Supernova Constraints on Lepton Flavor Violating Axions

Zuowei Liu (Nanjing University)

5th International Conference on Axion Physics and Experiment (Axion 2026)

Aug 9-13, 2026, Qingdao

Outline

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

[Yonglin Li, ZL, 2501.12075, PRD]

[Zi-Miao Huang, ZL, 2506.16922, JHEP]

[Zi-Miao Huang, Changqian Li, ZL, 2510.22523, JHEP]

1 Lepton Flavor Violating Axions

Lepton flavor violating axions/ALPs

Axions w/ lepton-flavor-changing couplings to electrons and muons

$$\mathscr{L}_{\text{int}} \sim \partial_\mu a\, \bar{e}\, \gamma^\mu (c_V + c_A \gamma_5)\, \mu + \text{h.c.}$$

[see e.g., Wilczek ’82, Calibbi, Redigolo, Ziegler, Zupan, 2006.04795]

For simplicity, consider only the axial-vector current. Using EOM, we have

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

Strong rare muon decay constraints for light axions with mass below the muon mass

2 Supernova (SN) cooling limits

Core-Collapse Supernovae

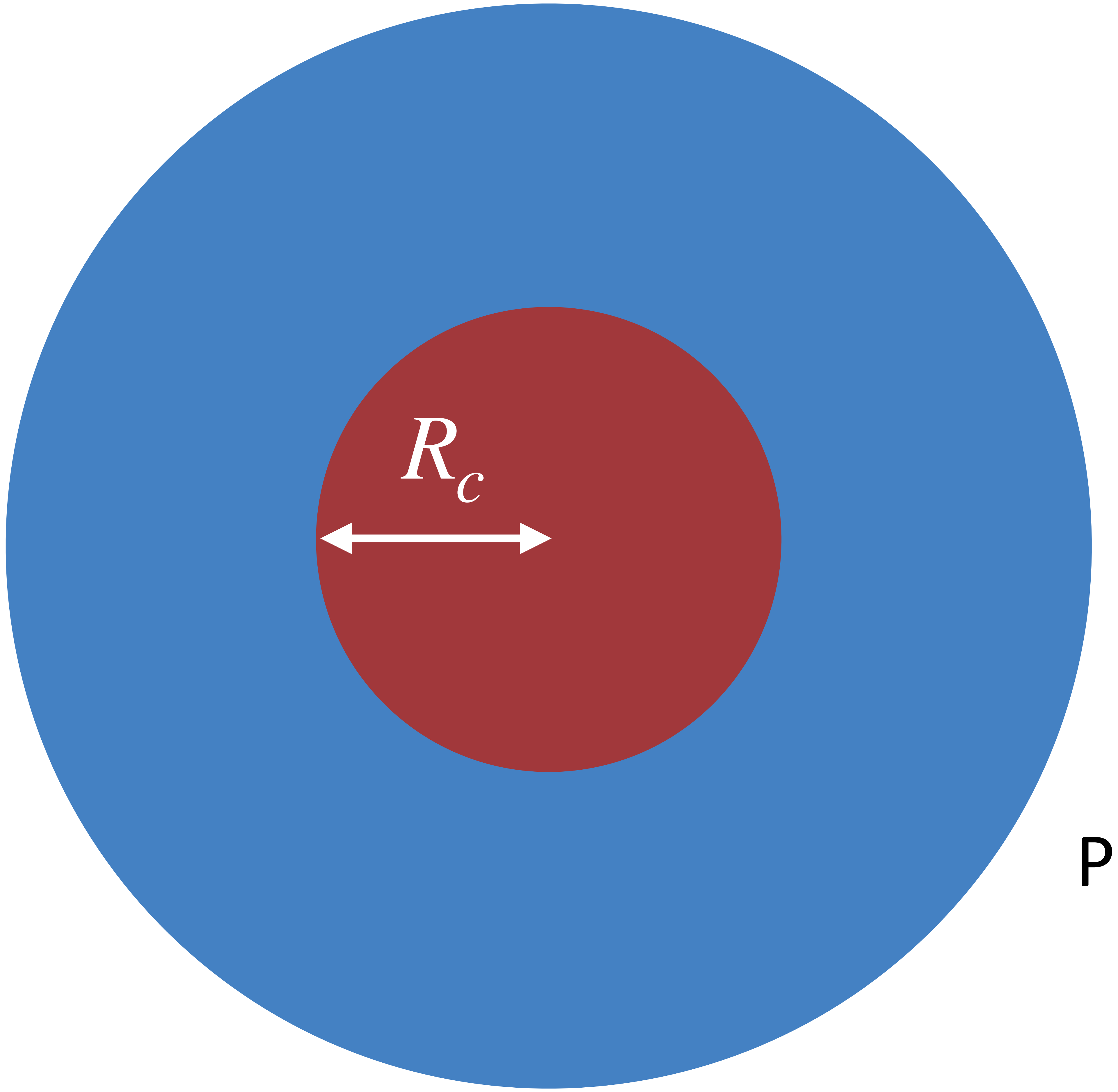
- massive star with $\gtrsim 8$ solar mass will form iron cores
- core > 1.4 solar mass (Chandrasekhar limit) $\rightarrow$ collapse
- implosion & explosion $\rightarrow$ neutron star or black hole

  $\rightarrow$ neutrino (SN1987A) & light & heavy elements

- proto-neutron star: high temperature & high density

  $\rightarrow$ ideal probes of light feebly interacting particles (FIPs) in BSM models

One-zone model for the supernova core



one zone model

Radius: $R_c = 12.9$ km

Temperature: $T_c = 30$ MeV

Nuclear Density: $\rho_c = 3 \times 10^{14}\, \mathrm{g/cm^3}$

Proton Abundance: $Y_p = 0.15$

[Caputo, Janka, Raffelt, Vitagliano, 2201.09890]

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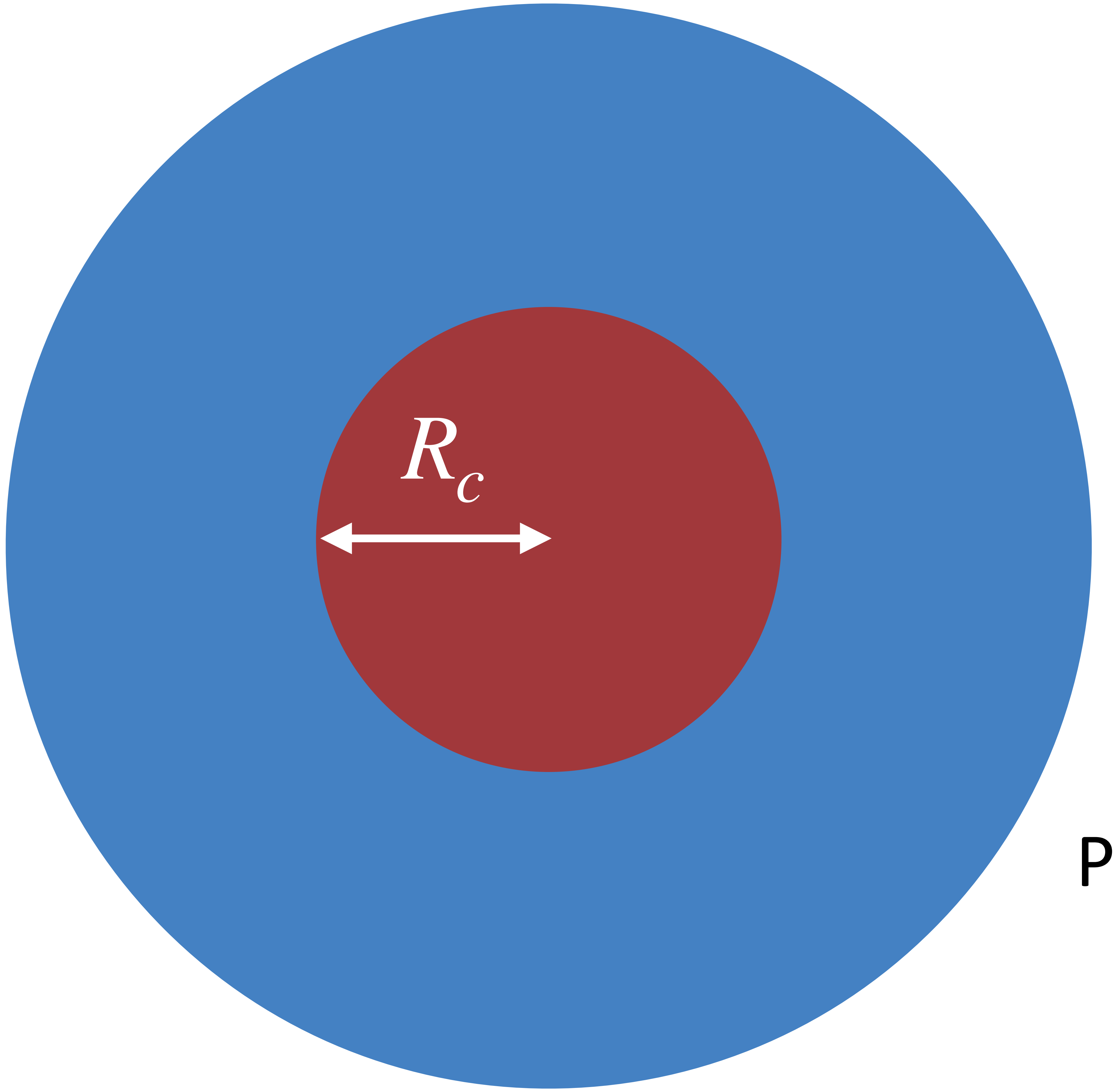


one zone model

Radius: $R_c = 12.9$ km

Temperature: $T_c = 30$ MeV → can probe mass > 100 MeV

Nuclear Density: $\rho_c = 3 \times 10^{14}\,\mathrm{g/cm^3}$

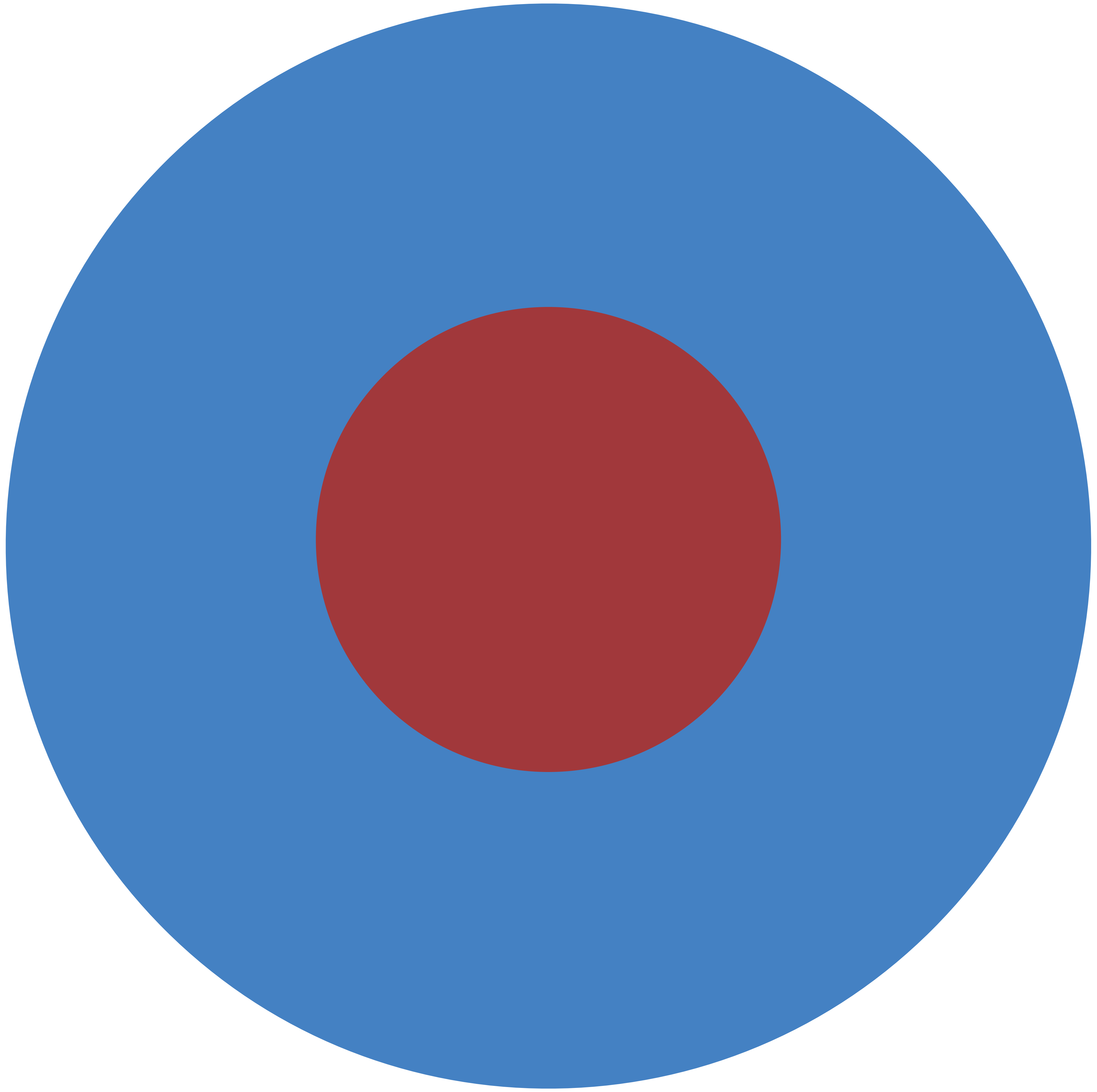
Proton Abundance: $Y_p = 0.15$

[Caputo, Janka, Raffelt, Vitagliano, 2201.09890]

Two kinds of supernova constraints

- cooling limits
- calorimetric limits

Supernova cooling limit (SN1987A)



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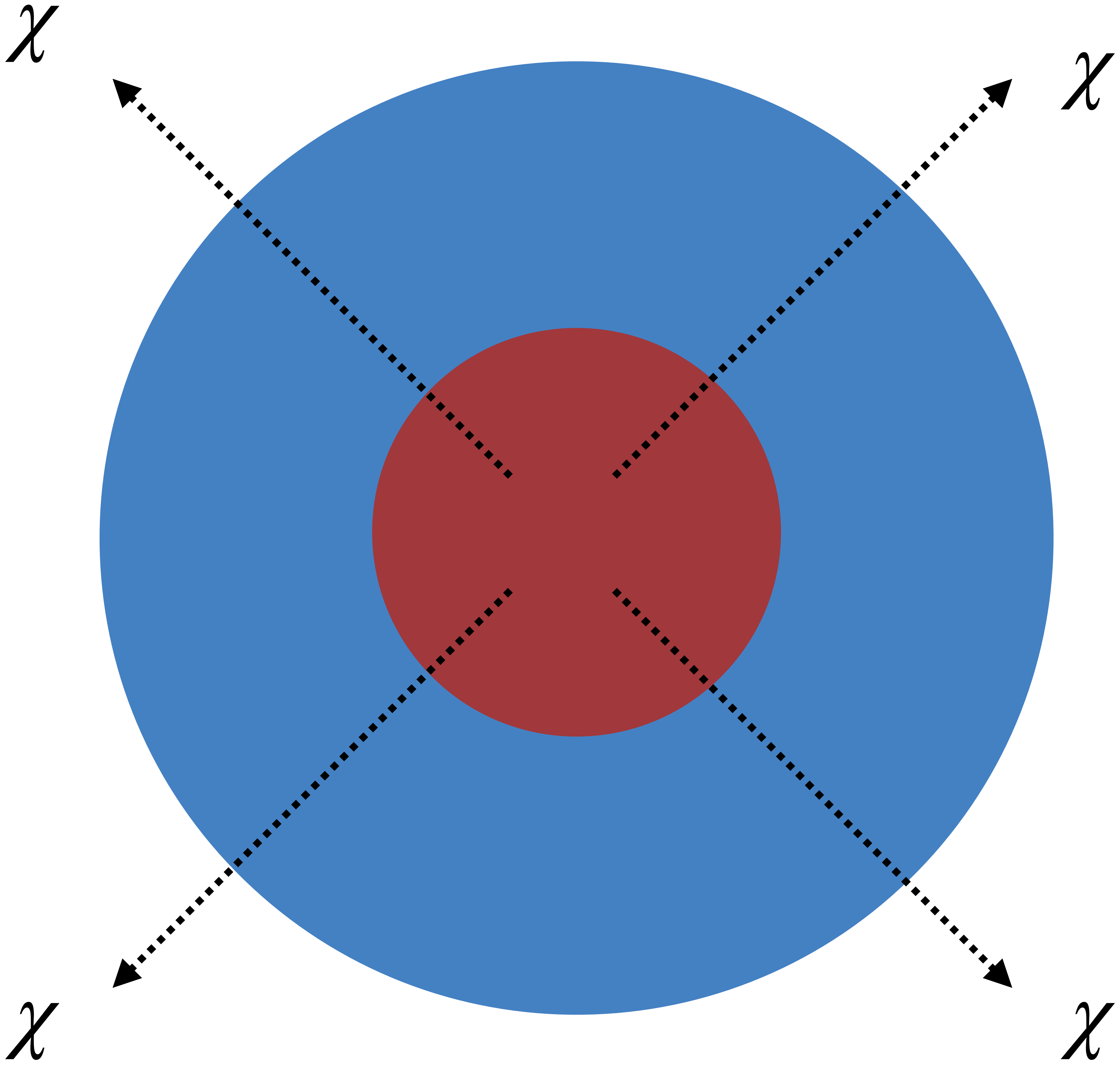

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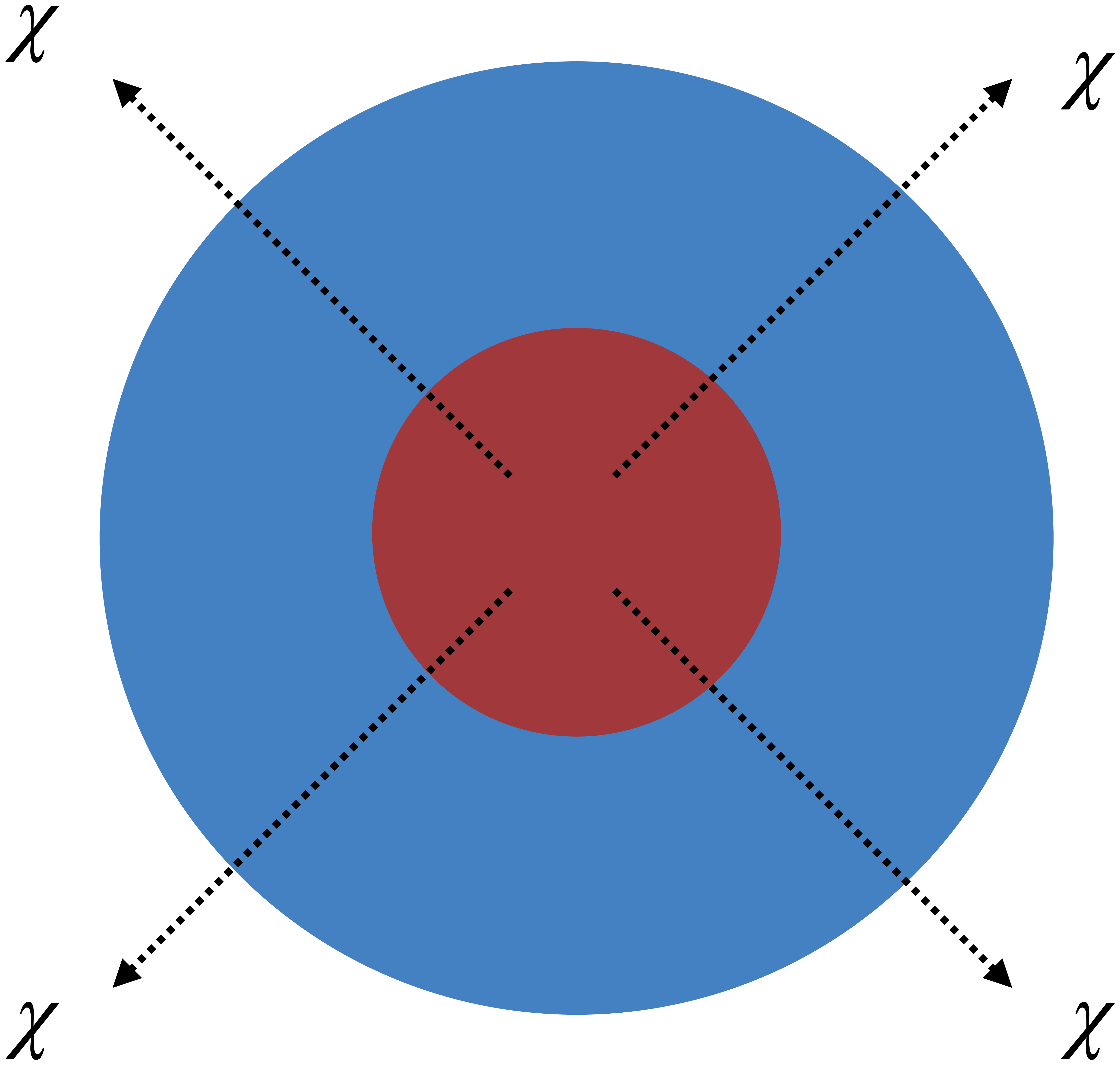

exotic energy loss $\Longrightarrow$ over-cooling

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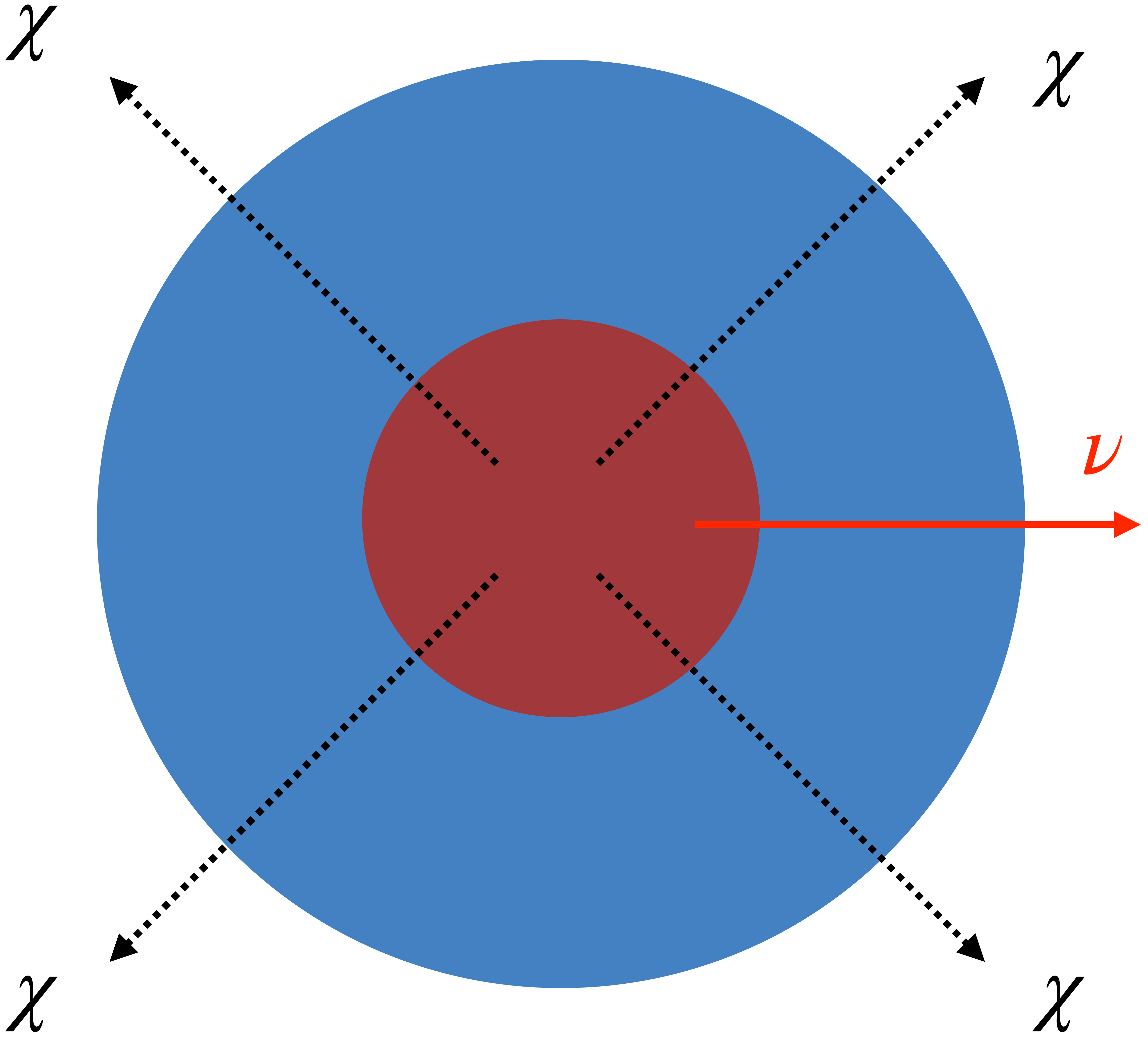

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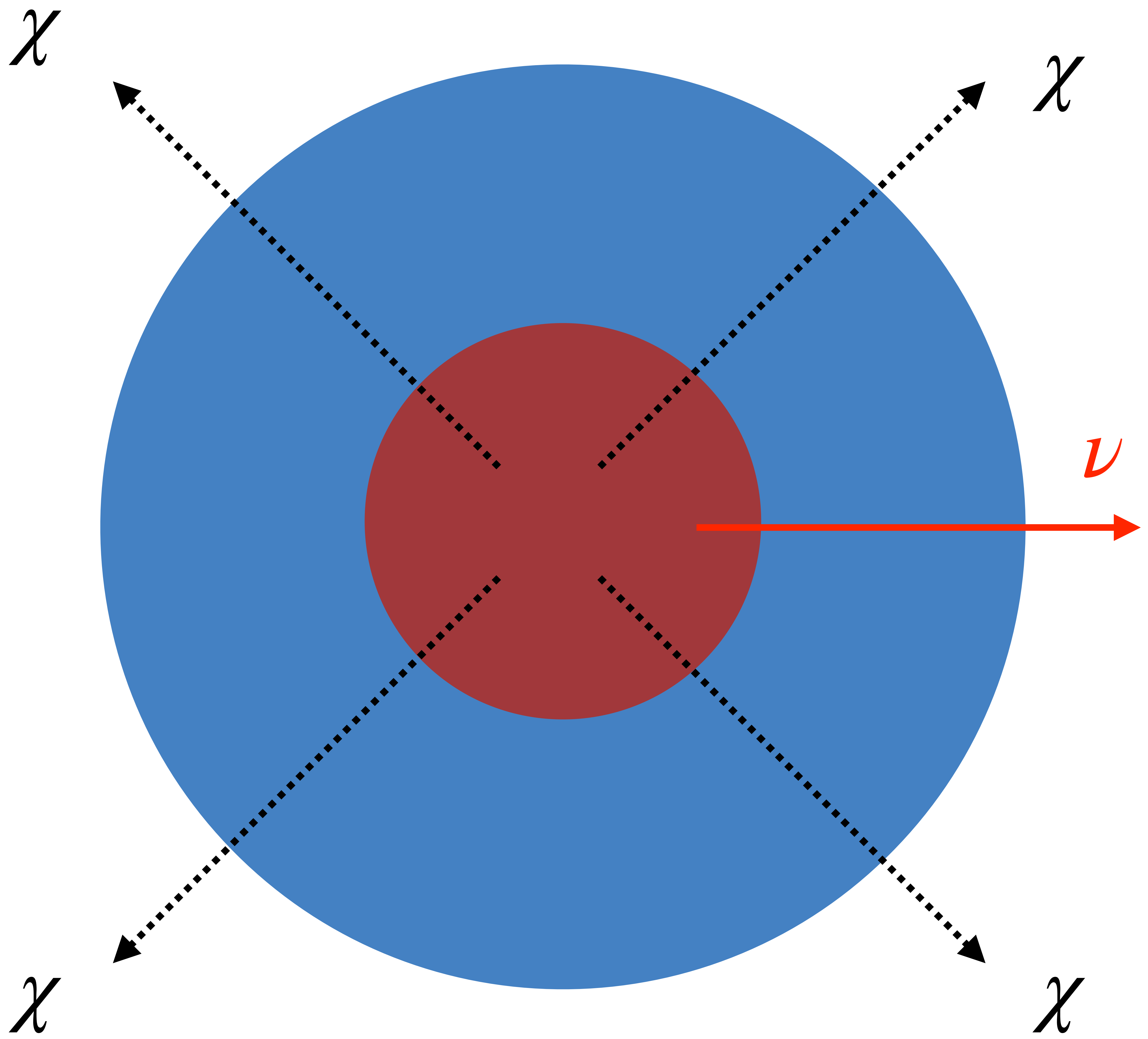


