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Collapsing Bose stars as source of repeating fast radio bursts

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Fast radio bursts

- The first FRB 010724 was discovered by Duncan Lorimer and his student David Narkevic in 2007 **[D.R. Lorimer et al., 2007]**
- At present about 70 sources of FRB are registered (www.frbcat.org). FRB 121102 and FRB 180814 are repeating.

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FRB 121102 properties:

- Frequency: 1 – 8 GHz
  or 10^{-6} - 10^{-5} eV
- Duration: ~ 1-10 milliseconds
  Size of the source: < 300 km
- Dispersion measure: ~ 580 pc cm^{-3}
  Extragalactic origin
- Flux density: ~ 1 Jy
  Total energy: 10^{39} erg ~ 10^{-15} Msun
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Collapsing Bose star properties:

- **Made of DM axions with m ~ 10^{-5} eV**
- **Size of the star ~100 km**
- **Bose star mass 10^{-12} Msun**
- **Strong activity during collapse**

Bose stars

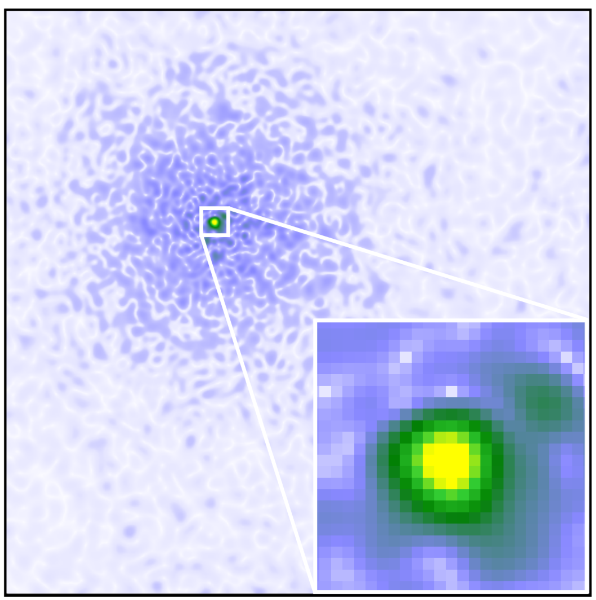
- Bose star formation observes in different models with axion-like dark matter.

QCD axion $(m \simeq 26\ \mu\text{eV})$

Bose condensation by gravitational interactions in miniclusters.

[D. Levkov et al, 2018] [cf. P. Sikivie, Q. Yang, 2009]

$$M_{bs} \sim 10^{-13} M_\odot \ ; \quad R_{bs} \sim 2000\ \text{km}$$

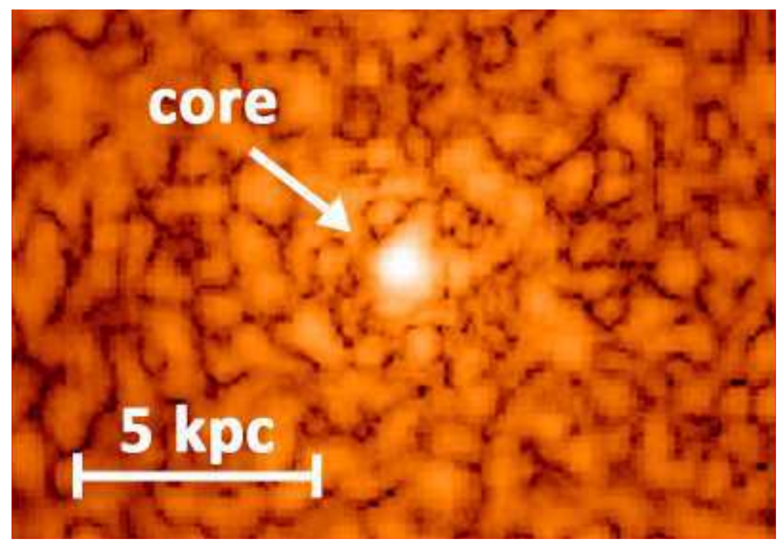


Fuzzy dark matter $(m \sim 10^{-22}\ \text{eV})$

Bose stars appear during structure formation in the center of each galaxy.

[H.-Y. Schive et al, 2014; J. Veltmaat et al 2018]

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



Properties of Bose stars

Nonrelativistic approximation for classical field:

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

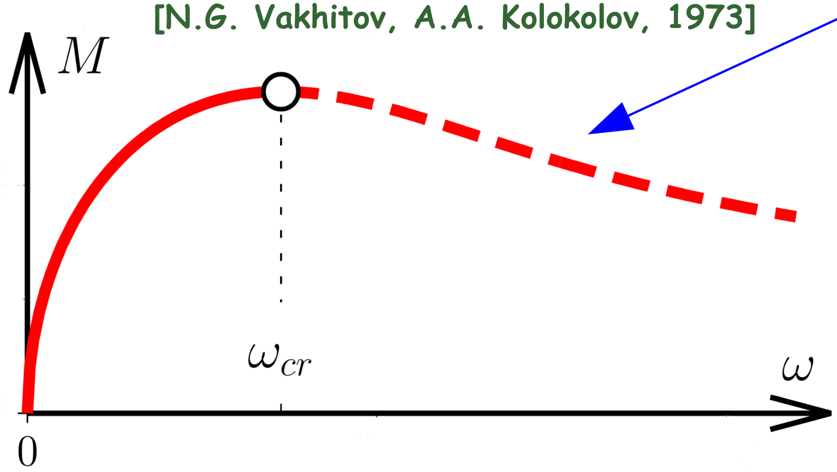
Gross-Pitaevskii-Poisson system

$$\begin{cases} i\partial_t\psi = -\Delta\psi/2m + m(\Phi - g_4^2|\psi|^2/8)\psi \\ \Delta\Phi = 4\pi G \times m^2 f_a^2 |\psi|^2 \end{cases}$$

Total mass: $M \equiv \int d^3x\, \rho = \int d^3x\, m^2 f_a^2 |\psi|^2$

Stability criterion $\boxed{dM/d\omega > 0}$ **unstable!** due to attractive self-interaction.

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



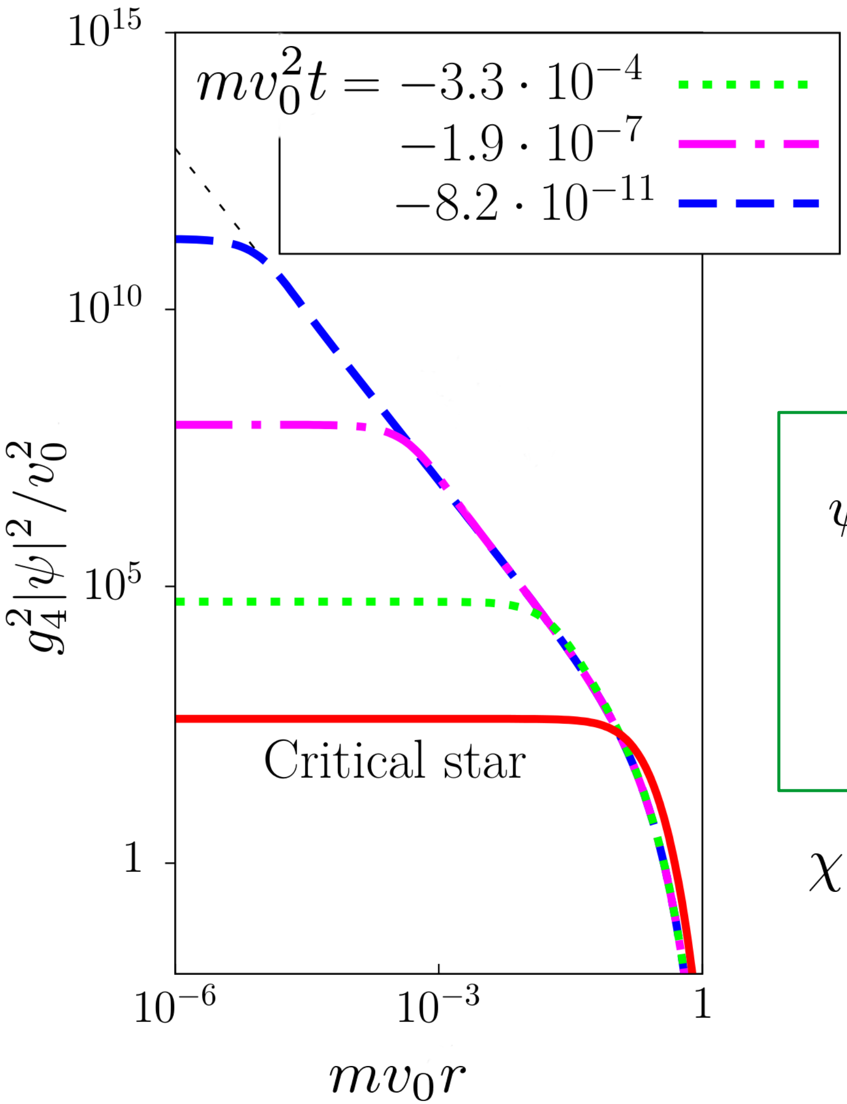
[P.H. Chavanis, 2011]

