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Axion Miniclusters: Stellar disruption and Radioastronomy

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The landscape of QCD axion models

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Abstract

We review the landscape of QCD axion models. Theoretical constructions that extend the window for the axion mass and couplings beyond conventional regions are highlighted and classified. Bounds from cosmology, astrophysics and experimental searches are reexamined and updated.

OUTLINE

1. The QCD axion as a DM candidate

2. Stellar disruption of axion miniclusters

3. Radioastronomy with axion miniclusters

Cosmic WISPers in the dark universe

Theory: Weakly Interacting Scalar Particles (WISPs) might arise as pseudo-scalar particles related to extensions of the Standard Model in quantum gravity (like string theory)

Lagrangian:

$$\mathcal{L} = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}|\nabla\phi|^2 - V(\phi)$$

Dark Matter: WISPs are produced in the early universe through phase transitions and pile up to the dark matter budget

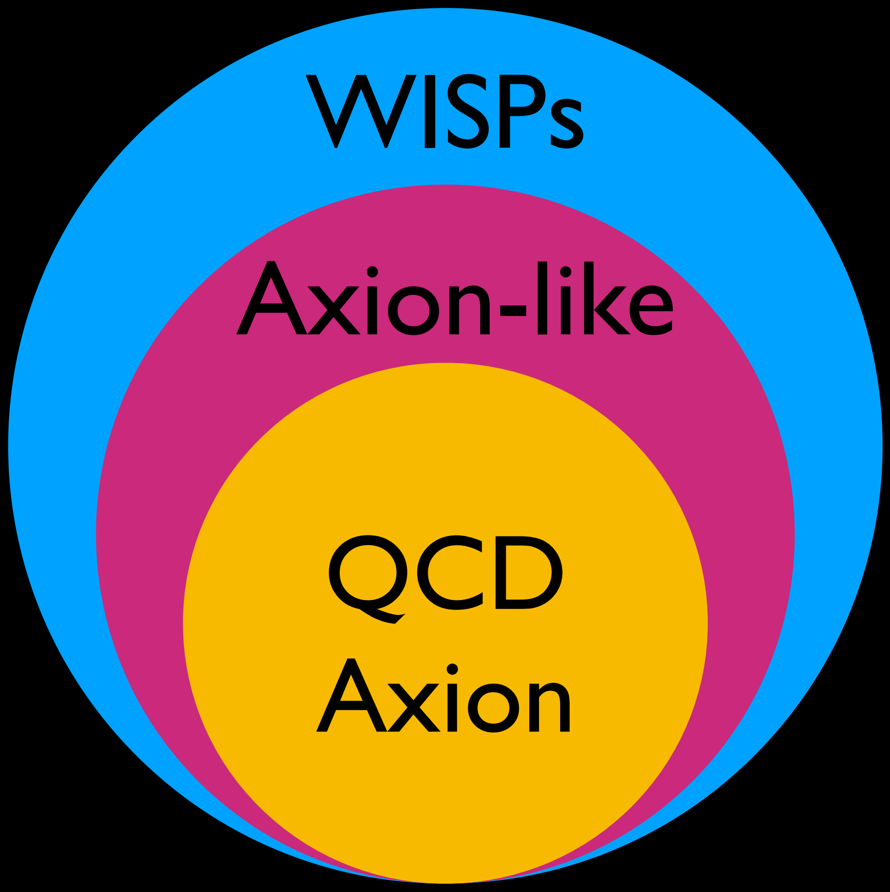
Energy density:

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \propto 1/R^3$$

Phenomenology: Vast array of other physics processes (stellar cooling, Bose condensation, spectral distortion in the CMB, …)

Interactions:

$$\mathcal{L}_{\phi\,\mathrm{SM}} \supset g_{\phi\gamma\gamma}\,\phi\tilde{F}F + g_{\phi\psi\psi}\,\phi\,\bar{\psi}\gamma^5\psi$$



Axions?

The axion is the archetype of the WISP

Strong force coupling

$$\mathcal{L}_{\rm QCD} \supset \bar{\theta}\frac{\alpha_s}{8\pi} G^{\mu\nu}\tilde{G}_{\mu\nu}$$

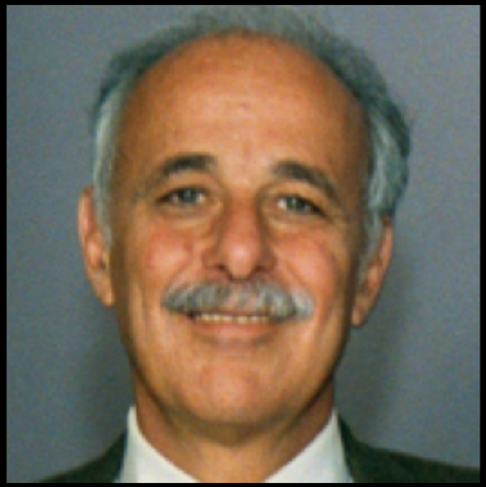
EM counterparts of gluon field

The value of $\bar{\theta}$ controls the matter-antimatter asymmetry in QCD

A similar term arises from EW, $\theta = \bar{\theta} + \theta_{\rm weak} \sim \mathcal{O}(1)$

No observation of C and CP violation in Nature, $|\theta| \lesssim 10^{-10}$

The QCD 



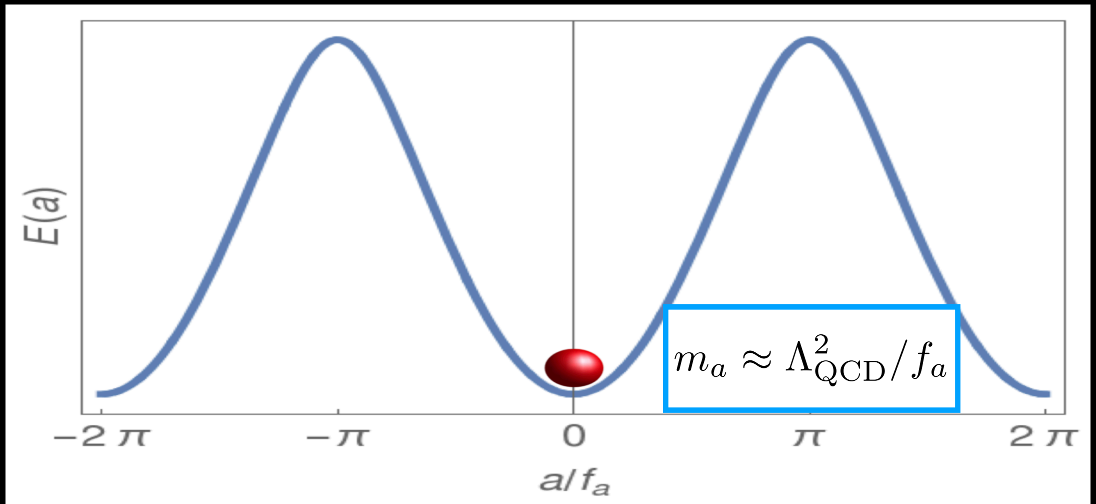
Roberto Peccei

Helen Quinn

Steven Weinberg

Frank Wilczek

Promote $\theta \to \theta(x)$ to a field, which rolls to zero dynamically



The theory can be quantised, leading to a new particle: <u>the axion</u>

$$\mathcal{L} \supset \frac{a}{f_a}\frac{\alpha_s}{8\pi} G^{\mu\nu}\tilde{G}_{\mu\nu}$$

