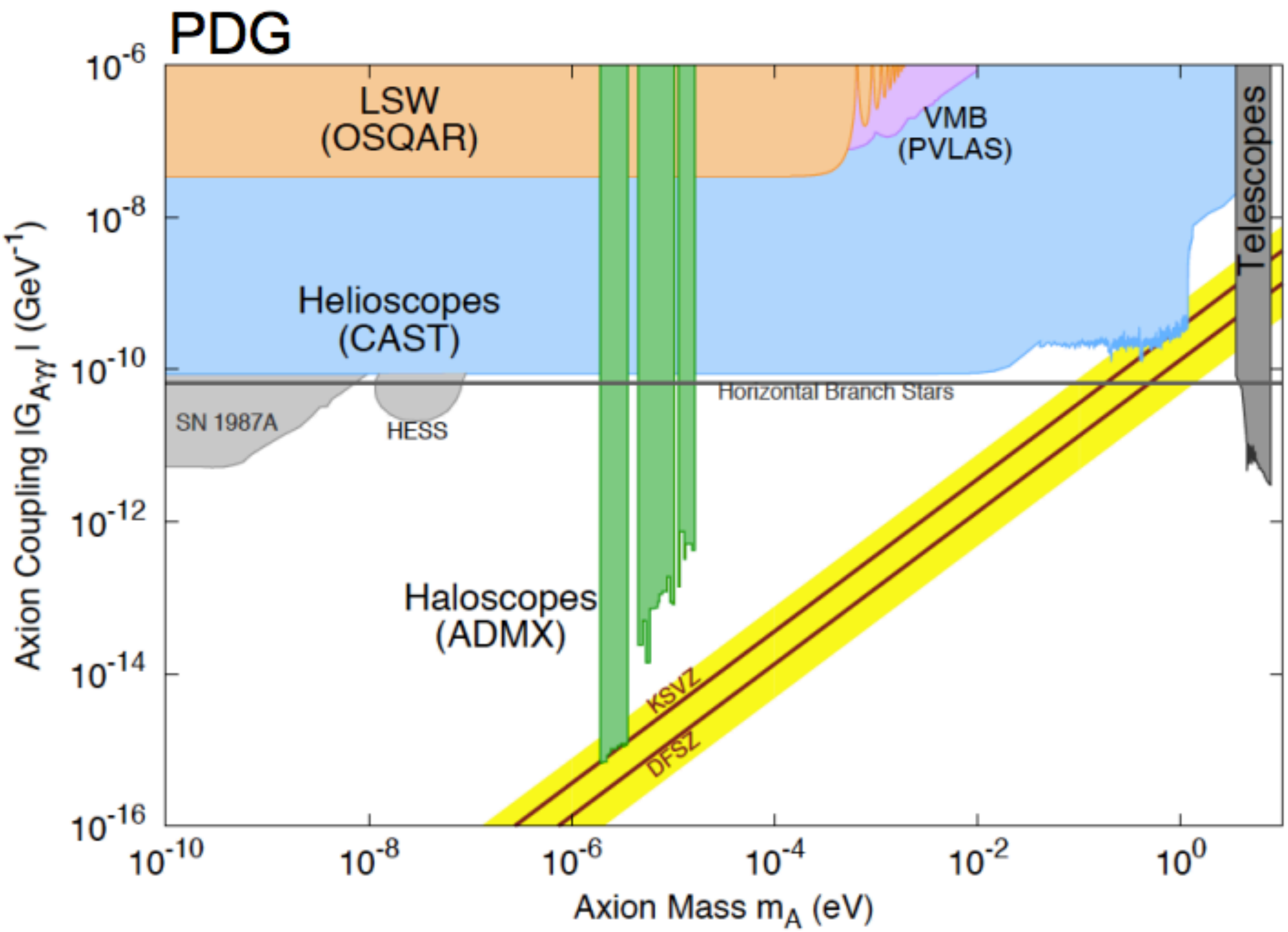
Fig. RESONAANCES.blogspot

On Axions and WIMPs



$$\phi \epsilon_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta}$$

On Axions and WIMPs



The QCD axion is essentially a one-parameter model.
Only one experiment has got into the range to probe DM.

What makes an ALP?

An ALP is a non-thermally produced classical scalar field.
ALPs differ from CDM in initial conditions & dynamics.

Symmetry breaking leading to axion relic density
→ Dense DM relics
→ "Miniclusters"
→ Microlensing constraints a la PBHs
→ Important for the standard QCD axion
→ Smallest DM structures

Uncertainty principle
→ Small-scale coherence and dynamic halos
→ Suppression of structure
→ Formation of solitonic "axion stars"
→ Pronounced for ultralight "Fuzzy DM", $m \sim 10^{-22}$ eV
→ Lightest DM particle

“Miniclusters”: dense clumps from initial conditions (c.f. MACHOs). Sub-lunar mass. Classic QCD axion window.

“Fuzzy DM”: diffuse due to macroscopic wavelength (c.f. warm DM). Dwarf galaxy scales.
String theory axions?

“Axion Stars”: dense, solitonic objects which form in high density regions. Potential GW sources or BH seeds?

The Life of Axions

Spontaneous Symmetry Breaking

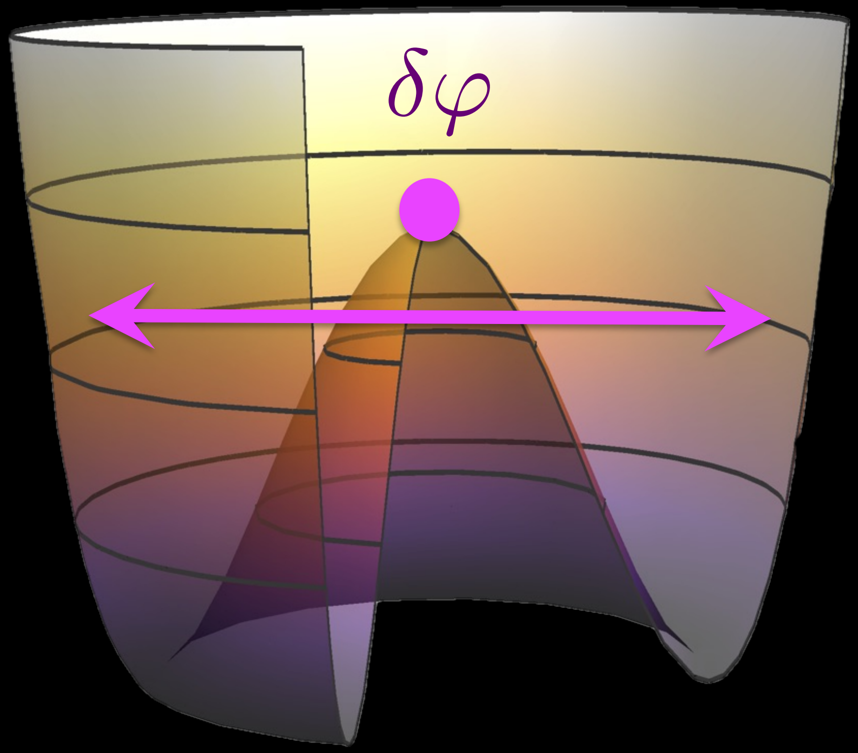
Spontaneous Symmetry Breaking → (p)NGB

The "decay constant" determines temperature of phase transition:

$$\delta\varphi \sim T \sim \frac{H_I}{2\pi}$$

$$T \gg f_a$$

$$\langle\varphi\rangle = 0$$



Spontaneous Symmetry Breaking

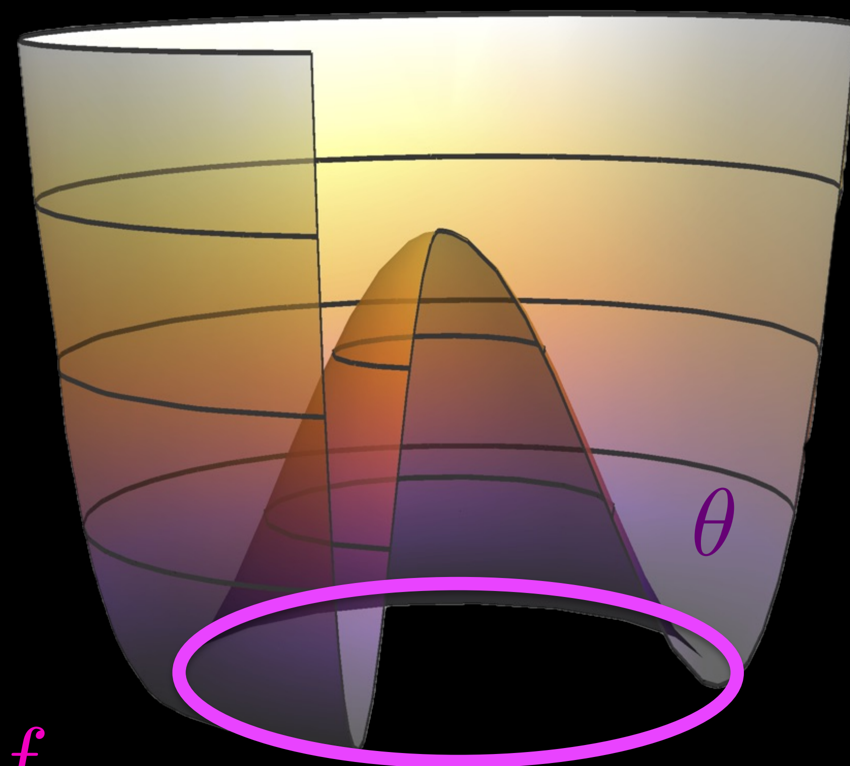
Spontaneous Symmetry Breaking → (p)NGB

The "decay constant" determines temperature of phase transition:

$$\delta\varphi \sim T \sim \frac{H_I}{2\pi}$$

$$T \ll f_a$$

$$\langle\varphi\rangle = f_a/\sqrt{2}$$



The axion is born: $\theta = \phi/f_a$

$$\theta \in \mathcal{U}[-\pi, \pi]$$

Symmetry breaking → relics

Vacuum Realignment

Axion acquires mass, evolves according to Klein-Gordon:

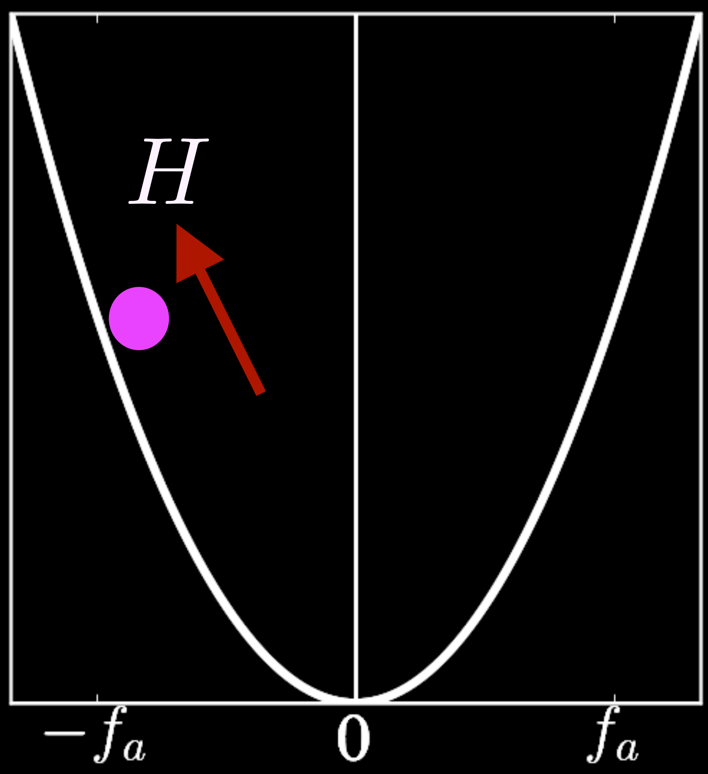
$$\ddot{\phi} + 3H\dot{\phi} + m_a^2\phi = 0$$

$$H \gg m_a$$

Axion is "frozen" by Hubble friction term.

$$\Rightarrow \rho_a \approx \mathrm{const.}$$

$$\Rightarrow w_a \approx -1$$



Vacuum Realignment

Axion acquires mass, evolves according to Klein-Gordon:

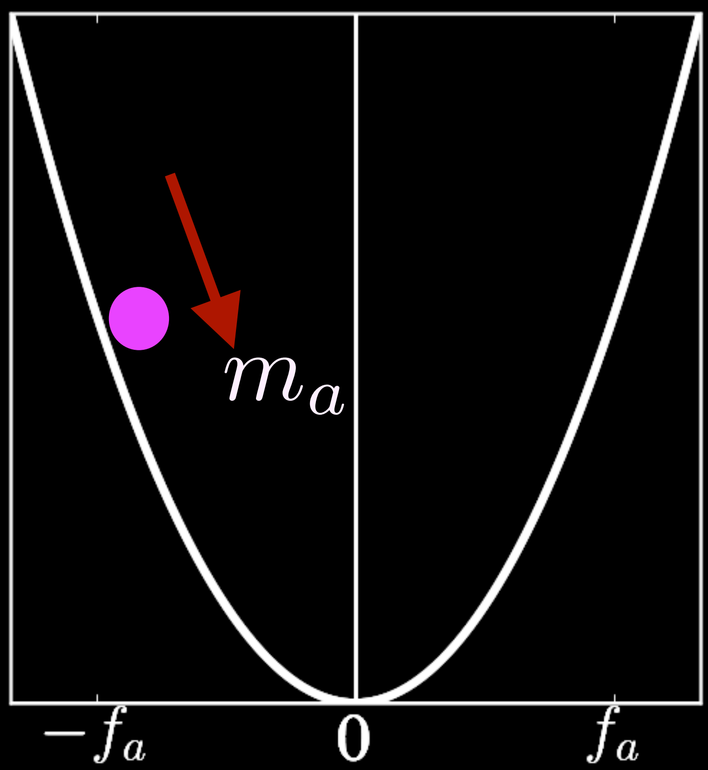
$$\ddot{\phi} + 3H\dot{\phi} + m_a^2\phi = 0$$

$$H \ll m_a$$

Field oscillates & damps.
WKB (or exact) →

$$\rho_a \approx \rho_a(a_{\rm osc})a^{-3}$$

Homogeneous scalar ~ matter
Inhomogeneities → gradients → pressure



Fuzzy Dark Matter

DJEM, Physics Reports (2016)
Hui et al PRD (2017)

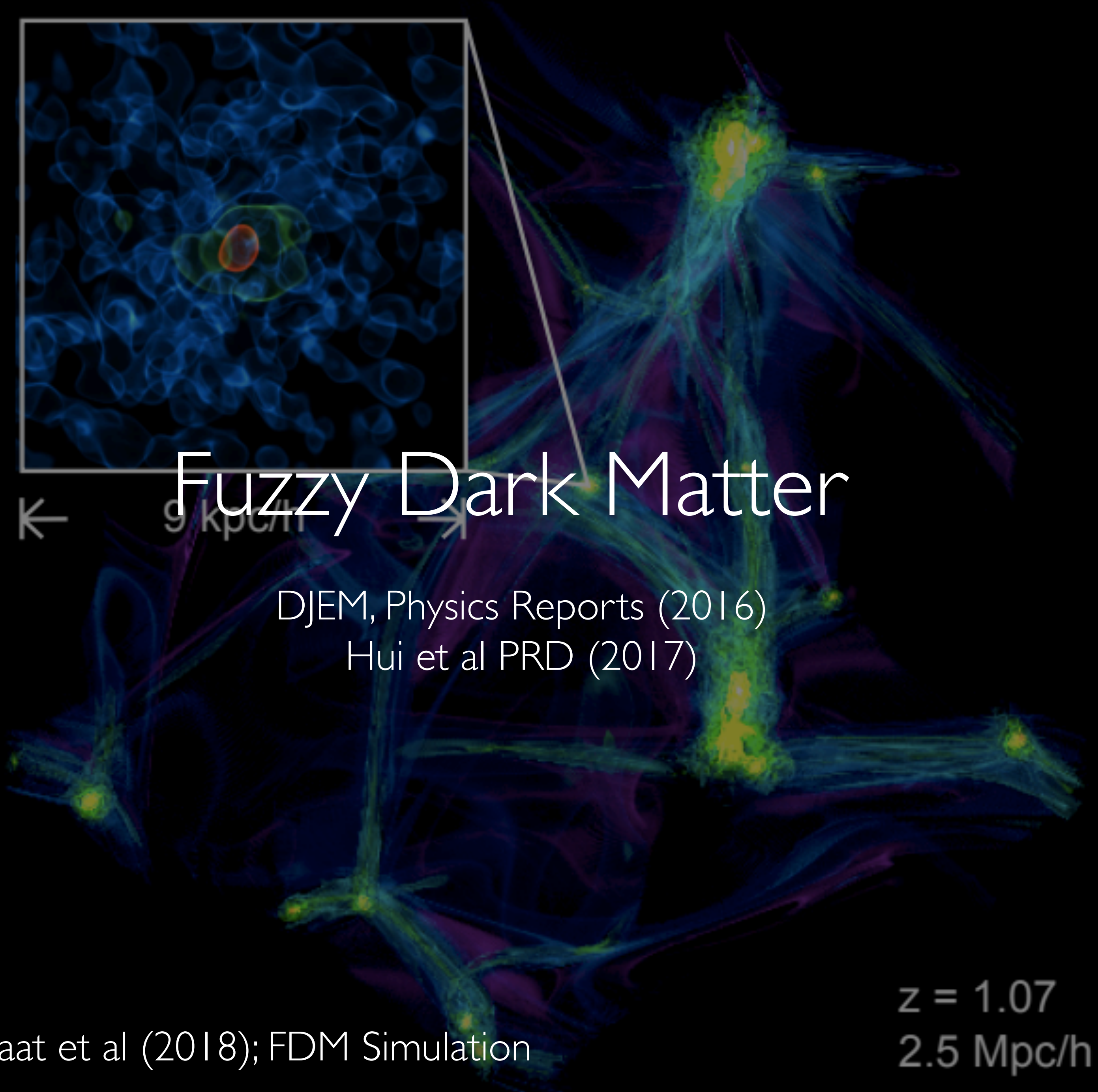
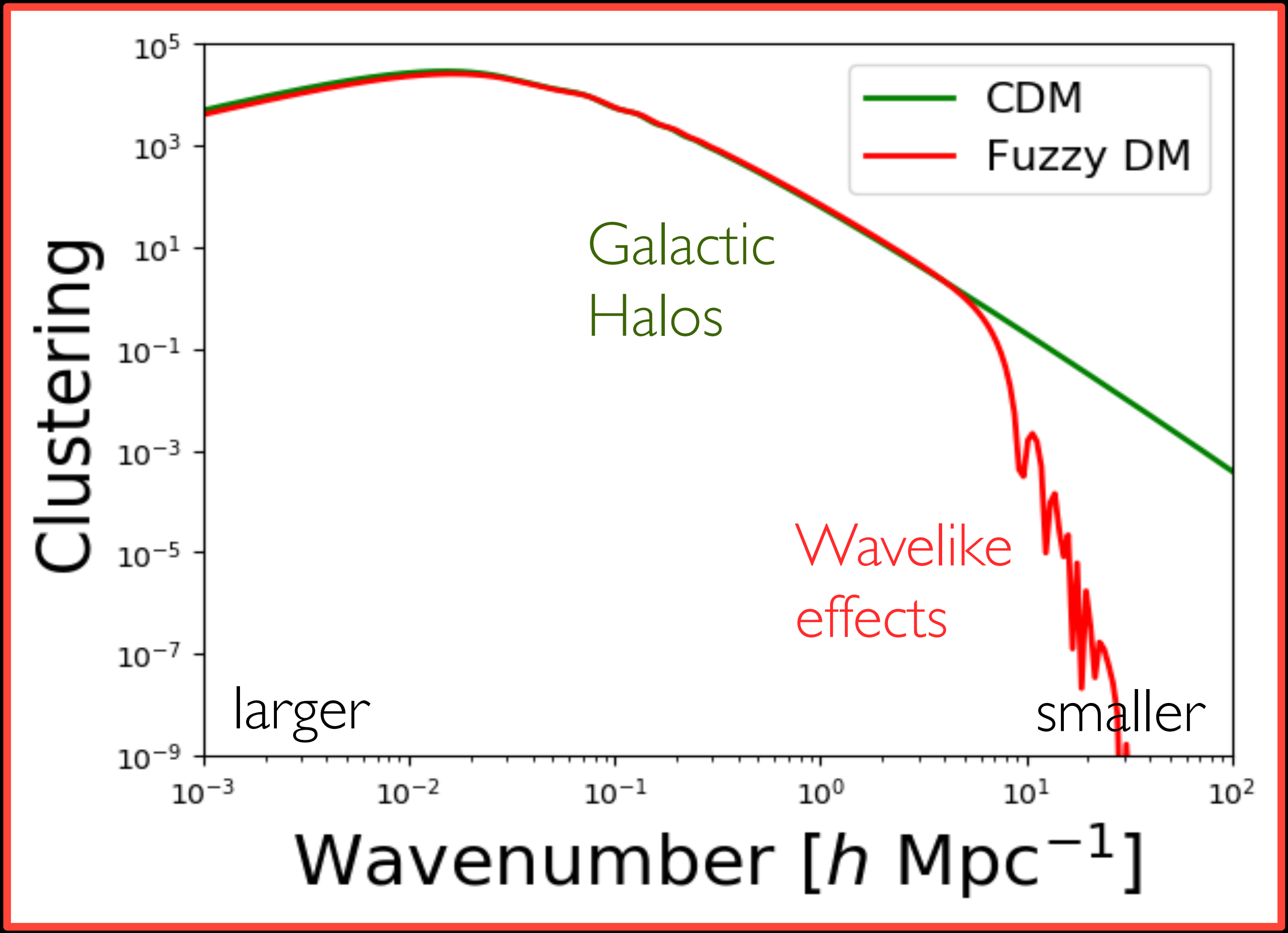


Image: Veltmaat et al (2018); FDM Simulation

Light axions depart from standard CDM in their dynamics.
De Broglie wavelegnth suppresses formation of structure.

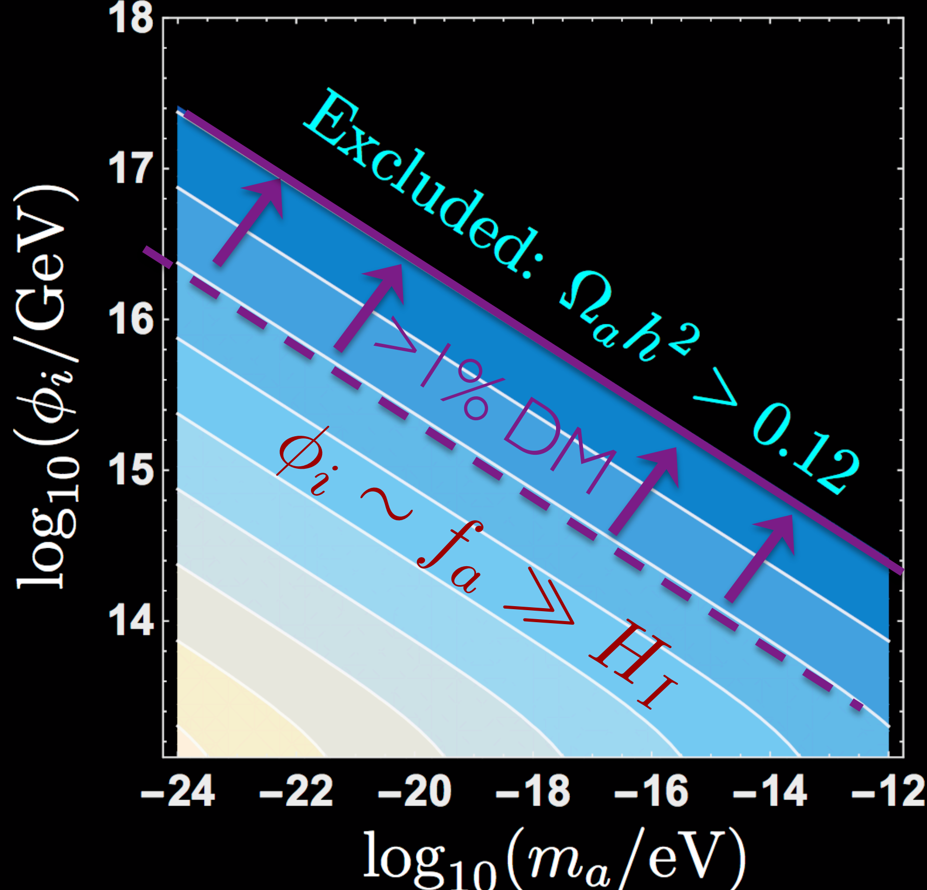


e.g. DJEM (2016)

$$k_{J,\mathrm{eq}} = 9(m_a/10^{-22}\mathrm{eV})^{1/2}\ \mathrm{Mpc}^{-1}$$

“The FDM Miracle”

Consider DM production by misalignment. ULAs + GUT scale fields.

