

Low-Energy Supernova Constraints on Millicharged Particles

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Outline

- 1 Millicharged particles (MCPs)
- 2 Low-energy supernovae (LESNe)
- 3 MCP production in the SN core
- 4 Energy deposition in the SN mantle
- 5 LESN constraints on MCPs

[Changqian Li, ZL, Wenxi Lu, Zicheng Ye, 2408.04953]

1

Millicharged particles (MCPs)

Millicharged particles (MCPs)

Hidden sector particle χ with a millicharge ϵ under the SM photon A_μ

$$e \epsilon A_\mu \bar{\chi} \gamma^\mu \chi + m_\chi \bar{\chi} \chi$$

- charge quantization
- neutrino millicharge
- dark matter millicharge

[see e.g., PandaX, Nature 23']

Millicharged particle χ in hypercharge portal models

A_μ = SM hypercharge $U(1)_B$ gauge boson; $X_\mu = U(1)_X$ gauge boson

kinetic mixing [Holdom 86'] [Foot & He 91'] mass mixing [Kors & Nath 04']

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[Feldman, ZL, Nath, [hep-ph/0702123](#), 395 cites]

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- (1) kinetic mixing: MCPs appear with a massless dark photon
- (2) mass mixing: MCPs appear with a massive dark photon or Z'

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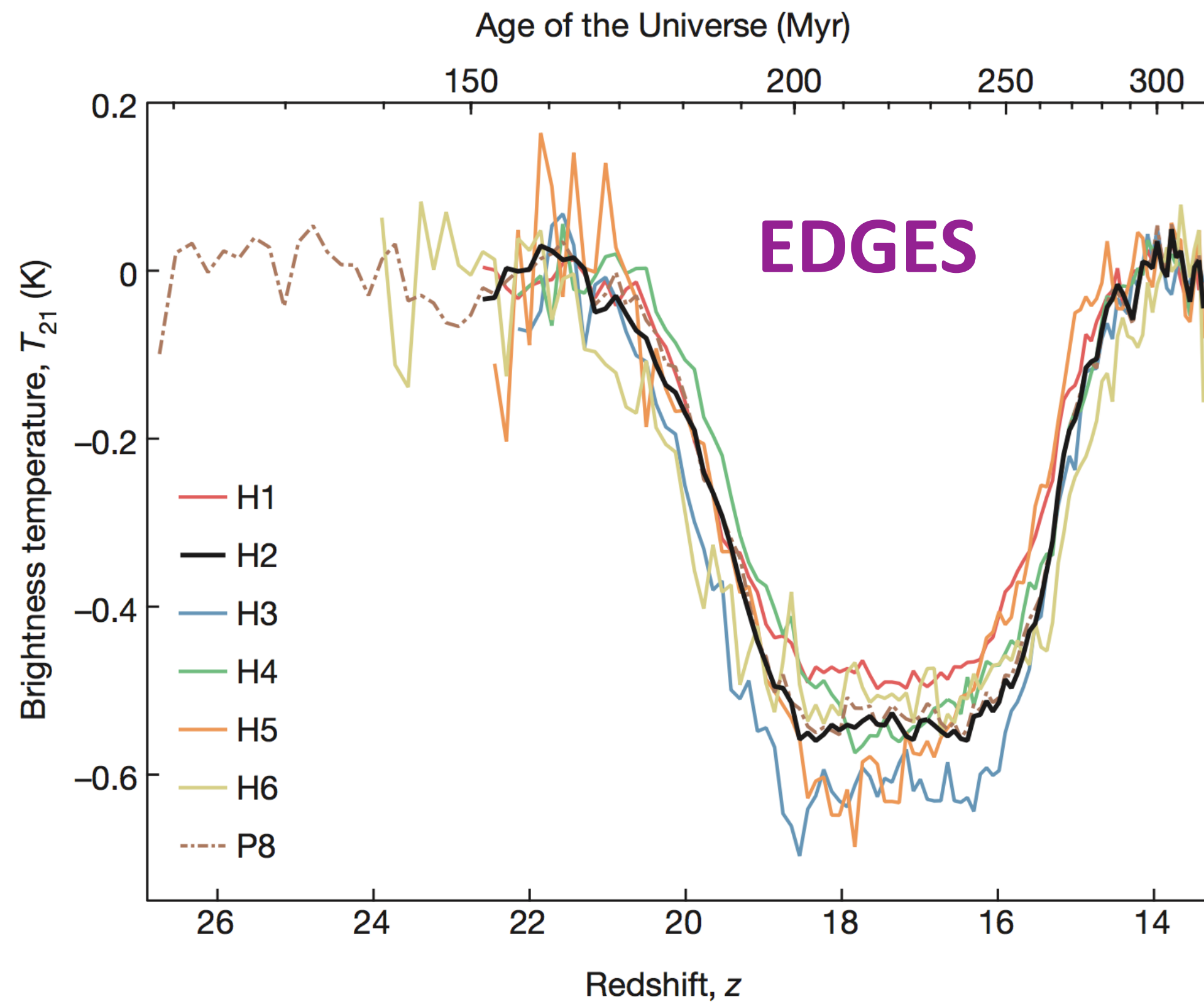
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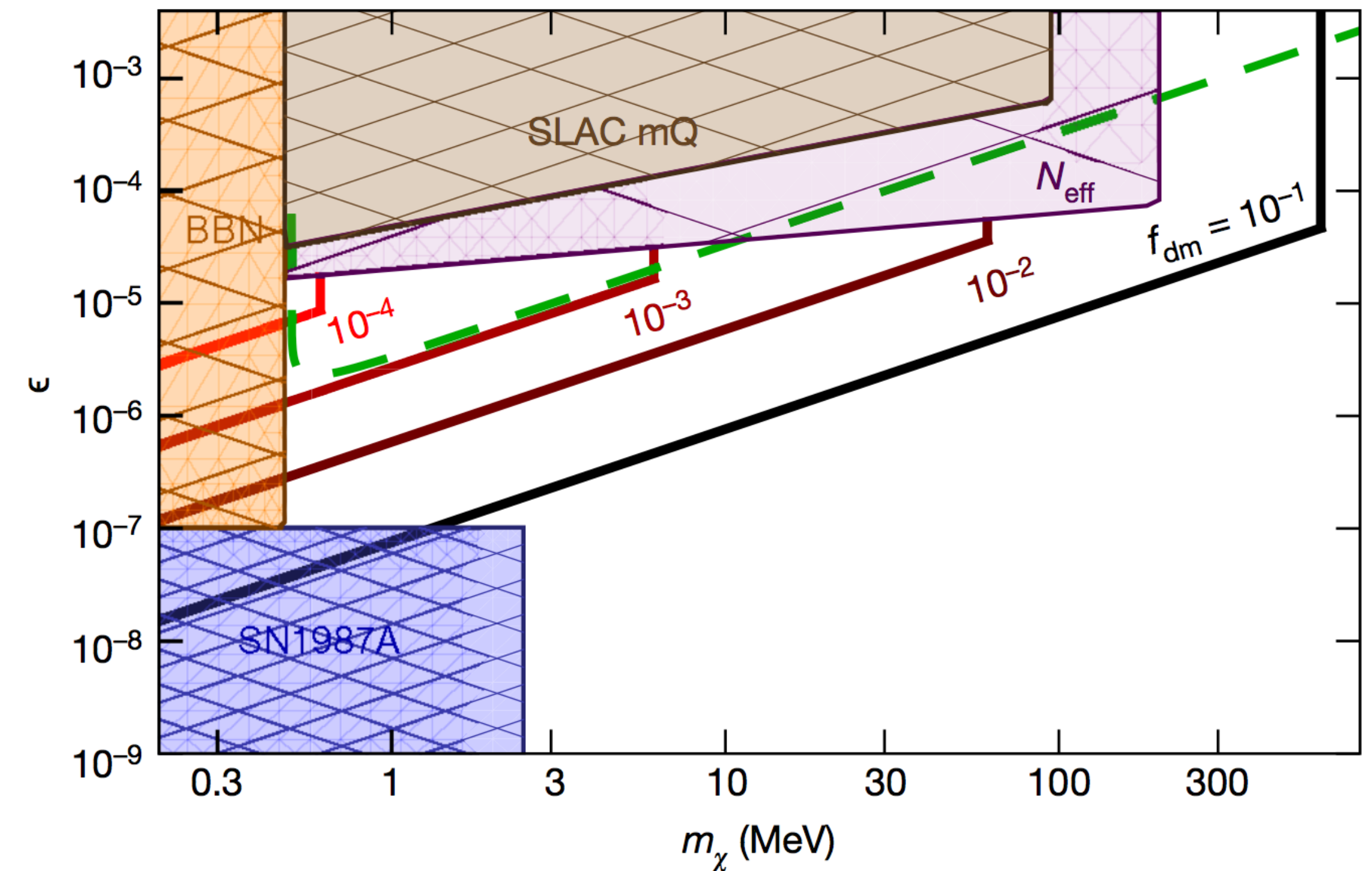
[see also Fabbrichesi+, 2005.01515, Dark Photon Review]

Millicharged dark matter can explain 21 cm anomaly

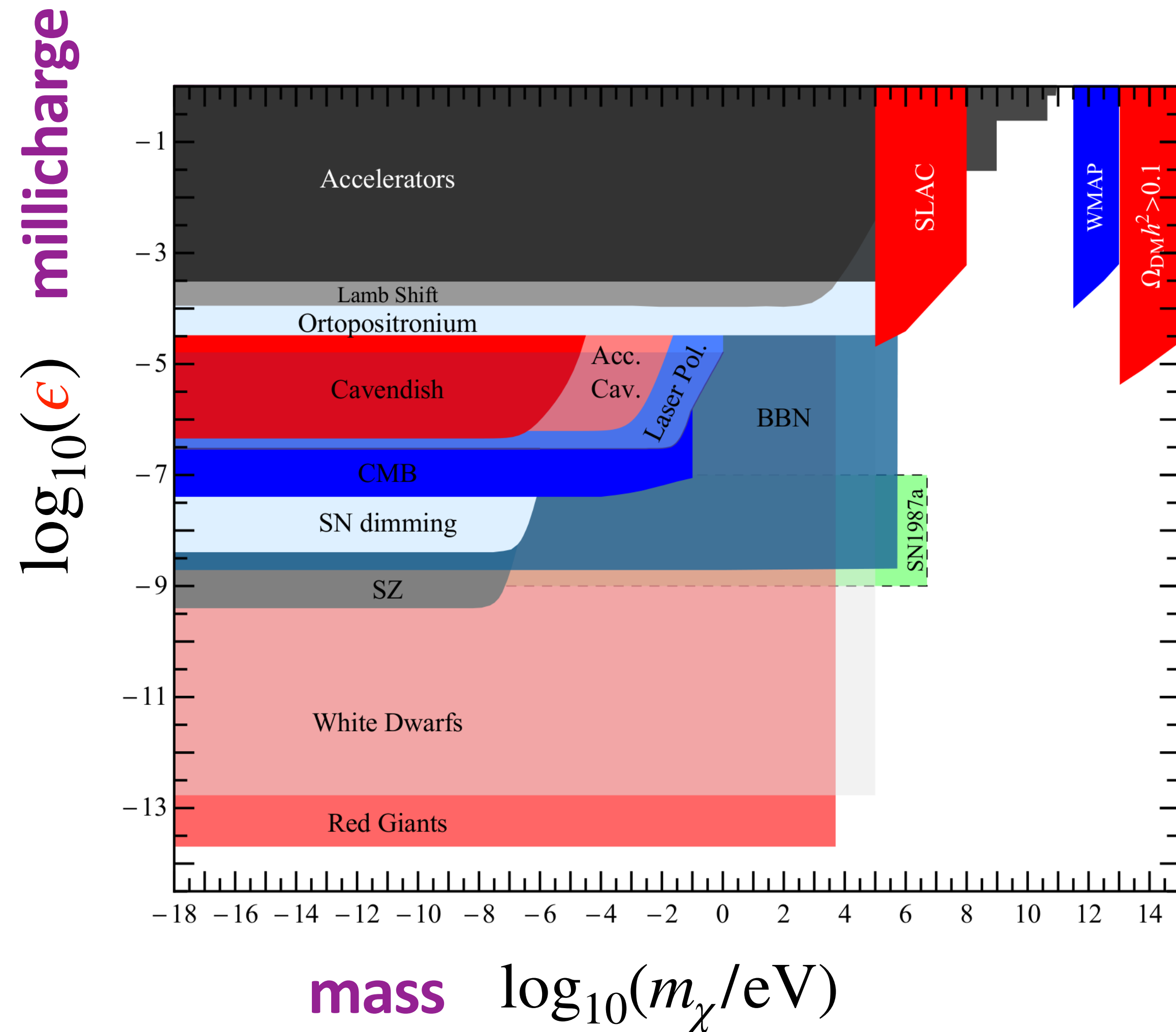
[Bowman+, Nature 18']



[Munoz & Loeb, Nature 18']



Constraints on millicharged particles



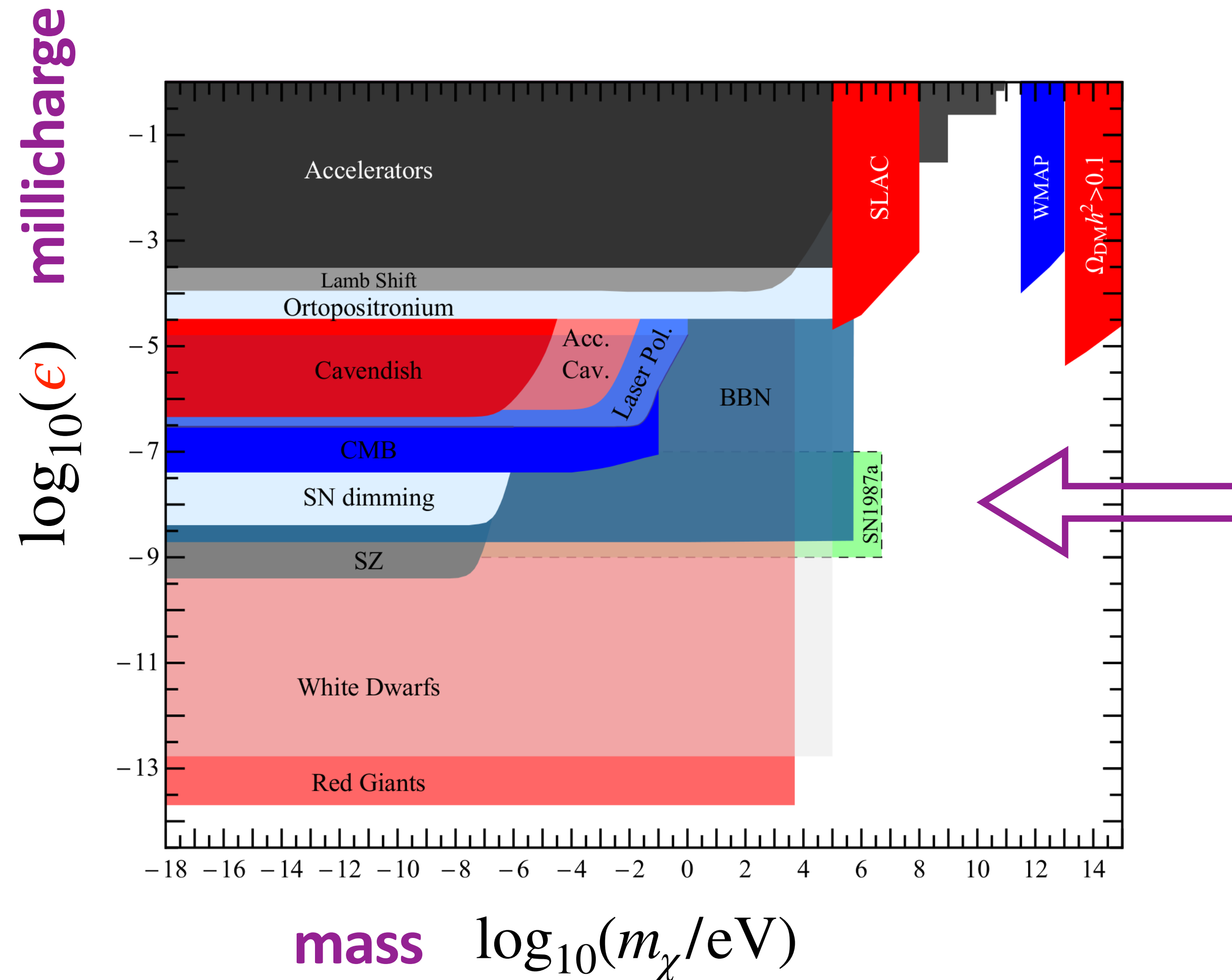
$$e \epsilon A_\mu \bar{\chi} \gamma^\mu \chi + m_\chi \bar{\chi} \chi$$

[Jaeckel & Ringwald, 1002.0329]

high-mass: accelerator

low-mass: stellar cooling

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Supernova constraints

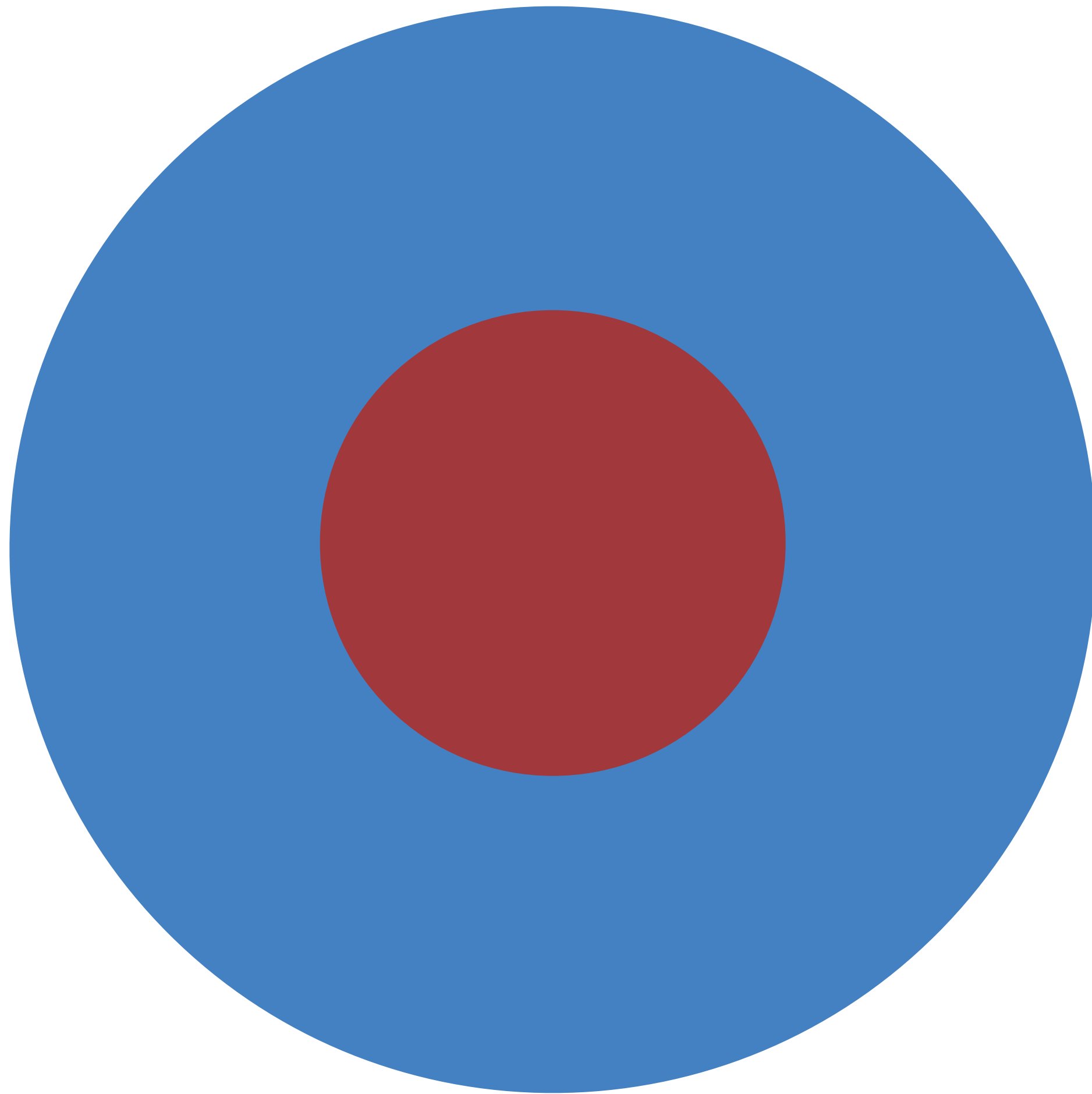
high-mass: accelerator

low-mass: stellar cooling

2

Low-energy supernovae (LESNe)

