Probing Velocity Dependent Self Interacting Dark Matter

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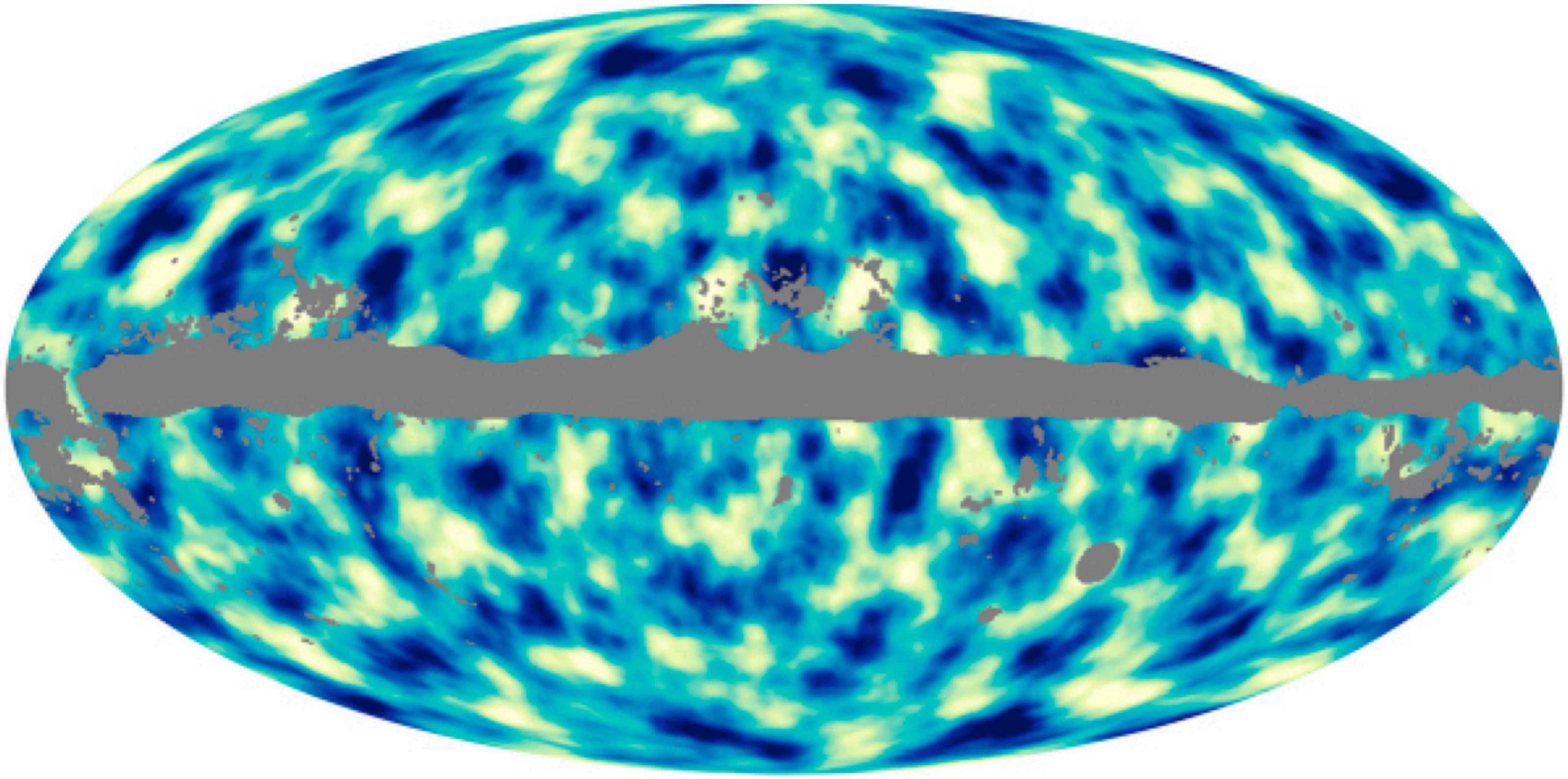
Outline

