UNIVERSITÀ DEGLI STUDI DI BARI ALDO MORO

INFN BARI
Istituto Nazionale di Fisica Nucleare
Sezione di Bari

Axions from Neutron stars mergers: production and detection signatures

FRANCESCA LECCE

BARI THEORY XMAS WORKSHOP 2024

DECEMBER 17, 2024

Overview

Axion and Axion-like particles

The QCD axion is a hypothetical particle postulated by Wilzcek and Weinberg in relation to the Peccei-Quinn mechanism ***[R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977)]*** to solve the strong-CP problem of the QCD ***[S. Weinberg, Phys. Rev. Lett. 40, 223 (1978)]***

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Non trivial structure of the QCD vacuum

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$U(1)_{PQ}$ SSB

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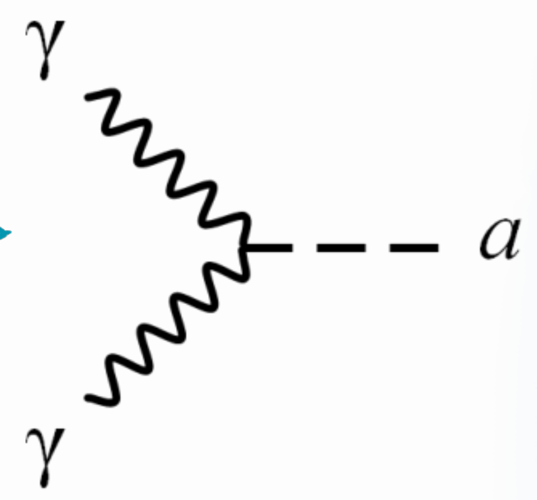

Binary Neutron Star Mergers

Binary Neutron Star systems can form dynamically from pre-existing binary systems or dynamically in dense environments ***[M. Renzo et al., 624, A66 (2019), S. Ye et al., Astr. Jou. 888, L10 (2019)].***

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Ringdown phase

$\Delta t \sim O(1)\,\mathrm{s}$

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Simulations of NSM are based on hydrodynamics equations including General Relativity effects.
The simulations used in this work were performed by the ***Relativistic Group at the GSI Helmotz Centre in Darmstadt.***

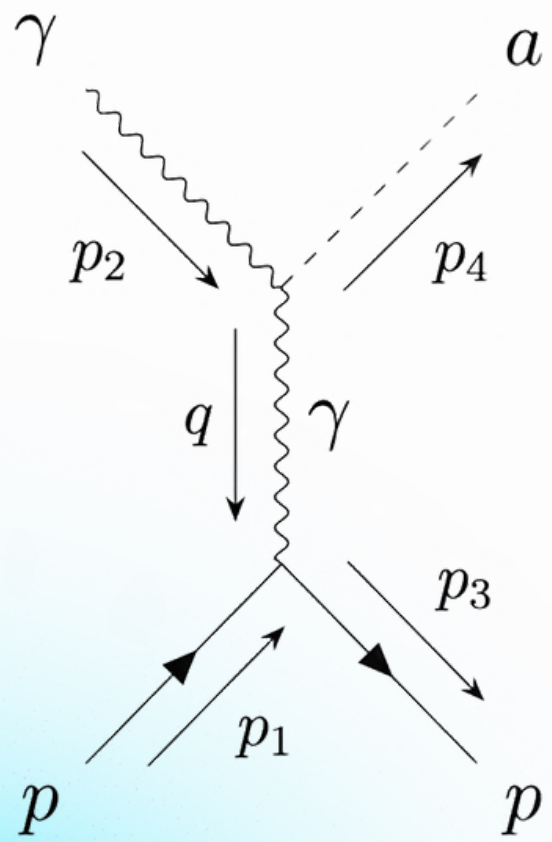
Aim of the Work

1. Study the production of ALPs from Binary Neutron Star Mergers, via Primakoff effect.

2. Determine the sensitivity of experiments and proposed experiment to the gamma-ray signal produced by ALP-photon conversion

Primakoff effect

Conversion of a thermal photon in a stellar plasma into an ALP in the fluctuation of electromagnetic field, generated by charged particles in the plasma. ***[H. Primakoff, Phys. Rev. 81, 899.(1951)]***



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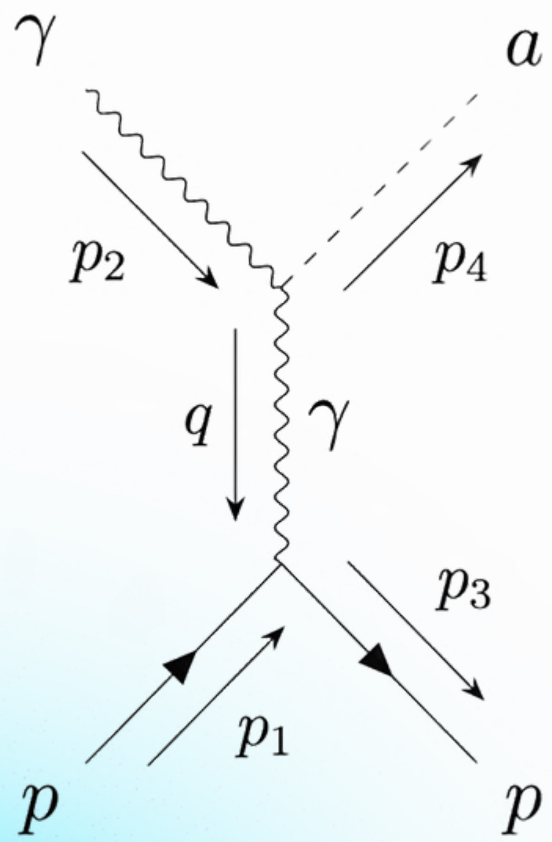
We considered of infinite proton mass, massless ALP and $m_\gamma = \sqrt{\frac{3}{2}}\omega_{\rm pl} \approx 16.3\,{\rm MeV}\,Y_e^{1/3}\,\rho_{14}^{1/3}$



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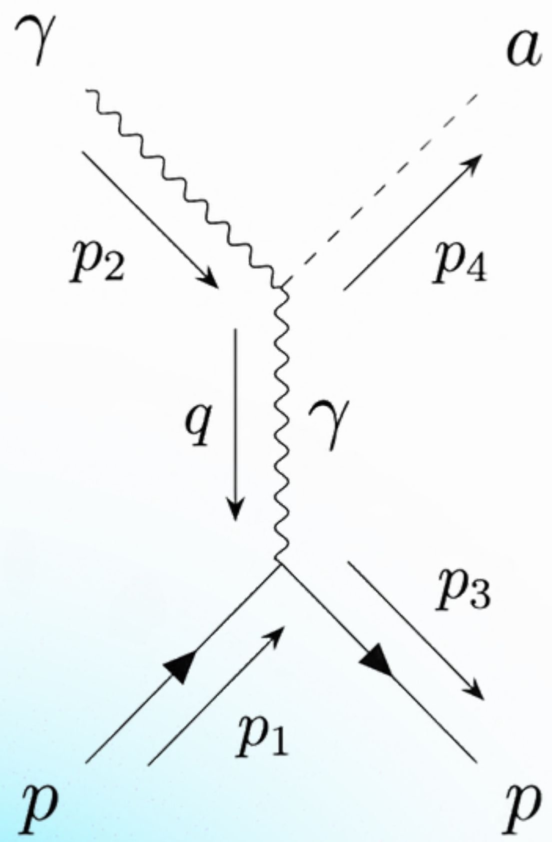

$$\sum_{\rm spin,pol} |\mathcal{M}|^2 = \frac{32\pi\alpha}{\mathbf{q}^2(\mathbf{q}^2+\kappa_s^2)} g_{a\gamma\gamma}^2 m_p^2 [\mathbf{p}_2^2\mathbf{p}_4^2 - (\mathbf{p}_2\cdot\mathbf{p}_4)^2]$$

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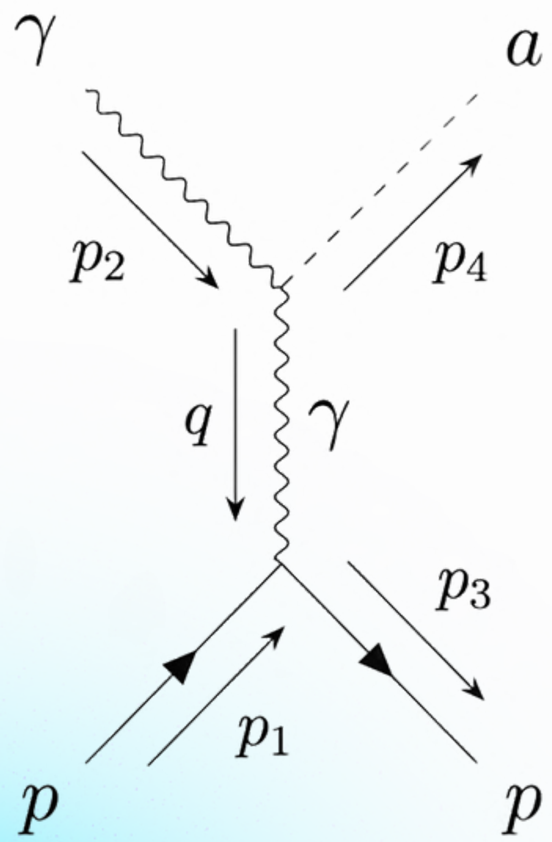

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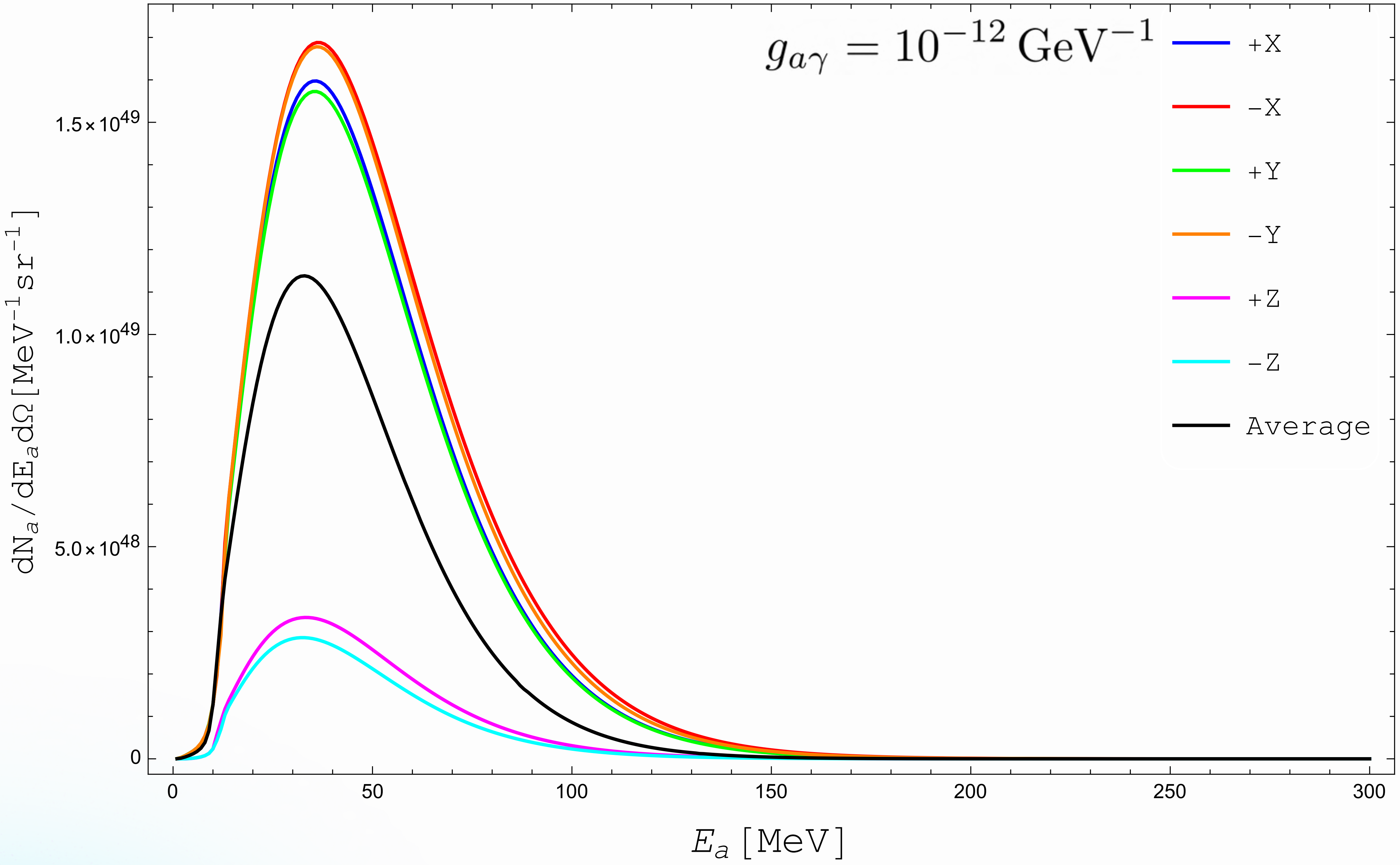
Screening effect in the Debye expression $\kappa_{\rm s}^2 = \frac{4\pi\alpha n_{\rm p}}{T}$

[P. Debye and E. Hückel, Phys. Zeit. 24.9, 185 (1923)]

