Supernova Constraints on Lepton Flavor Violating Axions

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Outline

1. Lepton flavor violating (LFV) axions/ALPs
2. Supernova (SN) cooling limits
3. Axion production in the SN core
4. Axion absorption in the SN
5. Supernova constraints on LFV axions

[Yonglin Li, ZL, 2501.12075]

1 Lepton Flavor Violating Axions

Lepton flavor violating axions/ALPs

Lepton flavor violating axions/ALPs

$$\mathscr{L}_{\rm int} = -\, i g_{ae\mu}\, a\, \bar{e}\, \gamma_5\, \mu + {\rm h.c.}$$

axions/ALPs couple to both electrons and muons

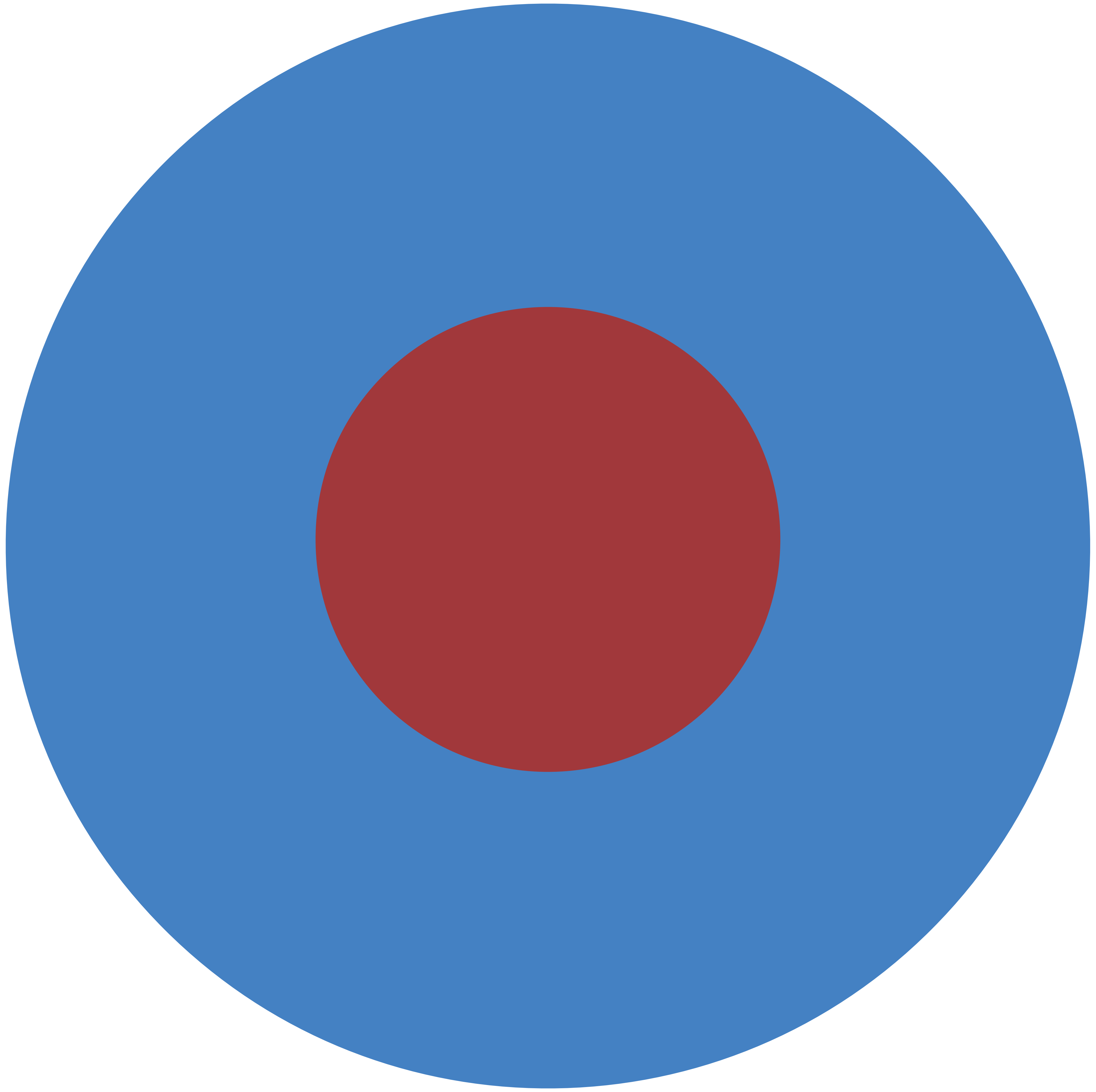
[F. Wilczek, 82']

[L. Calibbi, D. Redigolo, R. Ziegler, and J. Zupan, 2006.04795]

[H.-Y. Zhang, R. Hagimoto, and A. J. Long, 2309.03889]

2 Supernova constraints on LFV axions

Supernova (SN) cooling limit



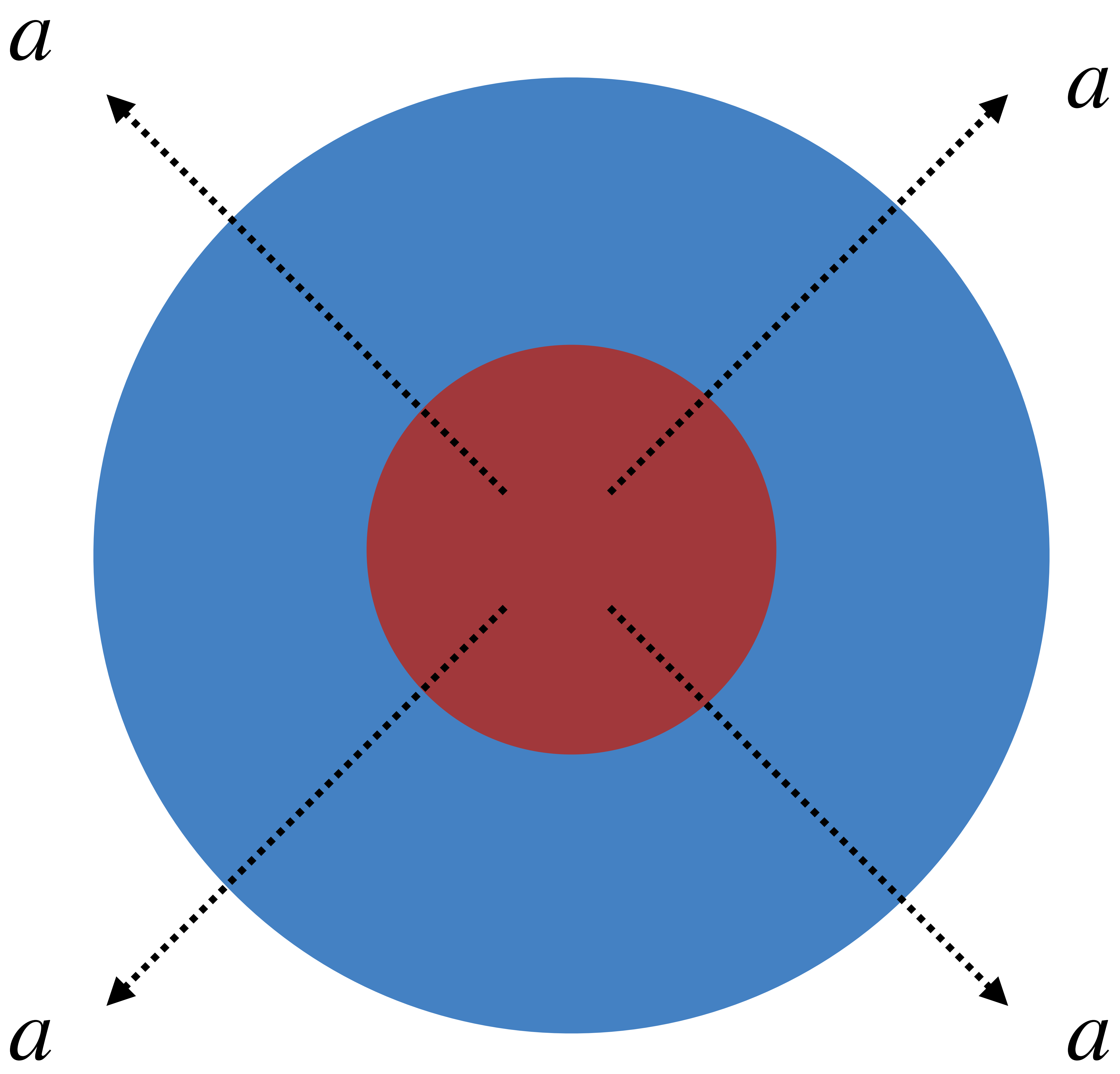
Raffelt criterion

Axion luminosity from the SN core should be smaller than that of neutrinos at about 1 second postbounce:

$$L_a \leq L_\nu = 3 \times 10^{52}\,\mathrm{erg}/s$$

[Raffelt, 96']

