Bose stars

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Light bosonic dark matter

- **Fits into the galaxy:**

$$(mv)^{-1} \lesssim R \quad \Rightarrow \quad \boxed{m \gtrsim 10^{-22}\,\mathrm{eV}}$$

- **Can be only bosonic:**

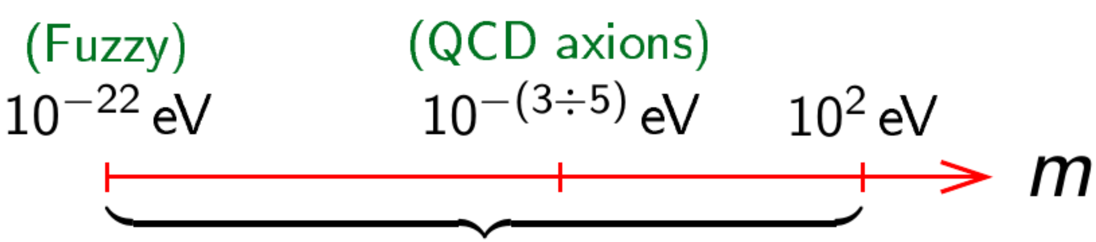
$$f \sim \frac{\rho/m}{(mv)^3} \gtrsim 1 \quad \Leftarrow \quad \boxed{m \lesssim 100\,\mathrm{eV}}$$

$$\gg 1 \quad \Rightarrow$$ classical field!

- **Forms BE condensate:**

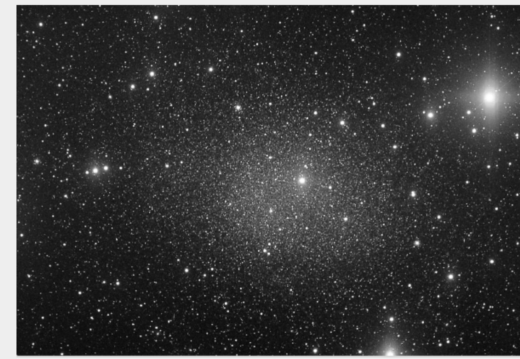
$$T < T_c \quad \Rightarrow$$

$$mv^2 \lesssim n^{2/3}/m \quad \Leftarrow \quad \boxed{m \lesssim 100\,\mathrm{eV}}$$



Interaction $\Rightarrow$ Bose-Einstein condensation!

any dwarf galaxy



Kinematics is known!

$\rho \sim 0.1\,\mathrm{M}_\odot/\mathrm{pc}^3$

$R \sim \mathrm{kpc}$

$v \sim 10\,\mathrm{km/s}$

Q: Do they interact strongly enough?

A: YES, gravitationally!

Axion-Like Particles (ALP)

$a(t, \mathbf{x})$

- (Pseudo)scalars
- Small mass m

} Pseudo-Nambu-Goldstone bosons

- Can form Cold DM via vacuum realignment

[Preskill, Wise, Wilczek '83]

[Abbott, Sikivie '83]

String axions (Fuzzy DM)

- Predicted by string theory
- Any mass m [Arvanitaki et al '10]
- Fuzzy DM: $m \sim 10^{-22}\,\mathrm{eV}$ [Hu et al '00]
- $\lambda_4 \sim 10^{-96}$

QCD axions

- Solve strong CP problem [Peccei, Quinn '77]
- Dark Matter: $m \sim 10^{-5}\,\mathrm{eV}$ [Klaer, Moore '17]

  $m \gtrsim 10^{-3}\,\mathrm{eV}$ [Gorghetto et al '20]
- $\lambda_4 \sim 10^{-44} - 10^{-52}$

Mass is small, selfinteraction is negligible!

Describing ALP DM

1. $f \gg 1$ ⇨ classical field $a(t, \mathbf{x})$: $\hbar = c = k_B = 1$

$$\Box a + m^2 a - \frac{g_4^2}{6} \frac{m^2}{f_a^2} a^3 + \ldots = 0$$

self-interaction

2. $v \ll 1$ ⇨ nonrelatisitic axions $E_a \simeq m$:

$$a = \frac{f_a}{\sqrt{2}} \left[\psi(t, \mathbf{x})\, \mathrm{e}^{-imt} + \mathrm{h.\,c.}\right],\ \text{where}\ \partial_{t,\mathbf{x}} \psi \ll m\psi$$

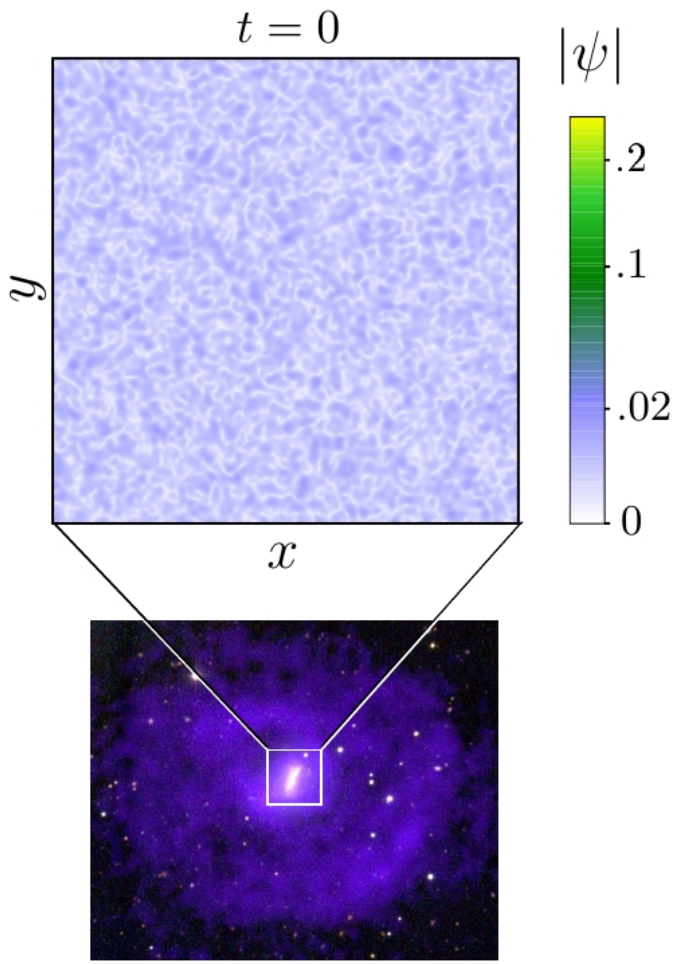
$$i\partial_t \psi = -\frac{\Delta \psi}{2m} + m \left(\Phi - \frac{g_4^2}{8} |\psi|^2 \right) \psi$$

