TBA

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Tim By Approximation

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Hunting for Dark Matter at Colliders

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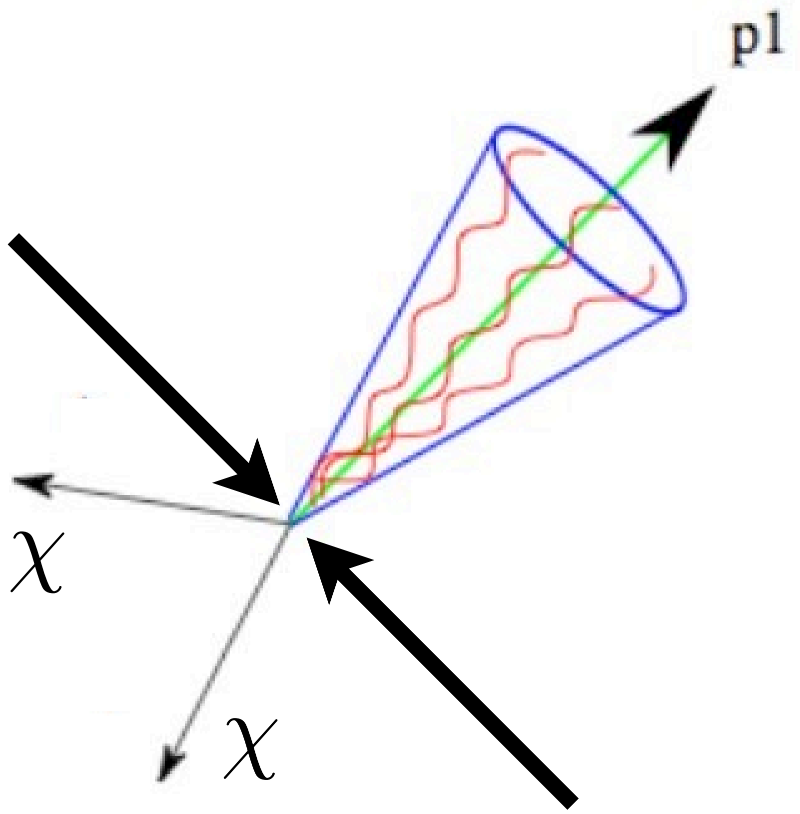
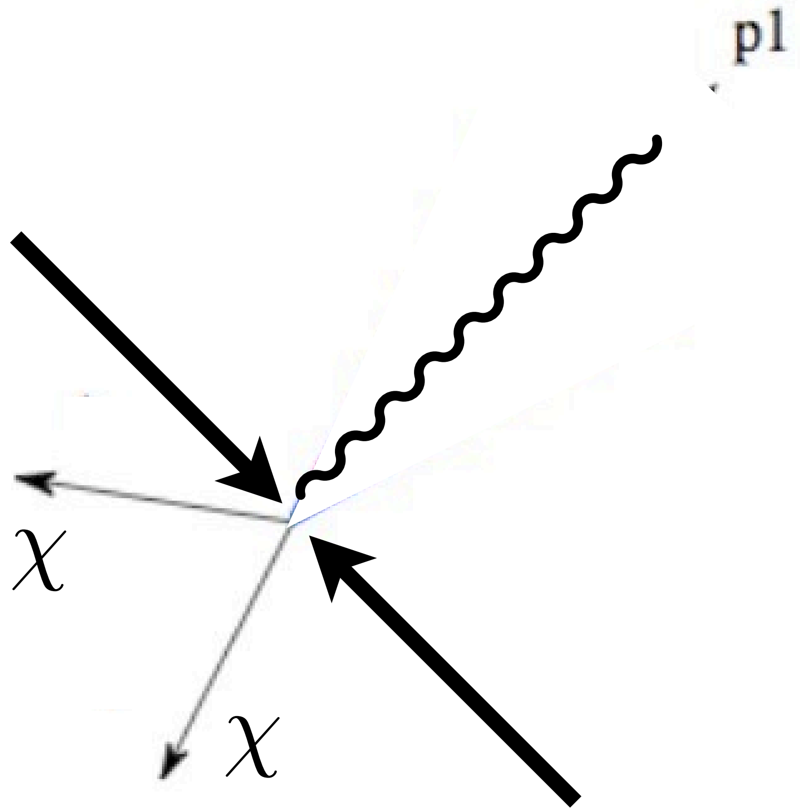


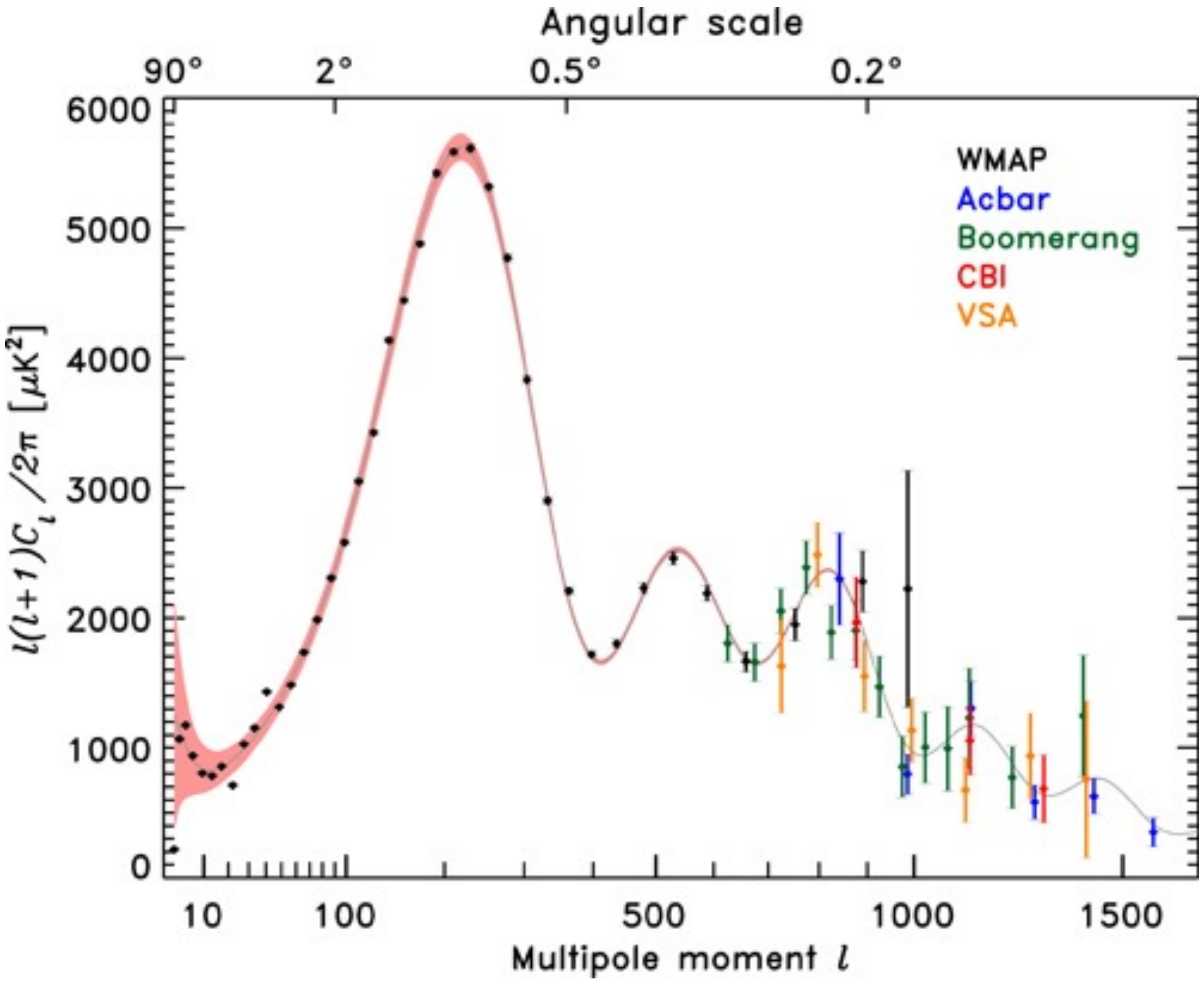
with Yang Bai and Roni Harnik
(arXiv:1005.3797)

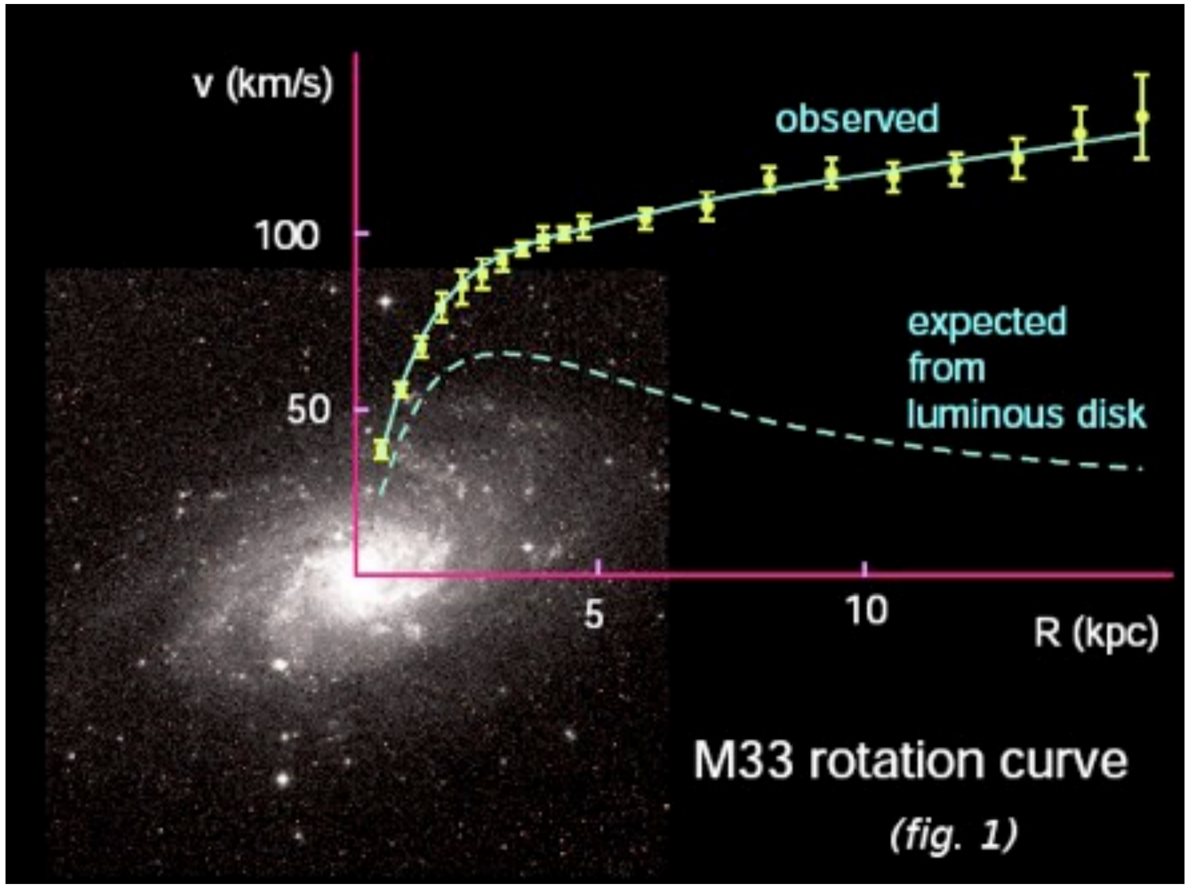


with Roni Harnik, Joachim Kopp and
Yuhsin Tsai
(to appear)

Dark Matter

Lots of evidence for non-baryonic matter:





Cosmological abundance

$$\Omega_{DM} = 0.213$$

Local abundance*

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

Dark Matter

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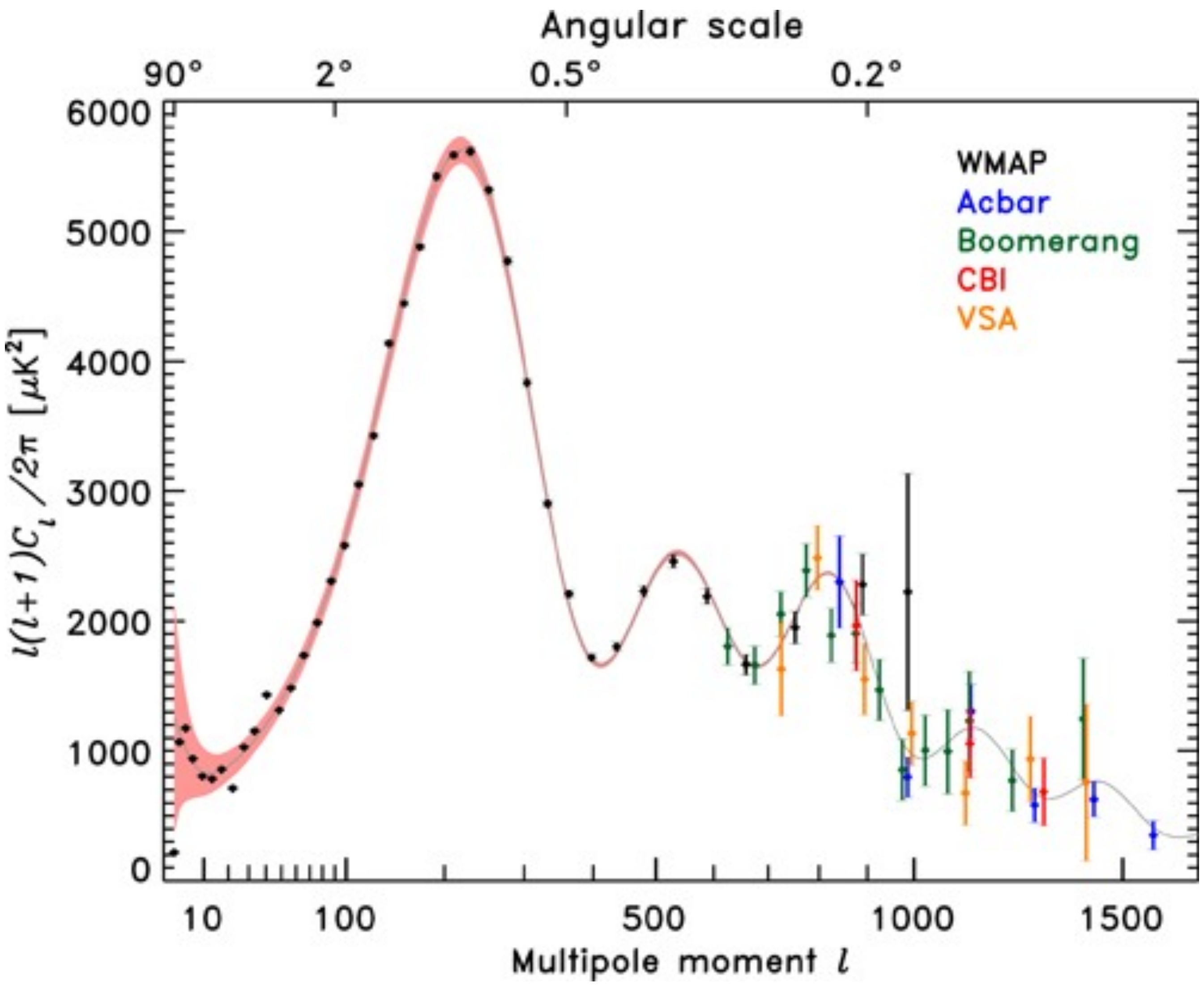

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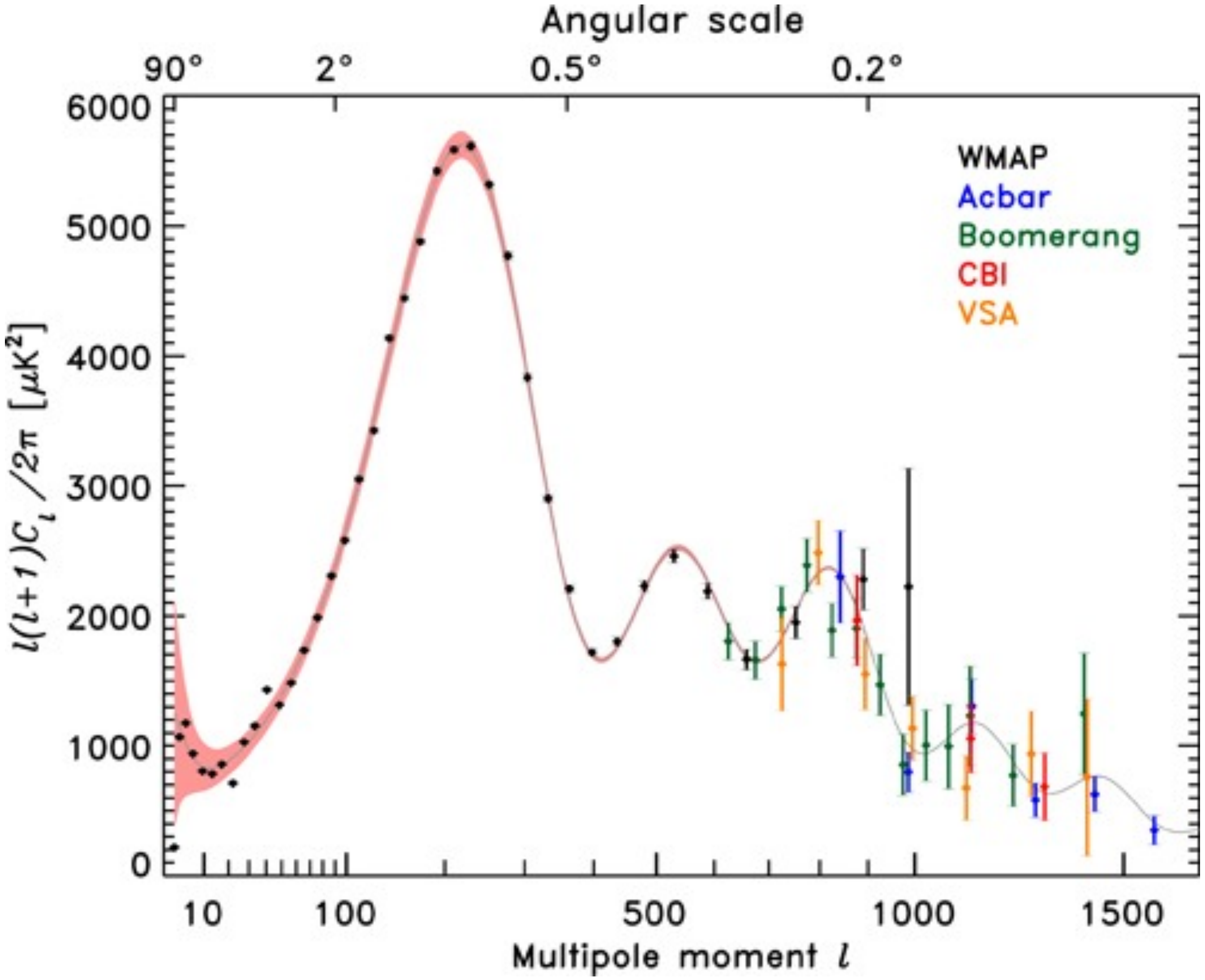


Cosmological abundance

Local abundance*

$$\Omega_{DM} = 0.213$$

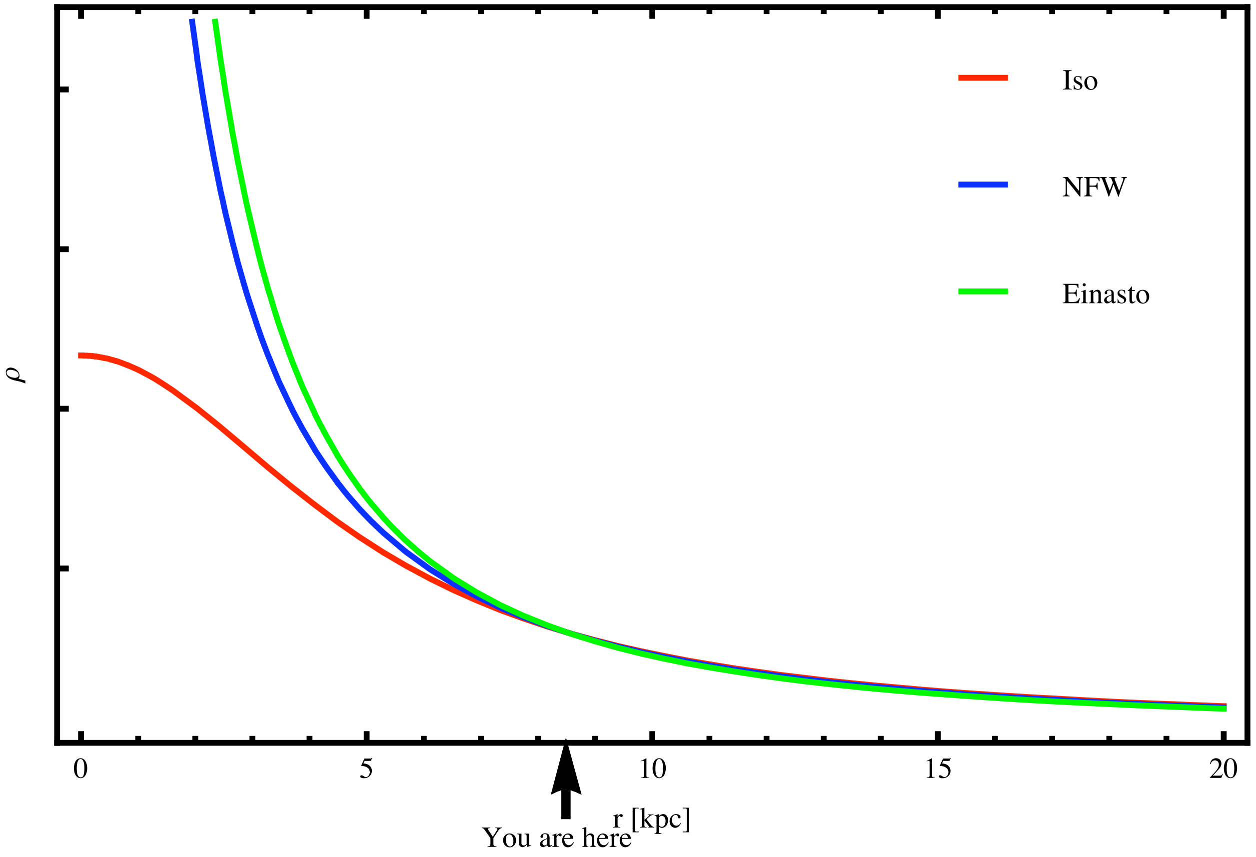
$$\rho_{DM} \sim 0.3 \text{ GeV cm}^{-3}$$

