# QCD axion coupling at finite density

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# QCD axion

- **Strong CP problem of QCD:** By observations of the neutron EDM the theta parameter is known to be $|\bar{\theta}| \lesssim 10^{-10}$

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- Most elegant solution: QCD axion with shift symmetry $a \rightarrow a + \kappa f_a$:

$$\mathscr{L}_a = \frac{1}{2}\left(\partial_\mu a\right)^2 + \mathscr{L}\left(\partial_\mu a, \psi\right) + \frac{g_s^2}{32\pi^2} \frac{a}{f_a} G\tilde{G}$$

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- **Phenomenology determined by one parameter** $f_a$
- Many ongoing experiments try to search for the (QCD) axion
- Strong bounds on $f_a$ from SN and NS cooling

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- For the KSVZ axion this corresponds to $m_a \lesssim 15\,\mathrm{meV}$

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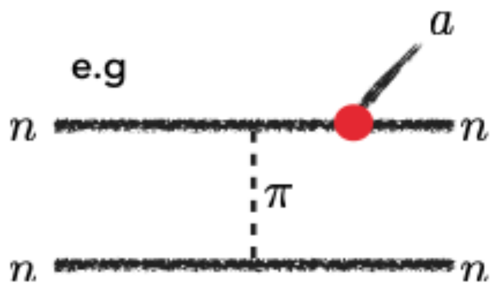


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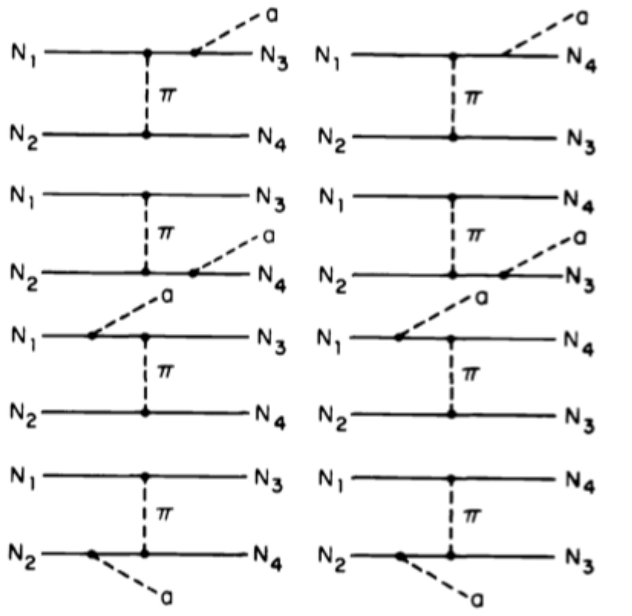

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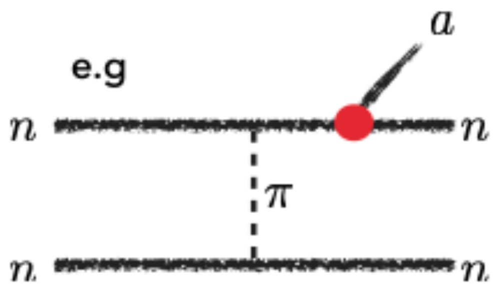


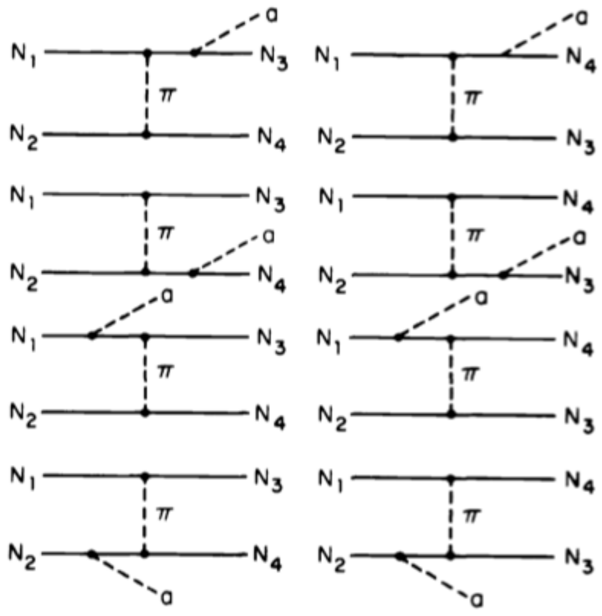

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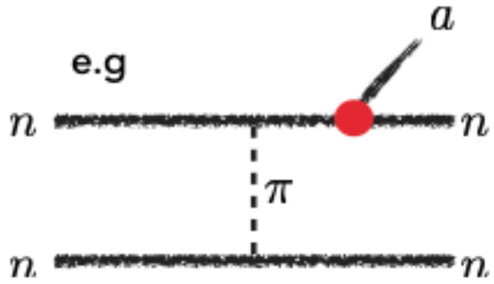
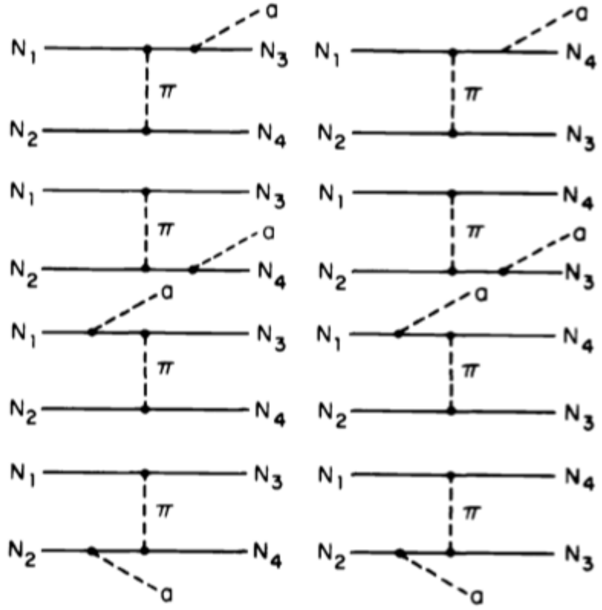
- Density effects are also highly relevant for **<u>neutron star cooling</u>**