3. Newtonian gravity: $\Phi(t, \mathbf{x}) \ll 1$

$$\Delta \Phi(t, \mathbf{x}) = 4\pi G m^2 f_a^2 |\psi|^2$$

Schrödinger-Poisson system: $\psi(t, \mathbf{x})$, $\Phi(t, \mathbf{x})$

Bose-Einstein condensation



random waves in
halo/minicluster

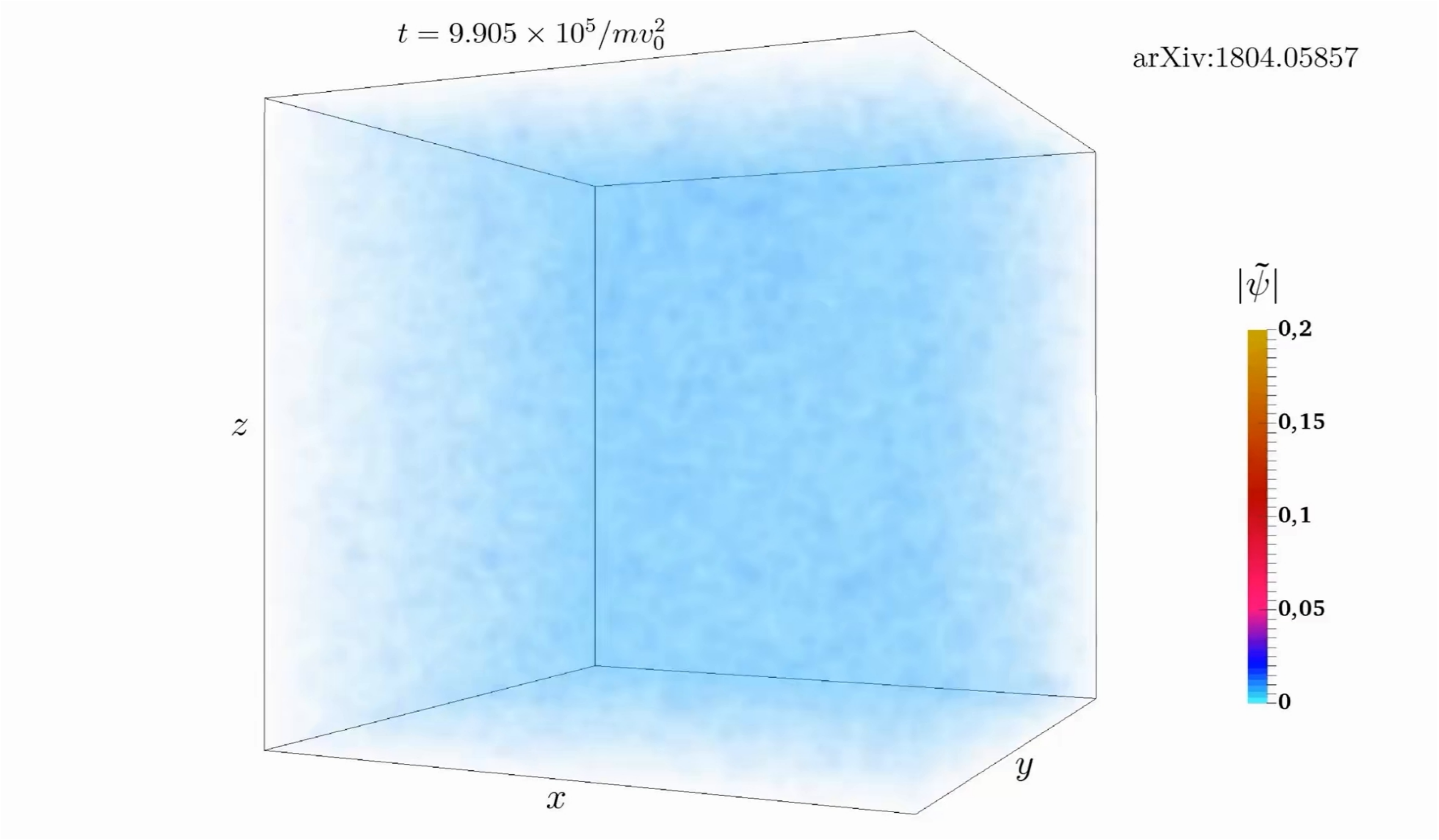
$$\psi_{\mathbf{p}} \propto \underbrace{e^{-\mathbf{p}^2/2(mv_0)^2}}_{\text{momentum distribution}} \times \underbrace{e^{iA_p}}_{\text{random phases}}$$

Take the smallest structure

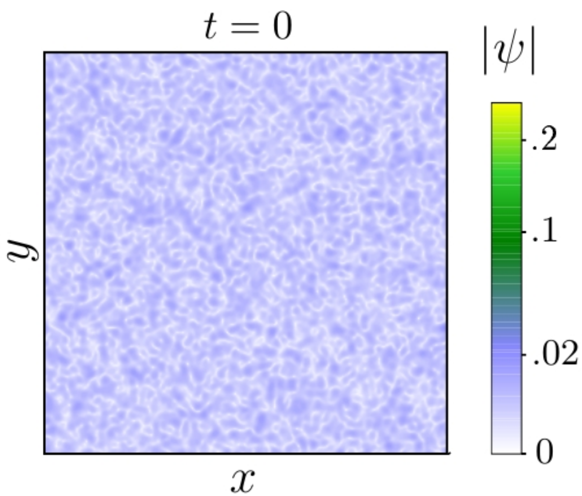
- Fuzzy DM ($m \sim 10^{-22}$ eV)
  dwarf galaxies, $M_{\text{halo}} \sim 10^9 M_\odot$
  [Schive, Chiueh, Broadhurst '14]
- QCD axion ($m \sim 10^{-5} - 10^{-3}$ eV)
  axion miniclusters, $M_{\text{mc}} \sim 10^{-13} M_\odot$
  [Levkov, Panin, Tkachev '18]
  [Eggemeier, Niemeyer '19]

