Neutron star cooling with lepton-flavor-violating axions

Hong-Yi Zhang, Rice University

@ Texas Rice TACOS

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Zhang & Long (+ Hagimoto) 2309.03889

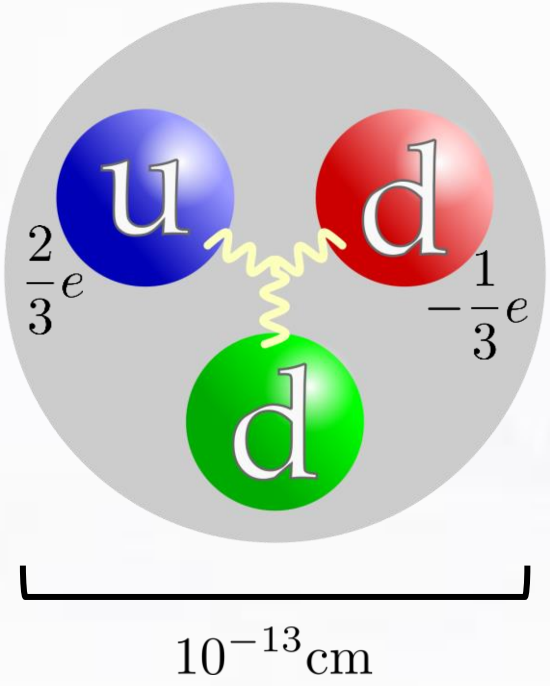


Talk structure

Neutron star (NS) cooling with lepton-flavor-violating (LFV) axions

- Axions
- Structure and cooling of NSs
- Axion emissivity and constraints
- Future directions and summary

Axions & axionlike particles



Order of magnitude guess
for neutron EDM $\sim 10^{-13} e\ \mathrm{cm}$

Strong CP problem: Why is $\bar{\Theta}$ so small?

Theoretically, neutron EDM $\sim \bar{\Theta}\ 10^{-16} e\ \mathrm{cm}$

Experimentally, neutron EDM $< 10^{-26} e\ \mathrm{cm}$

Peccei-Quinn mechanism can solve the problem

$$\text{Broken } U(1)_{\mathrm{PQ}}: \ \bar{\Theta} \to \bar{\Theta} - \frac{a}{f_a}$$

Peccei, Quinn (1977)
Weinberg (1978)
Wilczek (1978)

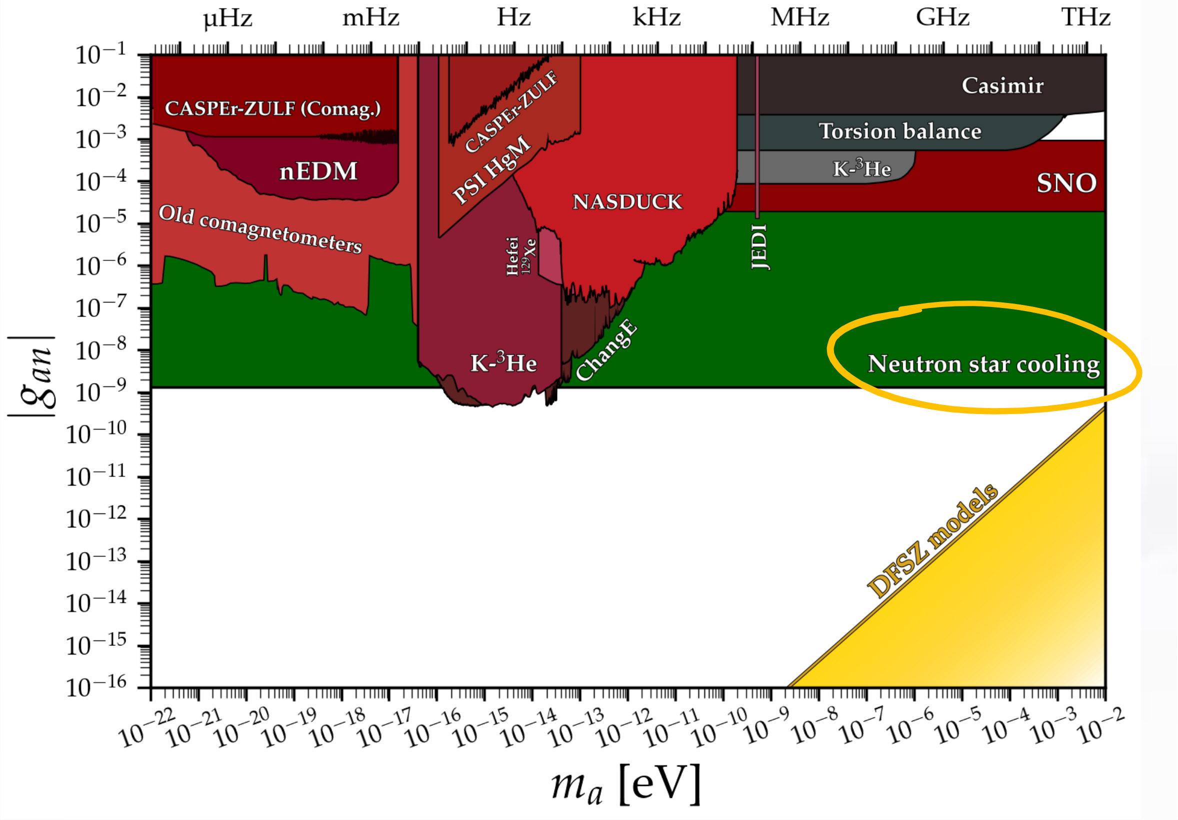
a is locked at the potential minimum $\bar{\Theta} f_a$

