Five Lectures on Dark Matter

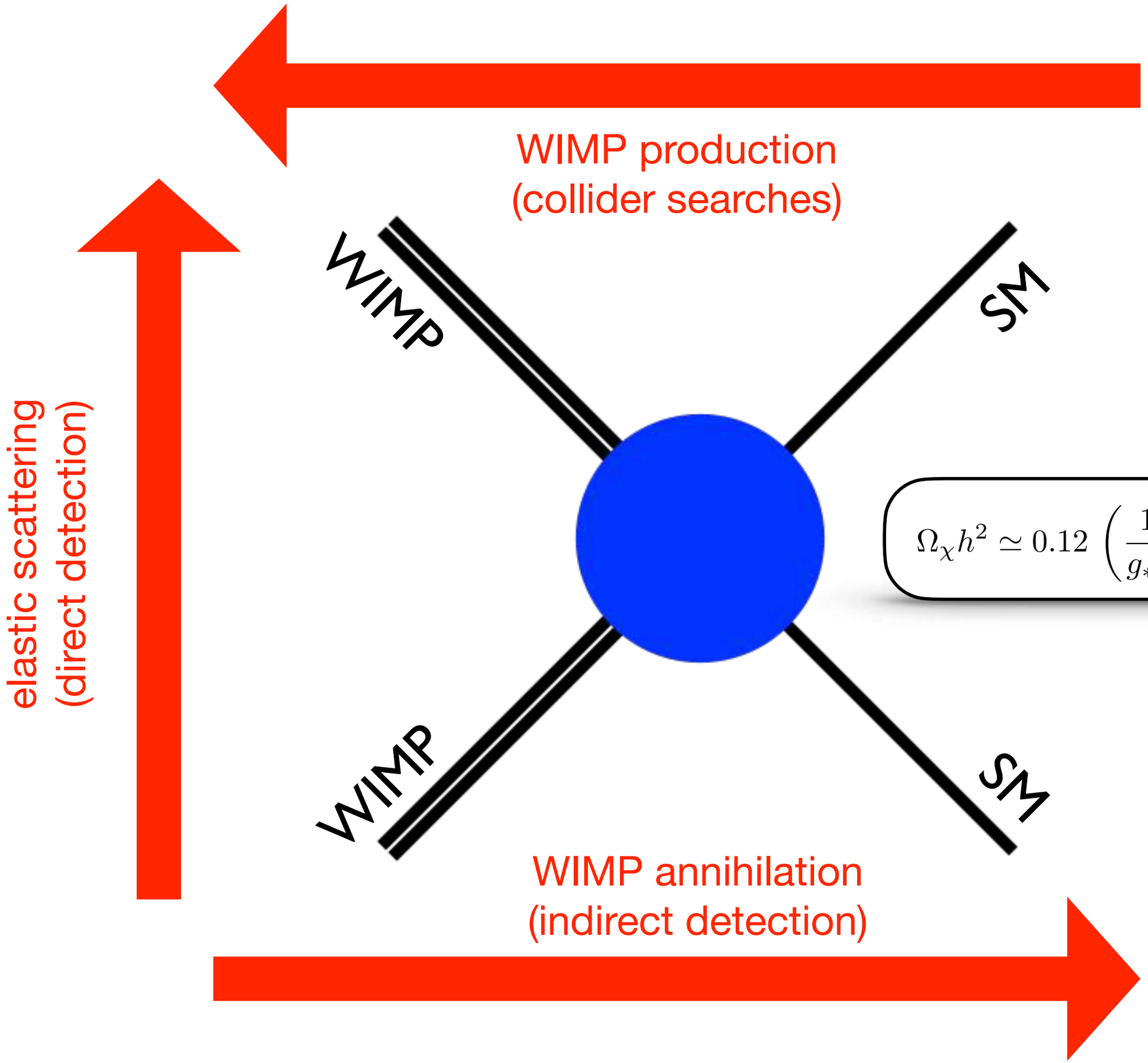
Fourth Lecture

UNIVERSITÀ DEGLI STUDI DI PADOVA

Francesco D'Eramo

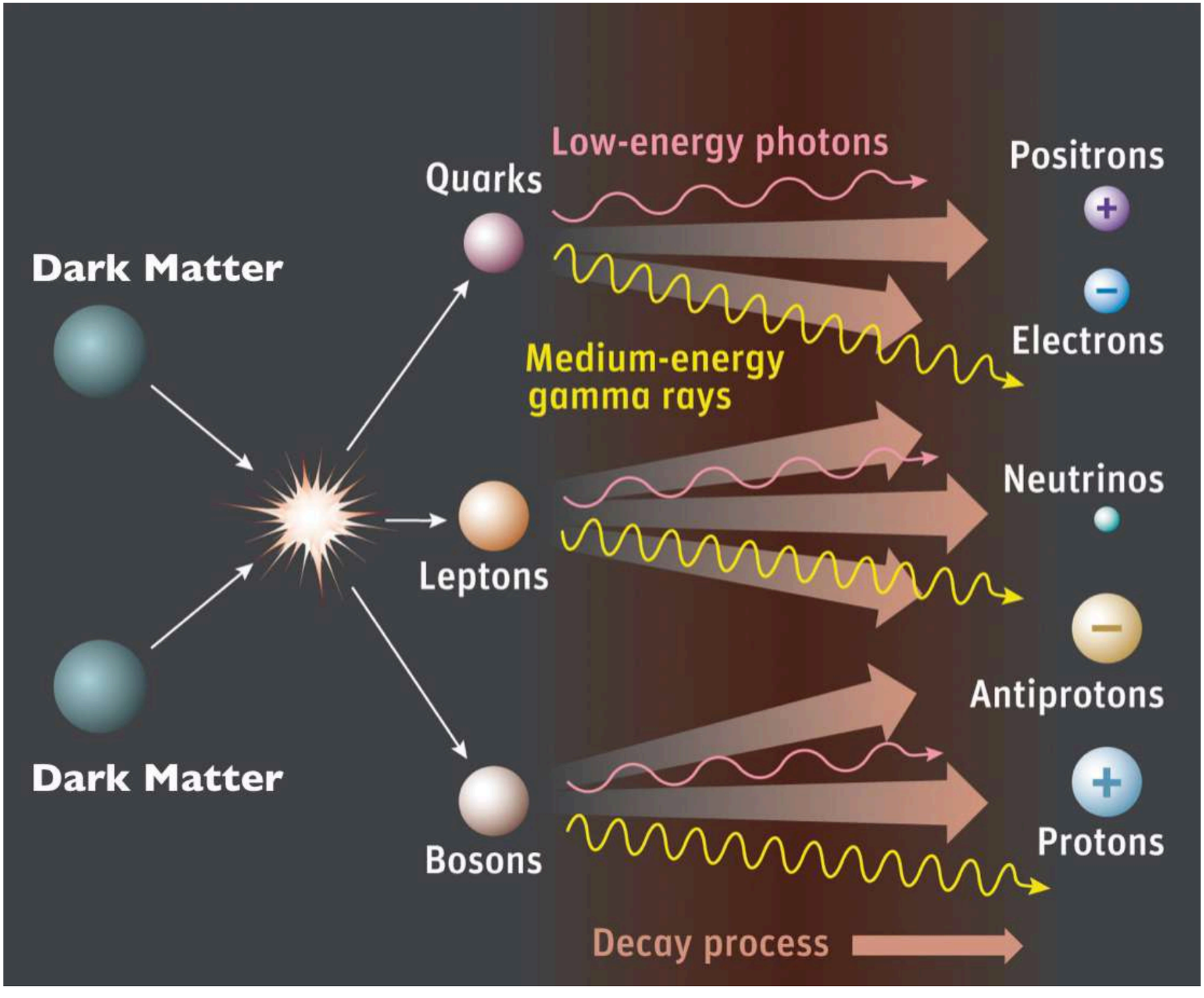
II Joint ICTP-Trieste/ICTP-SAIFR School on Particle Physics (June 22 — July 3, 2020)

Dark Matter Searches



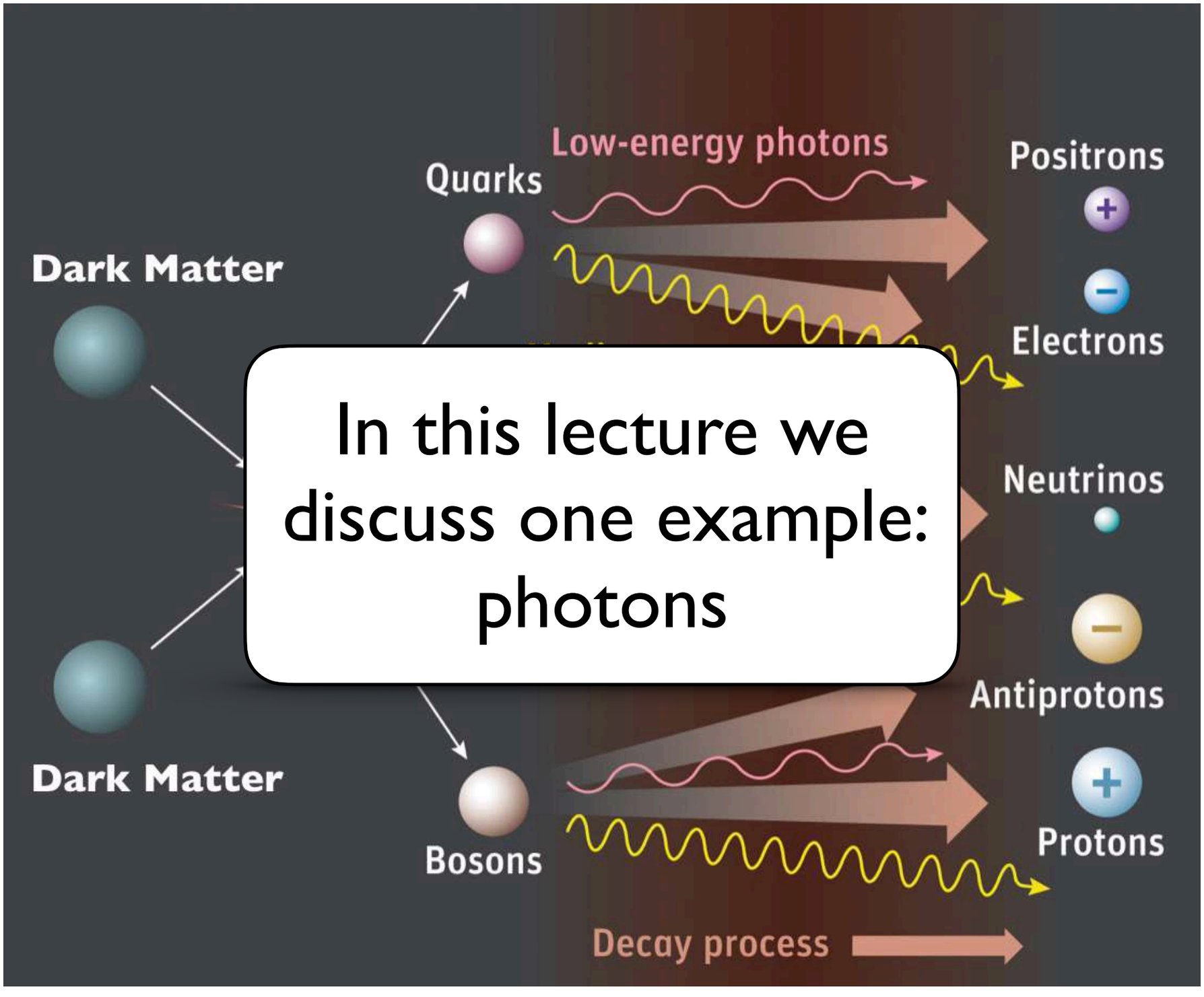
$$\Omega_\chi h^2 \simeq 0.12 \left(\frac{106.75}{g_*(T_{FO})}\right)^{1/2} \left(\frac{0.7\,\mathrm{pb}}{\langle\sigma v_{\mathrm{rel}}\rangle}\right)$$

Indirect Searches



Slatyer, TASI 2016 arXiv:1710.05137 [hep-ph]

Indirect Searches

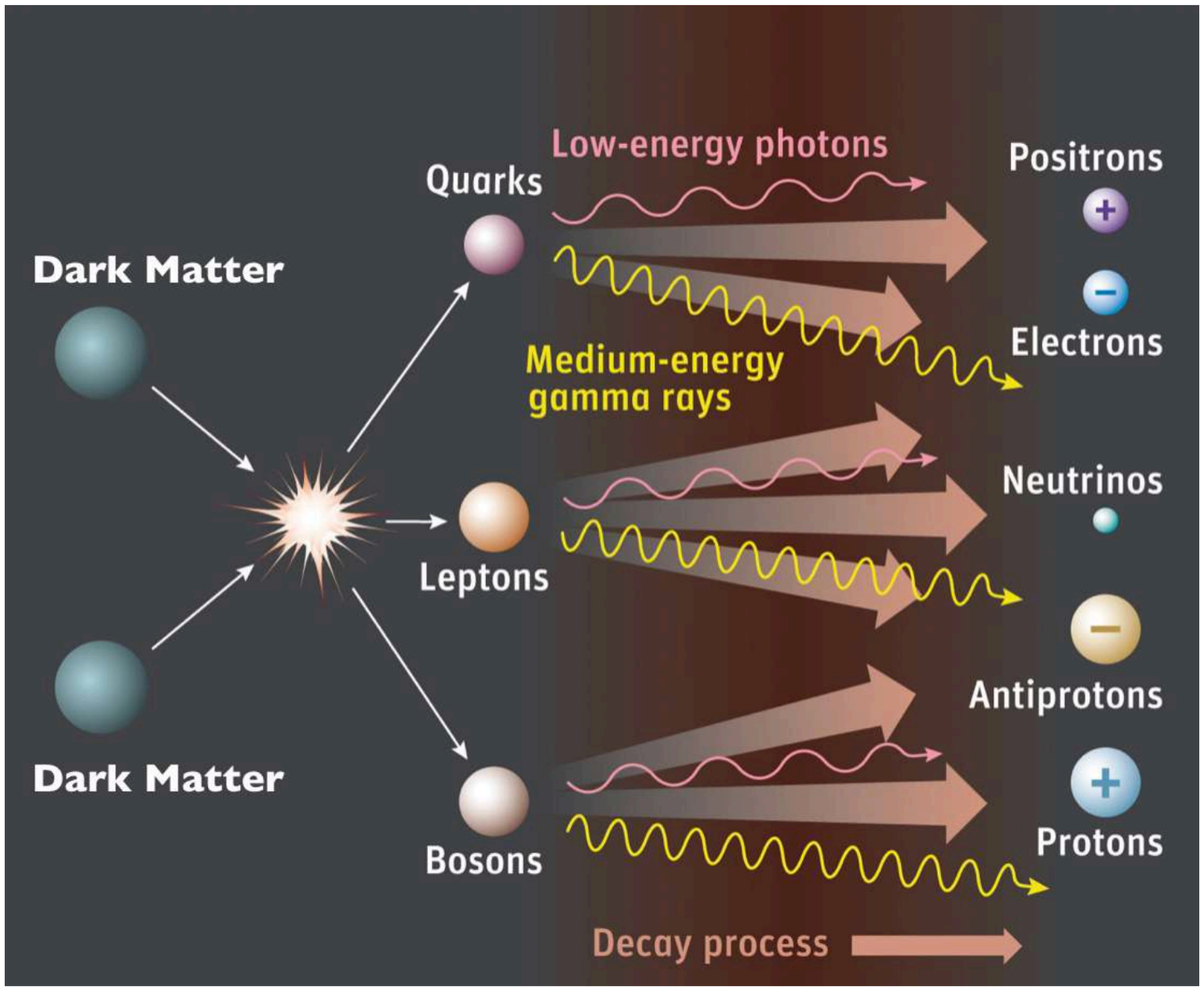


In this lecture we discuss one example: photons

Slatyer, TASI 2016 arXiv:1710.05137 [hep-ph]

Why Cosmic Photons?

$$\chi\chi \to \mathrm{SM}\,\mathrm{SM} \qquad \text{or} \qquad \chi \to \mathrm{SM}\,\mathrm{SM}$$



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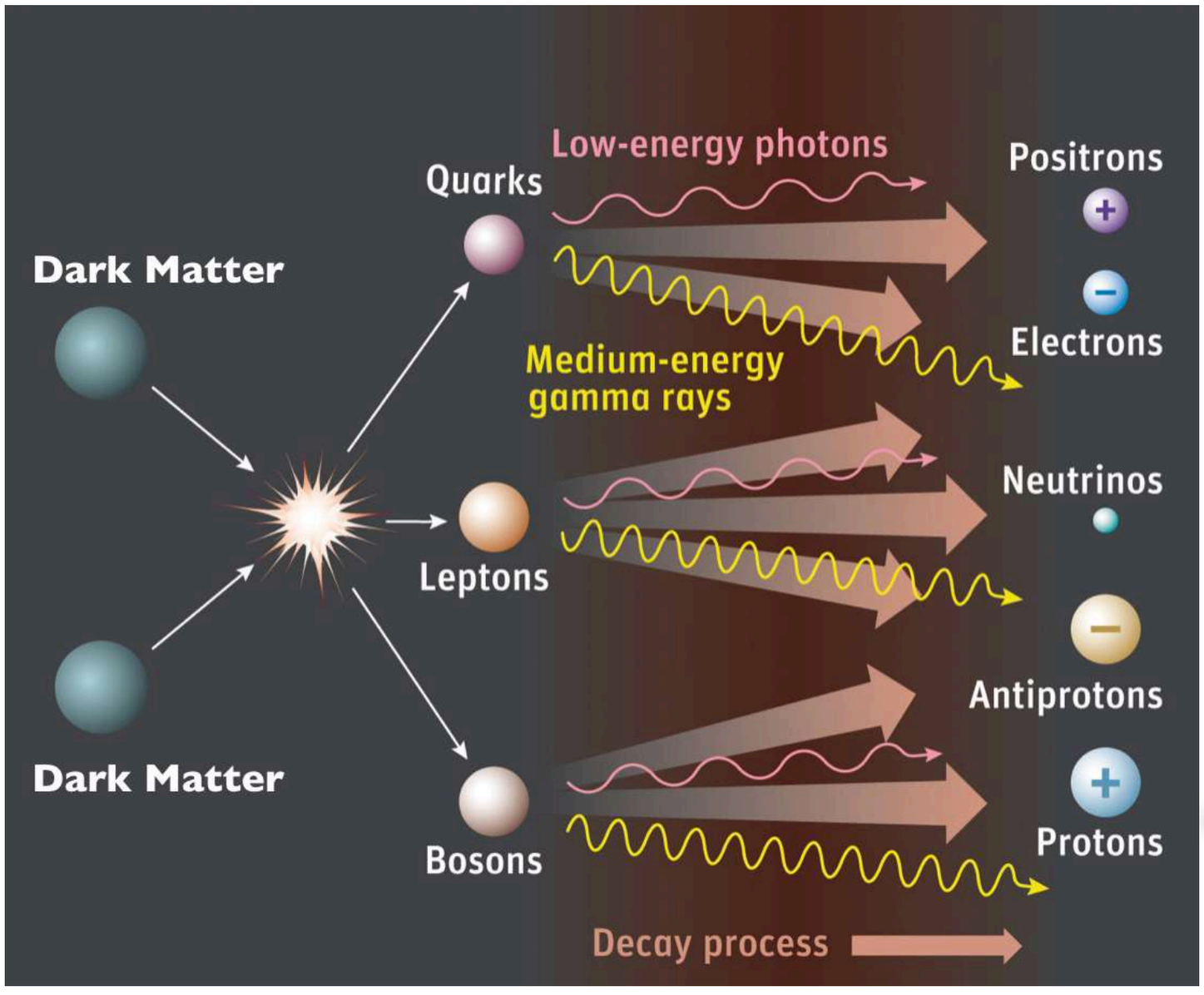

