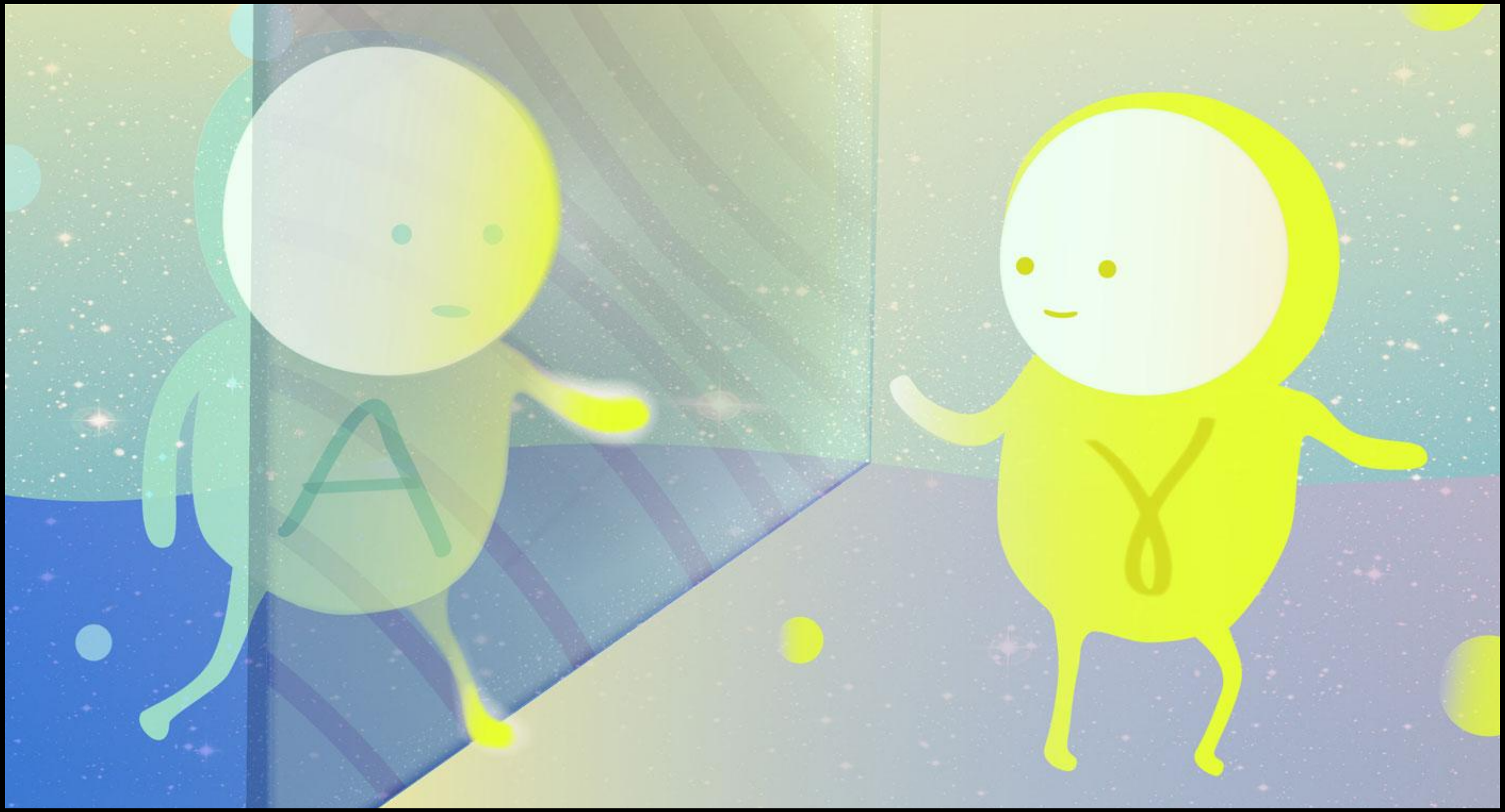
Probing the Early Universe with Axion Physics



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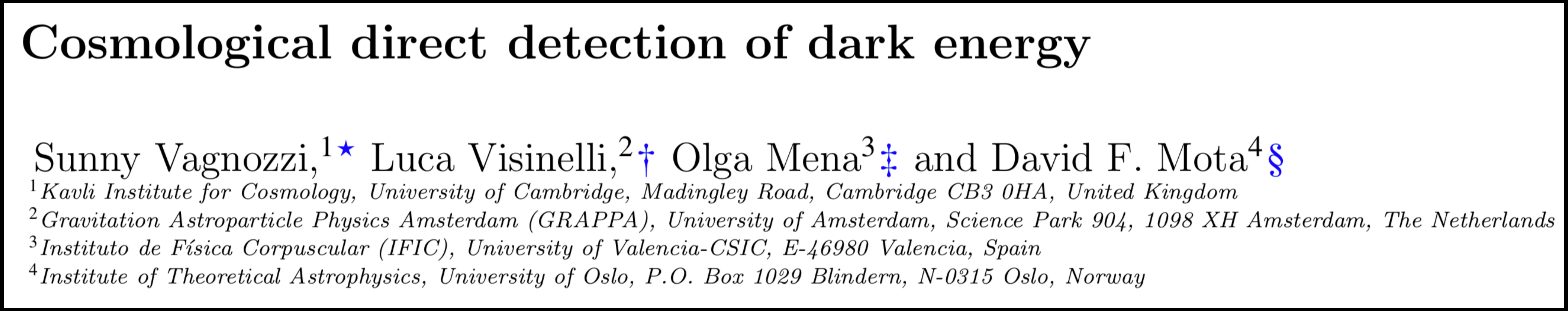
NEW PAPER OUT!!!



Cosmological direct detection of dark energy

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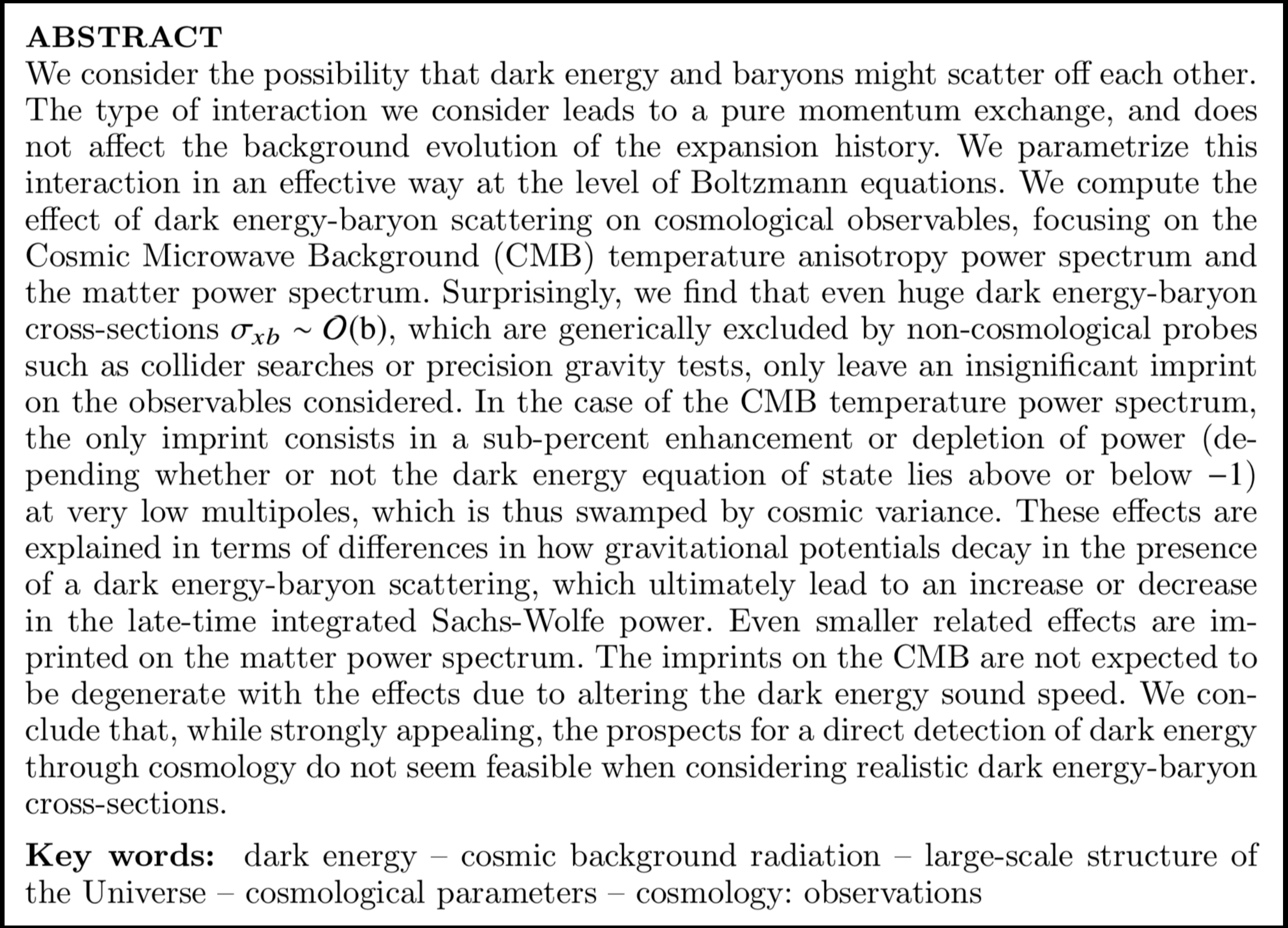
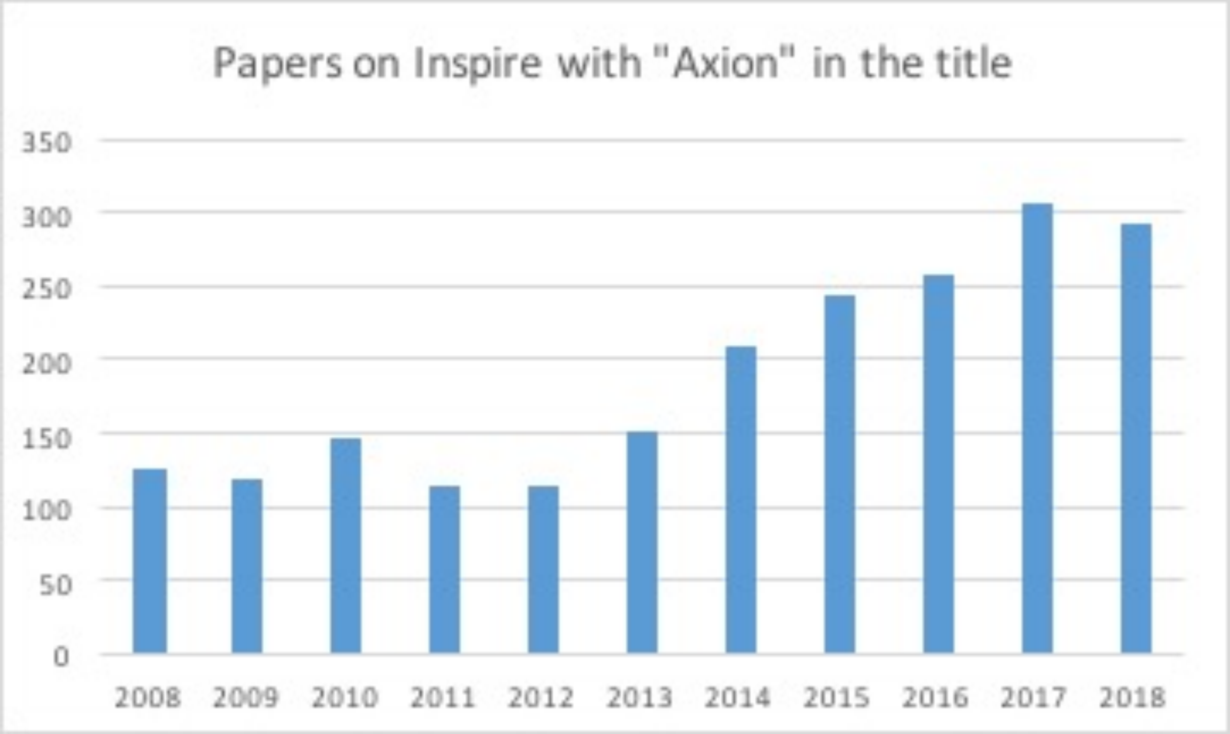


