IDM2023

L'Aquila, 9th July 2024

Axion-like particles as probes of the SN core

Based on: AL., F. Calore, P. Carenza, C. Eckner, M. Giannotti, G. Lucente, A. Mirizzi, *"Probing protoneutron stars with gamma-ray haloscopes"*, e-Print: 2405.02395

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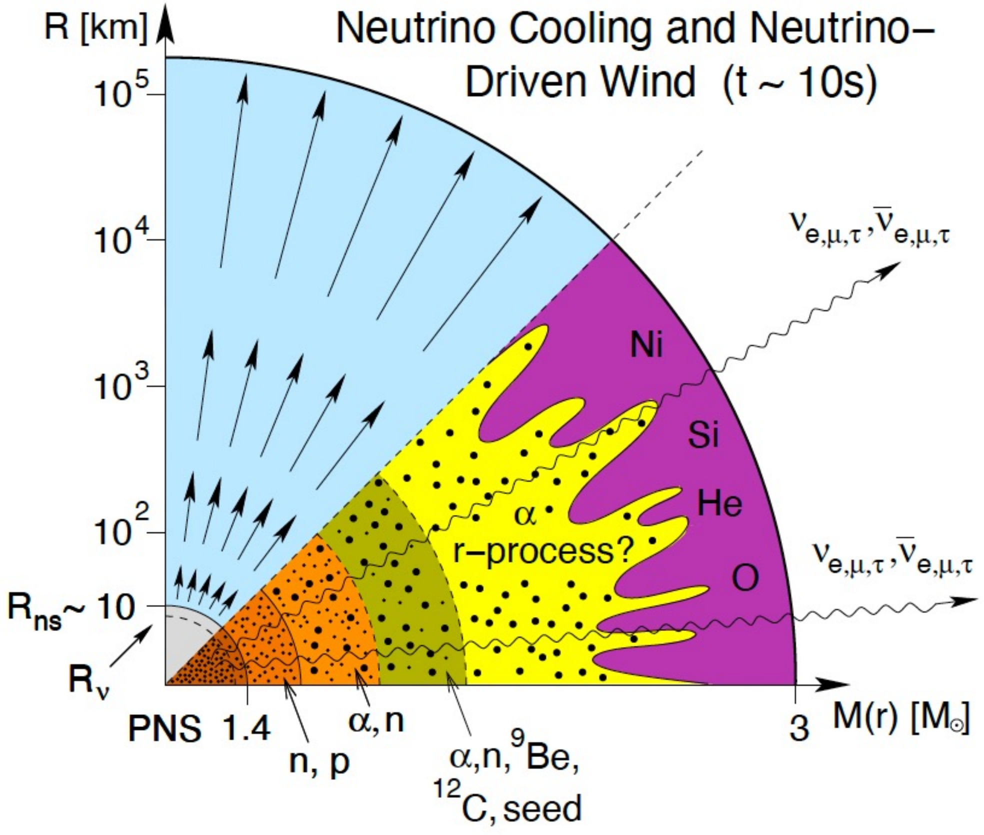
COSMIC WISPERS CA21106

Core-Collapse Supernovae

A core-collapse Supernova is the terminal phase of a massive star $[\mathrm{M} \geq 8\, M_{\odot}]$.
After the gravitational collapse, a shock-wave driven explosion occurs.

- Formation of a Proto-Neutron star
  - $R \sim 30\text{ km},\ \mathrm{M} \sim 1.5\, M_{\odot}$
- Cooling via neutrino emission from neutrino sphere at $R_{\nu} \simeq 20\text{ km}$
  - $E \sim 10^{53}\text{ erg}\ ,\ t \sim 10\text{ s}$
- Benchmark SN model employed: GARCHING SFHo-s18.80
  - $M_{\rm PNS} \simeq 1.35\, M_{\odot},\ M_{\rm prog} \simeq 18.8\, M_{\odot}.$



https://wwwmpa.mpa-garching.mpg.de/ccsnarchive//

ALP production in the PNS

- Extreme conditions in the SN nuclear medium
  - $T \sim 30 - 40\ \mathrm{MeV},\ \rho \sim 3{\times}10^{14}\mathrm{g/cm^3}$ → Enhancement in the emission of ALPs

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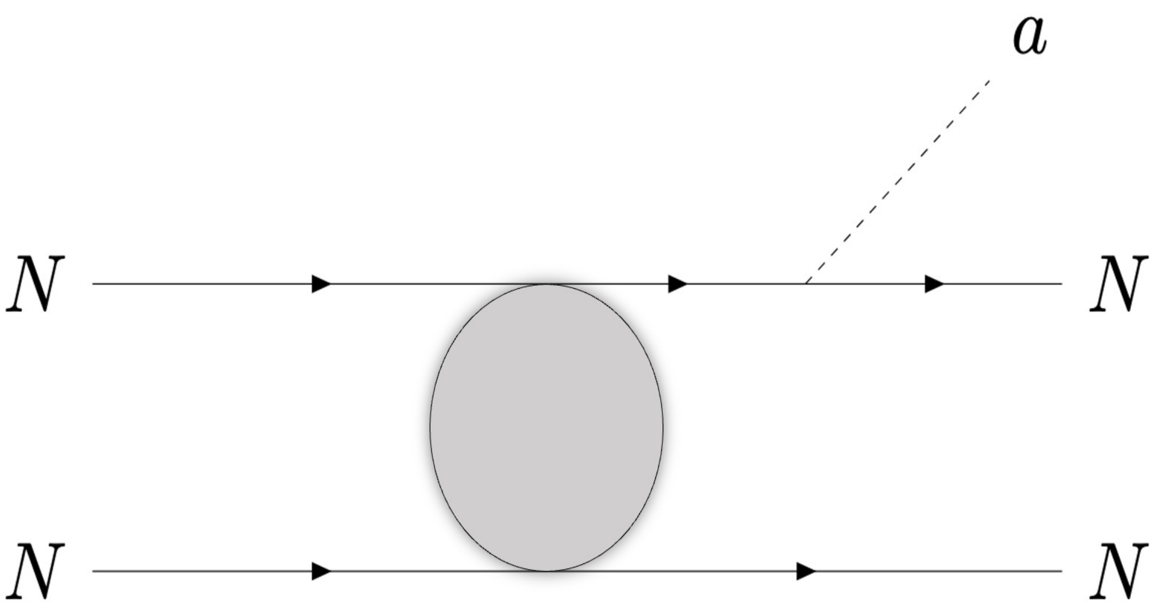
- In ChPT ALPs couple to nuclear matter *[Ho & al., Phys. Rev. D 107 (2023)]*

$$\mathcal{L}_{\text{int}} = g_a \frac{\partial_\mu a}{2m_N}\Big[C_{ap}\bar{p}\gamma^\mu\gamma_5 p + C_{an}\bar{n}\gamma^\mu\gamma_5 n + \\ + \frac{C_{a\pi N}}{f_\pi}(i\pi^+\bar{p}\gamma^\mu n - i\pi^-\bar{n}\gamma^\mu p) + \\ + C_{aN\Delta}\left(\bar{p}\,\Delta^+_\mu + \overline{\Delta^+_\mu}\,p + \bar{n}\,\Delta^0_\mu + \overline{\Delta^0_\mu}\,n\right)\Big]$$

ALP production in SNe

- Nucleon-Nucleon bremsstrahlung

[Ericson and Mathiot, Phys. Lett. B 219 (1989),
Raffelt & Seckel, Phys. Rev. D 52 (1995),
Hempel, Phys. Rev. C 91 (2015),
Carenza & al., JCAP 10 (2019) 10]



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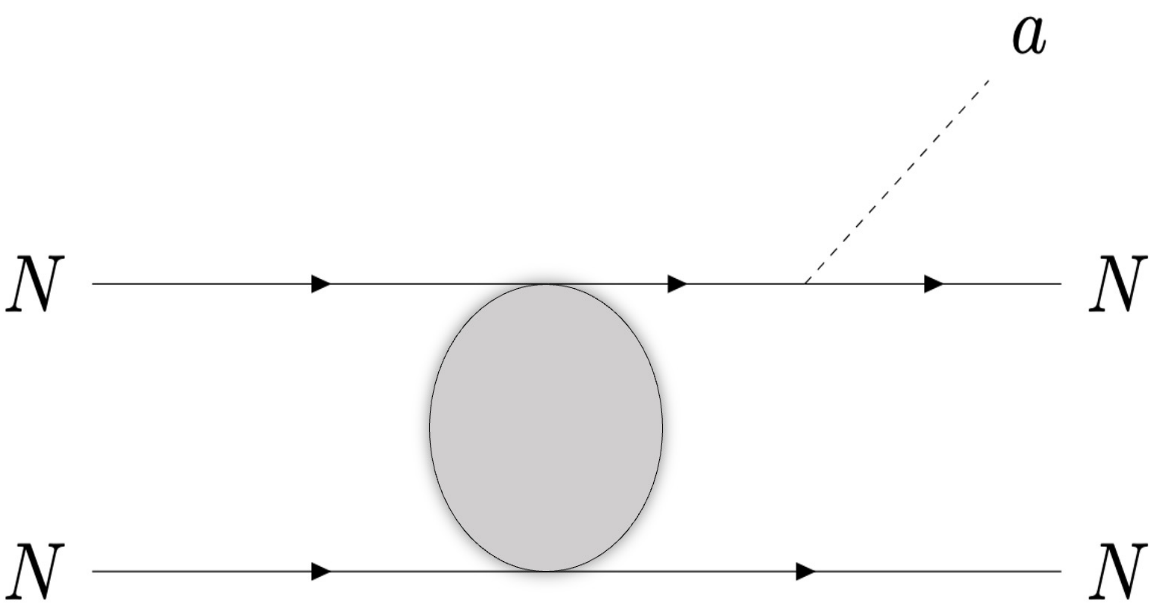


Strong dependence on SN conditions:

- Nuclear density in the core
- Effective nucleon masses $m_N \to m_N^*$
- Multiple scattering effects
- Nucleon momentum transfer dependent on T

ALP production in SNe

- Pion Conversions

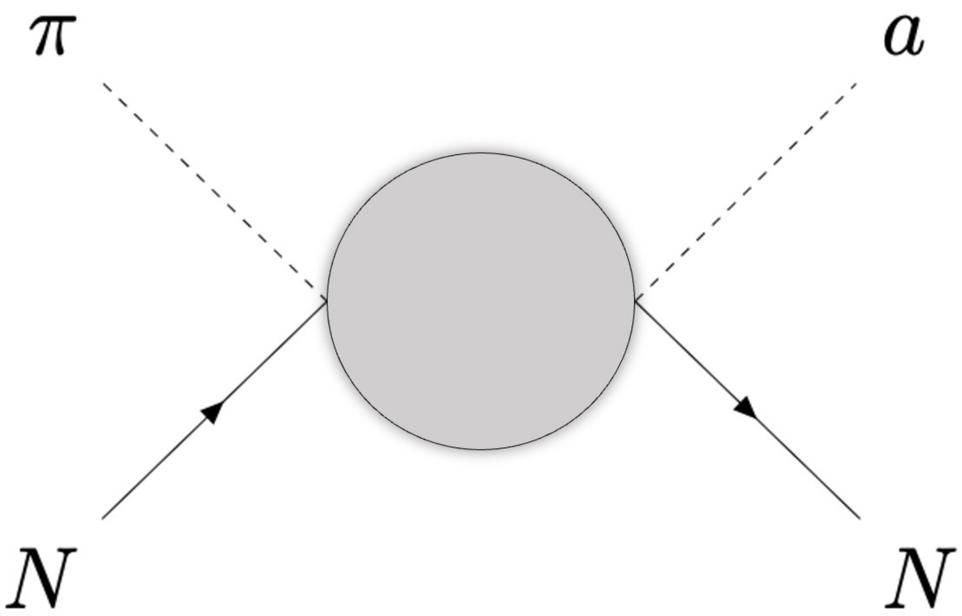
[Carenza & al., Phys.Rev.Lett. 126 (2021), *Choi & al., JHEP* 02 (2022) 143, *Ho & al., Phys. Rev. D 107 (2023)]*

[Fore & Reddy, Phys.Rev.C 101 (2020) 3]

