Probing diffuse supernovae ALP background from gamma-ray searches

Sougata Ganguly

Institute for Basic Science
CTPU-PTC

Based on arXiv: 2505.05567 with F. R. Candón, M. Giannotti, T. Kumar, A. Lella, and F. Mescia

@

The 7th International Workshop on

"Higgs as a probe of New Physics 2025"

HPNP 2025

University of Osaka , Japan

June 9-13, 2025

Outline

- Brief introduction of Axion
- Introduction of ALP and its effective interactions
- Brief introduction of core-collapse supernova
- Production of ALPs from from proto-neutron star
- Constraint on ALP parameter space
- Summary

Strong CP problem and QCD axion

Strong CP problem and QCD axion

- QCD Lagrangian contains

$$\mathscr{L}_\theta = \theta \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

Strong CP problem and QCD axion

- QCD Lagrangian contains

$$\mathscr{L}_\theta = \theta \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

- Quark mass diagonalization generates

$$\mathscr{L}' = \left(\mathrm{Arg}\,\det(m_u m_d)\right) \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

Strong CP problem and QCD axion

- **QCD Lagrangian contains**

$$\mathscr{L}_\theta = \theta \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

- **Quark mass diagonalization generates**

$$\mathscr{L}' = \left(\mathrm{Arg}\,\det(m_u m_d)\right) \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

$$\mathscr{L}_{\text{total}} = \bar{\theta} \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

$$\bar{\theta} = \theta + \mathrm{Arg}\,\det(m_u m_d)$$

Strong CP problem and QCD axion

- **QCD Lagrangian contains**

$$\mathscr{L}_\theta = \theta \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

- **Quark mass diagonalization generates**

$$\mathscr{L}' = \left(\text{Arg}\,\det(m_u m_d)\right) \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

$$\mathscr{L}_{\text{total}} = \bar{\theta} \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

$$\bar{\theta} = \theta + \text{Arg}\,\det(m_u m_d)$$

- **Neutron EDM measurements implies** $\bar{\theta} \lesssim 10^{-10}$

Strong CP problem and QCD axion

- **QCD Lagrangian contains**

$$\mathscr{L}_\theta = \theta \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

- **Quark mass diagonalization generates**

$$\mathscr{L}' = \left(\mathrm{Arg\,det}(m_u m_d)\right) \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

$$\longrightarrow \quad \mathscr{L}_{\text{total}} = \bar{\theta} \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

$$\bar{\theta} = \theta + \mathrm{Arg\,det}(m_u m_d)$$

- **Neutron EDM measurements implies** $\bar{\theta} \lesssim 10^{-10}$ ⟶ **Why $\bar{\theta}$ is so small???**

Strong CP problem

Strong CP problem and QCD axion

- QCD Lagrangian contains

$$\mathscr{L}_\theta = \theta \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

- Quark mass diagonalization generates

$$\mathscr{L}' = \left(\text{Arg}\,\det(m_u m_d)\right) \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

$$\mathscr{L}_{\text{total}} = \bar{\theta} \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

$$\bar{\theta} = \theta + \text{Arg}\,\det(m_u m_d)$$

- Neutron EDM measurements implies $\bar{\theta} \lesssim 10^{-10}$ → Why $\bar{\theta}$ is so small???

  Strong CP problem

Solution:

- Promote $\bar{\theta}$ to a dynamical field, called Axion which is a pNGB of a global $U(1)$ symmetry

  Pecci, Quinn 1977, Weinberg 1978, Wilczek 1978

Strong CP problem and QCD axion

- **QCD Lagrangian contains**

$$\mathscr{L}_\theta = \theta \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

- **Quark mass diagonalization generates**

$$\mathscr{L}' = \left(\text{Arg}\,\det(m_u m_d)\right) \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

$$\mathscr{L}_{\text{total}} = \bar{\theta} \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

$$\bar{\theta} = \theta + \text{Arg}\,\det(m_u m_d)$$

- **Neutron EDM measurements implies** $\bar{\theta} \lesssim 10^{-10}$ → **Why $\bar{\theta}$ is so small???**

Strong CP problem

Solution:

- **Promote $\bar{\theta}$ to a dynamical field, called Axion which is a pNGB of a global $U(1)$ symmetry**

Pecci, Quinn 1977, Weinberg 1978, Wilczek 1978

$$\mathscr{L}_{\text{new}} = \left(\bar{\theta} + \frac{a}{f_a}\right) \frac{g_s^2}{32\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

nEDM will be zero once $\langle a \rangle = -\bar{\theta} f_a$

Axion-like particles and its interactions

- For QCD axions, its couplings with SM is inversely proportional to the $U(1)$ breaking scale f_a and its mass is related to f_a

- However, more fundamental theories like string theory suggest the existence of Axion-like particles (ALPs)

Svrček et. al. 2006

Axion-like particles and its interactions

- For QCD axions, its couplings with SM is inversely proportional to the $U(1)$ breaking scale f_a and its mass is related to f_a

- However, more fundamental theories like string theory suggest the existence of Axion-like particles (ALPs)

Svrček et. al. 2006

- Interactions are similar to the QCD axions
- Mass and couplings are independent parameters

Axion-like particles and its interactions

- For QCD axions, its couplings with SM is inversely proportional to the $U(1)$ breaking scale f_a and its mass is related to f_a

- However, more fundamental theories like string theory suggest the existence of Axion-like particles (ALPs)

Svrček et. al. 2006

- Interactions are similar to the QCD axions
- Mass and couplings are independent parameters

ALP interactions with photons and nucleon:

Choi et. al. 2021 , Ho et. al. 2022

$$\mathscr{L}_{\text{int}} = -\frac{\partial^\mu a}{2m_N}\left[g_{ap}\,\bar{p}\gamma_\mu\gamma_5 p + g_{an}\,\bar{n}\gamma_\mu\gamma_5 n + \frac{g_{a\pi N}}{f_\pi}\left(i\pi^+\bar{p}\gamma_\mu n - i\pi^-\bar{n}\gamma_\mu p\right)\right]$$
$$-\frac{\partial^\mu a}{2m_N}\left[g_{aN\Delta}\left(\bar{p}\Delta^+_\mu + \overline{\Delta^+_\mu}p + \bar{n}\Delta^0_\mu + \overline{\Delta^0_\mu}n\right)\right] - \frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

Axion-like particles and its interactions

- For QCD axions, its couplings with SM is inversely proportional to the $U(1)$ breaking scale f_a and its mass is related to f_a

- However, more fundamental theories like string theory suggest the existence of Axion-like particles (ALPs)

Svrček et. al. 2006

- Interactions are similar to the QCD axions
- Mass and couplings are independent parameters

ALP interactions with photons and nucleon:

Choi et. al. 2021 , Ho et. al. 2022

$$\mathscr{L}_{\text{int}} = -\frac{\partial^\mu a}{2m_N}\left[g_{ap}\,\bar{p}\gamma_\mu\gamma_5 p + g_{an}\,\bar{n}\gamma_\mu\gamma_5 n + \frac{g_{a\pi N}}{f_\pi}\left(i\pi^+\bar{p}\gamma_\mu n - i\pi^-\bar{n}\gamma_\mu p\right)\right]$$
$$-\frac{\partial^\mu a}{2m_N}\left[g_{aN\Delta}\left(\bar{p}\Delta^+_\mu + \overline{\Delta^+_\mu}p + \bar{n}\Delta^0_\mu + \overline{\Delta^0_\mu}n\right)\right] - \frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

In our analysis, we assume $g_{an} = 0$ and this choice is motivated by the KSVZ model

Core Collapse Supernovae

- The terminal stage of a star with mass $\gtrsim 8M_\odot$ with iron in its core
- When the iron core mass reaches $1.4M_\odot$ then the electron degeneracy could not oppose the gravitational collapse
- However, when the density becomes $\sim 10^{14}\,\mathrm{gm/cm^3}$, neutron repulsion opposes the collapse. Then the iron core bounces back and triggering a shock wave which drives the SN explosion
- At the center, a dense object remains with density $\sim 10^{14}\,\mathrm{gm/cm^3}$ and temperature $\sim 30\,\mathrm{MeV}$ and it is known as proto-neutron star (PNS)

PNS contains:

- neutrons, protons and $n_p \simeq 0.3\, n_n$
- A small amount π^- and μ^- at the core and their abundance is $\sim \mathcal{O}(1\%)\ n_n$

Core Collapse Supernovae

- The terminal stage of a star with mass $\gtrsim 8M_\odot$ with iron in its core
- When the iron core mass reaches $1.4M_\odot$ then the electron degeneracy could not oppose the gravitational collapse
- However, when the density becomes $\sim 10^{14}\,\mathrm{gm/cm^3}$, neutron repulsion opposes the collapse. Then the iron core bounces back and triggering a shock wave which drives the SN explosion
- At the center, a dense object remains with density $\sim 10^{14}\,\mathrm{gm/cm^3}$ and temperature $\sim 30\,\mathrm{MeV}$ and it is known as proto-neutron star (PNS)

PNS contains:

- neutrons, protons and $n_p \simeq 0.3\, n_n$
- A small amount π^- and μ^- at the core and their abundance is $\sim \mathcal{O}(1\%)\ n_n$

Fore and Reddy, 2019

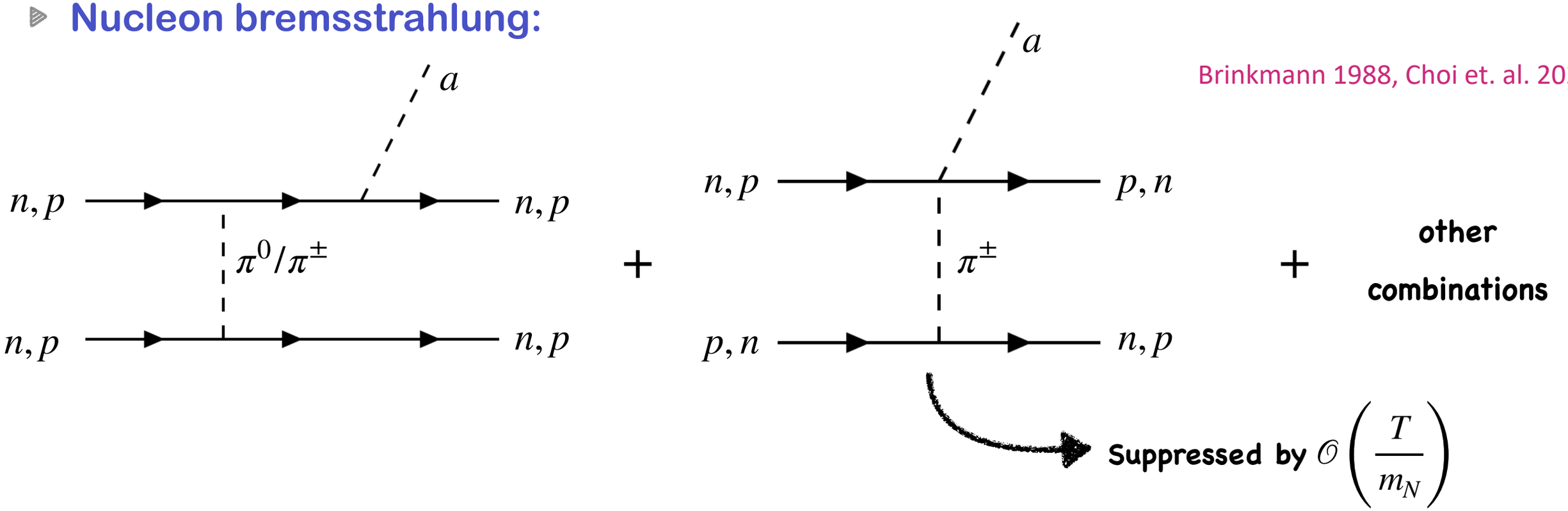
ALP production in PNS

ALP production in PNS

- Nucleon bremsstrahlung:

