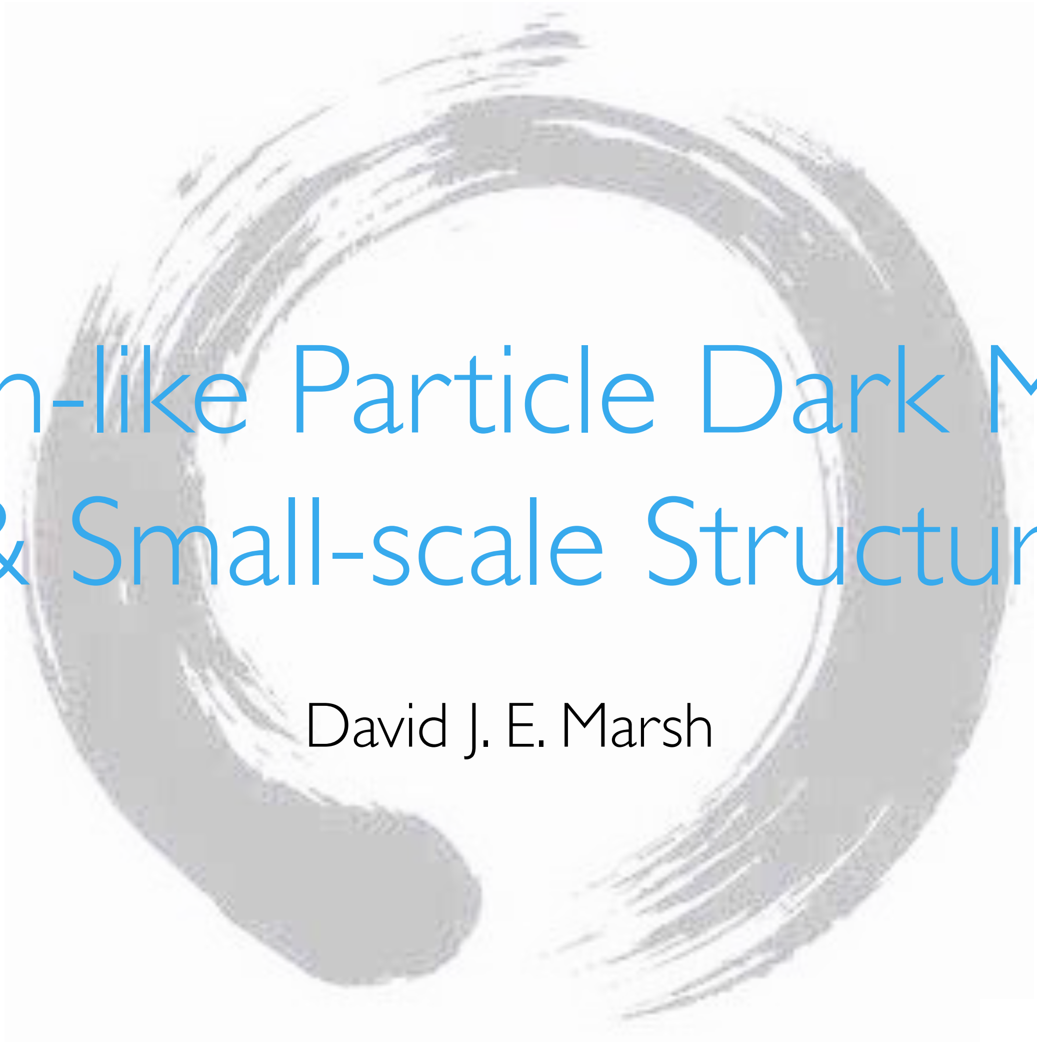

Axion-like Particle Dark Matter & Small-scale Structure

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GÖTTINGEN

Unterstützt von / Supported by

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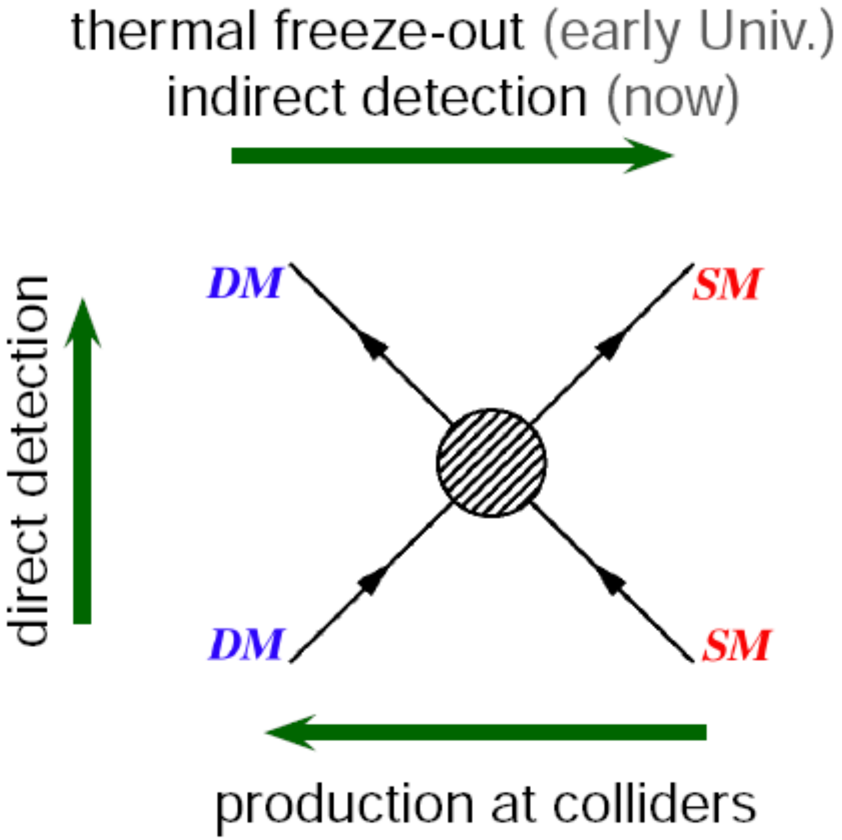
Two models of CDM

WIMPs	Axions
Predicted ~1970’s	Predicted ~1970’s
Naturally come from SUSY.	Come from strong-CP.
Heavy, nucleon mass.	v. light, sub-neutrino mass.
Thermal.	Non-thermal.
“Traditional” search strategies.	“Non-traditional” search strategies.
…	…
Cold due to small thermal velocities	“Cold” due to coherence and small wavelength
Collisions necessary for production	Interactions via wave equations

Axions are just a type of CDM, with different extreme limits than thermal DM

On Axions and WIMPs



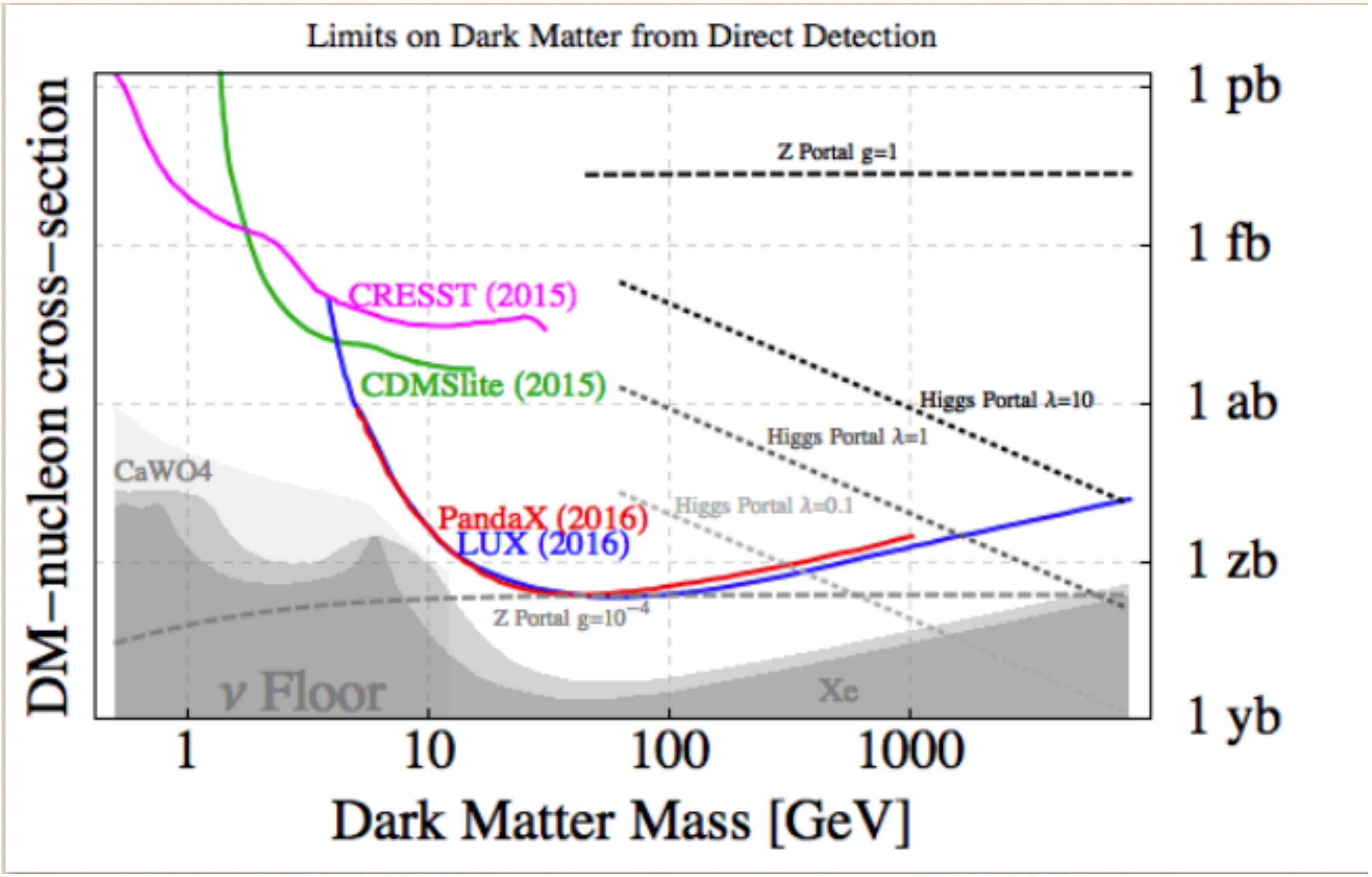
thermal freeze-out (early Univ.)
indirect detection (now)