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

$$R_{cr} \simeq 0.18 \frac{g_4 M_{Pl}}{m f_a} \simeq \underbrace{200\ \text{km}}_{\text{QCD axion}}$$

Bose star collapse

Overcritical stars collapse! [D. Levkov et al, 2016; T. Helfer et al, 2016; J. Eby et al, 2016]



$$i\partial_t\psi = -\frac{\Delta\psi}{2m} + \cancel{m\Phi\psi} - \frac{mg_4^2}{8}|\psi|^2\psi$$

The scaling symmetry appears:

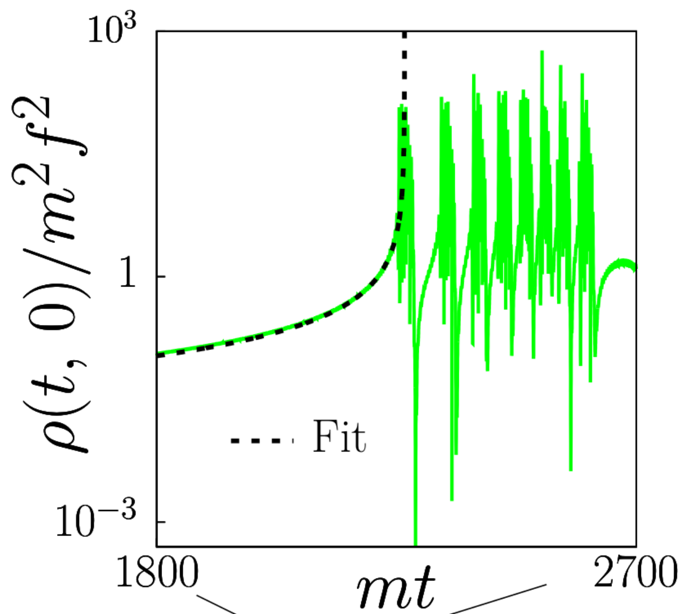
$$t \to \gamma^2 t\,, \quad x \to \gamma x\,, \quad \psi \to \psi e^{i\alpha}/\gamma\,.$$

$$\boxed{\psi = \frac{(-mv_0^2 t)^{i\omega_*}}{mv_0 r}\chi_*\underbrace{\left(\frac{\sqrt{m}\,r}{\sqrt{-t}}\right)}_{y} \qquad v_0 \equiv \frac{f_a}{g_4 M_{Pl}}}$$

χ_* – scaling solution

$$\begin{cases} \chi_*(+\infty) = \chi_0\cdot y^{-2i\omega_*} \\ \omega_* \simeq 0.54\,, \quad \chi_0 \simeq 2.84\,. \end{cases}$$

Bose star collapse: relativistic regime



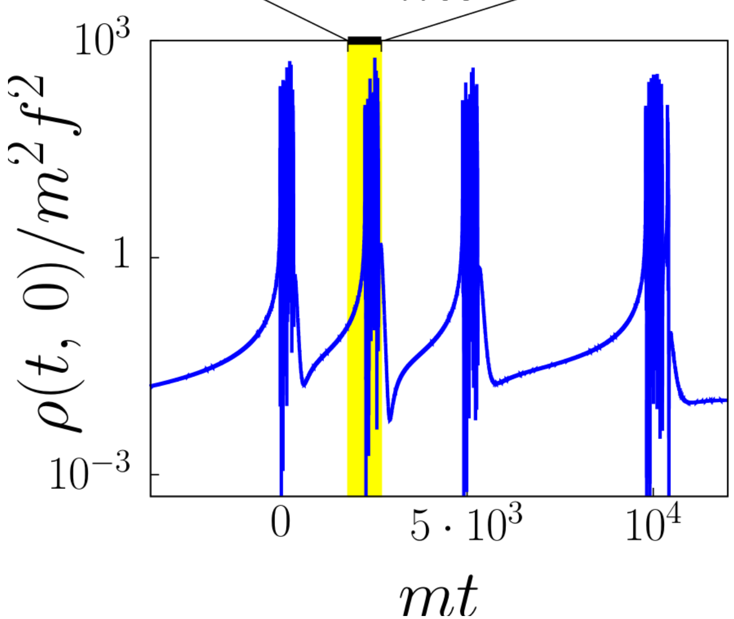
Equation: $\Box a = -(1+2\Phi)\,\mathcal{V}'(a/f_a)/f_a$

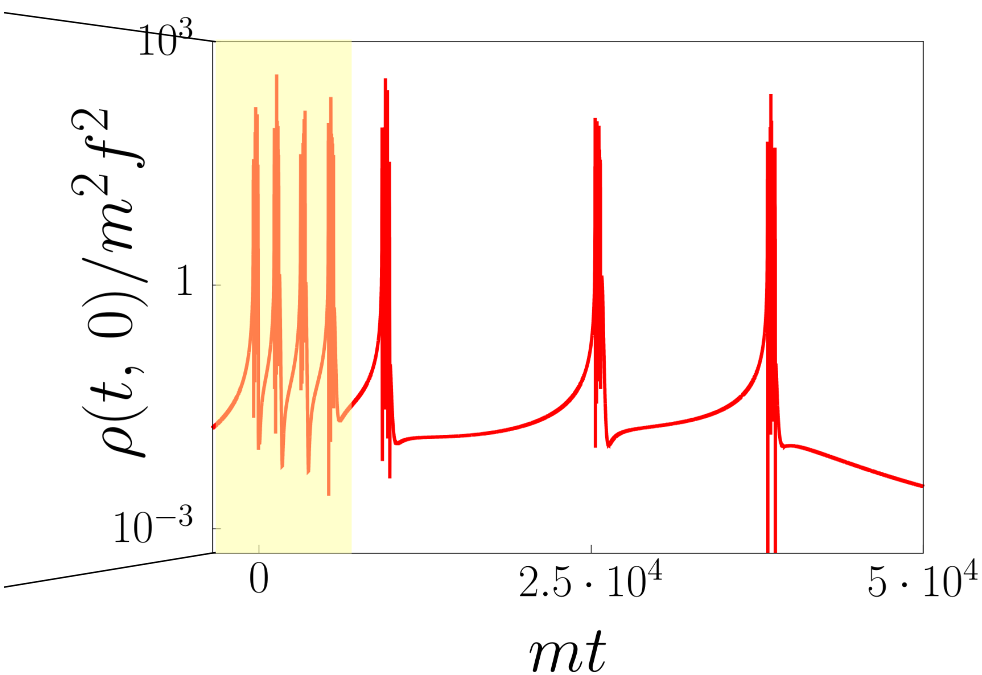
Potential:

$$\mathcal{V}(\theta) = -m_a^2 f_a^2\,(1+1/z)\,\sqrt{1+z^2+2z\cos\theta}$$

[G.G. di Cortona et al, 2015]

$$z \equiv m_u/m_d \approx 0.56$$





Axion-photon coupling

Axion field of Bose star oscillates coherently with time:

$$a/f_a = (\psi \mathrm{e}^{-imt} + \mathrm{h.c.})/\sqrt{2}$$ ⇨ May cause parametric resonance of photons!

