Probing Velocity Dependent Self Interacting Dark Matter

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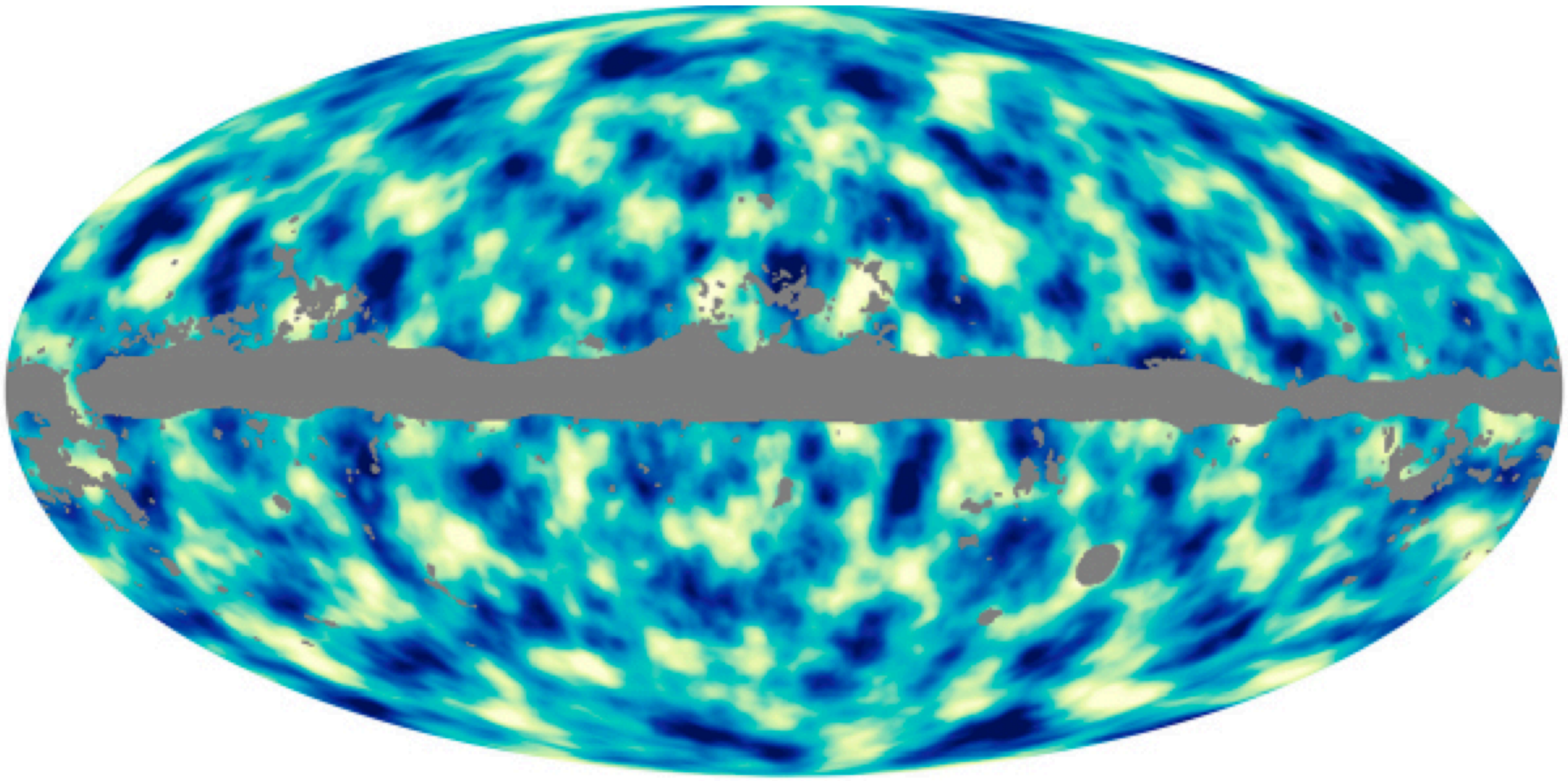
Outline

1. CDM Small Scale Potential Problems
   - DM Self-Interaction (SIDM) as possible solution
2. Probing SIDM with Neutrino Telescopes
   - enhanced ν flux from DM annihilation
   - estimate ν flux in IceCube and Current constraints on SIDM
3. Velocity Dependent SIDM (vdSIDM)
   - vdSIDM model
   - Neutrino Telescopes sensitivity do vdSIDM

Collisionless CDM

Extremely successful at large scales

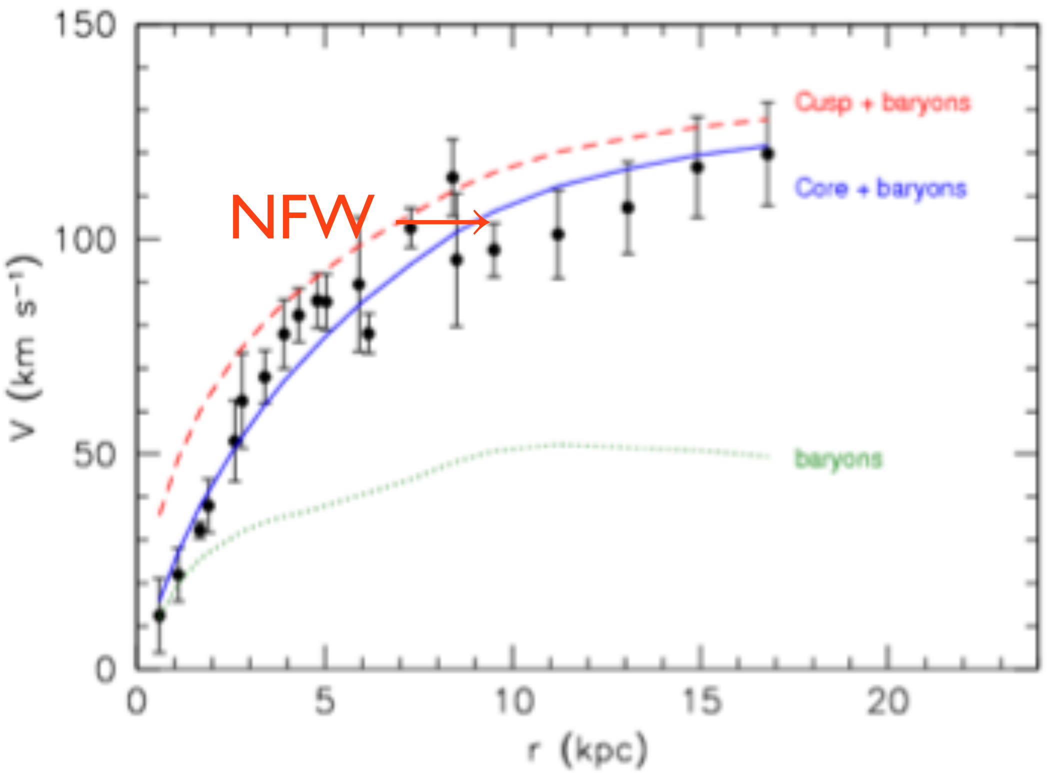


Date: 02 April 2013
Satellite: Planck
Depicts: All-sky map of dark matter distribution in the Universe
Copyright: ESA and the Planck Collaboration

CDM simulations fit very well large scale observations

CDM Potential Problems

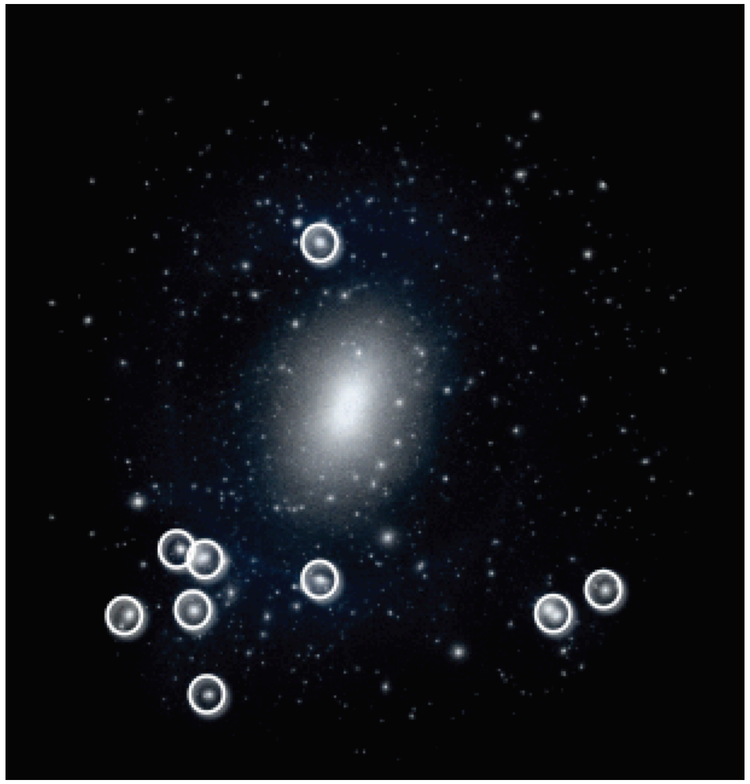
at small scale structure formation



Core / Cusp

CDM: too much DM ~ few Kpc

Majority of gal rot curves: better fit by cored profile



Too Big to Fail - Missing Satellites

⇔ 9 “classic" massive SIM DM subhalos

Weinberg et al. , Proc. Nat. Acad. Sci. **112** (2014)

Data: F568-3 (SSDS)

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

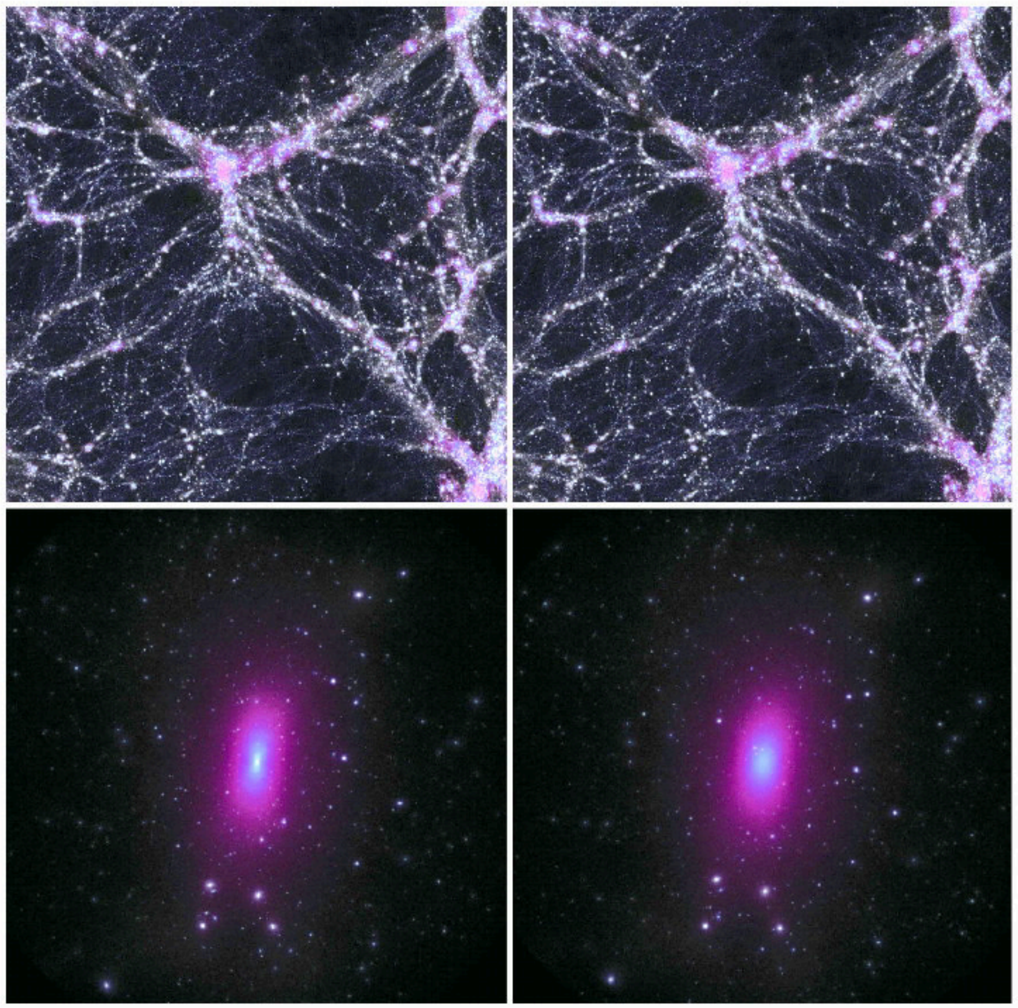
$$\frac{\sigma_{\chi\chi}}{\mathbf{m}_\chi} = \mathbf{8 \times 10^{-(25-22)}\ cm^2/GeV}$$
$$= \mathbf{4.5 - 450\ cm^2/g}$$

SIDM Qualitative Effects on Halo Structure:

energy exchange
isotropic velocity distribution
limited sub-halo destruction

SIDM Simulations

CDM and SIDM simulations

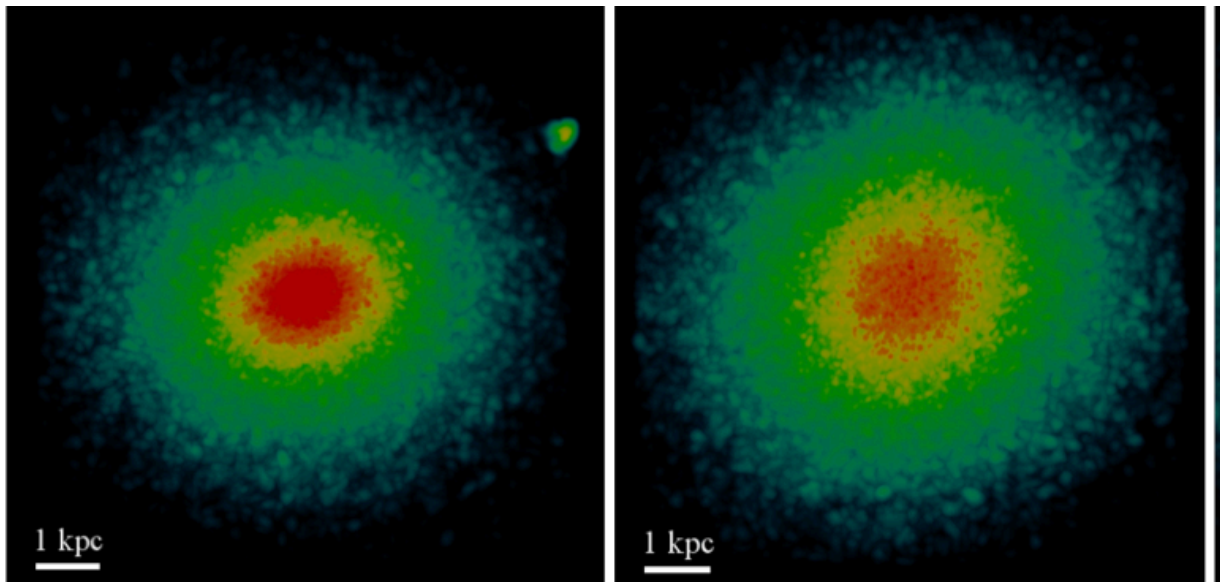


(M. Rocha et al., MNRAS **430**, 2013)