1. CDM Small Scale Potential Problems
    - DM Self-Interaction (SIDM) as possible solution
2. Current constraints on SIDM
3. Velocity Dependent SIDM (vdSIDM)
4. Enhanced ν flux from DM annihilation

Indirect Probes (ν) on vdSIDM models

Collisionless CDM

Extremely successful at large scales

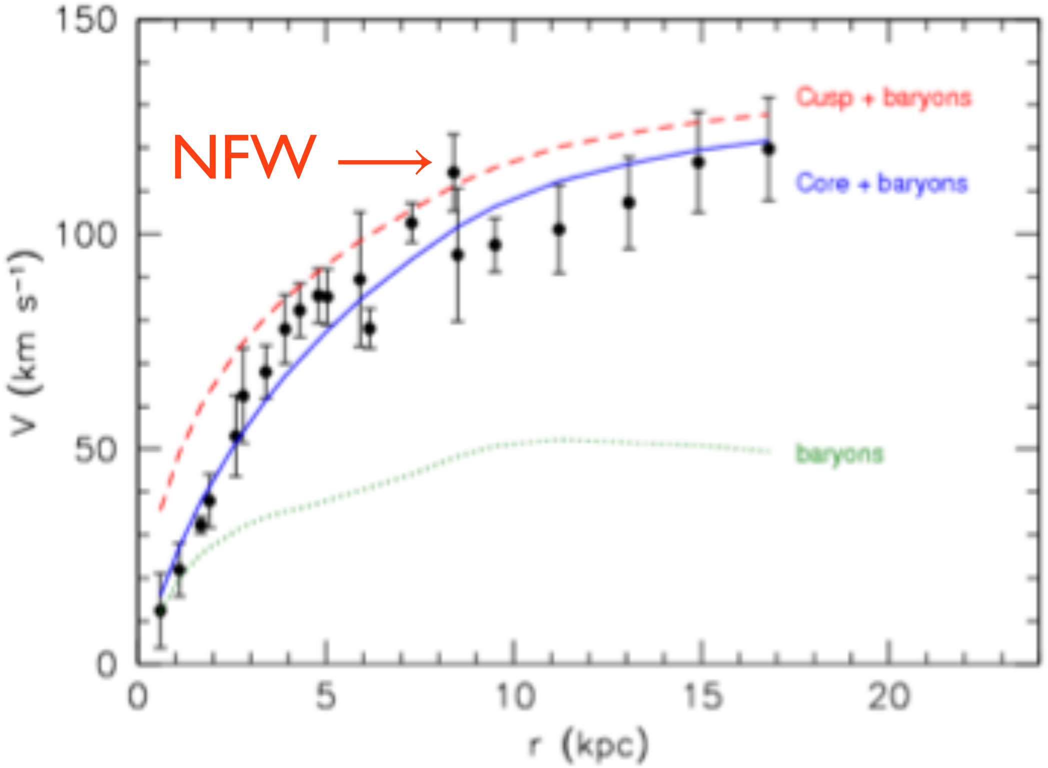


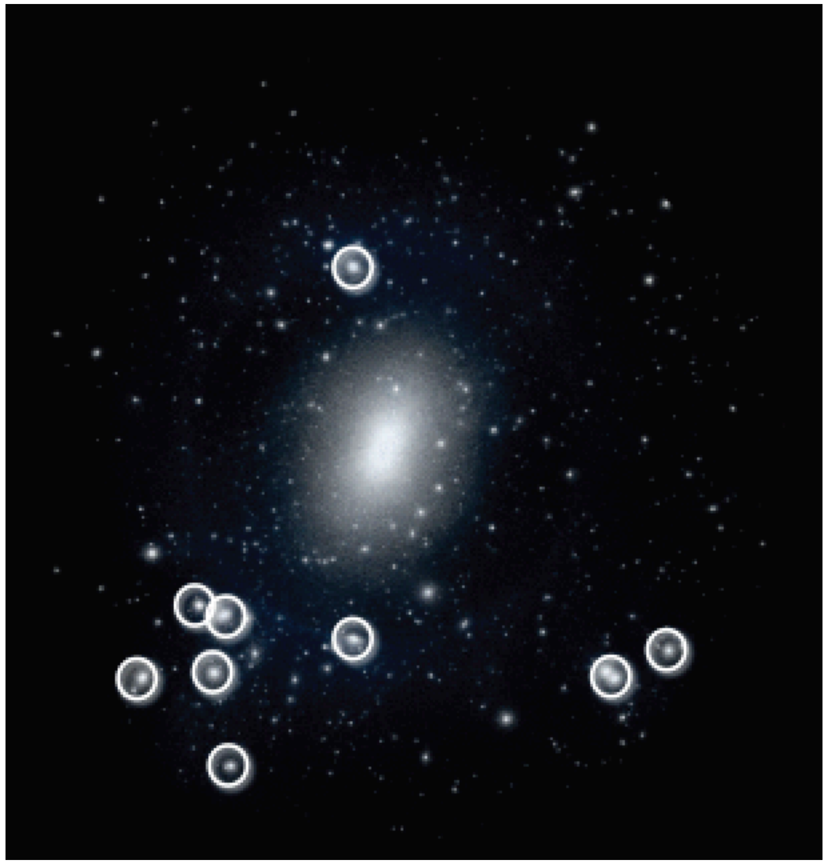
Date: 02 April 2013
Satellite: Planck
Depicts: All-sky map of dark matter distribution in the Universe
Copyright: ESA and the Planck Collaboration

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)

⇔

