Technische Universität München

CLOSING IN ON MASS-DEGENERATE DARK MATTER SCENARIOS

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in collaboration with Mathias Garny, Alejandro Ibarra and Stefan Vogl

arXiv:1207.1431

IDM 2012, Chicago, July 27th 2012

1. CONTEXT: THE QUEST FOR WIMPS

long-awaited data are being collected as we speak...

direct detection

DM scattering off nuclei underground

indirect detection

yields of DM annihilation or decay

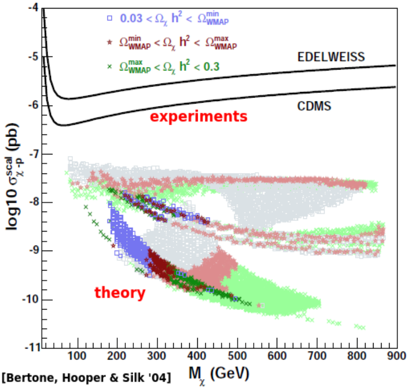
DM production in the lab

collider searches

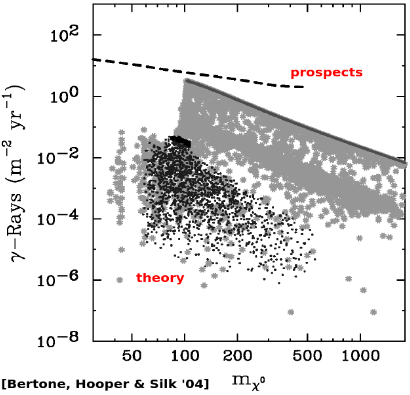
complementarity is key for wimp identification

1. CONTEXT: THE QUEST FOR WIMPS

before:



[Bertone, Hooper & Silk '04]



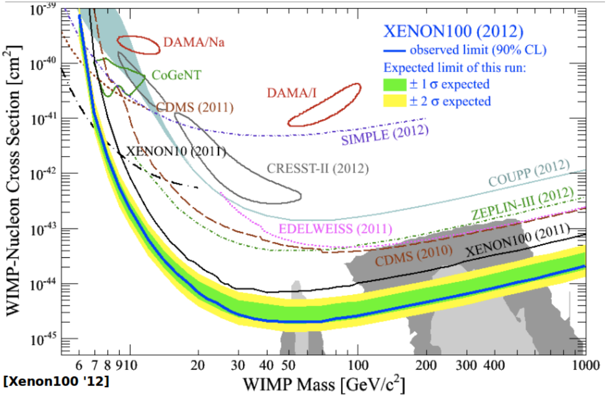
[Bertone, Hooper & Silk '04]

… a data-starved field

experiments lagged far behind predictions

1. CONTEXT: THE QUEST FOR WIMPS

now:



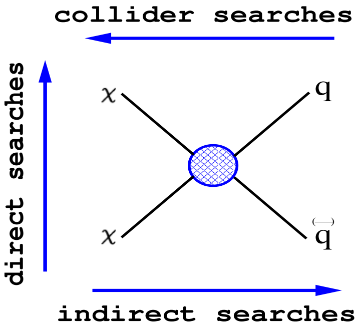
[Xenon100 '12]

... carving into theoretical models

"moment of truth for wimps" [Bertone '10]

1. COMPLEMENTARITY IN WIMP SEARCHES

the idea



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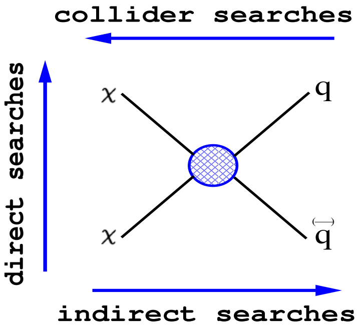
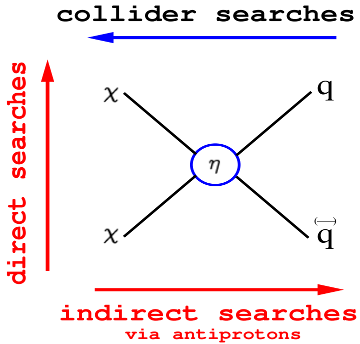


the complications

1. model-dependence
2. uncertainties

1. COMPLEMENTARITY IN WIMP SEARCHES

our approach [Garny+ '12, arXiv:1207.1431]



focus on mass-degenerate dark matter scenarios $m_\eta \gtrsim m_\chi$

.. enhanced direct and antiproton signals as $m_\eta \to m_\chi$

.. this is precisely the regime that escapes detection at colliders!