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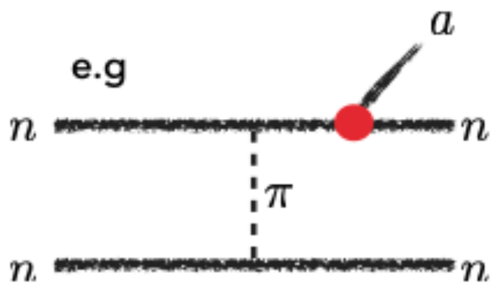


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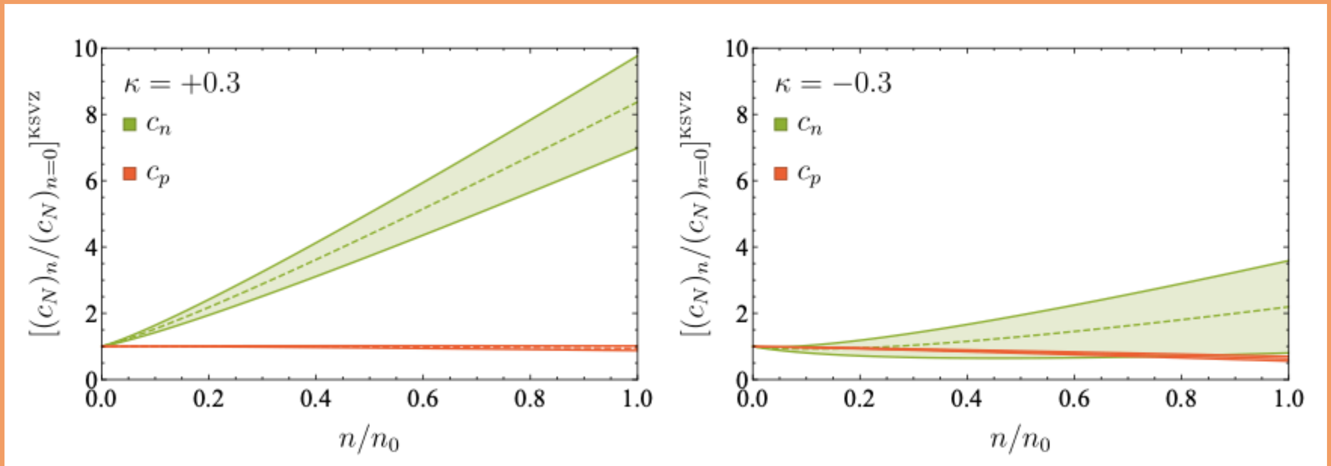
*(2003.04903)*



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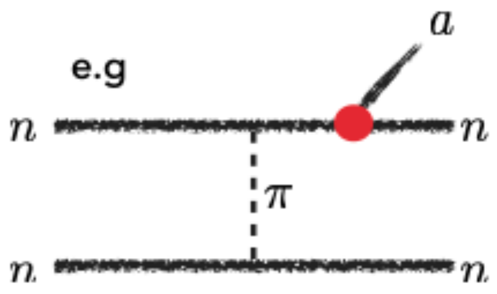


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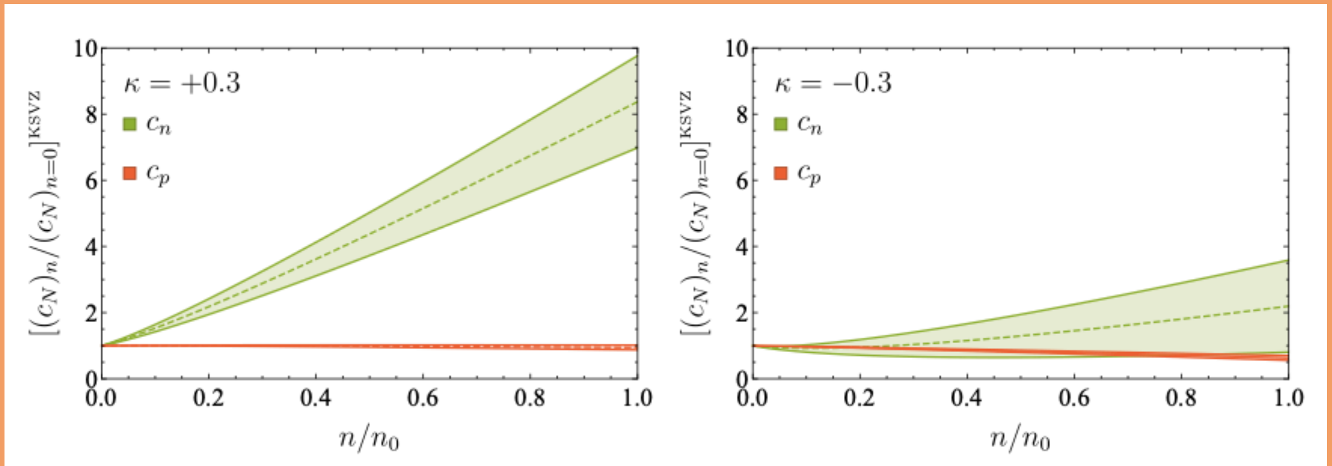


➡ **We now calculate this systematically**

# Chiral perturbation theory

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- Gauge bosons and other fields (e.g. axion, neutrino) can be consistently added to the theory

# Heavy baryon ChPT + finite density

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- Gives a systematic expansion in density $\frac{k_f^3}{(4\pi f_\pi)^2\Lambda_\chi} \sim \frac{n}{(4\pi f_\pi)^2\Lambda_\chi}$

