QCD axion coupling at finite density

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2. Chiral Perturbation theory

3. Density dependence of the axion coupling

4. Additional Temperature effects

QCD axion

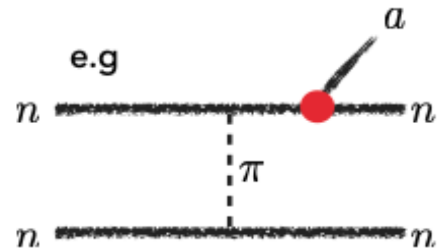
- Strong CP problem of QCD: $\theta < 10^{-10}$
- Most elegant solution: QCD axion
- Phenomenology determined by one parameter f_a
- Many ongoing experiments try to search for the (QCD) axion
- Current best bounds on f_a are from SN and NS cooling

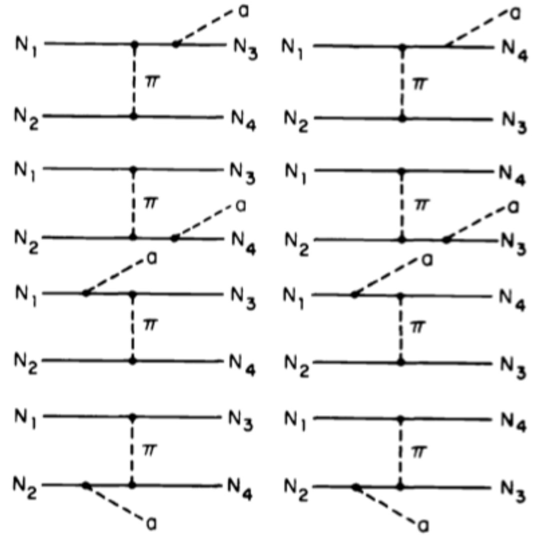
Axion bound from SN1987A

- Neutrino burst observed in two independent neutrino experiments
- ≈ 10 neutrinos in a time span of $\approx 10\,\mathrm{sec}$ were observed in each experiment
- By energy loss arguments additional new particles emitted by the SN would alter the signal duration
- This gives a constraint on the emissivity of possible new particles $\varepsilon_a \lesssim 1 \times 10^{19}\,\mathrm{erg}\,g^{-1}\ \mathrm{s}^{-1}$
- For the axion this means $m_a \lesssim 16\,\mathrm{meV}$ corresponding to $f_a \gtrsim 4 \times 10^8\,\mathrm{GeV}$

Supernova bound

- axion emission leads to an additional energy loss
- This would shorten the neutrino signal -> strong bound on f_a
- Typical calculations of the axion emissivity just involve tree level diagrams (*Brinkmann, Turner '88*), those are used to set bounds (see e.g arXiv:0611350 (*Raffelt*))
- At typical SN densities, loop corrections as well as density corrections can play a significant role
- Recent calculation include different corrections, but the calculations are not systematic
- Also density effects are highly relevant for neutron star cooling





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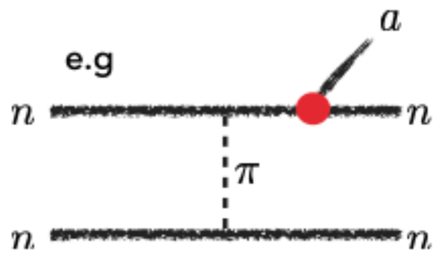

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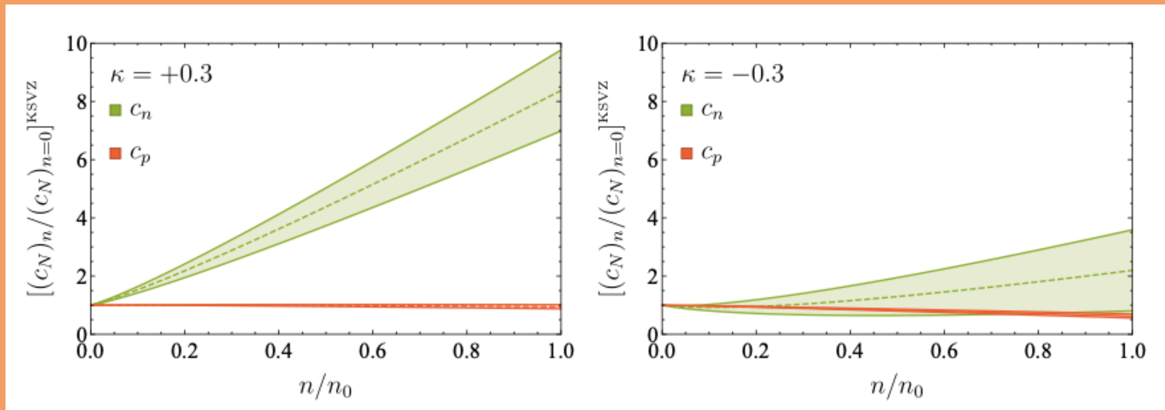
- **First studies have estimated that the couplings might change by a $\mathcal{O}(10)$ factor**