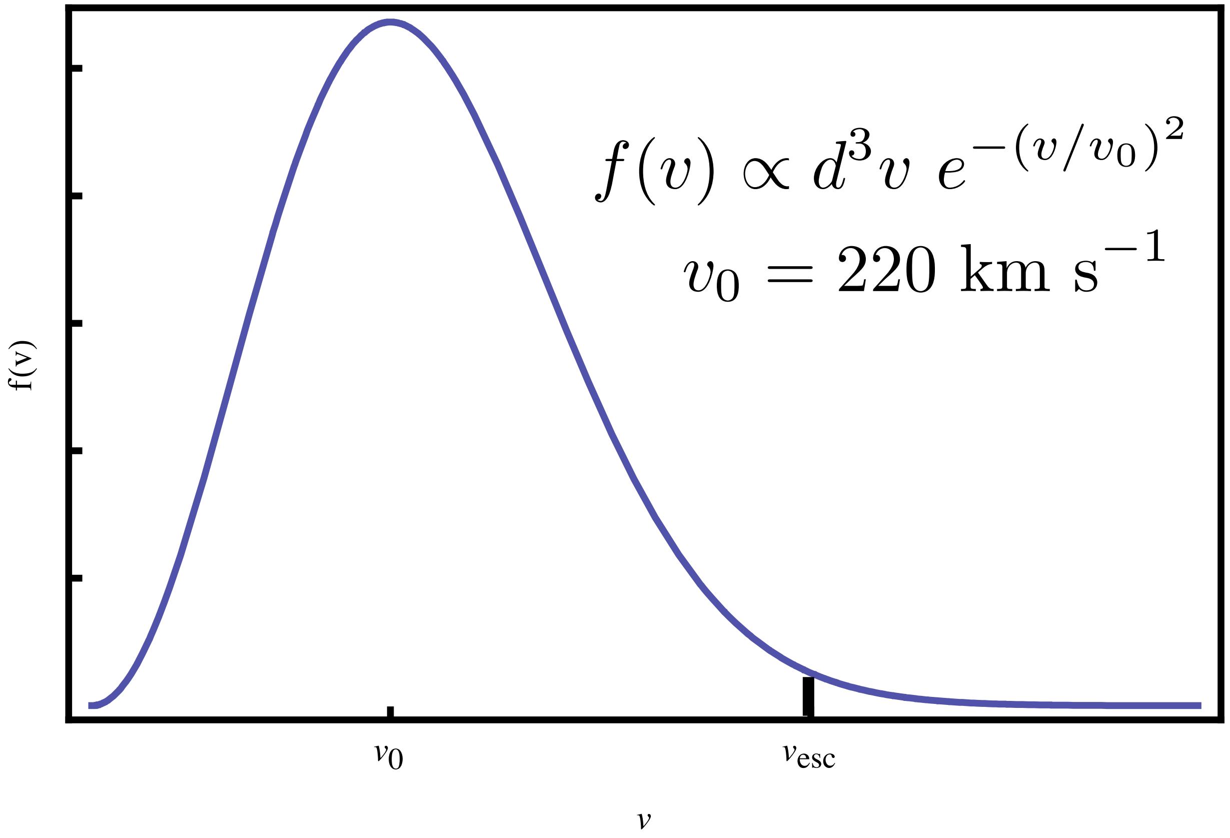
* ± a factor of two

Dark Matter

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

Maxwell-Boltzmann velocity distribution





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

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

Dark Matter

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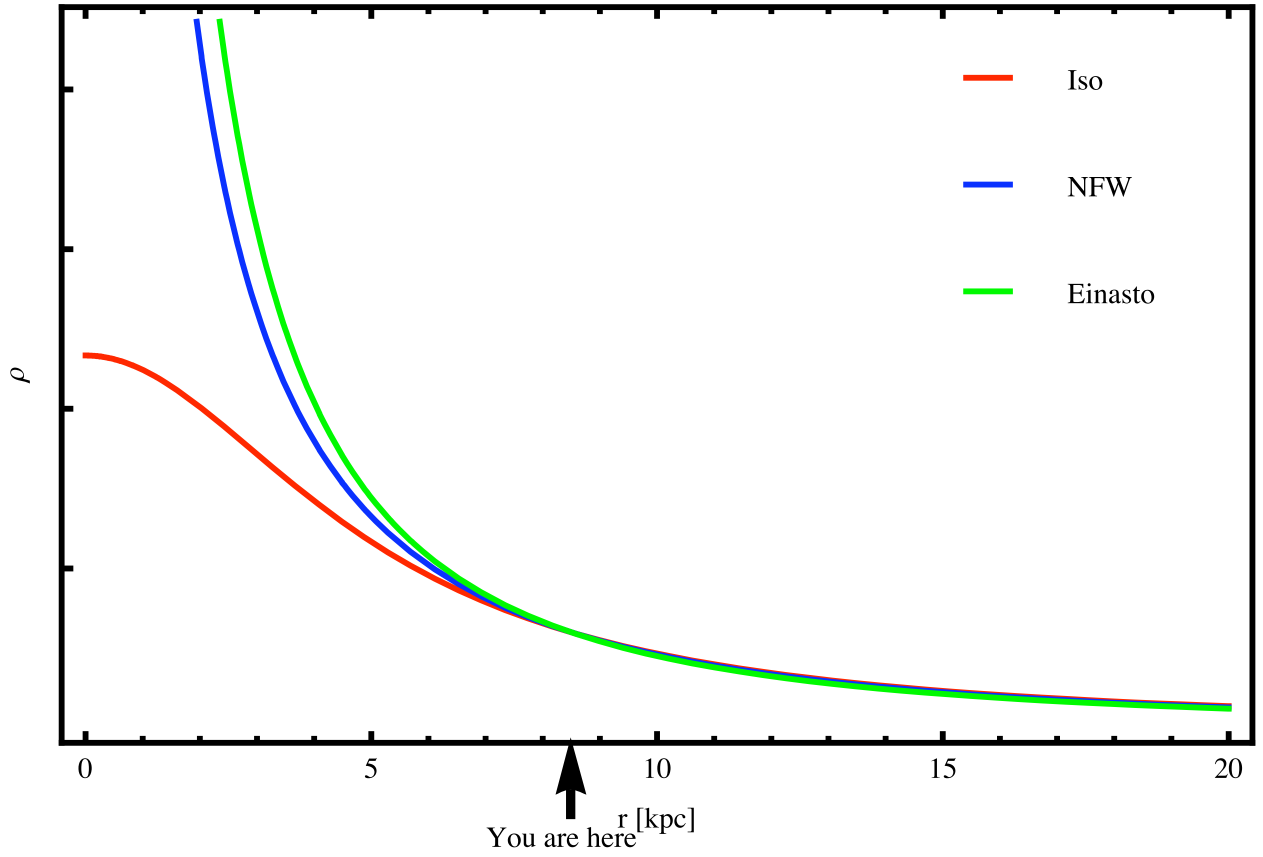

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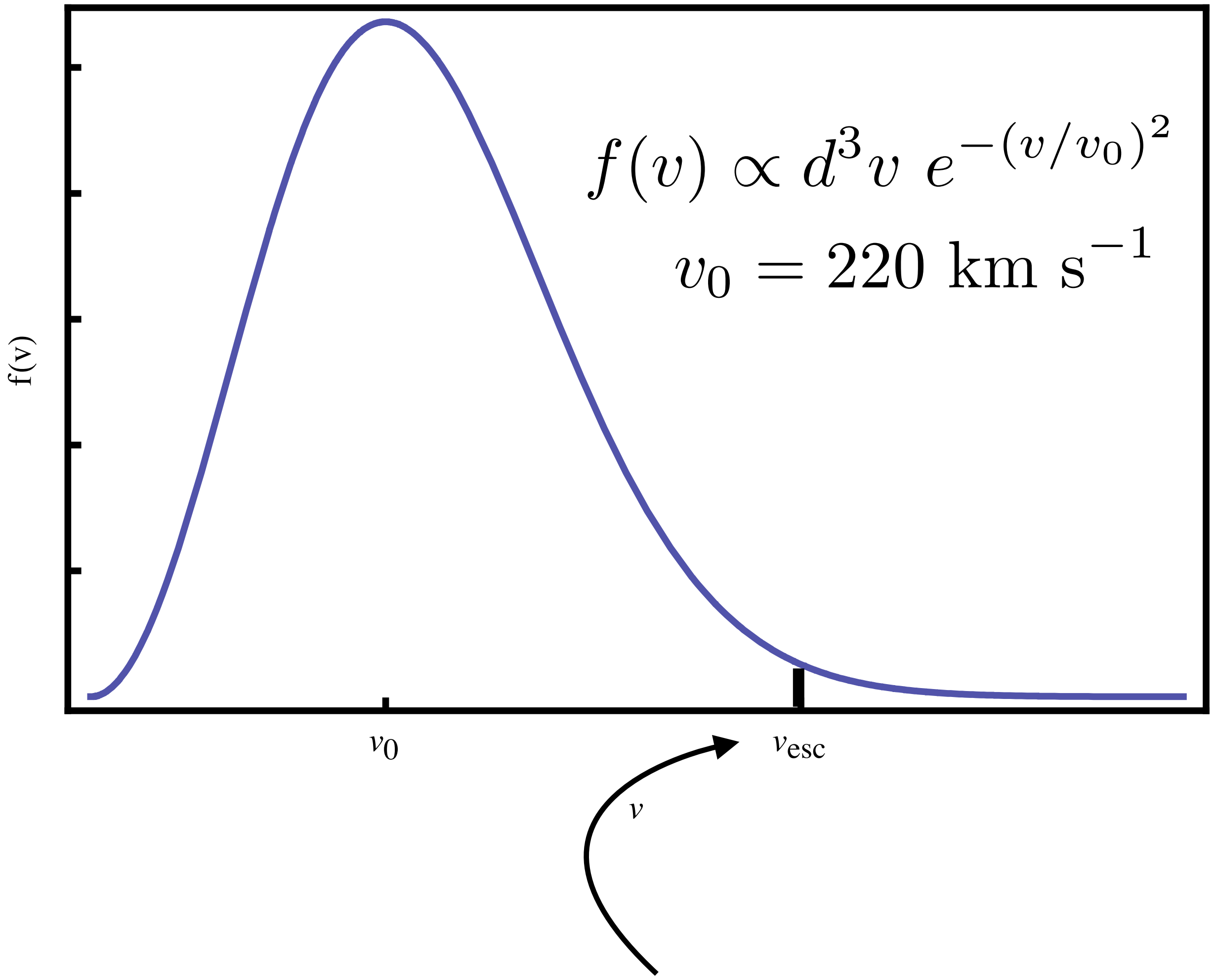

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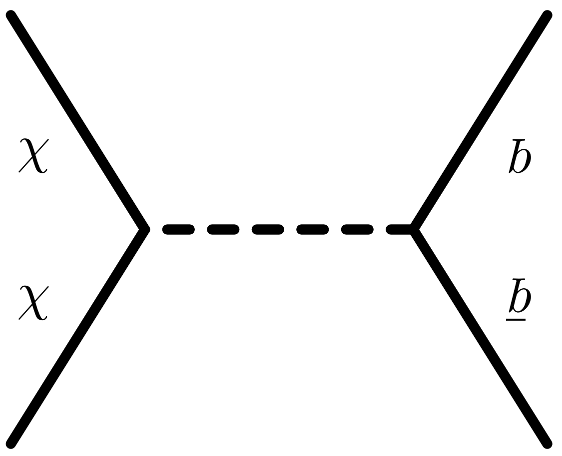
Searching for dark matter

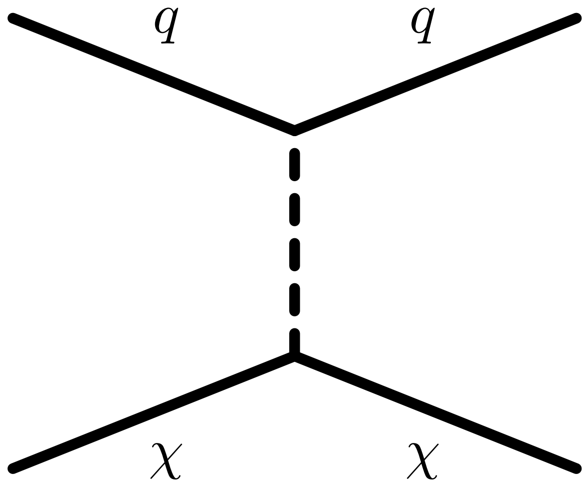
(here, there and everywhere)



Indirect detection

Look up

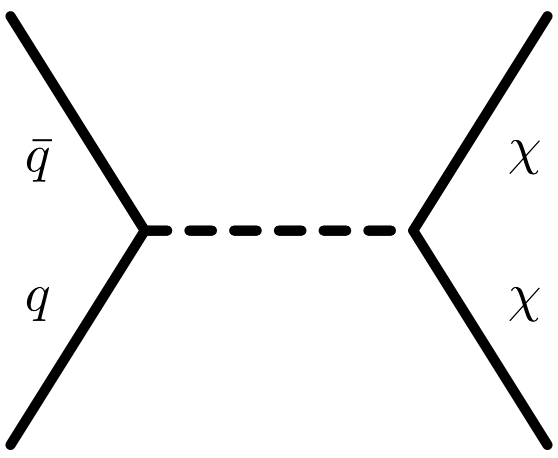
Anti-matter excesses in cosmic rays, photons from centre of galaxy



Direct detection

Look down

Low rate, low energy recoil events in underground labs



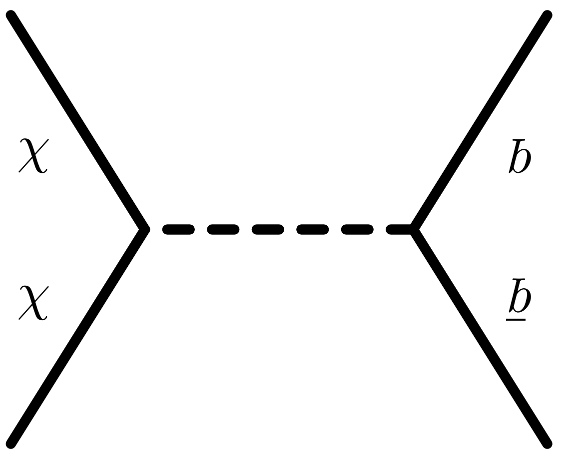
Collider searches

Look small

Missing energy events at colliders

Searching for dark matter

(here, there and everywhere)



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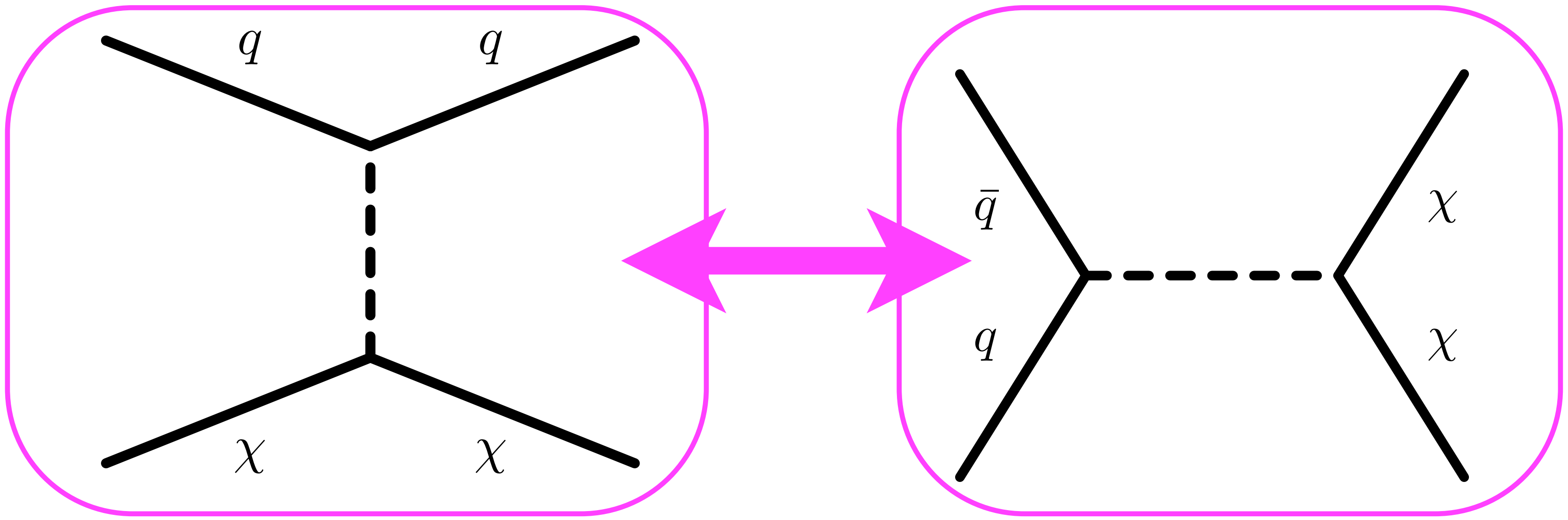

Direct detection

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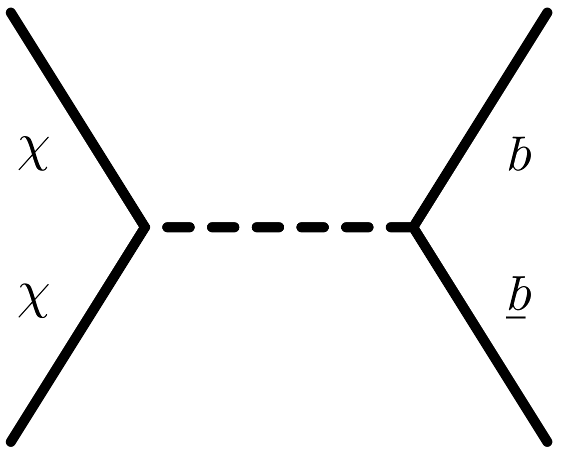

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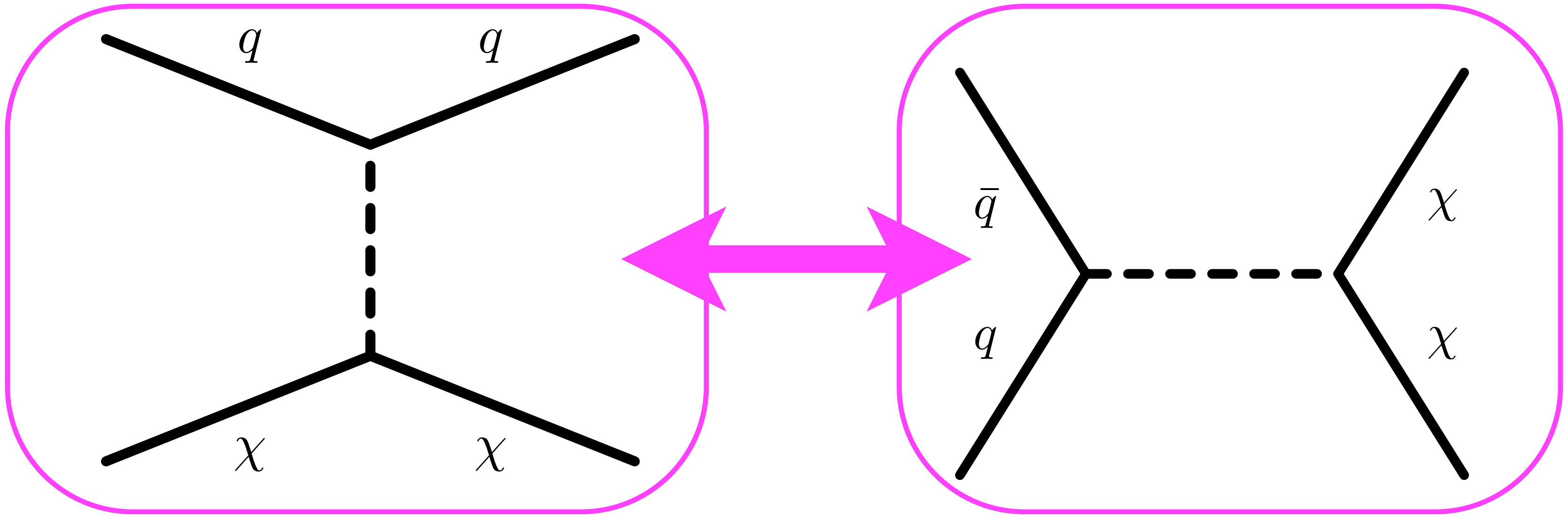


Direct detection

Collider searches

<u>Look up</u>

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

<u>Look down</u>

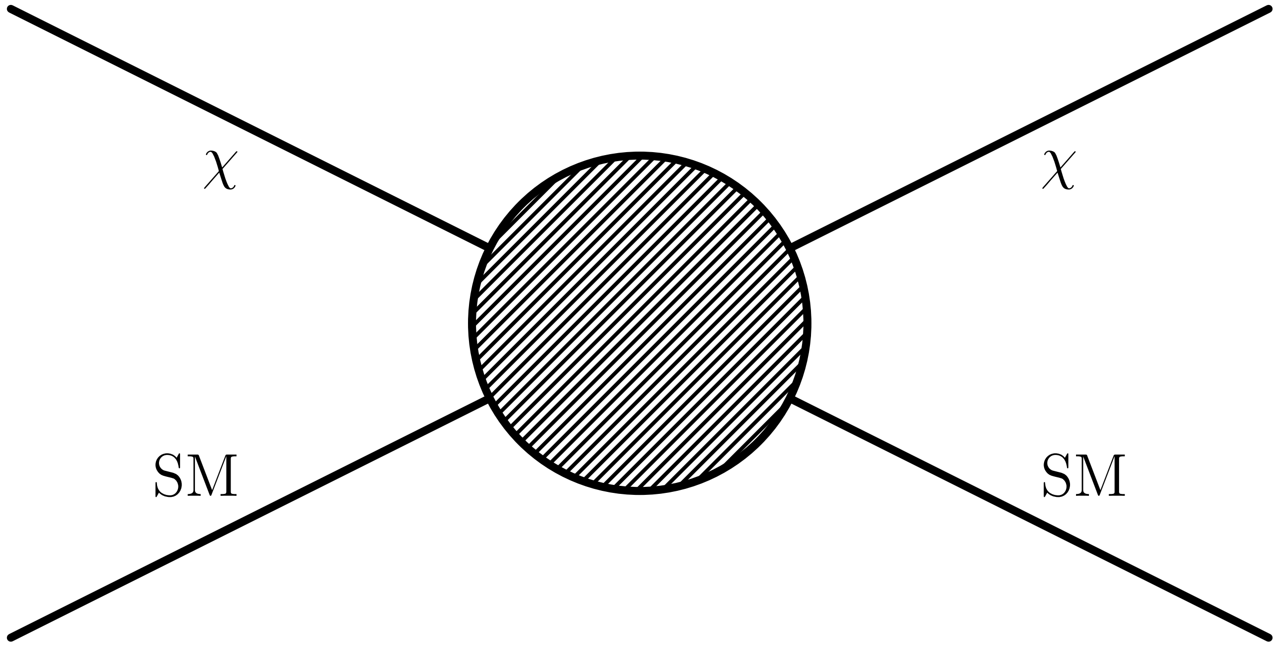
Low rate, low energy recoil events in underground labs

<u>Look small</u>

Missing energy events at colliders

Thermal relic? Predicts x-sec ~1 pb

Direct Detection



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

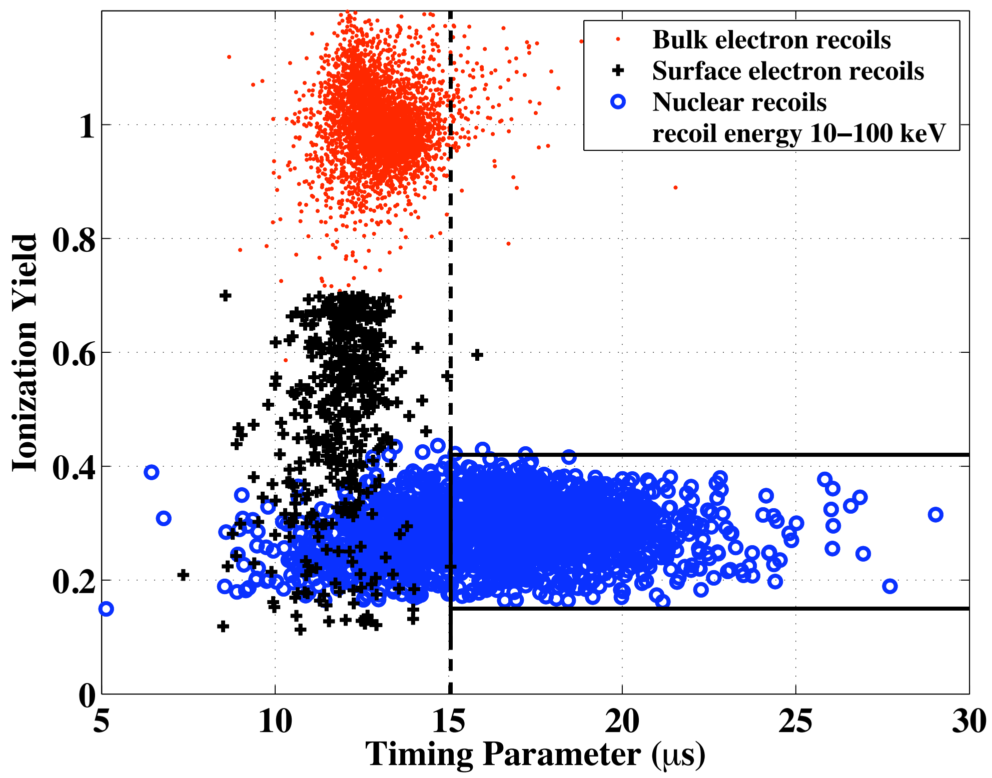
$$\boxed{R \sim N_T \frac{\rho_\chi}{m_\chi}\langle\sigma v\rangle \approx 1\ \mathrm{event/day/kg}}$$