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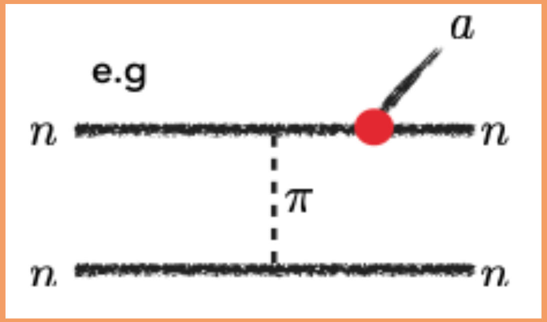
➡ **We use this to calculate the one-pion-exchange (OPE) process ($N + N \to N + N + a$) at leading order finite density**




*(Tree level OPE process)*

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- **Tree level Lagrangian**

$$\mathcal{L}^{(1)}_{\pi N} \supset g_A \bar{N} S^\mu u_\mu N + g_0^i \bar{N} S^\mu \hat{u}^i_\mu N, \quad N = (p, n)^T$$

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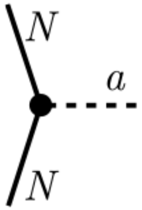


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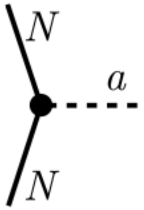


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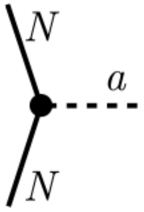


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**<u>Q: How do they look at finite density?</u>**

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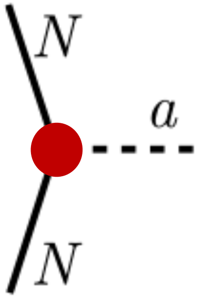

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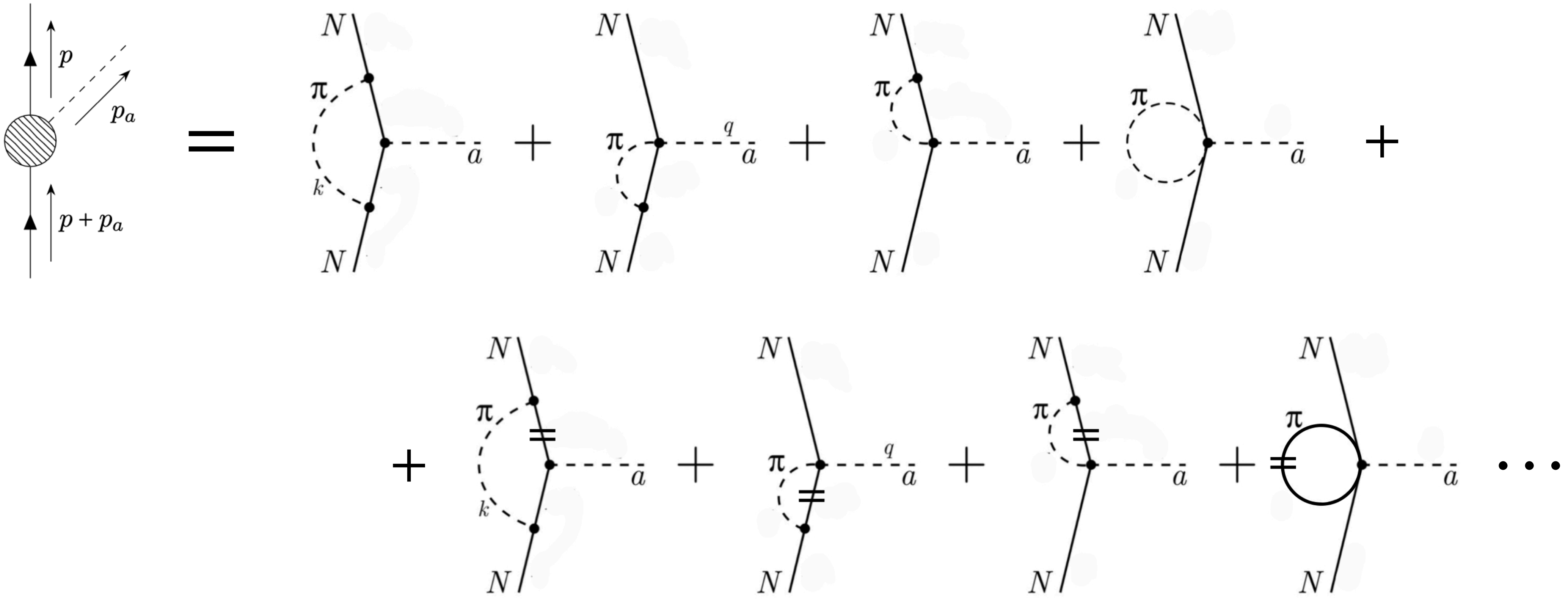

