Weaker than Weak physics at the intensity frontier

Theory Seminar - Fermilab - March 5th 2020

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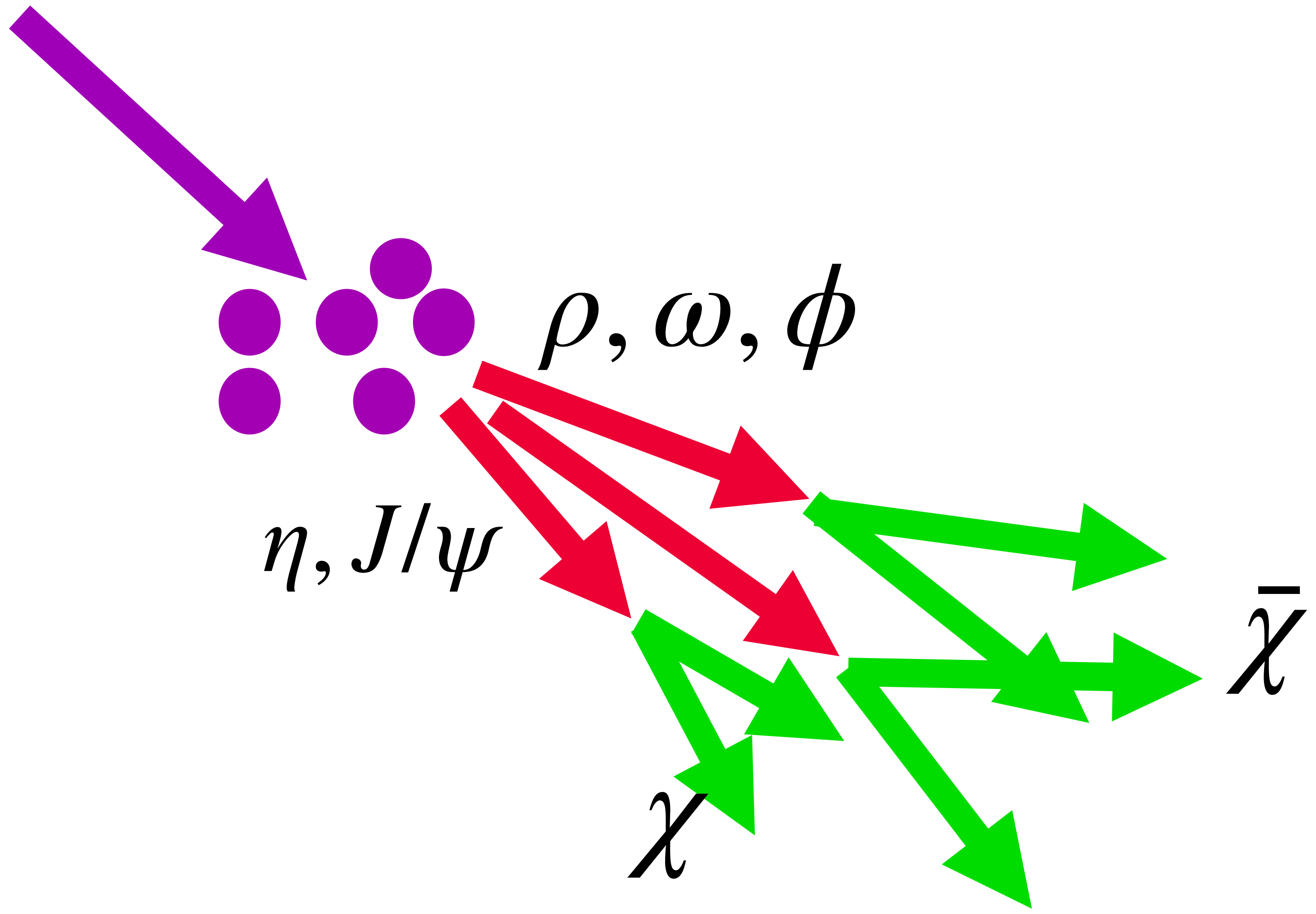
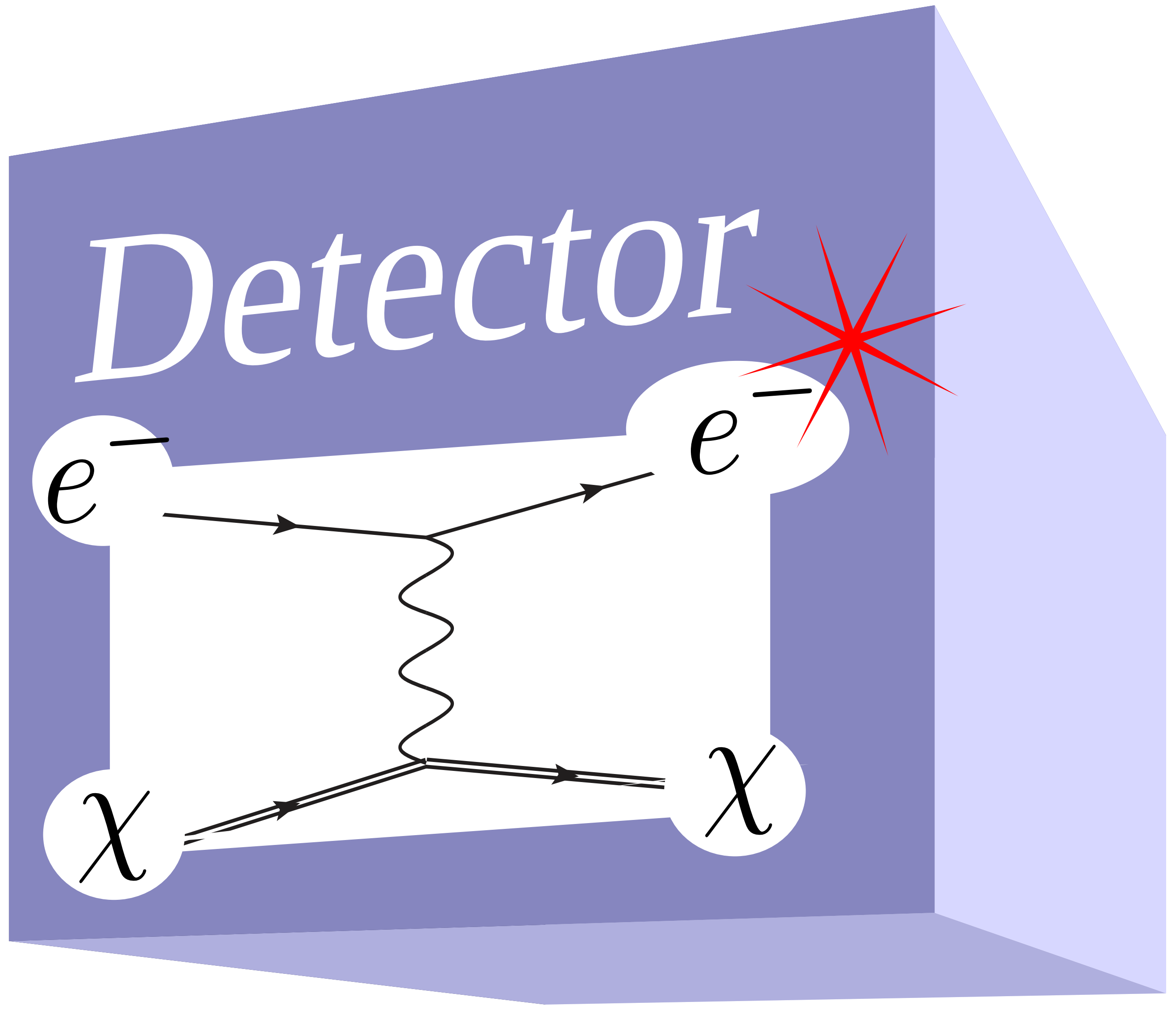
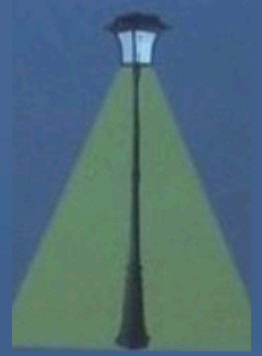
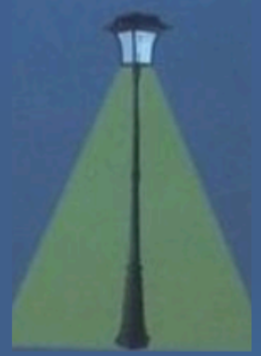


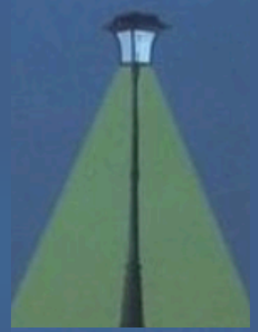
arXiv:2002.11732
arXiv:1806.03310
arXiv:1803.03262
arXiv:1710.08431
arXiv:1612.05642

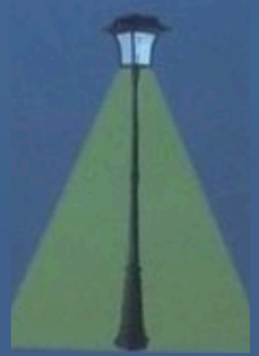


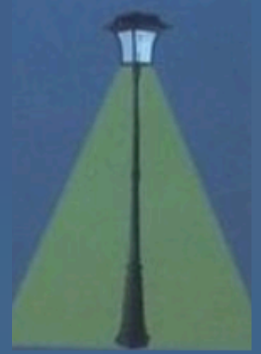
In collaboration with:
Gabriel Magill, Maxim Pospelov, Yu-Dai Tsai
Torsten Bringmann, Alexander Kusenko, Volodymyr Takhistov

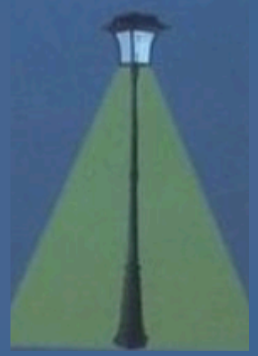


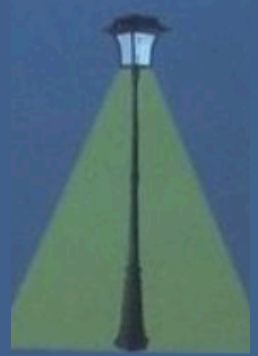


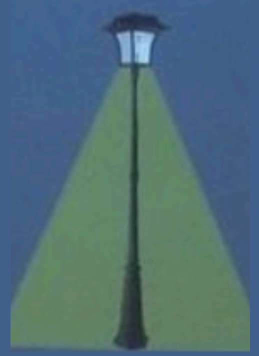


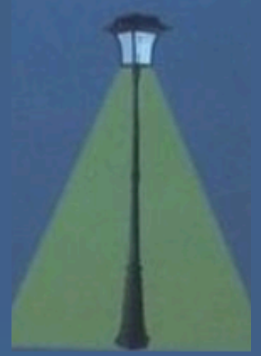


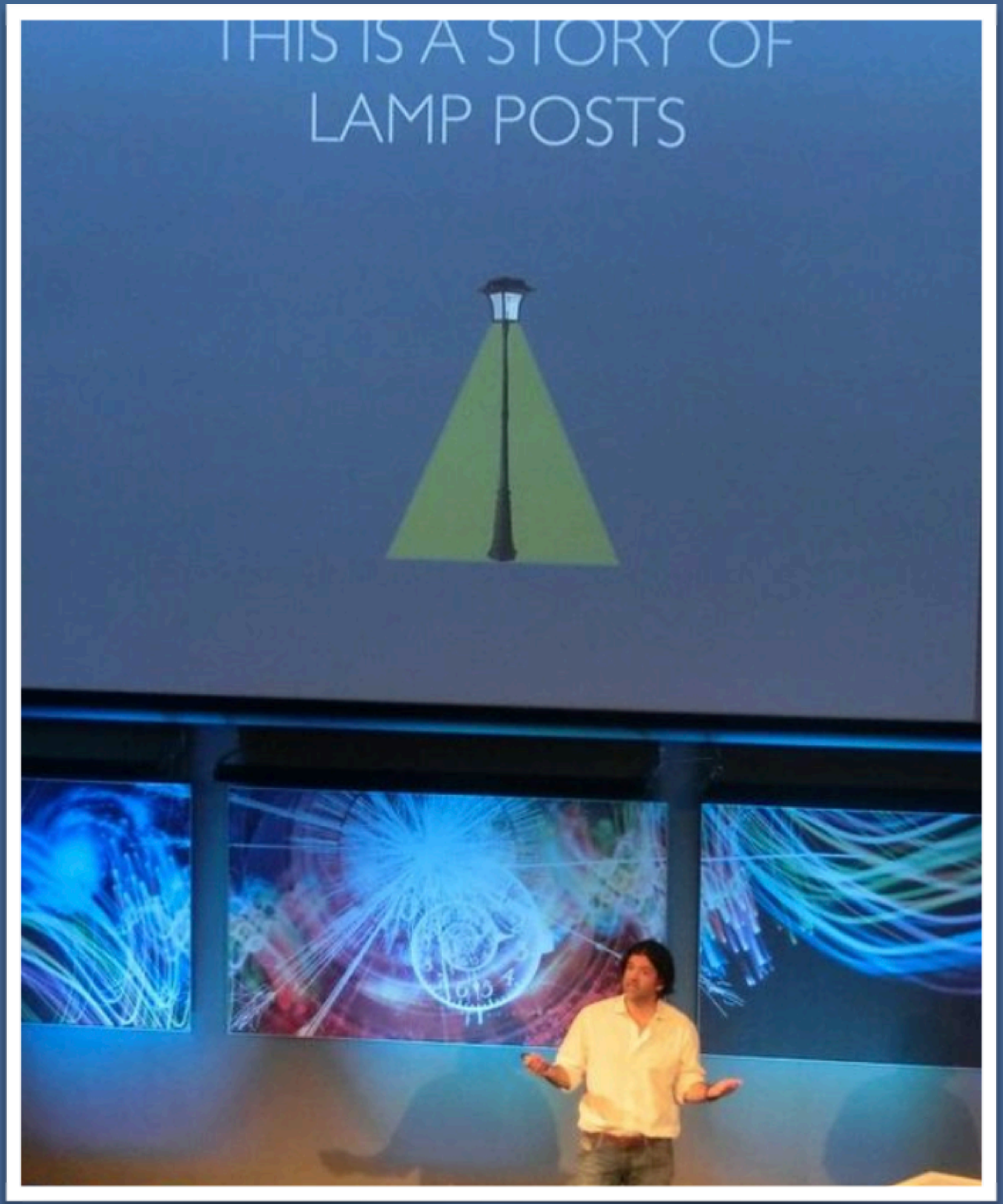












Neil Weiner circa 2015…ish

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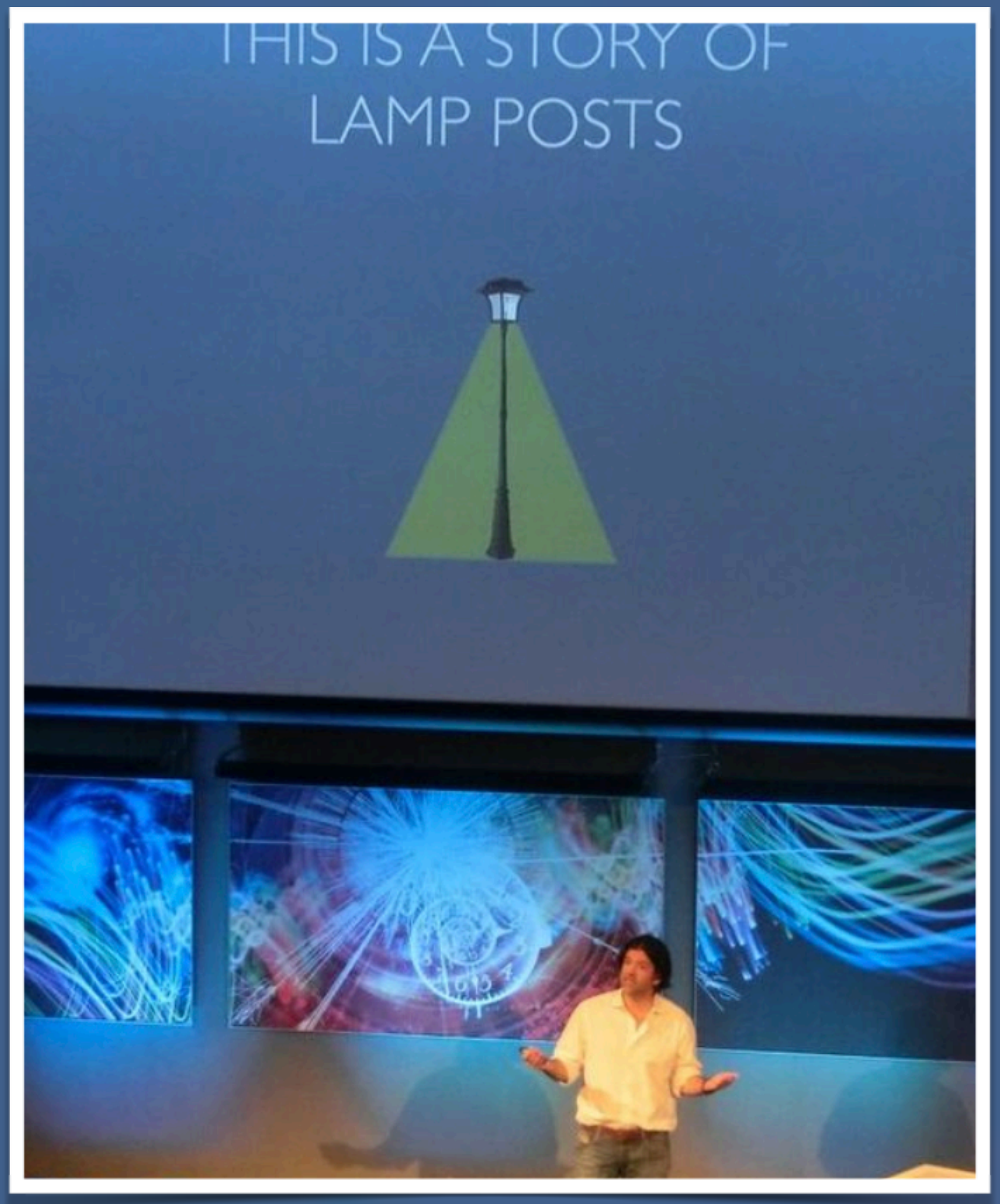

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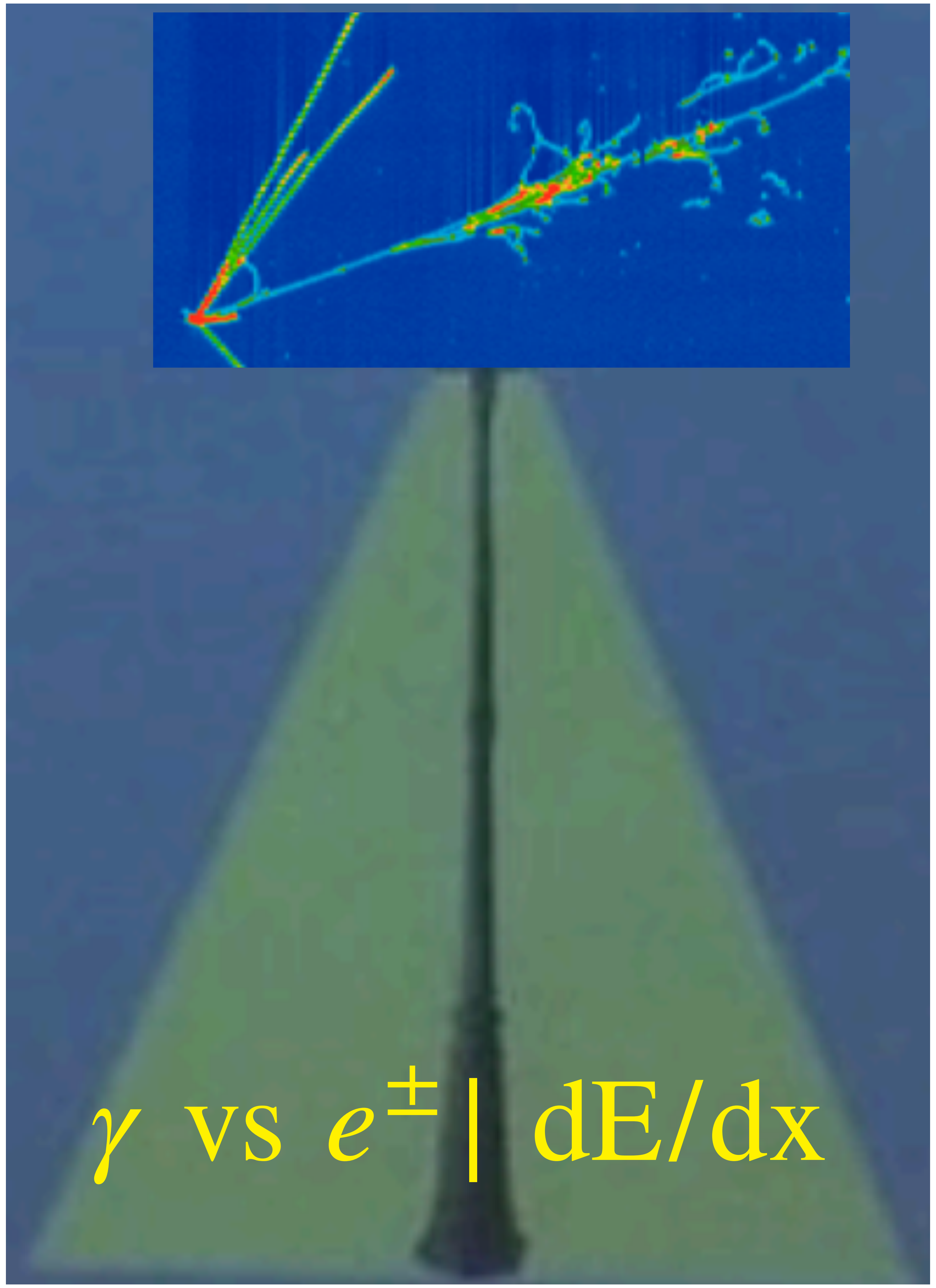
Intensity

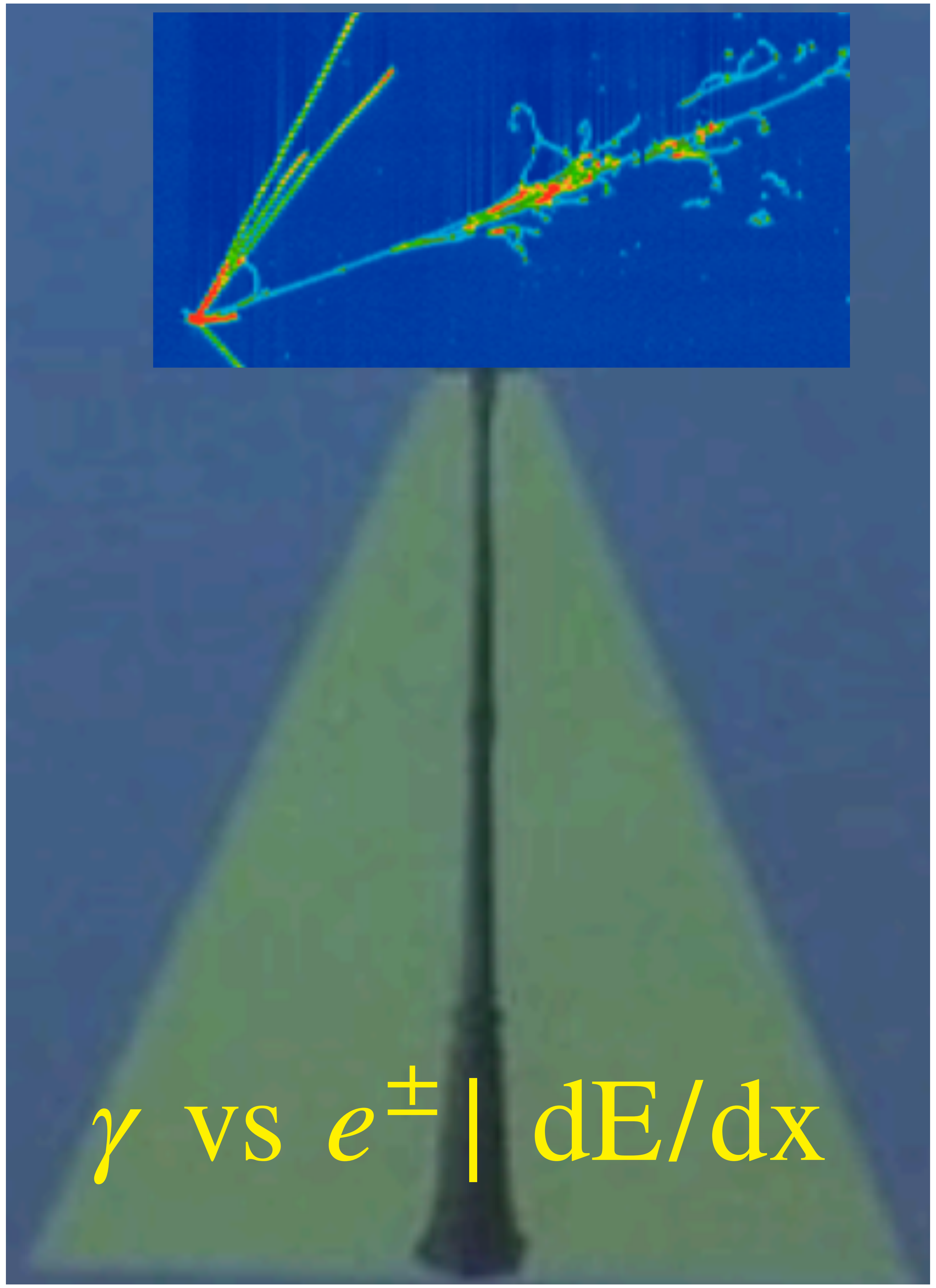
Intensity

Technology

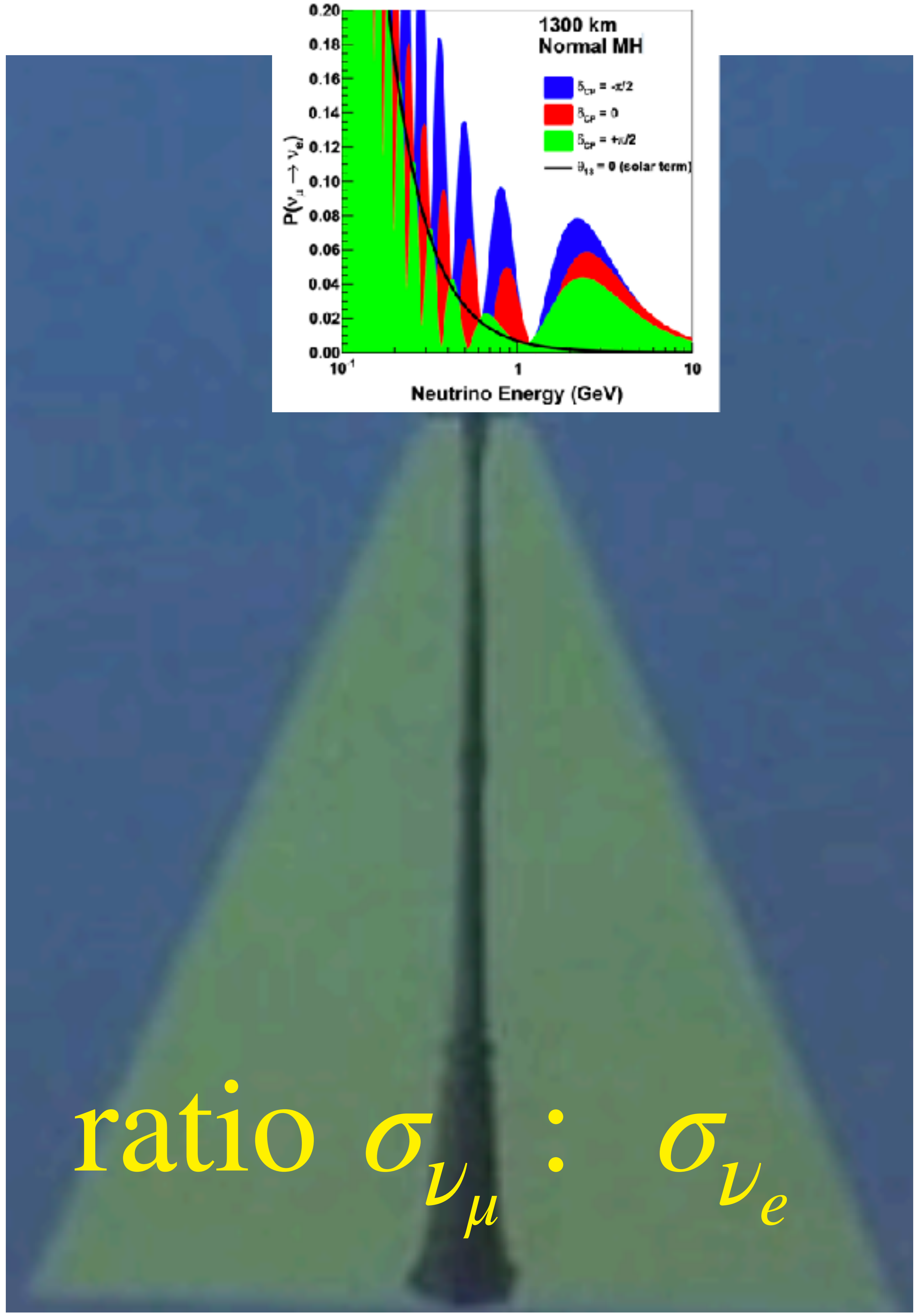


Intensity

Technology



Precision



Weaker than Weak

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- **Weak + Electromagnetic Standard Model processes**
- **Weakly coupled, light new physics**

Weaker than Weak

- Weak + Electromagnetic Standard Model processes
- Weakly coupled, light new physics

This Talk

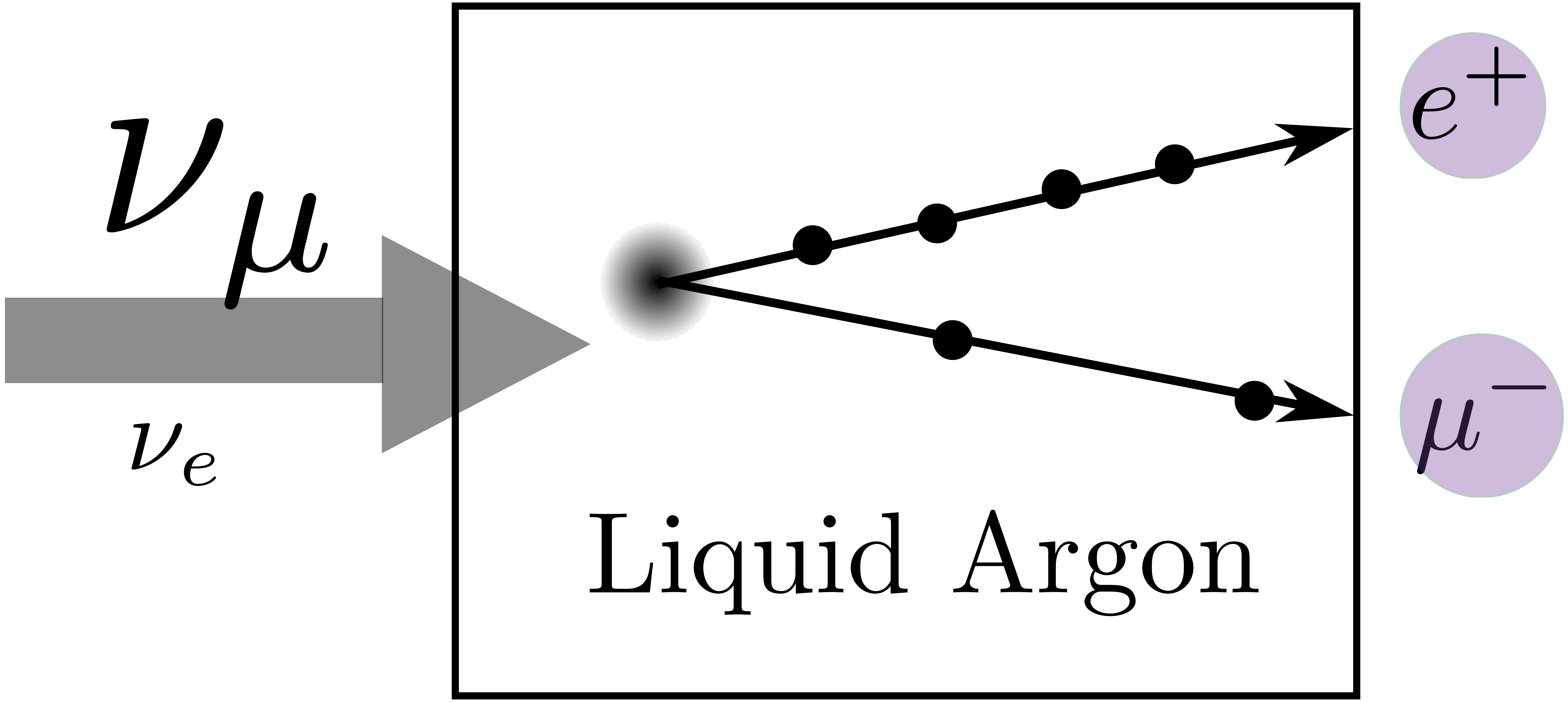
- Neutrino trident production
- Millicharged particles
- Dipole portal to HNL
- Outlook/future work

Neutrino Trident Production

arXiv:1710.08431

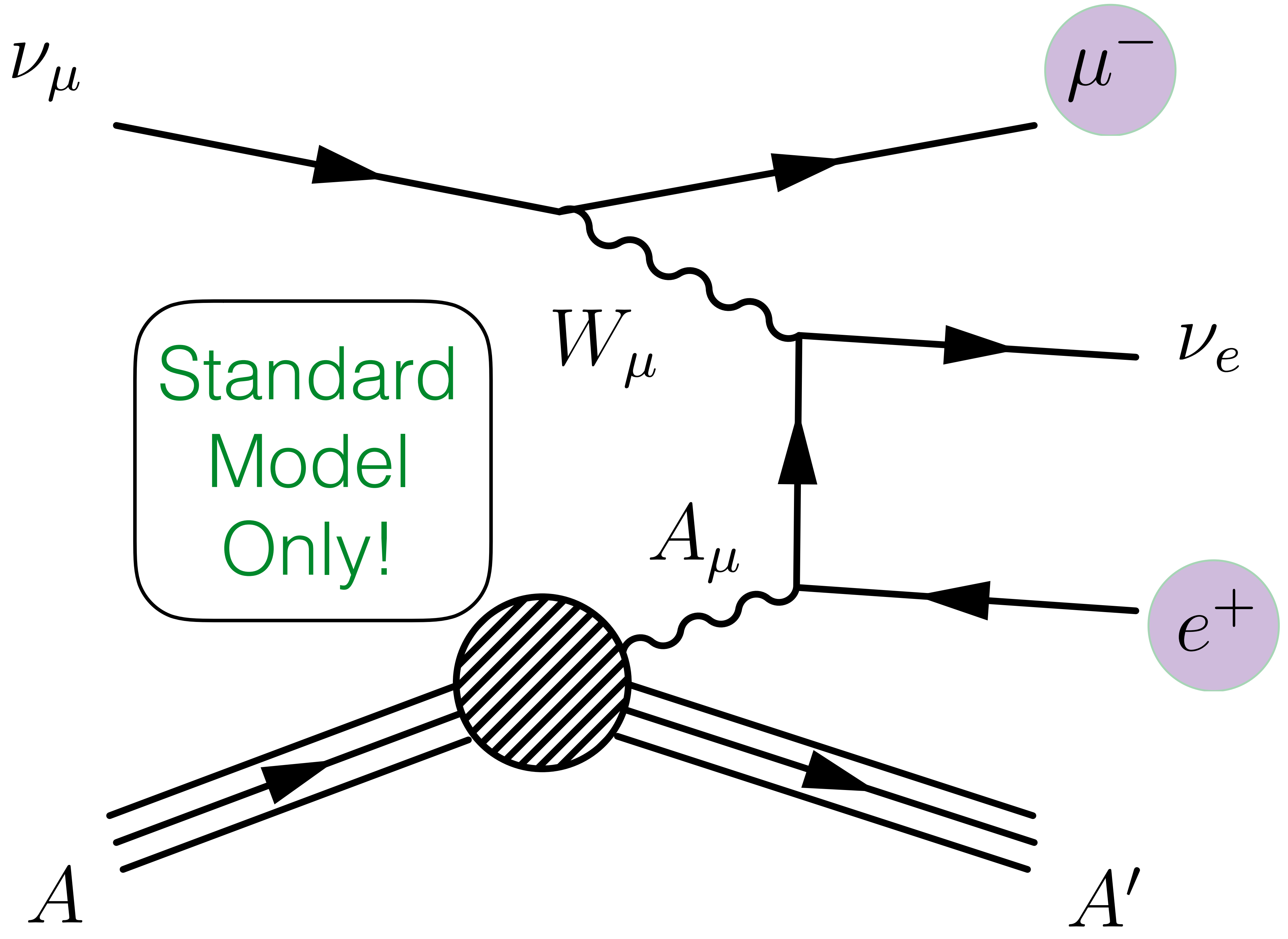
arXiv:1612.05642

Neutrino Trident Production



Lepton Flavour Violation?

Neutrino Trident Standard Model



Standard Model Only!

Can have any combination of
$e^\pm, \mu^\pm, \tau^\pm$
Important BSM background!

Process dependent

Rare Process

$$\sigma_{\nu A} \approx \frac{1}{2}(C_V^2 + C_A^2)\frac{2\ Z^2\alpha^2\ G_F^2}{9\pi^3} s_{\max} \log\left(\frac{s_{\max}}{(m_i + m_j)^2}\right)$$

$$\approx 10^{-45}\mathrm{cm}^2 Z^2 \left(\frac{E_\nu}{\mathrm{GeV}}\right) \approx 10^{-5}\sigma_{\mathrm{CC}}$$

Belusevic and Smith, PRD (1988)

Neutrino Trident

arXiv:1612.05642, PRD 2017 (RP, Gabriel Magill)

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$\nu_e \to \nu_e e^+ e^-$	$\overline{\nu}_e \to \overline{\nu}_e e^+ e^-$	$\frac{1}{2} + 2\sin^2\theta_w$	$\frac{1}{2}$	W,Z
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$\nu_e \to \nu_e \mu^+ \mu^-$	$\overline{\nu}_e \to \overline{\nu}_e \mu^+ \mu^-$	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$	Z
$\nu_\mu \to \nu_\mu e^+ e^-$	$\overline{\nu}_\mu \to \overline{\nu}_\mu e^+ e^-$	$-\frac{1}{2} + 2\sin^2\theta_w$	$-\frac{1}{2}$	Z
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$\nu_\mu \to \nu_\tau \mu^- \tau^+$	$\overline{\nu}_\mu \to \overline{\nu}_\tau \mu^+ \tau^-$	1	1	W
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TABLE I: Modified vector and axial coupling constants for different combinations of incident neutrino flavours and final states

Neutrino Trident

arXiv:1612.05642, PRD 2017 (RP, Gabriel Magill)

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Given (then current) DUNE CDR we projected ~100 events at DUNE

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DUNE has increased the planned size of the Near Detector

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Recent study (arXiv:1902.06765) including full DUNE Geant-4 simulation predicts ~ 1600 events / year at DUNE near detector in certain channels.

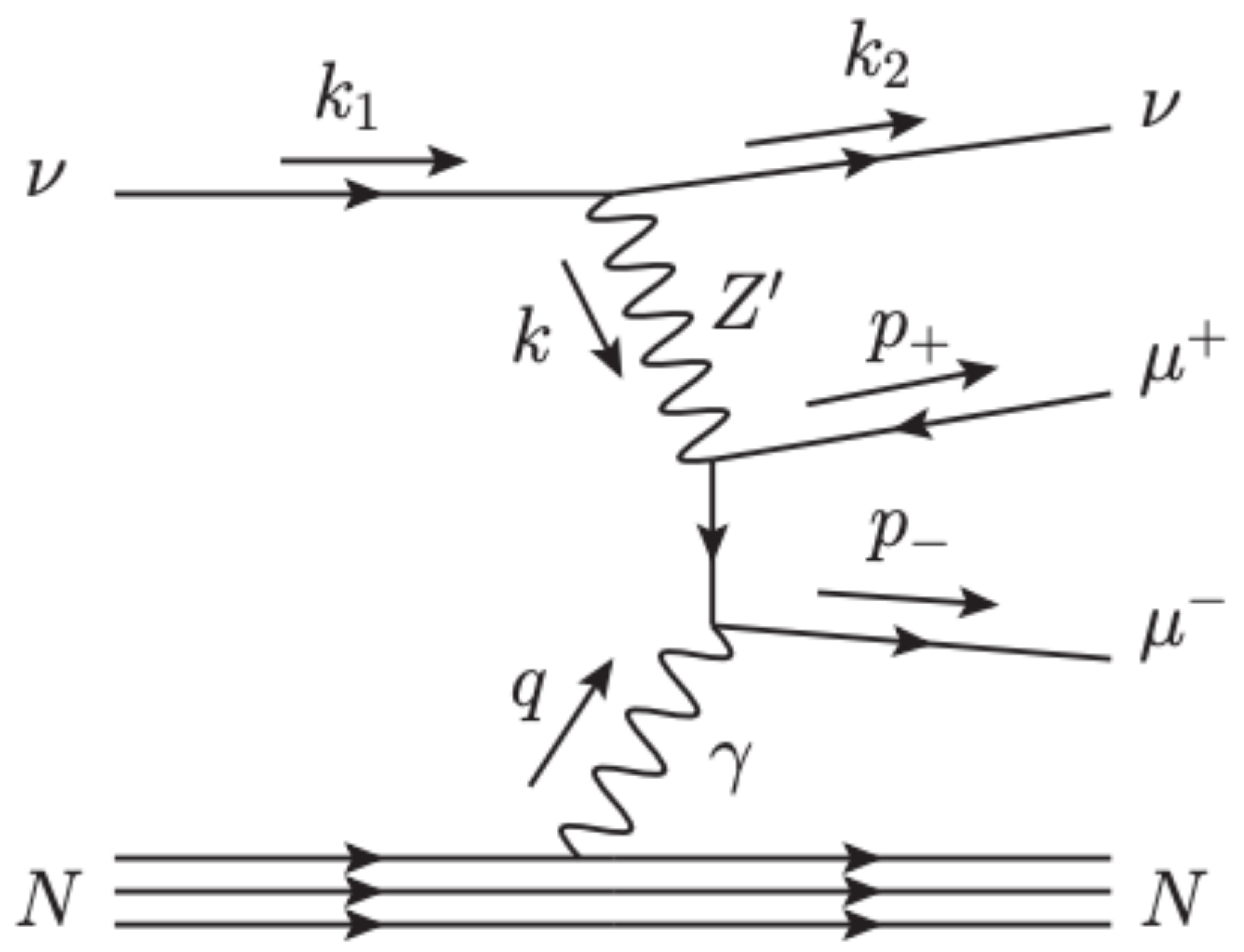
Determination of dimuon cross section at 40%

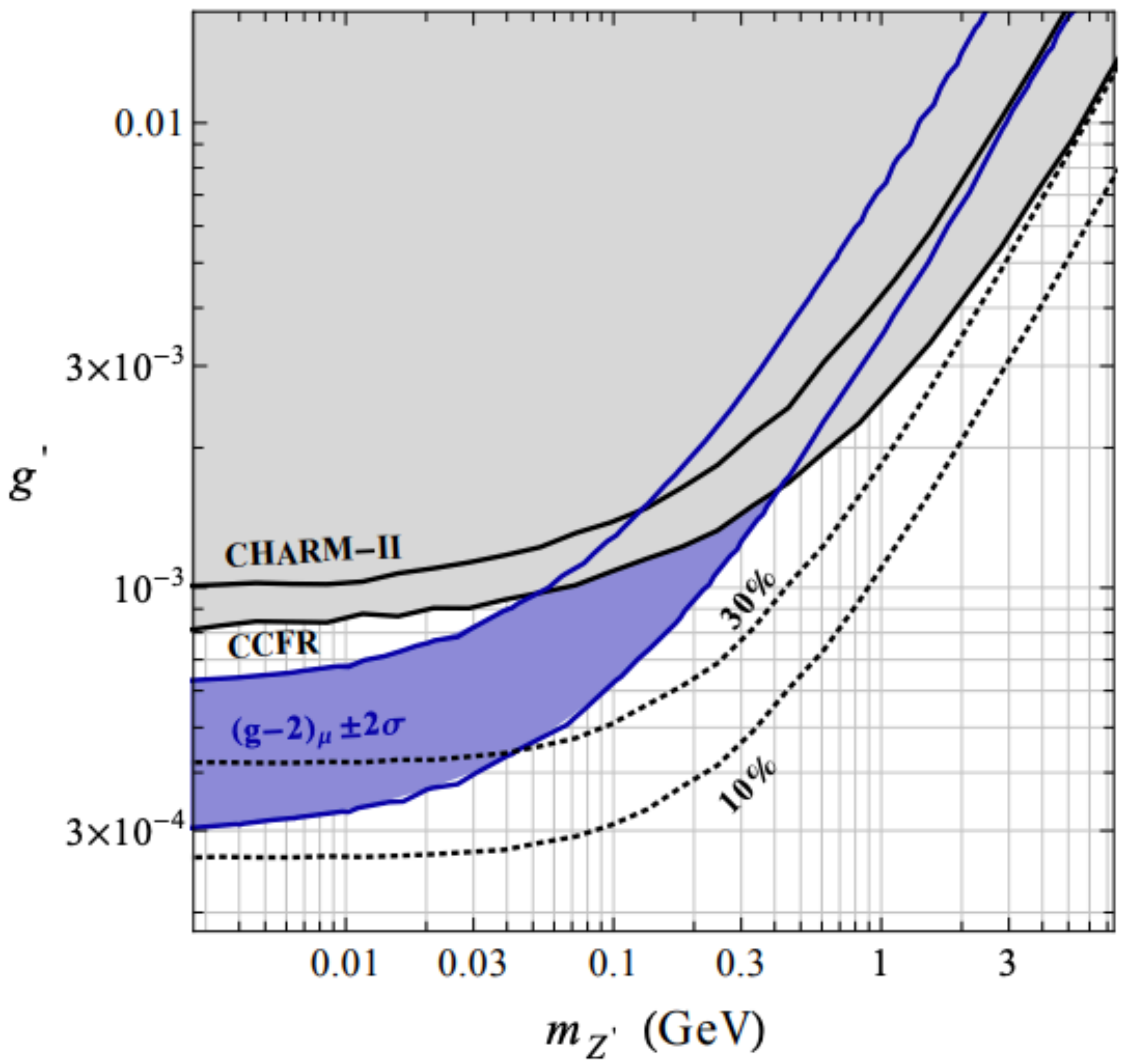
Neutrino Trident

New Physics

Altmannshofer, Gori, Pospelov, Yavin arXiv:1406.2332

$$\sigma_{\nu A} \approx \frac{1}{2}(C_V^2 + C_A^2)\frac{2\ Z^2\alpha^2\ G_F^2}{9\pi^3}$$





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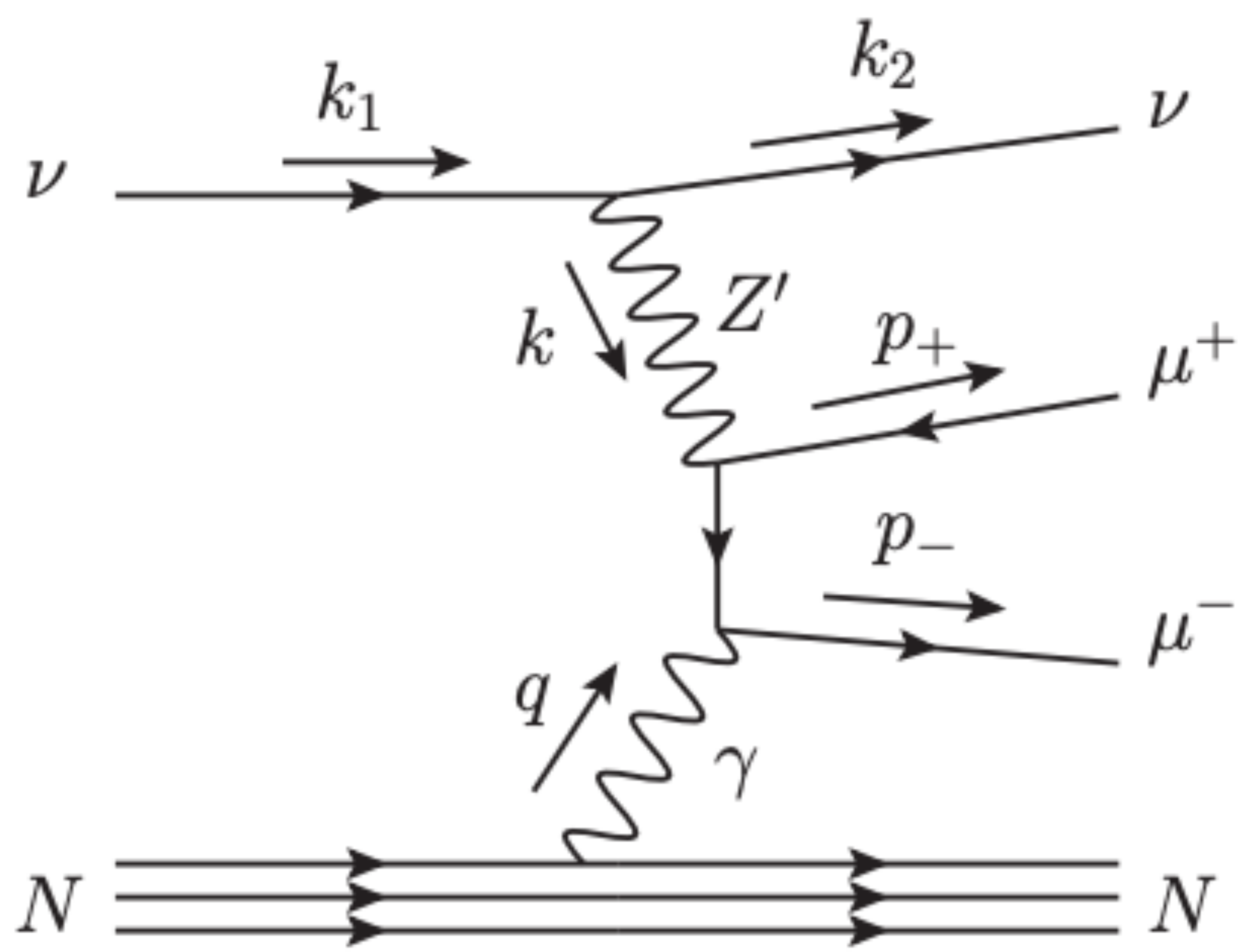

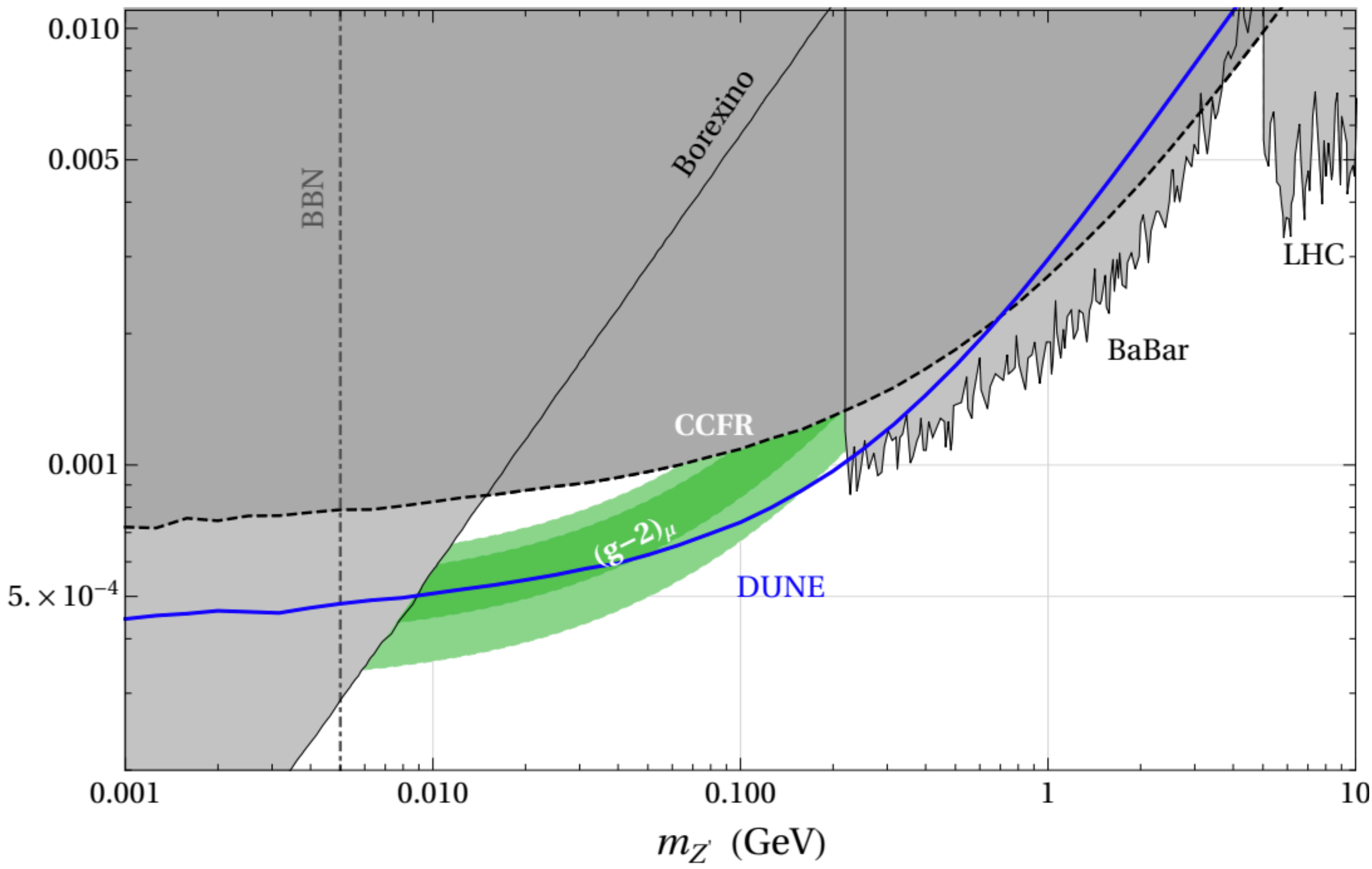

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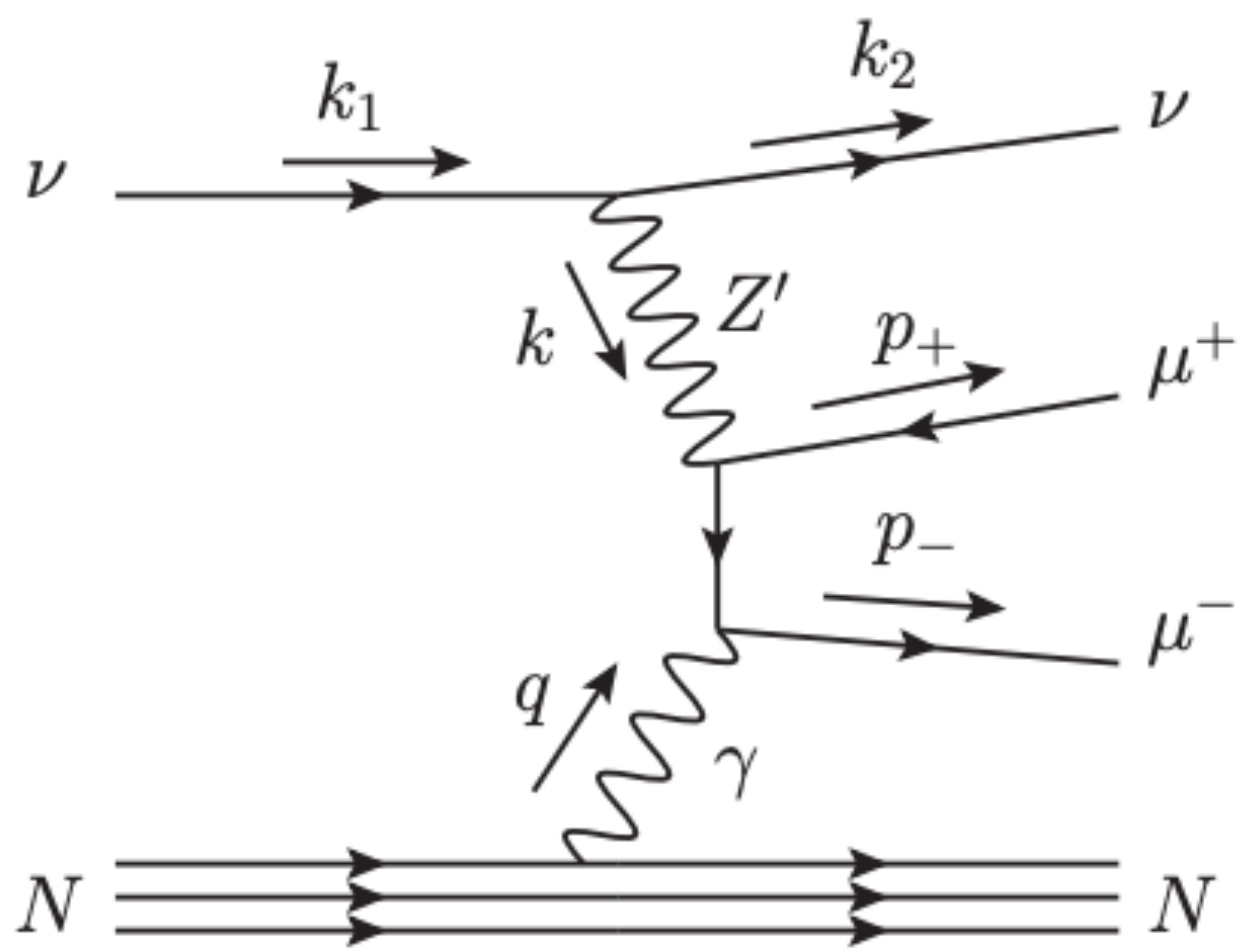

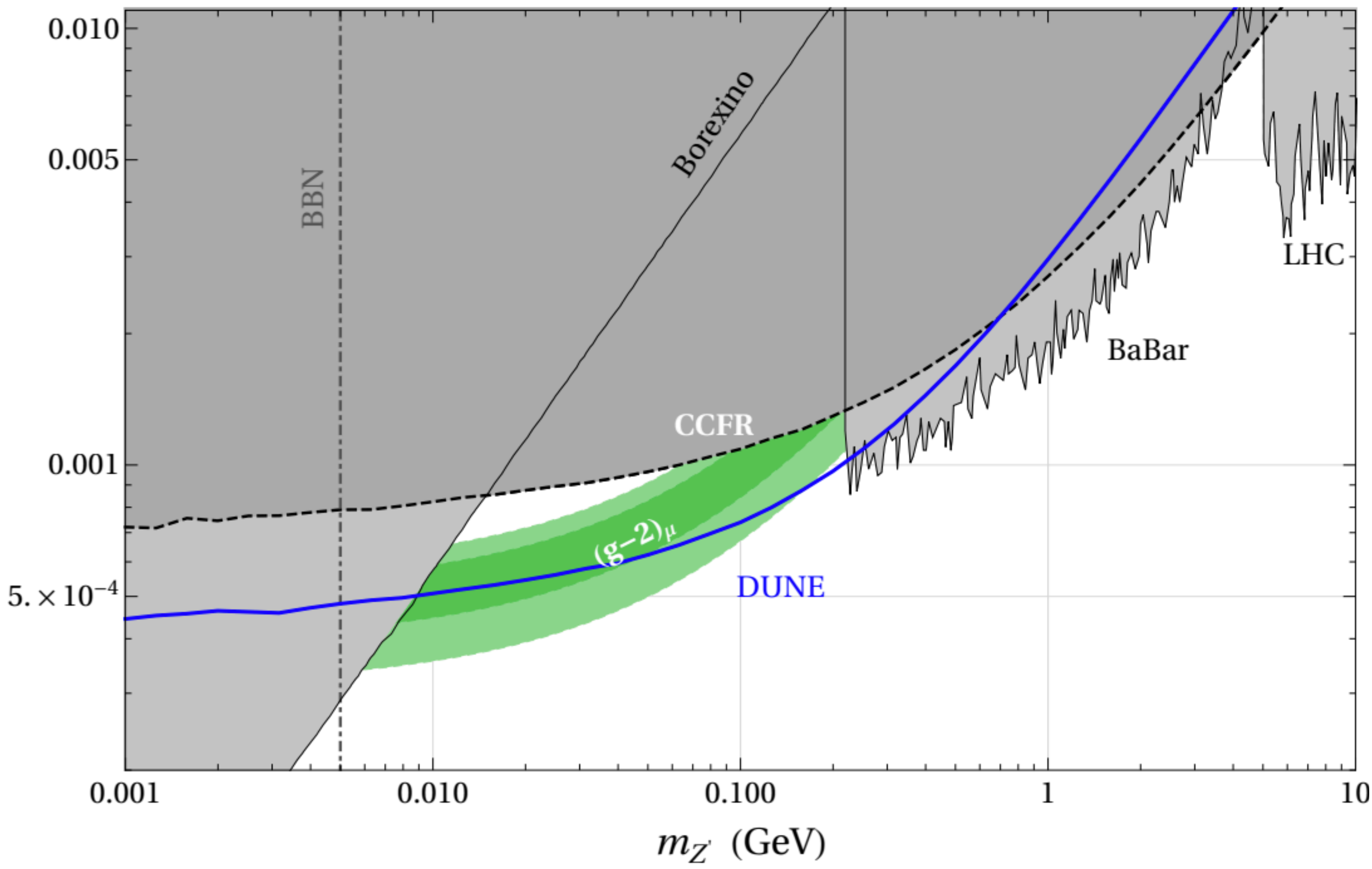

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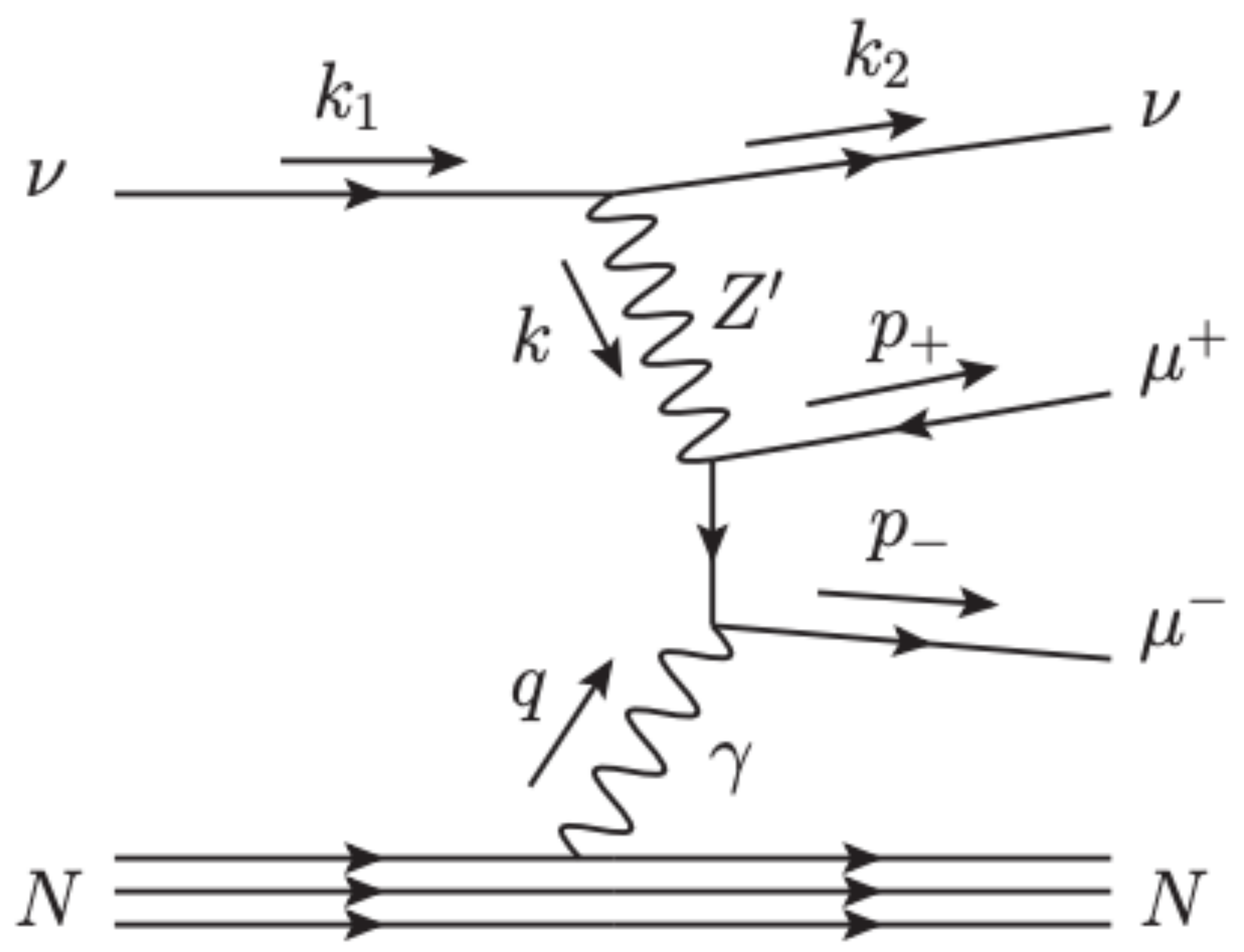

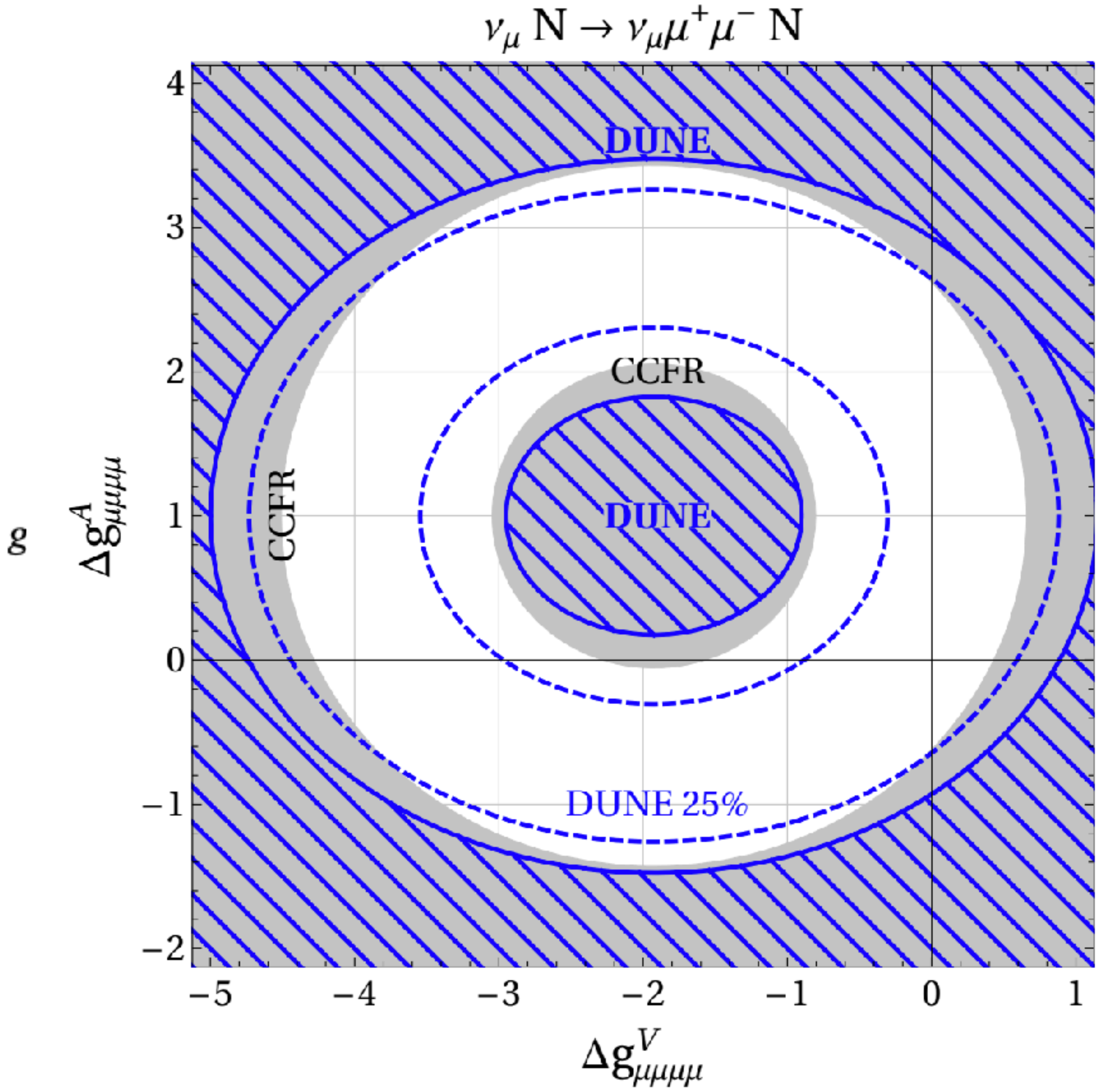

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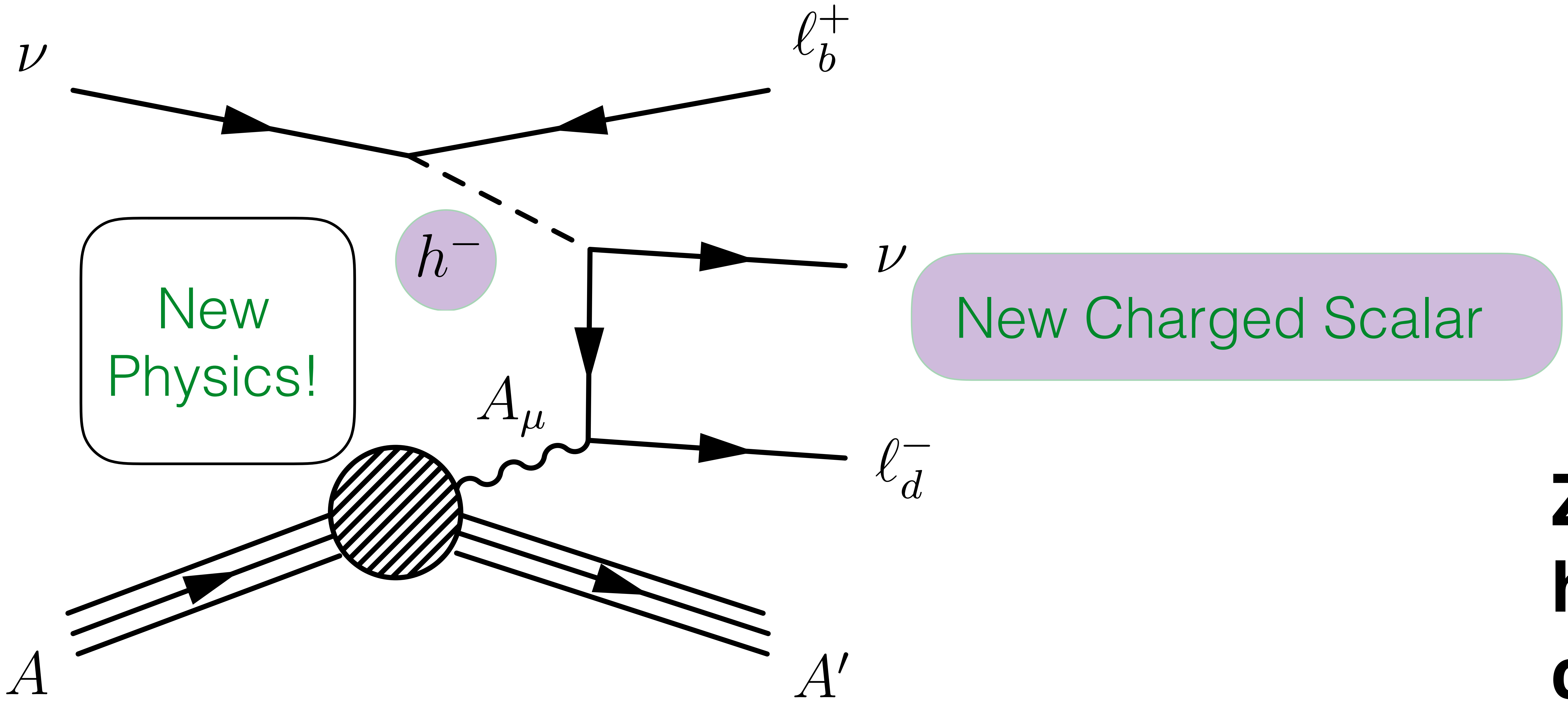


Probing allowed parameter space requires a 1% measurement of cross section.