fold in all uncertainties

direct searches – antiprotons – collider searches

2. THE MODEL

minimal extension of the standard model [Garny+ '12, arXiv:1207.1431]

extra: Majorana fermion χ (WIMP DM), scalar η

interaction: $\mathcal{L}_{int} = -f\bar{\chi}\Psi_R\eta + \text{h.c.}$

coupling scheme: light quarks + fiducial $\chi\chi \to b\bar{b}$
$\Psi = (u, d, s, uds, b)$

our parameter space

DM mass m_χ – mass splitting m_η/m_χ – coupling f

thermal freeze-out

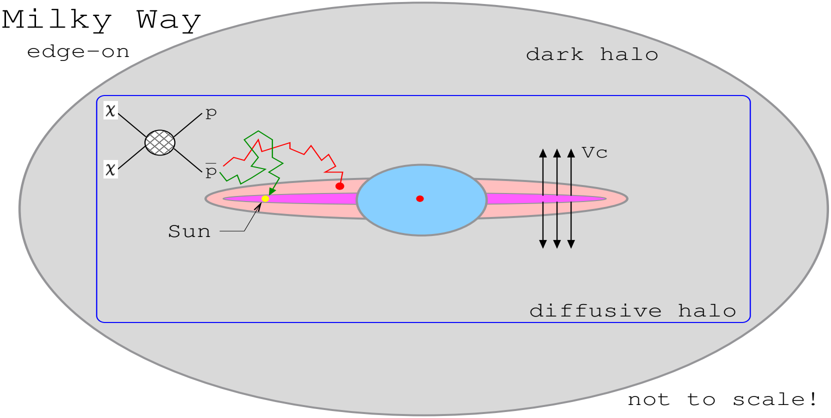
mass degeneracy $\to$ coannihilations ($\chi\eta \to qg$, $\eta\bar{\eta} \to gg$, $\eta\eta \to qq$)

use micromegas to compute $f_{thermal}$ corresponding to 7-yr WMAP Ω_{dm}

$\sigma v(\eta\bar{\eta} \to gg) \propto g_s^4/m_\eta^2$, so sizable even for $f \sim 0$!

thermal WIMPs $\to$ $m_\chi \gtrsim 200$ (1000) GeV for $m_\eta/m_\chi = 1.1$ (1.01)

3. ANTIPROTONS



$$0 = \frac{\partial f_{\bar{p}}}{\partial t} = \nabla \cdot (K(T,\vec{r})\nabla f_{\bar{p}}) - \nabla \cdot (\vec{V}_c(\vec{r}) f_{\bar{p}}) - 2h\delta(z)\Gamma_{\rm ann} f_{\bar{p}} + Q(T,\vec{r})$$

$$\Phi^{\rm IS}_{\bar{p}}(T) = \frac{v}{4\pi} f_{\bar{p}}(T, r_\odot)$$

solar modulation $\phi_F = 500$ MV

3. ANTIPROTONS

[Garny+ '12, arXiv:1207.1431]

on-site production

lowest order: $\chi\chi \to q\,\bar{q}$

s-wave helicity-suppressed ($\propto m_q^2$)

p-wave velocity-suppressed ($v/c \sim 1/1000$)

2→3 processes: $\chi\chi \to q\,\bar{q}\gamma$ $\chi\chi \to q\,\bar{q}\,g$ $\chi\chi \to q\,\bar{q}\,Z$

strongly enhanced when $m_\eta \to m_\chi$

formalism & uncertainties

source term: NFW – Einasto – isothermal profiles

fix $\rho_0 = 0.4$ GeV/cm^3

propagation: semi-analytical two-zone diffusion model

(L, δ, K_0, V_c) MIN – MED – MAX

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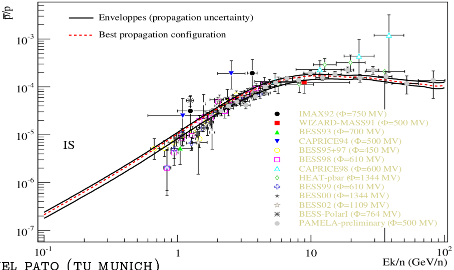
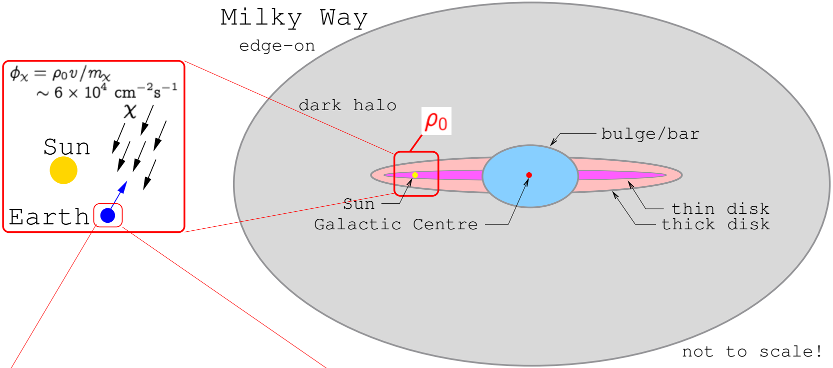
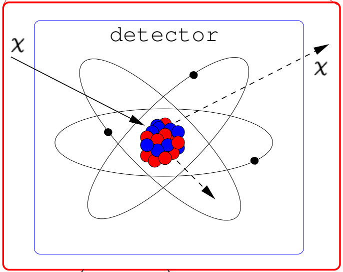


experimental data

draw 95% CL upper limit on f (given m_χ, m_η/m_χ)

