Relativistic axions from collapsing Bose stars

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in collaboration with
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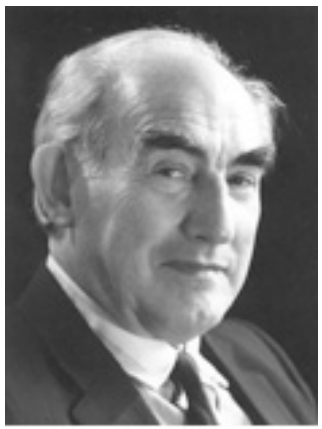
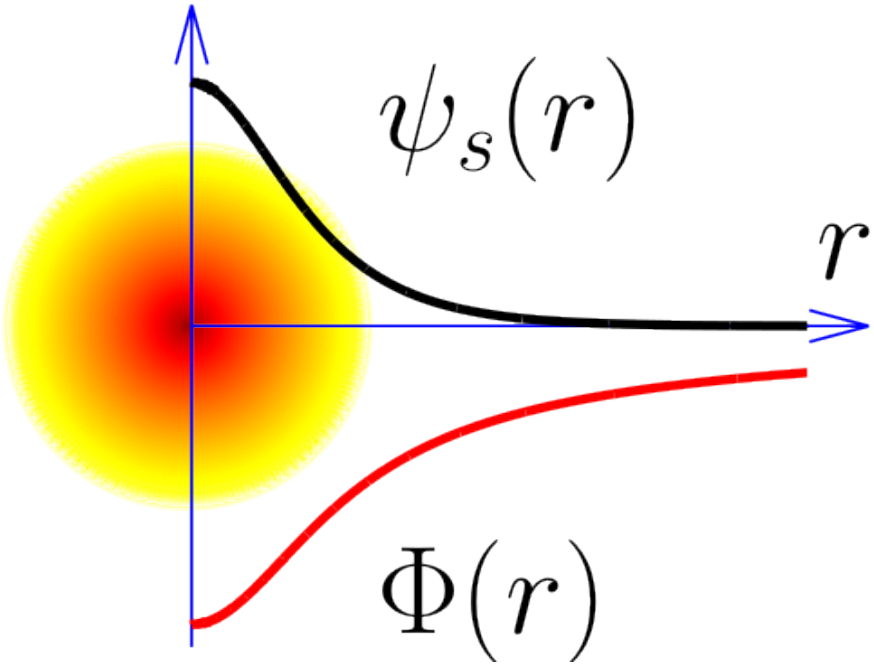


Ginzburg conference on physics,
Moscow, June 2, 2017.

PRL **118** (2017) 011301 [arXiv:1609.03611]

Bose stars: Bose condensate inside

N self-gravitating Bose particles



Ruffini, Bonazolla '69

Tkachev '86

Chavanis '11

Properties

- Coherent: $\psi = \psi_s(r)$
- Self-gravitating: $\Phi = \Phi(r)$
- Cold bosons!

Make them from CDM?

Need the coldest bosonic DM! $\Rightarrow$ ALP dark matter

ALP: Axion-Like Particles

$a(x)$

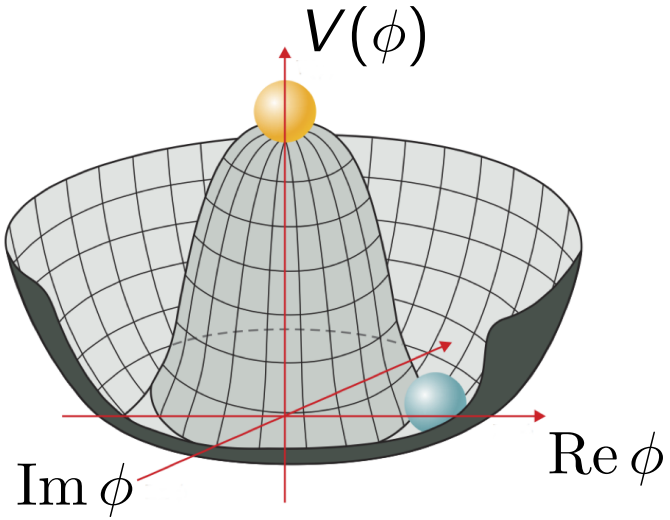
- (Pseudo)scalars
- Small mass m

} Pseudo-Goldstone Bosons!

$$\mathcal{L} = \tfrac{1}{2}(\partial_\mu a)^2 - \tfrac{1}{2} m^2 f_a^2 \, \mathcal{V}_{\rm eff}(\underbrace{a/f_a}_{\theta})$$

Explicit symmetry breaking

f_a — symmetry-breaking scale



Potential: $V_{\rm eff} = \theta^2 - g_4^2\theta^4 + \ldots$ $\qquad \theta \equiv a/f_a$

- Bounded from below
- Periodic $\Rightarrow -g_4^2 < 0$ attraction!