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

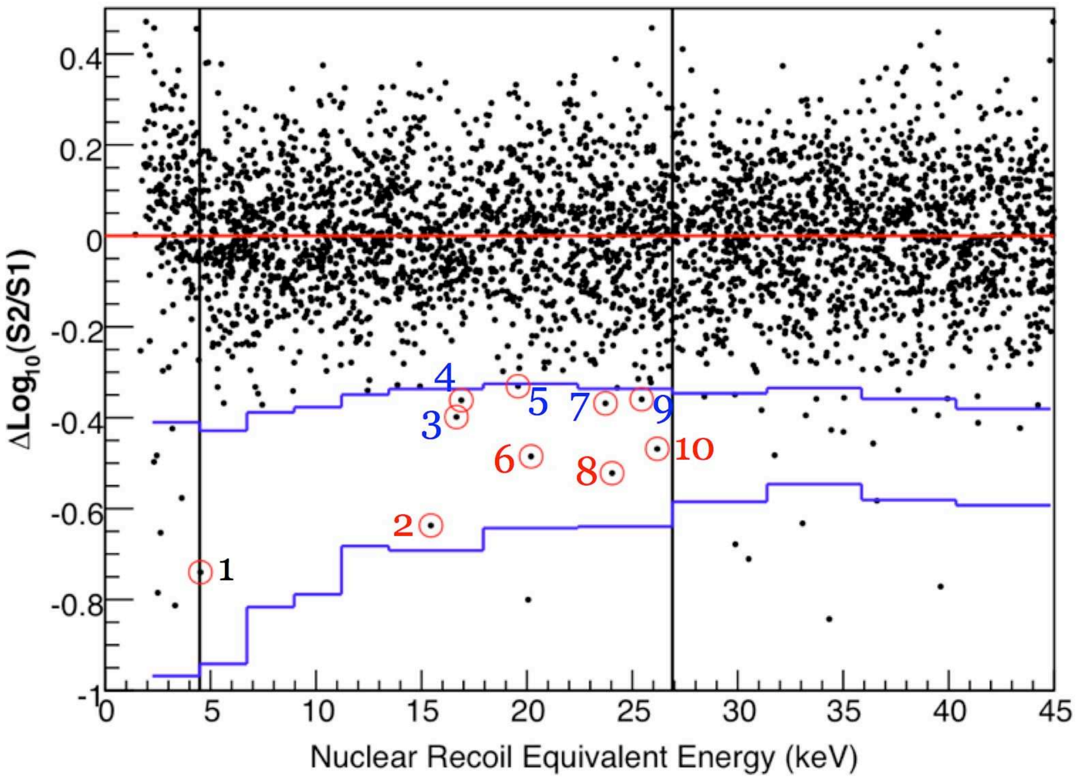
Direct Detection

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



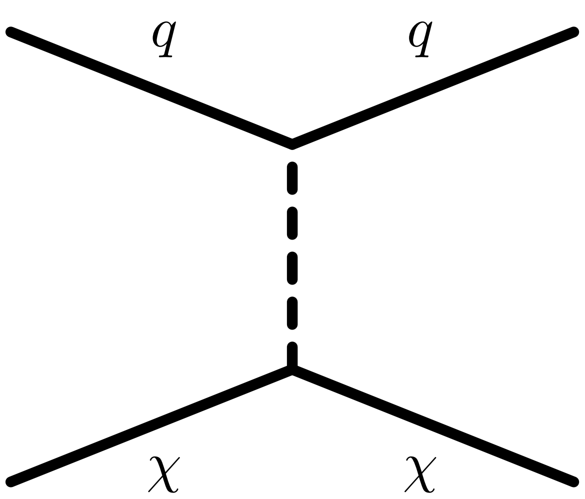
[CDMS collaboration]



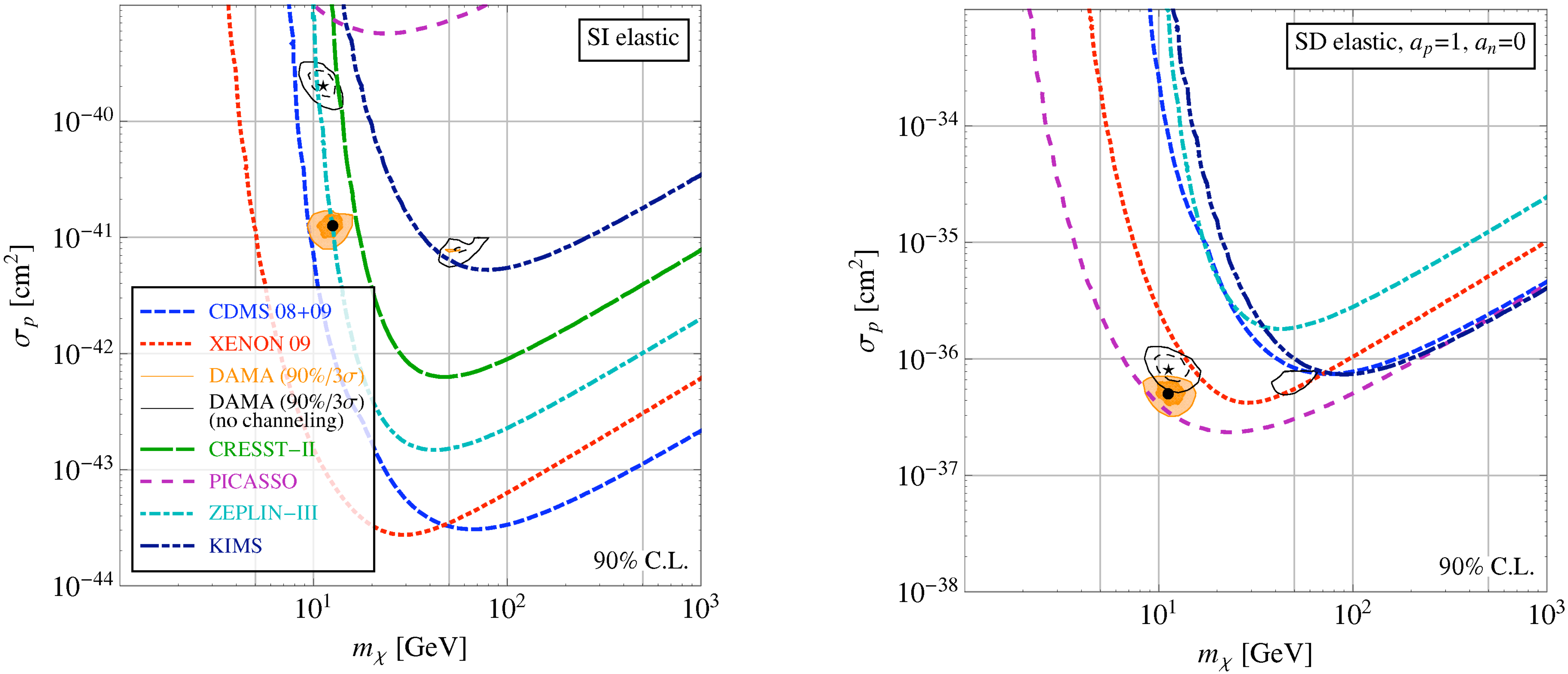
[XENON10 collaboration]

Existing DD bounds

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

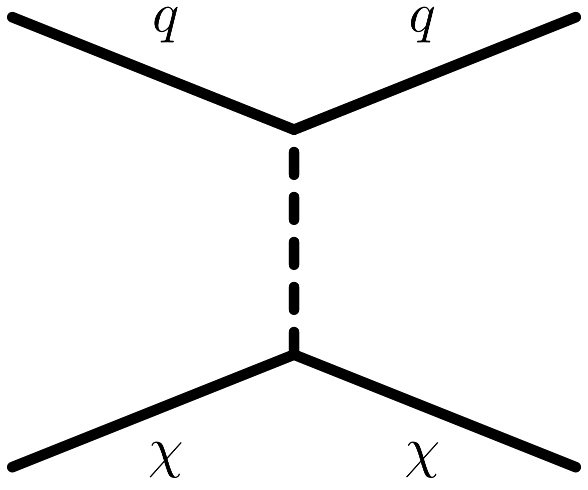


[Kopp, Schwetz and Zupan]

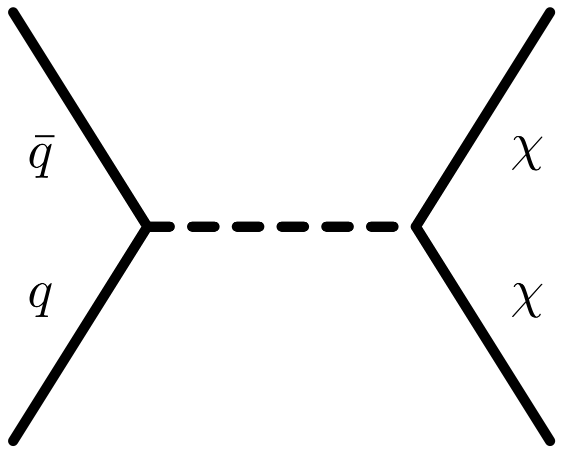


(Assume local abundance is 0.3 GeV/cm^3)

Direct detection vs Collider production



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



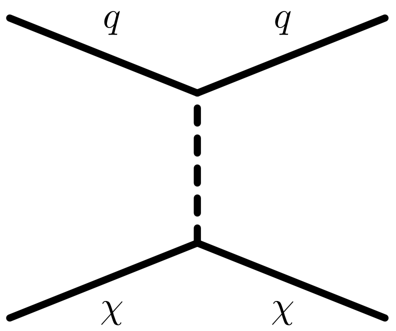
Collider searches $q \sim 10 - 100\ \mathrm{GeV}$

How does one search impact the other?

[Birkedal, Matchev and Perelstein]

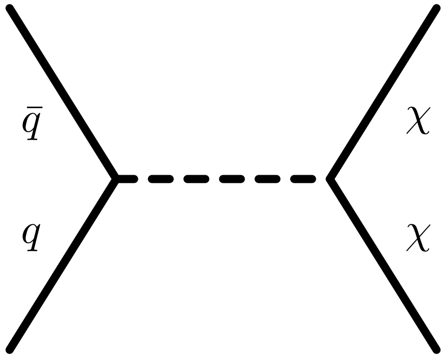
Mediator Mass dependence

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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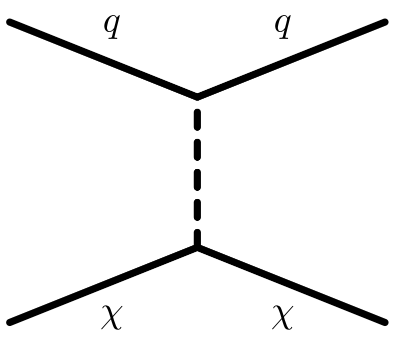

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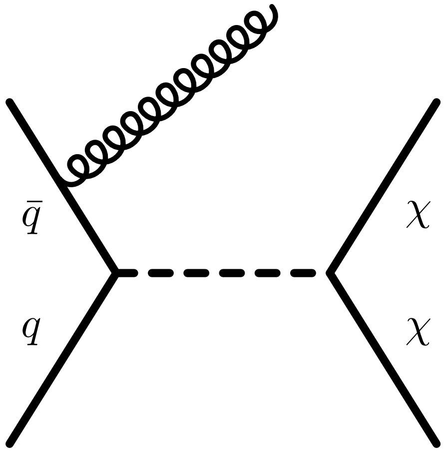

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Consider massive mediator:

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

$$\sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{p_T^2}{M^4}$$

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

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

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

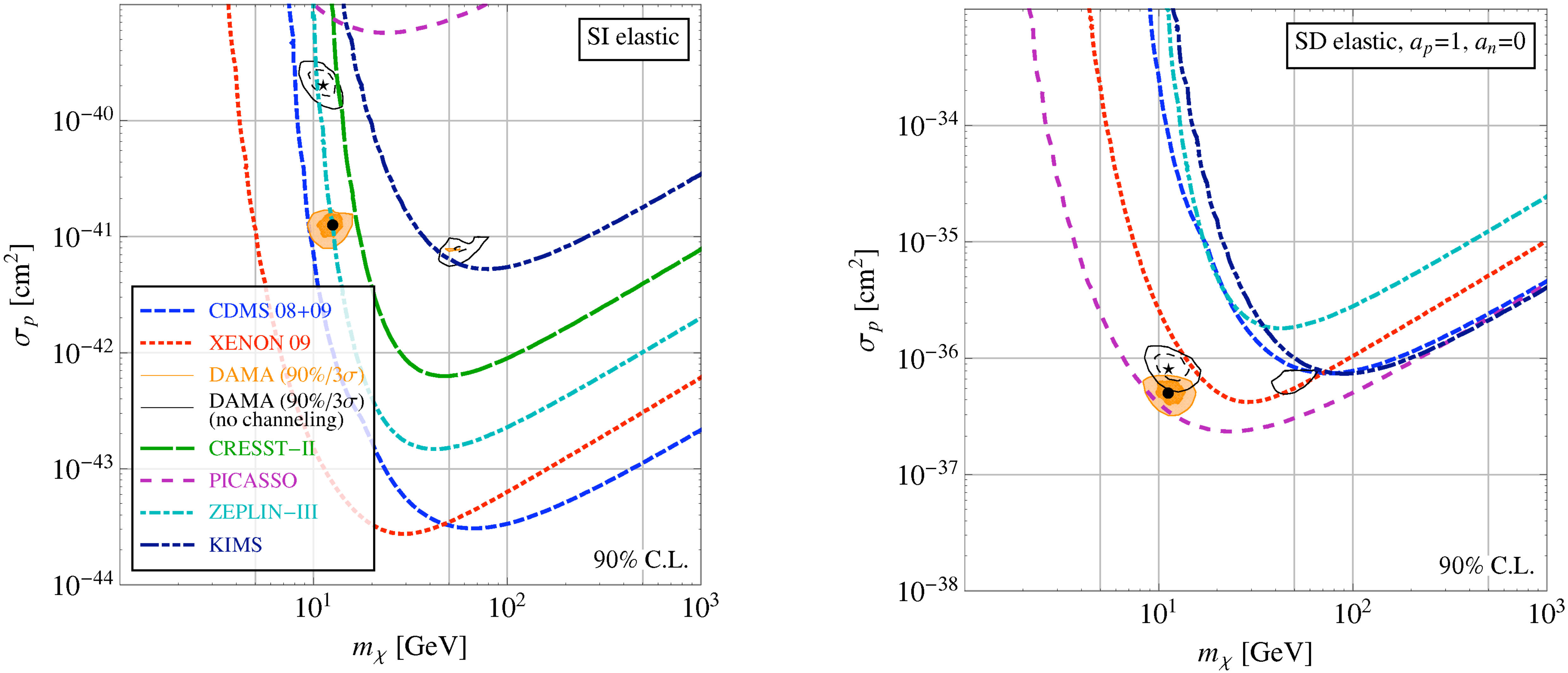
In 1 invfb CDF saw 8449 mono-jet events, expected 8663 $\pm$ 332

$\Rightarrow \quad \sigma_{1j} \lesssim 500\,\mathrm{fb}$

⇙

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

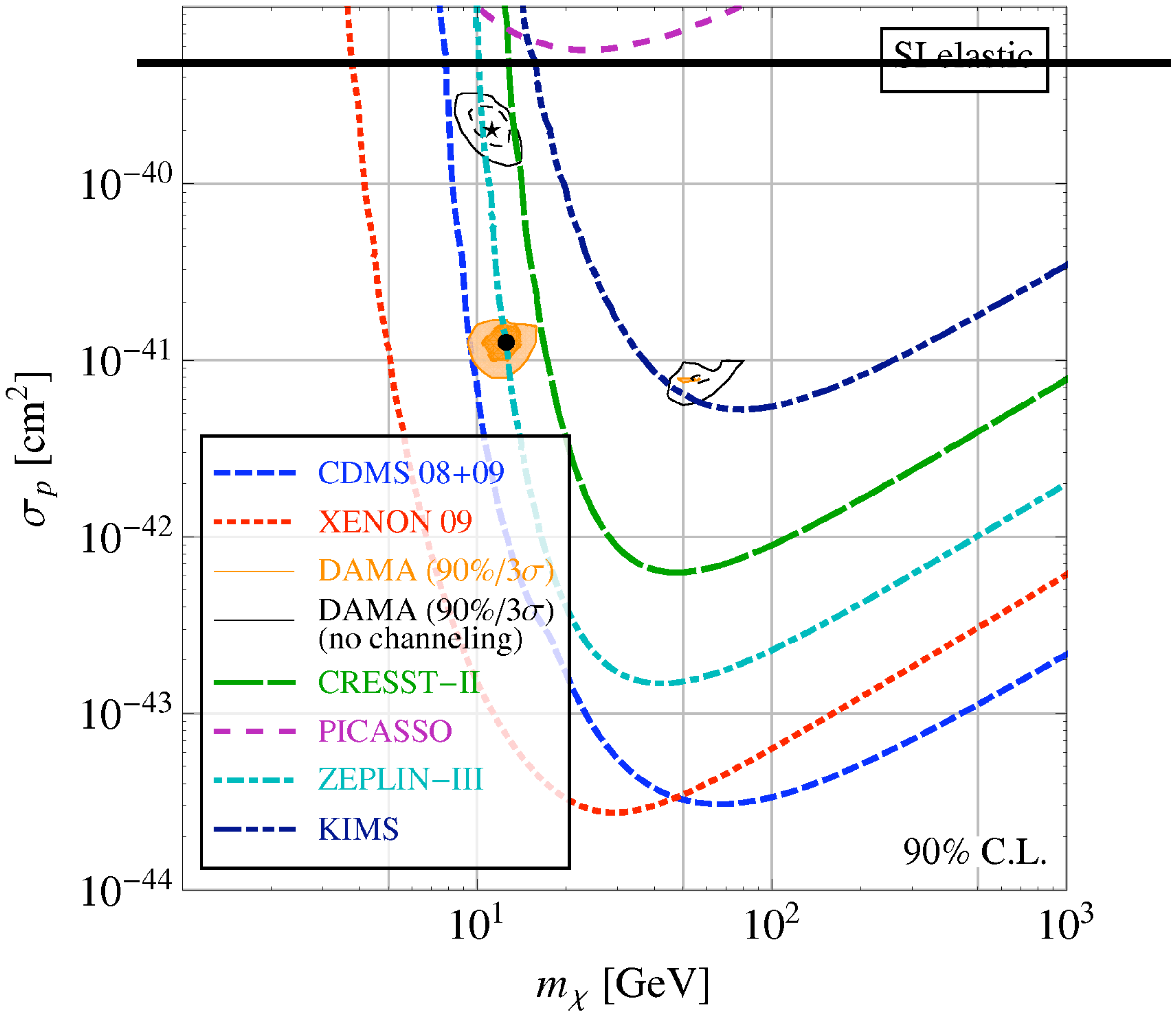
Existing DD bounds

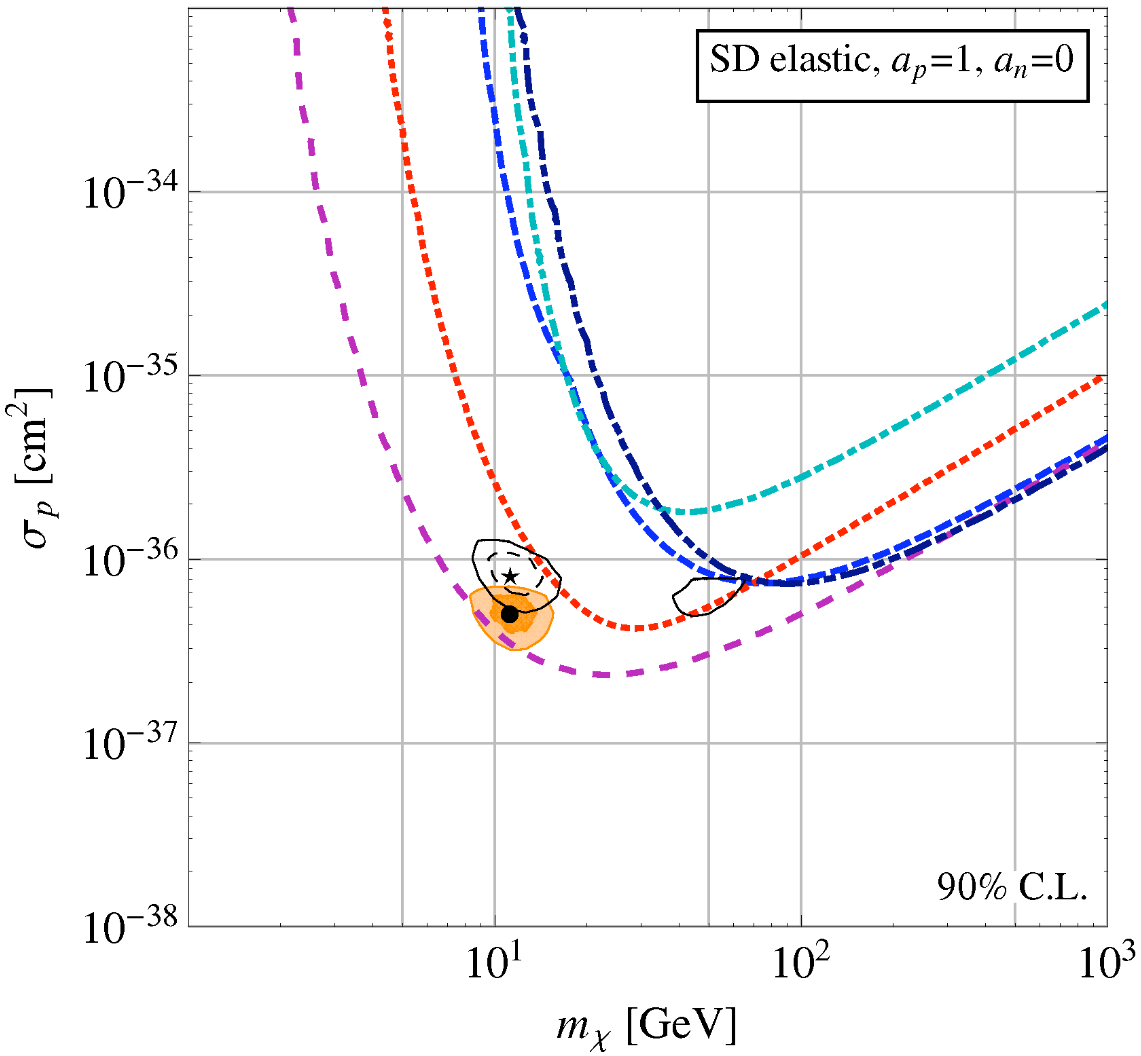


ROI’s

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

Existing DD bounds





ROI's

- Light mass DM
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- Velocity, momentum or spin suppression