ABSTRACT

We consider the possibility that dark energy and baryons might scatter off each other. The type of interaction we consider leads to a pure momentum exchange, and does not affect the background evolution of the expansion history. We parametrize this interaction in an effective way at the level of Boltzmann equations. We compute the effect of dark energy-baryon scattering on cosmological observables, focusing on the Cosmic Microwave Background (CMB) temperature anisotropy power spectrum and the matter power spectrum. Surprisingly, we find that even huge dark energy-baryon cross-sections $\sigma_{xb} \sim \mathcal{O}$(b), which are generically excluded by non-cosmological probes such as collider searches or precision gravity tests, only leave an insignificant imprint on the observables considered. In the case of the CMB temperature power spectrum, the only imprint consists in a sub-percent enhancement or depletion of power (depending whether or not the dark energy equation of state lies above or below -1) at very low multipoles, which is thus swamped by cosmic variance. These effects are explained in terms of differences in how gravitational potentials decay in the presence of a dark energy-baryon scattering, which ultimately lead to an increase or decrease in the late-time integrated Sachs-Wolfe power. Even smaller related effects are imprinted on the matter power spectrum. The imprints on the CMB are not expected to be degenerate with the effects due to altering the dark energy sound speed. We conclude that, while strongly appealing, the prospects for a direct detection of dark energy through cosmology do not seem feasible when considering realistic dark energy-baryon cross-sections.

Key words: dark energy – cosmic background radiation – large-scale structure of the Universe – cosmological parameters – cosmology: observations

Is the DM particle an axion?




PATRAS @ DESY 2009


PATRAS @ DESY 2018

Steady growth in the interest on the axion

Axion: Early-Universe dynamics

PQ Field $\Phi = \frac{1}{\sqrt{2}}(f_a + \rho_a)\exp\left(\frac{ia}{f_a}\right)$

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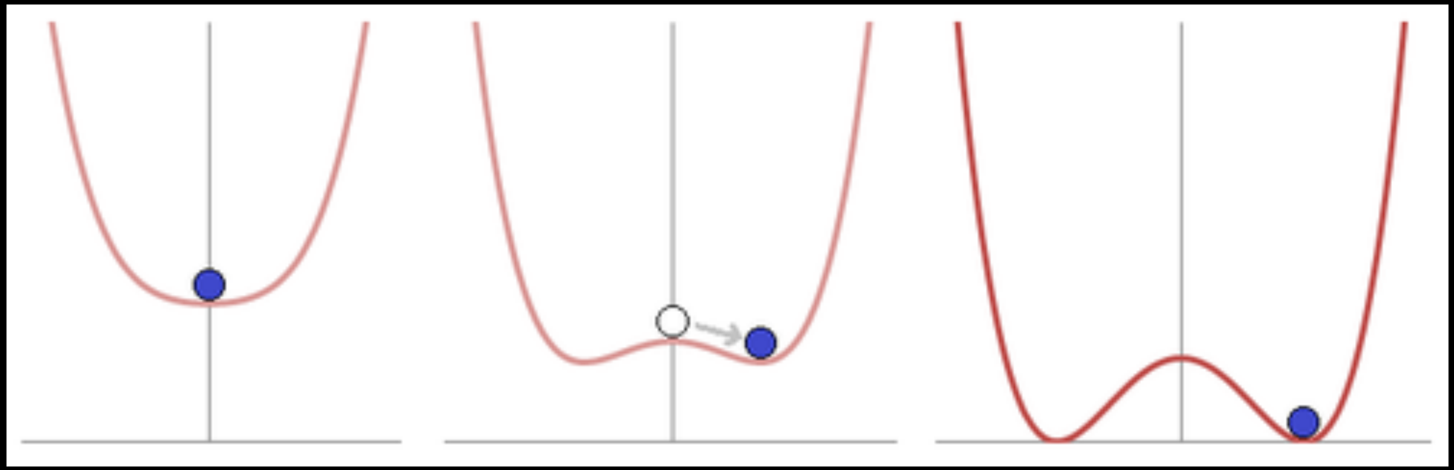

$$V(\Phi) = \lambda\left(|\Phi|^2 - \frac{f_a^2}{2}\right)^2$$

$T \gtrsim f_a$ $T \sim f_a$ $T \lesssim f_a$

Axion: Early-Universe dynamics

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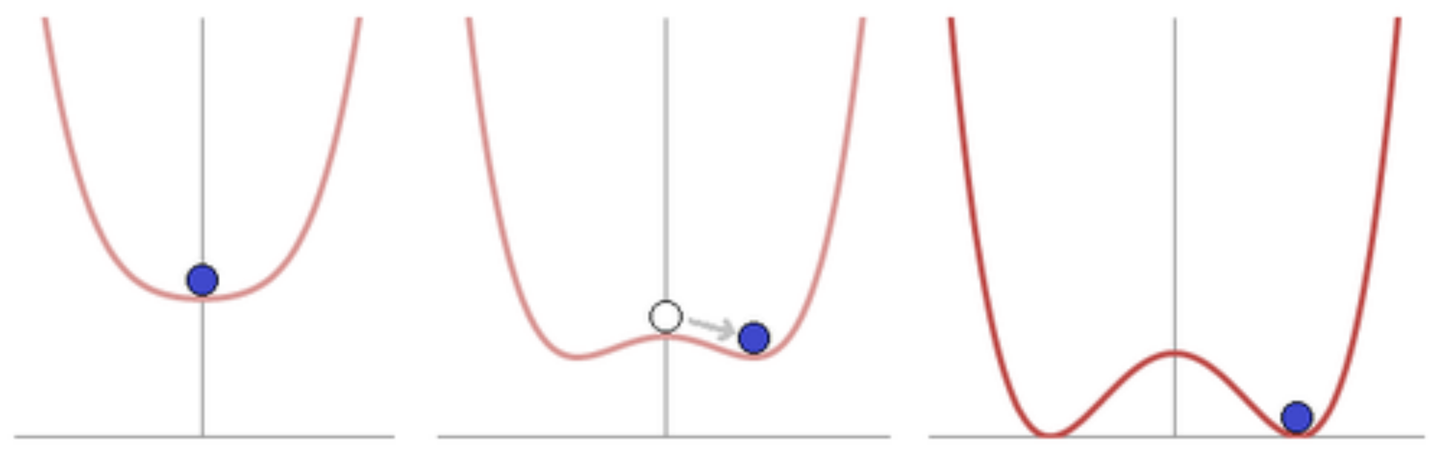

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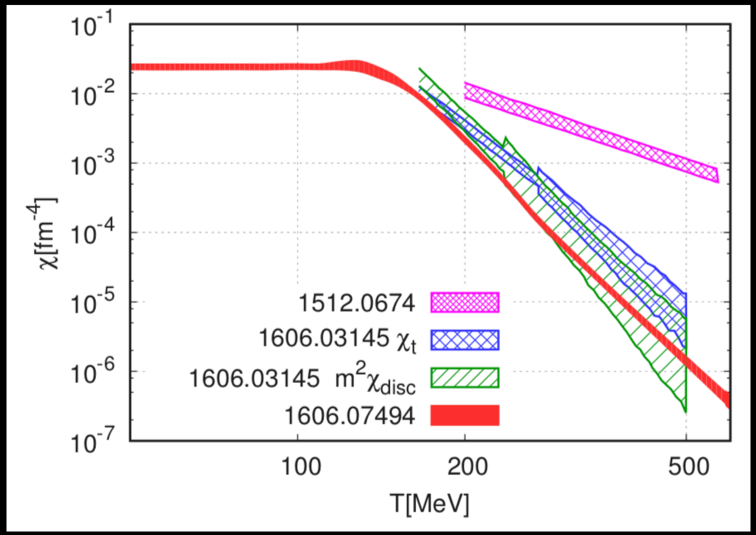
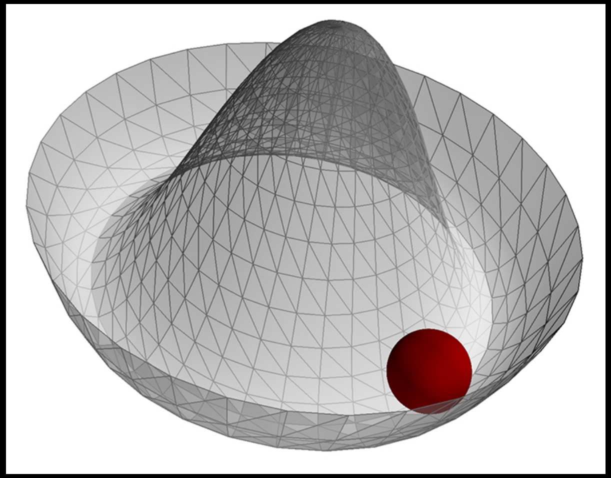
$T \gtrsim f_a$ $\quad$ $T \sim f_a$ $\quad$ $T \lesssim f_a$

Details on the temperature dependence still debated (semi-analytical, lattice simulations)