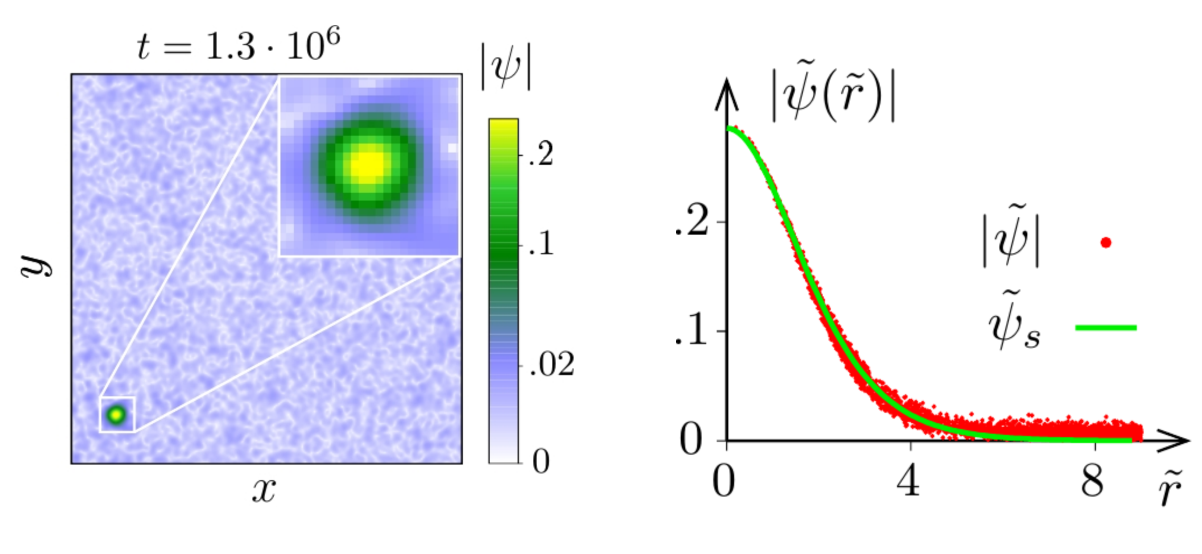
Solve SP equations numerically!

Bose-Einstein condensation

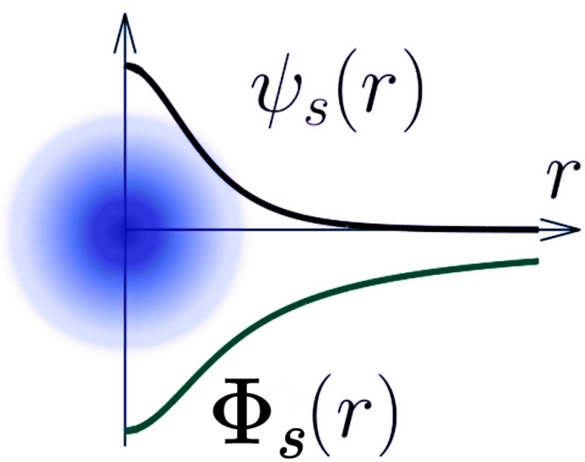


This is a Bose star





Bose star = BE condensate in state $\psi_s(r)$

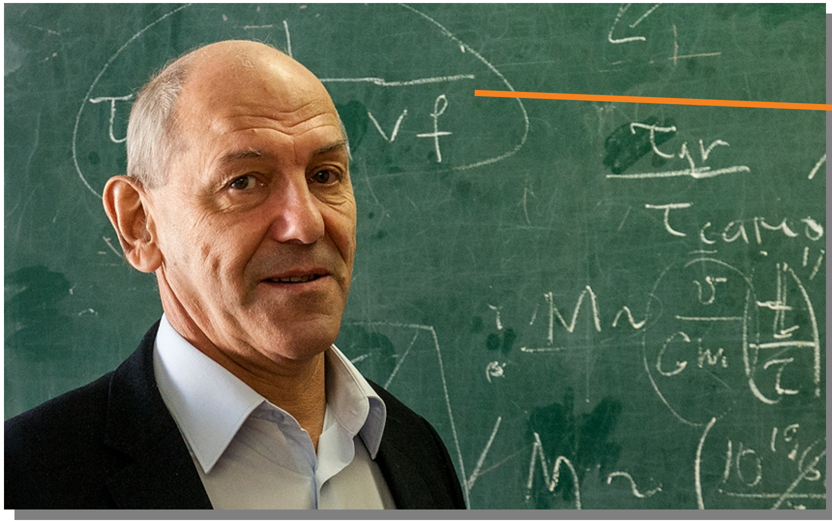


Solitonic solution

- $\psi = \psi_s(r) e^{-i\omega_s t}$ - ground state of Φ
- $\Phi = \Phi_s(r)$ - potential of $\psi_s(r)$
- $\omega_s < 0$ - energy level
- $M_s = M(\psi_s)$ - parameter

[Ruffini, Bonazolla '69; Tkachev '86]

Light DM Bose-condenses by gravitational scattering!



- Gravitational kinetic relaxation:

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

$b \sim 1$

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

phase-space density $f \propto (\rho/m)/(mv)^3$

$\Lambda = \log(mvR)$

Coulomb logarithm

$$\tau_{gr} = \frac{b\sqrt{2}}{12\pi^3} \frac{m^3 v^6}{G^2 \Lambda\, \rho}$$

[Levkov, Panin, Tkachev '18]

- $v \ll 1$ ⇒ gravity is enhanced & beats self-coupling $\sigma_{gr} \gg \sigma_\lambda$

- Bose factor $f \gg 1$

- Fuzzy DM in dwarf galaxies: $\tau_{gr} \simeq 10^6$ yr

- QCD axions in miniclusters: $\tau_{gr} \simeq 10^9$ yr

The Universe is packed with Bose stars!