Outline

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

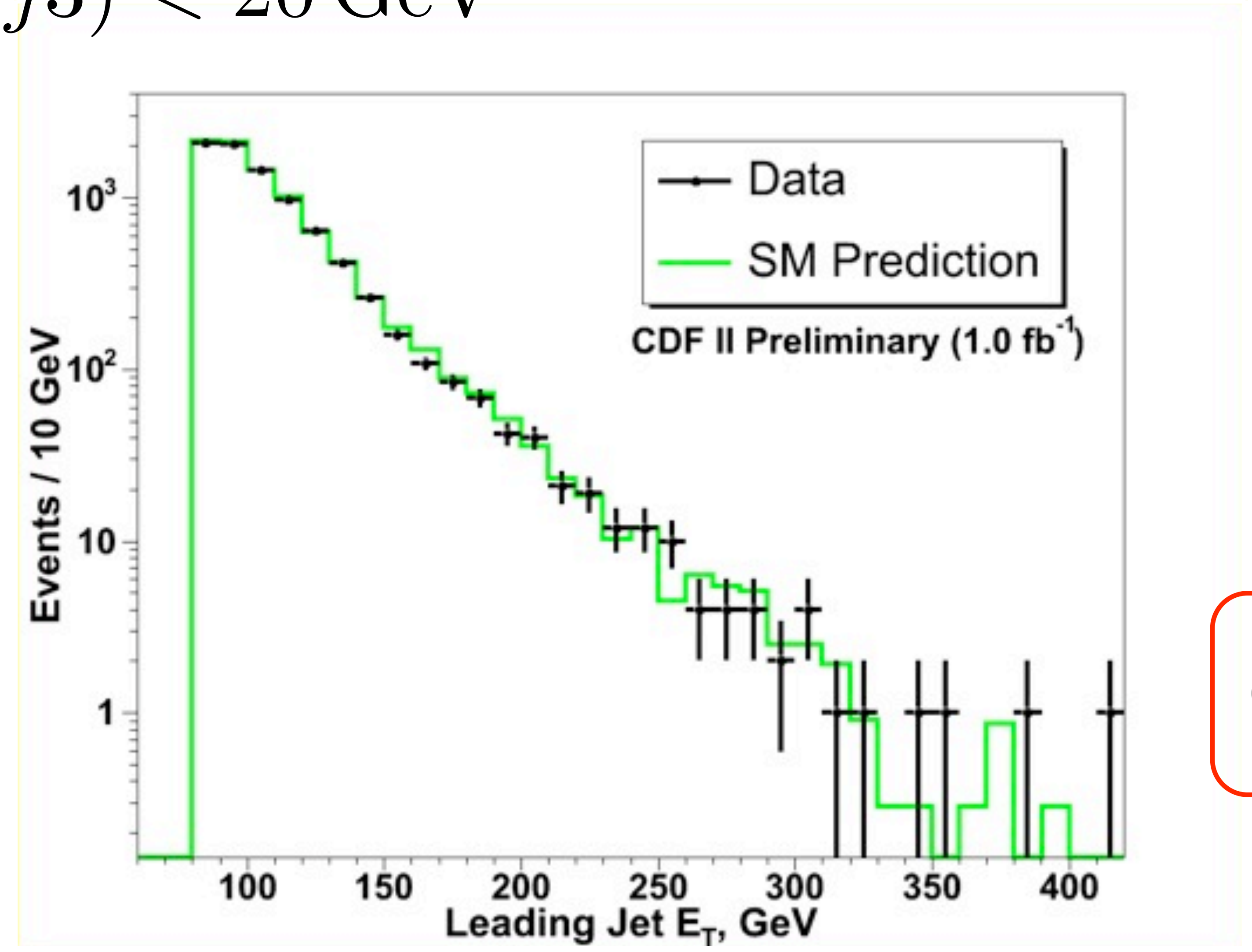
CDF mono-jet search

[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



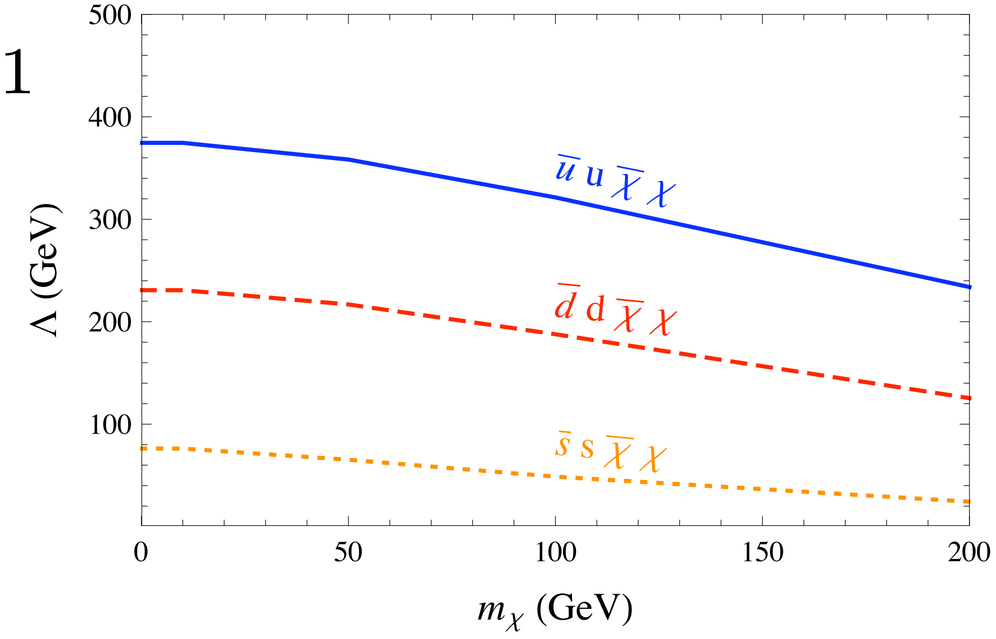
Observed: 8449 events

Bounds on operators

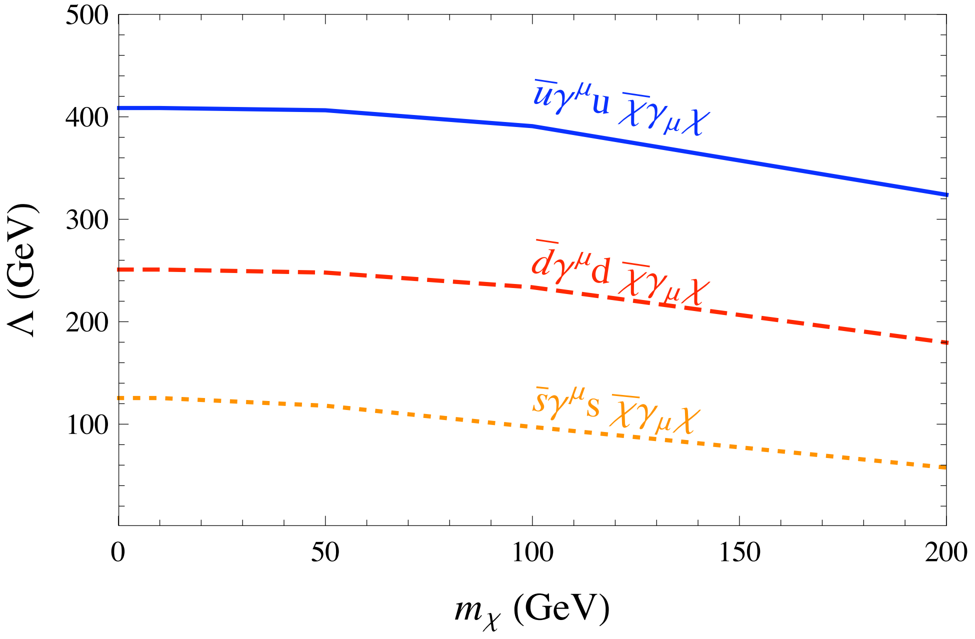
Assume a heavy mediator: $\Lambda = \dfrac{M}{\sqrt{g_\chi g_1}}$

Simulate events in calcHEP, one operator at a time

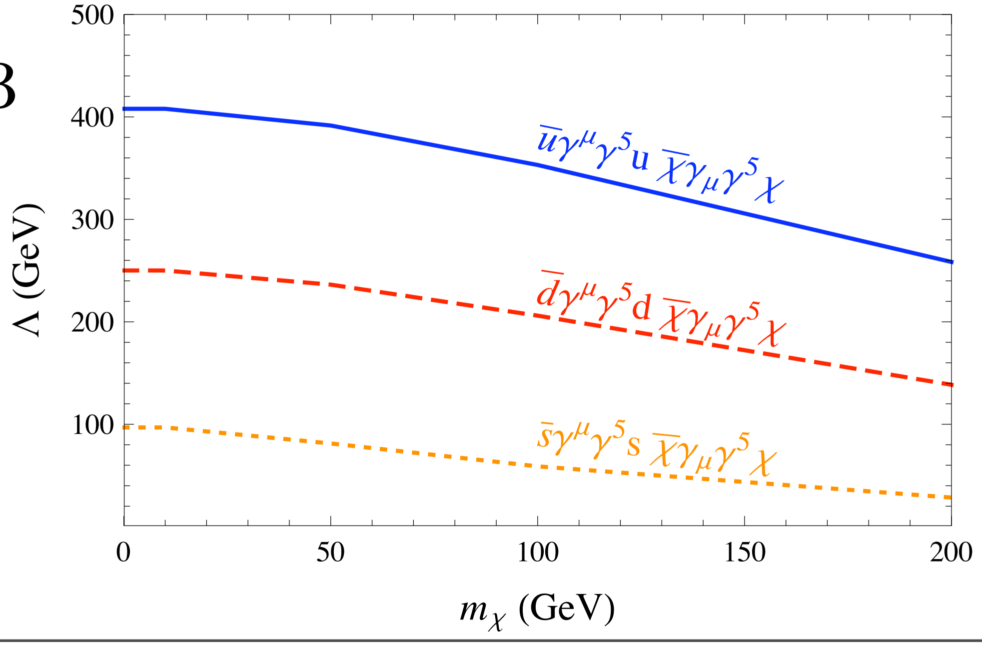
$\mathcal{O}_1$



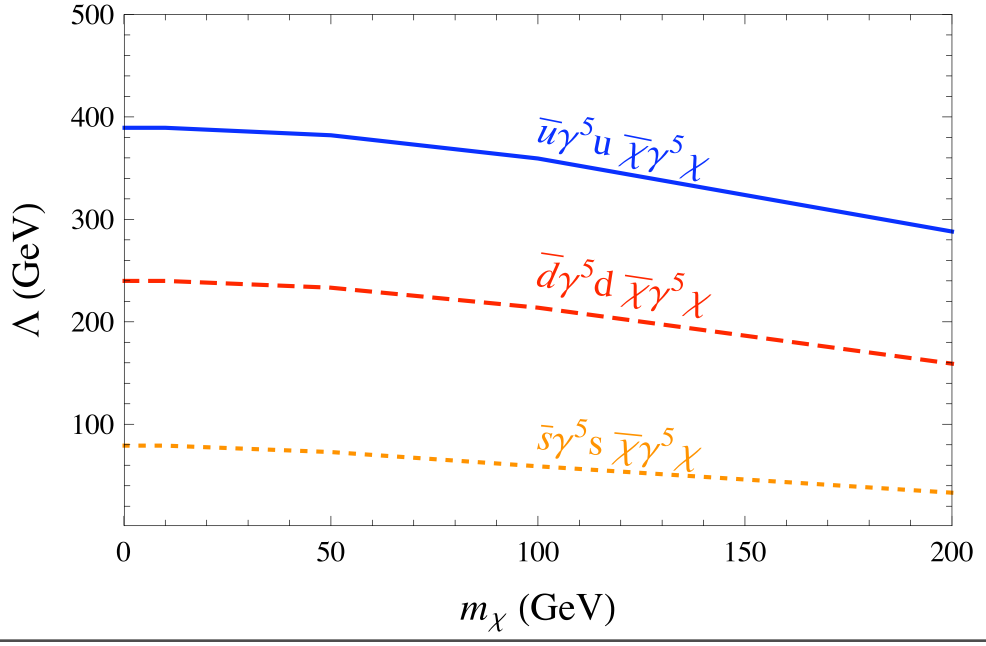
$\mathcal{O}_2$



$\mathcal{O}_3$



$\mathcal{O}_4$



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

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

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

$$\Rightarrow$$

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

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

$$B_u^p = B_d^n = 8.22 \pm 2.26\,,$$

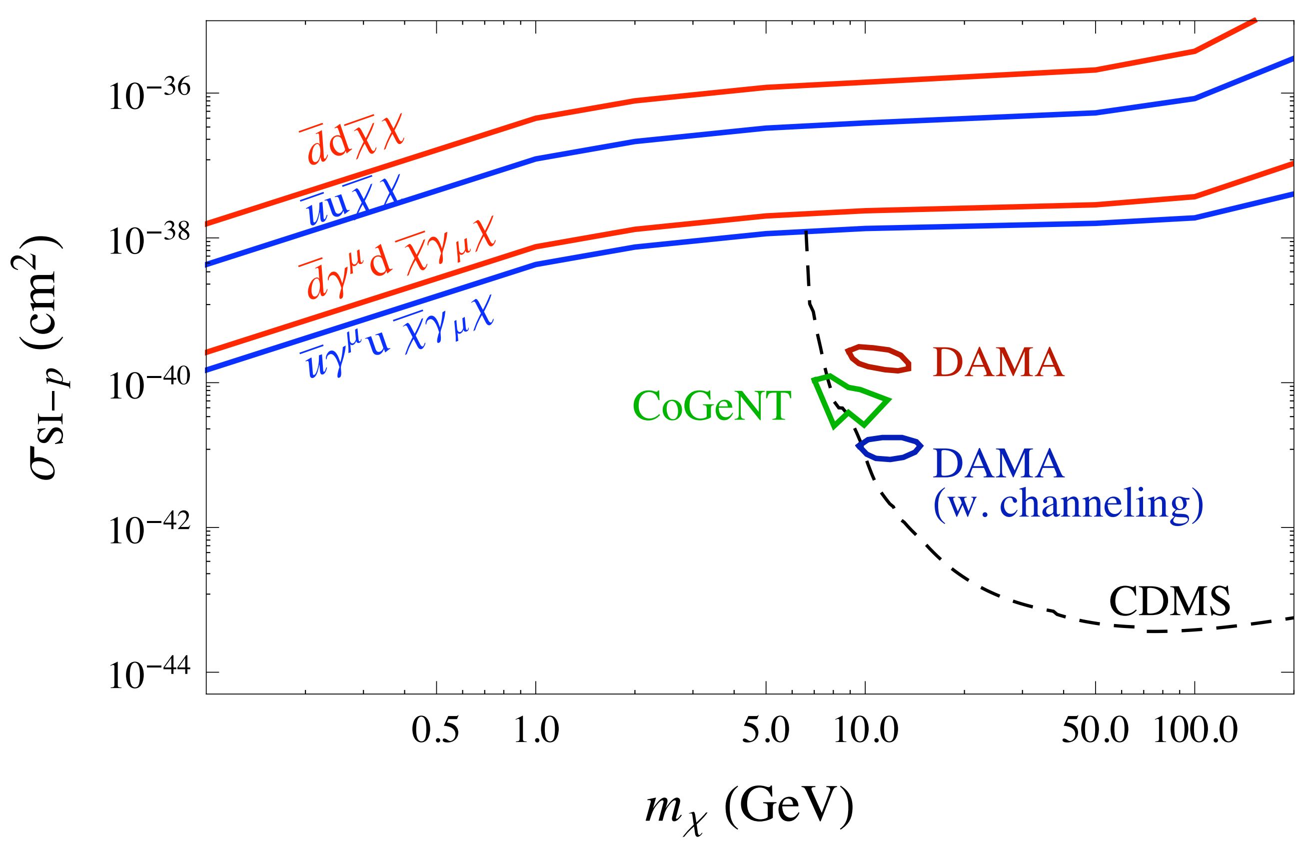
$$B_d^p = B_u^n = 6.62 \pm 1.92\,,$$

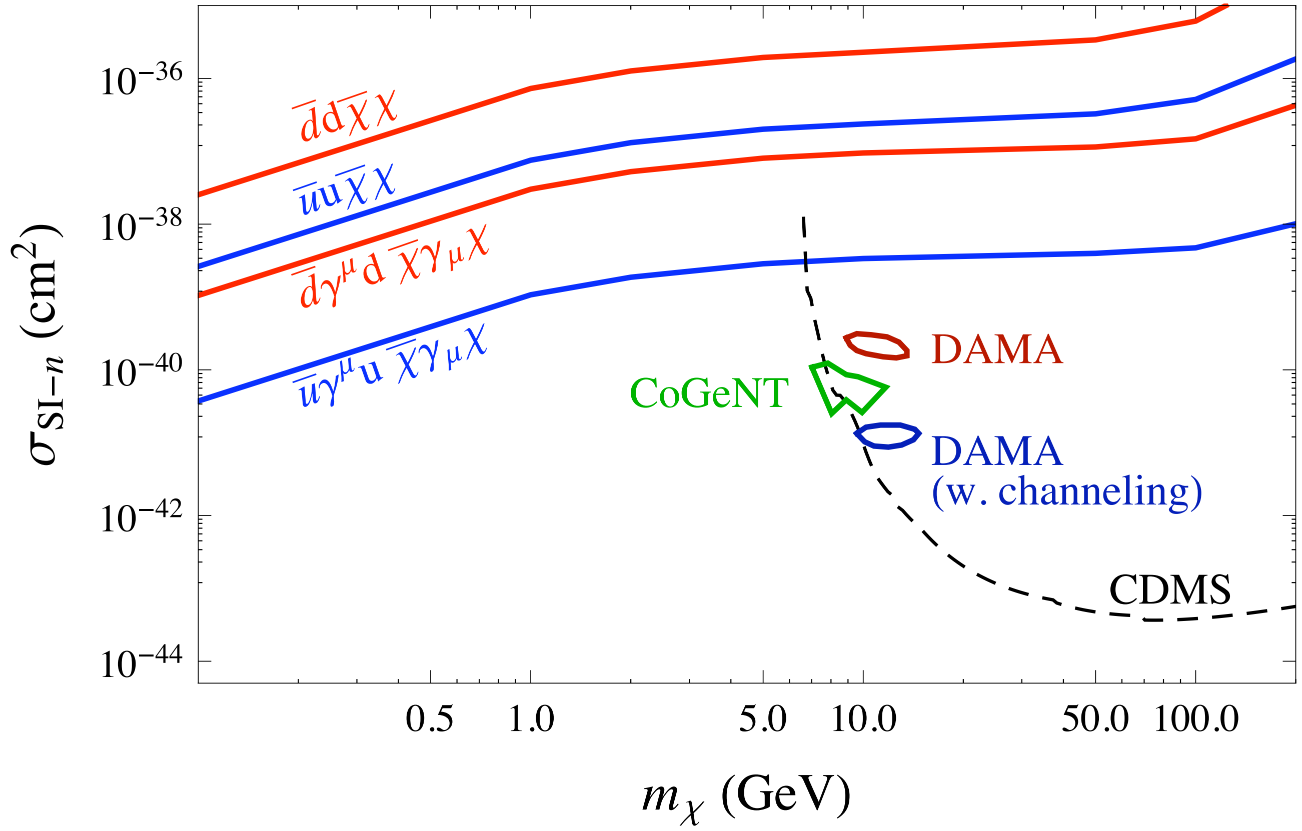
$$B_s^p = B_s^n = 3.36 \pm 1.45$$

$$f_u^p = f_d^n = 2$$

$$f_d^p = f_u^n = 1$$

otherwise $f = 0$





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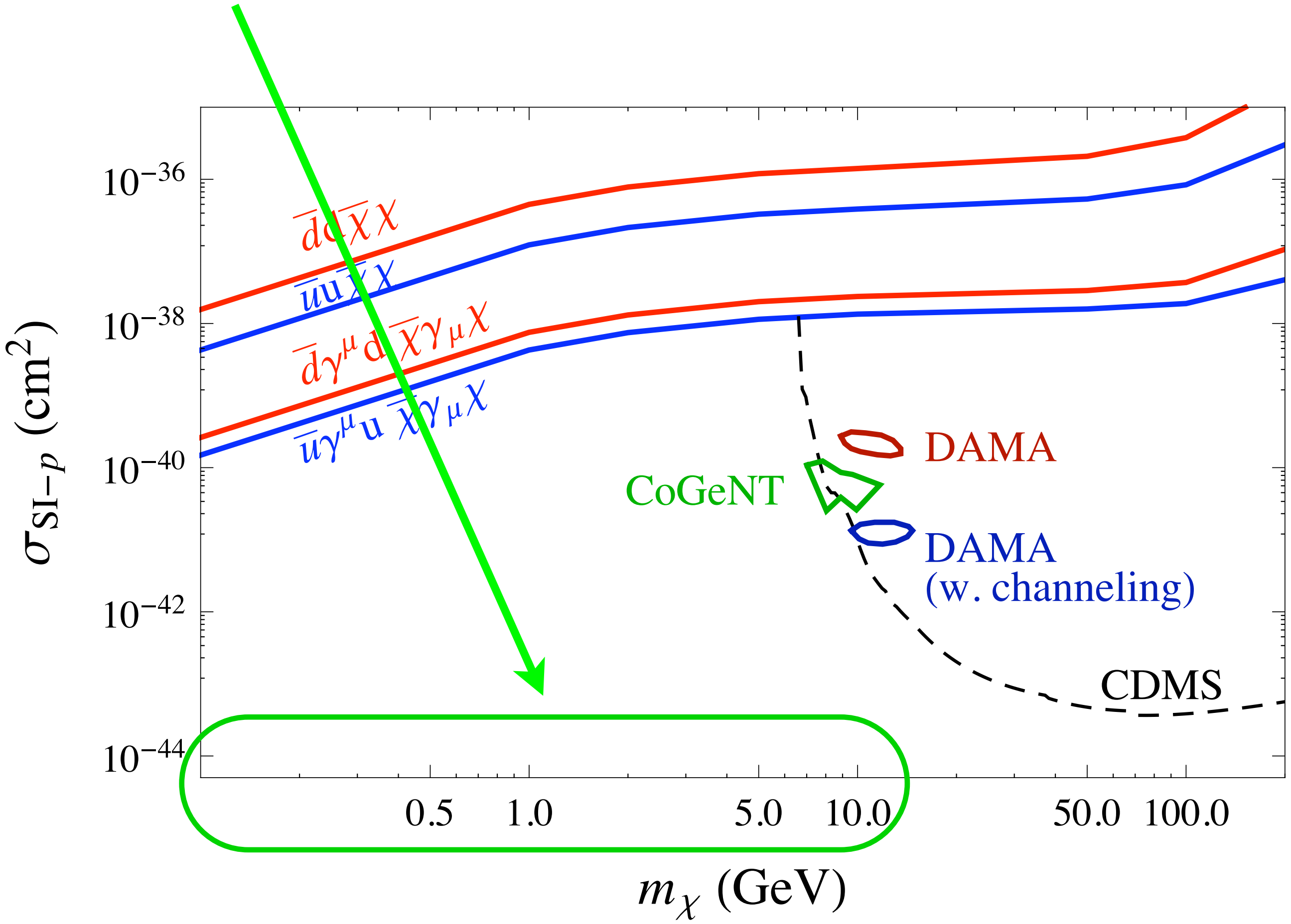
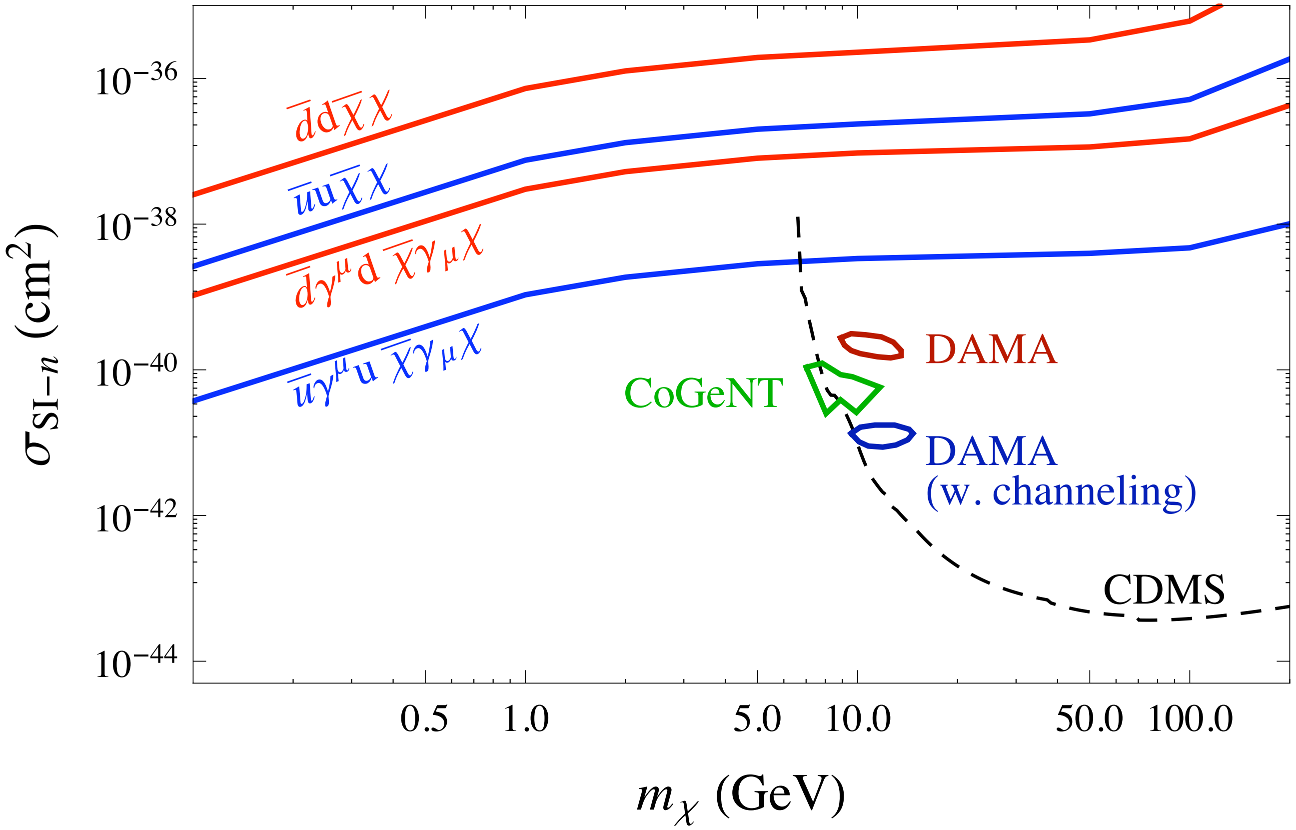
World's best limits at low mass





