Constraints on Self Interacting Dark Matter from IceCube Results

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CERN - June/July 2014

Outline

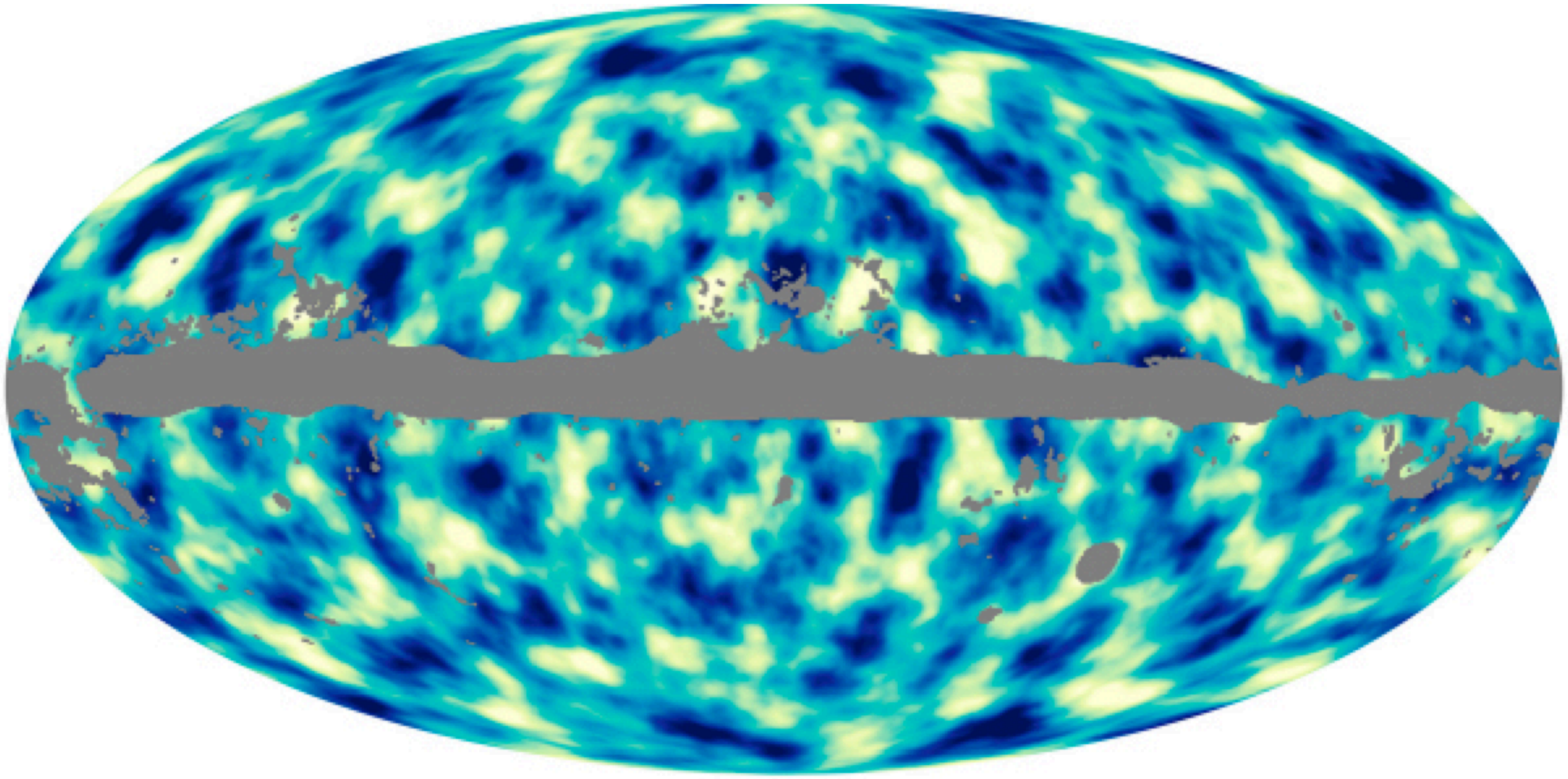
1. Small Scale Potential Problems
   - DM Self-Interaction (SIDM) as possible solution
2. Current constraints on SIDM
3. SIDM: enhances DM capture rate
4. Enhanced ν flux from DM annihilation
5. Estimate ν flux in IceCube
   - MC simulation prediction vs IceCube data:

Constraints on SIDM models

I.A, C. P. de Los Heros & Denis S. Robertson JCAP **02,** 2014

Collisionless CDM

Extremely successful at large scales

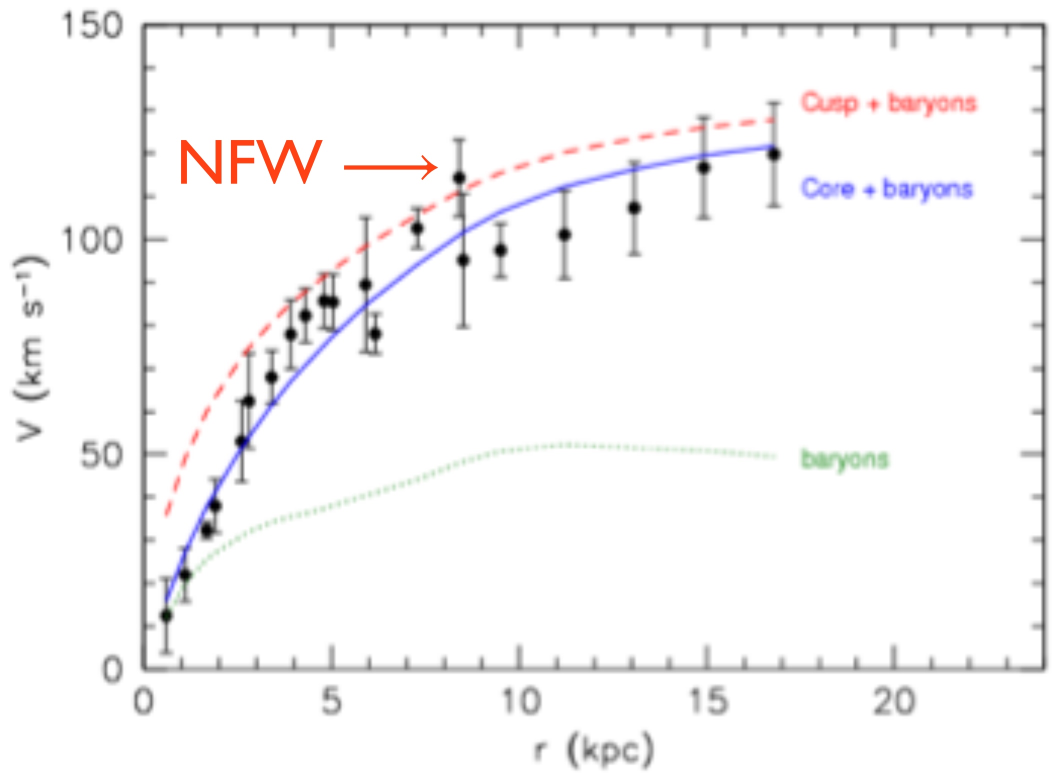


Date: 02 April 2013
Satellite: Planck
Depicts: All-sky map of dark matter distribution in the Universe
Copyright: ESA and the Planck Collaboration

CDM simulations fit very well large scale observations

CDM Potential Problems

at small scale structure formation



Core / Cusp

CDM: too much DM ~ few Kpc

Majority of gal rot curves: better fit by cored profile

(Weinberg et al. , arXiv:1306.0913)

Data: F568-3 (SSDS)

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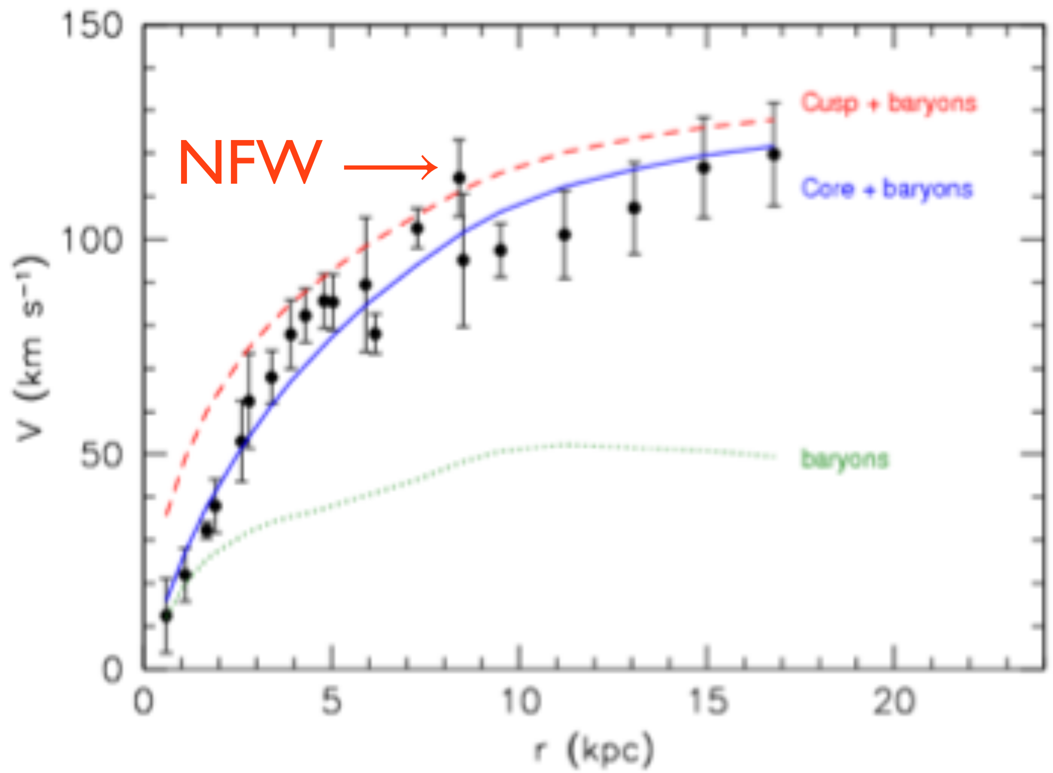

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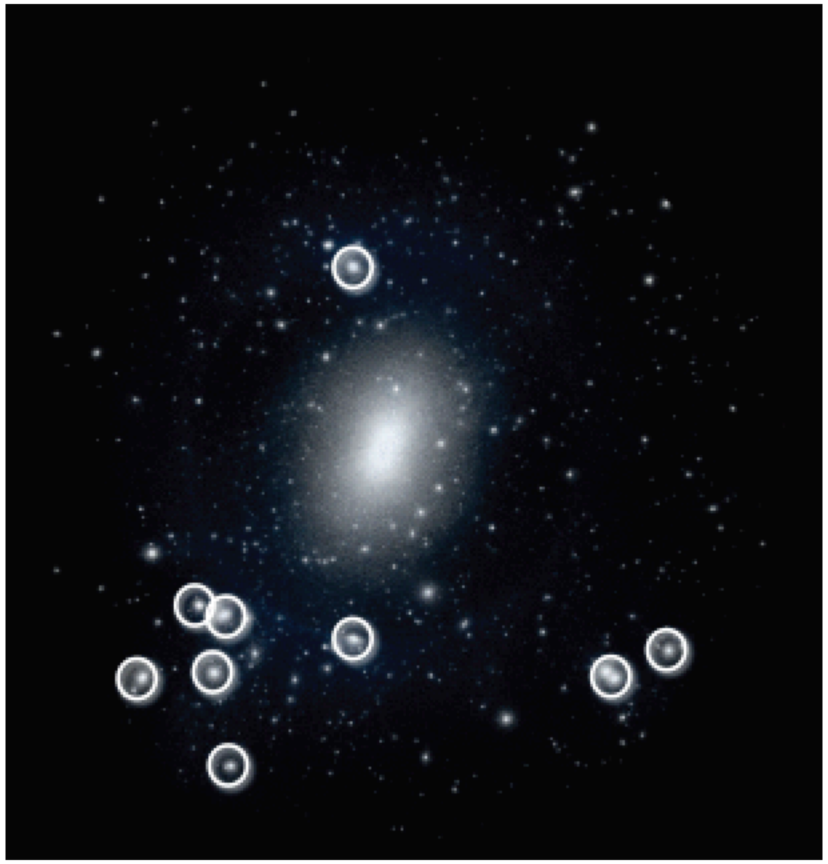

Too Big to Fail

9 massive SIM DM subhalos

M(center) ~ 5 M(stellar dyn)

Boylan-Kolchin et al. (MNRAS **415**, 2011)

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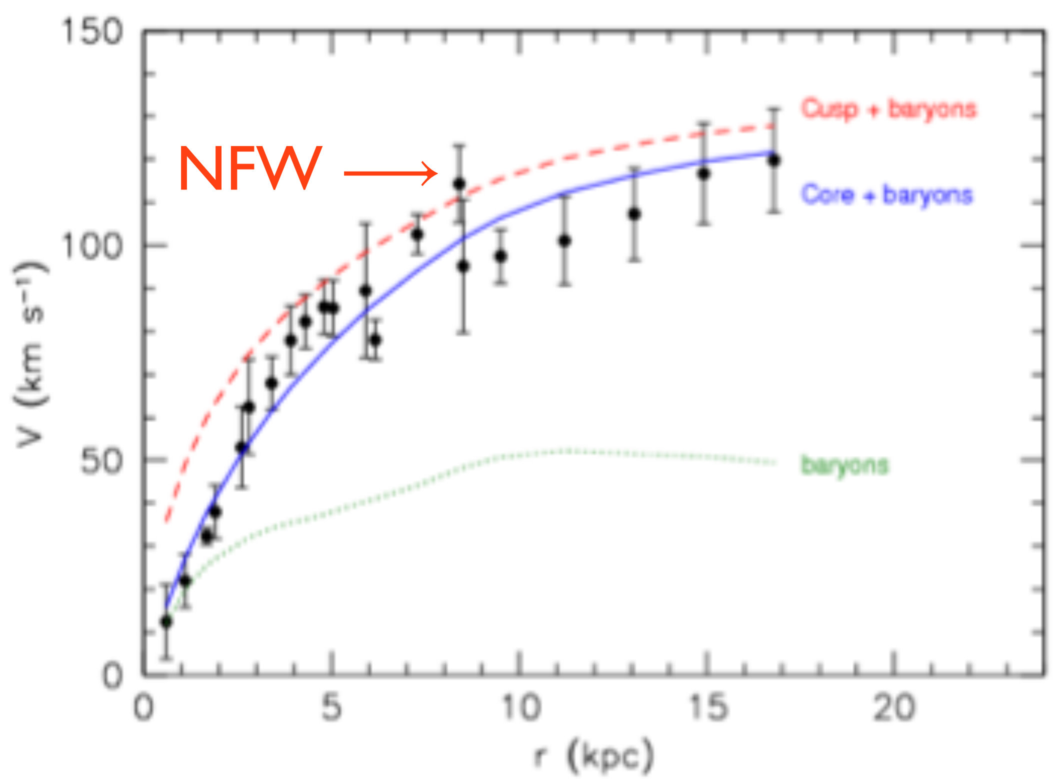

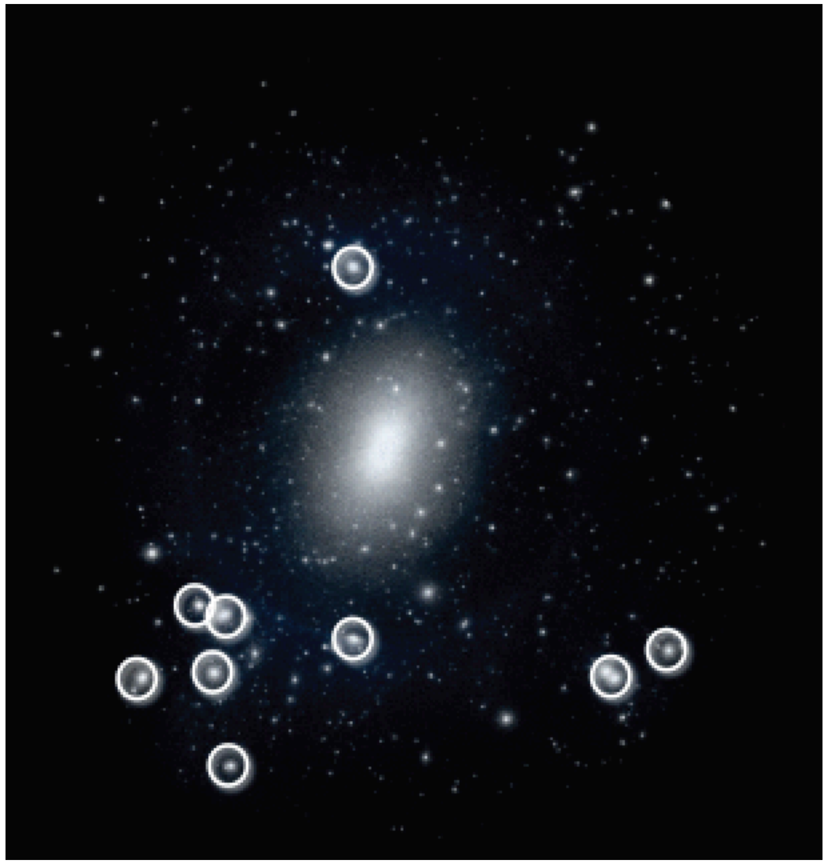

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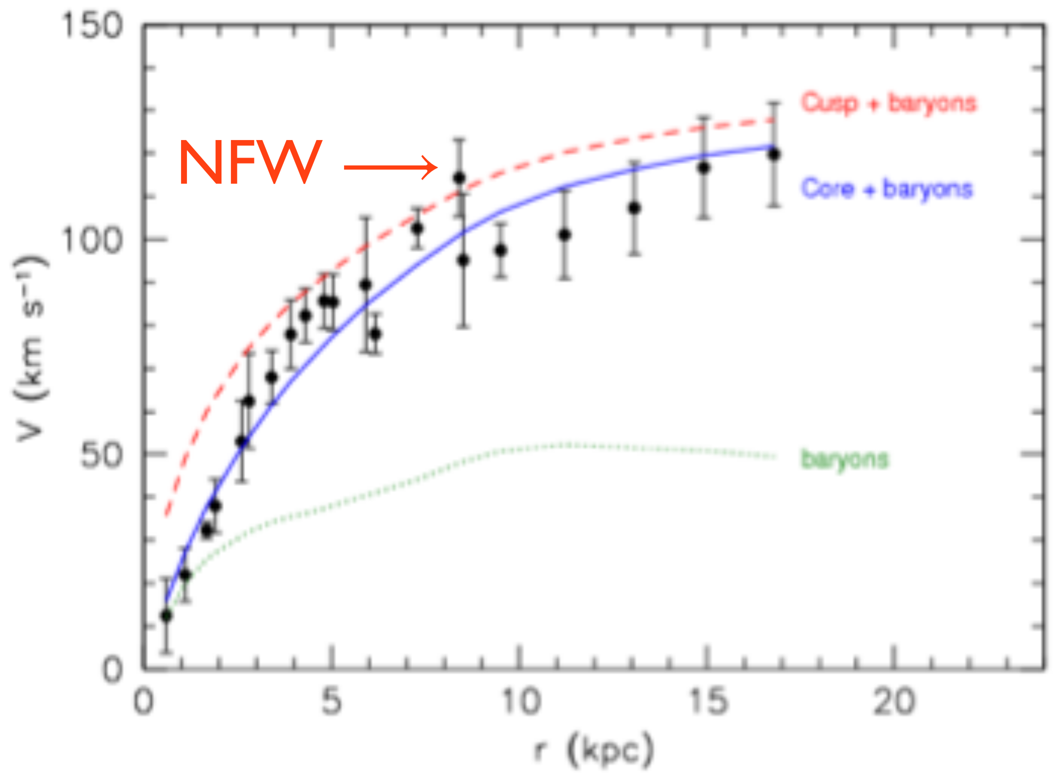