Too Big to Fail

9 “classic" massive SIM DM subhalos
Boylan-Kolchin et al. (MNRAS **415**, 2011)
(Weinberg et al. , arXiv:1306.0913)

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

Self Interacting Dark Matter

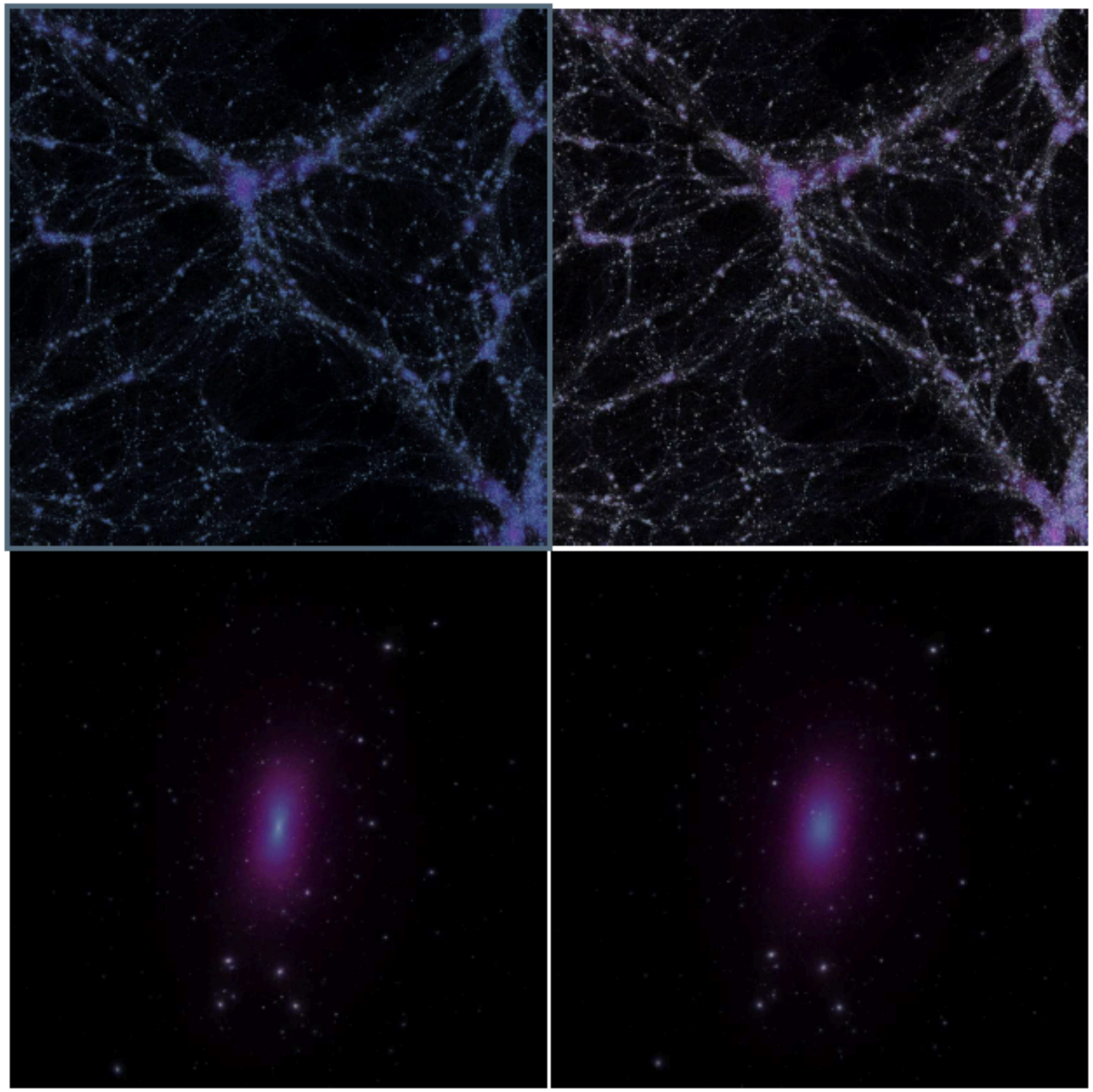
SIDM solves Small Scale Potential Problems

