Time-delayed gamma-ray signatures of heavy axions from core-collapse supernovae

Yujin Park, Rutgers University

Based on 2412.13247 with Benabou, Manzari, Prabhakar, Safdi, and Savoray

TeVPA 2025, Valencia, Spain

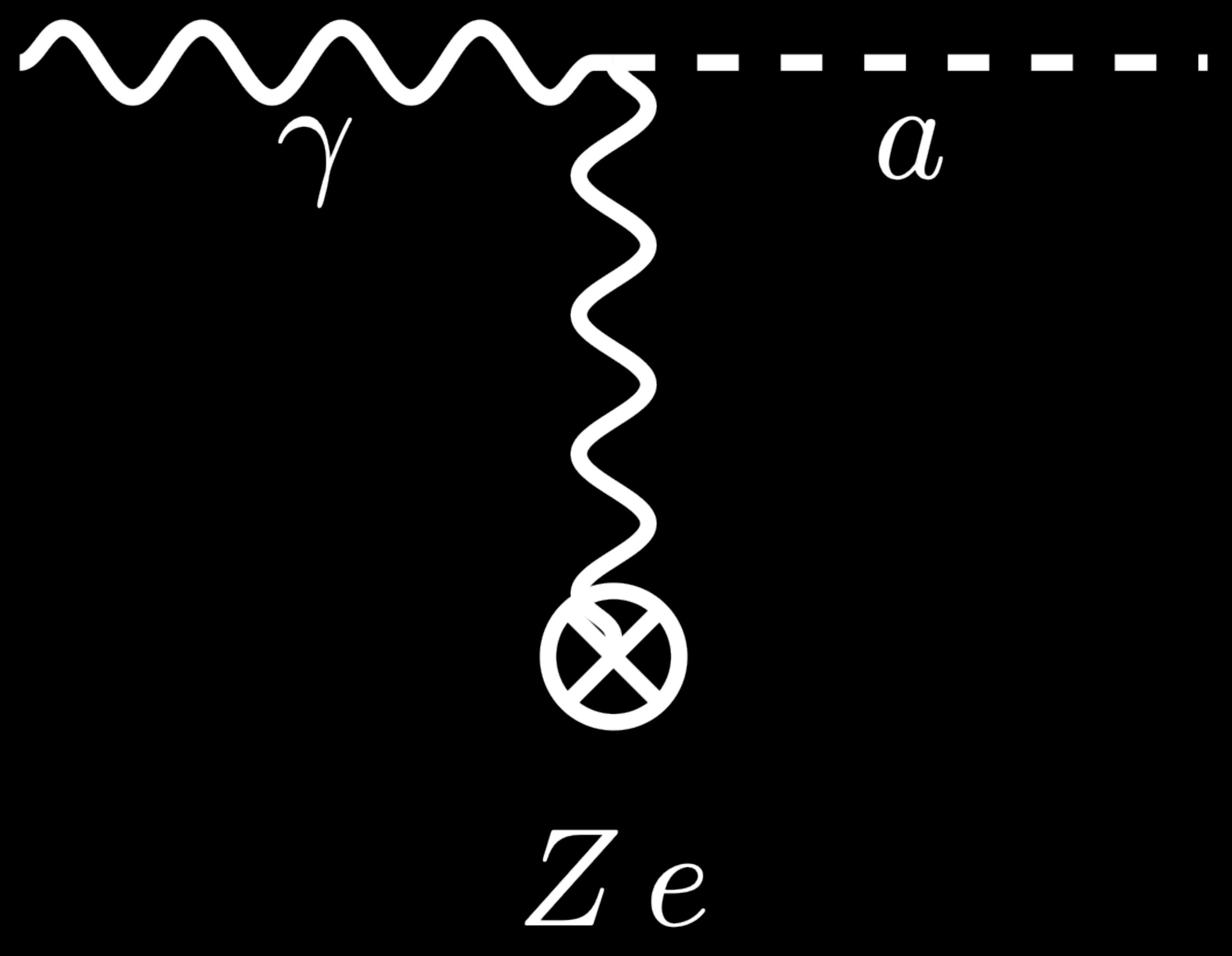
RUTGERS

Credit: Chandra X-ray Observatory

Axion

- Light pseudoscalar boson
- Addresses the strong CP problem
- Dark matter candidate

