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Laser effect for cosmic axions

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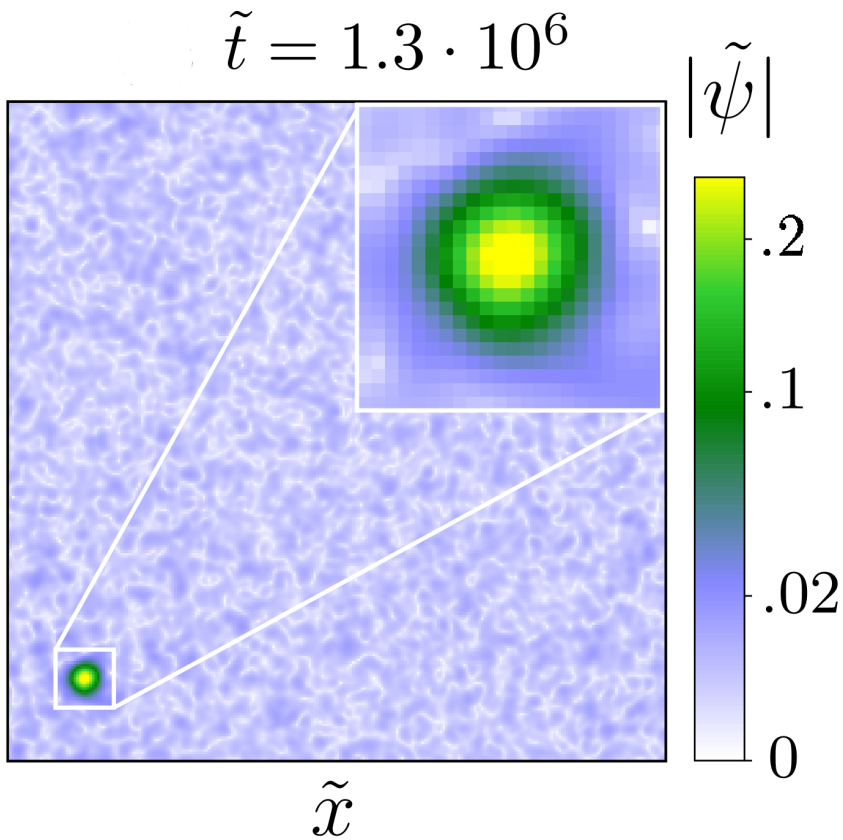
Bose star formation

QCD axion $(m \sim 10^{-5}\ \mathrm{eV})$

Bose condensation by gravitational interaction in miniclusters.

[D. Levkov et al, 2018]

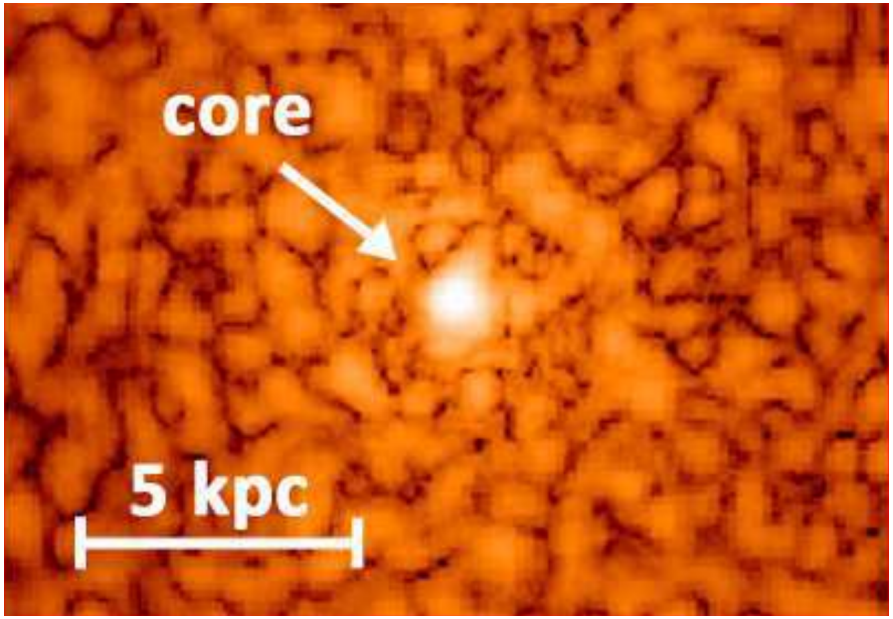
$M_{bs} \sim 10^{-11} M_\odot\,; \quad R_{bs} \sim 50\ \mathrm{km}$



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

Bose star appear during structure formation in the center of each galaxy. [H.-Y. Schive et al, 2014]

$M_{bs} \sim 10^{8} M_\odot\,; \quad R_{bs} \sim 100\ \mathrm{pc}$



Bose star properties

Nonrelativistic approximation:

$$a/f_a = (\psi e^{-imt} + \text{h.c.})/2 \quad \Leftarrow \quad \partial_t,\ \partial_x \ll m; \quad \Phi,\ \psi \ll 1$$

Gross-Pitaevskii-Puasson system

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

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

Using coordinate and field rescaling:

$$\tilde{t} = mv_0^2 t;\ \tilde{x} = mv_0 x$$

$$\tilde{\psi} = g_4\psi/v_0;\ \tilde{\Phi} = \Phi/v_0^2$$

$$\boxed{v_0 \equiv f_a/g_4 M_{Pl}}$$

All physical parameters disappear!