Axion energy scale

Vacuum realignment mechanism

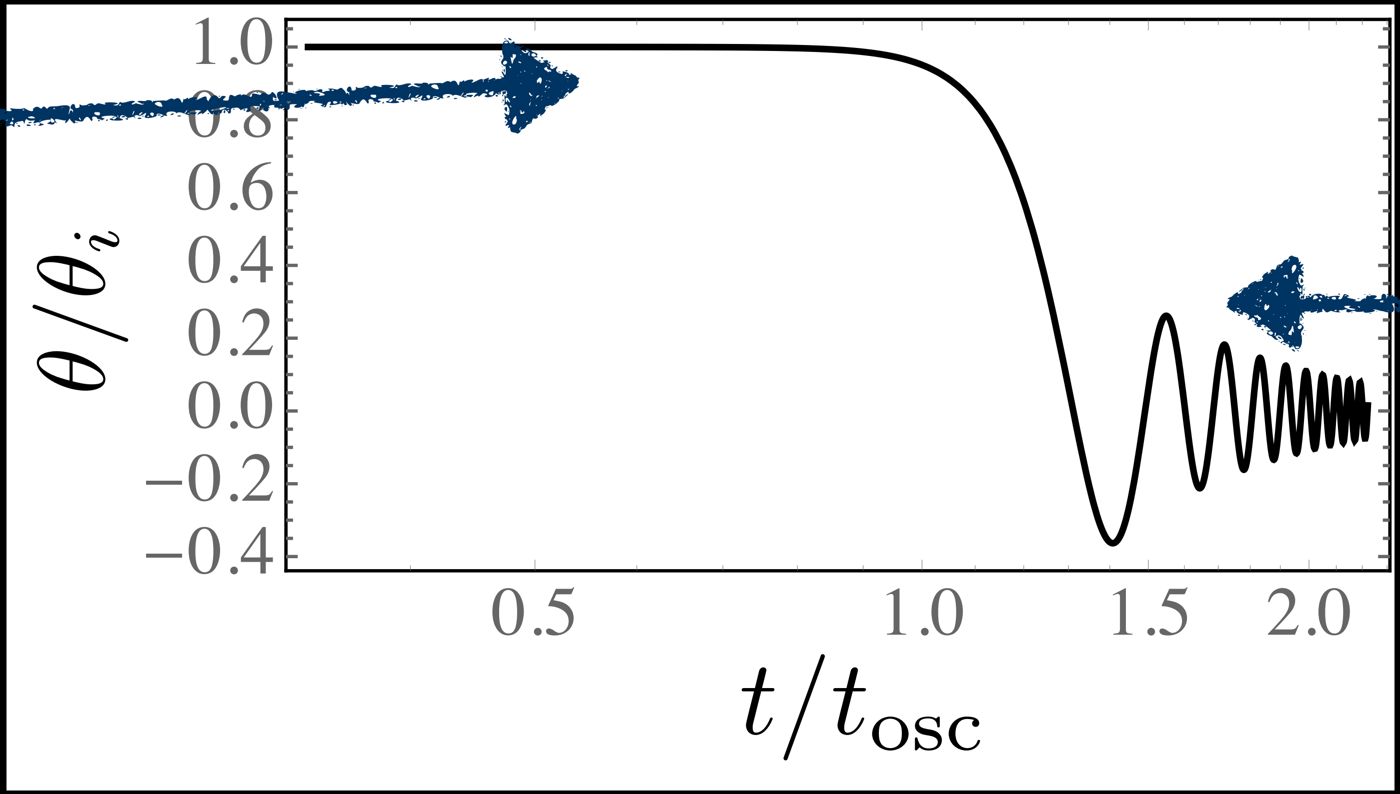
Equation of motion: $\ddot{\theta} + 3H\dot{\theta} + m_a^2 \sin\theta = 0$

(for super-horizon modes $|\nabla\theta| \approx 0$)

Behaves as dark energy

$\ddot{\theta} + 3H\dot{\theta} \approx 0$

$\rho \approx \text{const.}$



Behaves as dark matter

$\rho \propto R^{-3}$

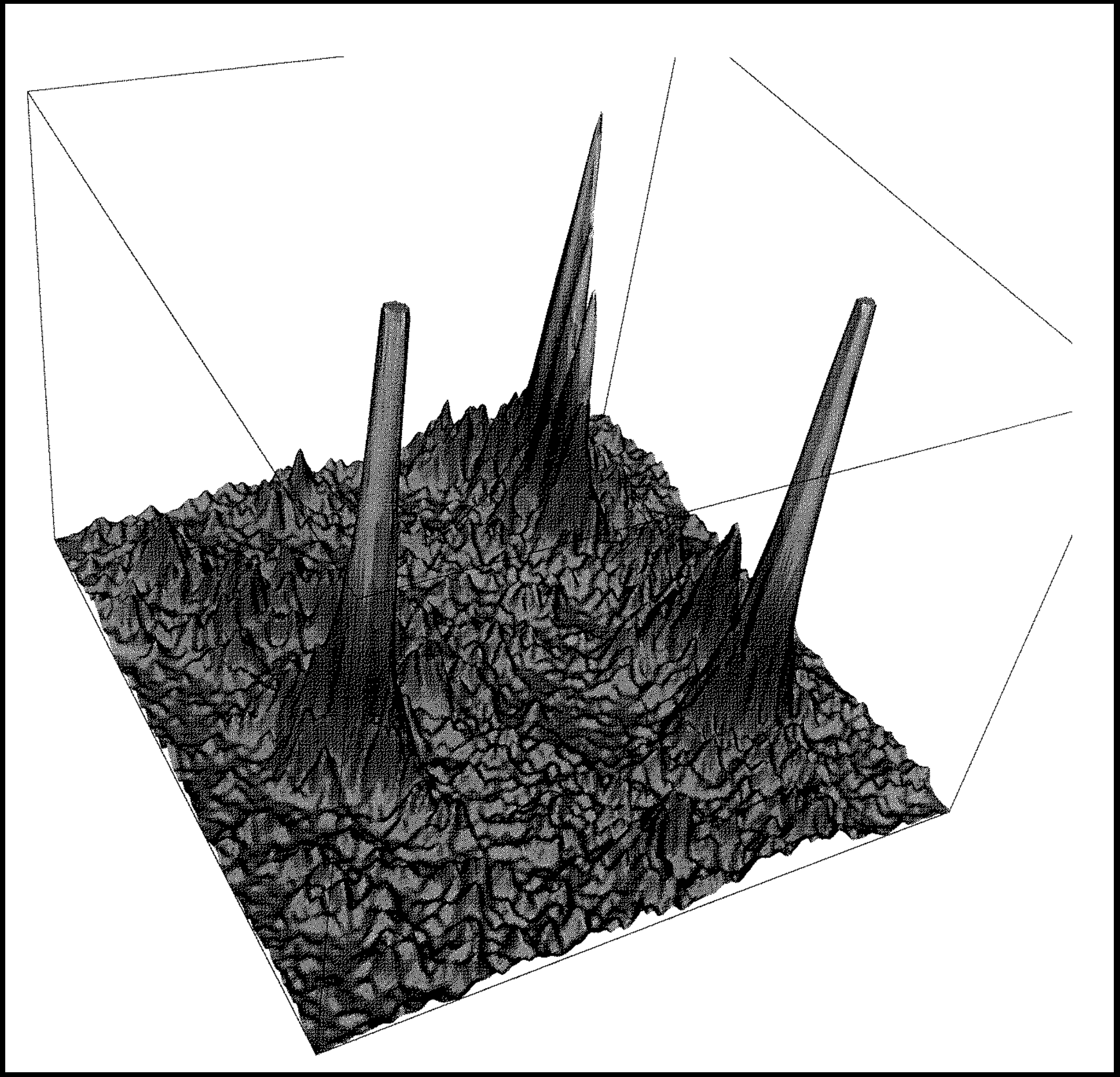
The transition is regulated by $3H(t_{\rm osc}) \approx m_a$