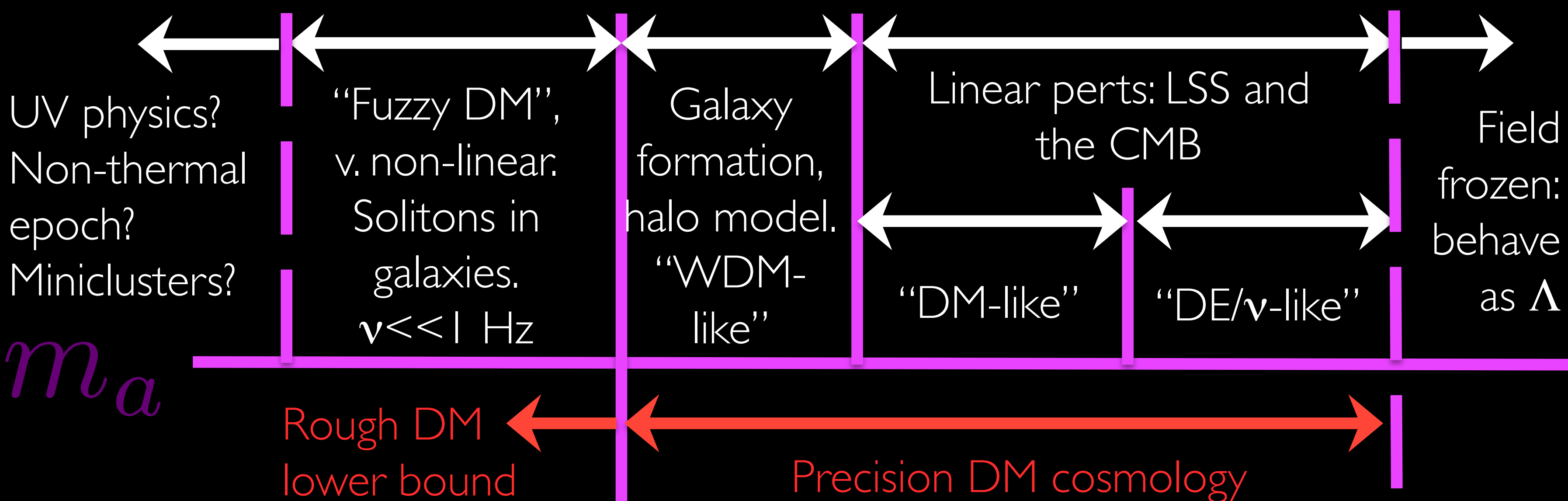


Masses selected in this manner have v. interesting effects on CMB + LSS

Scales of Interest

For details: see my COSMO talk

Non-thermal → compare mass to Hubble (not T).



Physics:	BBN	Size of dSph	Non-linear	Equality	Today
Hubble: [eV]	10^{-15}	10^{-22}	10^{-24}	10^{-28}	10^{-33}

Non-linear Scales

e.g. Widrow & Kaiser (1993); Chavanis (2011+); DJEM (2015,2016); Hui et al (2016)

Fundamentally different from CDM/WDM/SIDM

Non-rel limit of Klein-Gordon Einstein → Schrodinger-Poisson

$$i\dot{\psi} + \frac{1}{2m_a^2}\nabla^2\psi - m_a\Phi\psi = 0;\ \nabla^2\Phi = 4\pi G_N|\psi|^2$$

Related to the smoothed Vlasov equation. Field equation not a particle distribution function → "non-linear optics" regime.

Madelung transformation (polar co-ords) → fluid system:

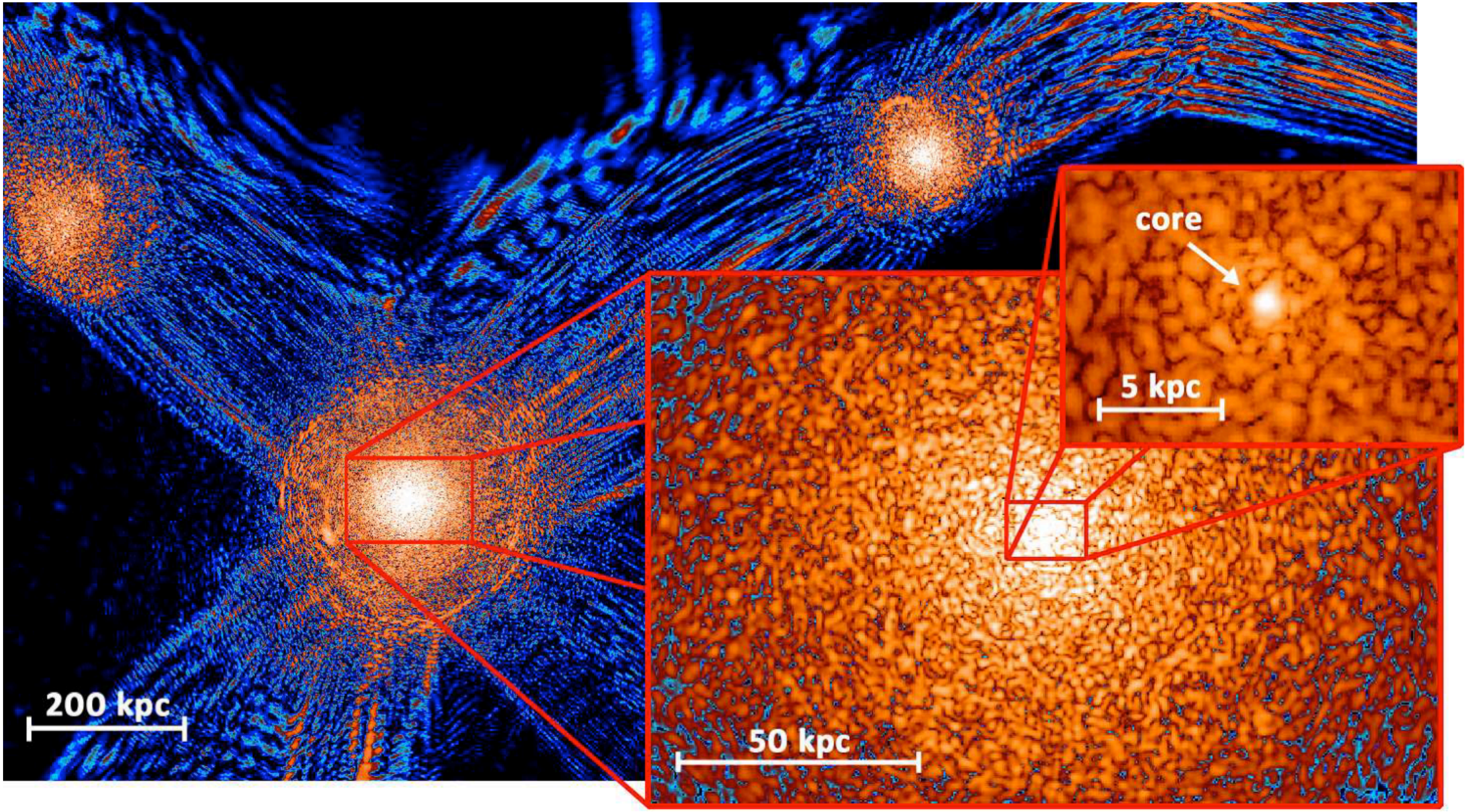
$$\dot{\delta} + \vec{v}\cdot\nabla\delta = (1+\delta)\nabla\cdot\vec{v}$$ continuity

$$\dot{\vec{v}} + (\vec{v}\cdot\nabla)\vec{v} = -\nabla(\Phi + Q)$$ Euler

$$Q = -\frac{1}{2m^2}\frac{\nabla^2\sqrt{1+\delta})}{\sqrt{1+\delta}}$$

Quantum Pressure : source of interference effects

FDM Simulations

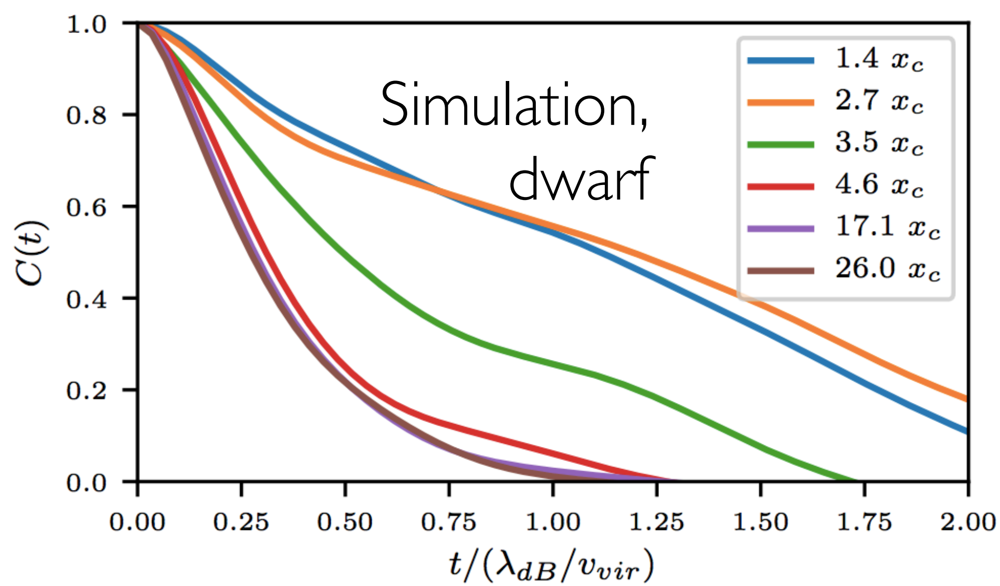


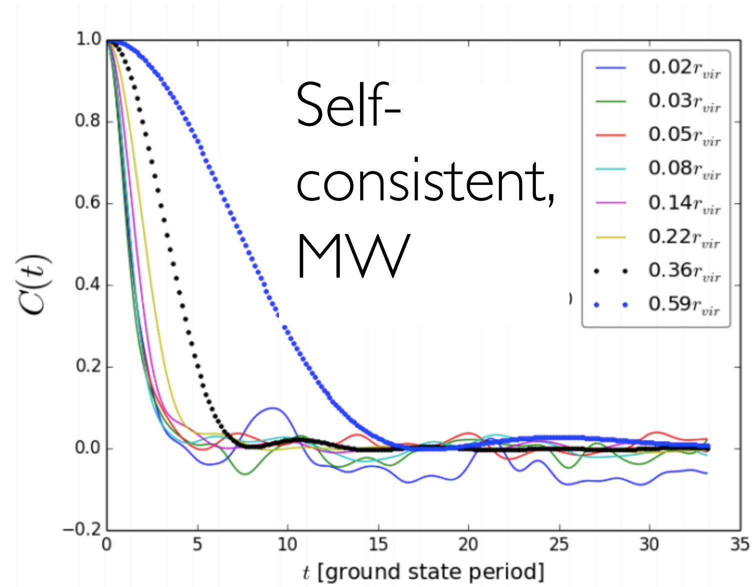
Schive et al (2014)

Dynamical Effects

Hui et al (2017); Veltmaat et al (2018)
Lin et al (2018); Khlemeninsky &Rubikov (2014)

The FDM halo is not static on times < $1/mv^2 \sim 10^6$ years.
Pressure oscillations on Compton times ➔ pulsar timing.
"Wavelets" → quasiparticles and dynamical relaxation.