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

DM scatters before reaching center of galaxy

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

SIDM Simulations



CDM and SIDM simulations

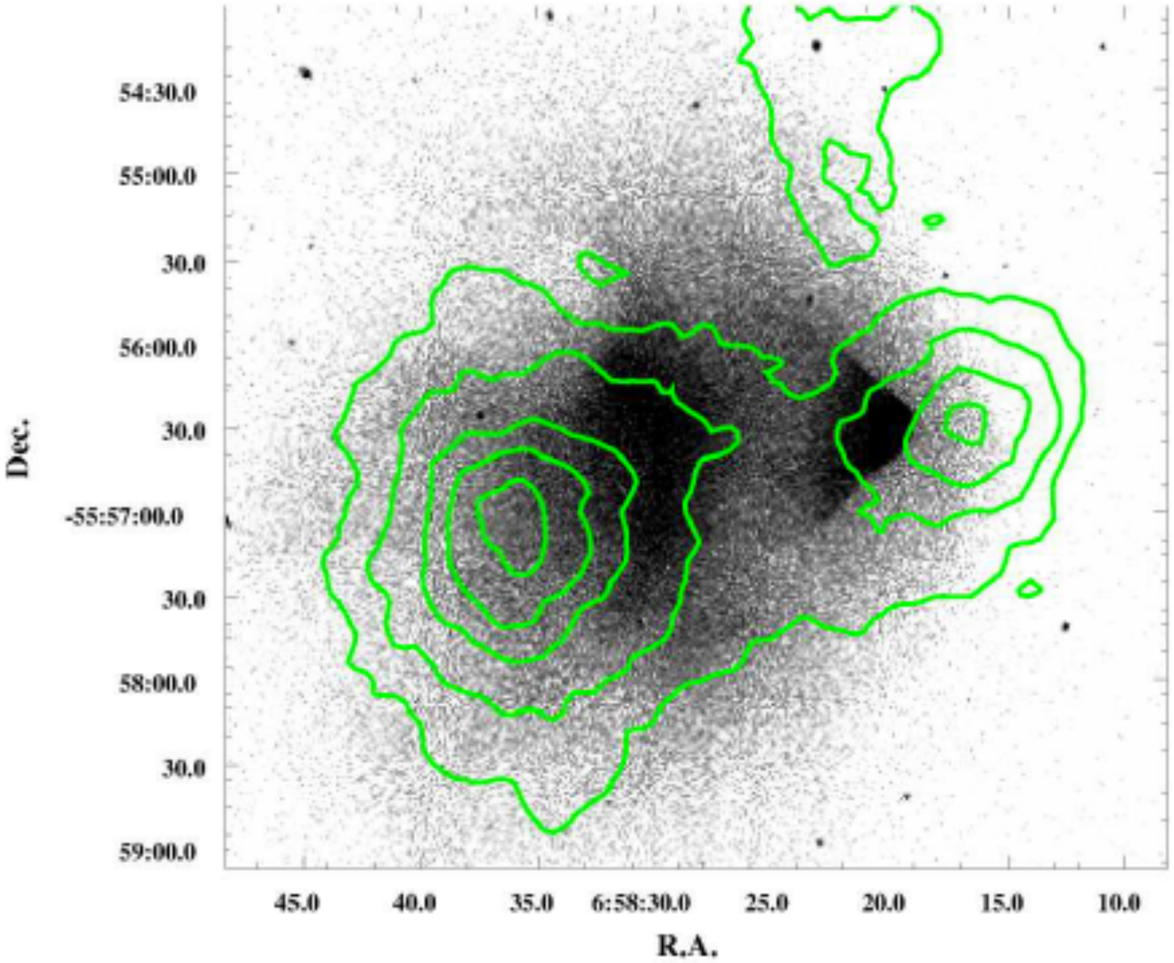
(M. Rocha et al., MNRAS **430**, 2013)

