Axion stars: formation and collapse

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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 applications

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.
  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

$$\left.\right\} \quad \boxed{\begin{array}{l} \psi(t,x) \\ U(t,x) \end{array}}$$

Field equations for light DM

Scrödinger-Poisson system:

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

Solving these equations, we find condensation!

Bose condensation by gravitational interactions

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

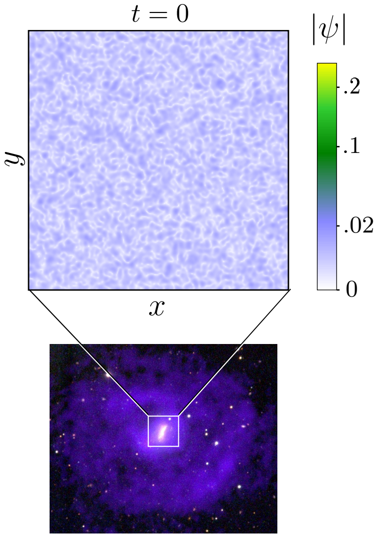
$$\boxed{\begin{aligned} l_{coh} \sim (mv)^{-1} &\ll R \\ (mv^2)^{-1} &\ll \tau_{gr} \end{aligned}}$$

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

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

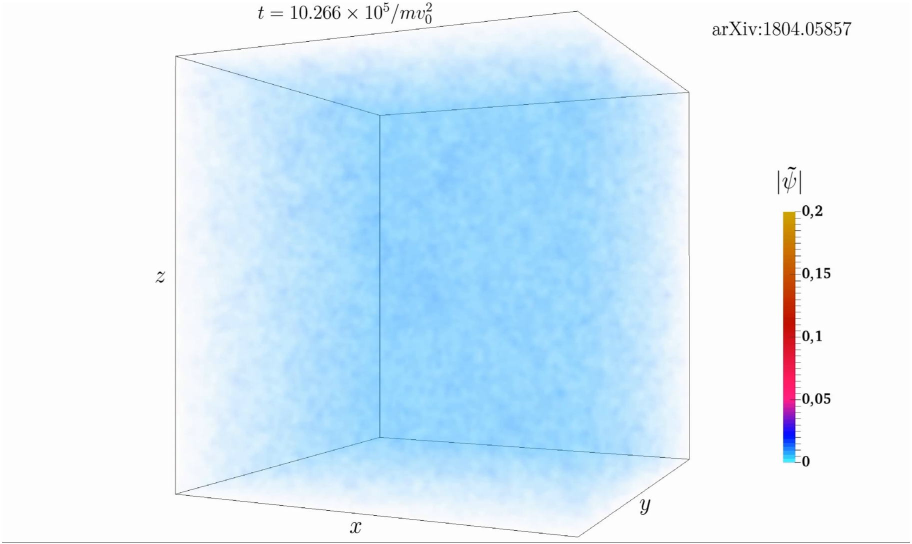
$$\langle \psi(x)\psi(y)\rangle \propto e^{-\frac{(x-y)^2}{l_{coh}^2}} \qquad \boxed{l_{coh} = \frac{2}{mv_0}}$$