ALP spectrum

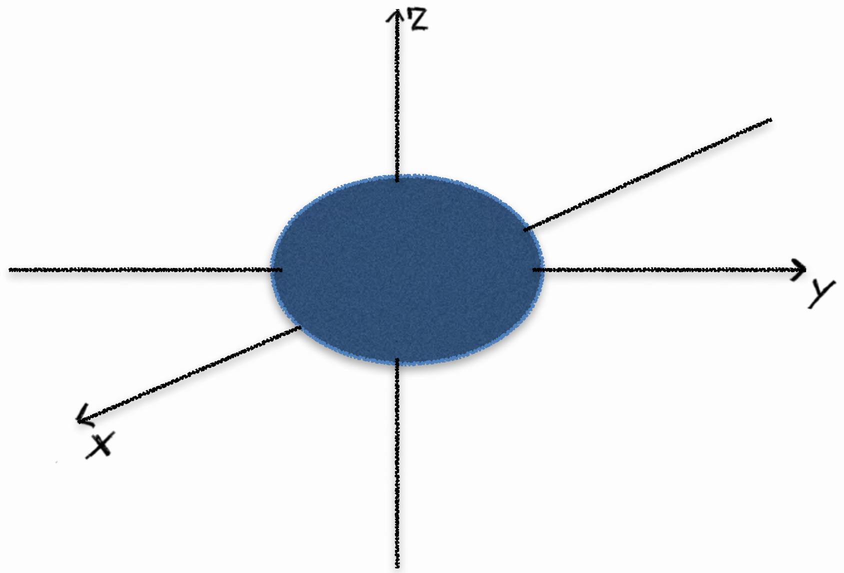


The lapse factor encodes the strong gravitational field effects and affects

$$E = E^*(r)e^{\Phi(r)}$$
$$dt = dt^*(r)e^{-\Phi(r)}$$

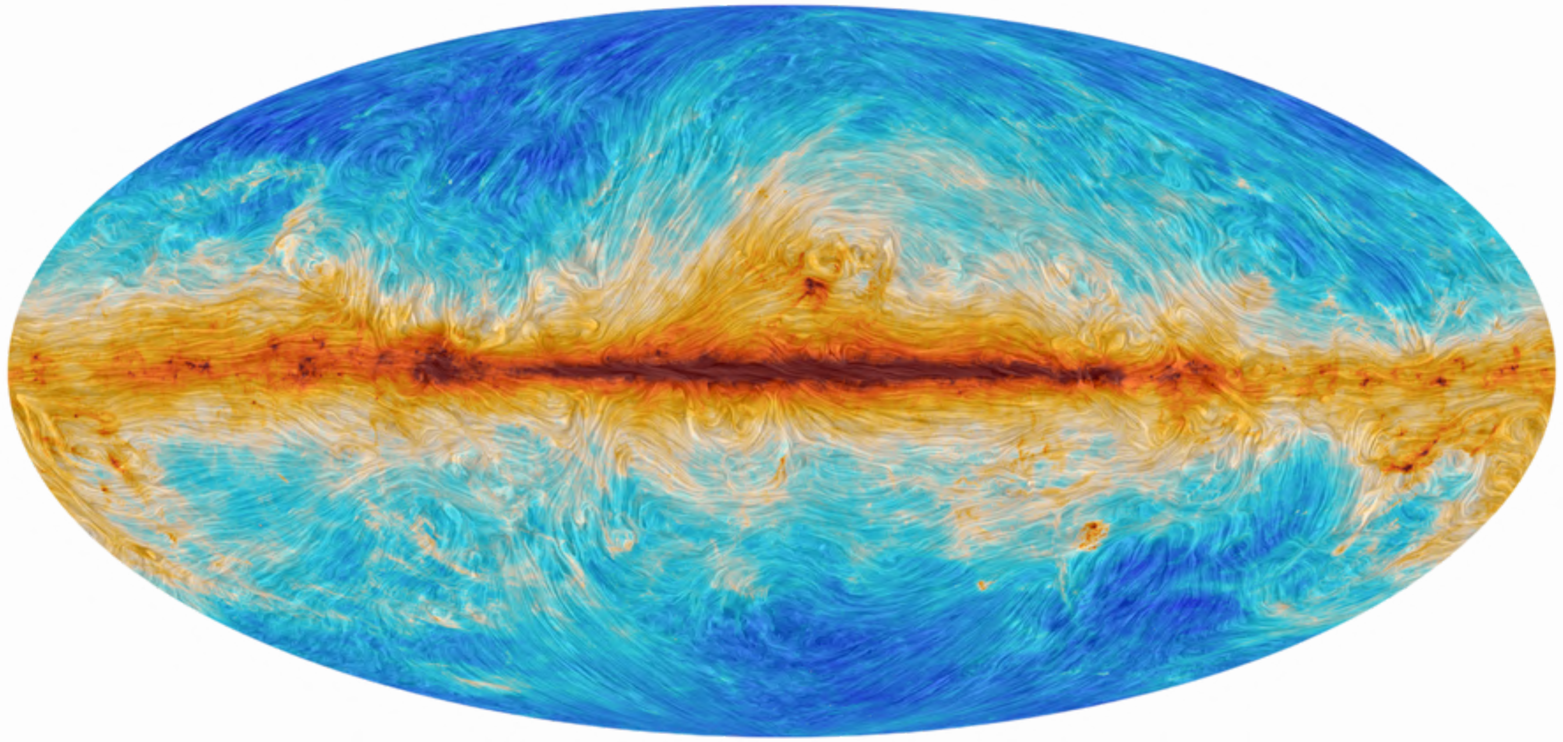
$$\frac{dN_a}{dE_a^*} = \frac{1}{4\pi}\int drr^2dt^*\frac{d\Gamma_{a\gamma}}{dE_a^*}\exp\left[-\Phi(r)\right]$$

$$\frac{dN_a}{dE_a^* d\Omega} = \int dr\cos\gamma\, r^2dt^*\frac{d\Gamma_{a\gamma}}{dE_a^*}\exp\left[-\Phi(r)\right]$$



ALP-photon conversion

ALPs can convert into photons while propagating in external magnetic fields thanks to the ALP-photon coupling ***[G. Raffelt and L. Stodolsky, Phys. Rev. D 37 , 1237 (1988)].***



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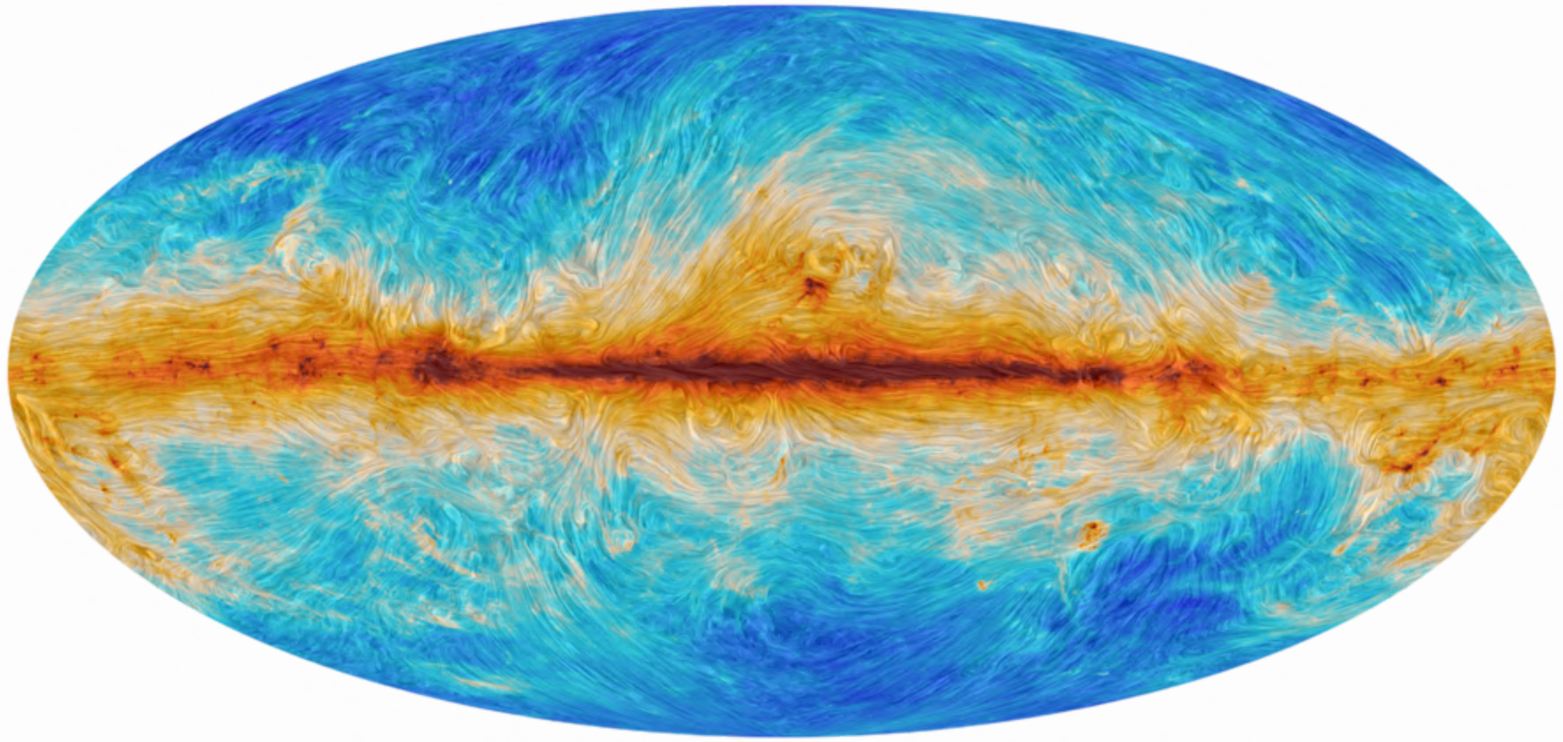
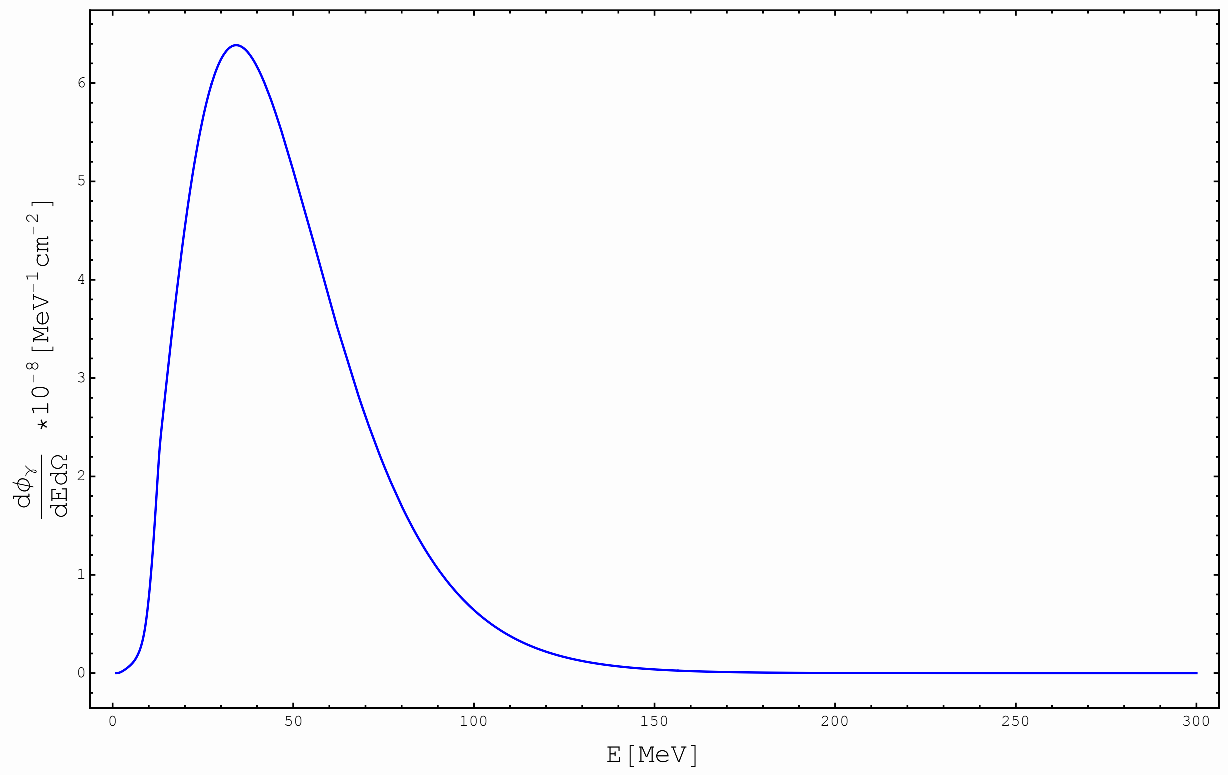


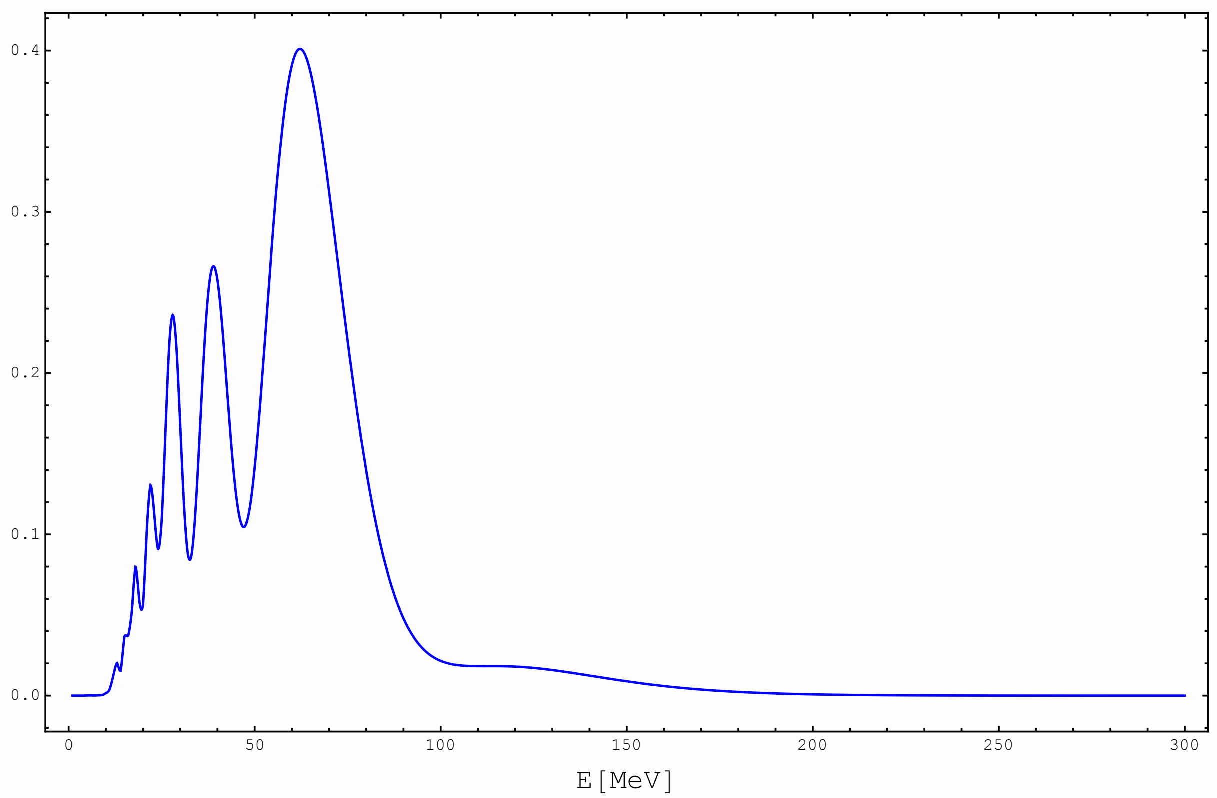
$$i\partial_z \begin{pmatrix} A_\perp(z) \\ A_\parallel(z) \\ a(z) \end{pmatrix} = \begin{pmatrix} \Delta_\parallel \sin^2\theta + \Delta_\perp \cos^2\theta & (\Delta_\parallel - \Delta_\perp)\cos\theta\sin\theta & \Delta_{a\gamma}\sin\theta \\ (\Delta_\parallel - \Delta_\perp)\cos\theta\sin\theta & \Delta_\parallel \cos^2\theta + \Delta_\perp \sin^2\theta & \Delta_{a\gamma}\cos\theta \\ \Delta_{a\gamma}\sin\theta & \Delta_{a\gamma}\cos\theta & \Delta_a \end{pmatrix} \begin{pmatrix} A_\perp(z) \\ A_\parallel(z) \\ a(z) \end{pmatrix}$$

