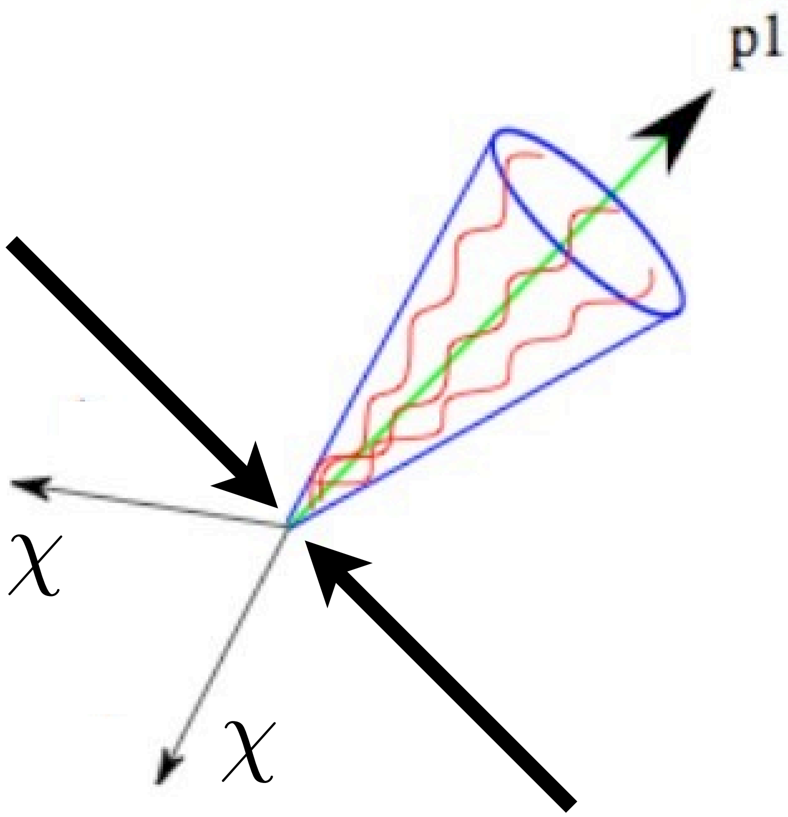
Hunting for Dark Matter with a Jet

Patrick Fox

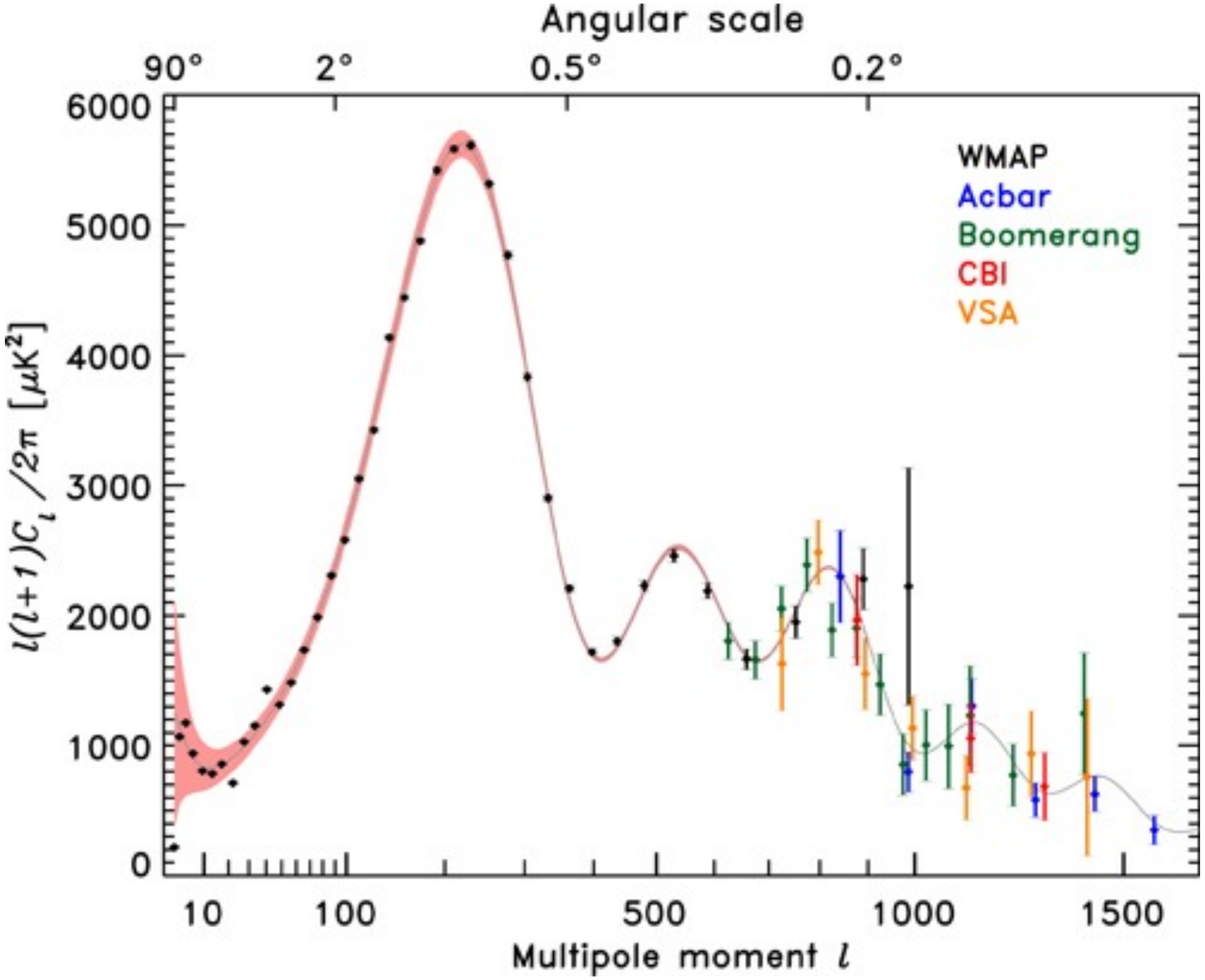
Fermilab

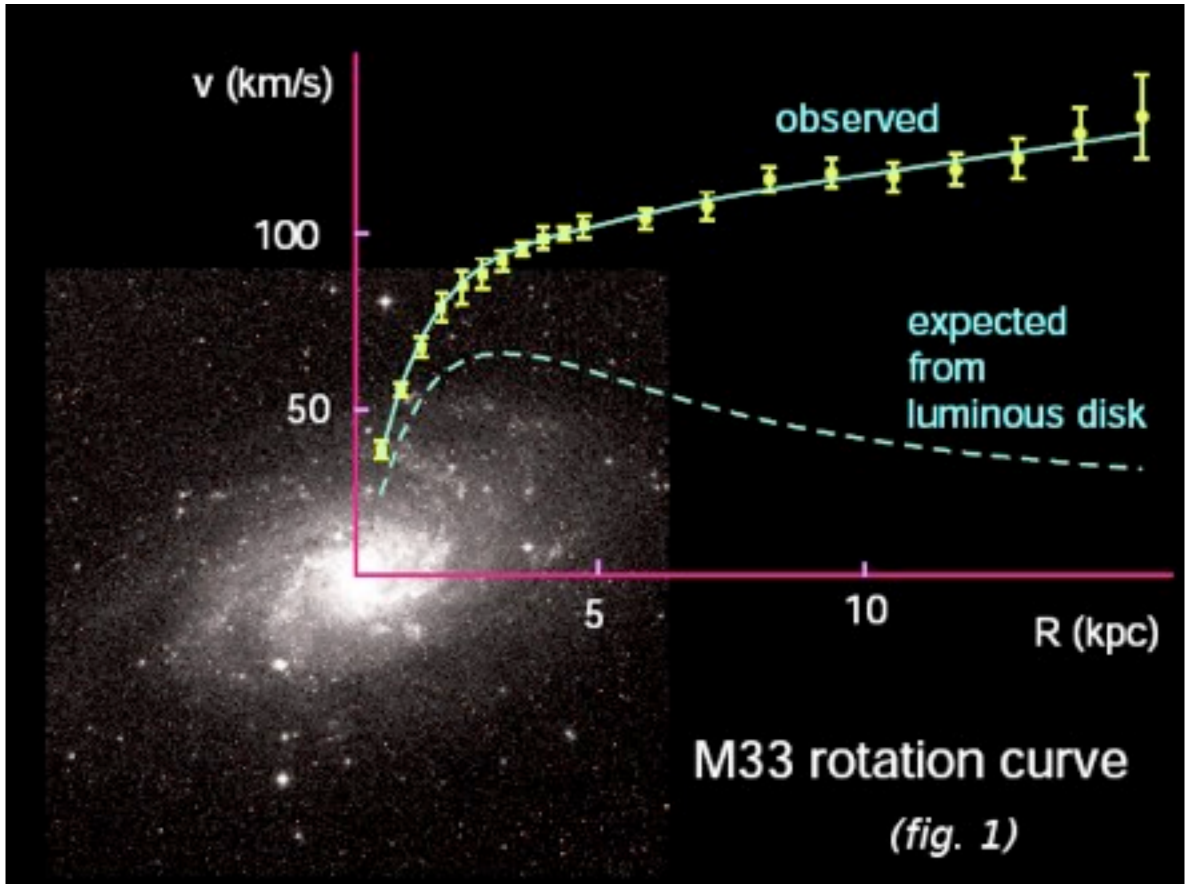


with Yang Bai and Roni Harnik
(arXiv:1005.3797)

Dark Matter

Lots of evidence for non-baryonic matter:





Cosmological abundance

$$\Omega_{DM} \sim 0.2$$

Local abundance

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

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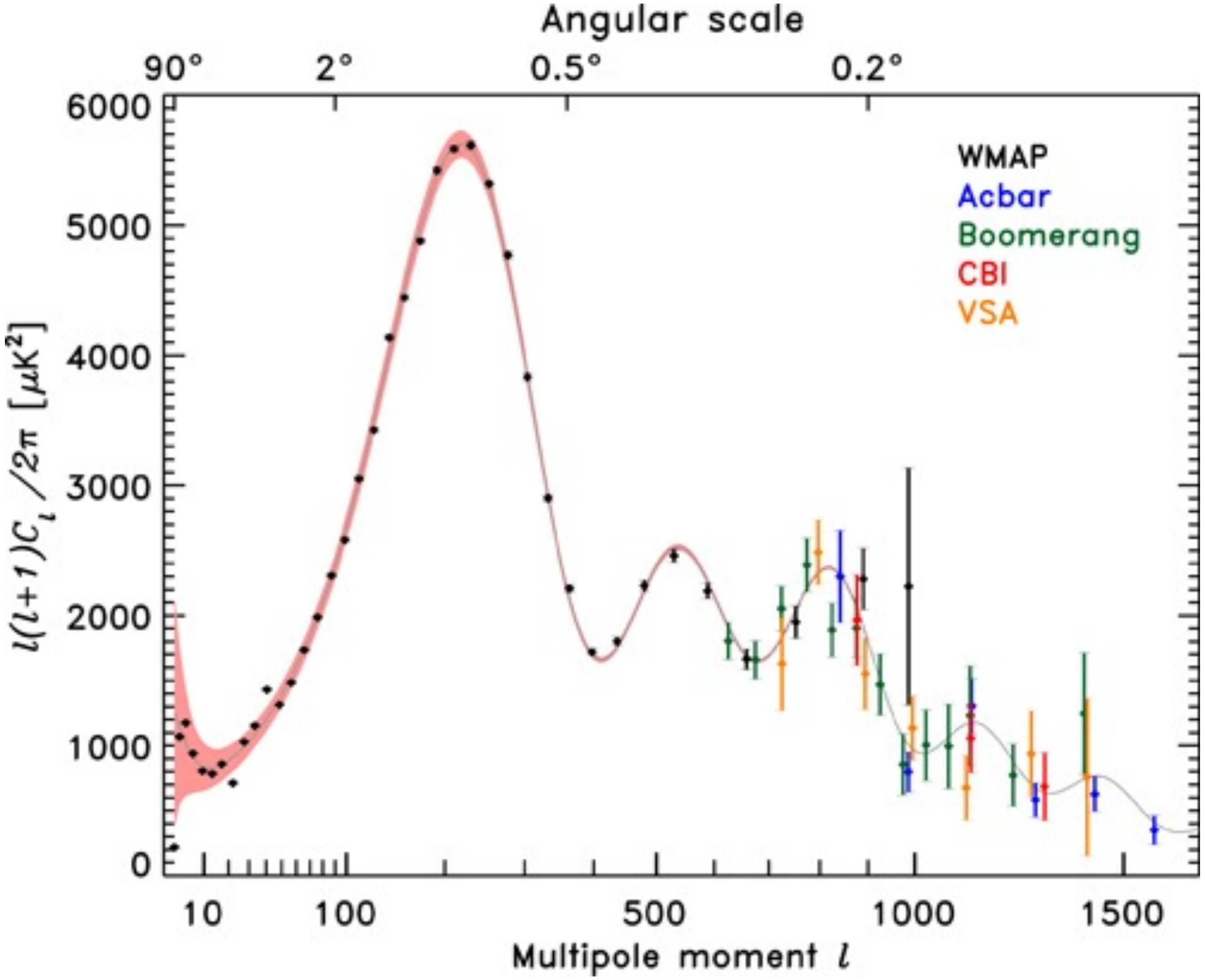

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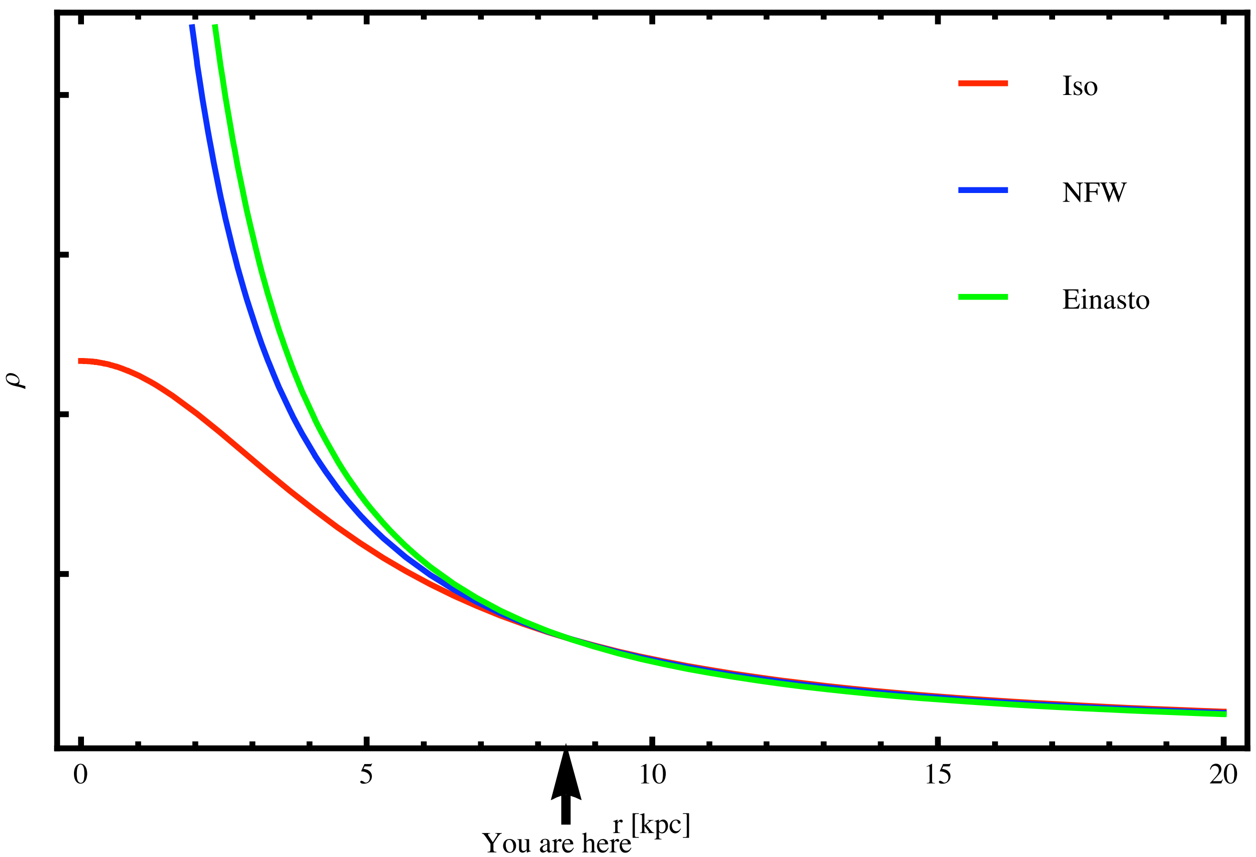
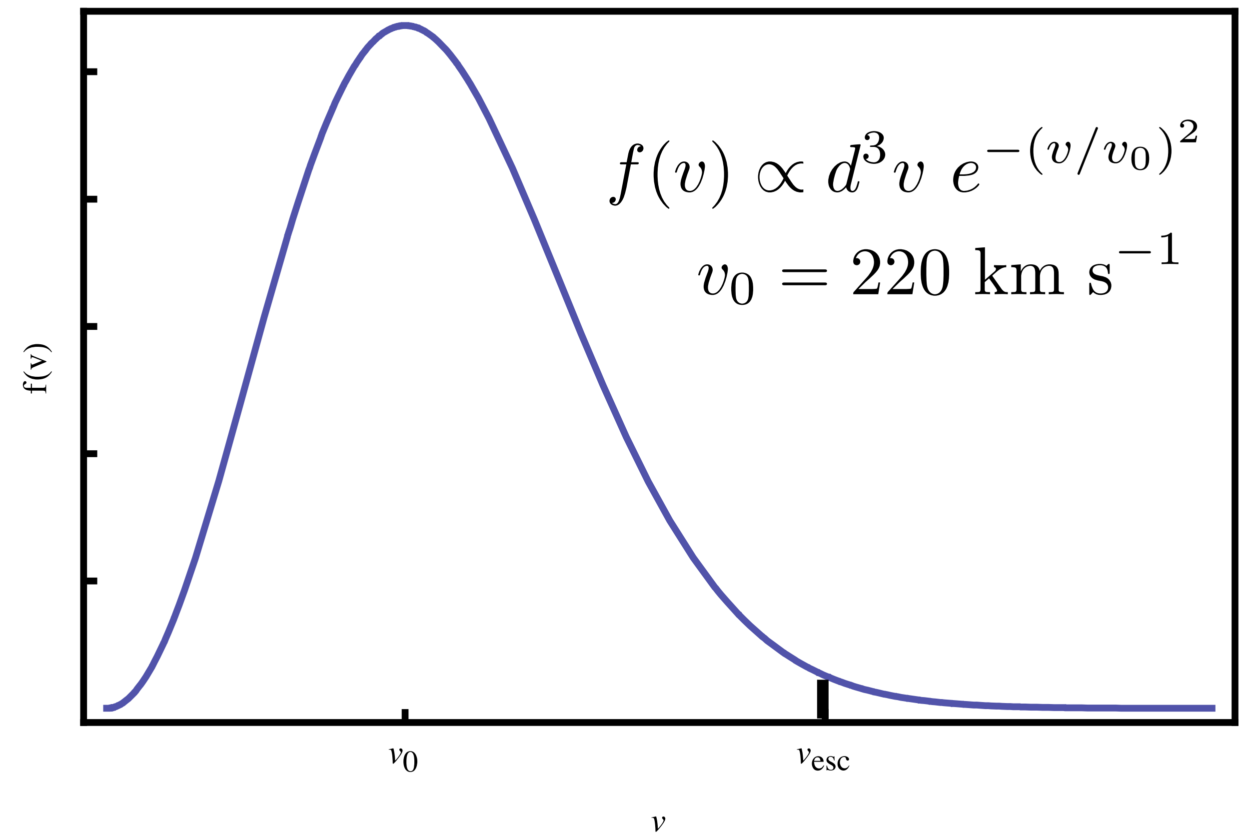
Dark Matter