ALP dark matter

Example 1: QCD axion

Peccei, Quinn '77

- Solves the strong CP problem
- $m \sim 10^{-4}$ eV, $f_a \sim 10^{11}$ GeV
- Chiral potential:

$$\mathcal{V}_{eff} = -\frac{1+z}{z}\sqrt{1+z^2+2z\cos\theta}$$

$z \approx 0.56$

Example 2: Fuzzy dark matter

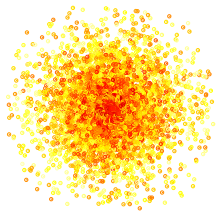
e.g. Arvanitaki et al '09

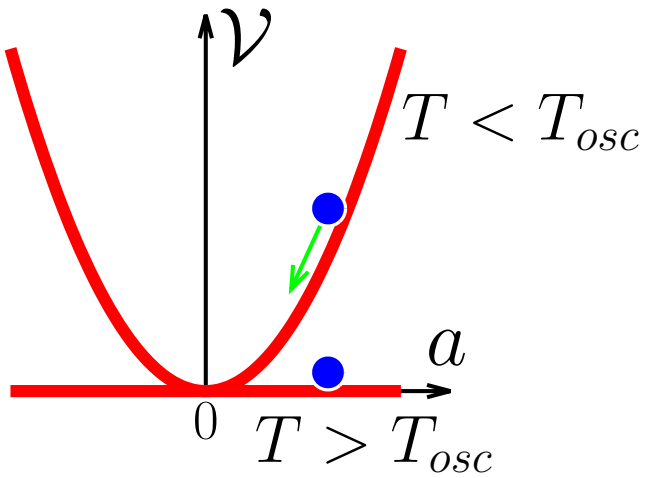
- Made of string axions
- $m \sim 10^{-22}$ eV, $f_a \sim 10^{17}$ GeV
- Periodic potential:

$$\mathcal{V}_{eff} = -\cos\theta$$

Generation: Vacuum realignment

- $p \approx 0$ — **nonrelativistic**
- $N \gg 1$ — **classical field**
- cold $\Rightarrow$ **clumpy**
  ALP miniclusters:





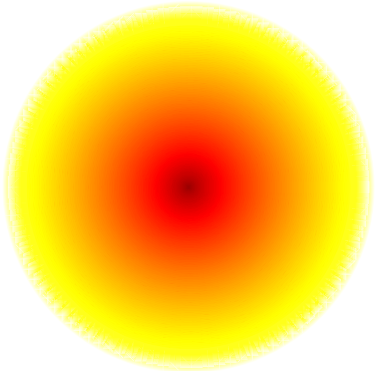
$$a/f_a = \psi(\mathbf{x}, t)\, e^{-imt} + \text{h.c.}$$

Nonrelativistic approximation:

$$a/f_a = \psi(t,\mathbf{x})\,\mathrm{e}^{-imt} + \text{h.c.}, \quad g_{00} = 1 + 2\Phi(t,\mathbf{x})$$

$$\partial_t,\ \partial_x \ll m; \quad \psi,\ \Phi \ll 1$$

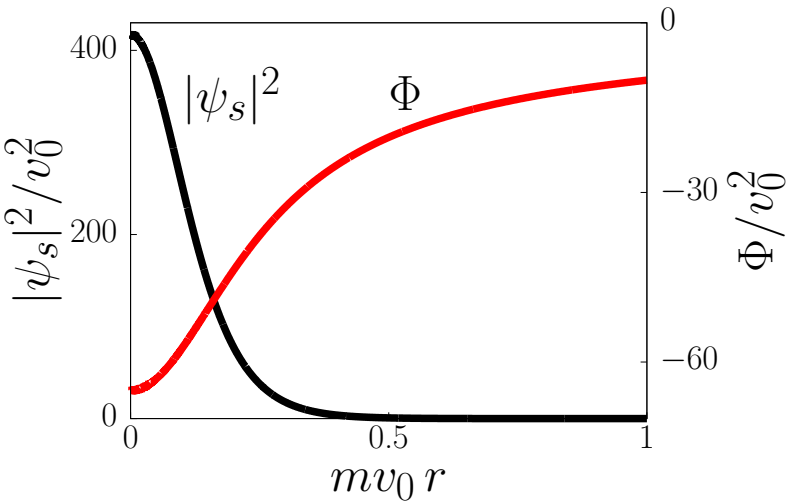
$\psi_s(r)$



$\Rightarrow$ Gross-Pitaevskii-Newton system

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

$$\Delta\Phi = 4\pi G(\underbrace{m^2 f_a^2 |\psi|^2}_{\rho})$$



$(v_0 \equiv f_a/M_{pl})$

Stationary solutions

- Conserved mass $M = \int d^3\mathbf{x}\,\rho$
- $E \to \min$, $M = \text{const}$

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

Bose condensate wave function

Do they form?