Symmetry: $\psi \to \mathrm{e}^{i\alpha}\psi$

$\Downarrow$

The total mass conservation

$$\tilde{M} \equiv \int d^3\tilde{\boldsymbol{x}}\,\tilde{\rho} = \int d^3\tilde{\boldsymbol{x}}\,|\tilde{\psi}|^2$$

Axion-photon coupling

Axion field of Bose star oscillates coherently with time:

$$a/f_a = (\psi e^{-imt} + \text{h.c.})/2$$

May cause parametric resonance of photons!

$$\mathcal{L}_{em} = -\frac{1}{4}F_{\mu\nu}F_{\mu\nu} - \frac{g_{a\gamma}}{4}aF_{\mu\nu}\tilde{F}_{\mu\nu}$$ axion-photons coupling

$$\boxed{\partial_\mu F_{\mu\nu} + g_{a\gamma}\partial_\mu a\tilde{F}_{\mu\nu} = 0}$$ modified Maxwell's equations

or

$$\boxed{\partial_\mu\partial_\mu A_\nu - \partial_\mu\partial_\nu A_\mu + 2\epsilon_{\mu\nu\lambda\rho}\, g_{a\gamma}\partial_\mu a\partial_\lambda A_\rho = 0}$$

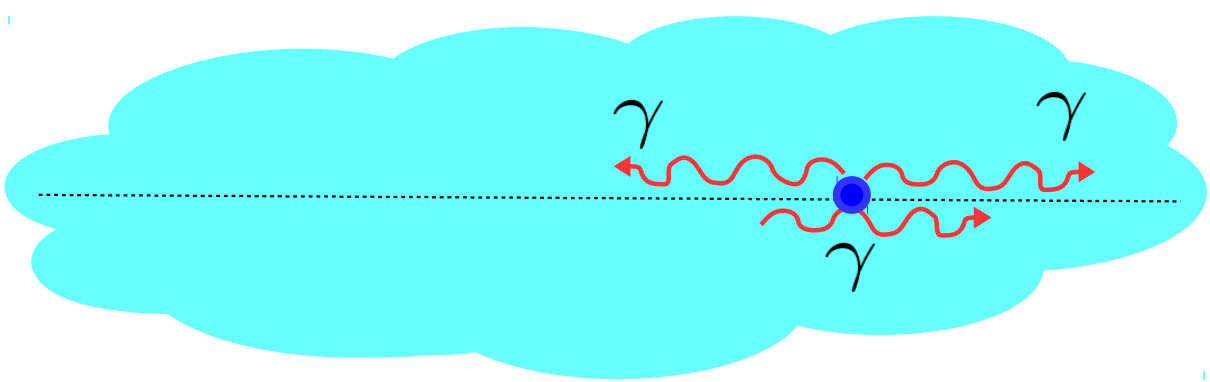
Resonance in homogeneous condensate

For homogeneous condensate, $\psi = \psi_0 = \text{const}$, we have

$$\ddot{A}_k + (k^2 \pm \sqrt{2} g_{a\gamma} f_a m k \cdot \psi_0 \sin(mt)) A_k = 0$$ – Mathieu equation!

$$A_k \propto c_k \, e^{\mu t} e^{\pm i \frac{m}{2}(t \pm x)}$$ with $$\boxed{\mu = \frac{g_{a\gamma} f_a m \psi_0}{2\sqrt{2}}}$$

Amplification coefficient: $$\boxed{D \equiv \mu \cdot R = \frac{g_{a\gamma} f_a m \psi_0}{2\sqrt{2}} \cdot R}$$



$D \gtrsim 1$ – <u>resonance!</u>

General case

$$a/f_a = (\psi e^{-imt} + \text{h.c.})/2\,, \quad \psi(t,x) \text{ – weakly depends on t, x}$$

Consider plane waves with frequency m/2 moving through a star:

$$\begin{cases} A_0 = 0 \quad \text{– gauge} \\ A_i = e^{i\frac{m}{2}z}\left(c_i^+(t,x)e^{i\frac{m}{2}t} + c_i^-(t,x)e^{-i\frac{m}{2}t}\right) + \text{h.c.} \end{cases}$$