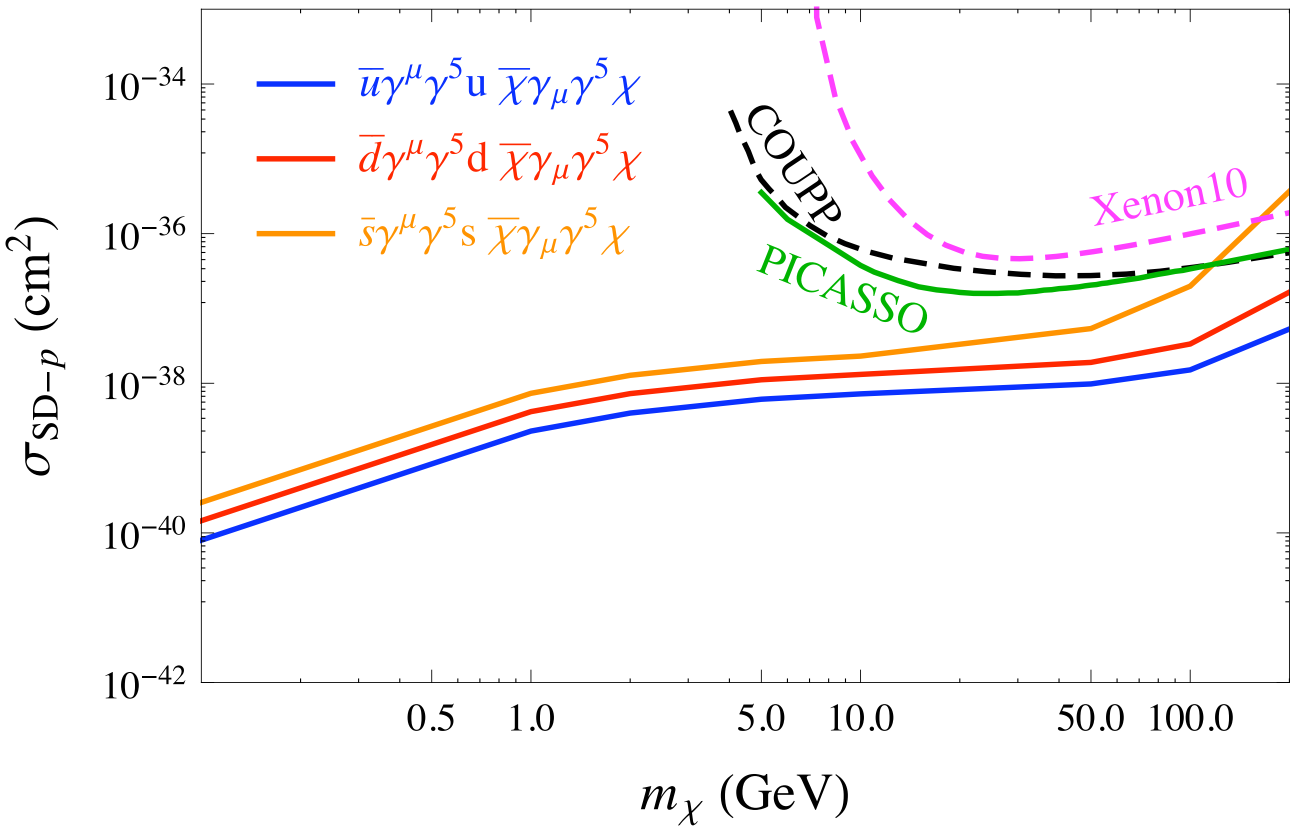
Spin dependent

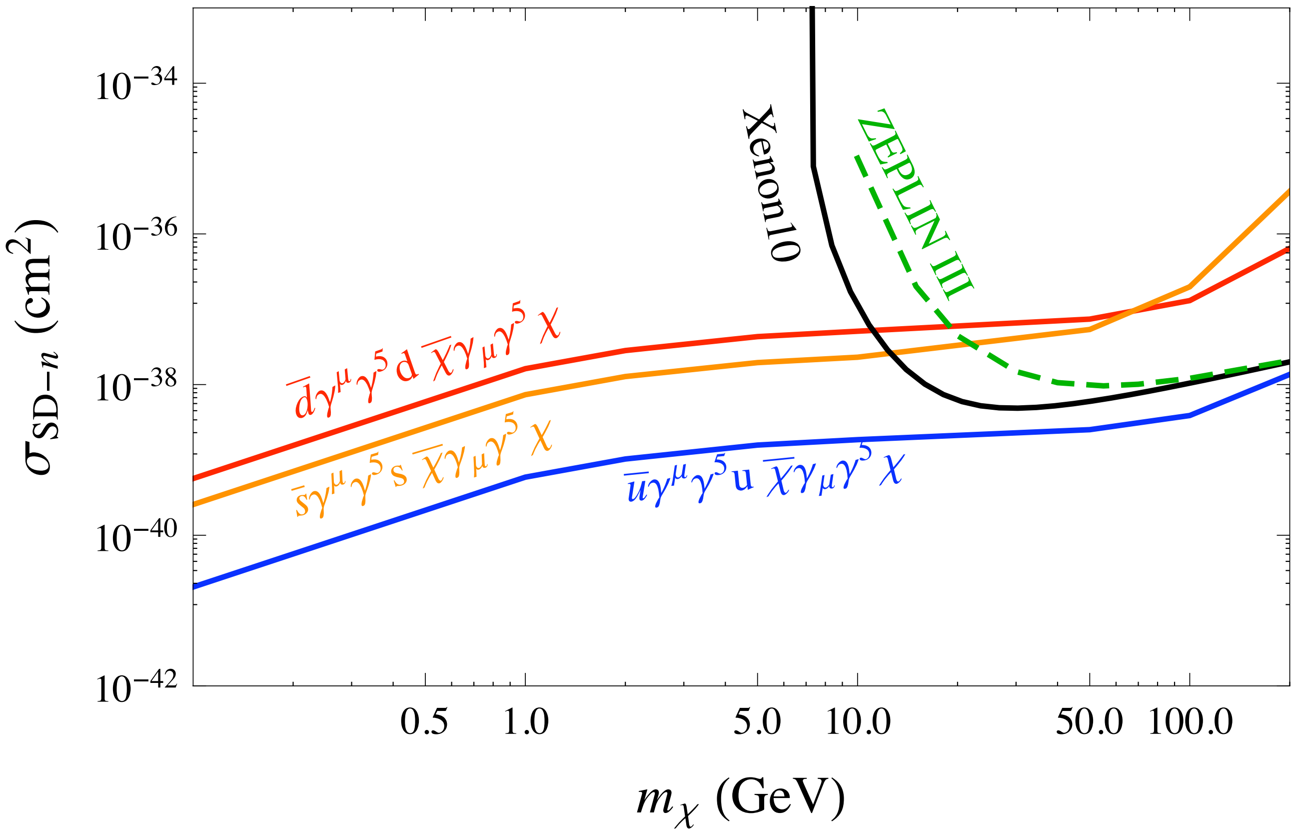
$$\mathcal{O}_3 = \frac{i\, g_\chi\, g_q}{q^2 - M^2} \left(\bar{q}\gamma_\mu\gamma_5 q\right) \left(\bar{\chi}\gamma^\mu\gamma_5\chi\right)$$

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

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

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





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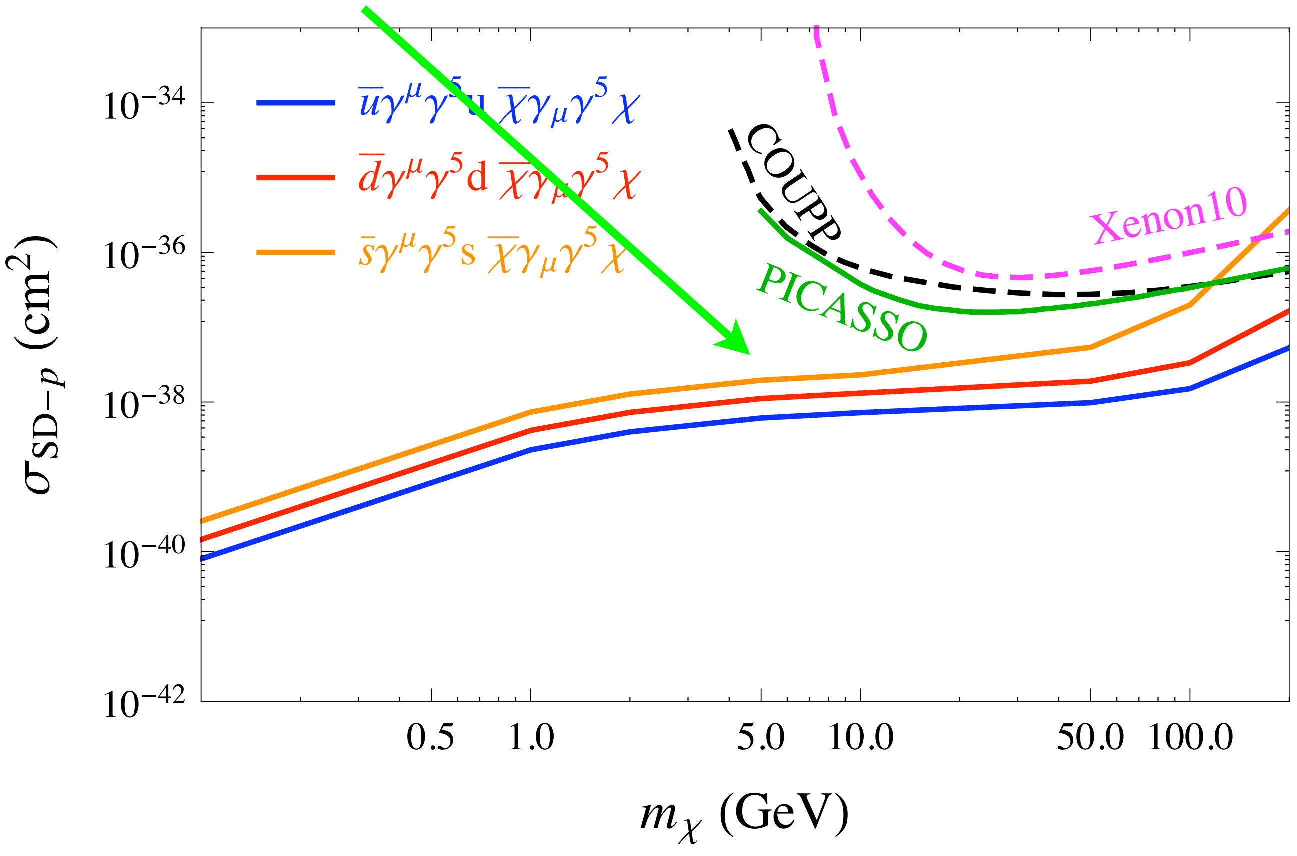
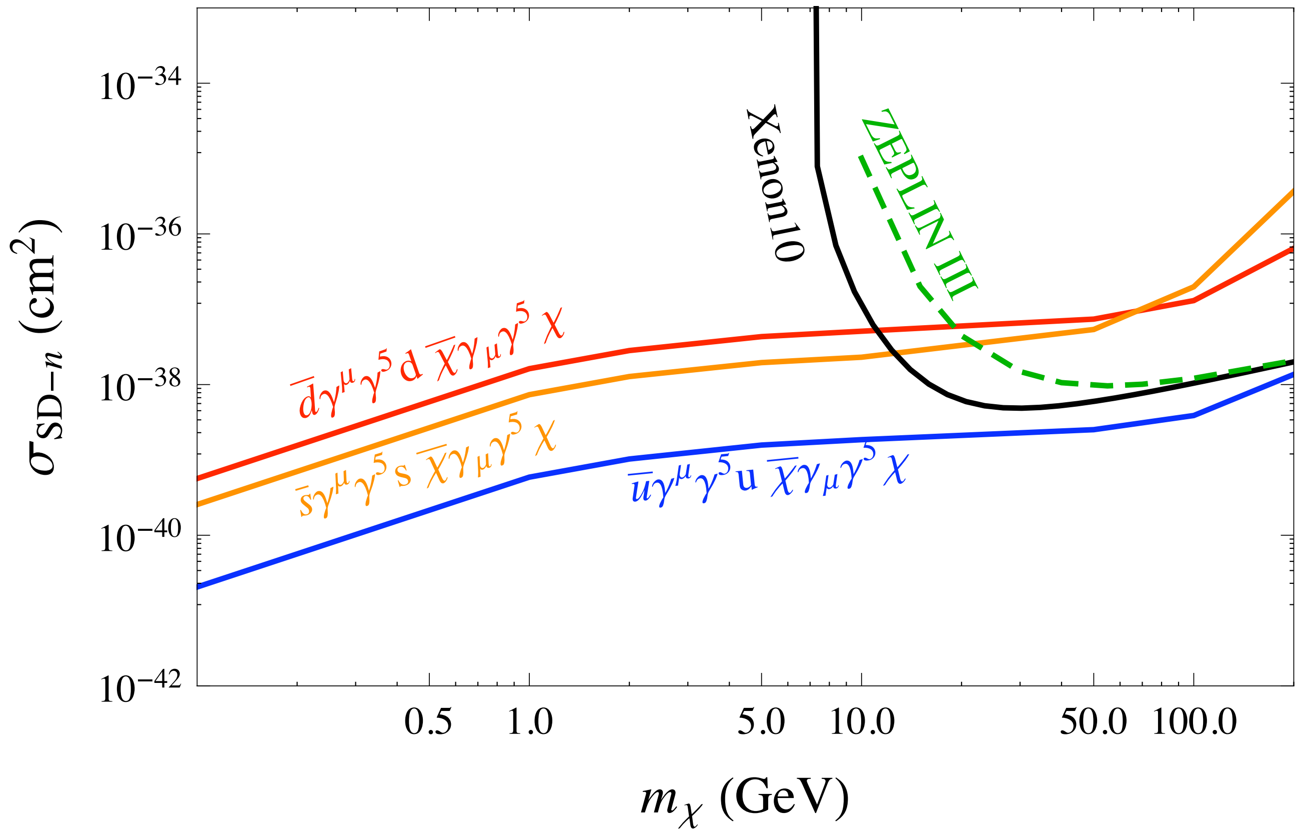
$$\mathcal{O}_3^{Nq} = \Delta_q^N \frac{\left(\bar{N}\gamma^\mu\gamma_5 N\right)\left(\bar{\chi}\gamma_\mu\gamma_5\chi\right)}{\Lambda^2}$$

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

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

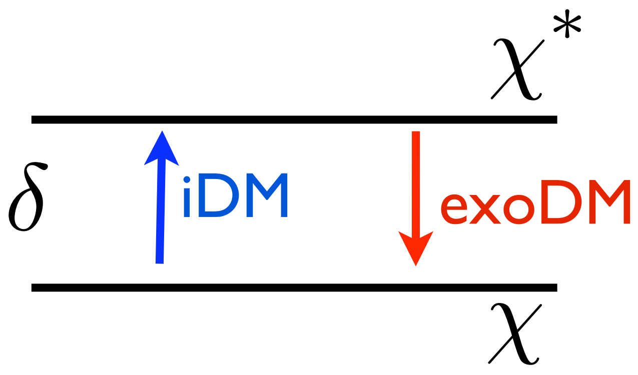
World's best limits, up to ~200 GeV



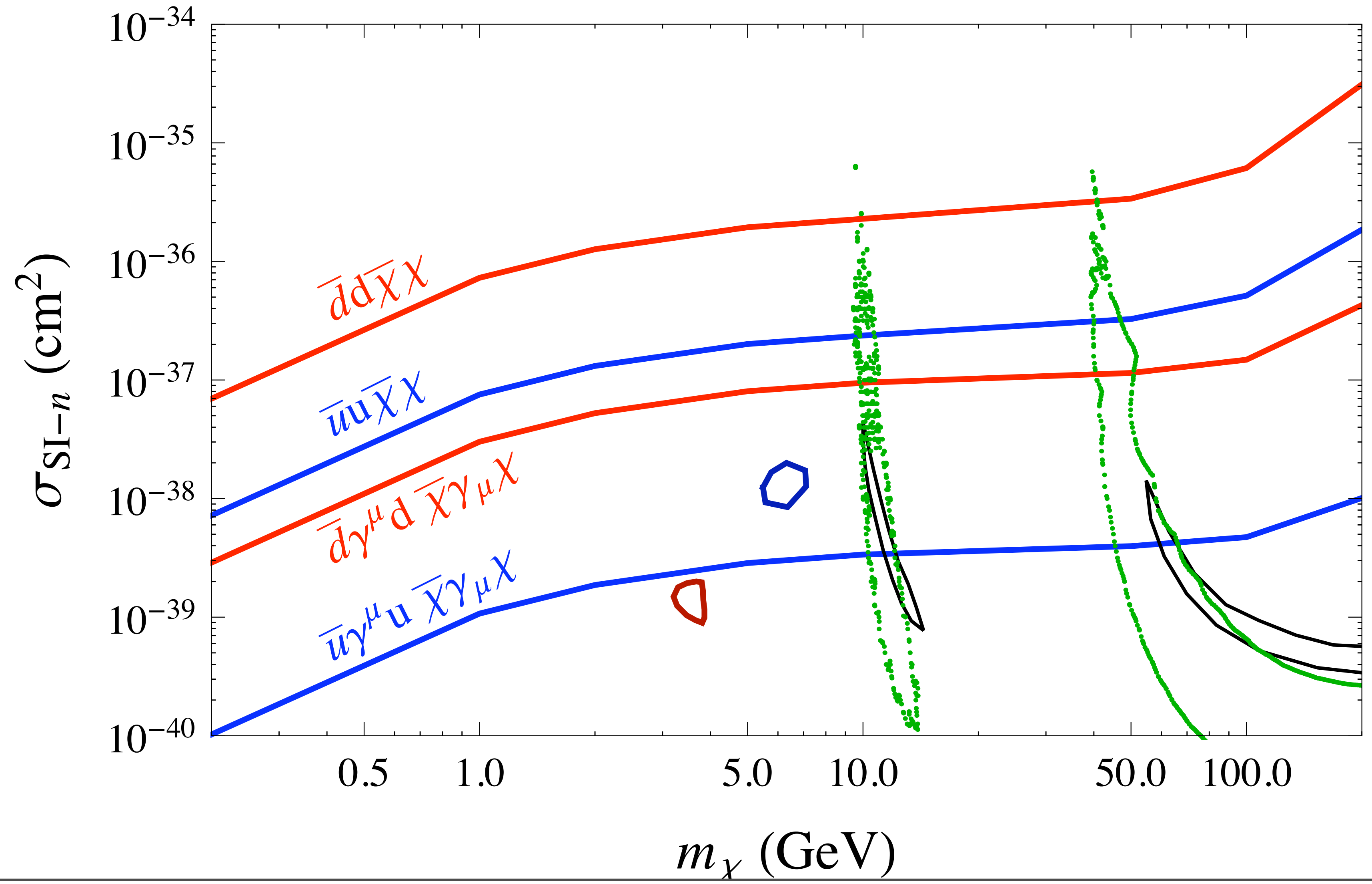


iDM, exothermic

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



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



iDM, exothermic

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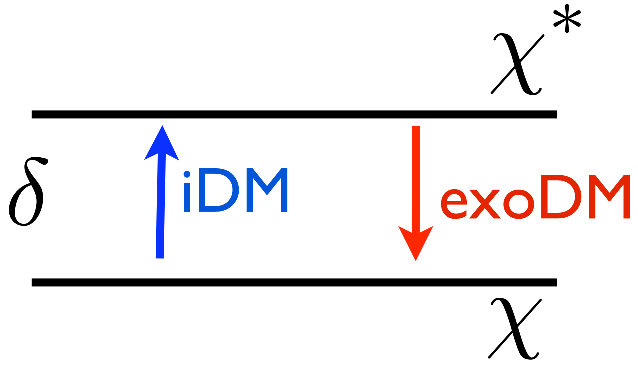
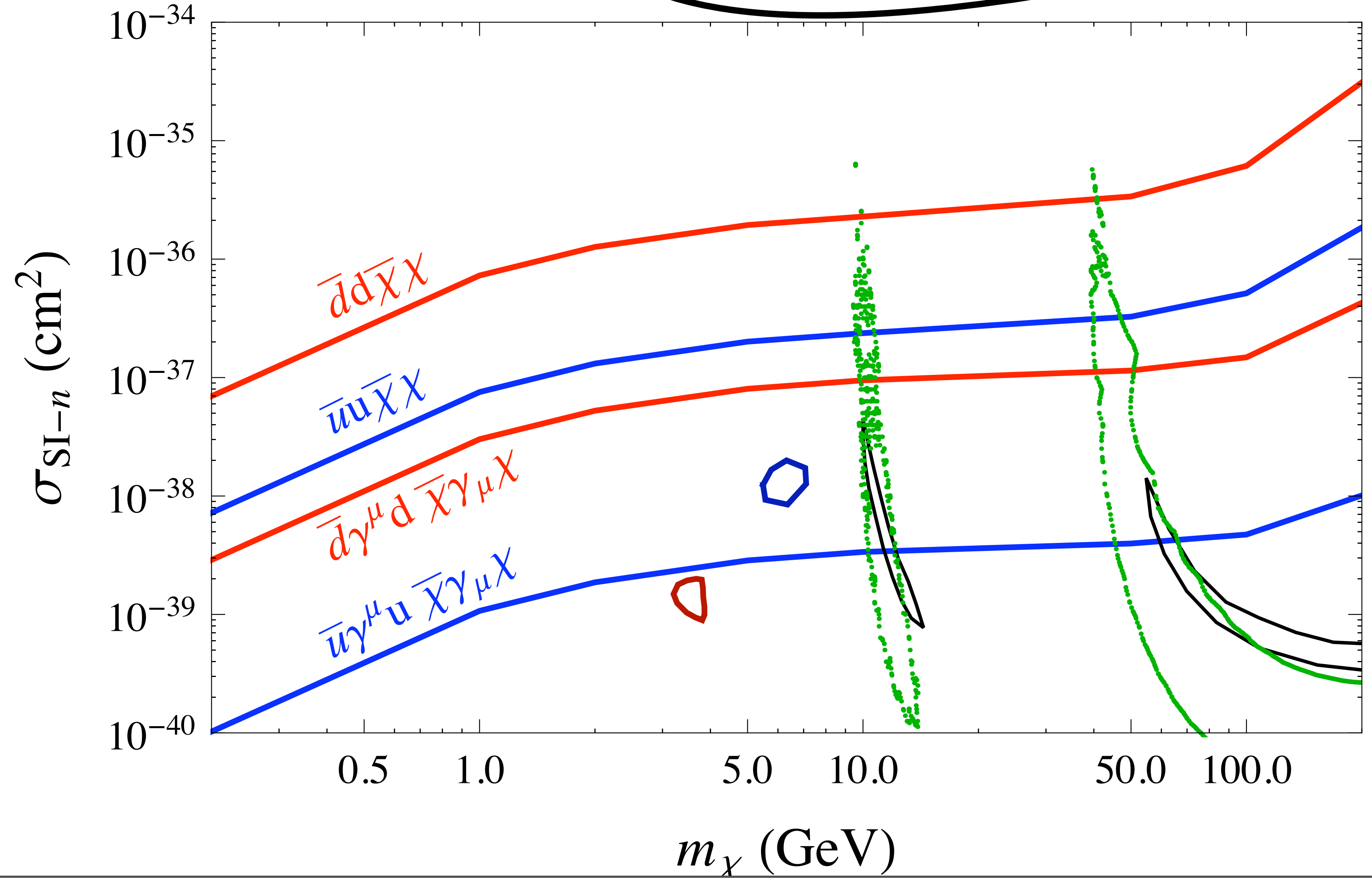


$$v_{min} = \sqrt{\frac{1}{2m_T E_R}}\left(\frac{m_T E_R}{\mu_T} + \delta\right)$$