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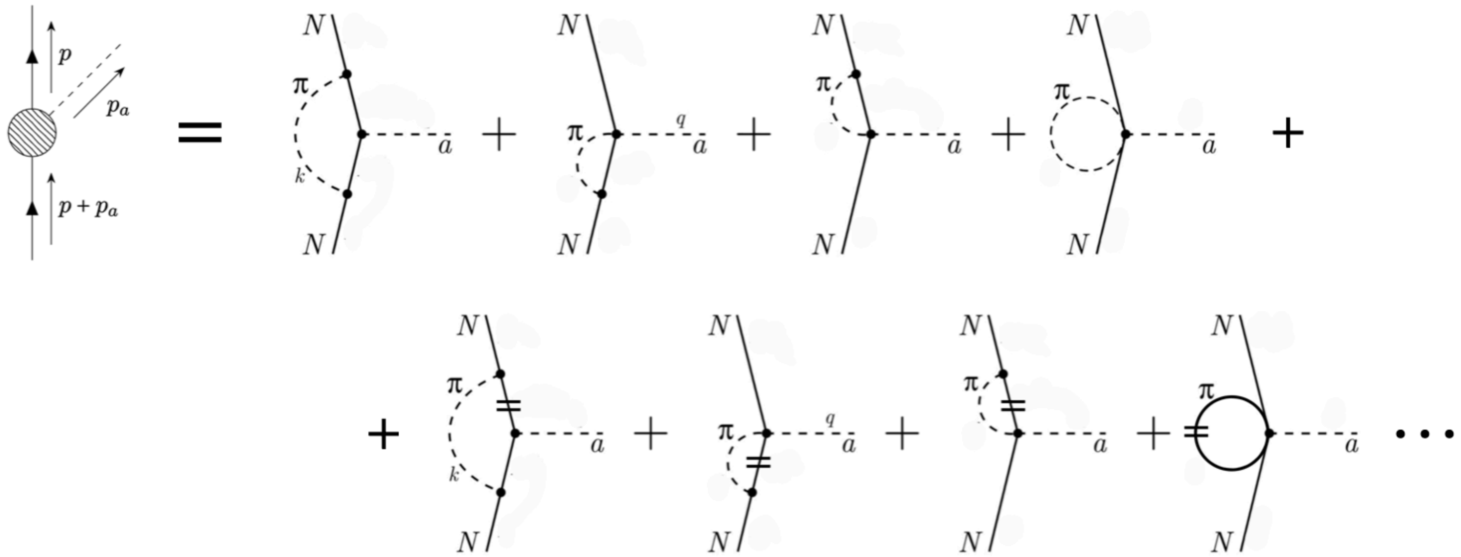

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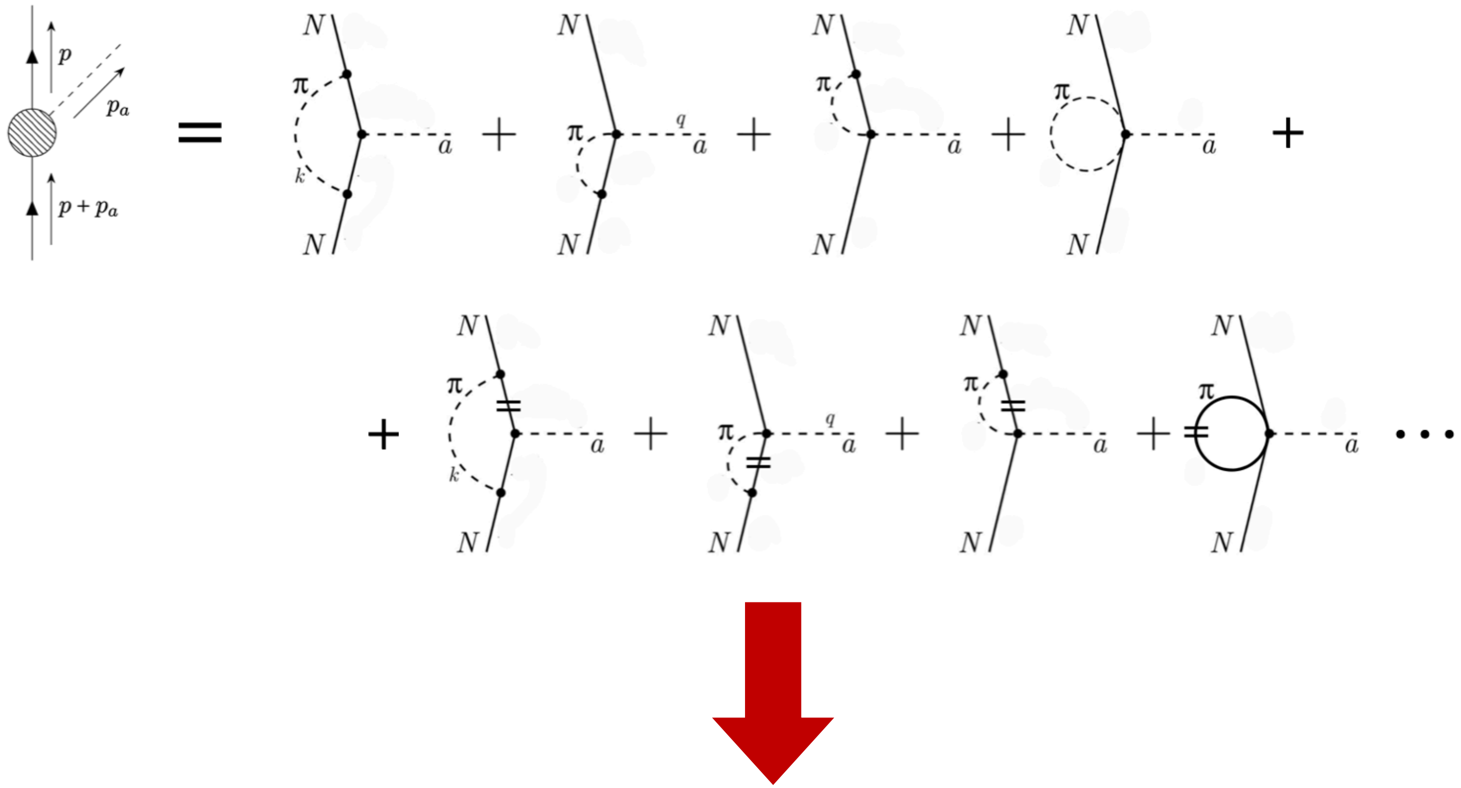