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

$$\frac{\sigma_{\chi\chi}}{\mathbf{m}_\chi} \simeq \mathbf{1\,cm^2/g} \Rightarrow \textbf{central density is TOO LOW}$$

$$\simeq \mathbf{0.1\,cm^2/g} \Rightarrow \textbf{consistent}$$

SIDM Constraints



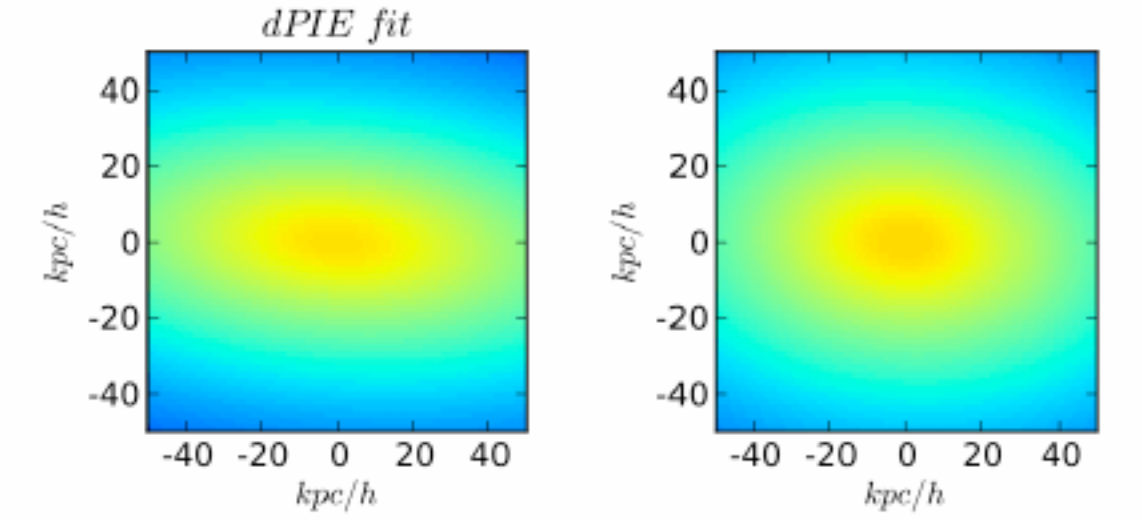
Bullet Cluster

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

Xray image and lensing contour

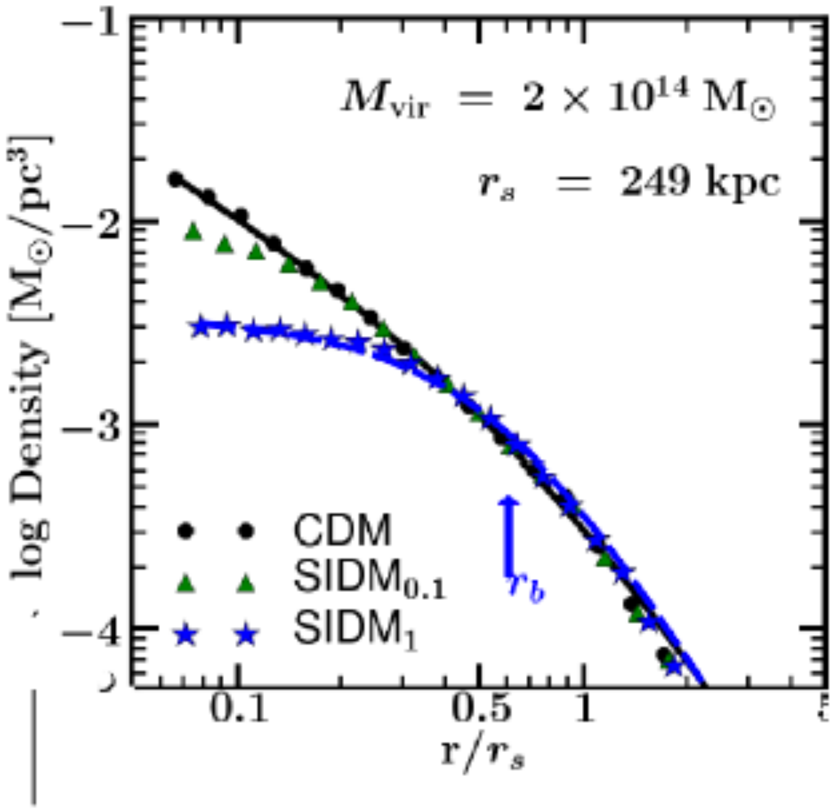
$$\frac{\sigma_{\chi\chi}}{\mathbf{m}_\chi} < \mathbf{1.25\ cm^2/g}$$

