UNIVERSITÀ DEGLI STUDI DI BARI ALDO MORO

Probing axion-like particles with multi messenger observations of neutron star mergers

FRANCESCA LECCE

20th Patras Workshop on Axions, WIMPs and WISPs

Tenerife September 23rd, 2025

Overview

1 AXION AND AXION LIKE PARTICLES

2 BINARY NEUTRON STAR MERGERS

3 ALP PRODUCTION AND CONVERSION

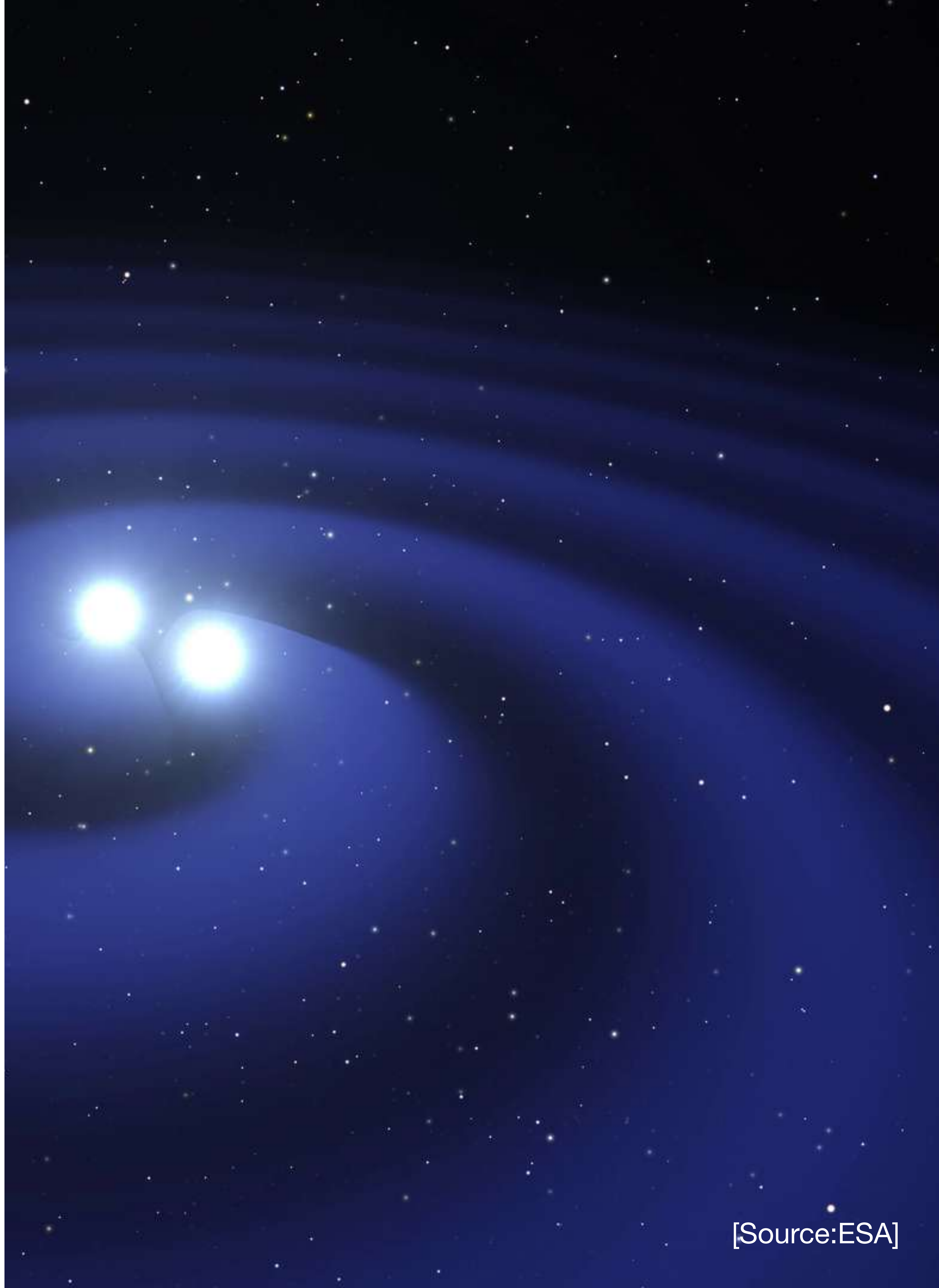
4 EXPERIMENTS SENSITIVITY

5 PROBABILITY OF JOINT DETECTION

6 CONCLUSIONS AND IMPROVEMENTS

arXiv:2504.02032

FL, Alessandro Lella, Giuseppe Lucente, Vimal Vijayan,
Andreas Bauswein, Maurizio Giannotti, Alessandro Mirizzi



Axion and Axion-Like Particles

The QCD axion is a hypothetical particle postulated by Wilzcek and Weinberg in relation to the Peccei-Quinn mechanism to solve the strong-CP problem of the QCD

[S. Weinberg, Phys. Rev. Lett. 40, 223 (1978)], [R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977)]

Axion-like particles (ALPs) are novel particles which behave similarly to the QCD axion. They emerge in UV completions of the Standard Model.

Axion and Axion-Like Particles

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

Axion-like particles (ALPs) are novel particles which behave similarly to the QCD axion. They emerge in UV completions of the Standard Model.

Axion and ALPs could interact with all the Standard model particles.
In this work we will use the coupling of ALPs with nucleons and photons.

Axion and Axion-Like Particles

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

Axion-like particles (ALPs) are novel particles which behave similarly to the QCD axion. They emerge in UV completions of the Standard Model.

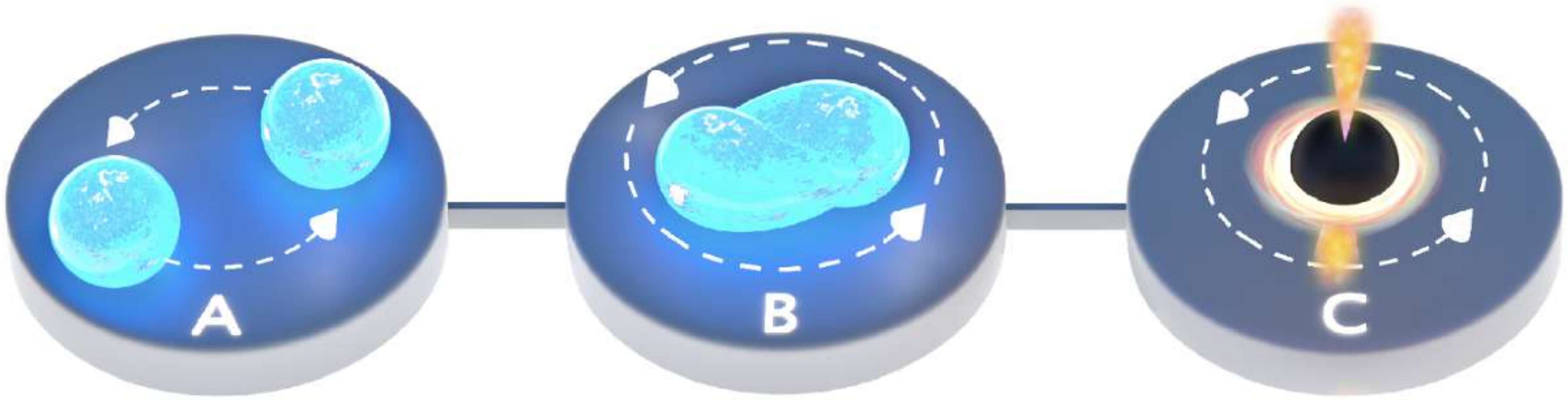
Axion and ALPs could interact with all the Standard model particles.
In this work we will use the coupling of ALPs with nucleons and photons.
In particular we use exemplary scenario inspired by the KSVZ axion model

$$g_{ap} = \frac{2\pi m_N}{\alpha} \frac{C_{ap}}{C_\gamma} g_{a\gamma}$$

Binary Neutron Star Mergers

Binary Neutron Star Merger (BNS) are ideal environments to produce ALPs.

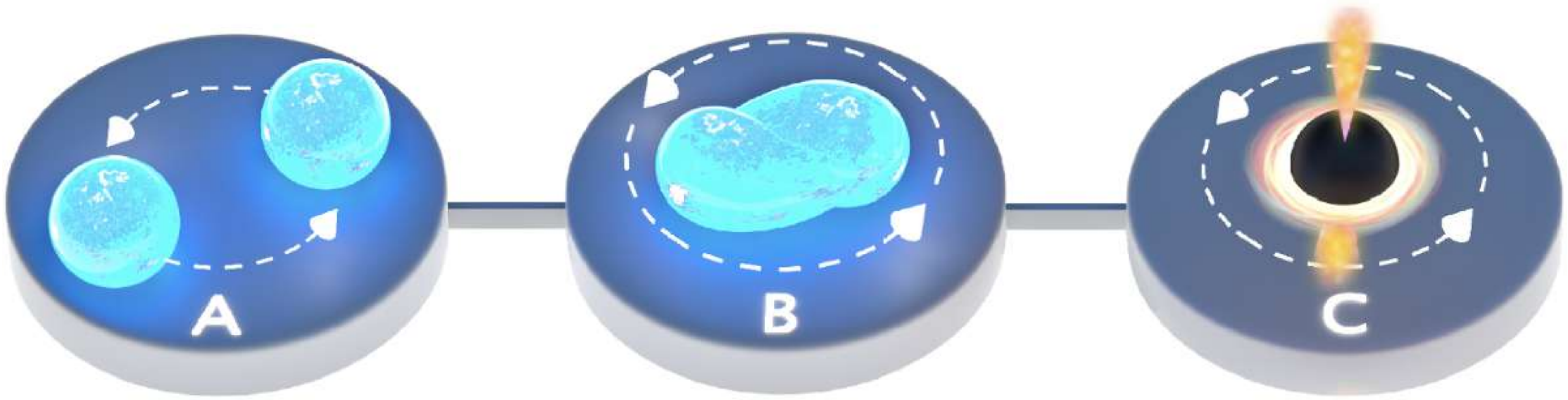
[Source: N. Sarin and P. D. Lasky., Gen. Rel. and Grav., 53 (2021)]



Binary Neutron Star Mergers

Binary Neutron Star Merger (BNS) are ideal environments to produce ALPs.

