Constraints on Self-Interacting Dark Matter from IceCube Results

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Astroparticle Physics 2014
A joint TeVPA/IDM conference

Amsterdam - June 24, 2014

Introduction: *CDM* Small-Scale Controversies

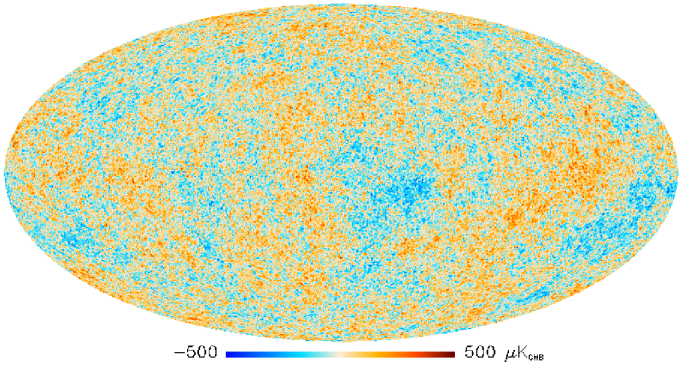

Figure: CMB map [Planck Col., Planck 2013 Results]

- Flat Universe
- Λ ($\sim 69\%$) and DM ($\sim 26\%$)
- DM: cold, non-baryonic, dissipationless and collisionless

ΛCDM is a huge success at large scales

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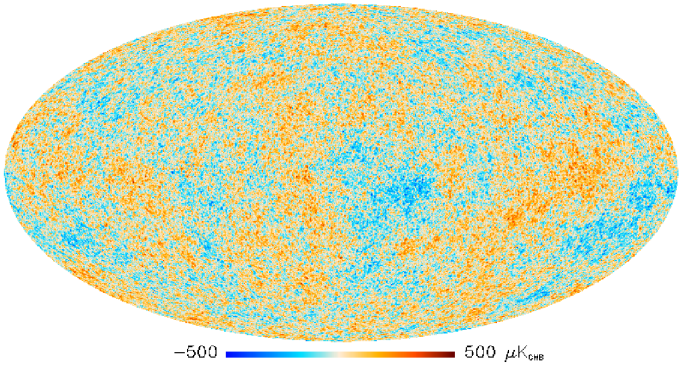

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Small-Scale Potential Problems:

- Core-Cusp

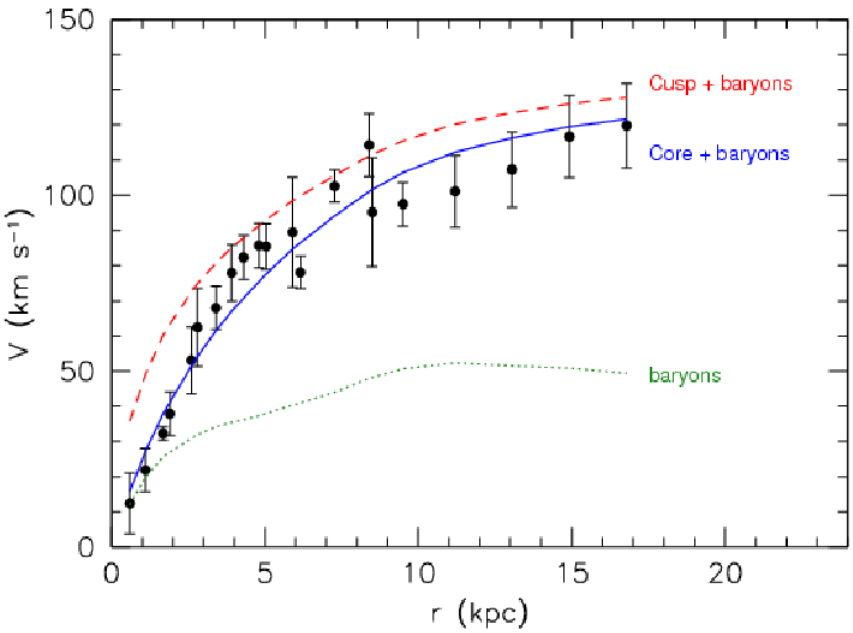

Figure: Rotation curve of galaxy F568-3. [D. Weinberg, et. al., arXiv:1306.0913]

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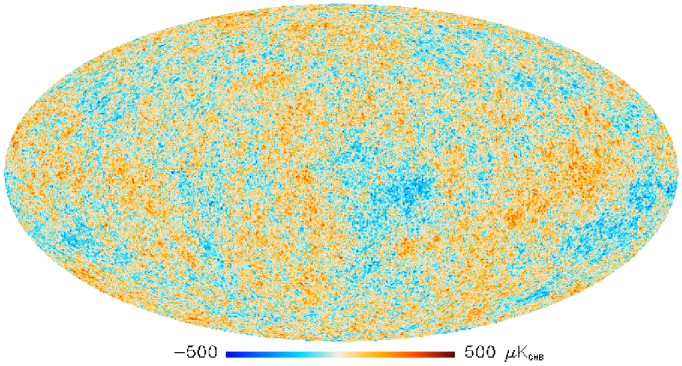

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Small-Scale Potential Problems:

- Core-Cusp
- Too Big to Fail

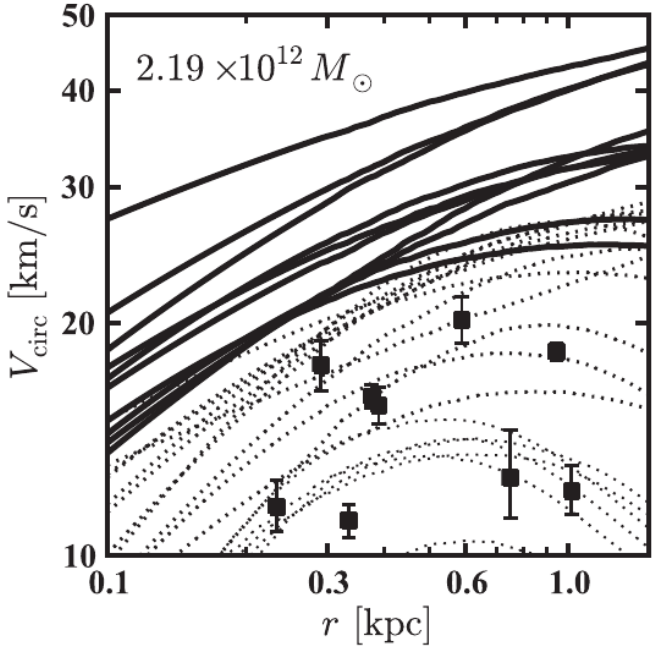

Figure: Rotation curves of sub-halos.

