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

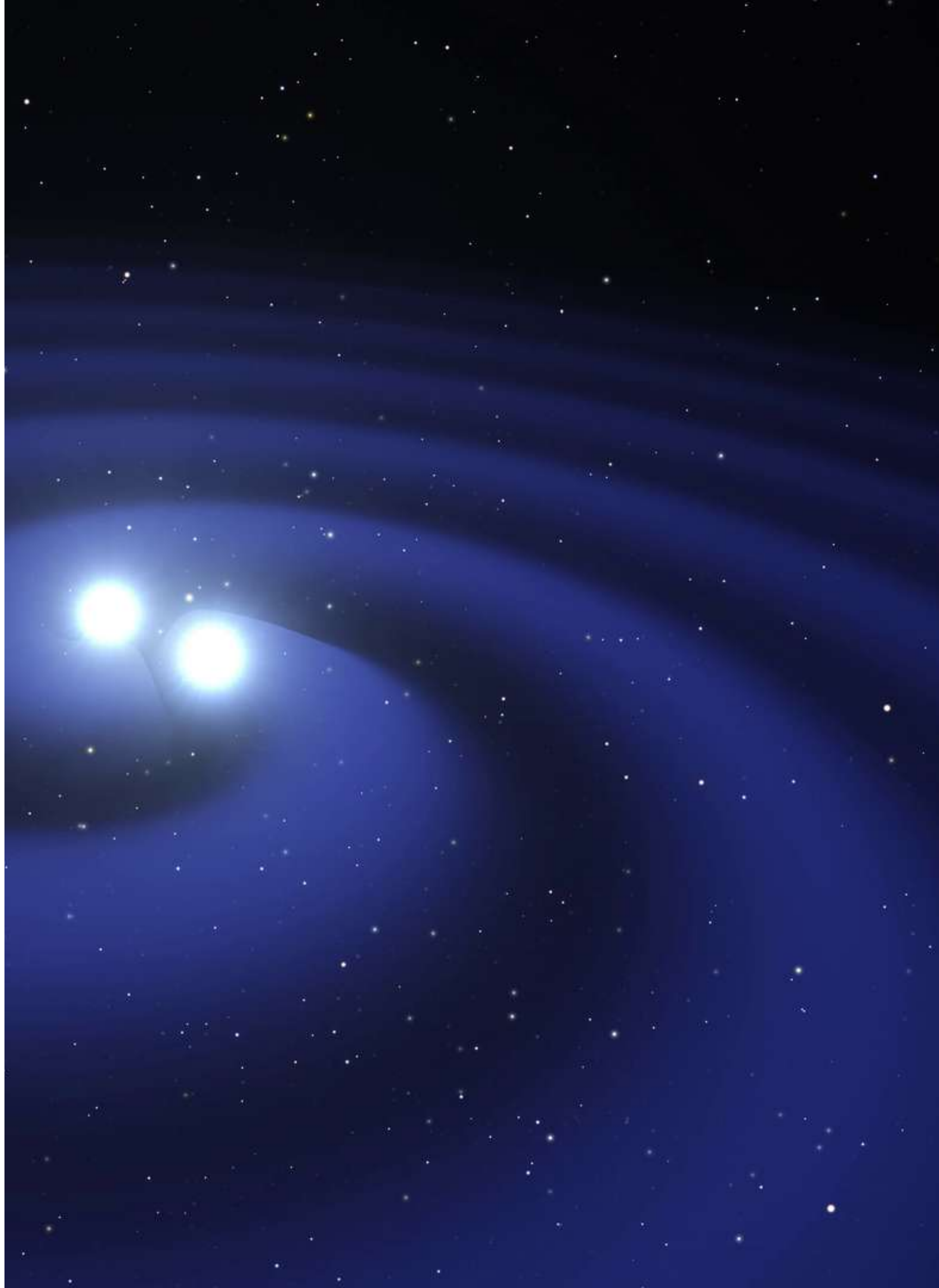
FRANCESCA LECCE

2nd VHEGAM meeting

May 26, 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

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)]

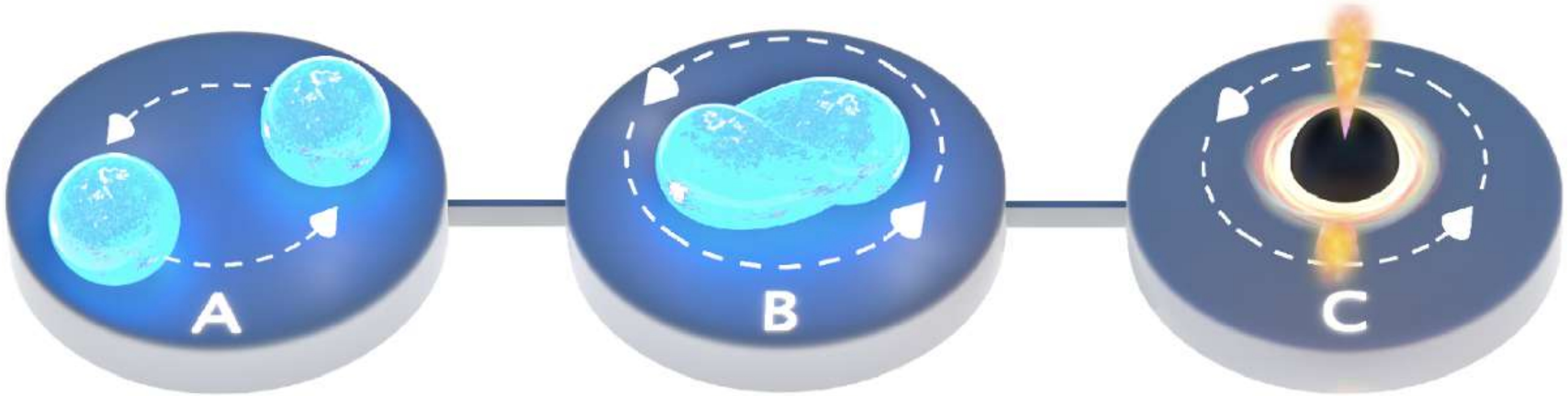
Axion-like particles (ALPs) are novel particles which behave similarly to the QCD axion. They emerge in UV completions of the Standard Model.