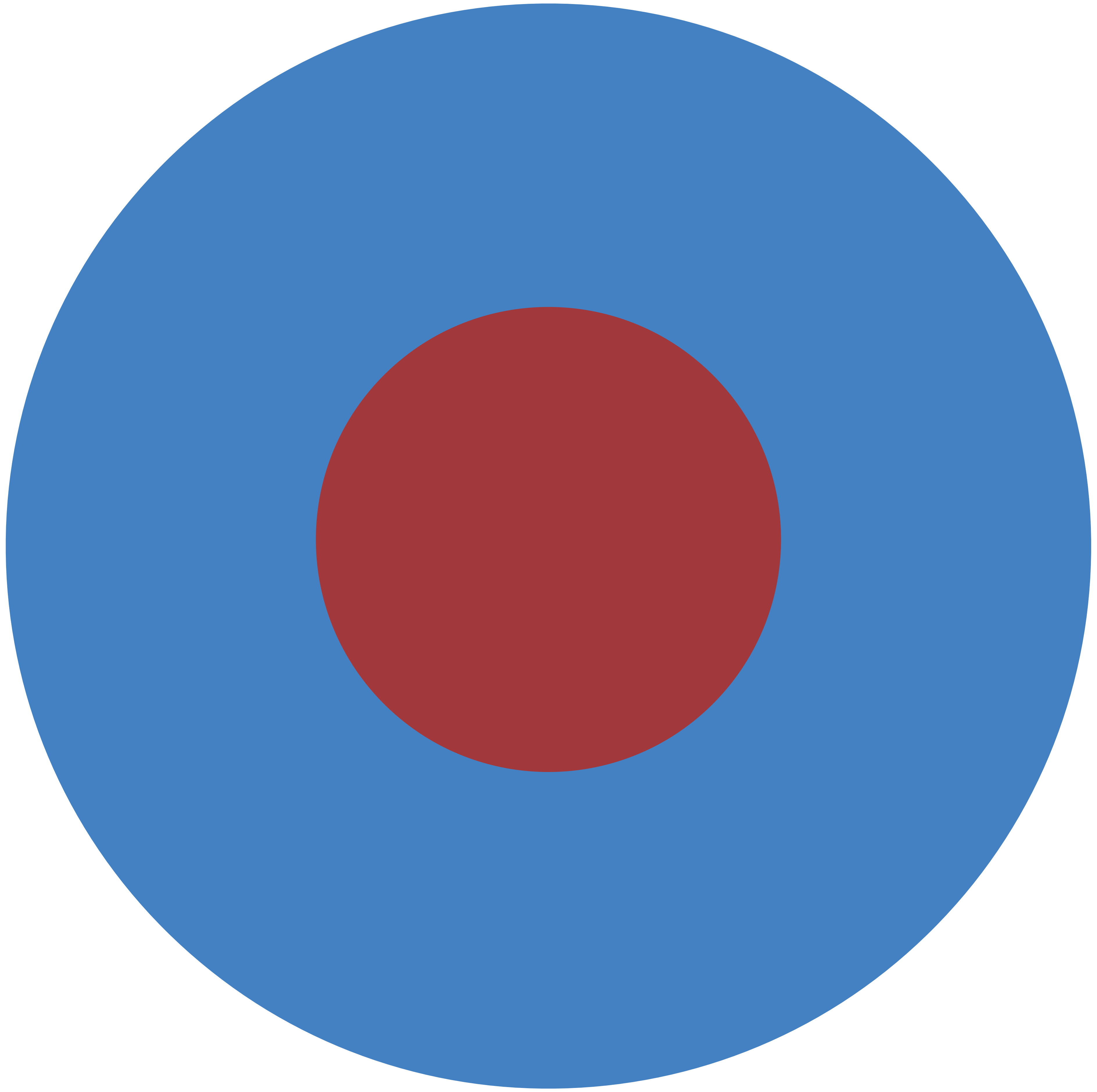
exotic energy loss $\Longrightarrow$ over-cooling

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

$$L_a \le L_\nu = 3 \times 10^{52}\,\mathrm{erg}/s$$ [Raffelt 1996]

10^{53} erg with 3 seconds

Supernova "calorimetric" limit



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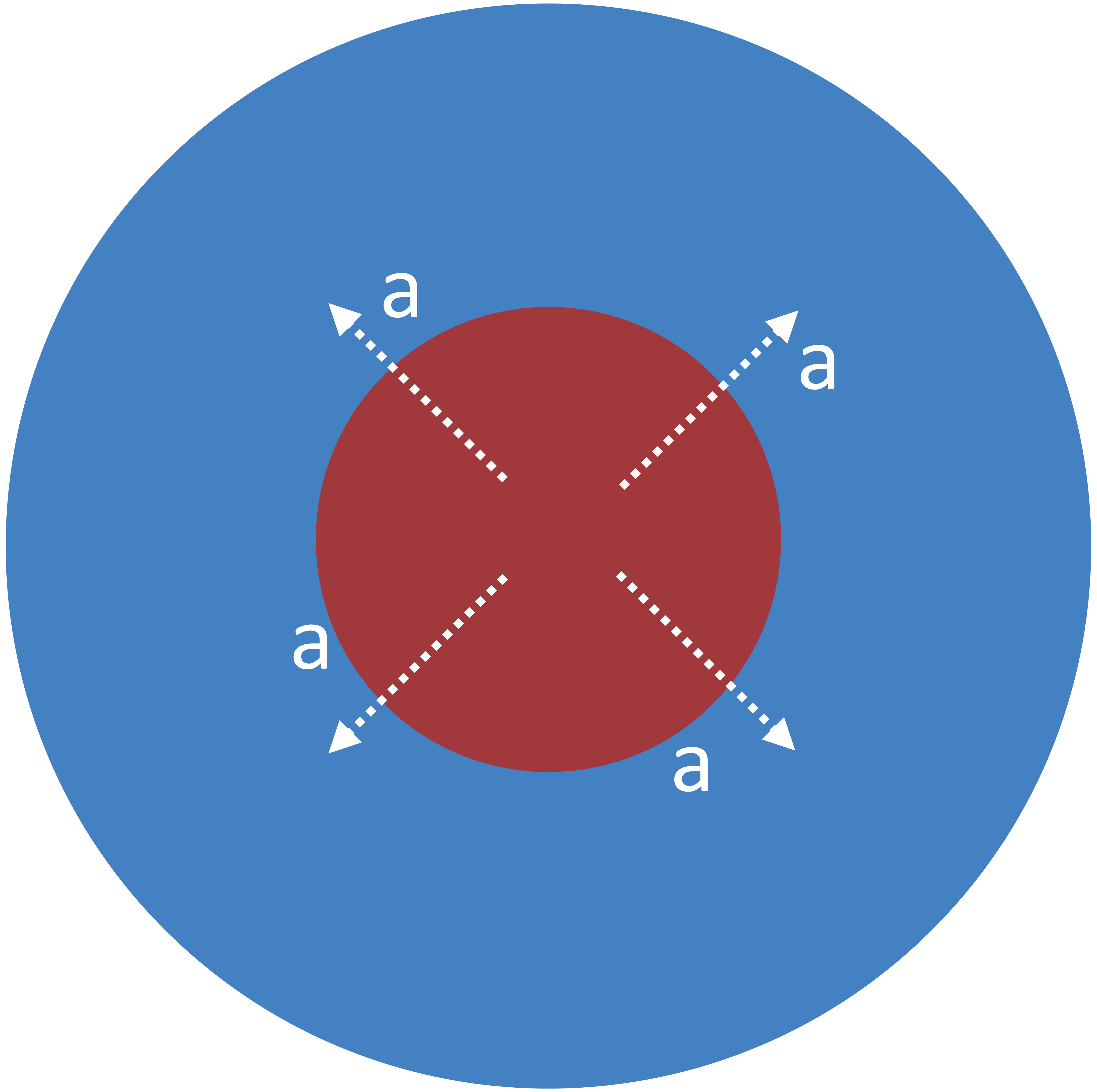

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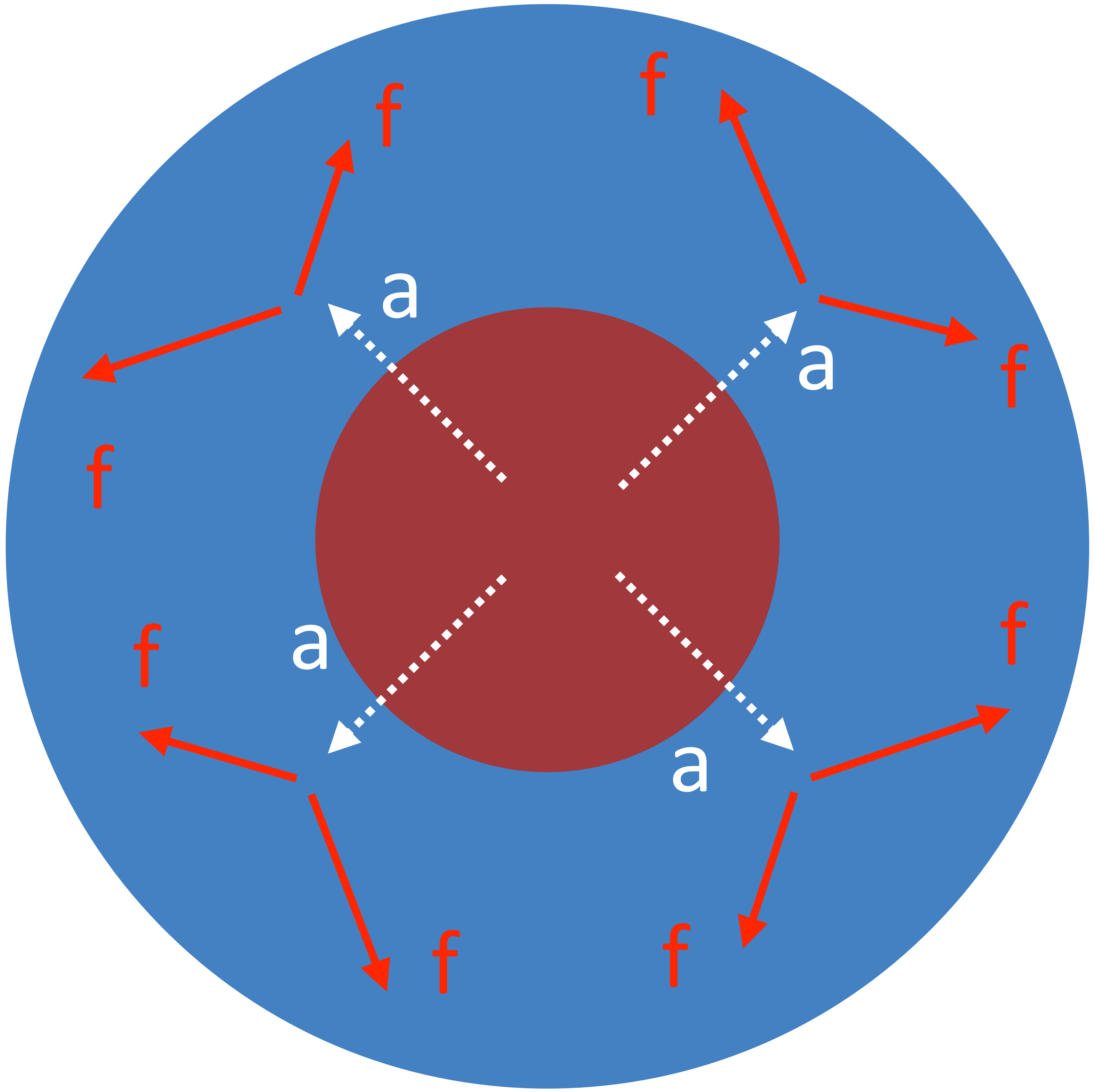

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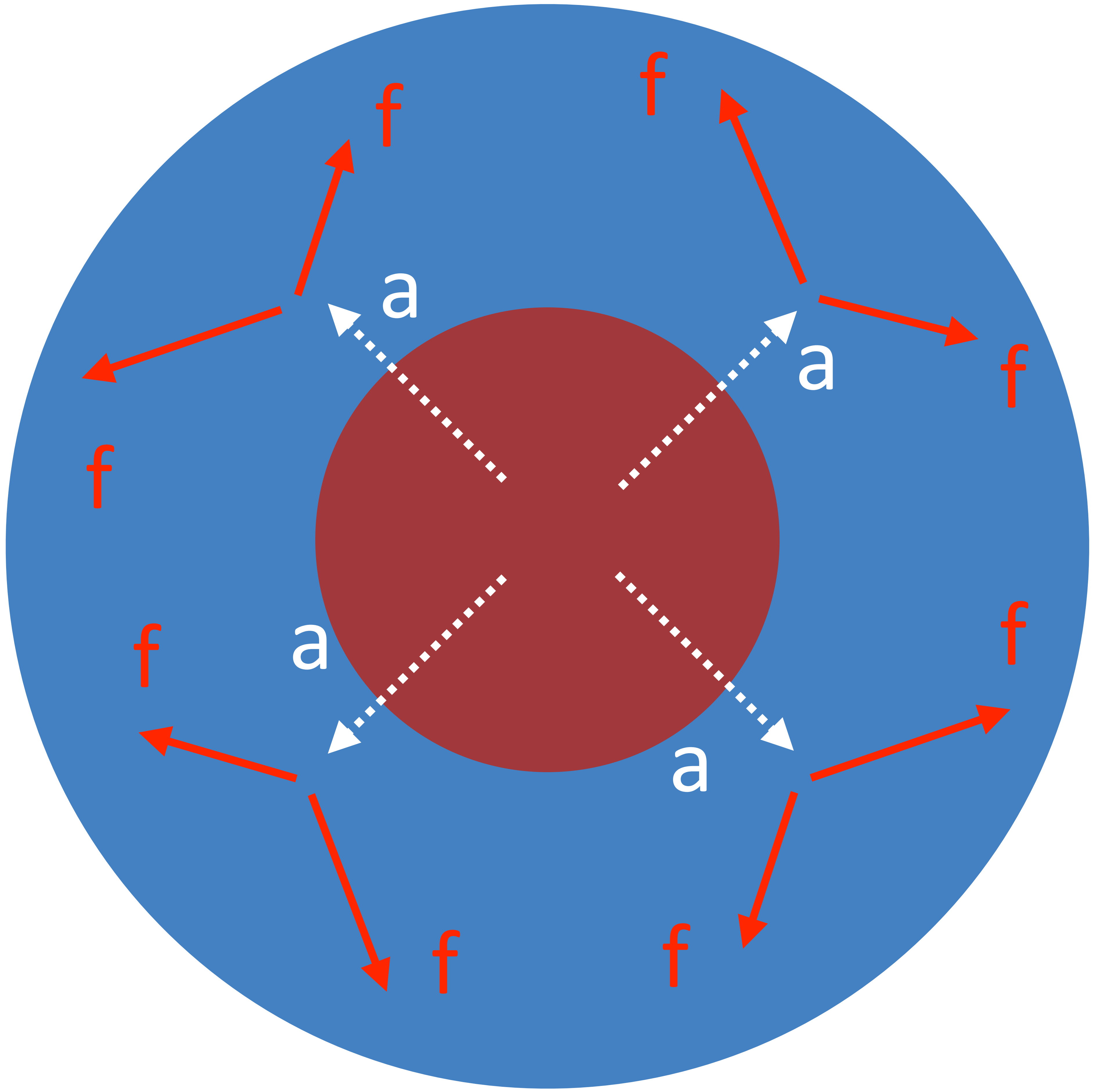


new-physics-induced energy deposition in the supernova mantle should be less than the measured explosion energy

[Falk, Schramm, 1978]

[Sung, Tu, Wu, 1903.07923]

[Caputo, Janka, Raffelt, Vitagliano, 2201.09890]

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

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

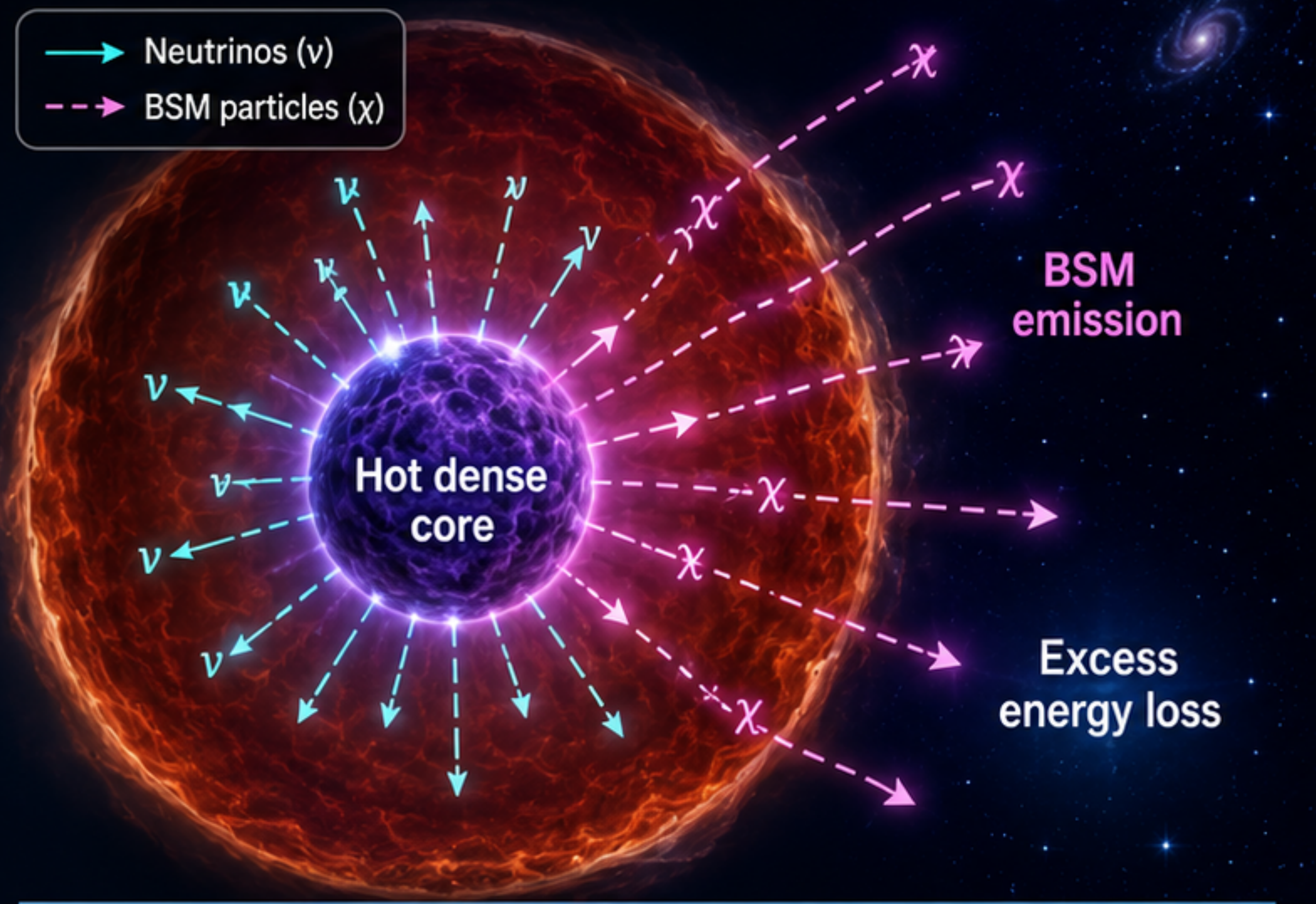
[Caputo, Janka, Raffelt, Vitagliano, 2201.09890]

[Burrows & Vartanyan, 2009.14157]

1000 times smaller than neutrino luminosity!!

Supernova Constraints on BSM Particles

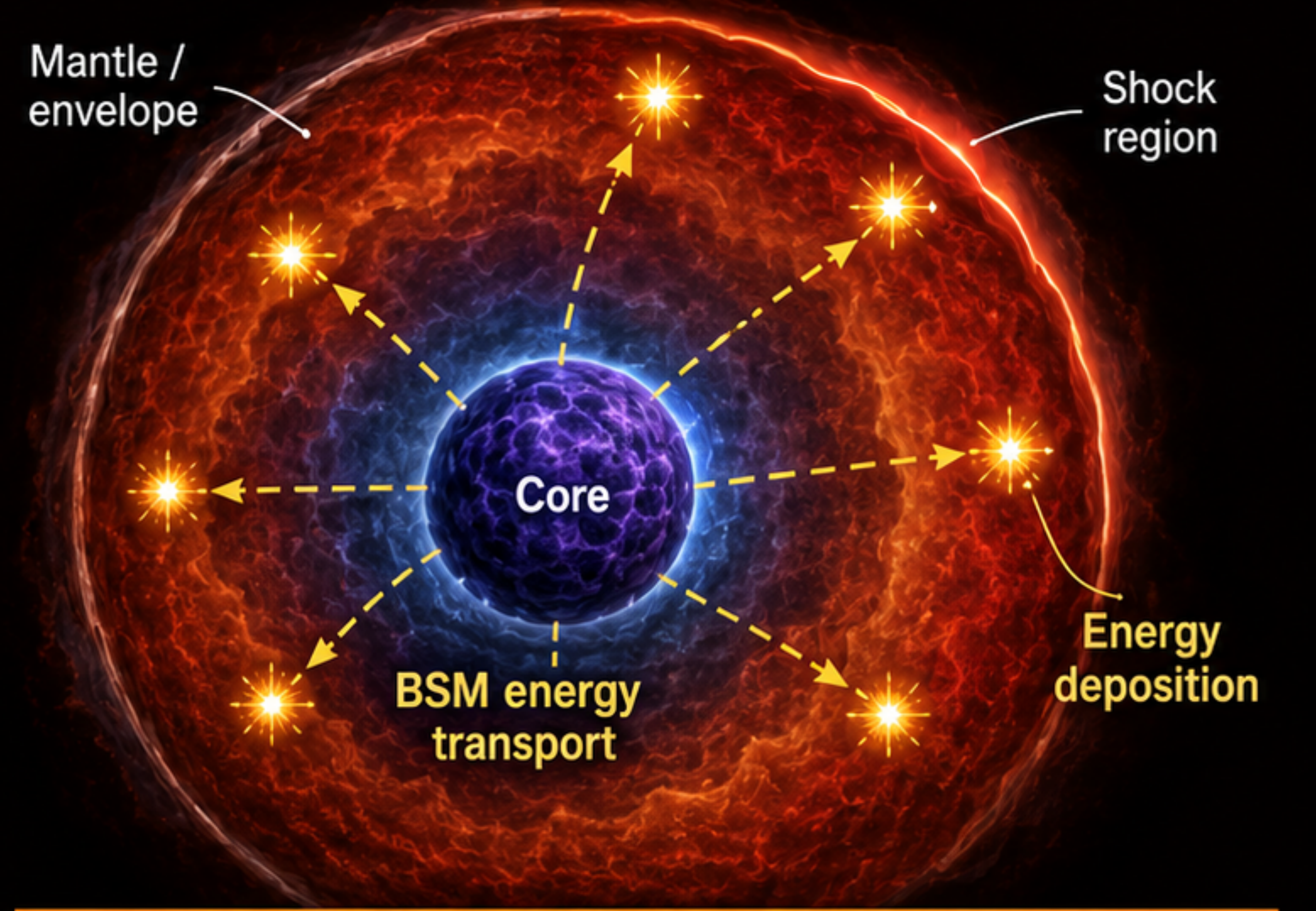
1. SN Cooling Constraint



Too much BSM emission cools the core and suppresses/shortens the neutrino signal

L_{BSM} must not be too large

2. SN Explosion Constraint



Too much transported energy would over-energize the observed explosion

$E_{\rm dep}^{BSM}$ must not exceed the observed explosion energy

AI-generated

3

Supernova (SN) cooling limits on lepton-flavor-violating axions/ALPs

Axion production in the SN core

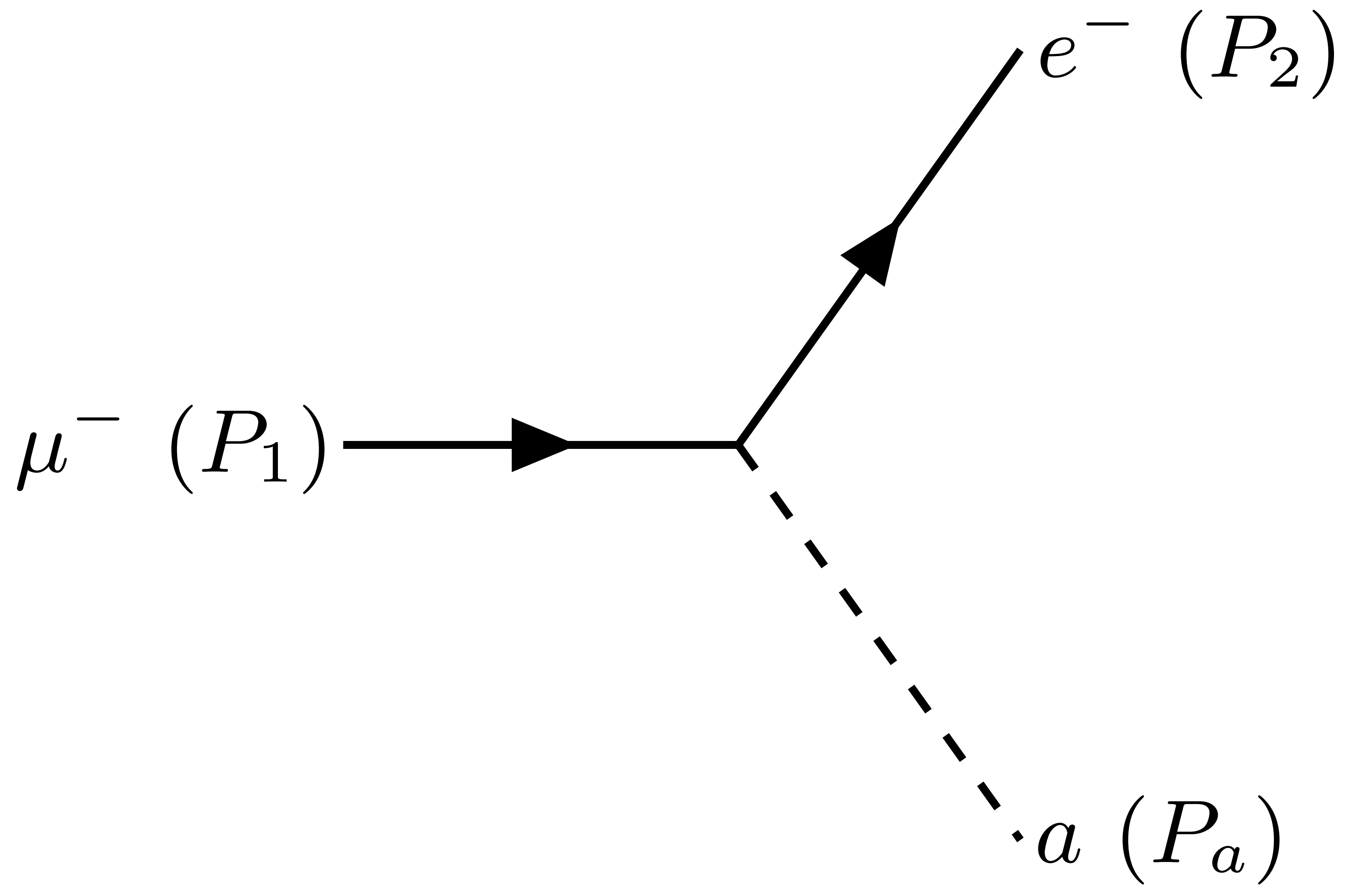
Axion production in the SN: (1) muon decay