Compact objects

Large inhomogeneities in the axion field lead to gravity-bound objects
Axion "miniclusters" [Hogan&Rees1988; Kolb&Tkachev 1993,1994]

Distribution of axion energy density
2D slice of comoving length 0.25 pc
[Kolb&Tkachev96]

$$T_{\rm collapse} \approx \frac{\delta\rho}{\rho} T_{\rm eq}$$

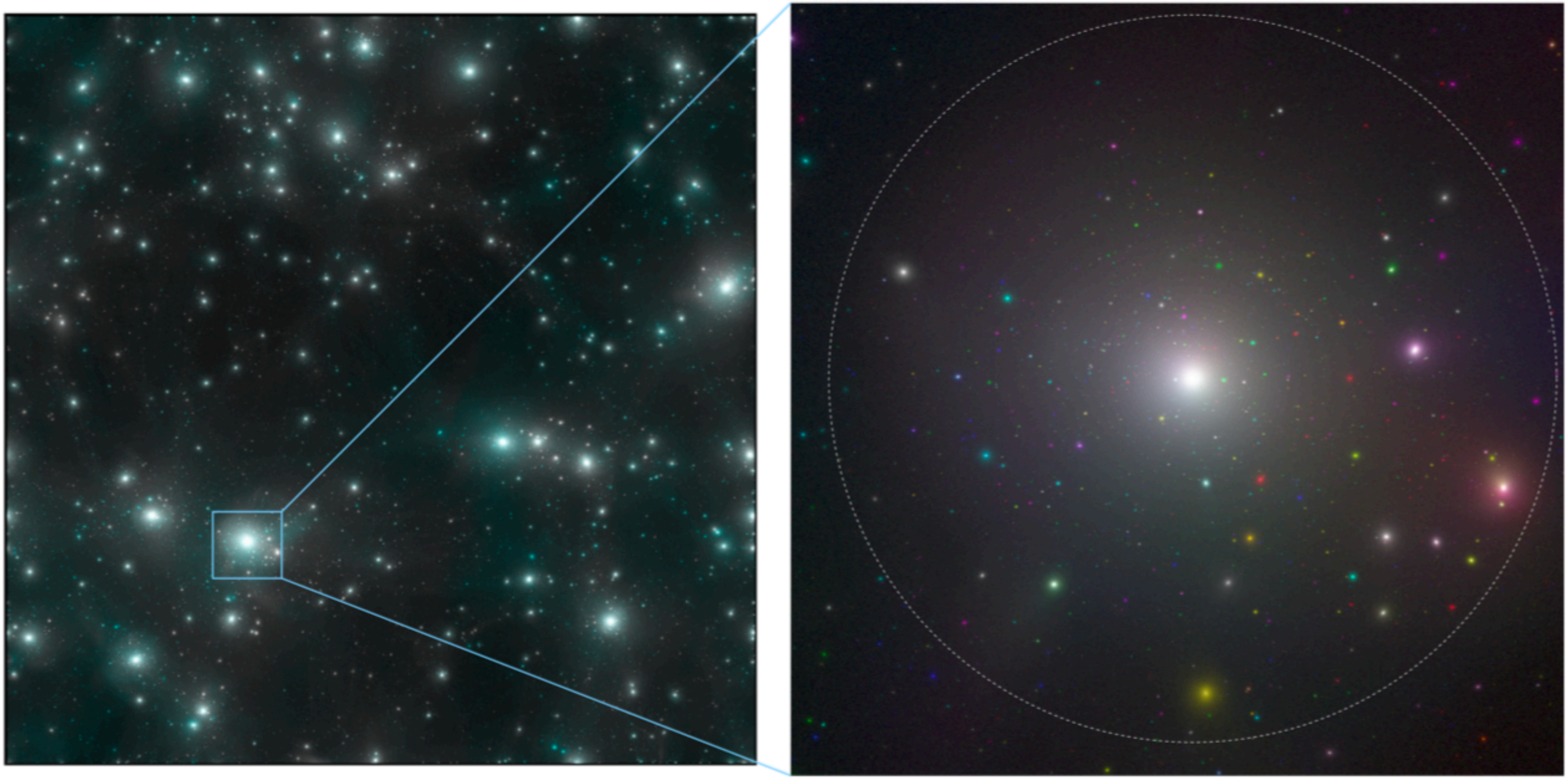


Typical mass $\sim 10^{-11}\, M_\odot$

Typical radius $\sim 10^{12}\,{\rm cm}$

