Hunting for Dark Matter at the Tevatron

Patrick Fox

Fermilab

with Yang Bai, Joachim Kopp, Roni Harnik and Yuhsin Tsai

(JHEP 1012 (2010) 048, arXiv: 1103.0240)

Dark Matter

Dark Matter

When?

(did it get made)

Dark Matter

What?
(is it)

When?
(did it get made)

Dark Matter

What?
(is it)

When?
(did it get made)

Why?
(is it around)

Dark Matter

What?
(is it)

When?
(did it get made)

Where?
(is it)

Why?
(is it around)

Dark Matter

What?
(is it)

How?
(much is there)

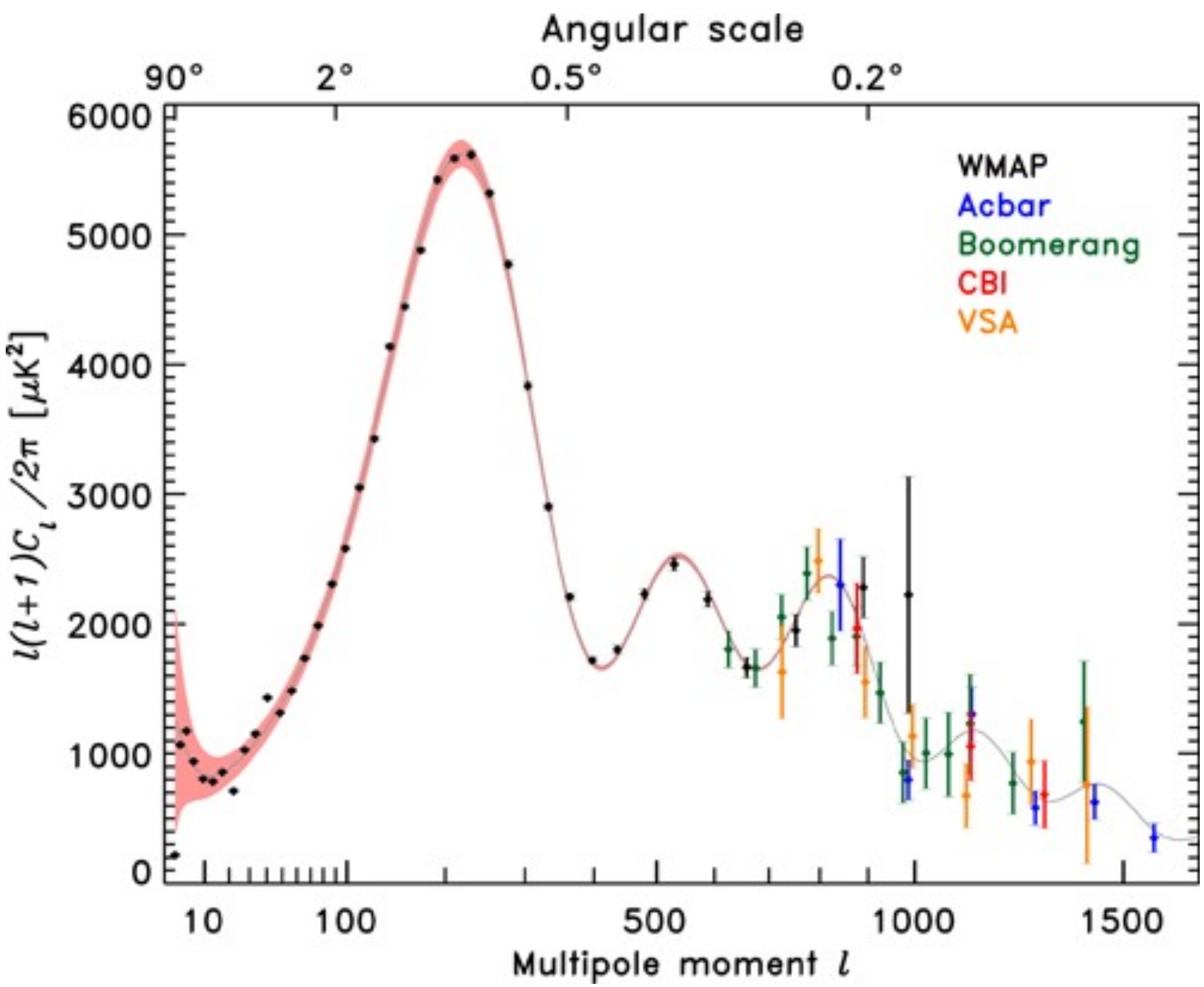
When?
(did it get made)

Where?
(is it)

Why?
(is it around)

DM abundance

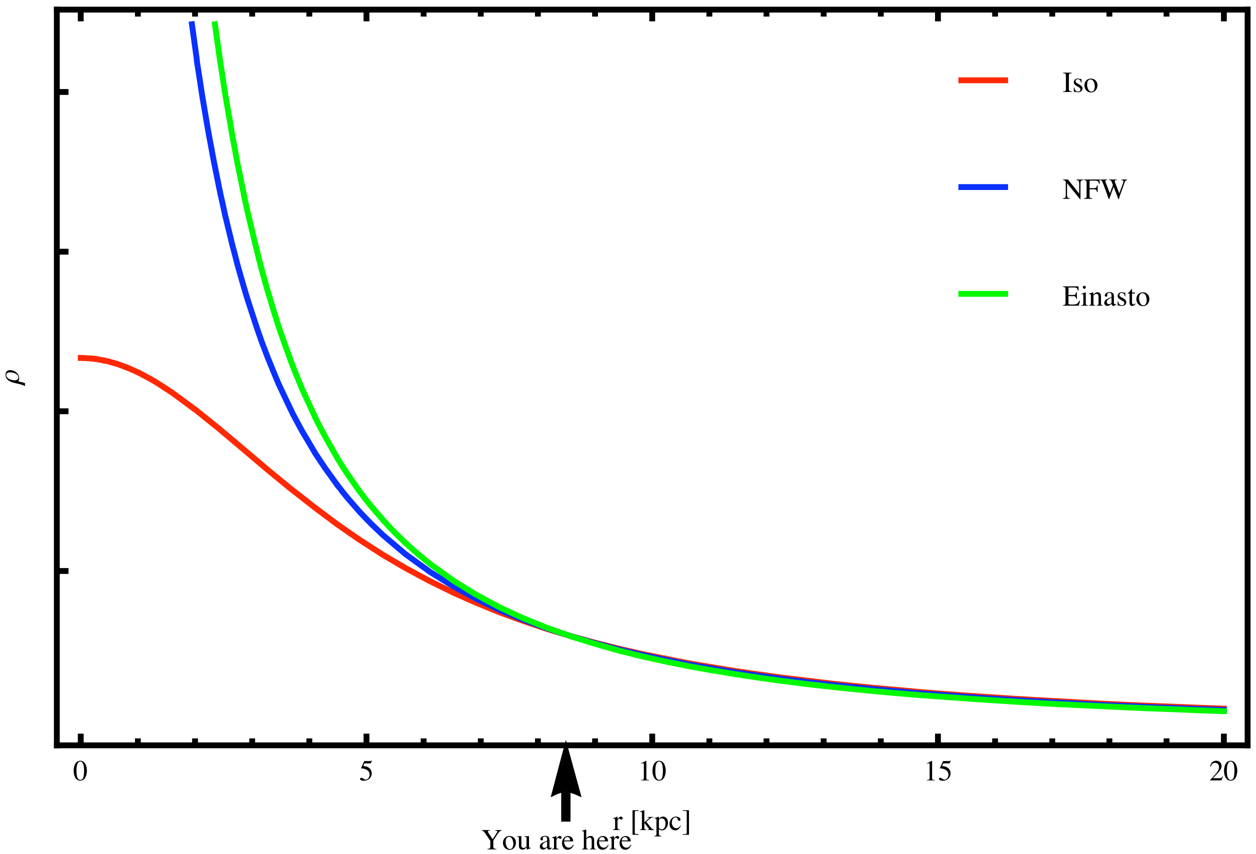
Cosmological abundance

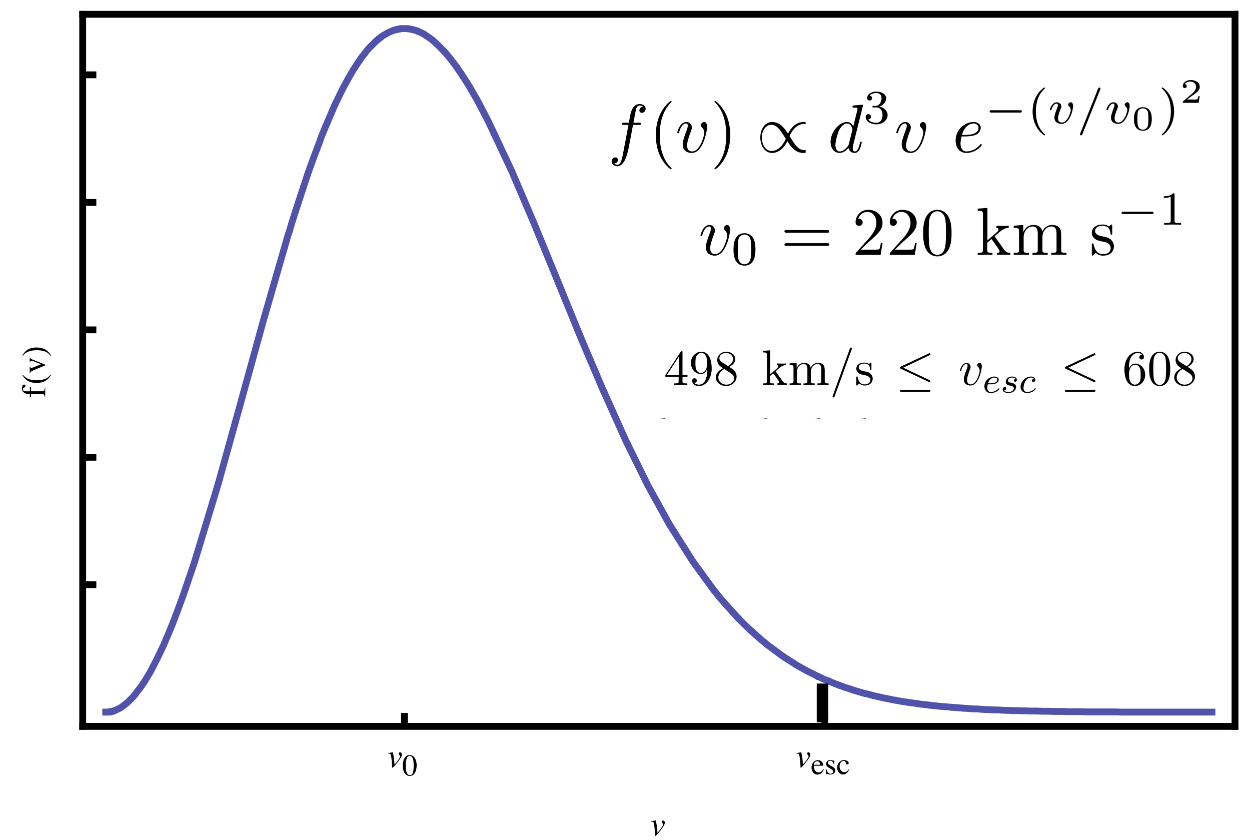


$$\Omega_{DM} = 0.213$$

DM abundance and distribution

Galactic abundance
N-body simulations and rotation curves





$$\rho_{DM} \sim 0.3 \text{ GeV cm}^{-3}$$

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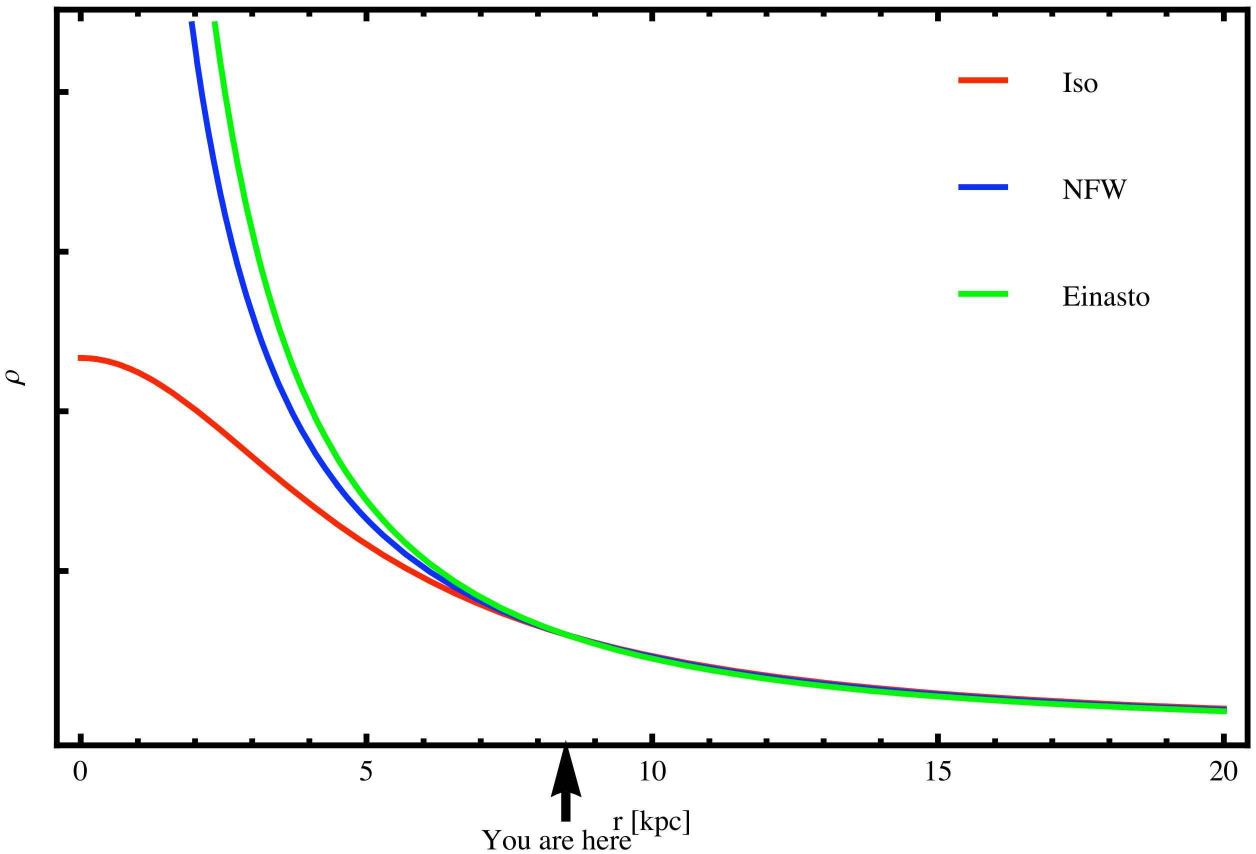