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

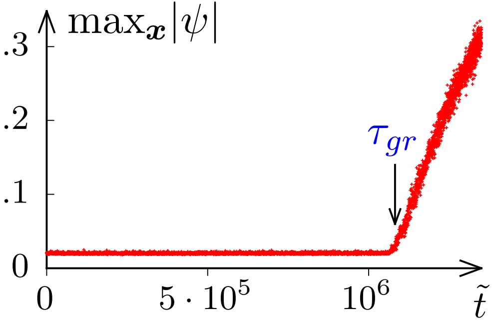


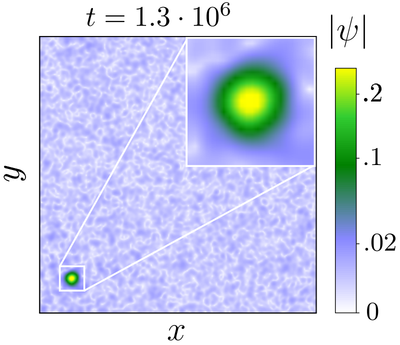
Virialized DM halo

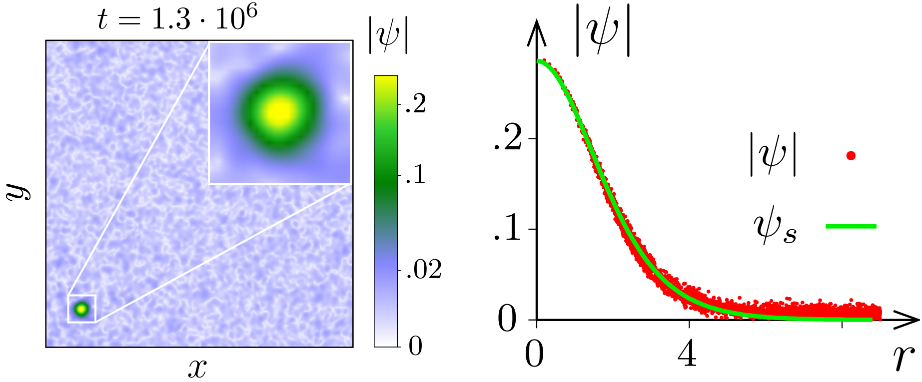
Time evolution



Maximum field value over the simulation box



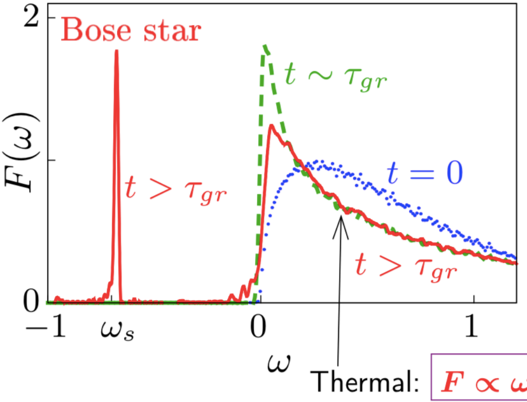




We observe formation of a Bose star at $t = \tau_{gr}$

Energy distribution at different moments of time

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



$\boxed{F \propto \omega^{-1/2}}$

Kinetics

Landau equation — derivation

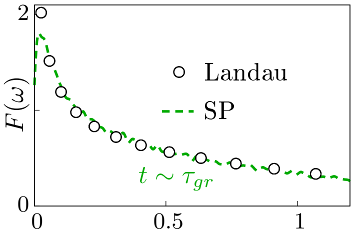
- Perturbative solution of Schrödinger-Poisson equation
- Kinetic approximations $(mv)^{-1} \ll x, \; (mv^2)^{-1} \ll t$
- Compute Wigner distribution

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

random phase average

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 $F(\omega)$

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

$$\Downarrow$$

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

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

Time to Bose star formation

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

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

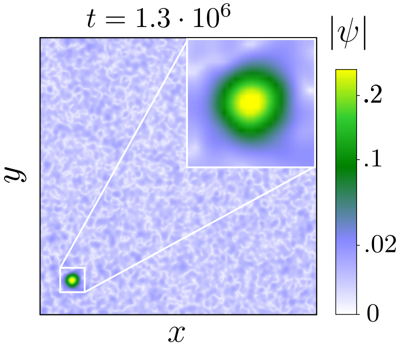
$$\boxed{\Lambda = \log(mvR)}$$

Coulomb logarithm

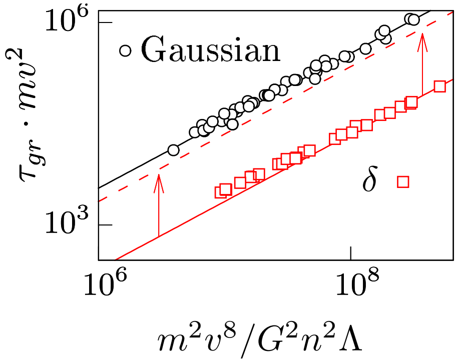
Average phase-space density: $f = 6\pi^2 n/(mv)^3$

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

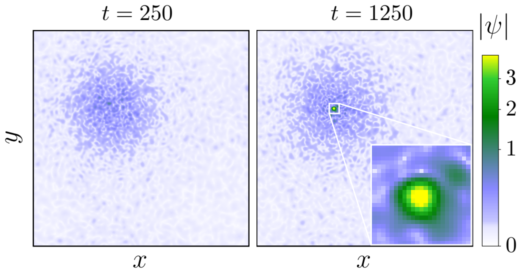
- Strongly depends on local quantities: n, v, f
- Involves global logarithm $\Lambda = \log(mvR)$