ALP production in PNS

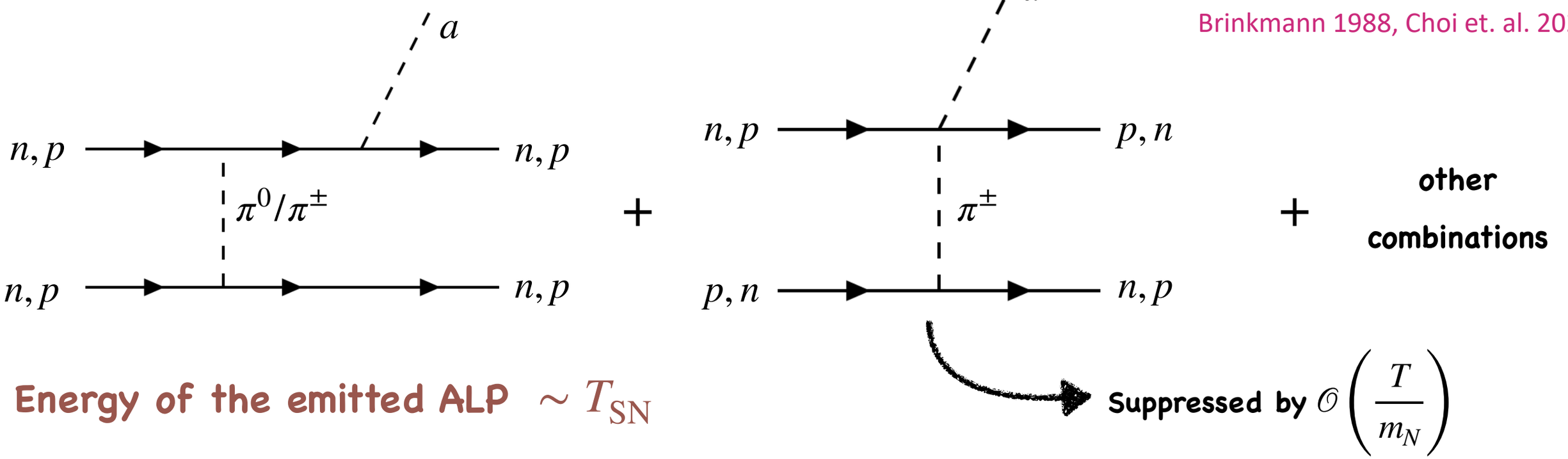
- **Nucleon bremsstrahlung:**



Brinkmann 1988, Choi et. al. 2021

ALP production in PNS

- **Nucleon bremsstrahlung:**

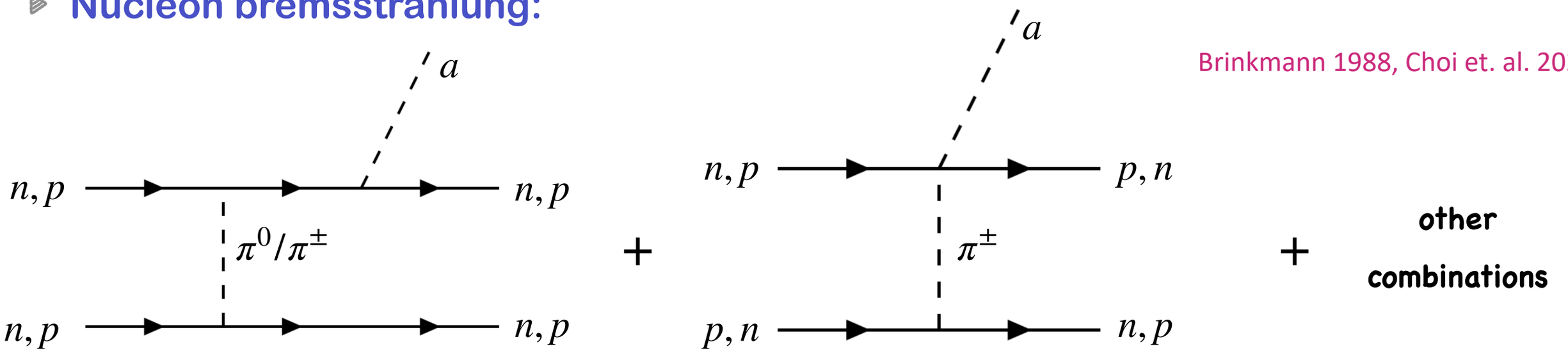


Brinkmann 1988, Choi et. al. 2021

Energy of the emitted ALP $\sim T_{\rm SN}$

ALP production in PNS

- **Nucleon bremsstrahlung:**



Brinkmann 1988, Choi et. al. 2021

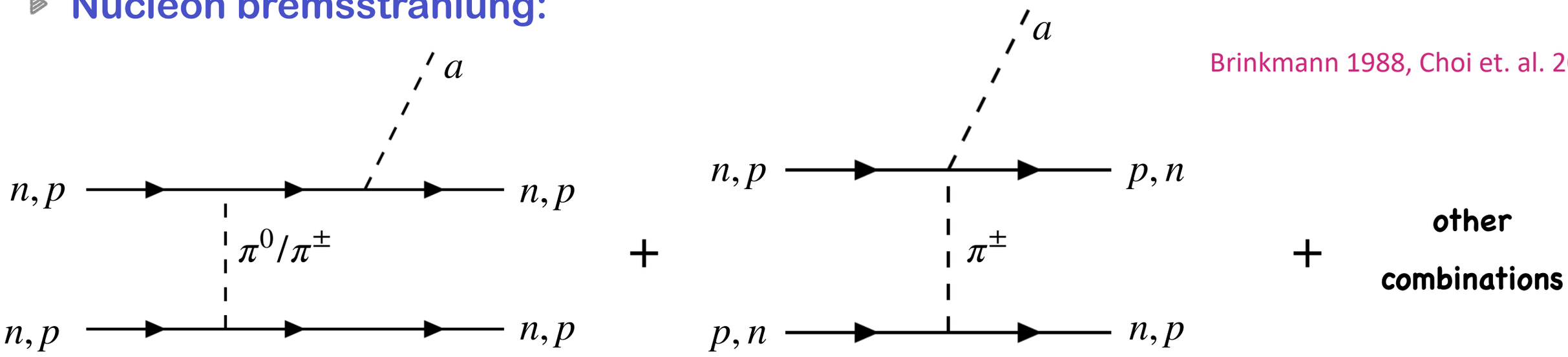
Energy of the emitted ALP $\sim T_{\rm SN}$