Supernova cooling limit

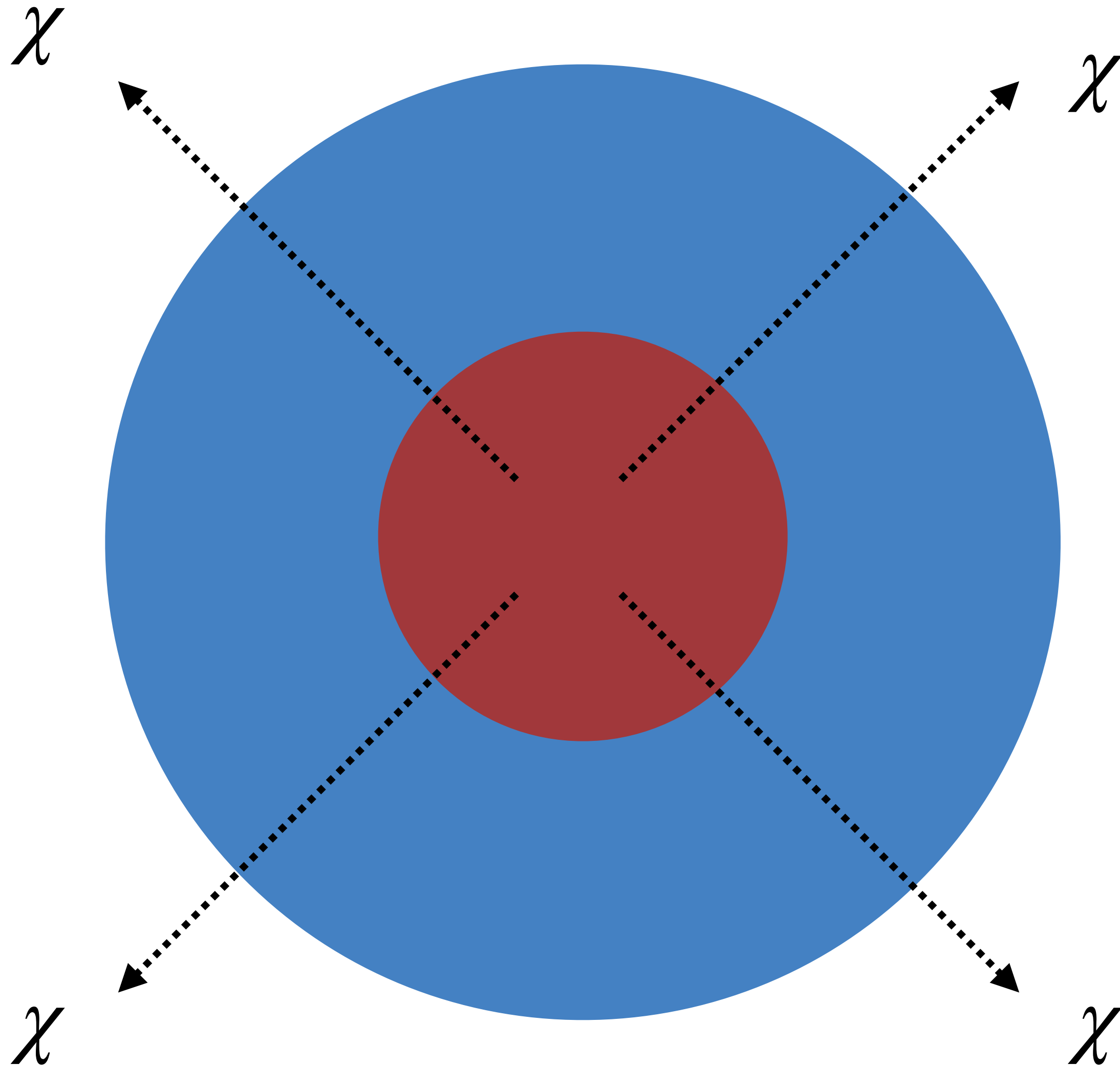


Raffelt criterion

$NP < \text{neutrino}$

[Raffelt, 96']

Supernova cooling limit

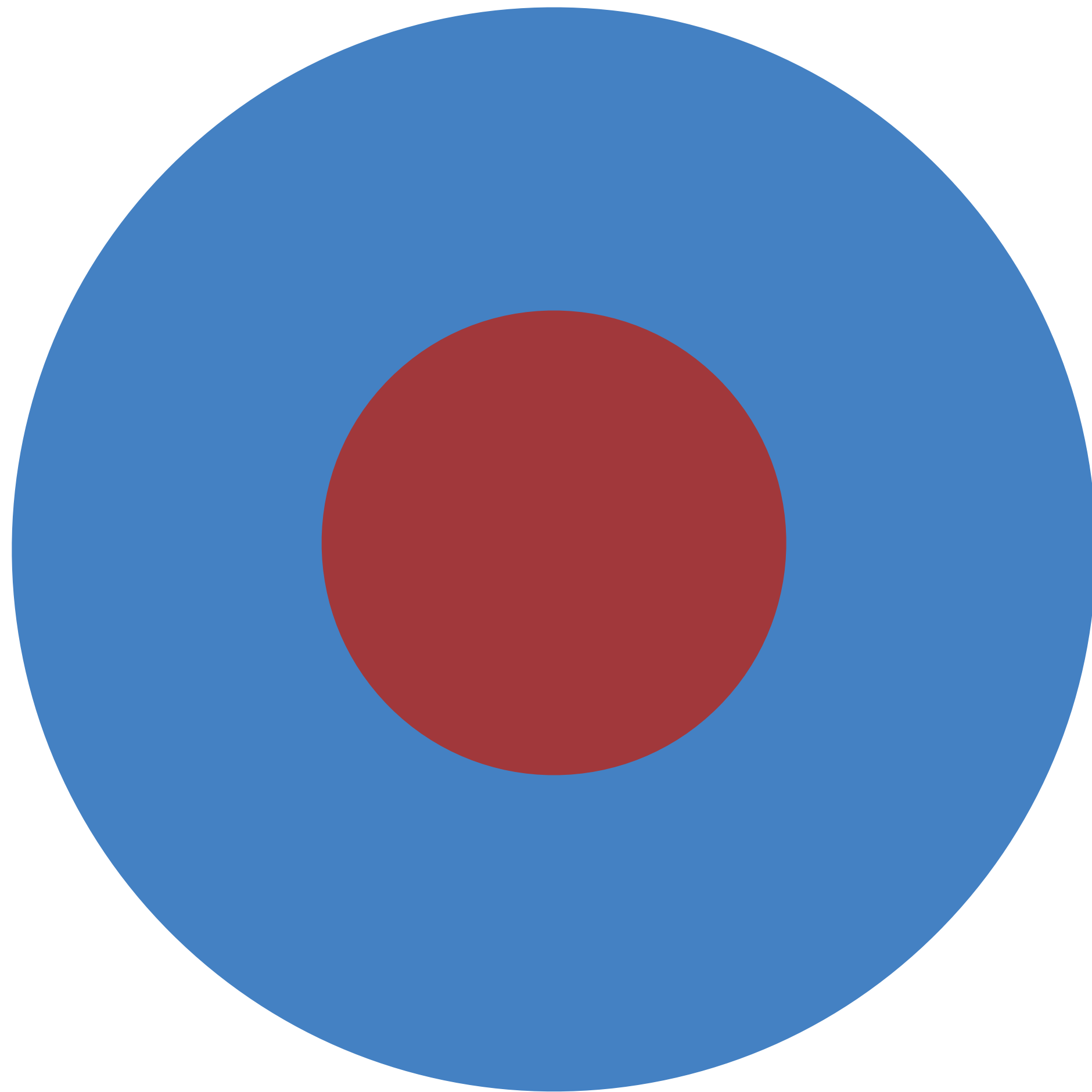


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$NP < \text{neutrino}$

[Raffelt, 96']

Supernova “calorimetric” limit



Energy transfer < explosion energy

[Falk & Schramm, 78']

[Sung+, 1903.07923]

[Caputo+, 2201.09890]

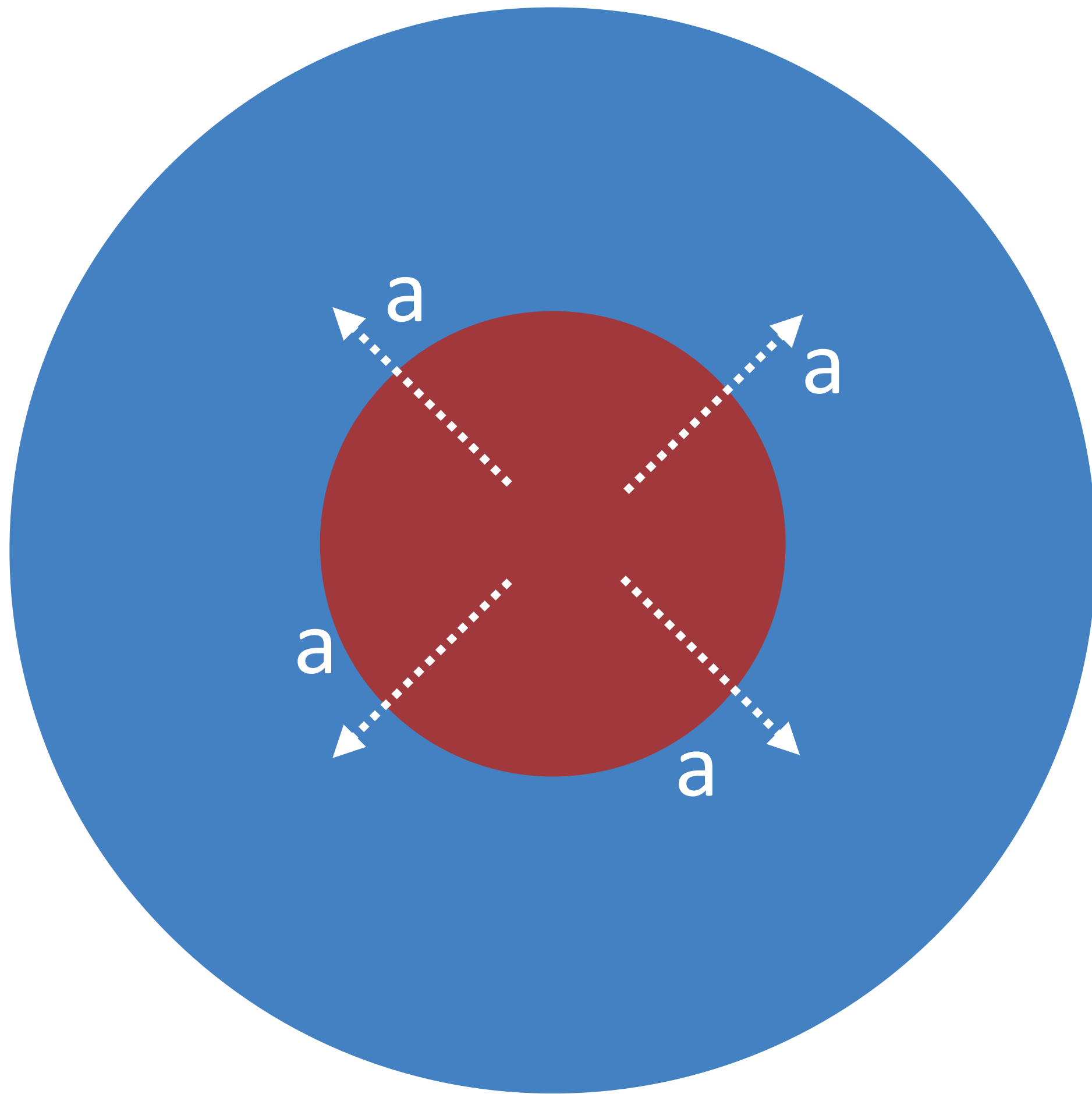
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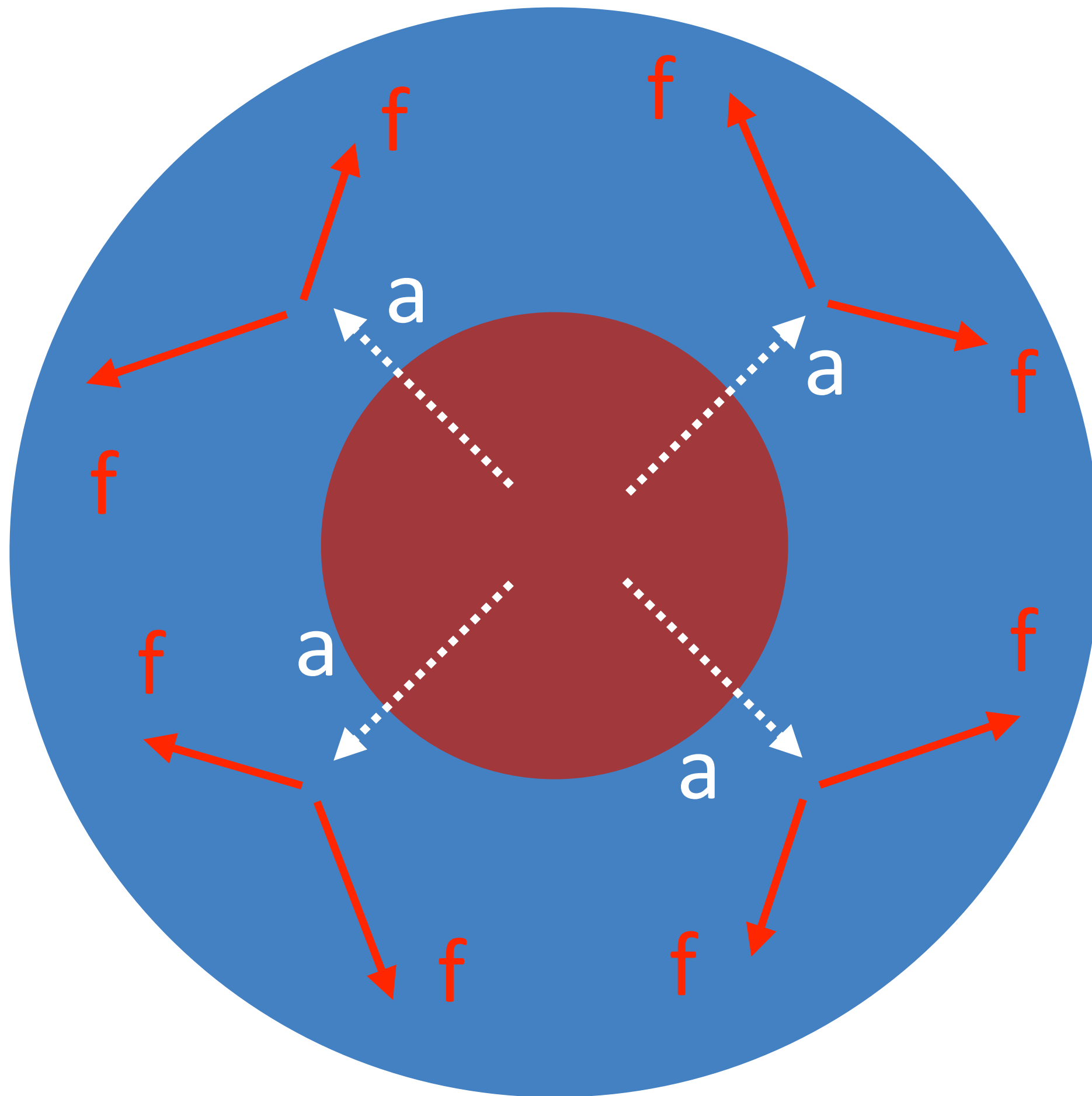
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[Caputo+, 2201.09890]



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

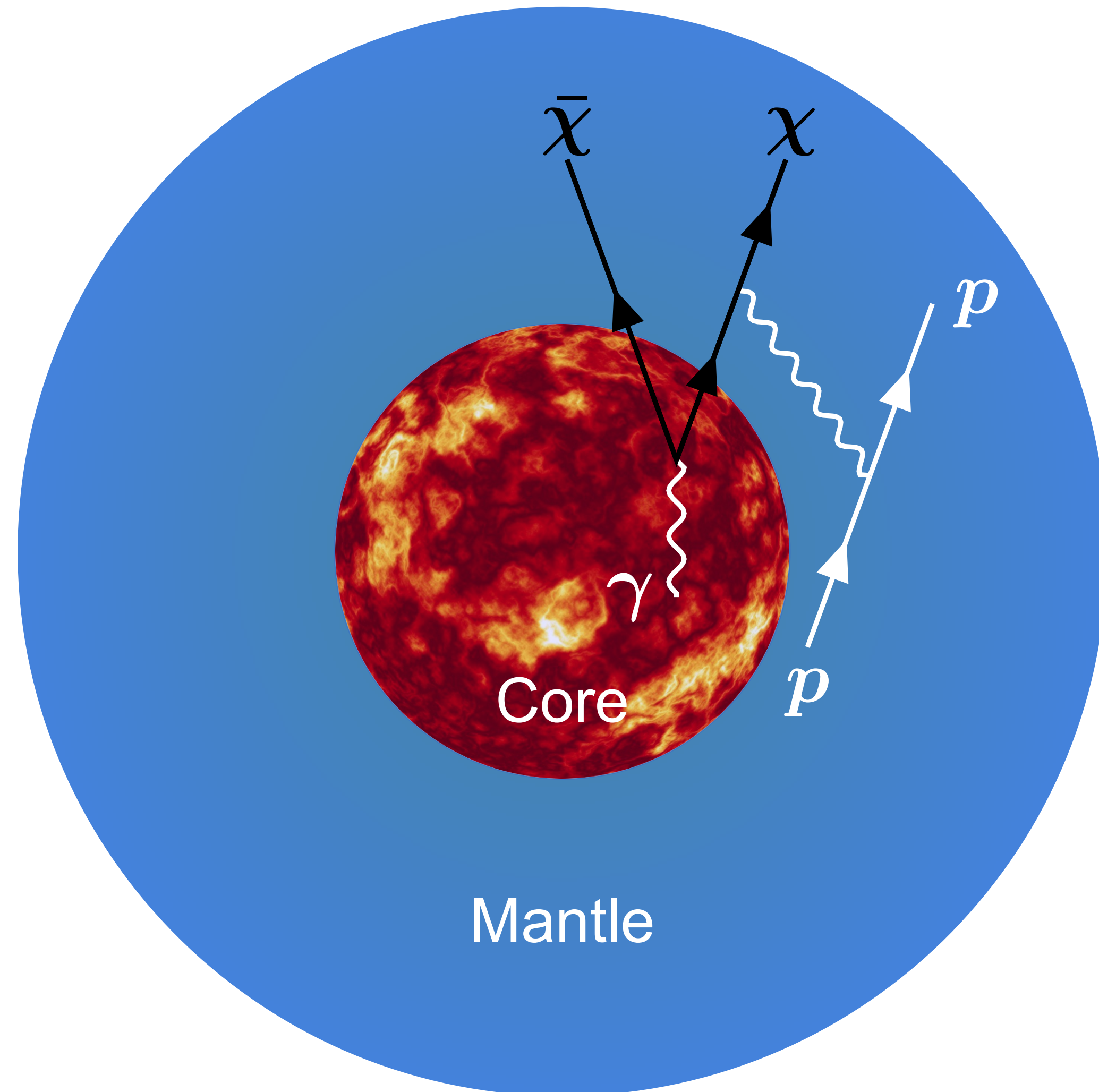
$$B = 10^{51} \text{ erg}$$



[Caputo+, 2201.09890]

[Burrows & Vartanyan, 2009.14157]