4. DIRECT DETECTION





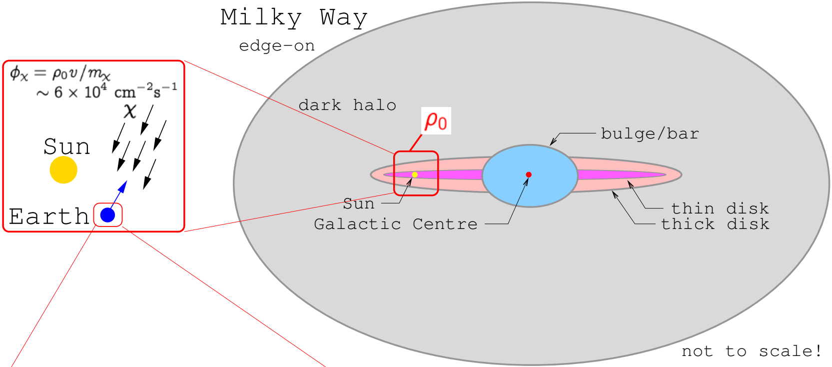
driving idea: detect WIMP scattering off nuclei

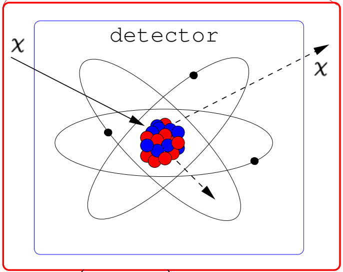
$$\frac{dR}{dE_R} = \frac{1}{m_N} \int_{v_{min}}^{\infty} d^3\vec{v}\, \frac{\rho_0 v}{m_\chi} f(\vec{v} + \vec{v}_e) \frac{d\sigma_{\chi-N}}{dE_R}$$

astrophysics

nuclear/particle physics

4. DIRECT DETECTION





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$$\sigma^{SD}_{\chi-N} \propto \left(a_p \langle S^N_p \rangle + a_n \langle S^N_n \rangle\right)^2$$

$$\sigma^{SI}_{\chi-N} \propto \left(Z f_p + (A - Z) f_n\right)^2$$

4. DIRECT DETECTION

in the framework of our minimal model...
[Garny+ '12, arXiv:1207.1431]

spin-dependent

$$a_p = \sum_{q=u,d,s} \frac{d_q}{\sqrt{2}G_F} \Delta q^{(p)} \qquad d_q = \frac{1}{8} \frac{f^2}{m_\eta^2 - (m_\chi + m_q)^2}$$

spin-independent

$$\frac{f_p}{m_p} = -\frac{m_\chi}{2} \sum_{q=u,d,s} f_{T_q}^{(p)} g_q - \frac{8\pi}{9} b f_{TG}^{(p)} - \frac{3}{2} m_\chi \sum_{q=u,d,s,b} g_q \left(q^{(p)}(2) + \bar{q}^{(p)}(2) \right)$$

$$g_q = -\frac{1}{8} \frac{f^2}{\left(m_\eta^2 - (m_\chi + m_q)^2\right)^2} \qquad b = \left(B_S - \frac{m_\chi}{2} B_{2S} - \frac{m_\chi^2}{4} B_{1S} \right) \propto f^2$$

mass degeneracy

d_q, g_q resonate at $m_\eta = m_\chi + m_q \rightarrow$ enhanced SD, SI signals [Hisano+ '11]
not too close to resonance: $m_\eta - m_\chi > 1$ GeV, $(m_\eta - m_\chi) \geq 2 m_q$

4. DIRECT DETECTION

uncertainties

[Garny+ '12, arXiv:1207.1431]

- astrophysics

$$\rho_0 = 0.4 \text{ GeV/cm}^3 \,, \; v_0 = 230 \pm 30 \text{ km/s} \,, \; v_{esc} = 544 \text{ km/s}$$

- nuclear physics

$$\Delta s^{(p)} = -0.09 \pm 0.03 \,, \; \Sigma_{\pi n} = 64 \pm 8 \text{ MeV} \,, \; \sigma_0 = 36 \pm 7 \text{ MeV} \,, \; q(2) \; \pm 15\%$$

$$\boxed{\frac{dR}{dE_R} = \frac{1}{m_N} \int_{v_{min}}^{\infty} d^3\vec{v} \, \frac{\rho_0 v}{m_\chi} f(\vec{v} + \vec{v}_e) \frac{d\sigma_{\chi-N}}{dE_R}}$$