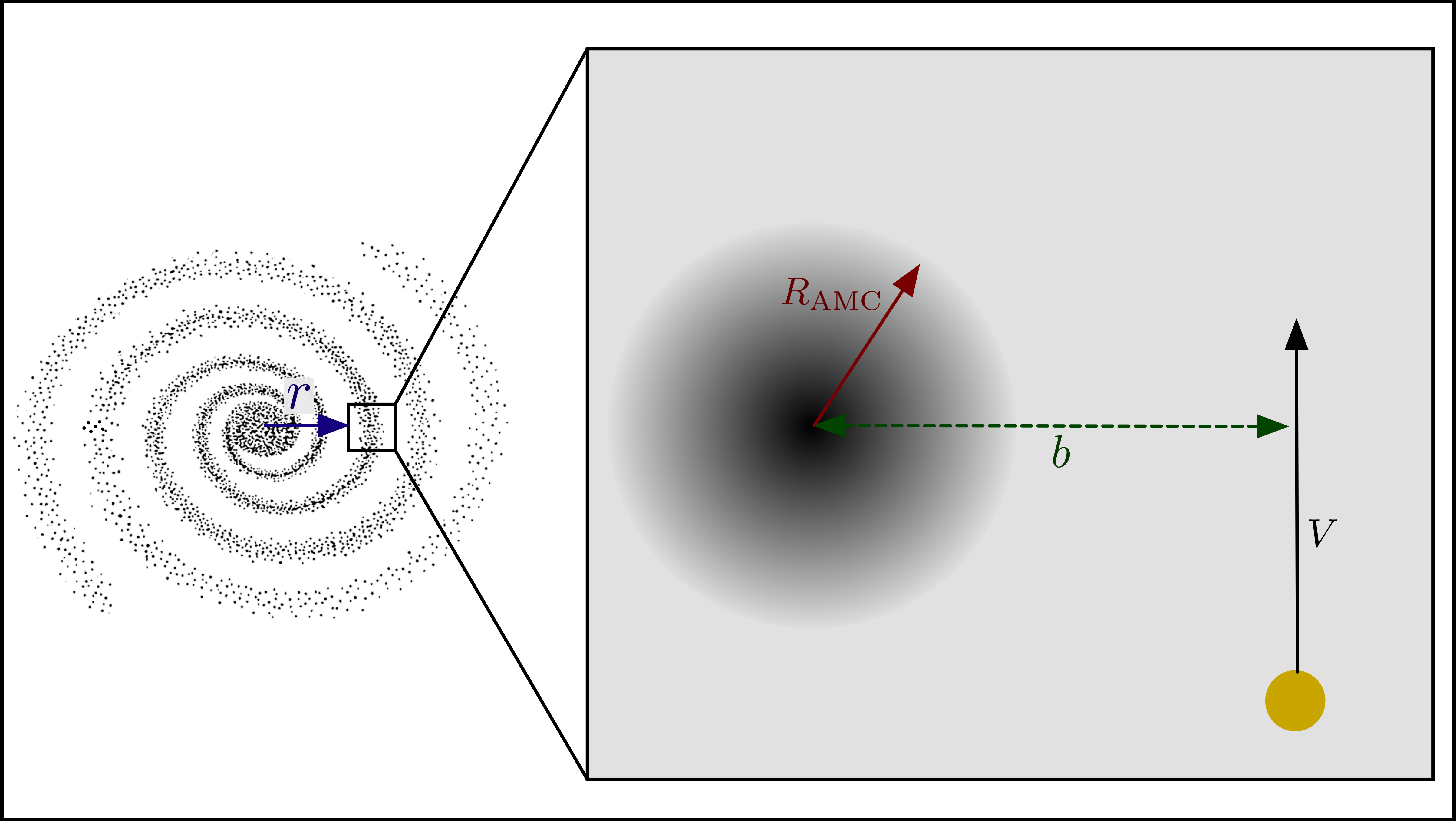
See e.g. **LV** & Redondo
1808.01879

N-body simulation



Eggemeier+ 1911.09417

Survival of axion miniclusters

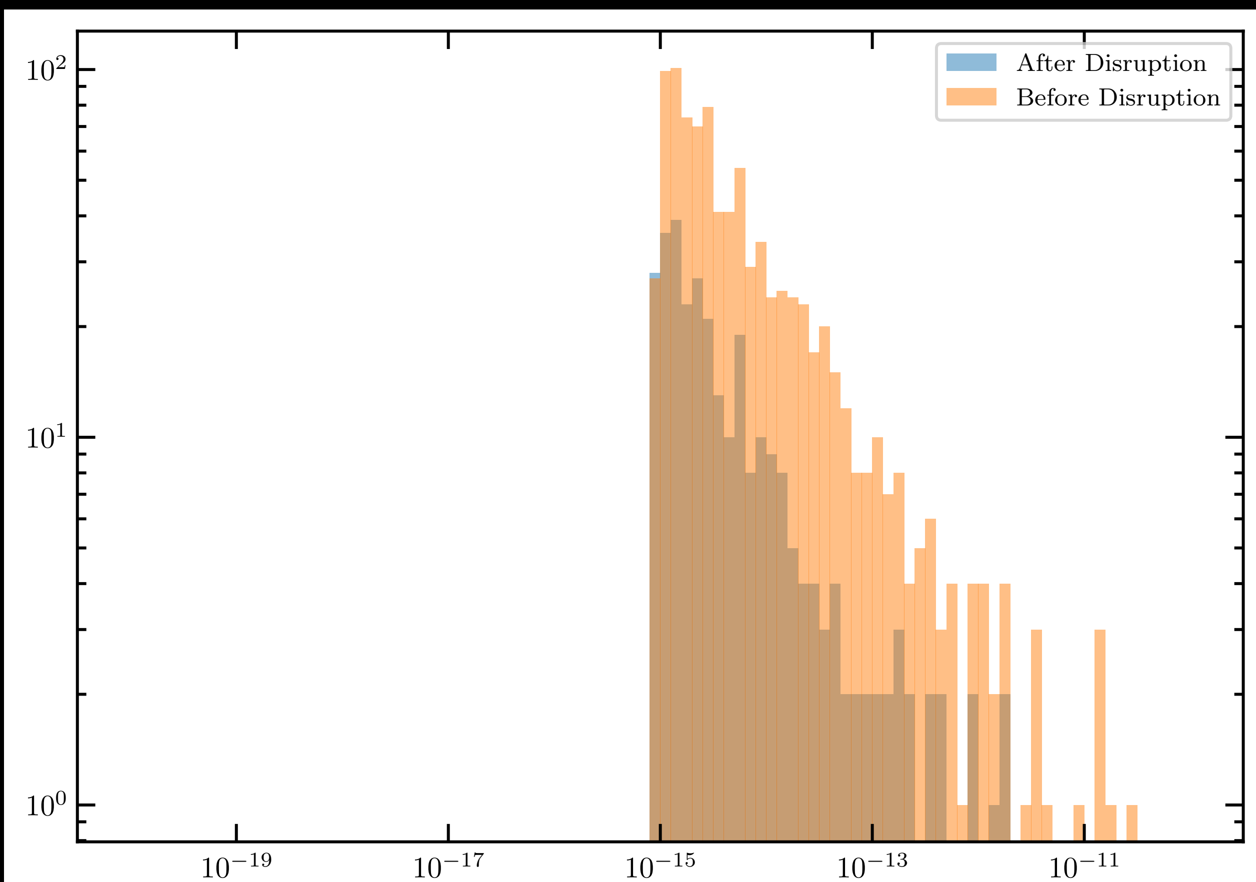


Survival of axion miniclusters

Axion miniclusters are disrupted by the encounter with stars

Initial halo mass function from N-body simulation

$$\frac{dn}{d\ln M} \propto M^{-0.7}$$



LV+, in preparation

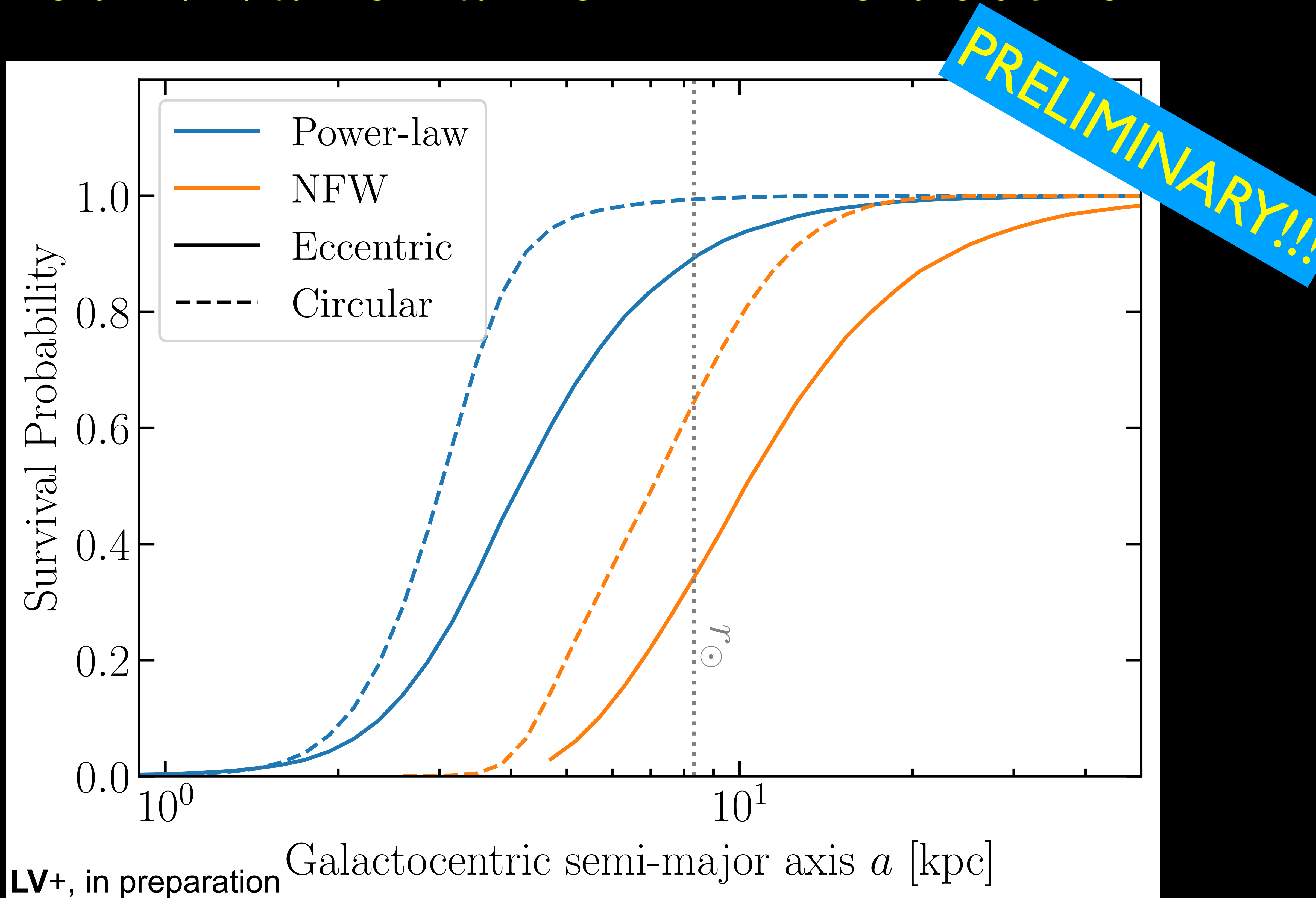
With:

Thomas Edwards

Bradley Kavanagh

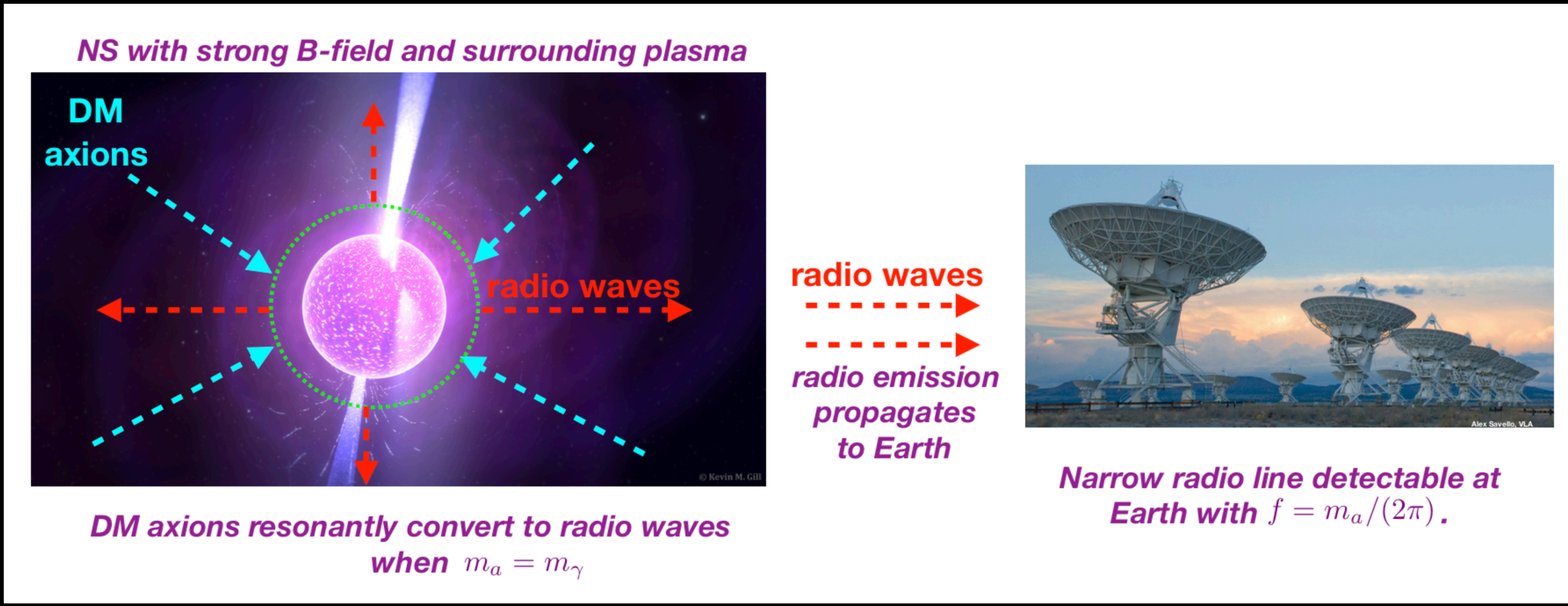
Christoph Weniger

Survival of axion miniclusters



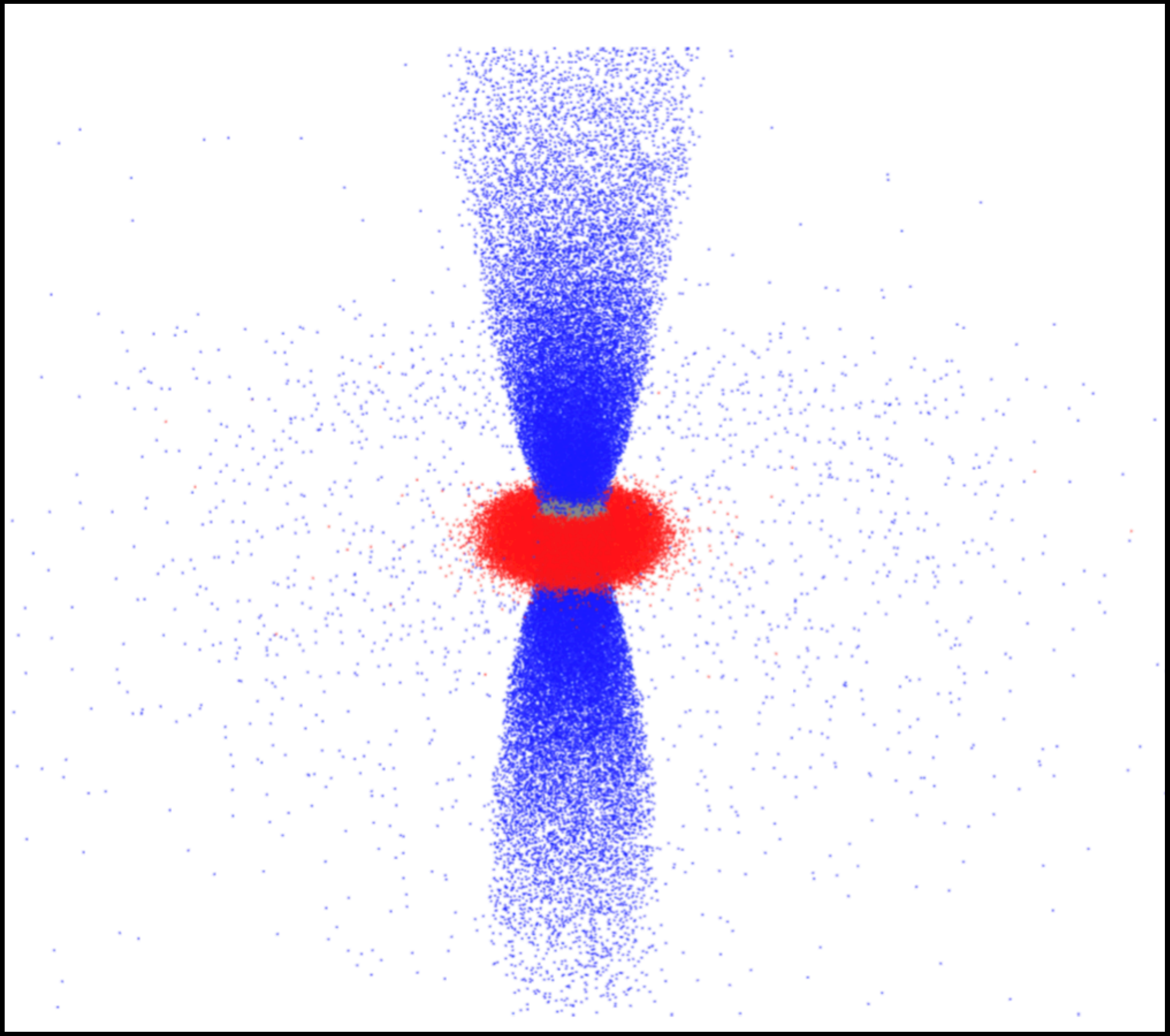
Future projects: Axion radioastronomy

Neutron stars “eat up” dark matter overdensities



Courtesy of Ben Safdi (Michigan)

