Axion stars: formation, death and astrophysical implications

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Outline

- Formation of Bose Stars

  D.Levkov, A.Panin, & IT, PRL 121 (2018) 151301

- Axion Bose Star collapse

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

- Cosmological and astrophysical implications

Bose-stars

- Bose star is self-gravitating field configuration in the lowest energy state. *Ruffini & Bonazzola, Phys. Rev. 187 (1969) 1767*
- May appear in Dark Matter models with light Bose particles. Mainstream candidates - QCD axion or ALP in general:

  Axion stars

  IT, Sov. Astron. Lett. 12 (1986) 305
- Vast literature, but little attention to the problem of their formation.

Bose-star formation

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- Interactions are needed to form Bose condensate
- But ALP couplings are extremely small

QCD axions

- Solve strong CP problem
- CDM: $m \approx 26\ \mu$eV
- $\lambda \sim 10^{-50}$

String axions

- Appear in string models
- Fuzzy DM: $m \sim 10^{-22}$ eV
- $\lambda \sim 10^{-100}$

- Relaxation time is enhanced due to large phase space density f

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

$$\boxed{\tau_R^{-1} \sim \sigma\, v\, n\, f} \qquad \text{where } f \sim \frac{n}{(mv)^3} \gg 1$$

which is still not enough to beat small λ (except in rare axion miniclusters)

Are we crazy?

- No
- $f \gg 1$ — classical fields
- $v \ll 1$ — nonrelativistic approximation
- Gravity but no other interactions

$\Bigg\}$ $\boxed{\begin{array}{c}\psi(t, x)\\ U(t, x)\end{array}}$

Field equations for light DM (Scrödinger-Poisson system)

$$i\partial_t\psi = -\Delta\psi/2m + mU\psi$$
$$\Delta U = 4\pi G(\underbrace{m|\psi|^2}_{\rho} - \langle\rho\rangle)$$

Bose star is a stationary solution:
$\psi = \psi_s(r)\mathrm{e}^{-i\omega t}$

Solving these equations in time, we find Bose condensation!

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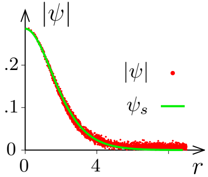


Solving these equations in time, we find Bose condensation!

- Maximally mixed (virialized) initial state
- Subsequent evolution in kinetic regime

$$l_{coh} \sim (mv)^{-1} \ll R$$
$$(mv^2)^{-1} \ll \tau_{gr}$$

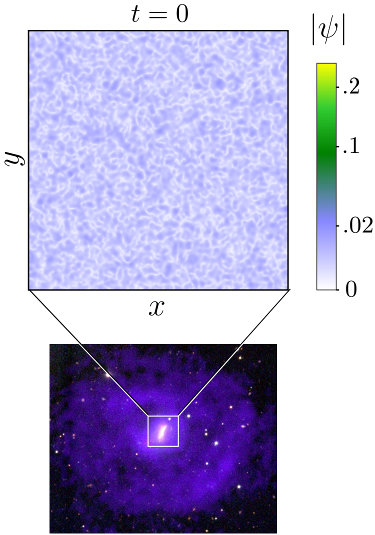
$\Rightarrow$ **Random initial field:**

$$\psi_p \propto \underbrace{e^{-p^2/2(mv_0)^2}}_{\text{momentum distribution}} \times \underbrace{e^{iA_p}}_{\text{random phases}}$$