direct detection

production at colliders

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

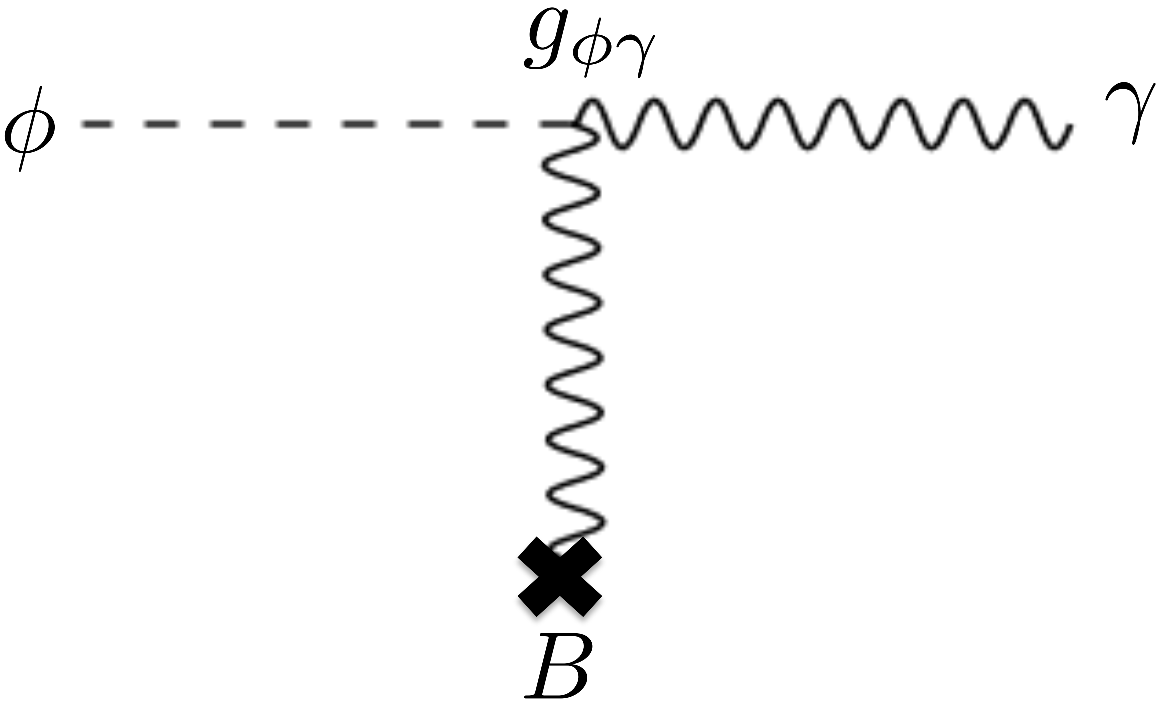
On Axions and WIMPs



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

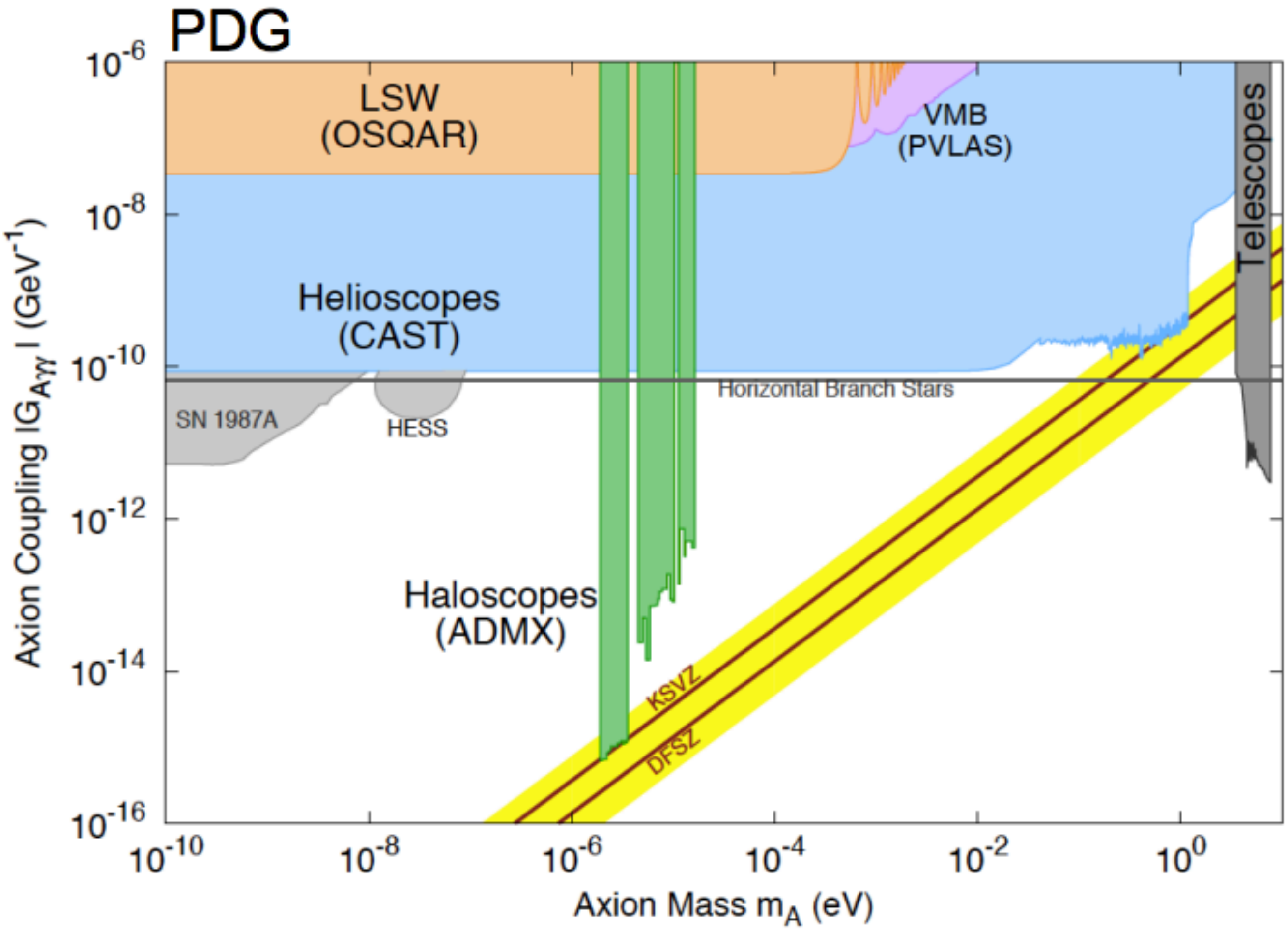
Fig. RESONAANCES.blogspot

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?

The Life of Axions

Spontaneous Symmetry Breaking

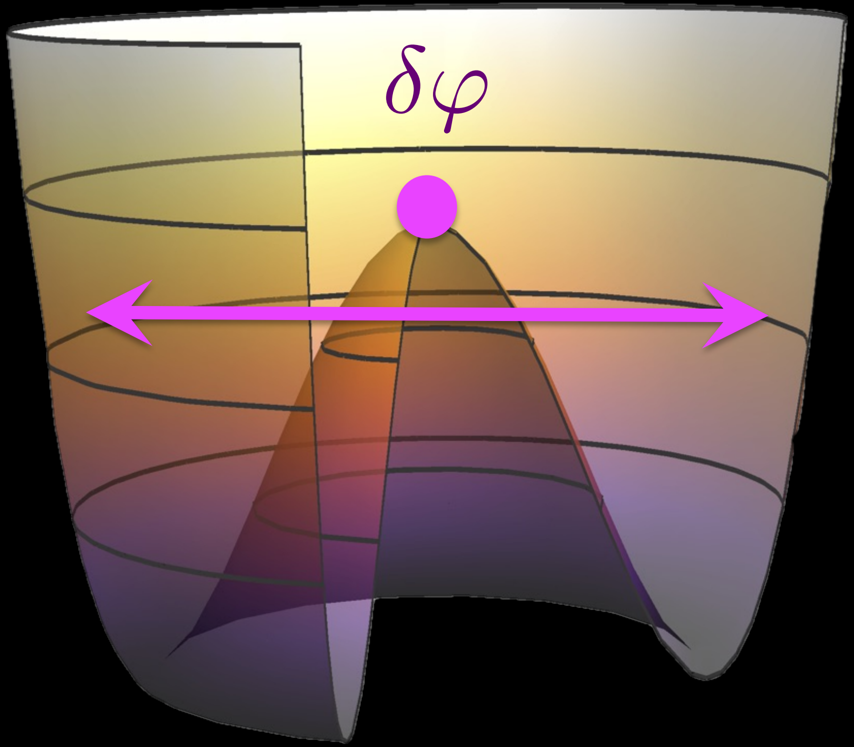
Spontaneous Symmetry Breaking → (p)NGB

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

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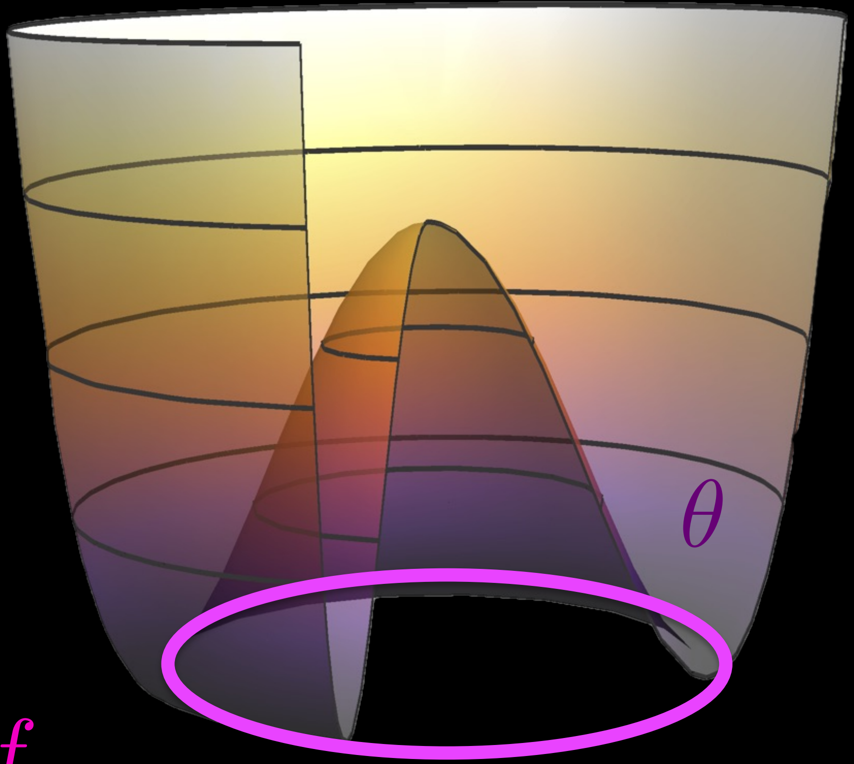
$$\delta\varphi \sim T \sim \frac{H_I}{2\pi}$$

$$T \ll f_a$$

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

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

Symmetry breaking → relics



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

Vacuum Realignment

Axion acquires mass, evolves according to Klein-Gordon:

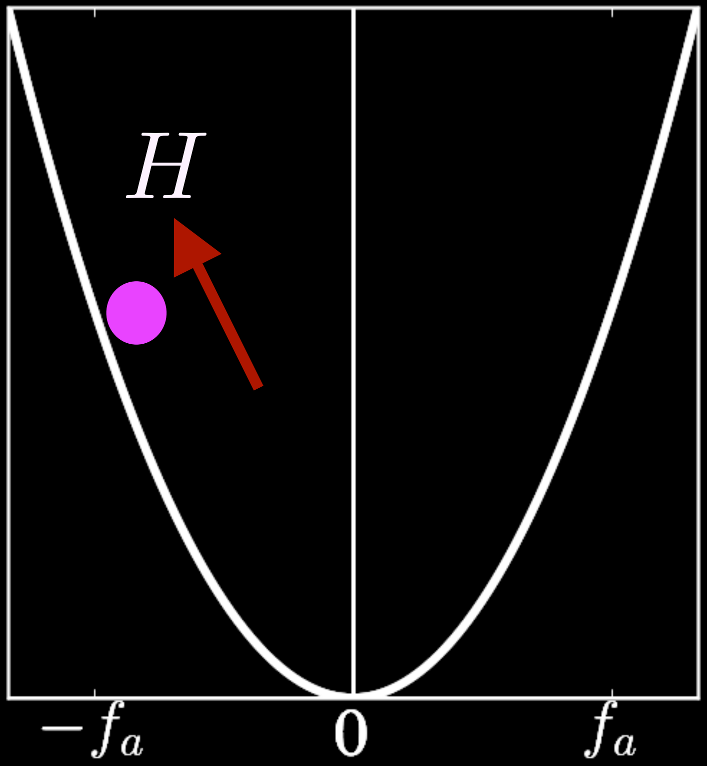
$$\ddot{\phi} + 3H\dot{\phi} + m_a^2\phi = 0$$

$$H \gg m_a$$

Axion is "frozen" by Hubble friction term.

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

$$\Rightarrow w_a \approx -1$$



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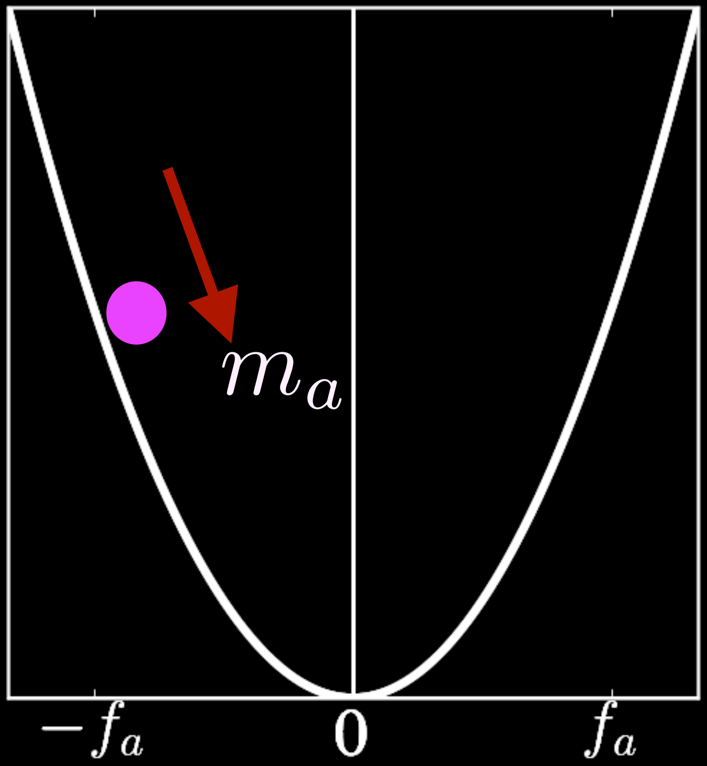