LESN constraints on MCPs



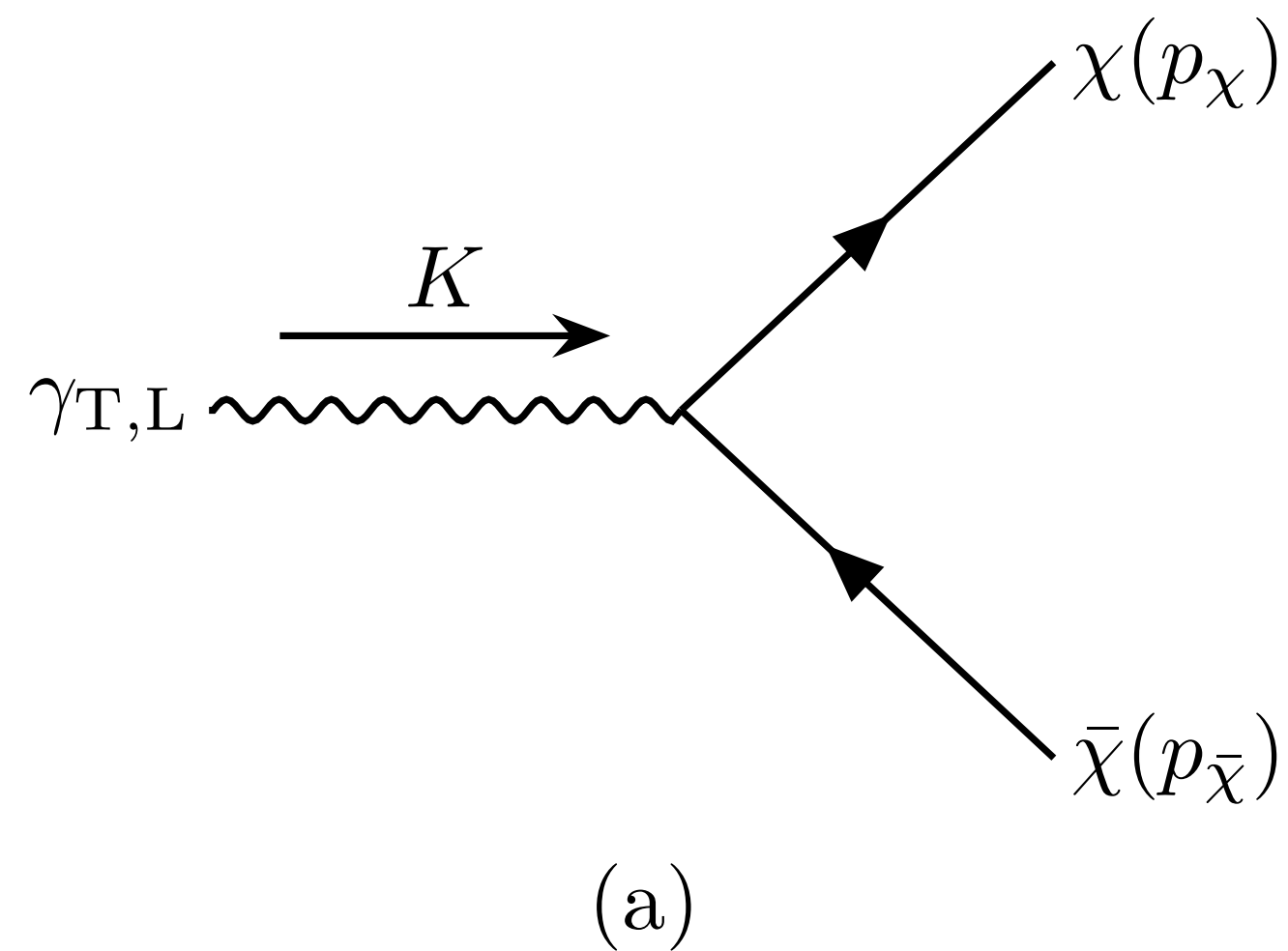
MCPs production in the core

Energy deposition: Coulomb scattering

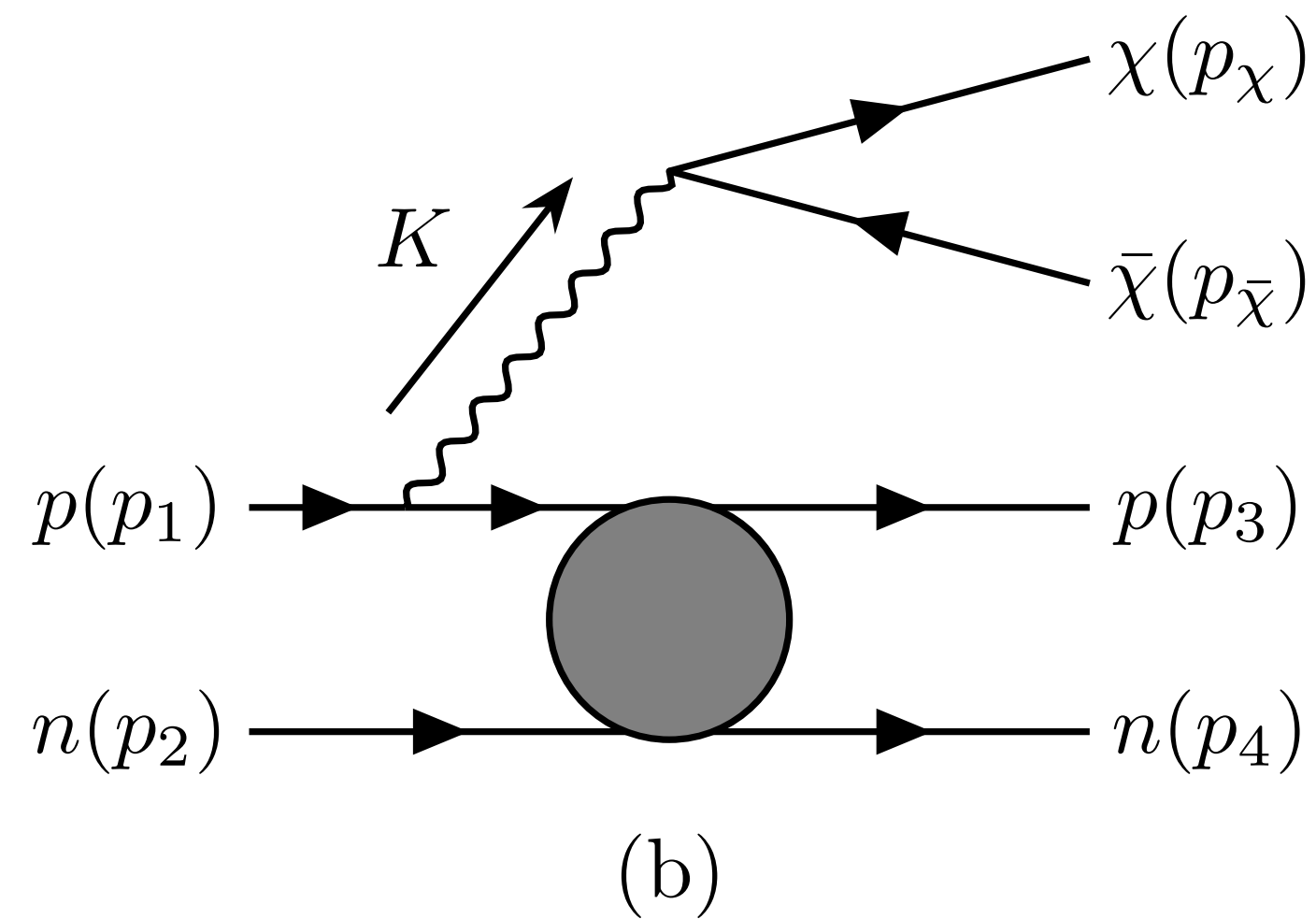
3

MCP production in the SN core

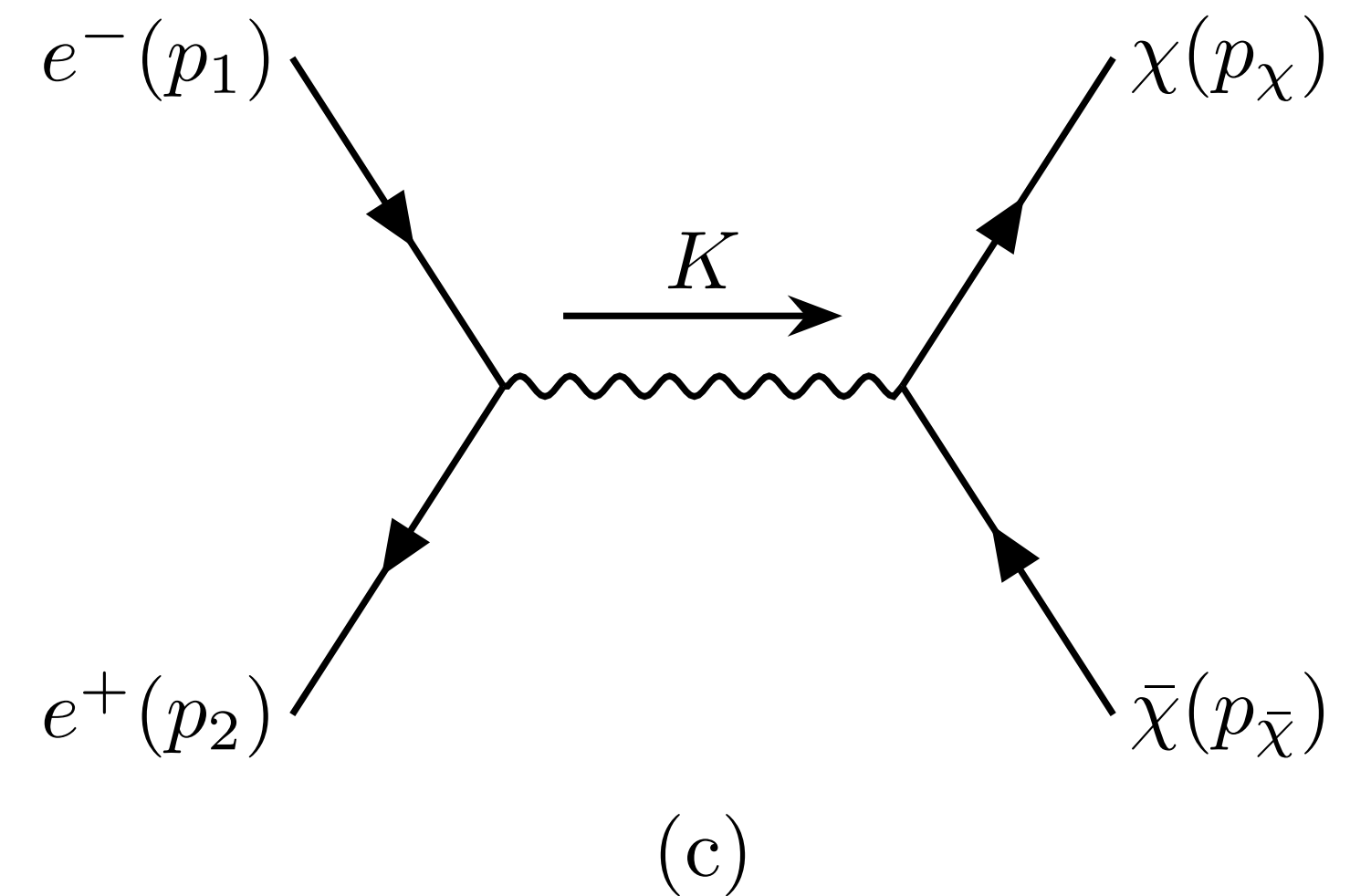
MCP production in the SN core



plasmon
decay



proton
bremsstrahlung

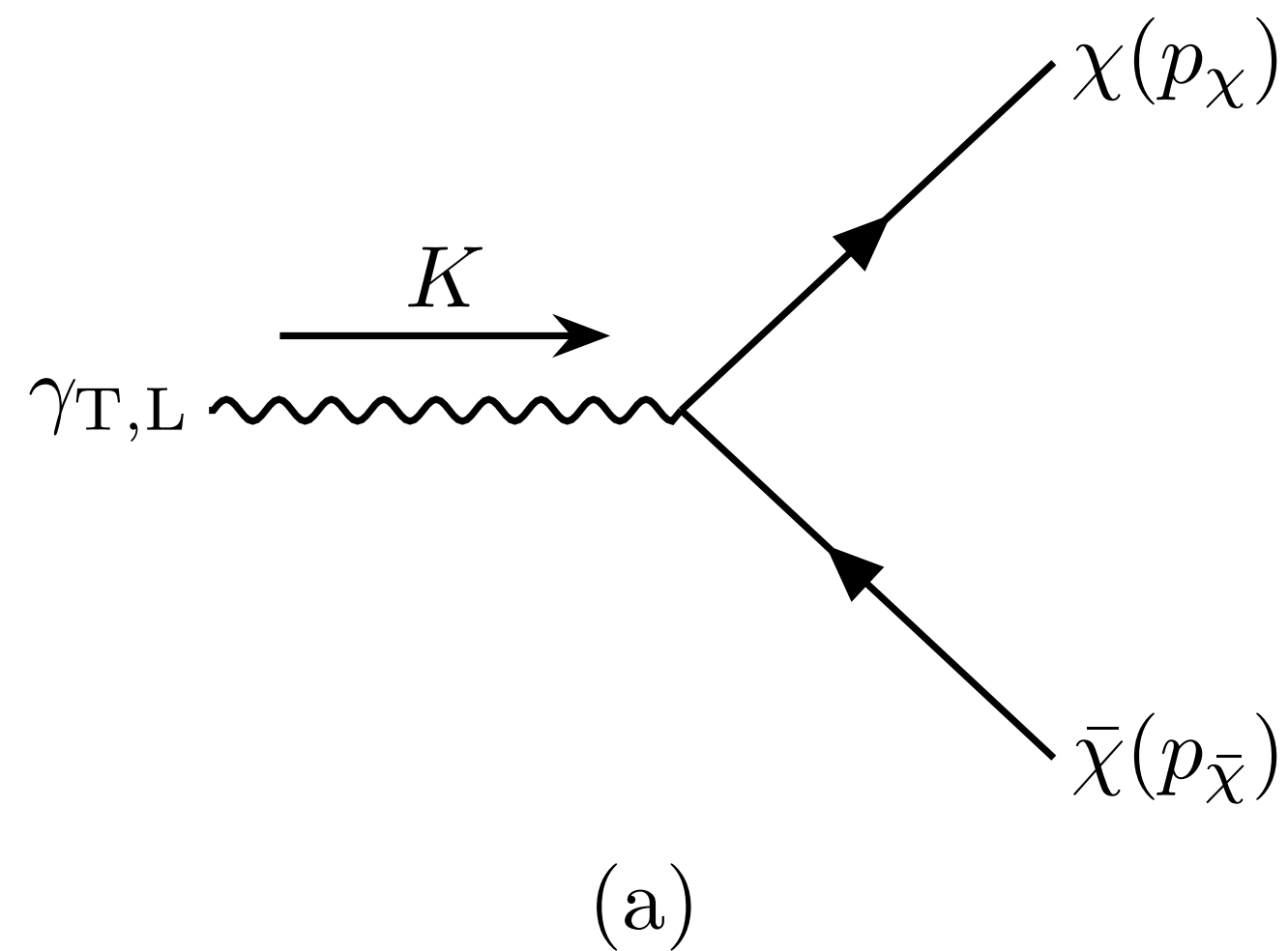


electron-positron
annihilation

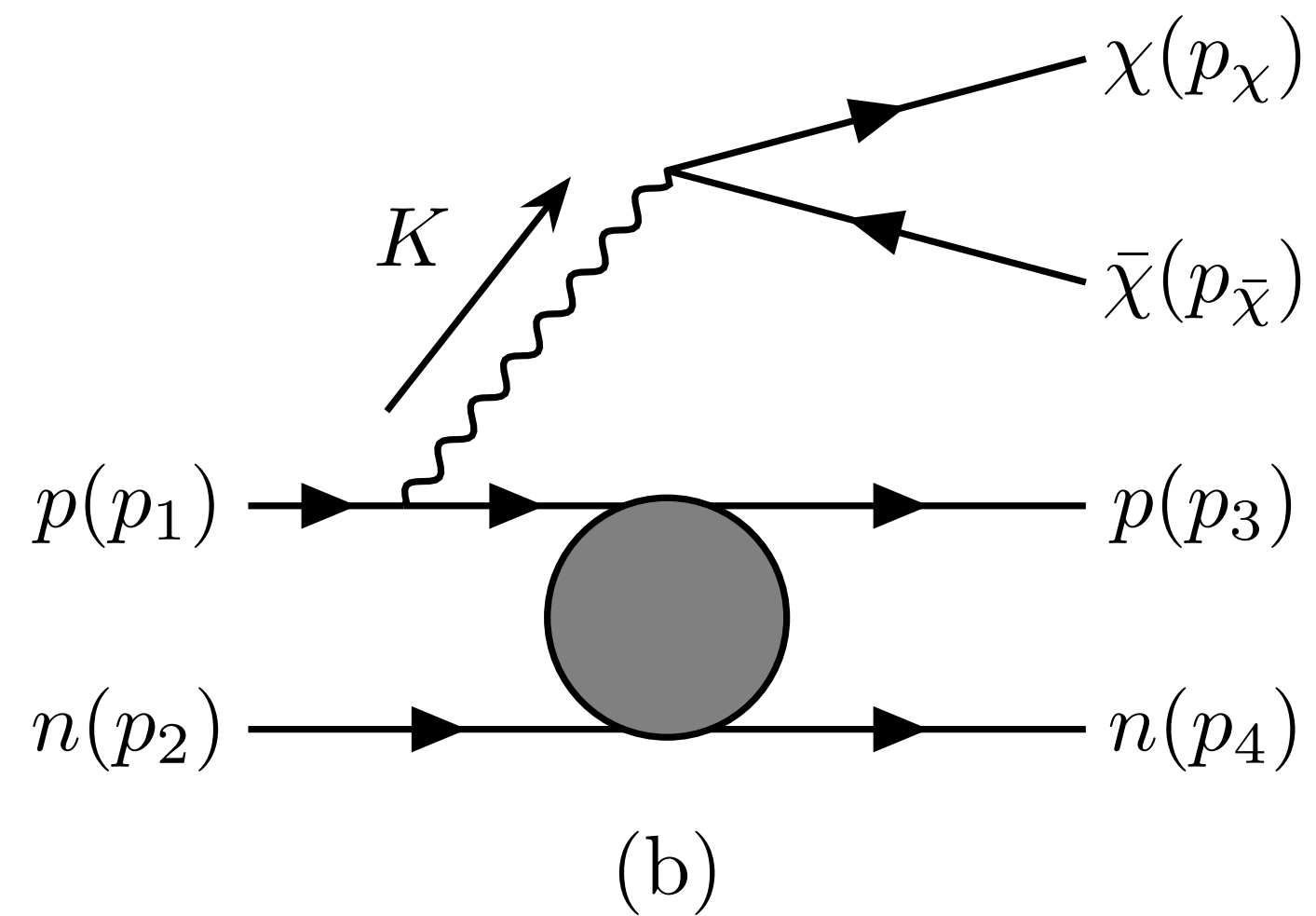
[Davidson+, hep-ph/0001179]

[Chang+, 1803.00993]

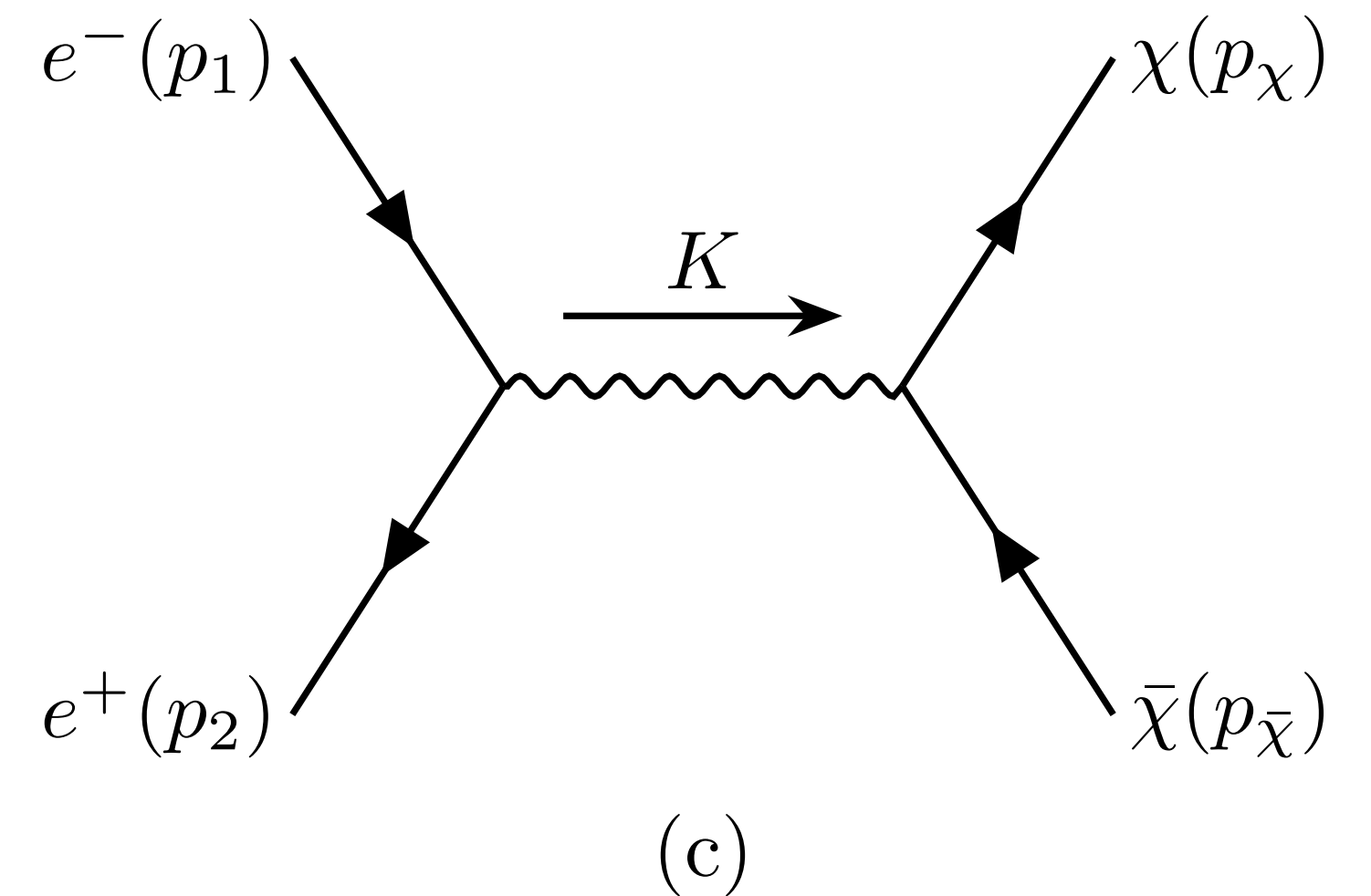
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[Davidson+, hep-ph/0001179]

[Chang+, 1803.00993]

(previously omitted for MCPs)

Plasma effects

Effective photon propagator in Lorenz gauge

[Raffelt, 96']

$$\tilde{D}^{\mu\nu}(\omega, k) = \sum_{a=\pm, L} \frac{i}{K^2 - \text{Re}\Pi_a(\omega, k) - i\text{Im}\Pi_a(\omega, k)} \epsilon_a^\mu \epsilon_a^{\nu*}$$

$$\epsilon_{\pm}^\mu = (0, 1, \pm i, 0)/\sqrt{2}$$

$$\epsilon_L^\mu = (k, 0, 0, \omega)/\sqrt{K^2}$$

LO contributions to real part of the EM polarization tensor

[Braaten & Segel, 93']

$$\text{Re}\Pi^{\mu\nu} = 16\pi\alpha \int \frac{d^3p}{(2\pi)^3} \frac{1}{2E} [f_{e^-}(E) + f_{e^+}(E)] \frac{K \cdot P (P^\nu K^\mu + P^\mu K^\nu - P \cdot K g^{\mu\nu}) - K^2 P^\mu P^\nu}{(K \cdot P)^2 - (K^2)^2/4}$$

$\implies$ dispersion relations & normalization

Plasma effects

The imaginary part of the EM polarization tensor is related to the photon absorption and production rates in the plasma

[Weldon, 82']

[An+, 1302.3884]

In the equilibrium case $\text{Im}\Pi = -\omega(1 - e^{-\omega/T})\Gamma_{\text{abs}}$

In the SN core, the dominant contributions to $\text{Im}\Pi$ (relevant for MCP production: photon is time-like with a positive energy):

- inverse-bremsstrahlung process of $\gamma pn \rightarrow pn$
- decay process of $\gamma \rightarrow e^+e^-$