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

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

Consider plane waves with frequency **m/2** moving through the star along z-axis.

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

slowly depend on x and t

⇕ **eikonal-like approximation**

In the nonrelativistic regime ψ slowly changes on the size of the order of photon wavelength.

Linear resonance a->2γ

$$\frac{\partial c_x^+}{\partial t} - \frac{\partial c_x^+}{\partial z} - i\frac{g_{a\gamma} m f_a}{\sqrt{2}}\psi^* c_y^- = 0$$

$$\frac{\partial c_y^-}{\partial t} + \frac{\partial c_y^-}{\partial z} + i\frac{g_{a\gamma} m f_a}{\sqrt{2}}\psi c_x^+ = 0$$

$c_y^+ = c_x^+, \; c_x^- = -c_y^-$

satisfy another pair of Eqs.

Boundary conditions:

no waves coming from infinity!

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

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

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

$$\begin{cases} \mu c_x^+ - \dfrac{\partial c_x^+}{\partial z} - i\dfrac{g_{a\gamma} m f_a}{\sqrt{2}}\psi^* c_y^- = 0 \\[2ex] \mu c_y^- + \dfrac{\partial c_y^-}{\partial z} + i\dfrac{g_{a\gamma} m f_a}{\sqrt{2}}\psi c_x^+ = 0 \end{cases}$$

Linear resonance a->2γ

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

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

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

Beginning of the resonance!

For $D > \frac{\pi}{2}$ solution have $\mu > 0$.

For general ψ we can solve boundary-value numerically

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

Spherically-symmetric approximation

When the amplitude of produced electromagnetic field becomes large, back reaction on the Bose star must be taken into account.

One can try to make 3d numerical simulation.

Unrealizable!

Bose star is much larger than the photon wavelength!
Time of the burst is much larger than the photon frequency.

Collapsing self-similar solution is spherically-symmetric attractor.

We numerically verified that it forms up in collapse of a Bose star perturbed by a large amplitude nonspherical perturbation.

Spherically symmetric approximation for the axion field.

Equations for 3d simulation

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

$$\begin{cases} \mathrm{div}\, \boldsymbol{D} = 0 \\ \partial_t \boldsymbol{D} = \mathrm{rot}\, \boldsymbol{B} \\ \mathrm{div}\, \boldsymbol{H} = 0 \\ \partial_t \boldsymbol{H} = -\mathrm{rot}\, \boldsymbol{E} \end{cases}$$

where $\boxed{A_0 = 0 \text{ - gauge}}$ and

$$\begin{cases} E_i = F_{0i} \\ H_i = -\frac{1}{2}\epsilon_{ijk} F_{jk} \\ B_i = H_i + g_{a\gamma\gamma} a E_i \\ D_i = E_i - g_{a\gamma\gamma} a H_i \end{cases}$$

Decompose vectors E, H, B and D into spherical-vector harmonics:

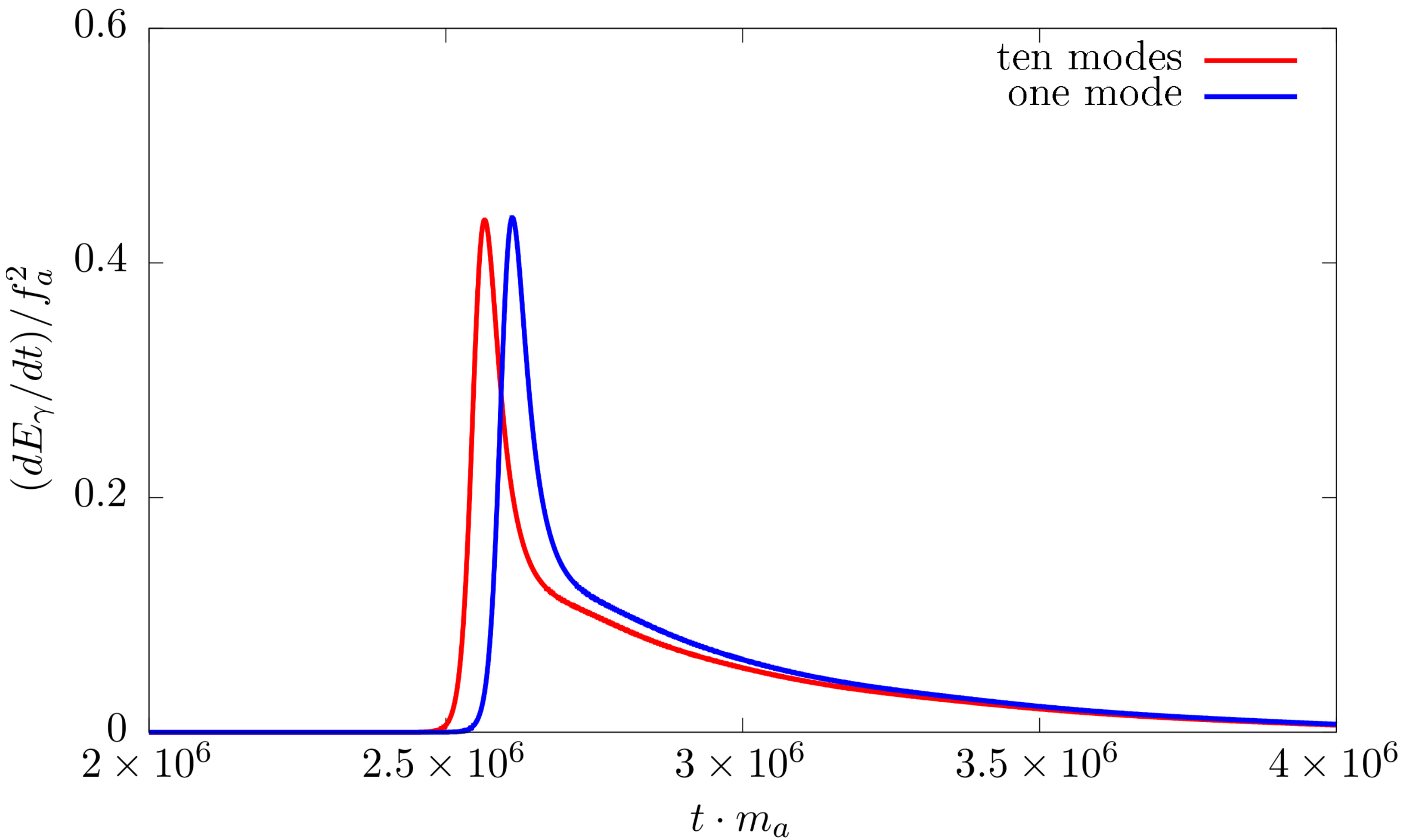
$$\begin{cases} \vec{\mathrm{Y}}_{lm} = \vec{n}\, \mathrm{Y}_{lm} \\ \vec{\Psi}_{lm} = \frac{r\vec{\nabla}}{\sqrt{l(l+1)}} \mathrm{Y}_{lm} \\ \vec{\Phi}_{lm} = \frac{\vec{\nabla} \times \vec{r}}{\sqrt{l(l+1)}} \mathrm{Y}_{lm} \end{cases}$$

$\Downarrow$

Solve equations for the {lm}-modes of these vectors and equation for the axion field numerically