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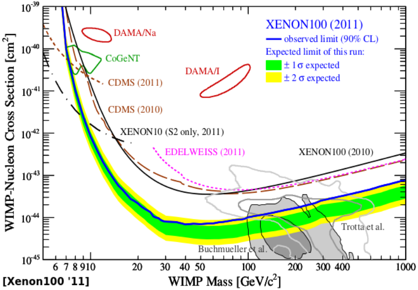
experimental data



[Xenon100 '11]

Xenon100 – best published SI limit

exposure of 1471 kg.day
$E_R = 8.4 - 44.6$ keV
$N_{obs} = 3 \,,\ N_{bkg} = 1.8$
Feldman-Cousins 95%CL $N_R \leq 6.45$

(new limit 3.5 times better)

4. DIRECT DETECTION

uncertainties

[Garny+ '12, arXiv:1207.1431]

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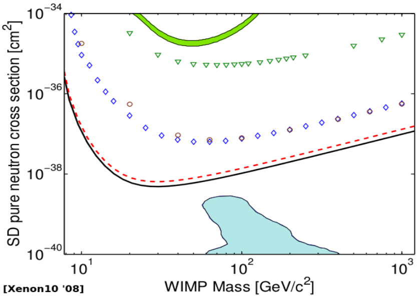

Xenon10 – best SD-n limit

exposure of 136 kg.day
$E_R = 4.5 - 27$ keV
$N_{obs} = 10 \,,\; N_{bkg} = 0$
Feldman-Cousins 95%CL $N_R \leq 17.82$

4. DIRECT DETECTION

uncertainties

[Garny+ '12, arXiv:1207.1431]

- astrophysics

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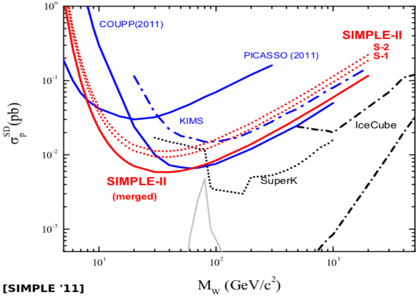
experimental data



[SIMPLE '11]

SIMPLE – within best SD-p limits

phase II = stage 1 + stage 2
exposure of (13.47+6.71) kg.day
$E_R = 8 - 100$ keV
$N_{obs} = 14 + 1\,,\ N_{bkg} = 12.07 + 1.70$
Feldman-Cousins 95%CL $N_R \leq 10.54$

4. DIRECT DETECTION

uncertainties

[Garny+ '12, arXiv:1207.1431]

- astrophysics

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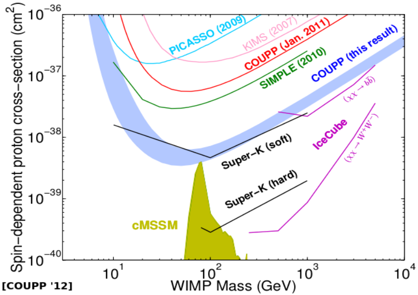


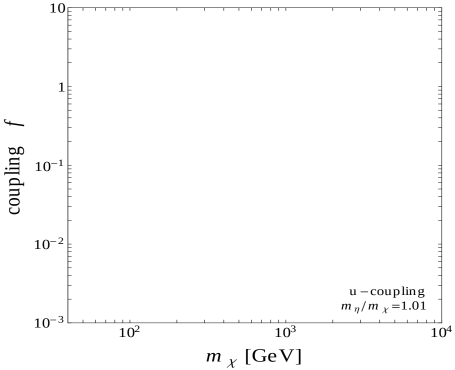
COUPP – within best SD-p limits

high-threshold run
exposure of 394.0 kg.day (×79.1%)
$E_R = 15.5 - 100$ keV
$N_{obs} = 8\,,\ N_{bkg} = 0$
Feldman-Cousins 95%CL $N_R \leq 15.29$

5. RESULTS: OUR METHODOLOGY

our parameter space

DM mass m_χ – mass splitting m_η/m_χ – coupling f



loose notes

[Garny+ '12, arXiv:1207.1431]

signals go as f^4!