Suppressed by $\mathcal{O}\left(\frac{T}{m_N}\right)$

- **Pion conversion**

ALP production in PNS

- **Nucleon bremsstrahlung:**

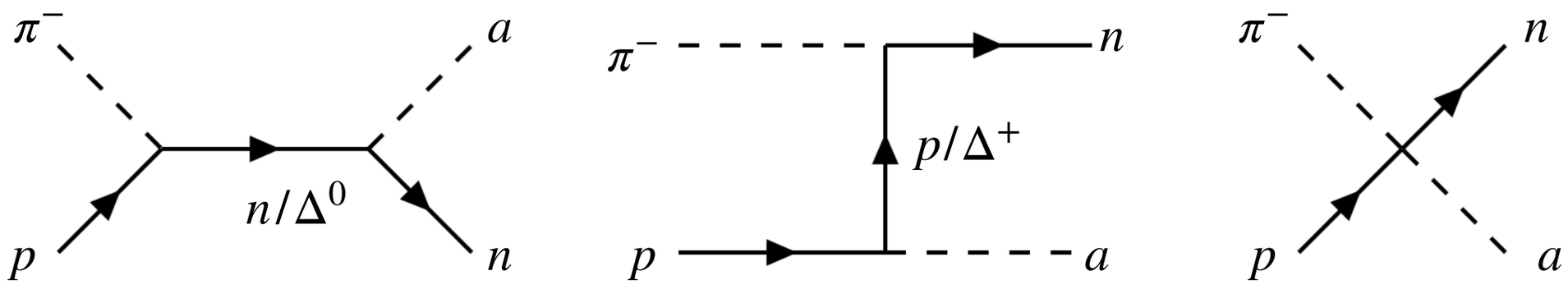


Brinkmann 1988, Choi et. al. 2021

Energy of the emitted ALP $\sim T_{\rm SN}$

Suppressed by $\mathcal{O}\left(\frac{T}{m_N}\right)$

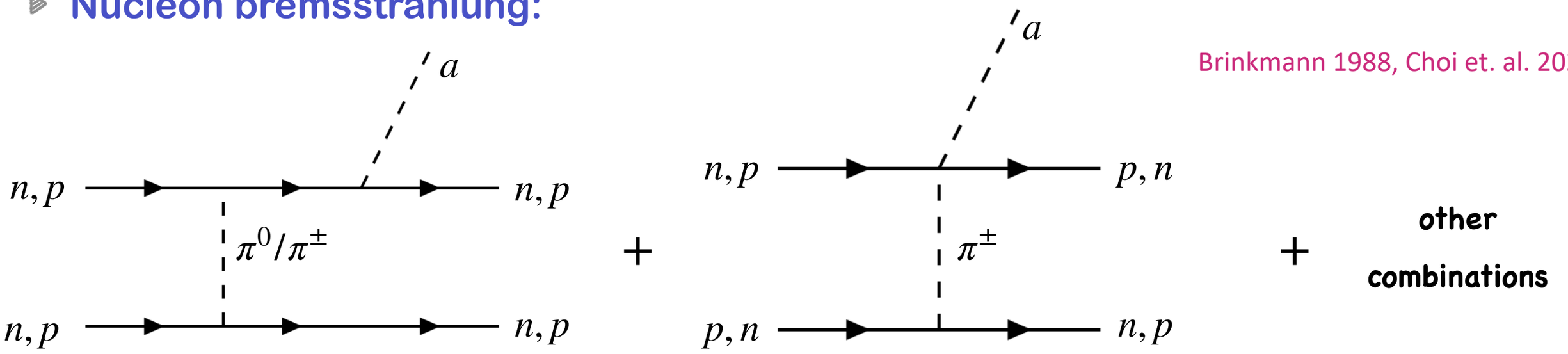
- **Pion conversion**



Ho et. al. 2022

ALP production in PNS

- **Nucleon bremsstrahlung:**

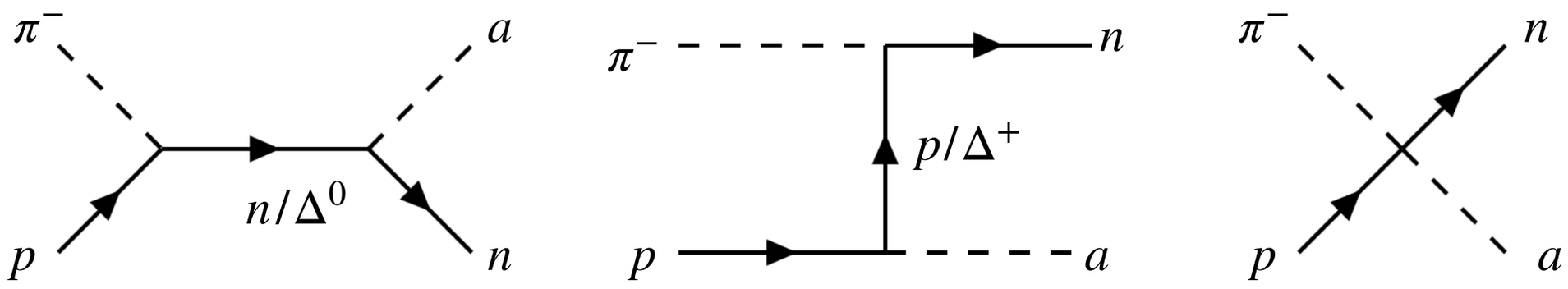


Brinkmann 1988, Choi et. al. 2021

Energy of the emitted ALP $\sim T_{\rm SN}$

Suppressed by $\mathcal{O}\left(\frac{T}{m_N}\right)$

- **Pion conversion**



Ho et. al. 2022

- **Pion conversion produces harder ALPs**
- **SN cooling bound becomes stronger by a factor of** ~ 2

Lella et. al. 2022

ALP production in PNS (contd..)

- **ALP emission rate via bremsstrahlung**

$$\left(\frac{d^2 n_a}{dE_a dt}\right)_{NN} = \frac{p_a}{4\pi^2}\int\left[\prod_{i=1}^{4} d\Pi_i\right](2\pi)^4\delta^4\left(P_1+P_2-P_3-P_4-P_a\right) S\,|\,\mathscr{M}\,|^2_{NN} f_1 f_2(1-f_3)(1-f_4)$$

- **ALP emission rate via pion conversion**

$$\left(\frac{d^2 n_a}{dE_a dt}\right)_{\pi N} = \frac{p_a}{4\pi^2}\int d\Pi_\pi d\Pi_n d\Pi_p (2\pi)^4\delta^4\left(P_p+P_\pi-P_n-P_a\right)|\,\mathscr{M}\,|^2_{\pi N} f_\pi f_p(1-f_n)$$

- **ALP spectrum**

$$\frac{dN_a}{dE_a} = \int d^3\vec{r}\int dt^*\ \alpha(r)^{-1}\left[\left(\frac{d^2 n_a}{dE_a^* dt^*}\right)_{NN} + \left(\frac{d^2 n_a}{dE_a^* dt^*}\right)_{\pi N}\right]_{E_a^*=E_a/\alpha(r)}$$

Lapse factor: responsible for gravitational redshift

Diffuse ALP spectrum

- ALP produced from all the past core-collapse supernovae give rise to a homogeneous isotropic ALP flux and it is known as Diffuse Supernovae ALP Background (DSALPB)

Diffuse ALP spectrum

- ALP produced from all the past core-collapse supernovae give rise to a homogeneous isotropic ALP flux and it is known as **Diffuse Supernovae ALP Background (DSALPB)**

$$\frac{d\phi_a}{dE_a} = \int_0^\infty (1+z)\frac{dN_a(E_a(1+z))}{dE_a} R_{\rm SN}(z) \left(\left| \frac{dt}{dz} \right| \right) dz$$

contains bremsstrahlung as well as pion conversion

Diffuse ALP spectrum

- ALP produced from all the past core-collapse supernovae give rise to a homogeneous isotropic ALP flux and it is known as **Diffuse Supernovae ALP Background (DSALPB)**

$$\frac{d\phi_a}{dE_a} = \int_0^\infty (1+z)\frac{dN_a(E_a(1+z))}{dE_a} R_{\rm SN}(z)\left(\left|\frac{dt}{dz}\right|\right) dz$$

contains bremsstrahlung as well as pion conversion

SN explosion rate

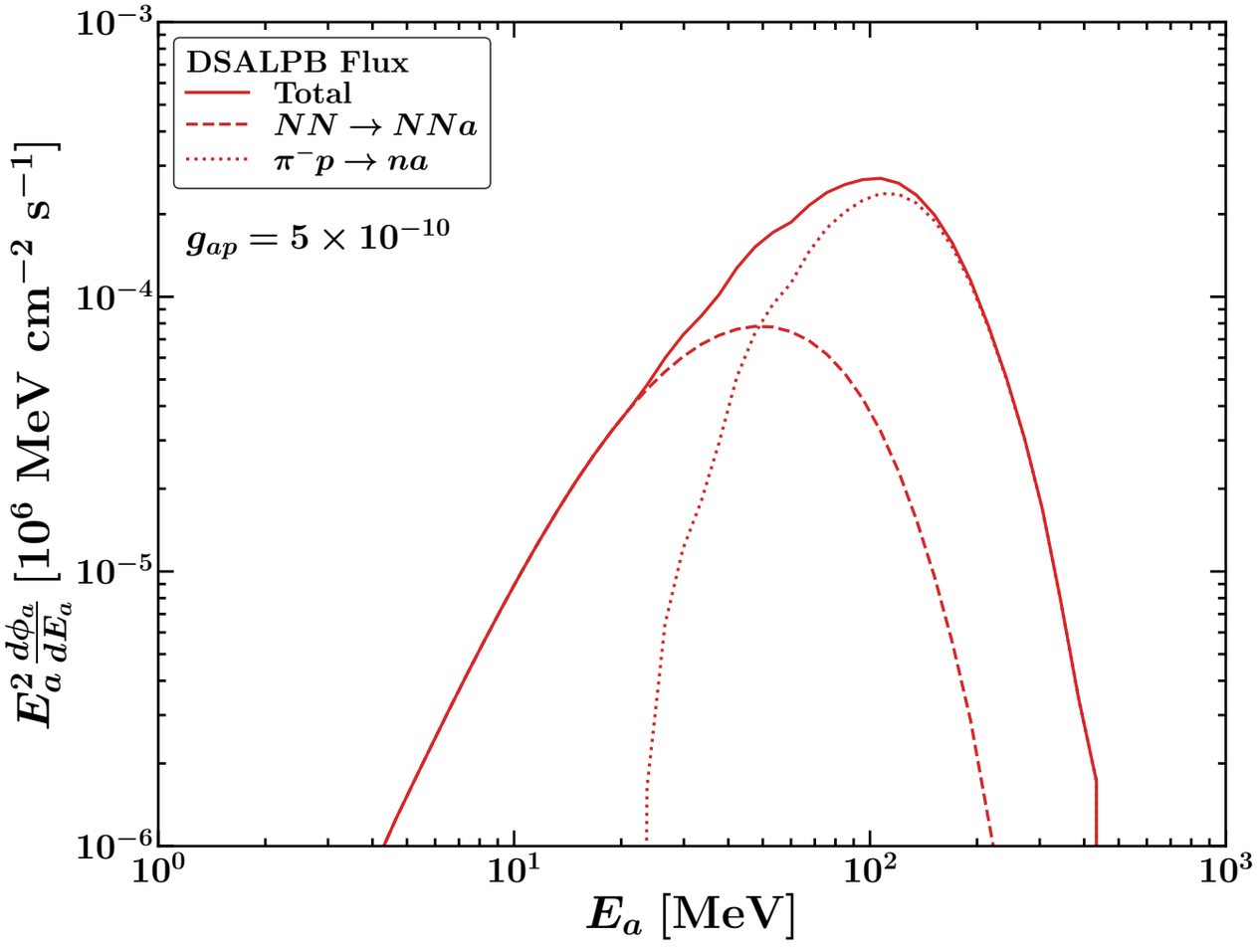
Diffuse ALP spectrum

- ALP produced from all the past core-collapse supernovae give rise to a homogeneous isotropic ALP flux and it is known as **Diffuse Supernovae ALP Background (DSALPB)**

$$\frac{d\phi_a}{dE_a} = \int_0^\infty (1+z)\frac{dN_a(E_a(1+z))}{dE_a} R_{\rm SN}(z)\left(\left|\frac{dt}{dz}\right|\right) dz$$

contains bremsstrahlung as well as pion conversion

SN explosion rate



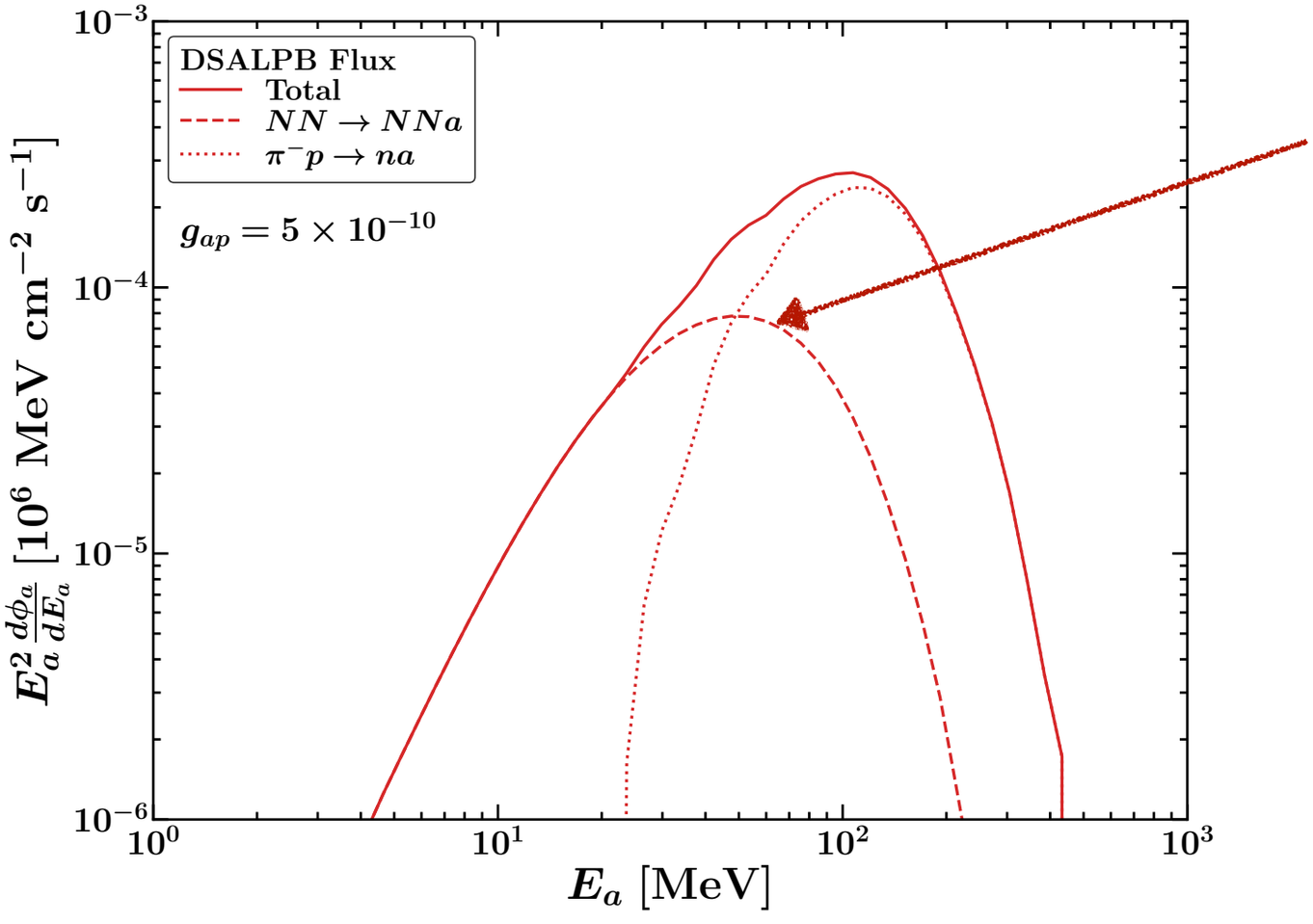
Diffuse ALP spectrum

- ALP produced from all the past core-collapse supernovae give rise to a homogeneous isotropic ALP flux and it is known as **Diffuse Supernovae ALP Background (DSALPB)**