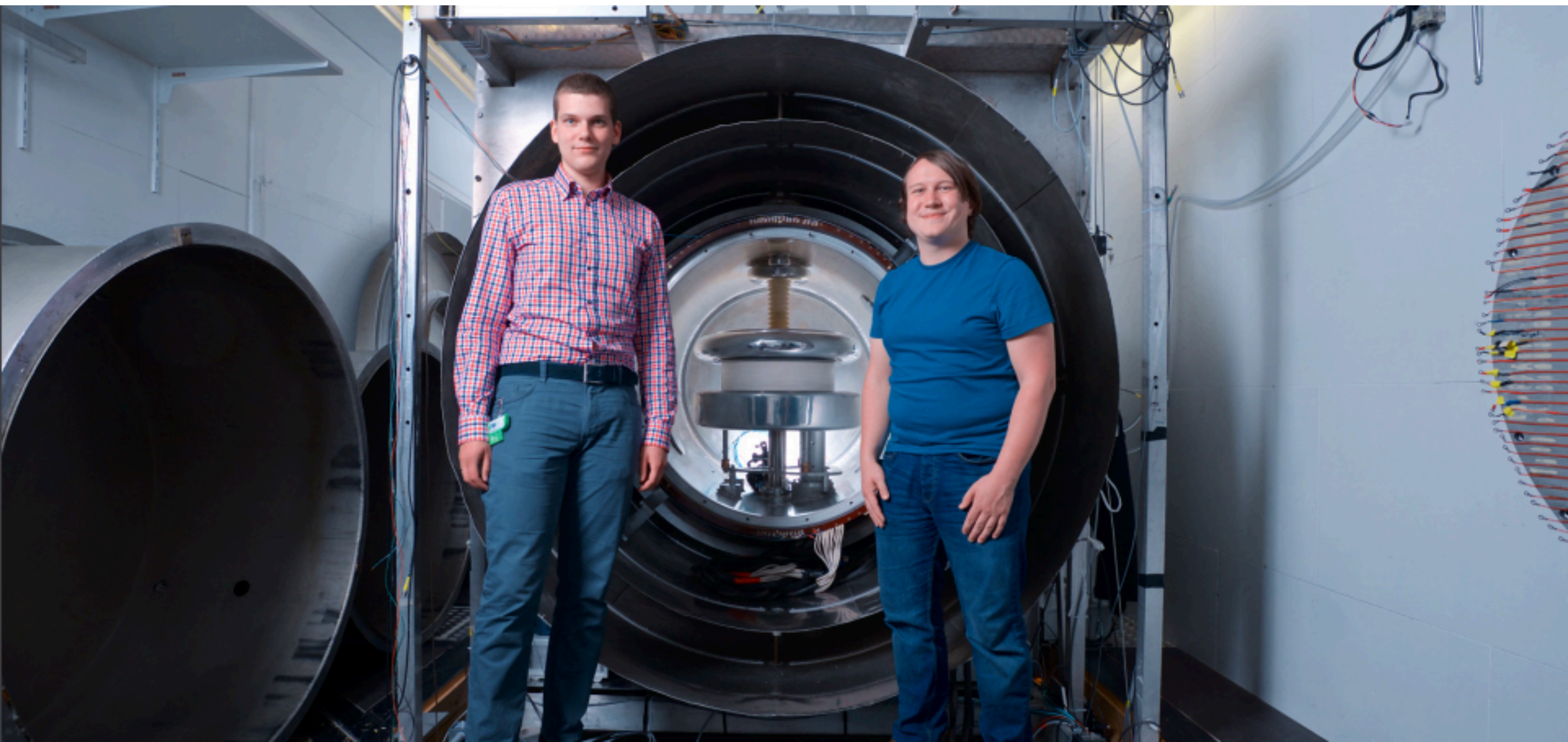


$$t_{\rm relax}(r) \sim \frac{0.4}{f_{\rm relax}} \frac{m^3 v^2 r^4}{\pi^3 \hbar^3} \sim \frac{1 \times 10^{10}\,{\rm yr}}{f_{\rm relax}} \left(\frac{v}{100\,{\rm km\,s^{-1}}}\right)^2 \left(\frac{r}{5\,{\rm kpc}}\right)^4 \left(\frac{m}{10^{-22}\,{\rm eV}}\right)^3$$

FDM with nEDM

Abel, DJEM et al (2017)
Students: Michal Rawlik, Nick Ayres

Detection relies on mass ➔ Compton frequency. FDM ~ 10^{-7} Hz.
Neutron EDM @ PSI and ILL measured for ’98-’02 and ‘15-’16.
→ First lab costraints on axions at this frequency (scalar DM easier)



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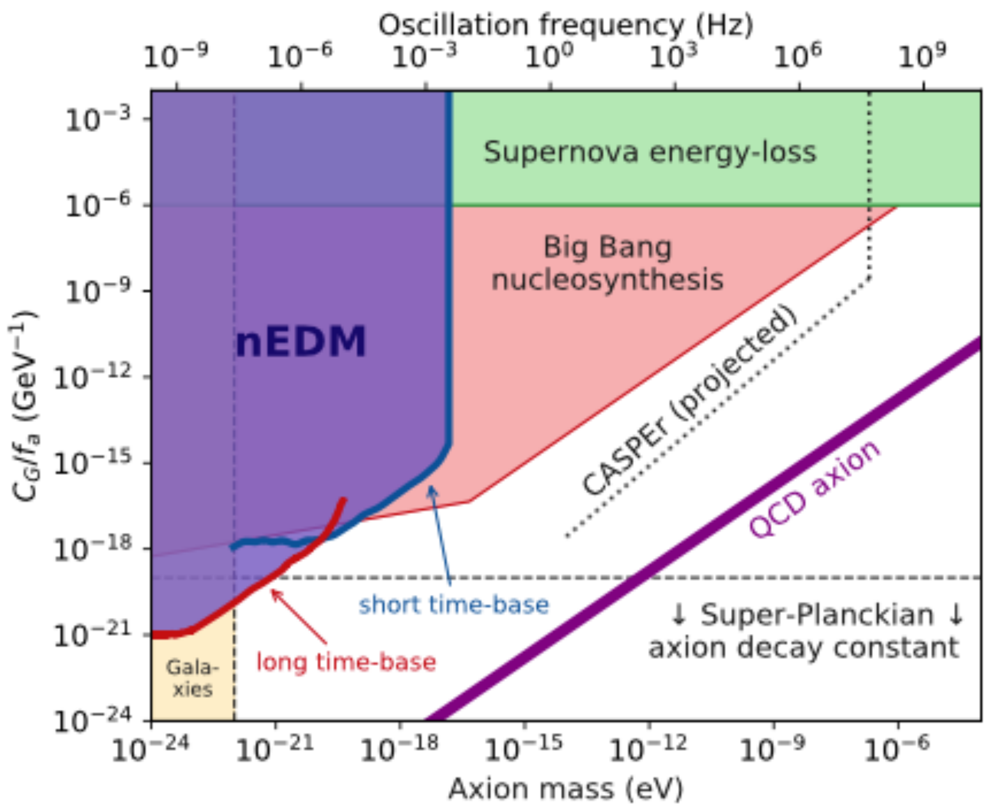
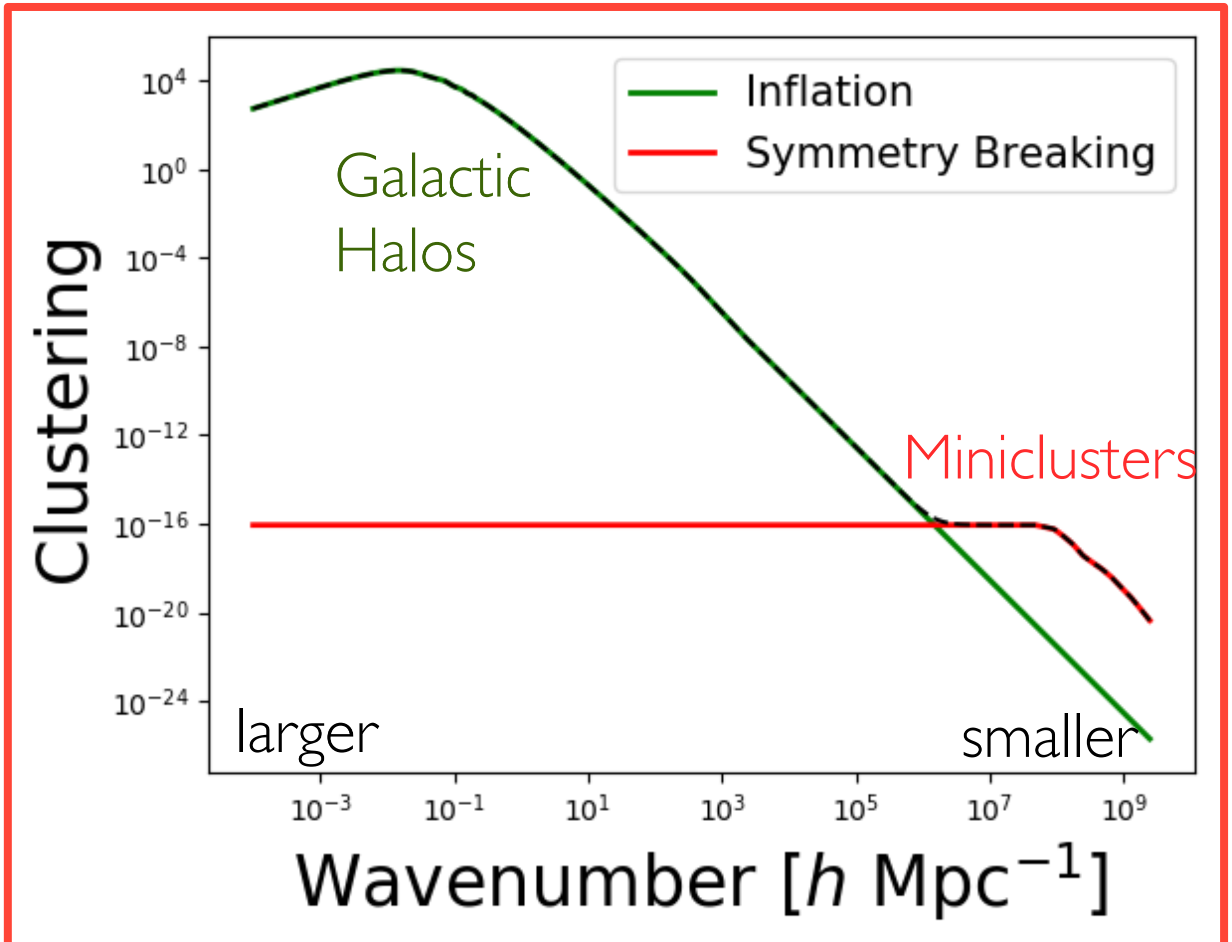


Miniclusters & Microlensing

Fairbairn, DJEM, Quevillon, PRL (2017);
Fairbairn, DJEM, Quevillon, Rozier, PRD (2017)

Image: the Subaru Hyper Supreme Cam

Miniclusters depart from standard CDM in initial conditions.
Post-inflation symmetry breaking → large field fluctuations + relics.
This extra source of fluctuations produces axion relics + structure.



QCD Axion Relic Density

Bae et al (2008);
di Cortona et al (2015)
Borsanyi et al (2016)

SSB after inflation leaves little room for free parameters, but some room for numerical error.

$$\Omega_a^{\rm total} = \frac{1}{6H_0^2 M_{pl}^2}(1+\alpha_{\rm dec})\frac{c_{\rm an}\pi^2}{3} m_a(T_{\rm CMB}) m_a(T_{\rm osc}) f_a^2 \left(\frac{a(T_{\rm osc})}{a(T_{\rm CMB})}\right)^3$$

Largest error arises from extrapolating simulations of string and domain wall decay.

See: Gorghetto et al (2018) and Kawasaki et al (2018).

QCD Axion Relic Density

Bae et al (2008);
di Cortona et al (2015)
Borsanyi et al (2016)

Allowing loosely for errors predicts a mass:

$$50\,\mu\text{eV} \lesssim m_a \lesssim 200\,\mu\text{eV}$$

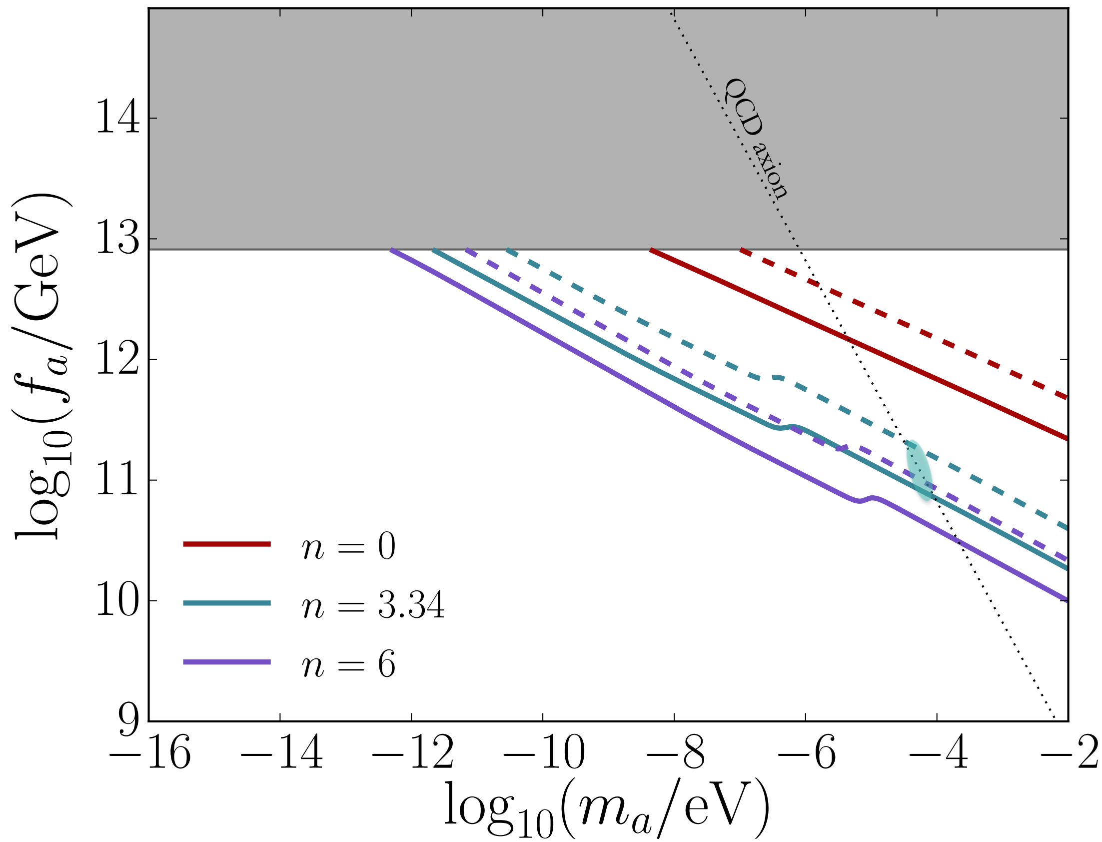


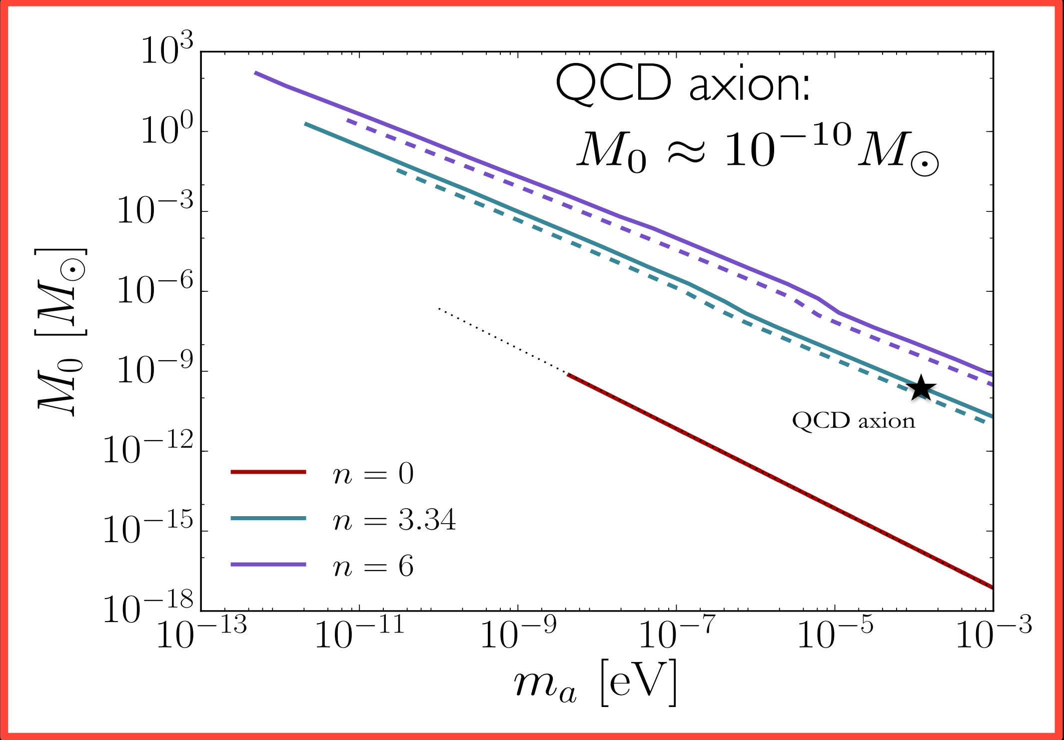
Fig: Fairbairn, DJEM et al (2017)

Minicluster Mass Scale

Hogan & Rees (1988)

Axion randomises beyond horizon → Large isocurvature fluctuations → Mass inside horizon when m~H collapses early.

$$M_0 = (4/3)\pi(\pi/k)^3$$



Smaller than smallest WIMP structures (10^{-6}). Axions are very cold.

The amount of DM in compact objects is strongly constrained:

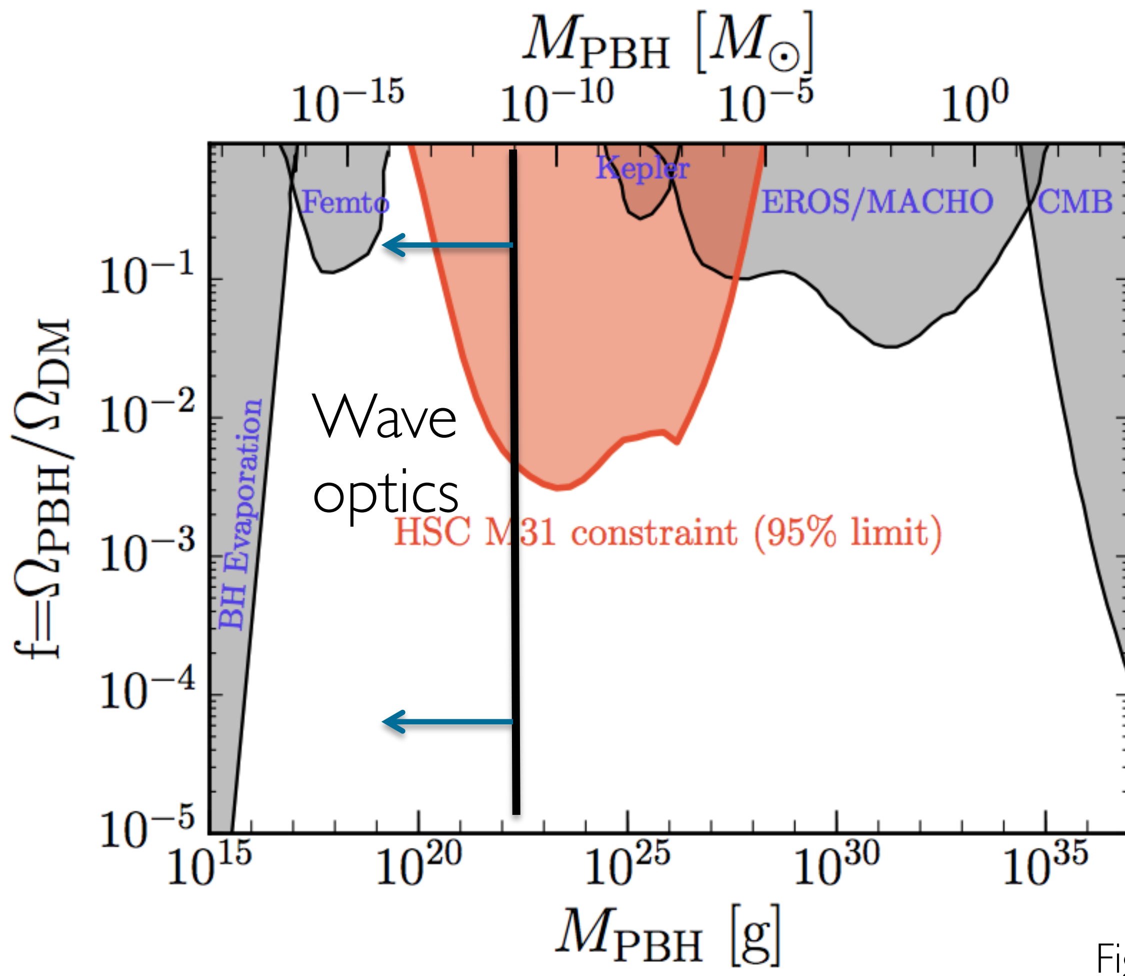
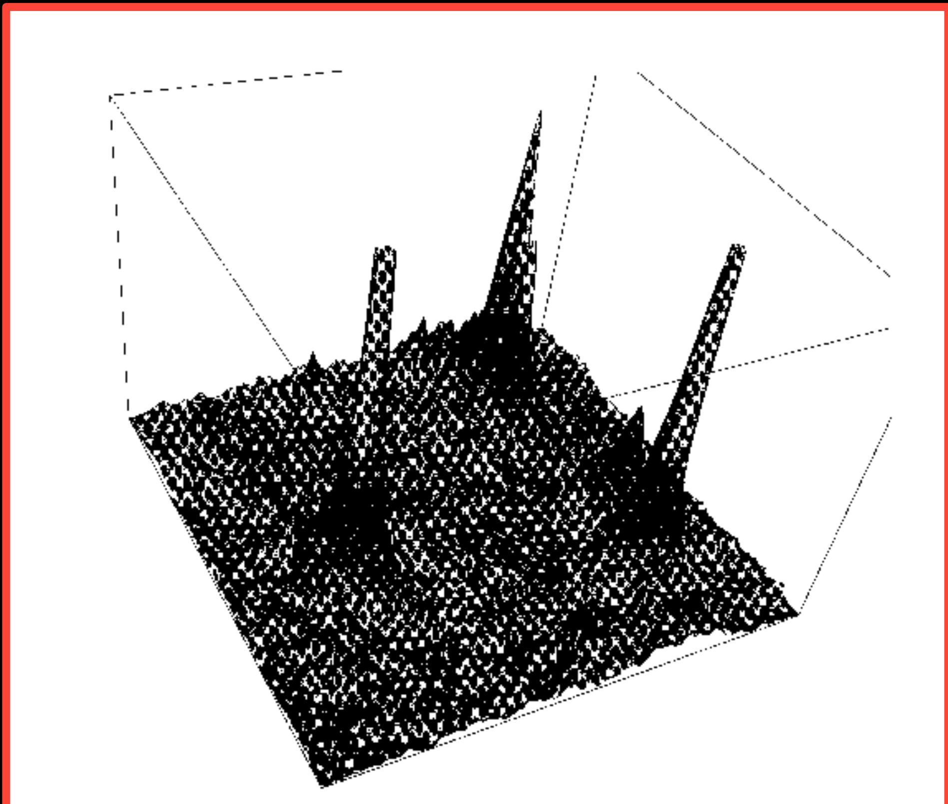


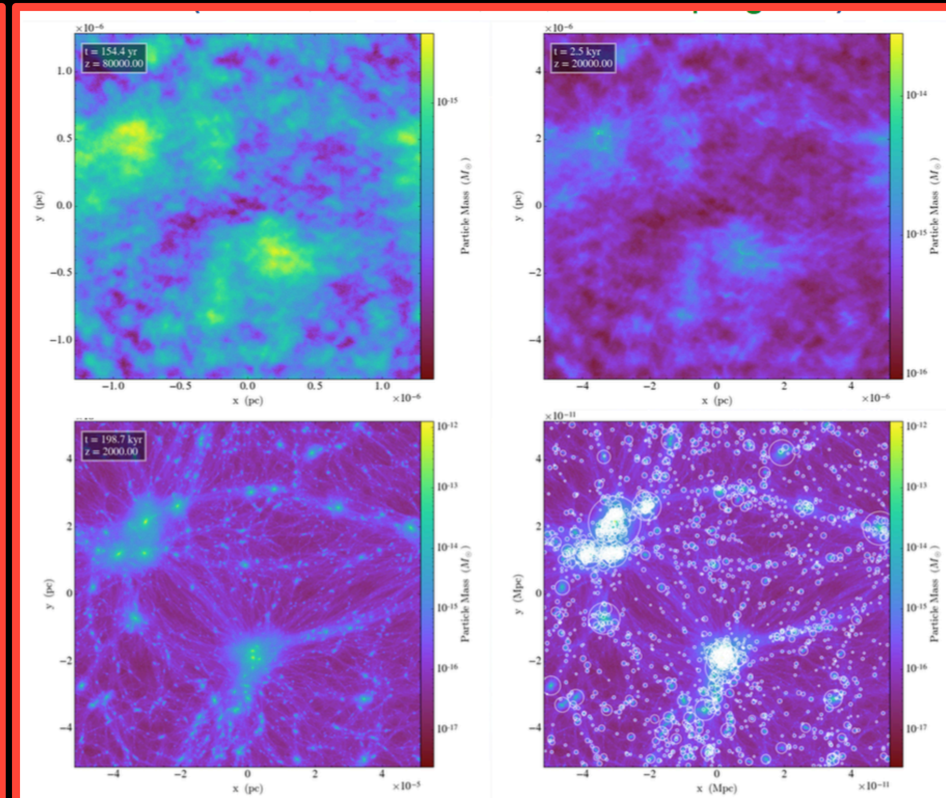
Fig: Niikura et al (2017)

How do these constraints translate to miniclusters (or e.g. UCMHs)?
What is the relic density, mass, and size distribution of miniclusters?

Numerical Simulations

See also Hardy (2017),
Zurek et al (2007)





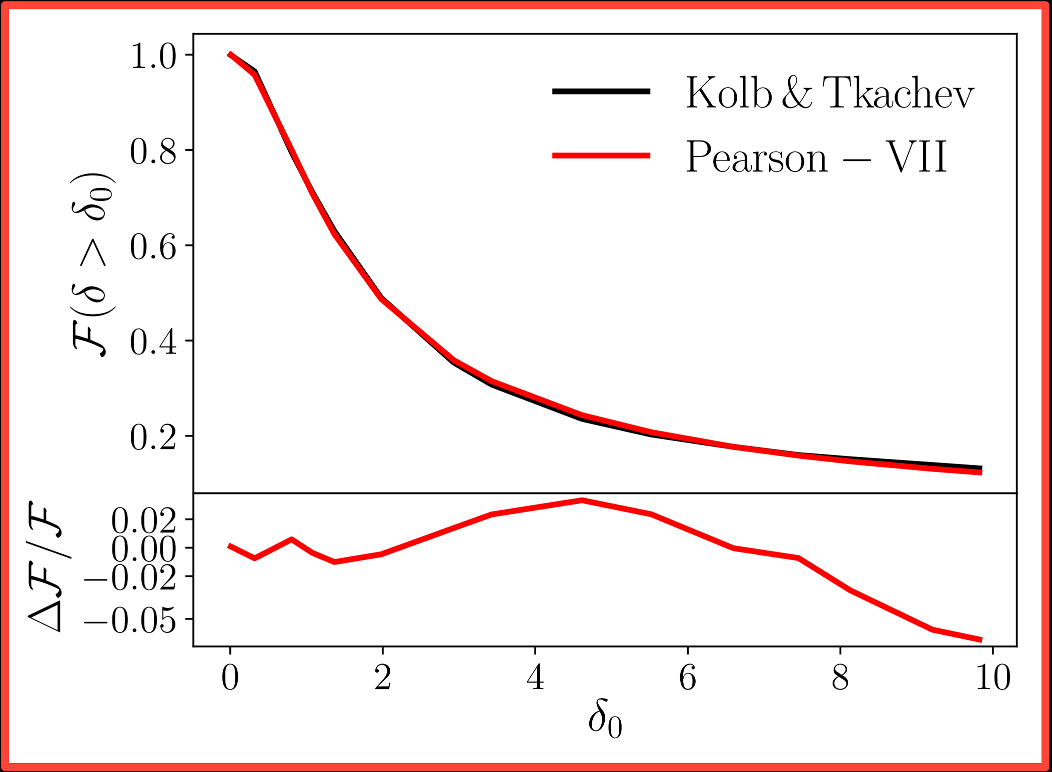
Kolb & Tkachev (1990's): field simulations w/ no gravity.
→ Mass and radius scale.