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

ALPs production from Binary Neutron Star Mergers

From the first detection of GW detection we now have a new source that we can study, Binary Neutron Star Merger (BNS).

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



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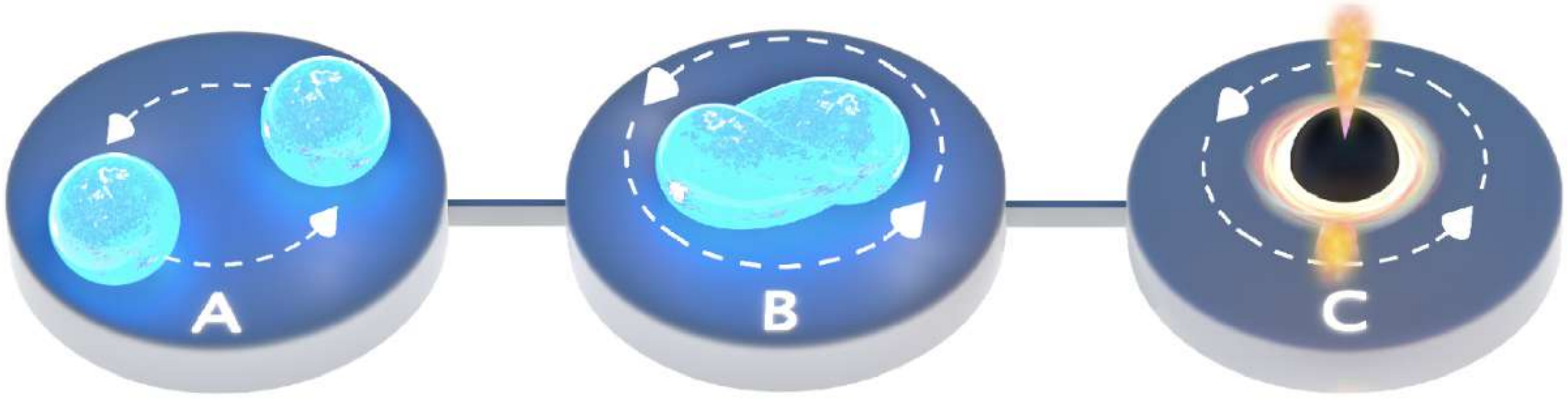

Inspiral phase

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

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

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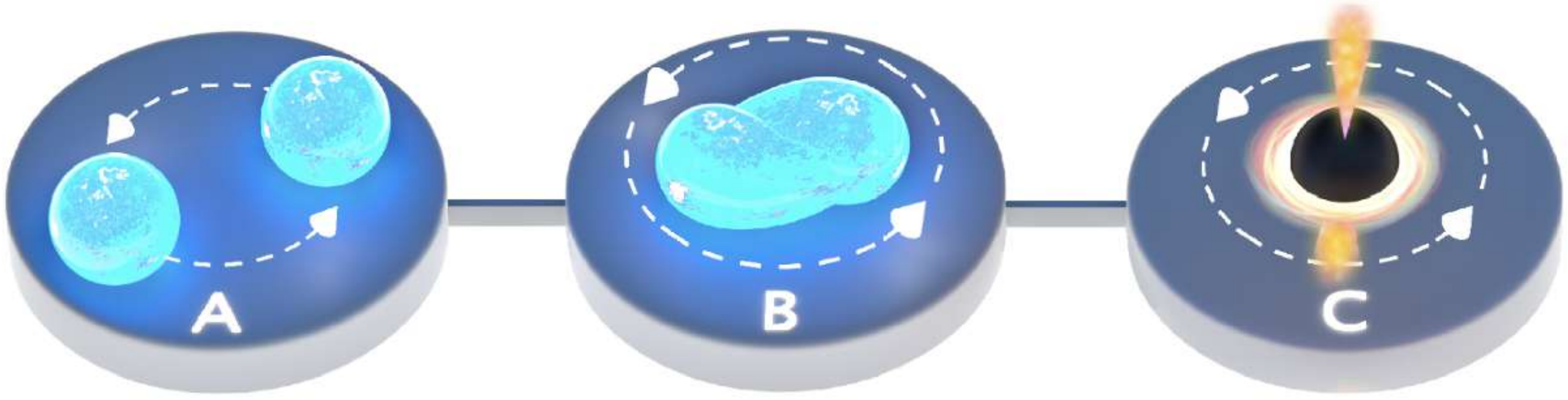