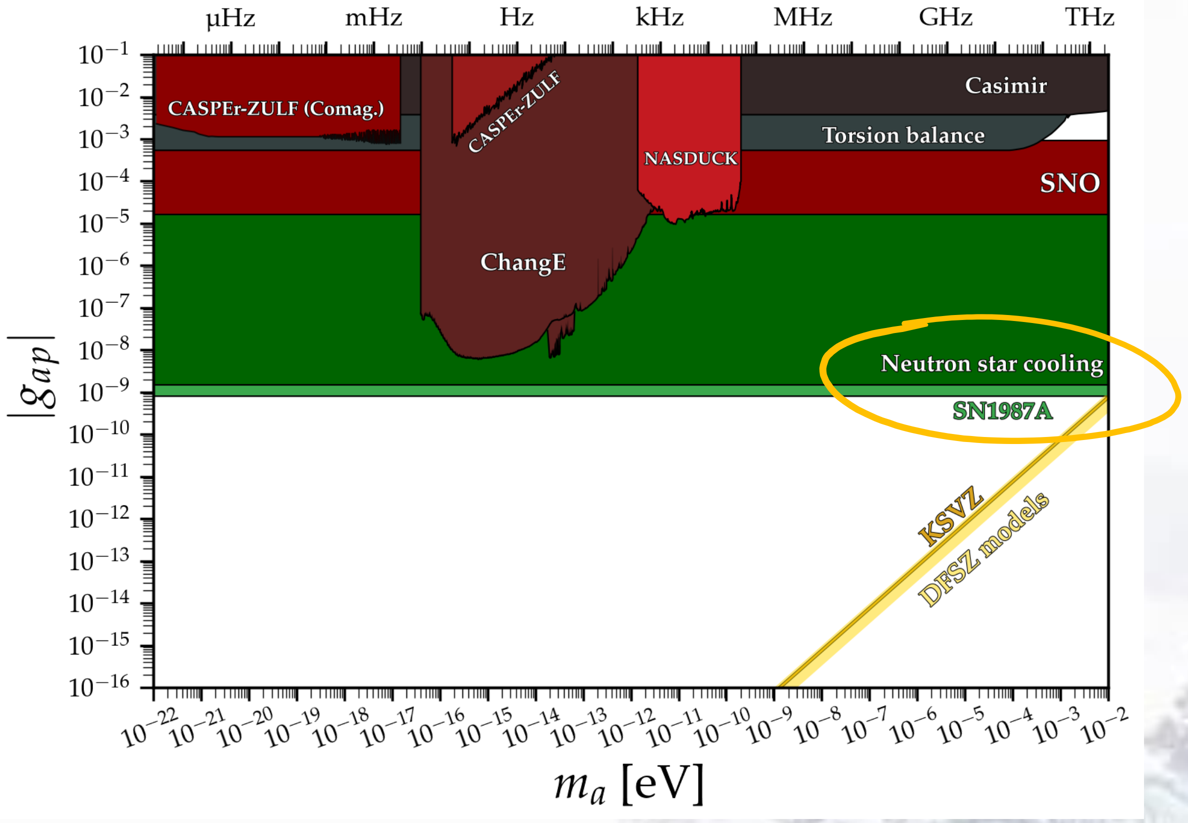
a is a new type of particles, called axions