Supernova (SN) cooling limit



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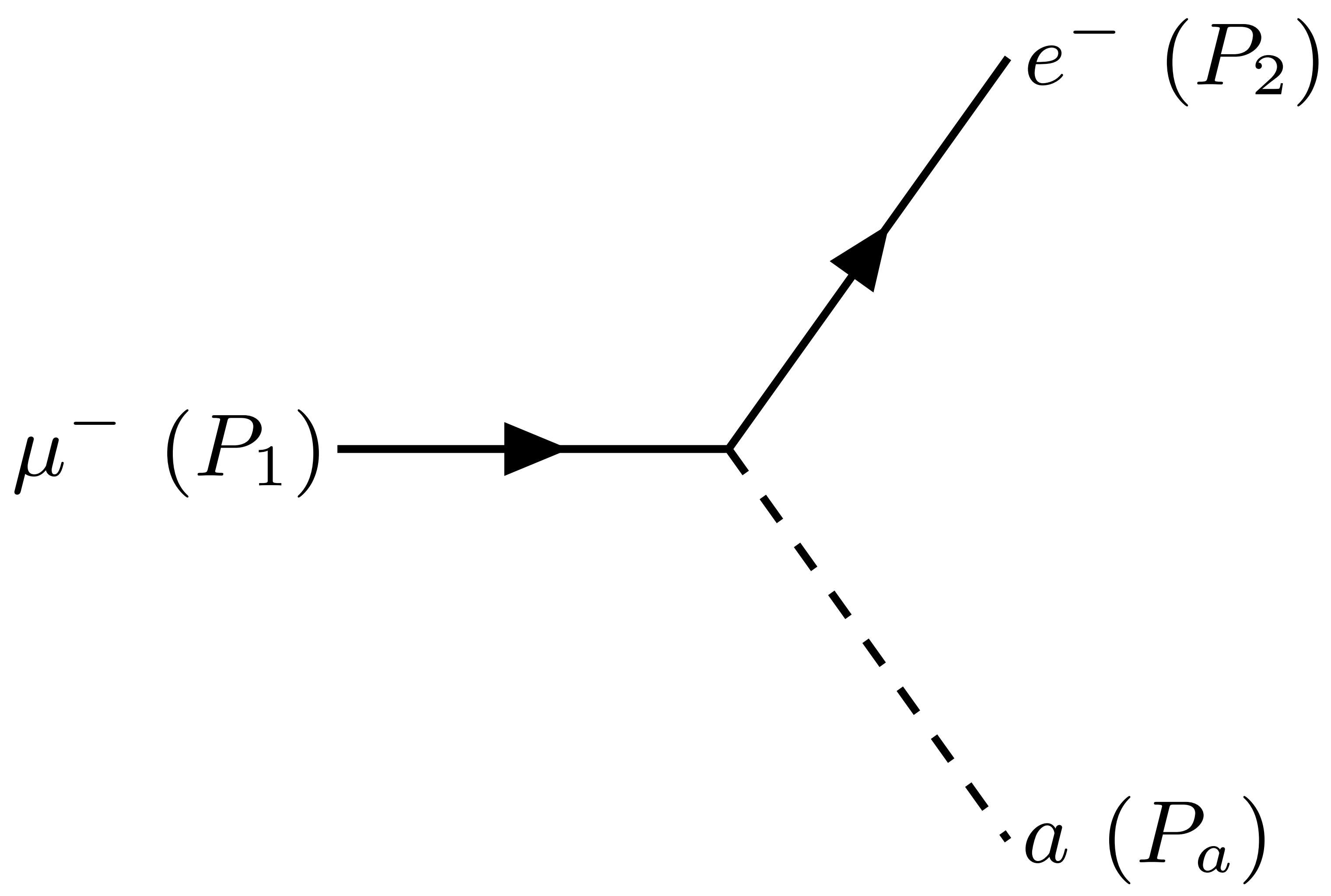
[Raffelt, 96']

Different axion production channels in the SN (1)

(1) muon decay

$$\mu^- \to e^- + a$$



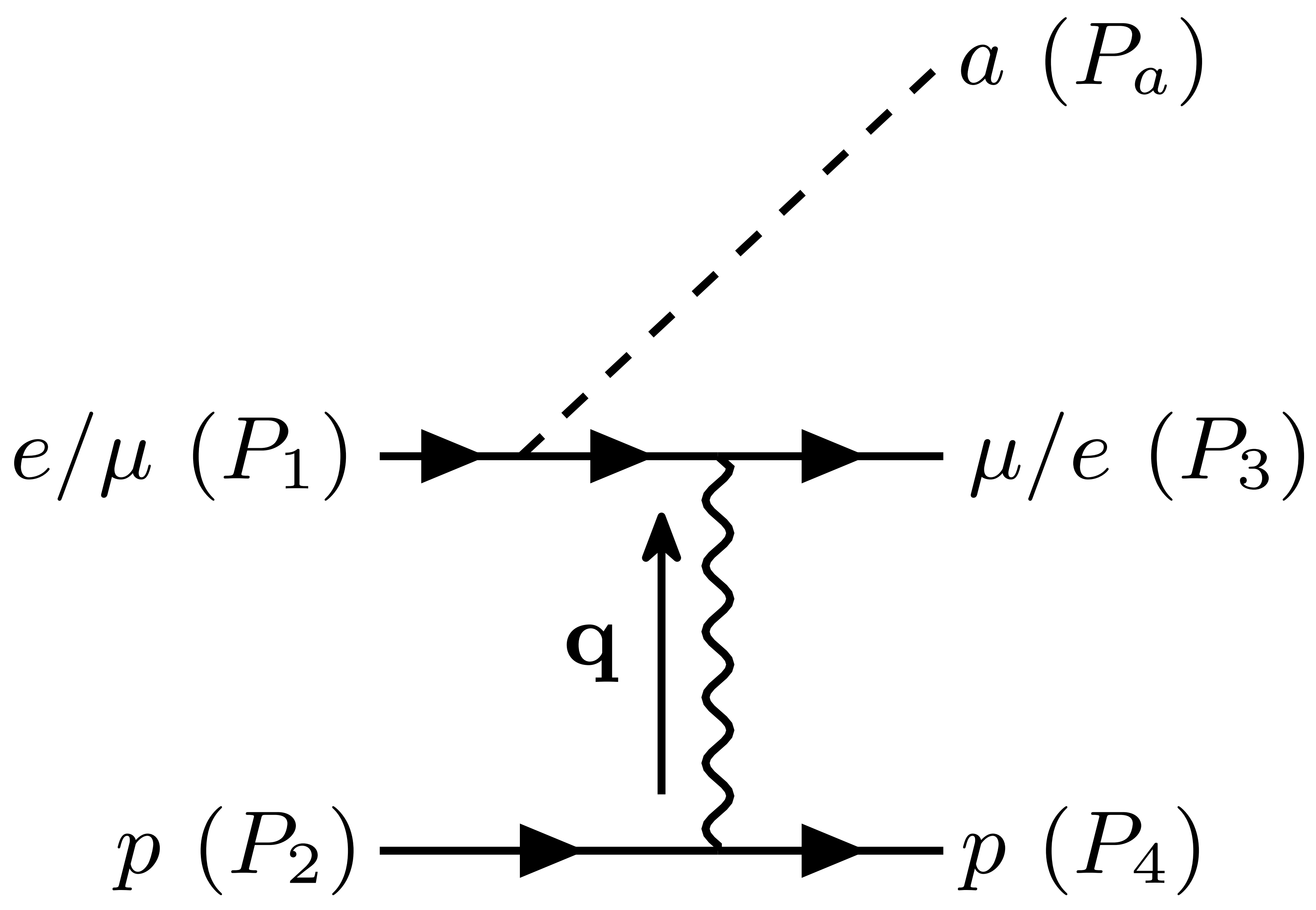
axion mass < muon mass

[L. Calibbi, D. Redigolo, R. Ziegler, and J. Zupan, 2006.04795]

Different axion production channels in the SN (2)

(2) bremsstrahlung

$$e/\mu + p \rightarrow \mu/e + p + a$$



[H.-Y. Zhang, R. Hagimoto, and A. J. Long, 2309.03889]