Axion radio-interferometry



Courtesy of Ben Safdi

$$B(\theta) = \frac{B_0}{2}\left(3\cos^2\theta + 1\right)^{1/2}$$

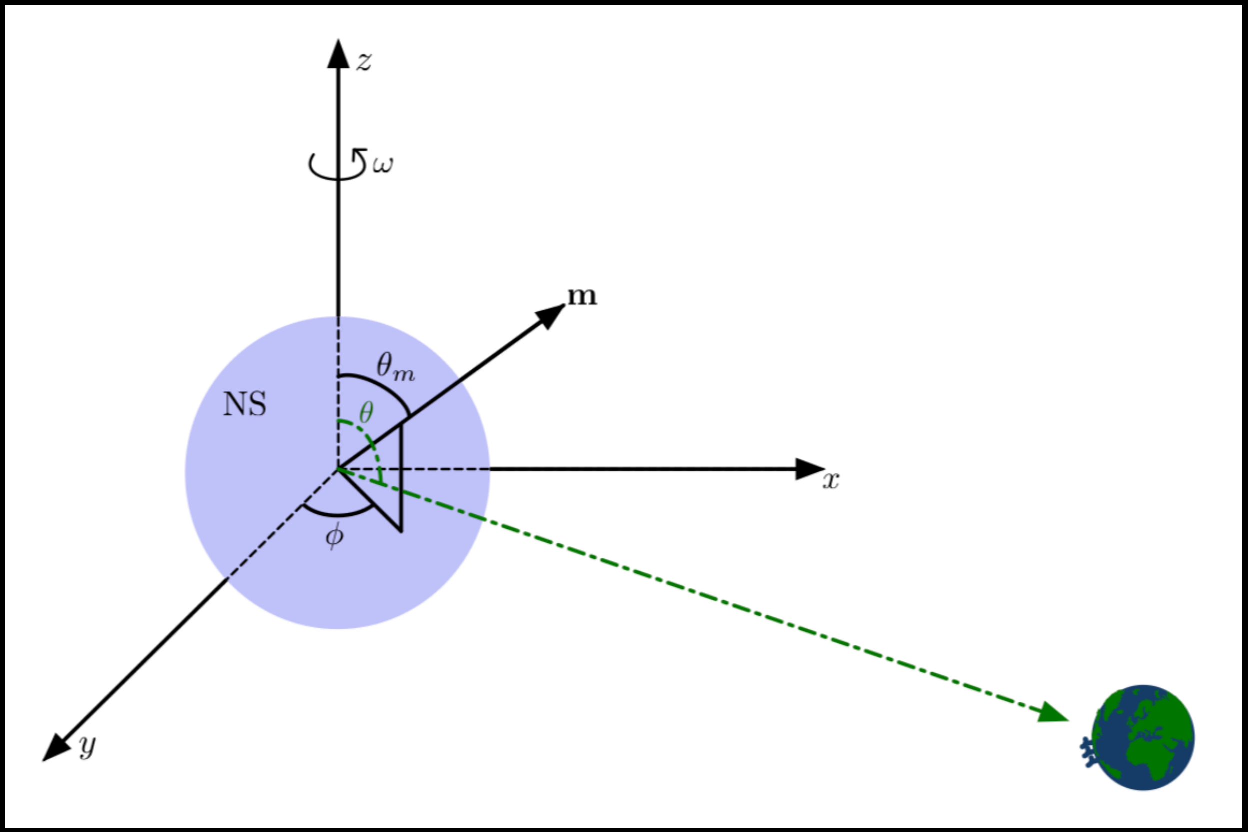
Goldreich–Julian Relation

$$n_c = \frac{2\mathbf{\Omega}\cdot\mathbf{B}}{e} + \text{(relativistic corrections)}$$

