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]

2 Millicharged particles (MCPs)

Millicharged particles (MCPs)

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

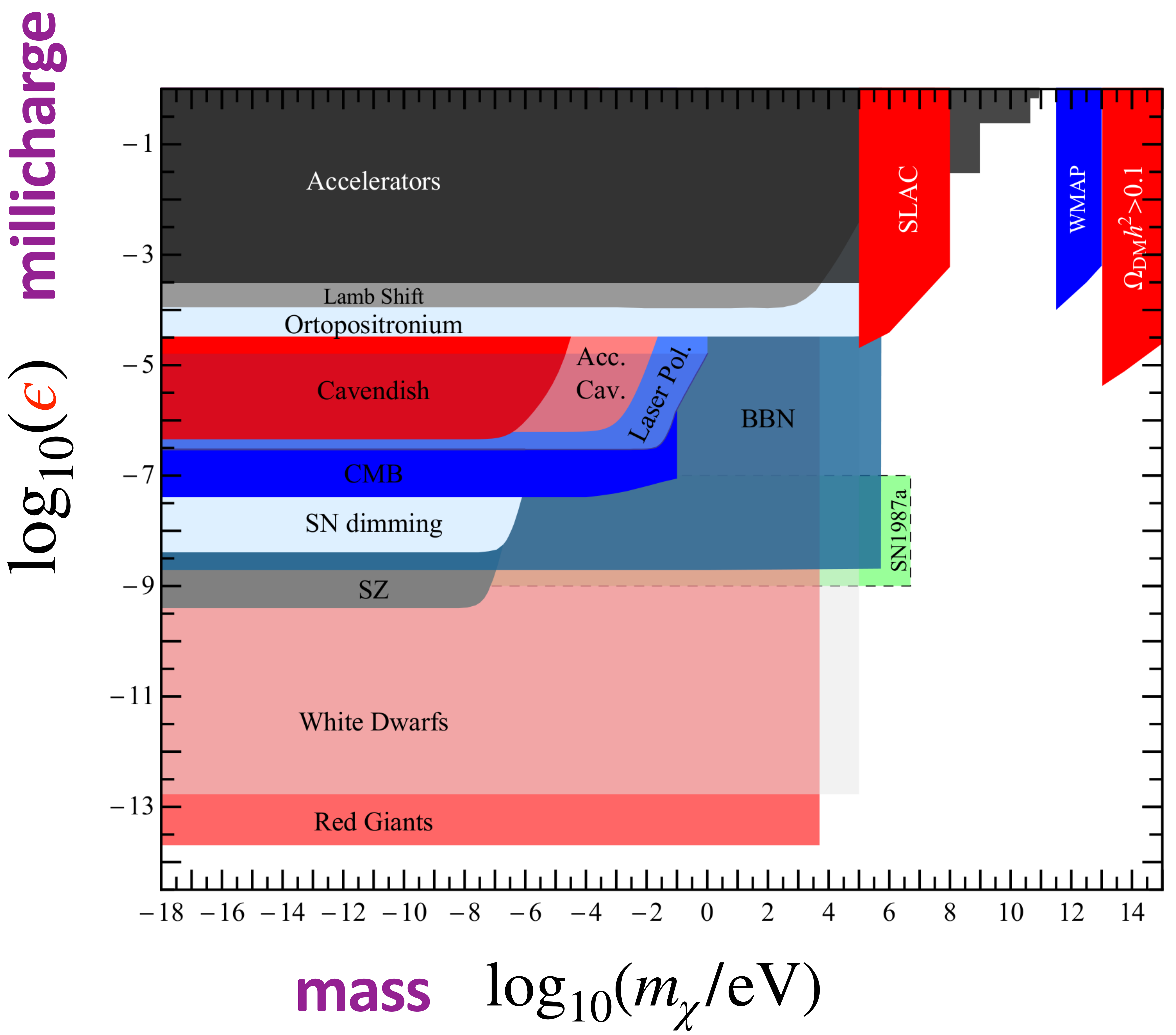
$$e\,\epsilon\,A_\mu\,\bar{\chi}\,\gamma^\mu\,\chi$$

- charge quantization
- neutrino millicharge
- dark matter millicharge

$U(1)_X$ models with kinetic mixing or mass mixing parameters

[Feldman, ZL, Nath, hep-ph/0702123, 394 cites]

Constraints on millicharged particles



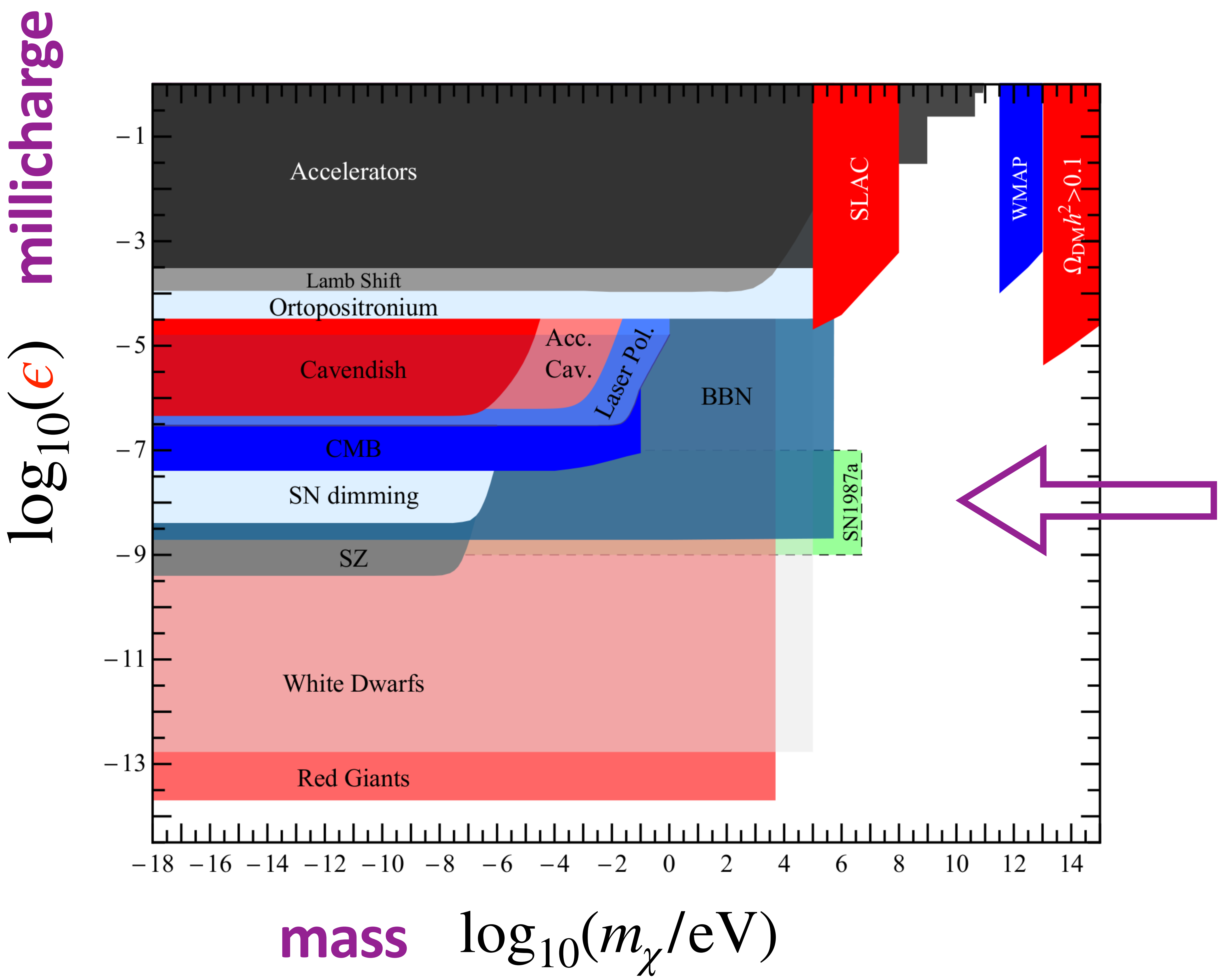
$$e\,\epsilon\,A_\mu\,\bar{\chi}\,\gamma^\mu\,\chi$$

[Jaeckel & Ringwald, 1002.0329]

high-mass: accelerator

low-mass: stellar cooling

Constraints on millicharged particles



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

[Jaeckel & Ringwald, 1002.0329]

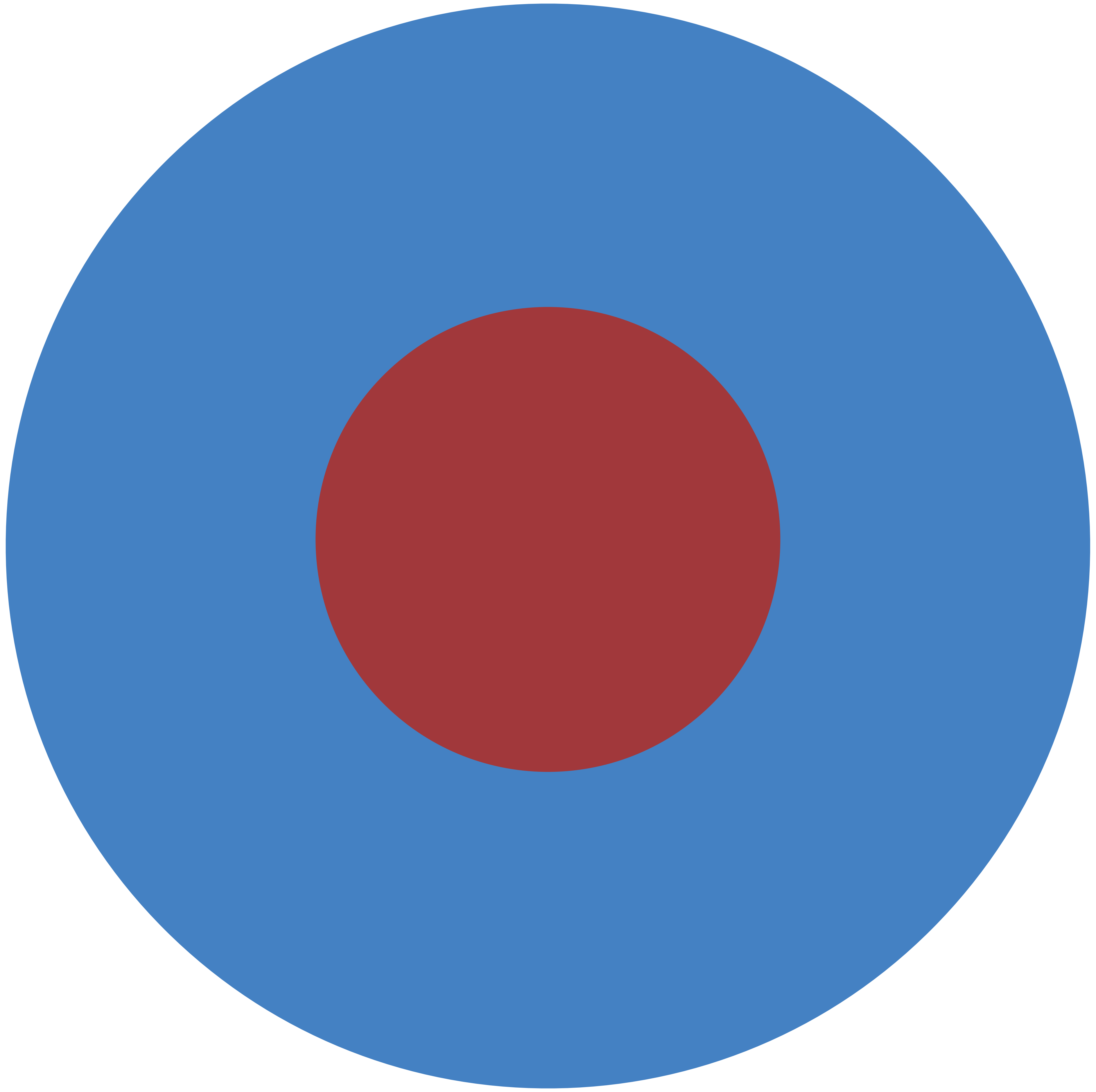
Supernova constraints

high-mass: accelerator

low-mass: stellar cooling

1 Low-energy supernovae (LESNe)

Supernova cooling limit

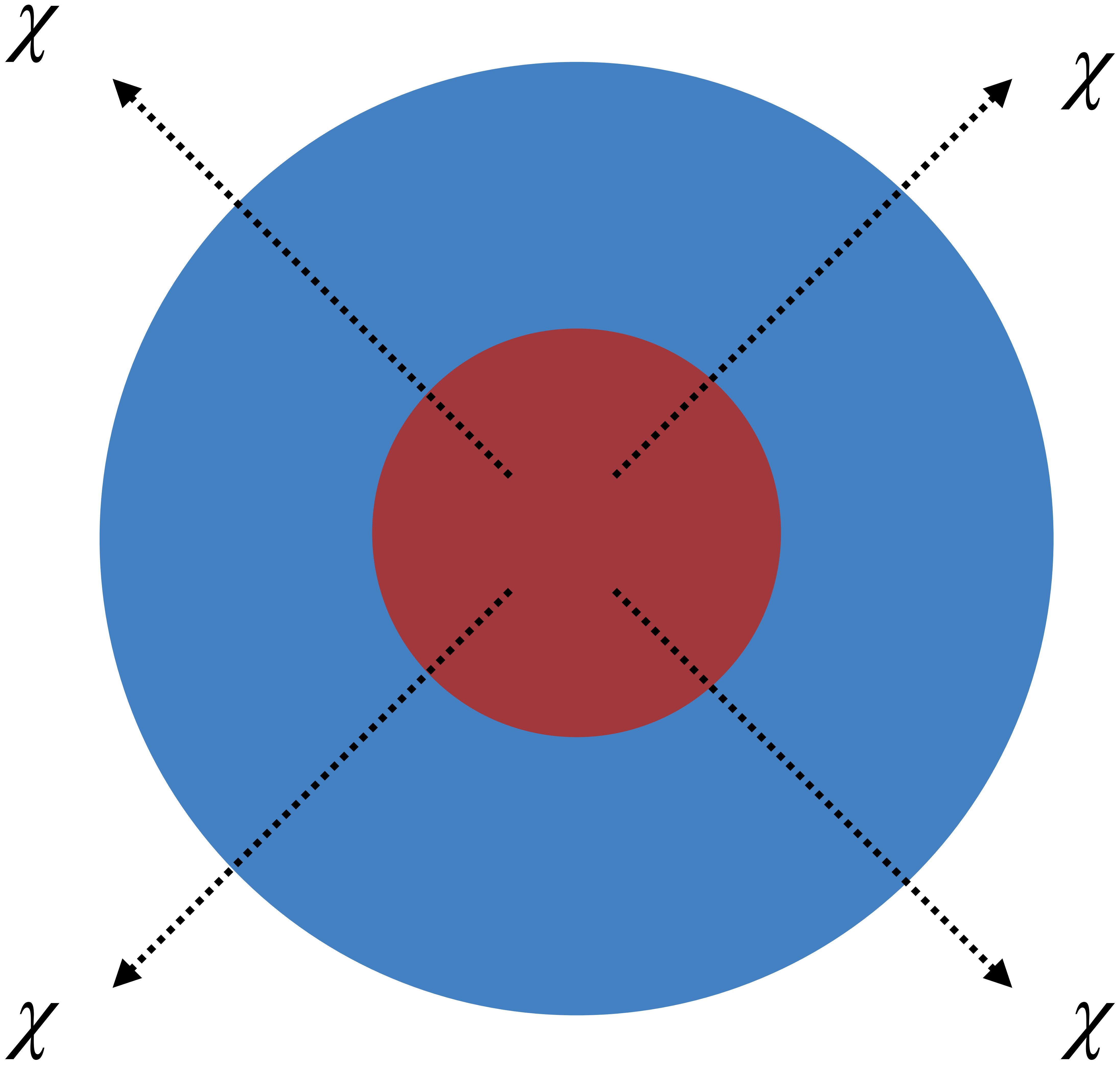


Raffelt criterion

NP < neutrino

[Raffelt, 1996]

Supernova cooling limit



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NP < neutrino

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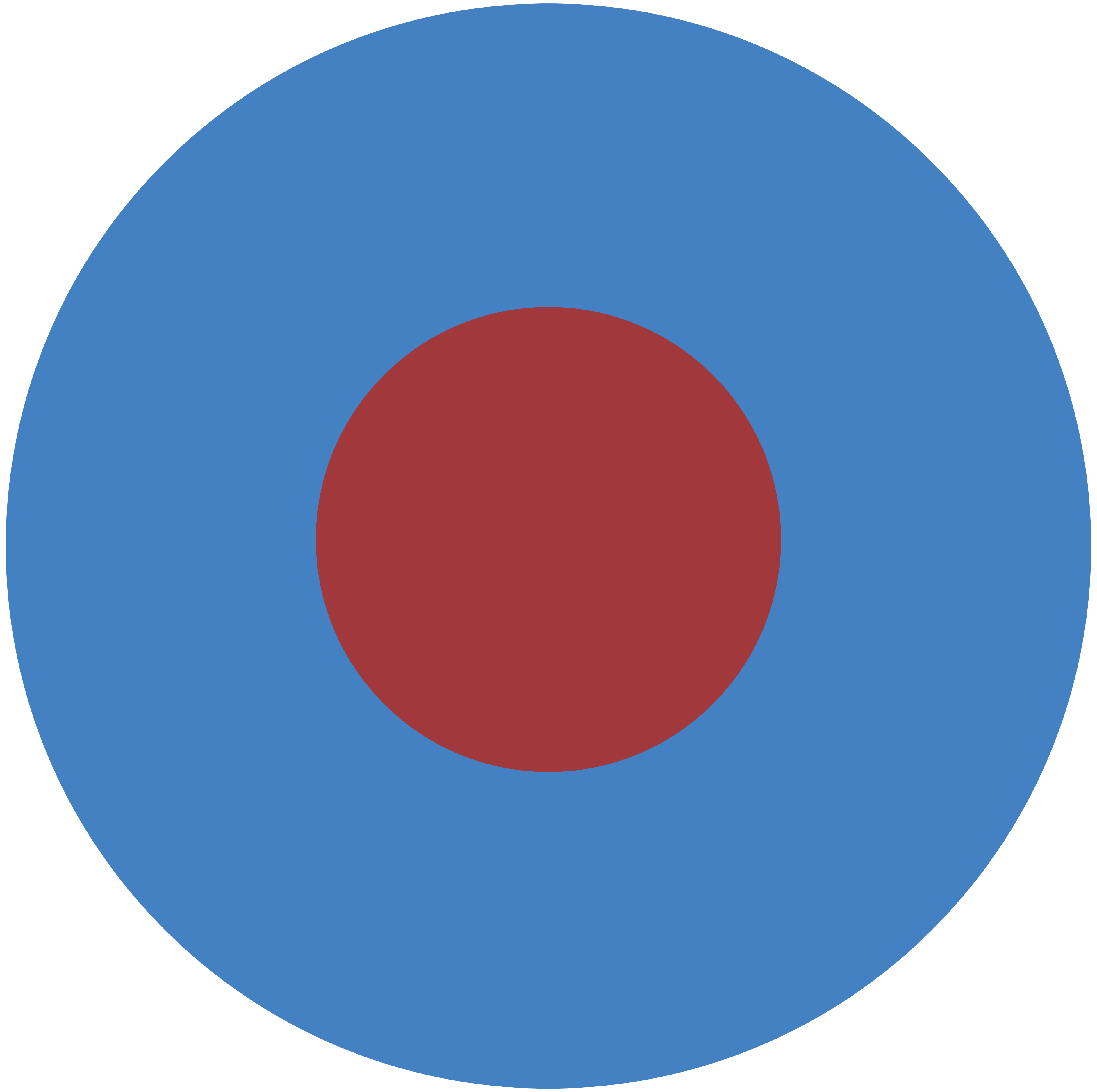
Supernova “calorimetric” limit