With $\Delta_{\parallel,\perp} = \Delta_{\mathrm{pl}} + \Delta_{\mathrm{QED}}^{\parallel,\perp} + \Delta_{\mathrm{CMB}}$, $\Delta_a = -\frac{m_a^2}{2E_a}$ and $\Delta_{a\gamma} = \frac{1}{2} g_{a\gamma} B_T$

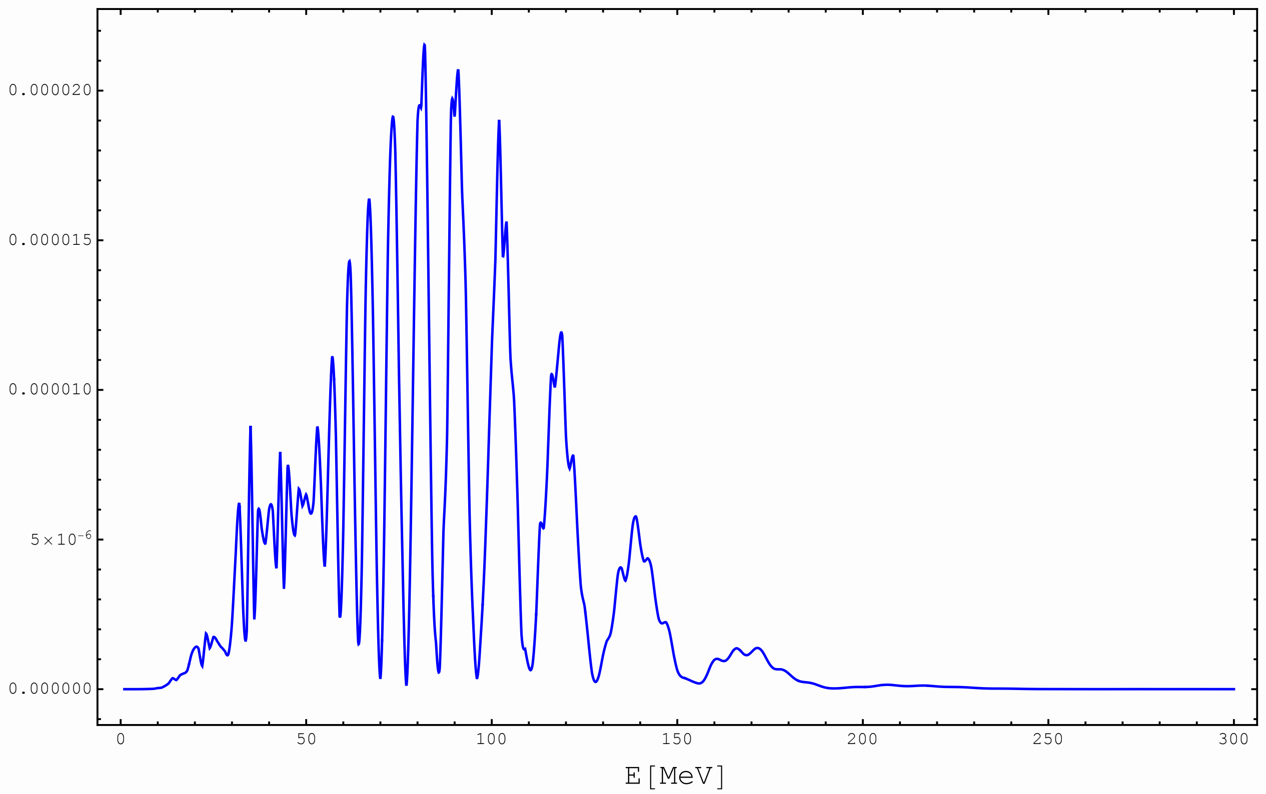
Observable photon flux



$m_a = 0.1\, neV$



$m_a = 1\, neV$

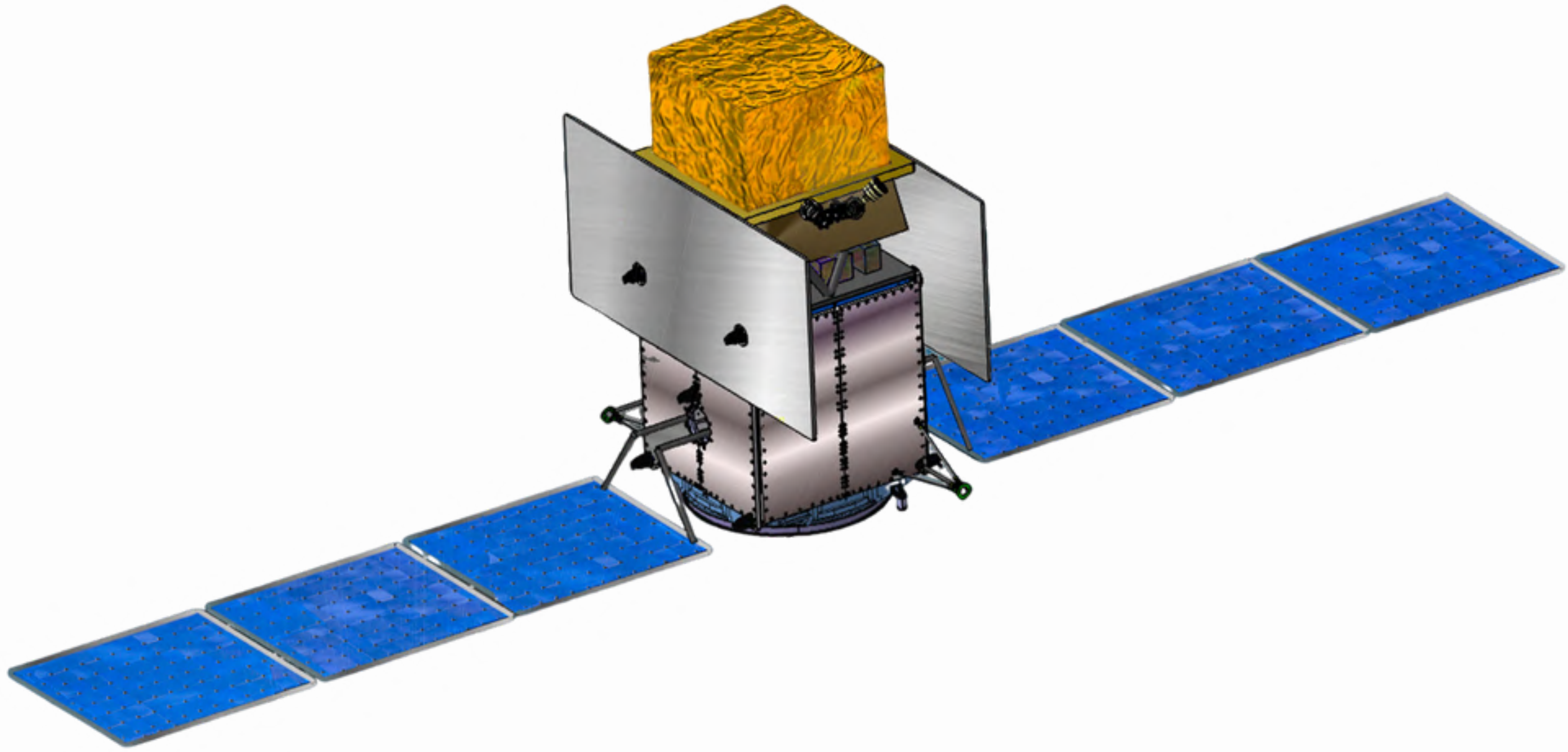


$m_a = 10\, neV$

Observable photon flux: $\frac{d\phi_\gamma}{dE} = \frac{1}{4\pi L^2}\frac{dN}{dE}P_{a\gamma}(E, m, d, l, b, g_{a\gamma})$ with $L = 40\, Mpc$,
$d = 20\, kpc$ and $g_{a\gamma} = 10^{-12} GeV^{-1}$

Experiments sensitivity

We quantified the sensitivity of Fermi-LAT and of the proposed e-ASTROGRAM, AMEGO-X and GRAMS experiment to the photon-ALP coupling, by studying the observed gamma-ray flux ***[A. De Angelis et al., Exp. Astr. 44.1 , 25 (2017)],[T. Aramaki et al., Astr. Phy. 114 , 107-114 (2020)],[R. Caputo et al., Jou. Astr. Tel. (2022)]***



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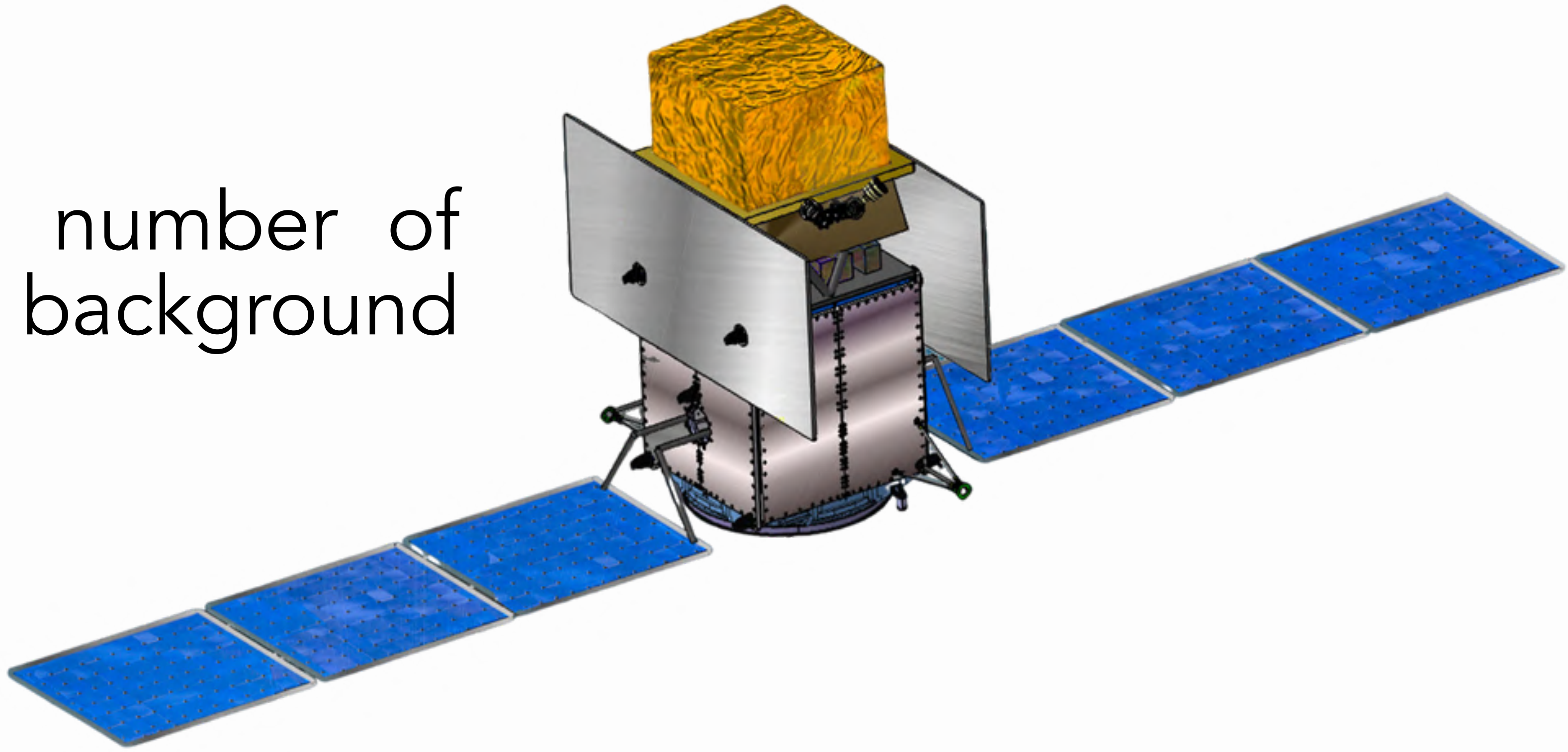
The sensitivity was obtained by requiring that the number of expected signal events is larger than the number of background events.



$$g_{a\gamma} \gtrsim 10^{-12} \left(\frac{N_{background}}{N_{event}} \right)^{\frac{1}{4}}$$