Plasmon decay

Plasmon decay

decay width (a = T, L) in the SN frame

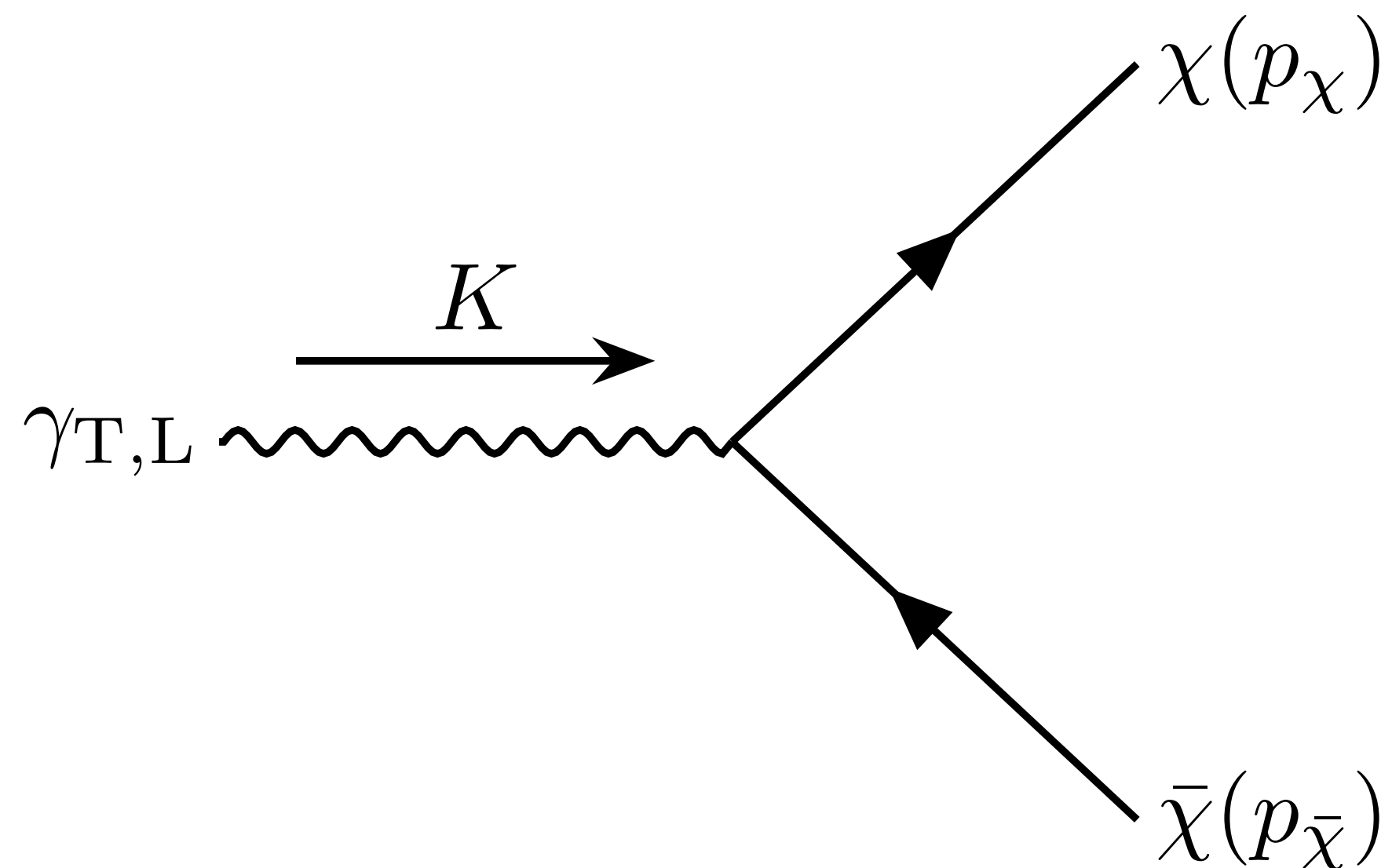
$$\Gamma_a = Z_a \frac{\epsilon^2 \alpha K^2}{3\omega_a} f\left(\frac{m_\chi^2}{K^2}\right)$$

$$f(x) \equiv \sqrt{1 - 4x} (1 + 2x)$$

photon momentum $K^\mu = (\omega, \mathbf{k})$

Lorenz gauge

Z_a = normalization



(a)

millicharged particle flux from plasmon decay

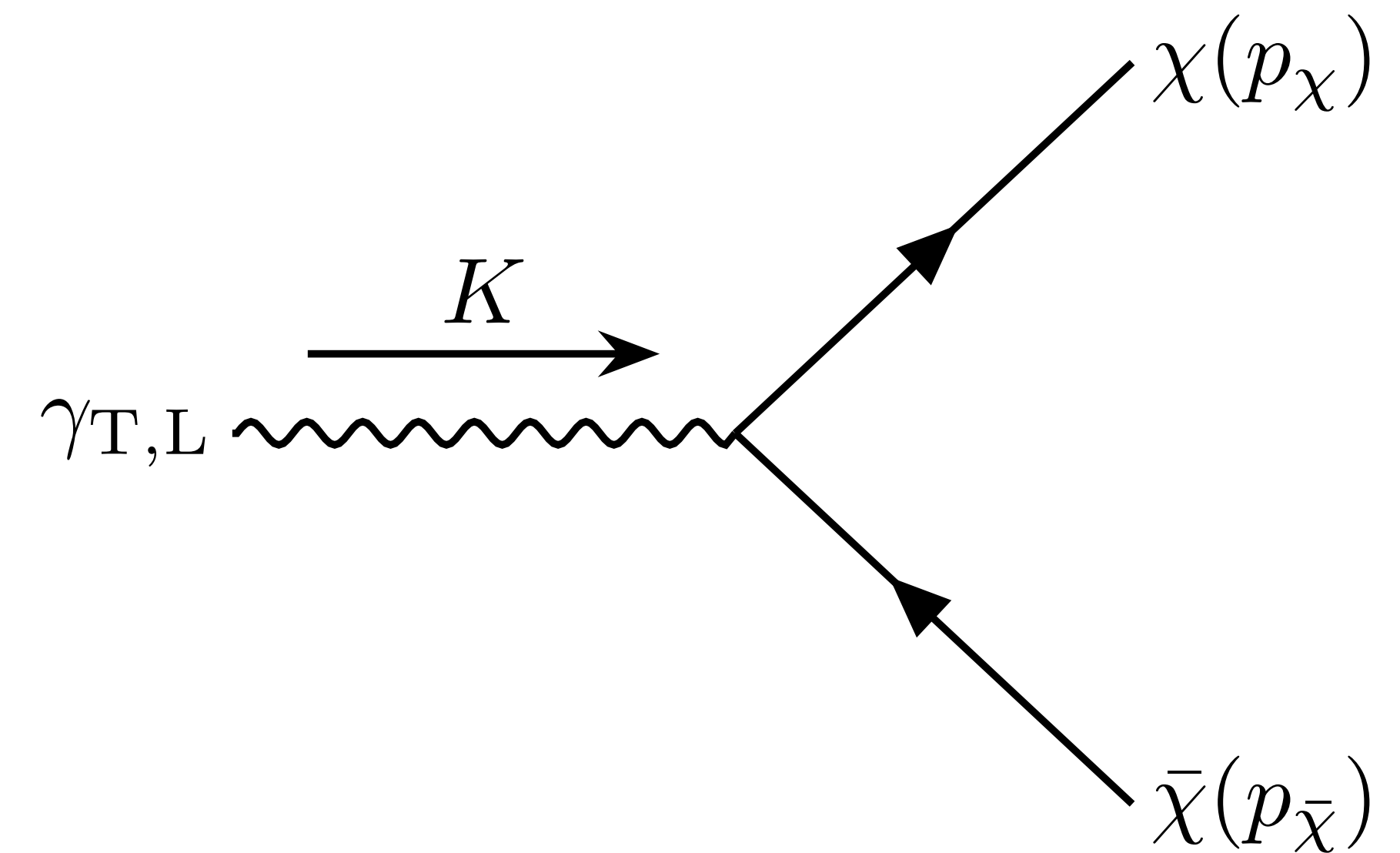
MCP production rate per unit volume per unit energy (relativistic limit) $k \equiv |\mathbf{k}|$

$$\frac{d\Phi_a}{dE_\chi} = \frac{g_a}{2\pi^2} \int_0^\infty dk k^2 \frac{\Gamma_a}{e^{\omega_a/T_c} - 1} g(E_\chi, m_\chi, K)$$

MCP energy spectrum per decay (plasma frame)

$$g(E_\chi, m_\chi, K) = 2 \frac{\Theta(E_\chi - E_\chi^-) \Theta(E_\chi^+ - E_\chi)}{E_\chi^+ - E_\chi^-}$$

$$E_\chi^\pm = \frac{1}{2} \left(\omega \pm k \sqrt{1 - 4m_\chi^2/K^2} \right)$$



(a)

One-zone model for the supernova

[Caputo+, 2201.09890]

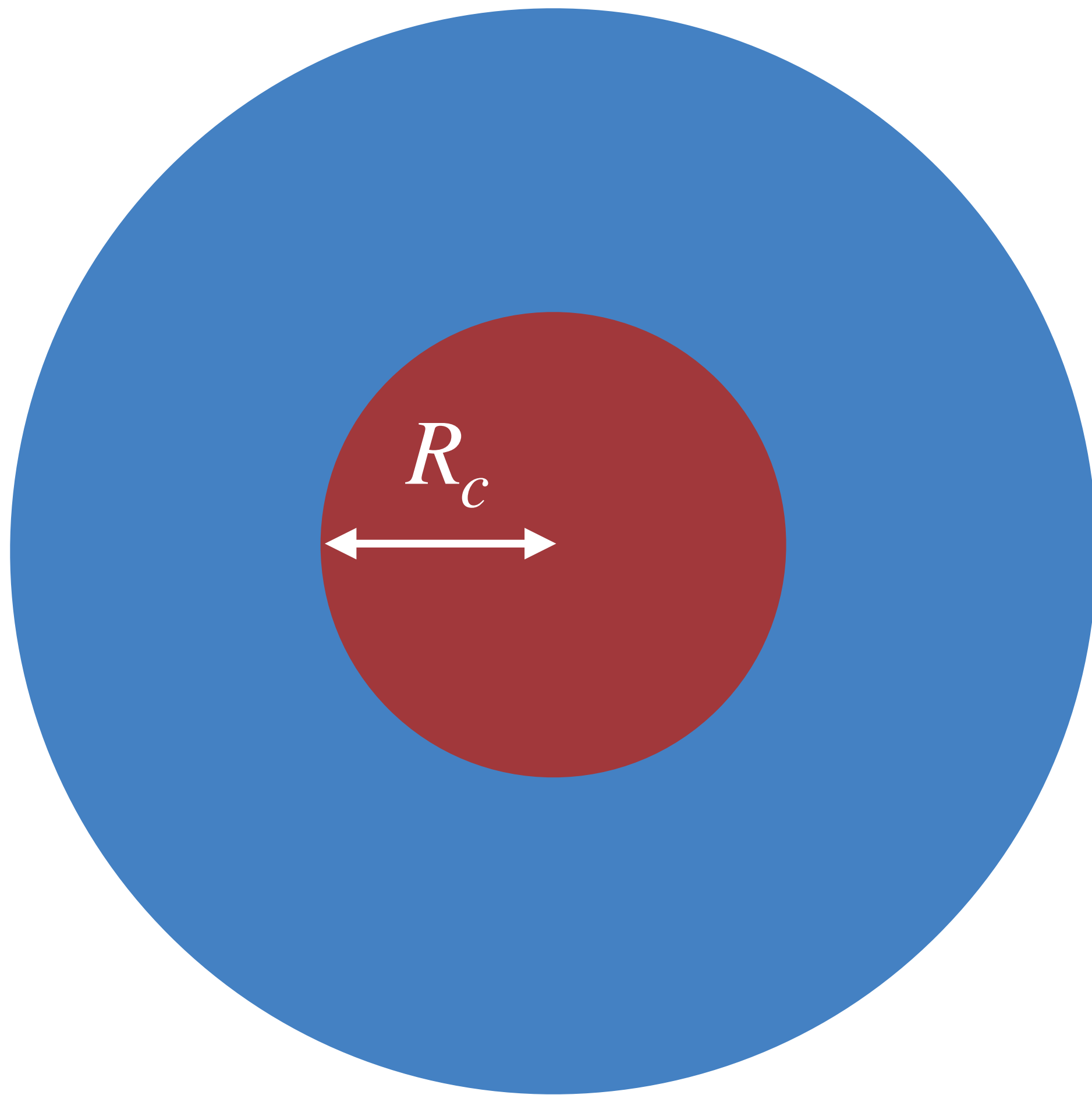
parameters for the SN core

Radius: $R_c = 12.9 \text{ km}$

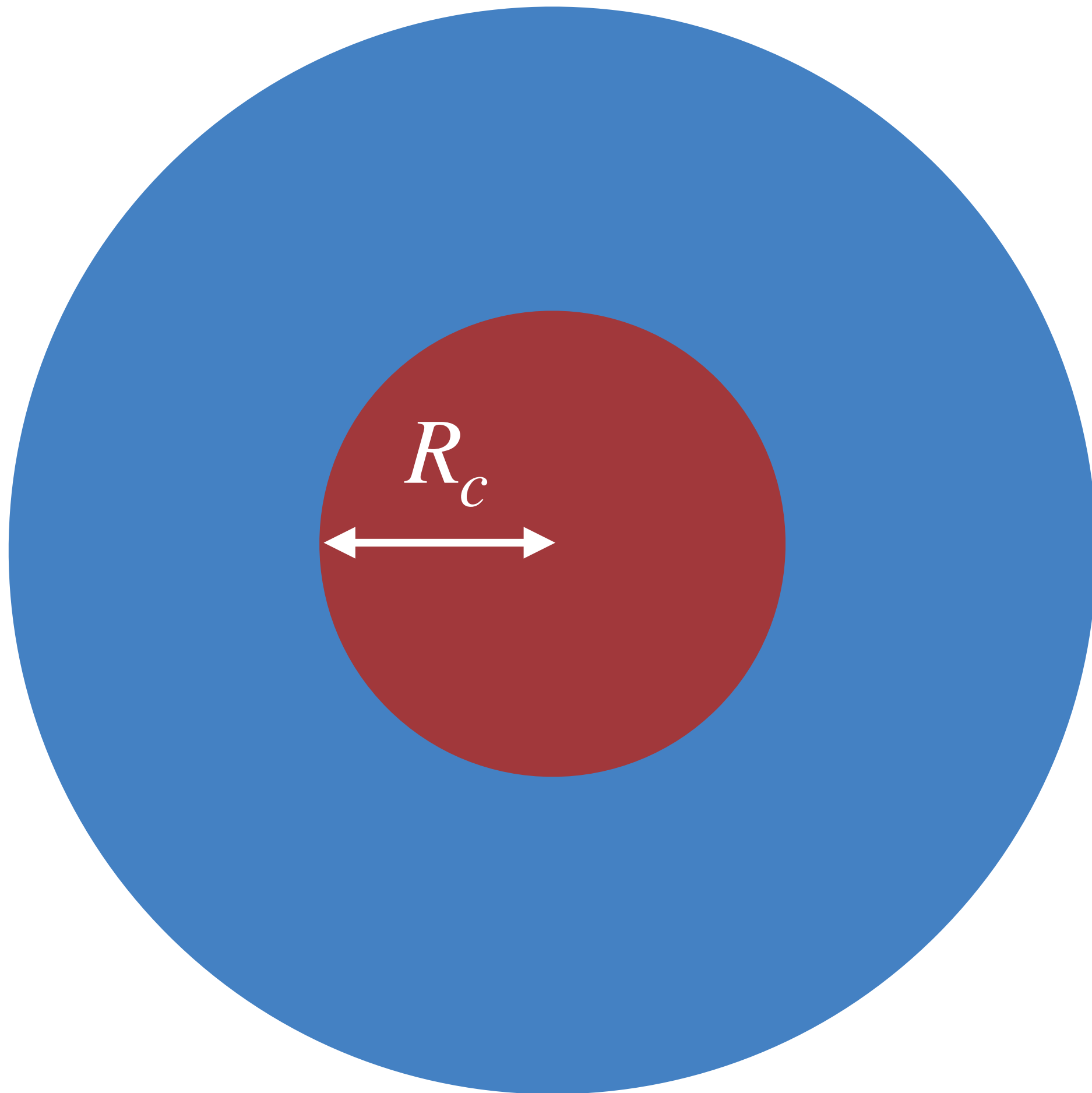
Temperature: $T_c = 30 \text{ MeV}$

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

Proton Abundance: $Y_p = 0.15$



Particle mass/energy in the one-zone model



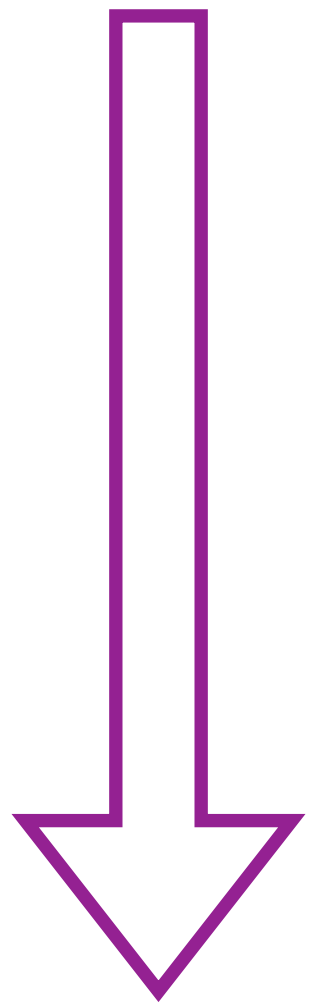
Photon mass < 12 MeV

Nucleon: $\langle E_n \rangle \simeq 45$ MeV

electron: $\langle E_{e-} \rangle \simeq 160$ MeV

positron: $\langle E_{e+} \rangle \simeq 90$ MeV

low-mass
 < 6 MeV



high-mass

Proton bremsstrahlung

Proton bremsstrahlung

2-to-4 xsec in terms of 2-to-3 xsec

$$\frac{d\sigma(np \rightarrow np\chi\bar{\chi})}{dK^2 d\omega} = \frac{\epsilon^2 \alpha}{3\pi} \frac{1}{K^2} \frac{d\sigma(np \rightarrow np\gamma)}{d\omega} f\left(\frac{m_\chi^2}{K^2}\right)$$

$$\frac{d\sigma(np \rightarrow np\gamma)}{d\omega} = 2\text{-to-3 xsec}$$

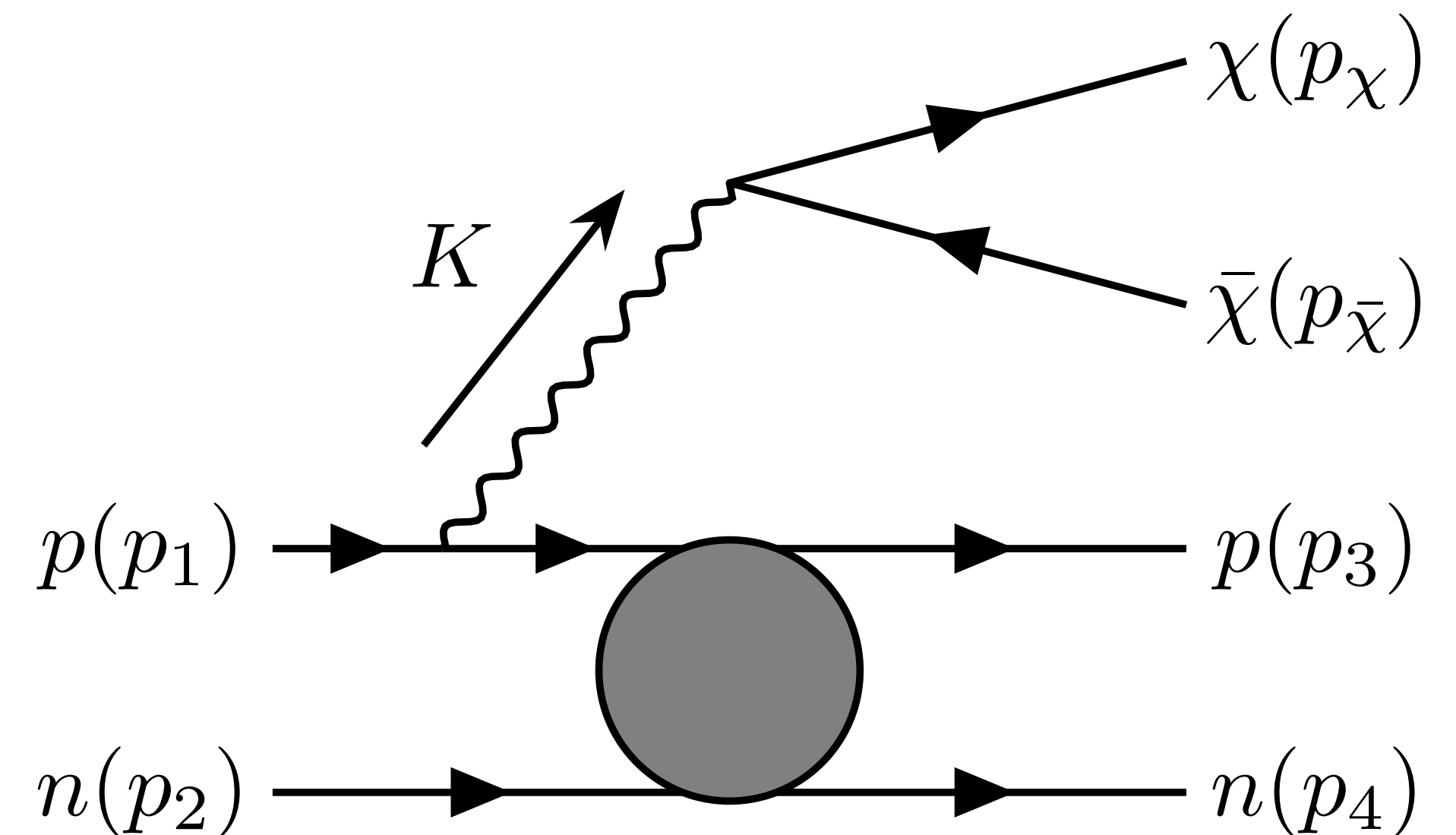
No plasmon corrections to the photon propagator to avoid double counting w/ plasmon decay

[Chu+, 1908.00553]

[Gninenko+, 1810.06856]

[Liang, ZL, Yang, 2111.15533]

[Du, Fang, ZL, 2211.11469]



