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Axions as Dark Matter

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With no sign of supersymmetry at LHC (see A. Gladyshev, this conference) - the axion (or ALP) is reviving popularity as DM candidate.

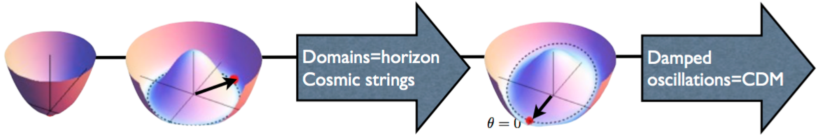
Axion as Dark Matter candidate is peculiar

	WIMP	Axion or ALP
Production mechanism	Thermal	Non-thermal
Phase-space density	$\ll \mathbf{1}$	$\gg \mathbf{1}$

Outline for today:

- Dense axion structures (miniclusters).
- Miniclusters and direct DM detection
- ALP Bose-stars and possible relation to observations

Axion production mechanism



Peccei-Quinn phase transition
at $T \sim f_a$

Axion potential switches on
at QCD epoch

$$V(a) = f_a m_a(T)\,[1 - \cos(\theta)]$$

where $\theta \equiv a/f_a$

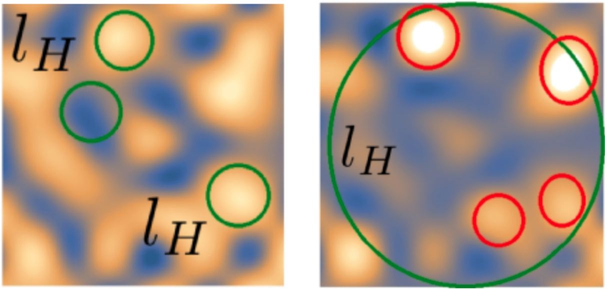
Axion oscillations start when

$$m_a(T) \approx 3H(T)$$

.
This happens at

$$T_{\rm osc} \approx 1\ \mathrm{GeV}$$

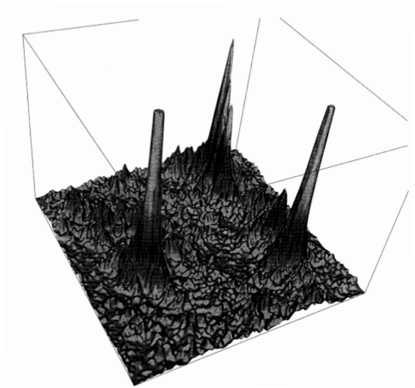
Miniclusters



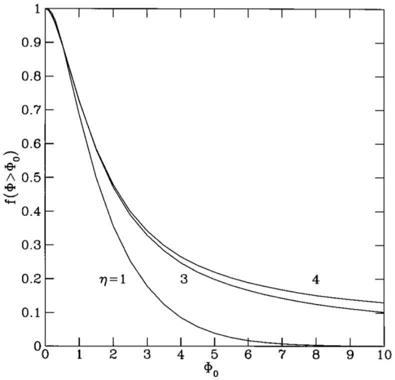
- Before axion mass turns on: $\theta \approx \mathbf{const}$ on a horizon scale l_H.
- After: $0 \lesssim \Delta\theta \lesssim \pi$. This is initial amplitude of oscillations:
  - $M \sim 10^{-12}\, M_\odot$ objects form, which is DM mass within l_H
  - Axion self-coupling is non-negligible
  - Non-linear objects form

Minicluster Formation

$$\delta\rho_a/\rho_a \equiv \Phi$$



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



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

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

Density of a minicluster now

Initially

$$\delta\rho_a/\rho_a \equiv \Phi$$

Clump separates from cosmological expansion at $T \approx \Phi\, T_{\mathrm{eq}}$, therefore minicluster density today

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

Valid for both miniclusters ($\Phi \gtrsim 1$) and minihalos ($\Phi \ll 1$)

Minicluster abundance

Typical miniclusters with $\Phi \approx 1$:

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

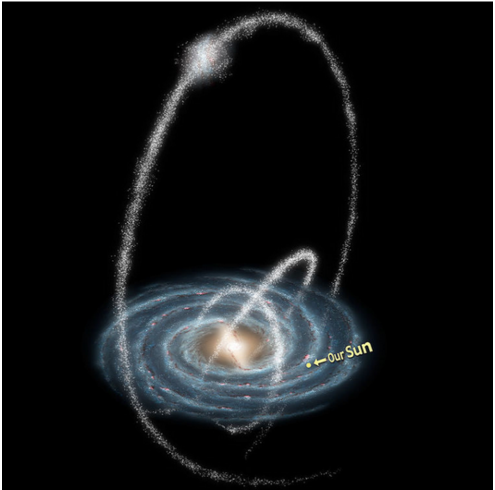
But, some miniclusters are destroyed in encounters with stars.
This may change the prospects for DM detection.