[M. Boylan-Kolchin, et. al., MNRAS 422: 1203-1218, 2012]

SIDM as a solution

CDM small-scale controversies could be solved if DM have strong self-interactions [D. Spergel and P. Steinhardt, PRL 84, 3760, 2000]:

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

Qualitative effects of SIDM:

- Heat transport
- Isotropization of the velocity
- Limited destruction of subestructures

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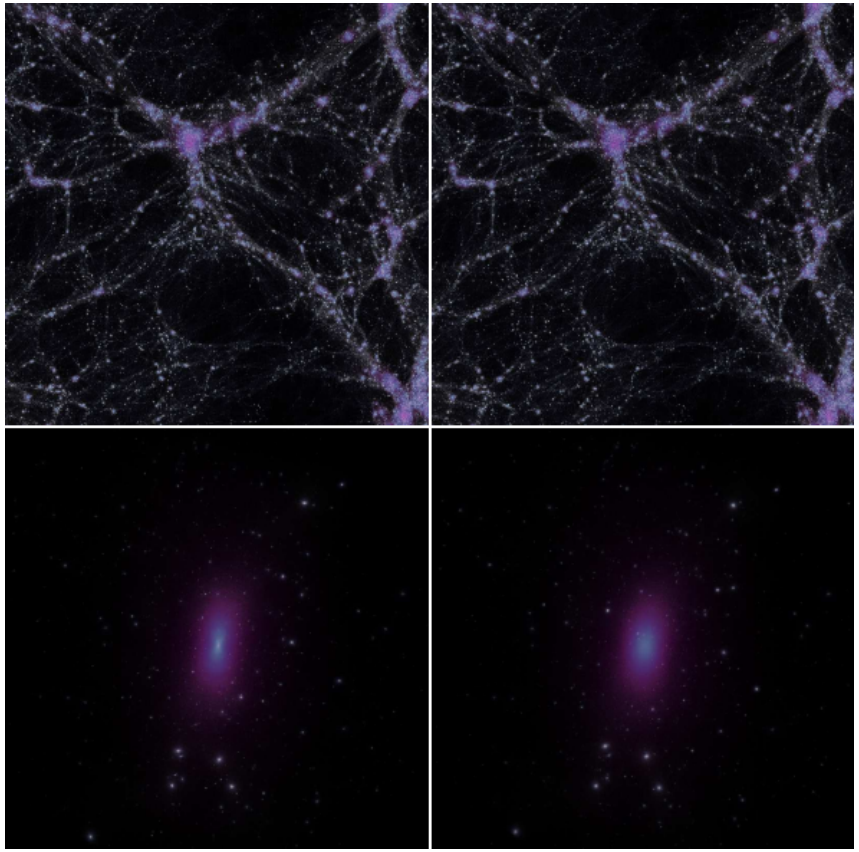

Figure: CDM and SIDM cosmological simulations. [M. Rocha, et. al., arXiv:1208.3025]

SIDM maintains CDM large scale success.

Constraints on SIDM

- Bullet Cluster

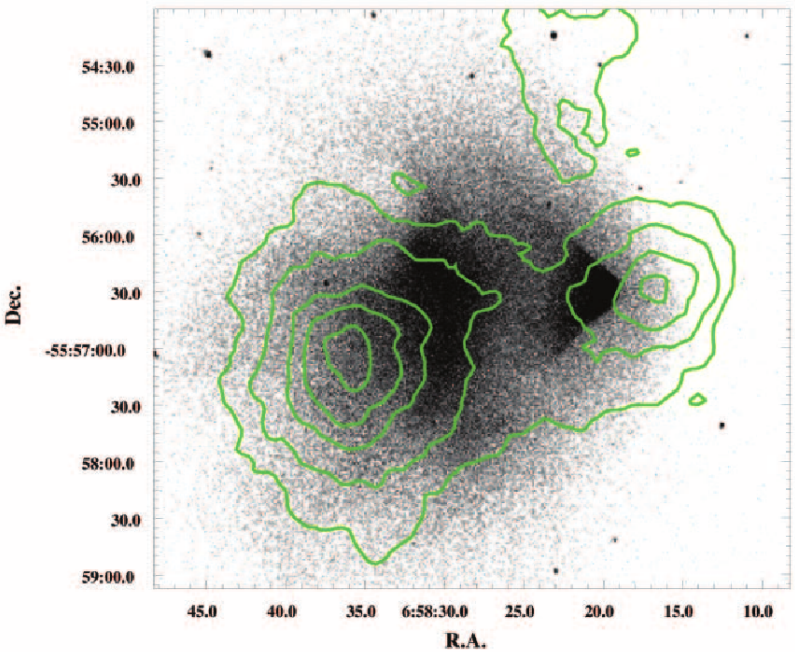

Figure: X-ray image and weak lensing mass contours. [S. Randall, et. al., ApJ 679:1173, 2008]

- $\sigma_{\chi\chi}/m_\chi < 1.25\ \mathrm{cm}^2/\mathrm{g}$

Constraints on SIDM

- Bullet Cluster (< 1.25 cm^2/g)
- Cosmological simulations

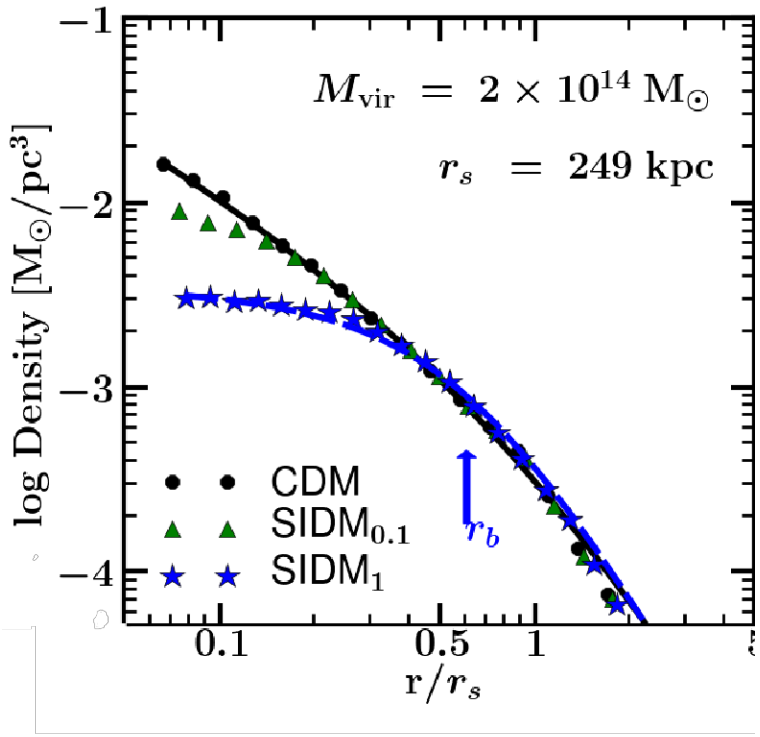

Figure: Density profiles of halos CDM , SIDM$_{0.1}$ and SIDM$_1$. [M. Rocha, et. al., MNRAS 430, 81-104 (2013)]

- $\sigma_{\chi\chi}/m_\chi = 1$ cm^2/g is likely ruled out
- but $\sigma_{\chi\chi}/m_\chi \sim 0.1$ cm^2/g could solve CDM controversies

Constraints on SIDM

- Bullet Cluster (< 1.25 cm^2/g)
- Cosmological simulations ($\lesssim 1$ cm^2/g, 0.1 cm^2/g: good)
- MW's dwarf spheroidals