$$m_a \approx 5.7 \left(\frac{10^9 \mathrm{GeV}}{f_a} \right) \mathrm{meV}$$

String theory predicts a landscape of pseudoscalars

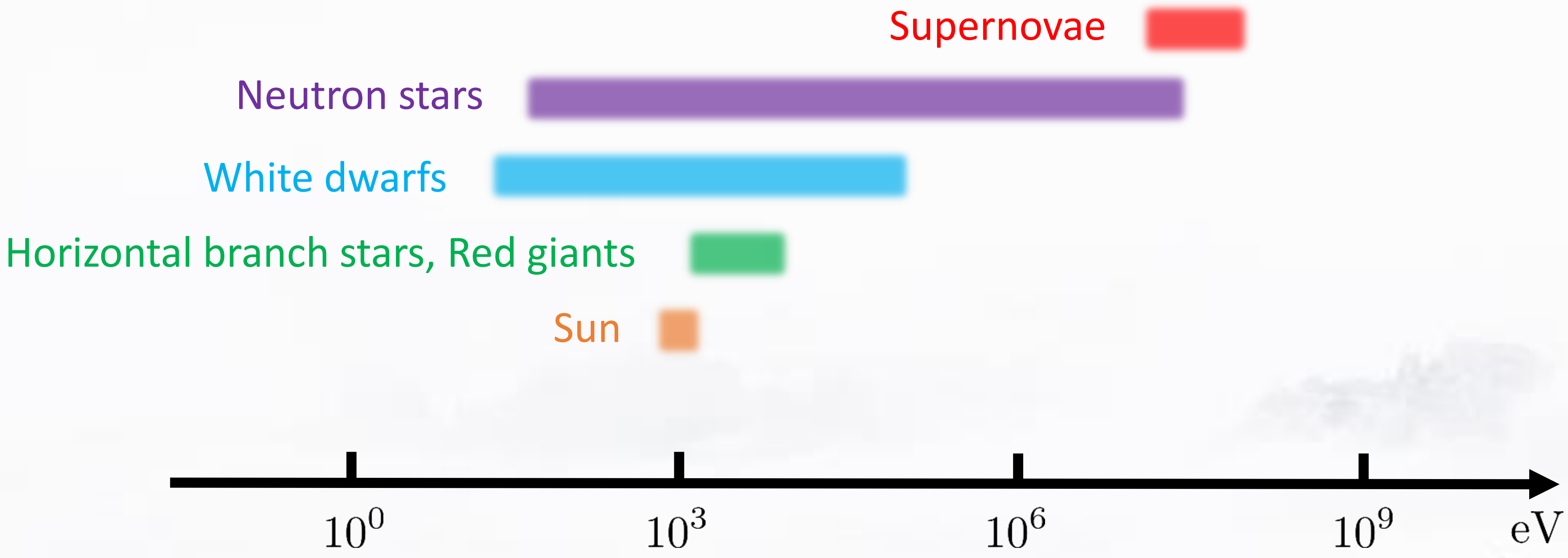
Axion constraints





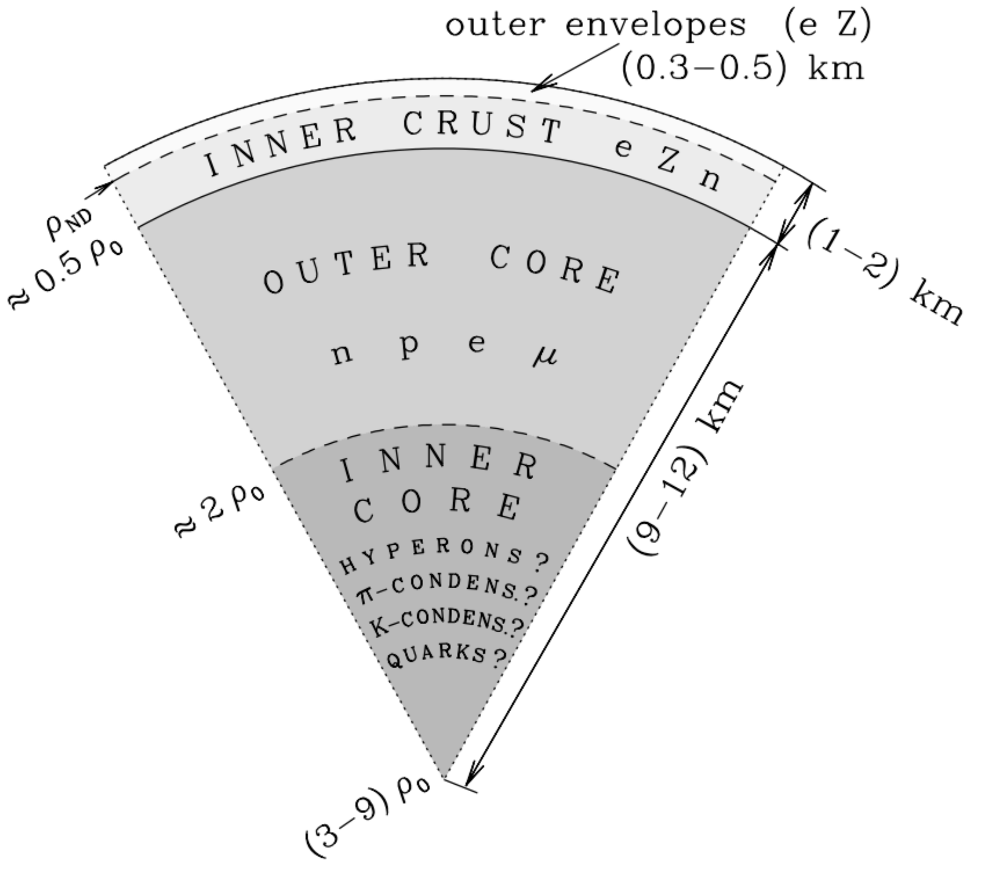
Credit: Ciaran O'Hare

Axion mass range in astrophysical probes



Astrophysical constraints apply for axions with a mass $\ll T$

Neutron star cooling 101



Haensel (2007)

$$\rho_{\rm ND} \approx 4 \times 10^{11} {\rm g/cm^3}$$
$$\rho_0 \approx 3 \times 10^{14} {\rm g/cm^3}$$