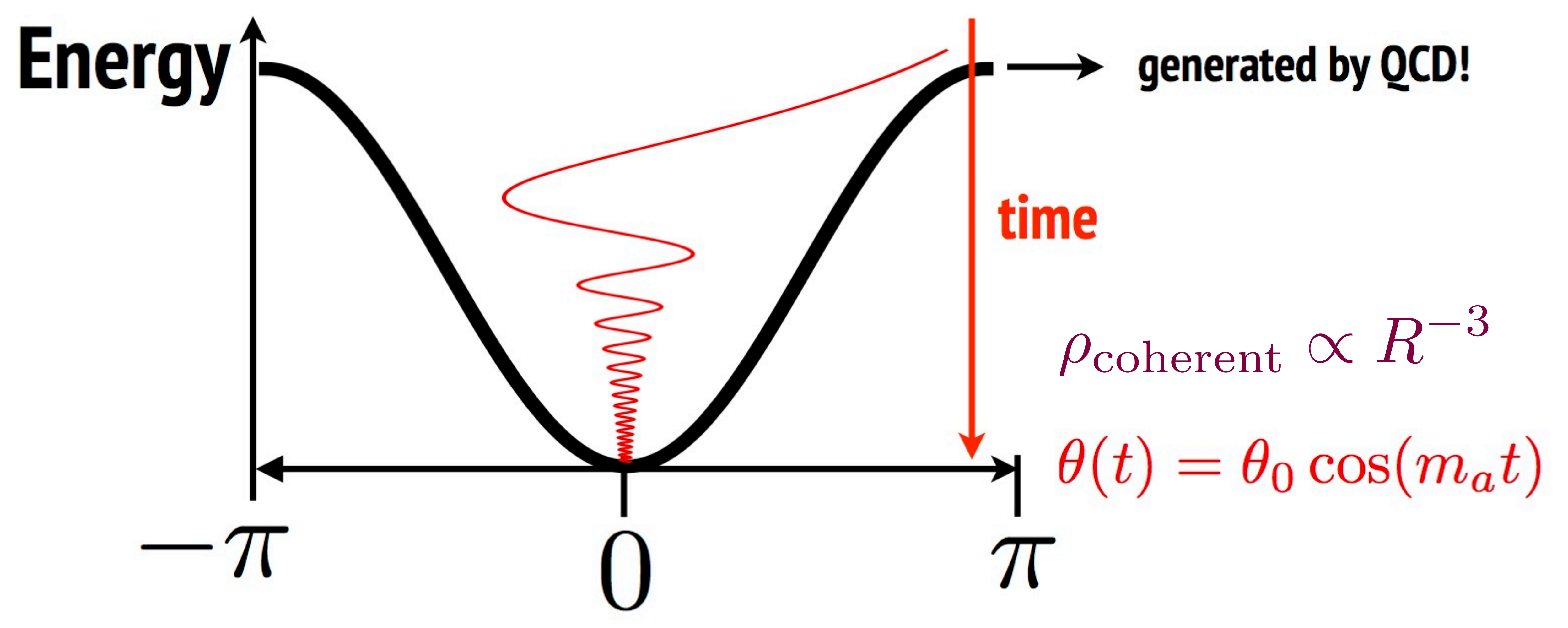




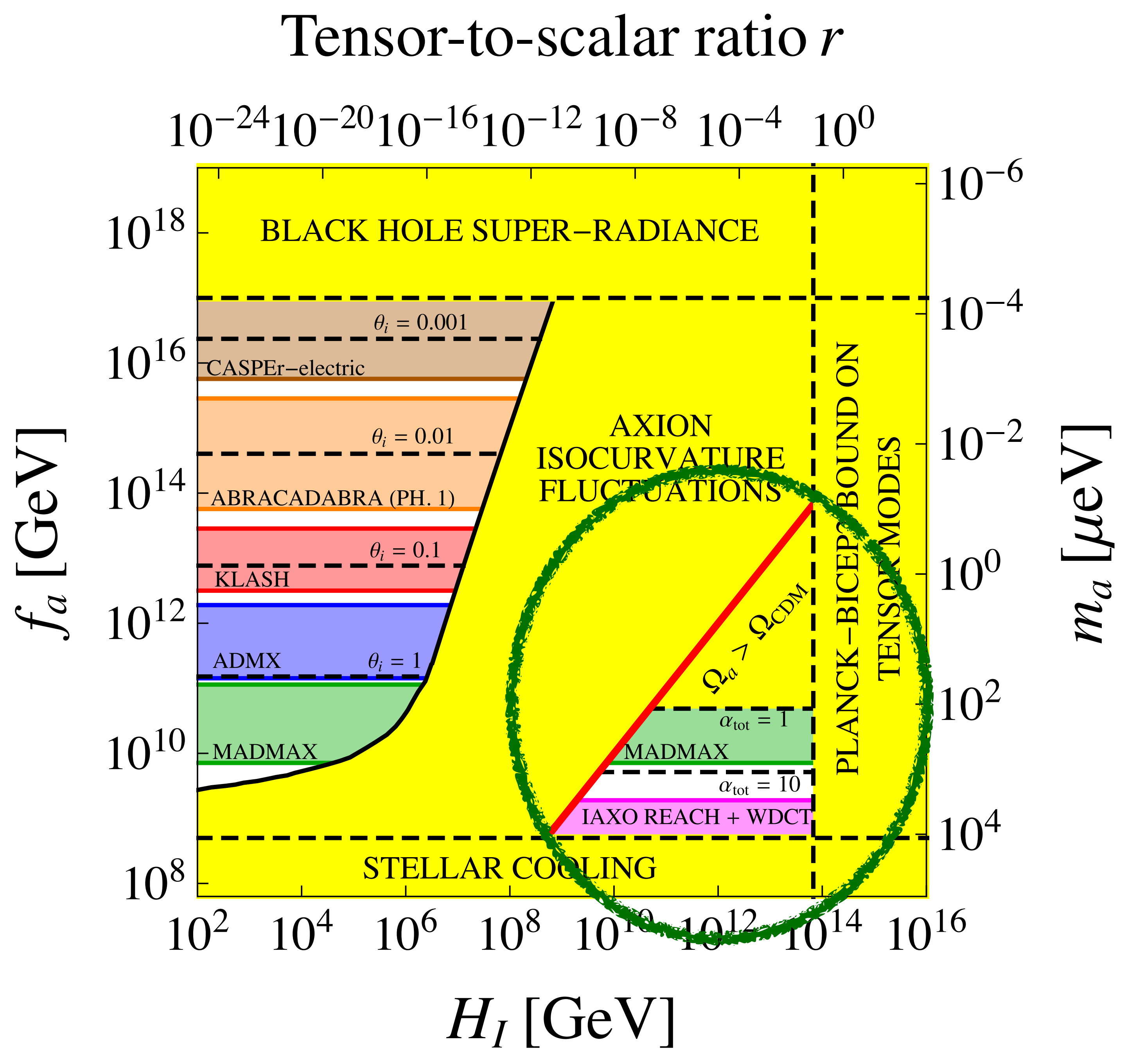
$T \sim \Lambda_{\rm QCD} \ll f_a$

Axion: Late-Universe dynamics

The axion angle $\theta = \theta(t, \mathbf{x})$ evolves towards zero



Scenario: Unbroken PQ symmetry during inflation



Wilczek, Turner '91; Beltran+ '06;
Hertzberg+ '08; Wantz, Shellard '09

LV, PRD 96 023013 (2017)
LV&Gondolo, PRL **113**, 011802 (2014)
PRD **81**, 063508 (2010)
PRD **80**, 035024 (2009)

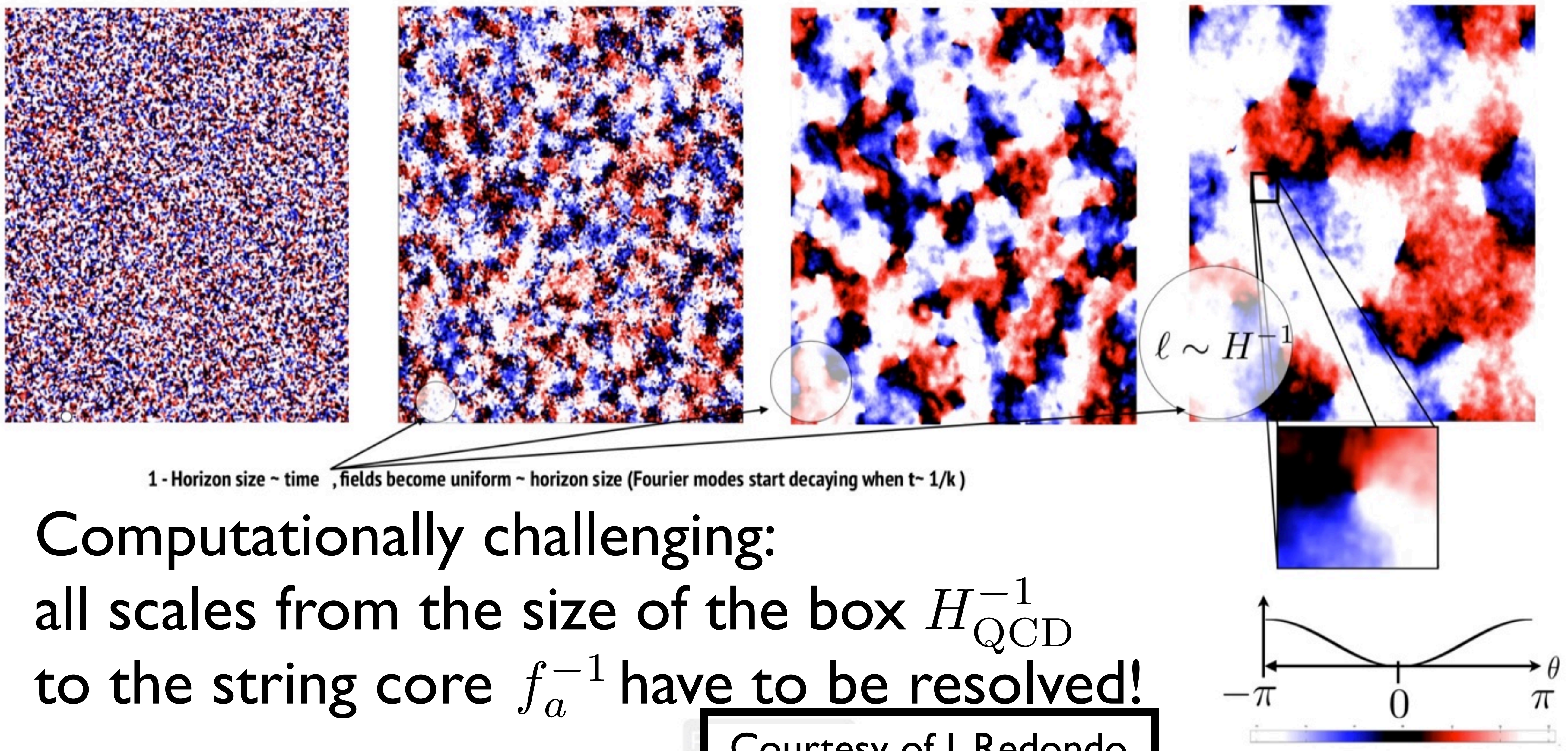
Scenario II - Unbroken PQ symmetry during inflation

$$T \sim f_a$$

The Kibble mechanism (Kibble76) leads to string network formation

$$T \sim T_{\rm QCD}$$

Domain walls form and dissipate (Sikivie82; Georgi+82)



Computationally challenging:

all scales from the size of the box $H_{\rm QCD}^{-1}$ to the string core f_a^{-1} have to be resolved!