Potential UV Realizations

$$\mathcal{L}_{\text{Zee-Babu}} \supset f^{ab} L_a L_b \mathcal{F} + s^{ab} \ell_a \ell_b \mathcal{S}$$

$$\mathcal{L}_{\text{Higgs Triplet}} \supset t^{ab} L_a \mathcal{T} L_b$$

Zee-Babu model tends to have many accidental cancellations

Higgs Triplet model has stronger bounds from doubly-charged scalars's LFV signatures

Three Things to Remember

1. **Neutrino trident production has only been measured in the di-muon channel.**

2. **Intensity + Technology = multi flavor tridents. Cross section is small, but enhanced by**
   - **Coherent effects**
   - **Large logarithms**

$$Z^2 \times \log(Q_{\max}/m_\ell)$$

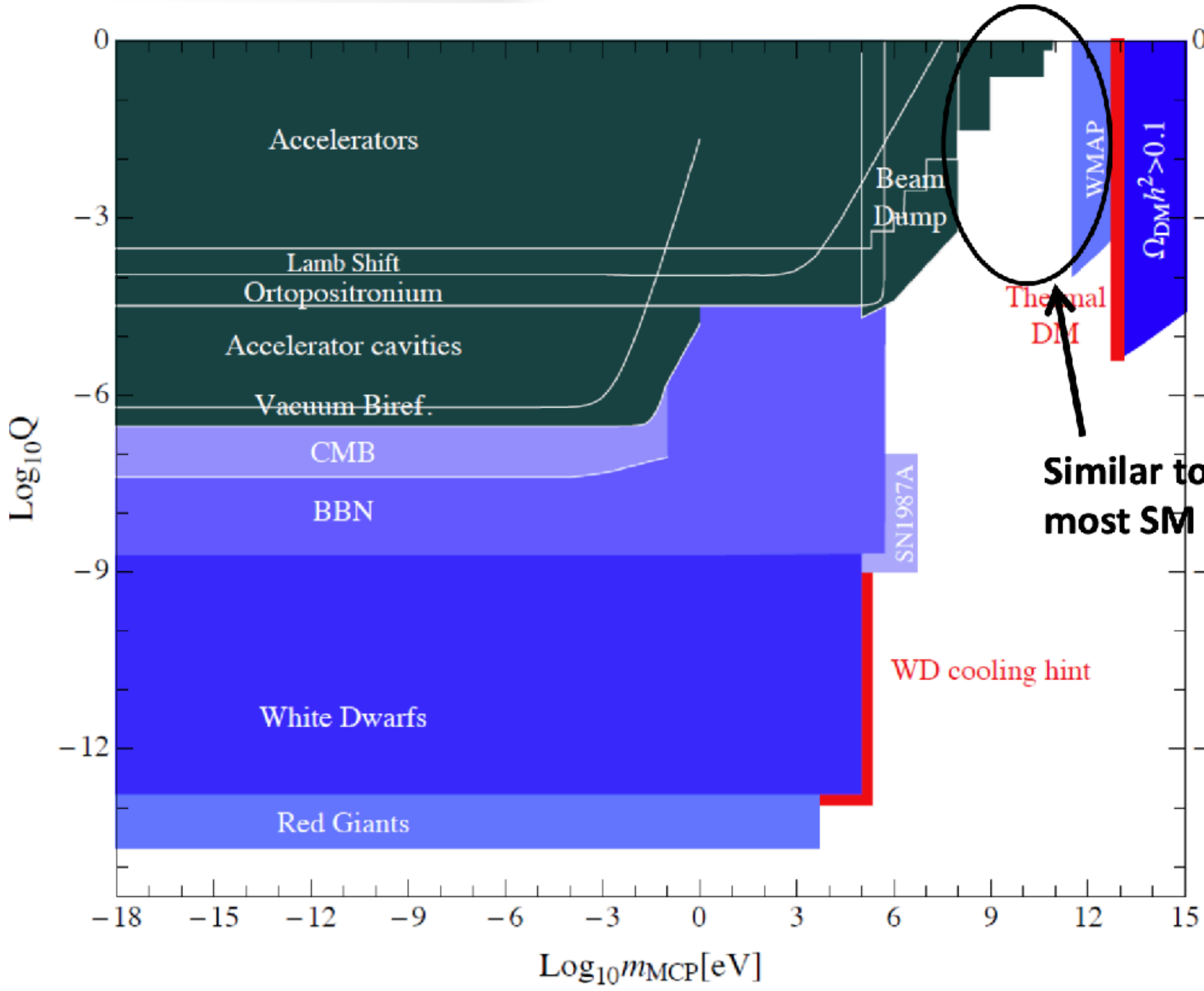
3. **Understanding these "new" Standard Model signals gives as a new tool for searching for new physics.**

Millicharged Particles

arXiv:2002.11732

arXiv:1806.03310

Who cares about a millicharge?



Andy Haas talk (2018)
https://tinyurl.com/t39r28w

Who cares about a millicharge?

Looking for milli-charged particles with a new experiment at the LHC

Andrew Haas,[1] Christopher S. Hill,[2] Eder Izaguirre,[3] and Itay Yavin[3,4]

[1] *Department of Physics, New York University, New York, NY, USA*
[2] *Department of Physics, The Ohio State University, Columbus, OH, USA*
[3] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada*
[4] *Department of Physics, McMaster University, Hamilton, ON, Canada*

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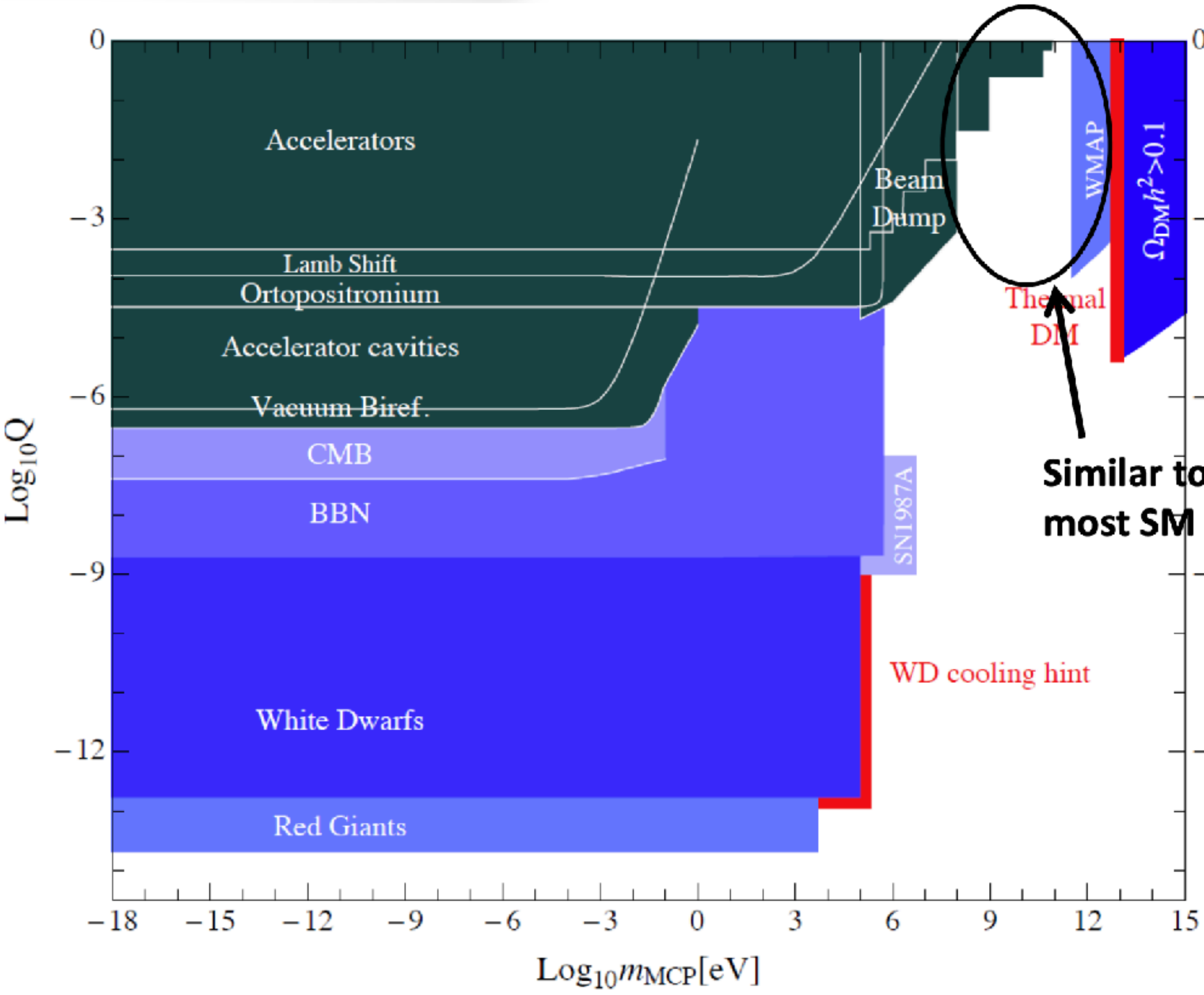

Andy Haas talk (2018)
https://tinyurl.com/t39r28w

Who cares about a millicharge?

Looking for milli-charged particles with a new experiment at the LHC

Andrew Haas,[1] Christopher S. Hill,[2] Eder Izaguirre,[3] and Itay Yavin[3,4]
[1]Department of Physics, New York University, New York, NY, USA
[2]Department of Physics, The Ohio State University, Columbus, OH, USA
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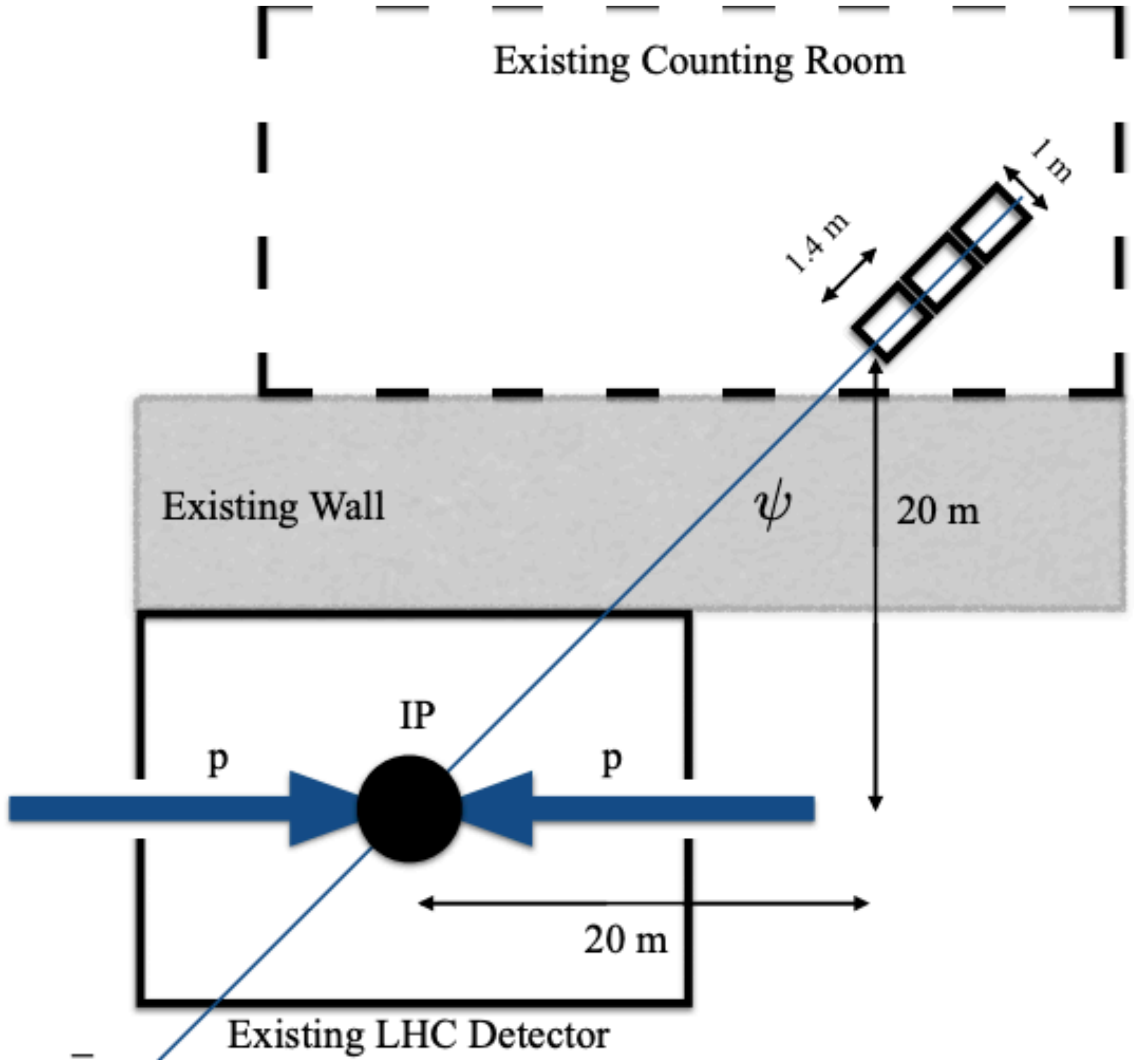

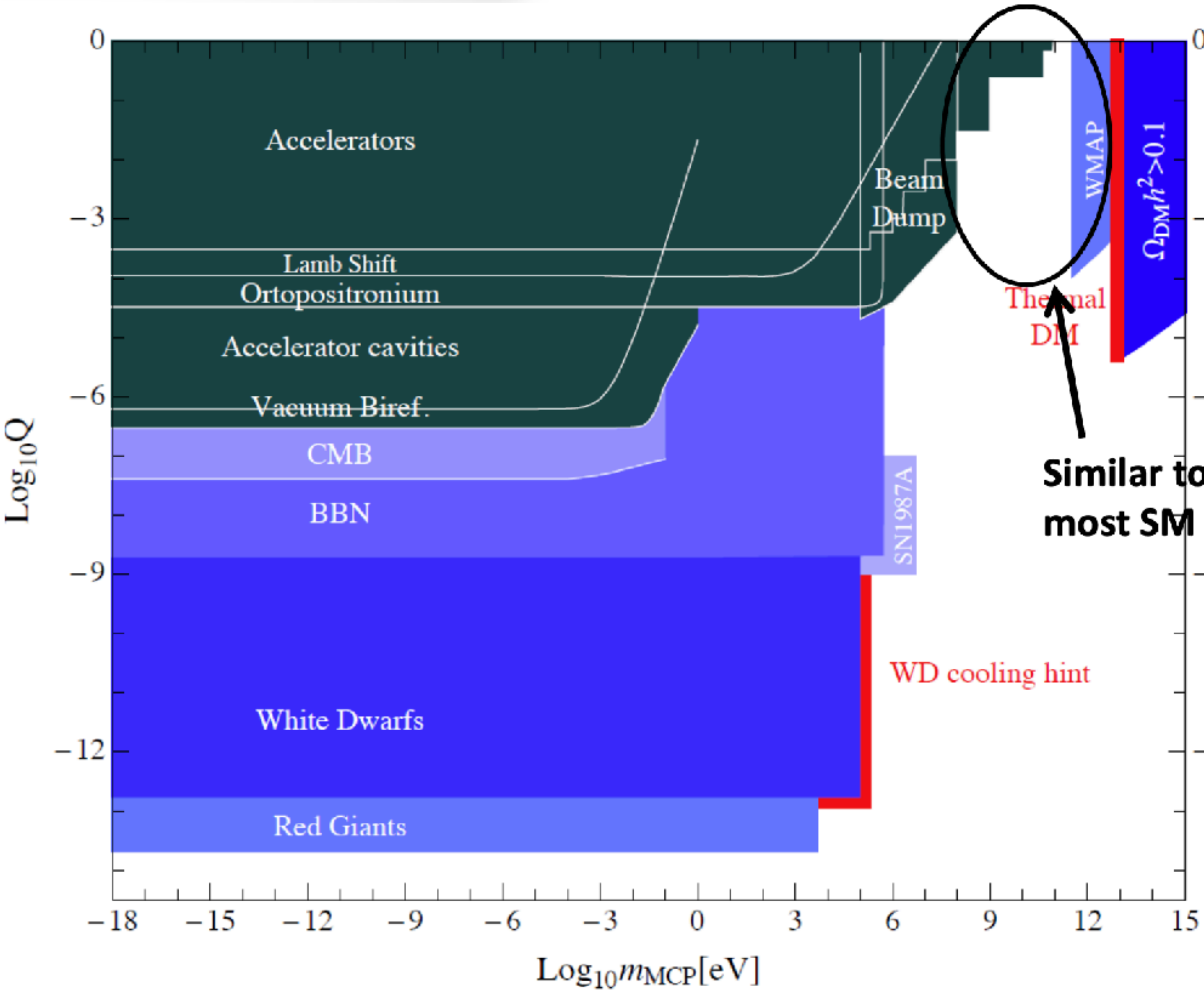

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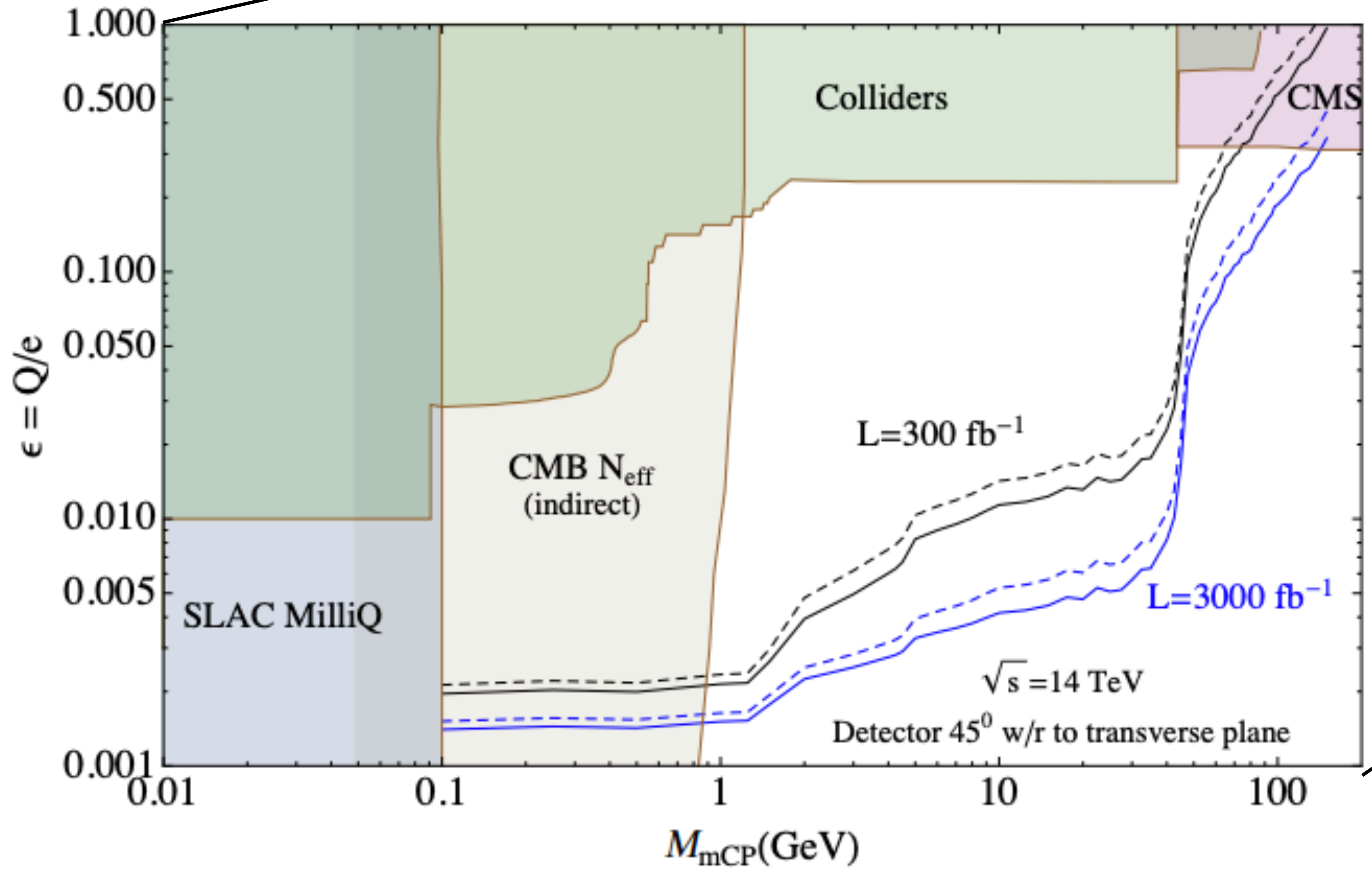

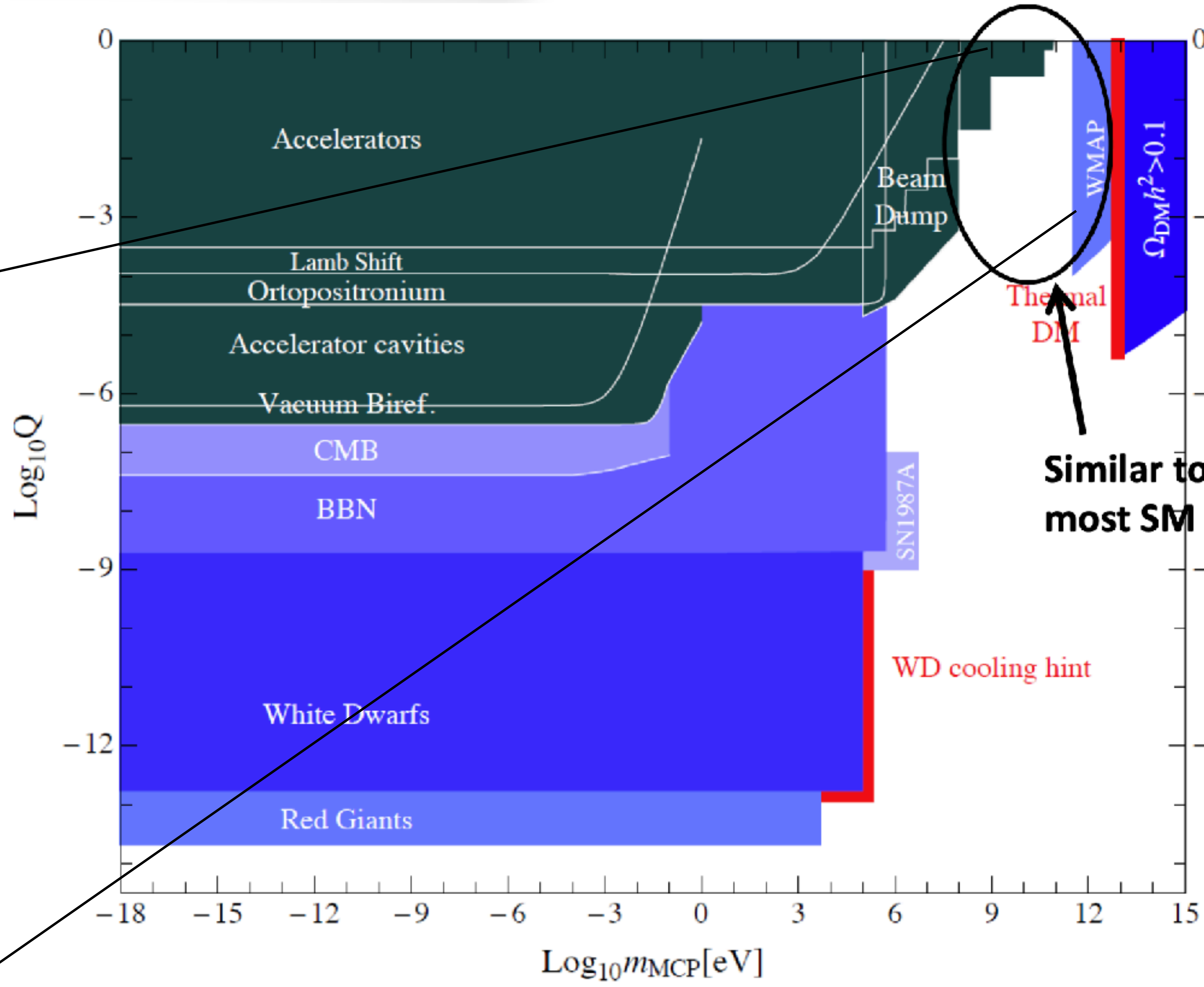

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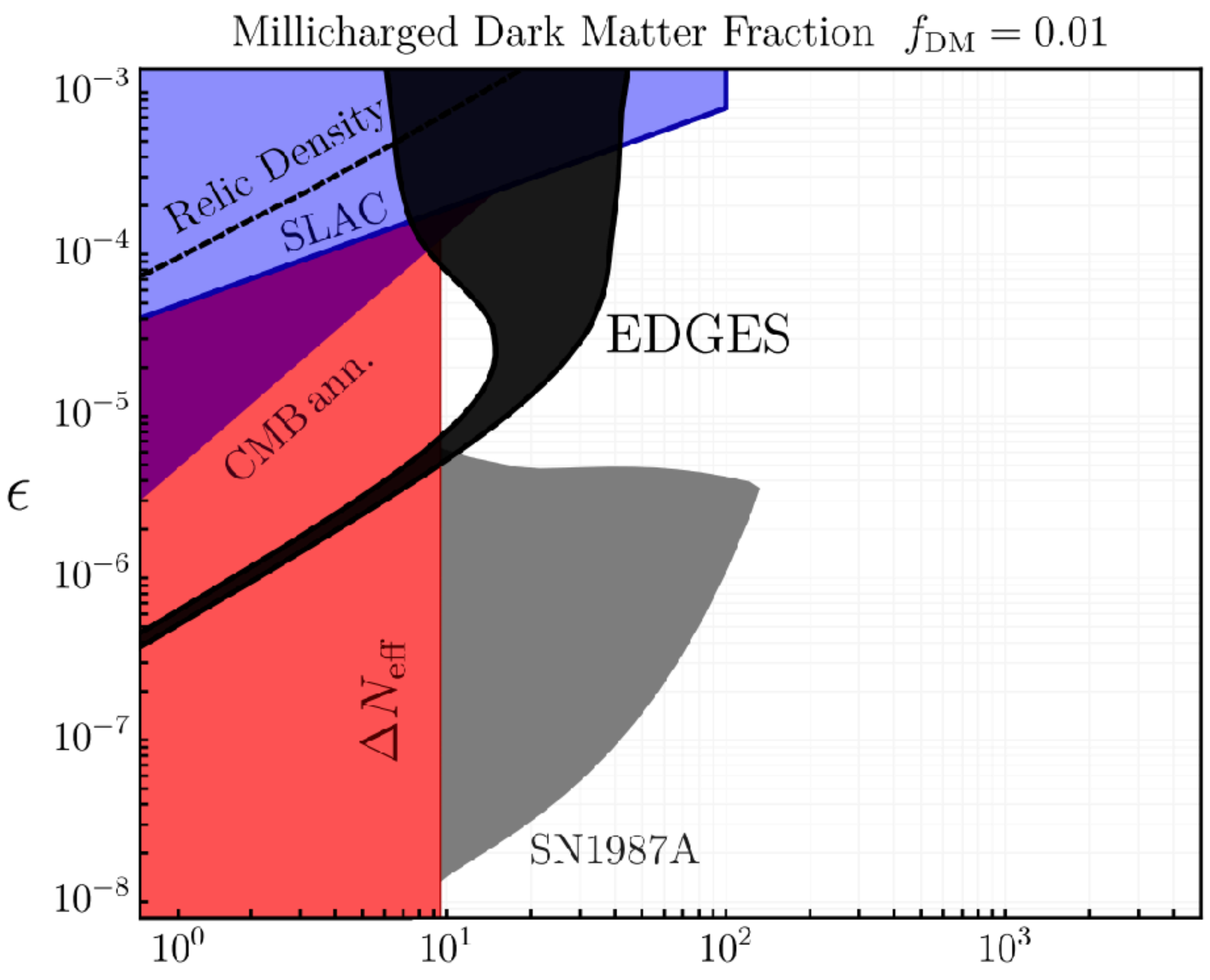
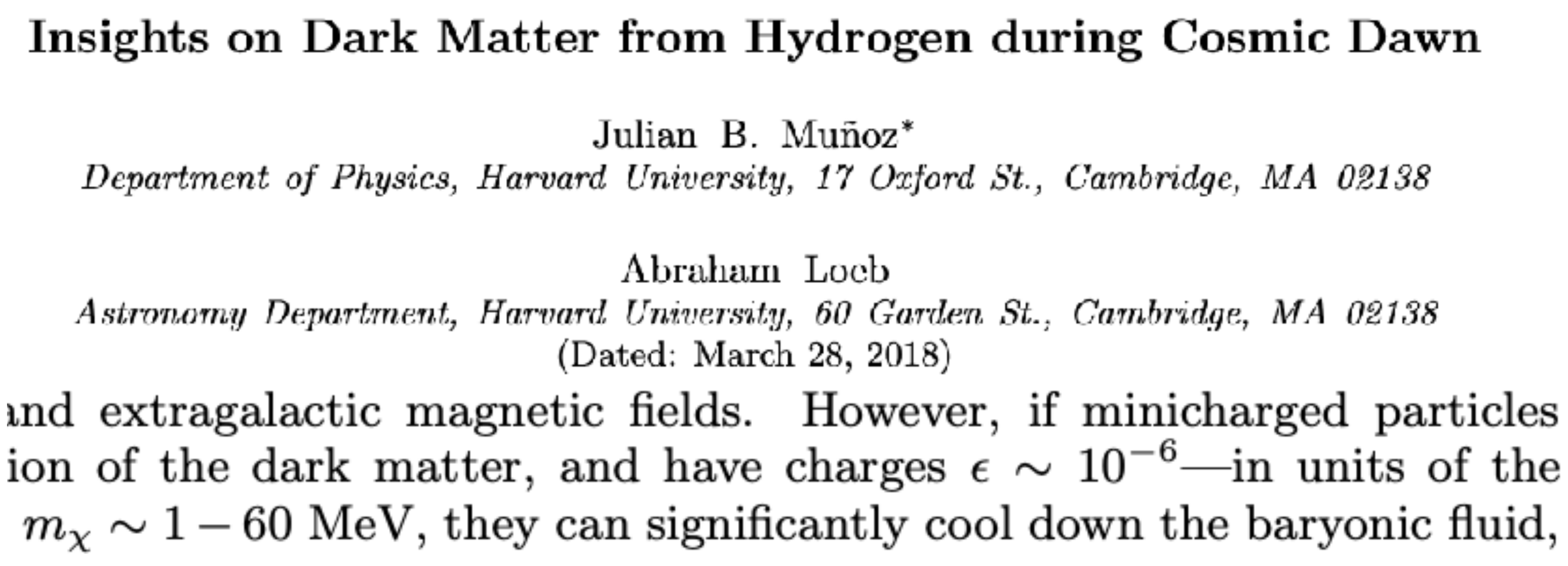


Berlin, Hooper, Krnjaic, McDermott arXiv:1803.02804



Insights on Dark Matter from Hydrogen during Cosmic Dawn

Julian B. Muñoz*
Department of Physics, Harvard University, 17 Oxford St., Cambridge, MA 02138

Abraham Loeb
Astronomy Department, Harvard University, 60 Garden St., Cambridge, MA 02138
(Dated: March 28, 2018)

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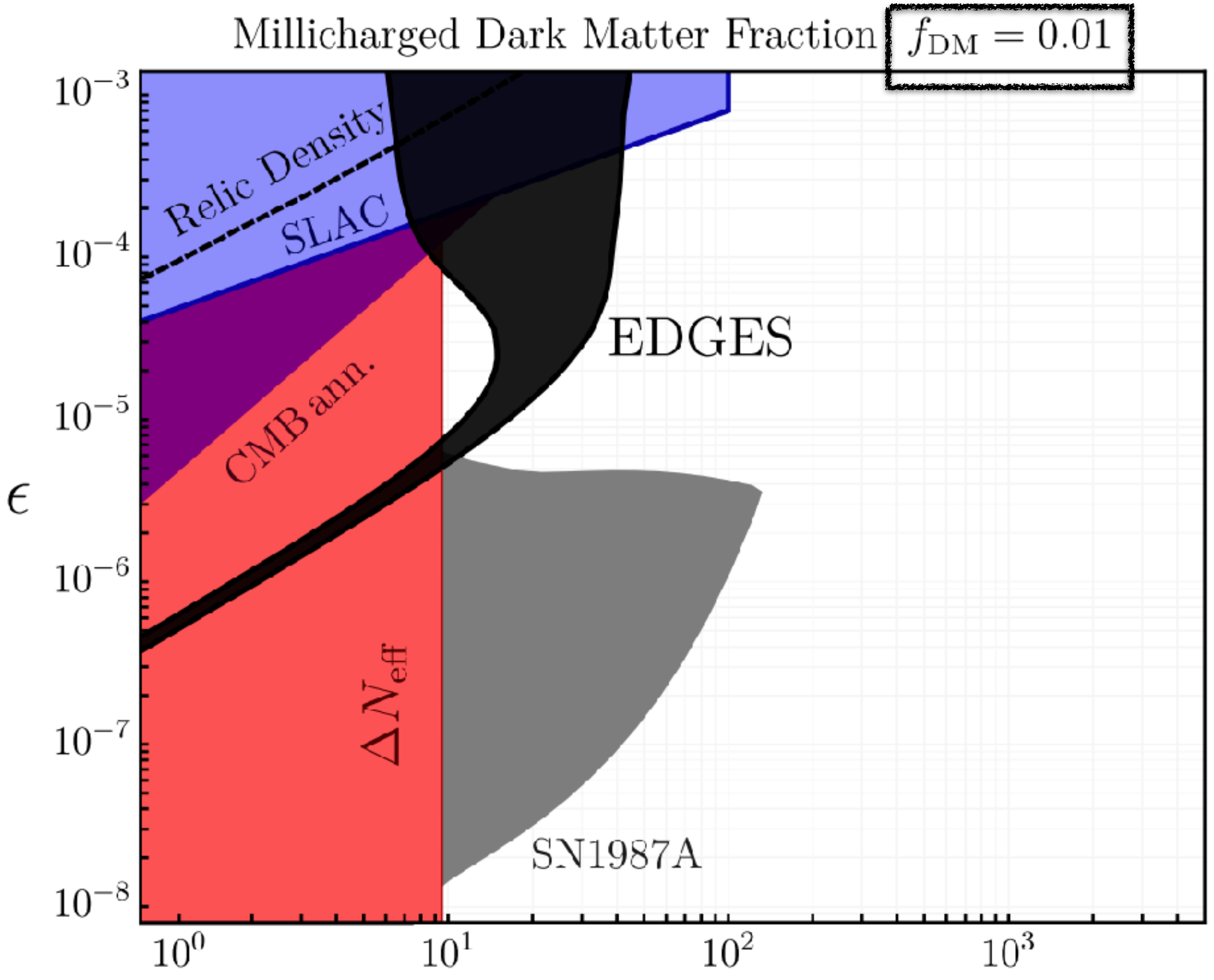
$m_\chi \sim 1-60$ MeV, they can significantly cool down the baryonic fluid,

$$T_{21} = T_{\rm hyperfine} - T_{\rm CMB}$$

$$T_{21}^{\rm EDGES} \sim 2 \times T_{21}^{\rm SM}$$

Who cares about a millicharge?



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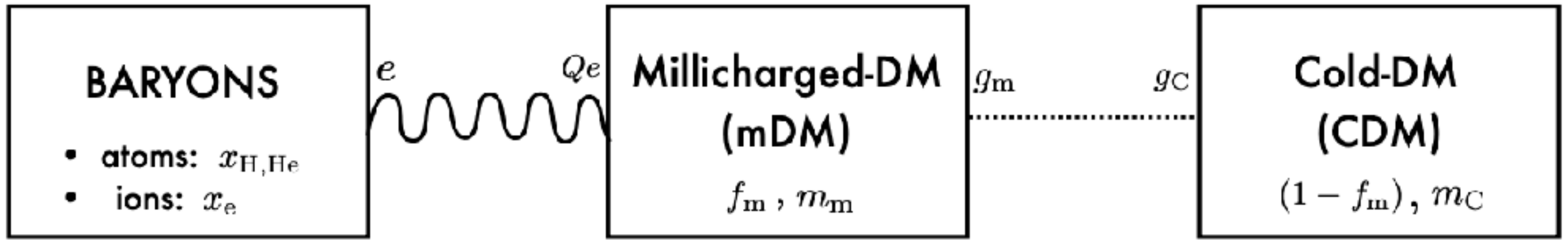
Who cares about a millicharge?

Reviving Millicharged Dark Matter for 21-cm Cosmology

Hongwan Liu,[1] Nadav Joseph Outmezguine,[2] Diego Redigolo,[2,3] and Tomer Volansky[2]

[1] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, U.S.A.*
[2] *Raymond and Beverly Sackler School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv 69978, Israe*
[3] *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot 7610001,Israel*



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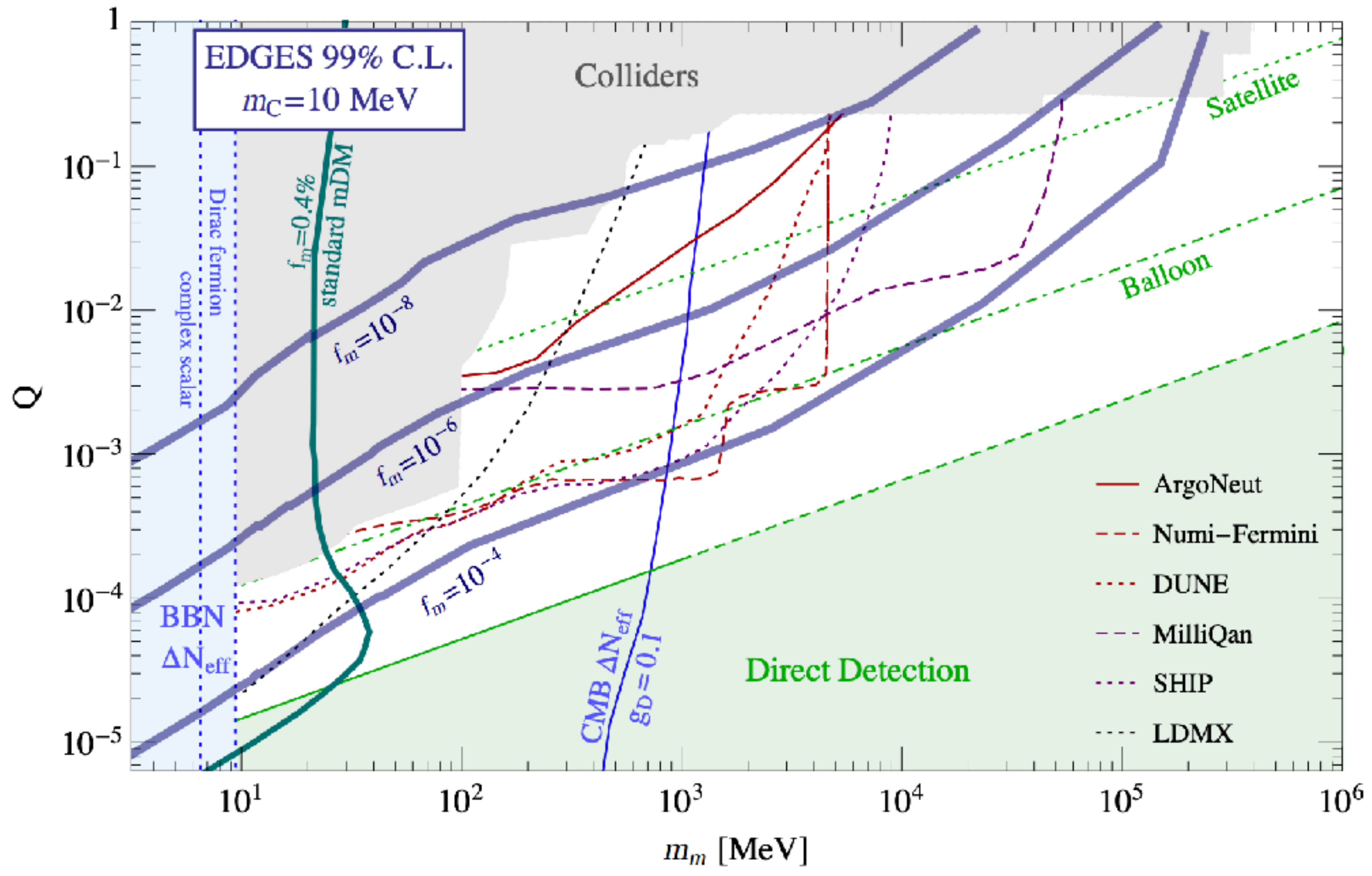

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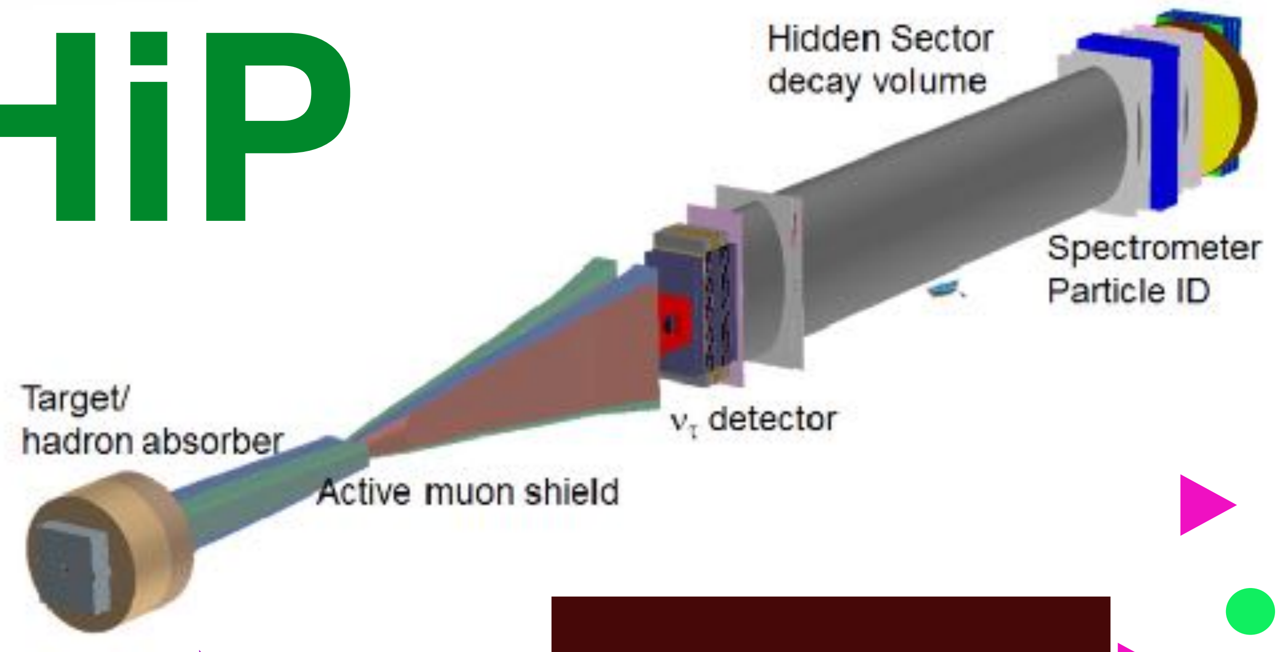
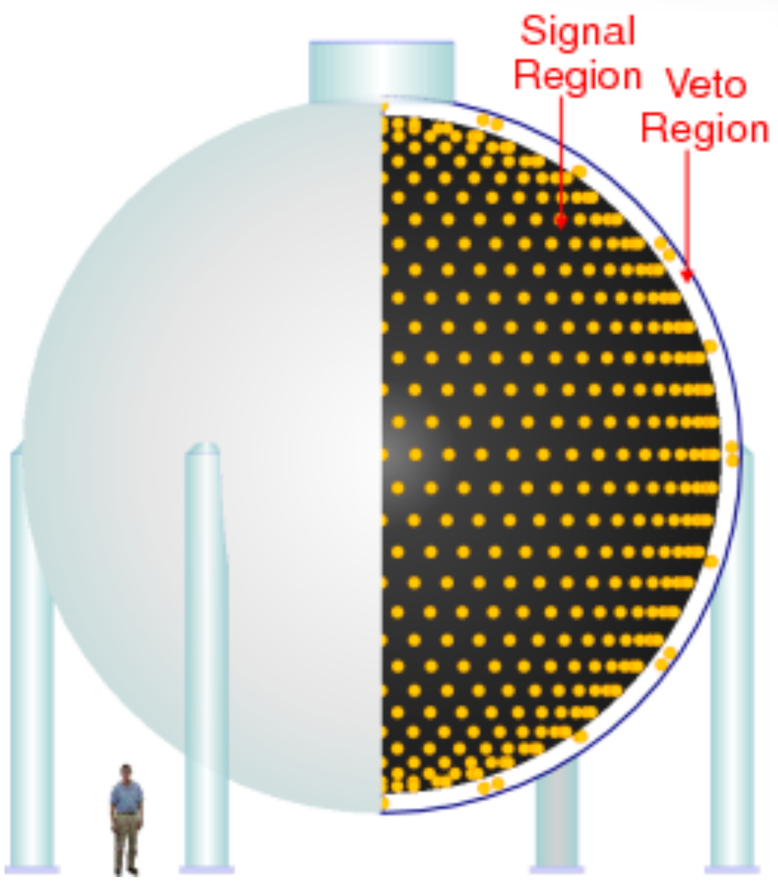
MCPs from Proton Beams

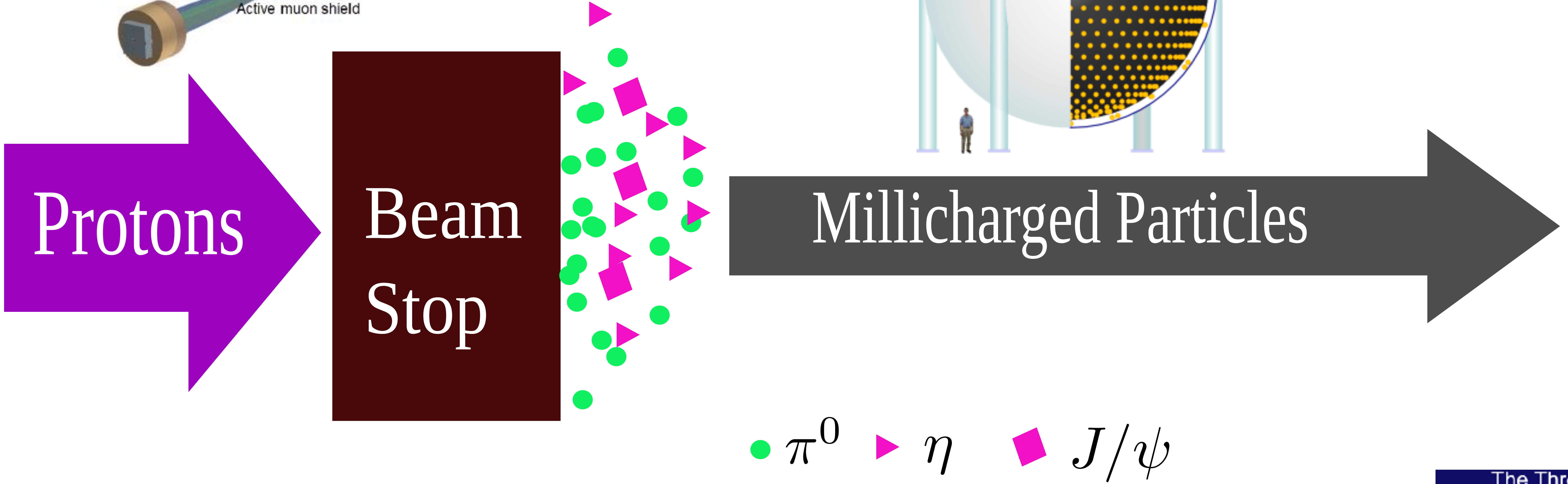
MCPs at Fixed Target Experiments

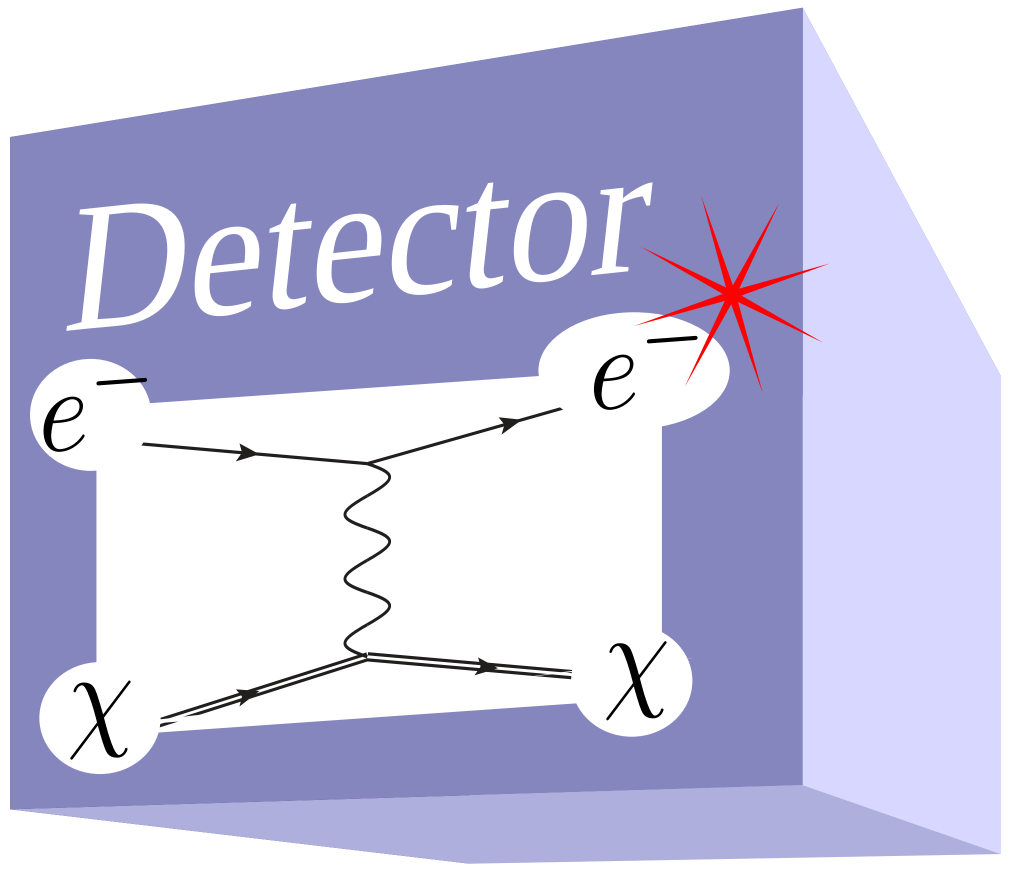
SHiP



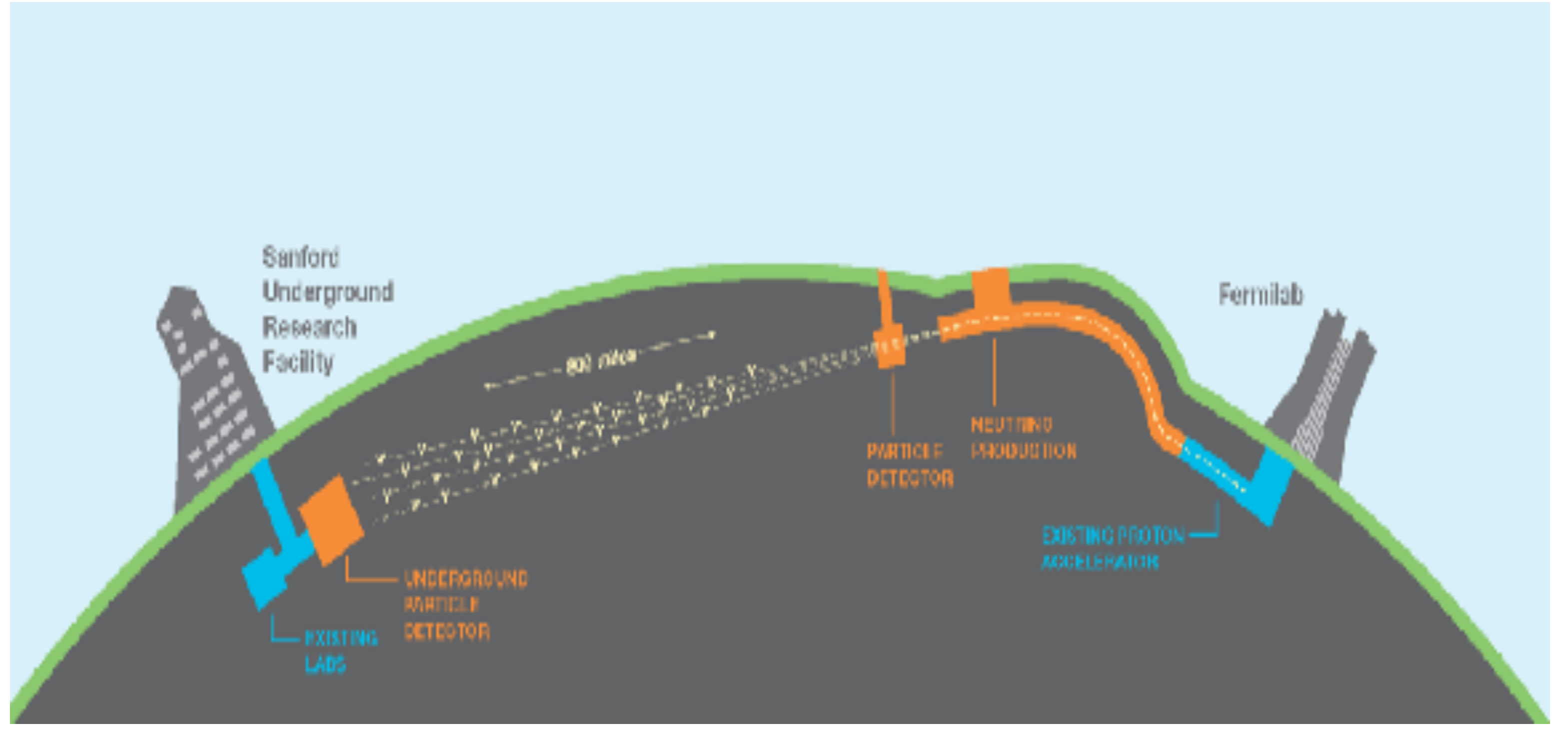


MiniBooNE



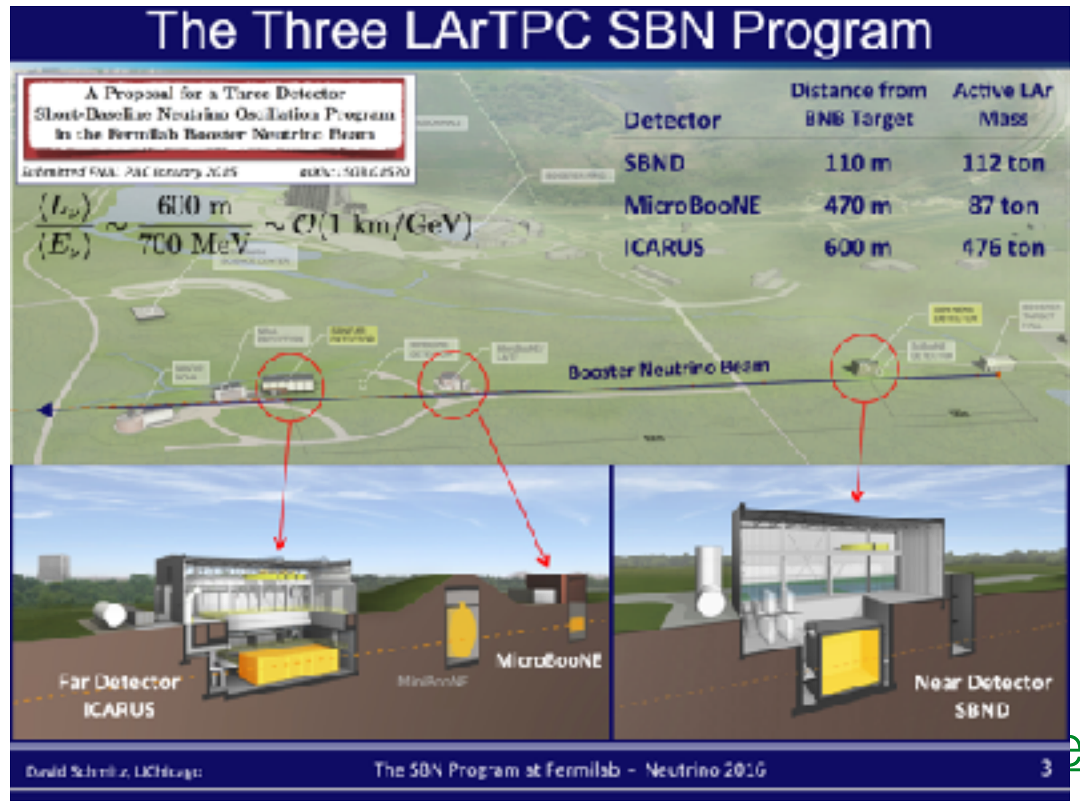


Detection Signal is Soft Electron Recoil



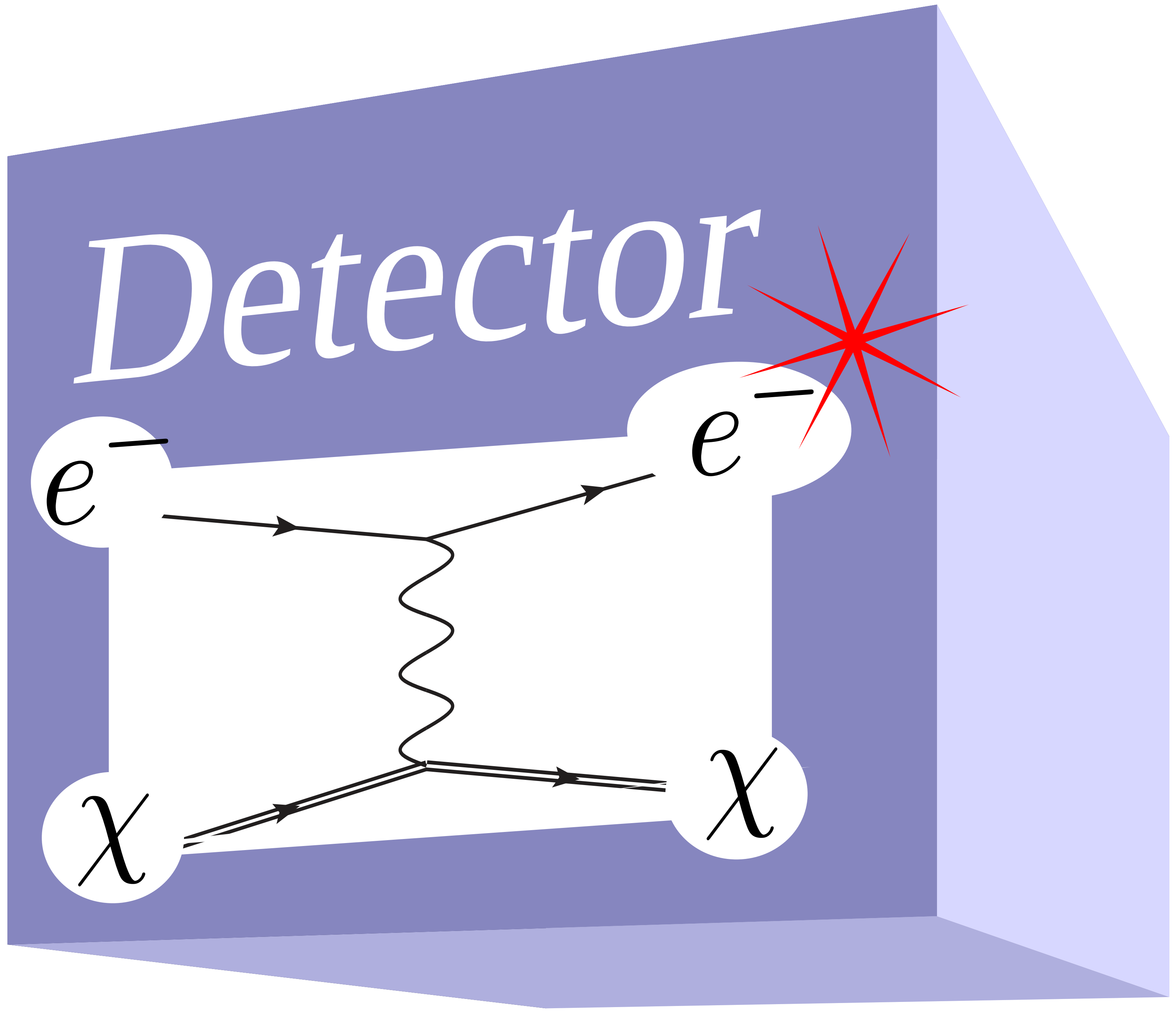
DUNE

SBN



estid@gmail.com

Detecting mCPs At Beam Dumps



Detection Signal is
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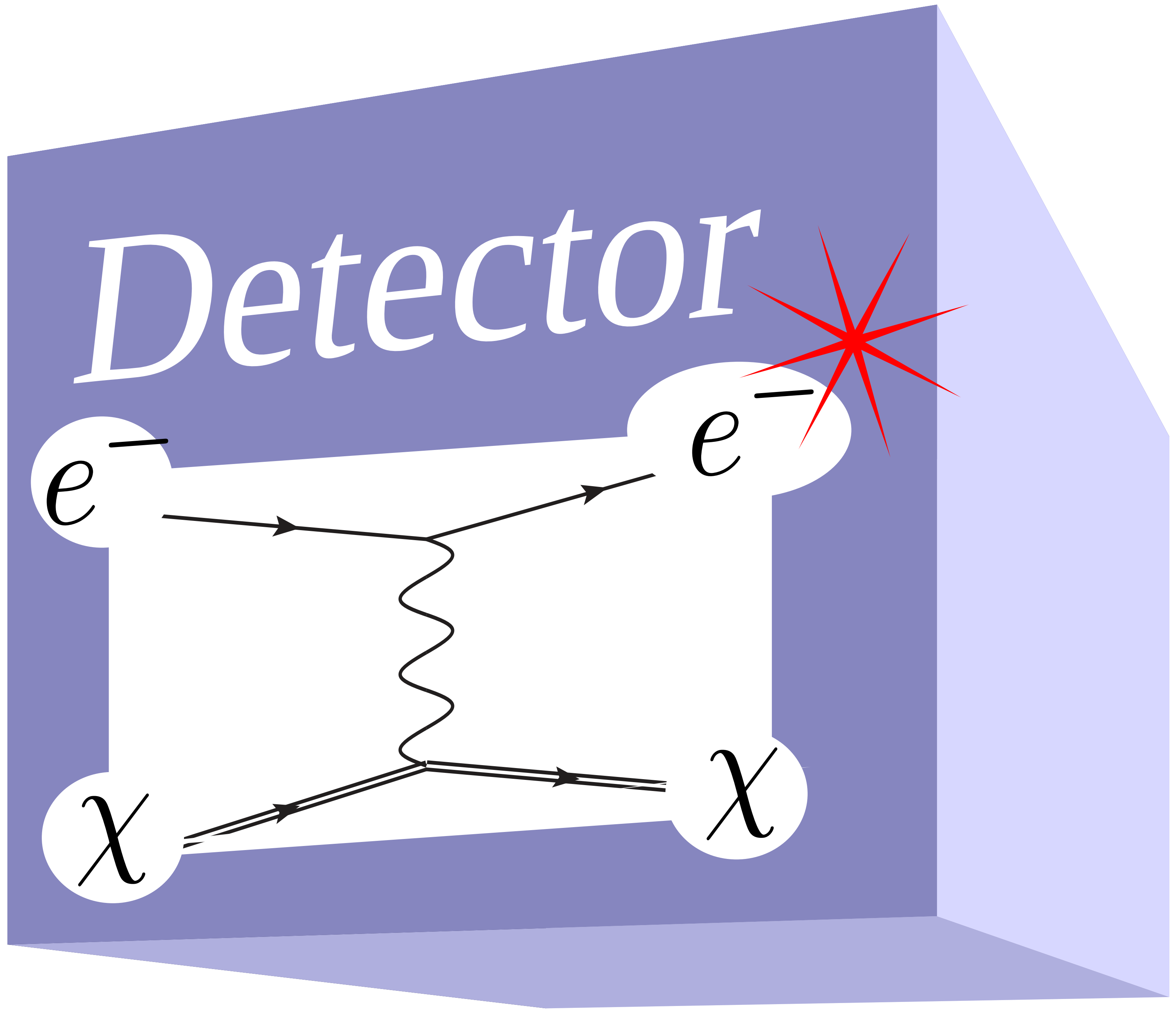
ryan.plestid@gmail.com

Detecting mCPs At Beam Dumps

$$\frac{\mathrm{d}\sigma_{e\chi}}{\mathrm{d}Q^2} = 2\pi\alpha^2\epsilon^2 \times \frac{2(s-m_\chi^2)^2 - 2sQ^2 + Q^4}{(s-m_\chi^2)^2 Q^4}$$

IR Sensitive Cross Section (Rutherford Scattering)



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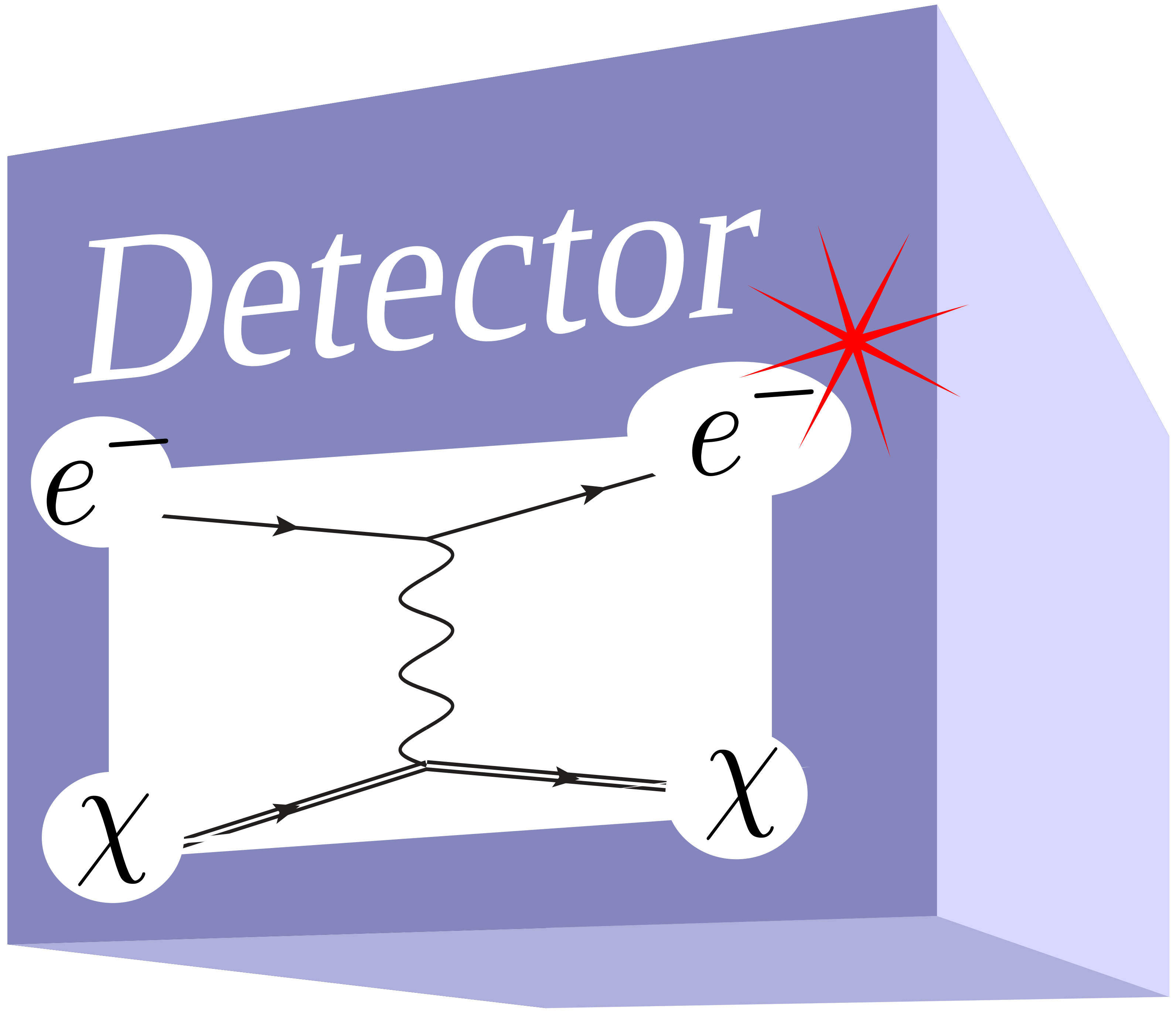

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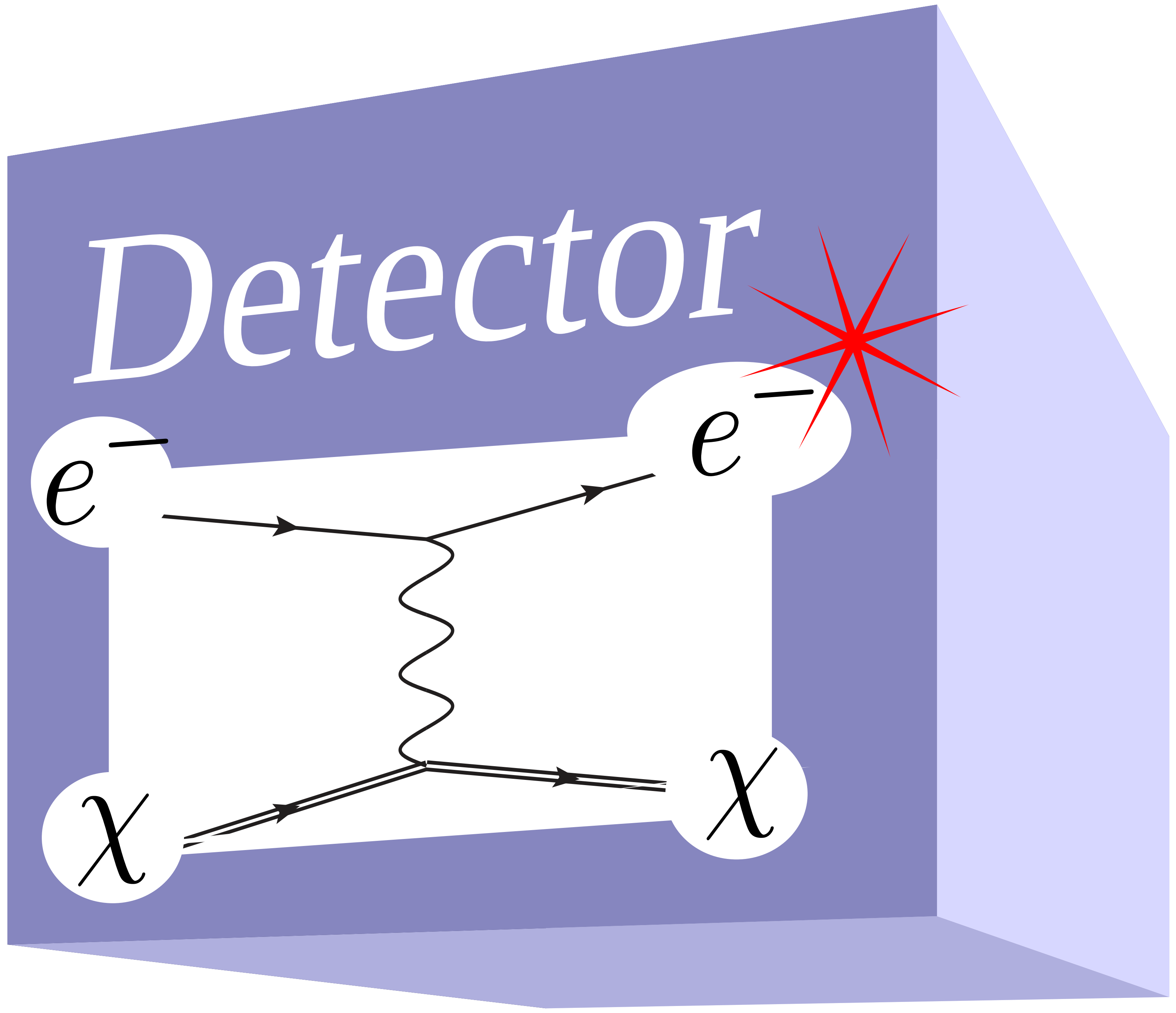
Prefers scattering with lightest particle.