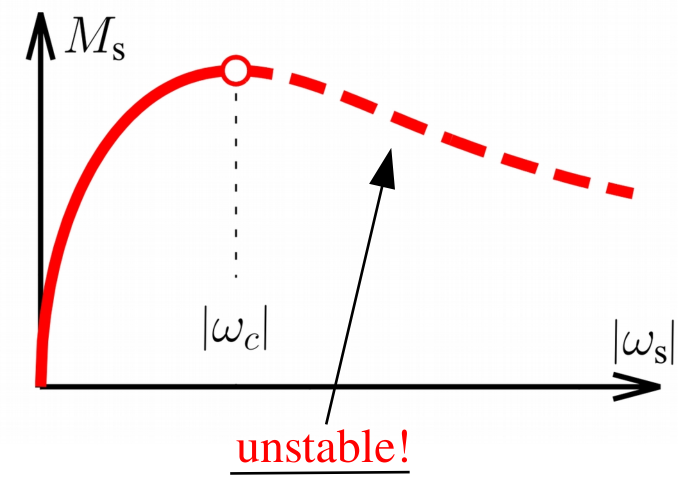
Plenty of time for mass growth!

See A.Dmitriev's talk

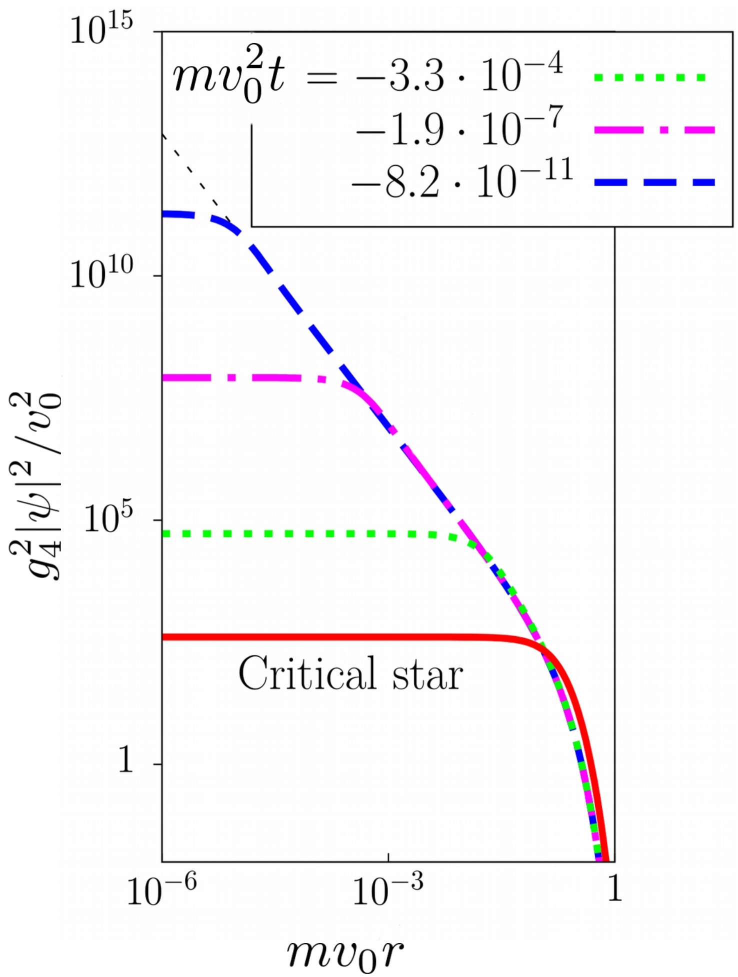
Bosenova

$$\begin{cases} i\partial_t \psi = -\dfrac{\Delta\psi}{2m} + m\left(\Phi - \dfrac{g_4^2}{8}|\psi|^2\right)\psi \\ \Delta\Phi(t,\mathbf{x}) = 4\pi G m^2 f_a^2 |\psi|^2 \end{cases}$$

attractive selfinteraction



[Vakhitov, Kolokolov '71; Chavanis '11]



Large-mass Bose stars are unstable!

$$M_{cr} \approx 10\frac{M_{Pl} f_a}{m g_4} \approx \mathbf{5\times 10^{-12}\,M_\odot}$$

$$R_{cr} \approx 0.18\frac{g_4 M_{Pl}}{m f_a} \approx \mathbf{70\,km}$$

QCD axion

[Levkov, Panin, Tkachev '17]

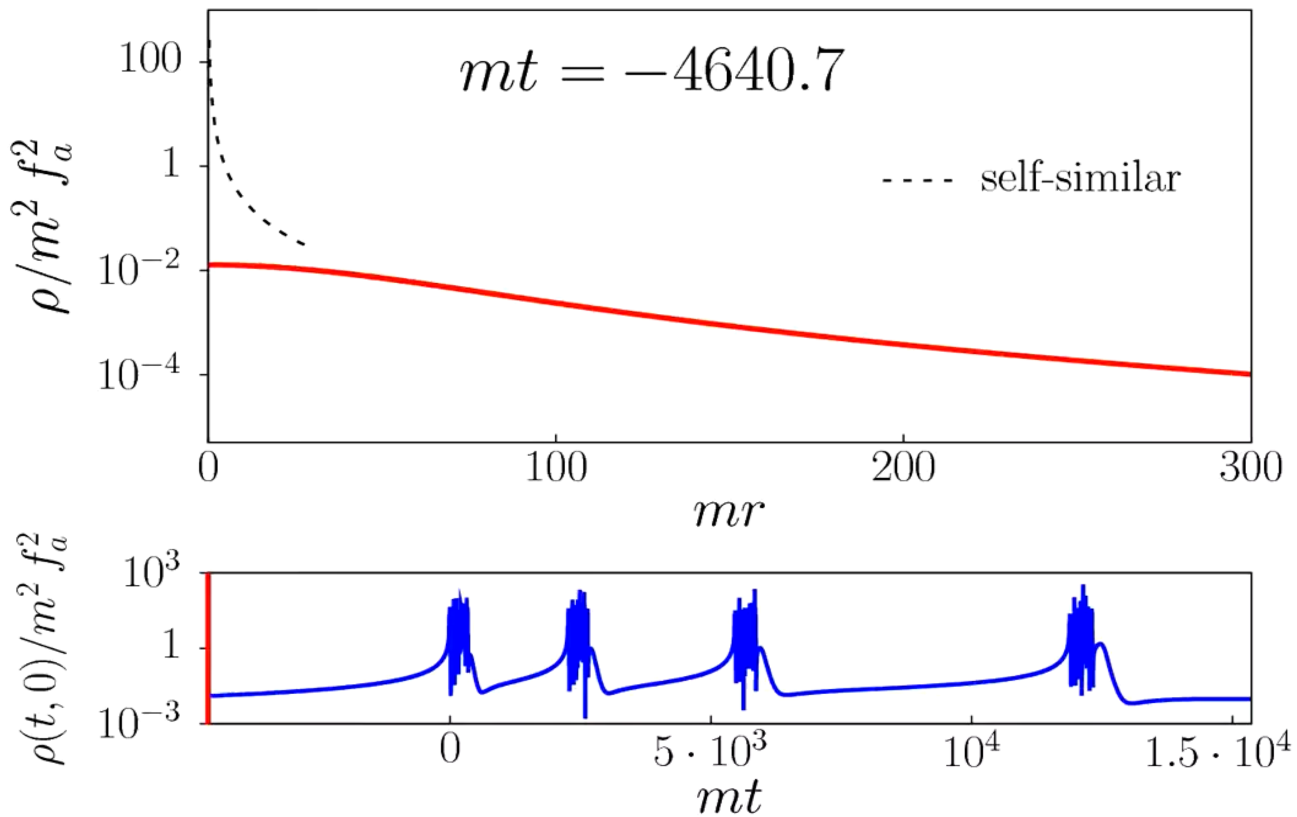
Q: What will happen to an unstable Bose star?