arXiv:2003.04903



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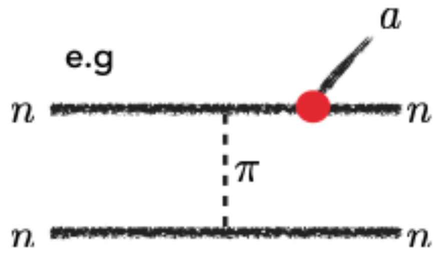

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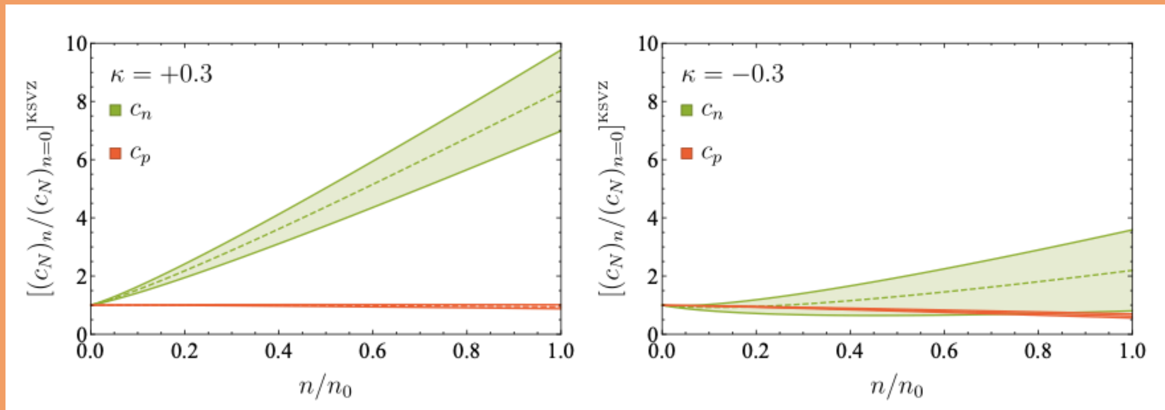
We now calculate this systematically



Chiral perturbation theory

- At low energies QCD confines and develops a chiral condensate $\left\langle \bar{q}_R q_L \right\rangle$, breaking the global symmetry

$$\boxed{SU(2)_L \times SU(2)_R \to SU(2)_{R+L}}$$

- Low energy d.o.f. are described as fluctuations of the condensate

$$U(\pi(x)) = e^{i\frac{\pi^a(x)\tau^a}{f_\pi}}$$

- Leads to EFT of mesons and baryons at low energies $E < \Lambda_\chi$

Chiral perturbation theory

- Systematic description of low energy (nuclear) physics by χPT

$$\mathscr{L}_{\pi}^{(2)} = \frac{1}{4} f_{\pi}^{2} \left\{ \mathrm{Tr} \left[\nabla_{\mu} U^{\dagger} \nabla^{\mu} U + \chi^{\dagger} U + \chi U^{\dagger} \right] \right\}$$

$$\mathscr{L}_{\pi N}^{(1)} = \overline{\mathscr{N}} \left(i\gamma_{\mu} D^{\mu} - m + \frac{g_A}{2} \gamma^{\mu} \gamma_5 u_{\mu} \right) \mathscr{N}$$

- Expansion in powers of $\frac{p}{\Lambda_\chi}$
- Well established effective field theory with many applications:
  - pion decay $\pi^+ \rightarrow \mu^+ \nu_\mu$; pion-pion scattering
  - pion-nucleon scattering
  - Interaction of pions and nucleons with gauge bosons and other fields

Heavy baryon ChPT + finite density

- Heavy baryon ChPT: non-relativistic limit of ChPT
- Adding density effects by a modified nucleon propagator:

$$iG(k) = (\not{p} + m)\left[\frac{i}{p^2 - m^2 + i\epsilon} - 2\pi\delta\left(p^2 - m^2\right)\theta\left(k_F - |\vec{p}|\right)\theta\left(p_0\right)\right]$$