Stars with mass $10 - 25 M_\odot$

↓

Supernova $T \sim 10^{12}{\rm K} \sim 100{\rm MeV}$

↓

Nascent NS $T \sim 10^{11}{\rm K} \sim 10{\rm MeV}$

↓

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

or

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

$T \sim 10^8{\rm K} \sim 10{\rm keV}$

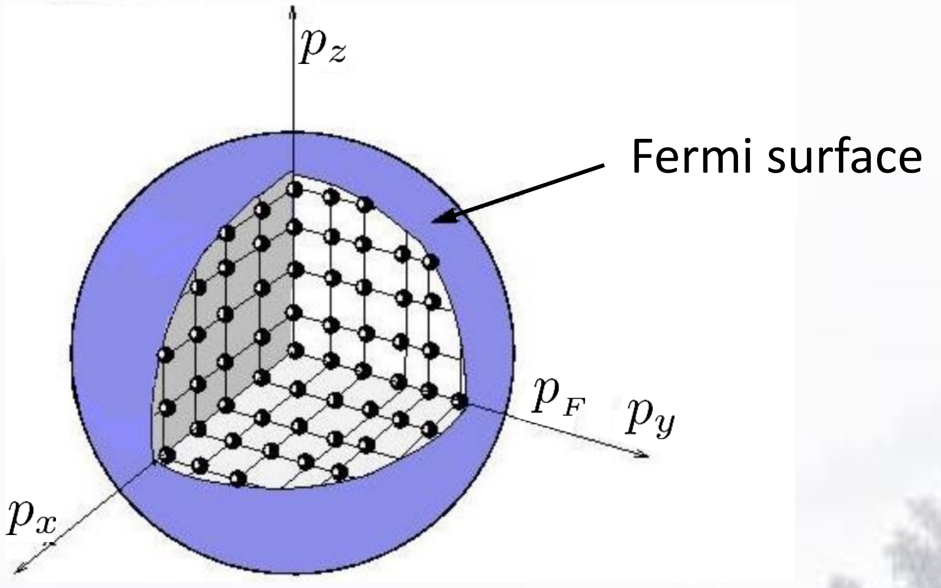
↓ Thermal radiation of photons

Fermi surface for degenerate particles

Typical Fermi kinetic energy
at $\rho \sim 10^{15} \mathrm{gm/cm^3}$

$$\mathcal{E}_n \sim 180\mathrm{MeV}$$
$$\mathcal{E}_p \sim 20\mathrm{MeV}$$
$$\mathcal{E}_e \sim 160\mathrm{MeV}$$
$$\mathcal{E}_\mu \sim 60\mathrm{MeV}$$

(assuming $m_N^* = 0.8 m_N$)



$$p_F = (3\pi^2 n)^{1/3}$$

Figure adapted from Matteo Baggioli (2016)

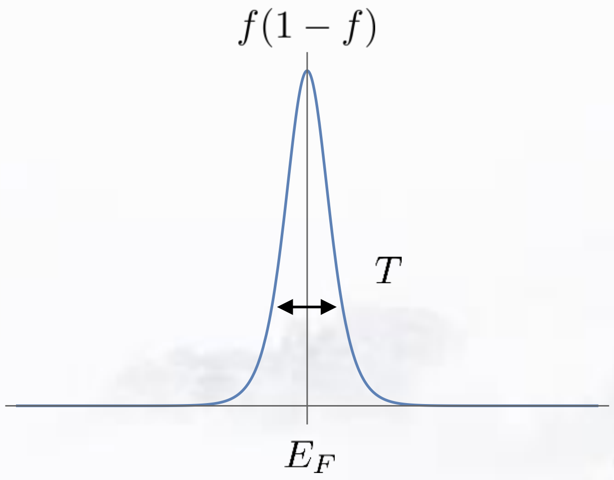
Constraining axions with neutron star cooling

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



$$f(E) \approx \theta(E - E_F)$$
$$1 - f(E) \approx \theta(E_F - E)$$

To be consistent with NS cooling observations, we require

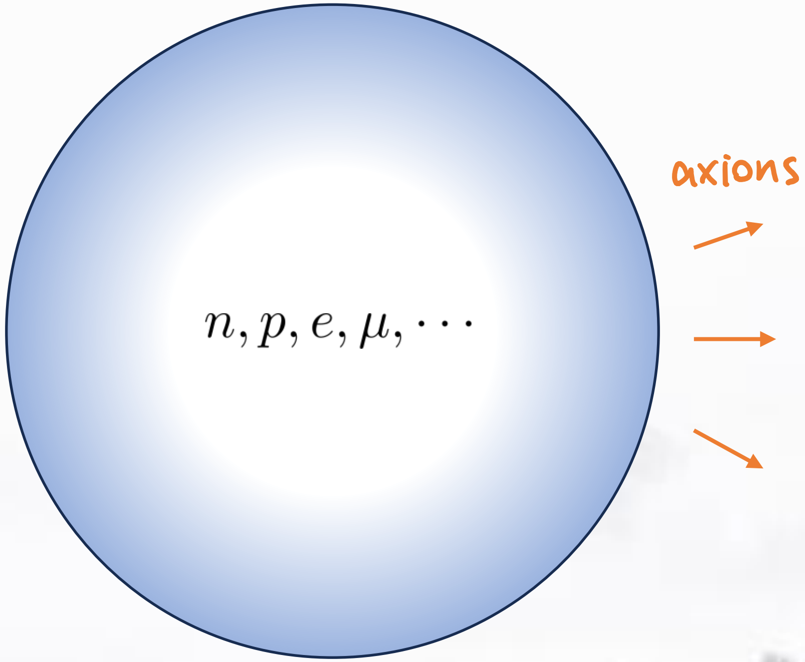
$$\varepsilon_a < \varepsilon_\nu$$

Lepton flavor violation

Why?