A: It's collapse!

Bosenova: full relativistic simulation

Solve numerically relativistic equation: $\Box a = -(1+2\Phi)\, \mathcal{V}'(a/f_a)/f_a$

$\mathcal{V}(\theta) = -m_a^2 f_a^2\,(1+1/z)\,\sqrt{1+z^2+2z\cos\theta}$, where $z \equiv m_u/m_d \approx 0.56$



Relativistic axions are emitted!

[Levkov, Panin, Tkachev '17]

Interaction with photons

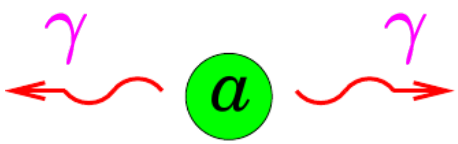
$$\partial_\mu (F_{\mu\nu} + g_{a\gamma\gamma} a \tilde{F}_{\mu\nu}) = 0$$

coherently oscillates

$$a = \frac{f_a}{\sqrt{2}} [\psi e^{-imt} + \text{h.c.}]$$

⇩

parametric resonance



$E_a \approx m$

⇨ $E_\gamma = p_\gamma \simeq m/2$

⇩

$$A_i = \underbrace{c_i^+(t,x)\, e^{im(z+t)/2}}_{\text{left-moving}} + \underbrace{c_i^-(t,x)\, e^{im(z-t)/2}}_{\text{right-moving}} + \text{h.c.}$$

⇩

$$\partial_t c_x^+ = \partial_z c_x^+ + i g_{a\gamma\gamma} f_a m \psi^* c_y^- / 2^{3/2}$$
$$\partial_t c_y^- = -\partial_z c_y^- - i g_{a\gamma\gamma} f_a m \psi c_x^+ / 2^{3/2}$$

← $\partial_{t,x} c_i^\pm \ll m c_i^\pm$

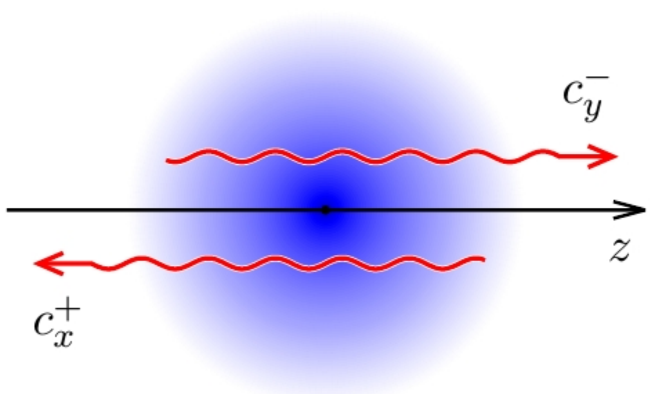
Simple equations for photons

$$\mu \cancel{\partial_t} c_x^+ = \partial_z c_x^+ + i g_{a\gamma\gamma} f_a m \psi^* c_y^- / 2^{3/2}$$

$$\mu \cancel{\partial_t} c_y^- = -\partial_z c_y^- - i g_{a\gamma\gamma} f_a m \psi c_x^+ / 2^{3/2}$$

- Boundary conditions:

$c_i^\pm \to 0$ as $z \to \pm\infty$



- Quasi-stationary approximation:

$$\begin{matrix} t_\gamma & \ll & t_a \\ \wr & & \wr \\ R & & R/v \end{matrix} \quad \Rightarrow \quad \begin{cases} c_i^\pm \propto e^{\int^t \mu(t')dt'} \\ vR^{-1} \ll \mu \ll R^{-1} \end{cases}$$

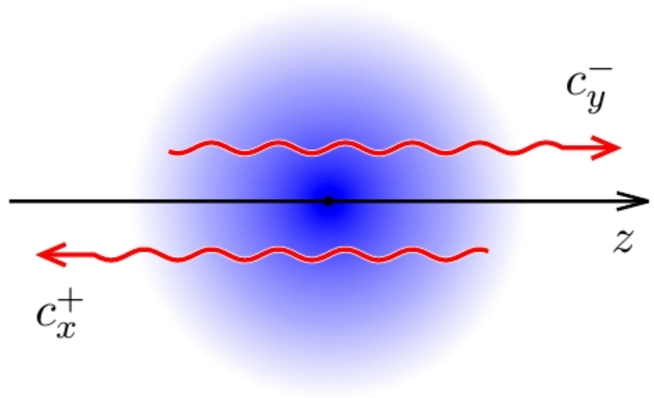
(start of resonance)

Restoring the solution:

$$A_i = \int d\mathbf{n}_z c_i^{(\mathbf{n}_z)}(x) e^{\int^t \mu(t')dt' + im(\mathbf{n}_z \mathbf{x} + t)/2}$$

Static coherent axions (Bose stars)