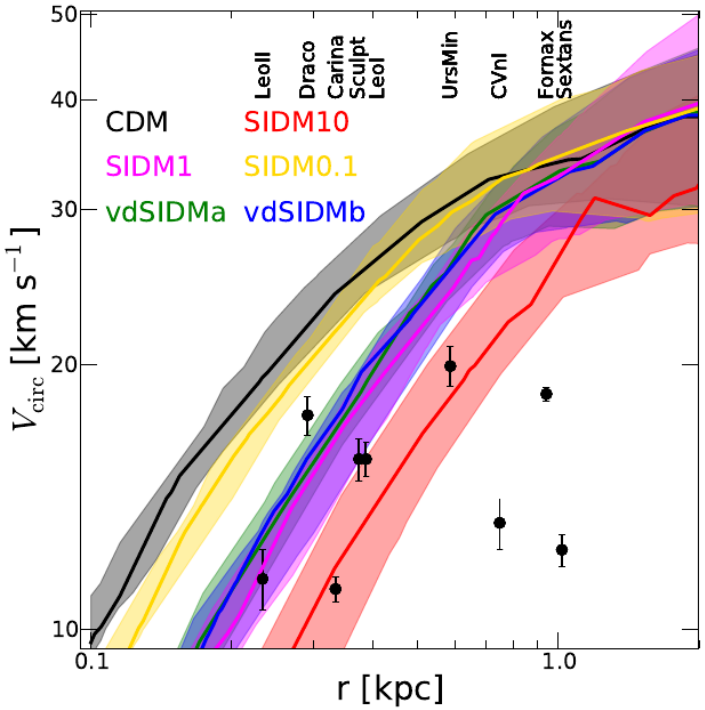

Figure: Circular velocity profiles of largest subhalos. [J. Zavala, et. al., MNRAS 431 (2013)]

- Too Big to Fail problem is resolved if:

$$\sigma_{\chi\chi}/m_\chi \gtrsim 1 \text{ cm}^2/\text{g}$$

- $\sigma_{\chi\chi}/m_\chi = 0.1$ cm^2/g is too low

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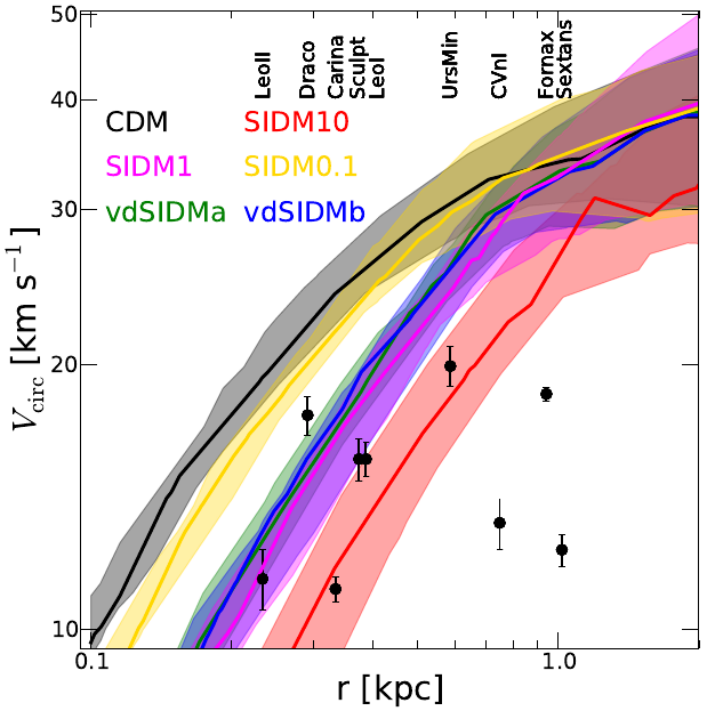

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Only Small Window

Interesting constant values:
$0.1\,\text{cm}^2\text{g}^{-1} < \sigma_{\chi\chi}/m_\chi < 1\,\text{cm}^2\text{g}^{-1}$

Probing SIDM independently: DM signal from the Sun

High energy ν flux from DM self-capture within the Sun

[A. Zentner, Phys. Rev. D 80, 063501 (2009)]

- Enhancements in the predicted signal from DM annihilations

Our work: Probing SIDM

1. Explore the parameter space of SIDM: $(m_\chi, \sigma_{\chi\chi}) \rightarrow$ Capture and Annihilation
2. Estimate the event rate in the IceCube detector
3. Compare predicted signal vs. IceCube results

DM Capture in the Sun

- The Sun captures DM particles while travelling around the galaxy.

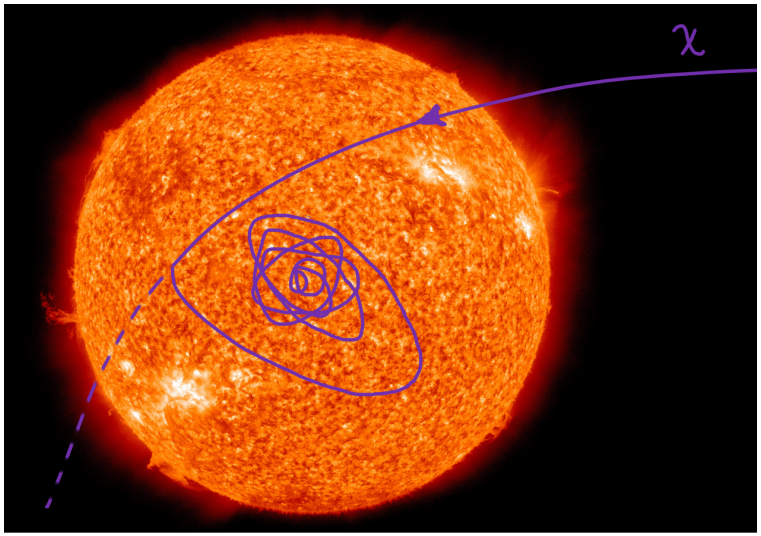

Figure: DM capture in the Sun

- Elastic scattering DM-nucleus
- When sufficient energy loss: capture!

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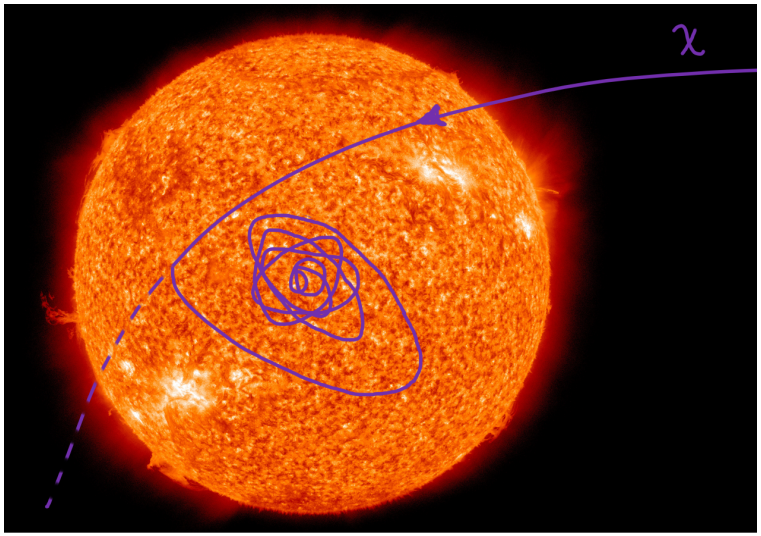

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- In the center of the Sun:
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$$\dot{N}_\chi = Cc - CaN_\chi^2$$

