Self-similar growth of axion stars

A. Dmitriev, Dmitry Levkov, A. Panin, I. Tkachev

INR RAS & ITMP MSU

ITMP MSU

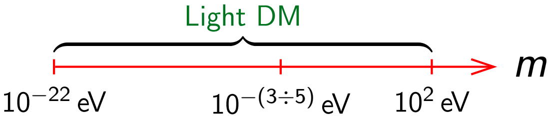
TWENTY-FIRST LOMONOSOV CONFERENCE ON ELEMENTARY PARTICLE PHYSICS
August, 24-30, 2023
MOSCOW STATE UNIVERSITY

DL, A. Panin, I. Tkachev, PRL **121** (2018) 151301

A. Dmitriev, DL, A. Panin, I. Tkachev, arXiv:2305.01005

Light bosonic (axion-like) dark matter

unknown mass!



String axions (Fuzzy DM)

- Predicted by string theory
- Any mass m

Arvanitaki et al '10

- Fuzzy DM: $m \sim 10^{-22}$ eV

e.g. Schive et al '04

$\Rightarrow$ Quantum at galaxy scales!

- $\lambda_4 \sim 10^{-100}$ — only gravity!

QCD axions

- Solve strong CP problem

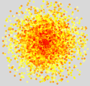
Peccei, Quinn '77

- Dark Matter:

$m \sim 10^{-5} - 10^{-3}$ eV

Klaer, Moore '17, Gorghetto et al '20

- Form miniclusters:



$M \sim 10^{-17} - 10^{-12}\, M_\odot$

Kolb, Tkachev '93; Pierobon et al '23

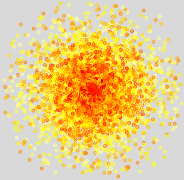
- $\lambda_4 \sim 10^{-50}$ — only gravity!

It's wave-like!

Any small structure

a dwarf galaxy

or axion minicluster



$\boldsymbol{\rho}, \boldsymbol{v}$ — known!

density, velocity

- **Large phase-space density!**

$$m \ll 10^2\,\text{eV} \quad \Rightarrow \quad f \sim \frac{\boldsymbol{\rho}/m}{(m\boldsymbol{v})^3} \gg 1$$

$$\Rightarrow \quad \textbf{classical field} \quad \boxed{\psi(t, \boldsymbol{x})}$$

- **Nonrelativistic approximation**

$v \ll 1 \Rightarrow$

Schrödinger-Poisson (SP) eqs

$$i\partial_t \psi = -\Delta\psi/2m + m\boldsymbol{U}\psi$$

$$\Delta \boldsymbol{U} = 4\pi G\, m|\psi|^2$$

grav. potential $U(t, x)$ field $\psi(t, x)$

Rich wave (quantum) phenomena?

Light DM Bose-condenses by gravitational scattering!

- **Gravitational kinetic relaxation:**

Levkov, Panin, Tkachev '18

$$t_{gr} = \frac{4\sqrt{2} m\, b}{\sigma_{gr}\, \boldsymbol{v}\, \boldsymbol{\rho}\, \boldsymbol{f}}$$

Rutherford cross section $\sigma_{gr} \propto (mG)^2 \Lambda / \boldsymbol{v}^4$

phase-space density $\boldsymbol{f} \propto (\boldsymbol{\rho}/m)/(m\boldsymbol{v})^3$

$$\boxed{t_{gr} = \frac{b\sqrt{2}}{12\pi^3} \frac{m^3 \boldsymbol{v}^6}{G^2 \Lambda \boldsymbol{\rho}^2}, \quad b \approx 0.9}$$

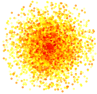
Coulomb logarithm: $\Lambda \equiv \log(mvR)$

- $\left.\begin{array}{l} \boldsymbol{v} \ll 1 \\ \boldsymbol{f} \gg 1 \end{array}\right\} \Rightarrow$ gravity is enhanced & beats self-coupling $\sigma_{gr} \gg \sigma_\lambda$