Small detection threshold means bigger cross sections

$$\sigma_{e\chi} = 2.6 \times 10^{-25}\mathrm{cm}^2 \times \epsilon^2 \times \frac{1\ \mathrm{MeV}}{E_e^{(\mathrm{min})} - m_e}$$



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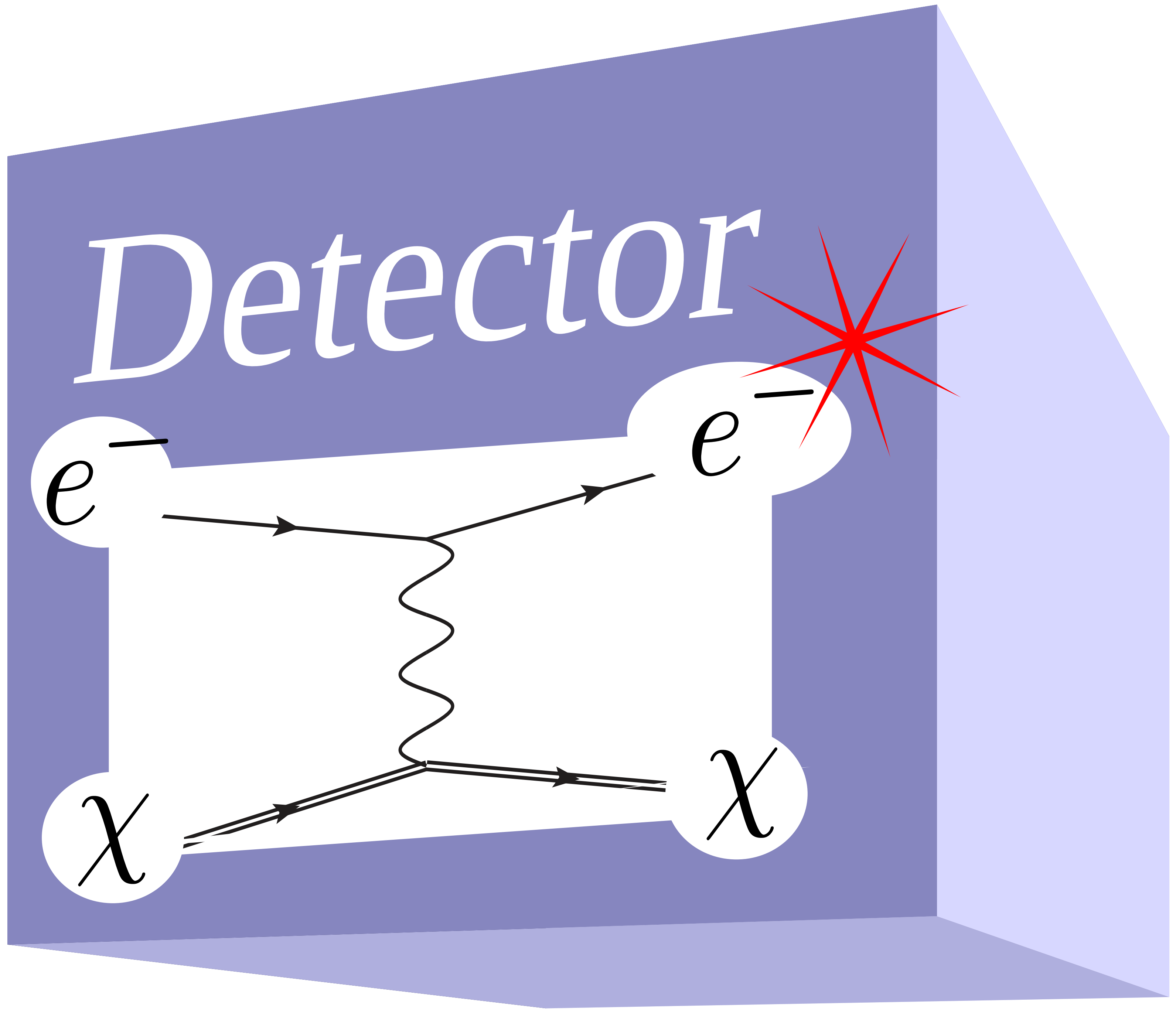

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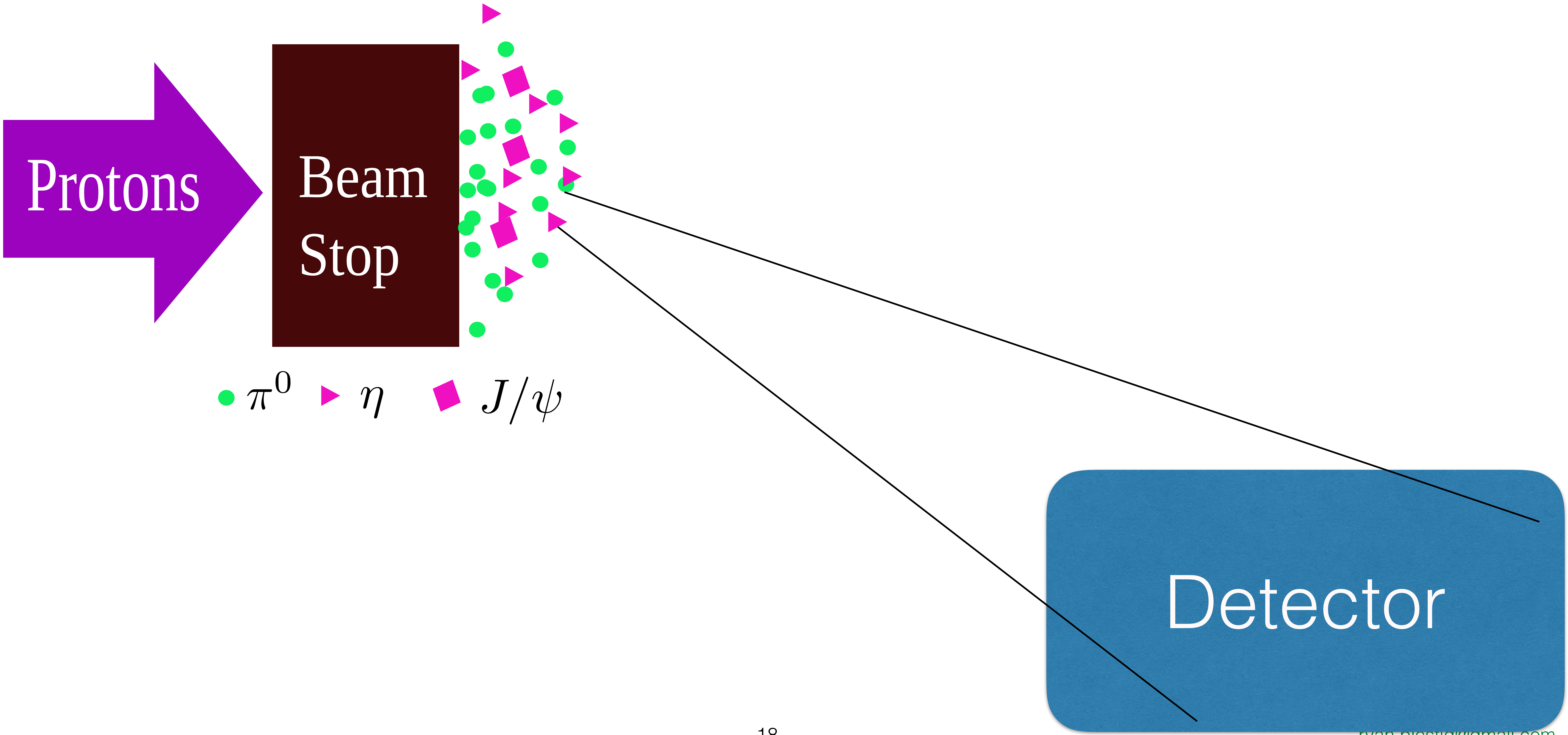
Meson Decays At Beam Dumps



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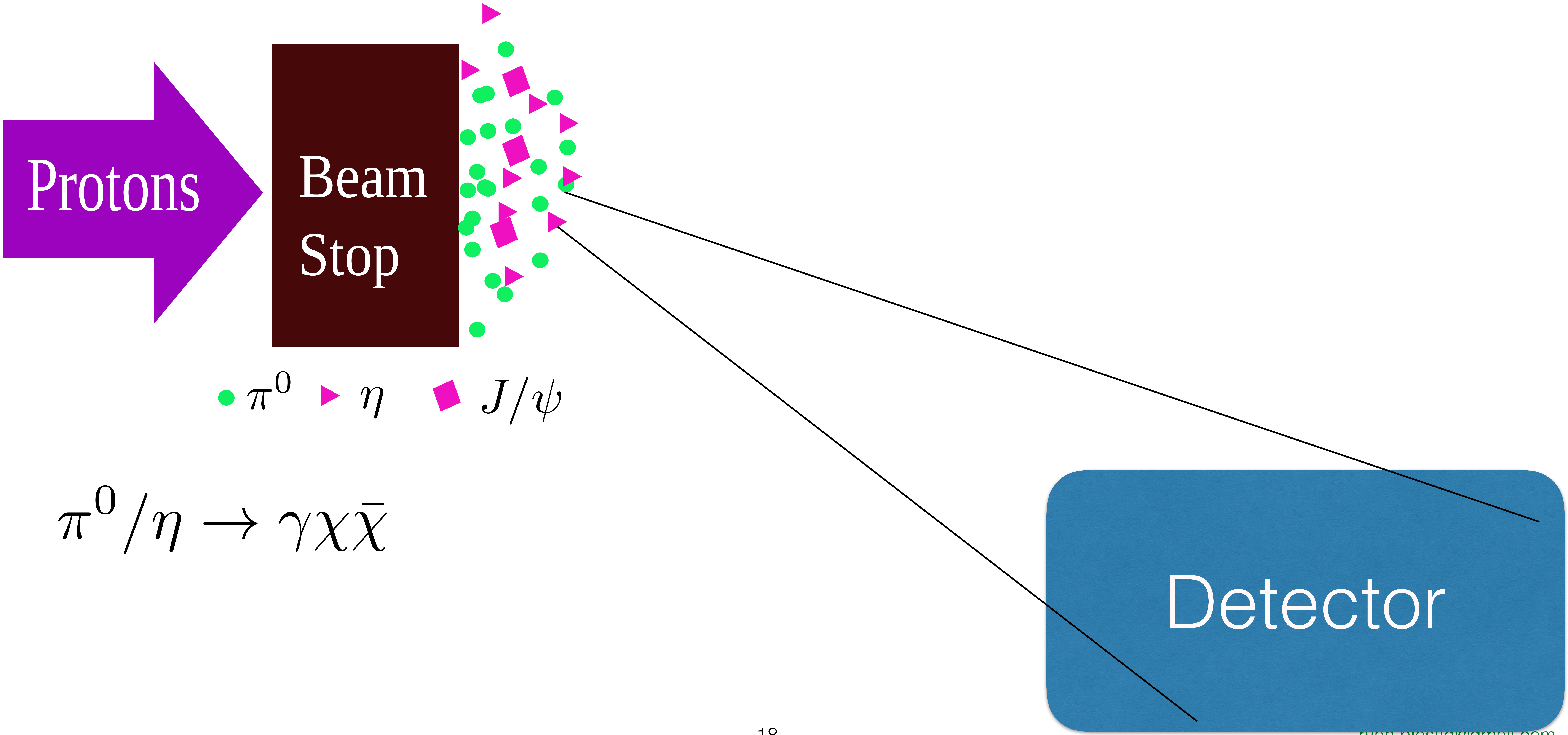

$$\pi^0/\eta \to \gamma\chi\bar{\chi}$$

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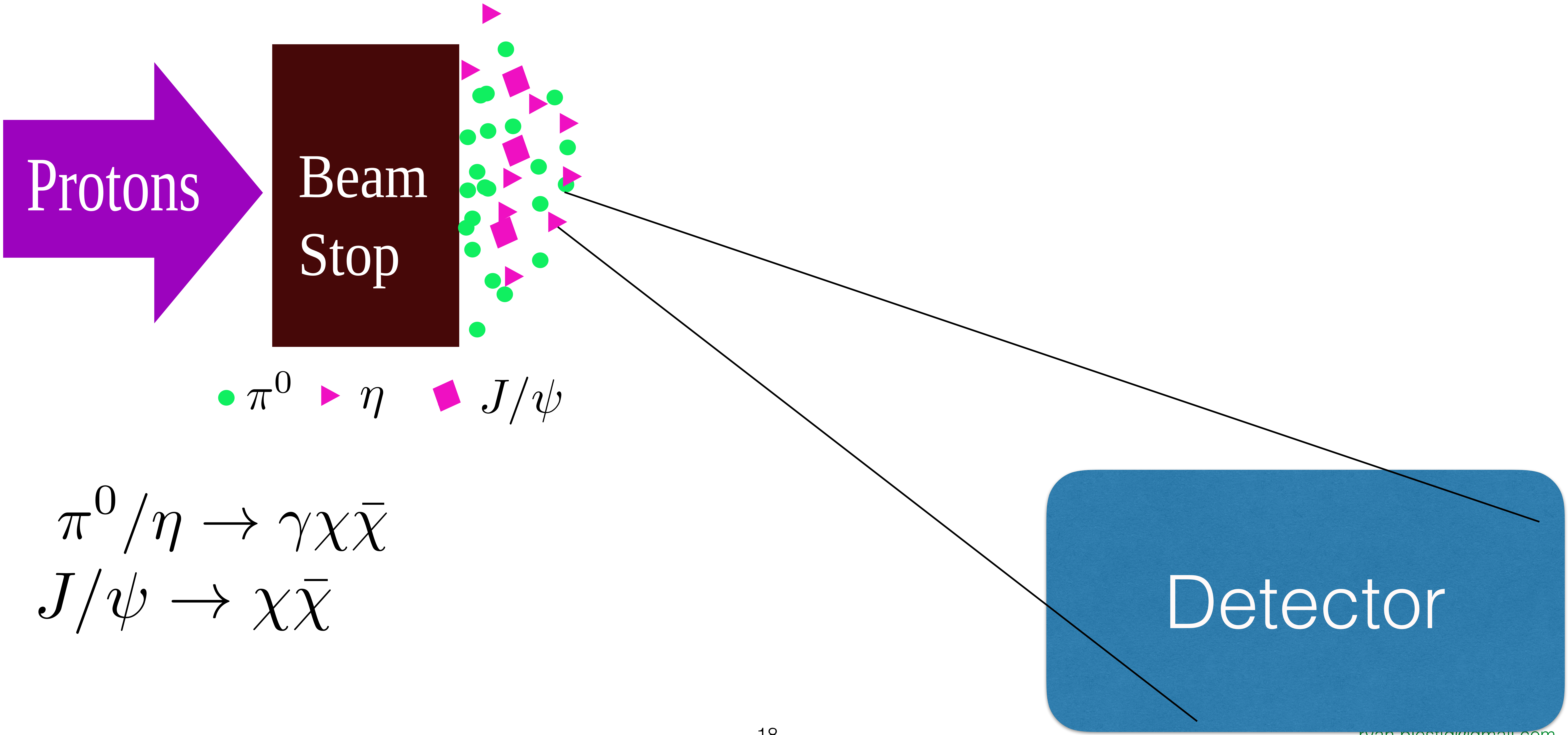

$$\pi^0/\eta \to \gamma\chi\bar{\chi}$$
$$J/\psi \to \chi\bar{\chi}$$

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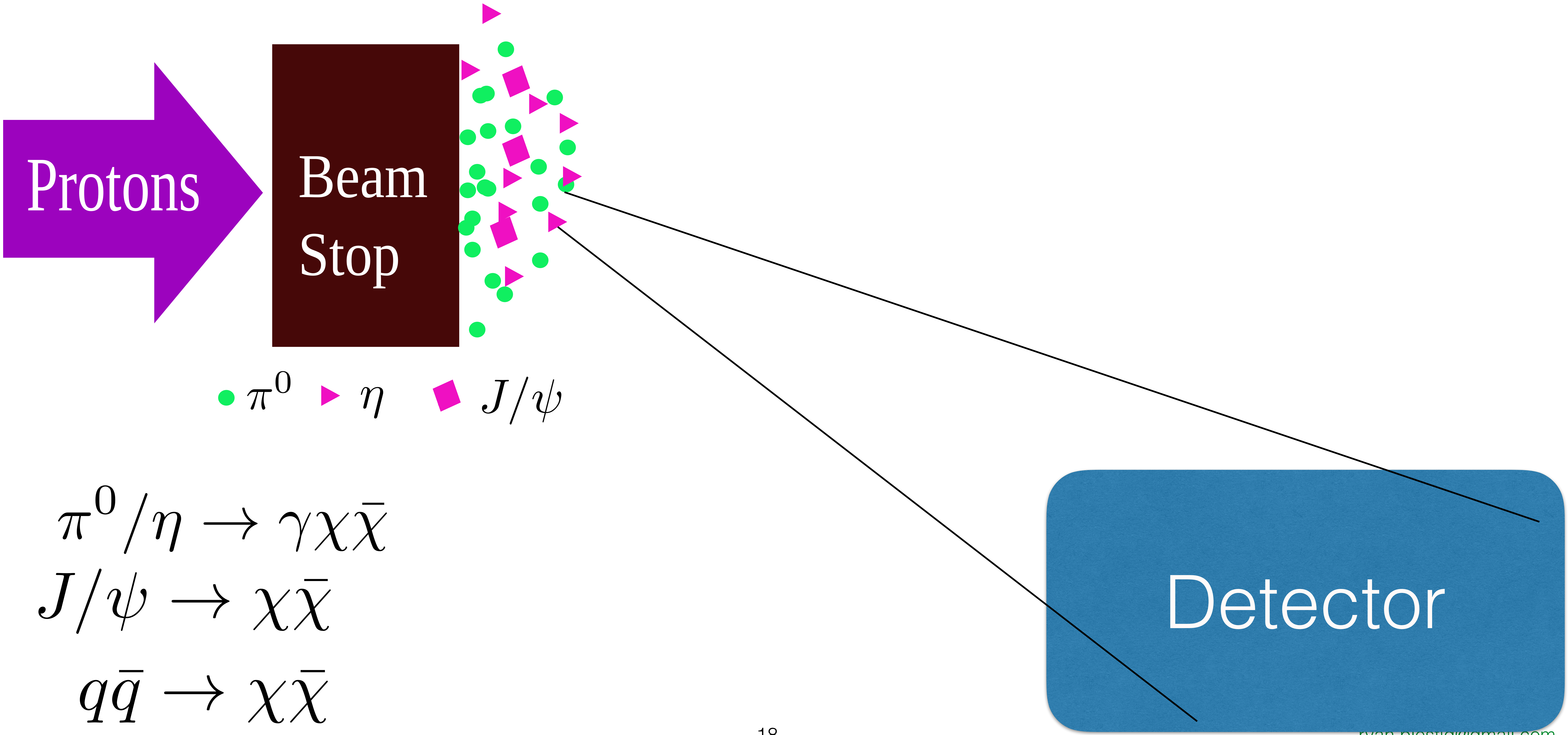
Meson Decays At Beam Dumps



$$\pi^0/\eta \to \gamma\chi\bar{\chi}$$
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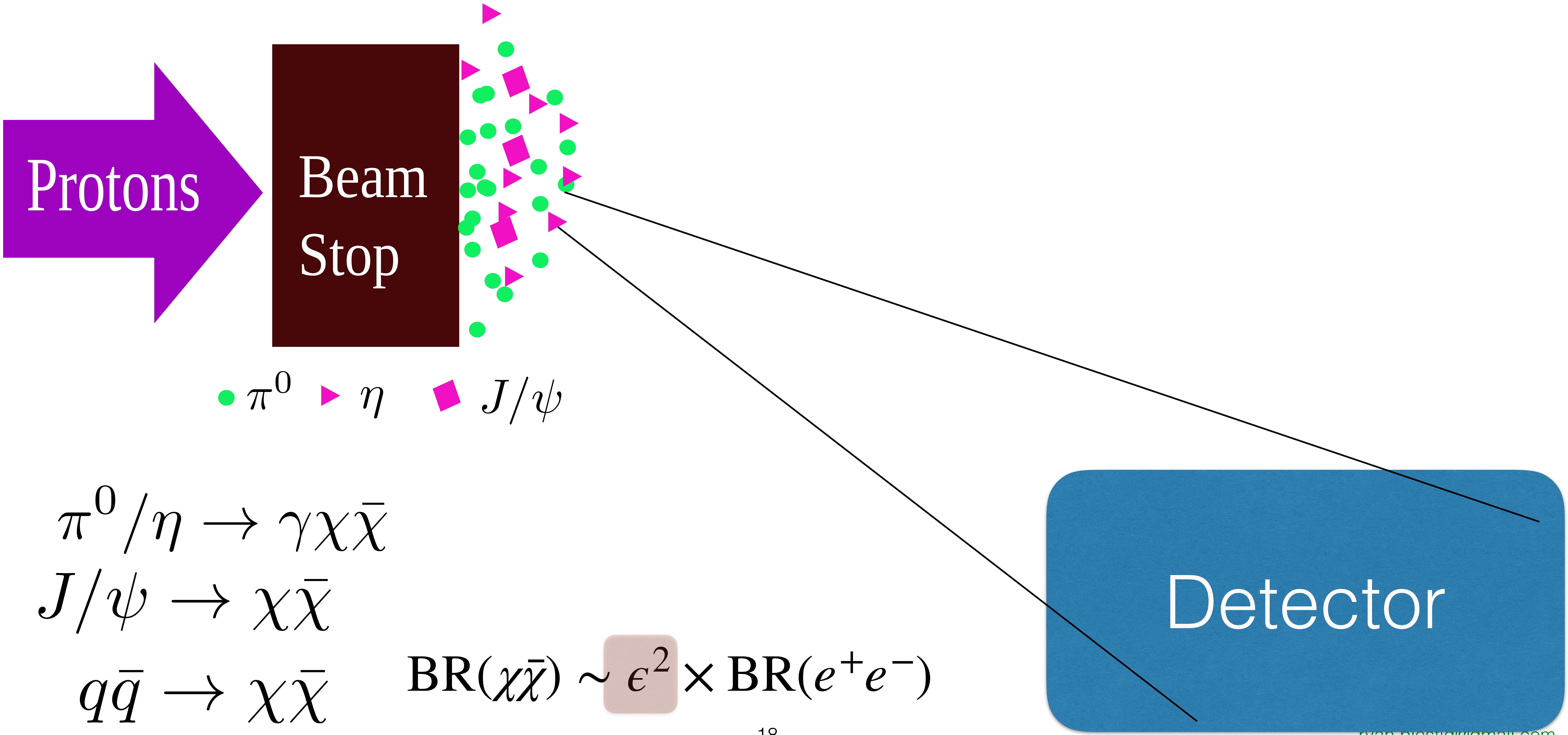

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$$\mathrm{BR}(\chi\bar{\chi}) \sim \epsilon^2 \times \mathrm{BR}(e^+e^-)$$

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Meson Decays At Beam Dumps

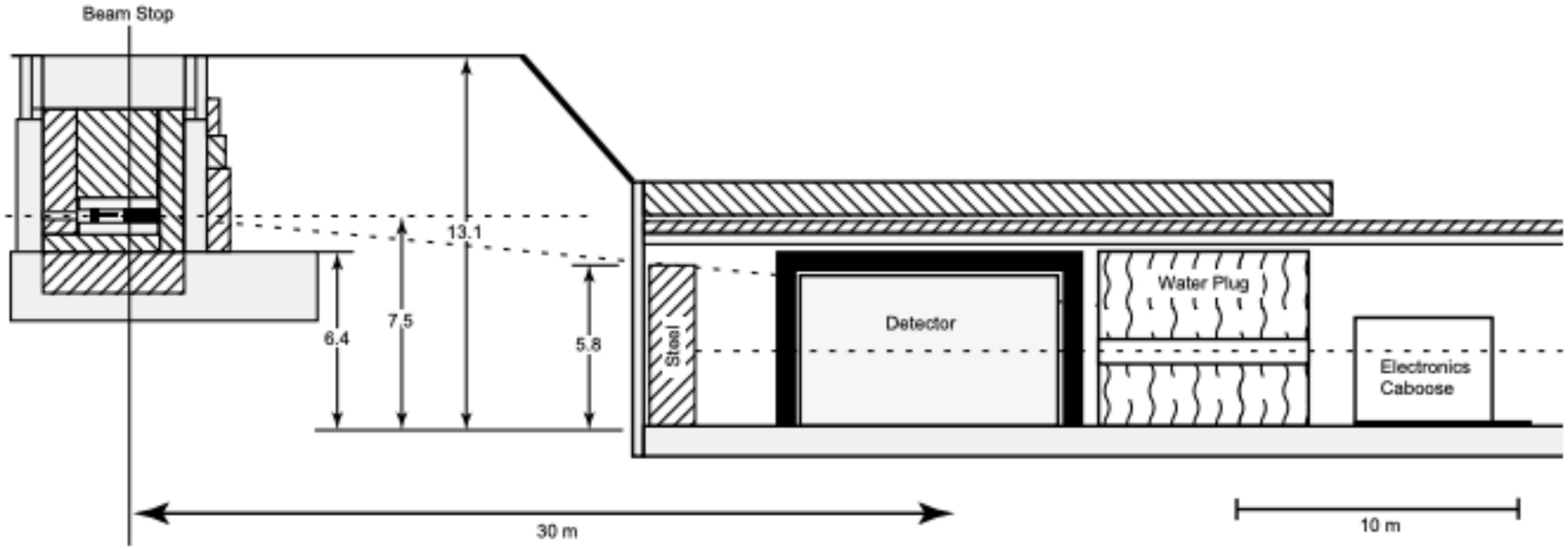

Figure 2: Detector enclosure and target area configuration, elevation view.

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Detector

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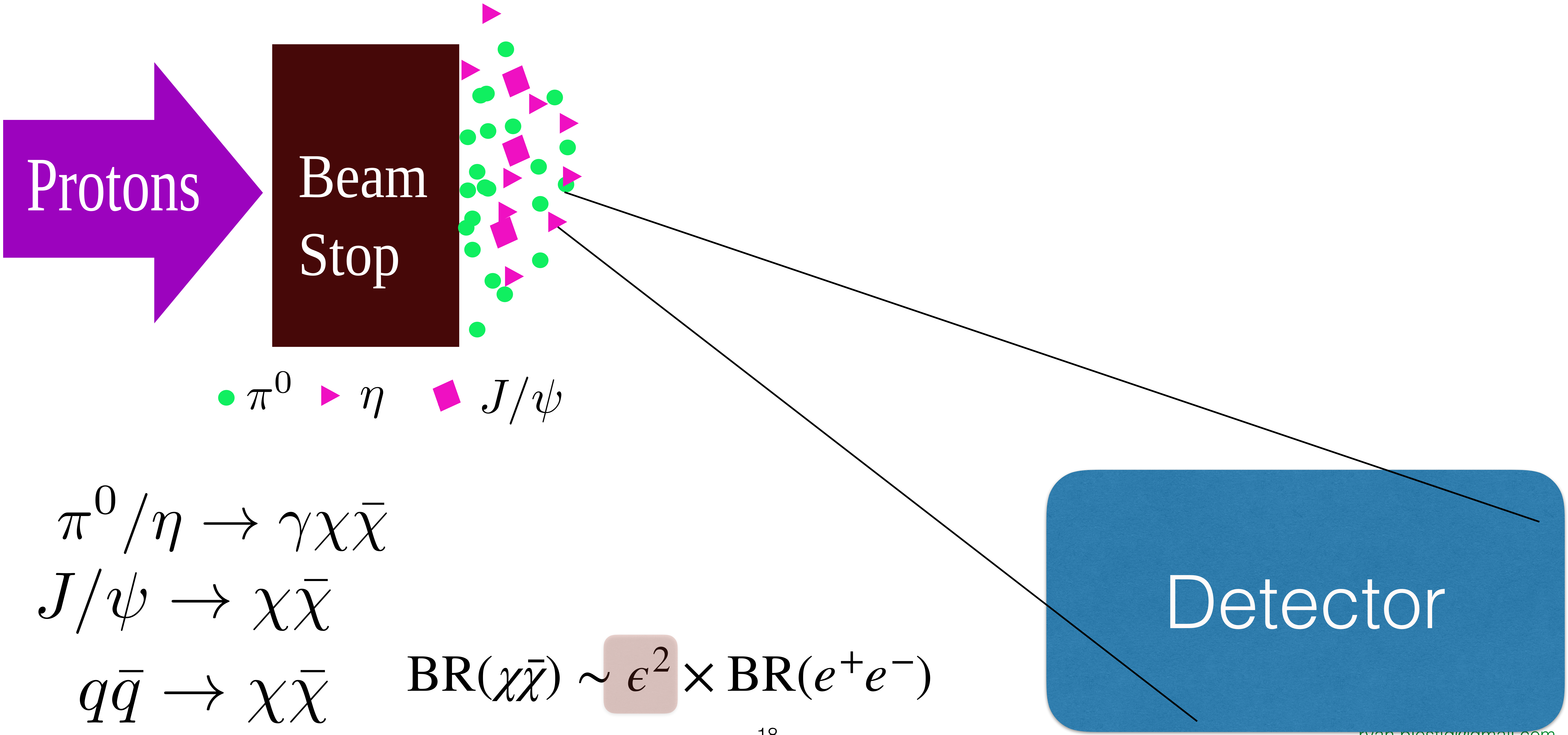
Meson Decays At Beam Dumps



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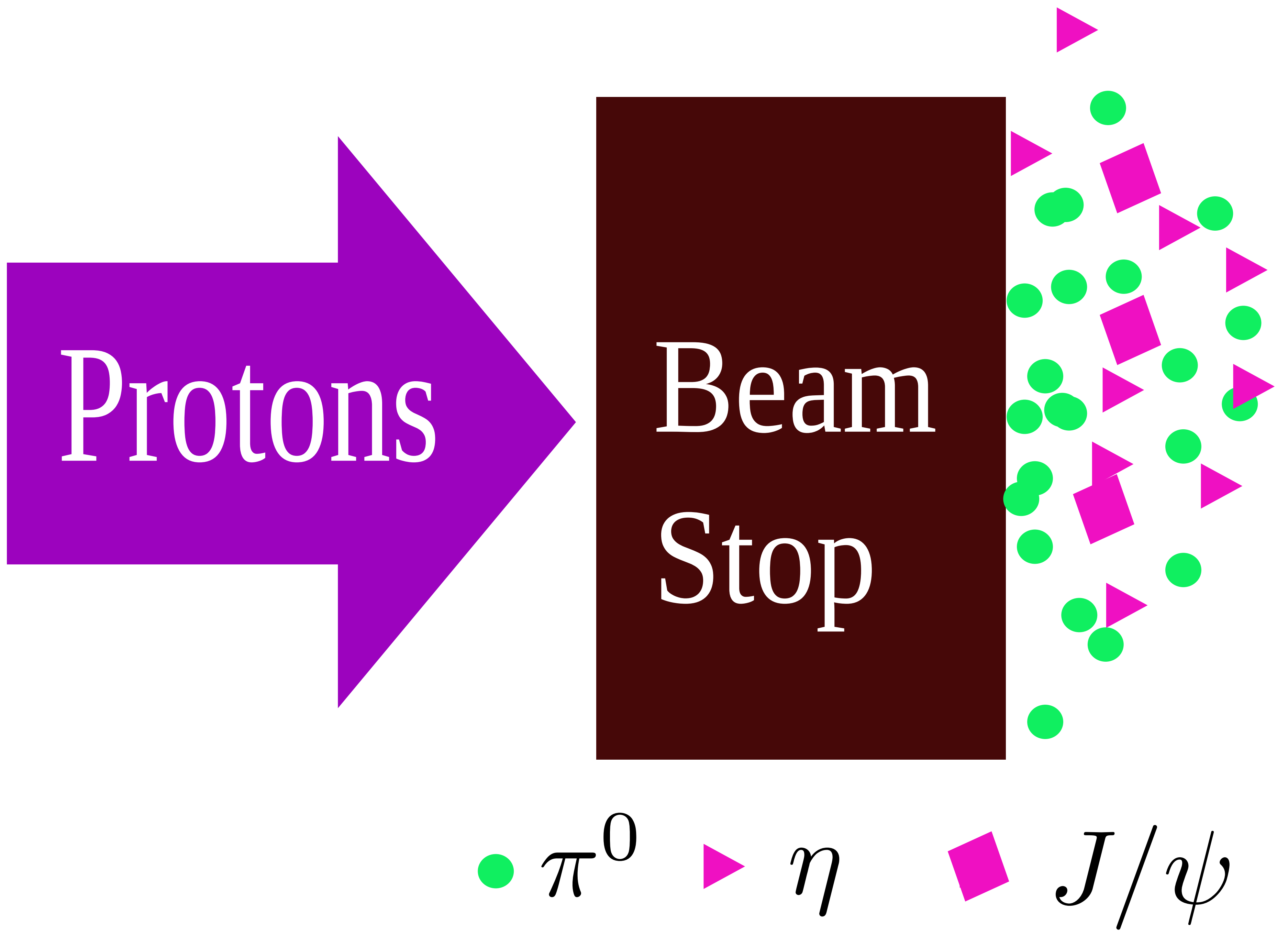

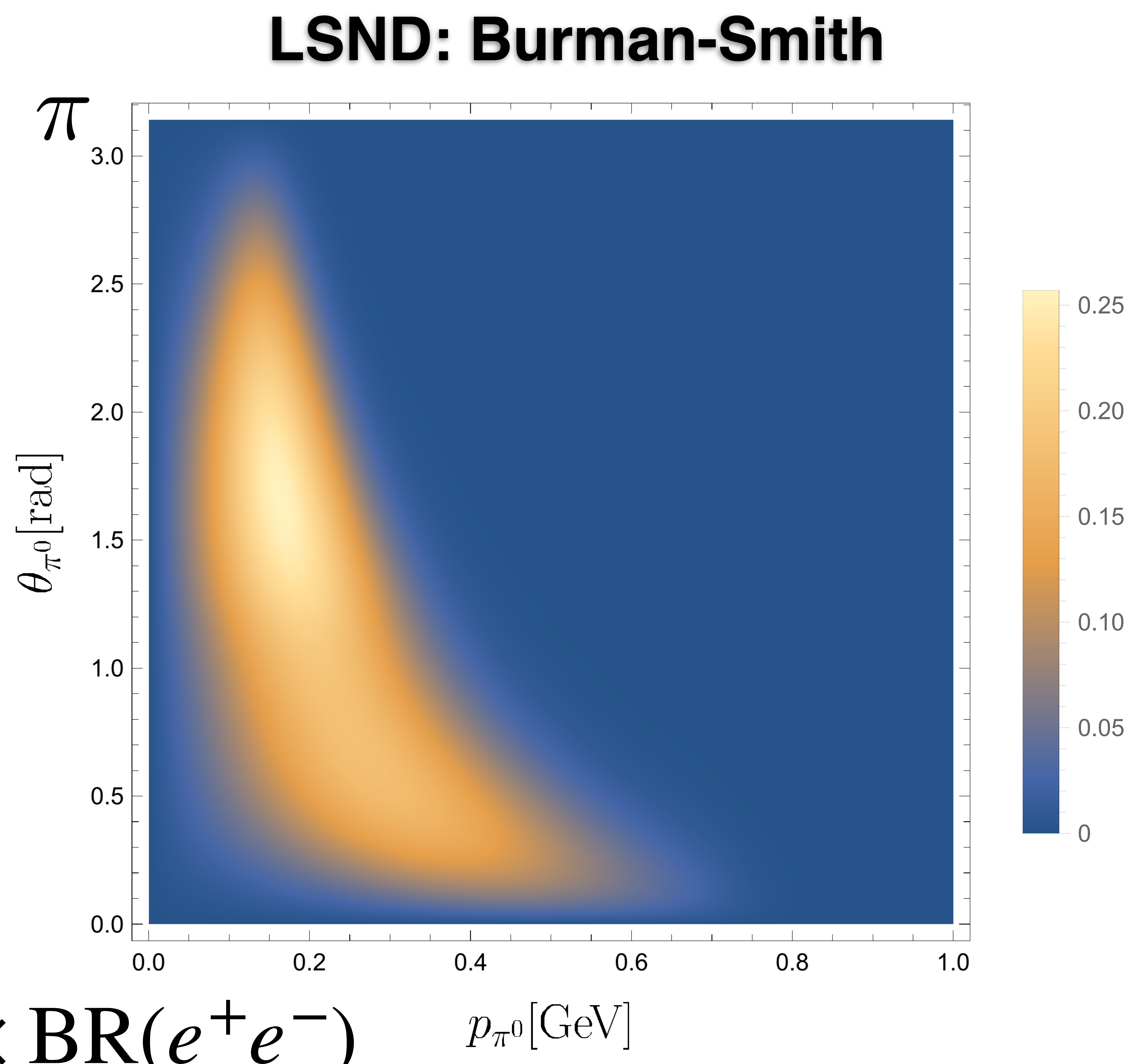

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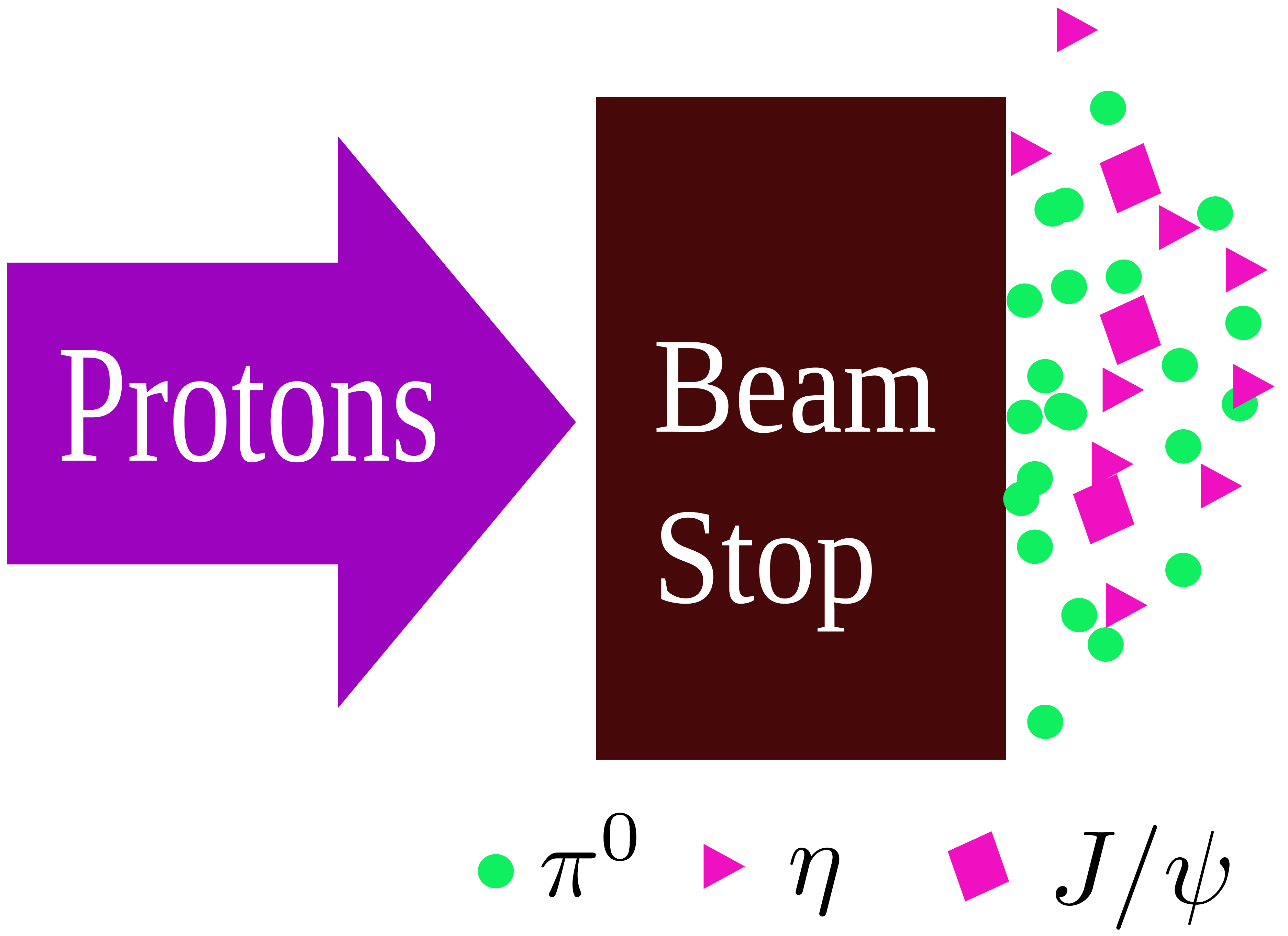

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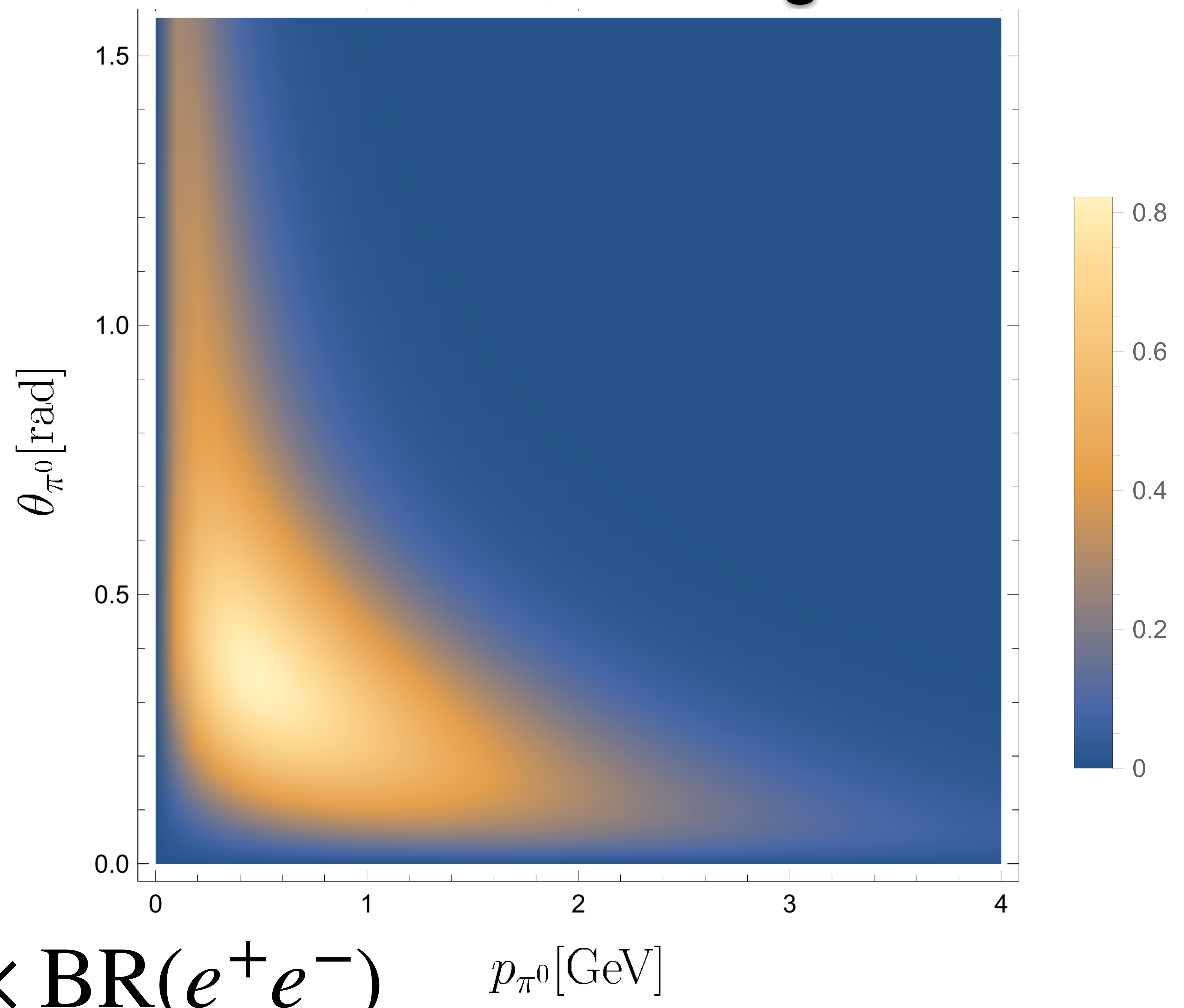
Booster Experiments: Sanford-Wang



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See also: Dipole portal to HNLs

arXiv:1803.03262

$$\mathcal{L}_{dim\ 5} \supset d_a \overline{\nu_L}_a \sigma_{\mu\nu} F^{\mu\nu} N - m\bar{N}N$$

Talk at PONDD 2018

https://tinyurl.com/HNL-portal

See also: Dipole portal to HNLs

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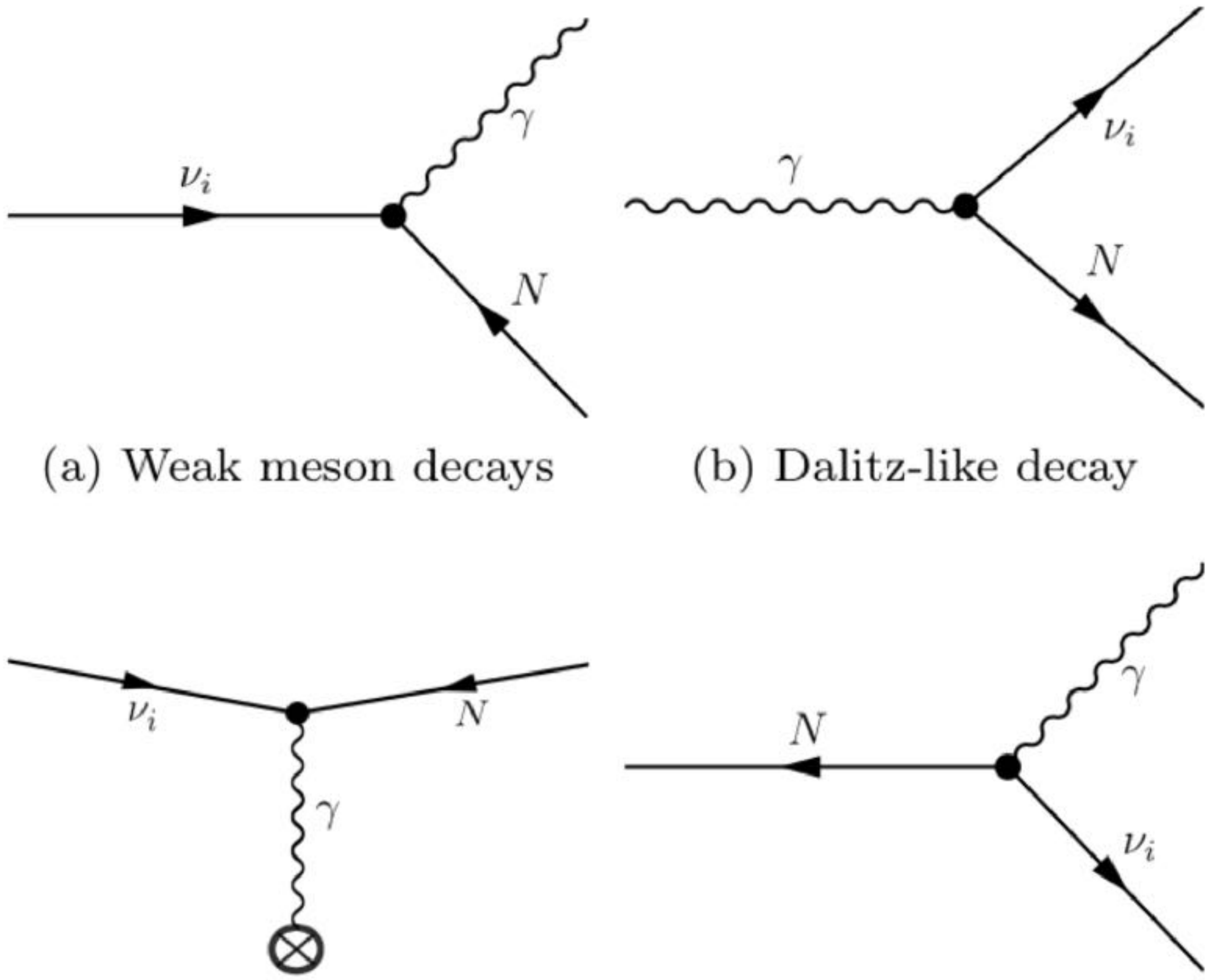

(a) Weak meson decays (b) Dalitz-like decay

(c) Primakoff upscattering (d) $N \to \gamma\nu$ (signal)

Talk at PONDD 2018

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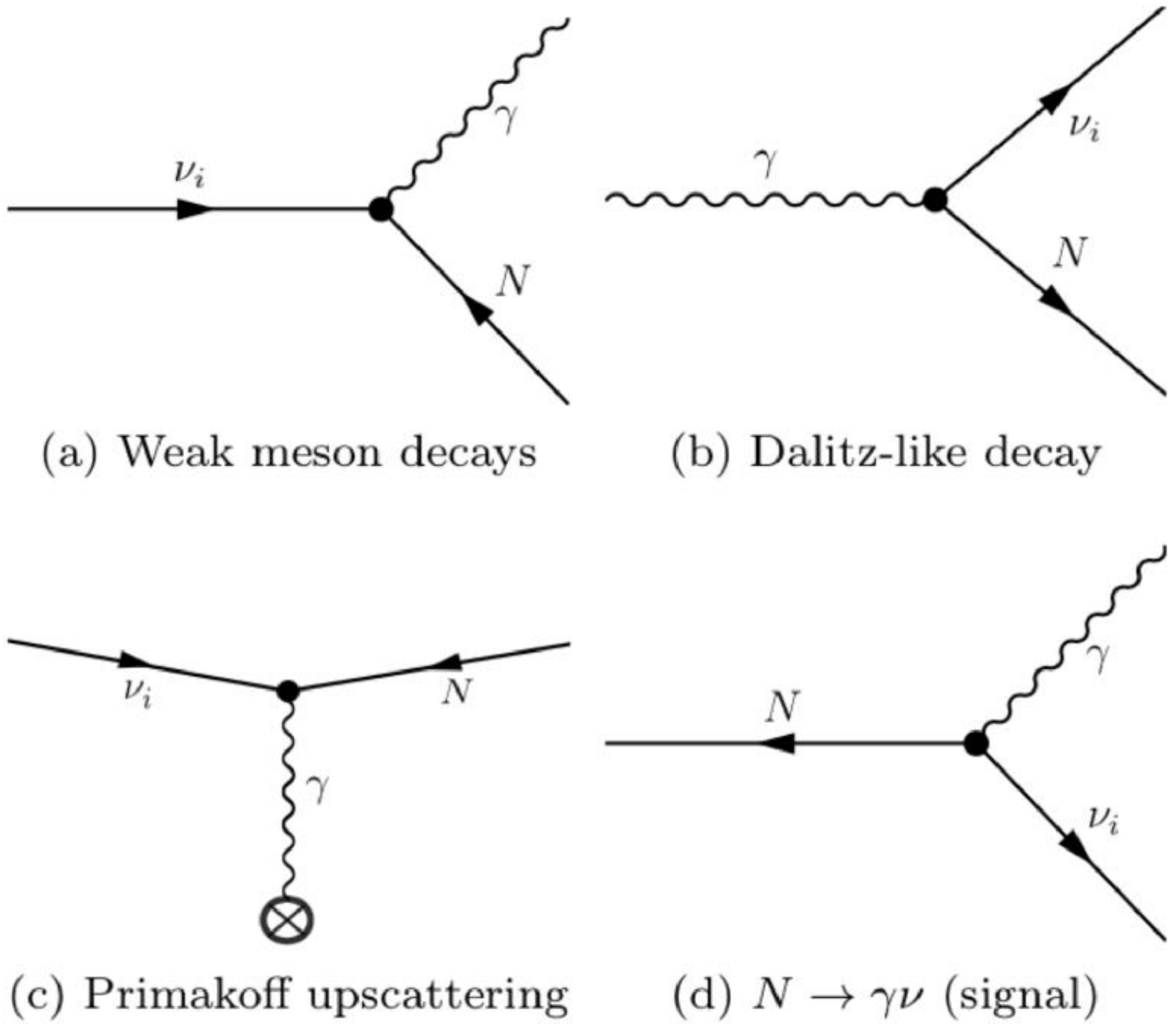
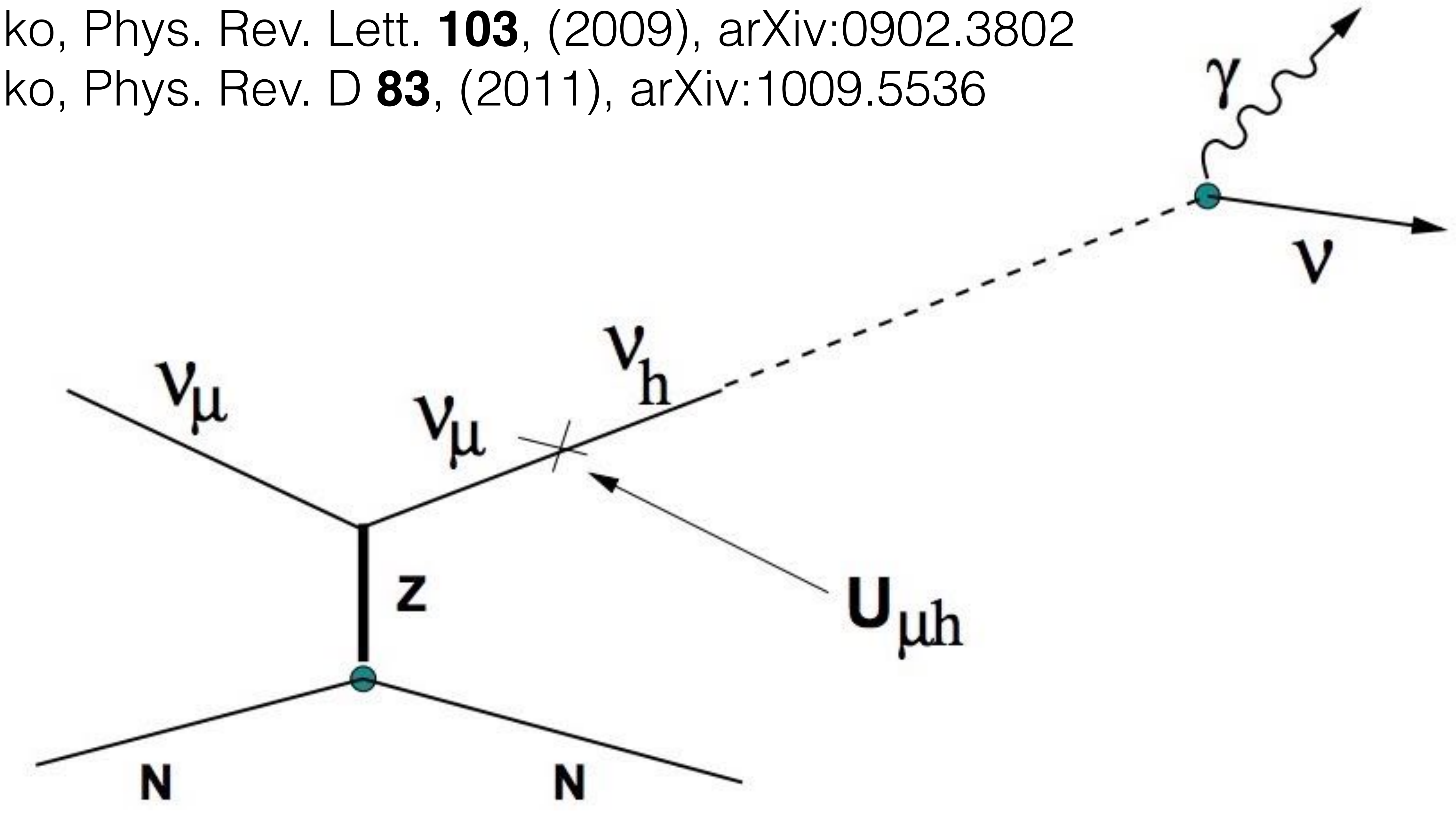


Gninenko, Phys. Rev. Lett. **103**, (2009), arXiv:0902.3802
Gninenko, Phys. Rev. D **83**, (2011), arXiv:1009.5536



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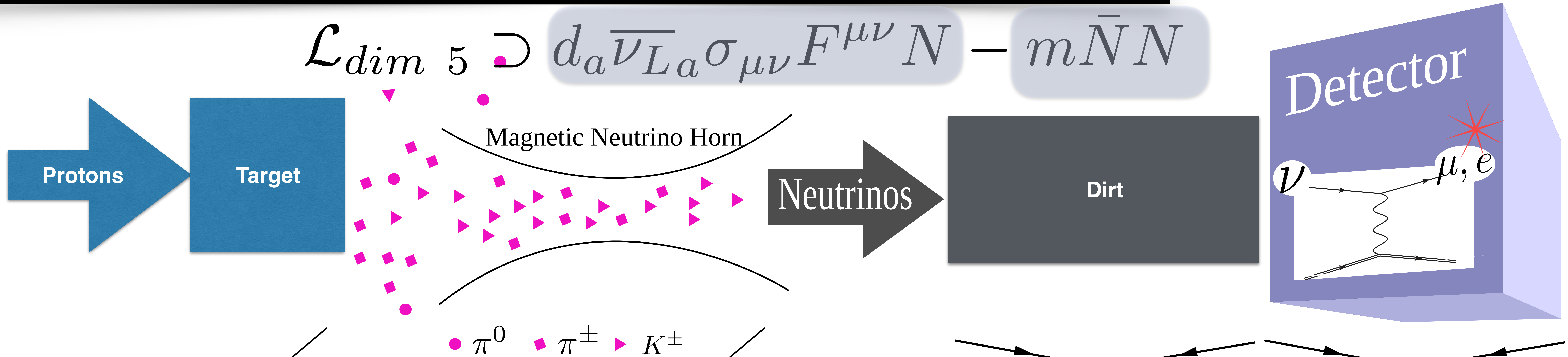
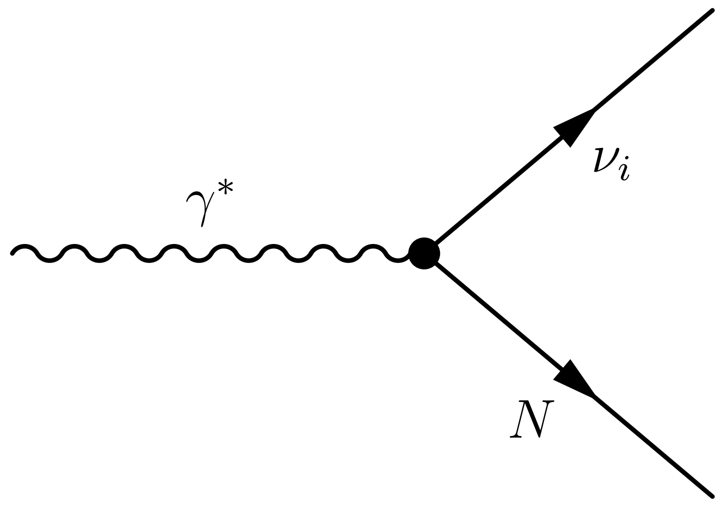
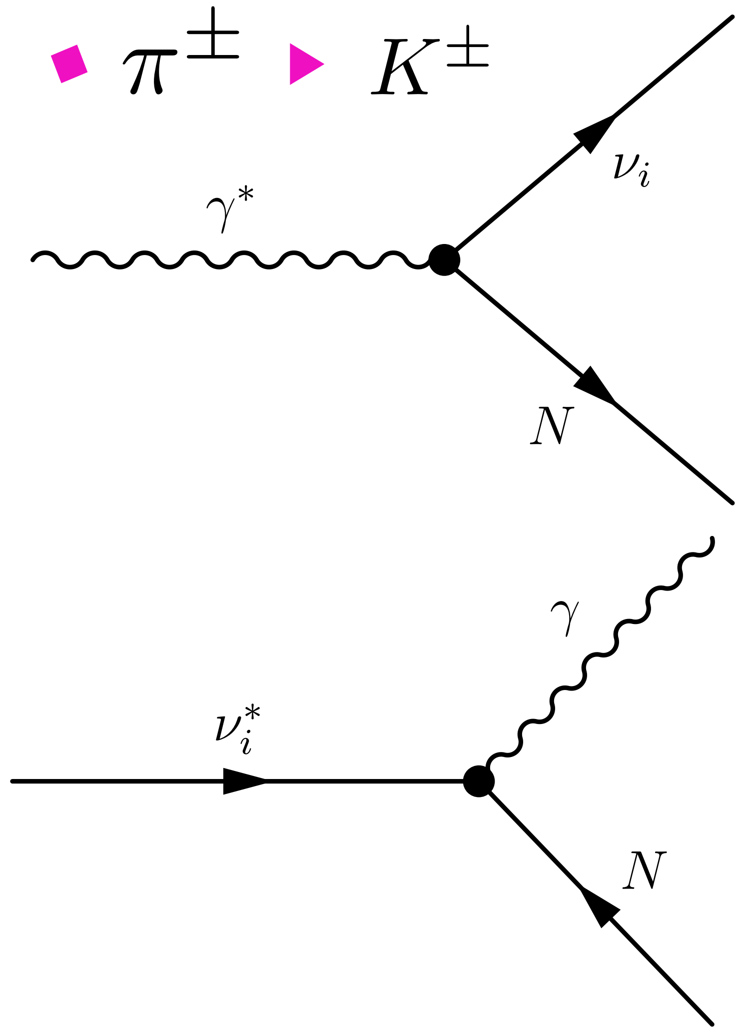
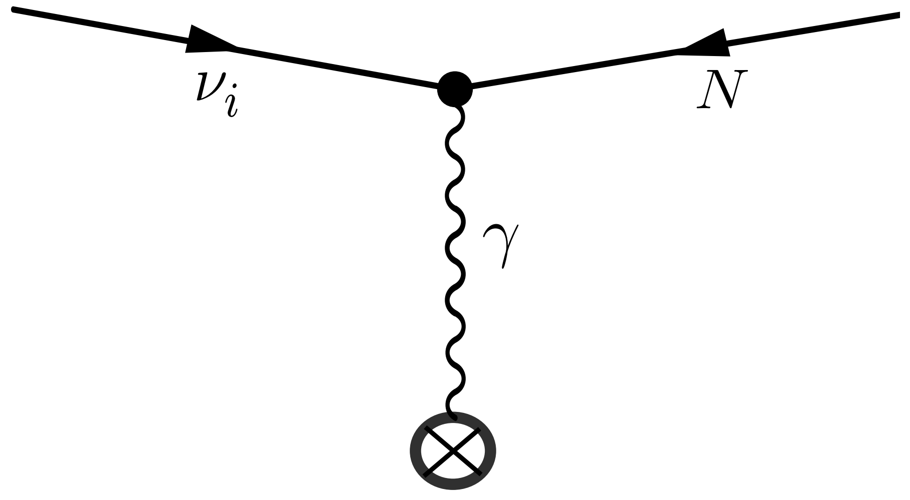




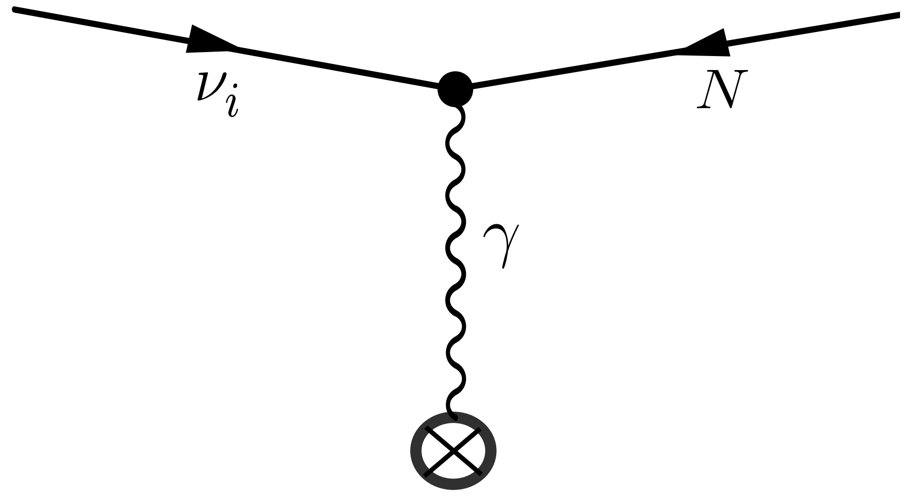
Drell-Yan-like production



Dalitz-like & weak meson decays



Coherent/diffractive upscattering in LOS



Coherent upscattering in detector

Talk at PONDD 2018

https://tinyurl.com/HNL-portal

See also: Dipole portal to HNLs

arXiv:1803.03262

$$\mathcal{L}_{dim\ 5} \supset d_a \overline{\nu_L}_a \sigma_{\mu\nu} F^{\mu\nu} N - m\bar{N}N$$

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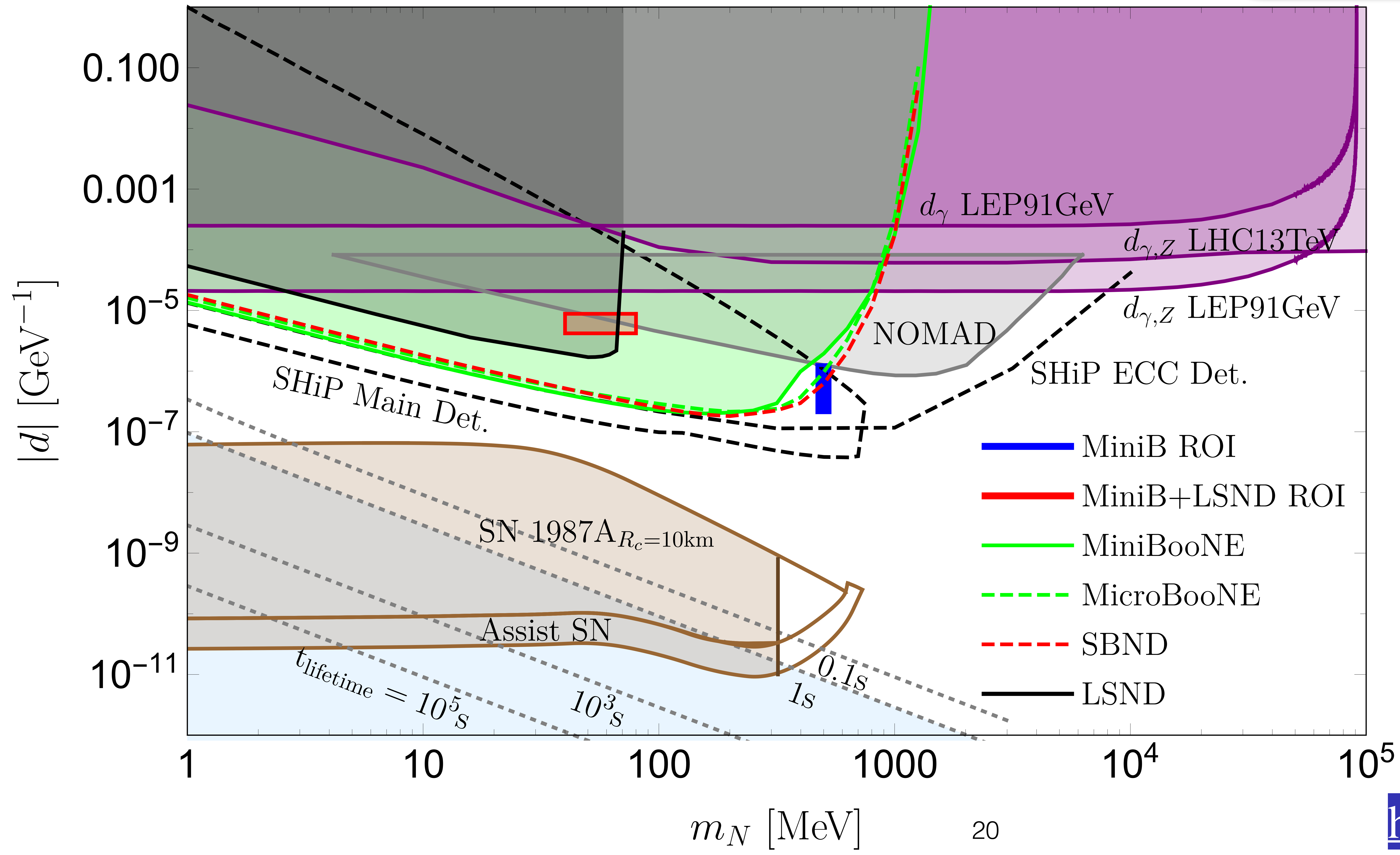

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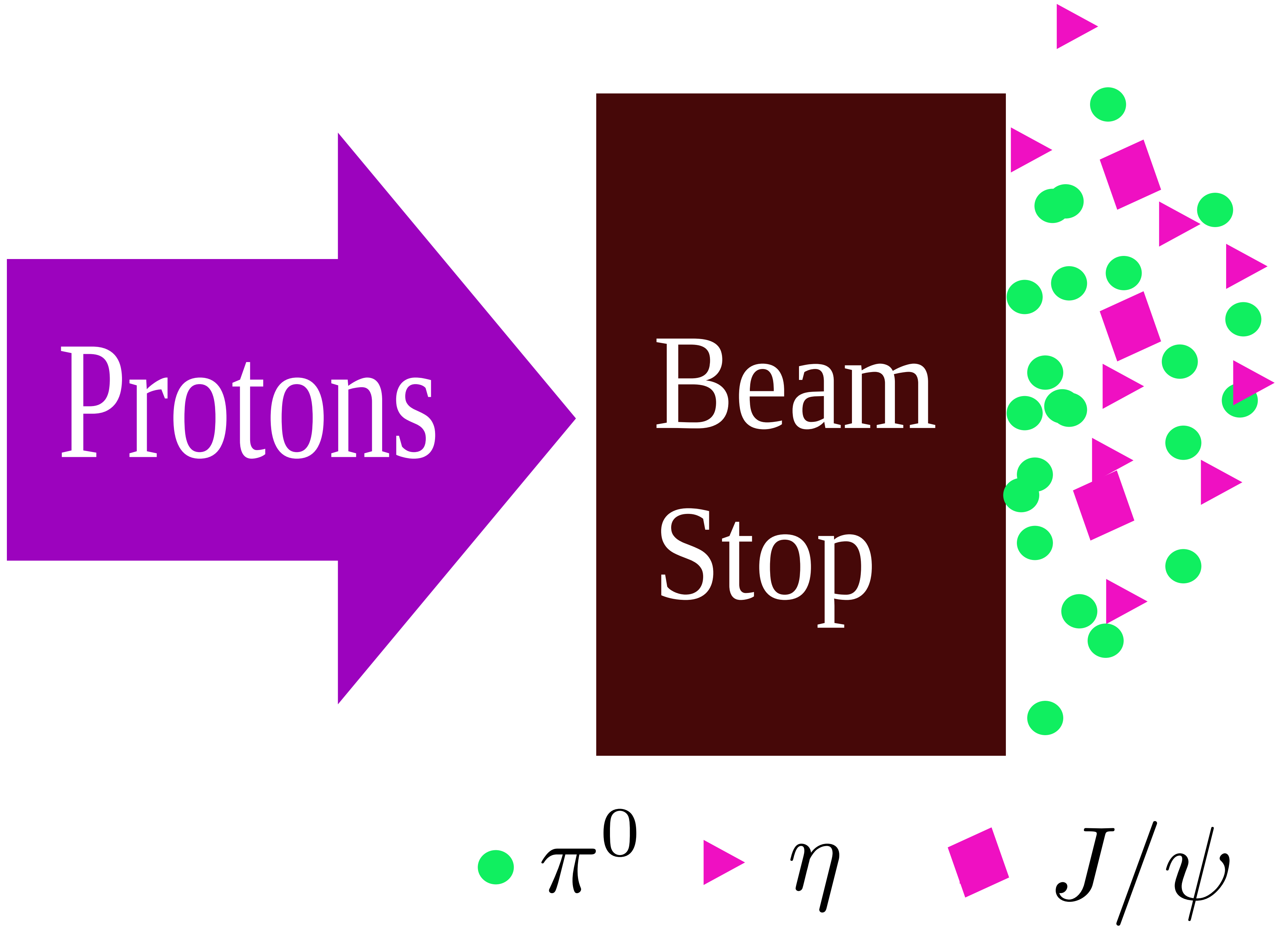
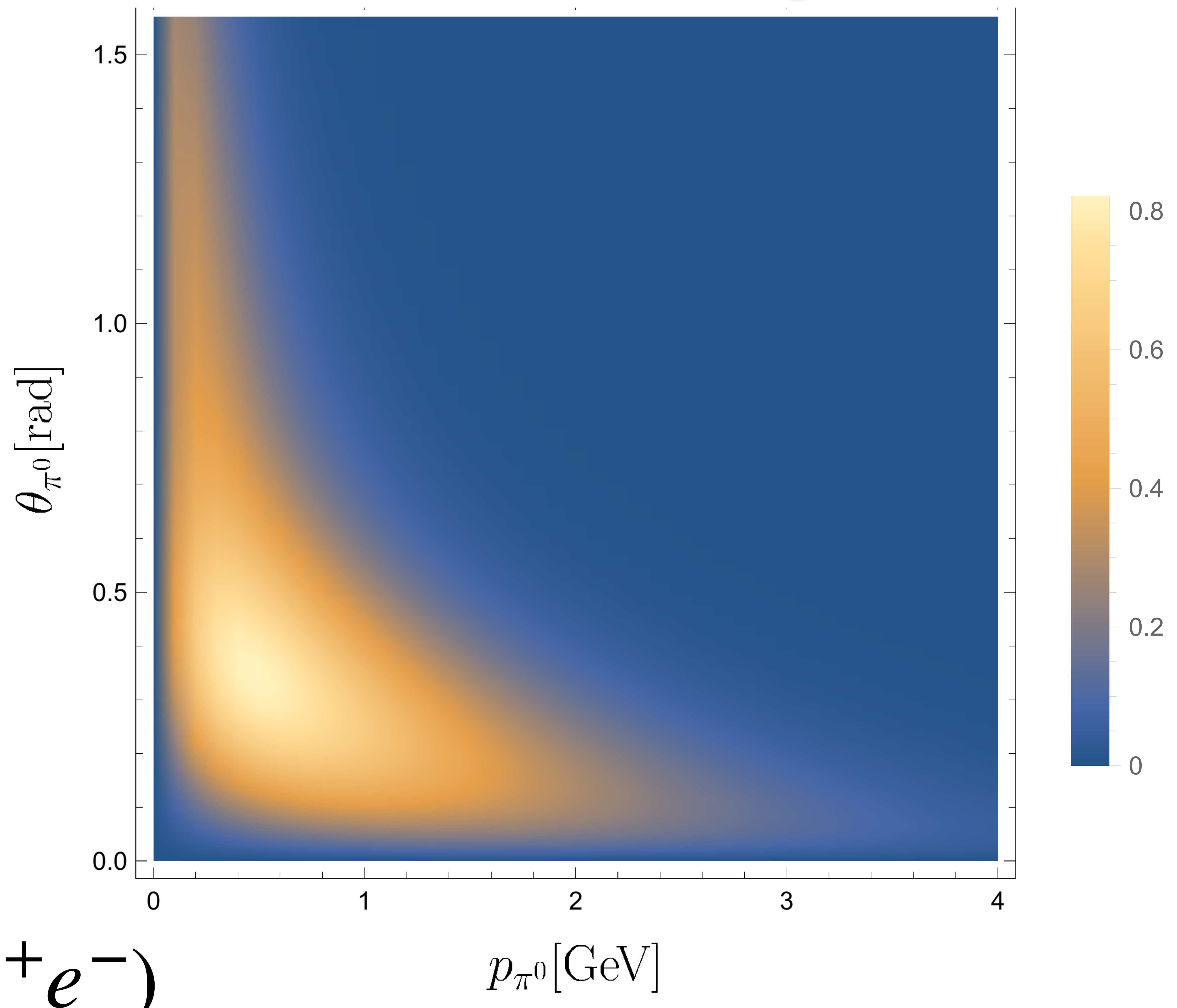
Back to millicharged particles



Booster Experiments: Sanford-Wang



$$\pi^0/\eta \to \gamma\chi\bar{\chi}$$

$$J/\psi \to \chi\bar{\chi}$$

$$q\bar{q} \to \chi\bar{\chi}$$

$$\mathrm{BR}(\chi\bar{\chi}) \sim \epsilon^2 \times \mathrm{BR}(e^+e^-)$$

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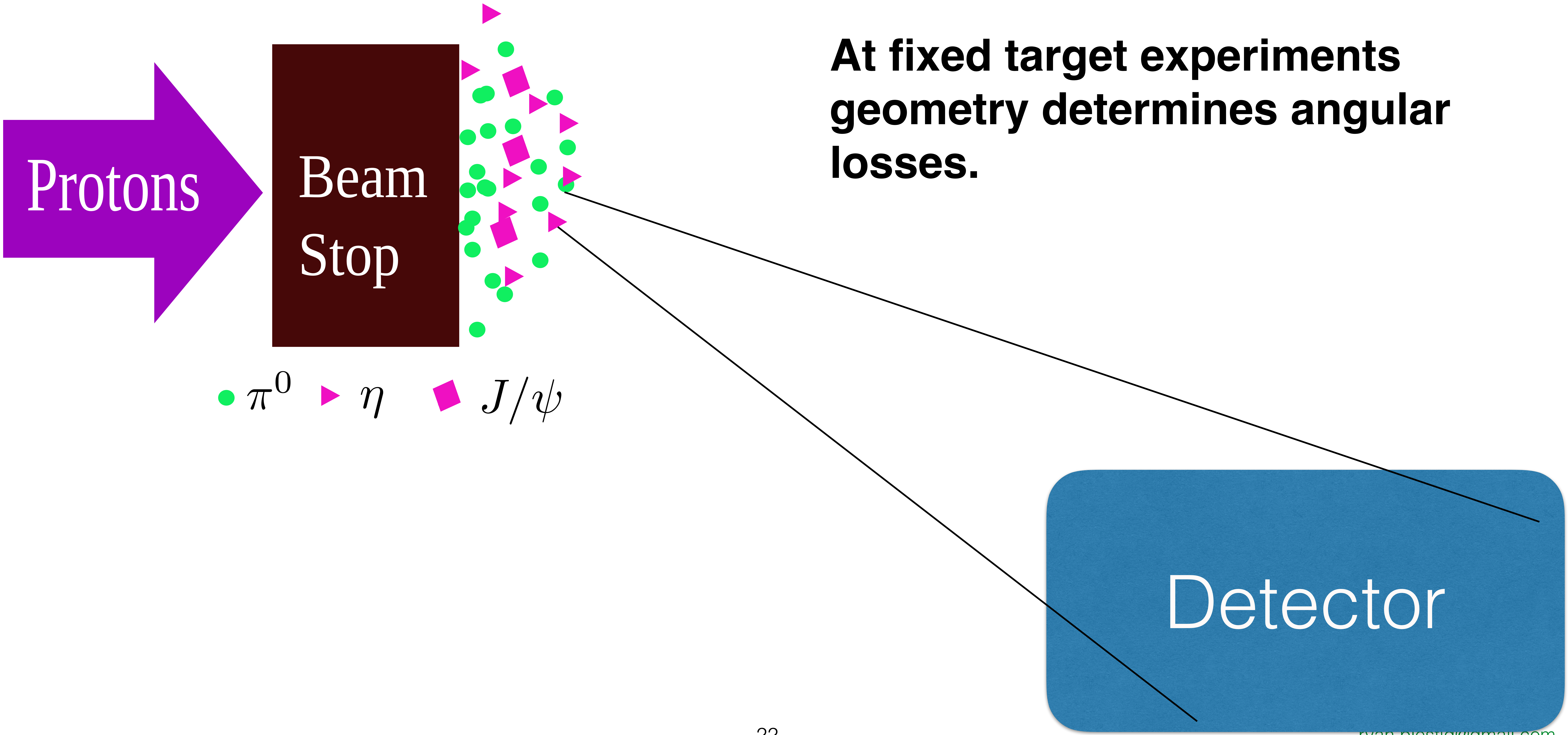
Meson Decays At Beam Dumps



At fixed target experiments geometry determines angular losses.