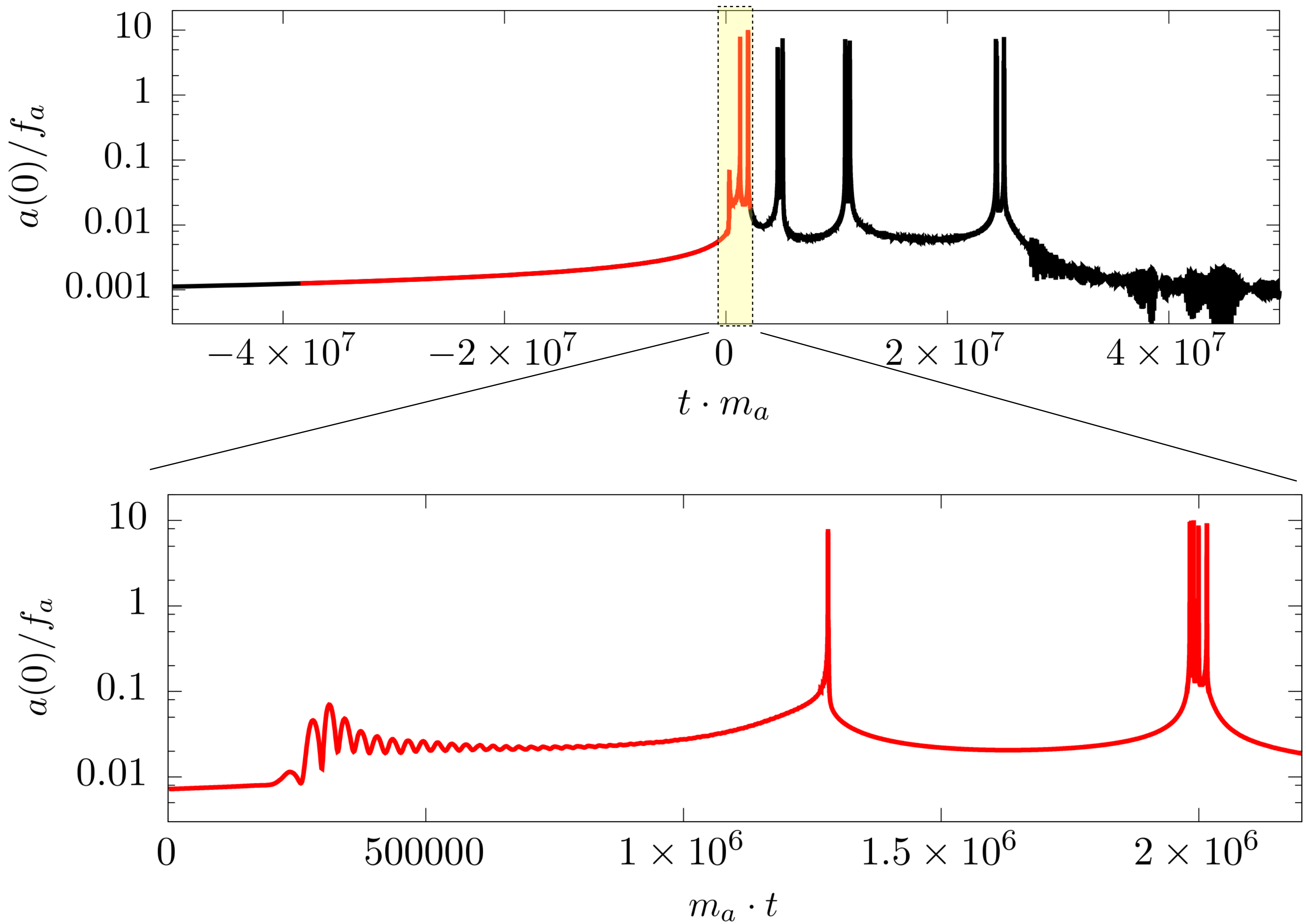
Back reaction of photons

Total energy current of radio-photons produced by Bose star in the model with $f_a = 4 \times 10^{14}$ GeV distributed to one (blue) and to ten (red) {lm}-harmonics.

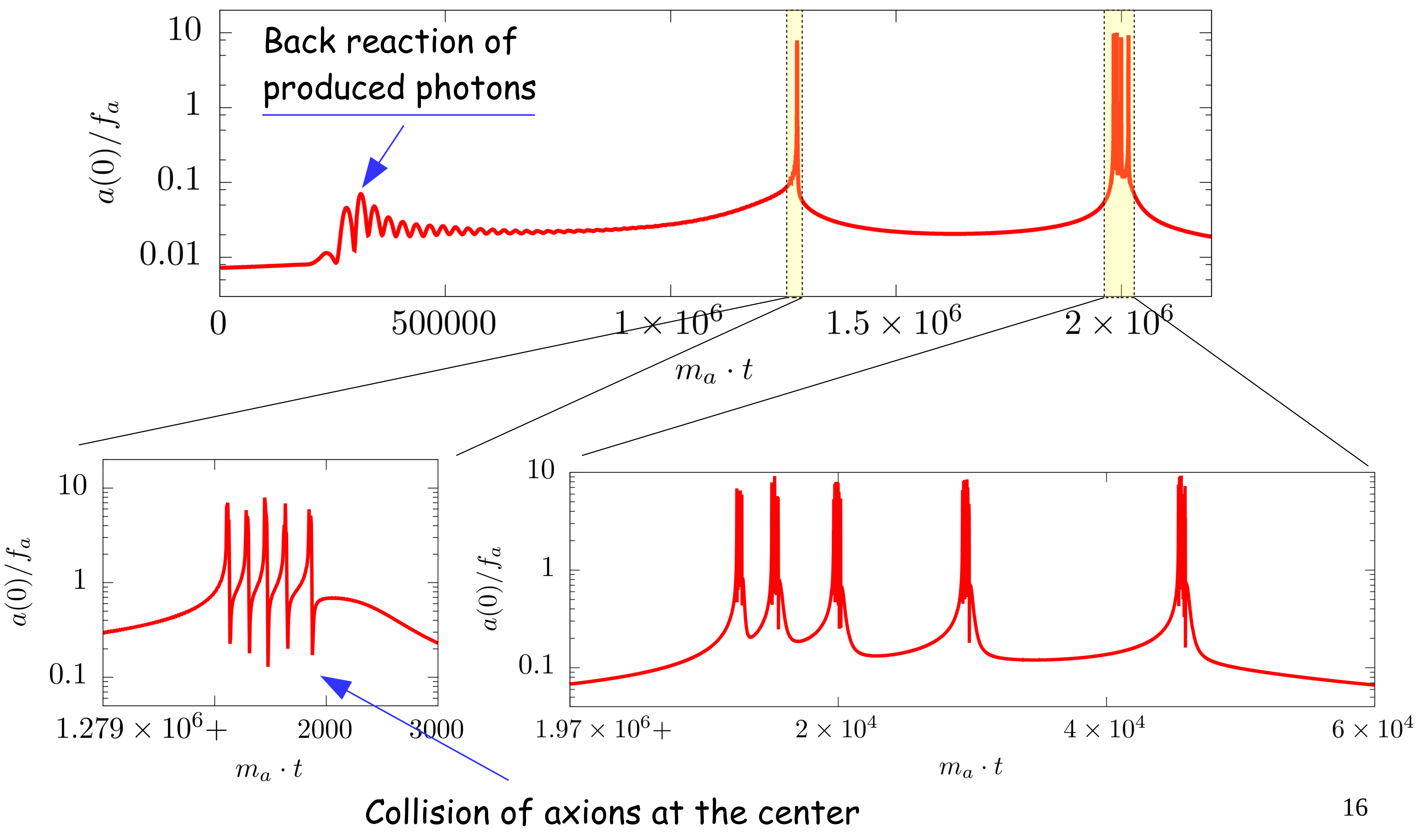


Numerical results for $f_a \simeq 4 \times 10^{13}$ GeV

Axion field in the center of collapsing Bose star intersecting with one l = 1 harmonics in the model with $f_a = 4 \times 10^{13}$ GeV and $g_{a\gamma\gamma} = 0.182/f_a$