Courtesy of J. Redondo

Compact objects

Regions with overdensities $\Phi = \delta\rho/\rho$

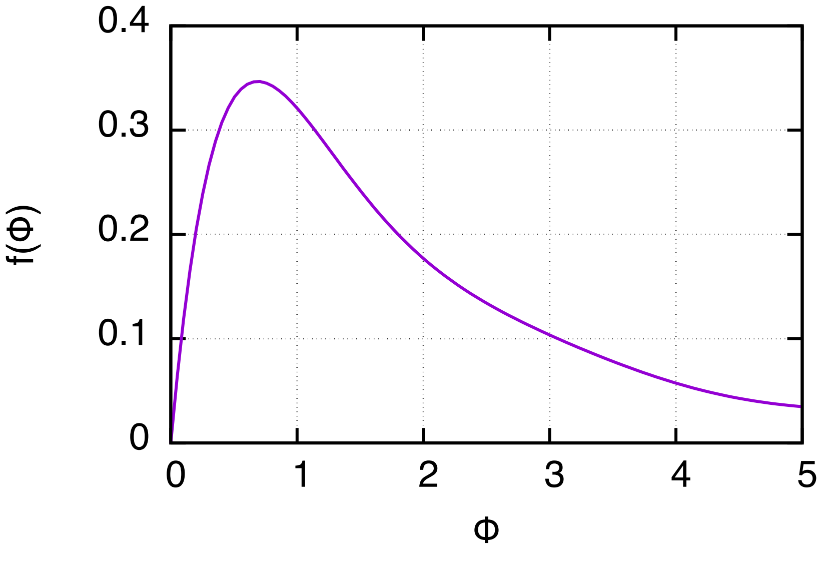
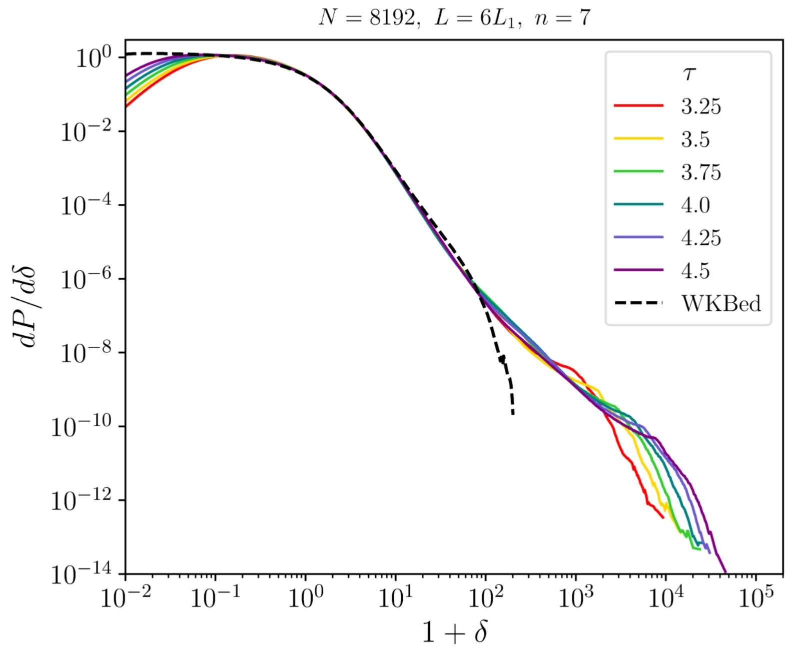


Figure 1. Mass fraction $f(\Phi)$ of axions in miniclusters with a given value of Φ.

Kolb&Tkachev1994



Vaquero+2018

collapse at temperature $T_{\rm collapse} = \Phi\, T_{\rm eq}$

Density of miniclusters $\rho \sim 140(1+\Phi)\Phi^3\rho_{\rm eq}$

Power injection at very small scales

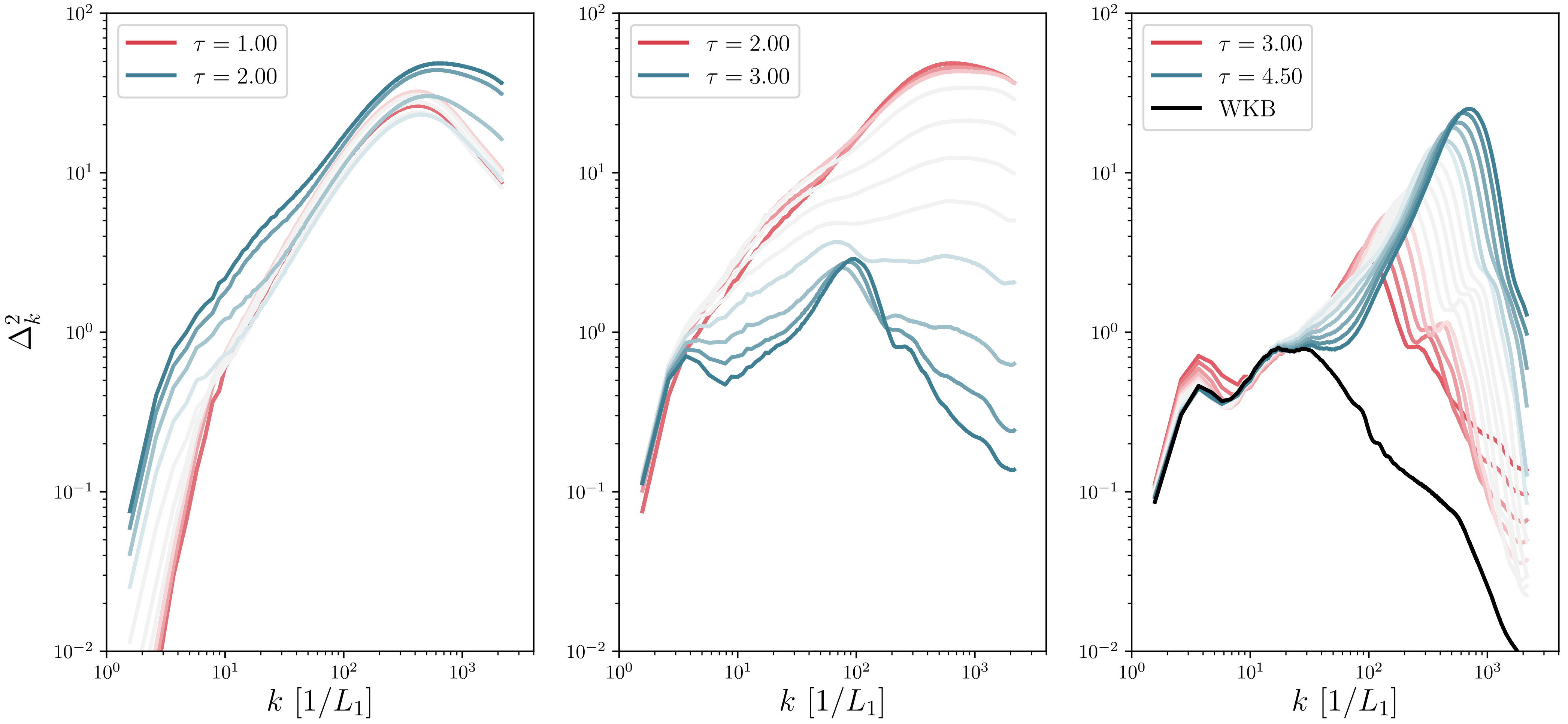


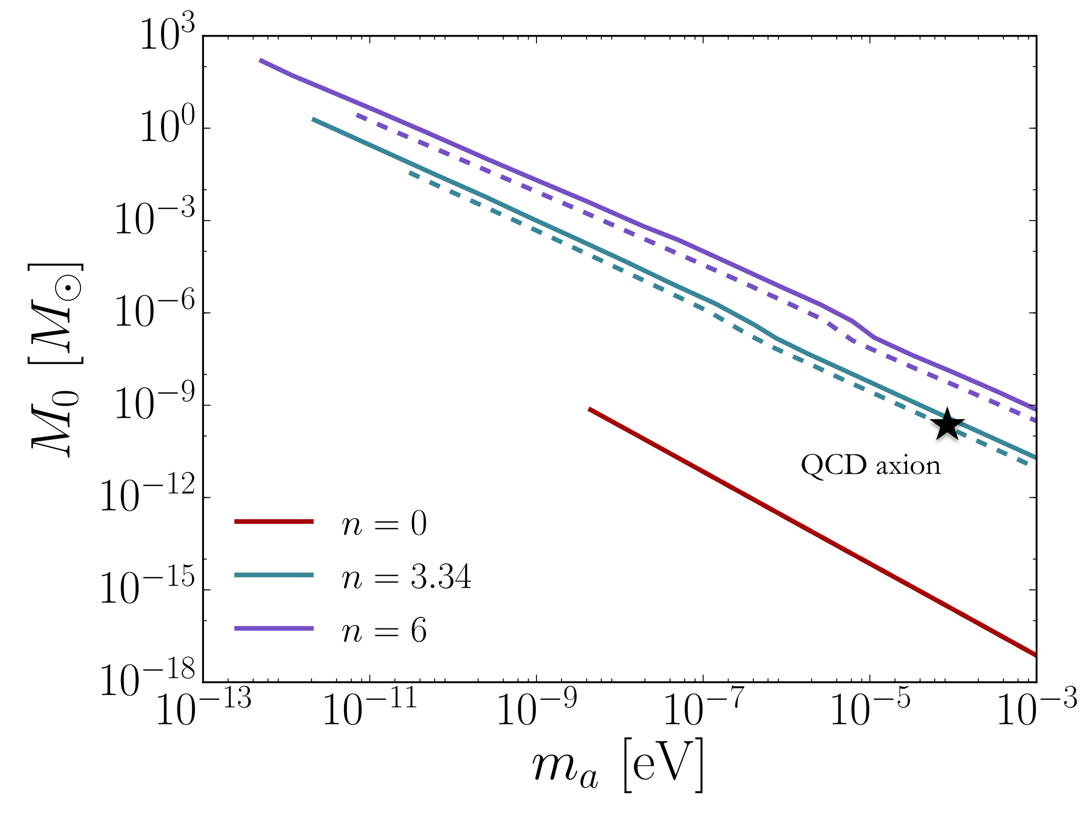
Figure 9: Time evolution of the dimensionless variance of axion energy density fluctuation as a function of momenta. Results are shown for an average over $L = 6L_1$, $N = 8192$ and $n = 7$ simulations. Different lines show the time evolution. For simplicity the legends quotes only the earliest and latest time shown in each plot, the remaining colors interpolate between these limits. The time difference between steps is $\Delta\tau = 0.1$. The three plots show the evolution through the three periods of our simulation: axions with strings, network destruction, non-relativistic period with axitons.

Vaquero+2018

Axion miniclusters

Mass $M_{\rm MC} \sim 10^{-10} M_\odot$ (enclosed at $H^{-1}_{\rm QCD}$)

Radius $R_{\rm MC} \sim 1\,{\rm AU}/\Phi$.



