Phenomenology of axion miniclusters

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Outline

- Axion cosmology and miniclusters
- Axion Bose stars, their formation and explosions

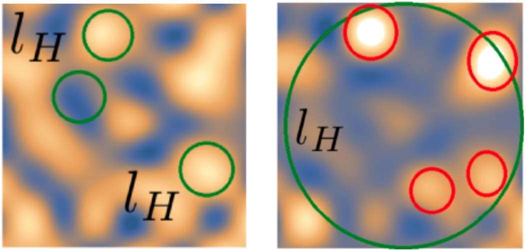
  see talks by D. Levkov and A. Panin, this conference
- Tidal streams from miniclusters and relation to direct detection

Axion cosmology

PQ phase transition before inflation is disfavored

see talk by K. Saikawa, this conference

PQ phase transition after inflation $\rightarrow$ Miniclusters



- After phase transition $0 < \theta < 2\pi$ from horizon to horizon, but $\theta \approx \mathrm{const}$ on a horizon scale, l_H.
- Peculiar initial amplitude of oscillations when m_a turns on.
- Dark Matter should be very clumpy

Axion cosmology

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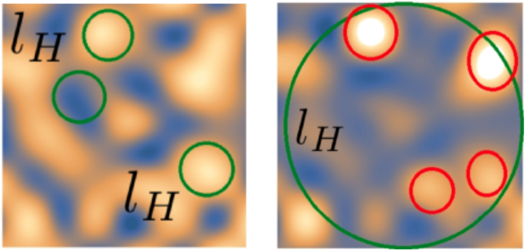
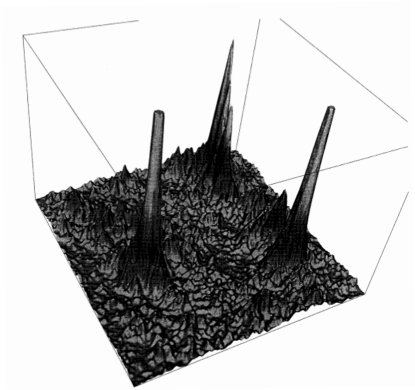
see talk by K. Saikawa, this conference

PQ phase transition after inflation $\rightarrow$ Miniclusters

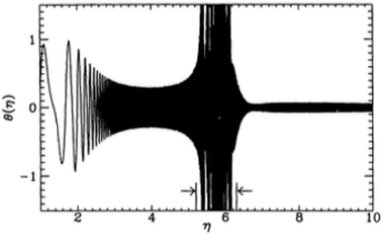


- Mass scale of the clumps is set by $M \sim 10^{-11}\, M_\odot$, which is DM mass within l_H^3 at $T_{\rm osc} \approx 1$ GeV
- Naively, initial DM density contrast is $\delta\rho/\rho \sim 1$
- In fact, very dense objects can form since for $\theta \sim \pi$ the axion attractive self-coupling is non-negligible

Minicluster Formation. Non-linear story.



Spatial distribution of energy density.



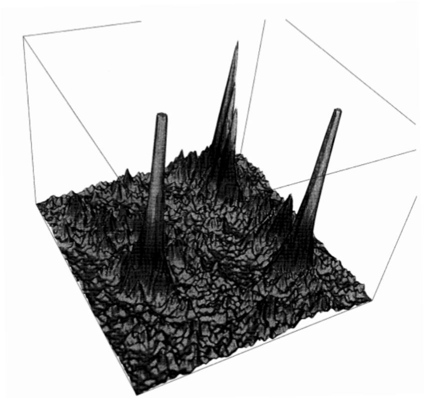
Time dependence of the field at the centre of a peak, $a(\eta) = \eta$.

E.Kolb & IT, Phys.Rev. D49 (1994) 5040

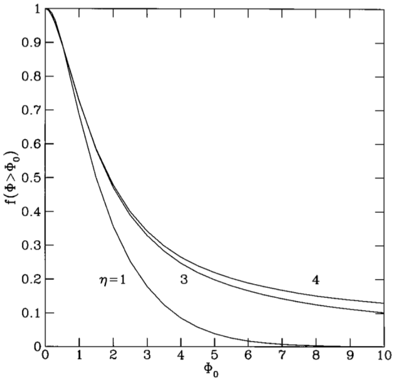
Axion cosmology

Minicluster Formation. Non-linear story.