Inspiral phase **Merger phase**

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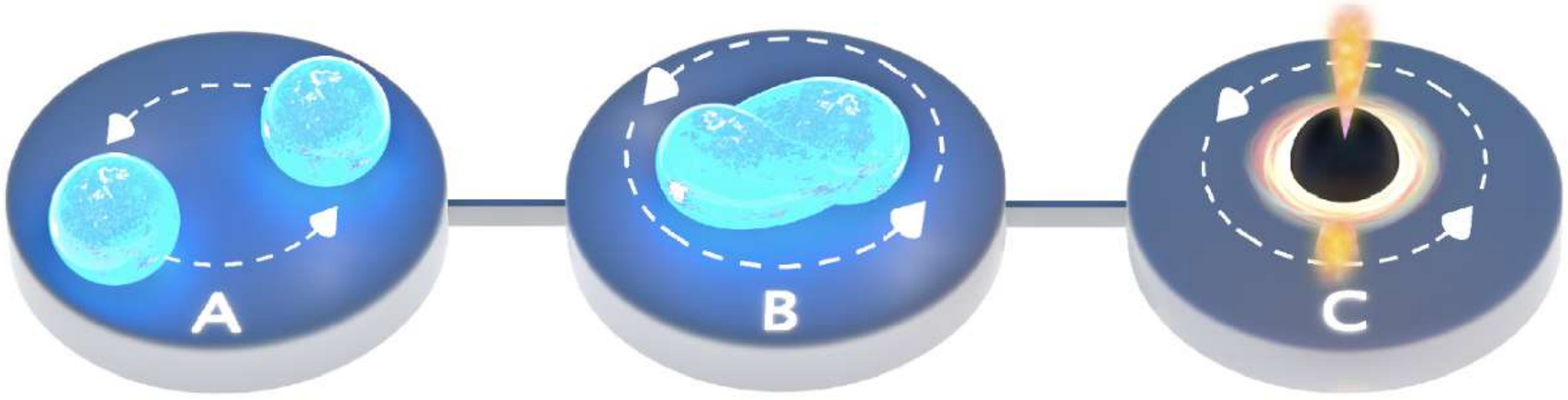

Inspiral phase | **Merger phase** | **Ringdown phase**

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

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

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

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

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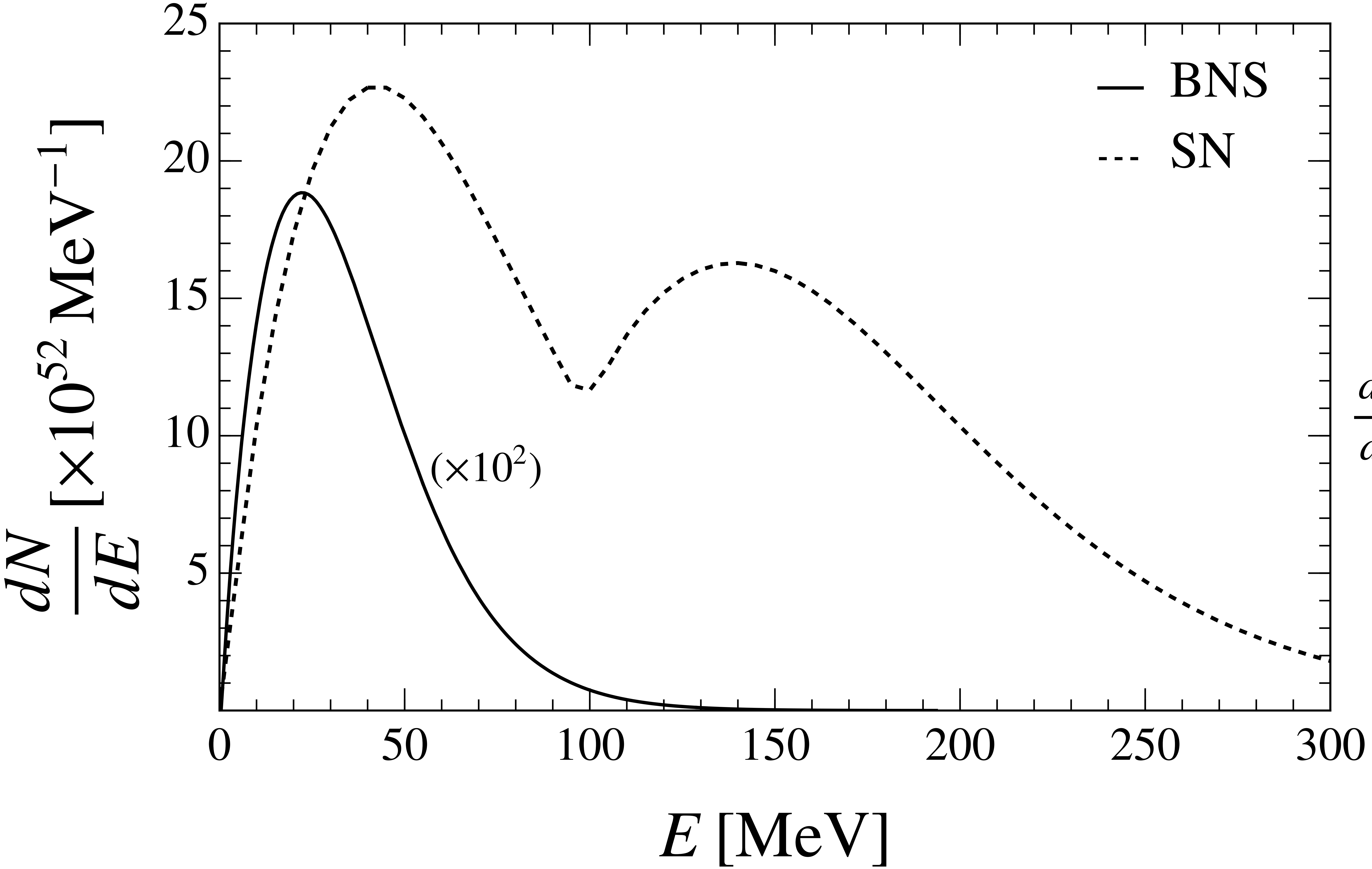
The landmark in Binary Neutron Merger is the observation of **GW170817**
[B.P. Abbott et al., Phys. Rev. Lett. 119, 16 (2017)]