- Gives a systematic expansion in density $\frac{k_f^3}{(4\pi f_\pi)^2\Lambda_\chi} \sim \frac{n}{(4\pi f_\pi)^2\Lambda_\chi}$
- gauge bosons and other fields (e.g. axion, neutrino) can be added to the theory

Coupling axion-nucleon

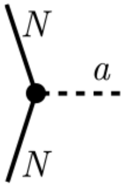
- **Tree level Lagrangian**

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

- **Leads to the couplings**

$$c_p = +g_A c_- + g_0^{ud} c_+$$
$$c_n = -g_A c_- + g_0^{ud} c_+$$

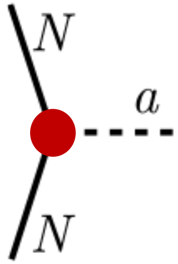
$$c_\pm \equiv (c_u \pm c_d)/2$$



$$= \frac{\vec{\sigma} \cdot \vec{p}_a}{2 f_a} c_{n/p}$$

$$(c_p)_0^{\rm KSVZ} = -0.47(3)$$
$$(c_n)_0^{\rm KSVZ} = -0.02(3)$$

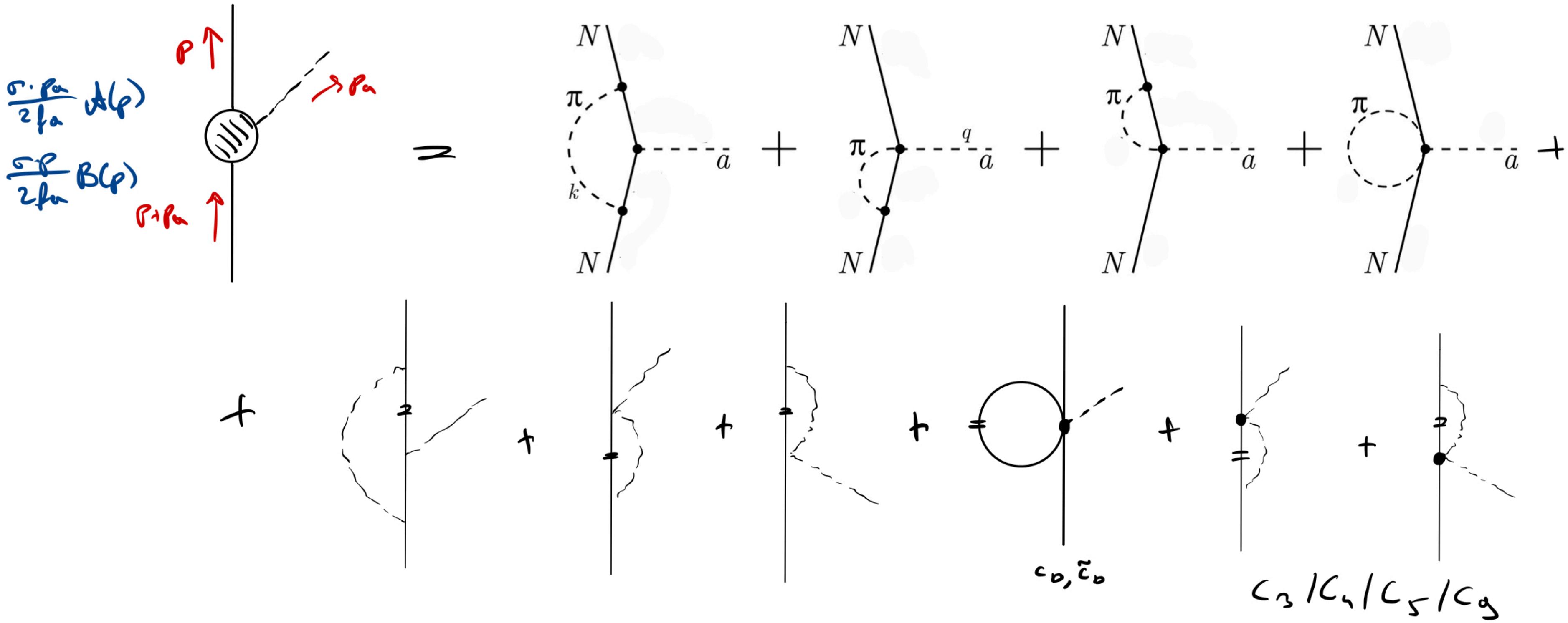
Accidental cancelation!