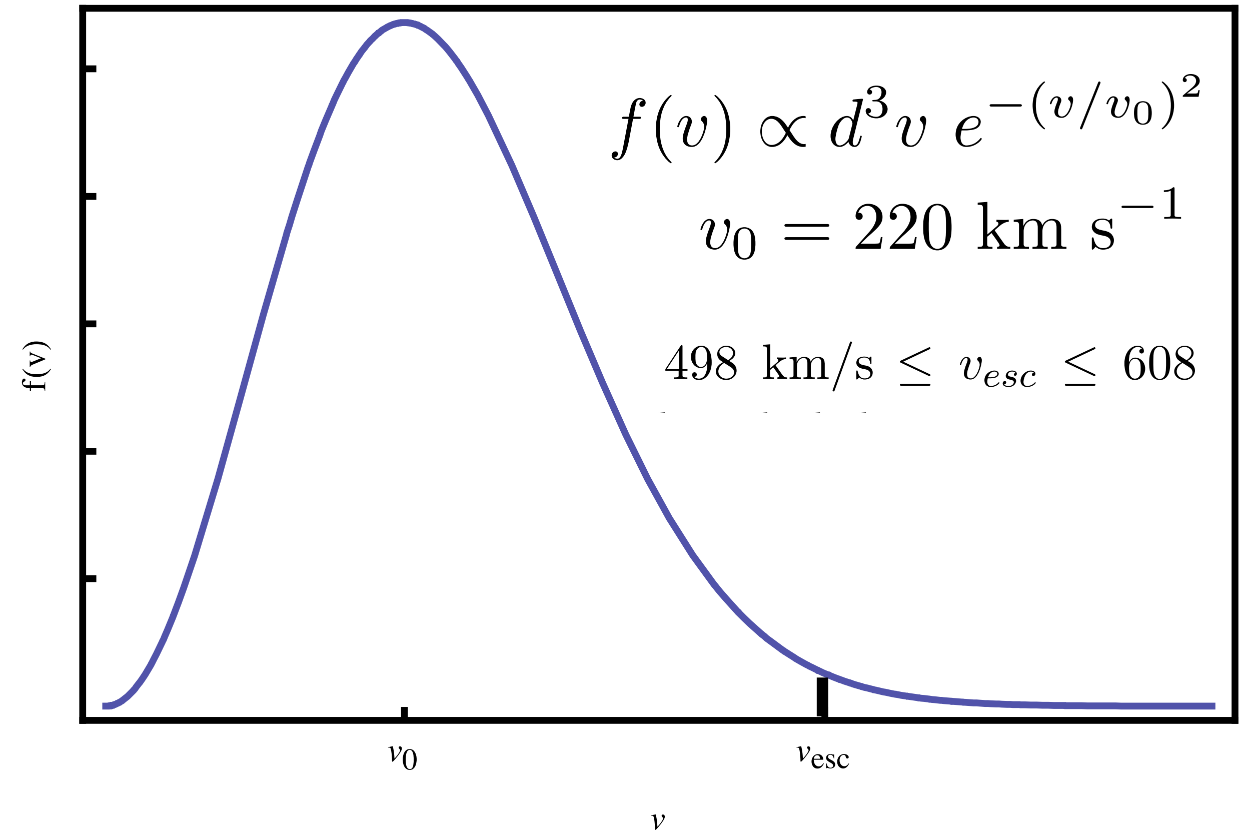

$$* \rho_{DM} \sim 0.3\ \mathrm{GeV\ cm^{-3}}$$

$* \pm$ a factor of two

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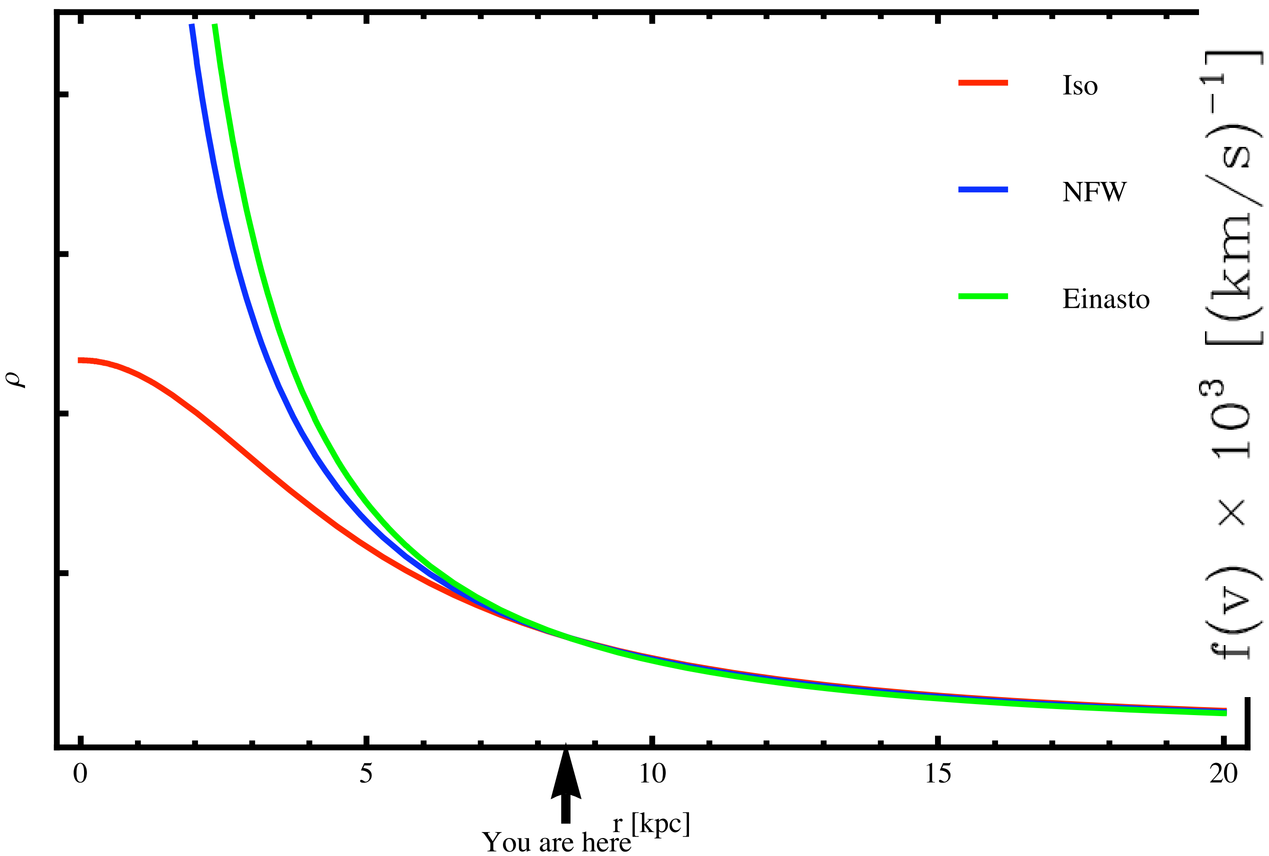
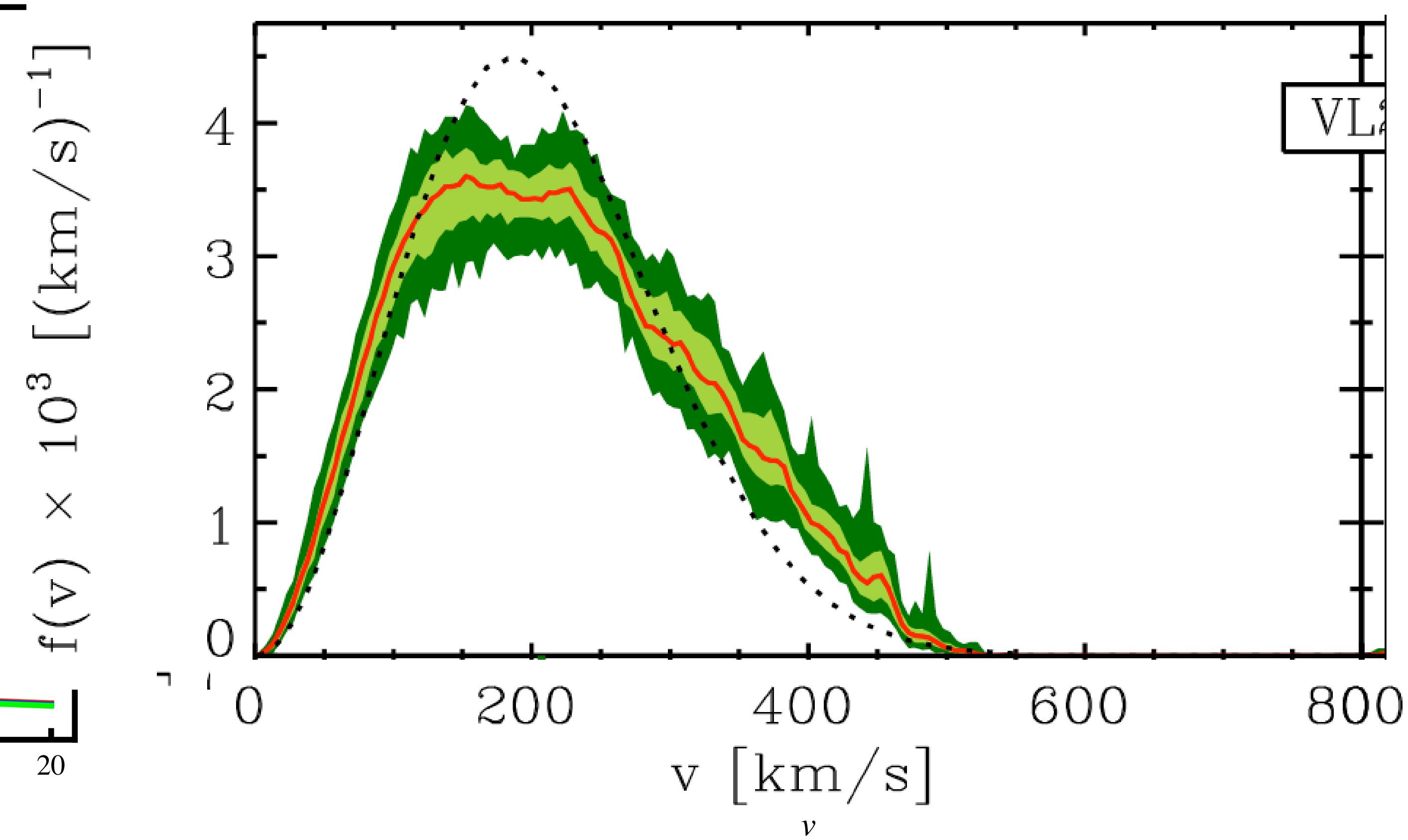


Via Lactea II



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DM's properties

- "Cold" dark matter
- Non-baryonic
- Stable on cosmological time scales
- "Dark", i.e. neutral under SM

Possible candidates:

- Axions
- Gravitinos
- Primordial black holes
- MACHOs
- WIMPs e.g. SUSY neutralino, KK-mode of UED, techni-baryons, lightest T-odd little Higgs particle, LPOPs....

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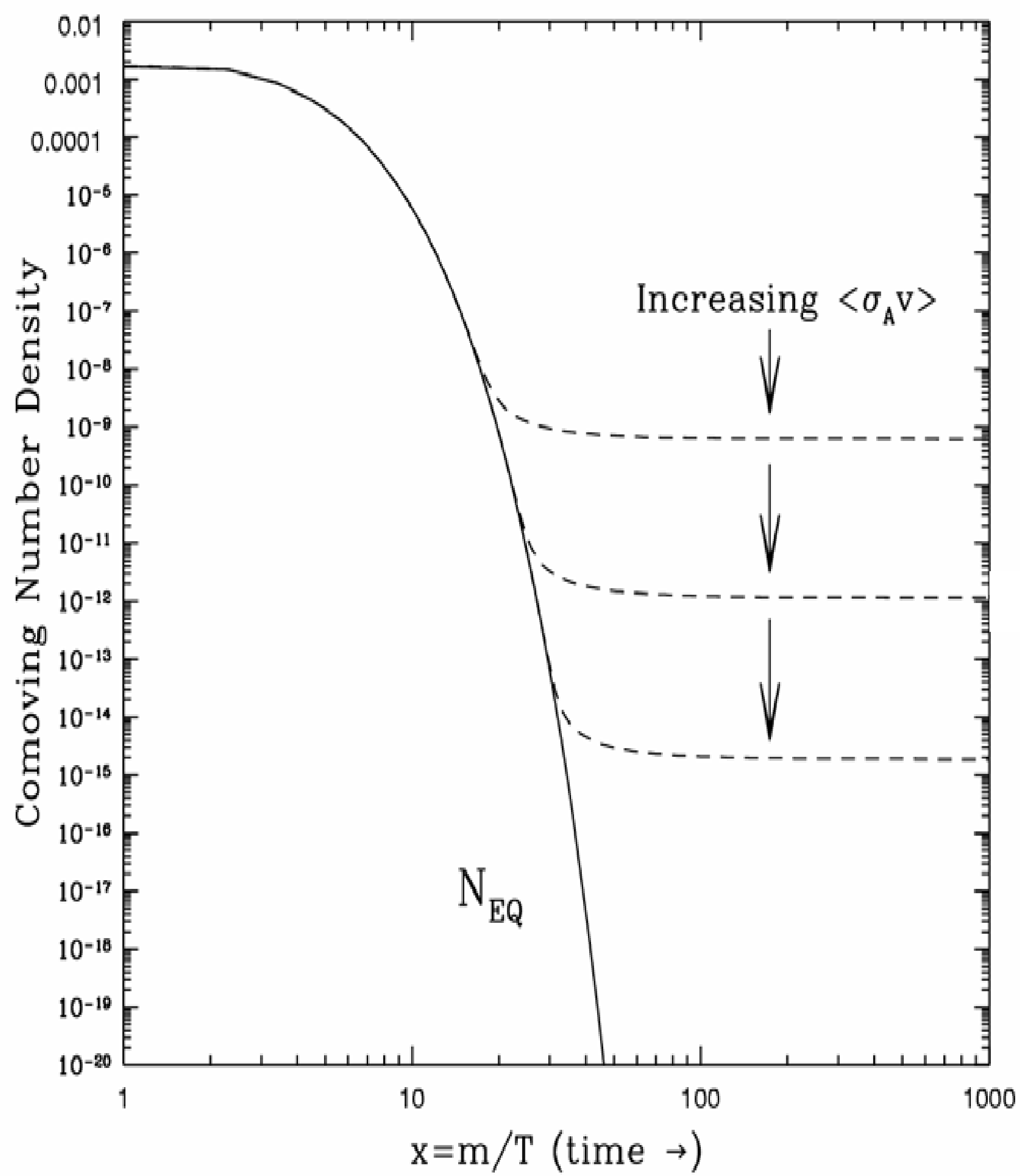
(probably needs a new name)

DM as a thermal relic

"The weak shall inherit the Universe"

A weak scale particle (WIMP) freezes out to leave the correct relic abundance - the WIMP "miracle"



$$\chi\chi \leftrightarrow \bar{f}f$$

$$\Omega h^2 \approx 0.1 \left(\frac{m/T}{20}\right)\left(\frac{g_*}{80}\right)^{-1}\left(\frac{3\times 10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}}{\sigma v}\right)$$

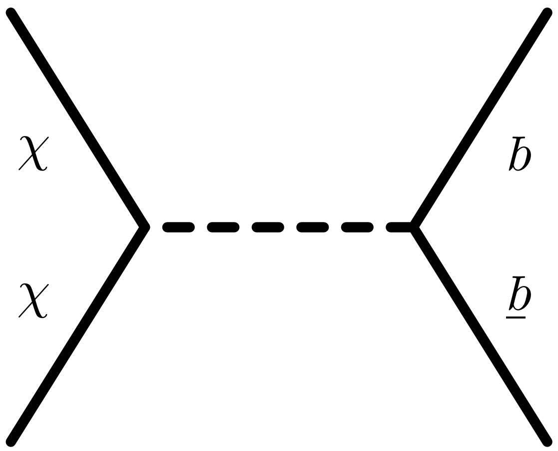
Amazing (misleading?) fact:

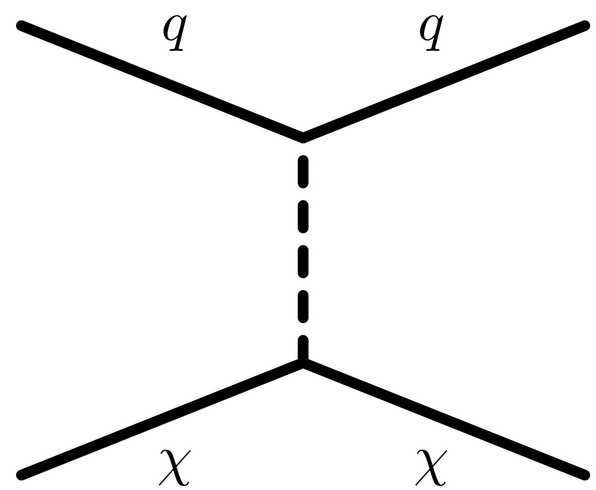
[Feng and Kumar]

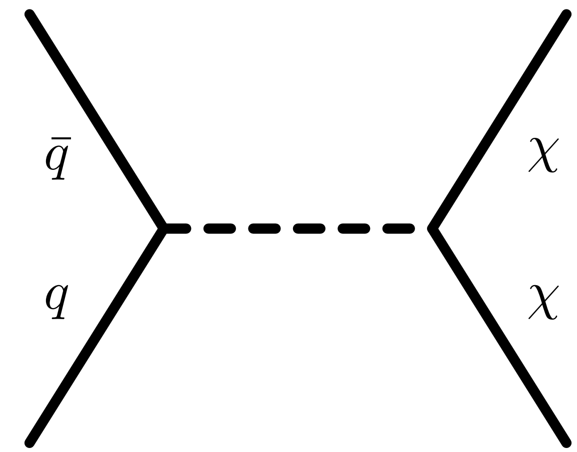
$$\langle\sigma v\rangle \sim \frac{\alpha_W^2}{M_W^2} \sim 1\,\mathrm{pb} \sim 3\times 10^{-26}\mathrm{cm}^2\mathrm{s}^{-1}$$

Searching for dark matter

(here, there and everywhere)







Indirect detection	Direct detection	Collider searches
<u>Look up</u>	<u>Look down</u>	<u>Look small</u>
Anti-matter excesses in cosmic rays, photons from centre of galaxy	Low rate, low energy recoil events in underground labs	Missing energy events at colliders

Searching for dark matter

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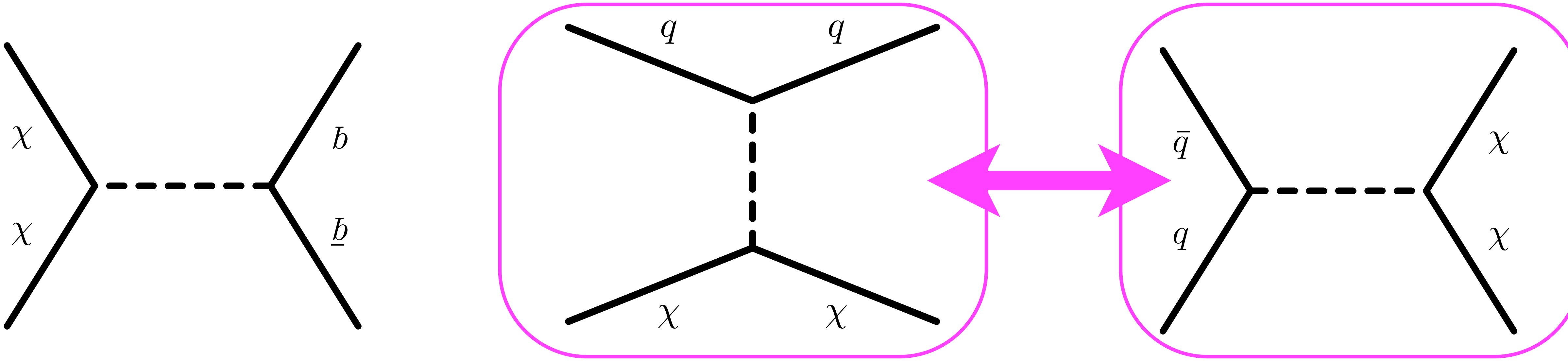

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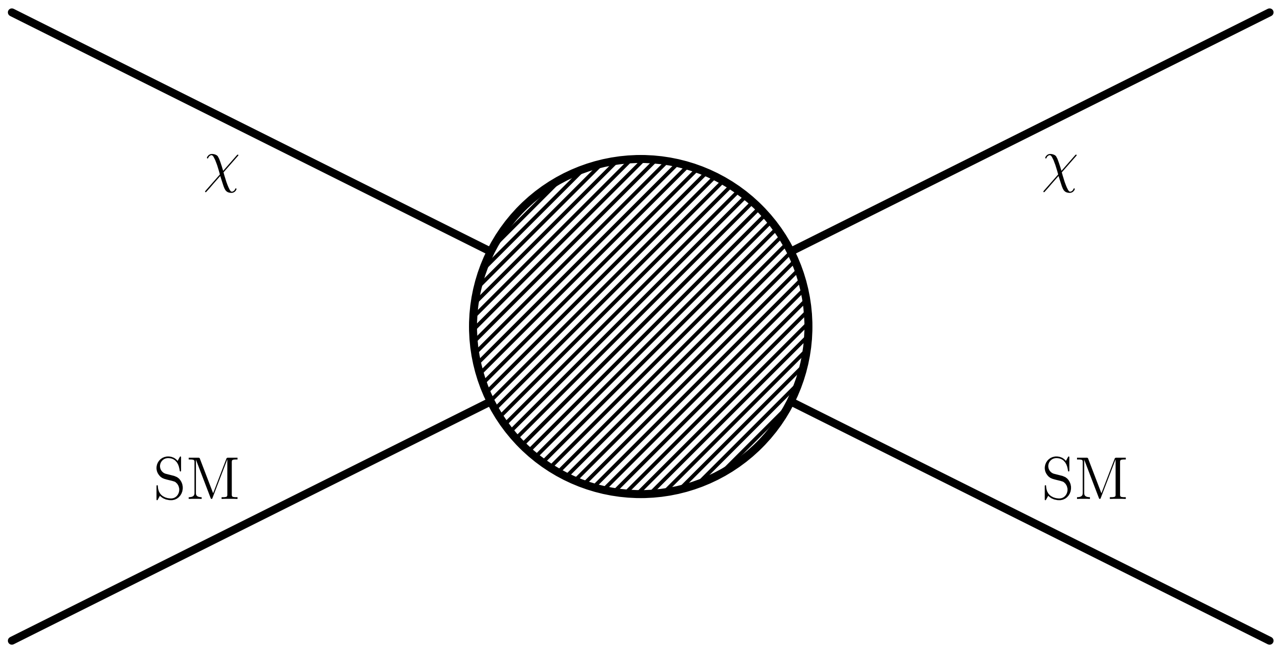
Direct Detection



