Neutron star cooling with lepton-flavor-violating axions

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Introduction & Research question

Neutron star cooling history

Stars with mass $10-25M_\odot$

↓

Supernova $T\sim10^{12}\mathrm{K}\sim100\mathrm{MeV}$

↓

Nascent neutron star $T\sim10^{11}\mathrm{K}\sim10\mathrm{MeV}$

Direct URCA process: $n\to p+e^-+\bar{\nu}_e$

and/or

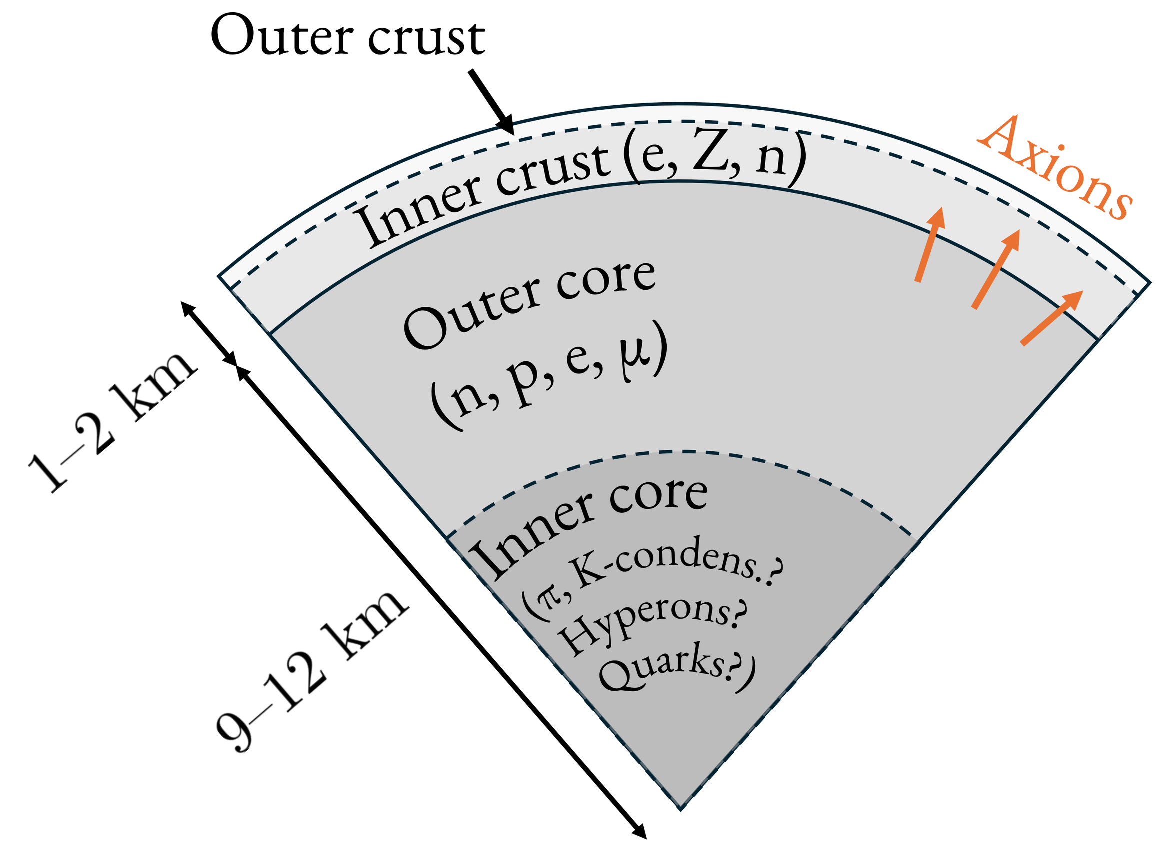
Modified URCA process: $n+n\to n+p+e^-+\bar{\nu}_e$, $n+p+e^-\to n+n+\nu_e$