GSI

NN Bremmstrhalung



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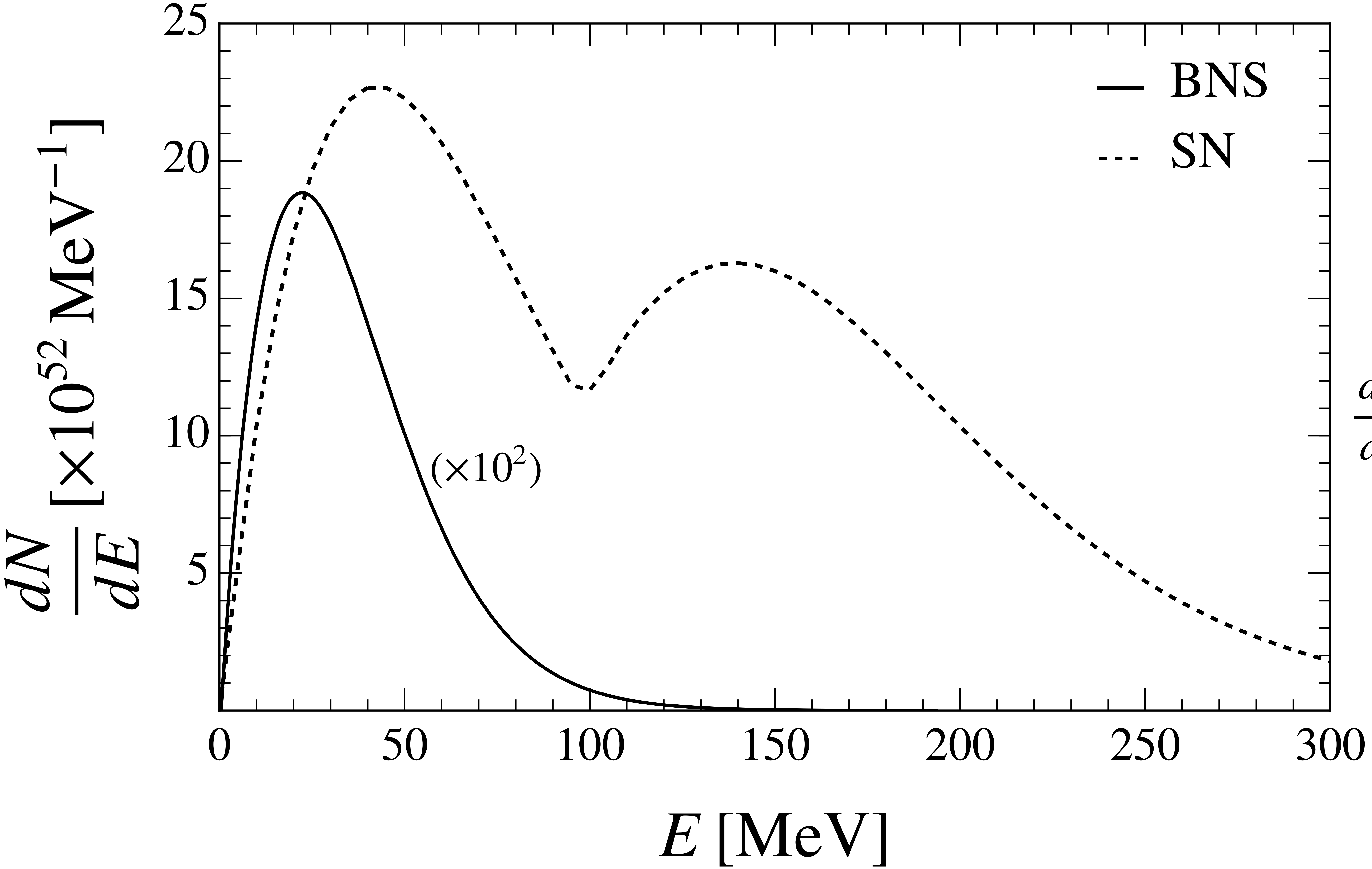

