Supernova Constraints on Lepton Flavor Violating Axions

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辽宁师范大学第四届高能物理理论与实验融合发展研讨会

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Outline

1. Lepton flavor violating (LFV) axions/ALPs
2. Supernova (SN) cooling limits
3. Low-Energy SN (LESN) constraints

[Yonglin Li, ZL, 2501.12075]

[Zi-Miao Huang, ZL, 2506.16922]

1 Lepton Flavor Violating Axions

Lepton flavor violating axions/ALPs

Lepton flavor violating axions/ALPs

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

axions/ALPs couple to both electrons and muons

[F. Wilczek, 82']

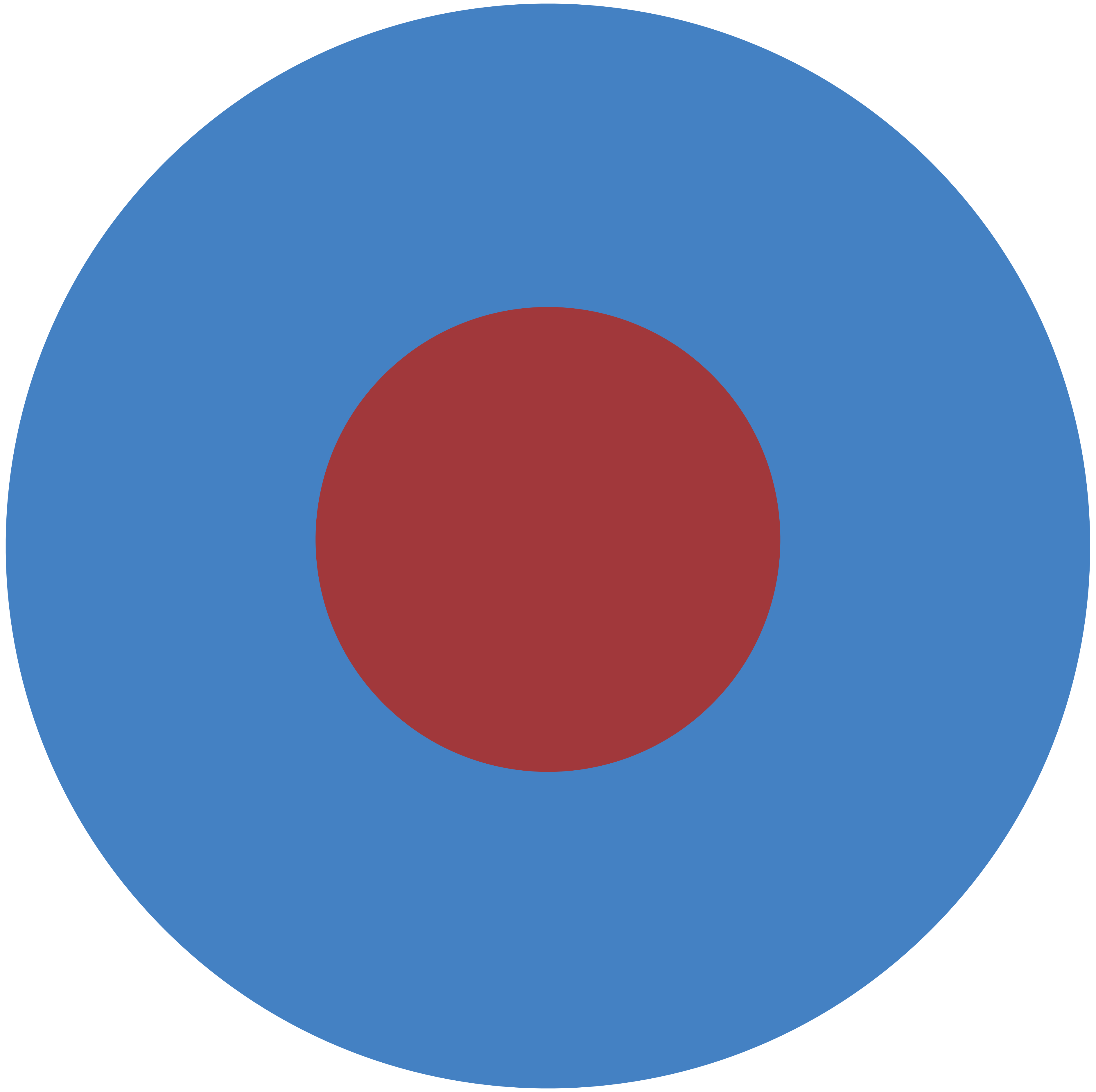
[L. Calibbi, D. Redigolo, R. Ziegler, and J. Zupan, 2006.04795]

a new muon decay channel (thus leading to muon-decay constrainnts)

2 Supernova (SN) cooling limits

Two types of supernova constraints

Supernova (SN) cooling limit



Energy loss due to NP particles escaping the SN core, leading to over-cooling of SN

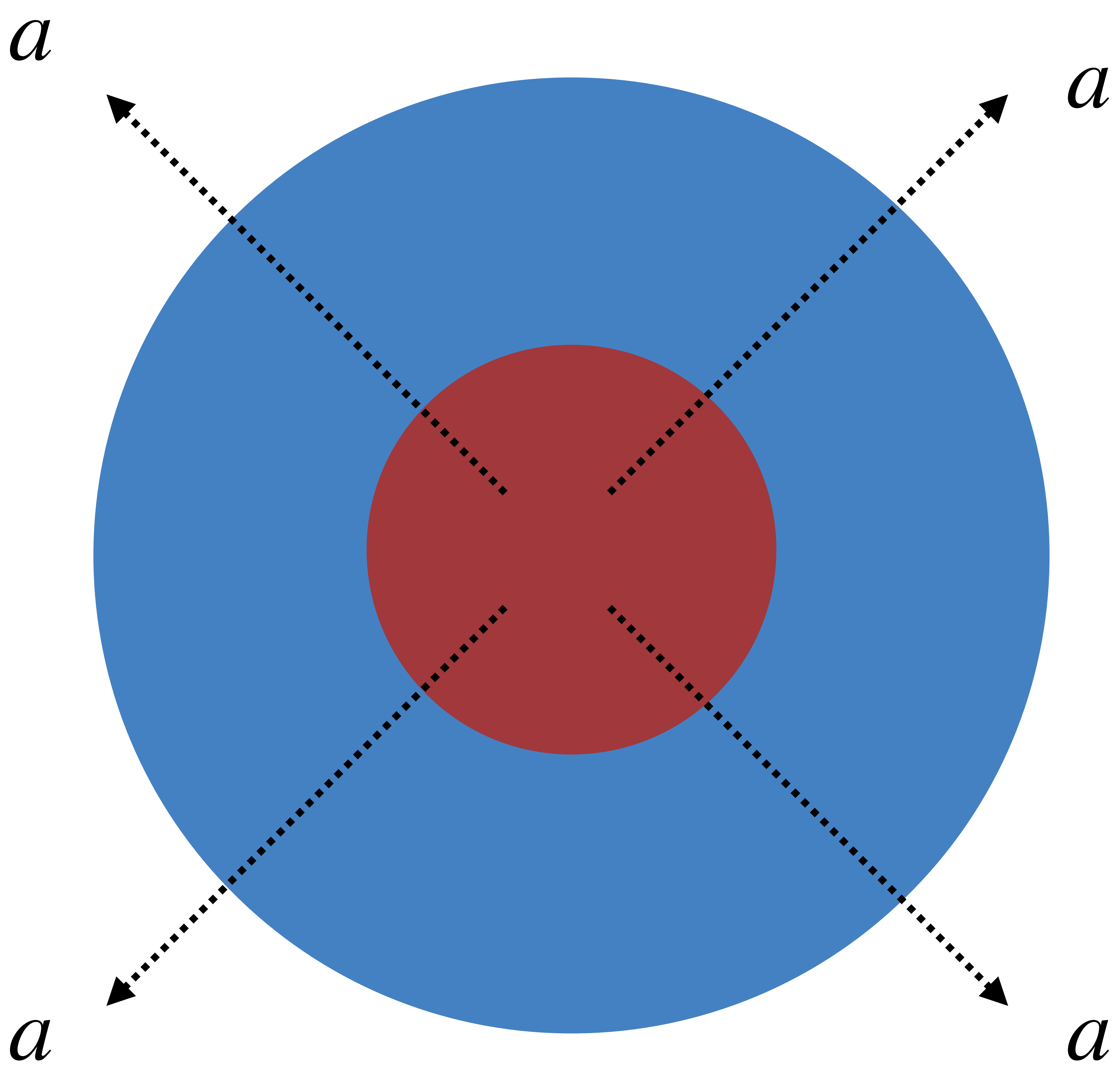
Raffelt criterion

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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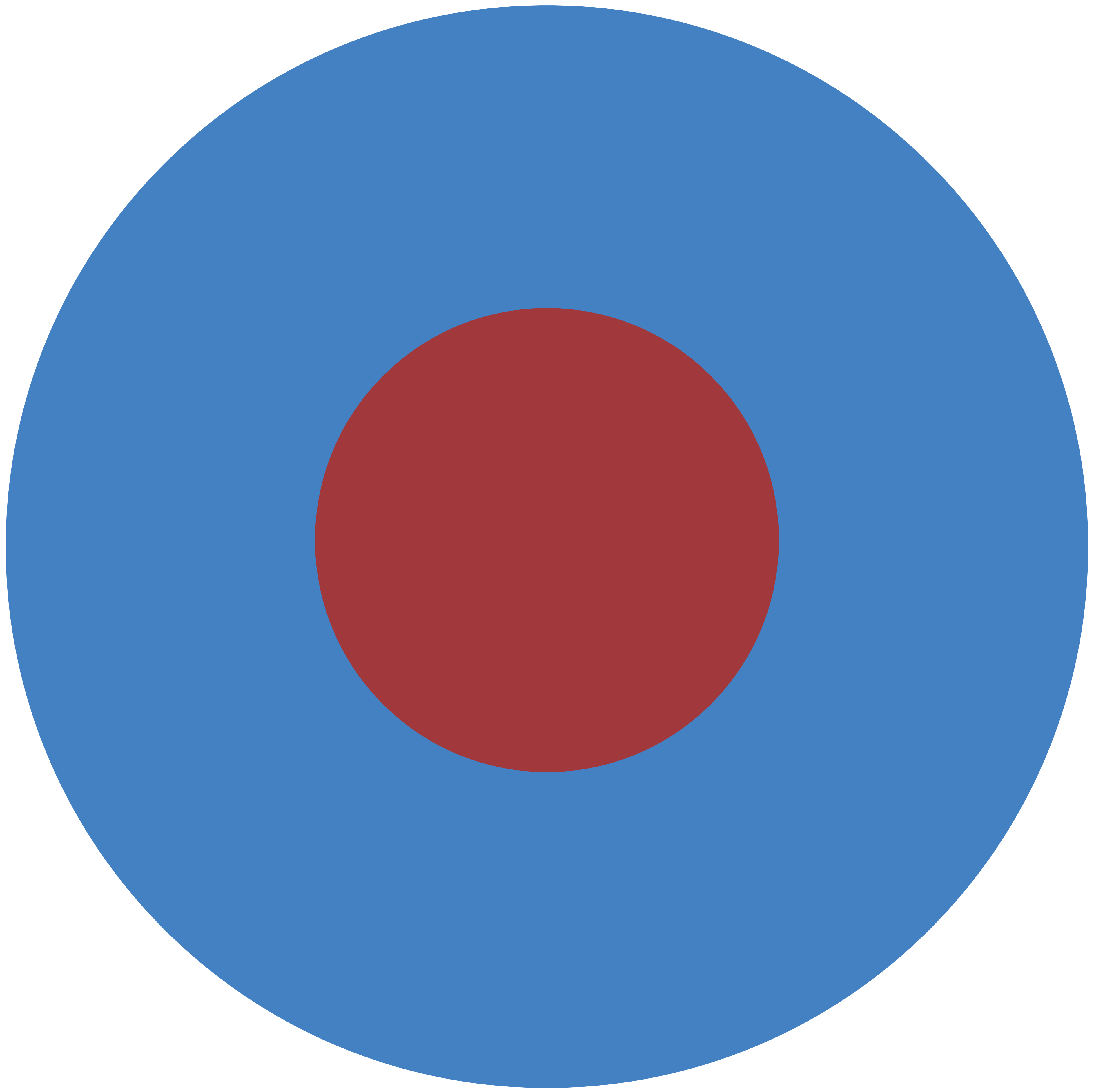
Supernova “calorimetric” limit



axion-induced energy transfer (from core to mantle) should not exceed SN explosion energy

[Falk & Schramm, 78’]

[Sung+, 1903.07923]

[Caputo+, 2201.09890]