Strong interactions enhance the π^- abundance

$$Y_{\pi^-} \sim \mathcal{O}(10^{-2})$$

Pion conversion competetive with NN bremsstrahlung



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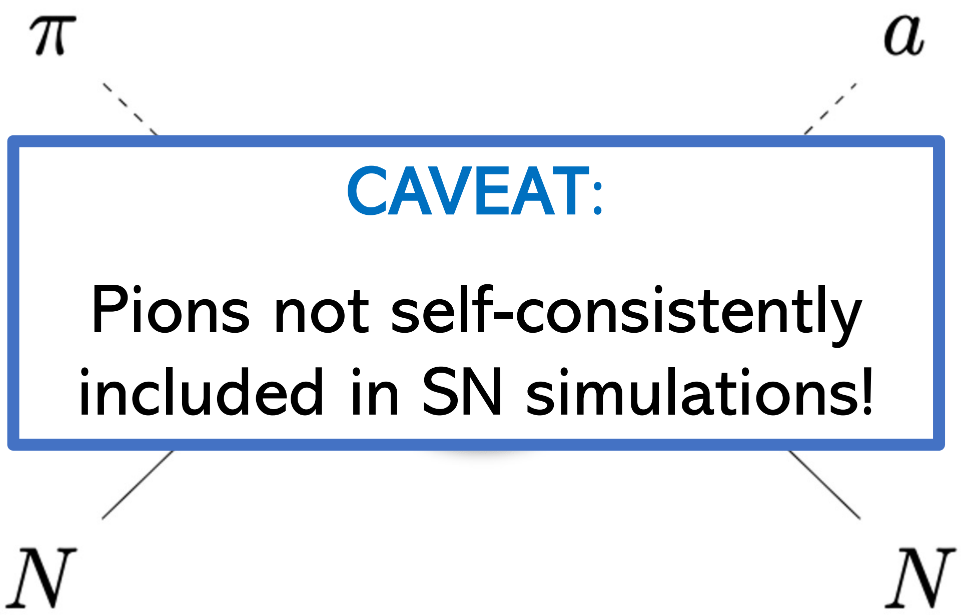
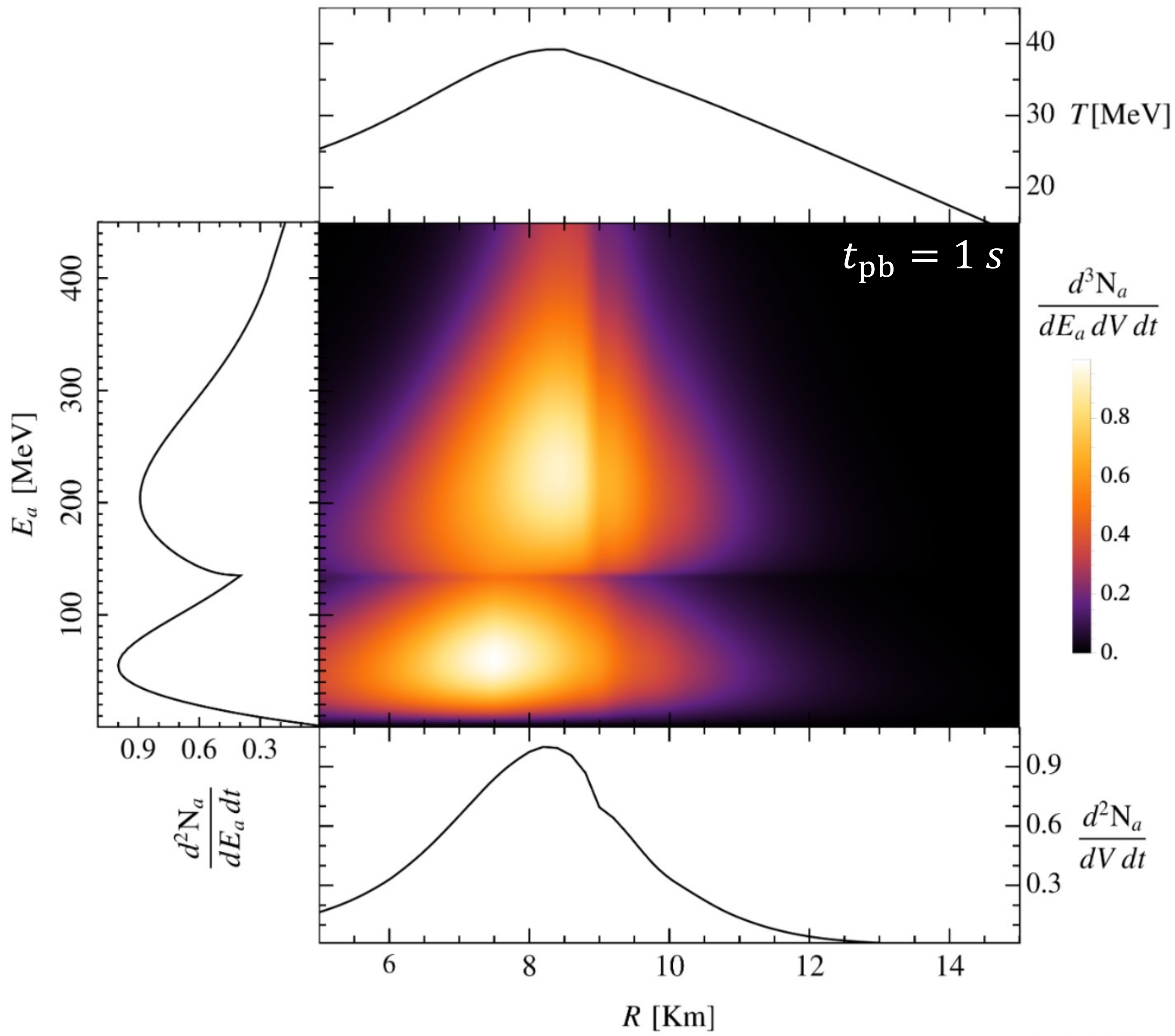


CAVEAT:

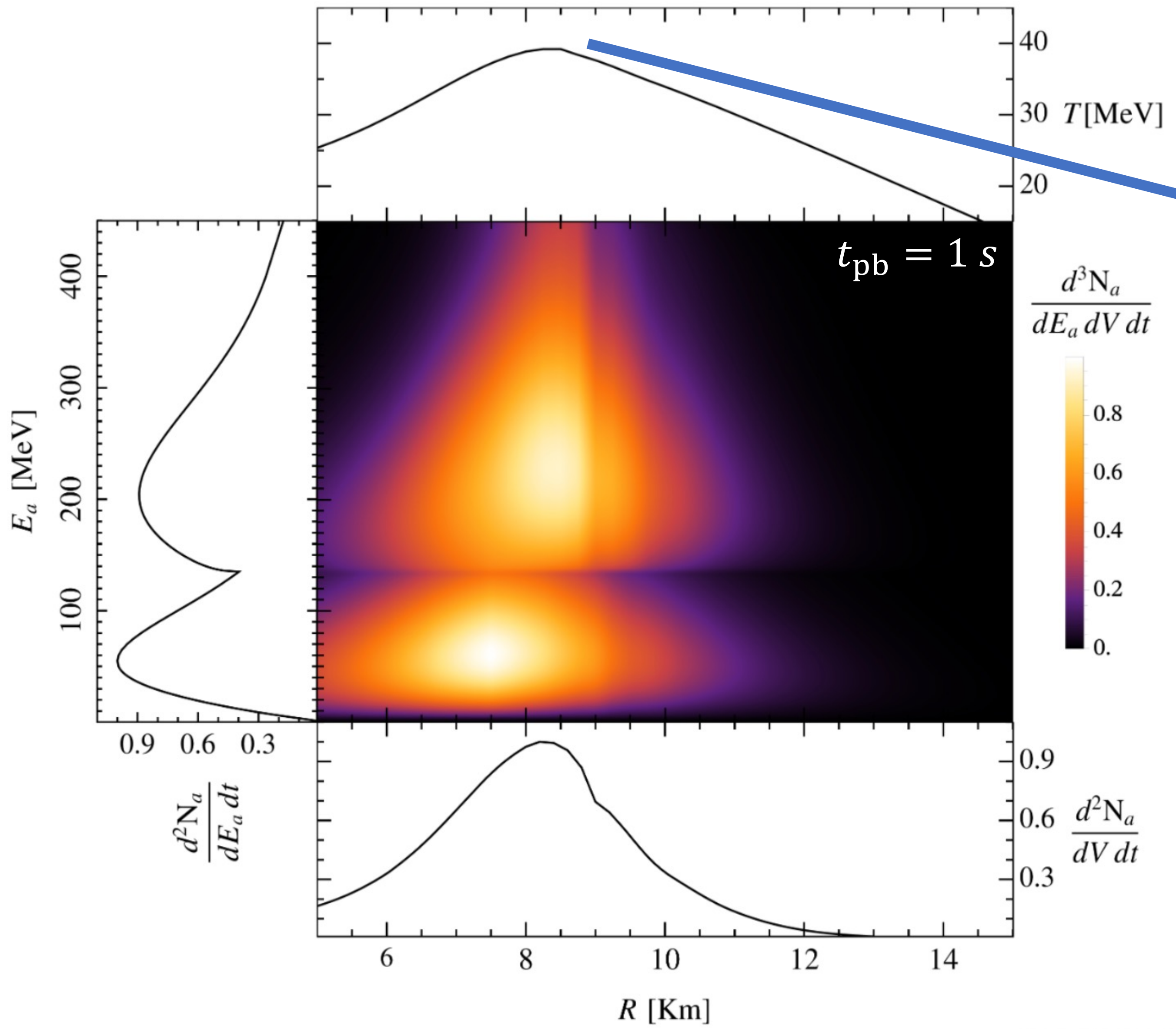
Pions not self-consistently included in SN simulations!

ALPs as messengers of PNS



ALPs can provide a lot of information about the PNS *[AL et al., e-Print: 2405.02395]*

ALPs as messengers of PNS



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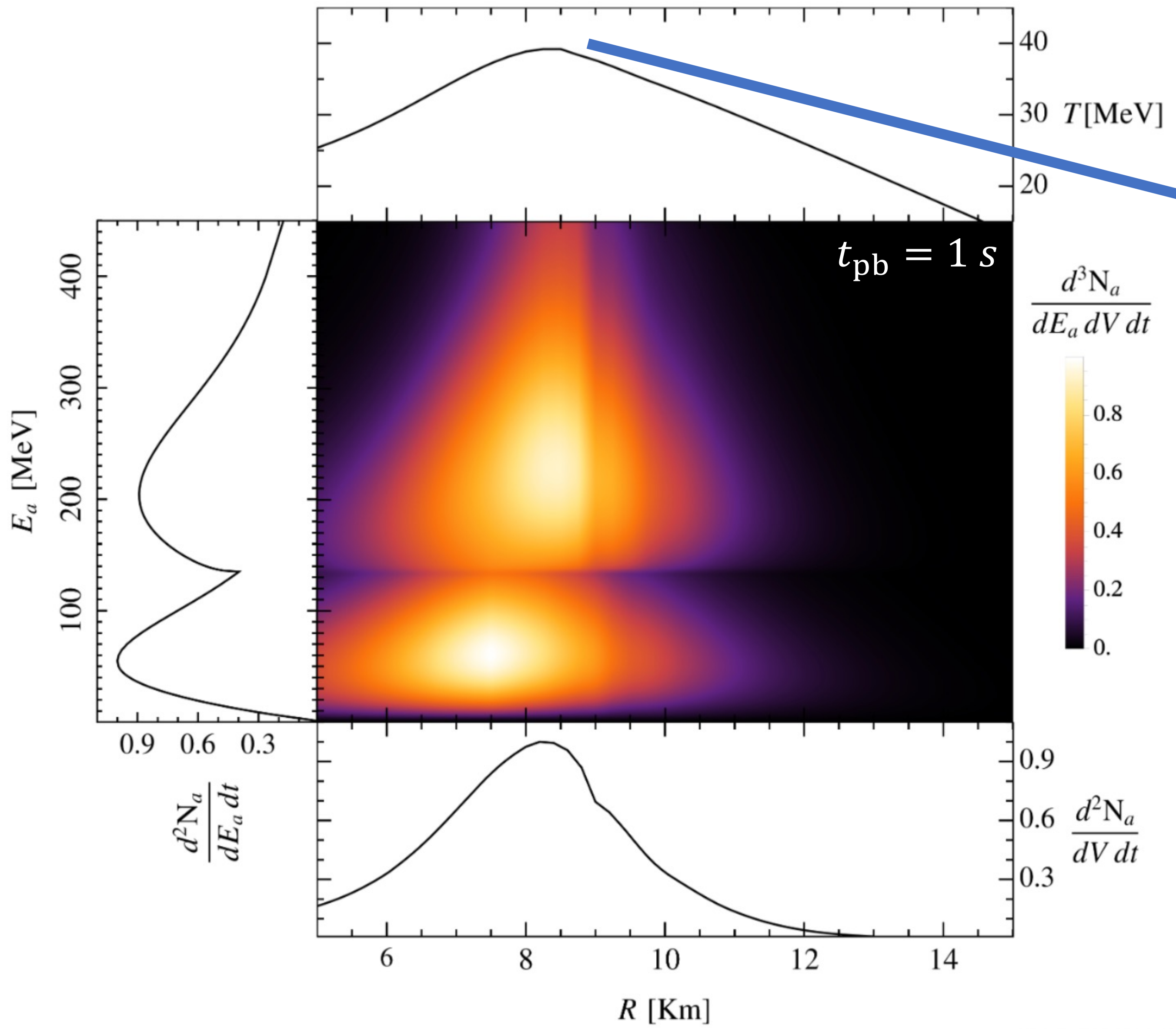
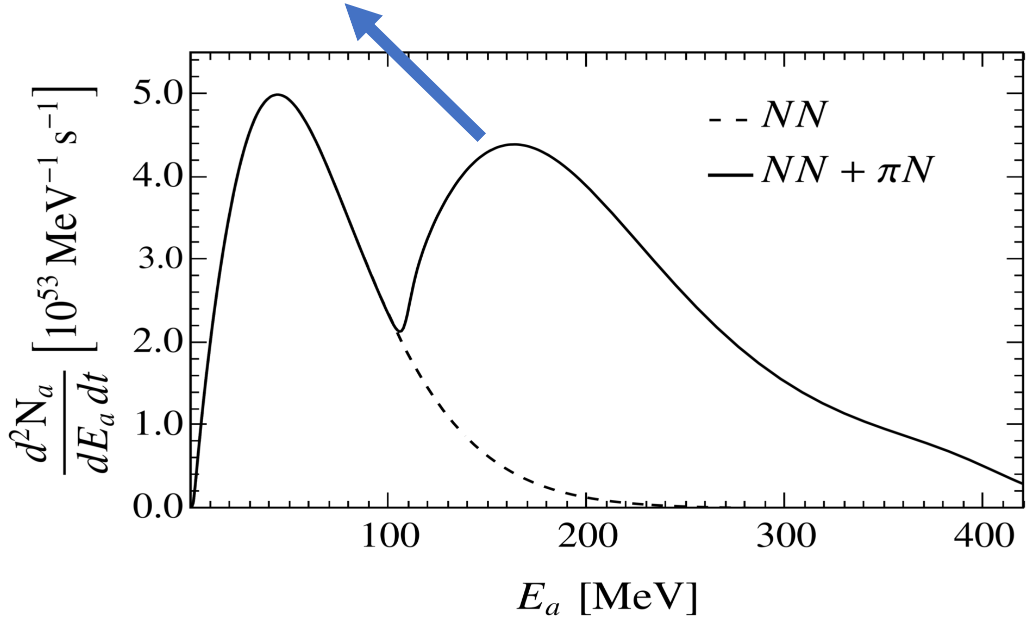
- ALP production sensitive to the PNS temperature peak

