Axion stars and their possible astrophysical manifestations

I. Tkachev

INR RAS, Moscow

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Outline

- Formation of Bose Stars

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

  - QCD axion miniclusters

- Axion Bose Star collapse

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

- Cosmological and astrophysical implications

Bose-stars

- Bose star is a self-gravitating clump of Bosons 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-condensation

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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*

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

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

$$\boxed{\begin{matrix}\psi(t, x) \\ U(t, x)\end{matrix}}$$

Field equations for light DM (Scrödinger-Poisson system)

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

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

Solving these equations in time, we find Bose condensation!

Bose condensation by gravitational interactions

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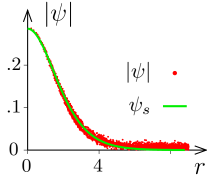


Solving these equations in time, we find Bose condensation!

Initial conditions

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

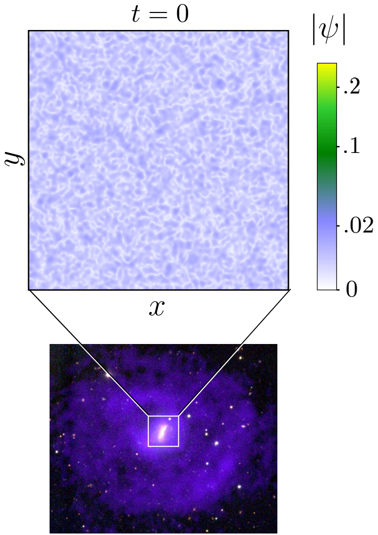
$$\boxed{\begin{aligned} l_{coh} \sim (mv)^{-1} &\ll R \\ (mv^2)^{-1} &\ll \tau_{gr} \end{aligned}}$$

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

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

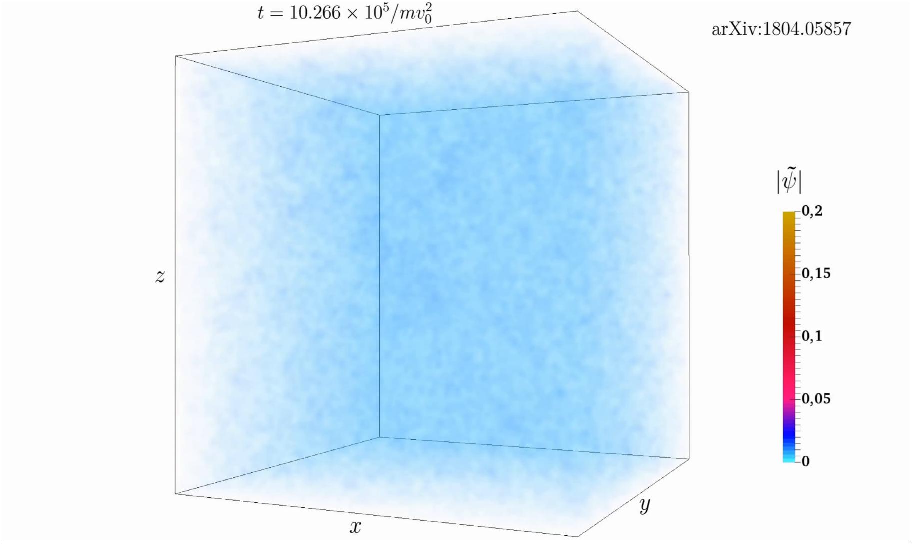
$$\langle \psi(x)\psi(y) \rangle \propto e^{-\frac{(x-y)^2}{l_{coh}^2}} \qquad \boxed{l_{coh} = \frac{2}{mv_0}}$$