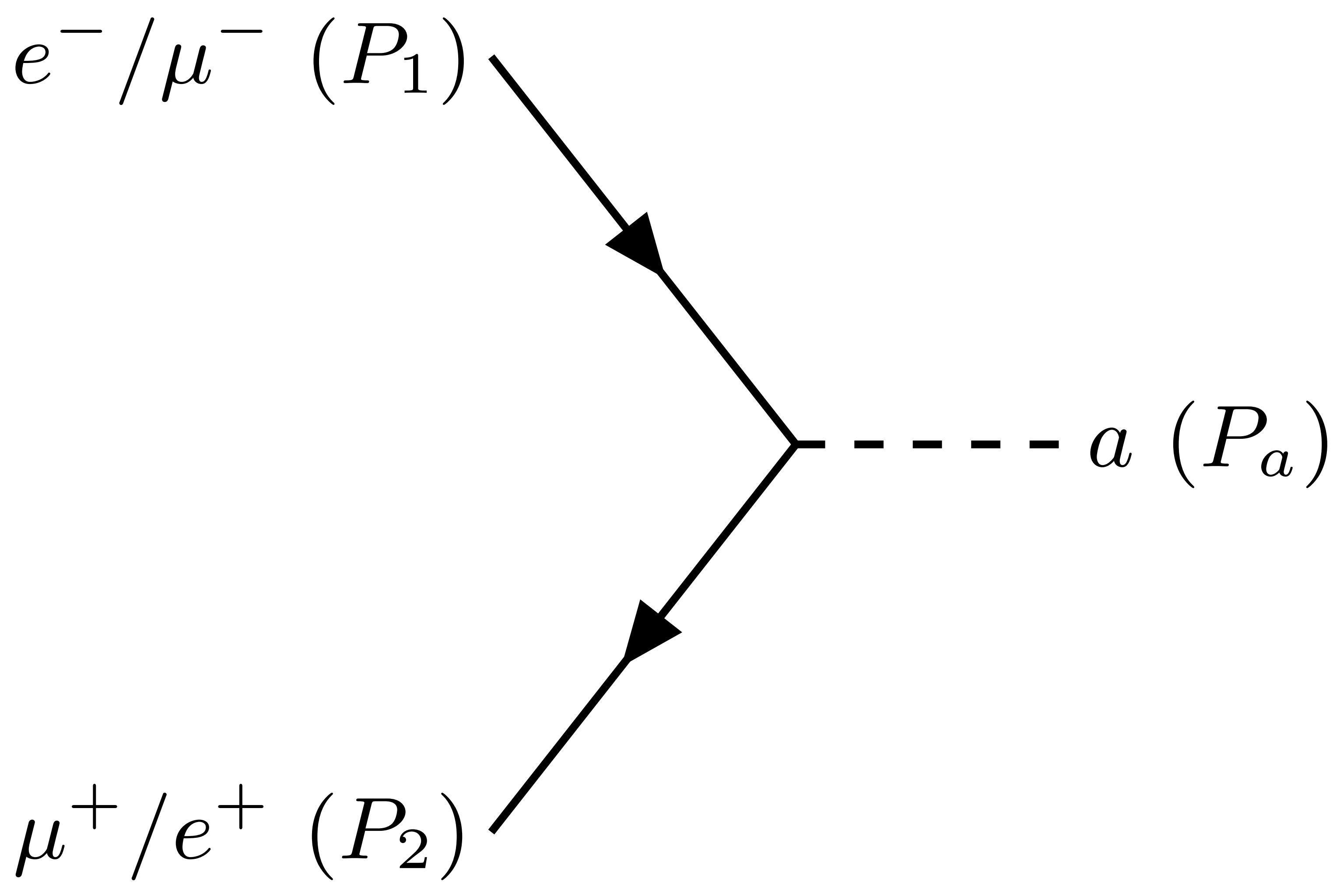
Different axion production channels in the SN (3)

(3) electron-muon coalescence

$$e^-/\mu^- + \mu^+/e^+ \to a$$

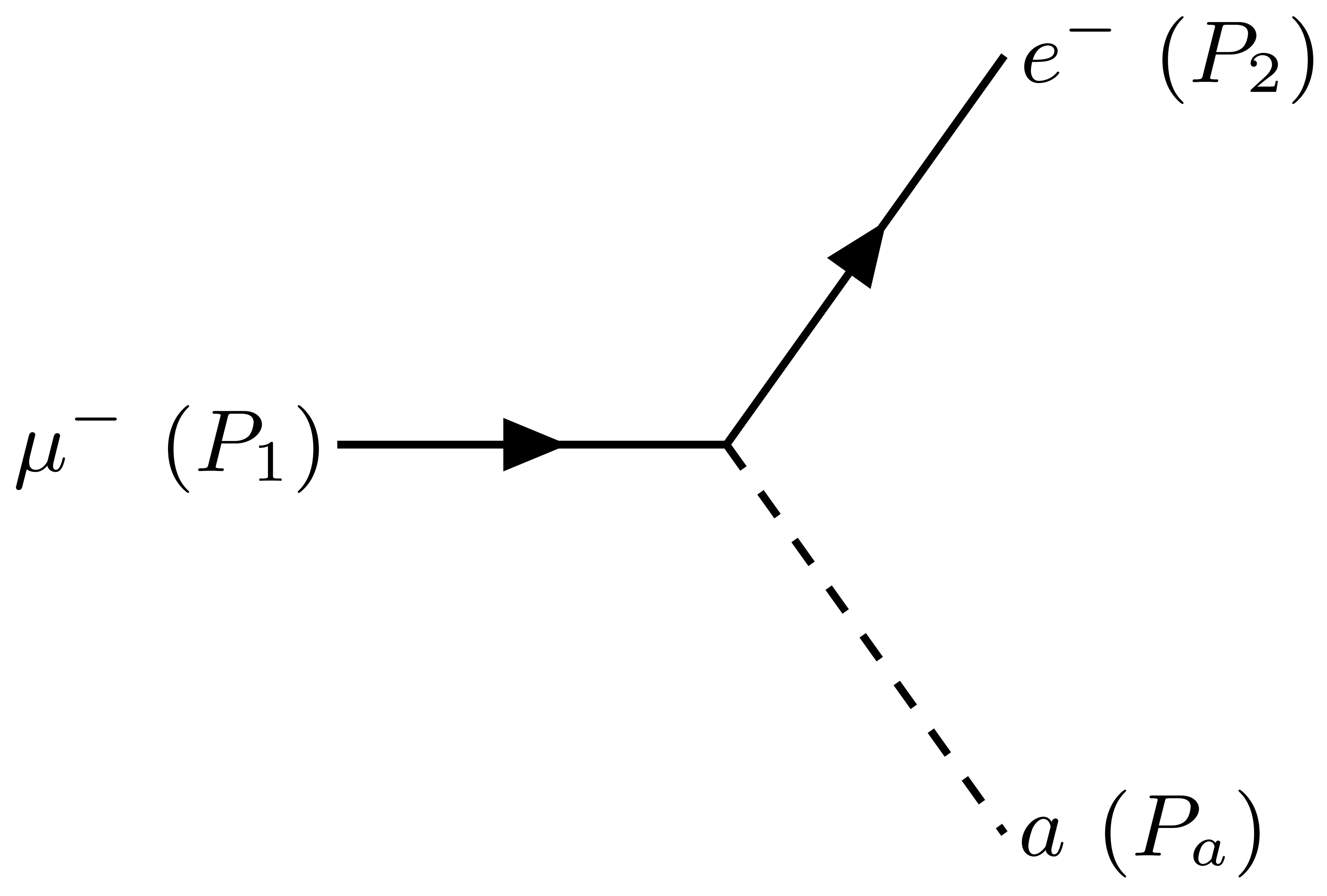
axion mass > muon mass

[Li, ZL, 2501.12075]