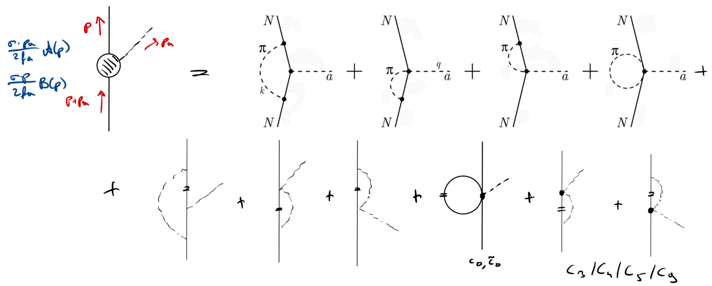
<u>Q: How do they look at finite density?</u>

$$(c_p)_n{}^{\rm KSVZ} = ??$$
$$(c_n)_n{}^{\rm KSVZ} = ??$$

Vertex corrections



Vertex corrections results

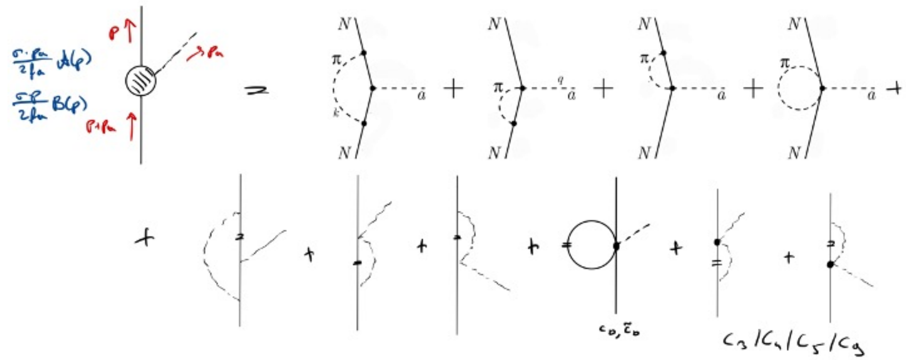


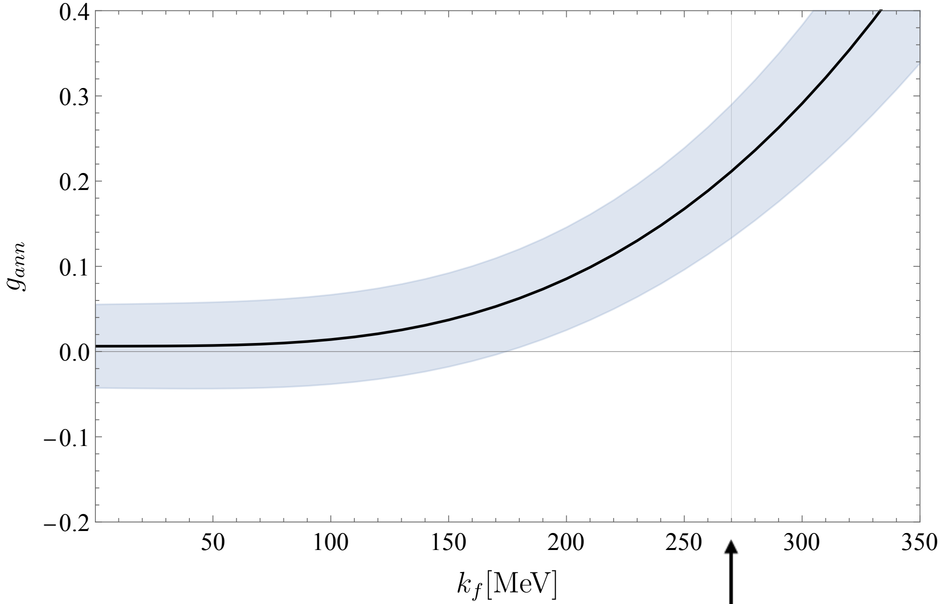
$$\frac{(\vec{\sigma}\cdot\vec{p}_a)}{2f_a}\mathcal{A}(p,k_f,p_a) \quad \Longleftrightarrow \quad \begin{cases} \frac{(\vec{\sigma}\cdot\vec{p}_a)}{2f_a} g_A c_{u-d}\tau^3 \left\{\left(\frac{k_f^2}{(4\pi f_\pi)^2}\right)\left(f_1(p,k_f,p_a) + (-g_A^2) f_2(p,k_f,p_a)\right) + \right. \\ \quad \left. + \left(\frac{k_f^3}{(4\pi f_\pi)^2\Lambda_\chi}\right)\left(\frac{8c_D}{3g_A} + (\tilde{c}_3) f_4(p,k_f,p_a) + (\tilde{c}_4) f_5(p,k_f,p_a)\right)\right\} \\ \frac{(\vec{\sigma}\cdot\vec{p}_a)}{2f_a} g_0 c_{u+d} \left\{\left(\frac{k_f^2}{(4\pi f_\pi)^2}\right)\left((3g_A^2) f_2(p,k_f,p_a)\right) + \right. \\ \quad \left. + \left(\frac{k_f^3}{(4\pi f_\pi)^2\Lambda_\chi}\right)\left(\frac{8\tilde{c}_D}{3g_0} + \left(\frac{3g_A\tilde{c}_9}{2g_0}\right) f_4(p,k_f,p_a) + \left(\frac{g_A\tilde{c}_5 c_{ud}}{g_0 c_{u+d}}\right) f_6(p,k_f,p_a)\right)\right\} \end{cases}$$