$$\langle \psi(x)\psi(y) \rangle \propto e^{-\frac{(x-y)^2}{l_{coh}^2}}$$

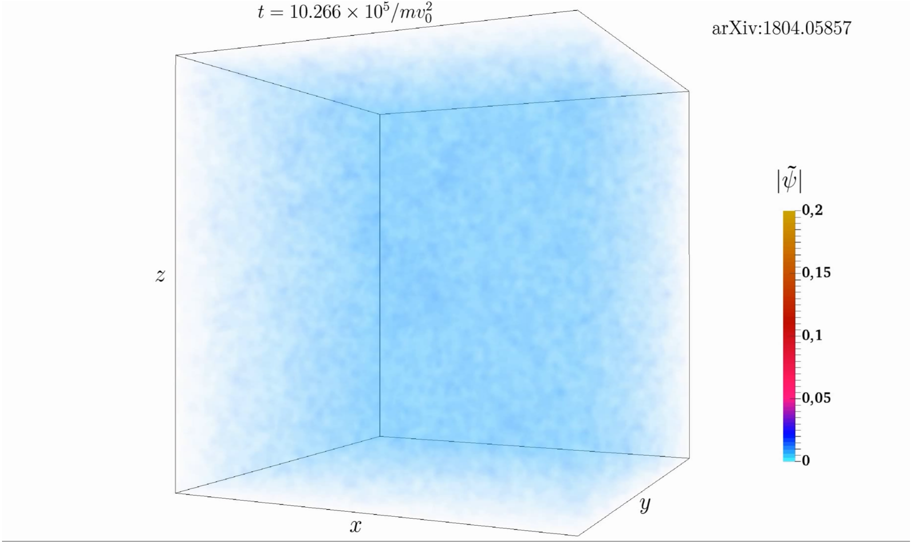
$$l_{coh} = \frac{2}{mv_0}$$

and $R \gg (mv_0)^{-1}$ is assumed

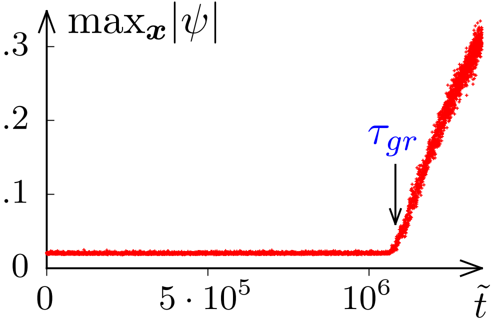


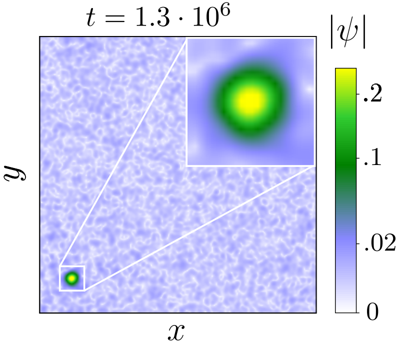
Virialized DM halo

Time evolution

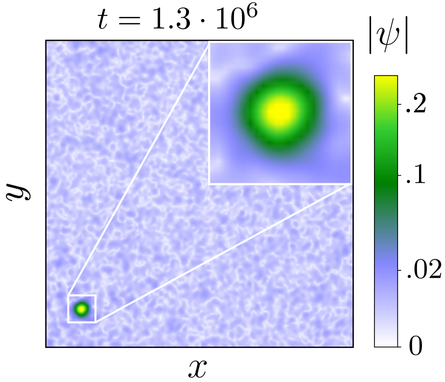


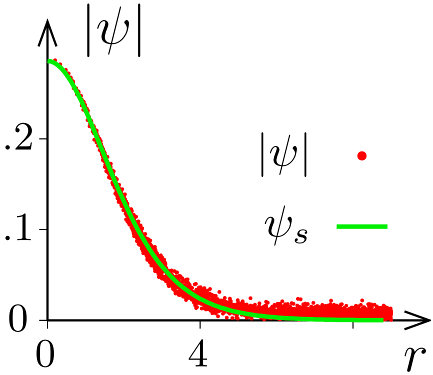
Maximum field value over the simulation box





This is not a Jeans instability

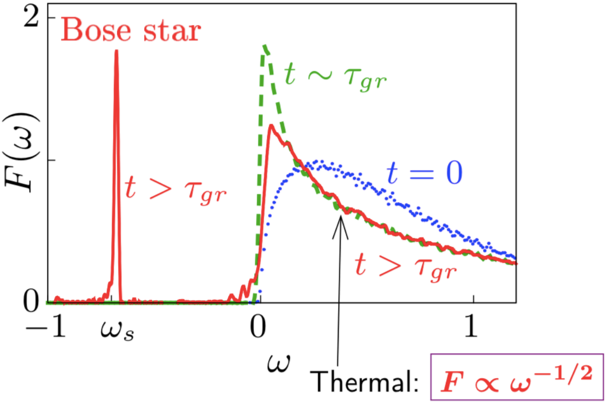




We observe formation of a Bose star at $t = \tau_{gr}$

Energy distribution at different moments of time

$$F(\omega,\, t) \equiv \frac{dn}{d\omega} = \int d^3x \int \frac{dt_1}{2\pi}\, \psi^*(t,x)\psi(t+t_1,x)\, \mathrm{e}^{i\omega t_1 - t_1^2/\tau_1^2}$$



