Bose condensation and decay of ALP dark matter

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Outline

- Formation of axion Bose stars

  D.Levkov, A.Panin, & IT, arXiv:1804.05857
- Explosions of axion Bose stars
  - Explosions to relativistic axions

    D.Levkov, A.Panin, & IT, PRL 118 (2017) 011301
  - Explosions to radiophotons

    D.Levkov, A.Panin, & IT, to appear

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

Bose condensation by gravitational interactions

Are we crazy?

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

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

Field equations for light DM

Scrödinger-Poisson system:

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

Solving these equations, we find condensation!

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Different setup to previous simulations

Previously: $\xcancel{l_{coh} \sim (mv)^{-1} \ll R}$ which gives non-kinetic regime

Coherent initial states:

- Smooth wavepacket

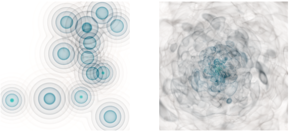
  Seidel, Suen '94

  Guzman, Urena-Lopez '06

- Many Bose stars

  Schive et al '14

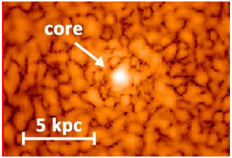
  Schwabe, Niemeyer, Engels '16 →



- Cosmological Bose condensate

  Schive, Chiueh, Broadhurst '14

  Veltmaat, Niemeyer, Schwabe '18 →



- Random fields in small box, $R \sim (mv)^{-1}$

  Khlebnikov '99

Initial conditions

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

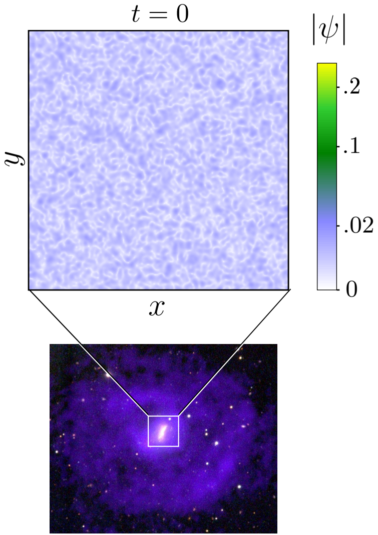
$$\boxed{\begin{aligned} l_{coh} \sim (mv)^{-1} &\ll R \\ (mv^2)^{-1} &\ll \tau_{gr} \end{aligned}}$$