Constraints from Simulations



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

CMB and SIDM 0.1



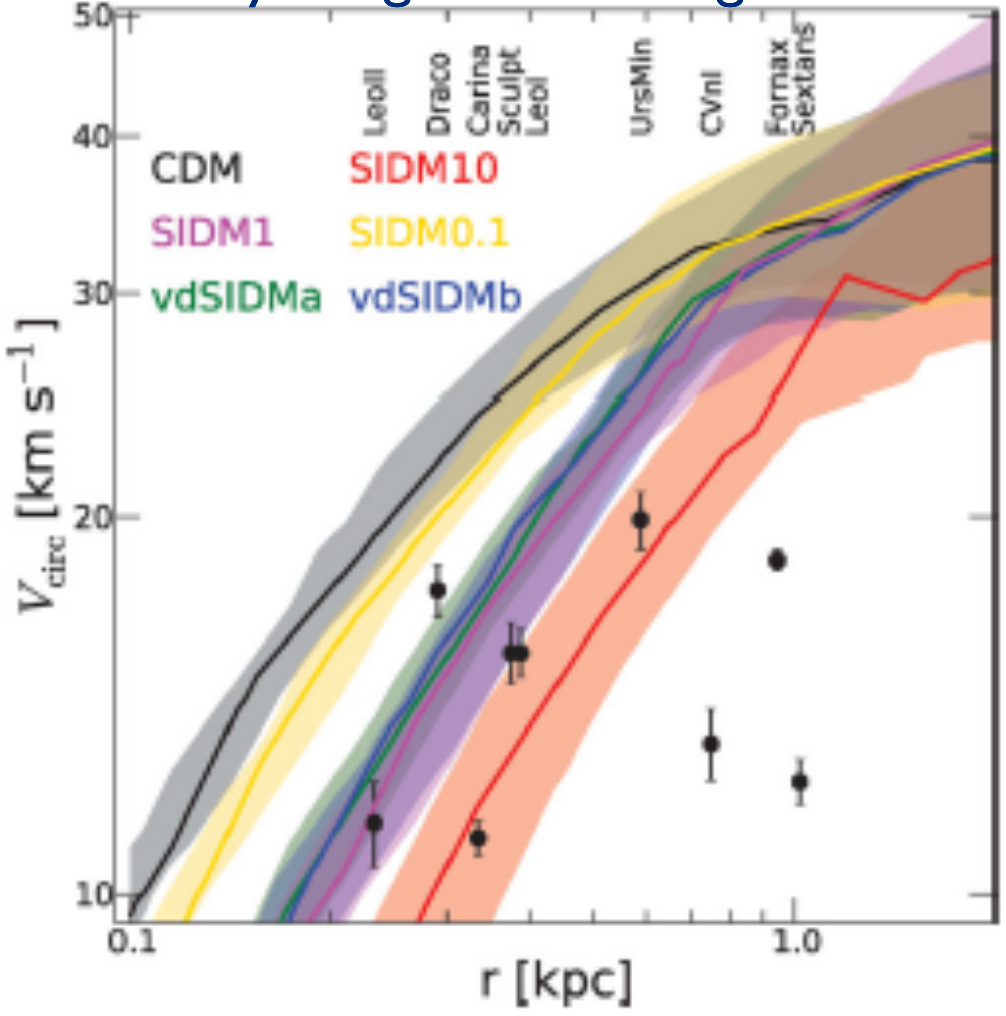
DM halos surface densities

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

Milky Way Dwarfs Kinematics

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