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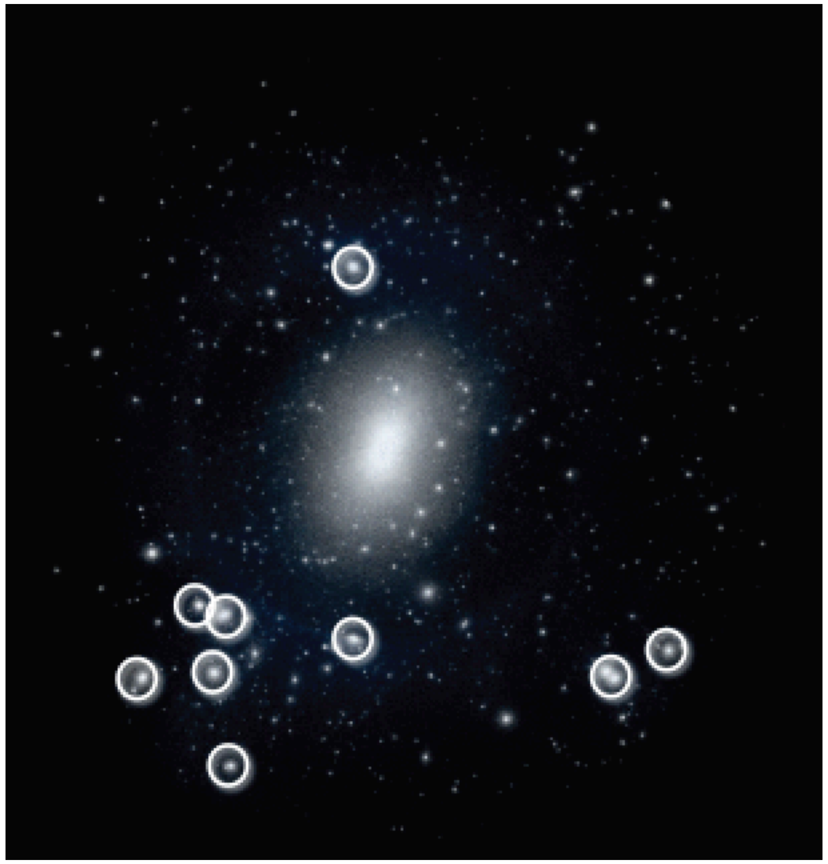

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CDM simulations predict too much mass in halos and subhalos central regions

Self Interacting Dark Matter

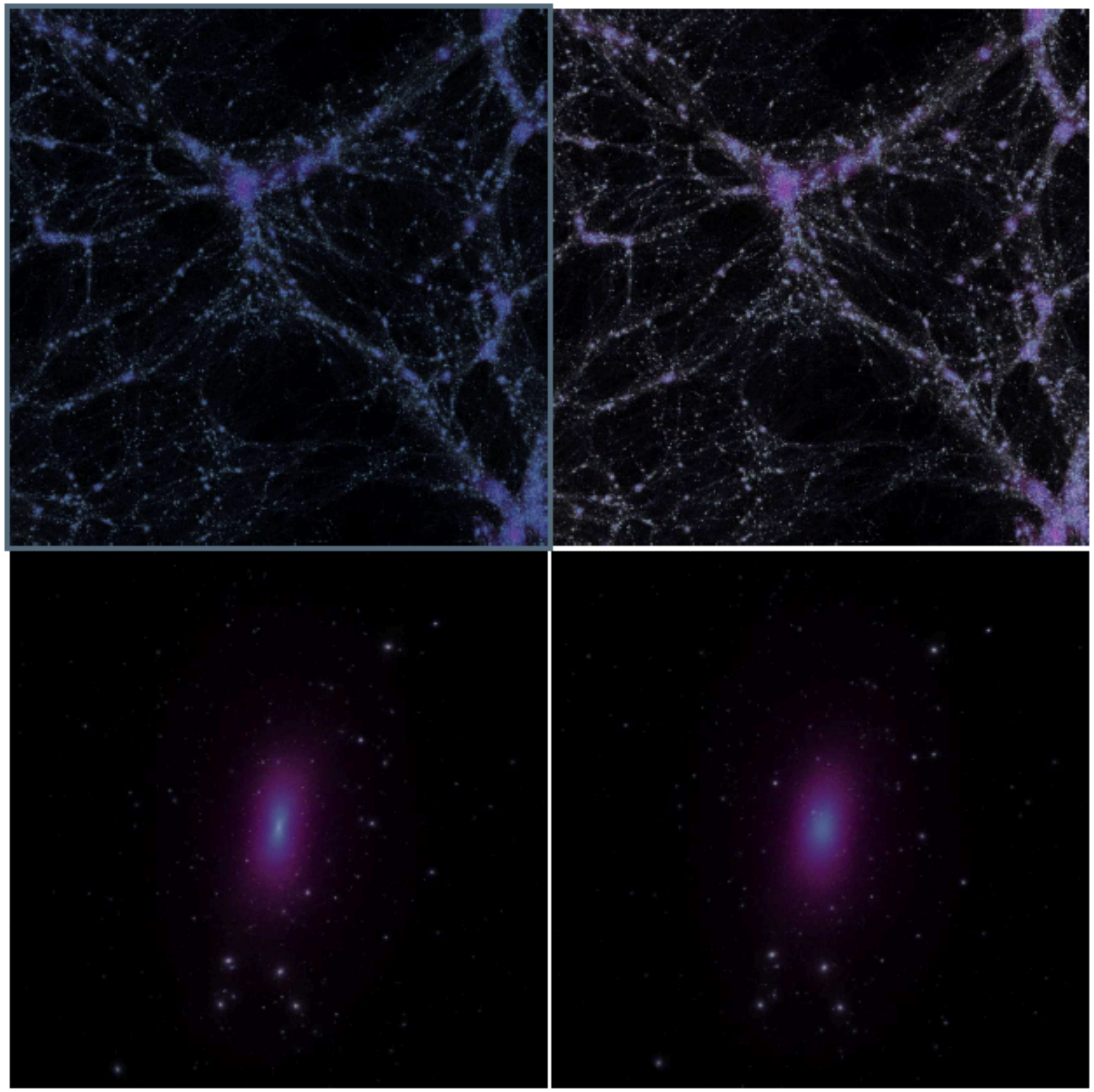
SIDM solves Small Scale Potential Problems

(Spergel and P. Steinhardt, PRL **84**, 2000)

DM scatters before reaching center of galaxy

$$\frac{\sigma_{\chi\chi}}{\mathbf{m}_\chi} = \mathbf{8 \times 10^{-(25-22)}\, cm^2/GeV}$$
$$= \mathbf{4.5 - 450\ cm^2/g}$$

SIDM Simulations



CDM and SIDM simulations

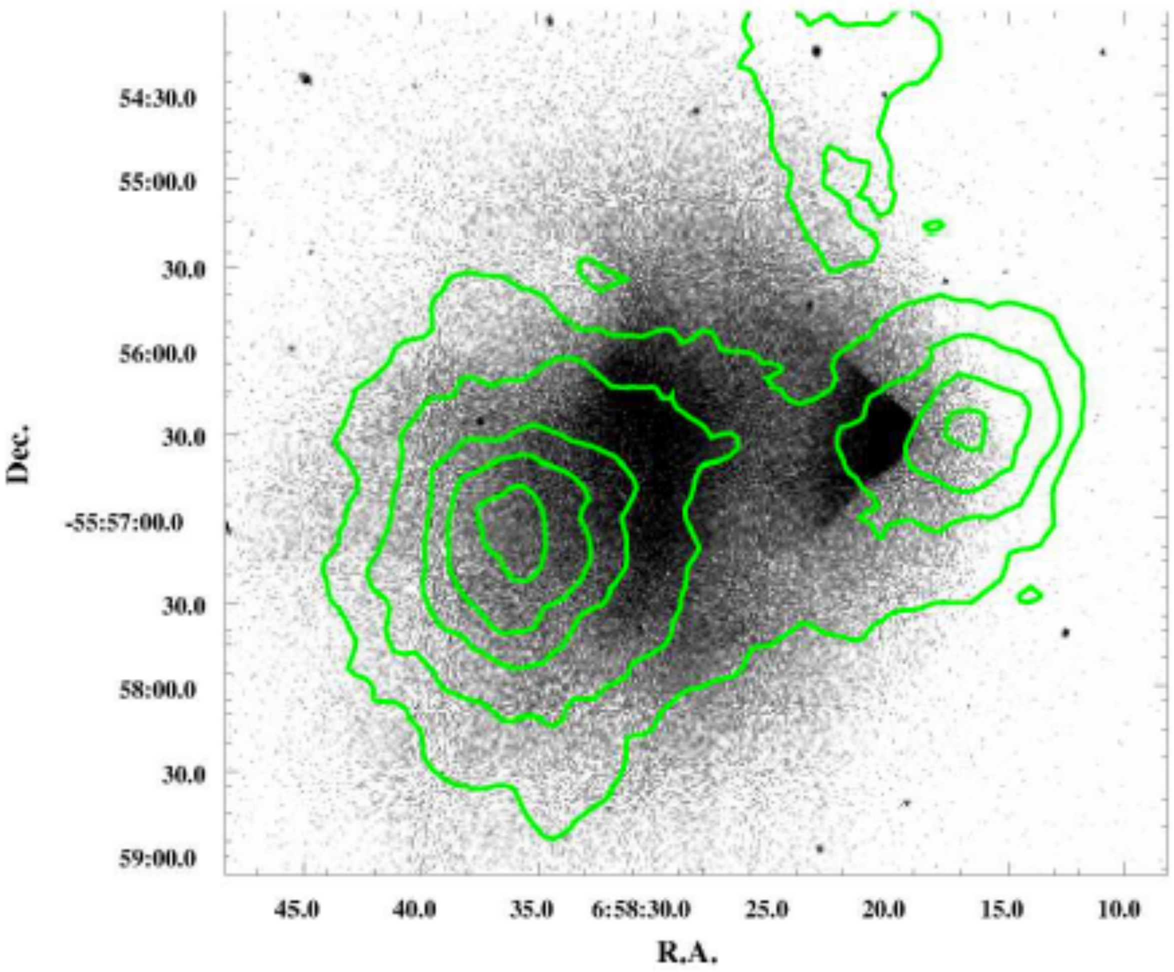
(M. Rocha et al., MNRAS **430**, 2013)

- SIDM numerical simulation
- constant density cores: much reduced central density
- subhalo content is modestly reduced

$$\frac{\sigma_{\chi\chi}}{m_\chi} \simeq 1\ \mathrm{cm^2/g} \Rightarrow \text{central density is TOO LOW}$$

$$\simeq 0.1\ \mathrm{cm^2/g} \Rightarrow \text{consistent}$$

SIDM Constraints

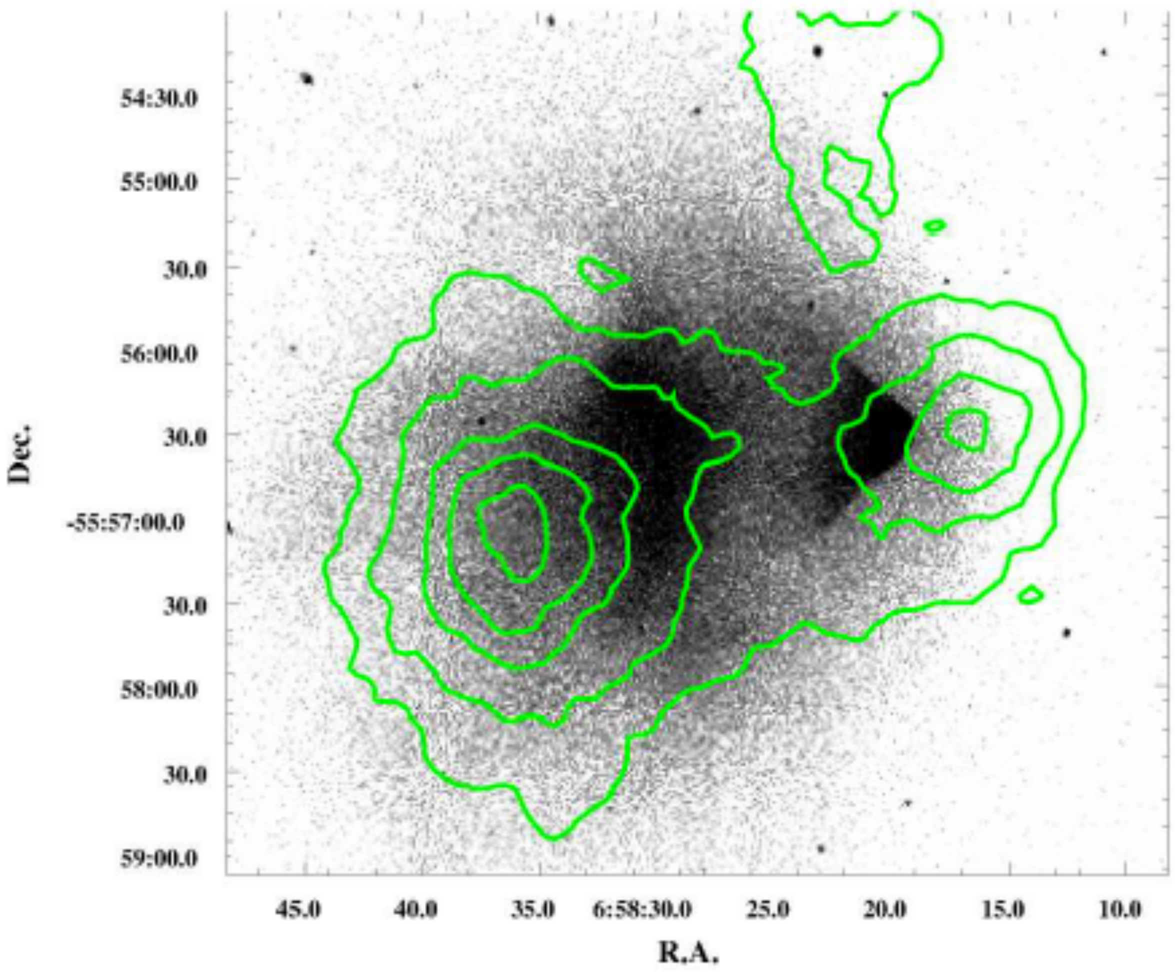


Bullet Cluster

(S. Randall et al., ApJ **679**, 2008)

Xray image and lensing contour

SIDM Constraints



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$$\frac{\sigma_{\chi\chi}}{\mathbf{m}_\chi} < \mathbf{1.25\ cm^2/g}$$