Fuzzy dark matter ($m \sim 10^{-22}$ eV)

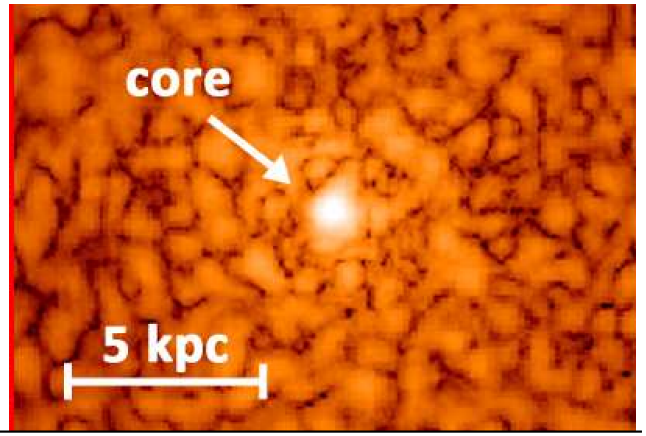
Schive, Chiueh, Broadhurst '14

Simulation of structure formation:

Bose star in the center of each galaxy!

$R_s \sim$ kpc

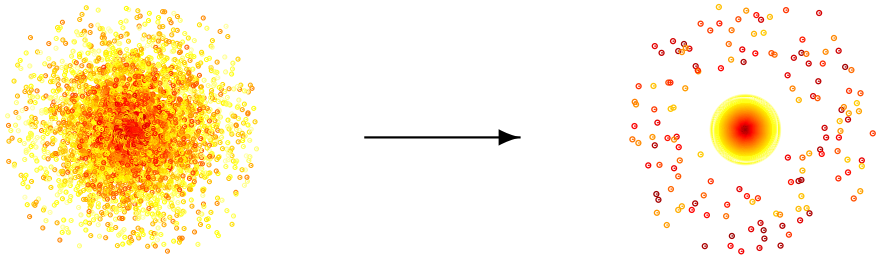
$M_s \sim 4 \cdot 10^8\, M_\odot$



QCD axion ($m \sim 10^{-4}$ eV)

Kolb, Tkachev '94

Formation from miniclusters?



$R_{mc} \sim 10^8$ km

$M_{mc} \sim 5 \cdot 10^{-11}\, M_\odot$

$R_s \sim 100\,\mathrm{km}$

$M_s \sim 10^{-11}\, M_\odot$

Relaxation via self-coupling? Gravitational cooling?

Critical mass

Bose stars: one-parametric family (M)

Rescaling: $\tilde{t} = m v_0^2\, t$, $\tilde{\mathbf{x}} = m v_0\, \mathbf{x}$, $\tilde{\psi} = \frac{g_4}{v_0}\psi$, $\tilde{\Phi} = \Phi / v_0^2$, $v_0 \equiv \frac{f_a}{g_4 M_{pl}}$

$$i\tilde{\partial}_t \tilde{\psi} = -\frac{\tilde{\Delta}\tilde{\psi}}{2\cancel{m}} + \cancel{m}(\tilde{\Phi} - \cancel{g_4^2}|\tilde{\psi}|^2/8)\tilde{\psi}$$

$$\tilde{\Delta}\tilde{\Phi} = 4\pi \cancel{G m^2 f_a^2}\,|\tilde{\psi}|^2$$

Universal dependence on parameters!

Critical mass

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$$i\tilde{\partial}_t \tilde{\psi} = -\frac{\tilde{\Delta}\tilde{\psi}}{2m} + m(\tilde{\Phi} - \underbrace{g_4^2 |\tilde{\psi}|^2/8}_{E<0})\tilde{\psi}$$