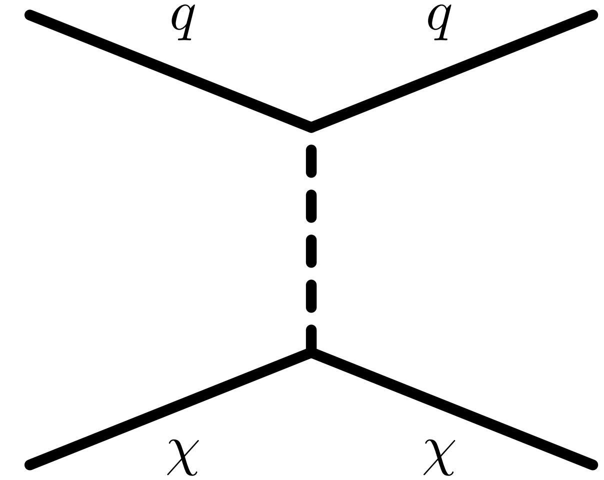
$$E_R \sim \frac{q_\chi^2}{2\,M_T} \sim 100\,\mathrm{keV}$$

$$R \sim N_T \frac{\rho_\chi}{m_\chi} \langle \sigma v \rangle \approx 1 \text{ event/day/kg}$$

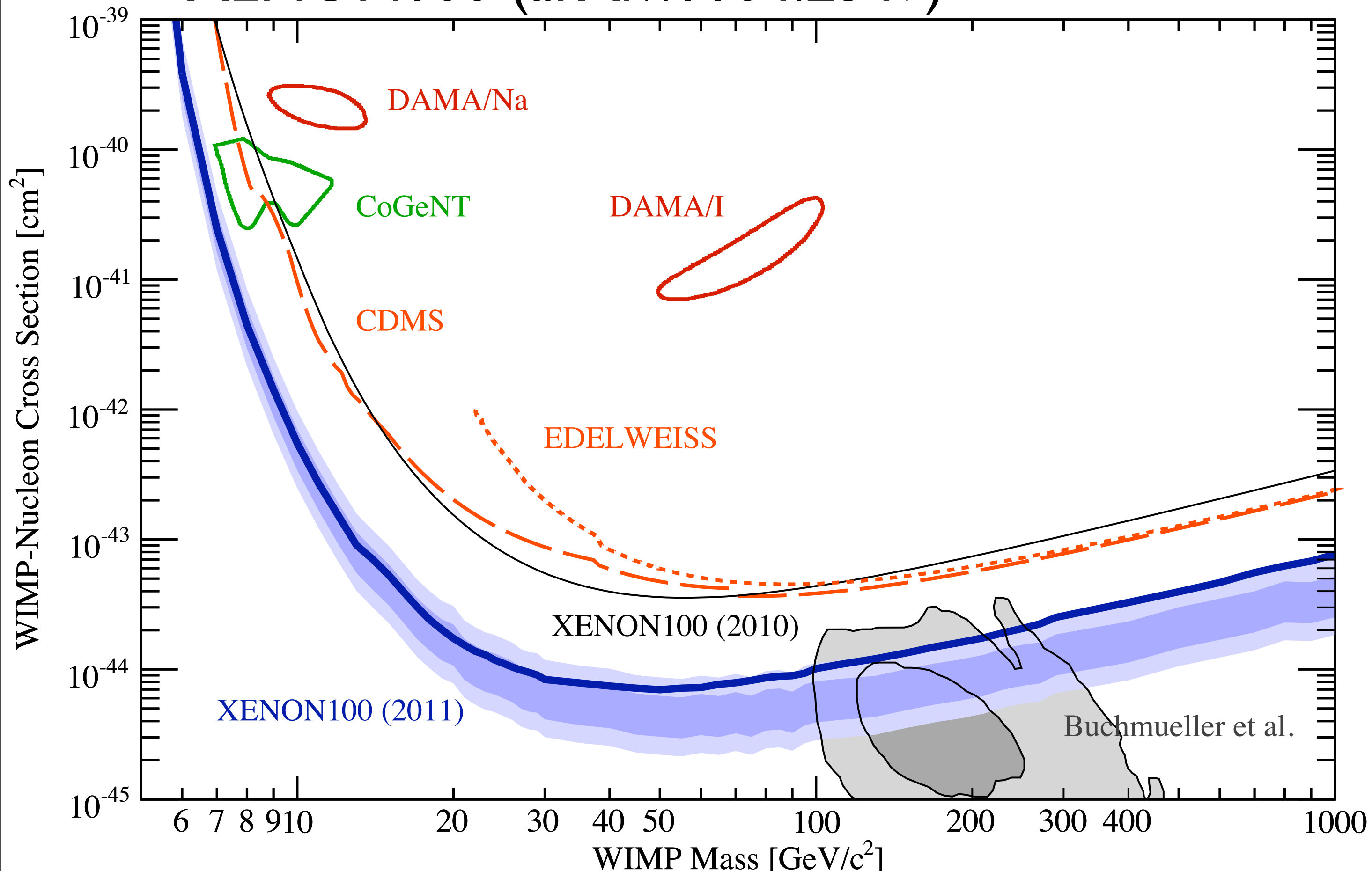
How to distinguish this small number of low energy events from backgrounds?

Existing DD bounds

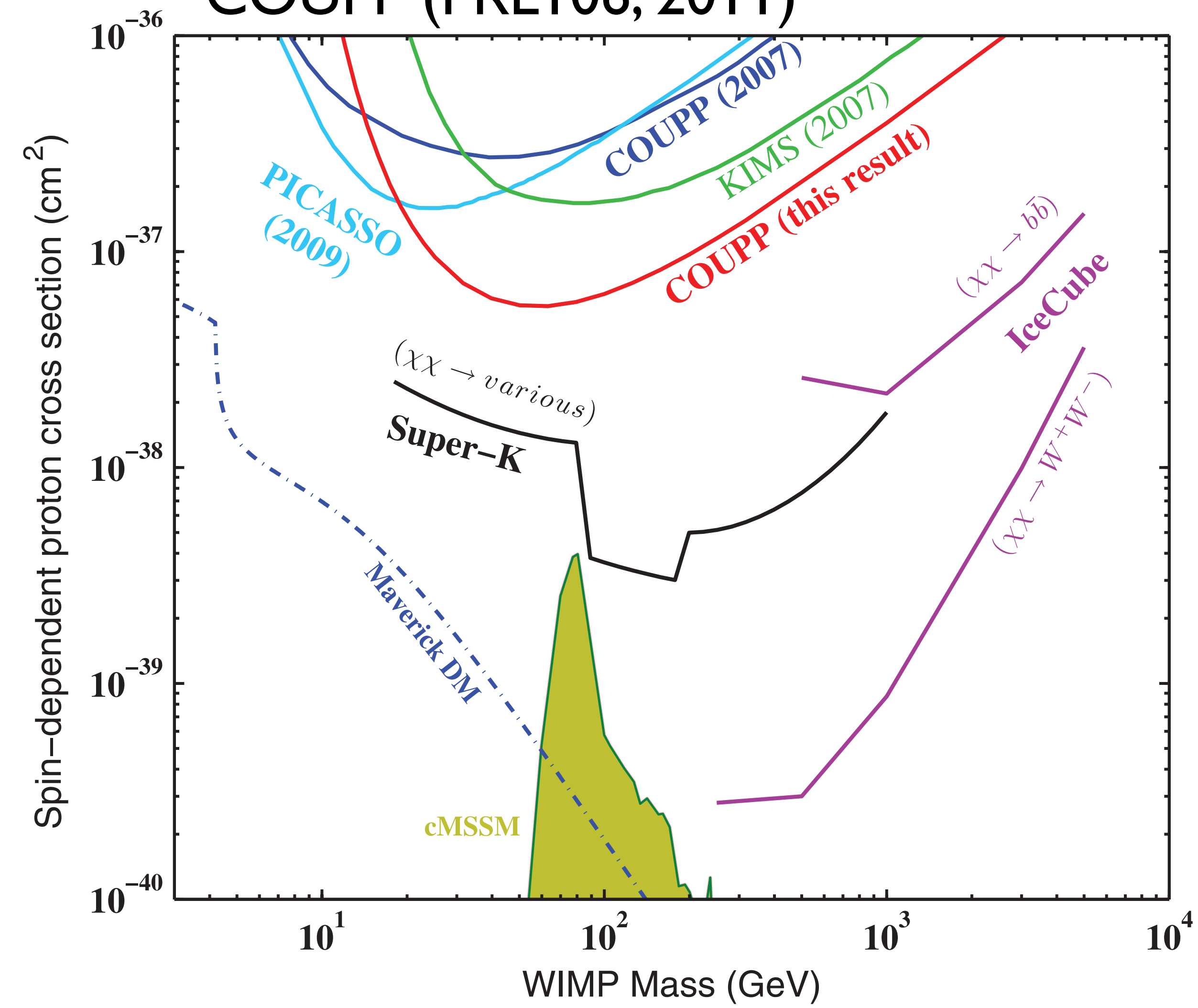
CDMS, XENON, DAMA,
CoGeNT, COUPP,
CRESST, ...



XENON100 (arXiv:1104.2549)



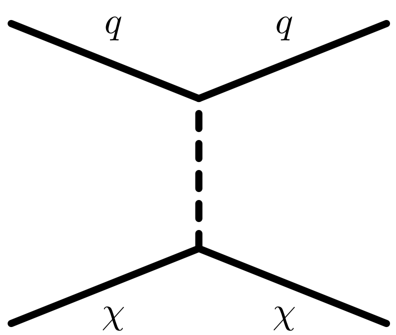
COUPP (PRL106, 2011)



(Assume local abundance is 0.3 GeV/cm^3)

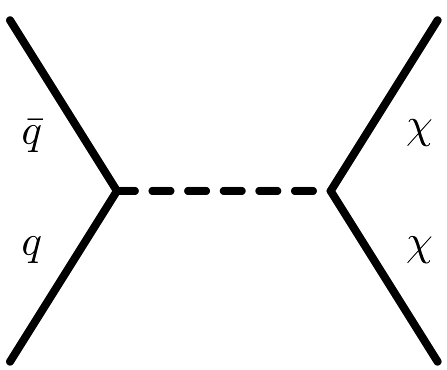
The Tevatron and DM

Only consider mediators with mass $M \gtrsim 100\ \mathrm{MeV}$



$$\sigma_{\mathrm{DD}} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4}$$

$$\mu = \frac{m_\chi m_n}{m_\chi + m_n}$$



Mono-jet + $\not{E}_T$

$$\sigma_{1j} \sim \begin{cases} \alpha_s\, g_\chi^2\, g_q^2\, \frac{1}{p_T^2} & M \lesssim p_T \\ \alpha_s\, g_\chi^2\, g_q^2\, \frac{p_T^2}{M^4} & M \gtrsim p_T \end{cases}$$

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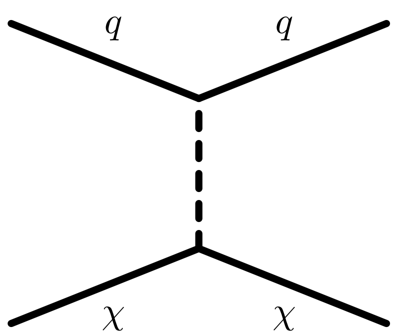

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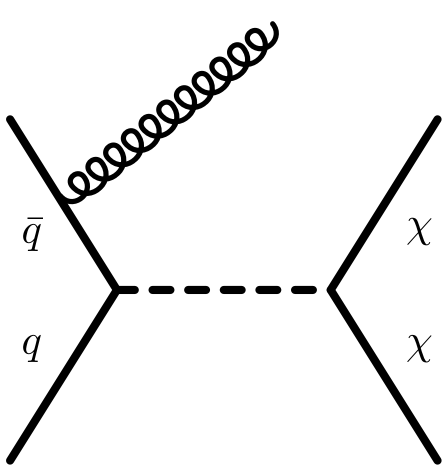

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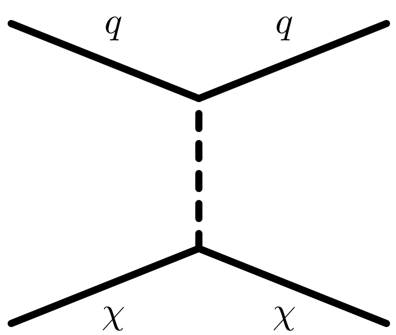

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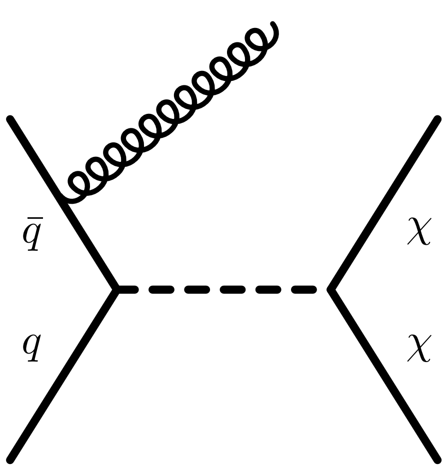

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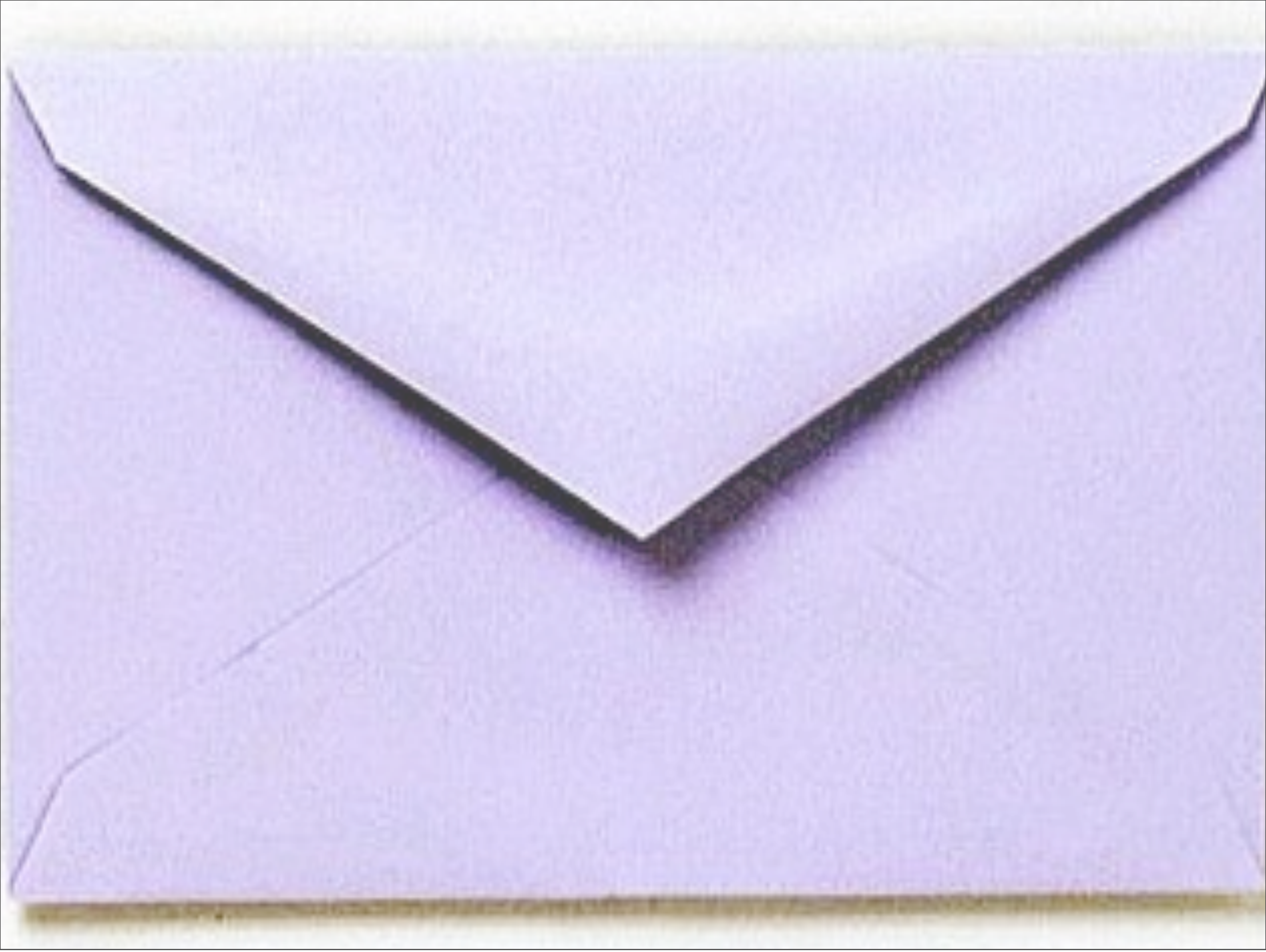