Landau equation — derivation

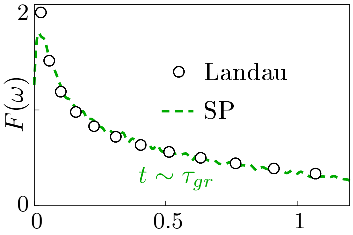
- Perturbative solution of Schrödinger-Poisson equation
- Kinetic approximations $(mv)^{-1} \ll x,\ (mv^2)^{-1} \ll t$
- Compute Wigner distribution

$$f_p(t,x) = \int d^3y\, \mathrm{e}^{-ipy} \langle \psi(x+y/2)\psi^*(x-y/2)\rangle$$

random phase average

e.g. Zakharov, L'vov, Falkovich '92

$$\partial_t f_p + \frac{p}{m}\nabla_x f_p - m\nabla_x \bar{U}\nabla_p f_p = \mathrm{St}\, f_p$$



Good agreement of lattice and kinetic $F(\omega)$

Kinetics

Landau equation — derivation

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- Kinetic approximations $(mv)^{-1} \ll x, \ (mv^2)^{-1} \ll t$
- Compute Wigner distribution

$$f_p(t,x) = \int d^3y \, e^{-ipy} \langle \psi(x+y/2)\psi^*(x-y/2) \rangle$$

random phase average

e.g. Zakharov, L'vov, Falkovich '92

$$\partial_t f_p + \frac{p}{m}\nabla_x f_p - m\nabla_x \bar{U}\nabla_p f_p = \mathrm{St}\, f_p \sim \frac{f_p}{\tau_{kin}} \leftarrow \text{relaxation time}$$

$$\mathrm{St}\, f_p \ni f_p^3 \leftarrow \text{Bose amplification}$$

Time to Bose star formation: $\tau_{gr} = b\,\tau_{kin} = \dfrac{4\sqrt{2}b}{\sigma_{gr} v\, n f}$

b: $O(1)$ correction

$$\tau_{gr} = \frac{4\sqrt{2}b}{\sigma_{gr} v n f}$$

Rutherford cross section: $\sigma_{gr} \approx 8\pi(mG)^2\Lambda/v^4$

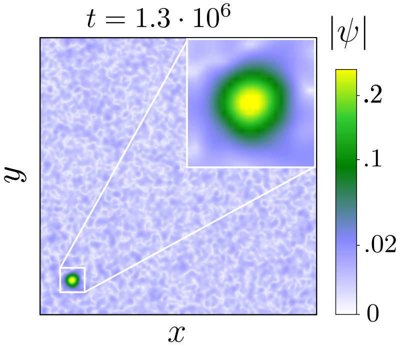
$$\Lambda = \log(mvR)$$

Coulomb logarithm

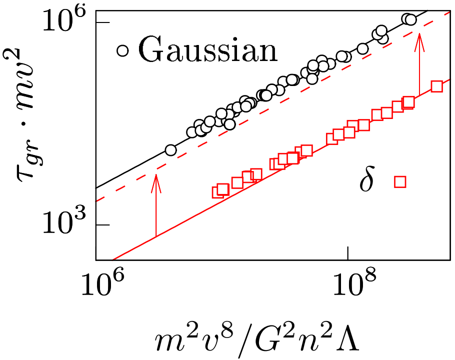
Average phase-space density: $f = 6\pi^2 n/(mv)^3$

$$\tau_{gr} = \frac{b\sqrt{2}}{12\pi^3} \frac{mv^6}{G^2\Lambda n^2} = \frac{b\sqrt{2}\pi}{3G^2 m^5 \Lambda} f^{-2}$$

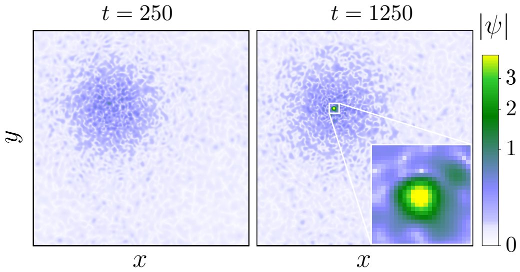
- Strongly depends on local quantities: n, v, f
- Involves global logarithm $\Lambda = \log(mvR)$