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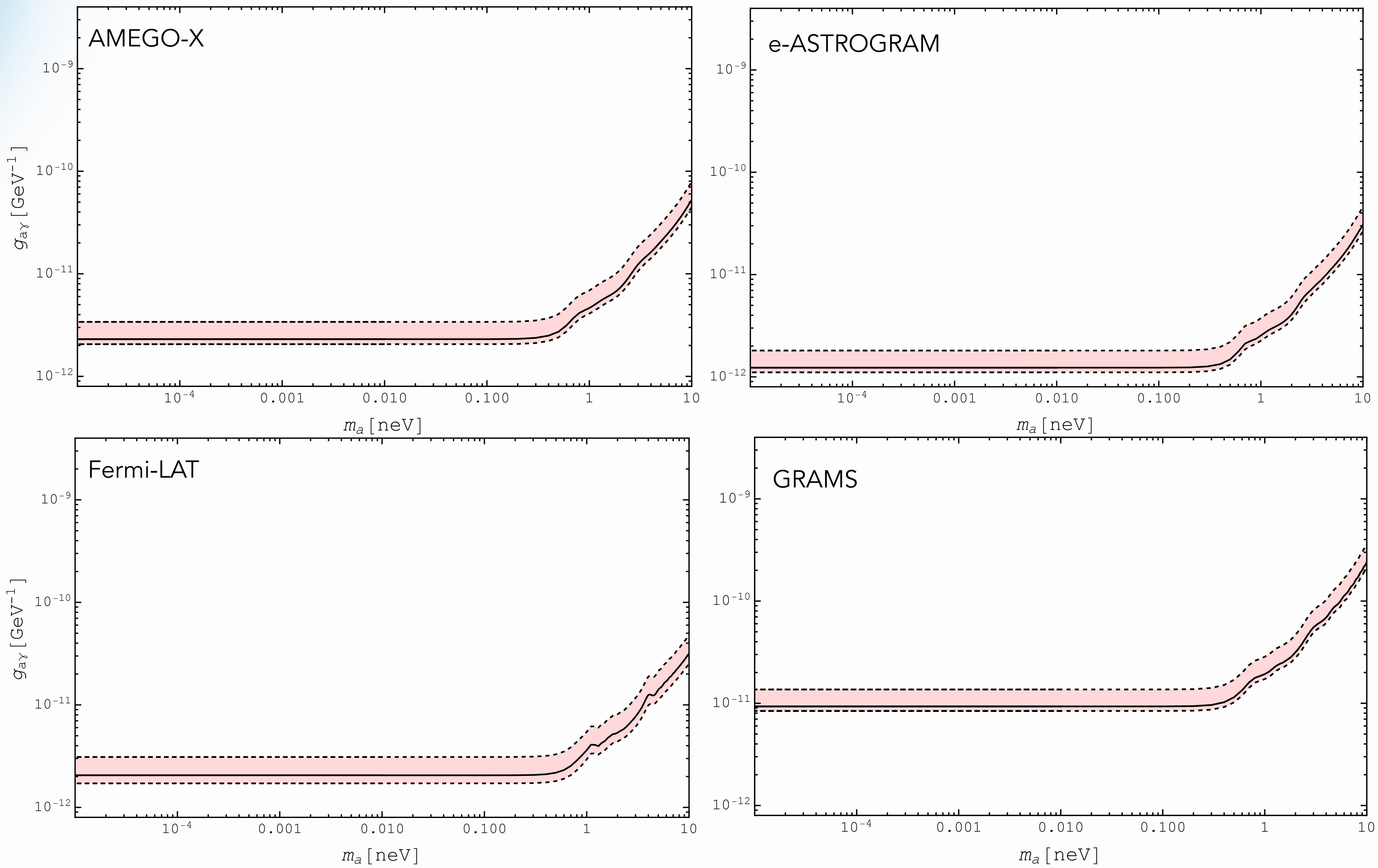

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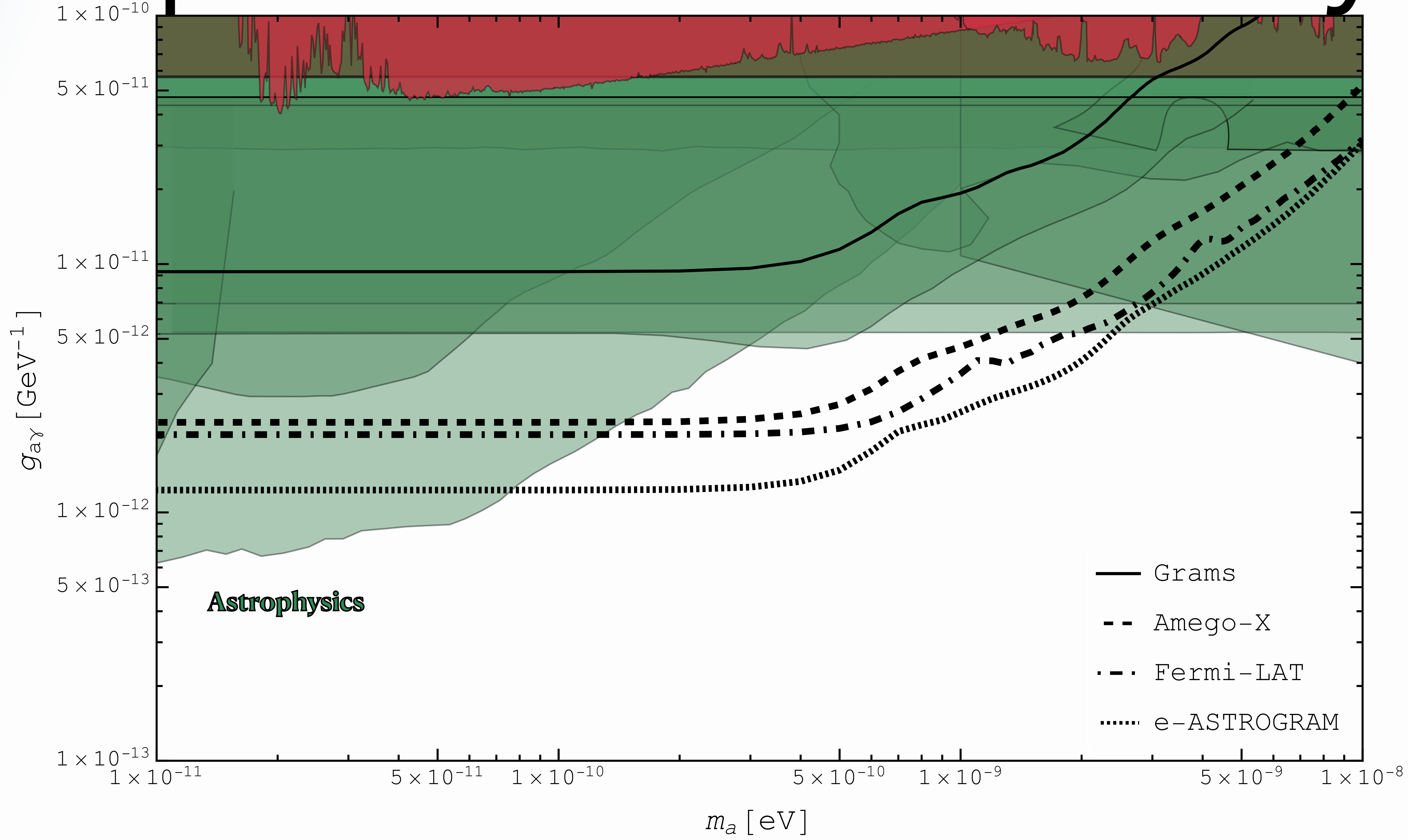
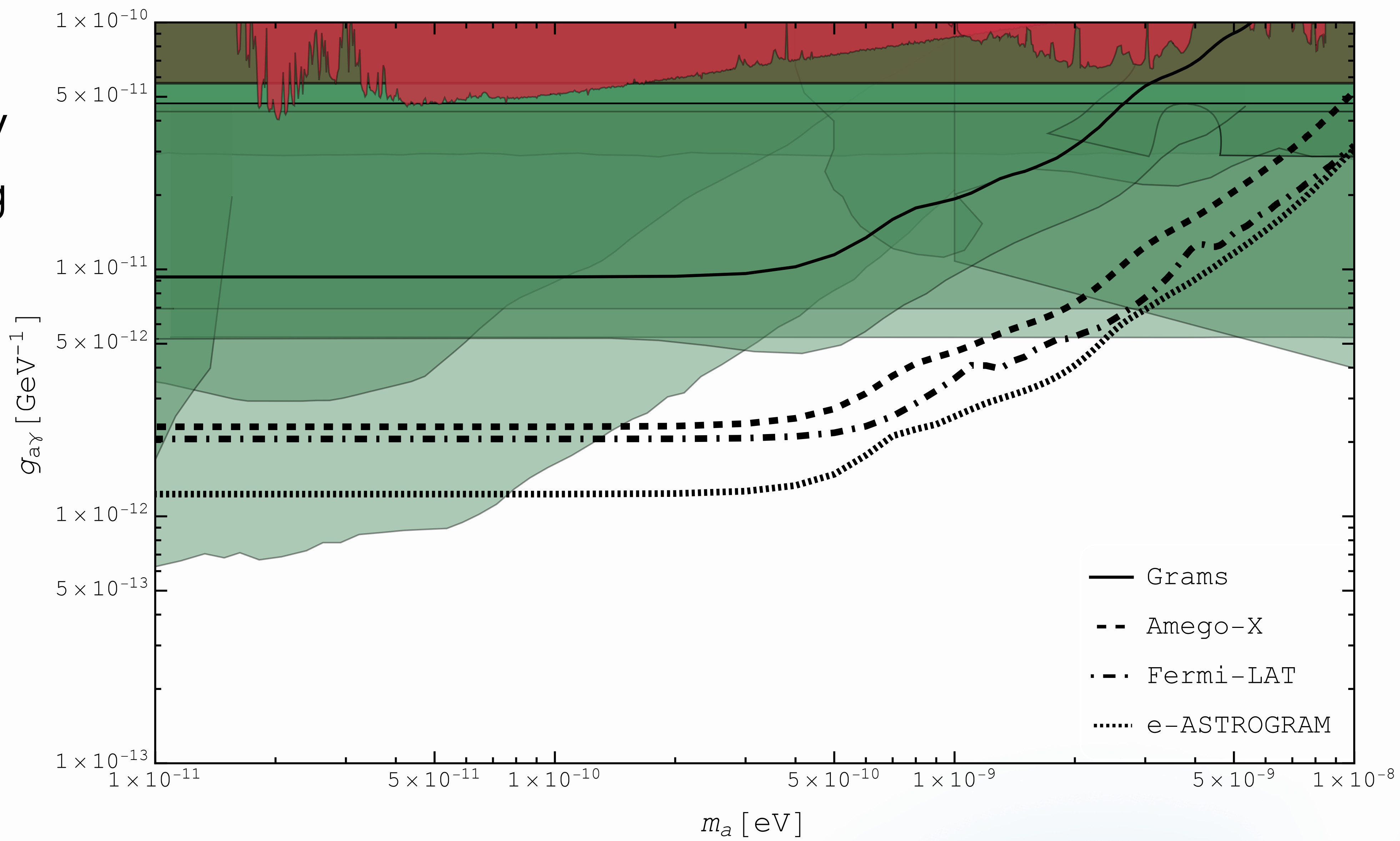


Conclusions

We have evaluated the flux of ALPs from Binary Neutron Star Merger and the corresponding gamma-ray flux reaching the Earth.

The sensitivities obtained show a potential improvement also with respect to the current gamma-ray constraints from SN 1987A ***[S. Hoof and L. Schulz., Jour. of Cosm. and Astro. Phys. 2023.03, 054 (2023)]***

$$g_{a\gamma} \lesssim 4.2 \times 10^{-12} GeV^{-1}$$



What's next?

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Hence, with the current experiments and proposed ones we could see a joint event of GW and γ-ray experiment every $54 - 186$ years!

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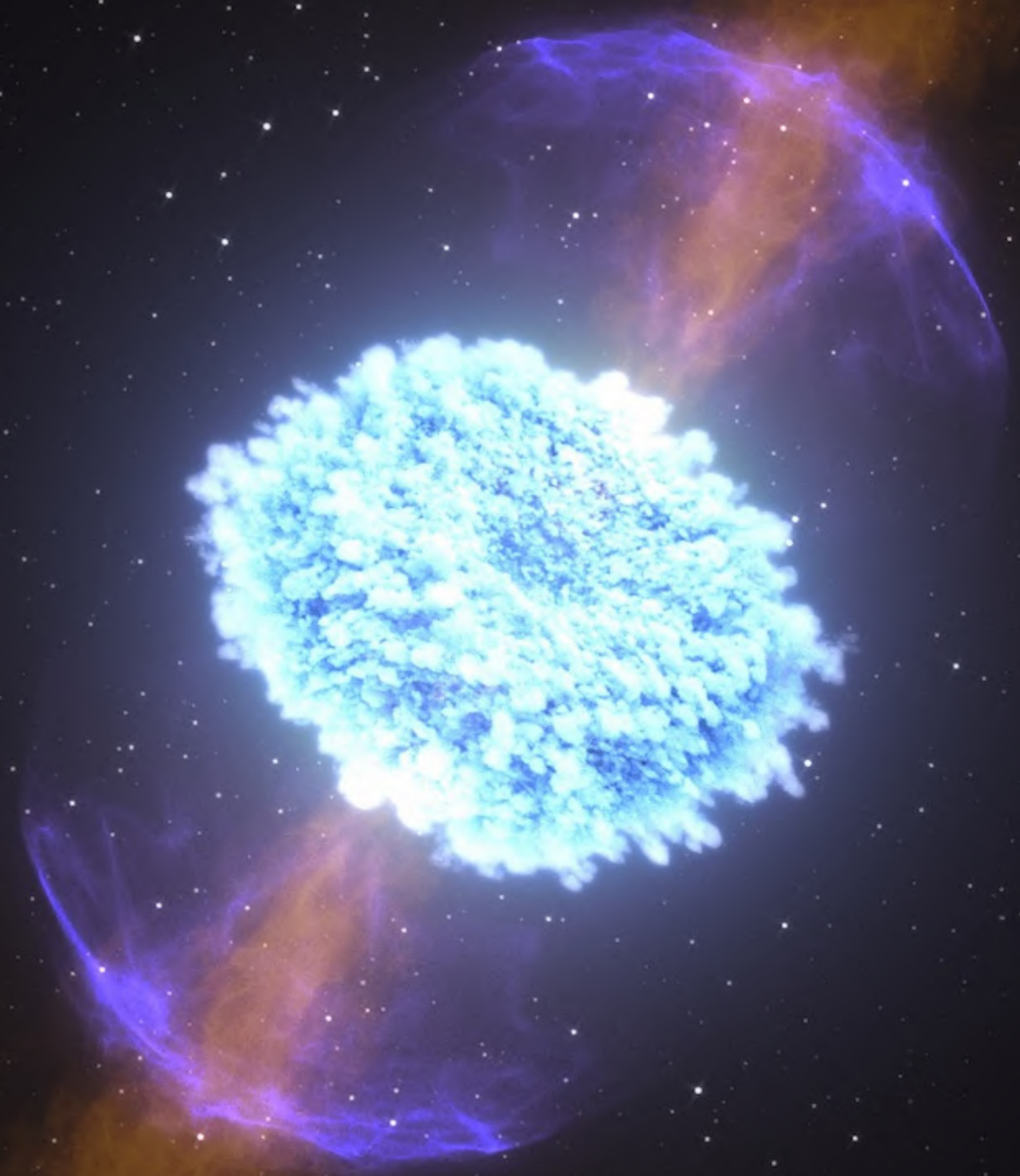