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



Maxwell-Boltzmann velocity distribution



Escape velocity in galactic frame $498 \text{ km/s} \leq v_{esc} \leq 608$

$$f(v) = \frac{1}{(\pi v_0^2)^{3/2}} e^{-v^2/v_0^2}$$

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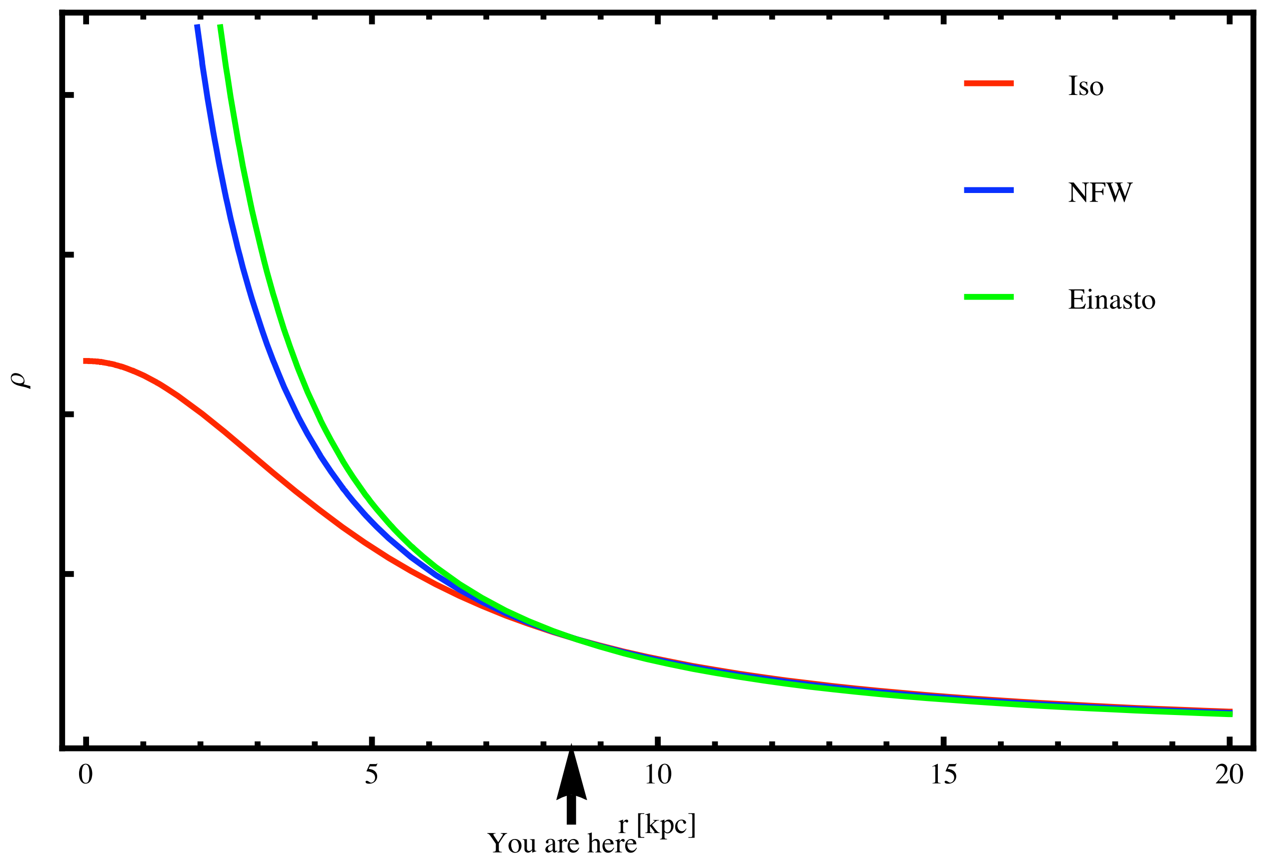

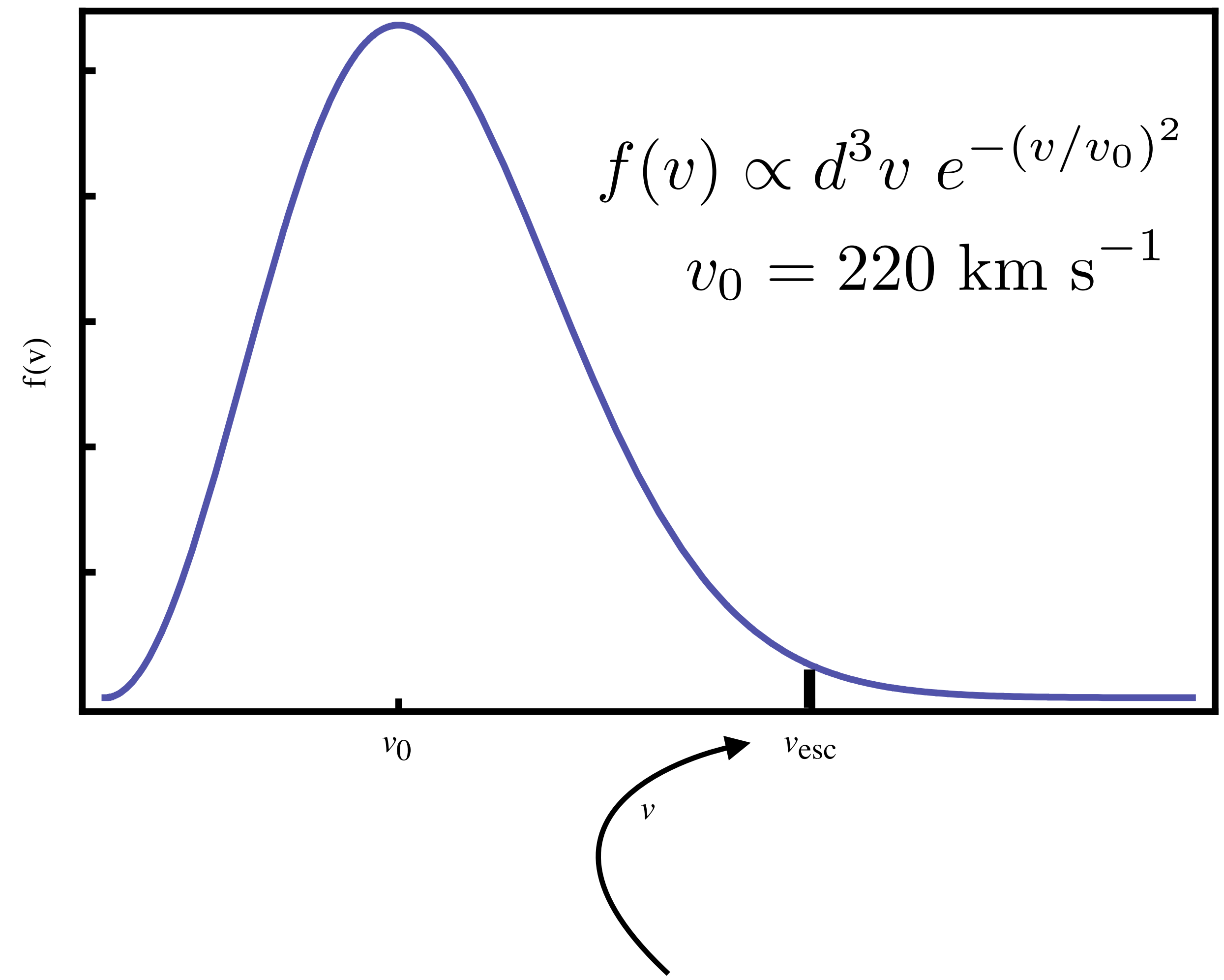

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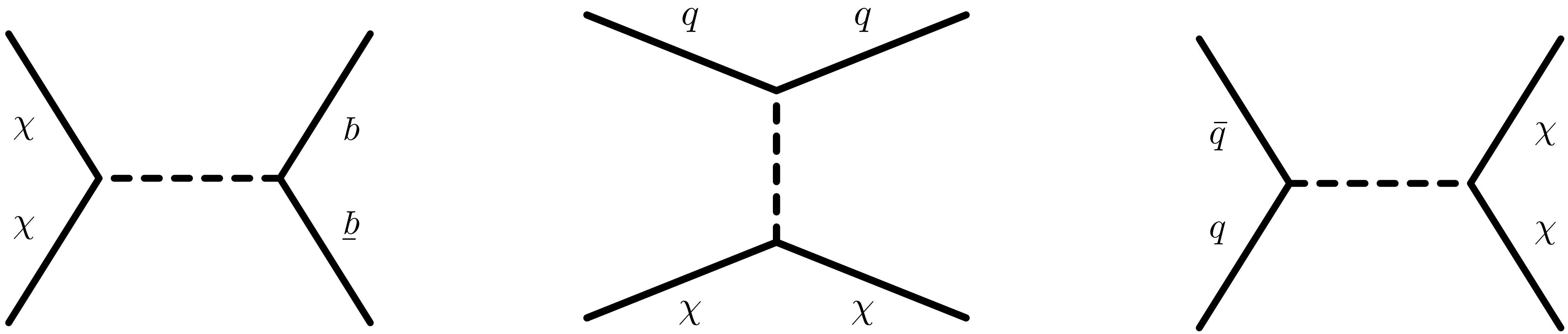
Searching for dark matter

(here, there and everywhere)



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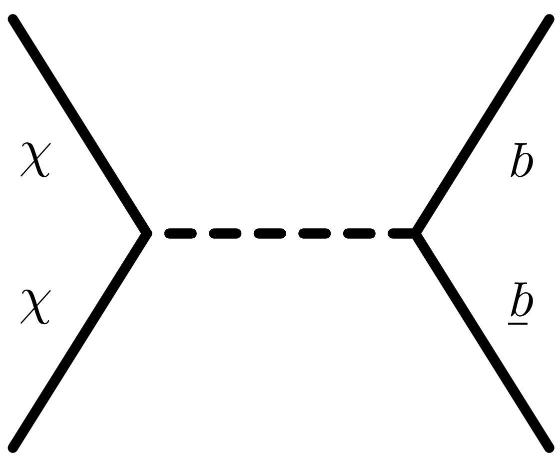
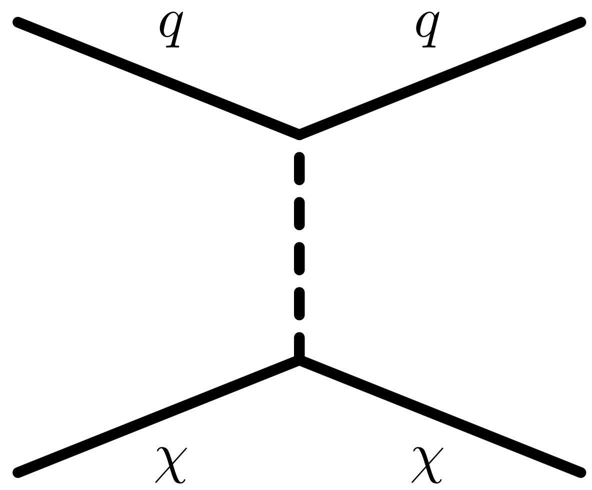
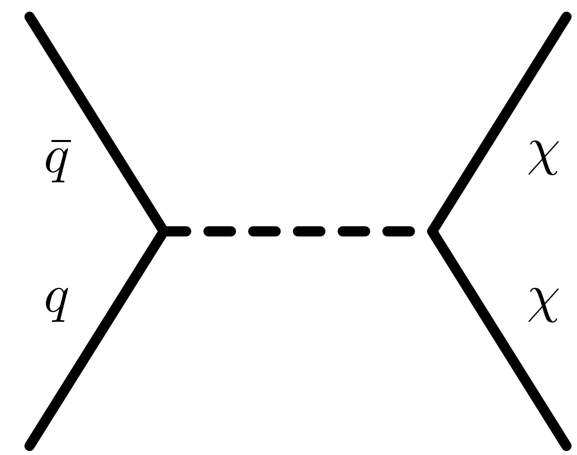


Type I



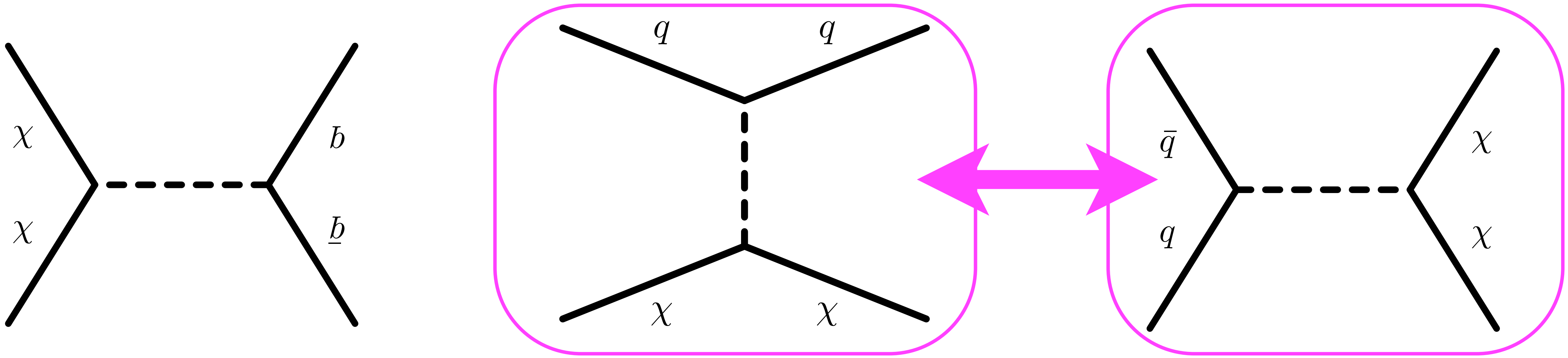
Type IIA



Type IIB

Searching for dark matter

(here, there and everywhere)



Type I

Type IIA

Type IIB

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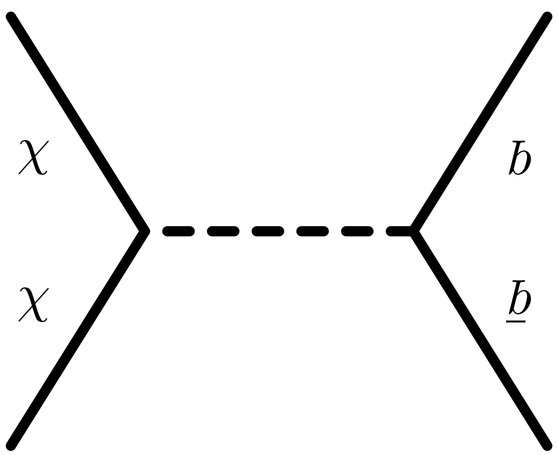
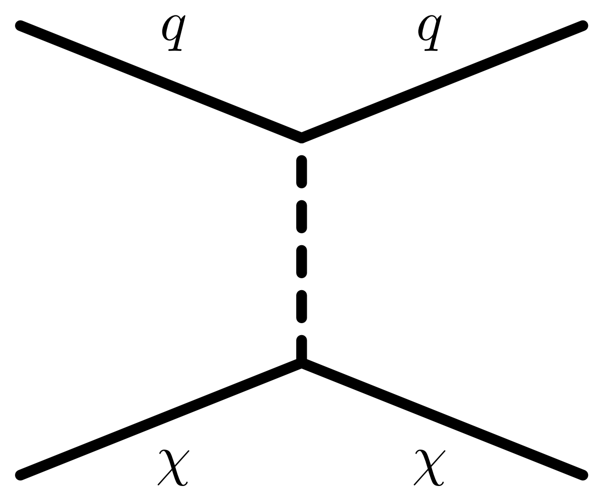
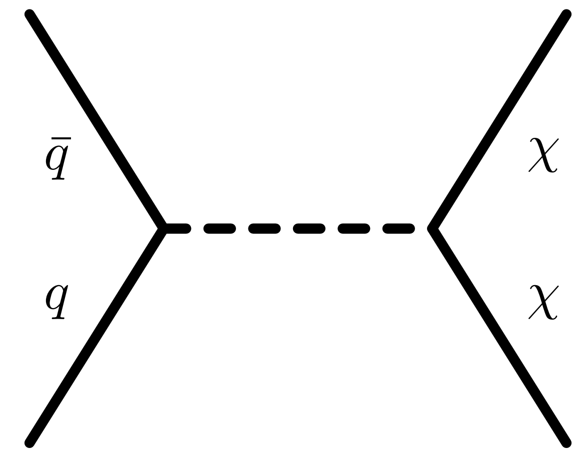






Indirect detection

Look up

Anti-matter excesses in cosmic rays, photons from centre of galaxy

Direct detection

Look down

Low rate, low energy recoil events in underground labs

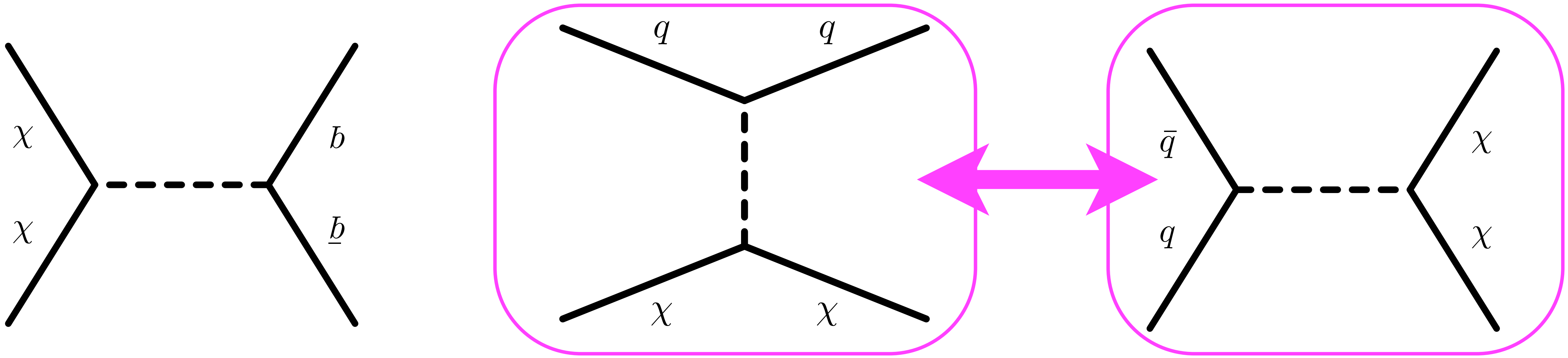
Collider searches

Look small

Missing energy events at colliders

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

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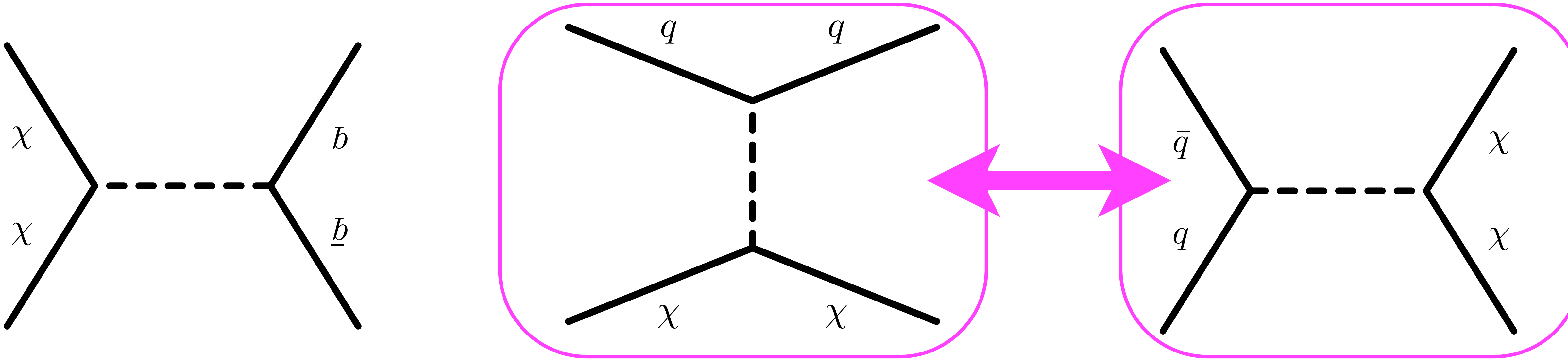

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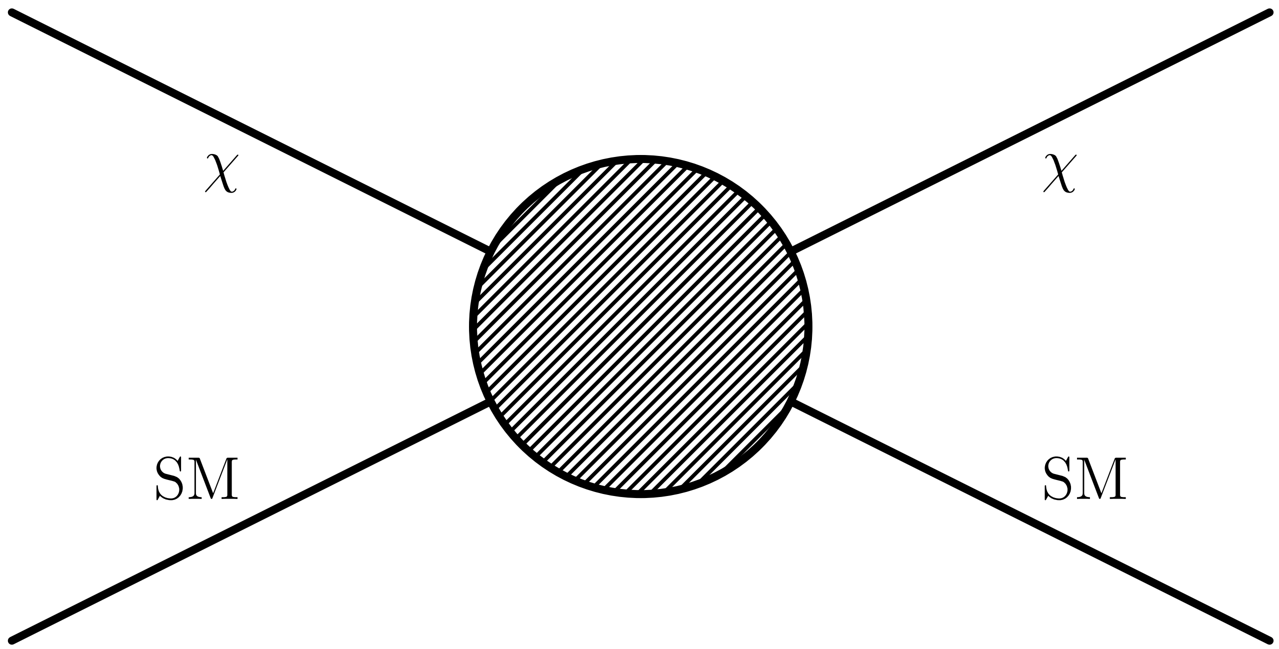
Thermal relic? Predicts x-sec ~1 pb