↓

Old neutron star $T\sim10^{8}\mathrm{K}\sim10\mathrm{keV}$

↓ Thermal radiation of photons

Neutron star structure & Axion emission

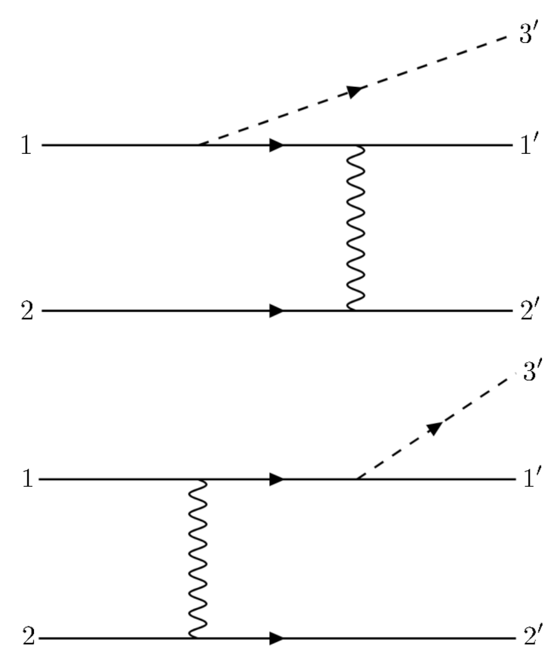


Axions provide additional cooling channels and make neutron stars cool down in a rate faster than expected. To be consistent with observations, their emission rate had better be less than that of neutrinos, which has been investigated in the literature. Can we use this effect to constrain axion interactions?

Lepton-flavor-changing processes & Axion emission rates & Constraints

Consider the following interactions:

$$l+f\to l'+f+a \quad \begin{cases} l=e,\mu \\ l'=\mu,e \\ f=p,e,\mu \end{cases}$$



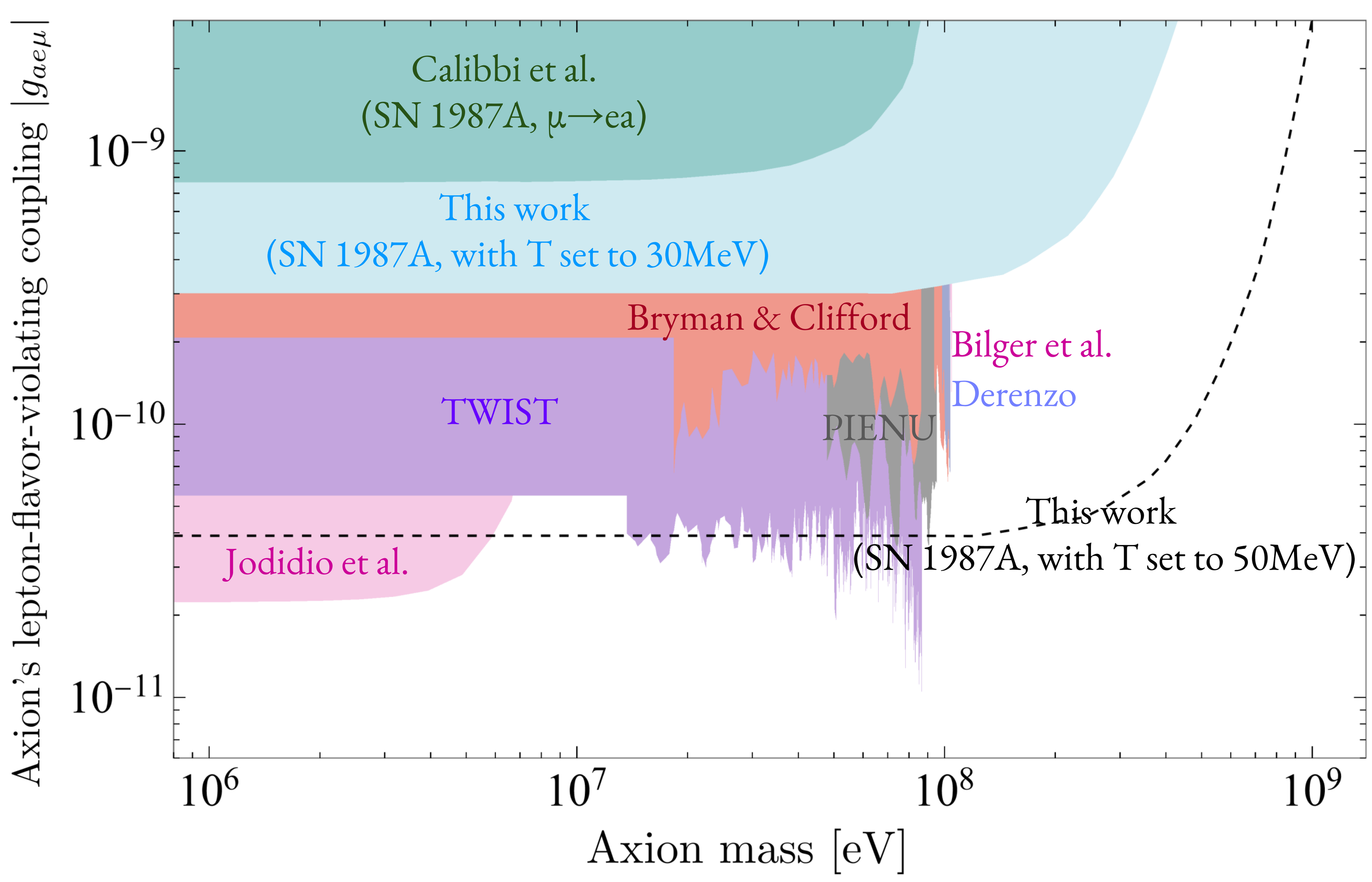
where a lepton l is converted to another lepton l' by scattering with a spectator fermion f.