Field oscillates & damps.
WKB (or exact) →

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

Homogeneous scalar ~ matter

Inhomogeneities → gradients → pressure

Fuzzy Dark Matter

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

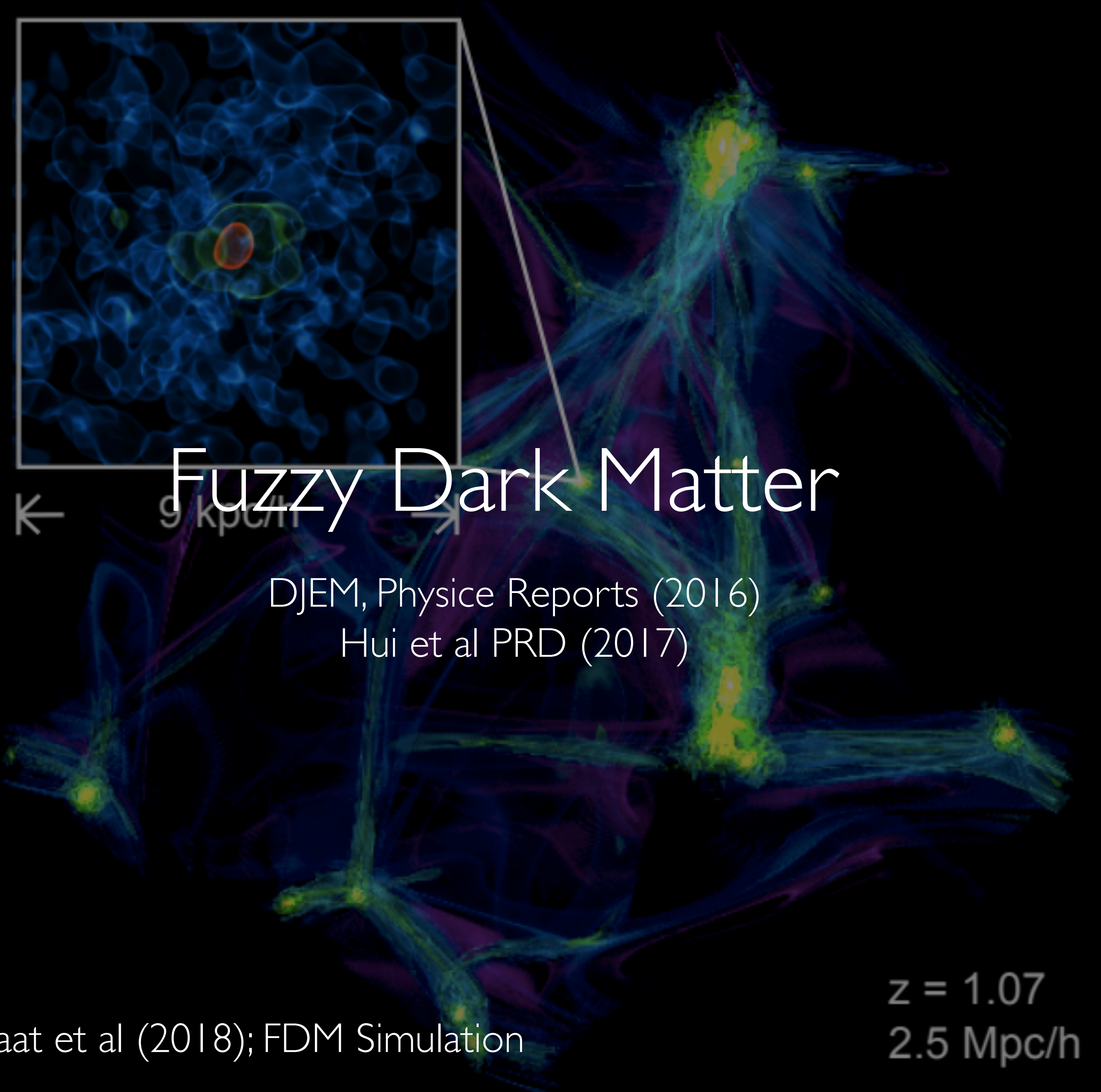
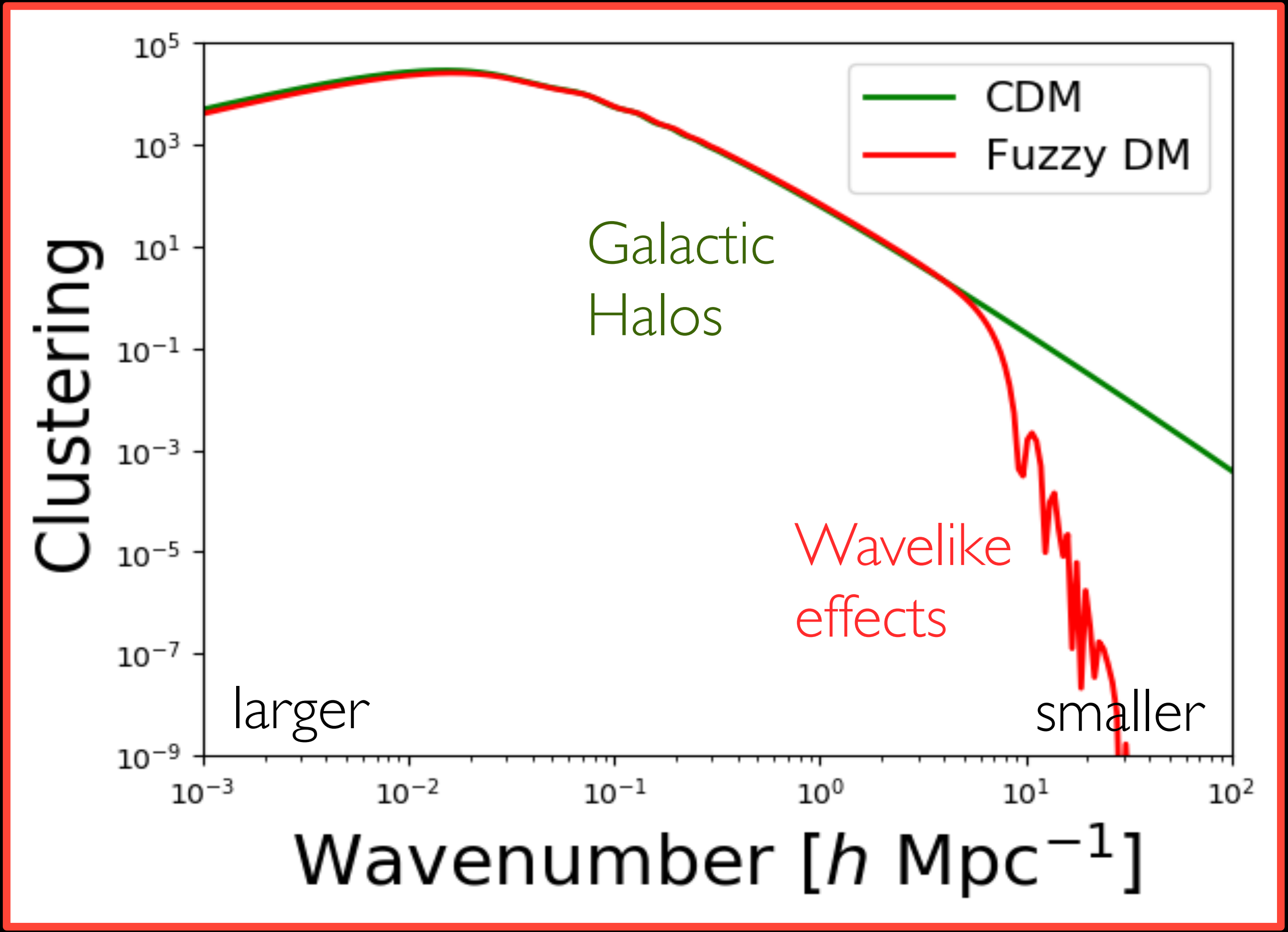


Image: Veltmaat et al (2018); FDM Simulation

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

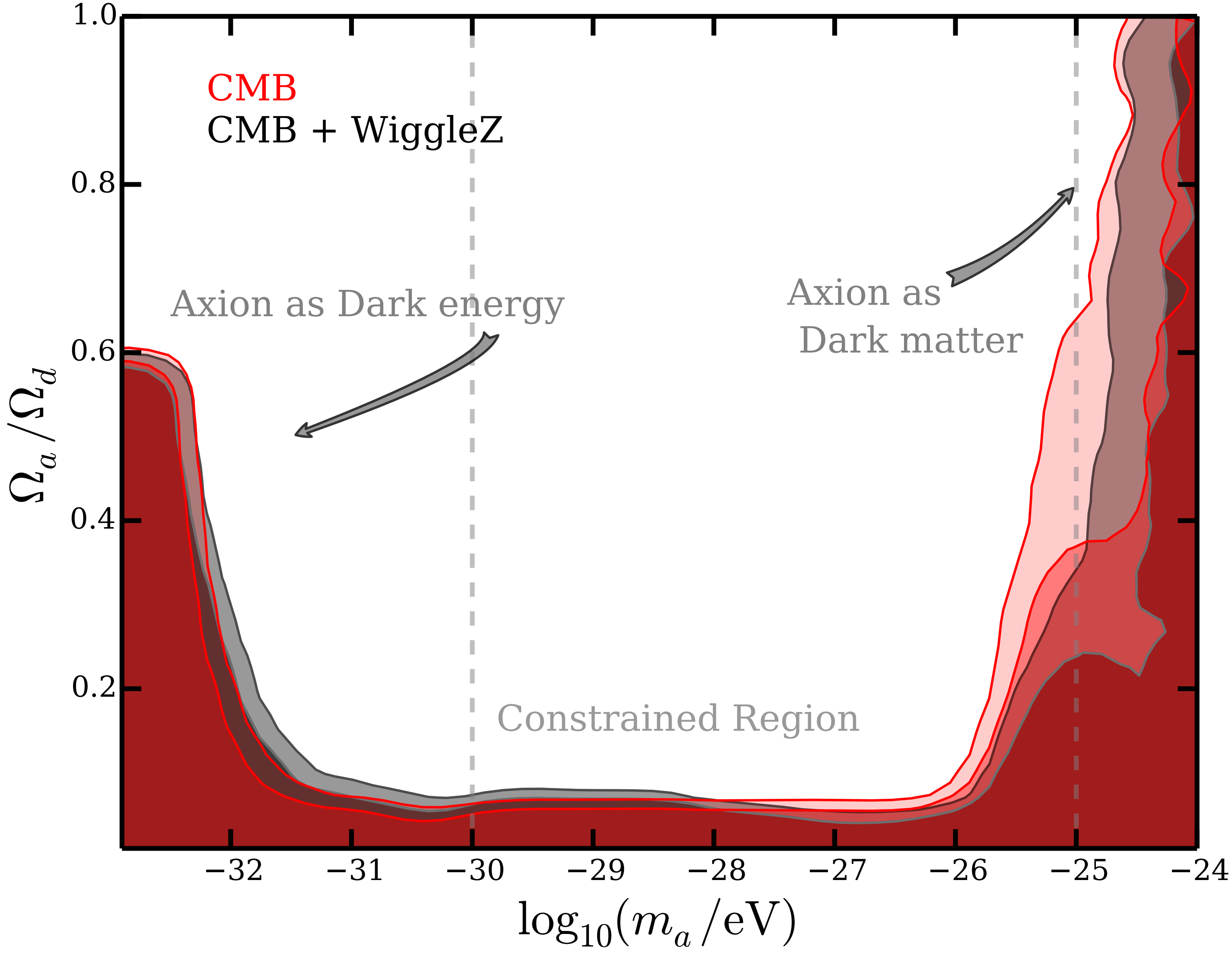


e.g. DJEM (2016)

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

CMB Baseline

Amendola & Barbieri (2006)
Hlozek, DJEM et al (2015) axionCAMB



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

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

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

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

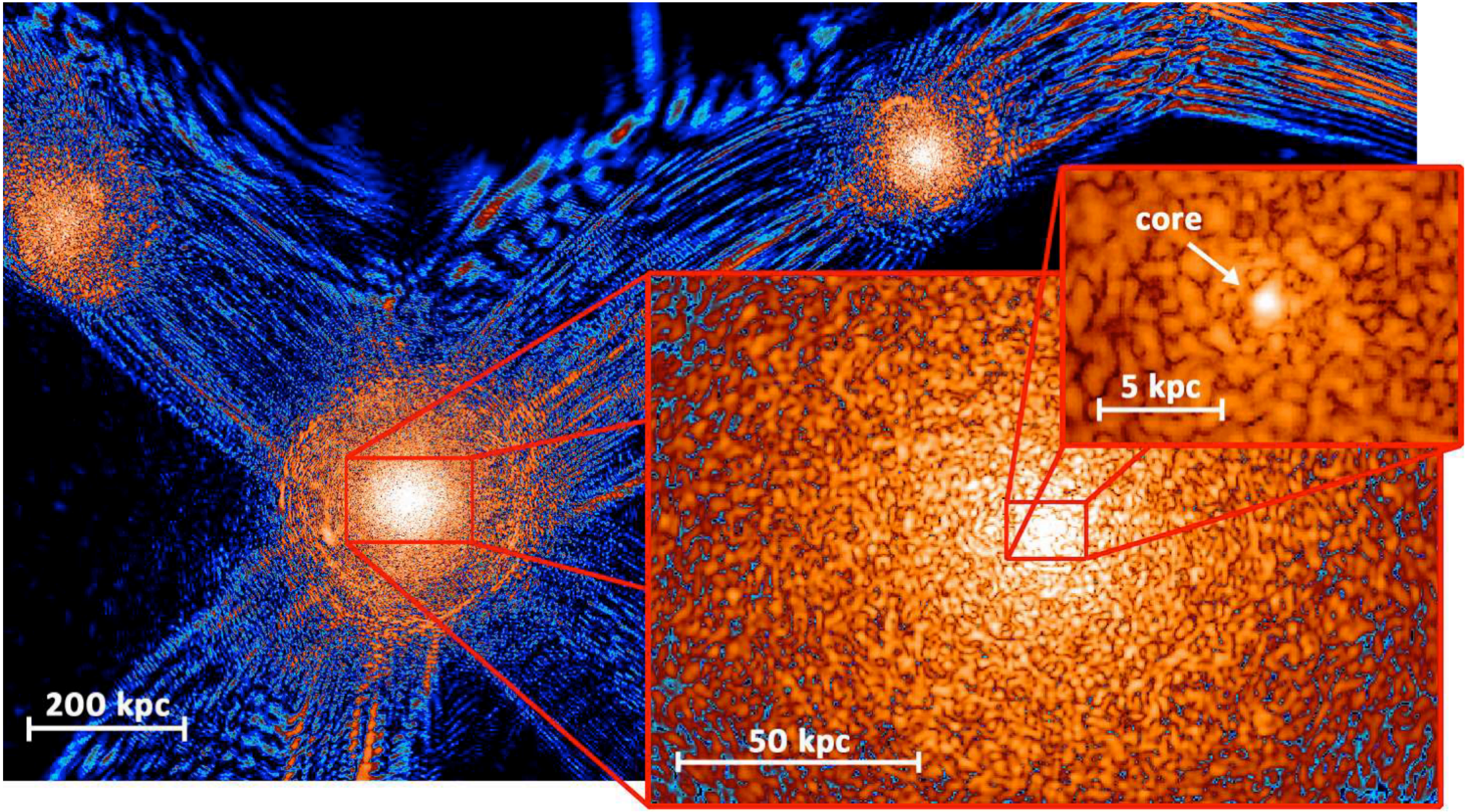
$$\boxed{\begin{aligned} &\dot{\delta} + \vec{v}\cdot\nabla\delta = (1+\delta)\nabla\cdot\vec{v} \\ &\dot{\vec{v}} + (\vec{v}\cdot\nabla)\vec{v} = -\nabla(\Phi + Q) \\ &Q = -\frac{1}{2m^2}\frac{\nabla^2\sqrt{1+\delta})}{\sqrt{1+\delta}} \end{aligned}}$$