Direct Detection



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

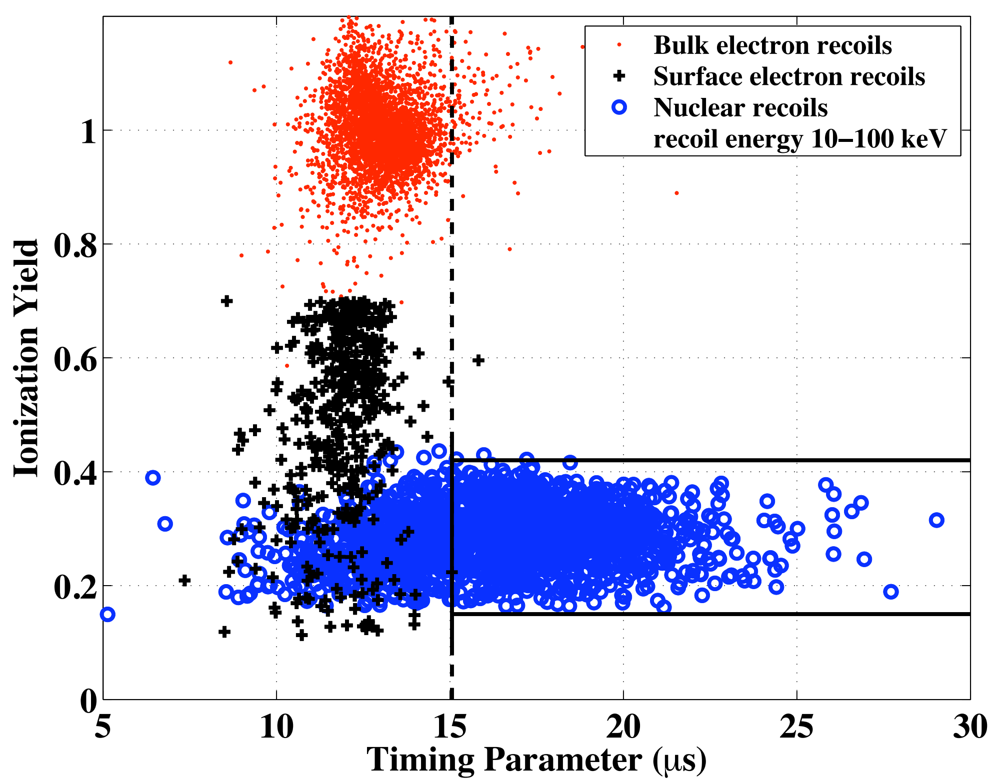
$$R \sim N_T \frac{\rho_\chi}{m_\chi} \langle \sigma v \rangle \approx 1 \text{ event/day/kg}$$

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

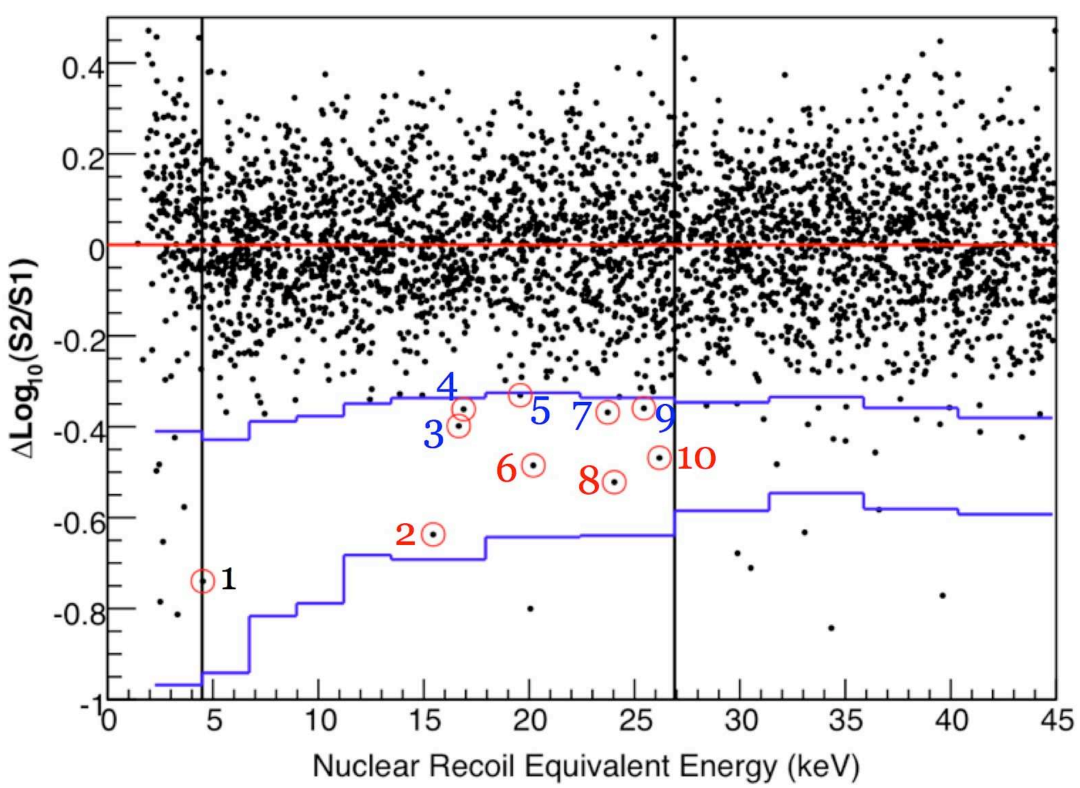
Direct Detection

One Way:

- Remove cosmic backgrounds by going underground
- Shield experiment from radioactive elements
- Cool equipment
- Take multiple measurements to distinguish background from nuclear recoils e.g. ionization, scintillation, phonons



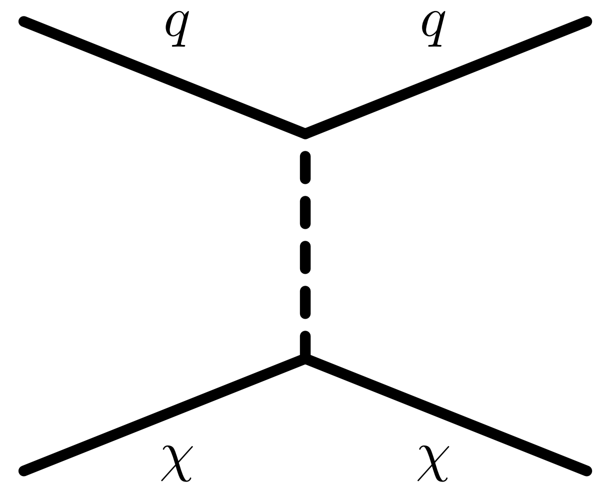
[CDMS collaboration]

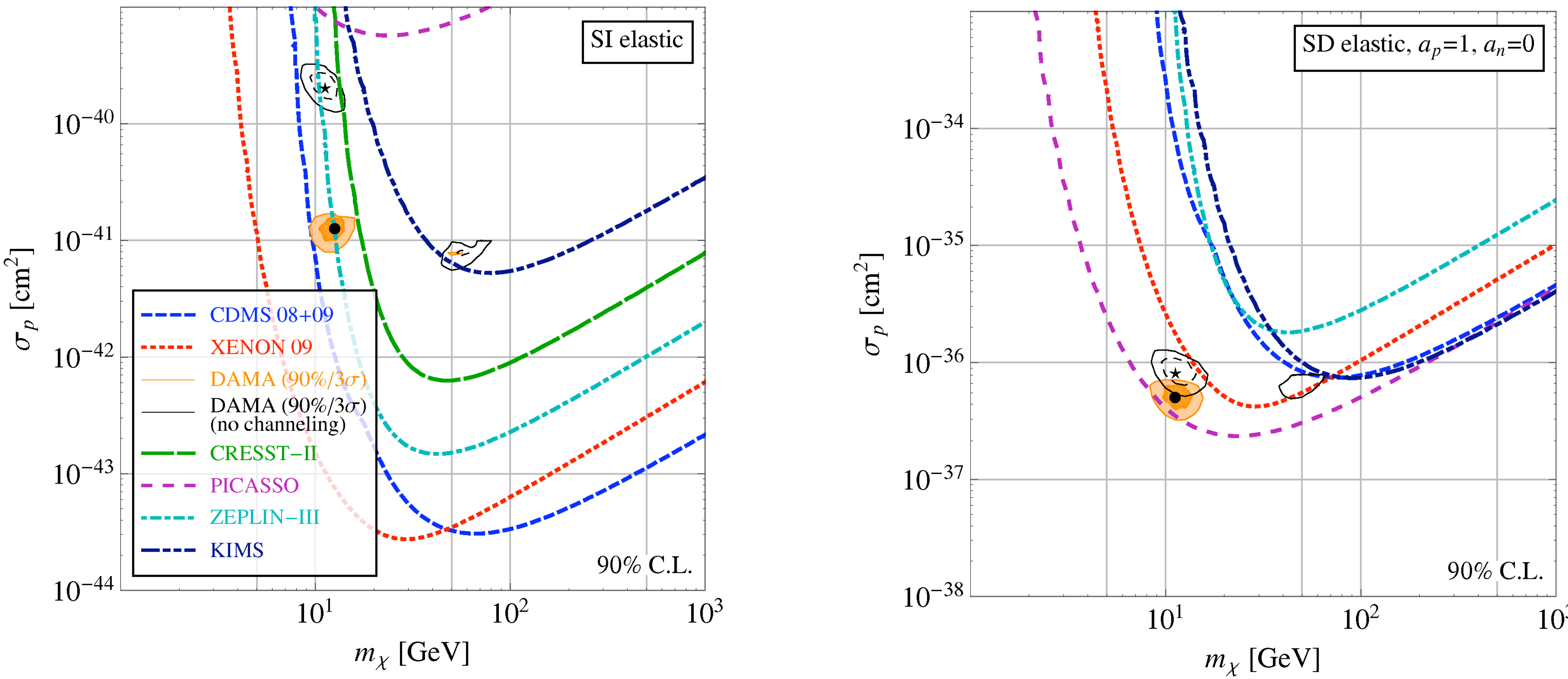


[XENON10 collaboration]

Existing DD bounds

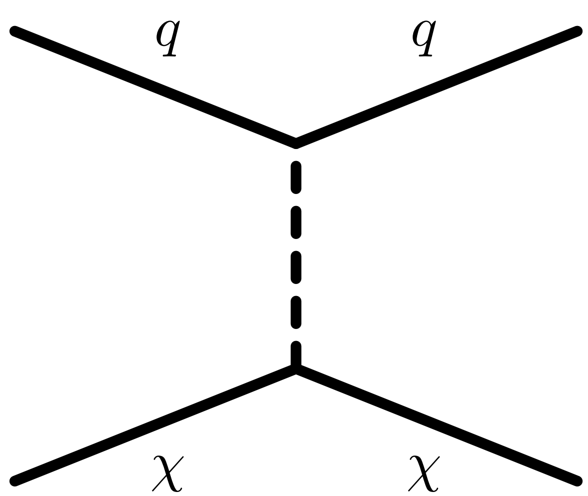
CDMS, XENON, DAMA,
CoGeNT, COUPP,
CRESST, ...



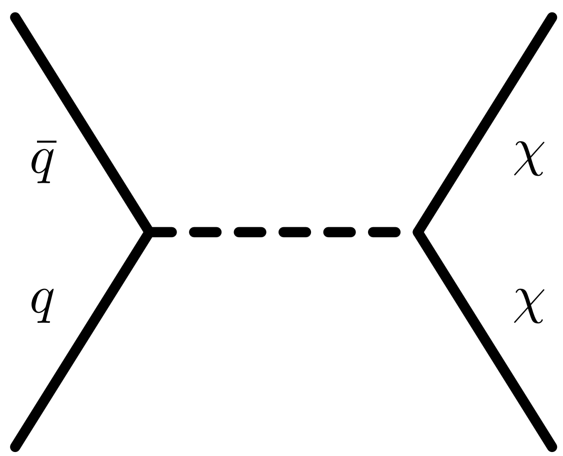


(Assume local abundance is 0.3 GeV/cm^3)

Direct detection vs Collider production



Direct detection $q \sim 100\ \mathrm{MeV}$



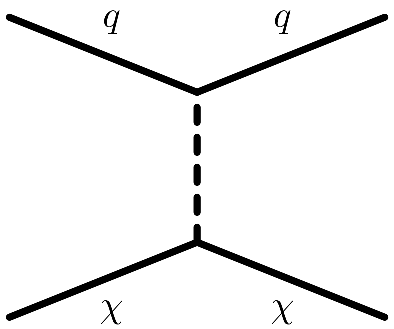
Collider searches $q \sim 10 - 100\ \mathrm{GeV}$

How does one search impact the other?

[Birkedal, Matchev and Perelstein]

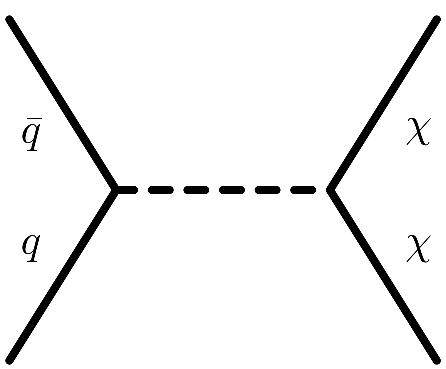
Mediator Mass dependence

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



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

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



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

$$\sigma_{1j} \sim \begin{cases} \alpha_s\, g_\chi^2\, g_q^2\, \frac{1}{p_T^2} & M \lesssim 100\ \mathrm{GeV} \\ \alpha_s\, g_\chi^2\, g_q^2\, \frac{p_T^2}{M^4} & M \gtrsim 100\ \mathrm{GeV} \end{cases}$$

CDF analysed $1\,\mathrm{fb}^{-1}$ and saw no significant deviation

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

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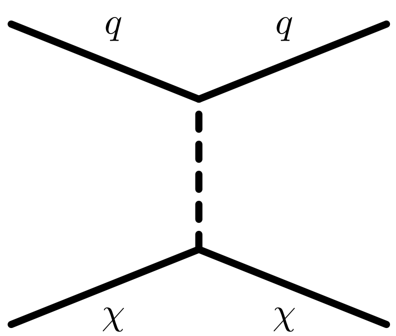

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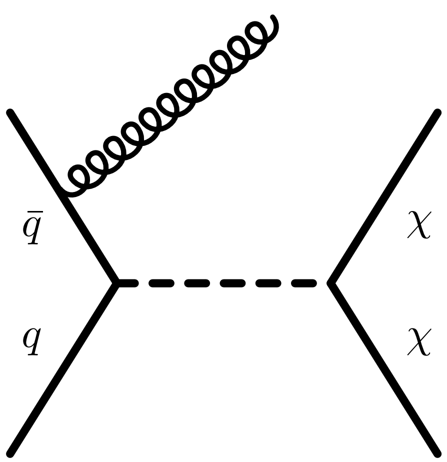

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Consider massive mediator:

$(p_T \sim 100\,\mathrm{GeV})$ $\qquad$ $(\mu \sim 1\,\mathrm{GeV})$

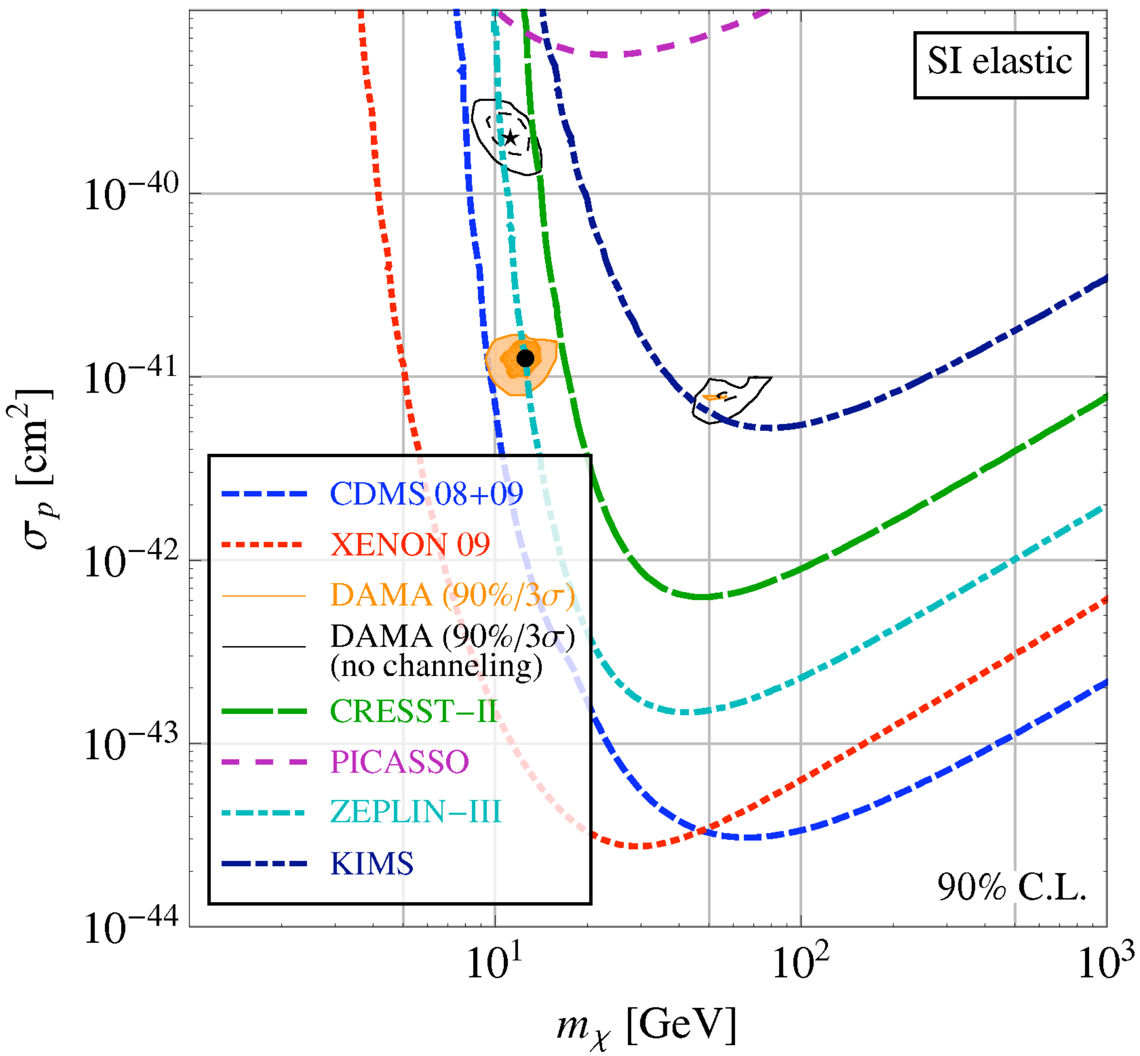
$$\sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{p_T^2}{M^4} \qquad \sigma_{\mathrm{DD}} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4}$$