$$\frac{d\phi_a}{dE_a} = \int_0^\infty (1+z)\frac{dN_a(E_a(1+z))}{dE_a} R_{\rm SN}(z)\left(\left|\frac{dt}{dz}\right|\right) dz$$

contains bremsstrahlung as well as pion conversion

SN explosion rate



DSALPB energy is $\mathcal{O}(50\,\mathrm{MeV})$ if we only consider bremsstrahlung

Calore et. al. 2020

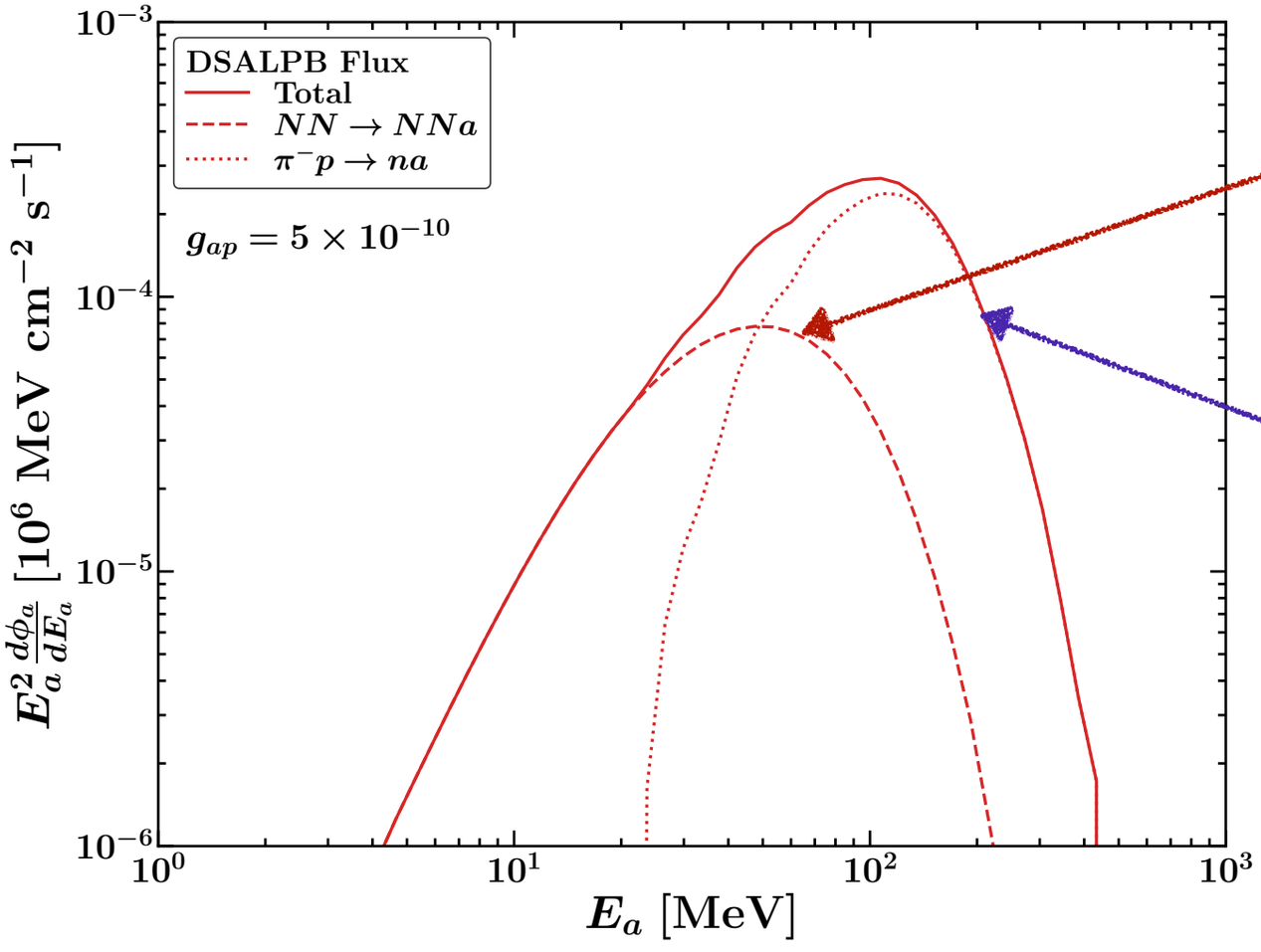
Diffuse ALP spectrum

- ALP produced from all the past core-collapse supernovae give rise to a homogeneous isotropic ALP flux and it is known as **Diffuse Supernovae ALP Background (DSALPB)**

$$\frac{d\phi_a}{dE_a} = \int_0^\infty (1+z)\frac{dN_a(E_a(1+z))}{dE_a} R_{\rm SN}(z)\left(\left|\frac{dt}{dz}\right|\right) dz$$

contains bremsstrahlung as well as pion conversion

SN explosion rate



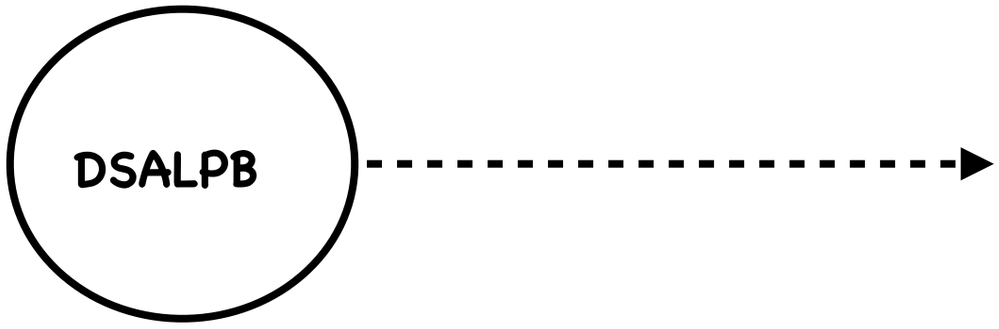
DSALPB energy is $\mathcal{O}(50\,\mathrm{MeV})$ if we only consider bremsstrahlung

Calore et. al. 2020

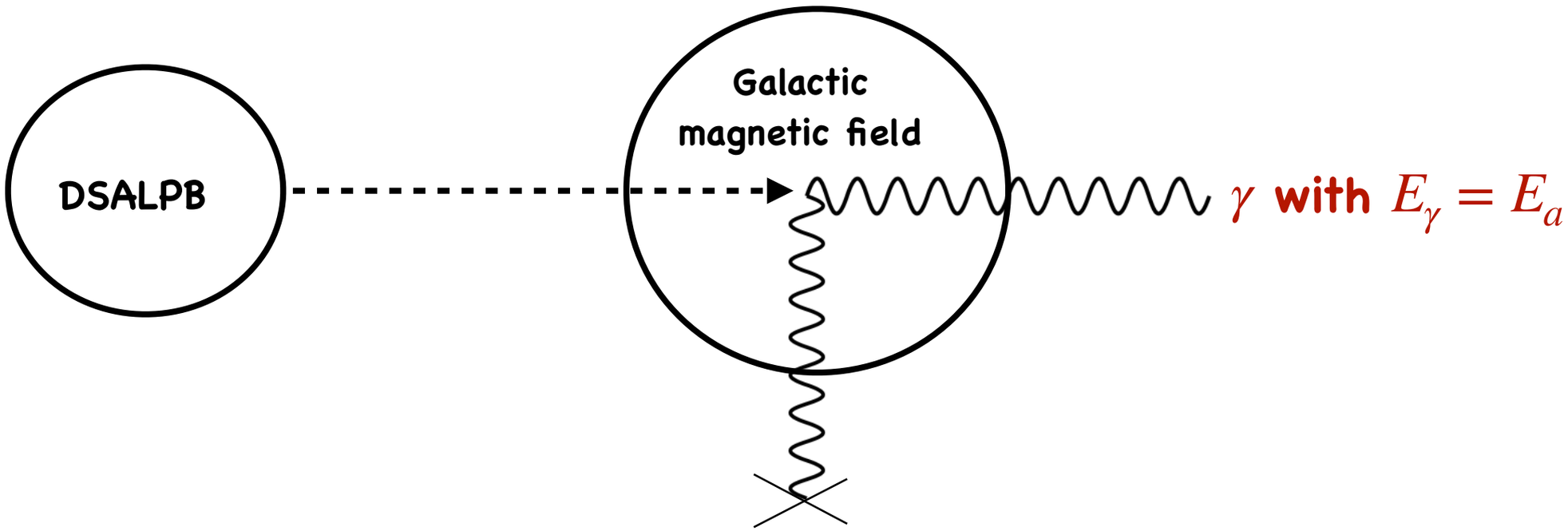
Inclusion of pion conversion makes DSALPB energy $\mathcal{O}(100\,\mathrm{MeV})$