[Source: N. Sarin and P. D. Lasky., Gen. Rel. and Grav., 53 (2021)]



Inspiral phase

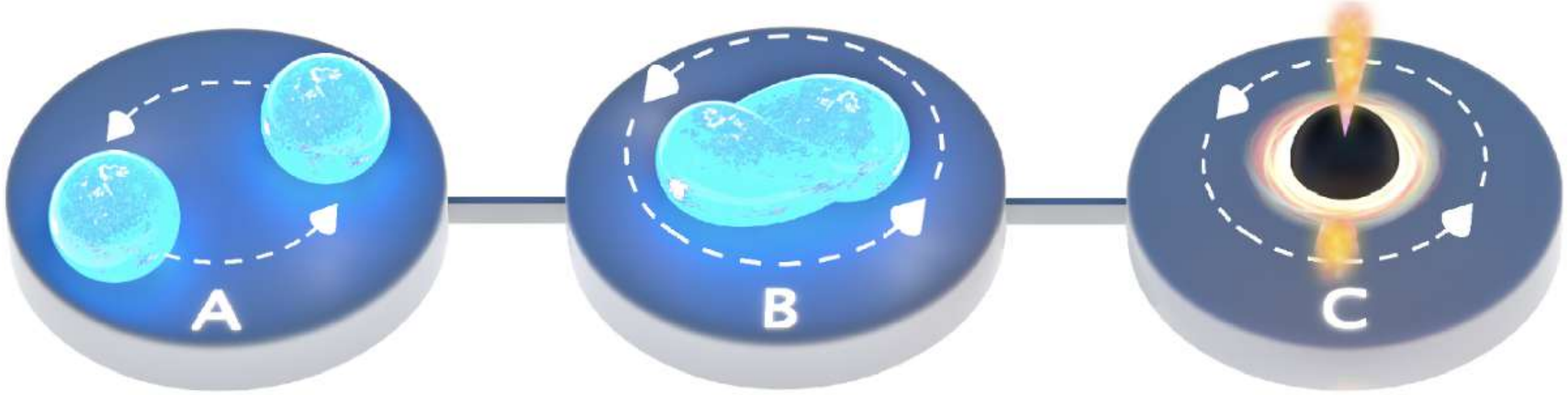
Initial phase $\Delta t \gtrsim 85\,\mathrm{Myr}$

Latter phase $O(1)\,\mathrm{min} \lesssim \Delta t \lesssim O(1)\,\mathrm{hrs}$

Binary Neutron Star Mergers

Binary Neutron Star Merger (BNS) are ideal environments to produce ALPs.

[Source: N. Sarin and P. D. Lasky., Gen. Rel. and Grav., 53 (2021)]



Inspiral phase | **Merger phase**

Initial phase $\Delta t \gtrsim 85\,\mathrm{Myr}$

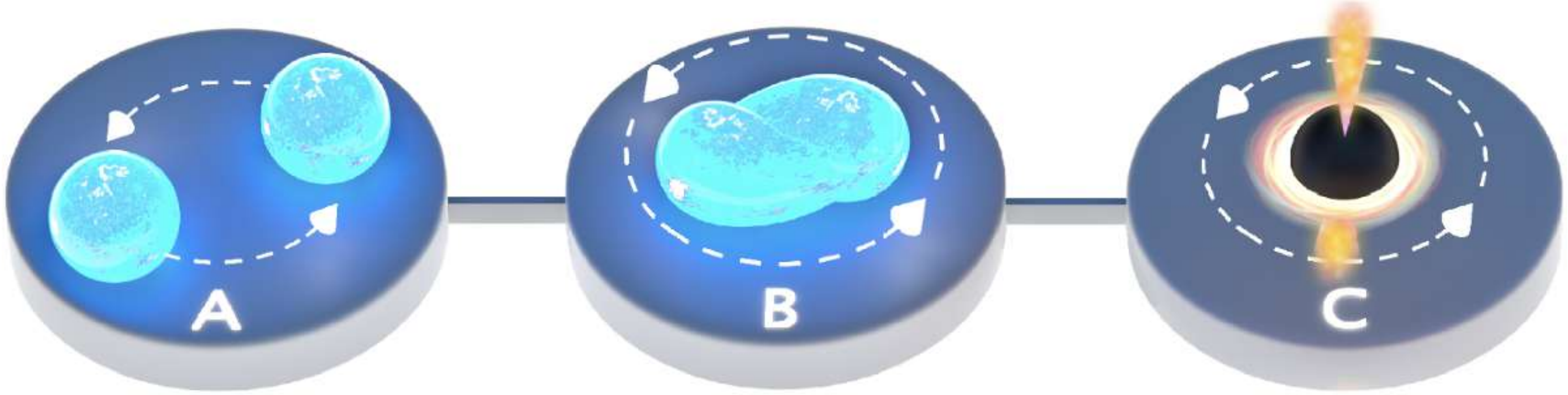
Latter phase $O(1)\,\mathrm{min} \lesssim \Delta t \lesssim O(1)\,\mathrm{hrs}$

$\Delta t \sim O(20)\,\mathrm{ms}$

Binary Neutron Star Mergers

Binary Neutron Star Merger (BNS) are ideal environments to produce ALPs.

[Source: N. Sarin and P. D. Lasky., Gen. Rel. and Grav., 53 (2021)]



Inspiral phase — Initial phase $\Delta t \gtrsim 85\,\mathrm{Myr}$; Latter phase $O(1)\,\mathrm{min} \lesssim \Delta t \lesssim O(1)\,\mathrm{hrs}$

Merger phase — $\Delta t \sim O(20)\,\mathrm{ms}$

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

Binary Neutron Star Mergers

The merger of a Binary Neutron Star system has four predicted outcomes:

Binary Neutron Star Mergers

The merger of a Binary Neutron Star system has four predicted outcomes:

↳ **Gravitational Waves**

Binary Neutron Star Mergers

The merger of a Binary Neutron Star system has four predicted outcomes:

- Gravitational Waves
- Kilonovae transient

Binary Neutron Star Mergers

The merger of a Binary Neutron Star system has four predicted outcomes:

- Gravitational Waves
- Kilonovae transient
- Short Gamma-Ray Bursts

Binary Neutron Star Mergers

The merger of a Binary Neutron Star system has four predicted outcomes:

- Gravitational Waves
- Kilonovae transient
- Short Gamma-Ray Bursts
- Burst of MeV or GeV neutrinos

Binary Neutron Star Mergers

The merger of a Binary Neutron Star system has four predicted outcomes:

- Gravitational Waves
- Kilonovae transient
- Short Gamma-Ray Bursts
- Burst of MeV or GeV neutrinos

The landmark in Binary Neutron Merger is the observation of ***GW170817***

[B.P. Abbott et al., Phys. Rev. Lett. 119, 16 (2017)]

Binary Neutron Star Mergers

The merger of a Binary Neutron Star system has four predicted outcomes:

- Gravitational Waves
- Kilonovae transient
- Short Gamma-Ray Bursts
- Burst of MeV or GeV neutrinos

The landmark in Binary Neutron Merger is the observation of ***GW170817***

[B.P. Abbott et al., Phys. Rev. Lett. 119, 16 (2017)]

Tag the ALP-induced photon signal with the Gravitational Wave signal.

Binary Neutron Star Mergers

The merger of a Binary Neutron Star system has four predicted outcomes:

- Gravitational Waves
- Kilonovae transient
- Short Gamma-Ray Bursts
- Burst of MeV or GeV neutrinos

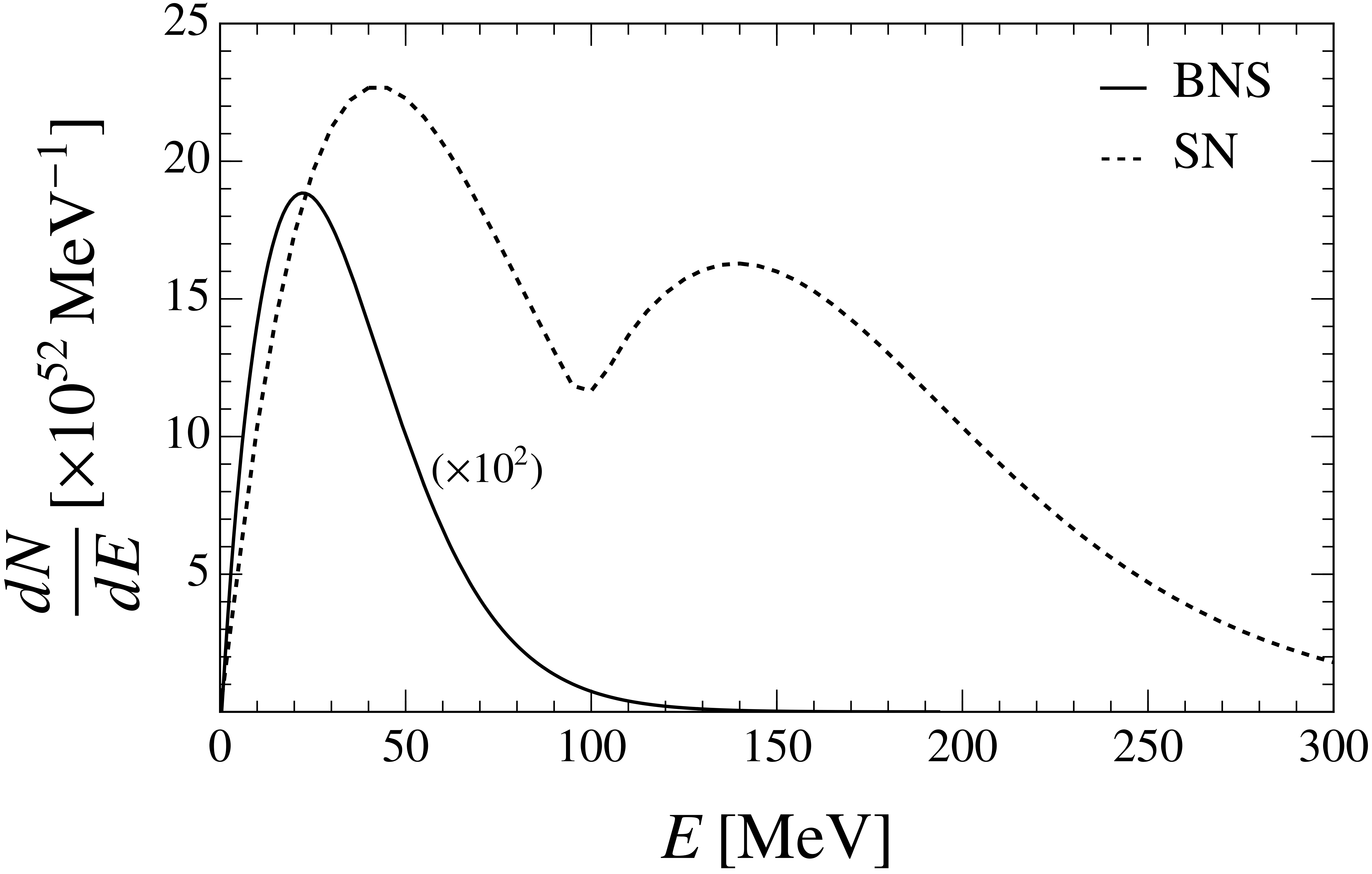
The landmark in Binary Neutron Merger is the observation of ***GW170817***

[B.P. Abbott et al., Phys. Rev. Lett. 119, 16 (2017)]

Tag the ALP-induced photon signal with the Gravitational Wave signal.