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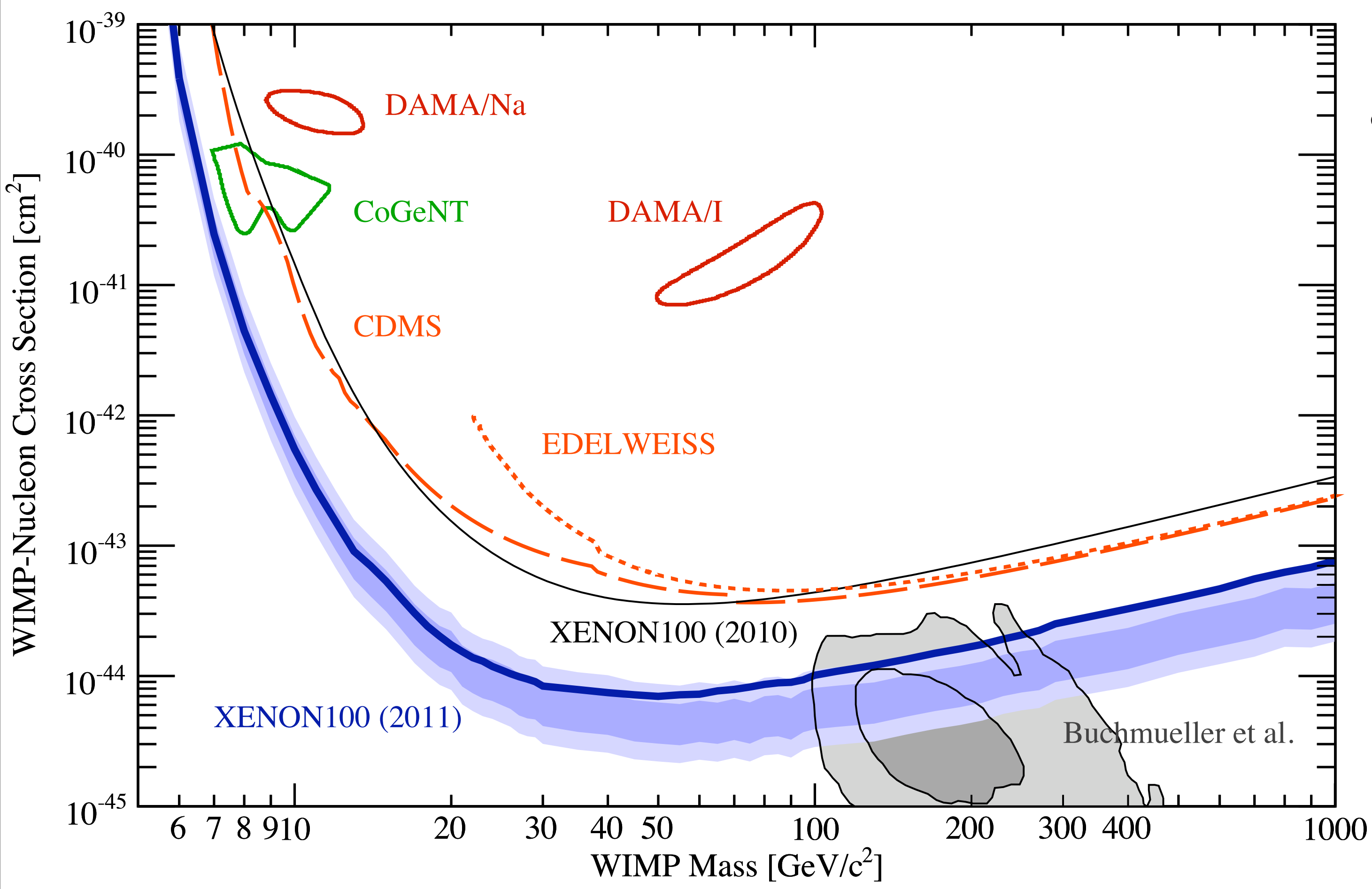
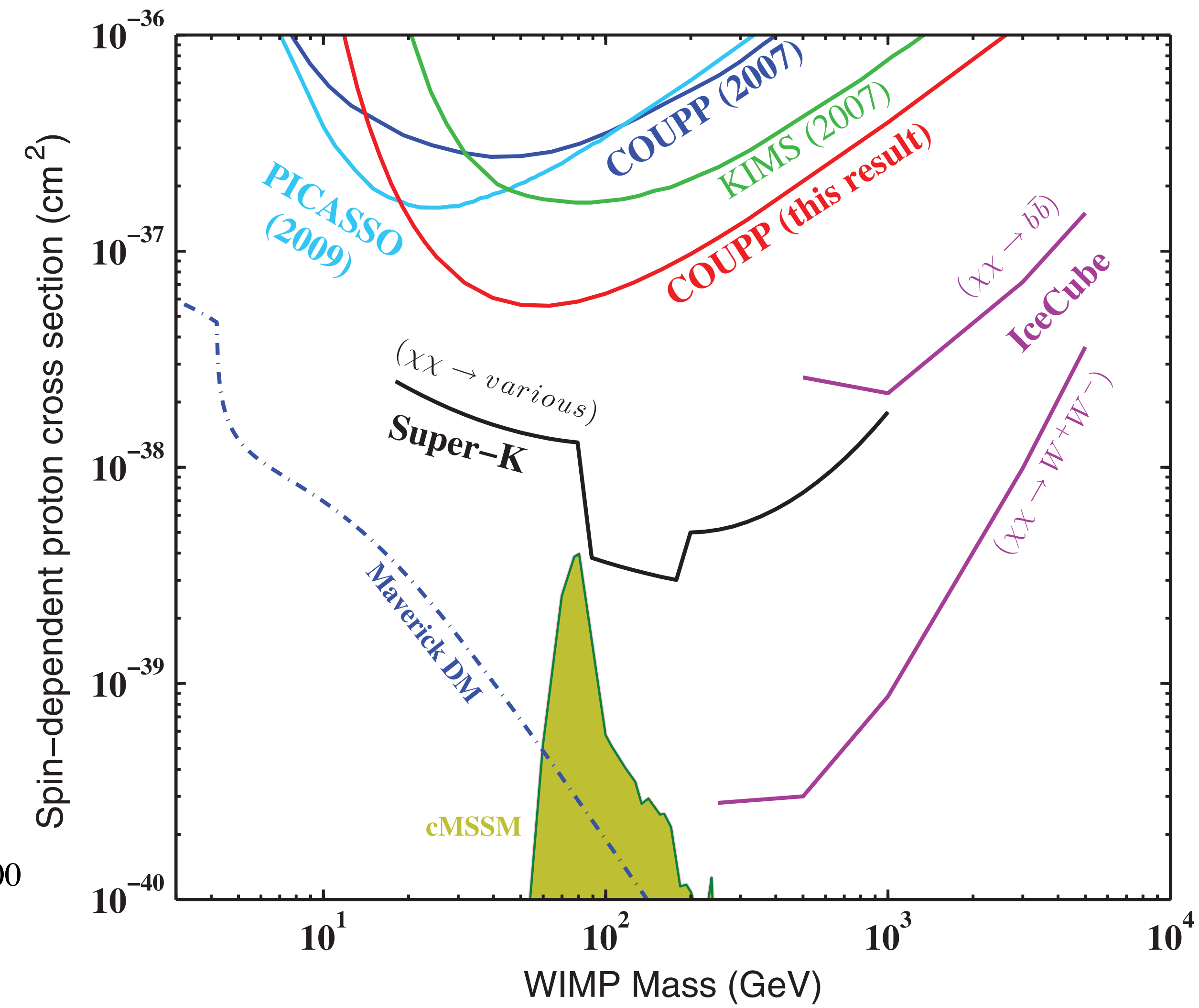
$$\sigma_{DD} \lesssim 0.5\,\mathrm{fb} = 5 \times 10^{-40}\mathrm{cm}^2$$

The Tevatron and DM



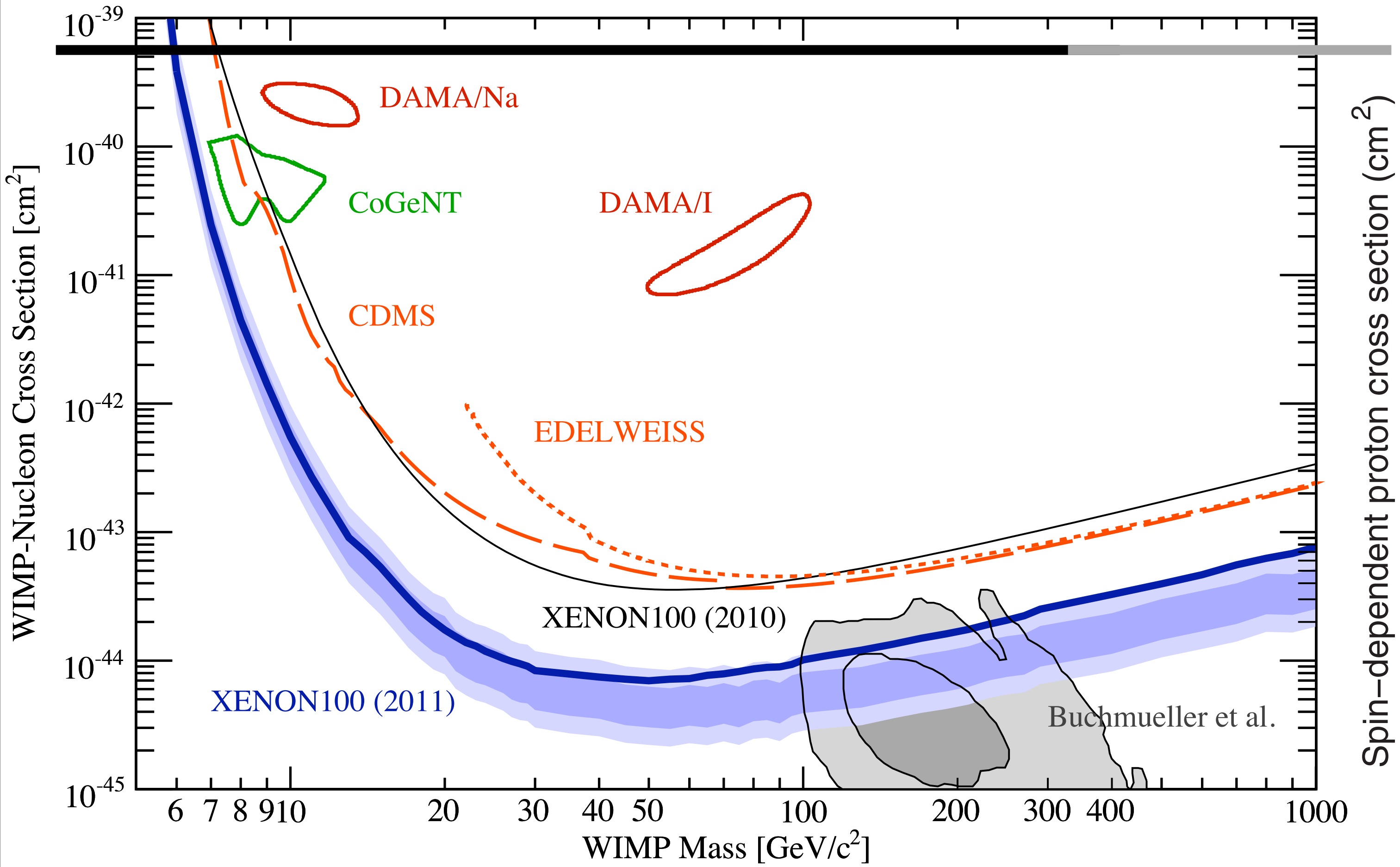


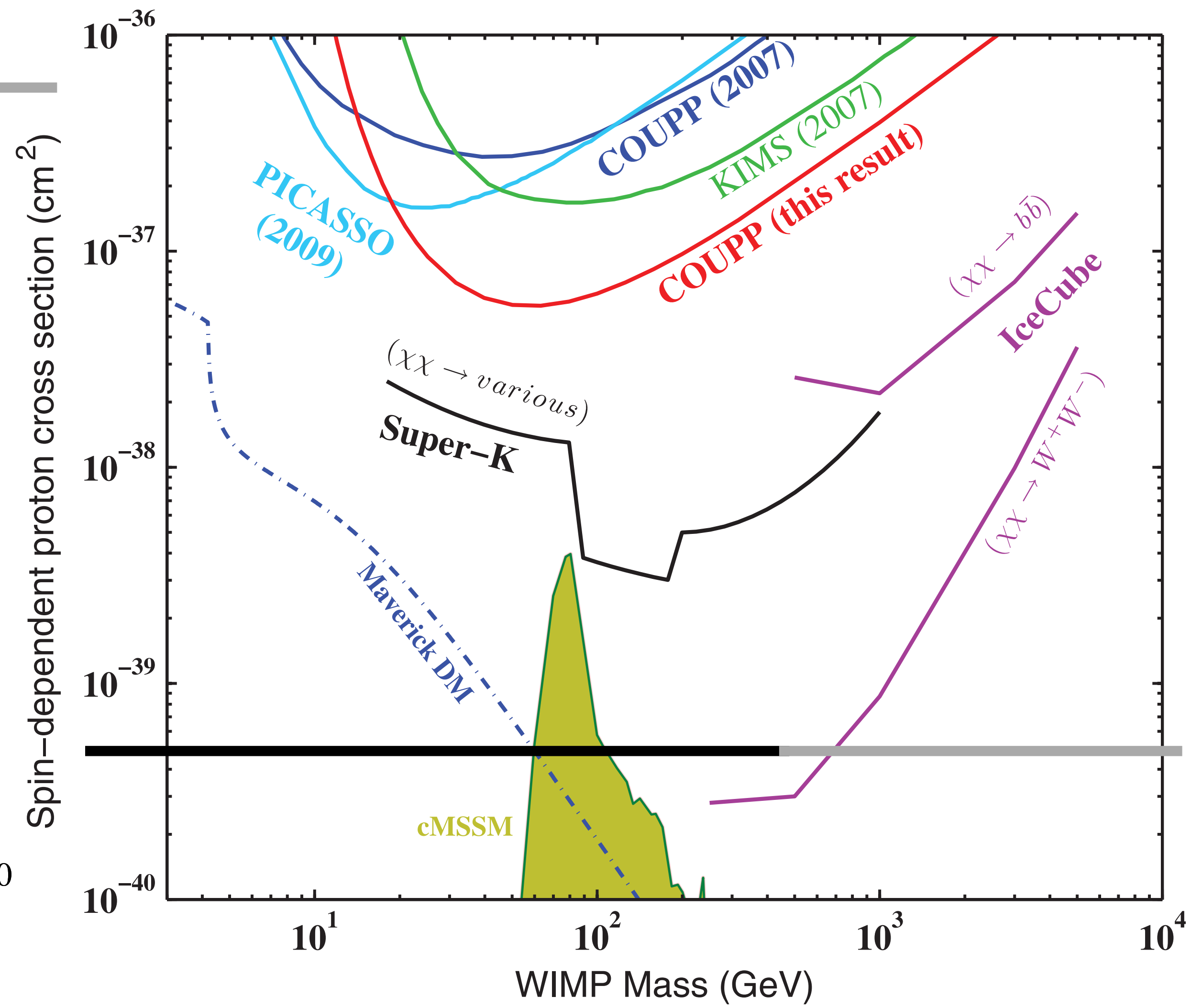
Bounds are "model independent", and astrophysics independent

SI low mass

SD all masses (other suppressed DM x-secs, e.g. momentum, velocity suppression)

The Tevatron and DM





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Outline

- Motivation and estimation
- Operator analysis
- Heavy mediators
- Collider bounds
- Light mediators
- Conclusions

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Operators

$$\mathcal{O}_1 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q} q) (\bar{\chi} \chi) \;,$$

SI, scalar exchange

$$\mathcal{O}_2 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q} \gamma_\mu q) (\bar{\chi} \gamma^\mu \chi) \;,$$

SI, vector exchange

$$\mathcal{O}_3 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q} \gamma_\mu \gamma_5 q) (\bar{\chi} \gamma^\mu \gamma_5 \chi) \;,$$

SD, axial-vector exchange

$$\mathcal{O}_4 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q} \gamma_5 q) (\bar{\chi} \gamma_5 \chi) \;,$$

SD and mom. dep., psuedo-scalar exchange

- DM a Dirac fermion
- Consider each operator, and each flavour separately

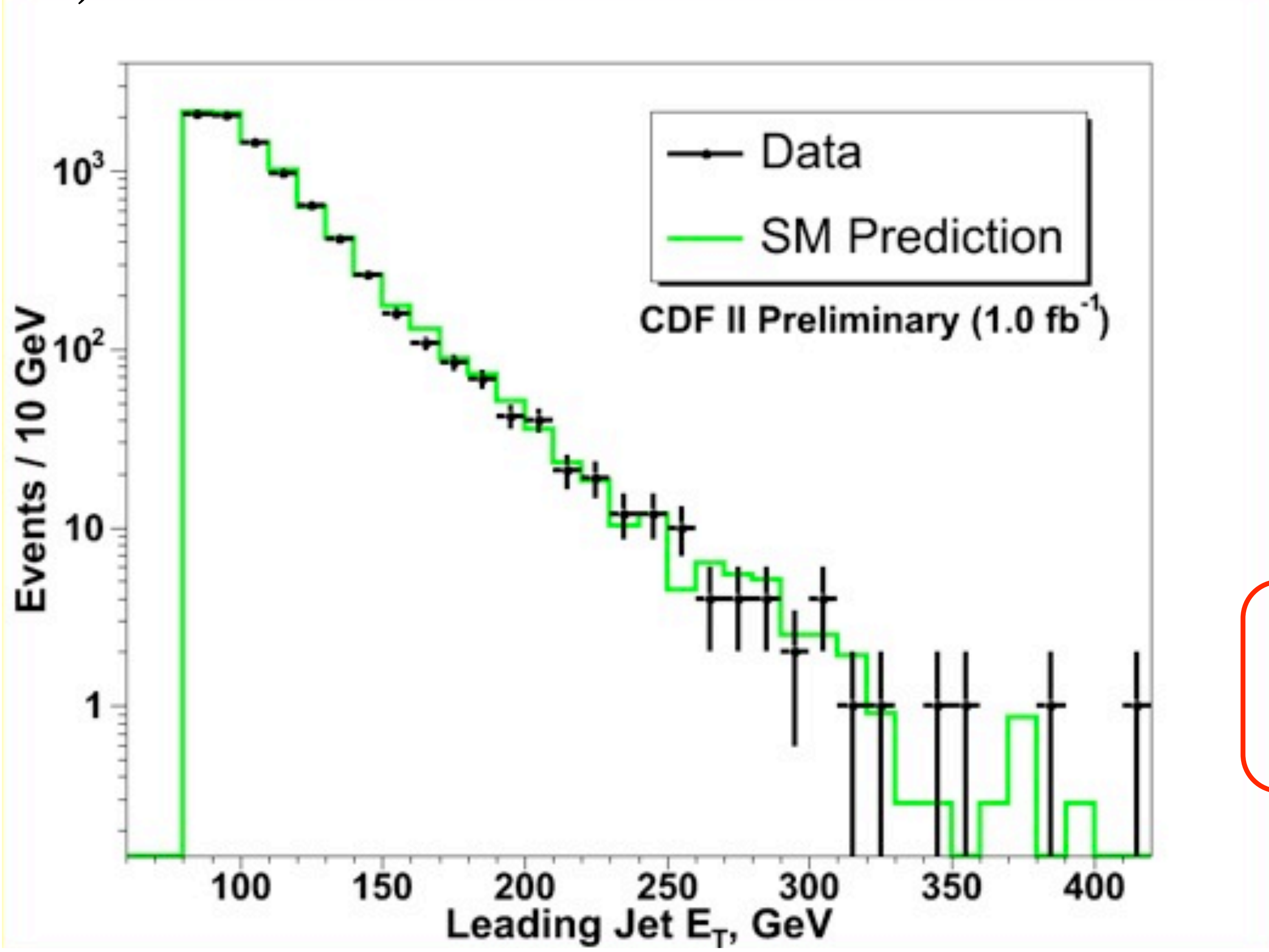
CDF mono-jet search

[http://www-cdf.fnal.gov/physics/exotic/r2a/20070322.monojet/public/ykk.html]

- 1/fb analysed

$$\not{E}_T > 80\,\mathrm{GeV}$$
$$p_T(j1) > 80\,\mathrm{GeV}$$
$$p_T(j2) < 30\,\mathrm{GeV}$$
$$p_T(j3) < 20\,\mathrm{GeV}$$

Background	Number of Events
Z -> nu nu	3203 +/- 137
W -> tau nu	2010 +/- 69
W -> mu nu	1570 +/- 54
W -> e nu	824 +/- 28
Z -> l l	87 +/- 3
QCD	708 +/- 146
Gamma plus Jet	209 +/- 41
Non-Collision	52 +/- 52
Total Predicted	8663 +/- 332
Data Observed	8449