γ-ray from DSALPB

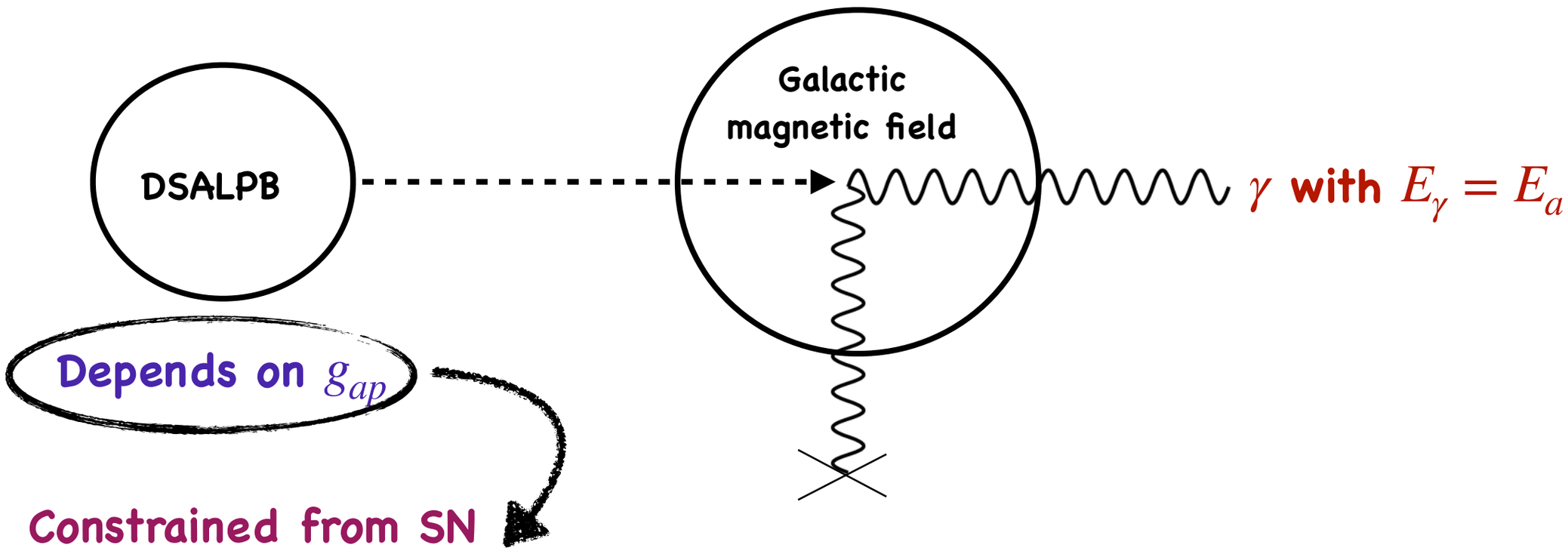
γ-ray from DSALPB



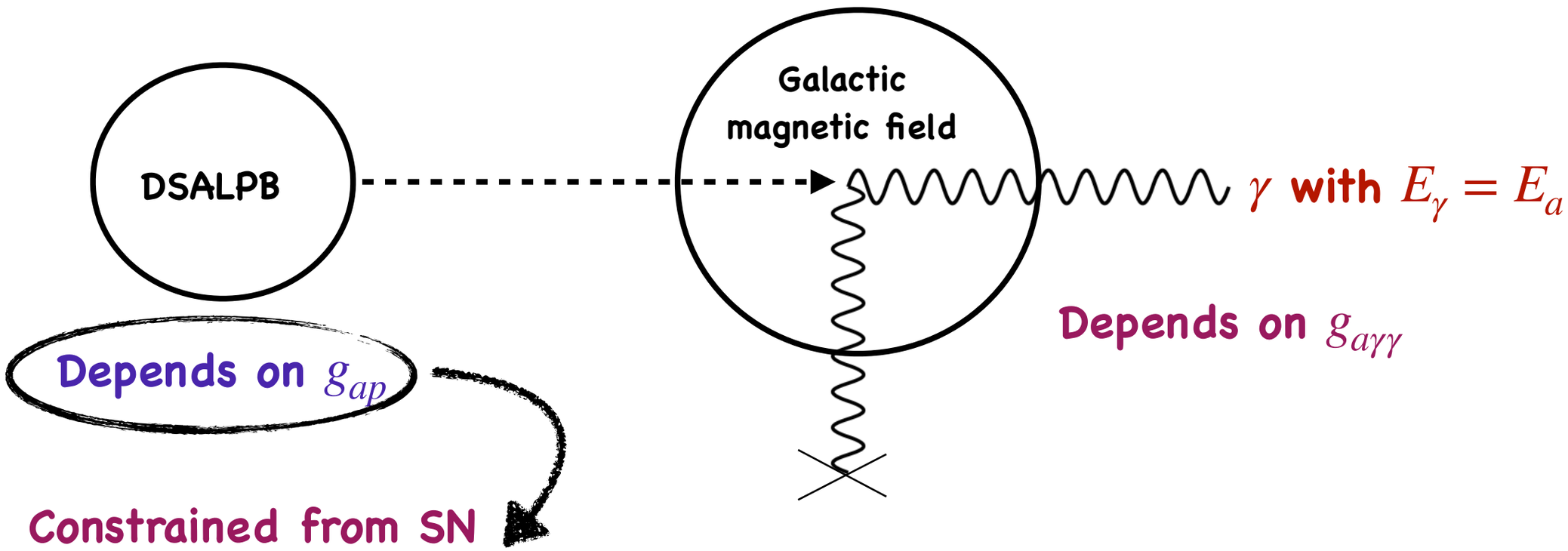
γ-ray from DSALPB



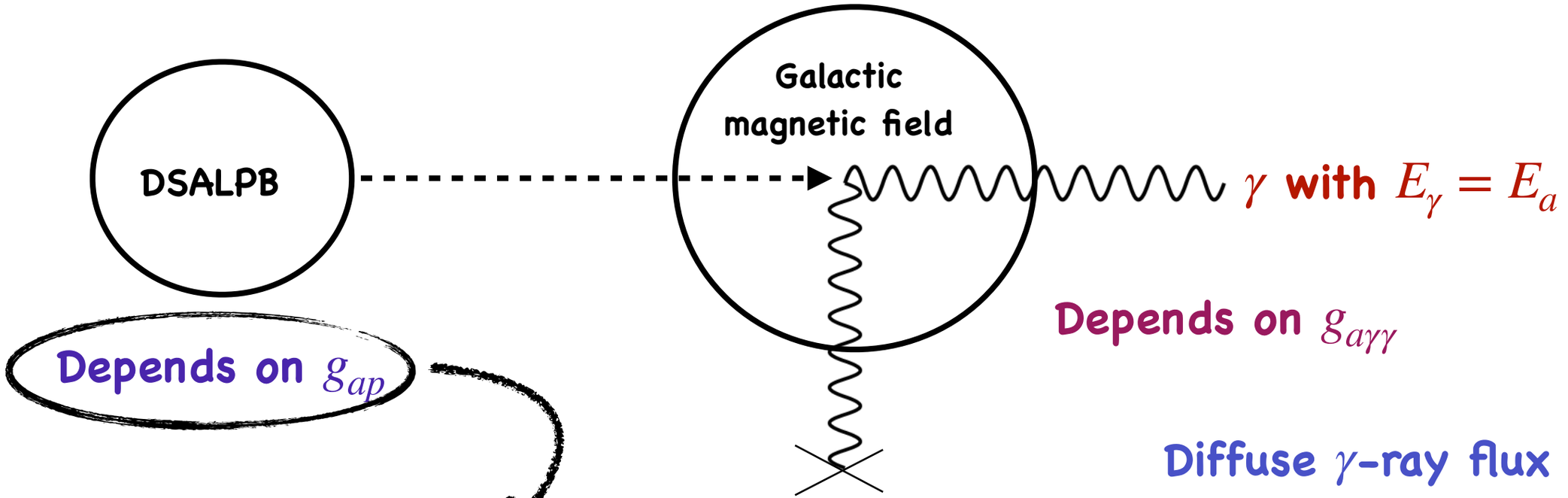
γ-ray from DSALPB



γ-ray from DSALPB



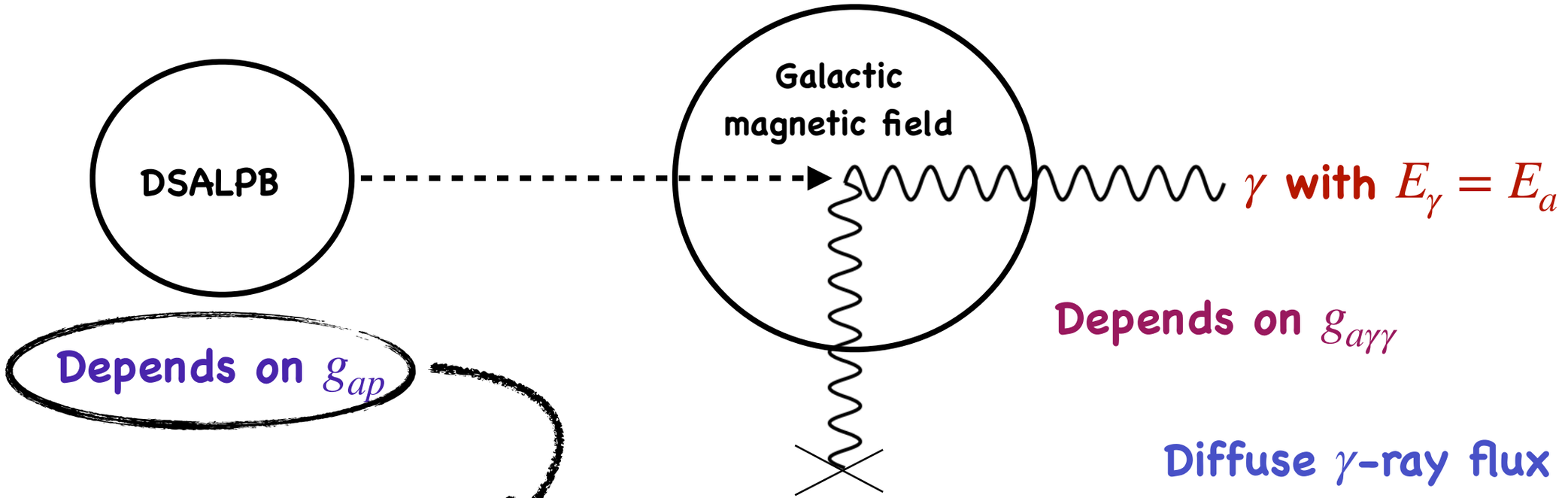
γ-ray from DSALPB



Diffuse γ-ray flux

$$\frac{d\phi_\gamma}{dE_\gamma} = P_{a\gamma} \times \frac{d\phi_a}{dE_\gamma}$$