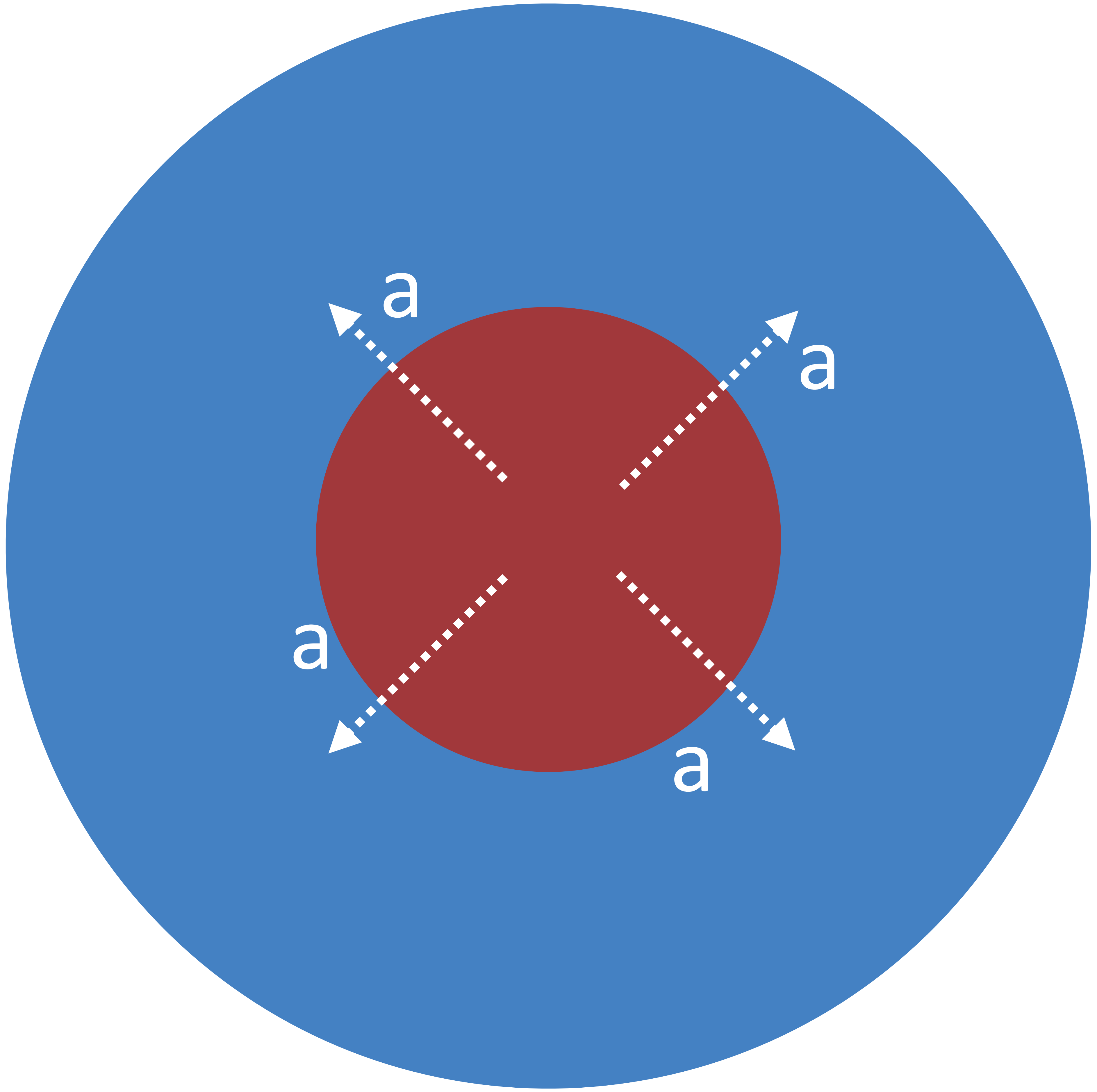
Energy transfer < explosion energy

[Falk & Schramm, 1978]

[Sung+, 1903.07923]

[Caputo+, 2201.09890]

Supernova "calorimetric" limit



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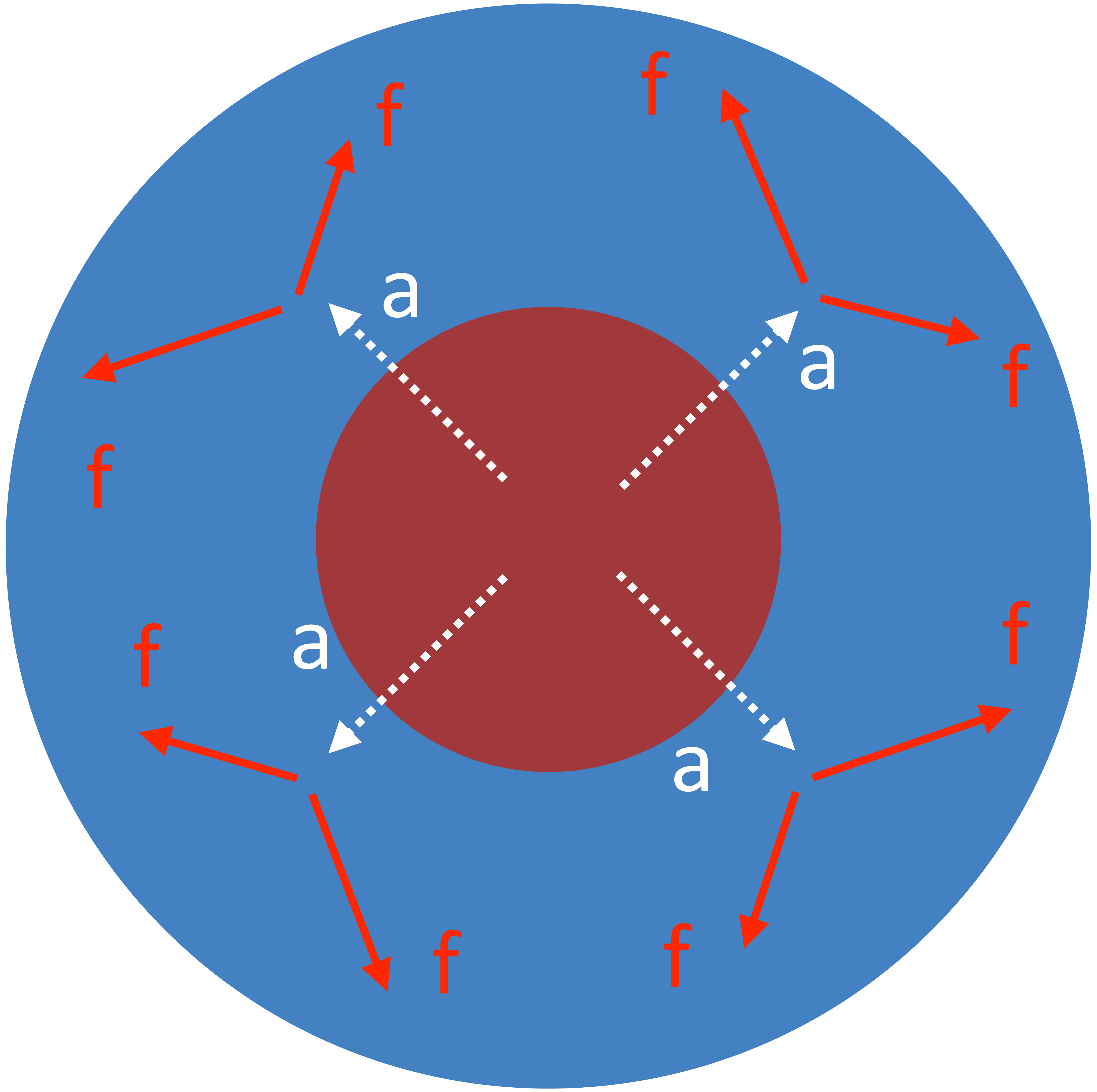

Energy transfer < explosion energy

[Falk & Schramm, 1978]

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[Caputo+, 2201.09890]

Low-Energy Supernovae (LESNe)

underluminous Type-II P SN

relatively small mass

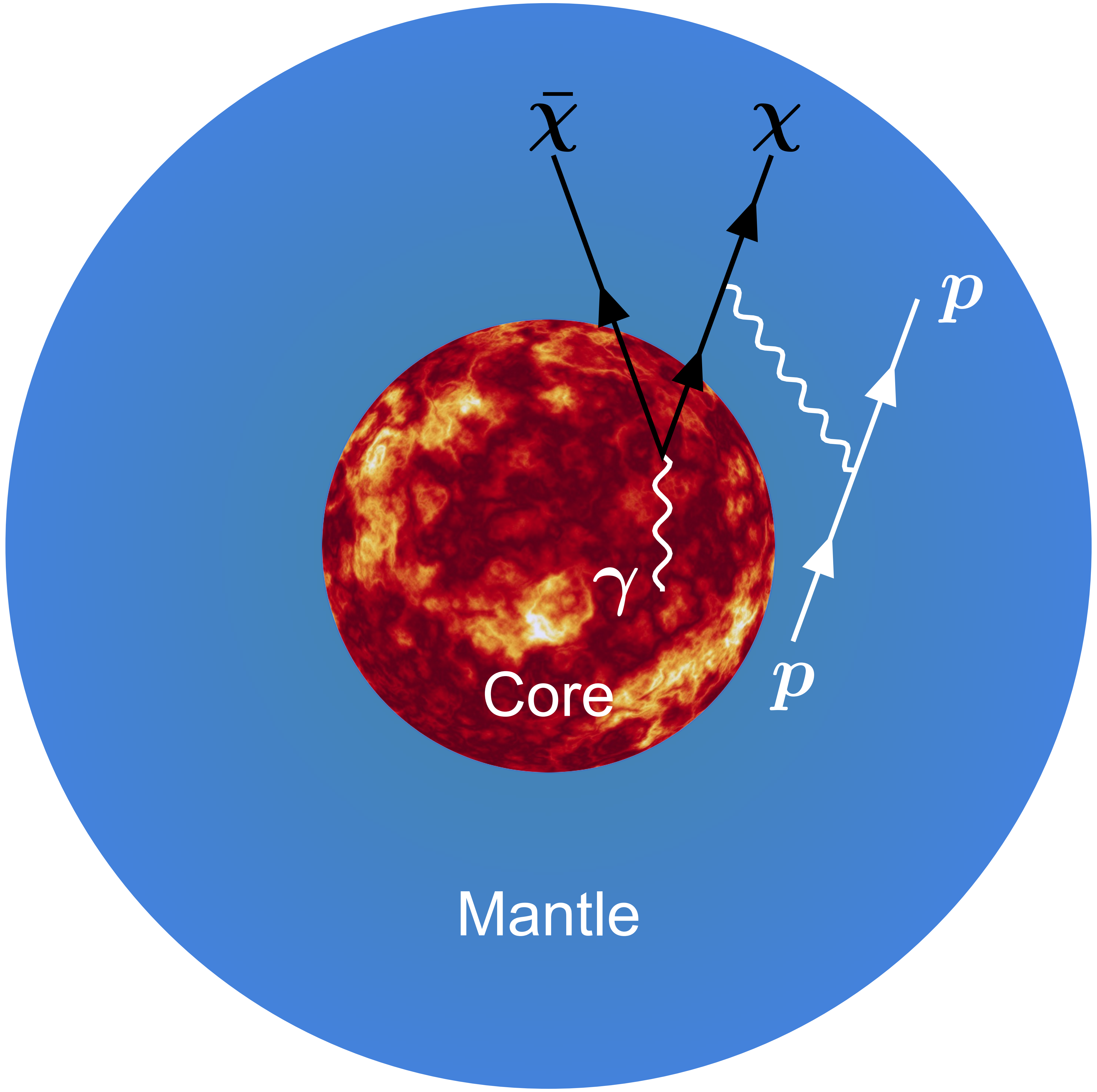
explosion energy as low as 0.1 B

$B = 10^{51}$ erg

[Caputo+, 2201.09890]

[Burrows & Vartanyan, 2009.14157]