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

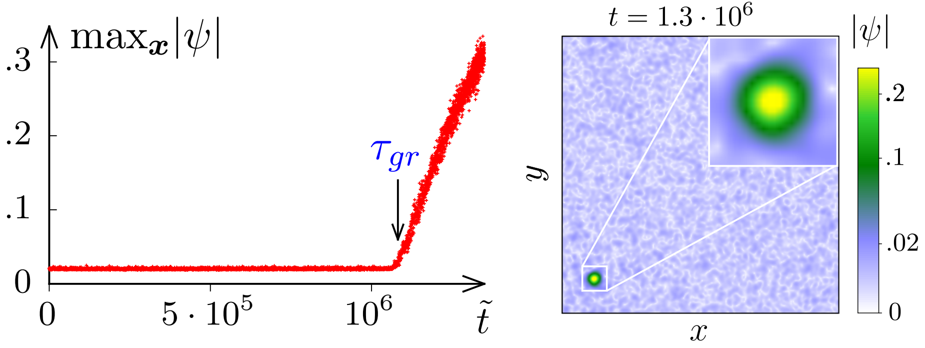


Virialized DM halo

Time evolution

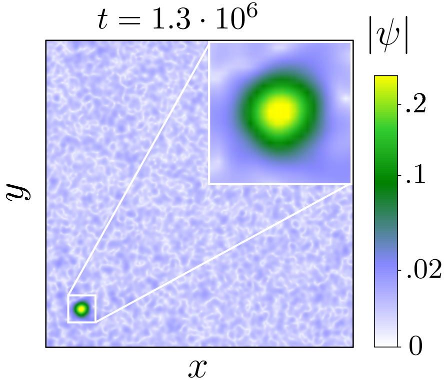


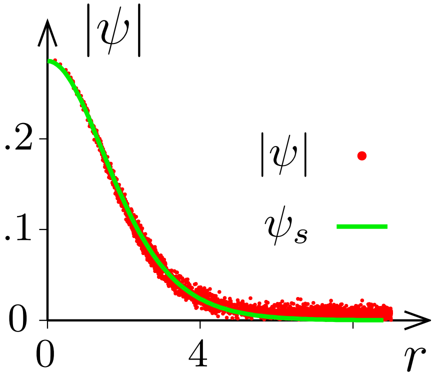
Maximum field value over the simulation box



This is not a Jeans instability

Simulation variables: $\boldsymbol{x} = \frac{\tilde{x}}{mv_0}$, $\boldsymbol{t} = \frac{\tilde{t}}{mv_0^2}$, $\boldsymbol{U} = v_0^2\tilde{U}$, $\boldsymbol{\psi} = v_0^2\tilde{\psi}\sqrt{\frac{m}{G}}$

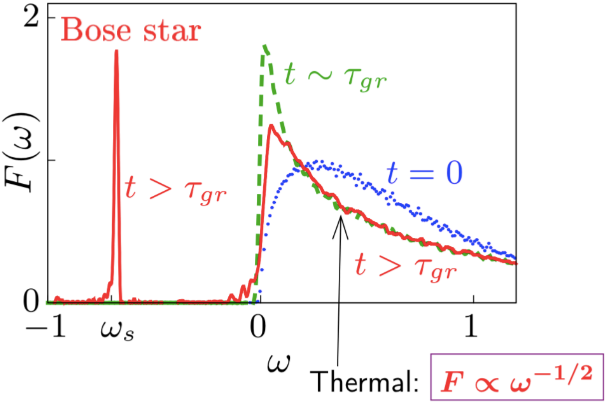




We observe formation of a Bose star at $t = \tau_{gr}$

Energy distribution at different moments of time

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



Kinetics

Landau equation — derivation

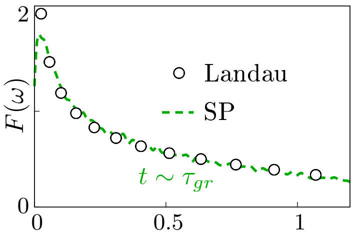
- Perturbative solution of Schrödinger-Poisson equation
- Kinetic approximations $(mv)^{-1} \ll x, \; (mv^2)^{-1} \ll t$
- Compute Wigner distribution

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

random phase average

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

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



Good agreement of lattice F and kinetic f,

$$F(\omega) = \frac{mpf_p}{2\pi^2}, \qquad \omega = \frac{p^2}{2m}$$

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$$\partial_t f_p + \frac{p}{m}\nabla_x f_p - m\nabla_x \bar{U}\nabla_p f_p = \mathrm{St}\, f_p \equiv \boxed{\frac{f}{\tau_R}} \leftarrow \text{relaxation time}$$

$$\Downarrow$$

$$f_p^3 \leftarrow \text{Bose amplification}$$

Time to Bose star formation: $\tau_{gr} = \underset{\substack{\uparrow \\ O(1)\ \text{correction}}}{b}\, \tau_R = \dfrac{4\sqrt{2}b}{\sigma_{gr} v\, n f}$