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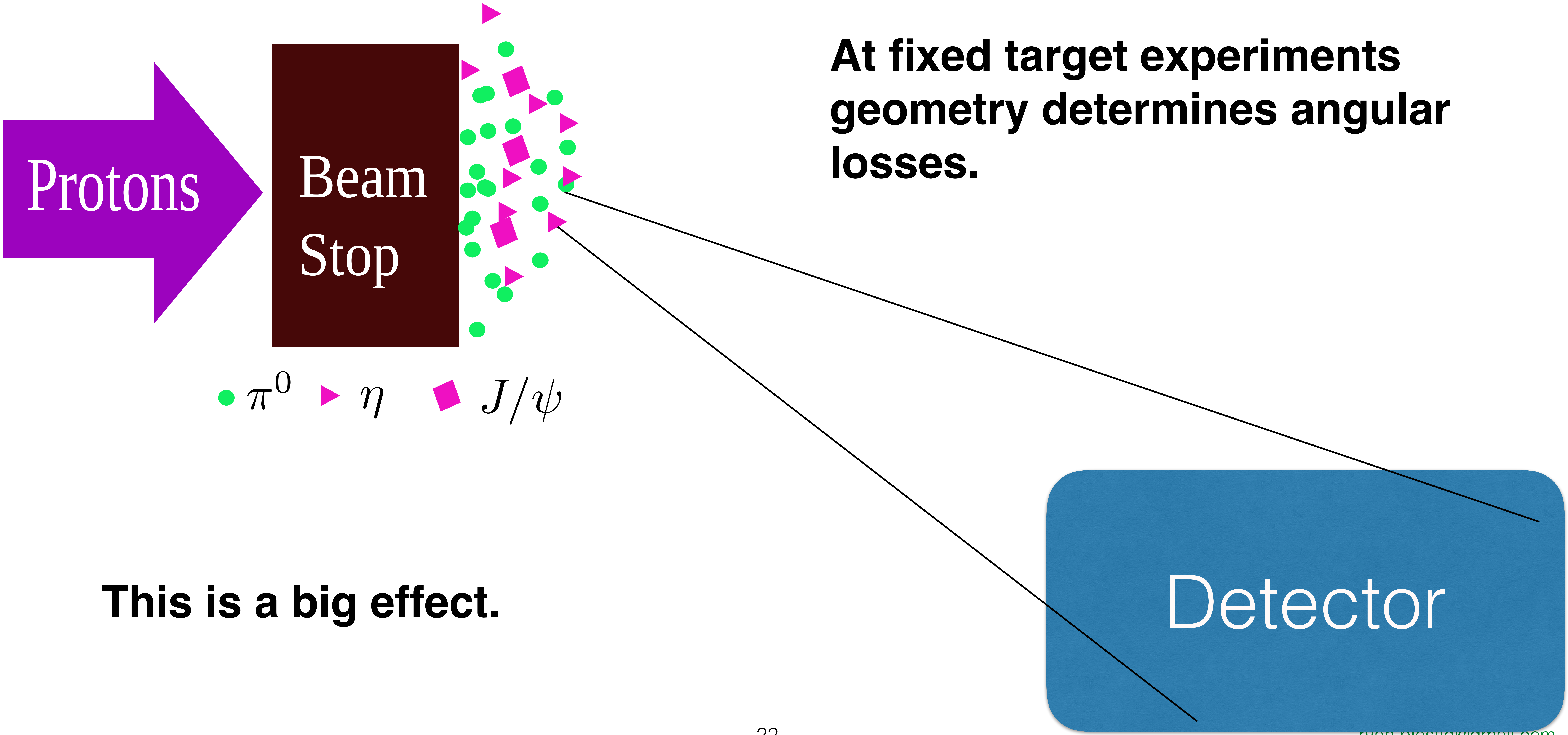

This is a big effect.

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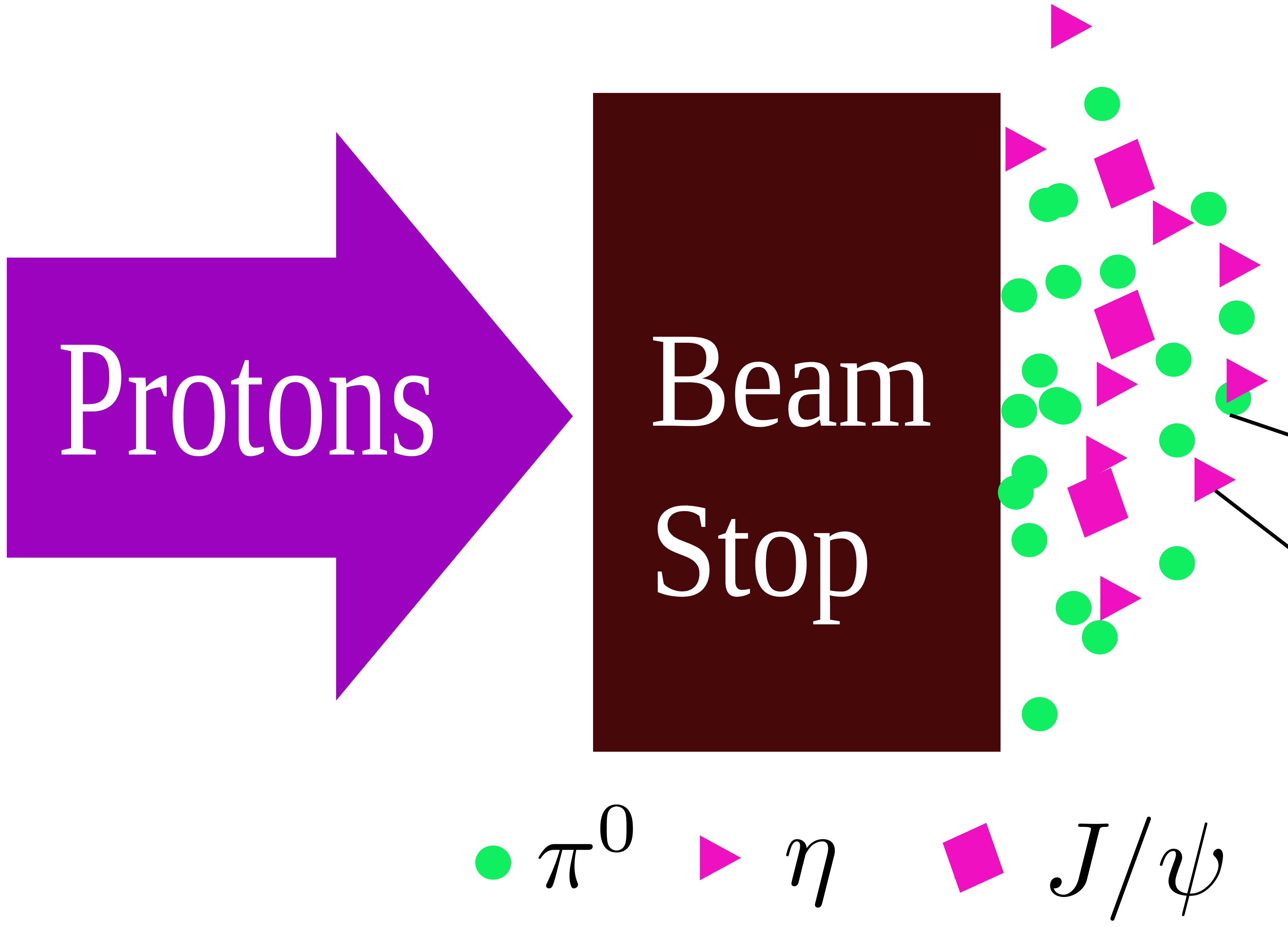

	N [$\times 10^{20}$]		$A_{\text{geo}}(m_\chi)[\times 10^{-3}]$		Cuts [MeV]		
Exp.	π^0	η	1 MeV	100 MeV	E_e^{min}	E_e^{max}	Bkg
LSND	130	—	20	—	18	52	300
mBooNE	17	0.56	1.2	0.68	130	530	2k
mBooNE*	1.3	0.04	1.2	0.68	75	850	0*
μBooNE	9.2	0.31	0.09	0.05	2	40	16
SBND	4.6	0.15	4.6	2.6	2	40	230
DUNE	830	16	3.3	5.1	2	40	19k
SHiP	4.7	0.11	130	220	100	300	140

TABLE I. Summary of the lifetime meson rates (N), mCP detector acceptances (A_{geo}), electron recoil energy cuts, and backgrounds at each of the experiments considered in this paper. In all experiments a cut of $\cos\theta > 0$ is imposed in our analysis (*except for MiniBooNE's dark matter run where a cut of $\cos\theta > 0.99$ effectively reduces backgrounds to zero [44, 45]). For the SHiP and DUNE experiments, we also include J/ψ and Υ mesons as well as Drell-Yan production which are discussed in the text. We use an efficiency of $\mathcal{E} = 0.2$ for Cherenkov detectors, $\mathcal{E} = 0.5$ for nuclear emulsion detectors, and $\mathcal{E} = 0.8$ for liquid argon time projection chambers. The data at LSND and MiniBooNE is taken from [46] and [24, 44] respectively. Projections at MicroBooNE [47], SBND [26], DUNE [27] and SHiP [48] are based on expected detector performance.

This is a big effect.

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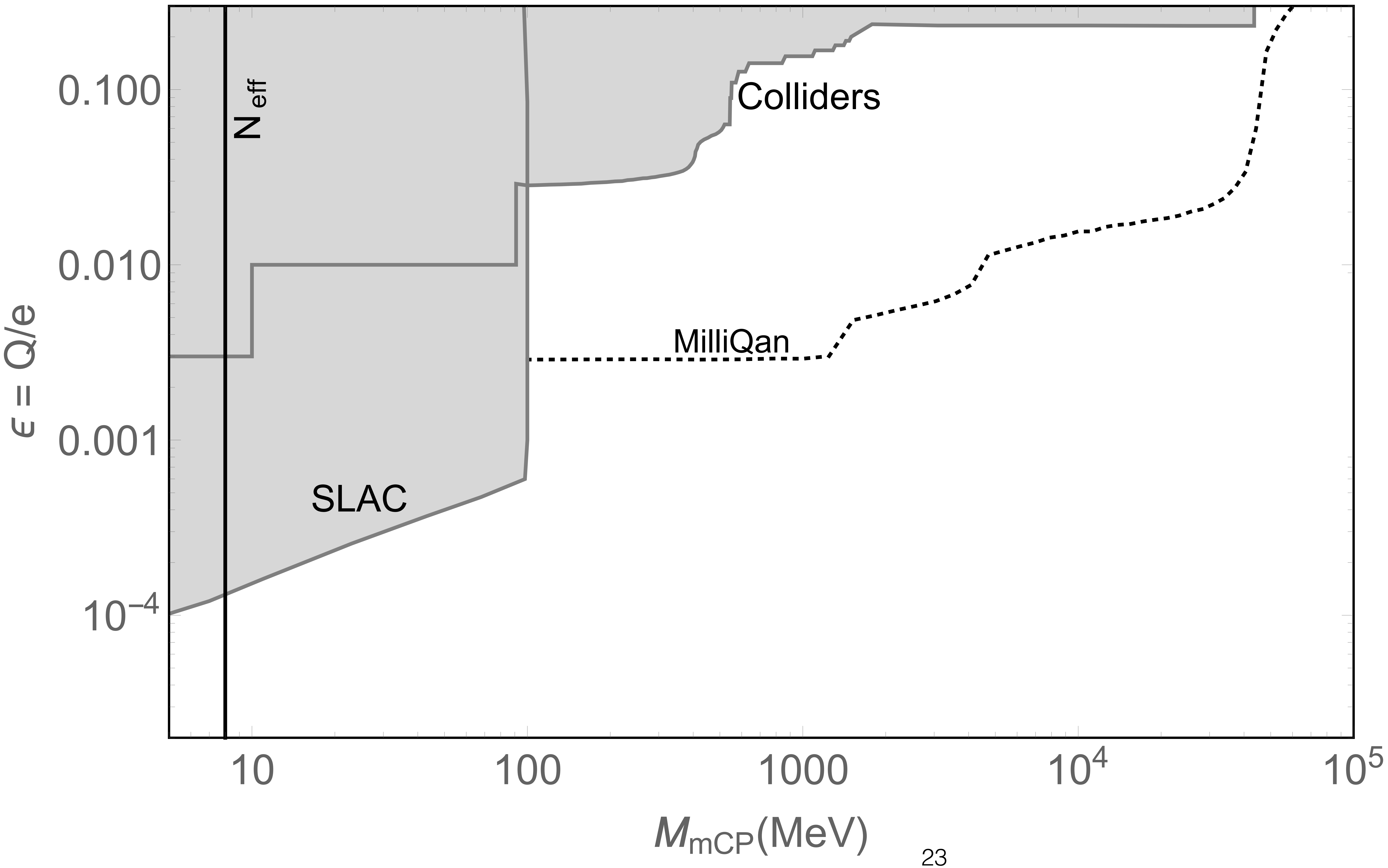
Results



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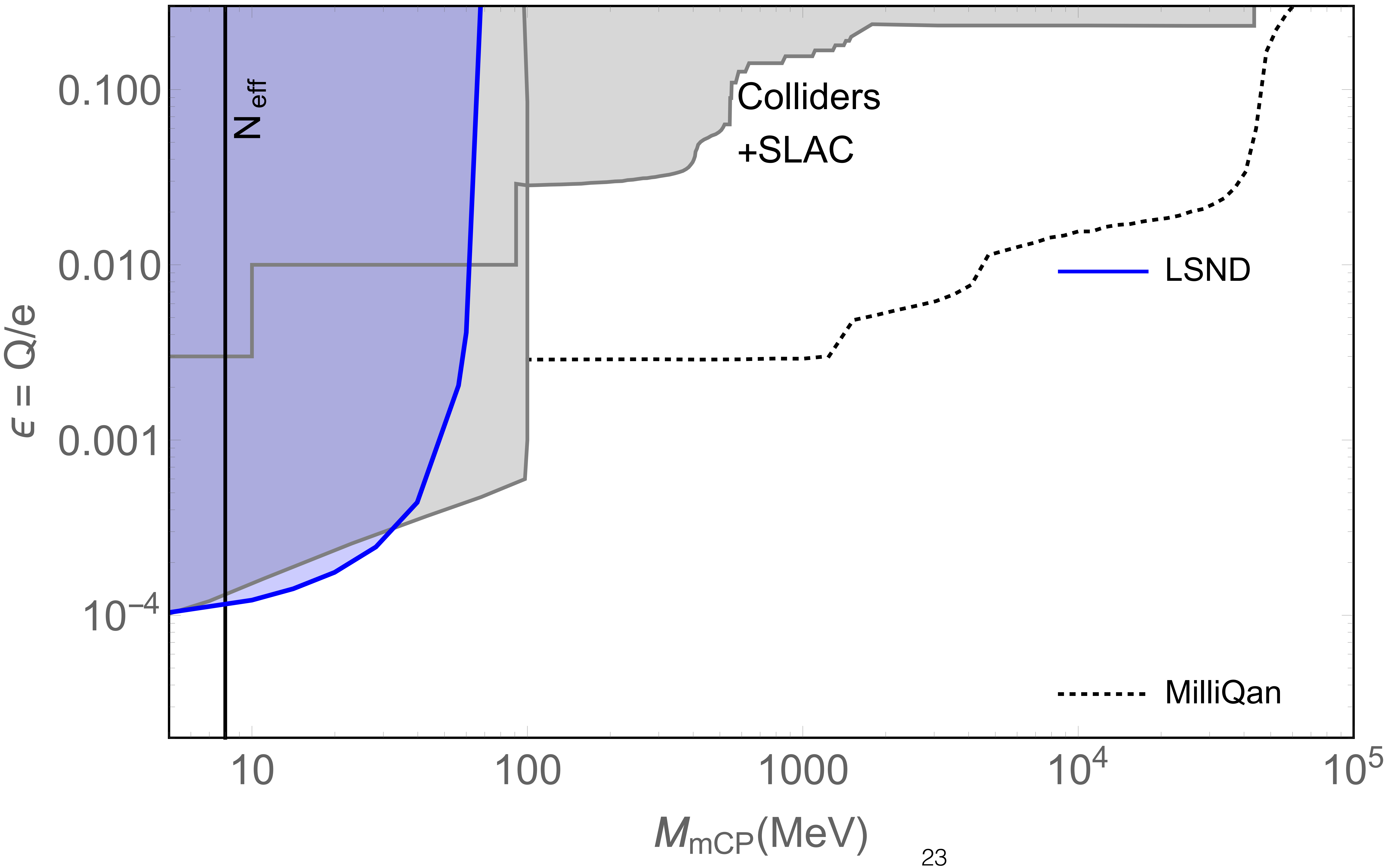

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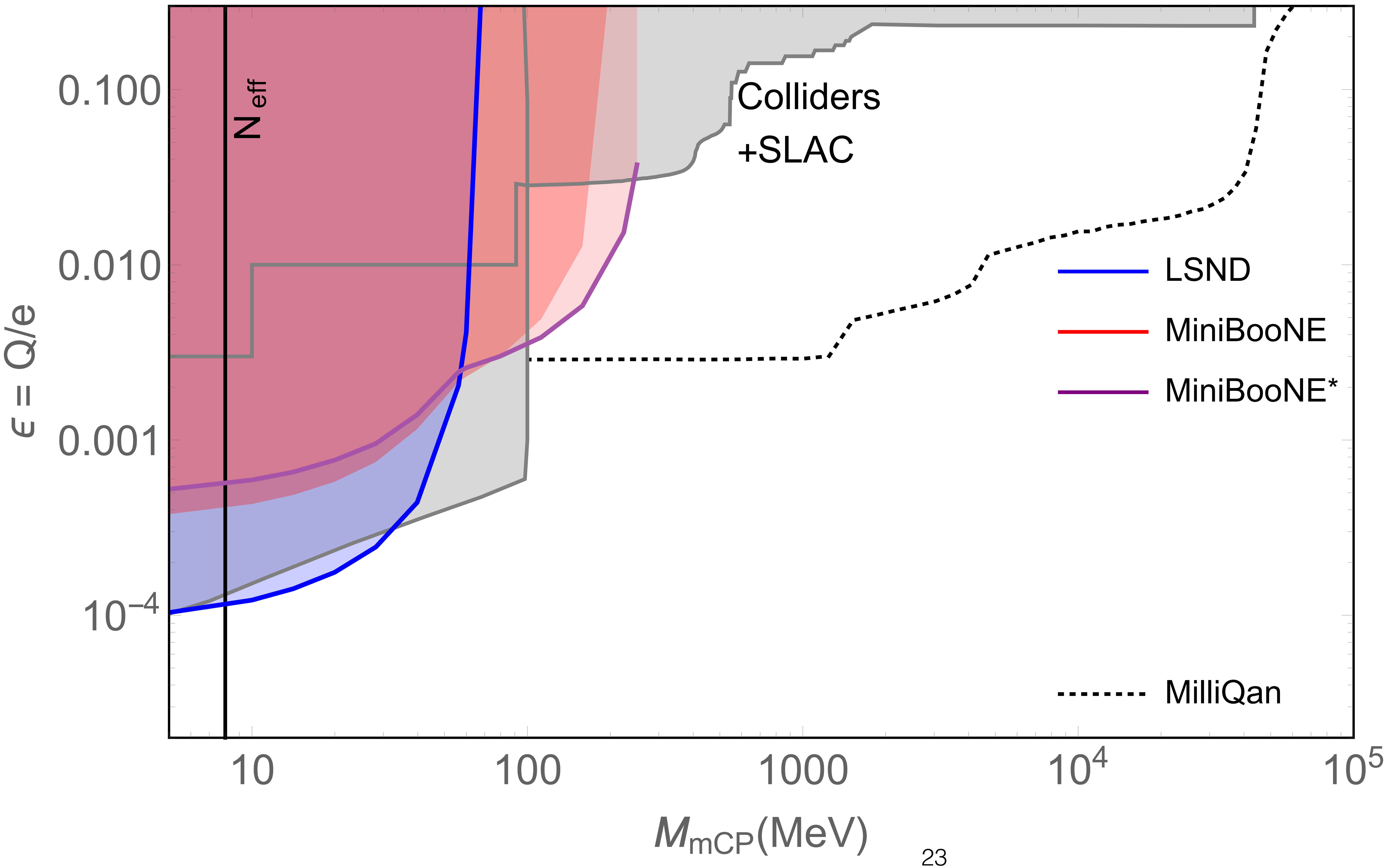

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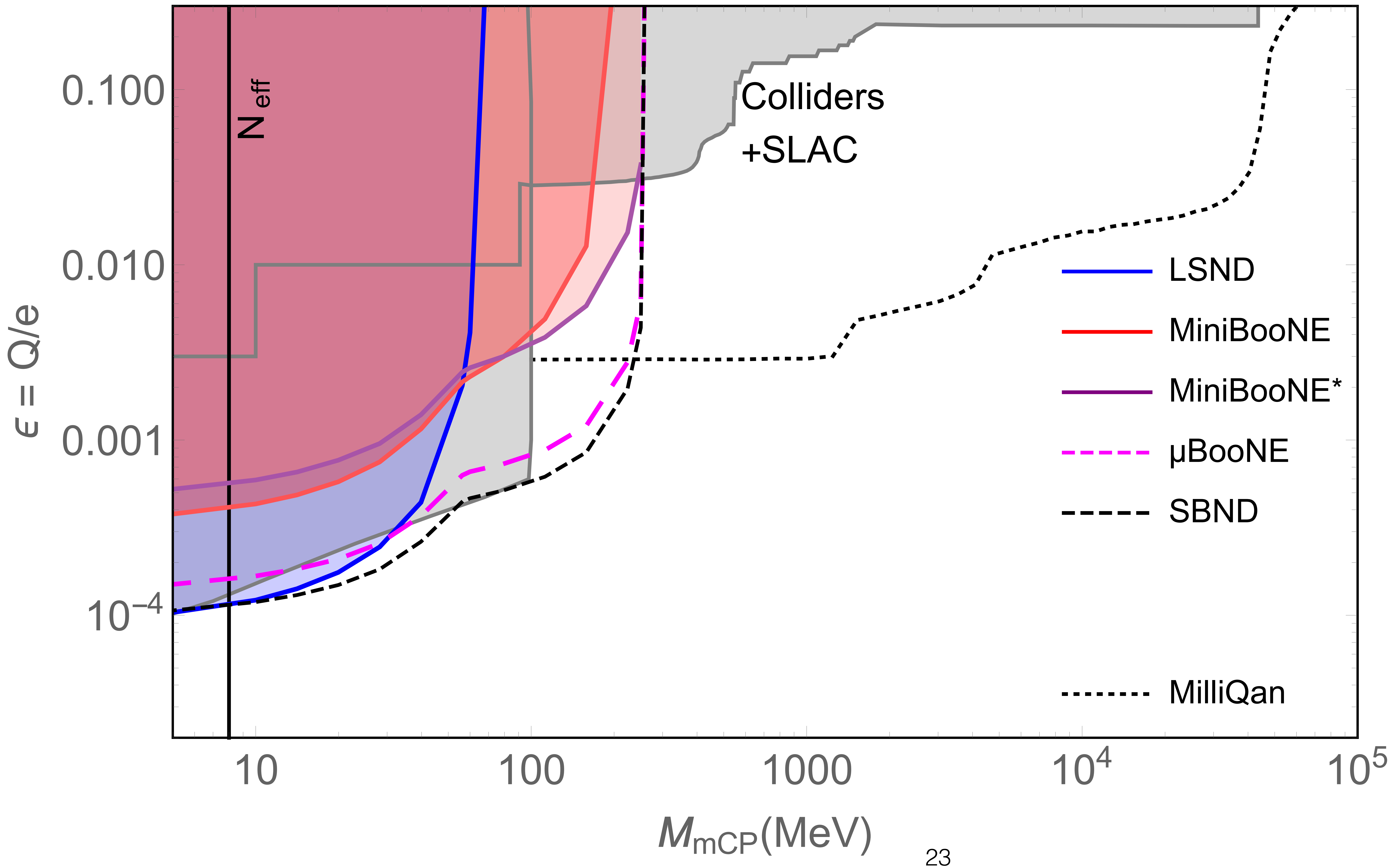

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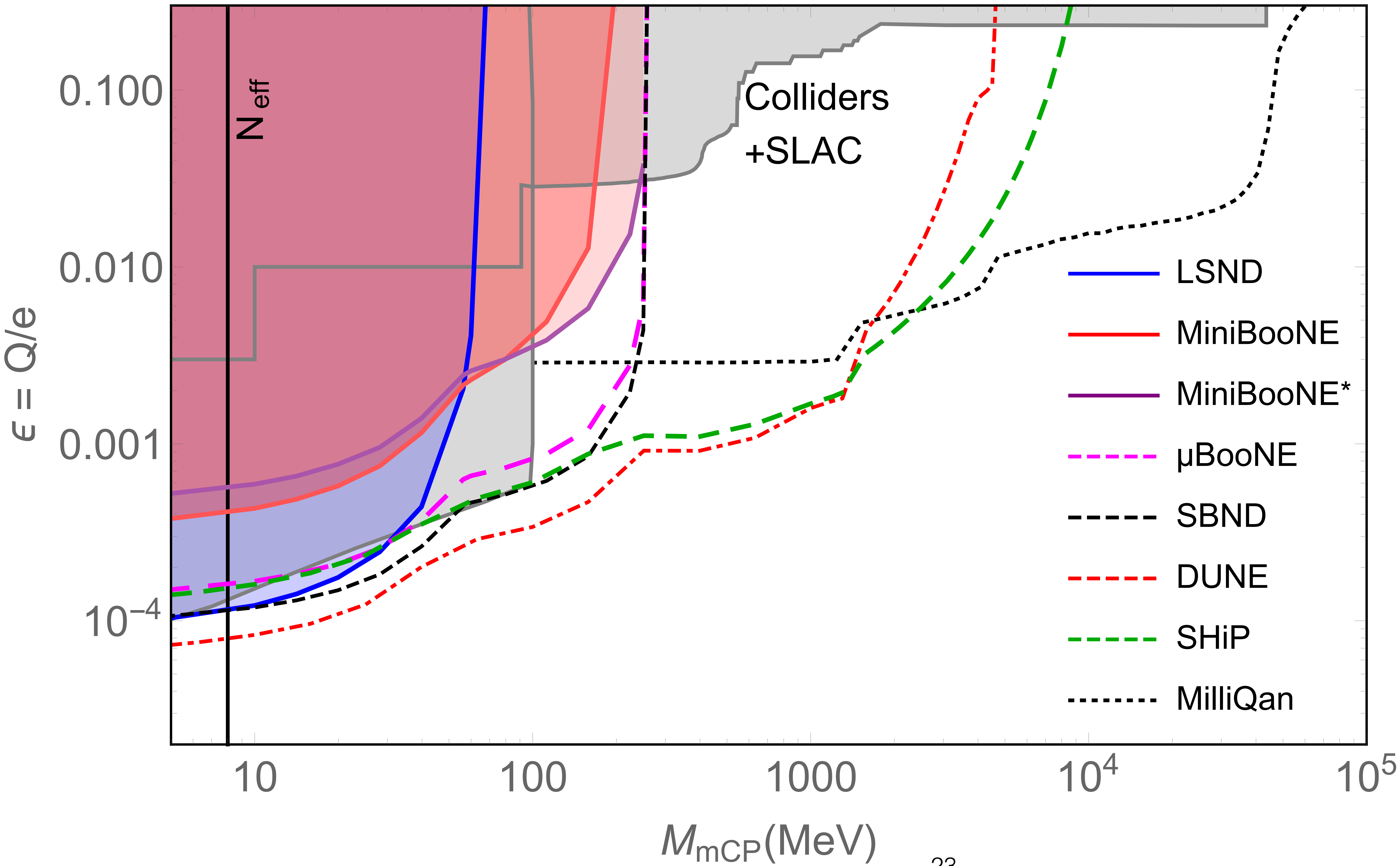

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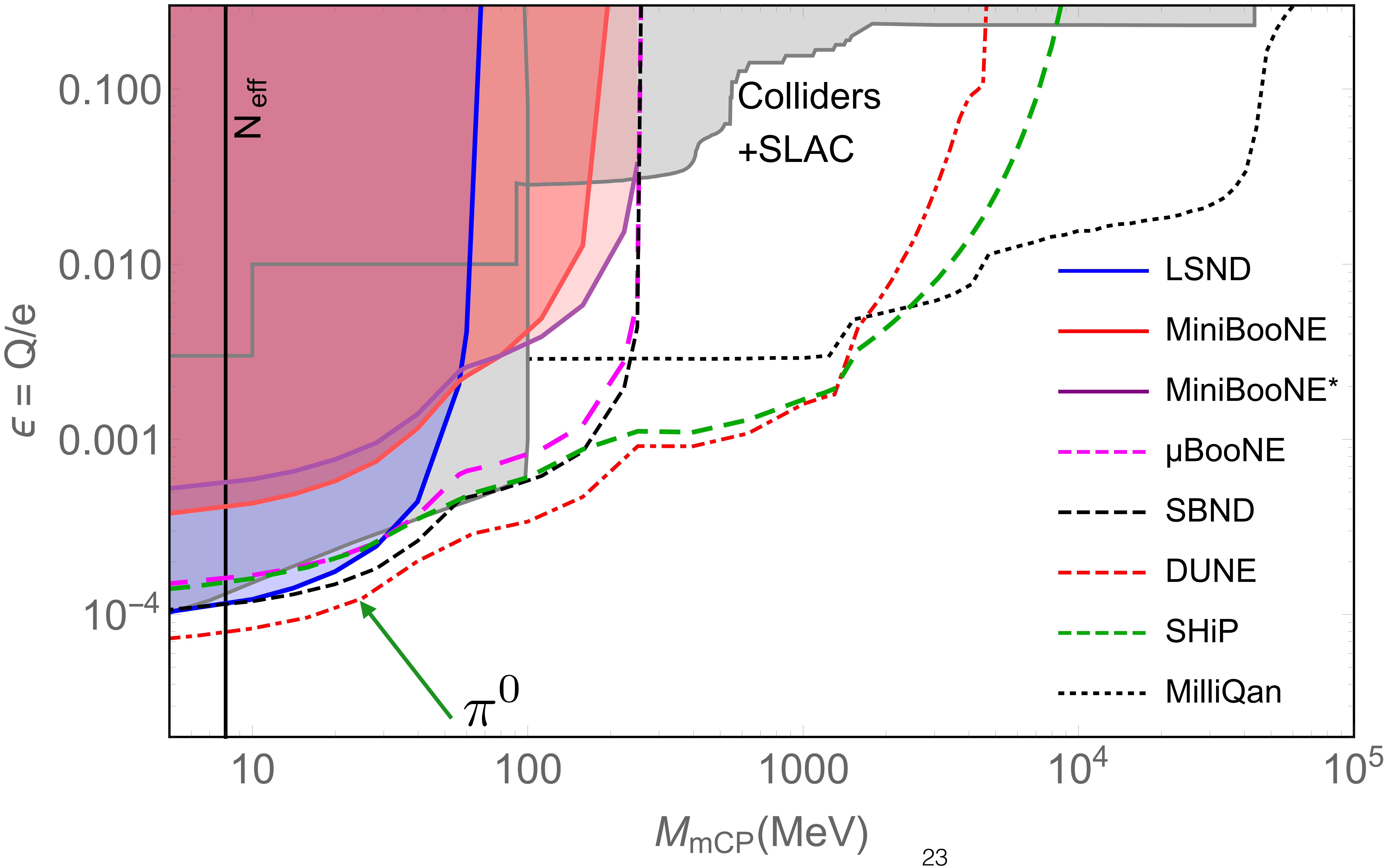

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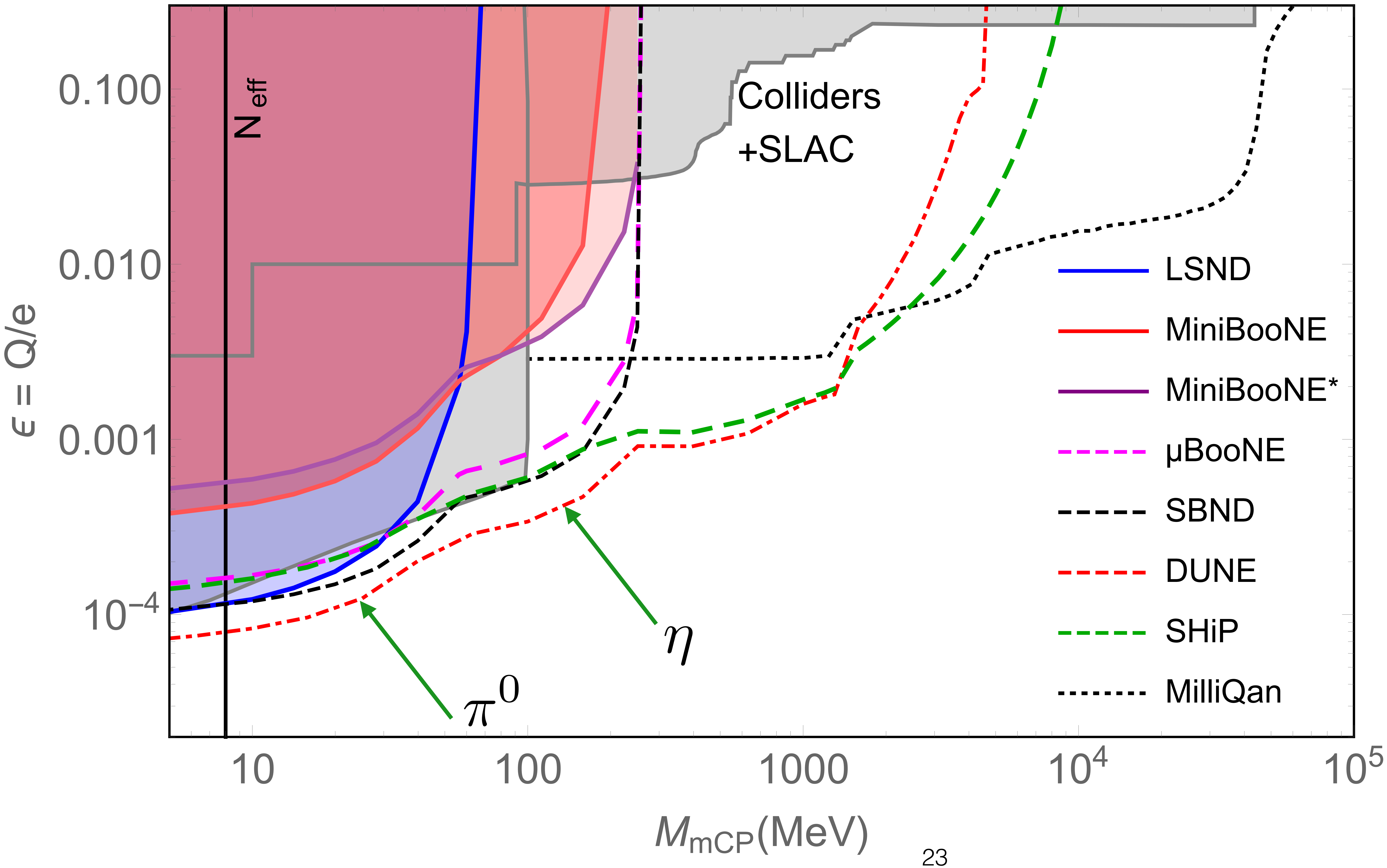

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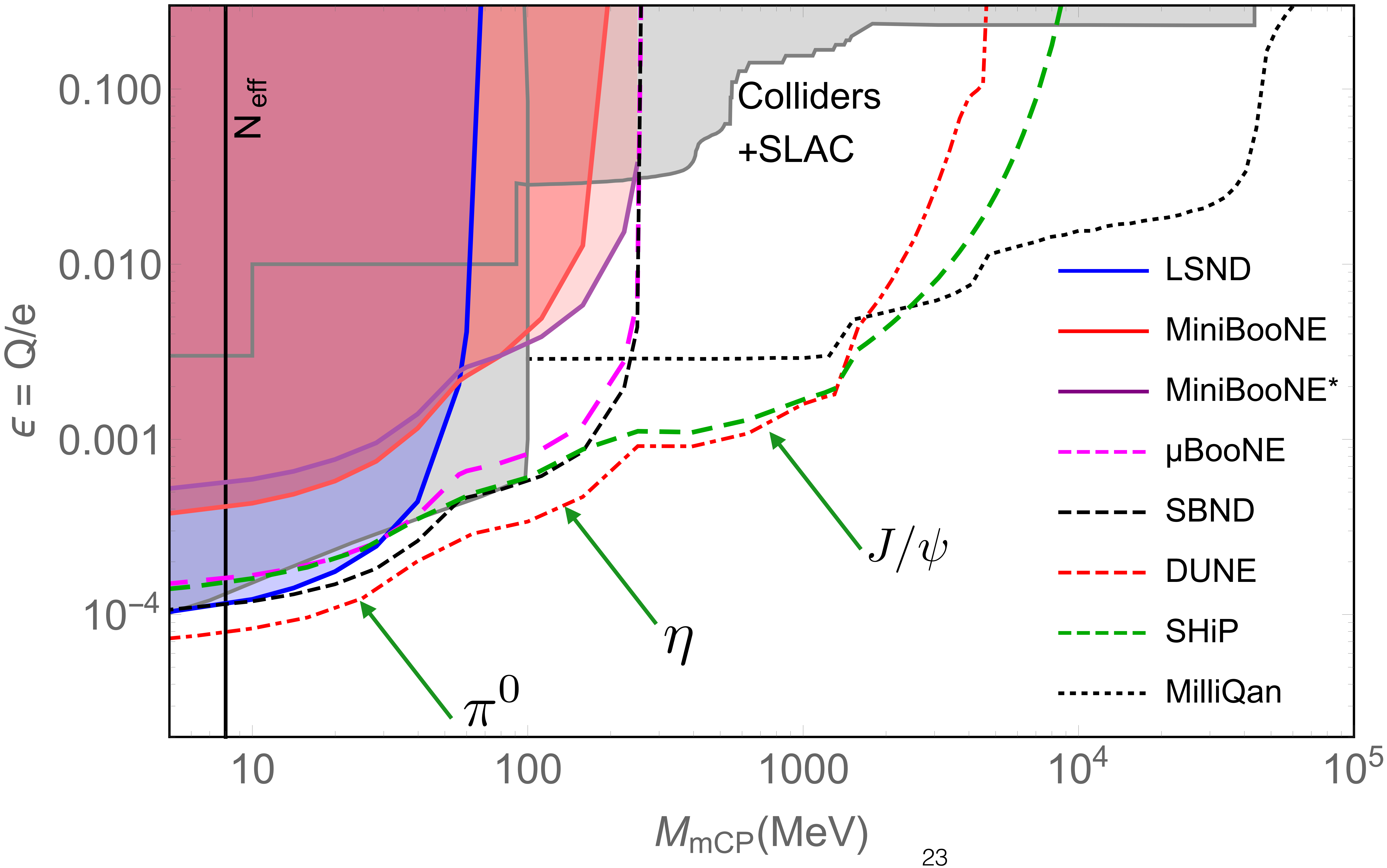

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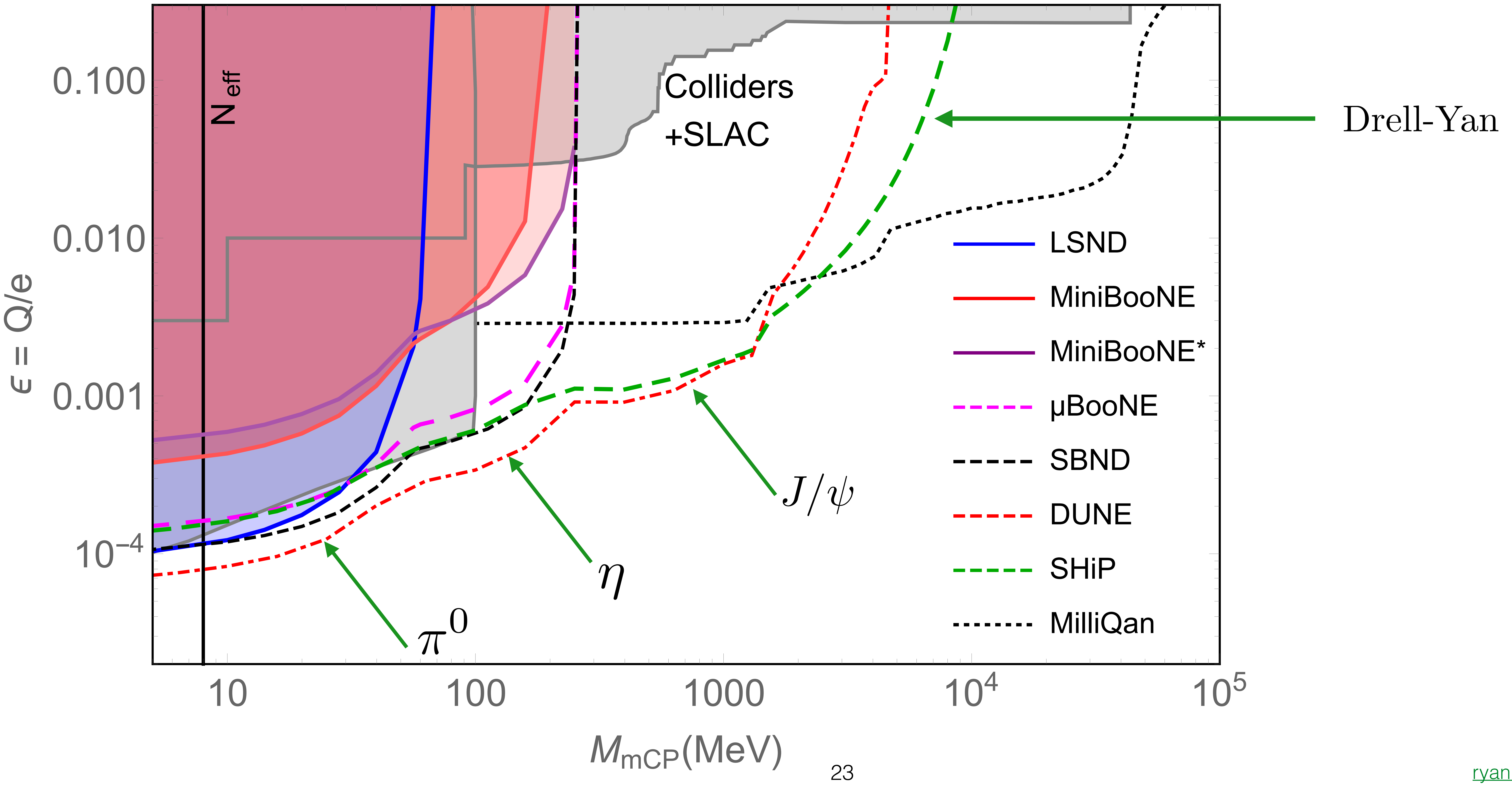
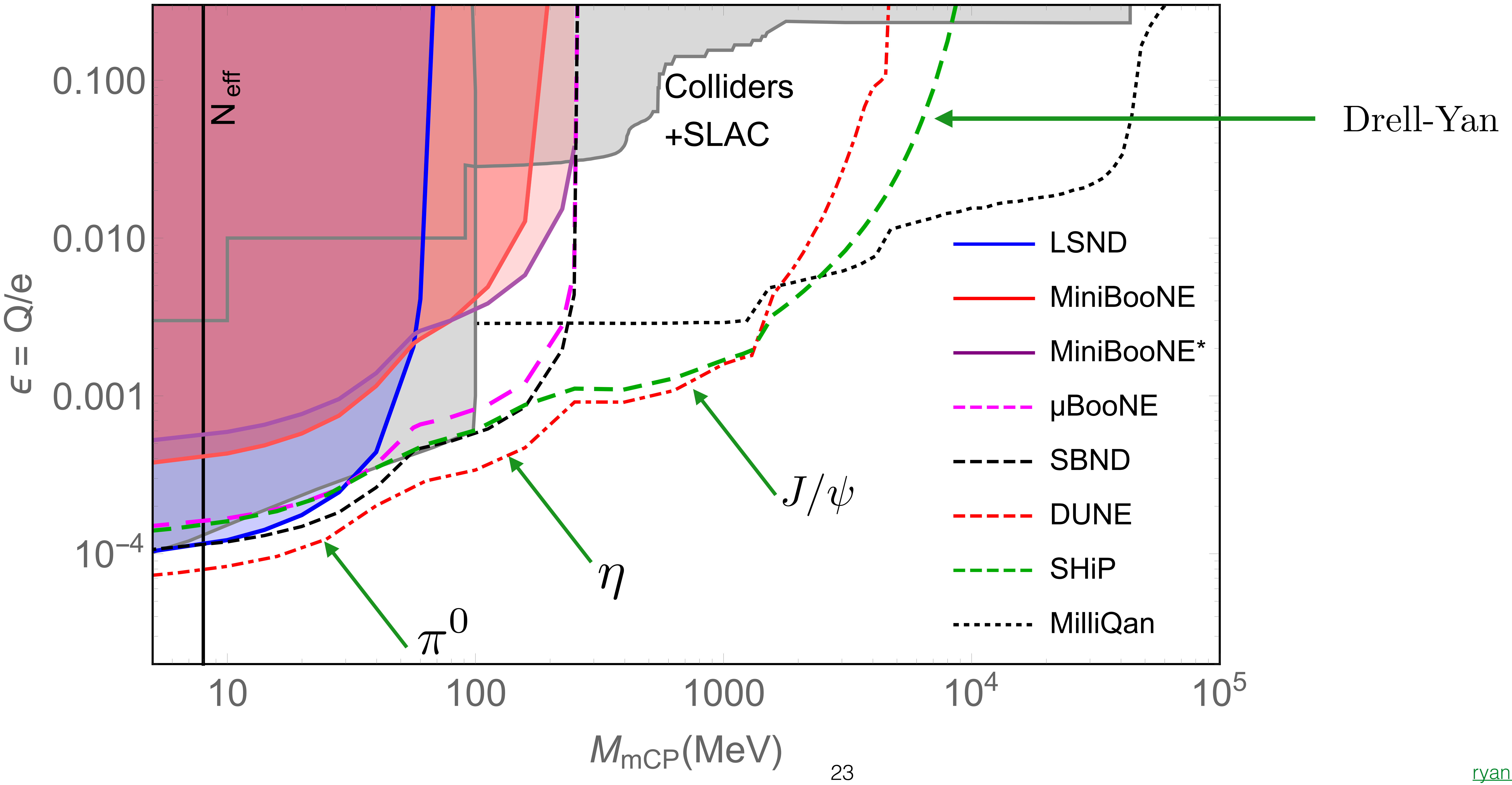


0.100
0.010
0.001
10^-4
ε = Q/e
N_eff
Colliders
+SLAC
Drell-Yan
LSND
MiniBooNE
MiniBooNE*
μBooNE
SBND
DUNE
SHiP
MilliQan
J/ψ
η
π^0
10
100
1000
10^4
10^5
M_mCP(MeV)

Results

$$s_{\text{up}} = \sum_{\text{Energies}} \epsilon^4 \times N_\chi(E_i) \times \frac{N_e}{\text{Area}} \times \sigma_{e\chi}(E_i;\ m_\chi) \times \mathcal{E}$$



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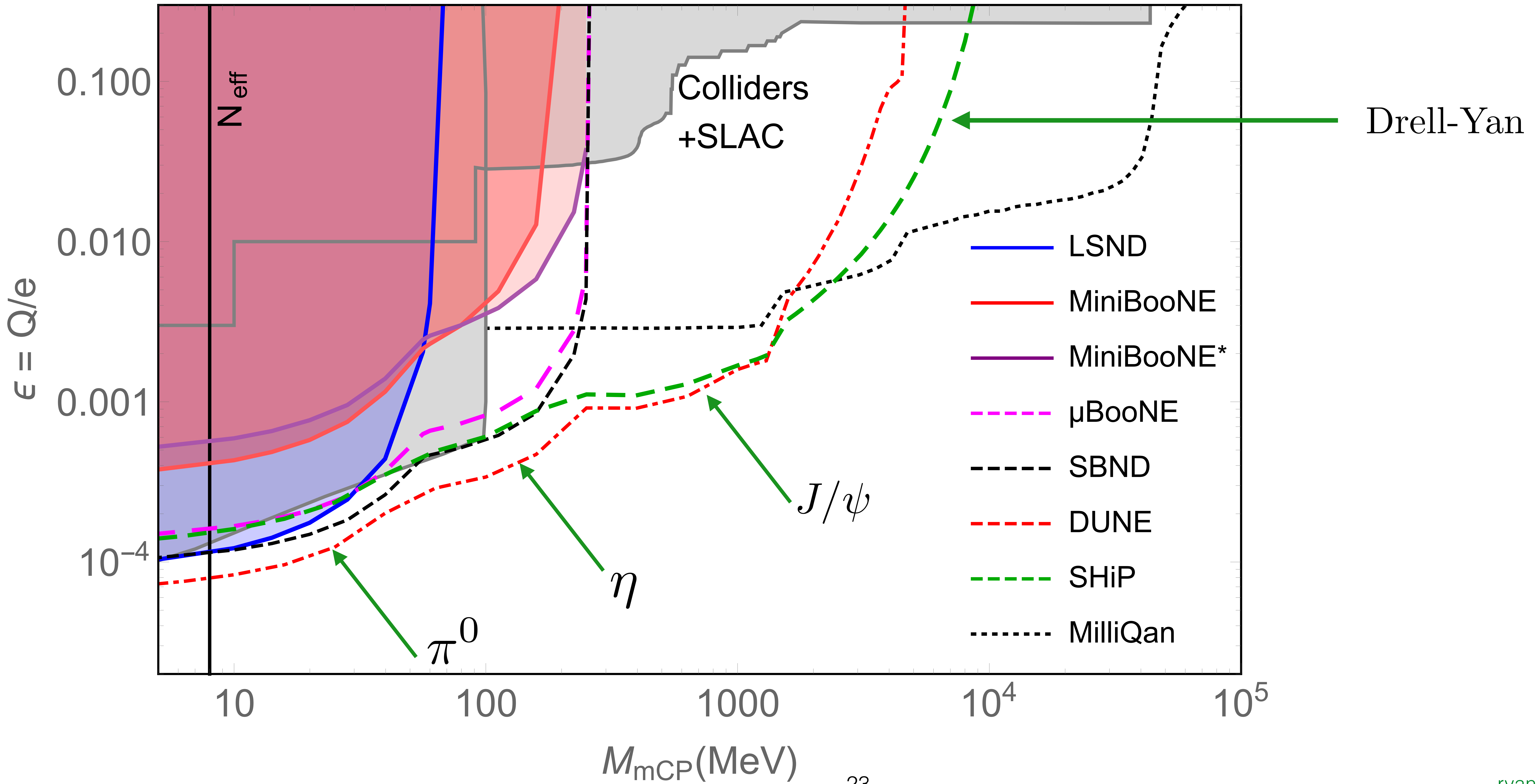

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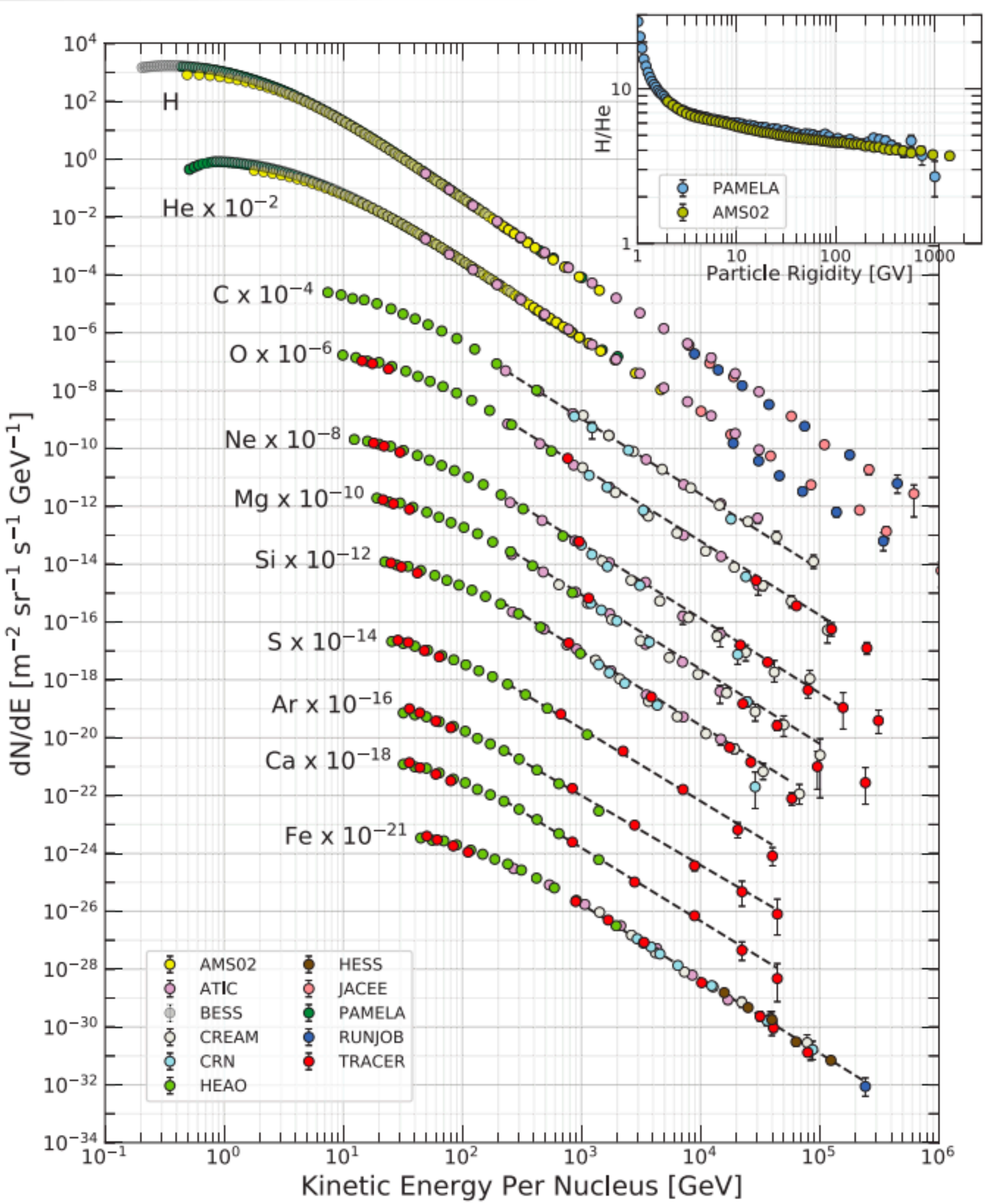
MCPs from Cosmic Rays

A brief review of cosmic rays

A brief review of cosmic rays



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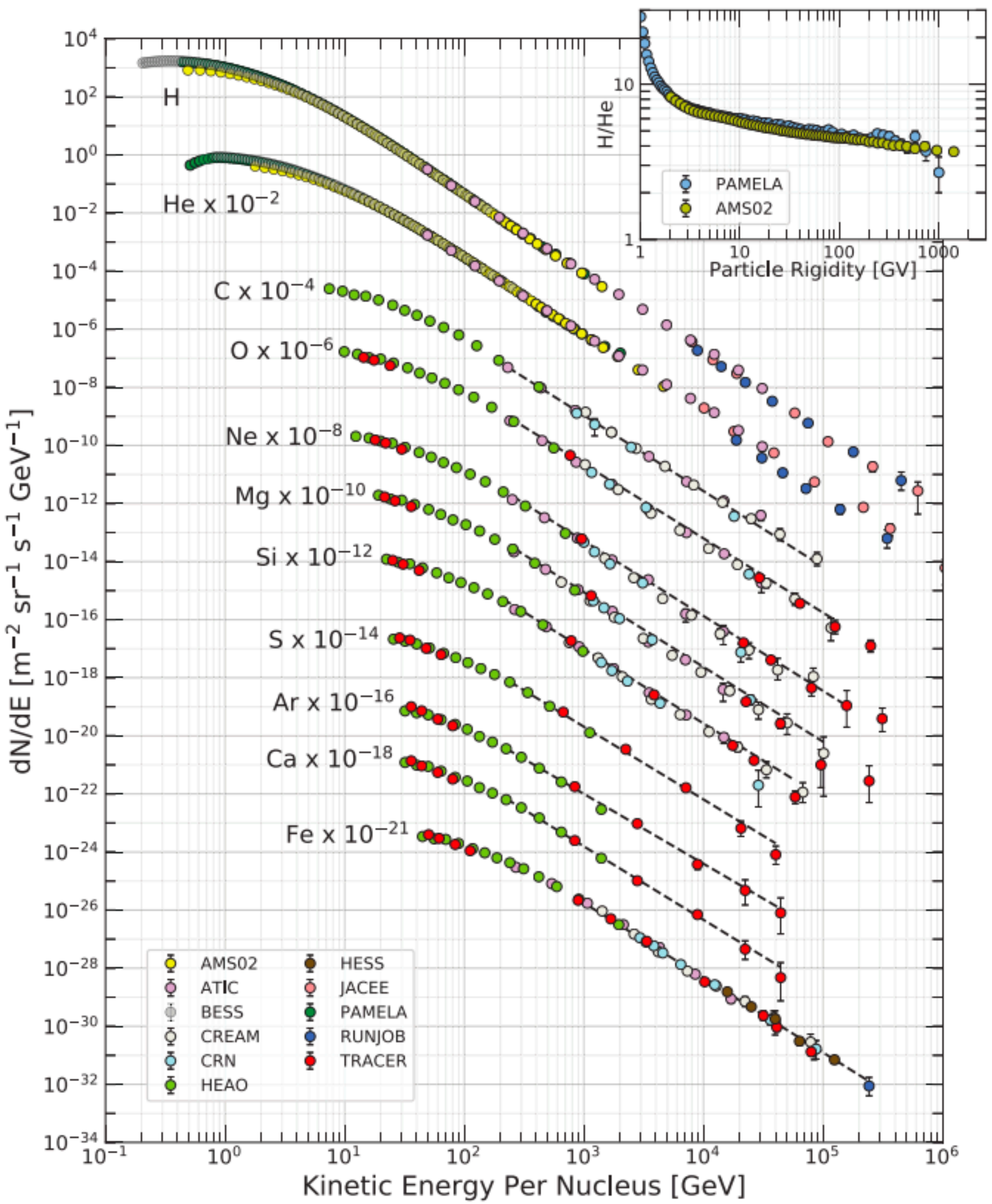

Flux of H >> Flux of He

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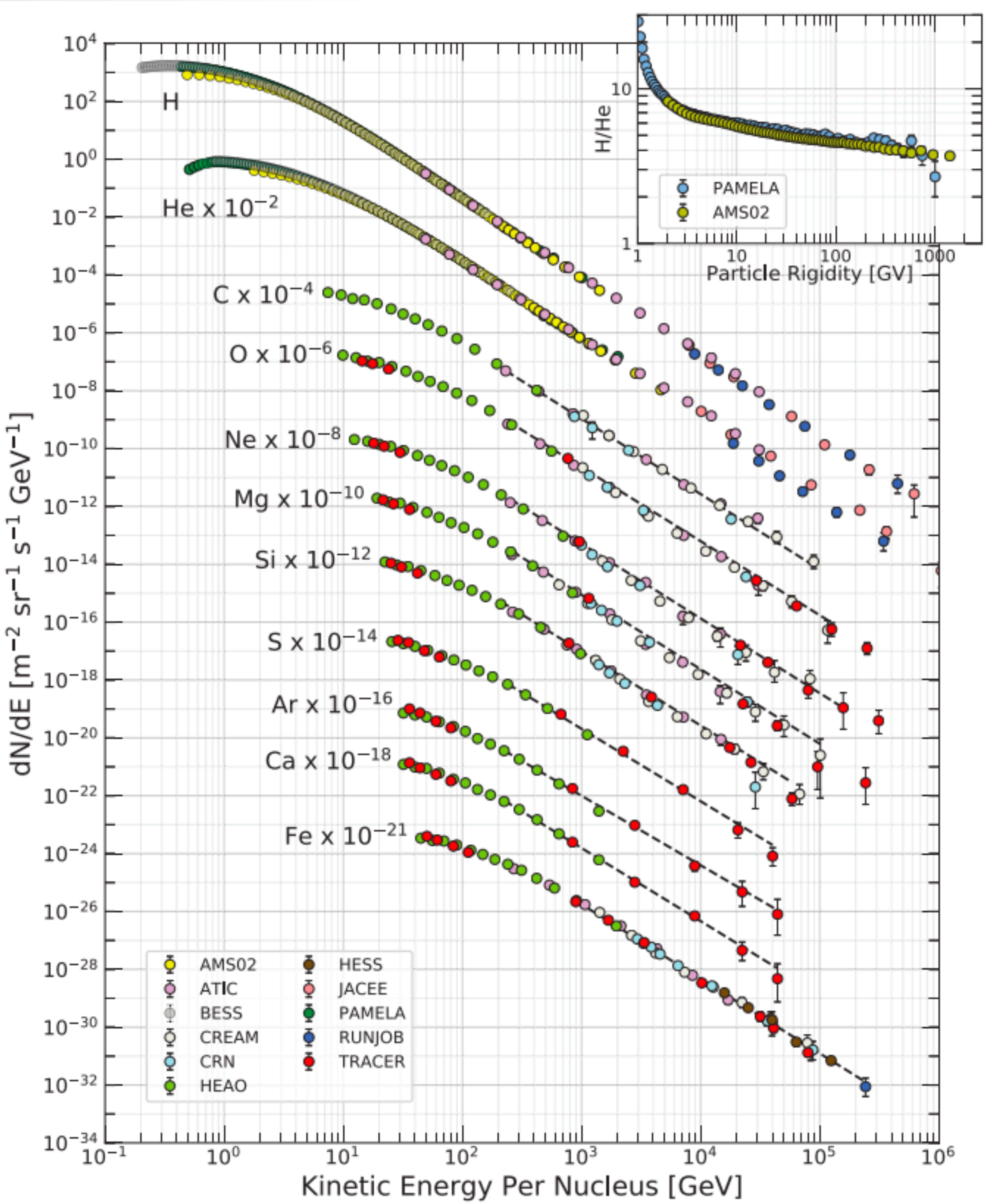


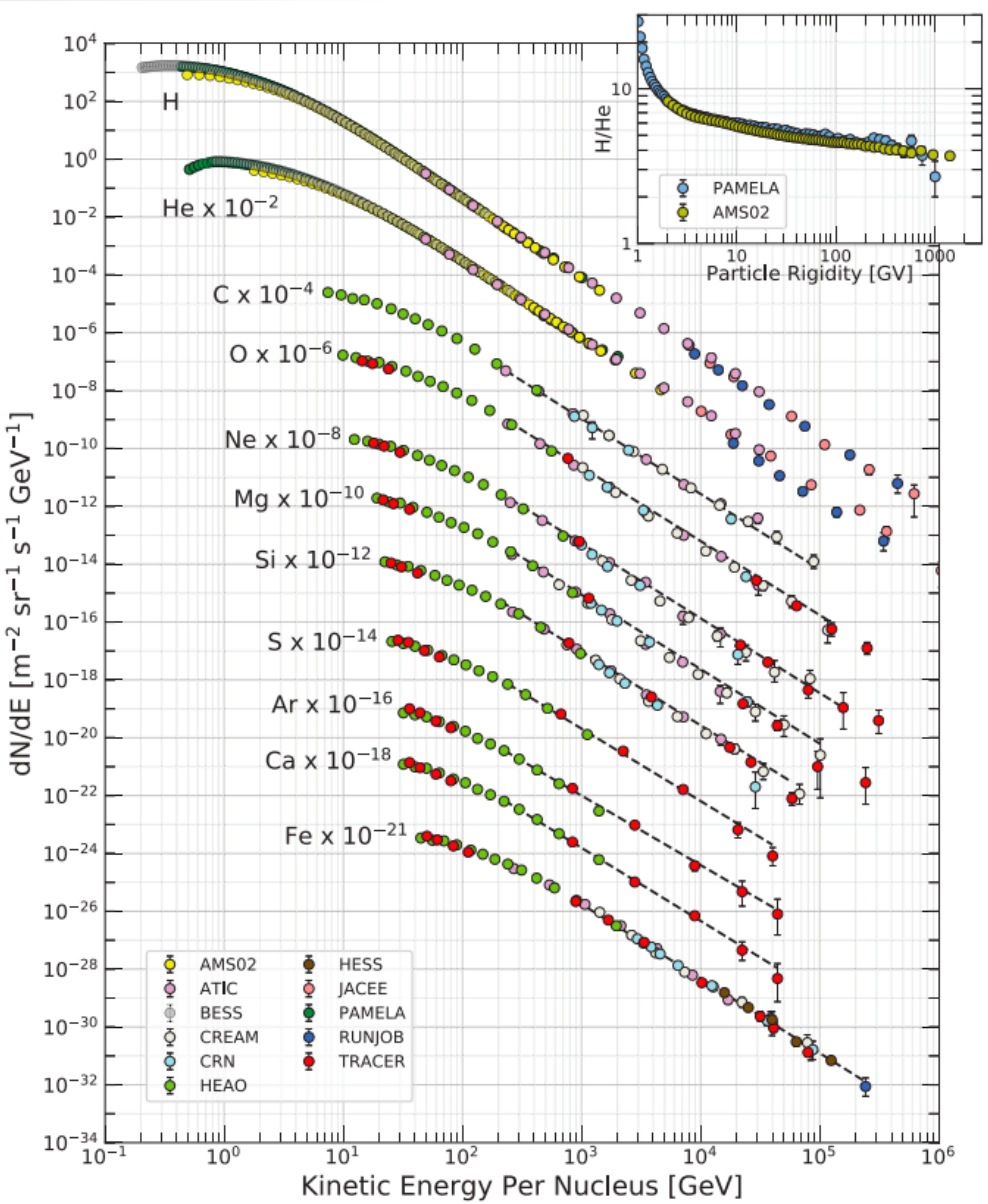
Flux of H >> Flux of He

$$\lambda_{\mathrm{MFP}} = \frac{1}{n_p \sigma_{\mathrm{inel}}(pp)}$$

$$\approx \frac{1}{(3.82 \times 10^{20}\mathrm{cm}^{-2}) \times (3 \times 10^{-26}\mathrm{cm}^2)}$$

$$\approx \frac{1}{1\ \mathrm{km}}$$

A brief review of cosmic rays



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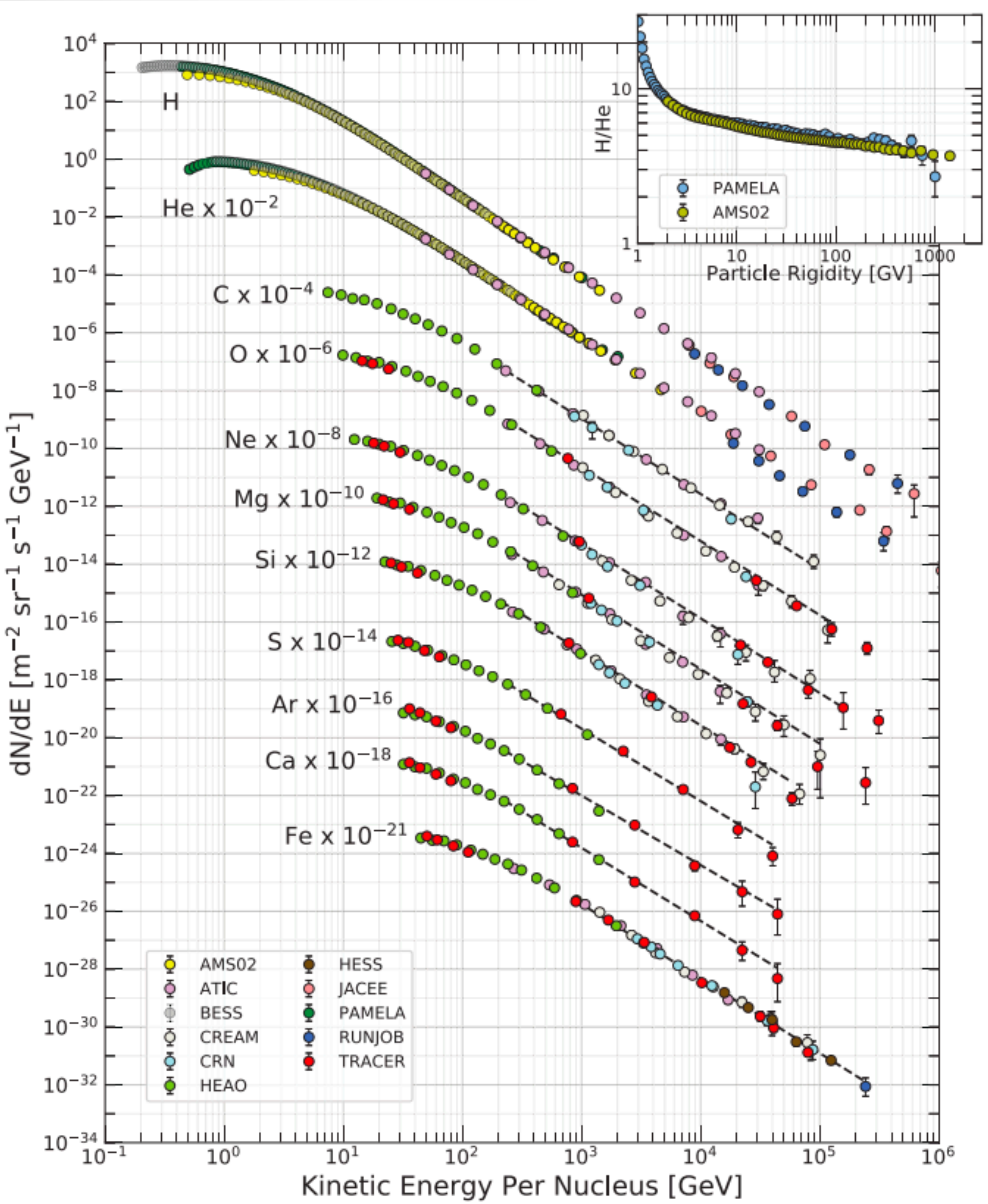
$$P({\rm survival}) = 1 - \exp\left[-\int_0^{50\ {\rm km}} \frac{{\rm d}z}{\lambda_{\rm MFP}}\right]$$

A brief review of cosmic rays



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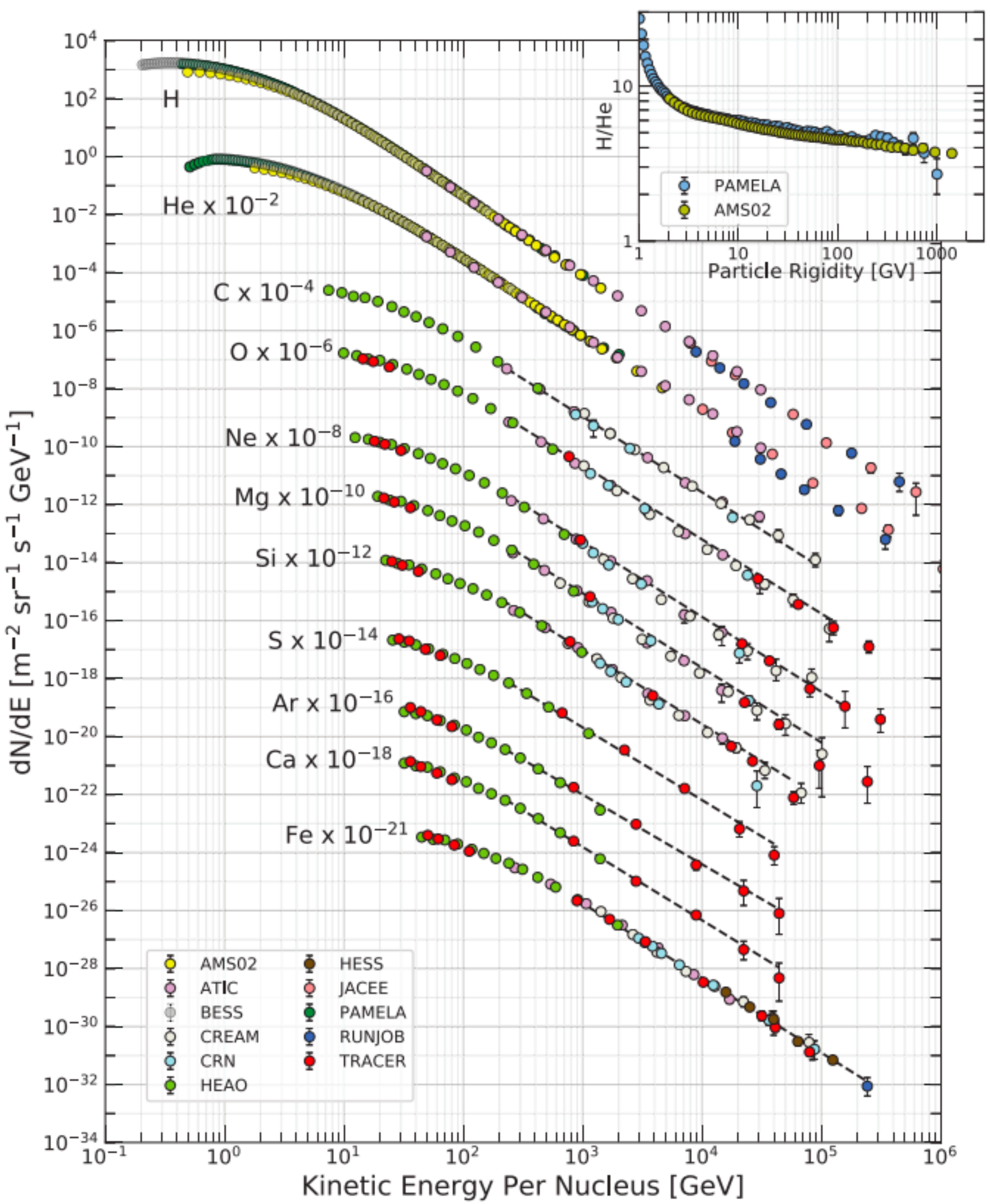