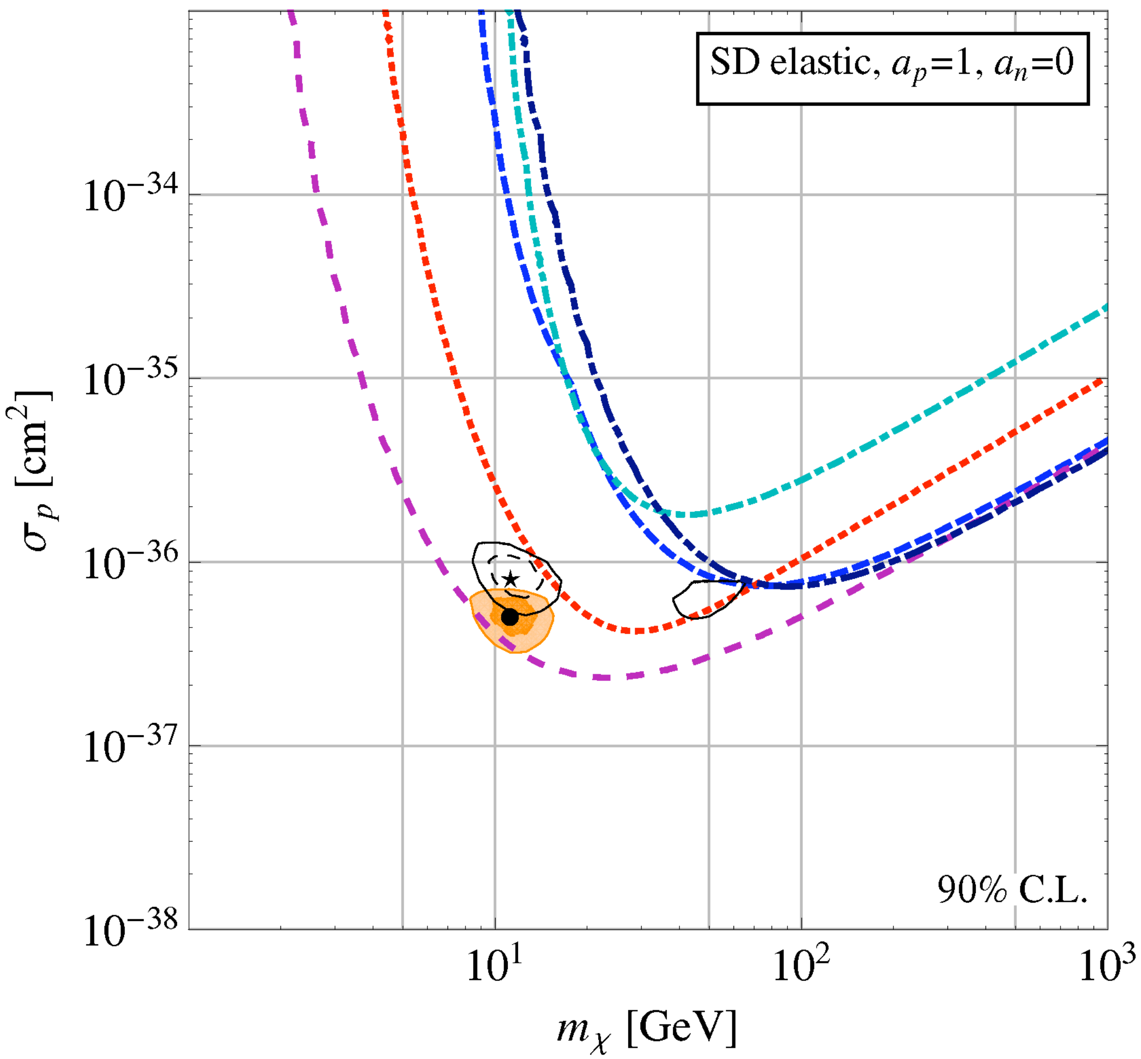
$$\frac{\sigma_{1j}}{\sigma_{DD}} \sim \mathcal{O}(1000)$$

In 1 invfb CDF saw 8449 mono-jet events, expected 8663 ± 332 $\Rightarrow$ $\sigma_{1j} \lesssim 500\,\mathrm{fb}$

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

Existing DD bounds

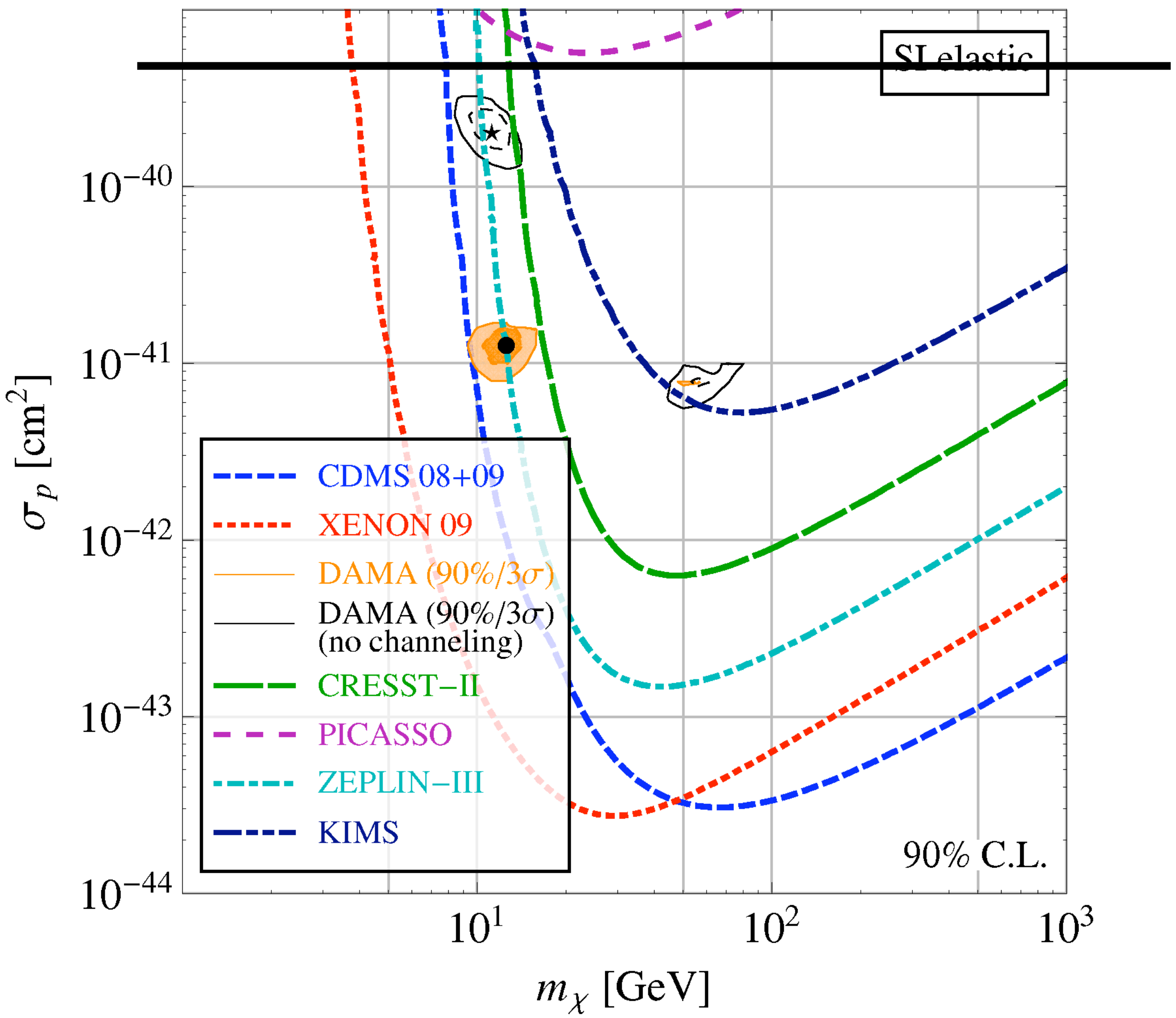


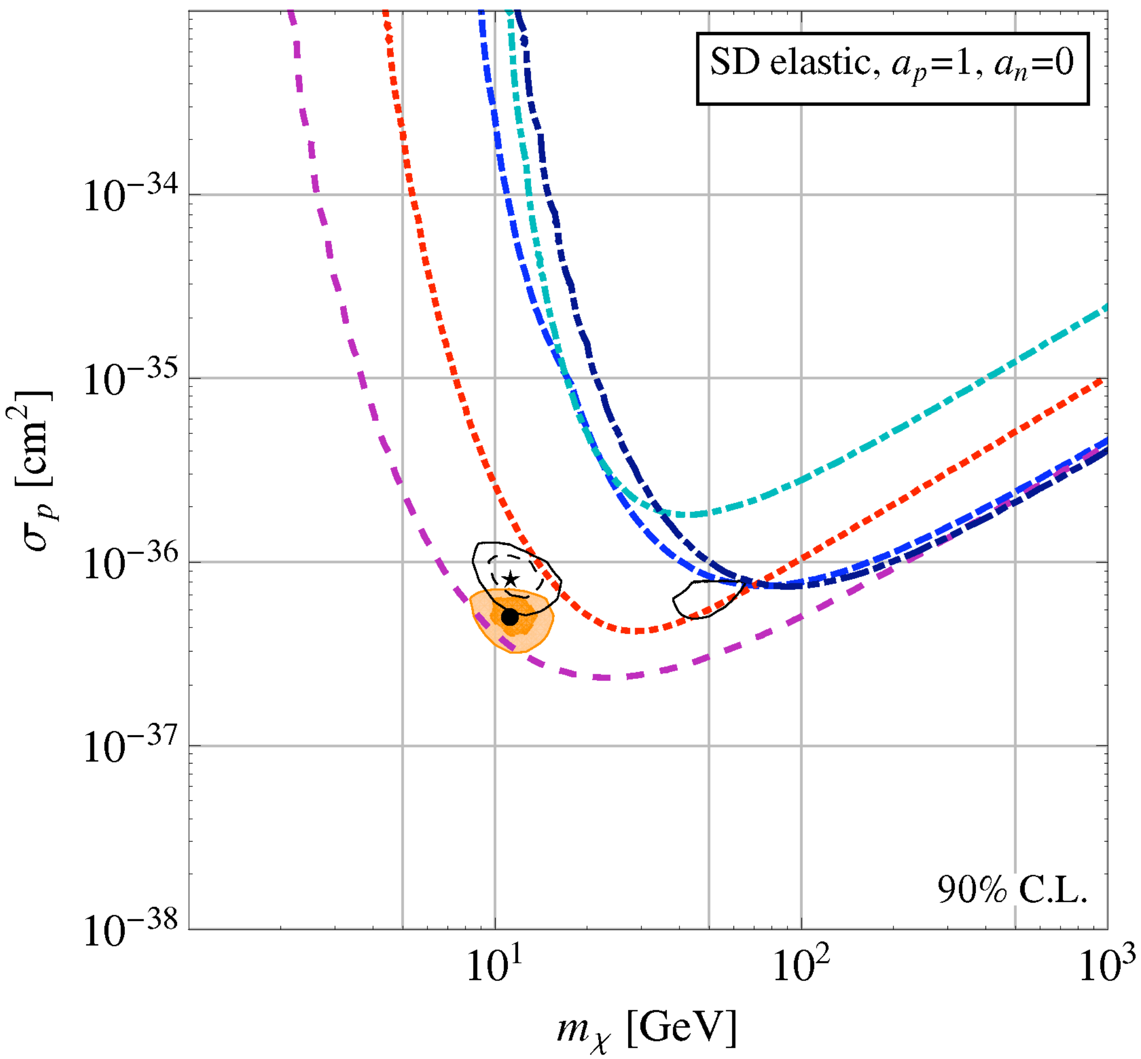


ROI's

- Light mass DM
- Non-standard DM introduced to explain DAMA
- Velocity, momentum or spin suppression

Existing DD bounds





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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

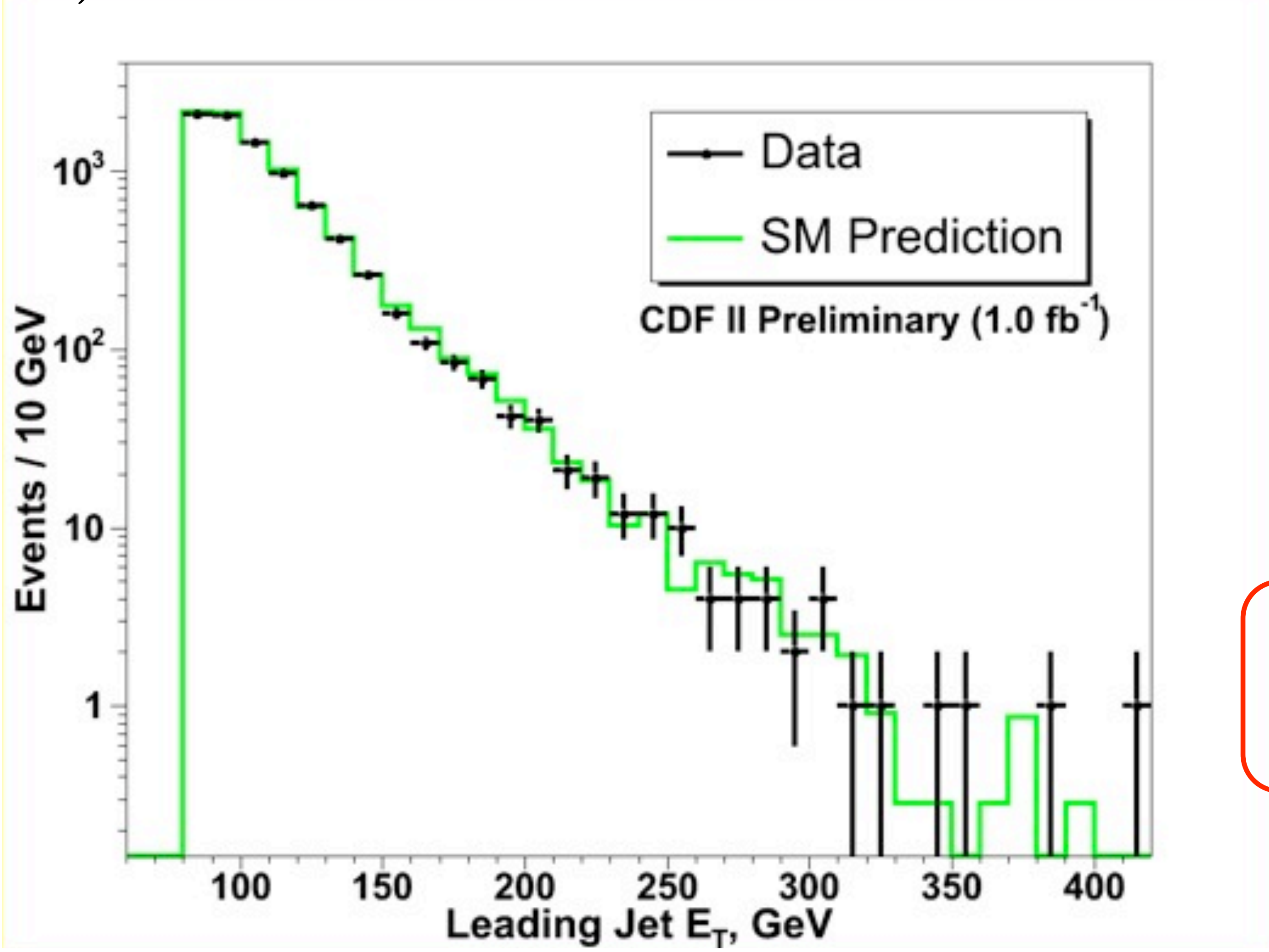
- DM a Dirac fermion
- Consider each operator, and each flavour separately

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 ->ll	87 +/- 3
QCD	708 +/- 146
Gamma plus Jet	209 +/- 41
Non-Collision	52 +/- 52
Total Predicted	8663 +/- 332
Data Observed	8449

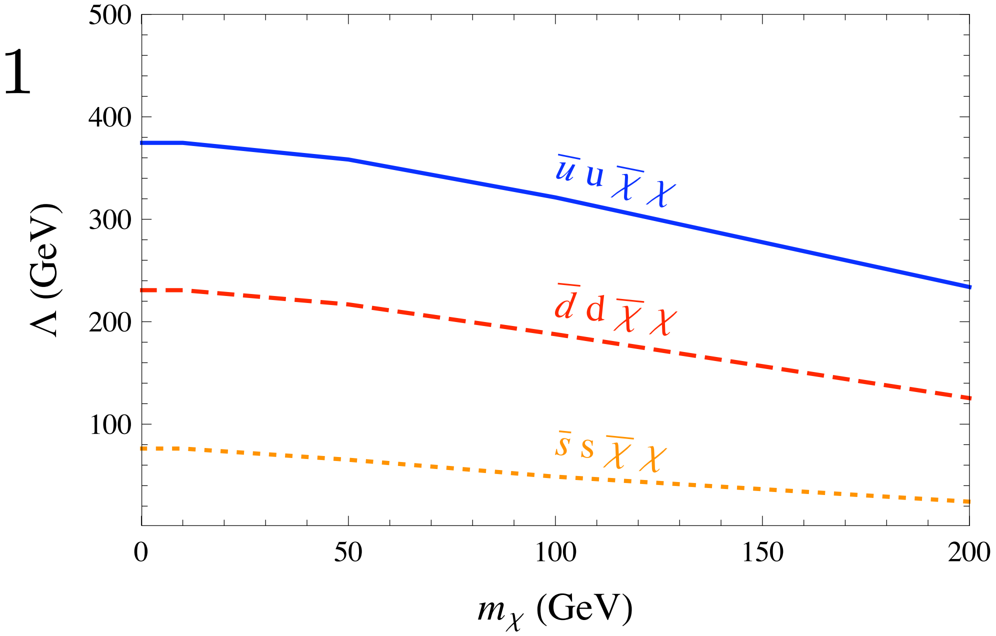
Observed: 8449 events

Bounds on operators

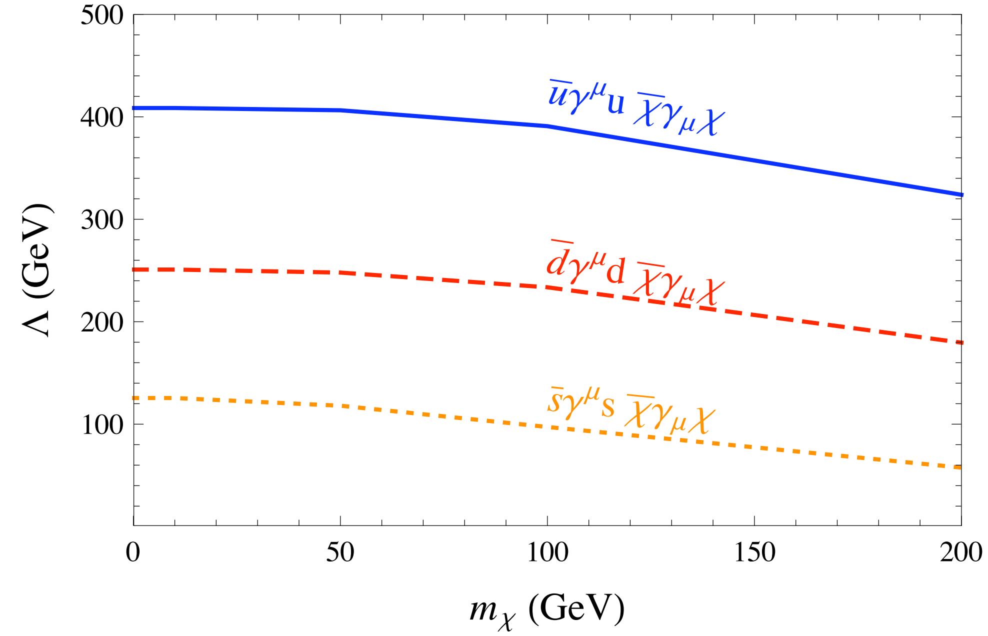
Assume a heavy mediator: $\Lambda = \dfrac{M}{\sqrt{g_\chi g_1}}$

Simulate events in calcHEP, one operator at a time

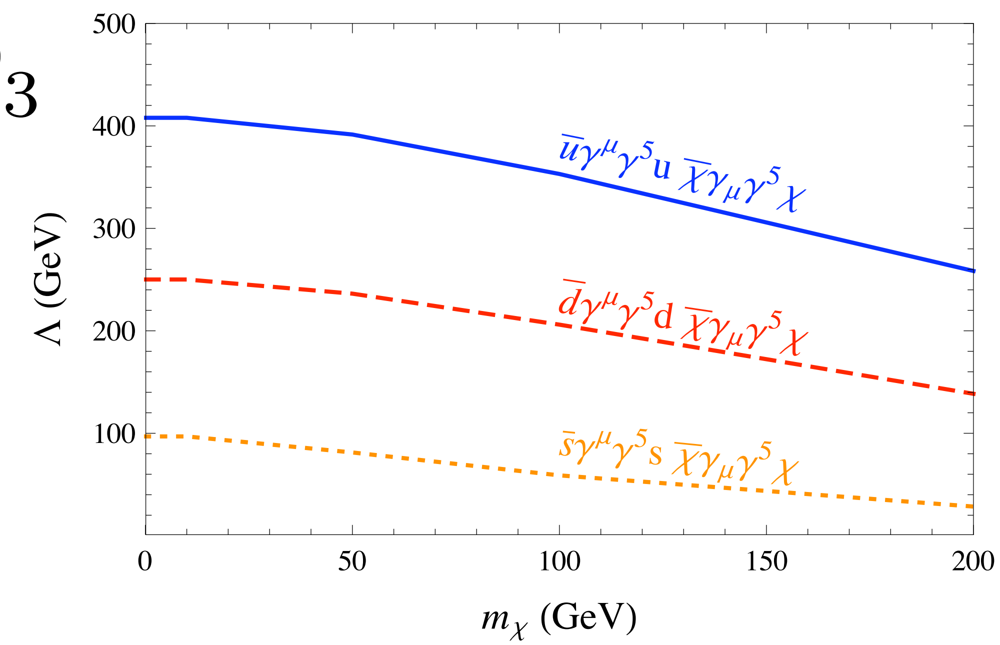
$\mathcal{O}_1$



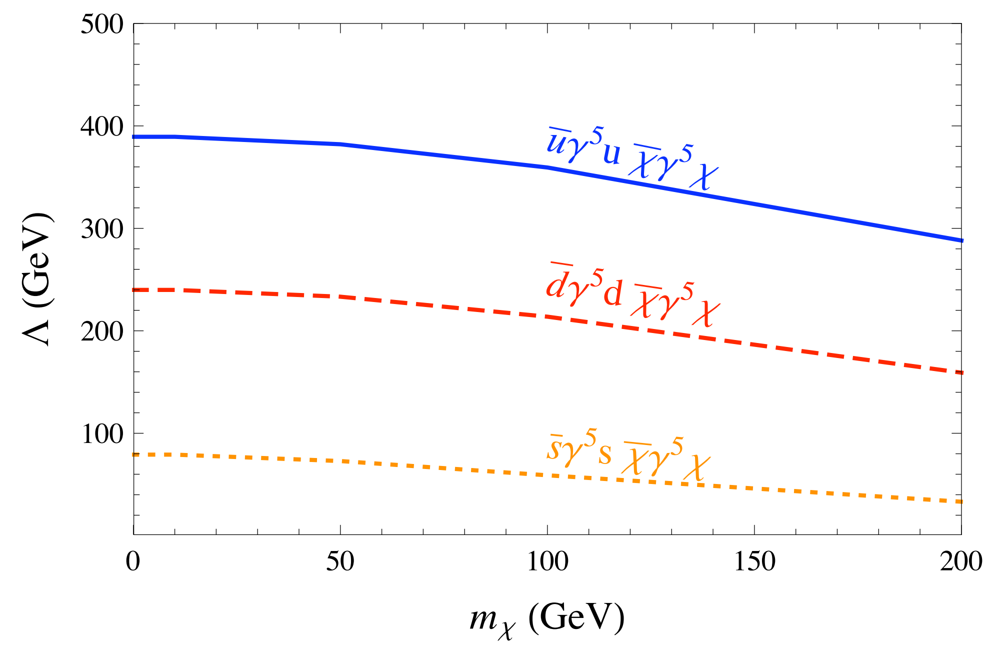
$\mathcal{O}_2$



$\mathcal{O}_3$



$\mathcal{O}_4$



Collider bounds on direct detection

- Up quark bounds typically strongest
- Collider bounds relatively strongest when DD suppressed e.g. SD, MDDM, light, ...
- iDM splitting not important at colliders
- Tevatron not constrained by velocity distribution - low mass DM
- DM with vector couplings to 2 or 3 gen. quarks
- .....