$\delta \sim 100\,\mathrm{keV},\ \ 5\,\mathrm{keV}$



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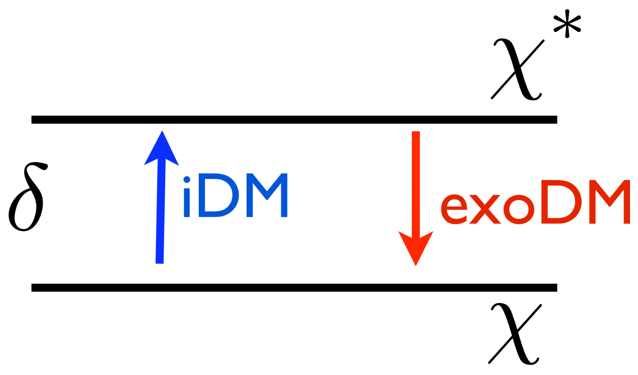

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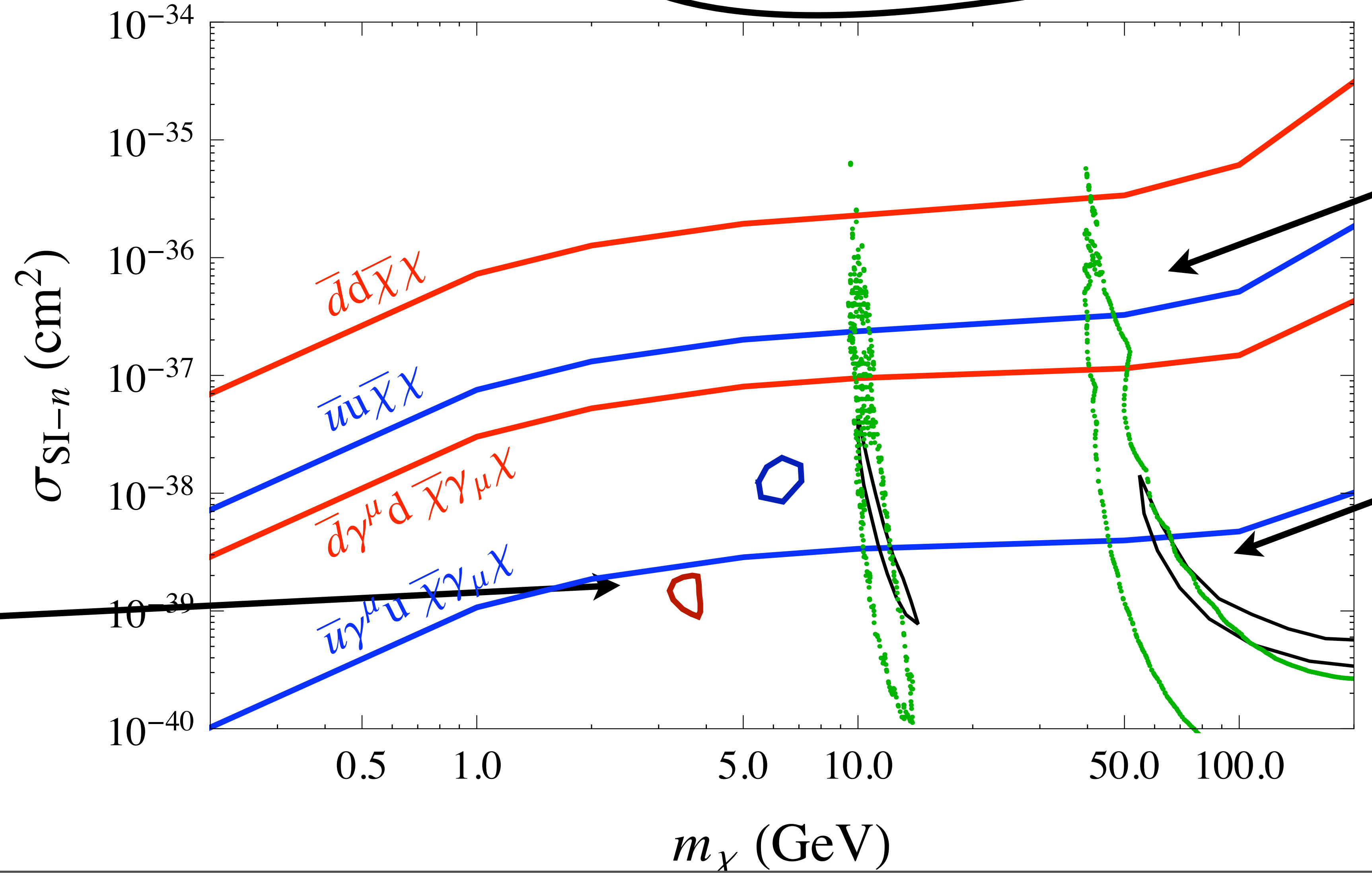

[Kopp et al.]

[Chang et al.]

[Graham et al.]

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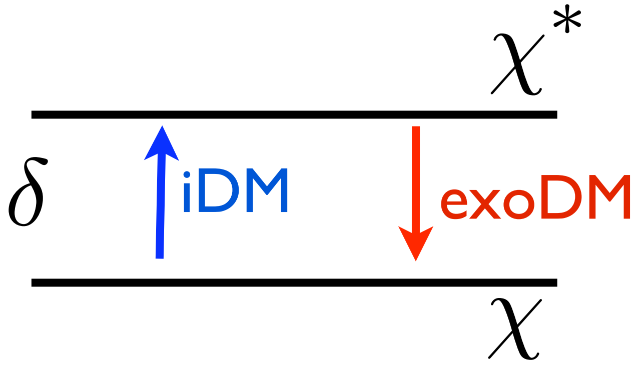

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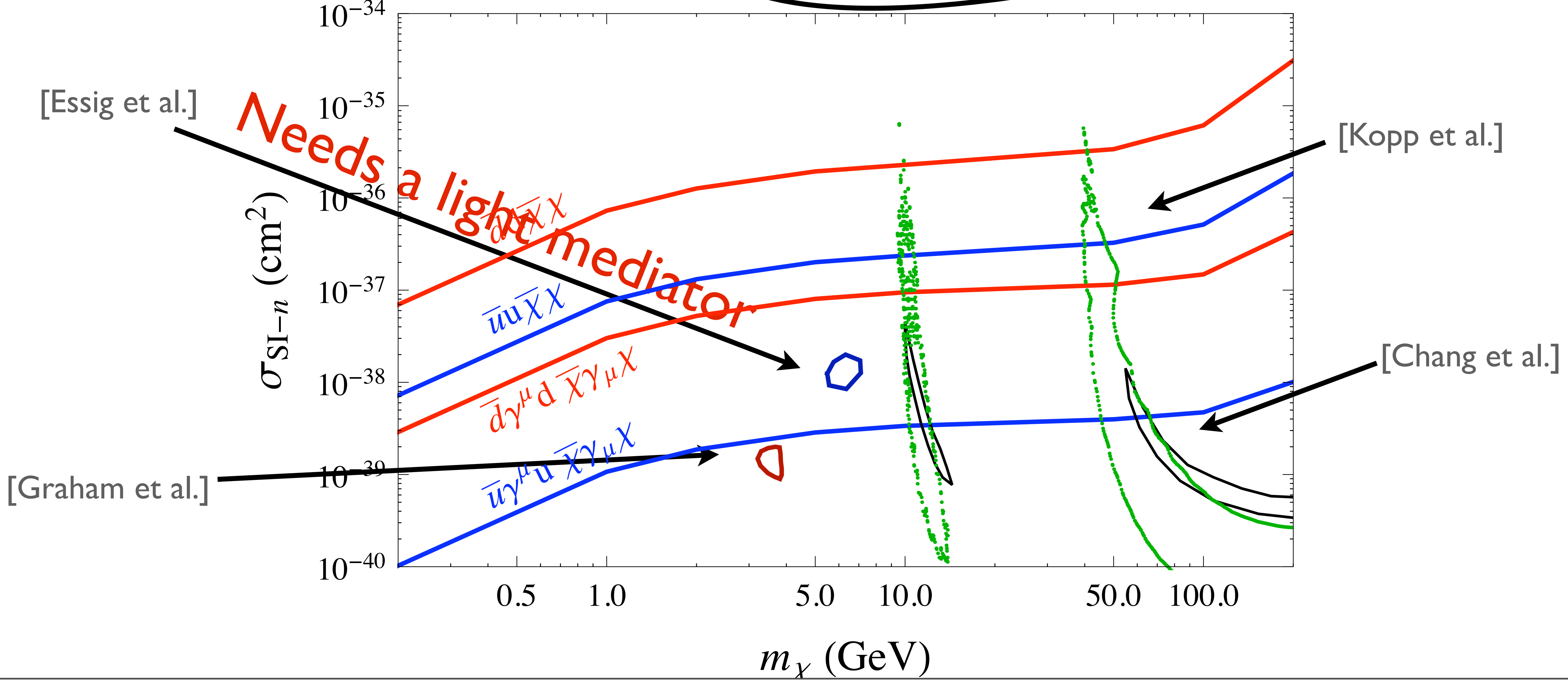


[Essig et al.]

Needs a light mediator

[Kopp et al.]

[Chang et al.]

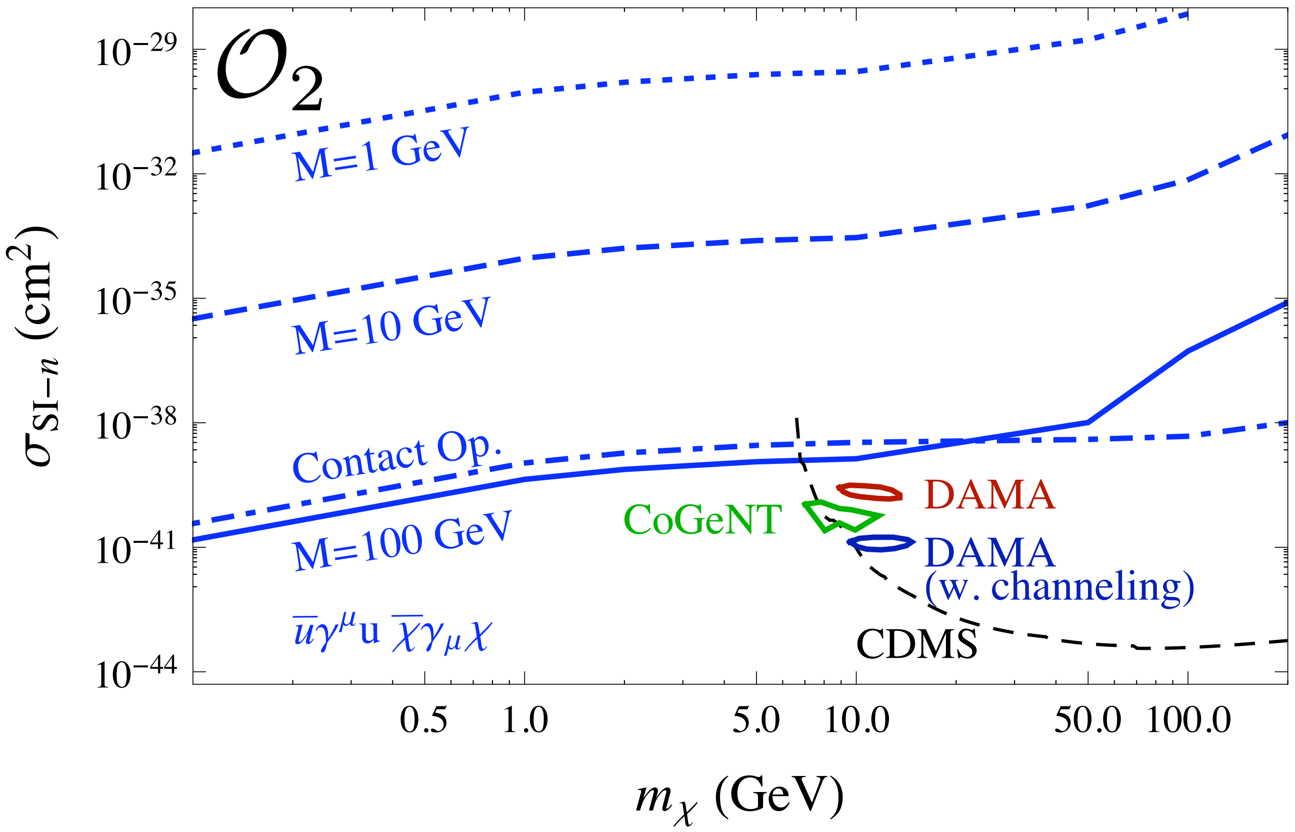
[Graham et al.]

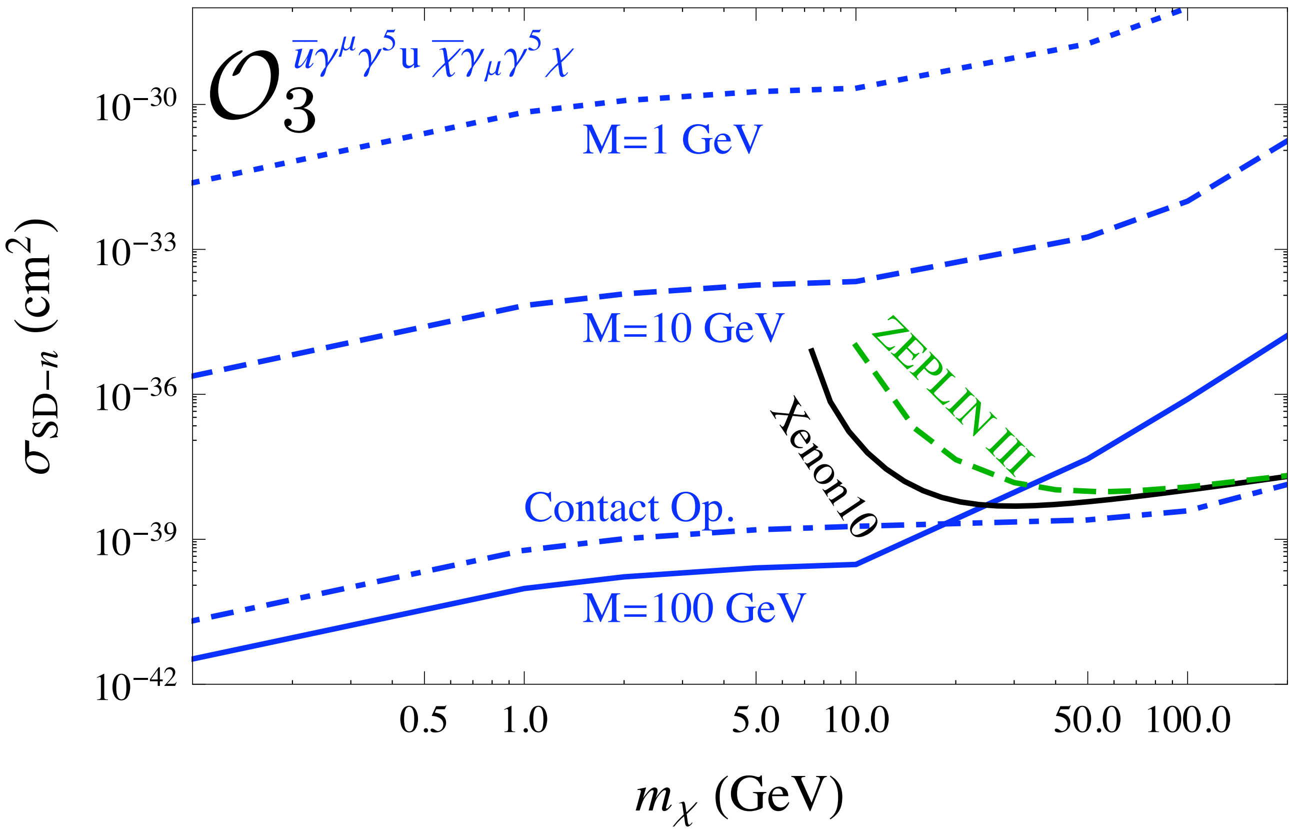
Light mediators

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

Direct detection wins

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





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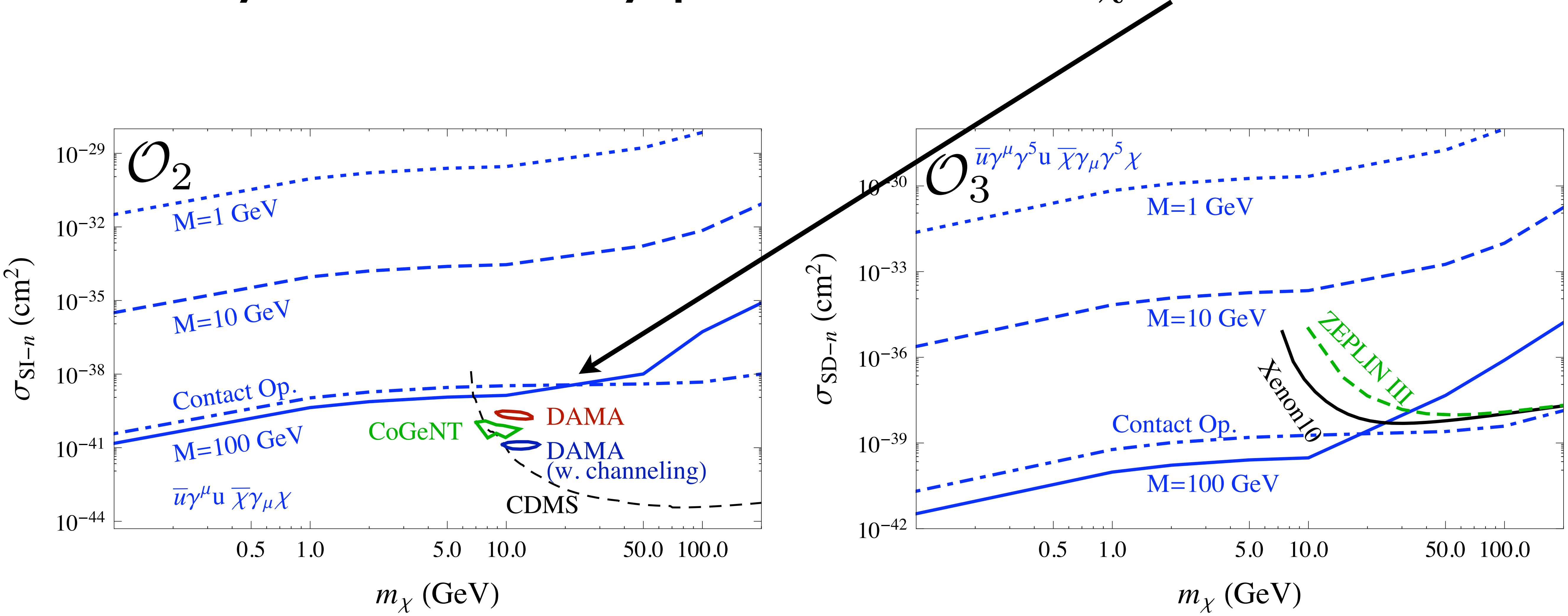
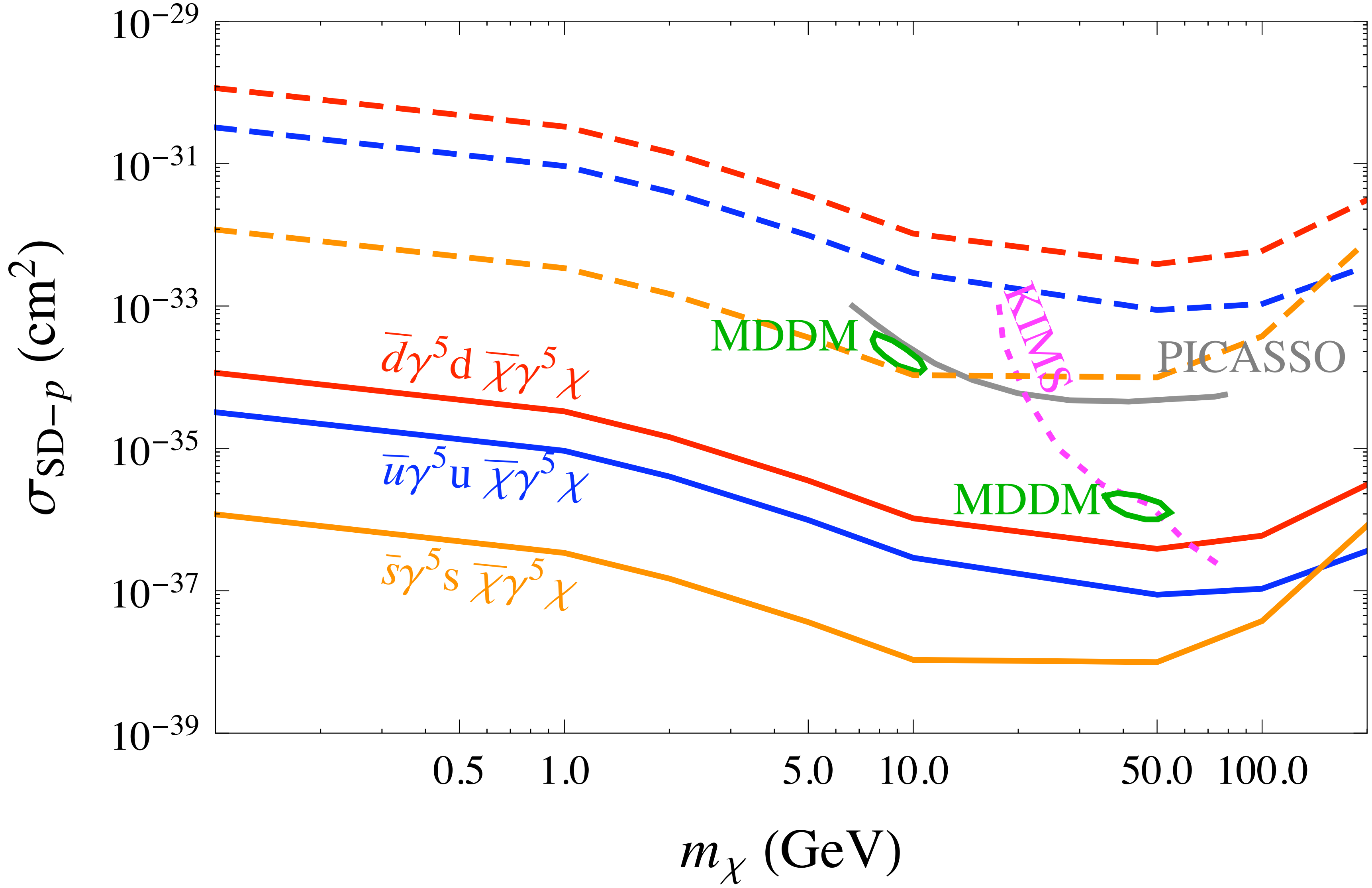