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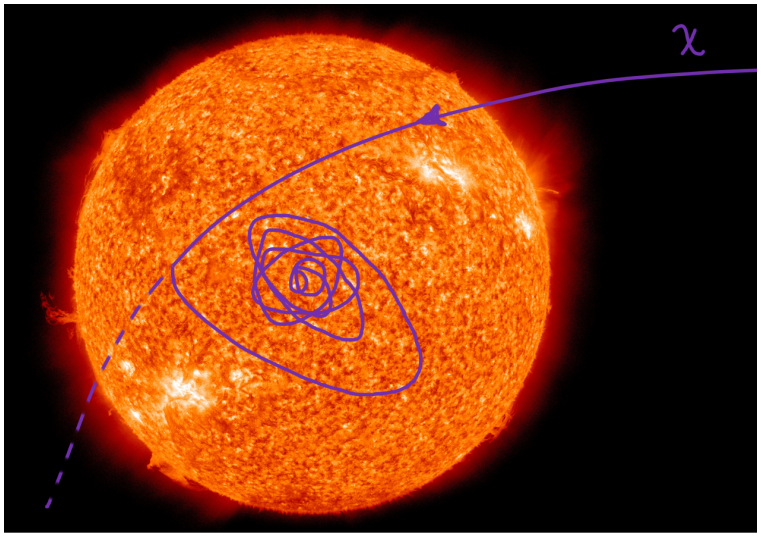

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- DM particles already captured are also a target:

Self-capture

$$\boxed{\dot{N}_\chi = Cc + CsN_\chi - CaN_\chi^2}$$

Self-interactions increase N_χ

SIDM Enhances the Annihilation Rate

$$\Gamma_A = \frac{1}{2} C_a N_\chi^2$$

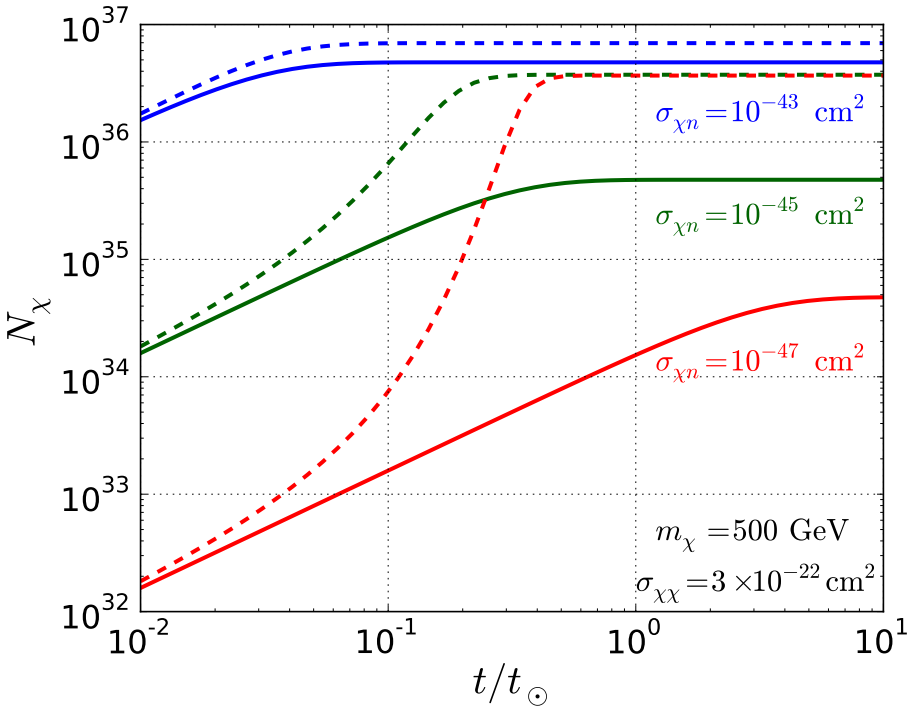


Figure: N_χ evolution in time

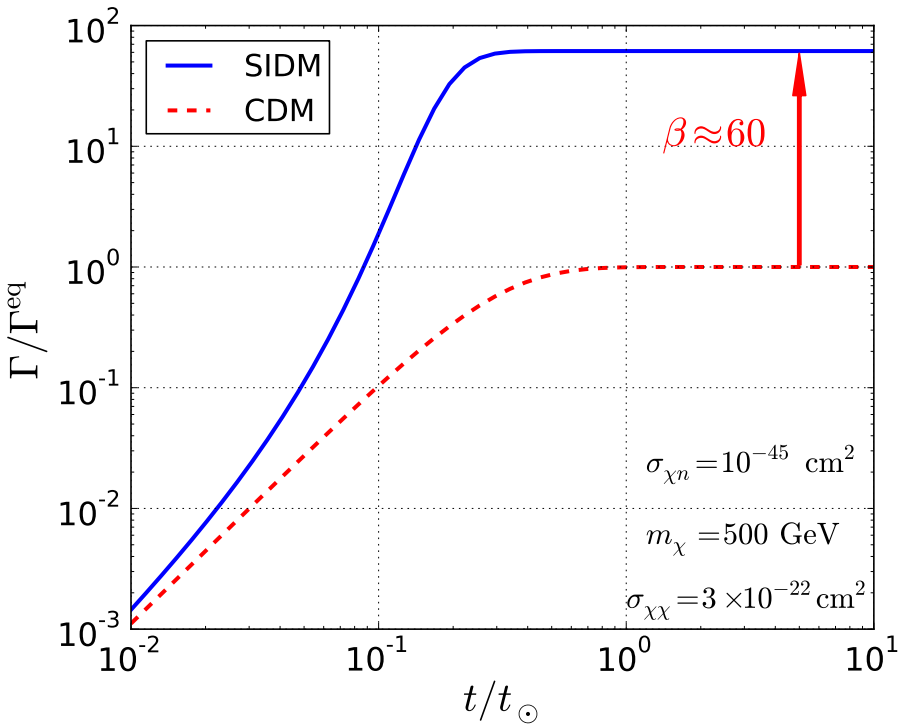


Figure: Evolution of the annihilation rate.

Dark Matter Annihilation

- m_χ : 20 GeV to 5 TeV
- Annihilation channels selected:
  - $\chi\bar{\chi} \to b\bar{b}$
  - $\chi\bar{\chi} \to W^+W^-/\tau^+\tau^-$
- We follow the produced ν's: they could escape the Sun and reach the Earth

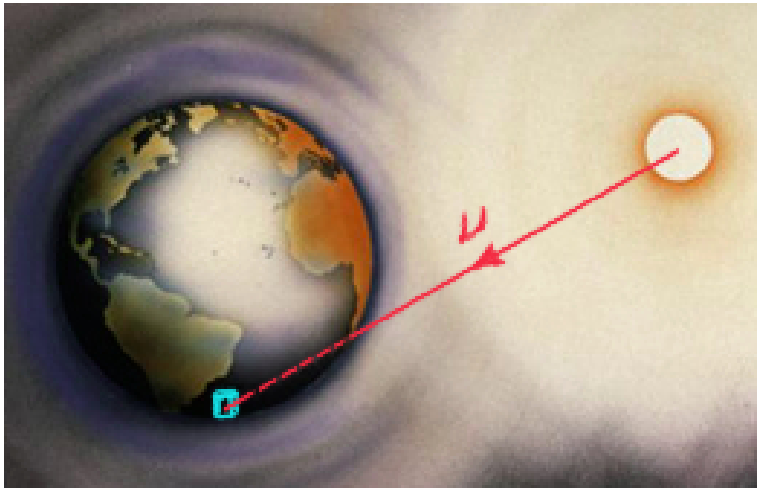


Figure: ν's are propagated from the Sun to the detector [UCAR]