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



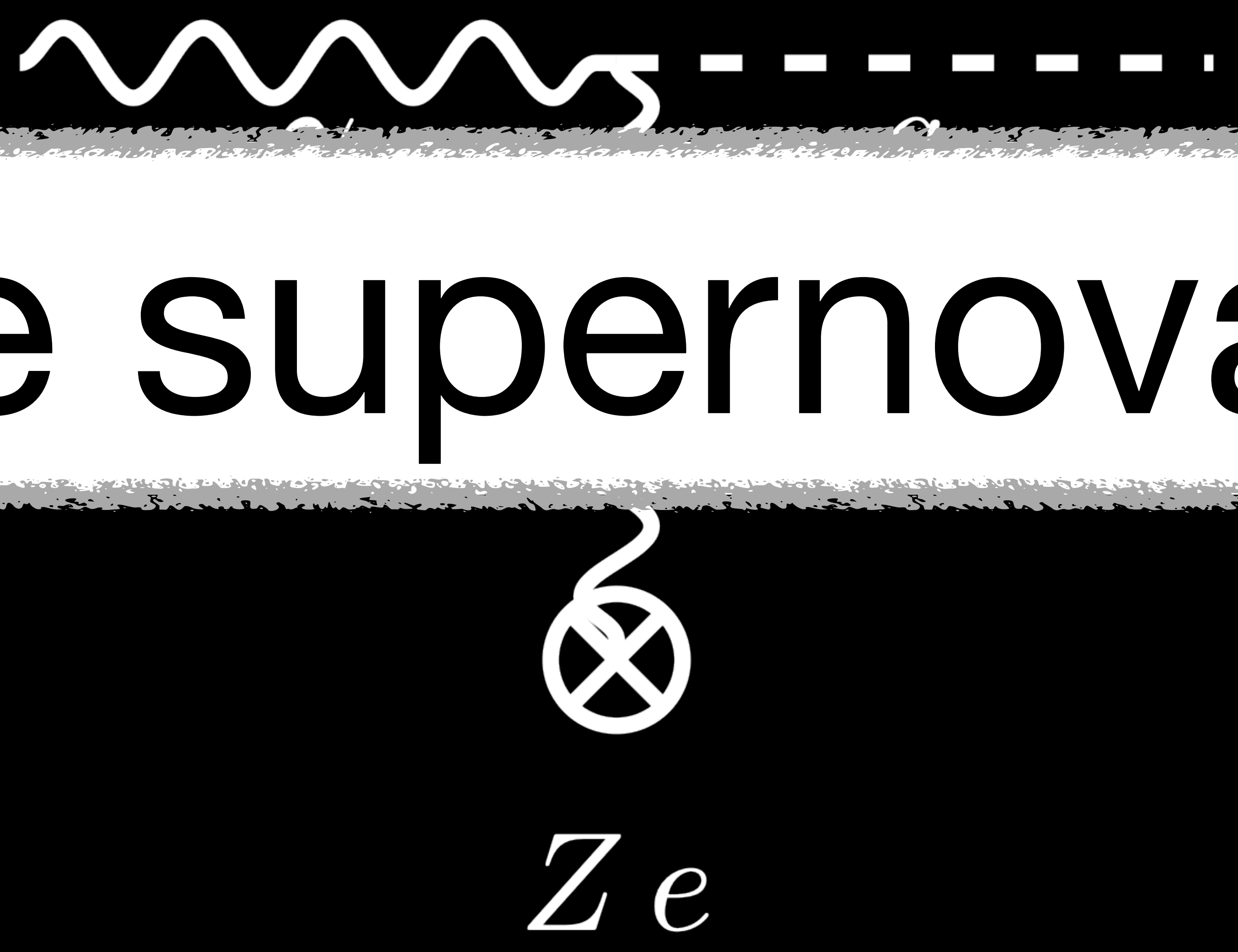
Ex. Primakoff

Axion

- Light pseudoscalar boson
- Addresses the strong CP problem

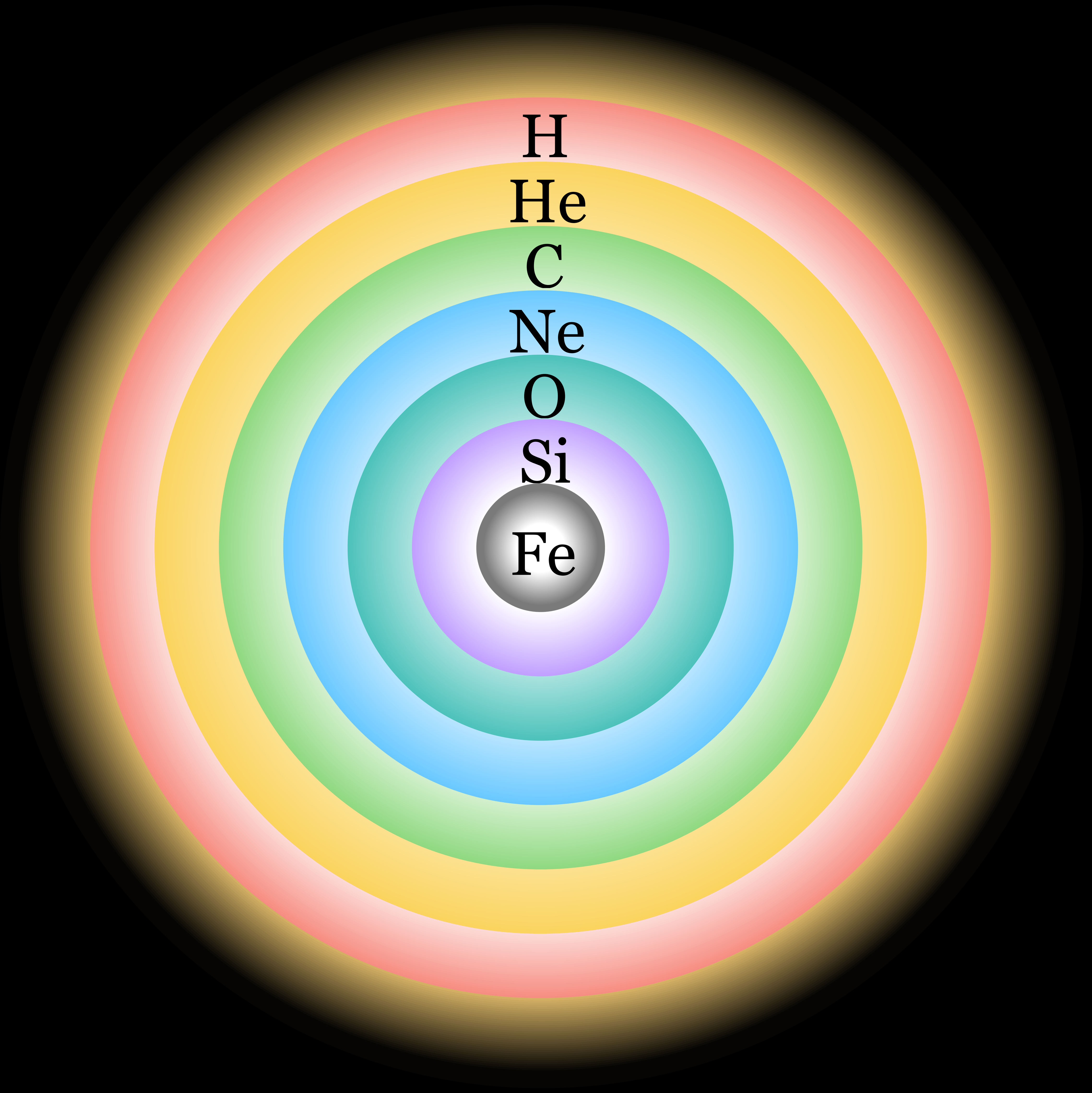
Search in core-collapse supernovae

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



Ex. Primakoff

Core-collapse supernovae



Core-collapse supernovae

Core collapse
without fusion to
support pressure

Core-collapse supernovae

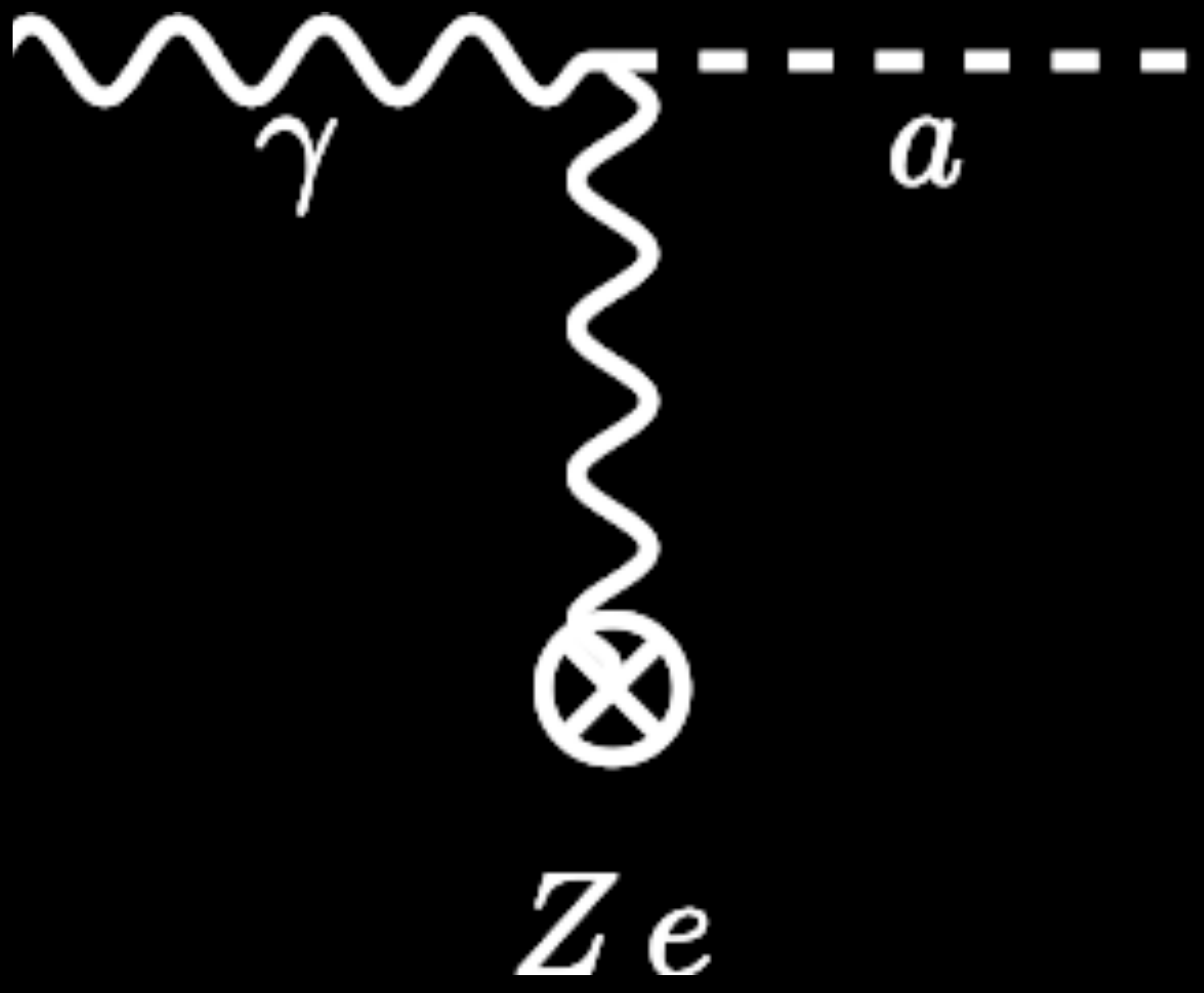
Core-collapse supernovae

Core-collapse supernovae

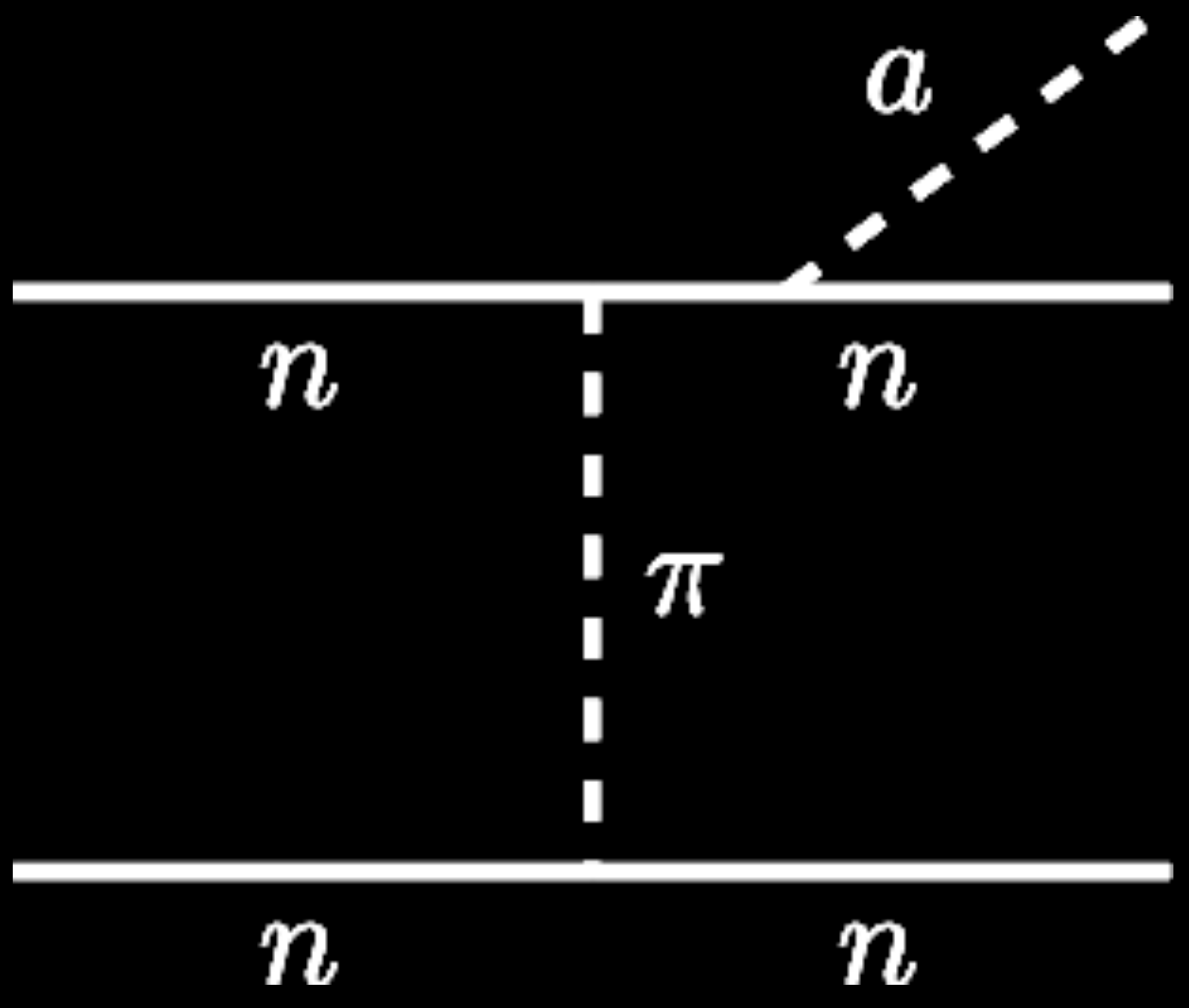
Core collapse without fusion to support pressure

Previously in TeVPA 2024..