γ-ray from DSALPB

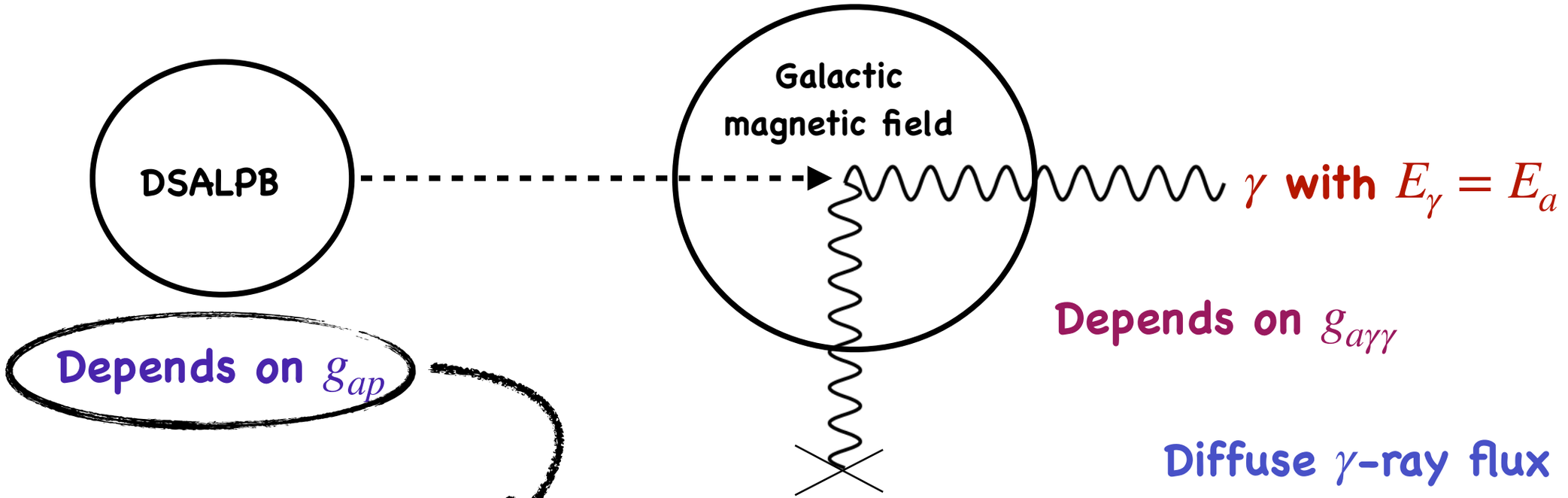


Diffuse γ-ray flux

$$\frac{d\phi_\gamma}{dE_\gamma} = P_{a\gamma} \times \frac{d\phi_a}{dE_\gamma}$$

γ-ray produced from the ALP in the presence of the galactic magnetic field can contribute to the diffuse γ ray background

γ-ray from DSALPB



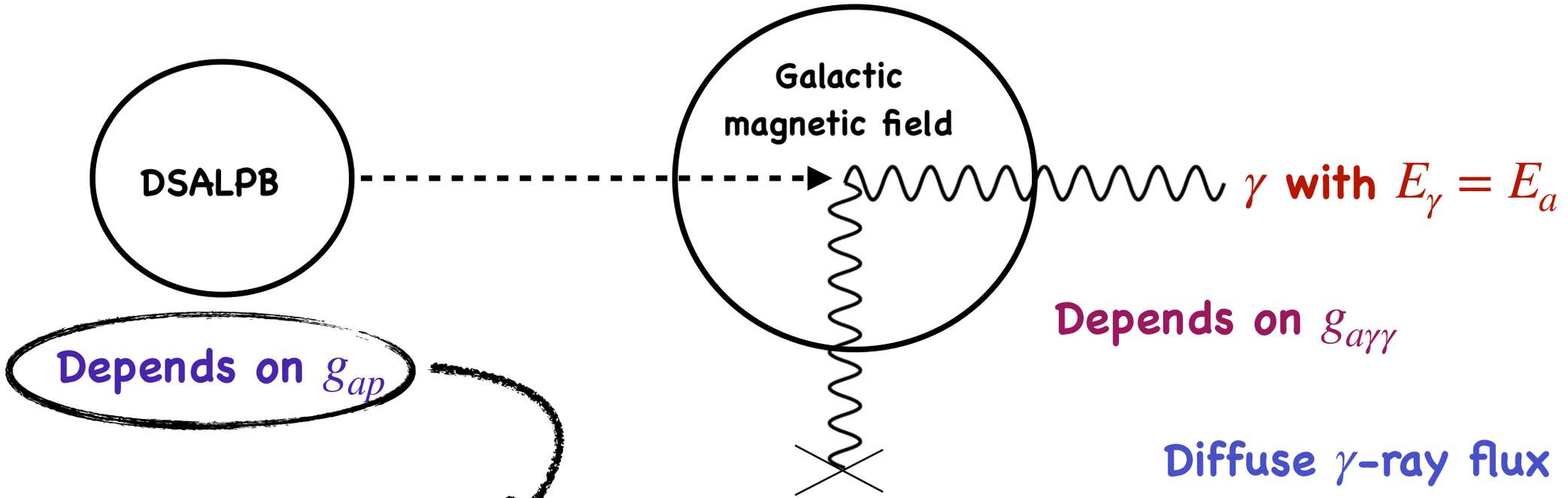
Diffuse γ-ray flux

$$\frac{d\phi_\gamma}{dE_\gamma} = P_{a\gamma} \times \frac{d\phi_a}{dE_\gamma}$$

γ-ray produced from the ALP in the presence of the galactic magnetic field can contribute to the diffuse γ ray background

The important feature is its energy is $\mathcal{O}(100\,\mathrm{MeV})$

γ-ray from DSALPB



Diffuse γ-ray flux

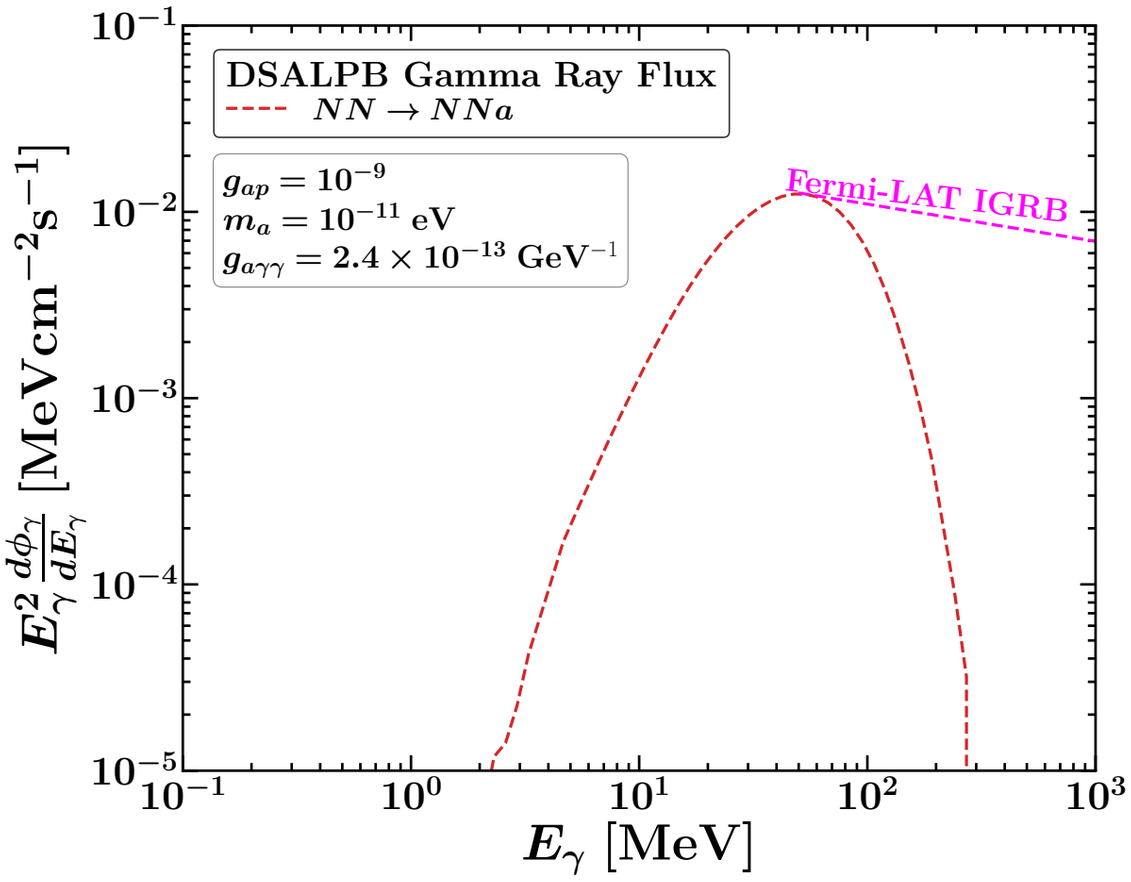
$$\frac{d\phi_\gamma}{dE_\gamma} = P_{a\gamma} \times \frac{d\phi_a}{dE_\gamma}$$

γ-ray produced from the ALP in the presence of the galactic magnetic field can contribute to the diffuse γ ray background

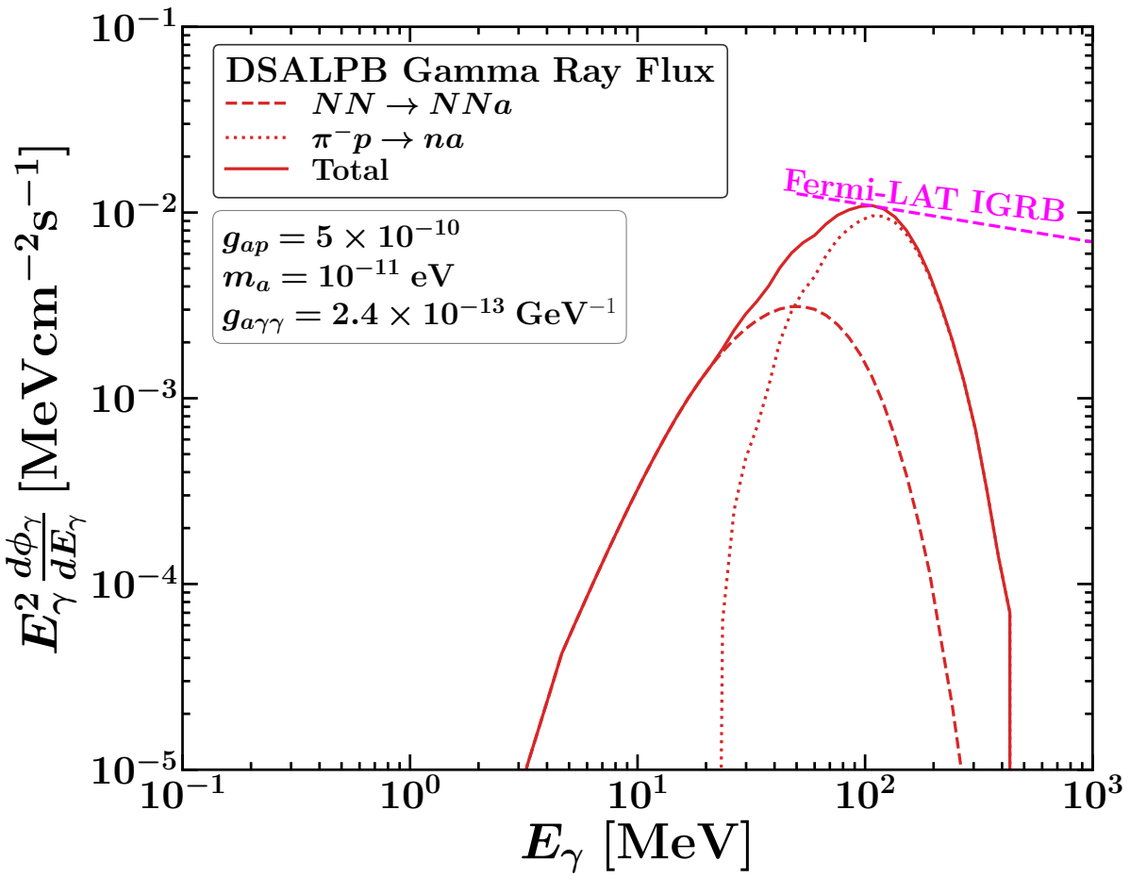
The important feature is its energy is $\mathcal{O}(100\,\mathrm{MeV})$ → Fermi-LAT as well as future γ-ray telescopes are sensitive in this energy range

Gamma-ray from DSALPB (contd...)