Let's define $\delta\rho_a/\rho_a \equiv \Phi$ (for final configuration at large η)



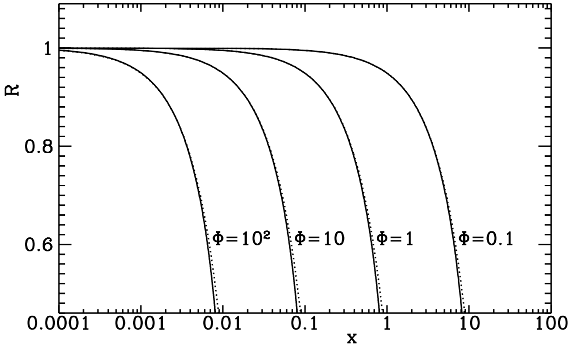
Spatial distribution of energy density. The height of the plot is cut at $\Phi = 20$.



Mass fraction in miniclusters with $\Phi > \Phi_0$ as a function of Φ_0.

E.Kolb & IT, Phys.Rev. D49 (1994) 5040

Minicluster evolution around equality



Clump radius as a function of $x \equiv a/a_{\rm eq}$

A clump separates from cosmological expansion at $T \approx \Phi\, T_{\rm eq}$, therefore minicluster density today

$$\rho_{\rm mc} \approx 140\Phi^3(1+\Phi)\bar{\rho}_a(T_{\rm eq})$$

E.Kolb & IT, Phys.Rev. D50 (1994) 769

Phenomenological implications

- Large Φ. Implications for indirect axion searches
  - Gravitational microlensing and femtolensing by miniclusters
  - Bose-star formation inside miniclusters
    - Relation to FRB?
- Small Φ. Implications for direct axion searches
  - Less diffuse DM -> smaller signals in DM detectorts
  - But rare strong signals during encounters with debris of tidally disrupted miniclusters

Bose-condensation in miniclusters

Relaxation time is enhanced due to large phase space density

$$\tau_R^{-1} \sim \sigma\, v\, n\, \mathcal{N}$$

IT, Phys. Lett. B **261** *(1991) 289*

Miniclusters with $\Phi > 30$ Bose condense due to axion selfcoupling, forming "Bose-stars"

E.Kolb & IT, PRL **71** *(1993) 3051*

Bose-condensation by gravitational interactions is much more efficient

$$\tau_{gr} \sim \frac{10^9\,\text{yr}}{\Phi^3(1+\Phi)} \left(\frac{M_c}{10^{-13}\,M_\odot}\right)^2 \left(\frac{m}{26\,\mu\text{eV}}\right)^3$$

see talk by D. Levkov, this conference

Fast Radio Bursts and axion Bose-stars

FRB - mysterious astrophysical phenomena

- Short radio flash, $\mathbf{1\ ms}$
- Cosmological origin, $z \sim 1$
- Energy release $\mathbf{10^{38} - 10^{40}\ ergs}$
- Huge brightness temperature $T_B \sim \mathbf{10^{36}\ K}$
- Rate: $\sim \mathbf{10^4\ events/day}$ for the whole sky.

- Radius of axion Bose-star $\mathbf{1\ ms}$
- Minicuster mass $10^{-12} M_\odot = 2 \times 10^{42}\ \mathrm{ergs}$
- Bose-star can explode in a burst of coherent radiation
- We have 10^{24} miniclusters just in a Galaxy

Can FRBs be explained by axion star explosions into pure radiation?

IT, JETP Letters 101 (2015) 1

A. Iwazaki, PRD 91(2015) 023008

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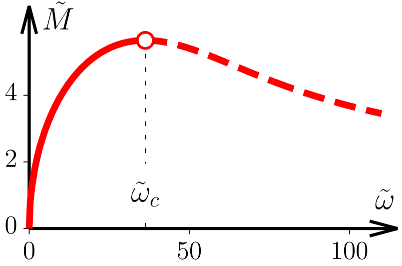
ALP Bose star instability

$$V(a) = m^2 f_a^2 \left(\frac{1}{2}\,\theta^2 - \frac{g_4^2}{4!}\,\theta^4 + \dots \right) \,, \qquad \theta \equiv a/f_a \,,$$