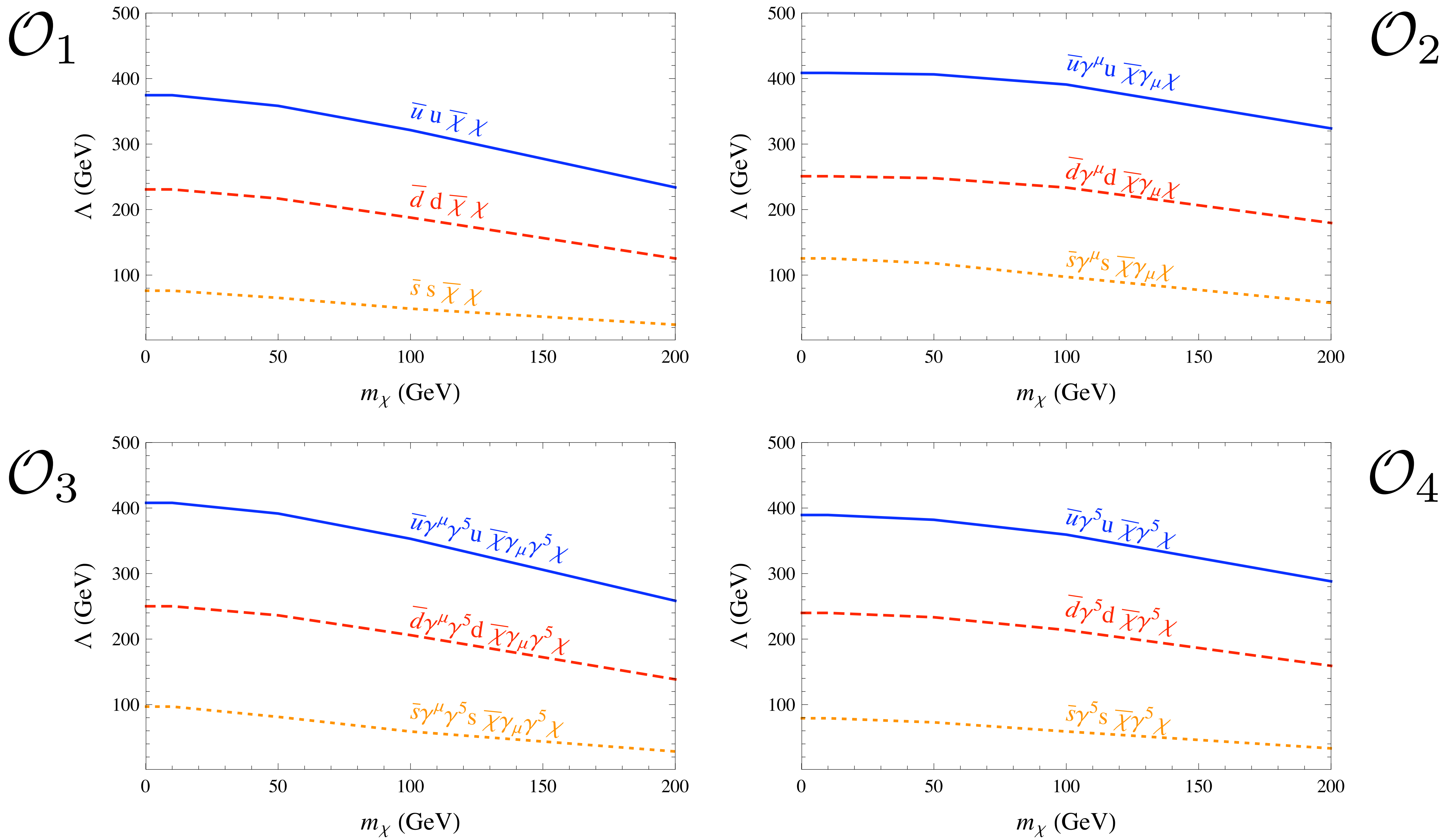


Observed: 8449 events

Bounds on operators

Assume a heavy mediator: $\Lambda = \dfrac{M}{\sqrt{g_\chi g_1}}$

Simulate events in calcHEP, one operator at a time



Spin independent

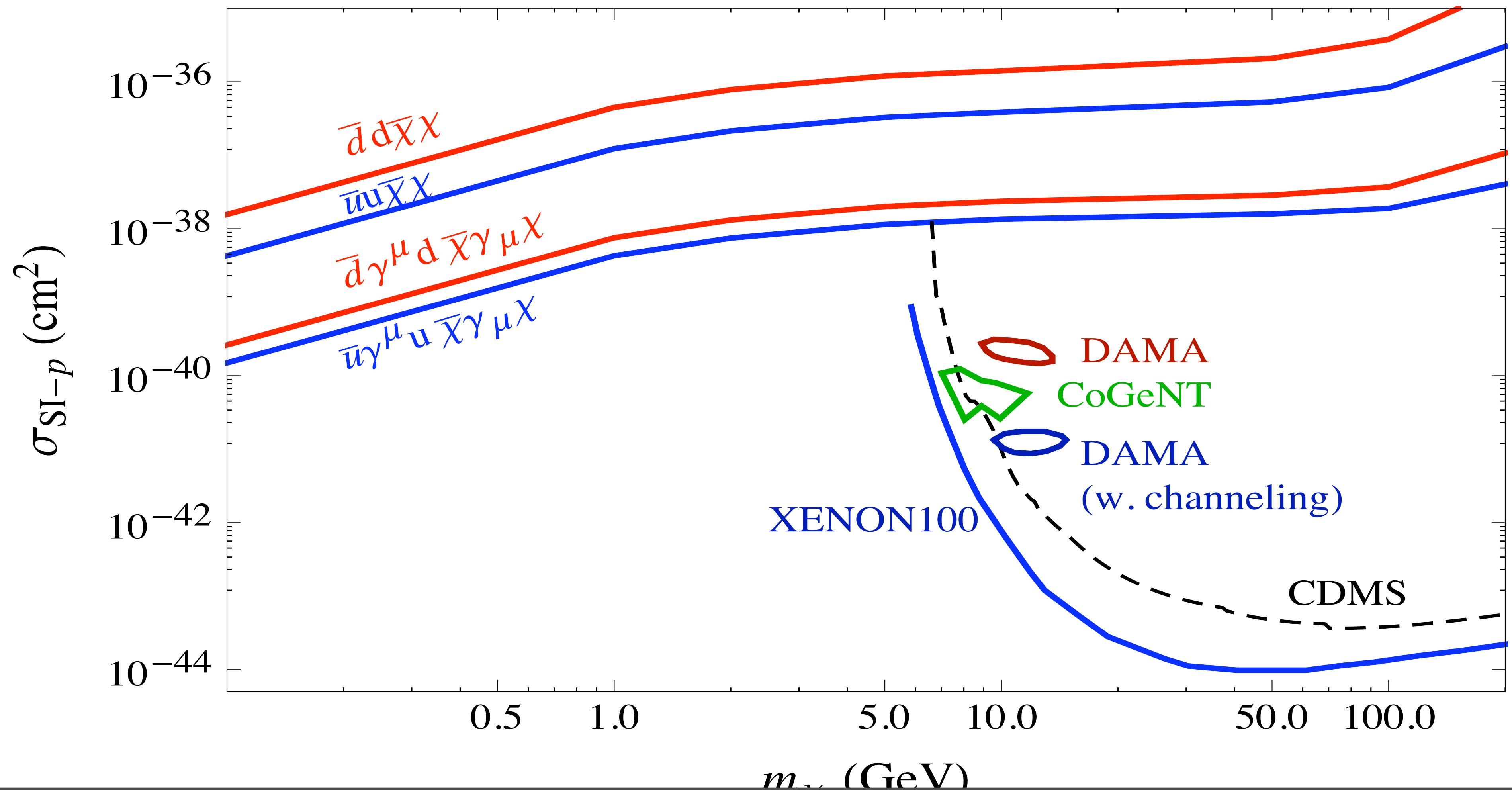
$$\mathcal{O}_1 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}q)(\bar{\chi}\chi)\,, \qquad \sigma_1^{Nq} = \frac{\mu^2}{\pi\Lambda^4} B_{Nq}^2\,,$$

$$\Rightarrow$$

$$\mathcal{O}_2 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}\gamma_\mu q)(\bar{\chi}\gamma^\mu\chi) \qquad \sigma_2^{Nq} = \frac{\mu^2}{\pi\Lambda^4} f_{Nq}^2\,,$$

$$B_u^p = B_d^n = 8.22 \pm 2.26\,,$$
$$B_d^p = B_u^n = 6.62 \pm 1.92\,,$$
$$B_s^p = B_s^n = 3.36 \pm 1.45$$

$$f_u^p = f_d^n = 2$$
$$f_d^p = f_u^n = 1$$
otherwise $f = 0$



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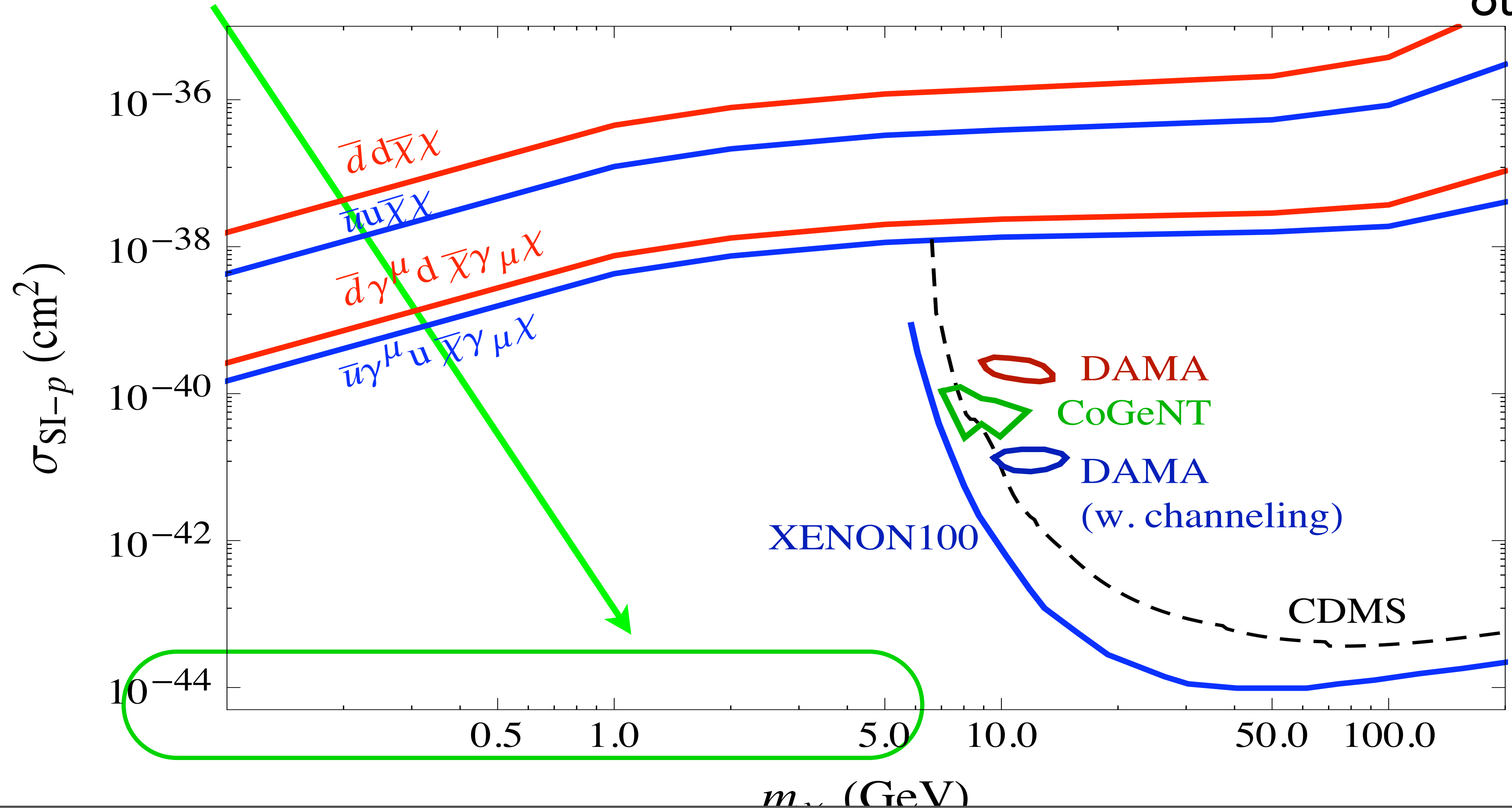
World's best limits
at low mass



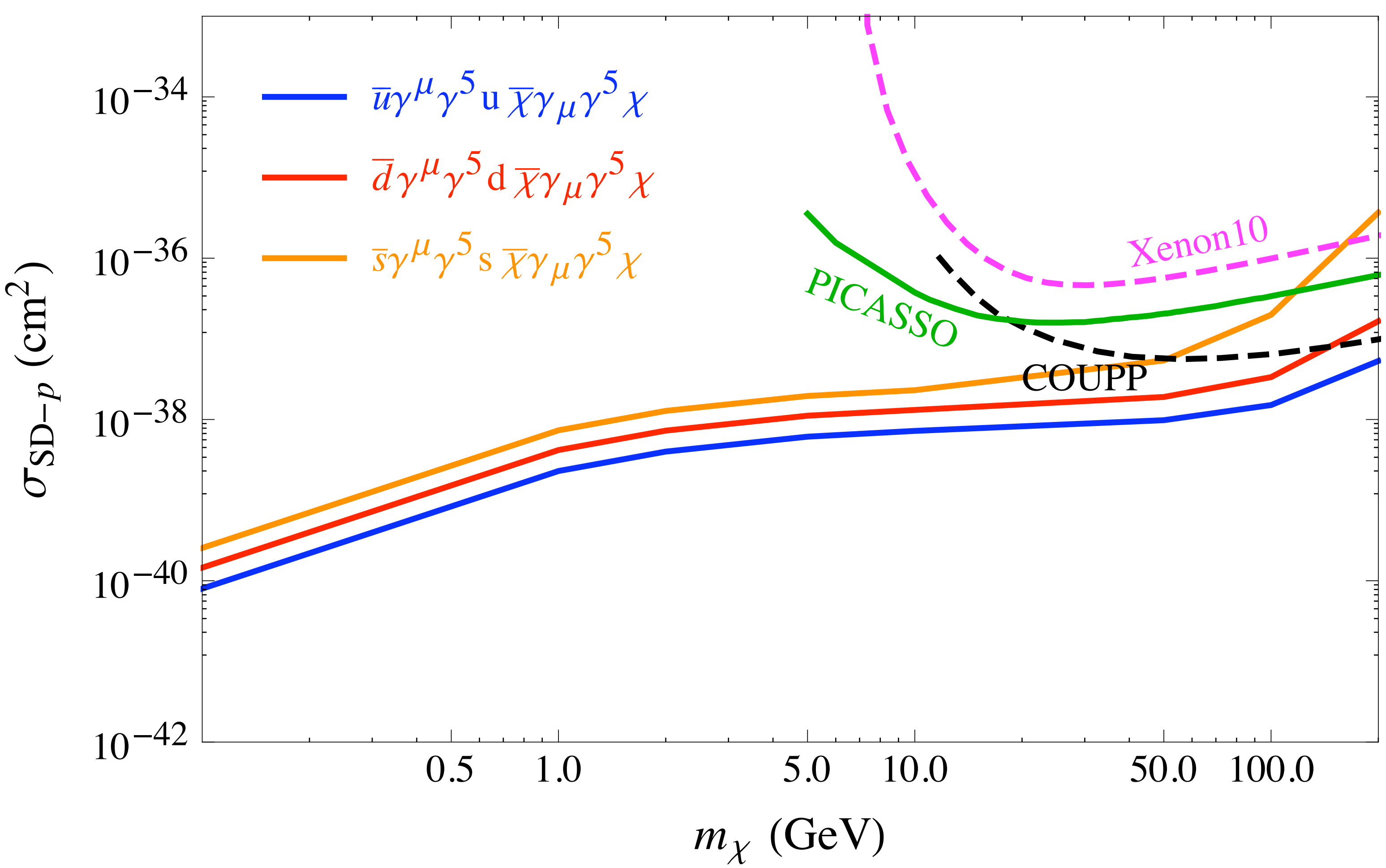
Spin dependent

$$\mathcal{O}_3 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} \left(\bar{q}\gamma_\mu\gamma_5 q\right)\left(\bar{\chi}\gamma^\mu\gamma_5\chi\right)$$

$$\mathcal{O}_3^{Nq} = \Delta_q^N \frac{\left(\bar{N}\gamma^\mu\gamma_5 N\right)\left(\bar{\chi}\gamma_\mu\gamma_5\chi\right)}{\Lambda^2}$$

$$\sigma_3^{Nq} = \frac{3\,\mu^2}{\pi\,\Lambda^4}\left(\Delta_q^N\right)^2$$

$$\begin{aligned} \Delta_u^p &= \Delta_d^n = 0.842 \pm 0.012\,, \\ \Delta_d^p &= \Delta_u^n = -0.427 \pm 0.013\,, \\ \Delta_s^p &= \Delta_s^n = -0.085 \pm 0.018\,. \end{aligned}$$



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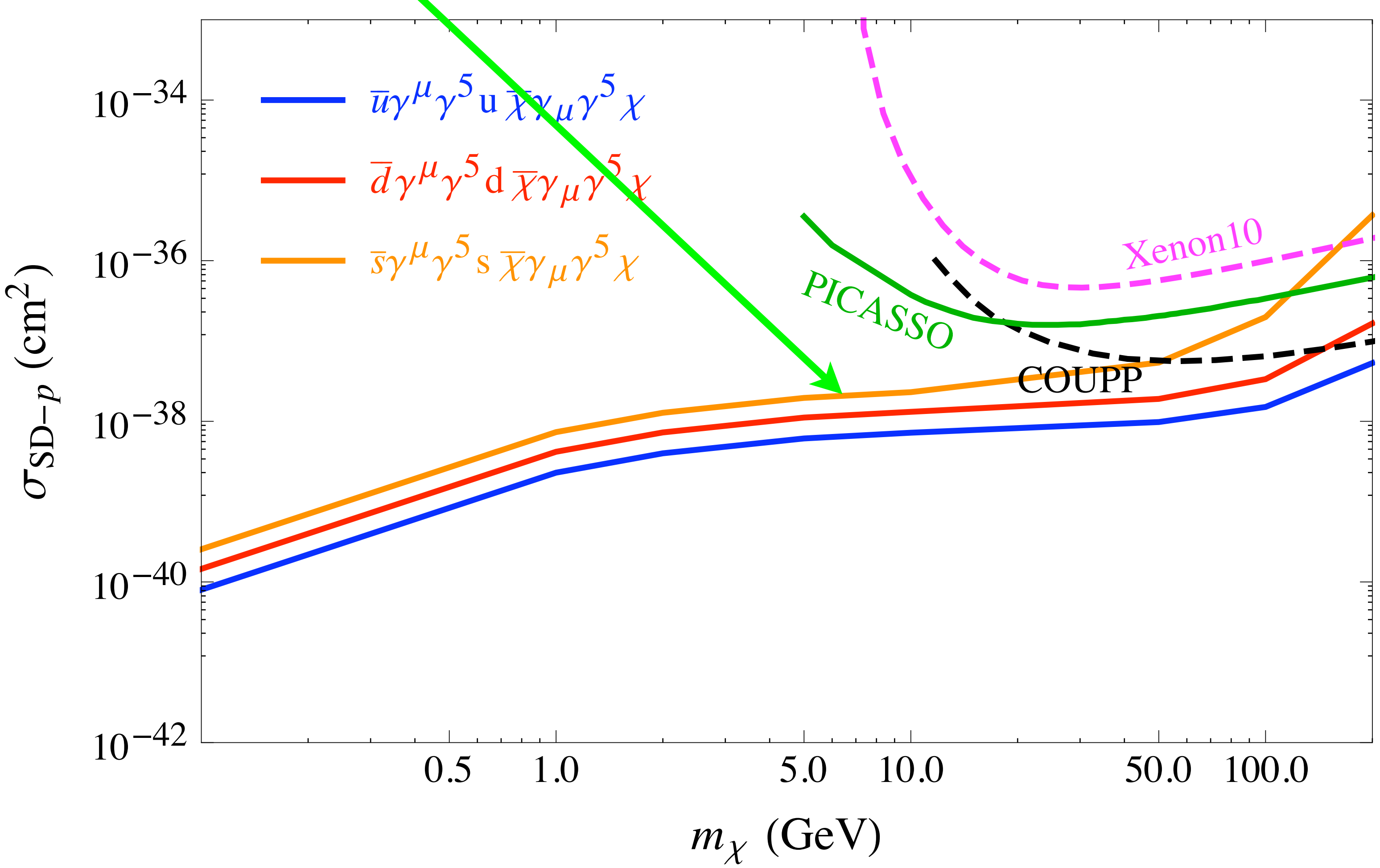
World's best limits, up to ~200 GeV