Fairbairn+2017

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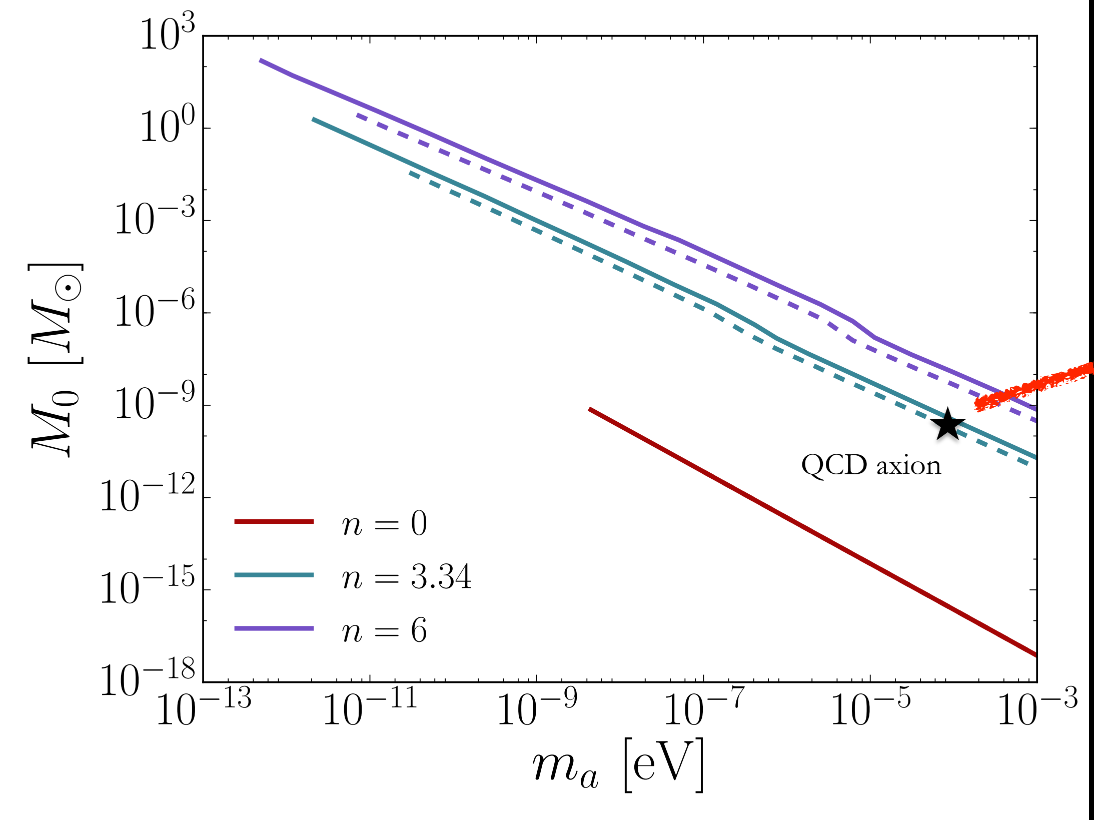
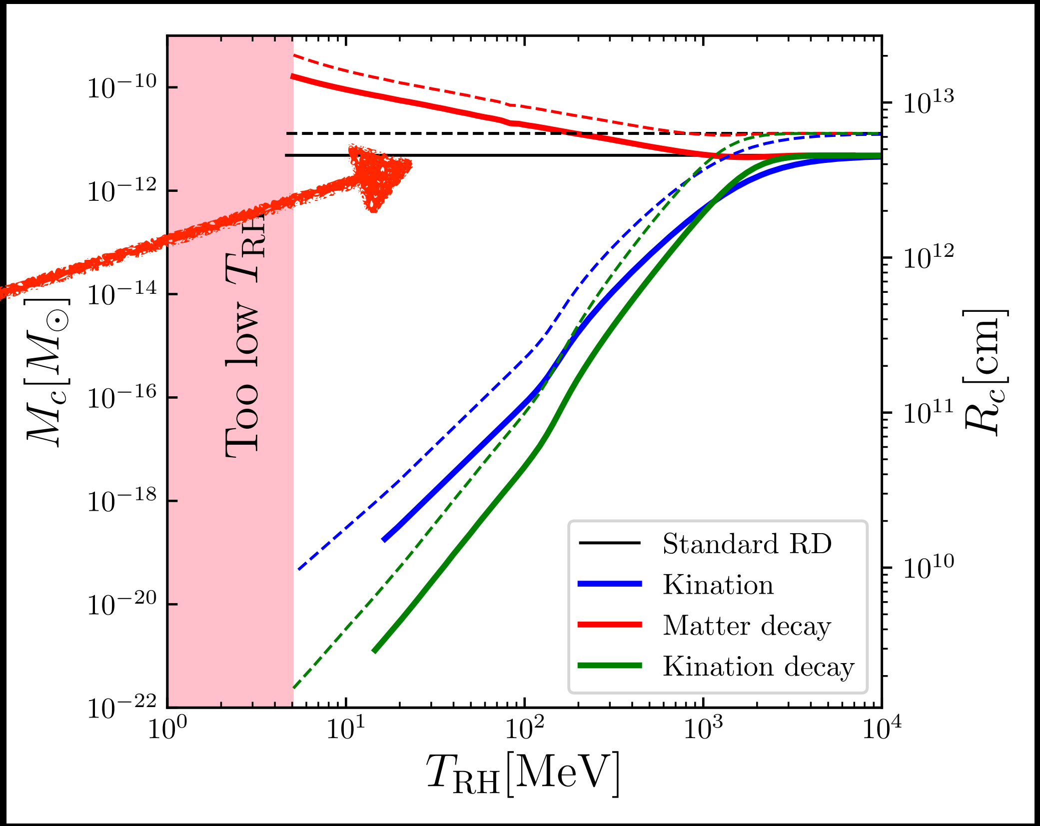
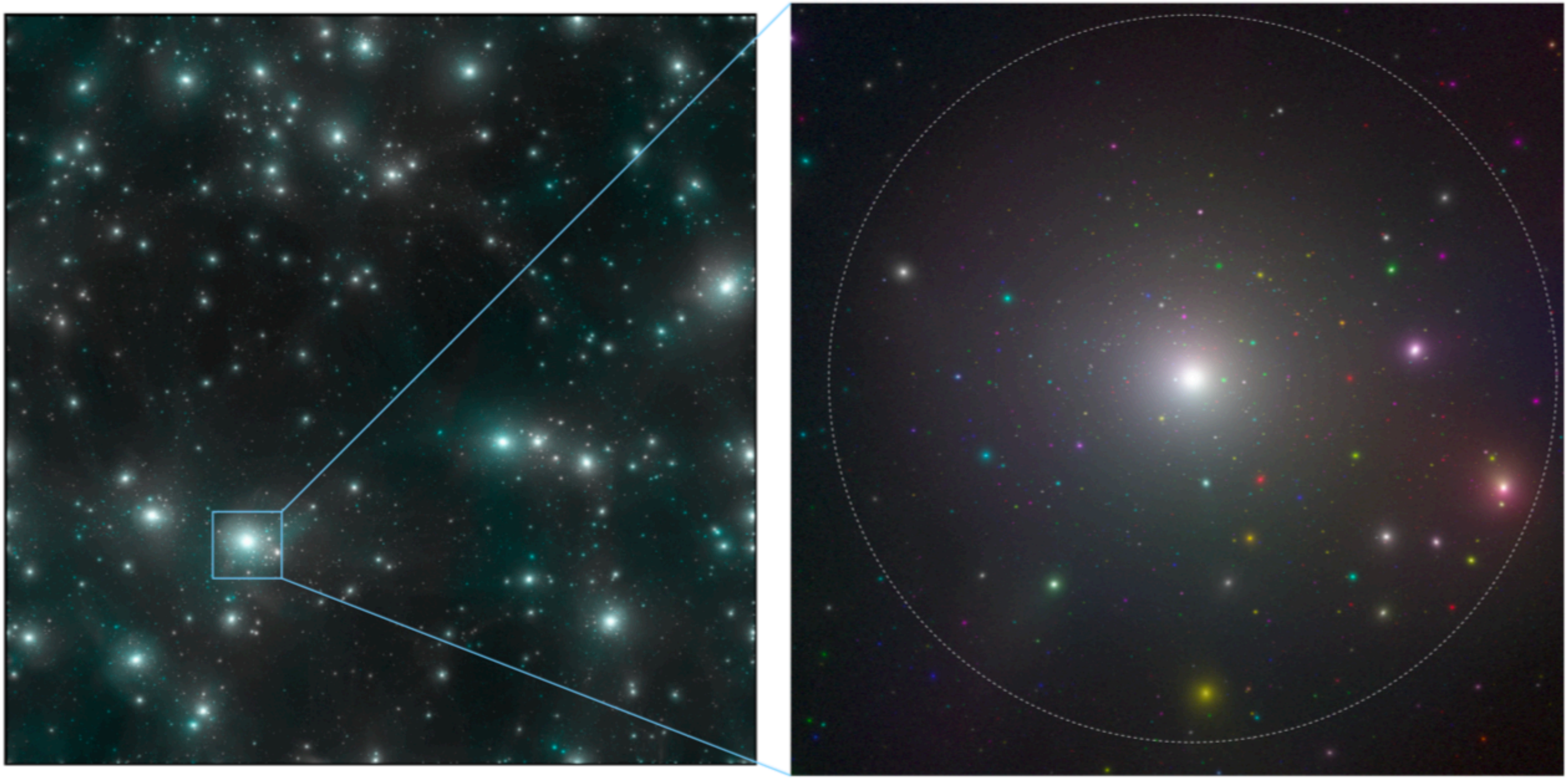