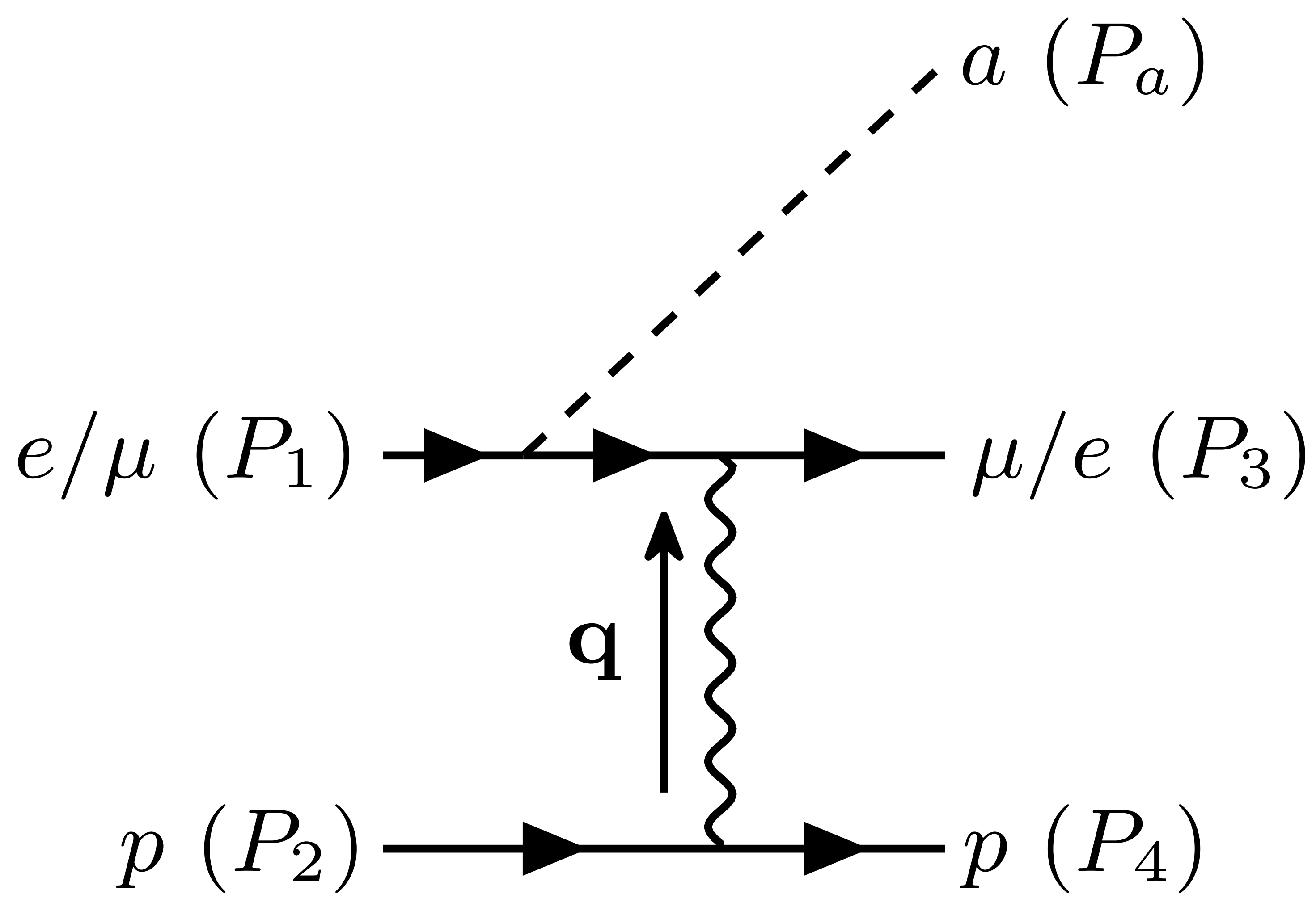


3 Axion production in the SN core

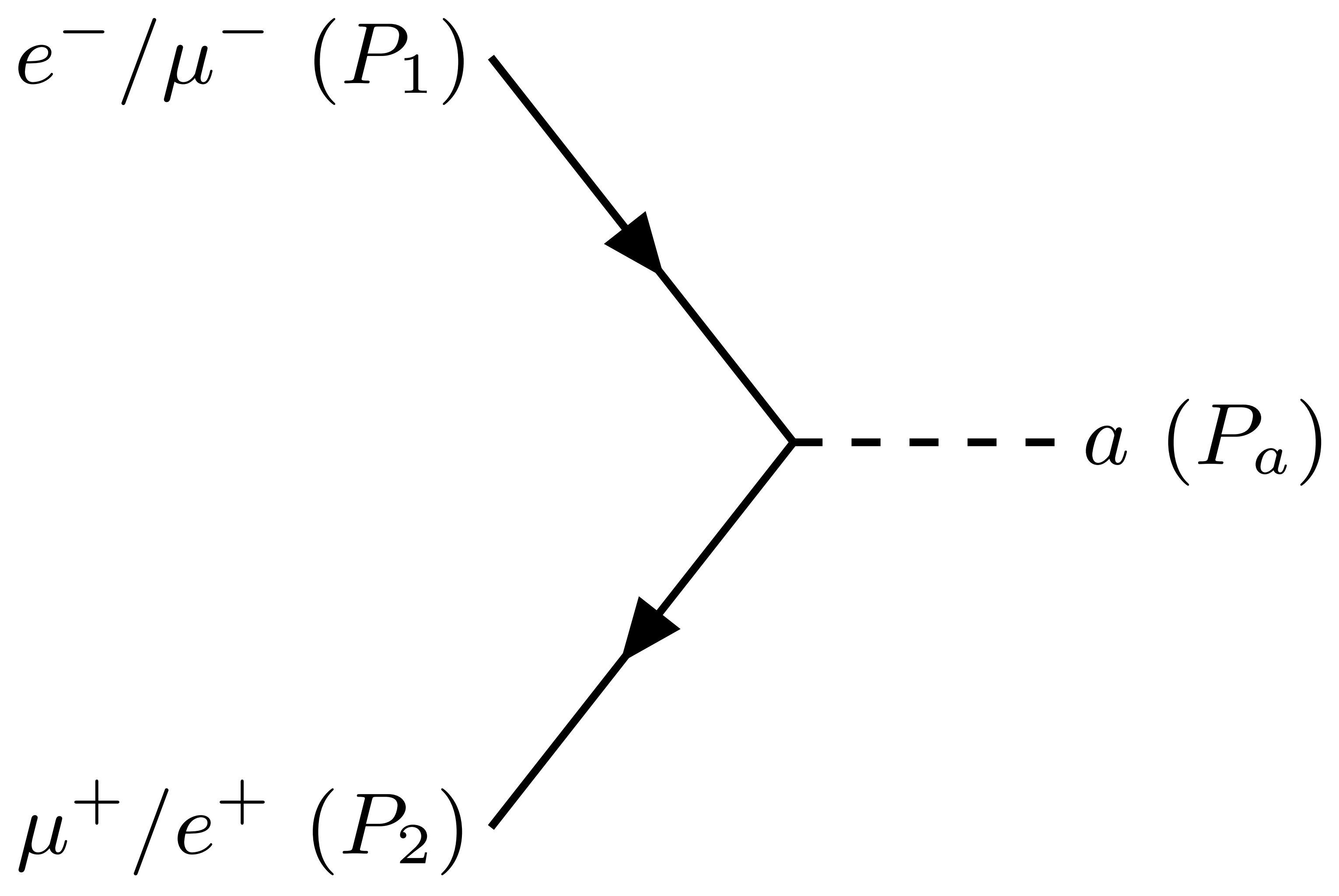
Three production channels in the SN



(1) muon decay

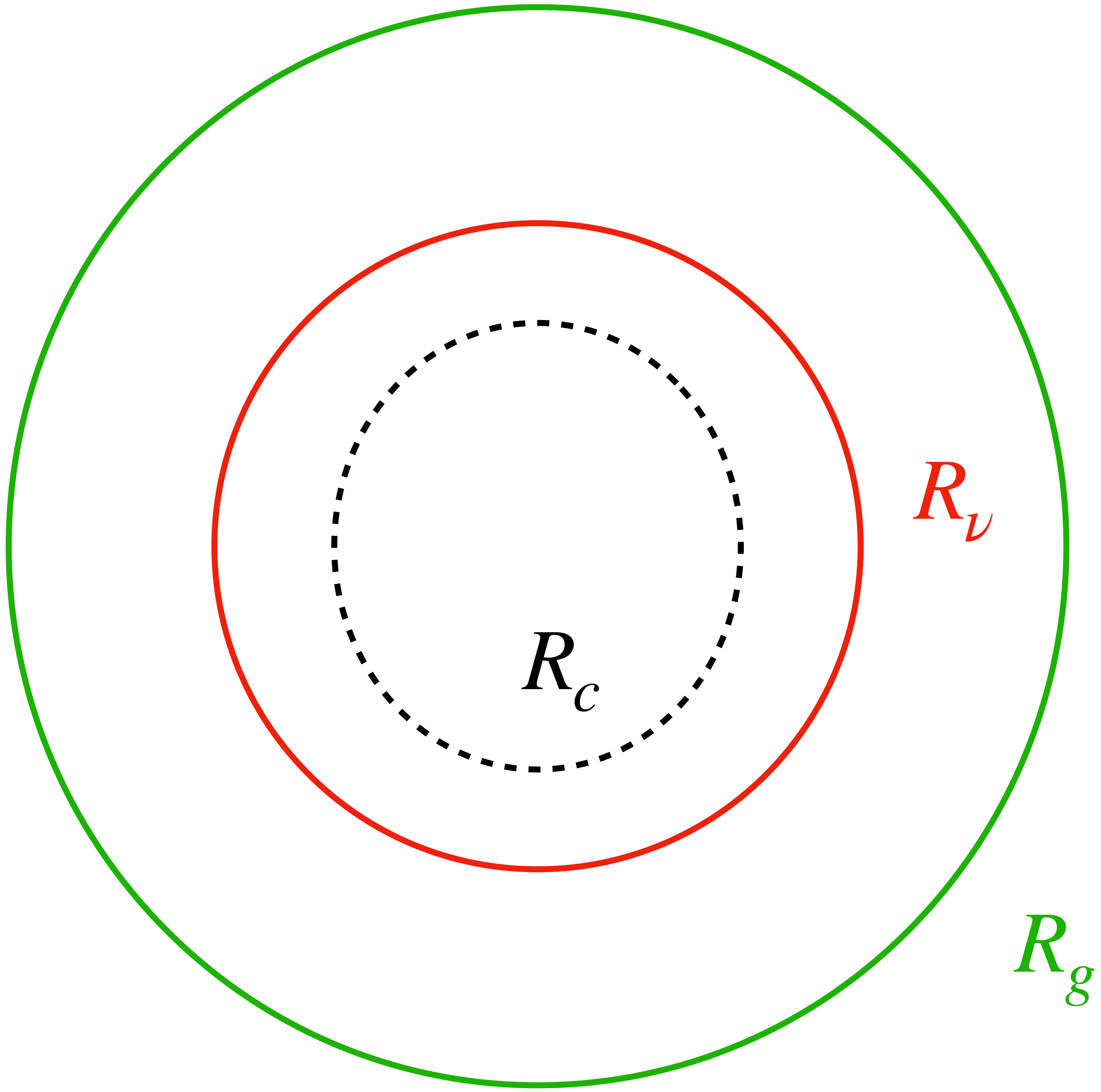


(2) bremsstrahlung



(3) electron-muon coalescence

Gain radius, neutrino-sphere, and the SN core



SN core (naive cooling analysis)

neutrino-sphere: R_ν = MFP

gain radius:

neutrino cooling = neutrino heating

Axions escaping $R_g \rightarrow$ cooling

Axion luminosity at the gain radius

Axion luminosity at the gain radius R_g is obtained via the volume integration:

$$L_a = \int_0^{R_g} dr\ 4\pi r^2\, \text{lapse}(r)^2 (1 + 2v_r) \int_{m_a'}^{\infty} dE_a\ E_a \frac{d^2 n_a}{dtdE_a} \left\langle e^{-\tau_a(R_g, E_a, r)} \right\rangle$$

[A. Caputo, G. Raffelt, and E. Vitagliano, 2204.11862]

r = position of production

lapse(r) = gravitational effects

v_r = radial velocity of the emitting material: $v_r \ll 1$

$m_a' = m_a/\text{lapse}$

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↓ Differential axion production rate

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Absorption term