SN cooling bound considering only bremsstrahlung, $g_{ap} = 10^{-9}$



SN cooling bound considering bremsstrahlung and pion conversion, $g_{ap} = 5 \times 10^{-10}$



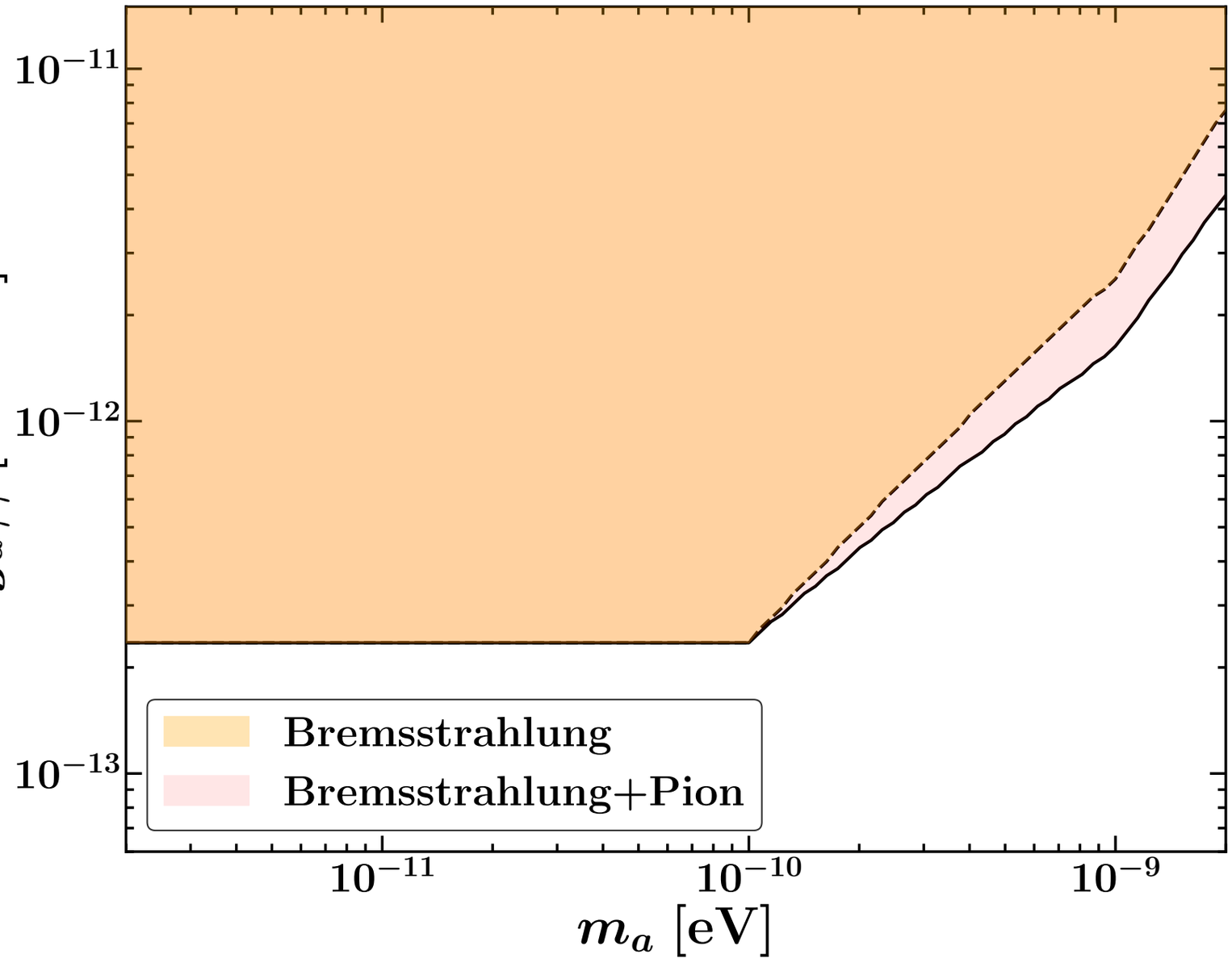
- Pion conversion makes cooling bound stronger by a factor of 2
- In spite of 4 times smaller DSALPB production, the constraint does not become weaker due to the harder ALP production from pion

Bounds from Fermi-LAT

Bounds from Fermi-LAT

- For bremsstrahlung

  we use $g_{ap} = 10^{-9}$,
  maximum allowed value
  from SN 1987A cooling



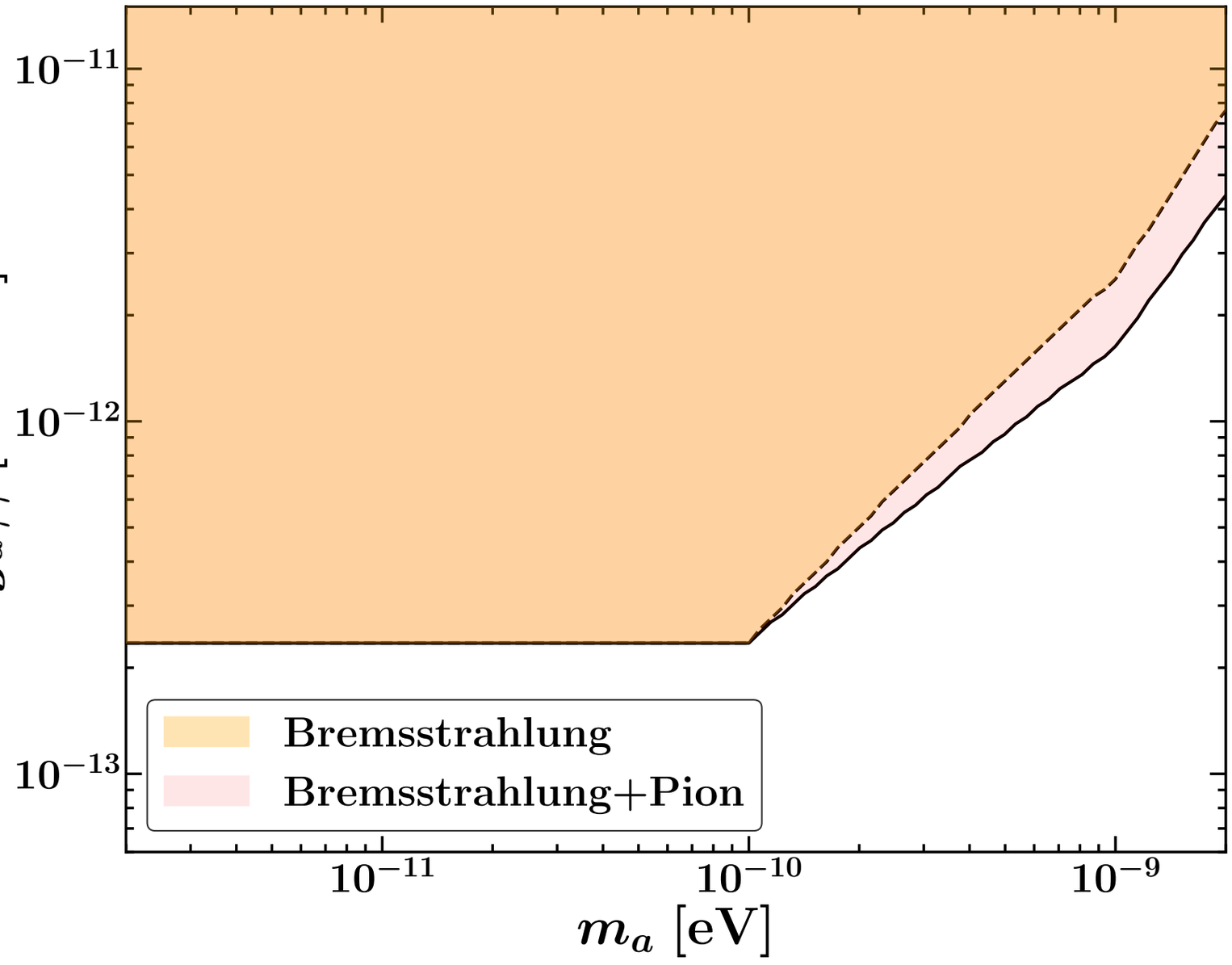
Bounds from Fermi-LAT

- For bremsstrahlung

  we use $g_{ap} = 10^{-9}$,
  maximum allowed value
  from SN 1987A cooling

- For bremsstrahlung + pion conversion

  we use $g_{ap} = 5 \times 10^{-10}$,
  maximum allowed value
  from SN 1987A cooling



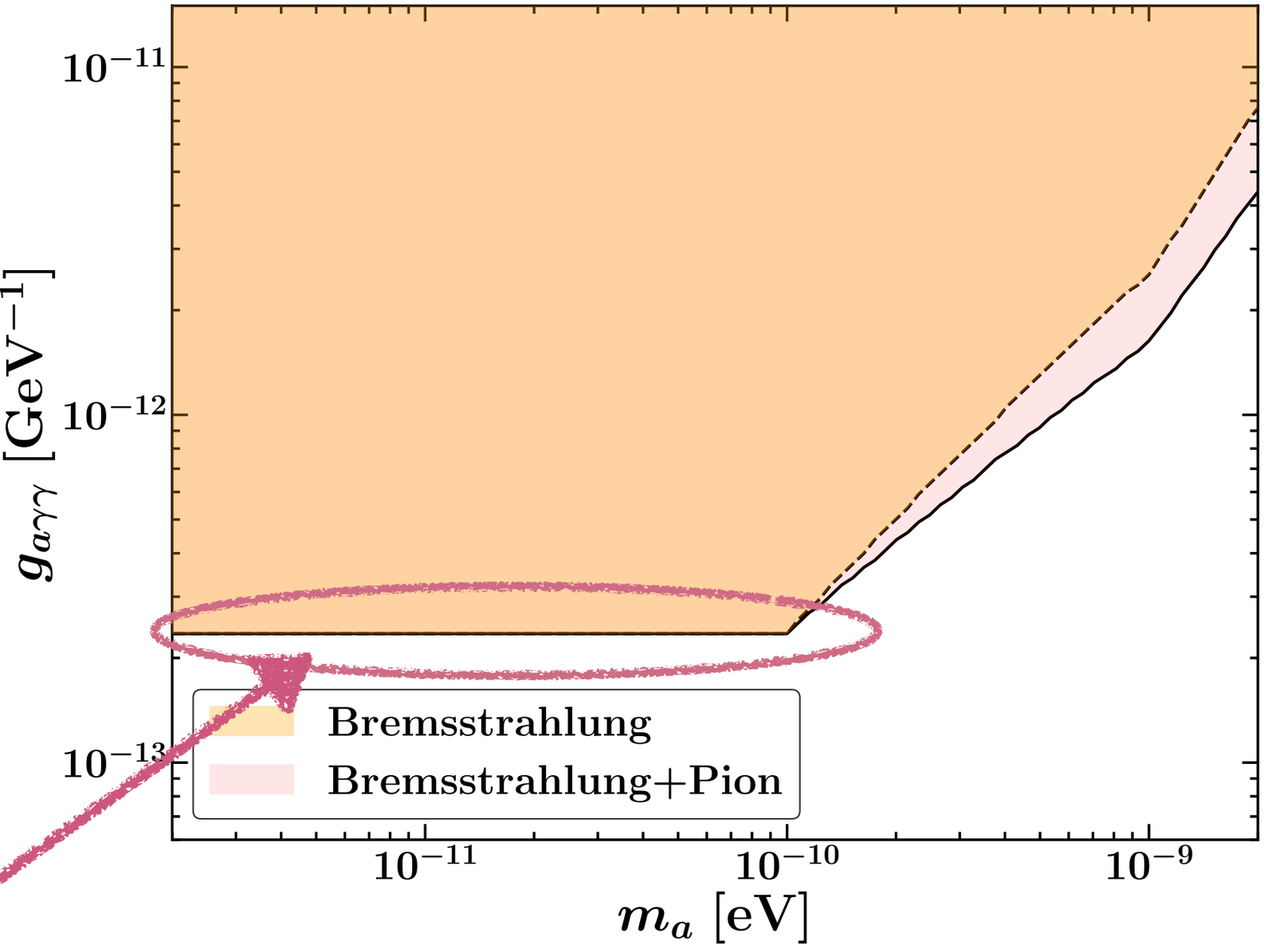
Bounds from Fermi-LAT

- For bremsstrahlung

  we use $g_{ap} = 10^{-9}$,
  maximum allowed value
  from SN 1987A cooling

- For bremsstrahlung + pion conversion

  we use $g_{ap} = 5 \times 10^{-10}$,
  maximum allowed value
  from SN 1987A cooling