Momentum dependent

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

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

$$\begin{aligned} C_u^p &= 168.5, & C_u^n &= -165.2\,, \\ C_d^p &= -164.2, & C_d^n &= 165.8\,, \\ C_s^p &= -4.3, & C_s^n &= -0.67\,. \end{aligned}$$



Momentum dependent

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

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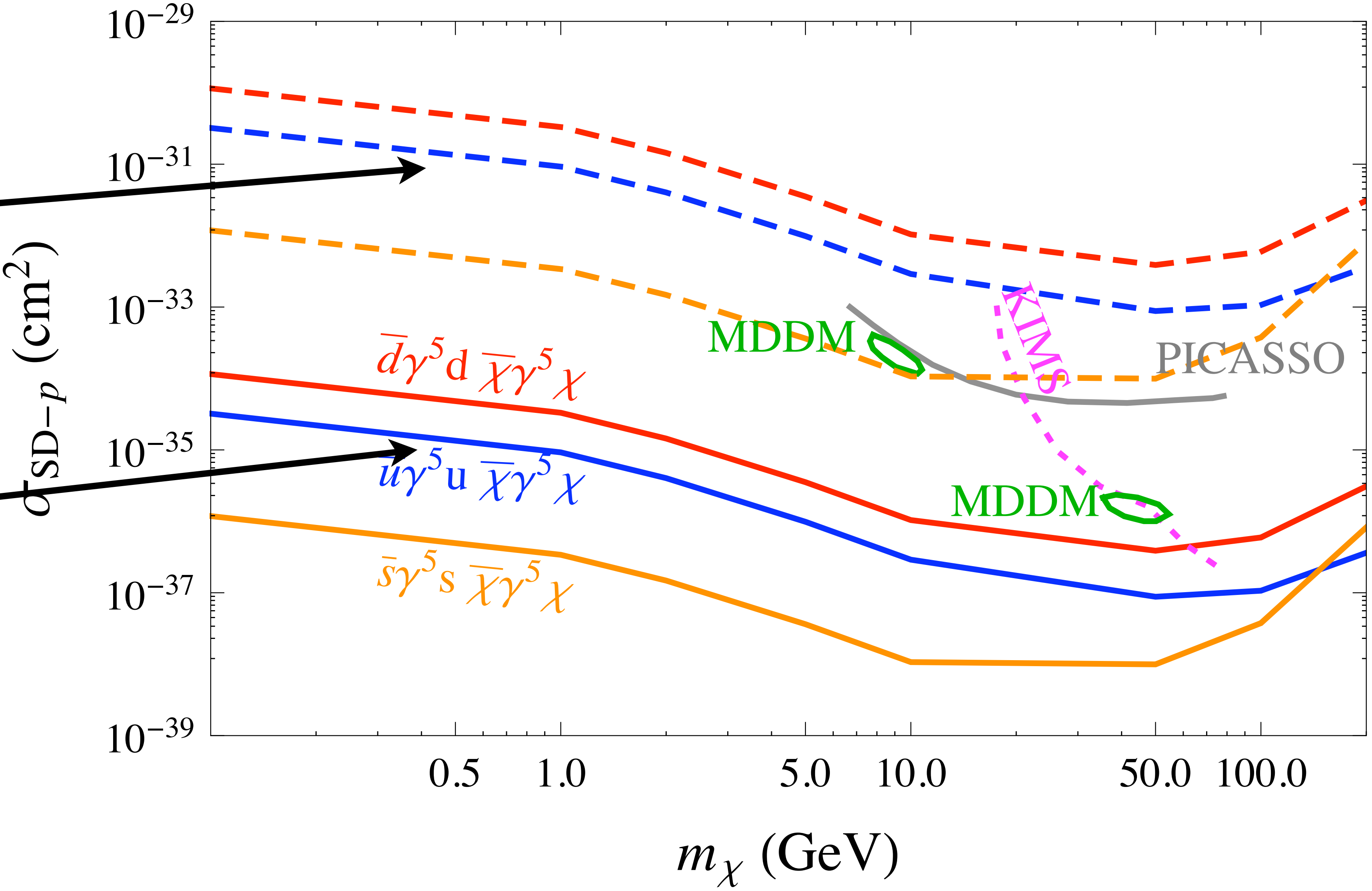
M=1GeV

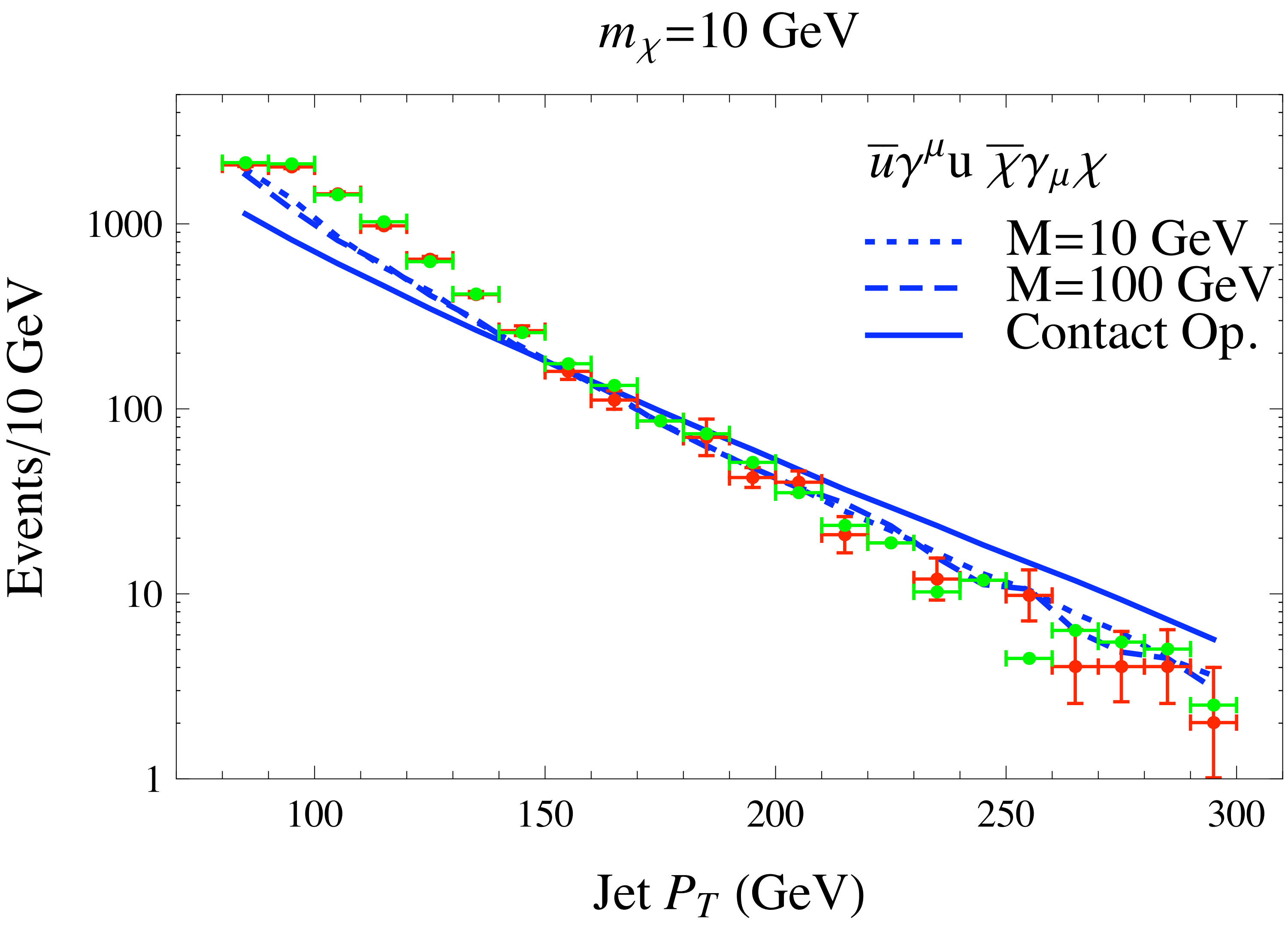
M=10 GeV



Improvements?

So far only CDF analysis on 1/fb

Mono-photon could also be done



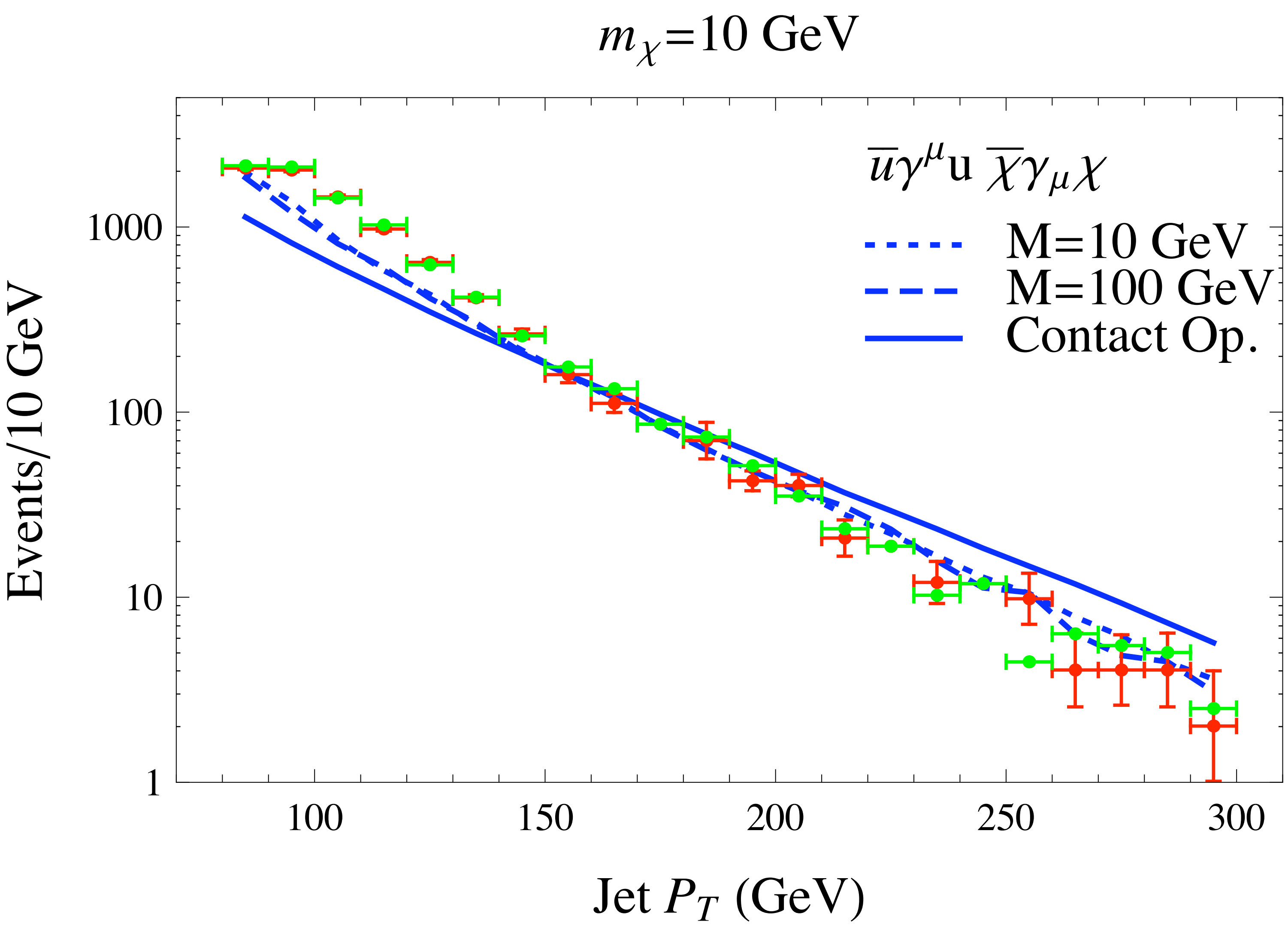
Use shape information

Tevatron reach limited to ~300 GeV

Improvements?

So far only CDF analysis on 1/fb

Mono-photon could also be done



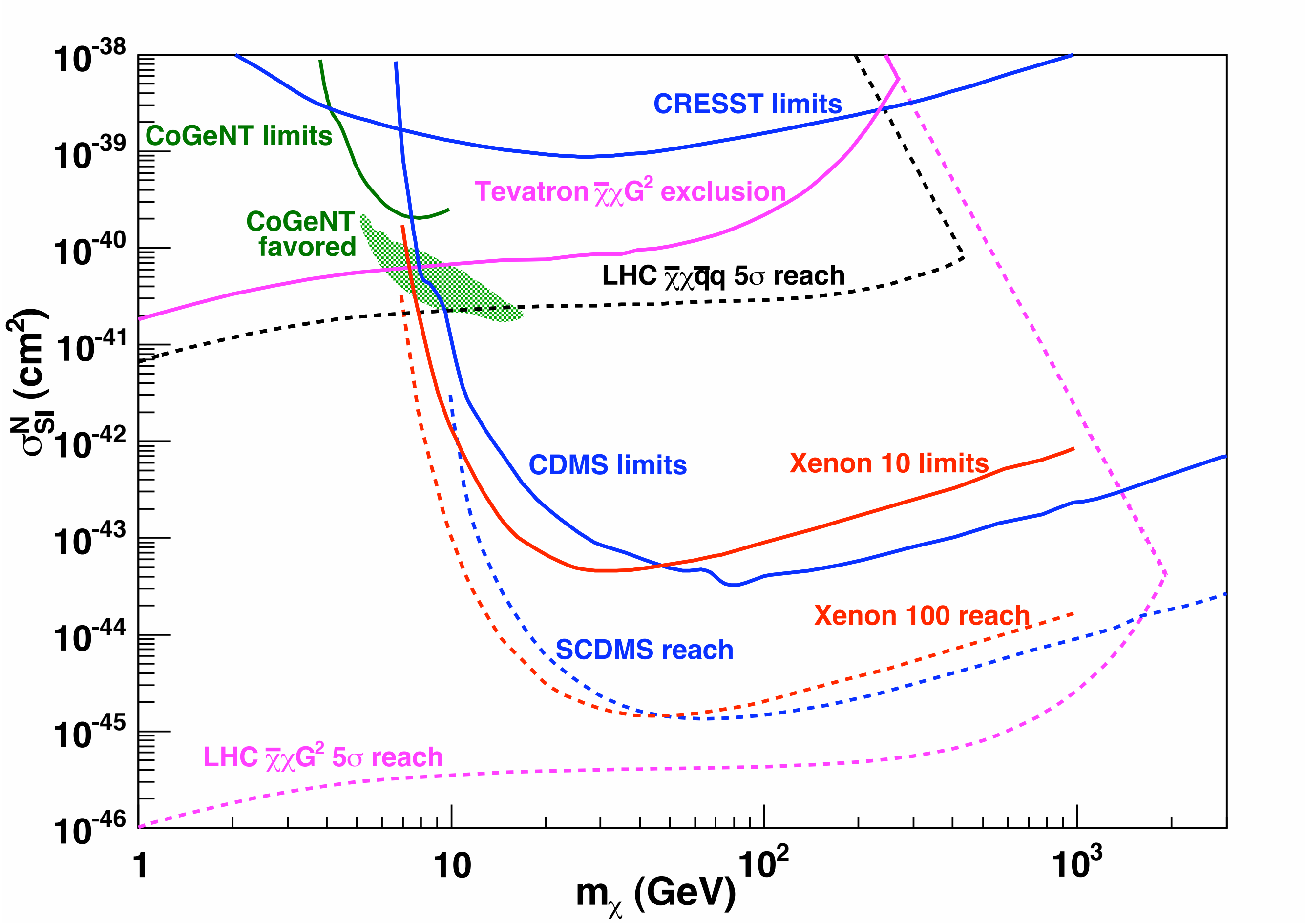
Use shape information

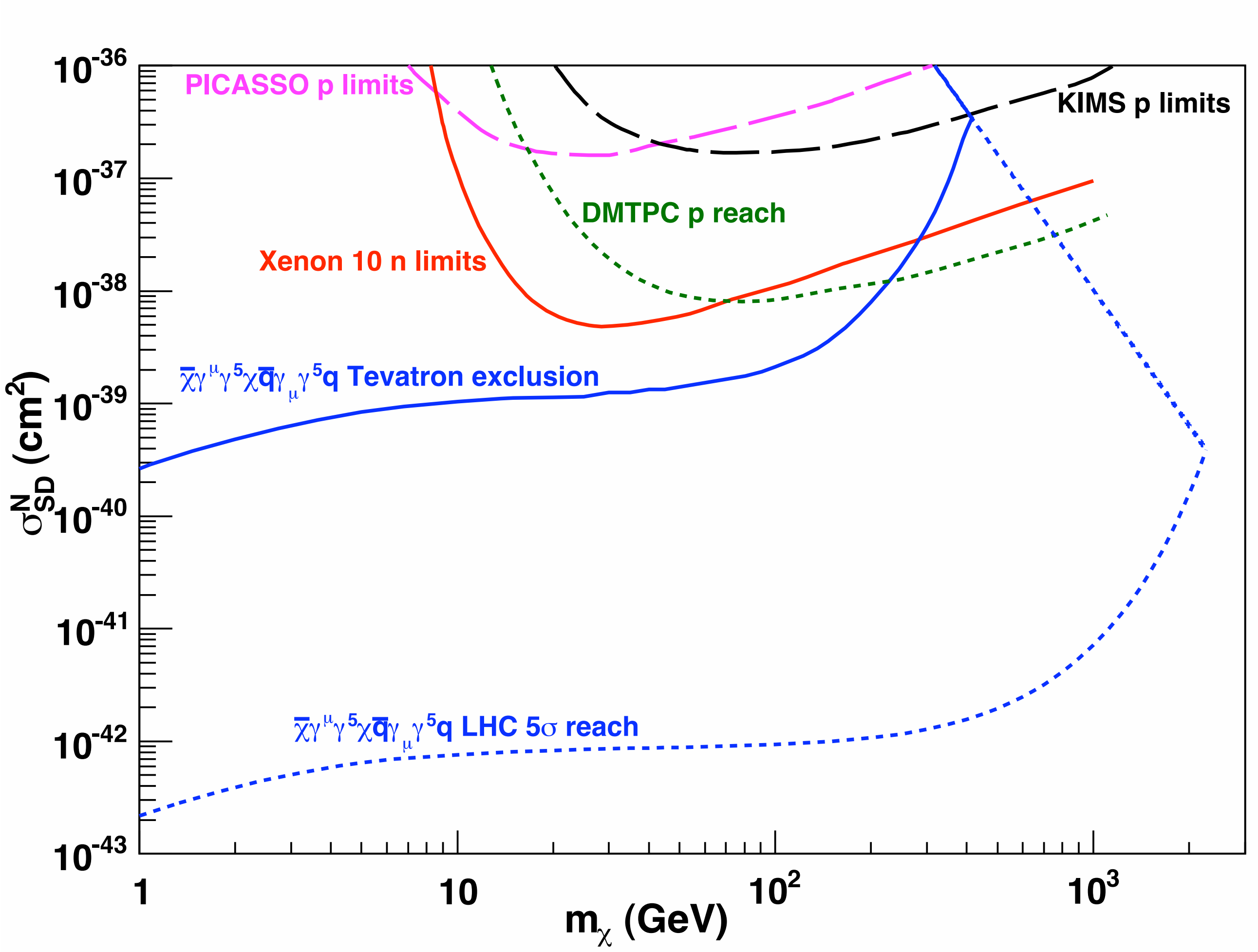
Recently CDF + Bai, Harnik, PJF have started a "real" analysis on full data set!