DM halos surface densities

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

Dwarf Cores



Elbert, Bullock et al., MNRAS **453** (2015)

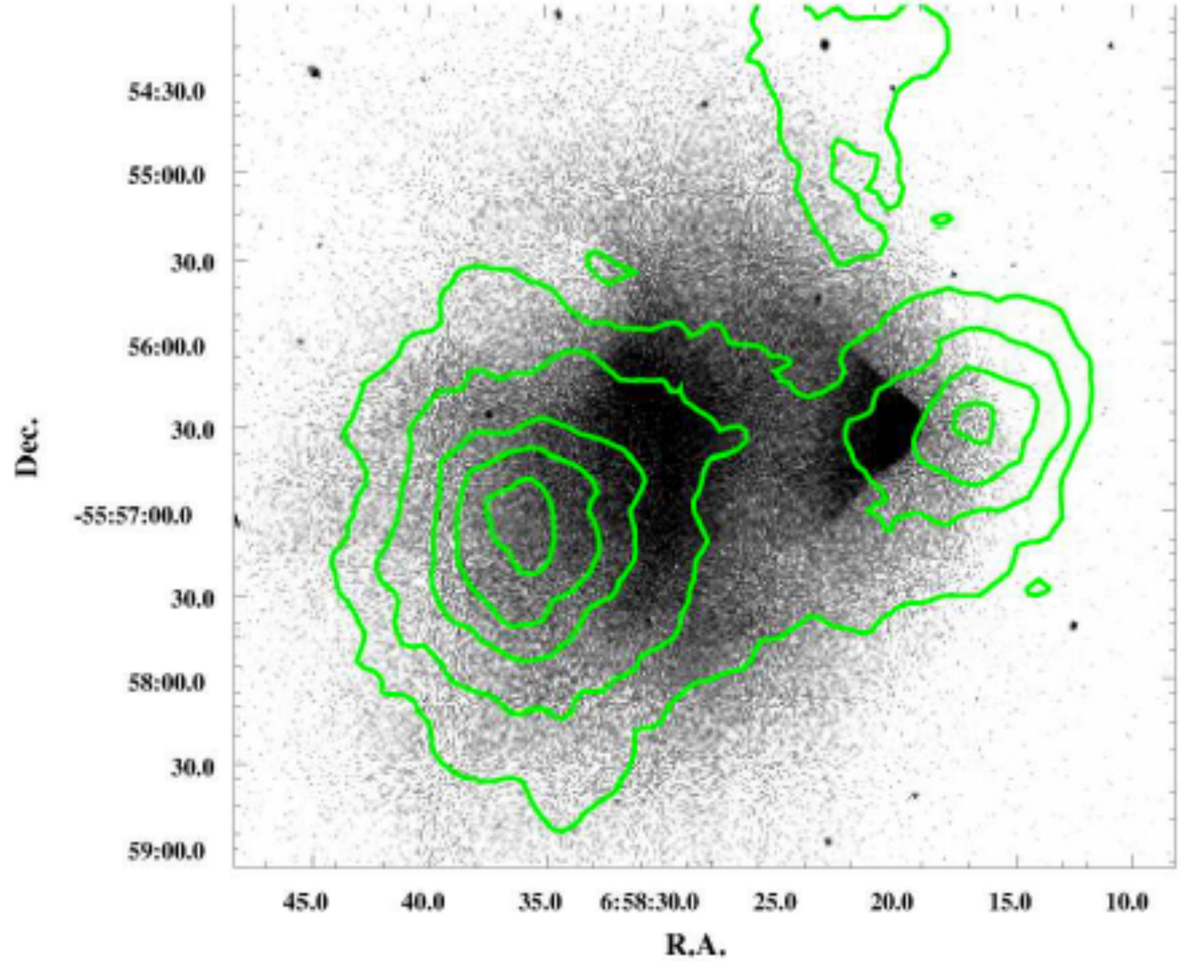
- constant density cores: much reduced central density
- subhalo content is modestly reduced

Milky Way Dwarfs Kinematics

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

Xray image and lensing contour

SIDM Constraints



Bullet Cluster

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

Xray image and lensing contour

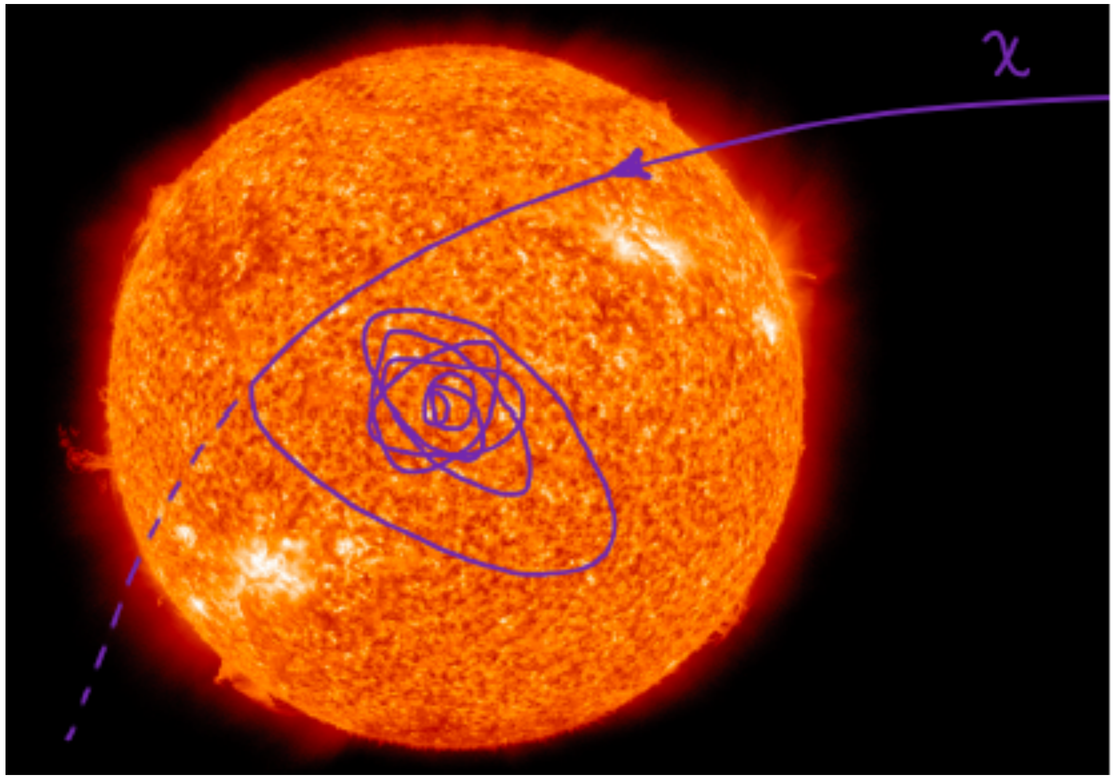
$$\frac{\sigma_{\chi\chi}}{\mathbf{m}_\chi} < \mathbf{1.25\ cm^2/g}$$

SIDM will be effective if

$$\mathbf{0.1} < \frac{\sigma_{\chi\chi}}{\mathbf{m}_\chi} < \mathbf{1\ cm^2/g}$$

Probing SIDM with neutrinos

Self-Interaction enhances DM capture in the Sun



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

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

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

SIDM enhances capture in the Sun but not in the Earth

SI elastic scattering ejects DM from Earth

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

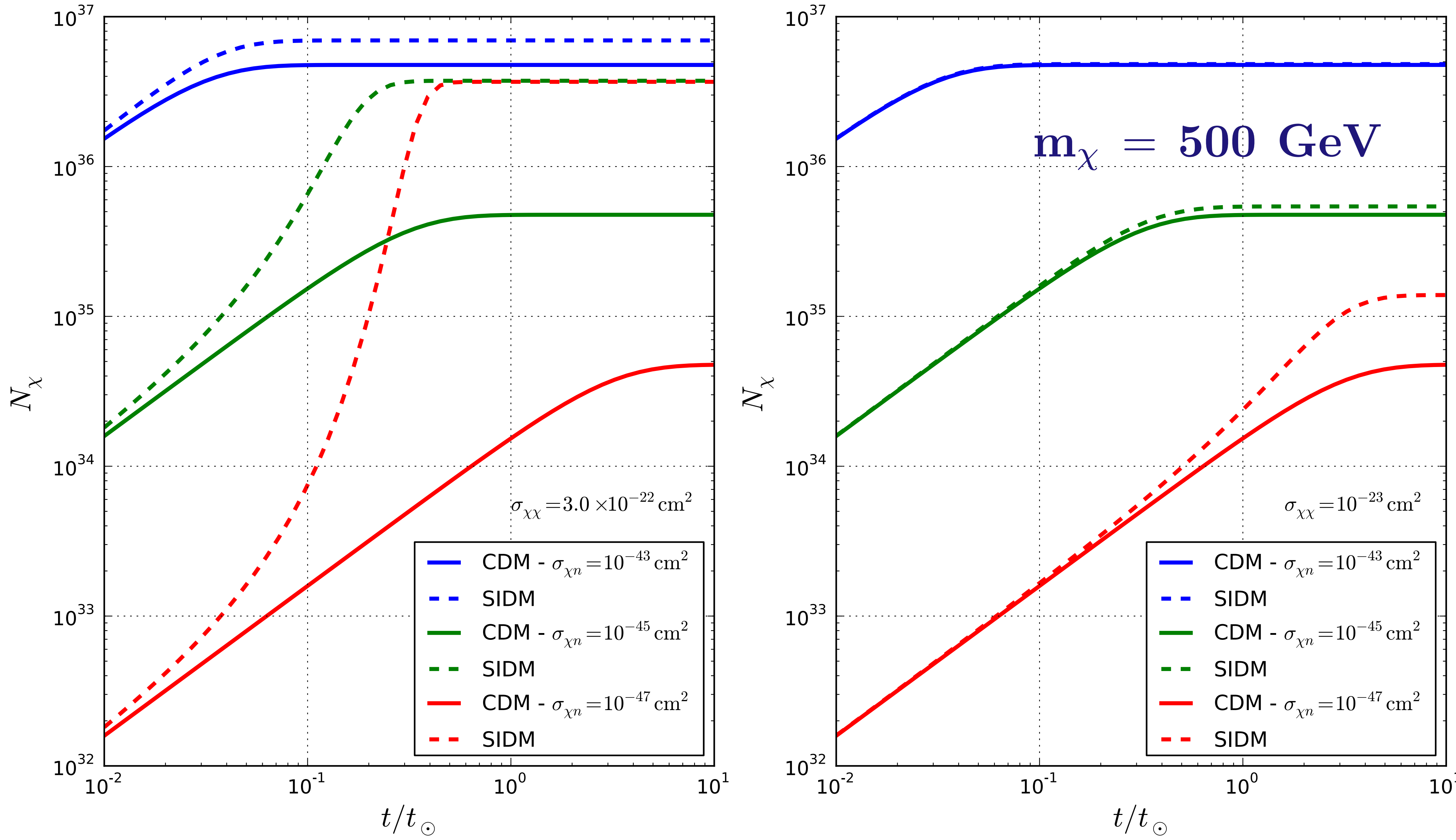
Equilibrium among capture and annihilation rates

=> maximum annihilation rate

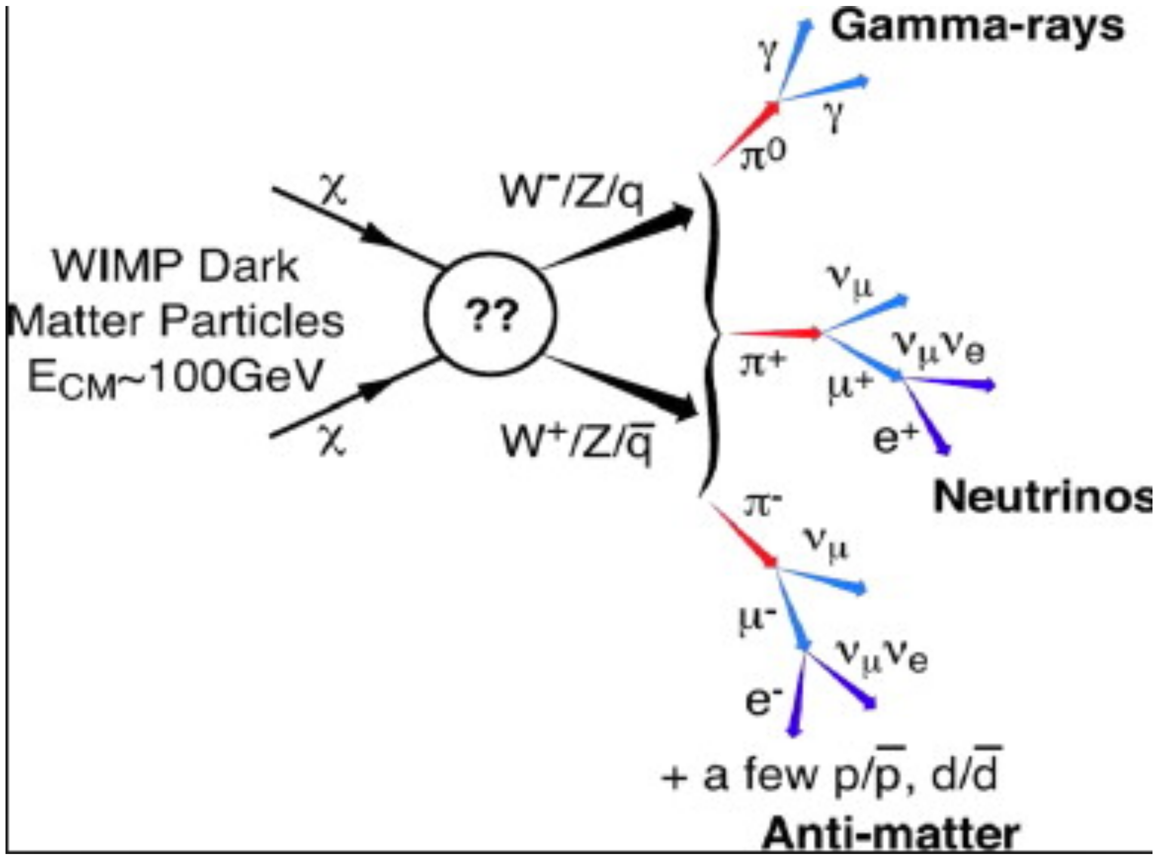
$$\mathbf{\Gamma_A} = \frac{\mathbf{C_A N^2}}{\mathbf{2}} = \mathbf{f(\Gamma_C, \Gamma_{\chi\chi})}$$