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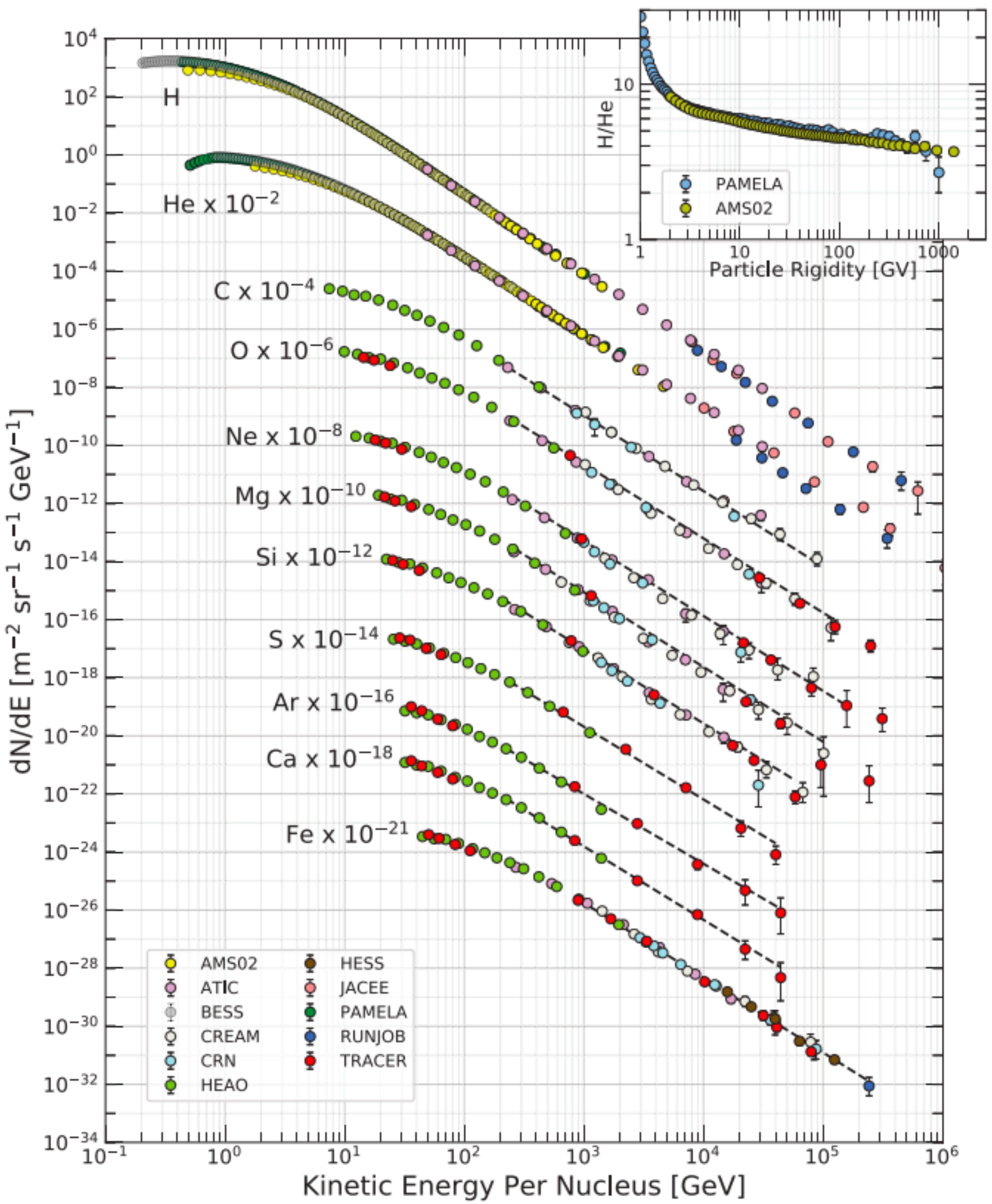

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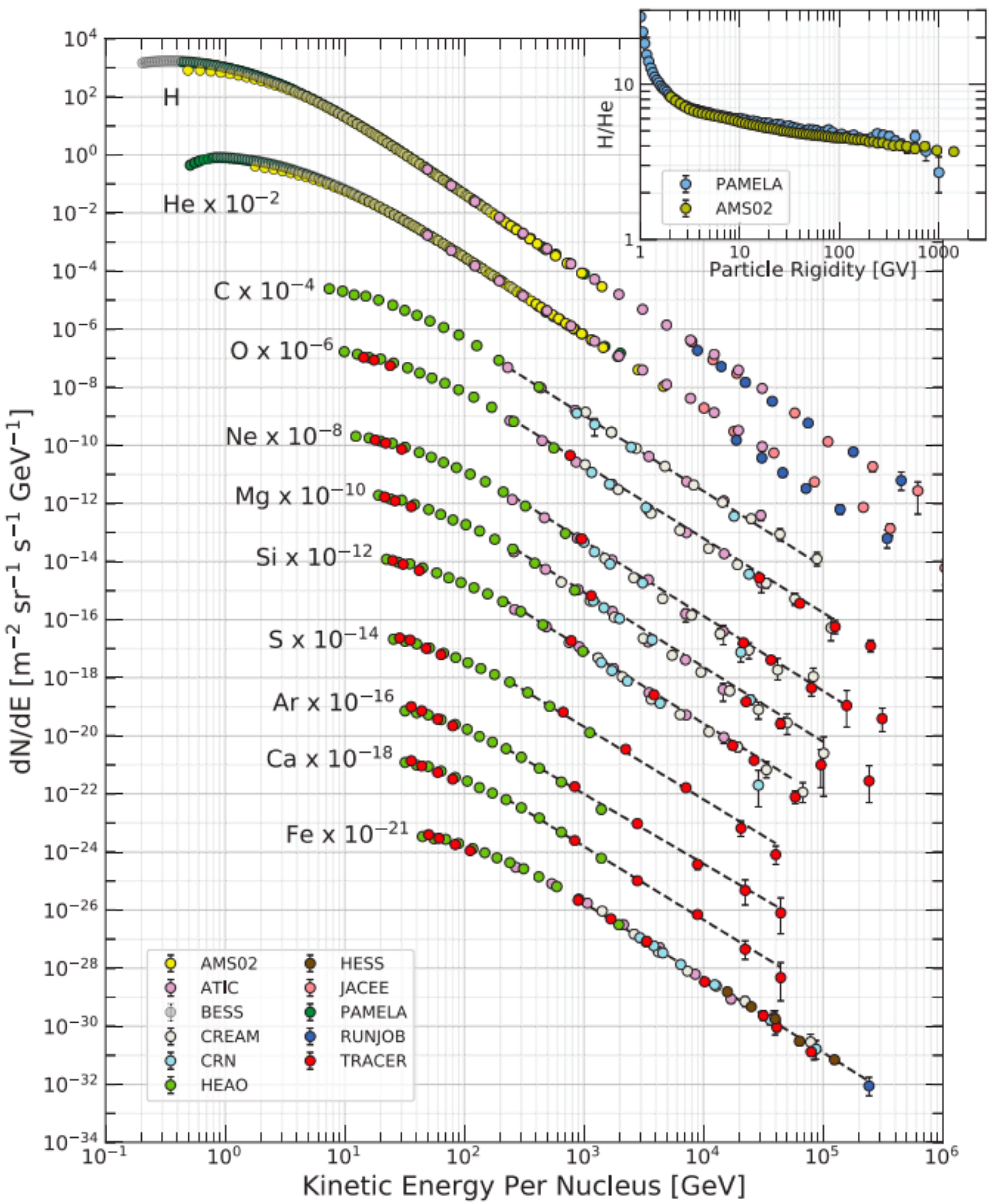

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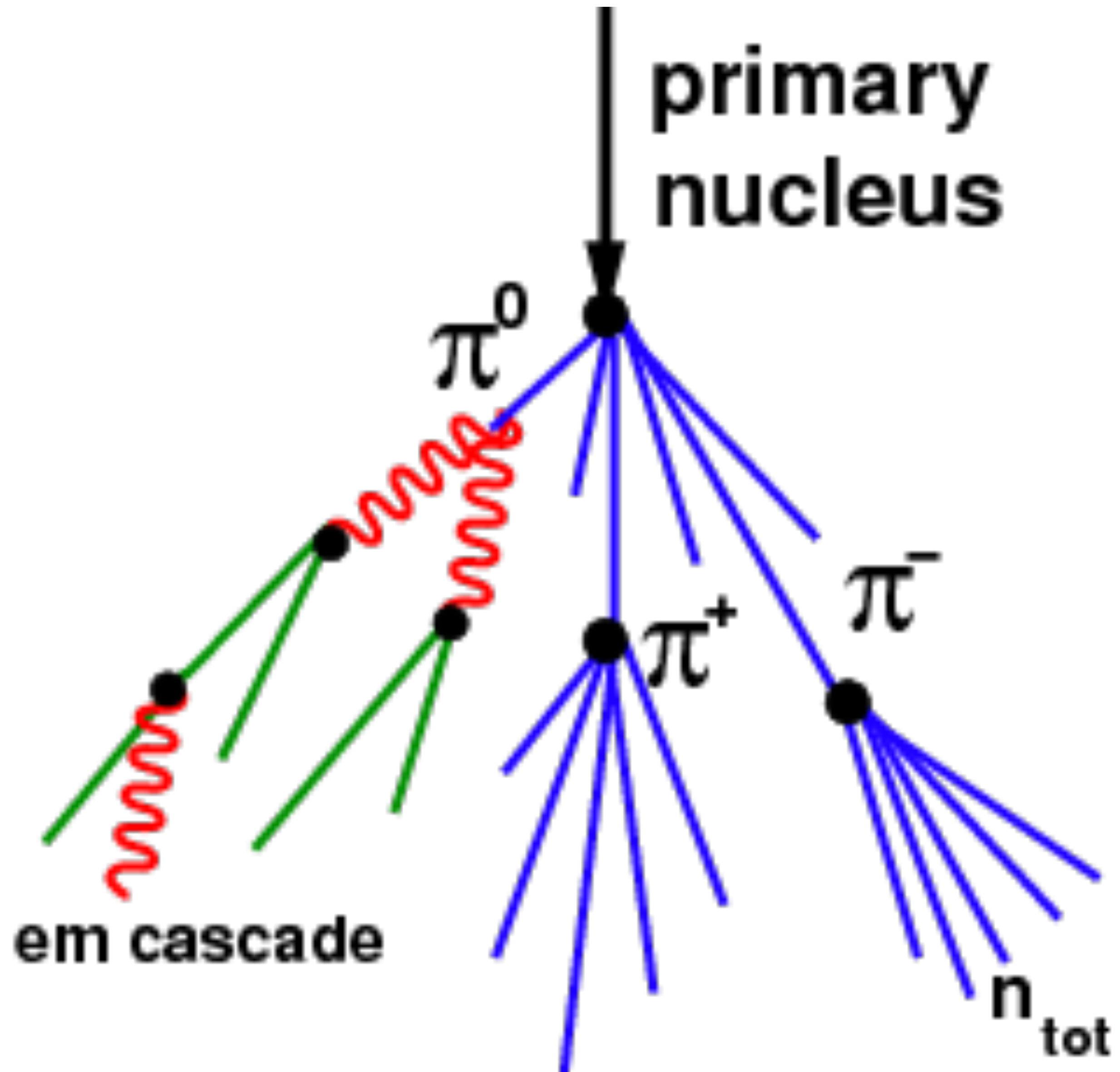

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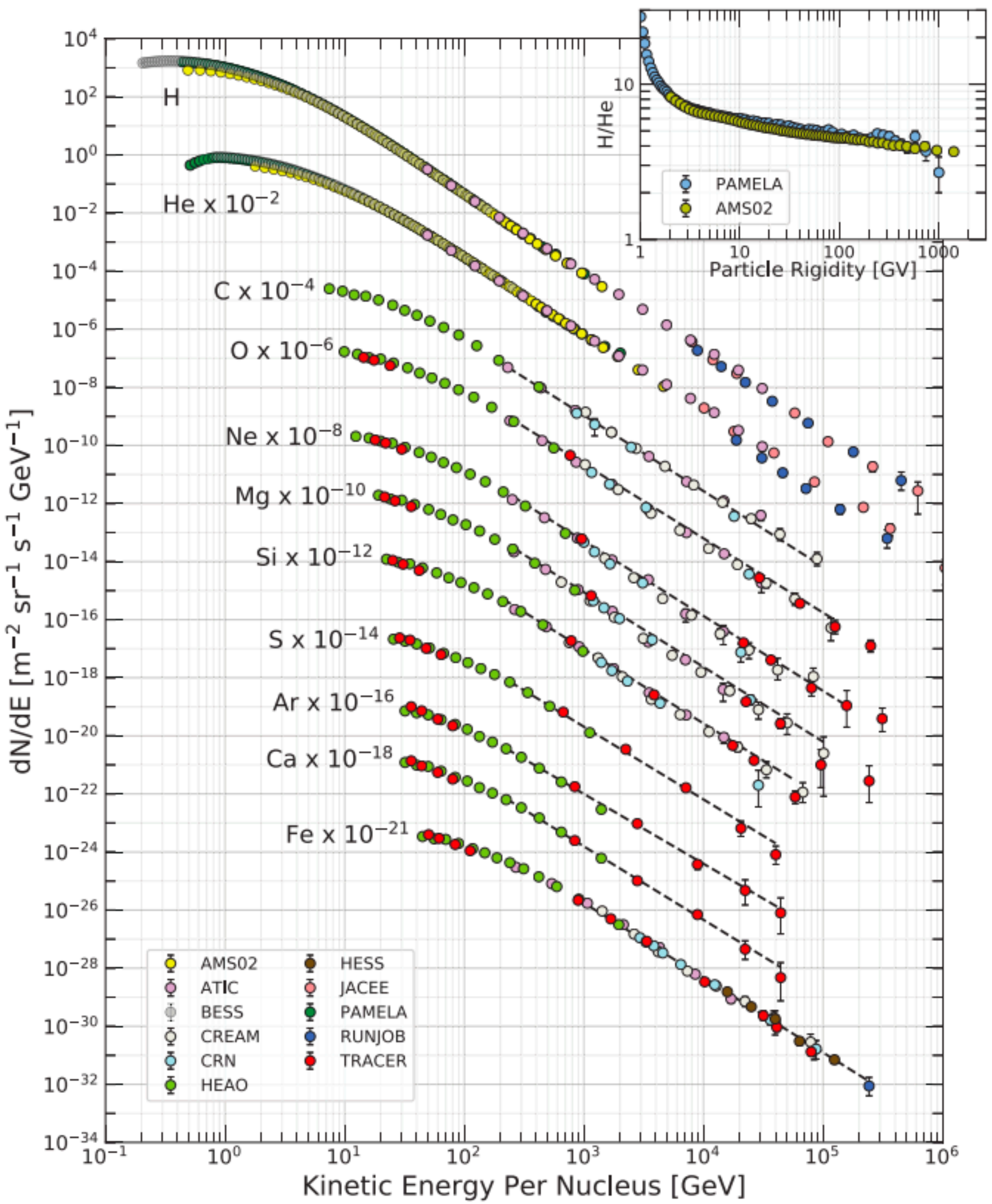

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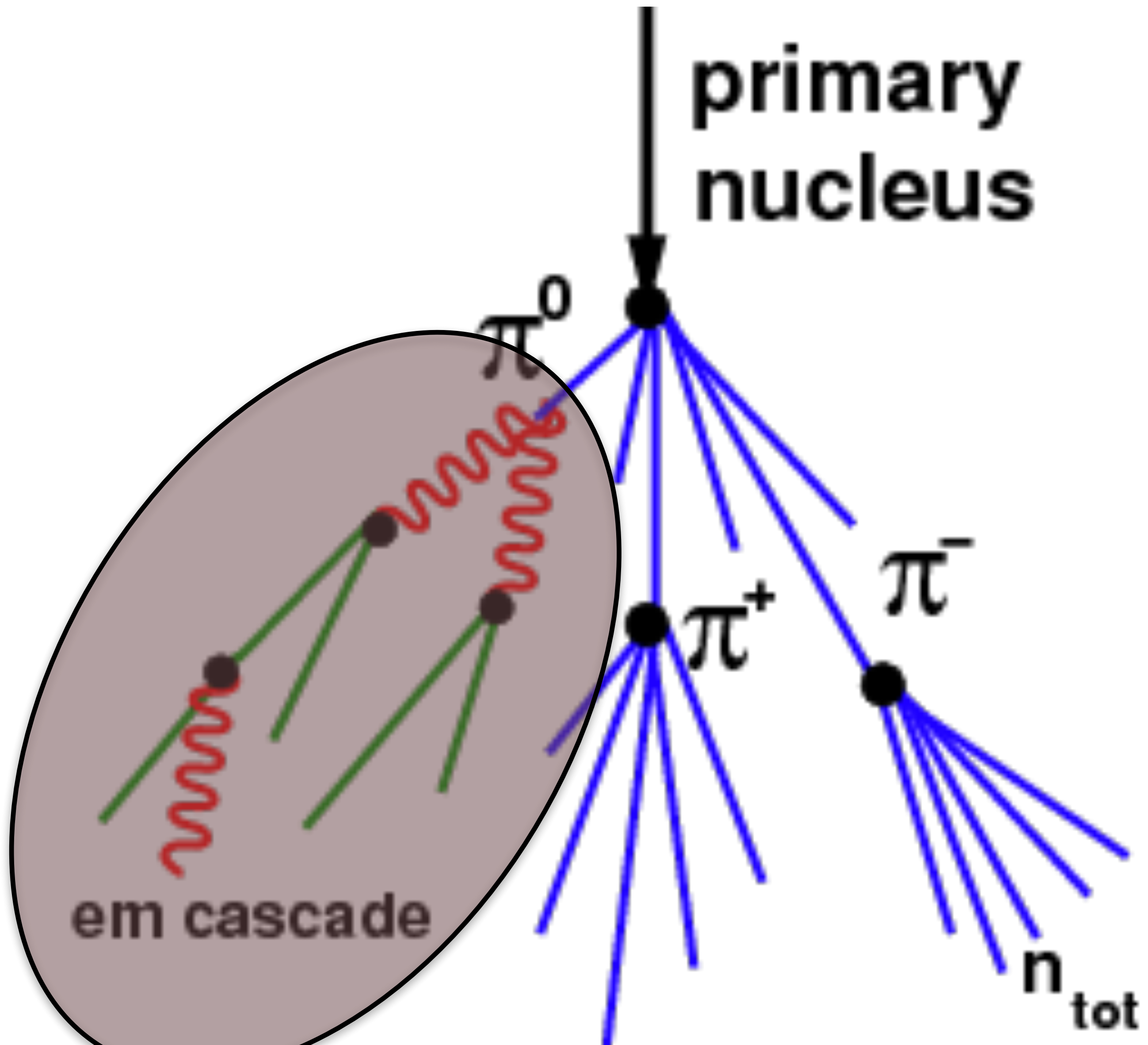
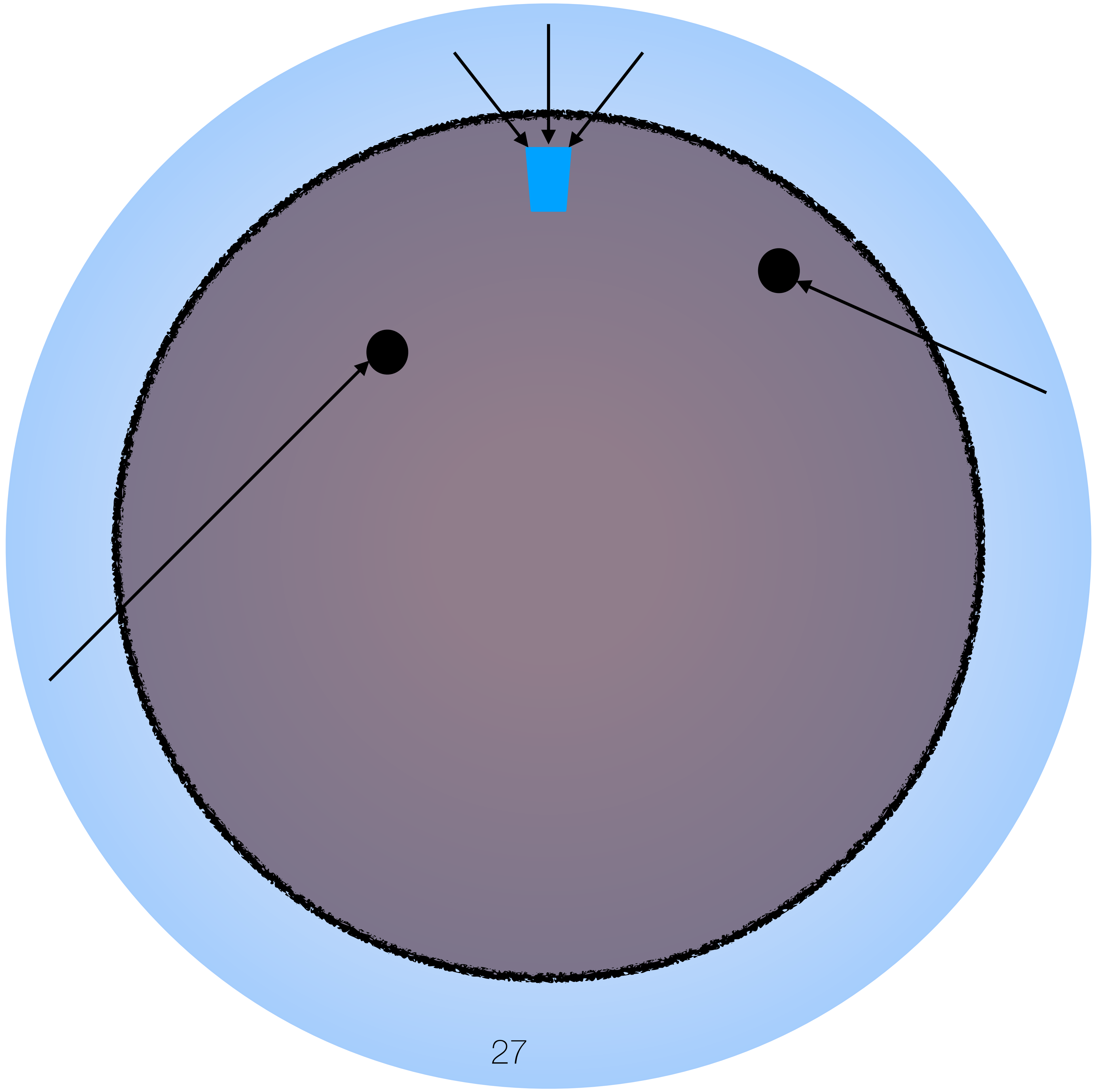


MCPs in the Upper Atmosphere



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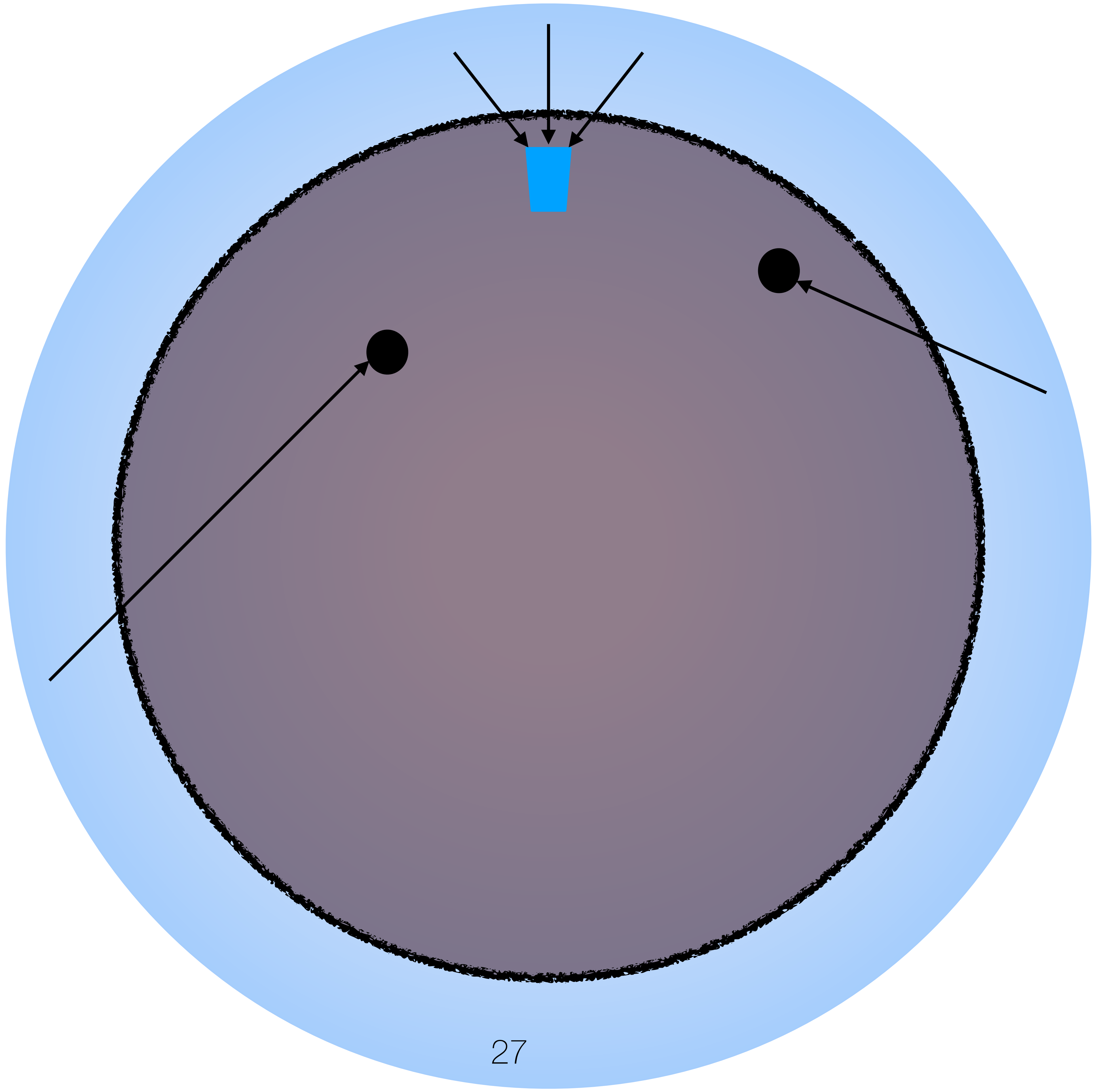
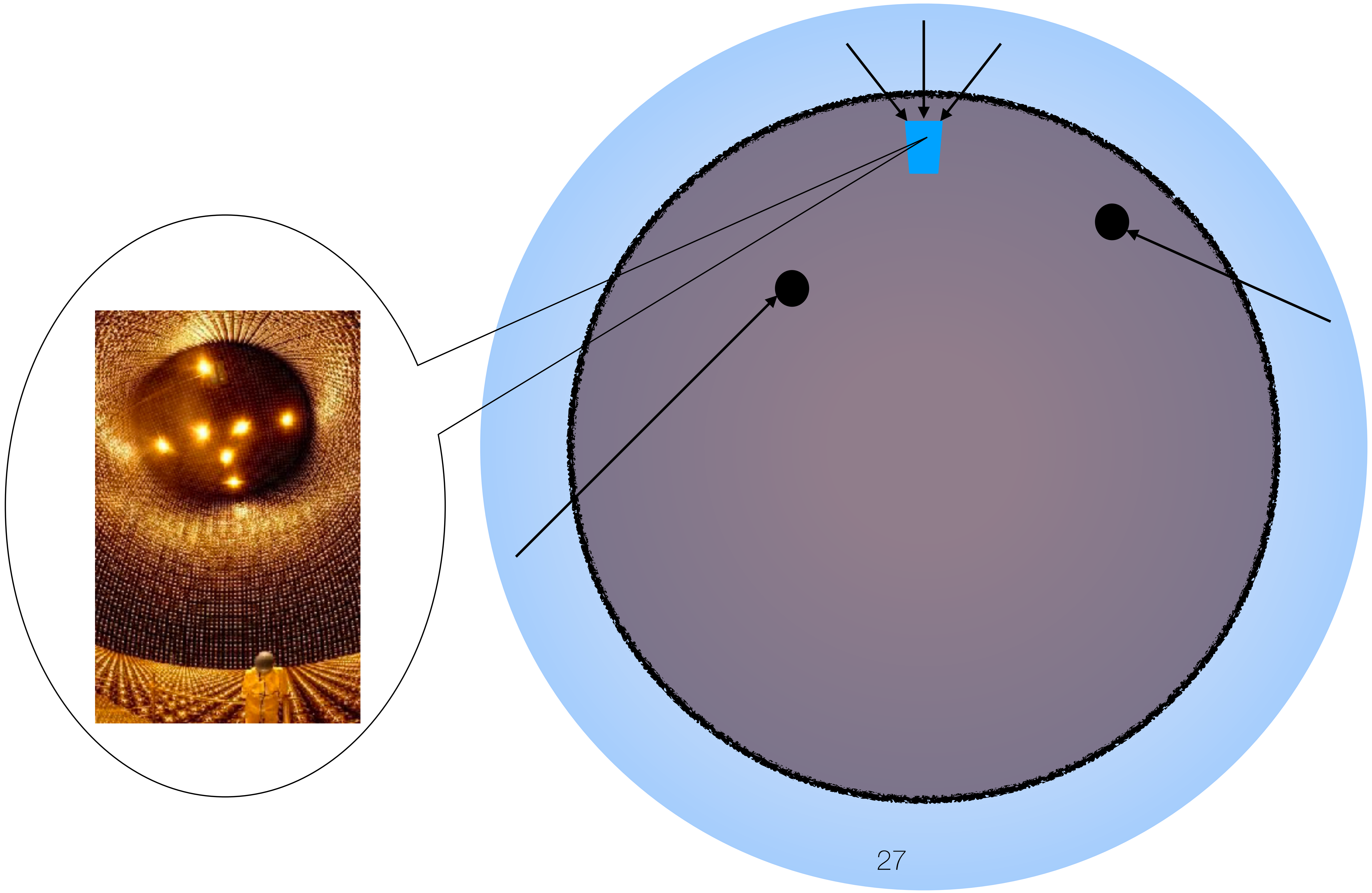


MCPs impinge from all angles

MCPs passing through ~R_{Earth} of earth's crust are absorbed.

MCPs in the Upper Atmosphere



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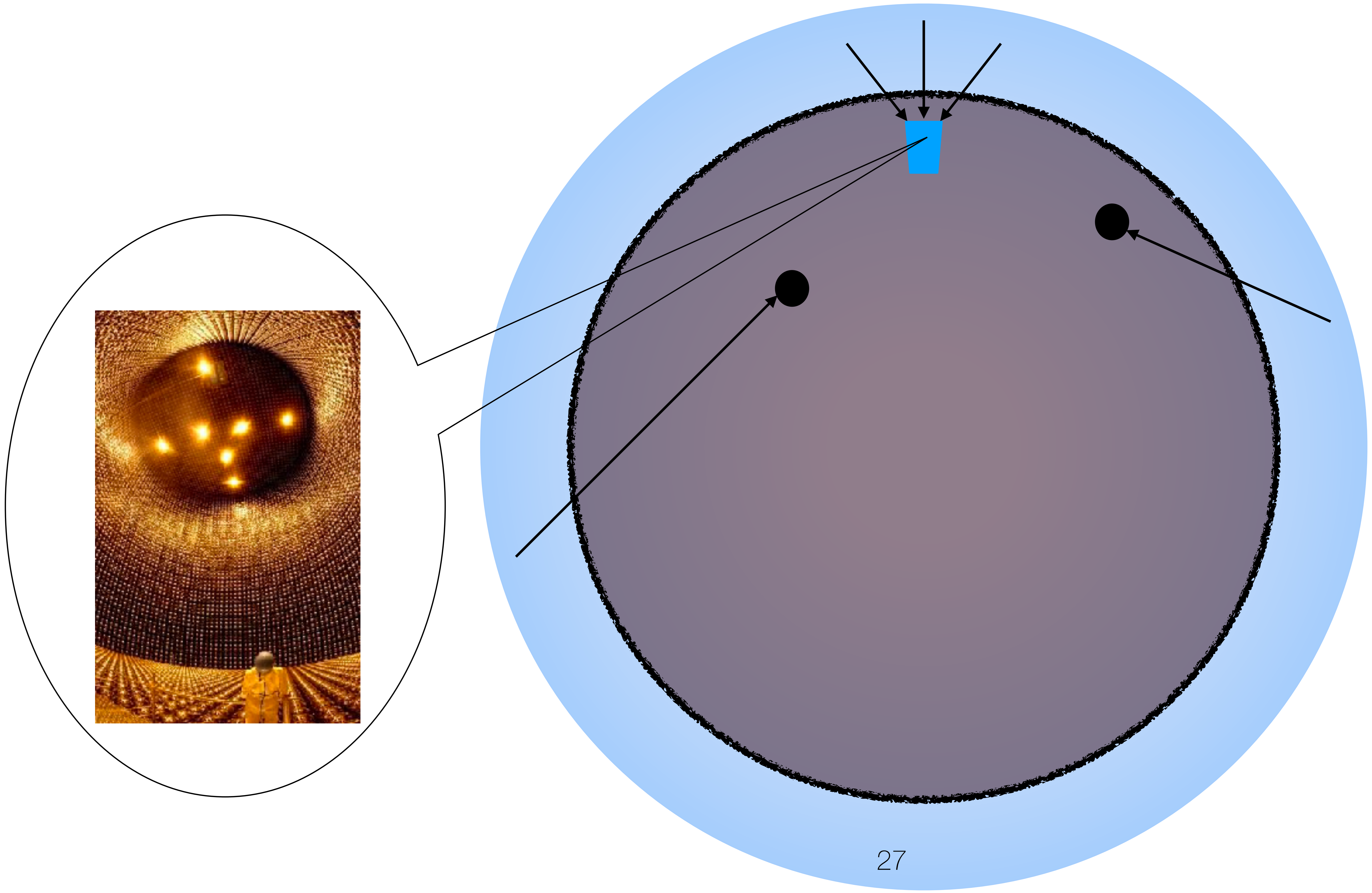

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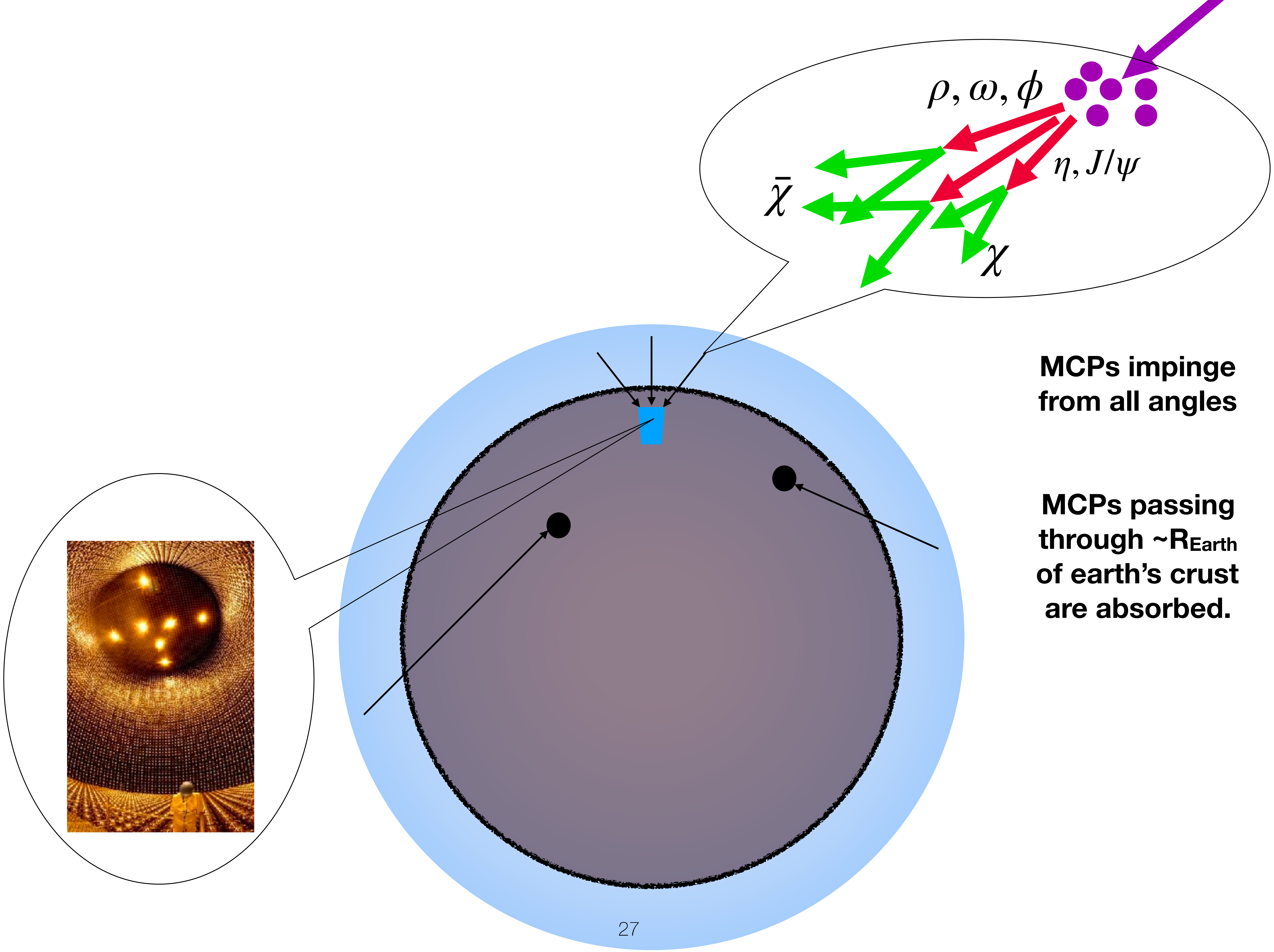
ρ, ω, ϕ
$\eta, J/\psi$
$\bar{\chi}$
χ
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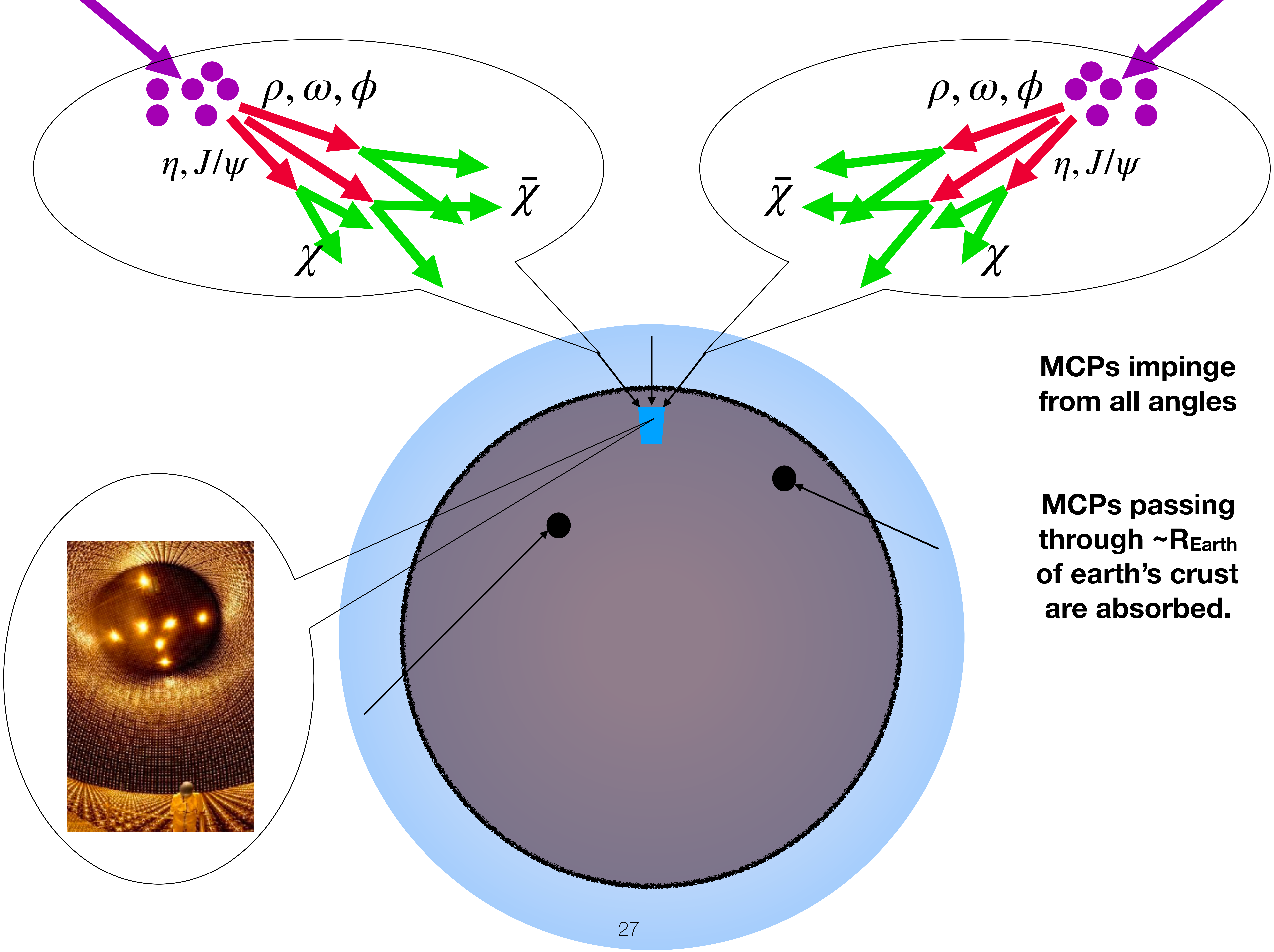

ρ, ω, ϕ
$\eta, J/\psi$
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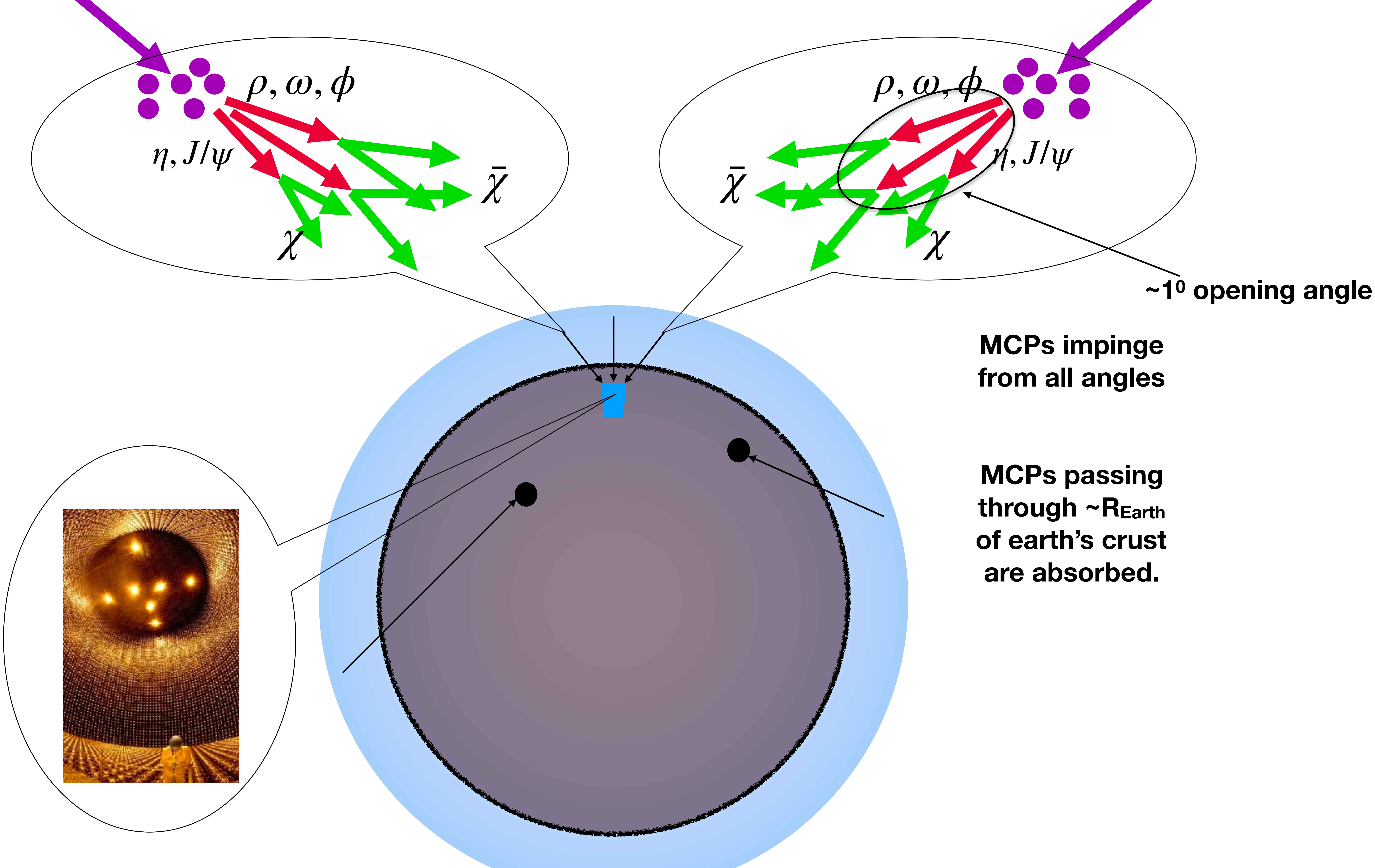
ρ, ω, ϕ
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χ
~1⁰ opening angle
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MCPs passing through ~R_{Earth} of earth's crust are absorbed.


ρ, ω, ϕ
$\eta, J/\psi$
$\bar{\chi}$
χ
ρ, ω, ϕ
$\eta, J/\psi$
$\bar{\chi}$
χ
~1⁰ opening angle
MCPs impinge from all angles
MCPs passing through ~R_{Earth} of earth's crust are absorbed.

Flux of MCP Φ_χ
Boost Factor γ_χ
0
5
10
15
20
25
30
m_χ=0.1 GeV
m_χ=0.4 GeV
$\bar{\chi}$
ρ, ω, ϕ
$\eta, J/\psi$
χ
~1^0 opening angle
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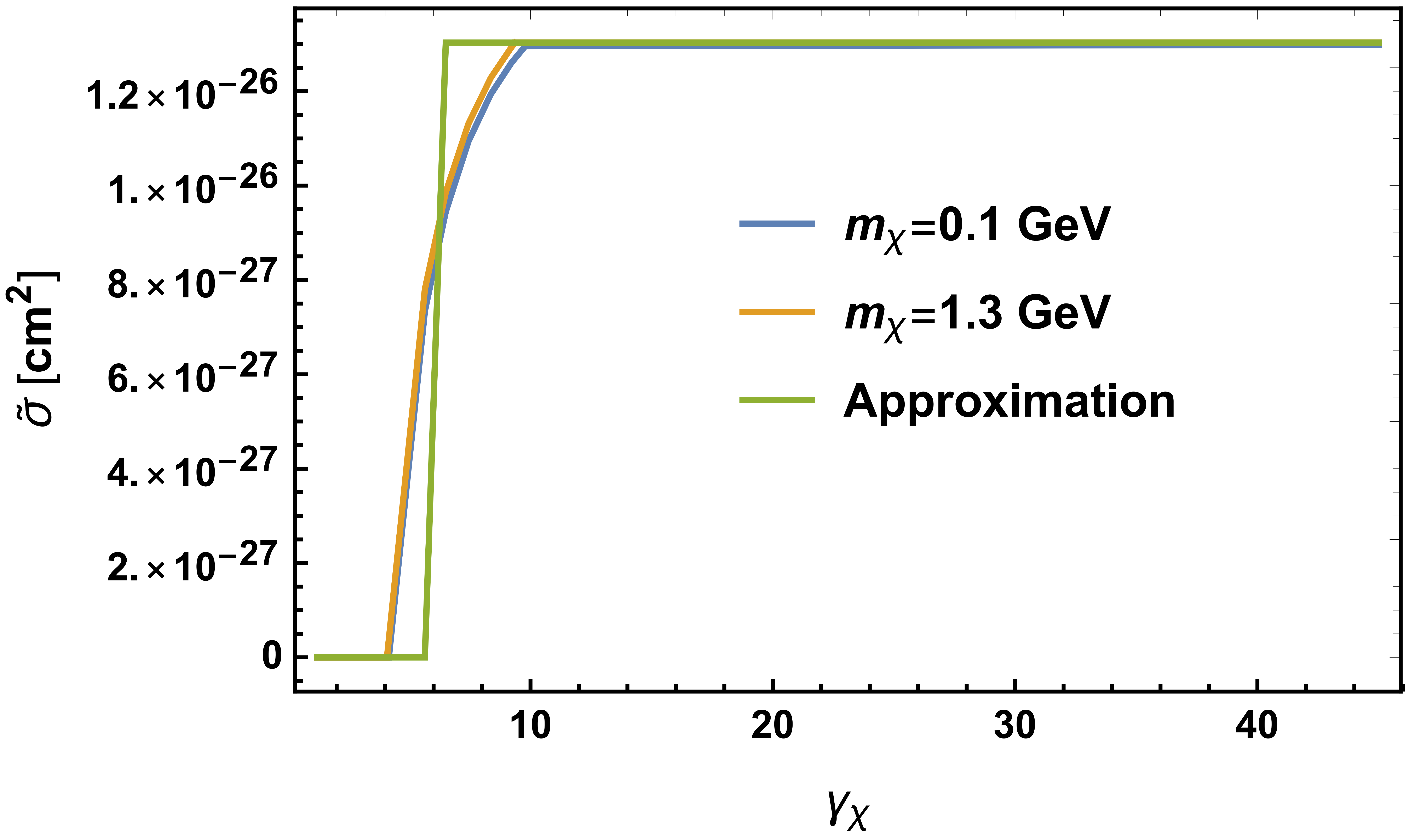
Detecting MCPs with Neutrino Telescopes



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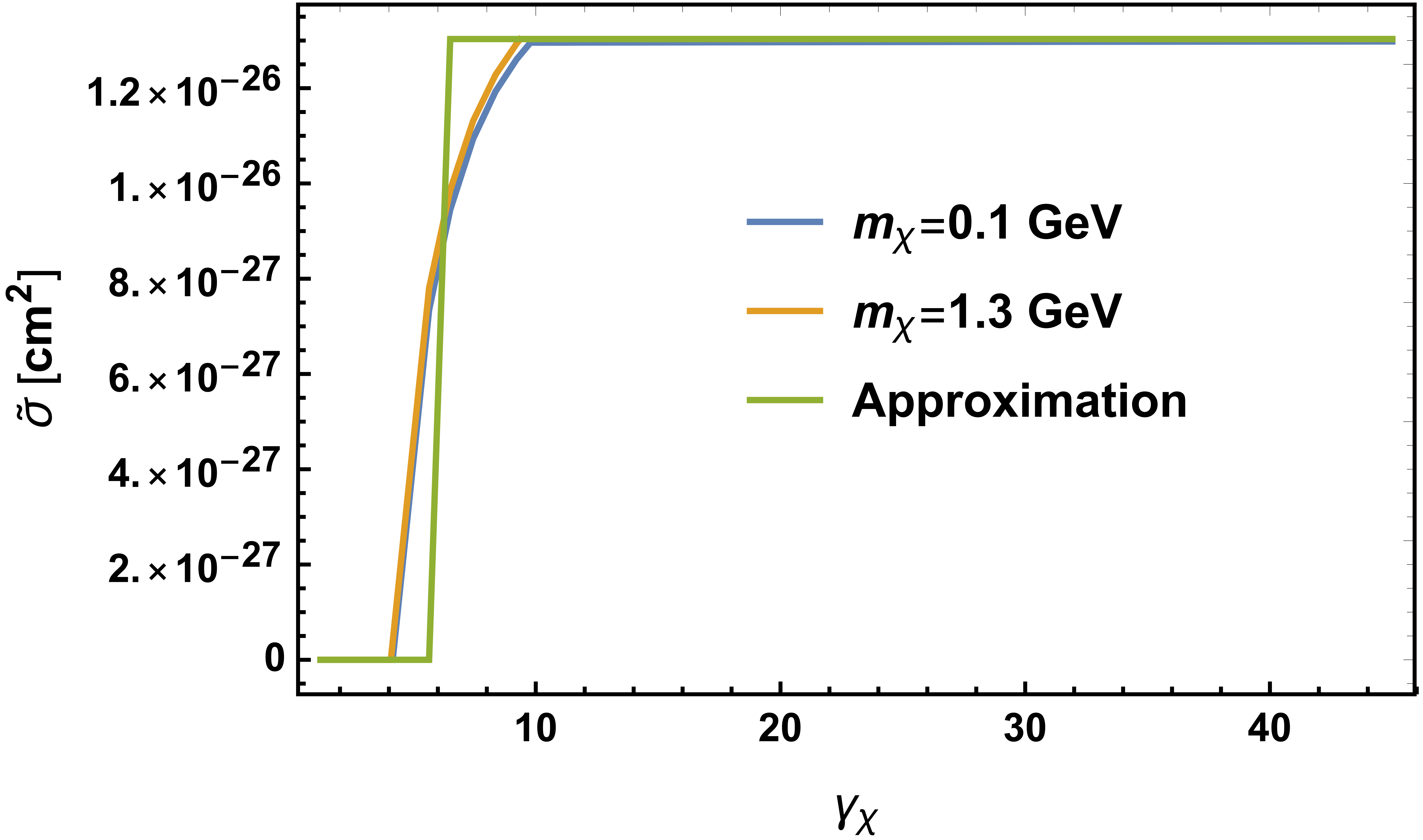

$$T_e \leq 2m_e(\beta_\chi\gamma_\chi)^2$$

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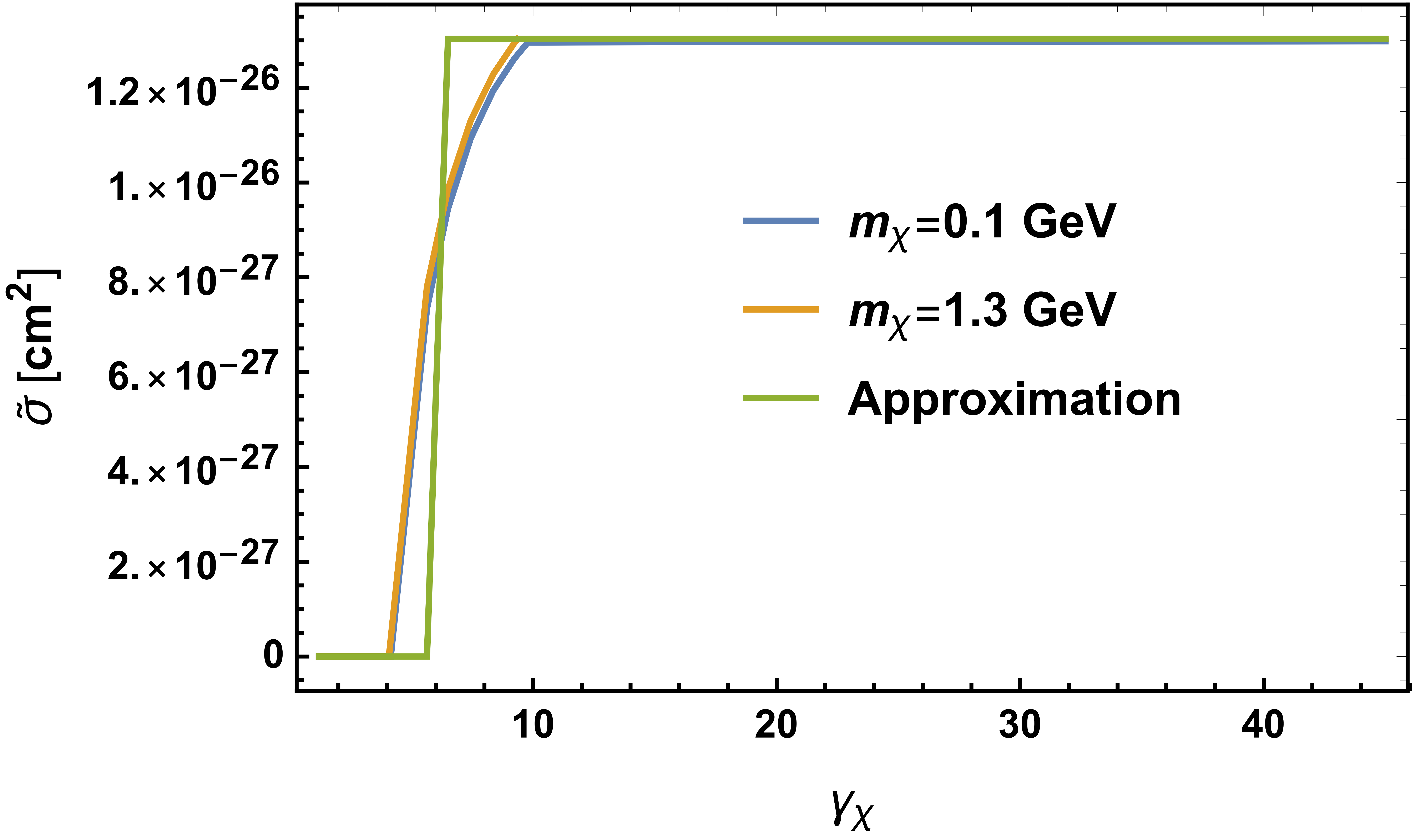

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Each experiment's recoil threshold translates into a boost-factor threshold

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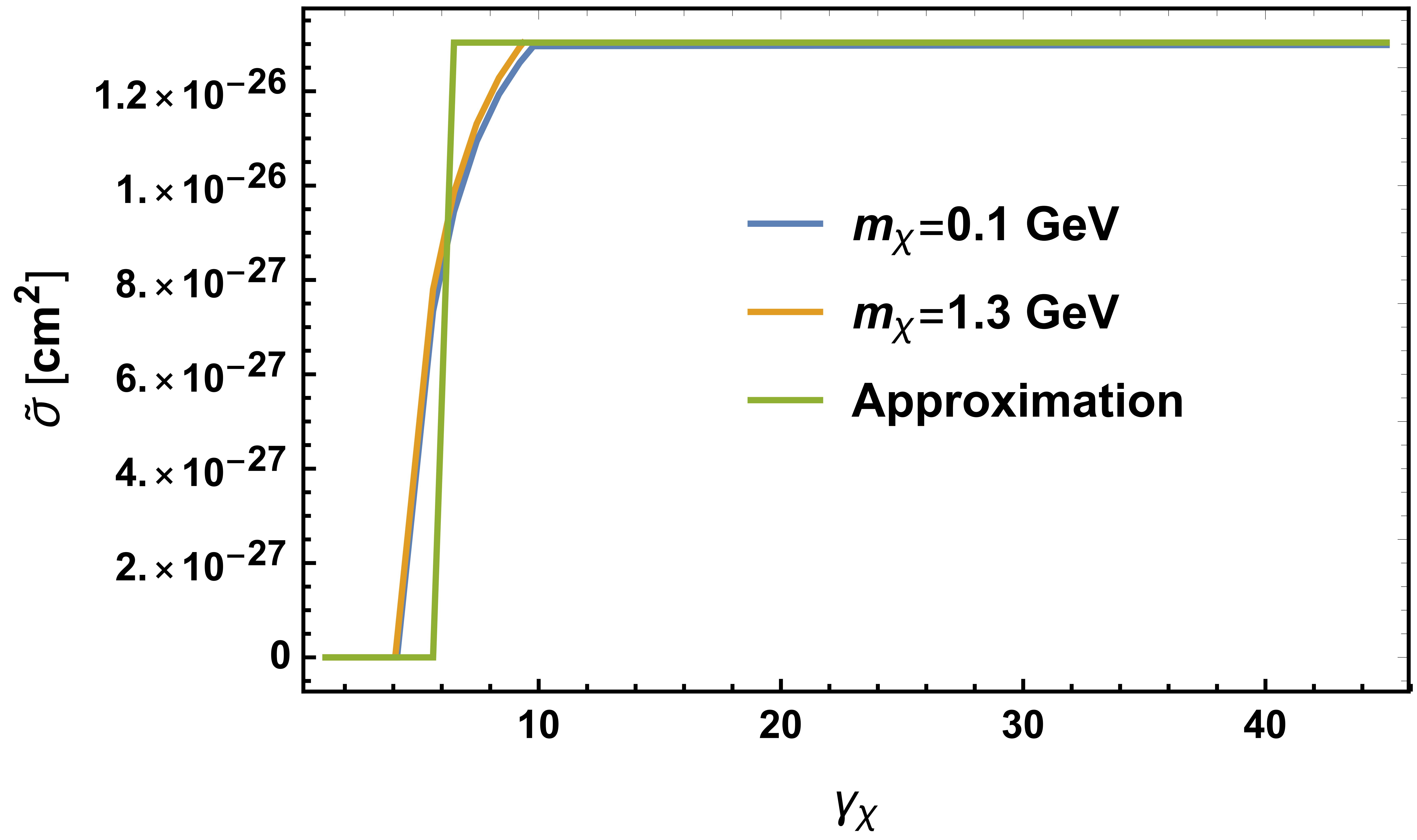

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$$\gamma_\chi > \gamma_{\text{cut}}$$

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MCPs in the Upper Atmosphere

1. Cosmic rays act as a ``broad band” proton beam.
   The atmosphere acts like a (very thick) fixed target.

2. Because cosmic rays come from every direction on the sky, angular losses are less important.

3. Broadband = broad MCP spectrum.
   Detector thresholds place a cut on the kinematics of the incident MCP

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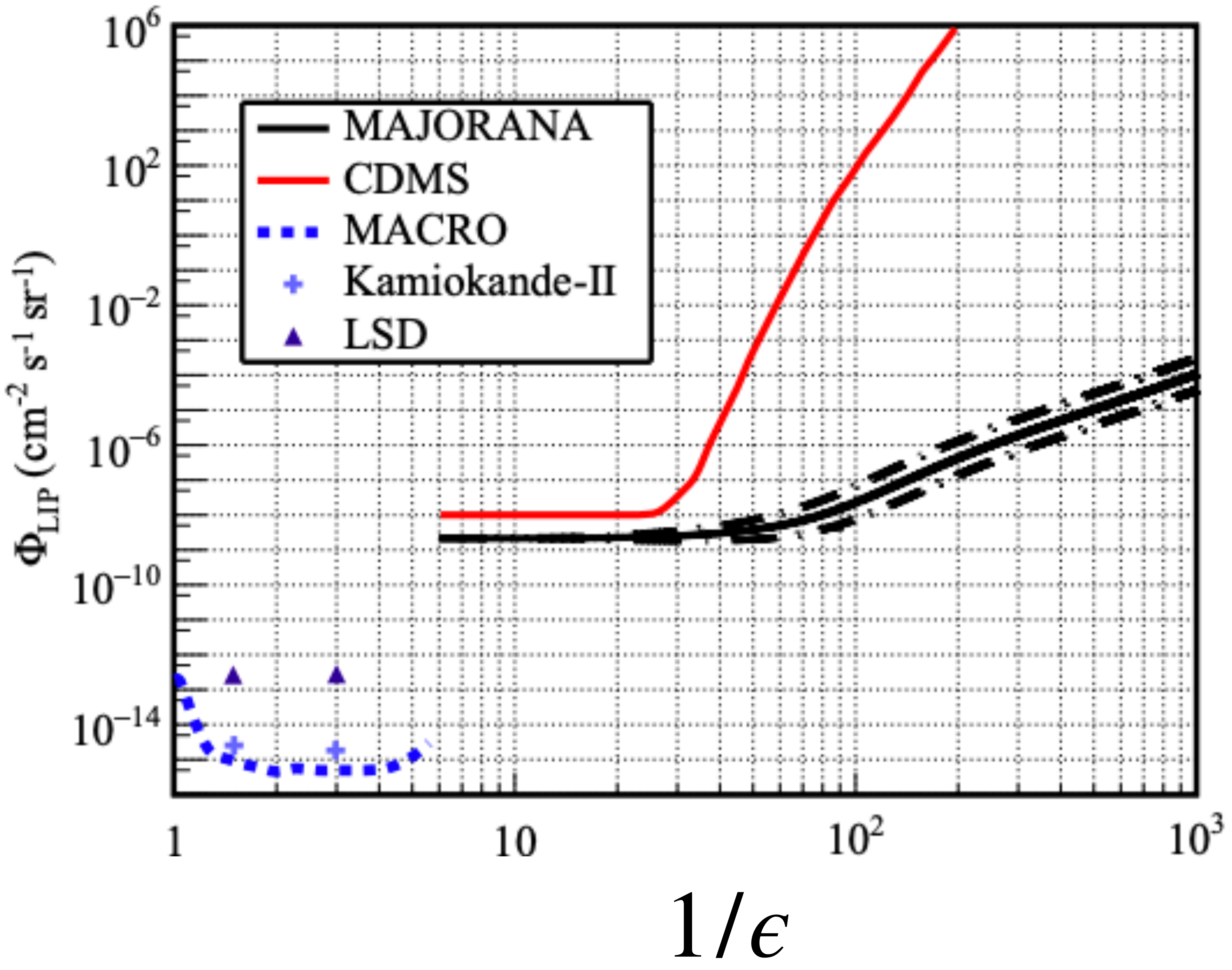
Old Ionization Experiments

- **Underground experiments with low thresholds have long published bounds on "light ionizing particles" e.g. Majorana, MACRO etc.**

- **Bounds are quoted as a flux as a function of charge**

$$\Phi_\chi < \Phi_{\rm ion}(\epsilon)$$

- **How does this translate to charge vs mass?**



arXiv:1801.10145

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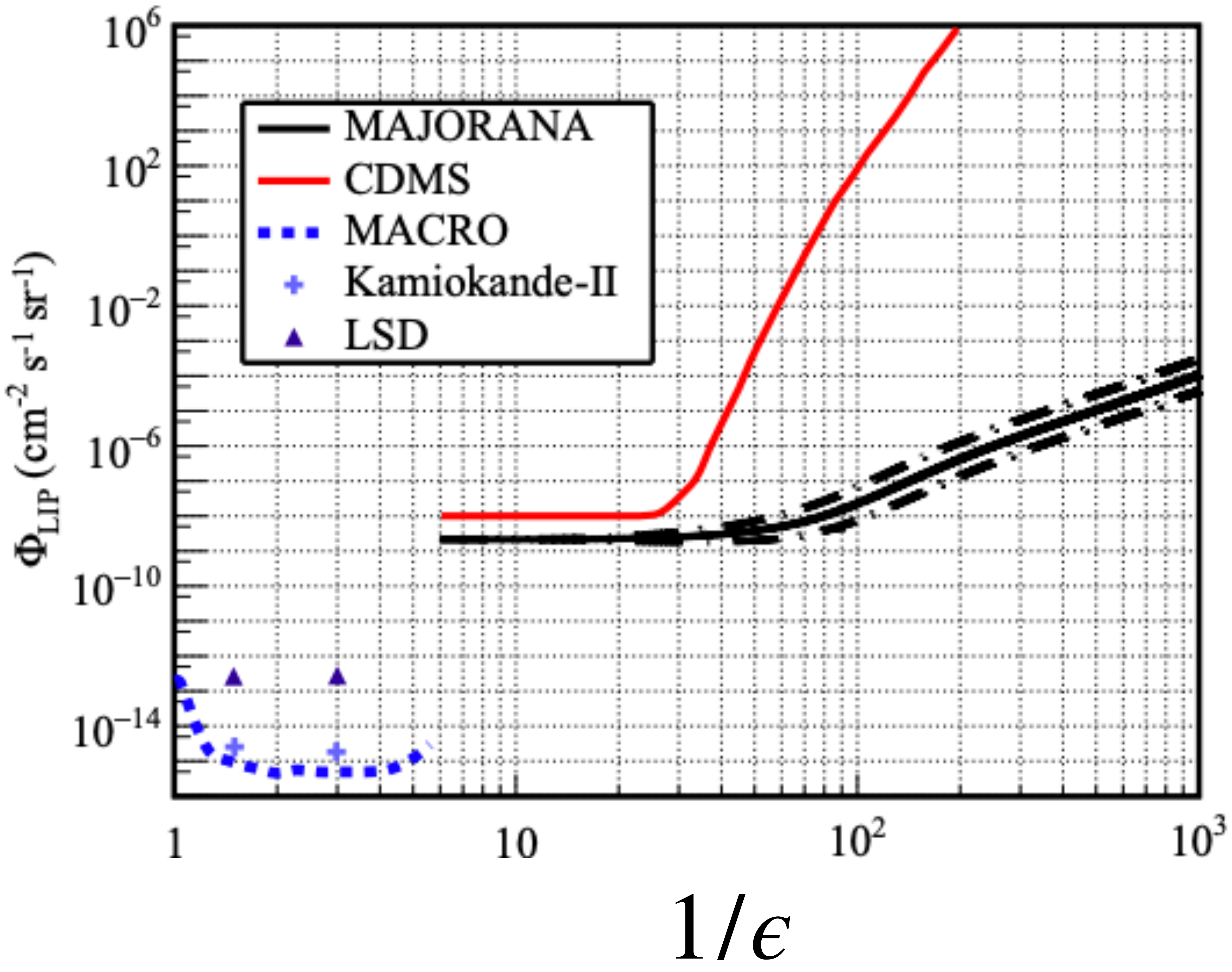

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Meson production

$$\Phi_{\mathfrak{m}}^{(\mathrm{tot})} = \int \mathrm{d}\gamma \quad I_{\mathrm{CR}}(\gamma) \frac{\sigma_{\mathfrak{m}}(\gamma)}{\sigma_{\mathrm{inel}}(\gamma)}$$

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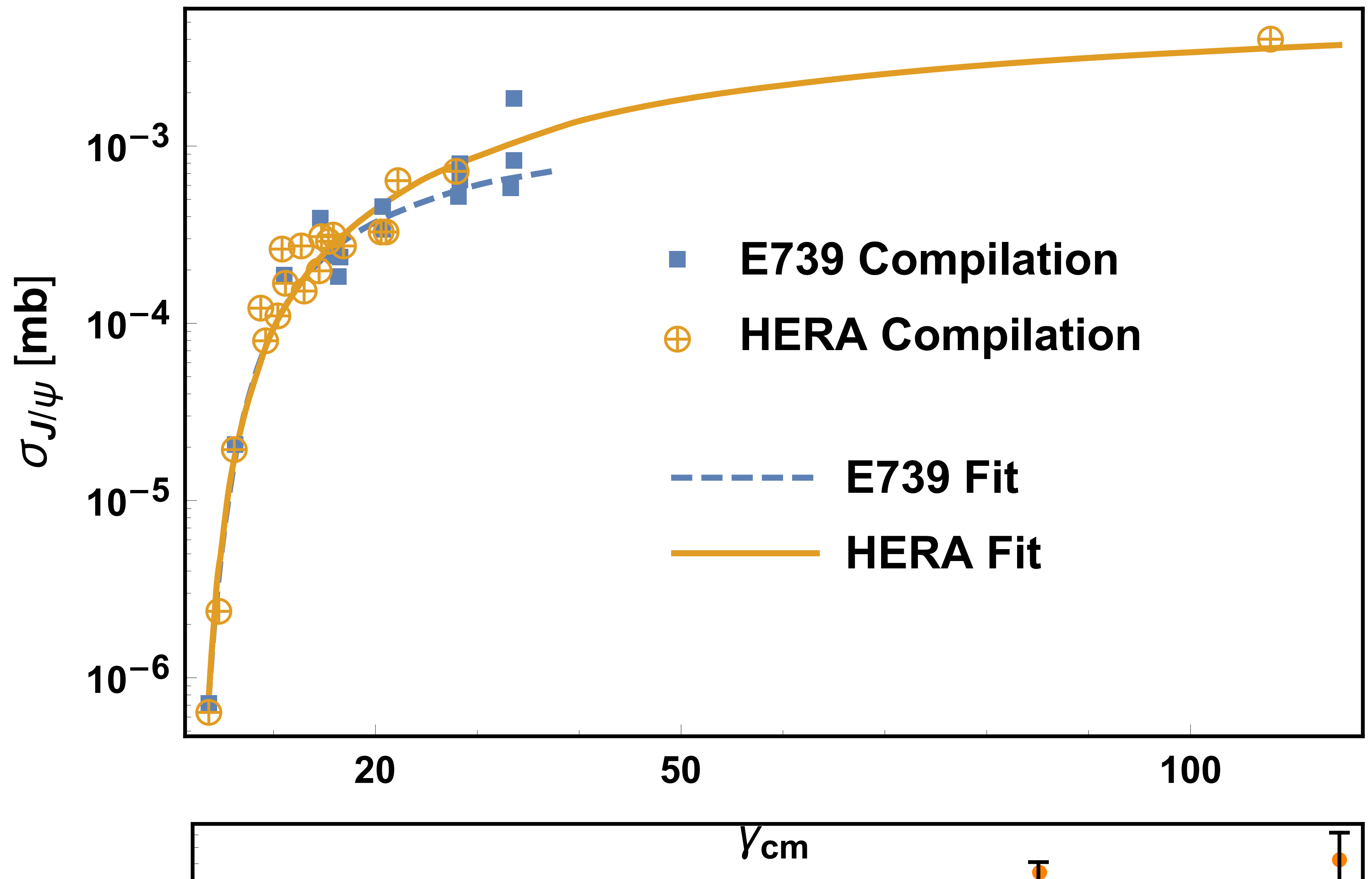