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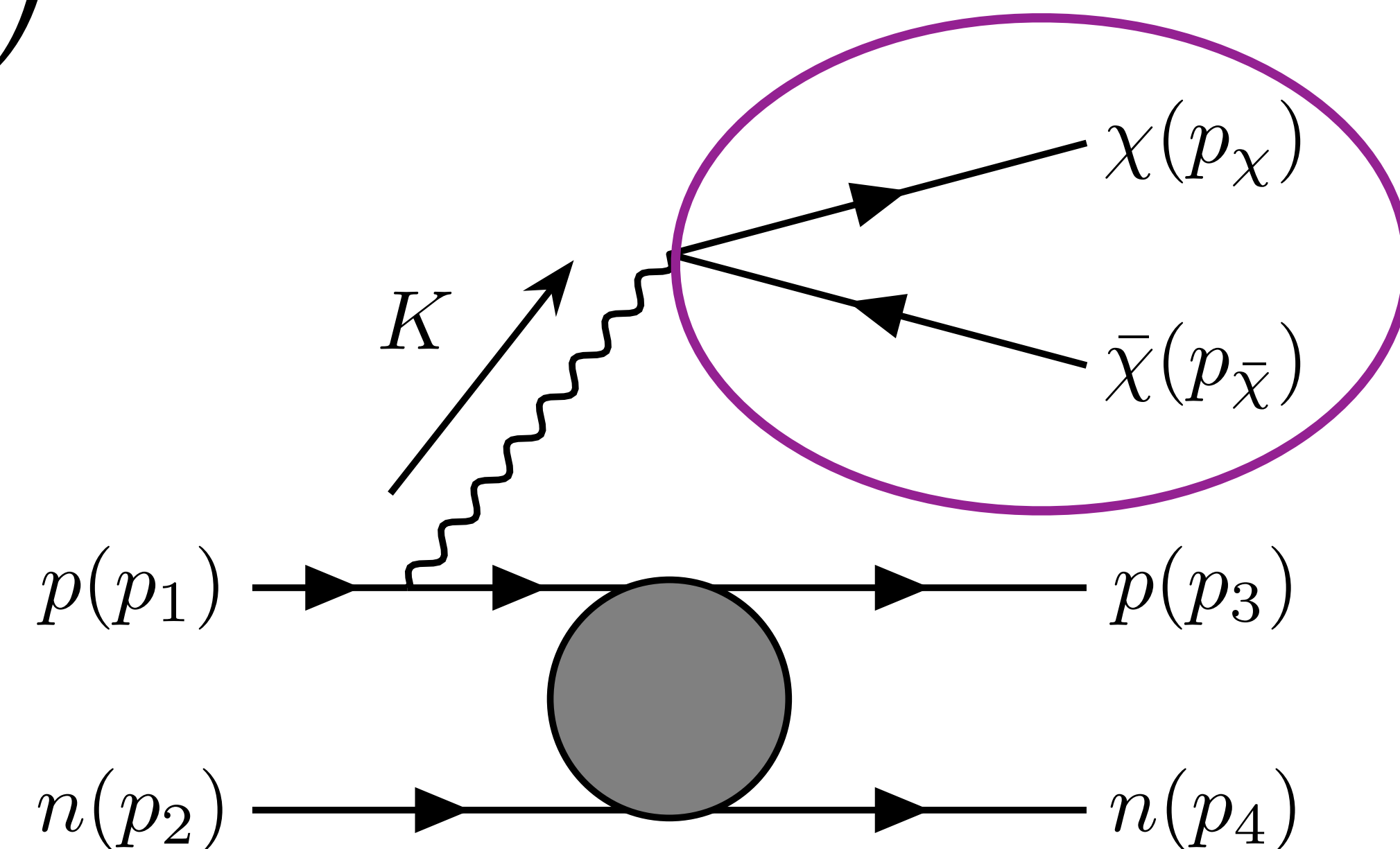
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Photon emission in soft radiation approximation (SRA)

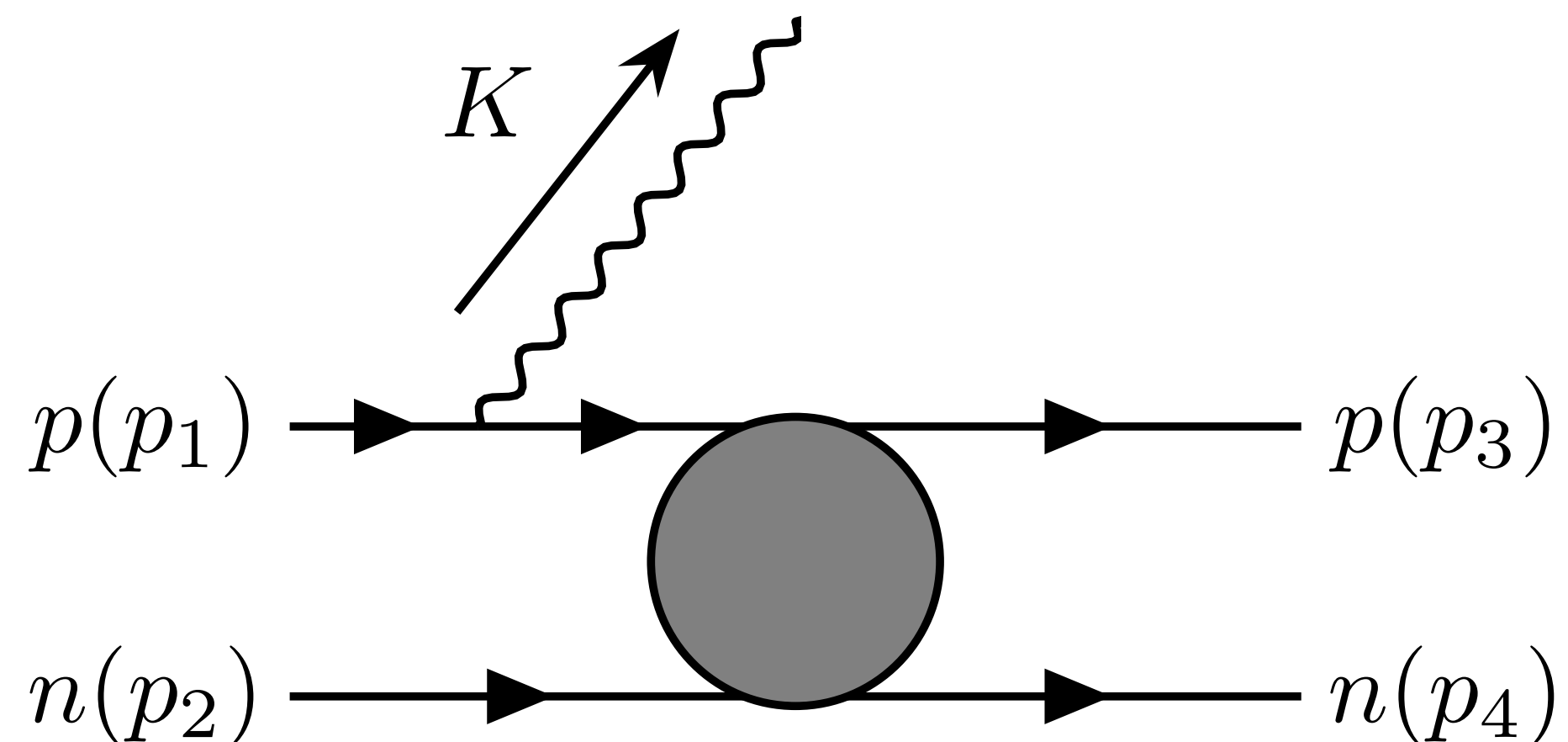
$$\frac{d\sigma(np \rightarrow np\gamma)}{d\omega} = \sigma_{np}^T \frac{d\mathcal{P}}{d\omega}$$

[Chu+, 1908.00553]

[Rrapaj & Reddy, 1511.09136]

σ_{np}^T = transport xsec of $(np \rightarrow np)$

$\frac{d\mathcal{P}}{d\omega}$ = photon splitting kernel



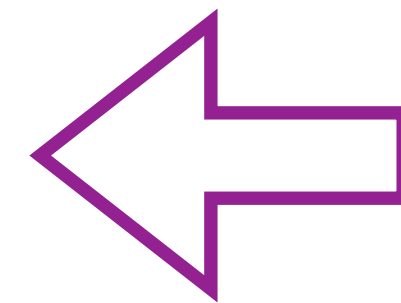
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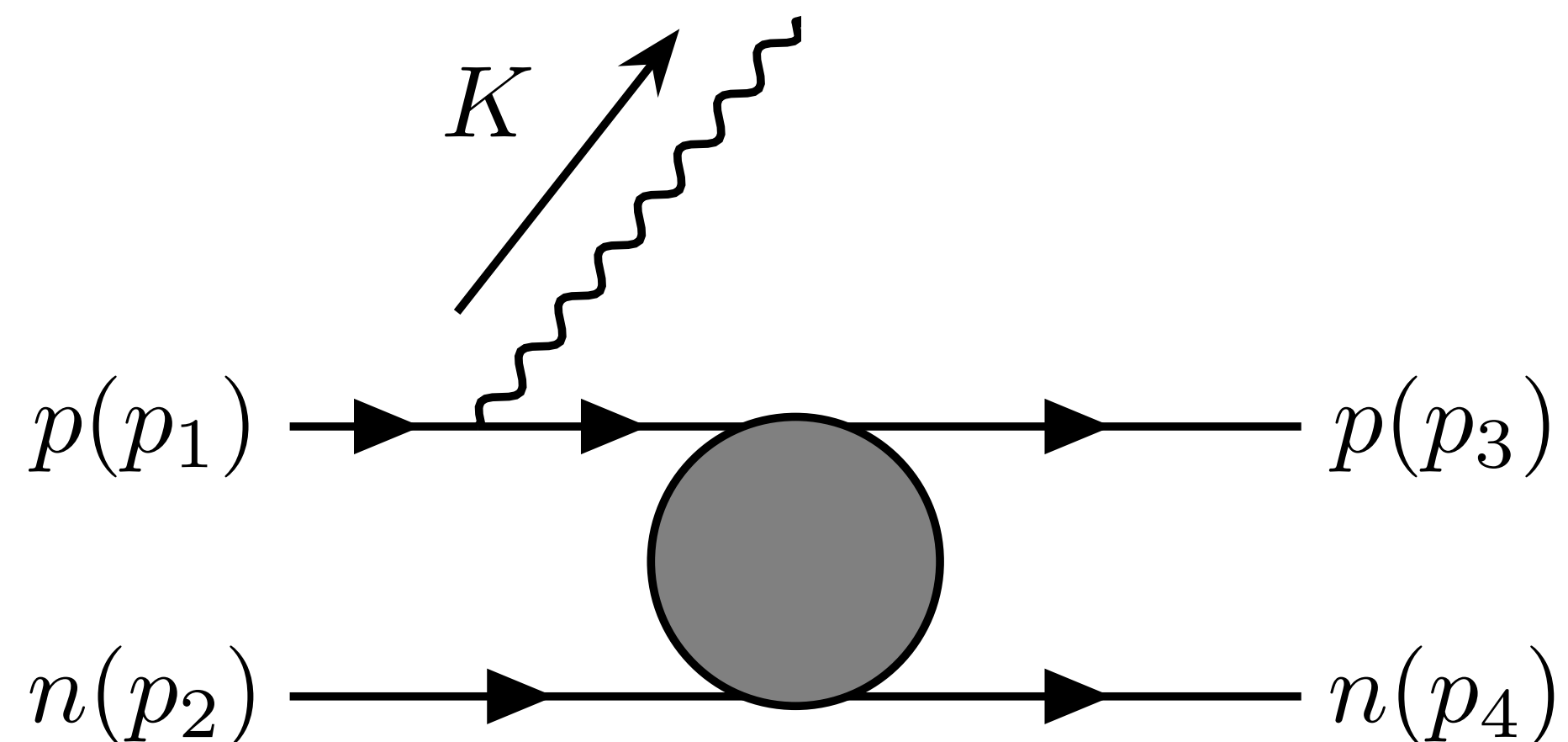
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use data

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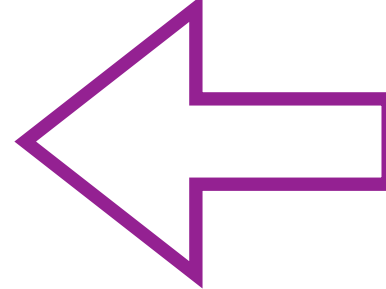


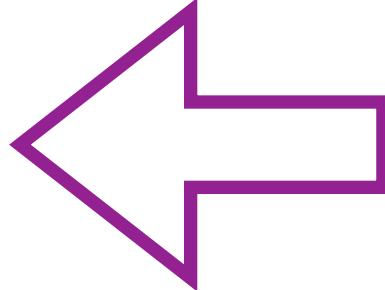
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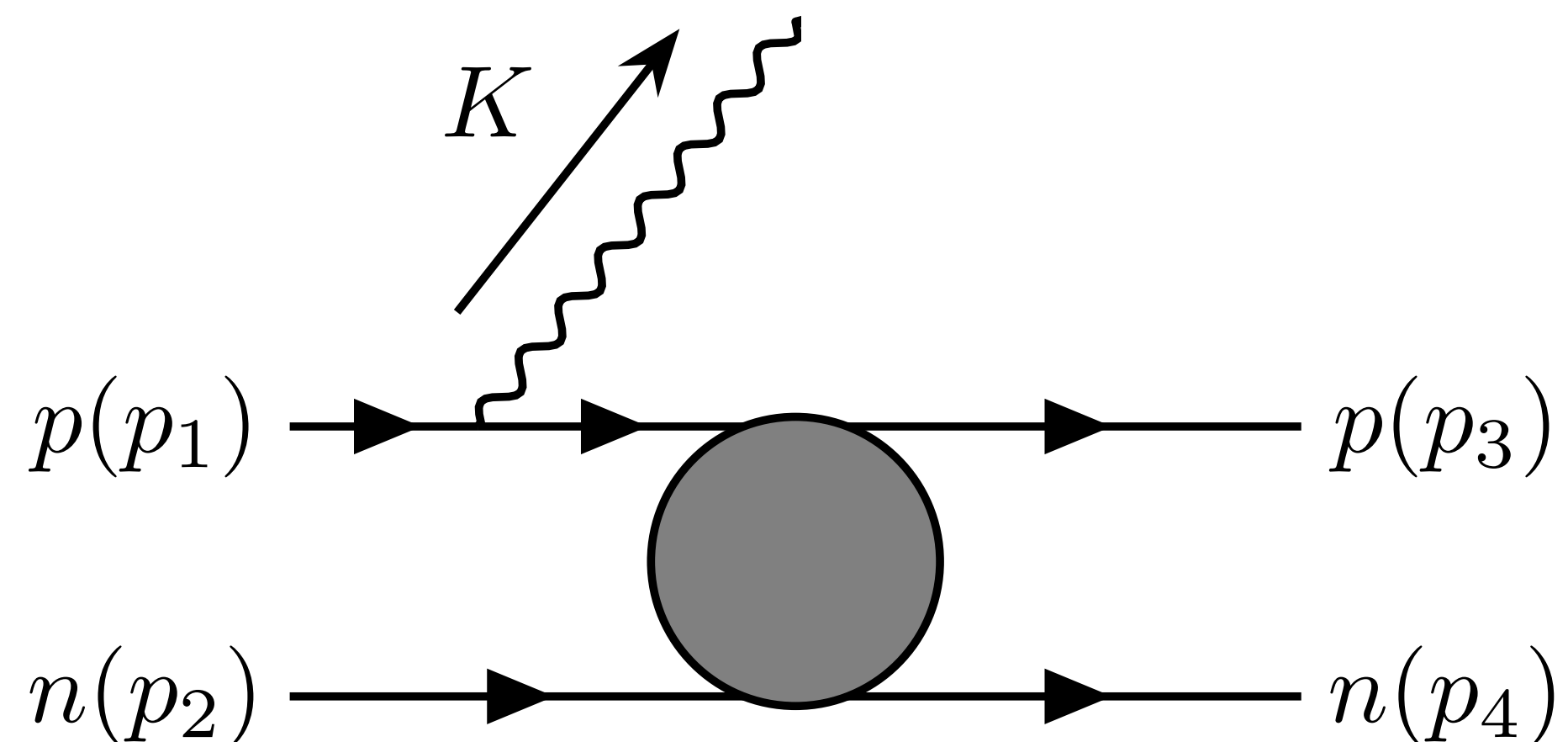
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σ_{np}^T = transport xsec of $(np \rightarrow np)$  use data

$\frac{d\mathcal{P}}{d\omega}$ = photon splitting kernel 



In SRA

$$\frac{d\mathcal{P}}{d\omega} = \frac{4\alpha}{3\pi\omega} \frac{E_{\text{cm}}}{m_N} f\left(\frac{K^2}{4\omega^2}\right)$$

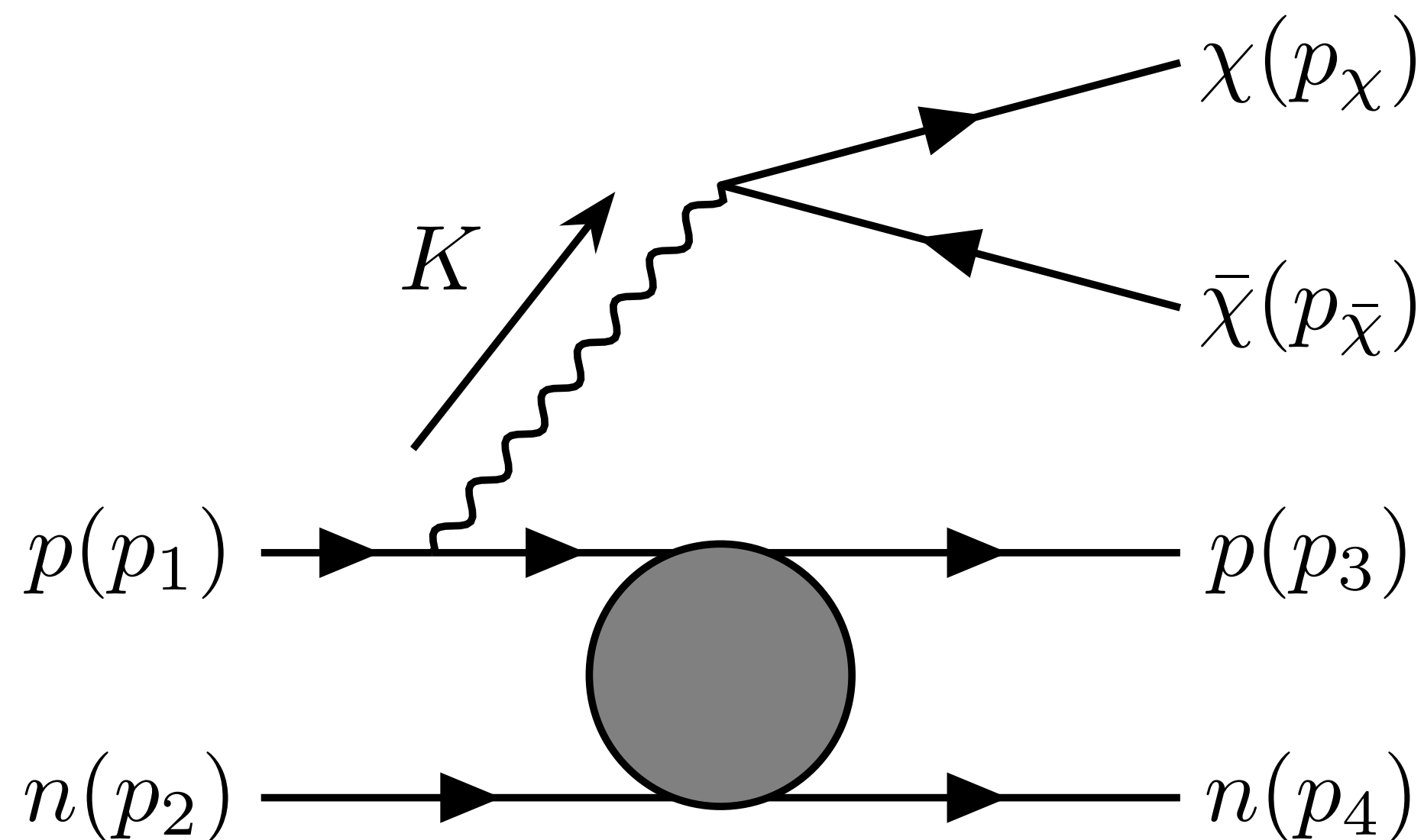
$$E_{\text{cm}} = \frac{(\mathbf{p}_1 - \mathbf{p}_2)^2}{4m_N} \simeq 90 \text{ MeV}$$

millicharged particle flux in proton bremsstrahlung

MCP flux in the PB process

$$\frac{d\Phi_{\text{pb}}}{dE_\chi} = \frac{4n_1n_2\epsilon^2\alpha}{3\sqrt{m_N\pi^3T_c^3}} \int_{2m_\chi}^{\infty} dE_{\text{cm}} E_{\text{cm}} e^{-E_{\text{cm}}/T_c} \sigma_{np}^T(E_{\text{cm}})$$

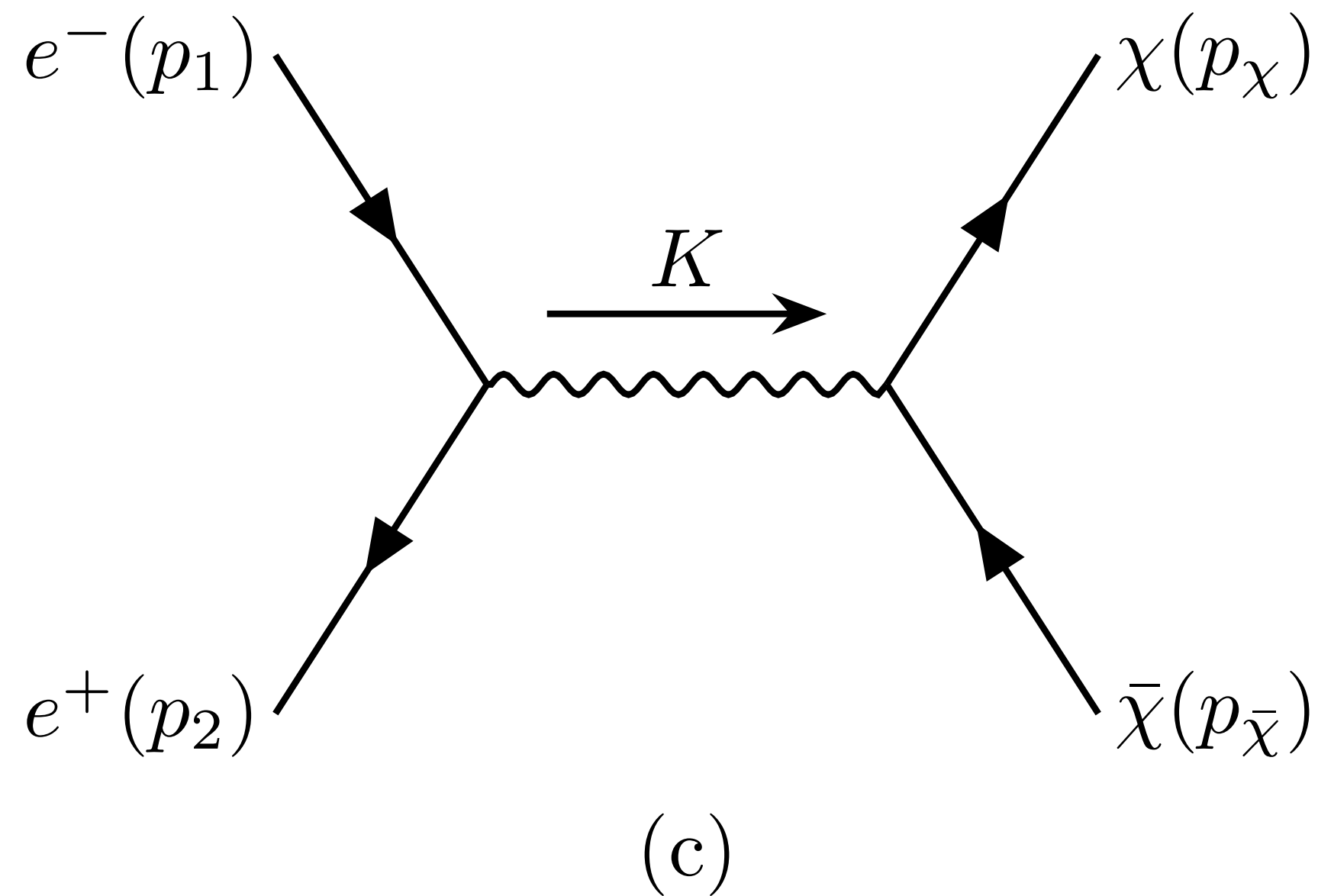
$$\times \int_{4m_\chi^2}^{E_{\text{cm}}^2} \frac{dK^2}{K^2} f\left(\frac{m_\chi^2}{K^2}\right) \int_{\sqrt{K^2}}^{E_{\text{cm}}} d\omega \frac{d\mathcal{P}}{d\omega} g(E_\chi, m_\chi, K)$$