Spin independent

$$\mathcal{O}_1 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q} q)(\bar{\chi}\chi) \,, \qquad \mathcal{O}_2 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}\gamma_\mu q)(\bar{\chi}\gamma^\mu\chi)$$

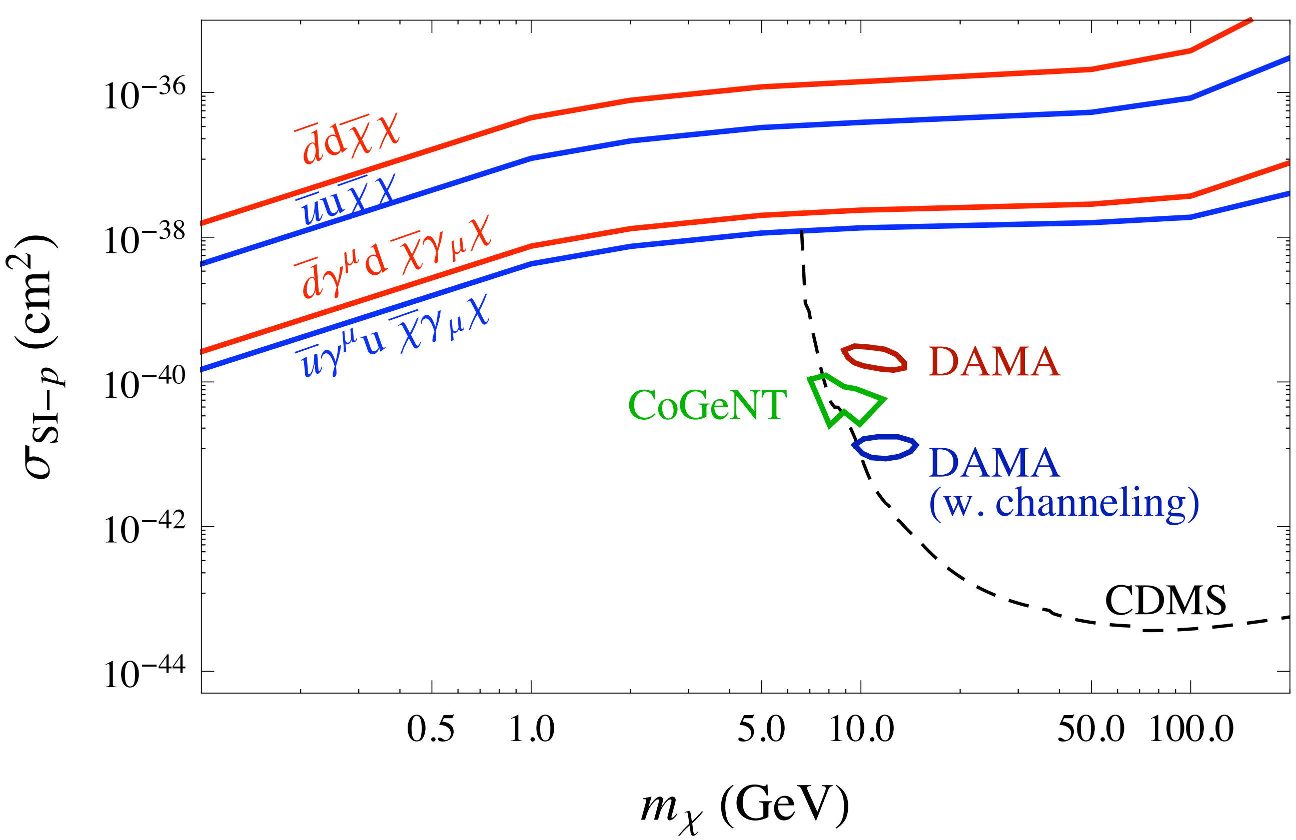
$$\Rightarrow$$

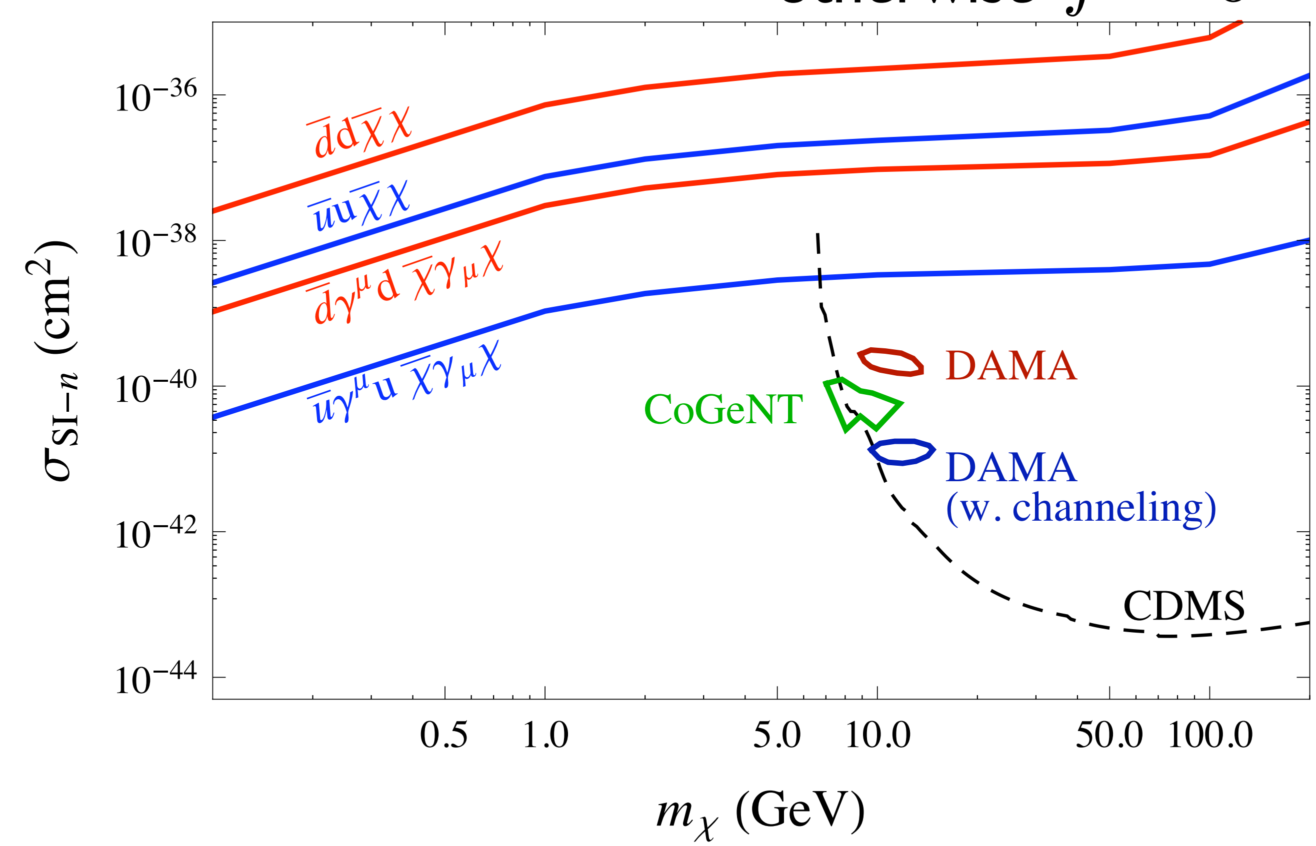
$$\sigma_1^{Nq} = \frac{\mu^2}{\pi\Lambda^4} B_{Nq}^2 \,, \qquad \sigma_2^{Nq} = \frac{\mu^2}{\pi\Lambda^4} f_{Nq}^2 \,,$$

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

$$f_u^p = f_d^n = 2 \qquad f_d^p = f_u^n = 1$$

otherwise $f = 0$





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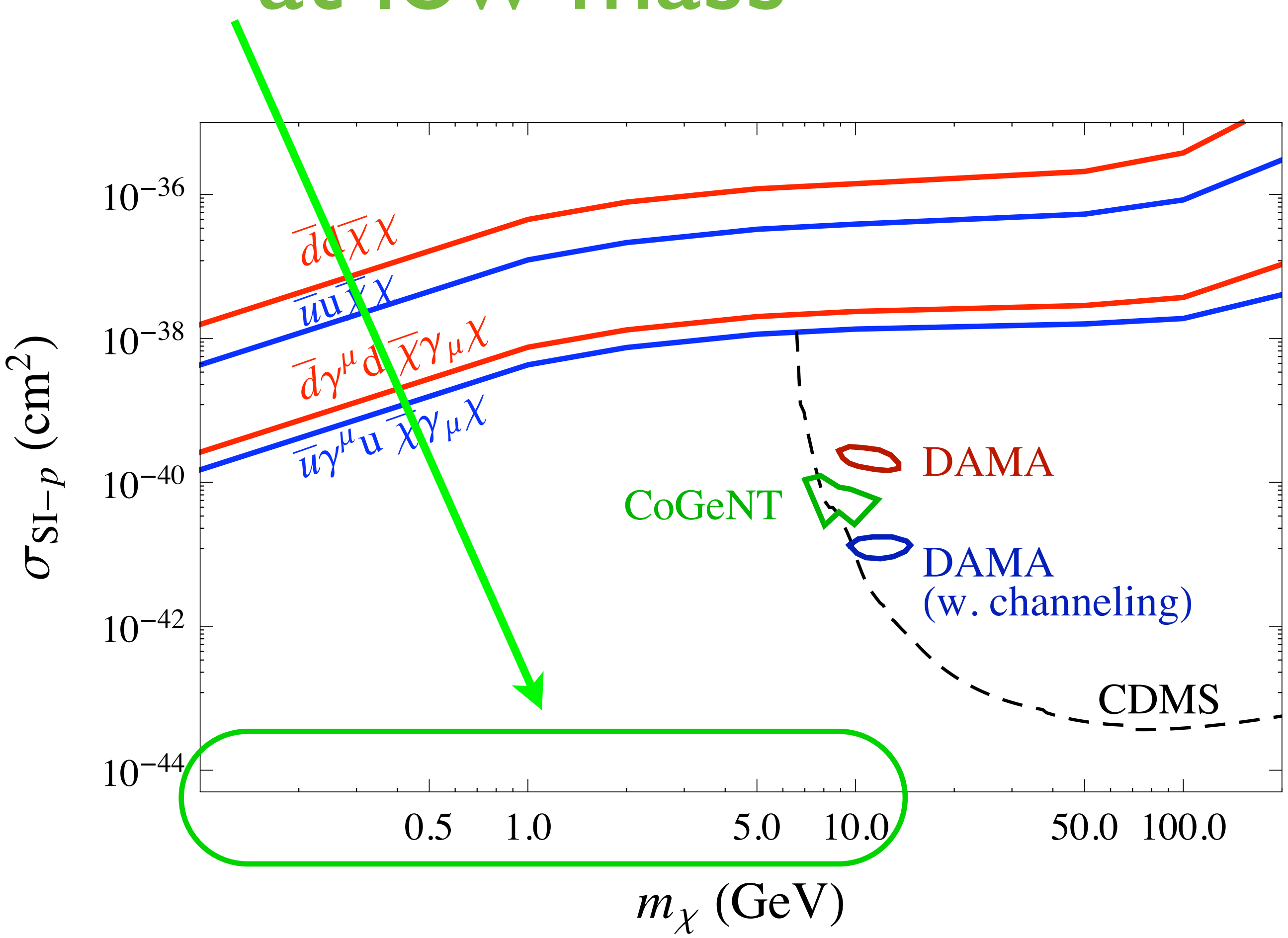
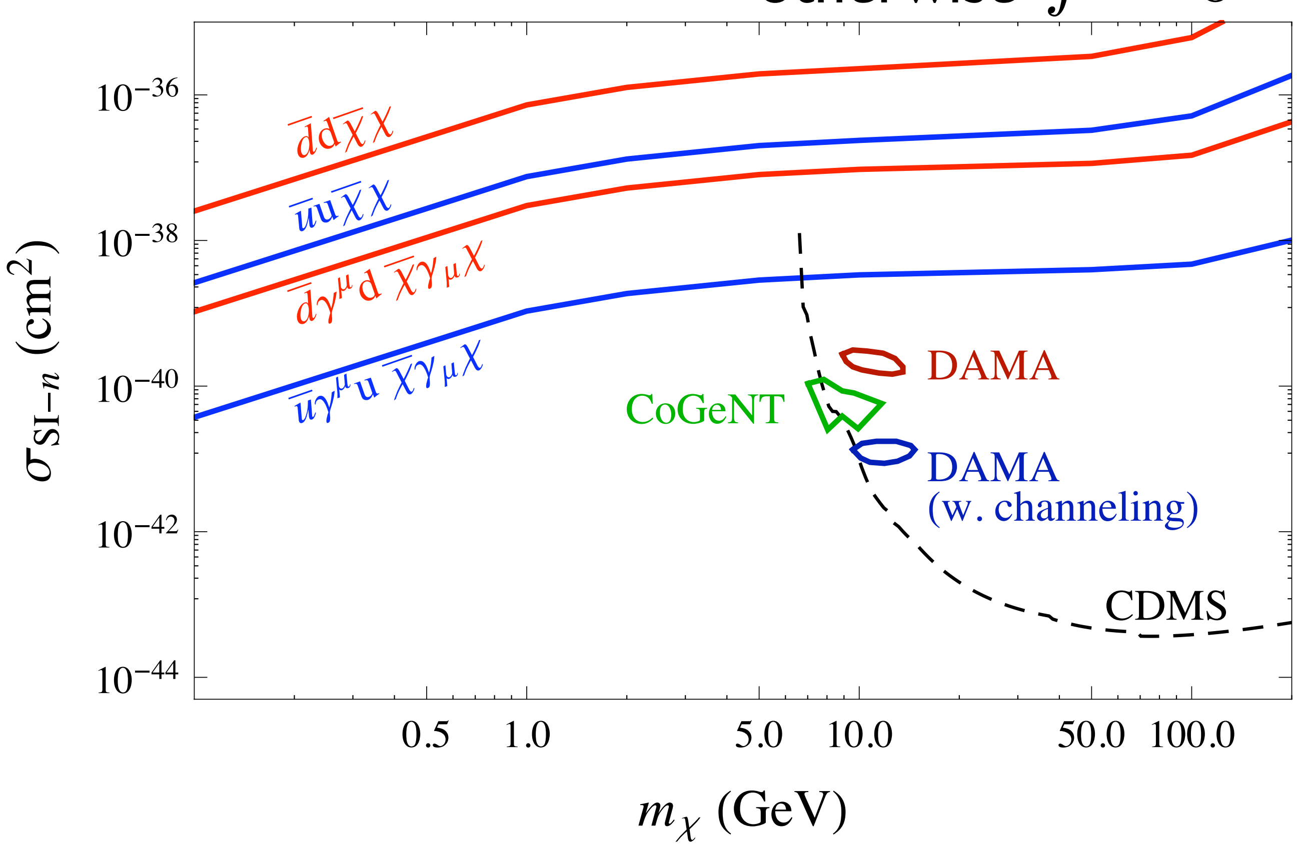
World's best limits at low mass