$$\tilde{\Delta}\tilde{\Phi} = 4\pi G m^2 f_a^2 |\tilde{\psi}|^2$$

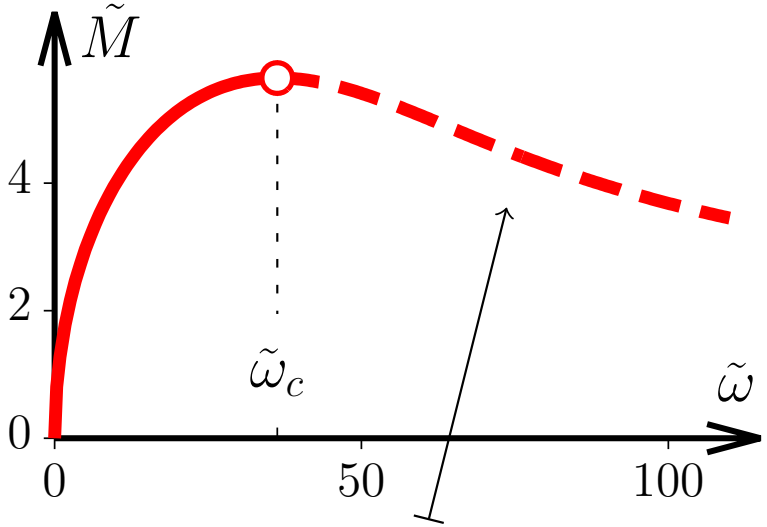
Universal dependence on parameters!

$$\tilde{\psi} = \tilde{\psi}_s(\tilde{r})\, e^{+i\tilde{\omega}\tilde{t}}$$

$$M_{cr} \approx 10\, \frac{M_{pl} f_a}{m g_4} \approx 5 \cdot 10^{-12}\, M_\odot$$

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

QCD axion



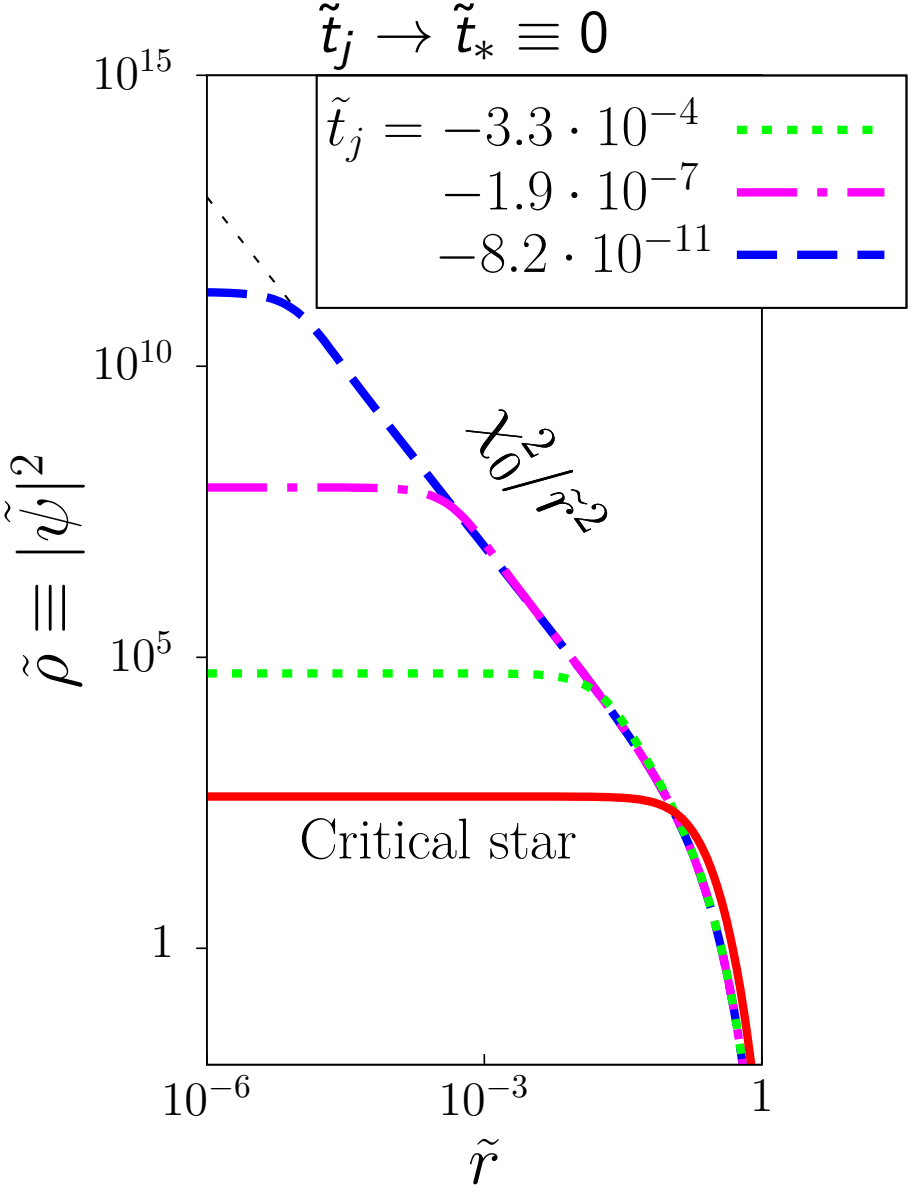
Vakhitov-Kolokolov criterium: $dM/d\omega > 0$

unstable!