Time to Bose star formation

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

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

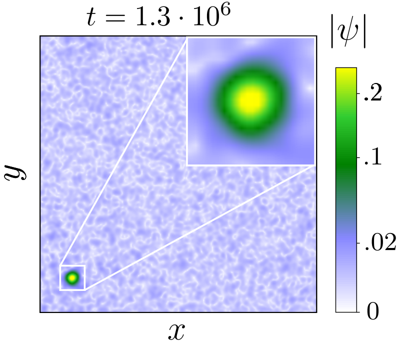
$$\boxed{\Lambda = \log(mvR)}$$

Coulomb logarithm

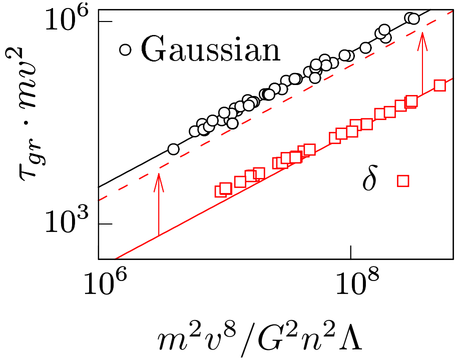
Average phase-space density: $f = 6\pi^2 n/(mv)^3$

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

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

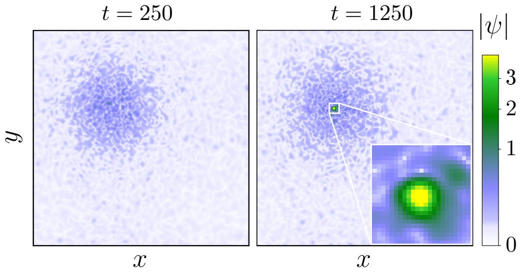


Kinetic scaling of τ_{gr} with parameters

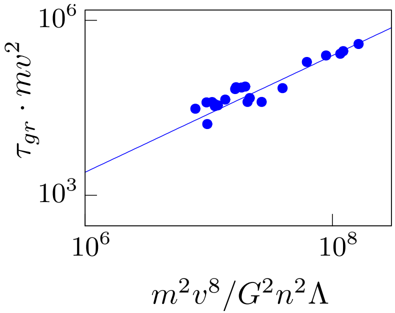


- Gaussian: $f_p \propto |\psi_p|^2 \propto \mathrm{e}^{-p^2/(mv_0^2)}$, $b \approx 0.9$
- δ: $f_p \propto \delta(|p - p_0|)$, $b \approx 0.6$

Bose star formation in halo/minicluster



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



Virial velocity: $v^2 \sim 4\pi G m n R^2/3$

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

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

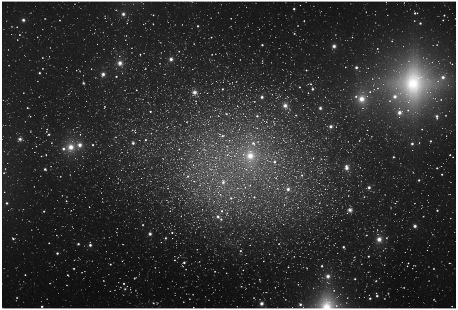
$Rmv \sim 1$ — condense immediately

Models: fuzzy dark matter

String axions

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

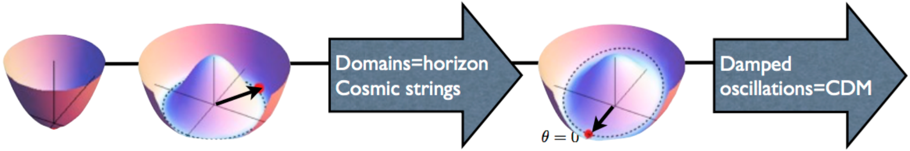
Fornax dwarf galaxy



$$\begin{aligned} v &\sim 11\ \text{km/s} \\ \rho &\sim 0.1\,M_\odot/\text{pc}^3 \\ \tau_{bs} &\sim 1000\ \text{yr} \end{aligned}$$

Universe filled with Bose stars!