Xenon100 dominates direct detection limits (for our models)

taking bino couplings, exclusion at $m_\chi \lesssim 215$ GeV

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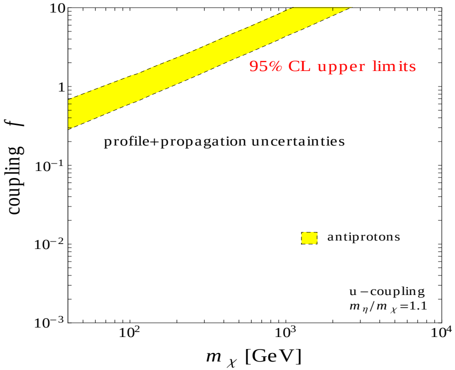

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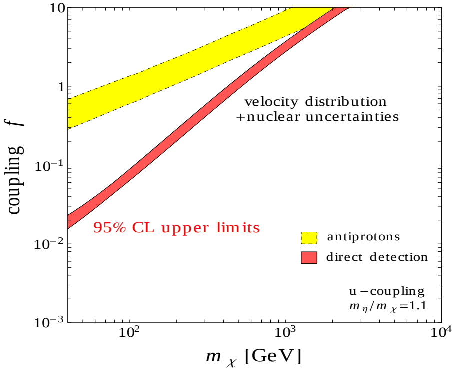

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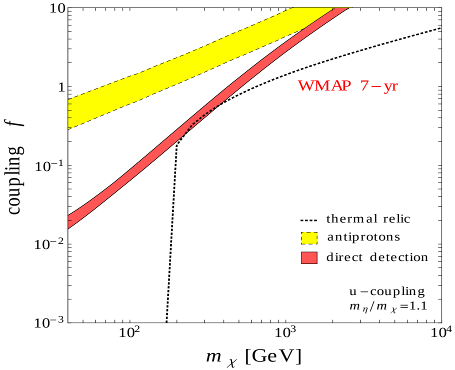

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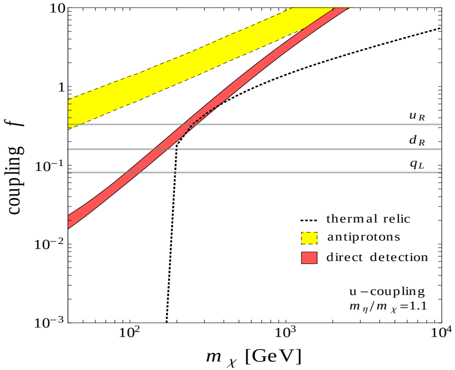

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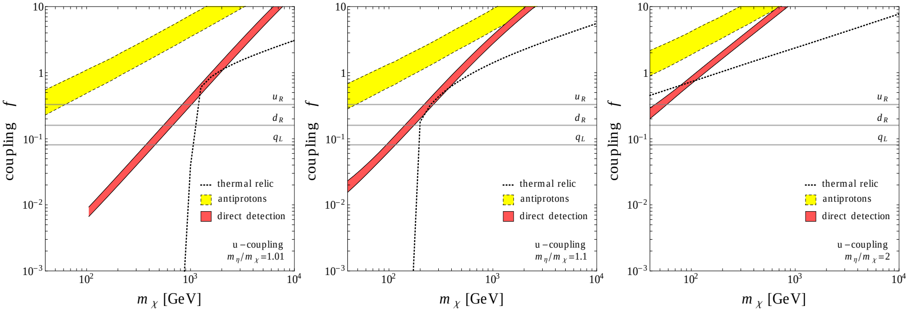
5. RESULTS: MASS DEGENERACY

[Garny+ '12, arXiv:1207.1431]



mass degeneracy $m_\chi \leftarrow m_\eta$

both direct detection and antiprotons enhanced as $m_\eta \to m_\chi$

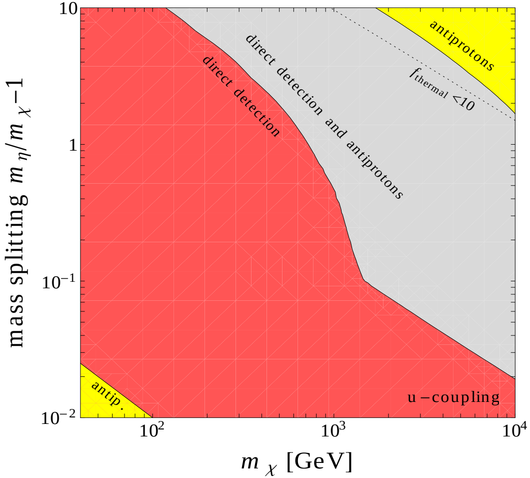
but: enhancement much stronger in direct detection

direct detection takes the lead over antiprotons for $m_\chi \lesssim$ few TeV

(thermal relic cut-off due to $\sigma v(\eta\bar{\eta} \to gg) \propto g_s^4/m_\eta^2$)

5. RESULTS: DOMINANT CONSTRAINT?

[Garny+ '12, arXiv:1207.1431]