Photons

- Direction
- Energy

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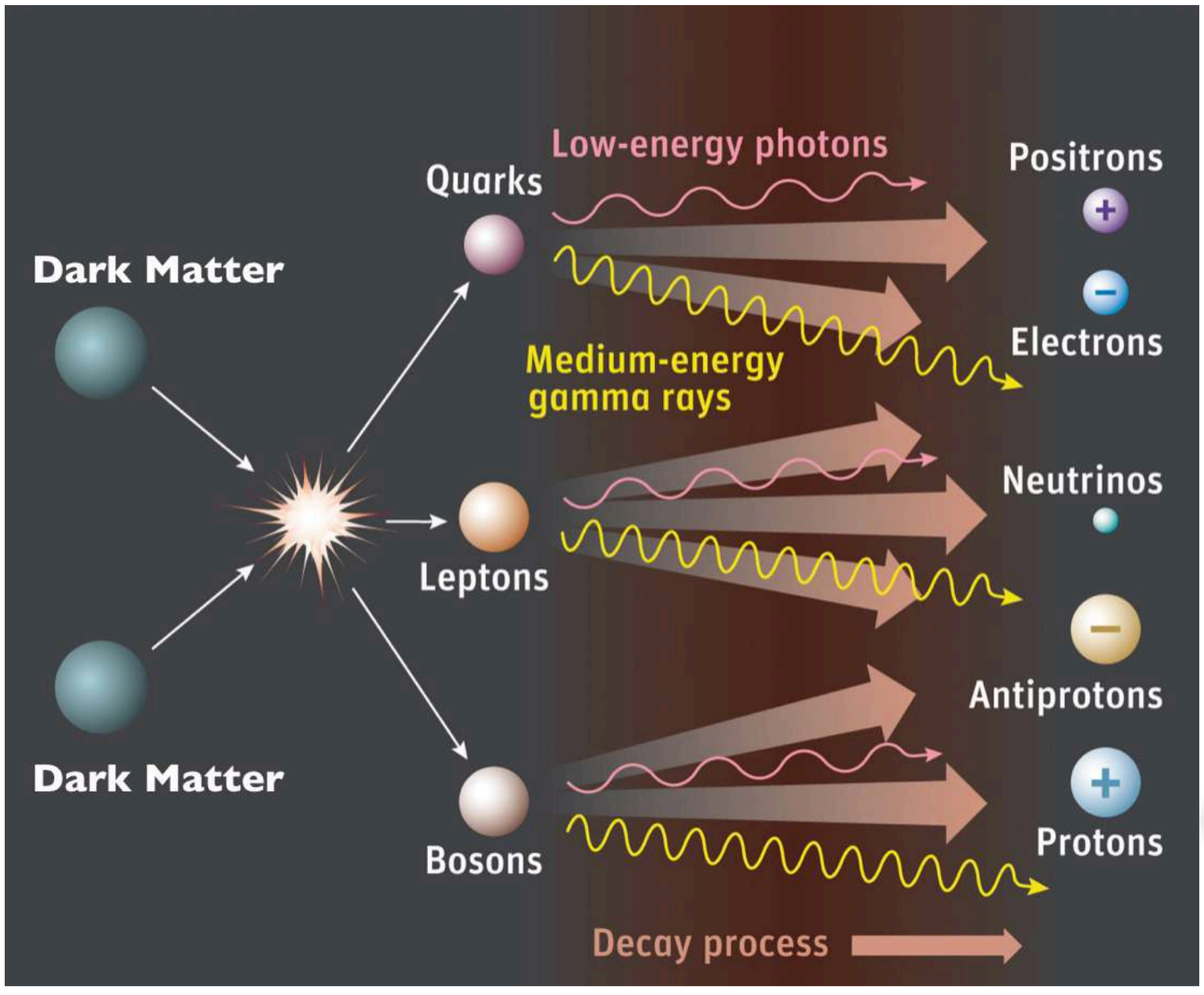

Photons

- Direction
- Energy

Astrophysical background

Cosmic Photon Spectra

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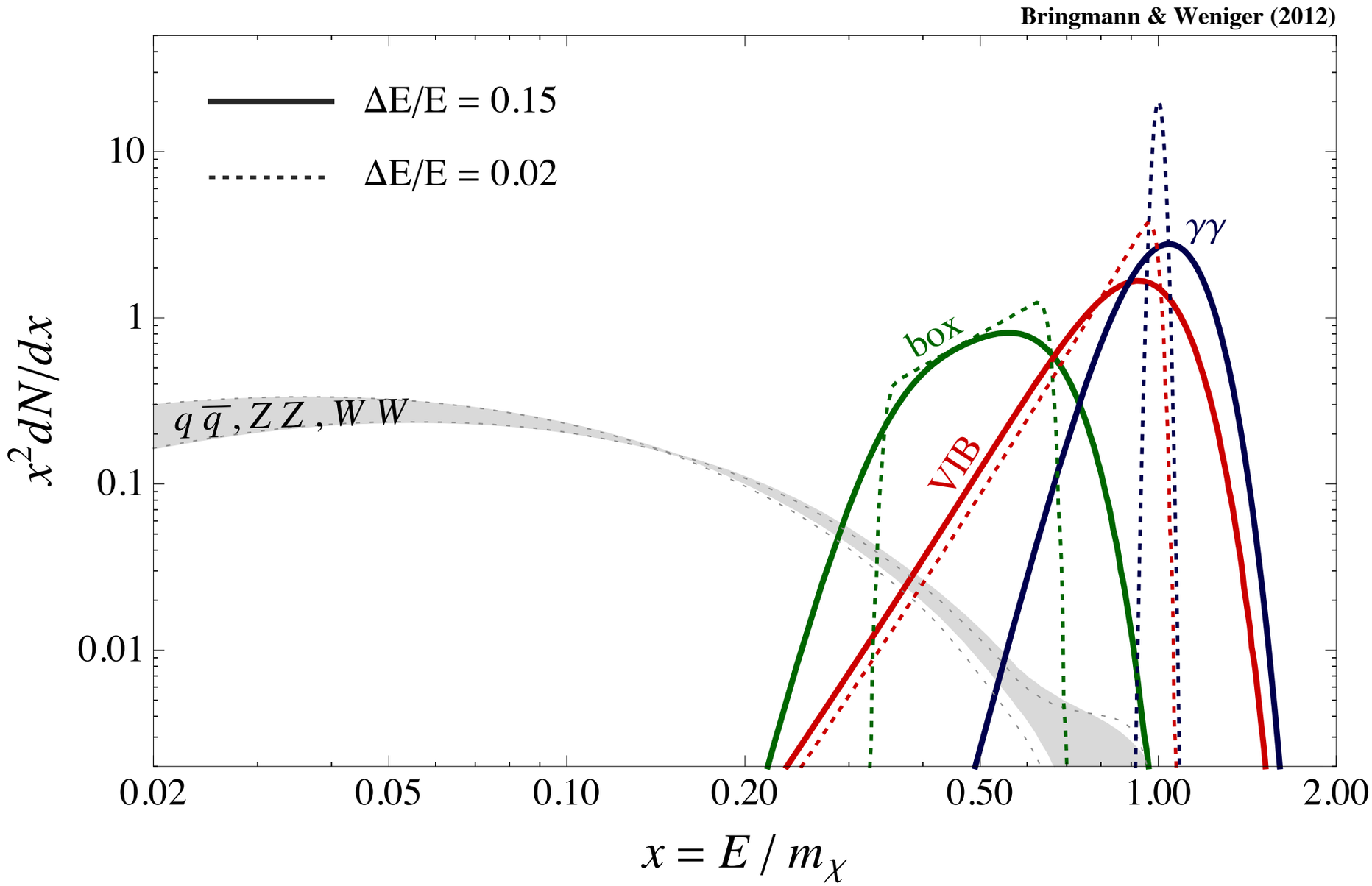

Bringmann, Weniger, Phys.Dark Univ. 1 (2012) — arXiv:1208.5481

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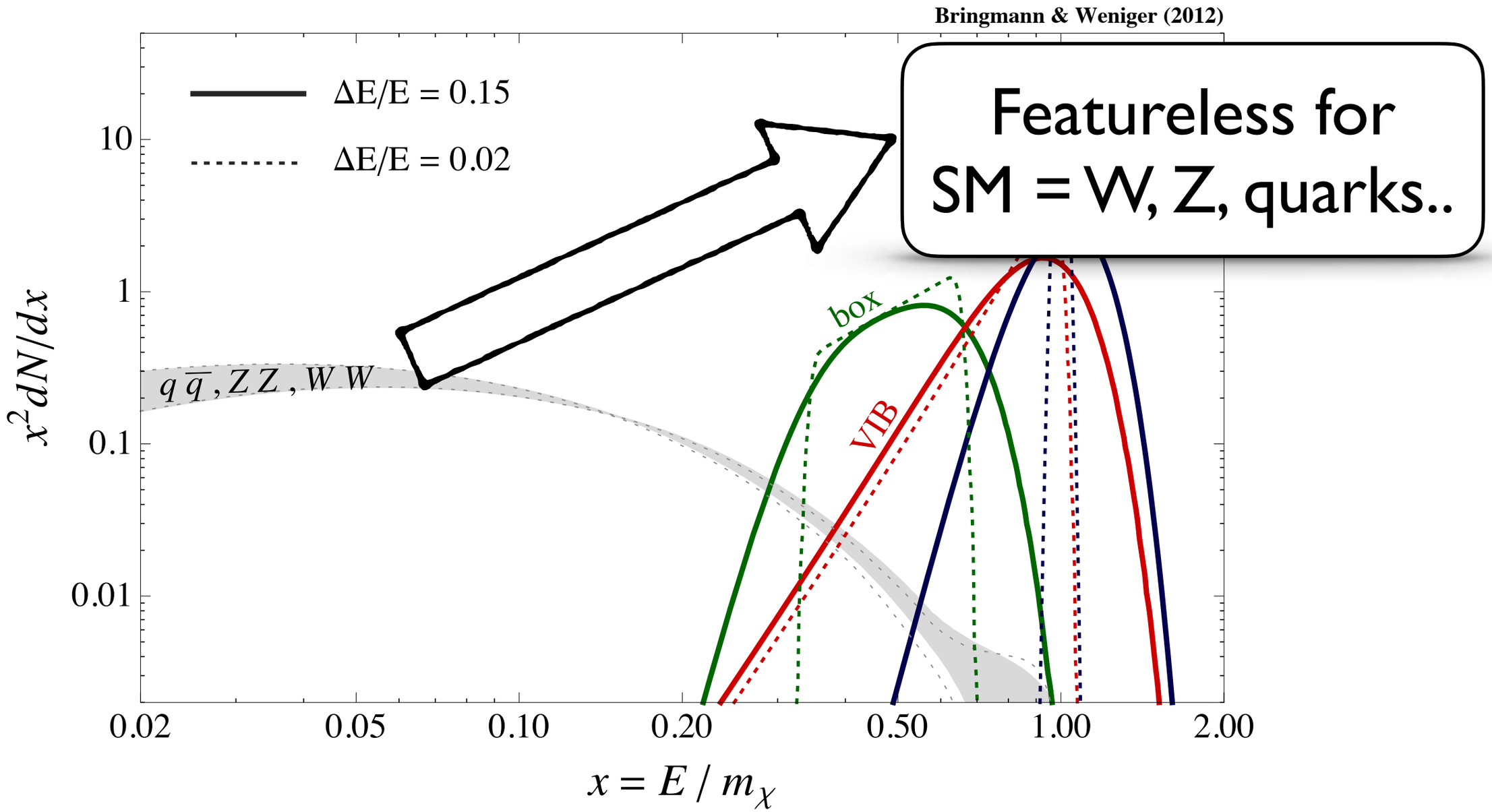


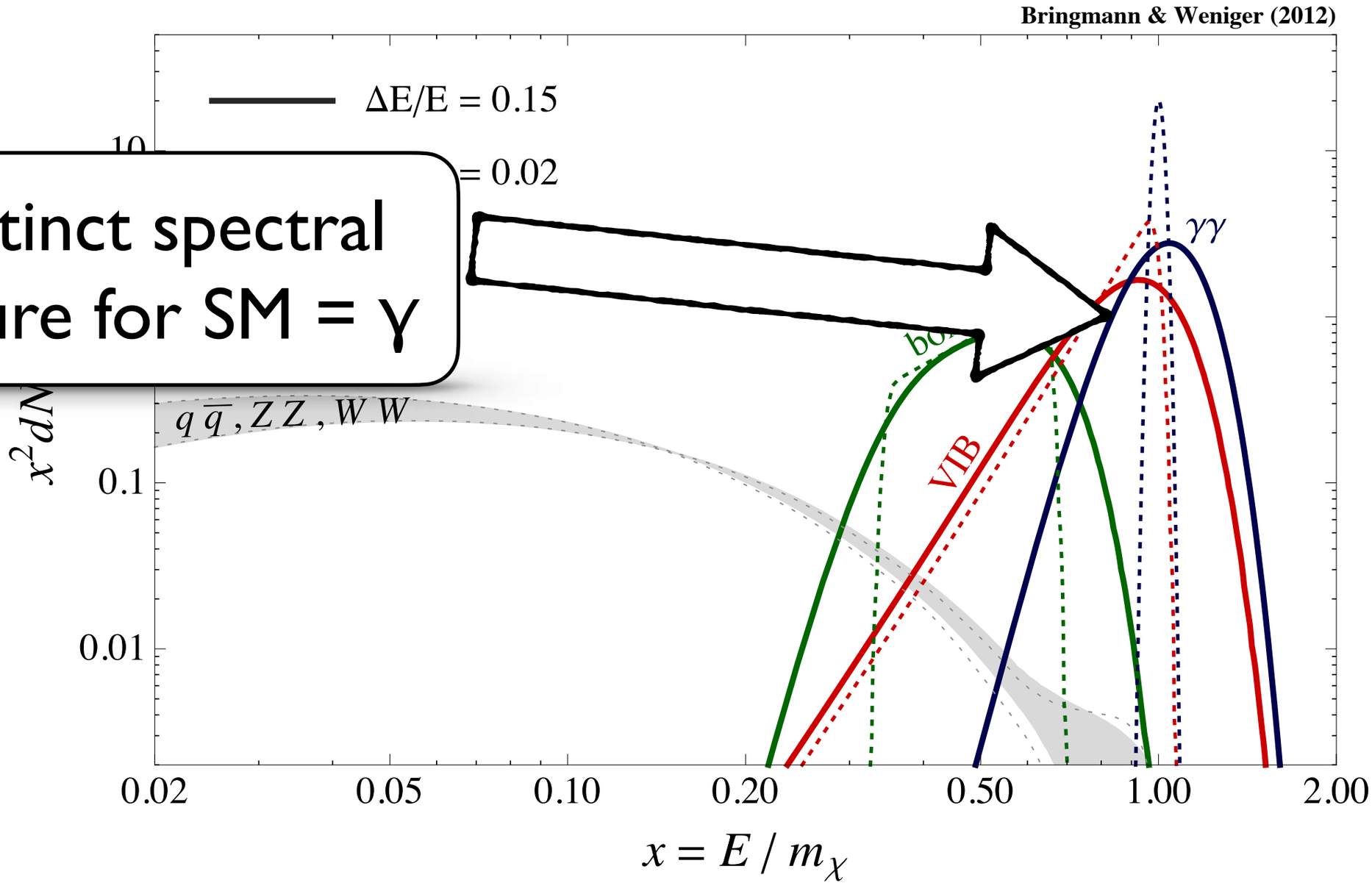
Featureless for SM = W, Z, quarks..

Bringmann, Weniger, Phys.Dark Univ. 1 (2012) — arXiv:1208.5481

Cosmic Photon Spectra

$$\chi\chi \to \mathrm{SM}\,\mathrm{SM} \qquad \text{or} \qquad \chi \to \mathrm{SM}\,\mathrm{SM}$$

Distinct spectral feature for SM = γ



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Prediction for the Flux

$$\frac{dN_\gamma}{dE_\gamma} = \frac{1}{4\pi r^2} \times \frac{dn_\gamma(m_\chi)}{dE_\gamma} \times \frac{1}{2} n_\chi^2 \langle \sigma v_{\rm rel} \rangle \times \Delta V \times \Delta A \, \Delta t$$

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Detector

Prediction for the Flux

$$\frac{dN_\gamma}{dE_\gamma} = \frac{1}{4\pi r^2} \times \frac{dn_\gamma(m_\chi)}{dE_\gamma} \times \frac{1}{2} n_\chi^2 \langle \sigma v_{\rm rel} \rangle \times \Delta V \times \Delta A \, \Delta t$$

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Particle Physics

Prediction for the Flux

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Standard Model

Prediction for the Flux

$$\frac{dN_\gamma}{dE_\gamma} = \frac{1}{4\pi r^2} \times \frac{dn_\gamma(m_\chi)}{dE_\gamma} \times \frac{1}{2} n_\chi^2 \langle \sigma v_{\rm rel} \rangle \times \Delta V \times \Delta A \, \Delta t$$

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Astrophysics

Prediction for the Flux

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$$\frac{d\Phi_\gamma}{dE_\gamma d\Omega} = \frac{\langle \sigma v_{\rm rel} \rangle}{m_\chi^2} \frac{dn_\gamma(m_\chi)}{dE_\gamma} J$$

J-FACTOR

$$J_{\rm ann} \equiv \frac{1}{8\pi} \int_{l.o.s.} dl \, \rho_\chi^2$$

What about decays?

The calculation for the photon flux
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$$n_\chi^2 \langle \sigma v_{\rm rel} \rangle \quad \rightarrow \quad n_\chi \Gamma_\chi$$

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J-FACTORS

$$J_{\rm ann} \equiv \frac{1}{8\pi} \int_{l.o.s.} dl\, \rho_\chi^2 \qquad J_{\rm decay} \equiv \frac{1}{8\pi} \int_{l.o.s.} dl\, \rho_\chi$$

Photon *morphology* can distinguish between the two cases

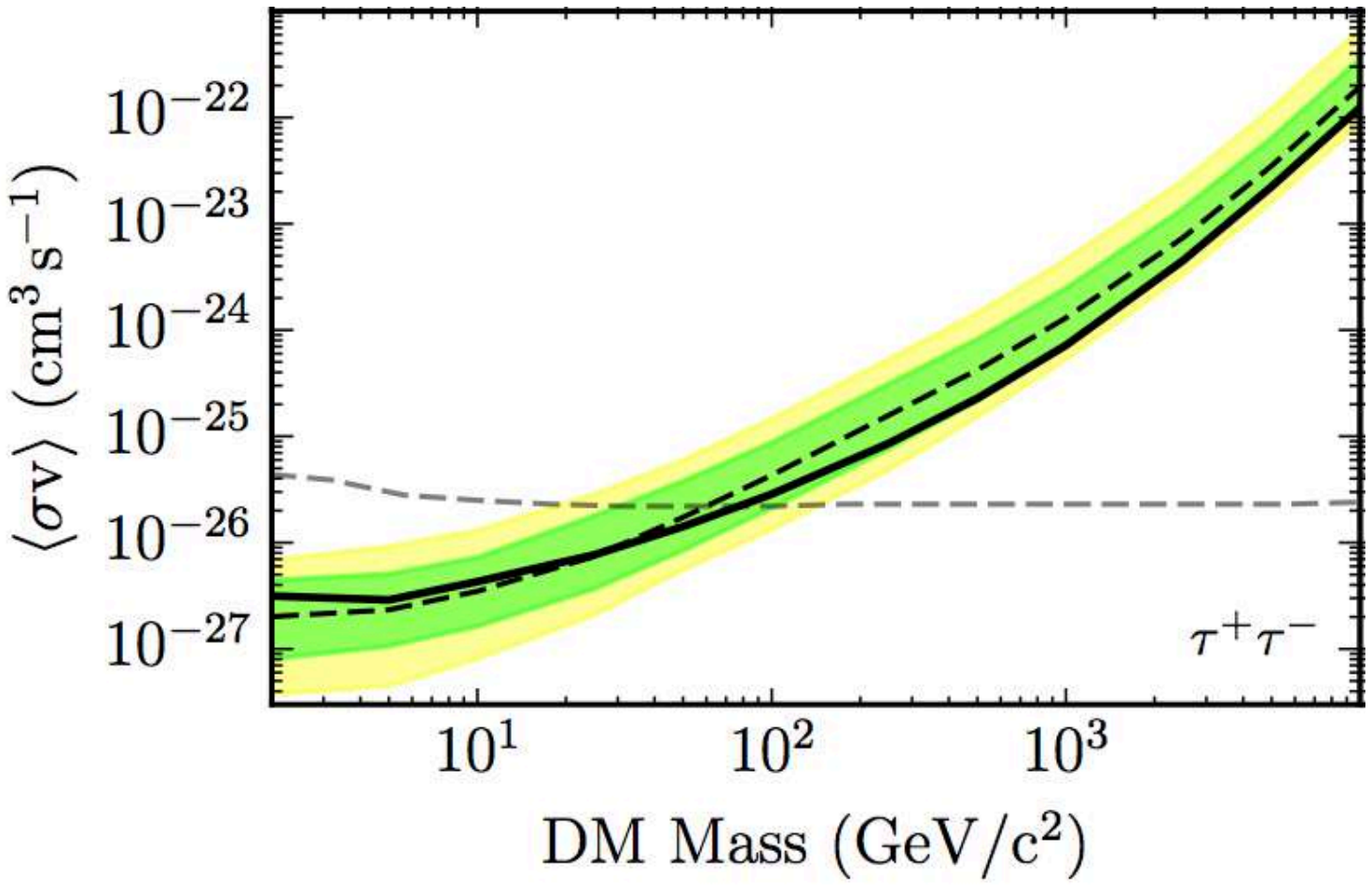
Gamma Ray Bounds

Benchmark (Thermal) Annihilation Cross Section:

$$\langle \sigma v_{\rm rel} \rangle \simeq 3 \times 10^{-26}\,{\rm cm}^3{\rm s}^{-1}$$