PRESENTATION BY FRANCESCA LECCE

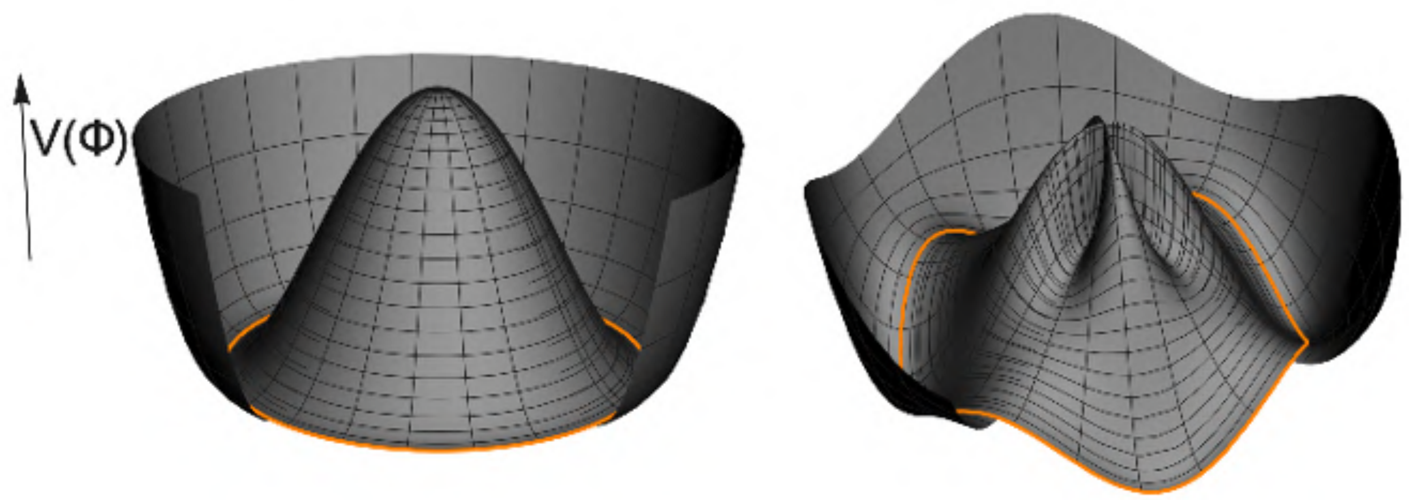
DECEMBER 17, 2024

The QCD axion

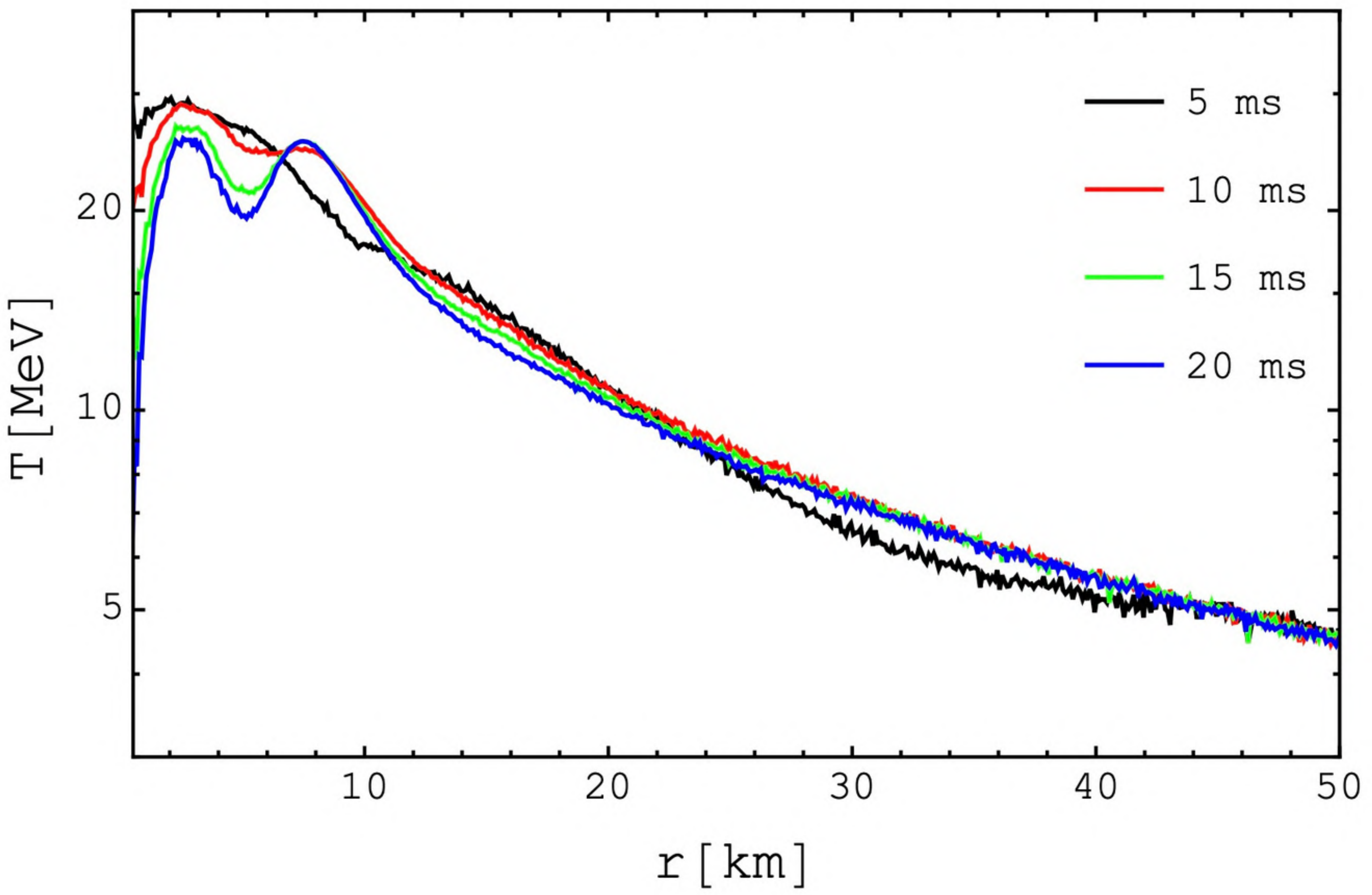
The QCD axion is a pseudoscalar particle postulated in relation to the ***Peccei-Quinn (PQ) mechanism*** to solve the *Strong-CP problem* in QCD.

↳ The introduction of a global symmetry $U(1)_{\mathrm{PQ}}$ spontaneously broken at f_a and the Goldstone boson is the axion ***[Peccei & Quinn, Phys. Rev. Lett. 38 (1977)]***

The coupling constant depnds on the energy scale

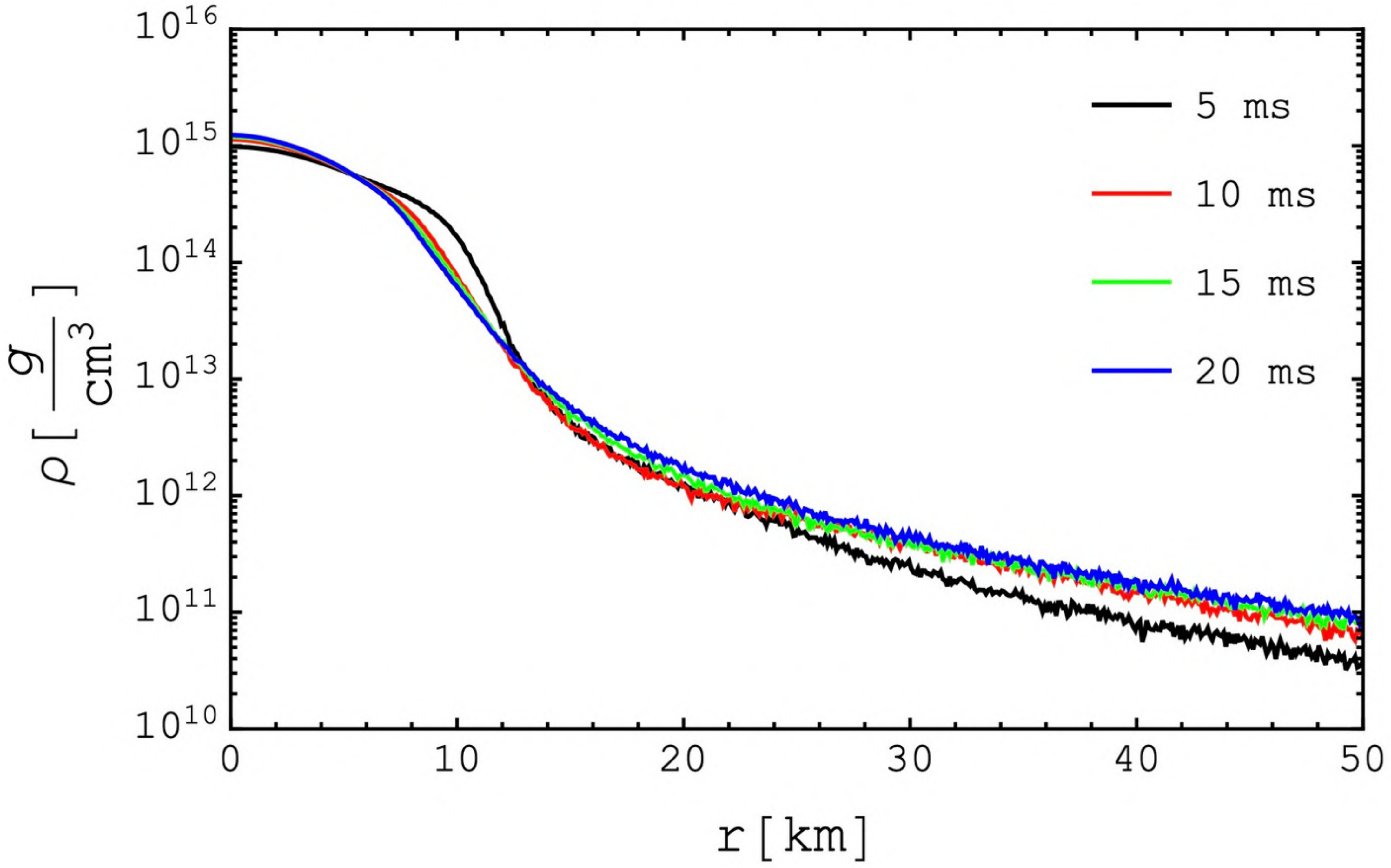


Temperature



Radial evolution of the Temperature at t=5, 10, 15, 20 ms after merging.

Matter density



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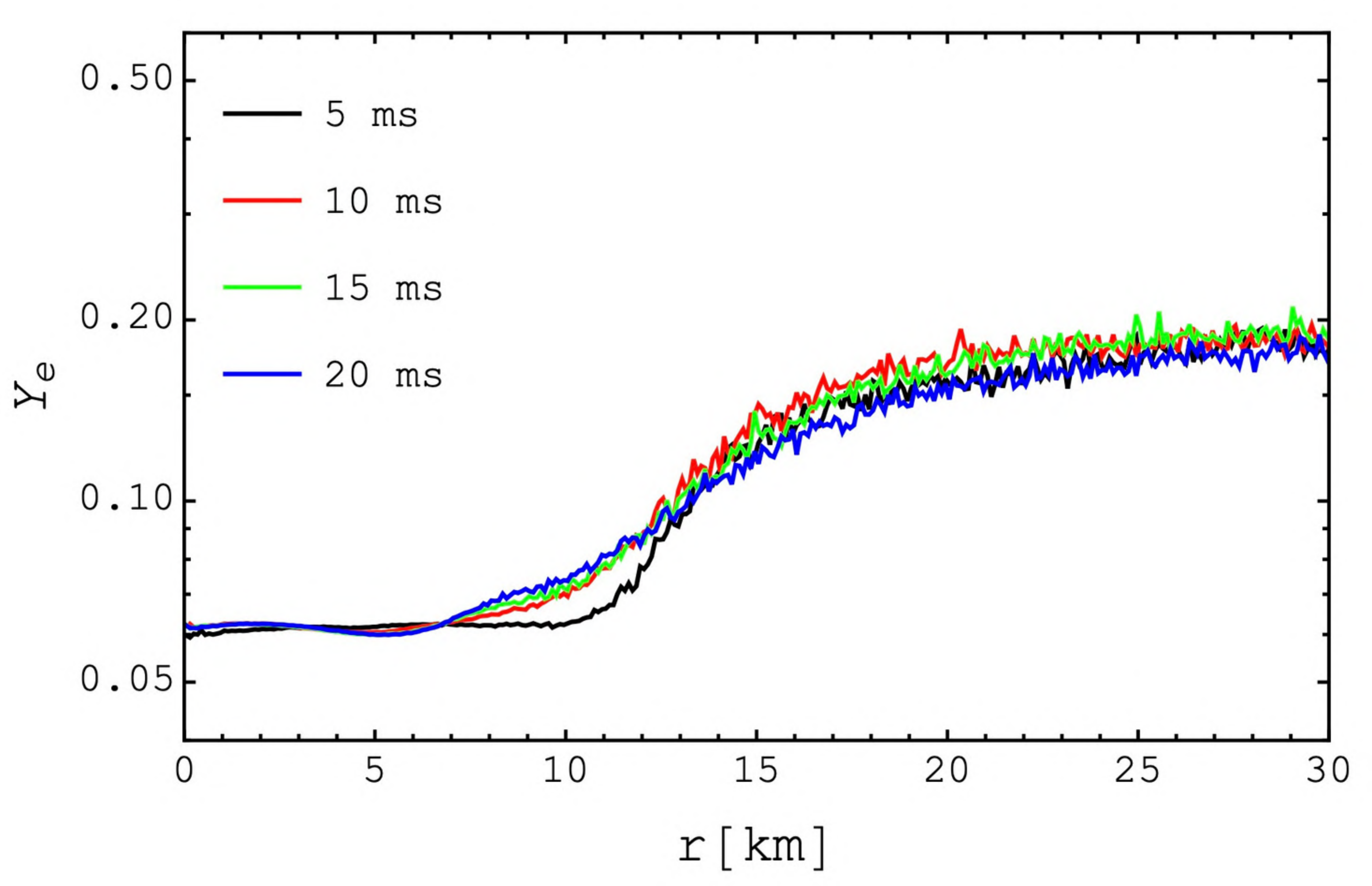
Electron fraction