SIDM Capture Enhancement

Expedites time scale for capture and annihilation equilibrium



Enhanced Neutrino Flux



Capture ⬆

Annihilation rate ⬆

ν flux ⬆

M_χ : 20 GeV → 5 TeV

Annihilation Channels:

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

IceCube Results:

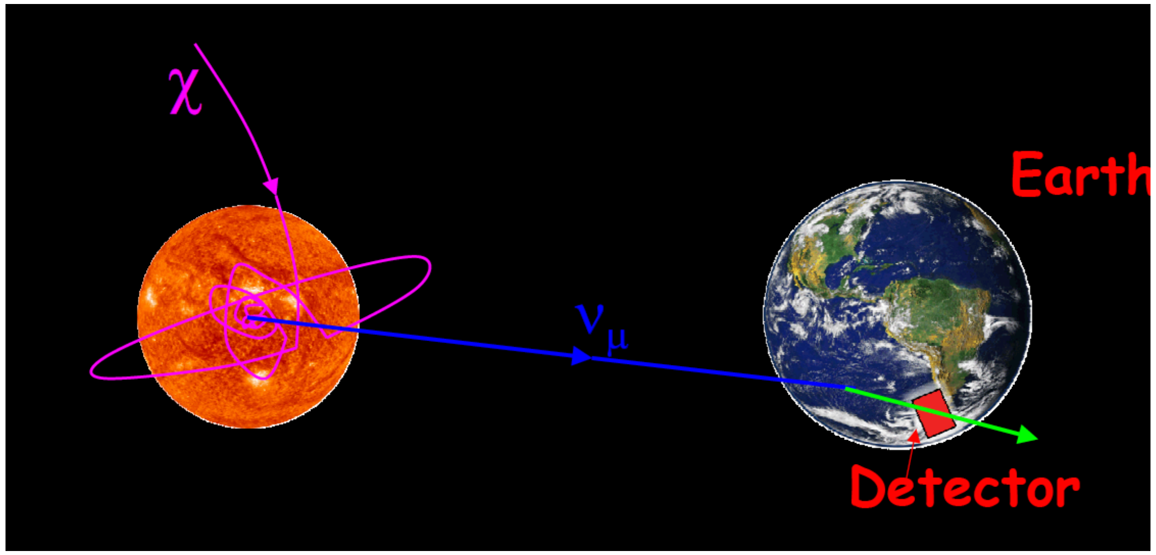
Winter High (E_ν > 95 GeV)

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

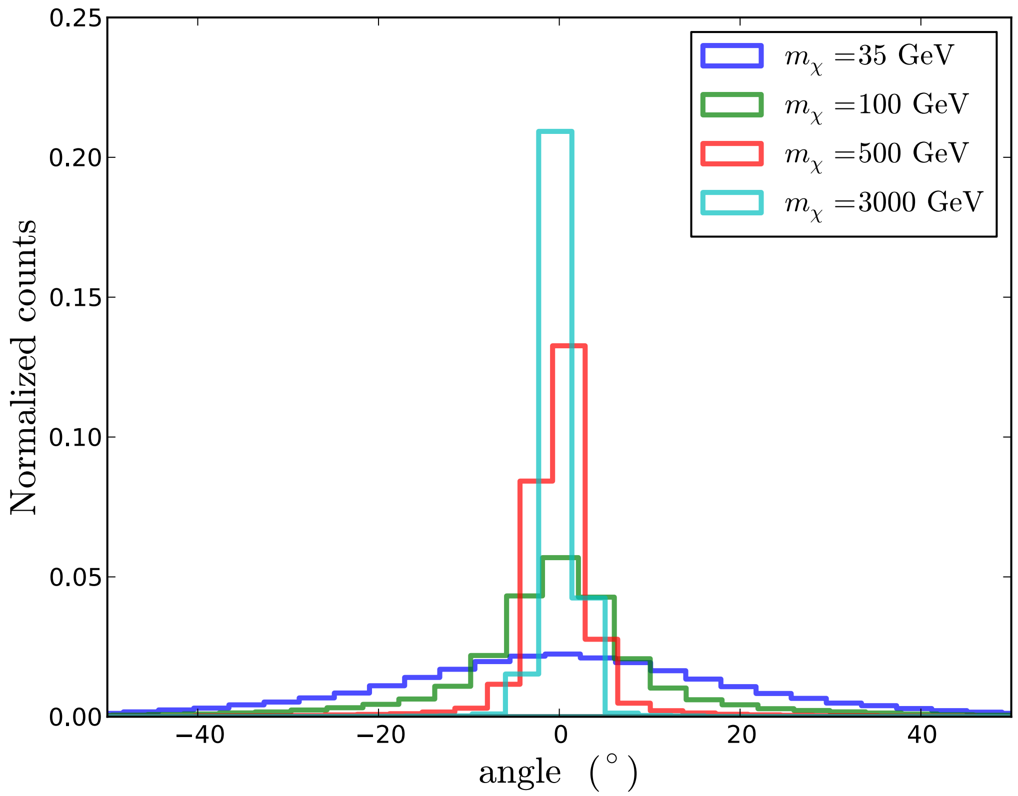
- Number of μ at given angular region Ω at IceCube:

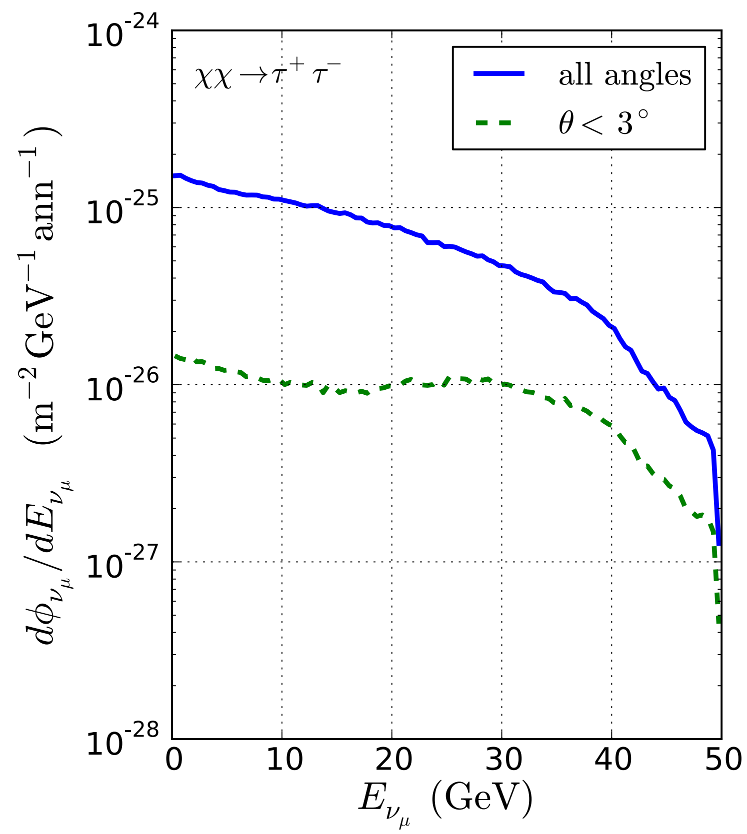
$$\mathbf{N_{\mu} = \Gamma_A\, t_{exp} \int_{E_{thr}} \frac{d\Phi_{\nu_\mu}}{dE_\nu} A_{eff}(E)\, dE}$$