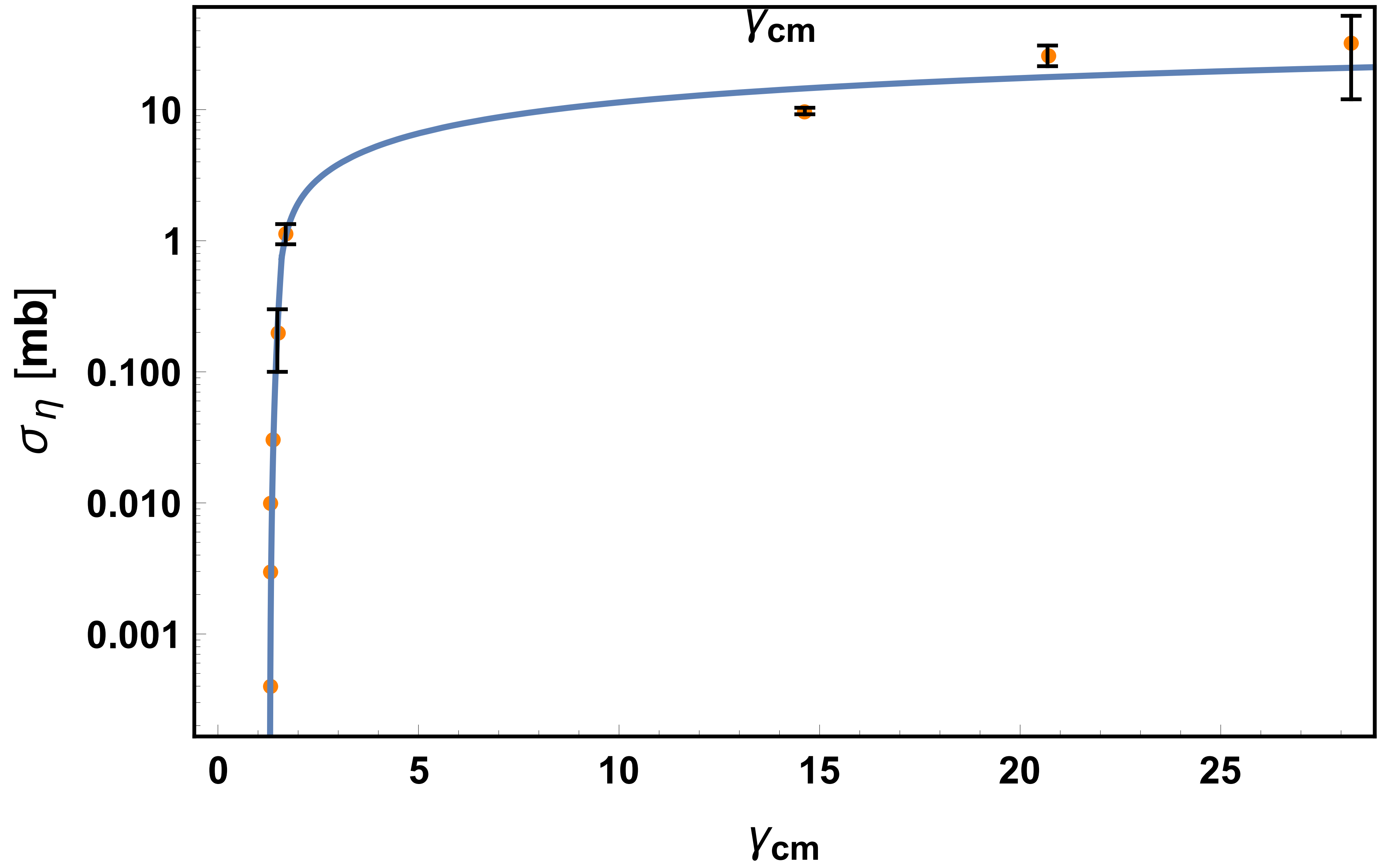

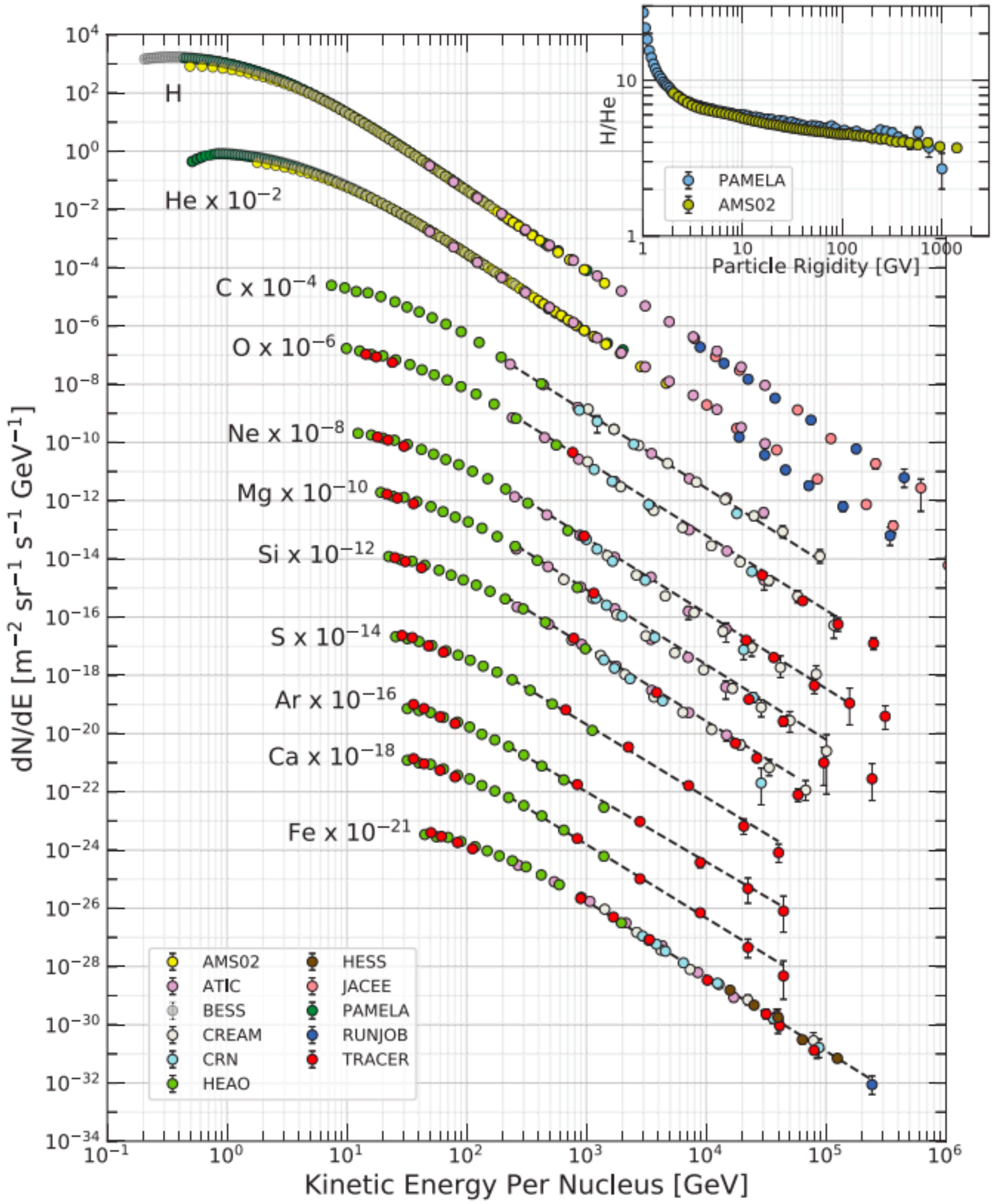

Meson production

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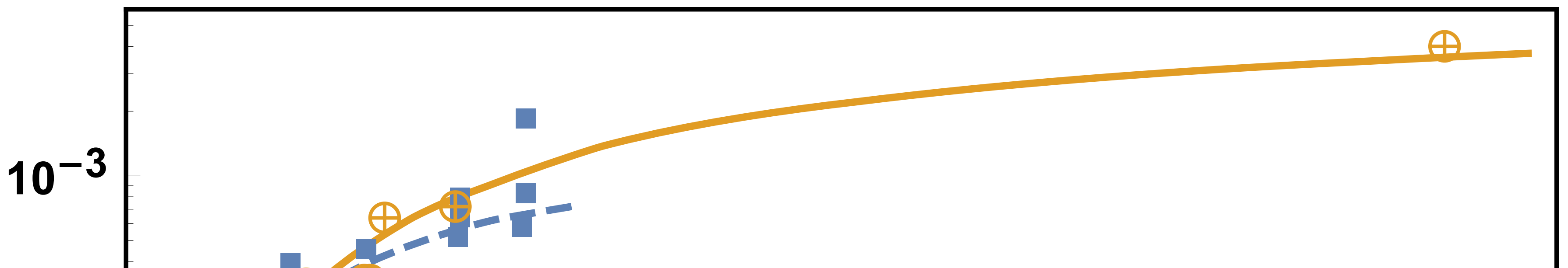

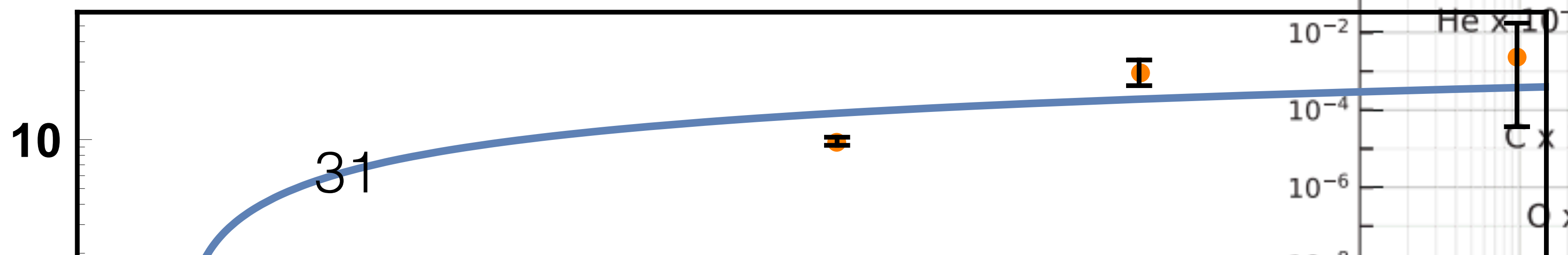

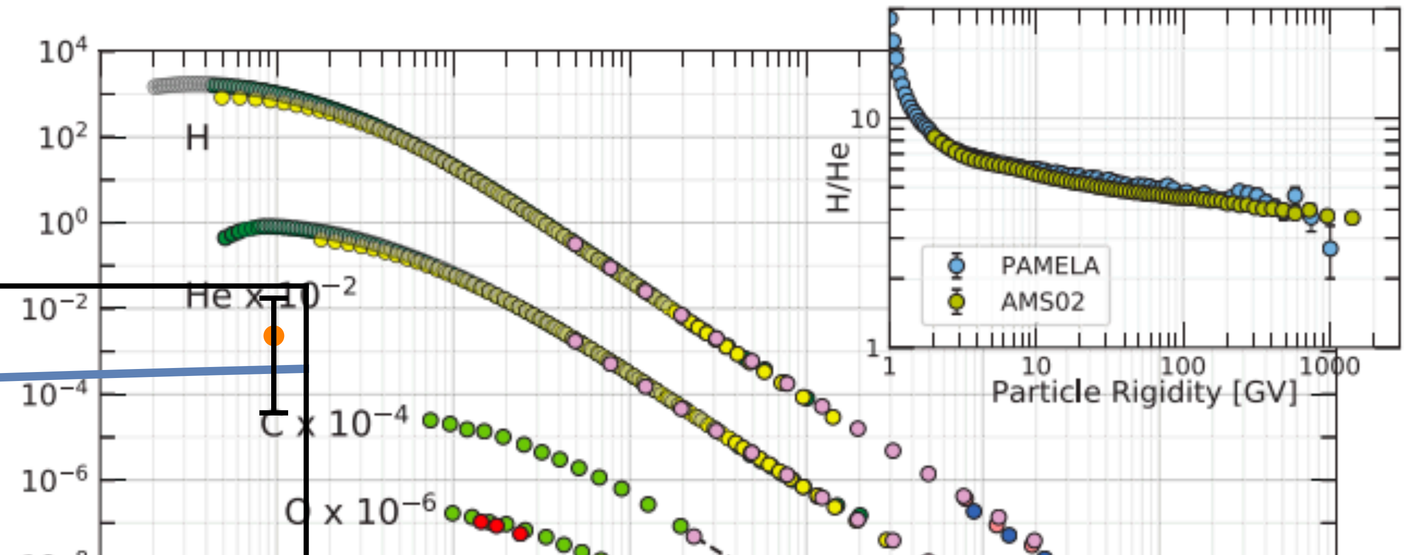

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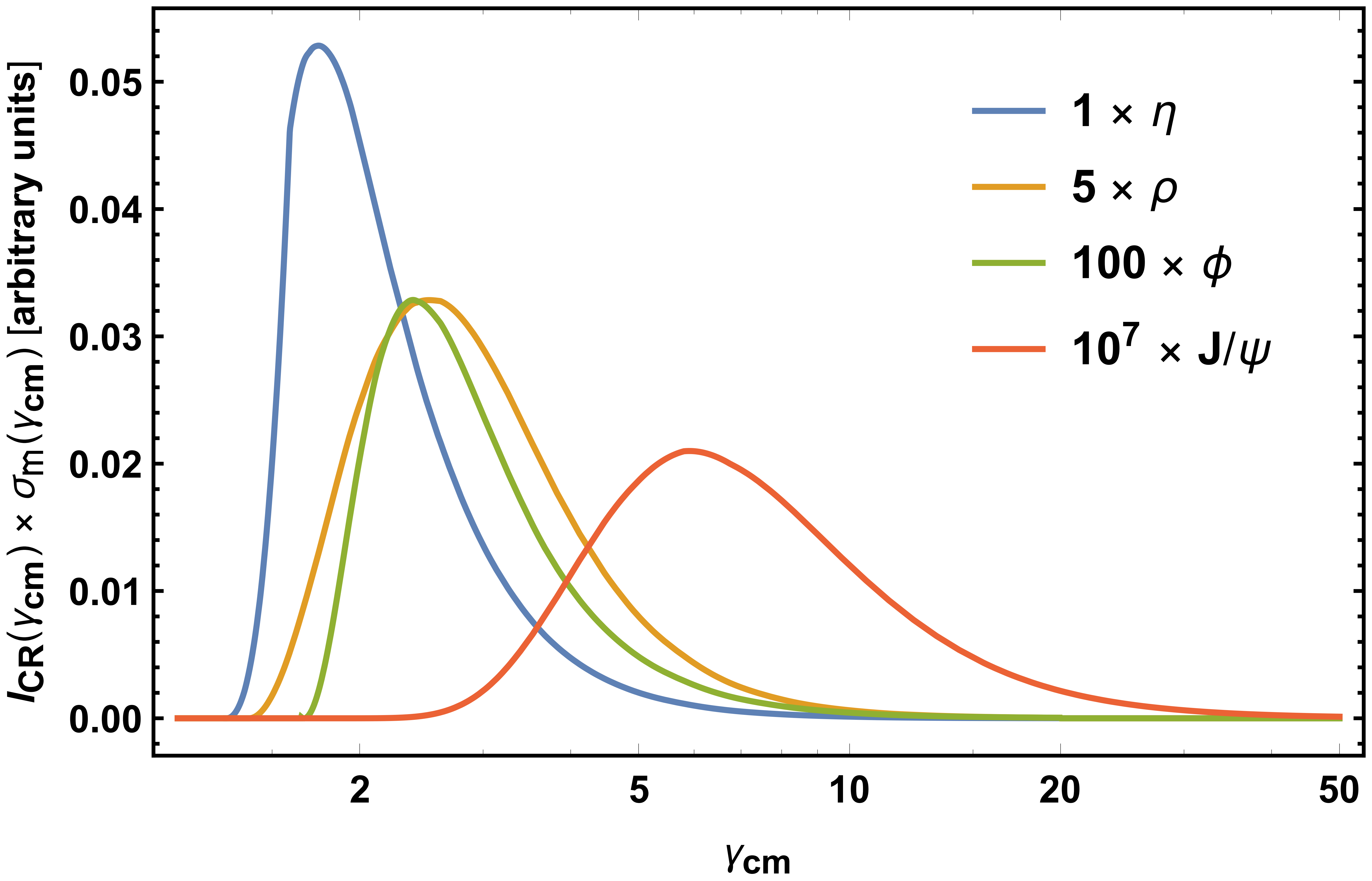

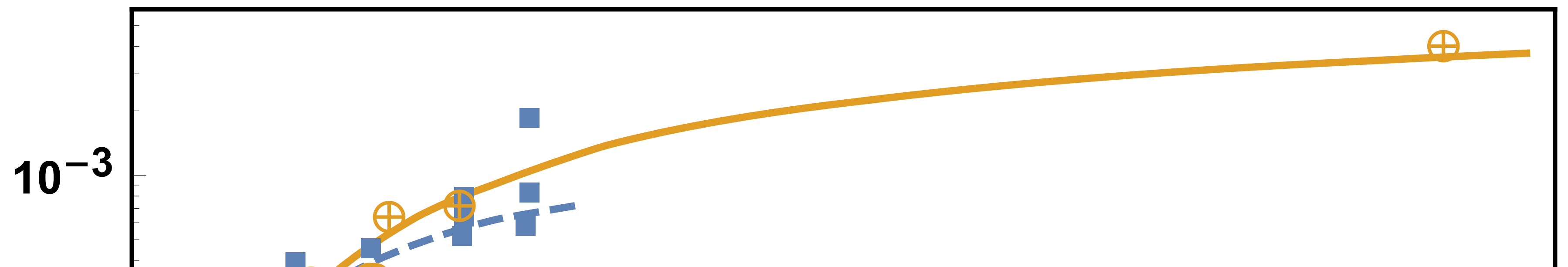

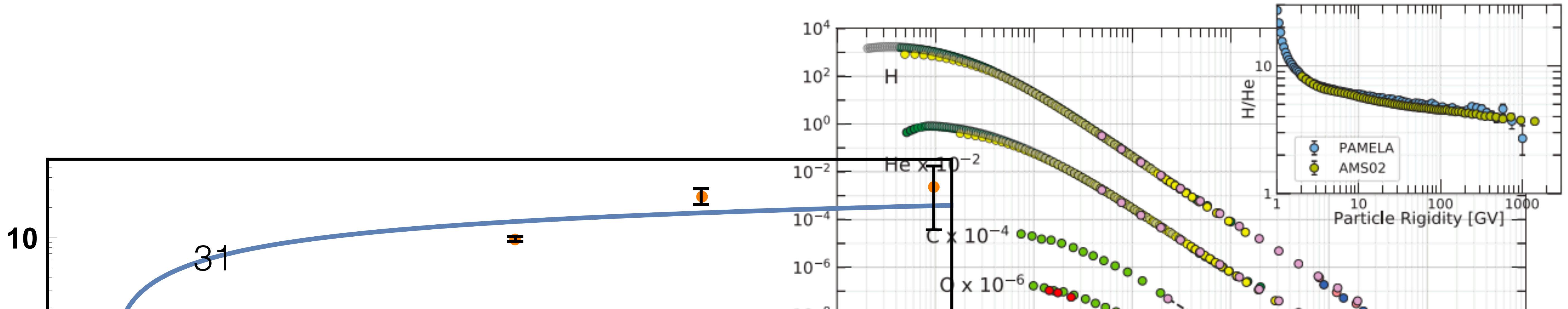

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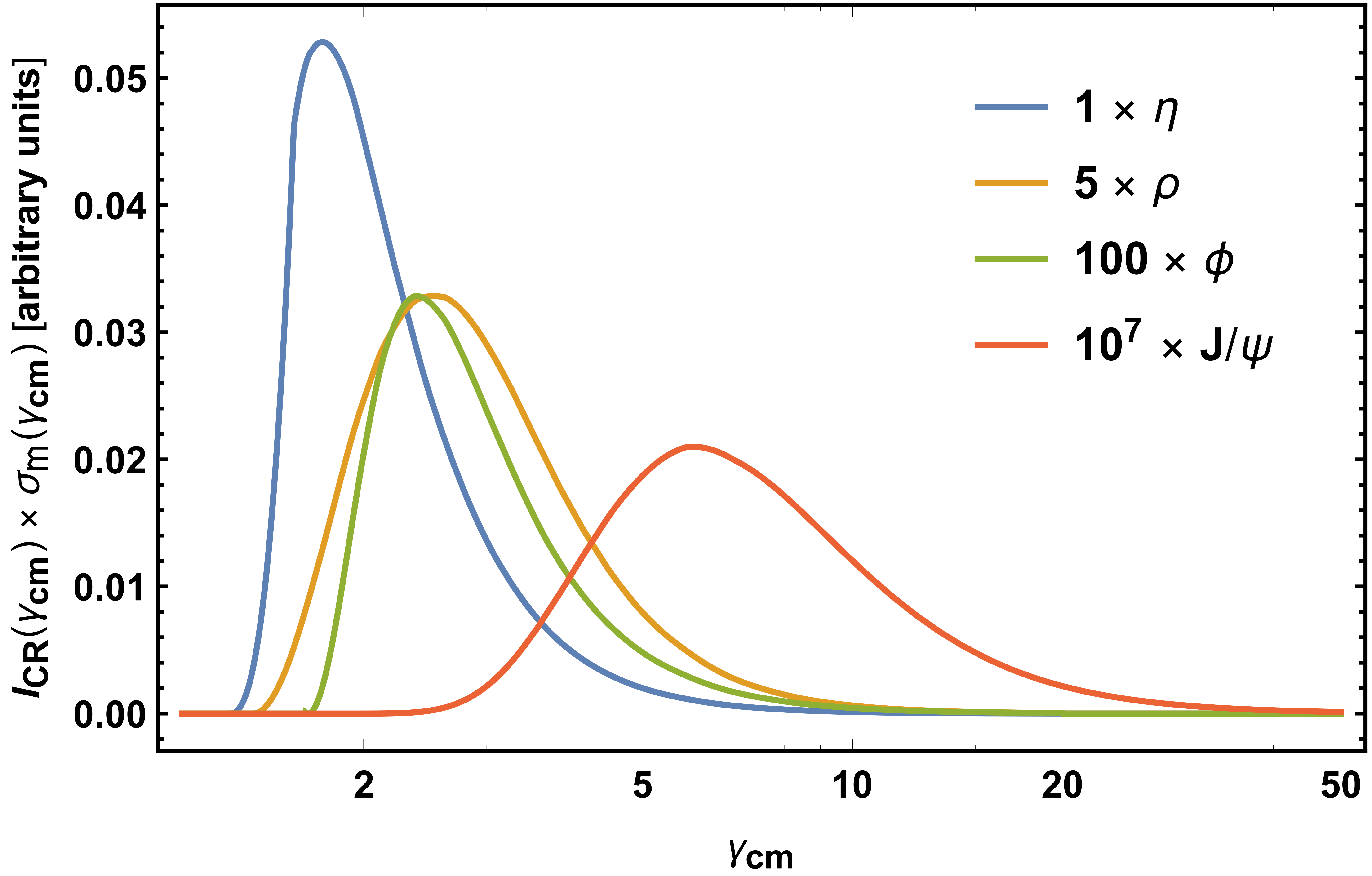
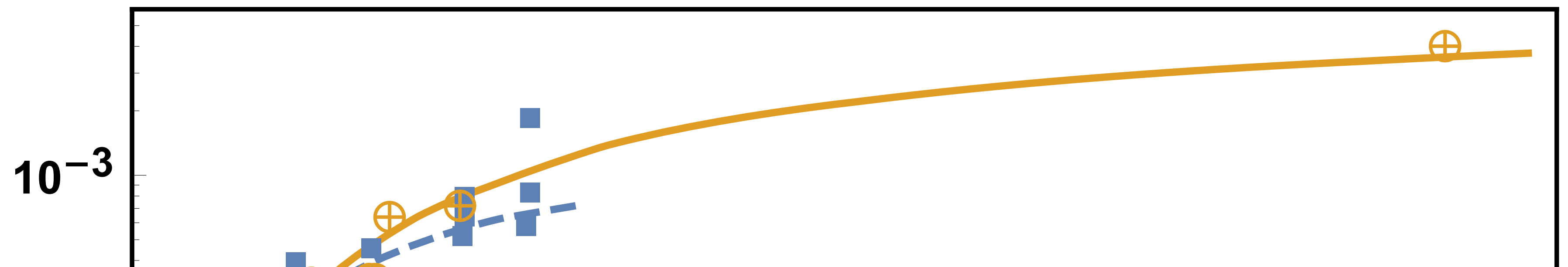
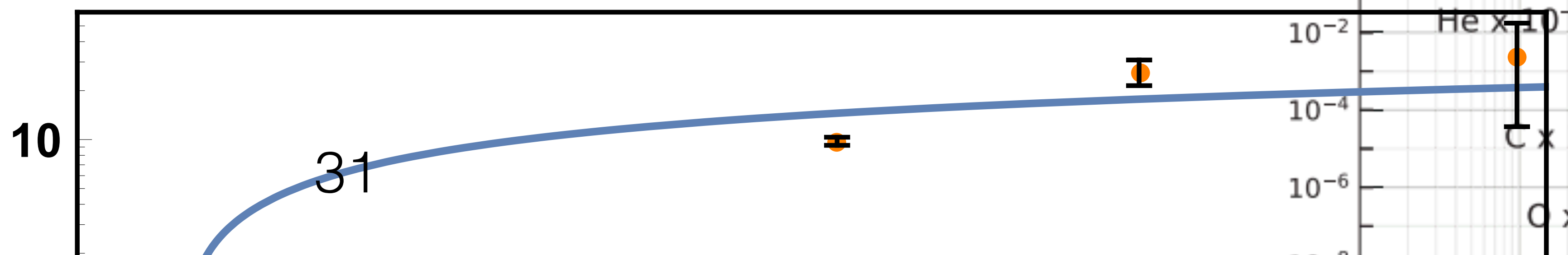
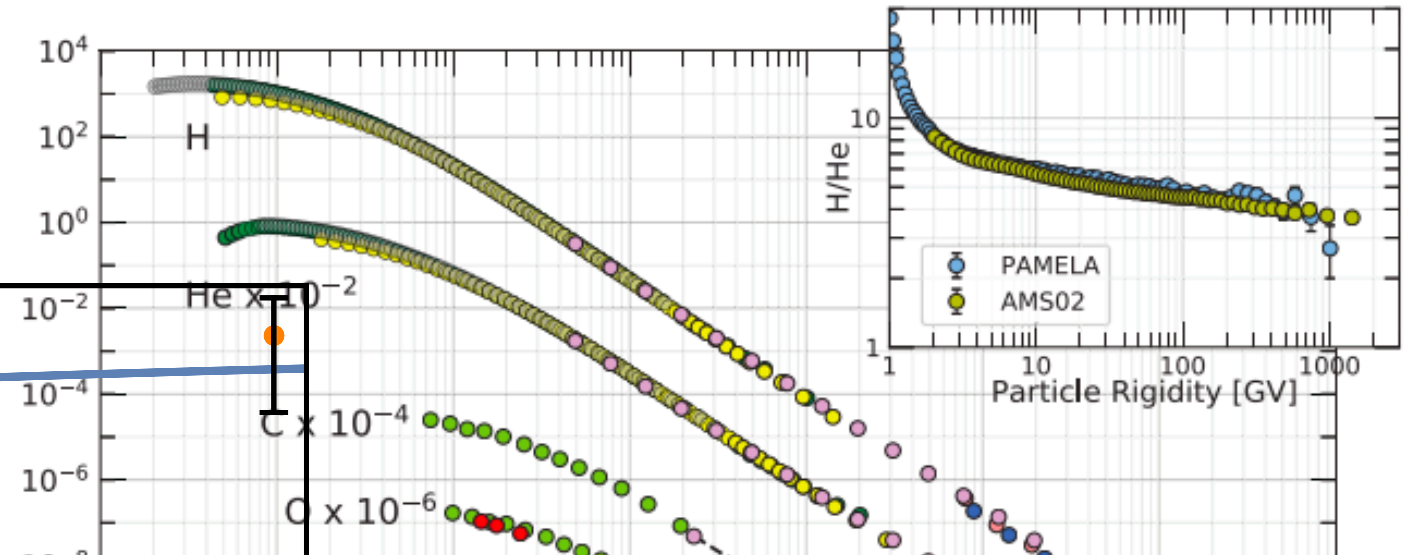


What about the boost distribution?







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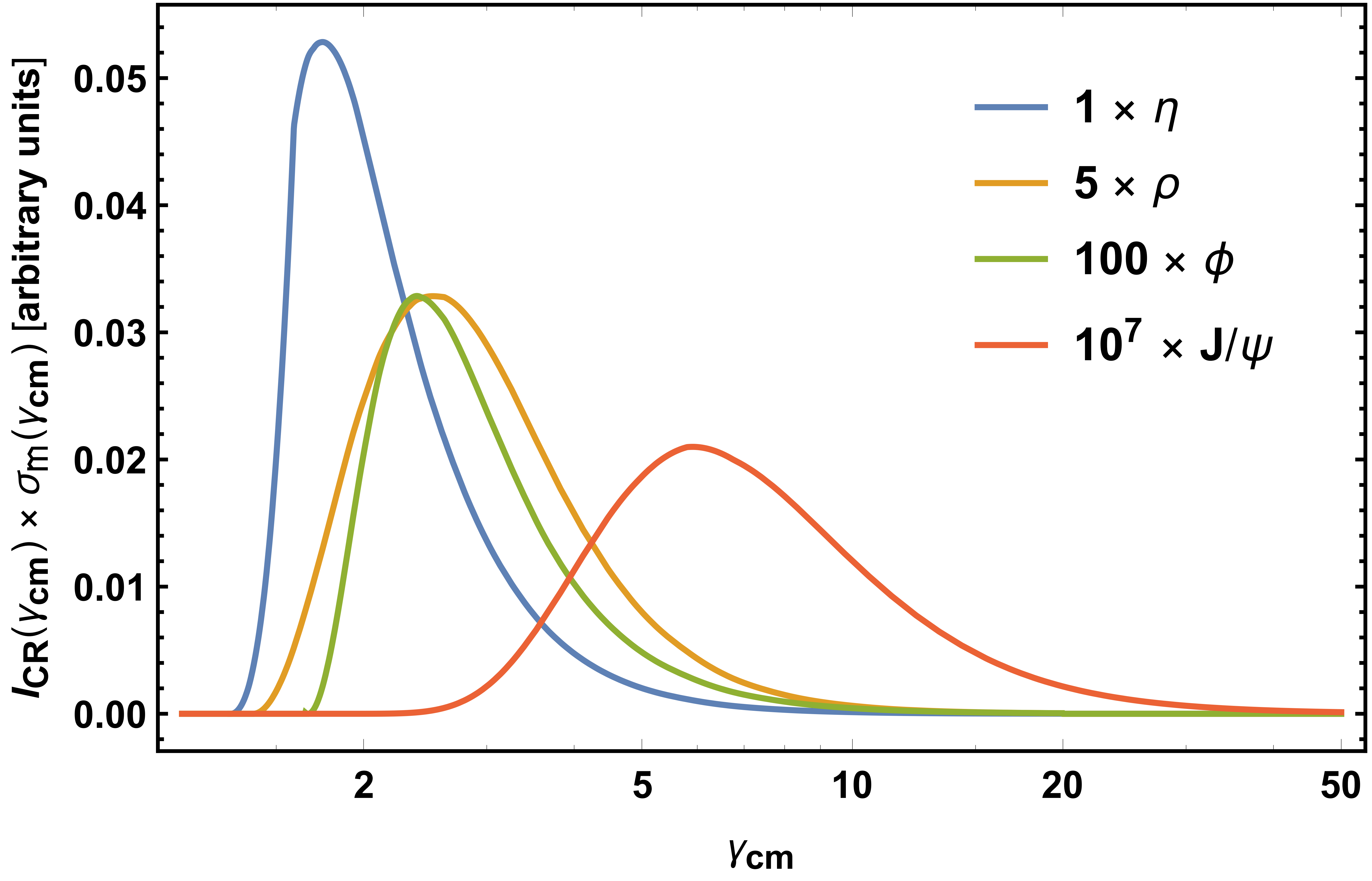
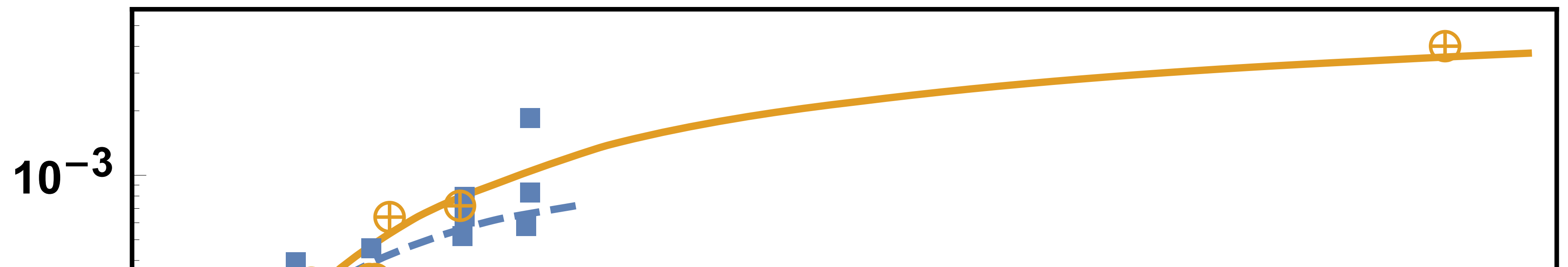
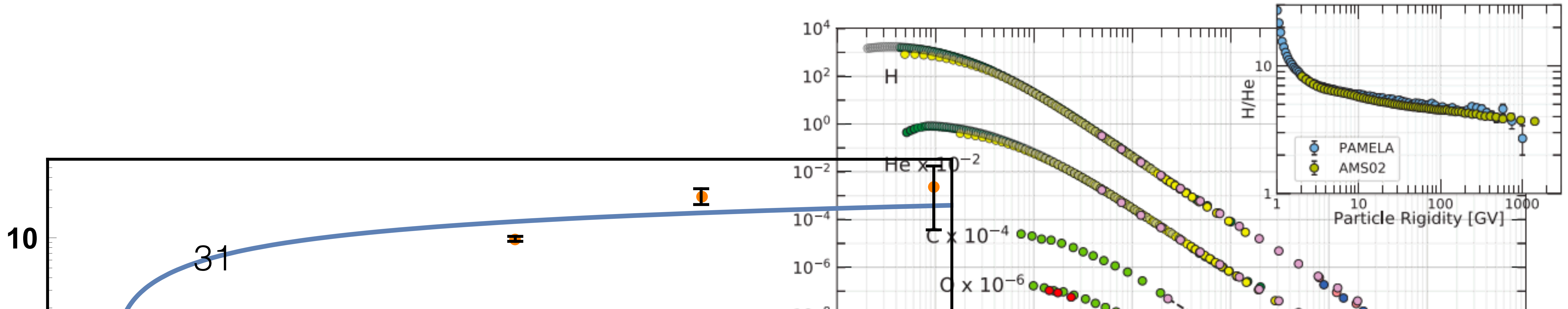


What about the boost distribution?

$$P(\gamma_{\mathfrak{m}} \,|\, \gamma_{\mathrm{cm}})$$





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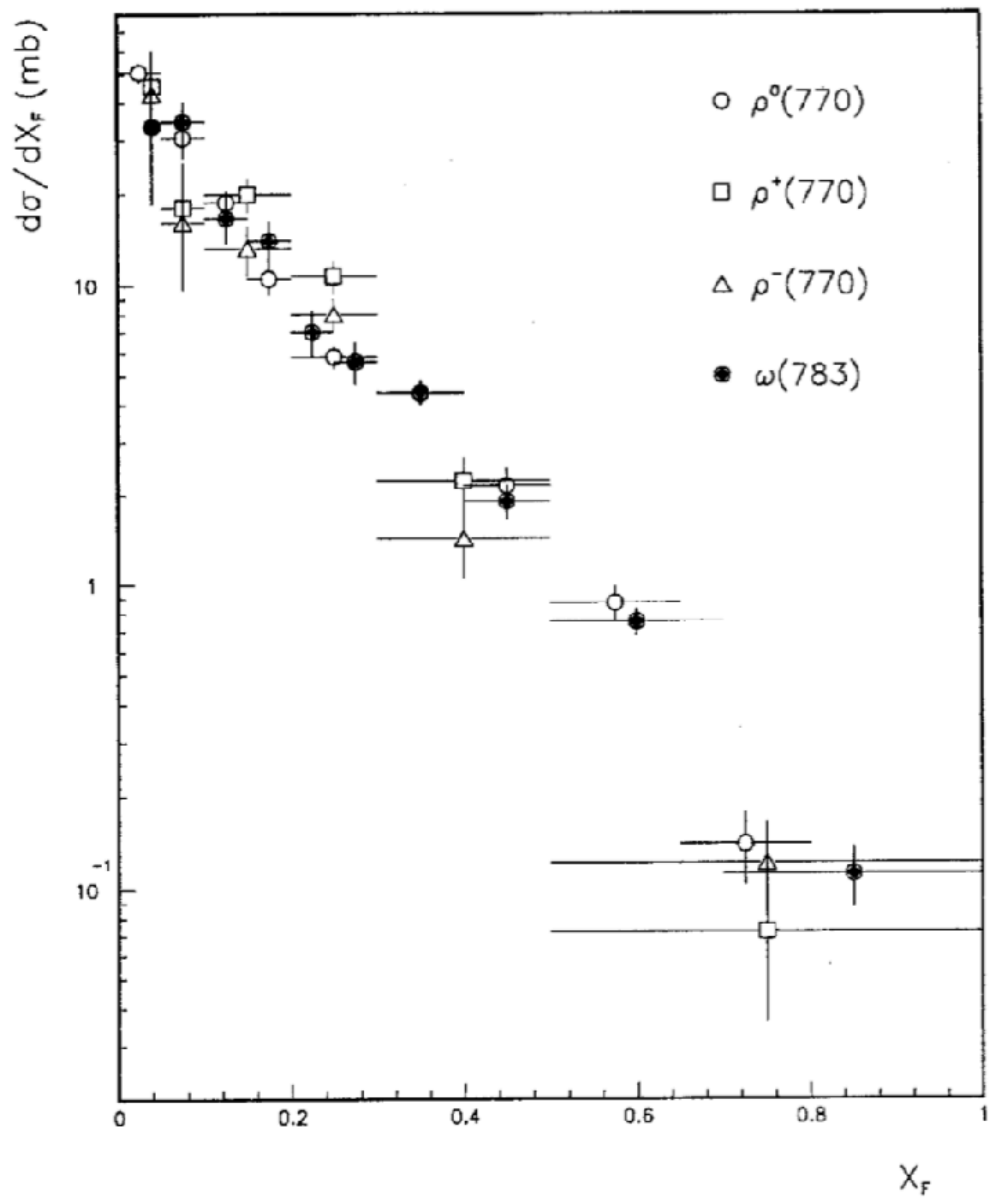


Fig. 22. The $d\sigma/dx_F$ distributions for $\rho(770)$ and $\omega(783)$ mesons

Meson production

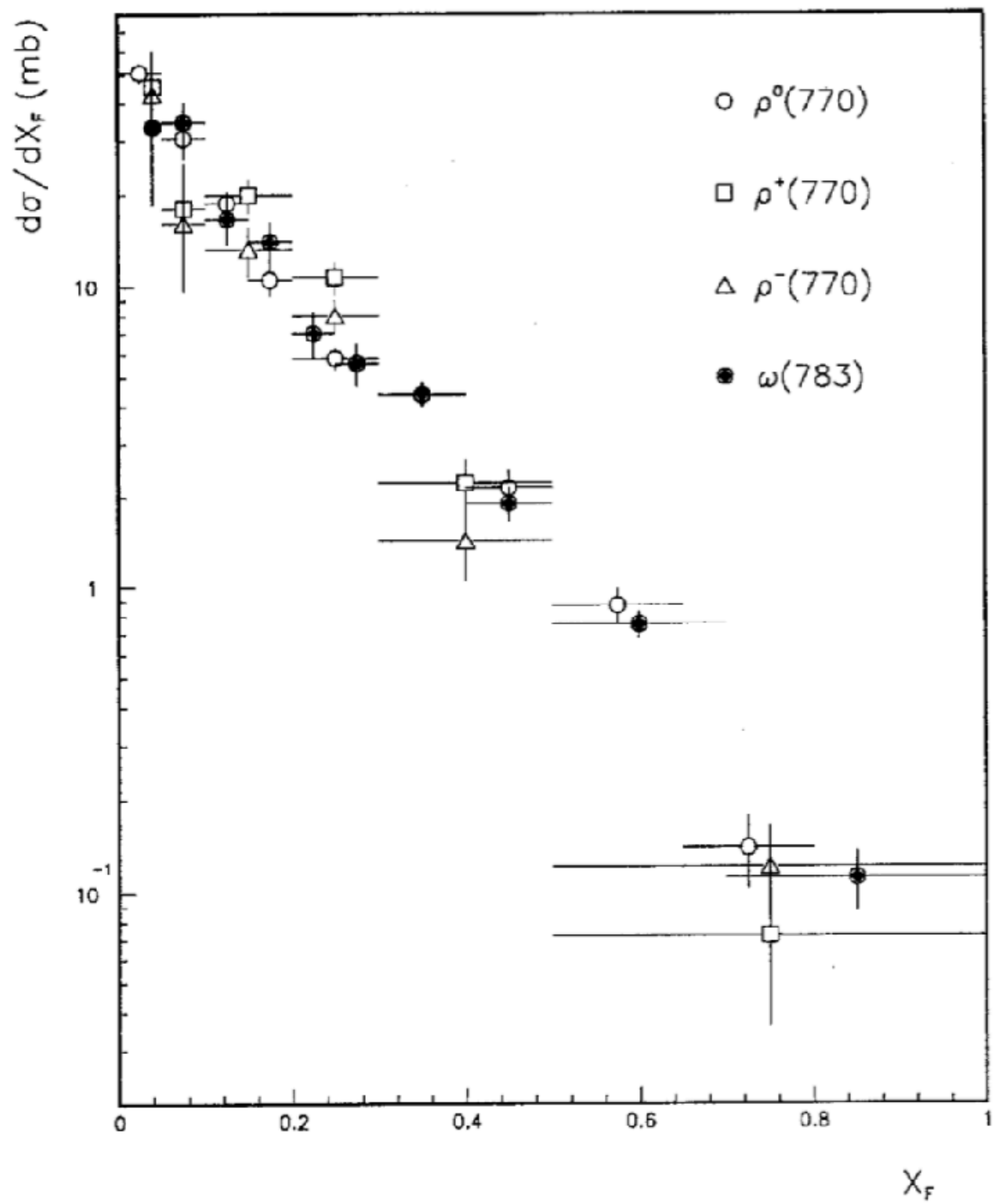
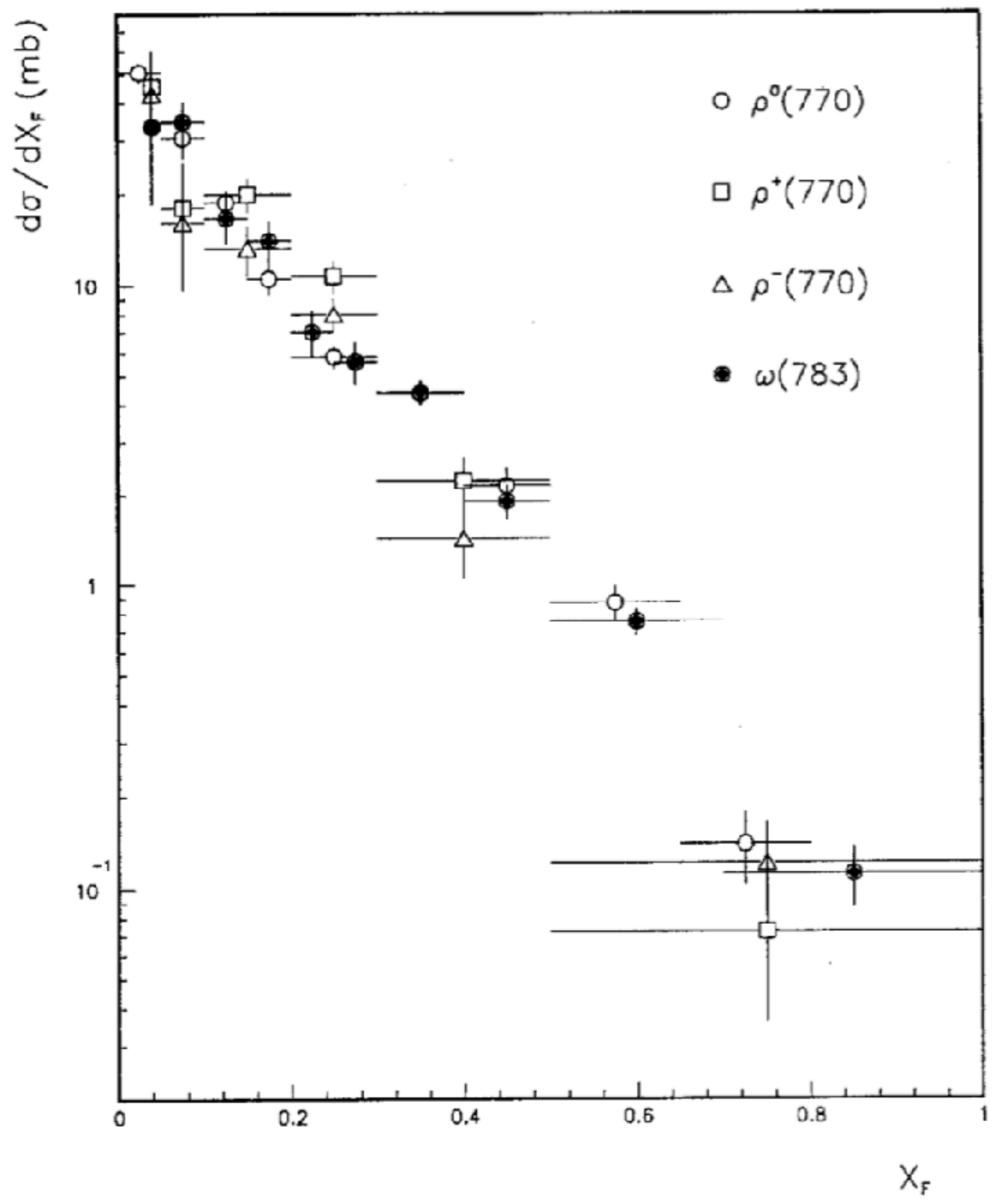


Fig. 22. The $d\sigma/dx_F$ distributions for $\rho(770)$ and $\omega(783)$ mesons

$$p_\parallel \gg p_\perp$$

Meson production



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$$p_{\parallel} \gg p_{\perp}$$

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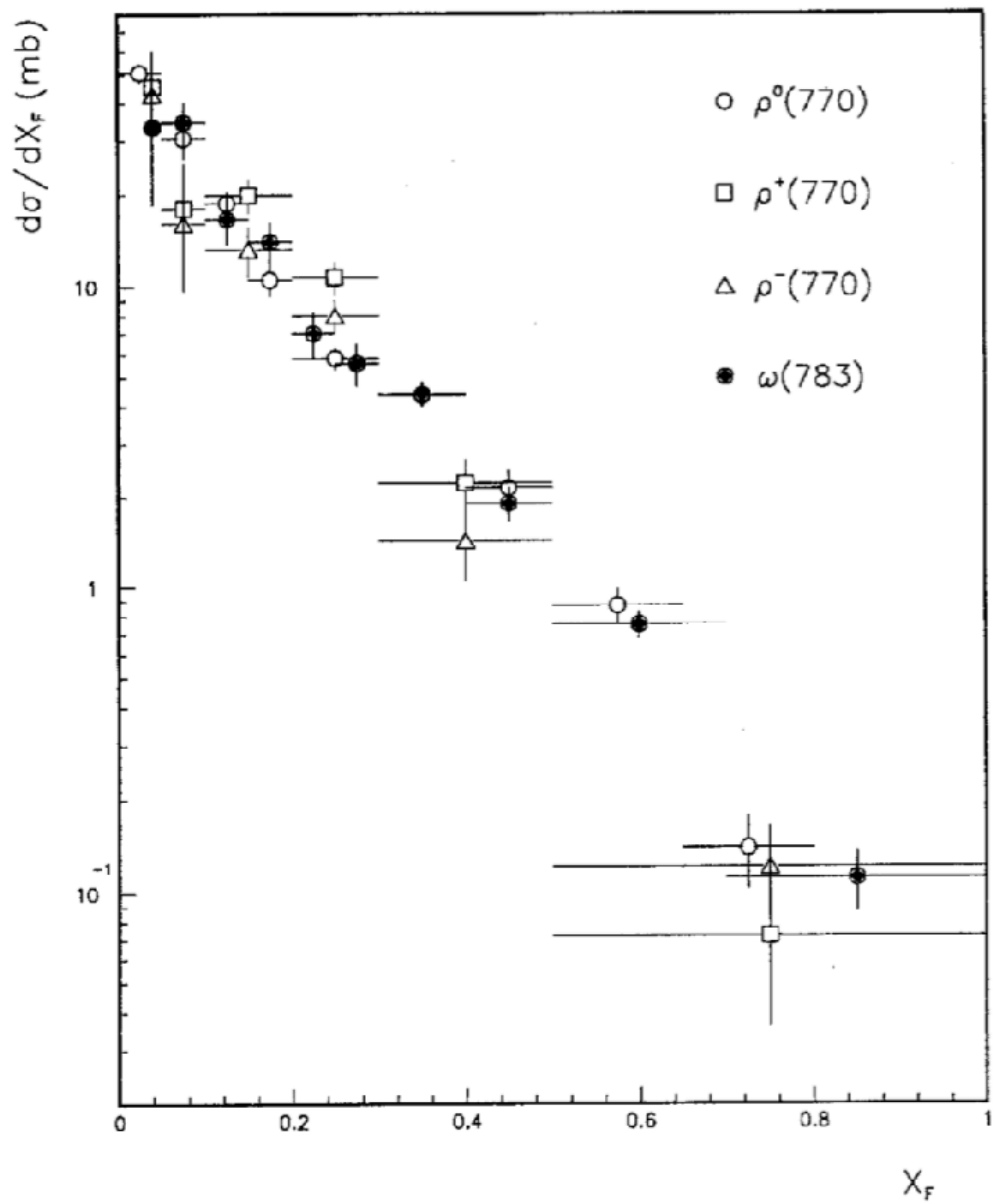

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$$\gamma_{\mathfrak{m}} = f(\gamma_{\rm cm}, x_F)$$

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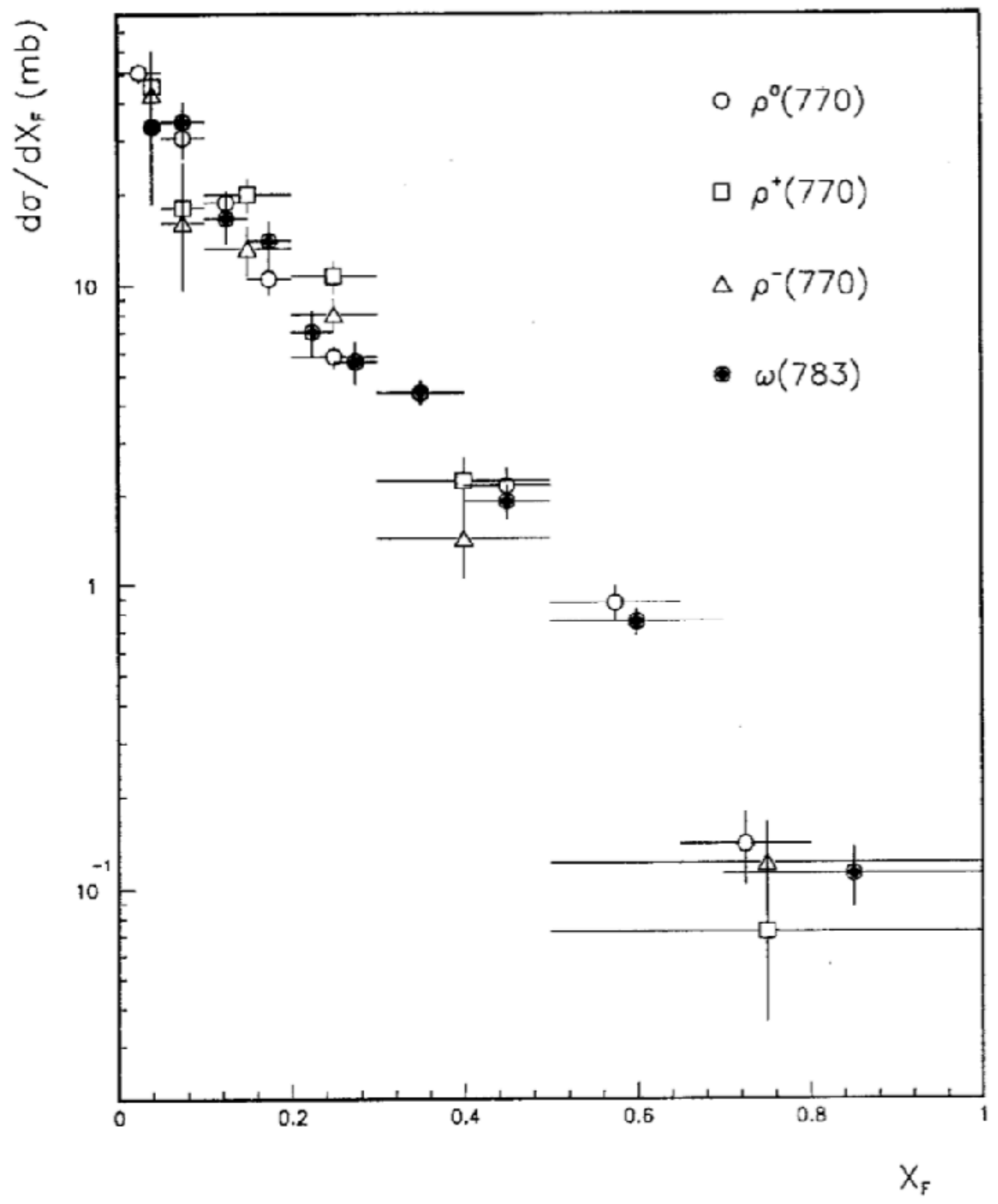

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$$\gamma_{\mathfrak{m}} = f(\gamma_{\rm cm}, x_F)$$

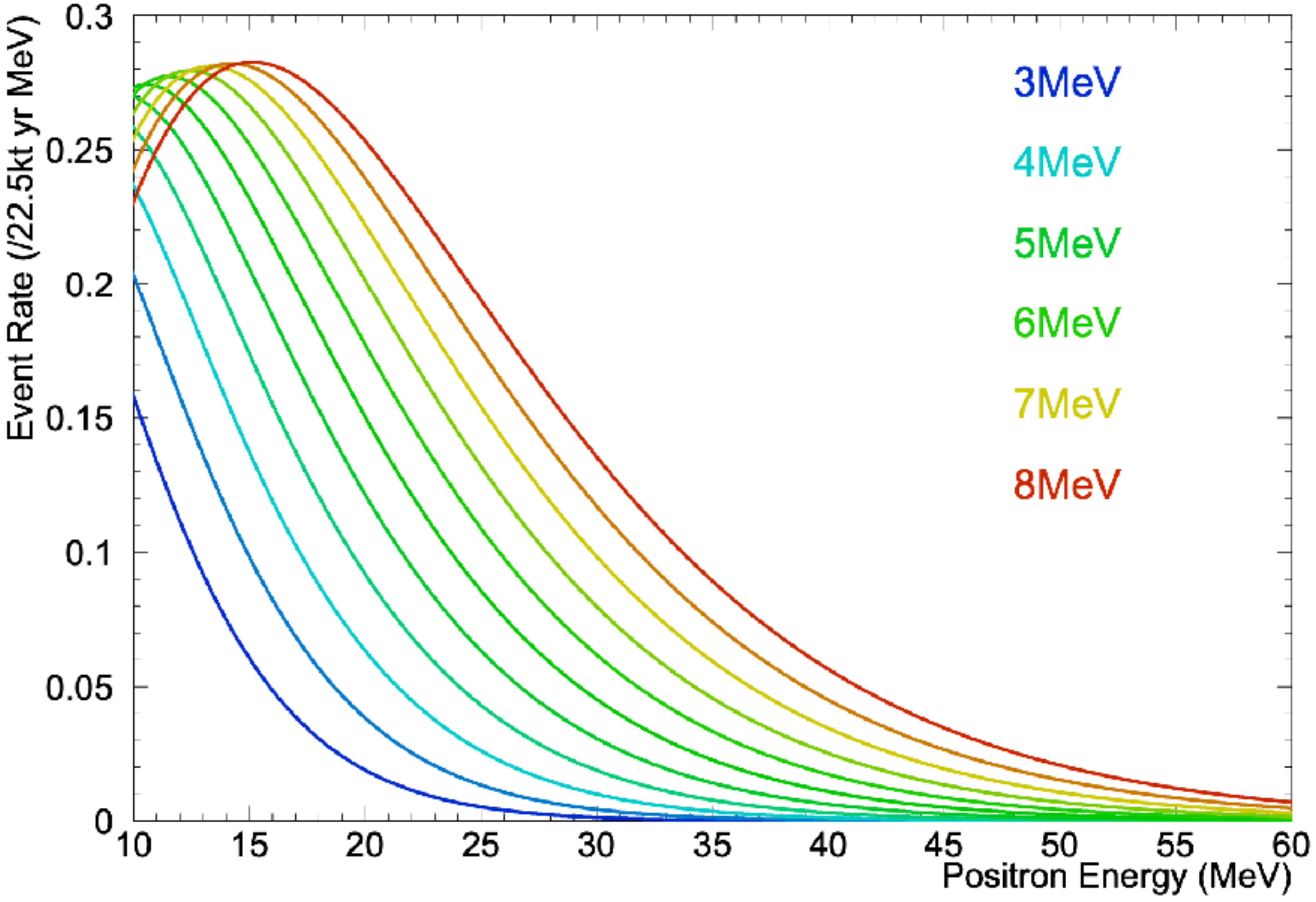
$$P(x_F \,|\, \gamma_{\rm cm}) = \frac{1}{\sigma(\gamma_{\rm cm})} \frac{d\sigma(\gamma_{\rm cm})}{dx_F}$$

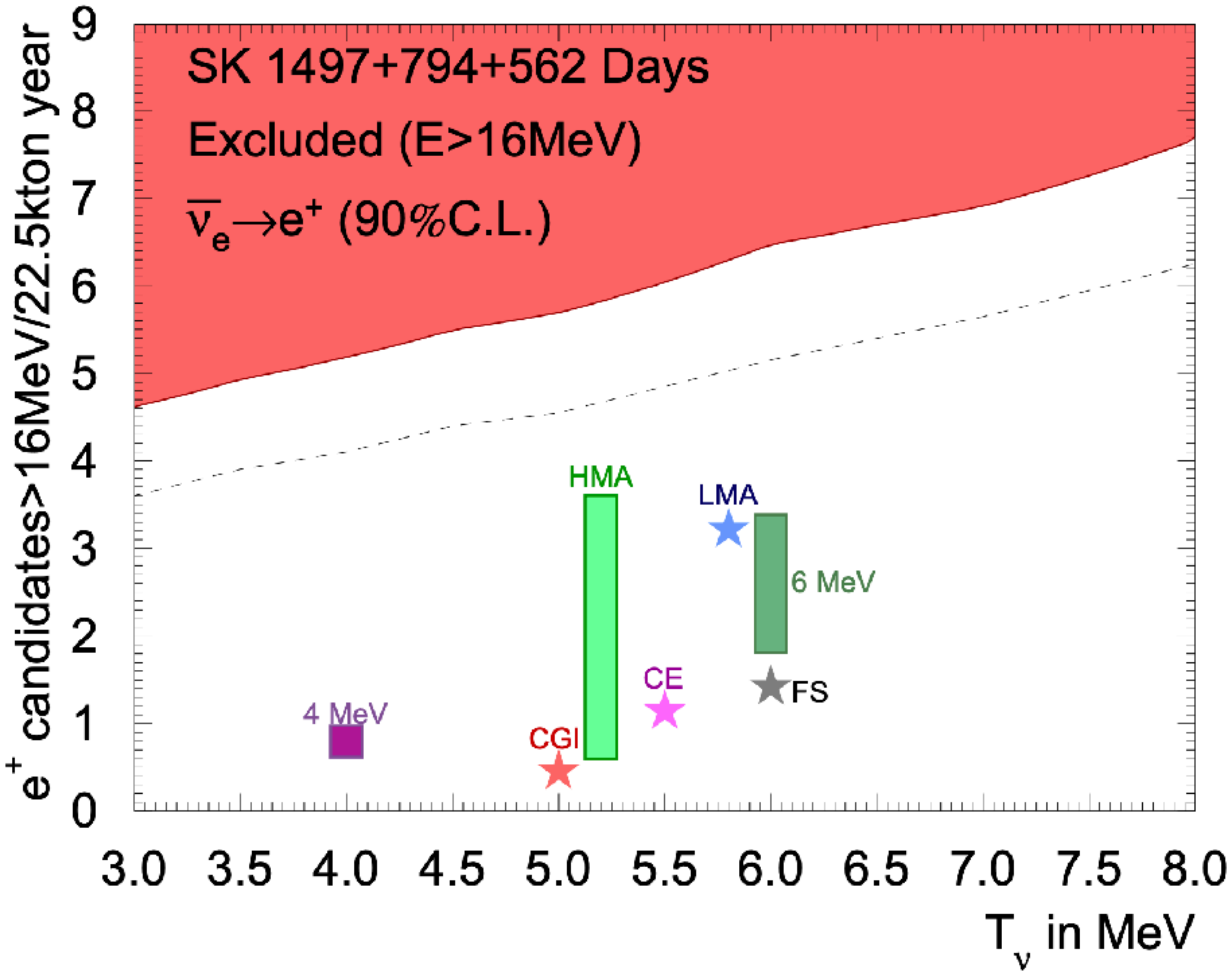
1. **Everything I have told you applies to any stable particle produced in meson decays.**

2. **We compiled data for electromagnetic decaying mesons. Other new particles might need e.g. D-meson or Kaon distributions**

3. **We are only including primary mesons (no cascades).**

Super Kamiokande search for SNB





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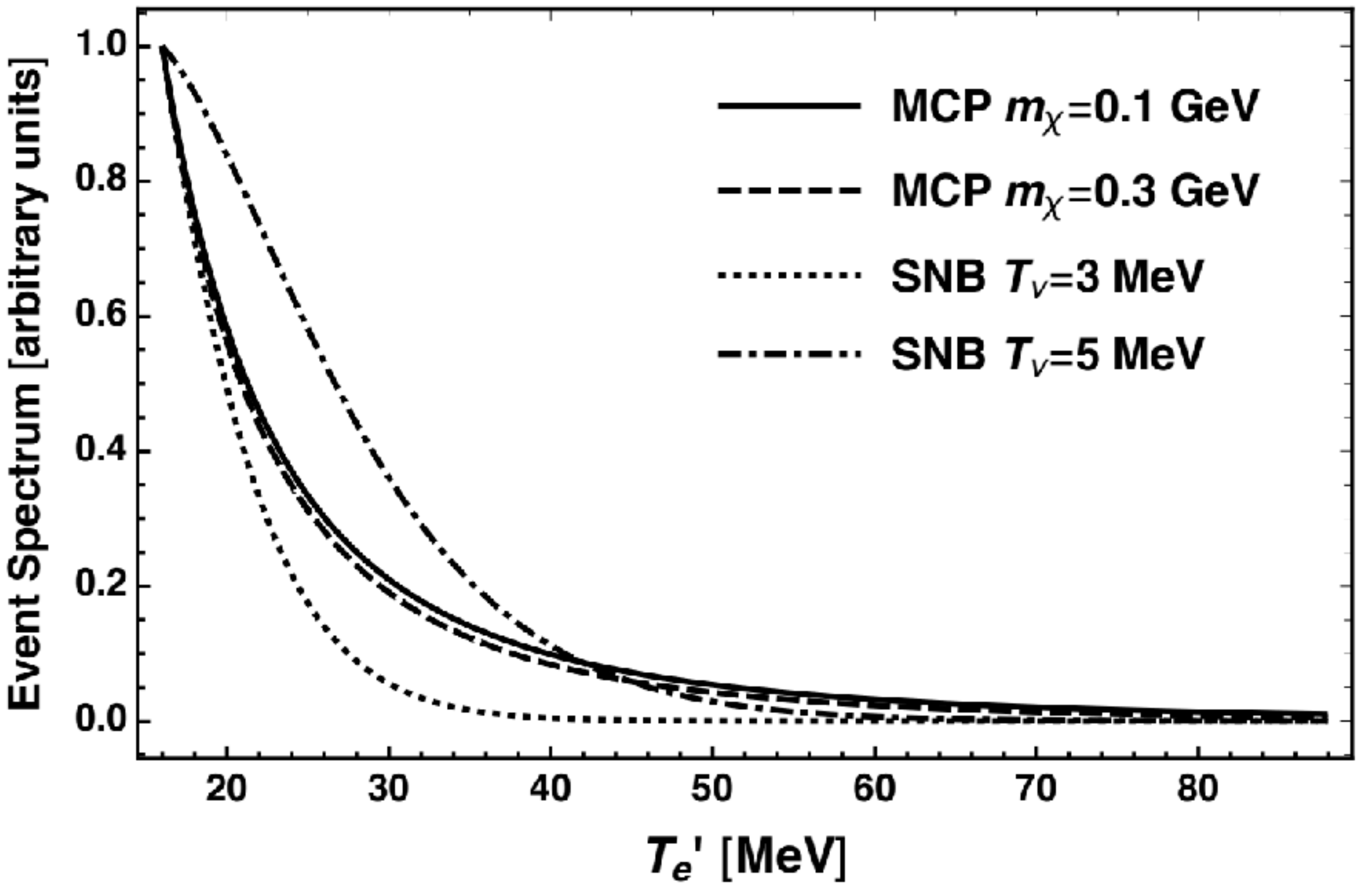

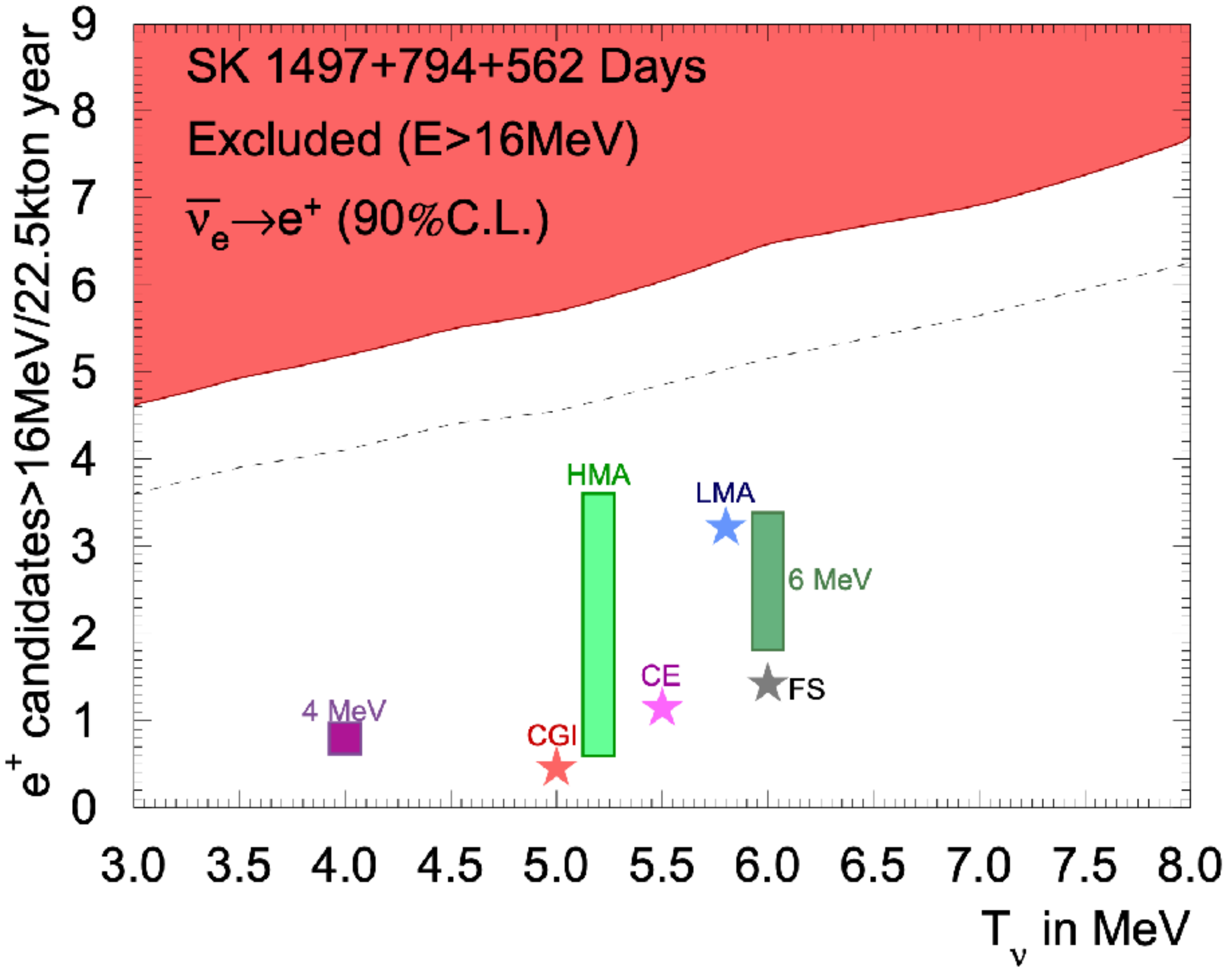

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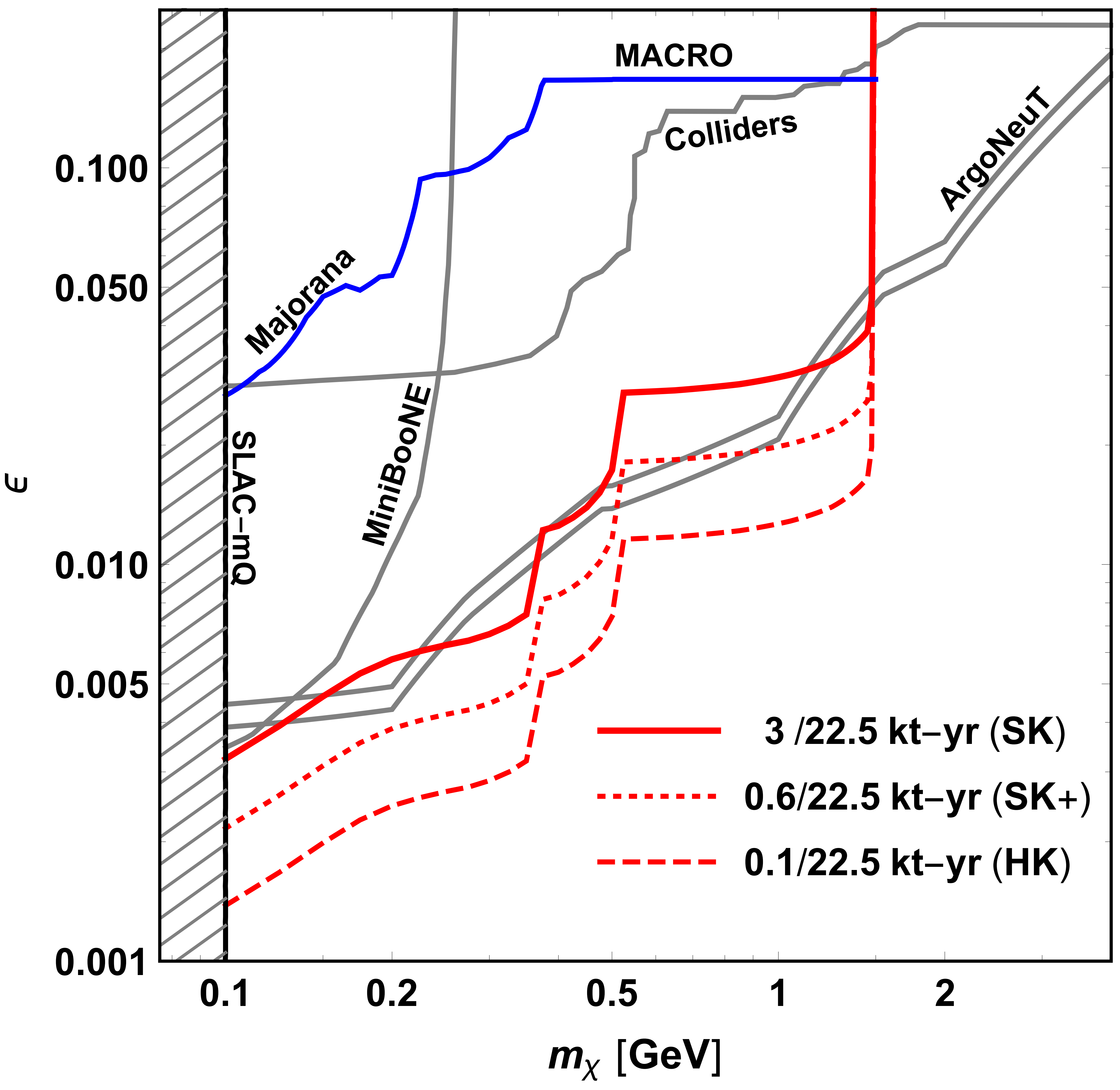
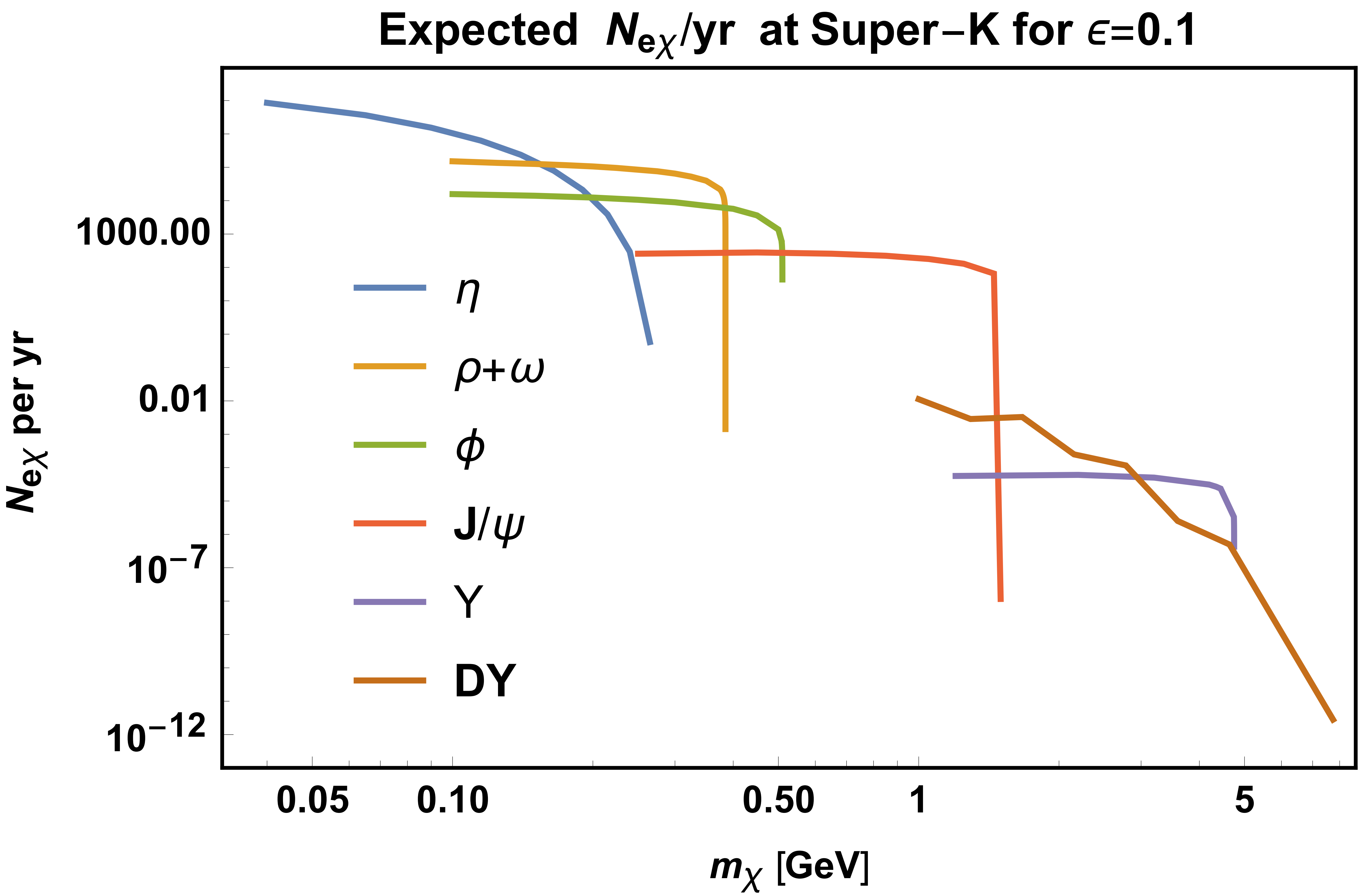
Results from cosmic rays



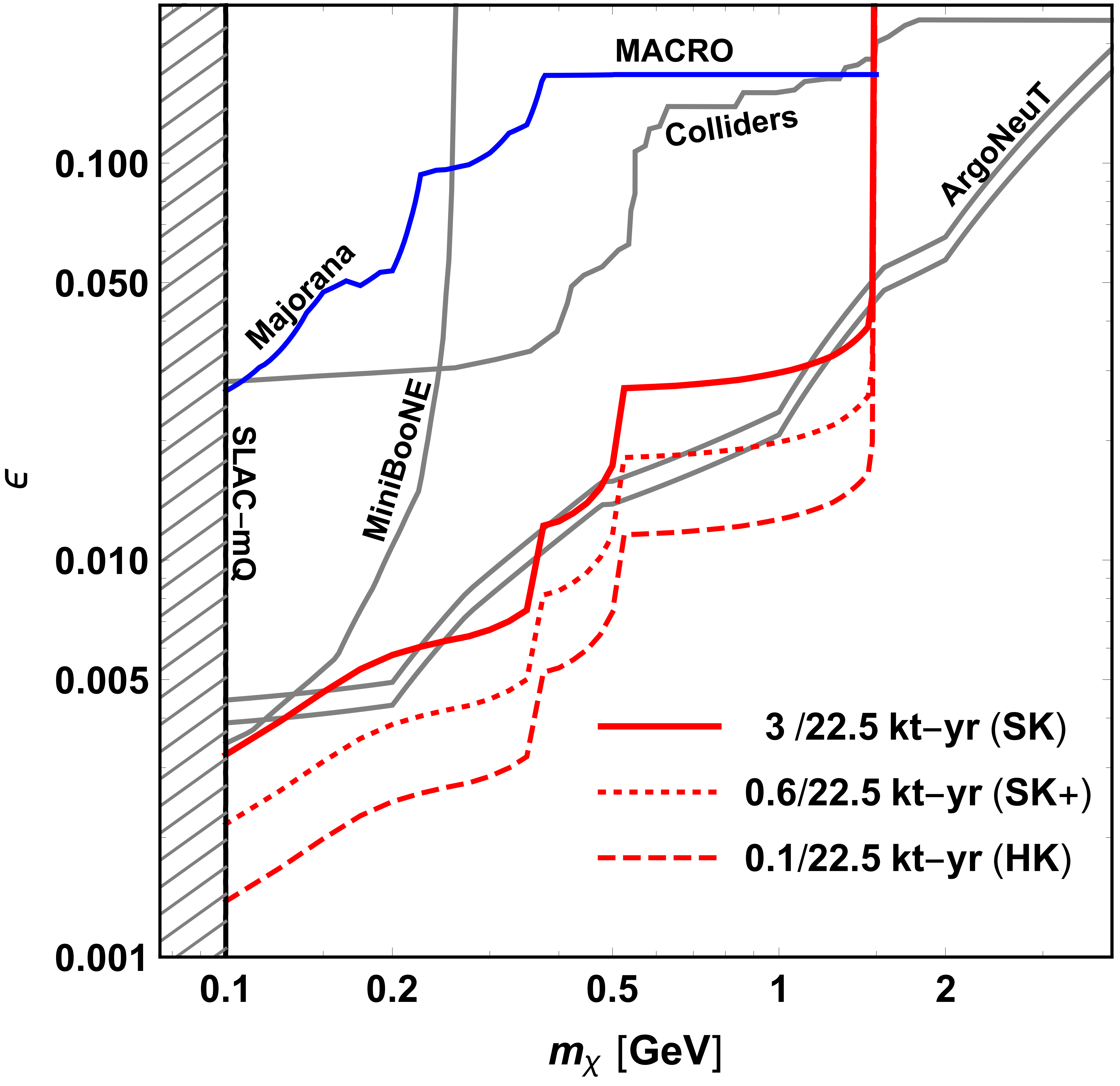


Conclusions

- Fixed target experiments and cosmic ray induced ``beams'' can provide model independent bounds on millicharged dark-sector models.