$v = 0, \quad \mu \ll R^{-1}$



1 Analytic solution for any ψ!

$$\left.\begin{aligned} c_x^+ &= A e^{\mu z} \cos(D(z)) \\ c_y^- &= -iA e^{-\mu z} \sin(D(z)) \end{aligned}\right\} \times e^{\int^t \mu dt}$$

$$D(z) = g_{a\gamma\gamma} f_a m 2^{-3/2} \int_{-\infty}^{z} \psi dz'$$

2 Growth exponent: $\mu = \dfrac{D(+\infty) - \pi/2}{\int dz \sin(2D(z))}$

3 Condition for resonance: $D(+\infty) \geq \pi/2$

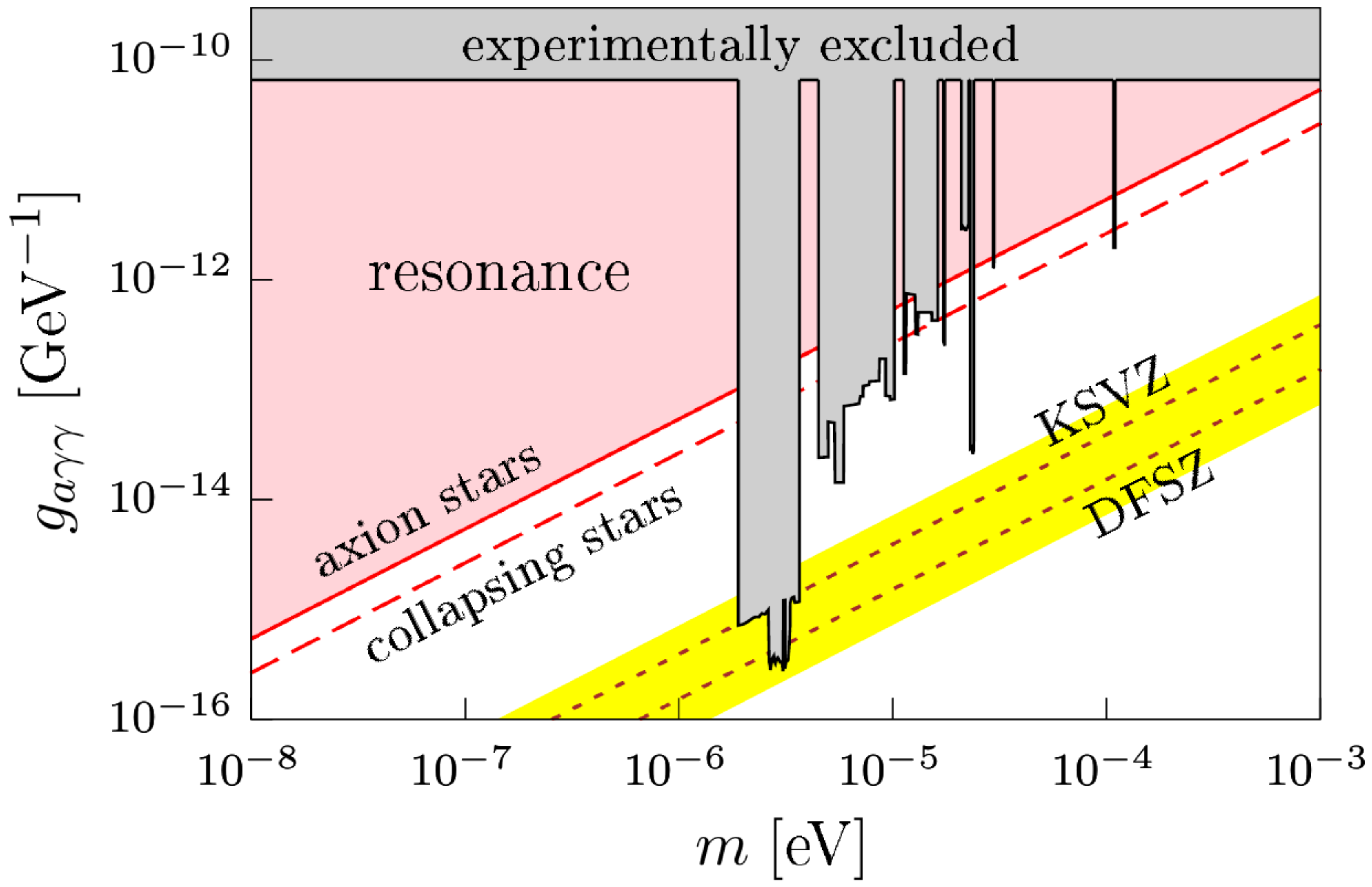
Need massive Bose stars! $M \geq M_0 = 7.66 M_{Pl}/(m g_{a\gamma\gamma})$

4 QCD axions: $M \leq M_{cr}$ ⇨ $g_{a\gamma\gamma} \geq 0.31/f_a$

or collapse

Exclusion plot for QCD axions

$$g_{a\gamma\gamma} \geq 0.31/f_a$$

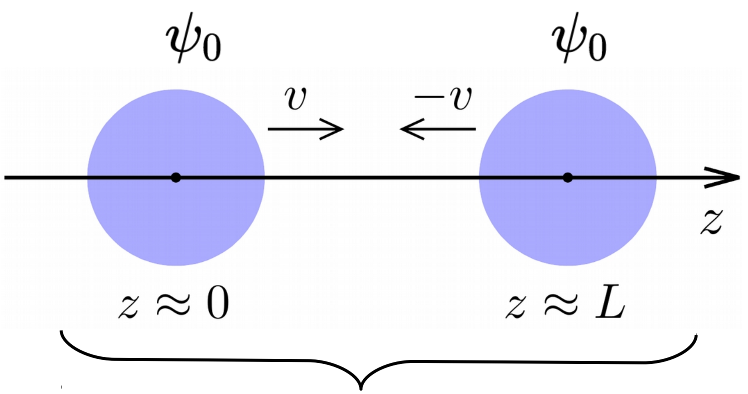


[Hertzberg, Schiappacasse '18; Levkov, Panin, Tkachev '18]