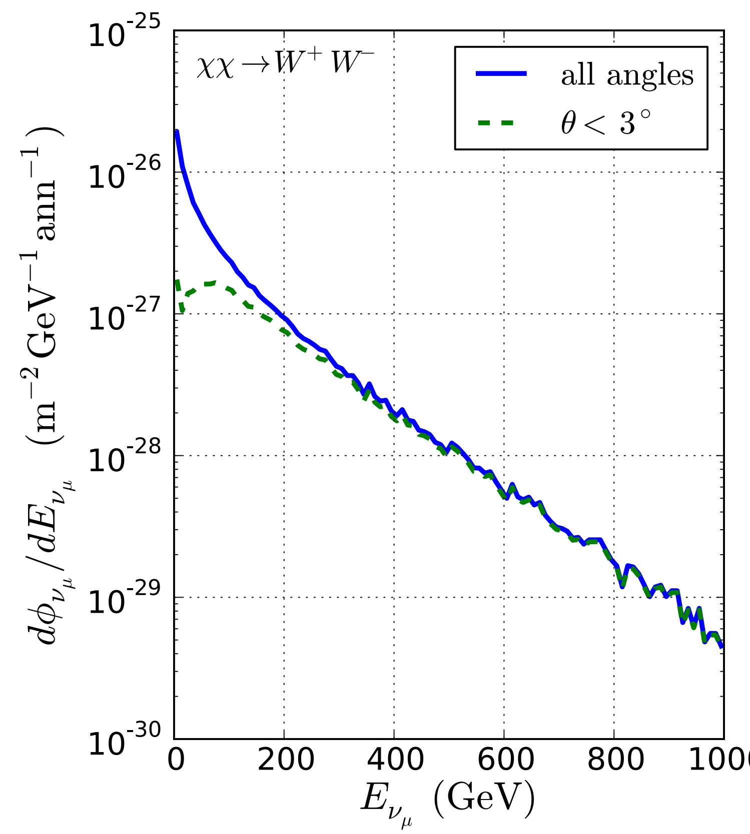
Angular Smearing

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

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



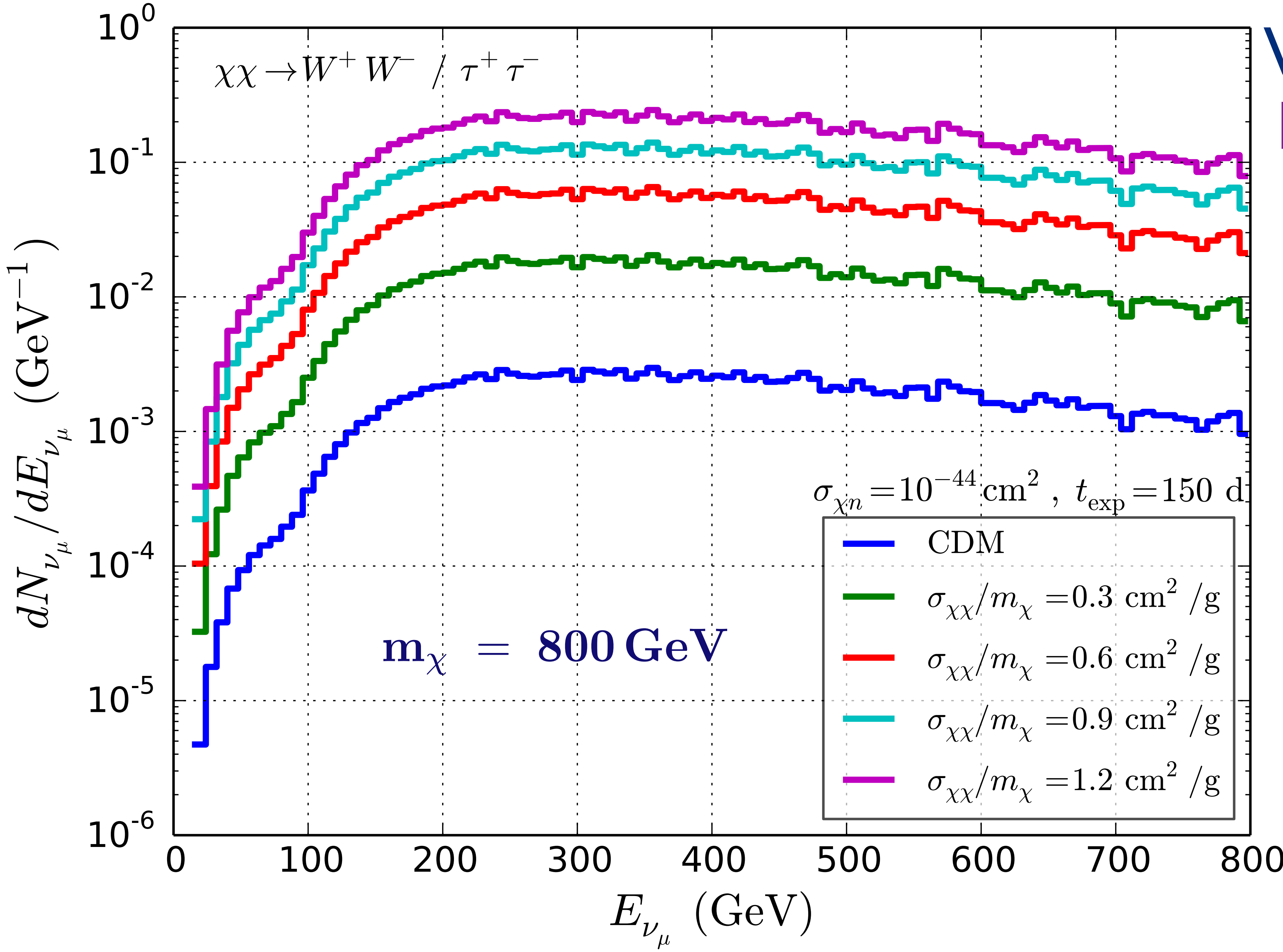




Mχ = 50 GeV

Mχ = 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
1.4	0.05

t_{exp} = 150 days

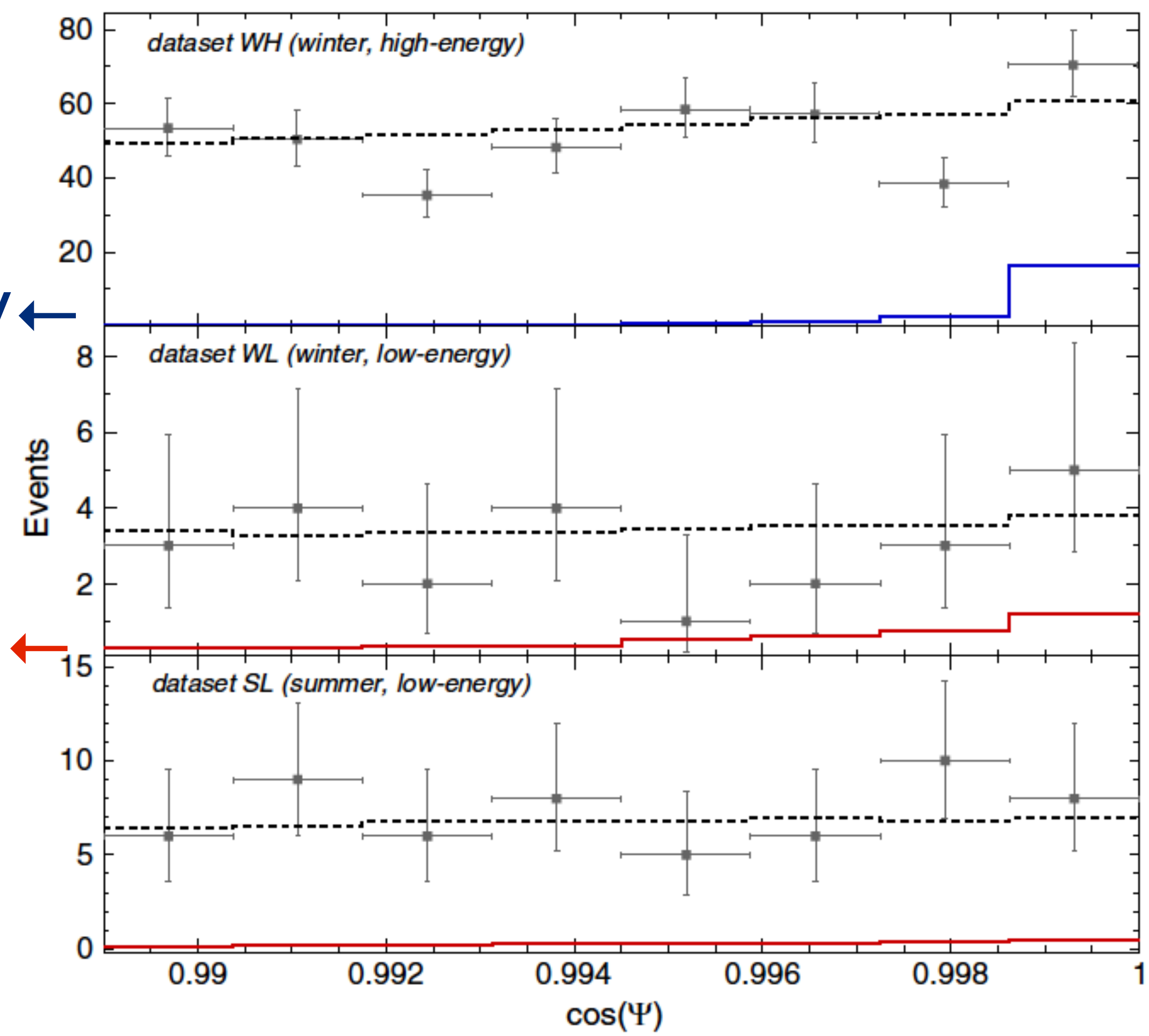
IceCube-79 DM Search

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

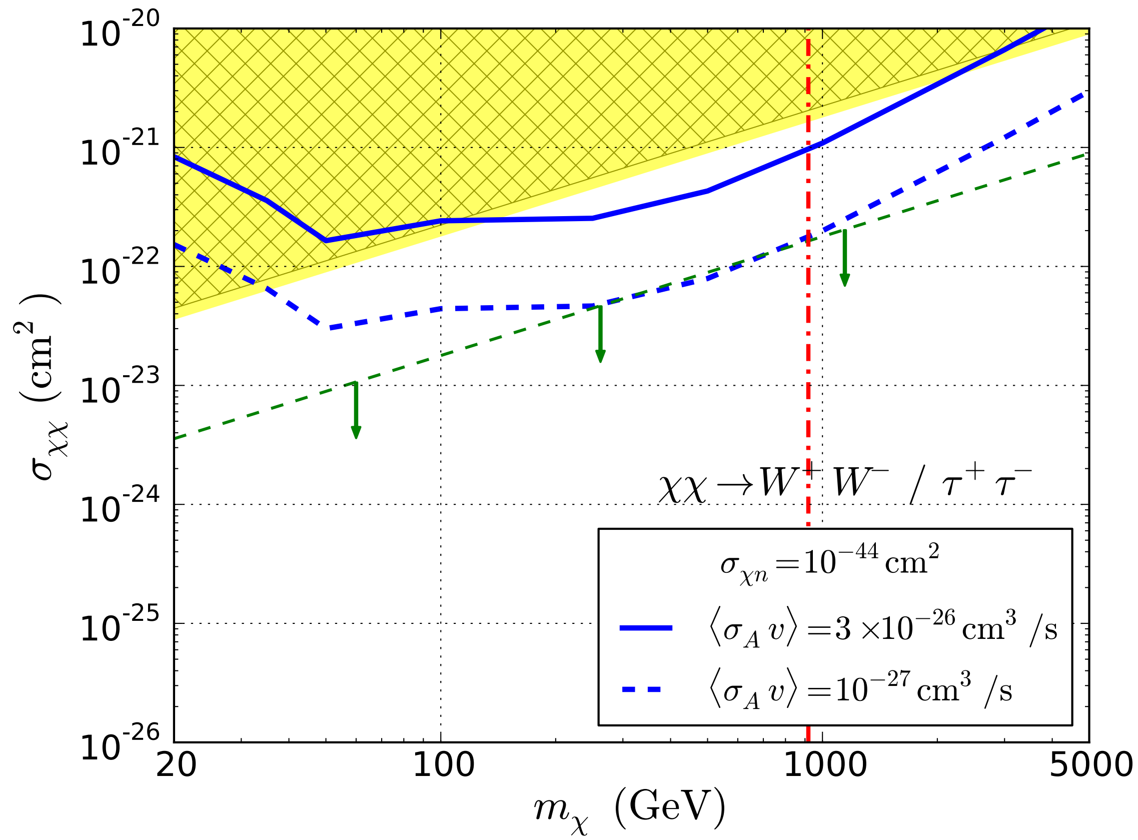
TABLE I. Results from the combination of the three independent data sets. The upper 90% limits on the number of signal events μ_s^{90}, the WIMP annihilation rate in the Sun Γ_A, the muon flux Φ_μ and neutrino flux Φ_ν, and the WIMP-proton scattering cross sections (spin independent, $\sigma_{\mathrm{SI},p}$; 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.

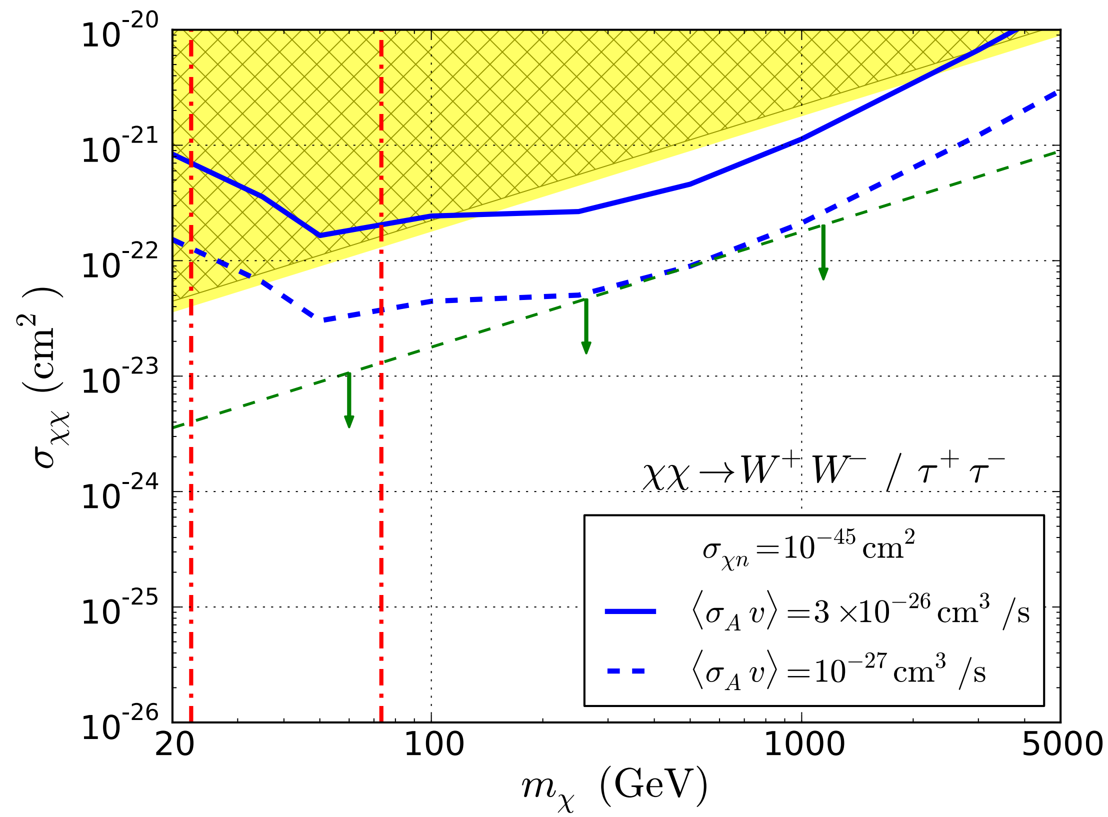
m_χ (GeV/c^2)	Channel	μ_s^{90}	Γ_A (s^{-1})	$\bar{\Phi}_\mu$ (km^{-2}y^{-1})	Φ_μ (km^{-2}y^{-1})	Φ_ν (km^{-2}y^{-1})	$\sigma_{\mathrm{SI},p}$ (cm^2)	$\sigma_{\mathrm{SD},p}$ (cm^2)
20	$\tau^+\tau^-$	162	2.46×10^{25}	5.26×10^{4}	9.27×10^{4}	2.35×10^{15}	1.08×10^{-40}	1.29×10^{-38}
35	$\tau^+\tau^-$	70.2	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}

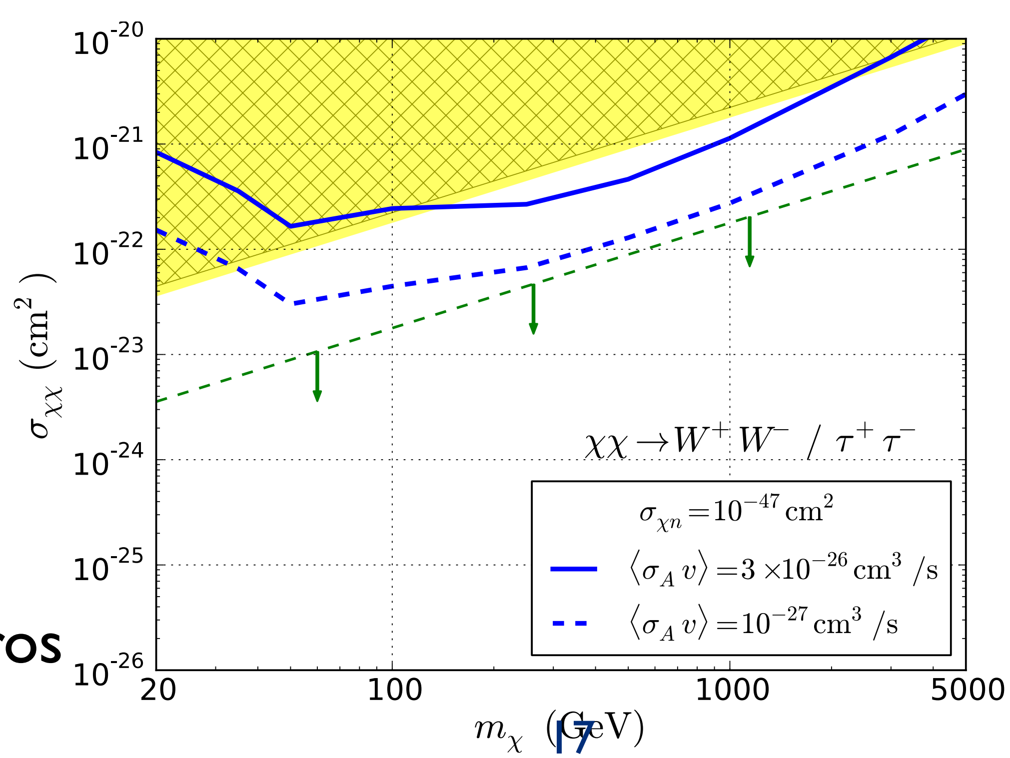
Models which predict more events can be excluded