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

(1) muon decay

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

axion mass < muon mass



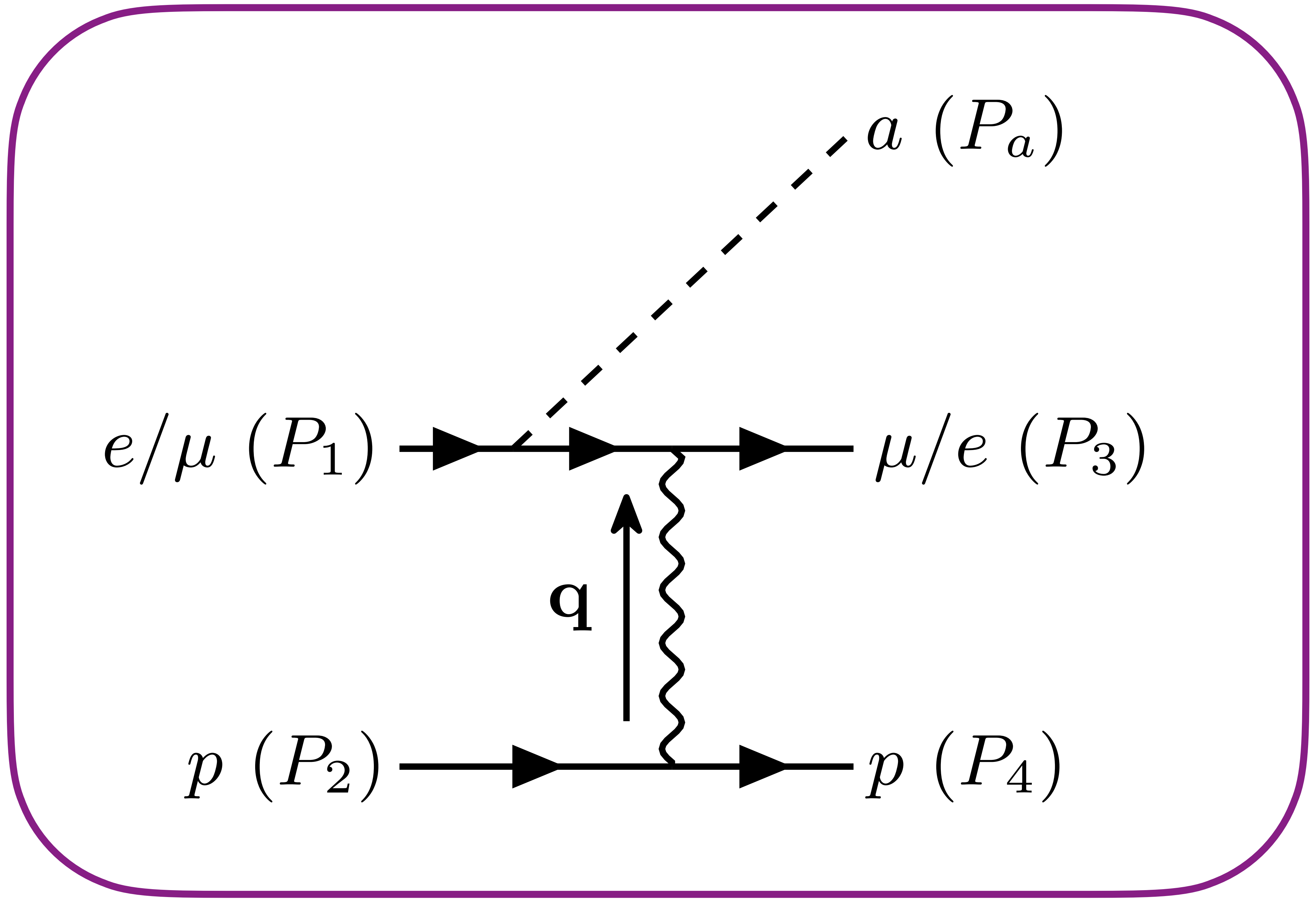
[Calibbi, Redigolo, Ziegler, Zupan, 2006.04795]

also occurs in rare muon decay experiments

Axion production in the SN: (2) bremsstrahlung

(2) bremsstrahlung

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



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

[Zhang, Hagimoto, Long, 2309.03889]

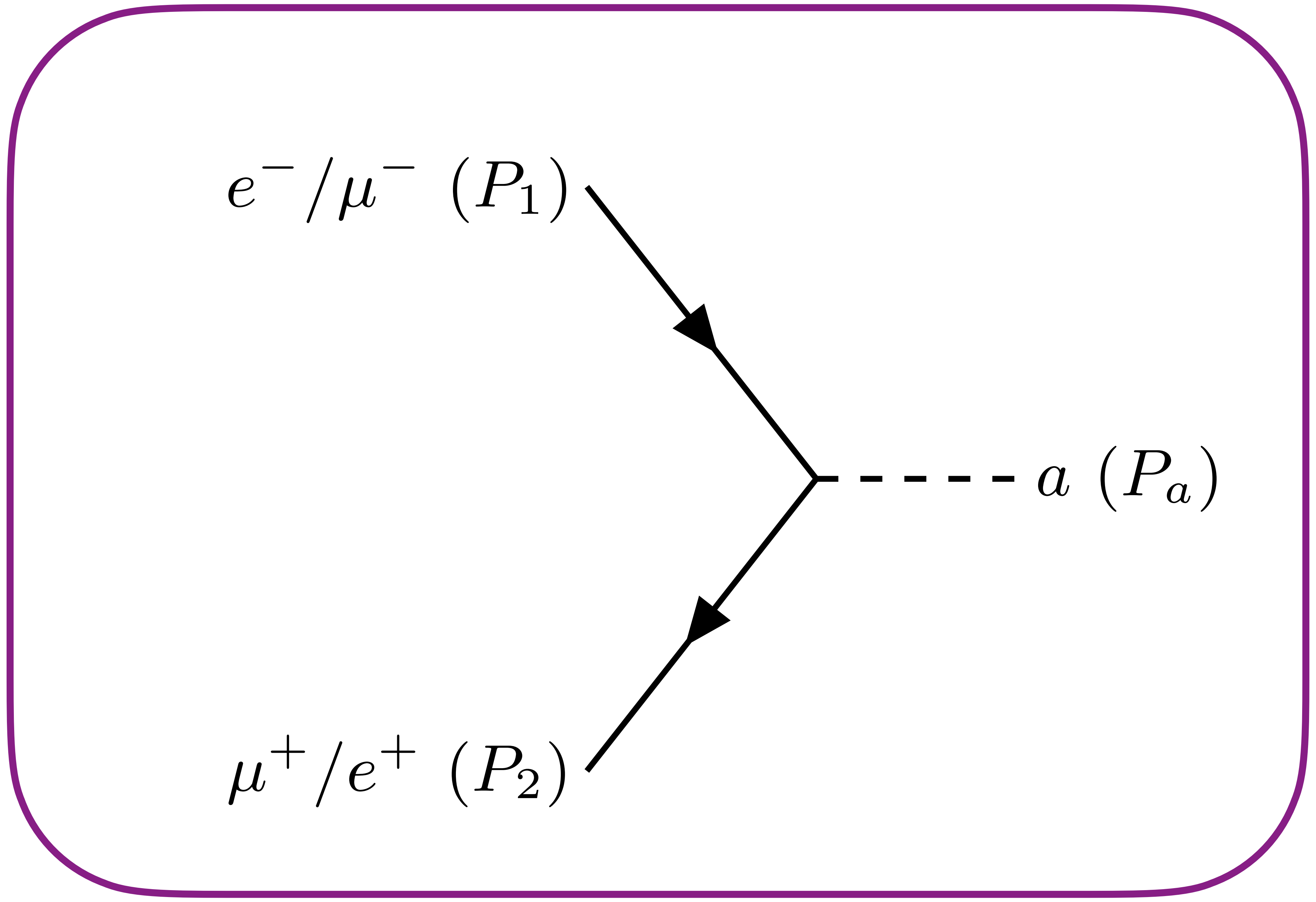
Axion production in the SN: (3) e-mu coalescence

(3) electron-muon coalescence

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

axion mass > muon mass

[Li, ZL, 2501.12075]



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

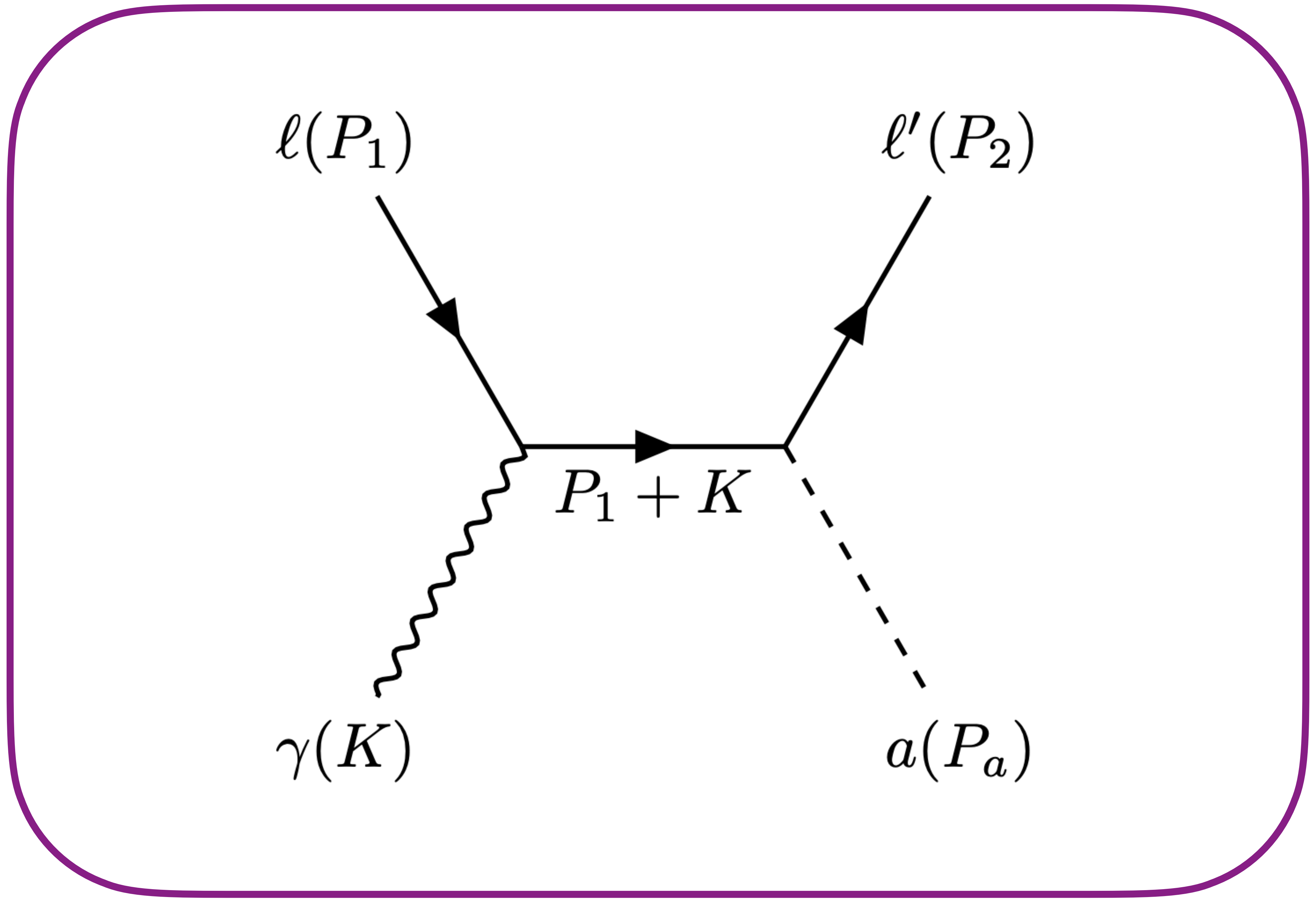
Axion production in the SN: (4) semi-Compton

(4) semi-Compton

$$\mu(e) + \gamma \to e(\mu) + a$$

[Huang, Li, ZL, 2510.22523]

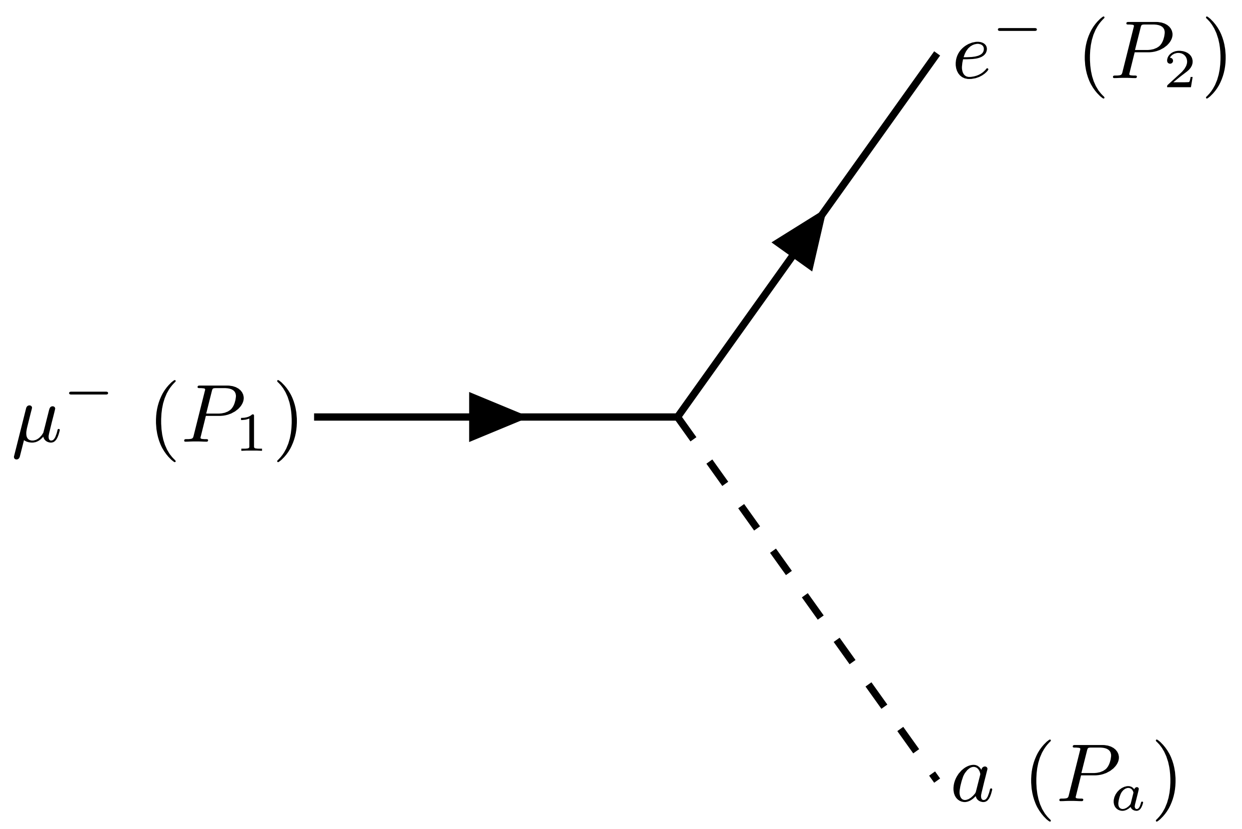
[see also 2503.15630 for electron couplings]



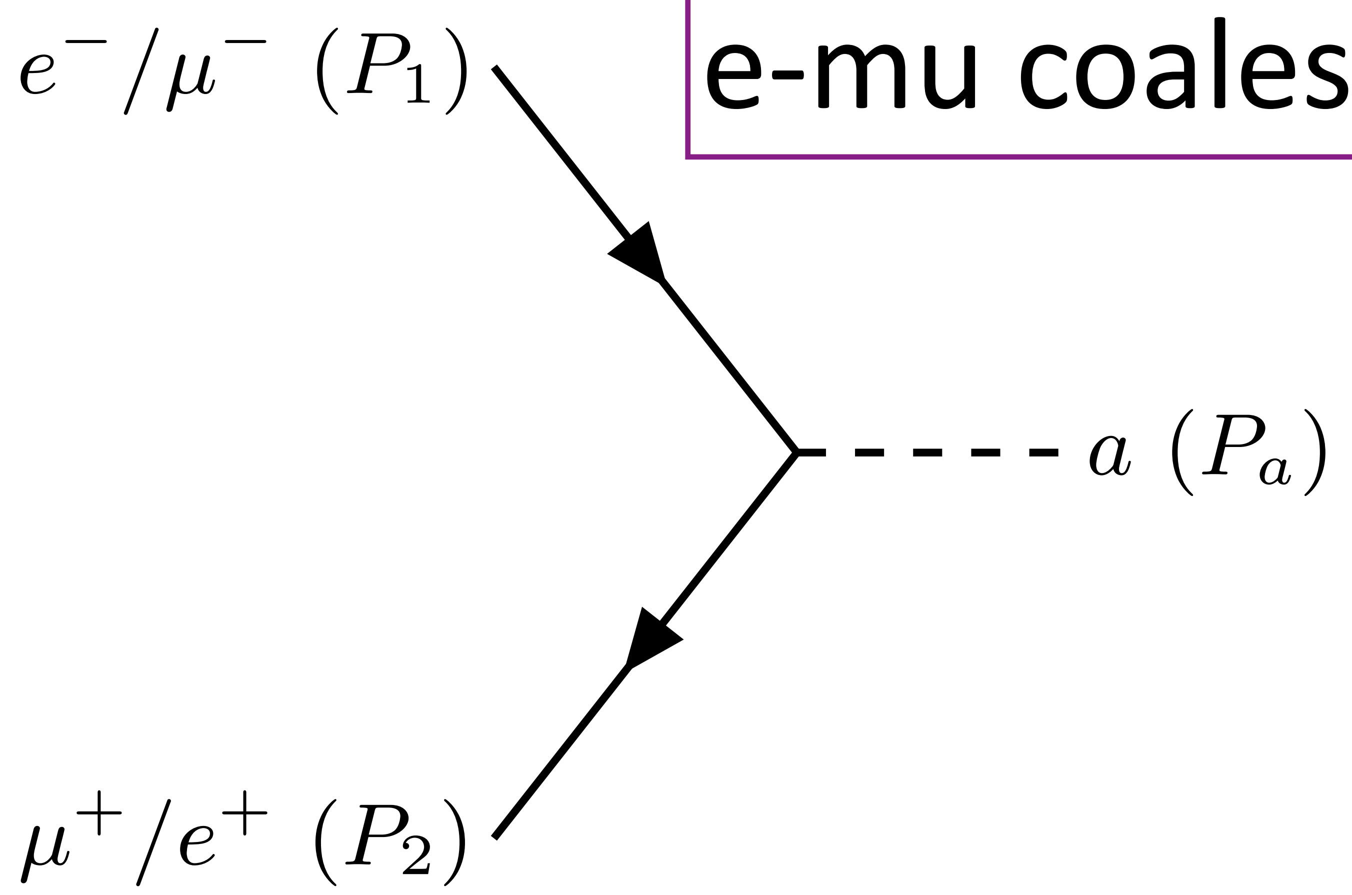
$$\mathscr{L}_{\rm int} = -ig_{ae\mu}\, a\, \bar{e}\, \gamma_5\, \mu + h.c.$$