- ν's oscillations and charged and neutral current interactions
- Sun's and Earth's densities
- Detector location and time of the event are important:
  - Sun-Earth distance
  - How much of the Earth the neutrinos traverse
- We used WimpSim MC code [J. Edjsö, http://www.fysik.su.se/~edsjo/wimpsim]

ϕ_{ν_μ} obtained at IceCube

Angular Smearing and Cut

- IceCube angular resolution is energy dependent
  - $E_\nu = 40$ GeV: $\bar{\theta} \approx 10°$
  - $E_\nu = 1000$ GeV: $\bar{\theta} \approx 1°$

[M. Danniger, Searches for DM with IceCube and DeepCore]

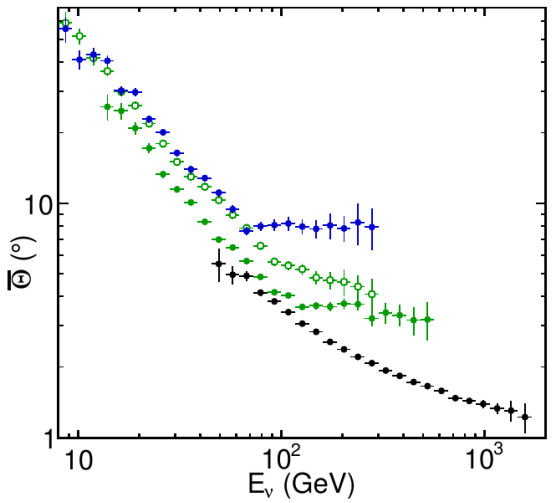


Figure: Angular error and smearing about the Sun-IceCube axis.

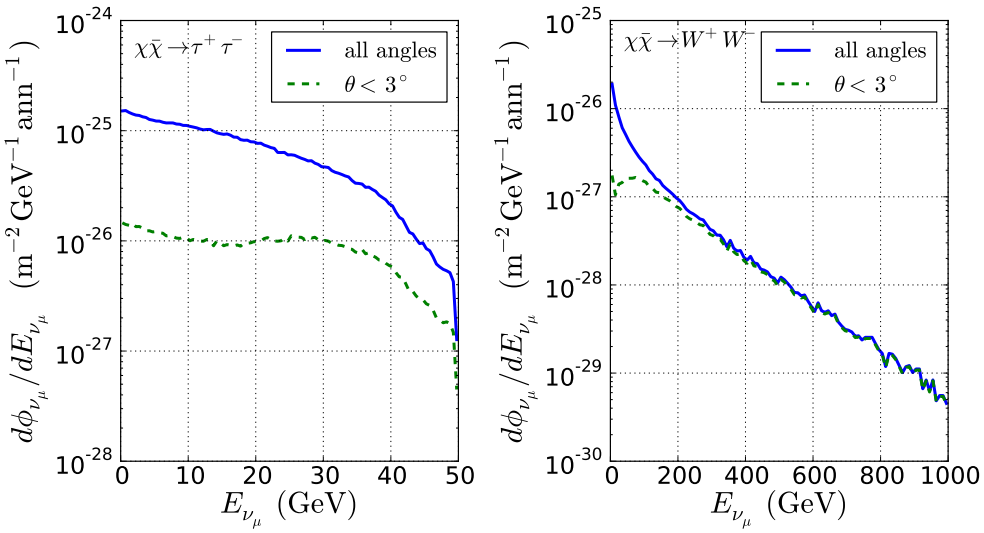


Figure: Neutrino flux spectrum and angular cut.

Muon Neutrino Events at IceCube-79

- Considering IceCube-79 effective area we obtain the expected number of events

- Number of expected ν_μ's in IceCube:

$$N_{\nu_\mu} = \Gamma_A t_{\text{exp}} \times \int_{E_{\text{th}}} \frac{d\Phi_{\nu_\mu}}{dE} A_{\text{eff}}(E) dE$$

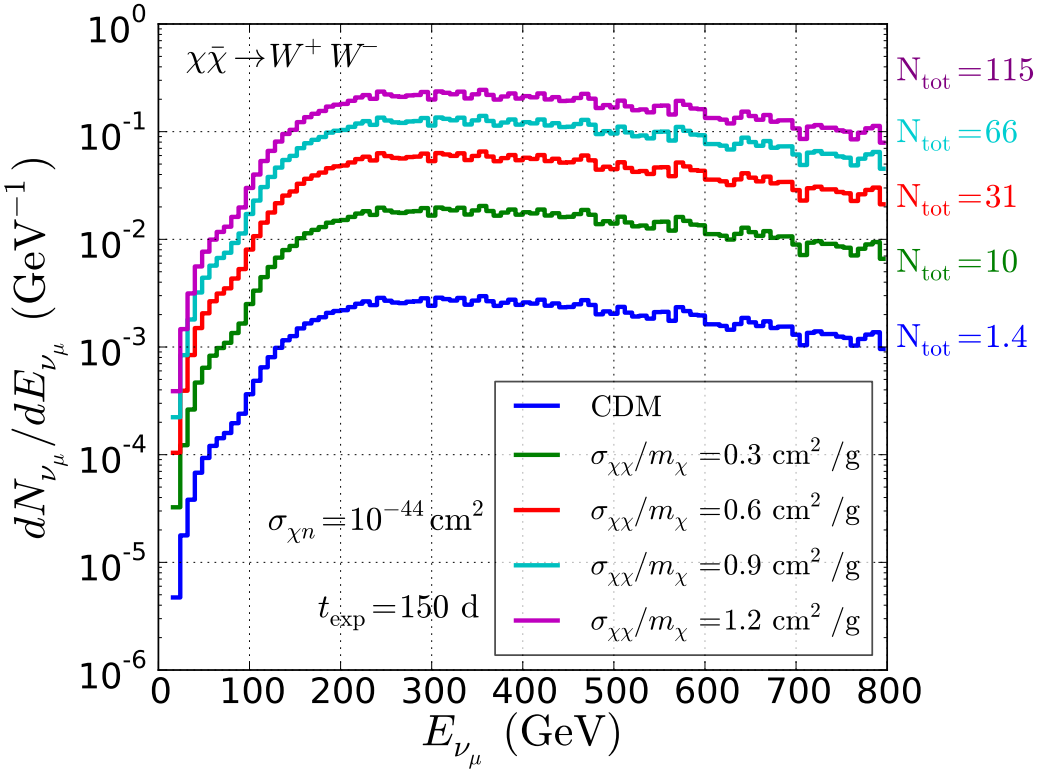


Figure: Muon neutrino event spectrum for W^+W^- channel.