Two moving Bose stars

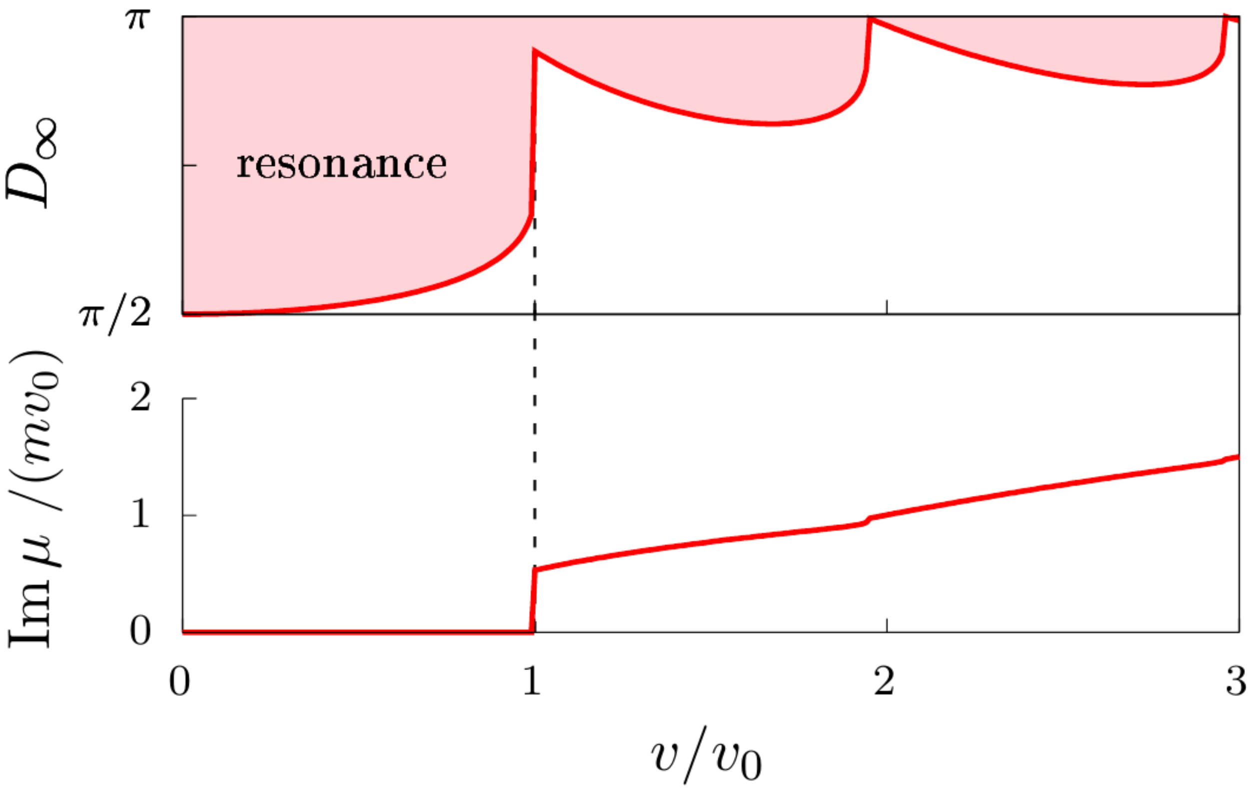
$$\mu \not{\partial_t} c_x^+ = \partial_z c_x^+ + i g_{a\gamma\gamma} f_a m \psi^* c_y^- / 2^{3/2}$$

$$\mu \not{\partial_t} c_y^- = -\partial_z c_y^- - i g_{a\gamma\gamma} f_a m \psi c_x^+ / 2^{3/2}$$



$$\psi = \psi_1(z) e^{imvz} + \psi_2(z) e^{-imv(z-L)}$$

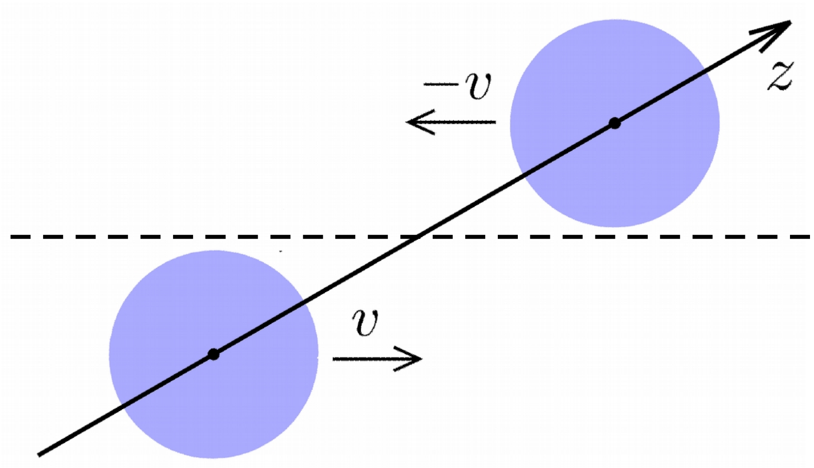
Analytic solution:



Velocity scale:

$$v_0 = \frac{g_{a\gamma\gamma} f_a \psi_0}{\sqrt{2}} \sim (mR)^{-1} \ll 1$$

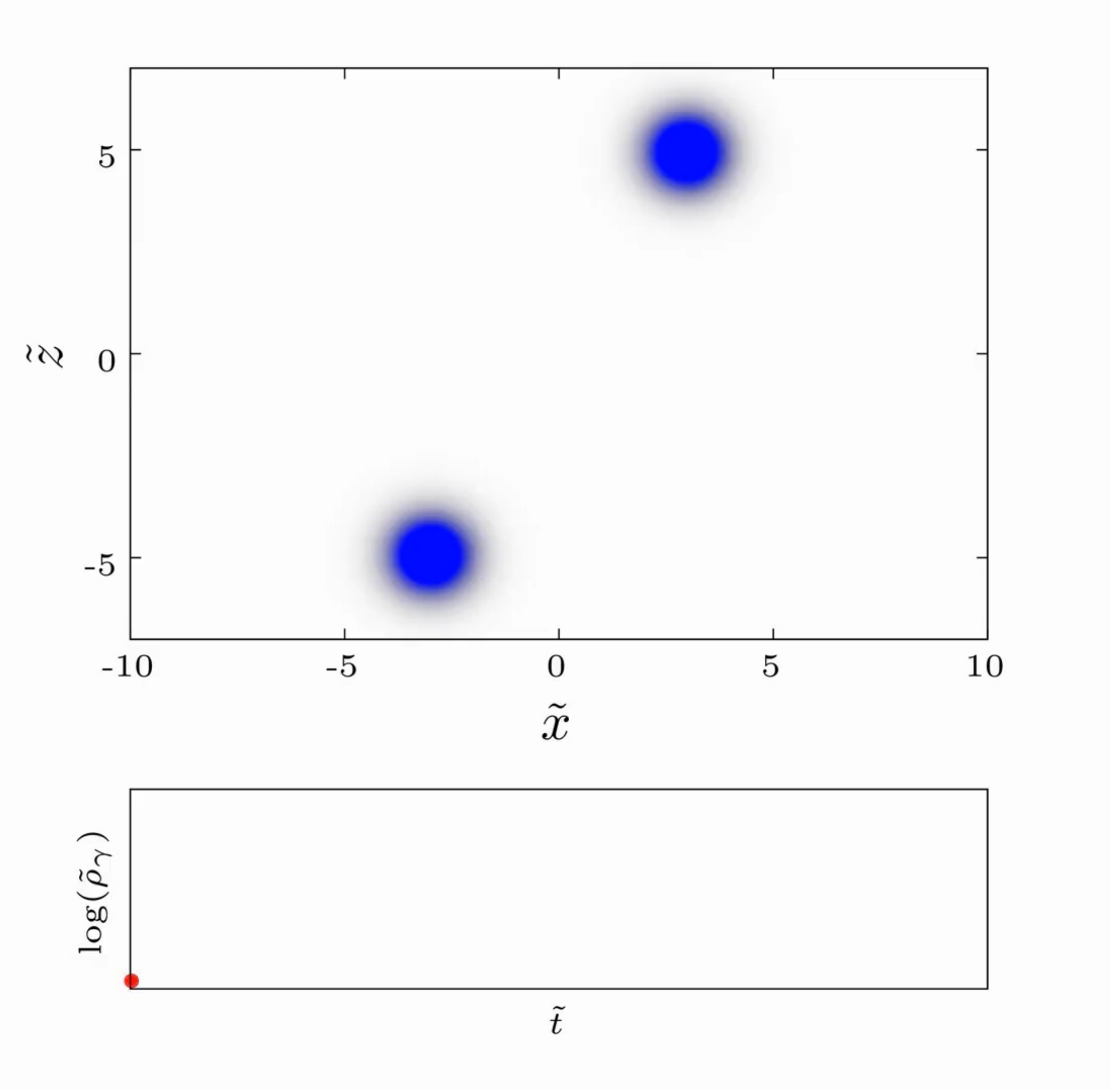
Two moving Bose stars: numerical simulation



$$
\begin{cases}
\partial_t c_x^+ = \partial_z c_x^+ - \dfrac{i}{m}(\partial_x^2 + \partial_y^2) c_x^+ + i g_{a\gamma\gamma} f_a m \psi^* c_y^- / 2^{3/2} \\
\partial_t c_y^- = -\partial_z c_y^- + \dfrac{i}{m}(\partial_x^2 + \partial_y^2) c_y^- - i g_{a\gamma\gamma} f_a m \psi c_x^+ / 2^{3/2} \\
i\partial_t \psi = -\dfrac{\Delta\psi}{2m} + m\left(\Phi - \dfrac{g_4^2}{8}|\psi|^2\right)\psi - \dfrac{m g_{a\gamma\gamma}}{2^{3/2} f_a} \epsilon_{\alpha\beta} c_\alpha^- c_\beta^{+*} \\
\Delta\Phi = 4\pi G(m^2 f_a^2 |\psi|^2 + \rho_\gamma)
\end{cases}
$$

backreaction

Two moving Bose stars: numerical simulation



Fast Radio Bursts

- ~ 500 FRB sources *[CHIME/FRB Collaboration '21; https://www.chime-frb.ca/catalog]*
- 18 are repeating
- Frequency (0.1 ÷ 8) GHz = (10^{-1} ÷ 10) μeV

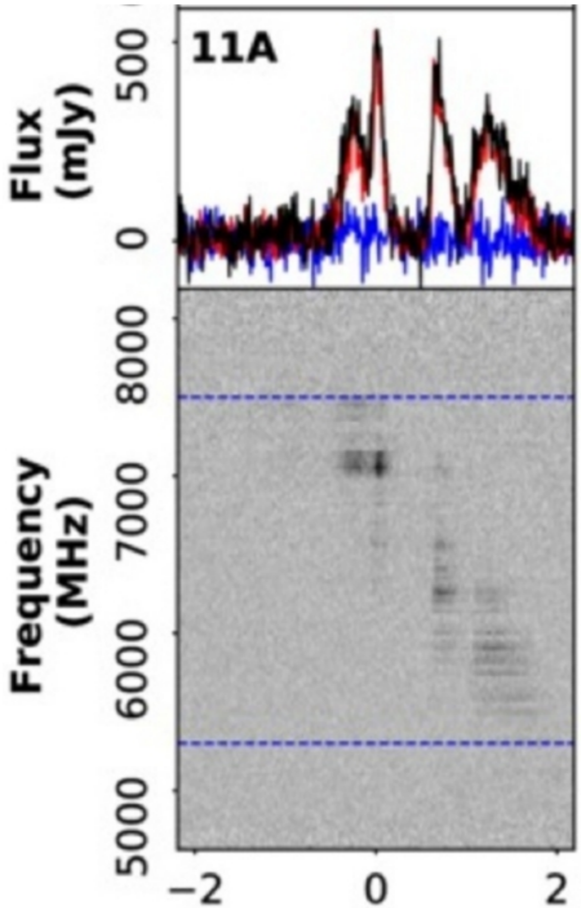
  QCD axion mass
- Duration (1 – 10) msec ~ 100 km

  Size of QCD axion Bose star
- Total energy 10^{39} erg ~ $10^{-15}\, M_\odot$

  ~ Mass of QCD axion Bose star
- Wide spectrum

  But: sharp 7 GHz peak + wide afterglow

FRB 20121102A



time (msec)

FRBs = Bose stars?

Conclusions: 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 heat the cosmological medium

  [Escudero et al ’23]
- Bosenovas: additional flux of axions in DM detectors

  [Levkov, Panin, Tkachev ’17; Eby et al ’22]

THANK YOU FOR ATTENTION!

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