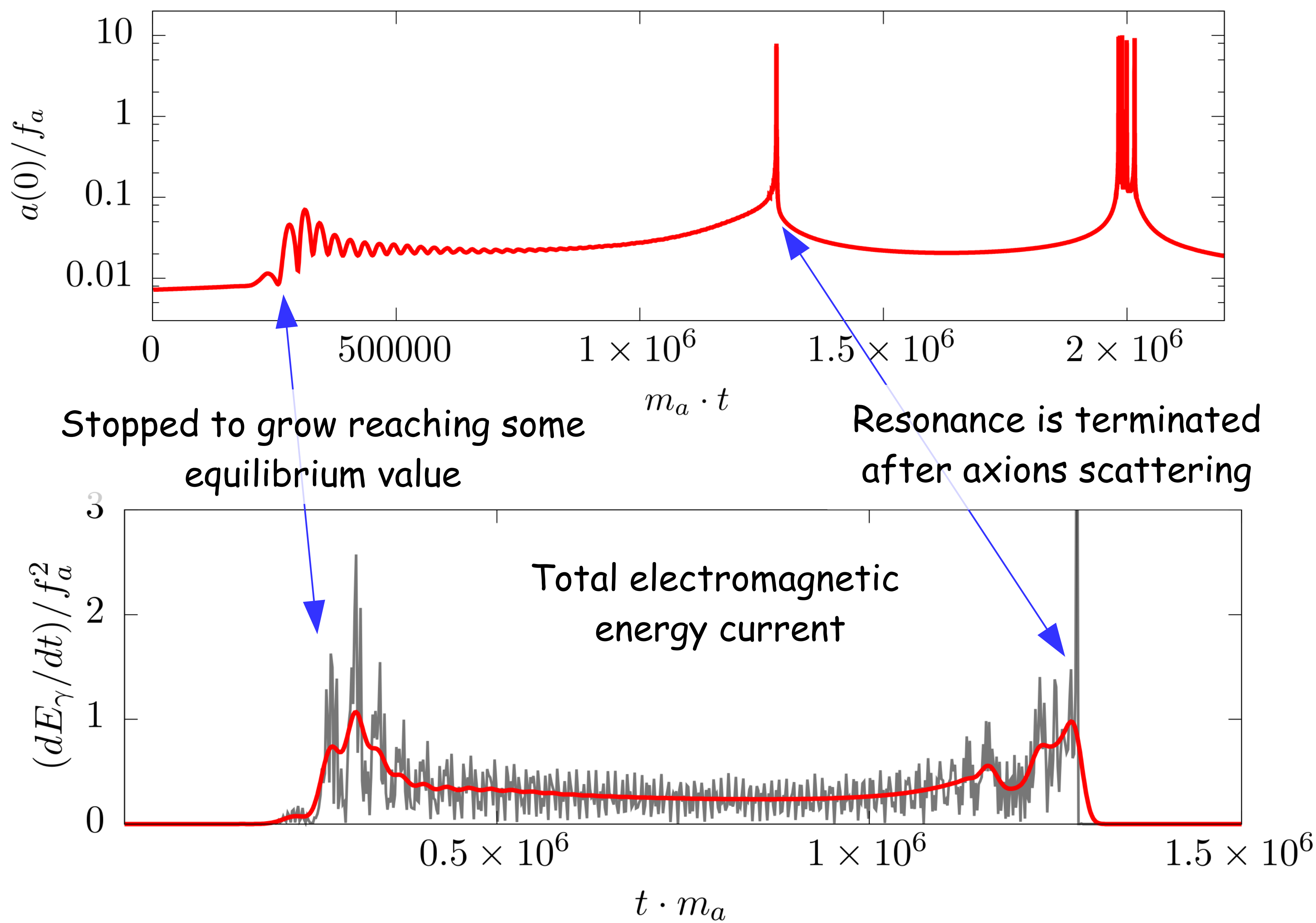


First burst



Back reaction of produced photons
10
1
0.1
0.01
$a(0)/f_a$
0
500000
1×10^6
1.5×10^6
2×10^6
$m_a \cdot t$
10
1
0.1
$a(0)/f_a$
$1.279 \times 10^6 +$
2000
3000
$m_a \cdot t$
10
1
0.1
$a(0)/f_a$
$1.97 \times 10^6 +$
2×10^4
4×10^4
6×10^4
$m_a \cdot t$
Collision of axions at the center

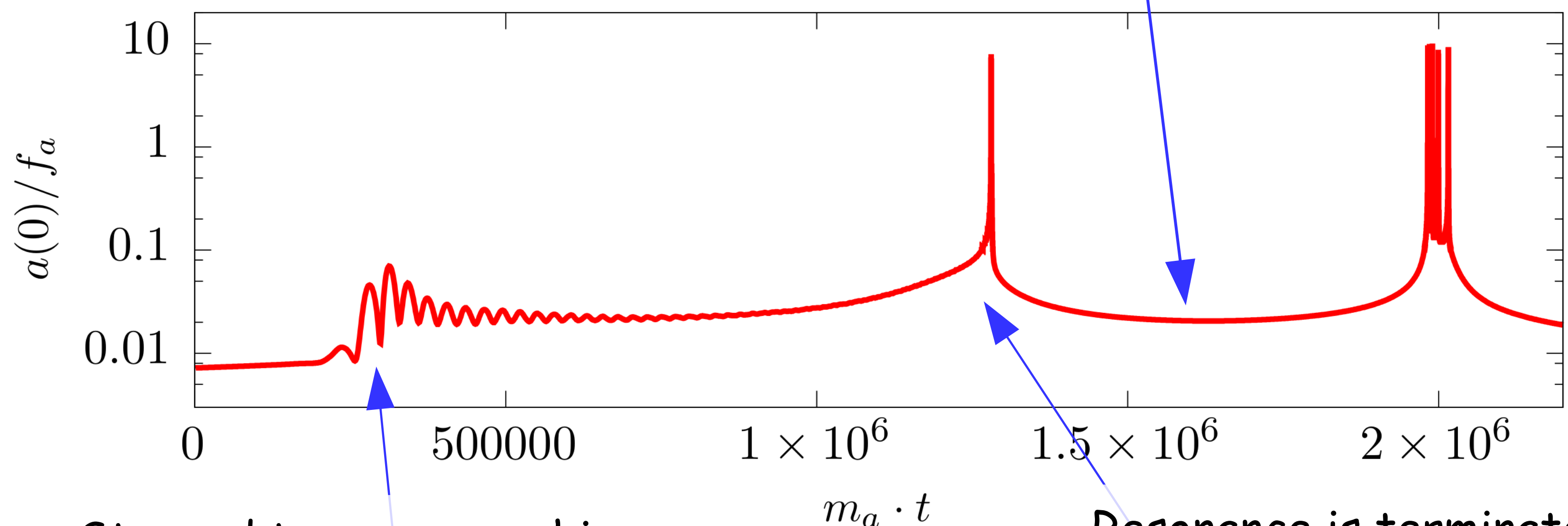
First burst



$a(0)/f_a$
10
1
0.1
0.01
0
500000
1×10^6
1.5×10^6
2×10^6
$m_a \cdot t$
Stopped to grow reaching some equilibrium value
Resonance is terminated after axions scattering
3
2
1
0
$(dE_\gamma/dt)/f_a^2$
Total electromagnetic energy current
0.5×10^6
1×10^6
1.5×10^6
$t \cdot m_a$

First burst

Has not enough time to develop resonance during subsequent collapse.