IceCube79's Search for DM Annihilations in the Sun

- 317 days of data between June 2010 and May 2011
- First time of DeepCore: Lower E_{th} and Summer days

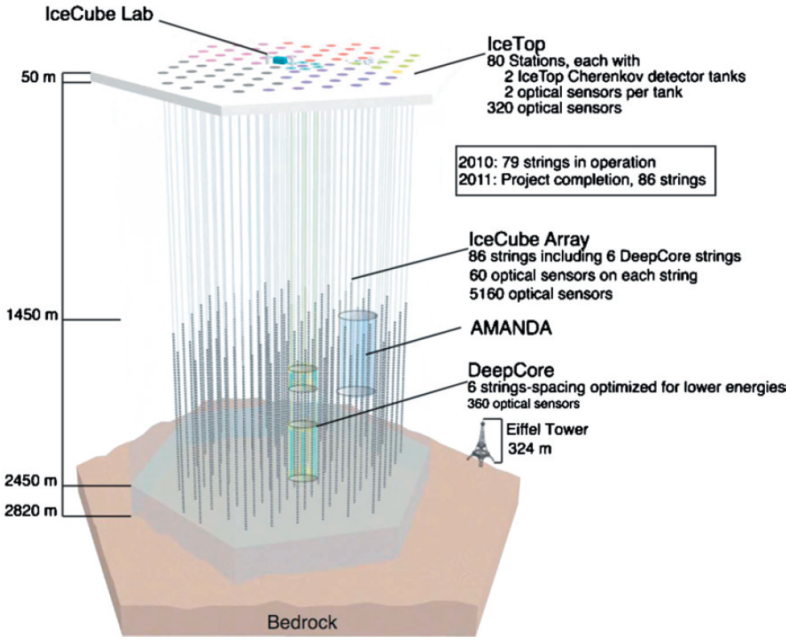


Figure: The IceCube detector.

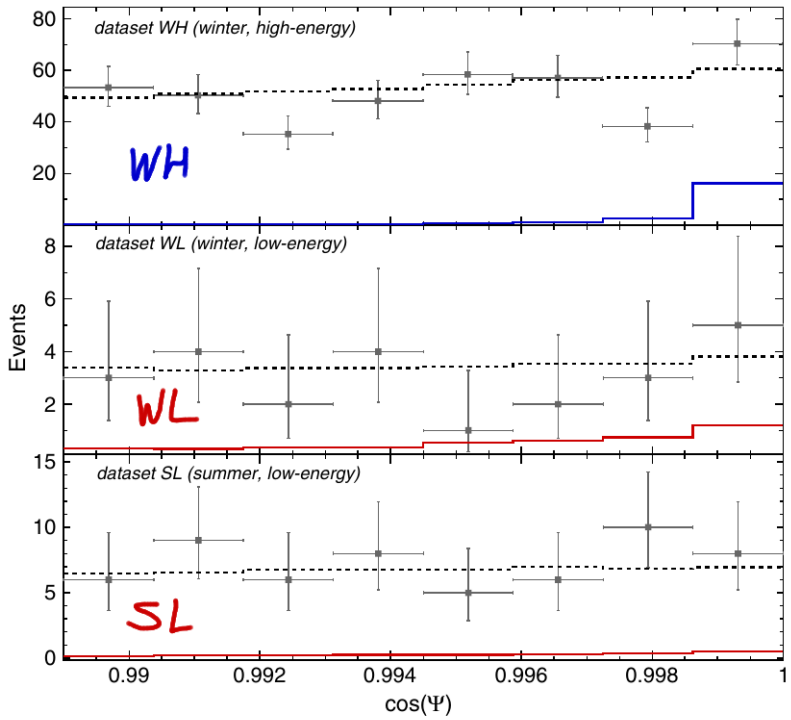
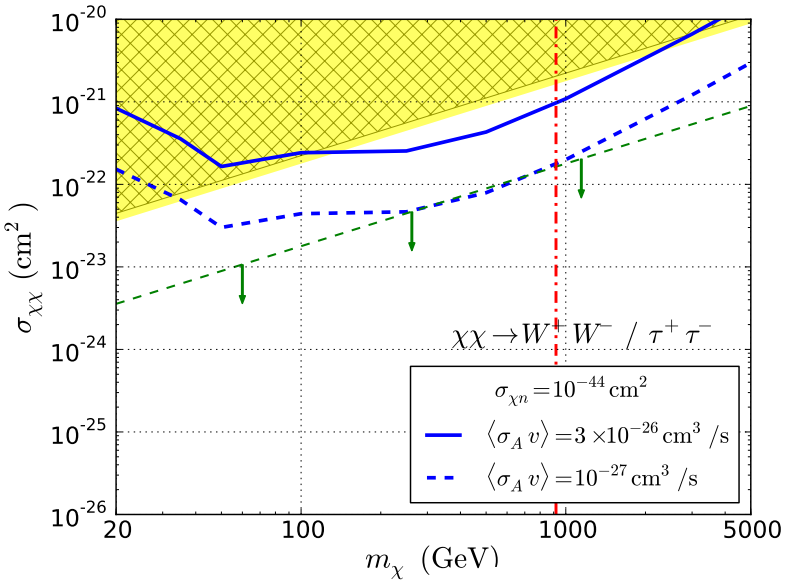


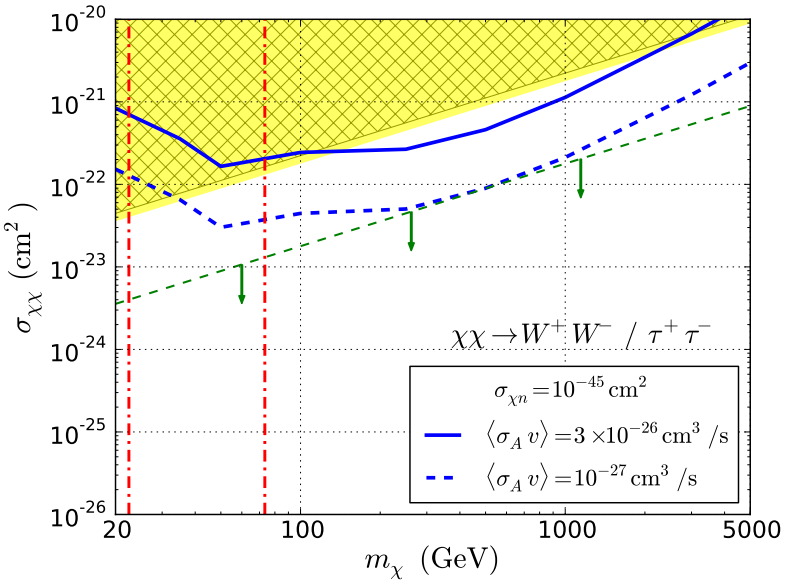
Figure: IceCube events angular distribution. [IceCube Col., PRL 110, 131302 (2013)]

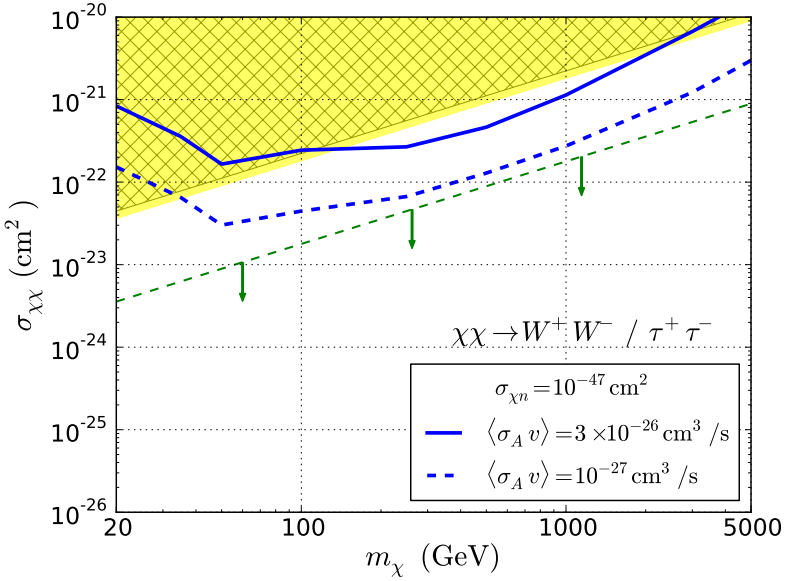
Results consistent with background-only hypothesis.