Weakly depends on space and time: **eikonal-like approximation**

$$\boxed{\nu = x} \qquad \frac{\partial c_x^+}{\partial t} - \frac{\partial c_x^+}{\partial z} - i\frac{g_{a\gamma} m f_a}{\sqrt{2}}\psi^* c_y^- = 0 \qquad (1) \qquad \times e^{i\frac{m}{2}t}$$

$$\boxed{\nu = y} \qquad \frac{\partial c_y^-}{\partial t} + \frac{\partial c_y^-}{\partial z} + i\frac{g_{a\gamma} m f_a}{\sqrt{2}}\psi c_x^+ = 0 \qquad (2) \qquad \times e^{-i\frac{m}{2}t}$$

$c_y^+ = c_x^+$, $c_x^- = -c_y^-$ satisfy another pair of Eqs.

Boundary conditions:
no waves coming from infinity!

$$\boxed{\begin{aligned} c_{x,y}^+(z=+\infty) &= 0 \\ c_{x,y}^-(z=-\infty) &= 0 \end{aligned}}$$

Boundary value problem

Substituting $c^{\pm}_{x,y}(t,z) = e^{\mu t} c^{\pm}_{x,y}(z)$

we obtain the boundary value problem for $c^{\pm}_{x,y}(z)$.

$$\begin{cases} \mu c^+_x - \dfrac{\partial c^+_x}{\partial z} - i\dfrac{g_{a\gamma} m f_a}{\sqrt{2}} \psi^* c^-_y = 0 \\ \mu c^-_y + \dfrac{\partial c^-_y}{\partial z} + i\dfrac{g_{a\gamma} m f_a}{\sqrt{2}} \psi c^+_x = 0 \end{cases}$$

For real ψ and $\mu = 0$ we have analytic solution:

$$c^+_x(z) = A\cos(S(z))$$

$$c^-_y(z) = A\sin(S(z))$$

where $S(z) = \dfrac{g_{a\gamma} m f_a}{\sqrt{2}} \displaystyle\int_{-\infty}^{z} \psi(z')dz'$ and

$$S(+\infty) = \boxed{D = \frac{g_{a\gamma} m f_a}{\sqrt{2}} \int_{-\infty}^{+\infty} \psi(z')dz' = \frac{\pi}{2}}$$

from boundary condition $c^+_{x,y}(z = +\infty) = 0$

Resonance condition!

Solutions with $\mu > 0$ exist if $D > \dfrac{\pi}{2}$.

Spherically symmetric case

<u>Any direction is in resonance.</u>

One can expand A_i in terms of **vector** spherical harmonics:

$$\vec{Y}^{(1)}_{lm} = \frac{r\vec{\nabla}\, Y_{lm}}{\sqrt{l(l+1)}}\ ;$$

$$\vec{Y}^{(2)}_{lm} = \frac{\vec{\nabla}\, Y_{lm} \times \vec{r}}{\sqrt{l(l+1)}}\ ;$$

Y_{lm} – **scalar** spherical harmonics.

Eigenvectors of the total angular momentum $\hat{\vec{J}}$

At some distance from the center, $lmr \gg 1$:

$$\vec{A}(t,x) = \frac{e^{i\frac{m}{2}r}}{r}\left(\underbrace{c^{+}_{\alpha}(t,r)}e^{i\frac{m}{2}t} + \underbrace{c^{-}_{\alpha}(t,r)}e^{-i\frac{m}{2}t}\right)\vec{Y}^{(\alpha)}_{lm} + \text{h.c.}$$

Weakly depends on space and time: **eikonal-like approximation**

Very similar equations for $c^{\pm}_{\alpha}$ and **<u>the same</u>** resonance condition.

Bose stars

$$i\partial_{\tilde t}\tilde\psi = -\frac{\tilde\Delta\tilde\psi}{2} + \left(\tilde\Phi - \frac{1}{8}|\tilde\psi|^2\right)\tilde\psi$$