Electron-positron annihilation

Electron-positron annihilation

$$\sigma_{\text{ann}} = \sigma_T + \sigma_L$$



For transverse (T) and longitudinal (L) photons

$$\sigma_a = \frac{2\pi\epsilon^2\alpha^2}{3\beta_e} \frac{N_a K^2 f(m_\chi^2/K^2)}{(K^2 - \text{Re}\Pi_a)^2 + (\text{Im}\Pi_a)^2}$$

$$\beta_e = \sqrt{1 - 4m_e^2/K^2}$$

EM polarization tensor: $\Pi_a = \text{Re}\Pi_a + i \text{Im}\Pi_a$

$$N_L = 1 - E_-^2/(E_+^2 - K^2)$$

$$N_T = 1 + 4m_e^2/K^2 + E_-^2/(E_+^2 - K^2)$$

$$E_\pm \equiv E_1 \pm E_2$$

EM polarization tensor in the off-shell region

e^+e^- annihilates at $\sqrt{K^2}$ larger than the photon mass

One-zone model: $m_\gamma < 12 \text{ MeV}$ & $m_e \simeq 9 \text{ MeV} \implies m_\gamma < 2m_e$

In the relativistic limit, we use on-shell dispersion relations to compute $\text{Re}\Pi$

[Braaten & Segel, 93']

[Scherer & Schutz, 2405.18466]

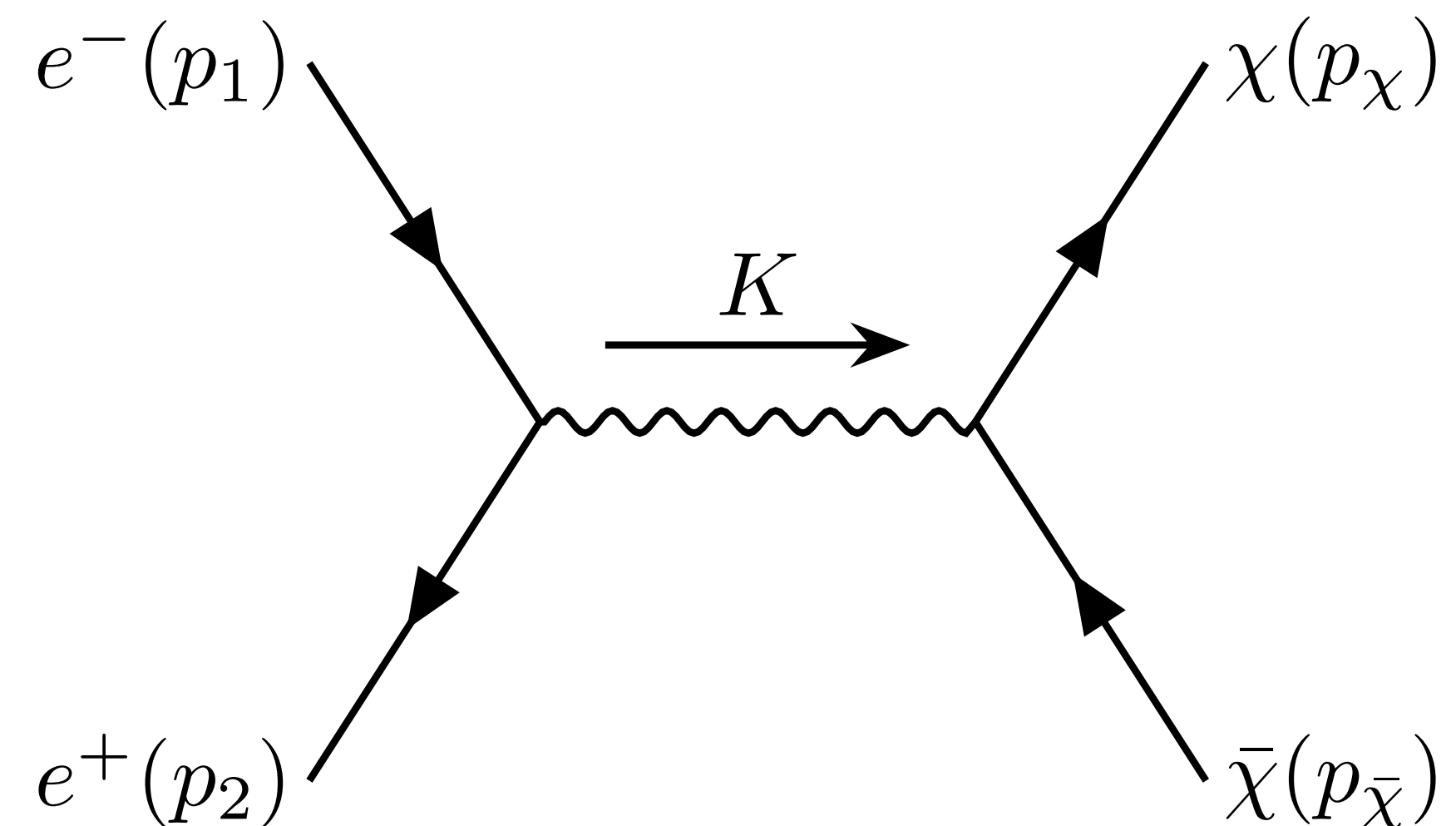
Dominant contributions to $\text{Im}\Pi$: proton bremsstrahlung & its inverse $\implies \lesssim 2\%$

millicharged particle flux in e^+e^- annihilation

$$\frac{d\Phi_{\text{ann}}}{dE_\chi} = \frac{1}{16\pi^4} \int_{4m_{\text{th}}^2}^{\infty} dK^2 K^2 \beta_e \int_{\sqrt{K^2}}^{\infty} dE_+ \int_{-E_-^m}^{E_-^m} dE_- f_1(E_1) f_2(E_2) \sigma_{\text{ann}} g(E_\chi, m_\chi, K)$$

$$E_-^m \equiv \beta_e \sqrt{E_+^2 - K^2}$$

$$m_{\text{th}} \equiv \max\{m_e, m_\chi\}$$



(c)

4

Energy deposition in the SN mantle

Energy deposition in the mantle for a single χ

Energy loss due to Coulomb scattering with protons in the mantle (for a single χ)

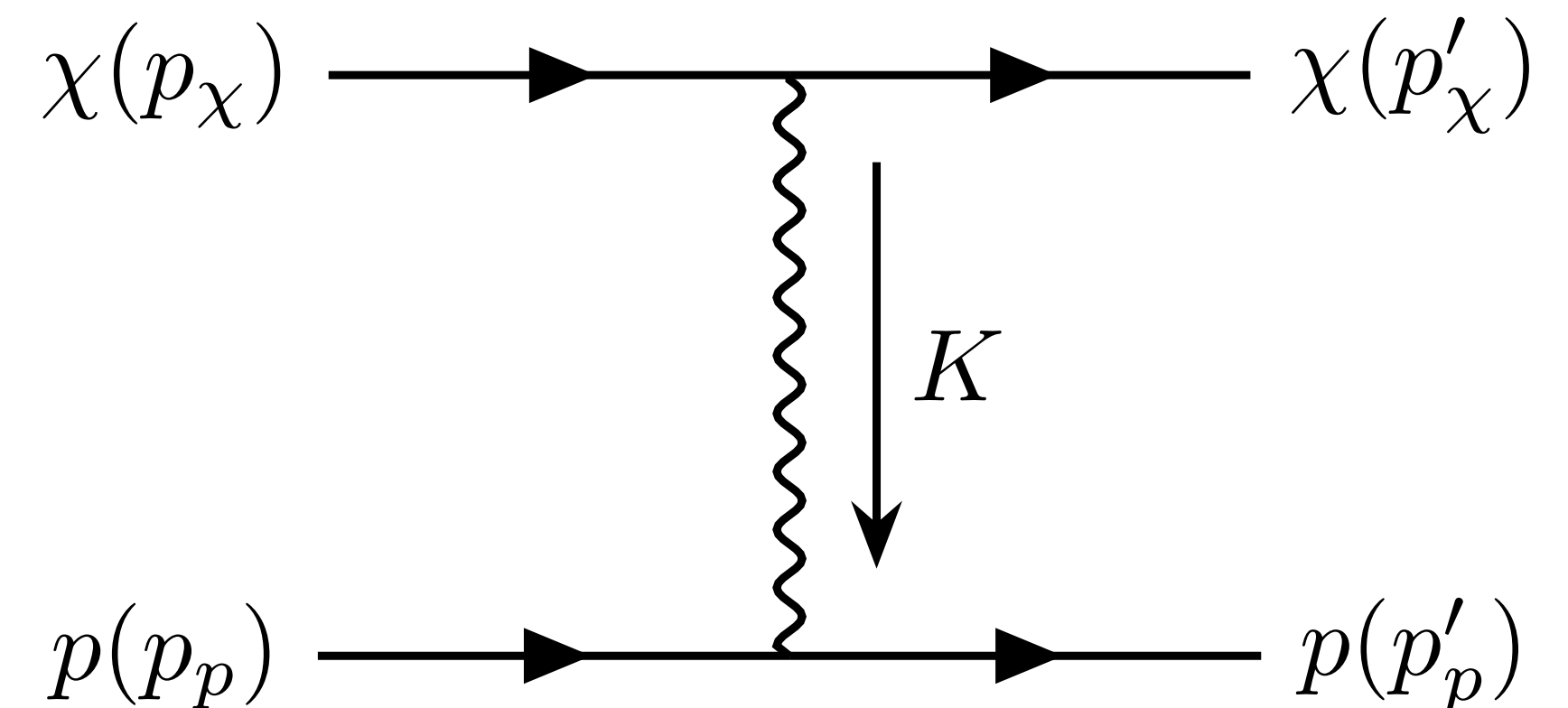
$$\frac{dE_\chi}{dx} = -n_p \int dE_R \frac{d\sigma_{\chi p}}{dE_R} E_R \quad \Rightarrow \quad \Delta E_\chi = \frac{1}{2} \int dx n_p E_R^{\max} \sigma_{\chi p}^T$$

distance = 3 light-seconds

$E_R^{\max}$ = maximum recoil energy

$\sigma_{\chi p}^T$ = transport xsec w/ Debye screening

[Davidson+, hep-ph/0001179]



Total energy transfer from the core to the mantle

Total energy transfer from the core to the mantle

$$E_m = \text{lapse}^2 \times 4\pi\Delta t \int_0^{R_c} dr r^2 \int_{m'_\chi}^\infty dE_\chi \frac{d\Phi}{dE_\chi} \Delta E_\chi \leq \mathbf{0.1 B}$$

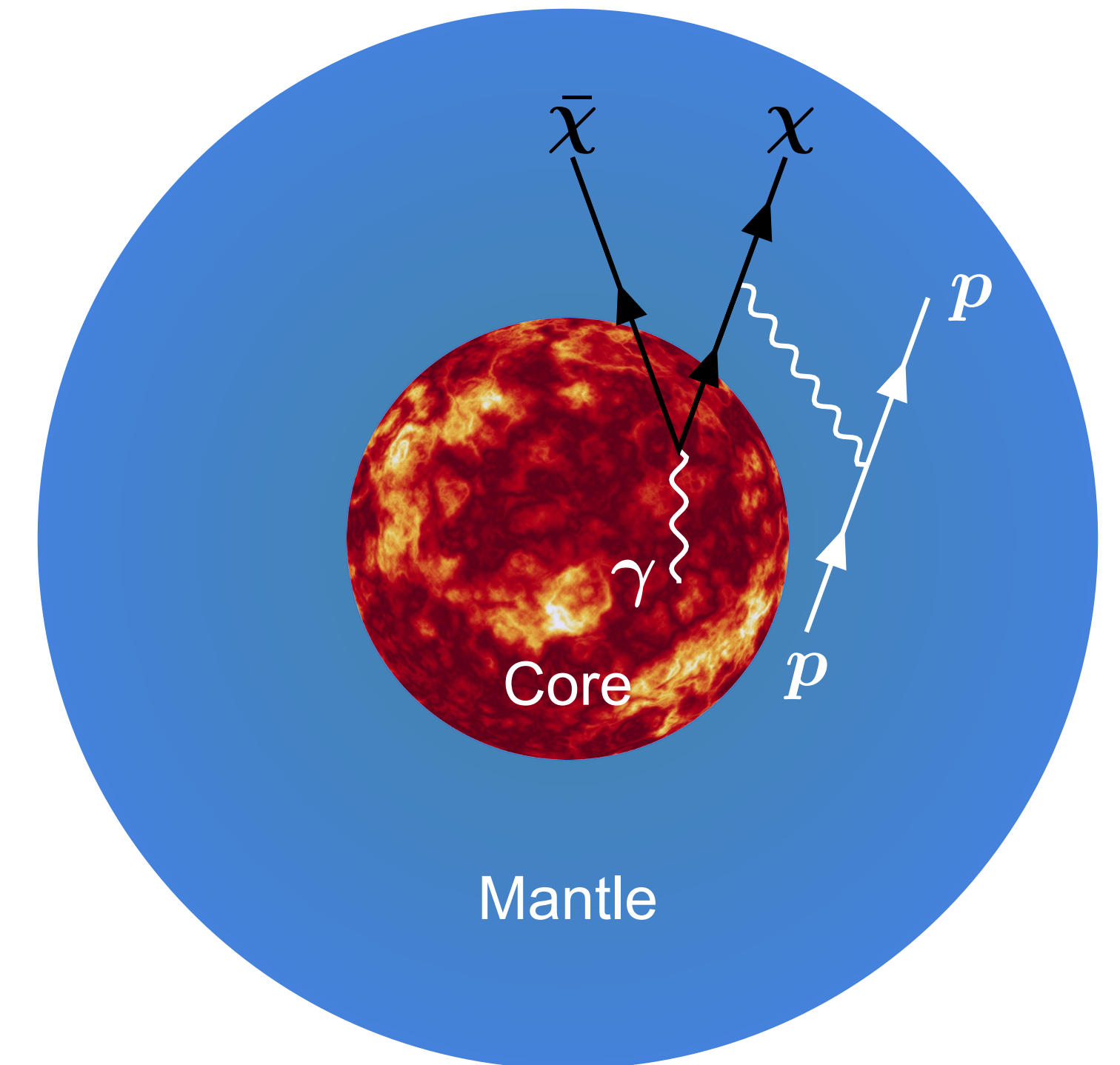
ΔE_χ = energy deposited by a single χ in the mantle

$$\Delta t = 3 s$$

$$\frac{d\Phi}{dE_\chi} = \text{total } \chi \text{ flux (3 production channels)}$$

$$\text{lapse} \equiv \sqrt{1 - \frac{2GM}{R_c}} = \text{gravitational redshift} \ \& \ m'_\chi = \frac{m_\chi}{\text{lapse}}$$

[Caputo+, 2201.09890]



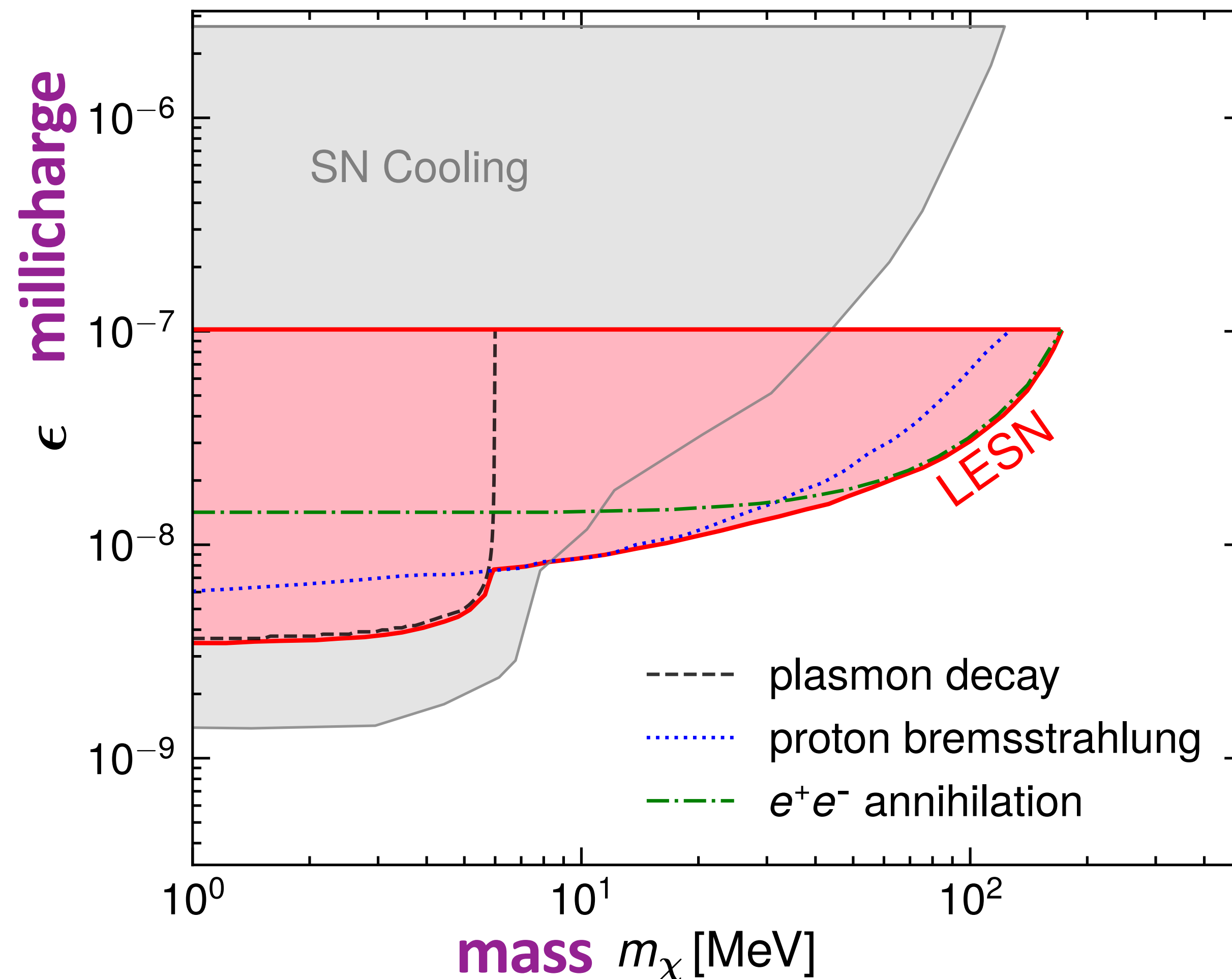
5

LESN constraints on millicharged particles

Low-energy supernova limits on millicharged particles

[Li, ZL, Lu, Ye, 2408.04953]

$$e \epsilon A_\mu \bar{\chi} \gamma^\mu \chi$$



probe new para space for $m \gtrsim 10$ MeV

better than SN cooling in high-mass region

[Davidson+, hep-ph/0001179]

[Chang+, 1803.00993]

plasmon decay: $m \lesssim 6$ MeV

proton bremsstrahlung: $6 \lesssim m \lesssim 30$ MeV

electron-positron annihilation: $m \gtrsim 30$ MeV

Summary

- Low-energy supernovae (LESNe) can have an explosion energy as low as 0.1 B, imposing strong constraints on the energy transfer from the core to the mantle
- We study LESH constraints on millicharged particles, by considering three production channels in the SN core
 - plasmon decay [Li, ZL, Lu, Ye, 2408.04953]
 - proton bremsstrahlung
 - electron-positron annihilation $\Rightarrow$ important for high-mass (previously omitted)
- Energy deposition in the mantle occurs via Coulomb scattering with protons
- LESNe impose the most stringent constraints on millicharged particles in the mass range of $\sim (10 - 200)$ MeV, surpassing the supernova cooling limit

2024年紫金山暗物质研讨会

Oct 11 – 15, 2024
Asia/Shanghai timezone

<https://indico.ihep.ac.cn/event/23320/>

Overview
Registration
Participant List

探索暗物质本质是粒子物理、天文学和宇宙学领域的前沿课题。近年来，世界各科技大国都在积极开展暗物质相关的理论和实验研究。我国也将暗物质研究纳入了国家中长期科学规划，并取得了一系列国际领先的科研成果，如成功发射DAMPE暗物质科学卫星，建成了锦屏地下实验室，开展了暗物质直接探测实验CDEX和PandaX等。在国内外暗物质研究蓬勃发展的背景下，我们将召开2024年紫金山暗物质研讨会。本次研讨会旨在进一步推动暗物质研究，促进理论家与实验家的交流，并加强暗物质研究与其他相关领域的合作。

会议的主题包括但不限于：最新的暗物质实验结果、暗物质的理论研究、新的暗物质探测方法、暗物质与超出标准模型新物理研究等。我们希望此次研讨会能够为相关领域的专家提供一个讨论的平台，促进学科间交流合作，并激发新的科研思路。