Tidal streams

Probability of a minicluster disruption

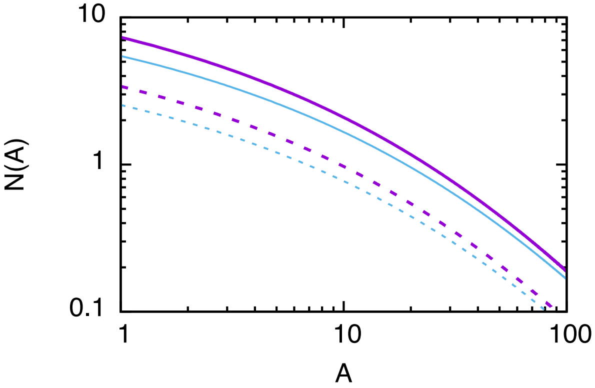
$$P(\Phi) = 0.022 \left(\frac{n}{100}\right) \Phi^{-3/2} (1 + \Phi)^{-1/2}$$

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



Crossing tidal streams

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



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

Bose-condensation

Relaxation time is enhanced in axionic halo due to large phase space density

$$t_R^{-1} \sim \lambda_a^2 \rho_a^2 v_e^{-2} m_a^{-7}$$

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

Miniclusters with $\Phi > 30$ Bose condense, forming "Bose-stars"

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

Radius of the star $\sim \mathbf{300\ km}$, light propagates across of it in $\mathbf{1\ ms}$.

Fast Radio Bursts and Axion Miniclusters

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 $T_B \sim 10^{36}\ \mathrm{K}$
- Rate: $\sim 10^4$ **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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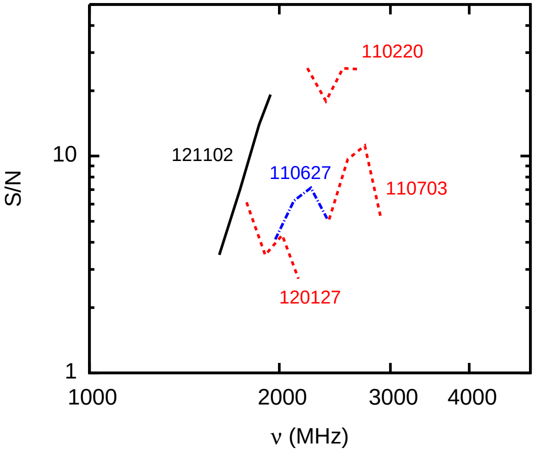
FRB spectra shifted to their rest frame

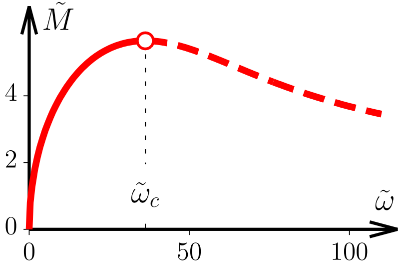


IT, JETP Letters 101 (2015) 1

Bose star instability

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

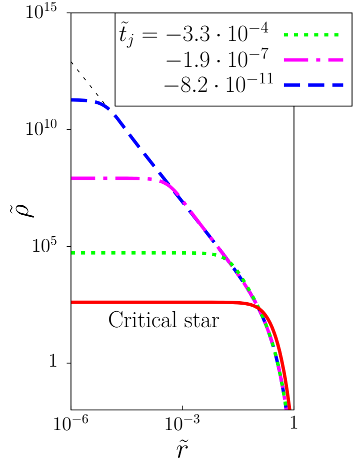
Self-coupling of axions is negative and axion Bose stars are unstable against collapse.



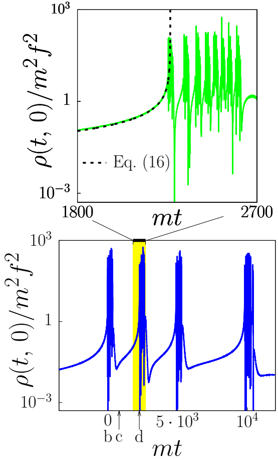
D.Levkov, A.Panin, & IT, arXiv:1609.03611

Bose star collapse

Self-similar wave collapse



Repeated explosions

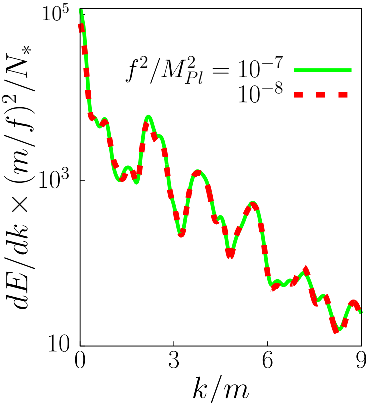


But black hole does not form for $f_a < M_{Pl}$

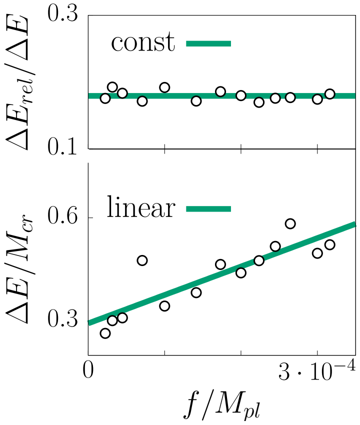
D.Levkov, A.Panin, & IT , arXiv:1609.03611