  - Long-range $\sigma_{gr} \propto \boldsymbol{v}^{-4}$
  - Bose-factor $\boldsymbol{f}$

- **Fuzzy DM in dwarf galaxies:** $t_{gr} \gtrsim 10^3$ **yr**

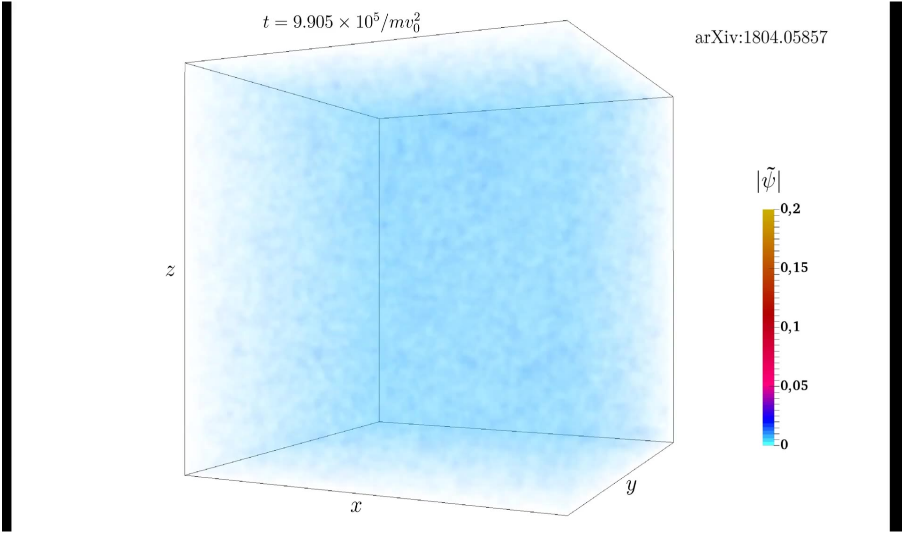
- **QCD axions in miniclusters:** $t_{gr} \gtrsim$ **hr**

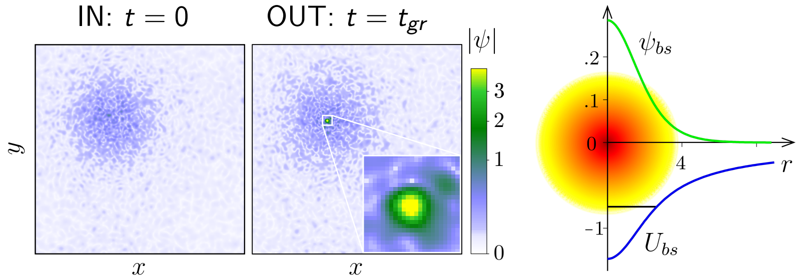


- $\boldsymbol{f} \gg 1$: **Relaxation $\Rightarrow$ Bose-condensation**

Simulation: solve SP equations!

starting from random (virialized) waves





- **Bose star** $=$ Bose-condensate on a single level of U_{bs}
- DM is light $\Rightarrow$ **The Universe is packed with Bose stars!**

How do the Bose stars grow?

- A difficult problem
- Numerical simulations: conflicting results

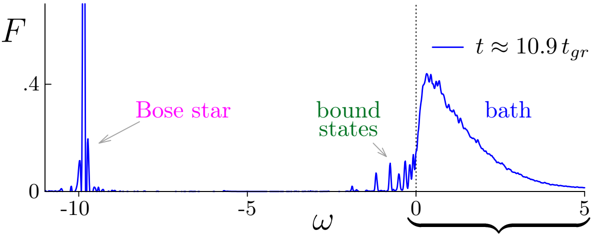
$$M_{bs} \propto t^{1/2},\ t^{1/4},\ t^{1/8}$$

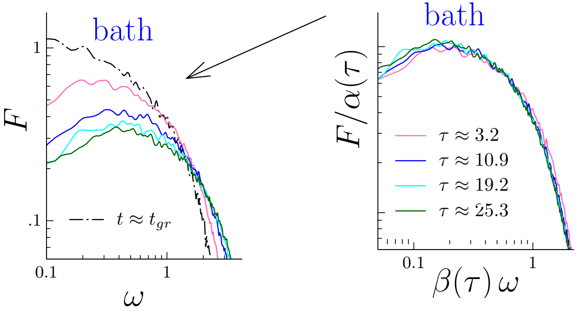
e.g. Levkov et al '18, Eggemeier et al '19, Chan et al '22

But the solution is simple and analytical!