Inclusion of pion does not make the bound weaker

in spite of 4 times smaller DSALPB production

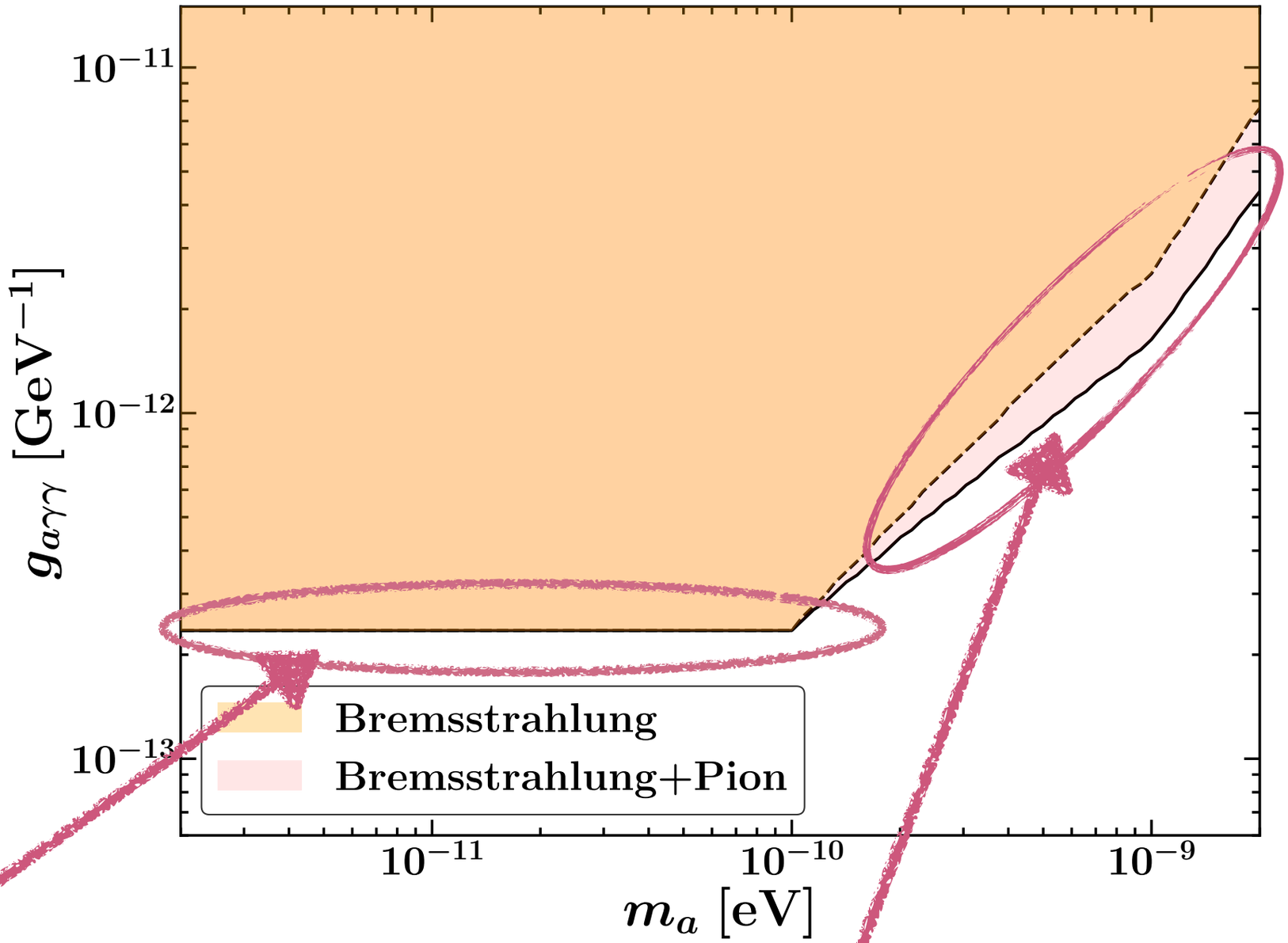
Bounds from Fermi-LAT

- For bremsstrahlung

  we use $g_{ap} = 10^{-9}$,
  maximum allowed value
  from SN 1987A cooling

- For bremsstrahlung + pion conversion

  we use $g_{ap} = 5 \times 10^{-10}$,
  maximum allowed value
  from SN 1987A cooling



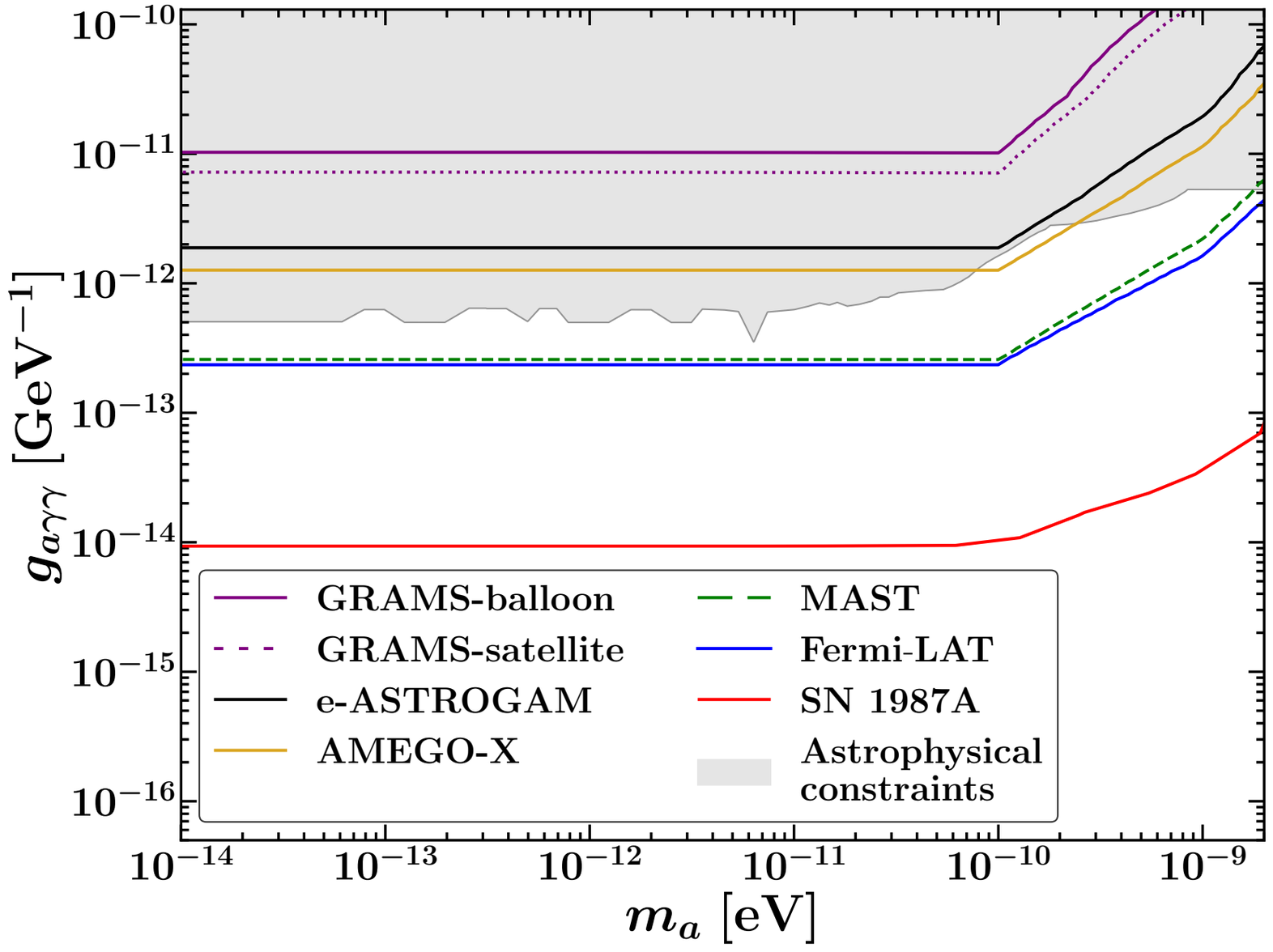
Inclusion of pion does not make the bound weaker

in spite of 4 times smaller DSALPB production

The bound becomes stronger since

$P_{a\gamma}$ is larger for high energy ALP

Bounds from future telescopes



Summary

- We have calculated the diffuse ALP spectrum from all the past core-collapse SNe considering bremsstrahlung and previously ignored pion contribution

- Measurement of diffuse γ-ray background by Fermi-LAT can constrain DSALPB and inclusion of pion conversion strengthen the bound for $m_a \gtrsim 10^{-10}\,\mathrm{eV}$

- We have also derived the bounds on DSALPB from future telescopes

- We havre also updated the constraint from the non-observation of ALP induced γ-ray burst from SN 1987A

- SN 1987A constraint is almost an order of magnitude stronger than that derived from the γ-ray telescopes.

Summary

- We have calculated the diffuse ALP spectrum from all the past core-collapse SNe considering bremsstrahlung and previously ignored pion contribution

- Measurement of diffuse γ-ray background by Fermi-LAT can constrain DSALPB and inclusion of pion conversion strengthen the bound for $m_a \gtrsim 10^{-10}\,\mathrm{eV}$

- We have also derived the bounds on DSALPB from future telescopes

- We havre also updated the constraint from the non-observation of ALP induced γ-ray burst from SN 1987A

- SN 1987A constraint is almost an order of magnitude stronger than that derived from the γ-ray telescopes.

Thank you!!!!!