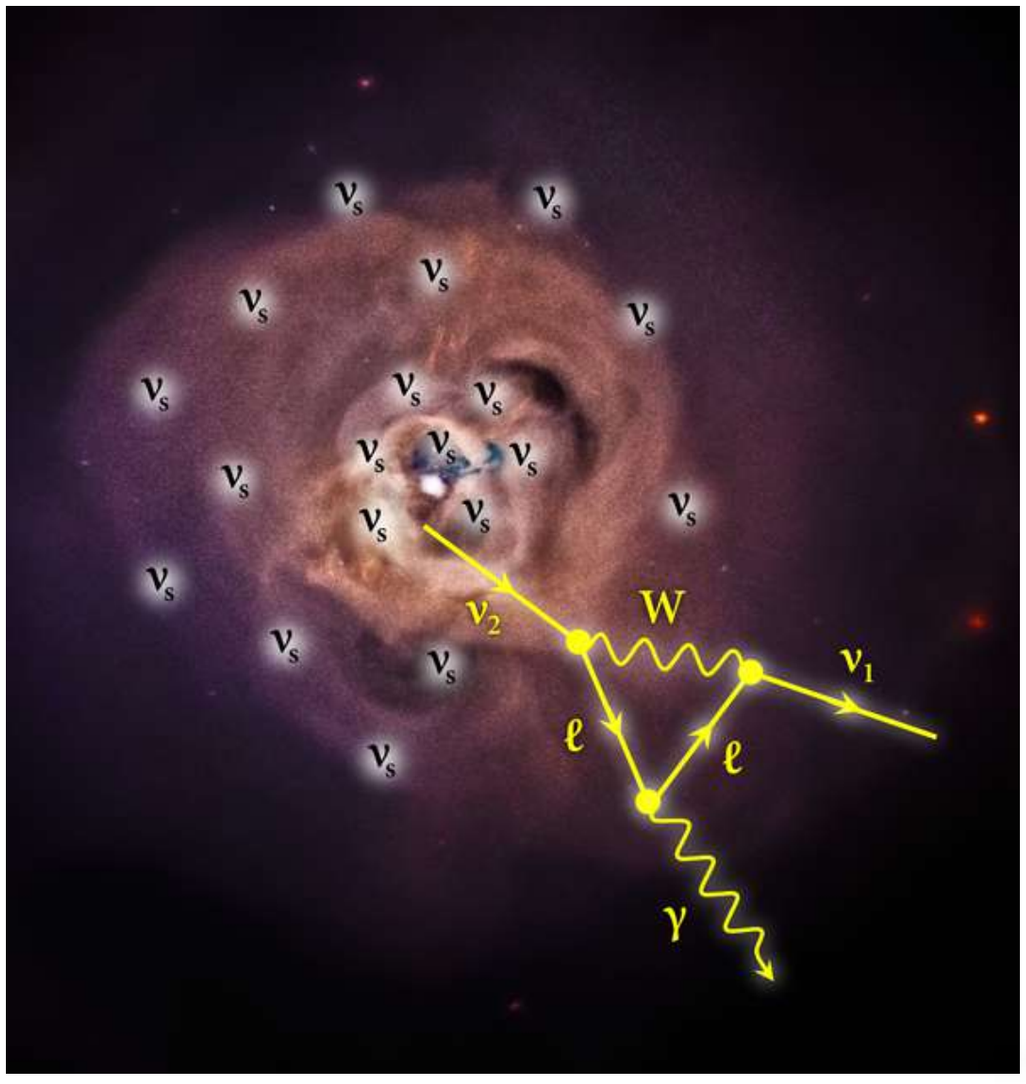
Thermal relic lighter than 100 GeV excluded by Fermi

The Cherenkov Telescope Array (CTA) will probe higher masses



Fermi-LAT Collaboration, PRL115 (2015)

X-rays



STERILE NEUTRINOS

Produced through oscillations

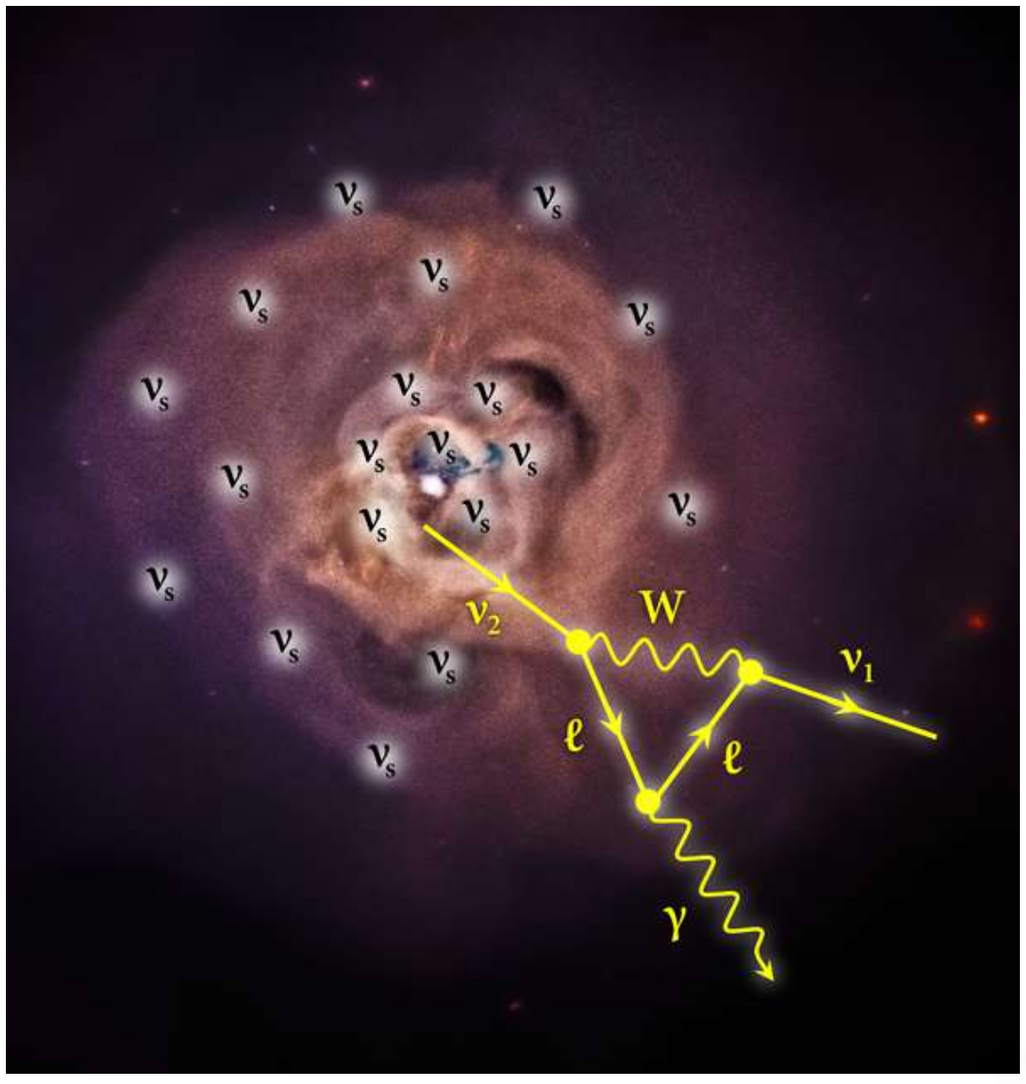
$$\Omega_{N_R} h^2 \simeq 0.1 \, \frac{\sin^2 2\theta}{10^{-8}} \left(\frac{m_{N_R}}{3\,\mathrm{keV}} \right)^{1.8}$$

Dodelson, Widrow, PRL72 (1994)

Production can be enhanced by lepton asymmetry

Shi, Fuller, PRL82 (1999)

X-rays



STERILE NEUTRINOS

X-ray lines source

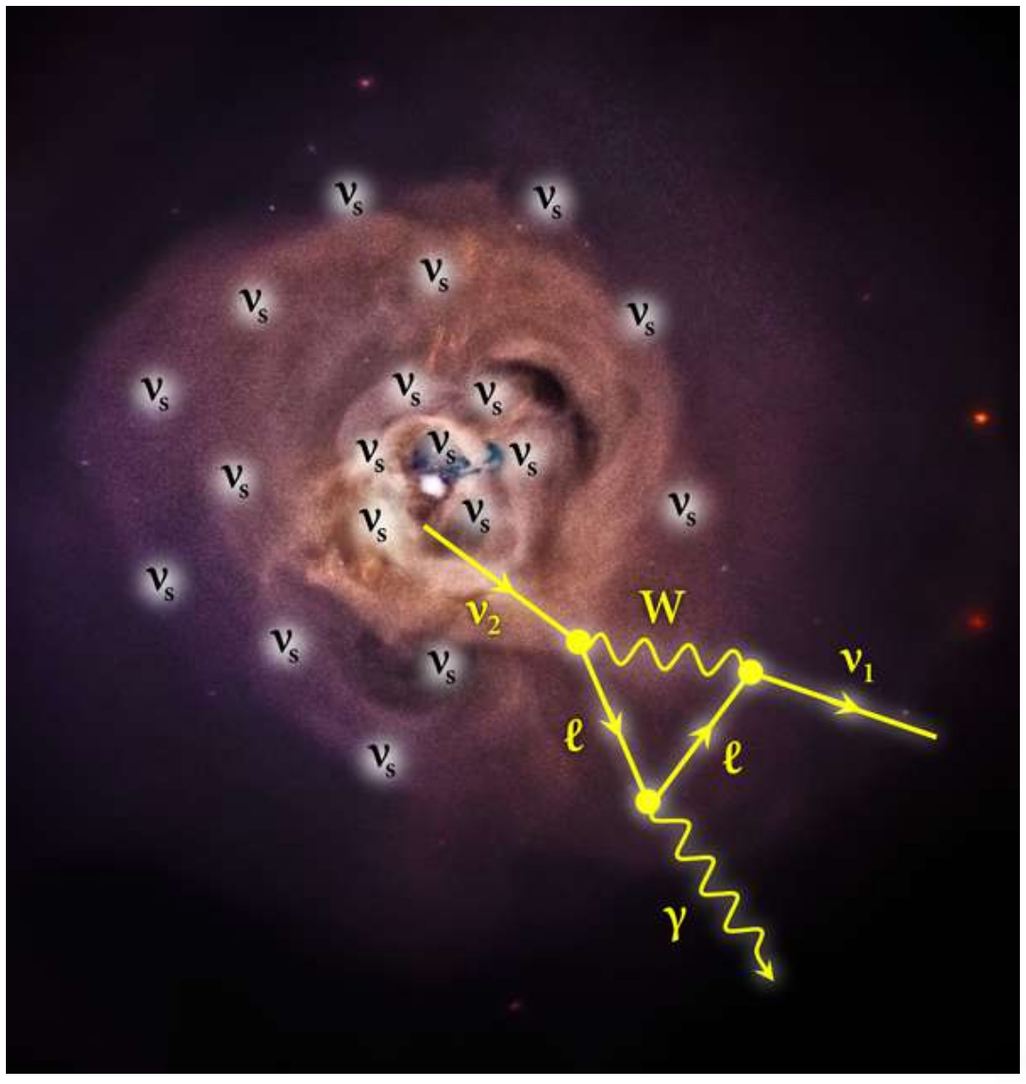
$$N_R \;\to\; \nu_L\,\gamma$$

$$E_\gamma \simeq m_{N_R}/2$$

$$\Gamma_{N_R\to\nu_L\,\gamma} \simeq \frac{1}{1.5\times10^{32}\,\mathrm{sec}}\,\frac{\sin^2 2\theta}{10^{-10}}\left(\frac{m_{N_R}}{\mathrm{keV}}\right)^5$$

Pal, Wolfenstein, PRD25 (1982)

X-rays



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Other dark matter candidates produce X-ray lines via annihilations, decays and other mechanisms

An X-ray Line at 3.5 keV

Discovered in 2014

Stacked clusters and Perseus ✓
Bulbul et al., Astrophys.J.789 (2014)

Center of the Milky Way ✓
Jeltema and Profumo, MNRAS450 (2015)

M31 (Andromeda) ?
Boyarsky et al., PRL113 (2014)
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A sterile neutrino can account for the line!

$$N_R \;\to\; \nu_L\,\gamma$$

$$m_{N_R} \simeq 7\,\mathrm{keV}$$
$$\sin^2(2\theta) \simeq 7\times 10^{-11}$$

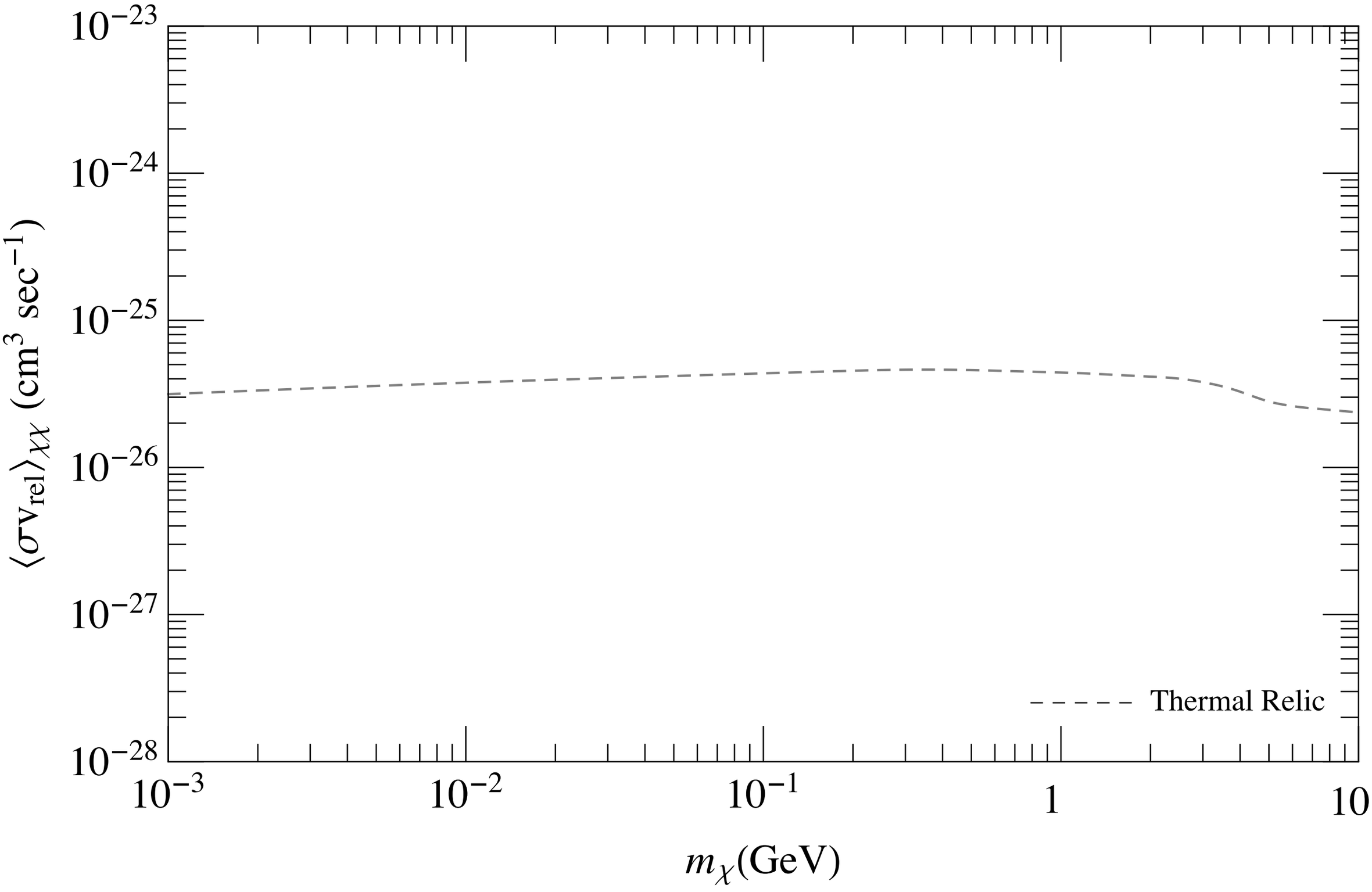
Early time annihilations

Out-of-equilibrium dark matter annihilations may deposit energy into the plasma and alter CMB formation

Same for dark matter decays

Severe bounds!

Early time annihilations



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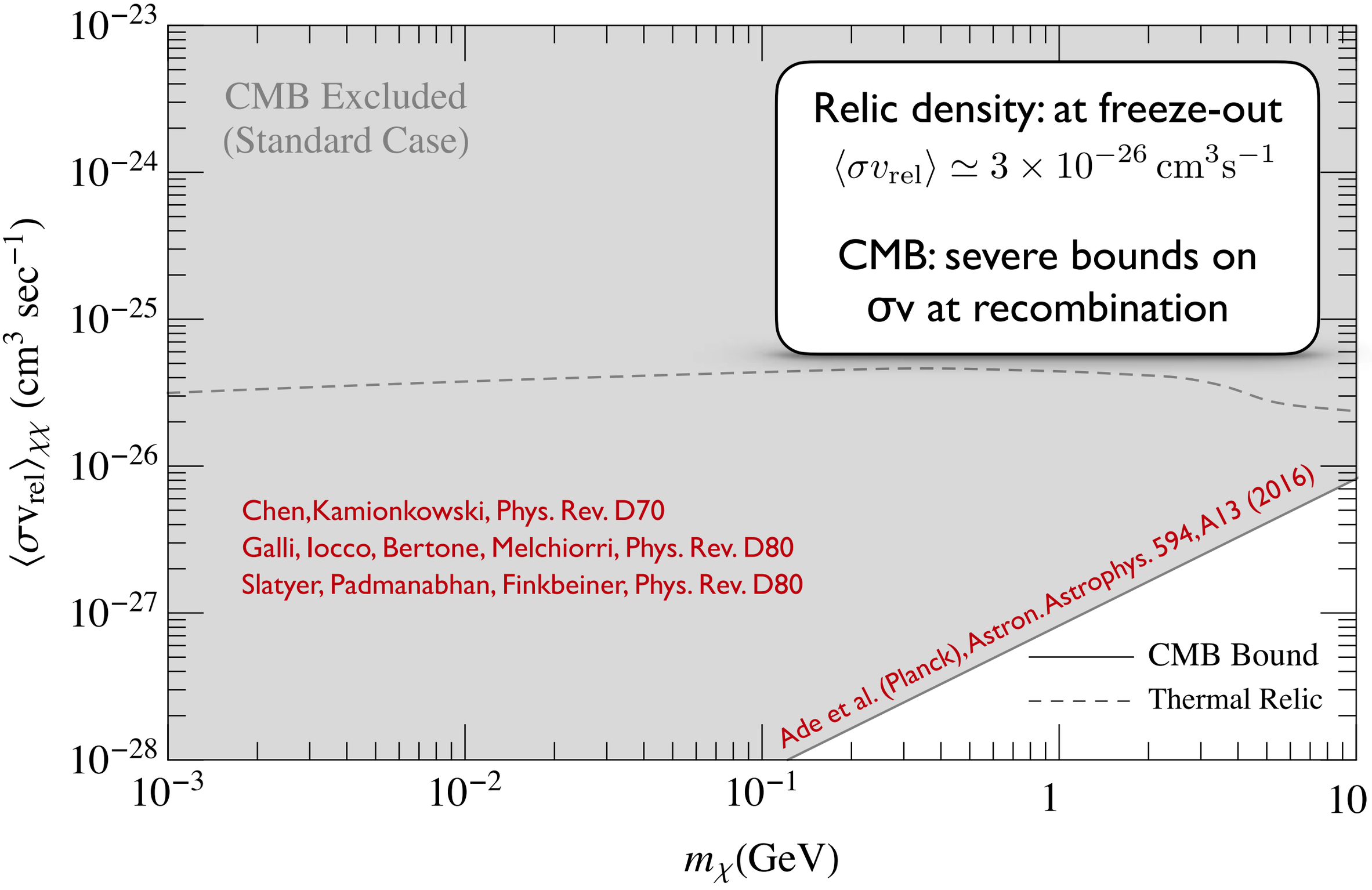