$$\tilde\Delta\tilde\Phi = 4\pi|\tilde\psi|^2$$

$$\tilde t = m v_0^2 t;\ \tilde x = m v_0 x$$

$$\tilde\psi = g_4\psi/v_0;\ \tilde\Phi = \Phi/v_0^2$$

$$v_0 \equiv f_a/g_4 M_{Pl}$$

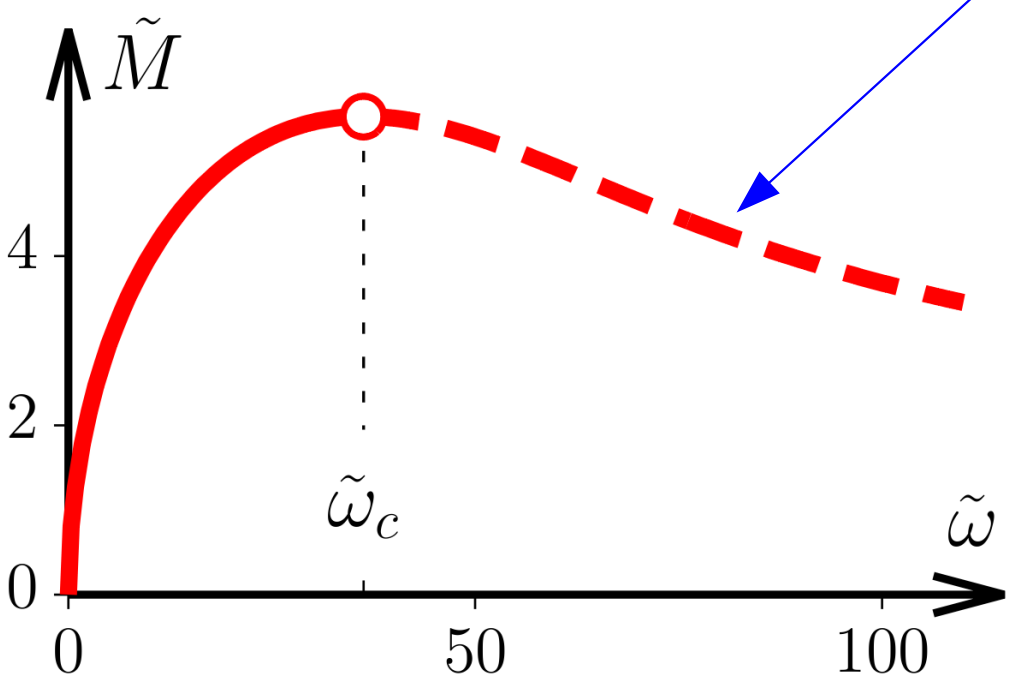
Attractive interaction!

Stability criterion $dM/d\omega > 0$ unstable!

[N.G. Vakhitov, A.A. Kolokolov, 1973]

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

Bose star profile



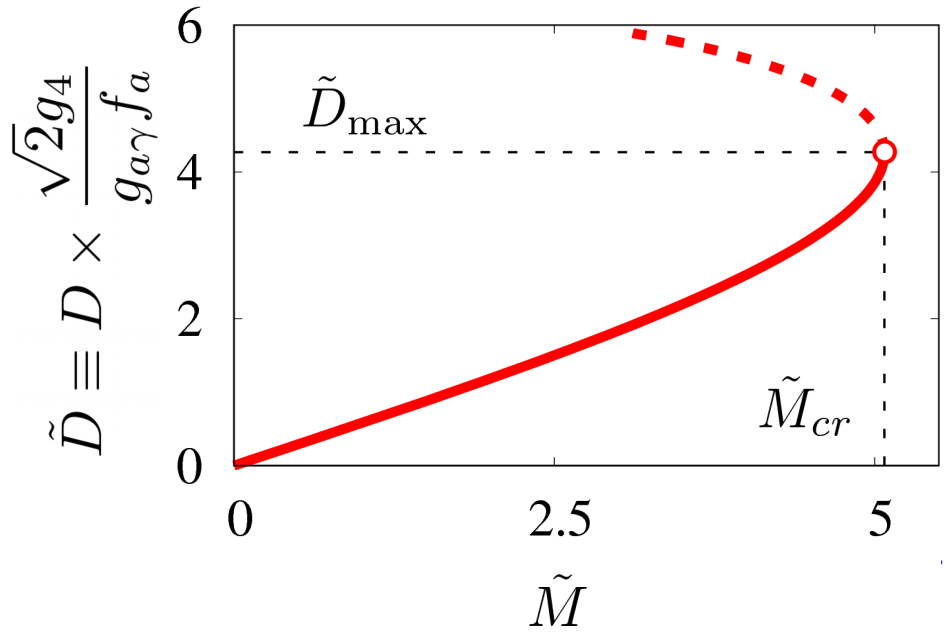
$$M_{cr} \simeq 10\frac{M_{Pl} f_a}{g_4 m} \simeq 5\times 10^{-12} M_\odot$$