LESN constraints on MCPs

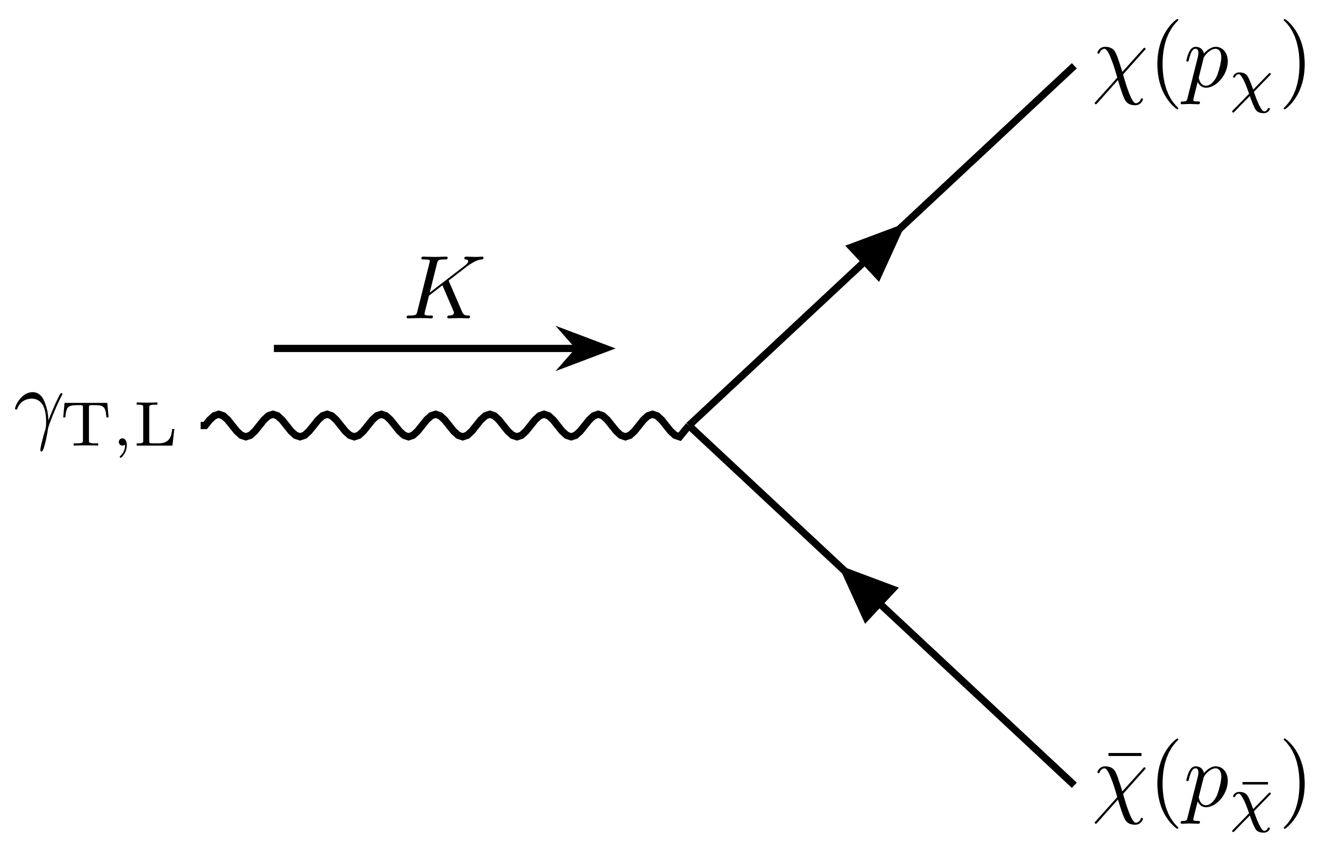


MCPs production in the core

Energy deposition: Coulomb scattering

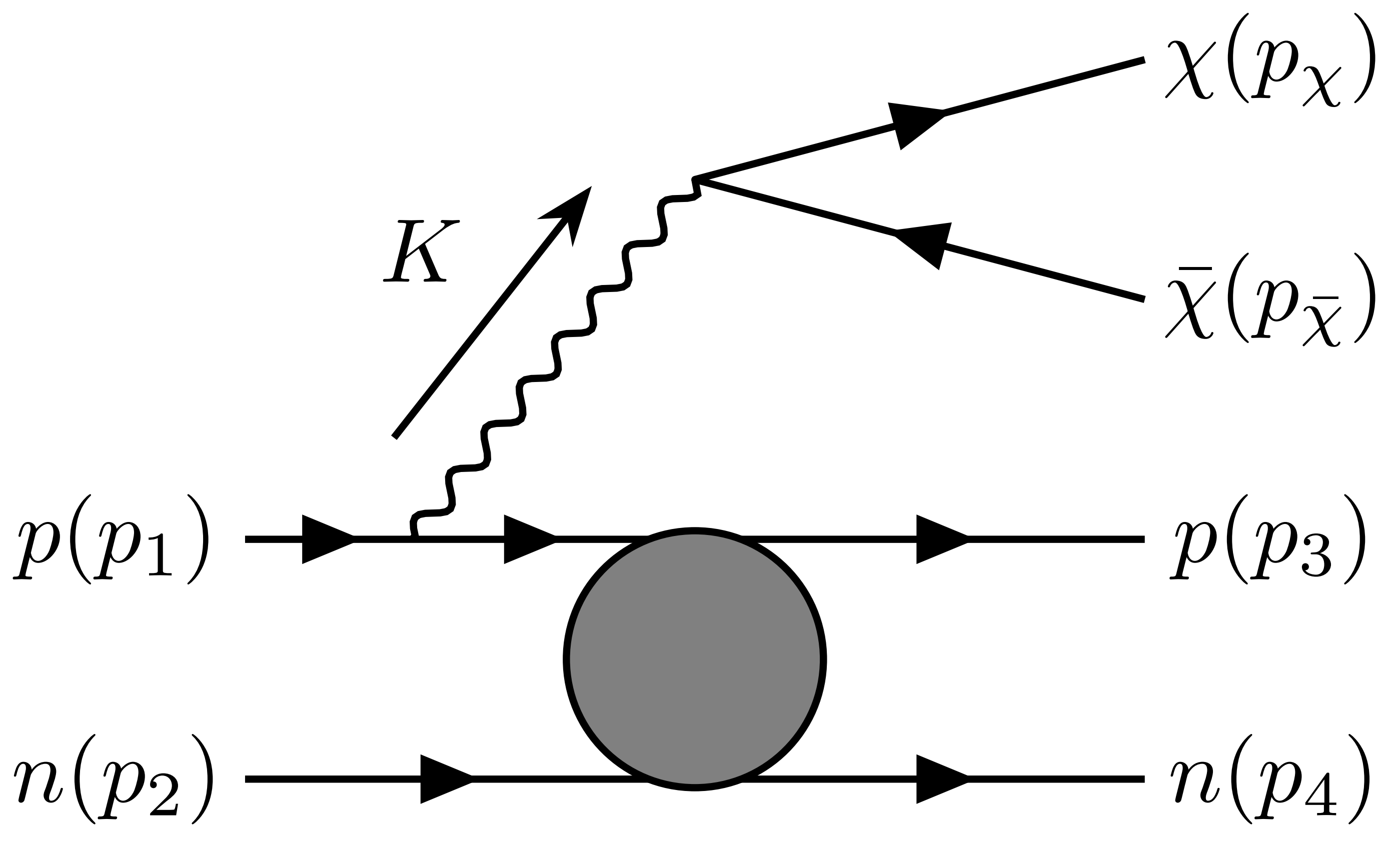
3 MCP production in the SN core

MCP production in the SN core



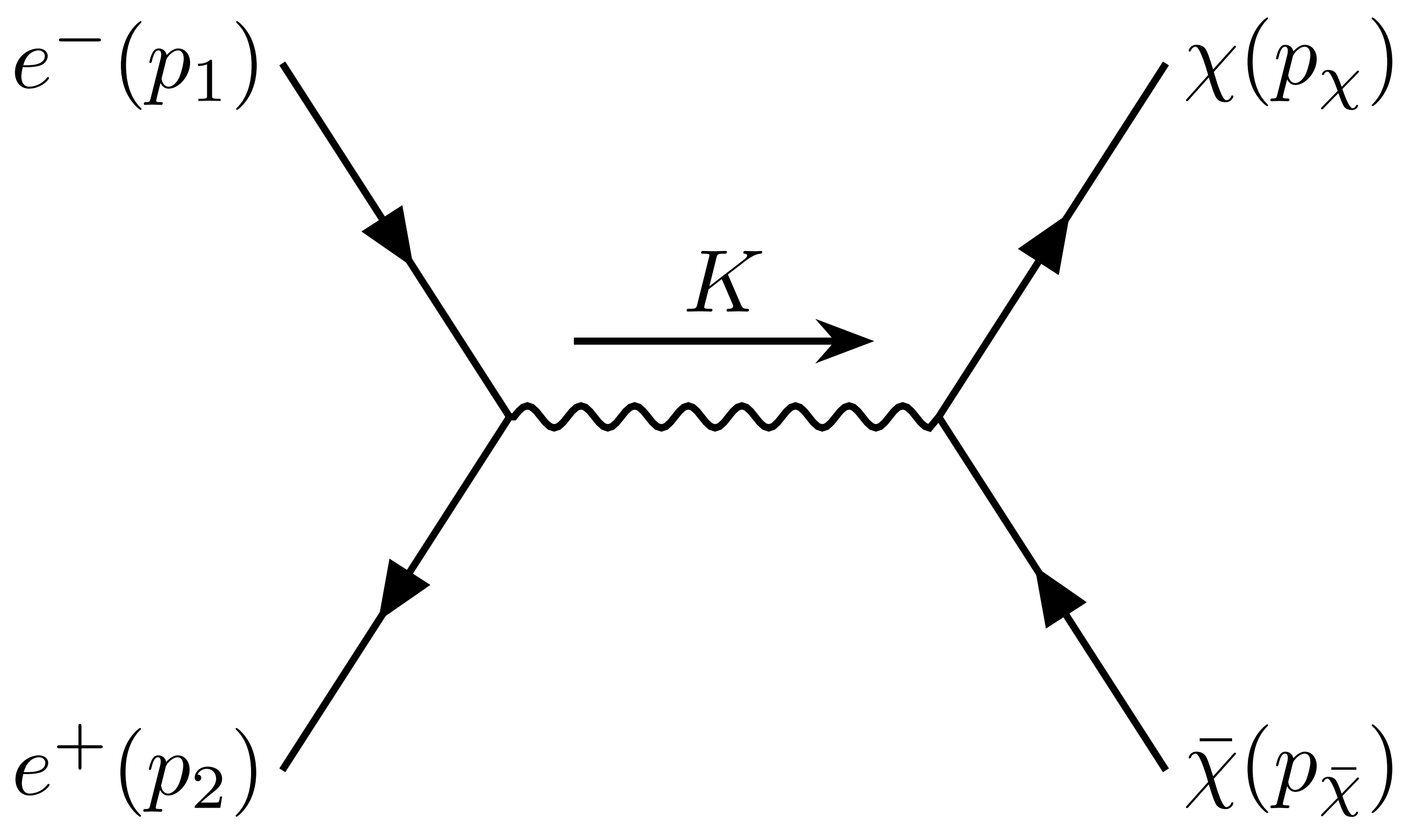
(a)

plasmon
decay



(b)

proton
bremsstrahlung



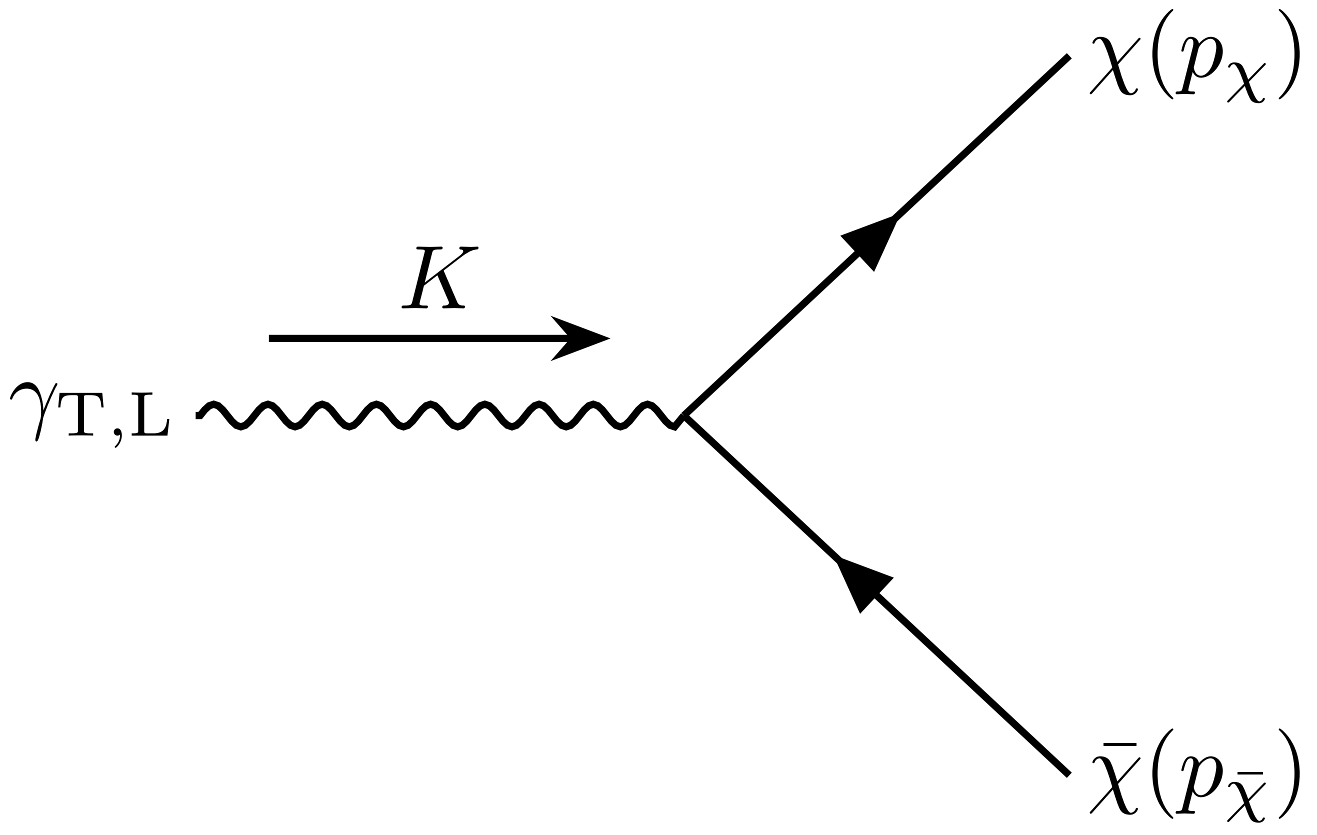
(c)

electron-positron
annihilation

[Davidson+, hep-ph/0001179]

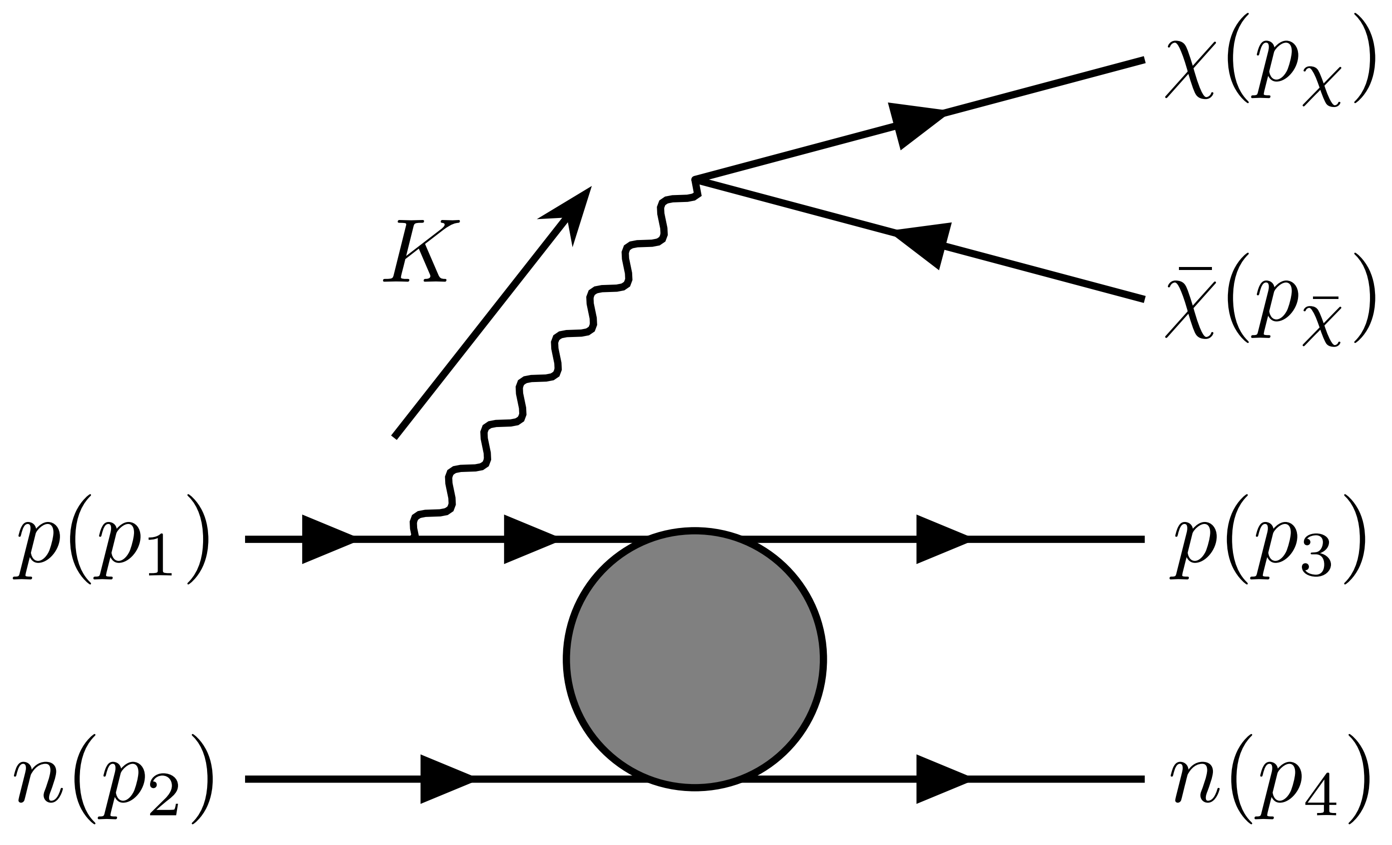
[Chang+, 1803.00993]

MCP production in the SN core



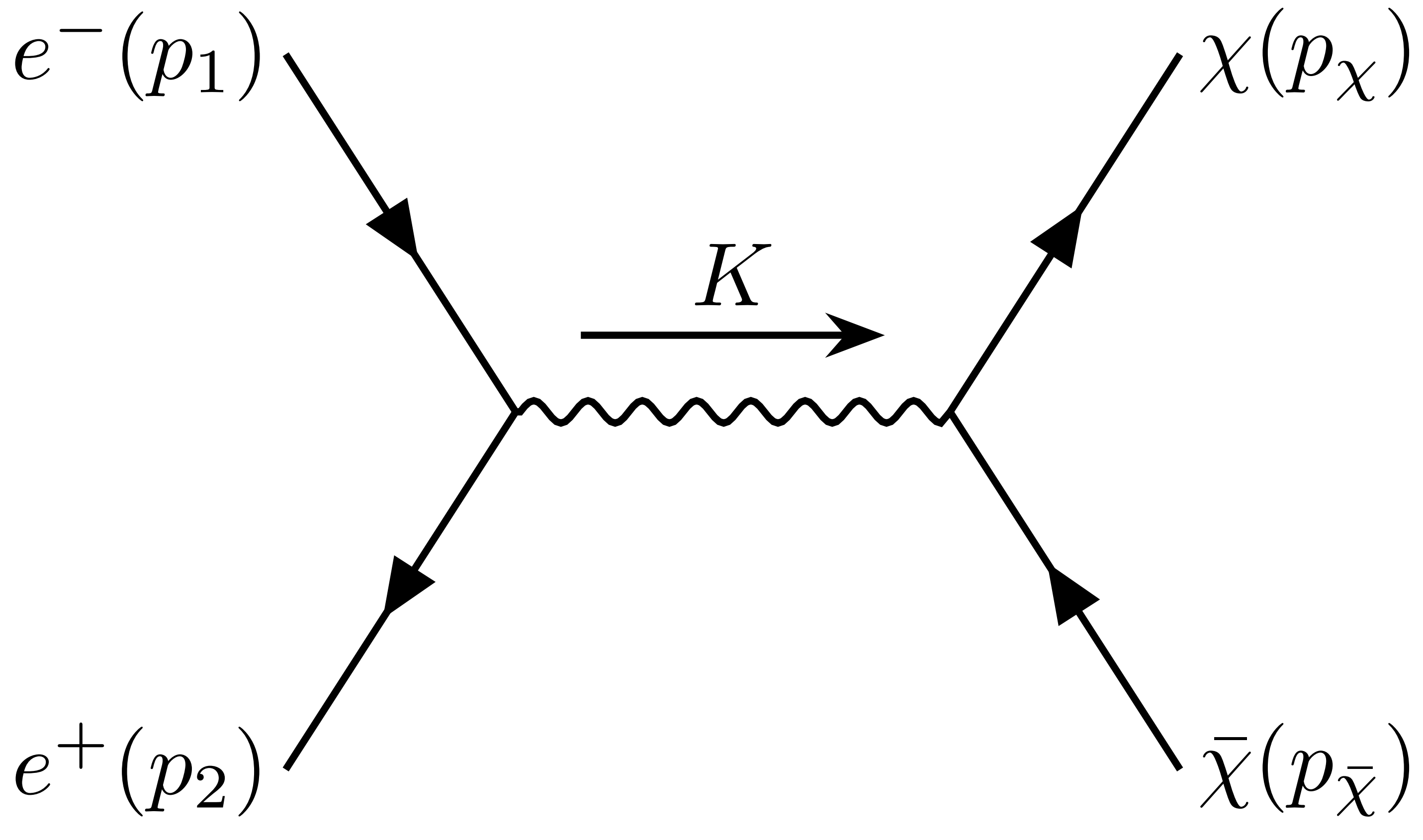
(a)

plasmon decay



(b)

proton bremsstrahlung



(c)

electron-positron annihilation

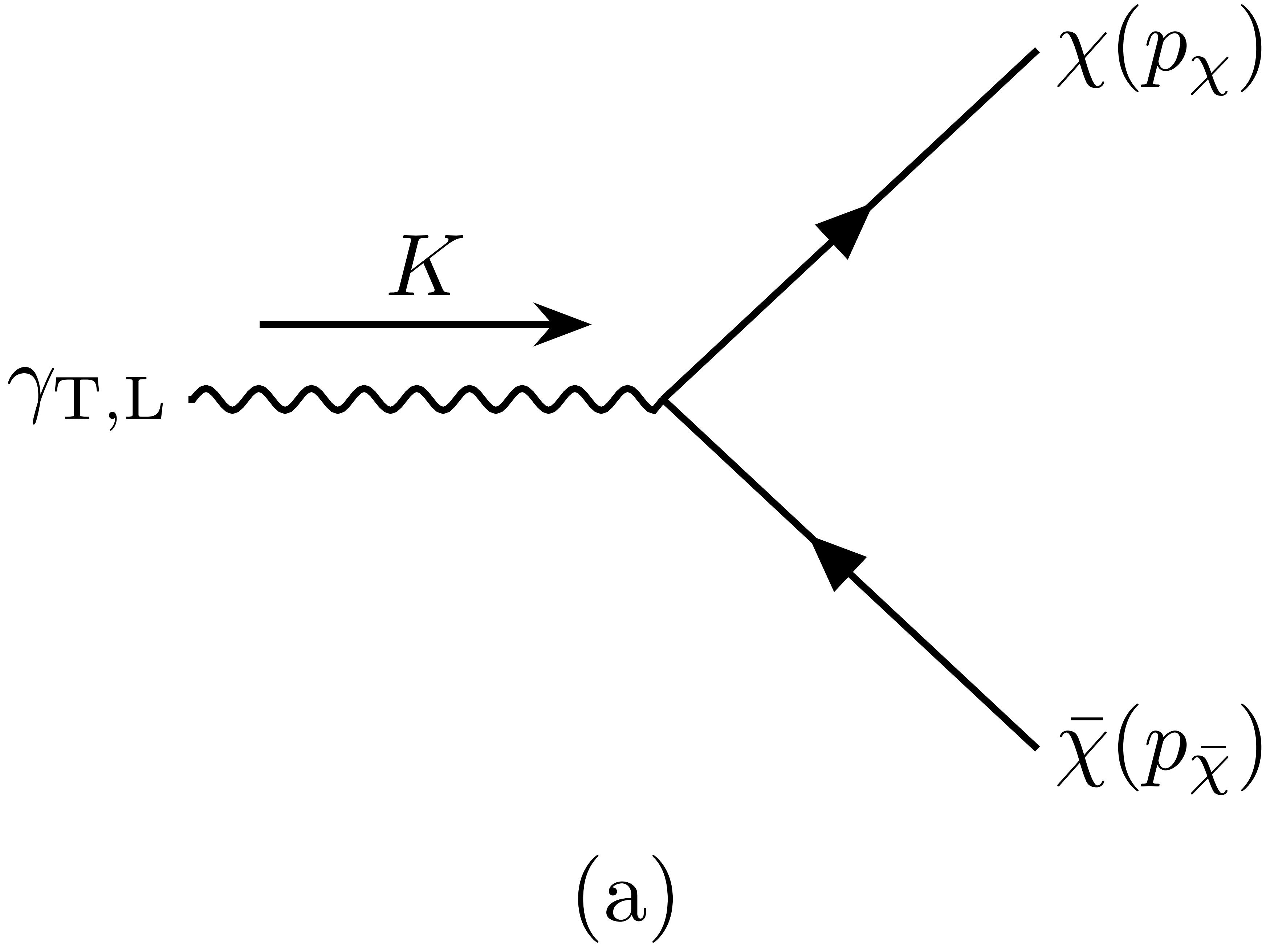
[Davidson+, hep-ph/0001179]