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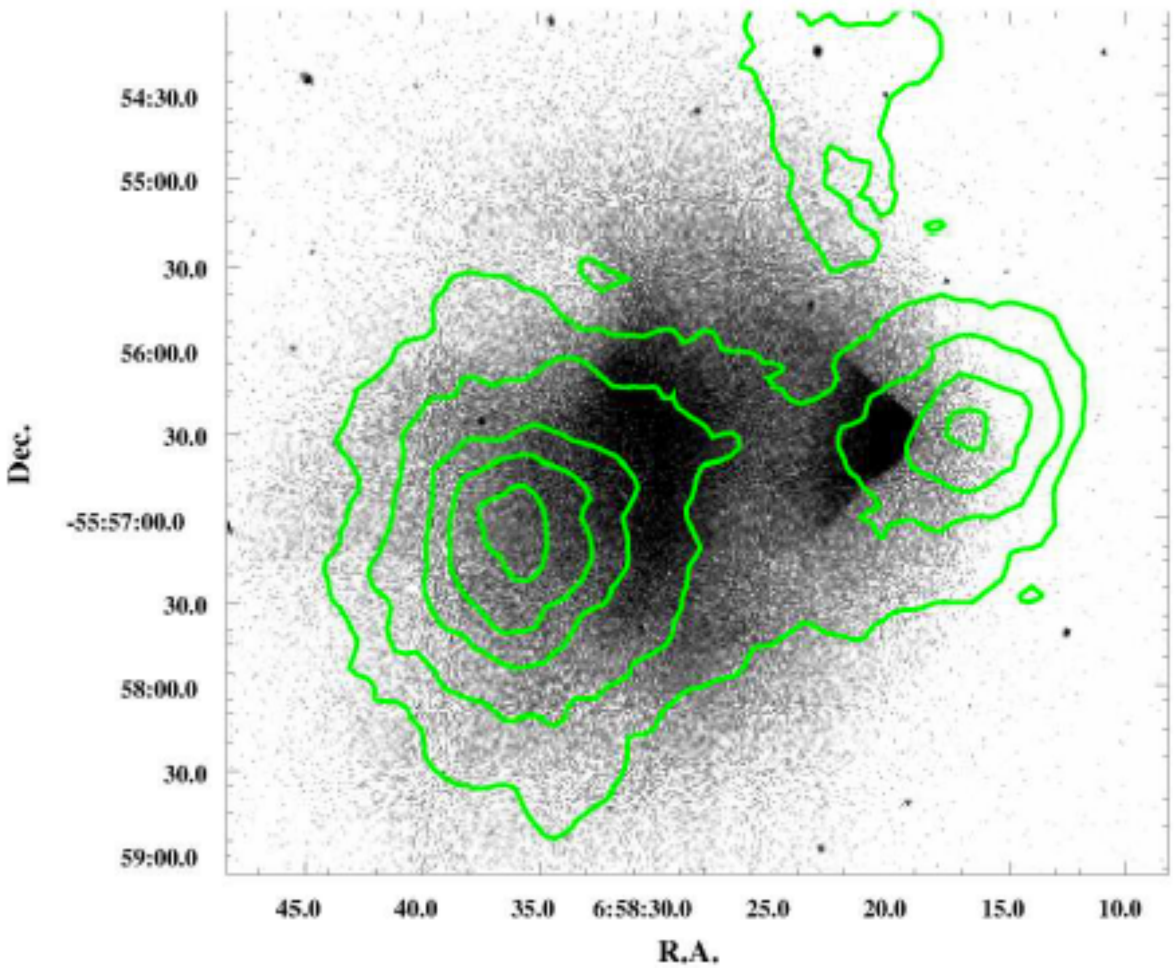

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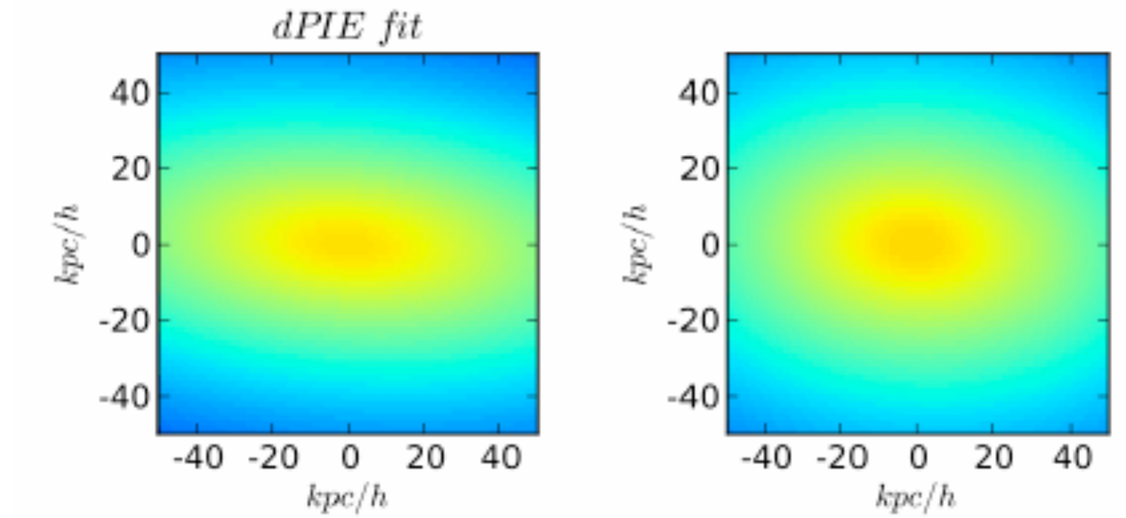
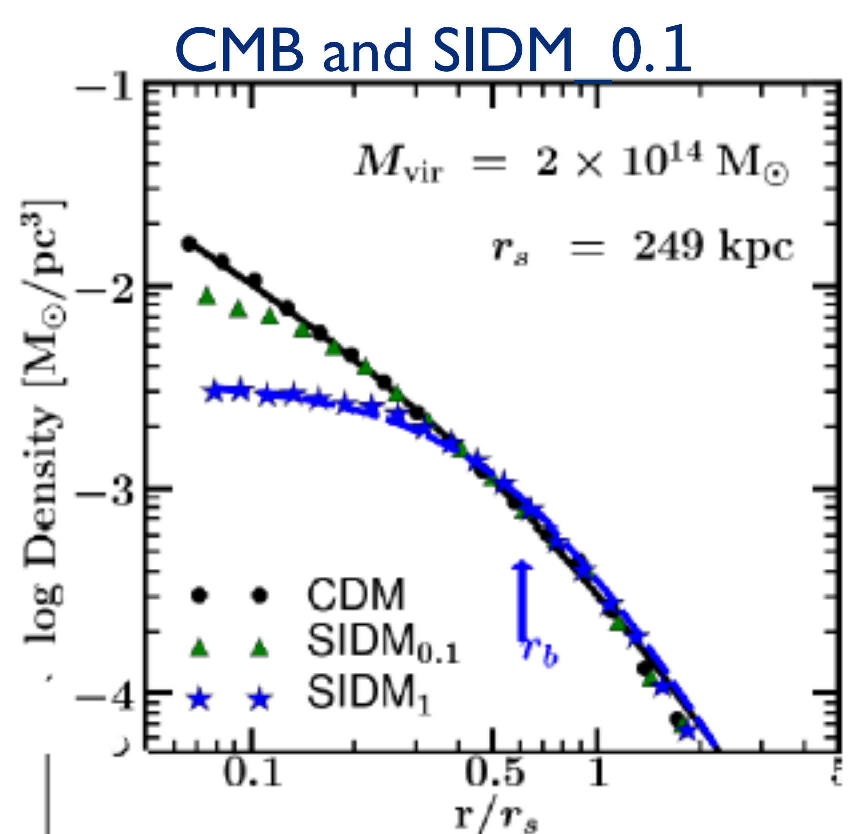
Cosmological Simulations



(A.Peter et al., arXiv:1208.3026)



DM halos surface densities

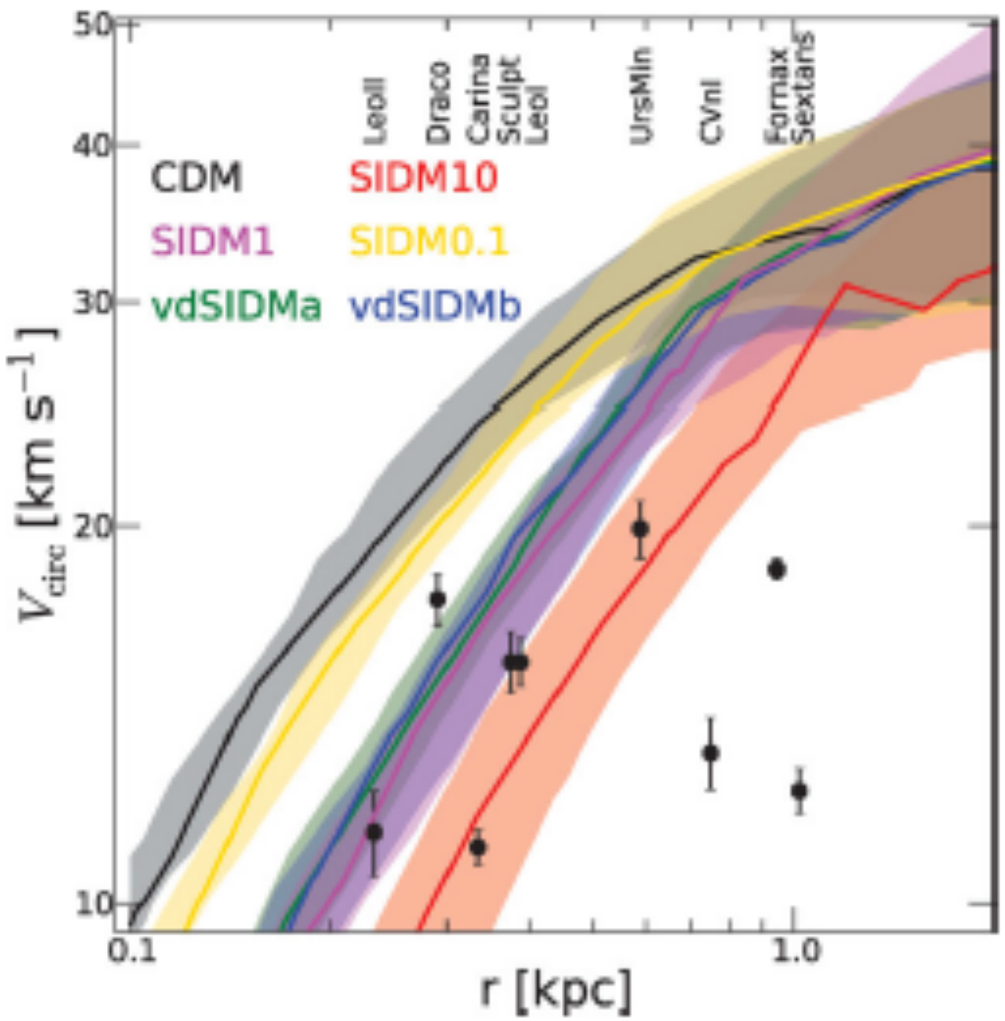
(A.Peter et al., MNRAS **430**, 2013)

SIDM Constraints

Milky Way Dwarfs Kinematics

(Zavala et al., MNRAS **431**, 2013)

Xray image and lensing contour



Too big to fail is solved if:

$$\frac{\sigma_{\chi\chi}}{\mathbf{m}_\chi} \geq \mathbf{1\ cm^2/g}$$

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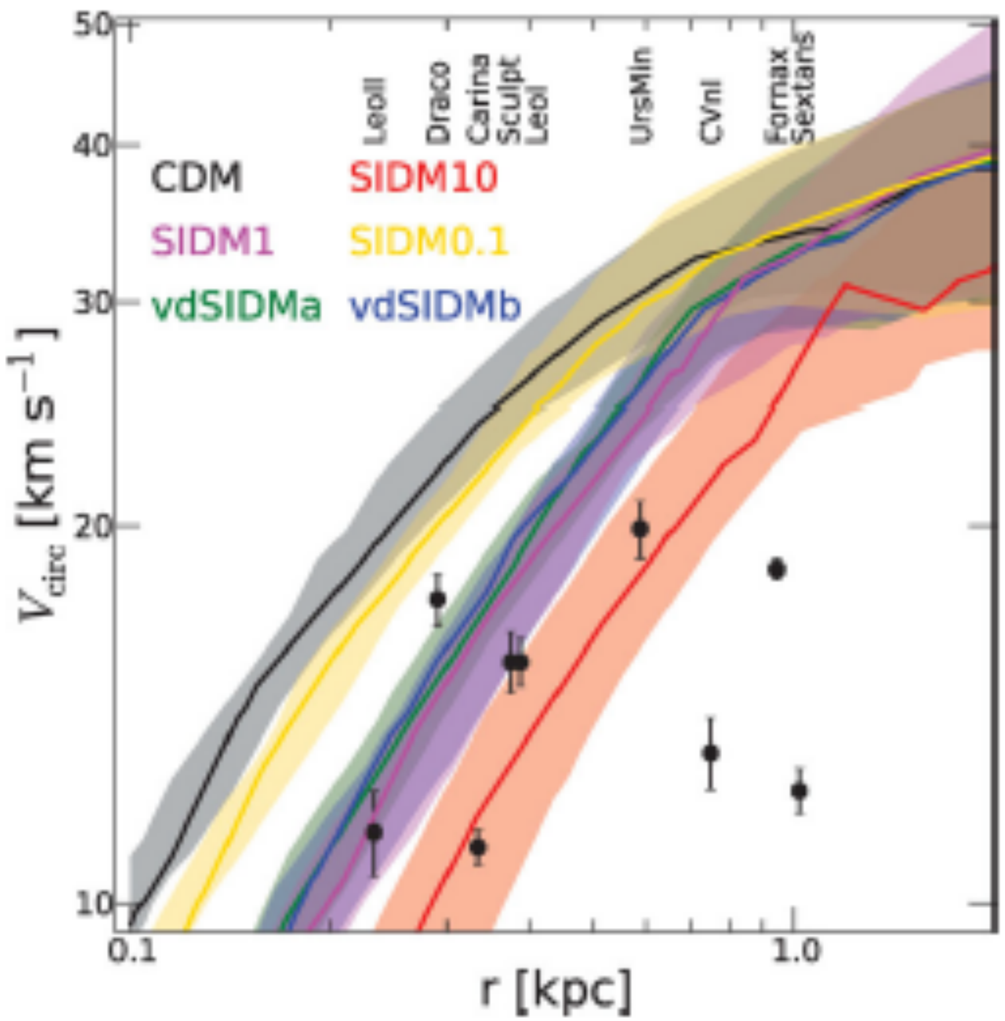

Too big to fail is solved if:

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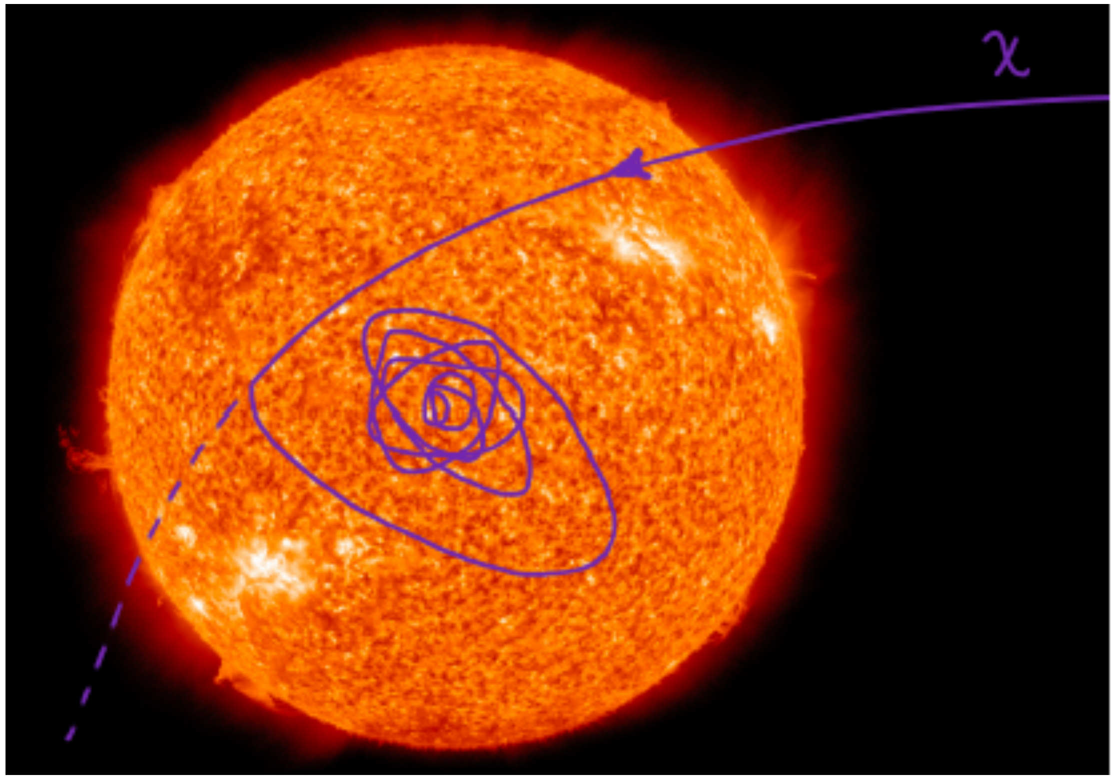
SIDM will be effective if

$$0.1 < \frac{\sigma_{\chi\chi}}{m_\chi} < 1\ \mathrm{cm^2/g}$$

Probing SIDM with neutrinos

Self-Interaction enhances DM capture in the Sun



ν flux from DM annihilation will also be enhanced

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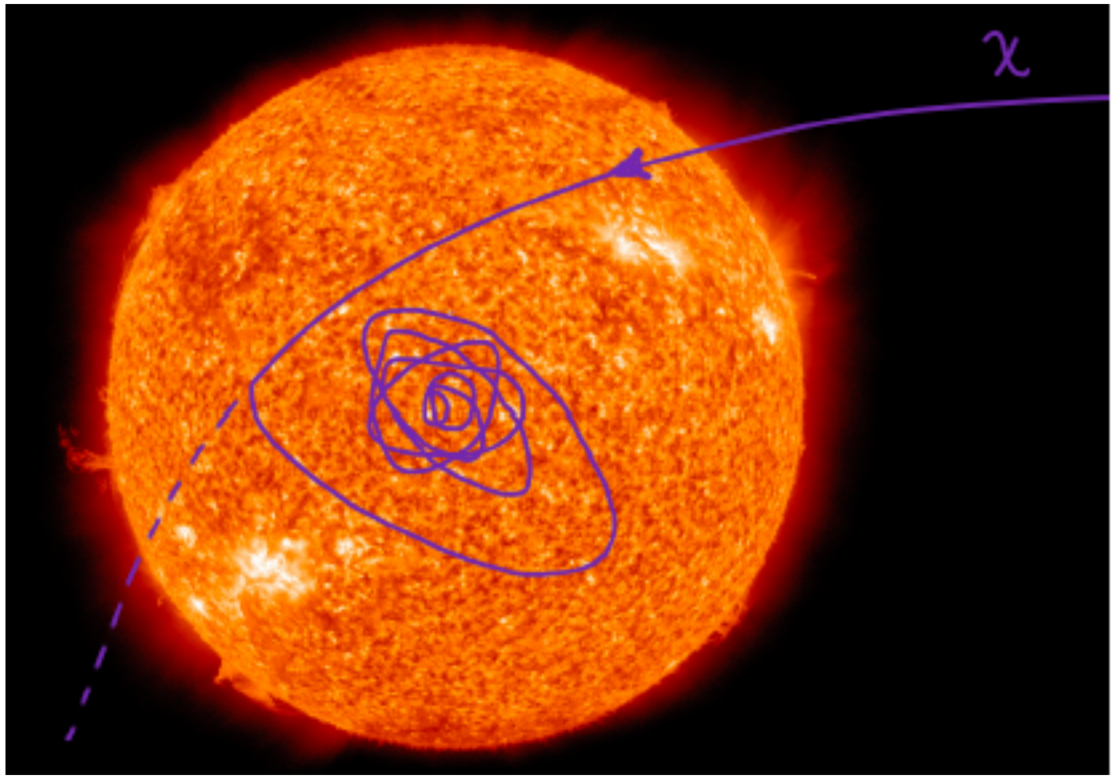