Fairbairn+2017



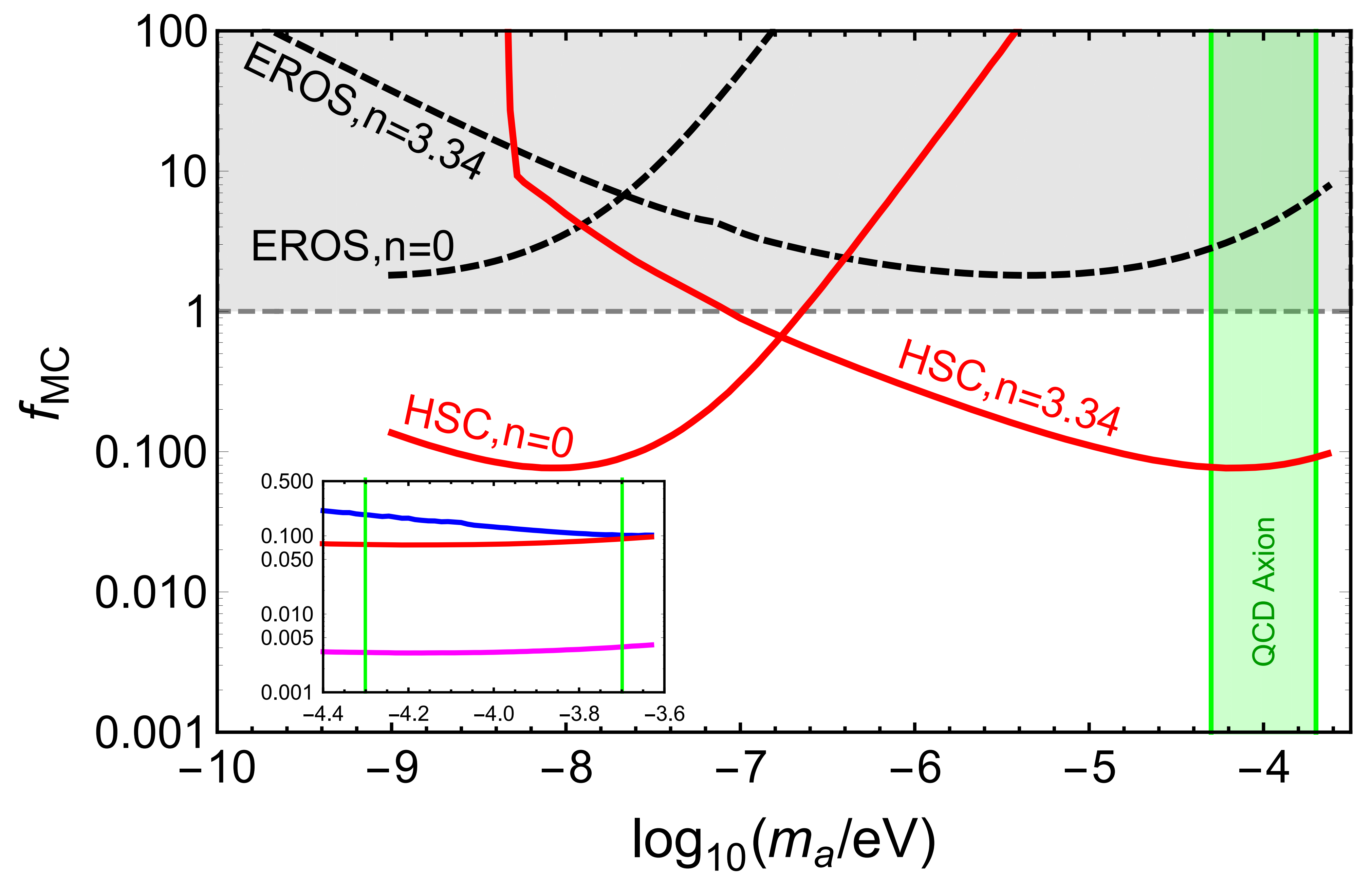
LV & Redondo 1808.01879

Axion miniclusters



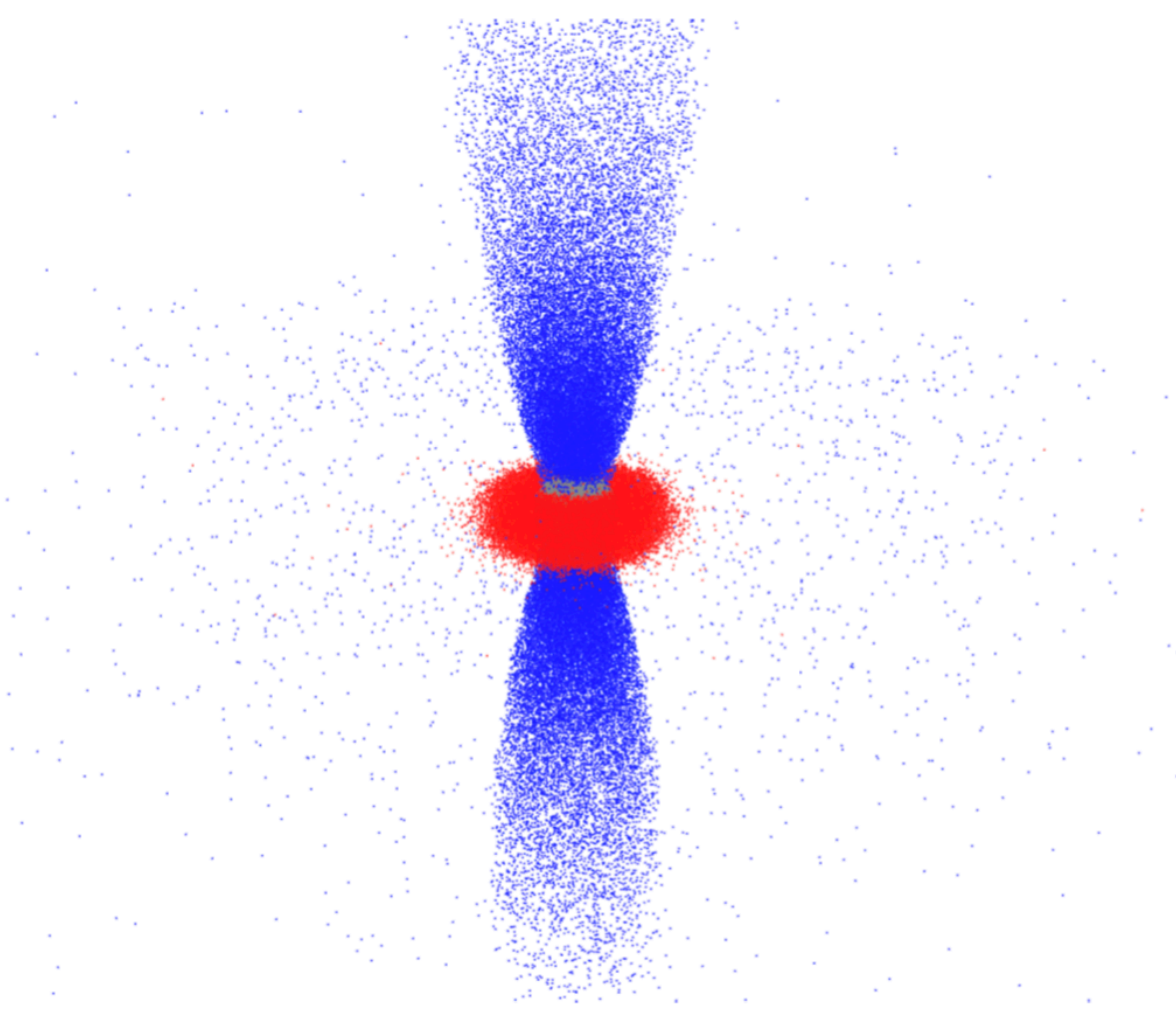
Eggemeier+2019

Microlensing



Fairbairn+2017

Axion radio-interferometry



Goldreich & Julian NS magnetosphere model

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

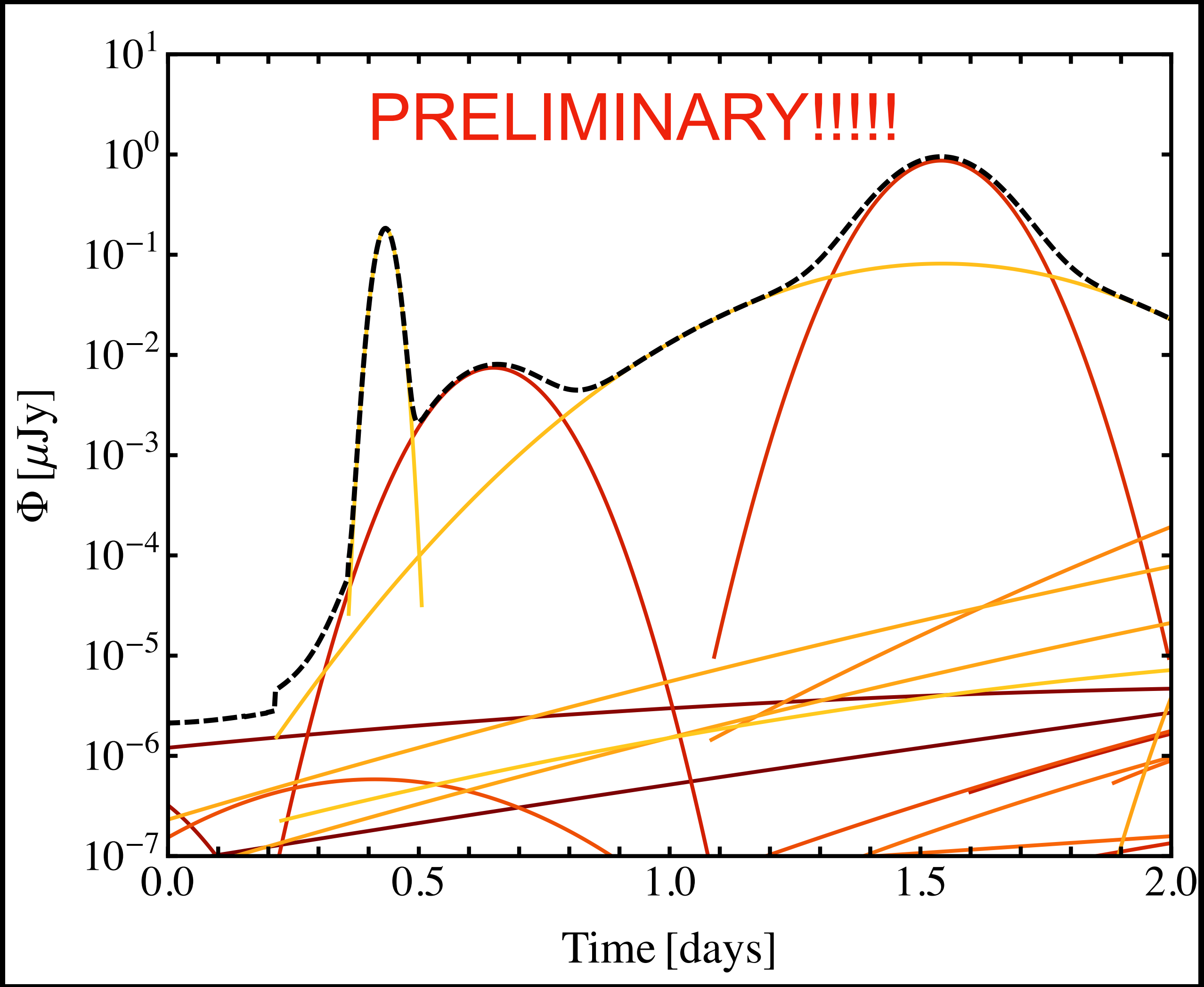
$$n_c = \frac{2\mathbf{\Omega}\cdot\mathbf{B}}{e} + \text{(relativistic corrections)}$$