[Chang+, 1803.00993]

(previously omitted for MCPs)

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

millicharged particle flux from plasmon decay

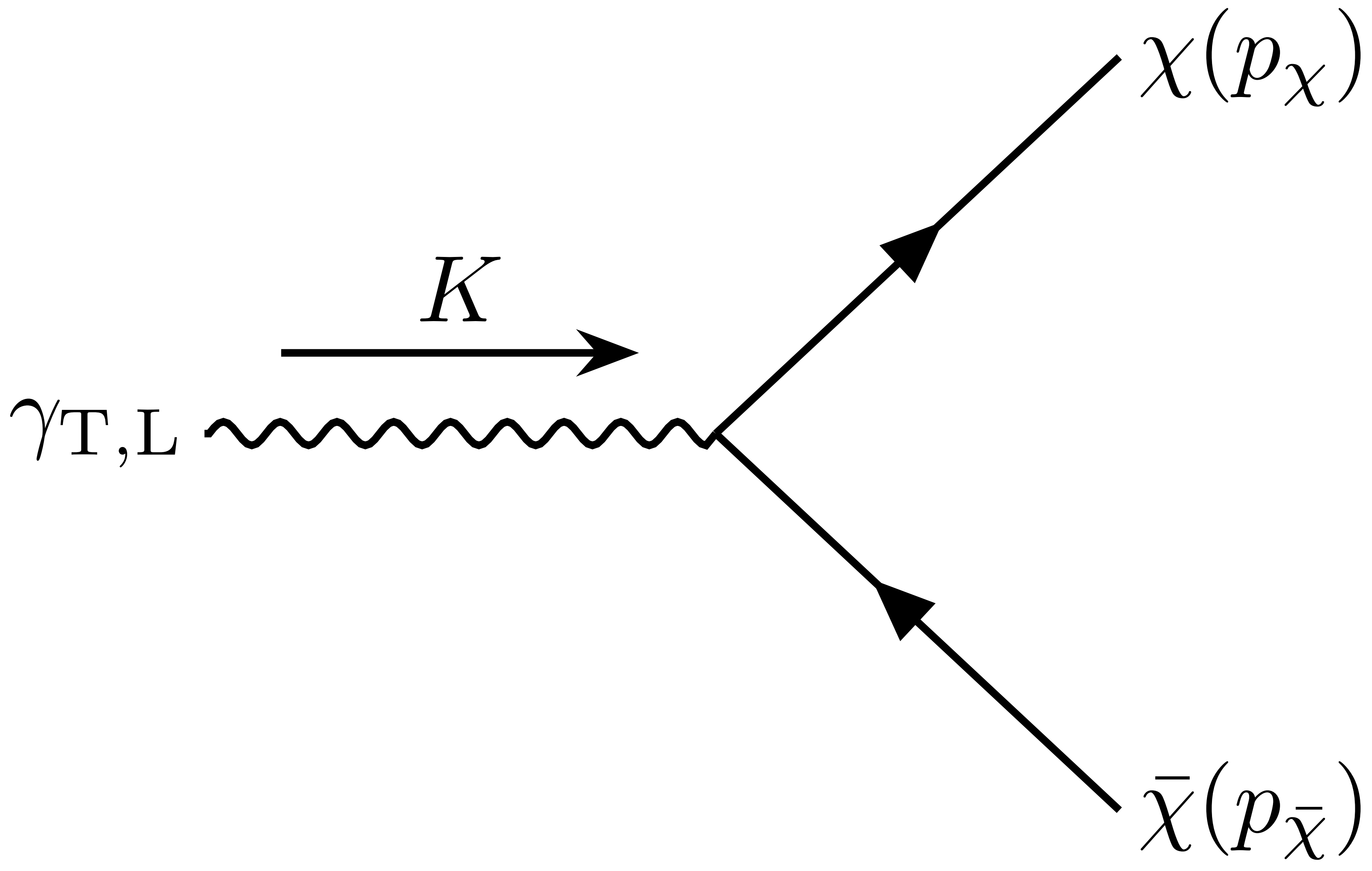
MCP production rate per unit volume per unit energy (relativistic limit) $k \equiv |\mathbf{k}|$

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

MCP energy spectrum per decay (plasma frame)

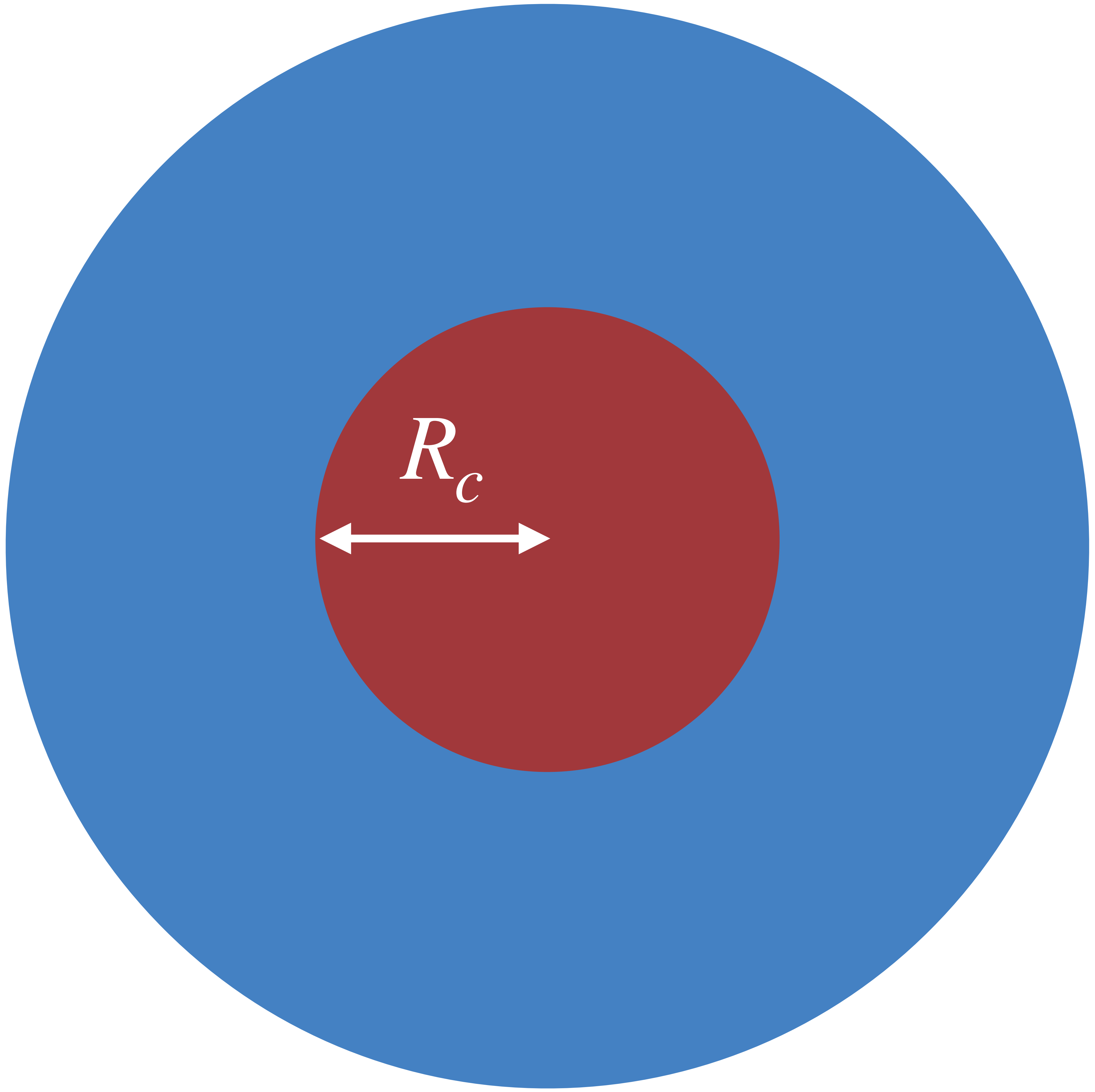
$$g(E_\chi, m_\chi, K) = 2\frac{\Theta(E_\chi - E_\chi^-)\Theta(E_\chi^+ - E_\chi)}{E_\chi^+ - E_\chi^-}$$

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



(a)

One-zone model for the supernova



[Caputo+,2022]

parameters for the SN core

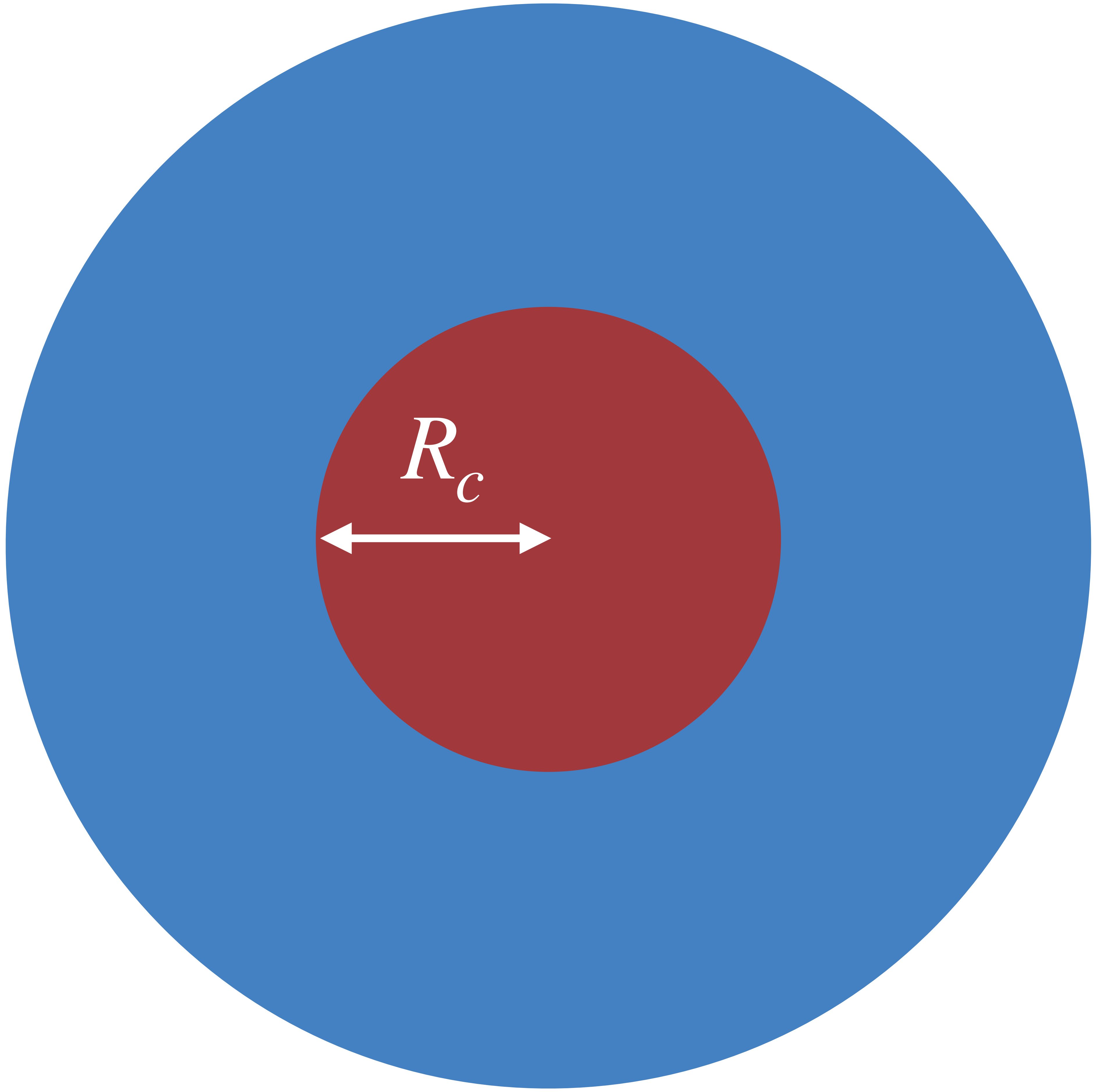
Radius: $R_c = 12.9$ km

Temperature: $T_c = 30$ MeV

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

Proton Abundance: $Y_p = 0.15$

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

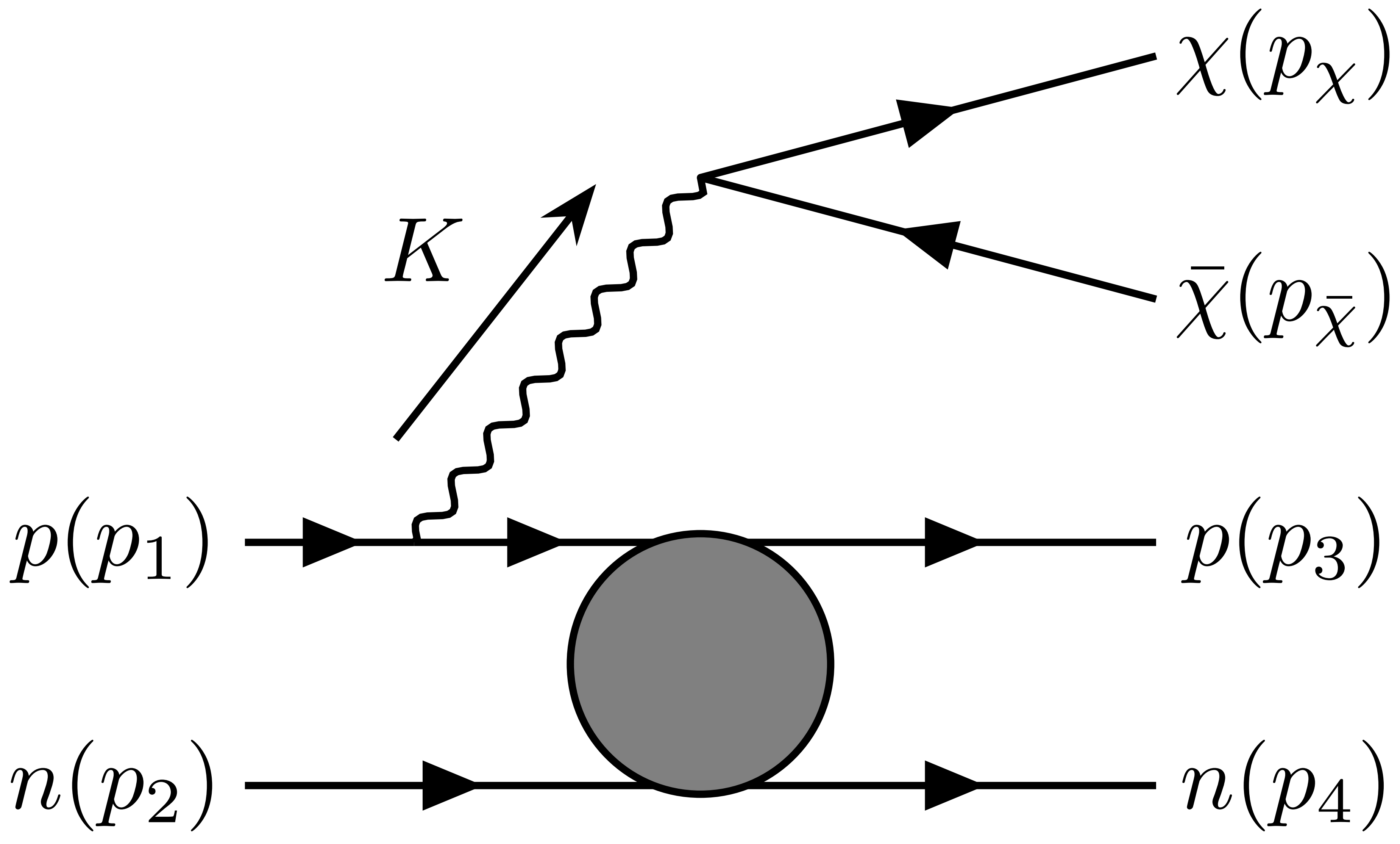
[Gninenko+, 1810.06856]

[Liang, ZL, Yang, 2111.15533]

[Du, Fang, ZL, 2211.11469]

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

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



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

[Chu+, 1908.00553]

Photon emission in soft radiation approximation (SRA)