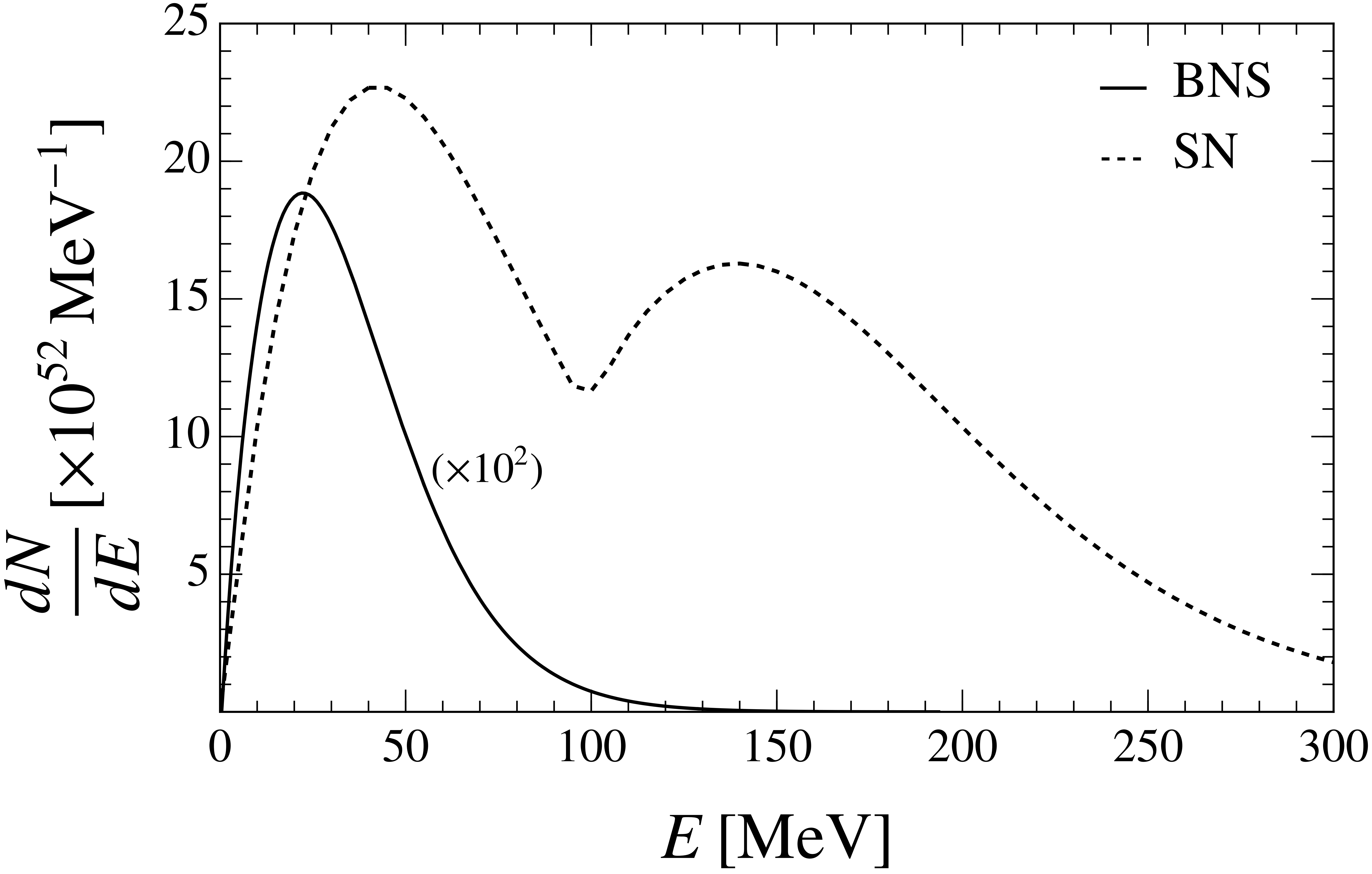
Equal mass system of two Neutron Stars with $1.375\, M_{\odot}$ and EOS DD2

NN Bremsstrahlung

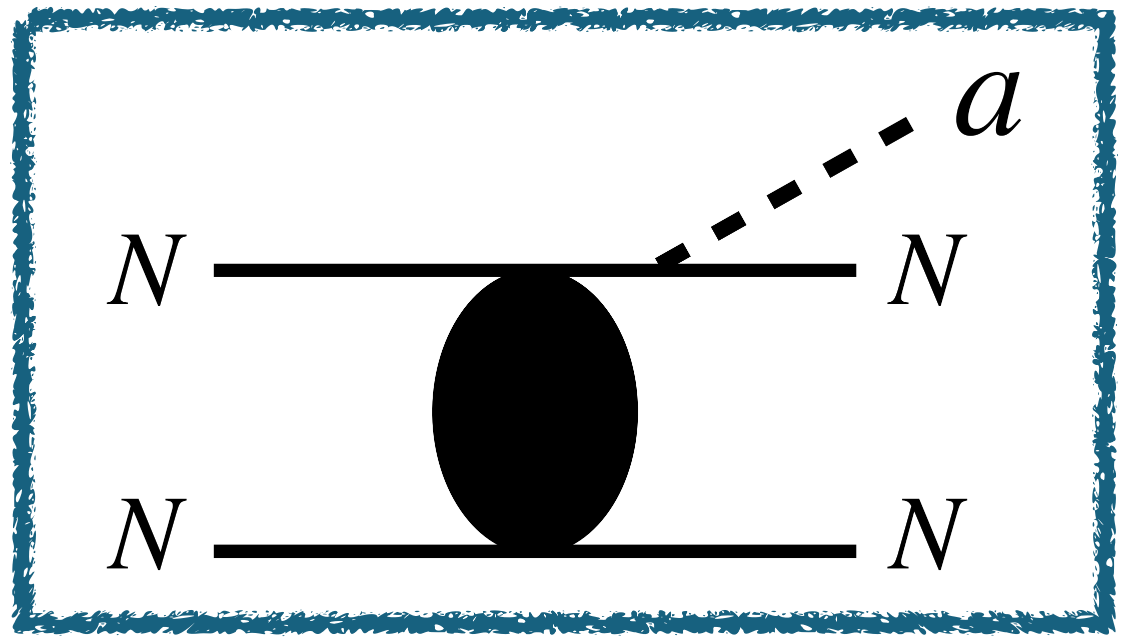


$$\frac{dN}{dE} = \int dV\, dt^* \frac{d^2 n_a}{dt^*\, dE^*}\, \alpha_{\rm GR}^{-1}(r)$$

NN Bremsstrahlung

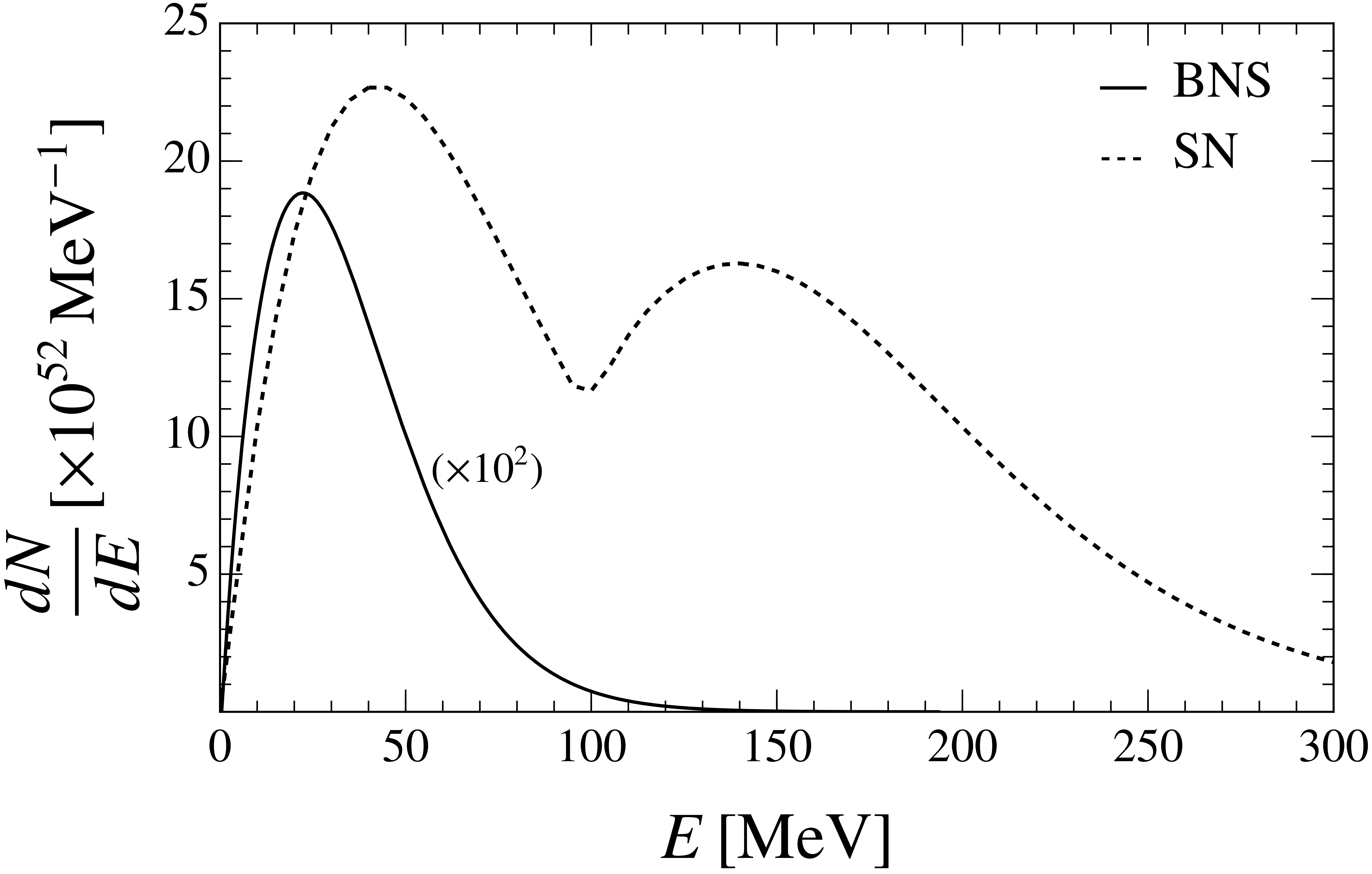


[Carenza et al., JCAP 10 (2019) 016]