Decay of Bose star on relativistic axions

Spectra of emitted particles



Total emitted energy fraction



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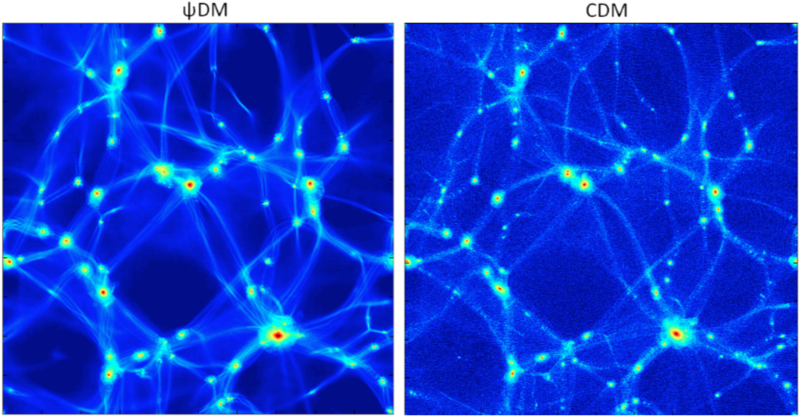
Why decay on relativistic itself is interesting?

Structure formation with ultra-light ALP



Hsi-Yu Schive et al, Nature Phys. 10 (2014) 496

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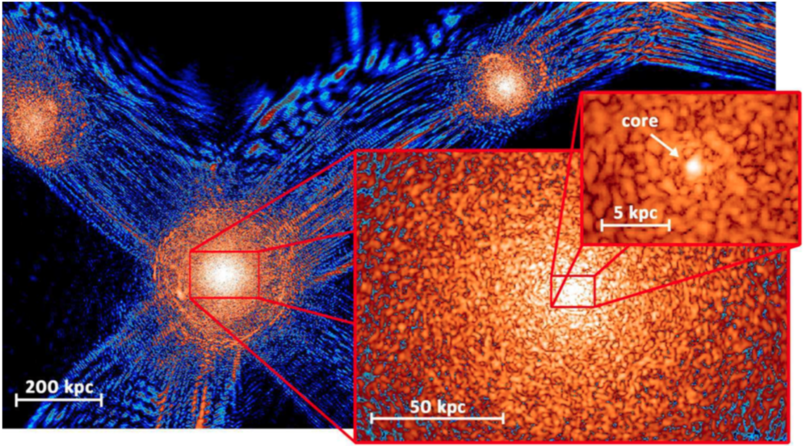


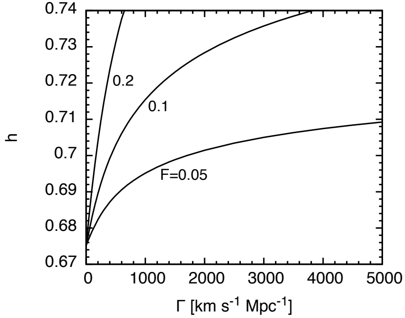
Hsi-Yu Schive et al, Nature Phys. 10 (2014) 496

Cores are heavy Bose-stars. It was speculated they collapse into black holes...

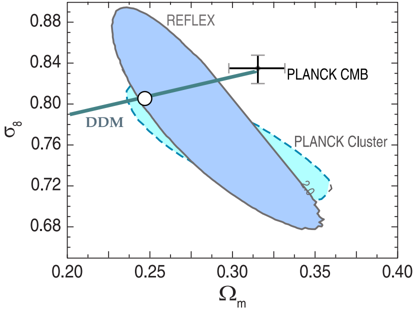
Why decay on relativistic itself is interesting?

Decaying Dark Matter may reconcile tension between low and high z measurements of cosmological parameters. E.g., direct measurements give $H_0 = (73.00 \pm 1.75)$, while best fit Planck cosmology $H_0 = 67.3 \pm 0.7$.

H_0 in DDM



σ_8 in DDM



Z. Berezhiani, A. Dolgov, & IT, Phys.Rev. D92 (2015) 061303

Coinclusions

- Axion miniclusters can have interesting phenomenological consequences and the subject requires further thorough studies.
- Density perturbations originating from most abundant miniclusters may lead to a phenomenologically interesting random density field. This may change strategy for direct axion searches.