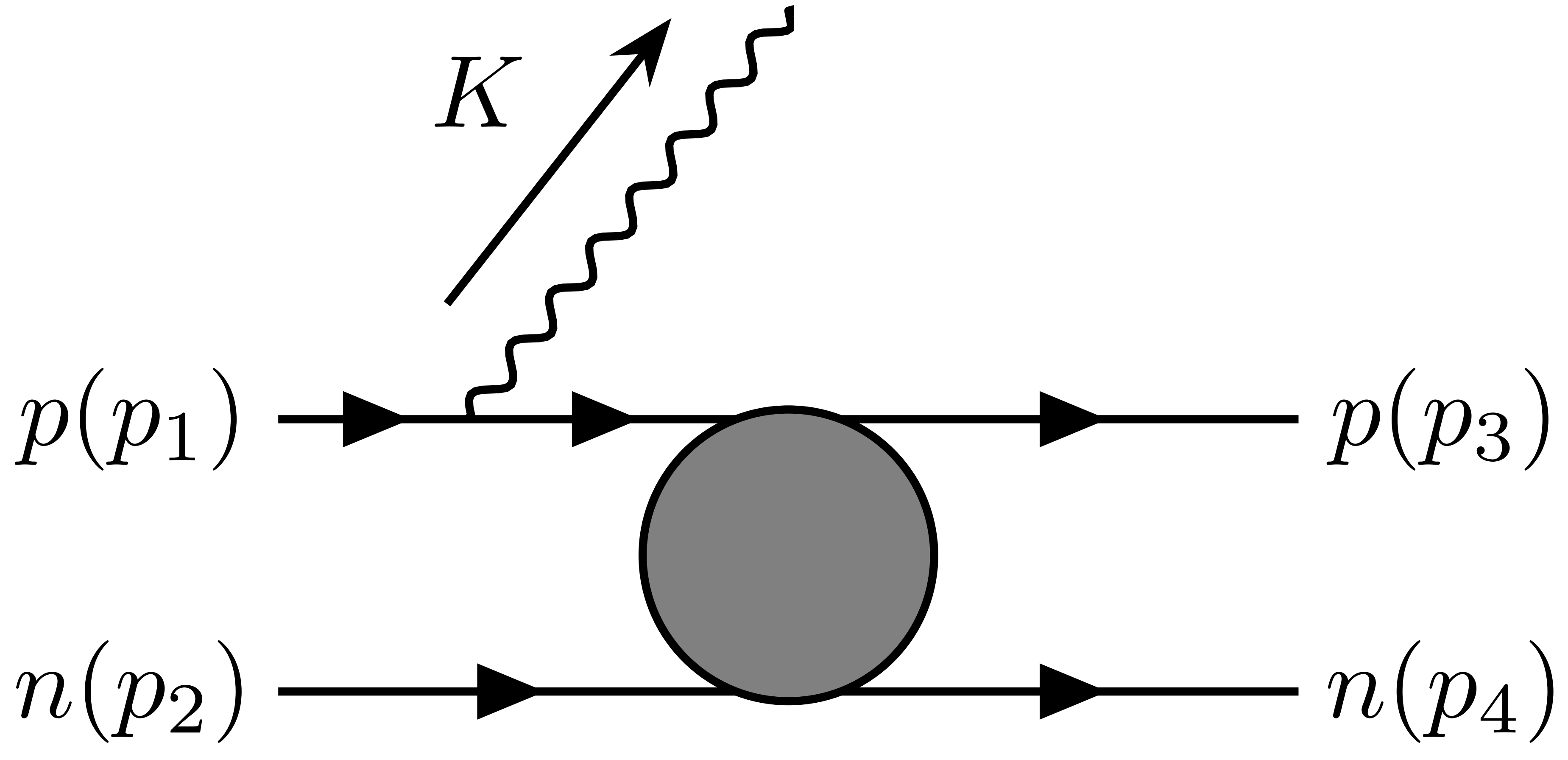
$$\frac{d\sigma(np \to np\gamma)}{d\omega} = \sigma^{T}_{np} \frac{d\mathscr{P}}{d\omega}$$

[Chu+, 1908.00553]

[Rrapaj & Reddy, 1511.09136]

σ^{T}_{np} = transport xsec of $(np \to np)$

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



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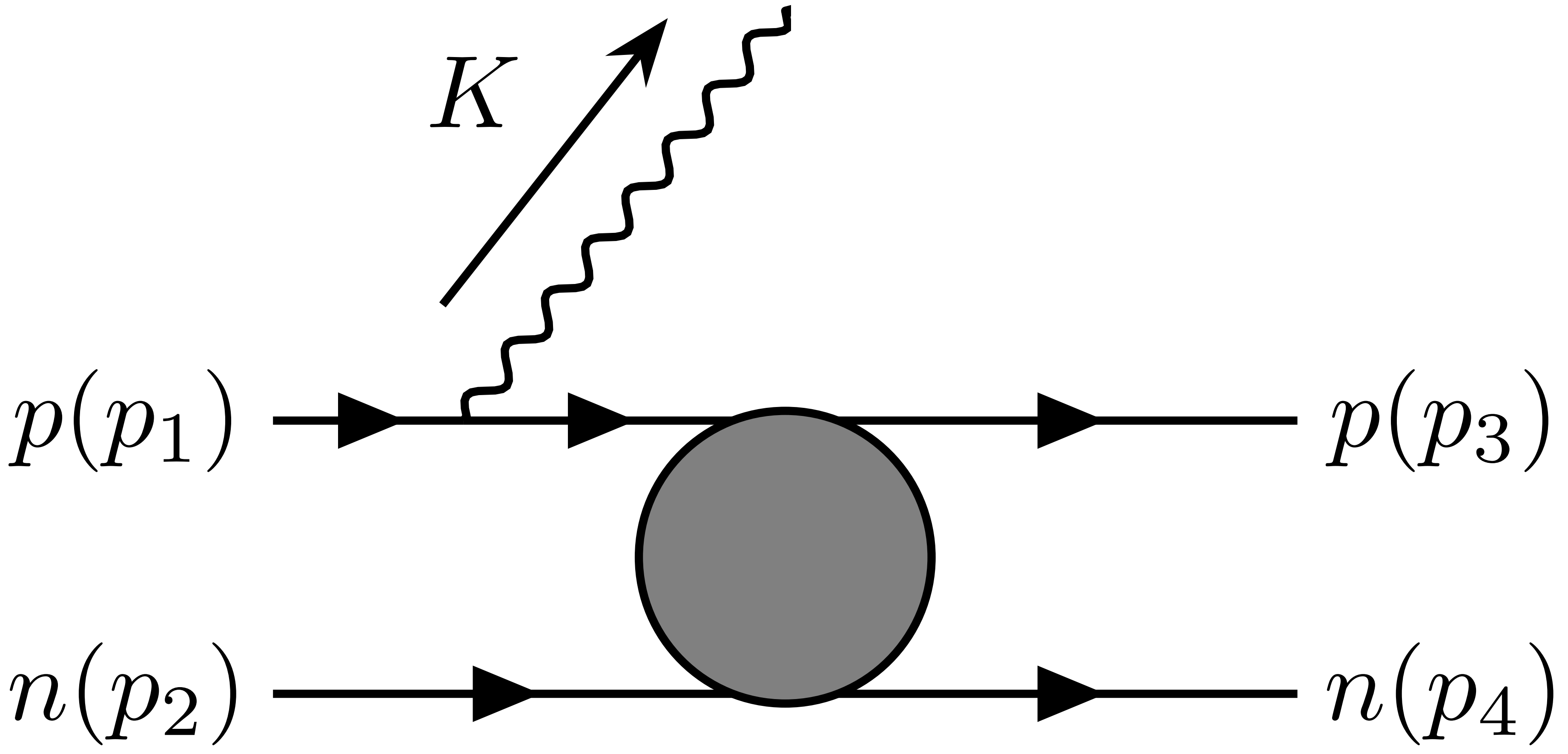

Photon emission in soft radiation approximation (SRA)

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

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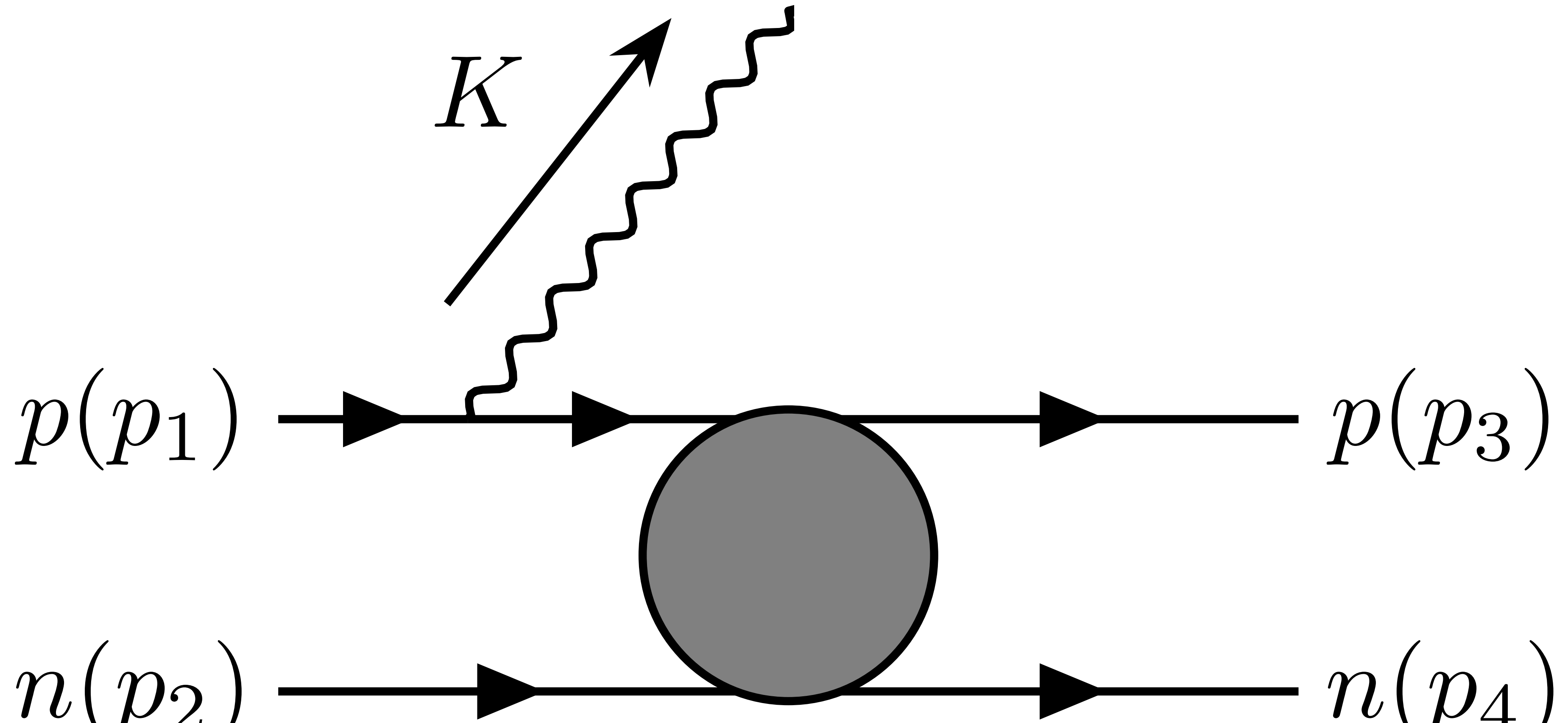


In SRA

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

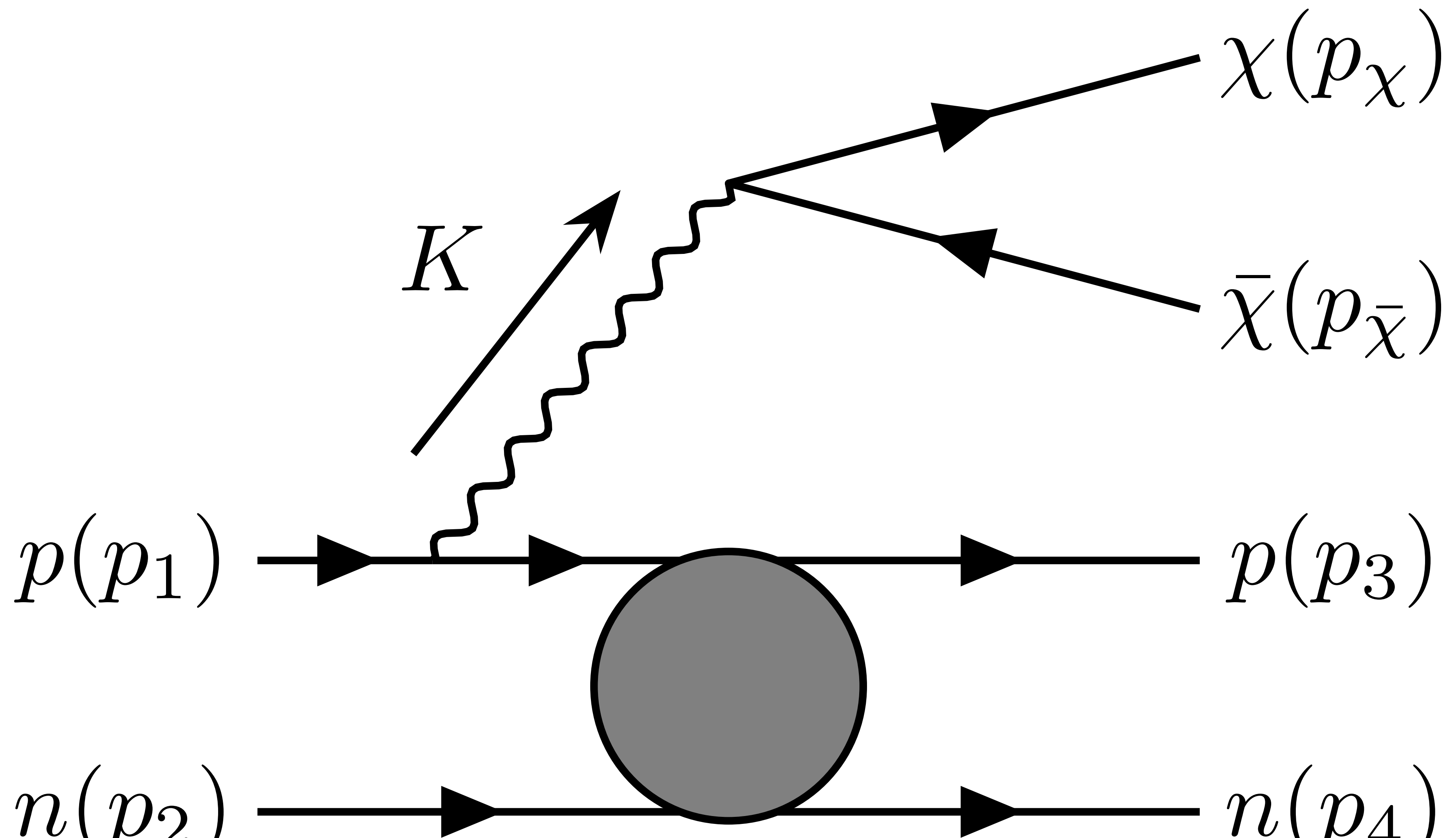
$$E_{\rm cm} = \frac{(\mathbf{p}_1 - \mathbf{p}_2)^2}{4m_N} \simeq 90\,\mathrm{MeV}$$

millicharged particle flux in proton bremsstrahlung

MCP flux in the PB process

$$\frac{d\Phi_{\rm pb}}{dE_\chi} = \frac{4n_1 n_2 \epsilon^2 \alpha}{3\sqrt{m_N \pi^3 T_c^3}} \int_{2m_\chi}^{\infty} dE_{\rm cm} E_{\rm cm} e^{-E_{\rm cm}/T_c} \sigma_{np}^T(E_{\rm cm})$$

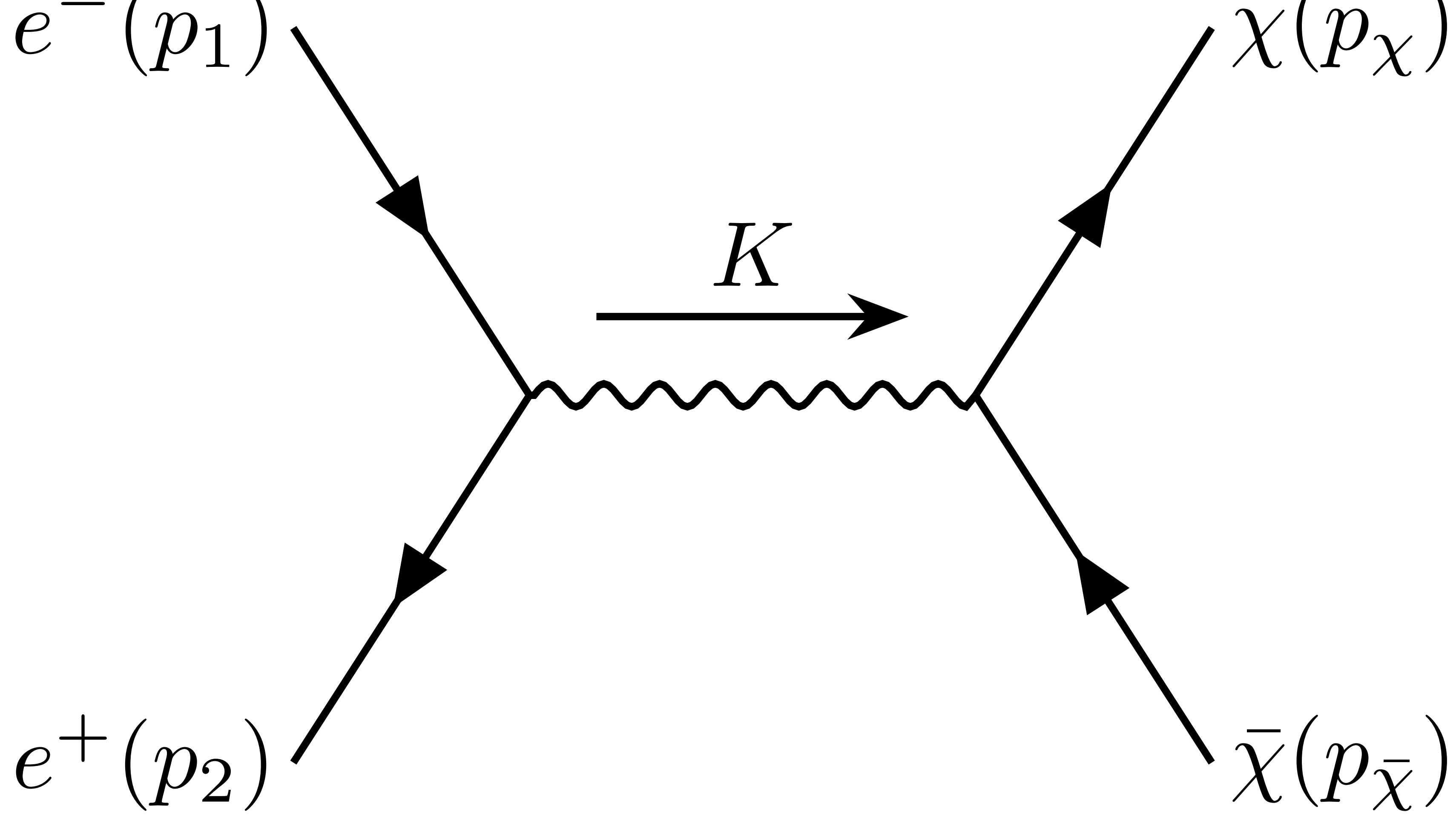
$$\times \int_{4m_\chi^2}^{E_{\rm cm}^2} \frac{dK^2}{K^2} f\left(\frac{m_\chi^2}{K^2}\right) \int_{\sqrt{K^2}}^{E_{\rm cm}} d\omega \frac{d\mathscr{P}}{d\omega} g(E_\chi, m_\chi, K)$$