Probing SIDM models

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







Region above blue curve: excluded at 90% CL

Bullet Cluster

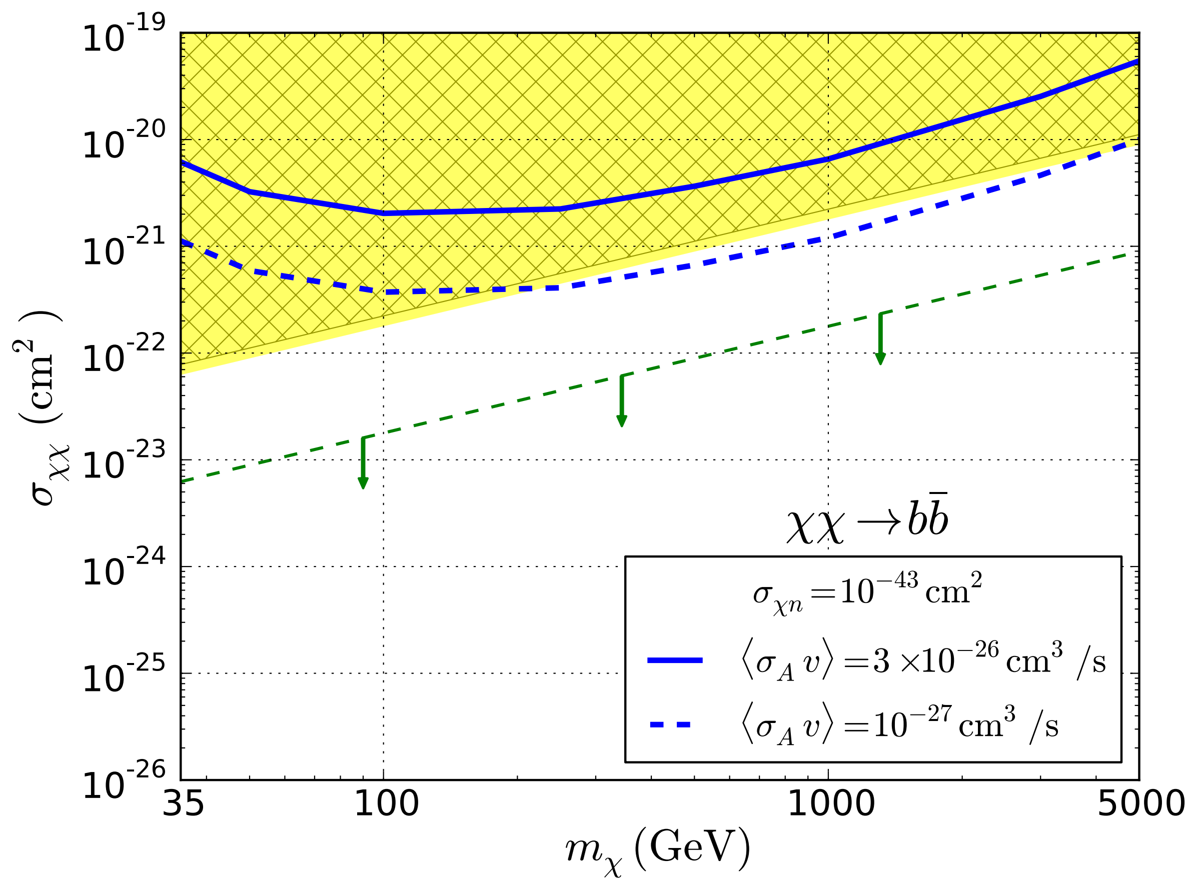
Halo Shapes

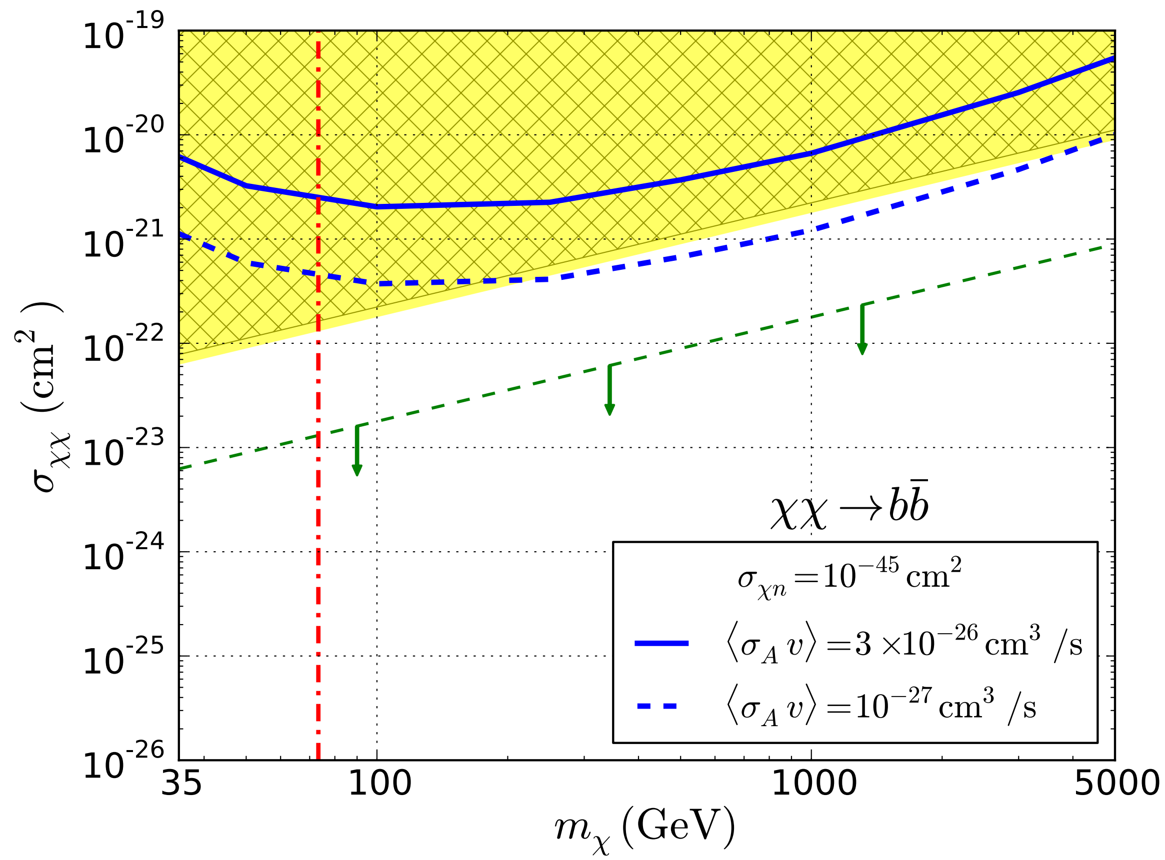
--- SIDM too low

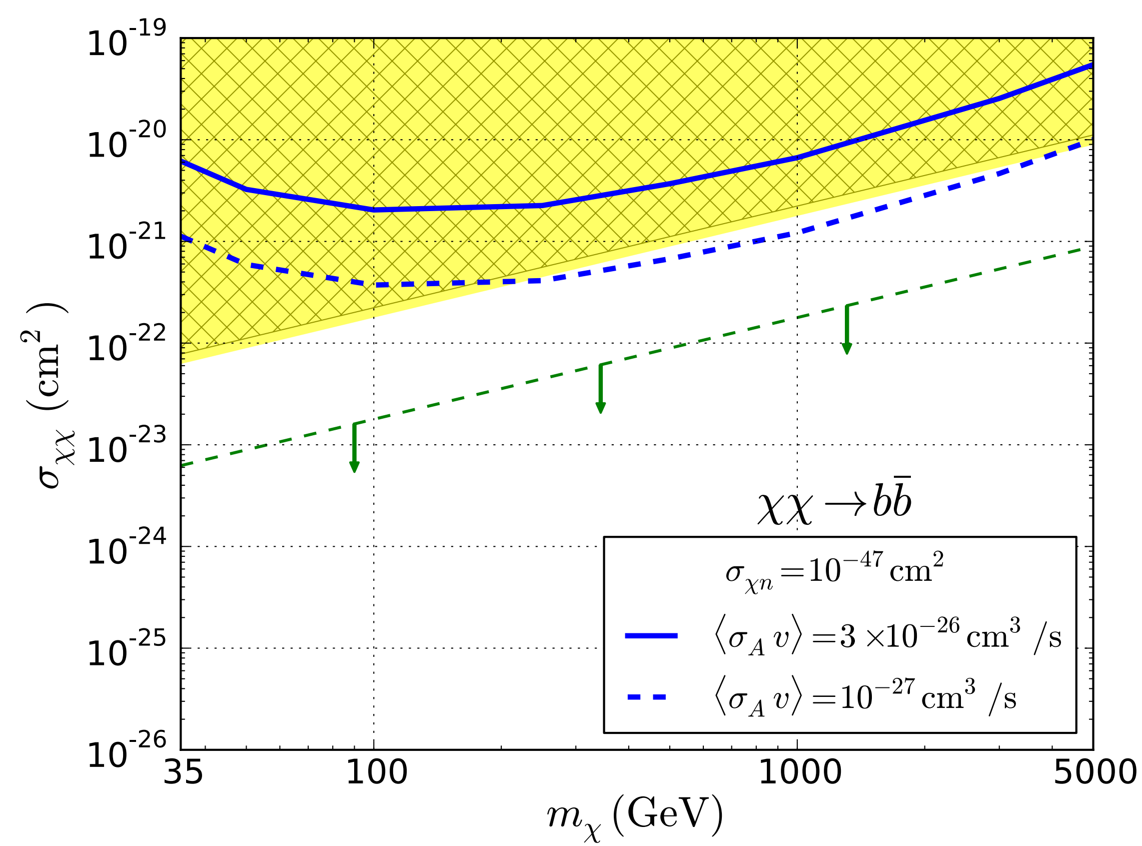
--- LUX (to the left or between lines)

I.A.,D. Robertson, C.P Los Heros
JCAP **02** (2014)

$b\bar{b}$ - Spin Independent







- weaker limits
- independently confirms bullet results

SIDM Constraints from IceCube

- SIDM is severely constrained if annihilates into WW

$$\frac{\sigma_{\chi\chi}}{m_\chi} < 0.6\ \mathrm{cm^2/g} \quad \text{if} \quad \langle \sigma v \rangle = 3 \times 10^{-26} \mathrm{cm^3/s}$$

$$\frac{\sigma_{\chi\chi}}{m_\chi} < 0.1\ \mathrm{cm^2/g} \quad \text{if} \quad \langle \sigma v \rangle = 1 \times 10^{-27} \mathrm{cm^3/s}$$

most SIDM effective models are ruled out

- $b\bar{b}$ analysis independently confirms bullet cluster results

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

vdSIDM Enhances DM Capture and Annihilation

Why velocity dependent SIDM?

- Clusters: v ~1000 Km/s; $\frac{\sigma_{\chi\chi}}{\mathbf{m}_\chi} < \mathbf{0.47\ cm^2/g}$
- Dwarfs: v ~10 Km/s; $\mathbf{0.1 - 0.5} \leq \frac{\sigma_{\chi\chi}}{\mathbf{m}_\chi} \leq \mathbf{10 - 50\ cm^2/g}$

$$\dot{\mathbf{N}} = \mathbf{\Gamma_C} + \mathbf{\Gamma}_{\chi\chi} - \mathbf{\Gamma_A}$$

$$\mathbf{\Gamma}_{\chi\chi} \propto \sigma_{\chi\chi}(\mathbf{v}_{\rm rel})$$

$$\sigma(\mathbf{v}_{\rm rel}) \rightarrow \text{Sommerfeld enhanced}$$

$$\Gamma_{\rm A} \rightarrow \qquad ||$$

vdSIDM Model

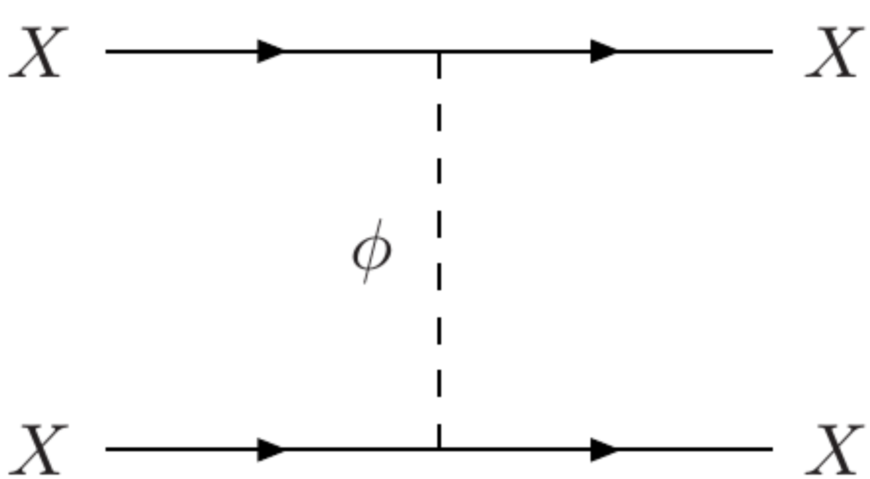
Tulin, Yu & Zurek
PRD **87** (2013)

DM Elastic Scattering

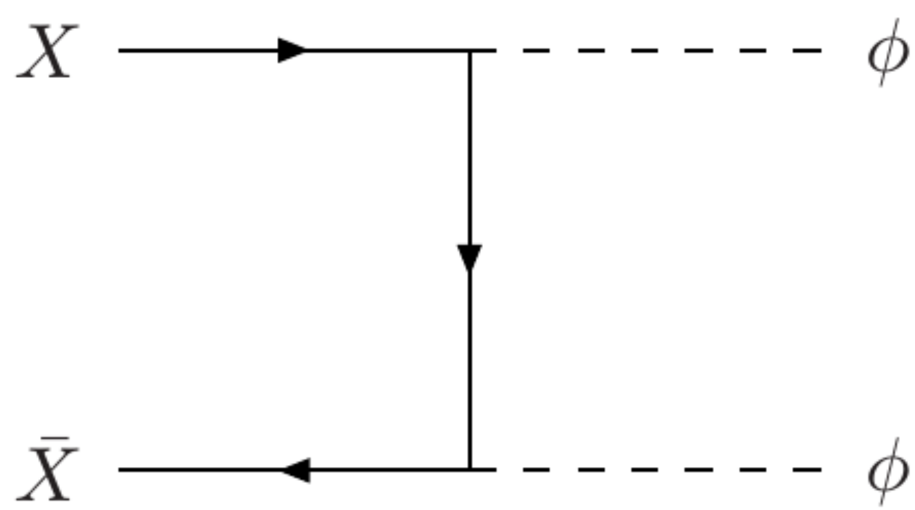
$$\mathcal{L}_{\mathbf{int}} = \mathbf{g}_\chi \, \overline{\chi} \, \gamma^\mu \, \chi \, \phi_\mu$$

$\chi \equiv$ DM Fermion

$\phi \equiv$ vector mediator



Self Interaction



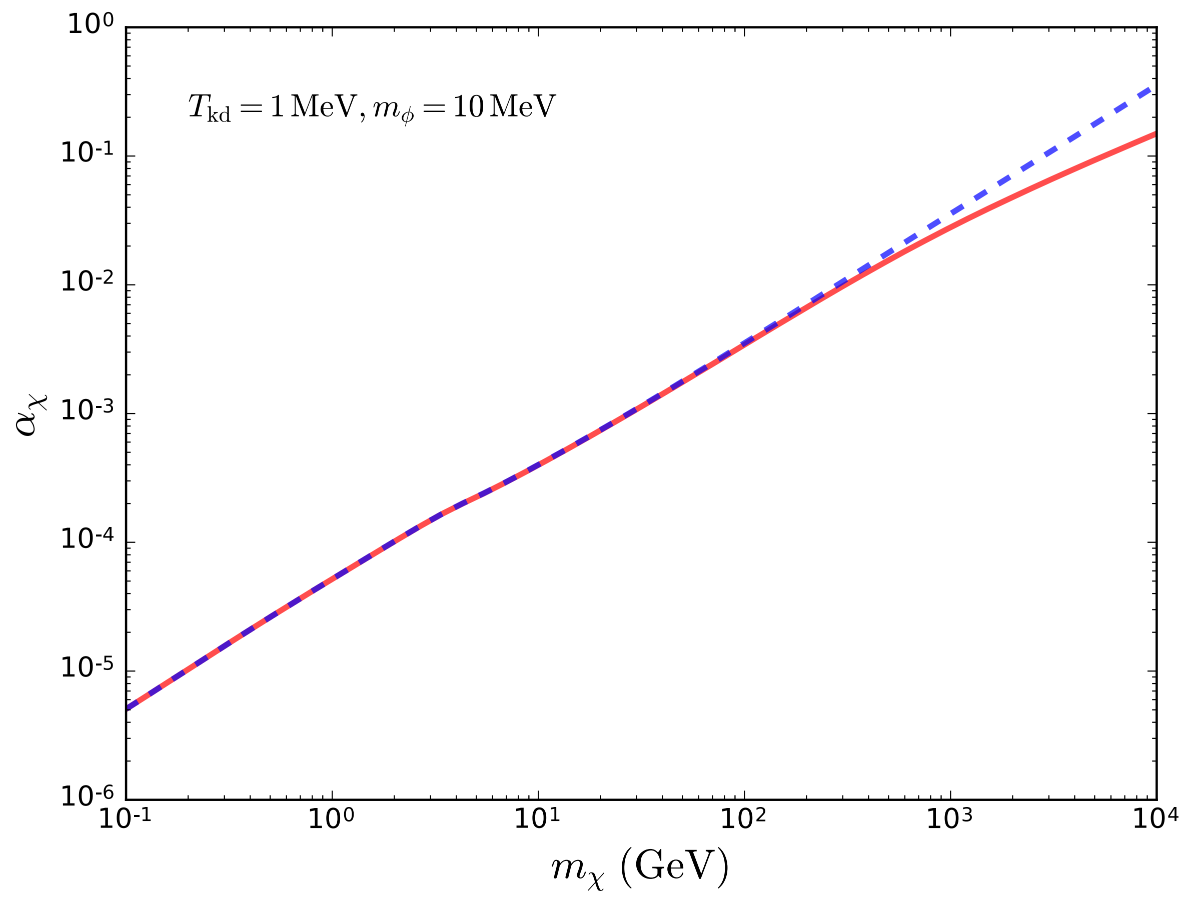
DM Annihilation

vdSIDM Model

Parameters: $\alpha_\chi = \frac{\mathbf{g}_\chi}{4\pi}$, $\mathbf{m}_\chi$, $\mathbf{m}_\phi$