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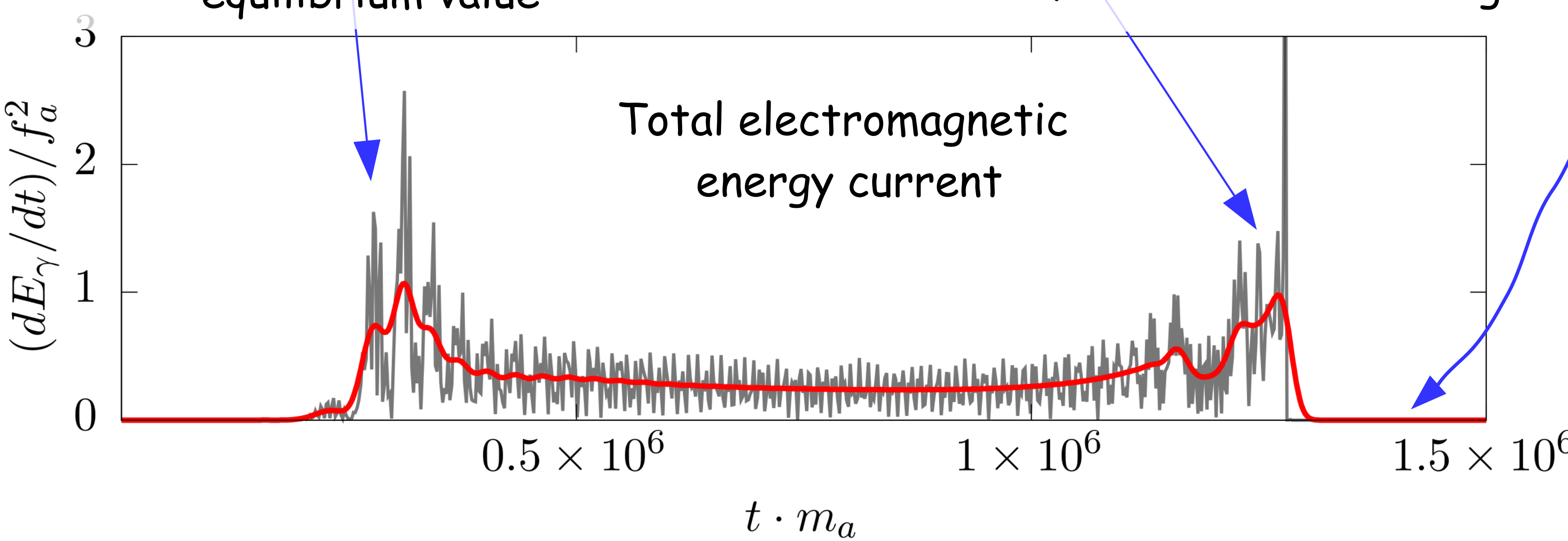
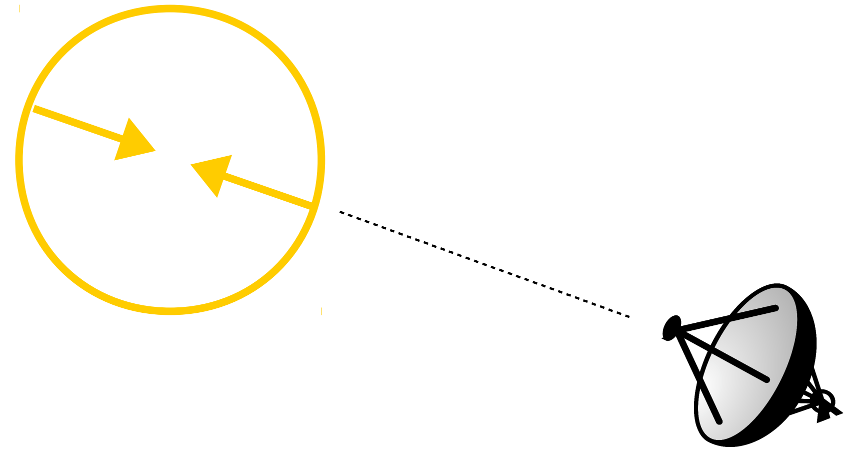
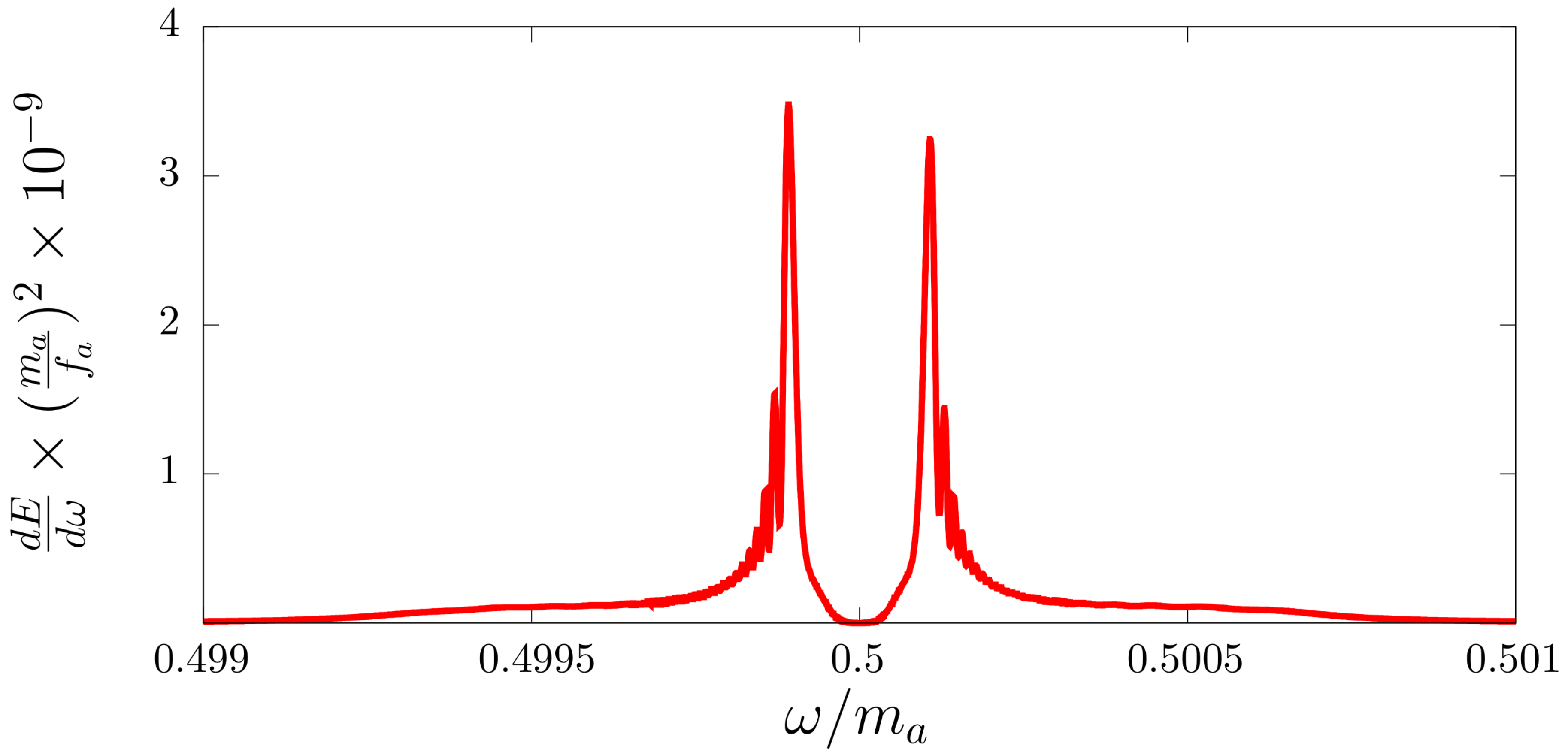
Resonance is terminated after axions scattering