$$R_{cr} \simeq 0.18\frac{g_4 M_{Pl}}{m f_a} \simeq 70\ \text{km}$$

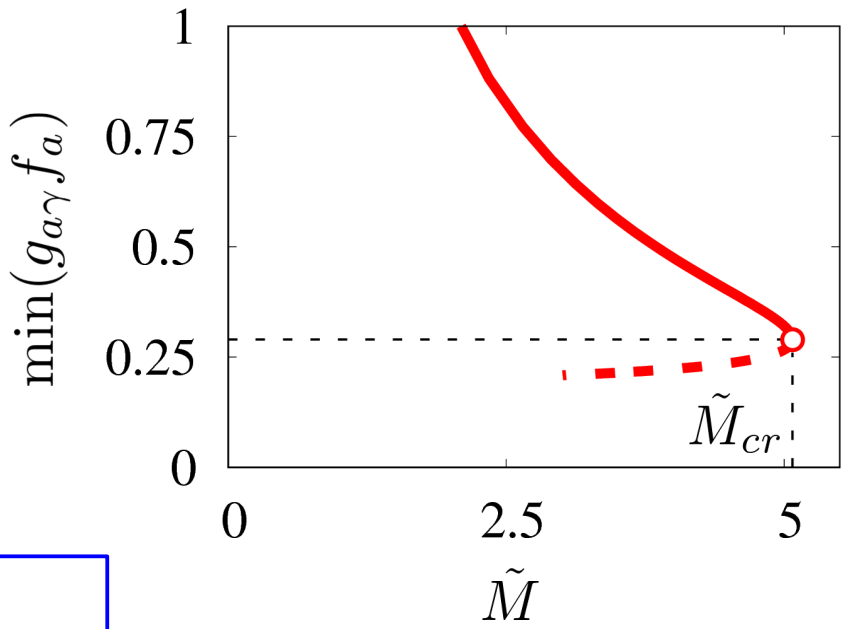
QCD axion

Bose stars

Amplification coefficient for Bose stars.



Minimal value for axion-photon coupling constant required for resonance.



<u>Additional axions captured by Bose star will be converted into photons.</u>

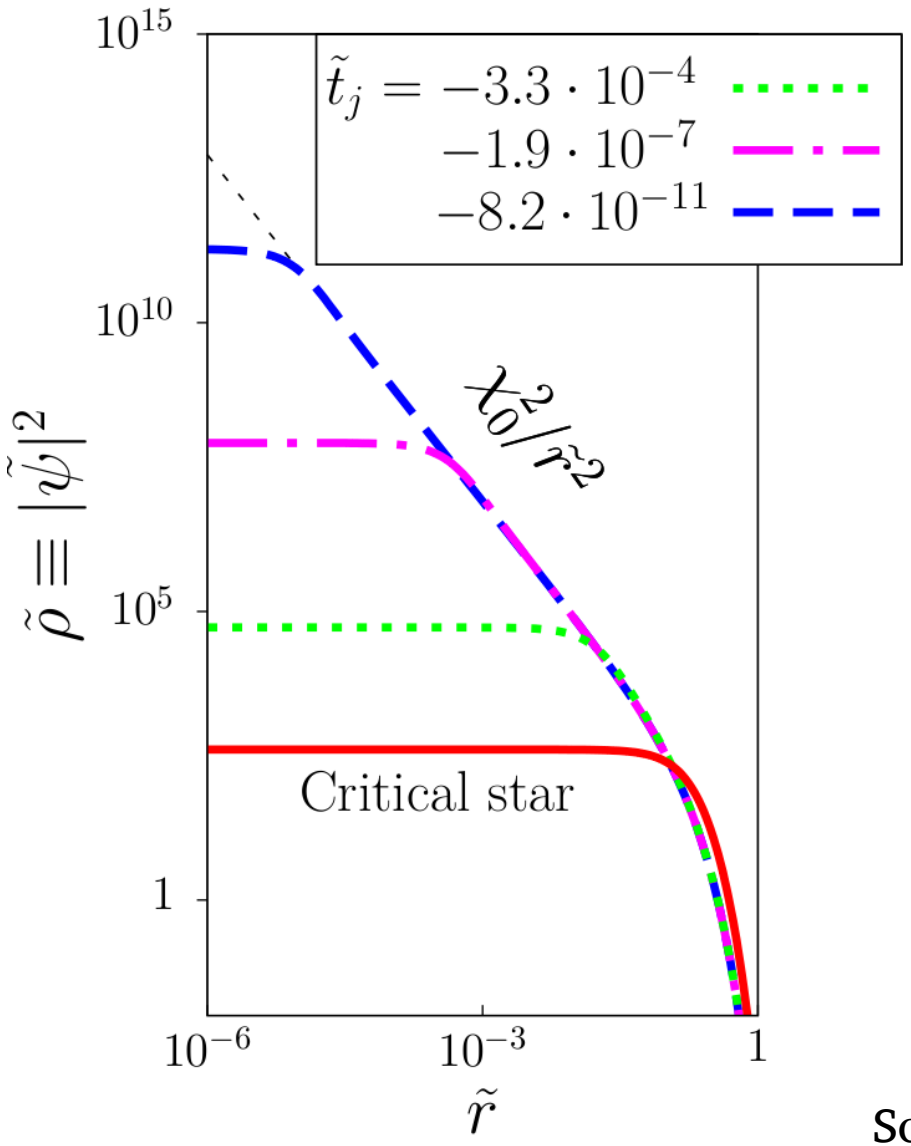
Contribution to the radio background !

For minimal axion models $g_{a\gamma} f_a \sim \alpha = 1/137$ ⇨ Relevant for photofilic axion

Bose star collapse

What happens with overcritical Bose star? ⇨ It is collapse!