$\mathbf{m}_\phi \sim \mathbf{1 - 100\,MeV}$ to solve small scale problems

(Tulin, Yu, Zurek - PRD **87** (2013))



Assuming Ω_{DM} is set by thermal freeze-out

Coupling to SM

Kaplinghat, Tulin & Yu
PRD **89** (2014)

ϕ mediator couples to SM through γ or Z mixing

$$\mathcal{L}_{\mathbf{mix}} = \frac{\epsilon_\gamma}{\mathbf{2}} \phi_{\nu\mu} \mathbf{F}^{\mu\nu} + \mathbf{m_Z^2} \epsilon_{\mathbf{Z}} \phi_\mu \mathbf{Z}^\mu$$

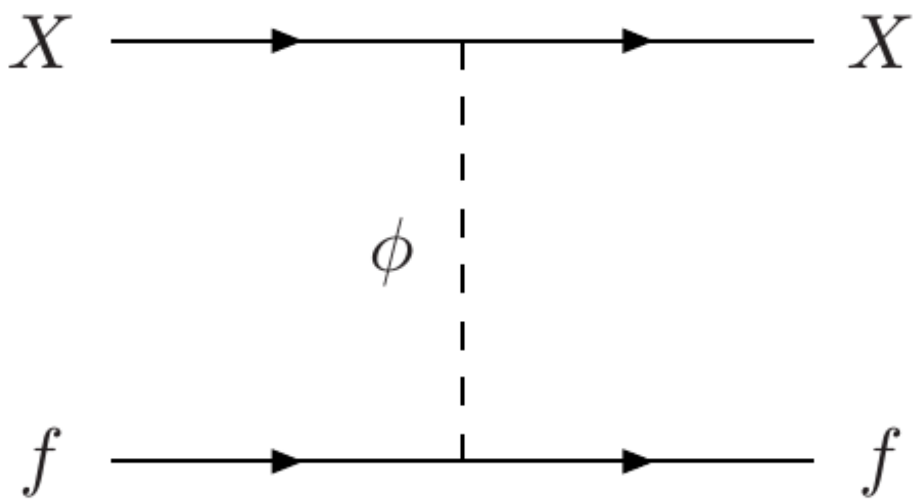
$$\mathcal{L}_{\mathbf{int}} = \mathbf{e}\phi_\mu \left(\epsilon_{\mathbf{p}} \overline{\mathbf{p}} \gamma^\mu \mathbf{p} + \epsilon_{\mathbf{n}} \overline{\mathbf{n}} \gamma^\mu \mathbf{n} \right)$$

$$\epsilon_{\mathbf{p}} = \epsilon_\gamma + \mathbf{0.05}\epsilon_{\mathbf{Z}}$$

$$\epsilon_{\mathbf{n}} = -\mathbf{0.6}\,\epsilon_{\mathbf{Z}}$$

$$\epsilon_\gamma \quad \text{and} \quad \epsilon_{\mathbf{Z}} << \mathbf{1}$$

$\eta = \varepsilon_n / \varepsilon_p \neq 1$ => isospin violation



DM - nucleon scattering

Capture in the Sun

Scattering with Sun's Nuclei

$$\mathbf{\Gamma_C \propto n_\chi \, n_N \, \sigma_{\chi N}}$$

$$\sigma_{\chi \mathbf{N}}(\mathbf{q^2 = 0}) = \mathbf{16}\pi\alpha_{\mathbf{em}}\alpha_\chi \frac{\mu^{\mathbf{2}}_{\chi \mathbf{N}}}{\mathbf{m}^{\mathbf{2}}_\phi} \left[\epsilon_{\mathbf{p}}\mathbf{Z} + \epsilon_{\mathbf{n}}\left(\mathbf{A} - \mathbf{Z}\right)^{\mathbf{2}}\right]$$

$\mathbf{m_\phi \sim 1 - 100\,MeV}$ is about same order as momentum transfer

suppression factor:

$$\sigma_{\chi \mathbf{N}} = \sigma_{\chi N}(q^2 = 0) \times \frac{m_\phi^4}{\left(m_\phi^2 + q^2\right)^2}$$

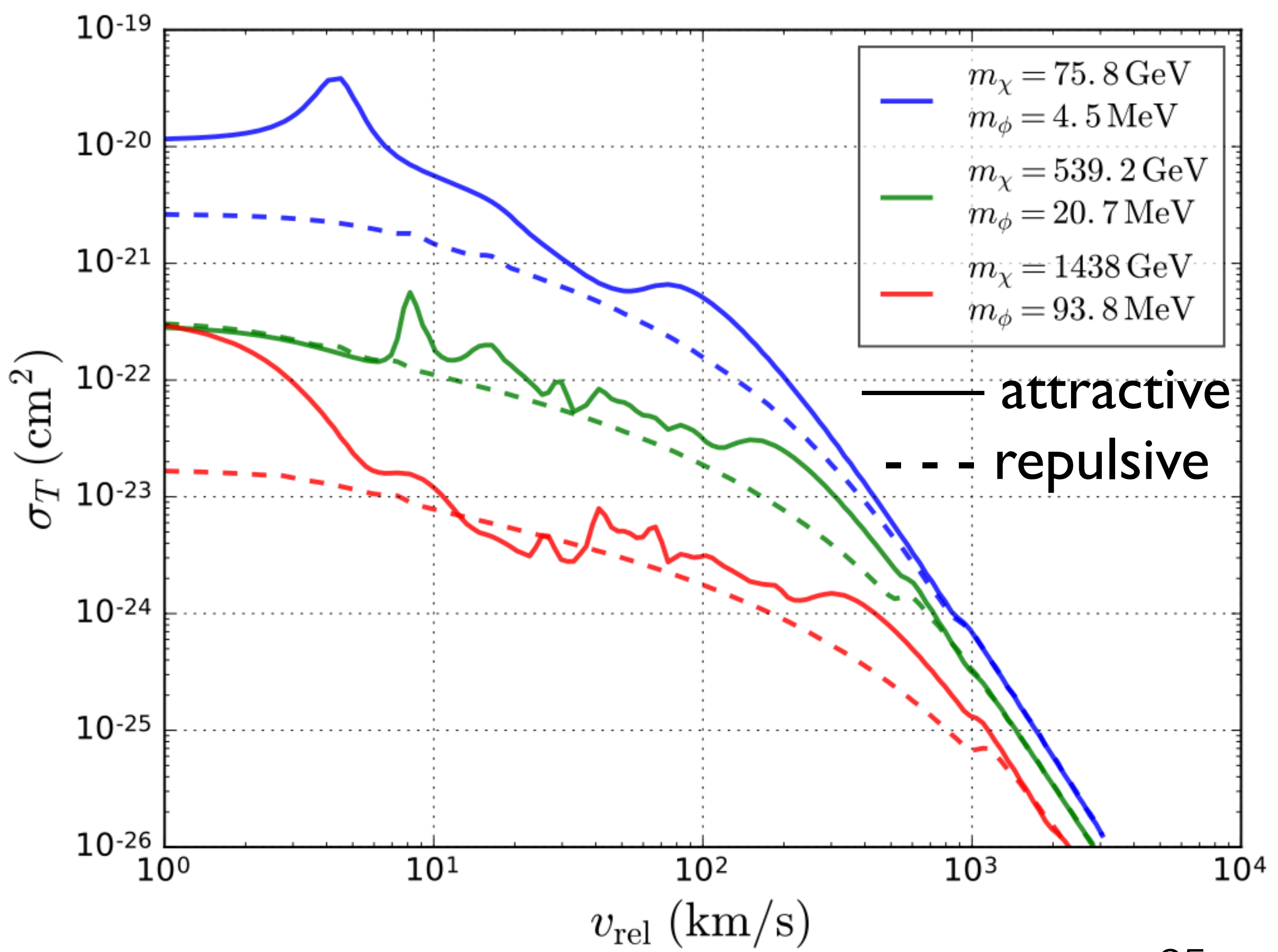
Capture in the Sun

DM Self Scattering

non relativistic limit => Yukawa potential

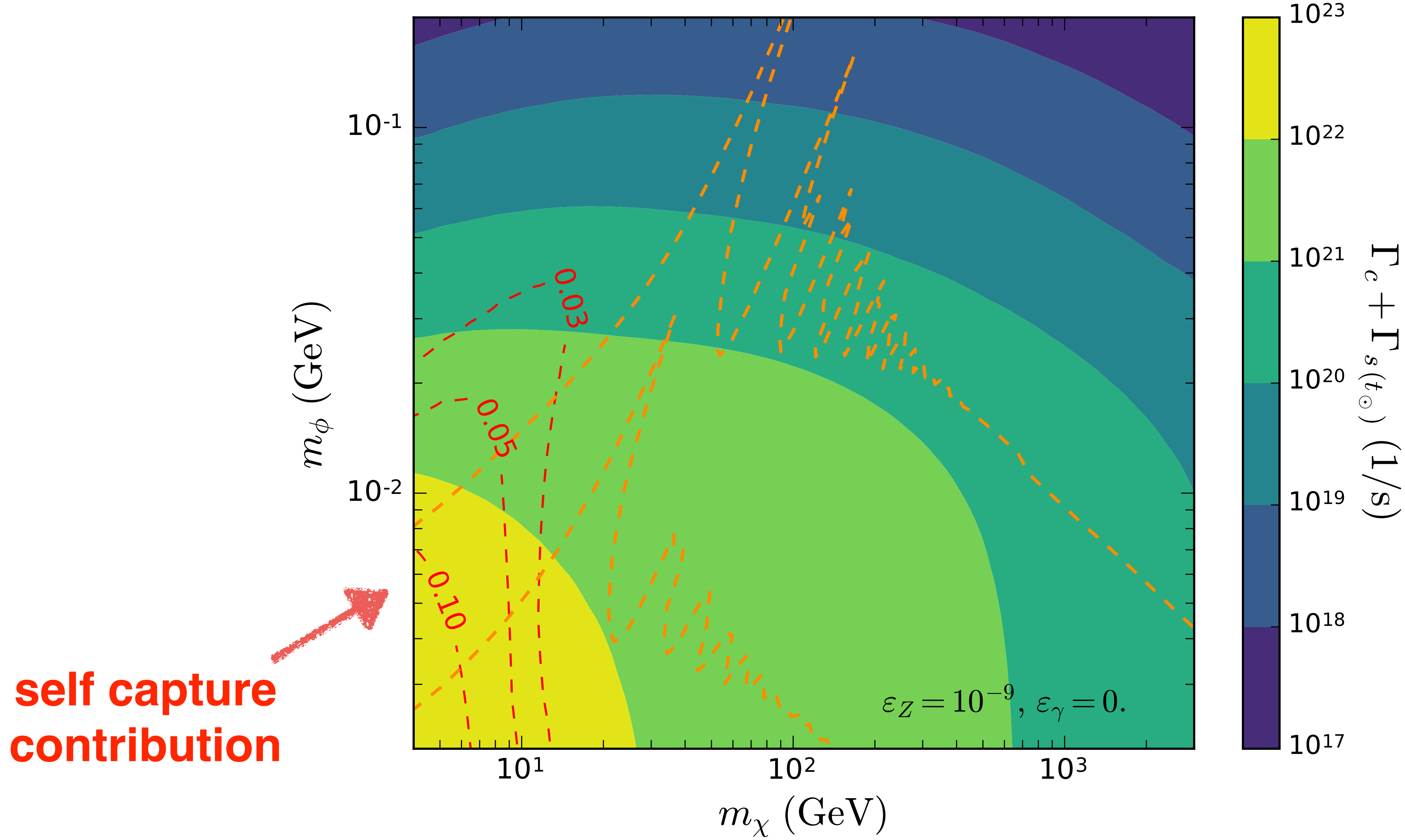
$$\mathbf{V}(\mathbf{r}) = \pm \frac{\alpha_\chi}{\mathbf{r}} \exp(-\mathbf{m}_\phi \mathbf{r}) \qquad - \rightarrow \quad \textbf{attractive } (\chi\overline{\chi})$$

$$+ \rightarrow \quad \textbf{repulsive } (\chi\chi \textbf{ or } \overline{\chi\chi})$$



Tulin, Yu & Zurek
PRD **87** (2013)

Capture with vdSIDM



Sommerfeld effect does not play a crucial role
=> v ~ 1400 km/s

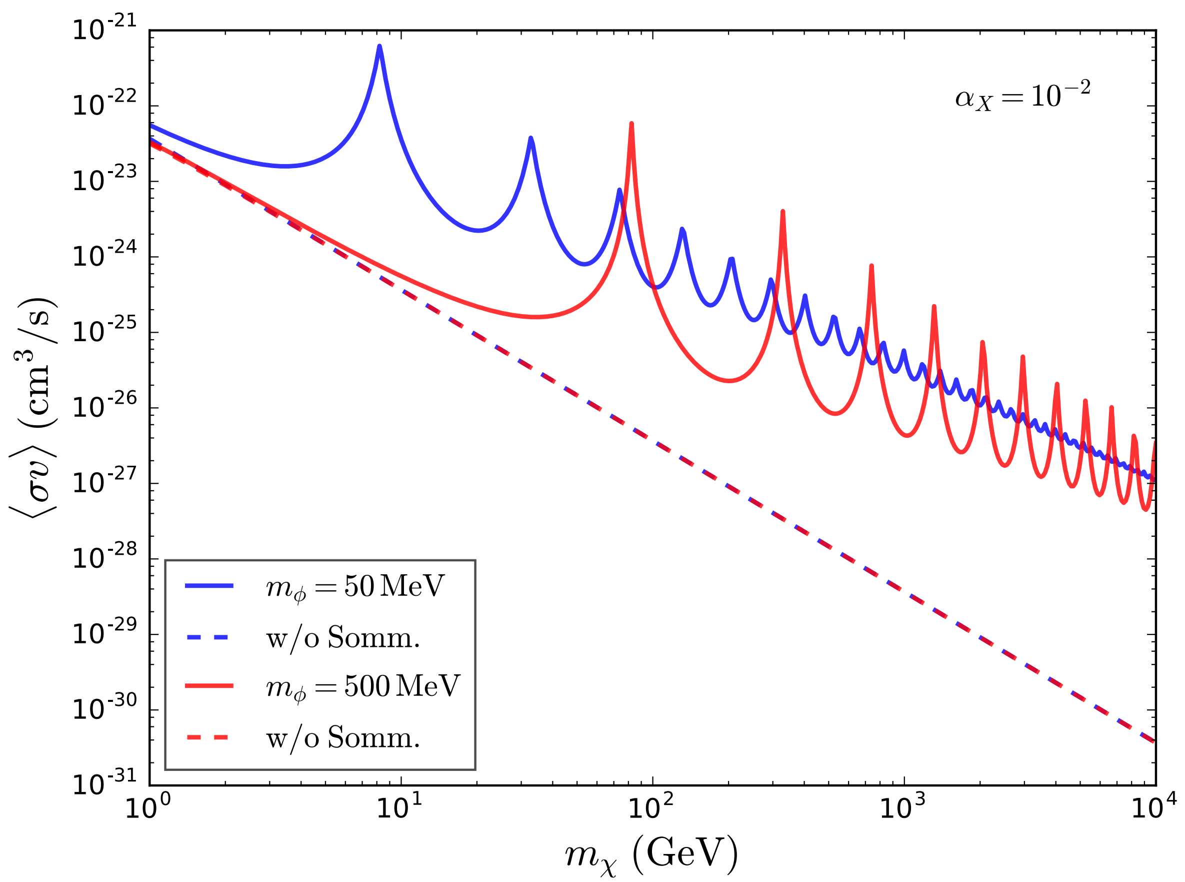
Annihilation in the Sun

$$\Gamma_A = \frac{1}{2} < \sigma_A v > V_{eff}$$

$$< \sigma_A v > = \frac{1}{2} \left(\frac{m_\chi}{\pi T_\chi} \right)^{3/2} \int S(\sigma_a v)^{tree} v^2 e^{-\frac{m_\chi v^2}{4T_\chi}} dv$$