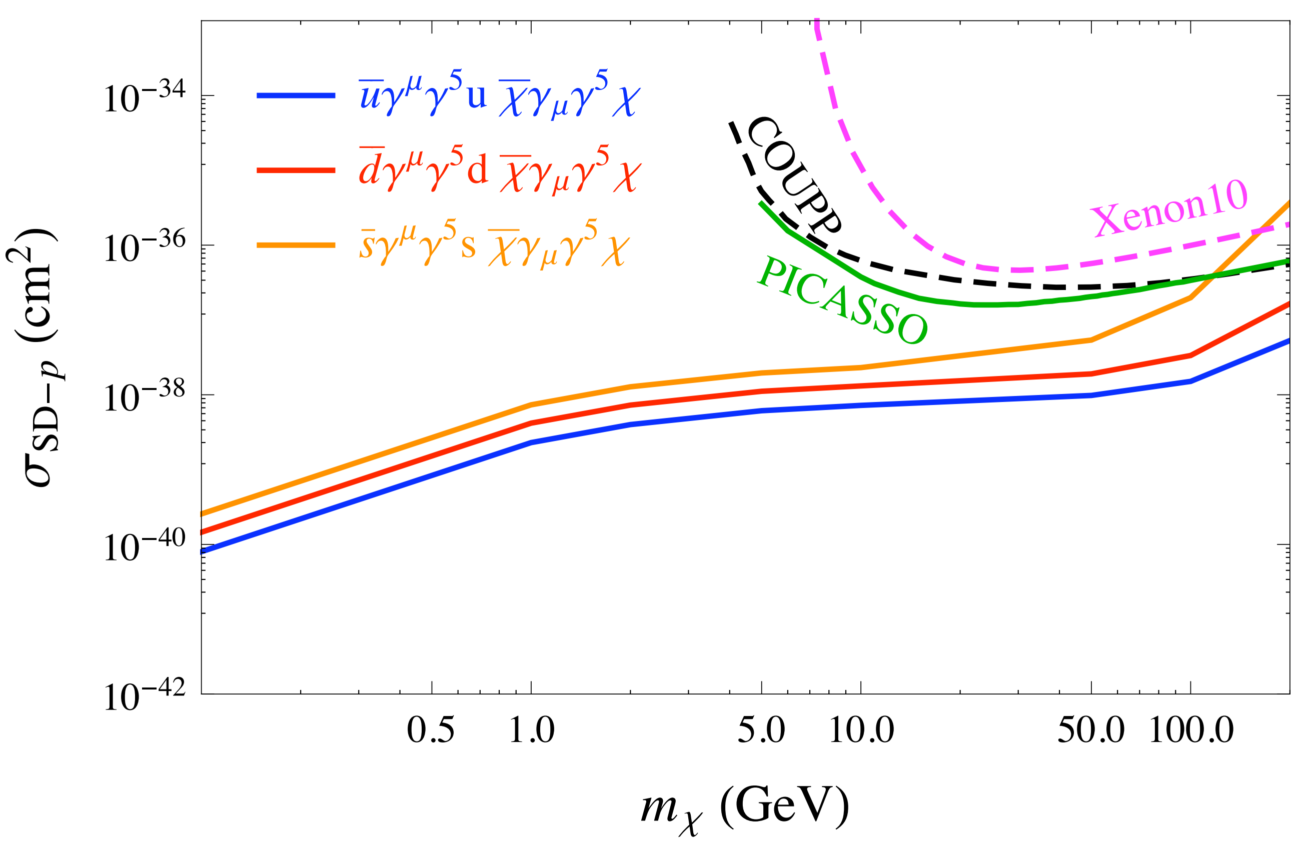
Spin dependent

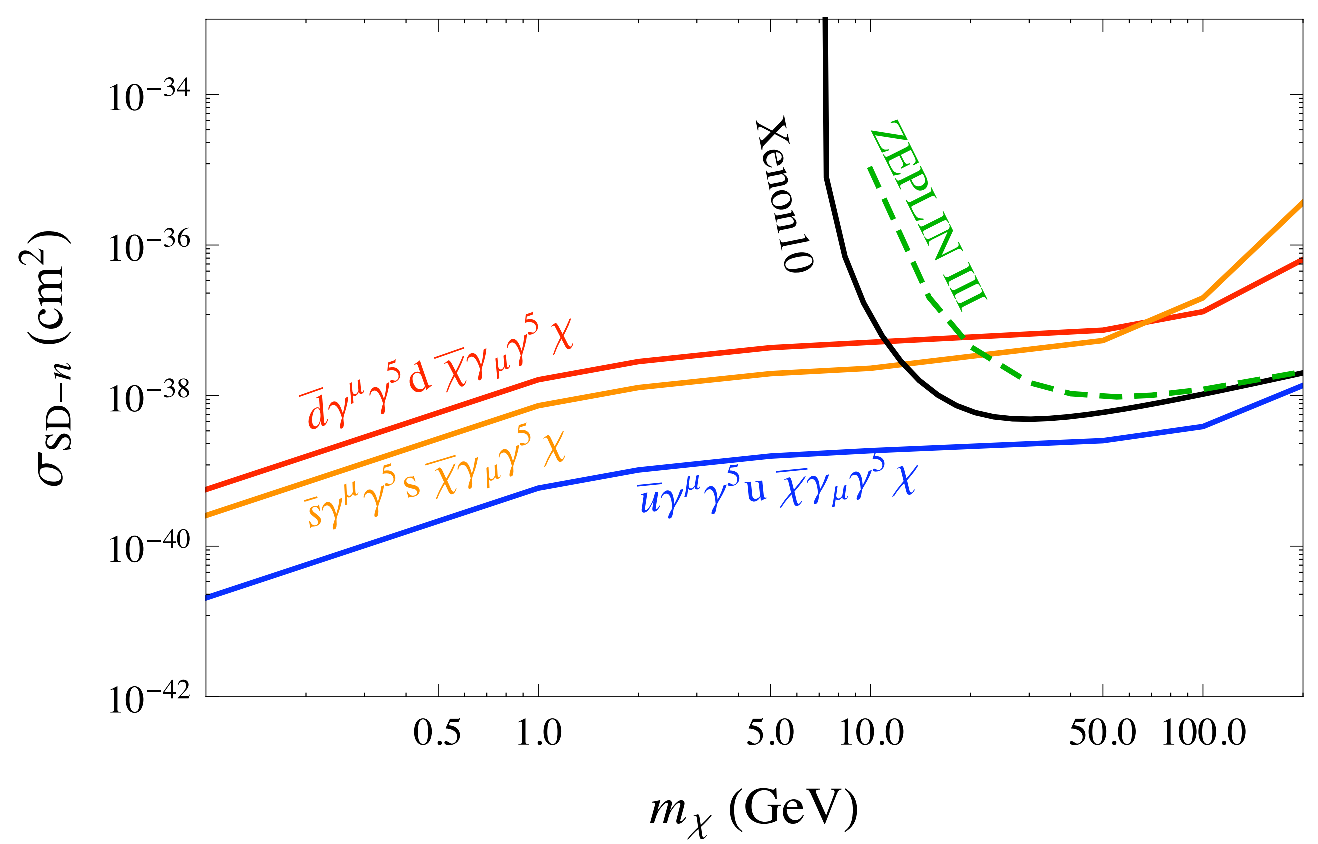
$$\mathcal{O}_3 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} \left(\bar{q}\gamma_\mu\gamma_5 q\right)\left(\bar{\chi}\gamma^\mu\gamma_5\chi\right)$$

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

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

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





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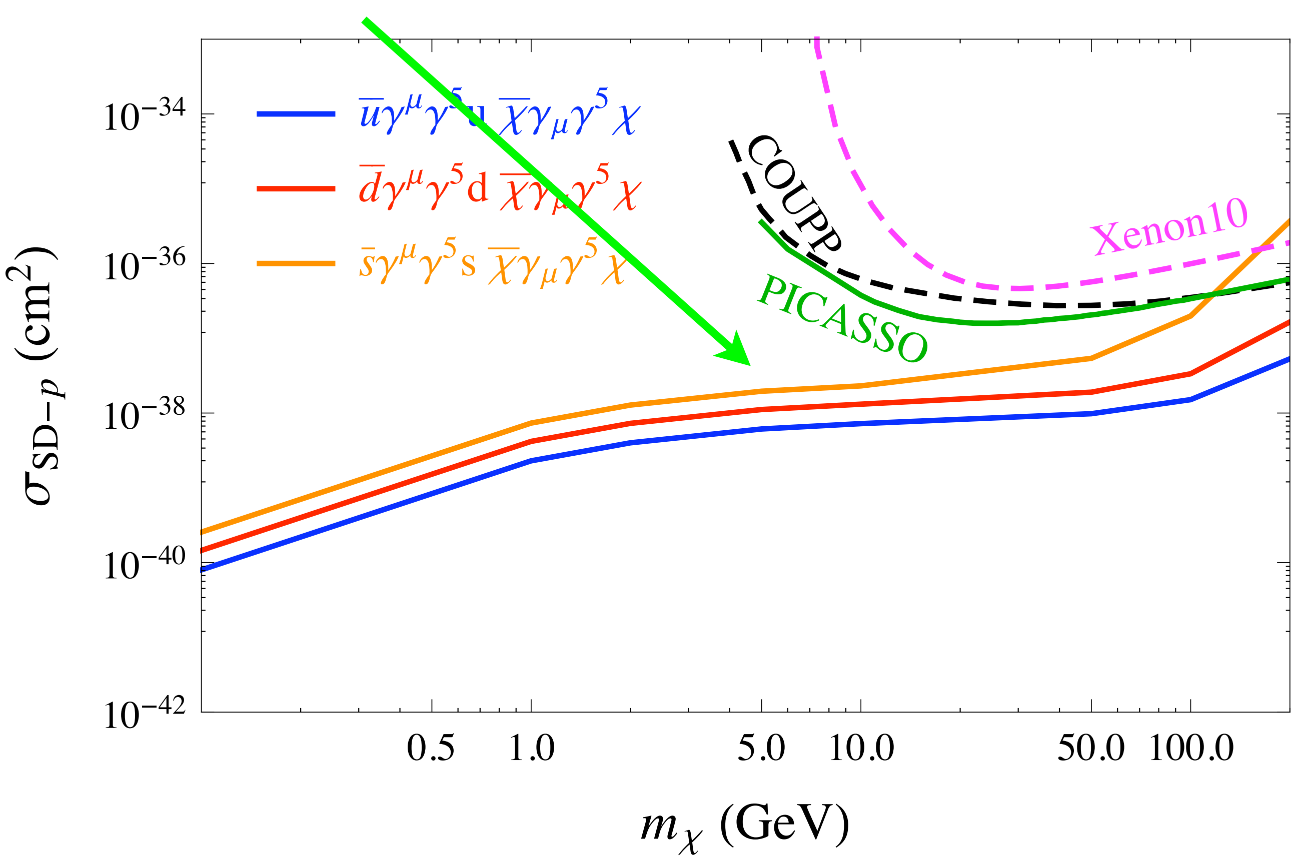
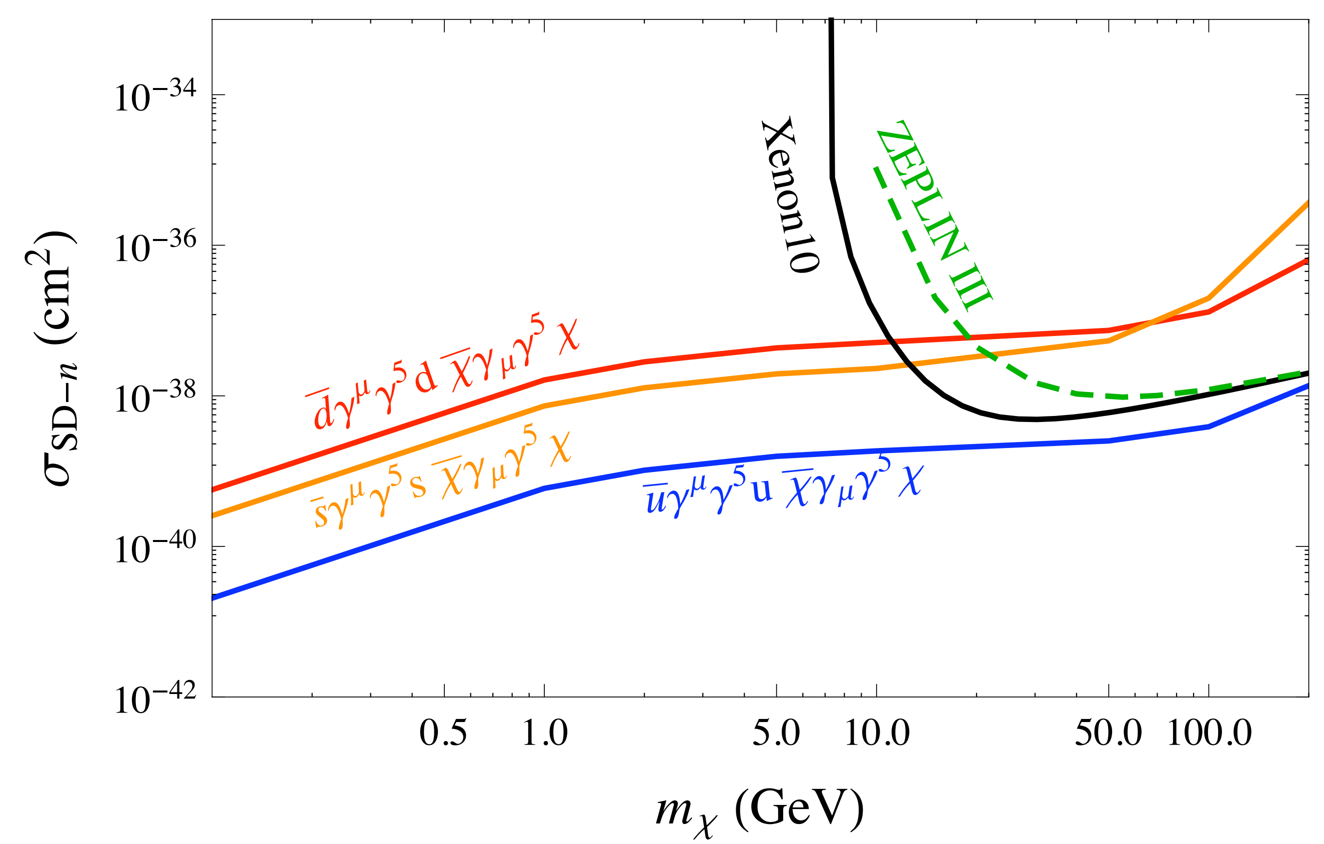
$$\begin{aligned} \Delta_u^p &= \Delta_d^n = 0.842 \pm 0.012\,, \\ \Delta_d^p &= \Delta_u^n = -0.427 \pm 0.013\,, \\ \Delta_s^p &= \Delta_s^n = -0.085 \pm 0.018\,. \end{aligned}$$

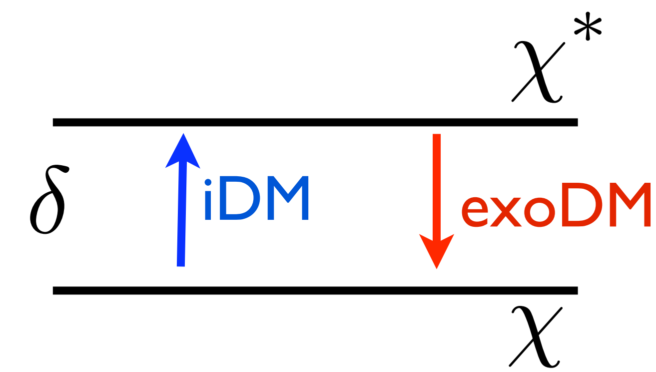
World's best limits, up to ~200 GeV



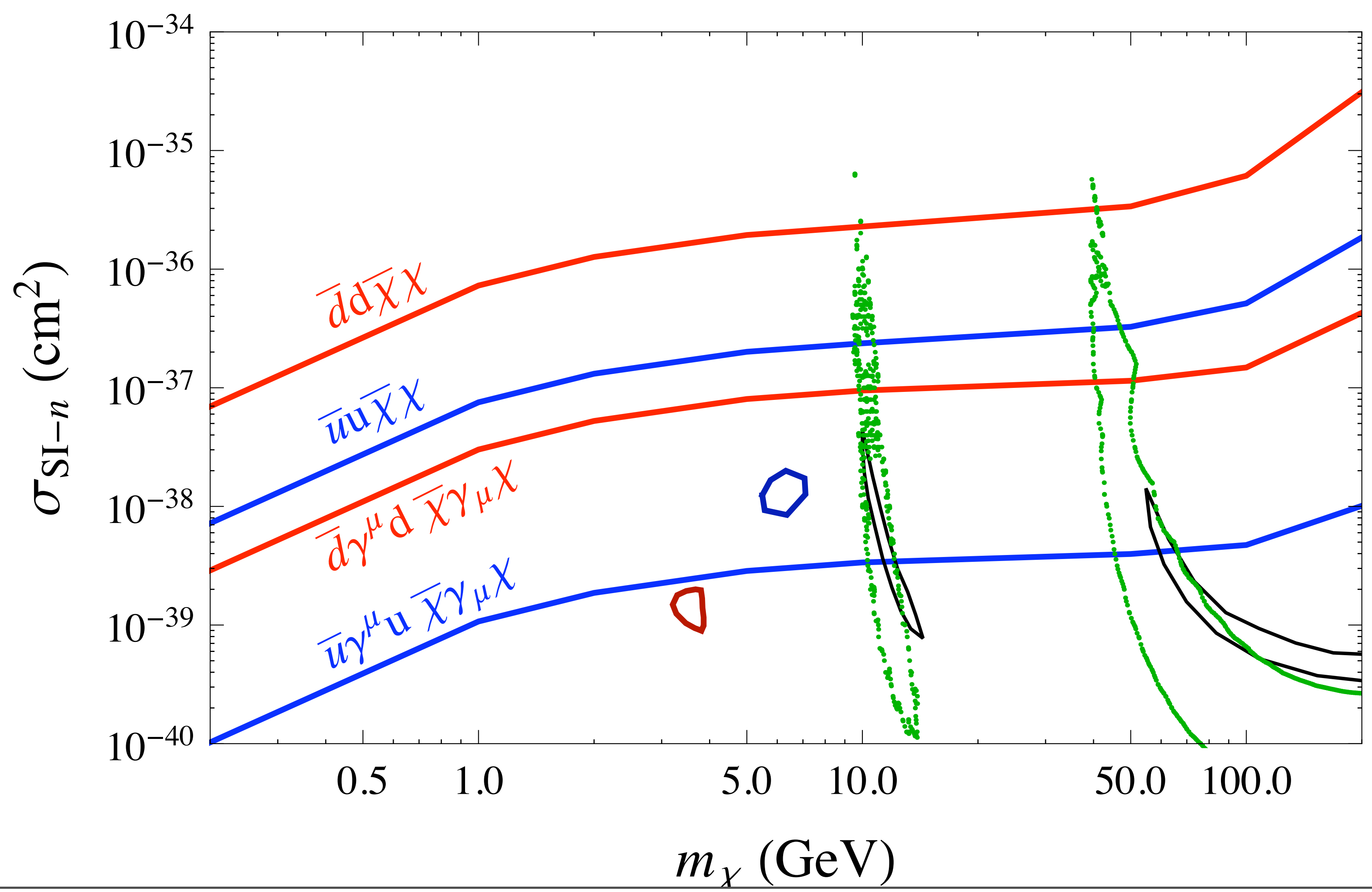


iDM, exothermic

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



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



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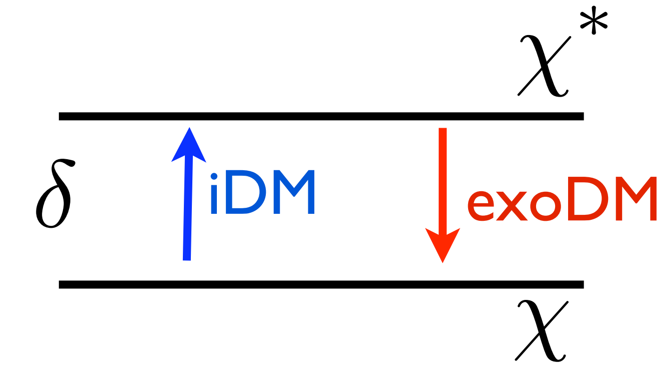
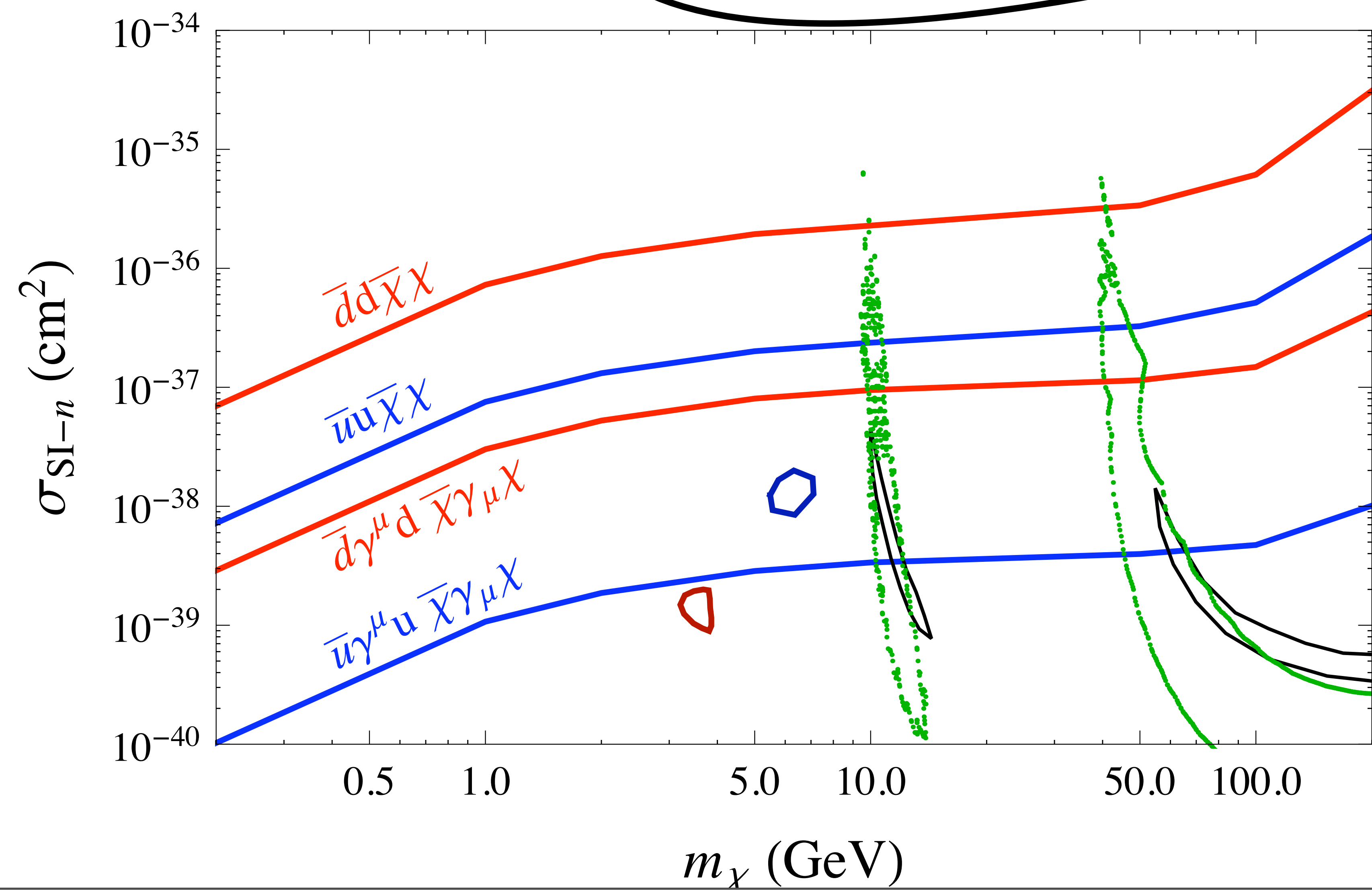


$$v_{min} = \sqrt{\frac{1}{2 m_T E_R}} \left(\frac{m_T E_R}{\mu_T} + \delta \right)$$

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



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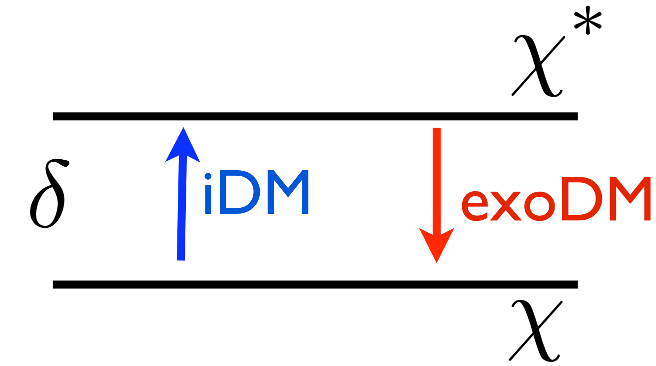