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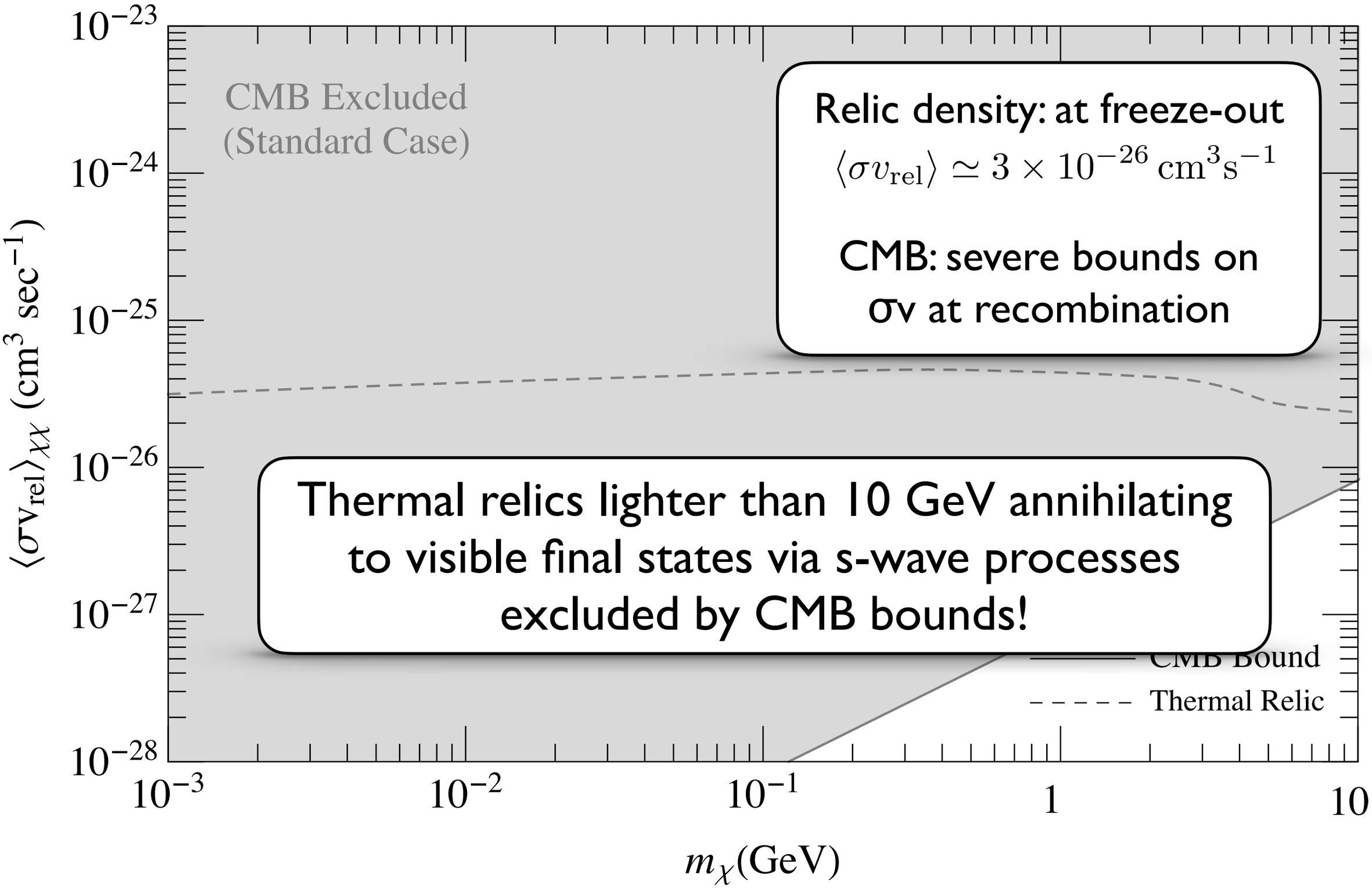
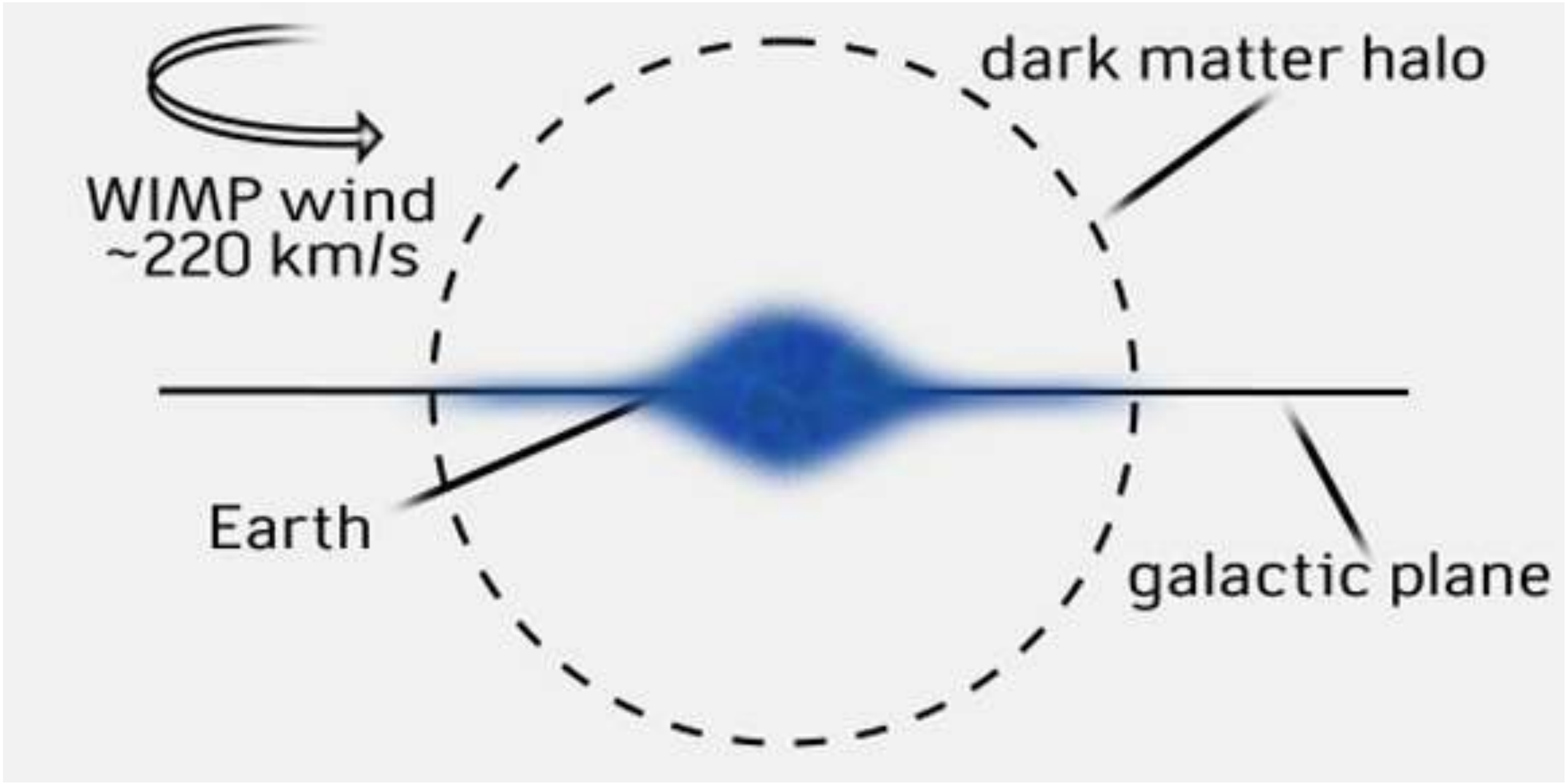
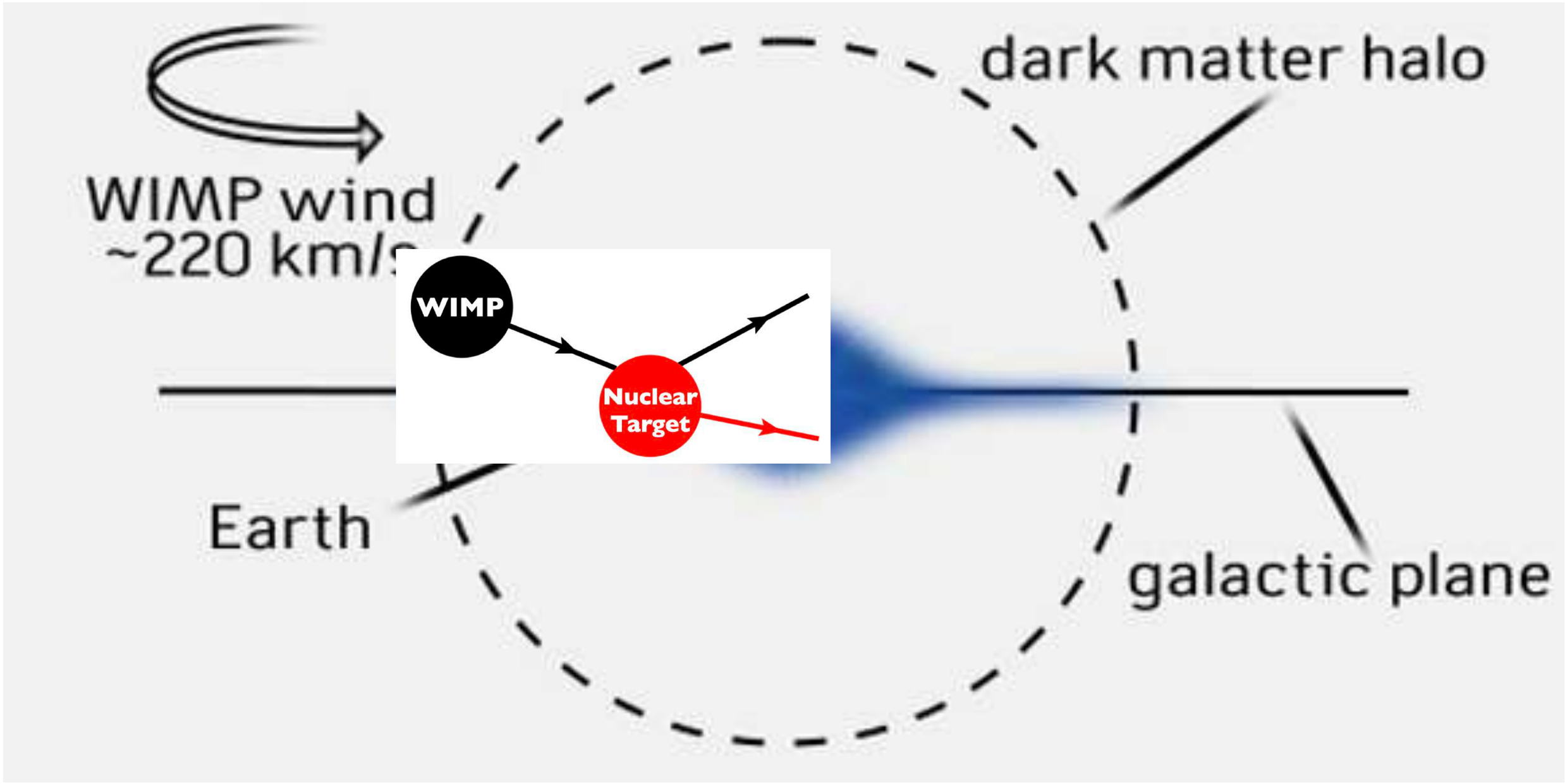


Direct Searches



Schnee, TASI 2009, arXiv:1101.5205

Direct Searches



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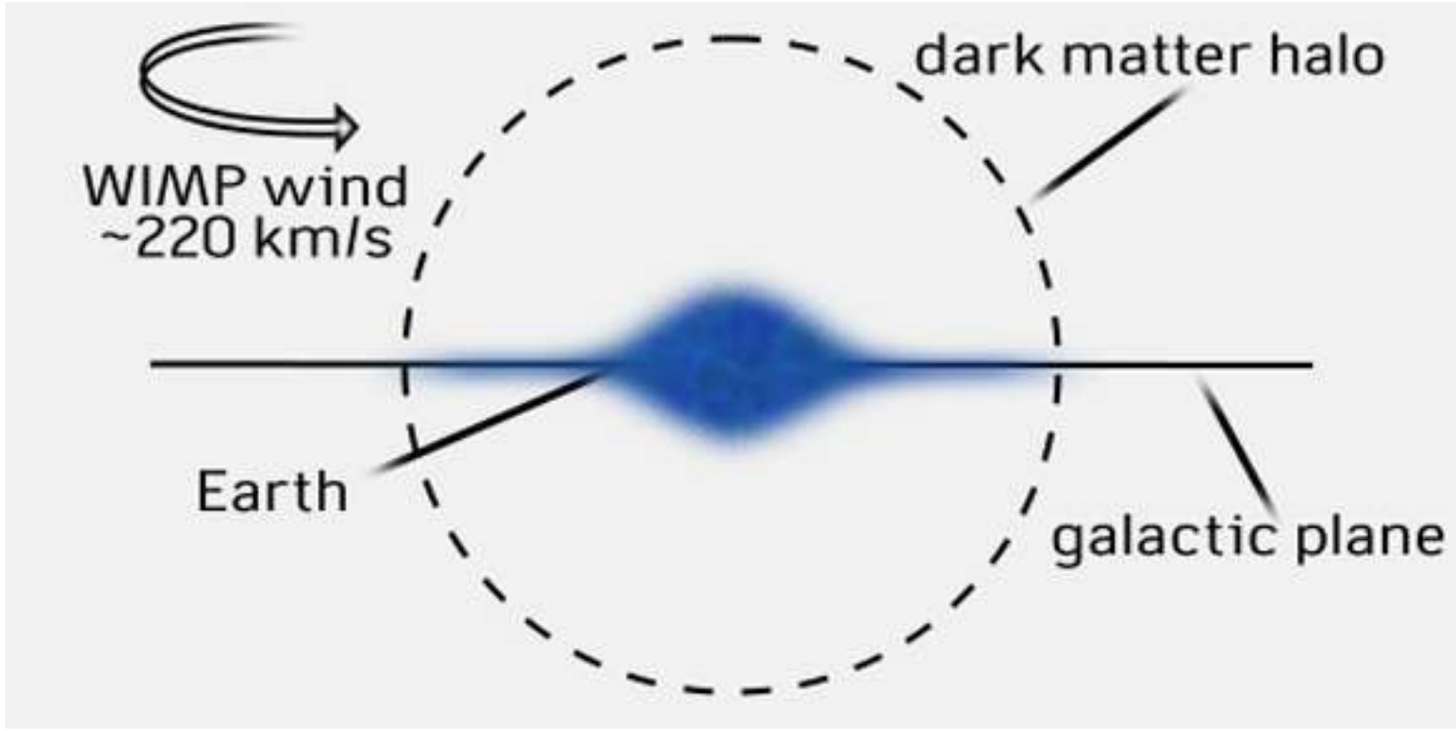
Dark Matter Flux

Local dark matter density and flux

$$\rho_{\rm DM}^{\rm (local)} \simeq 0.3\,{\rm GeV\,cm^{-3}}$$

$$\phi_{\rm DM} = n_{\rm DM}\, v_{\rm DM} = \frac{\rho_{\rm DM}^{\rm (local)}}{m_{\rm DM}}\, v_{\rm DM}$$



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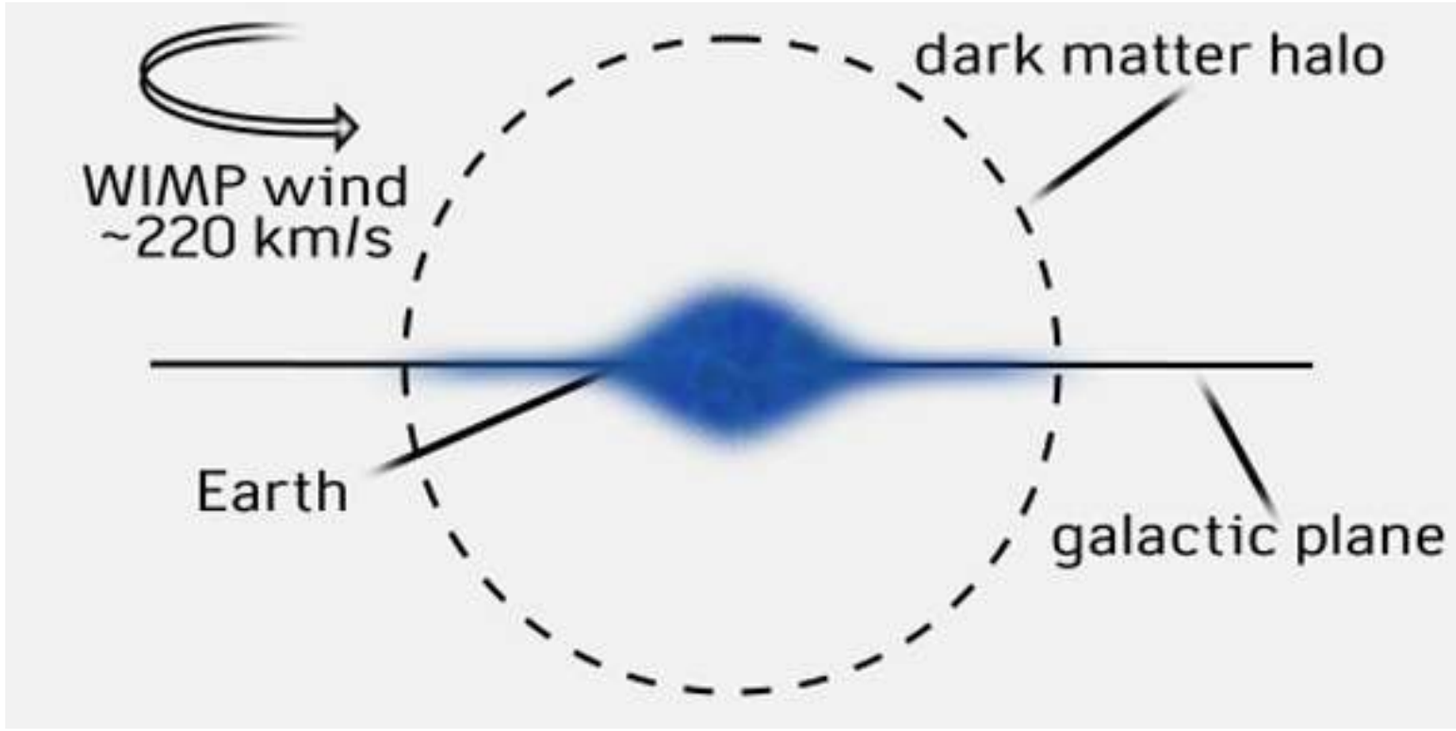
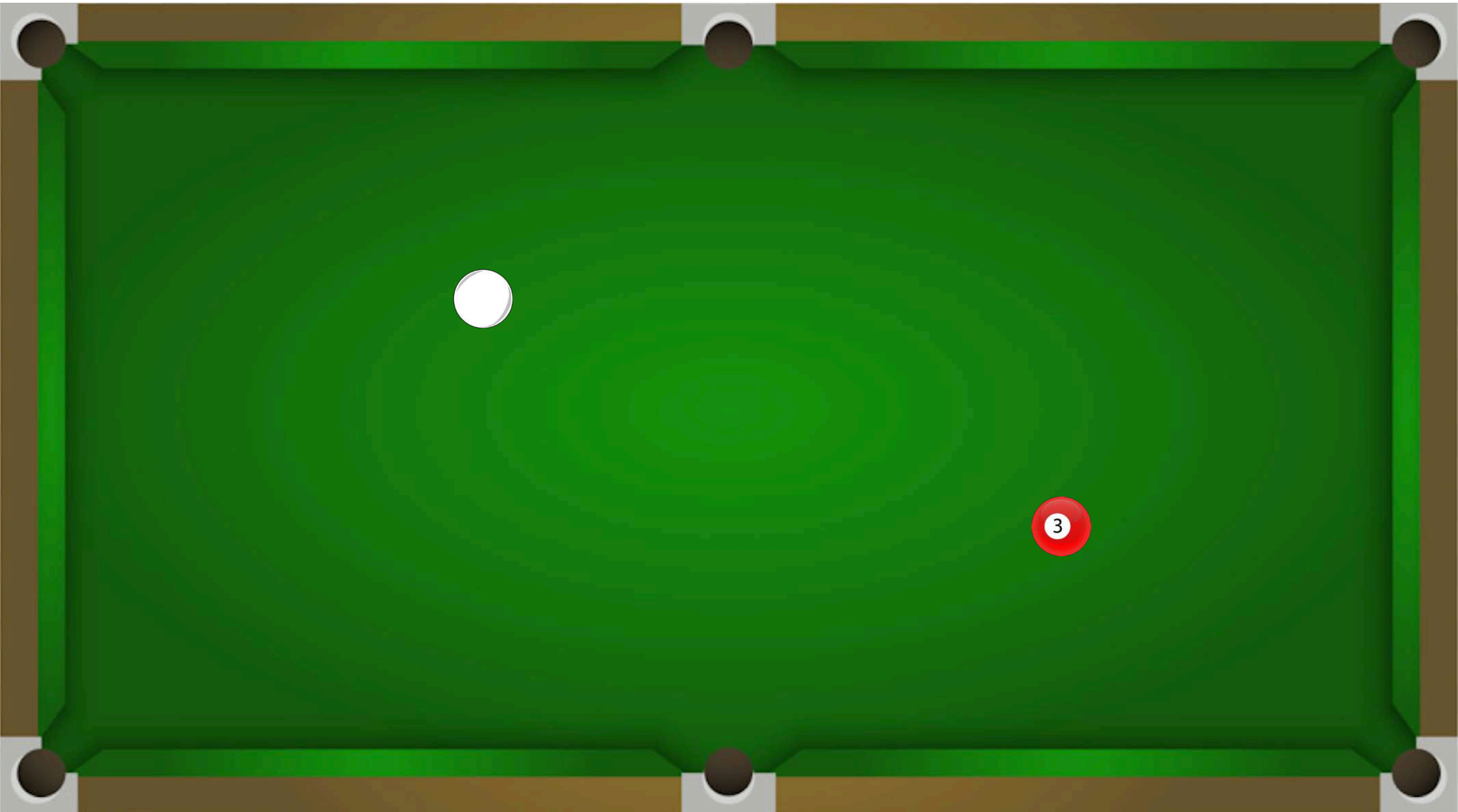


$$\phi_{\rm DM}\big|_{m_{\rm DM}=100\,{\rm GeV}} = 9\times10^{4}\,{\rm cm^{-2}\,sec^{-1}}$$