Wiebe, Redondo, Niemeyer (2017): SSB i.c.'s w/ strings + N-body during rad. era.

Size Distribution

Size distribution: see also Ensander et al (2017)
Extrapolation: Javier Redondo private comm.

Minicluster density field is non-Gaussian due to axion interactions.
Kolb & Tkachev sims → wide distribution for characteristic density:

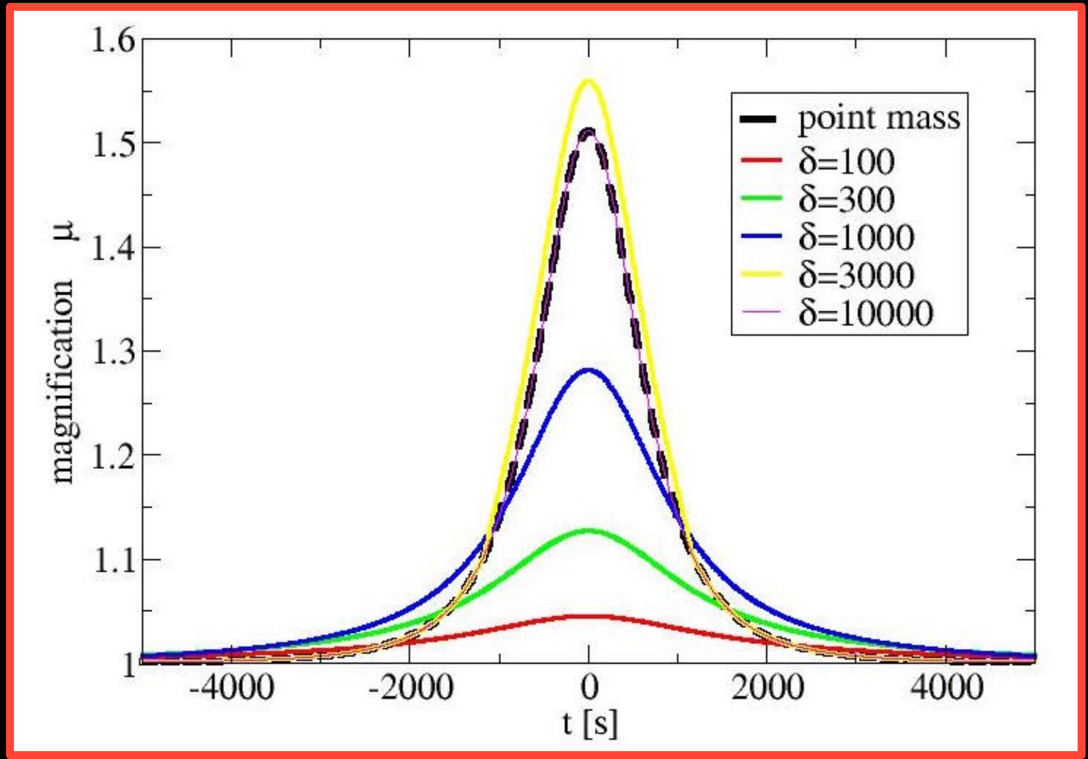


$$\rho_{\rm MC} = 140\delta^3(1+\delta)\bar{\rho}_a(1+z_{\rm eq})^3$$

We use this to set the radius of minicluster density profiles
→ Non-Gaussian distribution of sizes. Key to results.

Microlensing: non-pointlike objects

Paramterise the density profile based on initial overdensity, δ.



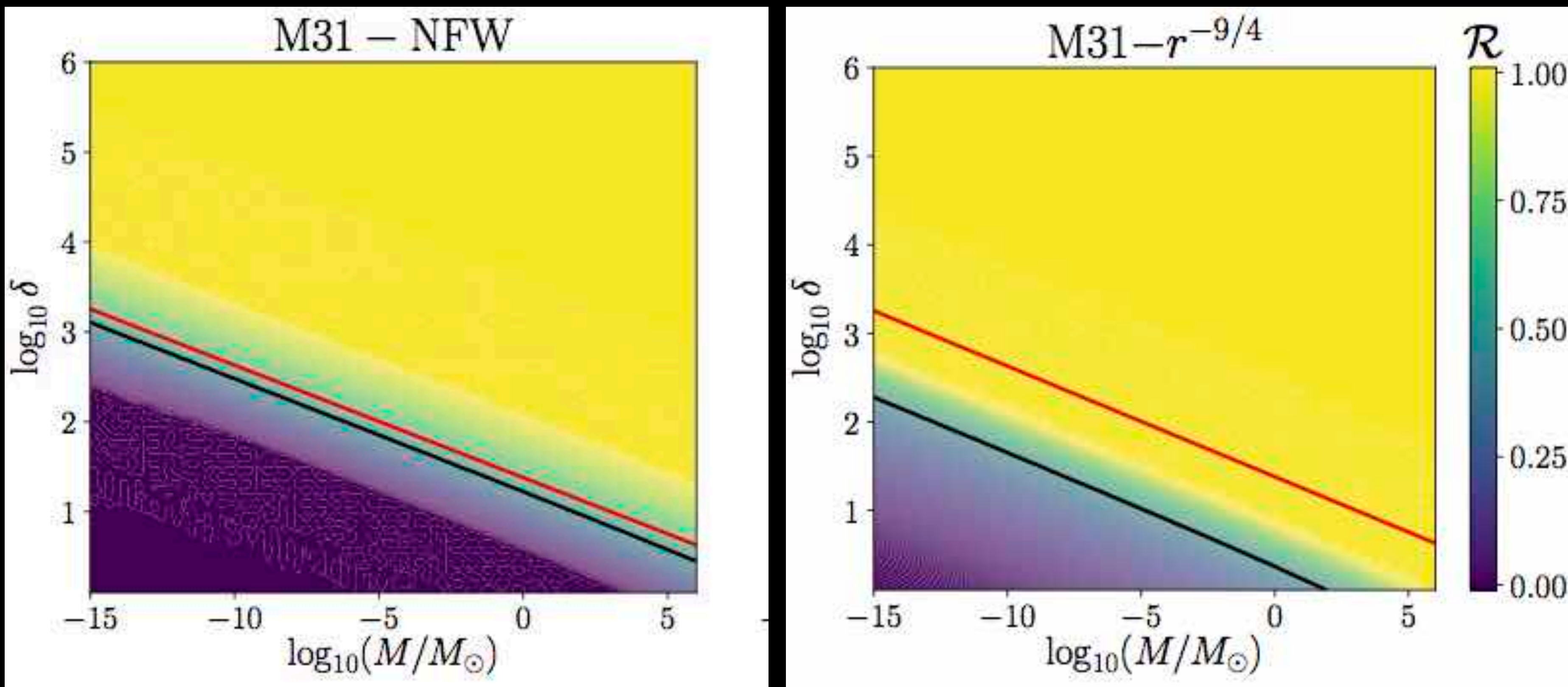
Effects described by a rescaling of the "microlensing tube":

$$R_{\mathrm{MC}}(\delta, M, x) = \mathcal{R}(\delta, M) R_{\mathrm{E}}(M, x)$$

lensing events depends on density profile and distribution of sizes.

Density Profiles

Above some value of δ miniclusters are effectively point-like lenses. The transition depends on the assumed density profile.



Self-similar infall → power law density profile for isolated objects.
Mergers + environment → NFW density profile.

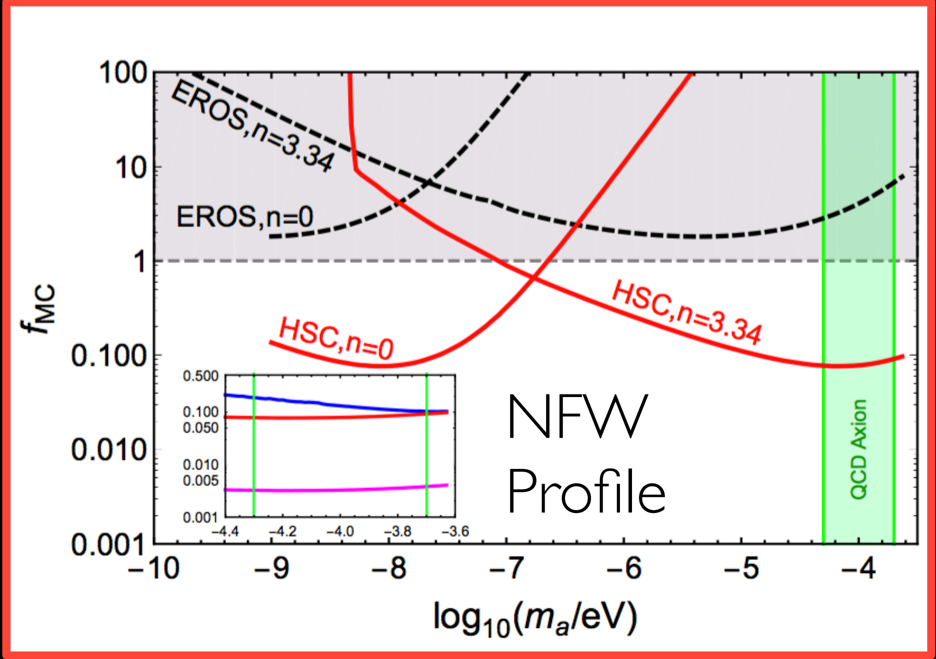
Constraints: EROS and HSC

Tisserand et al (2007)
Niikura et al (2017)
Fairbairn, DJEM et al (2017)

We constrain the allowed fraction of DM bound in MCs, f_{MC}.
Mass lower limit: telescope cadence. Upper limit: observing time.

Subaru HSC observed M31. Cadence ~2minutes → access to very low masses.

Constraints from single night observing!