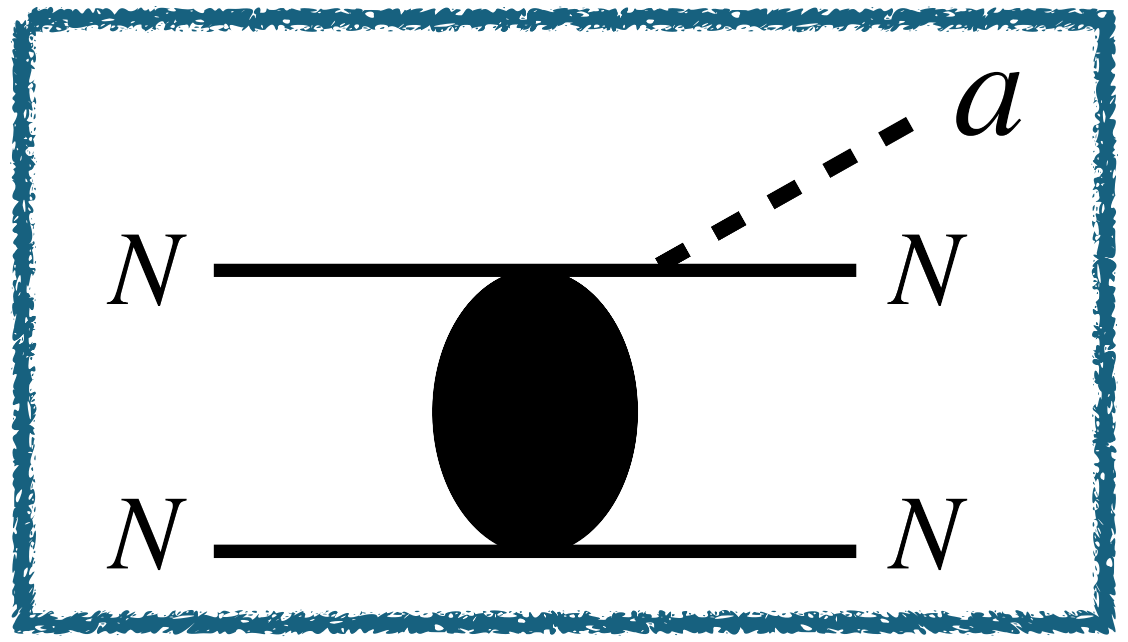


$$\frac{dN}{dE} = \int dV\, dt^* \frac{d^2 n_a}{dt^*\, dE^*} \alpha_{\rm GR}^{-1}(r)$$

NN Bremsstrahlung



[Carenza et al., JCAP 10 (2019) 016]



$$\frac{dN}{dE} = \int dV\, dt^* \frac{d^2 n_a}{dt^*\, dE^*} \alpha_{\rm GR}^{-1}(r)$$

The lapse factor encodes the **strong gravitational field effects**

$$dt = dt^*(r)\, \alpha_{\rm GR}^{-1}(r)$$
$$E = E^*(r)\, \alpha_{\rm GR}(r)$$

ALP-photon conversion

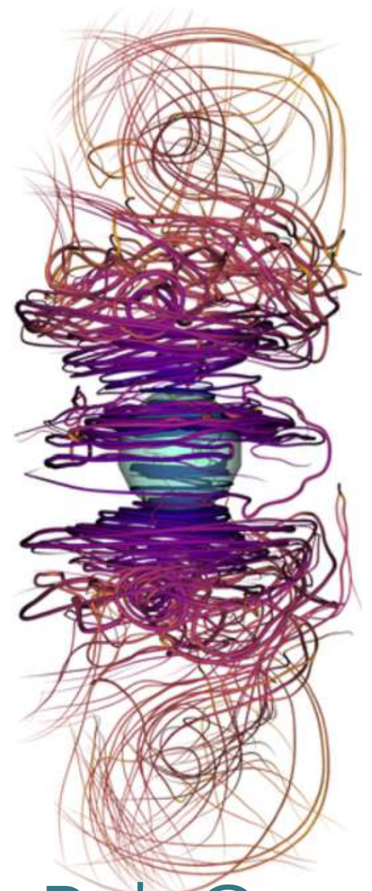
ALPs can convert into photons while propagating in external magnetic fields due to the ALP-photon coupling [G. Raffelt and L. Stodolsky, Phys. Rev. D 37 , 1237 (1988)].

ALP-photon conversion

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

In this work we consider:

↳ fields in the remnant to be of the order of $10^{15} - 10^{16}\,\mathrm{G}$
[R.Ciolfi, Gen. Red. Grab. 52, 59 (2020)].
More detailed study: arXiv:2509.13322



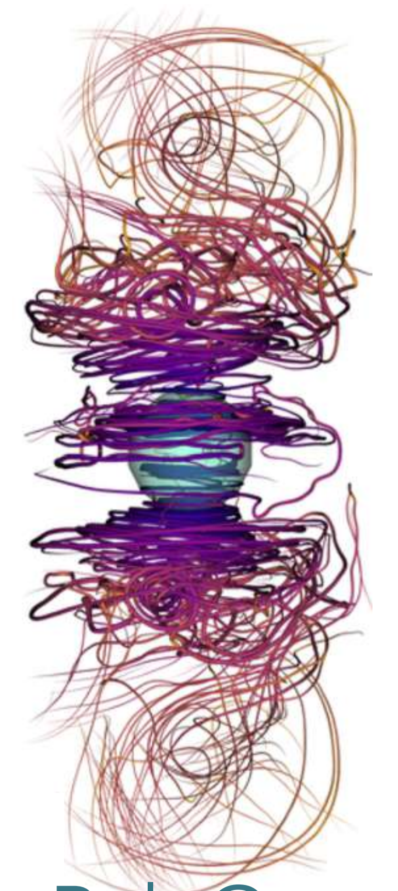
[Ciolfi, Gen. Rel. Grav. 52 (2020) 59]

ALP-photon conversion

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

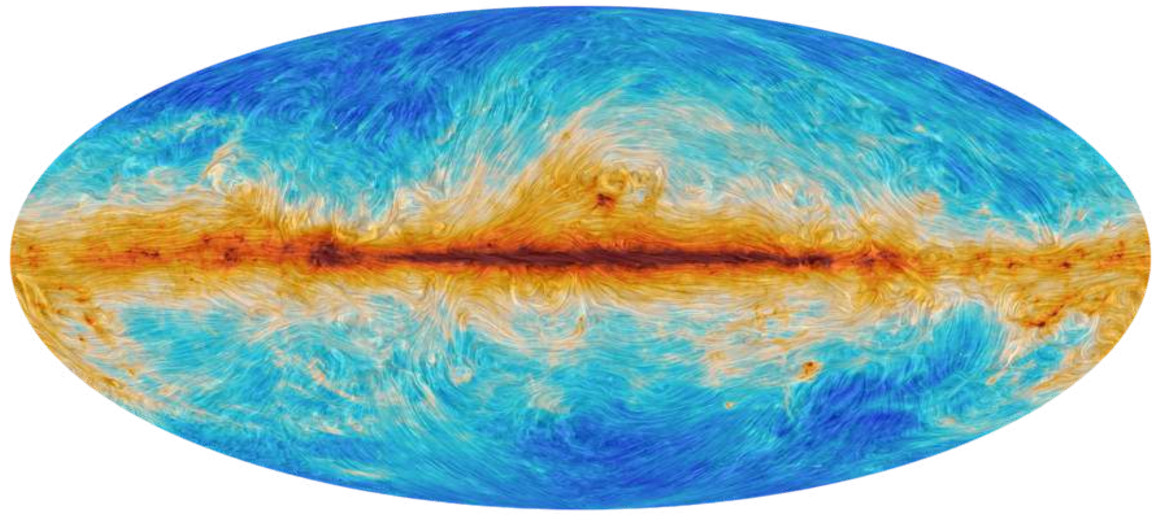
In this work we consider:

↳ fields in the remnant to be of the order of $10^{15} - 10^{16}\,\mathrm{G}$
[R.Ciolfi, Gen. Red. Grab. 52, 59 (2020)].
More detailed study: arXiv:2509.13322