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Independently probe SI interesting $\sigma_{\chi\chi}/m_{\chi\chi}$ region

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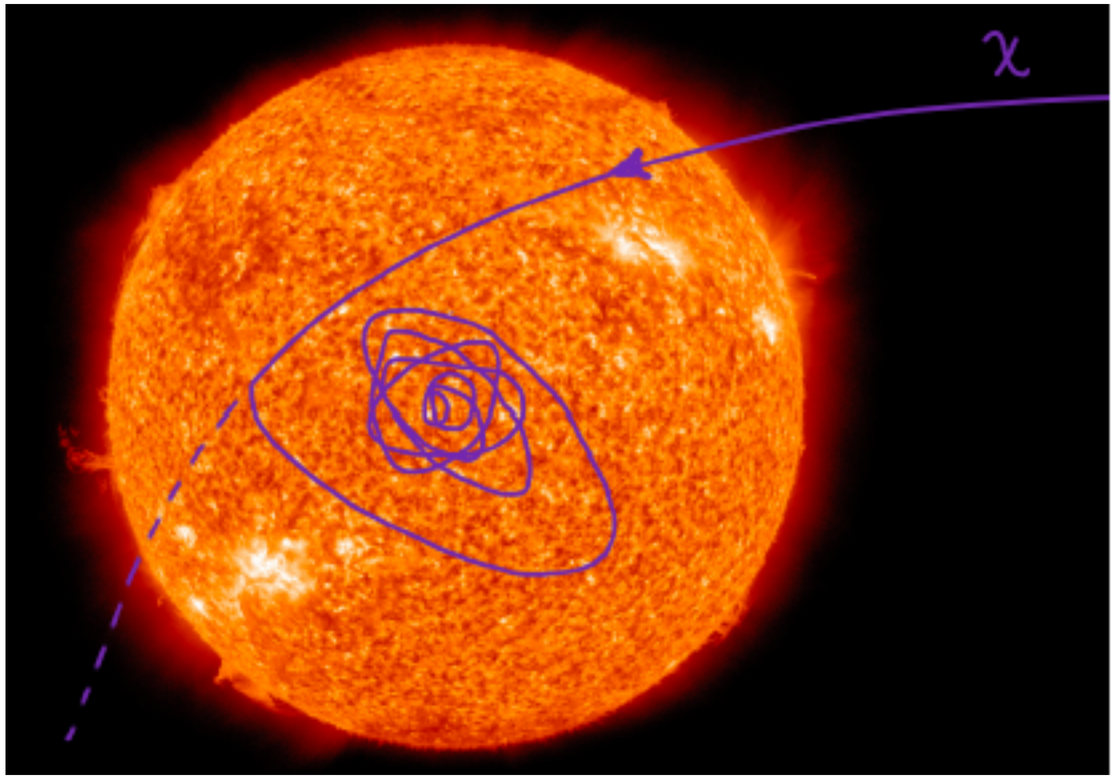


ν flux from DM annihilation will also be enhanced

Independently probe SI interesting $\sigma_{\chi\chi}/m_{\chi\chi}$ region

1. determine enhanced ν flux (simulation)
2. compare predictions with IceCube results

SIDM enhances DM Capture

$$\dot{N} = \Gamma_C + \Gamma_{\chi\chi} - \Gamma_A$$

$$\dot{N} = \Gamma_C + C_S N_\chi - C_A N_\chi^2$$

SIDM enhances capture in the Sun but not in the Earth

SI elastic scattering ejects DM from Earth

(Zentner, PRD **80**, 2009)

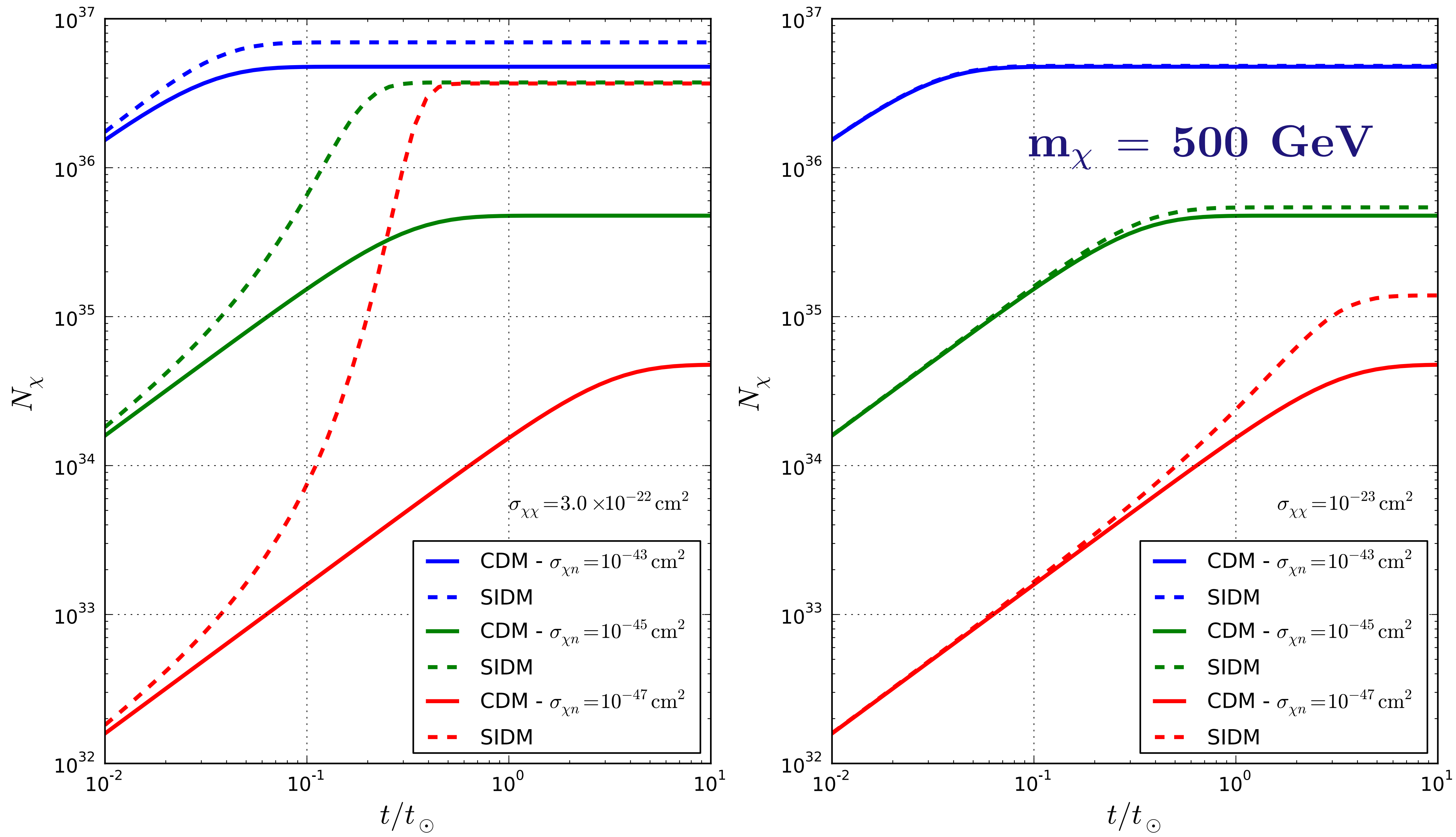
Equilibrium among capture and annihilation rates

=> maximum annihilation rate

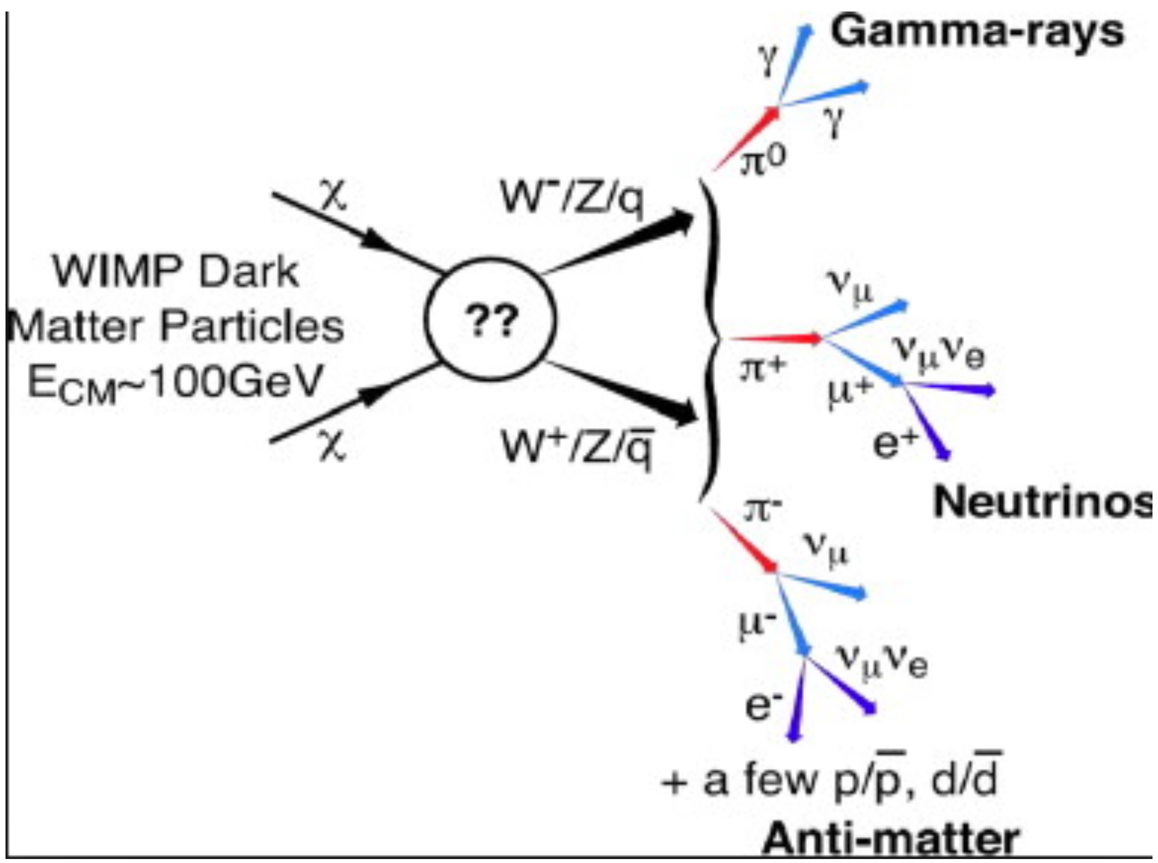
$$\Gamma_A = \frac{C_A N^2}{2} = f(\Gamma_C, \Gamma_{\chi\chi})$$

SIDM Capture Enhancement

Expedites time scale for capture and annihilation equilibrium



Enhanced Neutrino Flux



Annihilation Channels:

$$\chi\chi \rightarrow \mathbf{W^+W^-}$$
$$\tau^+ \tau^-$$
$$\chi\chi \rightarrow \mathbf{b\overline{b}}$$

Capture ⬆

Annihilation rate ⬆

ν flux ⬆

M_χ : 20 GeV → 5 TeV

IceCube Results:

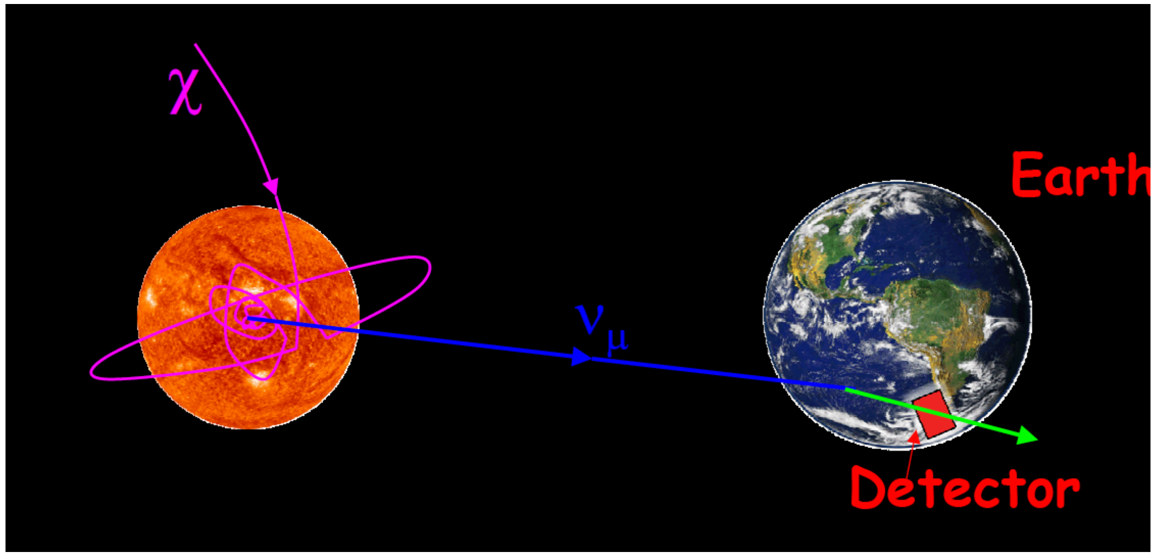
Winter High (E_ν > 95 GeV)

Winter Low ($E_\nu \leq$ 95 GeV)

Summer Low

ν production and propagation

- Monte Carlo Simulation: WIMPSIM code



(M. Blennow, J. Edsjo, T. Ohlsson JCAP **01** 2008)

=> CC and NC interactions

=> ν oscillations

- Output: ν_μ flux $\left(\frac{d\phi_\nu}{dE_\nu}\right)_d$ at the detector

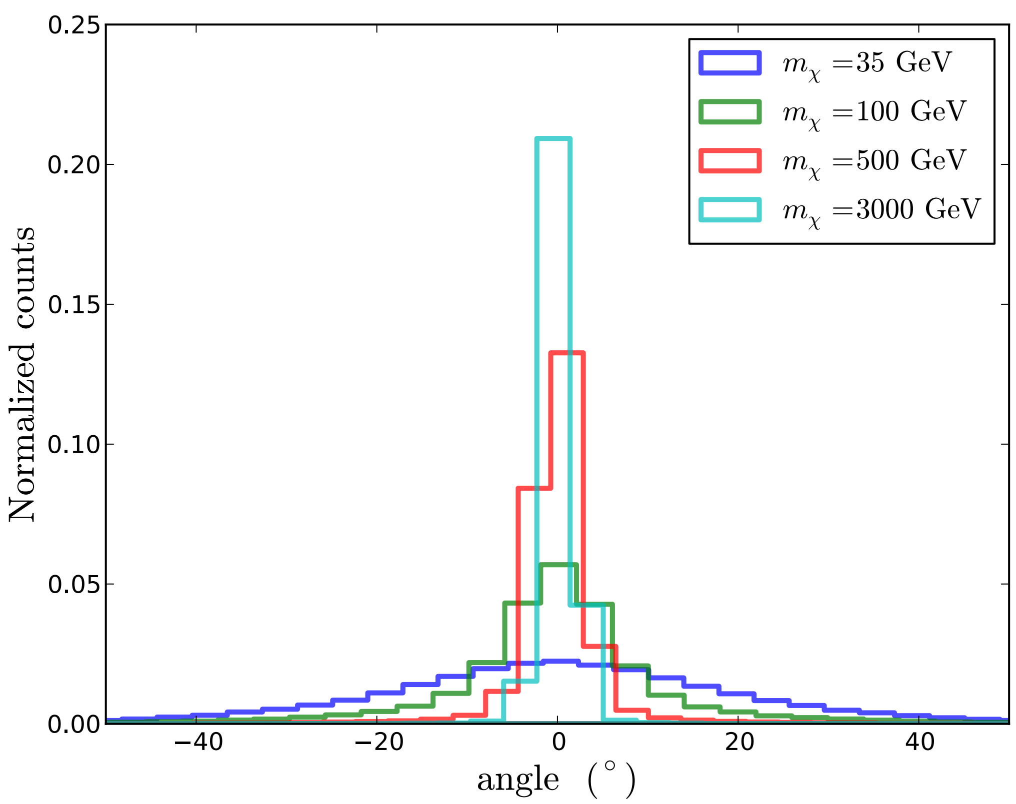
- Number of μ at given angular region Ω at IceCube:

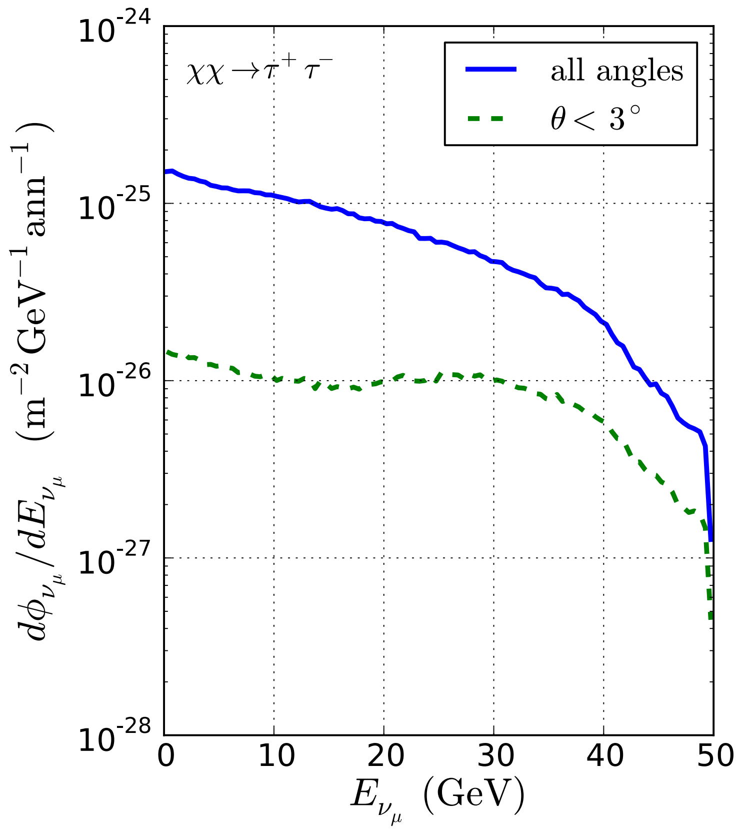
$$\mathbf{N}_\nu = \mathbf{\Gamma_A\, t_{exp}} \int_{\mathbf{E_{thr}}} \frac{\mathbf{d\Phi}_{\nu_\mu}}{\mathbf{dE}_\nu} \mathbf{A_{eff}(E)\, dE}$$

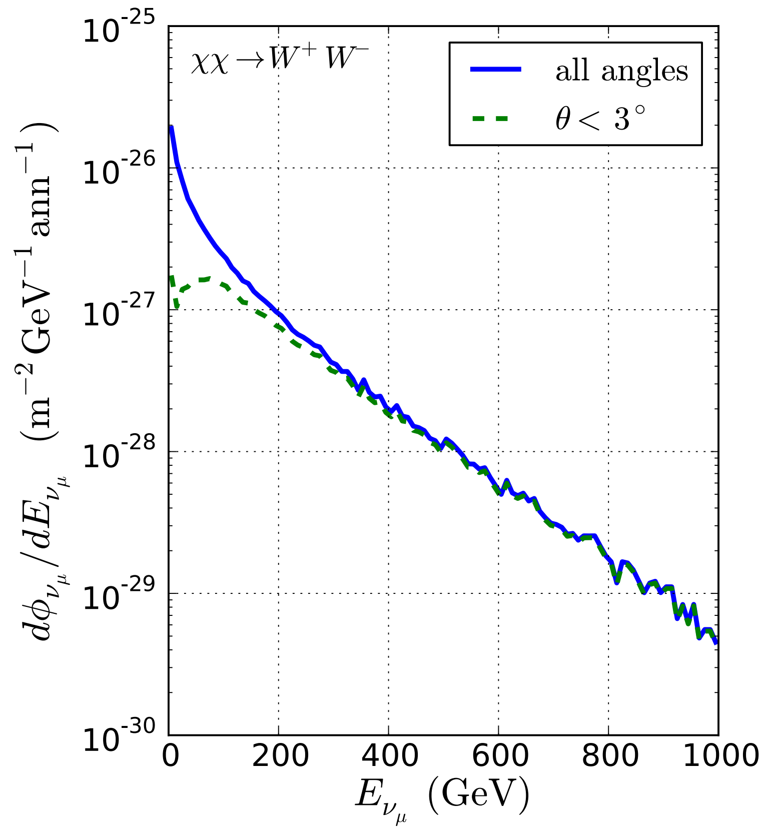
Angular Smearing

IceCube's angular resolution: ~ 4° for 100 GeV ν

Energy Dependent: increases (decreases) for lower (higher) energies (M. Danninger - PhD Thesis)



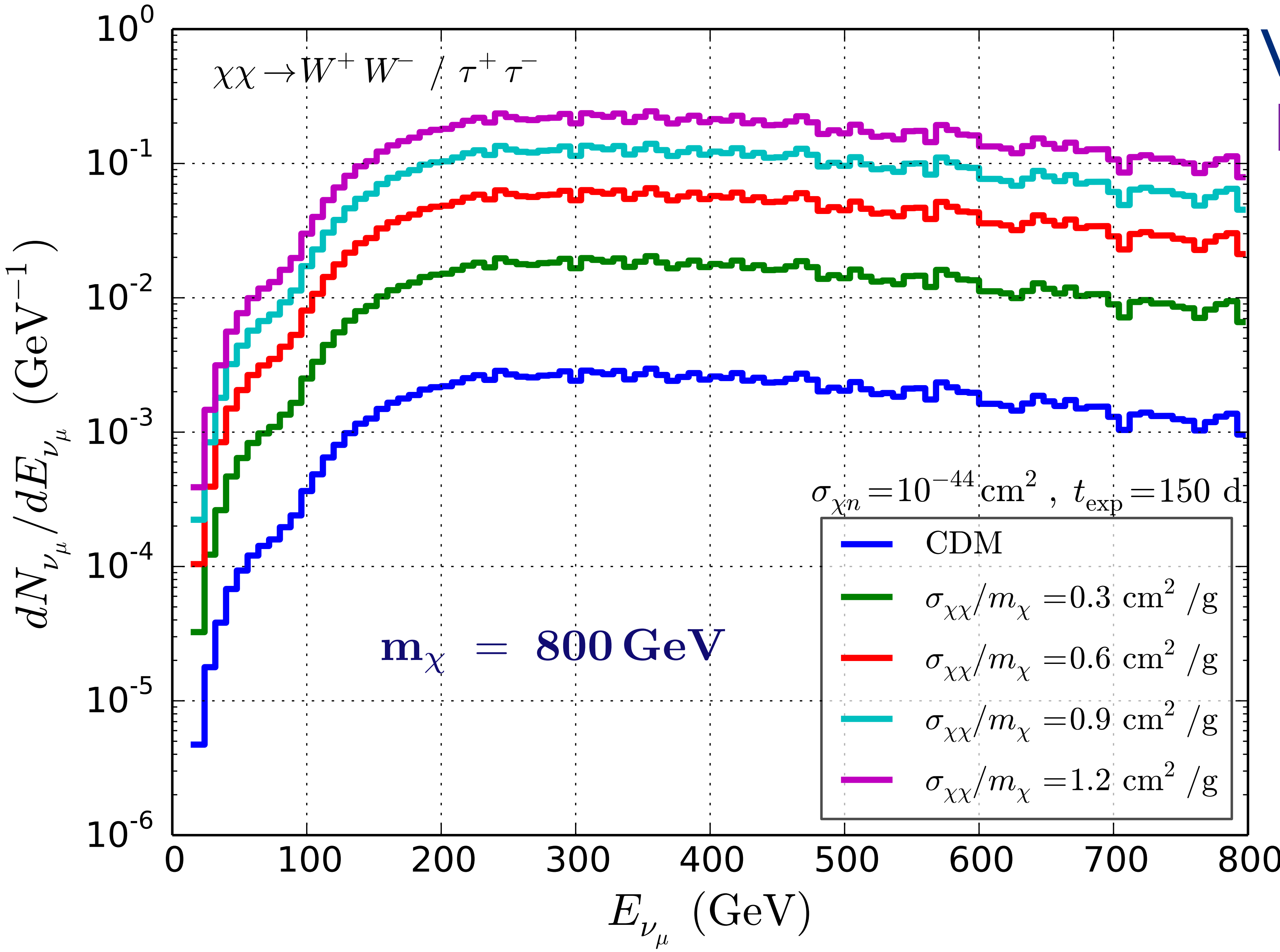




M_χ = 50 GeV

M_χ = 1000 GeV

Energy Spectrum at Detector



IceCube-79 effective area:

WW:	$b\bar{b}$:
115	4.3
66	2.4
31	1.1
10	0.4
14	0.05

t_{exp} = 150 days

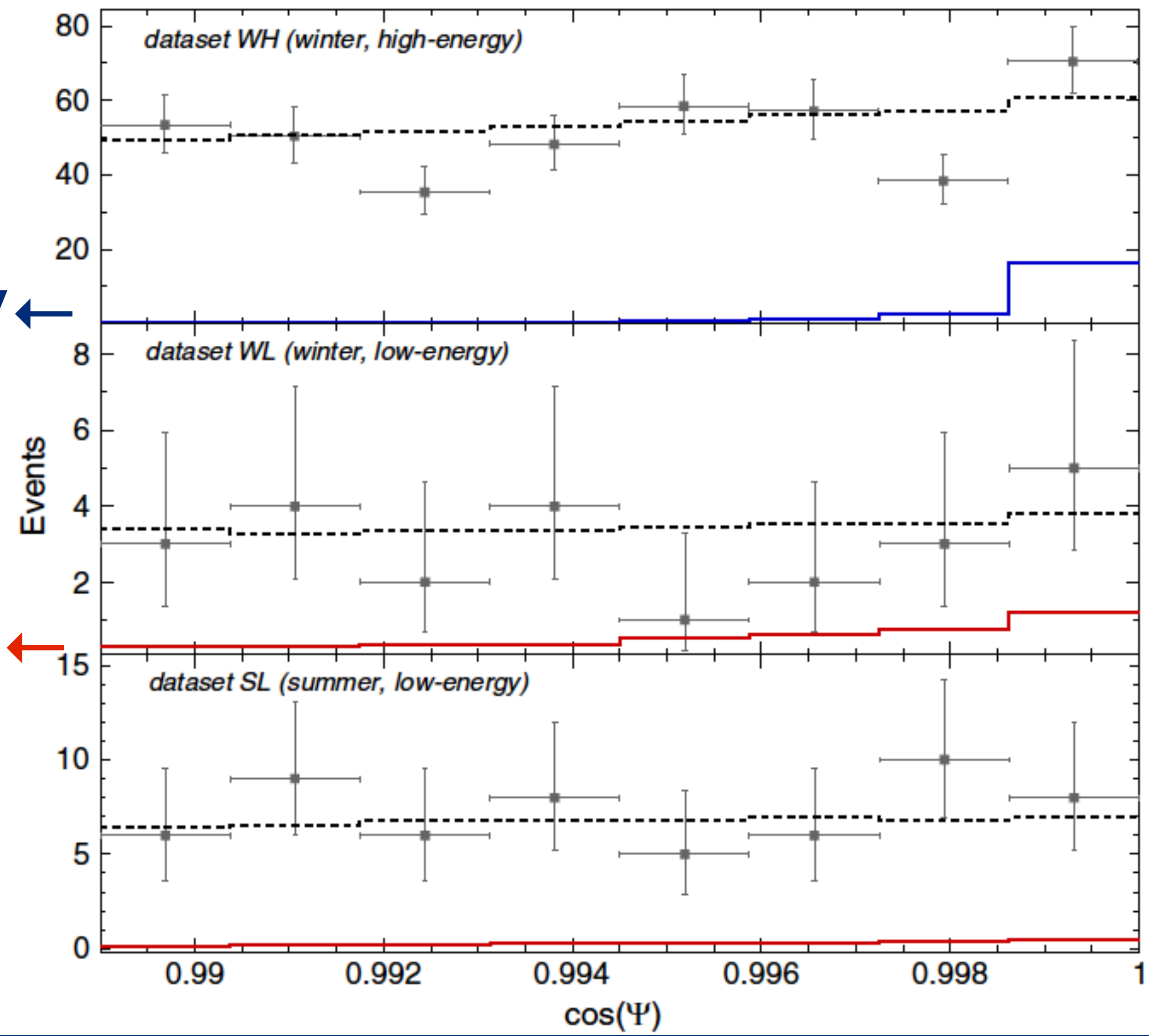
IceCube-79 DM Search

IceCube coll. (PRL **110 - 2013)**

- 317 data taking days (June 2010 - May 2011)
- Deep Core data: summer + lower energies

Simulated 1 TeV WW ←

50 GeV WW ←



Ψ => angle between reconstructed track and direction of the Sun

Results are consistent with atmospheric bckgrd

IceCube-79 DM Search

IceCube-79 results

PRL **110,** 131302 (2013) PHYSICAL REVIEW LETTERS week ending 29 MARCH 2013

TABLE I. Results from the combination of the three independent data sets. The upper 90% limits on the number of signal events μ_s^{90}, the WIMP annihilation rate in the Sun Γ_A, the muon flux Φ_μ and neutrino flux Φ_ν, and the WIMP-proton scattering cross sections (spin independent, $\sigma_{\mathrm{SI},p}$; spin dependent, $\sigma_{\mathrm{SD},p}$) at the 90% confidence level, including systematic errors. The sensitivity $\bar{\Phi}_\mu$ (see the text) is shown for comparison.

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20	$\tau^+\tau^-$	162	2.46×10^{25}	5.26×10^{4}	9.27×10^{4}	2.35×10^{15}	1.08×10^{-40}	1.29×10^{-38}
35	$\tau^+\tau^-$	70.2	1.03×10^{24}	1.03×10^{4}	1.21×10^{4}	1.02×10^{14}	6.59×10^{-42}	1.28×10^{-39}
35	$b\bar{b}$	128	1.99×10^{26}	5.63×10^{4}	1.04×10^{5}	6.29×10^{15}	1.28×10^{-39}	2.49×10^{-37}
50	$\tau^+\tau^-$	19.6	1.20×10^{23}	4.82×10^{3}	2.84×10^{3}	1.17×10^{13}	1.03×10^{-42}	2.70×10^{-40}
50	$b\bar{b}$	55.2	1.75×10^{25}	2.06×10^{4}	1.80×10^{4}	5.64×10^{14}	1.51×10^{-40}	3.96×10^{-38}
100	W^+W^-	16.8	3.35×10^{22}	1.49×10^{3}	1.19×10^{3}	1.23×10^{12}	6.01×10^{-43}	2.68×10^{-40}
100	$b\bar{b}$	28.9	1.82×10^{24}	7.57×10^{3}	5.91×10^{3}	6.34×10^{13}	3.30×10^{-41}	1.47×10^{-38}
250	W^+W^-	29.9	2.85×10^{21}	3.04×10^{2}	4.15×10^{2}	9.72×10^{10}	1.67×10^{-43}	1.34×10^{-40}
250	$b\bar{b}$	19.8	1.27×10^{23}	1.85×10^{3}	1.45×10^{3}	4.59×10^{12}	7.37×10^{-42}	5.90×10^{-39}
500	W^+W^-	25.2	8.57×10^{20}	1.46×10^{2}	2.23×10^{2}	2.61×10^{10}	1.45×10^{-43}	1.57×10^{-40}
500	$b\bar{b}$	30.6	4.12×10^{22}	8.53×10^{2}	1.02×10^{3}	1.52×10^{12}	6.98×10^{-42}	7.56×10^{-39}
1000	W^+W^-	23.4	6.13×10^{20}	1.19×10^{2}	1.85×10^{2}	1.62×10^{10}	3.46×10^{-43}	4.48×10^{-40}
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3000	W^+W^-	22.2	7.79×10^{20}	1.09×10^{2}	1.66×10^{2}	1.65×10^{10}	3.44×10^{-42}	5.02×10^{-39}
3000	$b\bar{b}$	26.1	4.88×10^{21}	2.52×10^{2}	3.47×10^{2}	1.89×10^{11}	2.17×10^{-41}	3.16×10^{-38}
5000	W^+W^-	22.8	8.79×10^{20}	1.01×10^{2}	1.58×10^{2}	1.77×10^{10}	1.06×10^{-41}	1.59×10^{-38}
5000	$b\bar{b}$	26.4	6.50×10^{20}	2.21×10^{2}	3.26×10^{2}	1.63×10^{11}	4.89×10^{-41}	7.29×10^{-38}

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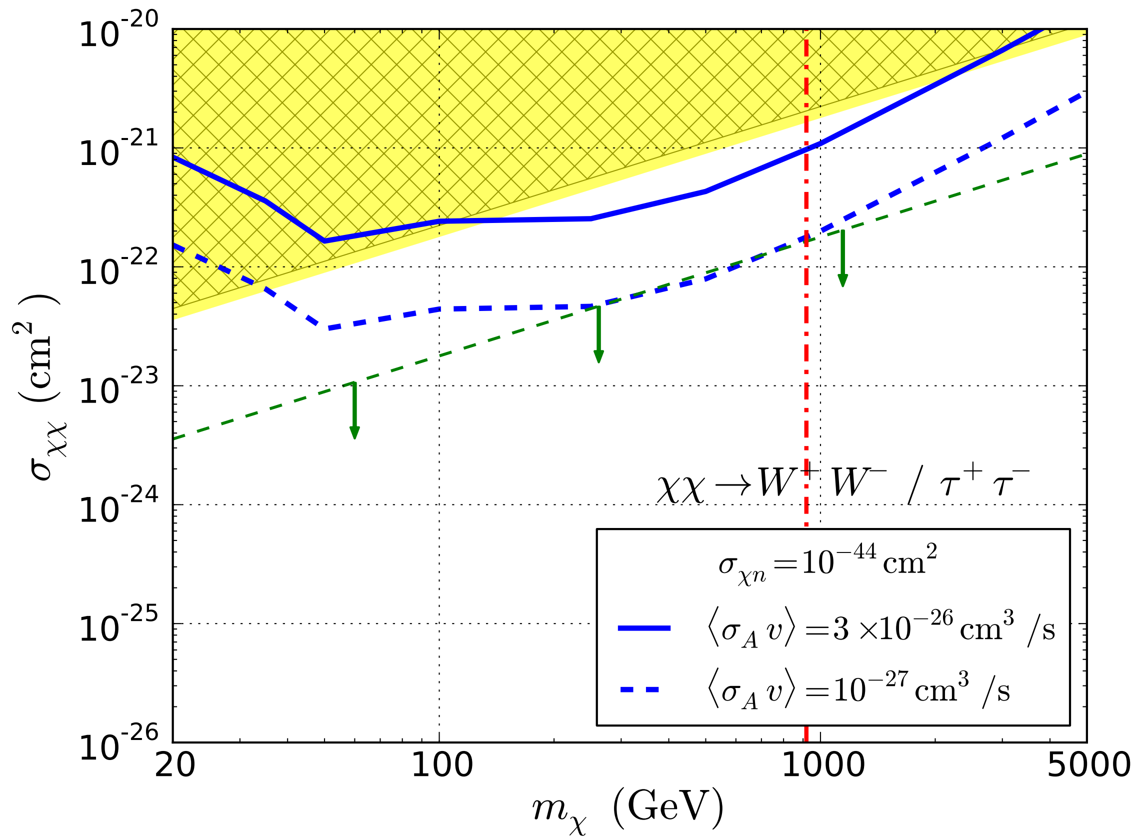
TABLE I. Results from the combination of the three independent data sets. The upper 90% limits on the number of signal events μ_s^{90}, the WIMP annihilation rate in the Sun Γ_A, the muon flux Φ_μ and neutrino flux Φ_ν, and the WIMP-proton scattering cross sections (spin independent, $\sigma_{\mathrm{SI},p}$; spin dependent, $\sigma_{\mathrm{SD},p}$) at the 90% confidence level, including systematic errors. The sensitivity $\bar{\Phi}_\mu$ (see the text) is shown for comparison.