Useful Analogy



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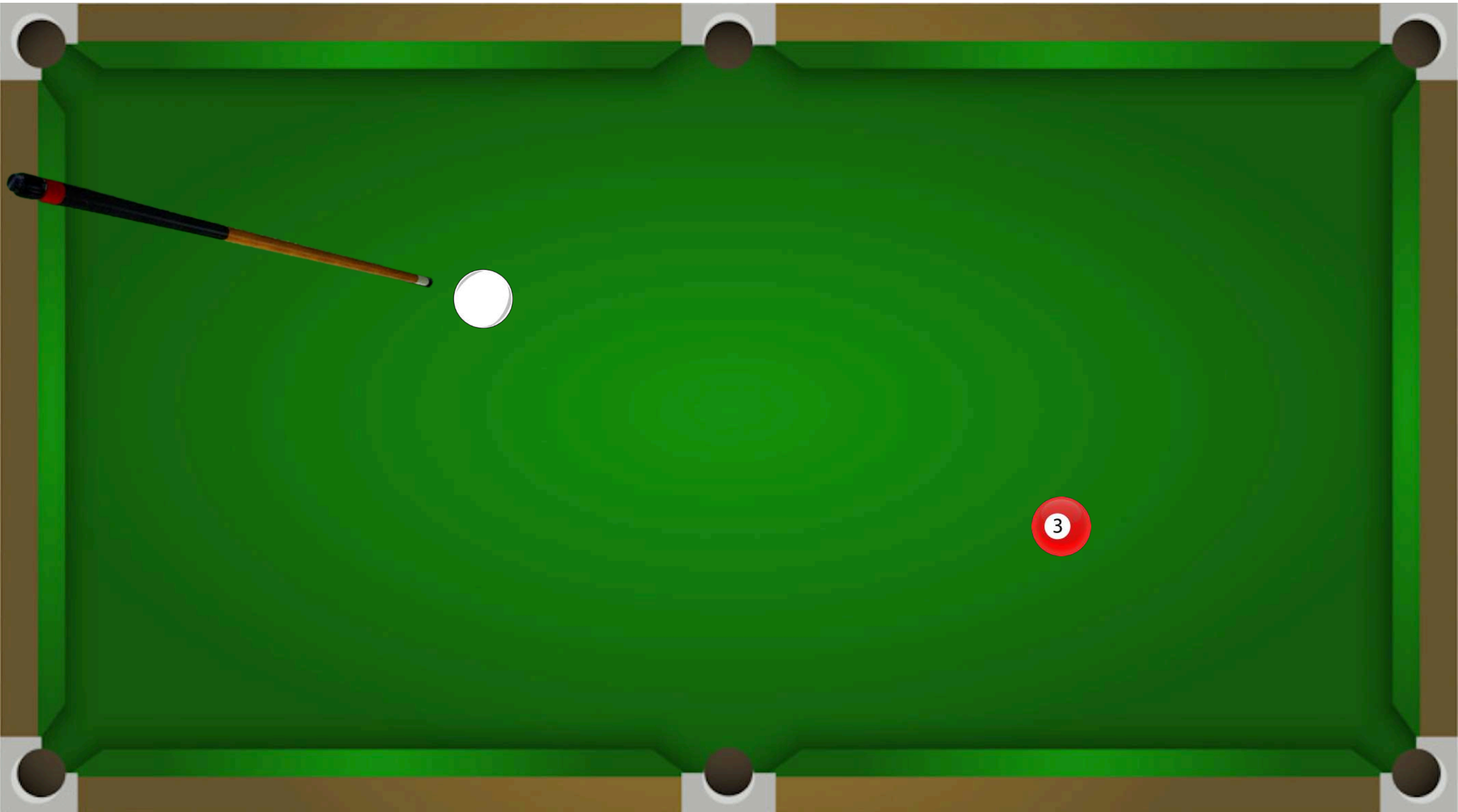

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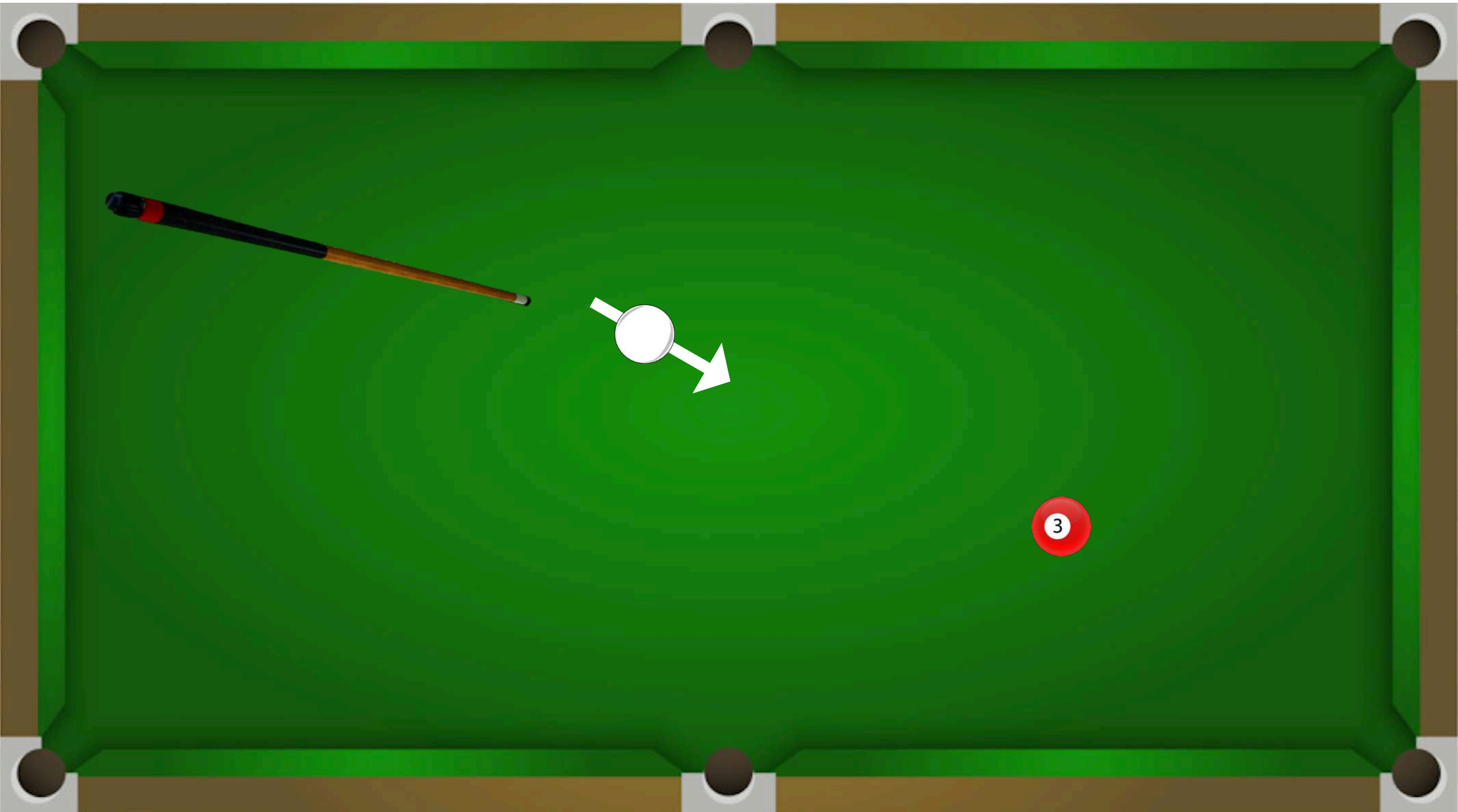

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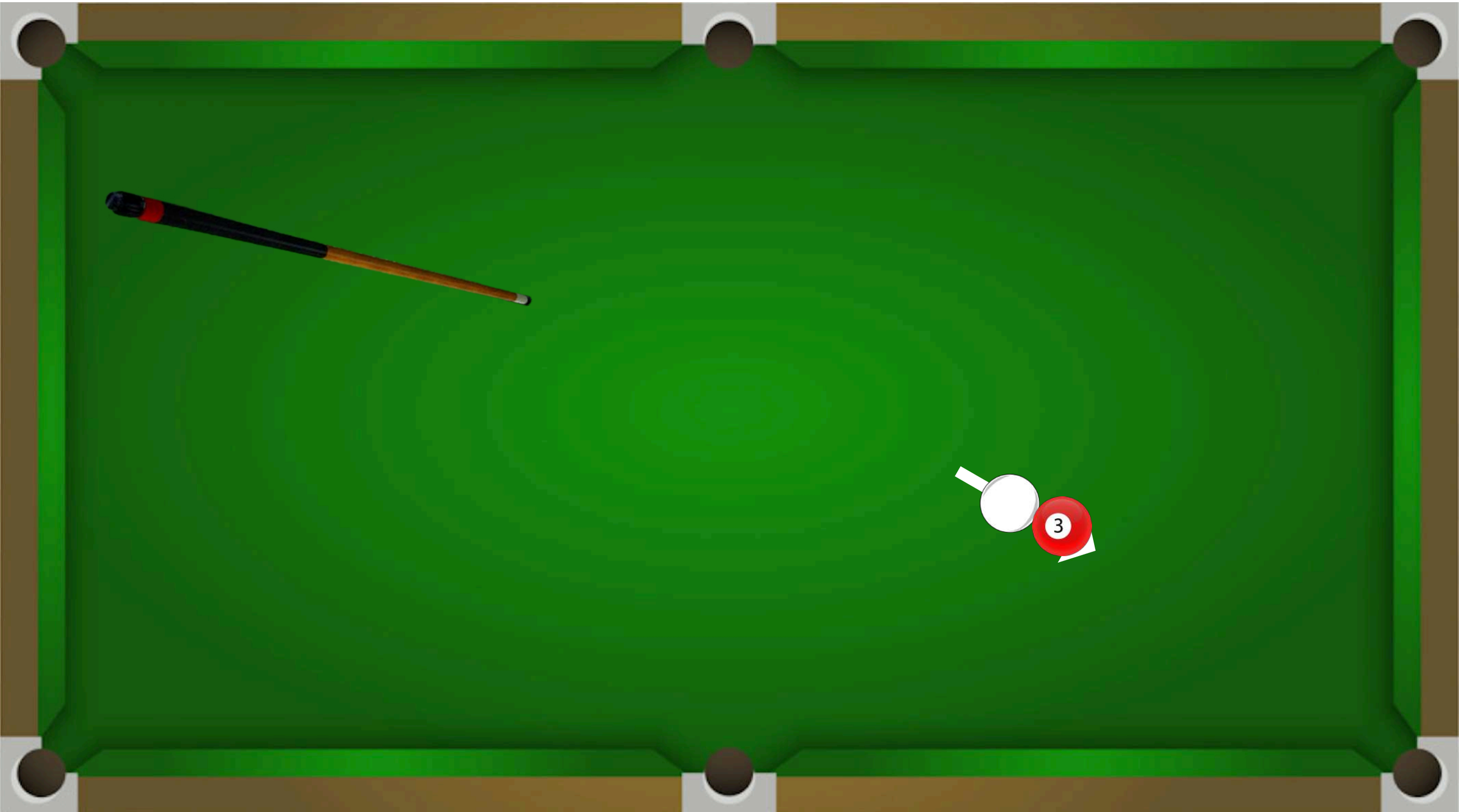

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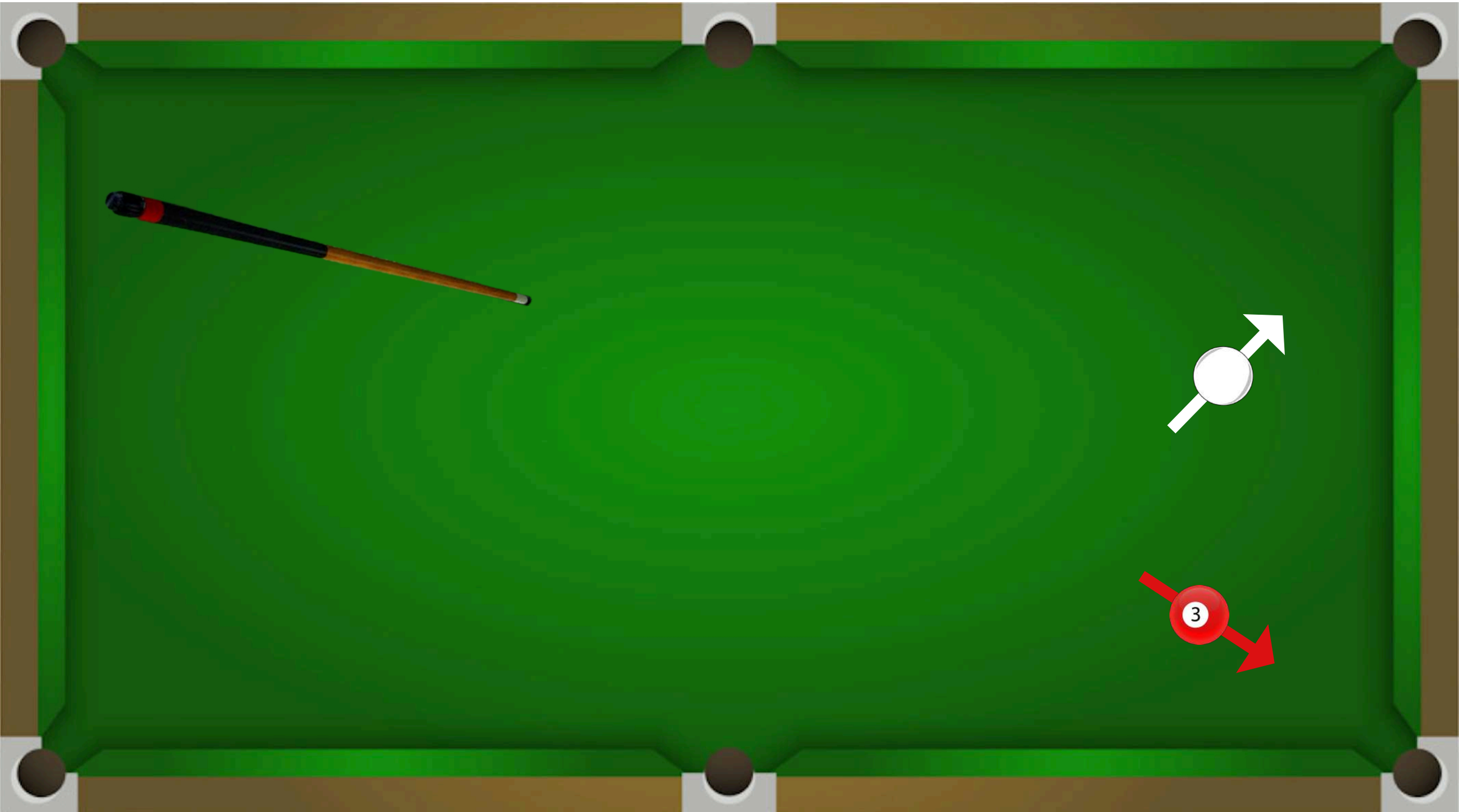
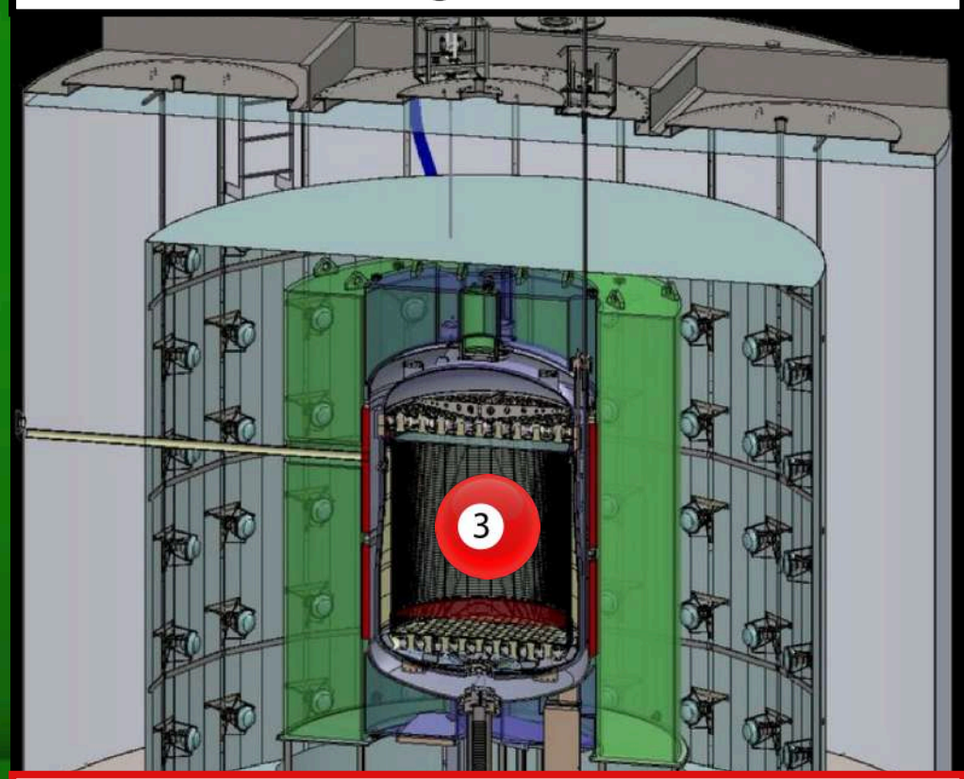