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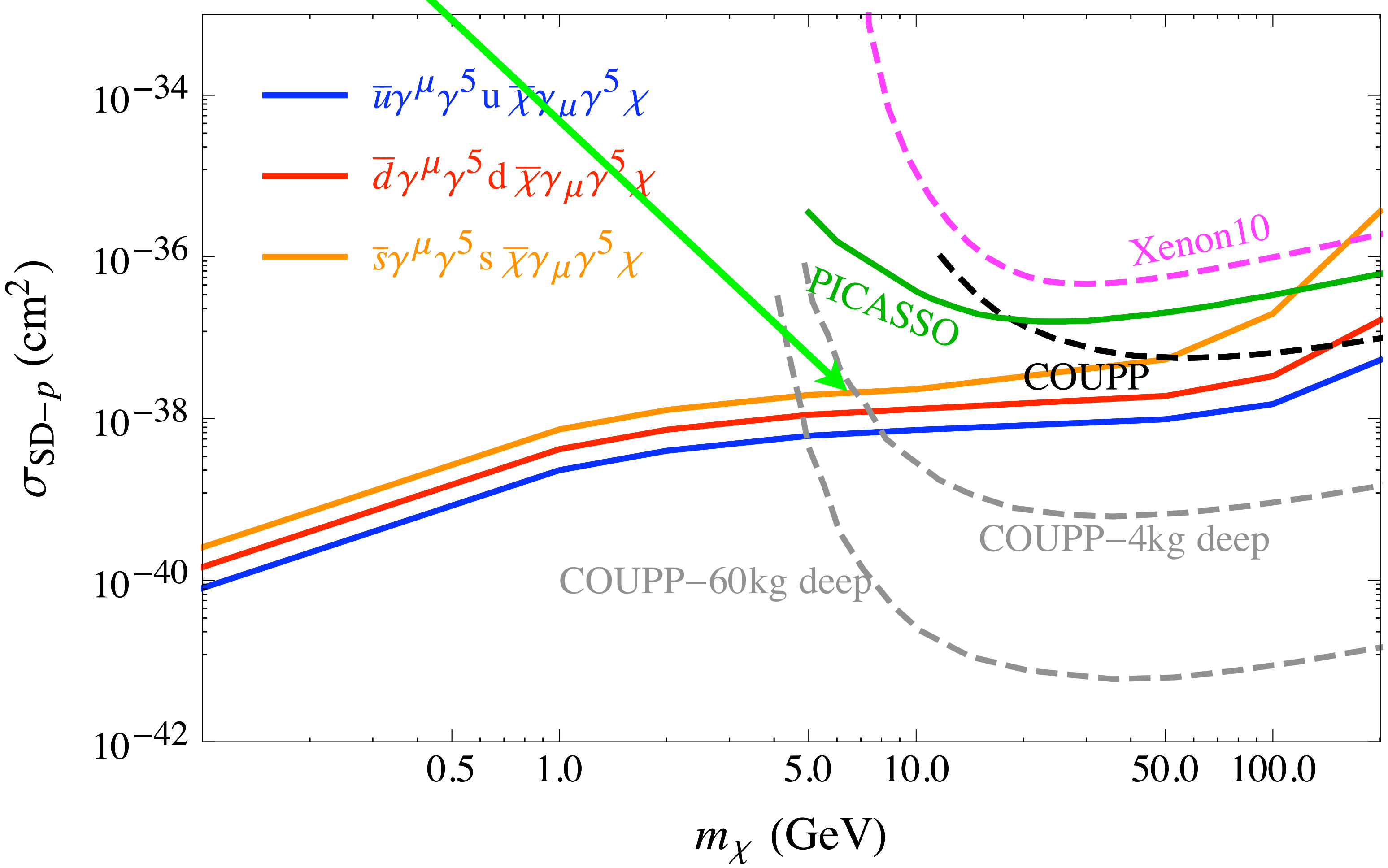
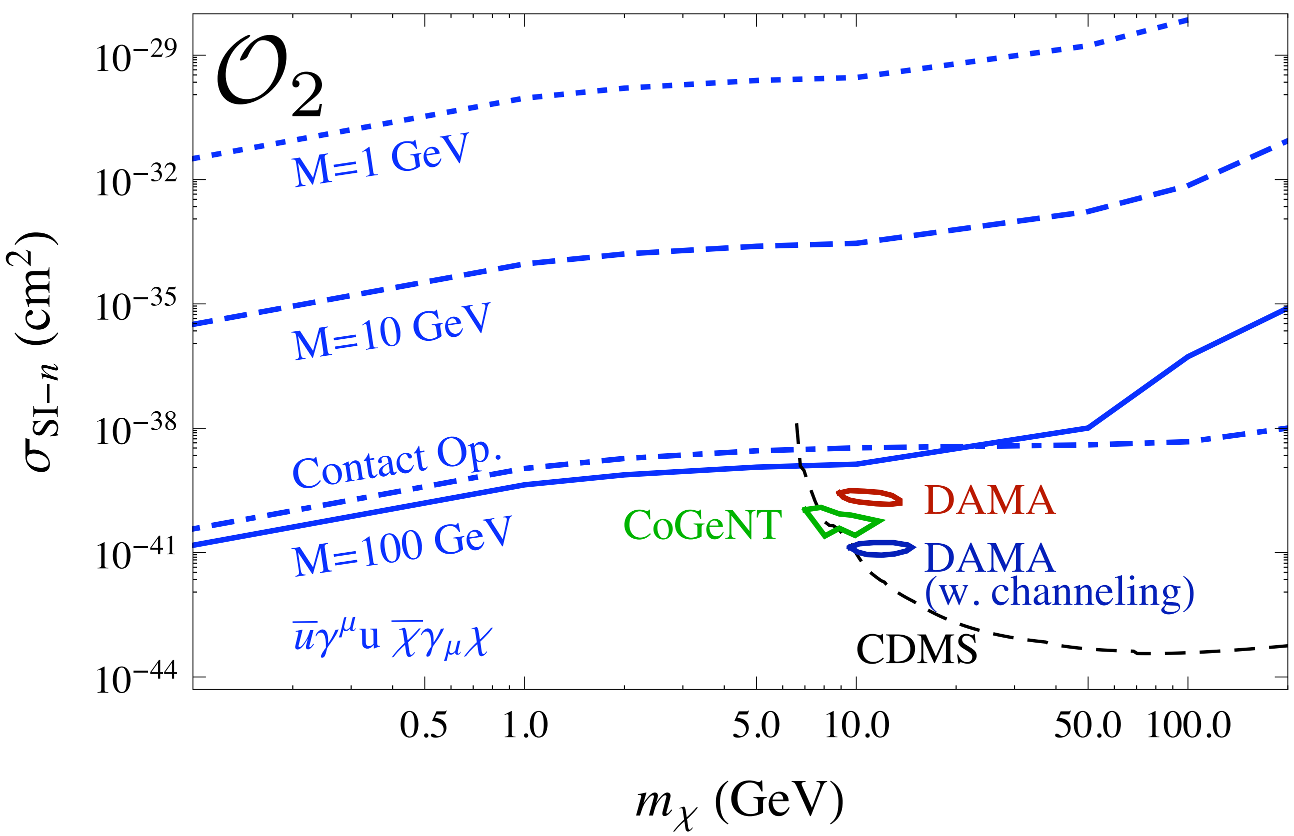


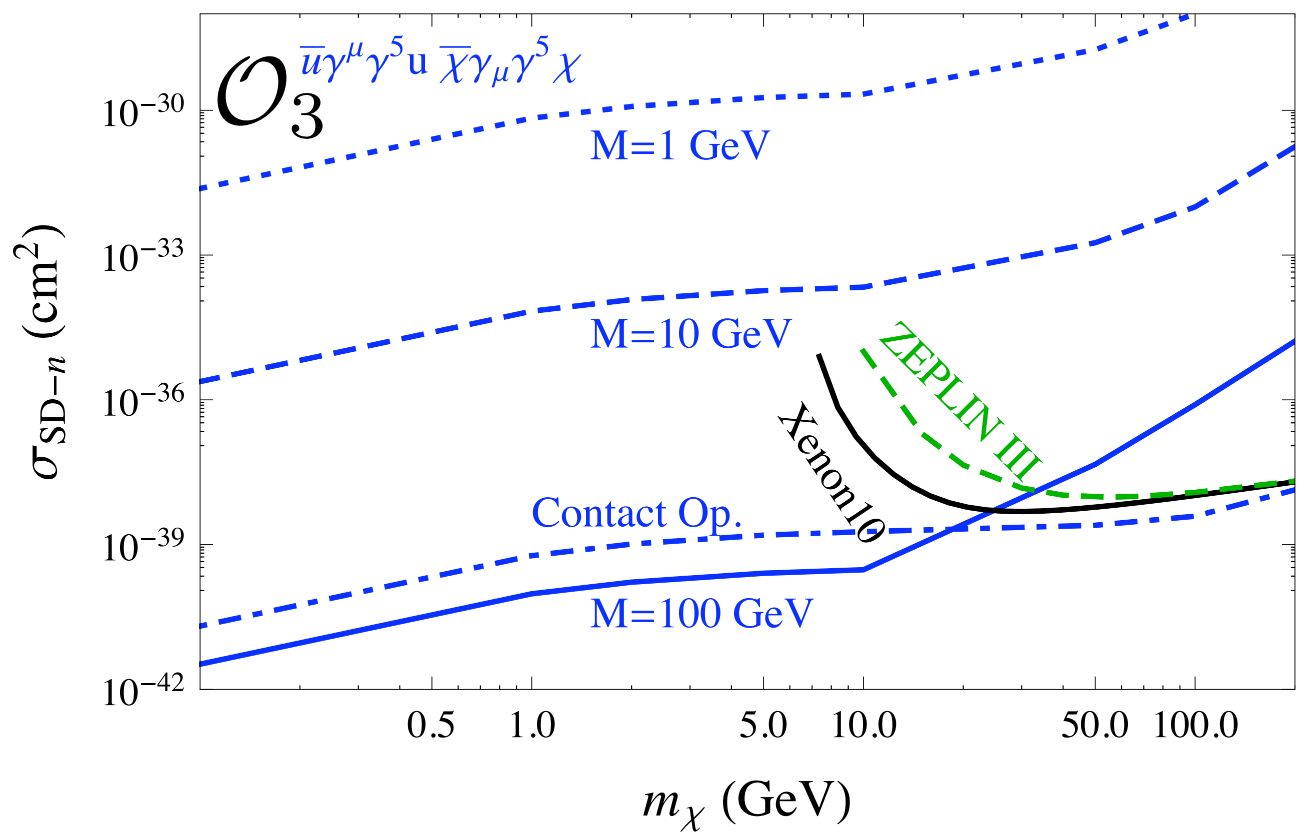
Light mediators

$$\sigma_{\rm DD} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4} \qquad\qquad \sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{1}{p_T^2}$$

Direct detection wins

Two body vs three body production: $2\, m_\chi < M < s^{1/2}$





Light mediators

$$\sigma_{\mathrm{DD}} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4} \qquad\qquad \sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{1}{p_T^2}$$

Direct detection wins

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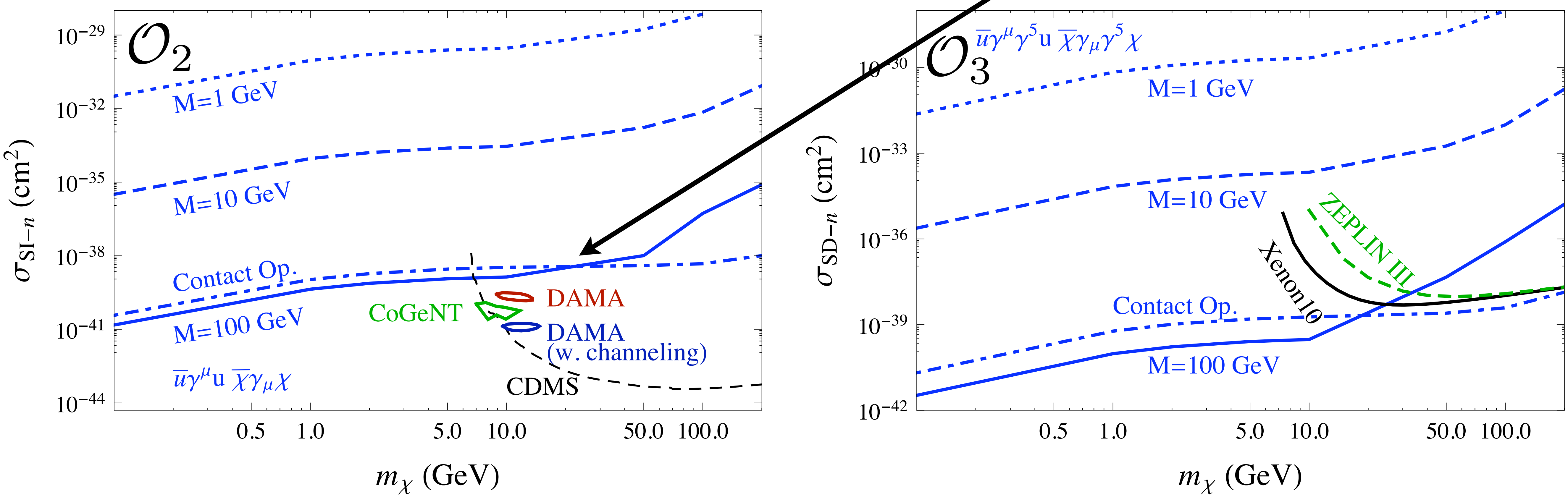
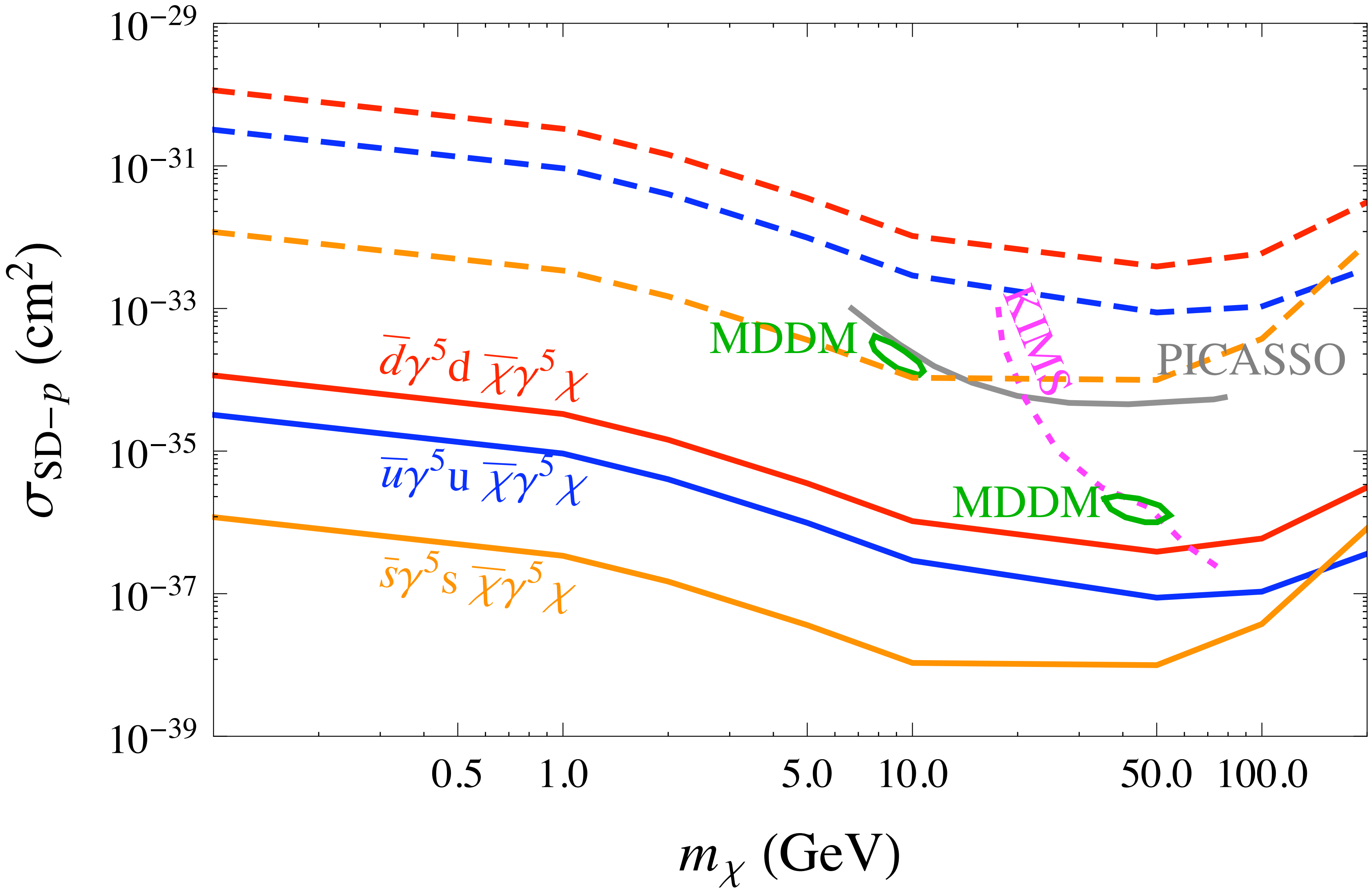


Momentum dependent

$$\mathcal{O}_4^{Nq} = -i\, C_q^N \frac{\left(\bar{N}\gamma_5 N\right)\left(\bar{\chi}\gamma_5\chi\right)}{\Lambda^2} \qquad \frac{d\sigma_4^{Nq}}{d\cos\theta} = \frac{1}{32\pi\Lambda^4}\,\frac{q^4}{(m_\chi + m_N)^2}\,(C_q^N)^2$$

$$C_u^p = 168.5, \quad C_u^n = -165.2\,,$$
$$C_d^p = -164.2, \quad C_d^n = 165.8\,,$$
$$C_s^p = -4.3, \quad C_s^n = -0.67\,.$$