continuity

Euler

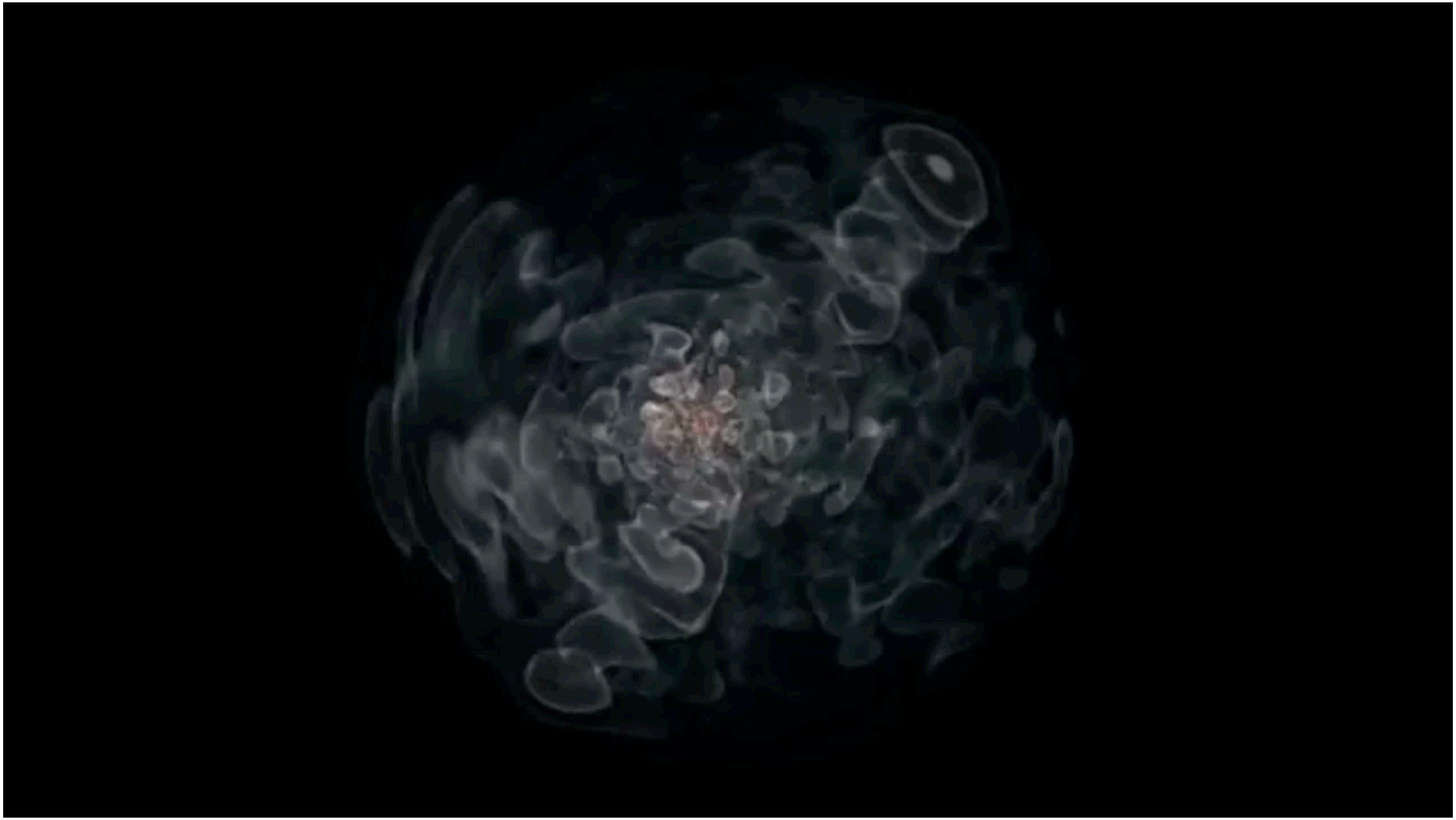
Quantum Pressure : source of interference effects

FDM Simulations



Schive et al (2014)

FDM Simulations



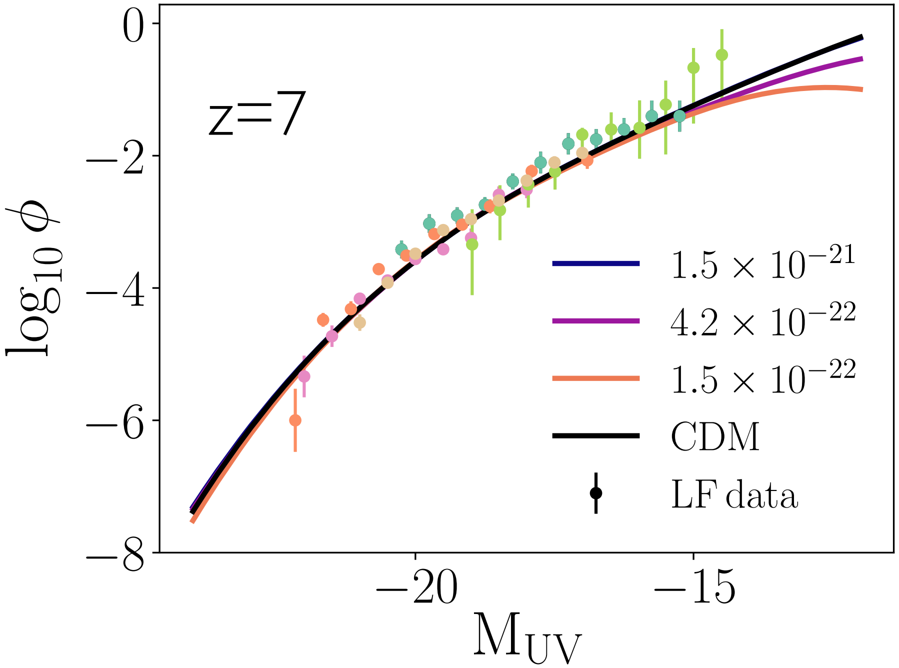
Schwabe et al (2016). Blob size ~ kpc, lifetime ~ 10^6 years (10^{-22} eV/m)

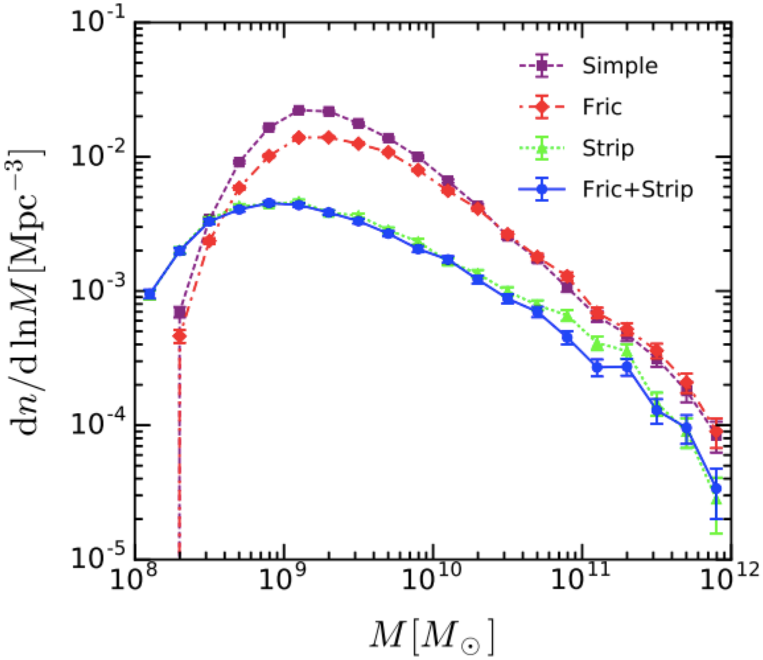
Halo Mass Function

DJEM & Silk (2014); Du et al (2016)
Corasaniti, DJEM et al (2017)

Suppressed power → no low mass halos/subhalos.

$$M_c \approx 10^8 (m/10^{-22}\mathrm{eV})^{-1.35} M_\odot$$





In the field: no high-z low mass halos → reduced early star formation → later reionization.

In the MW: no low mass satellites / subhalos.

Constrained by tidal streams?

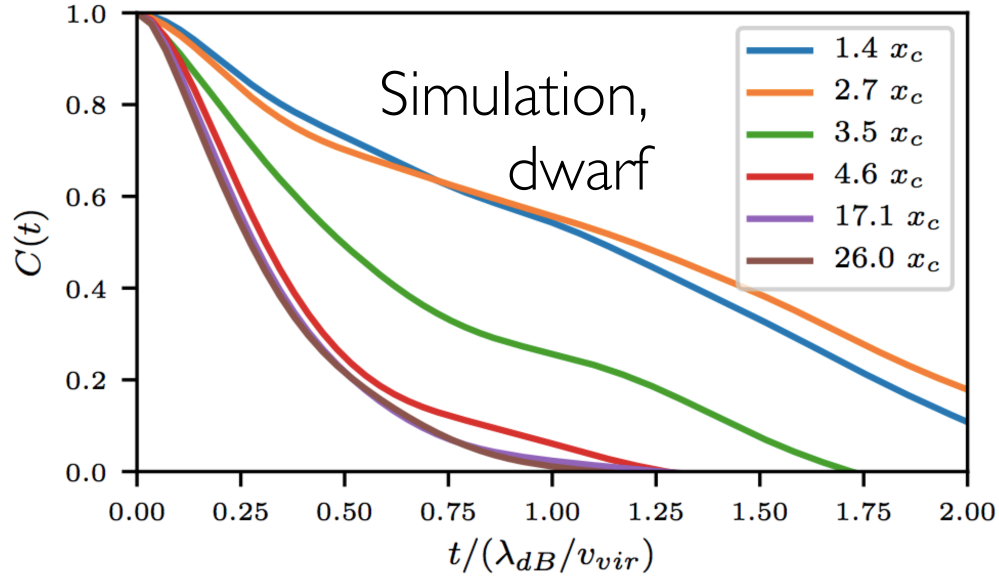
Dynamical Effects

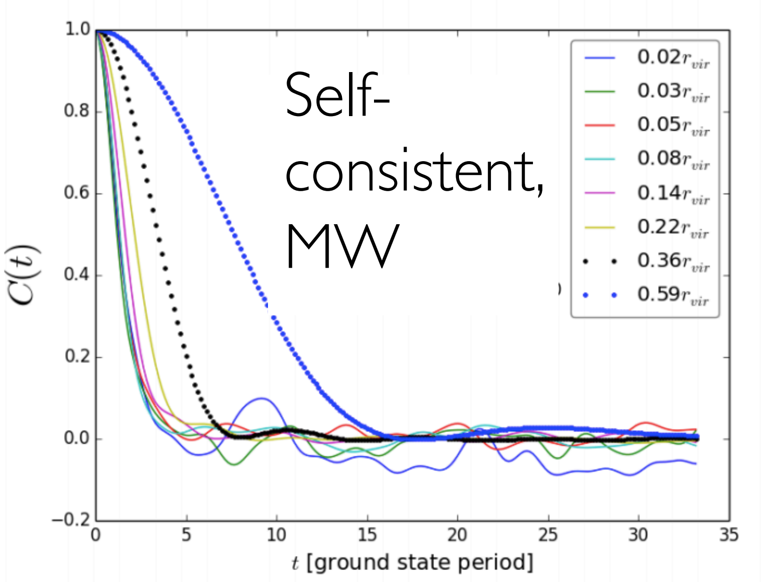
Hui et al (2017); Veltmaat et al (2018)
Lin et al (2018); Khlemeninsky &Rubikov (2014)

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.


Simulation, dwarf

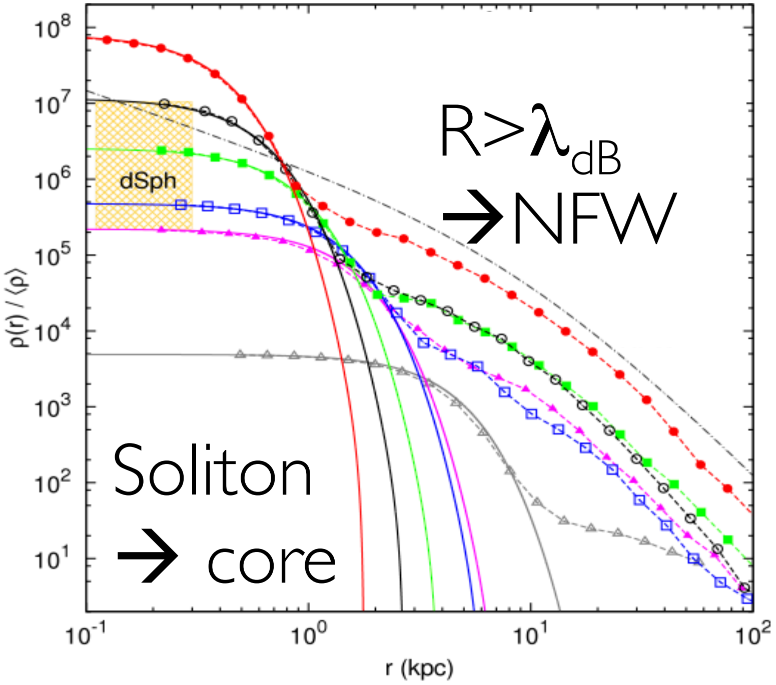

Self-consistent, MW

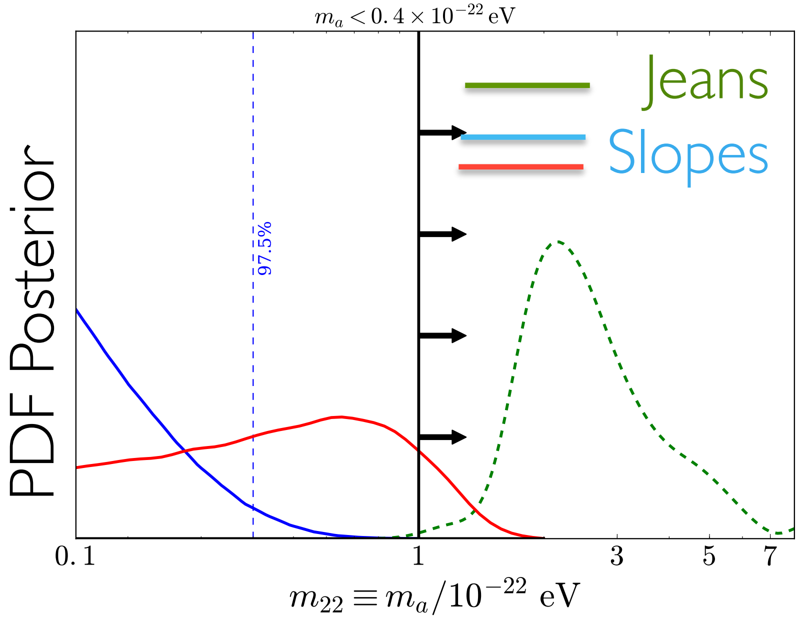
$$t_{\rm relax}(r) \sim \frac{0.4}{f_{\rm relax}}\frac{m^3v^2r^4}{\pi^3\hbar^3} \sim \frac{1\times 10^{10}\,{\rm yr}}{f_{\rm relax}}\left(\frac{v}{100\,{\rm km\,s^{-1}}}\right)^2\left(\frac{r}{5\,{\rm kpc}}\right)^4\left(\frac{m}{10^{-22}\,{\rm eV}}\right)^3$$

Axion Stars and Cores

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

Density profiles show prominent cores. Pressure supported solitons.