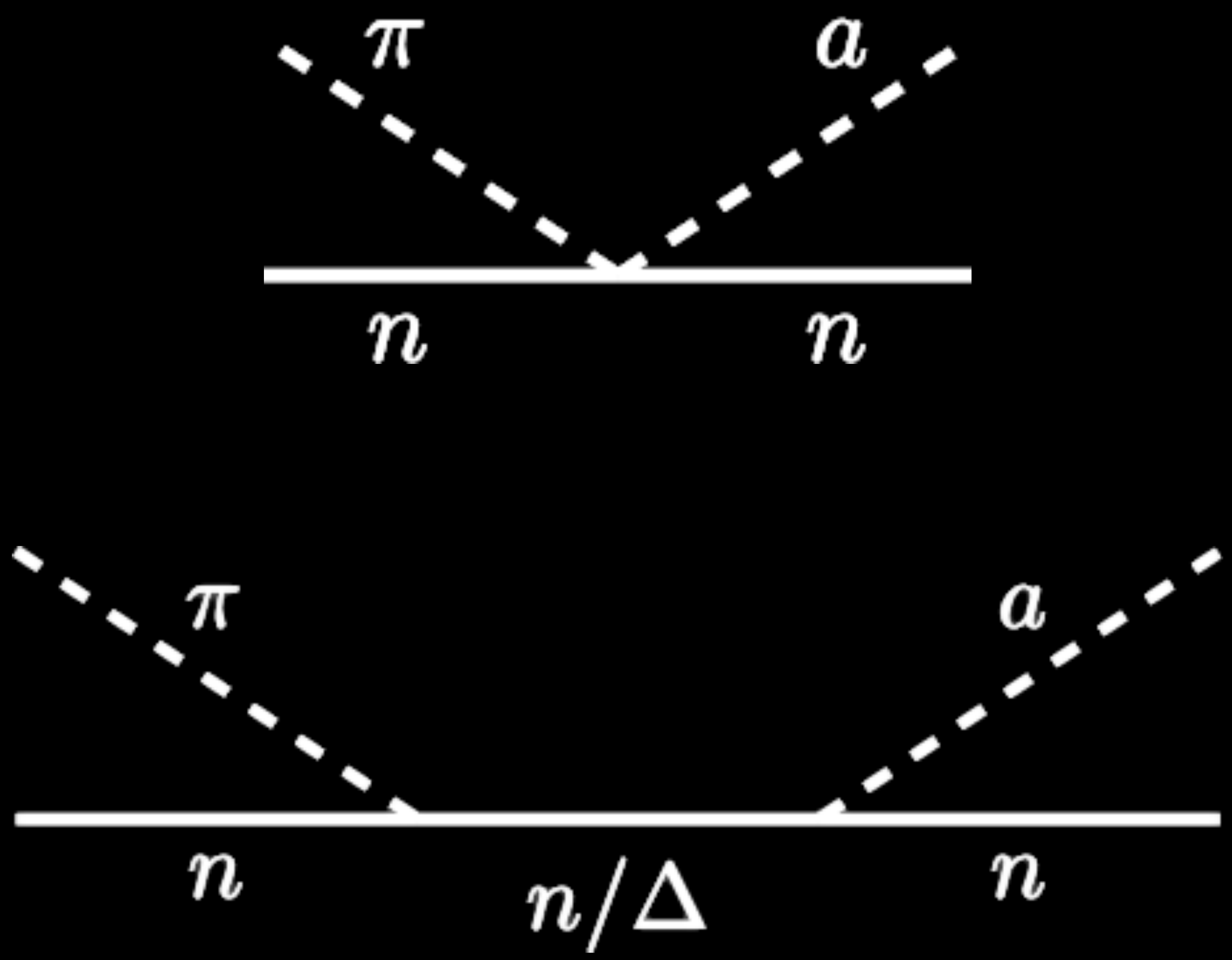
Light axion production



Primakoff



Nucleon bremsstrahlung

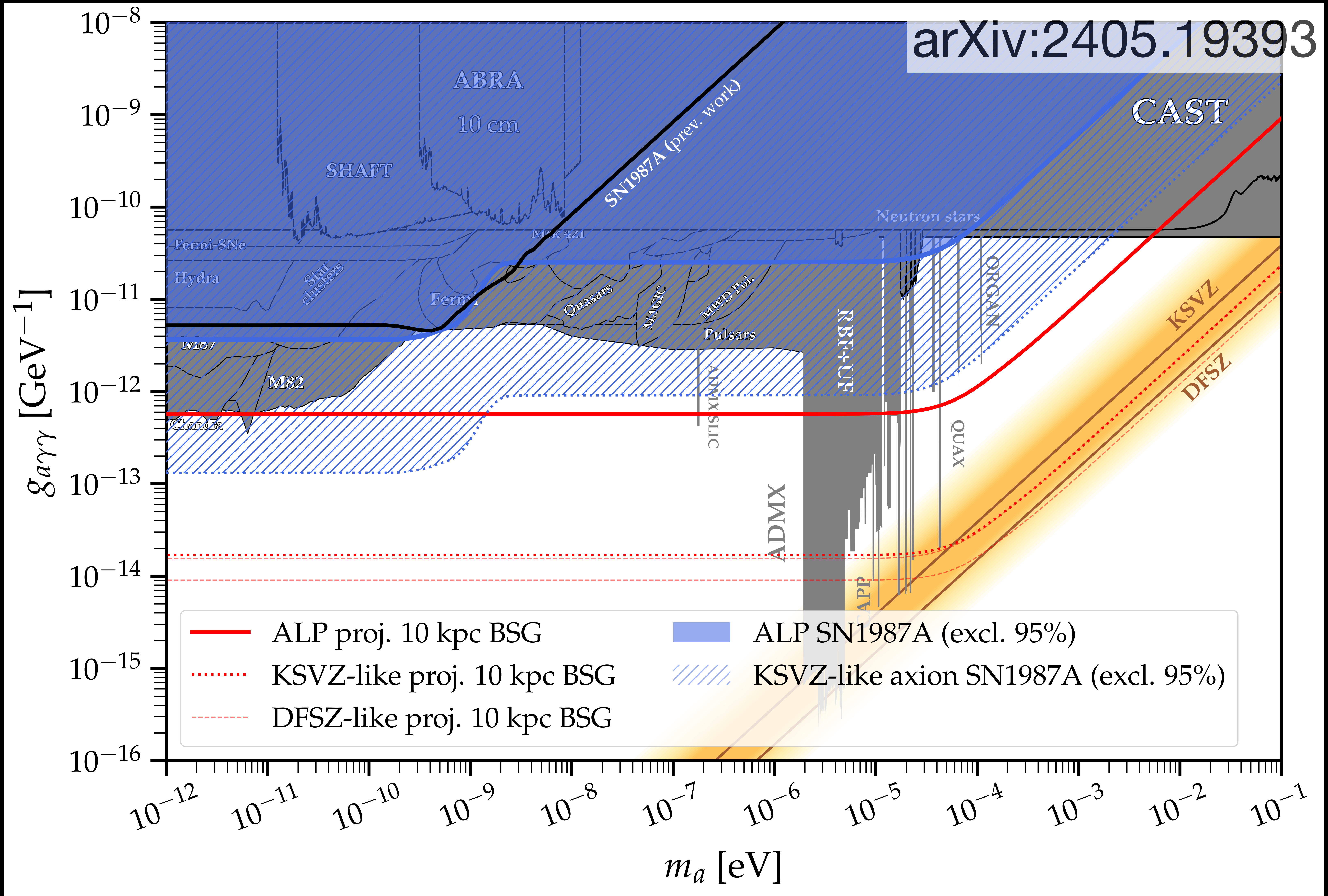


Pion conversion

Along with conversion in progenitor magnetic field…

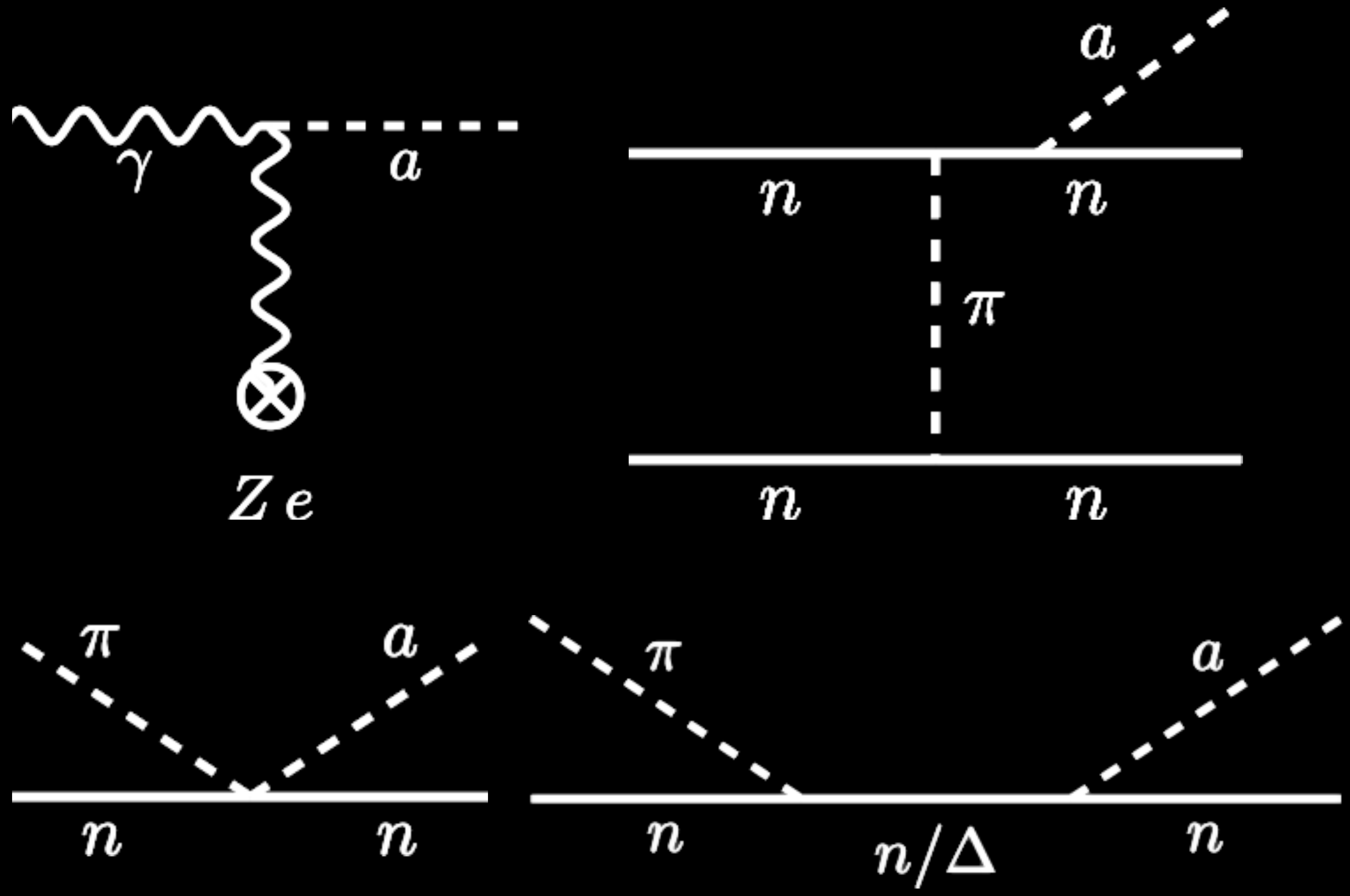
Previously in TeVPA 2024..