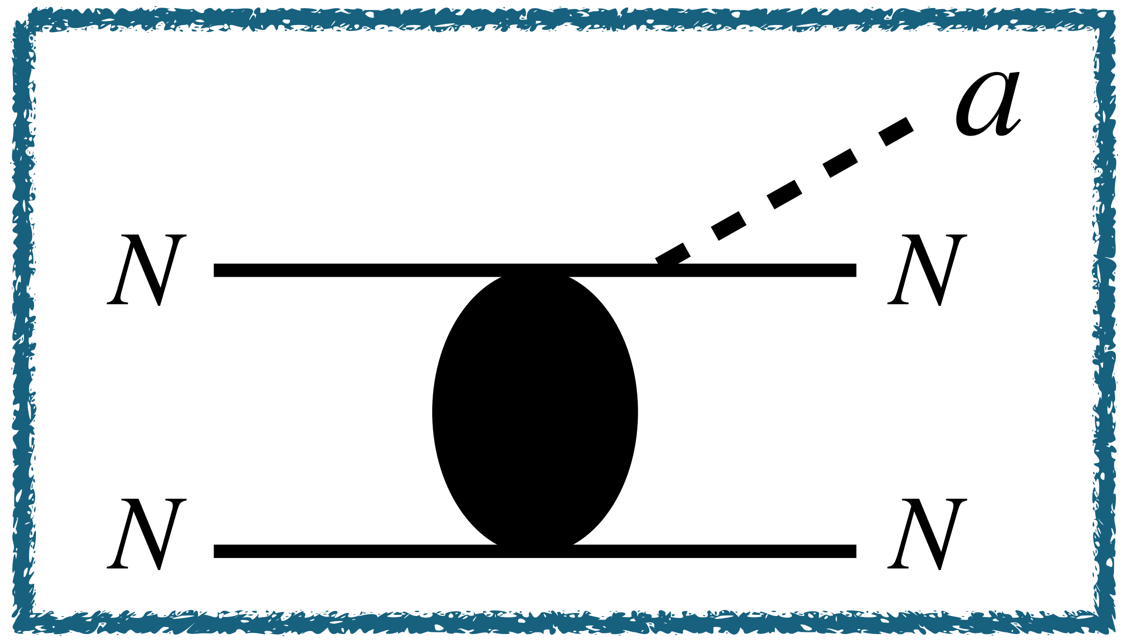

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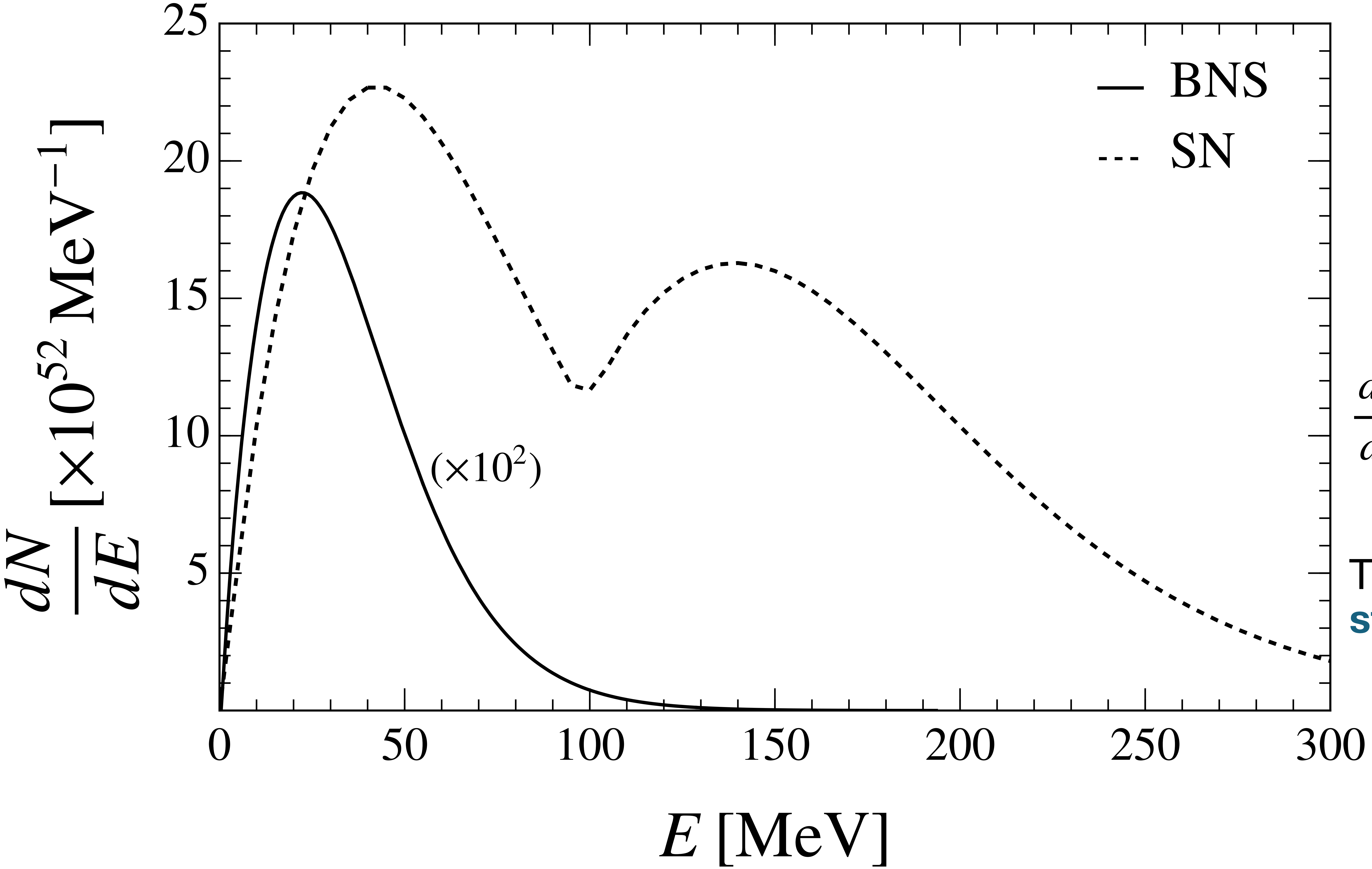