Four production channels in the SN

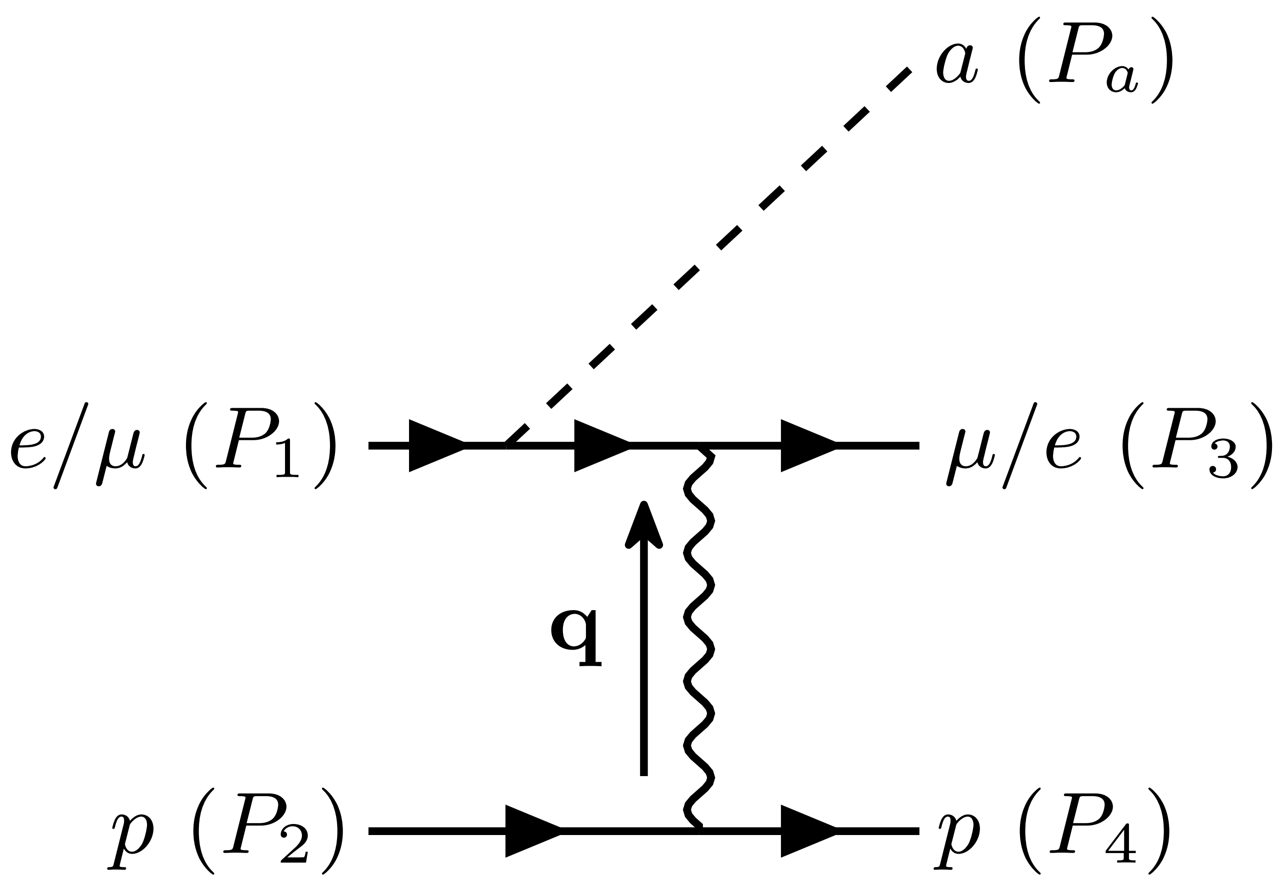
muon decay



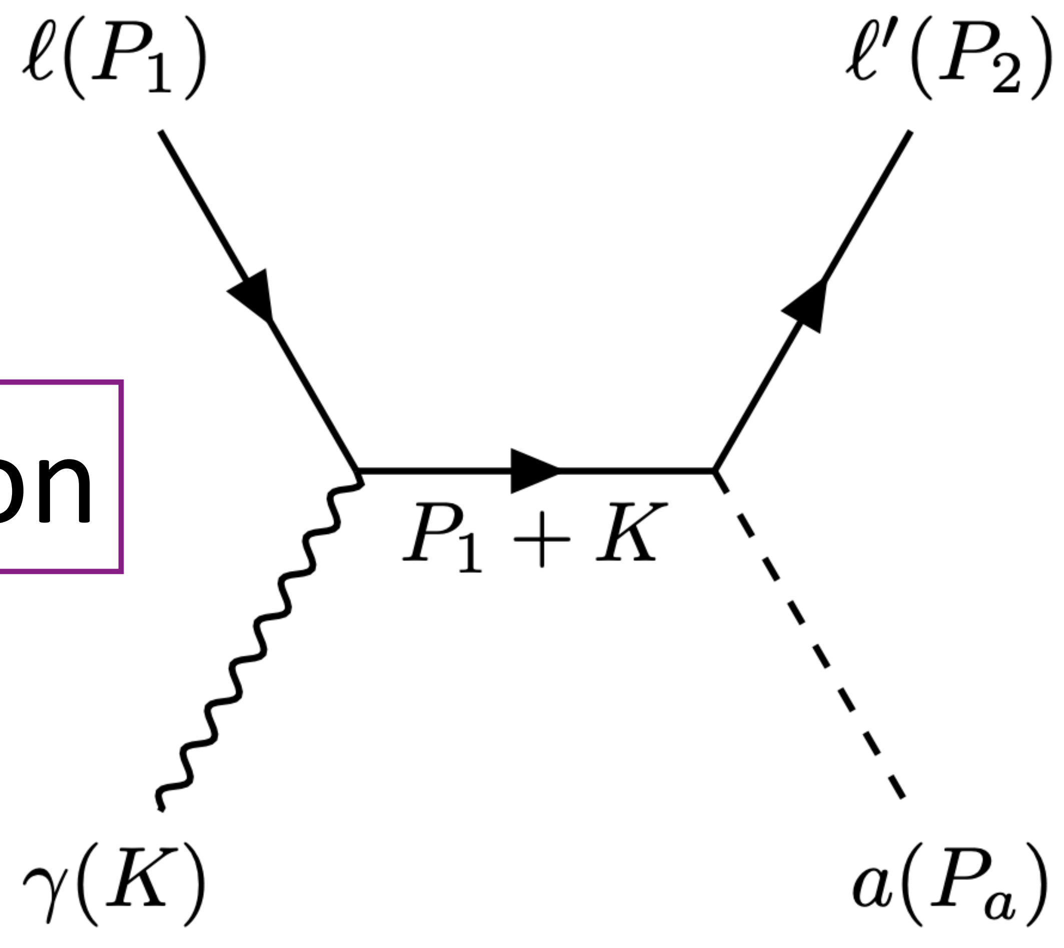
e-mu coalescence



bremsstrahlung

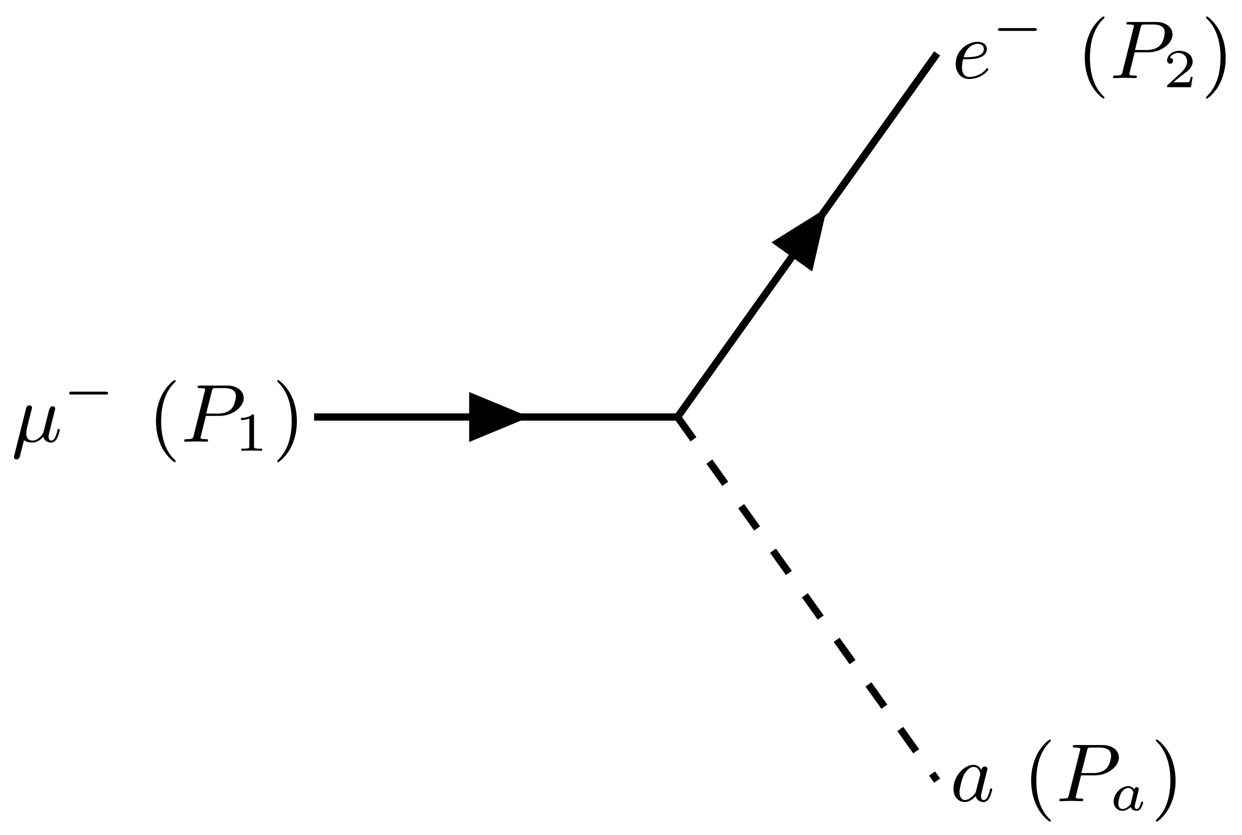


semi-Compton

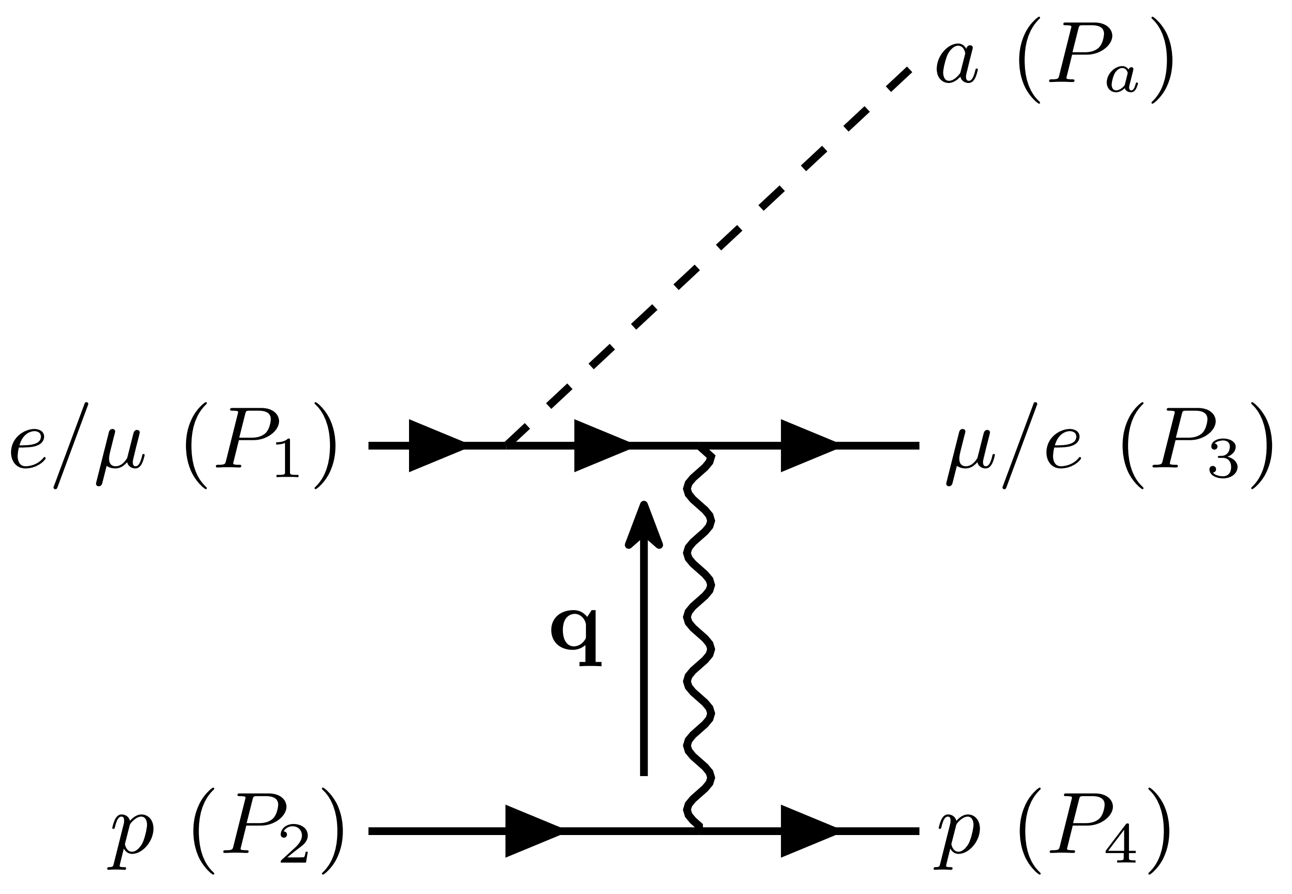


Four production channels in the SN

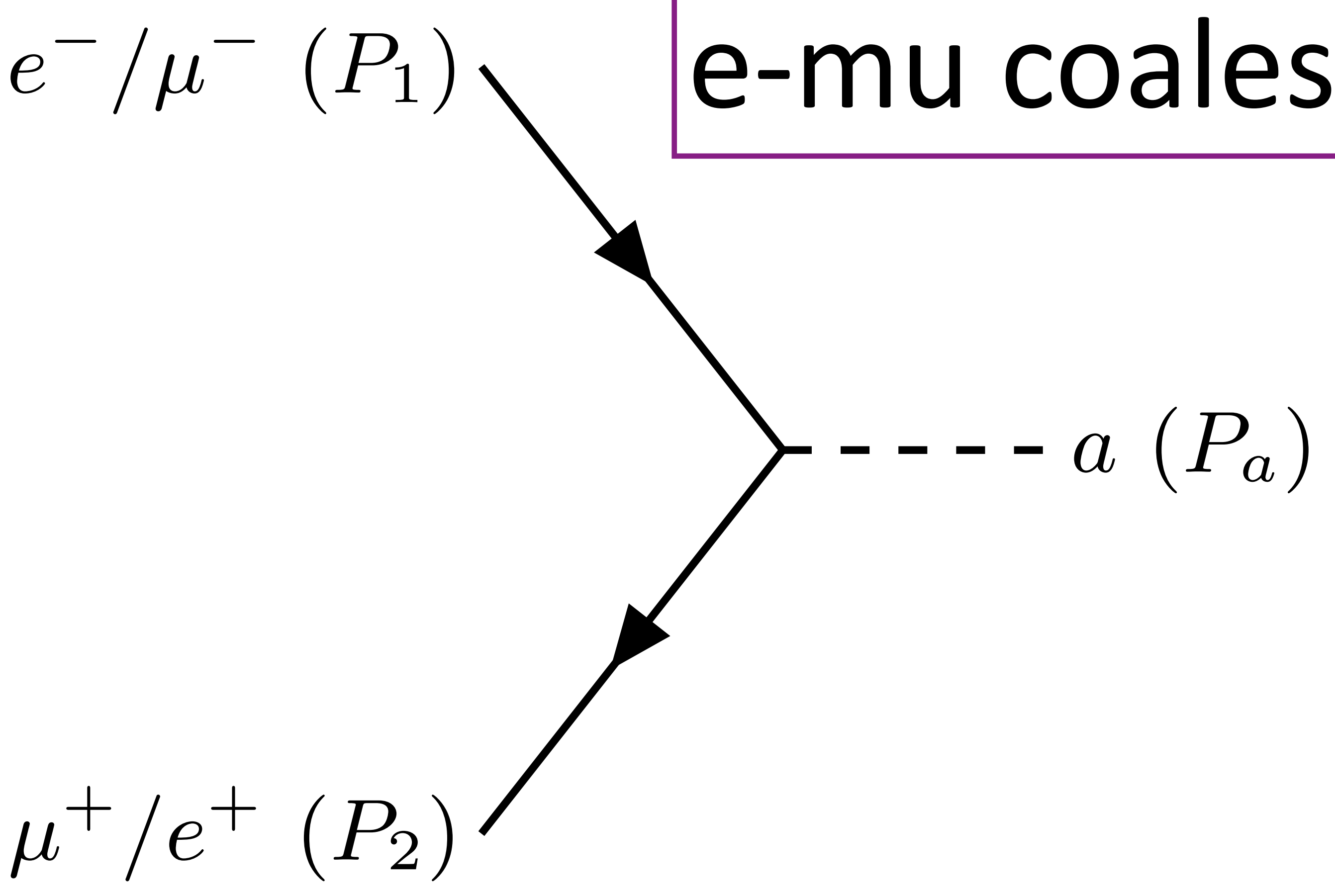
muon decay



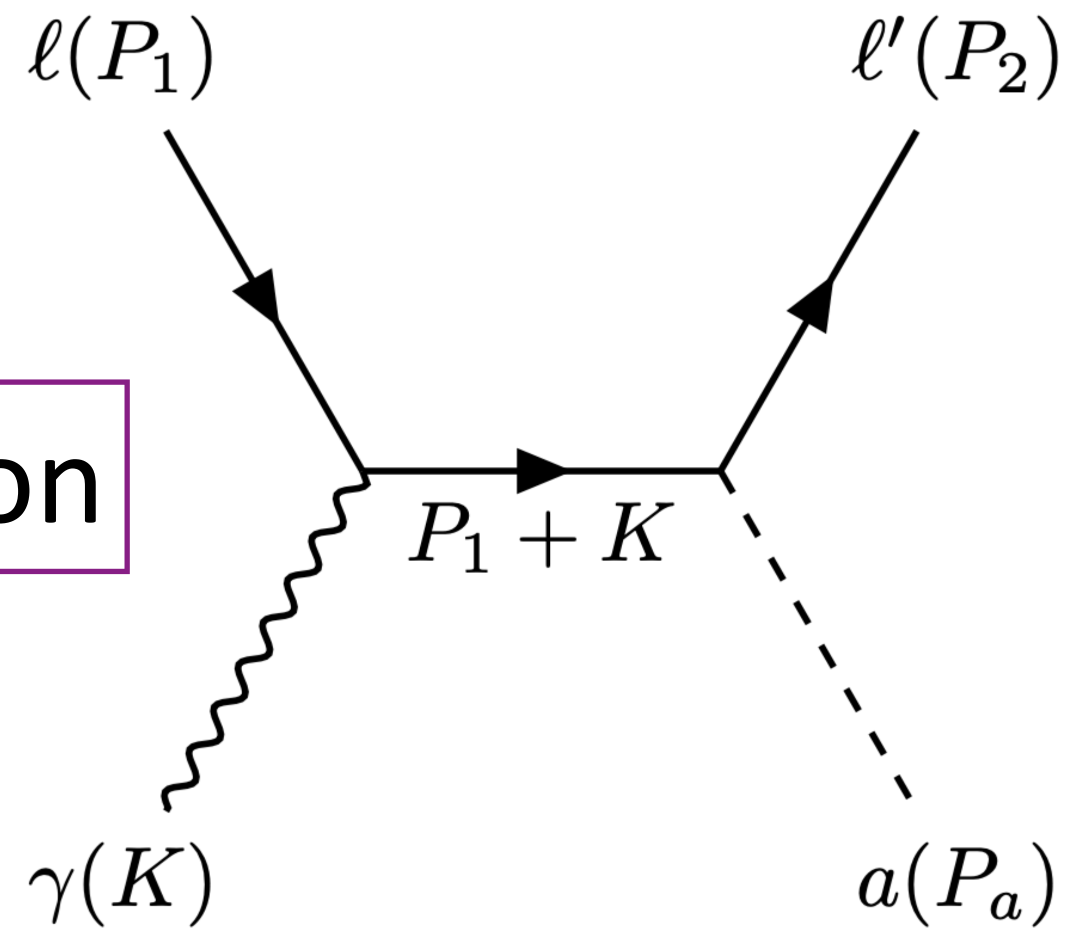
bremsstrahlung



e-mu coalescence

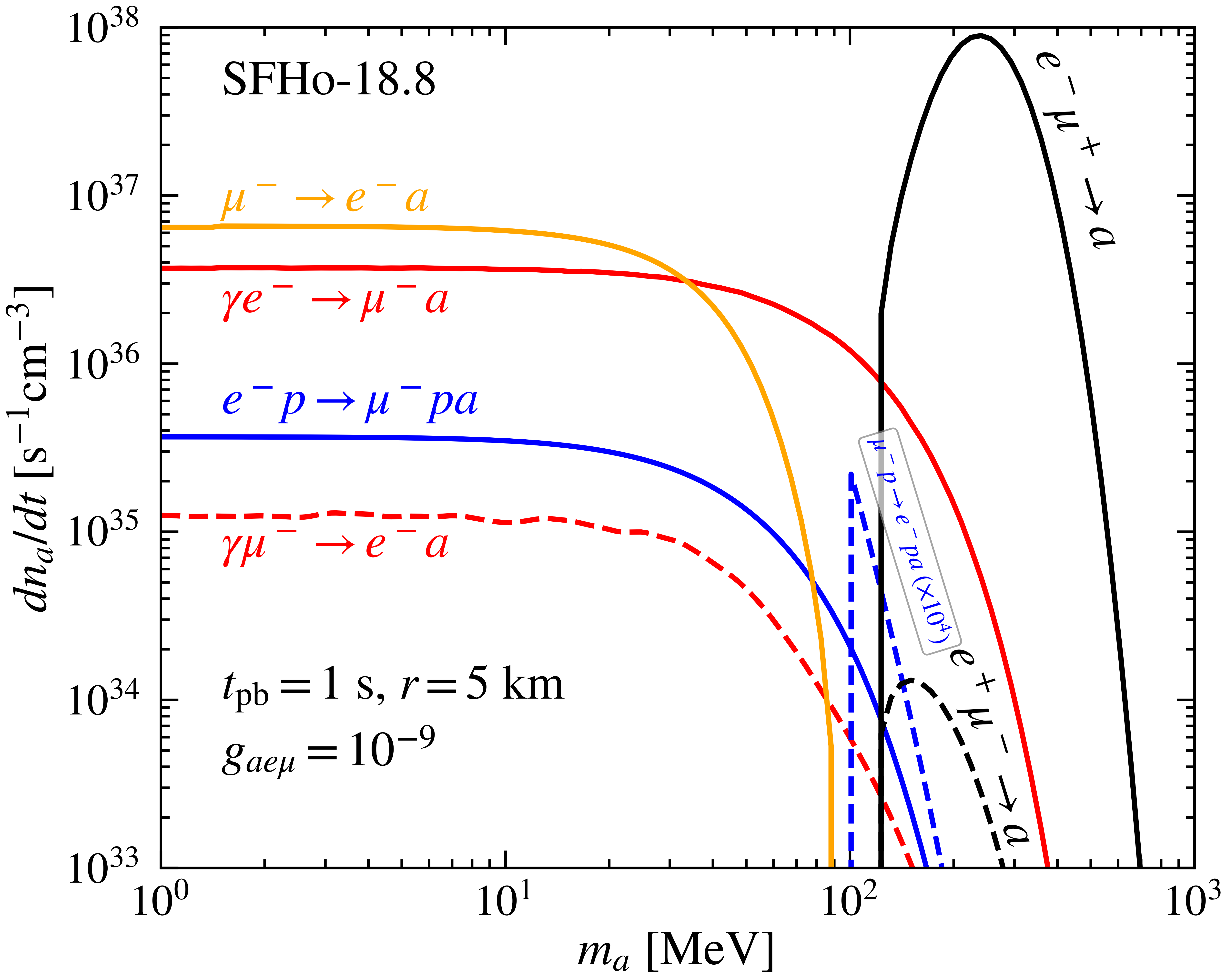


semi-Compton



not studied previously for LFV-ALPs

comparison between diff production channels



dominant production modes

$m_a \lesssim 30$ MeV: muon decay

$m_a \gtrsim 110$ MeV: e-mu coalescence

$30 \lesssim m_a \lesssim 110$ MeV: semi-Compton

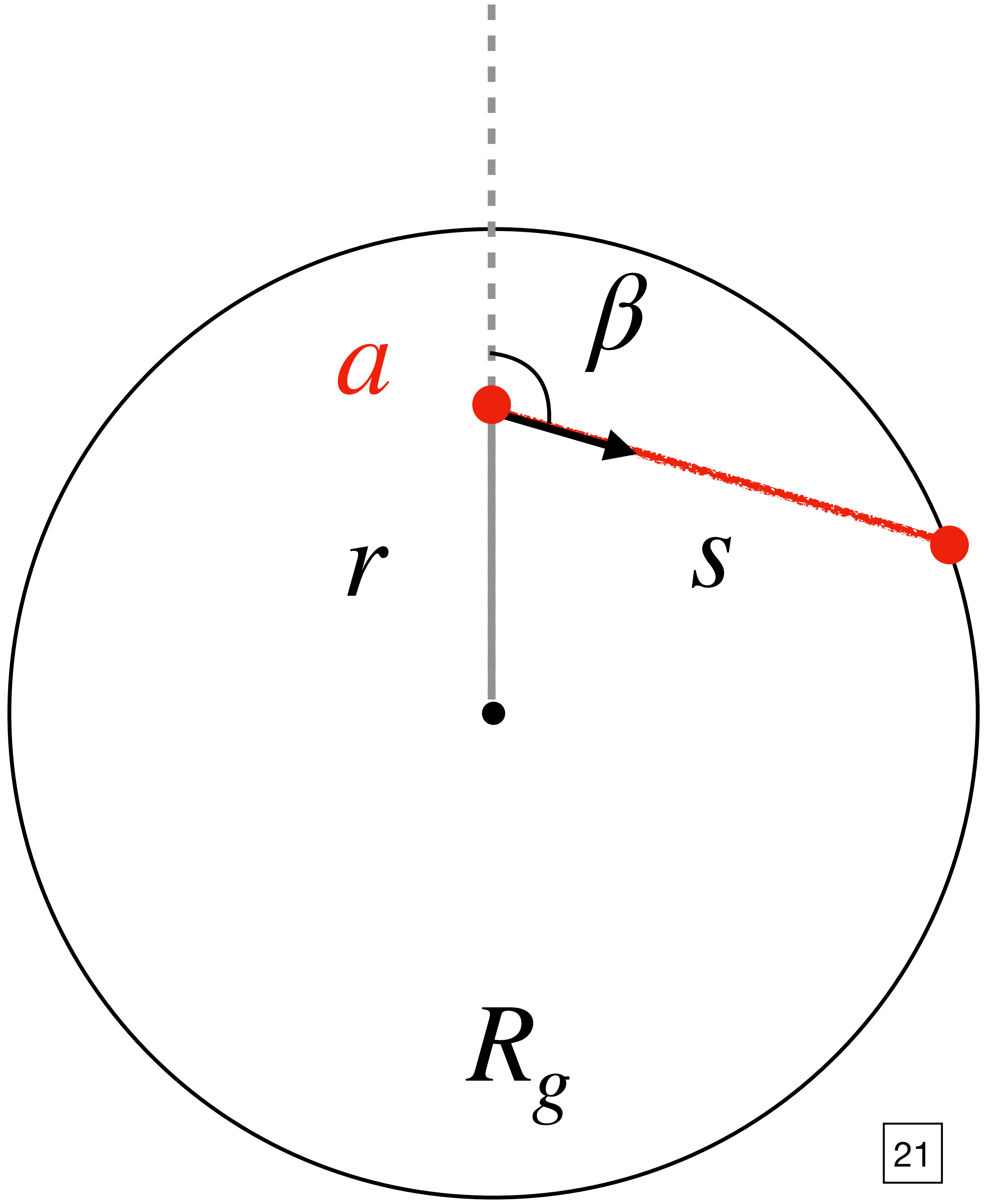
[Huang, Li, ZL, 2510.22523]

Axion luminosity at the gain radius

Axion luminosity @ R_g is obtained via the volume integration of the production rate & also taking into account the absorption effects

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

[Caputo, Raffelt, Vitagliano, 2204.11862]



r = position of production

lapse(r) = gravitational effects

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

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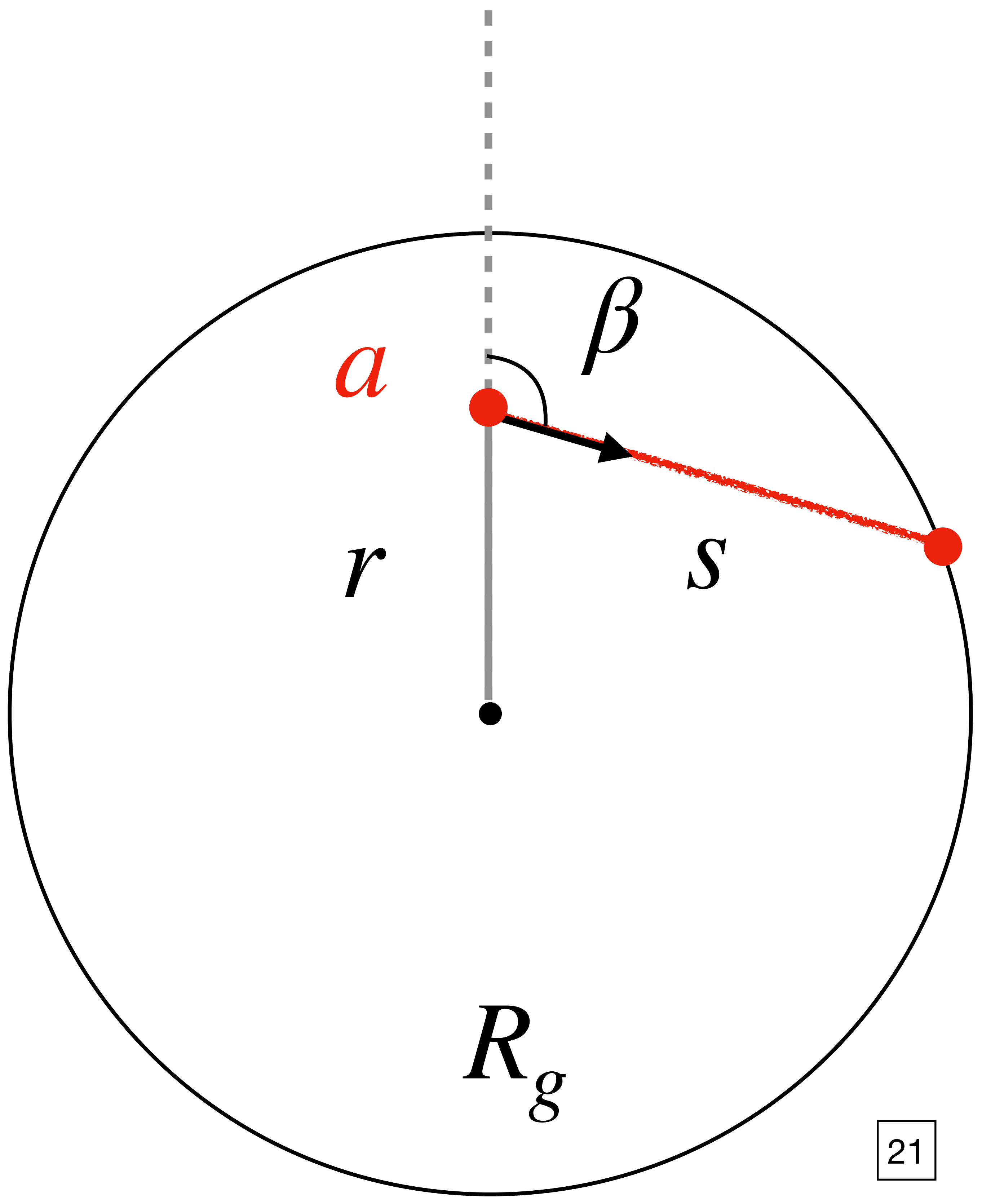
↓

production rate



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[Caputo, Raffelt, Vitagliano, 2204.11862]