ALPs as messengers of PNS



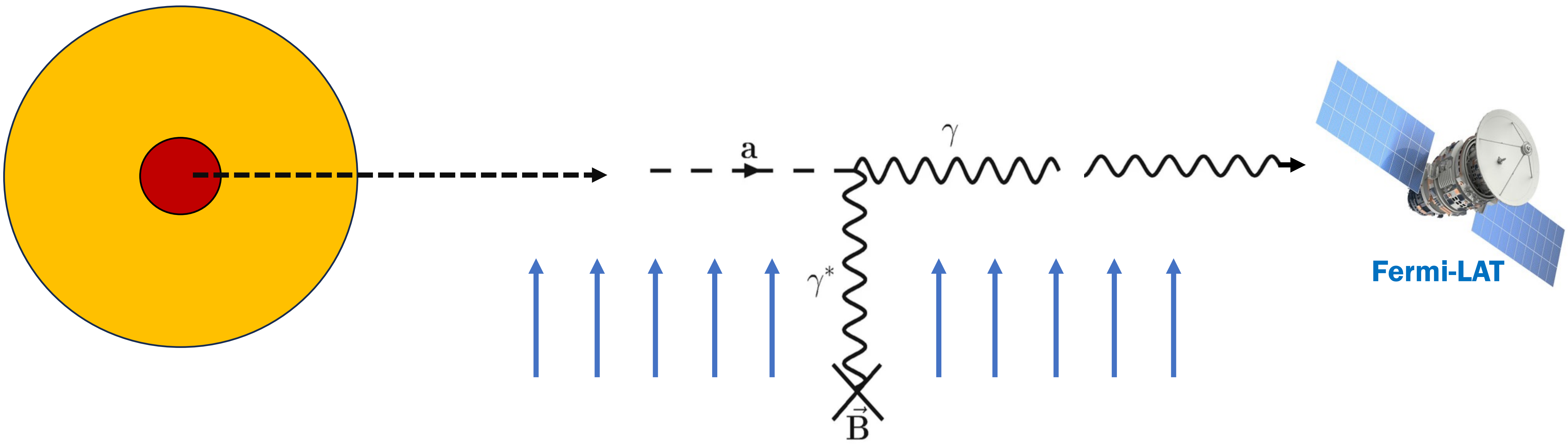
ALPs can provide a lot of information about the PNS *[AL et al., e-Print: 2405.02395]*

- ALP production sensitive to the PNS temperature peak
- Evidence for the presence of pions



Ultra-light ALP conversions

Once emitted from SNe, ultra-light ALPs $(m_a \leq \mathcal{O}(1)\ neV)$ can convert into photons in Galactic Magnetic fields



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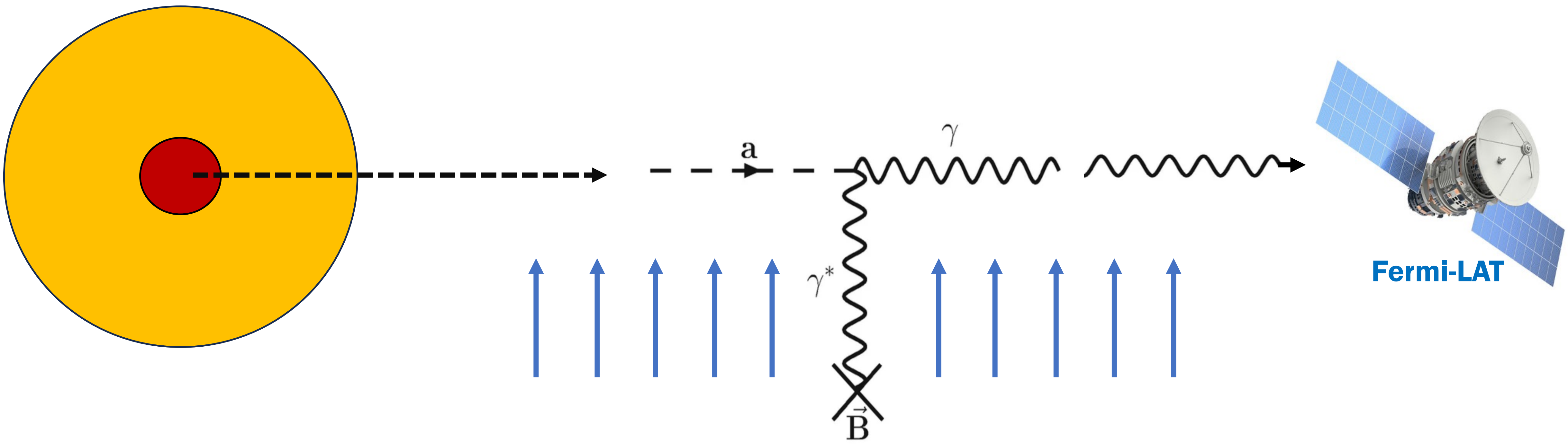


- Additional coupling to photons required → It emerges naturally for ALPs coupled to nuclear matter!

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

AL & al., e-Print: 2405.00153

Ultra-light ALP conversions

Ultra-light ALPs can convert into photons in Galactic Magnetic fields

$$P_{a\gamma} = (\Delta_{a\gamma} L)^2 \frac{\sin^2(\Delta_{\rm osc} L/2)}{(\Delta_{\rm osc} L/2)^2}$$

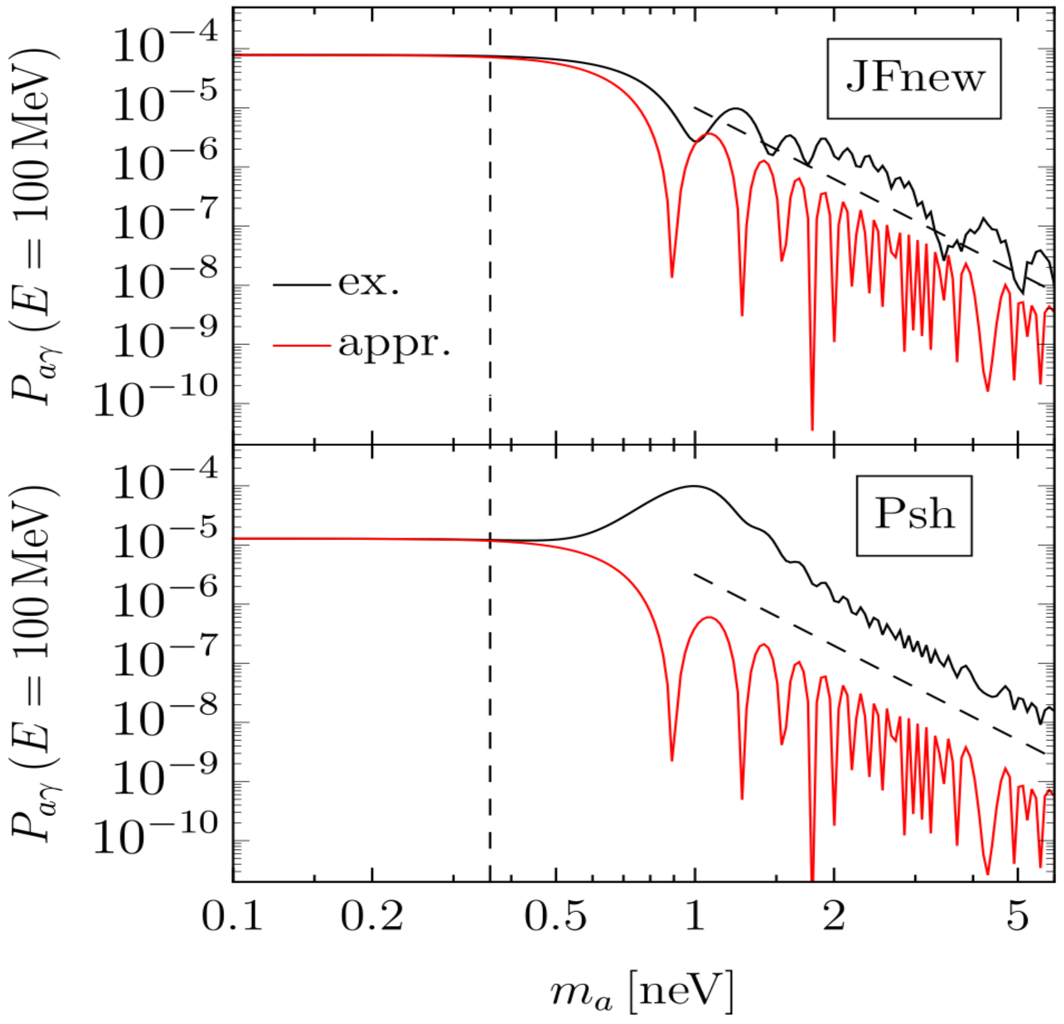
$$\Delta_{\rm osc} \equiv \left[(\Delta_a - \Delta_{\rm pl})^2 + 4\Delta_{a\gamma}^2\right]^{1/2}$$

$$\Delta_{a\gamma} \simeq 1.5 \times 10^{-3} \left(\frac{g_{a\gamma}}{10^{-12}\ {\rm GeV}^{-1}}\right)\left(\frac{B_T}{10^{-6}\ {\rm G}}\right) {\rm kpc}^{-1},$$

$$\Delta_a \simeq -7.8 \times 10^{-5} \left(\frac{m_a}{10^{-11}\ {\rm eV}}\right)^2 \left(\frac{E}{100\ \ {\rm MeV}}\right)^{-1} {\rm kpc}^{-1},$$

$$\Delta_{\rm pl} \simeq -7.8 \times 10^{-7} \left(\frac{\omega_{\rm pl}}{10^{-12}\ {\rm eV}}\right)^2 \left(\frac{E}{100\ {\rm MeV}}\right)^{-1} {\rm kpc}^{-1}.$$

[Calore et al., Phys. Rev. D 109 (2024)]



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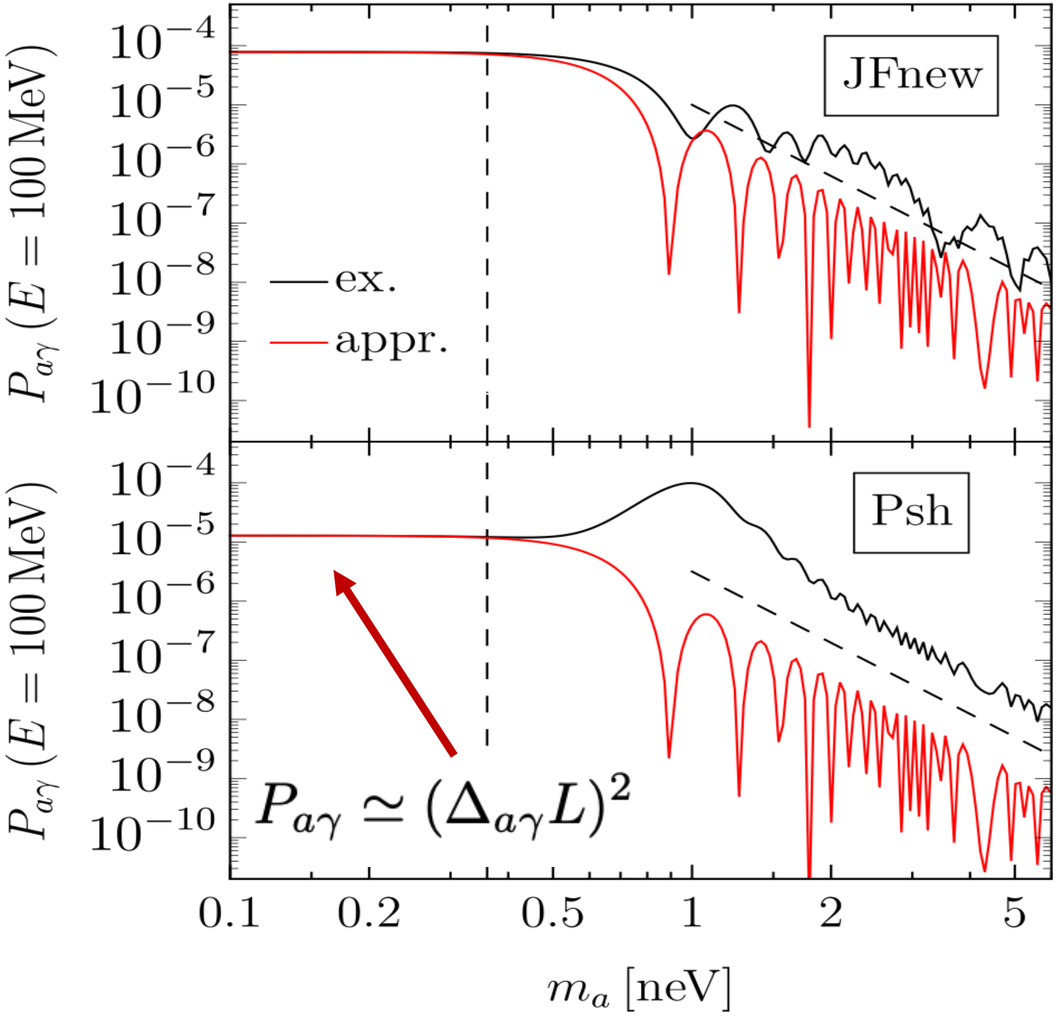
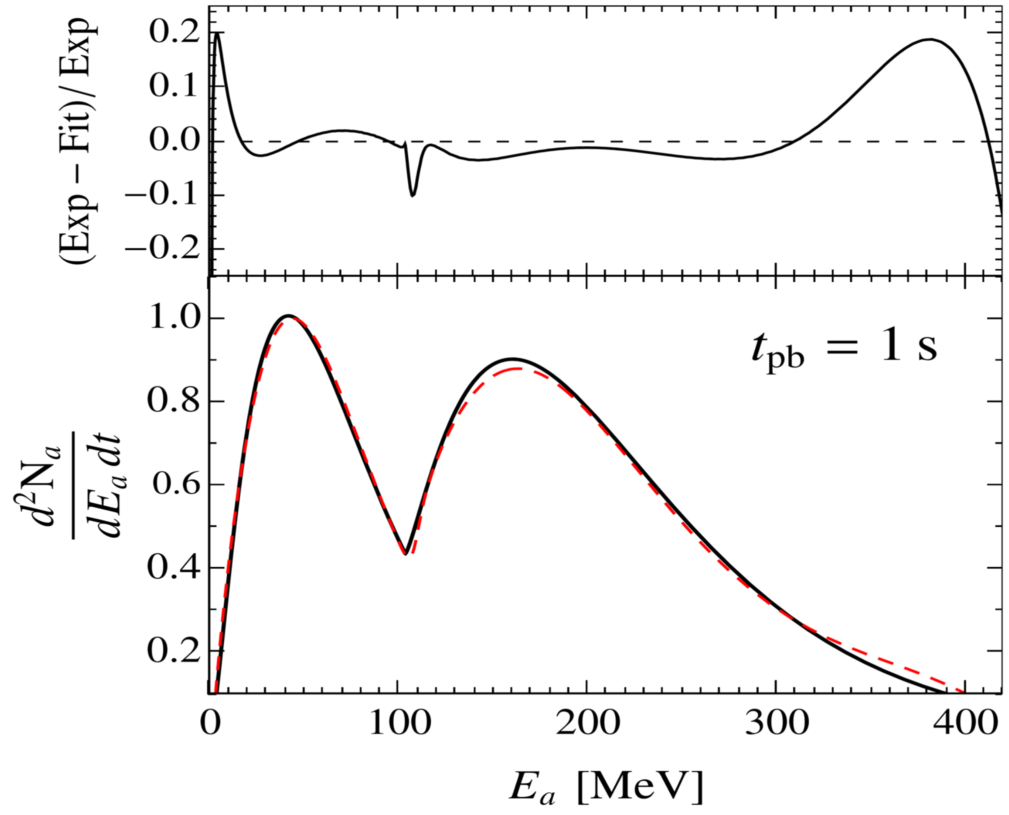