Distribution of particles over energies

$$F(t,\omega) \equiv \frac{1}{N}\frac{dN}{d\omega} = \int \frac{dt_1 d^3\mathbf{x}}{2\pi N}\, \psi(t,\mathbf{x})\, \psi^*(t+t_1,\, \mathbf{x})\, \mathrm{e}^{i\omega t_1 - t_1^2/\Delta t^2}$$





Scaling symmetry

$$F = \alpha F_s(\beta\omega)$$

$\alpha = \tau^{-1/D}$	$\beta = \tau^{2/D-1}$

$$\tau \equiv t/t_{gr}, \quad D = 2.8$$

Self-similar bath

- Consider the bath $\omega > 0$
- Ignore the Bose star potential ~~$U_{bs}(r)$~~

$\Rightarrow$ $\partial_t F = \mathrm{St}\, F$

bath kinetic eq.

Ansatz passes the equation!

$$F(\tau, \omega) = \alpha(\tau) \underbrace{F_s}_{\text{self-similar profile}} (\beta(\tau)\omega) \qquad \alpha = \tau^{-1/D}, \quad \beta = \tau^{2/D-1}$$

$\tau \equiv t/t_{gr}$

$\Rightarrow$ Profile Eq:

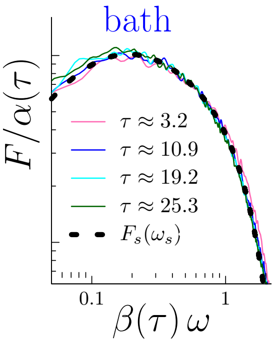
$$(2/D - 1)\omega_s \partial_{\omega_s} F_s - F_s/D = \mathrm{St}\, F_s$$

$\Rightarrow$ Power-law bath mass & energy

$$M_b \propto \tau^{1-3/D}, \quad E_b \propto \tau^{2-5/D}$$

$$E_b^3/M_b^5 \propto \tau$$

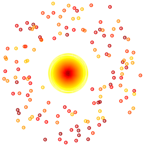
non-autonomous system!



- Nontrivial BC: Particle Flux $\neq 0$ at $\omega = 0$

Then the solution exists
And it is a kinetic attractor

Assumptions:



- Quasi-stationary & self-similar bath:

$$D = D(t) \quad \text{but still} \quad \boxed{E_b^3/M_b^5 \propto \tau}$$

- Energy & mass conservation:

$$E_b = E - E_{bs} - E_e, \qquad M_b = M - M_{bs} - M_e$$

Bose star (E_{bs}, M_{bs}); ex. states (E_e, M_e)

- Bose star energy:

$$E_{bs} = -\gamma M_{bs}^3, \quad \gamma \approx 0.0542\, m^2 G^2$$

constant

- Low occupancies of bound states:

$x_e \equiv M_e/M \approx \text{const}$, $E_e \approx 0$ — confirmed by simulations

$$\frac{(1 + x^3/\epsilon^2)^3}{(1 - x_e - x)^5} = \frac{\tau - \tau_i}{\tau_*}$$

- $x(\tau) \equiv M_{bs}/M$
- $\tau \equiv t/t_{gr}$

A simple and predictive law!