研讨会将于2024年10月11日至15日在南京大学苏州校区举行。本次研讨会由南京大学、中国科学院紫金山天文台、南京师范大学和国际理论物理中心-亚太地区共同主办，由南京大学承办。该系列研讨会始于2019年，由中国科学院暗物质与空间天文重点实验室首次举办。

1、会议地点：
南京大学苏州校区

2、会议时间：
2024年10月11日-15日（11日报到，15日离会）

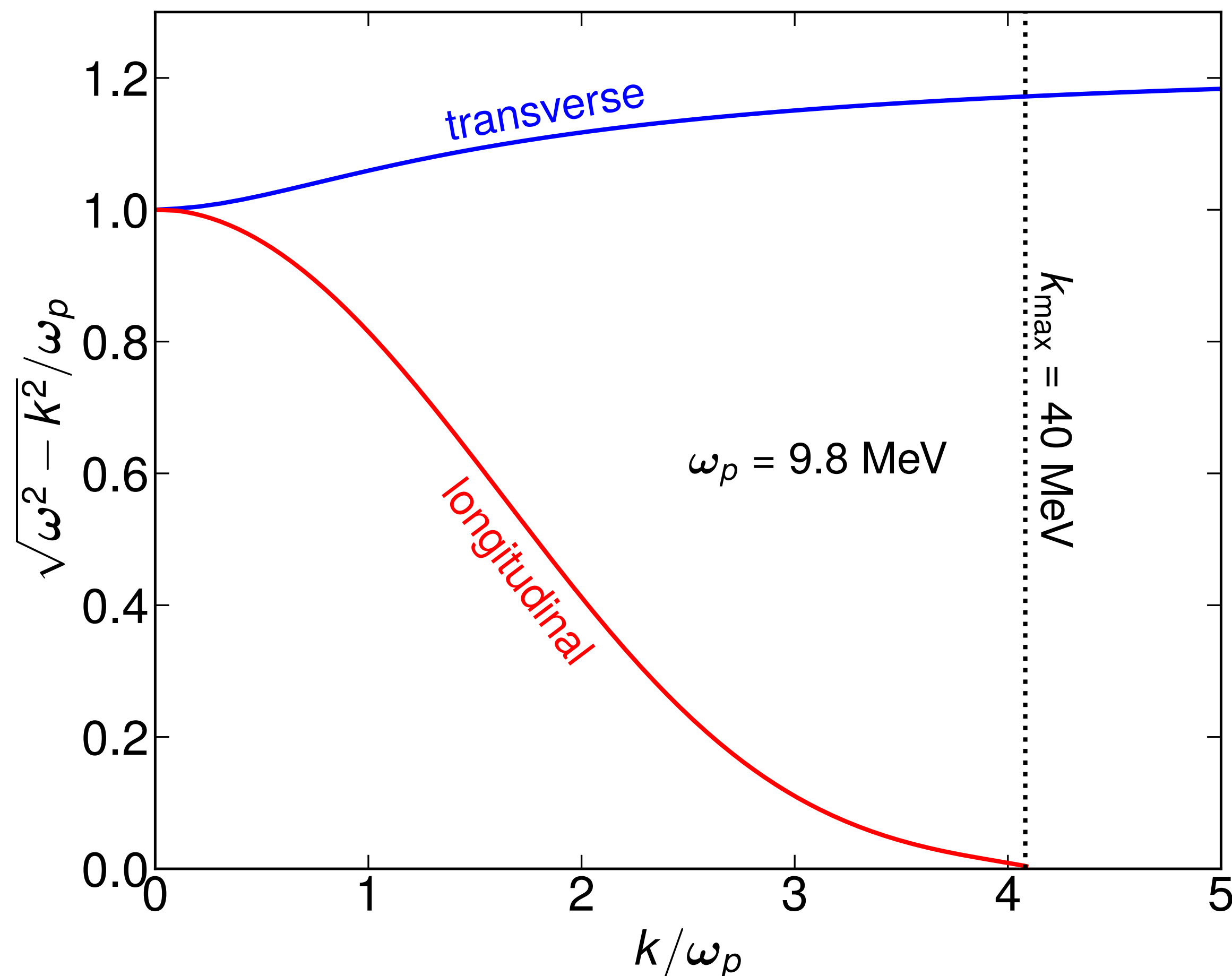
3、会议注册：会议注册和报告提交截止日期为2024年9月25日。
会议注册费：研究人员及博士后1500元/人，其他人员1000元/人。会议协助安排食宿，费用自理。

4、会议组织委员会：
马永亮（南京大学）
刘佐伟（南京大学）
范一中（中国科学院紫金山天文台）
武 雷（南京师范大学）
袁 强（中国科学院紫金山天文台）
蔡岳霖（中国科学院紫金山天文台）

5、会议联系人：
刘佐伟
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additional slides

Plasmon decay for low-mass MCPs



Photon mass $< 12 \text{ MeV}$

Plasmon decay is the dominant production channel for MCPs w/ mass $< 6 \text{ MeV}$

high-mass MCPs

- proton bremsstrahlung
- electron-positron annihilation

Kinetic mixing & mass mixing

$$SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X$$

[Feldman, ZL, Nath, [hep-ph/0702123](#), 395 cites]

$$\mathcal{L} = \underbrace{-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}}_{\text{photon}} \underbrace{-\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + g_D X_\mu \bar{\chi} \gamma^\mu \chi}_{\text{dark photon}} - \frac{\tilde{\delta}}{2} \underbrace{B_{\mu\nu}}_{\text{photon}} \underbrace{X^{\mu\nu}}_{\text{dark photon}} - \frac{M_1^2}{2} (\partial_\mu \sigma + X_\mu + \tilde{\epsilon} B_\mu)^2$$

↑ kinetic mixing ↑ mass mixing

kinetic mixing $\tilde{\delta}$ & mass mixing $\tilde{\epsilon}$ are **degenerate** (w/o χ): only $\epsilon \sim (\tilde{\epsilon} - \tilde{\delta})$ is physical

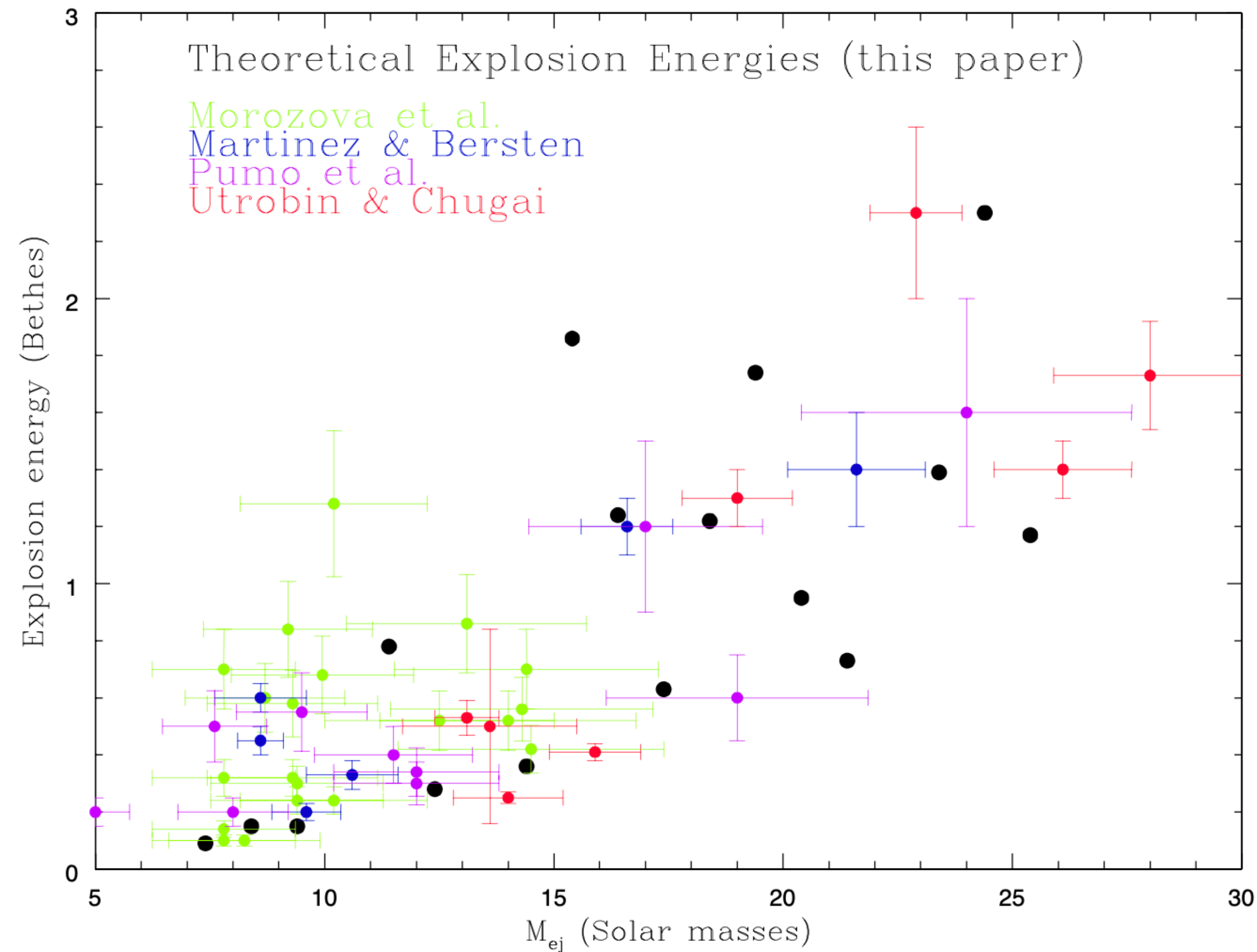
Supernova explosion energy

[Burrows & Vartanyan, 2009.14157]

Model	Explosion Energy	Run Time	Baryonic Mass	Gravitational Mass
[$M_{\odot}$]	[B]	[s]	[$M_{\odot}$]	[$M_{\odot}$]
9	0.09	2.34	1.35	1.23
10	0.15	3.36	1.49	1.35
11	0.15	3.52	1.51	1.37
12	-0.03	2.75	1.82	1.62
13	0.78	4.60	1.89	1.68
14	0.28	4.51	1.81	1.62
15	-0.17	1.04	1.93	1.71
16	0.36	4.45	1.75	1.56
17	1.86	4.66	2.05	1.81
18	1.24	4.58	1.80	1.60
19	0.63	4.45	1.87	1.66
20	1.22	4.56	2.10	1.85
21	1.74	3.76	2.27	1.97
22	0.95	4.74	2.06	1.81
23	0.73	4.55	2.04	1.80
25	1.39	3.11	2.11	1.85
26	2.3	4.60	2.15	1.88
26.99	1.17	4.60	2.12	1.86

Supernova explosion energy

[Burrows & Vartanyan, 2009.14157]

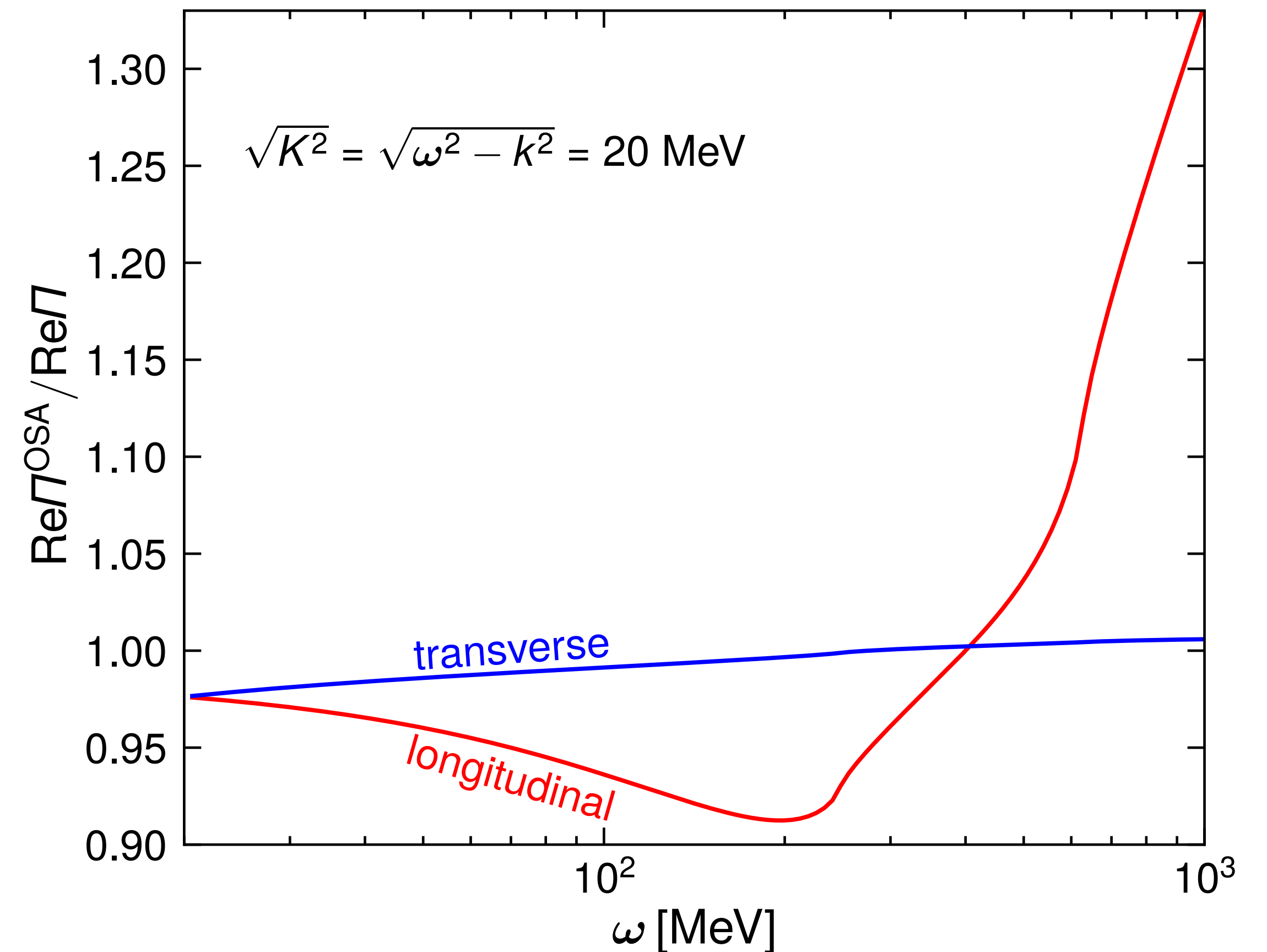
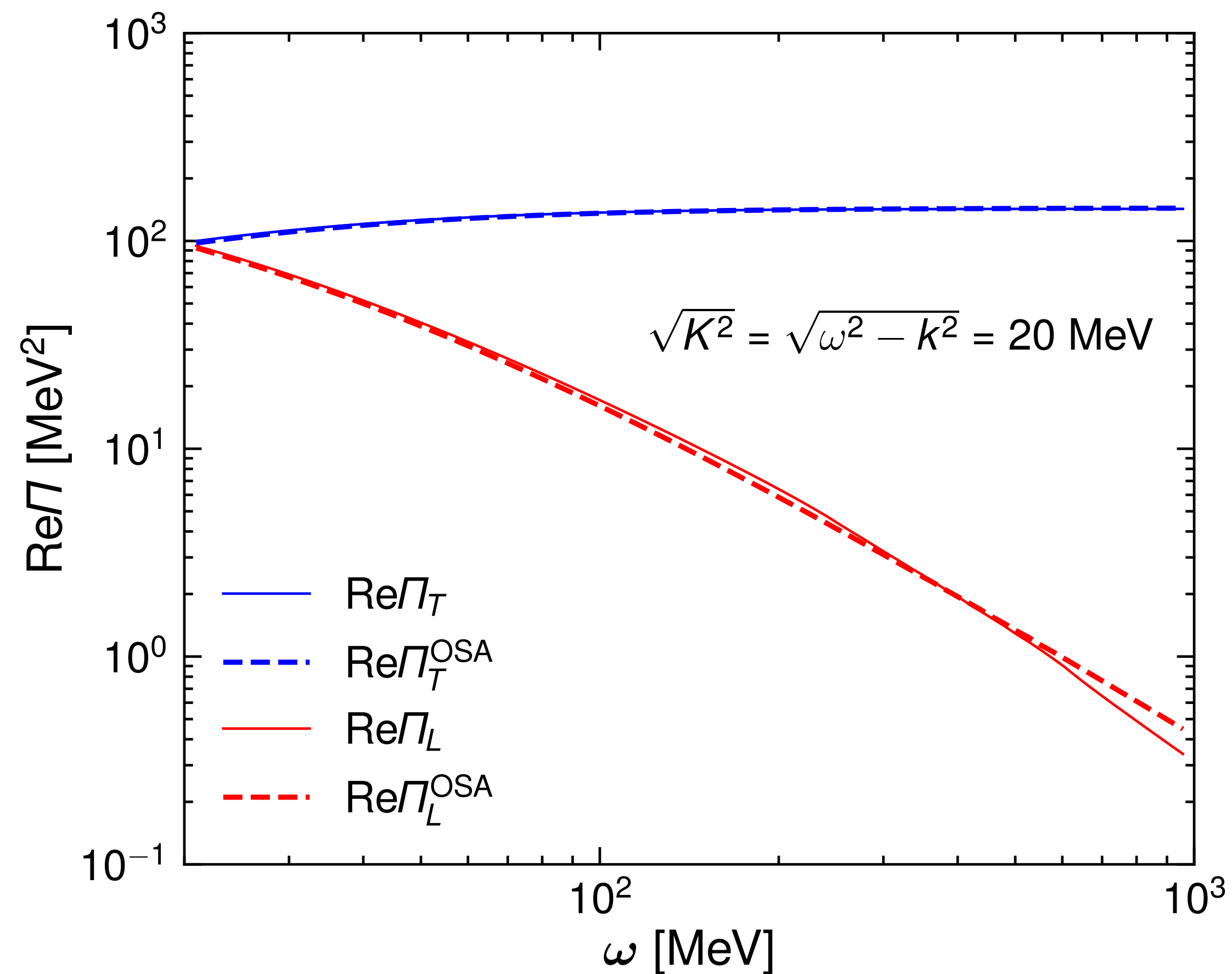


Empirically inferred explosion energies vs. the inferred ejecta masses, with error bars, for a collection of observed Type IIp (plateau) supernovae.

Black dots = theoretical explosion energies

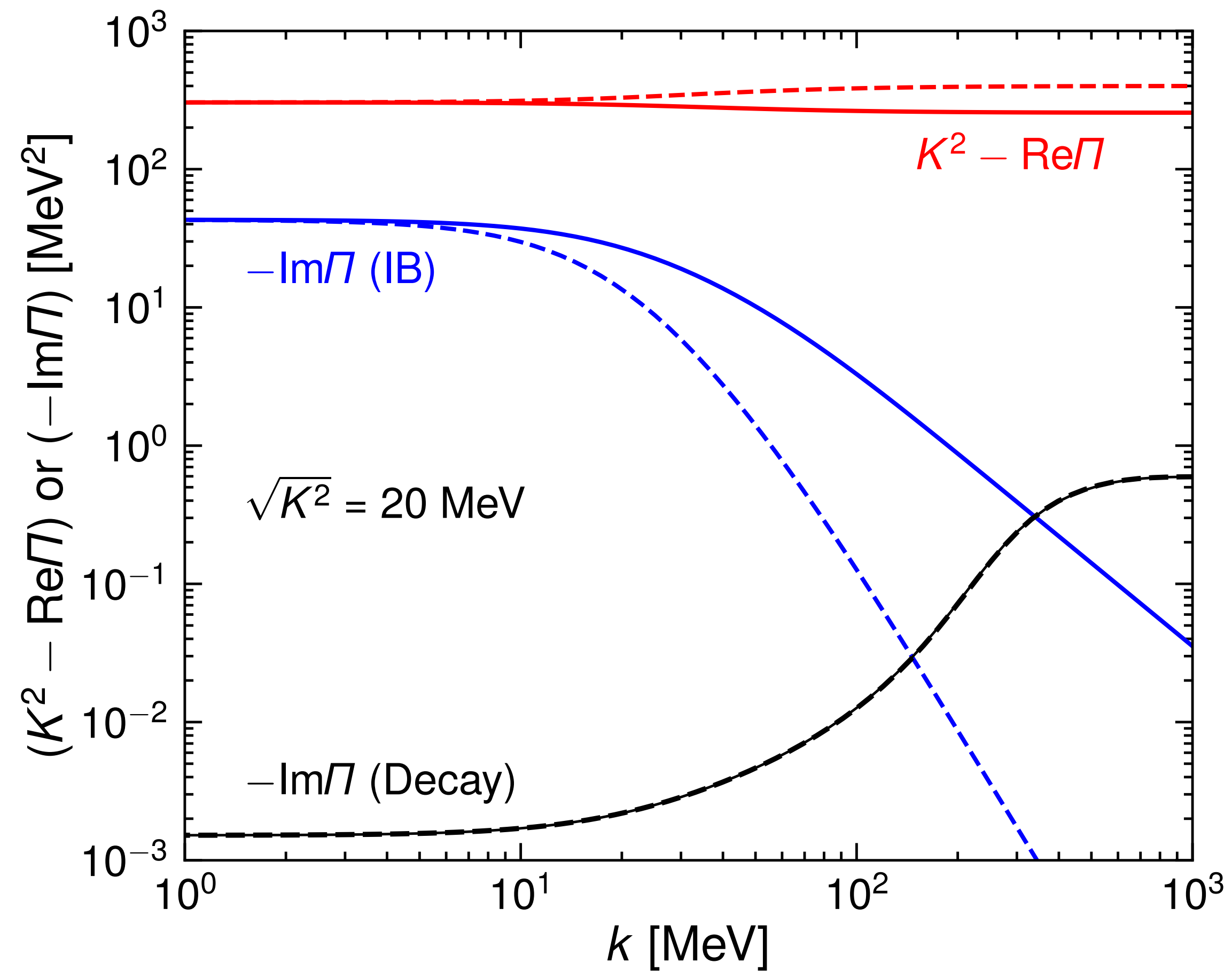
On-shell approximation (OSA) for $\text{Re}\Pi_a$ in off-shell region