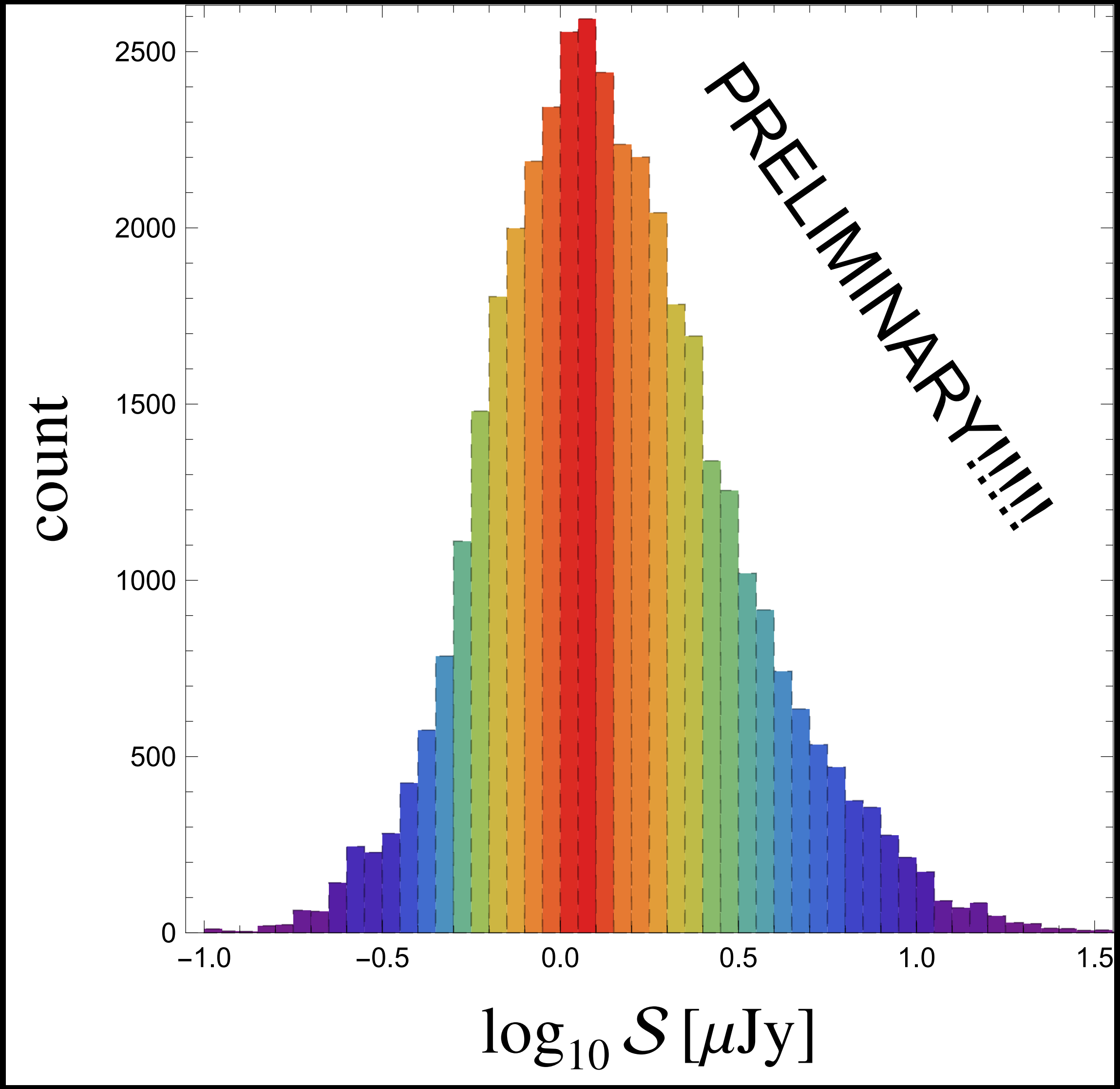
$$\omega_p(B) \approx m_a$$

Axion radio-interferometry

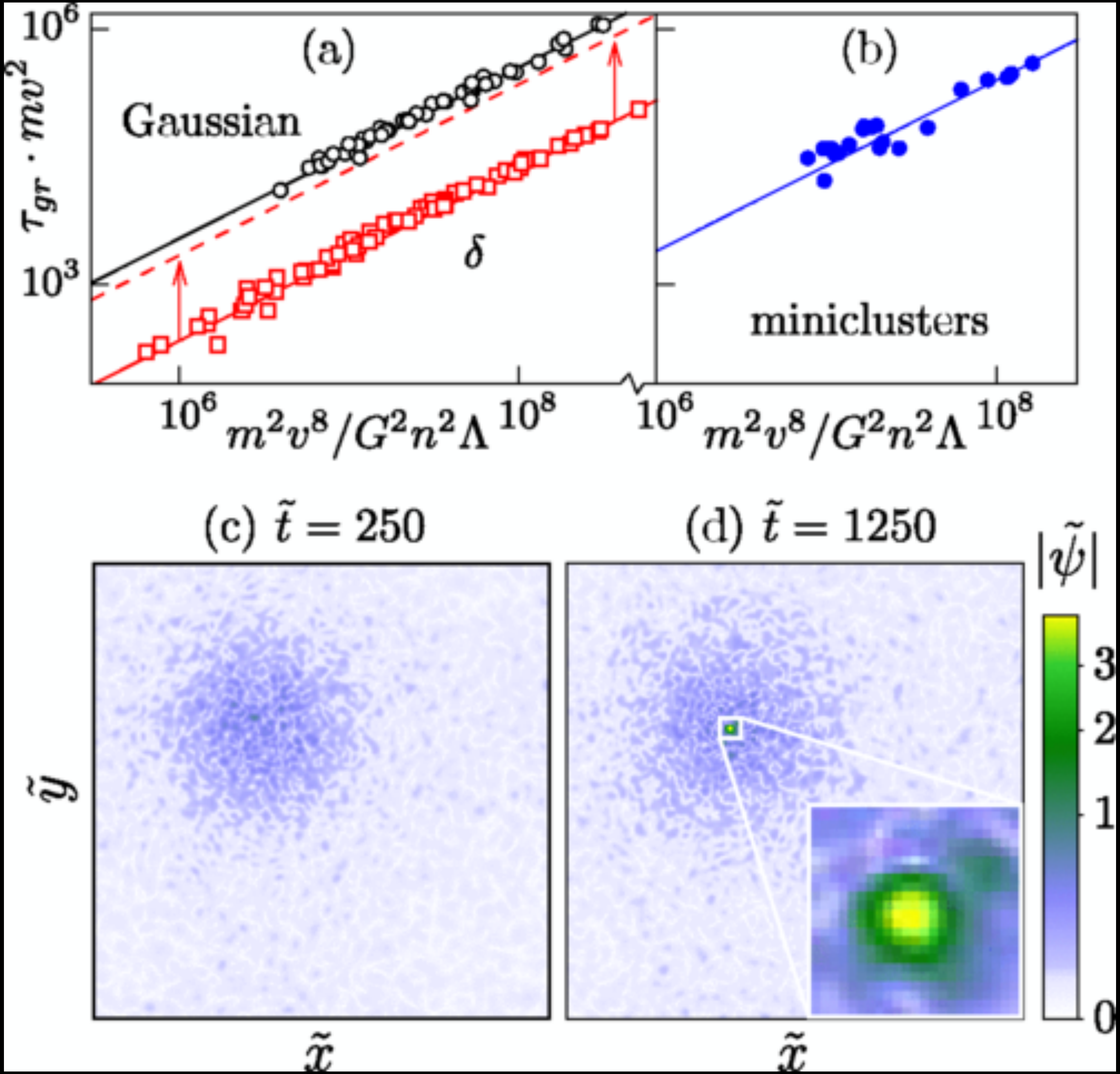
Signal at Earth from NS passing through axion miniclusters