Compare with simulations

Equation

$$\frac{(1 + x^3/\epsilon^2)^3}{(1 - x_e - x)^5} = \frac{\tau - \tau_i}{\tau_*}$$

Variables

- $x(\tau) \equiv M_{bs}/M$
- $\tau \equiv t/t_{gr}$

Parameters

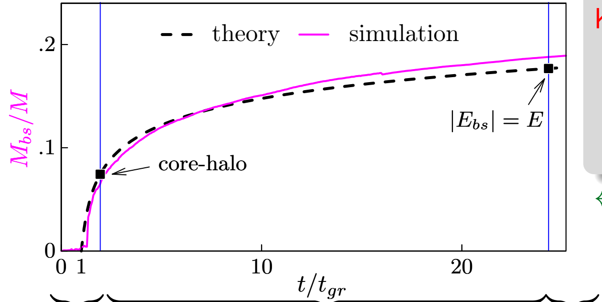
To fit:

- $x_e \equiv M_e/M$ — small
- $\tau_i \approx -0.1$ — universal

Known:

- $\epsilon^2 \equiv E/\gamma M^3$
- $\tau_* = \frac{1-\tau_i}{(1-x_e)^5}$ $\leftrightarrow$ $M_{bs}(1) = 0$

Comparison:



$\leftarrow$ $\epsilon = 0.074$, $x_e = 0.043$, $\tau_i = -0.1$

$M_{bs} \propto t$ $\quad t^{1/3} \quad t^{1/9}$ — like in simulations!

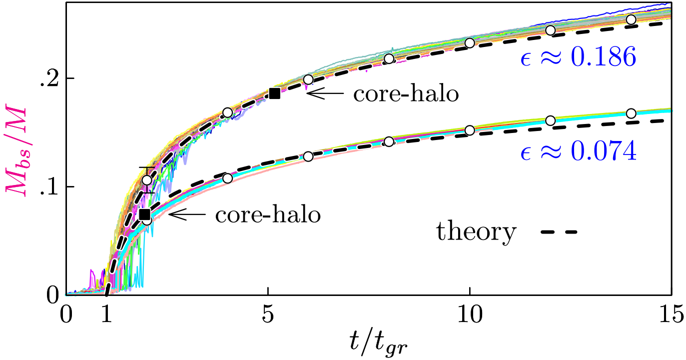
cf. Levkov et al '18, Eggemeier et al '19, Chan et al '22

core-halo: $|E_{bs}/M_{bs}| = E/M$ — stars in simulations "stop growing"

Schive et al '14

Statistical test

- 33 simulations
- Essentially different t_{gr} & two values of ϵ



Other performed tests

+ Nonzero self-interaction $\lambda_4 \neq 0$
+ Condensation in miniclusters

Applications to cosmology: String axions

$$\frac{(1 + x^3/\epsilon^2)^3}{(1-x)^5} \sim \frac{t}{t_{gr}}$$

$$x(t) \equiv \frac{M_{bs}}{M}$$

Core of Fornax dwarf

$M \sim 10^8\, M_\odot$
$v_{\mathrm{vir}} \sim 20$ km/s

- Parameters:

$$t_{gr} \sim 0.05\, \frac{m^3 (GM)^4}{\Lambda {v_{\mathrm{vir}}}^6}$$

$$\epsilon \sim 3\, \frac{v_{\mathrm{vir}}}{GmM}$$

- Time to "core-halo" slowdown:

$$t_{\mathrm{c/h}} \sim 9\epsilon t_{gr} \sim \Lambda^{-1} m^2 (GM)^3 / v_{\mathrm{vir}}^5$$

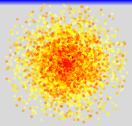
- Fuzzy DM in Fornax Dwarf ($m \sim 10^{-22}$ eV)
  $t_{\mathrm{c/h}} \sim 10^7\, yr$ — form & grow
- Experimental bound: $m \gtrsim 2 \cdot 10^{-20}$ eV
  $t_{\mathrm{c/h}} \gtrsim 10^{11}\, yr$ — do not grow! (in Fornax)
  Larger galaxies are worse!

Only small Bose stars exist in the Universe!