⇒ **Random initial field:**

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

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

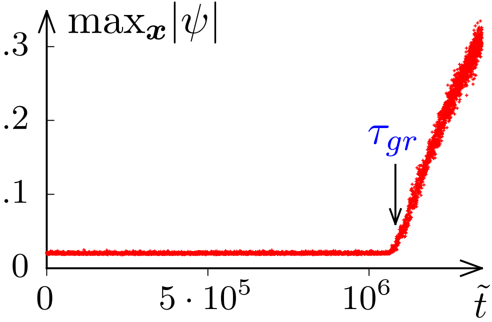
and $R \gg (mv_0)^{-1}$ is assumed

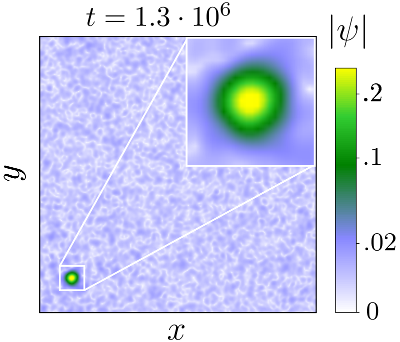


Virialized DM halo

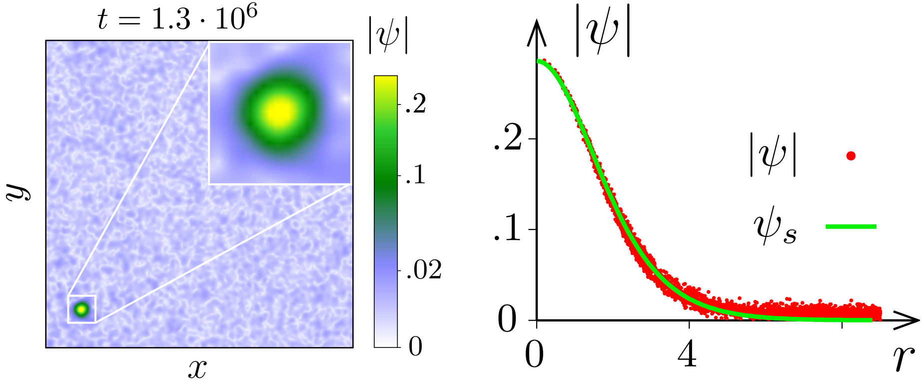
Time evolution

Maximum field value over the simulation box





It's a Bose star

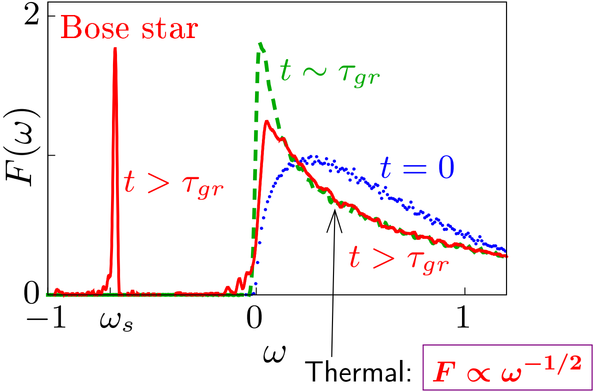


We observe formation of a Bose star at $t = \tau_{gr}$

Bose star signature: another view

Energy distributions at different moments of time

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



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

Kinetics

Landau equation — derivation

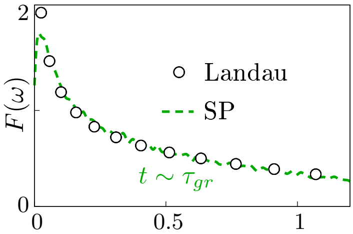
- Perturbative solution of Schrödinger-Poisson equation
- Kinetic approximations $(mv)^{-1} \ll x,\ (mv^2)^{-1} \ll t$
- Compute Wigner distribution

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

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 $F(\omega)$

Kinetics

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

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

$$\partial_t f_p + \frac{p}{m}\nabla_x f_p - m\nabla_x \bar{U} \nabla_p f_p = \underset{\underset{f_p^3 \,\leftarrow\, \text{Bose amplification}}{\Cup}}{\mathrm{St}\, f_p} \sim \frac{f_p}{\tau_{kin}} \leftarrow \text{relaxation time}$$

cf. Landau, Lifshitz, v. X

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

Time to Bose star formation

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

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

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

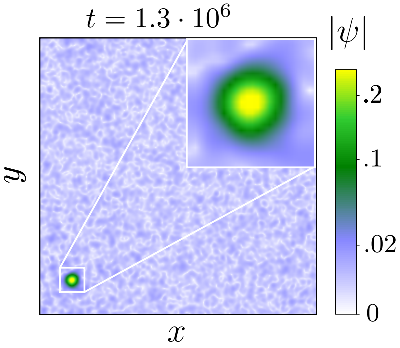
Coulomb logarithm

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

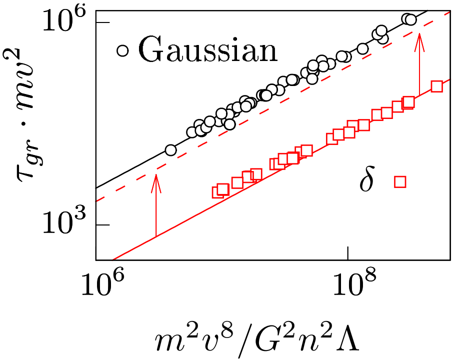
$$\boxed{\tau_{gr} = \frac{b\sqrt{2}}{12\pi^3}\,\frac{mv^6}{G^2\Lambda n^2} = \frac{b\sqrt{2}\pi}{3G^2m^5\Lambda}\; f^{-2}}$$

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

Time to Bose star formation

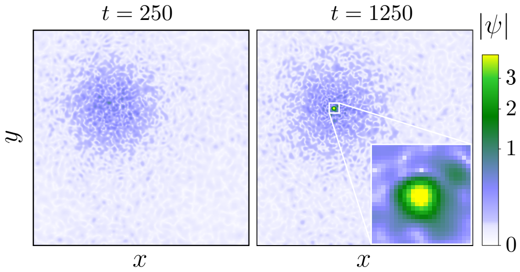


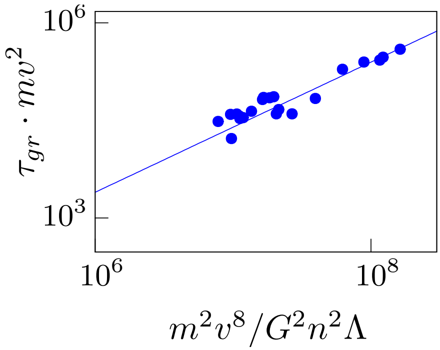
Kinetic scaling of τ_{gr} with parameters



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

Bose star formation in halo/minicluster





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

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

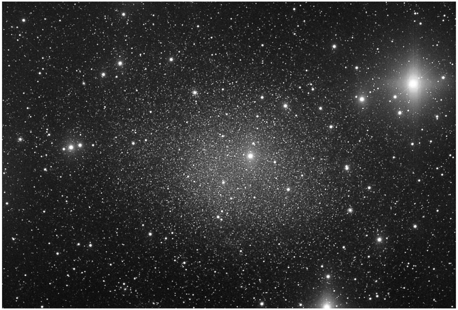
$\tau_{gr} \gg R/v$ ← free-fall time
$Rmv \sim 1$ — condense immediately