Distribution of the signal peak at Earth



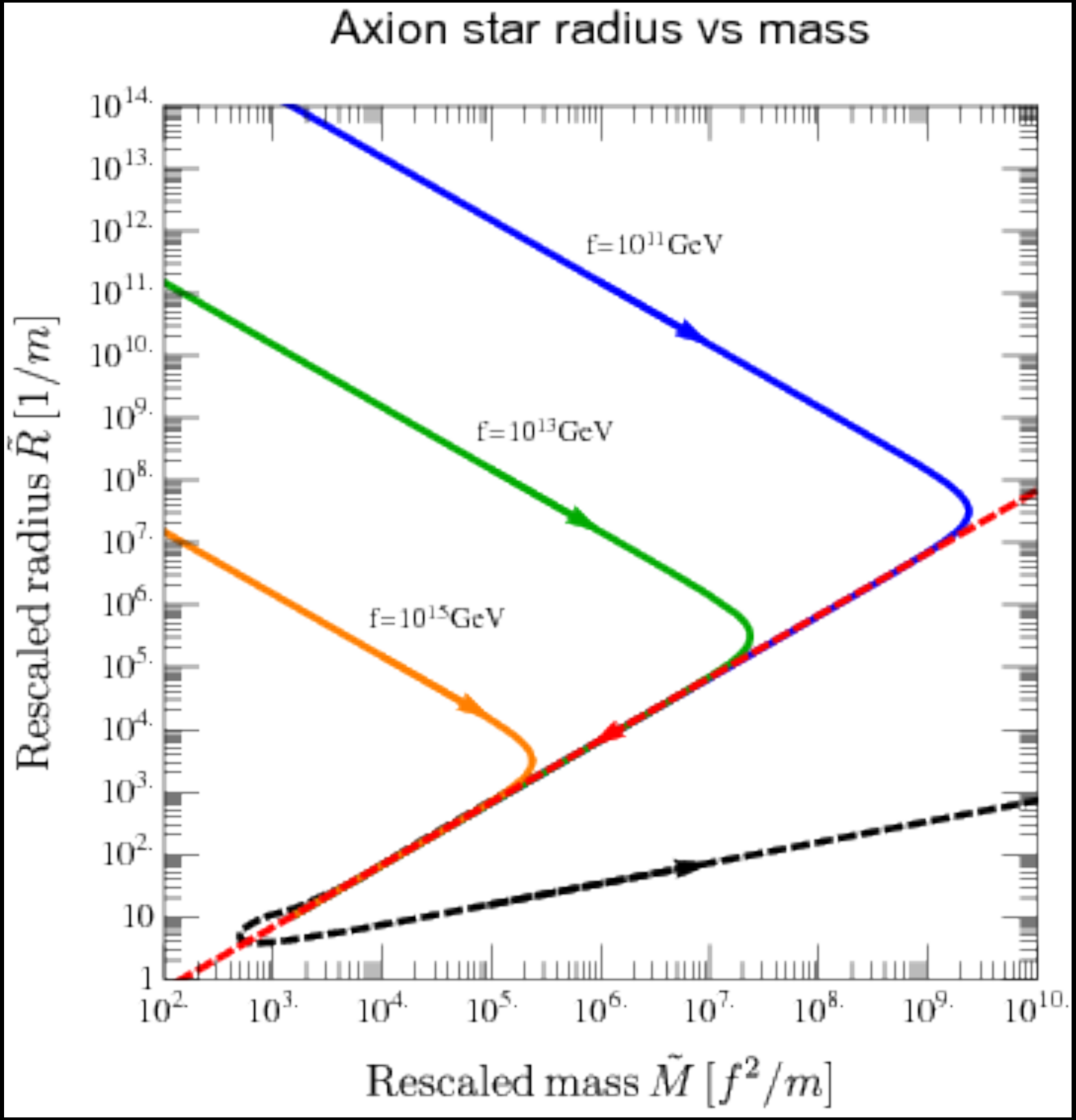


Axion stars



Levkov+2016

Axion stars: mass-radius relations

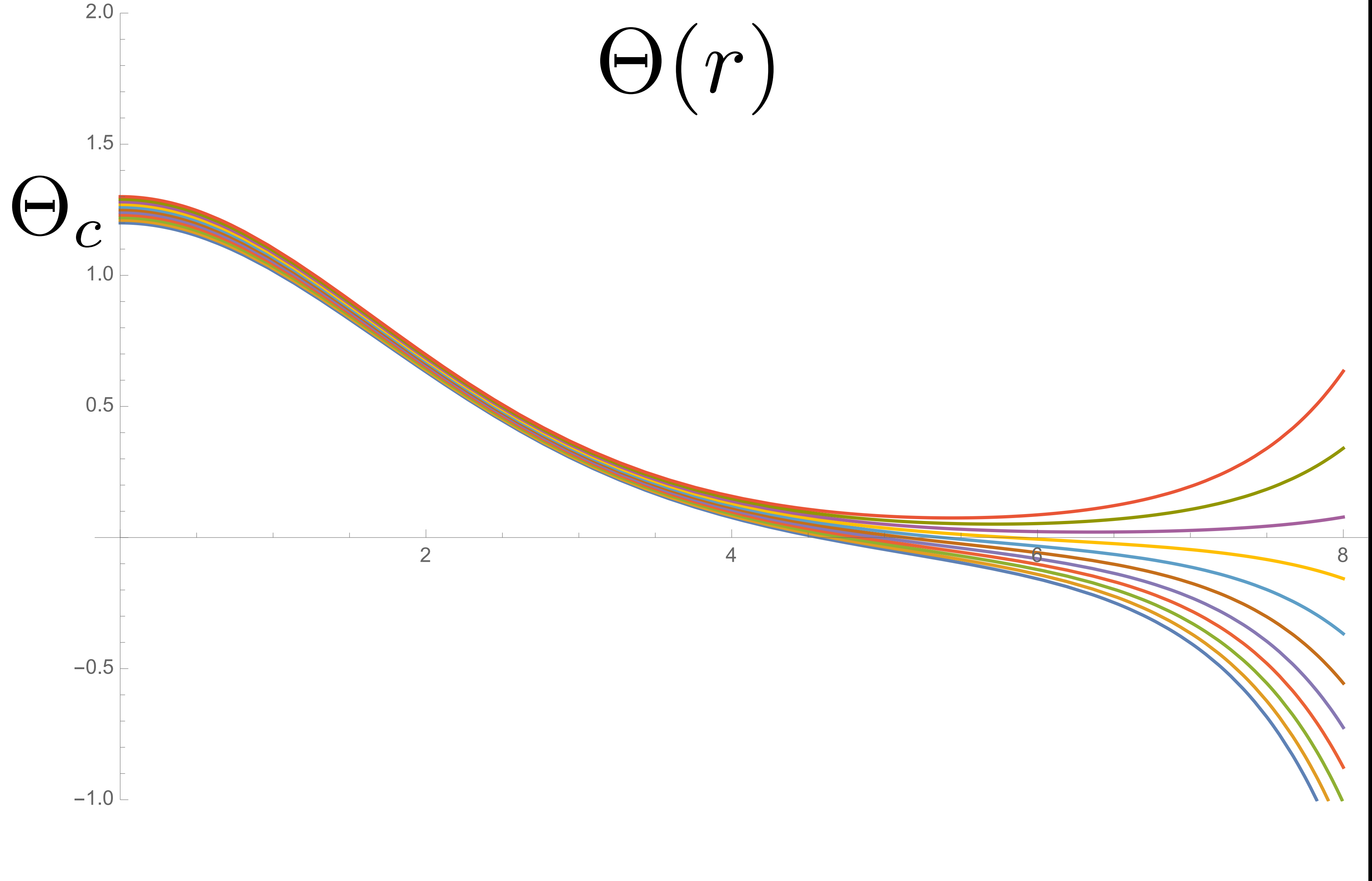


Visinelli+ PLB 777 64 (2018)


With K. Freese, S. Baum

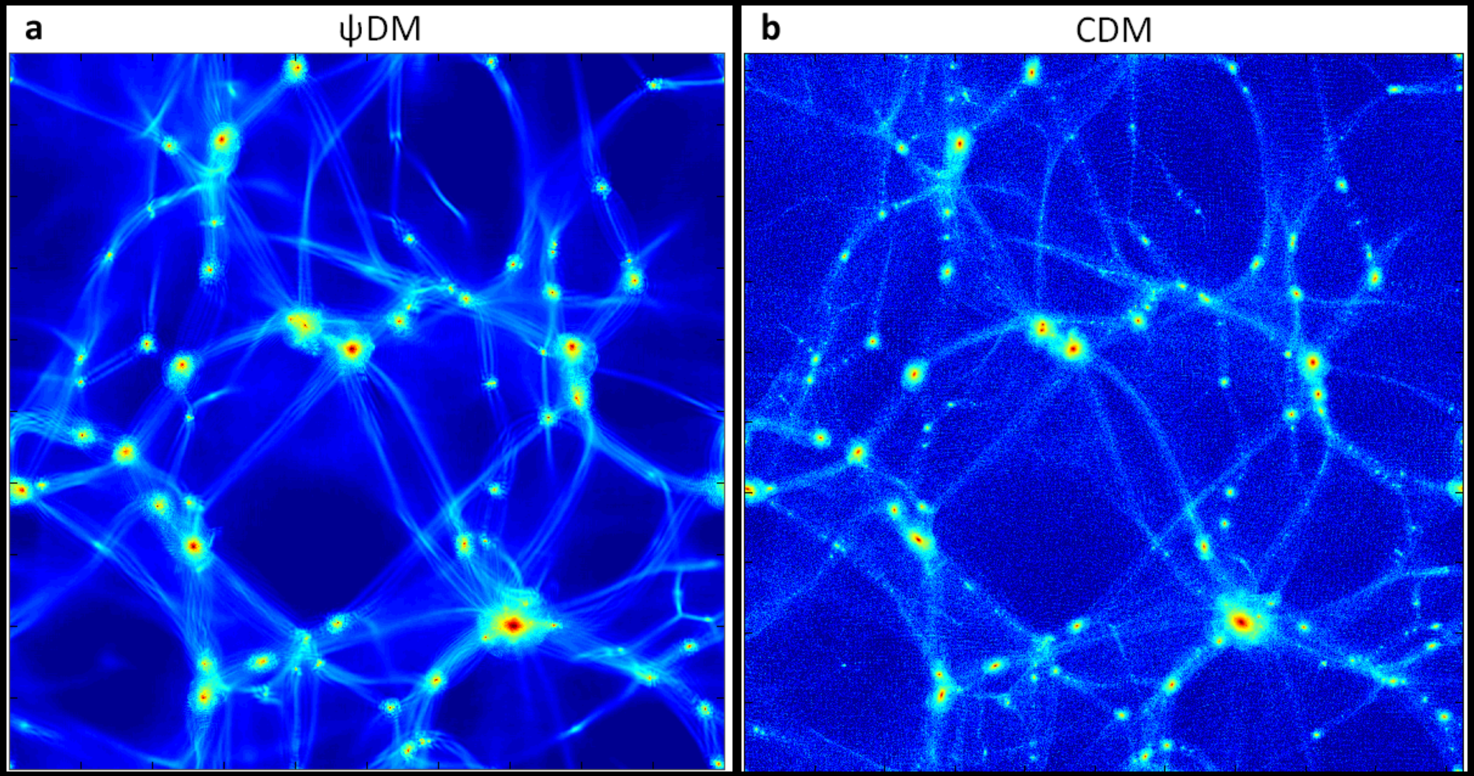

J. Redondo, F. Wilczek

Solving by shooting method



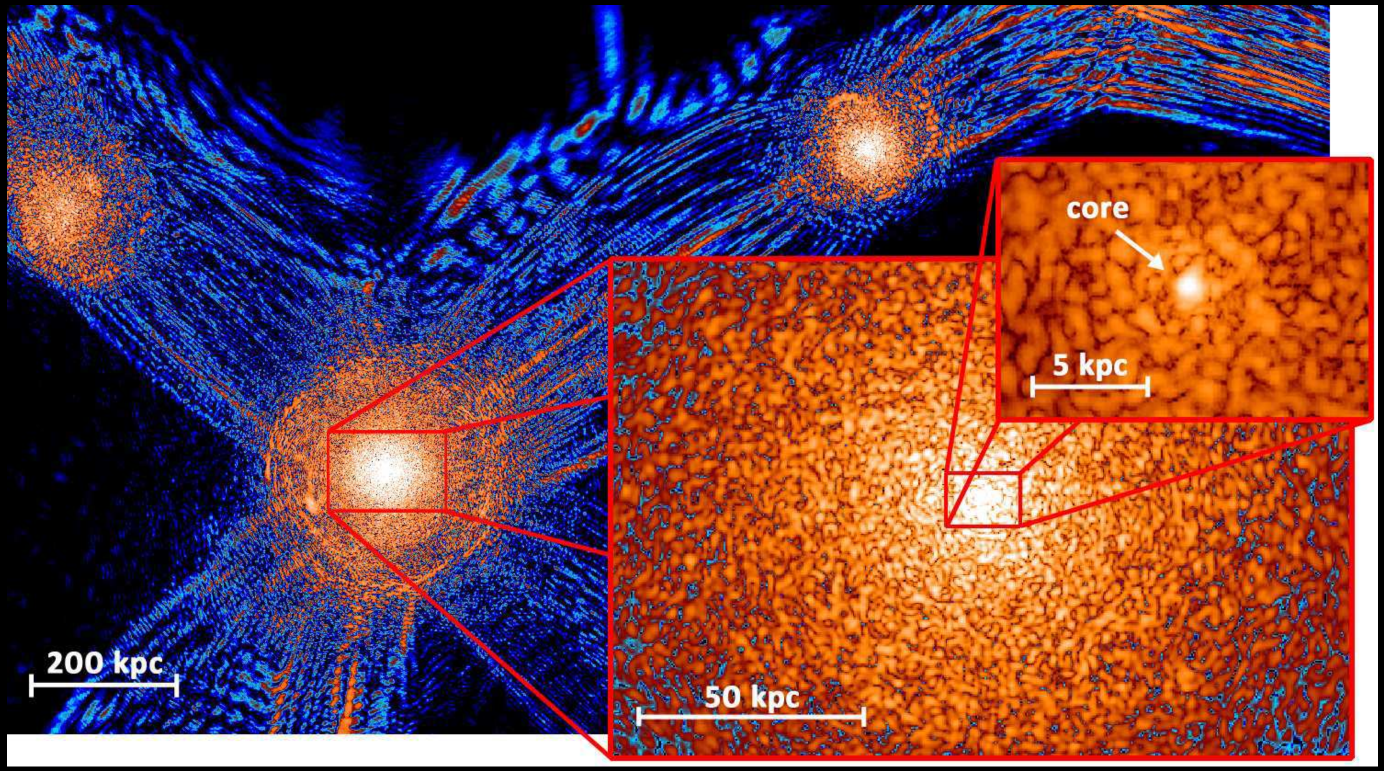
$$\boxed{M} = 4\pi\int_0^{+\infty} r^2\phi^2(r)dr \qquad 0.9M = 4\pi\int_0^{\boxed{R_{90}}} r^2\phi^2(r)dr$$

Soliton cores



Ultra-light axion DM
is indistinguishable
from CDM
on large scales....

... galactic-size
self-gravitating
soliton cores are
produced



Schive *et al.* Nature **10** 496 (2014)

Veeltman *et al.* PRD **98** 043509 (2018)

Conclusions

- It is an exciting period to work on dark matter compact objects!
- Details require much further efforts. Work in progress...
- Miniclusters and axion stars are possible laboratories!