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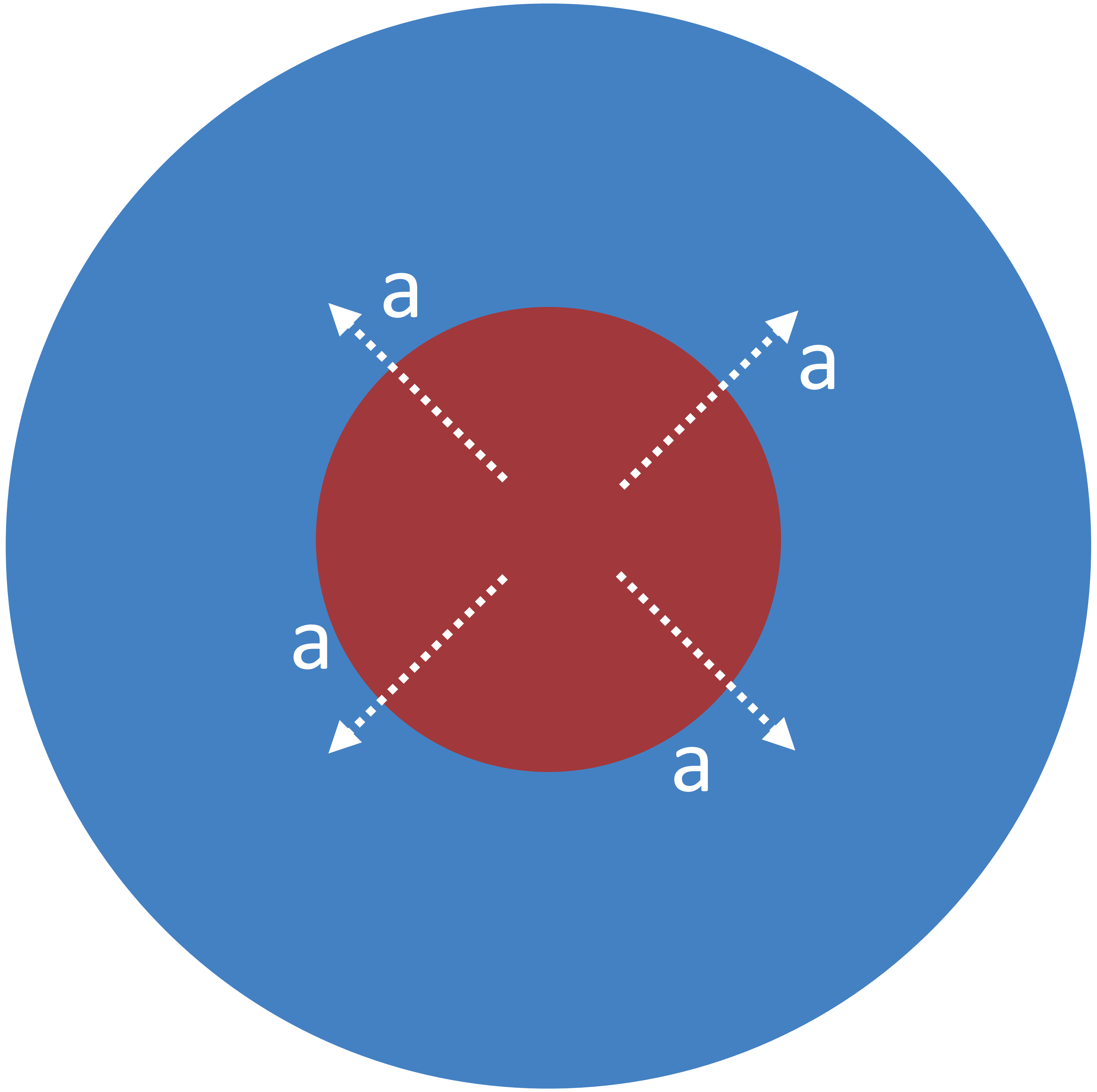

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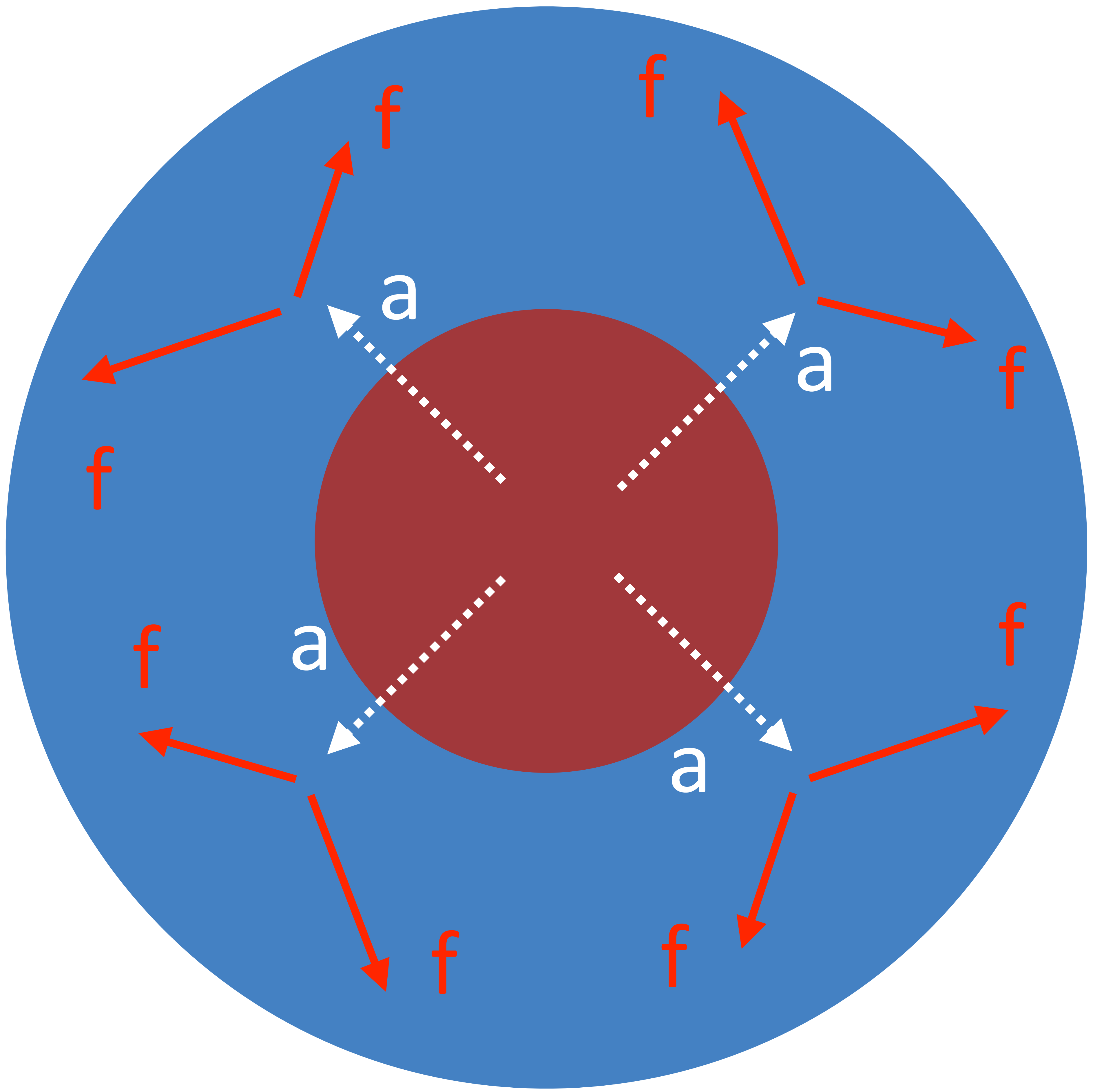


axion-induced energy transfer (from core to mantle) should not exceed SN explosion energy

[Falk & Schramm, 78’]

[Sung+, 1903.07923]

[Caputo+, 2201.09890]

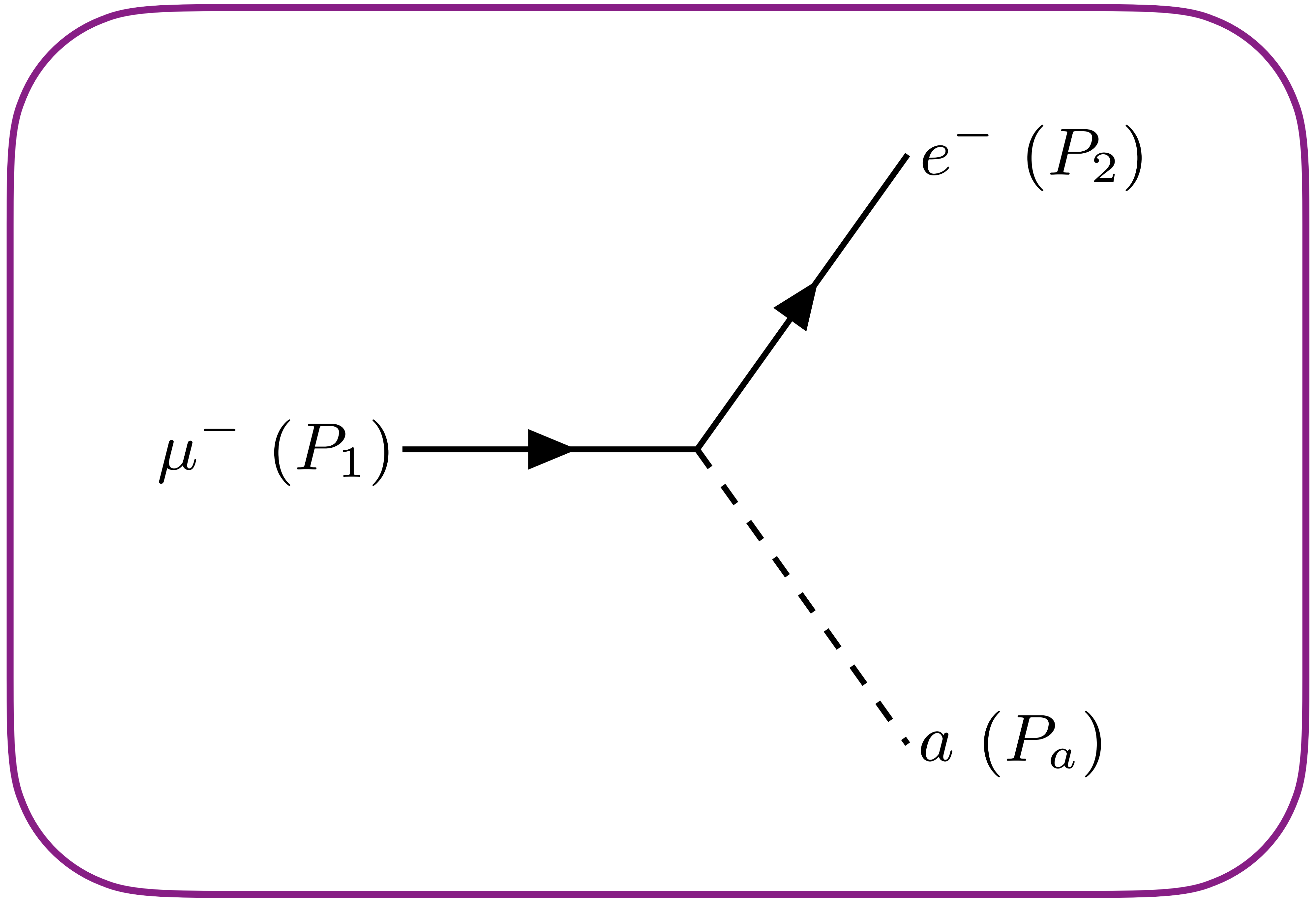
Axion production in the SN core

Different axion production channels in the SN (1)