Vakhitov, Kolokolov '71
Chavanis '11

Overcritical stars collapse!

Collapse, stage I: Self-similar evolution

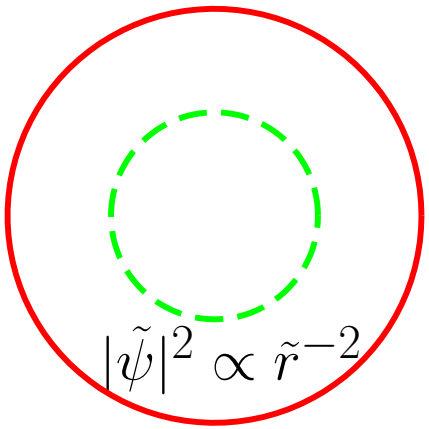


$M = M_{cr}(1+\epsilon)$, $\epsilon = 10^{-5}$

Physical explanation:

$$i\tilde{\partial}_t\tilde{\psi} = -\tfrac{1}{2}\tilde{\Delta}\tilde{\psi} + (\tilde{\Phi} \underbrace{-|\tilde{\psi}|^2/8}_{-\chi_0^2/\tilde{r}^2})\tilde{\psi}$$

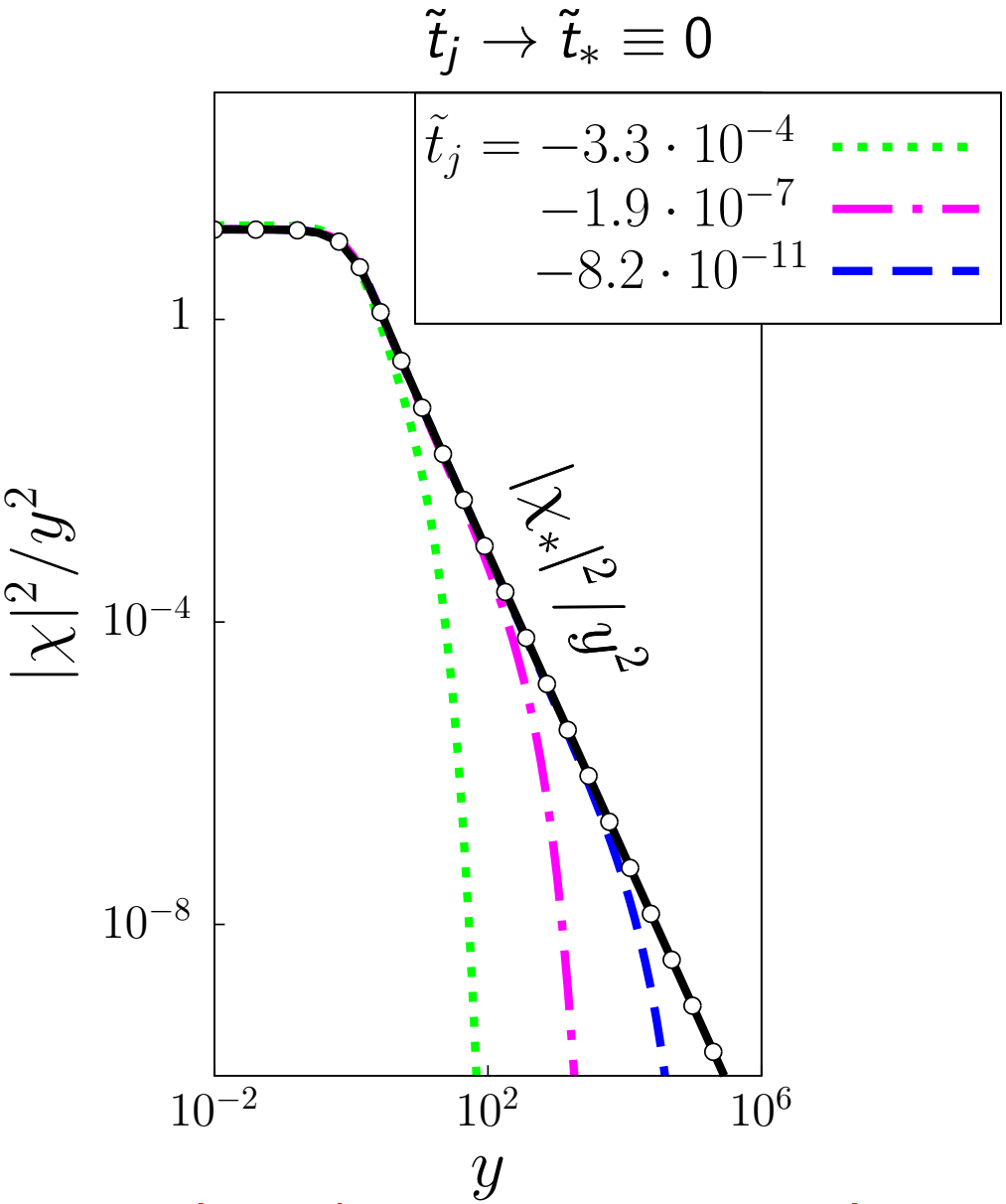
$\Rightarrow$ Fall onto the center!