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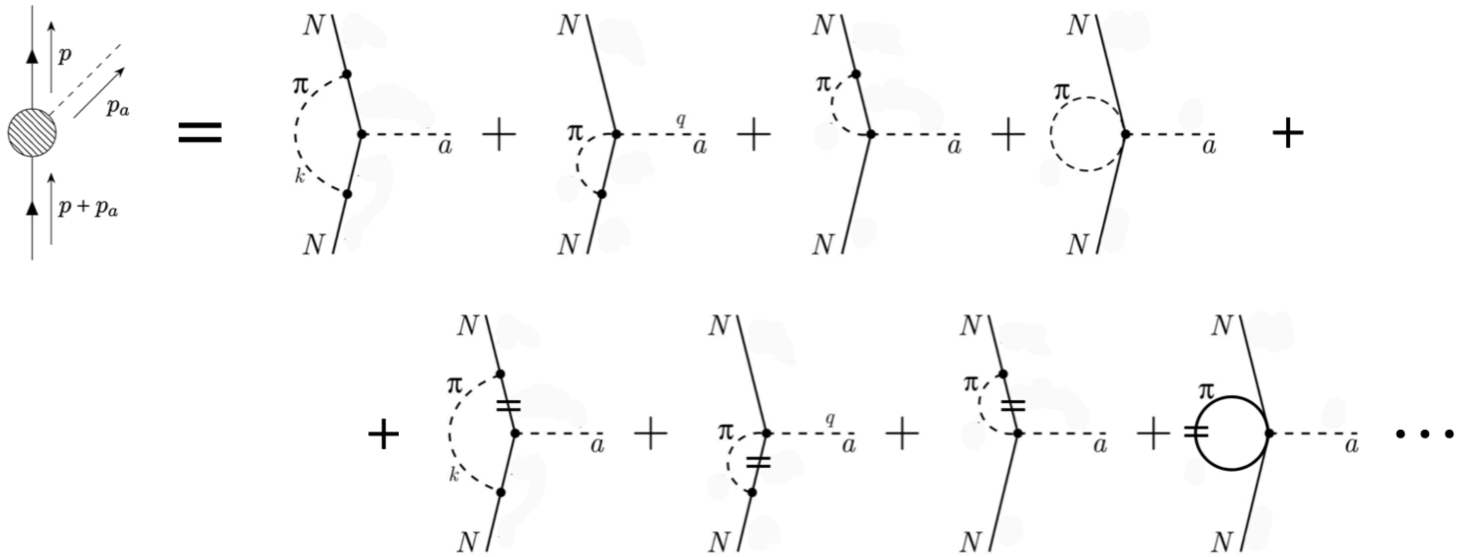


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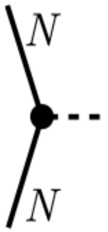
*<u>Tree level:</u>*

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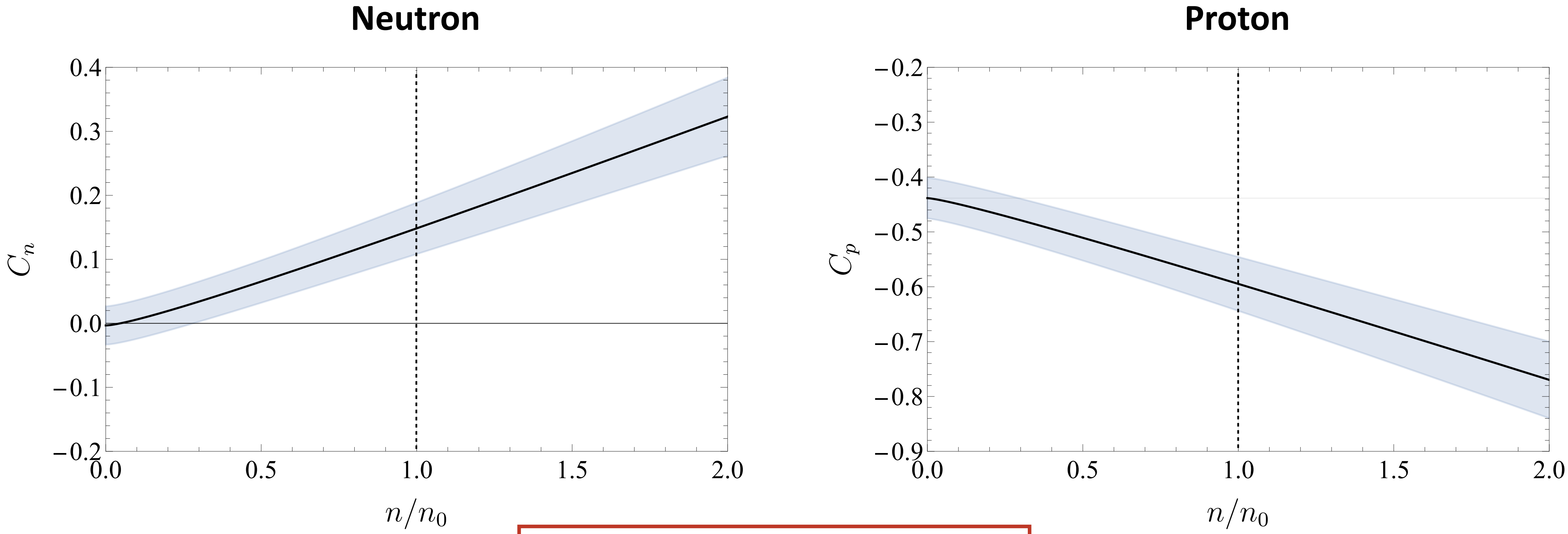