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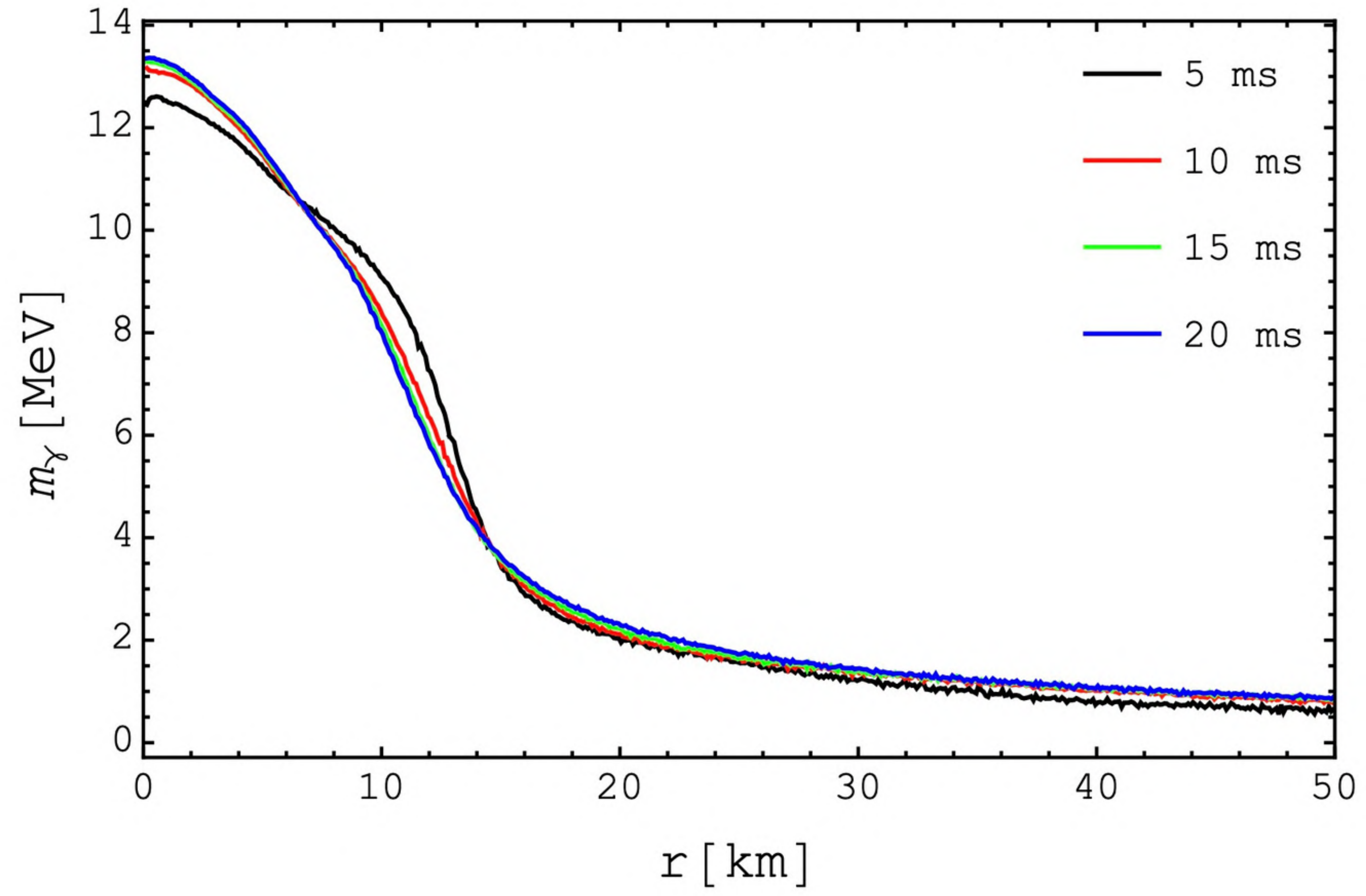
$$Y_e = \frac{n_e}{n_b}$$

Photon mass



Radial evolution of the mass of the photon at t=5, 10, 15, 20 ms after merging.

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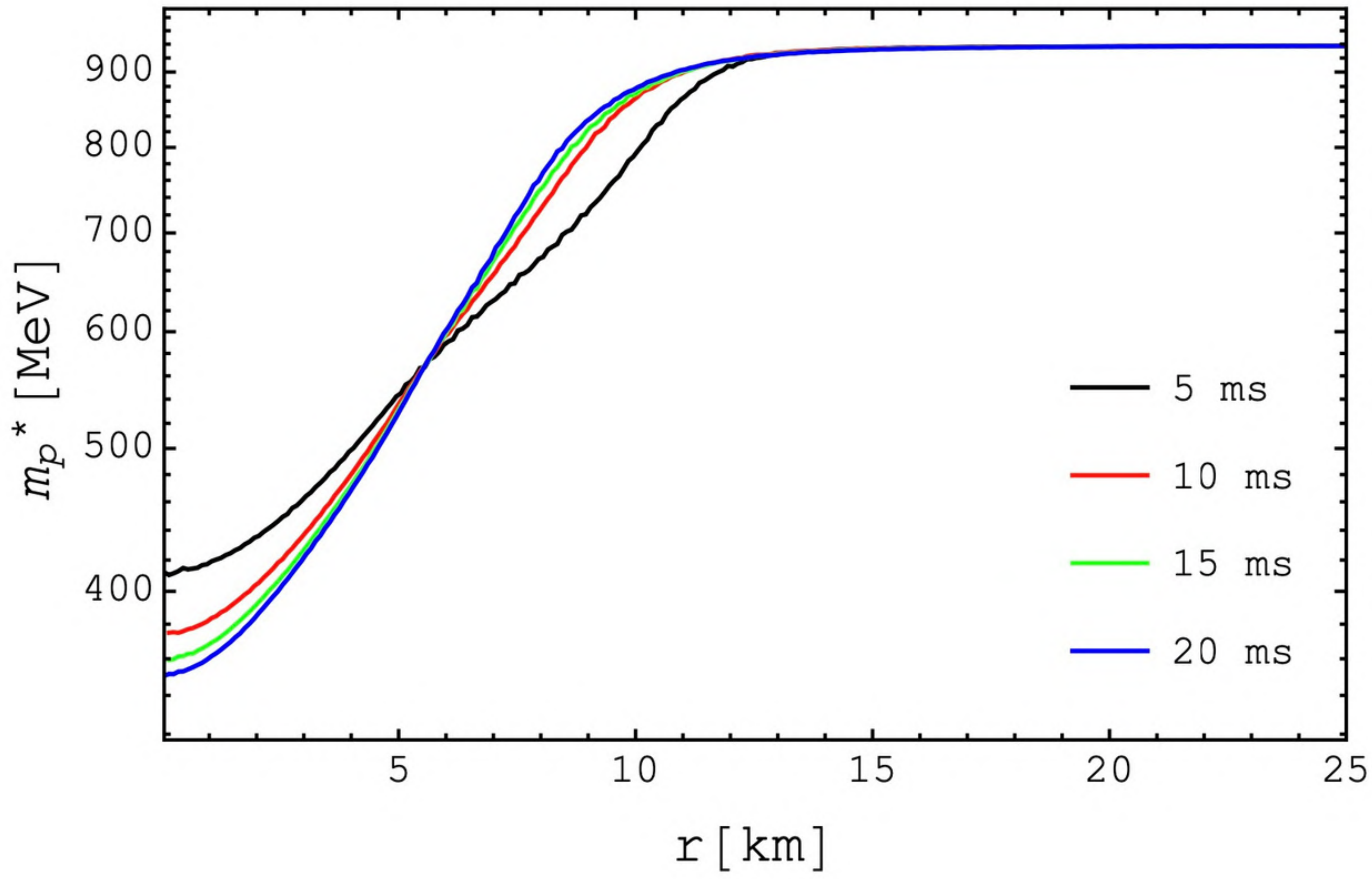
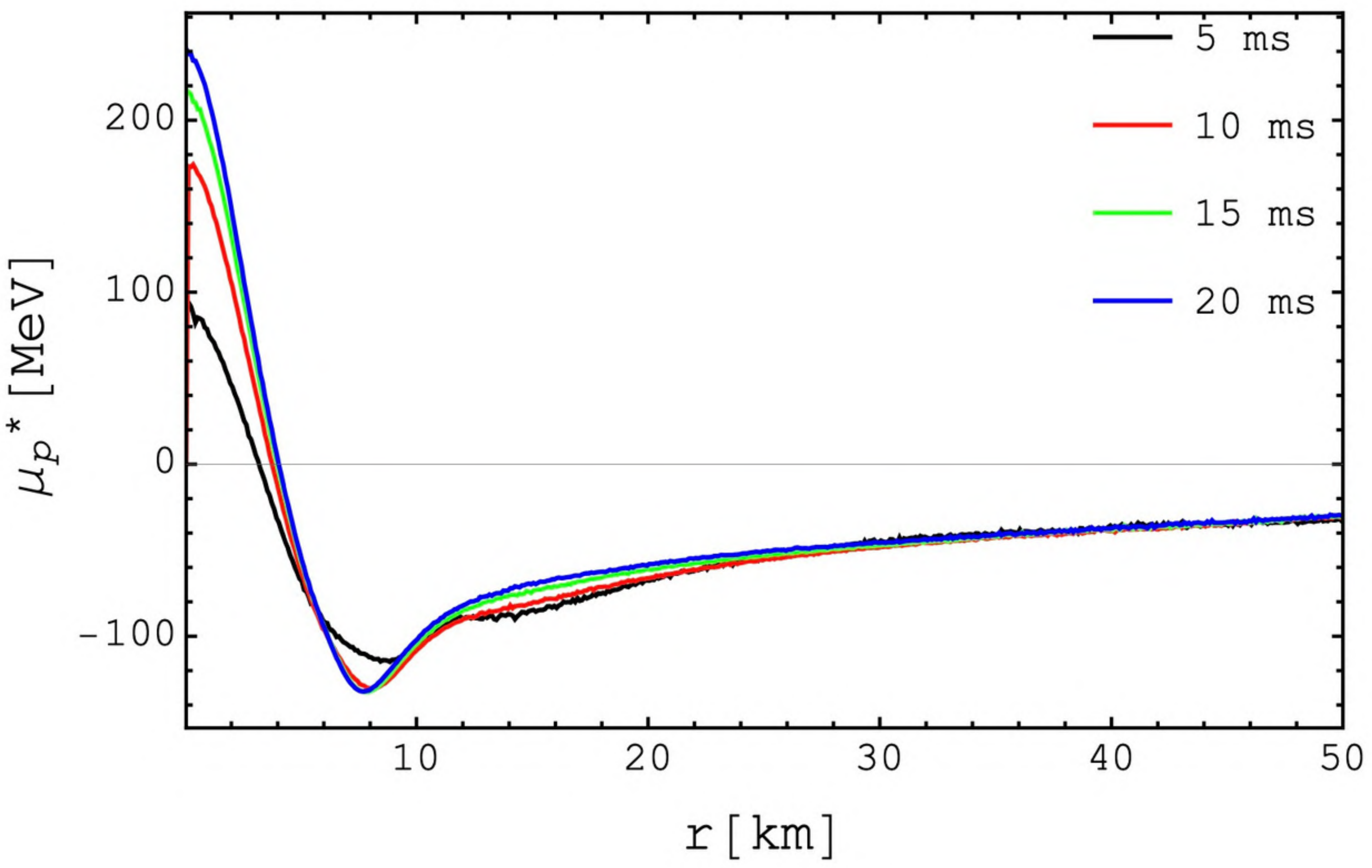
Proton effective mass



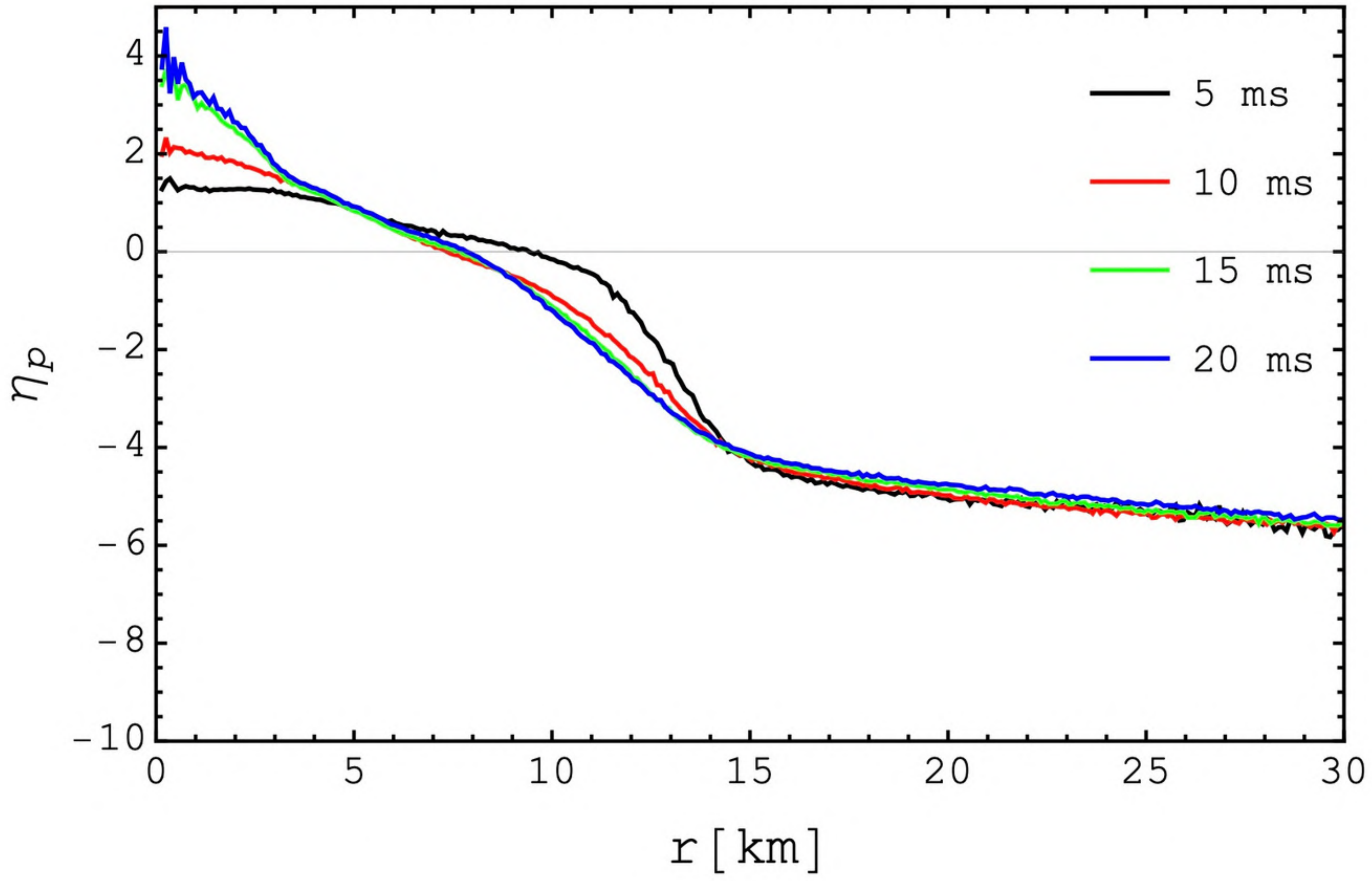
Radial evolution of the effective mass of the proton at t=5, 10, 15, 20 ms after merging.