(1) muon decay

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

axion mass < muon mass

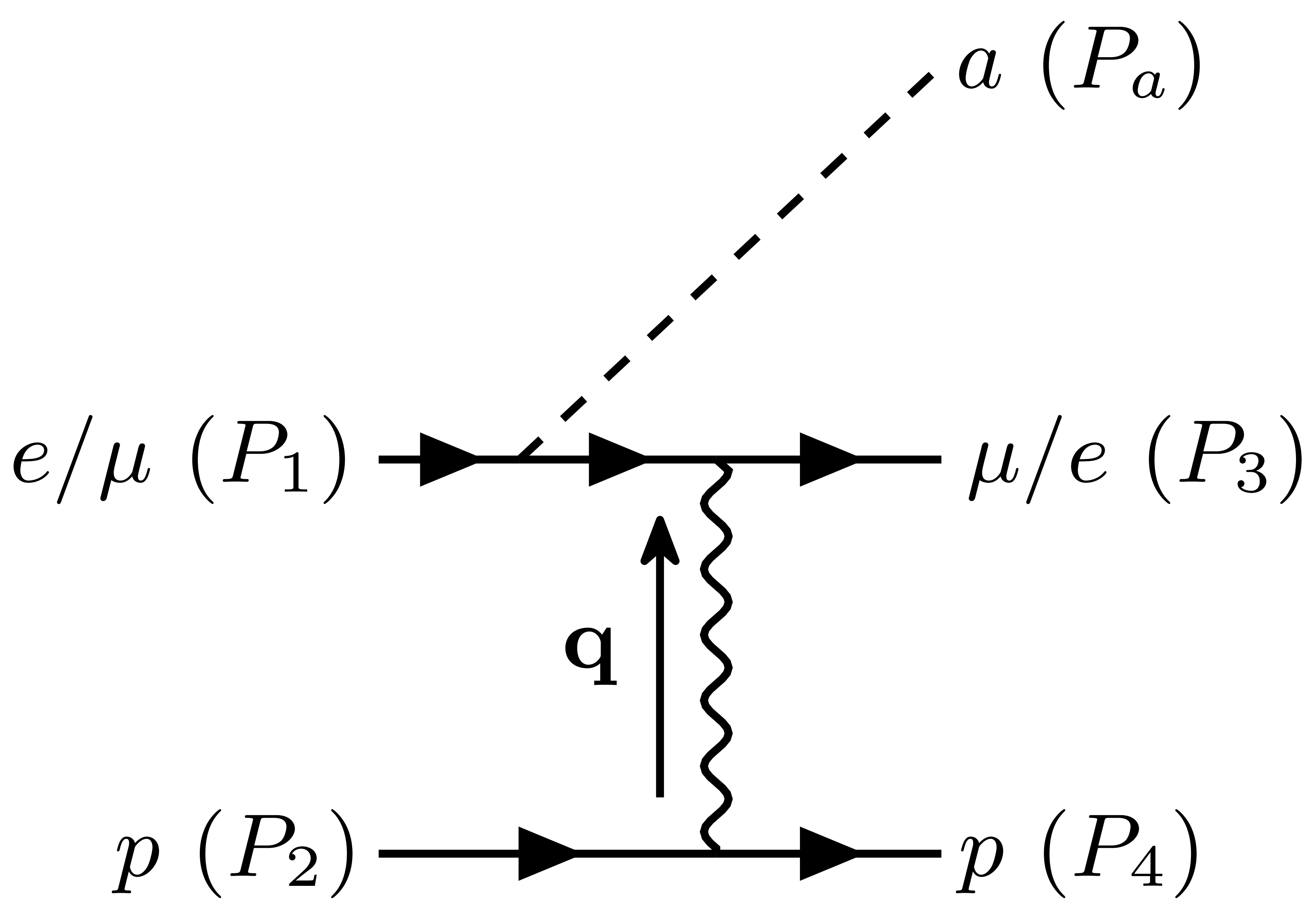


[L. Calibbi, D. Redigolo, R. Ziegler, and J. Zupan, 2006.04795]

Different axion production channels in the SN (2)

(2) bremsstrahlung

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



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

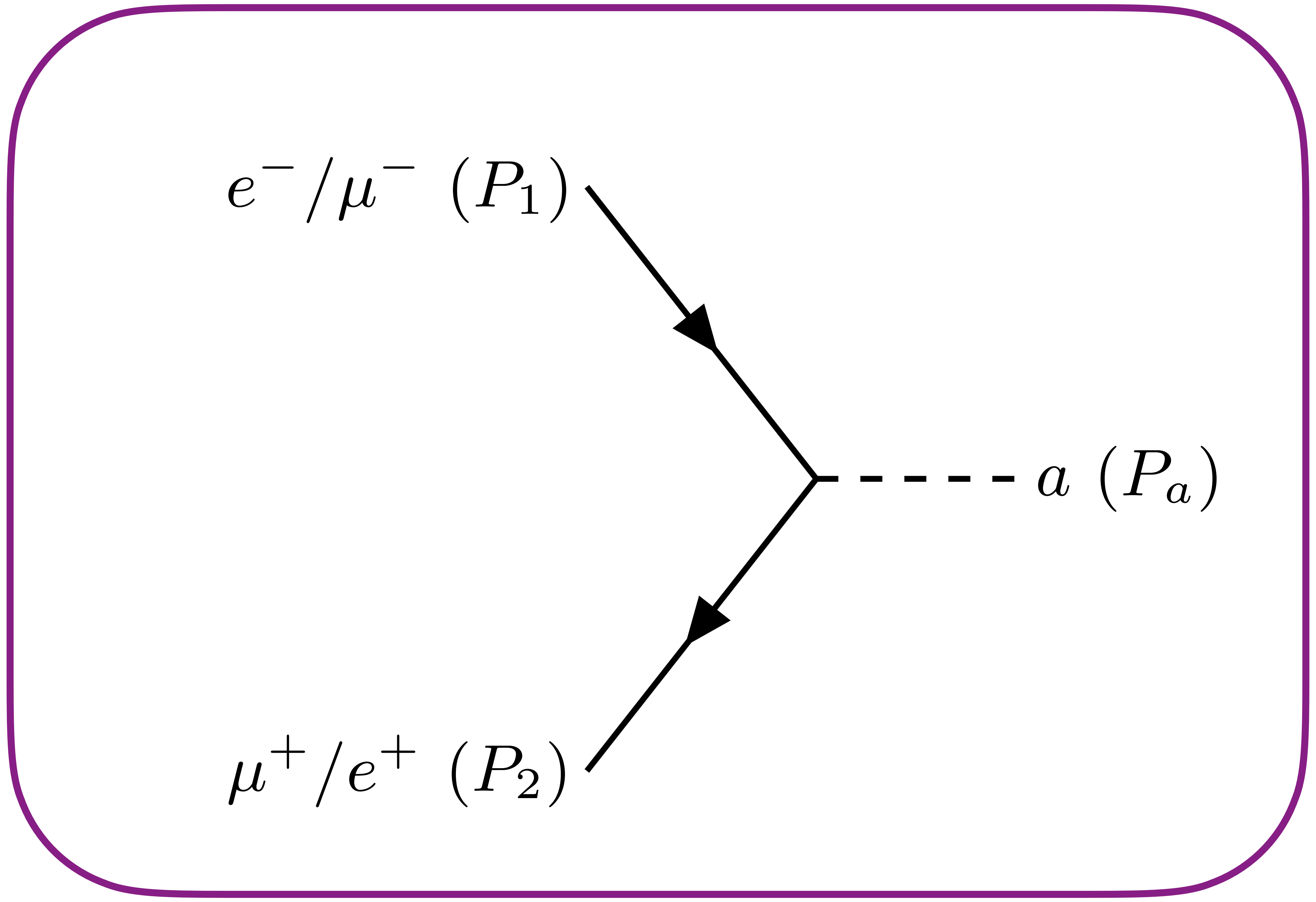
Different axion production channels in the SN (3)

(3) electron-muon coalescence

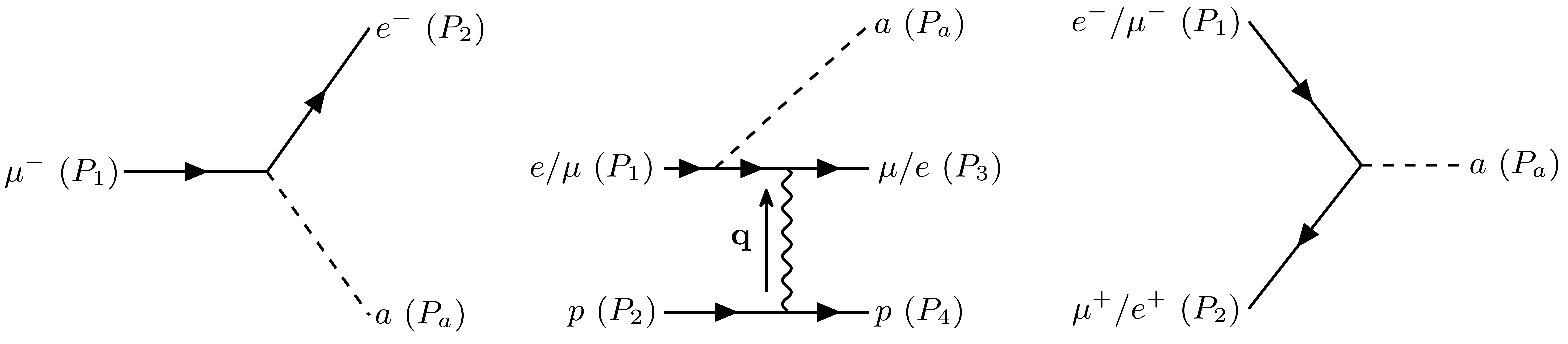
$$e^-/\mu^- + \mu^+/e^+ \rightarrow a$$

axion mass > muon mass

[Li, ZL, 2501.12075]