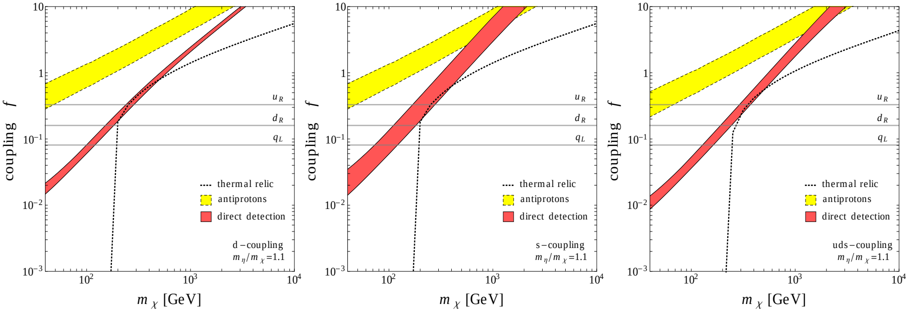


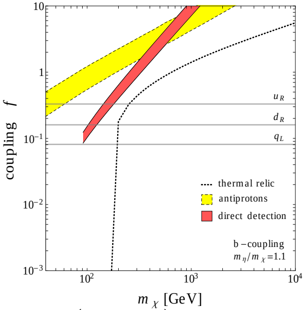
(note: not an exclusion plot!)

antiprotons constraints kick in only for $f \gtrsim 10$

5. RESULTS: COUPLING SCHEMES

[Garny+ '12, arXiv:1207.1431]





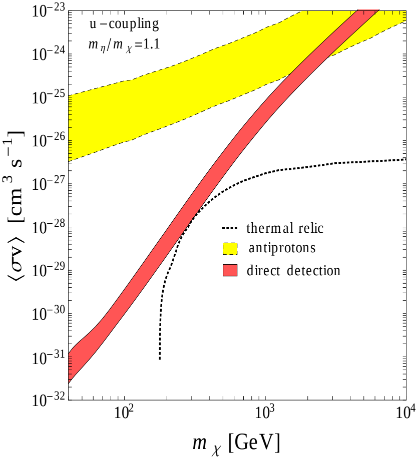
similar constraints for light quarks

weaker constraints for b-quark (through loop coupling to gluons)

but: still stronger than antiproton limits

5. RESULTS: USER-FRIENDLY PLOTS

[Garny+ '12, arXiv:1207.1431]



note: translation *is* model-dependent

again, antiprotons kick in at high masses where $f \gtrsim 10$

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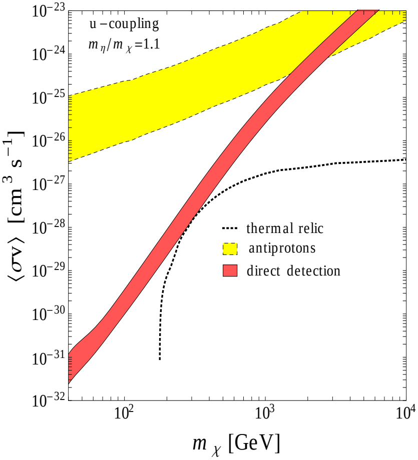

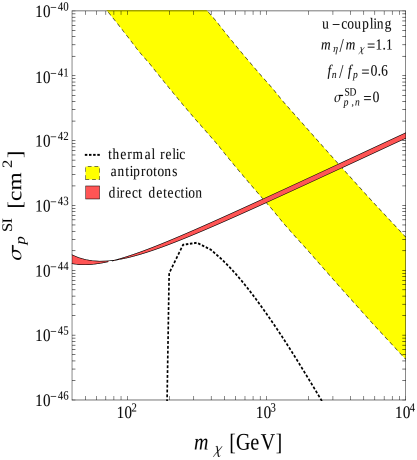

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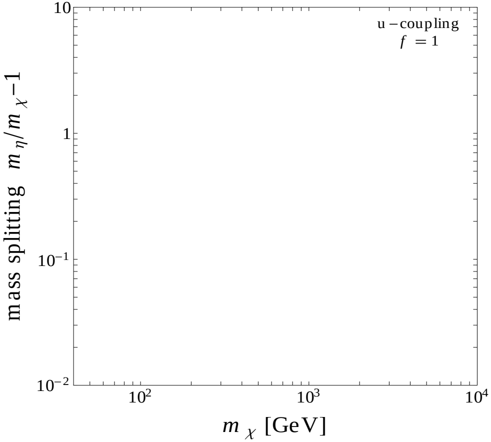

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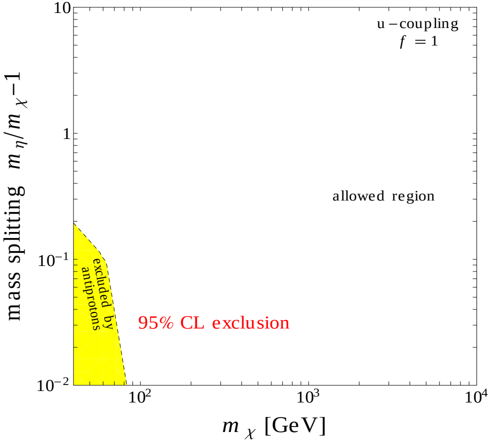