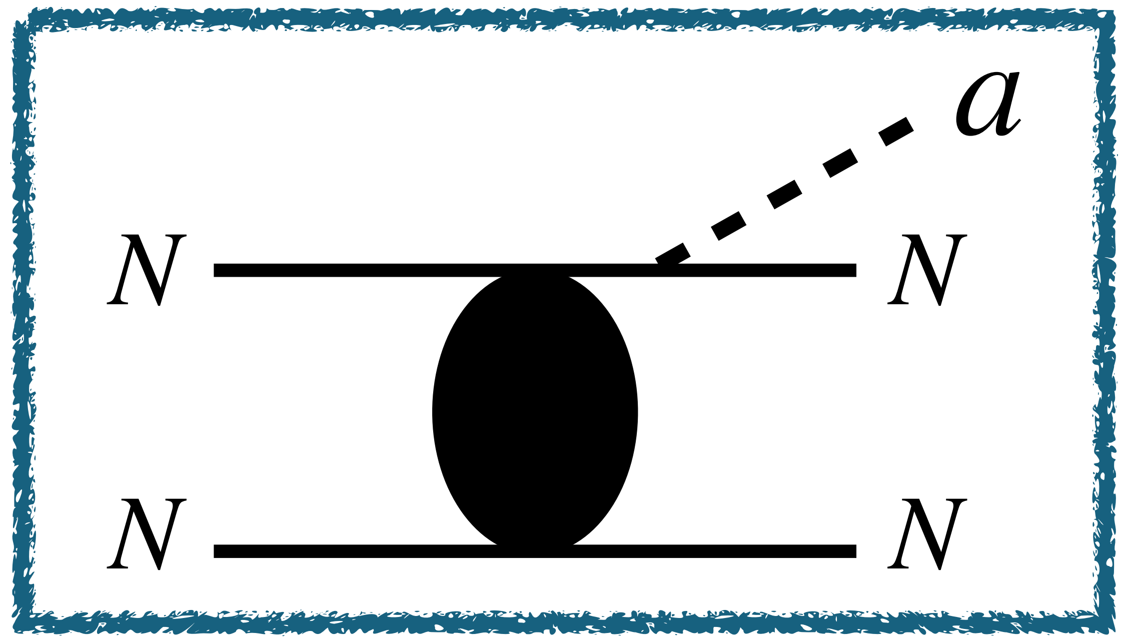

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The lapse factor encodes the **strong gravitational field effects**