Three production channels in the SN

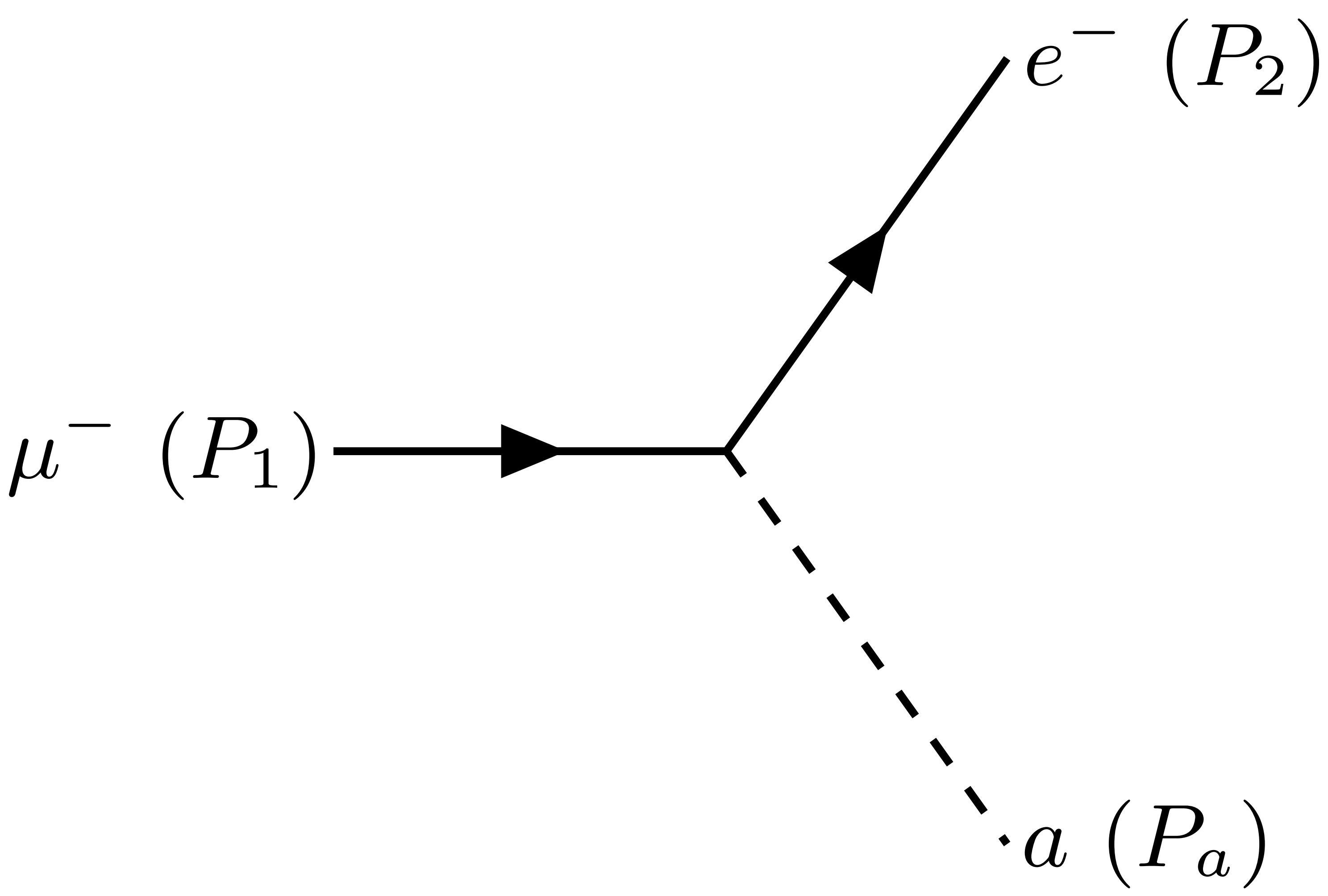


(1) muon decay

(2) bremsstrahlung

(3) electron-muon coalescence

Three production channels in the SN



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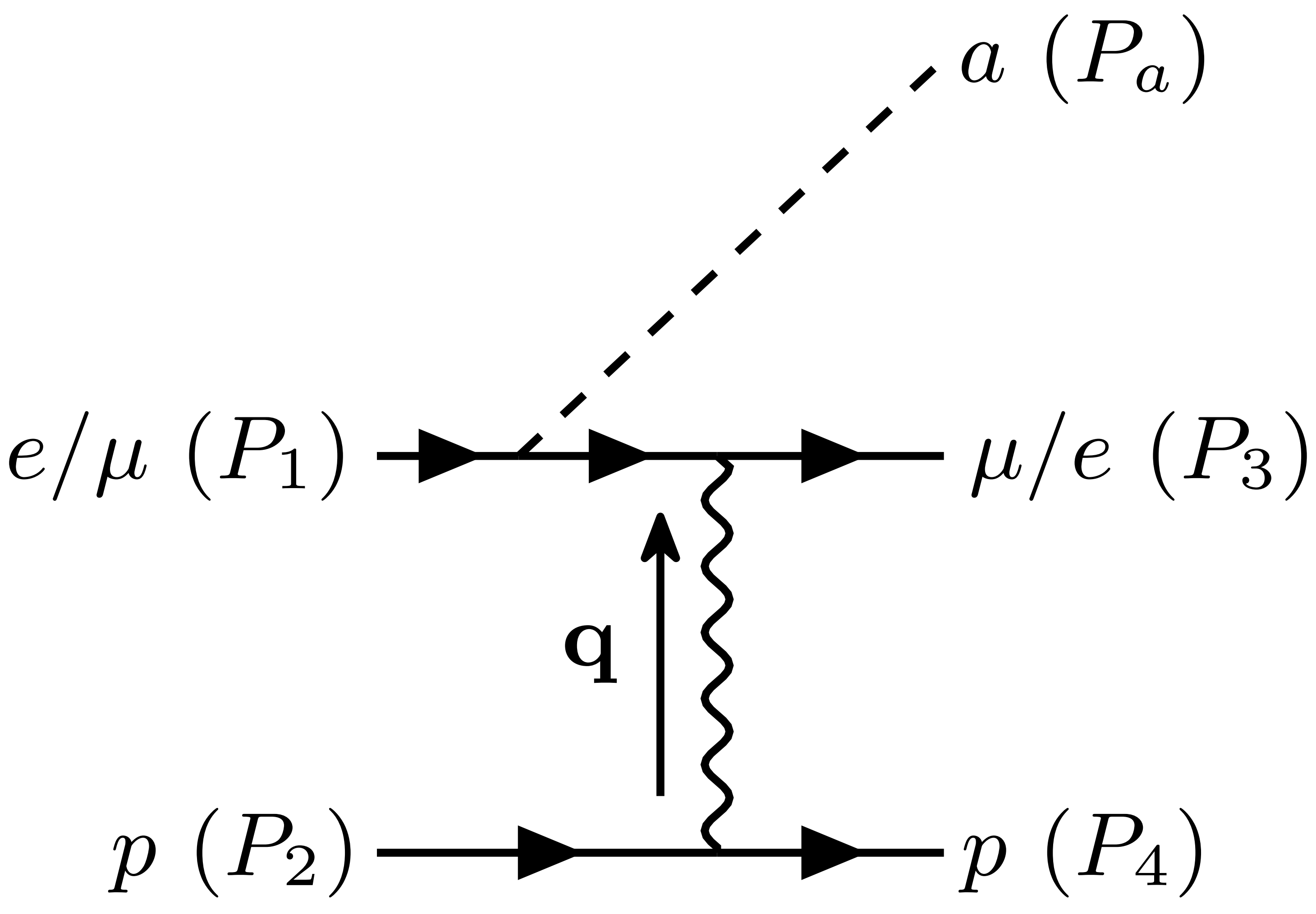
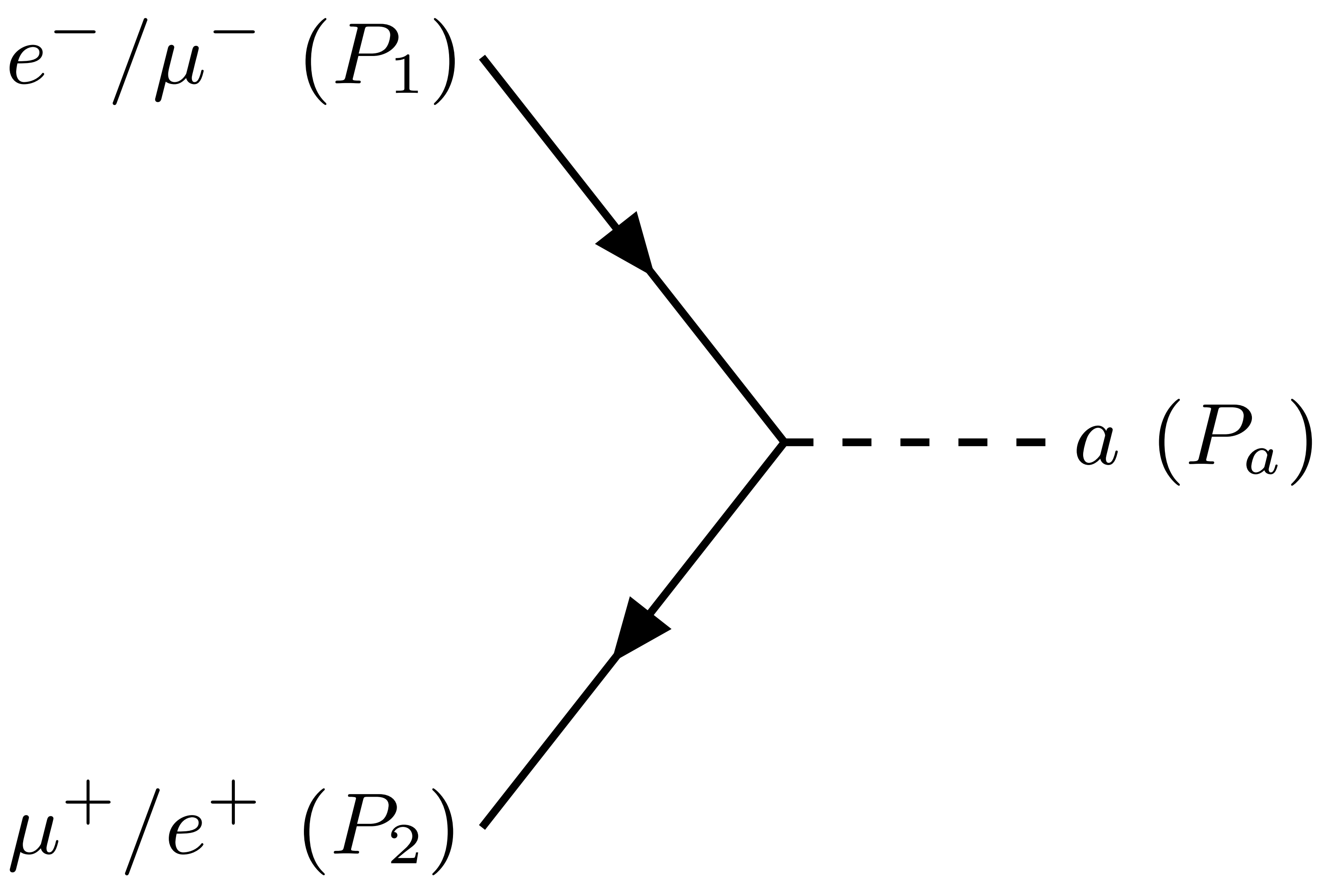


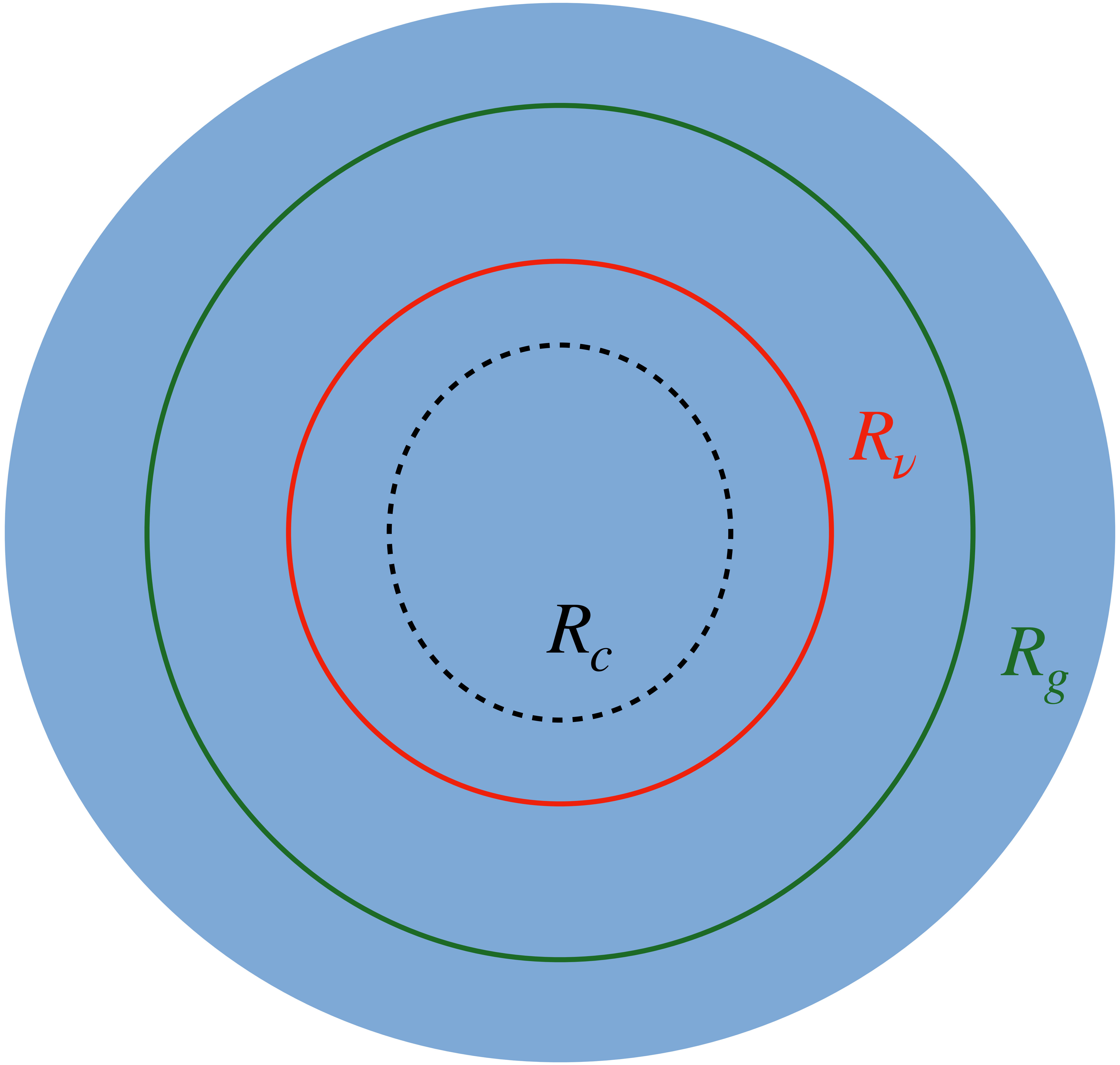
(2) bremsstrahlung



(3) electron-muon coalescence

not considered before

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:

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

[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: $v_r \ll 1$

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

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↓ Differential axion production rate

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$\frac{d^2 n_a}{dt dE_a}$ → Differential axion production rate

$\langle e^{-\tau_a(R_g, E_a, r)} \rangle$ → Absorption term

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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

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Absorption term

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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

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

Axion absorption

Absorption term (survival probability)

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

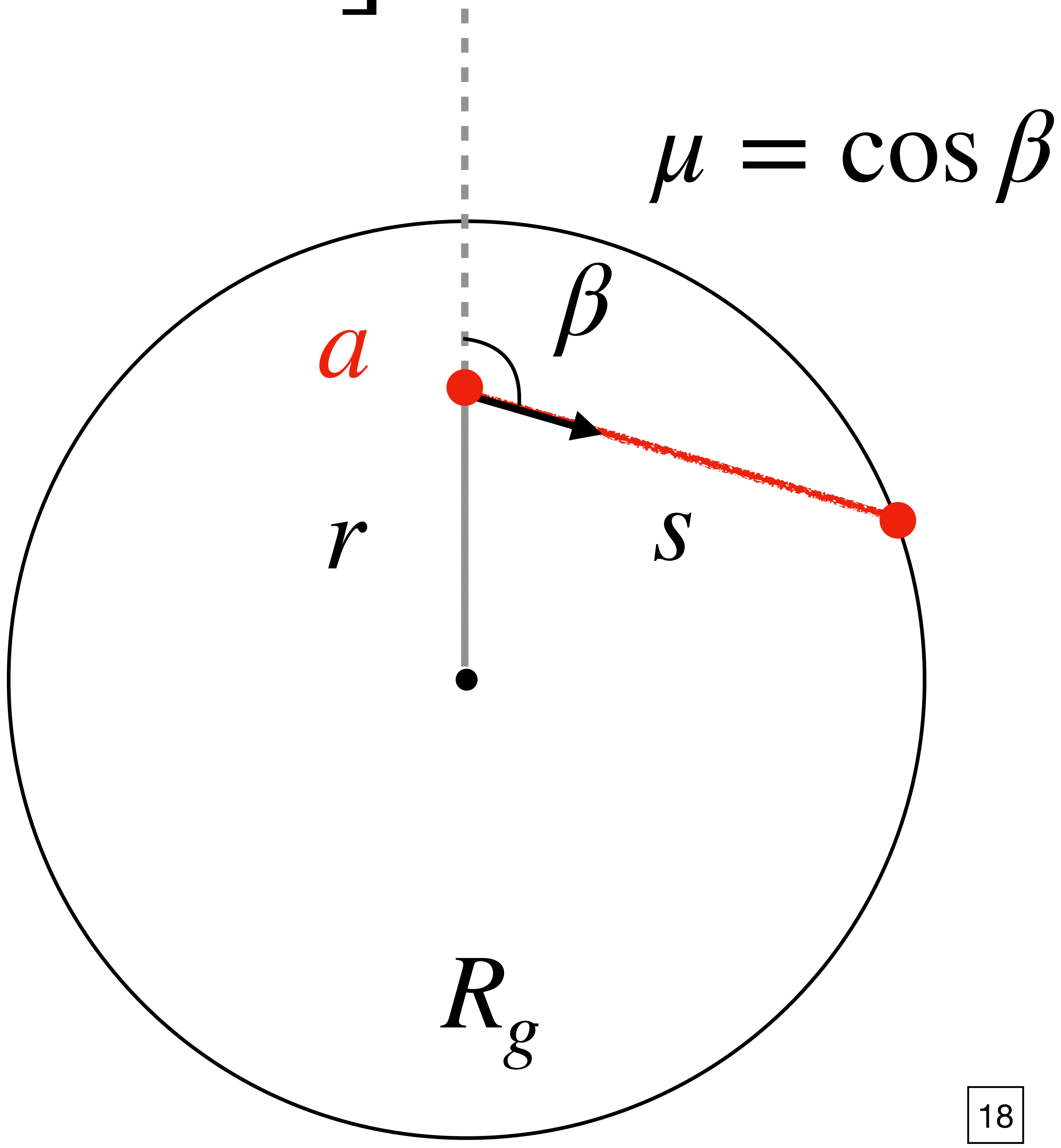
$\Gamma_{\rm abs}$ = Axion absorption width (ignore emission)