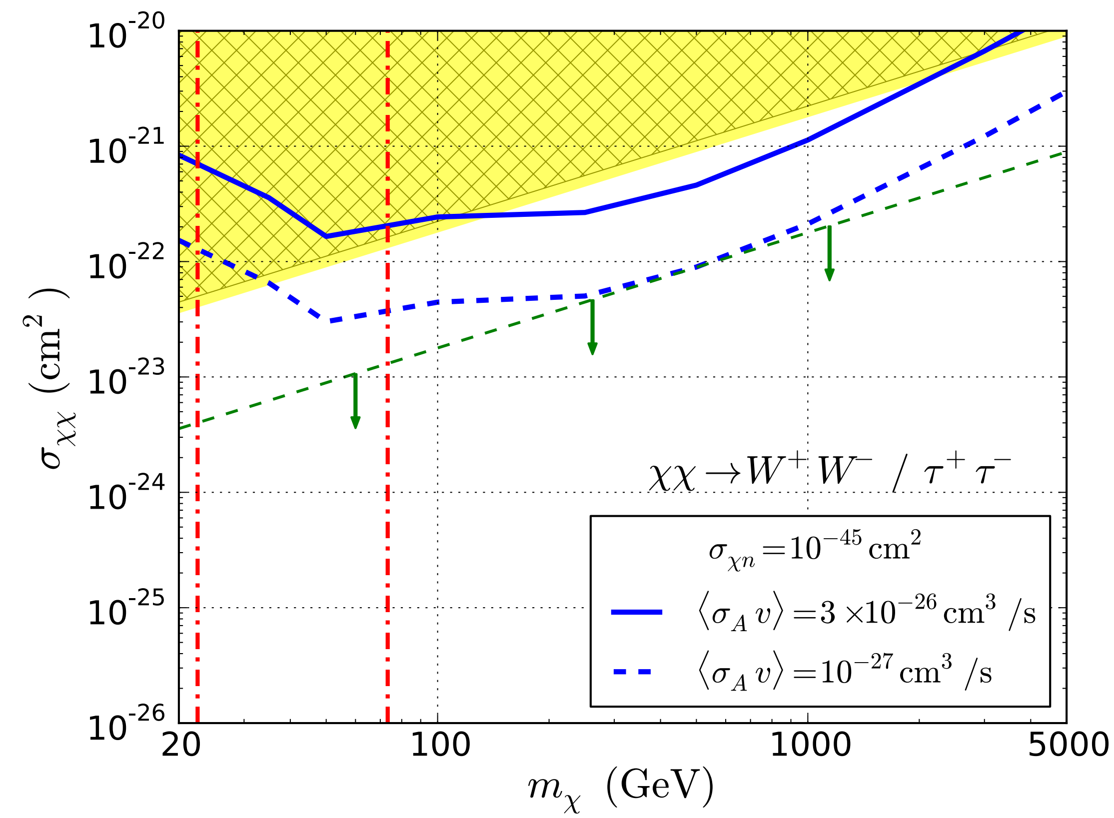
m_χ (GeV/c^2)	Channel	μ_s^{90}	Γ_A (s^{-1})	$\bar{\Phi}_\mu$ (km$^{-2}y^{-1}$)	Φ_μ (km$^{-2}y^{-1}$)	Φ_ν (km$^{-2}y^{-1}$)	$\sigma_{\mathrm{SI},p}$ (cm^2)	$\sigma_{\mathrm{SD},p}$ (cm^2)
20	$\tau^+\tau^-$	162	2.46×10^{25}	5.26×10^{4}	9.27×10^{4}	2.35×10^{15}	1.08×10^{-40}	1.29×10^{-38}
35	$\tau^+\tau^-$	70.2	1.03×10^{24}	1.03×10^{4}	1.21×10^{4}	1.02×10^{14}	6.59×10^{-42}	1.28×10^{-39}
35	$b\bar{b}$	128	1.99×10^{26}	5.63×10^{4}	1.04×10^{5}	6.29×10^{15}	1.28×10^{-39}	2.49×10^{-37}
50	$\tau^+\tau^-$	19.6	1.20×10^{23}	4.82×10^{3}	2.84×10^{3}	1.17×10^{13}	1.03×10^{-42}	2.70×10^{-40}
50	$b\bar{b}$	55.2	1.75×10^{25}	2.06×10^{4}	1.80×10^{4}	5.64×10^{14}	1.51×10^{-40}	3.96×10^{-38}
100	W^+W^-	16.8	3.35×10^{22}	1.49×10^{3}	1.19×10^{3}	1.23×10^{12}	6.01×10^{-43}	2.68×10^{-40}
100	$b\bar{b}$	28.9	1.82×10^{24}	7.57×10^{3}	5.91×10^{3}	6.34×10^{13}	3.30×10^{-41}	1.47×10^{-38}
250	W^+W^-	29.9	2.85×10^{21}	3.04×10^{2}	4.15×10^{2}	9.72×10^{10}	1.67×10^{-43}	1.34×10^{-40}
250	$b\bar{b}$	19.8	1.27×10^{23}	1.85×10^{3}	1.45×10^{3}	4.59×10^{12}	7.37×10^{-42}	5.90×10^{-39}
500	W^+W^-	25.2	8.57×10^{20}	1.46×10^{2}	2.23×10^{2}	2.61×10^{10}	1.45×10^{-43}	1.57×10^{-40}
500	$b\bar{b}$	30.6	4.12×10^{22}	8.53×10^{2}	1.02×10^{3}	1.52×10^{12}	6.98×10^{-42}	7.56×10^{-39}
1000	W^+W^-	23.4	6.13×10^{20}	1.19×10^{2}	1.85×10^{2}	1.62×10^{10}	3.46×10^{-43}	4.48×10^{-40}
1000	$b\bar{b}$	30.4	1.39×10^{22}	4.33×10^{2}	5.99×10^{2}	5.23×10^{11}	7.75×10^{-42}	1.00×10^{-38}
3000	W^+W^-	22.2	7.79×10^{20}	1.09×10^{2}	1.66×10^{2}	1.65×10^{10}	3.44×10^{-42}	5.02×10^{-39}
3000	$b\bar{b}$	26.1	4.88×10^{21}	2.52×10^{2}	3.47×10^{2}	1.89×10^{11}	2.17×10^{-41}	3.16×10^{-38}
5000	W^+W^-	22.8	8.79×10^{20}	1.01×10^{2}	1.58×10^{2}	1.77×10^{10}	1.06×10^{-41}	1.59×10^{-38}
5000	$b\bar{b}$	26.4	6.50×10^{20}	2.21×10^{2}	3.26×10^{2}	1.63×10^{11}	4.89×10^{-41}	7.29×10^{-38}

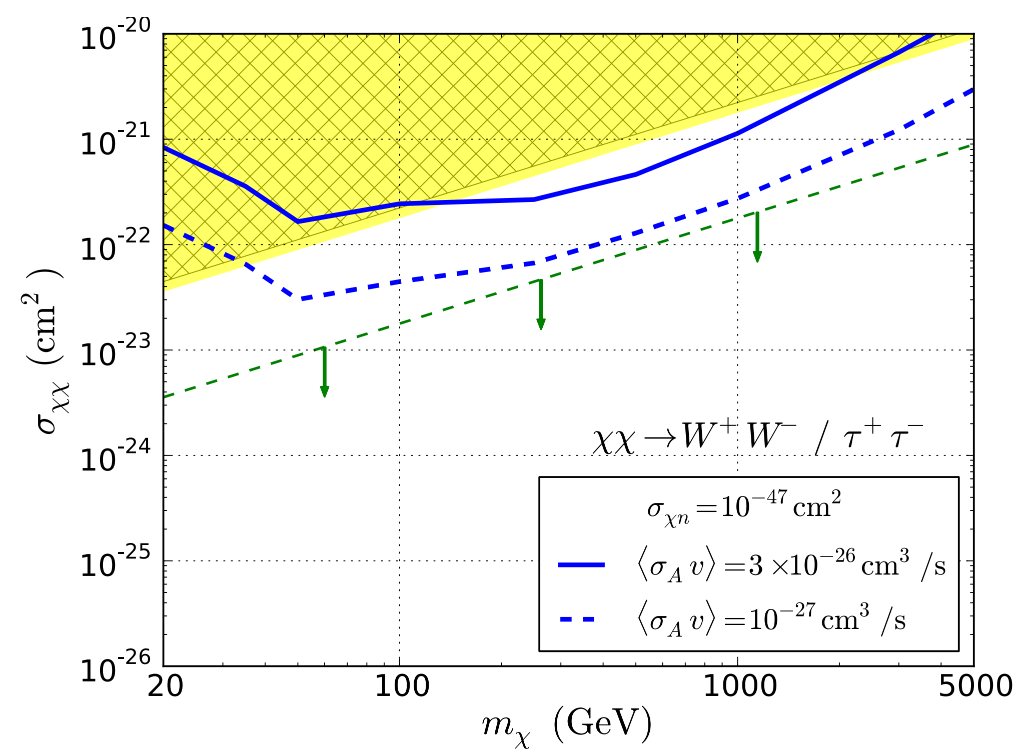
Models which predict more events can be excluded

Probing SIDM models

W^+W^- / $\tau^+\tau^-$ - Spin Independent







Bullet Cluster

Halo Shapes

--- SIDM too low

--- LUX (to the left or between lines

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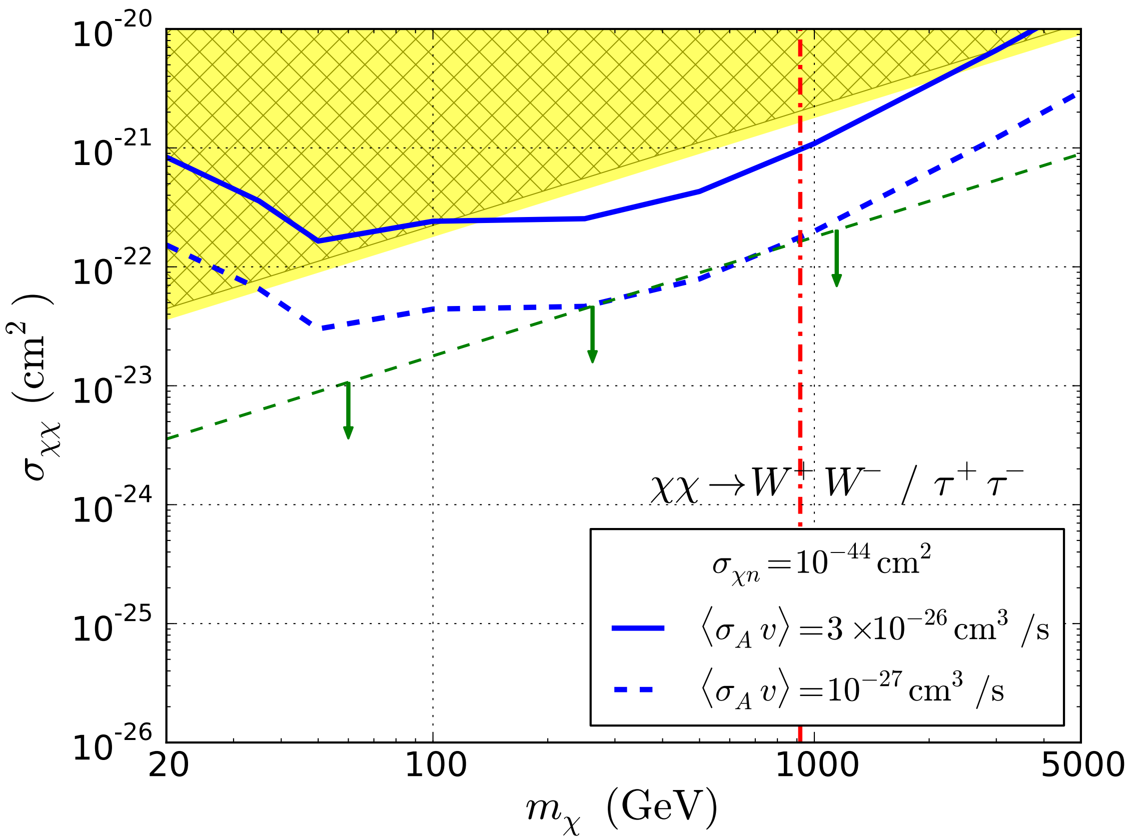
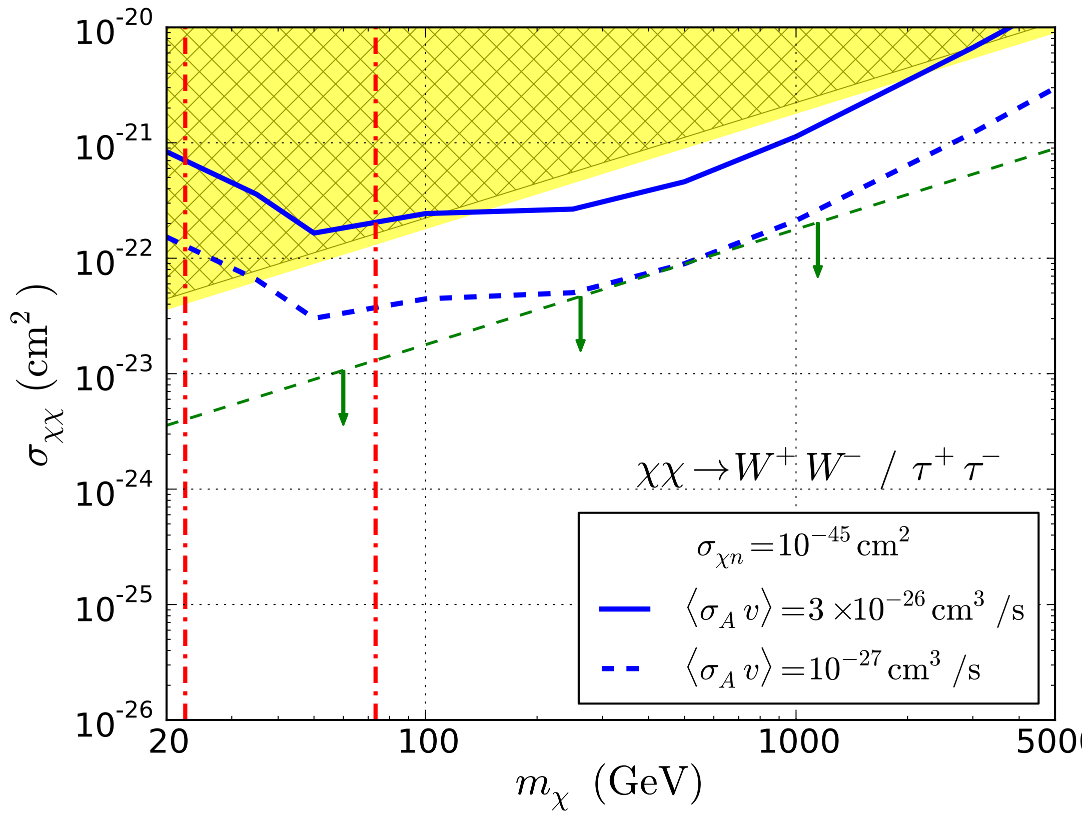
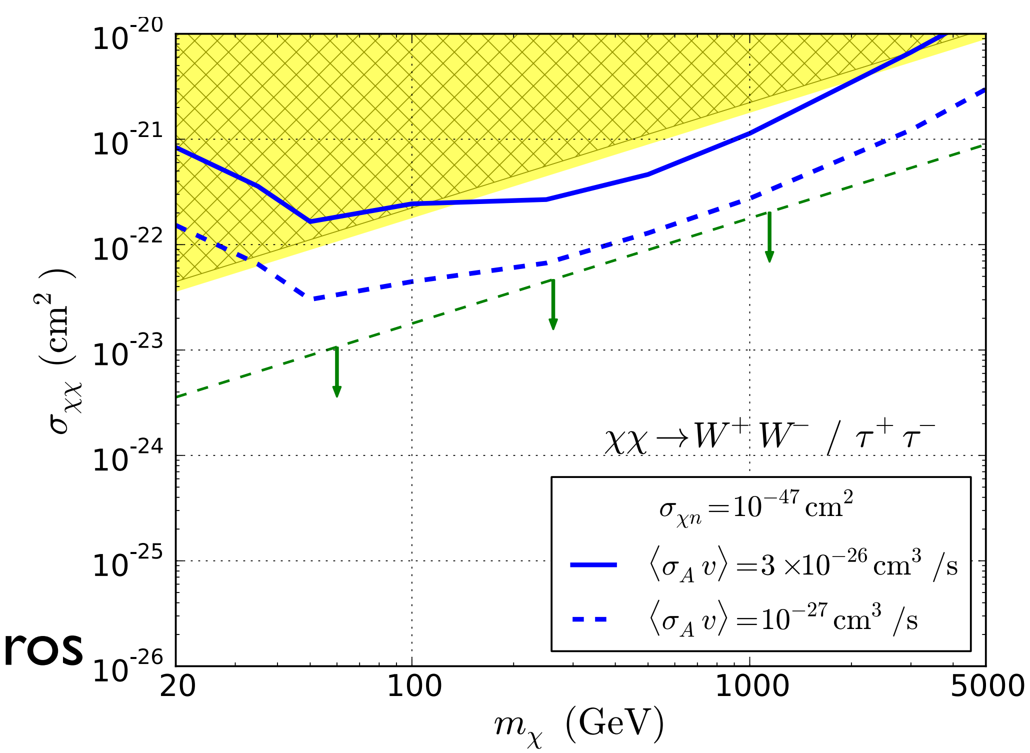