Electron-positron annihilation

Electron-positron annihilation

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



(c)

For transverse (T) and longitudinal (L) photons

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

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

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

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

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

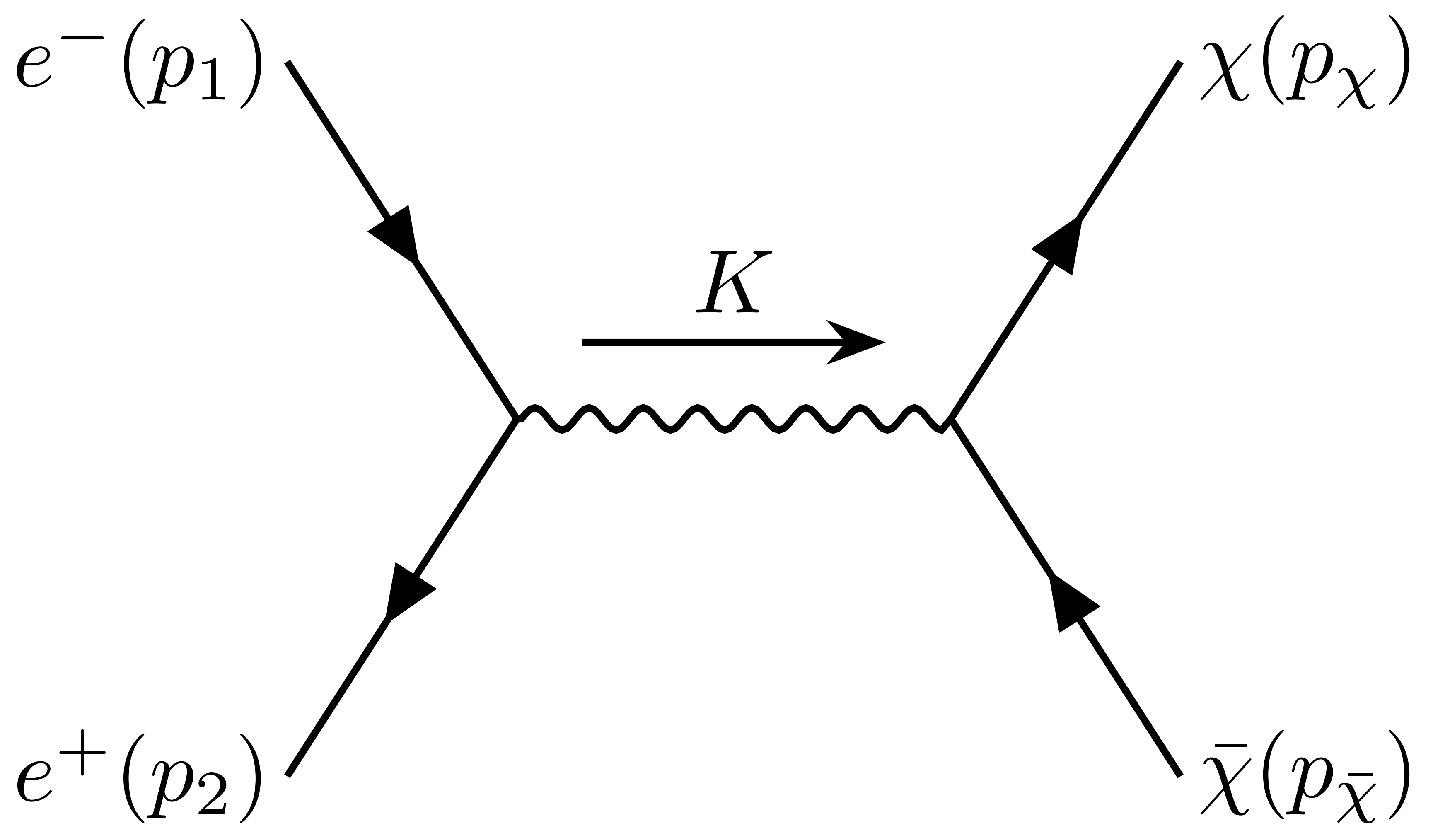
$$E_\pm \equiv E_1 \pm E_2$$

millicharged particle flux in e^+e^- annihilation

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

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

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



(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)

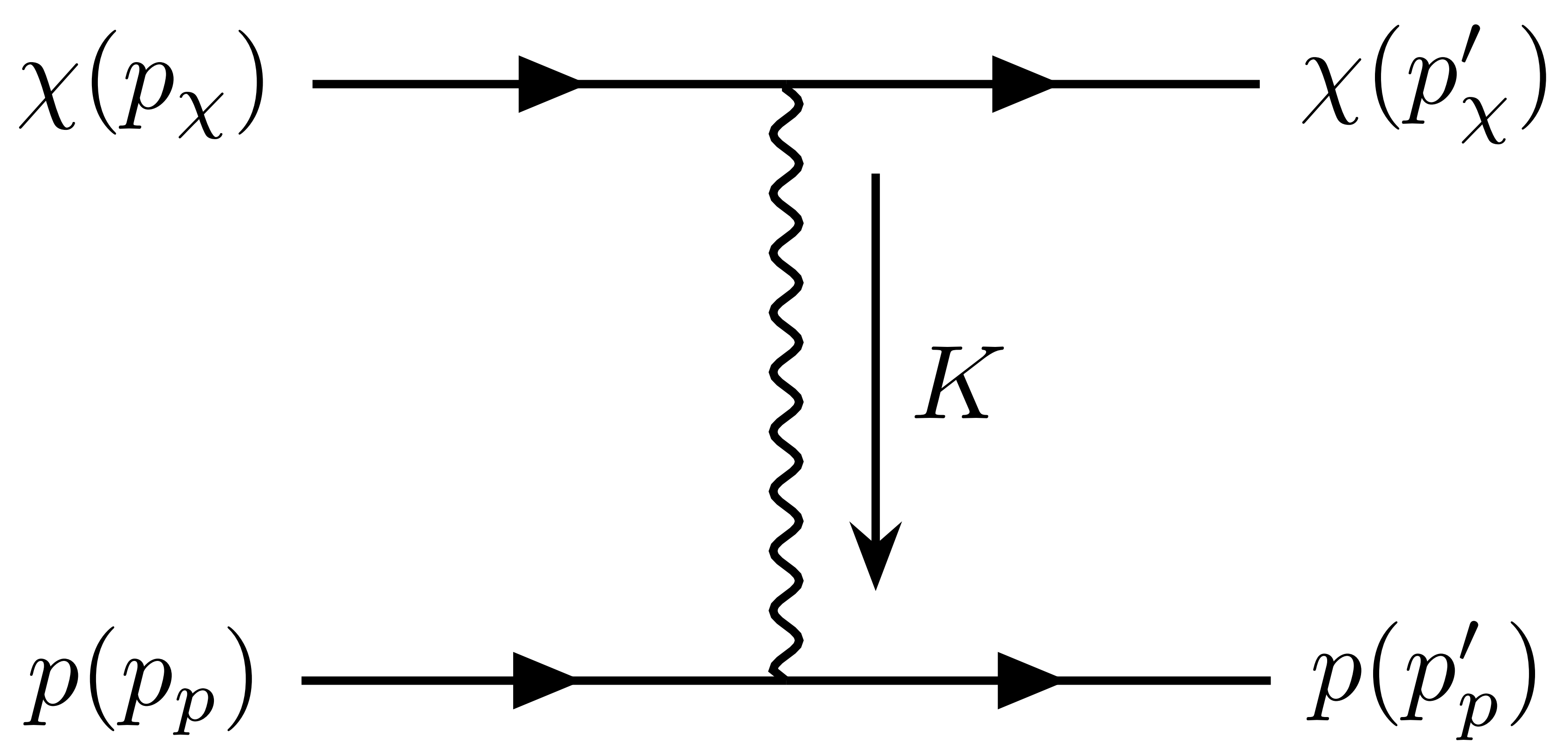
$$\frac{dE_\chi}{dx} = -n_p \int dE_R \frac{d\sigma_{\chi p}}{dE_R} E_R \quad \Rightarrow \quad \Delta E_\chi = \frac{1}{2}\int dx n_p E_R^{\max} \sigma_{\chi p}^T$$

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

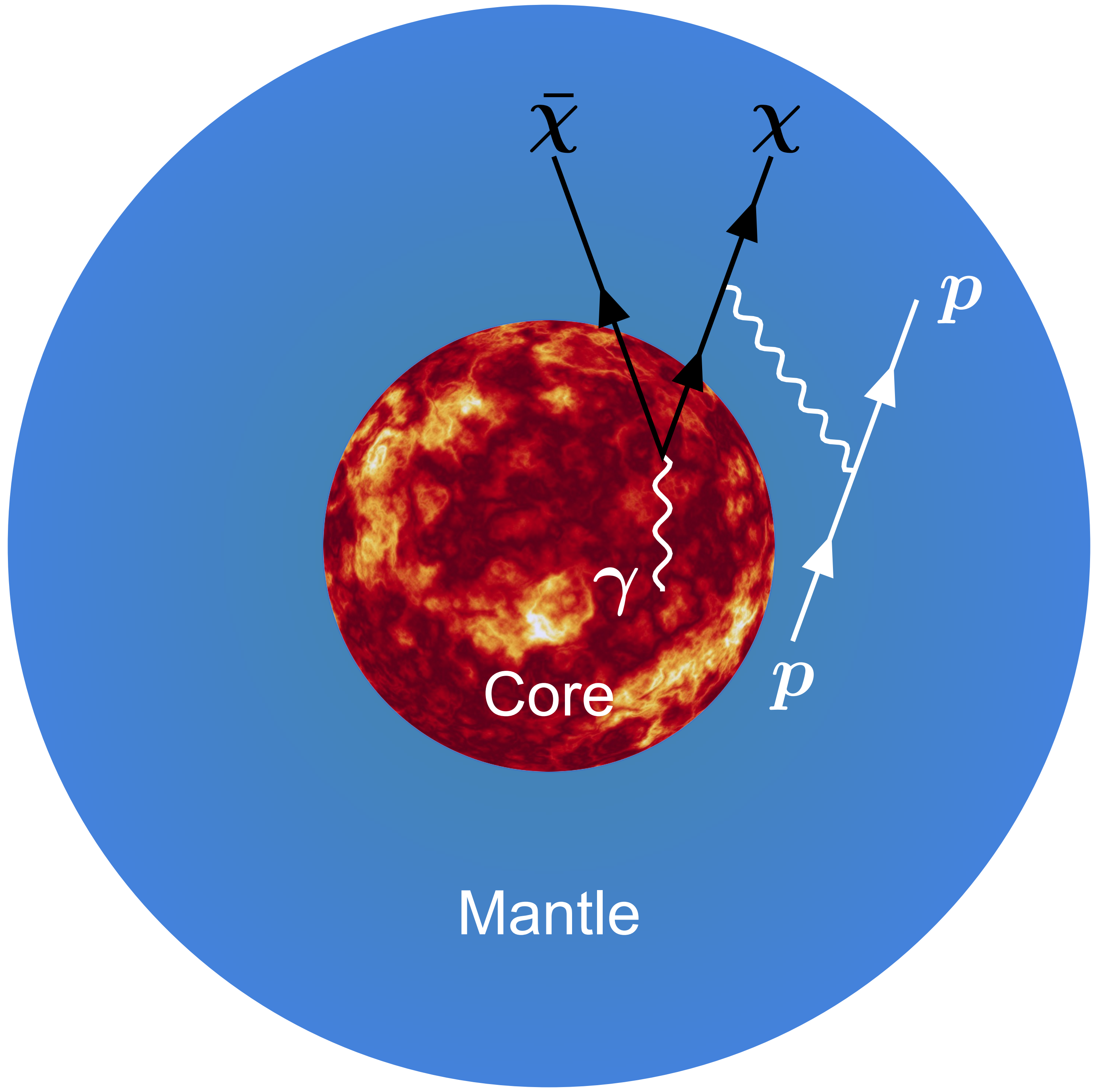
$$E_m = \text{lapse}^2 \times 4\pi\Delta t \int_0^{R_c} dr r^2 \int_{m'_\chi}^{\infty} dE_\chi \frac{d\Phi}{dE_\chi} \Delta E_\chi \leq 0.1\ B$$

ΔE_χ = energy deposited by a single χ in the mantle

$\Delta t = 3\ s$

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

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



[Caputo+,2022]

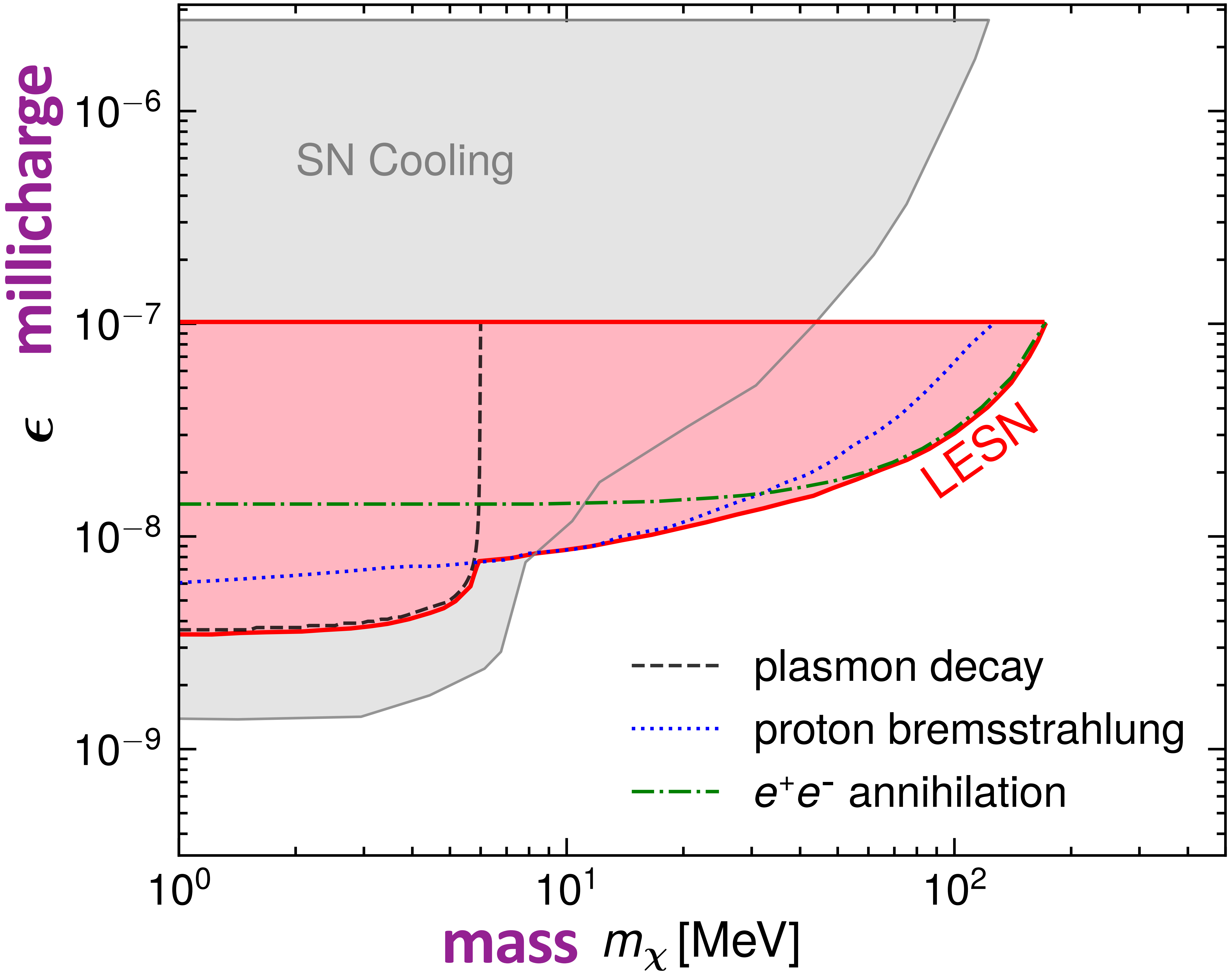
5

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 LESN constraints on millicharged particles, by considering three production channels in the SN core
  - plasmon decay
  - proton bremsstrahlung
  - electron-positron annihilation ⇒ important for high-mass (previously omitted)

[Li, ZL, Lu, Ye, 2408.04953]

- 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

additional slides

Plasma effects

Effective photon propagator in Lorenz gauge **[Raffelt, 1996]**

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

$$\epsilon_\pm^\mu = (0,1, \pm i,0)/\sqrt{2} \qquad \epsilon_L^\mu = (k,0,0,\omega)/\sqrt{K^2}$$

LO contributions to real part of the EM polarization tensor **[Braaten & Segel, 1993]**

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

$\Longrightarrow$ 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, 1982]

[An+, 1302.3884]

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

In the SN core, the dominant contributions to photons in MCP production (time-like with a positive energy):

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

EM polarization tensor in the off-shell region

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

One-zone model: $m_\gamma < 12$ MeV & $m_e \simeq 9$ MeV $\Longrightarrow m_\gamma < 2m_e$