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]



Absorption term (survival probability)

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

optical depth

$\Gamma_{\rm abs}$ = Axion absorption width (ignore emission)

r = axion production point

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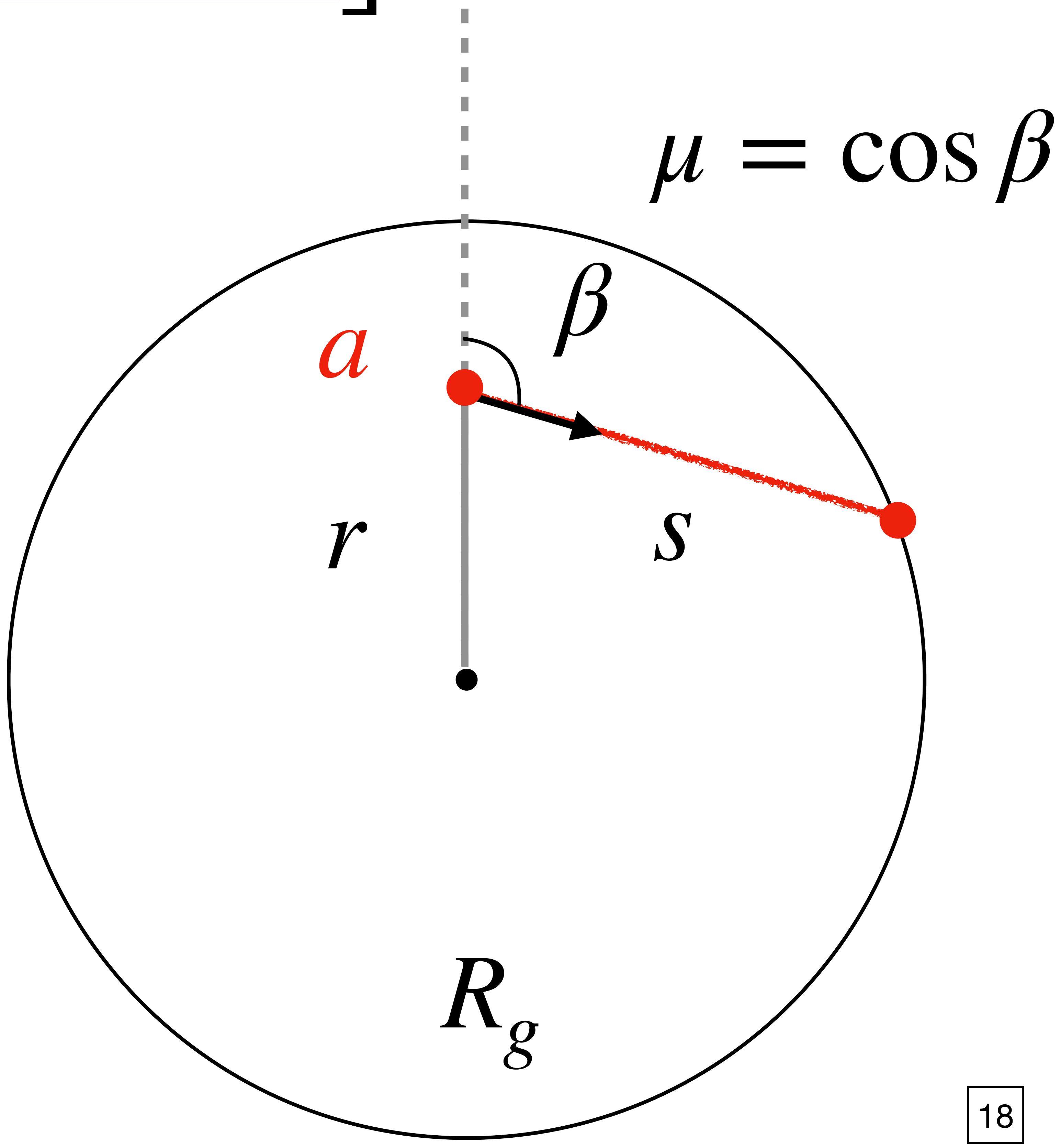
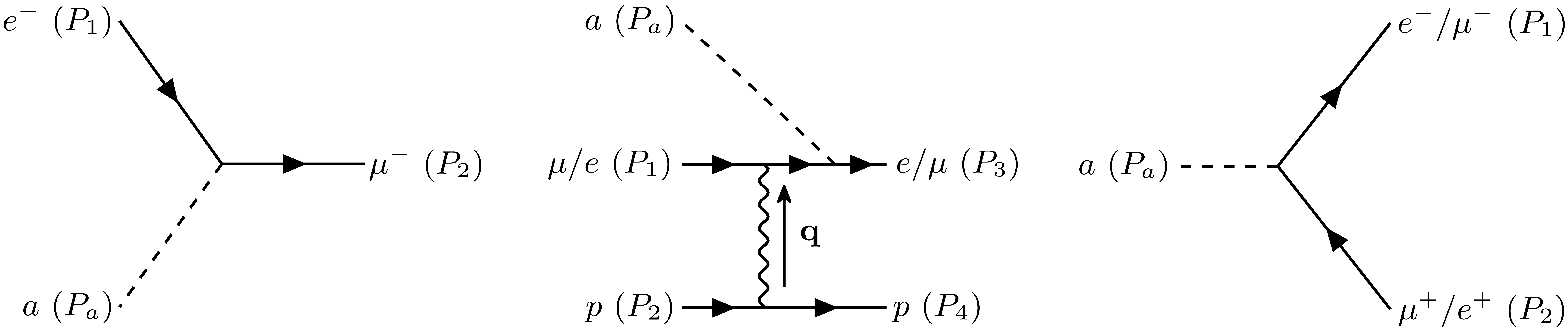


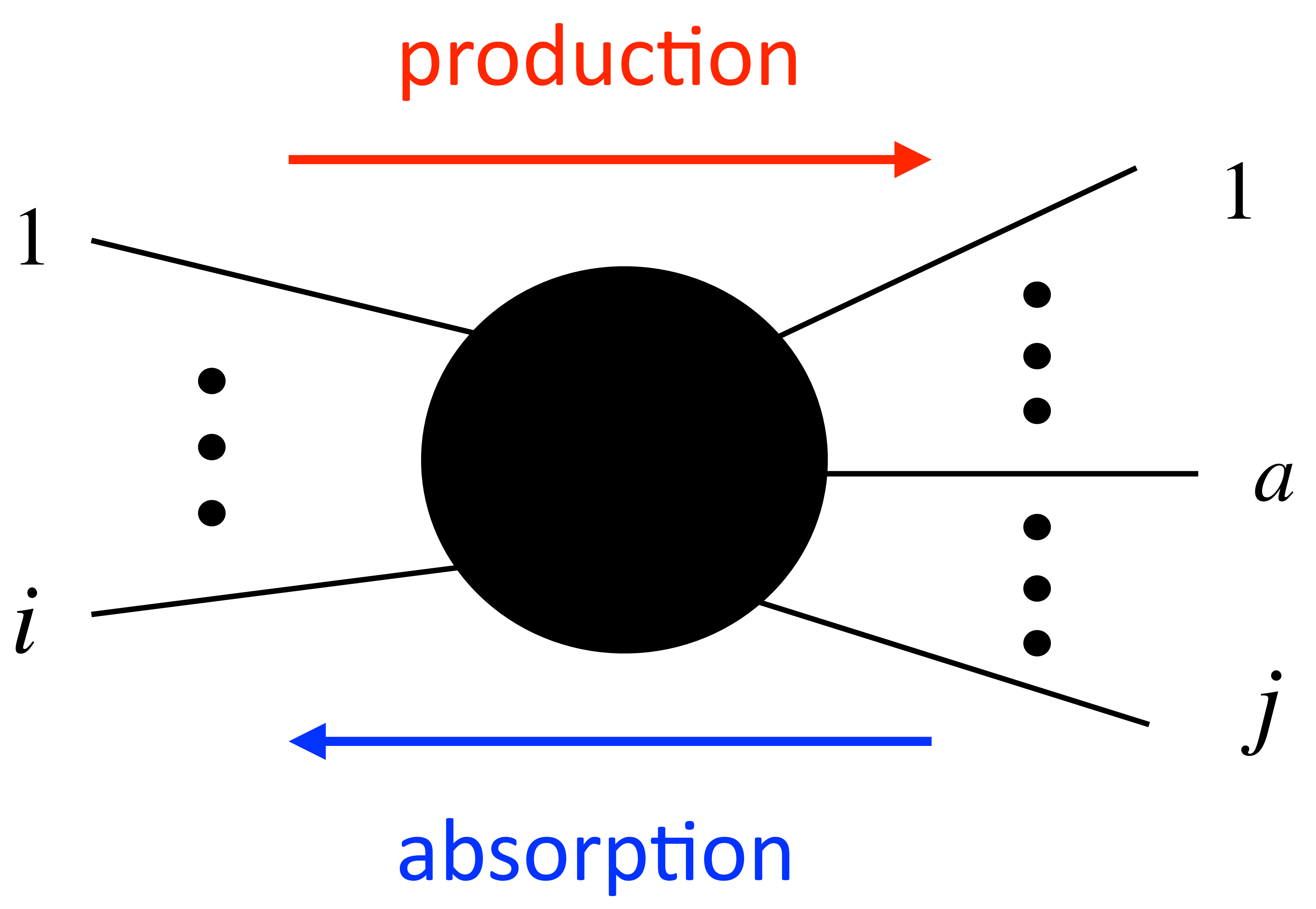
[A. Caputo, G. Raffelt, and E. Vitagliano, 2204.11862]

Three absorption channels in the supernova



(1) electron-axion coalescence (2) inverse bremsstrahlung (3) axion decay

these are the inverse processes of the production channels



ALP production & absorption in SN

Production rate (changing rate of # density per energy) (n_a = axion # density)

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

Absorption rate (dimension df/dt w/ f = occupation function) (decay width for decay)

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

[Kolb & Turner, 90']

Absorption rate in terms of production rate

for Fermi-Dirac & Bose-Einstein distributions $1 \pm f = e^{(E-\mu)/T} f$ $\qquad f = \dfrac{1}{e^{(E-\mu)/T} \pm 1}$