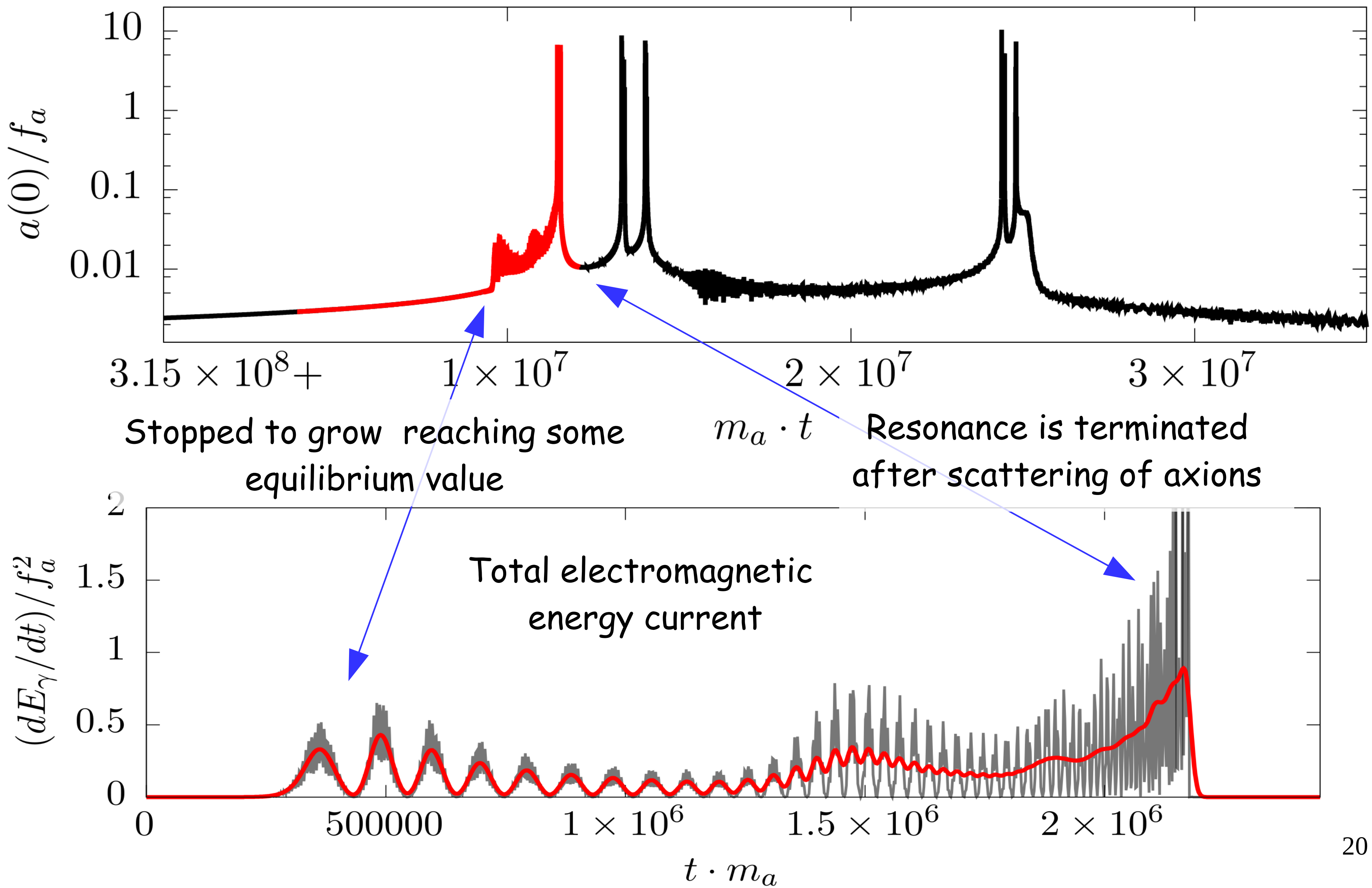
First burst

Two peaks of spectrum are due to velocities of axions falling to the Bose star center.