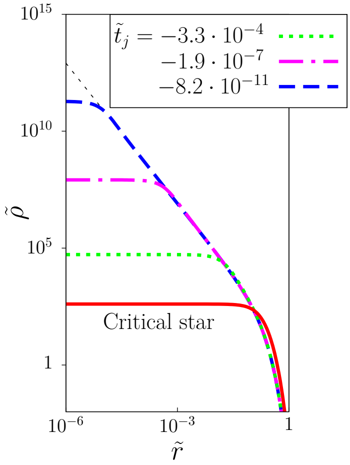
Self-coupling of axions is negative and axion Bose stars are unstable against collapse.



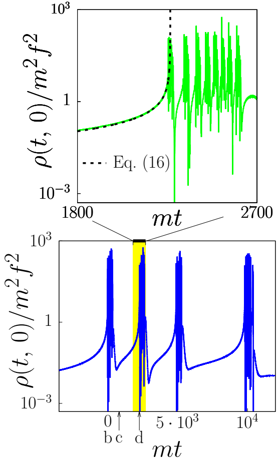
D.Levkov, A.Panin, & IT, PRL 118 (2017) 011301

ALP Bose star collapse

Self-similar wave collapse



Repeated explosions

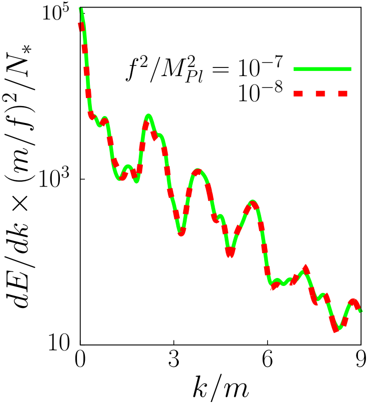


Black hole does not form for $f_a < M_{Pl}$

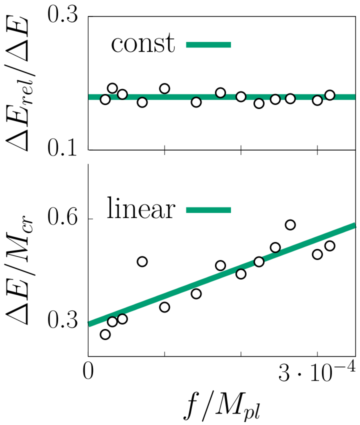
D.Levkov, A.Panin, & IT, PRL 118 (2017) 011301

Decay of Bose star on relativistic axions

Spectra of emitted particles



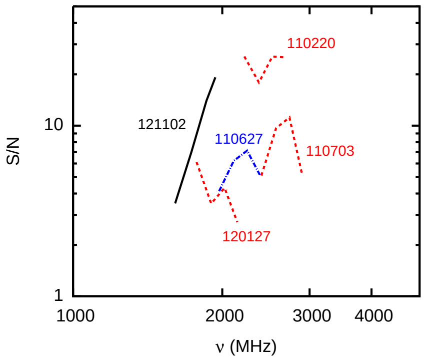
Total emitted energy fraction



D.Levkov, A.Panin, & IT, PRL 118 (2017) 011301

Fast Radio Bursts and axion Bose-stars

FRB spectra shifted to their rest frame



IT, JETP Letters 101 (2015) 1

Study of axion Bose star decay into radiophotons is underway

see talk by A.Panin, this conference

Minicluster abundance

Typical miniclusters with $\Phi \approx 1$:

- 10^{24} in the Galaxy
- 10^{10} pc^{-3} in the Solar neighborhood
- Minicluster radius $\sim 10^{7}$ km
- Direct encounter with the Earth once in 10^{5} years
- During encounter density increases by a factor 10^{8} for about a day

But, some miniclusters are destroyed in encounters with stars.
This may change the prospects for DM detection.