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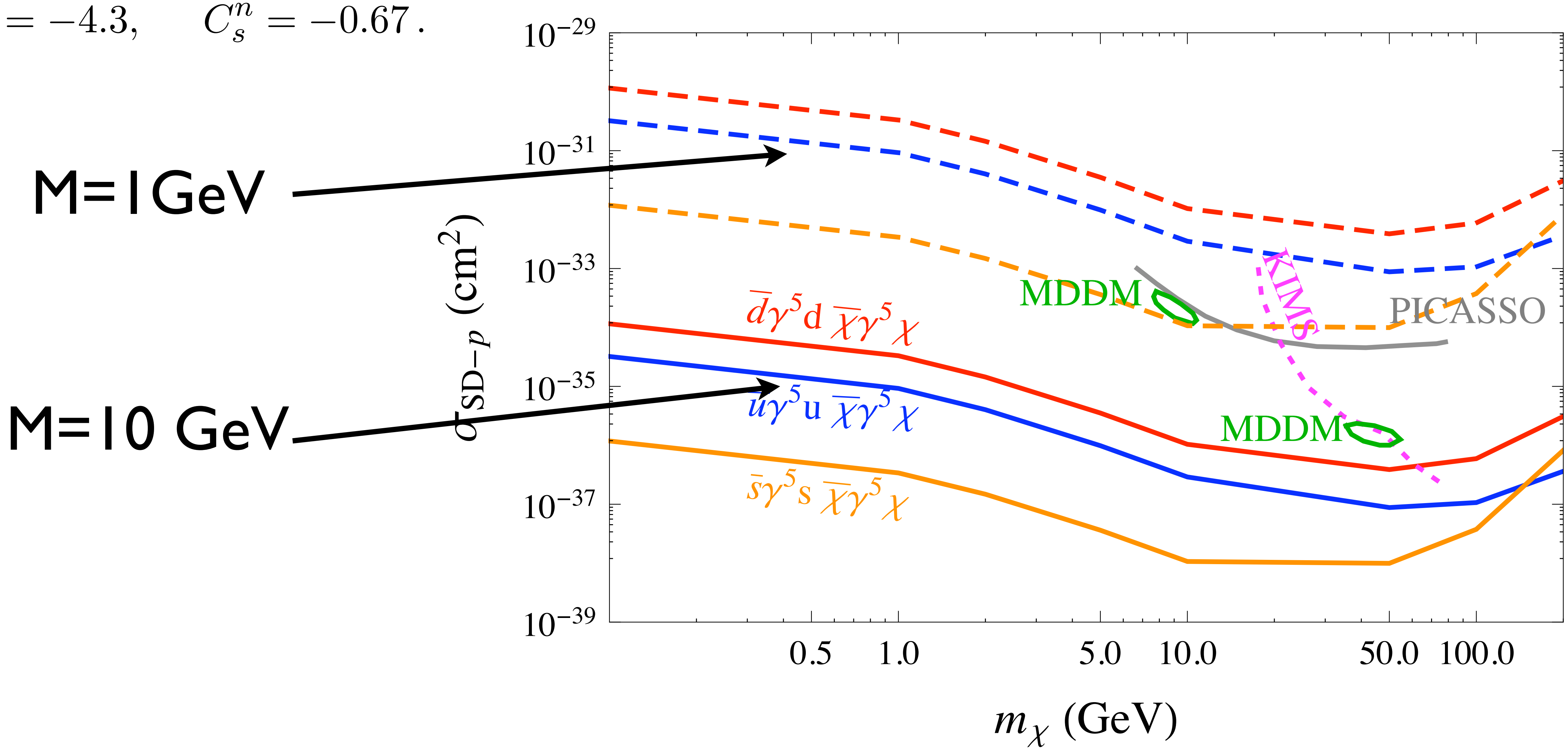
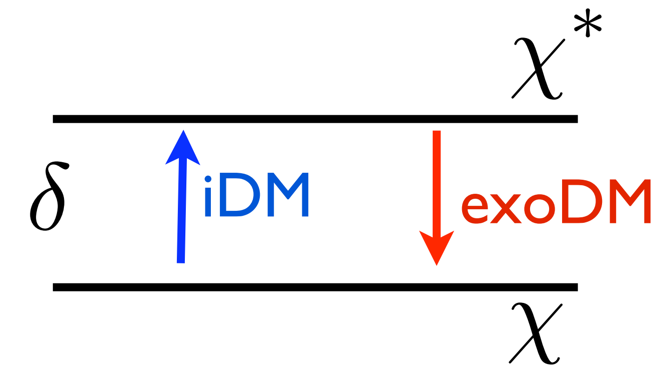


iDM, exothermic DM

Tucker-Smith and Weiner

Graham, Harnik, Rajendran, Saraswat

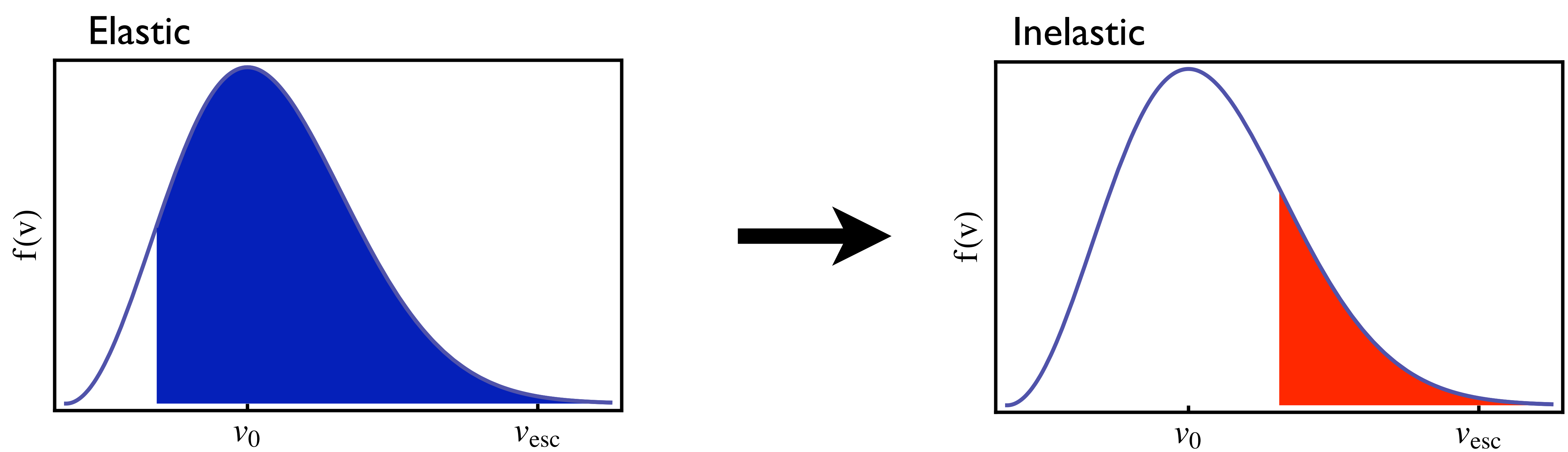


DM is in a 2 state system

Originally motivated by DAMA

$$\frac{dR}{dE_R} \propto n_\chi \sigma_N \int_{v_{min}}^{v_{esc}} \frac{f(v)}{v} dv \,,$$

$$v_{min} = \sqrt{\frac{1}{2m_T E_R}} \left(\frac{m_T E_R}{\mu_T} + \delta \right)$$



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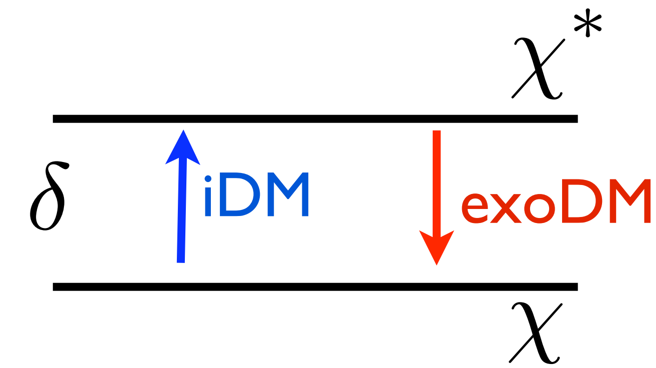

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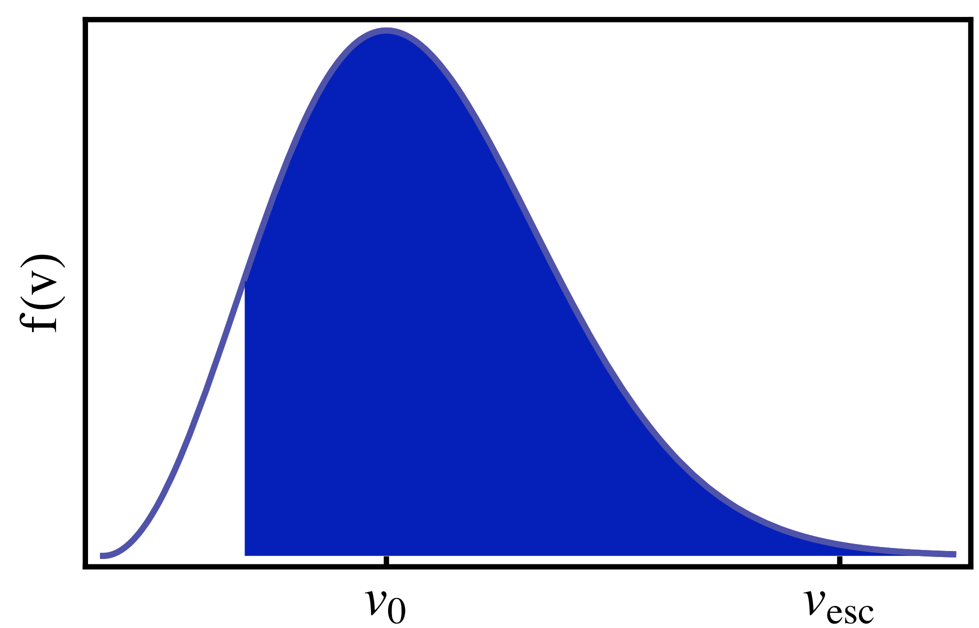
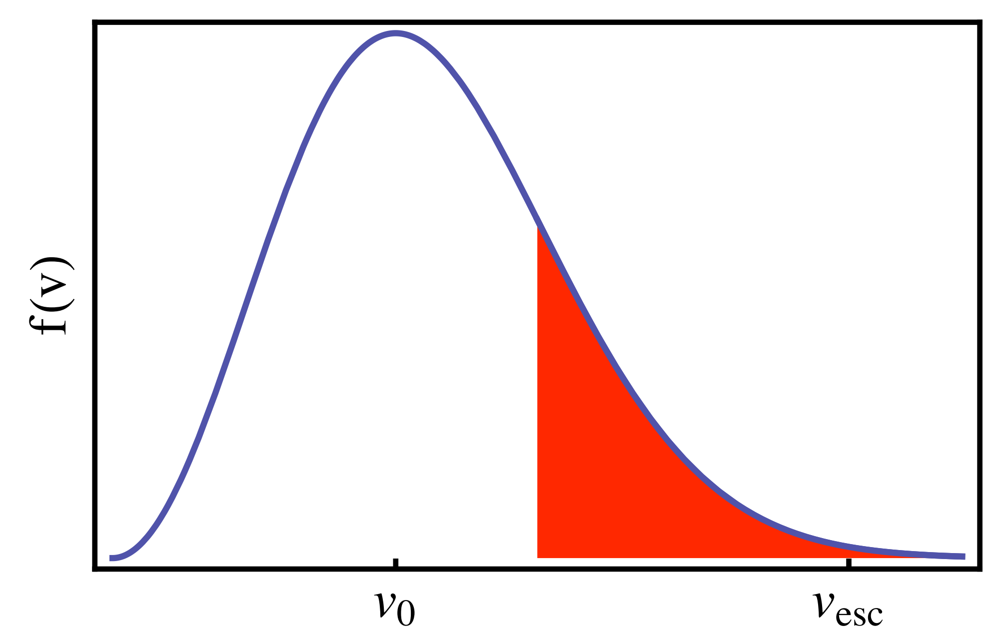
$$v_{min} = \sqrt{\frac{1}{2 m_T E_R}} \left(\frac{m_T E_R}{\mu_T} + \delta \right)$$

$\delta \sim 100\,\text{keV}, \;\; 5\,\text{keV}$

Elastic

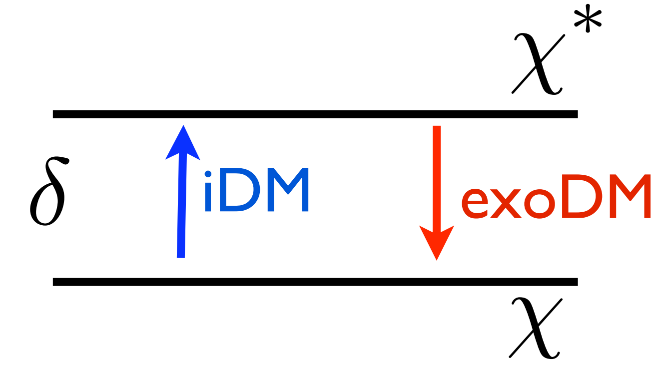


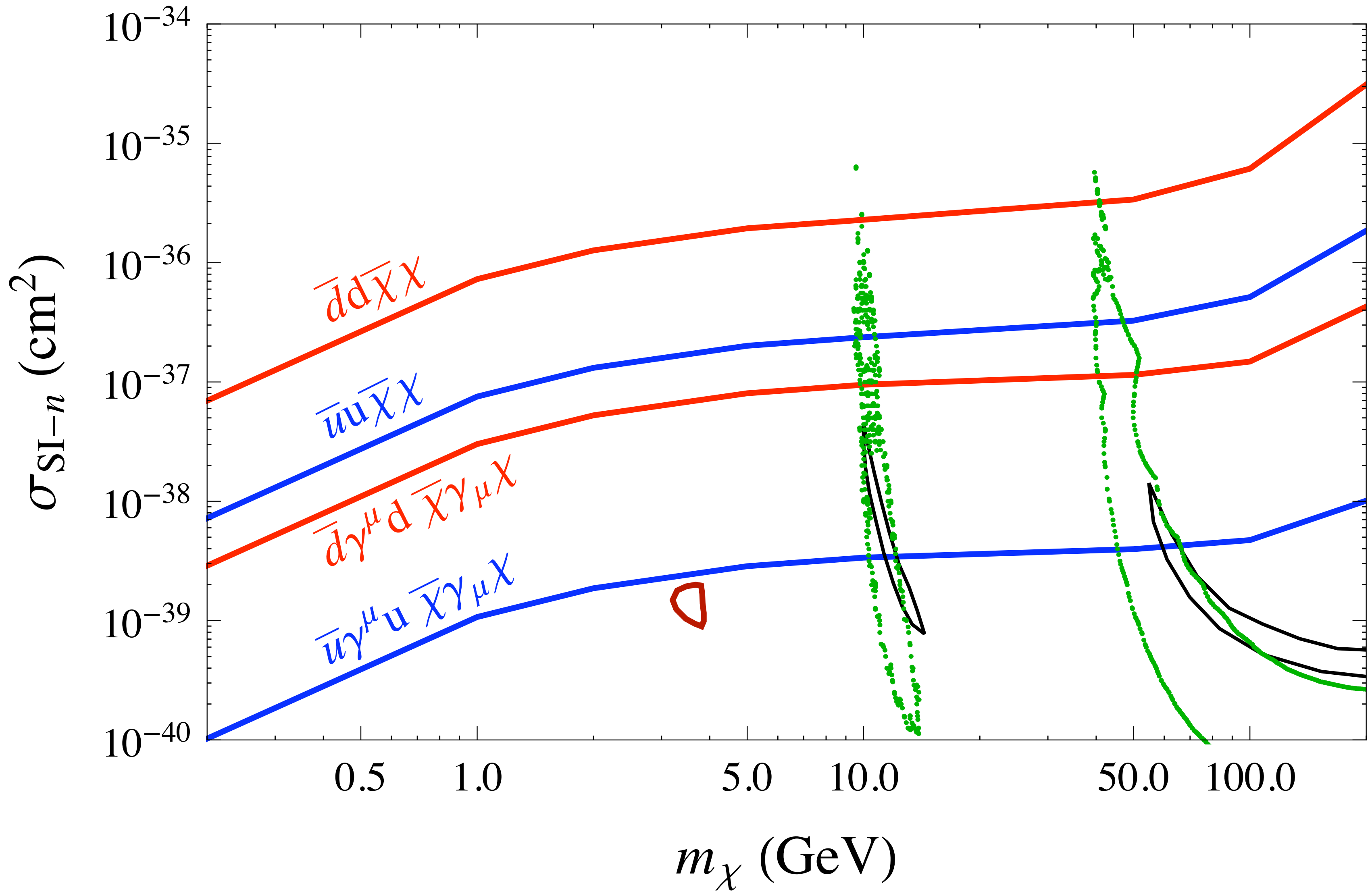
Inelastic



iDM, exothermic DM

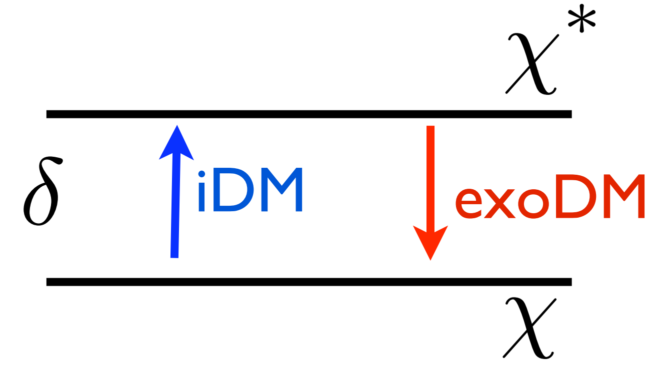
Tucker-Smith and Weiner   Graham, Harnik, Rajendran, Saraswat