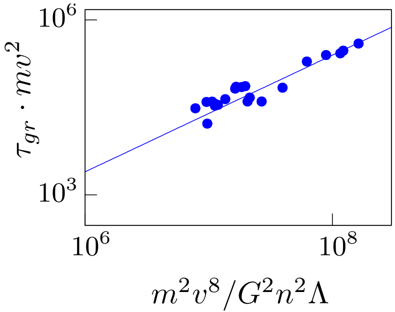


Kinetic scaling of τ_{gr} with parameters



- Gaussian: $f_p \propto |\psi_p|^2 \propto e^{-p^2/(mv_0^2)}$, $b \approx 0.9$
- 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: $v^2 \sim 4\pi G m n R^2/3$

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

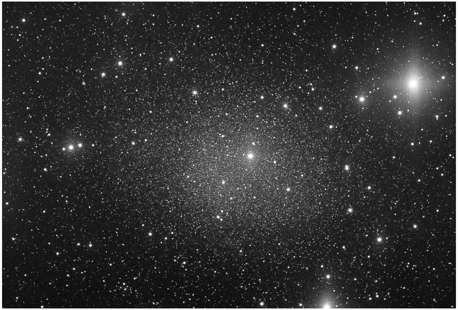
$\tau_{gr} \gg R/v \leftarrow$ free-fall time
$Rmv \sim 1$ — condense immediately

Models: fuzzy dark matter

String axions

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

Fornax dwarf galaxy

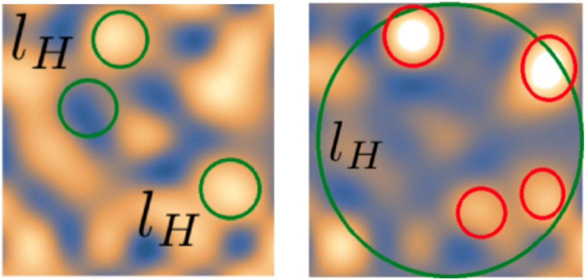


$$\begin{aligned} v &\sim 11\ \text{km/s} \\ \rho &\sim 0.1\,M_\odot/\text{pc}^3 \\ \tau_{gr} &\sim 1000\ \text{yr} \end{aligned}$$

Universe filled with Bose stars!

Models: QCD axions

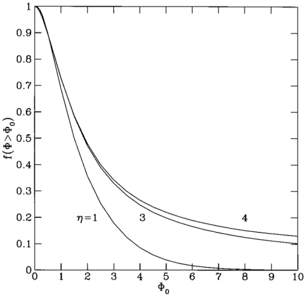
PQ phase transition before inflation is disfavored
PQ phase transition after inflation $\rightarrow$ Miniclusters



- 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
- Resulting DM density contrast at QCD epoch $\delta\rho_a/\rho_a \equiv \Phi \gg 1$

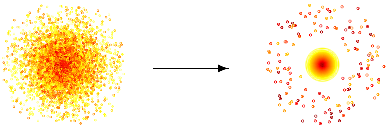
Kolb, Tkachev '93 - '96

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



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

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



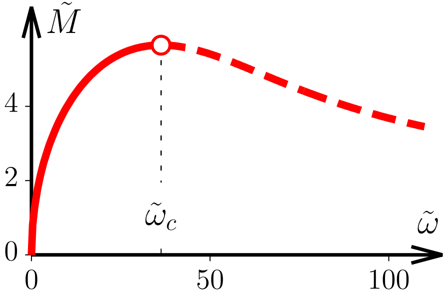
- $\Phi \sim 1 \Rightarrow \tau_{gr} \sim 10^9$ yr
- $\Phi \sim 10^3 \Rightarrow \tau_{gr} \sim$ hr

Universe filled with Bose stars!