- No compelling reason for zero LFV
- Radiative corrections
- No exact global symmetry is expected in quantum gravity
- …

$$\mathcal{L} \supset \frac{g_{ae\mu}}{4m_e}(\overline{\psi}_e \gamma^\rho \gamma_5 \psi_\mu + \overline{\psi}_\mu \gamma^\rho \gamma_5 \psi_e)\partial_\rho a$$

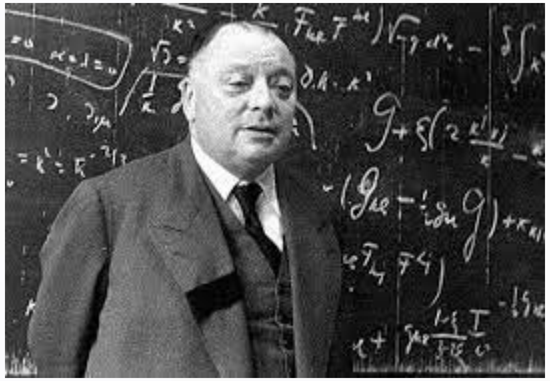


Lepton flavor violation

$$\mu \to e + a \qquad \mathrm{Br}(\mu \to ea) \approx 7.0 \times 10^{15} g_{ae\mu}^2$$

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

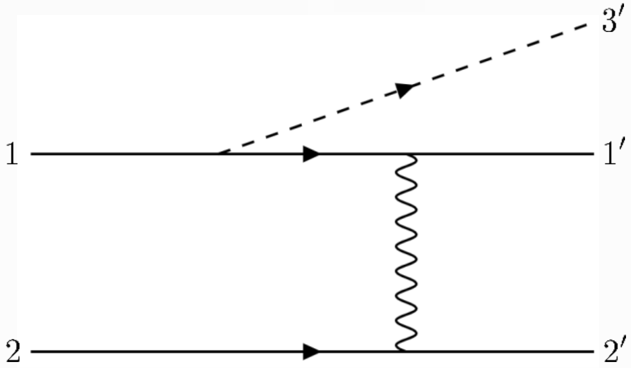
Lepton flavor violation

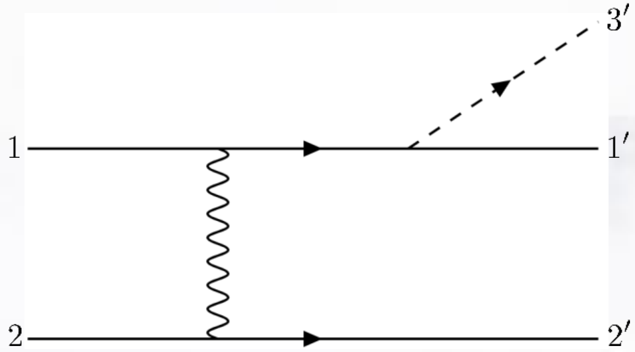


Muon decay is Pauli blocked

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

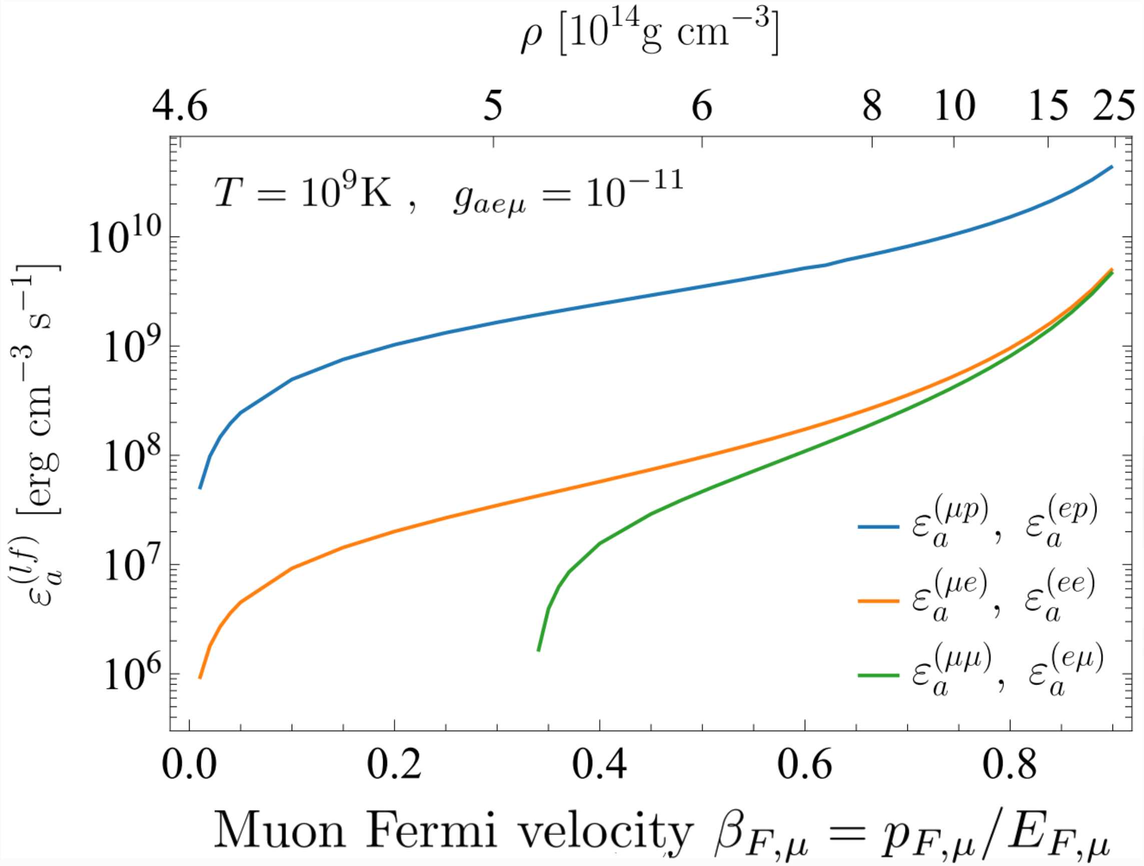
Momentum threshold: $p_{F,f} > \frac{p_{F,e} - p_{F,\mu}}{2}$