Zakharov '12

$=$ "Wave collapse"

Collapse, stage I: Self-similar evolution



This solution is an attractor!

Zakharov, 2012

Analytically:

$$i\tilde{\partial}_t\tilde{\psi} = -\tfrac{1}{2}\tilde{\Delta}\tilde{\psi} + (\cancel{\tilde{\Phi}} - |\tilde{\psi}|^2/8)\tilde{\psi}$$

$\Rightarrow$ Scaling symmetry!

$$t \to \lambda^2 t, \quad \mathbf{x} \to \lambda \mathbf{x}, \quad \psi \to \psi\, e^{i\alpha}/\lambda$$

$\Rightarrow$ Scale-invariant solution!

$$\tilde{\psi}(\tilde{t}, \tilde{r}) = \frac{(-\tilde{t})^{i\omega_*}}{\tilde{r}}\, \chi_* \left(\underbrace{\frac{\tilde{r}}{\sqrt{-\tilde{t}}}}_{y} \right)$$

Finite energy:
$$\begin{cases} \chi_*(0) = 0 \\ \chi_*(+\infty) = \chi_0 \cdot y^{-2i\omega_*} \end{cases}$$

Solution: $\omega_* \approx 0.54$, $\chi_0 \approx 2.84$

Singularity of self-similar solution

$$\psi(t_*,\, r) \to \chi_0 \cdot (mr)^{-2i\omega_* - 1} \quad \text{at} \quad r \to 0$$

Universal profile!

At $mr < 1$

- Nonrelativistic approximation is broken:
  $v \sim \dfrac{1}{mr} > 1$
- Small-field approximation is broken:
  $\dfrac{a}{f_a} \sim \psi \sim \dfrac{1}{mr} > 1$

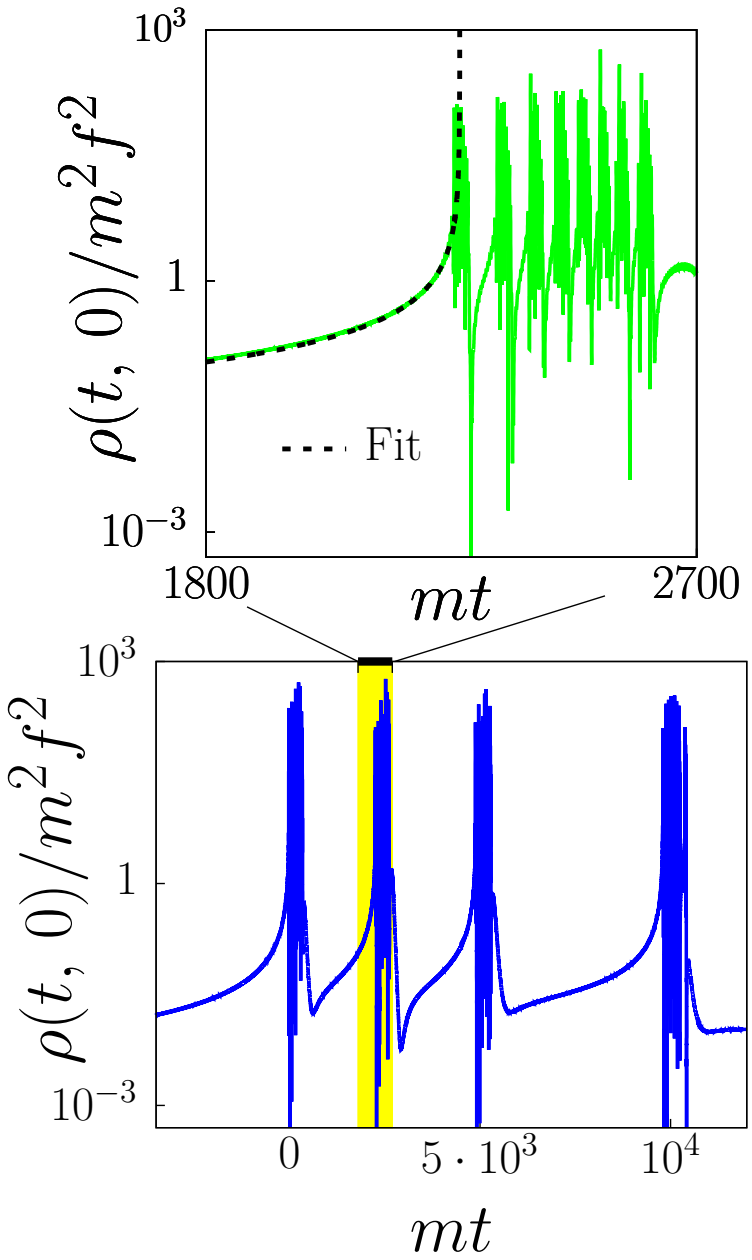
Full relativistic simulation is needed!