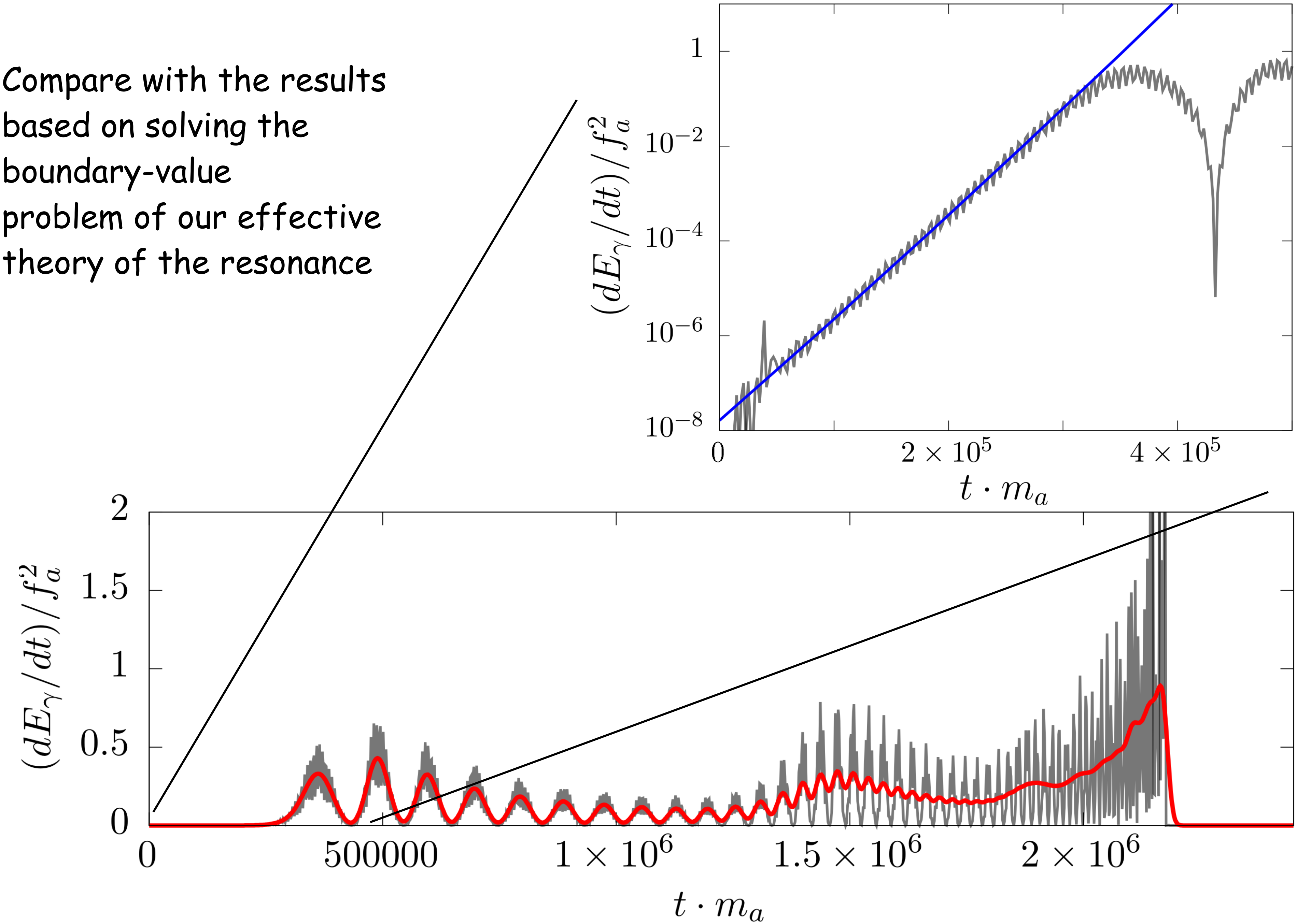


Second burst

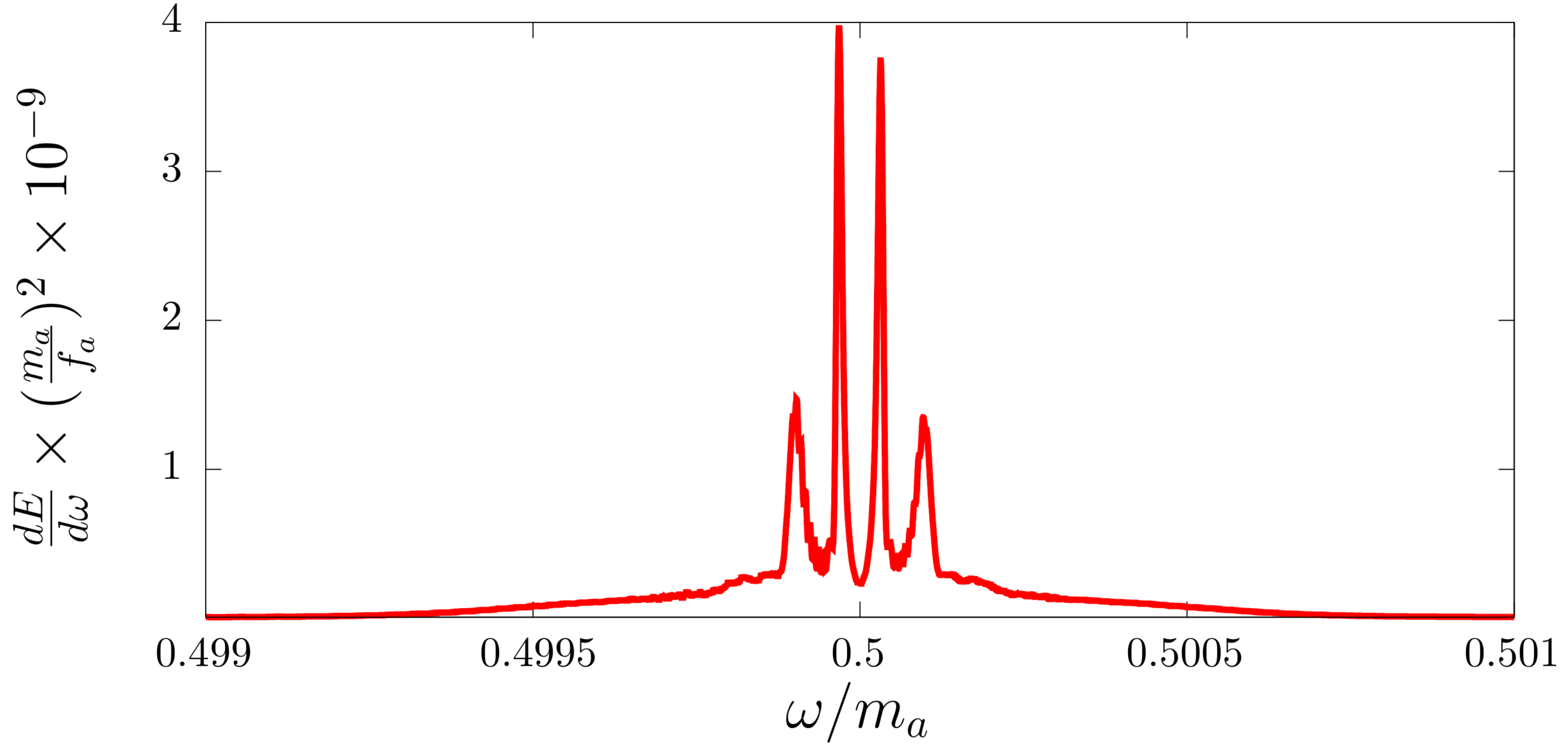


Second burst

Compare with the results based on solving the boundary-value problem of our effective theory of the resonance



Second burst



Bursts parameters

in the model with $f_a \simeq 4 \times 10^{13}$ GeV

First burst

$$E_\gamma \simeq 10^{44} \times \left(\frac{f_a}{4 \times 10^{13}\ \mathrm{GeV}} \right)^2 \mathrm{erg}$$

$$t \simeq 0.07\ \mathrm{msec}$$

Second burst

$$E_\gamma \simeq 10^{44} \times \left(\frac{f_a}{4 \times 10^{13}\ \mathrm{GeV}} \right)^2 \mathrm{erg}$$

$$t \simeq 0.14\ \mathrm{msec}$$

Time delay between the bursts is $\Delta t \simeq 23\ \mathrm{msec}$

Resonance during Bose star collapse

1. **Radio frequencies** $\Rightarrow$ $\boxed{m \simeq 10^{-5}\ \mathrm{eV}}$

2. **Repeatability during several hours**

Collapse duration is of order of free fall time $\Rightarrow$ $t_{col} \simeq 10^{-2} \frac{M_{Pl}^2}{m f_a^2} \simeq 1\ \mathrm{hr}$

$\Downarrow$

$$\boxed{f_a \simeq 2 \times 10^{11}\ \mathrm{GeV}}$$

3. **Duration of one burst** $\Rightarrow$ $\boxed{g_{a\gamma\gamma} \simeq \frac{0.14}{f_a}}$

4. **Energy of one burst** $\Rightarrow$ $\boxed{E \simeq (10^{-2} - 10^{-3}) \cdot M_{BS} \simeq 10^{39}\ \mathrm{erg}}$

Conclusion

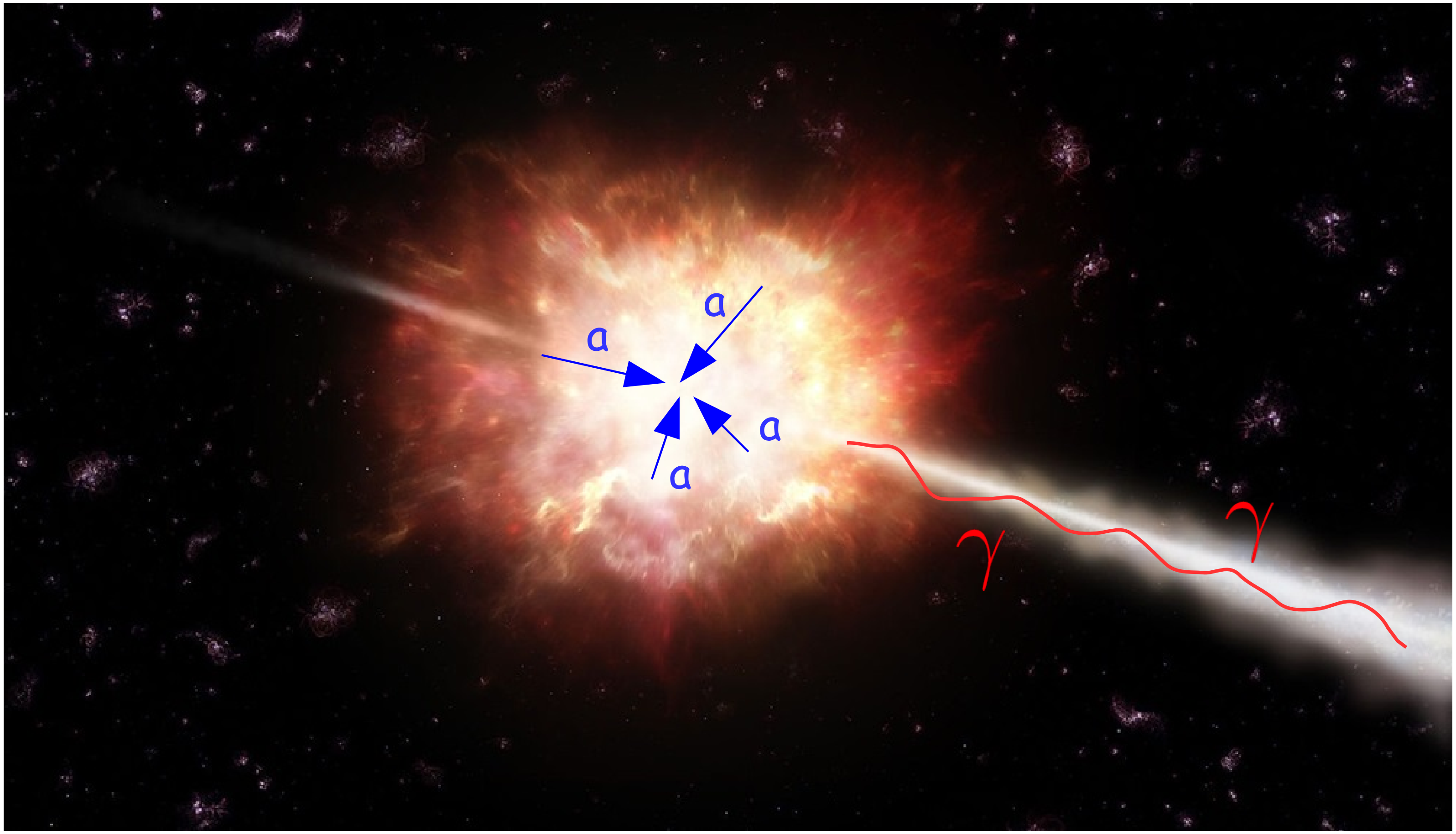
$m \simeq 10^{-5}\ \mathrm{eV}$

Very close to what we expect for dark matter made by QCD axion particles.

$f_a \simeq 2 \times 10^{11}\ \mathrm{GeV}$

$g_{a\gamma\gamma} \simeq \frac{0.14}{f_a}$

$E \simeq (10^{-2} - 10^{-3}) \cdot M_{BS} \simeq 10^{39}\ \mathrm{erg}$



Thank you for attention!