Solitons alone cannot explain dSph cores: "Catch 22" as WDM.

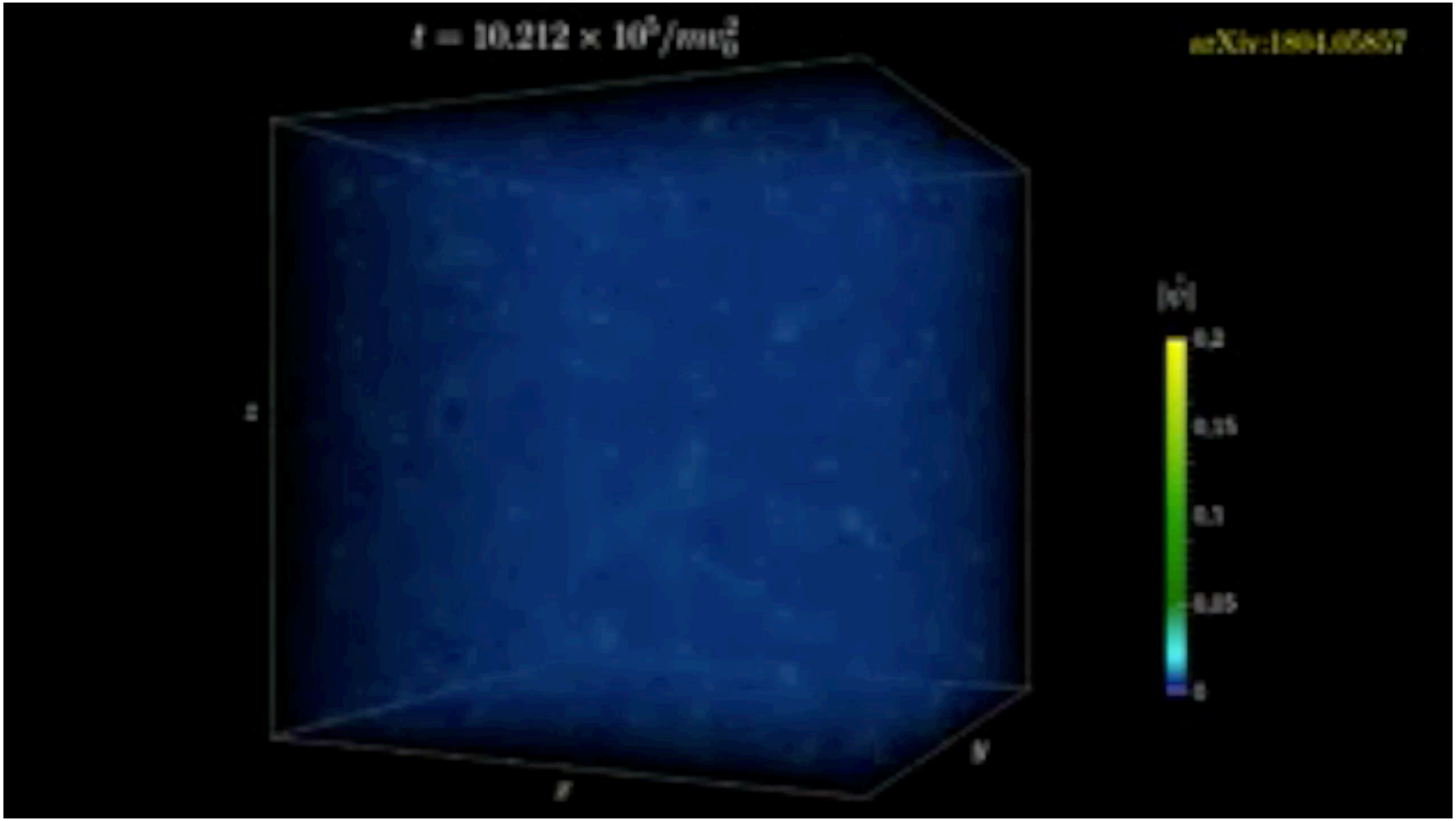
Other observational effects of enhanced density?

Recent simulations seem to show strong core oscillations.

Axion Star Birth & Death

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

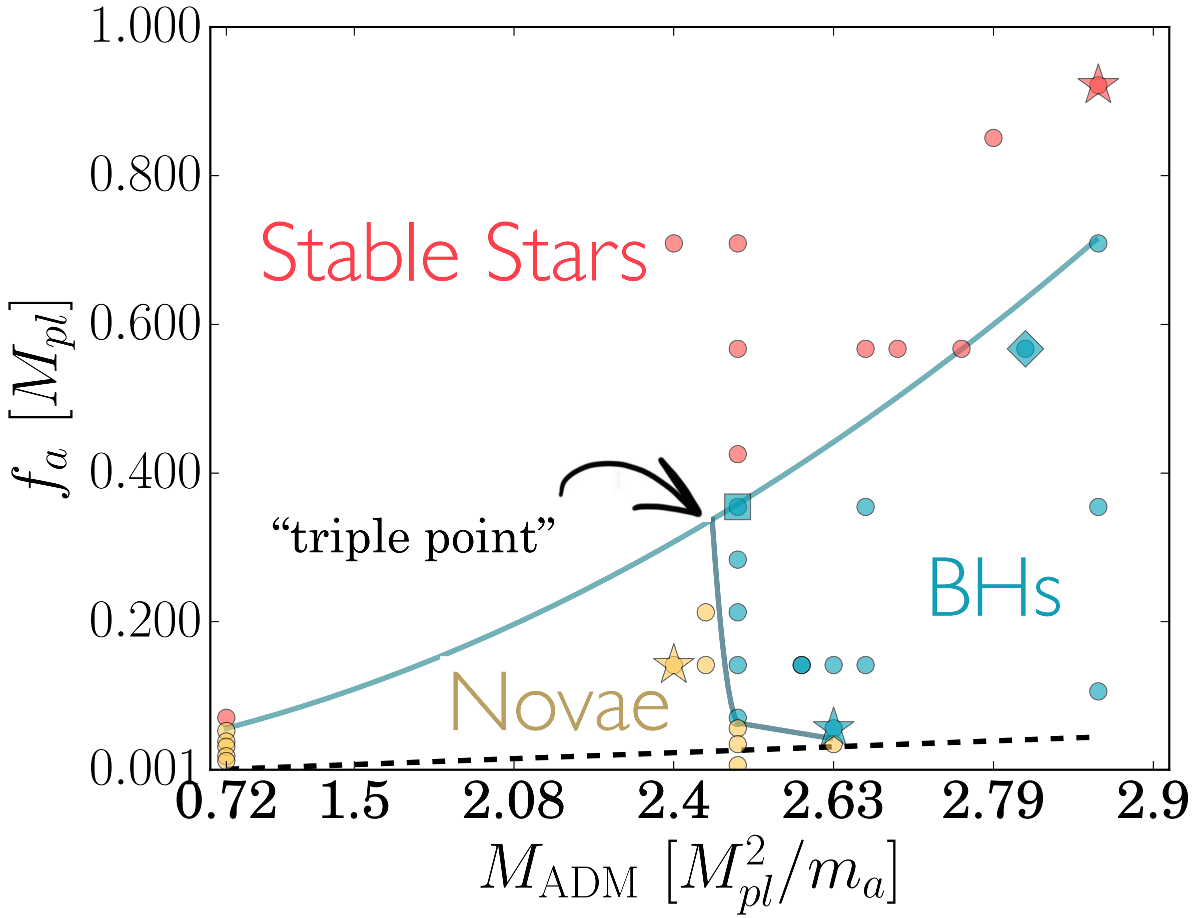
Axion stars are relevant beyond FDM. Should form in all models.



Axion Star Birth & Death

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

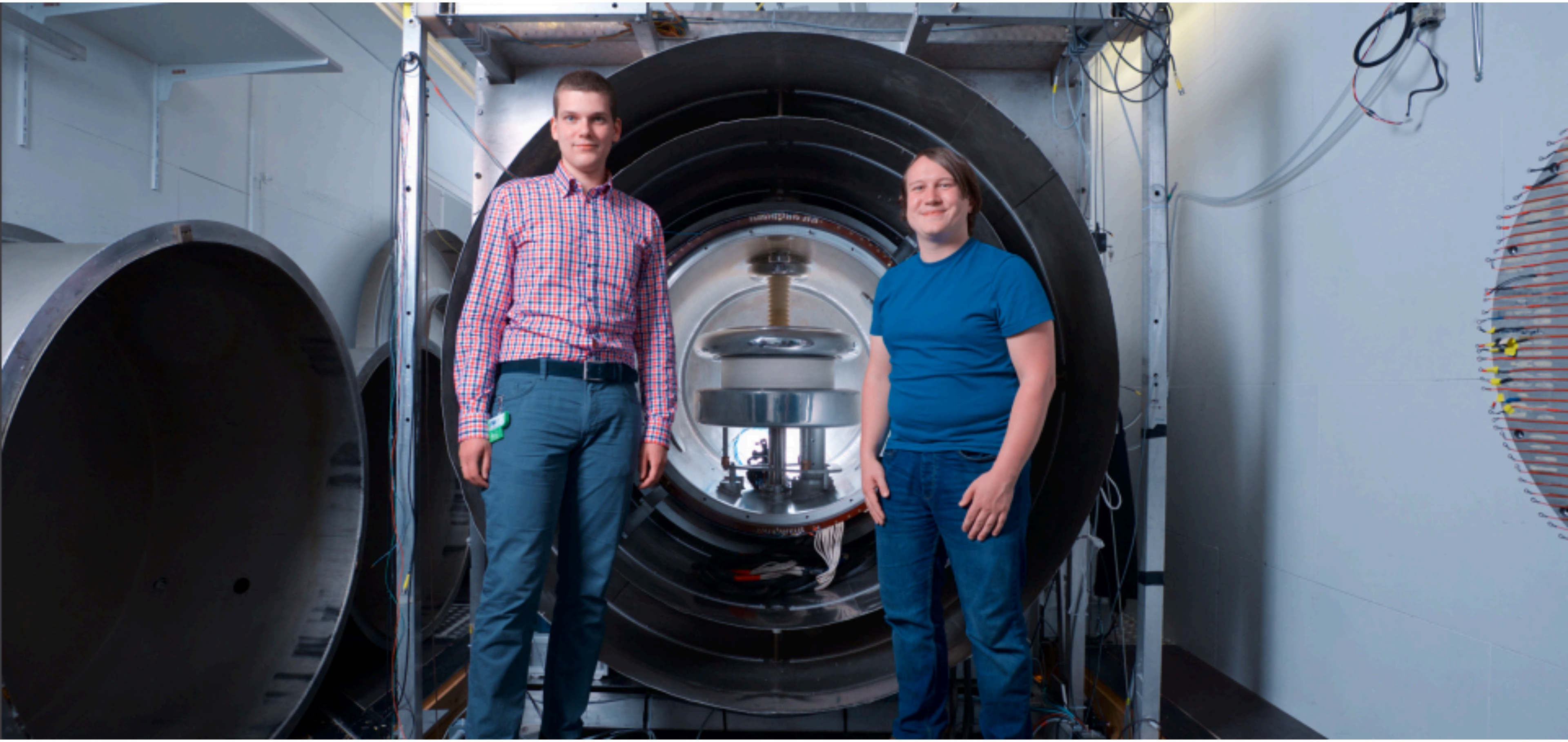
Core-halo mass relation → growth quenches for FDM. Are there relativistic axion stars? Axion novae? ECOs and GWs?