Tevatron reach limited to ~300 GeV

Improvements

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





LHC

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

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

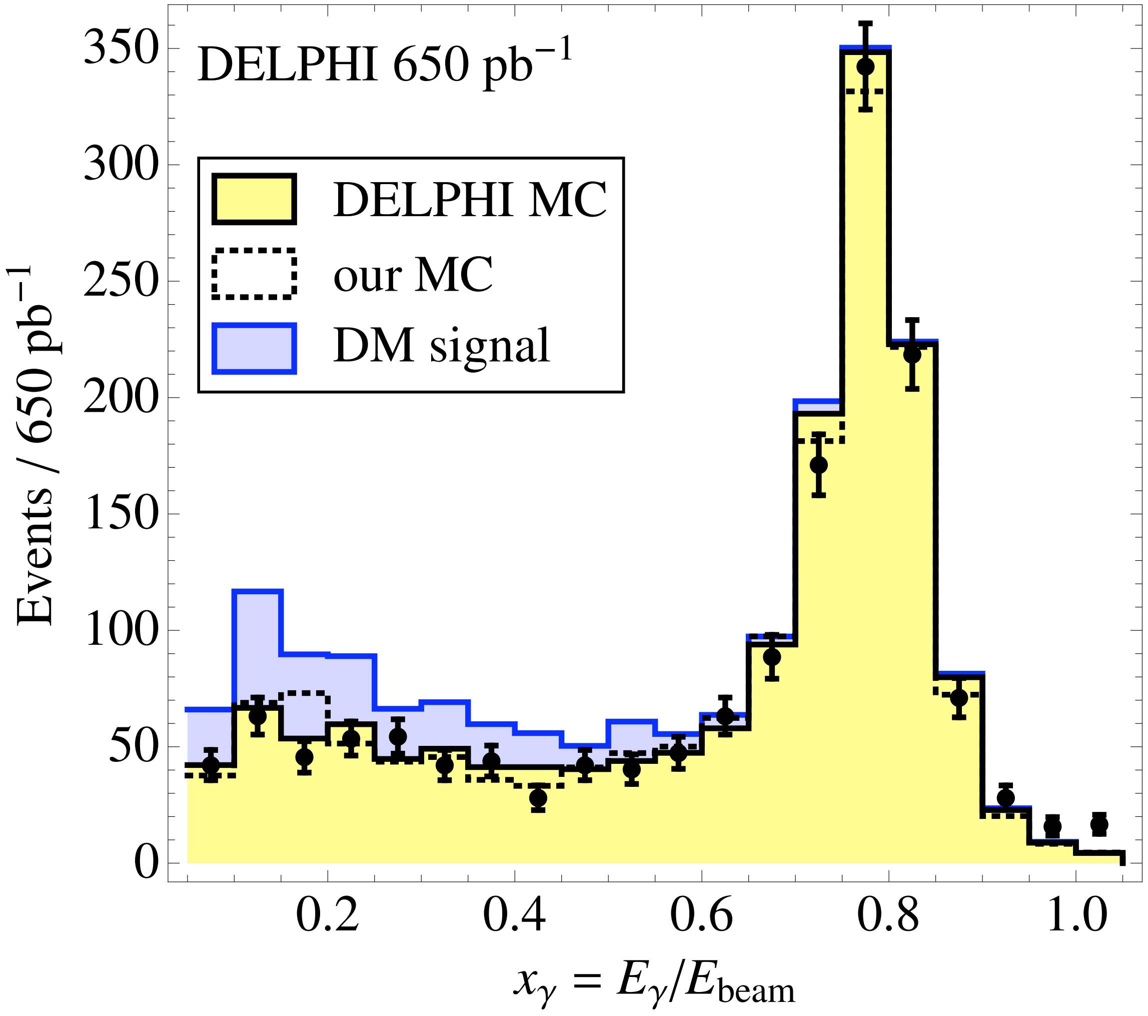
$$\not{E}_T > 500\ \text{GeV}$$

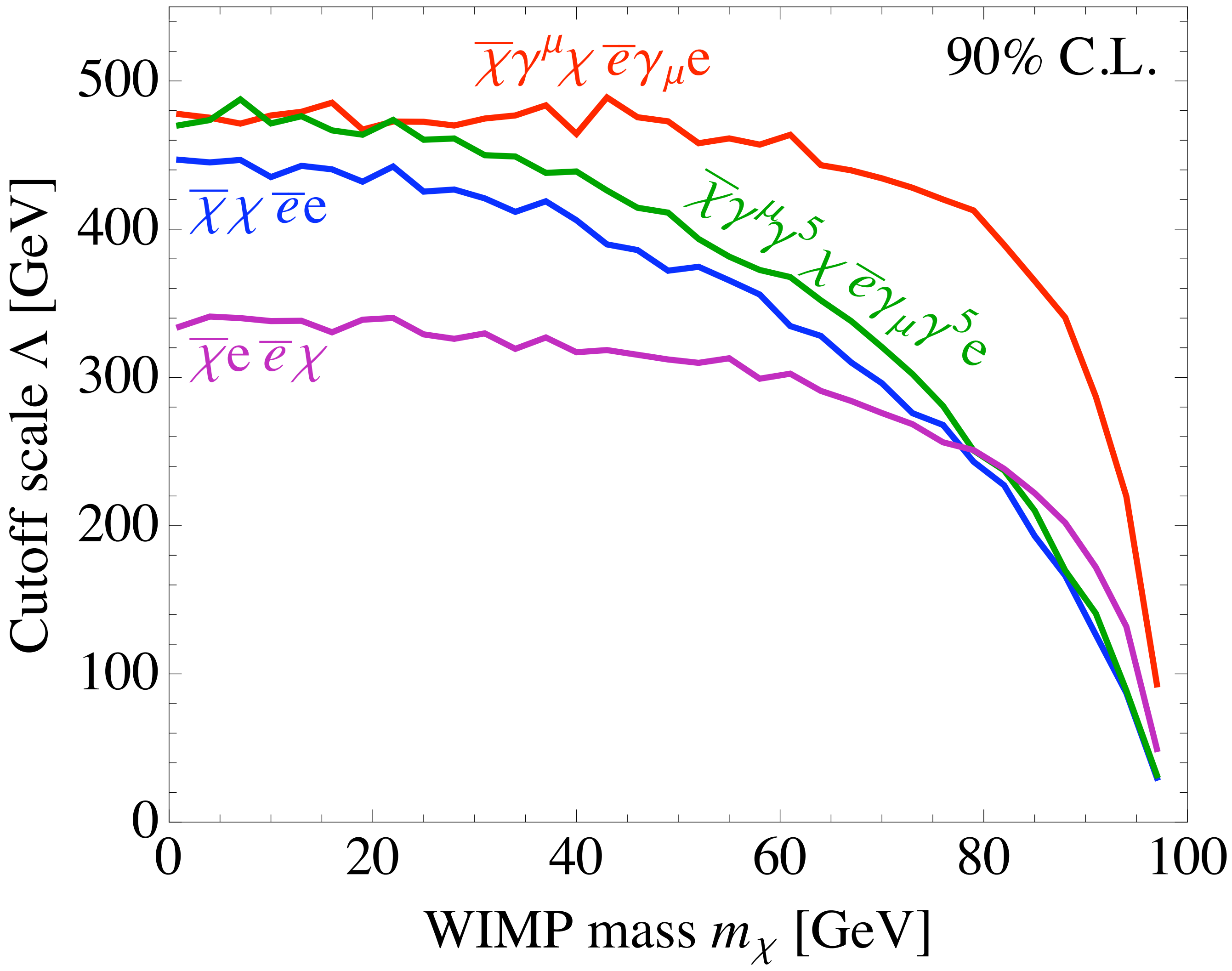
No longer monojet search

BSM backgrounds?

Leptophilic dark matter

Mono-photons at LEP





More model dependent than Tevatron constraints

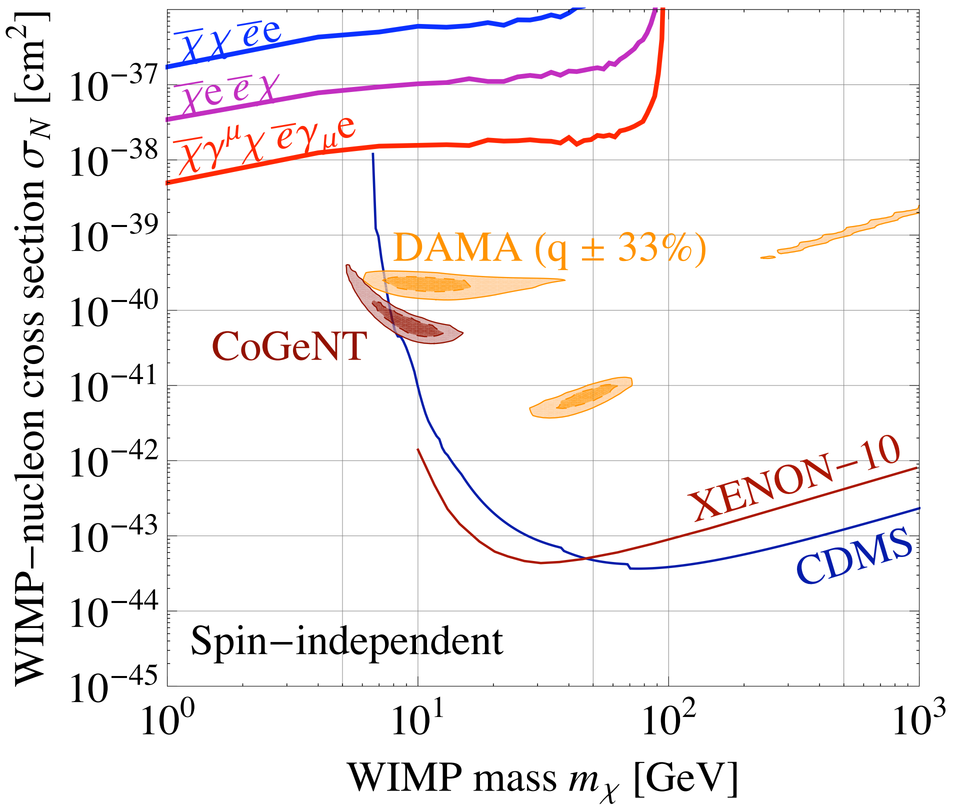
Consider two “extreme” hypotheses:

DM has equal coupling to all SM fermions

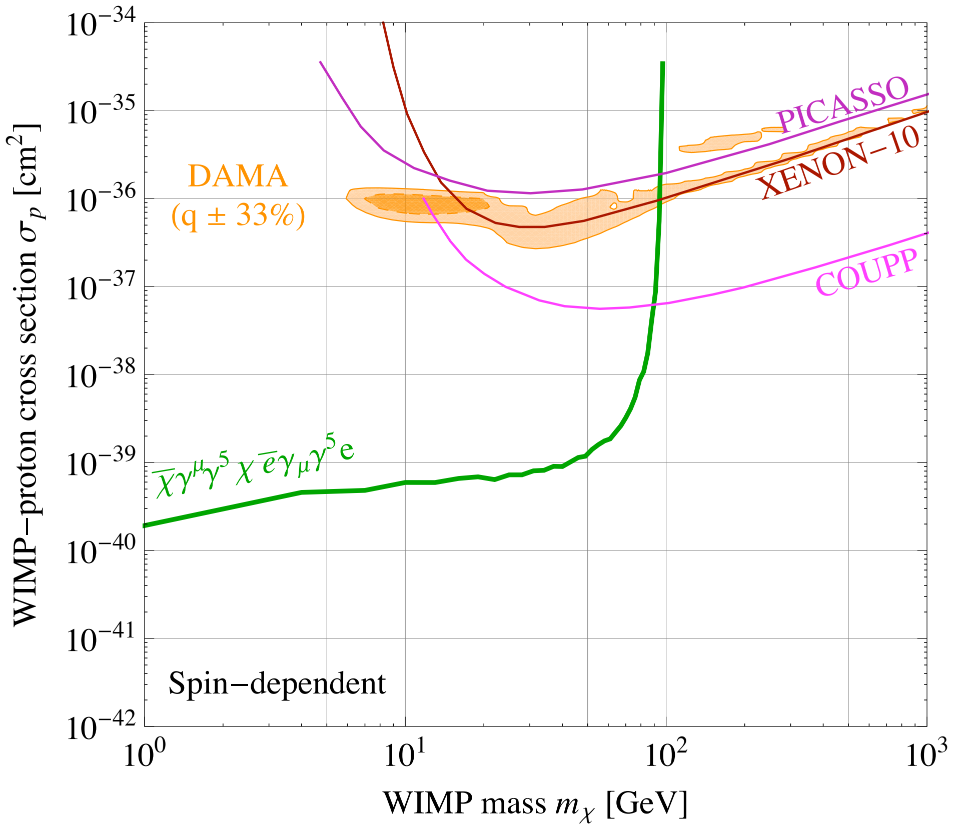
DM has equal coupling to all leptons

Leptophilic dark matter

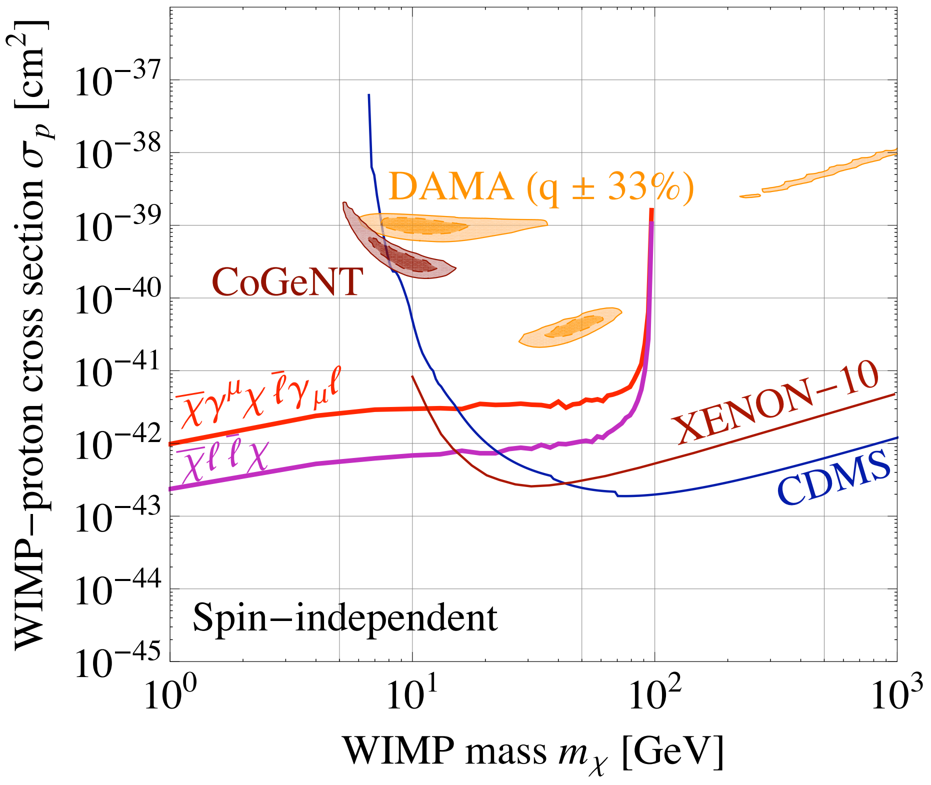
Equal couplings to all SM fermions



Equal couplings to all SM fermions



Couplings to leptons only

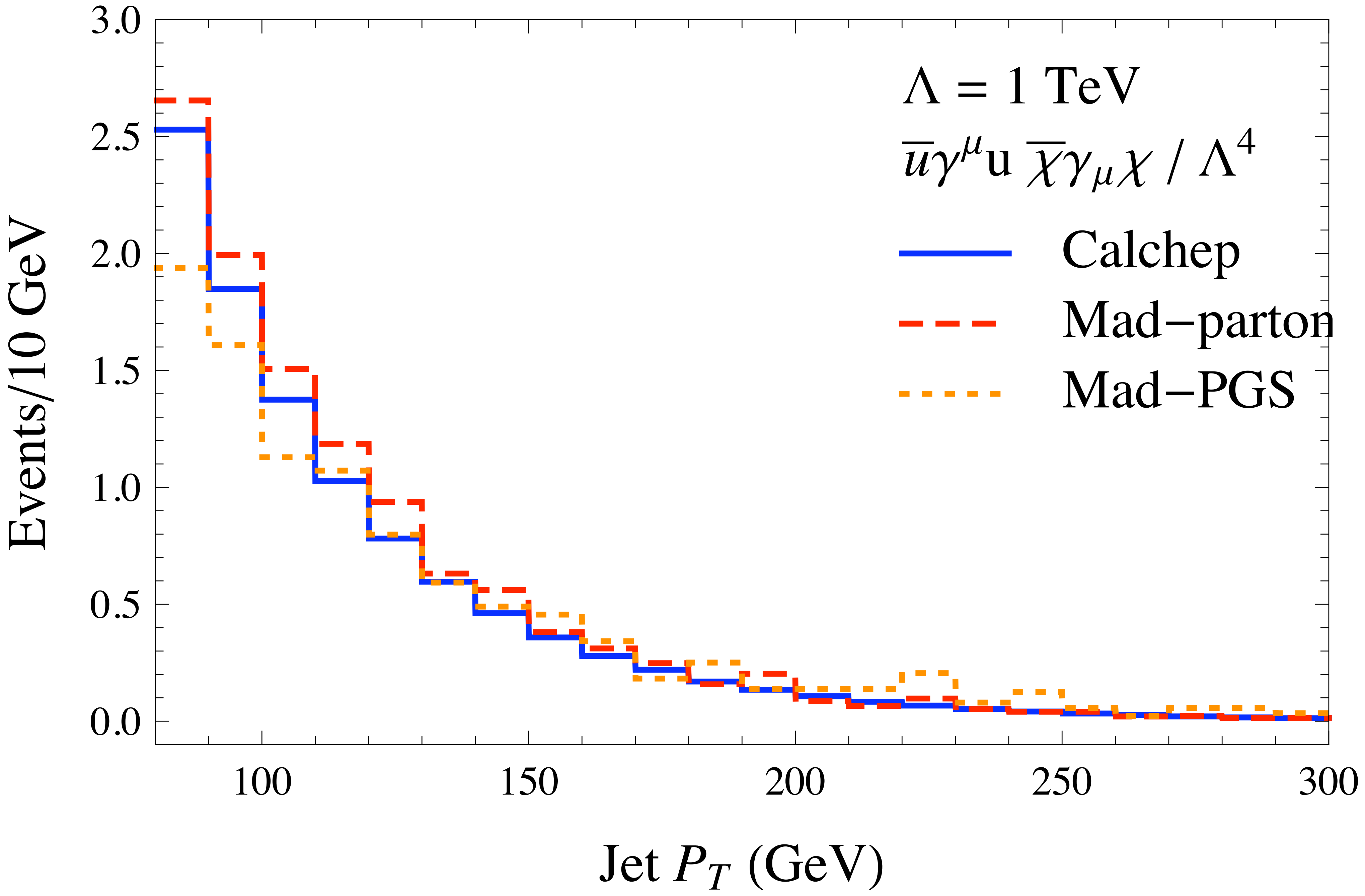


Conclusions

- 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


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

ADD analysis

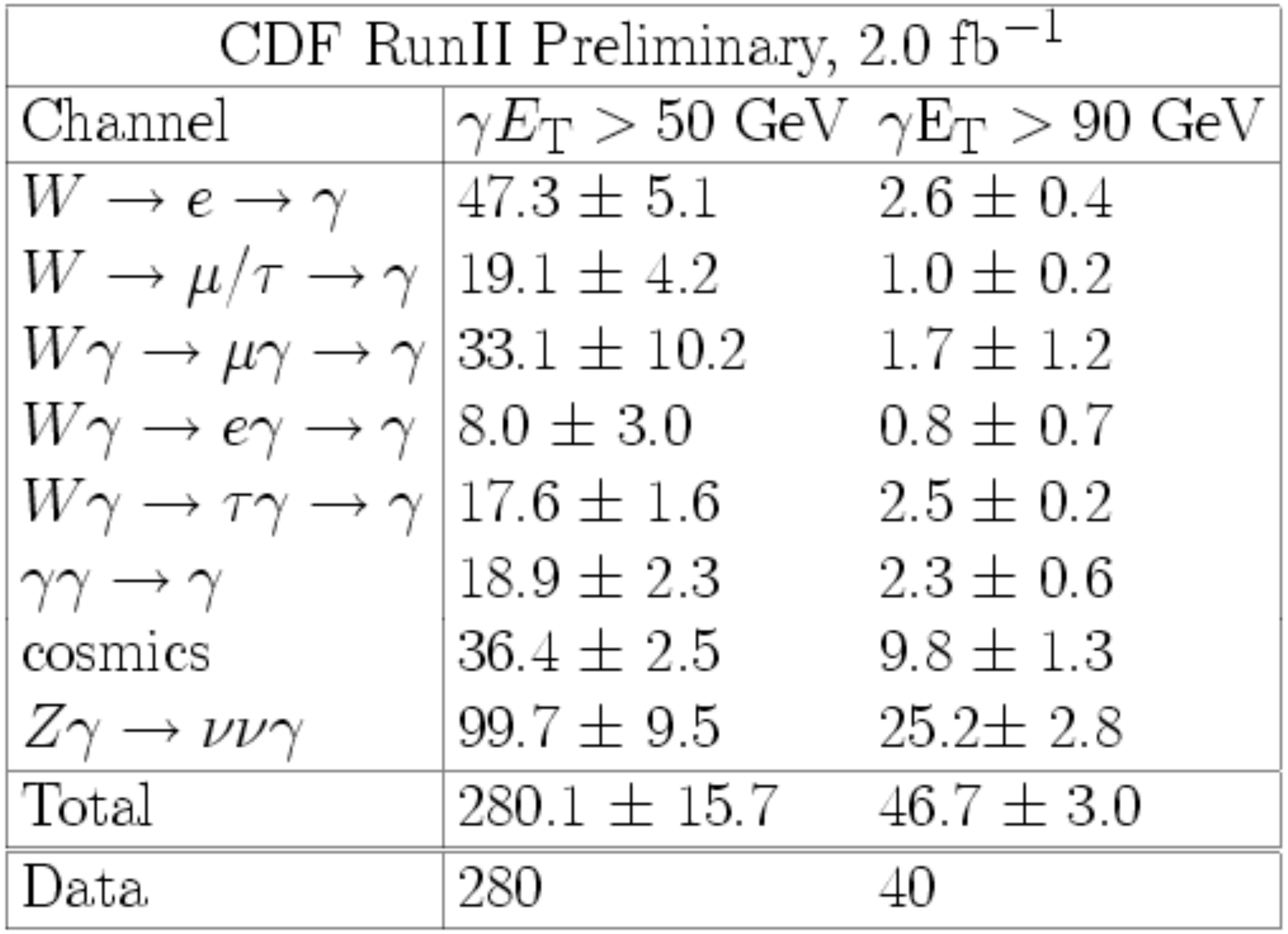
Phys.Rev.Lett.101:181602,2008

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

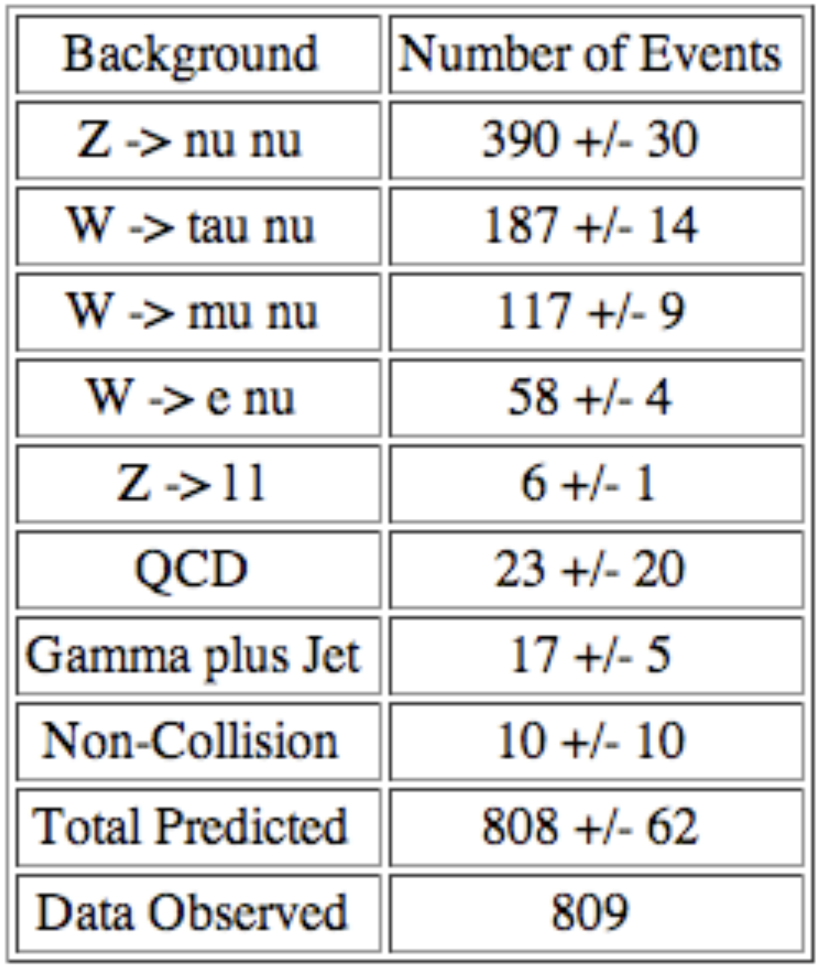
Background Predictions:



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