[D. Levkov et al, 2016]



$$i\partial_{\tilde{t}}\tilde{\psi} = -\frac{\tilde{\Delta}\tilde{\psi}}{2} + \cancel{\tilde{\Phi}\tilde{\psi}} - \frac{1}{8}|\tilde{\psi}|^2\tilde{\psi}$$

The scaling symmetry appears:

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

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

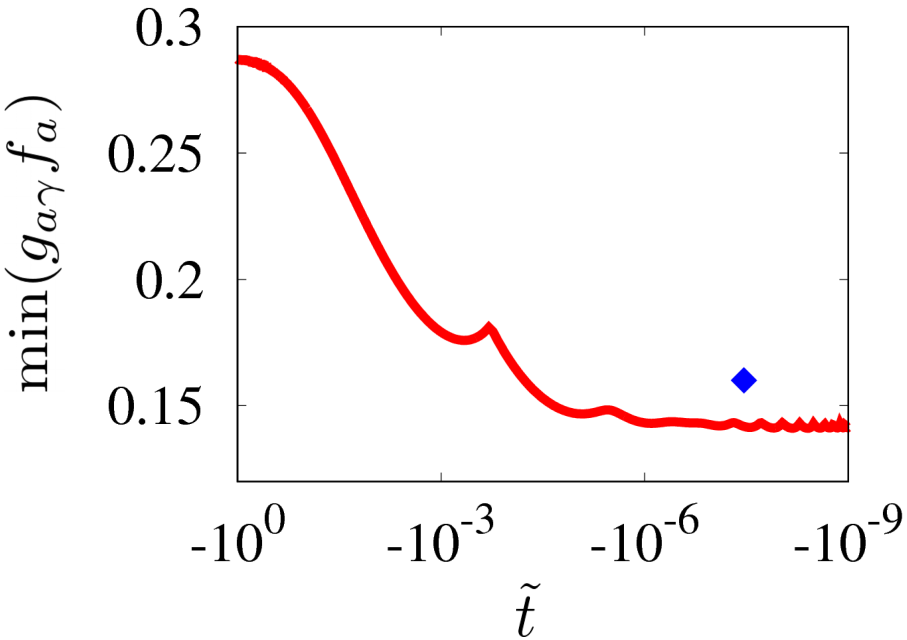
Finite energy ⇨ $\begin{cases} \chi_*(0) = 0 \\ \chi_*(+\infty) = \chi_0 \cdot y^{-2i\omega_*} \end{cases}$

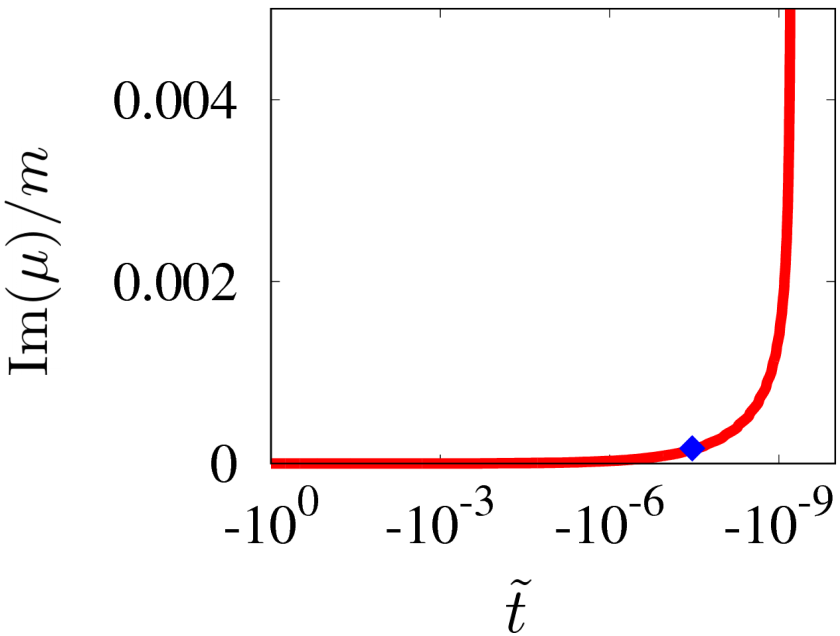
Solution: $\omega_* \approx 0.54,\ \chi_0 \approx 2.84$

Resonance during Bose star collapse

Numerical solution on collapsing Bose star background:

$\mathrm{Re}(\mu) = 0\,,\ \ \mathrm{Im}(\mu) \neq 0$ – due to nonzero axion velocities.





Resonance does not interrupted ⇦ New axions fall on the center due to self-similar collapse.

Fast radio burst! [I.I. Tkachev, 2014]

Resonance during Bose star collapse

To check the results we solve numerically relativistic equations in spherically-symmetric case.