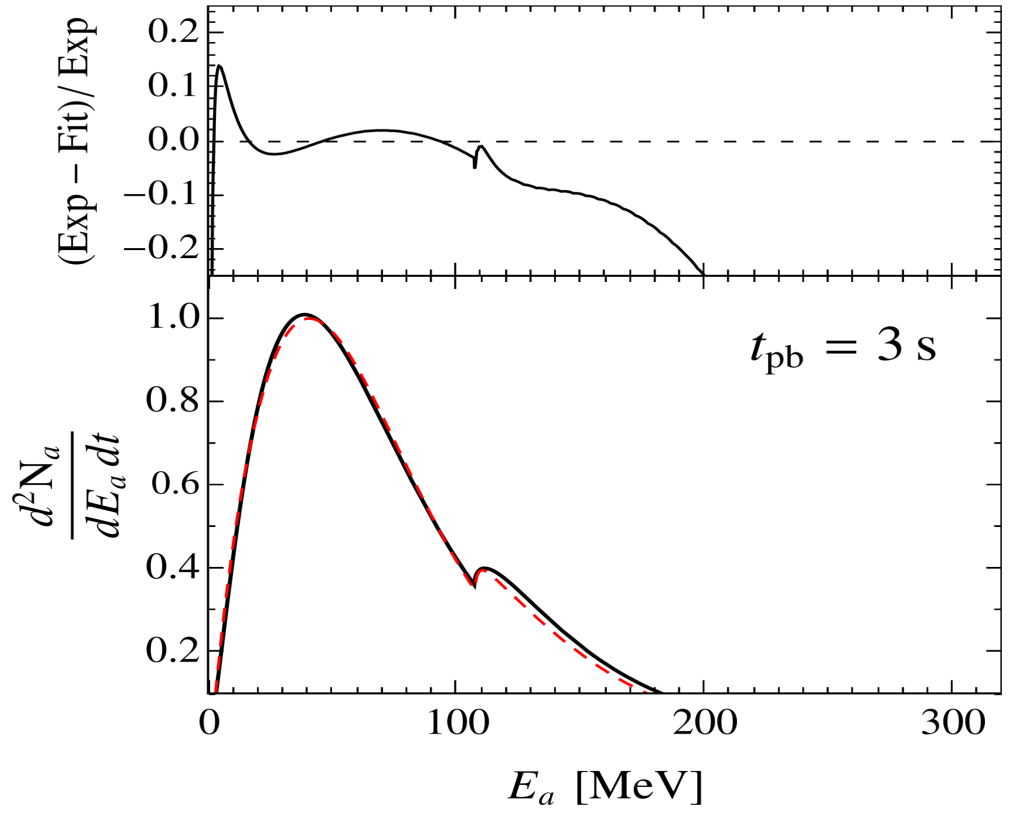
ALPs emission spectra

Complex ALP spectra functional forms can be fitted employing α-fits *[AL et al., e-Print: 2405.02395]*

$$\left(\frac{d^2N_a}{dE_a\,dt}\right)_{NN} \propto \left(\frac{E_a}{E^0_{NN}}\right)^{\beta_{NN}} \exp\left[-(\beta_{NN}+1)\,\frac{E_a}{E^0_{NN}}\right]$$

$$\left(\frac{d^2N_a}{dE_a\,dt}\right)_{\pi N} \propto \left(\frac{E_a-\omega_c}{E^0_{\pi N}}\right)^{\beta_{\pi N}} \exp\left[-(\beta_{\pi N}+1)\,\frac{E_a-\omega_c}{E^0_{\pi N}}\right]$$





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Bremsstrahlung is a thermal process $E^0_{NN} \propto T$

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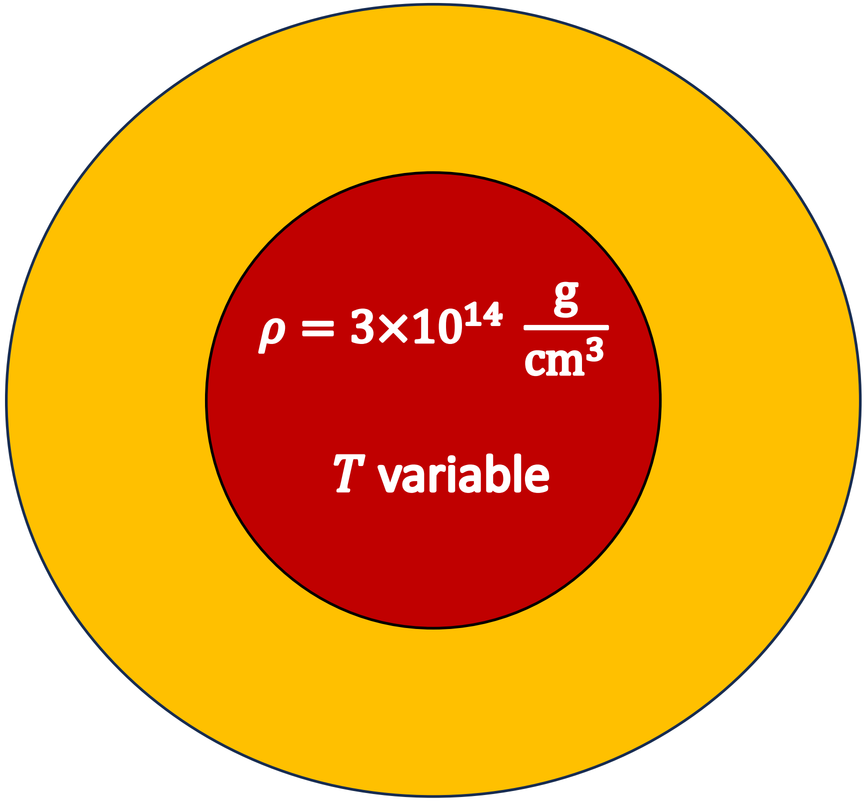
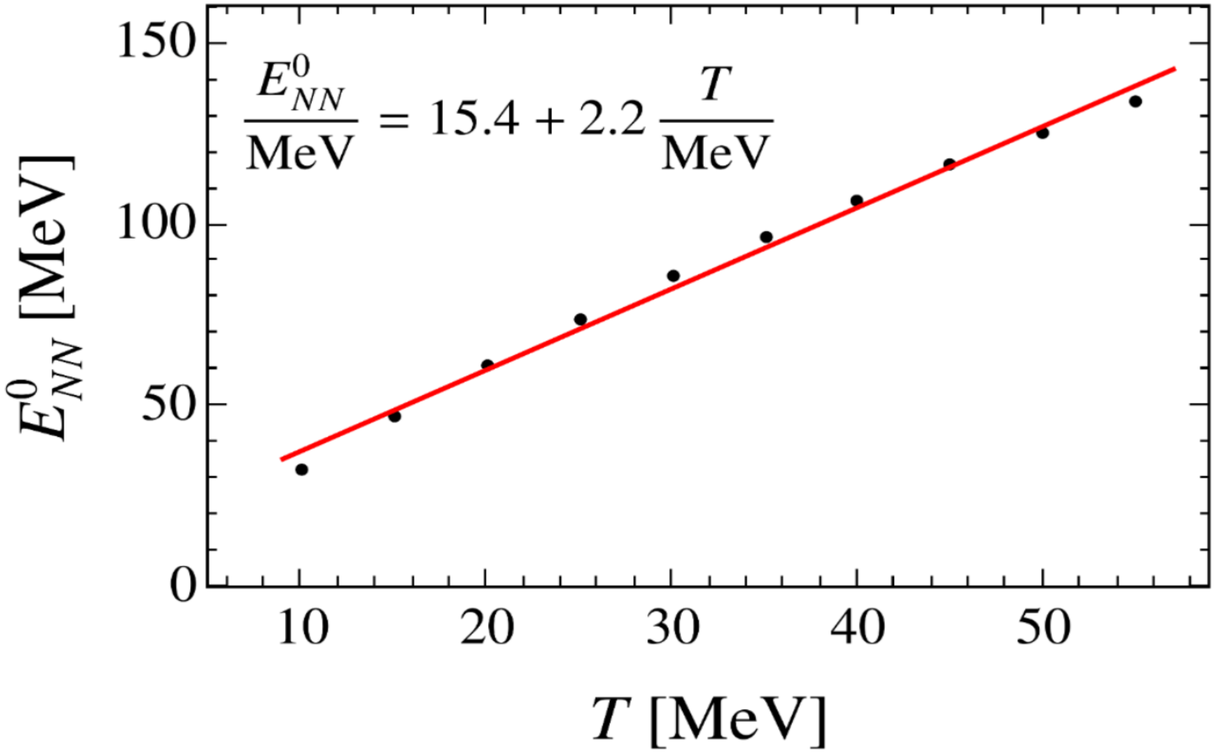
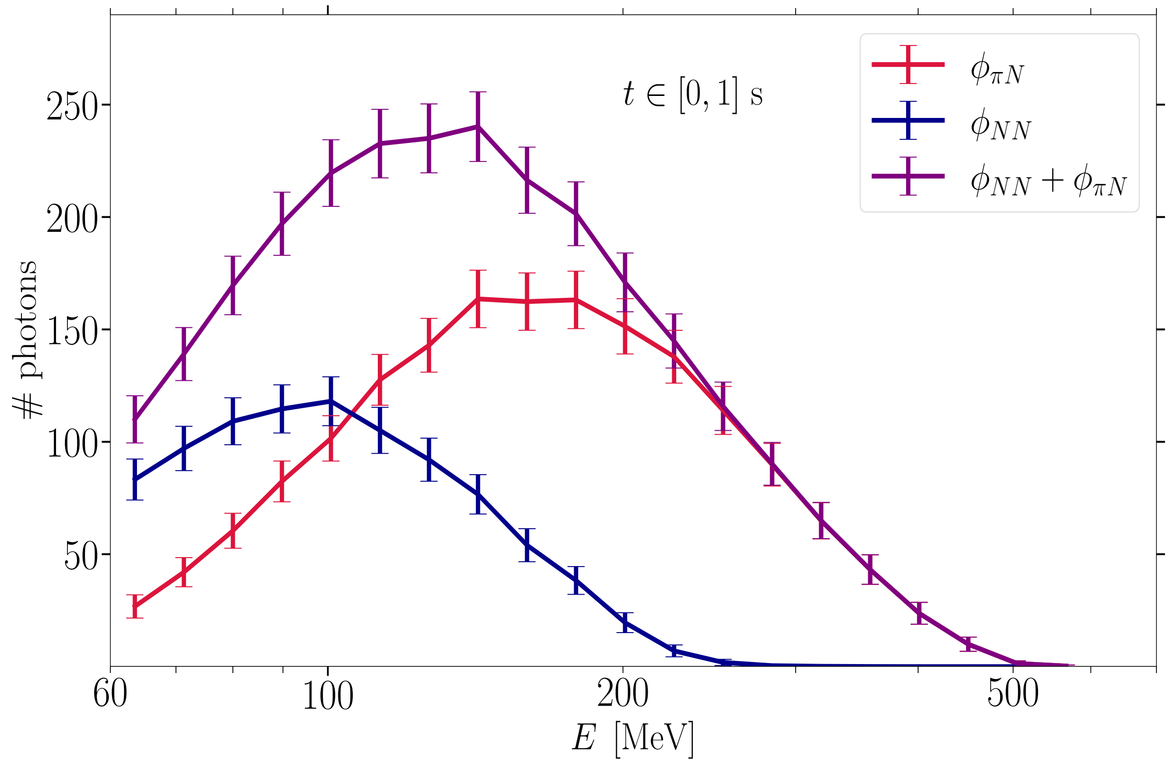
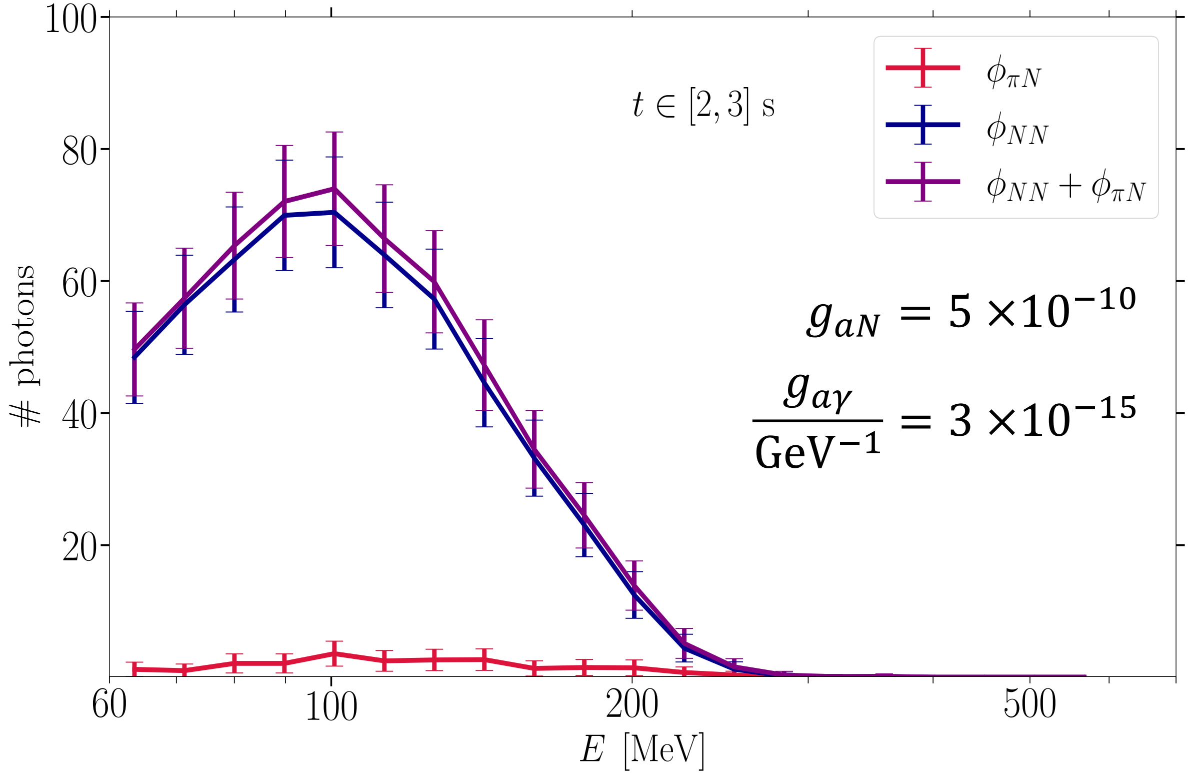