\+ exchange diagrams
(e.g., 1↔2)

Axion emissivity



At the typical value $\beta_{F,\mu} = 0.84$

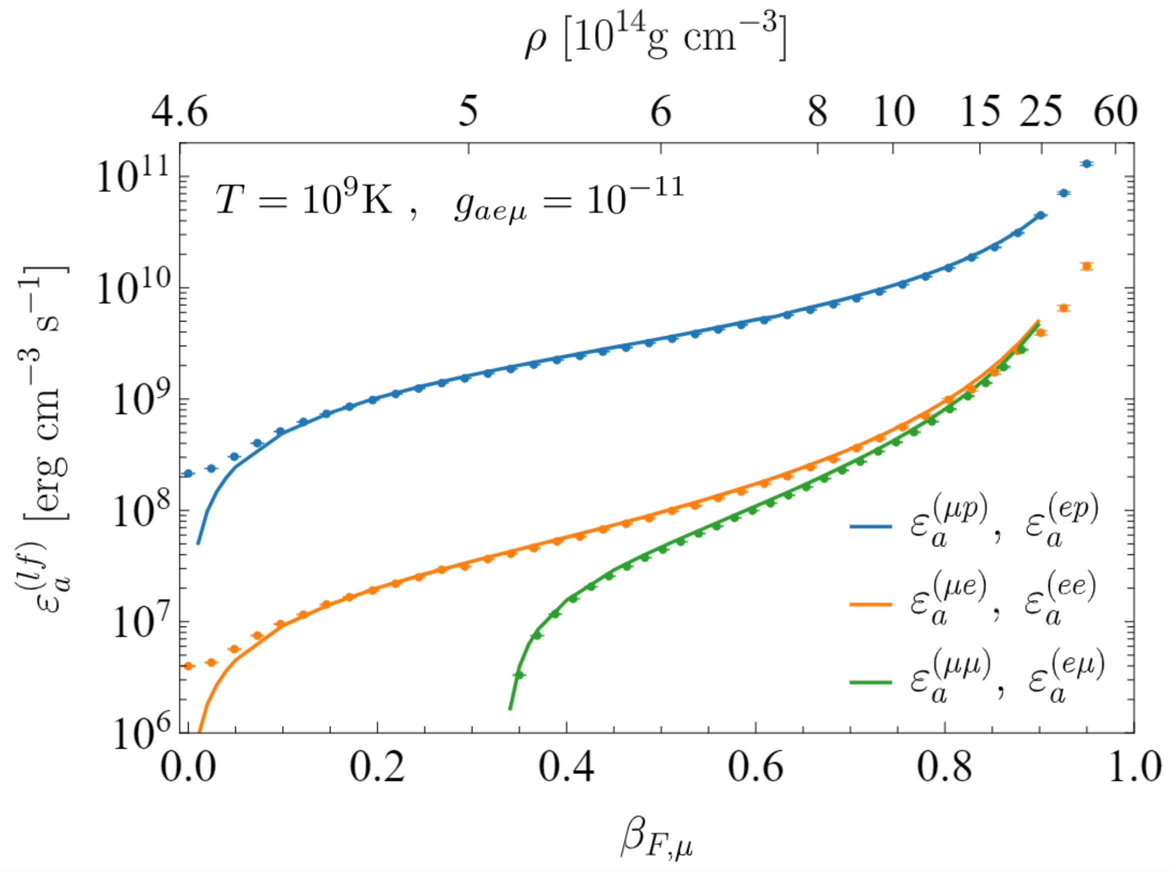
$$\varepsilon_a^{\mathrm{LFV}} = 4.8 \times 10^{32} g_{ae\mu}^2 \left(\frac{T}{10^9\mathrm{K}}\right)^8$$