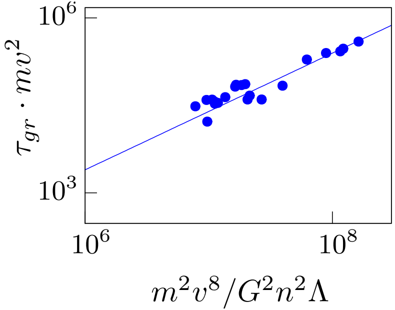
Kinetic scaling of τ_{gr} with parameters



- Gaussian: $f_p \propto |\psi_p|^2 \propto e^{-p^2/(mv_0^2)}$, $b \approx 0.9$
- δ: $f_p \propto \delta(|p - p_0|)$, $b \approx 0.6$



Large box $\Rightarrow$ Jeans instability
$\Rightarrow$ minicluster



$$\tau_{gr} = \frac{b\sqrt{2}}{12\pi^3}\,\frac{mv^6}{G^2\Lambda n^2}$$

Virial velocity: $v^2 \sim 4\pi GmnR^2/3$

$$\tau_{gr} \sim \frac{0.05}{\Lambda}\,\frac{R}{v}\,(Rmv)^3$$

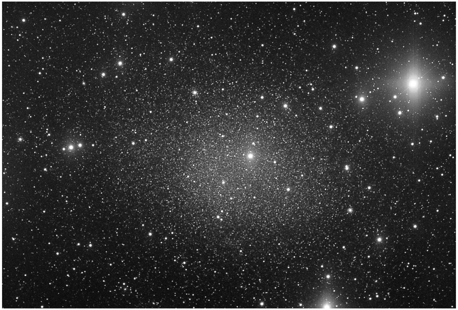
$\tau_{gr} \gg R/v \leftarrow$ free-fall time

$Rmv \sim 1$ — condense immediately

String axions

$$\tau_{gr} \sim 10^6\,\text{yr} \left(\frac{m}{10^{-22}\,\text{eV}}\right)^3 \left(\frac{v}{30\,\text{km/s}}\right)^6 \left(\frac{0.1\,M_\odot/\text{pc}^3}{\rho}\right)^2$$

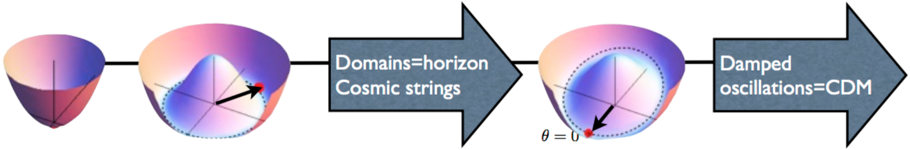
Fornax dwarf galaxy



$$v \sim 11\ \text{km/s}$$
$$\rho \sim 0.1\,M_\odot/\text{pc}^3$$
$$\tau_{gr} \sim 1000\ \text{yr}$$

Universe filled with Bose stars!

Models: QCD axion



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

Axion potential switches on at QCD epoch

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

$$\theta \equiv a/f_a$$

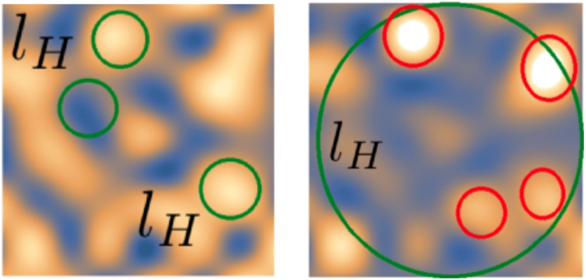
PQ phase transition before inflation is disfavored
PQ phase transition after inflation:

Three contributions to axion DM

- Coherent oscillations of axion field (misalignment angle)
- Decay of PQ strings
- Decay of QCD axion domain walls