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$$\int \prod_{j \neq a} d\Phi_j \, f_j \, \prod_i d\Phi_i \, (1 \pm f_i) = \int \prod_{j \neq a} d\Phi_j \, e^{-(E_j - \mu_j)/T} (1 \pm f_j) \, \prod_i d\Phi_i \, e^{(E_i - \mu_i)/T} f_i$$

$$= e^{(E_a - \mu_a^0)/T} \int \prod_{j \neq a} d\Phi_j \, (1 \pm f_j) \, \prod_i d\Phi_i \, f_i$$

$$E_a = \sum_i E_i - \sum_{j \neq a} E_j$$

$$\mu_a^0 \equiv \sum_i \mu_i - \sum_{j \neq a} \mu_j$$

Absorption rate in terms of production rate

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absorption rate in terms of production rate

$$\Gamma_{\text{abs}}(E_a) = e^{(E_a-\mu_a^0)/T} \frac{2\pi^2}{|\mathbf{p}_a| E_a} \frac{d^2 n_a}{dt dE_a}$$

$$E_a = \sum_i E_i - \sum_{j \neq a} E_j$$

$$\mu_a^0 \equiv \sum_i \mu_i - \sum_{j \neq a} \mu_j$$

Axion production for electron-muon coalescence

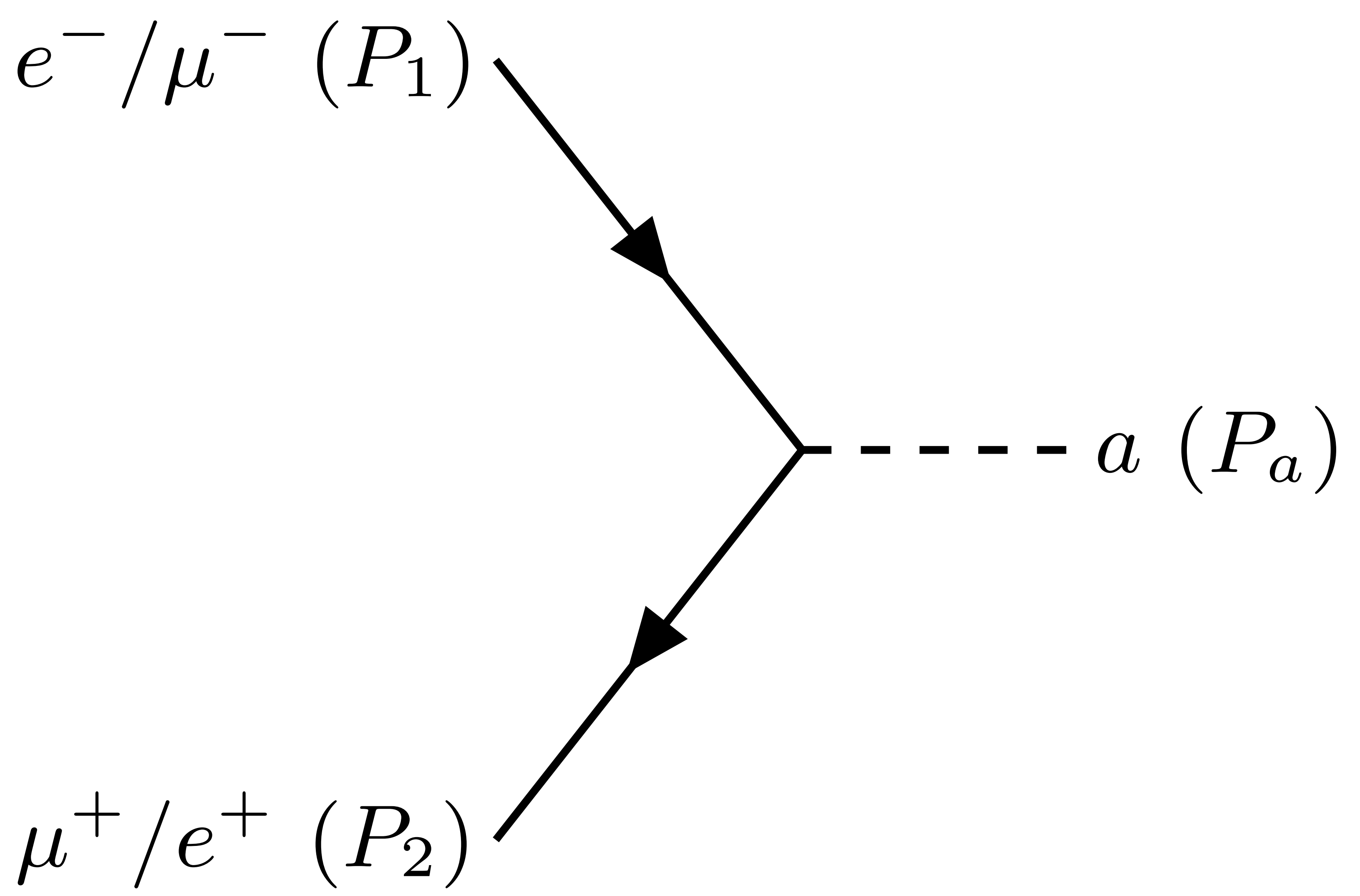
$$\frac{d^2 n_c}{dt dE_a} = \frac{\left|\mathcal{M}_c\right|^2}{32\pi^3}\int_{E_2^-}^{E_2^+} dE_2\,(f_\mu f_e^+ + f_e f_\mu^+),$$

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

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

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

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



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

Particle distributions in the supernova

Production (absorption) rate depends on the particle distributions

lepton & anti-lepton

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

leptonn chemical potential: $\mu_\ell = \mu_\ell(r)$

Temperature: $T = T(r)$

both μ & T are function of r:

SN profiles

Supernova model: the SFHo-18.8 model

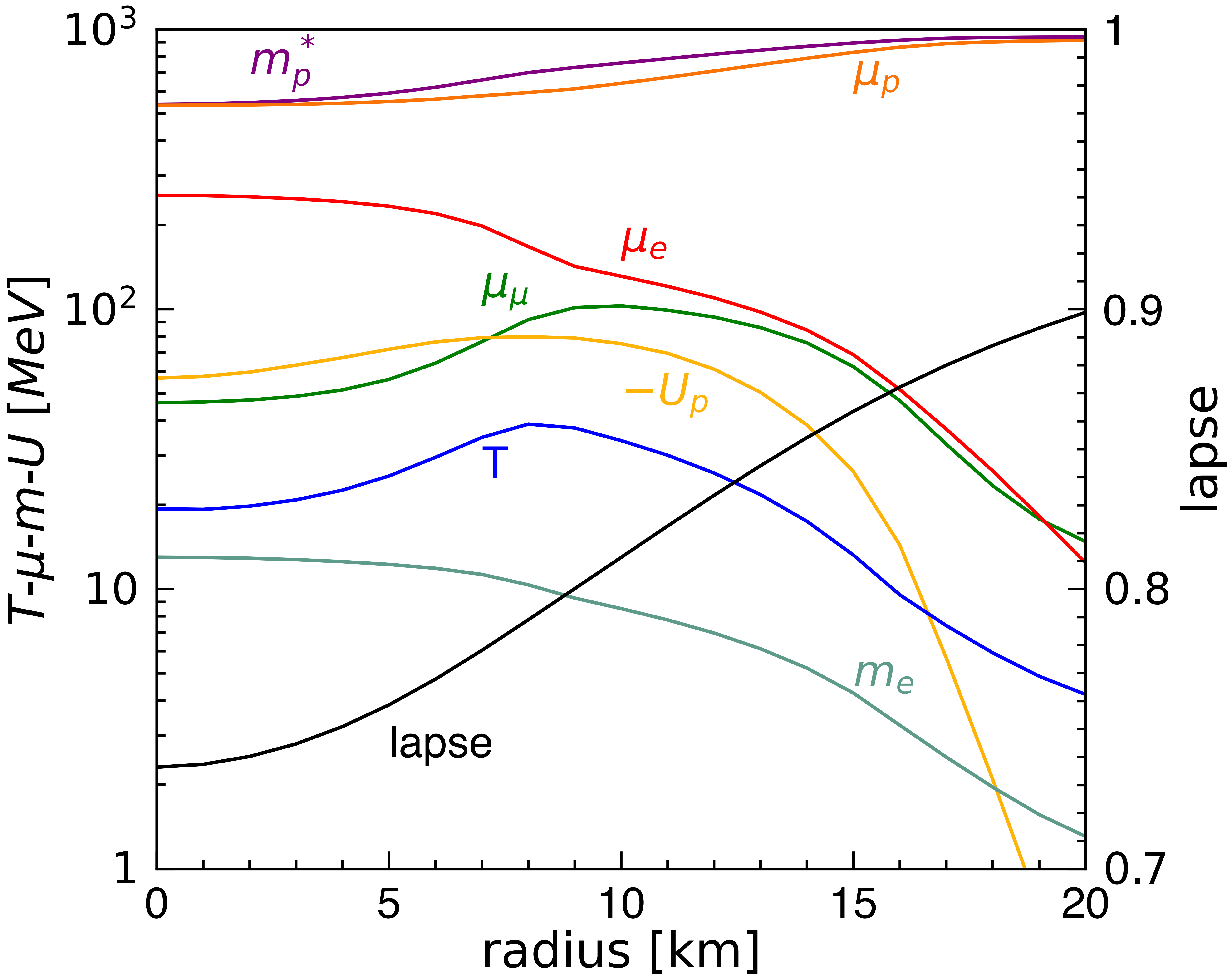
The SFHo-18.8 model: the modern SFHo equation of state

[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

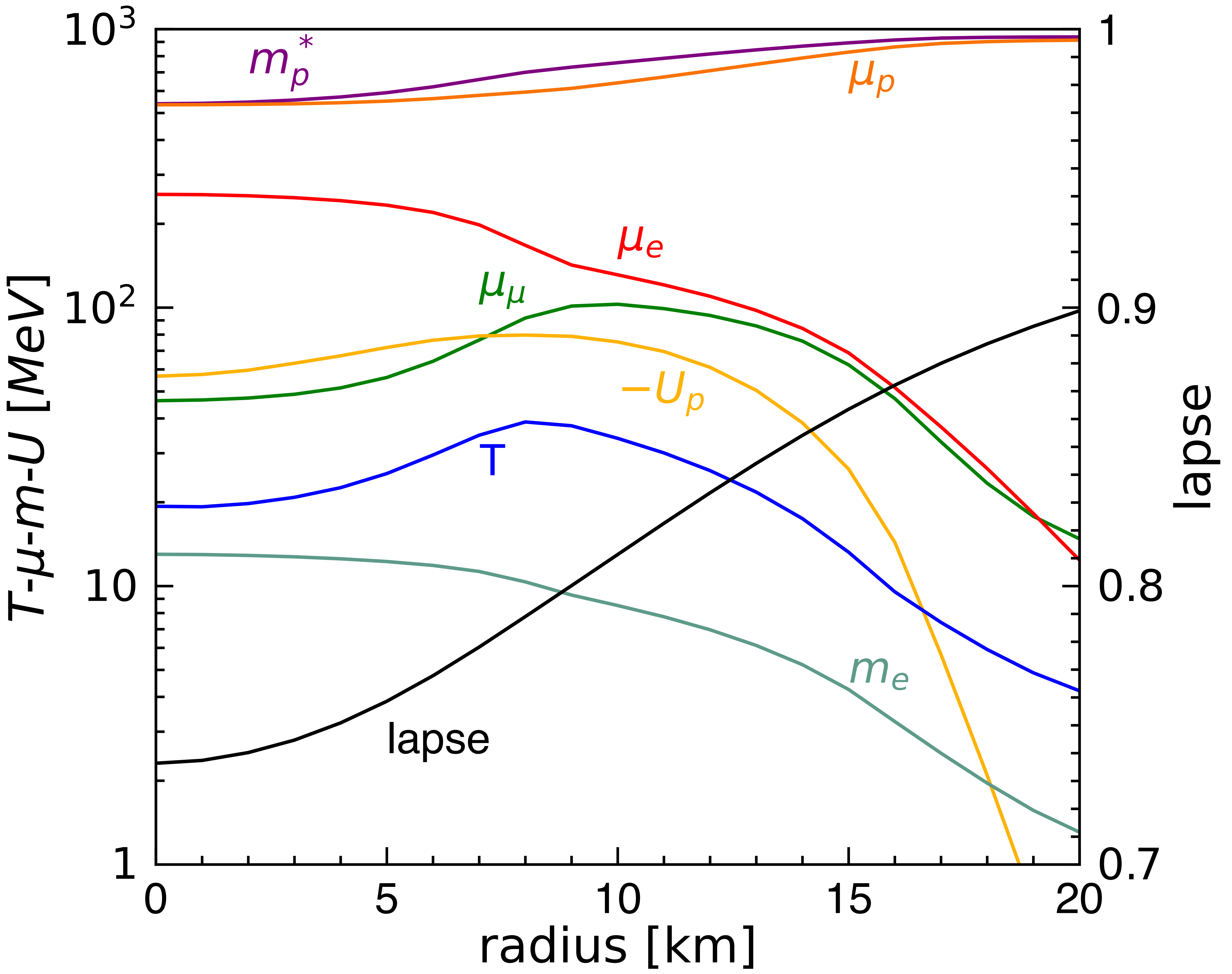


The profiles of chemical potentials of electrons, muons, and protons, temperature, proton effective mass, proton self-energy, and electron effective mass in the SN core of the SFHo-18.8 SN model.