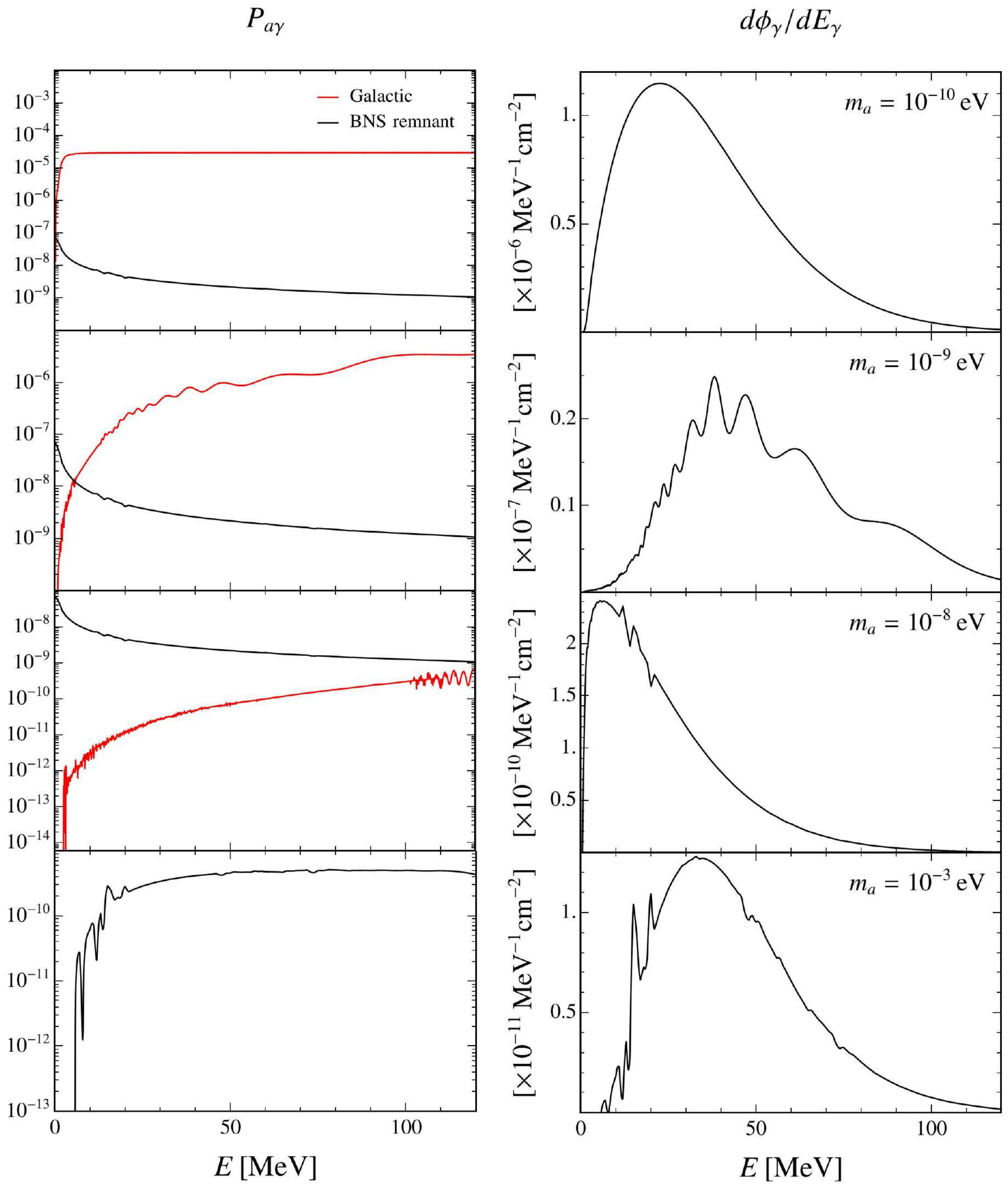
[Ciolfi, Gen. Rel. Grav. 52 (2020) 59]

↳ the **Jansson-Farrar model** as benchmark model for the Milky Way regular magnetic field
[R. Jansson and G. R. Farrar, Astro. J. 757, 14 (2012)].

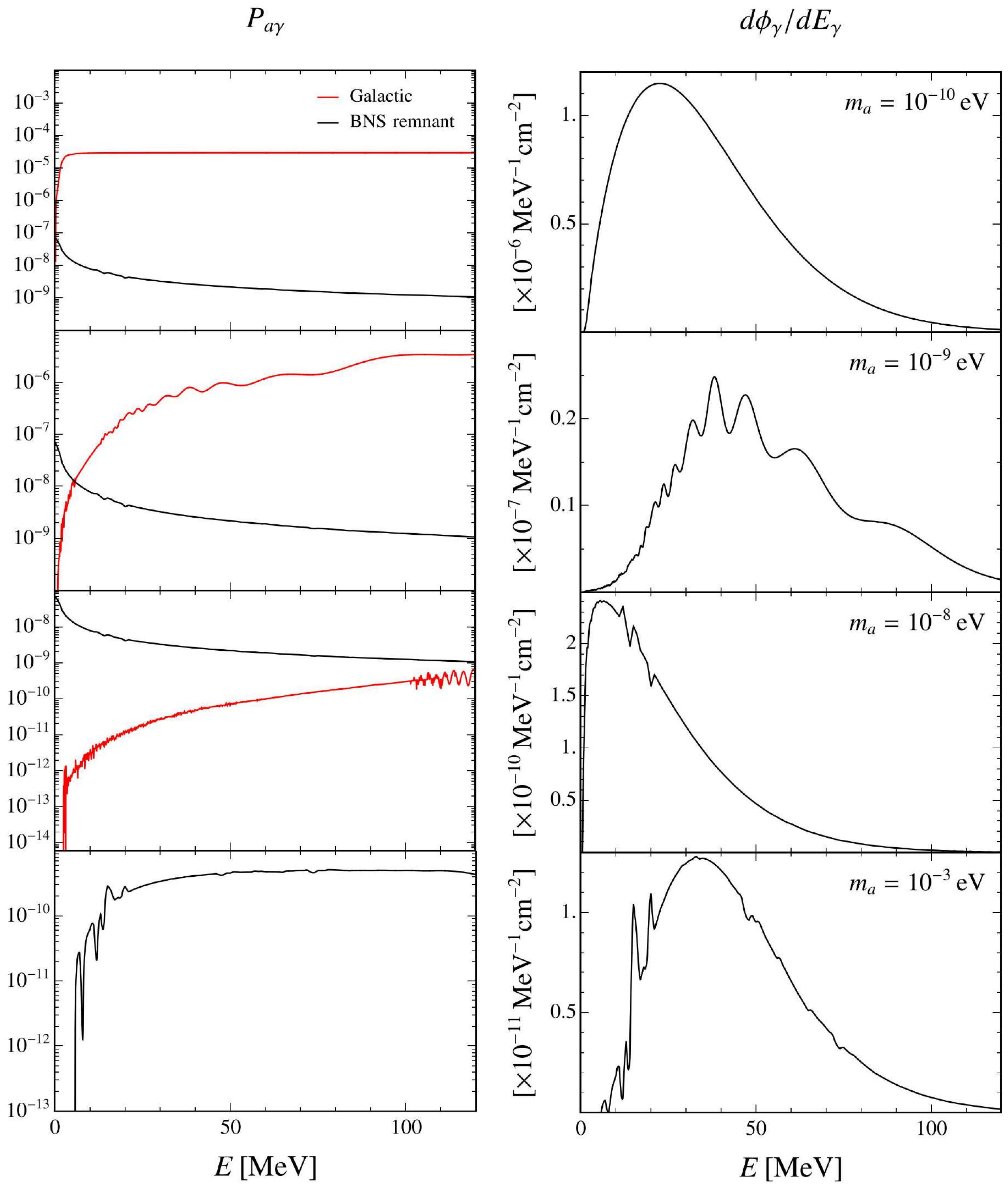


Source: ESA and Planck col.

ALP-photon conversion



ALP-photon conversion



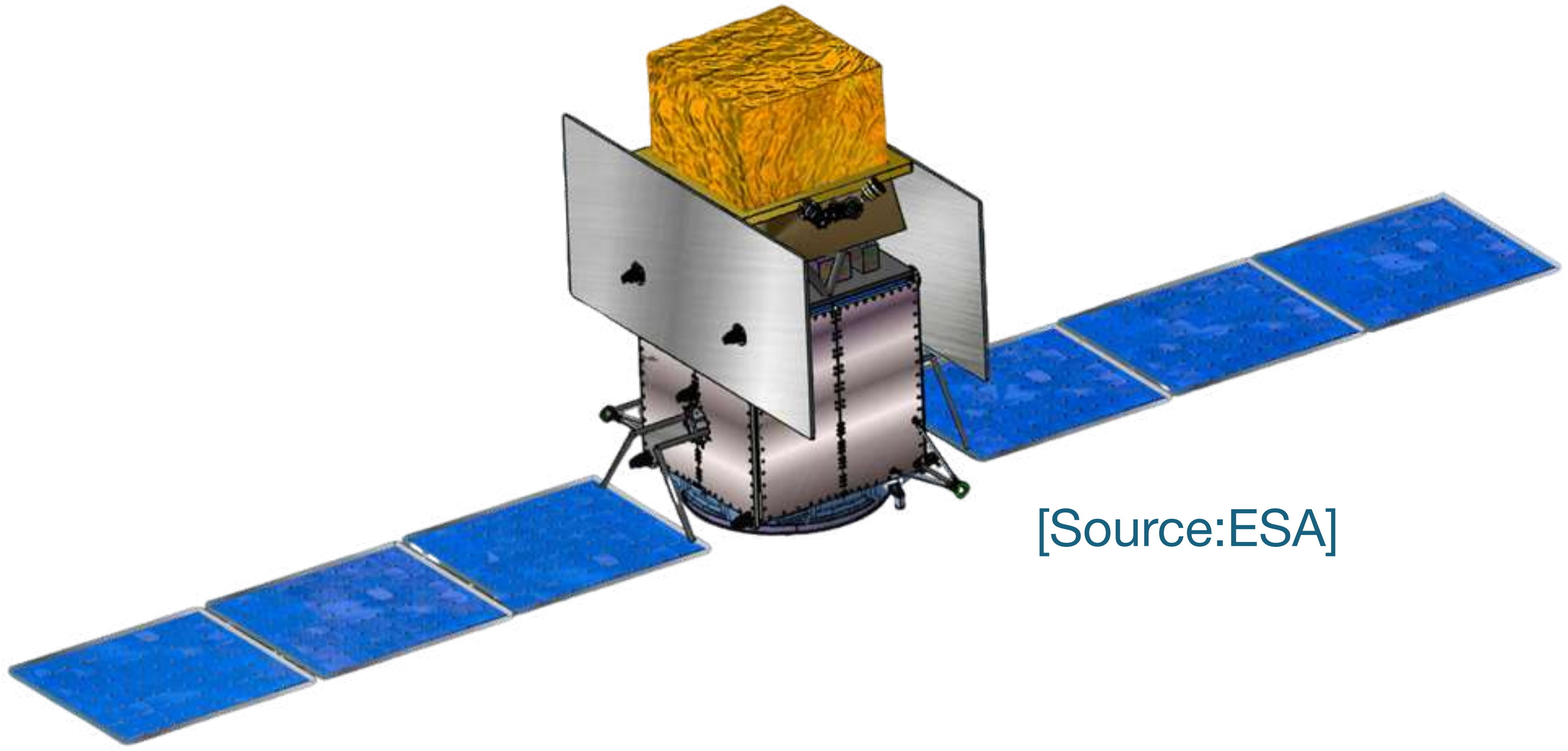
$$\frac{d\phi_\gamma}{dE_\gamma} = \frac{1}{4\pi L^2}\frac{dN}{dE}P_{a\gamma}(E, m, d, l, b, g_{a\gamma})$$

with d is the length of the region where $\overrightarrow{B}$ is present , $g_{a\gamma} = 10^{-12} GeV^{-1}$ from a generic source located in the same position of the GW170817 event at $L = 40\,Mpc$

Sensitivities of current and proposed γ-ray experiments to the ALP-induced signal

We quantified the sensitivity of Fermi-LAT and of the proposed e-ASTROGRAM, AMEGO-X, GRAMS balloon , GRAMS satellite and MAST 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)],
[T. Dzhatdoev and E. Podlesnyi, Astropart. Phys. 112 (2019) 1]