FDM Direct Detection

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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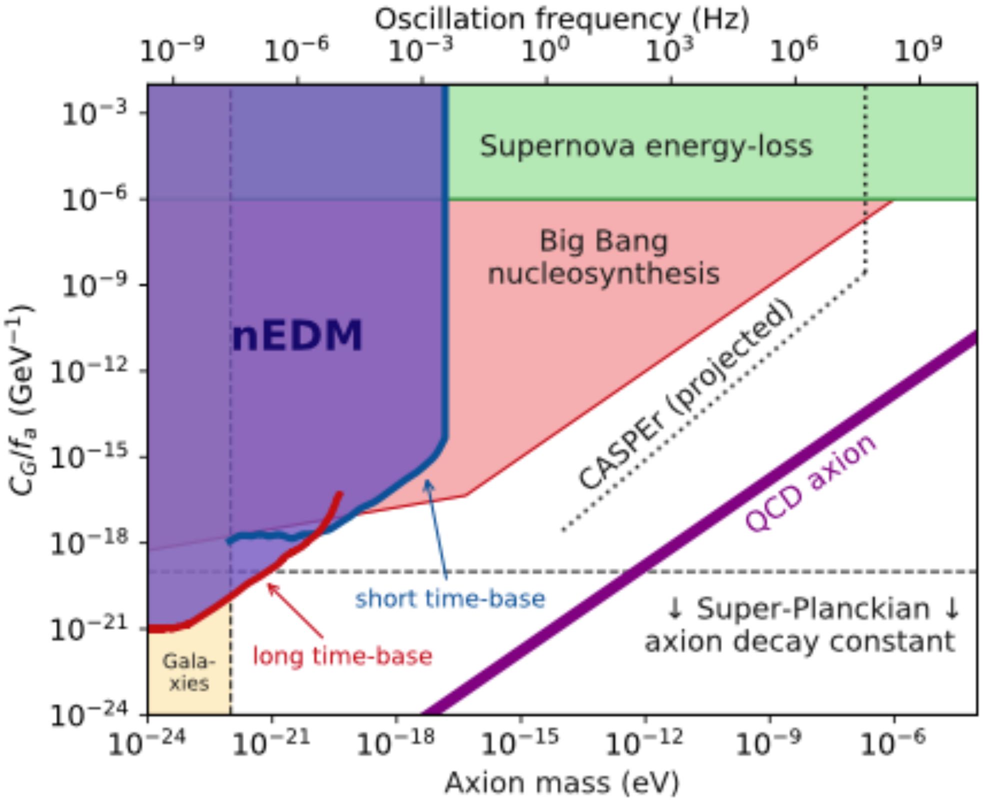
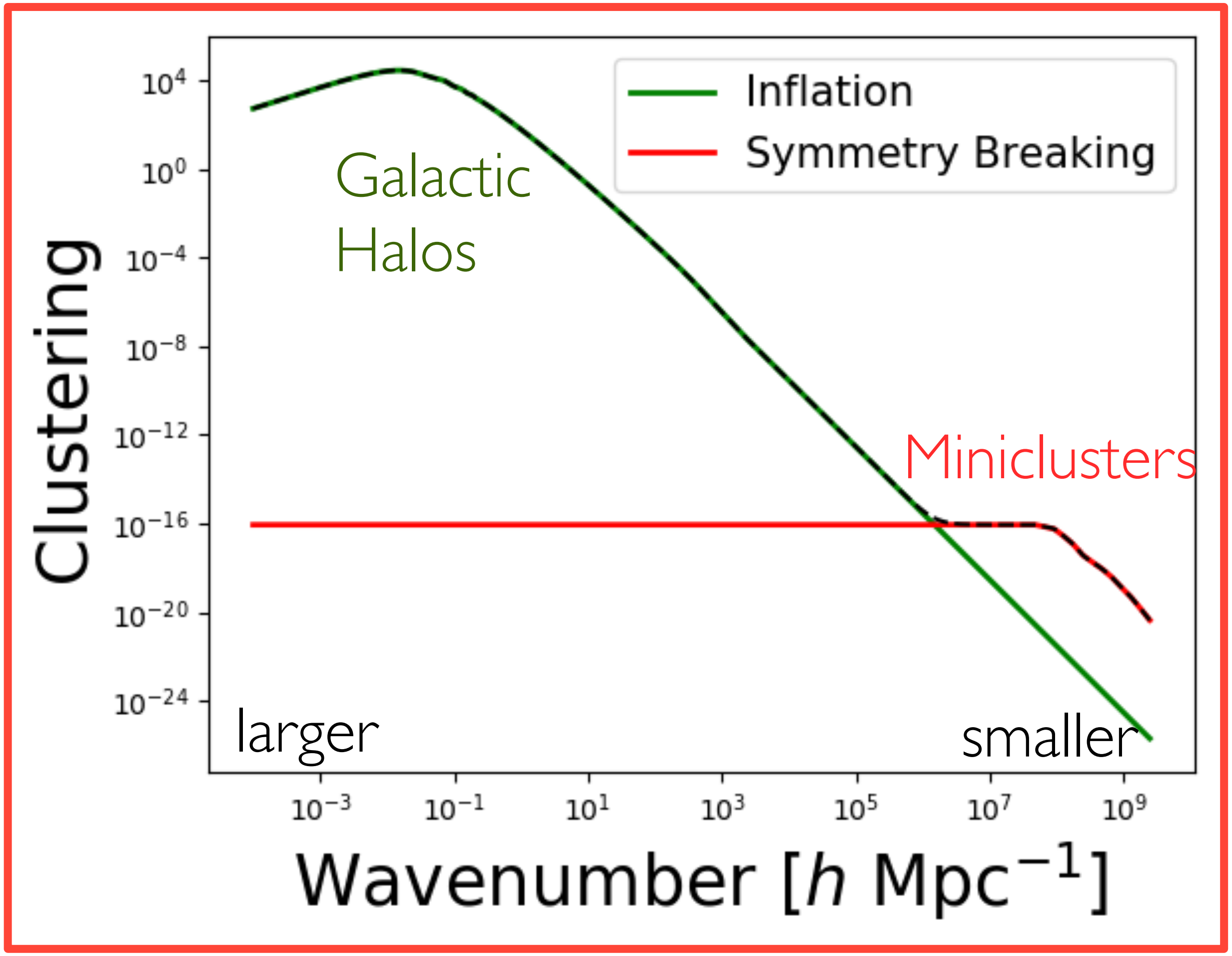


Miniclusters & Microlensing

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

Image: the Subaru Hyper Suprime 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.

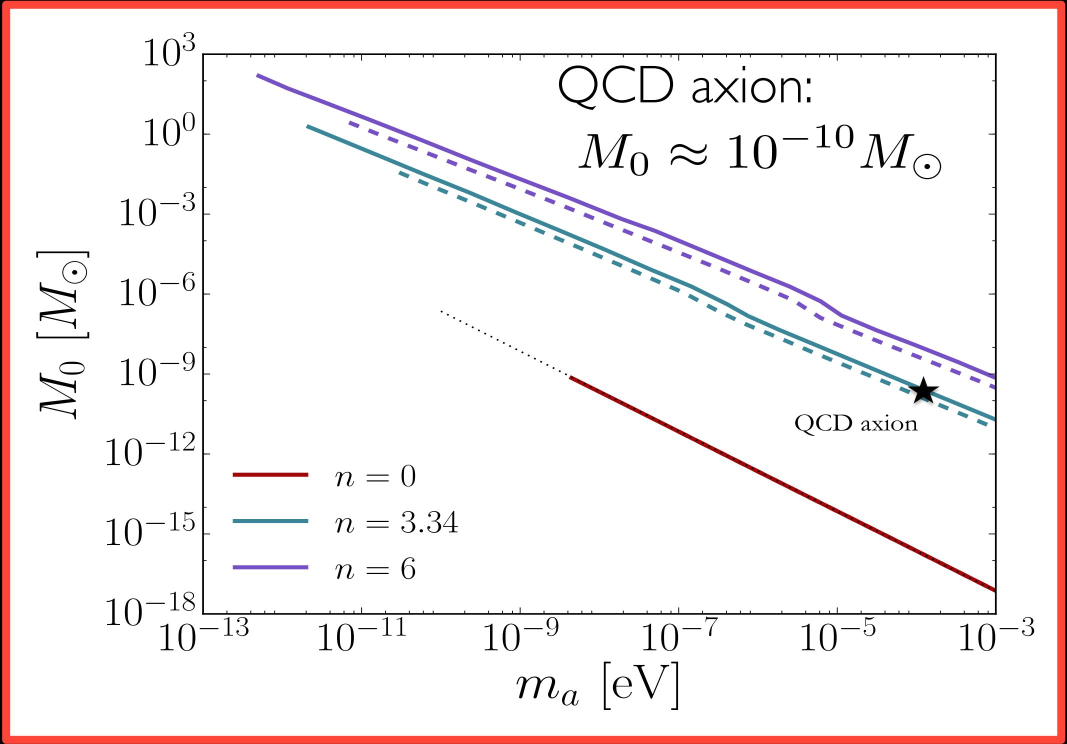


Minicluster Mass Scale

Hogan & Rees (1988)

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

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



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

The amount of DM in compact objects is strongly constrained:

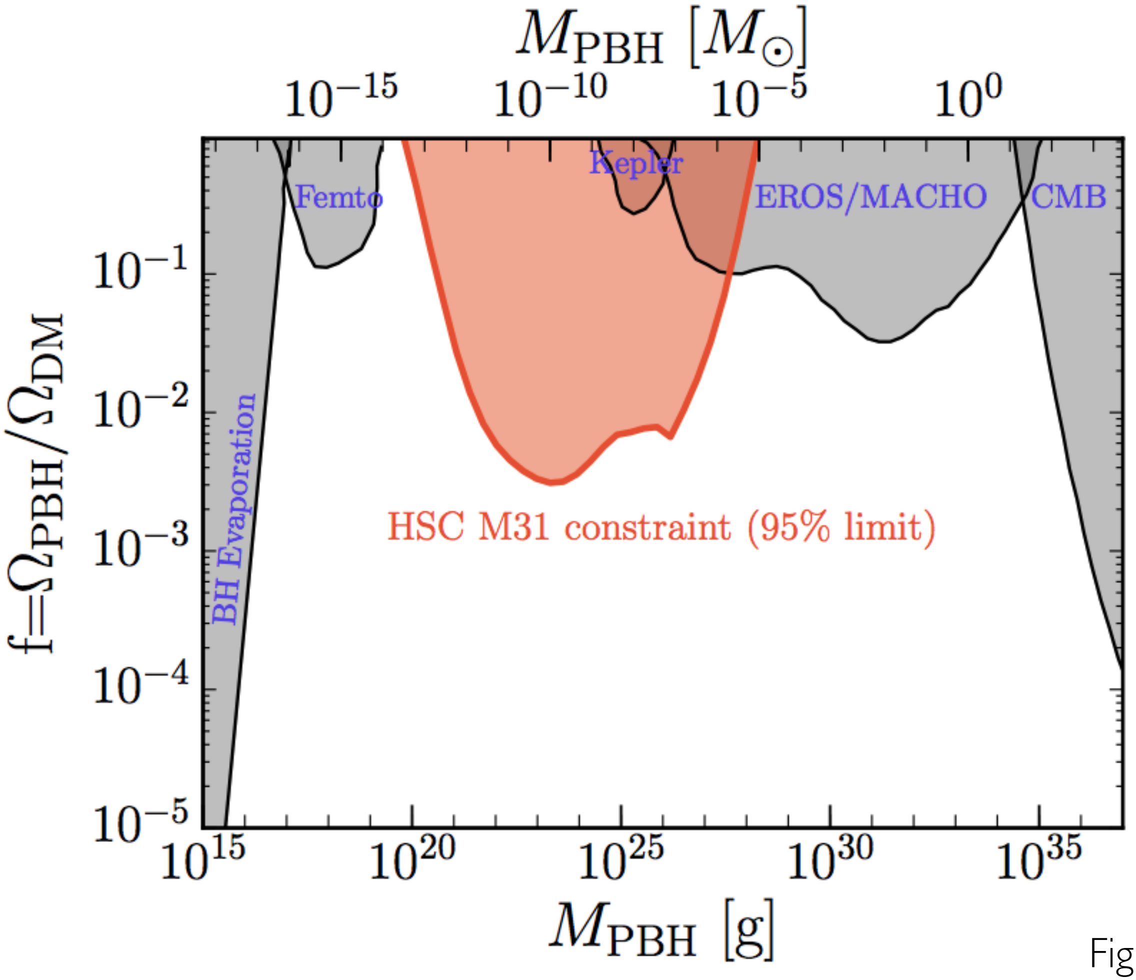
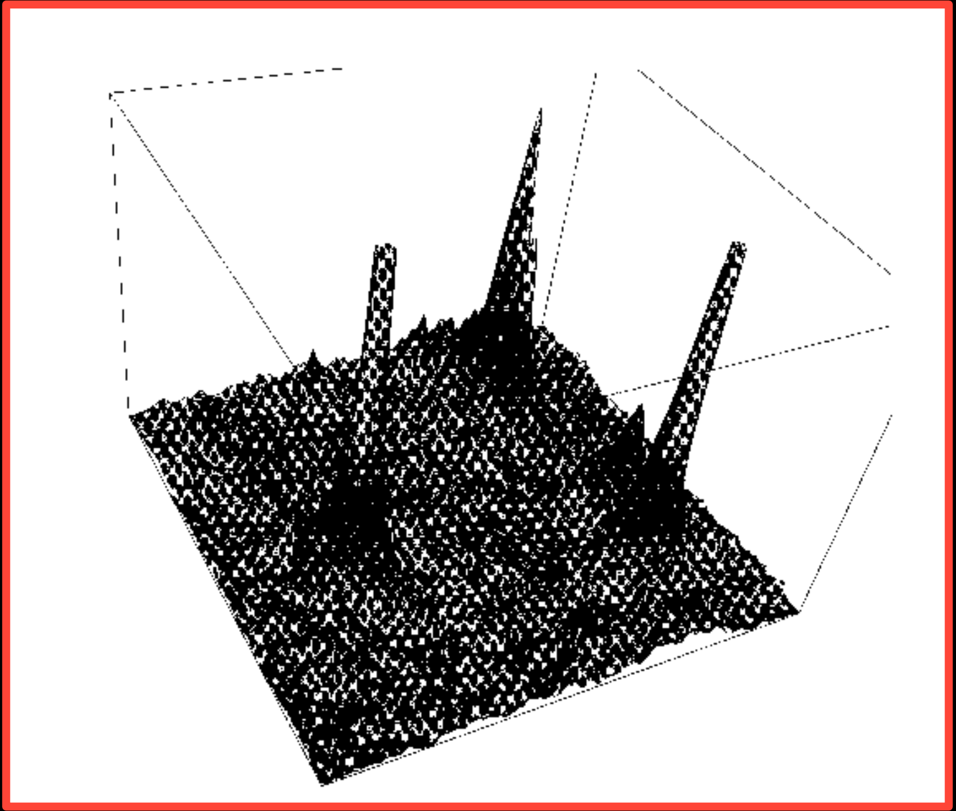