[R. Bollig et al., 2005.07141]

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

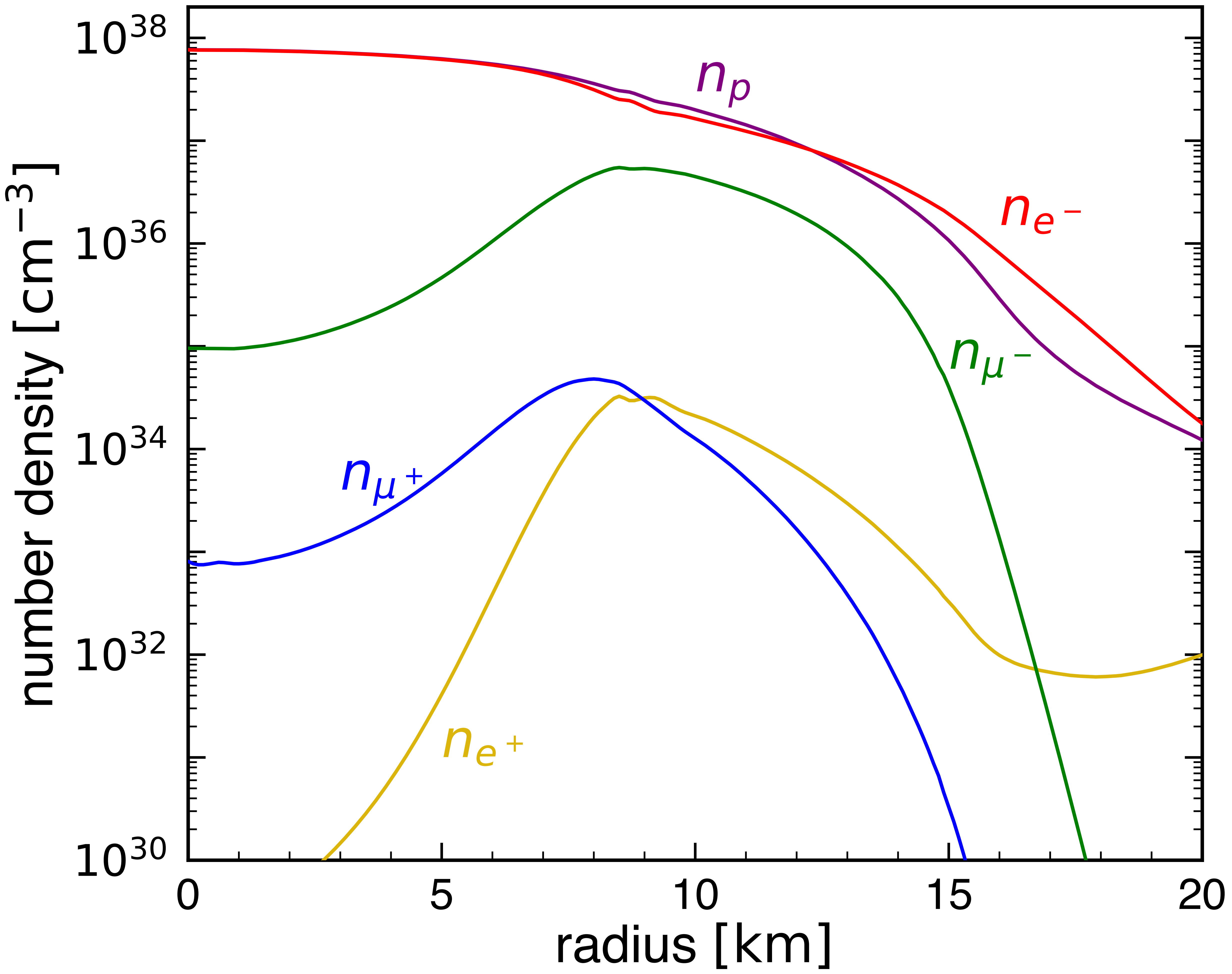
The SFHo-18.8 SN profile



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



number density: $n = g \int \frac{d^3p}{(2\pi)^3} f(\mathbf{p})$

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

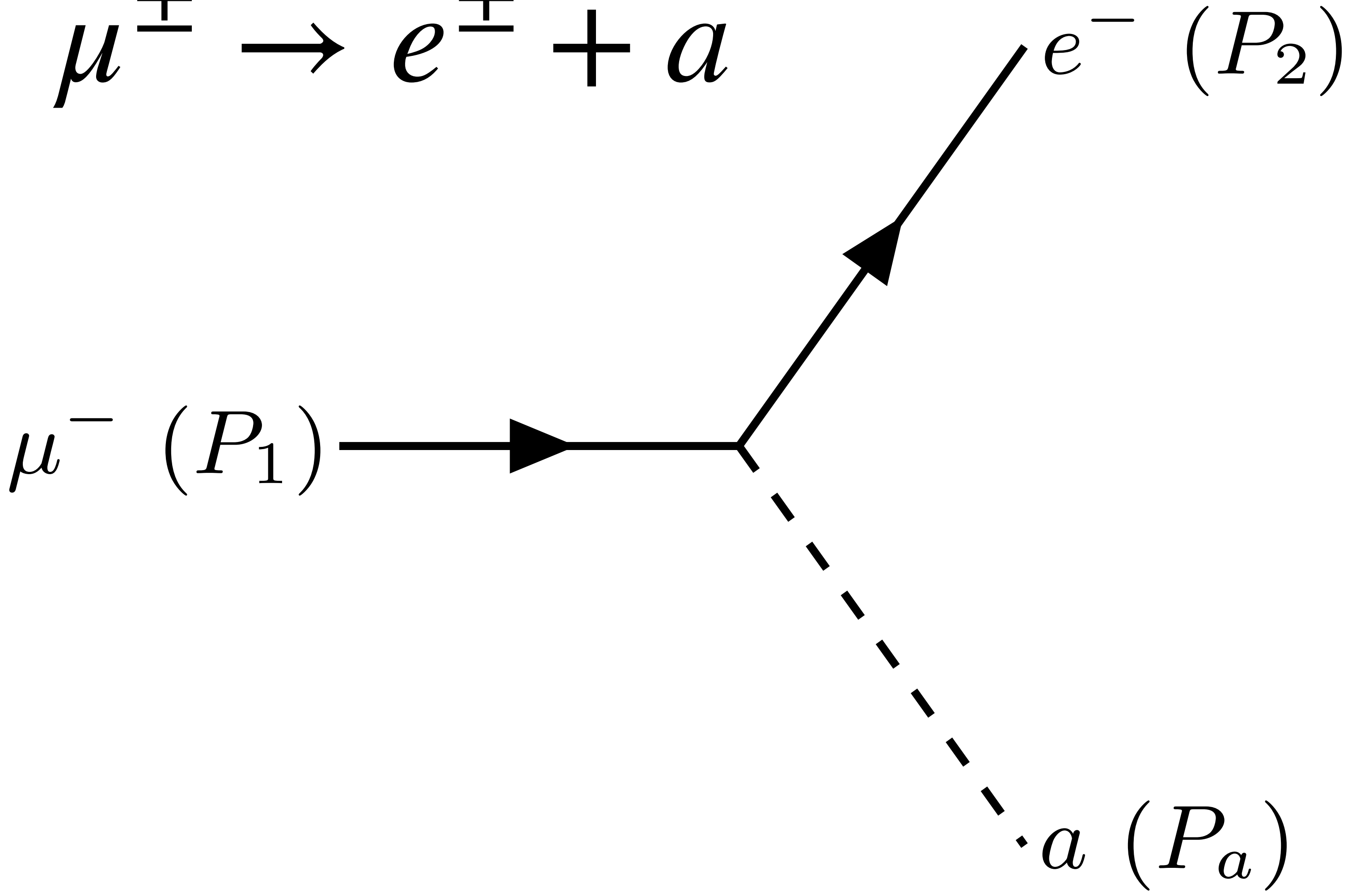
$$f_{\mu^\pm} = \frac{1}{e^{(E_\mu \pm \mu_\mu)/T} + 1}$$

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

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

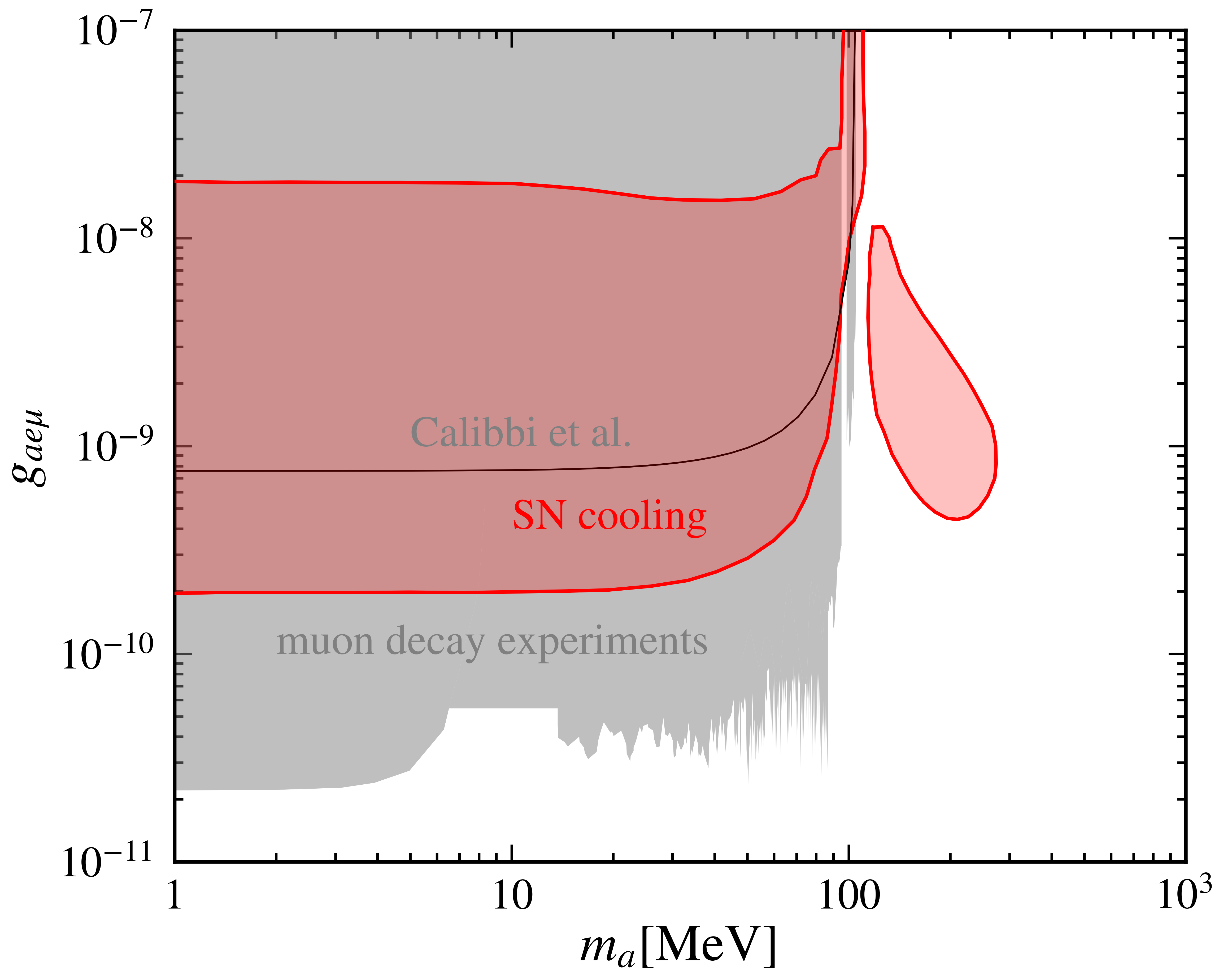
- Belle II
  [H. Davoudiasl et al., 2105.05866]
  [M. Endo, S. Iguro, and T. Kitahara, 2002.05948]
  [S. Iguro, Y. Omura, and M. Takeuchi, 2002.12728]

- 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]