↓ production rate

↓ absorption

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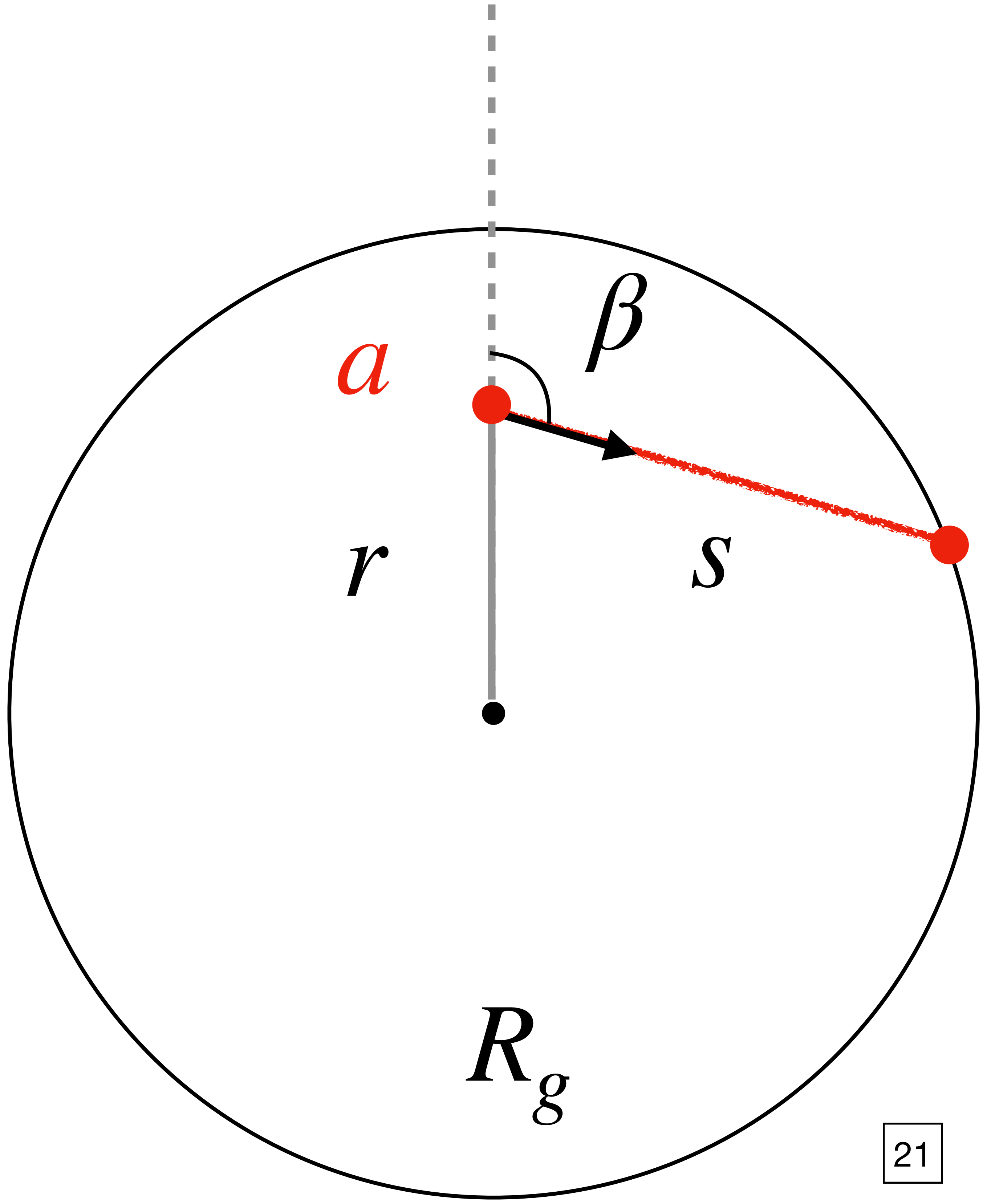
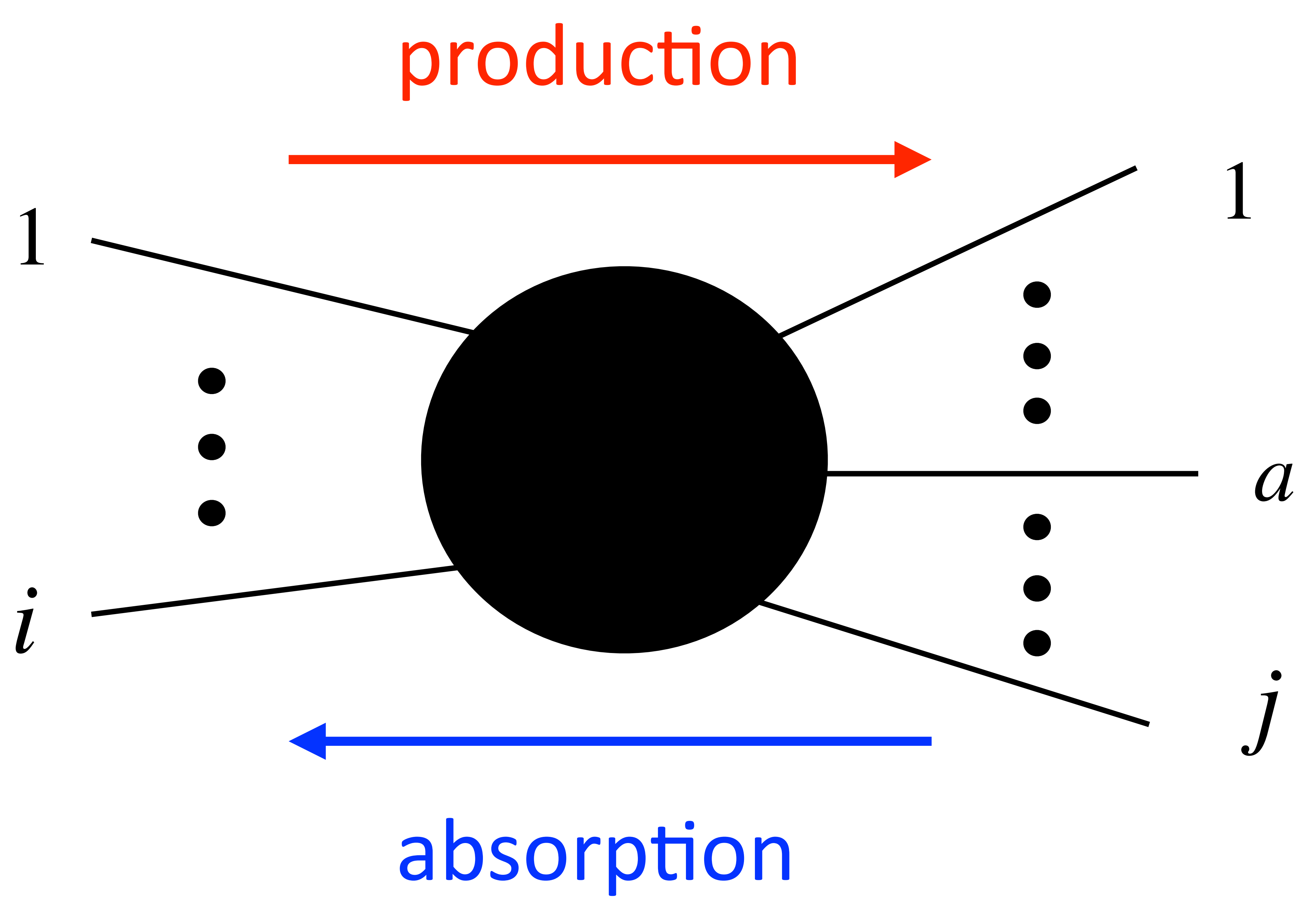




ALP production & absorption in SNe

[e.g. Weldon ’83, Kolb & Turner ’90]

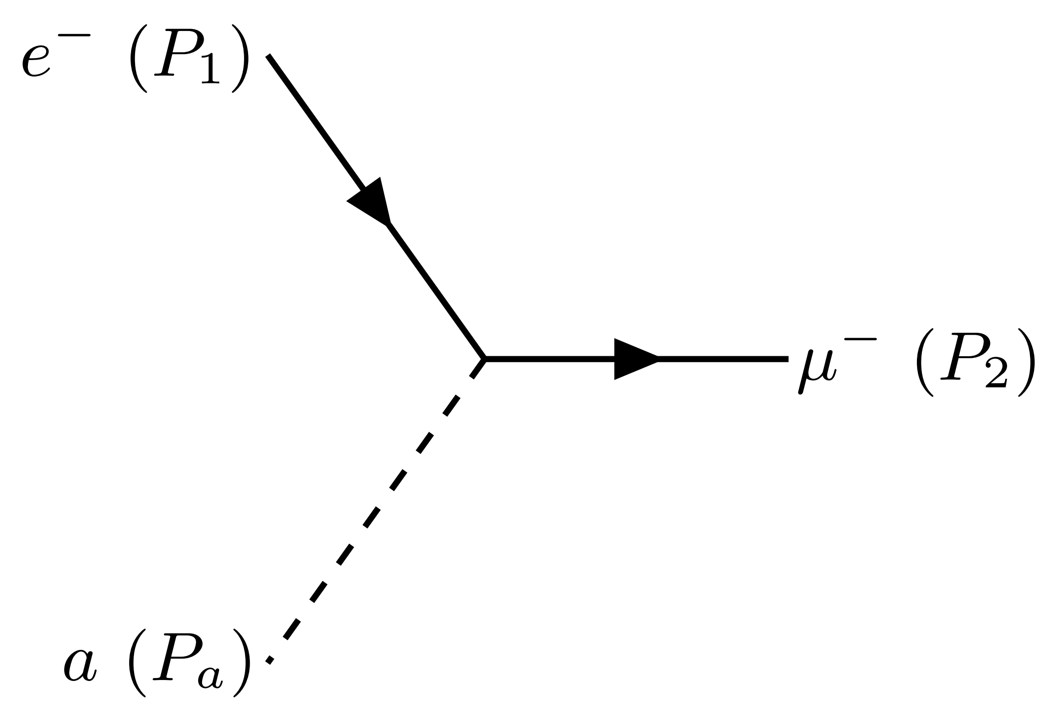
Production rate (n_a = # density, f = occupation function)

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

Absorption rate ($\sim df/dt$) (decay width for decay process)

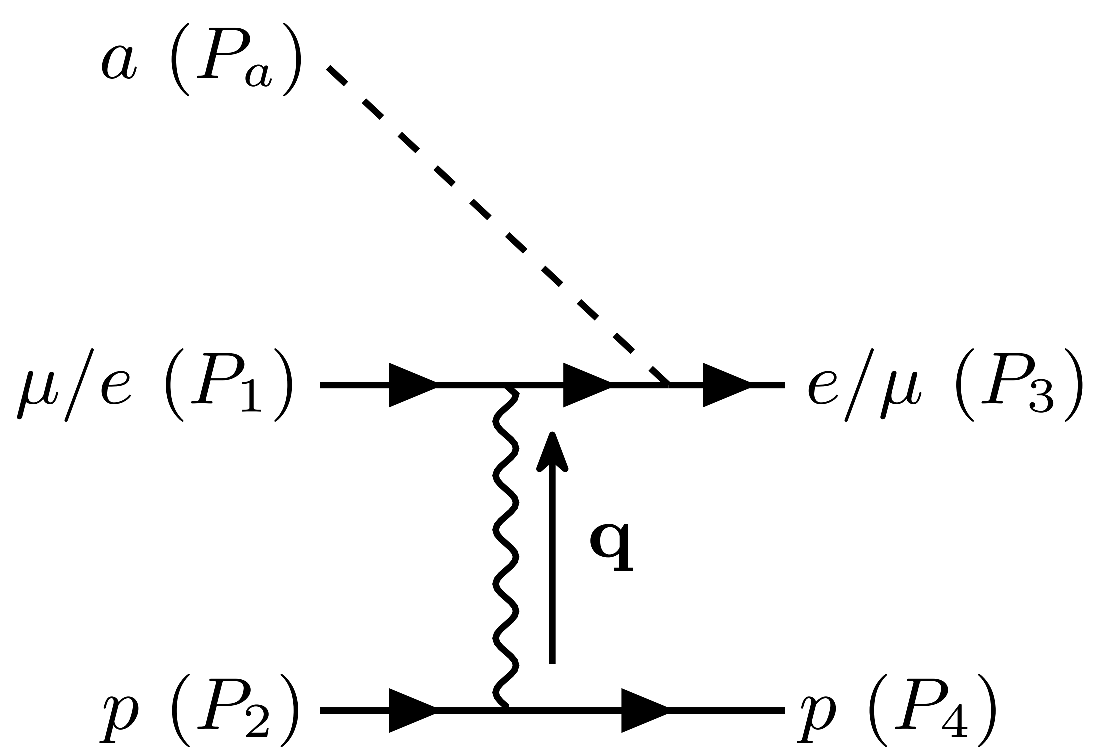
$$\Gamma_A(E_a, r) = \frac{1}{2E_a} \int \prod_{j \neq a} d\Phi_j \, f_j \prod_i d\Phi_i \, (1 \pm f_i) \, (2\pi)^4 \delta^{(4)}(P_j - P_i) \left| \mathscr{M} \right|^2$$

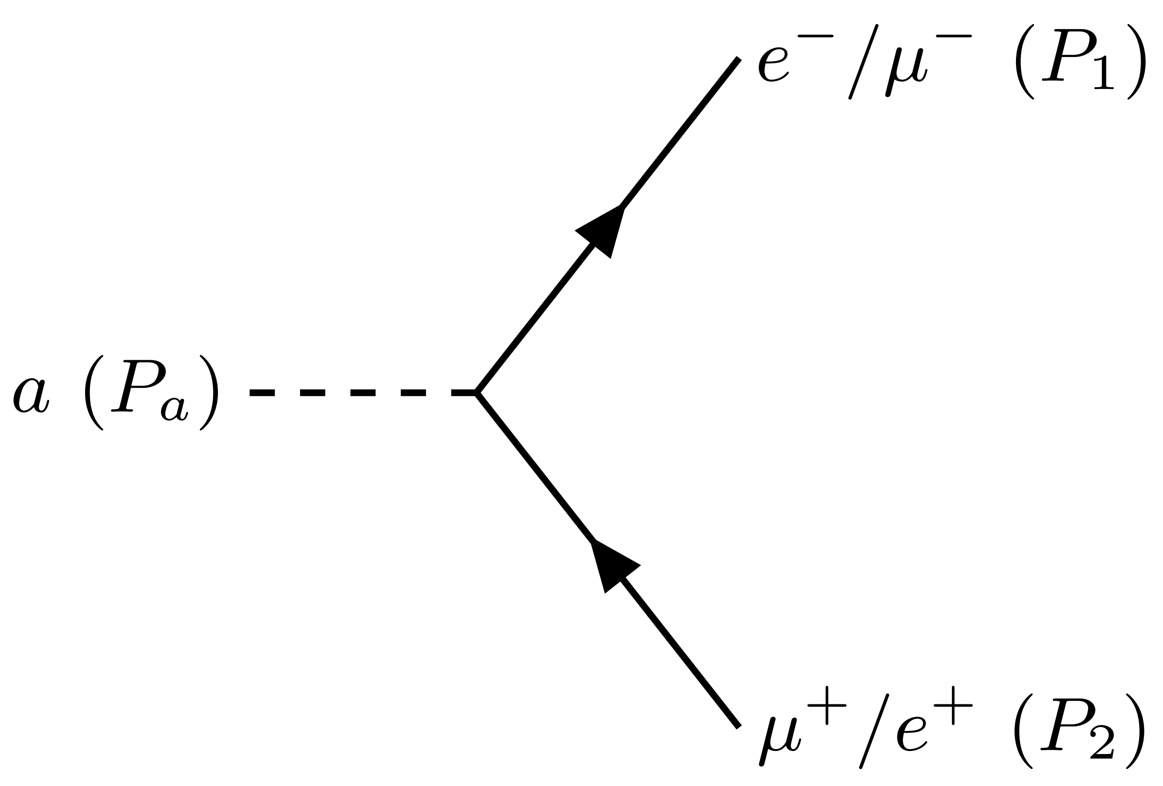
Absorption channels (inverse process of production)



e-a coalescence

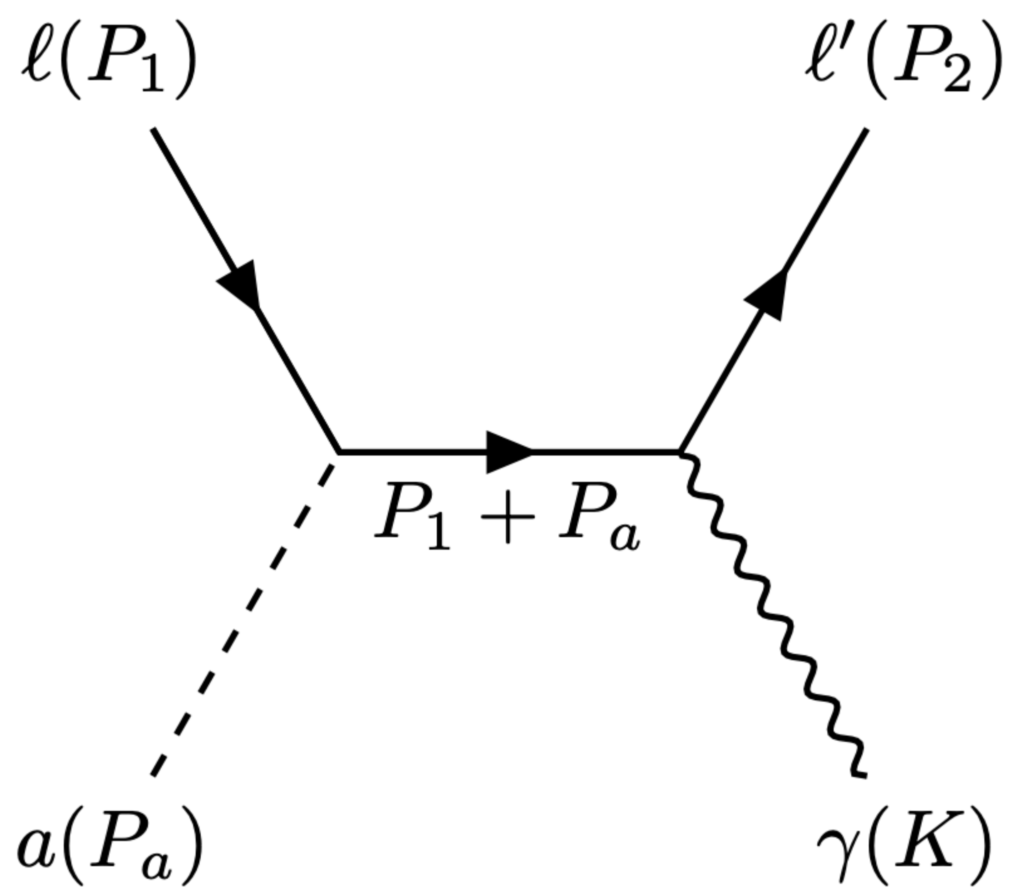
inverse bremsstrahlung





axion decay

inverse Compton



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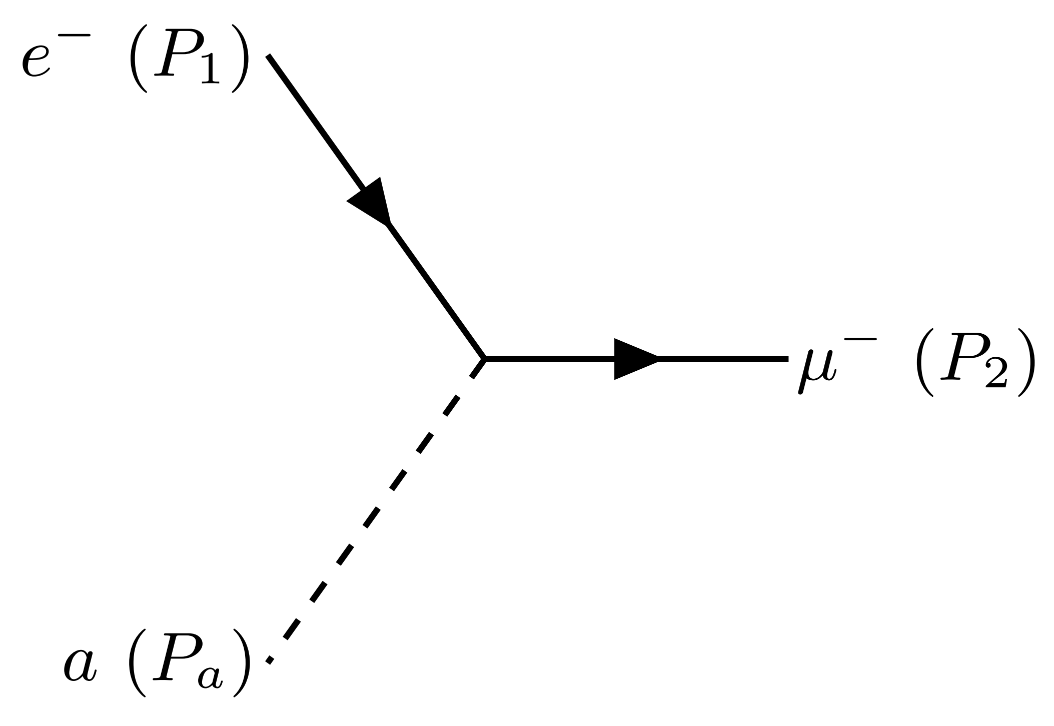

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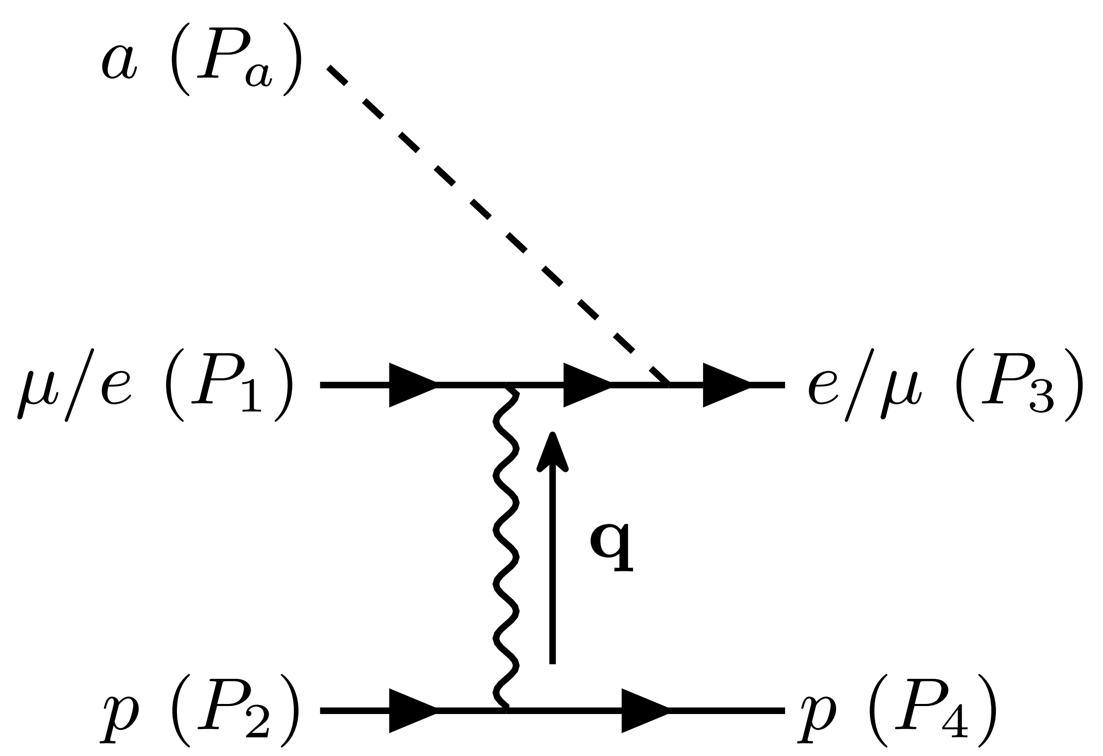