$n_0$: nuclear saturation density

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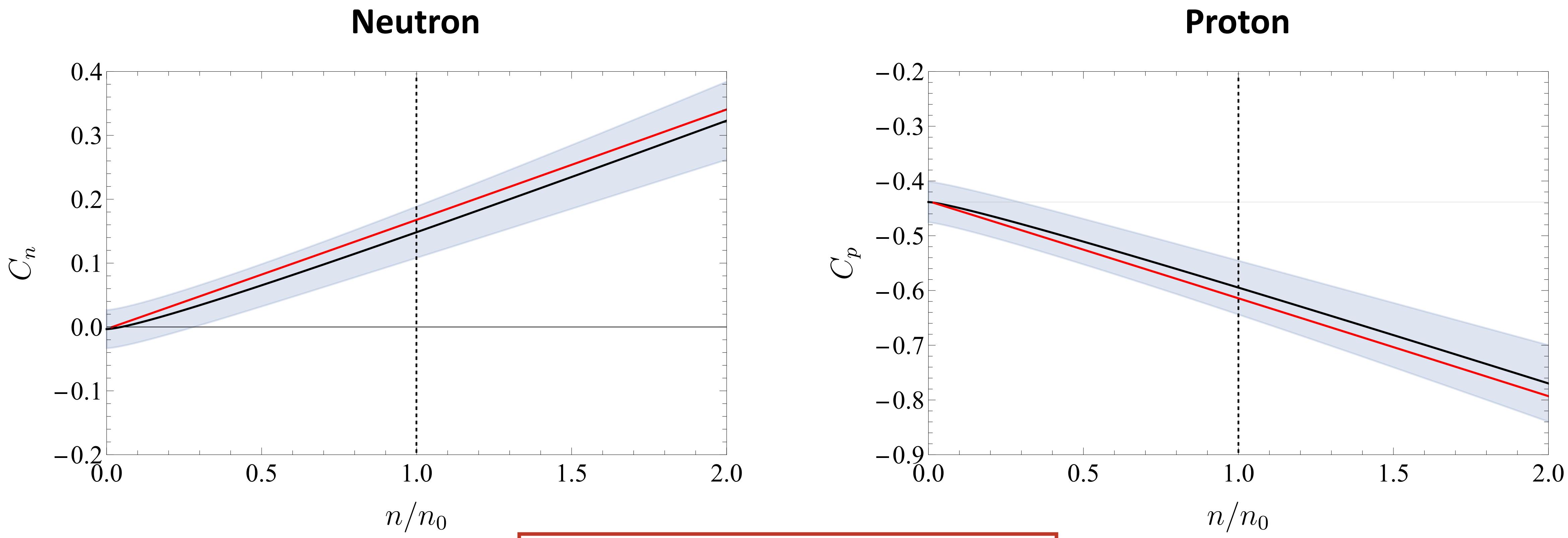
# Vertex corrections results including Temperatur

Black: $T = 0$

Red: $T = 50\,\mathrm{MeV}$

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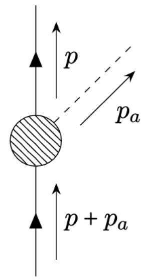


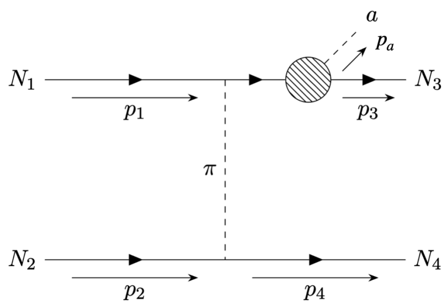

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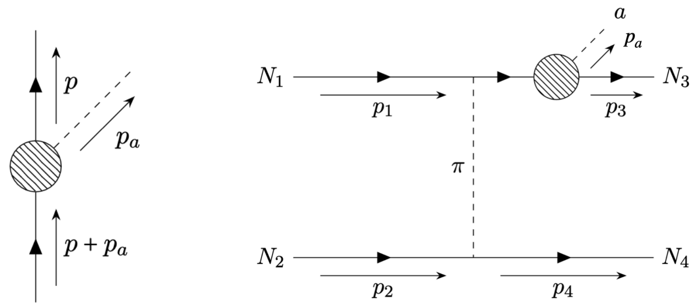
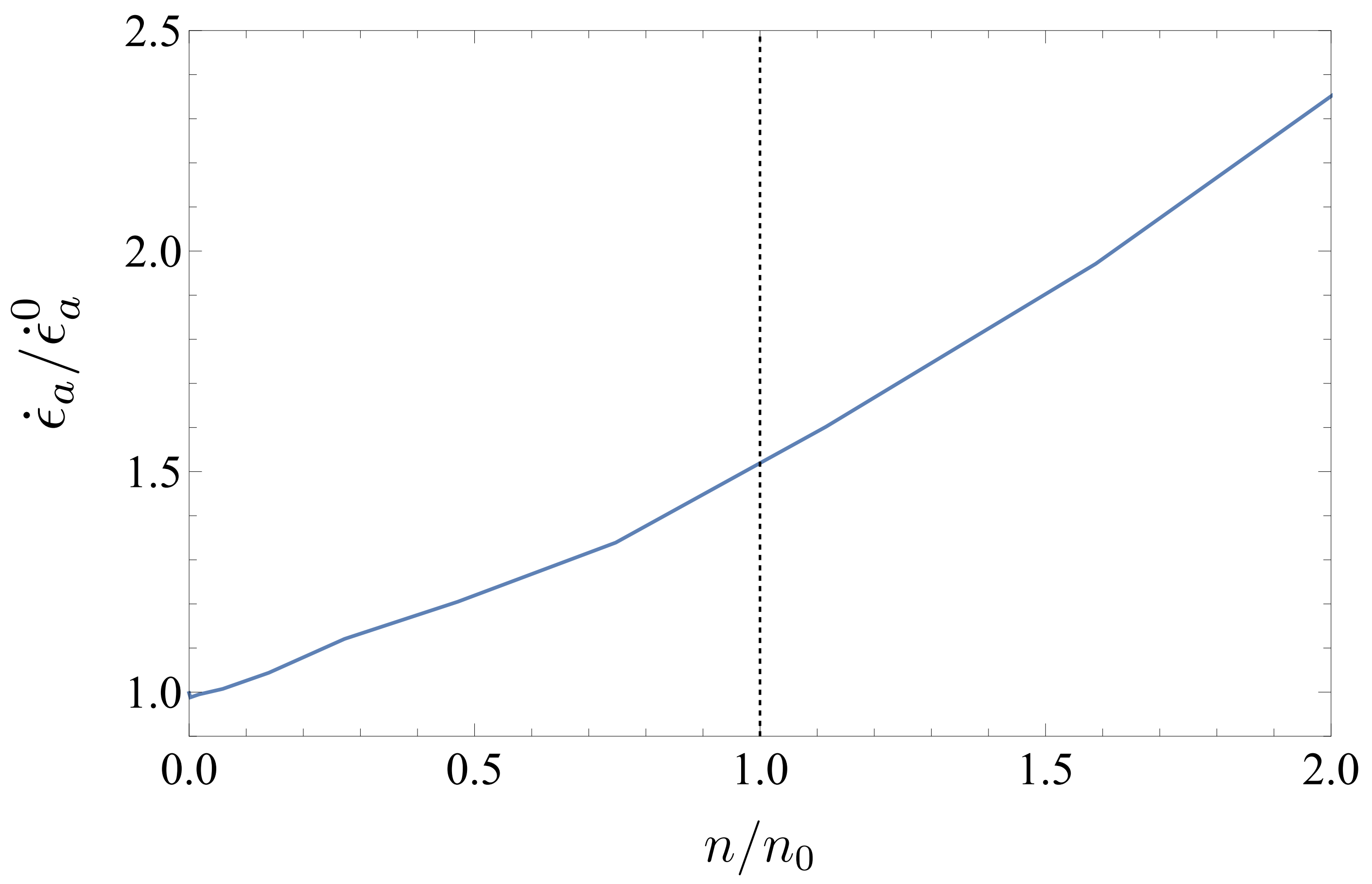