SN cooling limit

Supernova cooling limit 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

3 LESN constraints on LFV axions

Low-Energy Supernovae (LESNe)

underluminous Type-II P SN

core-collapse SN with a relatively small mass

10-100 times dimmer than typical CCSNe

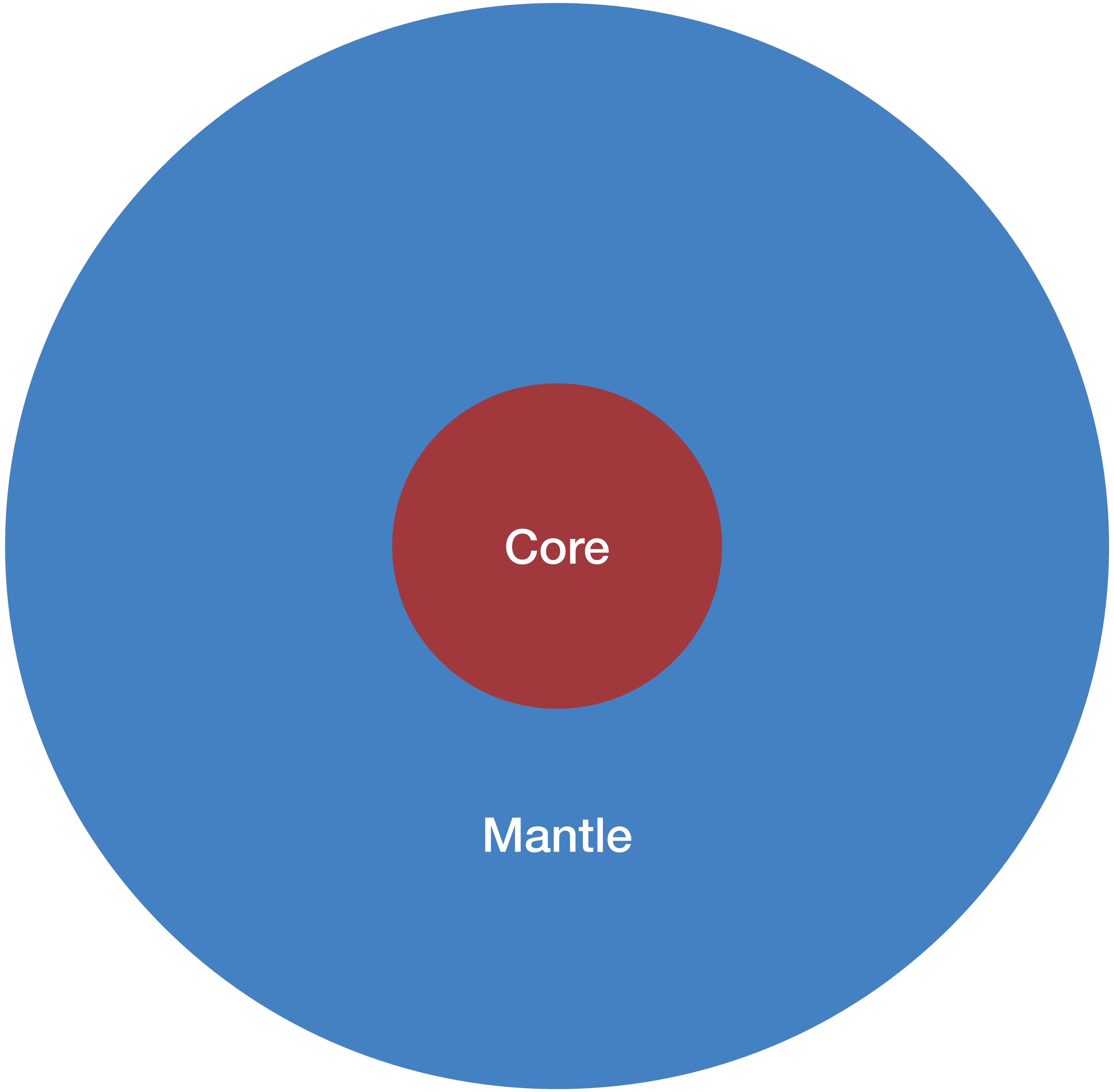
explosion energy as low as 0.1 B

$B = 10^{51}$ erg

[Caputo+, 2201.09890]

[Burrows & Vartanyan, 2009.14157]

Low-energy supernova (LESN) constraint



Axion-induced energy deposition in mantle should not exceed the LESN explosion energy

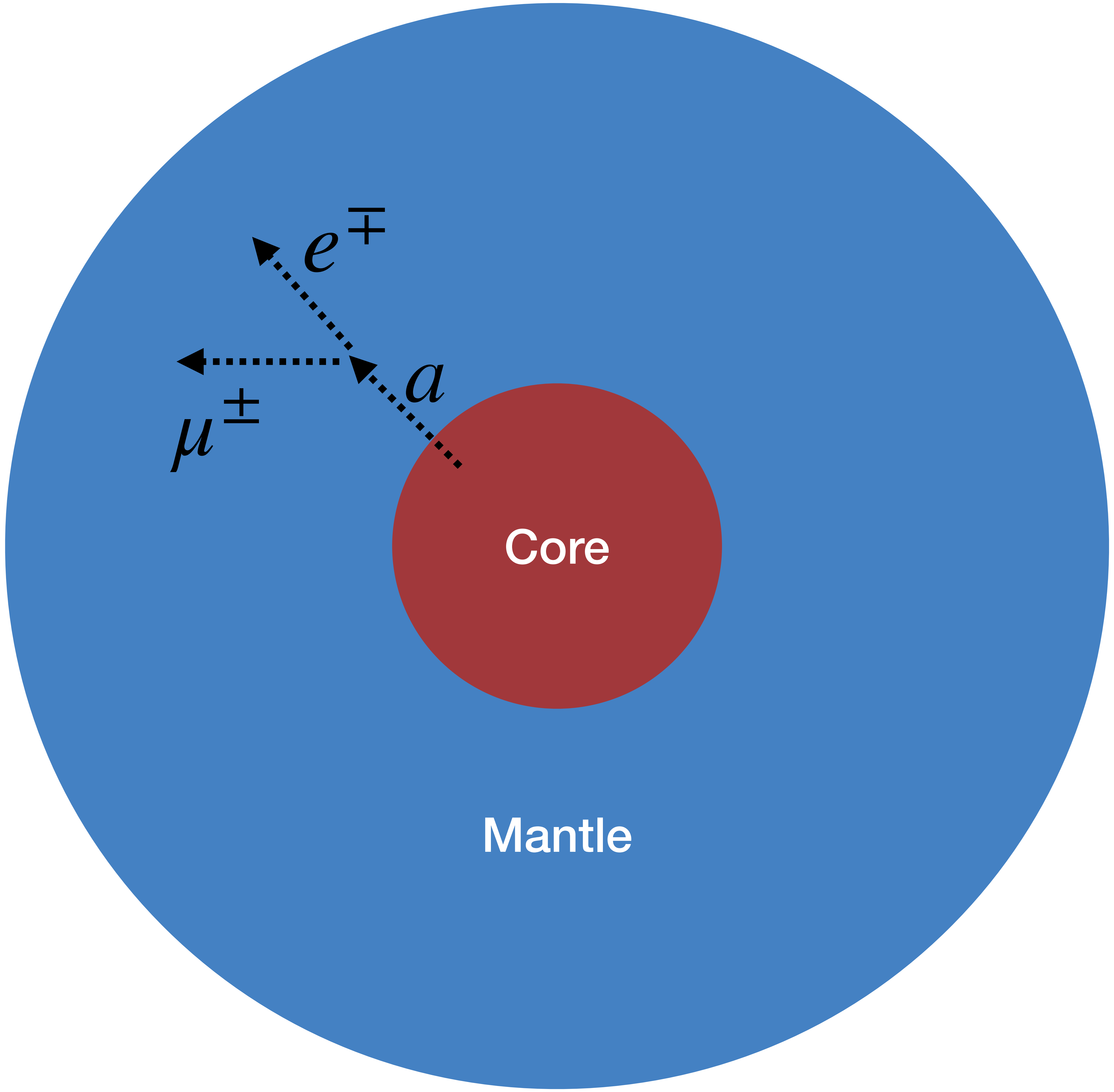
$$E_m \leq 0.1\,\mathrm{B}$$

[A. Caputo et al., 2201.09890]

[S. W. Falk et al., Phys. Lett. B 79 (1978) 511]

[A. Sung et al., 1903.07923]

Low-energy supernova (LESN) constraint



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[S. W. Falk et al., Phys. Lett. B 79 (1978) 511]

[A. Sung et al., 1903.07923]

Energy deposition in the SN mantle

Axion induced energy deposition in the SN mantle: [Huang, ZL, 2506.16922]

$$E_m = \Delta t \int_0^{R_{\rm NS}} dr \int_{m_a'(r)}^{\infty} dE_a \frac{dL_a\left(r, E_a, t\right)}{dr\, dE_a} \left[\exp\left(\frac{r - R_{\rm NS}}{\lambda_a(r)}\right) - \exp\left(\frac{r - R_*}{\lambda_a(r)}\right) \right],$$

[A. Caputo, H.-T. Janka, G. Raffelt, and E. Vitagliano, 2201.09890]

$\exp\left(\frac{r - R_{\rm NS}}{\lambda_a(r)}\right)$ → survival prob. at core surface

$\exp\left(\frac{r - R_*}{\lambda_a(r)}\right)$ → survival prob. at progenitor star surface

$\Delta t = 3\,\mathrm{s}$ (typical SN explosion duration)

$\lambda_a(r)$ = ALP mean free path

$R_{\rm NS} = 20\,\mathrm{km}$ (core radius)

$R_* = 3 \times 10^7\,\mathrm{km}$ (progenitor star radius)

LESN constraints on LFV axions

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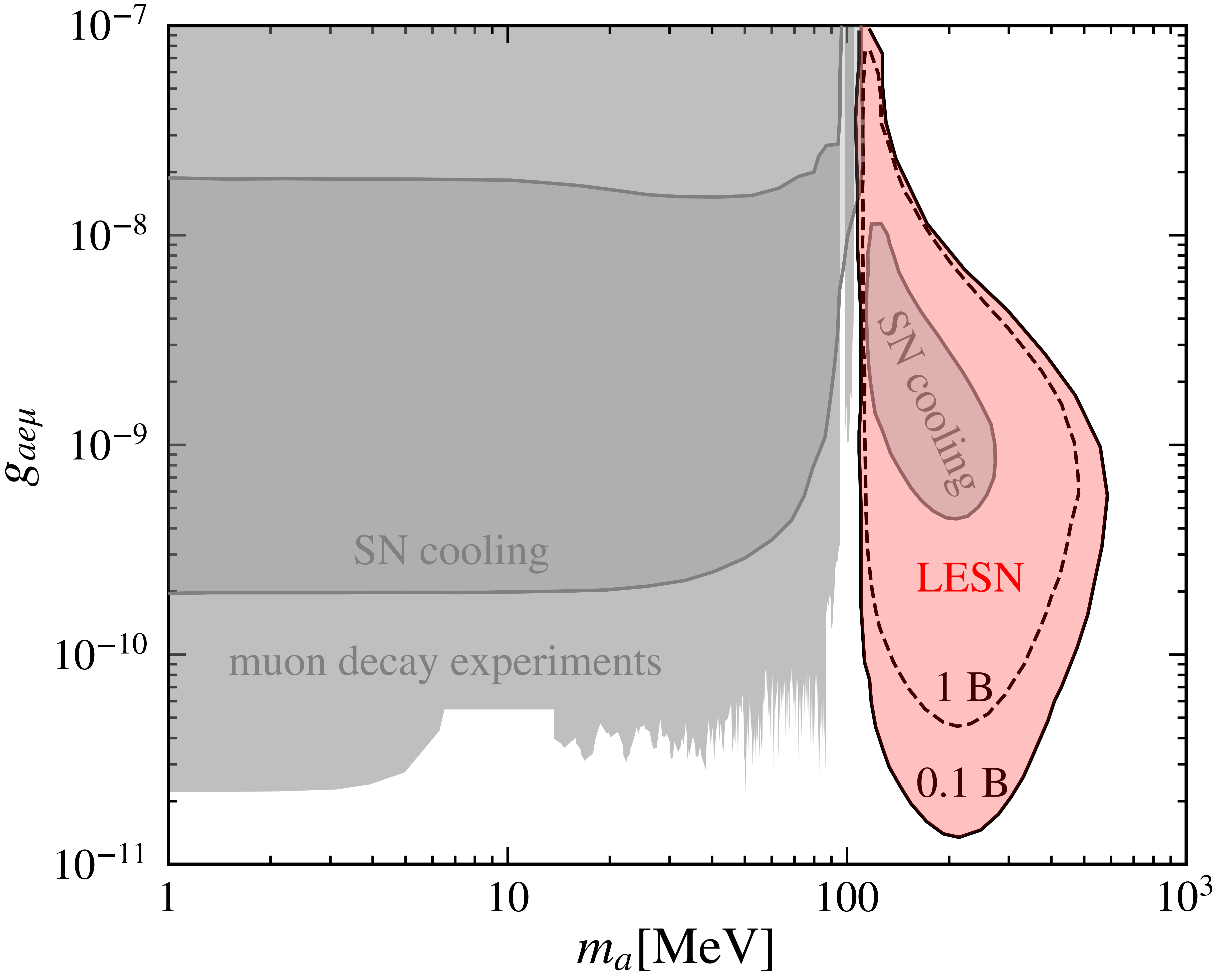

[Huang, ZL, 2506.16922]

focus on high mass (only e-mu coalescence)

LESN is better than SN cooling

Two explosion energy conditions: 0.1 & 1 B

$$1\,B = 10^{51}\text{ erg}$$

probe new para at $m_a \sim (110{,}550)\,\text{MeV}$

probe $g_{ae\mu}$ down to $\sim 10^{-11}$ at 200 MeV

Summary

- We compute supernova cooling limits and low-energy supernova constraints on lepton flavor violating axions/ALPs
- We compute the axion production (& absorption) via 3 different channels (& inverse)
  - muon decay
  - bremsstrahlung
  - electron-muon coalescence $\Rightarrow$ important for high-mass (previously omitted)
- The e-mu coalescence channel probes new parameter space
  - SN cooling limits: $m_a \sim [115{,}280]$ MeV, $g_{ae\mu} \sim [4 \times 10^{-9}, 10^{-8}]$
  - LESN limits: $m_a \sim [110{,}550]$ MeV, $g_{ae\mu} \sim [10^{-11}, 10^{-7}]$

[Li, ZL, 2501.12075]

[Huang, ZL, 2506.16922]