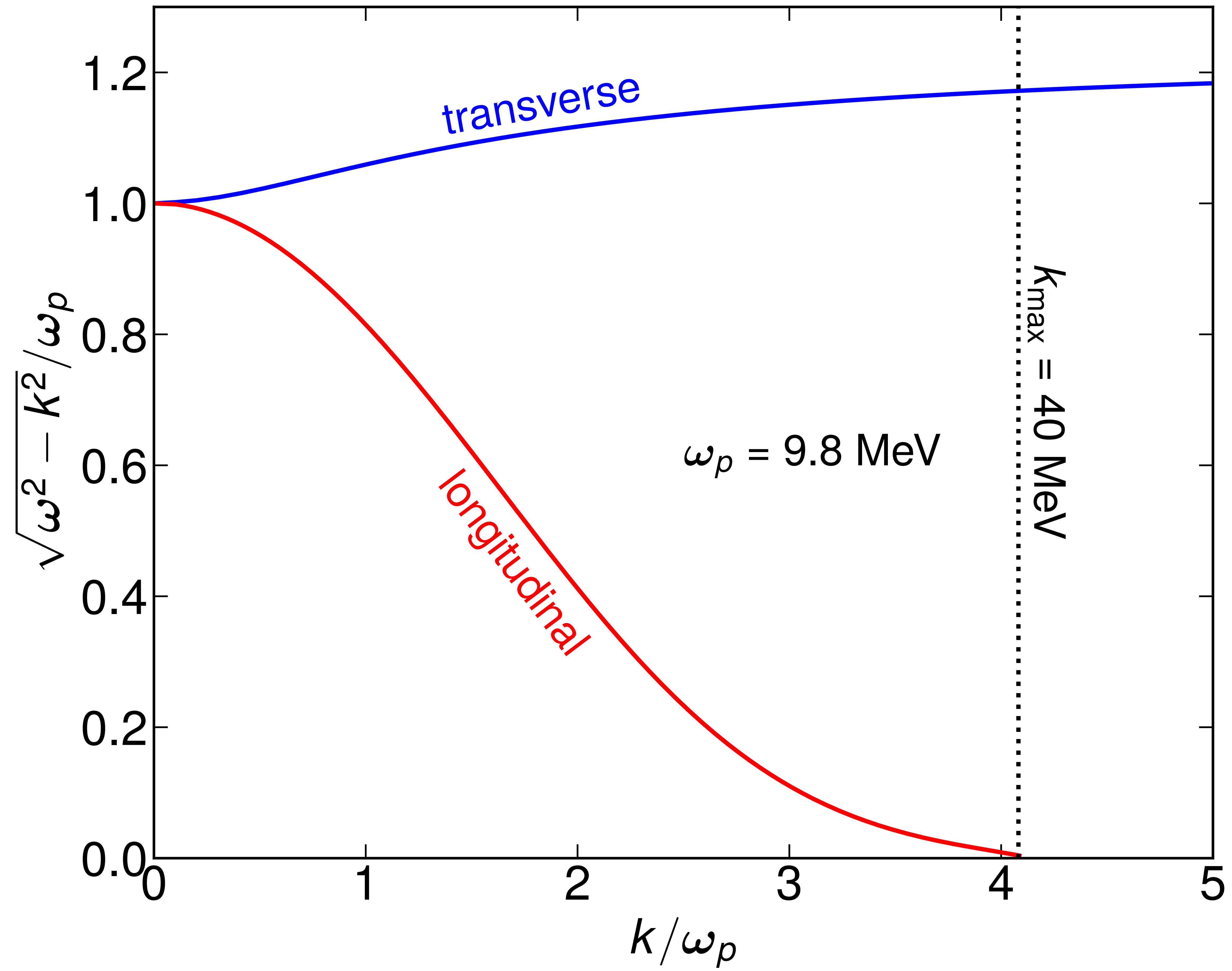
In the relativistic limit, we use on-shell dispersion relations to compute $\mathrm{Re}\Pi$

[Braaten & Segel, 1993]

[Scherer& Schutz, 2405.18466]

Dominant contributions to $\mathrm{Im}\Pi$: proton bremsstrahlung & its inverse $\Longrightarrow \; \lesssim 2\,\%$

Plasmon decay for low-mass MCPs



Photon mass < 12 MeV

Plasmon decay is the dominant production channel for MCPs w/ mass < 6 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, 394 cites]

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

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

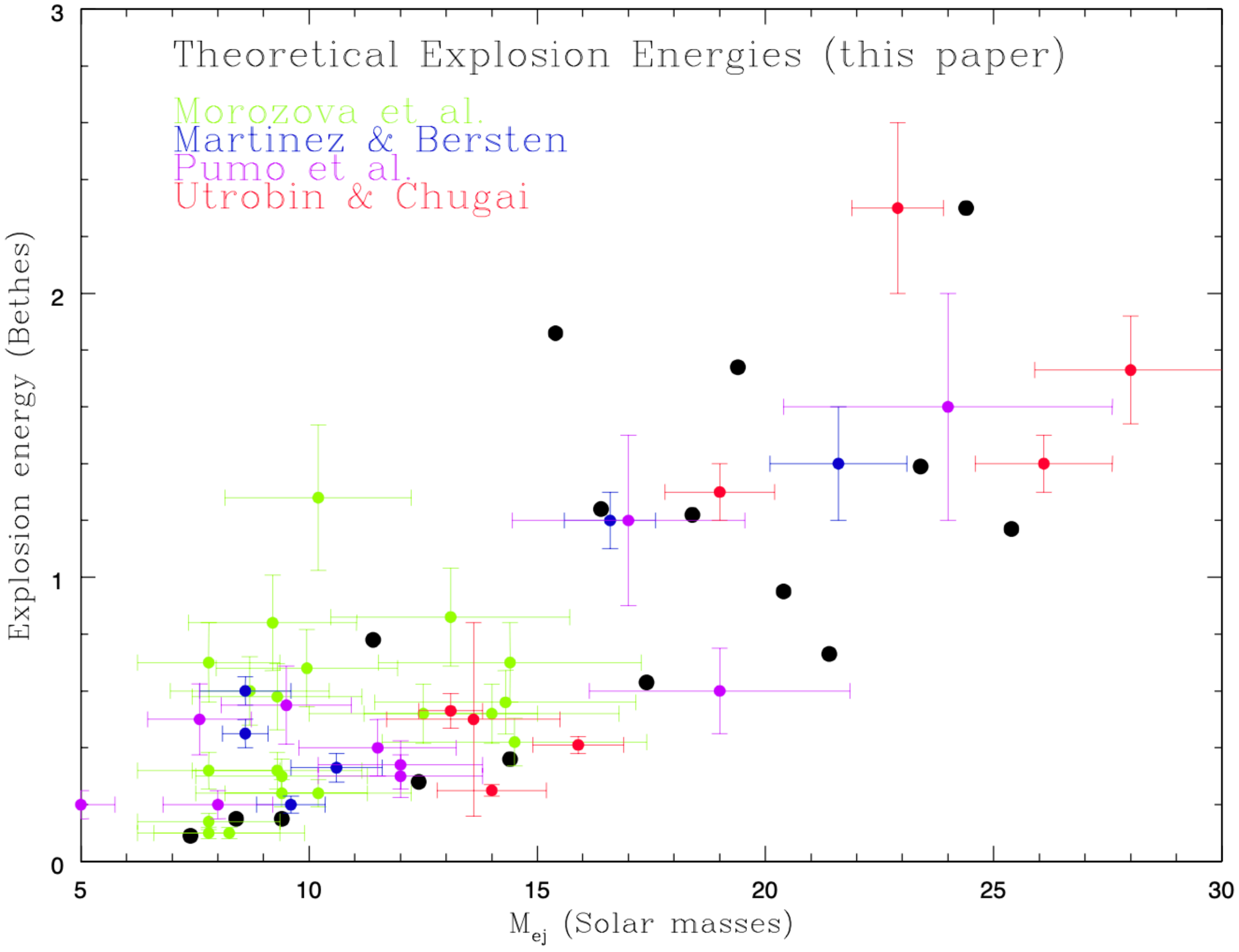
Supernova explosion energy

[Burrows & Vartanyan, 2009.14157]

Model [$M_\odot$]	Explosion Energy [B]	Run Time [s]	Baryonic Mass [$M_\odot$]	Gravitational Mass [$M_\odot$]
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]

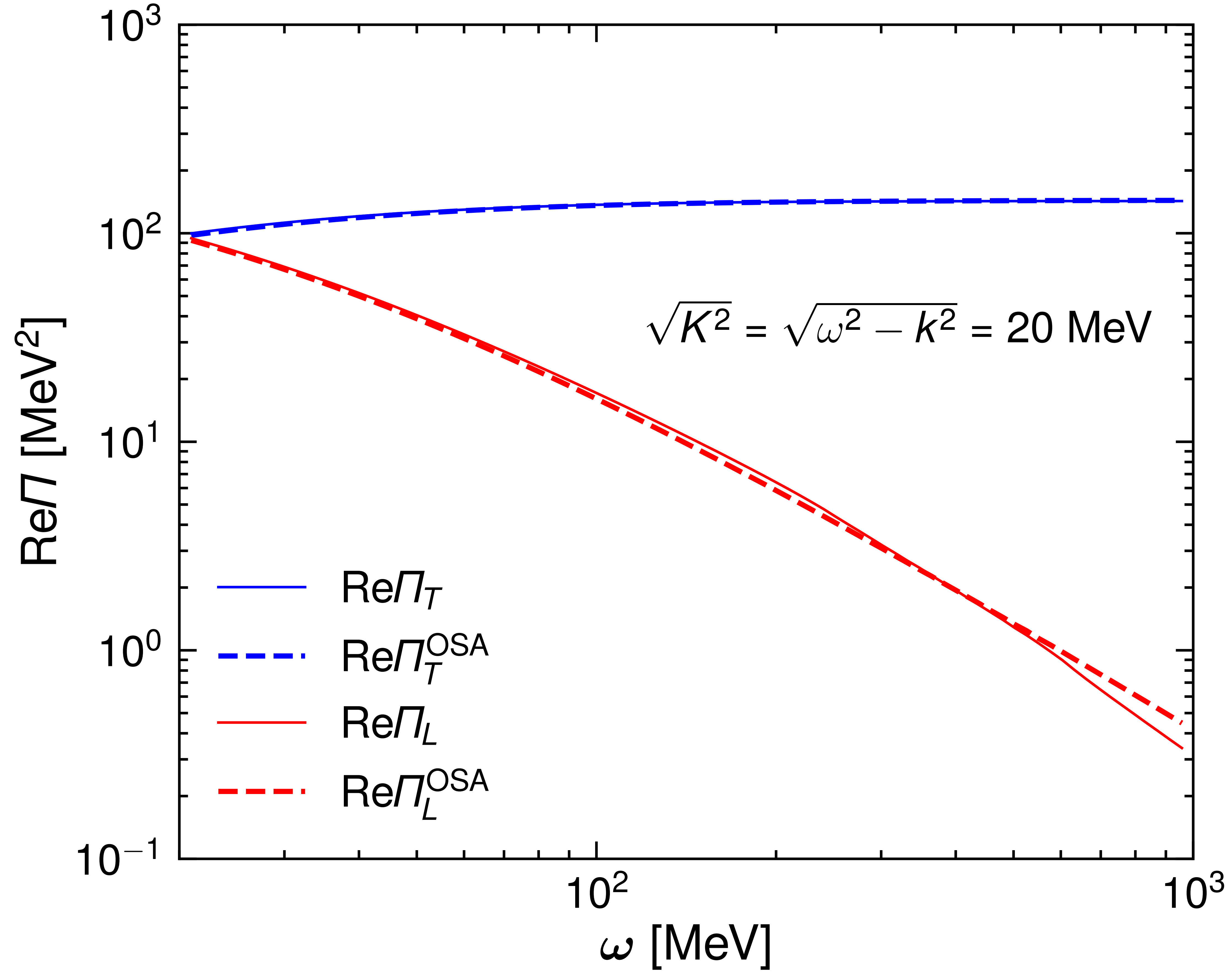


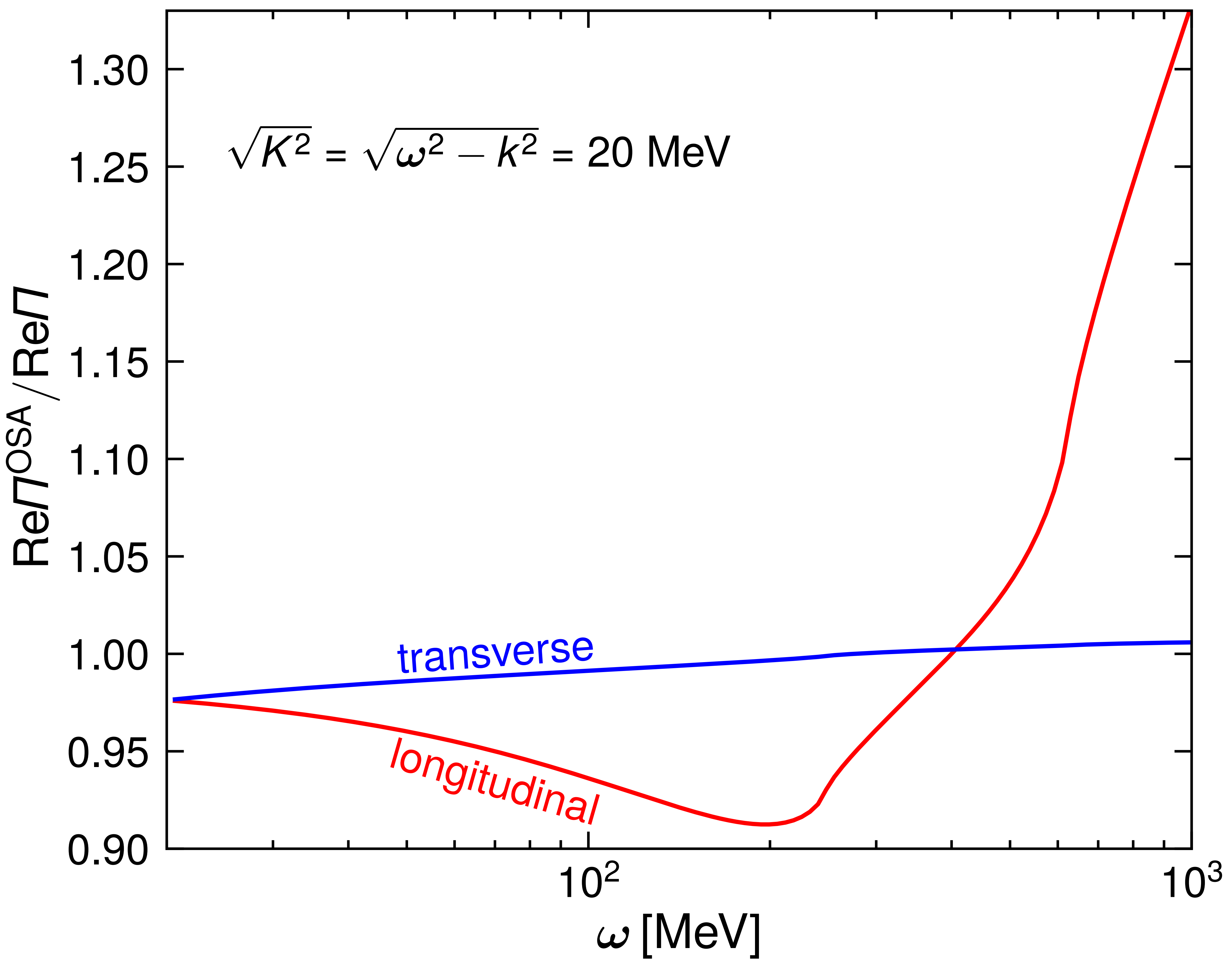
Empirically inferred explosion energies vs. the inferred ejecta masses, with error bars, for a collection of observed Type IIp (plateau) supernovae.

Black dots = theoretical explosion energies

On-shell approximation (OSA) for ReΠ_a in off-shell region

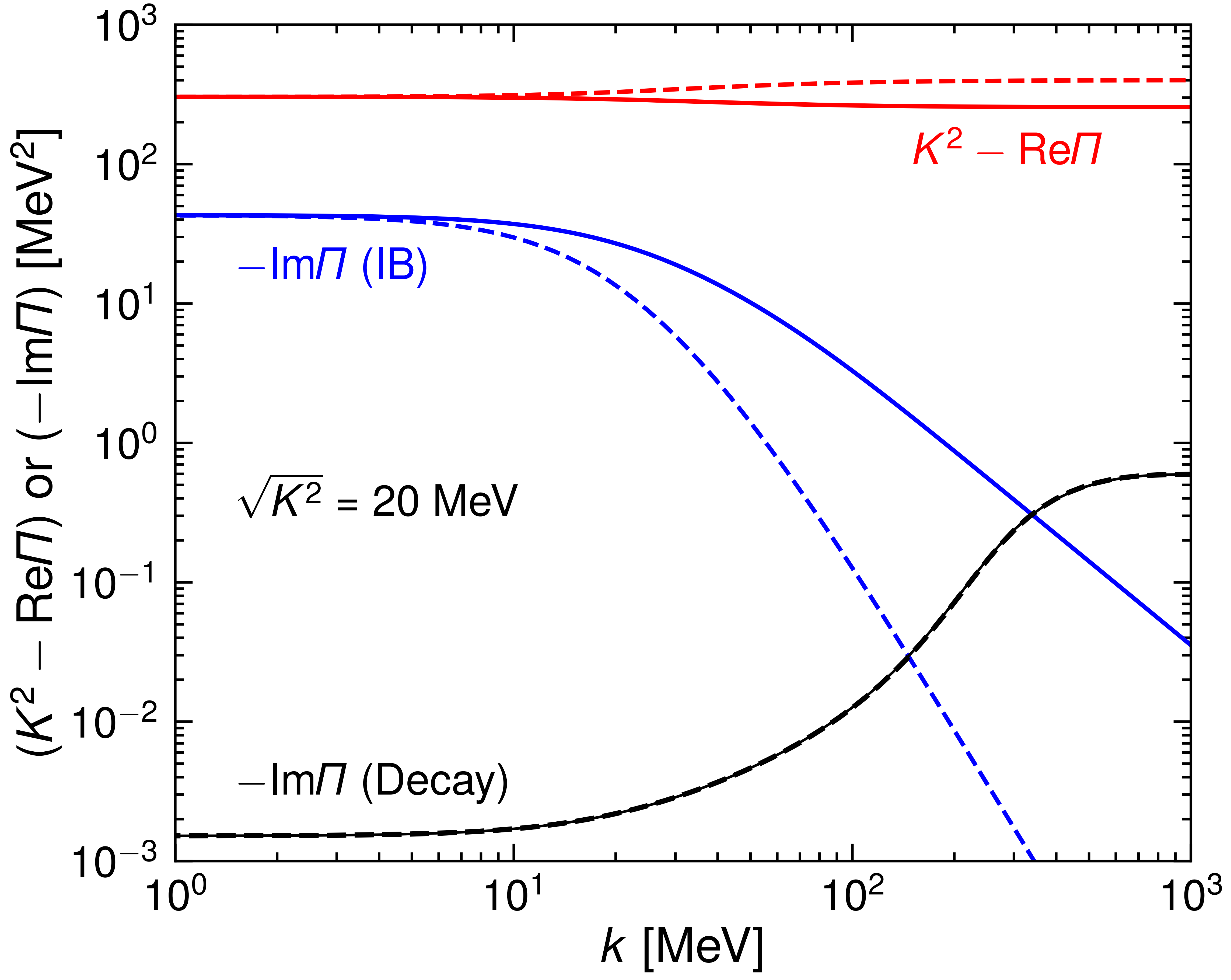
OSA: use on-shell dispersion relations to compute ReΠ_a in the off-shell region