Probing SIDM: Results for W^+W^- channel - si

[I. Albuquerque, C. de los Heros and DSR, JCAP 02(2014)047]







Results for $b\bar{b}$ channel - si

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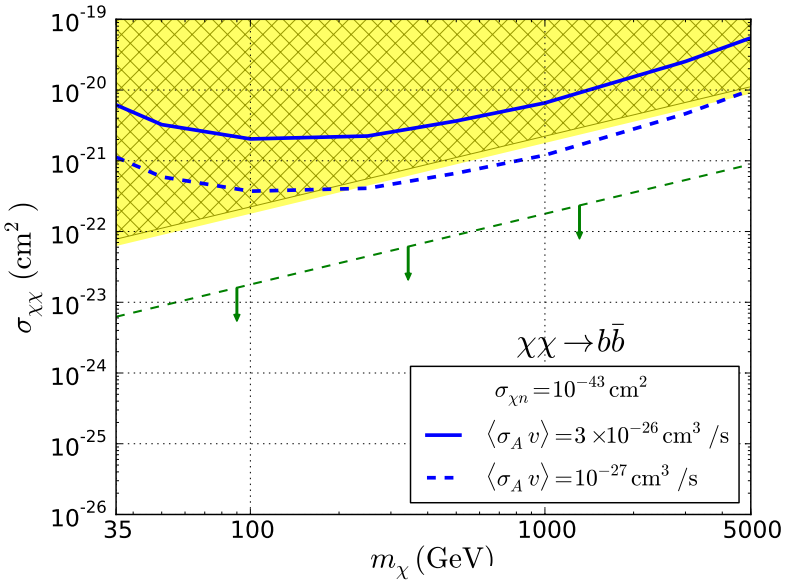

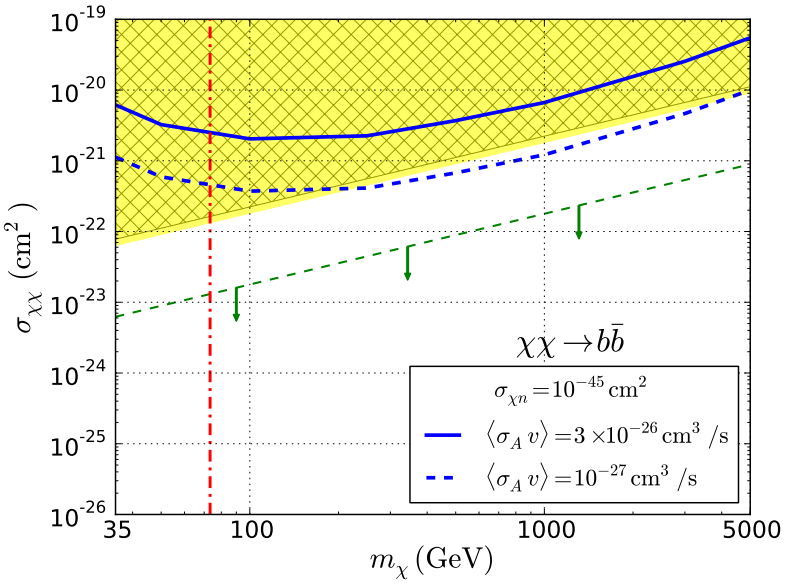

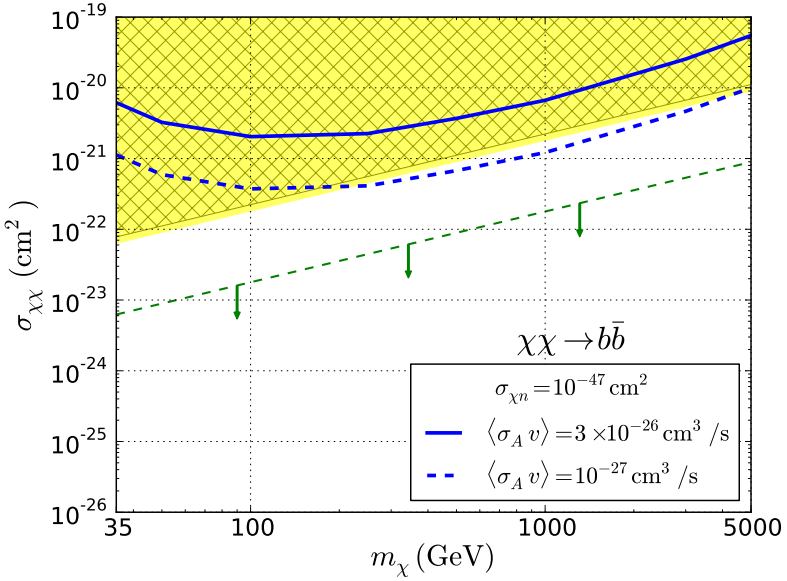

Results for W^+W^- channel - sd

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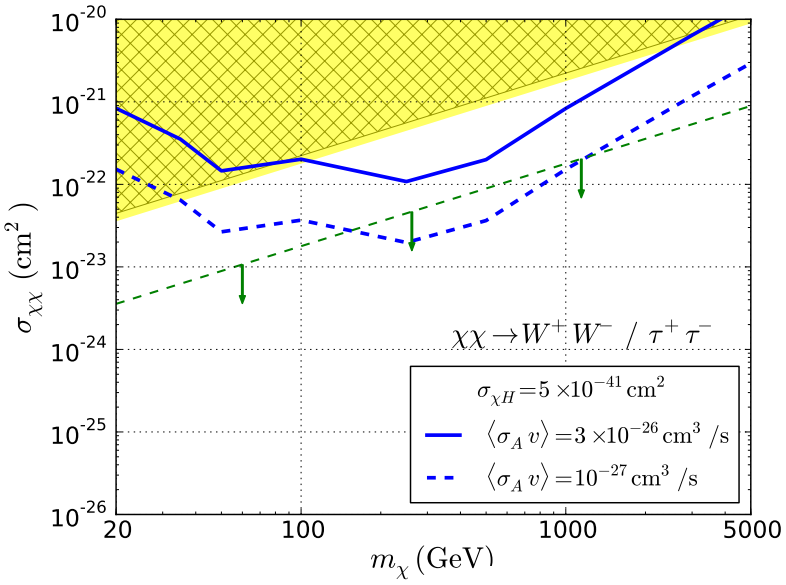