S ≡ Sommerfeld enhancement

Annihilation XS



Annihilation Channel:

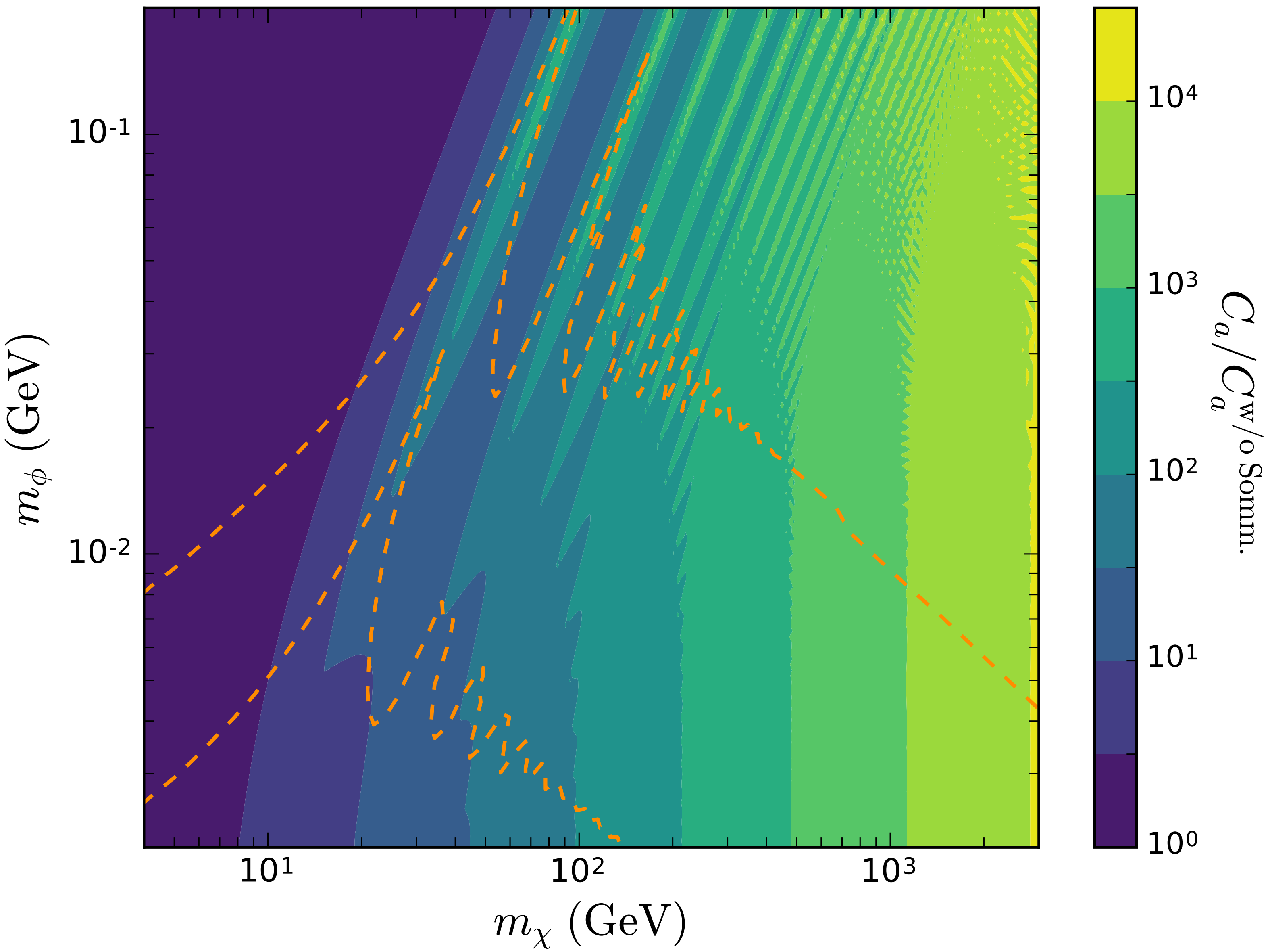
$$\chi \bar{\chi} \rightarrow \phi \phi \rightarrow 2\nu_l \, 2\overline{\nu_l}$$

Branching Ratio:

$$BR(\epsilon_\gamma = \epsilon_Z) = \frac{6}{7}$$

$$BR(\epsilon_\gamma = 0, \epsilon_Z) = 1$$

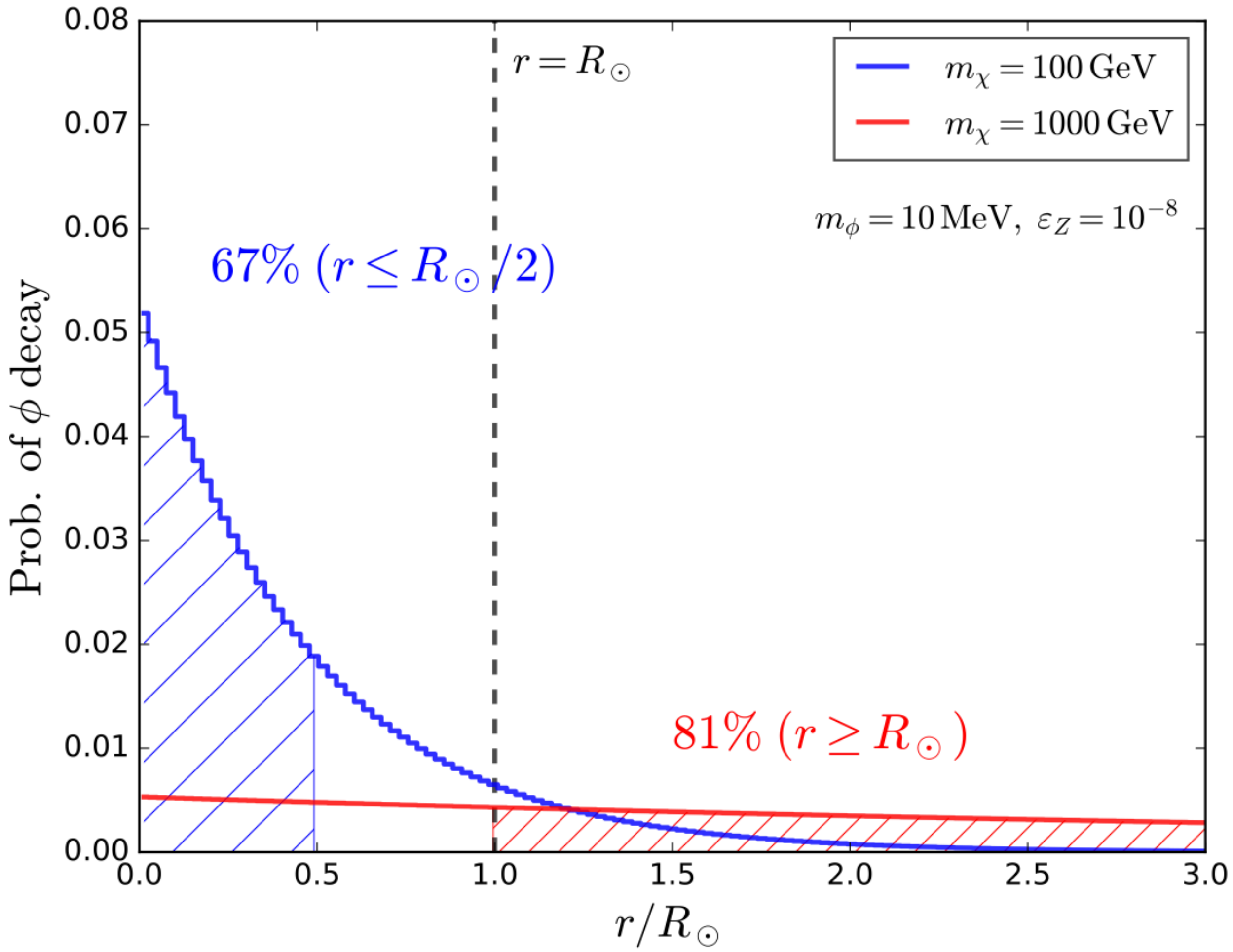
Annihilation with vdSIDM



Sommerfeld effect plays a significant role

ν Production and Propagation

ϕ lifetime is important



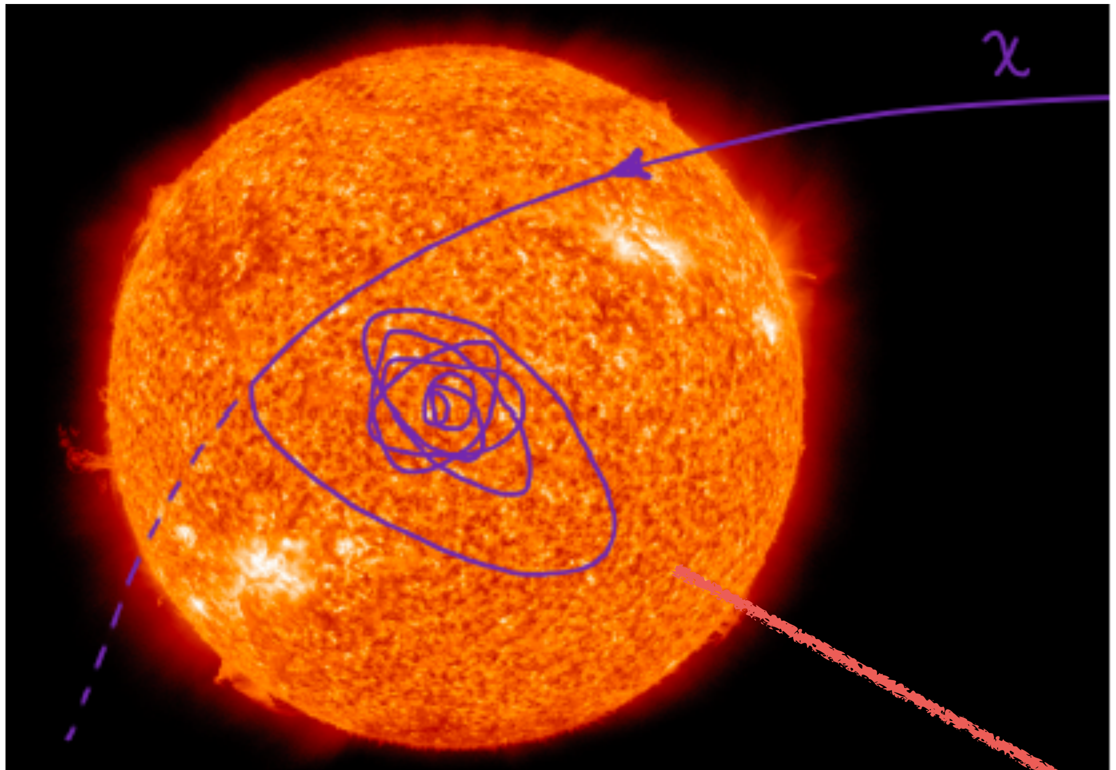
$$\lambda_\phi / R_\odot \approx 0.04 \left(\frac{10^{-8}}{\varepsilon_Z}\right)^2 \left(\frac{10\,\mathrm{MeV}}{m_\phi}\right)\left(\frac{m_\chi/m_\phi}{1000}\right)$$

Standard Wimp: ν production in Sun's core

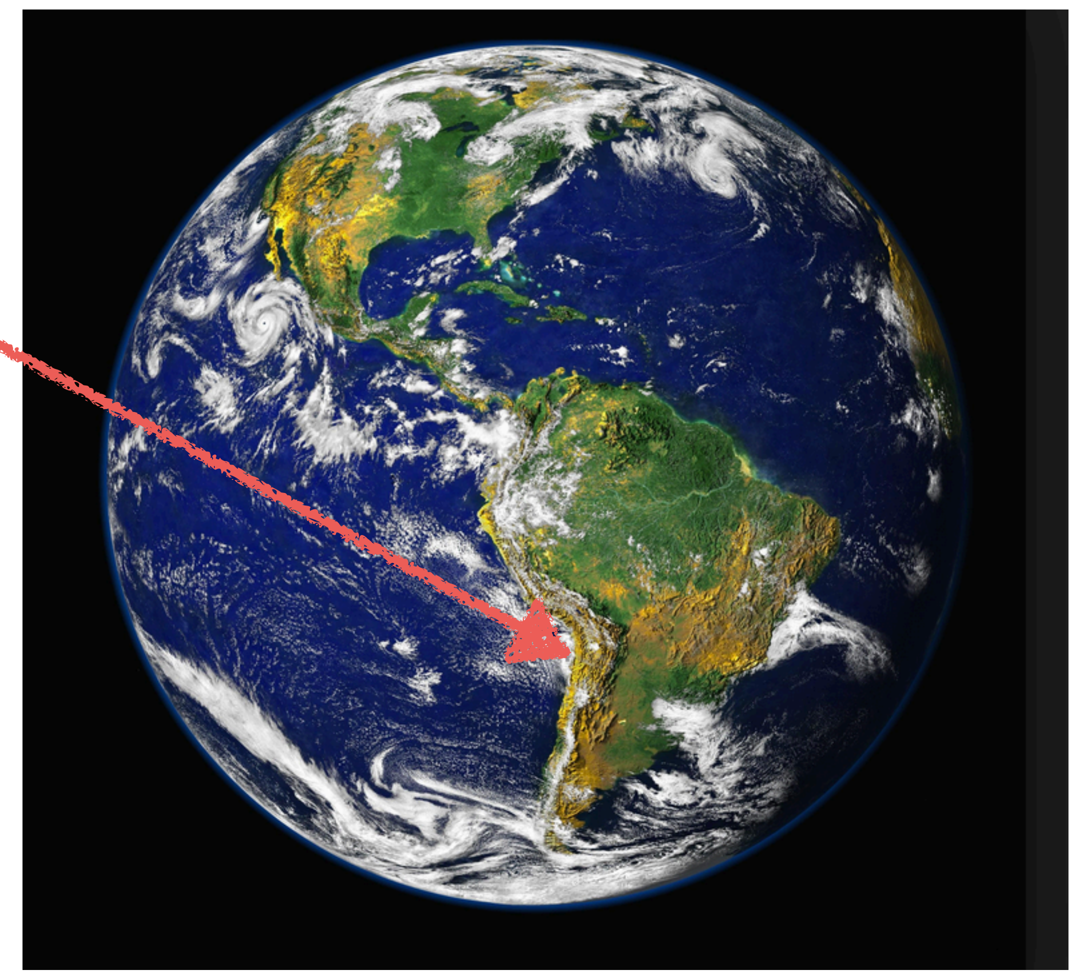
vdSIDMS: ν production not necessarily in the core

$$\tau_\phi = 1\,\mathrm{s} \left(\frac{10^{-10}}{\epsilon_Z}\right)^2 \left(\frac{m_\phi}{10\,\mathrm{MeV}}\right)$$