Applications to cosmology

String axions

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

Fornax dwarf galaxy

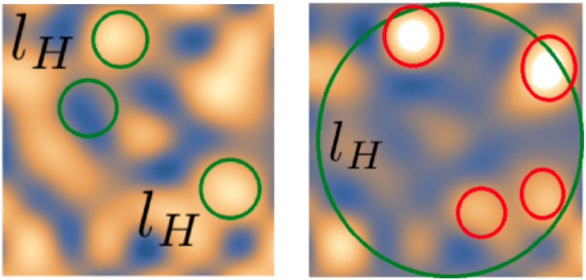


$$\begin{aligned} v &\sim 11\ \mathrm{km/s} \\ \rho &\sim 0.1\,M_\odot/\mathrm{pc}^3 \\ \tau_{gr} &\sim 1000\ \mathrm{yr} \end{aligned}$$

Universe filled with Bose stars!

Axion cosmology

PQ phase transition before inflation is disfavored
PQ phase transition after inflation → Miniclusters



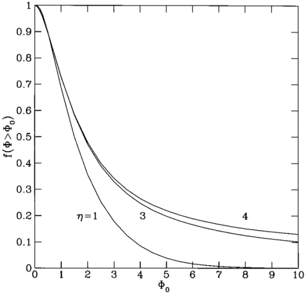
- Mass scale of the clumps is set by $M \sim 10^{-11}\, M_\odot$, which is DM mass within l_H^3 at $T_{\rm osc} \approx 1$ GeV
- Resulting DM density contrast at QCD epoch $\delta\rho_a/\rho_a \equiv \Phi \gg 1$

Kolb, Tkachev '93 - '96

Applications to cosmology

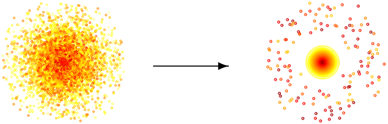
QCD axions

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



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!

Phenomenological implications

QCD axion Bose stars

- Less diffuse DM -> smaller signals in DM detectorts
- Gravitational microlensing and femtolensing
- Decay of Bose stars
    - Dark Matter decay
        - Relation to low and high z cosmological tension?

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

          IT, JETP Letters 101 (2015) 1

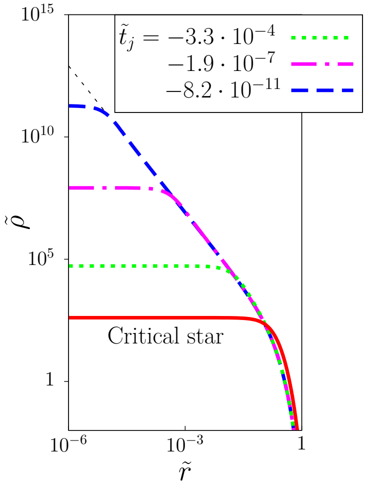
          A.Iwazaki, PRD 91(2015) 023008
        - Relation to ARCADE 2 excess?

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

          S.Fraser et al, arXiv:1803.03245

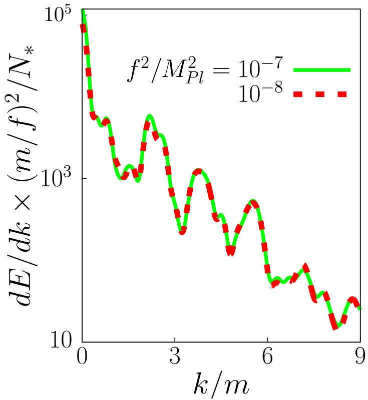
ALP Bose star collapse

Self-similar wave collapse



Black hole does not form if $\boldsymbol{f_a < M_{Pl}}$

Spectra of emitted relativistic axions



$\sim$ **30%** of Bose star is radiated away

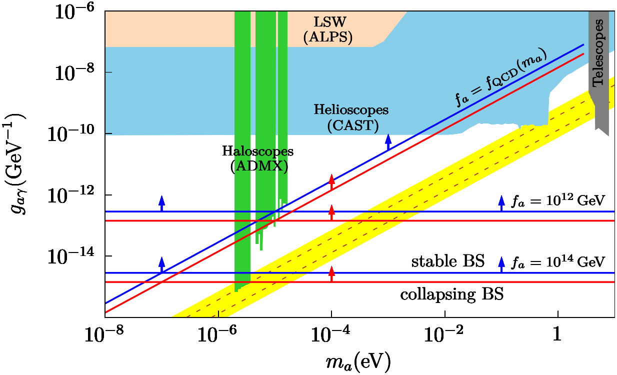
D.Levkov, A.Panin, & IT, PRL 118 (2017) 011301

Resonant photon production

$$D \equiv \frac{g_{a\gamma} m_a f_a}{\sqrt{2}} \int_{-\infty}^{+\infty} \psi(x) dx$$

Resonance condition in a finite volume $D > \pi/2$.
For a spherically symmetric critical star $\Rightarrow g_{a\gamma} \gtrsim 0.29/f_a \Rightarrow$ **conversion of Bose star into radiophotons**

D.Levkov, A.Panin, & IT, to appear



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