Fermi-LAT reconstruction of the signal

The expected SN ALP-induced gamma-ray signal simulated for 8 seconds with the Fermi Science Tools. $d_{SN} = 10\ \mathrm{kpc}$, $(l, b) = (199.79°, -8.96°)$. *fermi.gsfc.nasa.gov/ssc/data/analysis/software/*





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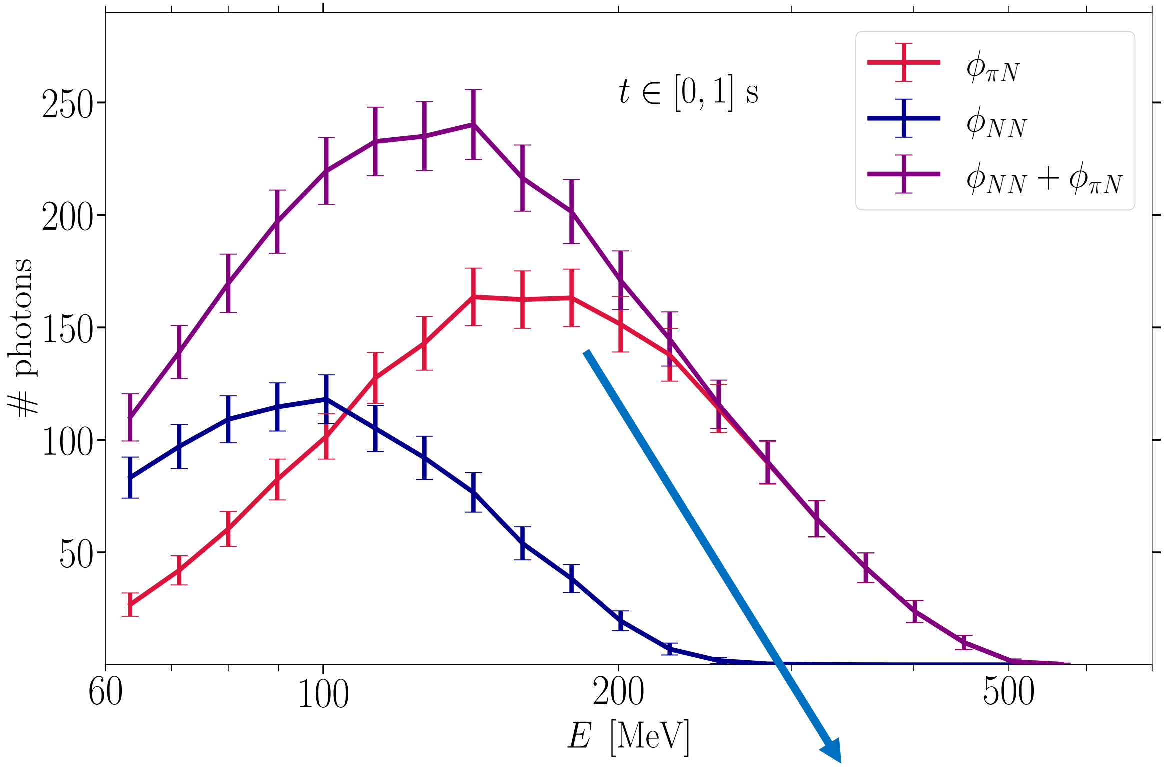
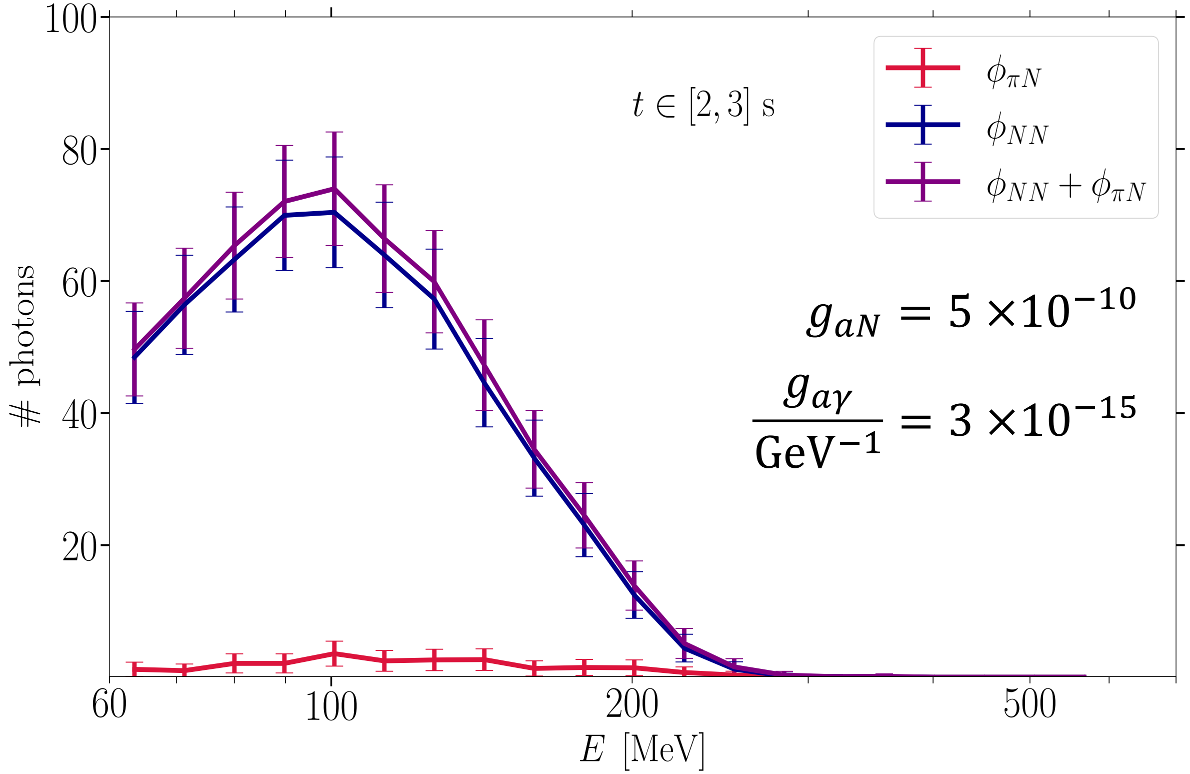


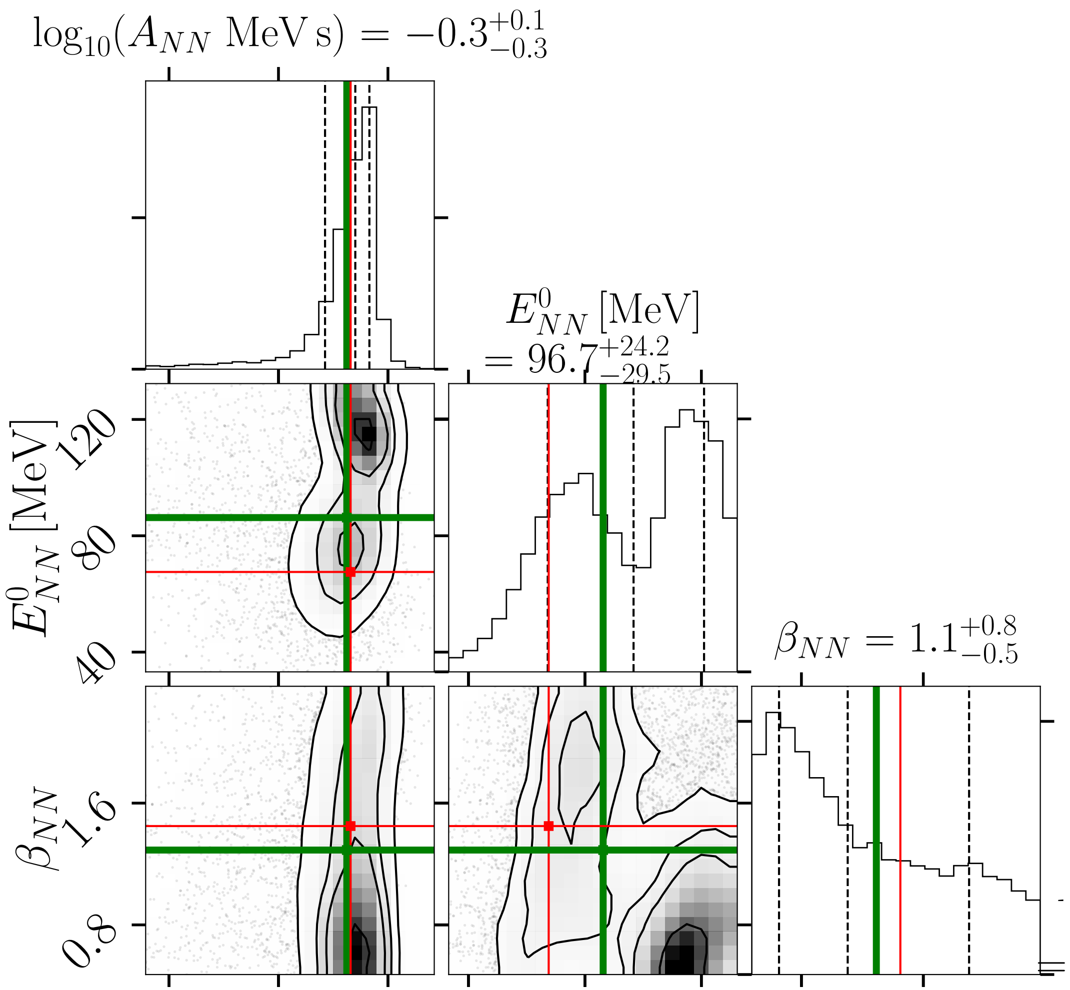
Bayesian evidence for the presence of pions in the core



Suppression of πN peak at $t_{pb} > 2$ s.

Fermi-LAT reconstruction of the signal

Parameter reconstruction $NN + \pi N$



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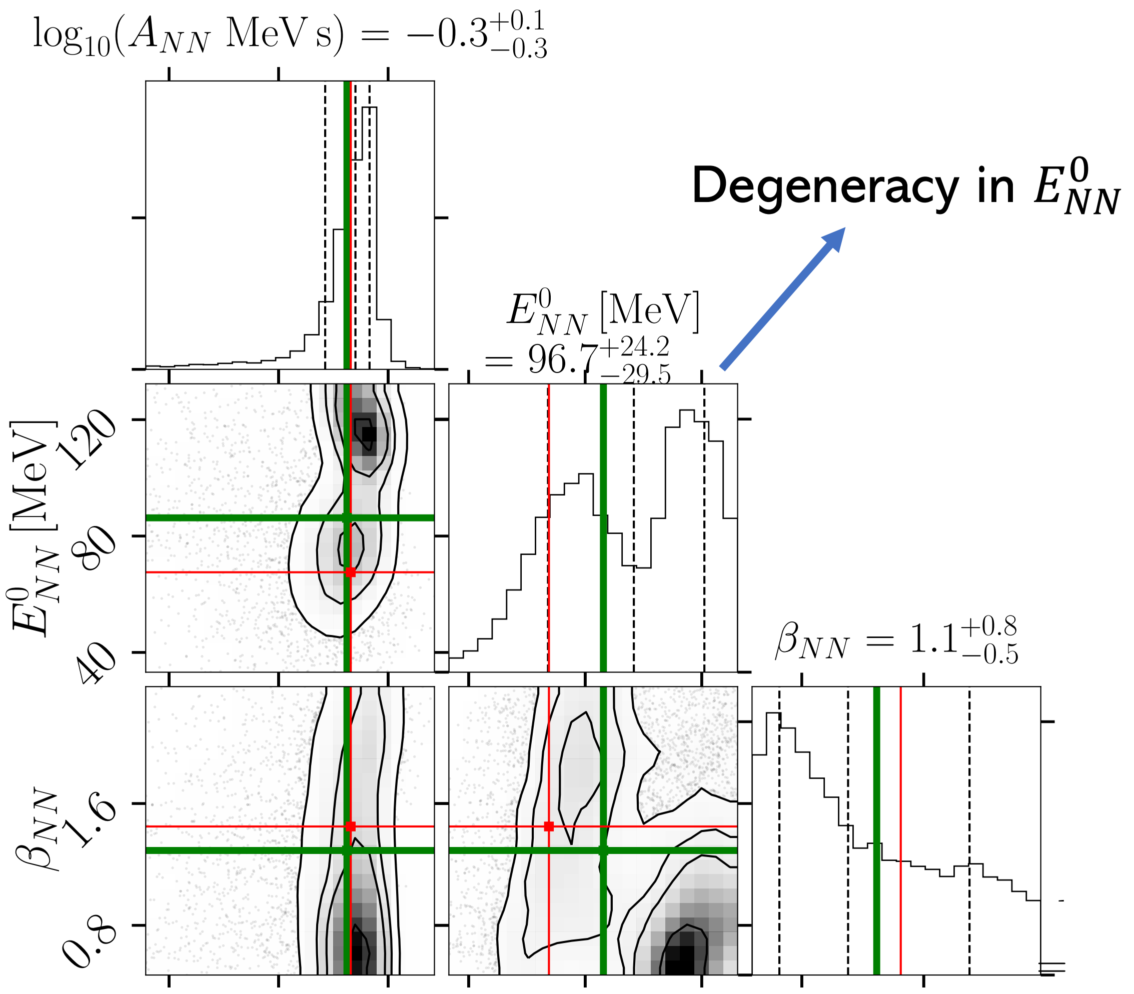