Equations

$$\begin{cases} \Box a = -(1+2\Phi)\,\mathcal{V}'_{\rm eff}(a/f_a)/f_a & \leftarrow \text{Full axion potential!} \\ \Delta\Phi = 4\pi G \underbrace{\rho}_{(\partial_t a)^2/2 + (\nabla_x a)^2/2 + \mathcal{V}_{\rm eff}} \end{cases}$$

Collapse, stage II: Relativistic Bosenova

Collapse, stage II: Relativistic Bosenova

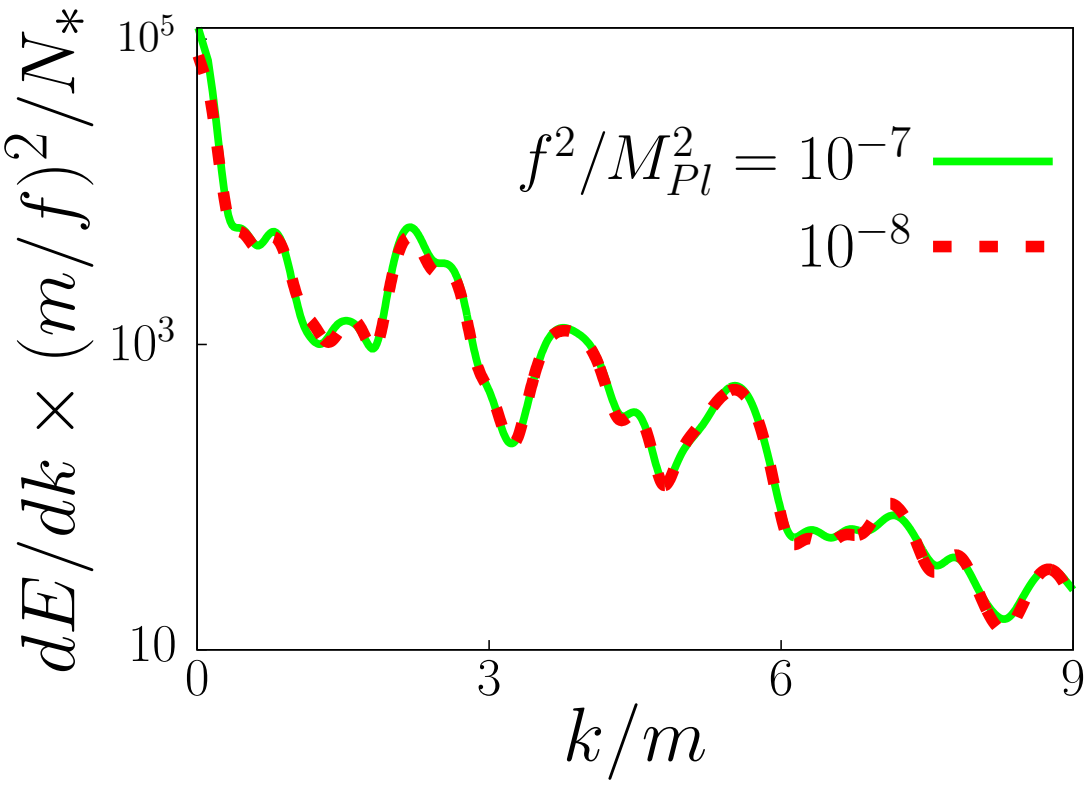


Two competitive processes

- Wave collision at $mr \sim 1$
  Center emptifies, out-waves!
- Build another self-similar solution
  Another singularity appears!