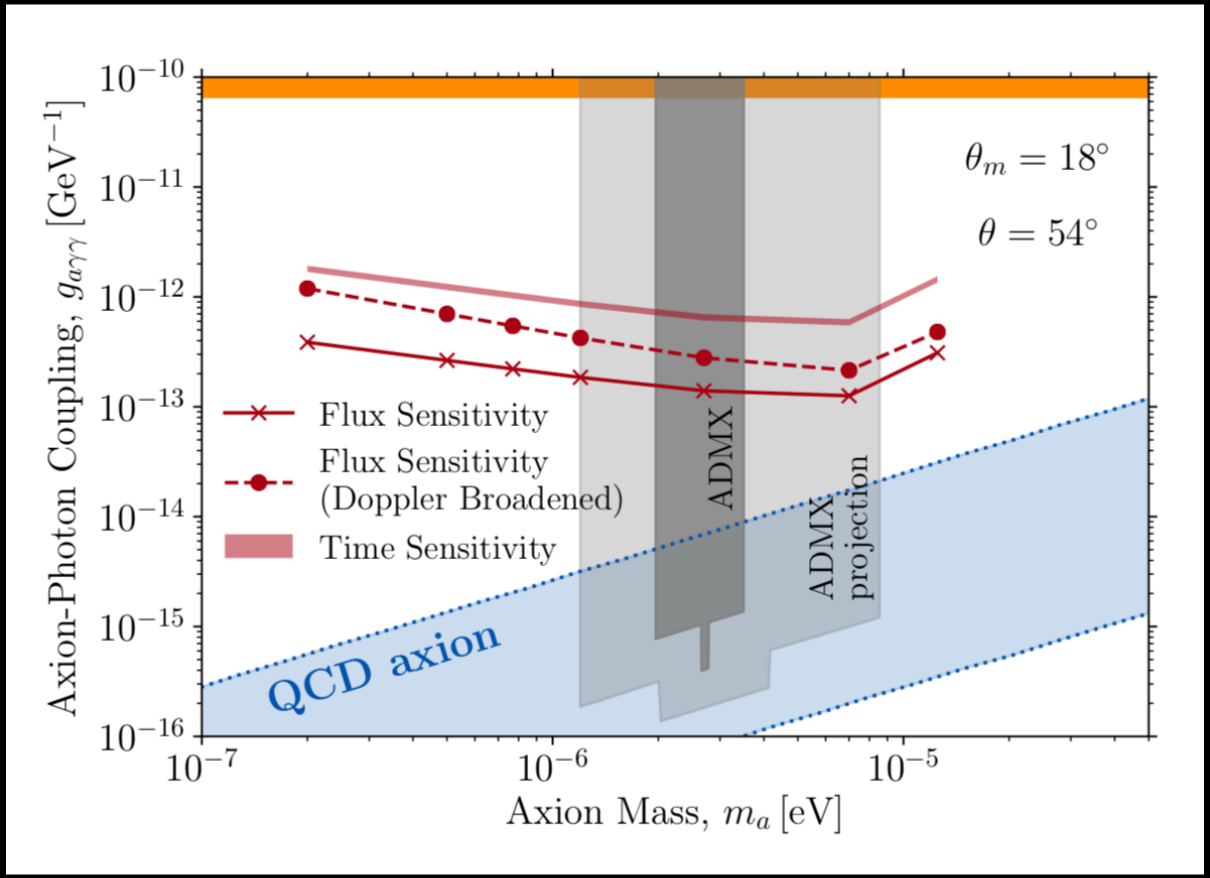
axion-photon conversion is possible for

$$\omega_p(B) \approx m_a$$

Axion radio-interferometry



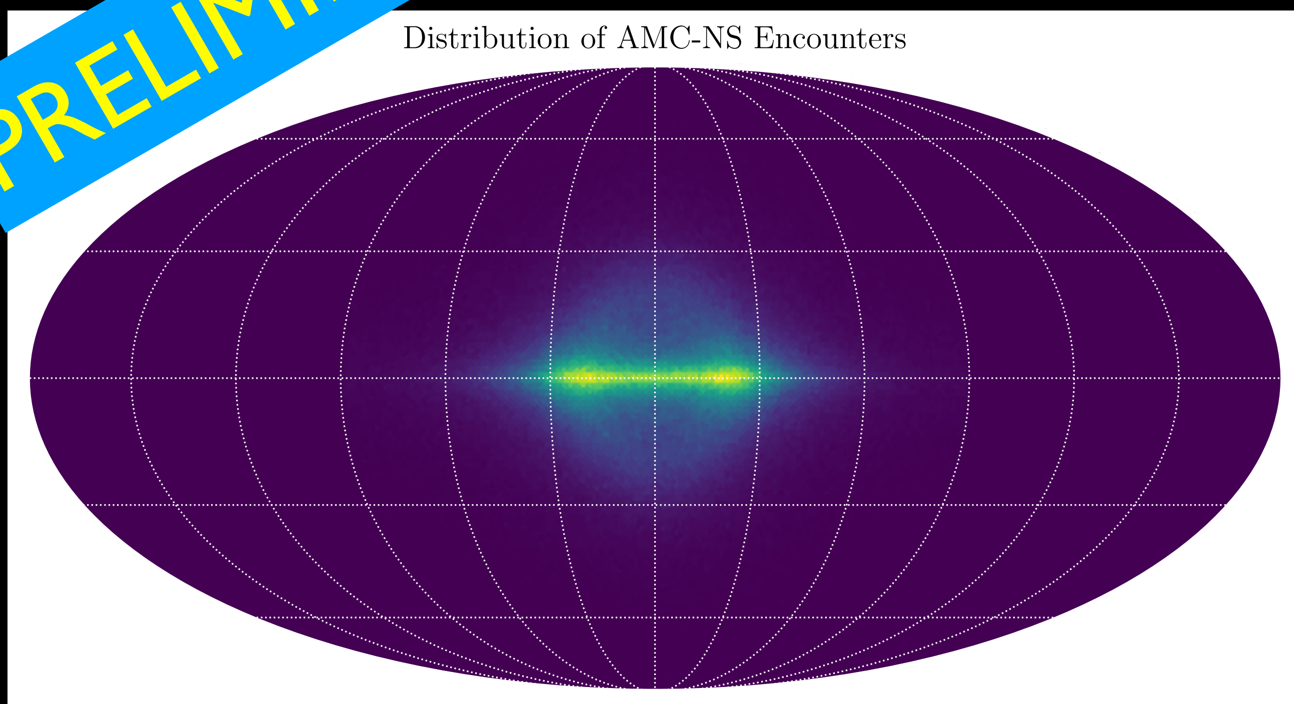
Leroy+1912.08815

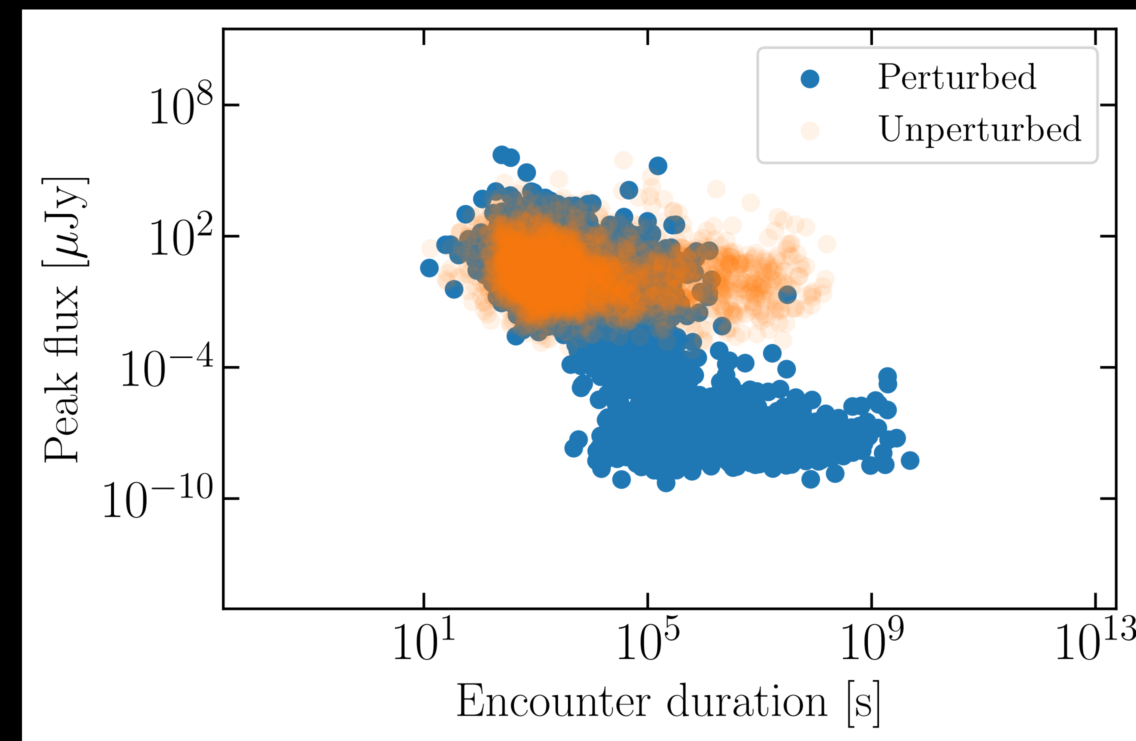


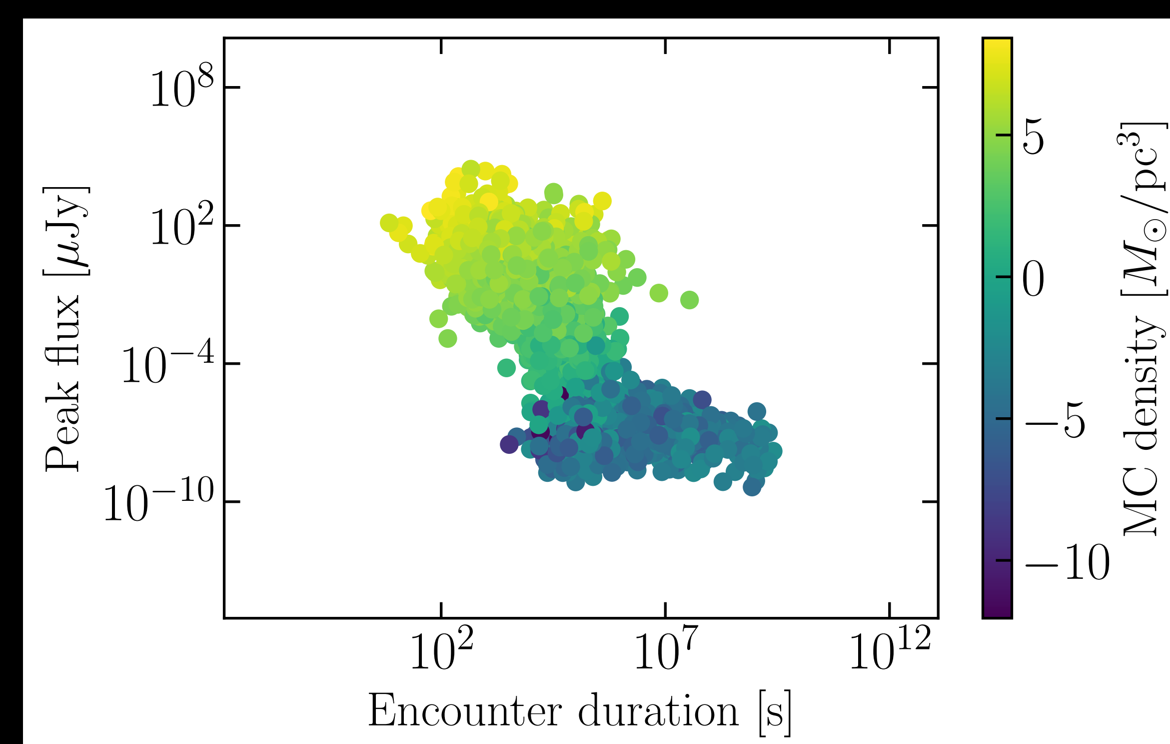
Leroy+1912.08815

Radioastronomy Axion Miniclusters

PRELIMINARY!!!







LV+, in preparation

$m_a \sim 25\,\mu\mathrm{eV}$ or $\nu = \dfrac{m_a}{2\pi} \sim 6\,\mathrm{GHz}$

Conclusions

- It is an exciting period to work on dark matter compact objects!

- Details require much further efforts. Work in progress...

- Axion Miniclusters and axion stars are laboratories for physics beyond the Standard Model!

Thank you all for the attention!