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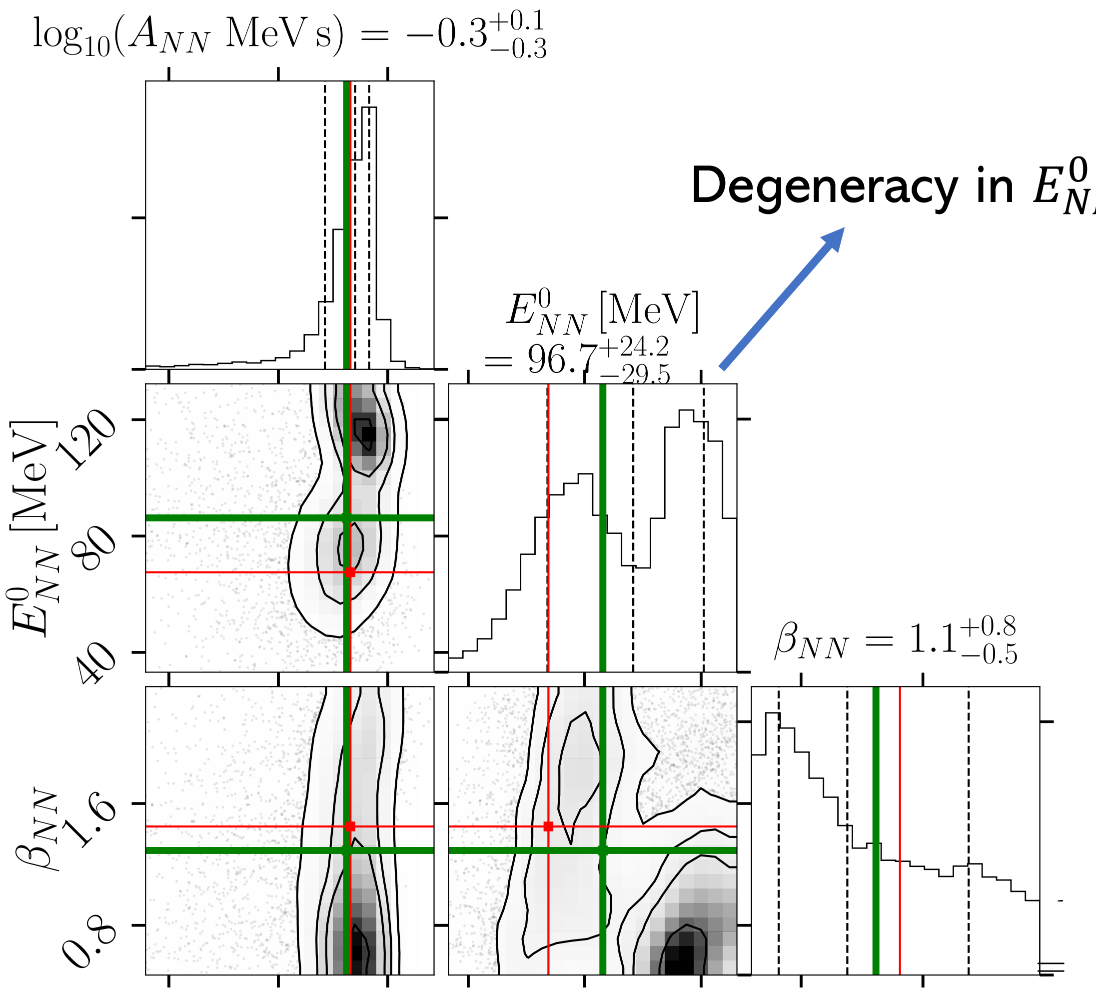
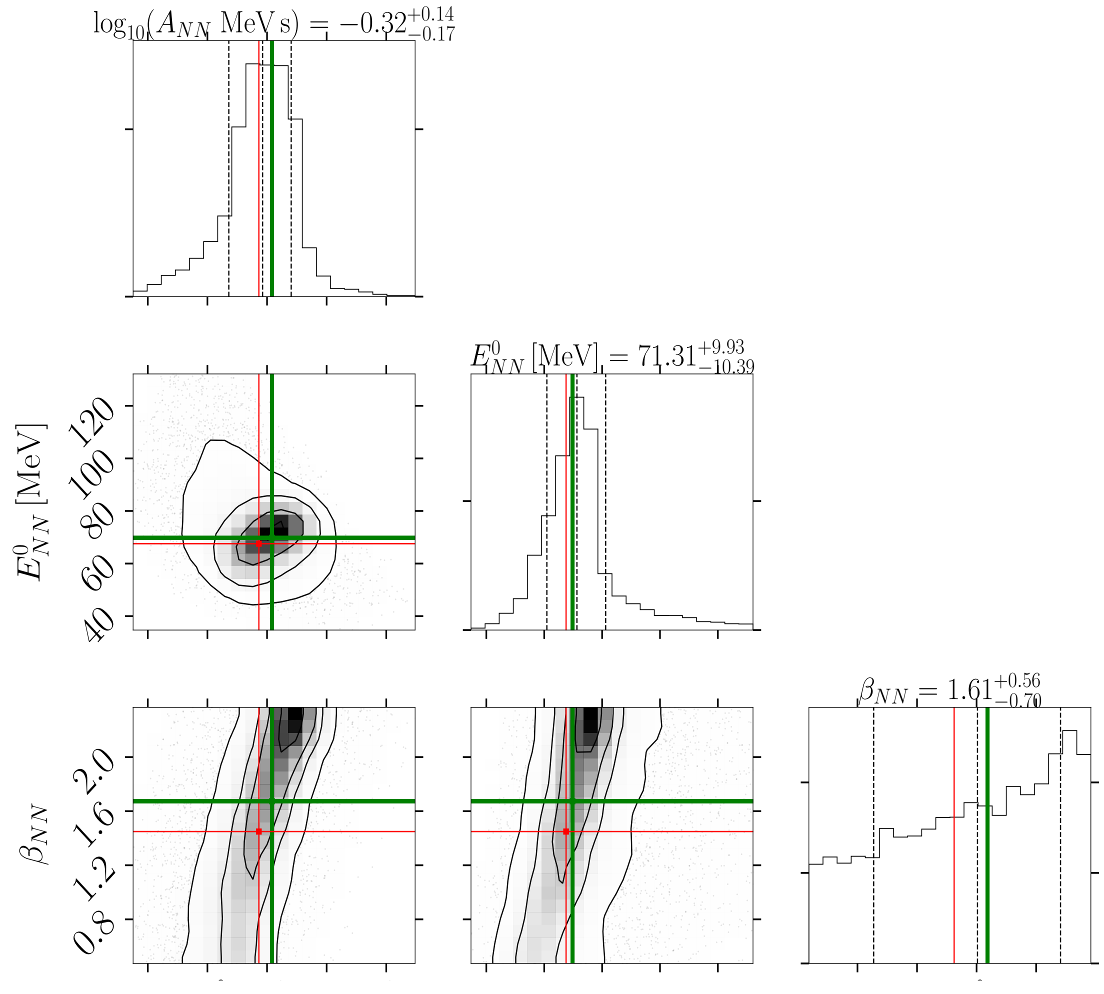