Applications to cosmology: QCD axion, $m = 10^{-4}$ eV

$$\frac{(1 + x^3/\epsilon^2)^3}{(1-x)^5} \sim \frac{t}{t_{gr}} \qquad x(t) \equiv \frac{M_{bs}}{M}$$

Axion minicluster



$M \sim 10^{-17\div 12}\, M_\odot$

$\Phi = \delta\rho_a/\bar{\rho}_a\big|_{RD} = 0 \div 10^3$

Hogan, Rees '88; Kolb, Tkachev '93

- Parameters:

$$t_{gr} \sim \frac{5\cdot 10^8\,\text{yr}}{\Phi^4} \left(\frac{M}{10^{-14}\,M_\odot}\right)^2 \left(\frac{m}{10^{-4}\,\text{eV}}\right)^3$$

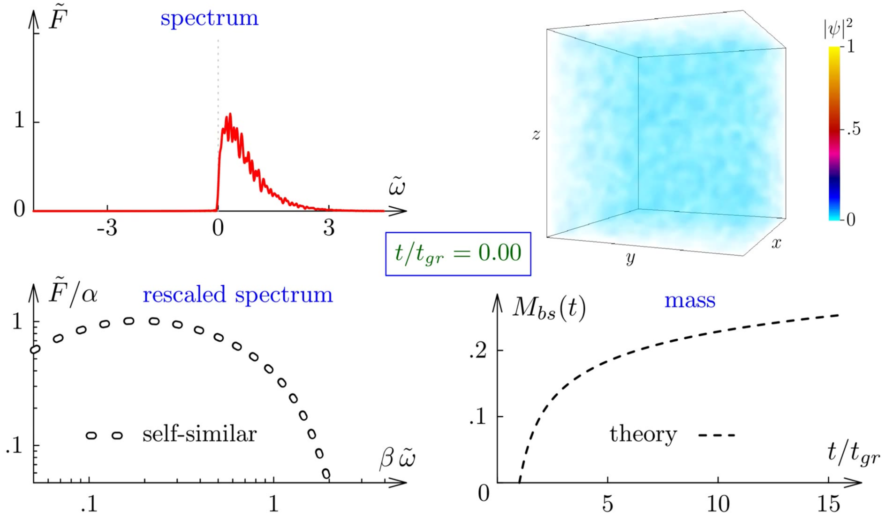
$$\epsilon \sim 0.02\,\Phi^{2/3} \left(\frac{M}{10^{-14}\,M_\odot}\right)^{-2/3} \left(\frac{m}{10^{-4}\,\text{eV}}\right)^{-1}$$

- Time to eat 10% of minicluster:

$$t_{10} \sim t_{gr}\frac{(10\%)^9}{\epsilon^6} < 10^{10}\,\text{yr} \qquad \text{if} \qquad \boxed{\Phi \gtrsim 1}$$

All denser miniclusters turn into axion stars

The Universe is packed with grown-up axion stars!



$\tilde{F}$
spectrum
1
0
$\tilde{\omega}$
-3
0
3
$t/t_{gr} = 0.00$
z
y
x
$|\psi|^2$
1
.5
0
$\tilde{F}/\alpha$
rescaled spectrum
1
.1
self-similar
$\beta\,\tilde{\omega}$
.1
1
$M_{bs}(t)$
mass
.2
.1
0
theory
t/t_{gr}
5
10
15

Conclusions II: Implications of Bose stars in axion cosmology

- Less diffuse DM ⇒ weaker signals in DM detectorts
- Gravitational microlensing and femtolensing

  Kolb, Tkachev '96; Fairbairn et al '17
- Radio lines from transient axion stars

  Witte et al '22
- Parametric resonance: radio explosions of heavy stars — explain FRB?

  Levkov, Panin, Tkachev '20; Chung-Jukko et al '22
- Radio-emitting stars reionize the cosmological medium

  Escudero et al '23
- Bosenovas: heavy stars collapse & emit relativistic axions

  Levkov, Panin, Tkachev '17; Eby et al '22

THANK YOU FOR ATTENTION!

This work was supported by the RSF grant 22-12-00215