[Source:ESA]

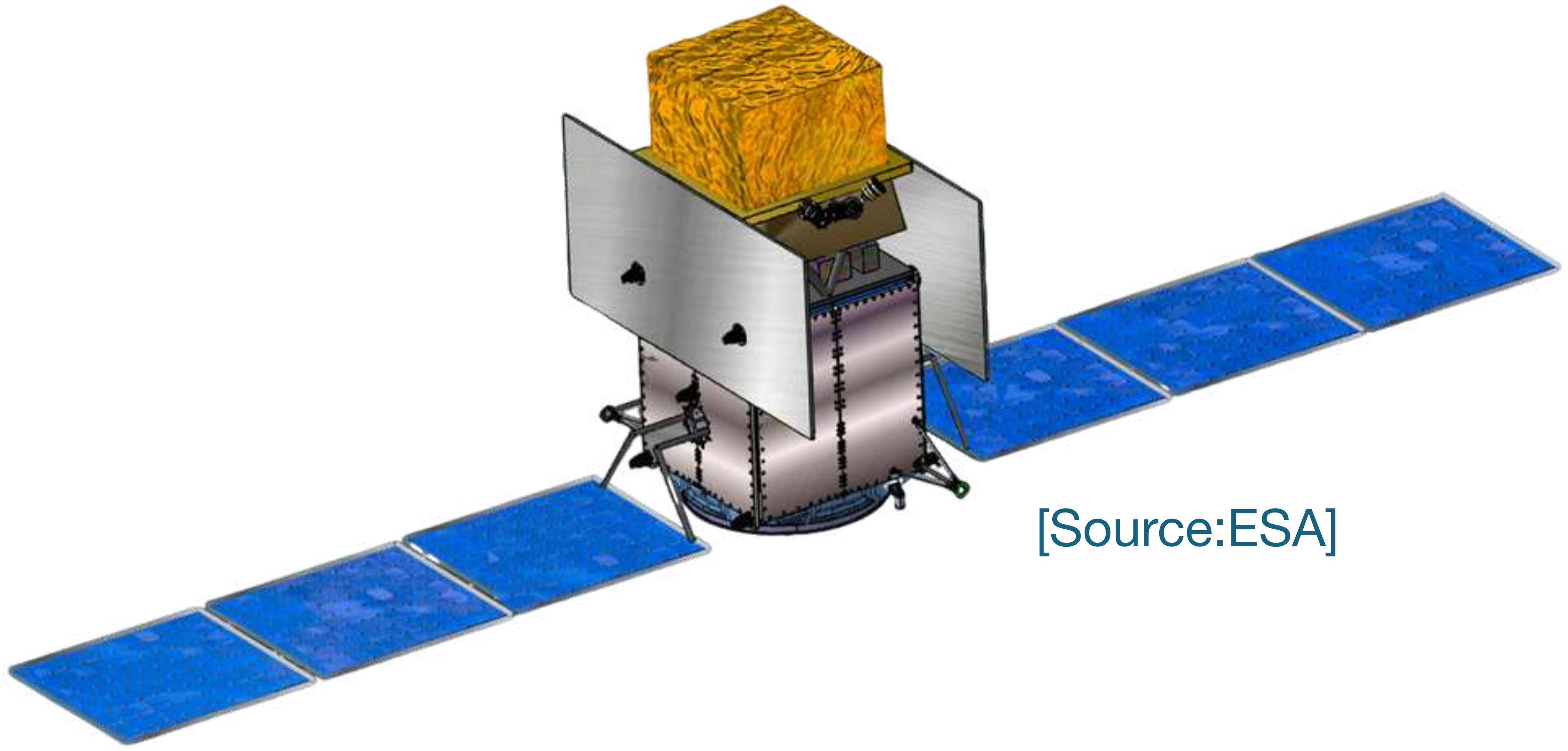
Sensitivities of current and proposed γ-ray experiments to the ALP-induced signal

We quantified the sensitivity of Fermi-LAT and of the proposed e-ASTROGRAM, AMEGO-X, GRAMS balloon , GRAMS satellite and MAST 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)],
[T. Dzhatdoev and E. Podlesnyi, Astropart. Phys. 112 (2019) 1]

Background free model

$$N_{event} \gtrsim 3$$



[Source:ESA]

Sensitivities of current and proposed γ-ray experiments to the ALP-induced signal

Probability of joint GW-γ detection

The typical rate at which a gamma-ray signal and a GW signal from a BNS can be detected in coincidence is given by

Probability of joint GW-γ detection

The typical rate at which a gamma-ray signal and a GW signal from a BNS can be detected in coincidence is given by

↳ the probability of detecting the BNS merger event with GW detector

Probability of joint GW-γ detection

The typical rate at which a gamma-ray signal and a GW signal from a BNS can be detected in coincidence is given by

- ↳ the probability of detecting the BNS merger event with GW detector
- ↳ the probability of detecting the ALP-induced gamma ray event

Probability of joint GW-γ detection

The typical rate at which a gamma-ray signal and a GW signal from a BNS can be detected in coincidence is given by

- the probability of detecting the BNS merger event with GW detector
- the probability of detecting the ALP-induced gamma ray event

Starting with the estimated rate of BNS in the Milky Way, one can extrapolate it to extra-galactic
[N. Pol, M. McLaughlin and D.R.Lorimer Astro. J. 870 , 71 (2019)]

$$\mathcal{R}_{\rm GW} = \mathcal{R}_{\rm MW}\left(\frac{L_{\rm total}(d)}{L_{\rm MW}}\right)$$

Probability of joint GW-γ detection

Choosing as a GW detector horizon 100 Mpc, as in the case of advanced LIGO

[N. Pol, M. McLaughlin and D.R.Lorimer Astro. J. 870 , 71 (2019)]

$$\mathscr{R}_{GW} \sim 0.18^{+0.13}_{-0.06} \times \left(\frac{d}{100\,Mpc}\right)^3 yr^{-1}\,.$$

Probability of joint GW-γ detection

Choosing as a GW detector horizon 100 Mpc, as in the case of advanced LIGO
[N. Pol, M. McLaughlin and D.R.Lorimer Astro. J. 870 , 71 (2019)]

$$\mathscr{R}_{GW} \sim 0.18^{+0.13}_{-0.06} \times \left(\frac{d}{100\,Mpc}\right)^3 yr^{-1}\,.$$

Finally, one can estimate the time interval between two joint detection events by advanced LIGO and gamma-ray detectors

$$T_{\rm joint} \simeq (\mathscr{R}_{LIGO} \times P_{\rm on} \times P_{\rm FoV})^{-1}$$

Probability of joint GW-γ detection

Choosing as a GW detector horizon 100 Mpc, as in the case of advanced LIGO
[N. Pol, M. McLaughlin and D.R.Lorimer Astro. J. 870 , 71 (2019)]

$$\mathcal{R}_{GW} \sim 0.18^{+0.13}_{-0.06} \times \left(\frac{d}{100\,Mpc}\right)^3 yr^{-1}\,.$$

Finally, one can estimate the time interval between two joint detection events by advanced LIGO and gamma-ray detectors

$$T_{\rm joint} \simeq (\mathcal{R}_{LIGO} \times P_{\rm on} \times P_{\rm FoV})^{-1}$$

Experiment	$T_{\rm joint}$		
	$d = 4\,\rm Mpc$	$d = 40\,\rm Mpc$	$d = 100\,\rm Mpc$
Fermi-LAT, e-ASTROGRAM, AMEGO-X, MAST	$\sim (3–8) \times 10^5$ yr	$\sim (3–8) \times 10^2$ yr	$\sim 20–50$ yr
GRAMS-balloon, GRAMS-satellite	$\sim (1–3) \times 10^5$ yr	$\sim (1–3) \times 10^2$ yr	$\sim 8–20$ yr

Probability of joint GW-γ detection

These results highlight the importance of achieving **wider sky coverage.**

Probability of joint GW-γ detection

These results highlight the importance of achieving **wider sky coverage.**

Assuming the employment of the three most sensitive experiments in orbit at different points of the sky at the same time:

$$P_{\mathrm{FoV}} \sim 88\,\%$$

Probability of joint GW-γ detection

These results highlight the importance of achieving **wider sky coverage.**

Assuming the employment of the three most sensitive experiments in orbit at different points of the sky at the same time:

$$P_{\mathrm{FoV}} \sim 88\,\%$$

Under such conditions, the joint detection of a BNS event at 100 Mpc

$$T_{\mathrm{joint}} \simeq (\mathscr{R}_{LIGO} \times P_{\mathrm{FoV}})^{-1} \simeq 4 - 9\,\mathrm{yr}$$

Conclusions and improvements

We have:

- used GW signal as **external trigger** to tag the gamma-ray signal
- can reach sensitivities down to $g_{a\gamma} \gtrsim \text{few} \times 10^{-12}\,\text{GeV}^{-1}$,
  assuming ALP coupled with photons and nucleons as in a canonical KSVZ mode
- shown that a joint detection could happen within 5-10 years (100 Mpc)

Conclusions and improvements

We have:

↳ used GW signal as **external trigger** to tag the gamma-ray signal

↳ can reach sensitivities down to $g_{a\gamma} \gtrsim \text{few} \times 10^{-12}\,\text{GeV}^{-1}$,
assuming ALP coupled with photons and nucleons as in a canonical KSVZ mode

↳ shown that a joint detection could happen within 5-10 years (100 Mpc)

These results could be improved:

↳ with **stacked analysis** over time

Conclusions and improvements

We have:

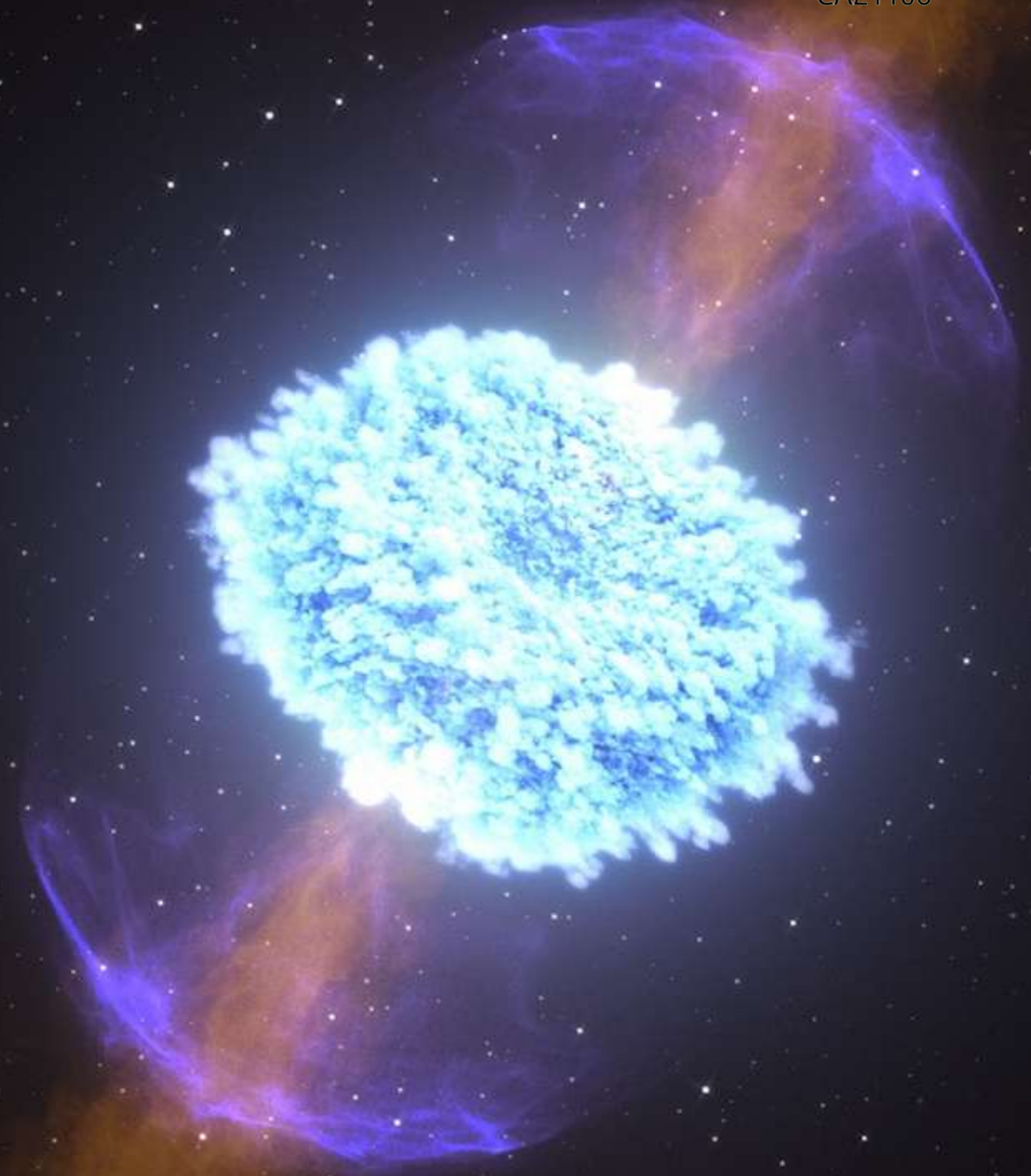
- used GW signal as **external trigger** to tag the gamma-ray signal
- can reach sensitivities down to $g_{a\gamma} \gtrsim \text{few} \times 10^{-12}\,\text{GeV}^{-1}$, assuming ALP coupled with photons and nucleons as in a canonical KSVZ mode
- shown that a joint detection could happen within 5-10 years (100 Mpc)

These results could be improved:

- with **stacked analysis** over time
- with new generation GW detectors (2030s), which can give us the location hours or days in advance!

EINSTEIN TELESCOPE

UNIVERSITÀ DEGLI STUDI DI BARI ALDO MORO



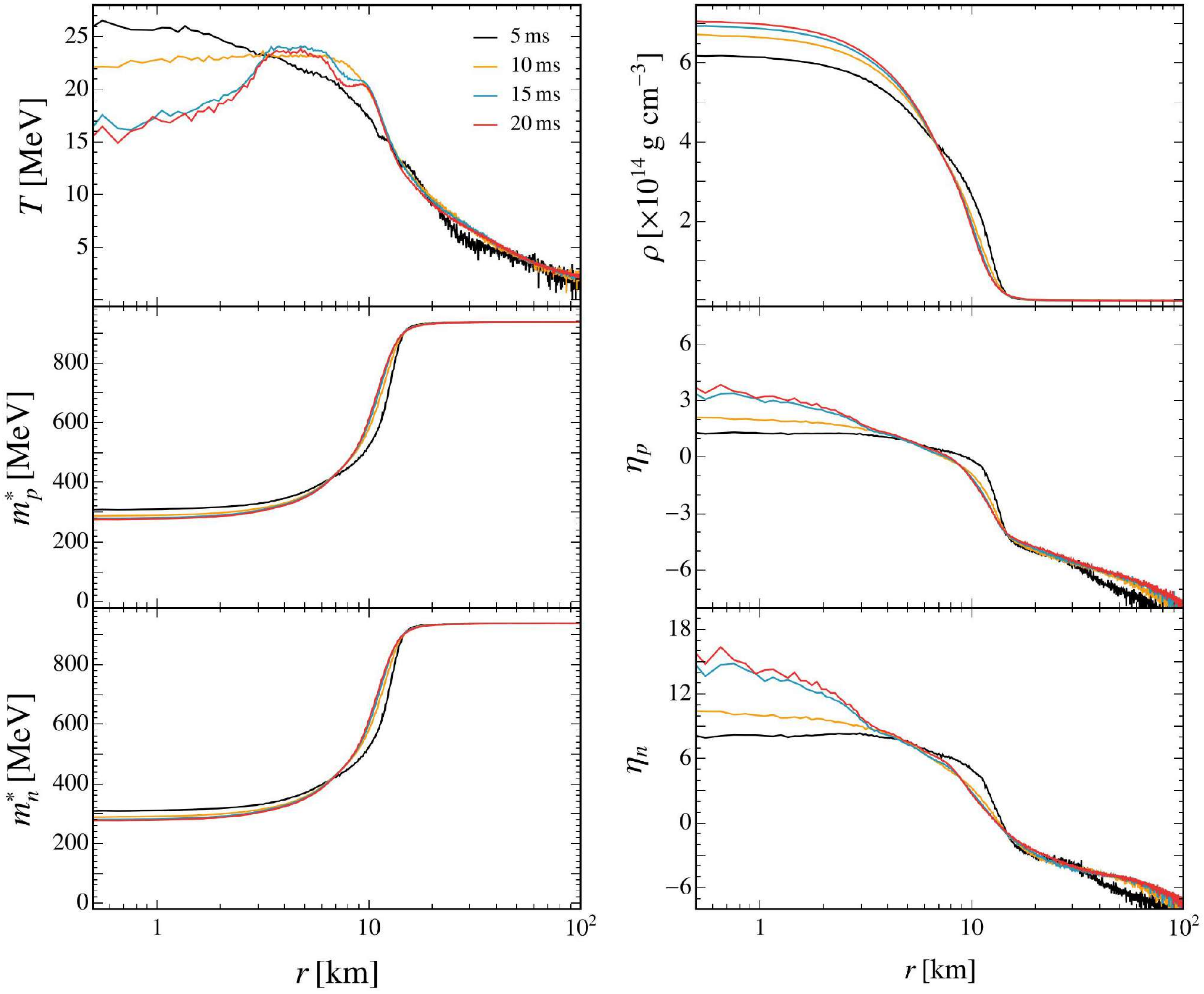
f.lecce5@phd.uniba.it
francesca.lecce@ba.infn.it

20th Patras Workshop on Axions, WIMPs and WISPs

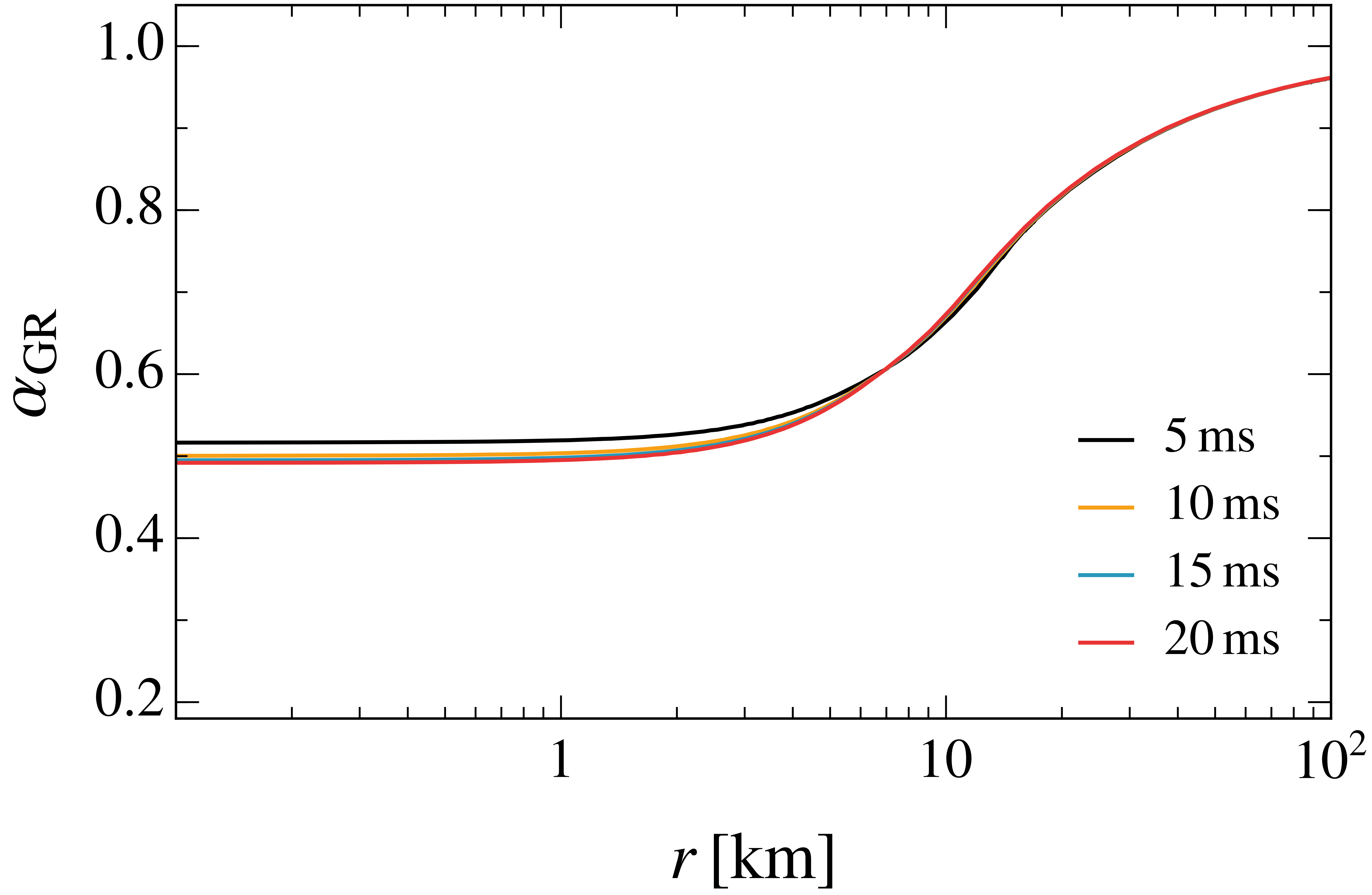
Tenerife September 23rd, 2025

[Source:UC Berkeley]