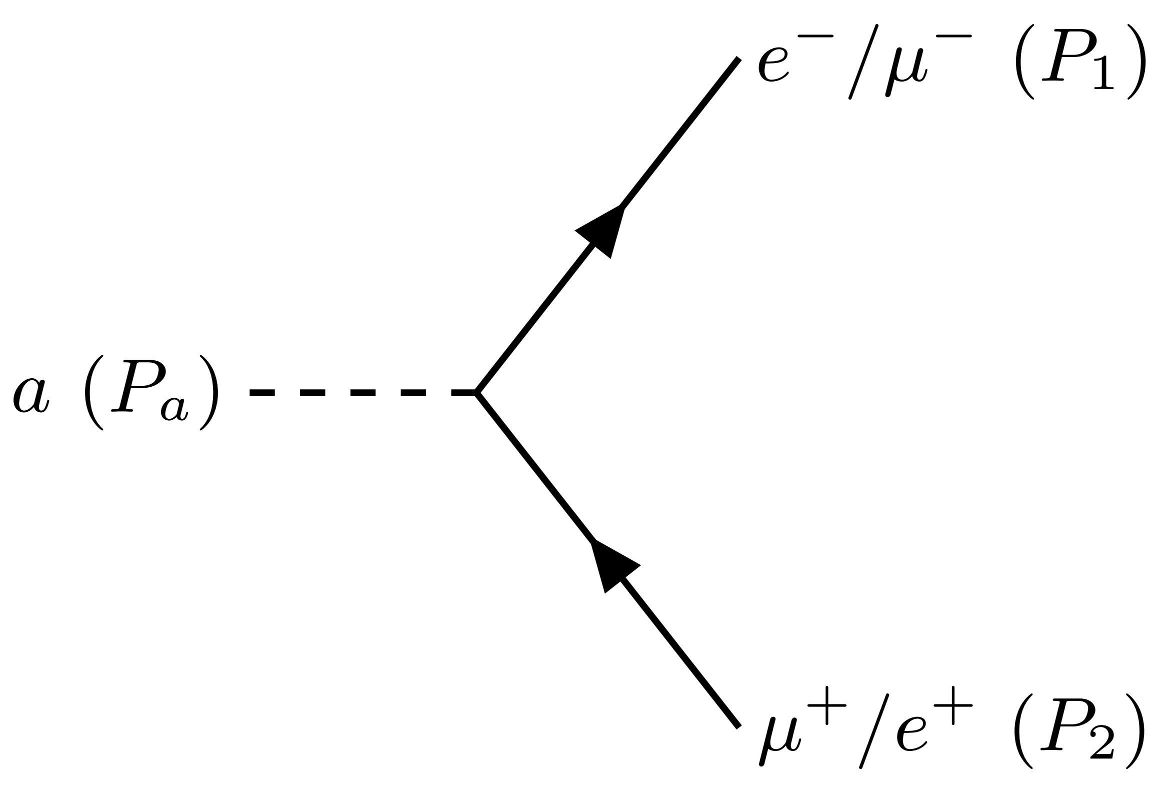

axion decay

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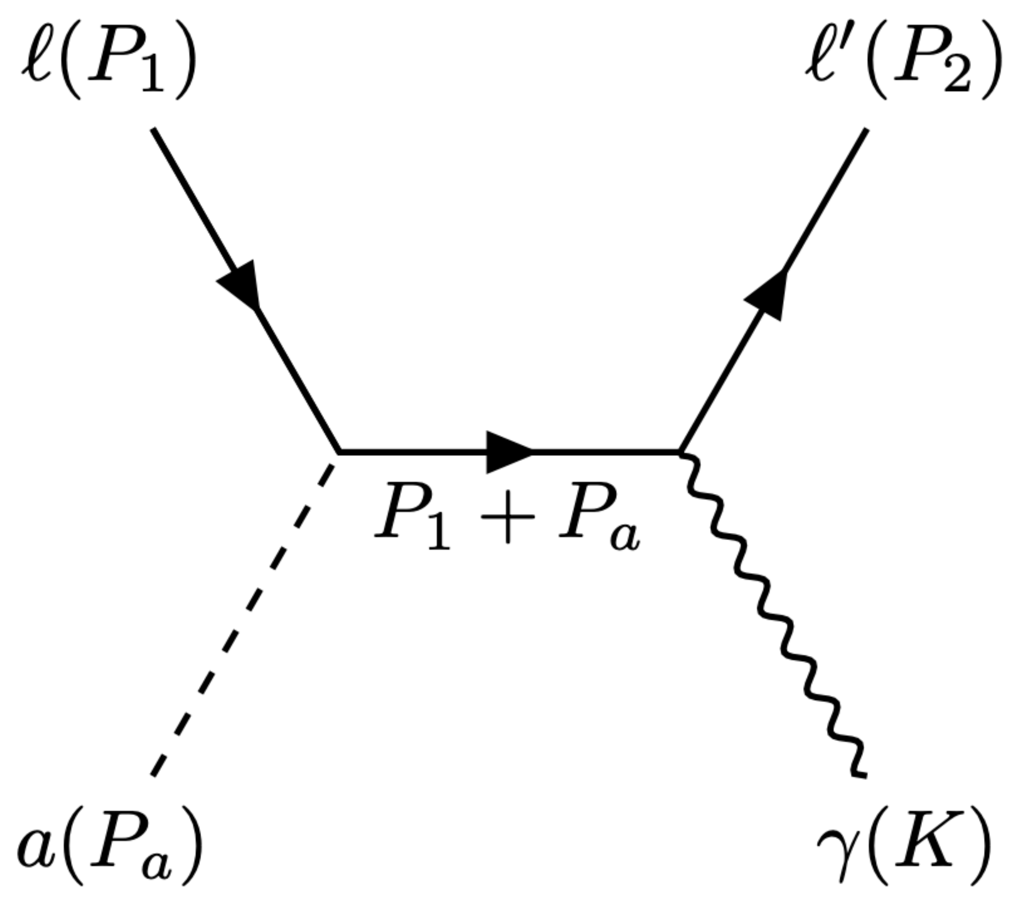


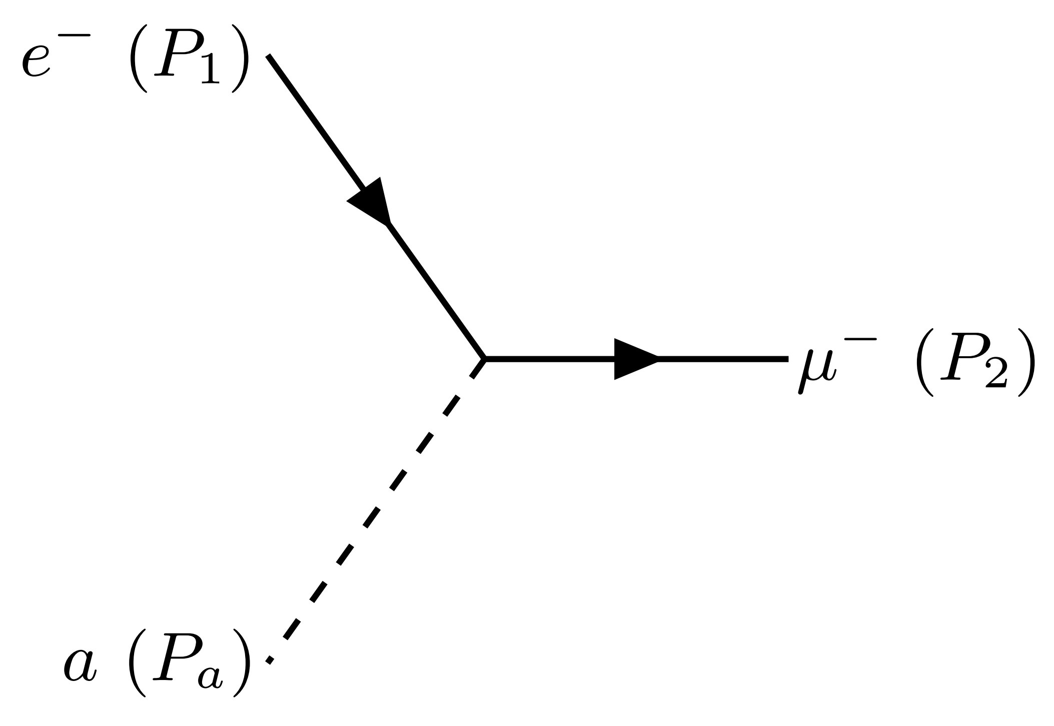
absorption rate in terms of production rate

$$\Gamma_A(E_a) = e^{(E_a-\mu_a^0)/T}\frac{2\pi^2}{|\mathbf{p}_a|E_a}\frac{d^2n_a}{dtdE_a}$$

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

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

Absorption channels (inverse process of production)



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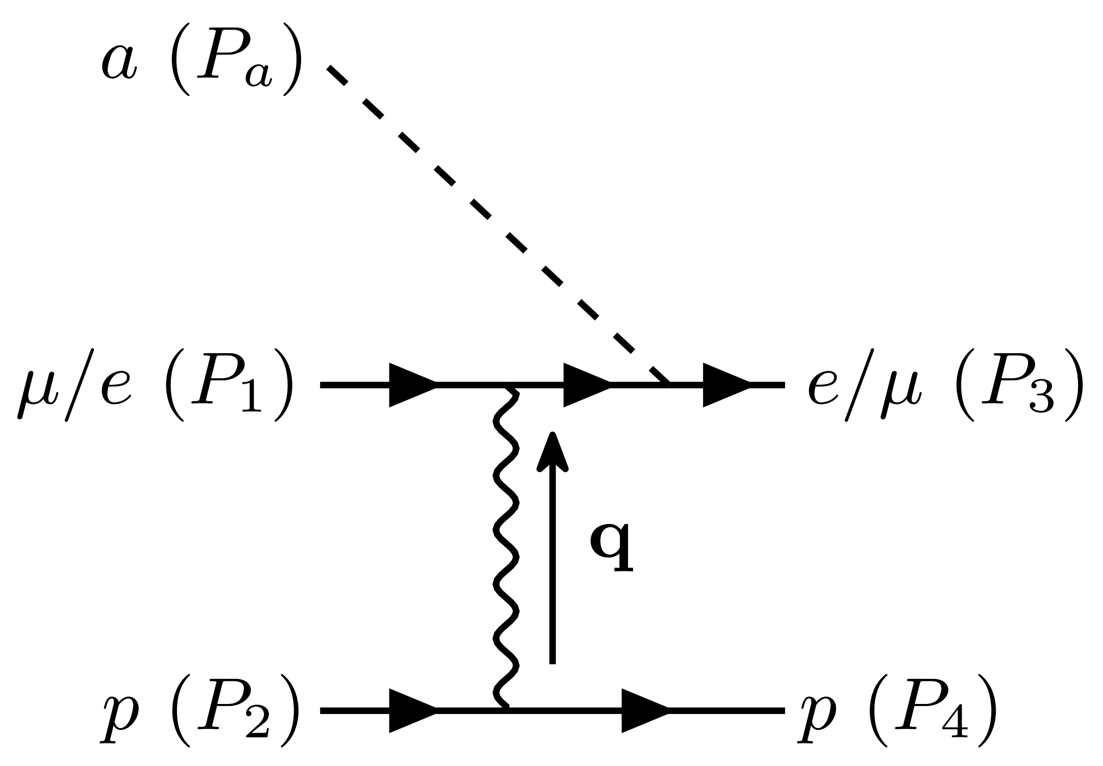
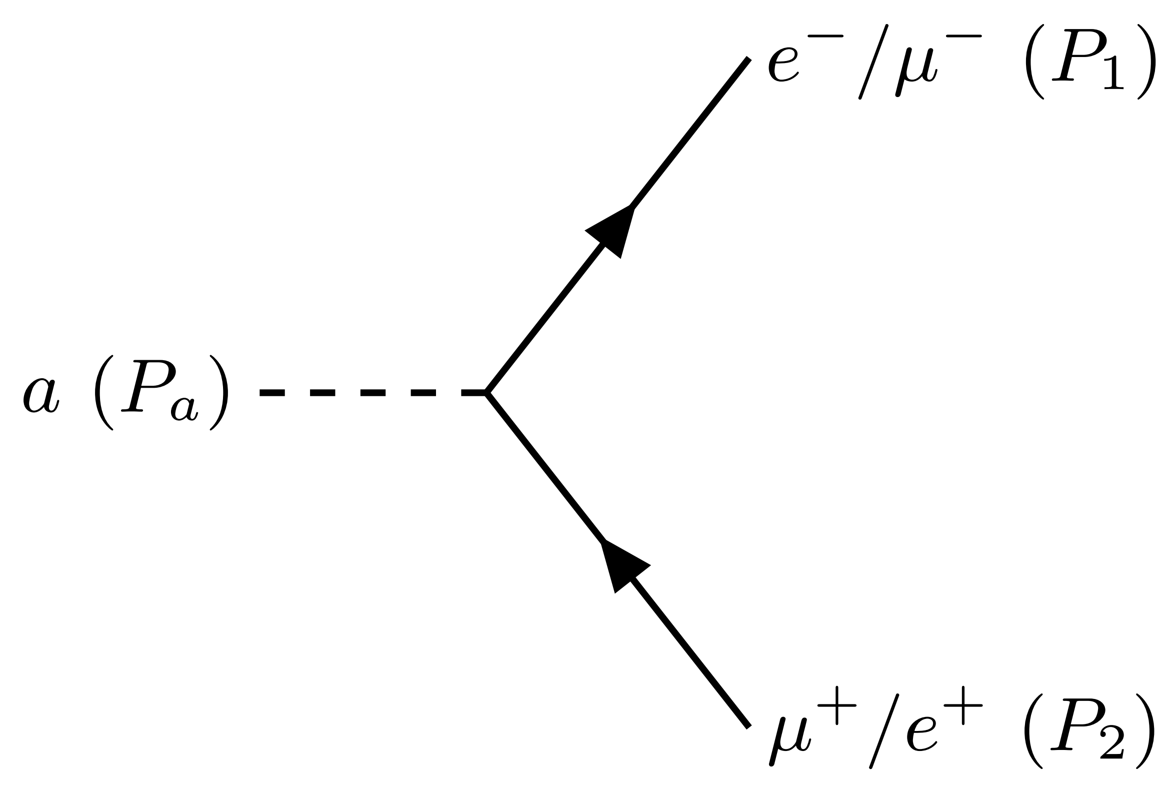
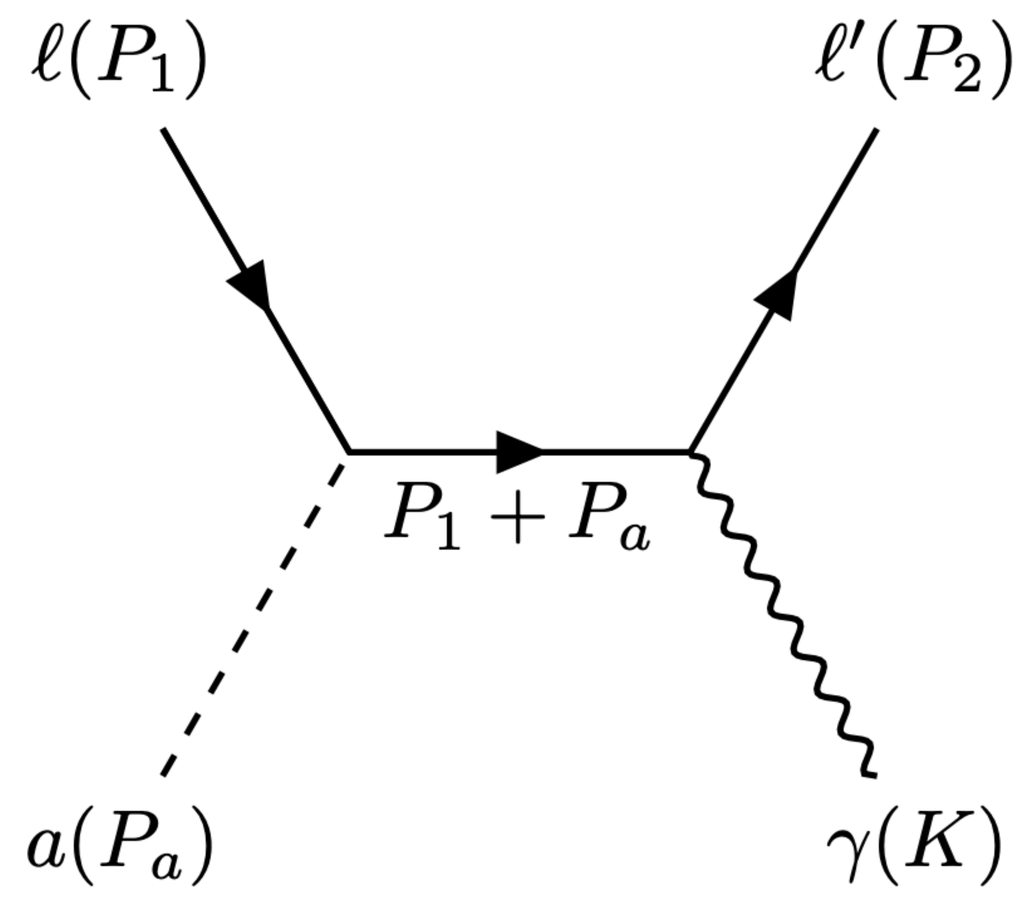




axion decay

inverse Compton



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

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

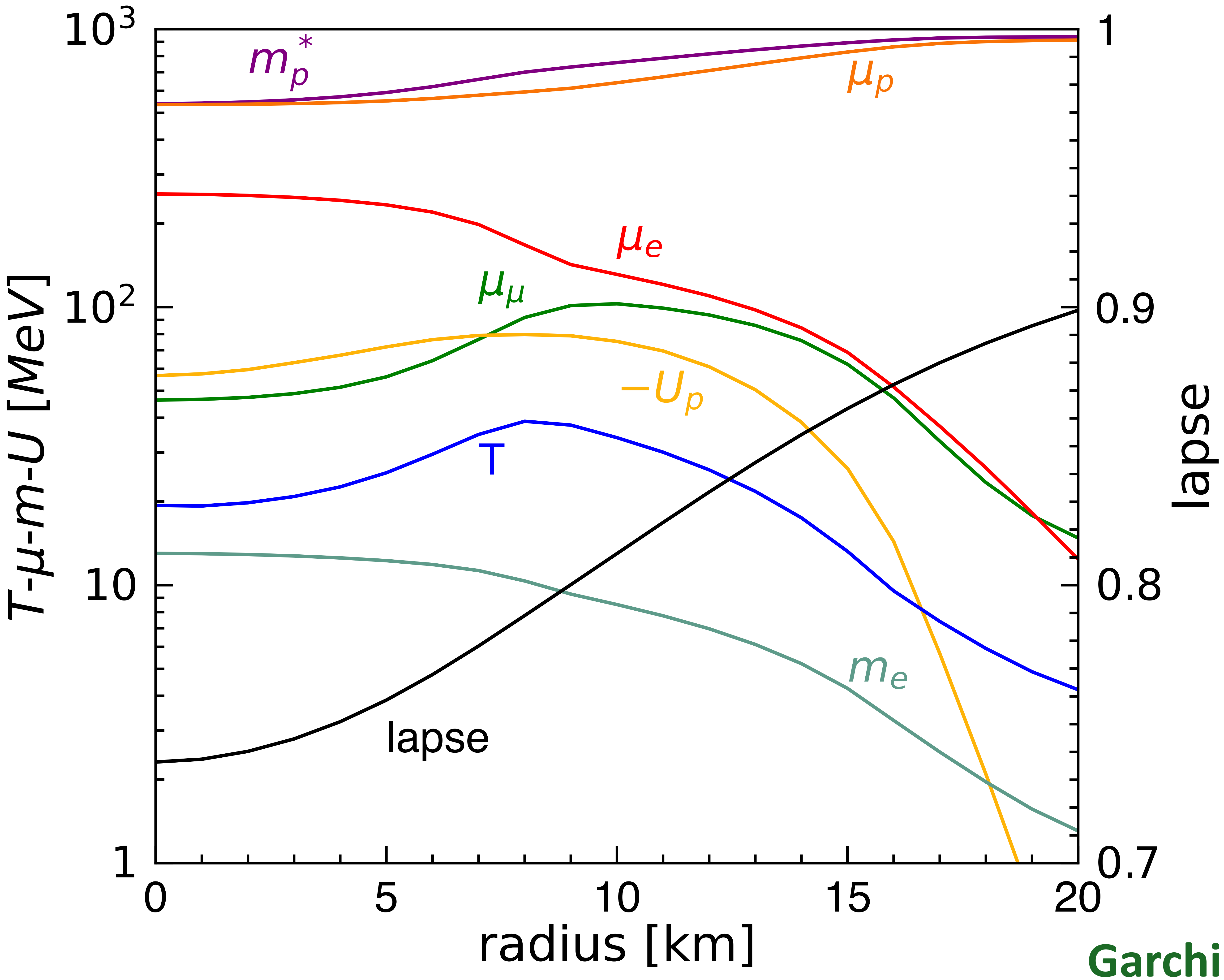
SN profiles

Production (absorption) rate depends on the particle distributions

lepton & anti-lepton $$f_{\ell^\mp} = \left[e^{(E_\ell \mp \mu_\ell(r))/T(r)} + 1\right]^{-1}$$

SN profiles: Lepton chemical potential $\mu_\ell(r)$ & Temperature $T(r)$

The SFHo-18.8 SN profiles (SN core)



- chemical potentials of e, mu, & p
- temperature
- proton effective mass
- electron effective mass
- proton self-energy
- lapse factor

[R. Bollig et al., 2005.07141]

Garching core-collapse supernova research archive

Absorption term (survival probability)

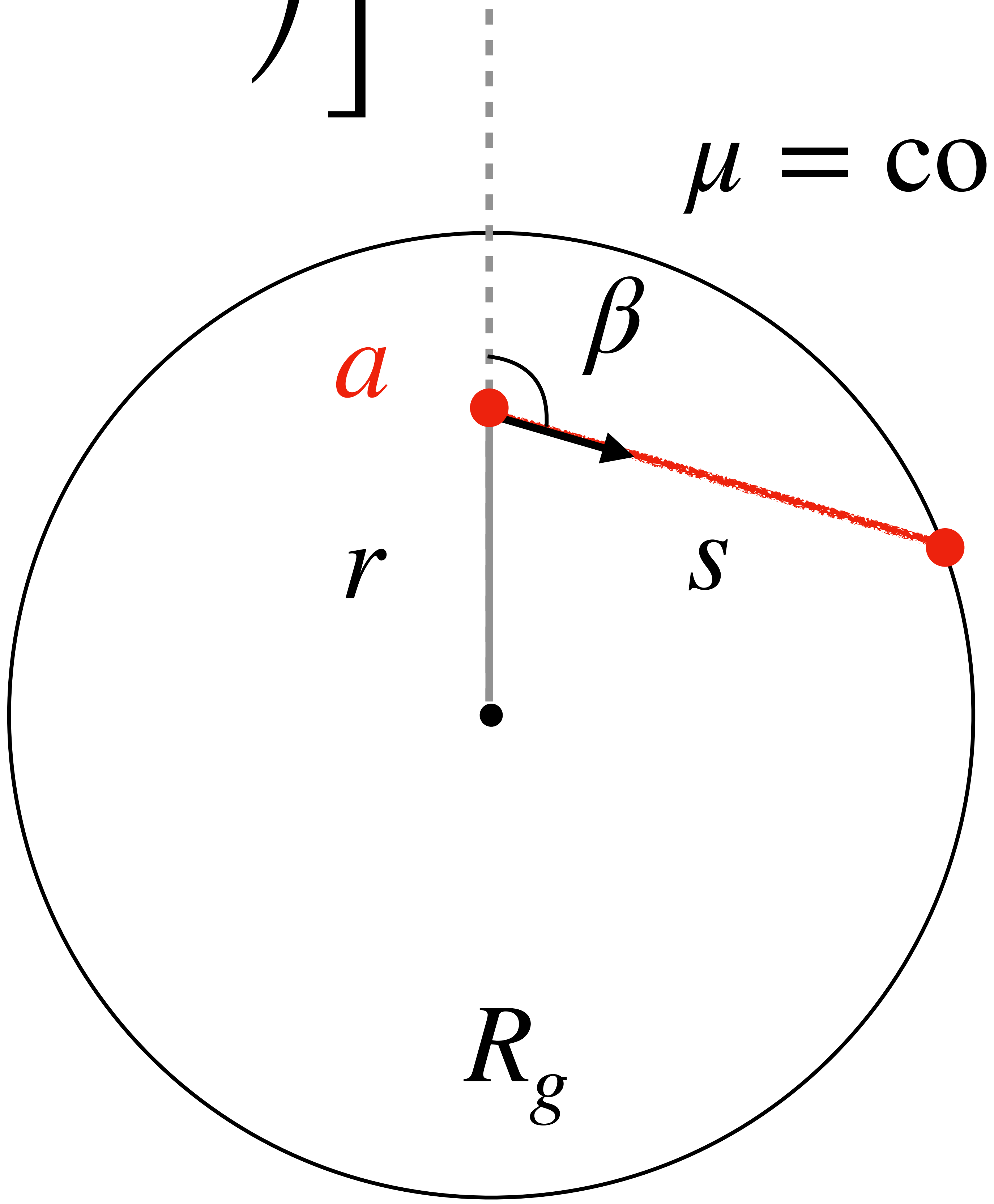
$$\langle e^{-\tau_a(R_g,E_a,r)} \rangle = \int_{-1}^{1} \frac{d\mu}{2} \exp\left[-\int_0^{s_{\max}} \frac{ds}{v}\, \Gamma\left(E_a, \sqrt{r^2+s^2+2rs\mu}\right)\right]$$

$\Gamma = \Gamma_A - \Gamma_E$ with Γ_A (Γ_E) = absorption (emission) rate

r = axion production point

s = axion propagation distance between r and R_g

β = angle between trajectory & radial direction



[see e.g., Caputo, Raffelt, Vitagliano, 2204.11862]