Proton effective chemical potential



Radial evolution of the effective chemical potential of the proton at t=5, 10, 15, 20 ms after merging.

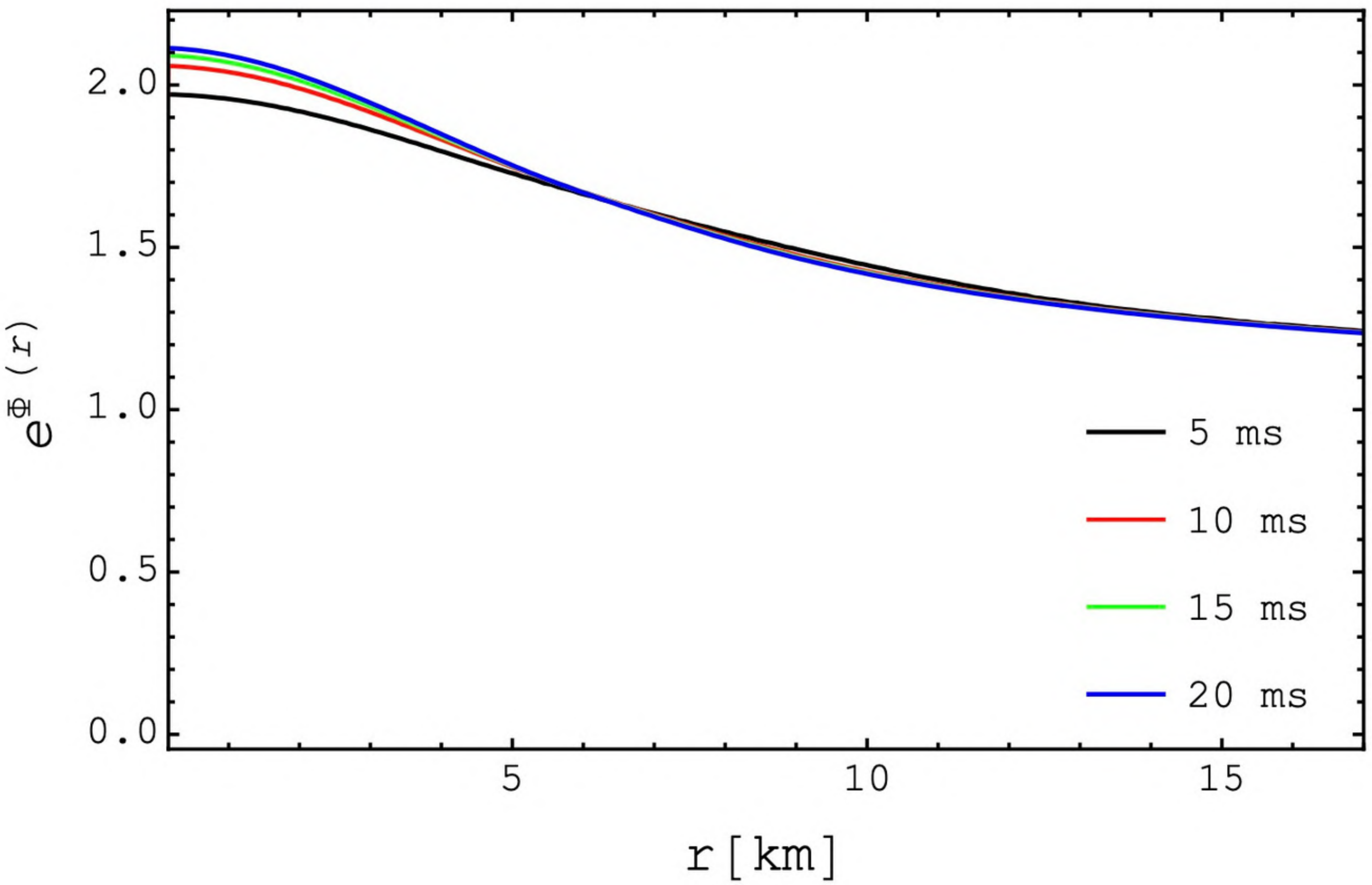
Degeneracy parameter



$$\eta_p = \frac{\mu_p^* - m_p^*}{T}$$

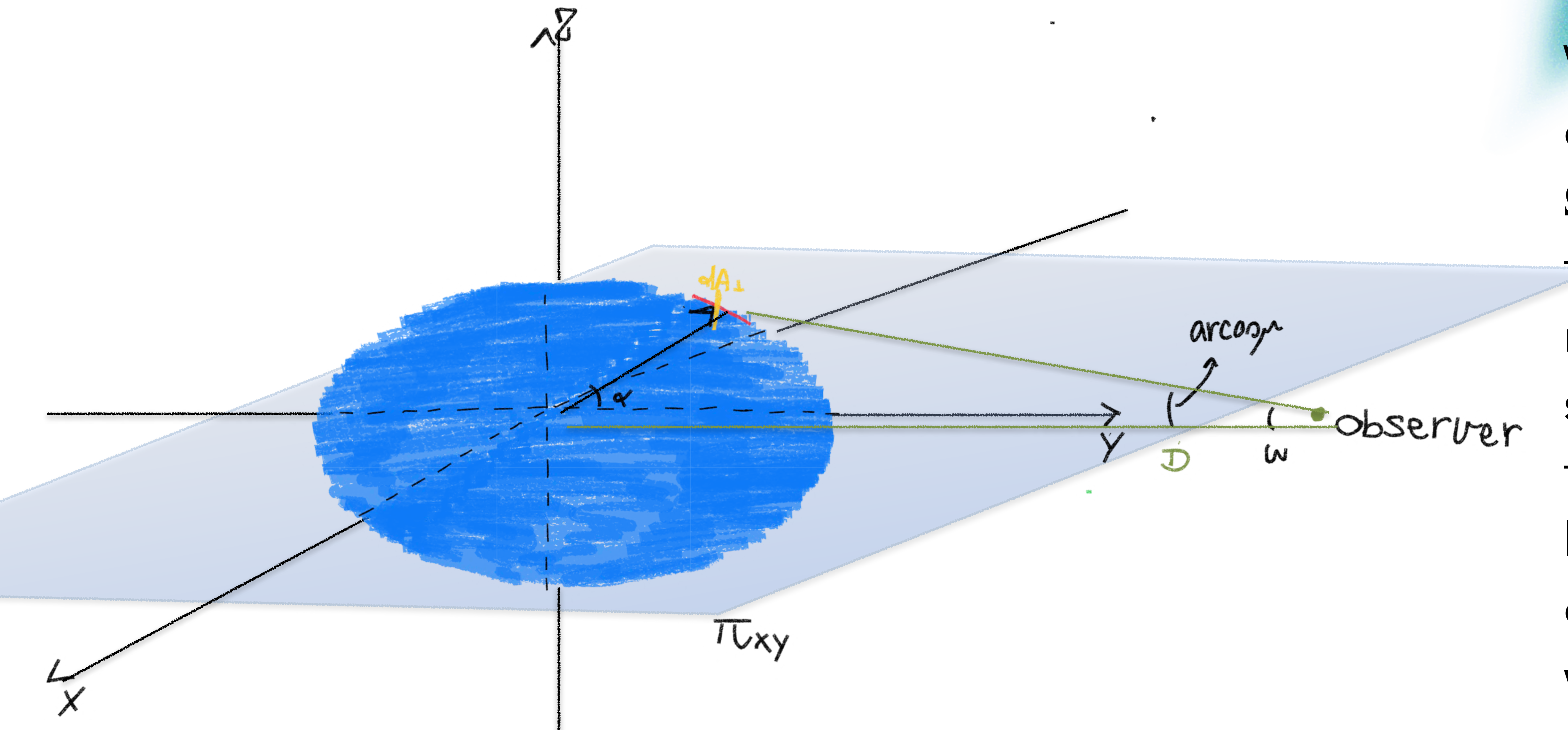
Radial evolution of the degeneracy parameter of the proton at t=5, 10, 15, 20 ms after merging.

Lapse factor



Radial evolution of the lapse factor at t=5, 10, 15, 20 ms after merging.

ALP spectrum



We are in the case $D \gg R$ and the observer is in an arbitrary direction $\Omega(\Theta, \Phi)$. The angle $\omega(\theta, \phi)$ describes the angular emission characteristic relative to the direction $\vec{R}$ on the surface. In order to obtain the energy flux at the location of the observer we have to integrate over $d\Omega'$, the surface of the source as seen by the observer, which is given by

$$d\Omega' = \cos\gamma \frac{dA}{D^2}$$

ALP production

We know the rules concerning the external legs and the lower vertex of the diagram but we don't know the rule for the upper vertex. We know the Lagrangian interaction term

$$\mathcal{L}_I = -\frac{1}{4} g_{a\gamma\gamma} \; F_{\mu\nu}\tilde{F}^{\mu\nu} a$$

In order to get the Feynman rule for the vertex we can use the generating functional formalism, where the rule is associated to the truncated connected three point Green function in the momentum space.

$$\begin{aligned} G^{(3)}(y_1, y_2, y_3) \quad &= \tfrac{1}{(i)^3} \tfrac{i}{2} \int -\tfrac{1}{2} g_{a\gamma\gamma} \left(\partial_\mu \tfrac{1}{i} D^{\mu\nu}(x - y_1)\right) \\ &\times \left(\partial_\rho \tfrac{1}{i} D^{\rho\sigma}(x - y_2)\right) \tfrac{1}{i} D(x - y_3) d^4x \end{aligned}$$

Therefore, the matrix element of the process

$$-\imath\mathcal{M} = \overline{u}(p_3)(i\sqrt{4\pi\alpha}\gamma^\mu)u(p_1)\frac{-ig_{\mu\nu}}{q^2}(-ig_{a\gamma\gamma}\epsilon^{\alpha\nu\rho\sigma} q_\rho p_{2\sigma}\epsilon_\alpha(p_2))$$

ALP production

Summing over the spins and the two transverse polarization of photons

$$\sum_{\text{spin, pol}} |\mathcal{M}|^2 = \frac{32\pi\alpha}{q^4} g_{a\gamma\gamma}^2 [m_p^2 m_\gamma^2 q^2 - m_p^2 (p_2 \cdot q)^2 - m_\gamma^2 (p_1 \cdot q)(p_3 \cdot q) + -q^2 (p_1 \cdot p_2)(p_2 \cdot p_3) + (p_1 \cdot q)(p_2 \cdot q)(p_2 \cdot p_3) +(p_2 \cdot q)(p_3 \cdot q)(p_1 \cdot p_2)]$$

In this computation we are interested in the limit of infinite proton mass. The momentum transferred $q = p_1 - p_3$ becomes $q \approx (0, \mathbf{q})$ as the proton mass dominates the proton energy and allows little energy transfer.

So the matrix element becomes

$$\sum_{\text{spin, pol}} |\mathcal{M}|^2 = \frac{32\pi\alpha}{\mathbf{q}^4} g_{a\gamma\gamma}^2 m_p^2 [\mathbf{p}_2^2 \mathbf{p}_4^2 - (\mathbf{p}_2 \cdot \mathbf{p}_4)^2]$$

ALP production

We must take into account the screening of the Coulomb interaction in order to do so we have to take in the screening. Moreover to get the ALP spectrum we need to integrate over the phase space

$$\Gamma_{a\gamma} = \int \frac{d^3p_1}{(2\pi)^3}\frac{d^3p_2}{(2\pi)^3}\frac{d^3p_3}{(2\pi)^3}\frac{d^3p_4}{(2\pi)^3}(2\pi)^4\delta^4(p_1+p_2-p_3-p_4)\frac{32\pi\alpha}{\mathbf{q}^2(\mathbf{q}^2+k_s^2)}g_{a\gamma\gamma}^2 m_p^2 \times \frac{[\mathbf{p}_2^2\mathbf{p}_4^2-(\mathbf{p}_2\cdot\mathbf{p}_4)^2]}{16E_1E_2E_3E_4}f_1g_2[1-f_3]$$

Now we can work with spherical coordinates. Hence, we have the freedom to chose the coordinates such that the photon momentum lies along the z axis and the axion momentum lies in the same plane as the photon momentum.

$$\Gamma_{a\gamma} = \frac{\alpha 16 m_p^*}{128\pi^7}g_{a\gamma\gamma}^2\int\int\int dp_1dp_2dp_4du\frac{p_1p_2^4p_4^4(1-u^2)}{E_2E_4(p_2^2+p_4^2-2p_2p_4u)^{3/2}} \frac{f_1g_2[1-f_3]}{(p_2^2+p_4^2-2p_2p_4u+k_s^2)}$$

ALP production

As a result we obtain, introducing also the lapse factor

$$\frac{d\Gamma_{a\gamma}}{dE_a^*} = \frac{\alpha m_p^{*\,2}}{8\pi^4} g_{a\gamma\gamma}^2 (E_a^*)^3 \times \int_0^\infty dp_2 \int_{-1}^1 du \frac{p_2^4(1-u^2)}{E_2^*(p_2^2+E_a^{*\,2}-2p_2E_a{}^*u)^{3/2}(p_2^2+E_a^{*\,2}-2p_2E_a{}^*u+\kappa_s^2)} \times \frac{E_2^*-T\log\xi}{(e^{\beta E_2^*}-1)(1-e^{\beta(E_a^*-E_2^*)})}$$

with

$$\xi = \frac{\exp\left[\beta(E_a+\mu_p^*-m_p^*\right]+\exp\left[\beta(E_2+\frac{p_{1min}^2}{2m_p^*})\right]}{\exp\left[\beta(\mu_p^*-m_p^*)\right]+\exp\left[\beta\frac{p_{1min}^2}{2m_p^*}\right]}$$

ALP-photon conversion

From the wave equation for time-varying part of the vector potential and for the ALP field we obtain the following Klein-Gordon equation of motion

$$\left[E_a^2 + \partial_z^2 + \begin{pmatrix} 2E_a^2(n_\perp - 1) & 2E_a^2 n_\mathrm{R} & 0 \\ 2E_a^2 n_\mathrm{R} & 2E_a^2(n_\parallel - 1) & g_{a\gamma} B_T E_a \\ 0 & g_{a\gamma} B_T E_a & -m_a^2 \end{pmatrix}\right] \begin{pmatrix} A_\perp(z) \\ A_\parallel(z) \\ a(z) \end{pmatrix} = 0$$