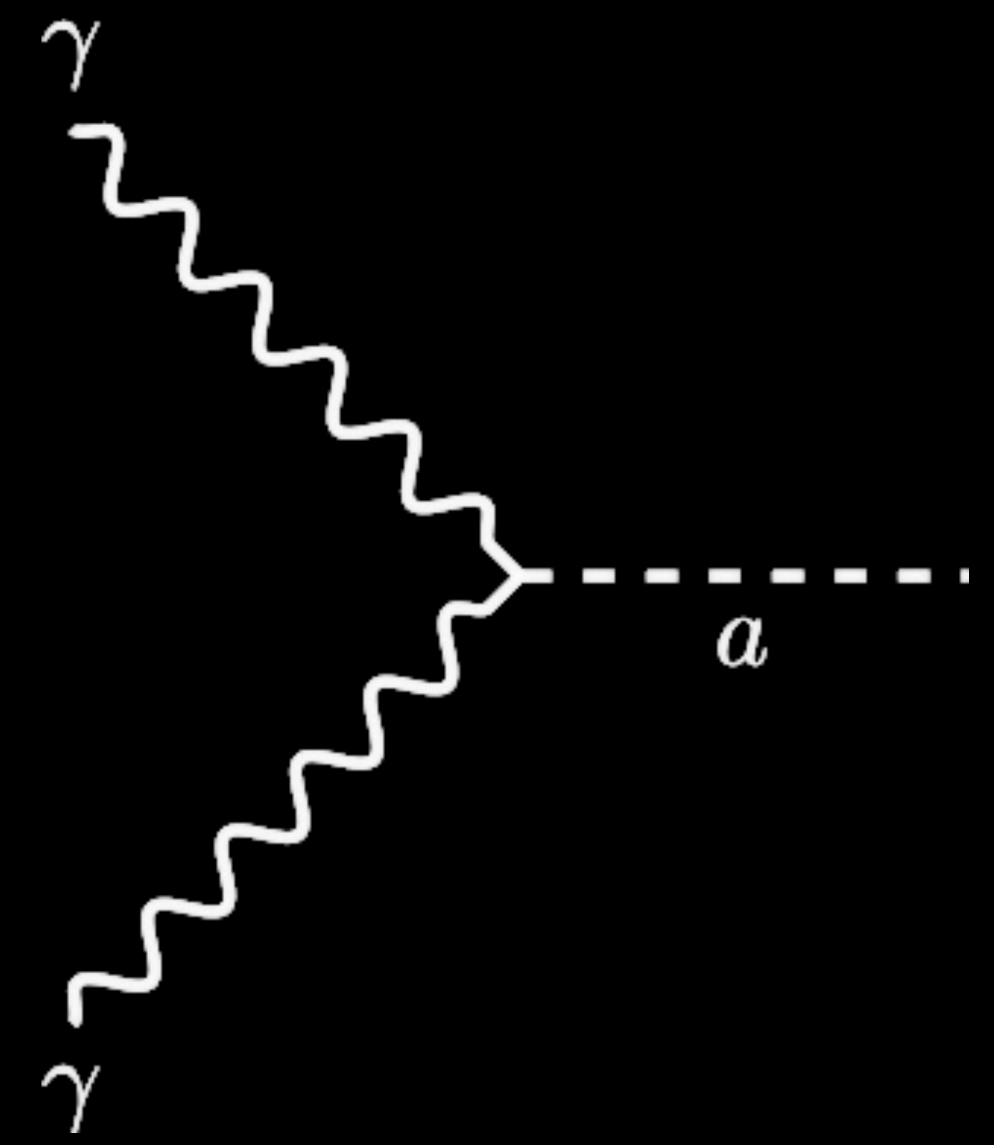
Bounds in parameter space



Shift to higher masses

Heavy axion production

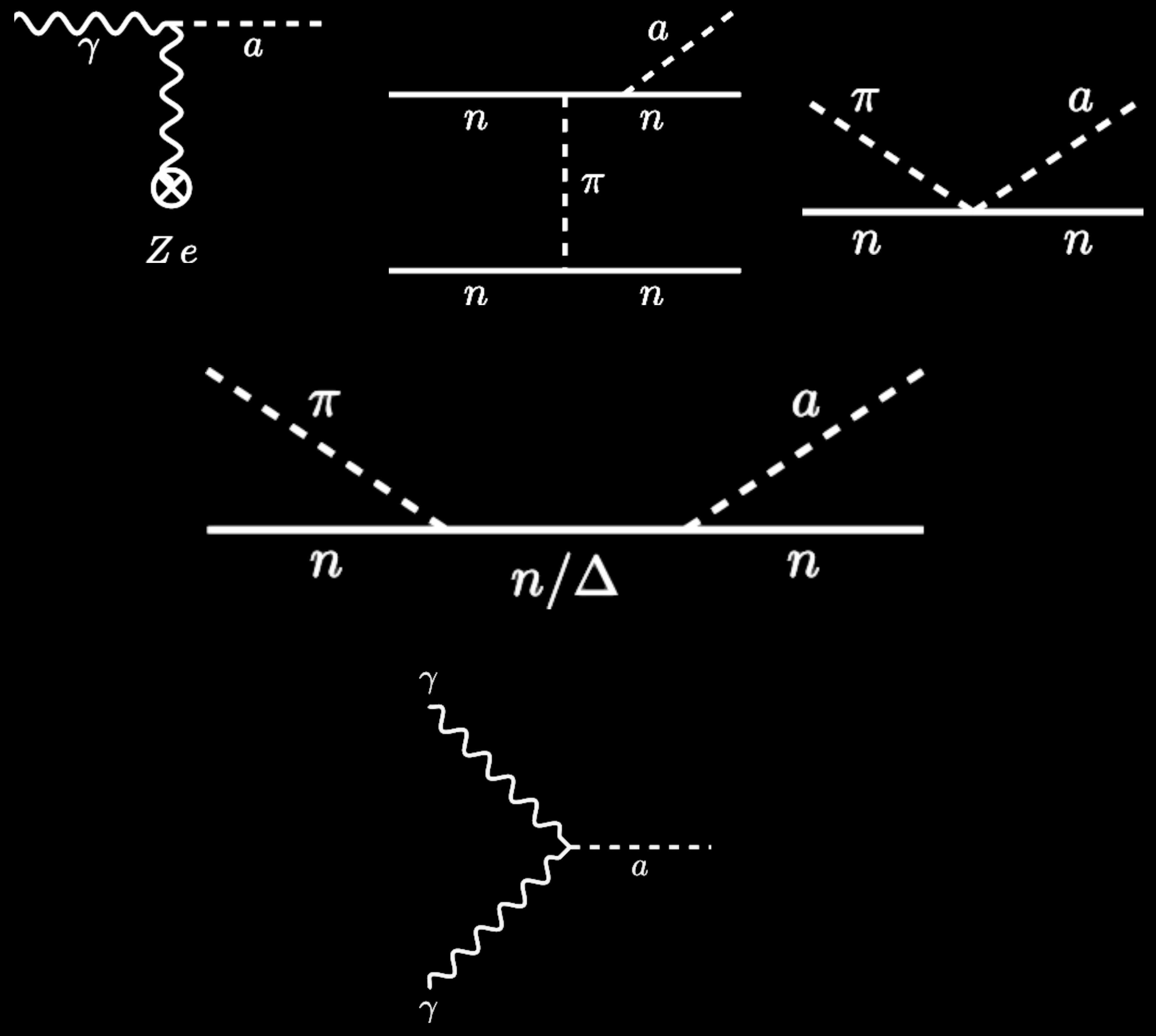




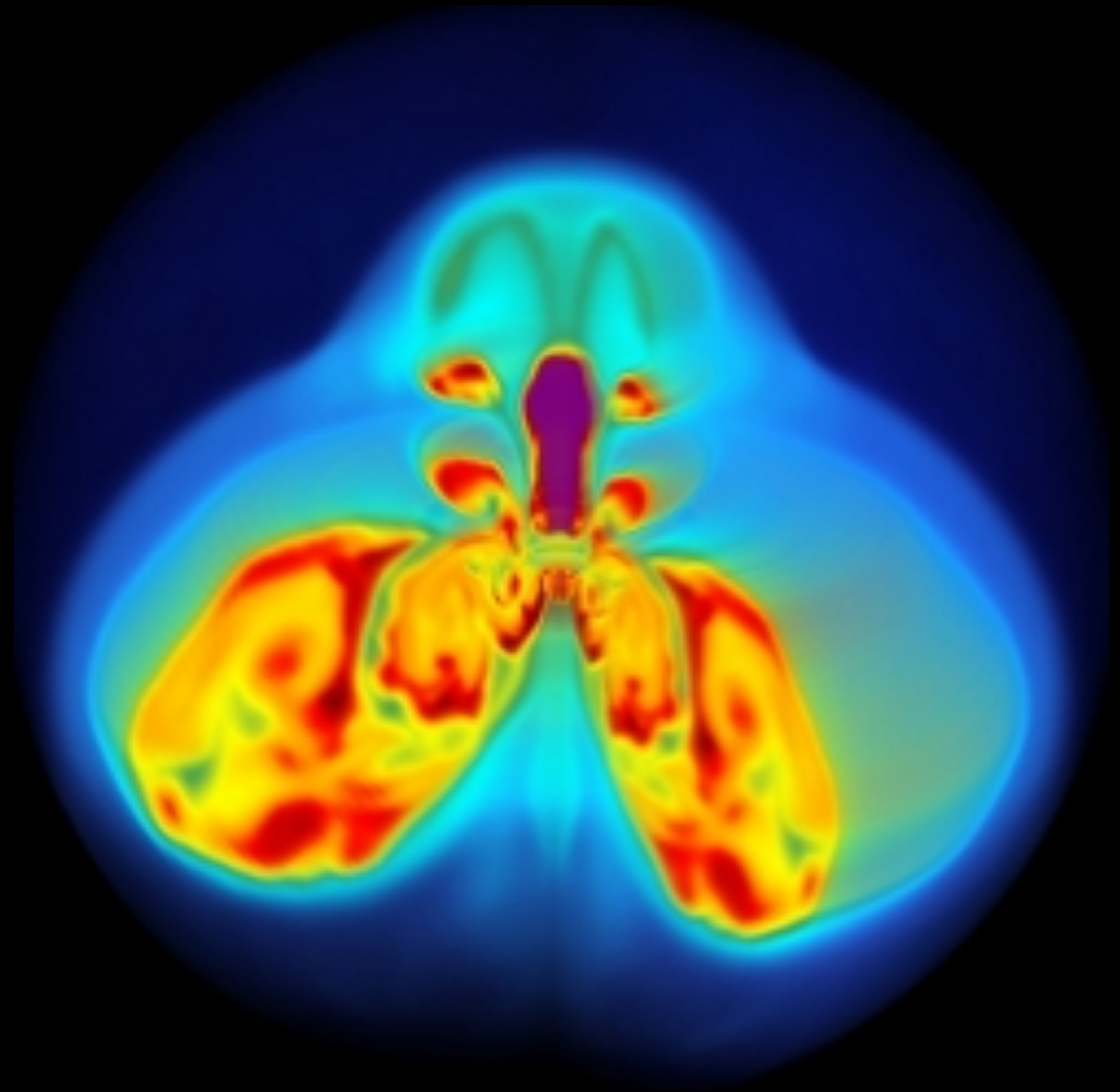