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[A. Caputo, G. Raffelt, and E. Vitagliano, 2204.11862]

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Axion luminosity: production & absorption

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↓ Differential axion production rate

Differential axion production rate = the number of axion produced

per unit volume, per unit time, per unit energy

Axion luminosity: production & absorption

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Absorption term

Differential axion production rate

[A. Caputo, G. Raffelt, and E. Vitagliano, 2204.11862]

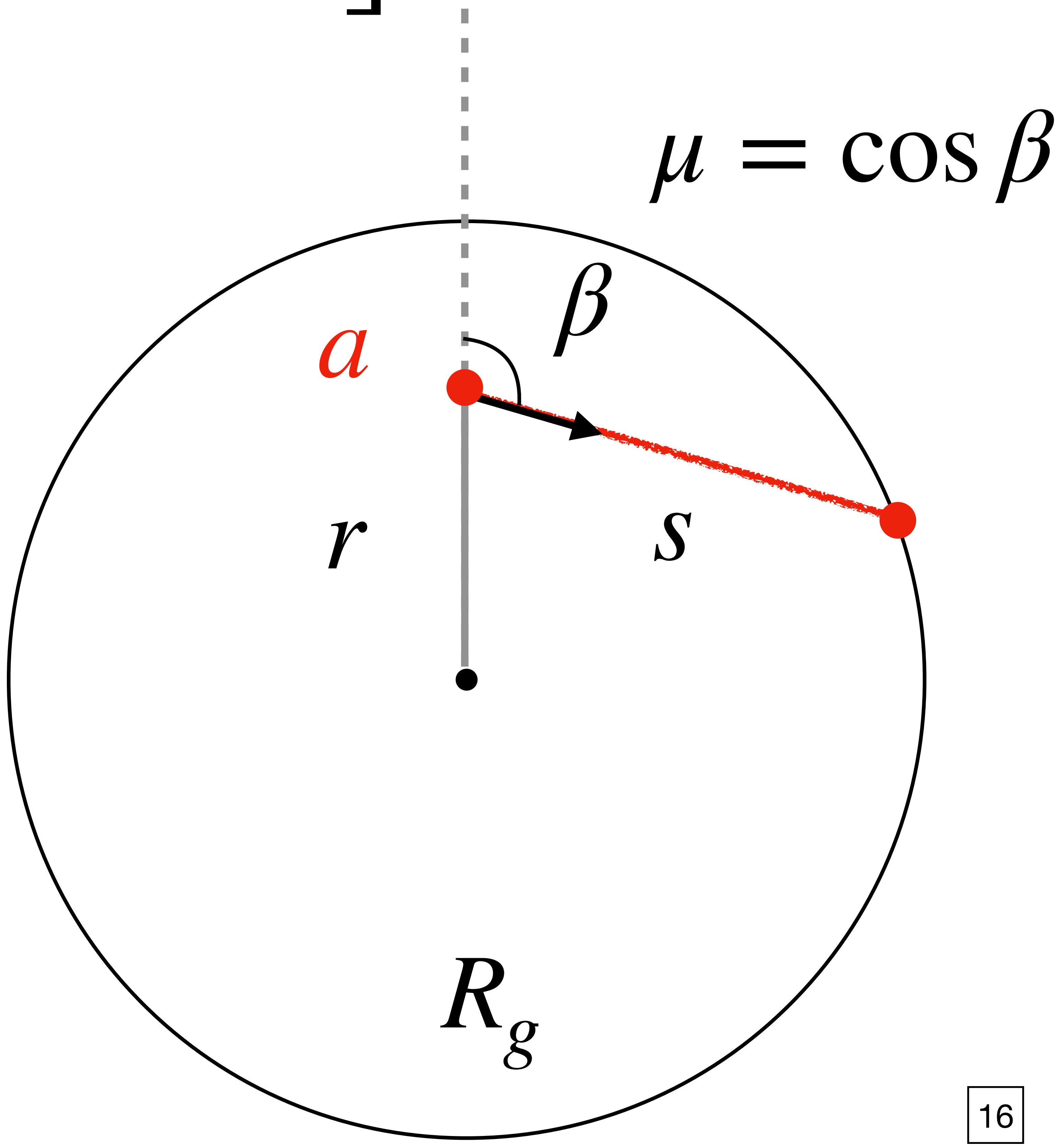
Differential axion production rate = the number of axion produced per unit volume, per unit time, per unit energy

Absorption term = the probability for an axion produced at r w/ energy E_a to escape the gain radius

4 Axion absorption

Absorption term

$$\langle e^{-\tau_a(R_g,E_a,r)} \rangle = \int_{-1}^{1} \frac{d\mu}{2} \exp\left[-\int_0^{s_{\max}} \frac{ds}{v}\, \Gamma_{\rm abs}\left(E_a, \sqrt{r^2+s^2+2rs\mu} \right) \right]$$