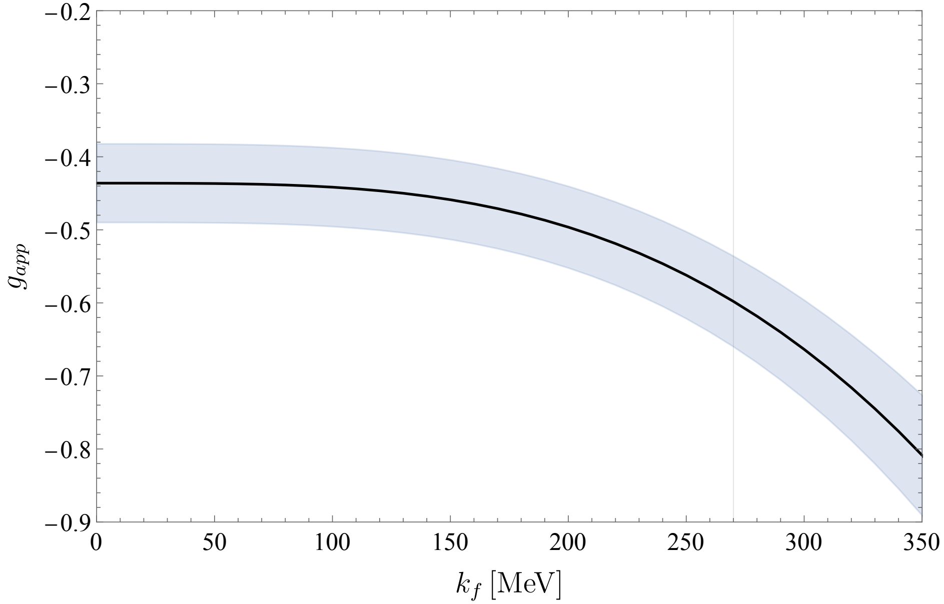
$$\frac{(\vec{\sigma}\cdot\vec{p})}{2f_a}\mathcal{B}(p,k_f,p_a) \quad \Longleftrightarrow \quad \begin{cases} \frac{(\vec{\sigma}\cdot\vec{p})}{2f_a} g_A c_{u-d}\tau^3 \left\{\left(\frac{k_f^2}{(4\pi f_\pi)^2}\right)\left(f_3(p,k_f,p_a)\right) + \left(\frac{k_f^3}{(4\pi f_\pi)^2\Lambda_\chi}\right)\left((\tilde{c}_3) f_7(p,k_f,p_a) + (\tilde{c}_4) f_8(p,k_f,p_a)\right)\right\} \\ \frac{(\vec{\sigma}\cdot\vec{p})}{2f_a} g_0 c_{u+d} \left\{\left(\frac{k_f^3}{(4\pi f_\pi)^2\Lambda_\chi}\right)\left(\left(\frac{3g_A\tilde{c}_9}{2g_0}\right) f_7(p,k_f,p_a) + \left(\frac{g_A\tilde{c}_5 c_{ud}}{g_0 c_{u+d}}\right) f_9(p,k_f,p_a)\right)\right\} \end{cases}$$

Leads to density dependence of the amplitude squared $|M|^2$

Vertex correction results







nuclear saturation density n_0

Vertex corrections results including Temperatur

(Here just the density loops at zero T are compared with density loops at finite T.)

1 MeV: Yellow - Dotted

10 MeV: Orange

50 MeV: Red