Photon coalescence

Heavy axion spectrum

Production mechanism



Supernova simluations

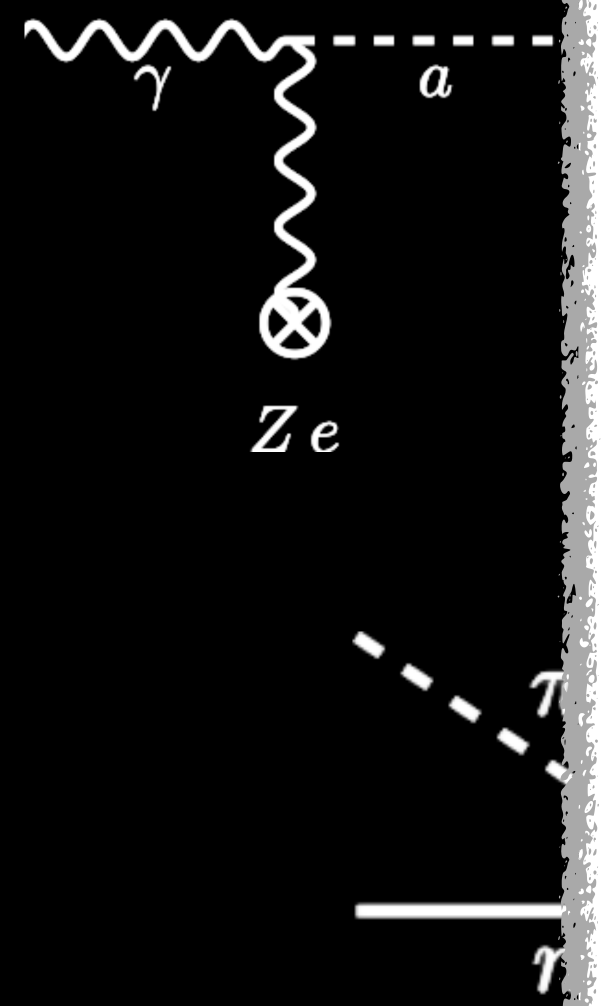


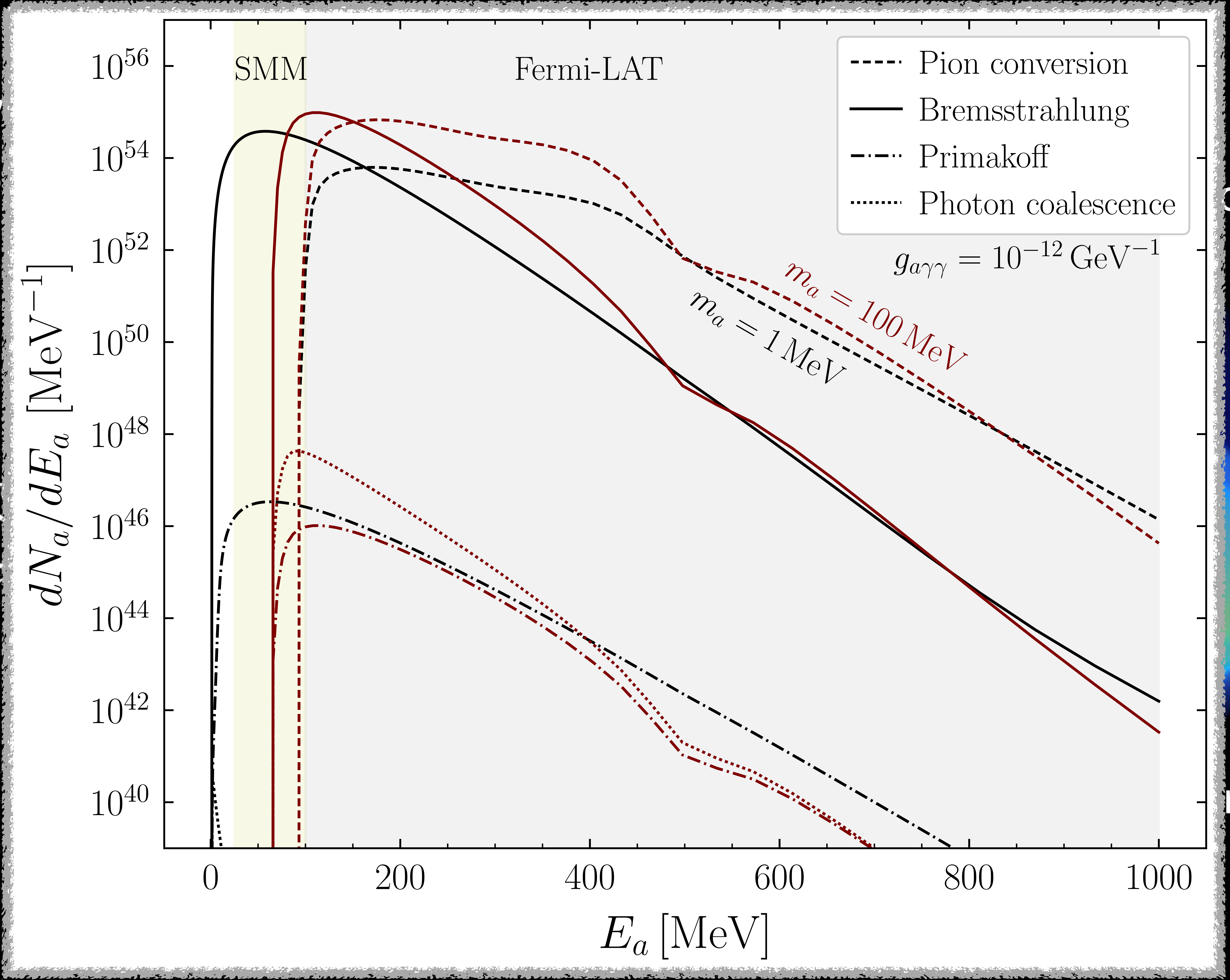
Garching Core Collapse Supernova Archive