$\Gamma_{\rm abs}$ = Axion absorption width

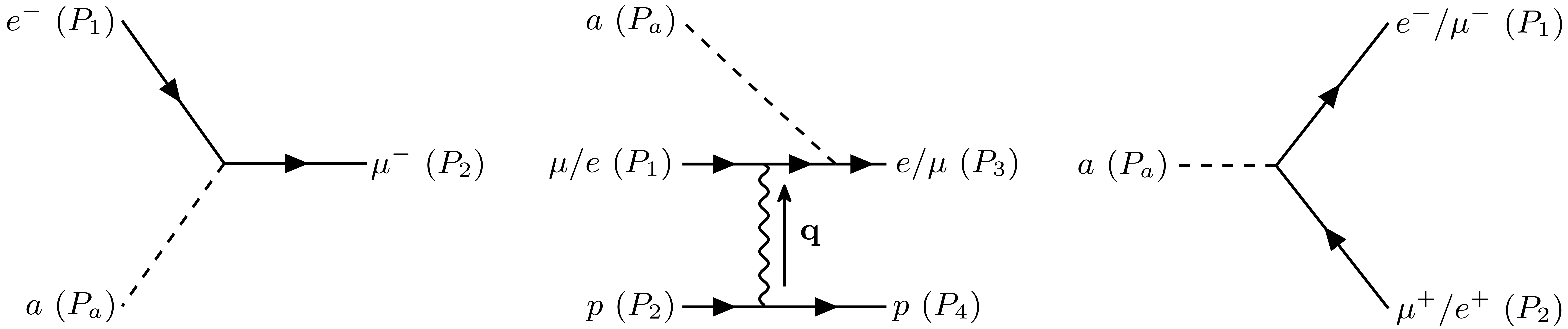
r = axion production point

s = axion propagation distance between r and R_g

β = angle between trajectory & radial direction

[A. Caputo, G. Raffelt, and E. Vitagliano, 2204.11862]

Three absorption channels in the supernova



(1) electron-axion coalescence

(2) inverse bremsstrahlung

(3) axion decay

these are the inverse of the production channels

Axion production & absorption

The production and absorption rates are:

$$\frac{d^2 n_a}{dt dE_a} = \frac{|\mathbf{p_a}|}{4\pi^2} \int \prod_i d\Phi_i \; f_i \; \prod_{j \neq a} d\Phi_j \; (1 \pm f_j) \; (2\pi)^4 \delta^{(4)}(P_i - P_j) \left| \mathscr{M} \right|^2$$

$$\Gamma_{\rm abs}(E_a, r) = \frac{1}{2E_a} \int \prod_{j \neq a} d\Phi_j \; f_j \; \prod_i d\Phi_i \; (1 \pm f_i) \; (2\pi)^4 \delta^{(4)}(P_j - P_i) \left| \mathscr{M} \right|^2,$$

initial & final state distributions f_i & f_j

[E.W. Kolb, M.S. Turner, 90']

Axion production for electron-muon coalescence

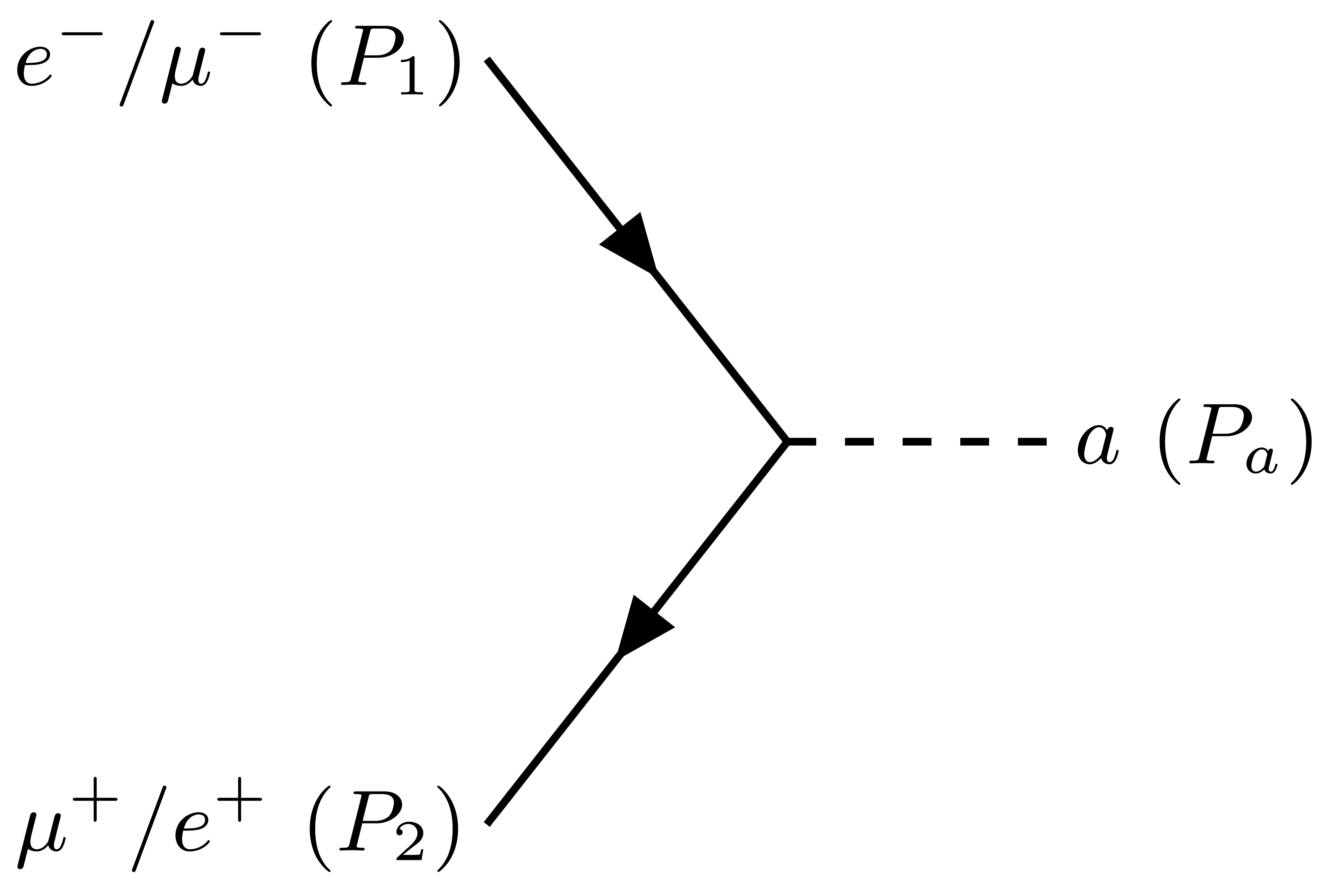
$$\frac{d^2 n_c}{dt dE_a} = \frac{|\mathcal{M}_c|^2}{32\pi^3} \int_{E_2^-}^{E_2^+} dE_2 \, (f_\mu f_e^+ + f_e f_\mu^+),$$

$$|\mathcal{M}_c|^2 = 2 g_{ae\mu}^2 [m_a^2 - (m_\mu - m_e)^2]$$

$$E_2^\pm = \frac{E_a(m_a^2 - m_1^2 + m_2^2)}{2m_a^2} \pm \frac{\sqrt{E_a^2 - m_a^2}}{2m_a^2} I$$

$$I = \sqrt{(m_1^2 - m_2^2 - m_a^2)^2 - 4 m_2^2 m_a^2}$$

$$\mathcal{L}_{\rm int} = -i g_{ae\mu} \, a \, \bar{e} \gamma_5 \mu + \mathrm{h.c.}$$



$$e^-/\mu^- + \mu^+/e^+ \to a$$

Particle distributions in the supernova

Production (absorption) rate depends on the particle distributions

Electron & positron: $$f_{e^\pm} = \frac{1}{e^{(E_e \pm \mu_e)/T} + 1}$$

electron chemical potential: $\mu_e = \mu_e(r)$

Temperature: $T = T(r)$

both μ & T are function of r:

SN profiles

Supernova model: the SFHo-18.8 model

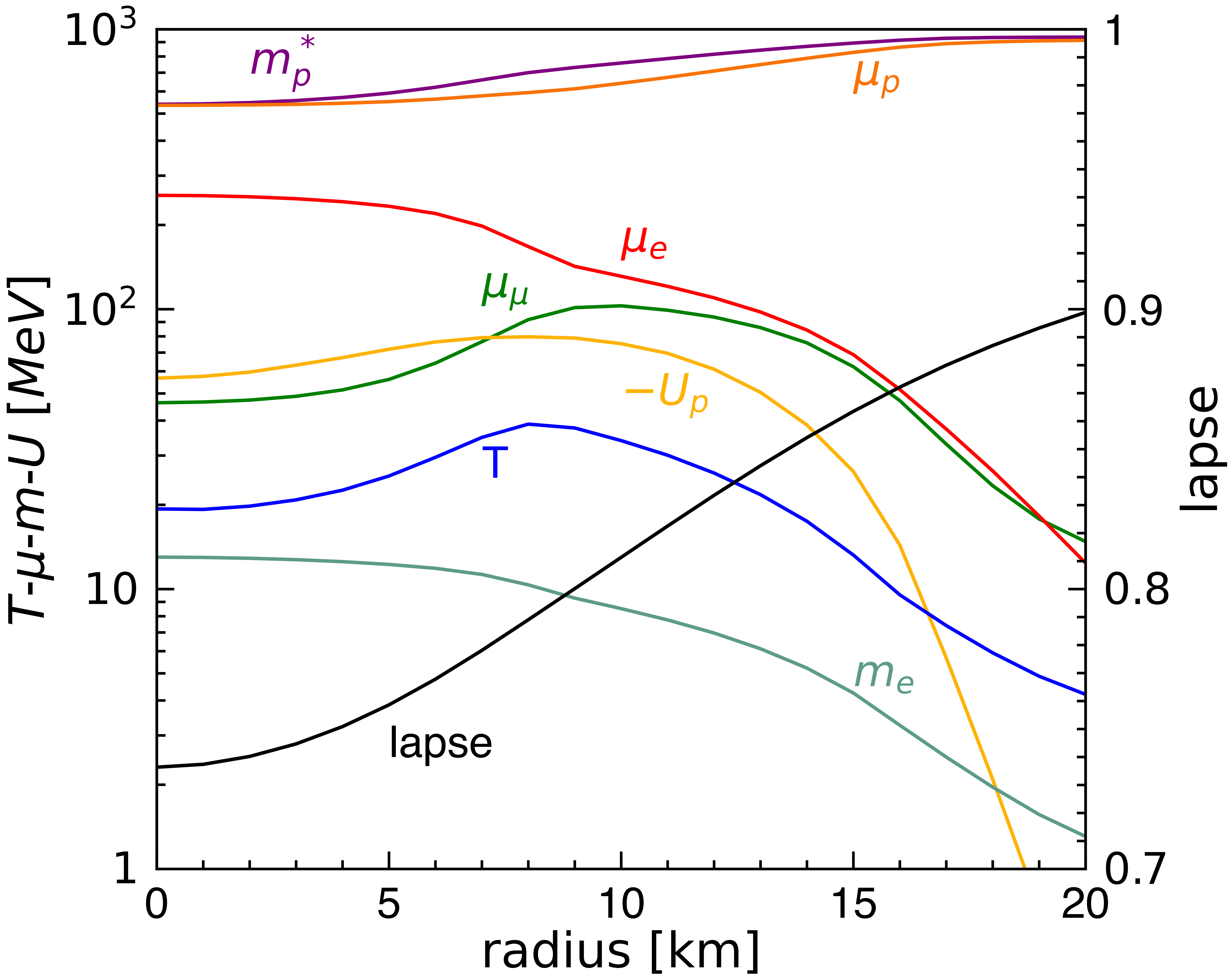
The SFHo-18.8 model: the modern SFHo equation of state

[A. W. Steiner, M. Hempel, and T. Fischer, 1207.2184]

The coldest model simulated by Bollig et al. [R. Bollig et al., 2005.07141]

The final neutron star mass of this model is at the lower edge of the allowed range of SN 1987A → conservative estimates of the constraint

The SFHo-18.8 SN profile

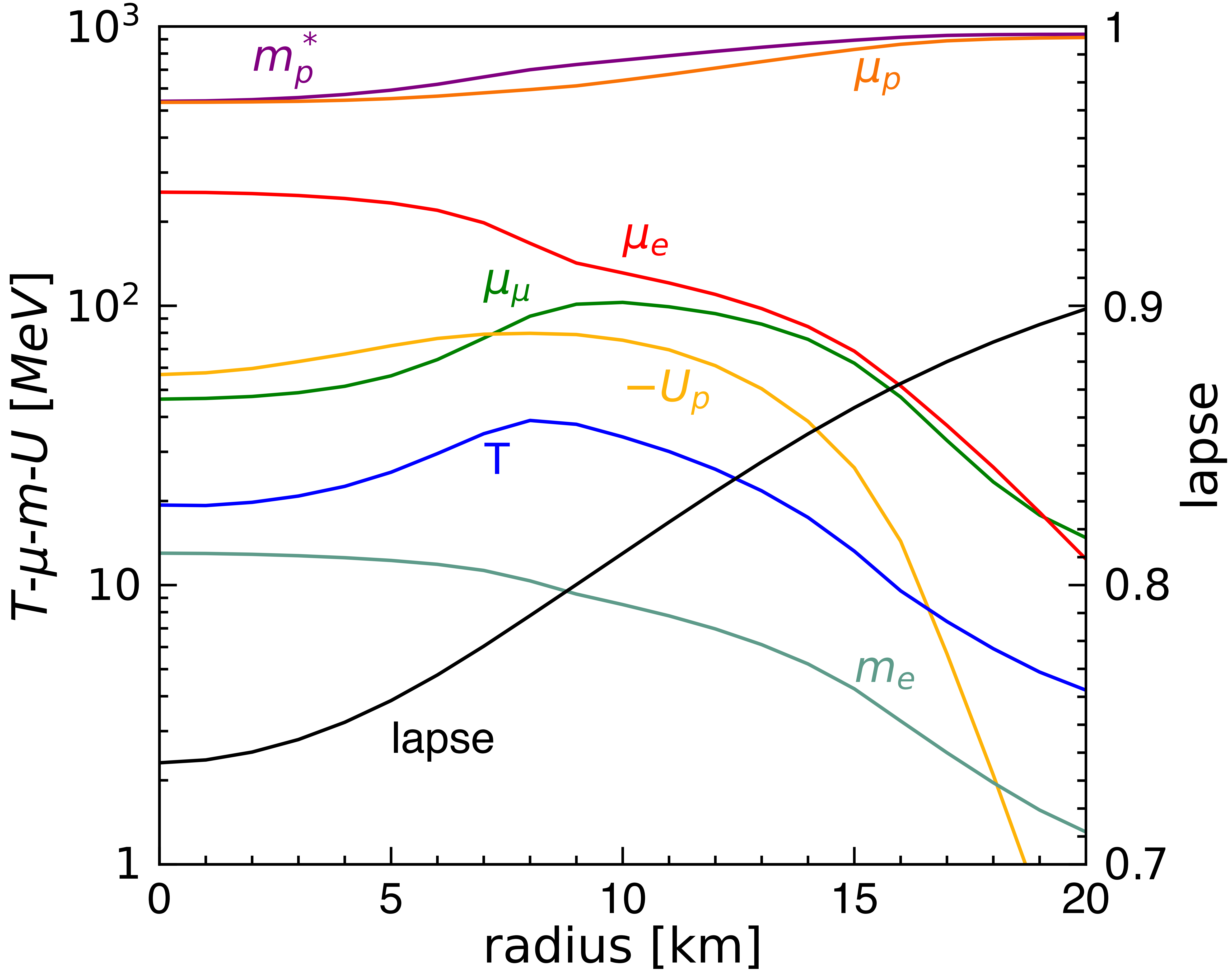


The profiles of chemical potentials of electrons, muons, and protons, temperature, proton effective mass, proton self-energy, and electron effective mass in the SN core of the SFHo-18.8 SN model.

[R. Bollig et al., 2005.07141]

Garching core-collapse supernova research archive, https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/