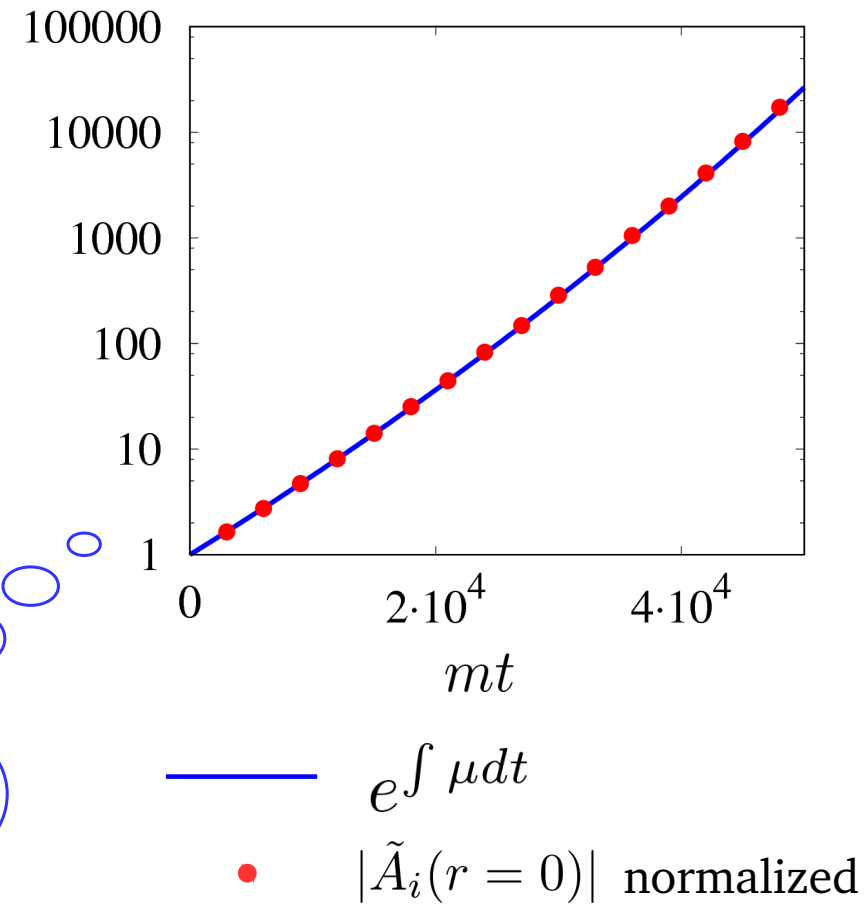
$$\begin{cases} \partial_\mu \partial_\mu a + V'(a) = 0 \\ \partial_\mu F_{\mu\nu} + g_{a\gamma} \partial_\mu a \tilde{F}_{\mu\nu} = 0 \end{cases}$$

$$\vec{A}(t,x) = a_\alpha(t,r) \vec{Y}^{(\alpha)}_{lm} + \text{h.c.}$$

Weak dependence on x, t is not assumed !

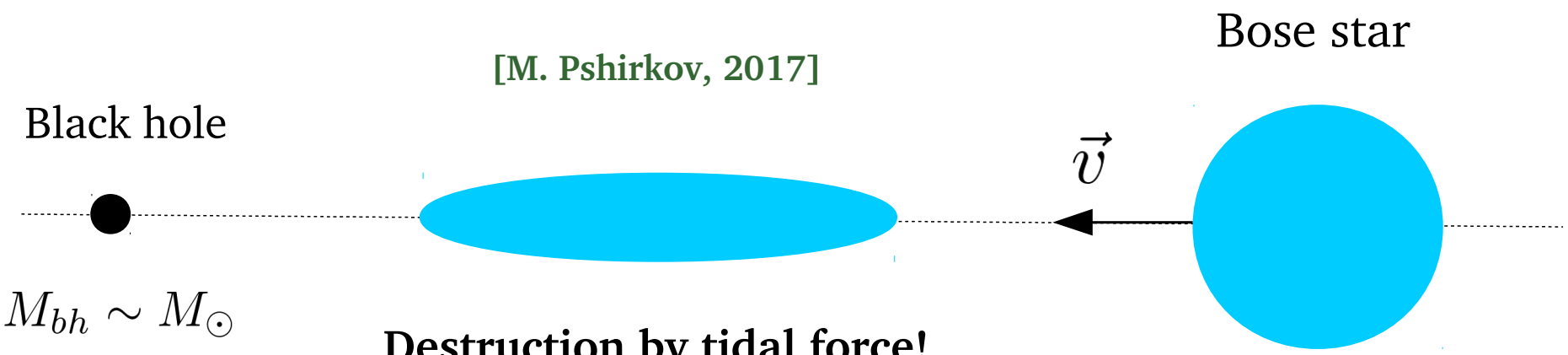
$$g_{a\gamma} f_a = 0.16$$

$$l = m = 0$$



Collision with black hole

[M. Pshirkov, 2017]



$M_{bh} \sim M_\odot$

$R_{bh} \sim 2$ km

Destruction by tidal force!