- This alters the axion emissivity $\dot{\epsilon}_a$:

$$\dot{\epsilon}_a = \int d\Pi_1 d\Pi_2 d\Pi_3 d\Pi_4 d\Pi_a (2\pi)^4 S\,|M|^2\,\delta^{(4)}\left(p_1 + p_2 - p_3 - p_4 - p_a\right) E_a f_1 f_2 \left(1 - f_3\right)\left(1 - f_4\right)$$

Density dependent

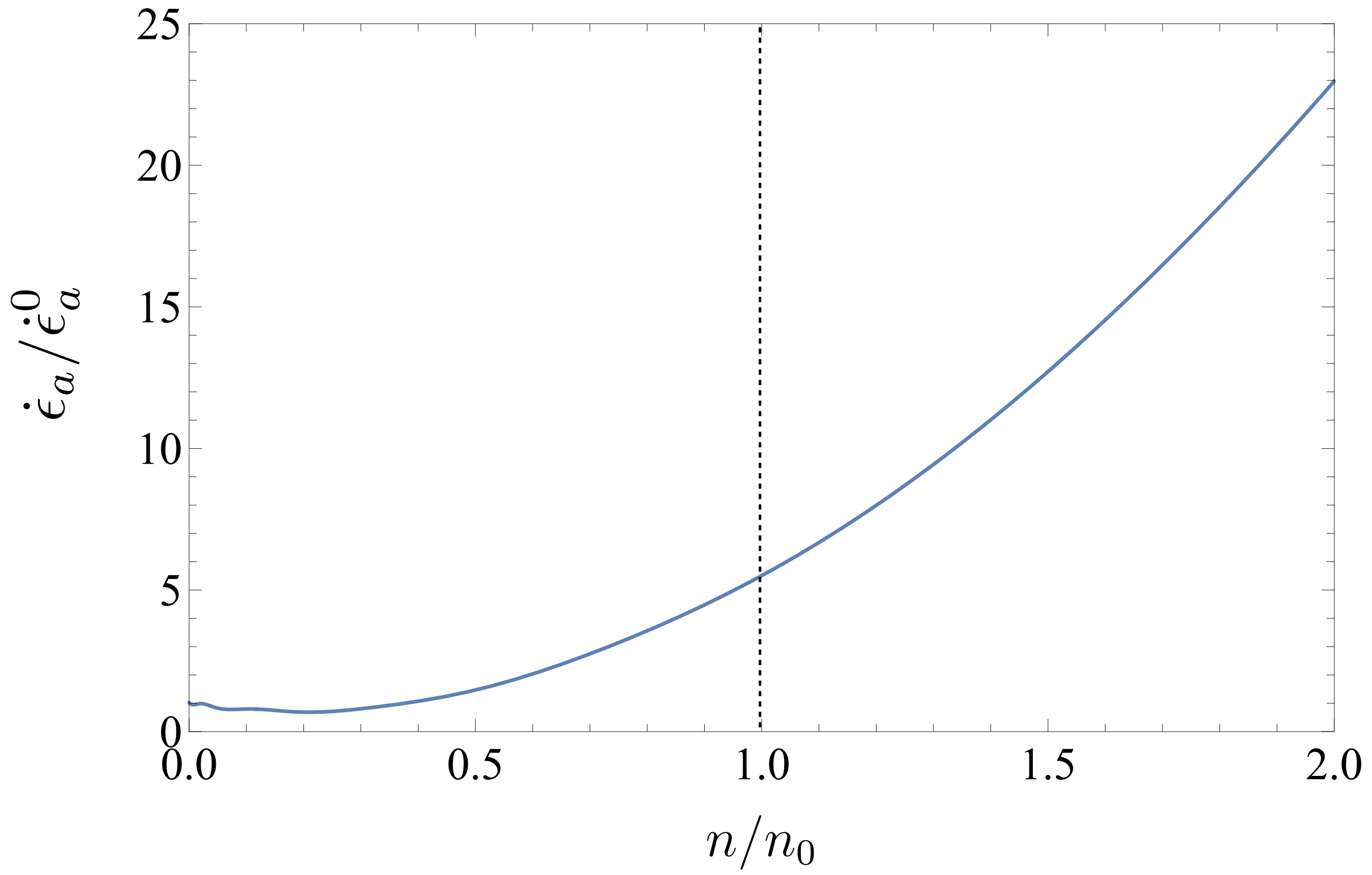
# Emissivity - proton-neutron matter (e.g. SN)