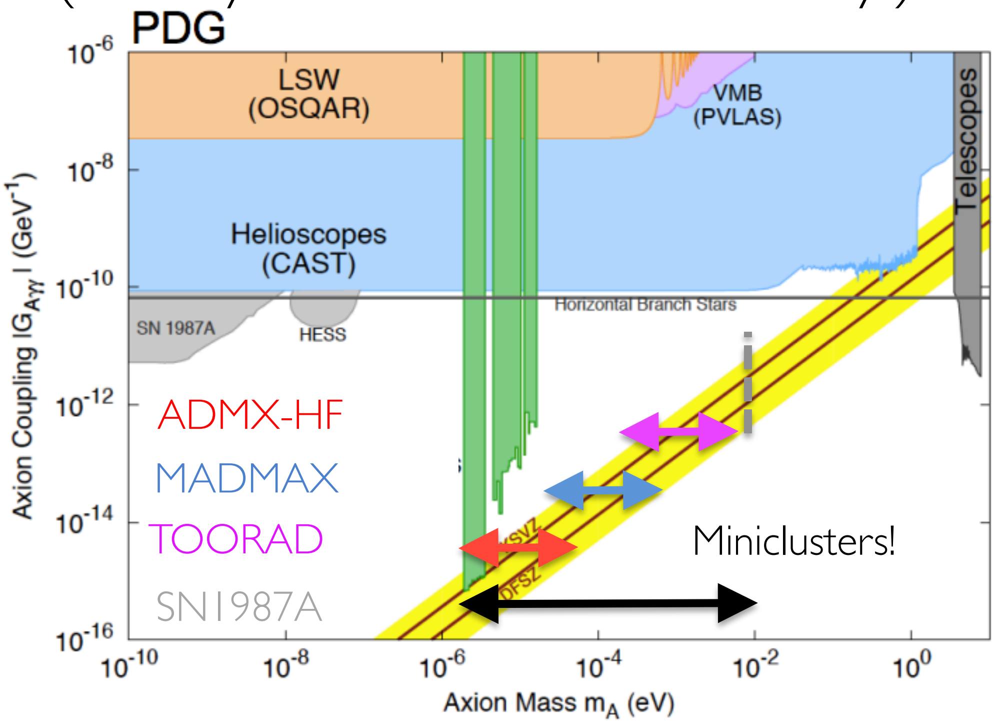


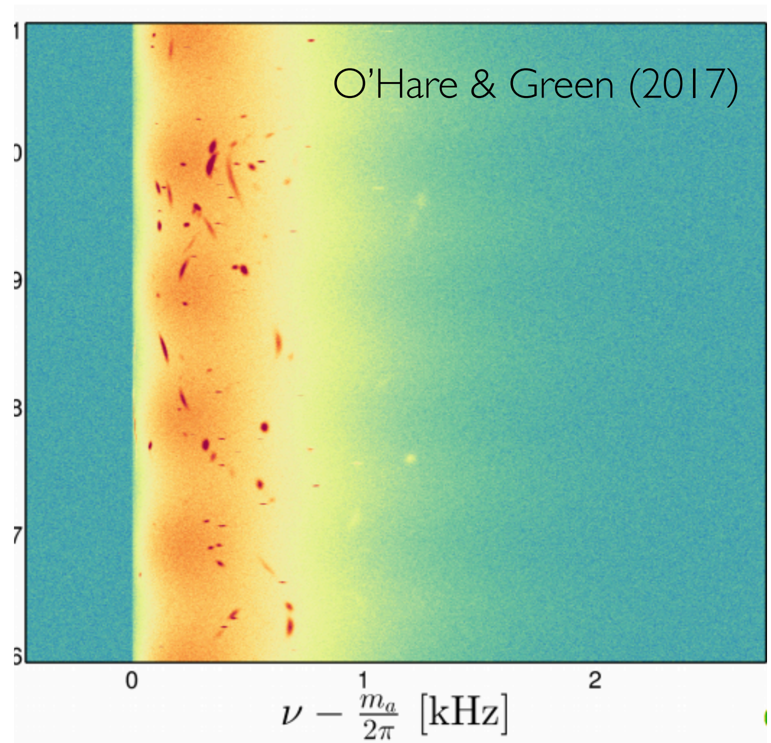
$$f_{\mathrm{MC}} < 0.083(m_a/100\mu\mathrm{eV})^{0.12}$$

Lots of assumptions in this number: improved modeling needed.

Miniclusters & Axion Astronomy

Many new high frequency (>GHz) axion experiments are being built.
(see my talk at CAPP on Tuesday!)





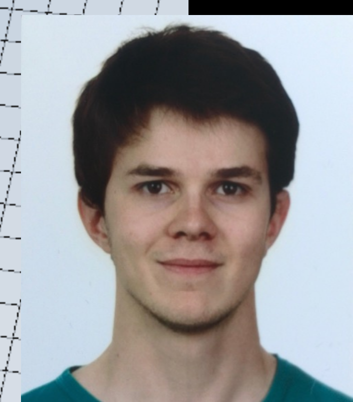
If miniclusters fraction is large → drastic effect on direct detection.
But, MC streams could be detected in spectra → measure halo.
Axion experiments can measure the whole DM phase space dist.!

Axion Stars

Numerical GR simulations with GRChombo

(Clough et al, 2015)

Open Source @ http://www.grchombo.org/

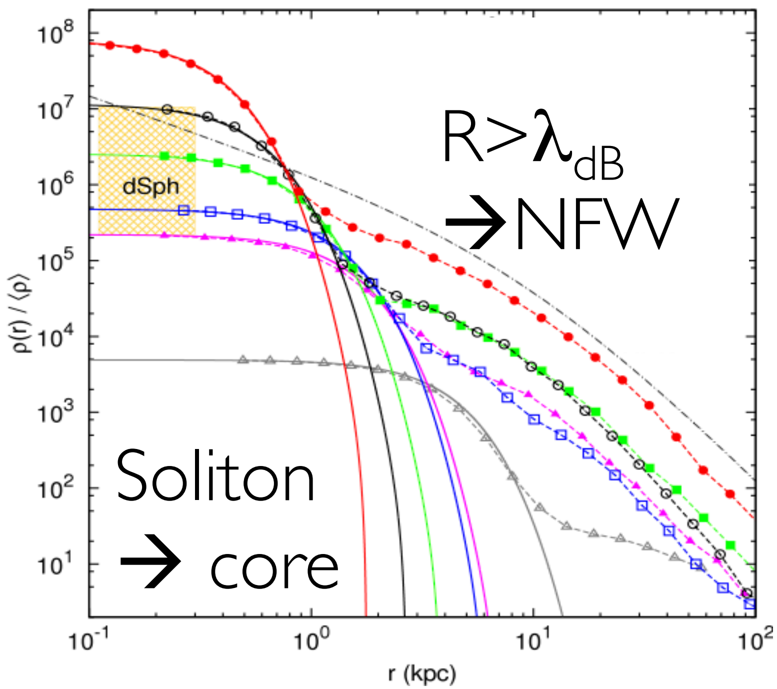


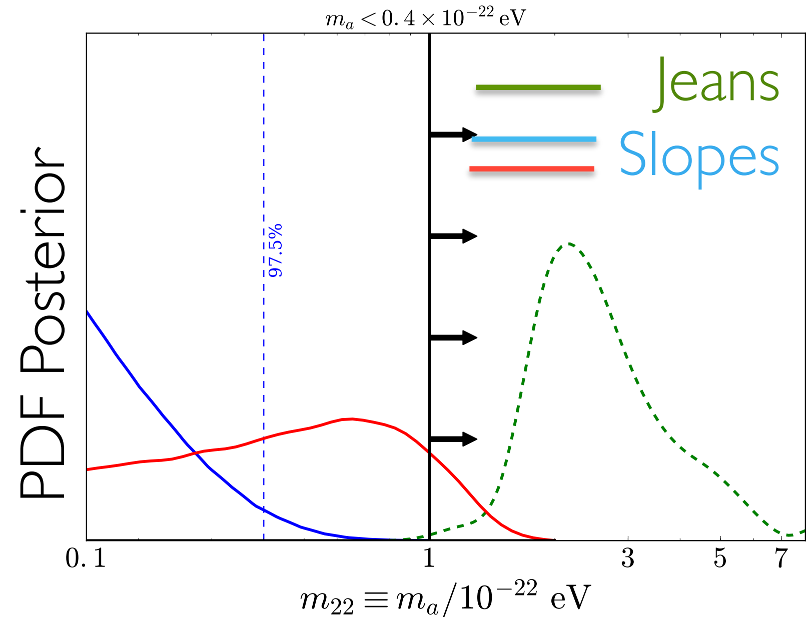
Axion Stars \neq Miniclusters!

Axion Stars and Cores

Schive et al (2014+); Veltmaat et al (2018)
Gonzalez-Morales, DJEM et al (2017)

FDM profiles show prominent cores. Pressure supported solitons.



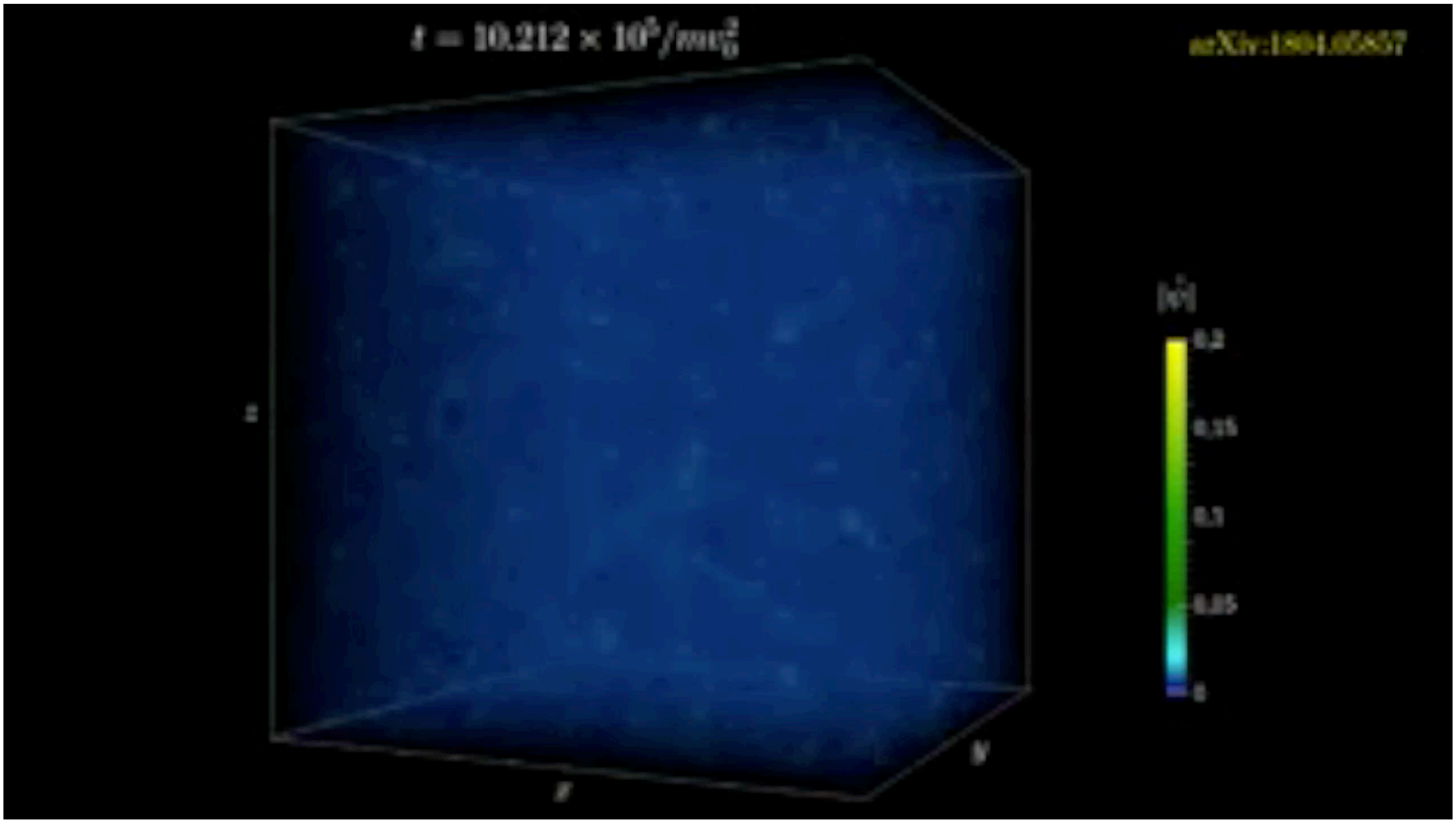


Solitons alone cannot explain dSph cores: "Catch 22" as WDM.
Other observational effects of enhanced density?
Recent simulations seem to show strong core oscillations.

Axion Star Birth

Levkov et al (2016)

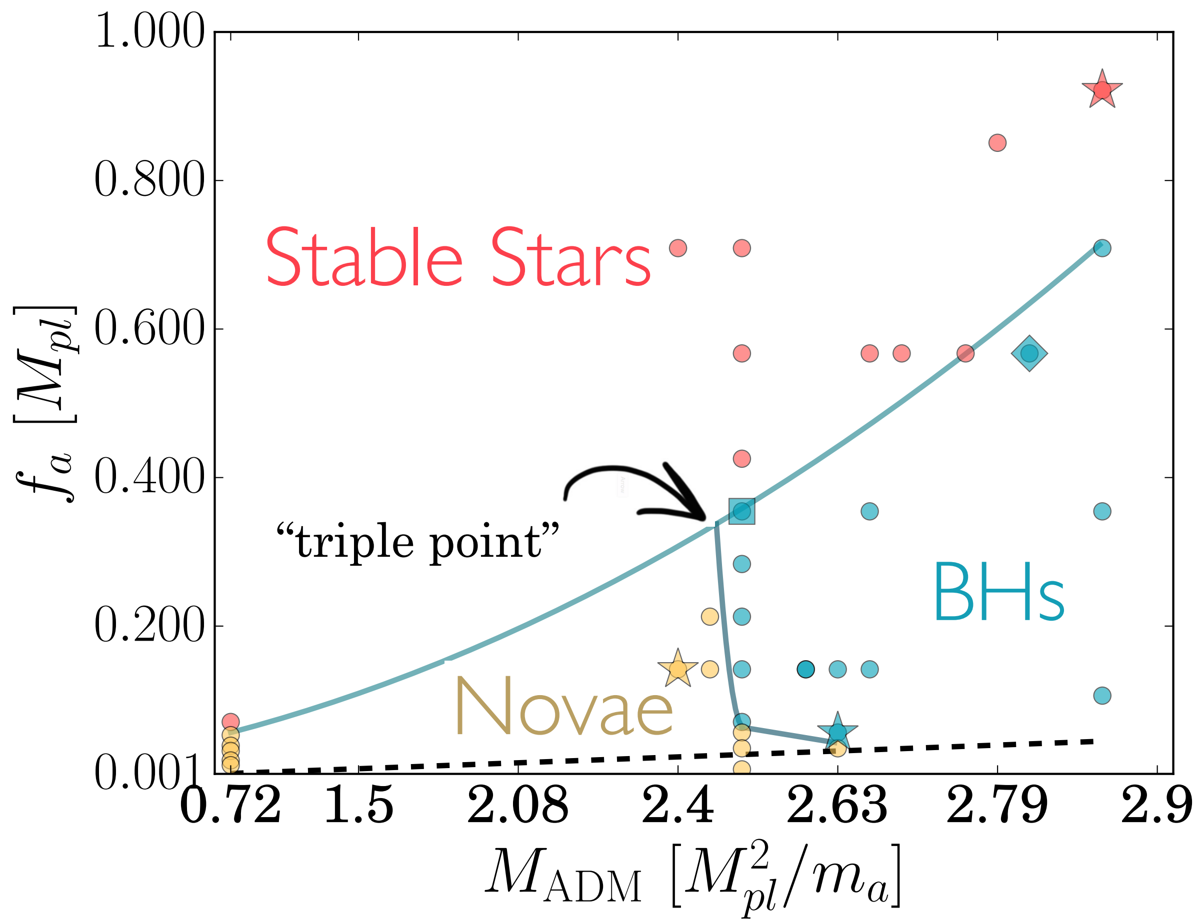
Axion stars are relevant beyond FDM. Should form in all models.