$M_{bs} \sim 10^{-11} M_\odot$

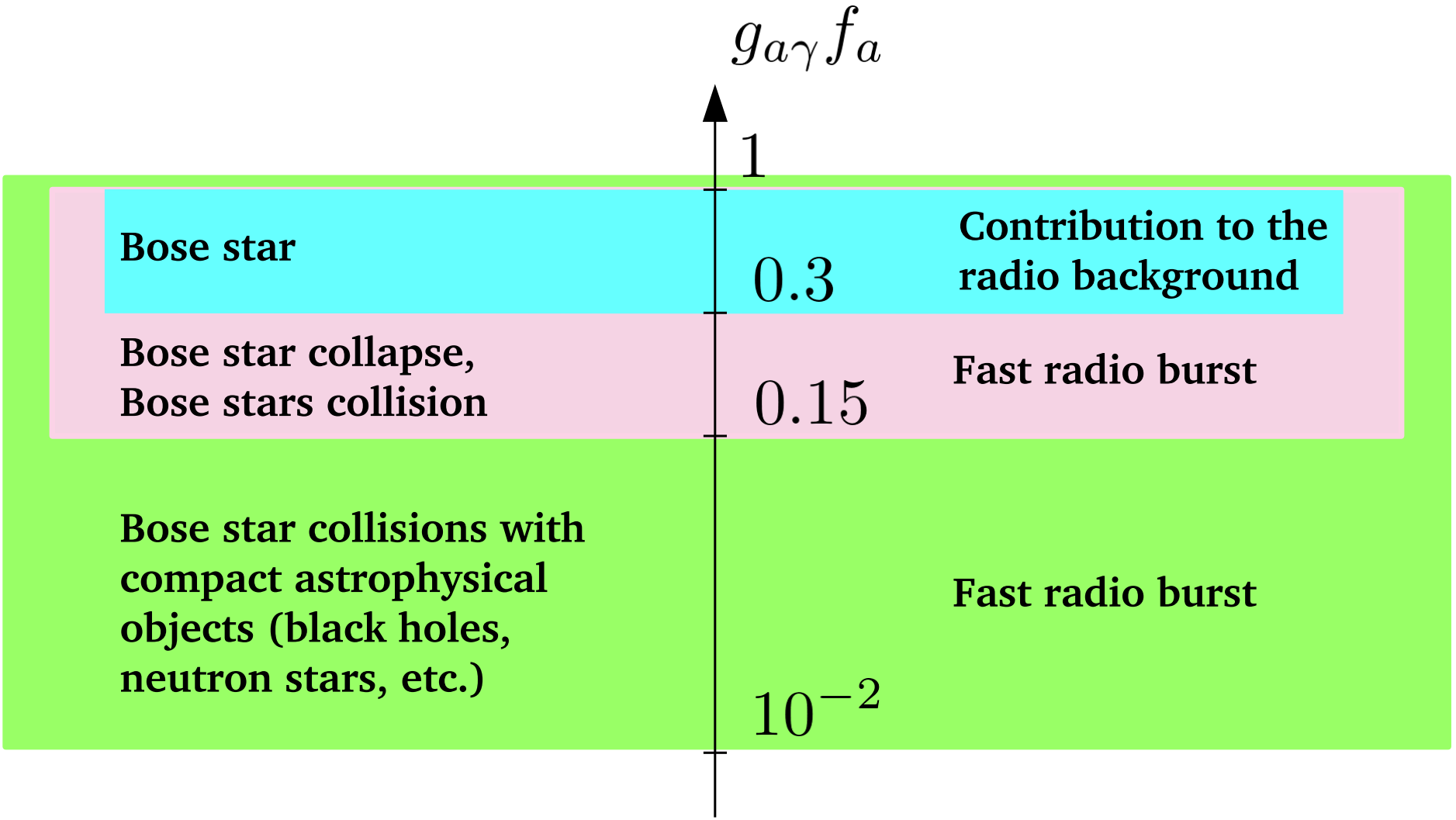
$R_{bs} \sim 50$ km

Amplification coefficient increases.

$$D \sim 10^2 g_{a\gamma} f_a \quad \text{and} \quad \min(g_{a\gamma} f_a) \sim 10^{-2}$$

Fast radio burst!

Summary


$g_{a\gamma} f_a$
1
0.3
0.15
10^{-2}
Bose star
Contribution to the radio background
Bose star collapse, Bose stars collision
Fast radio burst
Bose star collisions with compact astrophysical objects (black holes, neutron stars, etc.)
Fast radio burst

Thank you for attention!