Mixed nuclear matter (e.g. SN)

$T = 30\,\mathrm{MeV}$ and $\mu/T = -3$

# Emissivity - pure neutron matter (e.g. NS)

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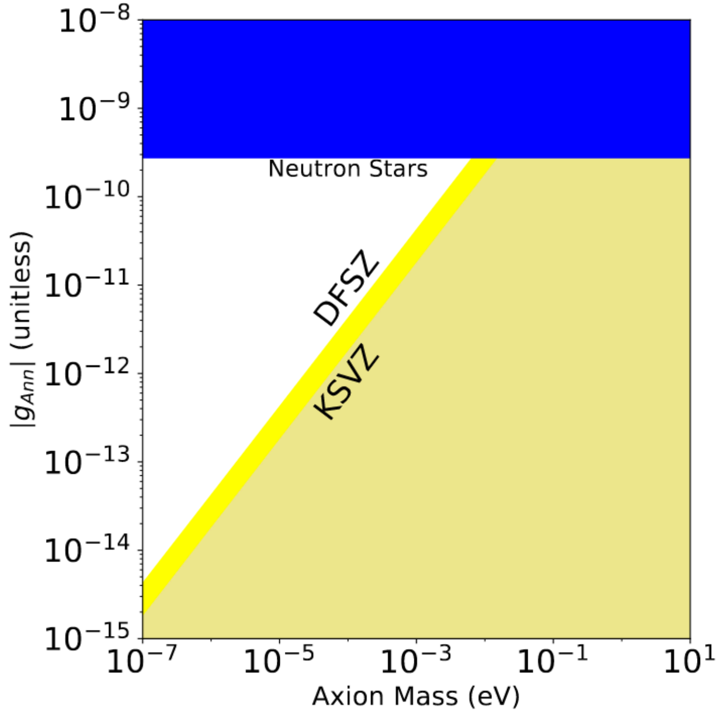

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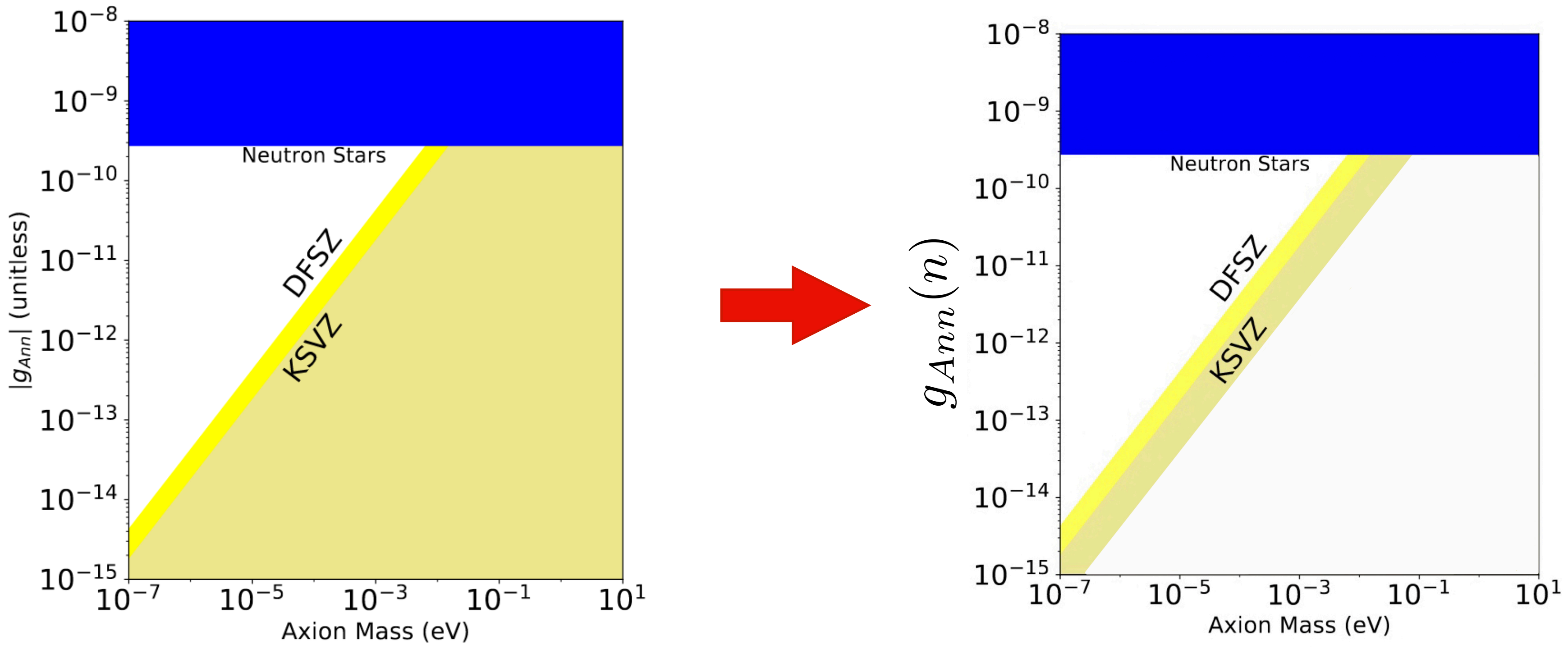
$$g_{Ann} = C_n \frac{m_N}{f_a}$$



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- Long term goal: calculate the whole $N + N \to N + N + a$ process @ finite density