OSA: use on-shell dispersion relations to compute $\text{Re}\Pi_a$ in the off-shell region

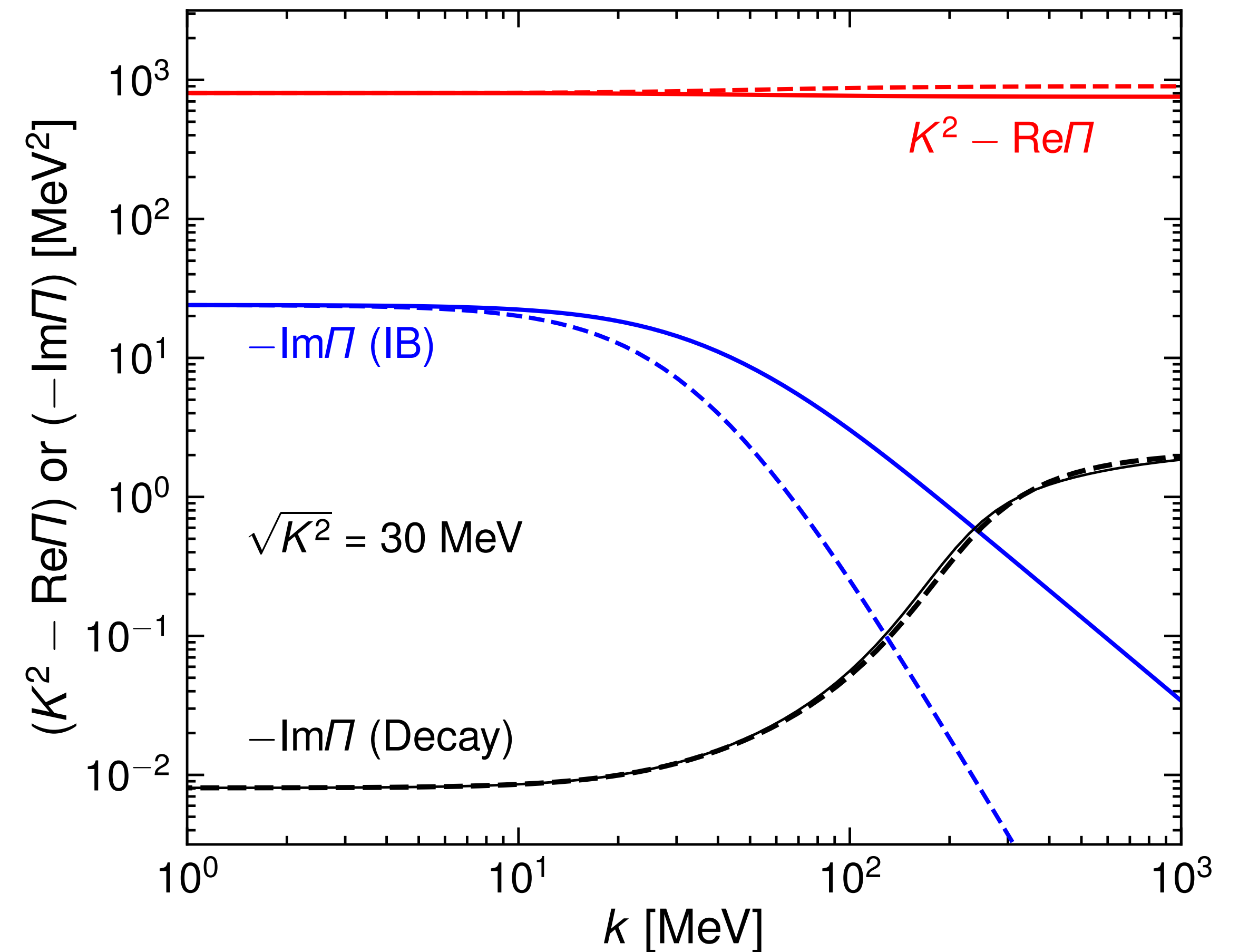


Imaginary part of Π_a in off-shell region

$$\sqrt{K^2} = 20 \text{ MeV}$$



$$\sqrt{K^2} = 30 \text{ MeV}$$



Energy deposition in the mantle

Coulomb scattering with protons in the mantle

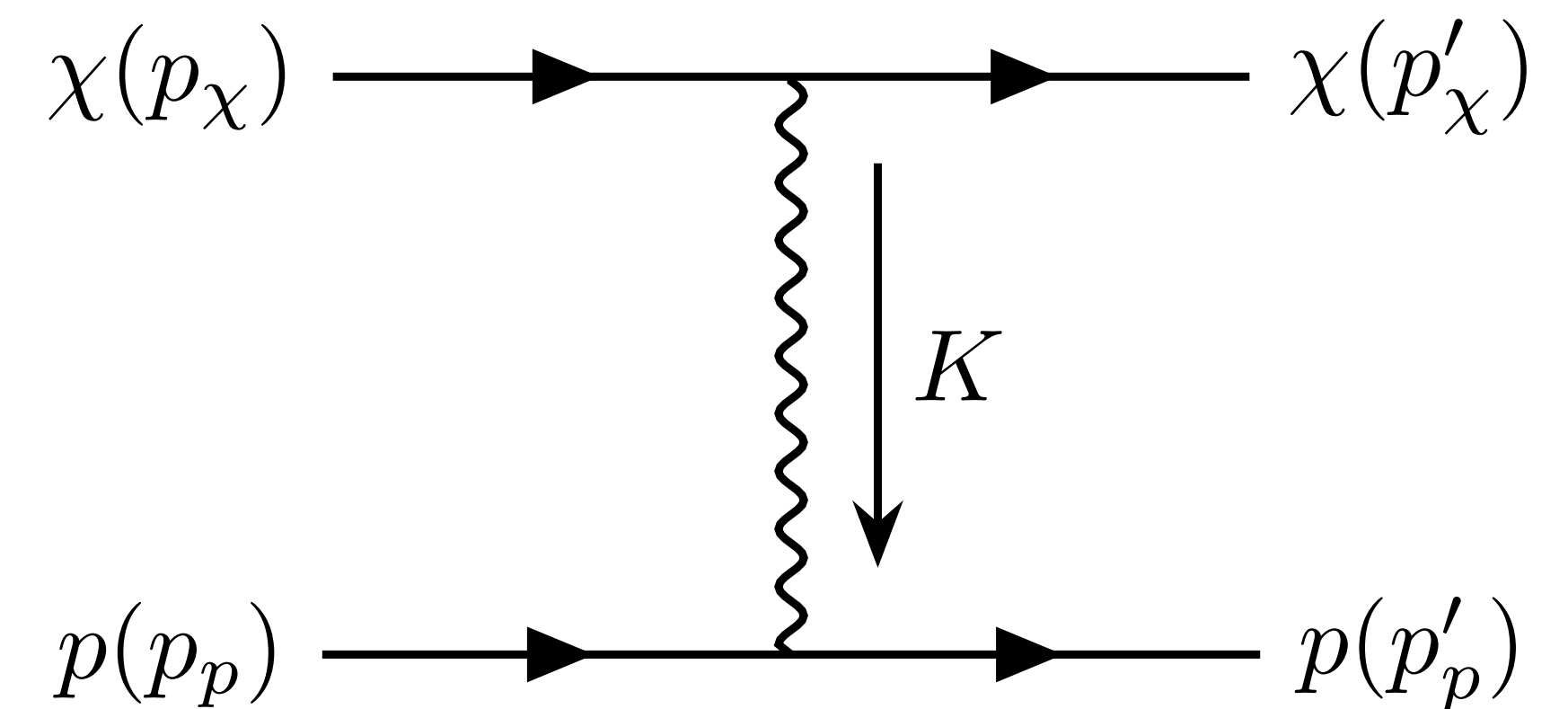
energy loss per unit length

$$\frac{dE_\chi}{dx} = -n_p \int dE_R \frac{d\sigma_{\chi p}}{dE_R} E_R$$

n_p = proton number density in the mantle

E_R = recoil energy received by protons in the mantle

$\frac{d\sigma_{\chi p}}{dE_R}$ = differential Coulomb scattering xsec



2-to-2 elastic scattering

For the 2-to-2 elastic scattering

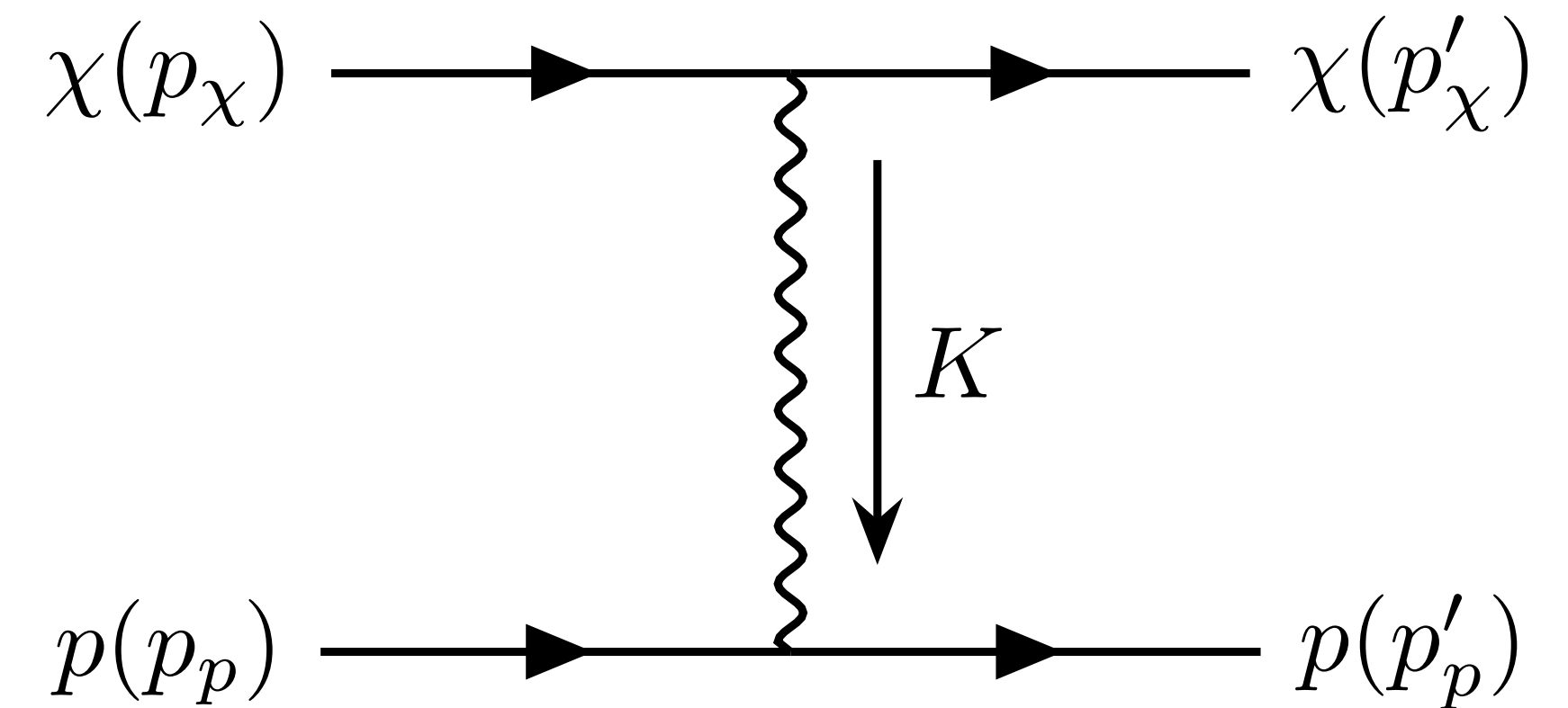
$$E_R = \frac{1}{2} E_R^{\max} (1 - \cos \theta)$$

θ = scattering angle in the CM frame

$E_R^{\max}$ = maximum recoil energy

$$\frac{dE_\chi}{dx} = -\frac{1}{2} n_p E_R^{\max} \sigma_{\chi p}^T$$

$$\sigma_{\chi p}^T = \int d\Omega \frac{d\sigma}{d\Omega} (1 - \cos \theta) = \text{transport xsec}$$



Debye screening

Debye screening effects

$$\sigma \rightarrow \sigma \frac{K^2}{(K^2 + k_D^2)}$$

[Davidson+, hep-ph/0001179]

Modified transport xsec

$$\sigma_{\chi p}^T = \frac{2\pi\epsilon^2\alpha^2}{E_\chi^2} \left[\frac{2+z}{2} \ln \left(\frac{2+z}{z} \right) - 1 \right]$$

$$\text{Debye scale: } k_D = 2\sqrt{\pi\alpha n_p/T}$$

$$z = k_D^2/2E_\chi^2$$

Energy deposition

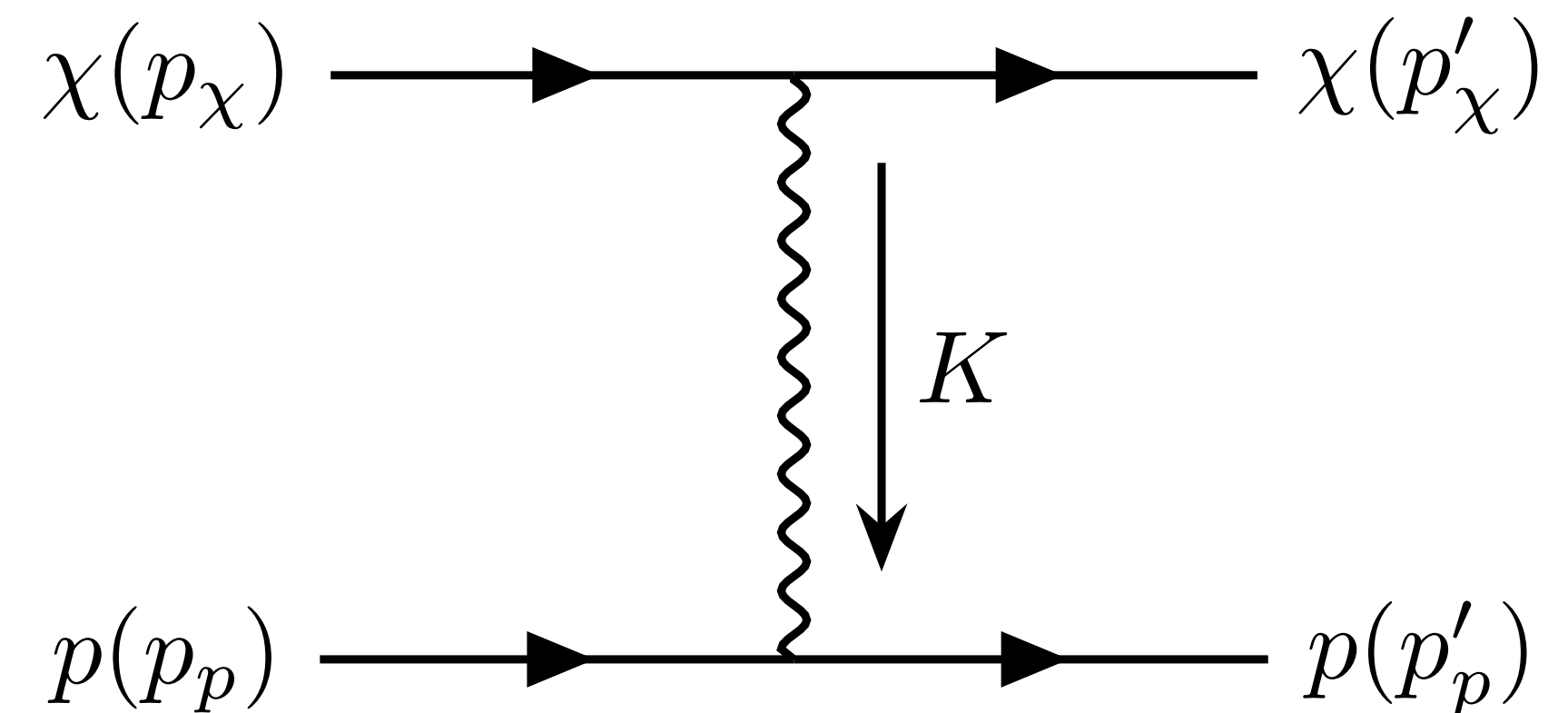
Mantle colder than core $\implies$ assume protons initially at rest

$$E_R^{\max} = \frac{2m_p(E_\chi^2 - m_\chi^2)}{m_p^2 + m_\chi^2 + 2m_p E_\chi}$$

energy deposited by a single MCP particle in the mantle

$$\Delta E_\chi = \frac{1}{2} \int dx n_p E_R^{\max} \sigma_{\chi p}^T$$

distance = 3 light-seconds



Mantle profiles

Proton number density & temperature profiles in the mantle

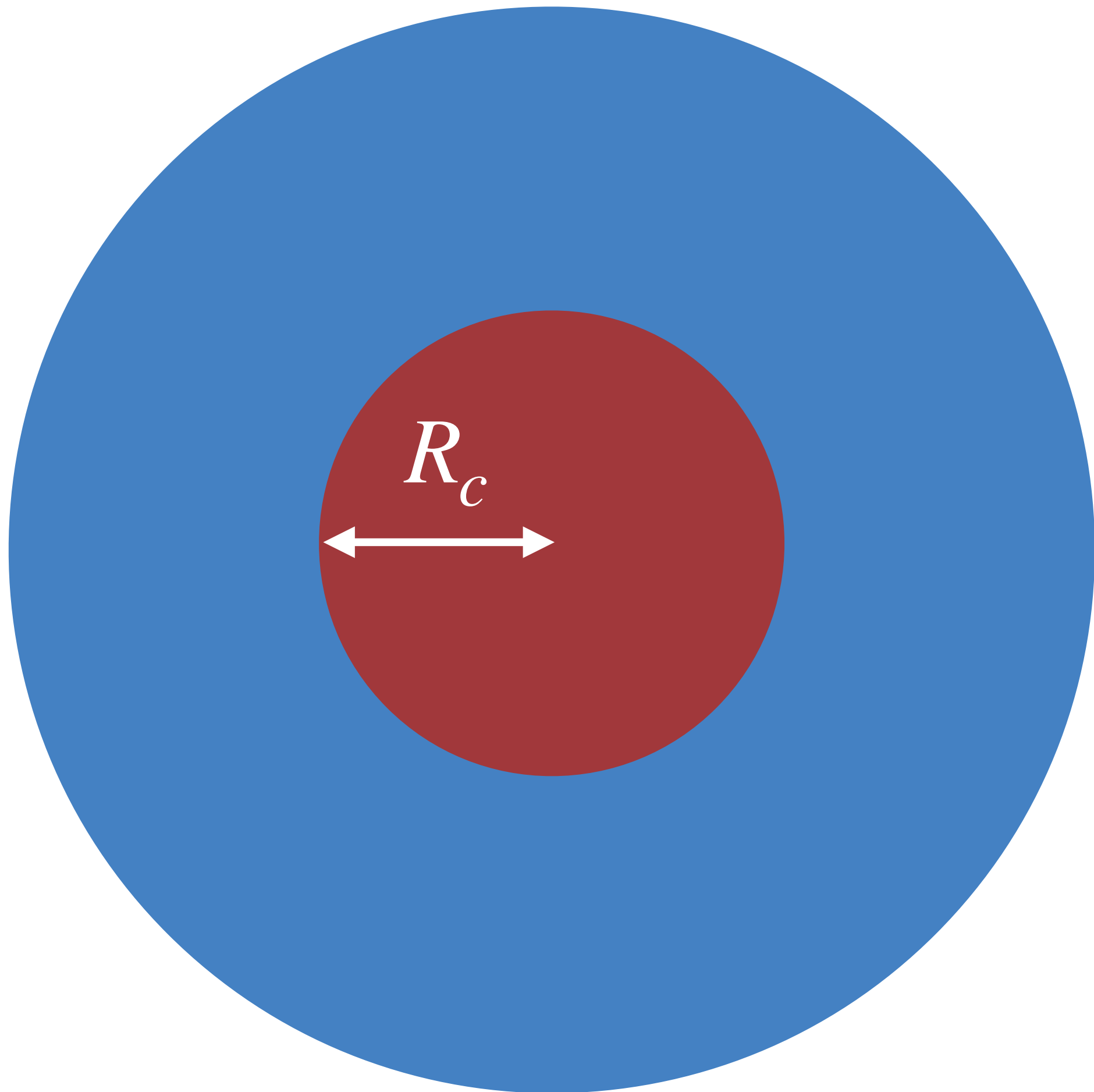
$$\rho(r) = \rho_c \times (r/R_c)^{-\nu} \quad r > R_c \quad [\text{Chang+}, 1611.03864]$$

$$T(r) = T_c \times (r/R_c)^{-\nu/3} \quad r > R_c$$

$$\nu = 5$$

$$Y_p = 0.15$$

Particle energies in the one-zone model



Photon mass < 12 MeV

Photon: $\langle E_\gamma \rangle \simeq 3T_c = 90$ MeV

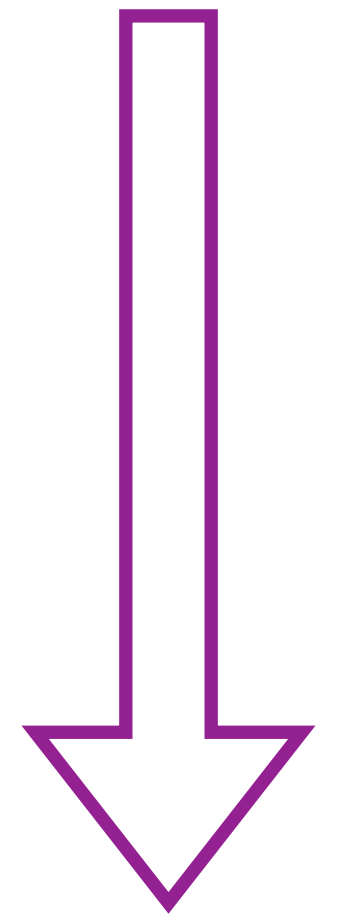
Nucleon: $\langle E_n \rangle \simeq 45$ MeV

electron chemical potential:
 $\mu \simeq 167$ MeV

electron: $\langle E_{e-} \rangle \simeq 160$ MeV

positron: $\langle E_{e+} \rangle \simeq 90$ MeV

low-mass
 < 6 MeV



high-mass