Fig: Niikura et al (2017)

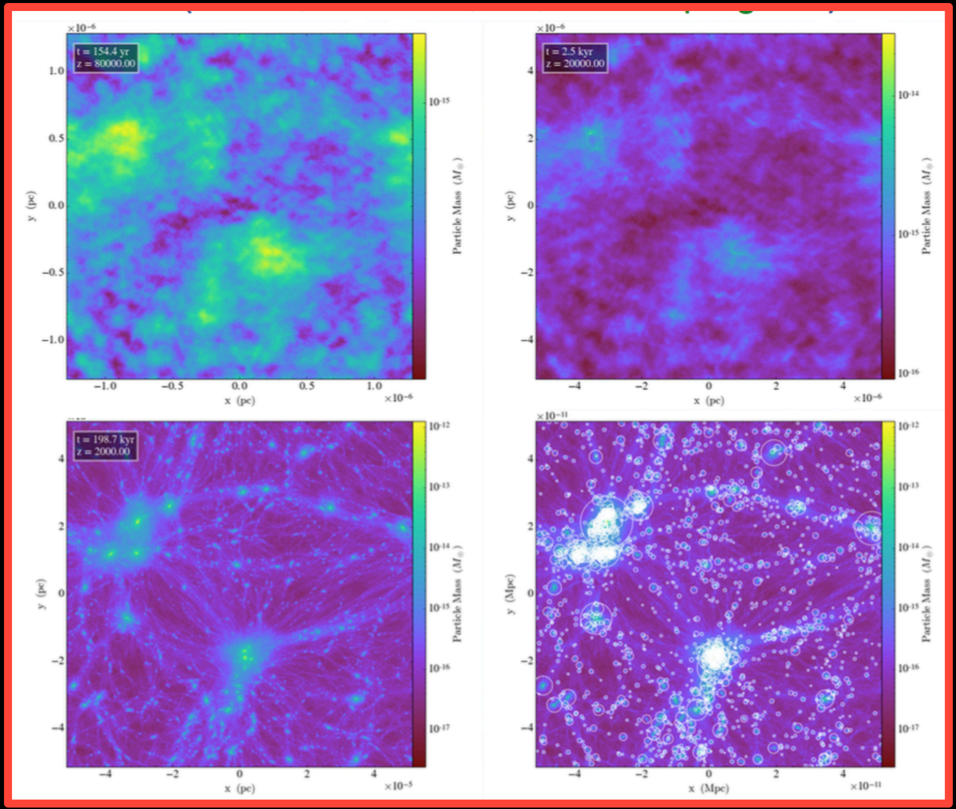
How do these constraints translate to miniclusters (or e.g. UCMHs)?
What is the relic density, mass, and size distribution of miniclusters?

Numerical Simulations

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



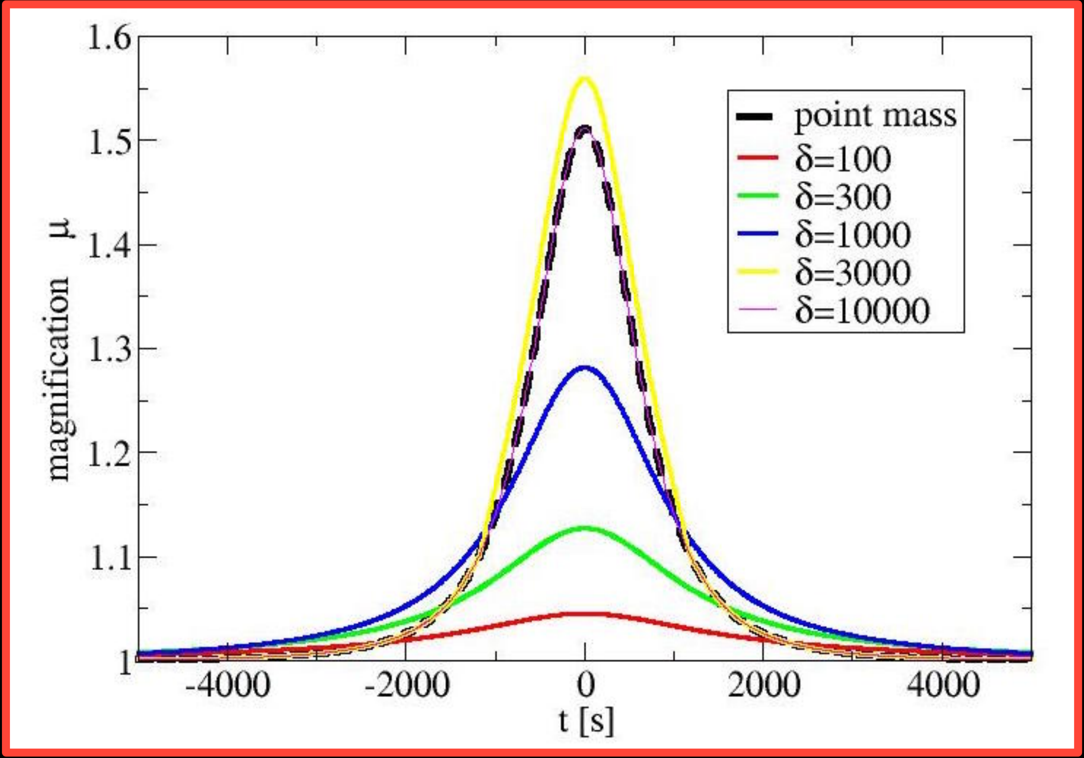
Kolb & Tkachev (1990's): field simulations w/ no gravity.
→ Mass and radius scale.



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

Microlensing: non-pointlike objects

Paramterise the density profile based on initial overdensity, δ.



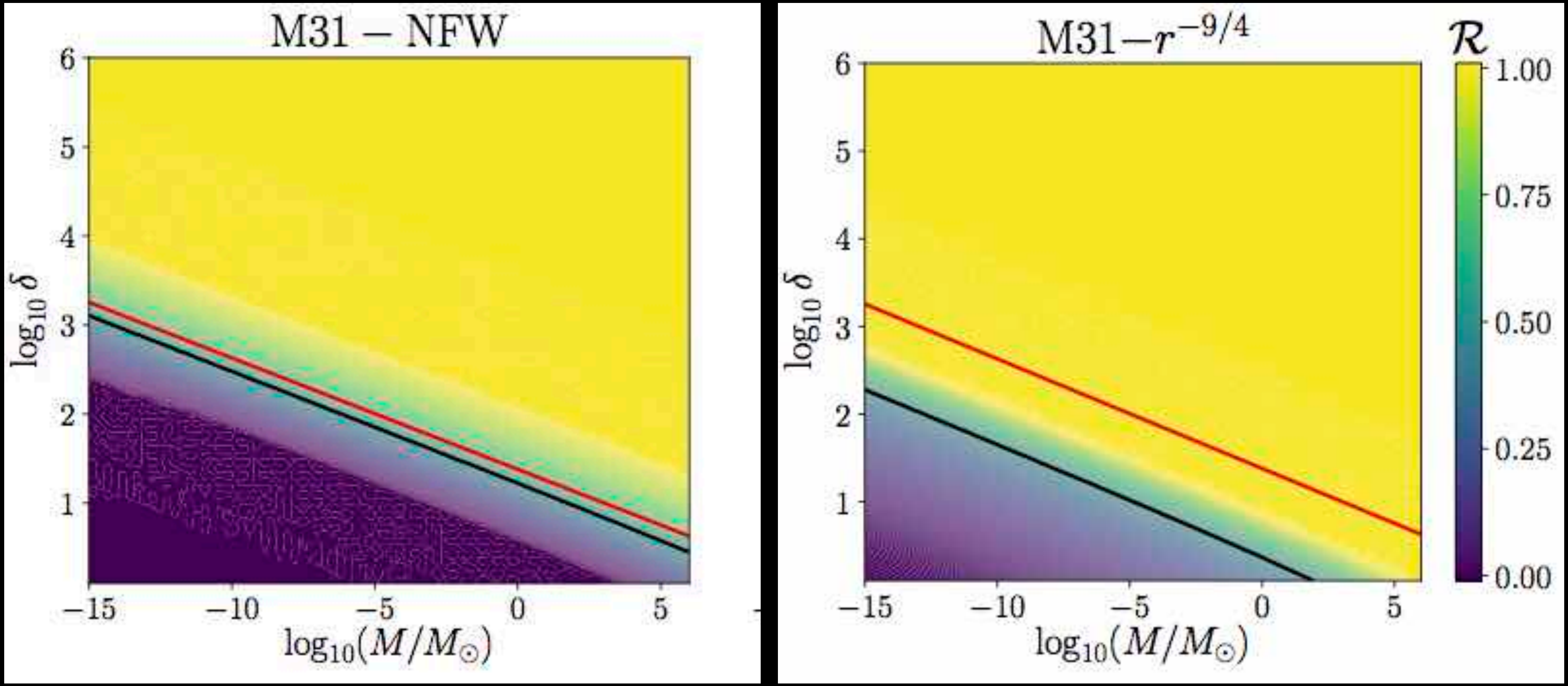
Effects described by a rescaling of the "microlensing tube":

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

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.

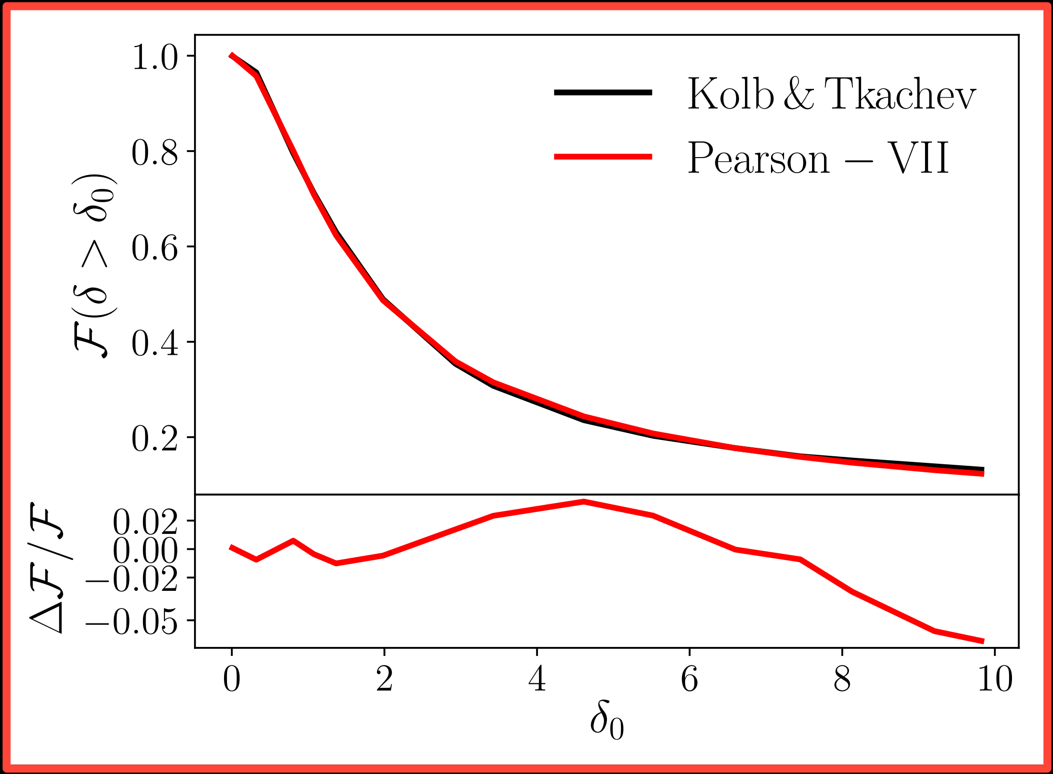


Self-similar infall → power law density profile for isolated objects.
Mergers + environment → NFW density profile.

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:



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

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

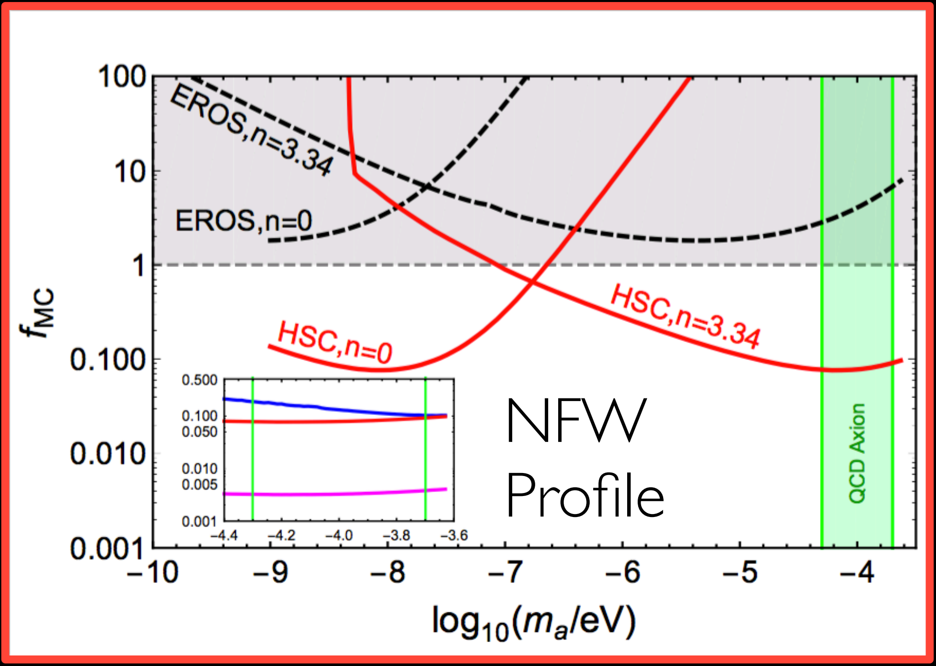
Tisserand et al (2007)
Niikura et al (2017)
Fairbairn, DJEM et al (2017)

Constraints: EROS and HSC

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!