Axion direct detection

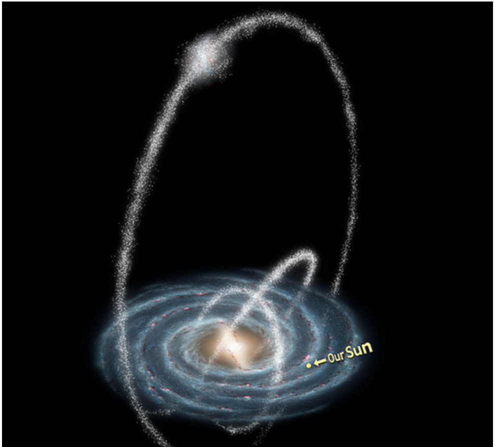
Tidal streams from miniclusters

Probability of a minicluster disruption

$$P(\Phi) = 0.022 \left(\frac{n}{100}\right) \Phi^{-3/2} (1+\Phi)^{-1/2}$$

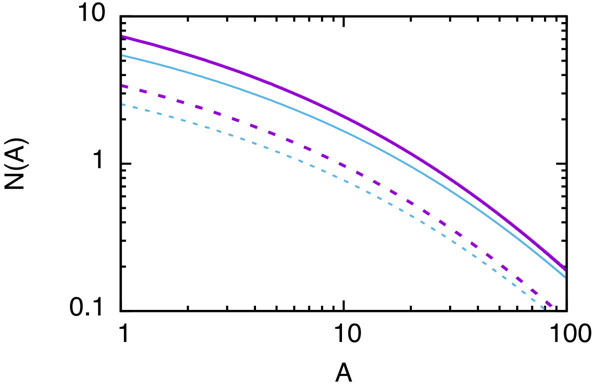
Just disk crossings. No actual orbits integration.

P.Tinyakov, IT and K. Zioutas, JCAP 1601 (2016) 035



Crossing tidal streams from miniclusters

Mean number of encounters with axion streams producing amplification factor larger than A, as a function of A. Twenty year observation interval is assumed.



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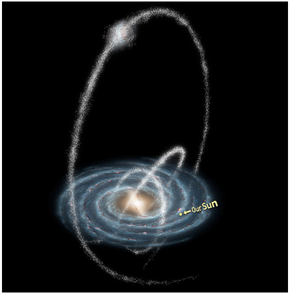
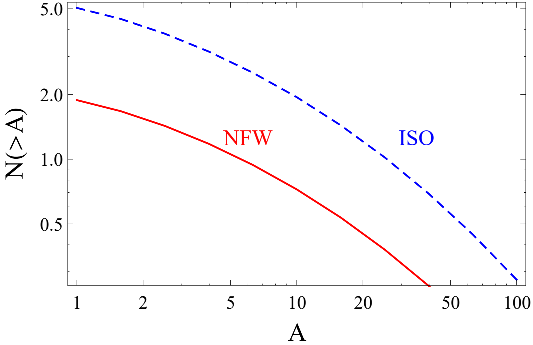
Actual history and distribution of orbits in a given DM profile was followed:

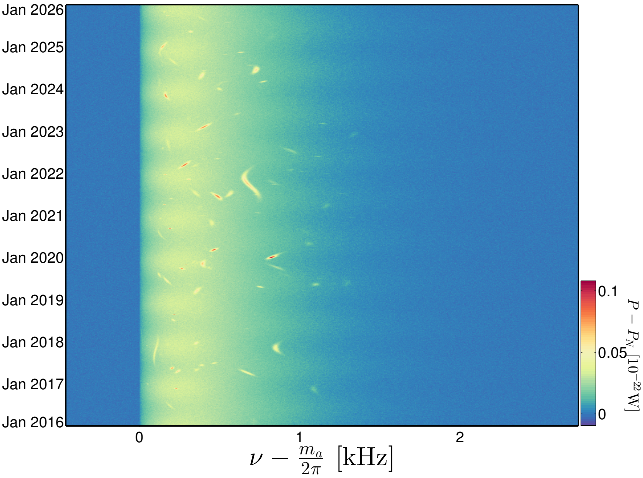




V. Dokuchaev, Yu. Eroshenko and IT, J.Exp.Theor.Phys. 125 (2017) 434

Crossing tidal streams from miniclusters

Simulation of expected PWS in cavity experiments



C. O'Hare and A. Green, Phys.Rev. D95 (2017) 063017

Conclusions

Axion miniclusters can have interesting phenomenological consequences and the subject requires further thorough studies.