Useful Analogy

Dark matter particle (invisible) reaching the Earth

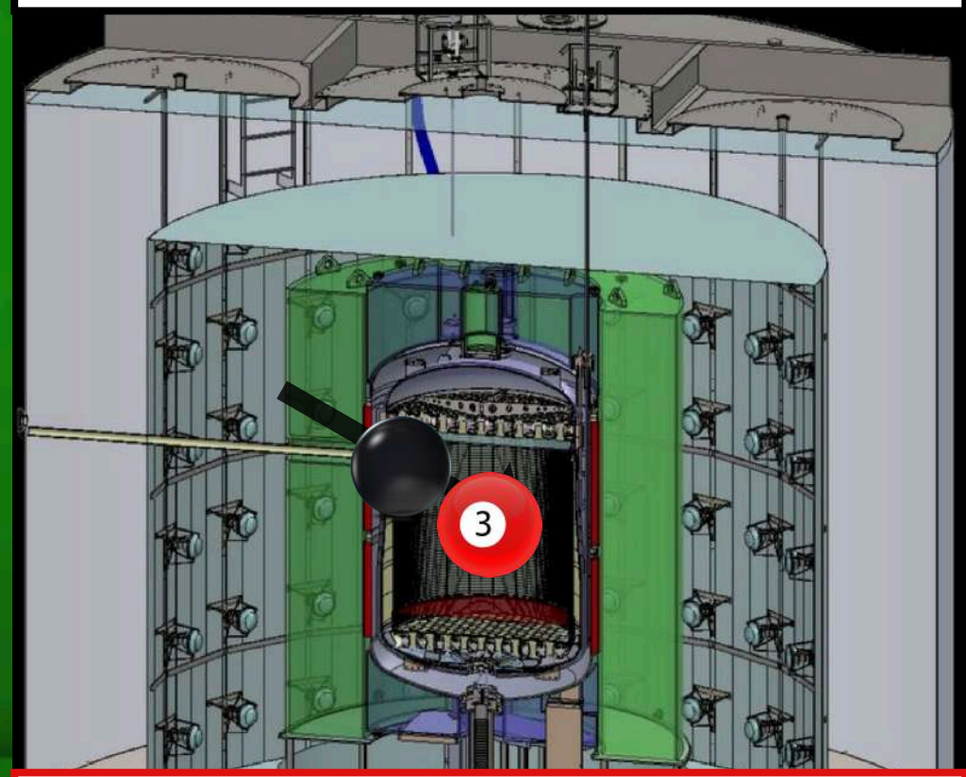
Underground Lab



Target Nucleus

Useful Analogy

Underground Lab



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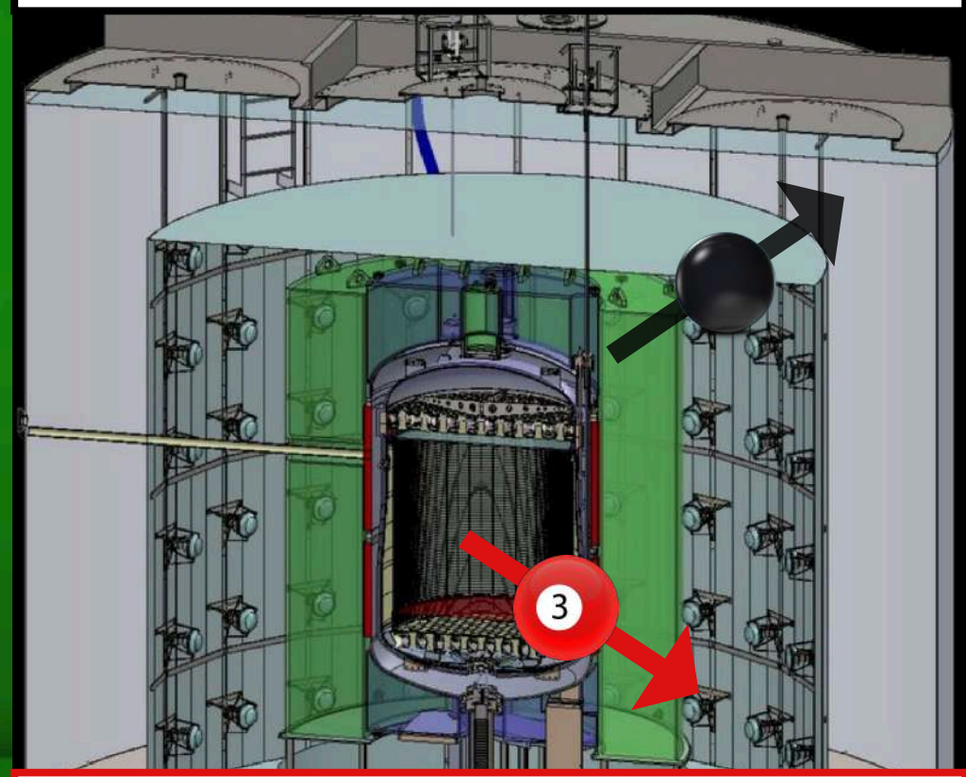
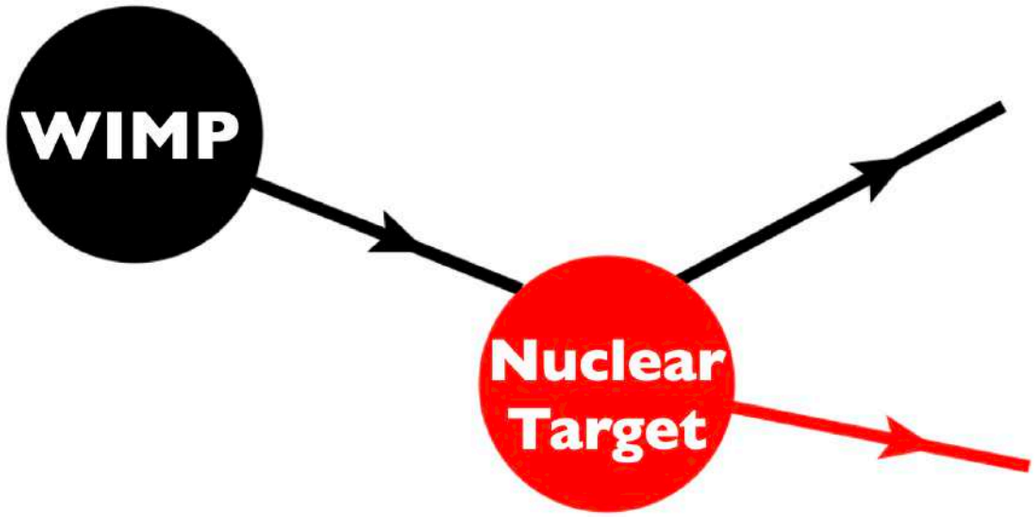
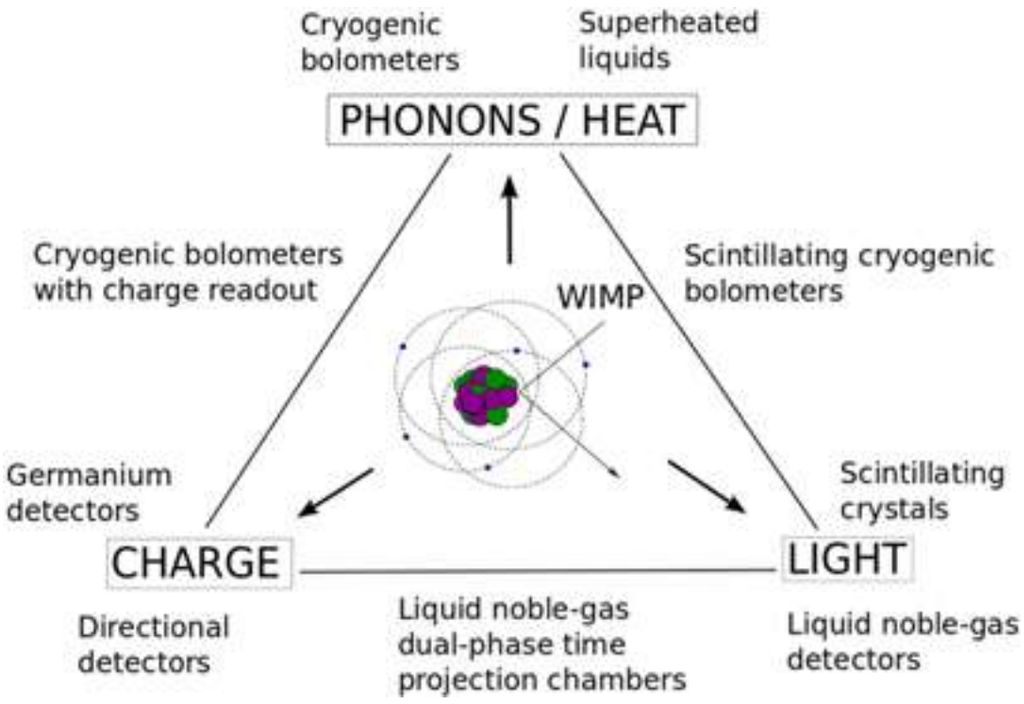


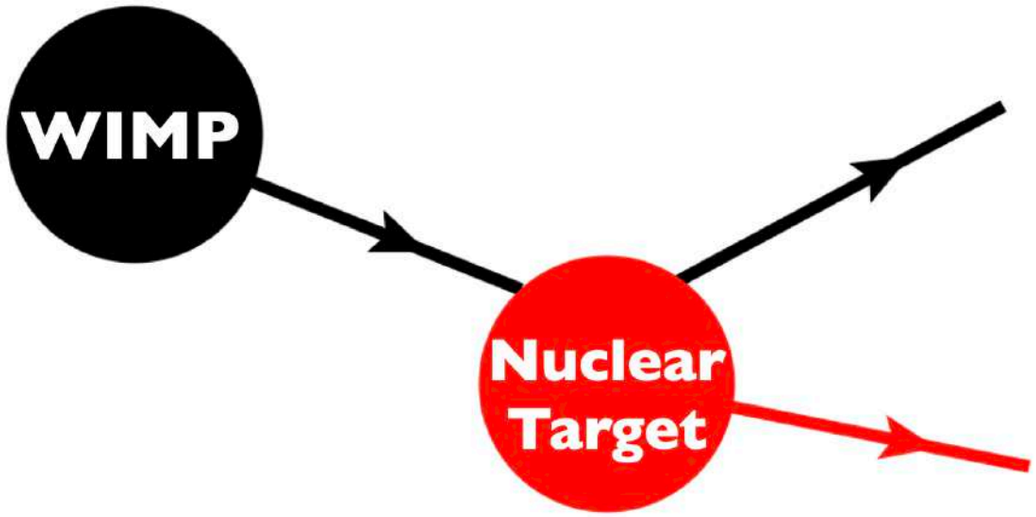
Target Nucleus

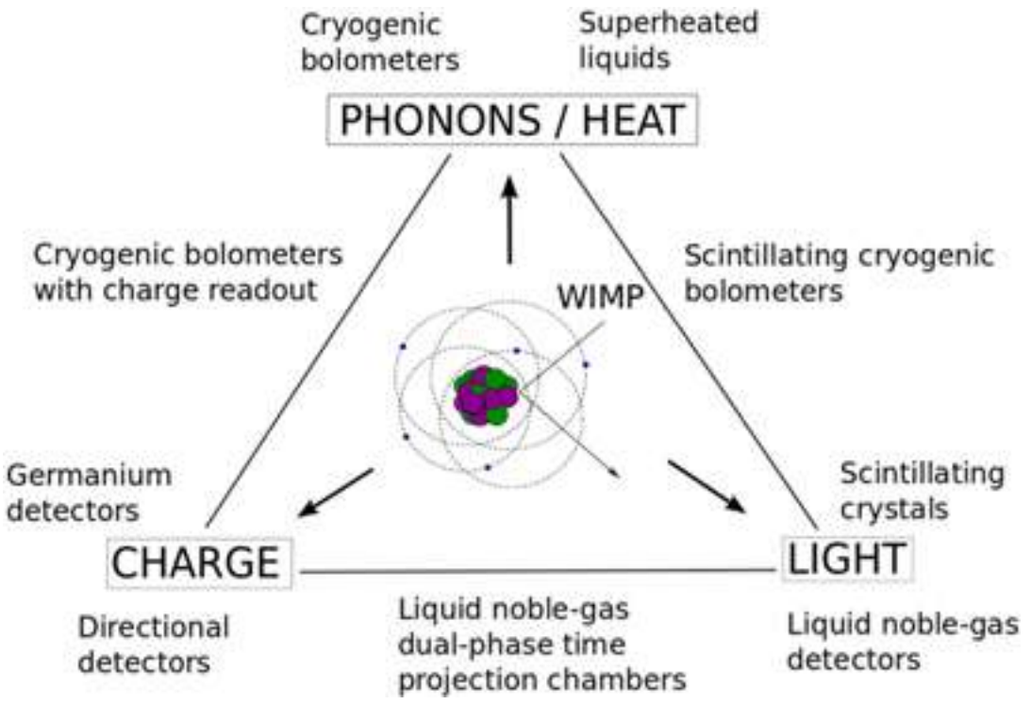
Recoil Energy





Recoil Energy





Interesting results also with electron recoil… (more tomorrow)

The New York Times

OUT THERE

Seeking Dark Matter, They Detected Another Mystery

Do signals from beneath an Italian mountain herald a revolution in physics?

Kinematics of Elastic Scattering

$$\chi \mathcal{N} \rightarrow \chi \mathcal{N}$$

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Initial state nucleus: at rest

Momentum transferred in the collision: q

$$E_R = \frac{q^2}{2m_{\mathcal{N}}}$$

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MAXIMUM RECOIL ENERGY

PROBLEM 1

$$E_R^{\max} = \frac{2\mu_{\chi\mathcal{N}}^2 v^2}{m_{\mathcal{N}}}$$

Kinematics of Elastic Scattering

$$\chi \mathcal{N} \rightarrow \chi \mathcal{N}$$

Initial state nucleus: at rest

Momentum transferred in the collision: q

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KINEMATICAL THRESHOLD

PROBLEM I

$$v_{\min} = \sqrt{\frac{m_{\mathcal{N}} E_R}{2\mu^2_{\chi\mathcal{N}}}} = \begin{cases} \sqrt{\frac{m_{\mathcal{N}} E_R}{2m_\chi^2}} & m_\chi \ll m_{\mathcal{N}} \\ \sqrt{\frac{E_R}{2m_{\mathcal{N}}}} & m_\chi \gg m_{\mathcal{N}} \end{cases}$$

Tiny Recoils

$$E_R^{\max} = \frac{2\mu_{\chi\mathcal{N}}^2 v^2}{m_{\mathcal{N}}}$$

Tiny Recoils

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RECOIL ENERGY FOR A WIMP

$$E_R^{\text{WIMP}} \simeq \frac{2\,(100\,\text{GeV})^2\;10^{-6}}{100\,\text{GeV}} \simeq 200\,\text{keV}$$

Tiny Recoils

$$E_R^{\max} = \frac{2\mu_{\chi\mathcal{N}}^2 v^2}{m_{\mathcal{N}}}$$

RECOIL ENERGY FOR A WIMP

$$E_R^{\rm WIMP} \simeq \frac{2\,(100\,{\rm GeV})^2\ 10^{-6}}{100\,{\rm GeV}} \simeq 200\,{\rm keV}$$

We need detectors with a
very low threshold energy

Dark Matter Scattering Rate

General equation for the differential rate

$$\frac{d\Gamma}{dE_R} = 2\pi \frac{N_T\, \rho_\chi m_{\mathcal{N}}}{\mu^2_{\chi\mathcal{N}} m_\chi v_{\rm rel}} \frac{d\sigma}{d\Omega_*} f_\chi(v_{\rm rel}) dv_{\rm rel}$$

PROBLEM 2

N_T	Number of target nuclei
ρ_χ	Dark matter mass density
$f(v_{\rm rel})$	Dark matter velocity distribution

Dark Matter Scattering Rate

General equation for the differential rate

$$\frac{d\Gamma}{dE_R} = 2\pi \frac{N_T\, \rho_\chi m_{\mathcal{N}}}{\mu^2_{\chi\mathcal{N}} m_\chi v_{\rm rel}} \frac{d\sigma}{d\Omega_*} f_\chi(v_{\rm rel}) dv_{\rm rel}$$

PROBLEM 2

SPIN-INDEPENDENT SCATTERING

$$\sigma^{(SI)}_{\chi\mathcal{N}} = \frac{[Z f_p + (A-Z) f_n]^2}{16\pi (m_\chi + m_{\mathcal{N}})^2} F(E_R)^2 = \sigma^{(SI)}_{\chi\mathcal{N}}\Big|_{E_R=0} F(E_R)^2$$

Spin-Independent Scattering

$$\frac{d\Gamma}{dE_R} = (N_T\, m_{\mathcal{N}}) \times \left(\frac{\sigma^{(SI)}_{\chi\mathcal{N}}\Big|_{E_R=0}}{\mu^2_{\chi\mathcal{N}} m_\chi} \right) \times F(E_R)^2 \times \left(\rho_\chi \int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{f_\chi(v_{\rm rel})}{2v_{\rm rel}} dv_{\rm rel} \right)$$

Spin-Independent Scattering

$$\frac{d\Gamma}{dE_R} = (N_T\, m_{\mathcal{N}}) \times \left(\frac{\sigma^{(SI)}_{\chi\mathcal{N}}\Big|_{E_R=0}}{\mu^2_{\chi\mathcal{N}} m_\chi} \right) \times F(E_R)^2 \times \left(\rho_\chi \int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{f_\chi(v_{\rm rel})}{2 v_{\rm rel}} dv_{\rm rel} \right)$$

Target

Spin-Independent Scattering

$$\frac{d\Gamma}{dE_R} = (N_T\, m_{\mathcal{N}}) \times \left(\frac{\sigma^{(SI)}_{\chi\mathcal{N}}\Big|_{E_R=0}}{\mu^2_{\chi\mathcal{N}} m_\chi} \right) \times F(E_R)^2 \times \left(\rho_\chi \int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{f_\chi(v_{\rm rel})}{2 v_{\rm rel}} dv_{\rm rel} \right)$$

Particle Physics

Spin-Independent Scattering

$$\frac{d\Gamma}{dE_R} = (N_T\, m_{\mathcal{N}}) \times \left(\frac{\sigma^{(SI)}_{\chi\mathcal{N}}\Big|_{E_R=0}}{\mu^2_{\chi\mathcal{N}} m_\chi} \right) \times F(E_R)^2 \times \left(\rho_\chi \int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{f_\chi(v_{\rm rel})}{2 v_{\rm rel}} dv_{\rm rel} \right)$$

Nuclear Physics

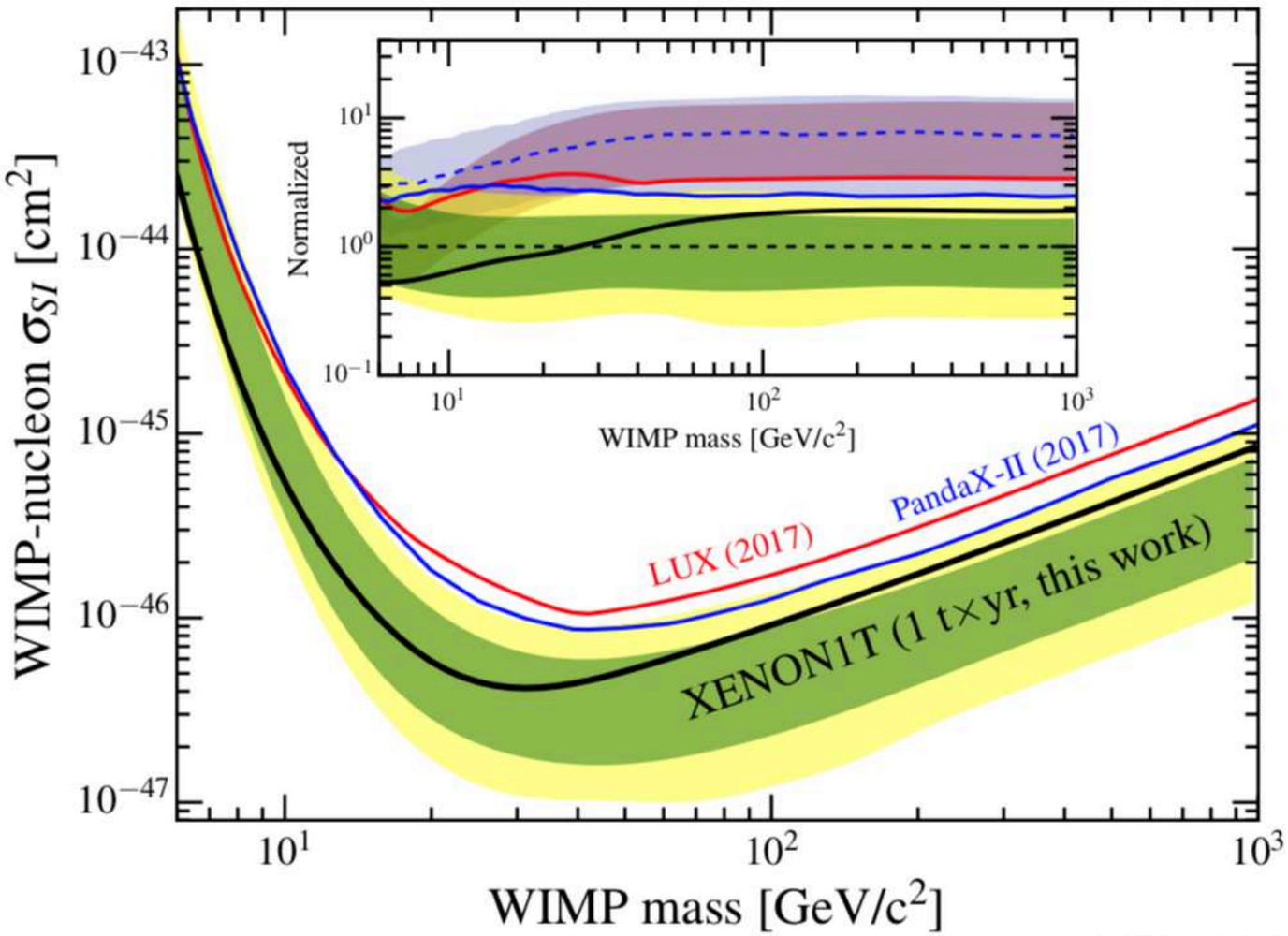
Spin-Independent Scattering

$$\frac{d\Gamma}{dE_R} = (N_T\, m_{\mathcal{N}}) \times \left(\frac{\sigma^{(SI)}_{\chi\mathcal{N}}\Big|_{E_R=0}}{\mu^2_{\chi\mathcal{N}} m_\chi} \right) \times F(E_R)^2 \times \left(\rho_\chi \int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{f_\chi(v_{\rm rel})}{2 v_{\rm rel}} dv_{\rm rel} \right)$$