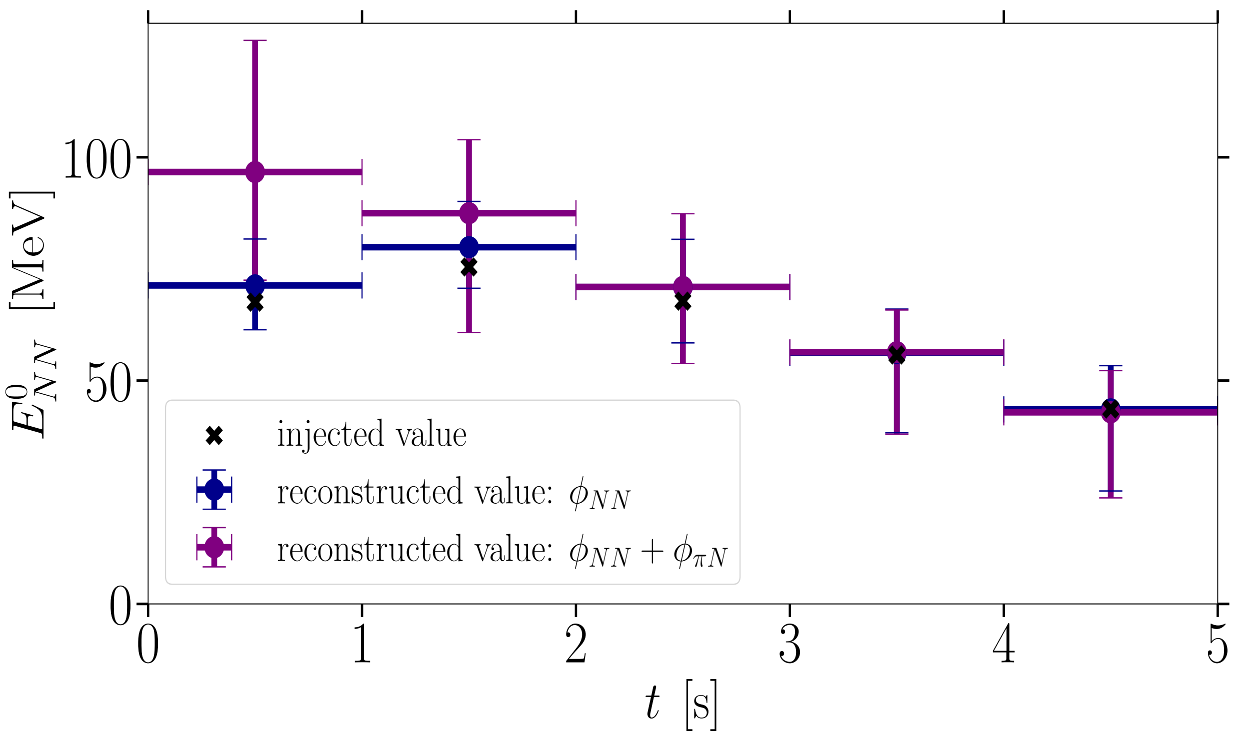
Degeneracy in E^0_{NN}

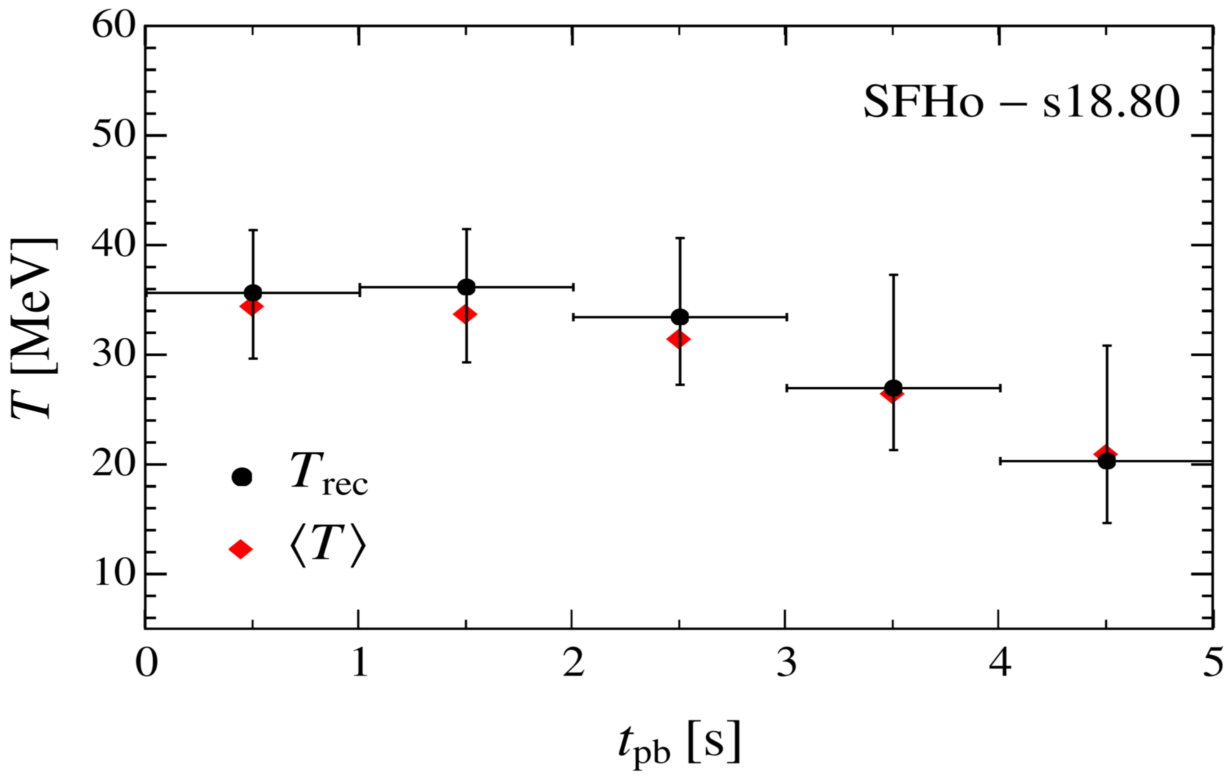
Parameter reconstruction only NN



Fermi-LAT reconstruction of the signal

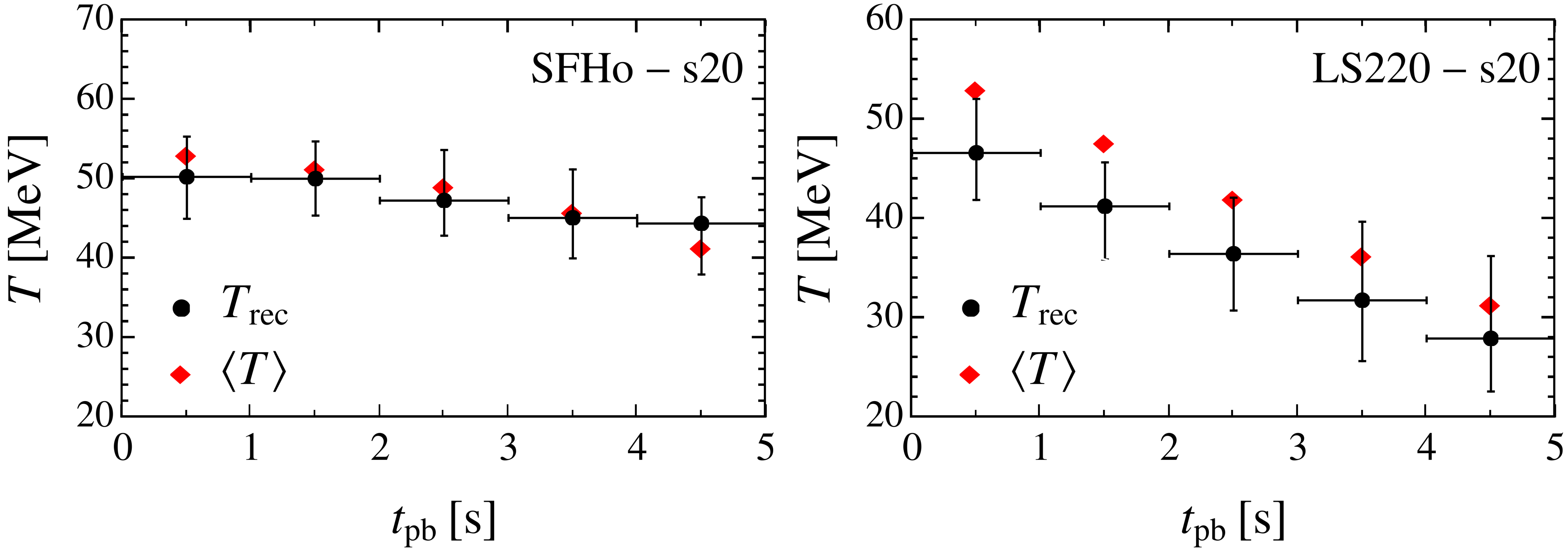
From parameter reconstruction one can estimate the average PNS temperature with high precision





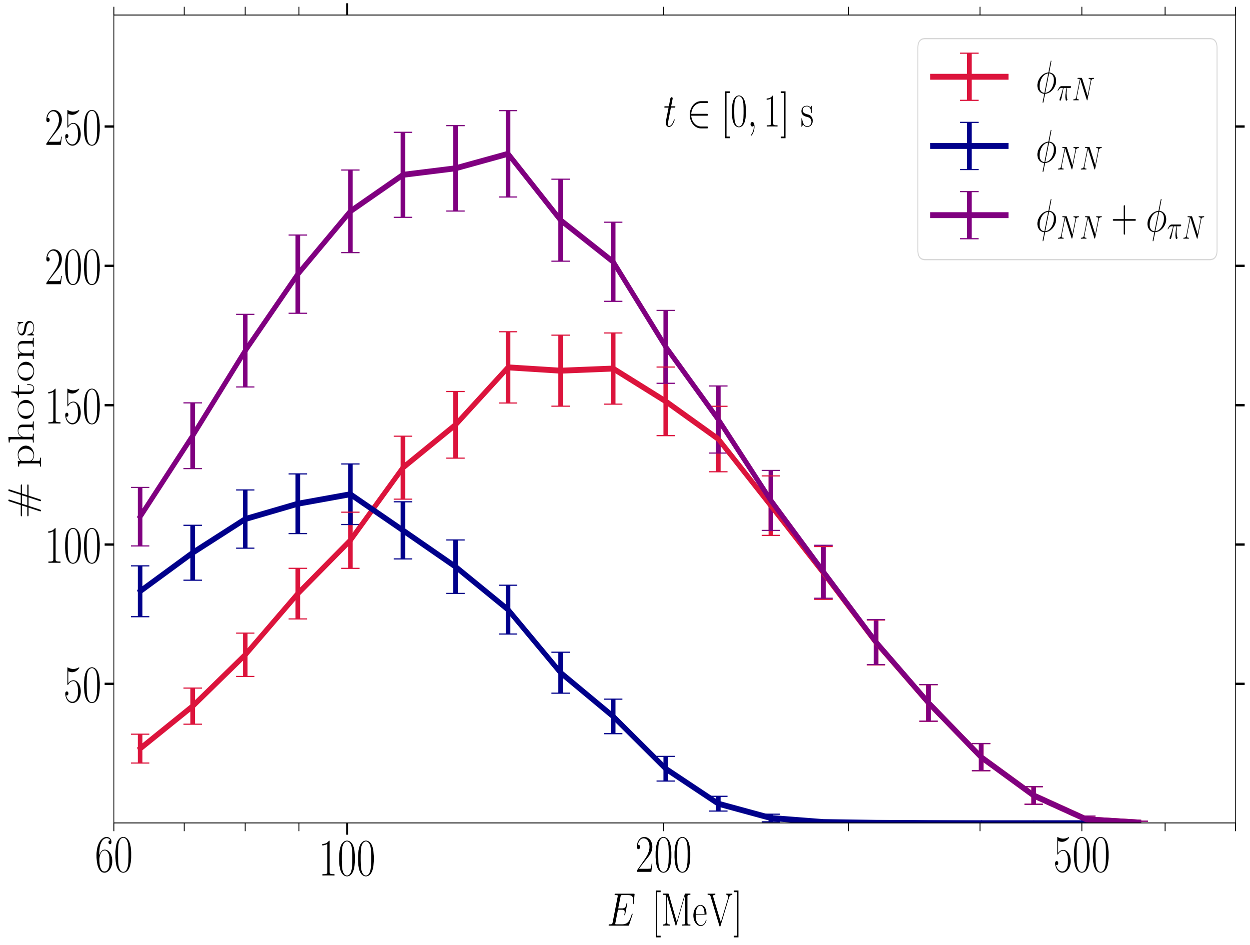
Fermi-LAT reconstruction of the signal

The procedure for temperature reconstruction has been applied also to SN models with different temperature profiles [$M_{PNS} \simeq 1.95\ M_{\odot}$].



Take-home messages

- Ultralight ALPs could be copiously produced in SNe via nuclear processes.
- ALP production spectra encode many properties of the inner SN core.
- Fermi-LAT experiment able to reconstruct the ALP-induced signal
- ALPs as probes for SN pion abundance and PNS temperature.




Thank you for your
attention

ALP emission spectra

- If ALPs interact weakly with nuclear matter, they can *free-stream* through the SN volume

$$\frac{d^2 N_a}{dE_a\,dt} = \int_0^\infty 4\pi r^2 dr \frac{d^2 n_a}{dE_a\,dt}$$

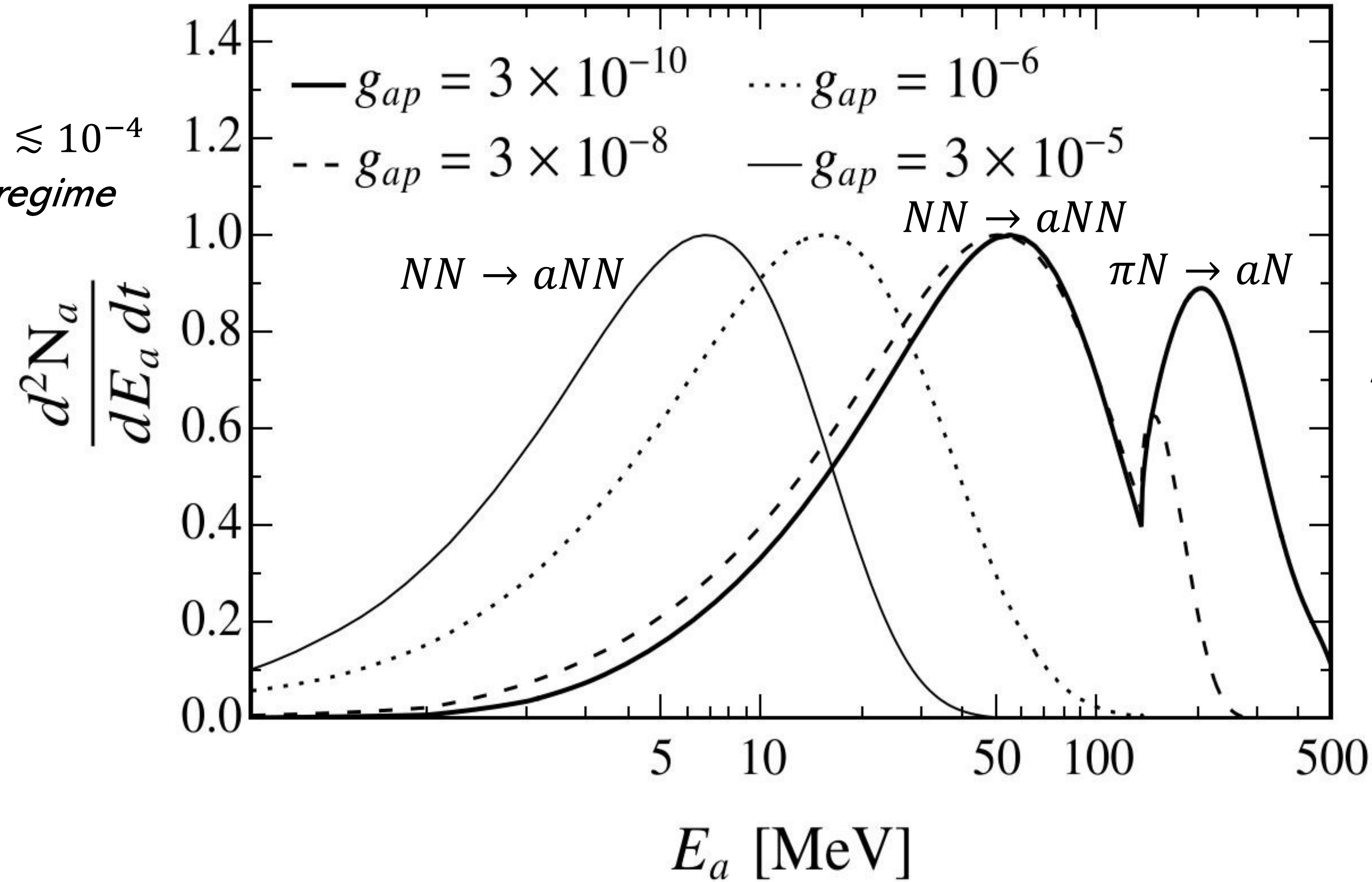
- In case of strongly coupled ALPs, they could enter the *Trapping regime*
  [Caputo & al., Phys. Rev. D 105 (2022)*]*

$$\frac{d^2 N_a}{dE_a\,dt} = \int_0^\infty 4\pi r^2 dr \left\langle e^{-\tau(E_a,r)} \right\rangle \frac{d^2 n_a}{dE_a\,dt}$$

$\tau \sim \int_0^\infty dr\, \lambda_a^{-1}$ optical depth for nuclear processes