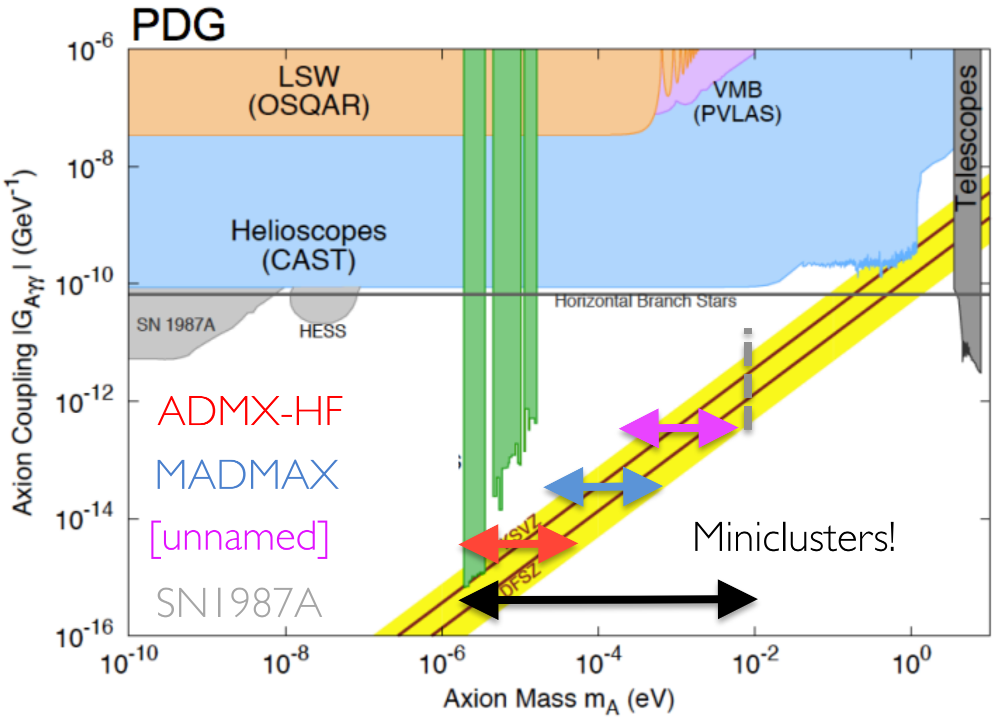


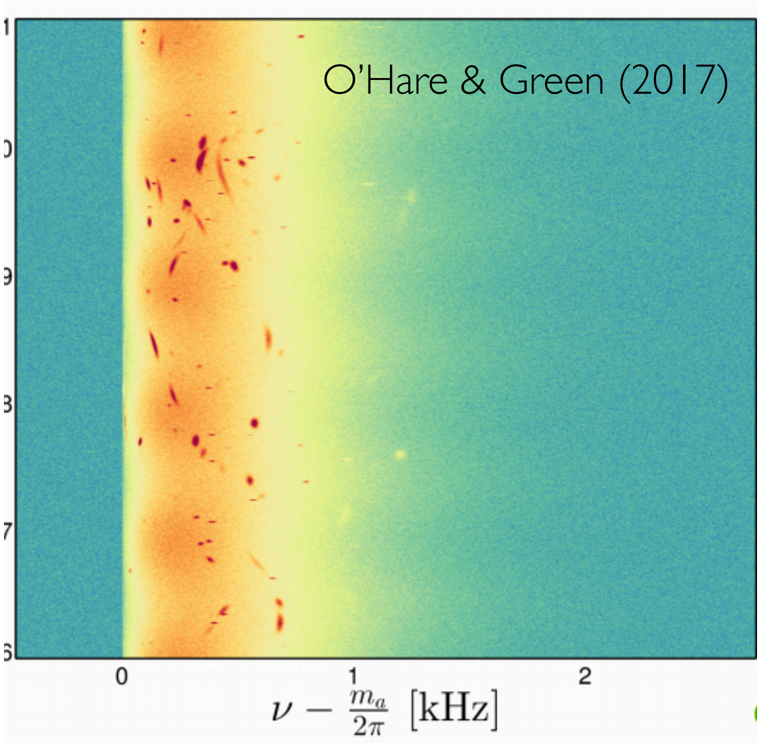
$$f_{\rm MC} < 0.083(m_a/100\mu{\rm eV})^{0.12}$$

Lots of assumptions in this number: improved modeling needed.

Miniclusters & Axion Astronomy

Many new high frequency (>GHz) axion experiments are being built.

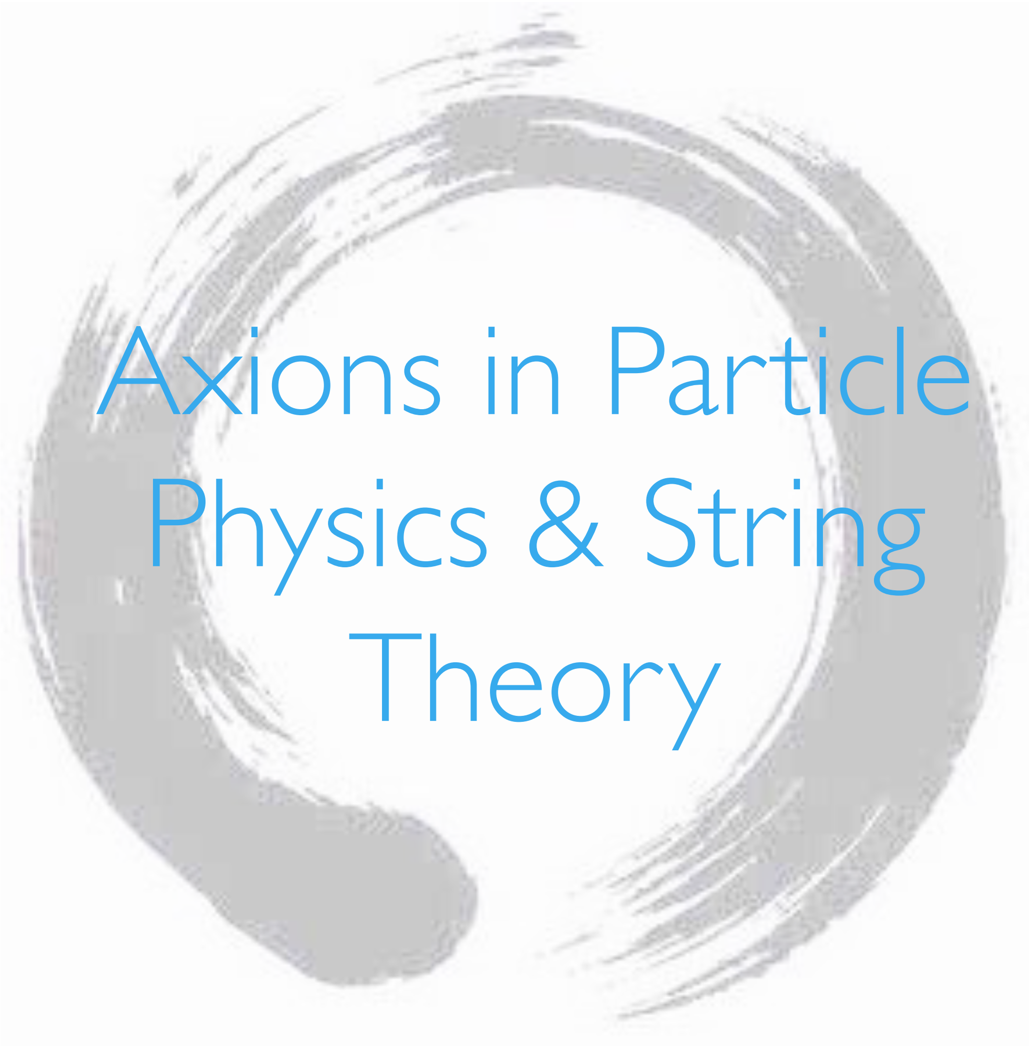



O'Hare & Green (2017)

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.!



Axions in Particle Physics & String Theory

Fine tuning in theoretical Physics

$$\mathcal{L} = (\text{number}) \times (\text{operator})$$

=the value you measure for the effect.

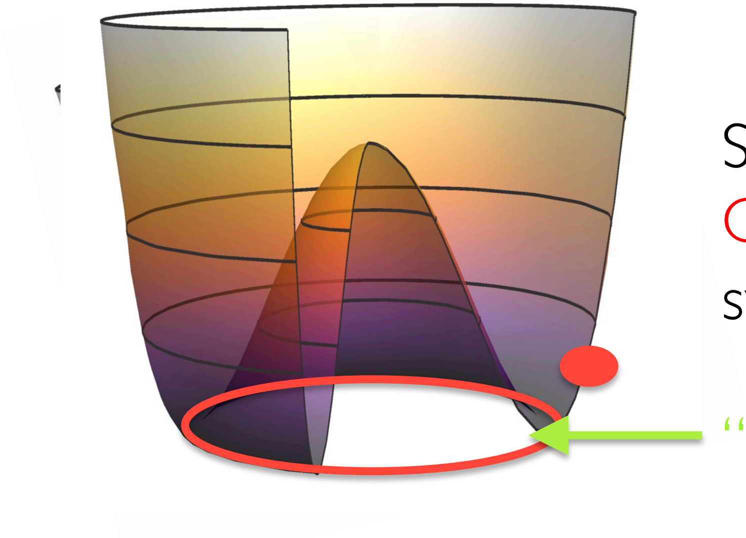
=physical effect. The neutron EDM.

$$(\text{number}) = \sum_{(\text{physics})} c_i \longrightarrow$$

Contributions from different sources. Strong and weak nuclear forces.

The nEDM is measured consistent with zero. This implies a delicate cancellation at $\sim 10^{-10}$. We don't like coincidences.

Cleaning up the mess



Spontaneous symmetry breaking: a Goldstone Boson, θ, has a continuous "shift symmetry", i.e. the underlying rotation.

"instantons"

Trick: couple a Goldstone to the problematic operator.

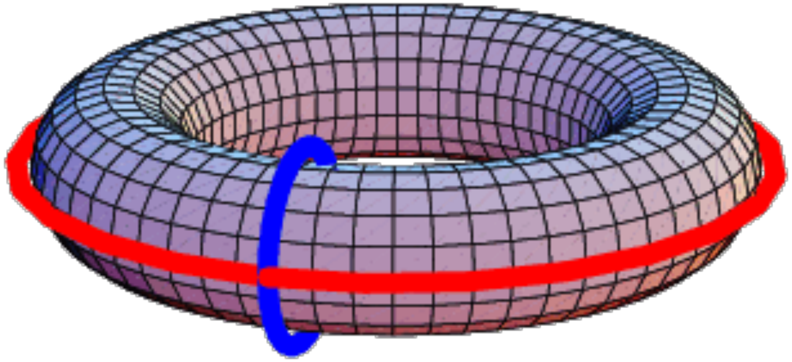
$$(\text{number}) \to (\text{number}) + \theta \to \theta$$

Now "tilt the wine bottle": θ will now dynamically move to a fixed value = 0 by symmetry → no problematic nEDM.

BONUS: the oscillations of θ carry energy density → DM!
BUT: axions are some 10^{15} times lighter than "WIMPs"!

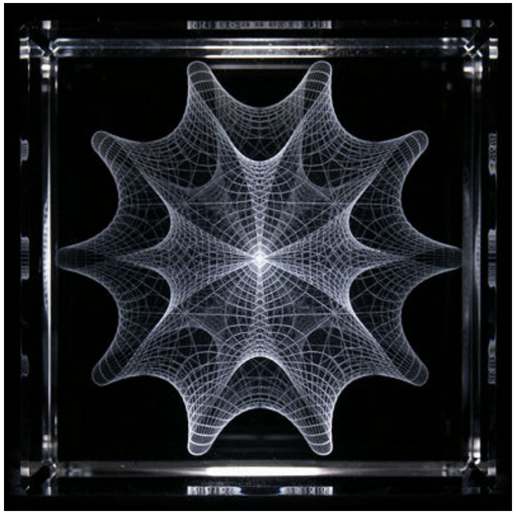
Kaluza-Klein and String Theory

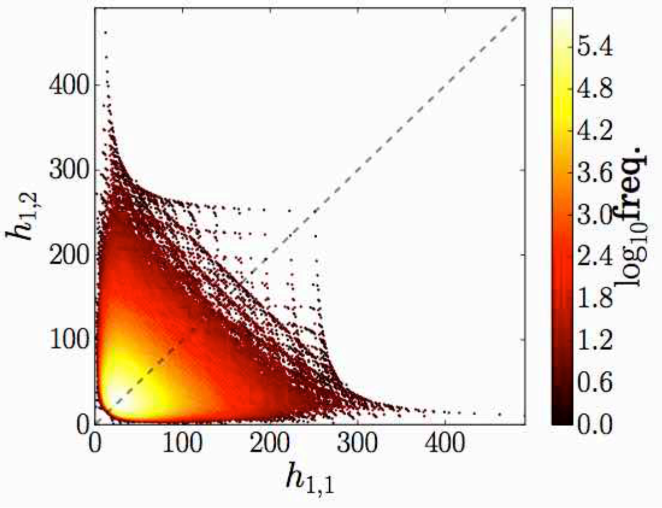
GR: fields describe the geometry of space. Cosmology: the scale factor.



A torus has two "moduli" that describe its shape.
In general, # of fields given by topology.

String theory → SUSY → moduli are "paired" with AXIONS.
10 dimensions can be a lot more complicated than a donut.





Extra dimensions and SUSY can both "hide" at high energies near the Planck scale. Many "flavours" of axions a generic, low-energy, prediction.