Axion Star Birth & Death

Levkov et al (2016)
Helfer, DJEM et al (2016)

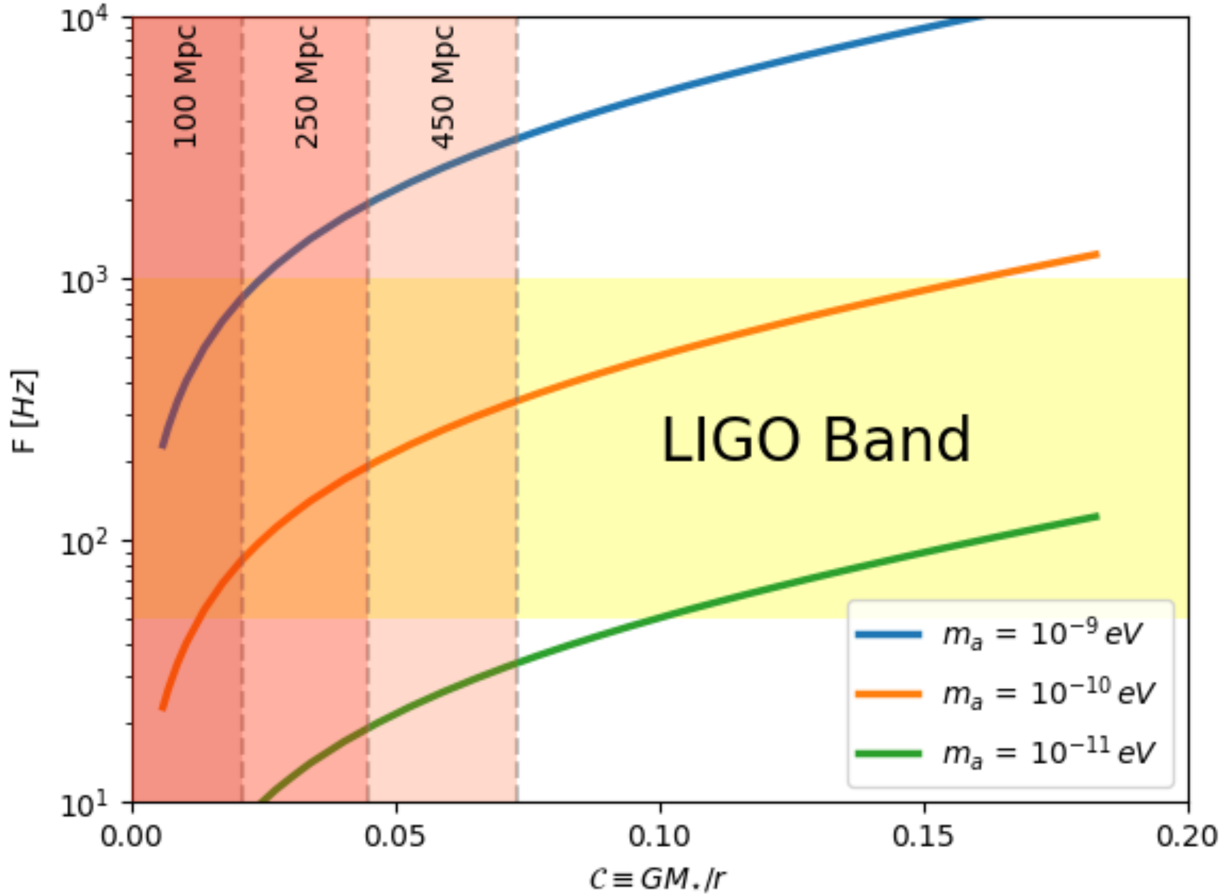
Core-halo mass relation → growth quenches for FDM. Are there relativistic axion stars? Axion novae? ECOs and GWs?



Stable Stars & GWs

Giudice, McCullough, Urbano (2016)
Widdicombe, DJEM et al (2018)

At high compactness, axion stars are "ECOs". How are they formed?

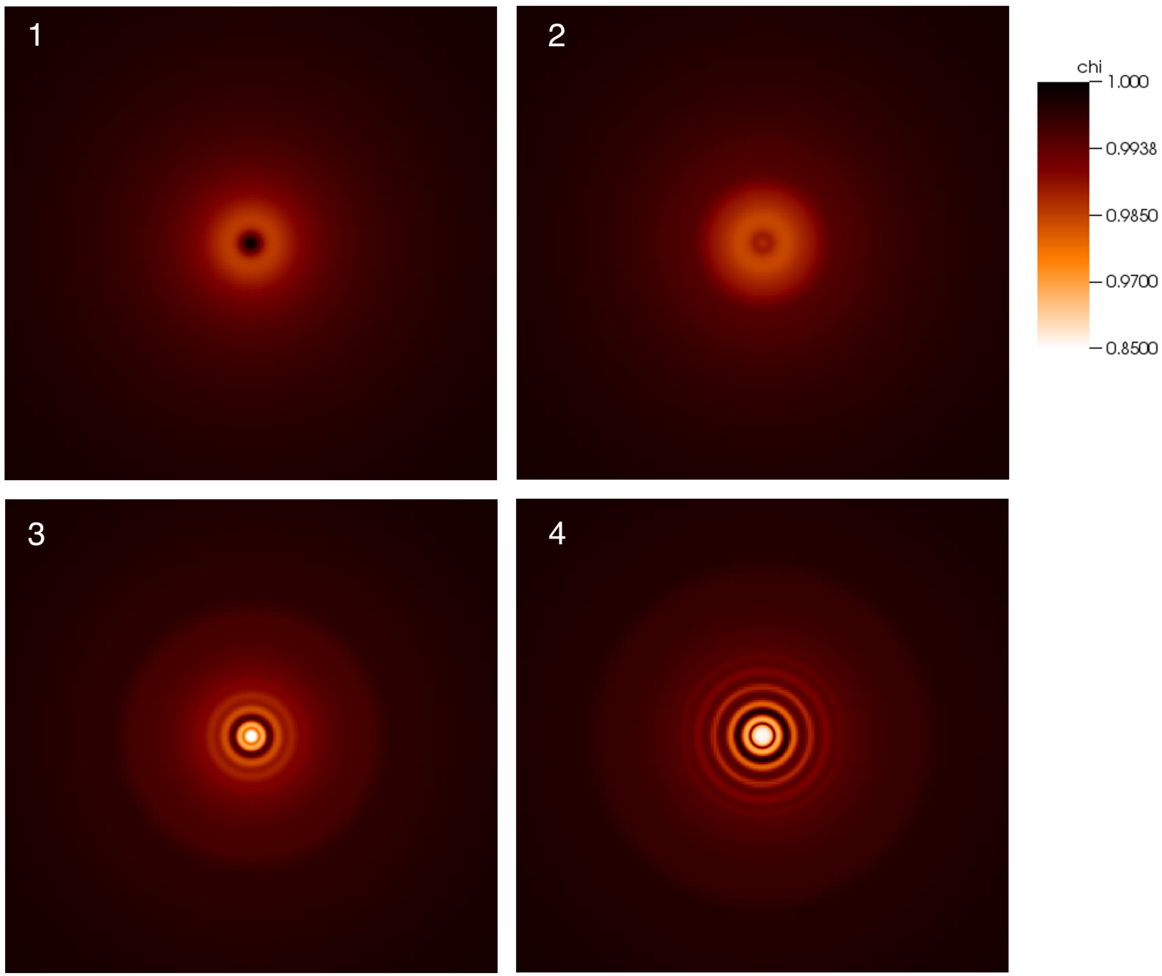


Helfer et al (2017) AS-AS, Clough et al (2018) AS-NS collisions.

Unstable Stars & Novae

Helfer, DJEM et al (2016)
Levkov et al (2016)

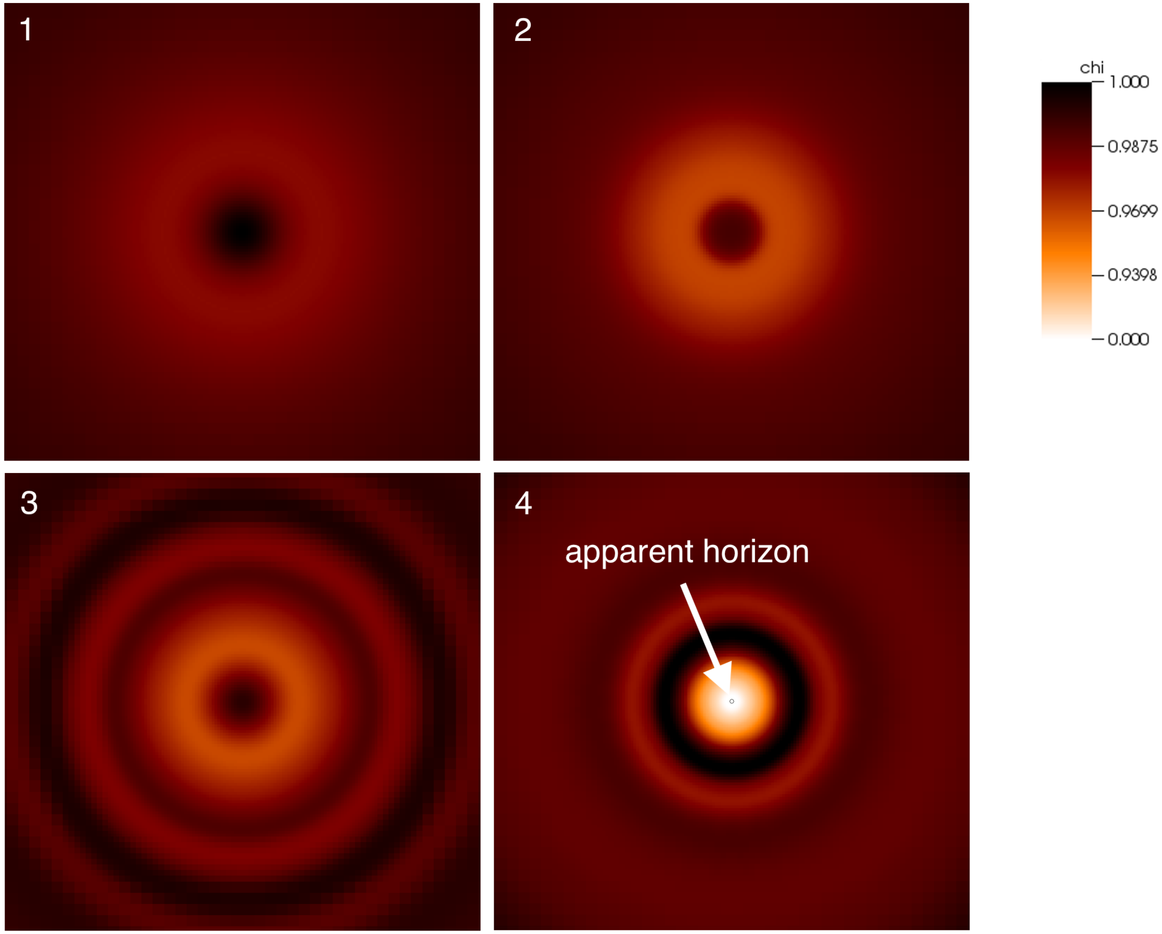
For low f, instability to decay. Convert DM axions into radiation?



BH Seeds

Helfer, DJEM et al (2016)

For f~Mpl, instability to BH formation. Possible seed for SMBH?



Thank You!