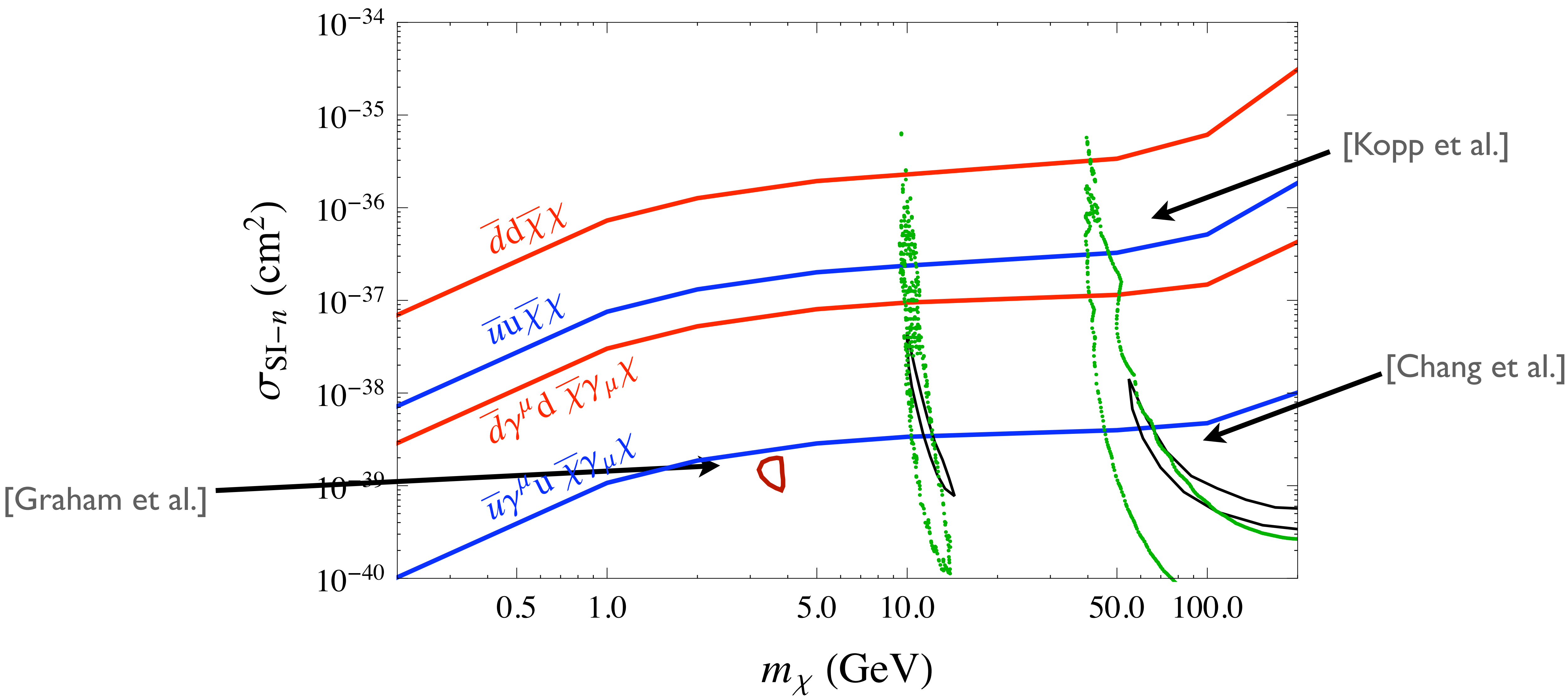




iDM, exothermic DM

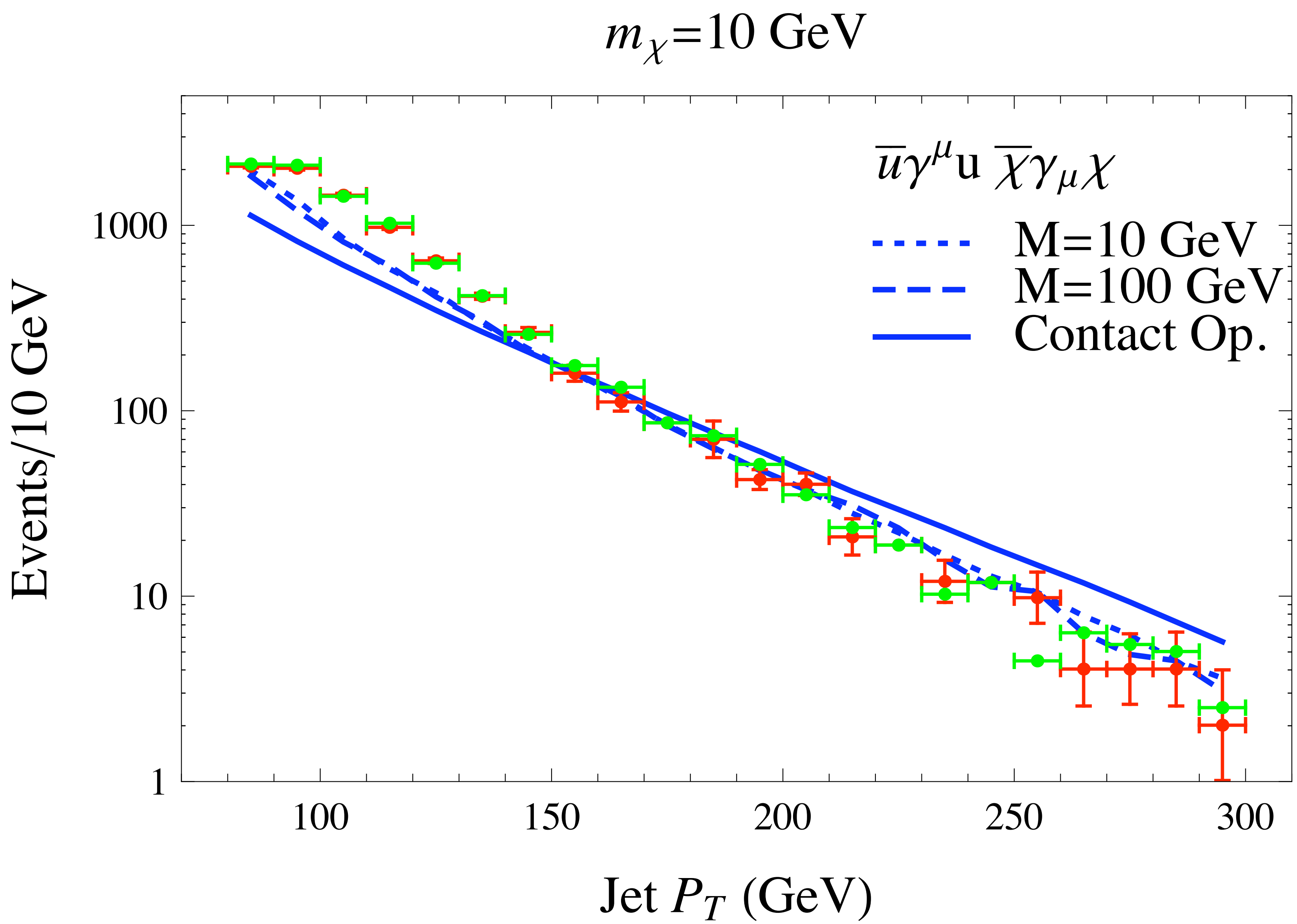
Tucker-Smith and Weiner Graham, Harnik, Rajendran, Saraswat





Improvements?

So far only CDF analysis on 1/fb
Mono-photon could also be done



Use shape information

Tevatron reach limited to ~300 GeV

Dedicated analysis

Dedicated CDF analysis

Based on the effective operators presented here

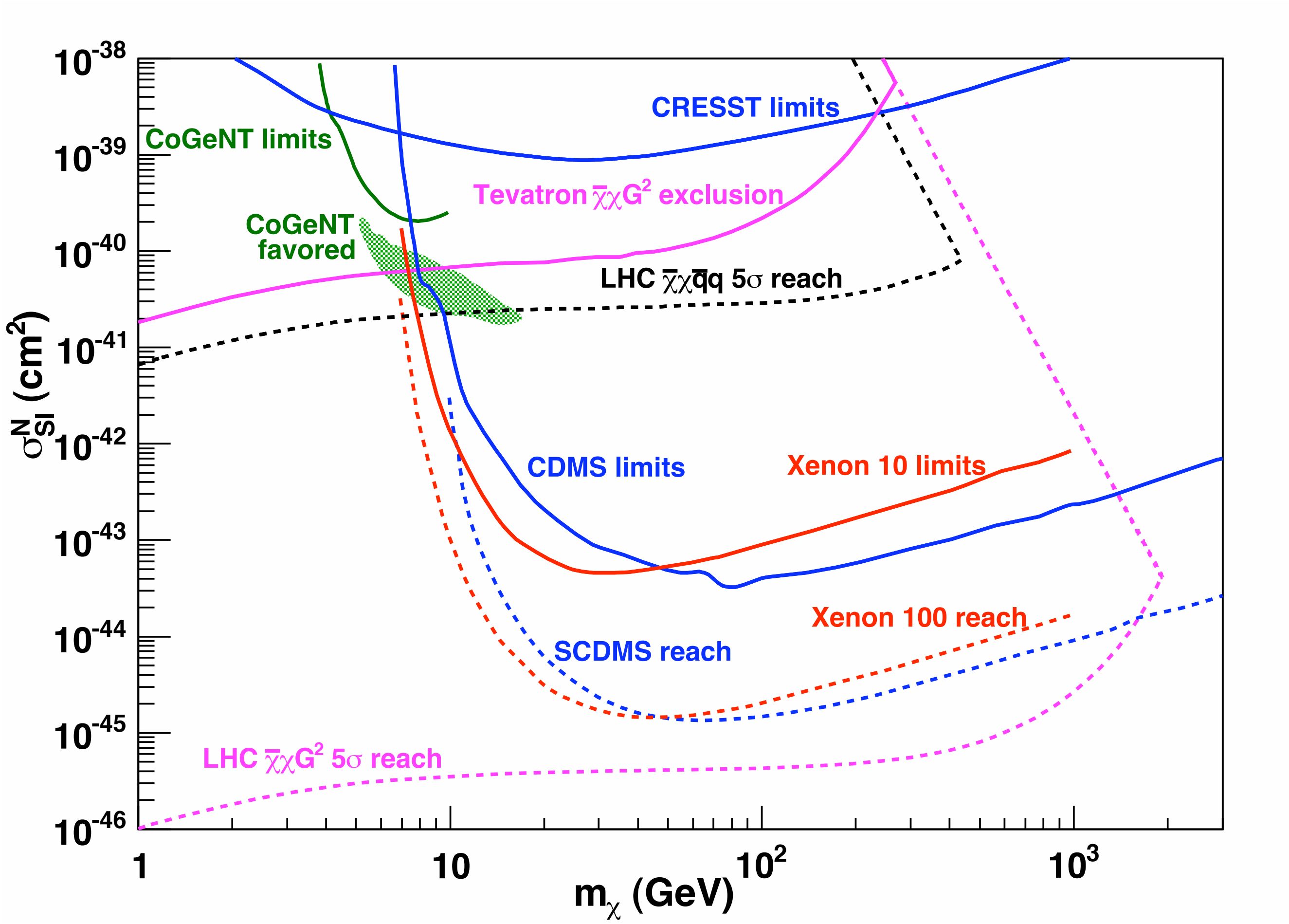
Using shape information

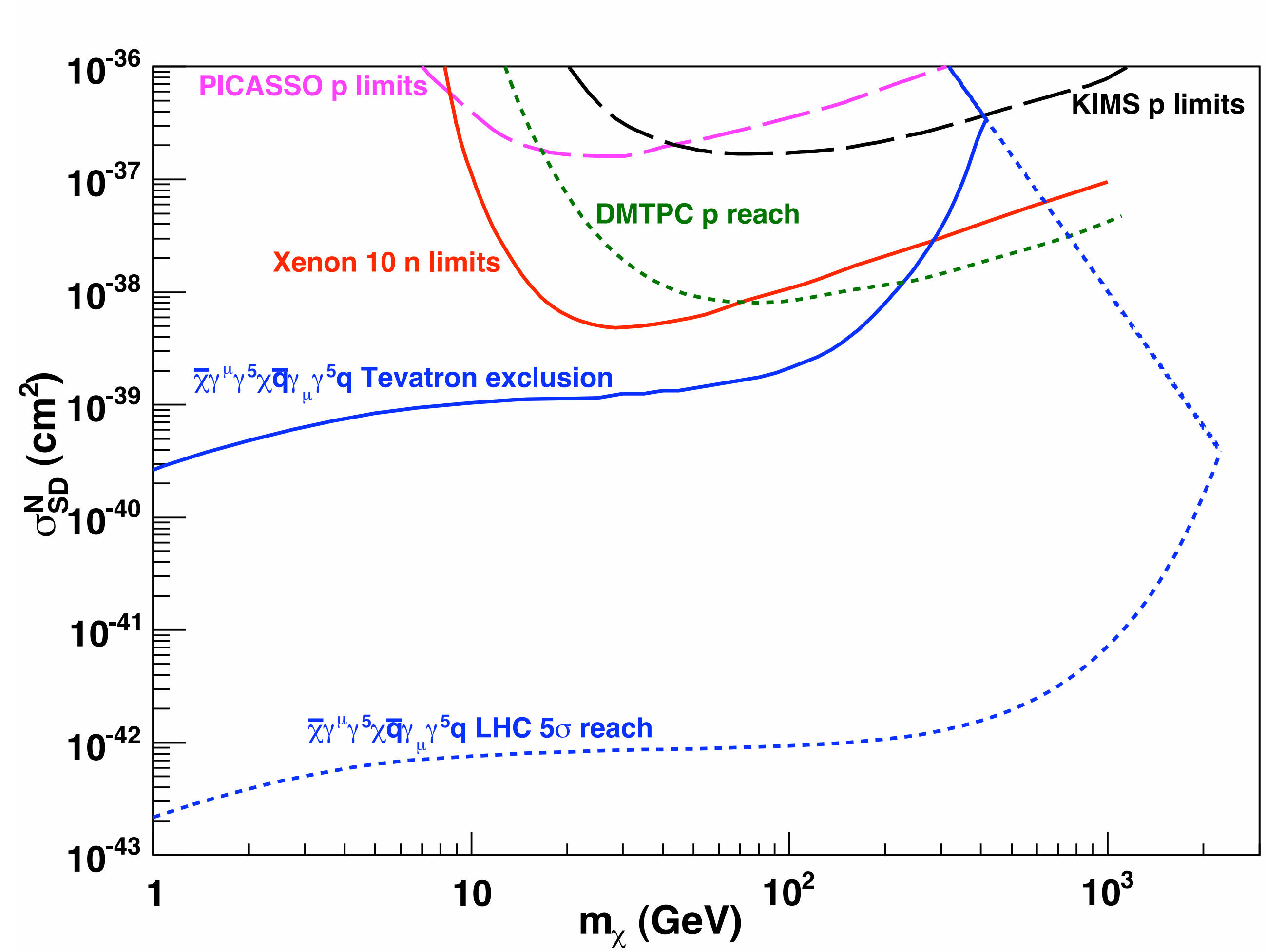
~6.7/fb

Results this summer?

Improvements

[Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu]





LHC

$$\sqrt{s} = 14 \text{ TeV}$$

$$\mathcal{L} = 100 \text{ fb}^{-1}$$

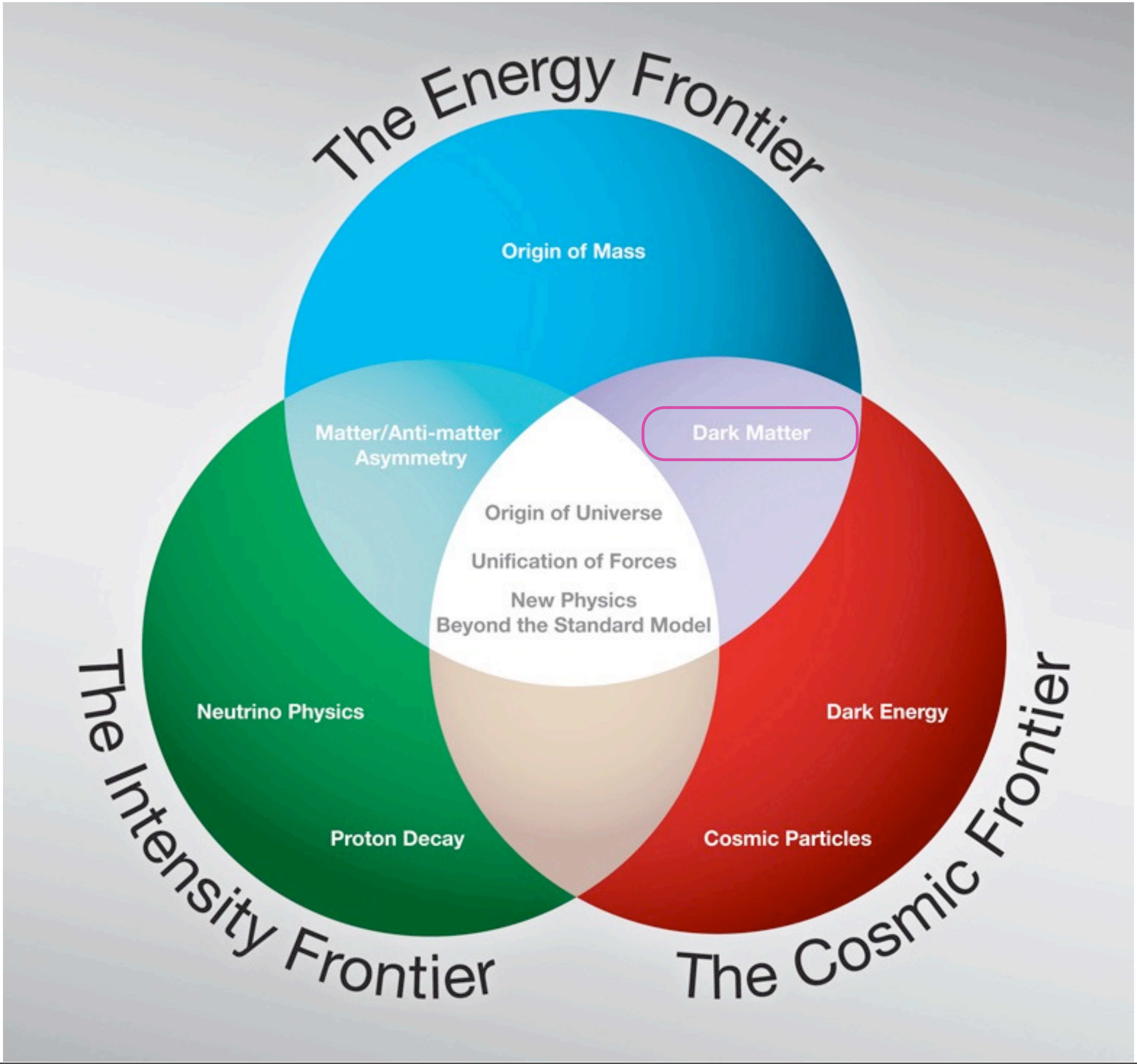
$$\not{E}_T > 500 \text{ GeV}$$

ATLAS are carrying out a dedicated analysis

Conclusions

- Mono-jet searches at the Tevatron already place strong constraints on dark matter
- Competitive with direct detection searches
  - Light DM
  - Spin dependent
  - Non-standard DM e.g. iDM, exoDM, MDDM
- Independent of all astrophysics uncertainties
- Shape information, more luminosity,...
- Light mediators weaken collider bounds
- If we see a DD signal in a region ruled out by colliders we have discovered 2 particles

Mono-jet + mono-photon analyses important


The Energy Frontier
Origin of Mass
Matter/Anti-matter
Asymmetry
Dark Matter
Origin of Universe
Unification of Forces
New Physics
Beyond the Standard Model
Neutrino Physics
Proton Decay
Dark Energy
Cosmic Particles
The Intensity Frontier
The Cosmic Frontier