Further enhances expected neutrino signal for some values of parameter space



ν Production point is determined based on ϕ decay probability



From there on: ν are propagated to detector

vdSIDM Probes at ν Telescopes

From IceCube via DeepCore to PINGU

IceCube

Instrumented volume:	1 Gt
Average DOM density:	5×10^{-6} m^{-3}
Target energy:	$\gtrsim$ 100 GeV

DeepCore

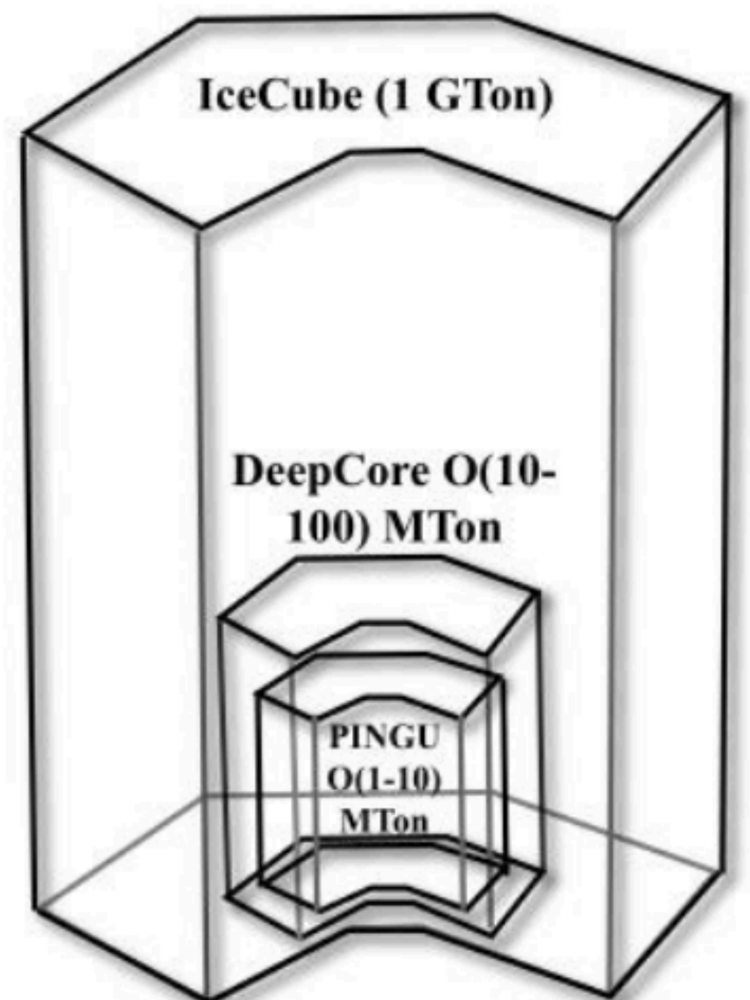
Instrumented volume:	10-100 Mt
Average DOM density:	20×10^{-6} m^{-3}
Target energy:	10 GeV - 100 GeV

PINGU

Instrumented volume:	1-10 Mt
Average DOM density:	$> 200\times10^{-6}$ m^{-3}
Target energy:	1 GeV - 20 GeV

PINGU talks at DPG:

Mo	T109.7	OM development
Mi	T89.8,T89.9	Oscillations / matter effects
Do	T104.5	Reconstruction



E. Resconi

Alexander Kappes | DPG-Frühjahrstagung, Dresden | 07.03.2013 | 4

ν_μ at IceCube / DeepCore and Pingu

Sensitivity to VdSIDM

IceCube-DeepCore DM data collection: t_{exp} = 532 days
(3 austral years) IceCube Coll. - Astropart. Phys. 35 (2012)
(Same t_{exp} for Pingu)

- Number of signal events: $N_\nu^{\rm s} = \Gamma_a t_{\rm exp} \times \int_{\Delta\Omega} \int_{E_{\rm th}}^{m_\chi} \frac{d^2\phi_\nu}{dE_\nu d\Omega} A_{\rm eff}(E_\nu) dE_\nu \, d\Omega$

3 samples: m_χ < 50 GeV => only DeepCore

m_χ > 500 GeV => full IceCube

500 < m_χ < 50 GeV => combined analysis

\+ Pingu

ν at IceCube / DeepCore and Pingu

- Number of background events: $N_{\nu}^{\mathrm{b}} = t_{\mathrm{exp}} \times \int_{E_{\mathrm{th}}}^{E_{\mathrm{max}}} \frac{d\phi_{\nu_{\mathrm{atm}}}}{dE_{\nu}} A_{\nu}(E_{\nu}) dE_{\nu} \times \Delta\Omega$

Honda et al., PRD **92** (2015)

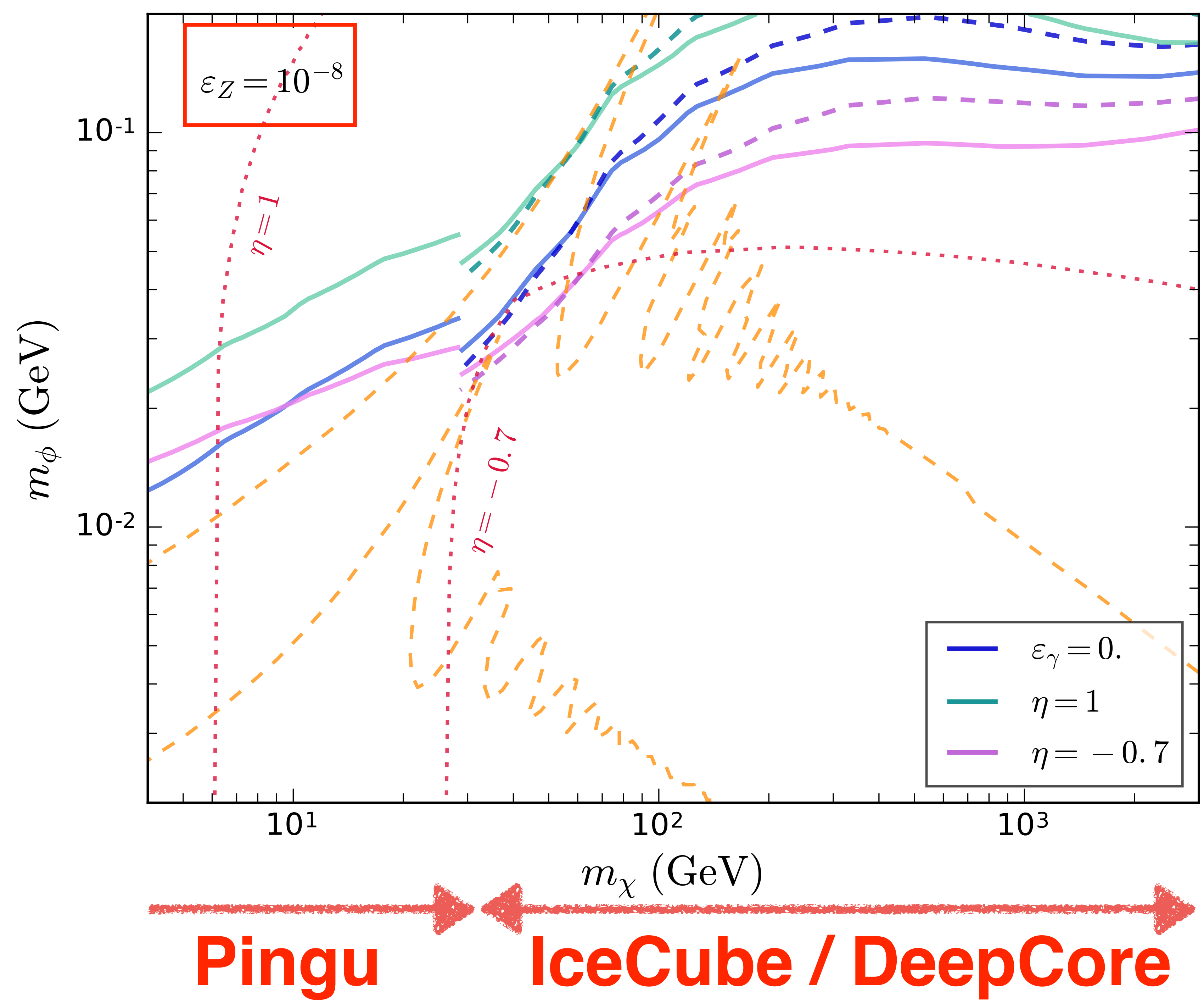
- Detector's effective areas and acceptance angles

$$\Delta\Omega = 2\pi(1 - \cos\Psi)$$

Ψ depends on energy

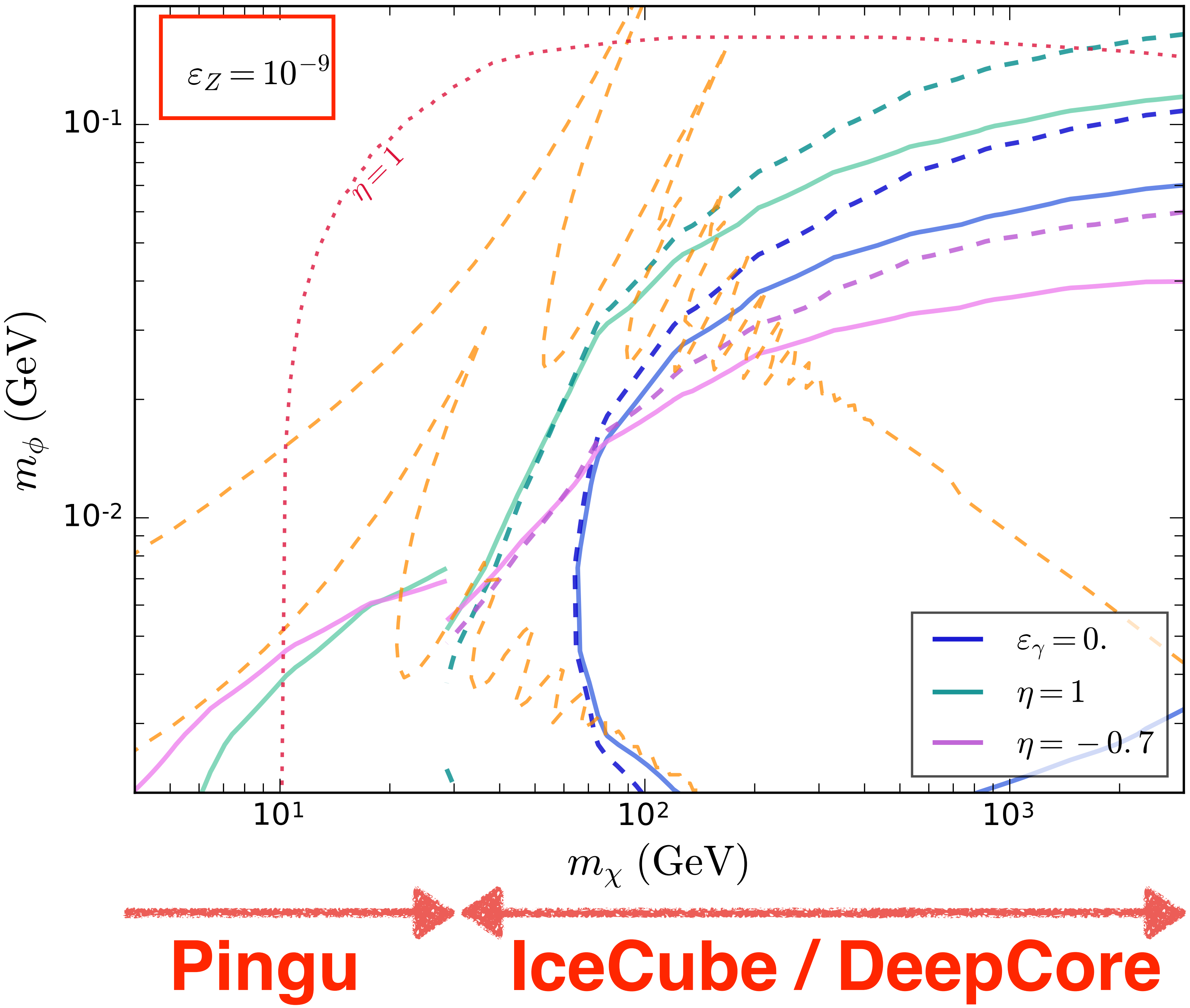
10 and 2.8° as reference

Results



Denis Robertson, IA
JCAP 1802 (2018)

Results



Denis Robertson, IA
JCAP 1802 (2018)

Conclusions

- SIDM is severely constrained if annihilates into WW
- SIDM annihilation into $b\bar{b}$ confirms bullet cluster results

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

- IceCube / DeepCore can probe vdSIDM with data already collected

★ for $\varepsilon_z = 10^{-9}$ sensitivity covers almost all interesting region PINGU will cover remaining parameter space

★ for $\varepsilon_z = 10^{-8}$ sensitivity decreases, but $m_\chi > 70$GeV can be probed

- IceCube / DeepCore are competitive with possible DD results and drastically better in the case of isospin violation

Denis Robertson, IA, JCAP **1802,** 2018