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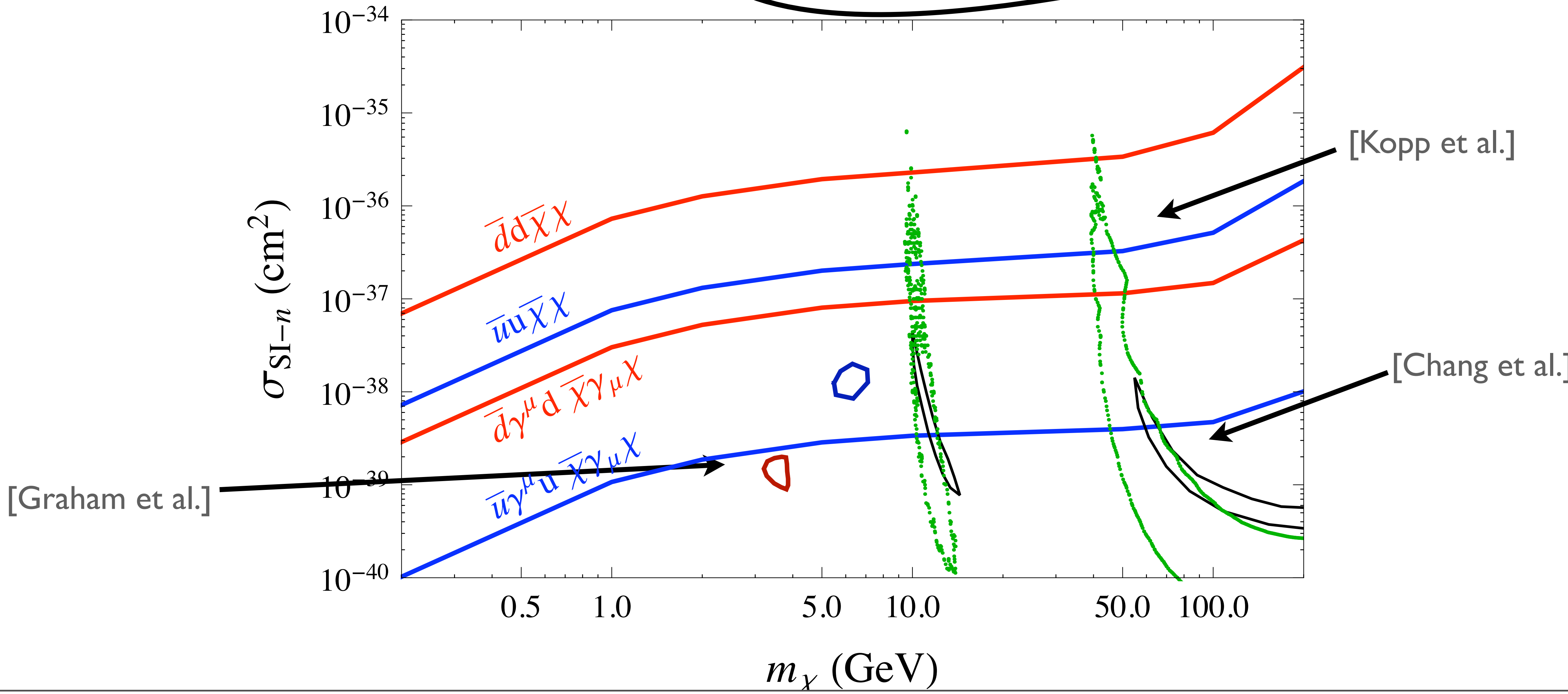

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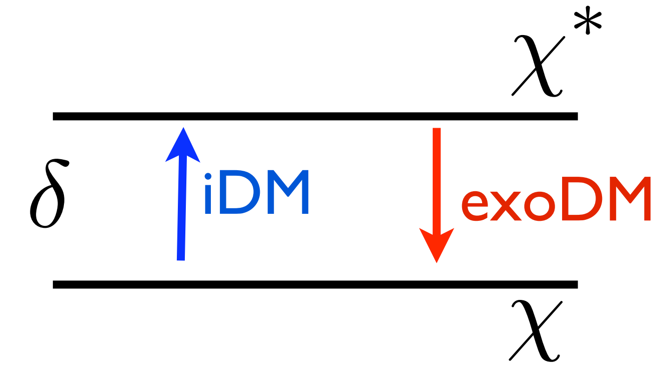

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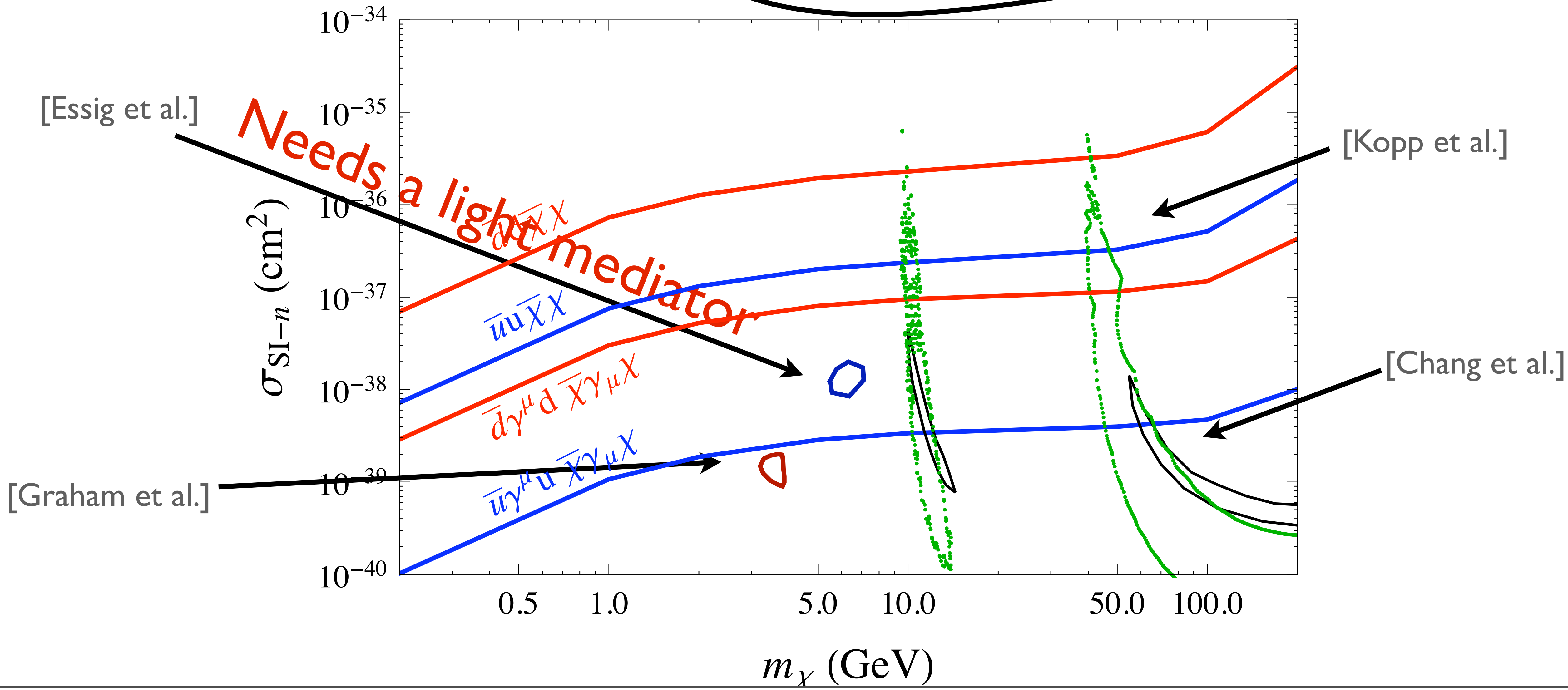
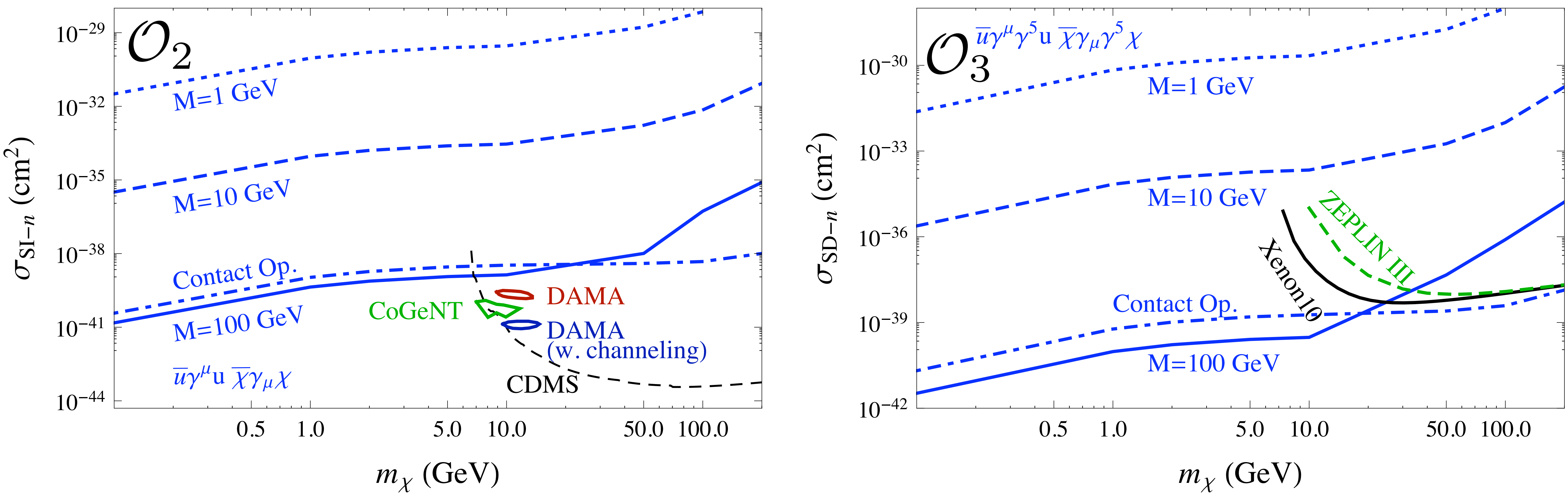


Light mediators

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

Direct detection wins

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



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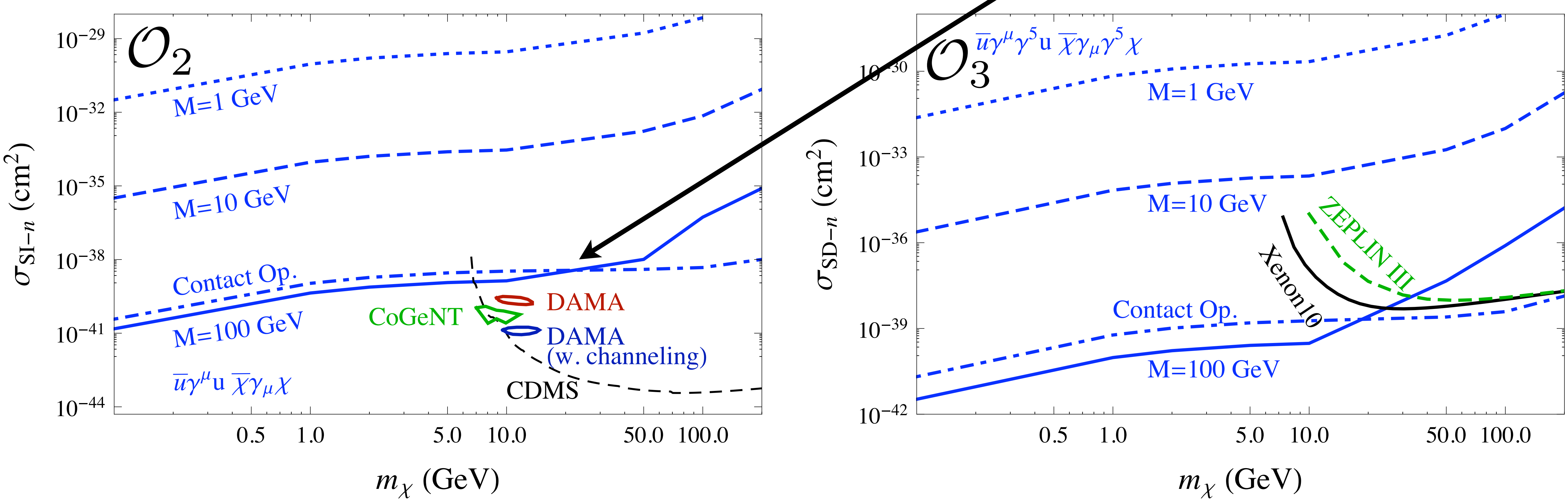
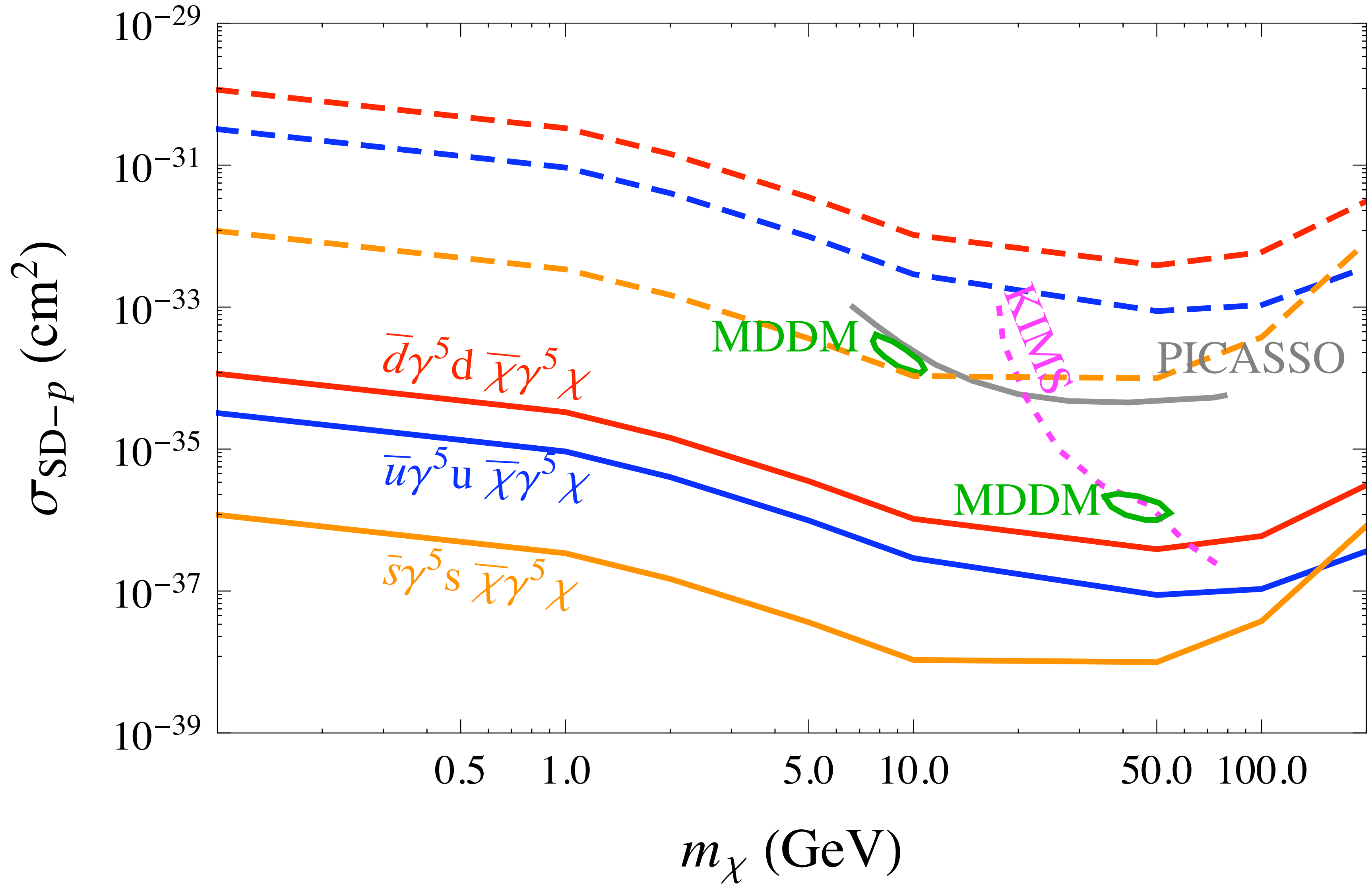


Momentum dependent

$$\mathcal{O}_4^{Nq} = -i\, C_q^N \frac{\left(\bar{N}\gamma_5 N\right)\left(\bar{\chi}\gamma_5\chi\right)}{\Lambda^2}$$

$$\frac{d\sigma_4^{Nq}}{d\cos\theta} = \frac{1}{32\pi\Lambda^4}\frac{q^4}{(m_\chi + m_N)^2}\left(C_q^N\right)^2 ,$$

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



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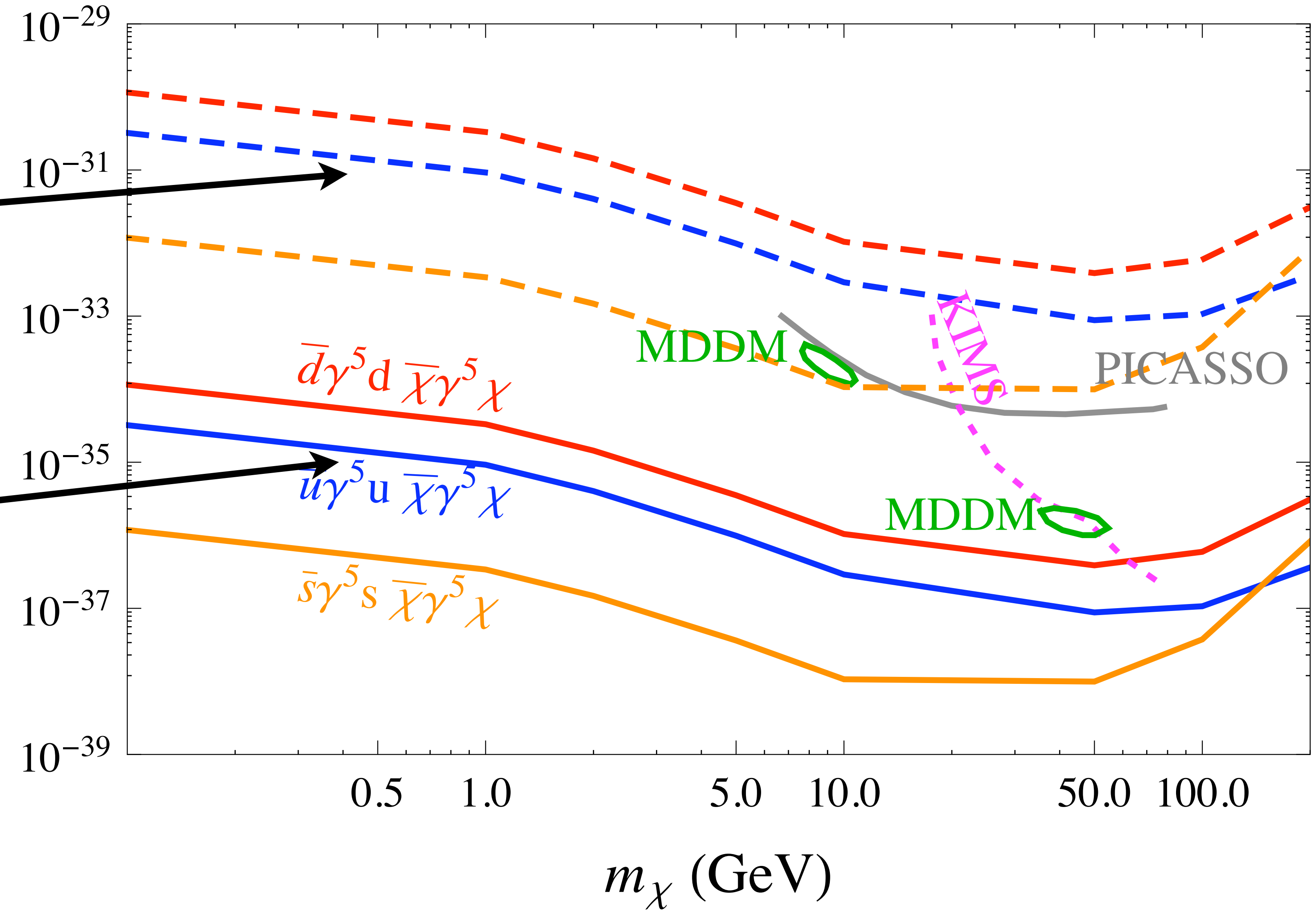
$$C_s^p = -4.3, \quad C_s^n = -0.67\,.$$