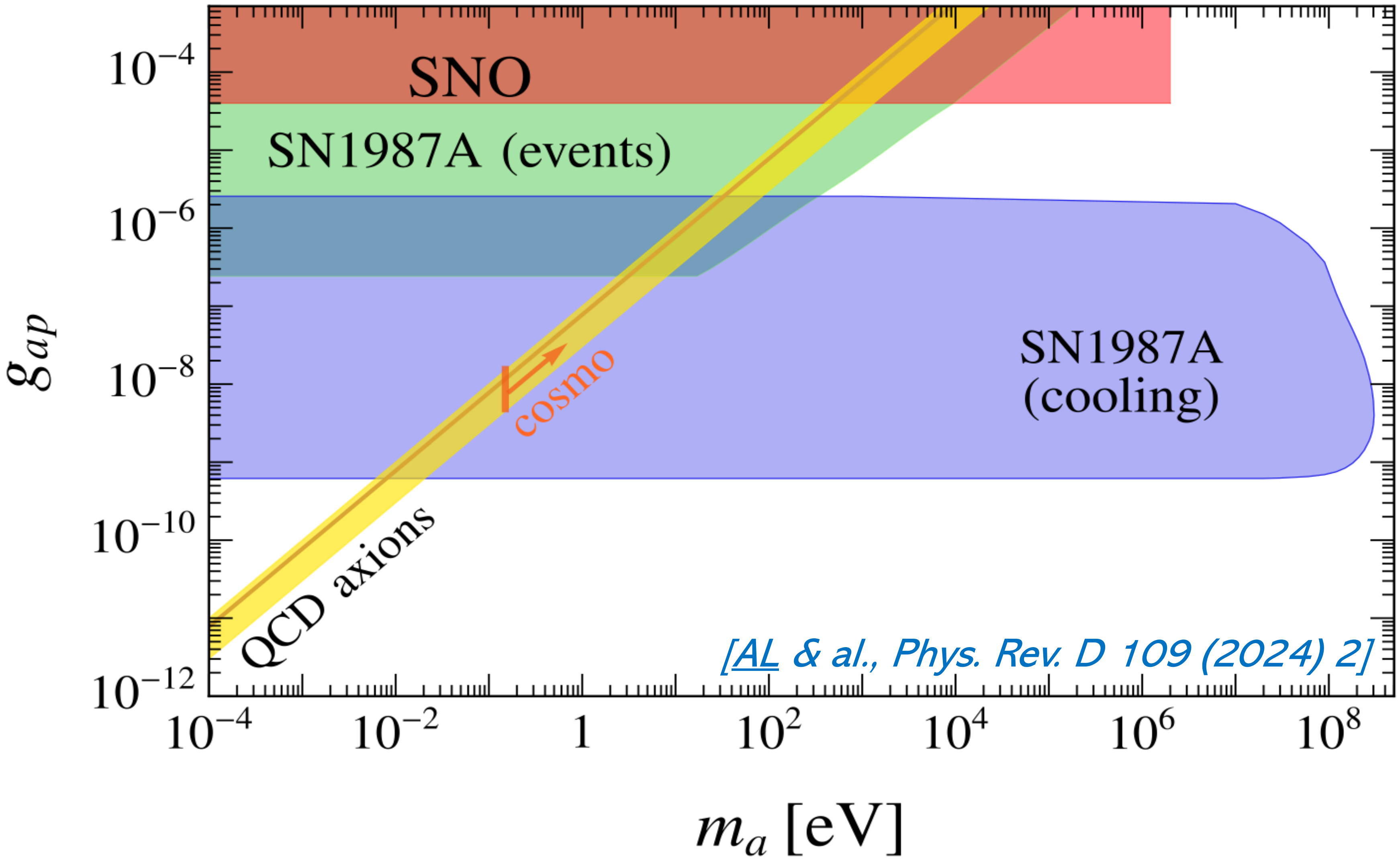
ALP emission spectra

$10^{-7} \lesssim g_{ap} \lesssim 10^{-4}$
trapping regime



$10^{-10} \lesssim g_{ap} \lesssim 10^{-7}$
free-streaming regime

SN bounds on ALPs coupled to nucleons



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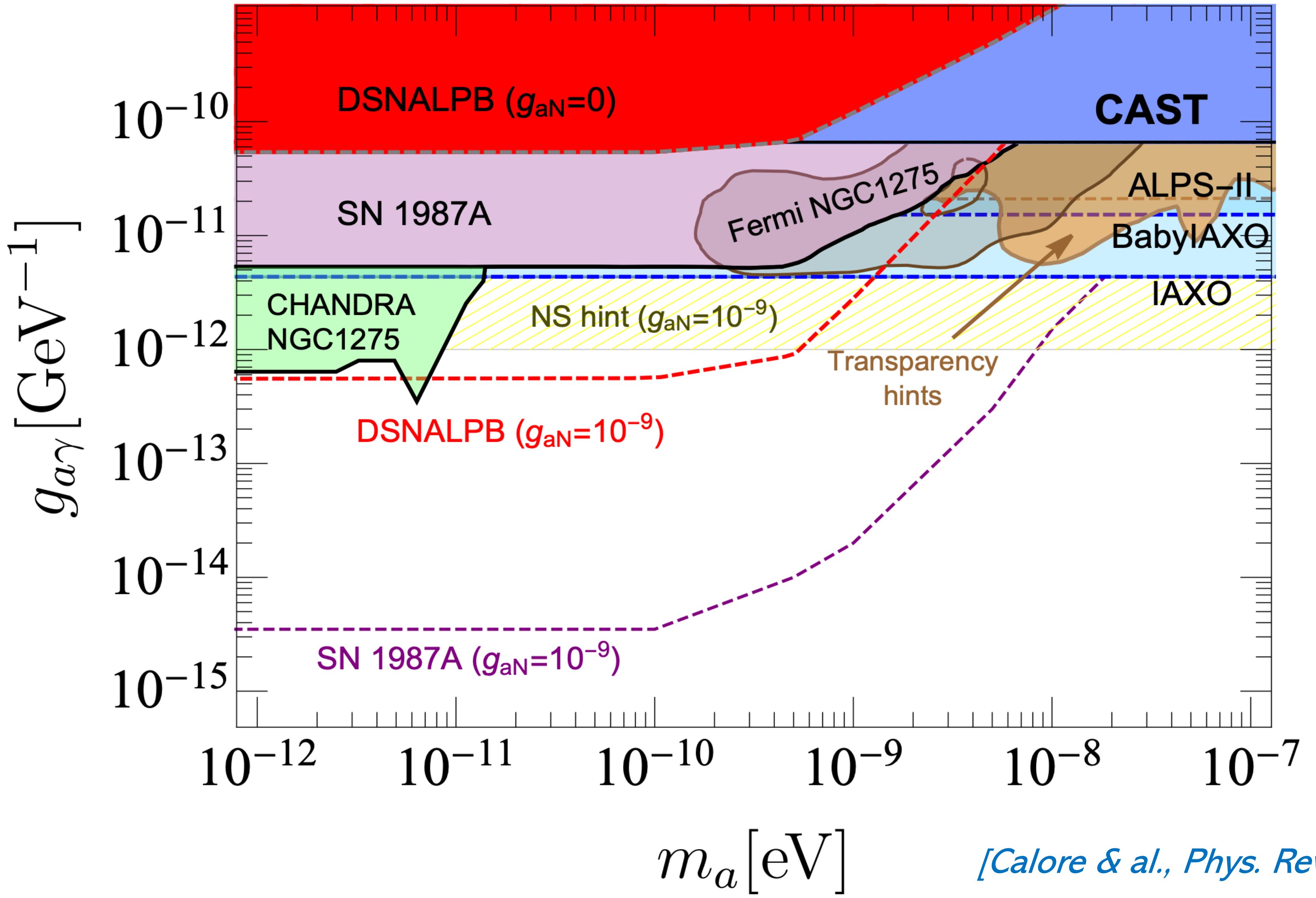

[Calore & al., Phys. Rev. D 102 (2020) 12]

NN Bremsstrahling emission rate

$$\left(\frac{d^2 n_a}{d\omega_a\, dt}\right)_{NN} = \frac{g_a^2}{16\pi^2}\frac{n_B}{m_N^2}(\omega_a^2 - m_a^2)^{\frac{3}{2}} \exp\left(-\frac{\omega_a}{T}\right) \times S_\sigma\left(\frac{\omega_a}{T}\right)\Theta(\omega_a - m_a)\,,$$

$$S_\sigma = \frac{\Gamma_\sigma}{\omega^2} s\left(\frac{\omega_a}{T}\right)$$

$$s(x) = s_{nn}(x) + s_{pp}(x) + s_{np}(x)$$

$$s_{nn}(x) = \frac{1}{3}Y_n^2 C_{an}^2(s_{\mathbf{k}} + s_{\mathbf{l}} + s_{\mathbf{kl}} - 3s_{\mathbf{k\cdot l}})$$

$$s_{pp}(x) = \frac{1}{3}Y_p^2 C_{ap}^2(s_{\mathbf{k}} + s_{\mathbf{l}} + s_{\mathbf{kl}} - 3s_{\mathbf{k\cdot l}})$$

$$s_{np}(x) = \frac{4}{3}Y_nY_p(C_+^2 + C_-^2)s_{\mathbf{k}} + \frac{4}{3}Y_nY_p(4C_+^2 + 2C_-^2)s_{\mathbf{l}} + -\frac{8}{3}Y_nY_p[(C_+^2 + C_-^2)s_{\mathbf{kl}} - (3C_+^2 - C_-^2)s_{\mathbf{k\cdot l}}]\,.$$

$$s_{\mathbf{k}} = \int \frac{d\cos\delta}{2}\frac{d\phi}{2\pi}\frac{\sqrt{w}dw}{\frac{\sqrt{\pi}}{2}}\frac{dz}{2}du \left[\frac{\rho Y_1}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1}\left[\frac{\rho Y_2}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1} e^{u-\eta_3}e^{w-\eta_4}\sqrt{u(u-x)}[H_u^+H_u^-H_v^+H_v^-F_+^2]_{v=u-x} \quad (3.49)$$

$$s_{\mathbf{l}} = \int \frac{d\cos\delta}{2}\frac{d\phi}{2\pi}\frac{\sqrt{w}dw}{\frac{\sqrt{\pi}}{2}}\frac{dz}{2}du \left[\frac{\rho Y_1}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1}\left[\frac{\rho Y_2}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1} e^{u-\eta_3}e^{w-\eta_4}\sqrt{u(u-x)}[H_u^+H_u^-H_v^+H_v^-F_-^2]_{v=u-x} \quad (3.50)$$

$$s_{\mathbf{kl}} = \int \frac{d\cos\delta}{2}\frac{d\phi}{2\pi}\frac{\sqrt{w}dw}{\frac{\sqrt{\pi}}{2}}\frac{dz}{2}du \left[\frac{\rho Y_1}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1}\left[\frac{\rho Y_2}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1} e^{u-\eta_3}e^{w-\eta_4}\sqrt{u(u-x)}[H_u^+H_u^-H_v^+H_v^-F_+F_-]_{v=u-x} \quad (3.51)$$

$$s_{\mathbf{k\cdot l}} = \int \frac{d\cos\delta}{2}\frac{d\phi}{2\pi}\frac{\sqrt{w}dw}{\frac{\sqrt{\pi}}{2}}\frac{dz}{2}du \left[\frac{\rho Y_1}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1}\left[\frac{\rho Y_2}{2m_N}\left(\frac{2\pi}{m_N T}\right)^{\frac{3}{2}}\right]^{-1} e^{u-\eta_3}e^{w-\eta_4}\sqrt{u(u-x)}\left[H_u^+H_u^-H_v^+H_v^-F_+F_-\frac{\xi}{3}\right]_{v=u-x} \quad (3.52)$$

Pion conversion emission rate

$$\left(\frac{d^2 n_a}{dE_a\, dt}\right)_{N\pi} = \frac{g_a^2 T^{1.5}}{2^{1.5}\pi^5 m_N^{0.5}} \left(\frac{g_A}{2f_\pi}\right)^2 \left(E_a^2 - m_a^2\right)^{\frac{1}{2}}$$
$$\times\, \mathcal{C}_a^{p\pi^-} \frac{\Theta(E_a - \max(m_a, m_\pi))}{\exp(x_a - y_\pi - \hat{\mu}_\pi) - 1} \left(E_a^2 - m_\pi^2\right)^{\frac{1}{2}} \frac{E_a^2}{E_a^2 + \Gamma^2}$$
$$\times \int_0^\infty dy\, y^2 \frac{1}{\exp(y^2 - \hat{\mu}_p) + 1} \frac{1}{\exp(-y^2 + \hat{\mu}_n) + 1},$$

$$\mathcal{C}_a^{p\pi^-} = \frac{m_N^2}{g_A^2} \beta_a^2 \mathcal{G}_a(|\mathbf{p}_\pi|)$$

$$\mathcal{G}_a(|\boldsymbol{k}_\pi|) = \frac{2g_A^2(2C_+^2 + C_-^2)}{3}\left(\frac{|\boldsymbol{k}_\pi|}{m_N}\right)^2 + C_{a\pi N}^2\left(\frac{E_\pi}{m_N}\right)^2 + \frac{8\sqrt{2}g_A C_{a\pi N} C_-}{3}\left(\frac{|\boldsymbol{k}_\pi|}{m_N}\right)^2\left(\frac{E_\pi}{m_N}\right)$$
$$+ \frac{4C_{aN\Delta}^2 \mathcal{C}^2}{81} \frac{E_\pi^2(\Delta m^2 + 2E_\pi^2 + \bar{\Gamma}_\Delta^2)}{\left[(\Delta m - E_\pi)^2 + \bar{\Gamma}_\Delta^2\right]\left[(\Delta m + E_\pi)^2 + \bar{\Gamma}_\Delta^2\right]}\left(\frac{|\boldsymbol{k}_\pi|}{m_N}\right)^2$$
$$- \frac{8\sqrt{3}g_A C_{aN\Delta}\mathcal{C}}{27} \frac{E_\pi\left[(\Delta m^2 - E_\pi^2)(C_+\Delta m + C_- E_\pi) + \bar{\Gamma}_\Delta^2(C_+\Delta m - C_- E_\pi)\right]}{\left[(\Delta m - E_\pi)^2 + \bar{\Gamma}_\Delta^2\right]\left[(\Delta m + E_\pi)^2 + \bar{\Gamma}_\Delta^2\right]}\left(\frac{|\boldsymbol{k}_\pi|}{m_N}\right)^2$$
$$- \frac{16\sqrt{6}C_{a\pi N}C_{aN\Delta}\mathcal{C}}{27} \frac{E_\pi^2(\Delta m^2 - E_\pi^2 - \bar{\Gamma}_\Delta^2)}{\left[(\Delta m - E_\pi)^2 + \bar{\Gamma}_\Delta^2\right]\left[(\Delta m + E_\pi)^2 + \bar{\Gamma}_\Delta^2\right]}\left(\frac{|\boldsymbol{k}_\pi|}{m_N}\right)^2\left(\frac{E_\pi}{m_N}\right) \quad (39)$$

The UV theory

Above $\Lambda_{QCD} \simeq 200\ \mathrm{MeV}$ interactions with quark and gluons

$$\mathcal{L}_{\mathrm{aQCD}} = c_g \frac{g_s^2}{32\pi^2}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \sum_q c_q \frac{\partial_\mu a}{2f_a}\bar{q}\gamma^\mu\gamma_5 q + \frac{(m_{a,0})^2}{2}a^2$$

Then, at loop level *[Bauer et al., JHEP 12 (2017)]*

$$C_\gamma(c_g, c_u, c_d) = -1.92\, c_g - \frac{m_a^2}{m_\pi^2 - m_a^2}\left[c_g \frac{m_d - m_u}{m_d + m_u} + (c_u - c_d)\right]$$

Irreducible photon coupling related to nuclear couplings ($C_n = 0, c_g = 1$)

$$g_{a\gamma} \simeq -9.5 \times 10^{-4}\ \mathrm{GeV}^{-1}\left[\frac{1.53}{c_d - 0.33} + \frac{c_d + 0.24}{c_d - 0.33}\frac{m_a^2}{m_\pi^2 - m_a^2}\right] g_{ap}$$

Time-behavior of fitting parameters