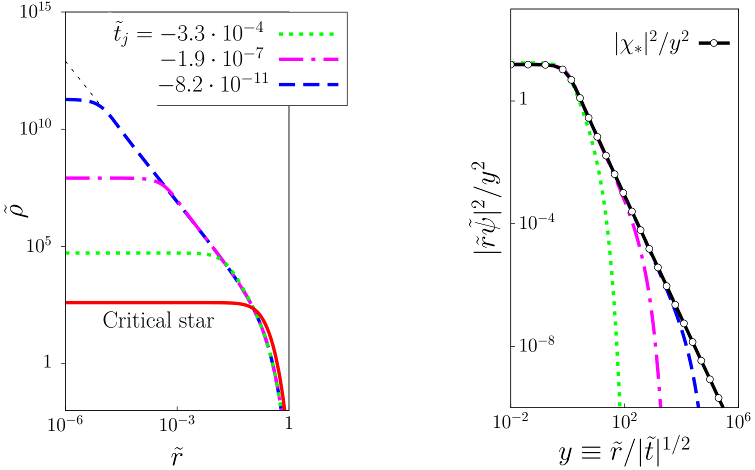
ALP Bose star instability

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

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



Self-similar wave collapse

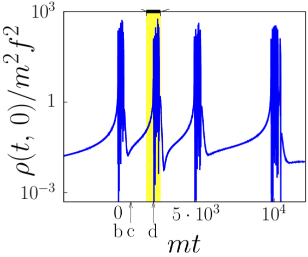


Black hole does not form for $f_a < M_{Pl}$

Repeated explosions

Field evolution in the center

Radial profiles at different times



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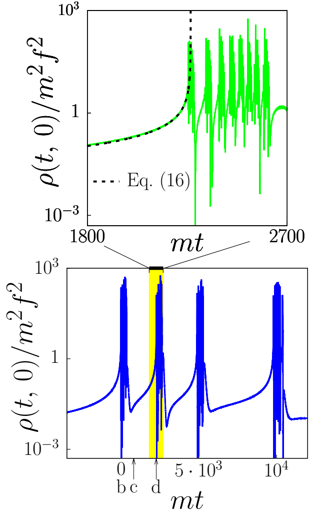

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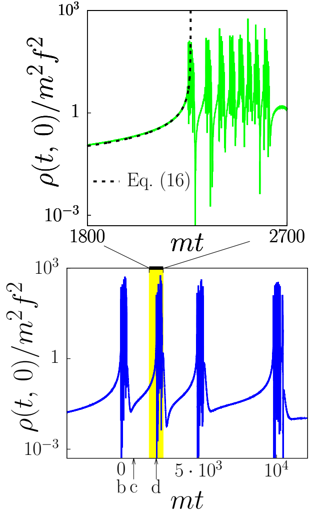

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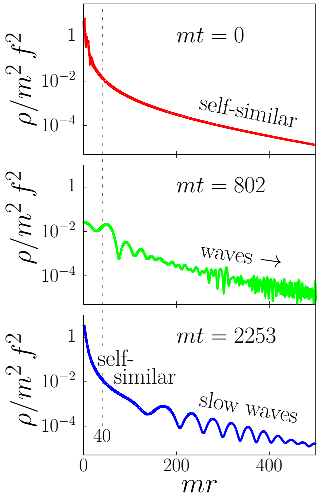
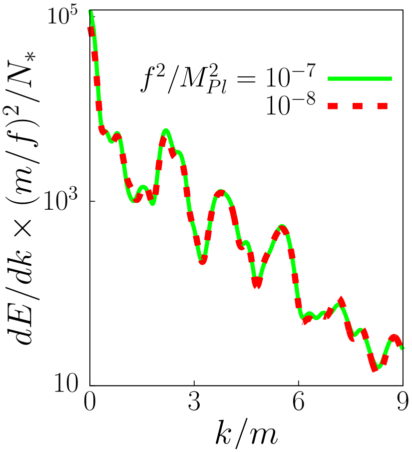
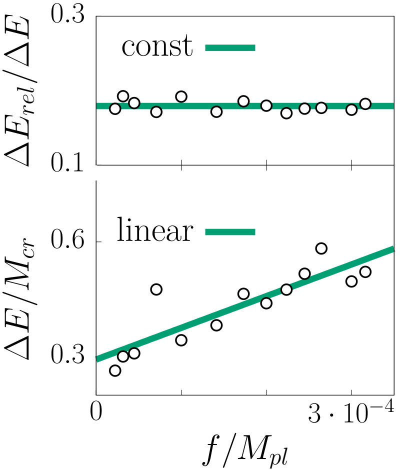


Decay of Bose star on relativistic axions

Spectra of emitted particles



Total emitted energy fraction



Phenomenological implications

QCD axion Bose stars

- Less diffuse DM -> smaller signals in DM detectorts
- Gravitational microlensing and femtolensing
- 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?

      J.Kehayias, T.Kephart & T.Weiler, JCAP 1510 (2015) 053
    - Relation to anomalous 21 cm signal?

      S.Fraser et al, arXiv:1803.03245

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