M. Nagasawa and M. Kawasaki, Phys. Rev. D50 (1994) 4821

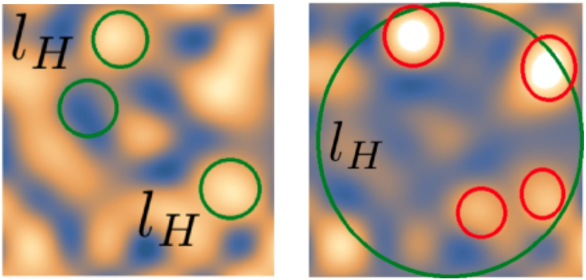
PQ phase transition after inflation $\rightarrow$ Miniclusters



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

QCD axion cosmology

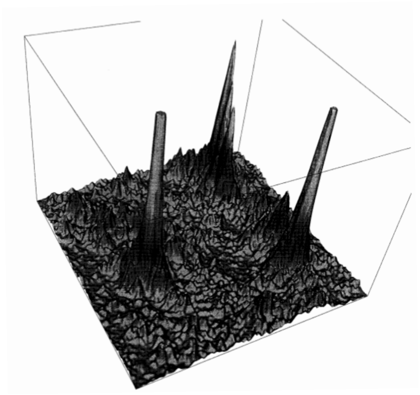
PQ phase transition after inflation → Miniclusters



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

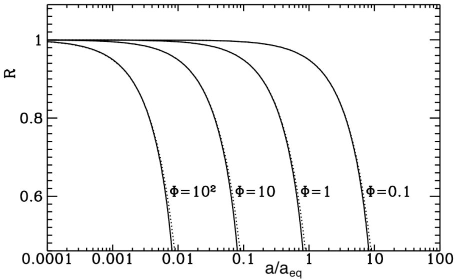
$$V(a) = m^2 f_a^2 \left(\frac{\theta^2}{2} - \frac{\theta^4}{4!} + \dots \right)$$

Minicluster Formation at QCD



The height of the plot is cut at $\mathbf{\Phi = 20}$.

Minicluster evolution around equality



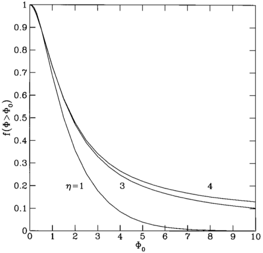
A clump becomes gravitationally bound at $\boldsymbol{T \approx \Phi\, T_{\rm eq}}$, i.e. its density today

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

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

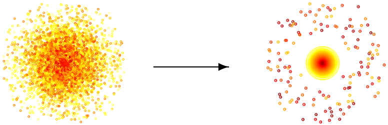
Models: QCD axions

$$\tau_{gr} \sim \frac{10^9\,\text{yr}}{\Phi^4}\left(\frac{M_c}{10^{-13}\,M_\odot}\right)^2\left(\frac{m}{26\,\mu\text{eV}}\right)^3$$



Mass fraction in miniclusters with $\Phi > \Phi_0$

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



- $\Phi \sim 1 \Rightarrow \tau_{gr} \sim 10^9$ yr
- $\Phi \sim 10^3 \Rightarrow \tau_{gr} \sim$ hr

Universe filled with Bose stars!

Abundance? Mass function?

Thorough study of axion production from from topological defects is needed

M. Kawasaki, K. Saikawa, T. Sekiguchi, Phys.Rev. D91 (2015) 065014

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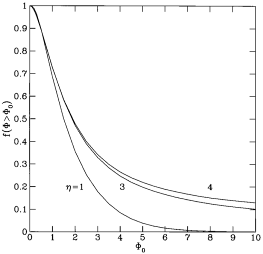

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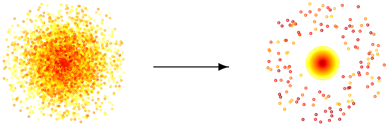