$\Rightarrow$ Repeating collisions in the center!

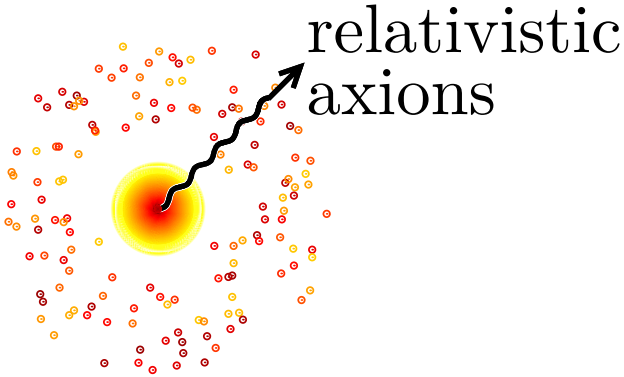
Spectrum of emitted exions

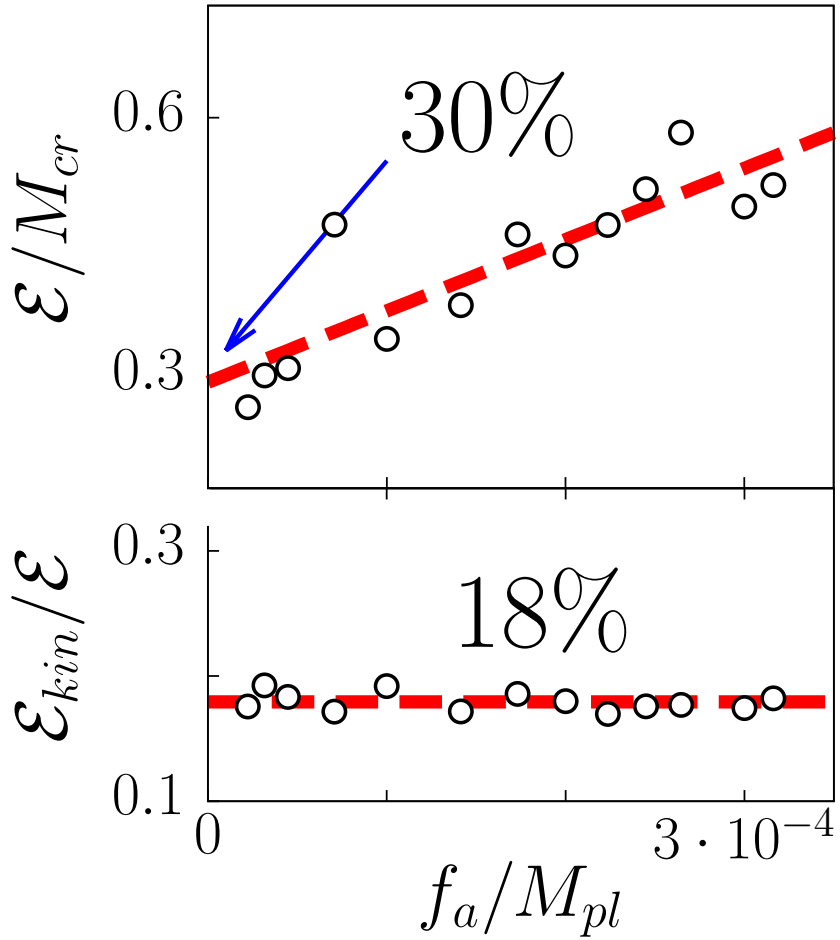


Universal χ_* $\Rightarrow$ universal spectrum per explosion!

Net result

Collapsing stars
emit relativistic axions
with universal spectrum





"Vacuum cleaners" ruining the miniclusters?

Applications

- Black holes are not formed in the collapse at $f_a \ll M_{pl}$!
- Fuzzy DM ($m \sim 10^{-22}$ eV)
  → At $f_a \gtrsim 10^{15}$ GeV the core of our galaxy collapses!
  Interesting cosmology!
  → We are **safe** at $f_a \gtrsim 10^{16}$ GeV *Diez-Tejedor, Marsh '17*
- QCD axions ($m \sim 10^{-4}$ eV)
  → Radioemission during the collapse
  Photophilic axion?
  Fast radio bursts via parametric resonance? *Tkachev '15*
  Contribution into the **radiobackground**?
- If many Bose stars
  → Collapse converts 18% of dark mass → radiation.
  Like **decaying dark matter!** *e.g. Chudaykin, Gorbunov, Tkachev '16*
  Warm DM may affect **structure formation!**

Thank you for the attention!