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

ALP-photon conversion in the remnant and in the Milky Way

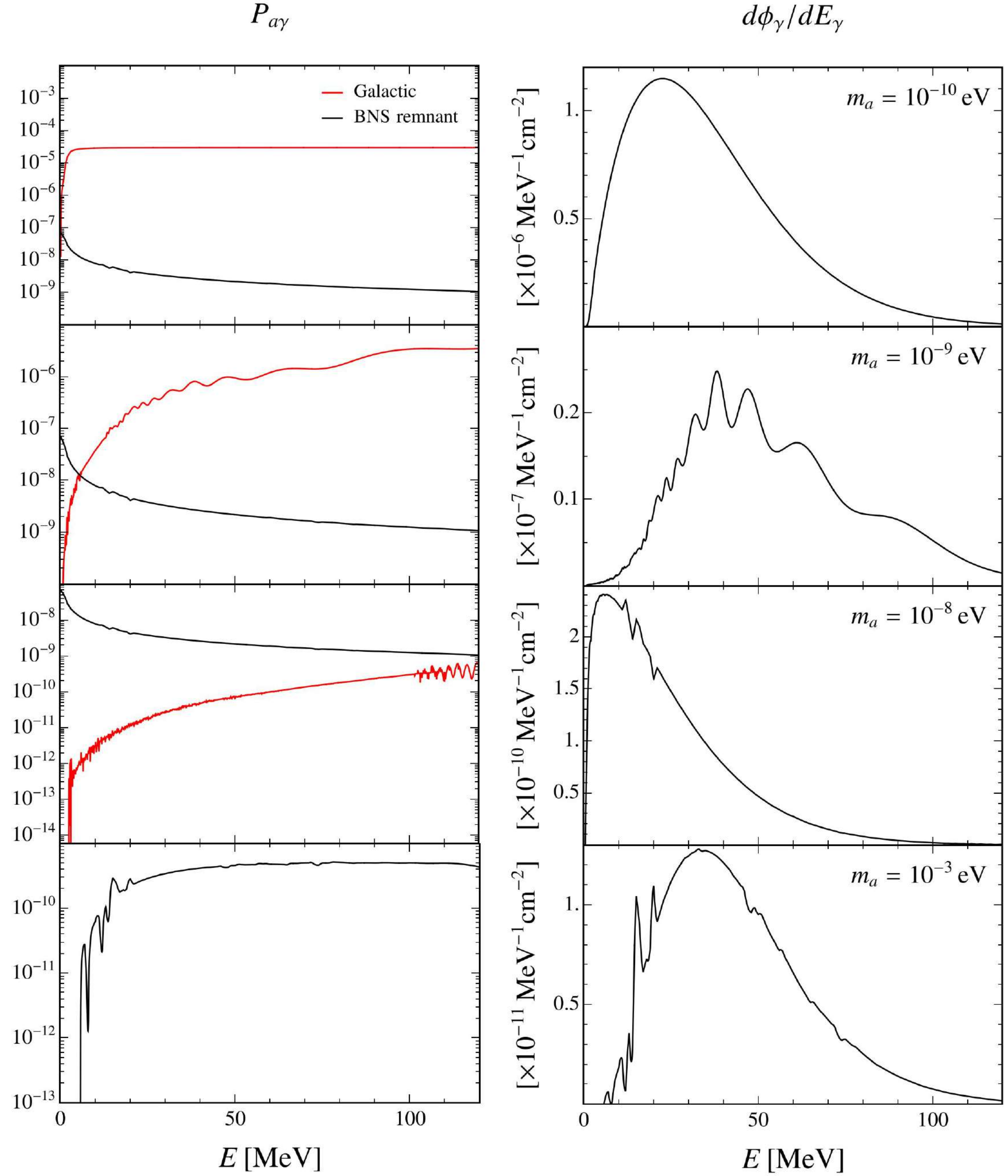
ALPs can convert into photons while propagating in external magnetic fields thanks to the ALP-photon coupling [G. Raffelt and L. Stodolsky, Phys. Rev. D 37 , 1237 (1988)].

In this work we assume:

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

↳ 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)].



ALP-photon conversion in the remnant and in the Milky Way

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

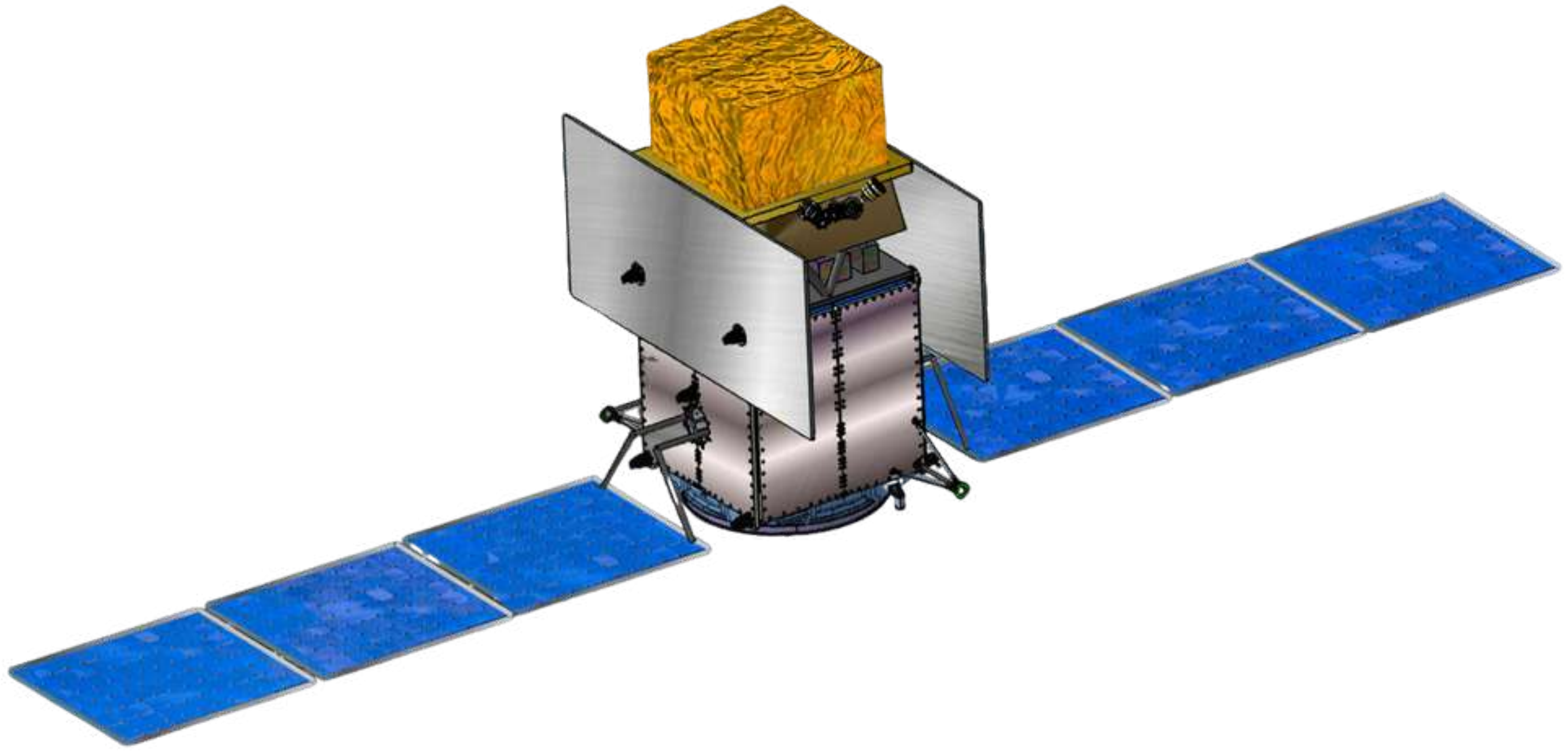
with d is the length of the region where $\overrightarrow{B}$ is present , $g_{a\gamma} = 10^{-12} GeV^{-1}$ from a generic source located in the same position of the GW170817 event at $L = 40\,Mpc$