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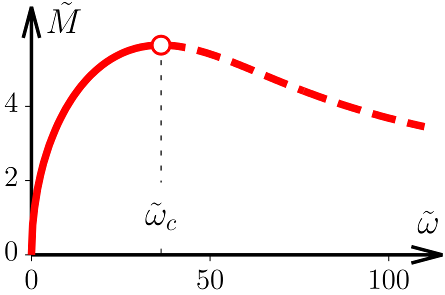
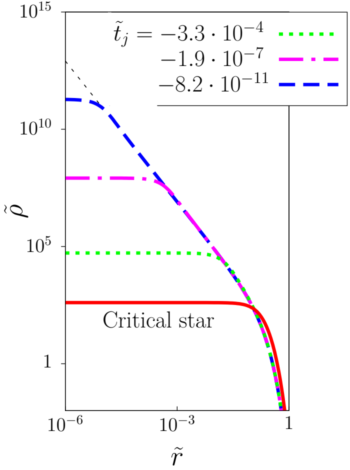
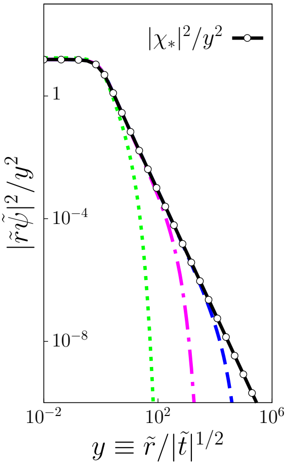
$$V(a) = m^2 f_a^2 \left(\frac{\theta^2}{2} - \frac{\theta^4}{4!} + \dots \right)$$

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



Self-similar wave collapse



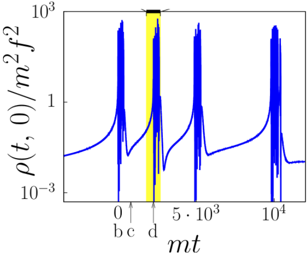


Black hole does not form for $f_a < M_{Pl}$

Repeated explosions

Field evolution in the center

Radial profiles at different times



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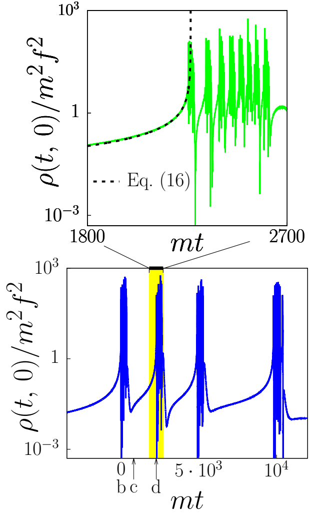

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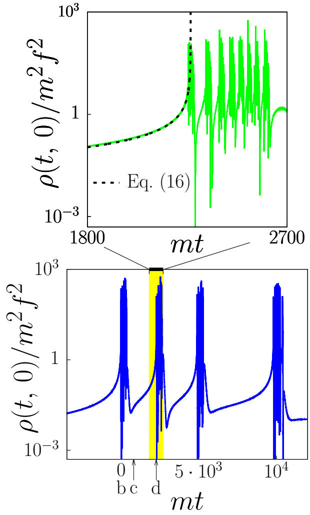

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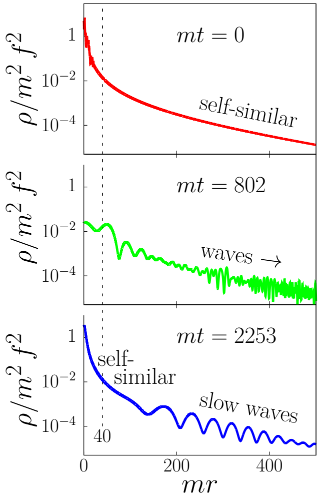
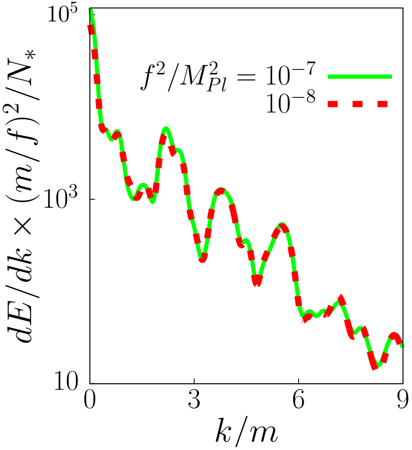
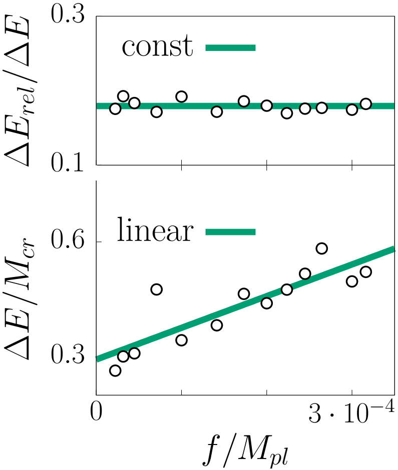