SFHo-18.6, SFHo-18.8, SFHo-20.0

Heav

P ons



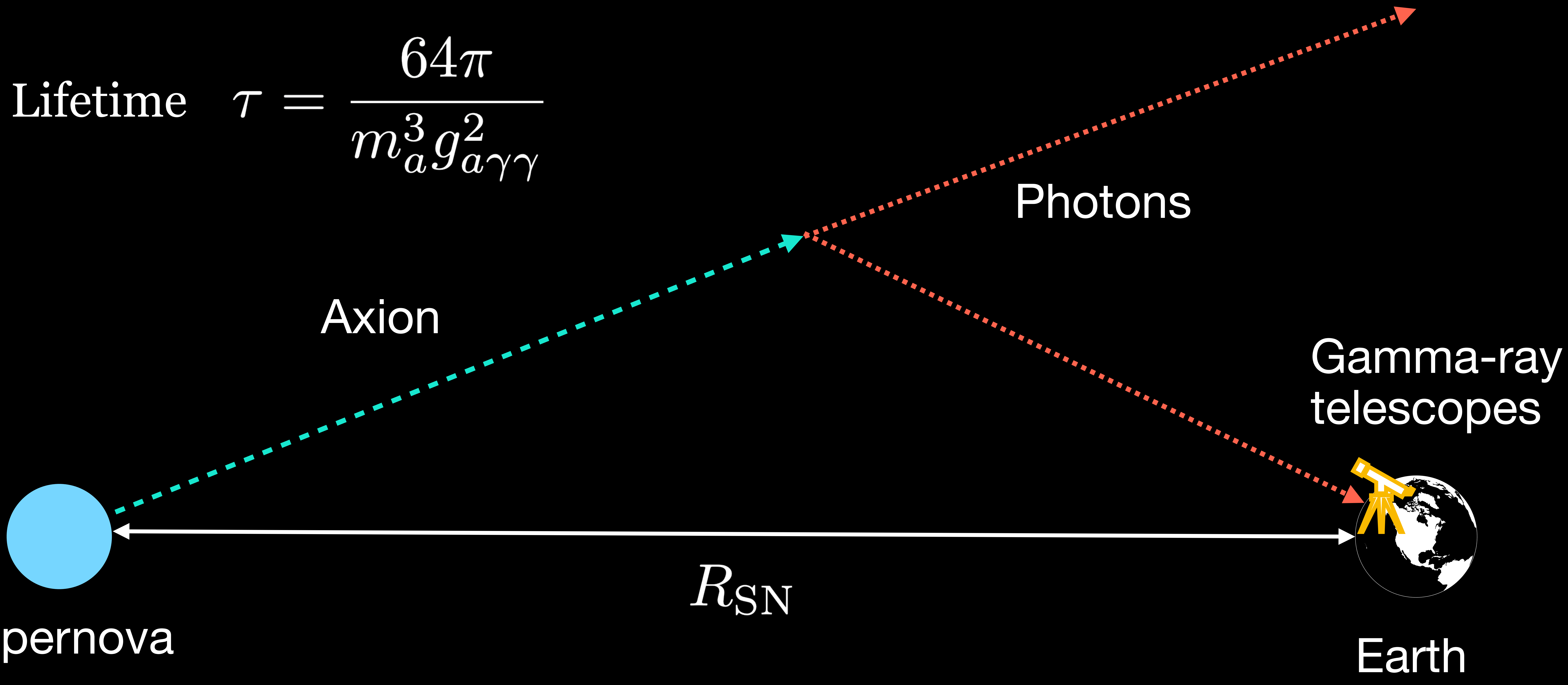


rnova Archive

Heavy axion decay

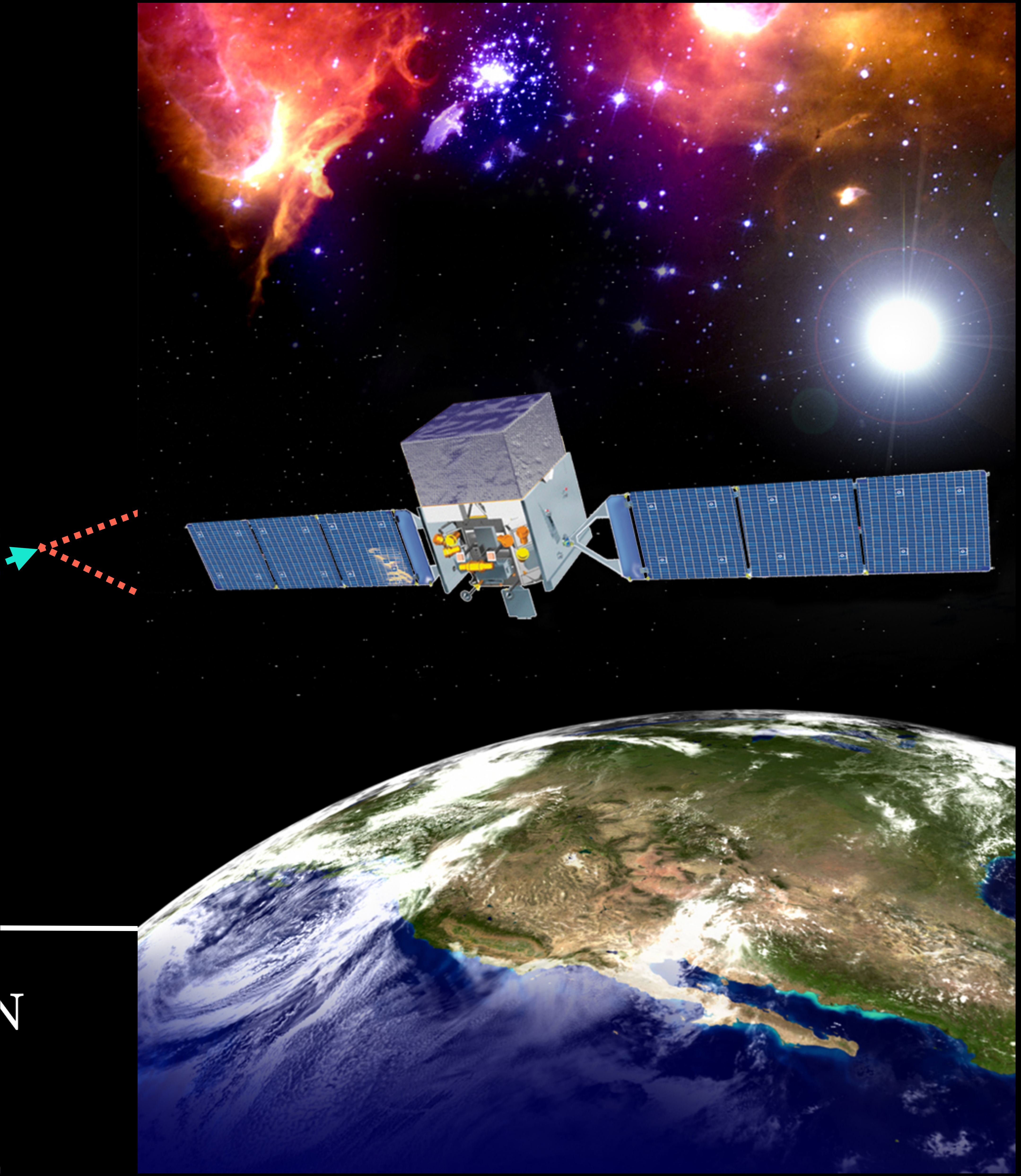
Schematic

Lifetime $\tau = \dfrac{64\pi}{m_a^3 g_{a\gamma\gamma}^2}$



Heavy axion decay
Schematic

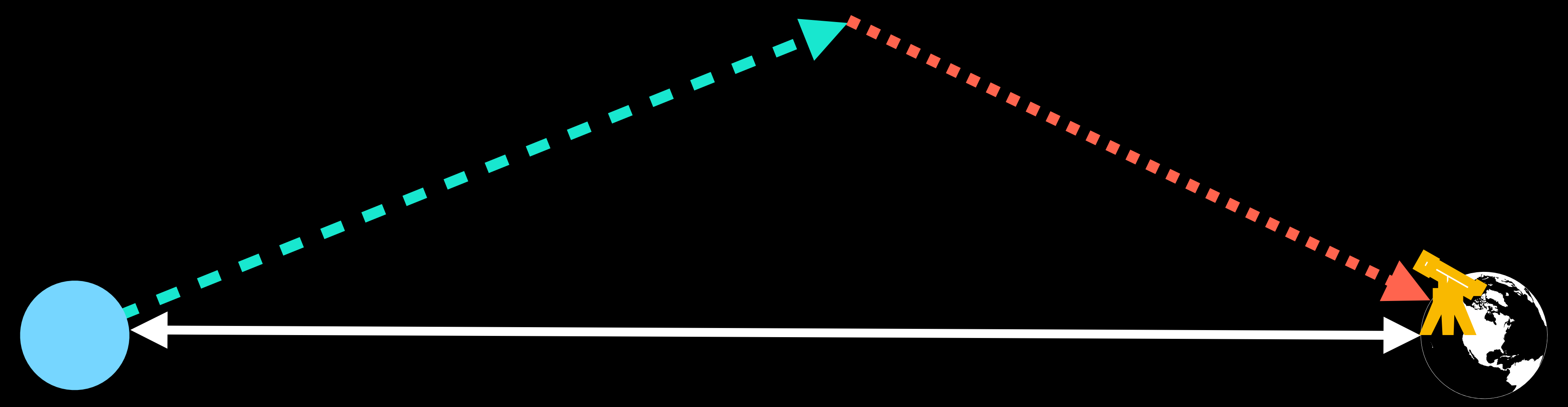
Solar Maximum Mission (credit:NASA)



Fermi Telescope (credit:NASA)

Heavy axion decay

Differential gamma-ray flux

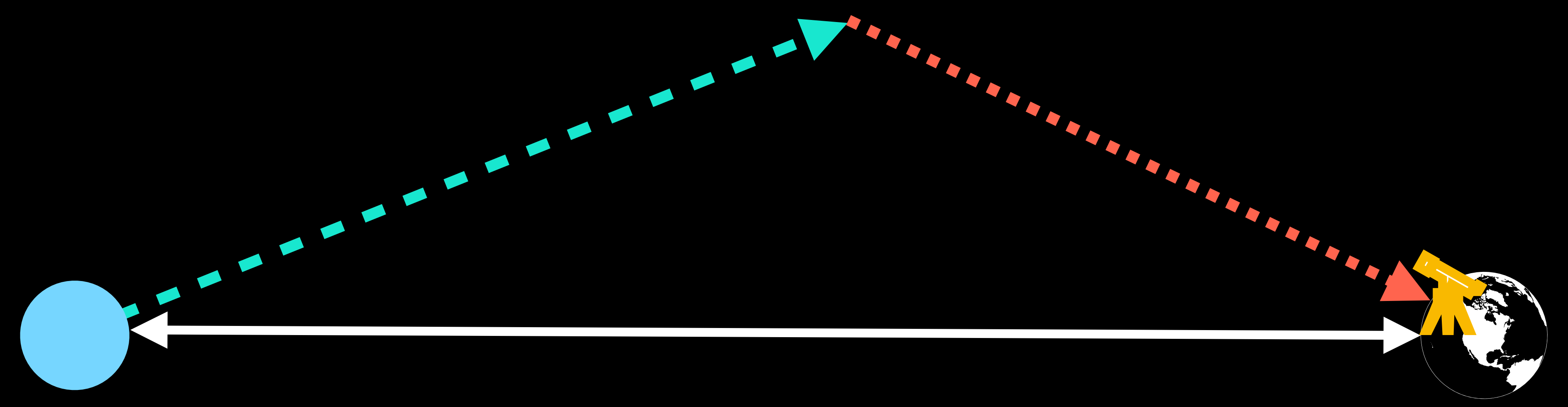


$$\frac{\mathrm{d}^3 F_\gamma}{\mathrm{d}E_\gamma \mathrm{d}t\ \mathrm{d}c_\theta} = \frac{2}{\tau_{a\to\gamma\gamma}} \frac{|c_\theta|}{(t/R_{\mathrm{SN}} + 1 - c_\theta)^2} \frac{\mathrm{d}N_a/\ \mathrm{d}E_a}{4\pi R_{\mathrm{SN}}^2}$$

$$\times \frac{m_a}{p_a} \exp\left[-\frac{R_{\mathrm{SN}}}{\tau_a}\frac{2E_\gamma}{m_a}\left(\frac{t}{R_{\mathrm{SN}}} + 1 - c_\theta\right)\right] \Theta_{\mathrm{cons.}}\ (E_\gamma, t, c_\theta)$$