Region above blue curve: excluded at 90% CL



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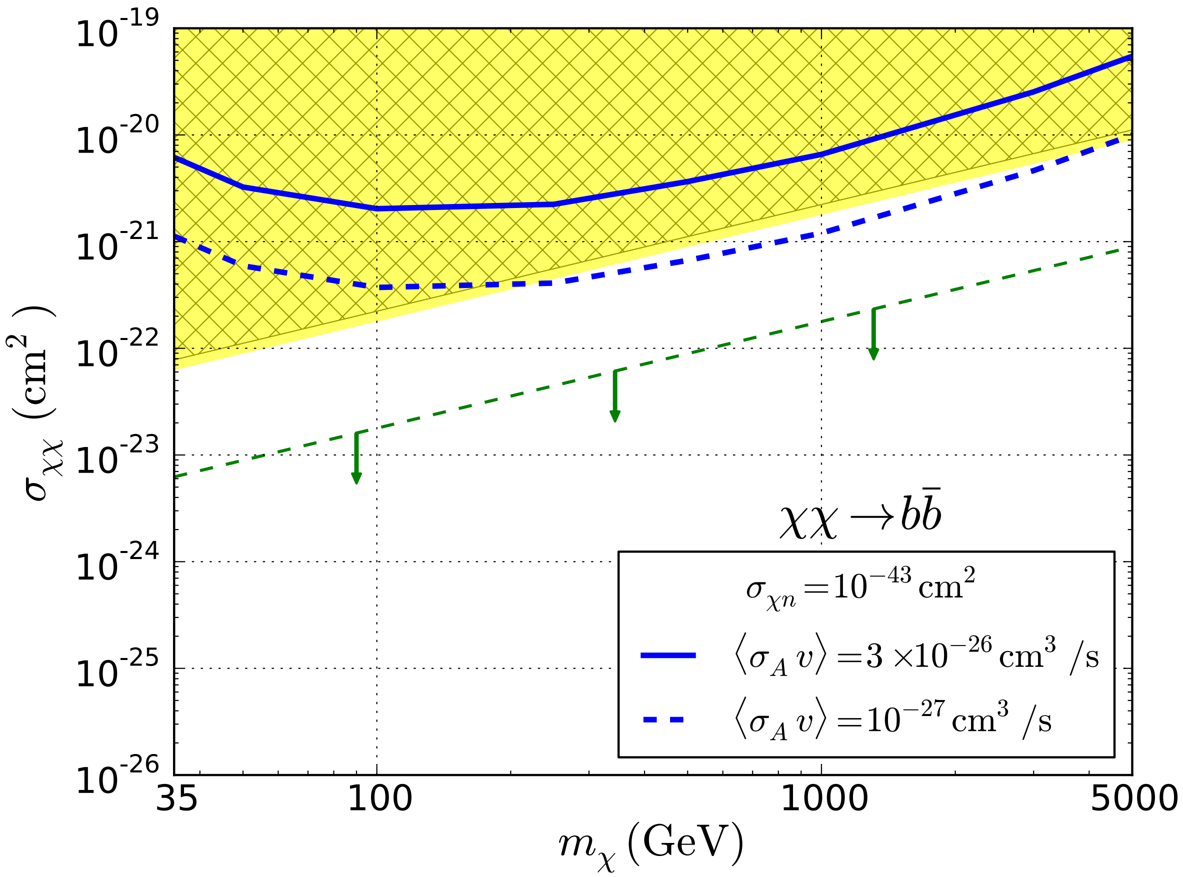
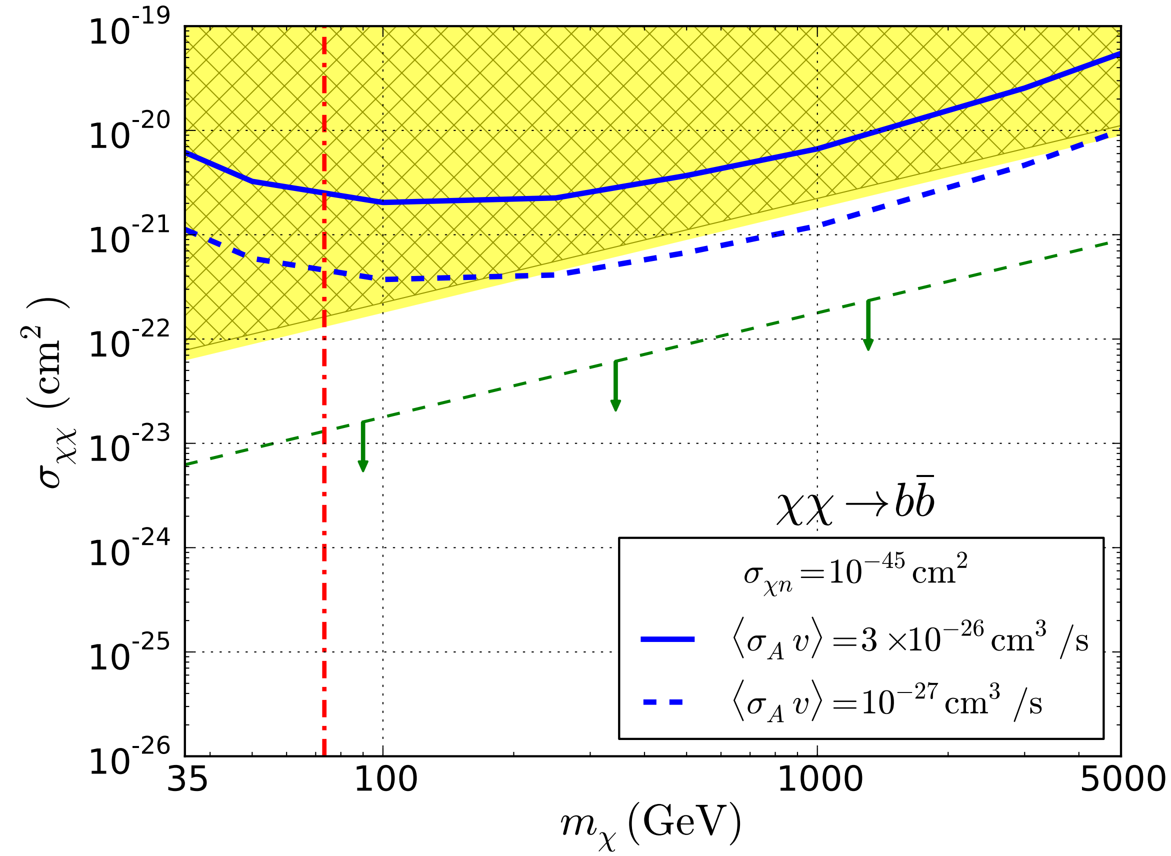
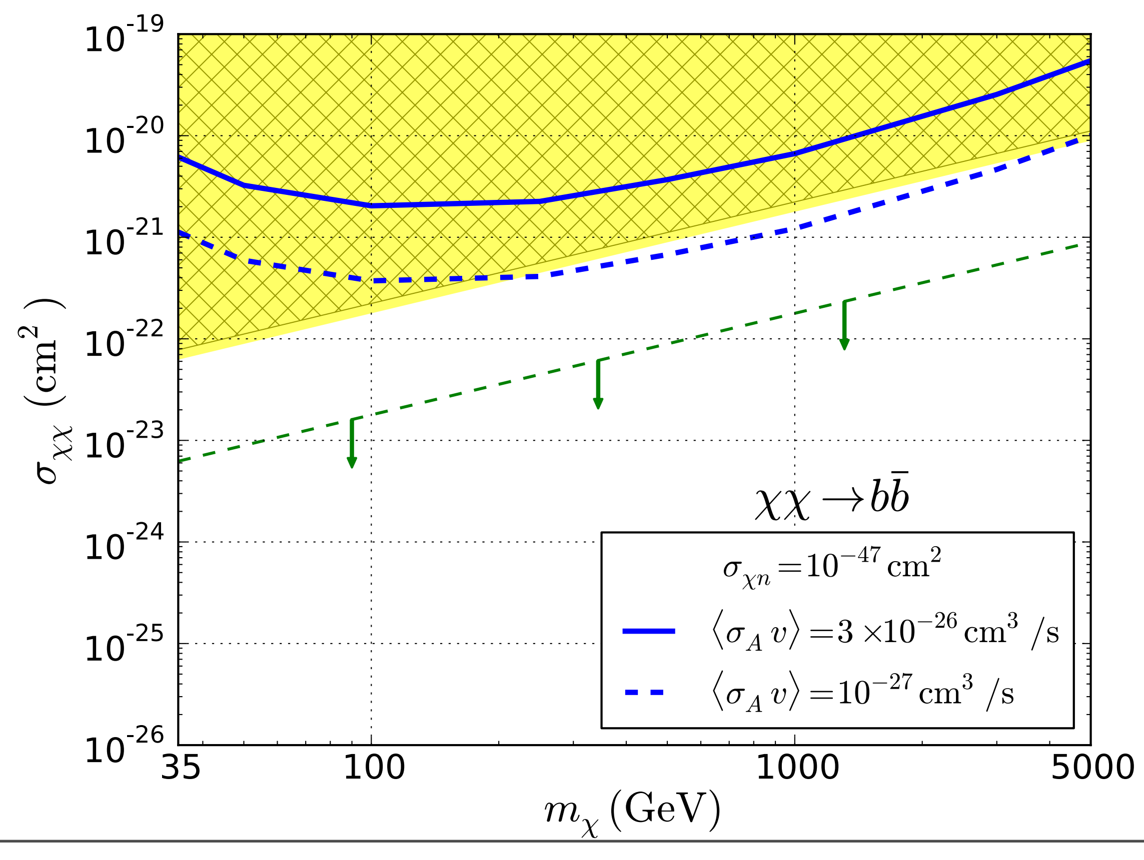
JCAP **02** (2014)