Decay of Bose star on relativistic axions

Spectra of emitted particles



Total emitted energy fraction



Phenomenological implications (QCD axions)

- Less diffuse DM -> smaller signals in DM detectorts
- But rare strong signals during encounters with debris of tidally disrupted miniclusters

  P.Tinyakov, IT and K. Zioutas, JCAP 1601 (2016) 035
- Gravitational microlensing and femtolensing

  E.Kolb & IT, Astrophys.J 460 (1996) L25

  M.Fairbairn, et. al, PRL 119 (2017) 021101
- Decay of Bose stars
  - Decay to relativistic self
    - Resolution of tension between low and high z observations?

      Z.Berezhiani, A.Dolgov & IT, Phys.Rev. D 92 (2015) 061303
  - Decay to radiophotons
    - Relation to FRB?

      IT, JETP Letters 101 (2015) 1

      A.Iwazaki, PRD 91(2015) 023008
    - Relation to ARCADE 2 excess and/or anomalous 21 cm signal?

      J.Kehayias, T.Kephart & T.Weiler, JCAP 1510 (2015) 053

      S.Fraser et al, arXiv:1803.03245

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

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

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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.

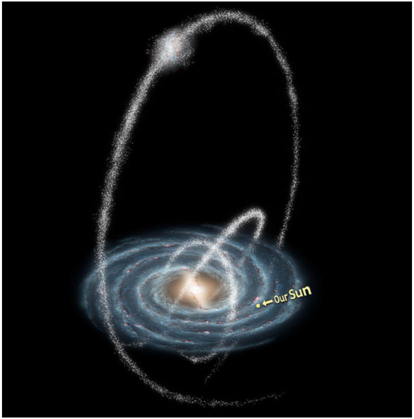
Tidal streams from miniclusters

Probability of a minicluster disruption

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

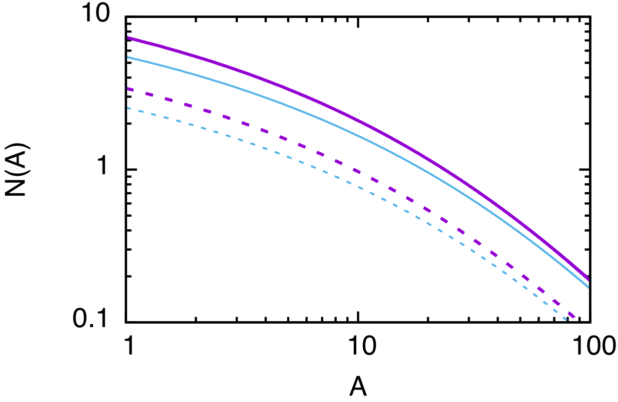
Just disk crossings. No actual orbits integration.

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



Crossing tidal streams from miniclusters

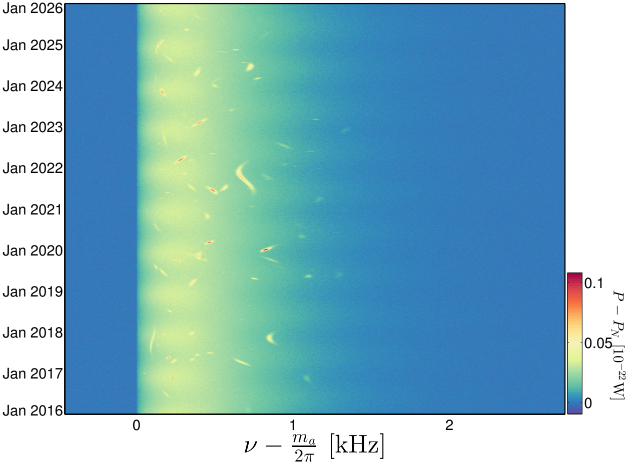
Mean number of encounters with axion streams producing amplification factor larger than A, as a function of A. Twenty year observation interval is assumed.



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

Crossing tidal streams from miniclusters

Simulation of expected PWS in cavity experiments



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

Conclusions

- Bose condensation by gravitational interactions is very effcient
- Large fraction of axion dark matter may consist of Bose stars
- Phenomenological implications of Bose star existence are reach and deserve further studies