Axion emissivity: Energy output / time / volume; Fermi-Dirac distribution

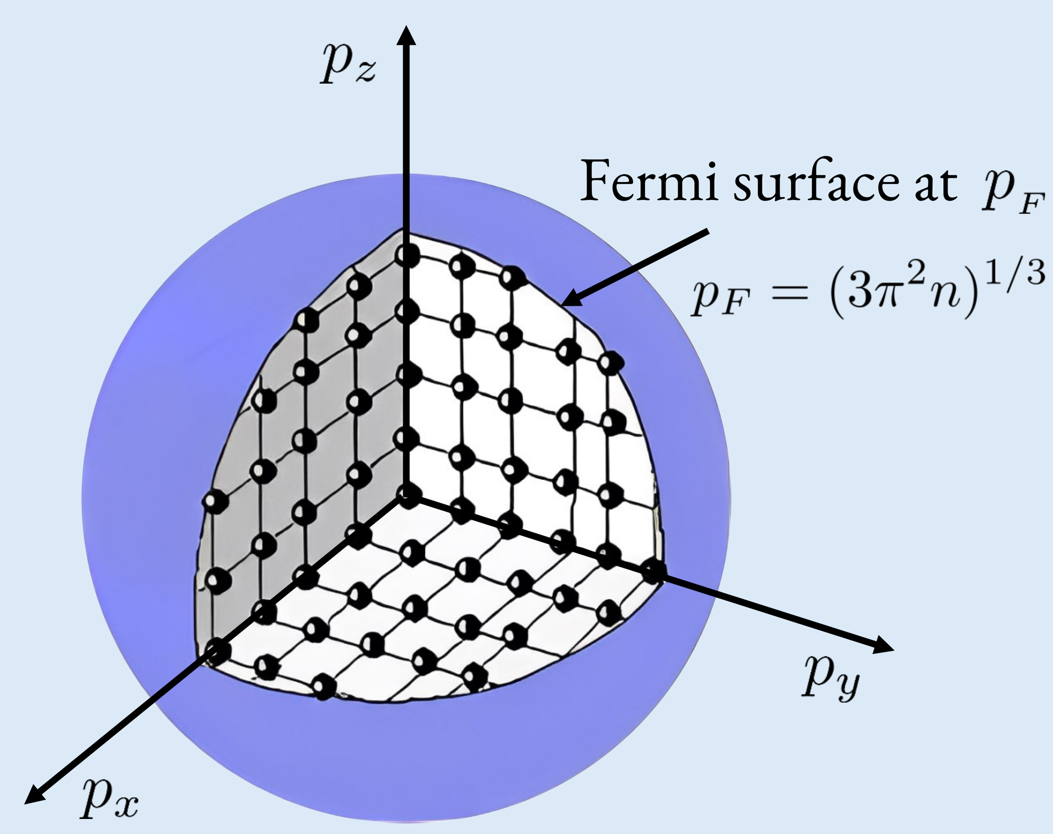
$$\varepsilon_a=\int\frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2}\frac{d^3p_1'}{(2\pi)^3 2E_1'}\frac{d^3p_2'}{(2\pi)^3 2E_2'}\frac{d^3p_a}{(2\pi)^3 2E_a}E_a f_1 f_2 \times(1-f_1')(1-f_2')(2\pi)^4\delta^4(p_1+p_2-p_1'-p_2'-p_a)\sum_{\text{spins}}|\mathcal{M}|^2$$

Pauli blocking factors; Spin-summed matrix element

Summing over all 6 processes: $\varepsilon_a^{\mathrm{LFV}}=4.8\times10^{32}g_{ae\mu}^2\left(\frac{T}{10^9\mathrm{K}}\right)^8\ \mathrm{erg\ cm^{-3}\ s^{-1}}$



Degenerate fermions



Only those particles near the Fermi surface can participate in the interactions; smaller and larger momenta do not contribute because of Pauli blocking or Boltzmann suppression.

$\mu\to e+a$ is suppressed if muons and electrons are degenerate.

Takeaways

1. Neutron star/supernova cooling provides strong constraints on axions.
2. Constraints on the lepton-flavor-violating (LFV) coupling inferred from hotter environments are stronger due to the T^8 dependence in axion emissivity.
3. Upper limits on the LFV coupling are inferred at the level of ~(10^{-11}–10^{-10}) based on the observation of SN1987A.