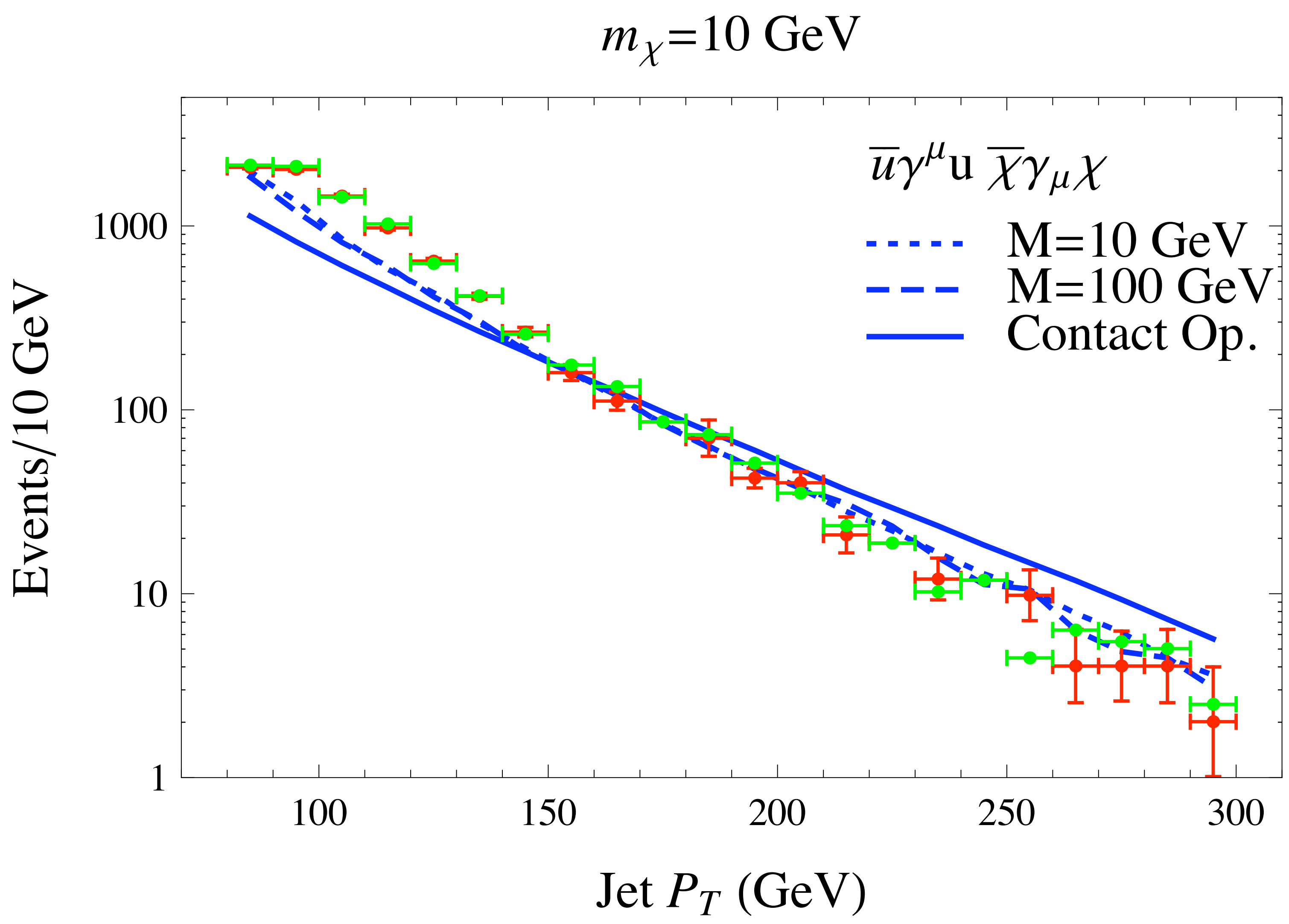
M=1GeV

M=10 GeV



Improvements?

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



Use shape information, limited by theory

Tevatron reach limited to ~300 GeV

Improvements?

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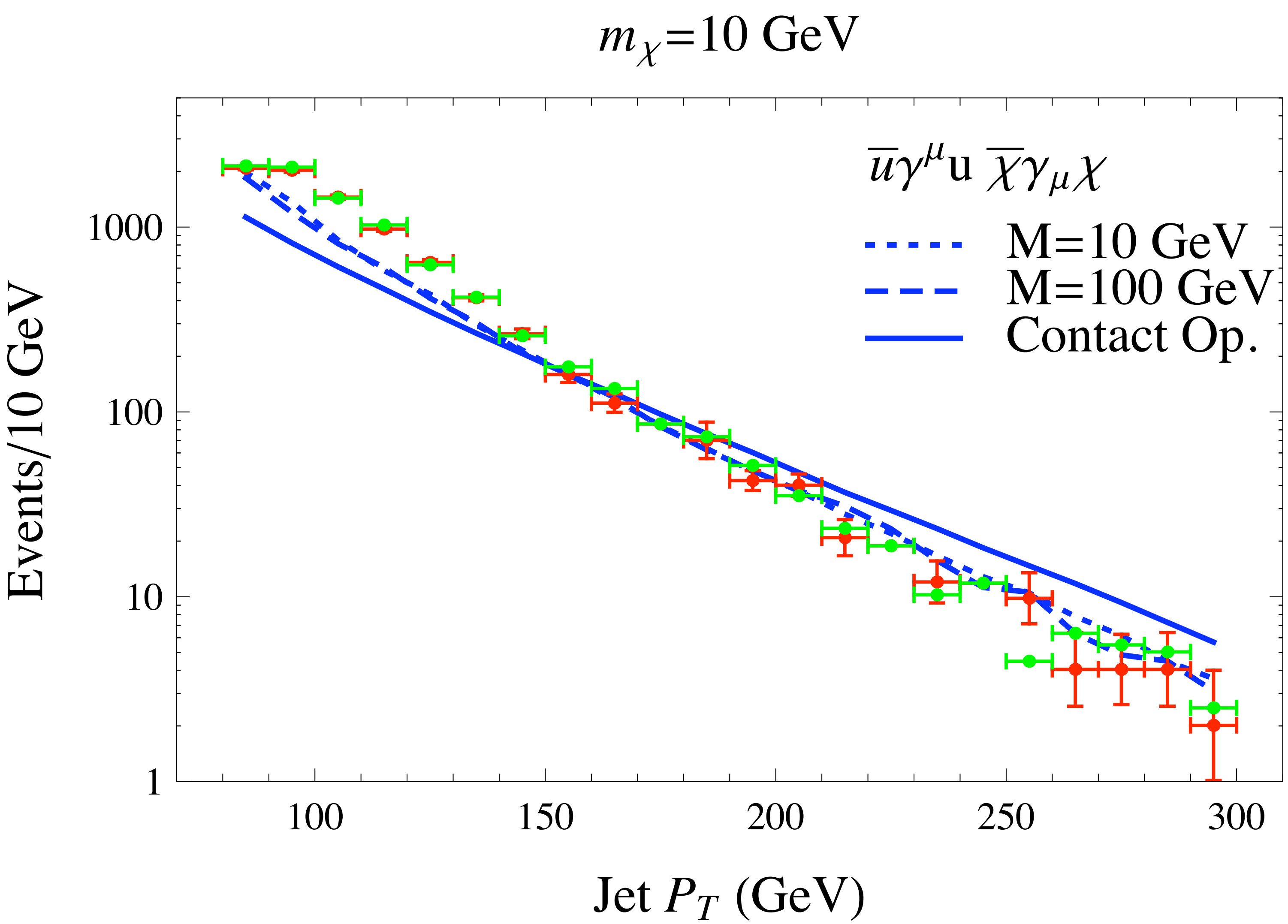
Mono-photon could also be done



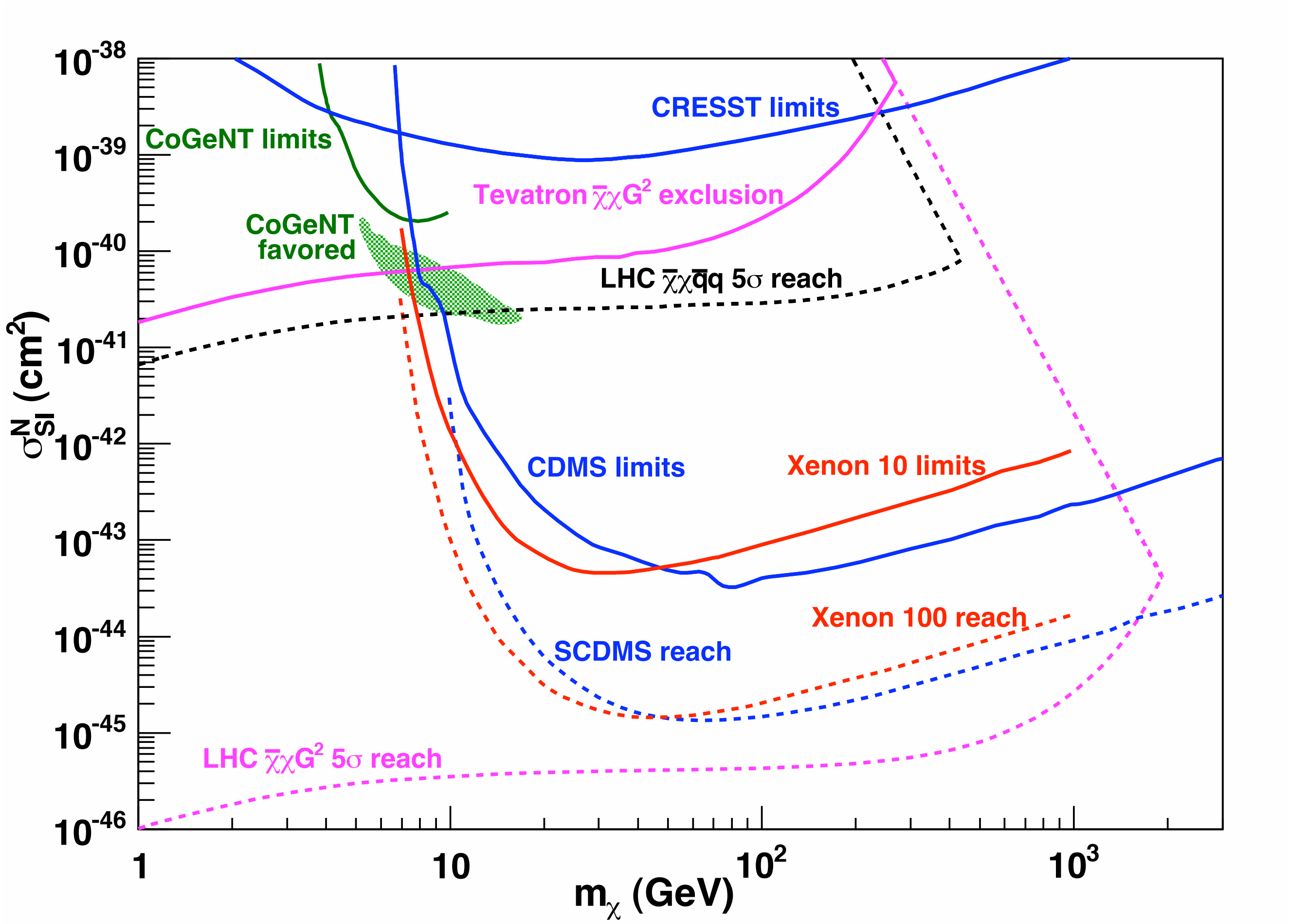
Use shape information, limited by theory

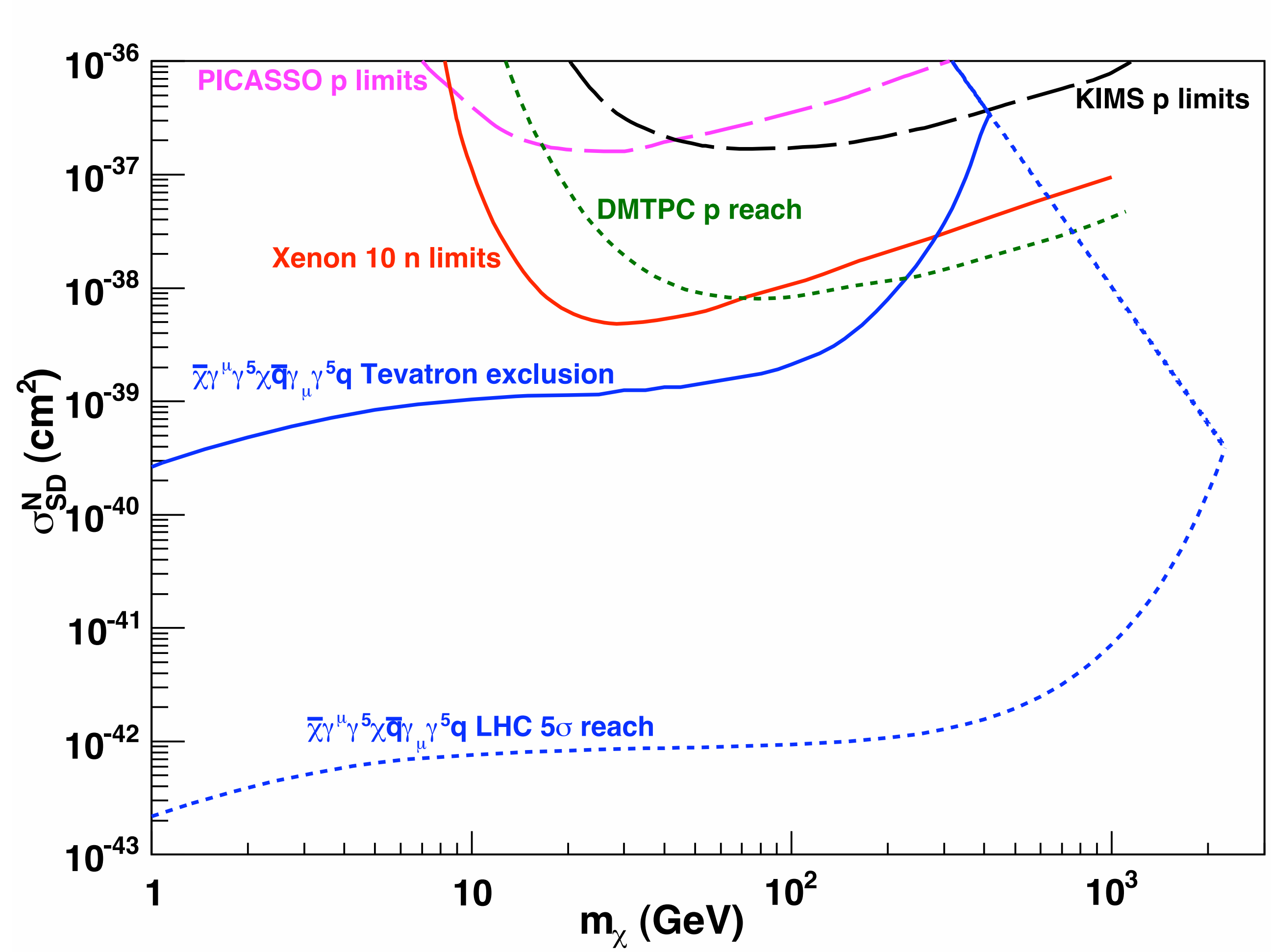
Recently CDF + Bai, Harnik, PJF have started a "real" analysis on full data set!

Tevatron reach limited to ~300 GeV

Improvements

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





LHC

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

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

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

No longer monojet search

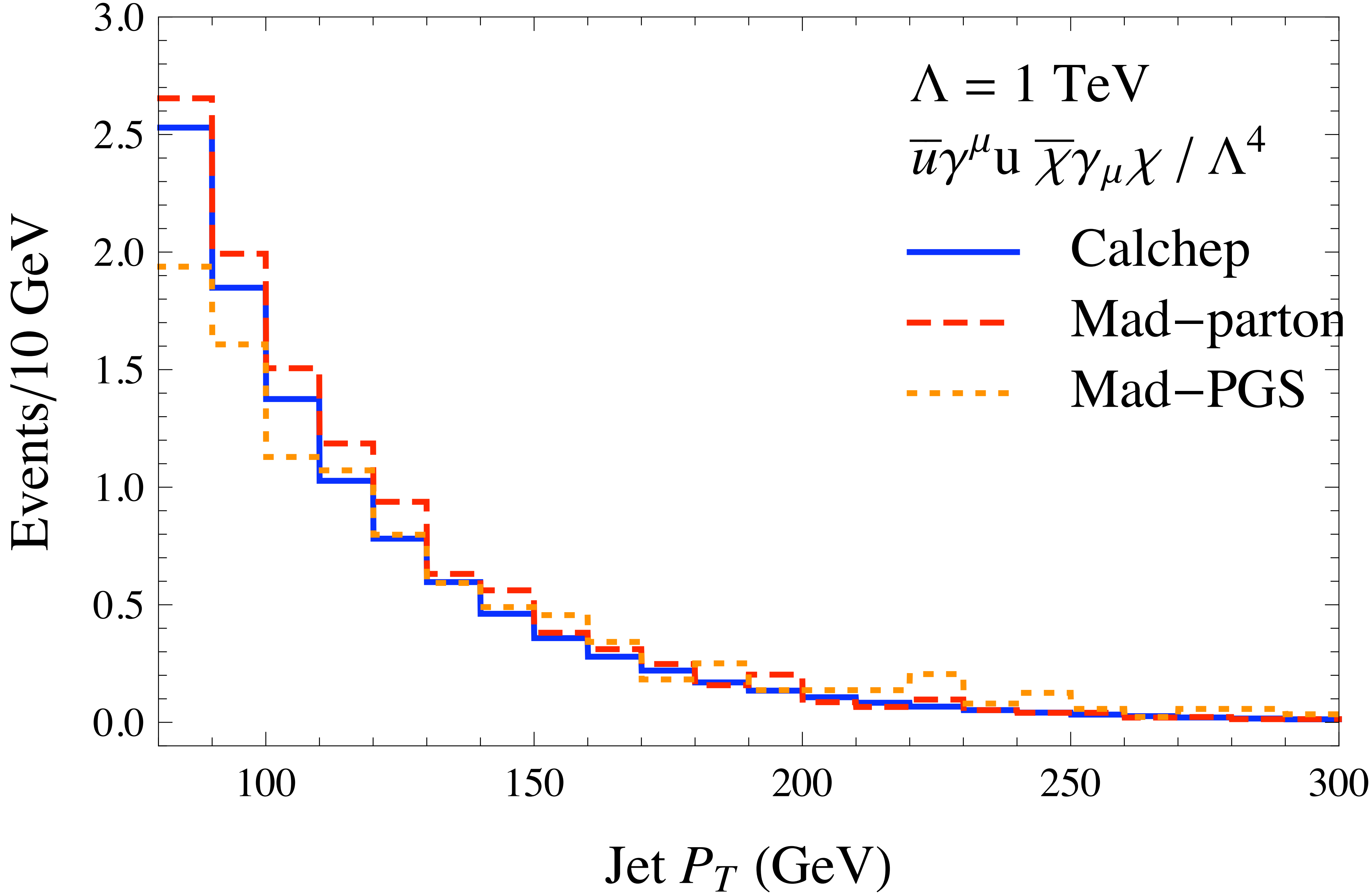
BSM backgrounds?

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, reduce theory errors,...
- 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

Backup Slides



$\Lambda = 1$ TeV
$\bar{u}\gamma^{\mu}u\ \bar{\chi}\gamma_{\mu}\chi\ /\ \Lambda^4$
Calchep
Mad−parton
Mad−PGS
Events/10 GeV
Jet P_T (GeV)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
100
150
200
250
300

ADD analysis

Phys.Rev.Lett.101:181602,2008

arXiv:0807.3132

Data Selection:

- Central Photon Et > 50 GeV
- Missing Et > 50 GeV
- No jets with Et > 15 GeV
- No tracks with Pt > 10 GeV
- At least 3 low Pt COT tracks

Background Predictions:

CDF RunII Preliminary, 2.0 fb^{-1}		
Channel	$\gamma E_T > 50$ GeV	$\gamma E_T > 90$ GeV
$W \to e \to \gamma$	47.3 ± 5.1	2.6 ± 0.4
$W \to \mu/\tau \to \gamma$	19.1 ± 4.2	1.0 ± 0.2
$W\gamma \to \mu\gamma \to \gamma$	33.1 ± 10.2	1.7 ± 1.2
$W\gamma \to e\gamma \to \gamma$	8.0 ± 3.0	0.8 ± 0.7
$W\gamma \to \tau\gamma \to \gamma$	17.6 ± 1.6	2.5 ± 0.2
$\gamma\gamma \to \gamma$	18.9 ± 2.3	2.3 ± 0.6
cosmics	36.4 ± 2.5	9.8 ± 1.3
$Z\gamma \to \nu\nu\gamma$	99.7 ± 9.5	25.2 ± 2.8
Total	280.1 ± 15.7	46.7 ± 3.0
Data	280	40

- **Optimized Search for LED:**
  - Leading Jet Et > 150 GeV
  - Event Missing Et > 120 GeV
  - Allow 2nd Jet with Et < 60 GeV
  - No 3rd Jet with Et > 20 GeV
- **Results:**
  - Background Predictions:

Background	Number of Events
Z -> nu nu	390 +/- 30
W -> tau nu	187 +/- 14
W -> mu nu	117 +/- 9
W -> e nu	58 +/- 4
Z -> ll	6 +/- 1
QCD	23 +/- 20
Gamma plus Jet	17 +/- 5
Non-Collision	10 +/- 10
Total Predicted	808 +/- 62
Data Observed	809