Astrophysics

Spin-Independent Scattering

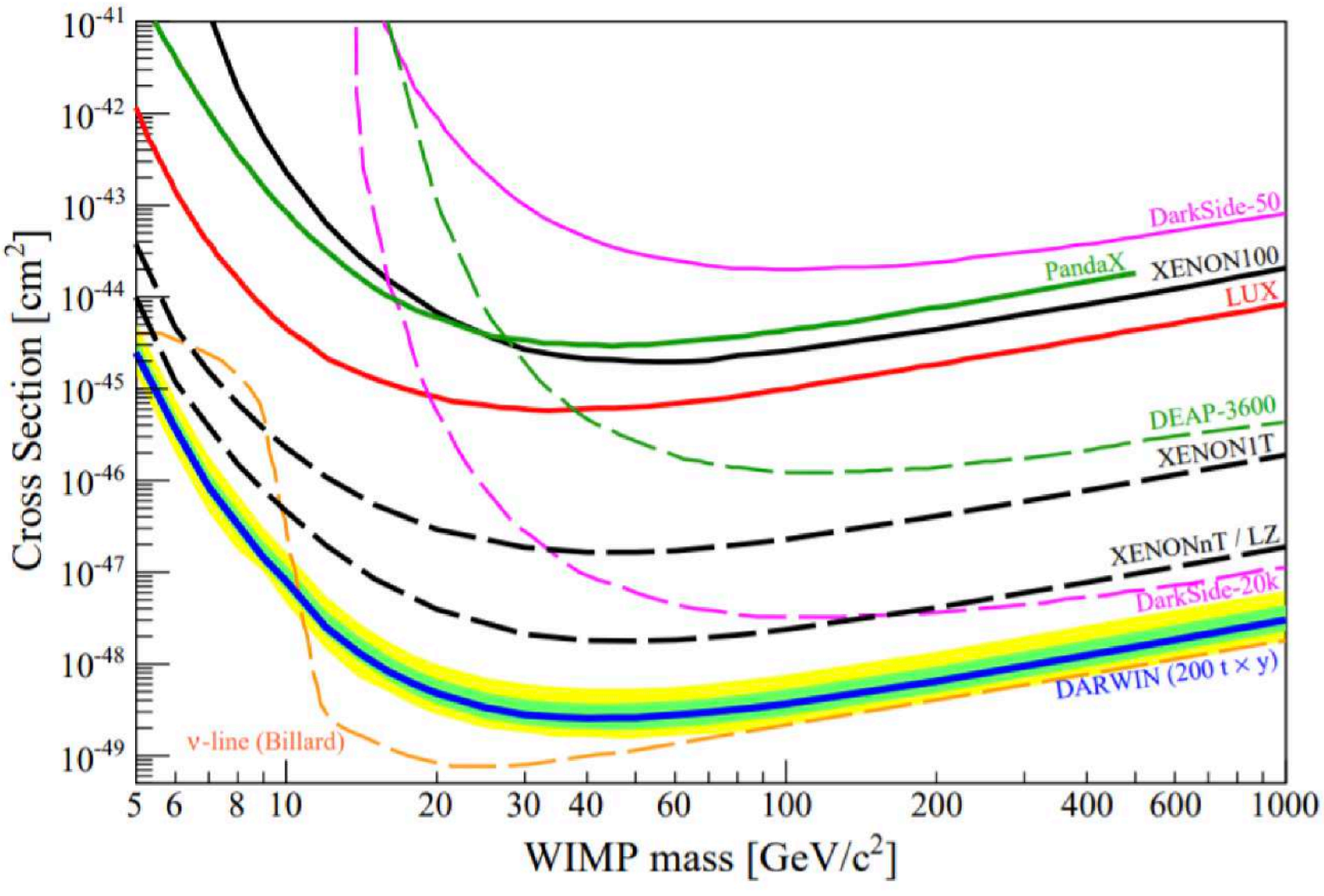
$$\frac{d\Gamma}{dE_R} = (N_T\, m_{\mathcal{N}}) \times \left(\frac{\sigma^{(SI)}_{\chi\mathcal{N}}\Big|_{E_R=0}}{\mu^2_{\chi\mathcal{N}} m_\chi} \right) \times F(E_R)^2 \times \left(\rho_\chi \int_{v_{\min}(E_R)}^{v_{\rm esc}} \frac{f_\chi(v_{\rm rel})}{2v_{\rm rel}} dv_{\rm rel} \right)$$



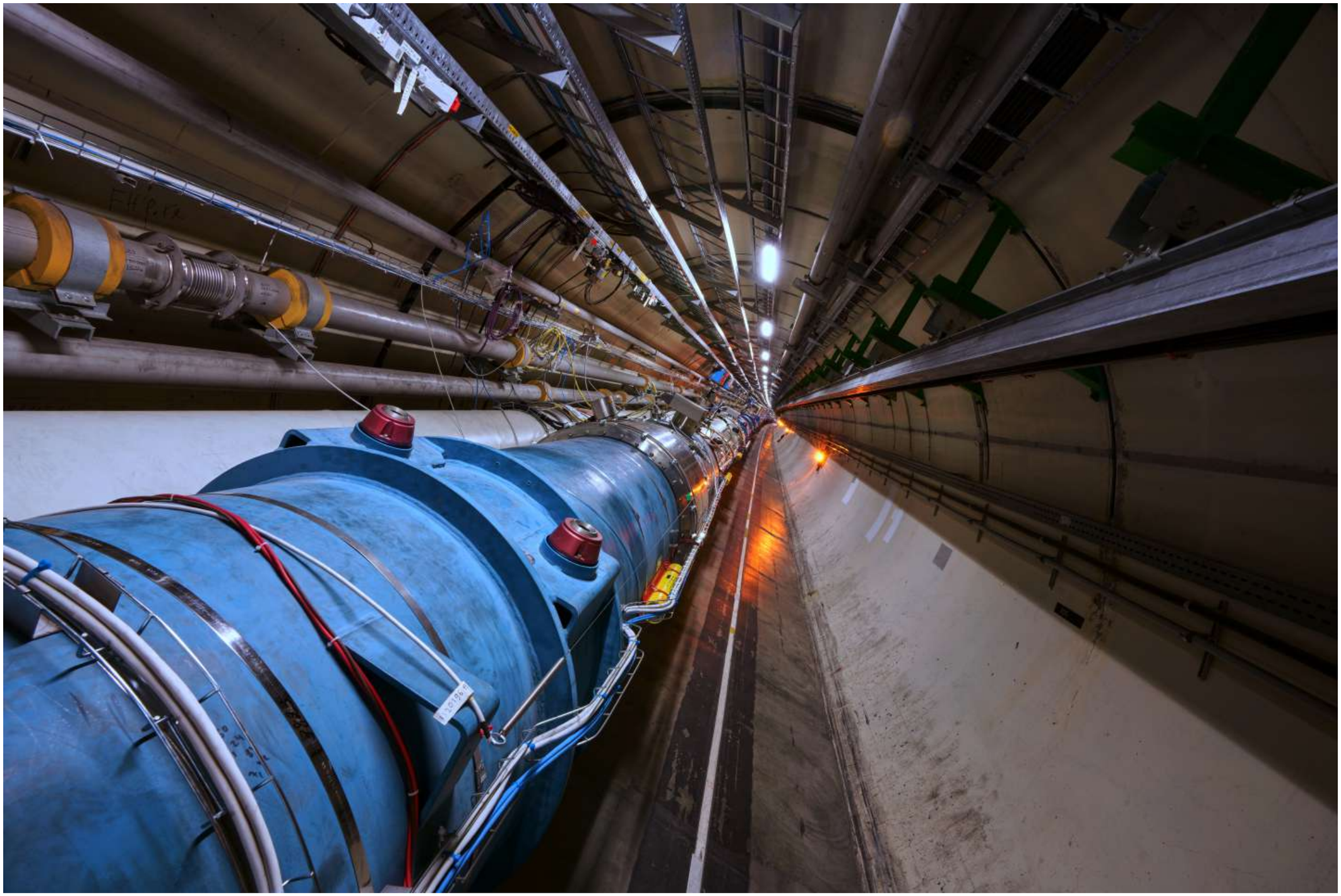
XENON, Phys.Rev.Lett. 119 (2017)

Spin-Independent Scattering

$$\frac{d\Gamma}{dE_R} = (N_T\, m_{\mathcal{N}}) \times \left(\frac{\sigma^{(SI)}_{\chi\mathcal{N}}\Big|_{E_R=0}}{\mu^2_{\chi\mathcal{N}} m_\chi} \right) \times F(E_R)^2 \times \left(\rho_\chi \int_{v_{\rm min}(E_R)}^{v_{\rm esc}} \frac{f_\chi(v_{\rm rel})}{2v_{\rm rel}} dv_{\rm rel} \right)$$

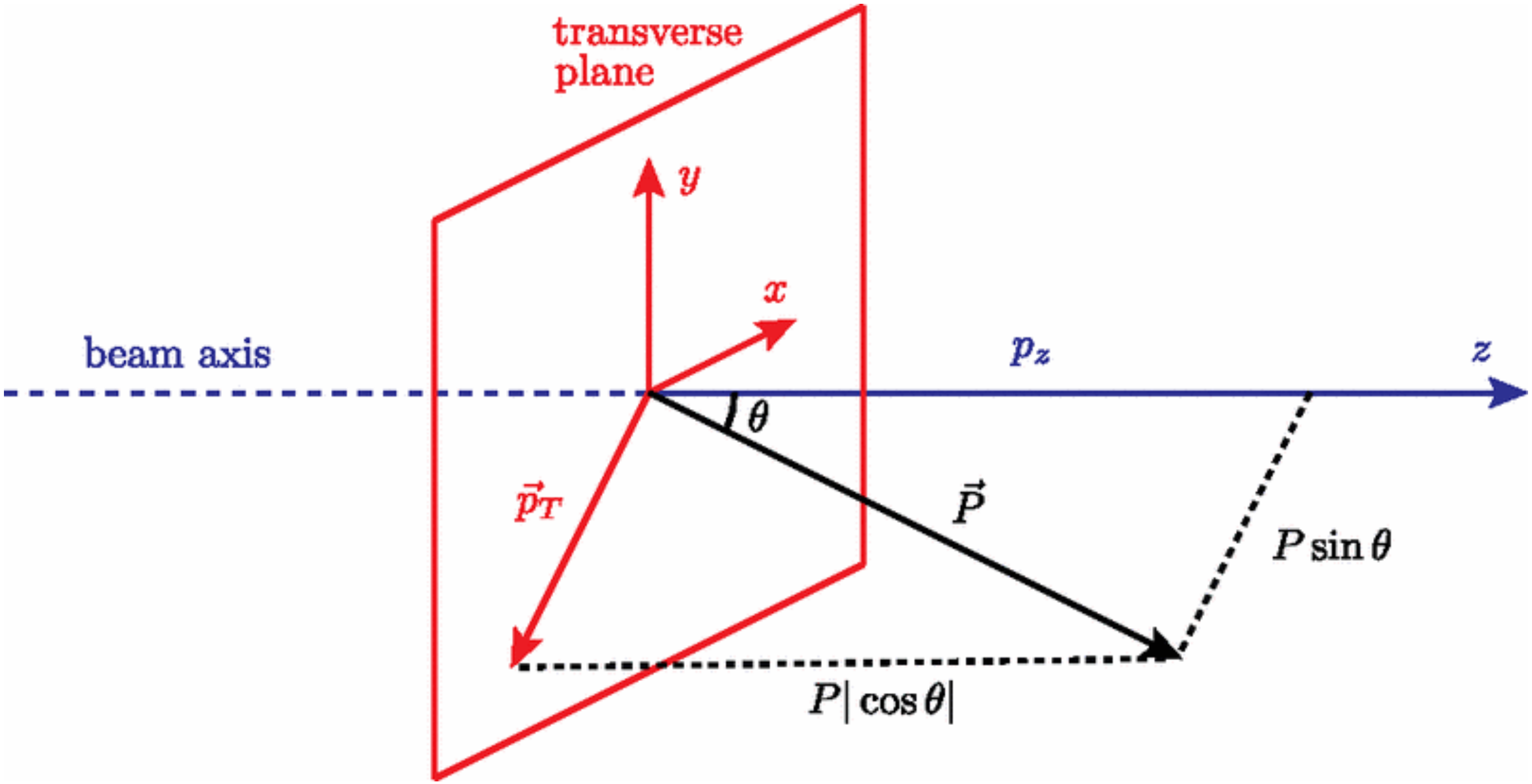


Collider Searches

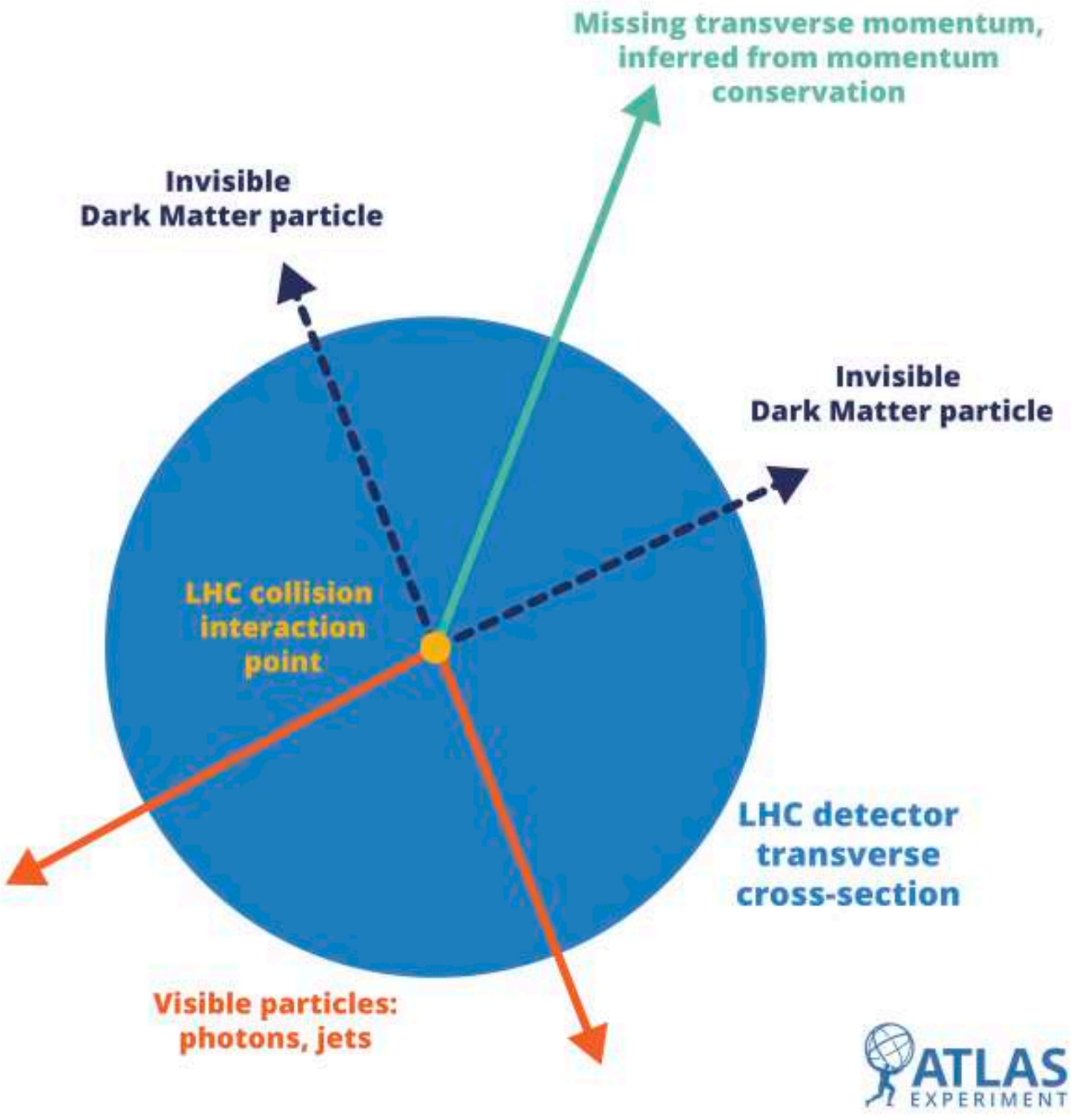


Boveia, Doglioni, Ann.Rev.Nucl.Part.Sci. 68 (2018)