Models: QCD axion



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

Axion potential switches on at QCD epoch

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

$$\theta \equiv a/f_a$$

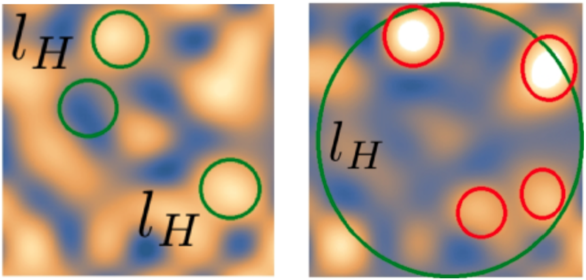
PQ phase transition before inflation is disfavored
PQ phase transition after inflation:

Three contributions to axion DM

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

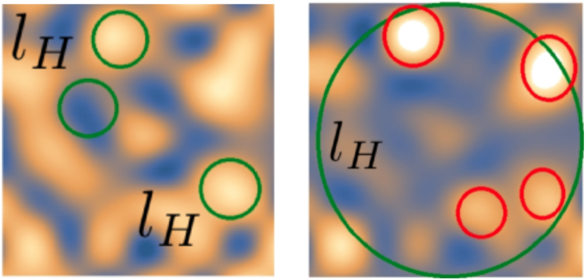
see lectures by David Marsh, this workshop

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
- Dark Matter should be very clumpy
- Mass scale of the clumps is set by $M \sim 10^{-11}\, M_\odot$, which is DM mass within horizon at $T_{\text{osc}} \approx 1$ GeV

PQ phase transition after inflation $\rightarrow$ Miniclusters

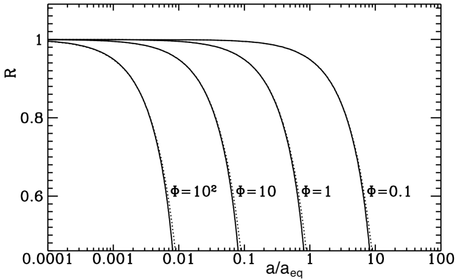


- Naively, initial DM density contrast is $\delta\rho_a/\rho_a \equiv \Phi \sim 1$
- In fact, very dense objects can form, $\Phi \gg 1$, since for $\theta \sim 1$ the axion attractive self-coupling is non-negligible,

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

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

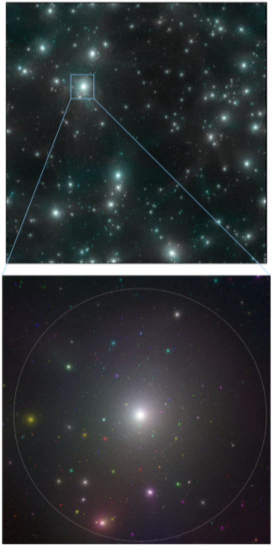
Minicluster formation around equality



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

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

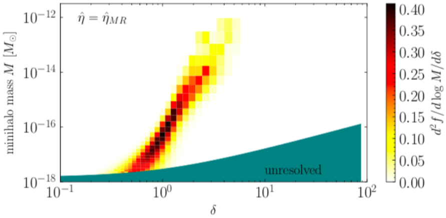
E.Kolb & IT, Phys.Rev. D50 (1994) 769



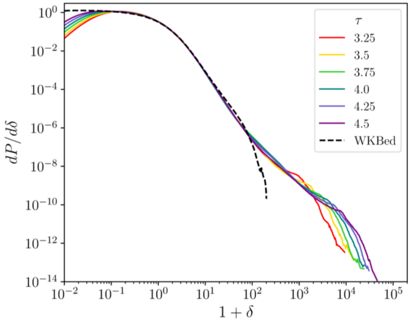
B.Eggemeier, et al arXiv:1911.09417

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

Mass fraction in miniclusters



M.Buschmann, J.Foster, B.Safdi, arXiv:arXiv:1906.00967



A.Vaquero et al (2019)

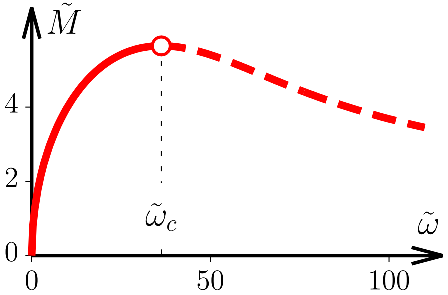
- $\Phi \sim 1$, $M \sim 10^{-16}\,M_\odot \;\Rightarrow\; \tau_{bs} \sim 10^3$ yr
- $\Phi \sim 5$, $M \sim 10^{-13}\,M_\odot \;\Rightarrow\; \tau_{bs} \sim 10^6$ yr

Universe filled with axion Bose stars!