We considered a photon beam traveling through a single magnetic domain, where the field is assumed to be homogeneous. Additionally, the optical activity is disregarded

$$n_\mathrm{R} = 0$$

Moreover, since we are focusing on the regime where $E_a \gg m_a$

the short-wavelength approximation is valid and the Klein-Gordon can be linearized

$$\left(i\frac{d}{dz} + E_a + \mathcal{M}\right) \begin{pmatrix} A_\parallel(z) \\ a(z) \end{pmatrix}$$

ALP-photon conversion

it is more convenient to work with the polarazation density matrix and in a single magnetic domain the mixing matrix can be brought into a diagonal form. By introducing a rotating matrix we obtain

$$D = \begin{pmatrix} \Delta_{\rm pl} & 0 & 0 \\ 0 & \Delta_{\rm pl}\cos^2\theta + \Delta_{a\gamma}\sin 2\theta + \Delta_a \sin^2\theta & -\frac{1}{2}\Delta_{\rm pl}\sin 2\theta + \Delta_{a\gamma}(\cos^2\theta - \sin^2\theta) + \frac{1}{2}\Delta_a \sin 2\theta \\ 0 & (\Delta_a - \Delta_{\rm pl})\frac{1}{2}\sin 2\theta + \Delta_{a\gamma}\cos 2\theta & -\Delta_{\rm pl}\sin^2\theta - \Delta_{a\gamma}\sin 2\theta + \Delta_a\cos^2\theta \end{pmatrix}$$

from which we obtain the mixing matrix

$$\theta = \frac{1}{2}\arctan\left(\frac{2\Delta_{a\gamma}}{\Delta_{\rm pl} - \Delta_a}\right)$$

the resulting density matrix will be

$$\rho = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \left(e^{iD_2 d} - e^{iD_3 d}\right)\left(e^{-iD_2 d} - e^{-iD_3 d}\right)\sin^2\theta\cos^2\theta & \left(e^{iD_2 d} - e^{iD_3 d}\right)\left(e^{-iD_2 d}\sin^2\theta - e^{-iD_3 d}\cos^2\theta\right) \\ 0 & \left(e^{iD_2 d} - e^{iD_3 d}\right)\left(e^{-iD_2 d} - e^{-iD_3 d}\right)\sin^2\theta\cos^2\theta & \left(e^{iD_2 d}\sin^2\theta + e^{iD_3 d}\cos^2\theta\right)\left(e^{-iD_2 d}\sin^2\theta - e^{-iD_3 d}\cos^2\theta\right) \end{pmatrix}$$

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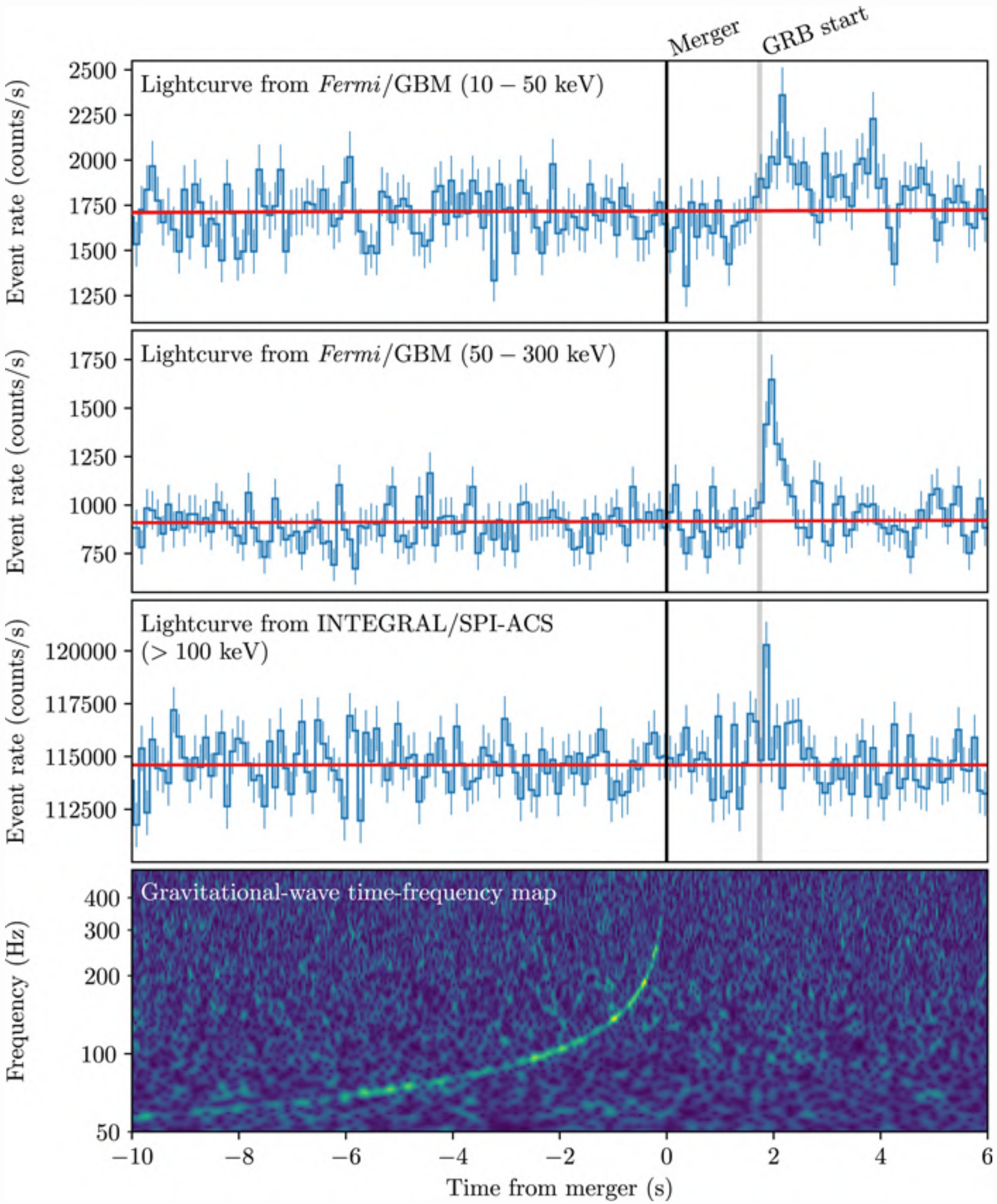
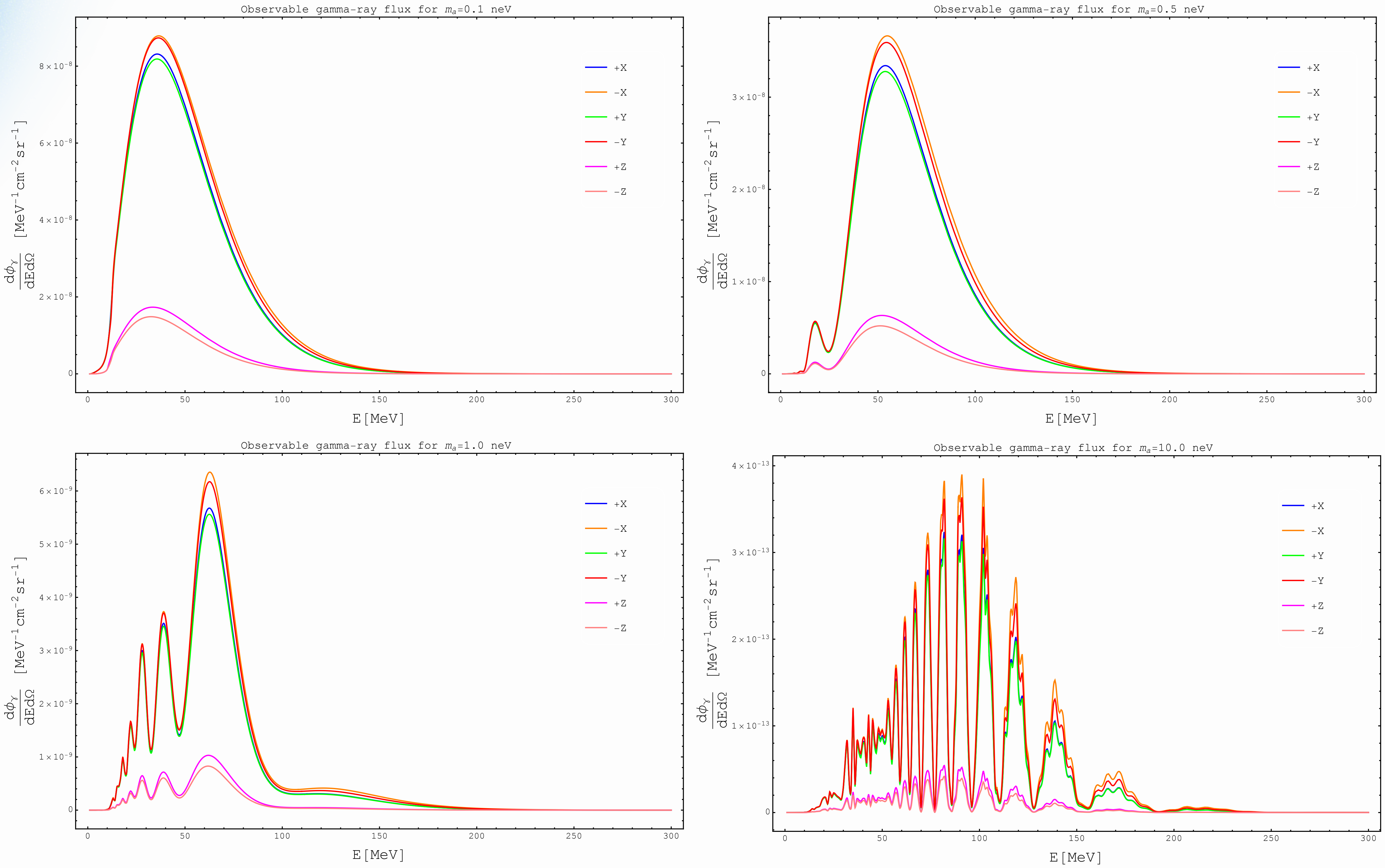
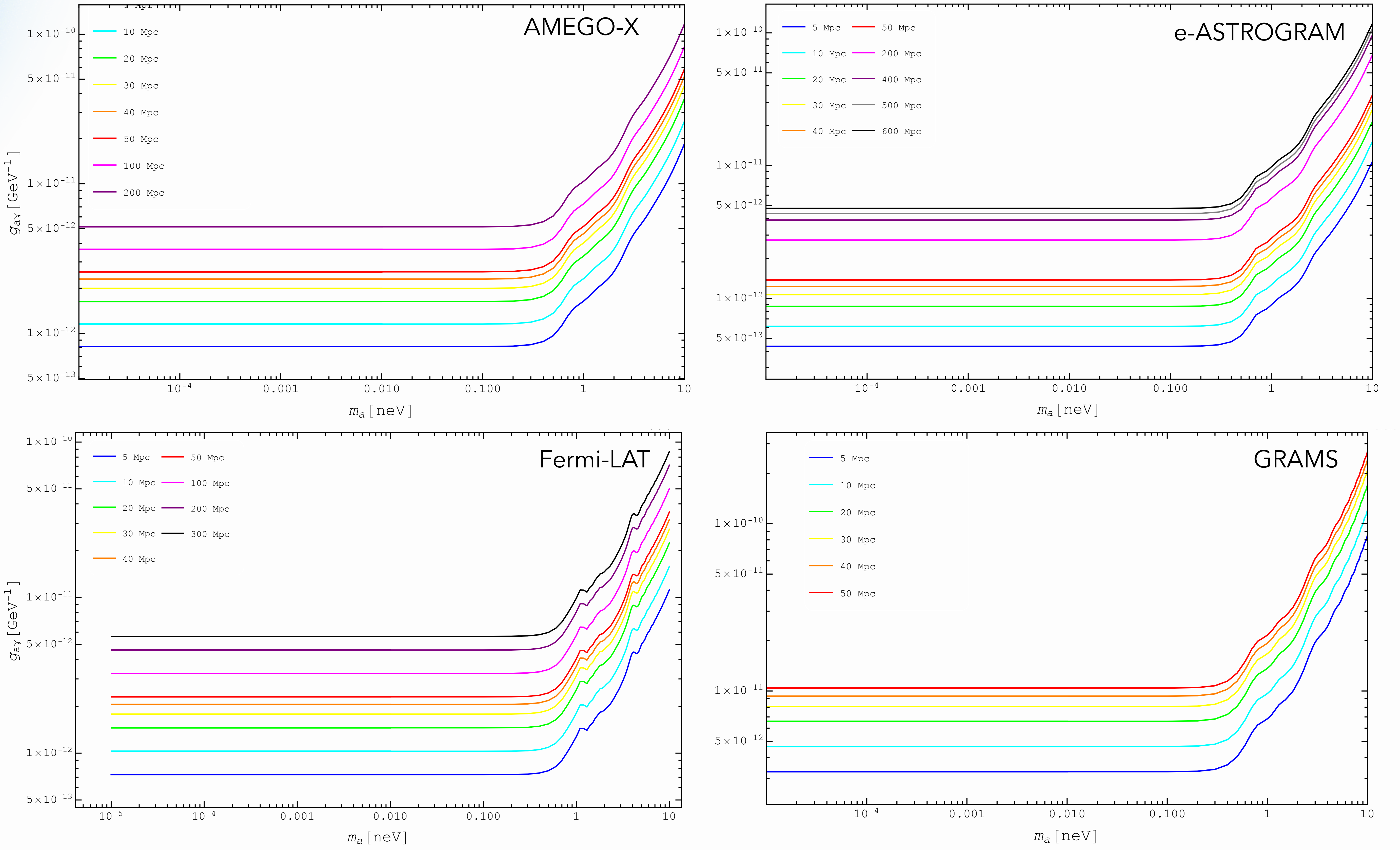


Merger
GRB start
Lightcurve from Fermi/GBM (10 – 50 keV)
Event rate (counts/s)
2500
2250
2000
1750
1500
1250
Lightcurve from Fermi/GBM (50 – 300 keV)
Event rate (counts/s)
1750
1500
1250
1000
750
Lightcurve from INTEGRAL/SPI-ACS
(> 100 keV)
Event rate (counts/s)
120000
117500
115000
112500
Gravitational-wave time-frequency map
Frequency (Hz)
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6
Time from merger (s)

Photon flux


Observable gamma-ray flux for m_a=0.1 neV
Observable gamma-ray flux for m_a=0.5 neV
Observable gamma-ray flux for m_a=1.0 neV
Observable gamma-ray flux for m_a=10.0 neV
+X
-X
+Y
-Y
+Z
-Z
$\frac{d\phi_\gamma}{dEd\Omega}$ [$MeV^{-1} cm^{-2} sr^{-1}$]
E [MeV]

Experiments sensitivity



Light-ALP parameter space