$b\bar{b}$ - Spin Independent







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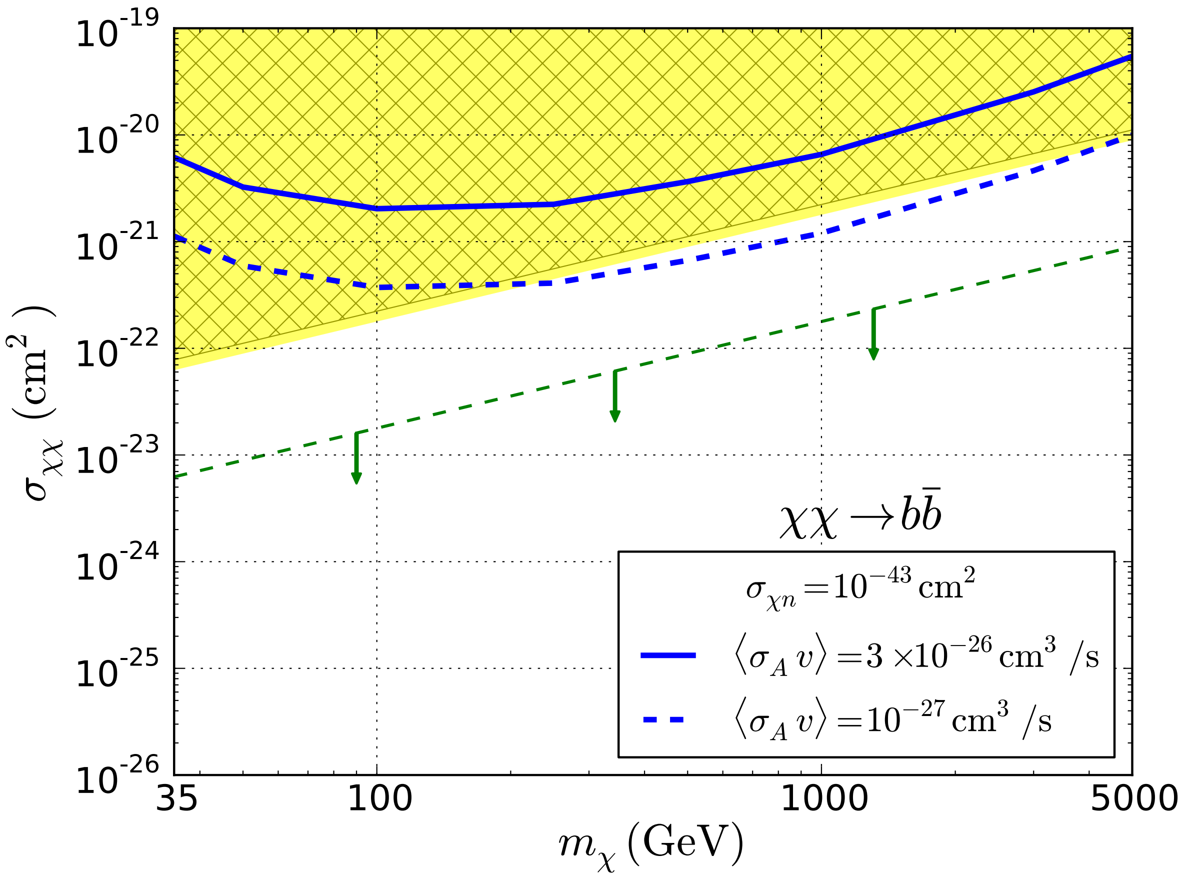
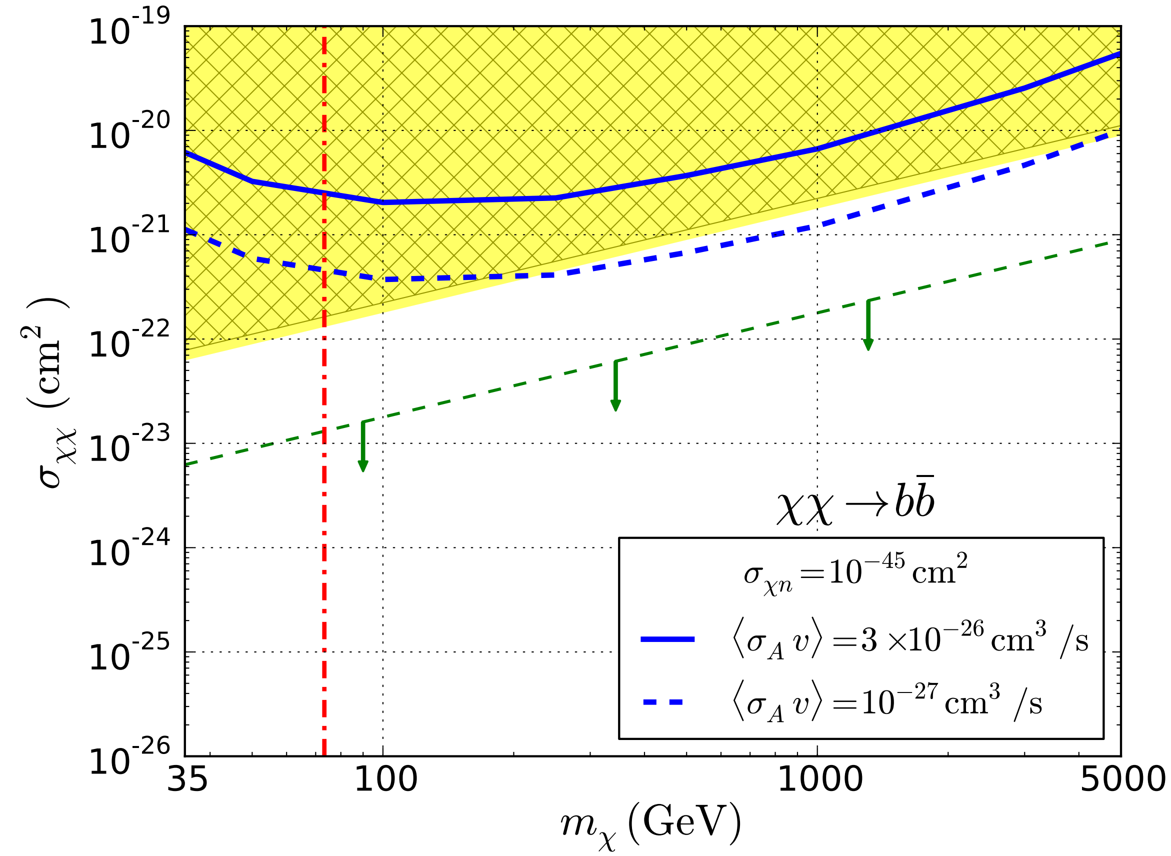
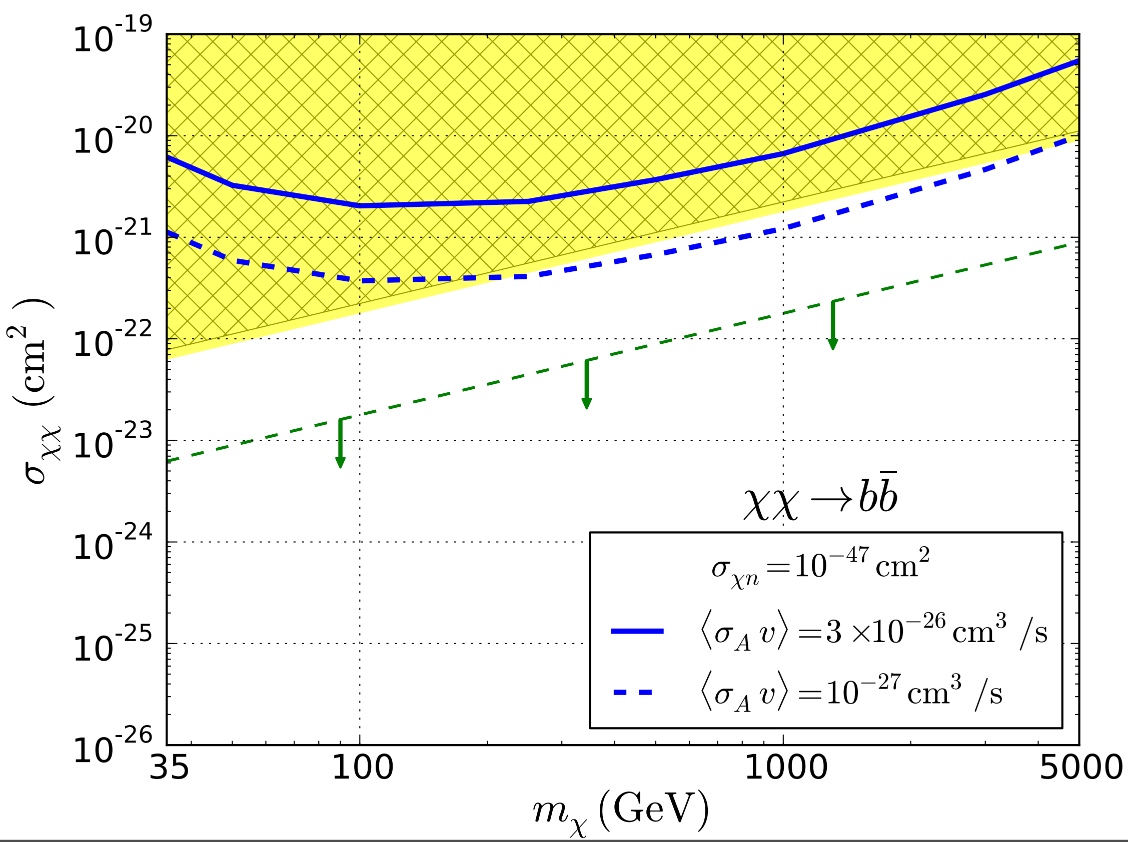
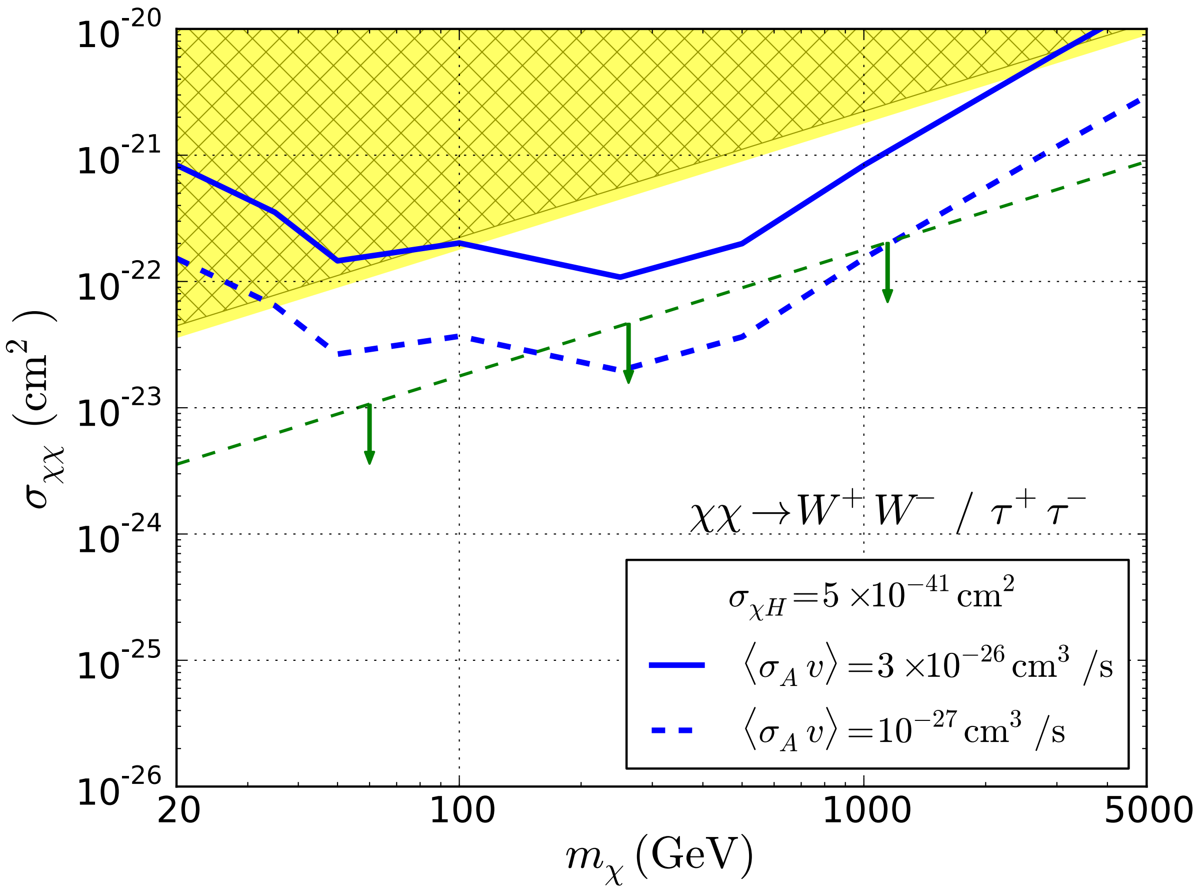


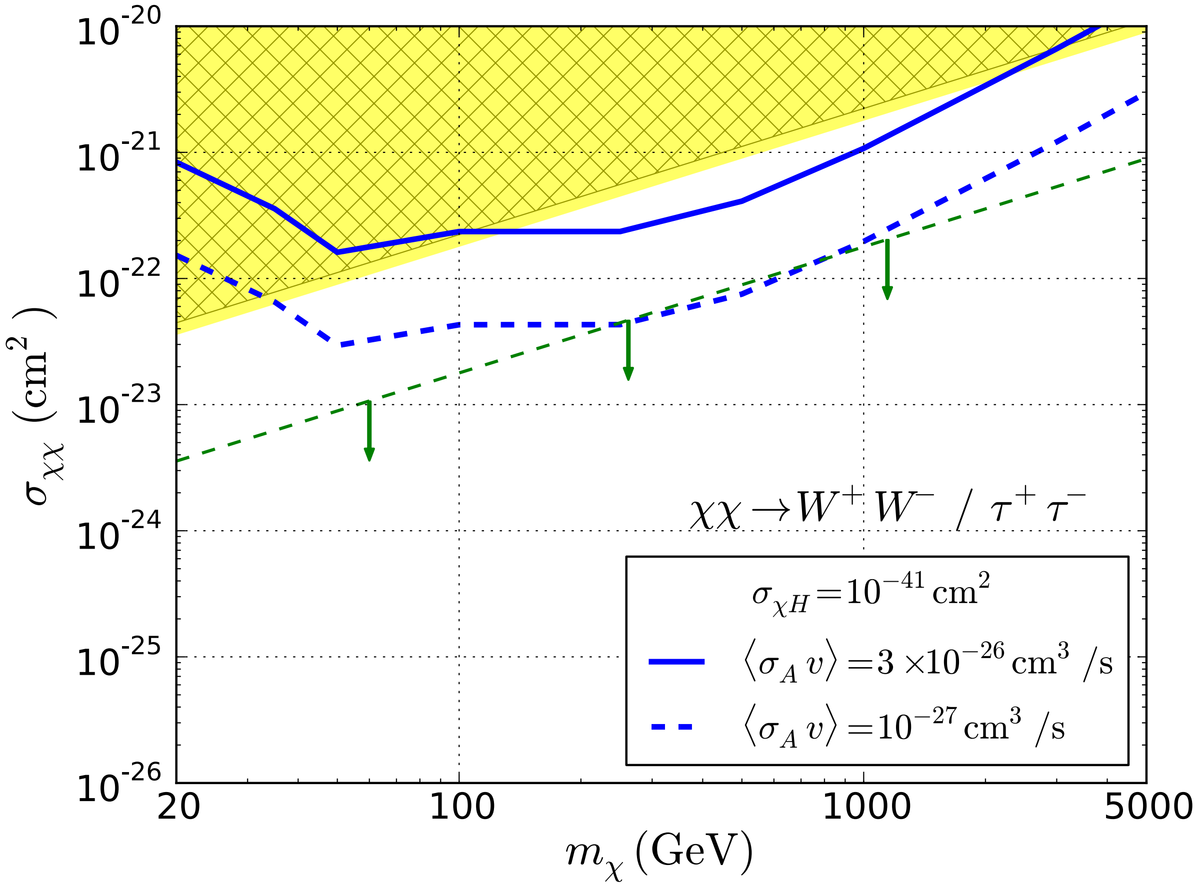


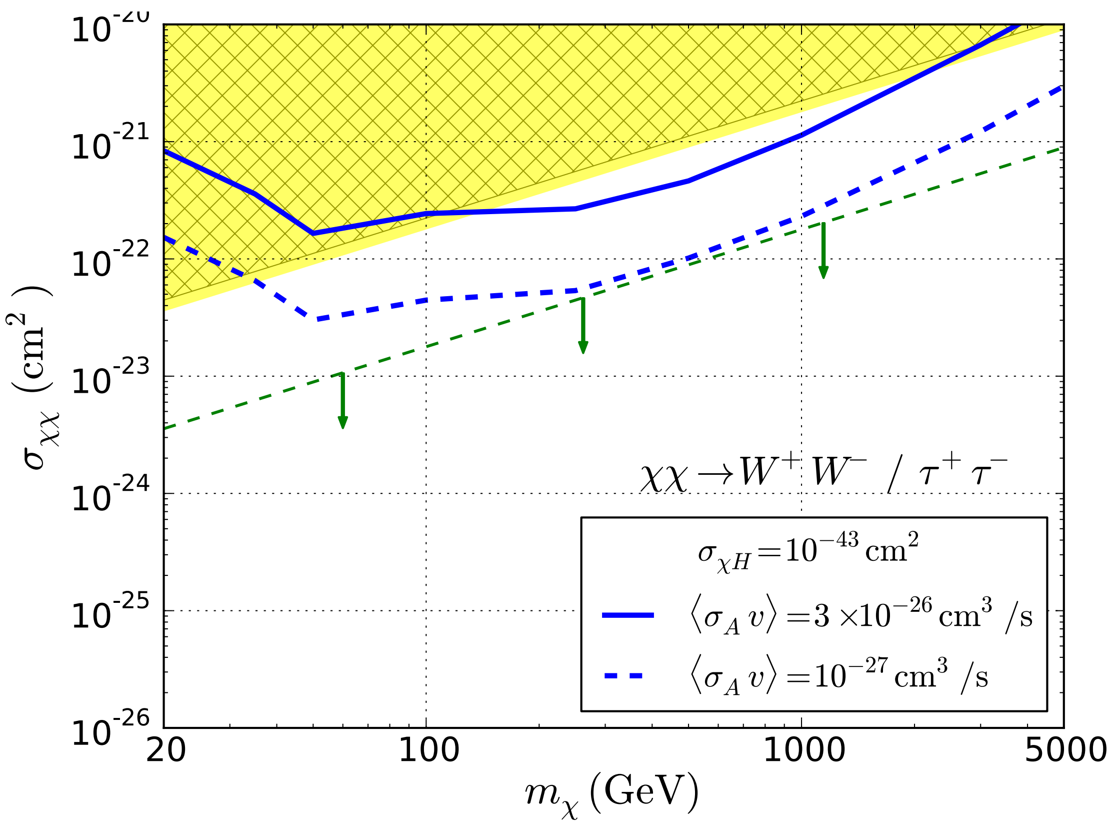


- weaker limits
- independently confirms bullet results

$W^+ W^-$ / $\tau^+ \tau^-$ - Spin Dependent







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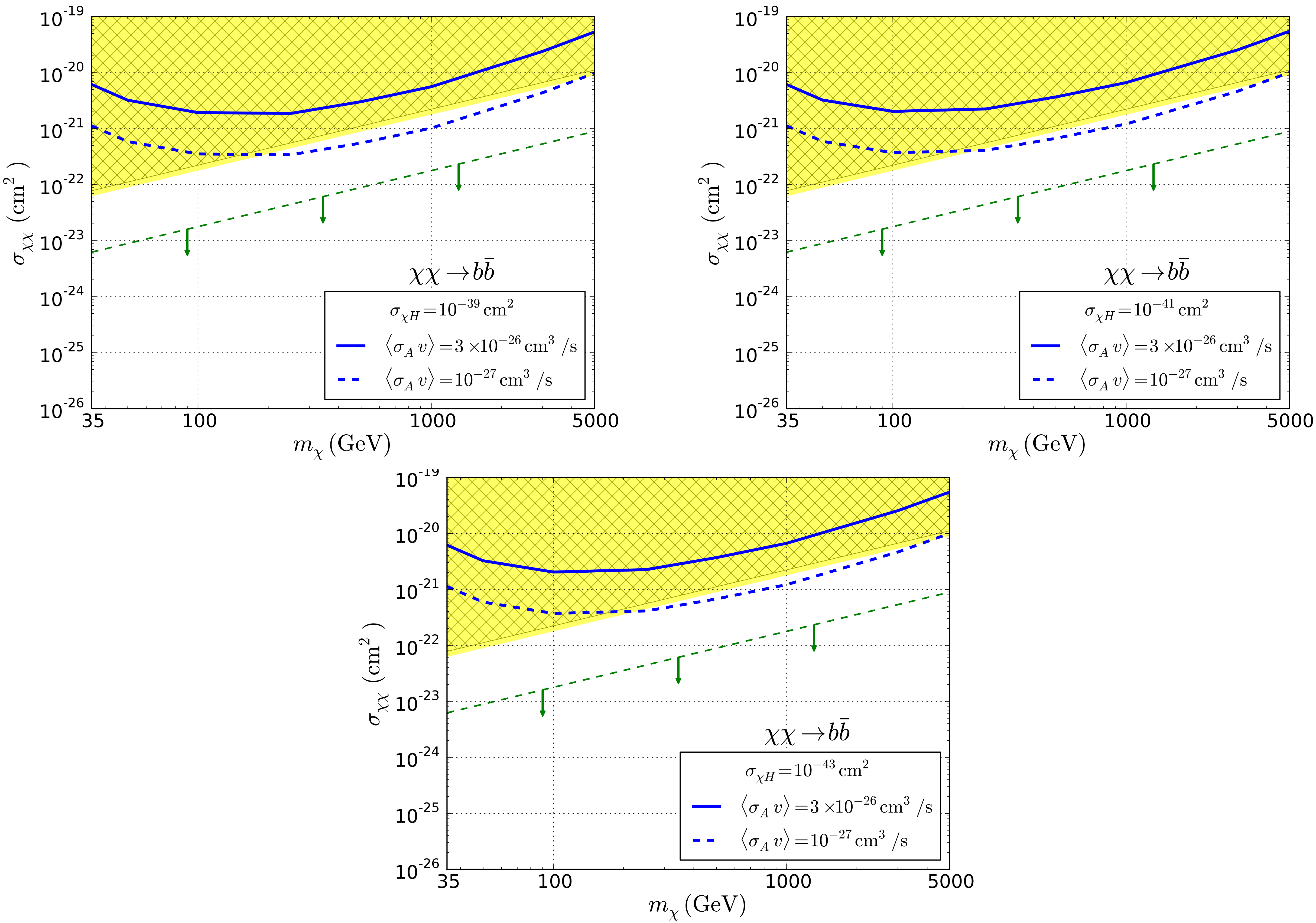

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SIDM can solve CDM potential small scale problems if:
Annihilation produces lower energy neutrinos
Self-scattering is velocity dependent

I.A, C. P. de Los Heros & Denis S. Robertson JCAP **02,** 2014