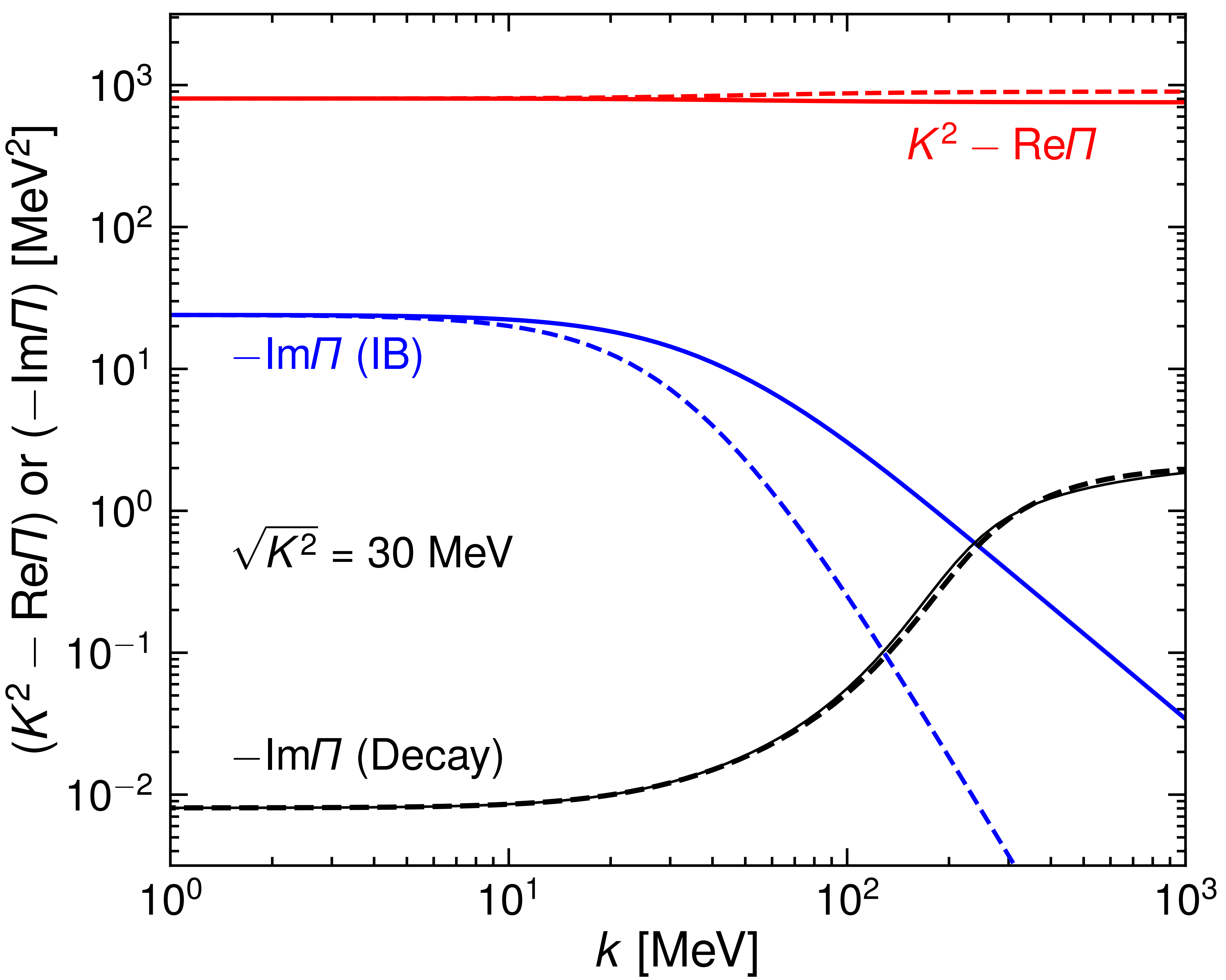


Imaginary part of Π_a in off-shell region

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



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

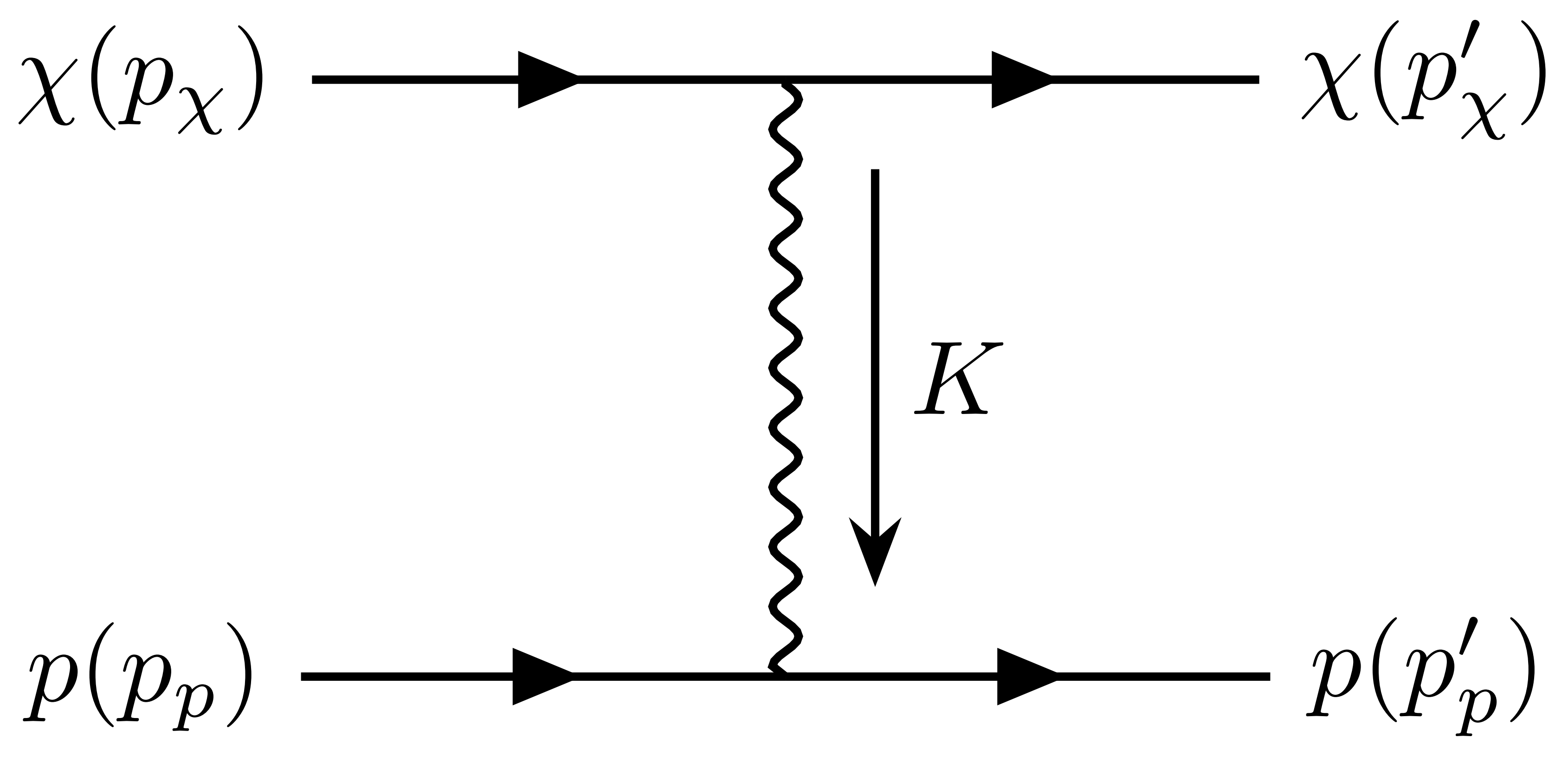


Energy deposition in the mantle

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

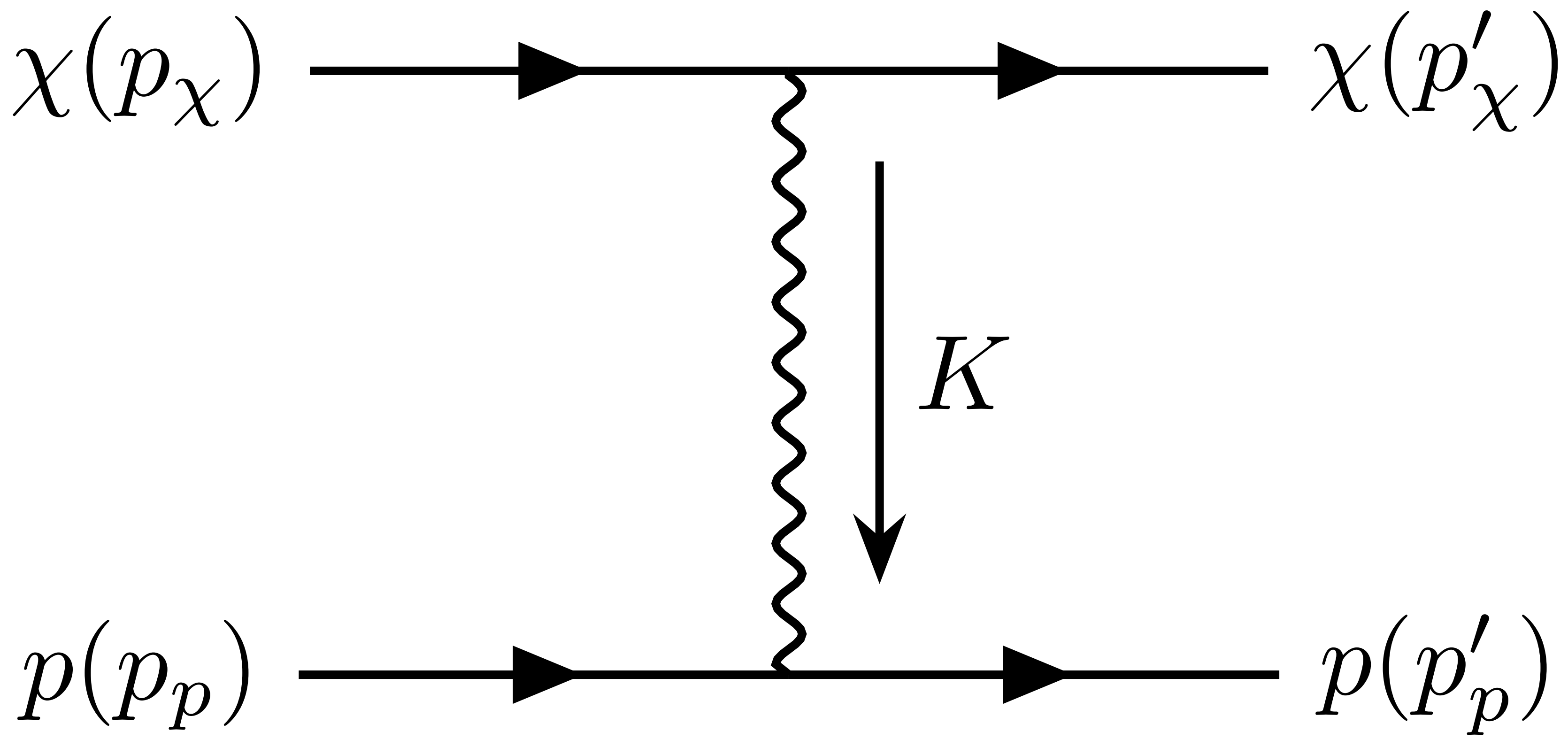
$$E_R = \frac{1}{2} E_R^{\max}(1 - \cos\theta)$$

θ = scattering angle in the CM frame

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

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

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



Debye screening

Debye screening effects $\sigma \to \sigma \frac{K^2}{(K^2 + k_D^2)}$ [Davidson+, hep-ph/0001179]

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

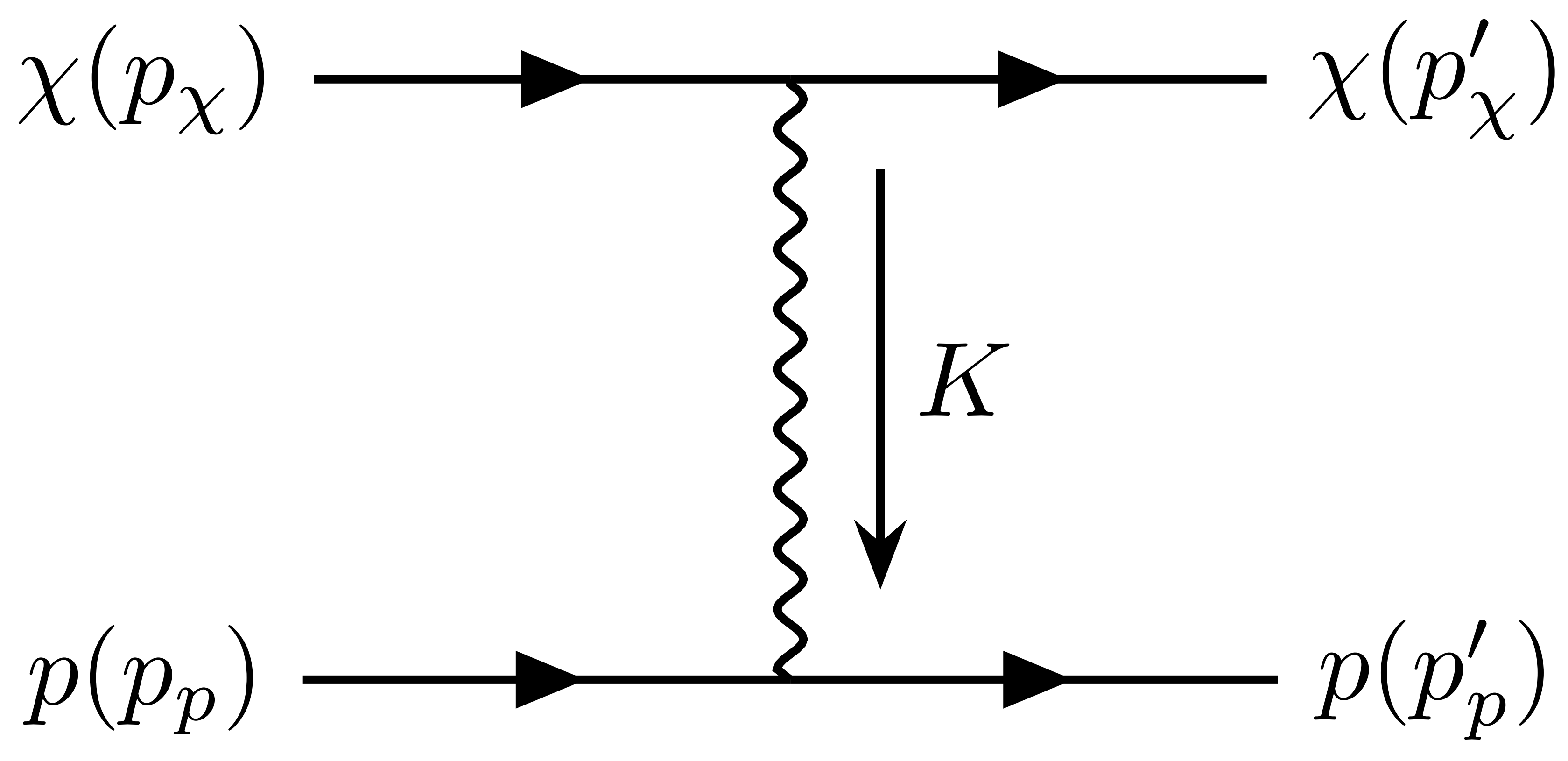
Debye scale: $k_D = 2\sqrt{\pi\alpha n_p / T}$

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

Energy deposition

Mantle colder than core $\Longrightarrow$ 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

$$\rho(r) = \rho_c \times (r/R_c)^{-\nu} \qquad r > R_c$$

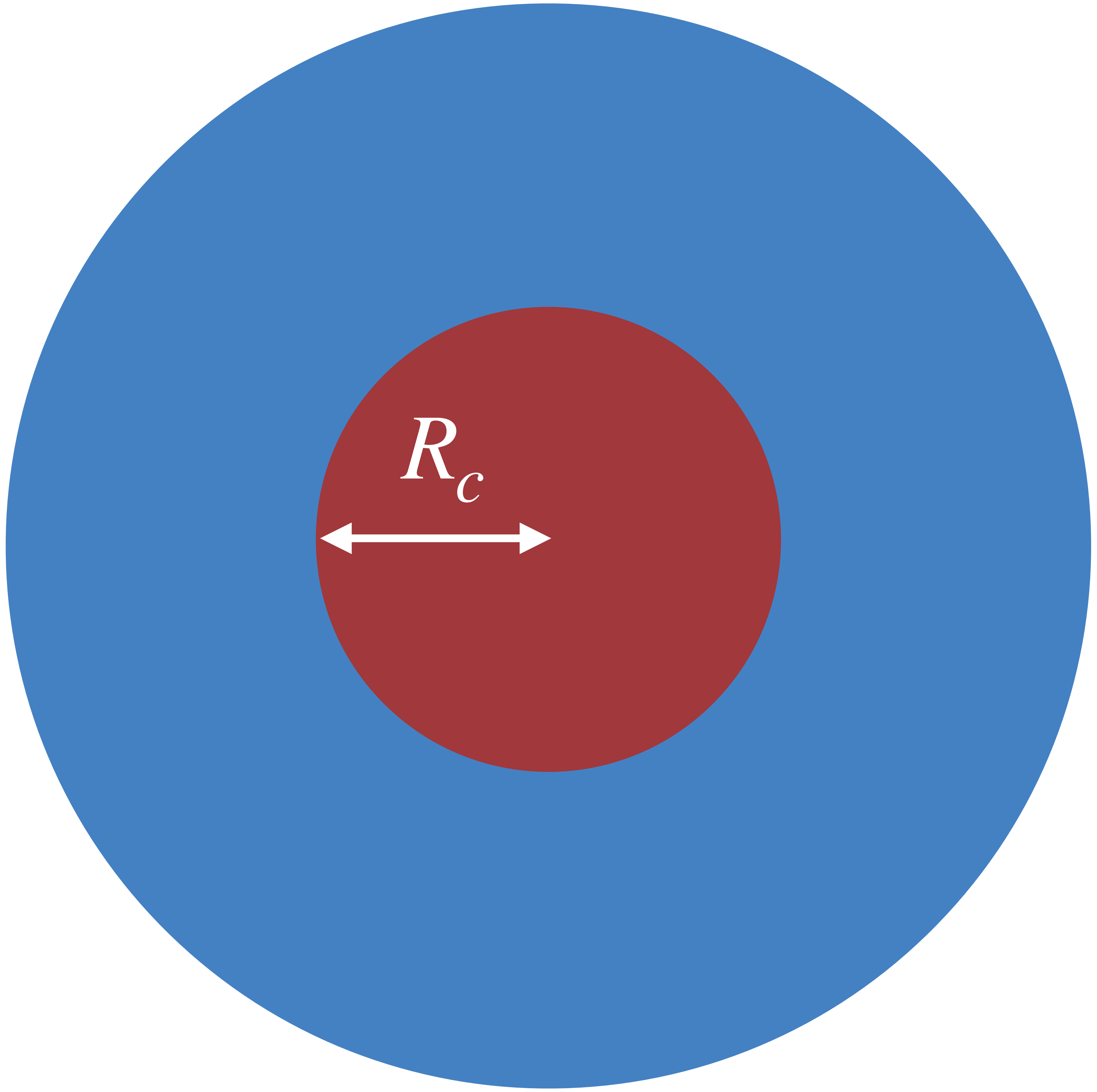
[Chang+, 1611.03864]

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

$$\nu = 5$$

$$Y_p = 0.15$$

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