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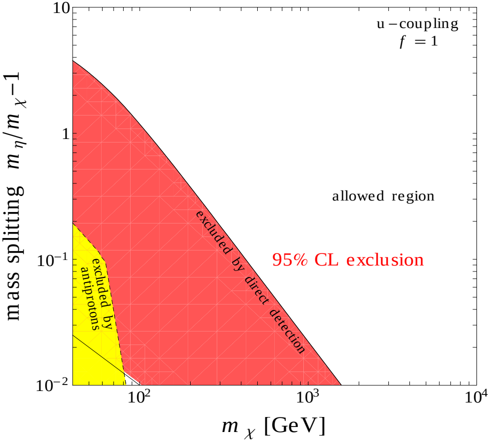

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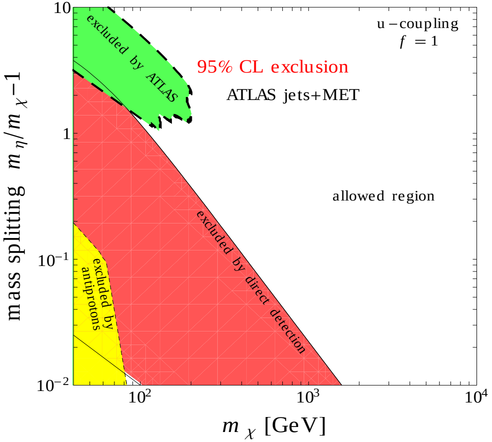

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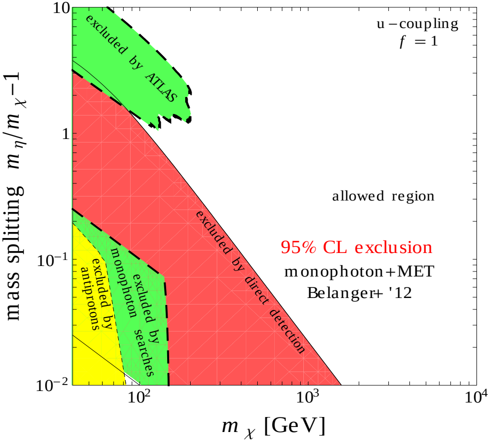

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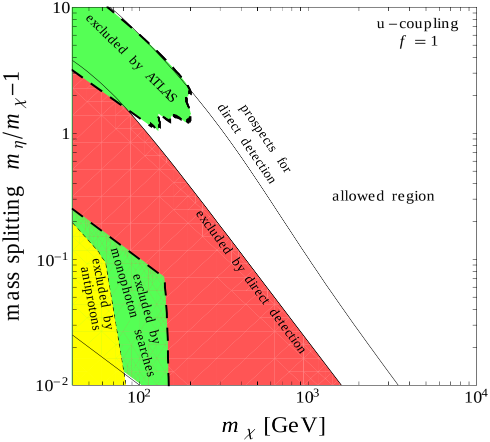

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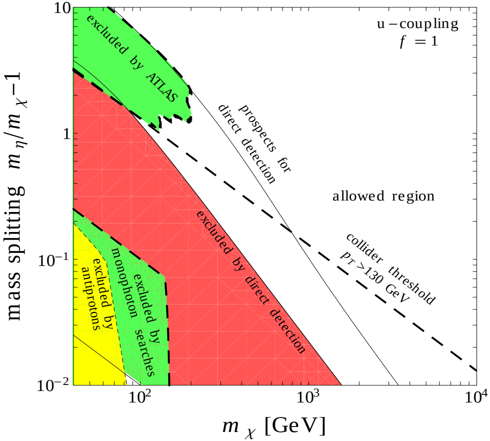
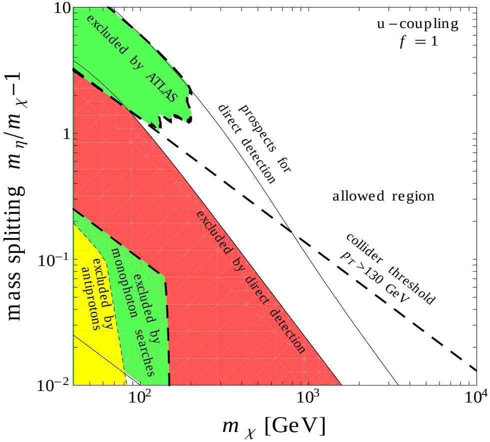


direct searches exclude low splittings, colliders probe high splittings
direct-collider complementarity looking good!