Heavy axion decay

Differential gamma-ray flux



Axion emission

$$\frac{\mathrm{d}^3 F_\gamma}{\mathrm{d}E_\gamma \mathrm{d}t\ \mathrm{d}c_\theta} = \frac{2}{\tau_{a\to\gamma\gamma}} \frac{|c_\theta|}{\left(t/R_{\mathrm{SN}} + 1 - c_\theta\right)^2} \frac{\boxed{\mathrm{d}N_a/\ \mathrm{d}E_a}}{4\pi R_{\mathrm{SN}}^2}$$

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Heavy axion decay

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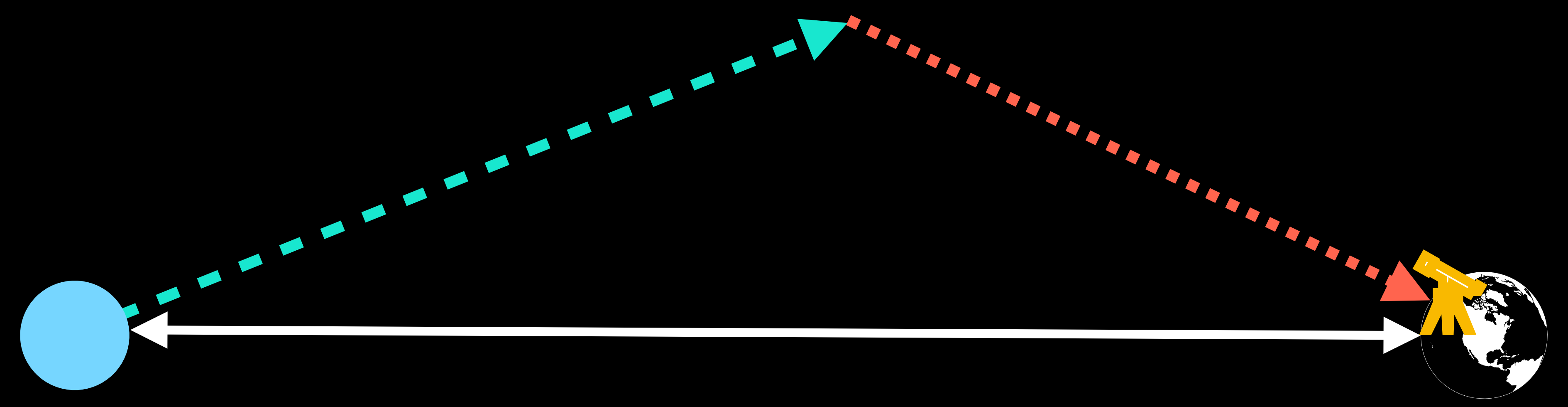

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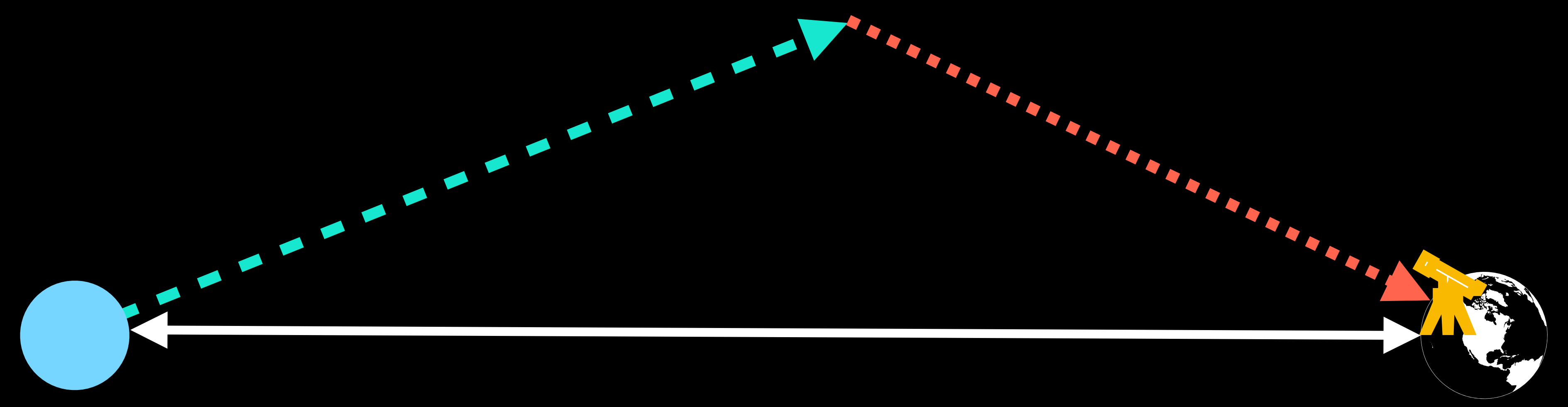
Exponential decay of axions

Heavy axion decay

Differential gamma-ray flux



Axion emission

$$\frac{\mathrm{d}^3 F_\gamma}{\mathrm{d}E_\gamma \mathrm{d}t\ \mathrm{d}c_\theta} = \frac{2}{\tau_{a\to\gamma\gamma}} \frac{|c_\theta|}{(t/R_{\mathrm{SN}}+1-c_\theta)^2} \frac{\boxed{\mathrm{d}N_a/\ \mathrm{d}E_a}}{4\pi R_{\mathrm{SN}}^2}$$

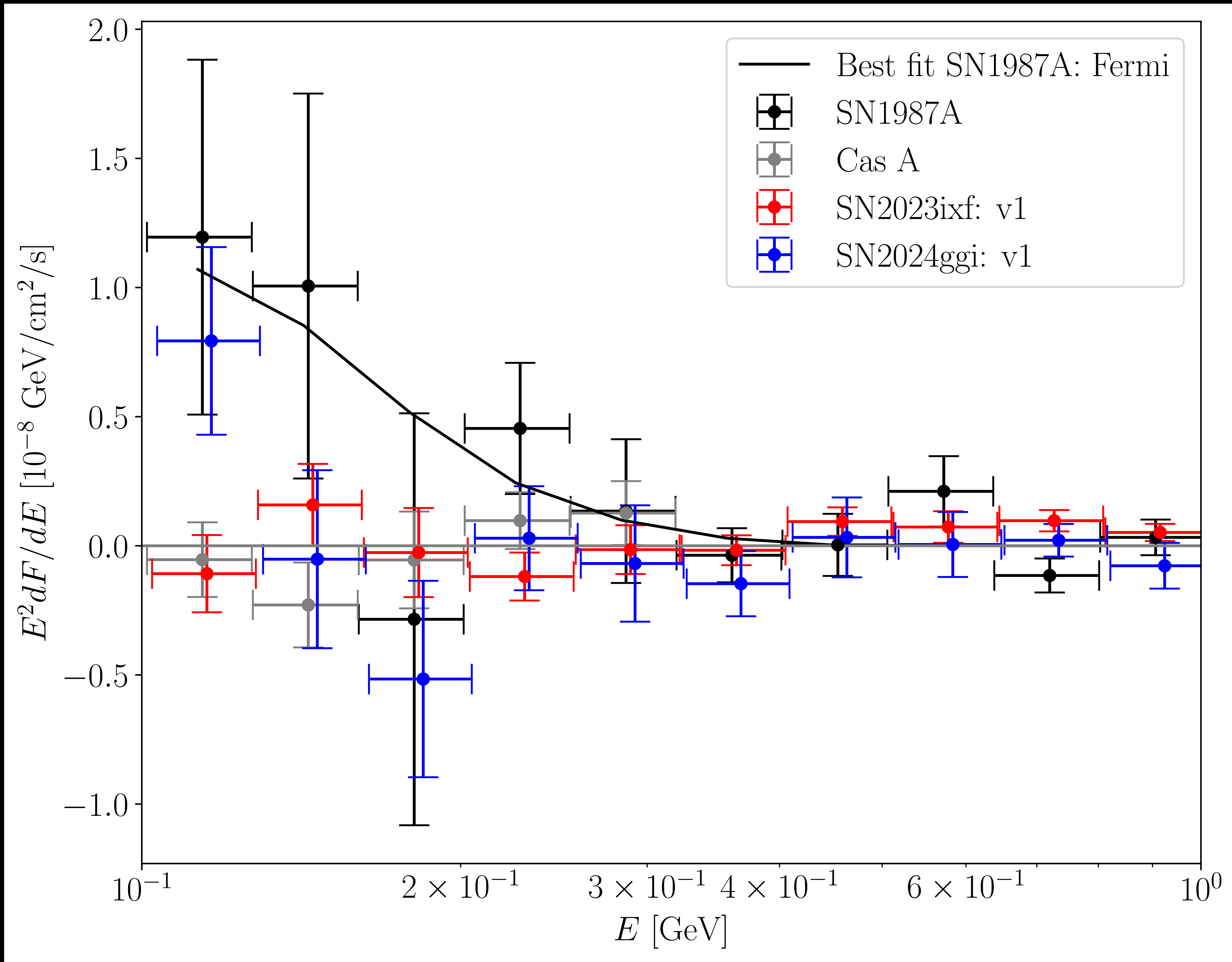
$$\times \frac{m_a}{p_a} \boxed{\exp\left[-\frac{R_{\mathrm{SN}}}{\tau_a}\frac{2E_\gamma}{m_a}\left(\frac{t}{R_{\mathrm{SN}}}+1-c_\theta\right)\right]} \boxed{\Theta_{\mathrm{cons.}}\ (E_\gamma, t, c_\theta)}$$