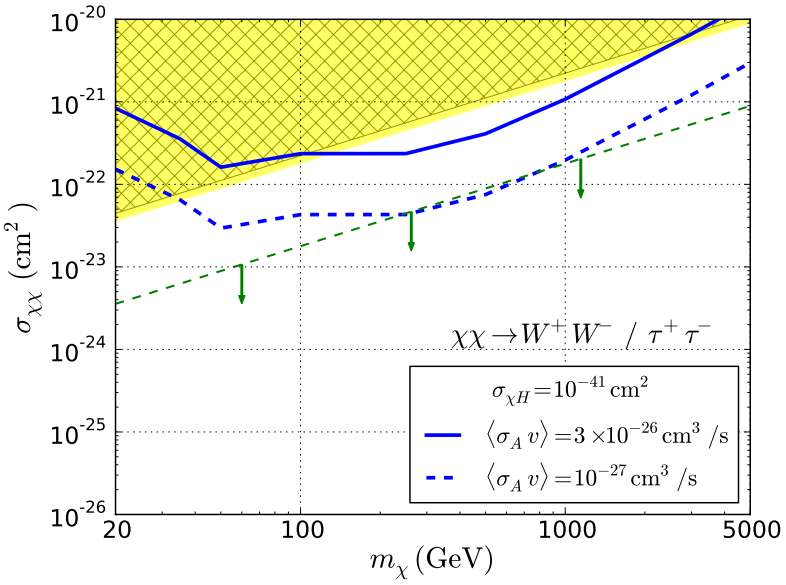

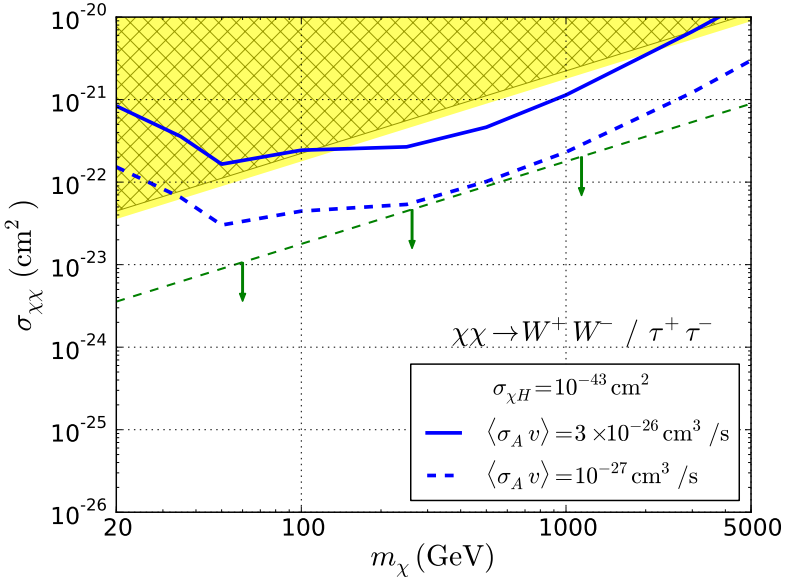

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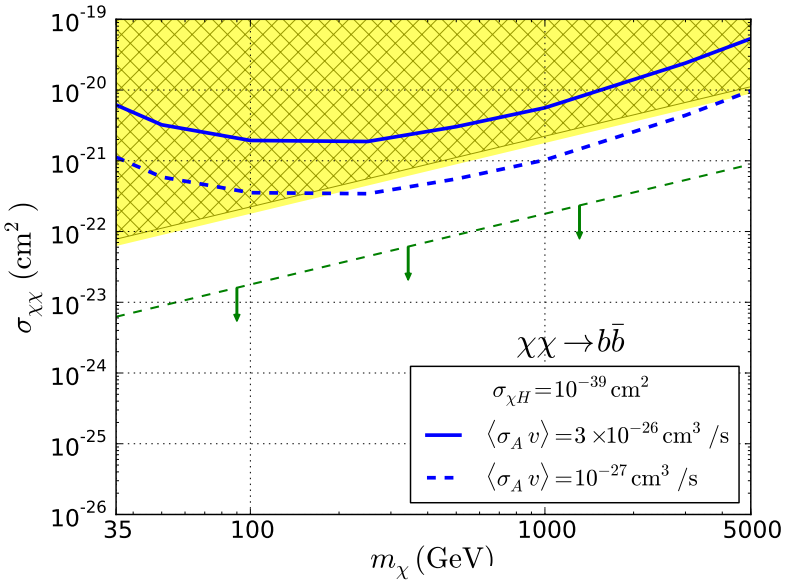

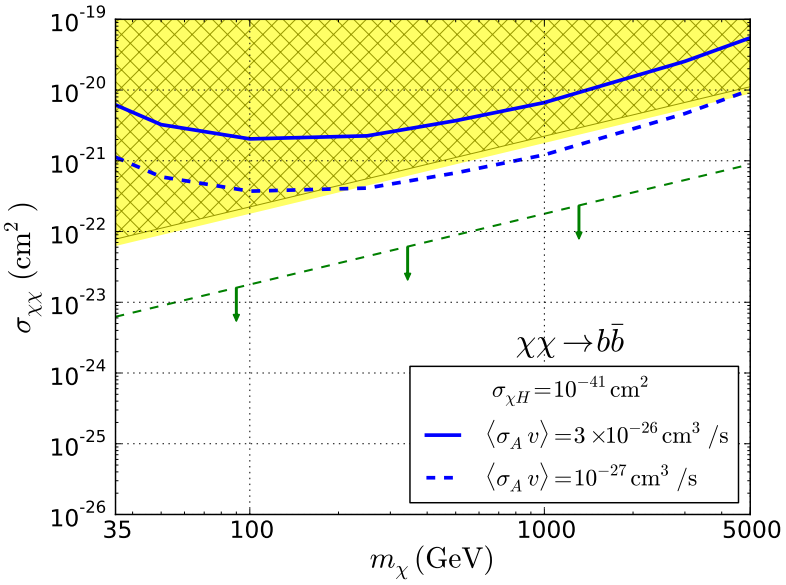

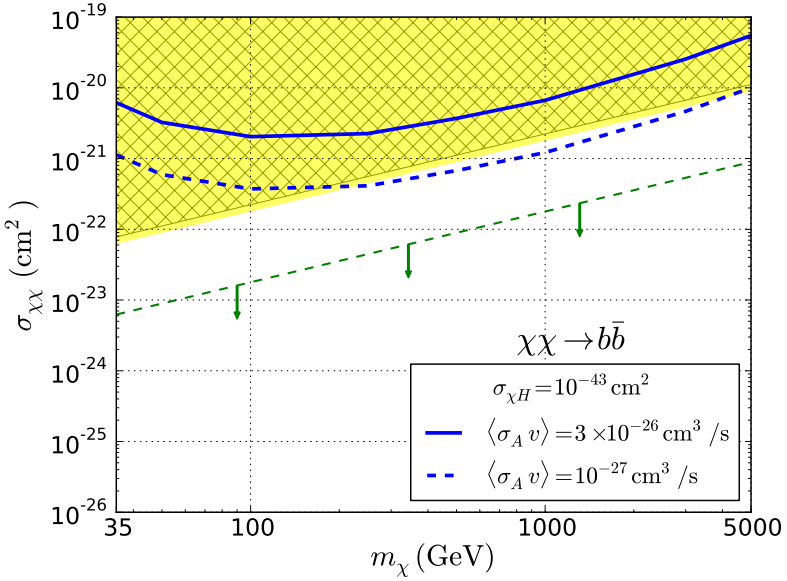

Conclusions

- Stringent constraints on SIDM if it annihilates into W^+W^-:
  - up to ~ 0.6 cm^2/g for $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^3/s
  - up to ~ 0.1 cm^2/g for $\langle \sigma v \rangle = 10^{-27}$ cm^3/s
    Most of SIDM parameter space is rule out
- Weaker constraints for the $b\bar{b}$ channel.
  We confirm constraints from the Bullet Cluster and cosmological simulations:
  - up to ~ 5.6 cm^2/g for $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^3/s
  - up to ~ 0.7 cm^2/g for $\langle \sigma v \rangle = 10^{-27}$ cm^3/s
- If the CDM small-scale controversies is to be solved within SIDM:
  - Annihilation produces few high energy neutrinos