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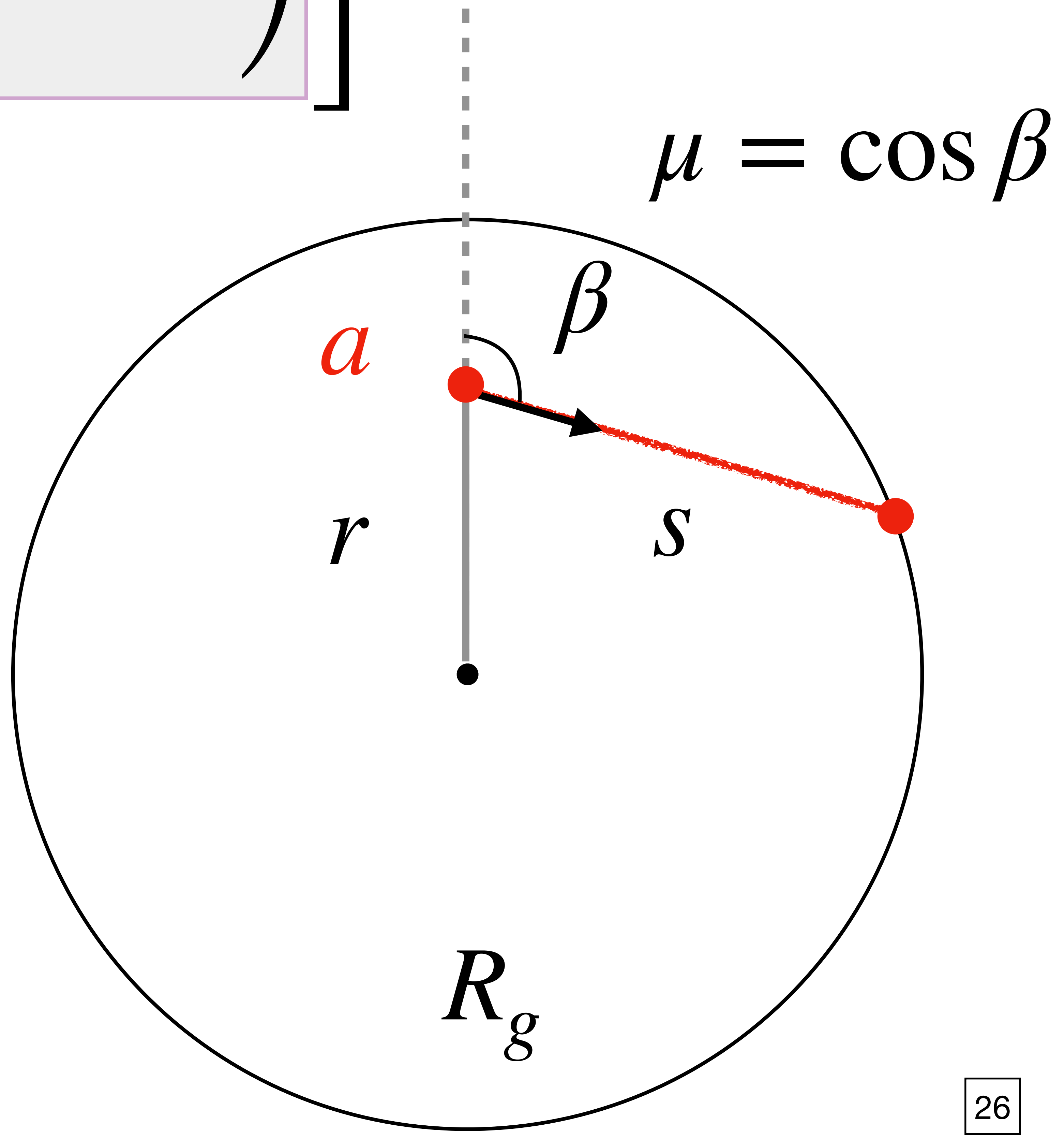
$$\langle e^{-\tau_a(R_g,E_a,r)}\rangle = \int_{-1}^{1}\frac{d\mu}{2}\exp\left[-\int_0^{s_{\max}}\frac{ds}{v}\,\Gamma\left(E_a,\sqrt{r^2+s^2+2rs\mu}\right)\right]$$

optical depth



$\Gamma = \Gamma_A - \Gamma_E$ with Γ_A (Γ_E) = absorption (emission) rate

r = axion production point

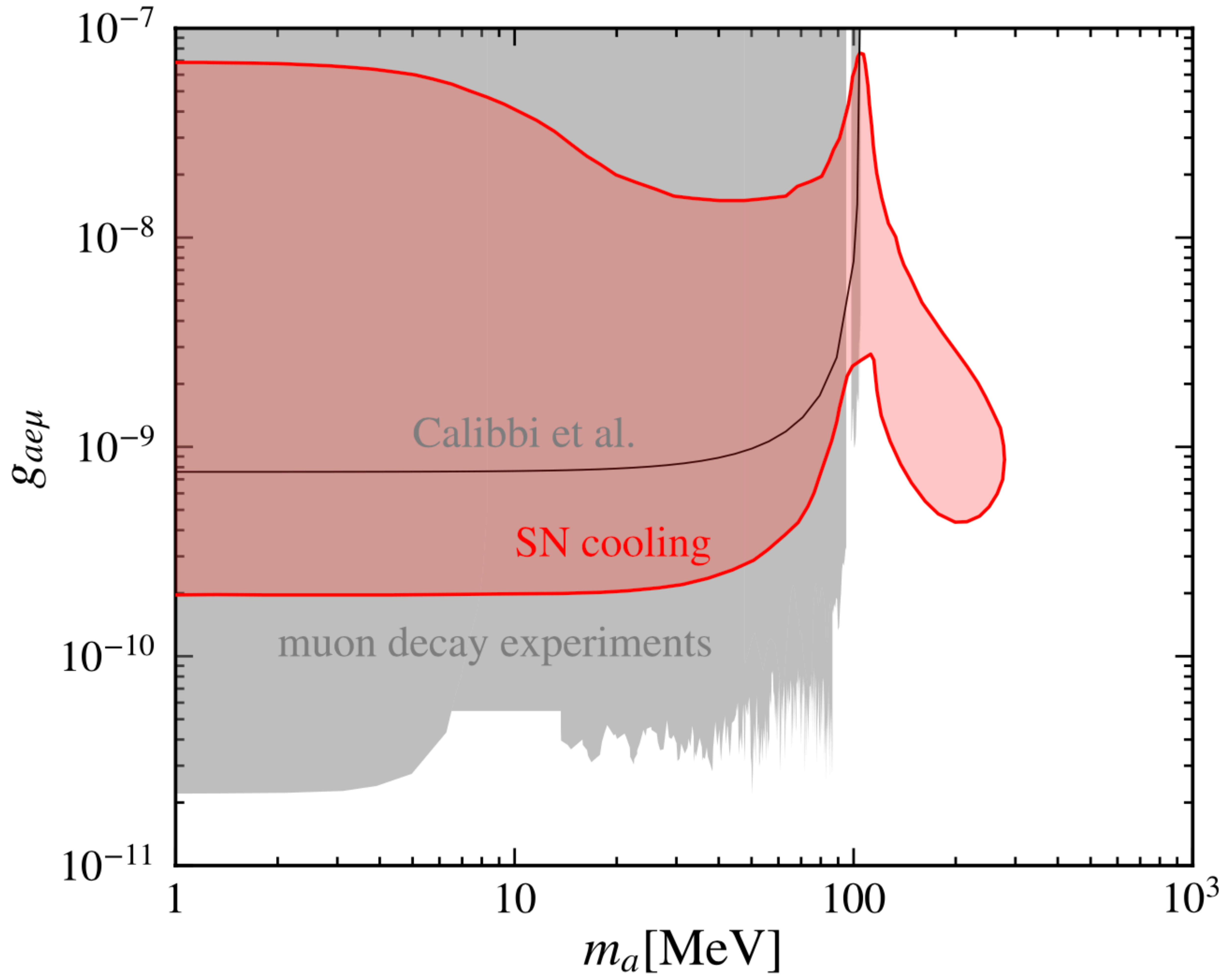
s = axion propagation distance between r and R_g

β = angle between trajectory & radial direction

[see e.g., Caputo, Raffelt, Vitagliano, 2204.11862]

SN cooling limit

Supernova cooling limit on LFV axions



our newly proposed e-mu coalescence channel (for $m_a > m_e + m_\mu$) probes new para space for $m \gtrsim$ 115 MeV

our analysis also improves SN limits for $m \lesssim$ 115 MeV (in part because of more accurate SN profiles)

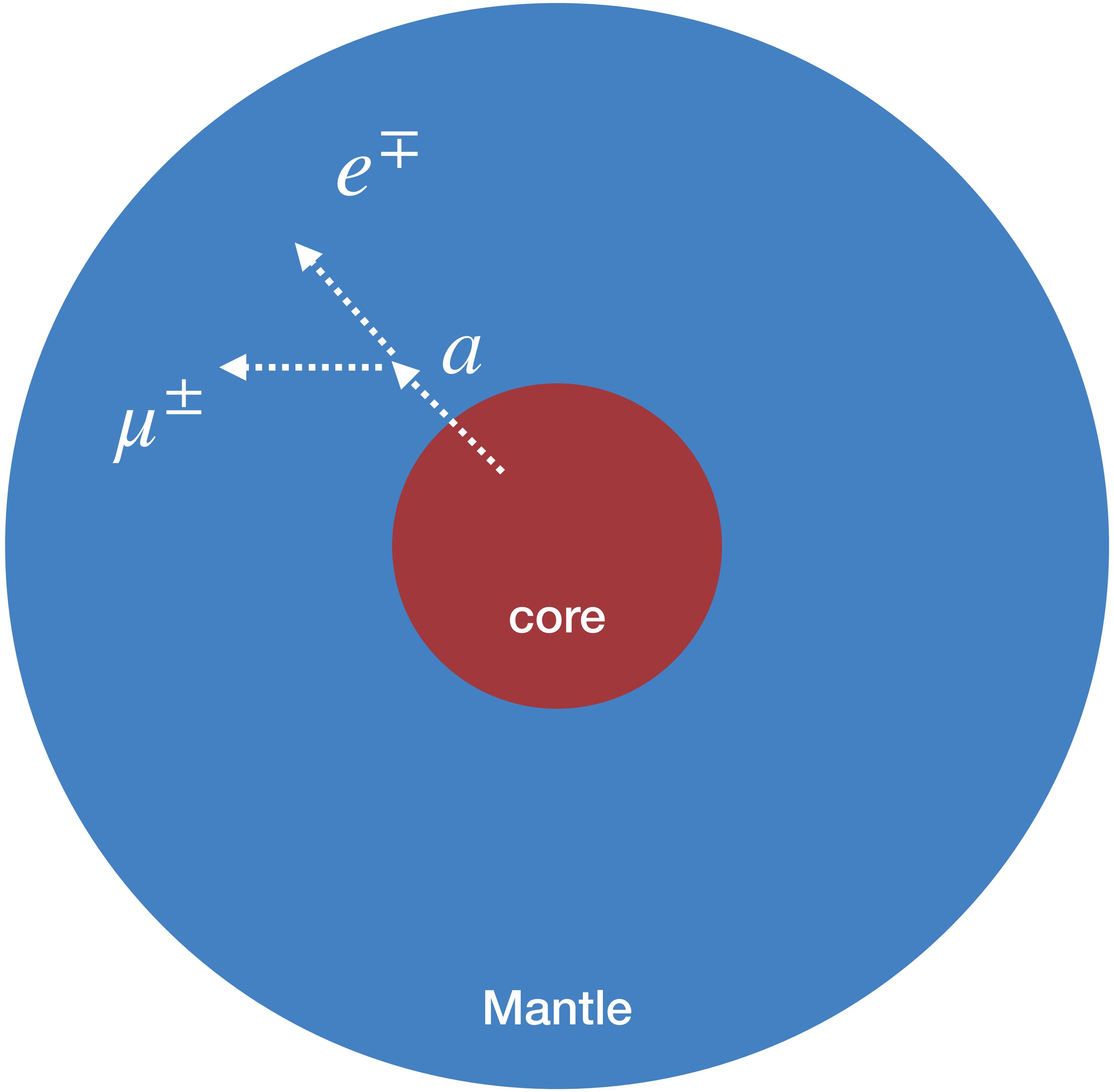
strong rare muon decay constraints for mass below the muon mass: $\mu \to ae$

[Li, ZL, 2501.12075]

4

Low-energy SN (LESN) constraints on lepton-flavor-violating axions/ALPs

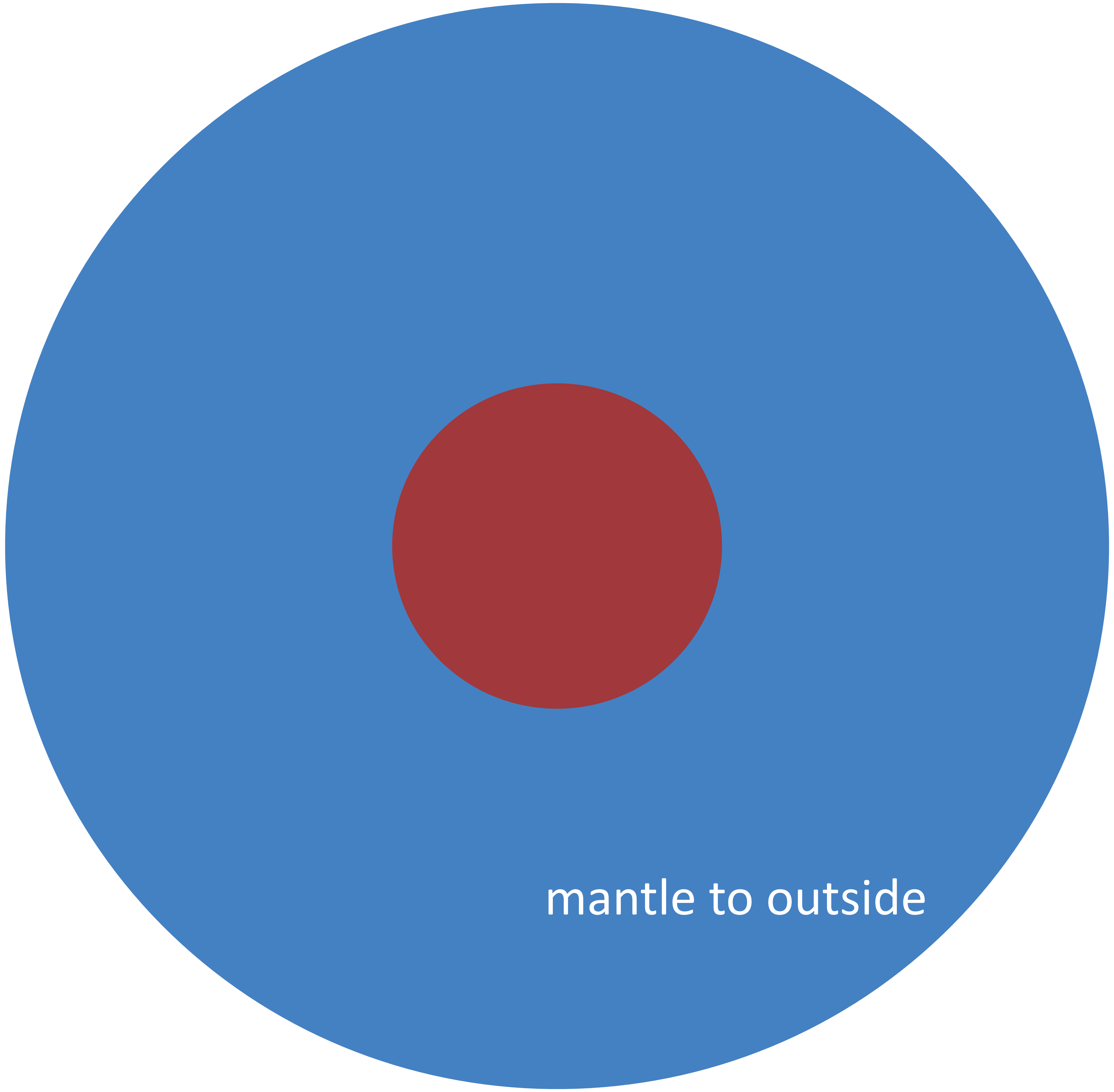
Low-energy supernova (LESN) constraints



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

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

Energy transfers between core and mantle



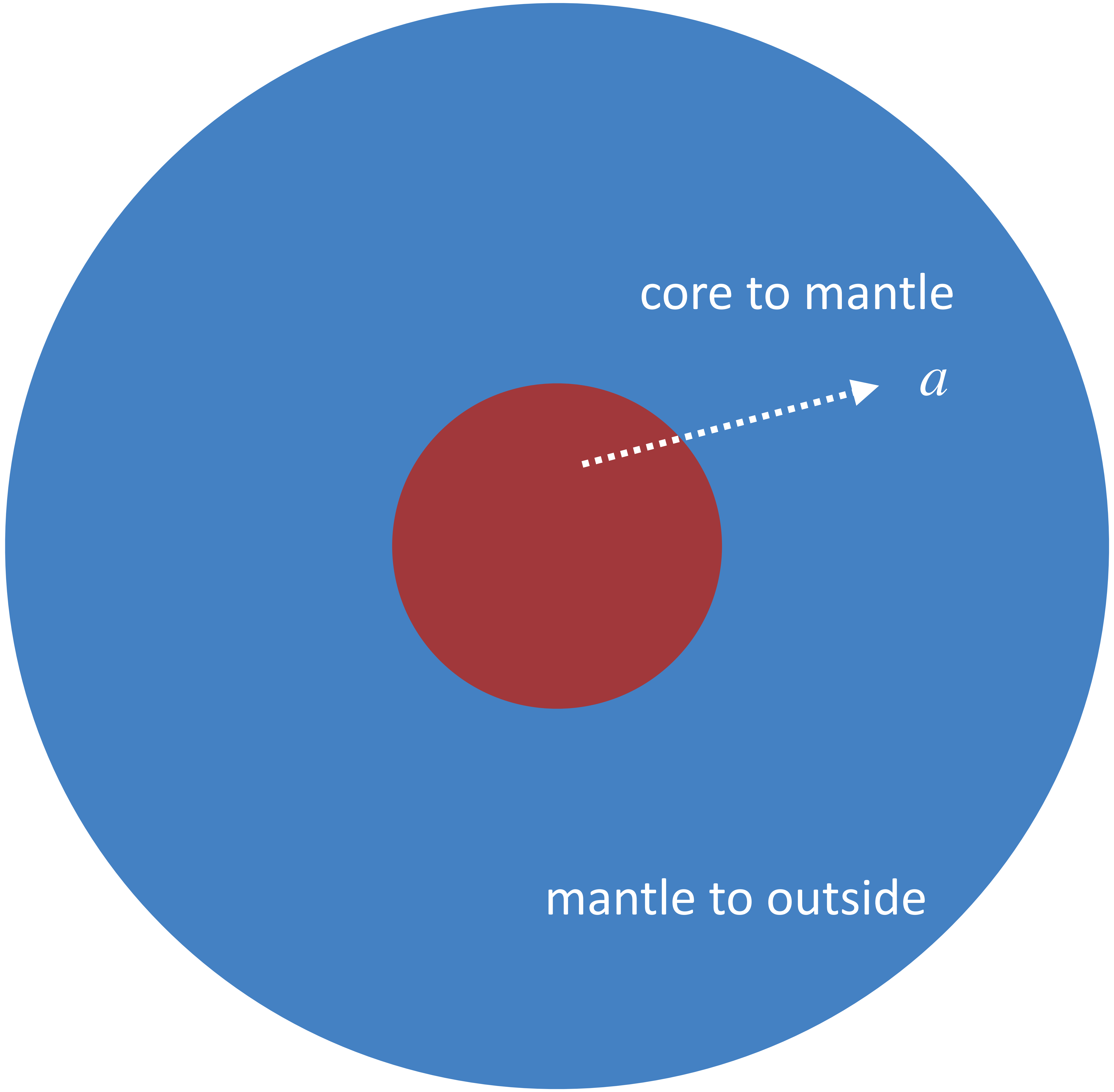
net energy deposition in the mantle

consists of 3 terms:

[Fiorillo, Pitik, Vitagliano, 2503.13653]

[Huang, Li, ZL, 2510.22523]

Energy transfers between core and mantle



net energy deposition in the mantle

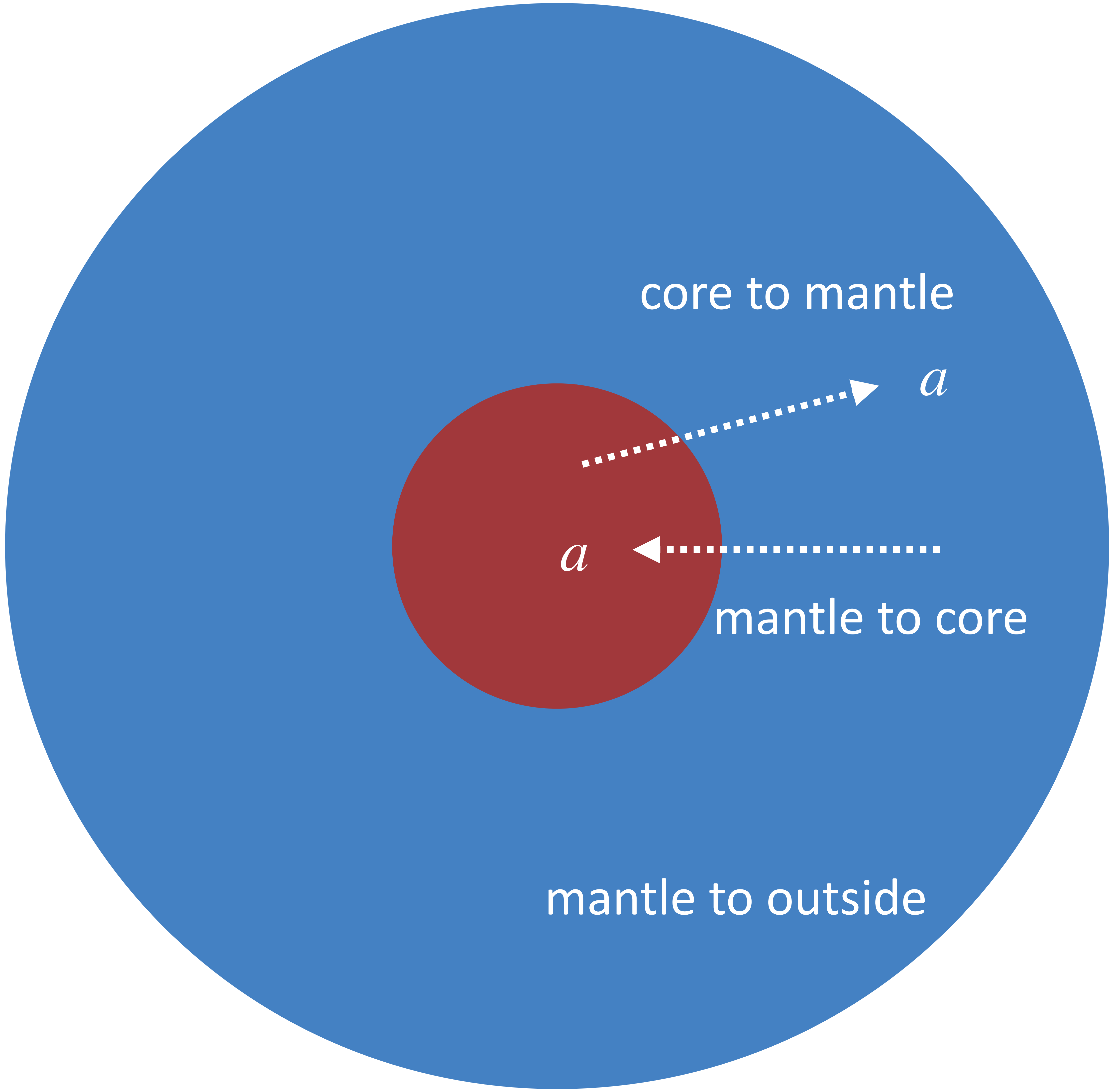
consists of 3 terms:

[1] energy transfer from core to mantle

[Fiorillo, Pitik, Vitagliano, 2503.13653]

[Huang, Li, ZL, 2510.22523]

Energy transfers between core and mantle



net energy deposition in the mantle

consists of 3 terms:

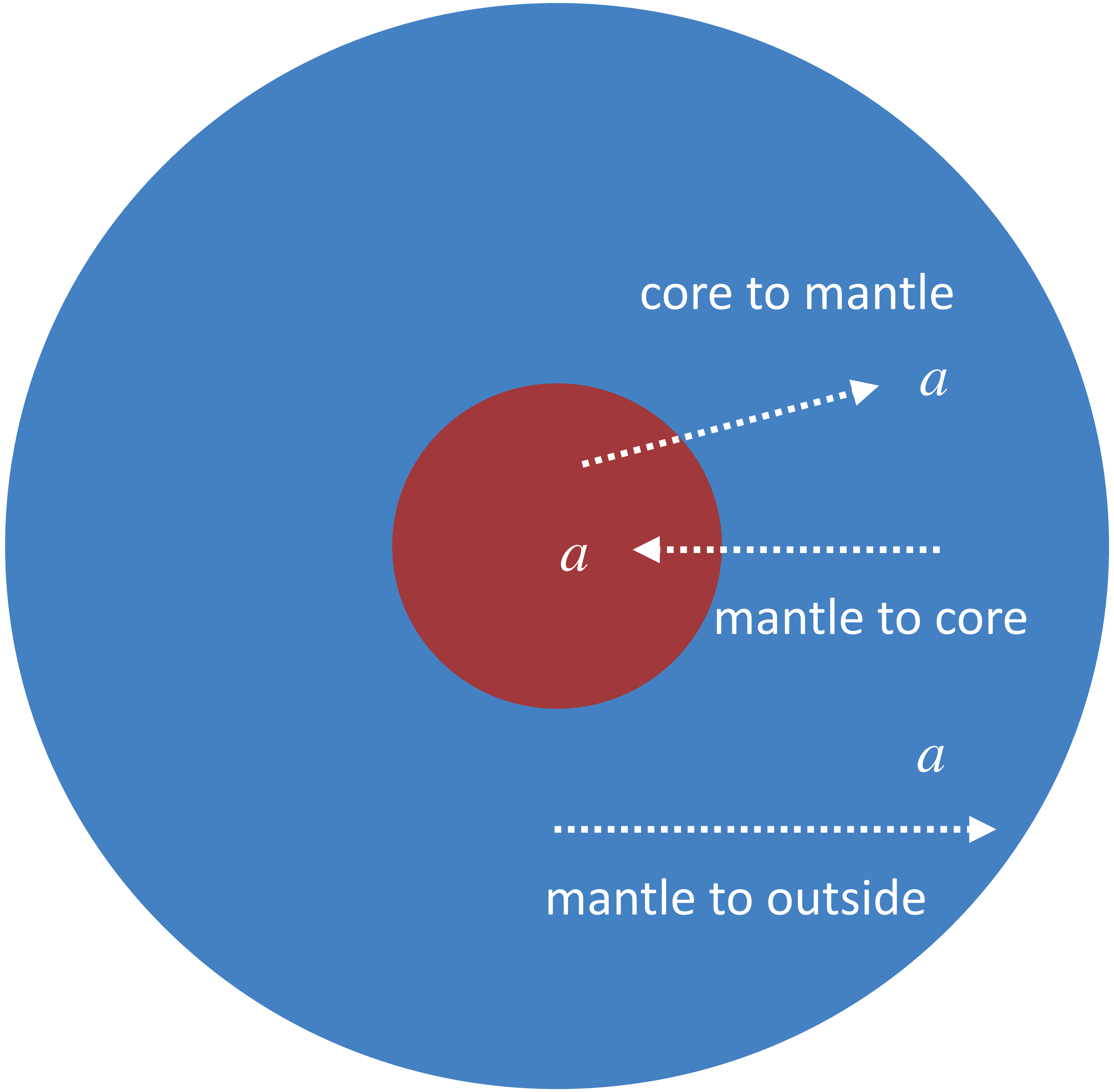
[1] energy transfer from core to mantle

[2] energy transfer from mantle to core

[Fiorillo, Pitik, Vitagliano, 2503.13653]

[Huang, Li, ZL, 2510.22523]

Energy transfers between core and mantle



net energy deposition in the mantle

consists of 3 terms:

[1] energy transfer from core to mantle

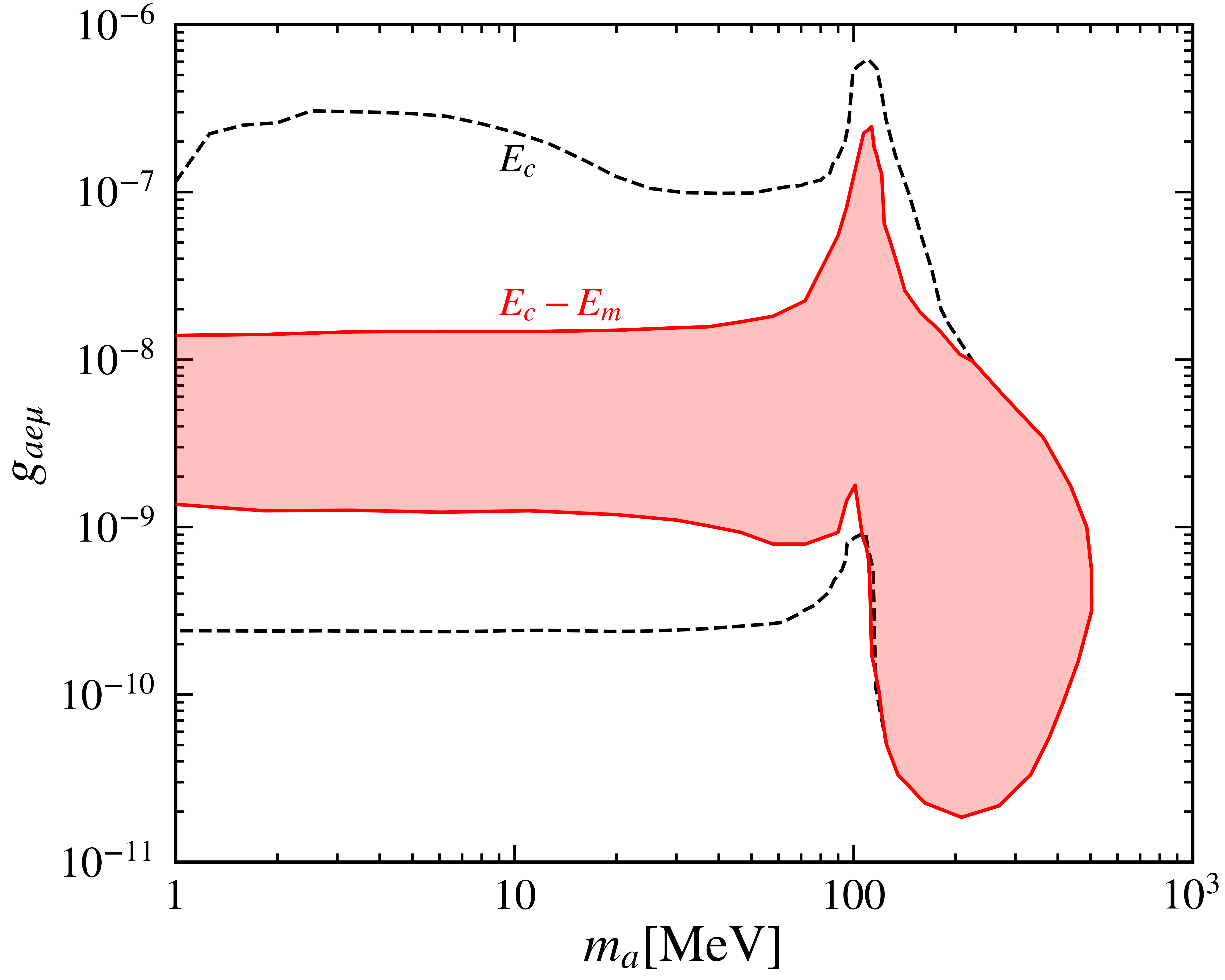
[2] energy transfer from mantle to core

[3] energy escaping progenitor from mantle

[Fiorillo, Pitik, Vitagliano, 2503.13653]