ALP Bose star instability

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

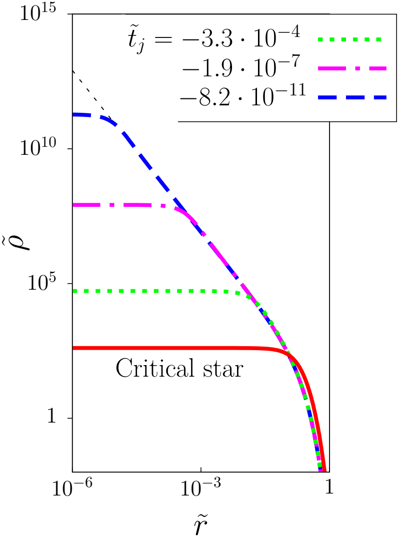
Self-coupling of axions is negative and axion Bose stars are unstable against collapse.



Here ω is gravitational binding energy,

$$\psi = \psi_s(r) \mathrm{e}^{-i\omega t}$$

Self-similar wave collapse



$$\rho \propto \frac{1}{r^2} \quad \Rightarrow$$

$$\Phi(r) \propto \log(r) \quad \Rightarrow$$

Black holes can form if

$$f_a \sim M_{\rm Pl}$$

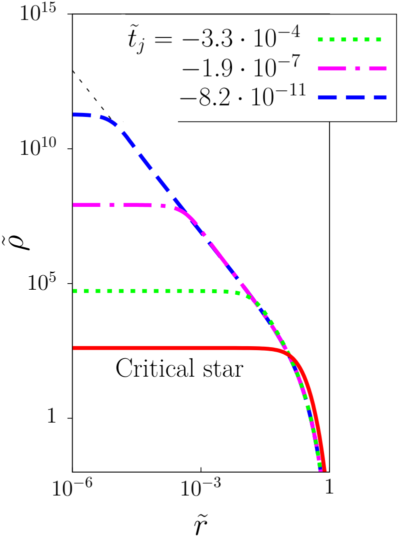
T. Helfer et al. JCAP 03 (2017) 055

Black holes does not form if

$$f_a < M_{\rm Pl}$$

What is outcome then?

Self-similar wave collapse



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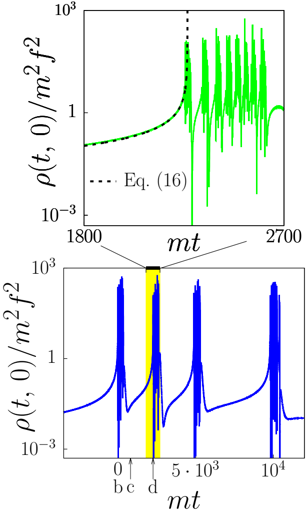
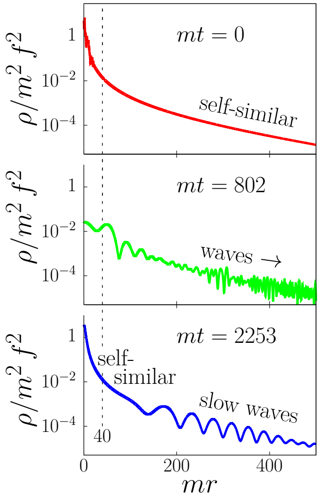
Repeated explosions

Field evolution in the center



Radial profiles at different times



Phenomenological implications

- Less diffuse DM $\Rightarrow$ smaller signals in DM detectorts
- Gravitational lensing, microlensing and femtolensing
- Decay of Bose stars
  - Can produce black holes if $f_a \sim M_{\rm Pl}$
  - Decay to relativistic self *D.Levkov, A.Panin, & IT, PRL 118 (2017) 011301*
    - Resolution of tension between low and high z observations?
  - Decay to radiophotons *D.Levkov, A.Panin, & IT, Phys.Rev.D 102 (2020) 023501*
    - Produces clear signature, emission line at $\nu = m_a/2$
    - Can produce excess radio-background (ARCADE?)
    - Relation to FRB?
- Coalesence $\Rightarrow$ specific signal in gravitational waves?

Conclusions

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