$$\varepsilon_a^{\mathrm{LFV}} < \varepsilon_{\mathrm{MURCA}} \Rightarrow |g_{ae\mu}| < 3 \times 10^{-6}$$

$$\varepsilon_a^{\mathrm{LFV}} < \varepsilon_{\mathrm{SN}} \Rightarrow |g_{ae\mu}| < 4 \times 10^{-11} \left(\frac{T}{50\mathrm{MeV}}\right)^4$$

(assuming $m_N^* = 0.8 m_N$)

Brute force calculations



Monte Carlo integration based on the VEGAS algorithm

Constraints on the LFV coupling

$\lvert g_{ae\mu}\rvert$	$\frac{2f_a}{C_{ae\mu}}$ [GeV]	$\mathrm{Br}(\mu \to ea)$	m_a [MeV]	Experiment
$< 3.0 \times 10^{-6}$	$> 3.5 \times 10^{4}$	< 1.0	$\lesssim 1$	NS cooling
$\lesssim 8 \times 10^{-10}$	$\gtrsim 1 \times 10^{8}$	$\lesssim 4 \times 10^{-3}$	$\lesssim 50$	SN 1987A, $\mu \to ea$
$< 4.2 \times 10^{-10}$	$> 2.5 \times 10^{8}$	$< 1.3 \times 10^{-3}$	$\lesssim 10^{-7}$	Cosmology, ΔN_{eff}
$< 2.9 \times 10^{-10}$	$> 3.7 \times 10^{8}$	$< 5.7 \times 10^{-4}$	$103 - 105$	Rare muon decay
$\lesssim 2 \times 10^{-10}$	$\gtrsim 5 \times 10^{8}$	$\lesssim 3 \times 10^{-4}$	< 104	Rare muon decay
$< 2 \times 10^{-10}$	$> 6 \times 10^{8}$	$< 2 \times 10^{-4}$	$98.1 - 103.5$	Rare muon decay
$< 1 \times 10^{-10}$	$> 9 \times 10^{8}$	$< 1 \times 10^{-4}$	$47.8 - 95.1$	Rare muon decay (PIENU)[a]
$< 5.5 \times 10^{-11}$	$> 1.9 \times 10^{9}$	$< 2.1 \times 10^{-5}$	< 13	Rare muon decay (TWIST)
$\lesssim 4 \times 10^{-11}$	$\gtrsim 3 \times 10^{9}$	$\lesssim 9 \times 10^{-6}$	$\lesssim 50$	SN 1987A, $lf \to l'fa$
$< 1.9 \times 10^{-11}$	$> 5.5 \times 10^{9}$	$< 2.6 \times 10^{-6}$	$\lesssim 10$	Rare muon decay

$2f_a/C_{ae\mu} = (m_e + m_\mu)/g_{ae\mu}$

Summary

NS cooling

Direct URCA, modified URCA, thermal radiation, …

Emission of LFV axions from NSs

- Fermi surface approximation
- Monte Carlo integration
- Emission rate $\propto T^8$

Upper limits on LFV coupling

- 3×10^{-6} (modified URCA), very weak limits
- 4×10^{-11} (SN 1987A), competitive with the best lab limit

More directions in the future?

- Baryon number violation
- Modeling the cooling history of NSs
- Constraints within established SN 1987A models
- Dark matter axions