- Cosmic rays + neutrino telescopes are competitive with (and surpass) fixed target experiments.

- MCPs are kind of case study in the impact of neutrino detectors for low-recoil signals.



Outlook and Ongoing Work

Radiative Corrections to charged current scattering

Requisite error budget for e.g. DUNE is ~1-3 %

What Standard Model physics is important at this level of precision?

$$\alpha/4\pi \sim 0.1\,\%$$

$$\times Z \sim \text{few}\,\%$$

Coulomb field of nucleus

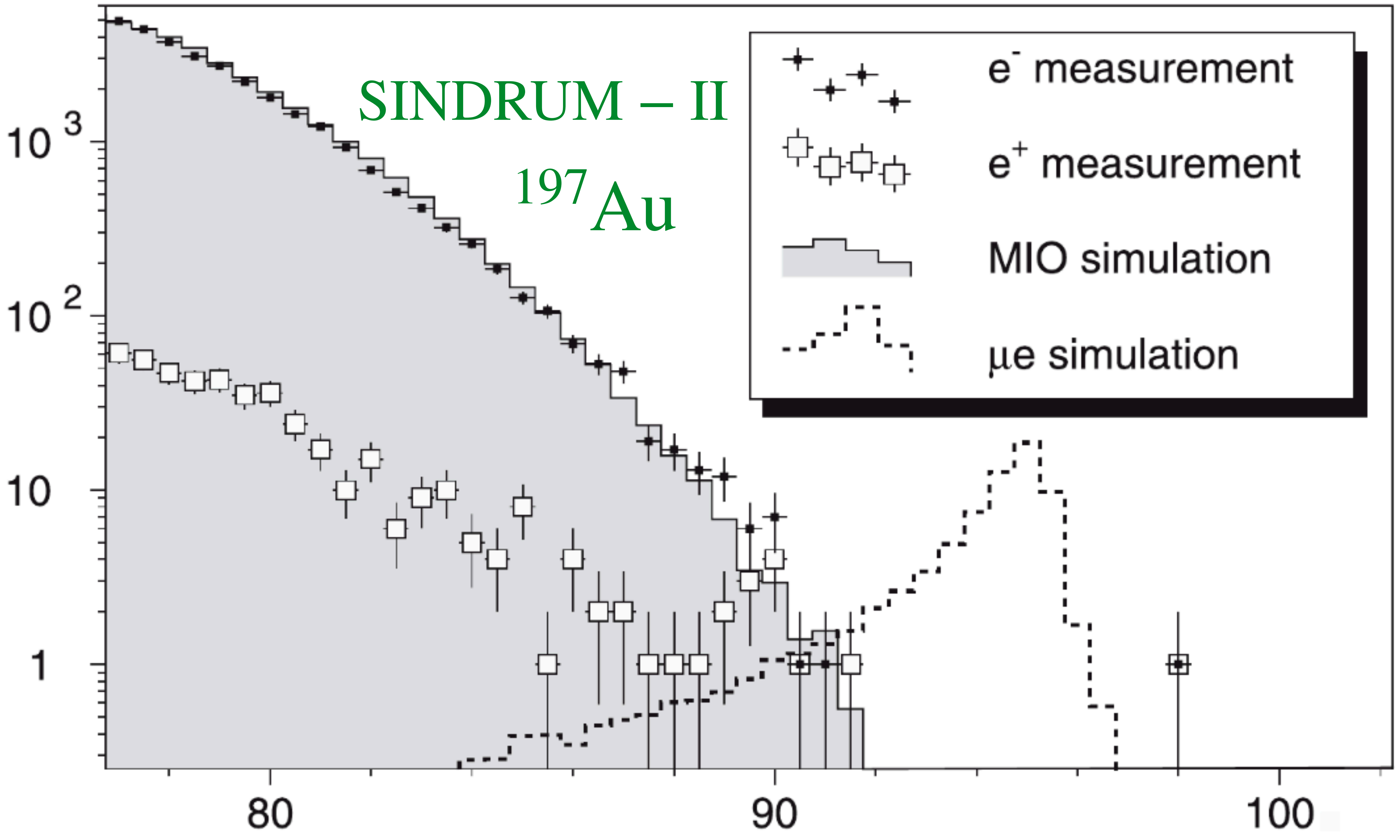
$$\times \log(Q_{\max}/m_\ell) \sim \text{few}\,\%$$

Large logs from radiative corrections

Work ongoing with RHJ Hill, and O Tomalak

See e.g.
Day and McFarland arXiv:1206.6745
Hill and Tomalak, arXiv:1907.03379

Mu2e Backgrounds from Radiative Muon Capture



Background

$\mu^- \ ^{27}\mathrm{Al} \rightarrow {}^{27}\mathrm{Mg}\ \gamma\ \nu_\mu$

$\gamma \rightarrow e^+ e^-$

Search for $\mu^- \rightarrow e^\pm$

Study RMC spectrum near endpoint

Summary and Conclusions

Conclusions

1. High intensity neutrino experiments are a fertile testing ground for SM and BSM physics.

2. Cosmic rays + Neutrino telescopes can function like a fixed target facility offering competitive reach.

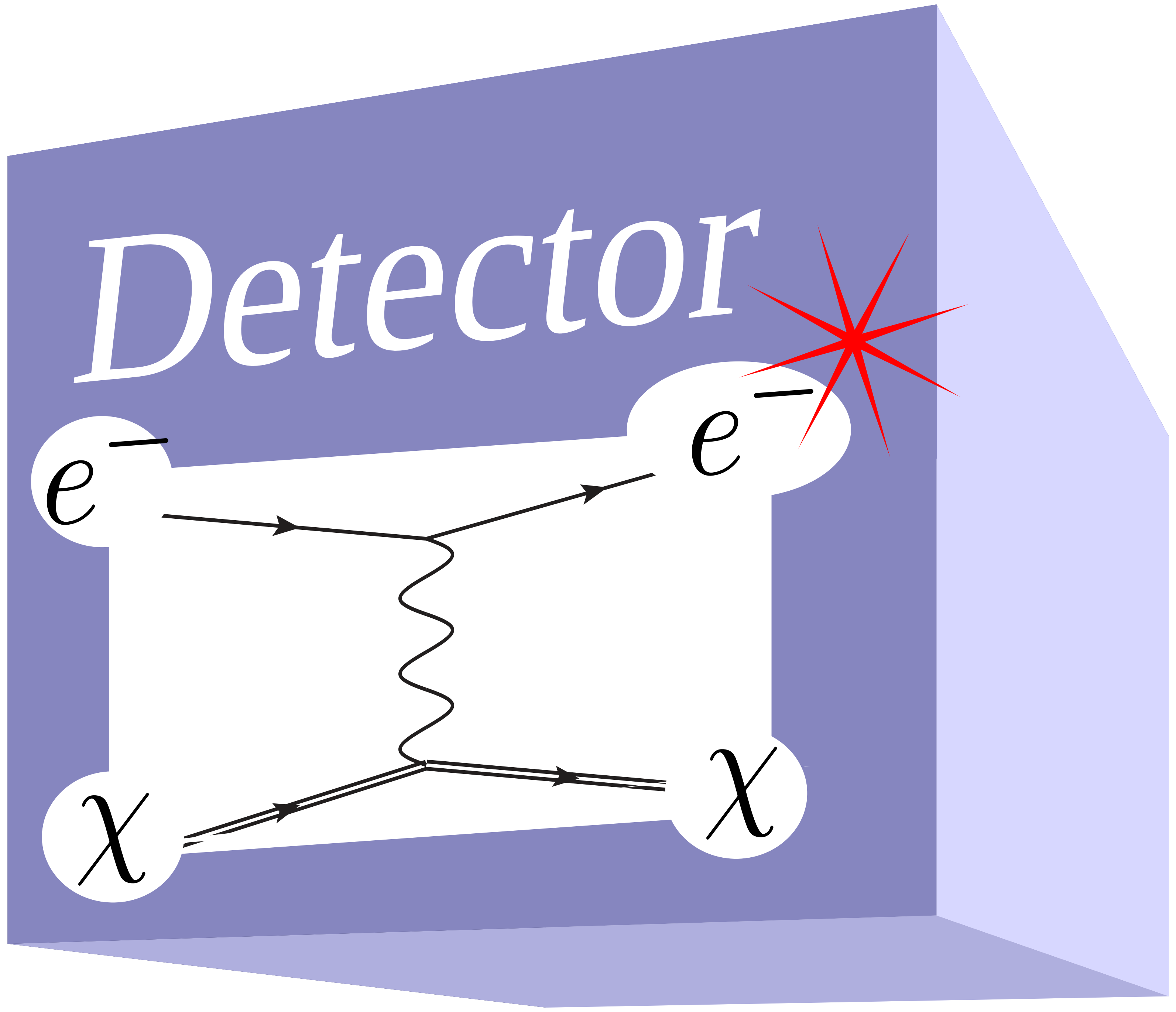
3. "New" SM physics can be impactful across a range of communities
   - Neturino flux determination
   - Expected background for CLFV & LNV searches

4. Studying alpha-suppressed SM physics teaches us how to use new detectors to cut down backgrounds.

Thank you for your attention

Details and Extras

Detecting MCPs with Neutrino Telescopes

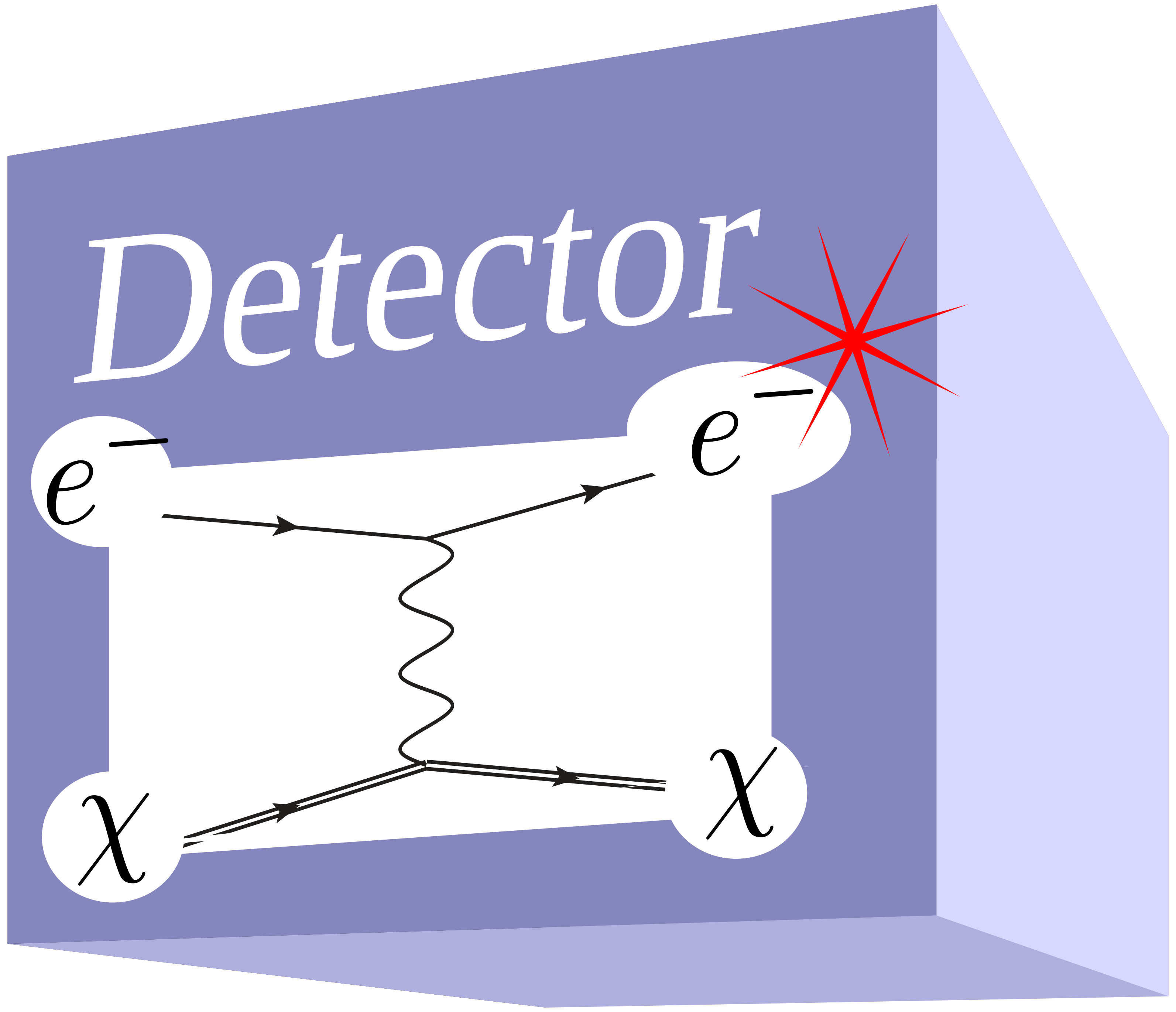


Detection Signal is
Soft Electron Recoil

ryan.plestid@gmail.com

Detecting MCPs with Neutrino Telescopes

$$Q^2_{\rm max} = 4P^2_{\rm cm}$$



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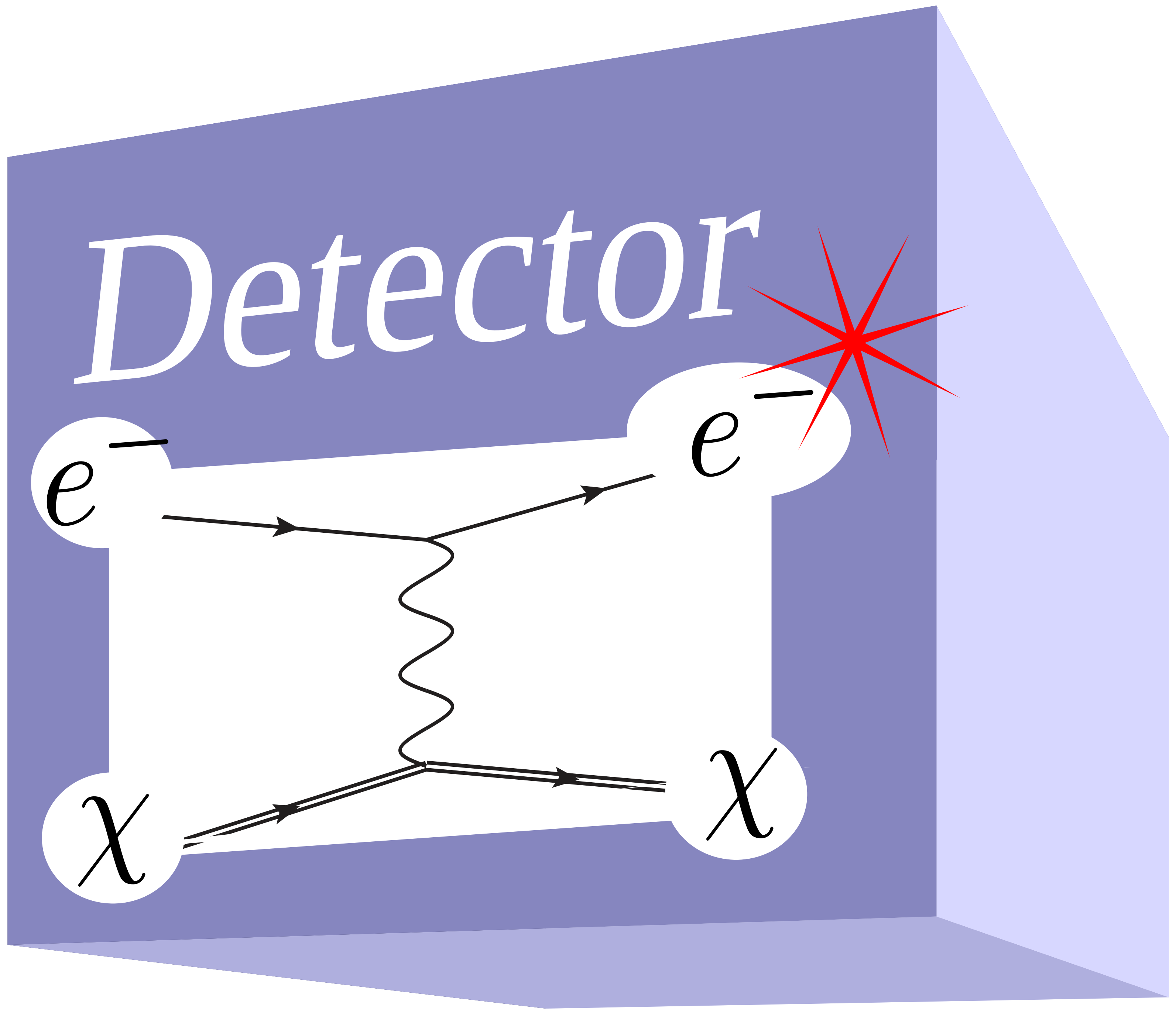
$$Q^2_{\rm max} = 4P^2_{\rm cm} \approx 2m_e^2 \left(\frac{P_\chi}{m_\chi}\right)^2$$



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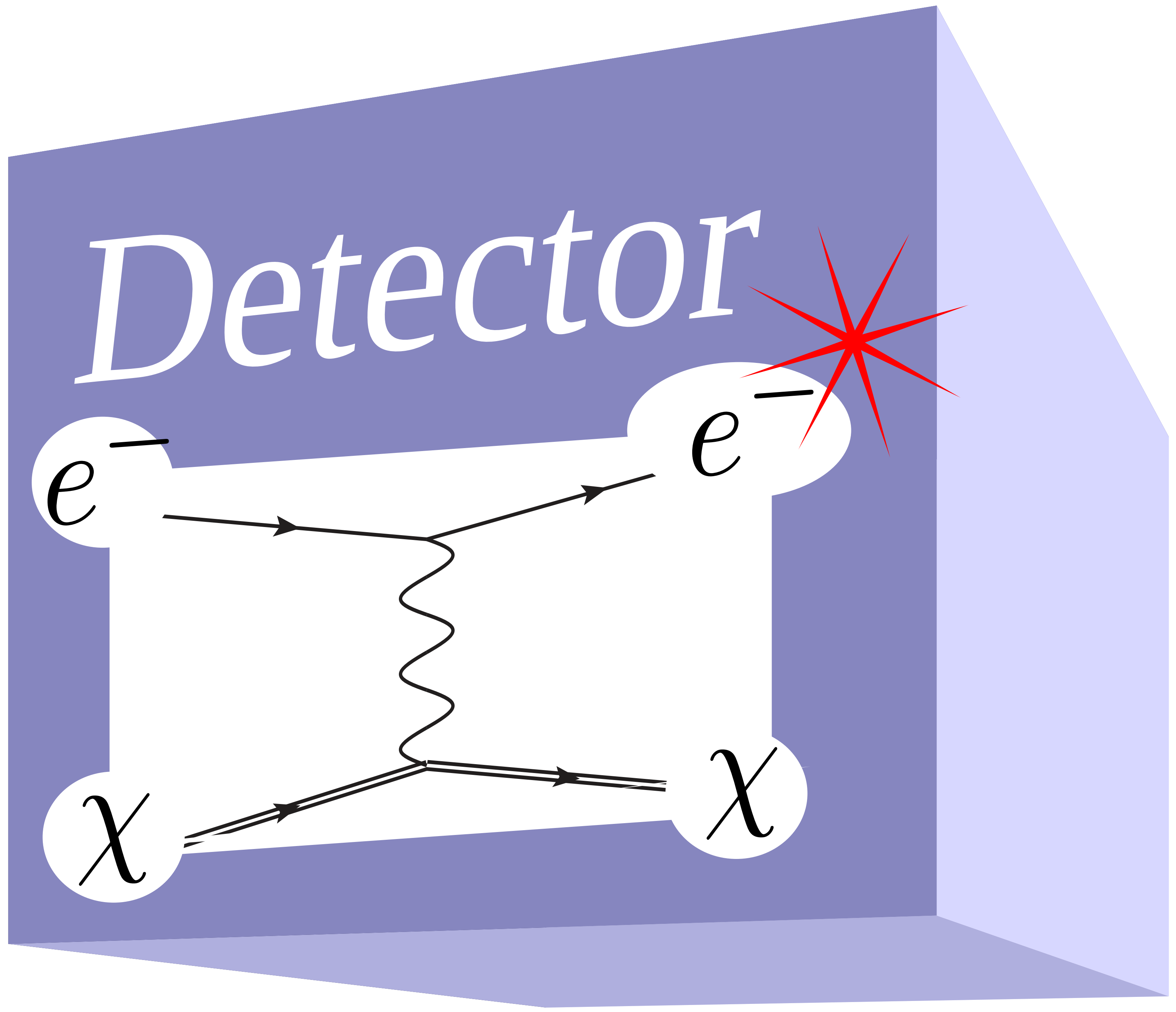
Detecting MCPs with Neutrino Telescopes

$$Q^2_{\max} = 4P^2_{\text{cm}} \approx 2m_e^2\left(\frac{P_\chi}{m_\chi}\right)^2 = 4m_e^2(\beta_\chi\gamma_\chi)^2$$



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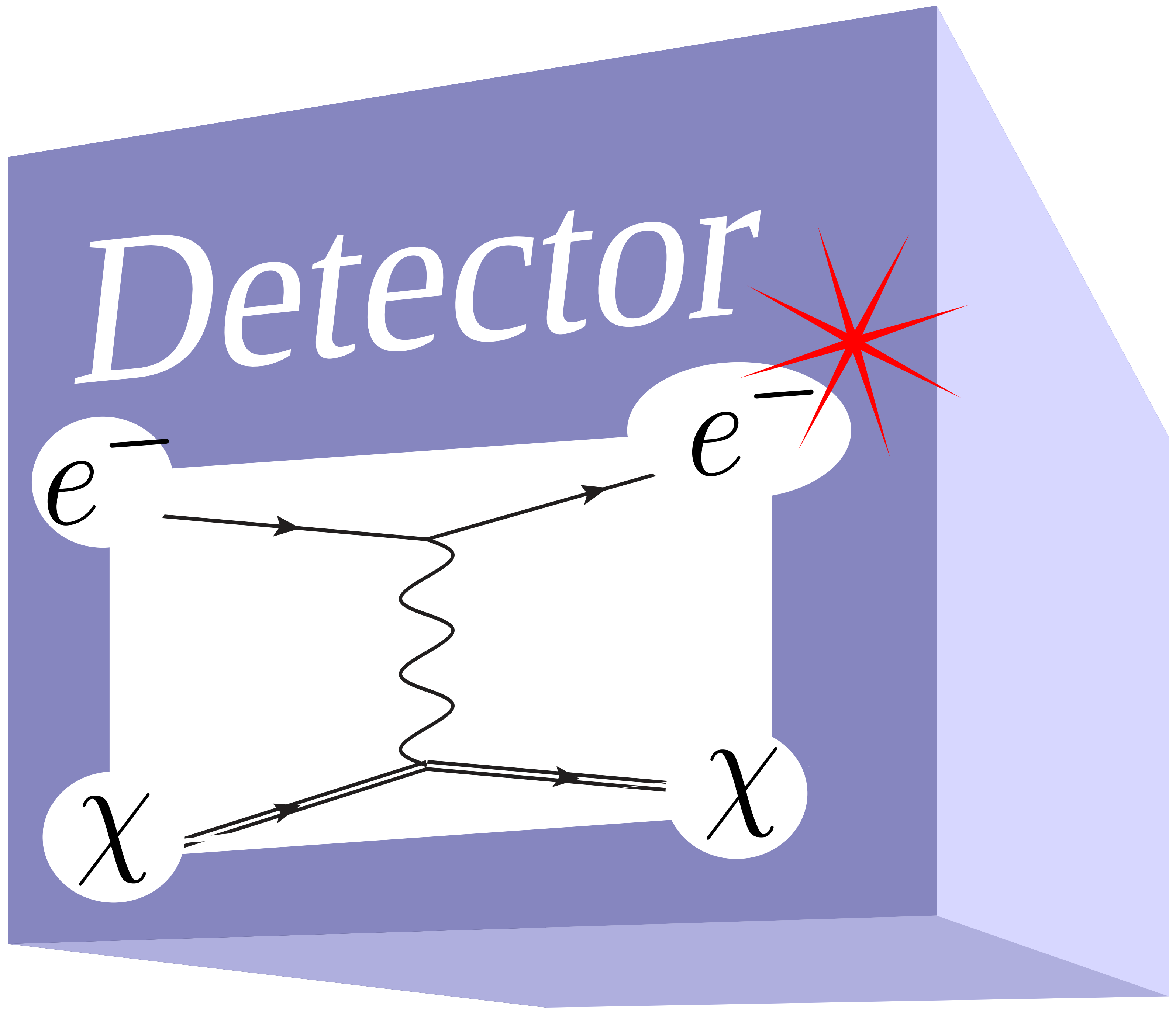

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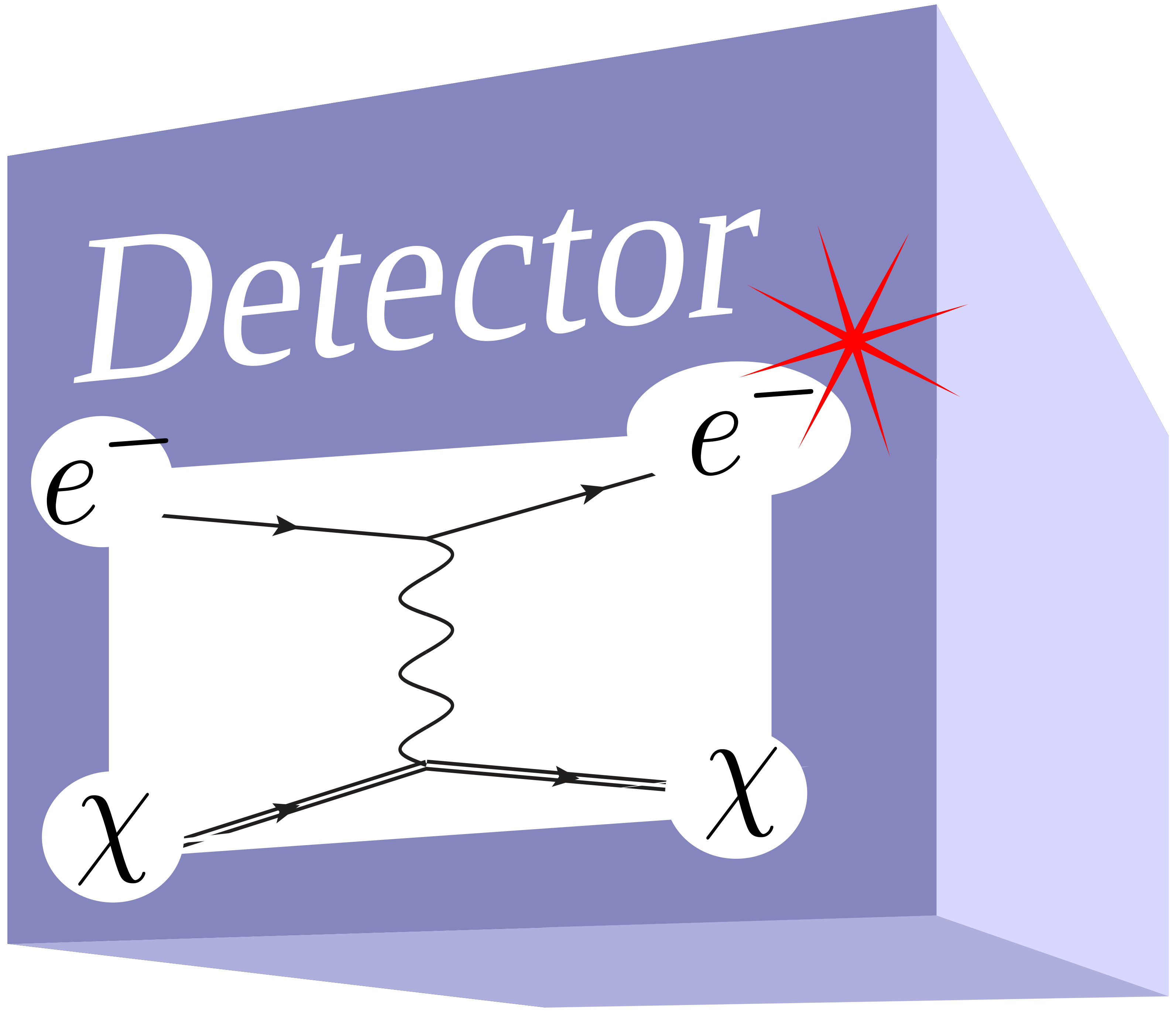

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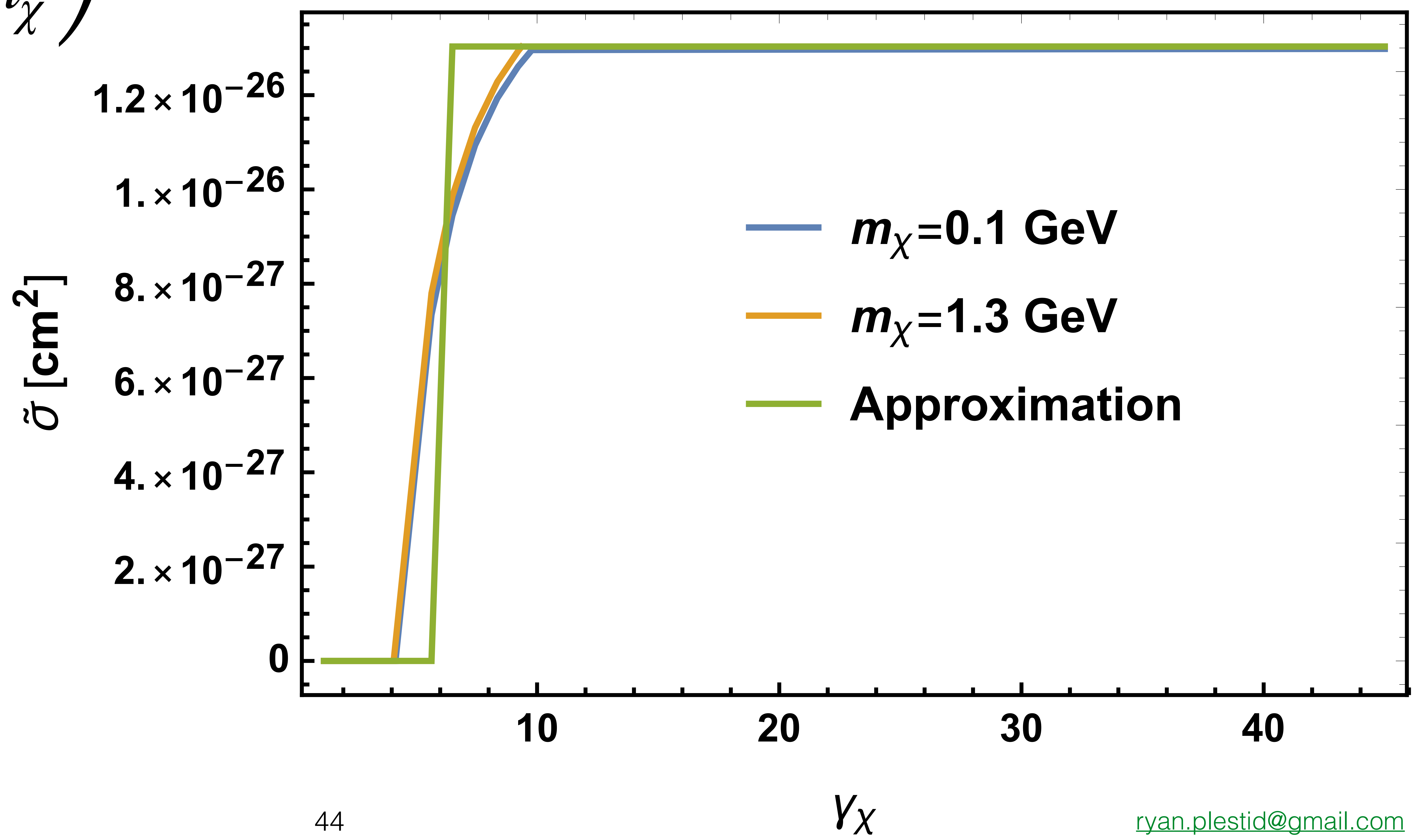

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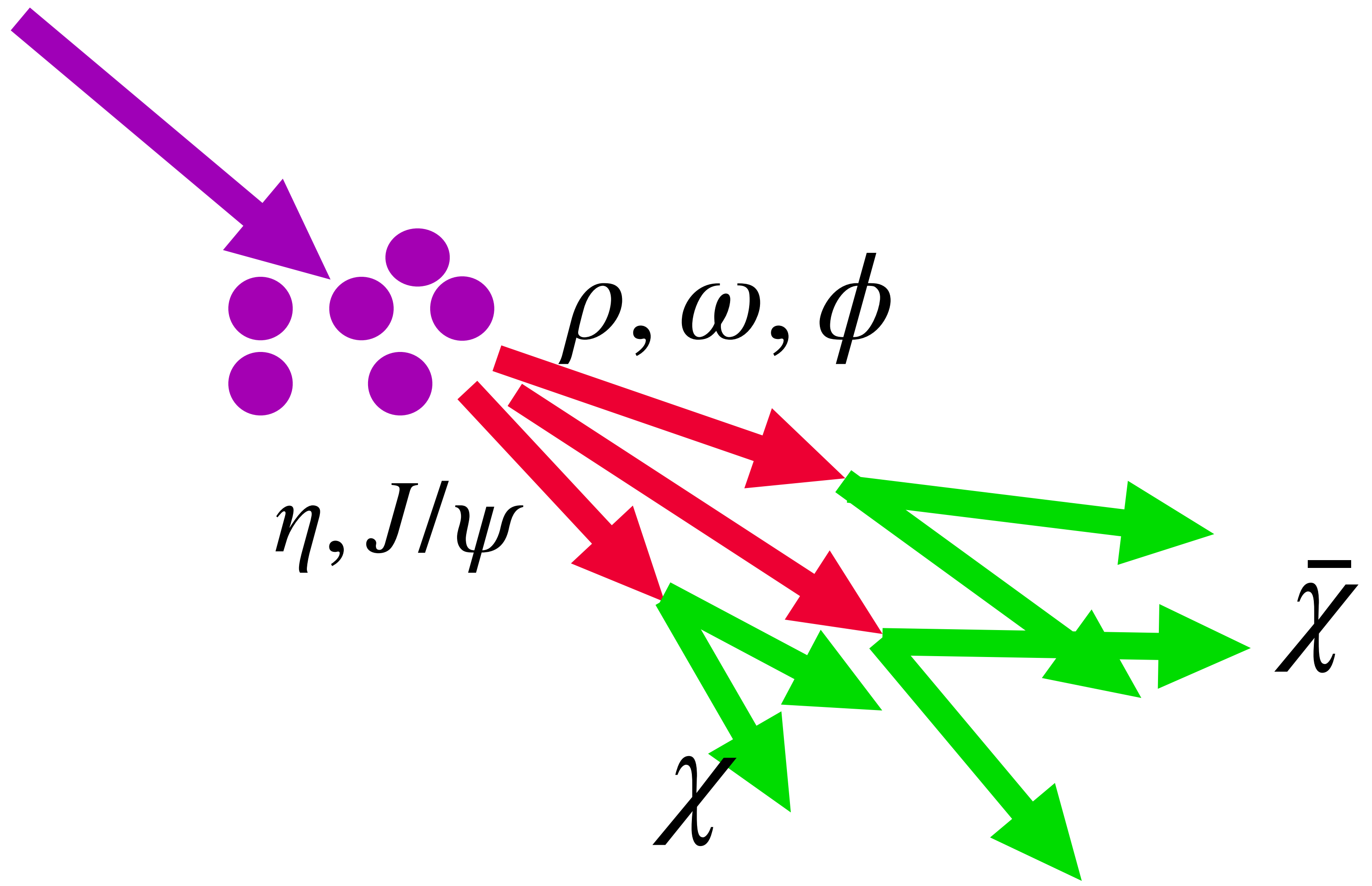
Calculating MCP flux



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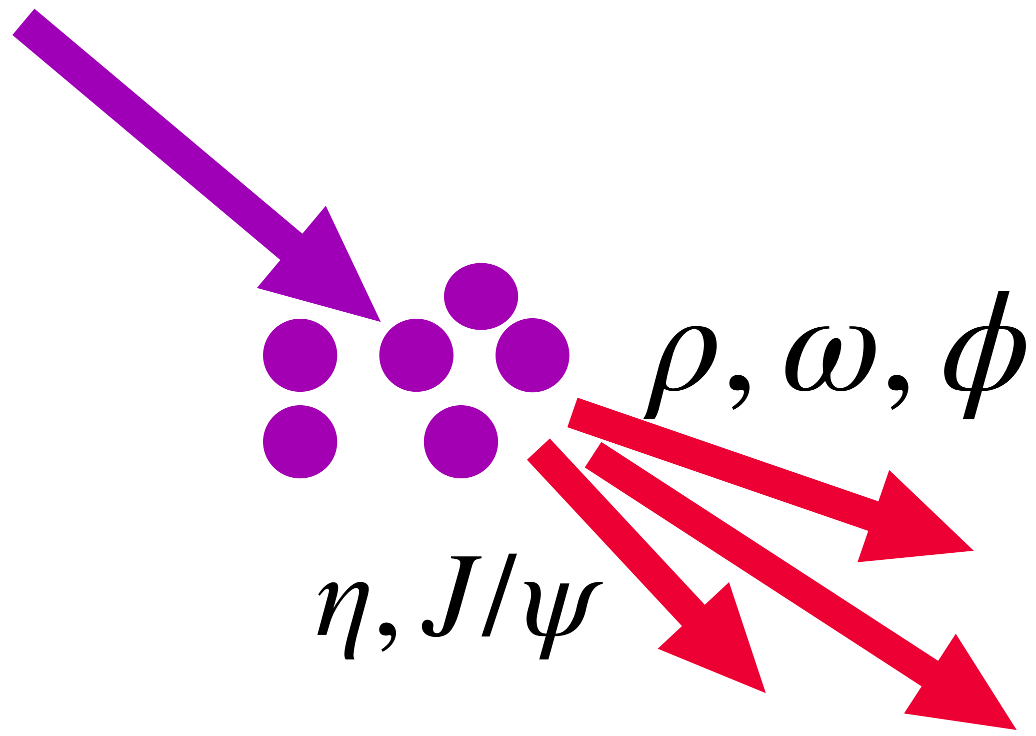

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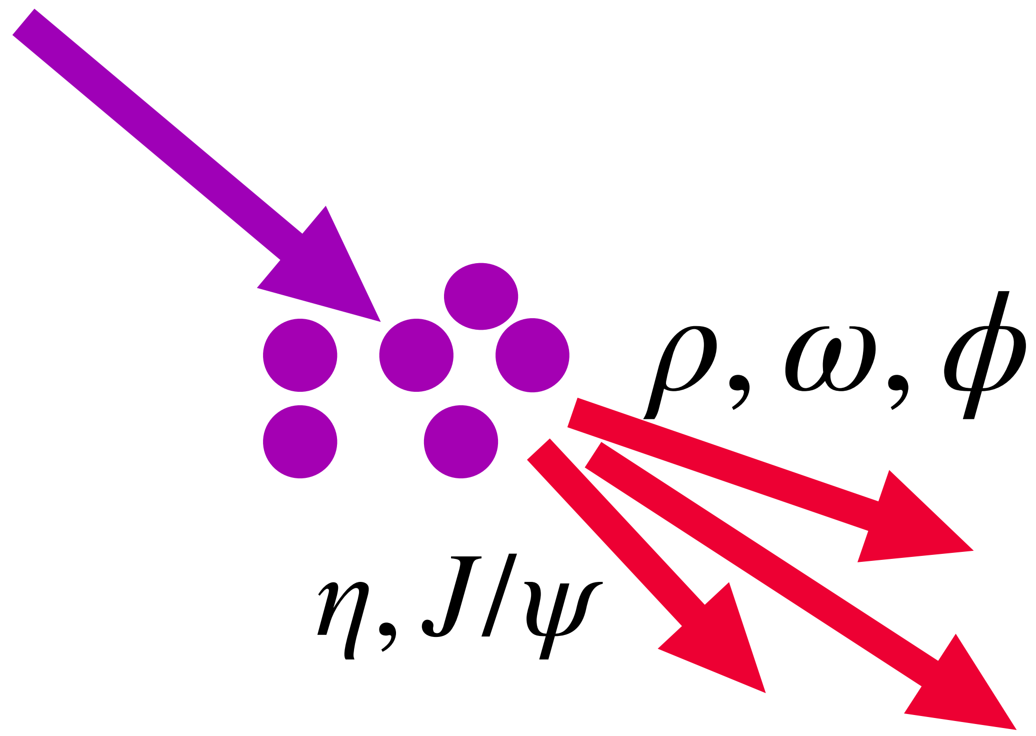

$$P(\gamma_{\mathfrak{m}} \,|\, E_{\text{cosmic}}) + I_{\text{CR}}(E_{\text{cosmic}})$$

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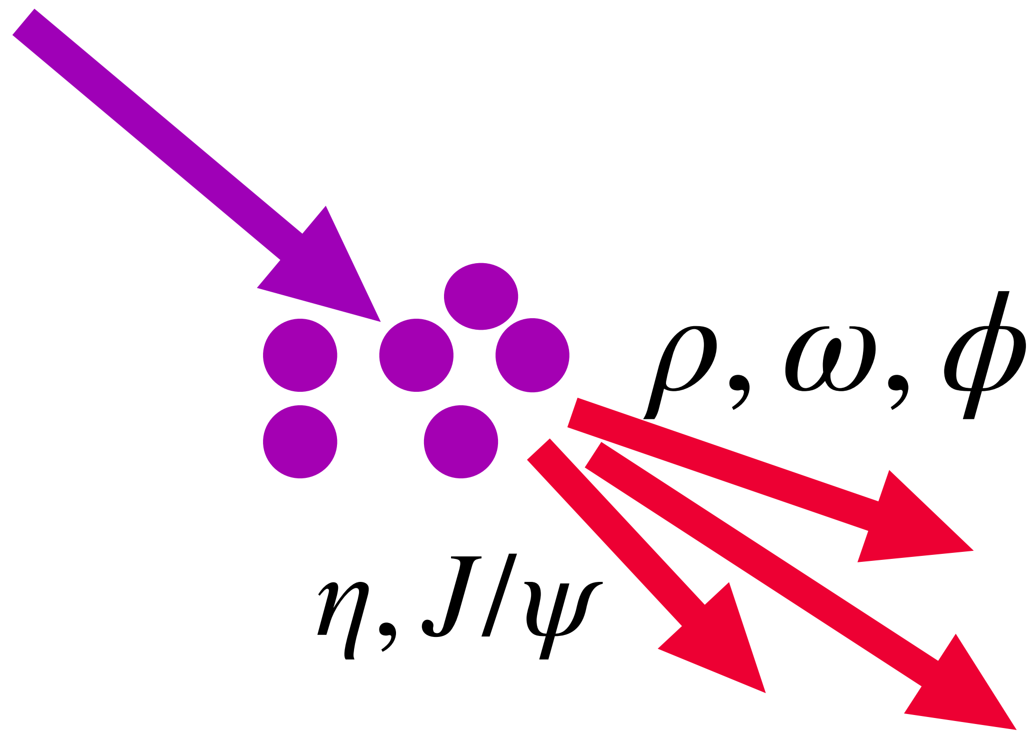

$$P(\gamma_{\mathfrak{m}} \,|\, \gamma_{\rm cm}) + I_{\rm CR}(\gamma_{\rm cm})$$

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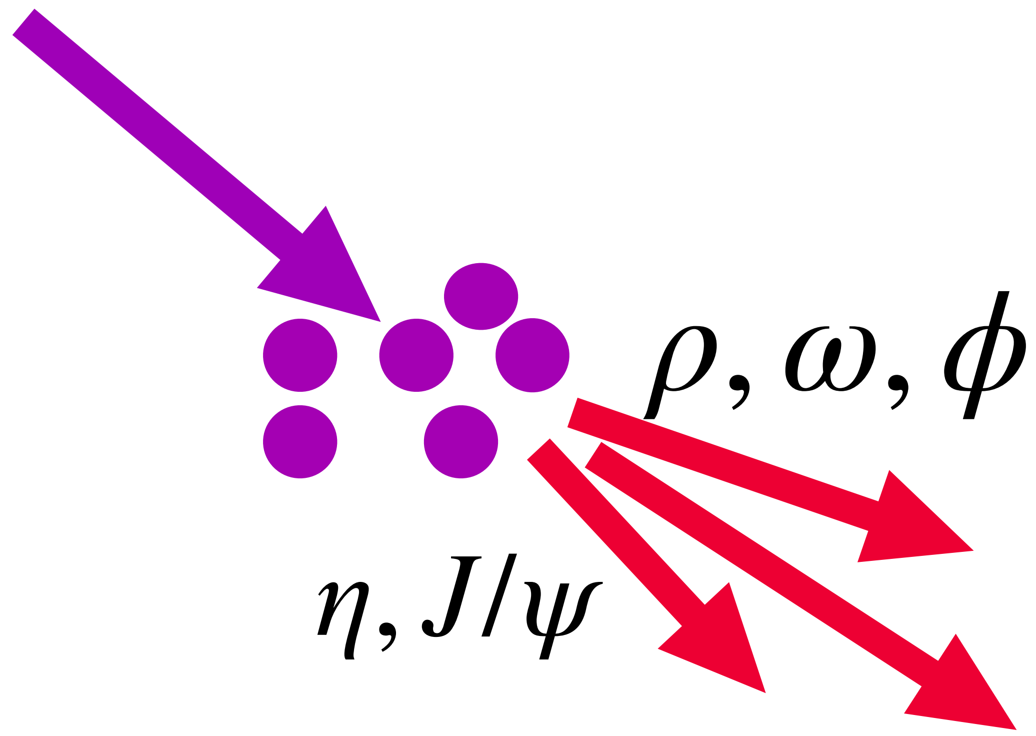

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$$\Phi_{\mathfrak{m}}(\gamma_{\mathfrak{m}})$$

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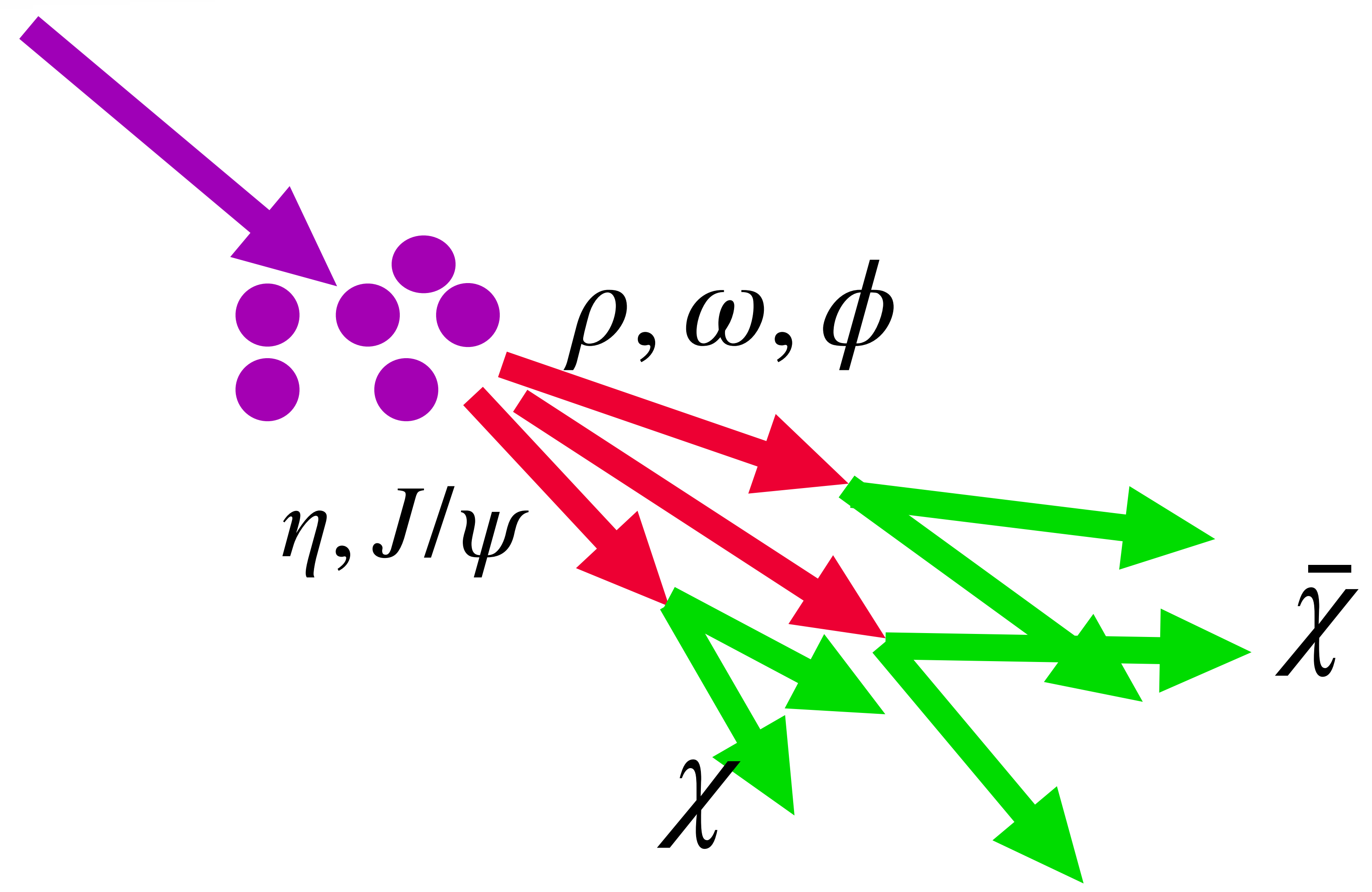

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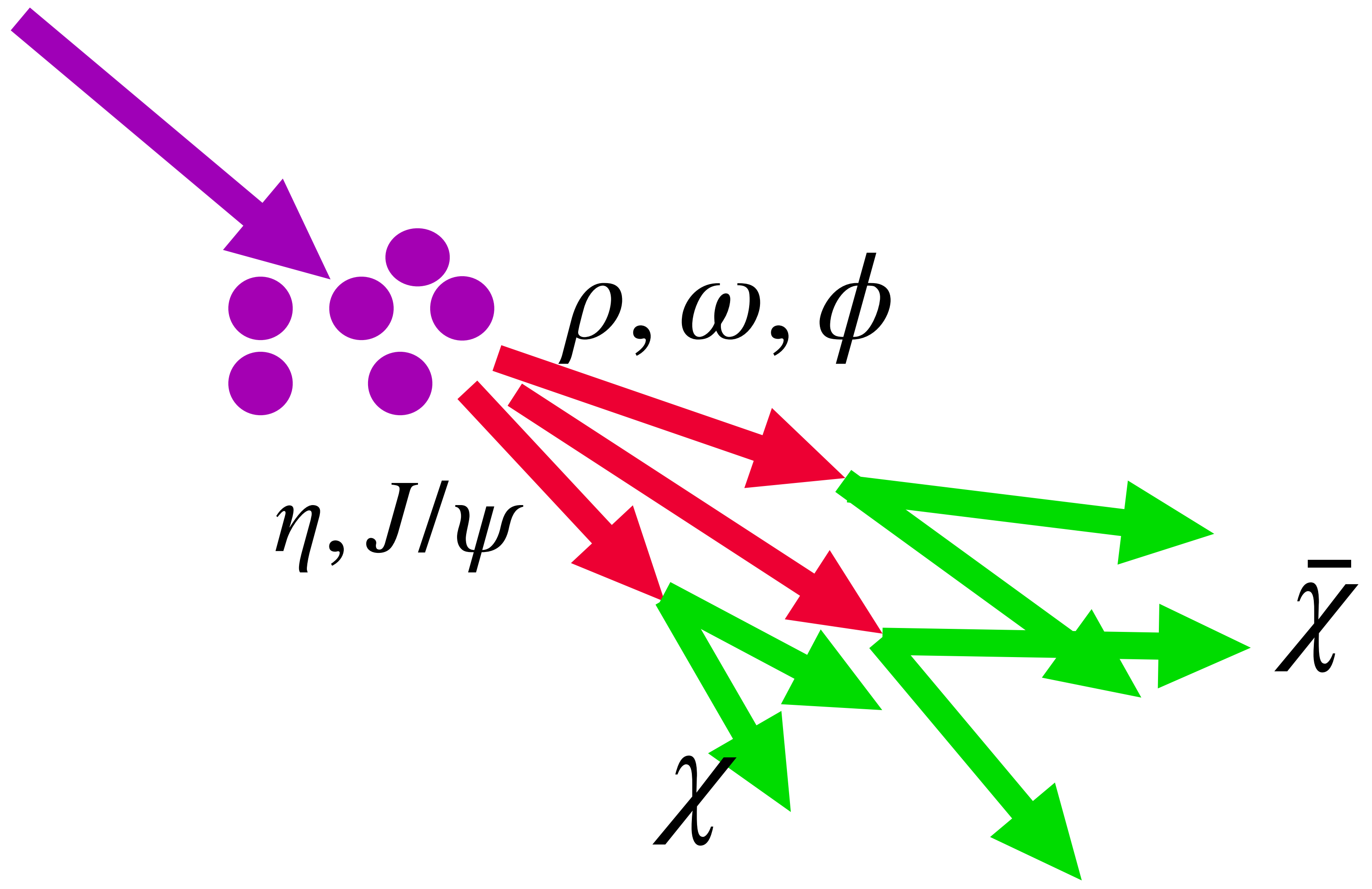
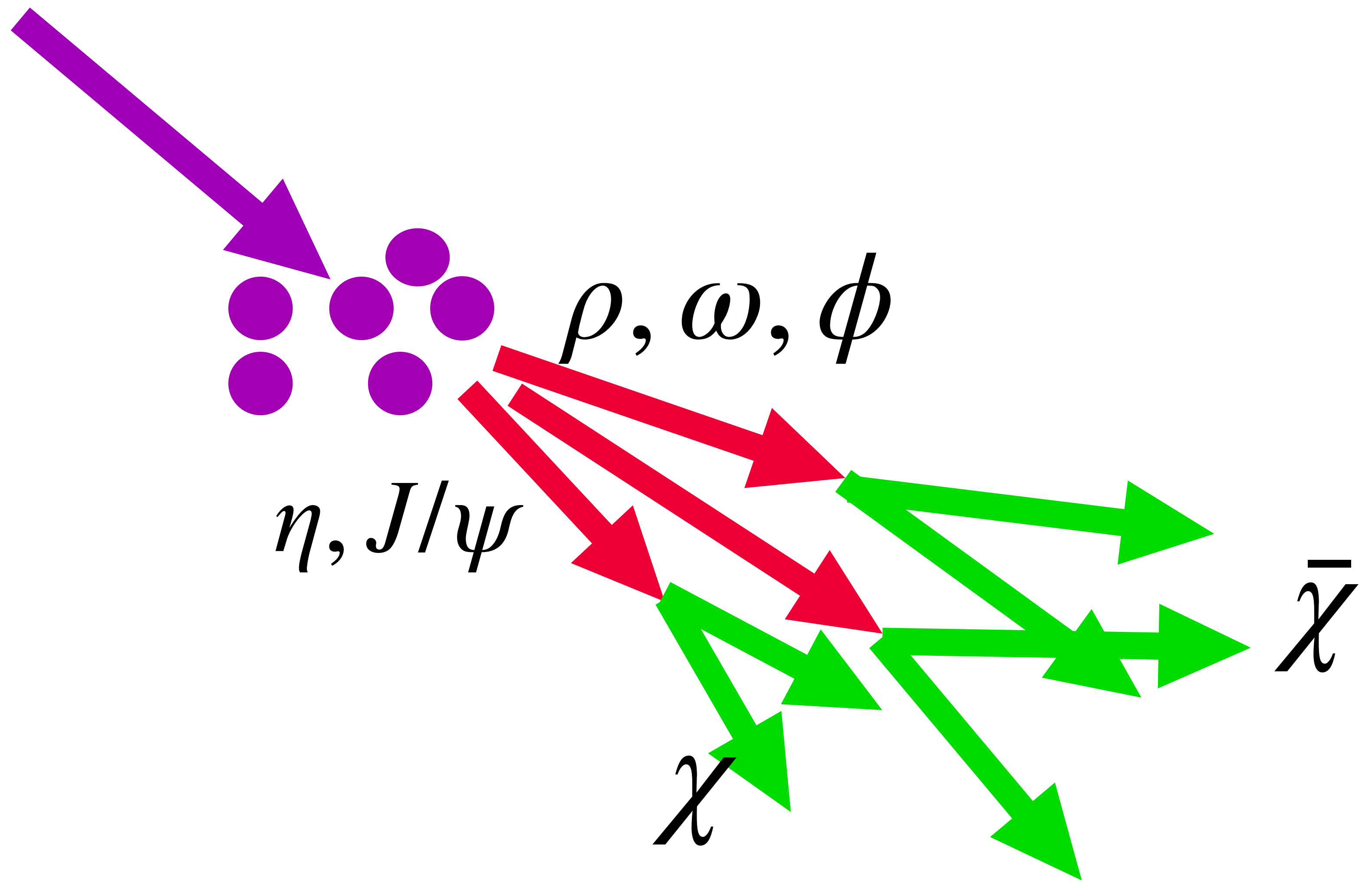


$$P(\gamma_{\mathfrak{m}} \,|\, \gamma_{\mathrm{cm}}) + I_{\mathrm{CR}}(\gamma_{\mathrm{cm}})$$

$$\Phi_{\mathfrak{m}}(\gamma_{\mathfrak{m}}) \longrightarrow \sum_{\mathfrak{m}} P(\gamma_{\chi} \,|\, \gamma_{\mathfrak{m}}) + \Phi_{\mathfrak{m}}(\gamma_{\mathfrak{m}})$$

Calculating MCP flux



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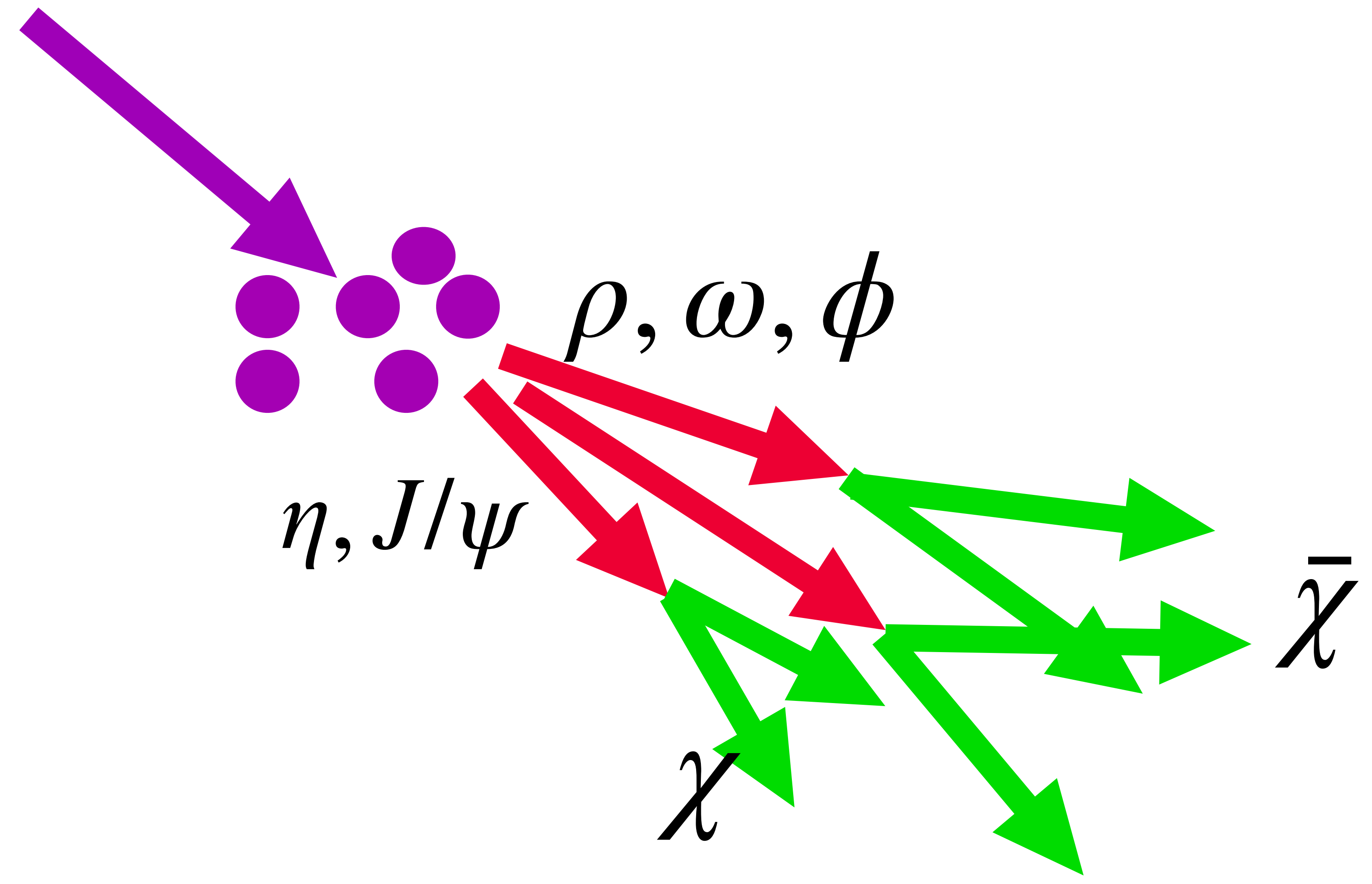

$$P(\gamma_{\mathfrak{m}} \,|\, \gamma_{\text{cm}}) + I_{\text{CR}}(\gamma_{\text{cm}})$$

$$\Phi_{\mathfrak{m}}(\gamma_{\mathfrak{m}})$$

$$\Phi_{\chi}(\gamma_{\chi})$$

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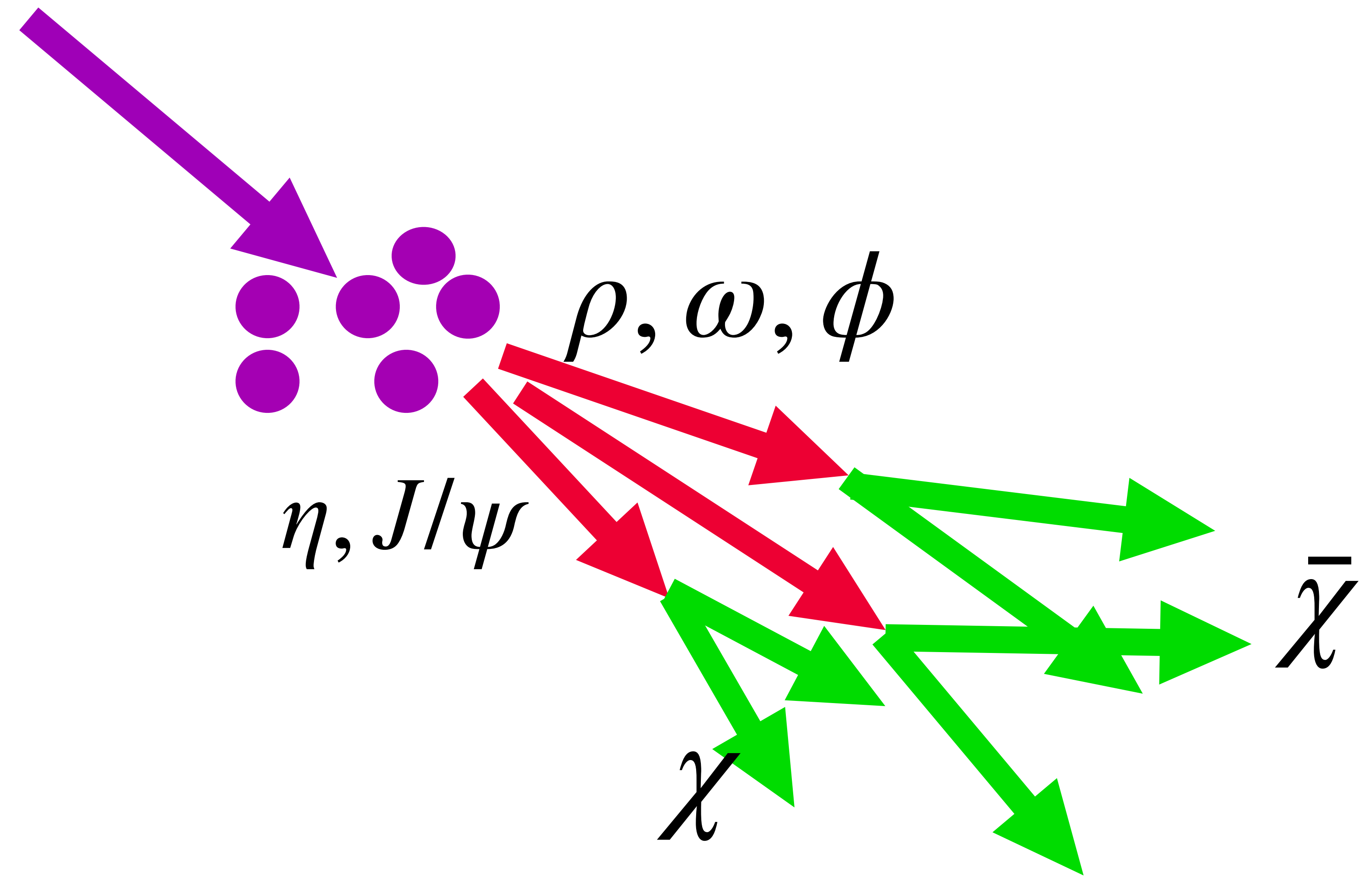
Calculating MCP flux



$$\Phi_\chi(\gamma_\chi) + \frac{\mathrm{d}\sigma(\gamma_\chi)}{\mathrm{d}T_e}$$

$$P(\gamma_{\mathfrak{m}} \,|\, \gamma_{\rm cm}) + I_{\rm CR}(\gamma_{\rm cm})$$

$$\Phi_{\mathfrak{m}}(\gamma_{\mathfrak{m}})$$

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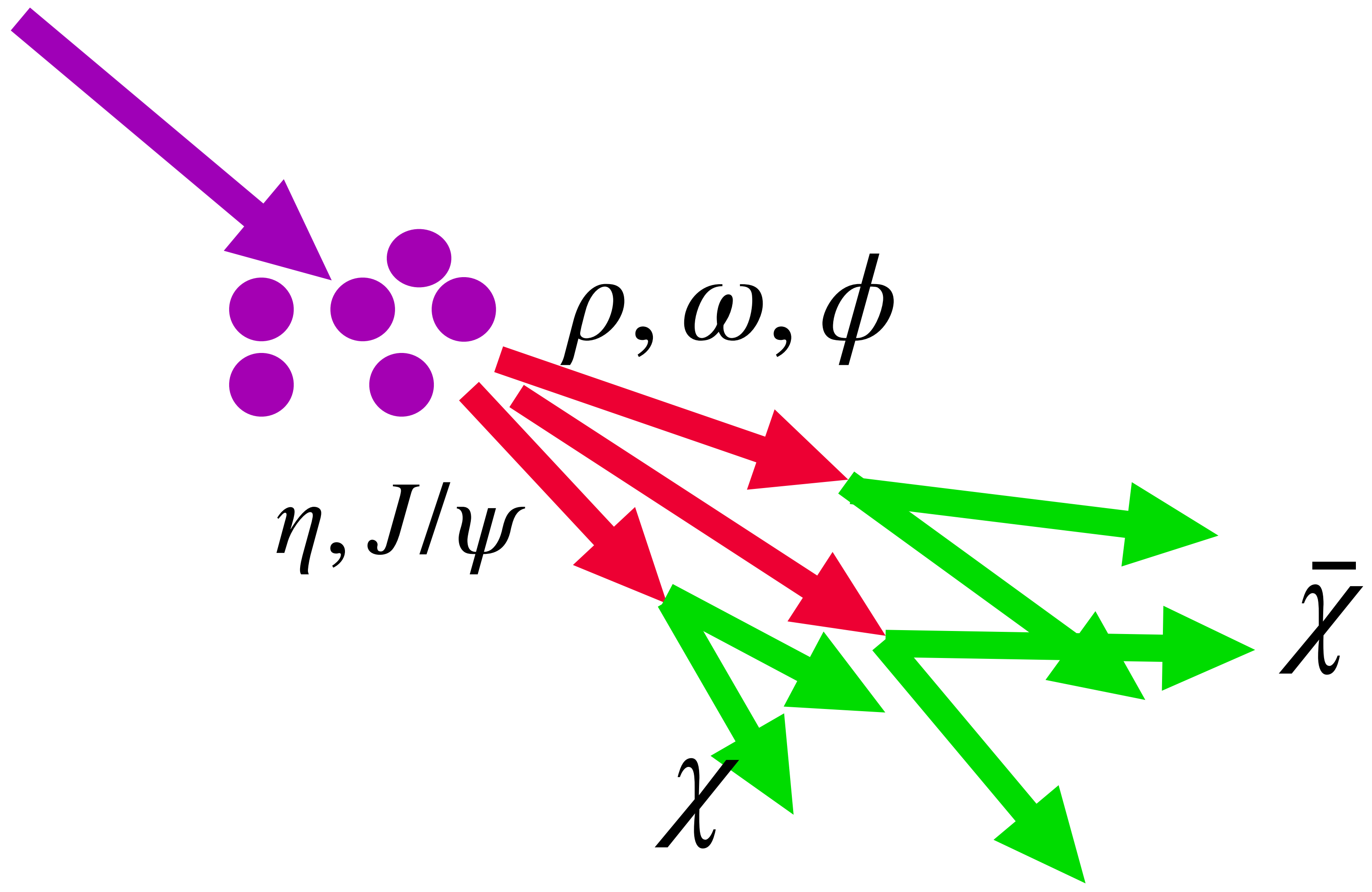
Calculating MCP flux