Exponential decay of axions

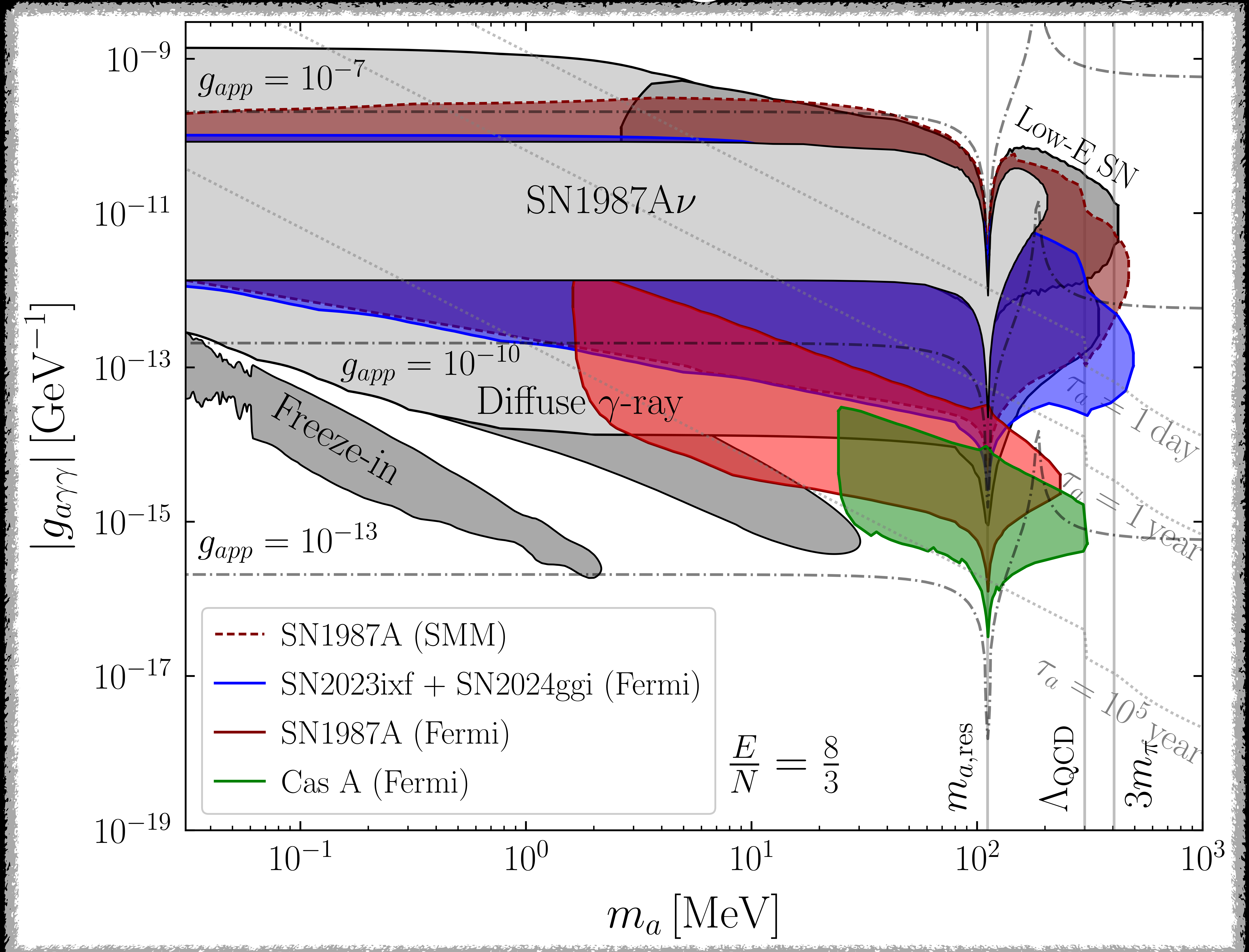
Enforces decay outside the photosphere

Fermi data analysis

- Fermi observation for different SN
- Full archive used for SN1987A and Cas A
- Data in relevant time windows used for SN2023ixf and SN2024ggi

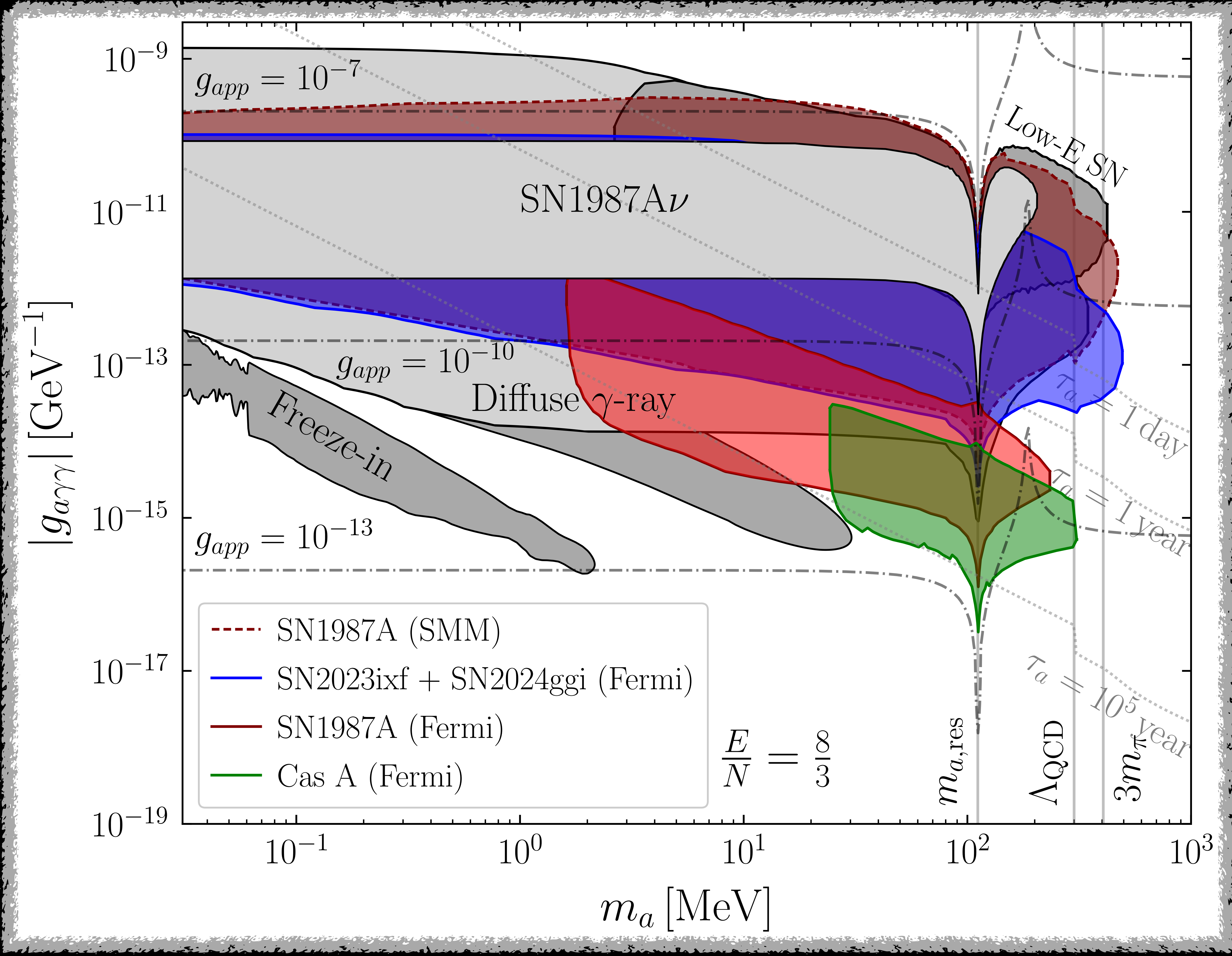


Exclusion from absent gamma-rays



Summary

- Heavy axion produced from supernovae
- Decay to photons and give time-delayed signals
- No evidence of gamma-ray excess and excluded regions of parameter space



Back-up slides

Heavy Axion Theory

Heavy axion couples to QED and QCD through operators

$$\mathcal{L} \supset \frac{a}{F_a}\left[\frac{\alpha_{\rm em}}{8\pi} E F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{\alpha_s}{8\pi} N G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right]$$

E : electromagnetic anomaly coefficient

N : color anomaly coefficient

$$\frac{E}{N} = \frac{8}{3}$$ Used as benchmark

Heavy Axion Theory

Vanishing photon coupling

$$g_{a\gamma\gamma} \equiv \frac{\alpha_{\mathrm{EM}}}{2\pi f_a} C_{a\gamma\gamma}$$

$$C_{a\gamma\gamma}(\mu > \Lambda_{\mathrm{QCD}}) = \frac{E}{N}$$

$$C_{a\gamma\gamma}(\mu < \Lambda_{\mathrm{QCD}}) \simeq \frac{E}{N} - 1.92 - \frac{m_a^2}{m_\pi^2 - m_a^2}\left[\frac{m_d - m_u}{m_d + m_u} + \frac{C_{auu}(2\mathrm{GeV}) - C_{add}(2\mathrm{GeV})}{2}\right]$$

$C_{a\gamma\gamma}$ disappears at $m_{a,\mathrm{res}}$

$$m_{a,\mathrm{res}} \approx m_\pi \left[1 + \frac{m_d - m_u}{m_d + m_u}(E/N - 1.92)^{-1}\right]^{-\frac{1}{2}}$$