Hydrodynamic Binary Neutron Star Mergers



Lapse factor Binary Neutron Star Mergers



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

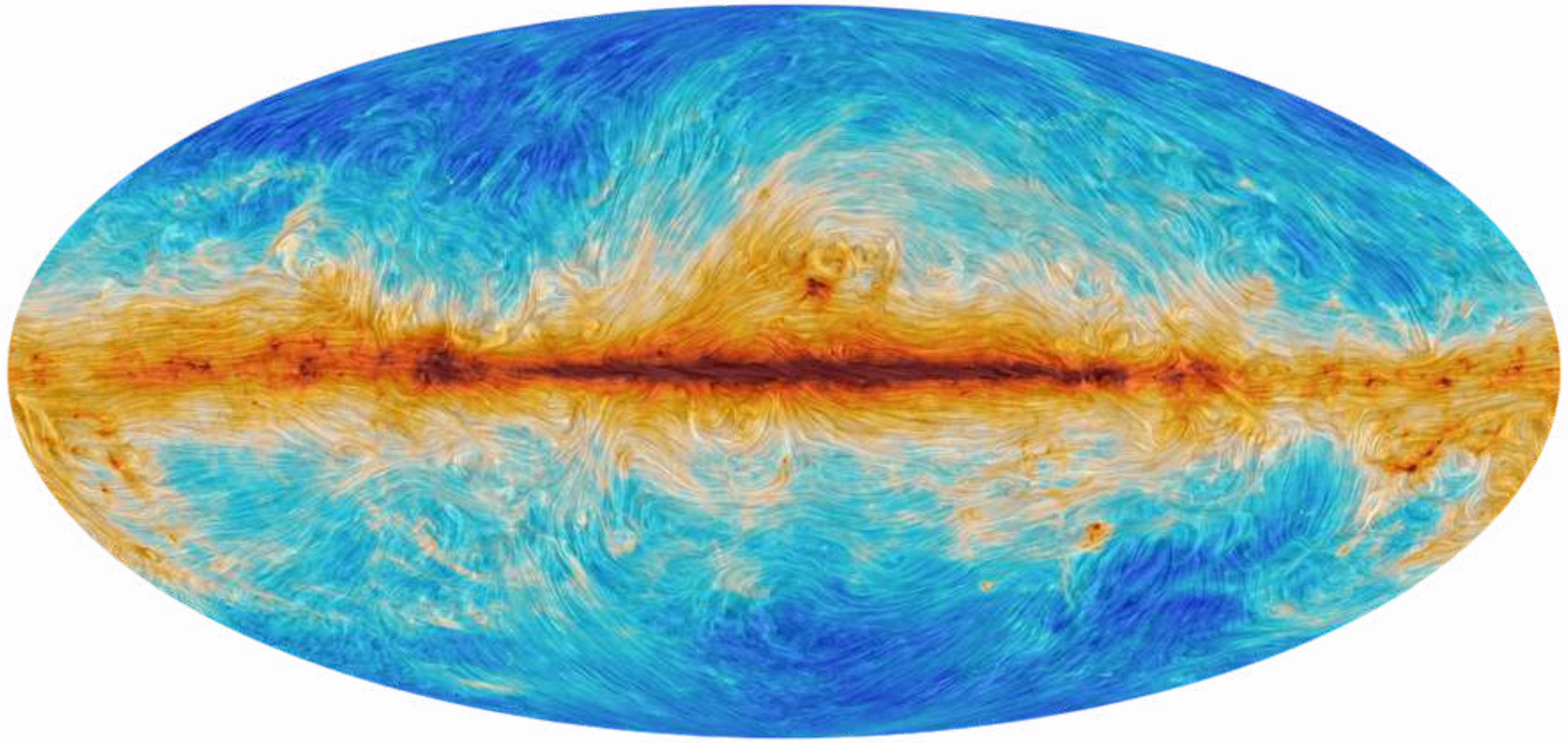
$$\theta = \frac{1}{2}\arctan\left(\frac{2\Delta_{a\gamma}}{\Delta_{\rm pl} - \Delta_a}\right)$$

the resulting density matrix will be

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

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)].*



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

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

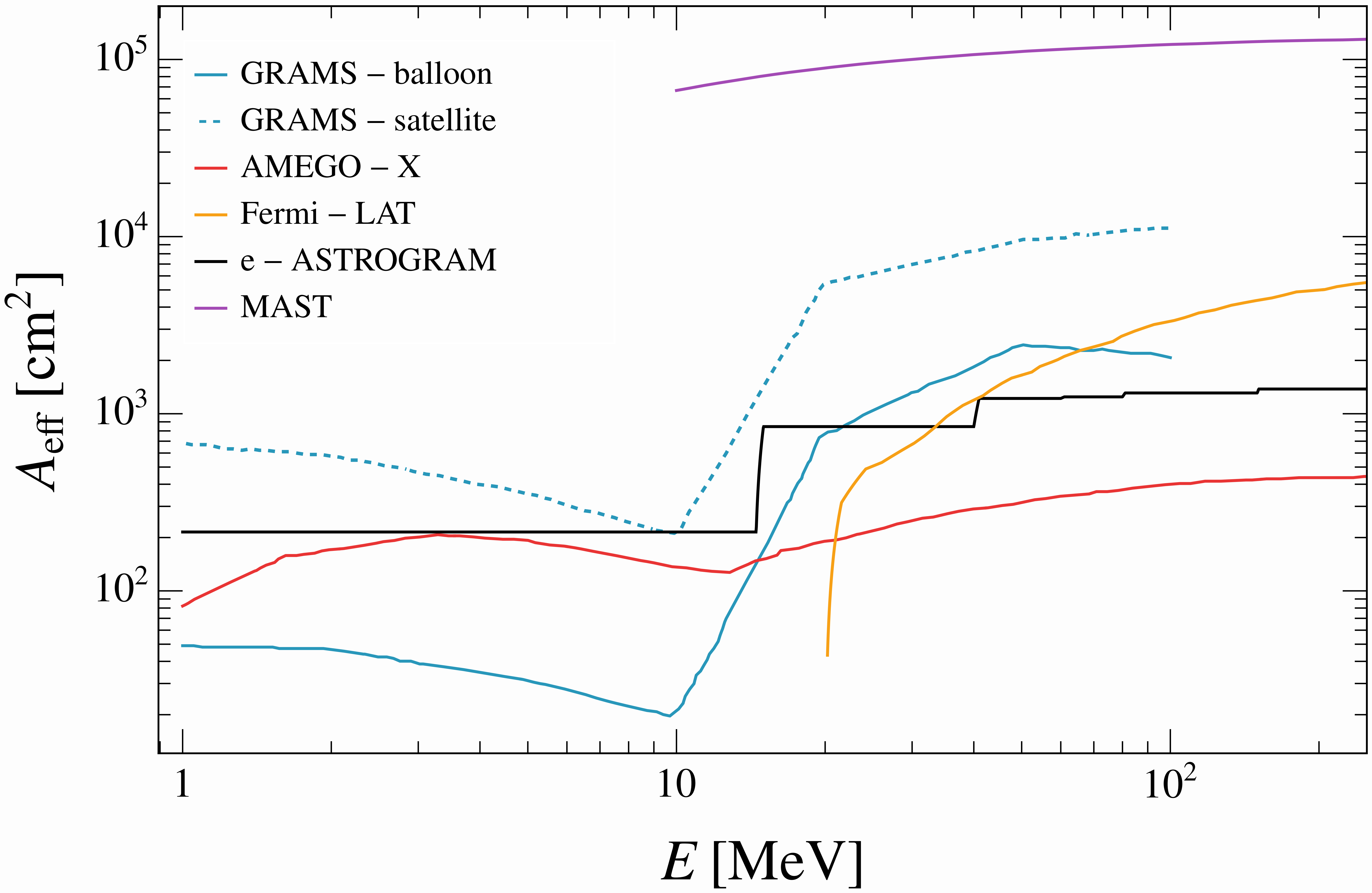
Gamma-ray experiment characterization

Experiment	FoV (sr)	$\delta\theta$ (°)	$N_{\rm bkg}$ (counts s^{-1})
e-ASTROGRAM [87]	$\gtrsim 2.5$	$\lesssim 1.5$	0.06
AMEGO-X [88]	2.5	3	0.25
Fermi-LAT [89]	2.4	$\lesssim 0.15$	0.08
GRAMS-balloon [90]	6.3	3	0.27
GRAMS-satellite [90]	6.3	1.8	0.35
MAST [91]	2.5	$\lesssim 1$	0.0004

with δE energy resolution, FoV observable portion of the sky at once, $\delta\theta$ angular resolution and $N_{\rm bkg}$ is the number of background events. In the case in which the background is given in terms of the flux

$$N_{\rm bkg} = \int_0^\infty dE\, \frac{d\phi_{\gamma,\rm bkg}}{dE}\, W(E)\, A_{\rm eff}(E)\, 2\pi\, (1 - \cos\delta\theta)$$

Gamma-ray experiment characterization



Gamma-ray detection probability

Experiment	$P_{\rm on}$	$P_{\rm FoV}$	$P_{\rm tot}$
Fermi-LAT, e-ASTROGRAM, AMEGO-X, MAST	85%	19%	16%
GRAMS-balloon, GRAMS-satellite	85%	50%	43%

$$P_{\rm tot} = P_{\rm on} \times P_{\rm FoV}$$

where $P_{\rm on}$ is the probability of the gamma-ray experiment being active during the occurrence of the BNS event and $P_{\rm FoV} = \frac{\rm FoV}{4\pi}$ is the probability of the event falling within the experiment FoV.

$P_{\rm on}$ has been evaluated by assuming a survey mode similar to that of Fermi -LAT accounting the turning off on the SAA

Sensitivities of current and proposed γ-ray experiments to the ALP-induced signal

Axions from Neutron stars mergers: production and detection signatures