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$$P(\gamma_{\mathfrak{m}} \,|\, \gamma_{\mathrm{cm}}) + I_{\mathrm{CR}}(\gamma_{\mathrm{cm}})$$

$$\Phi_{\mathfrak{m}}(\gamma_{\mathfrak{m}})$$

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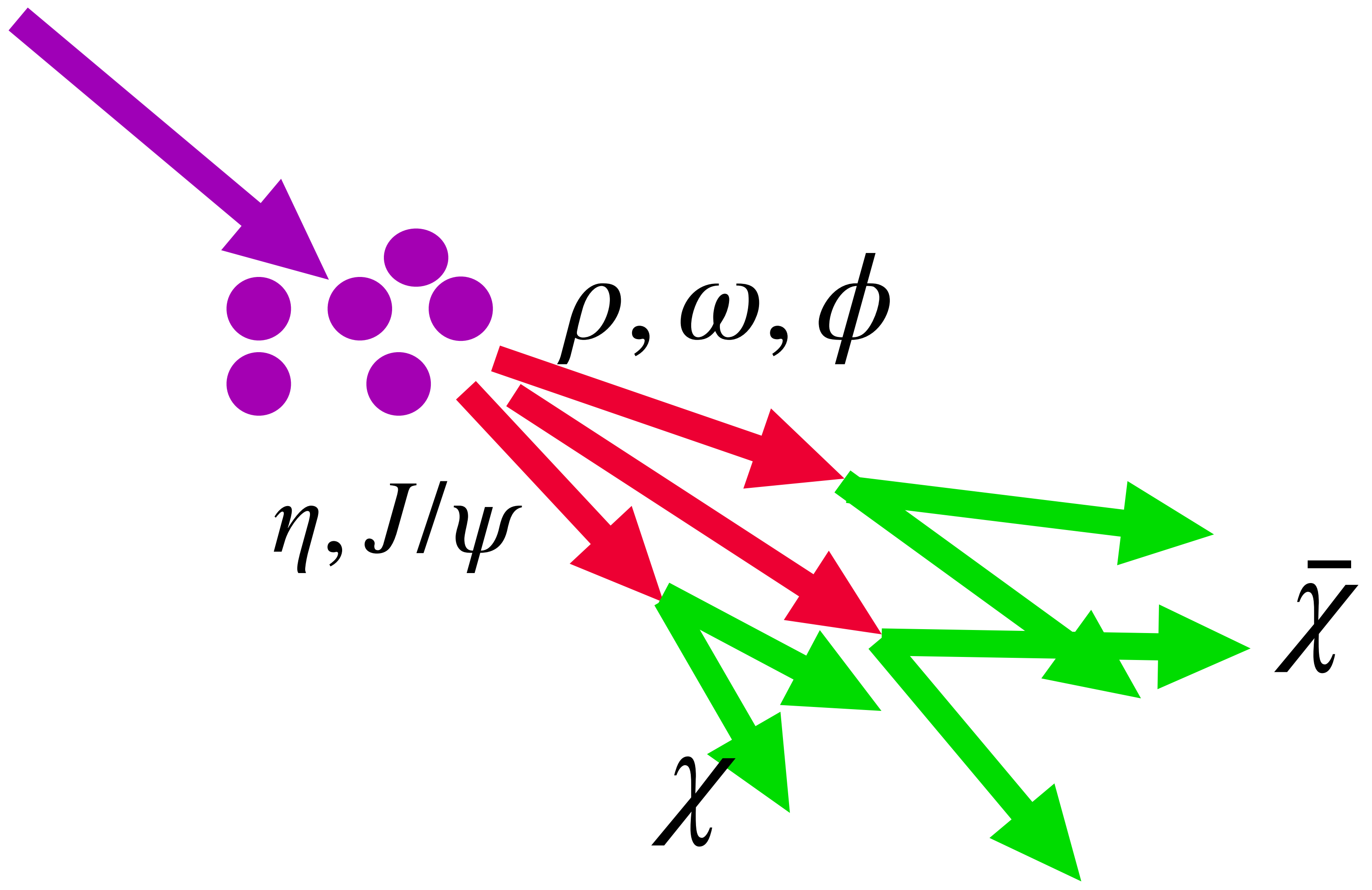
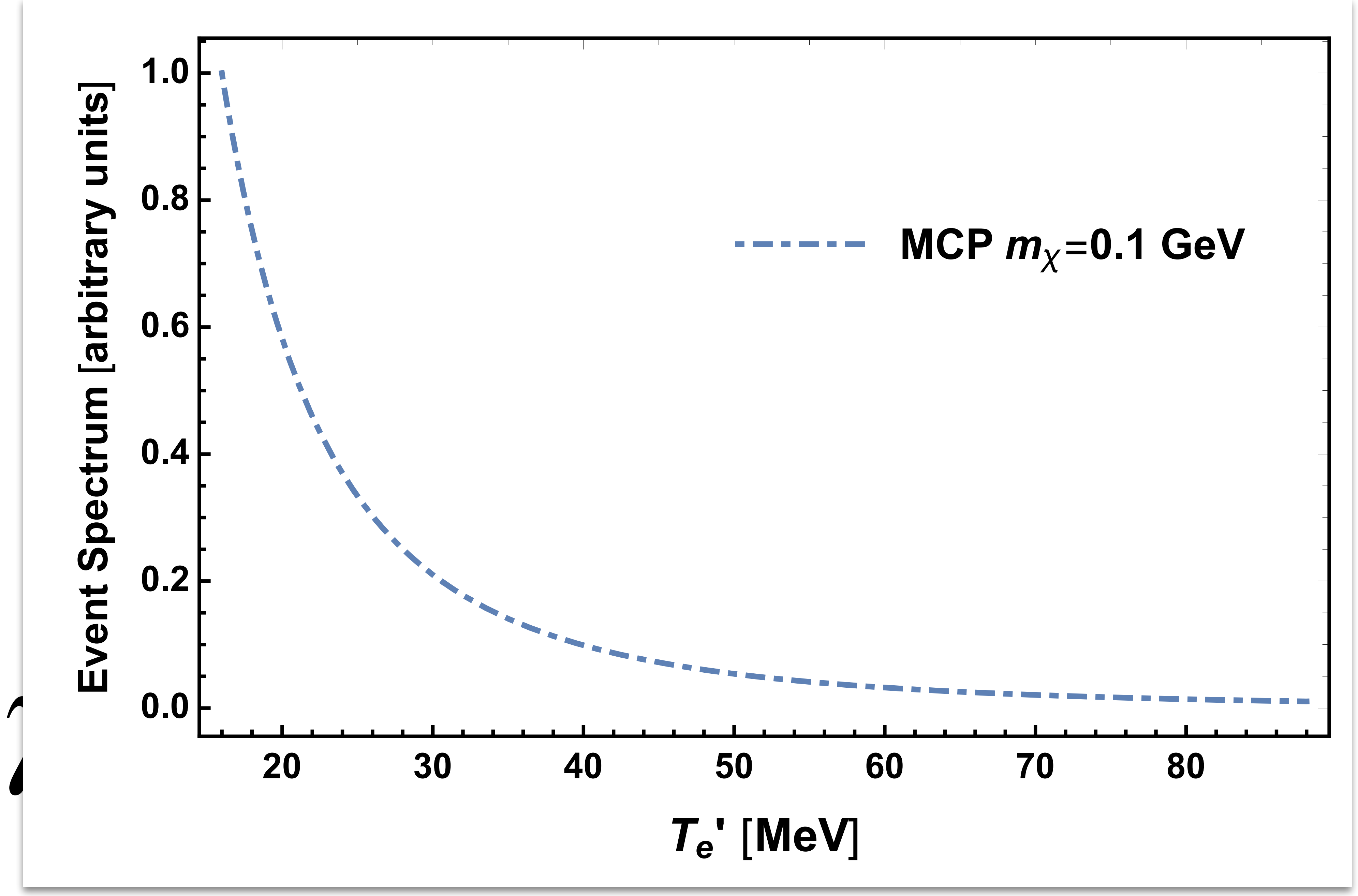


$$\Phi_\chi(\gamma_\chi) + \frac{d\sigma(\gamma_\chi)}{dT_e}$$



$$P(\gamma_{\mathfrak{m}} \,|\, \gamma_{\rm cm}) + I_{\rm CR}($$

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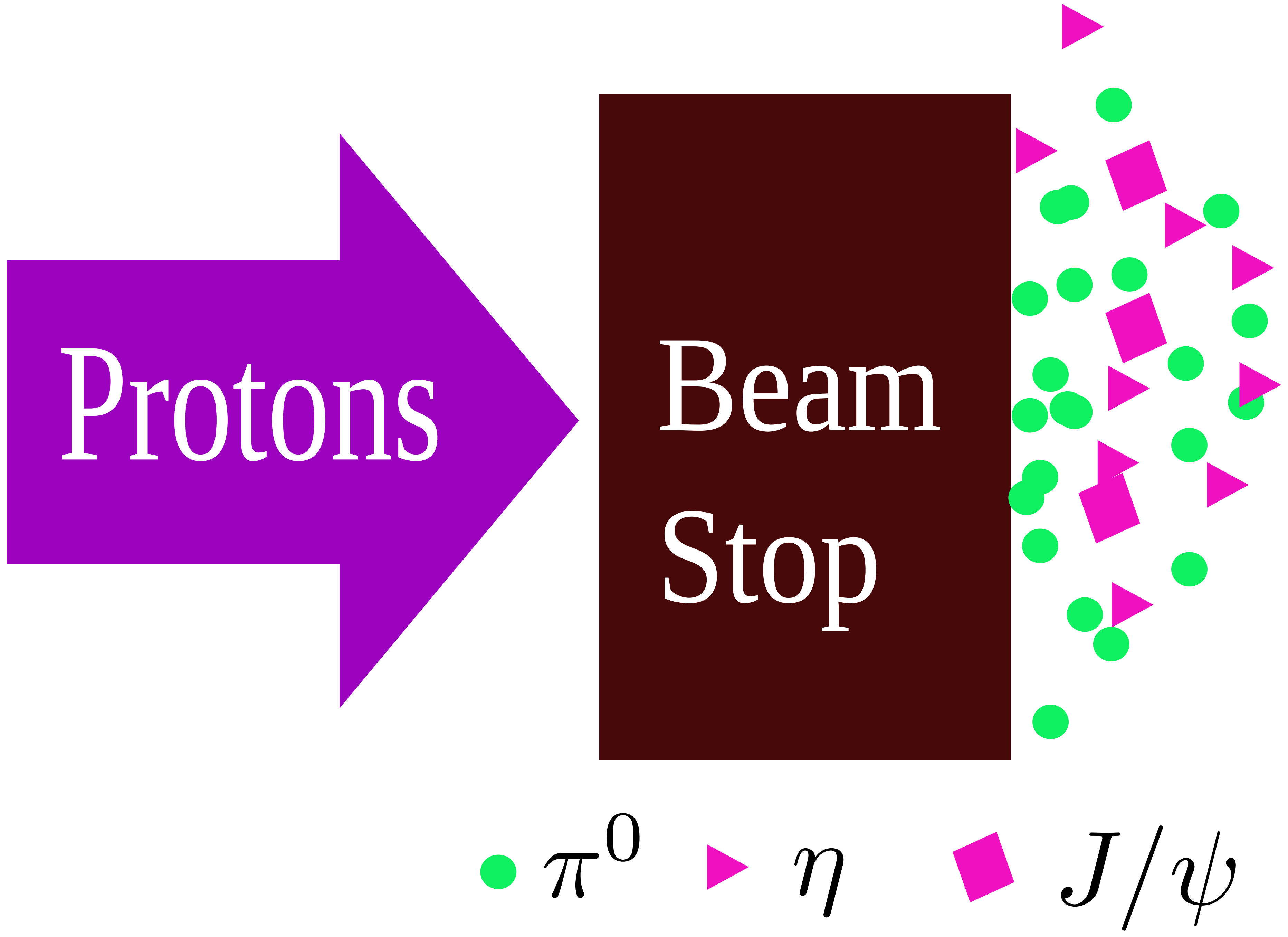
MCPs at Neutrino Experiments



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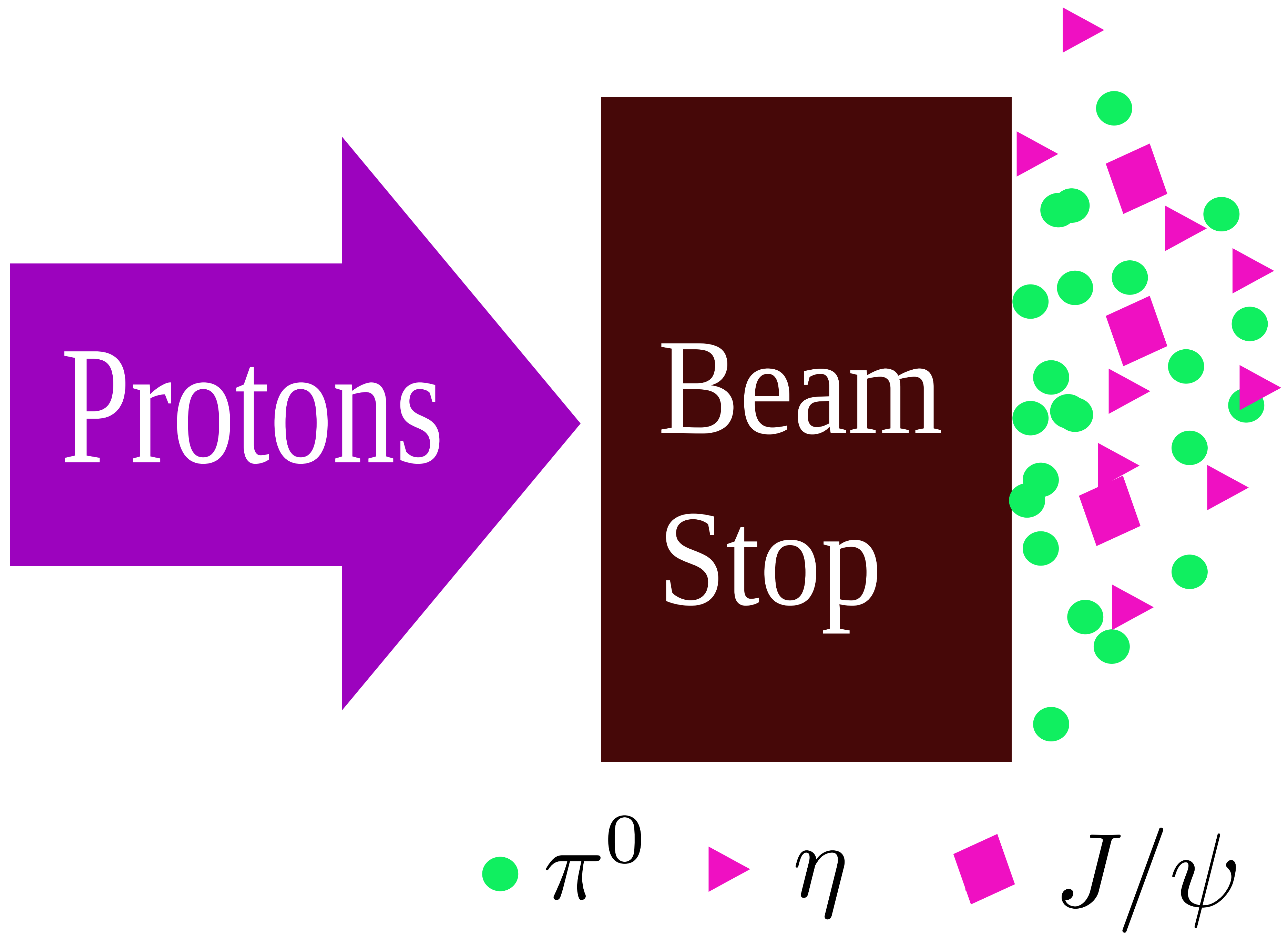
MCPs at Neutrino Experiments



Production Chanels

- Unlike dipole portal there is no upscattering production.
- Consequently meson decays are the only major source of mCPs.
- Need to include heavy mesons to get high-mass MCPs.
- Dalitz-decays dominate production for pseudo-scalar mesons
-

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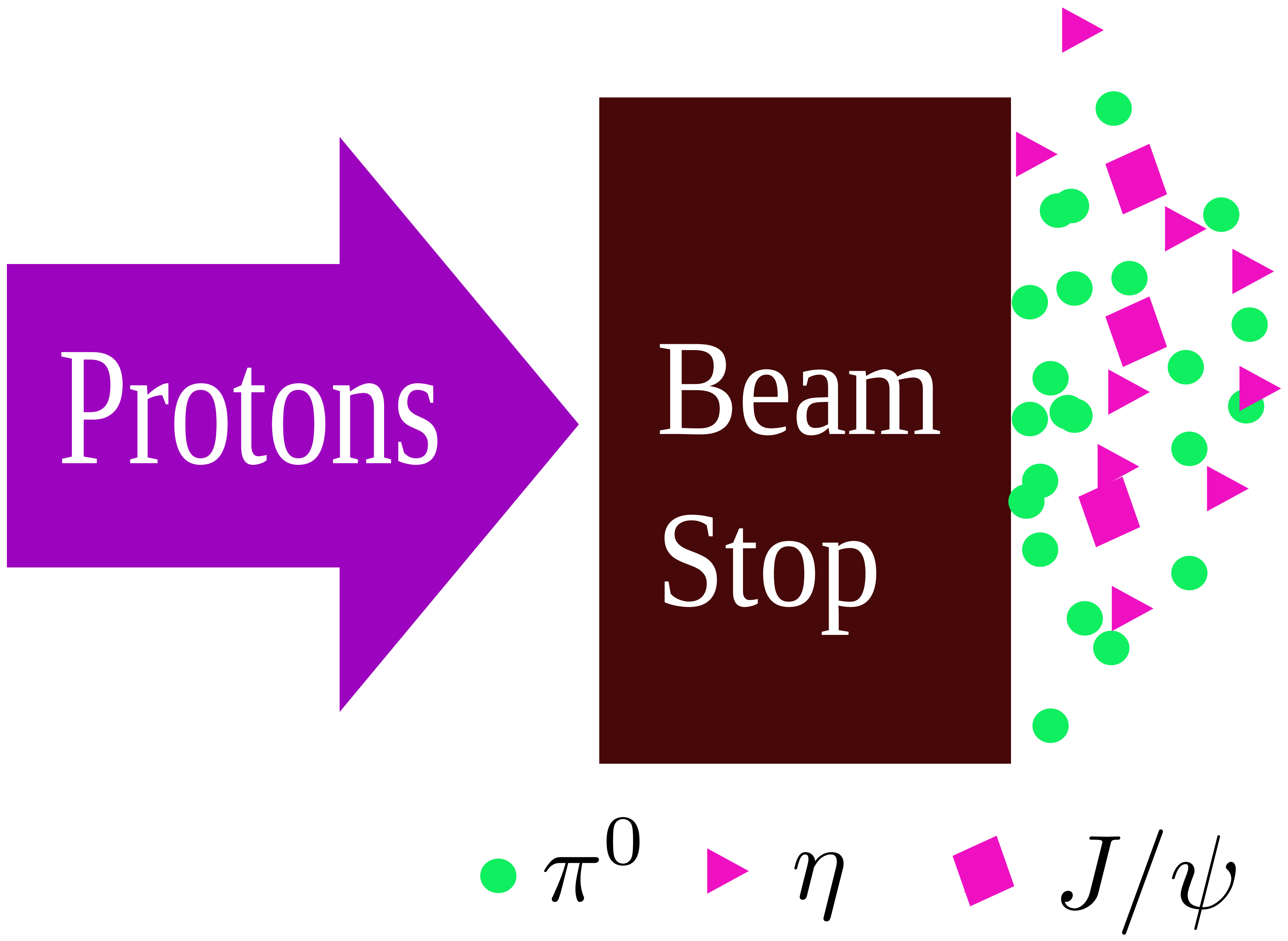
MCPs at Neutrino Experiments



$$\pi^0/\eta \to \gamma\chi\bar{\chi}$$

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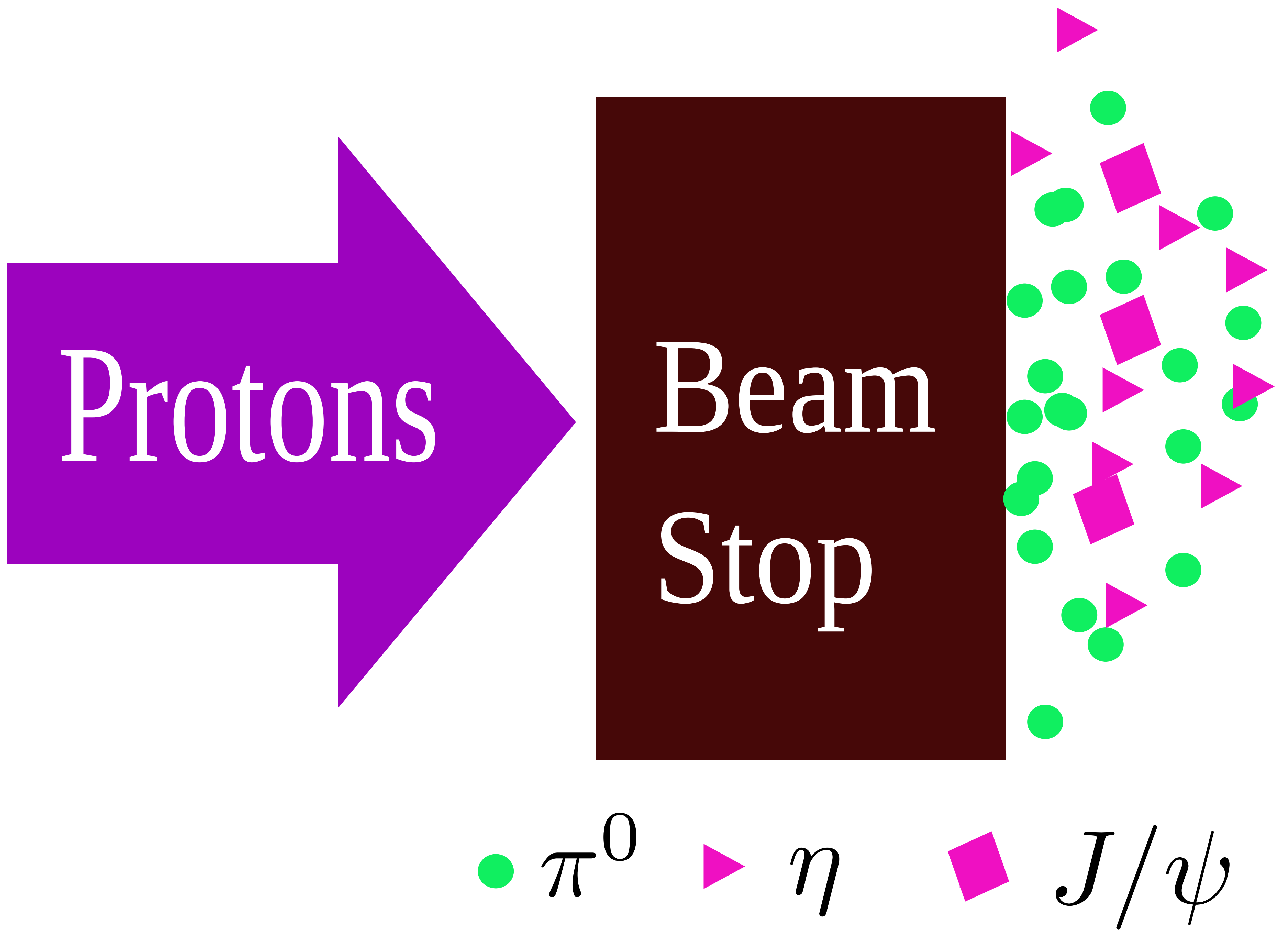
MCPs at Neutrino Experiments



$$\pi^0/\eta \to \gamma\chi\bar{\chi}$$
$$J/\psi \to \chi\bar{\chi}$$

Production Chanels

- Unlike dipole portal there is no upscattering production.
- Consequently meson decays are the only major source of mCPs.
- Need to include heavy mesons to get high-mass MCPs.
- Dalitz-decays dominate production for pseudo-scalar mesons

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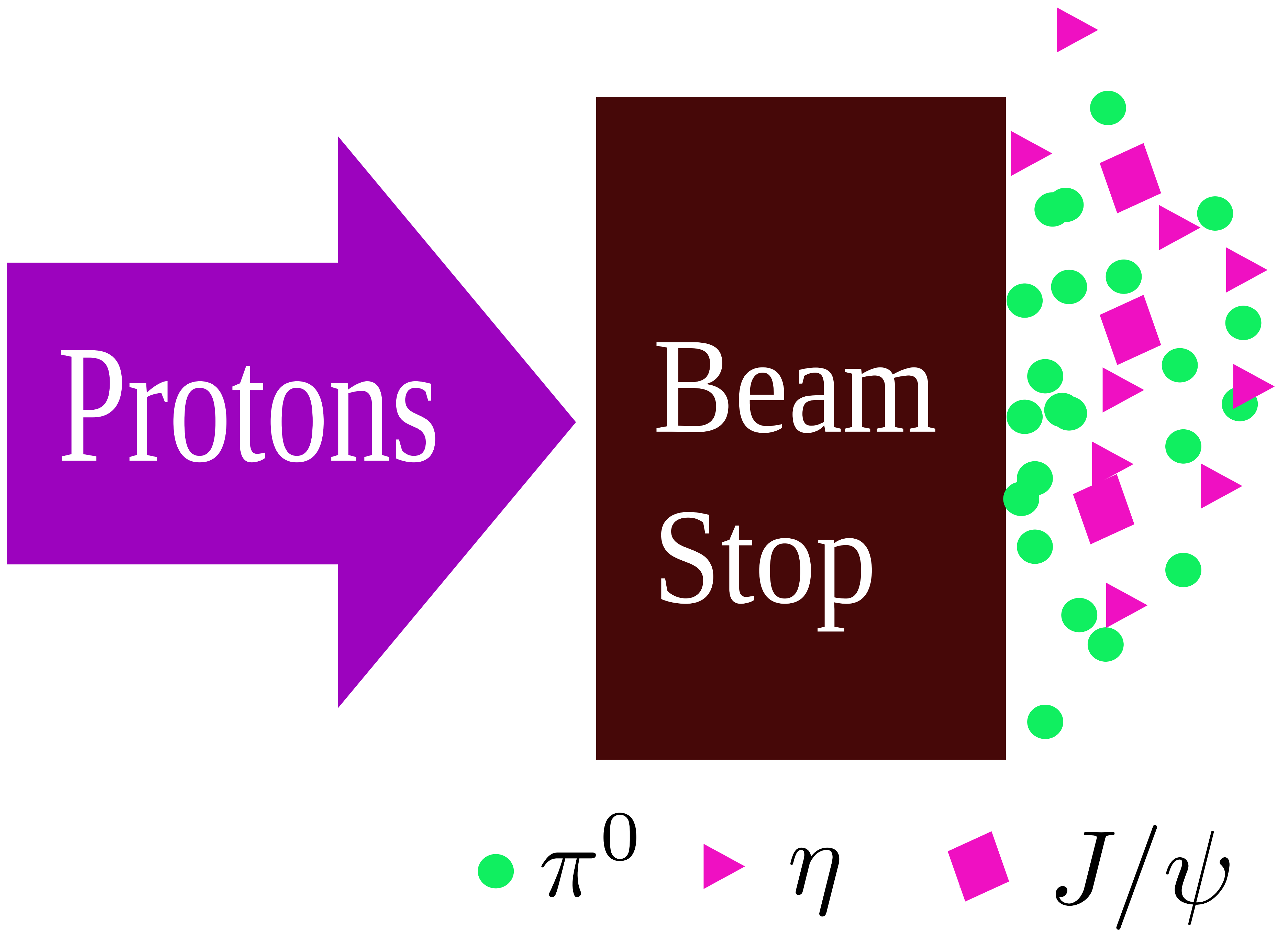

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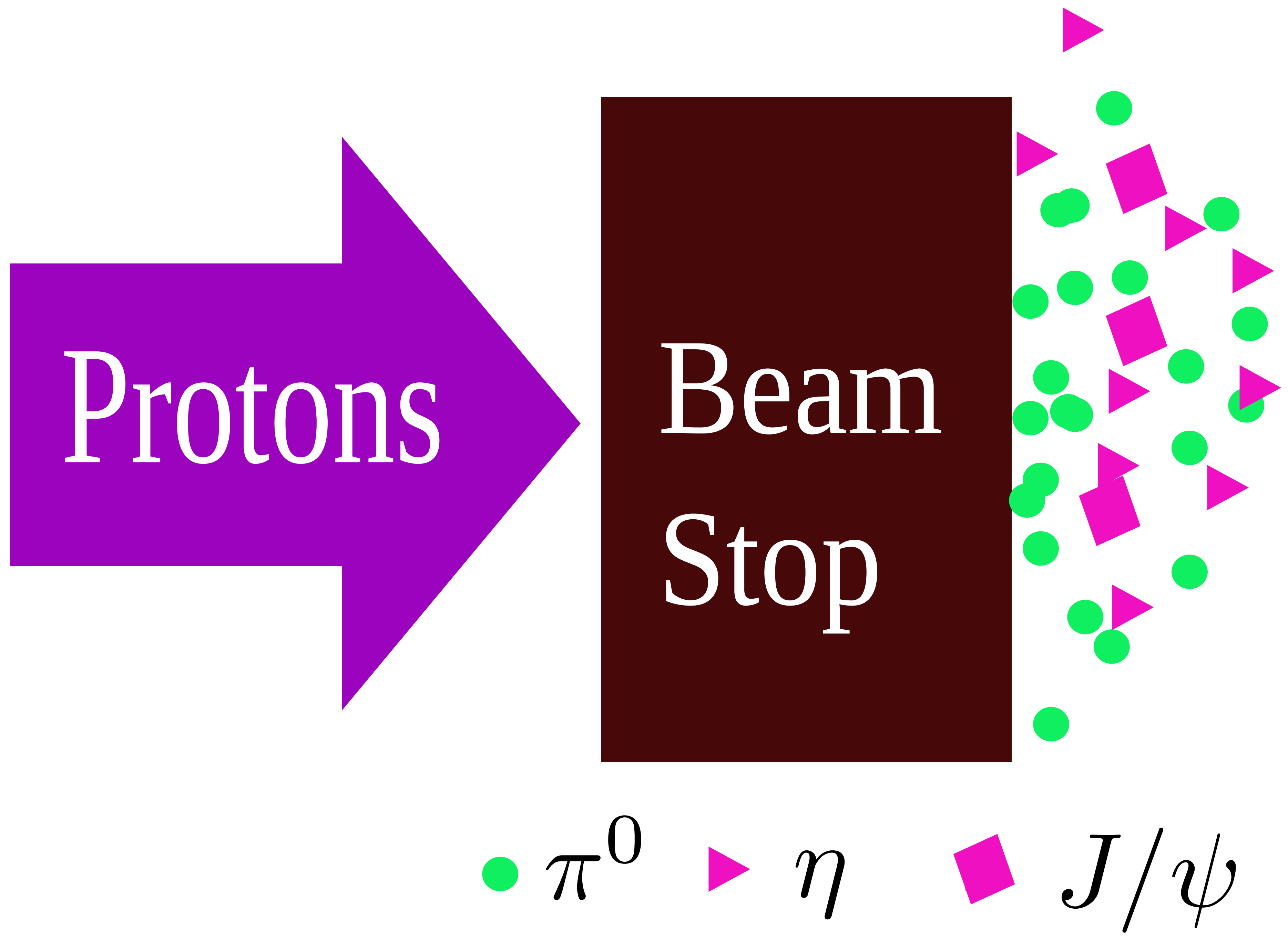

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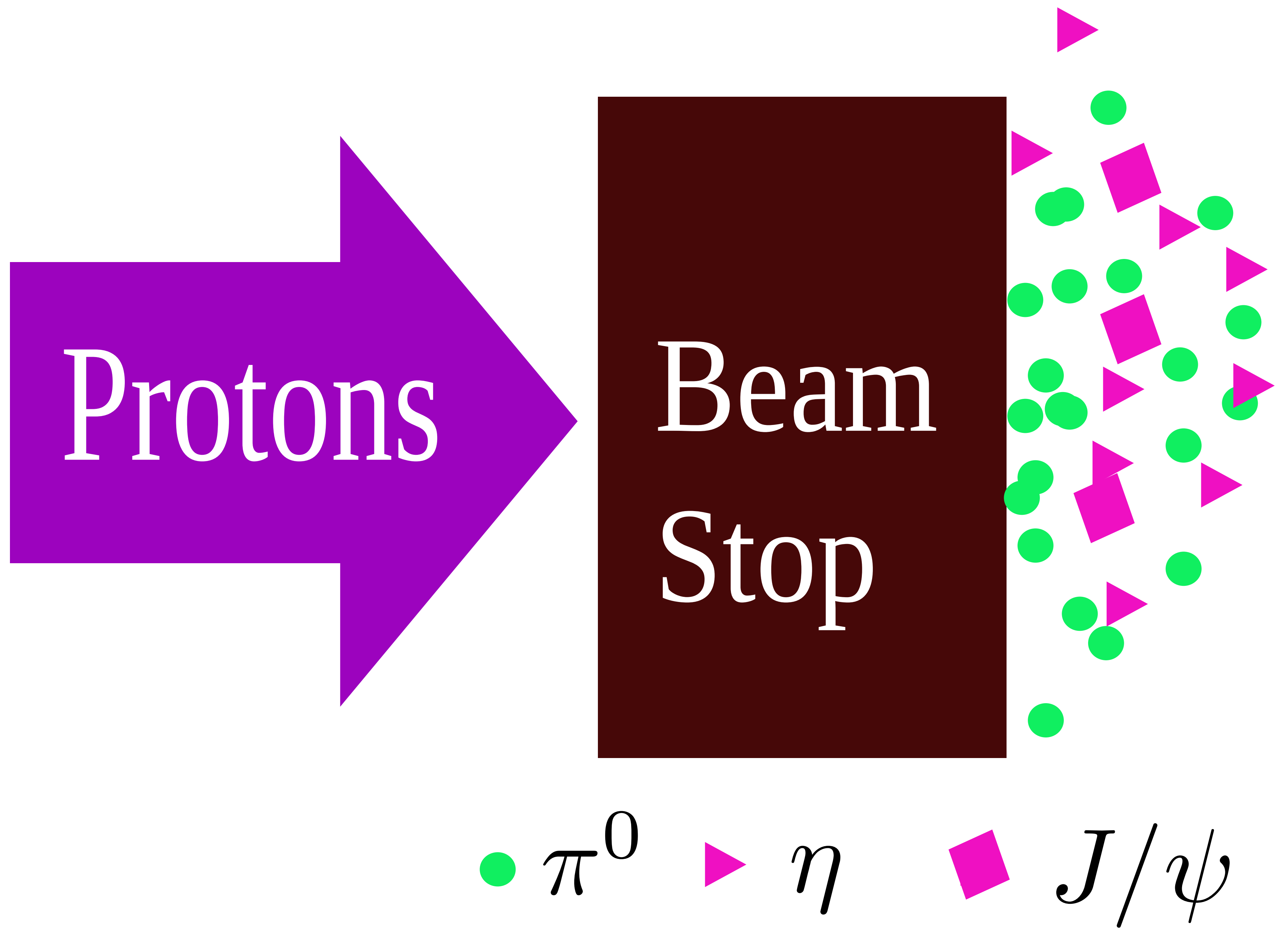

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Two-body final state

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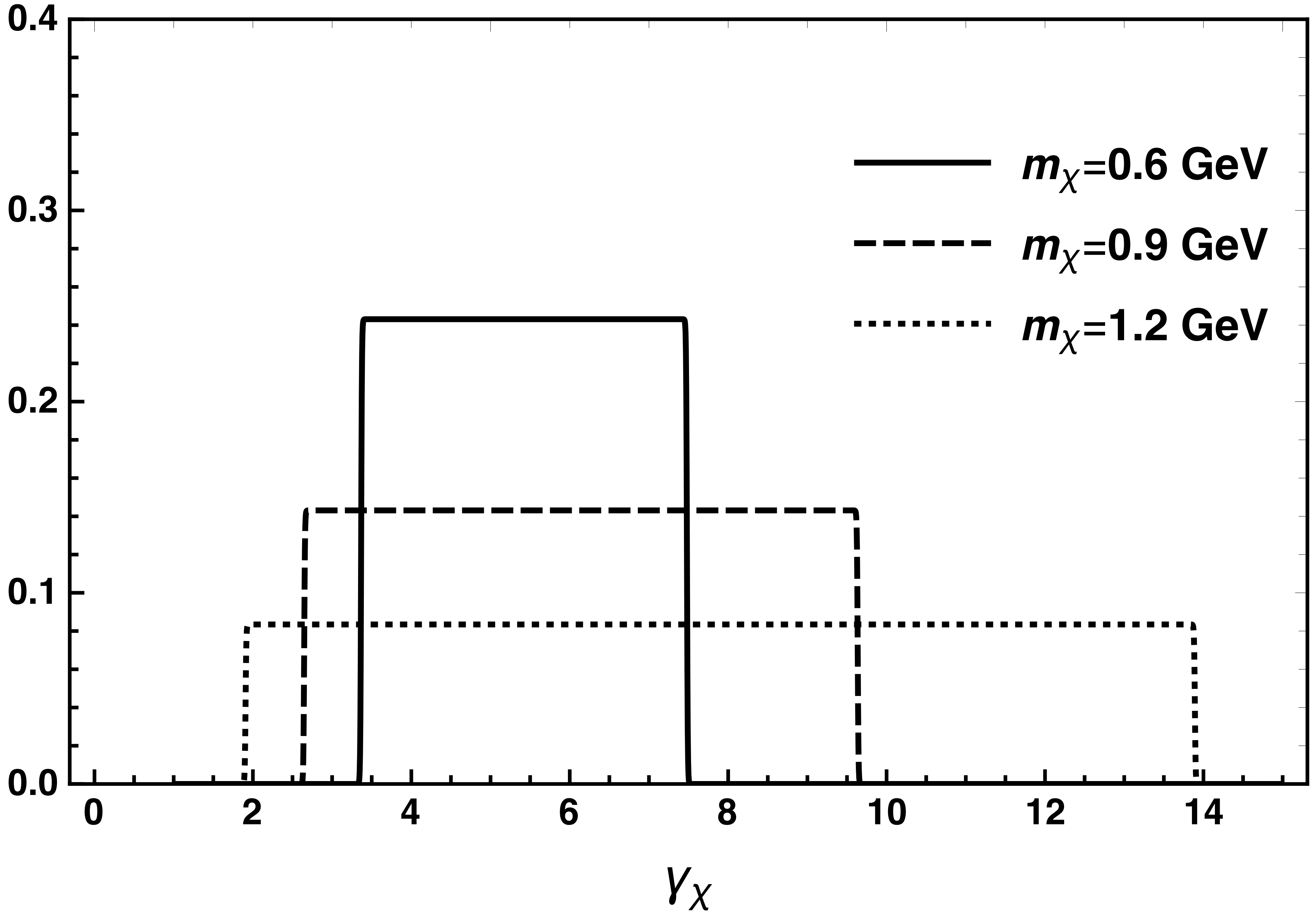
J/ψ $P(\gamma_\chi \mid \gamma_{J/\psi}=5)$ for different MCP masses



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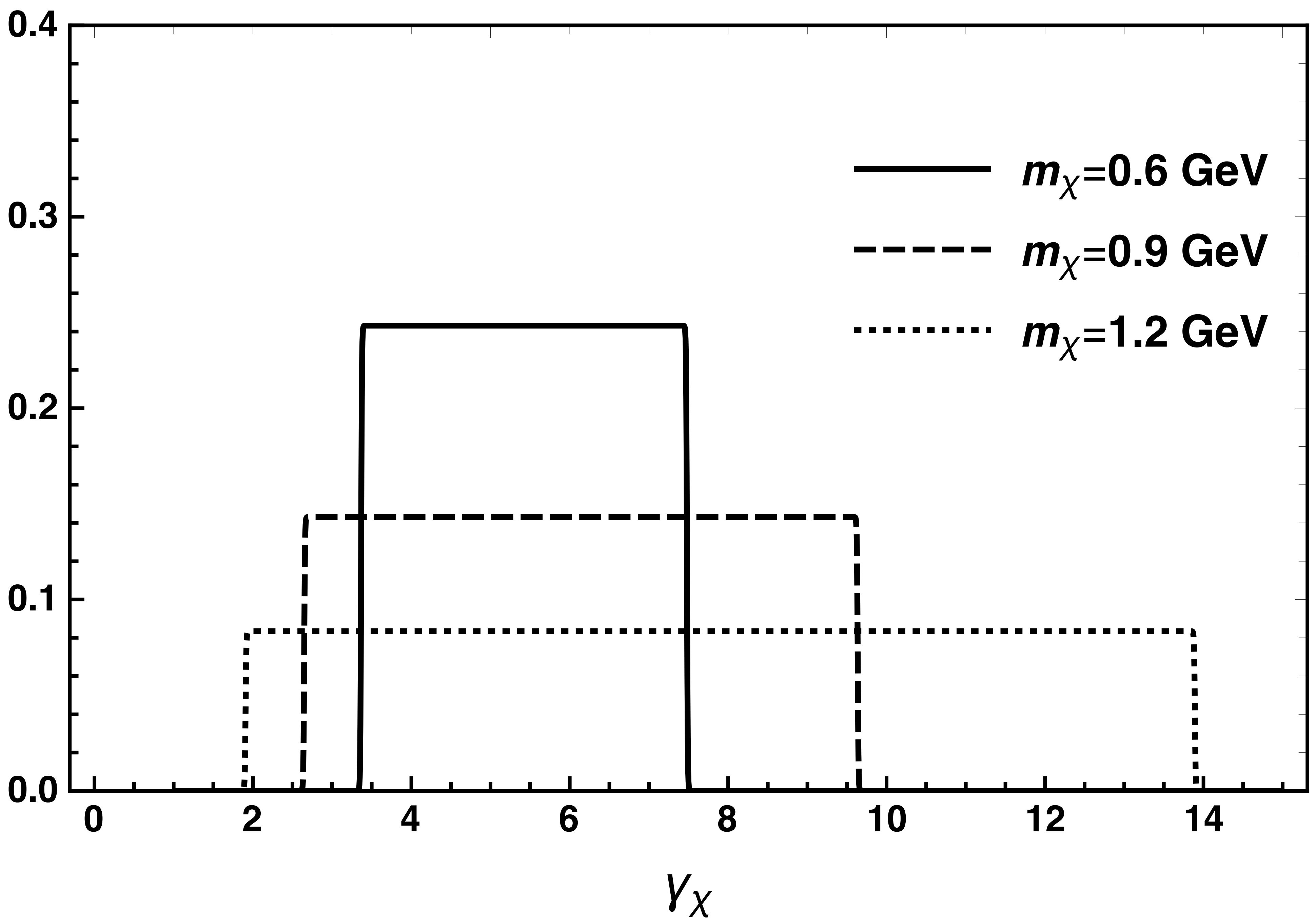
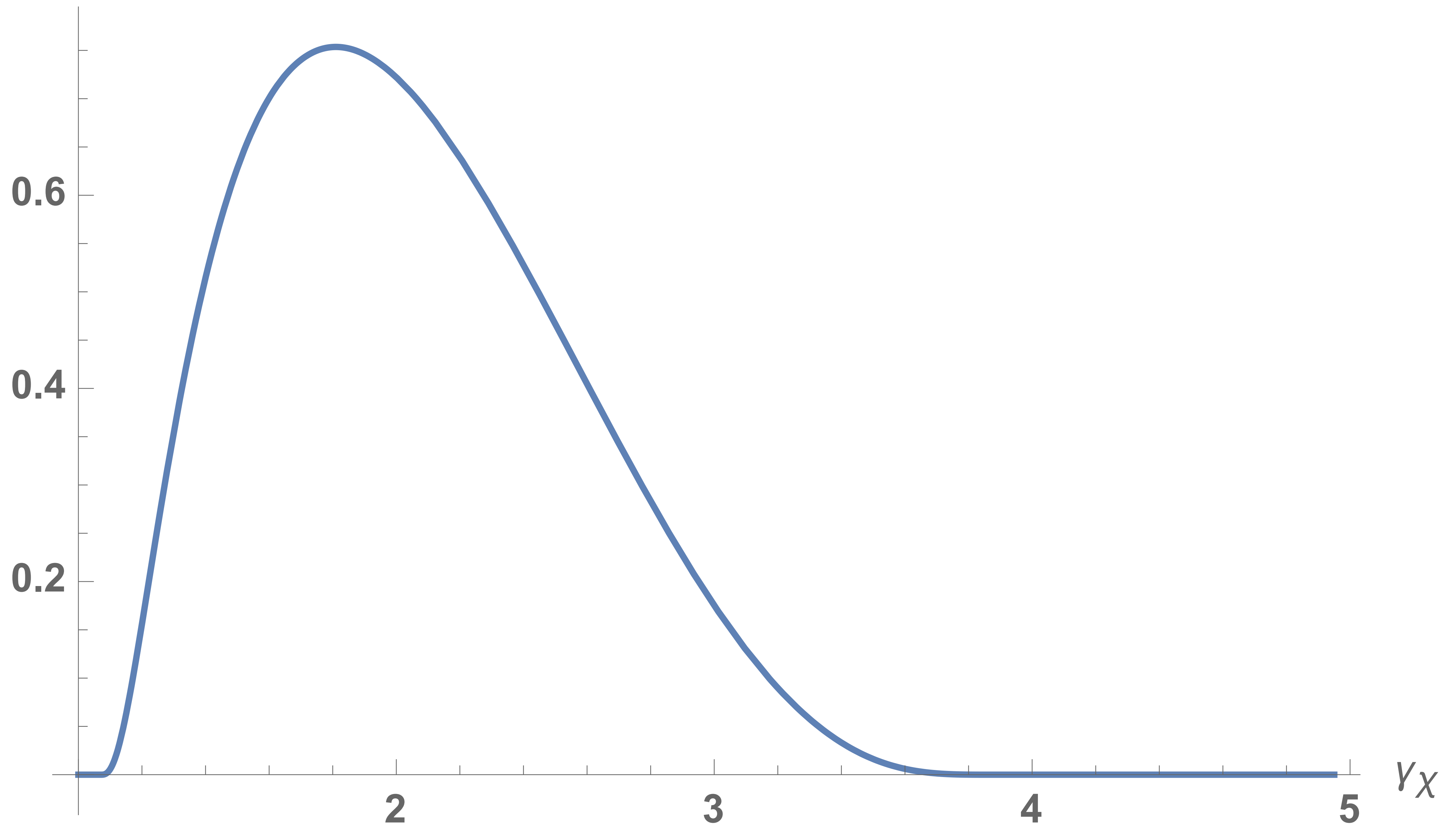
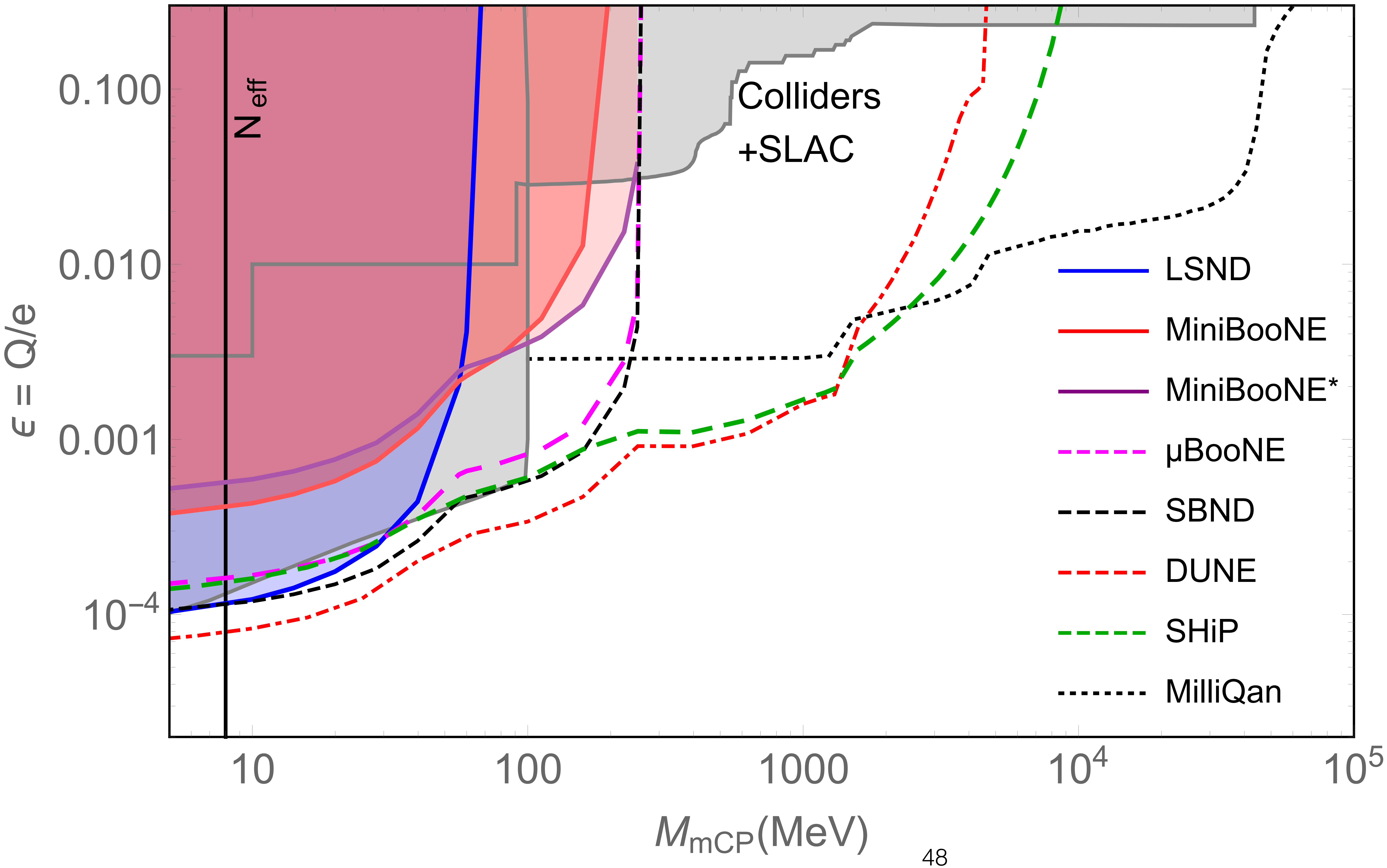


Probability of MCP boost for η DIF with γ_η=5.5 and m_χ=140



Fixed Target

$$s_{\rm up} = \sum_{\rm Energies} \epsilon^4 \times N_\chi(E_i) \times \frac{N_e}{\rm Area} \times \sigma_{e\chi}(E_i;\ m_\chi) \times \mathcal{E}$$



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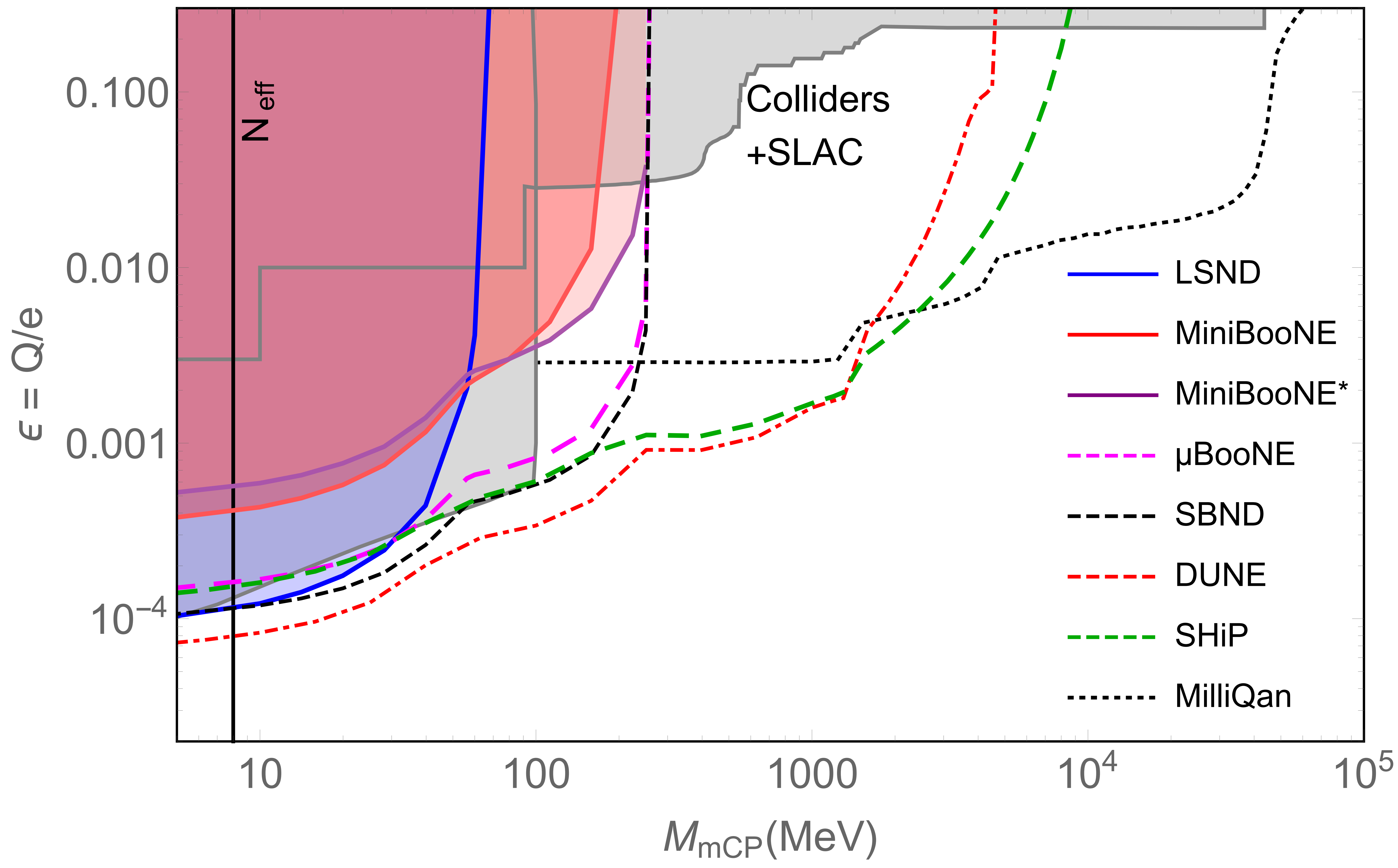

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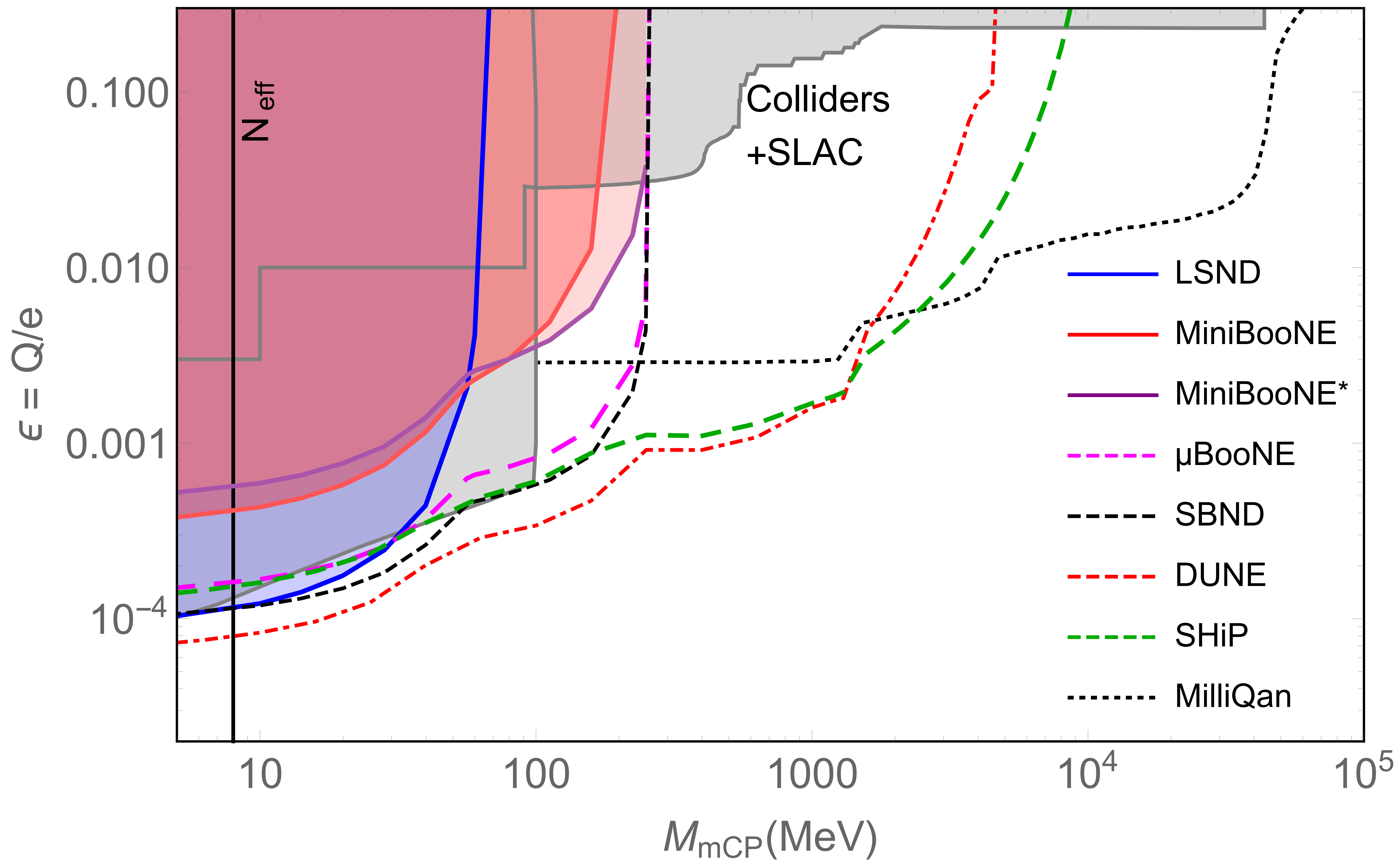

Conclusions

- LSND (secretly) had some of the best bounds on MCPs for 25 years!
- New experiments with LArTPCs (e.g. ArgoNeuT) are extremely well suited to these kinds of low-recoil events.
- Our analysis used some ~~slightly~~ extremely generous background assumptions.
- Main ingredients are mesons produced, recoil threshold and the geometric acceptance of the detector.

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Exp.	N [$\times 10^{20}$] π^0	η	$A_{\text{geo}}(m_\chi)$[$\times 10^{-3}$] 1 MeV	100 MeV	Cuts [MeV] E_e^{min}	E_e^{max}	Bkg
LSND	130	—	20	—	18	52	300
mBooNE	17	0.56	1.2	0.68	130	530	2k
mBooNE*	1.3	0.04	1.2	0.68	75	850	0*
μBooNE	9.2	0.31	0.09	0.05	2	40	16
SBND	4.6	0.15	4.6	2.6	2	40	230
DUNE	830	16	3.3	5.1	2	40	19k
SHiP	4.7	0.11	130	220	100	300	140

TABLE I. Summary of the lifetime meson rates (N), mCP detector acceptances (A_{geo}), electron recoil energy cuts, and backgrounds at each of the experiments considered in this paper. In all experiments a cut of $\cos\theta > 0$ is imposed in our analysis (*except for MiniBooNE's dark matter run where a cut of $\cos\theta > 0.99$ effectively reduces backgrounds to zero [44, 45]). For the SHiP and DUNE experiments, we also include J/ψ and Υ mesons as well as Drell-Yan production which are discussed in the text. We use an efficiency of $\mathcal{E} = 0.2$ for Cherenkov detectors, $\mathcal{E} = 0.5$ for nuclear emulsion detectors, and $\mathcal{E} = 0.8$ for liquid argon time projection chambers. The data at LSND and MiniBooNE is taken from [46] and [24, 44] respectively. Projections at MicroBooNE [47], SBND [26], DUNE [27] and SHiP [48] are based on expected detector performance.

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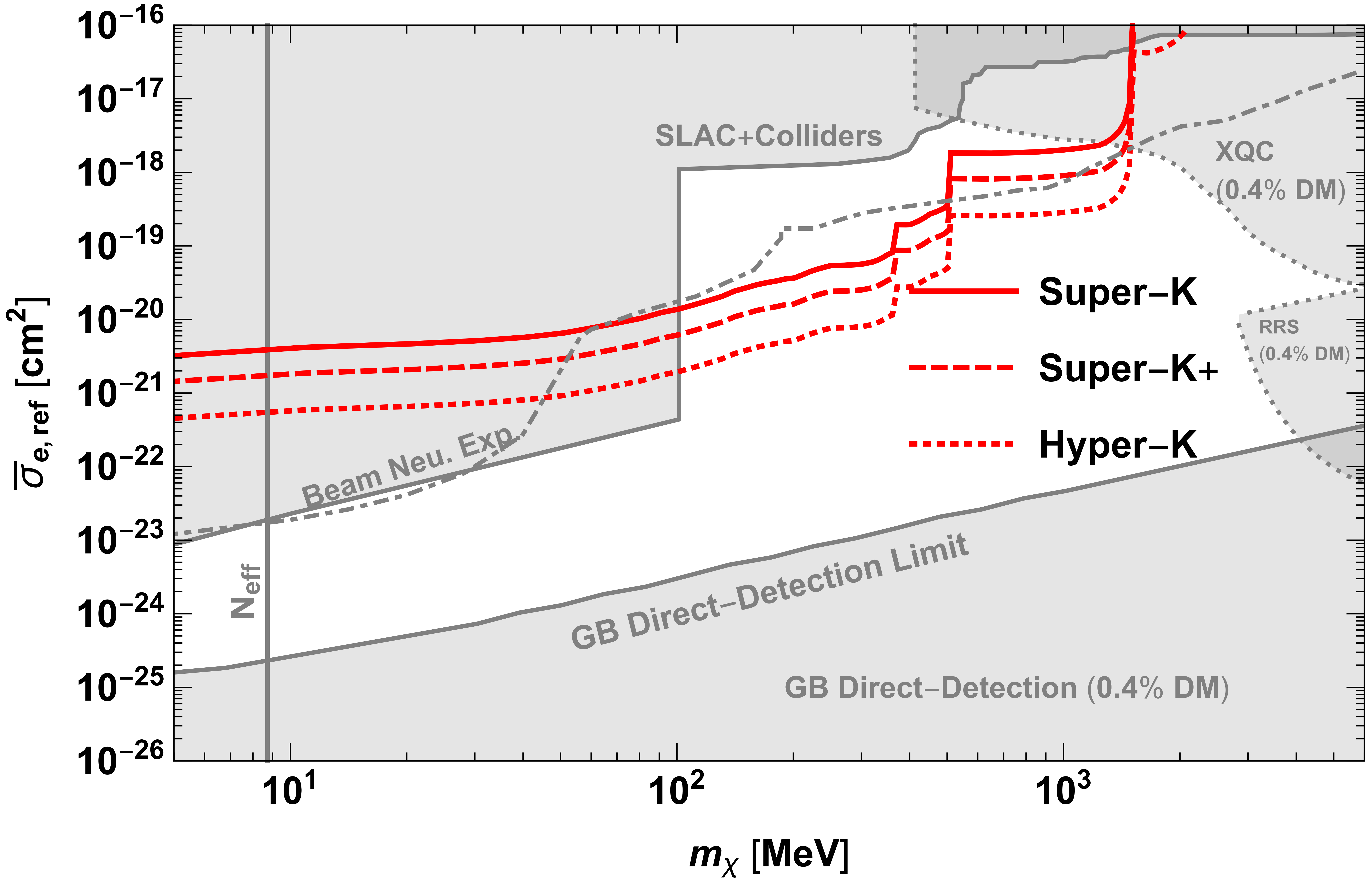
Results from cosmic rays

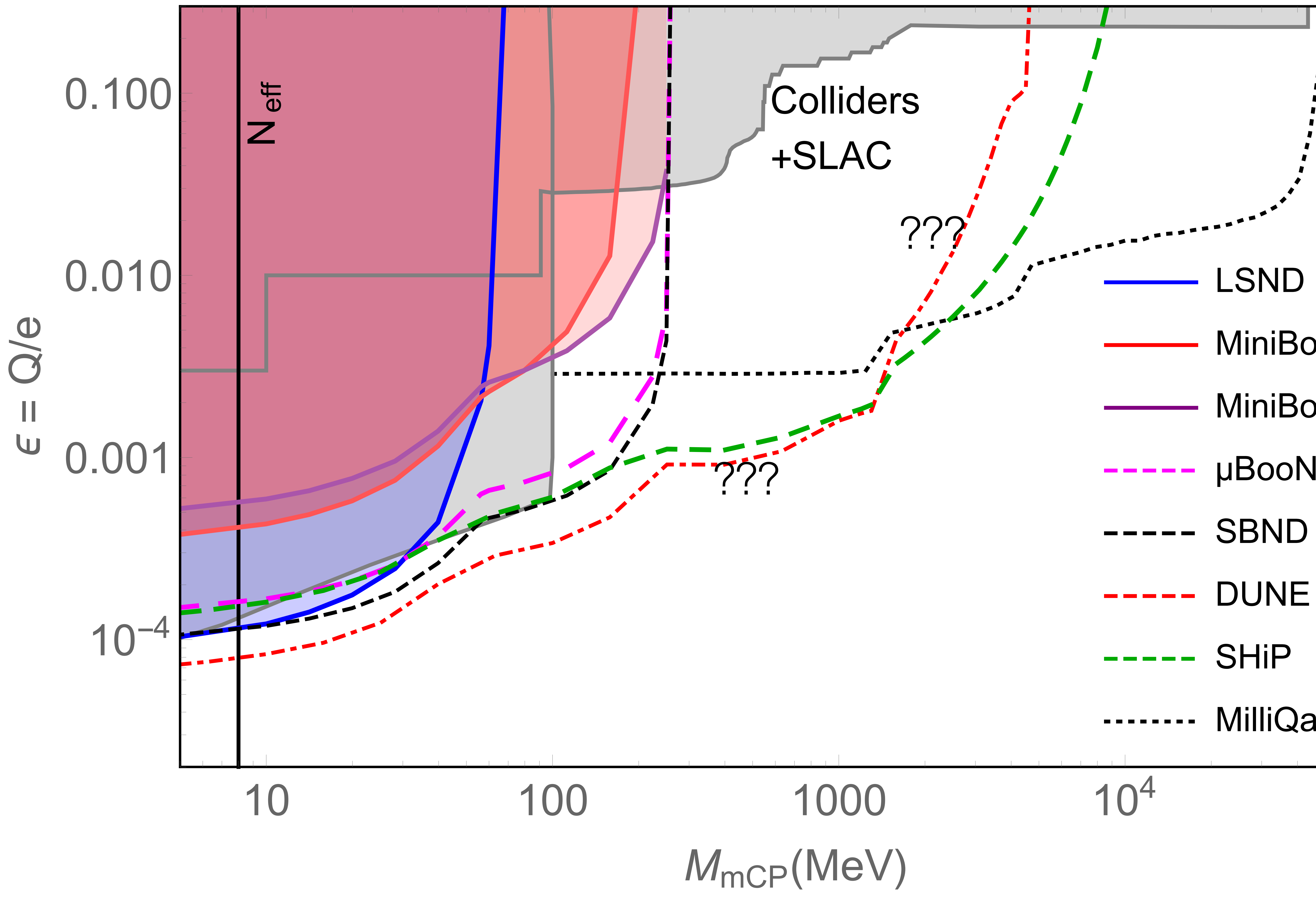


Backgrounds and Multiple Hits

Liu, Harnik, Palamara (2019)

Insider Knowledge

- **ArgoNeuT saw very large backgrounds that the collaboration believes to be beam-related**
- **Worse yet, these backgrounds are not necessarily under control.**



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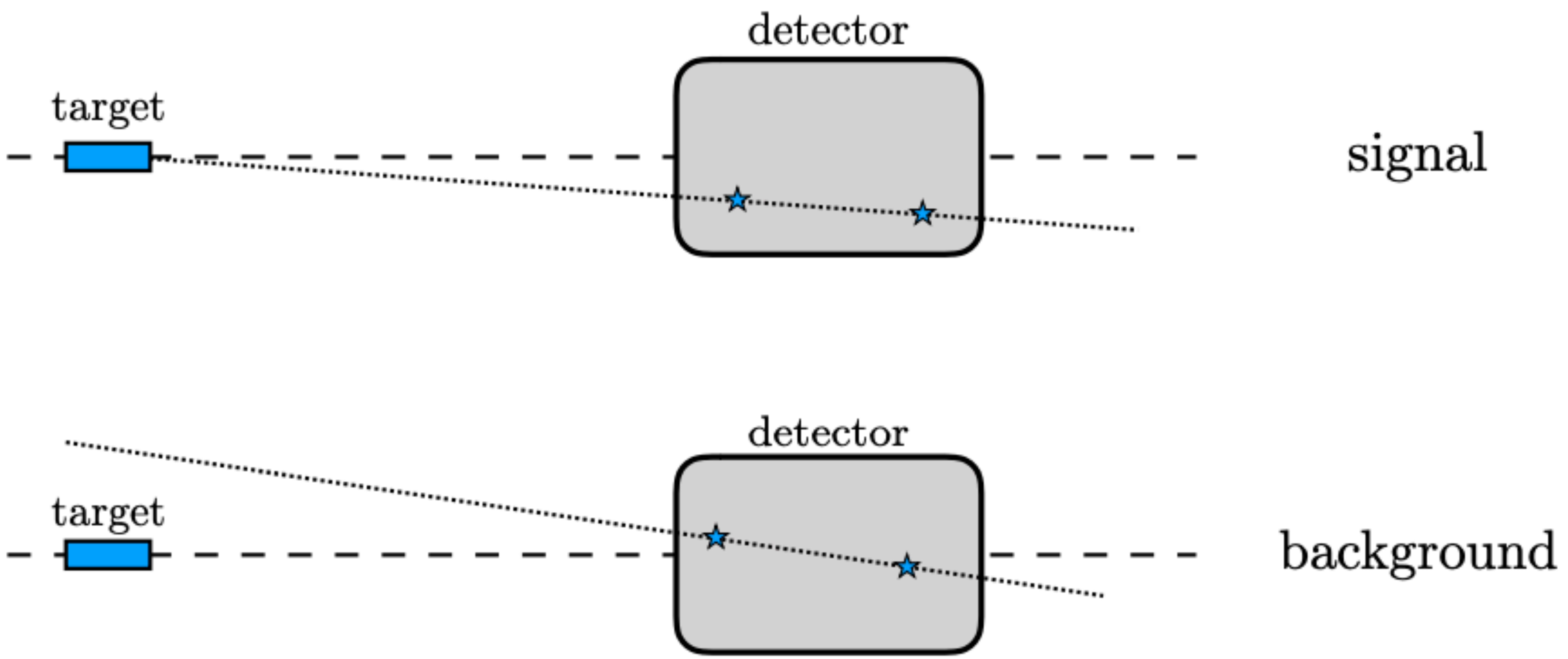

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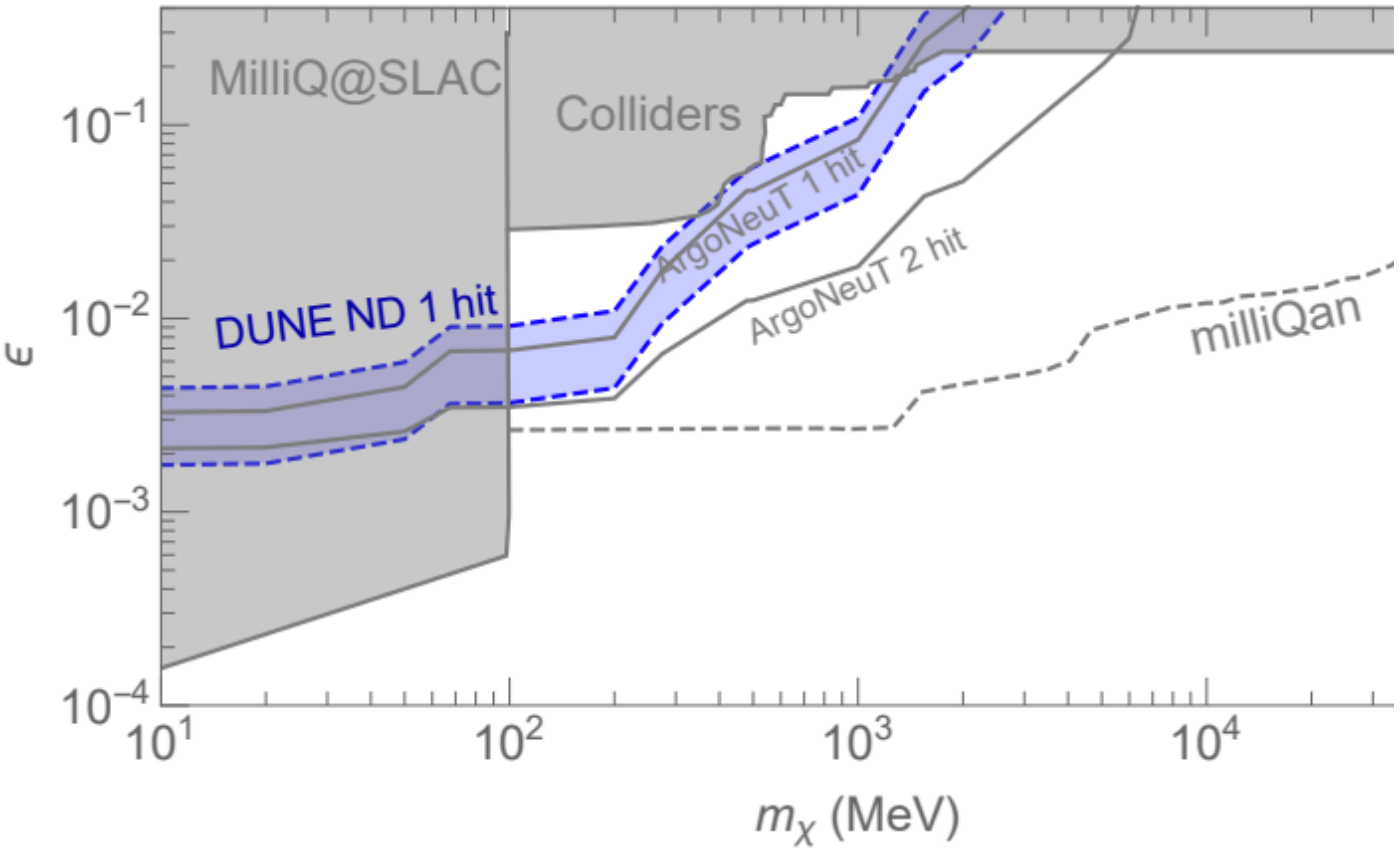

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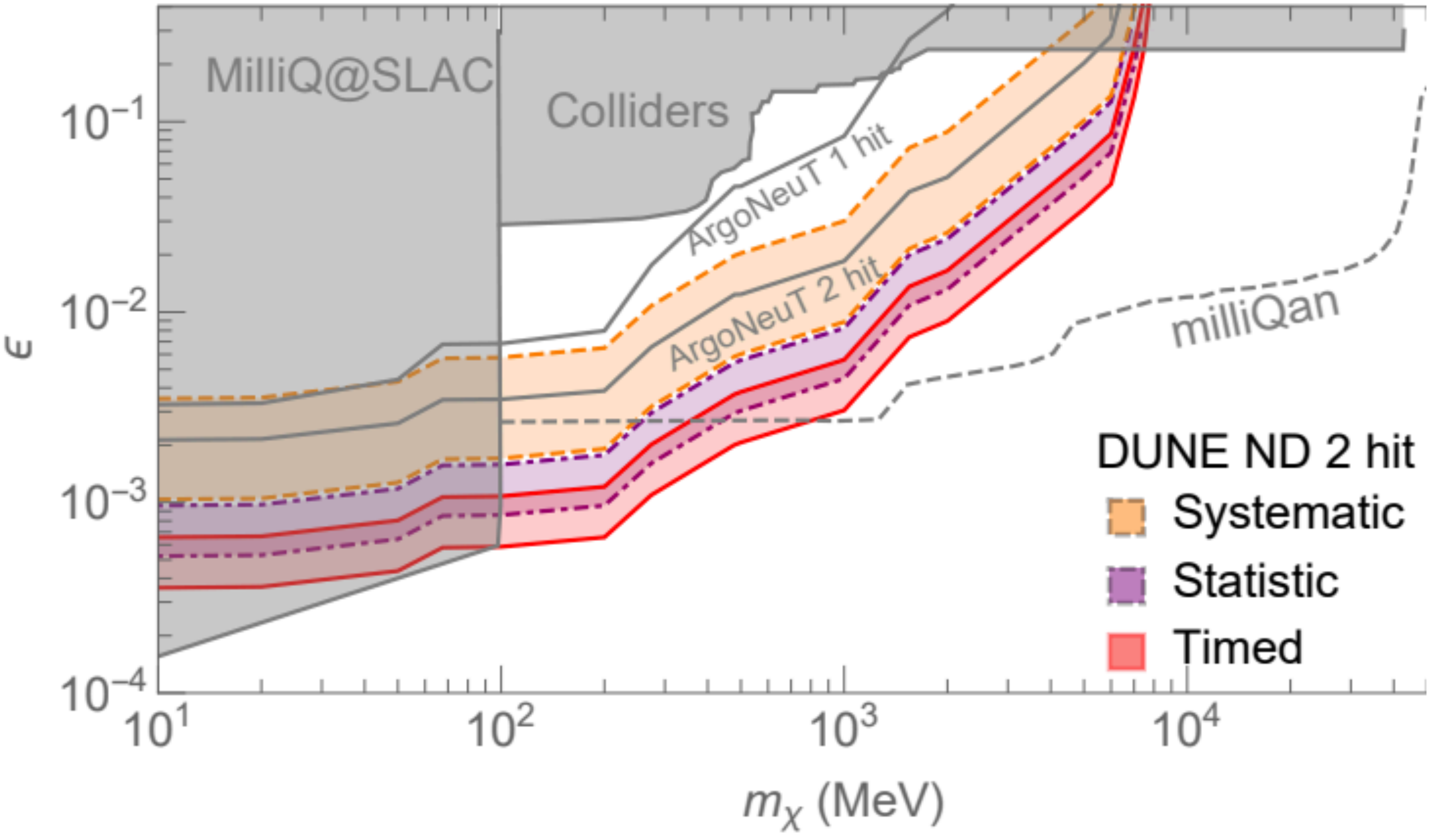

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Summary

1. Neutrino trident production will be observable at upcoming intensity frontier experiments.
    - As of yet unobserved SM physics
    - Probe of new physics.

2. Millicharged particles are testable at neutrino experiments (both new and old).

3. Cosmic rays can serve as a fixed target ``facility” with a broadband beam and huge downstream detectors.

4. We outline a simple procedure for generating cosmic ray flux