5. RESULTS: COMPLEMENTARITY AT ITS BEST



direct searches exclude low splittings, colliders probe high splittings
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two numbers, one disclaimer

Xe100 excludes splittings $\lesssim 19$ (2)% at $m_\chi = 300$ (1000) GeV ($f = 1$)
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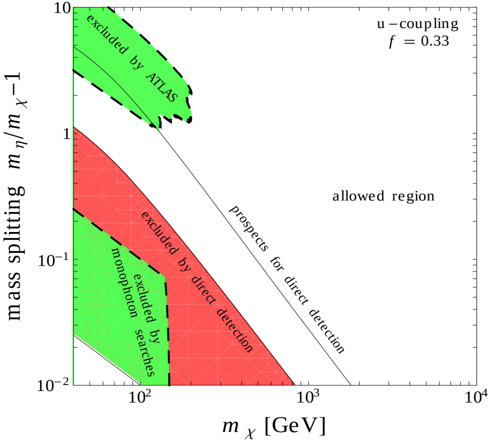

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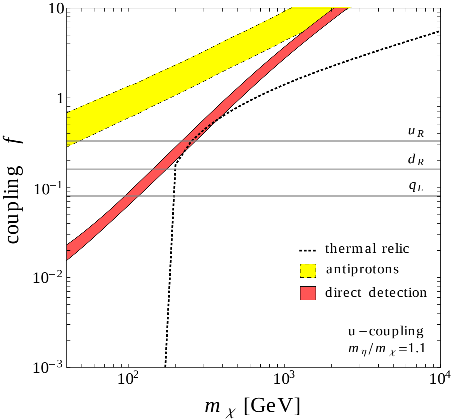
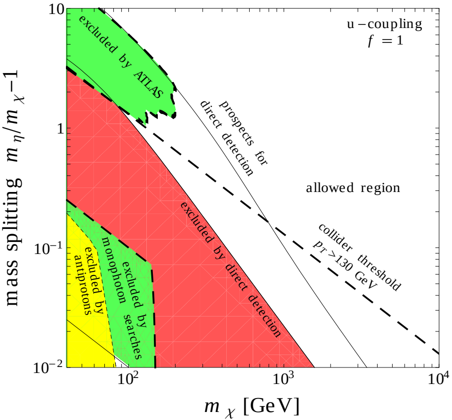
to be fair, collider searches don't depend on f

6. CONCLUSION

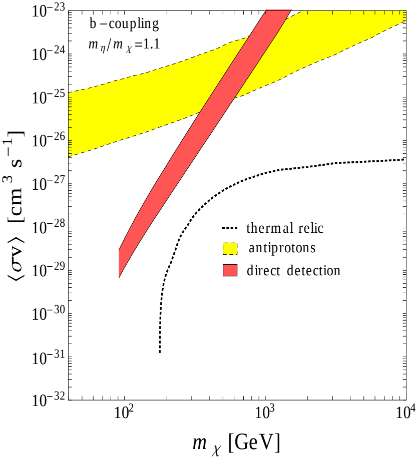
- .. mass degeneracy enhances direct and indirect signals
- .. antiproton constraints lag behind direct searches
- .. complementarity antiprotons-direct-collider looks promising
- .. closing in on degenerate setups is feasible within next few years





5. RESULTS: USER-FRIENDLY PLOTS

[Garny+ '12, arXiv:1207.1431]



note: translation *is* model-dependent

again, antiprotons kick in at high masses where $f \gtrsim 10$

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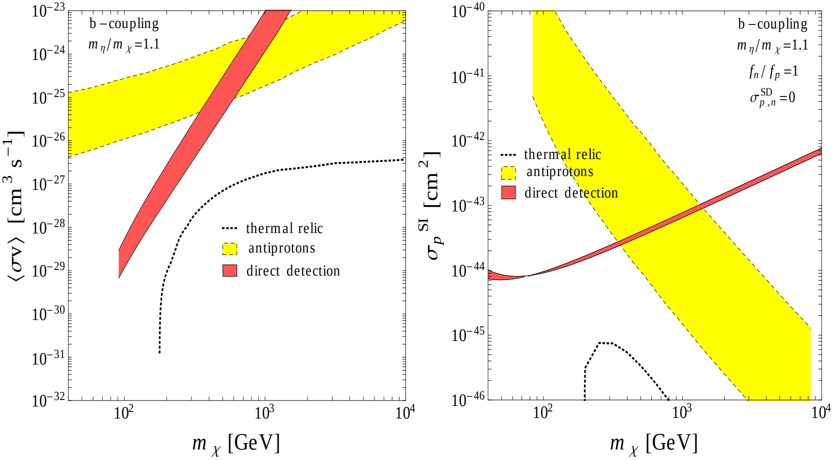

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