[Huang, Li, ZL, 2510.22523]

Effects due to energy drain from the mantle



dashed E_c: core to mantle only [1]

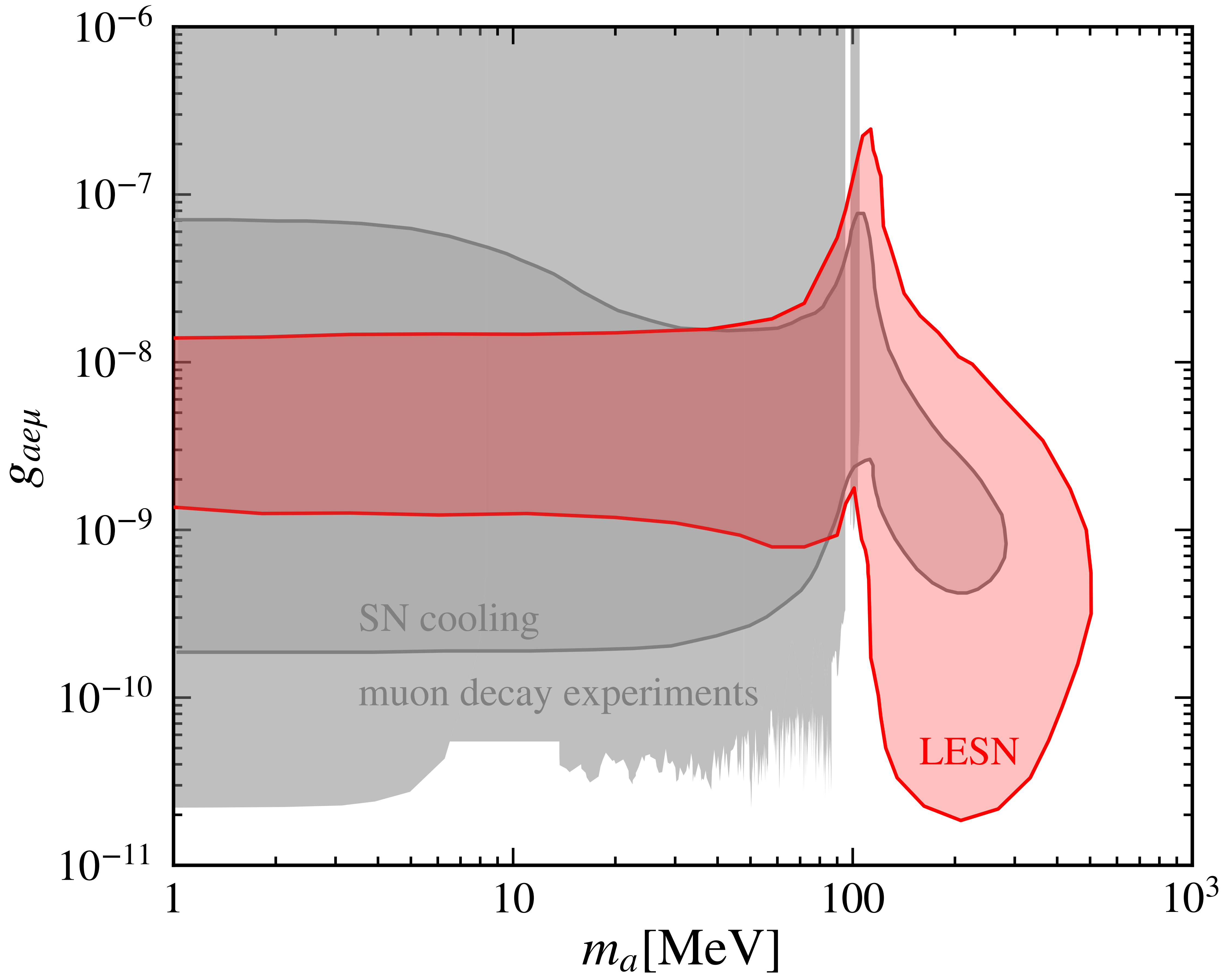
solid $E_c - E_m$:
mantle production included

[1] [2] [3] all included

energy drain from the mantle are significant for low masses for both strong & weak couplings (tree level decay closed); negligible for heavy masses (decay quickly)

[Huang, Li, ZL, 2510.22523]

LESN constraints on LFV ALPs



LESN is weaker than SN cooling for low masses for both strong & weak couplings

LESN is stronger than SN cooling for heavy masses

[Huang, Li, ZL, 2510.22523]

Summary

- We compute supernova cooling limits and low-energy supernova (LESN) constraints on electron-muon flavor violating axions/ALPs

- We compute the axion production (& absorption) by taking into account new channels including e-mu coalescence and semi-Compton, which dominate the heavy and intermediate axion mass regions.

- Our analysis takes into account energy drain from the mantle

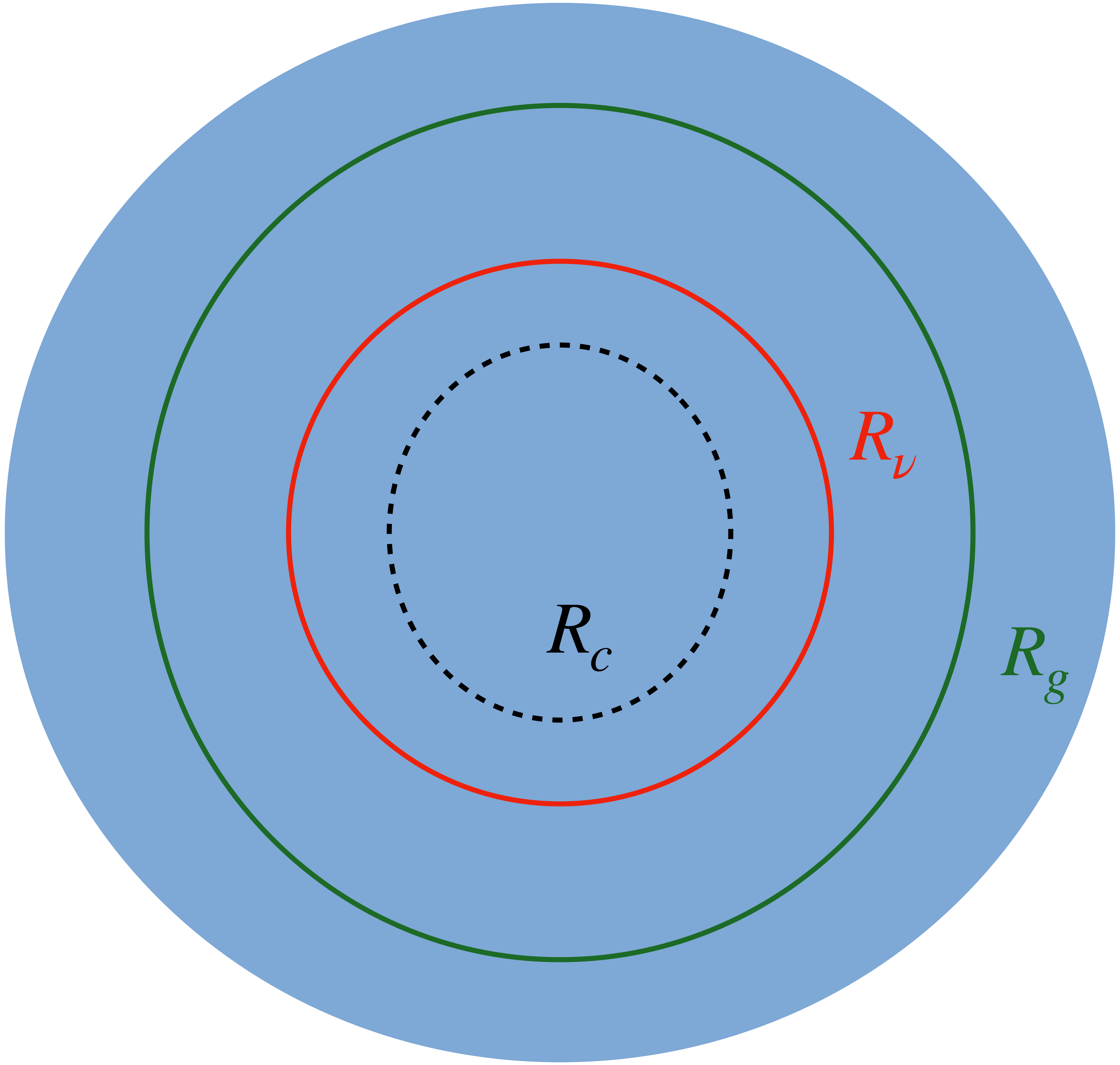
- The e-mu coalescence & semi-Compton channels probe new parameter space

  - 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] [Huang, Li, ZL, 2510.22523]

additional slides

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: production & absorption

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

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

Axion luminosity: production & absorption

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

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

↓ differential production rate

differential production rate = # of axion produced per unit volume,

per unit time, per unit energy

Axion luminosity: production & absorption

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

absorption term

differential production rate

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

differential production rate = # of axion produced per unit volume, per unit time, per unit energy

absorption term = probability for an axion produced at r with energy E_a to escape the gain radius

Absorption rate in terms of production rate

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

Absorption rate in terms of production rate

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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

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

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

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

absorption rate in terms of production rate

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

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

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

Axion production for electron-muon coalescence

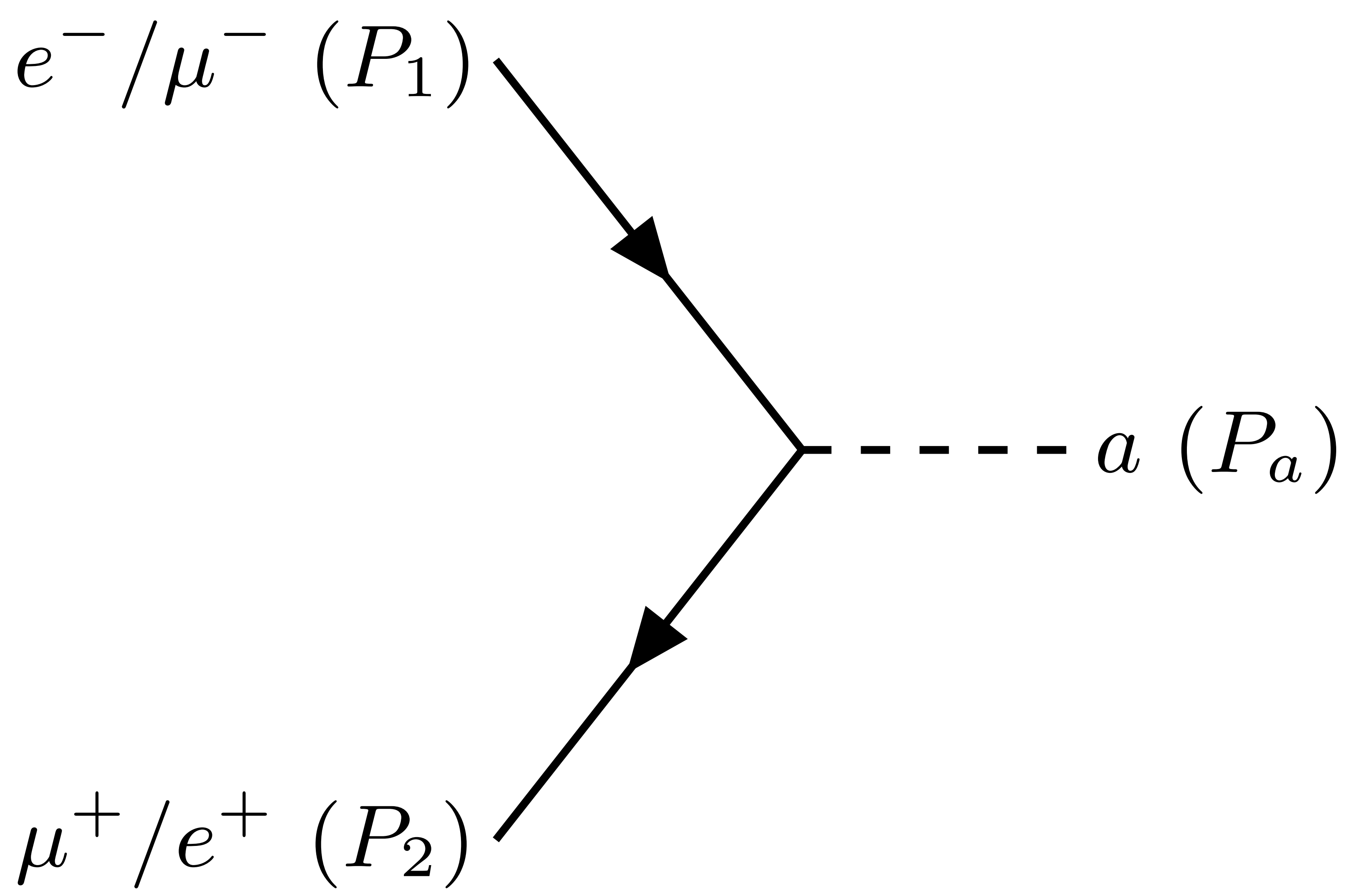
$$\frac{d^2 n_c}{dt dE_a} = \frac{\left|\mathscr{M}_c\right|^2}{32\pi^3} \int_{E_2^-}^{E_2^+} dE_2 \, (f_\mu f_e^+ + f_e f_\mu^+),$$

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

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

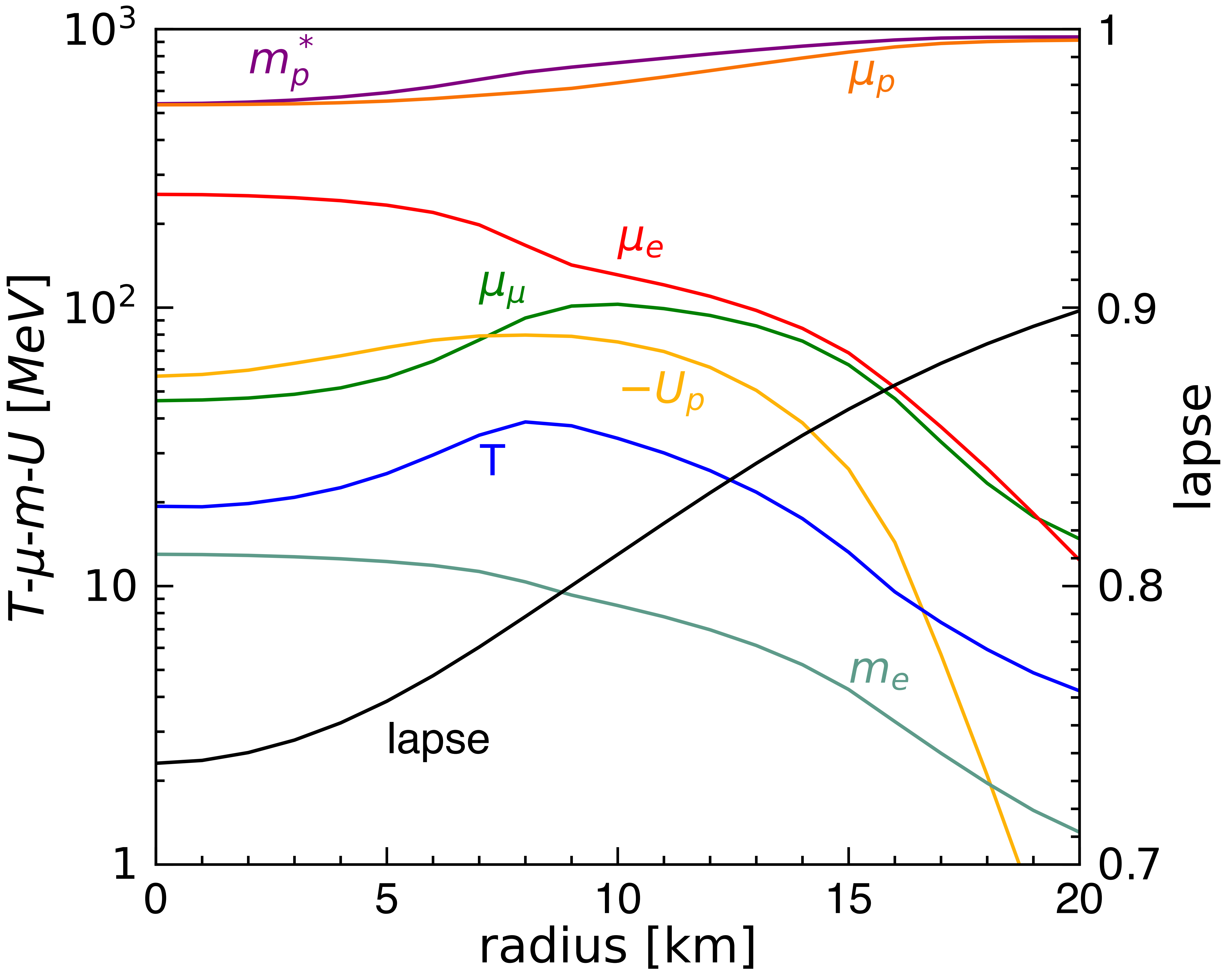
$$I = \sqrt{(m_1^2 - m_2^2 - m_a^2)^2 - 4 m_2^2 m_a^2}$$

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



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

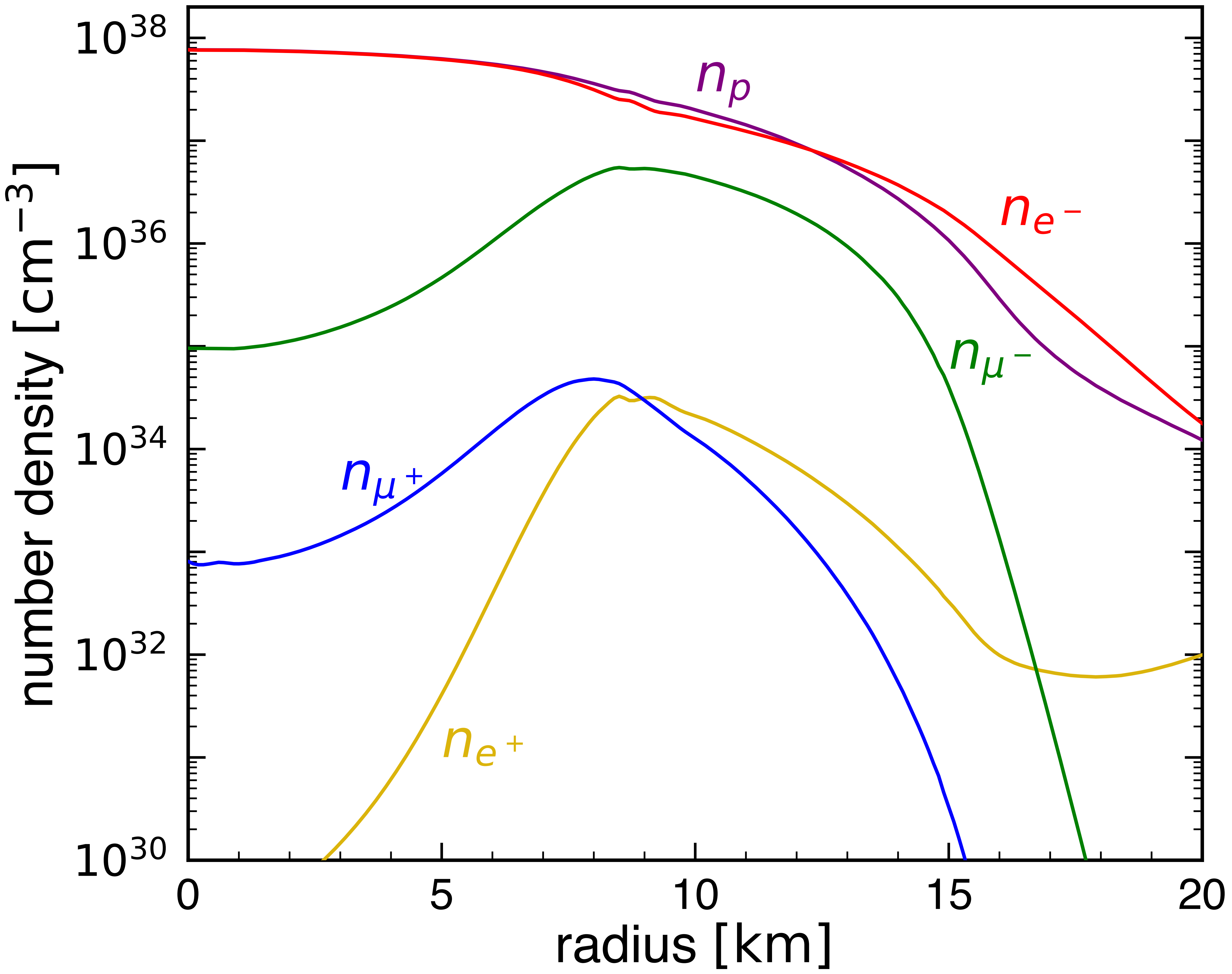
The SFHo-18.8 SN profile



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

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

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

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

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]

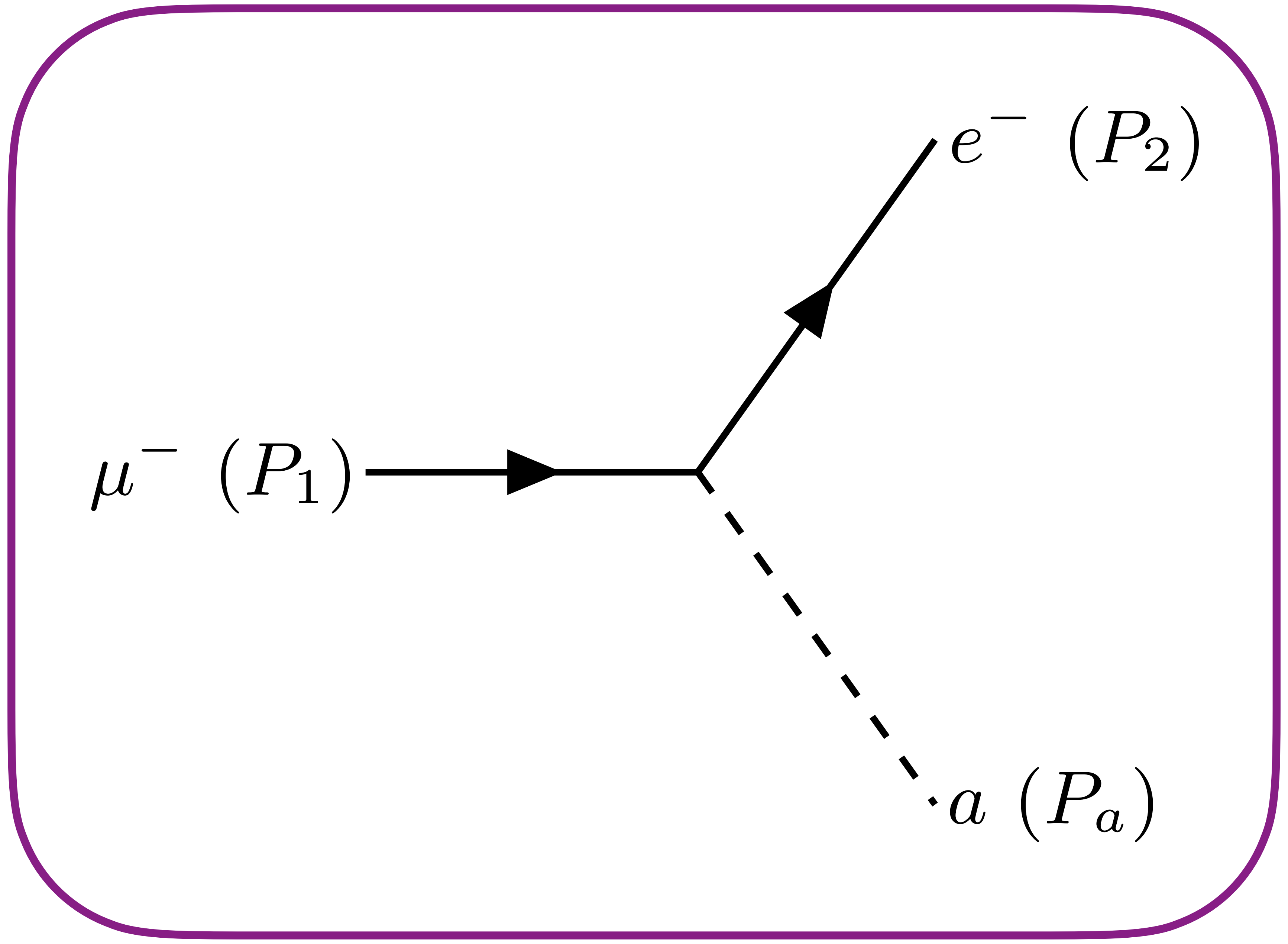
The coldest model simulated by Bollig et al. [R. Bollig et al., 2005.07141]

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

Experimental constraints

Rare muon decay constraints

- Derenzo — [Derenzo, '69]
- Jodidio et al. — [Jodidio et al., '86]
- Bilger et al. — [Bilger et al., '99]
- TWIST — [TWIST Collaboration, 1409.0638]
- PIENU — [PIENU Collaboration, 2002.09710]
- Mu3e — [Knapen, Langhoff, Opferkuch, Redigolo, 2311.17915]



Collider constraints on LFV axions

- Belle II

  [Davoudiasl et al., 2105.05866]

  [Endo, Iguro, Kitahara, 2002.05948]

  [Iguro, Omura, Takeuchi, 2002.12728]

- LHC

  [Araki et al., 2210.12730]

  [Davoudiasl et al., 2105.05866]

- EIC (Electron-Ion Collider)

  [Davoudiasl, Marcarelli, Neil, 2112.04513]

probe strong couplings