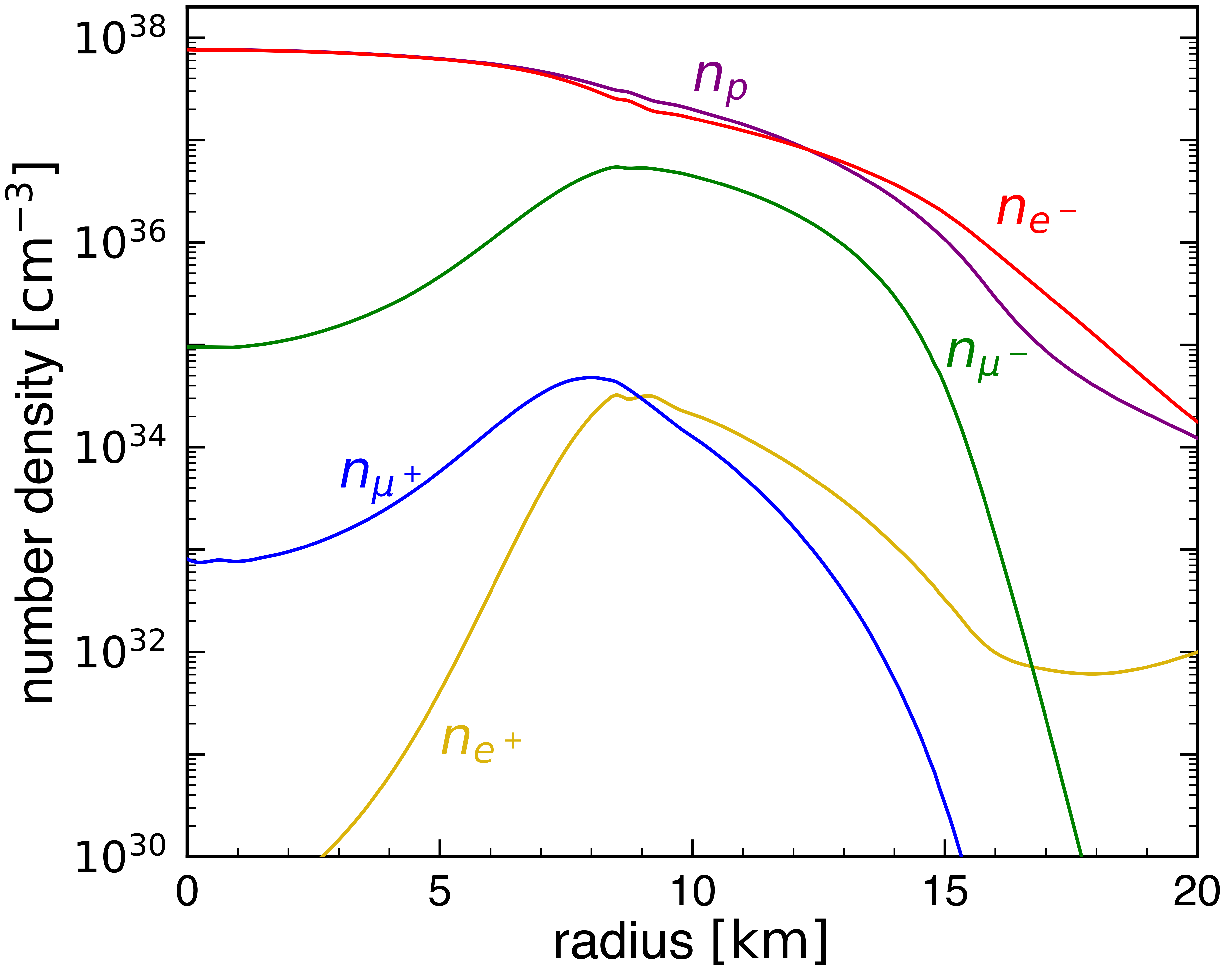
The SFHo-18.8 SN profile



In the extreme environment of SN core, the kinematical properties of protons and electrons are significantly modified. Their effective mass are significantly different from the vacuum mass of these particles.

[R. Bollig et al., 2005.07141]

The SFHo-18.8 SN profile



$$f_{e^\pm} = \frac{1}{e^{(E_e \pm \mu_e)/T} + 1}$$

$$f_{\mu^\pm} = \frac{1}{e^{(E_\mu \pm \mu_\mu)/T} + 1}$$

$$f_p = \frac{1}{e^{(E_p - \mu_p + U_p)/T} + 1}$$

Number densities of electron, positron, muon, anti-muon and proton in the SN

Other experimental constraints on LFV axions

(1) rare muon decay experiment

$$\mu^{\pm} \to e^{\pm} + a$$

- Derenzo [S.E. Derenzo, 69']
- Jodidio et al. [A. Jodidio et al., 86']
- Bilger et al. [R. Bilger et al., 99']
- TWIST [TWIST Collaboration, 1409.0638]
- PIENU [PIENU Collaboration, 2002.09710]
- Mu3e [S. Knapen, K. Langhoff, T. Opferkuch, and D. Redigolo, 2311.17915]

Other experimental constraints on LFV axions

(2) accelerator experiment

Scattering processes that produce axions or mediated by axions

- Belle II

[H. Davoudiasl et al., 2105.05866]

[M. Endo, S. Iguro, and T. Kitahara, 2002.05948]

[S. Iguro, Y. Omura, and M. Takeuchi, 2002.12728]

- LHC

[T. Araki et al., 2210.12730]

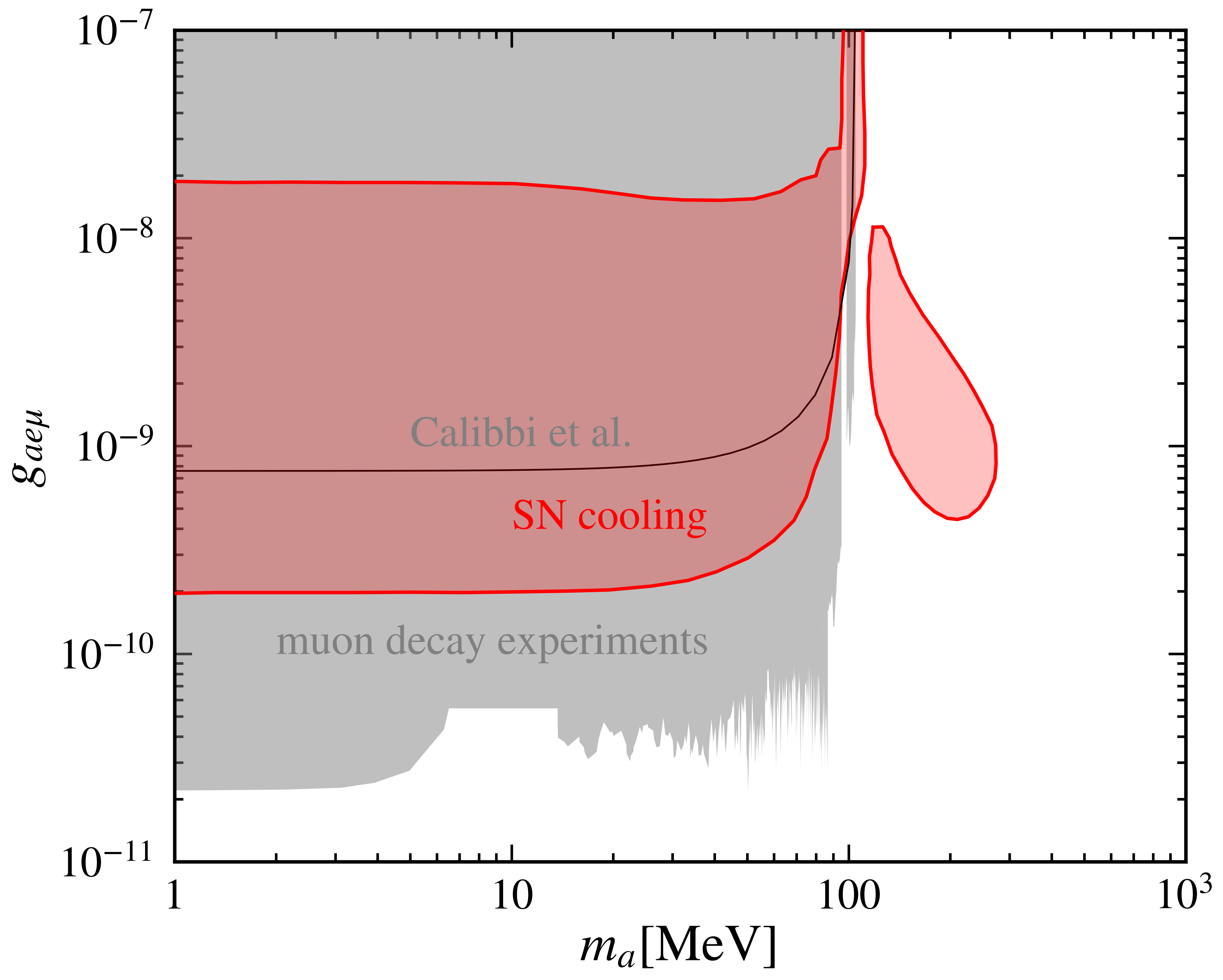
[H. Davoudiasl et al., 2105.05866]

- EIC (Electron-Ion Collider)

[H. Davoudiasl, R. Marcarelli, and E. T. Neil, 2112.04513]

5 Supernova constraints on LFV axions

Supernova constraints on LFV axions



[Li, ZL, 2501.12075]

probe new para space for $m \gtrsim$ 115 MeV

improve limits for $m \lesssim$ 115 MeV

Dominant production channel:

- For $m_a \lesssim 100$ MeV, muon decay process
- For $m_a \sim (100{,}110)$ MeV, bremsstrahlung process
- For $m_a \sim (115{,}280)$ MeV, electron-muon coalescence process

Summary

- We compute supernova constraints on lepton flavor violating axions/ALPs

- We compute the axion production in the supernova core via the following 3 channels
  - muon decay
  - bremsstrahlung
  - electron-muon coalescence $\Rightarrow$ important for high-mass (previously omitted)

- We find that the electron-muon coalescence production channel probes new parameter space: $m_a \sim [115{,}280]$ MeV, $g \sim [4 \times 10^{-9}, 10^{-8}]$

[Li, ZL, 2501.12075]