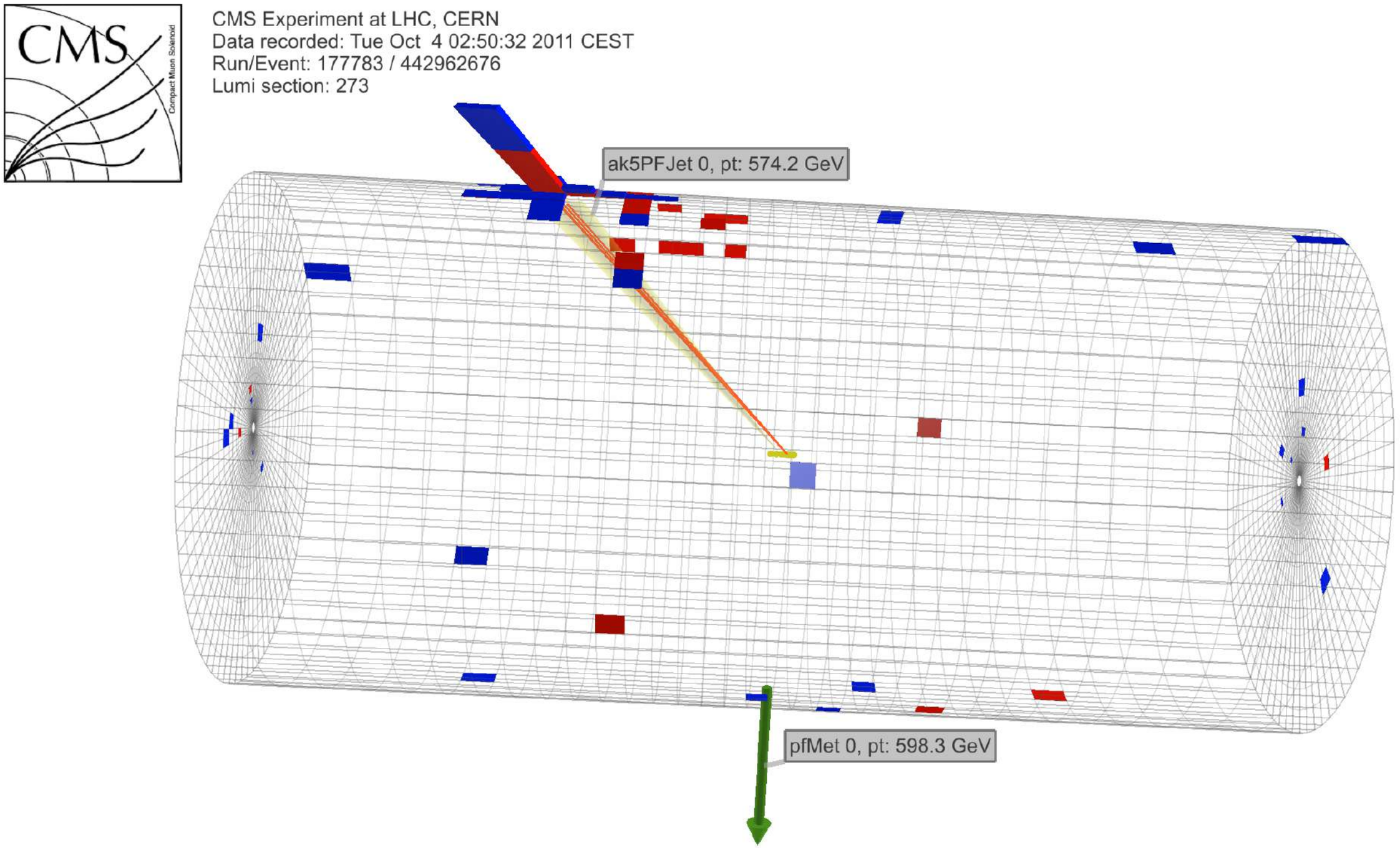
Transverse Plane



Missing Energy/Momentum

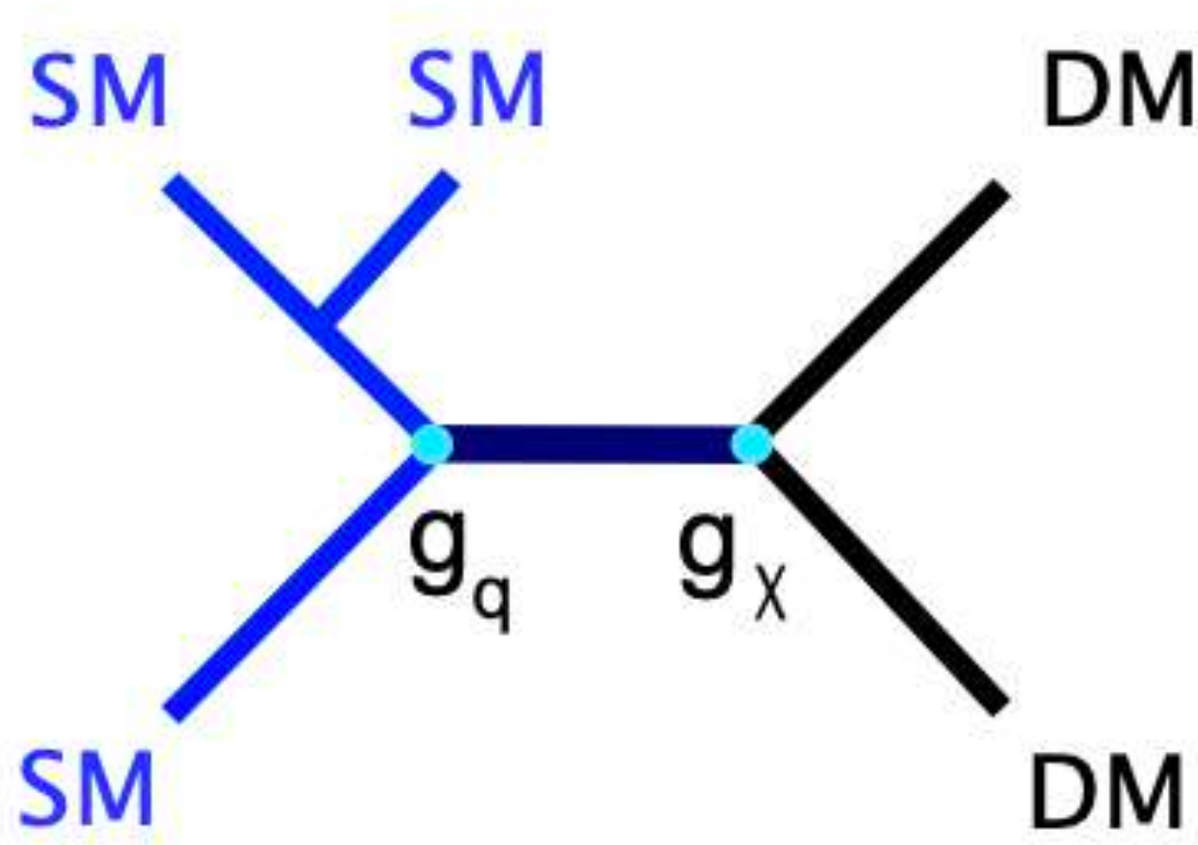


Missing Energy/Momentum



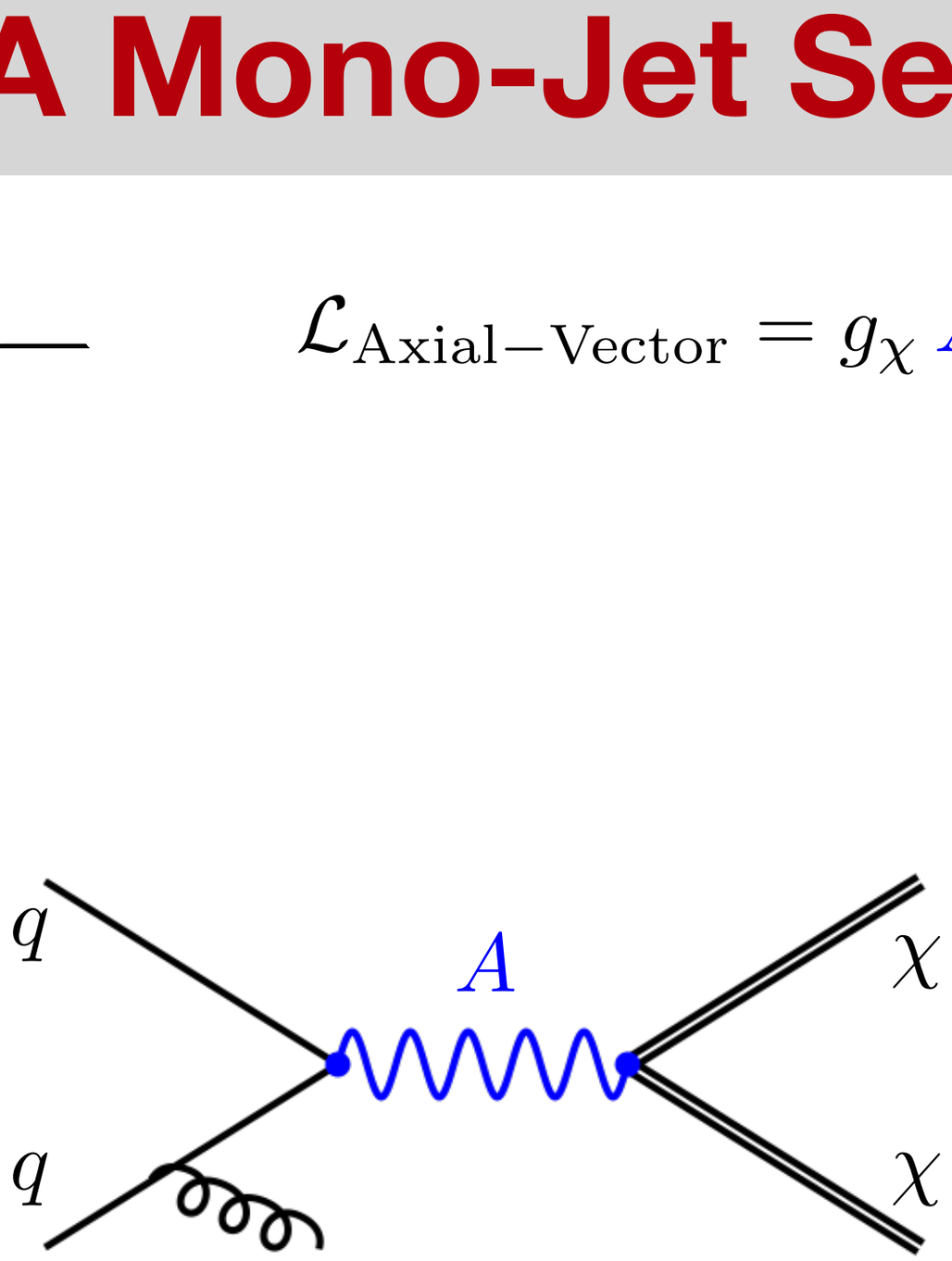
Mono-X Searches

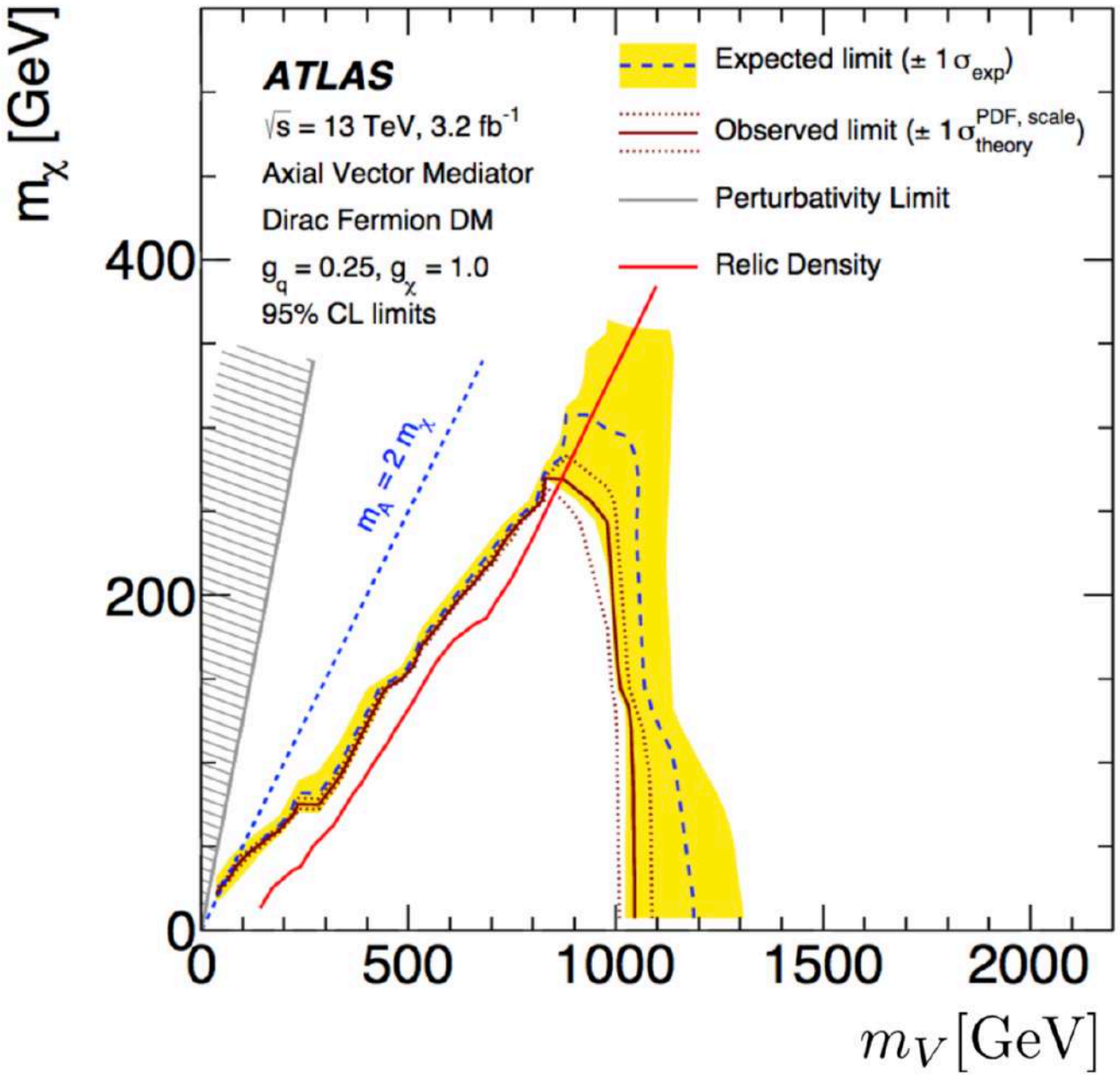
Final state: X (photons, jet, etc.) + missing energy



A Mono-Jet Search

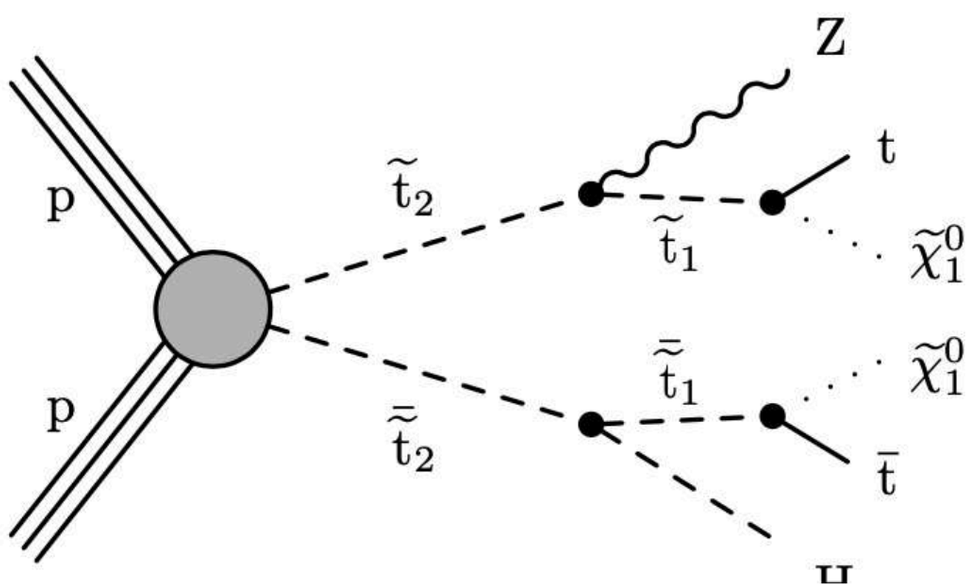
$$\mathcal{L}_{\mathrm{Axial-Vector}} = g_\chi \, A_\mu \, \overline{\chi} \gamma^\mu \gamma^5 \chi + g_q \, A_\mu \, \overline{q} \gamma^\mu \gamma^5 q$$

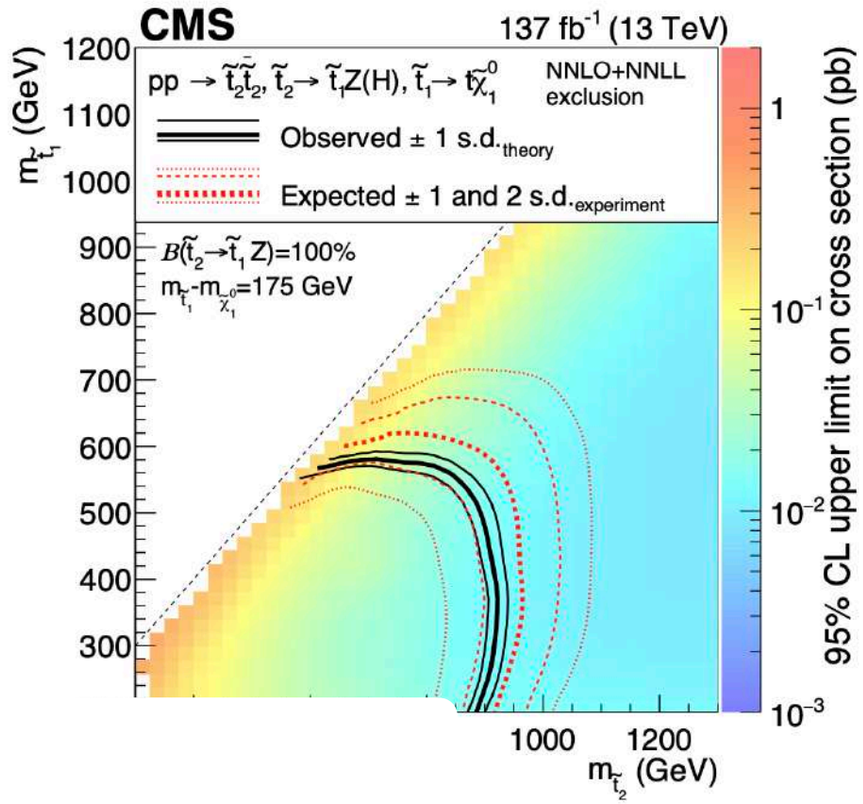




Other Collider Searches

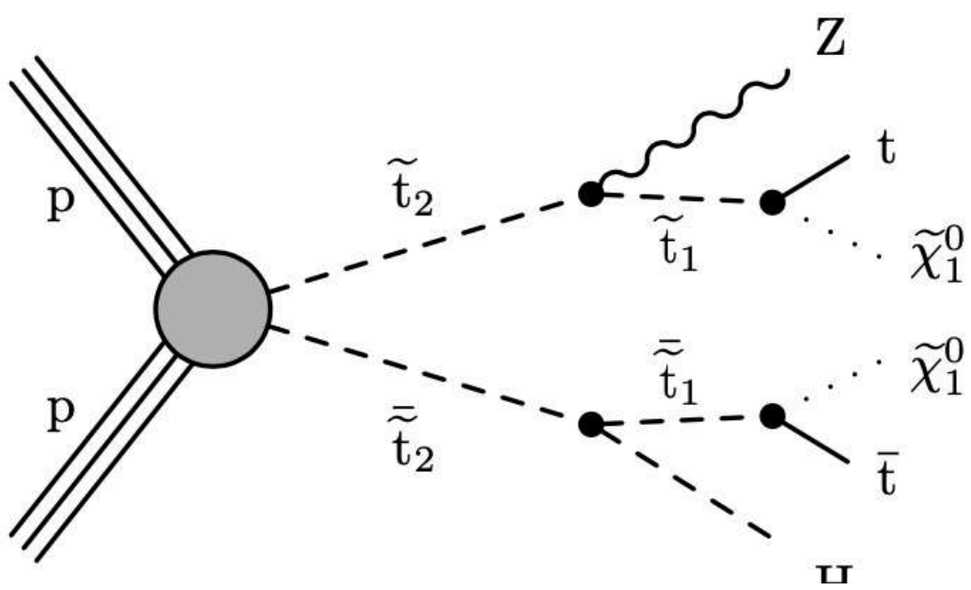
CASCADE DECAYS

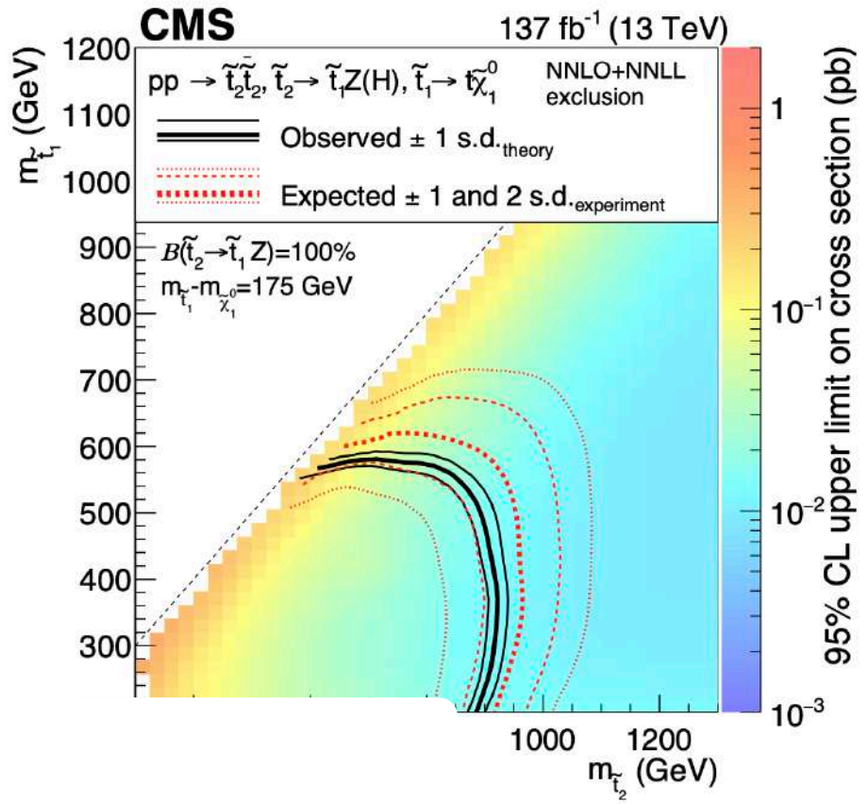




Other Collider Searches

CASCADE DECAYS



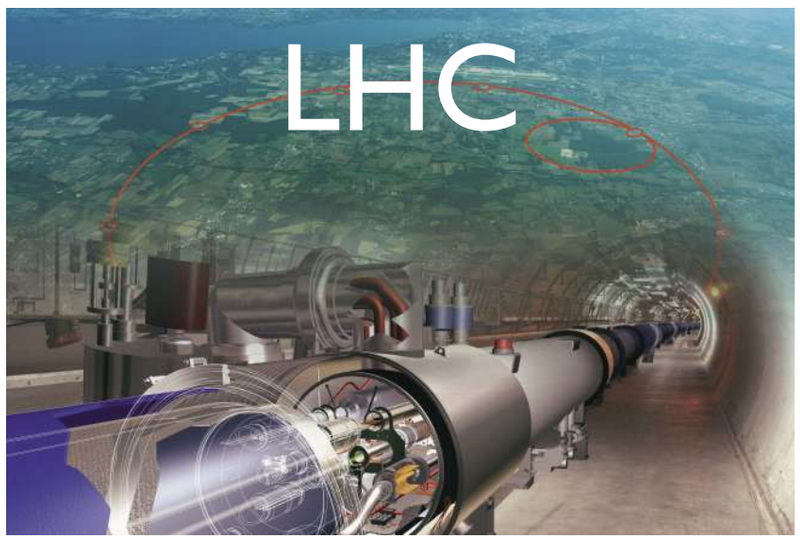


INVISIBLE DECAY WIDTHS

$$\mathrm{BR}(\psi_{\mathrm{SM}} \to \chi\chi) \equiv \frac{\Gamma(\psi_{\mathrm{SM}} \to \chi\chi)}{\Gamma_{\psi_{\mathrm{SM}}}}$$

Lots to Look Forward to!

Impressive Results by Current Experiments



We will learn much more soon (next 5-10 years)