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]

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



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:

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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)]

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

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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)]

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

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Experiment	$T_{\rm joint}$		
	$d = 4\,\mathrm{Mpc}$	$d = 40\,\mathrm{Mpc}$	$d = 100\,\mathrm{Mpc}$
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

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

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

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

Conclusions and improvements

We have:

↳ used as **external trigger** for such an event the detection of GW signal

↳ shown that the obtained sensitivities to ALP-photon comparable or even better than the long-standing bound from SN 1987A.

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These results could be improved by:

↳sensitivity improves over time with **stacked analysis**

↳new generation GW detectors (2030s), which can give us the location hours or days in advance!

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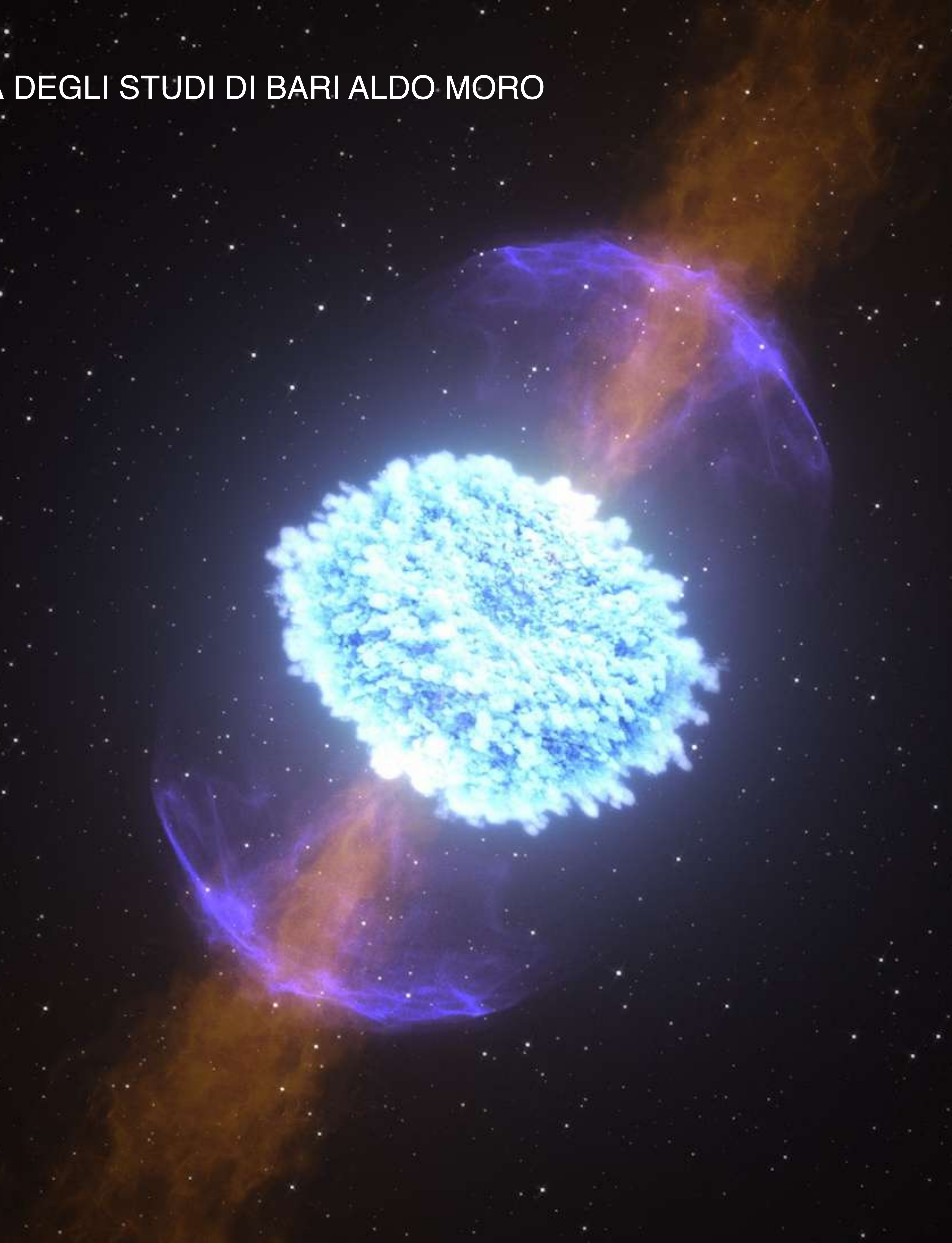

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