Xray image and lensing contour

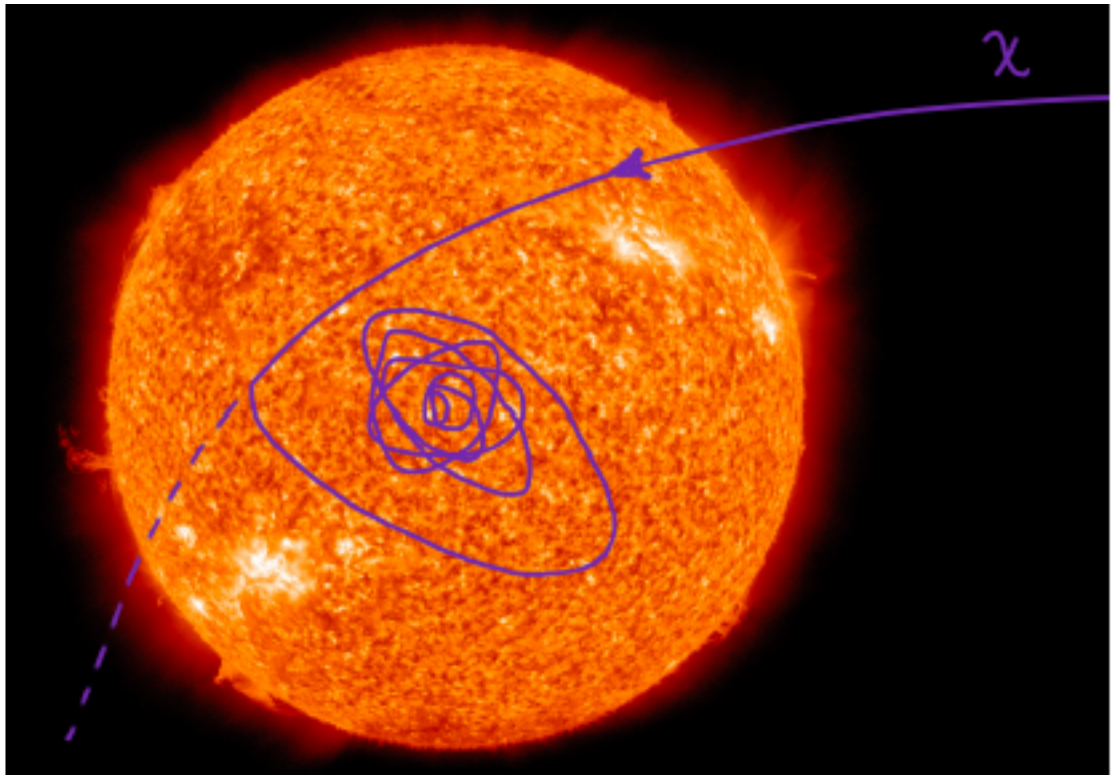


SIDM will be effective if

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

Probing SIDM with neutrinos

Self-Interaction enhances DM capture in the Sun



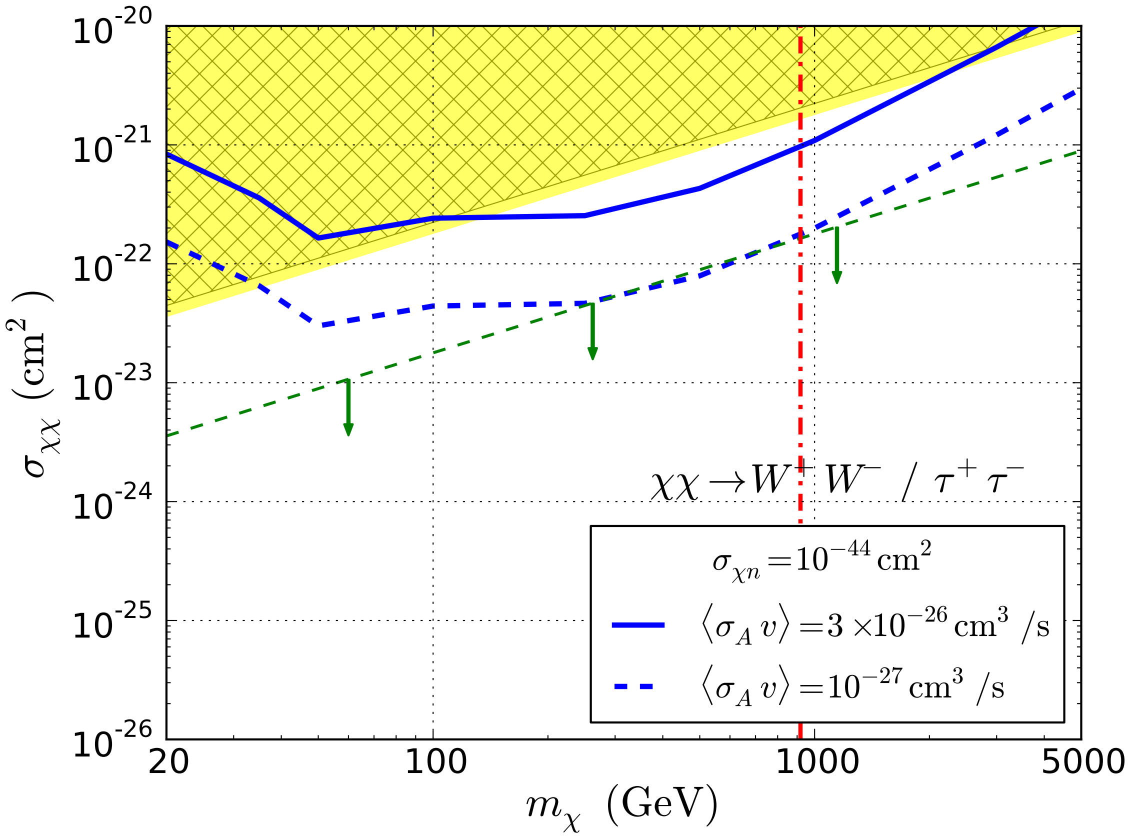
ν flux from DM annihilation will also be enhanced

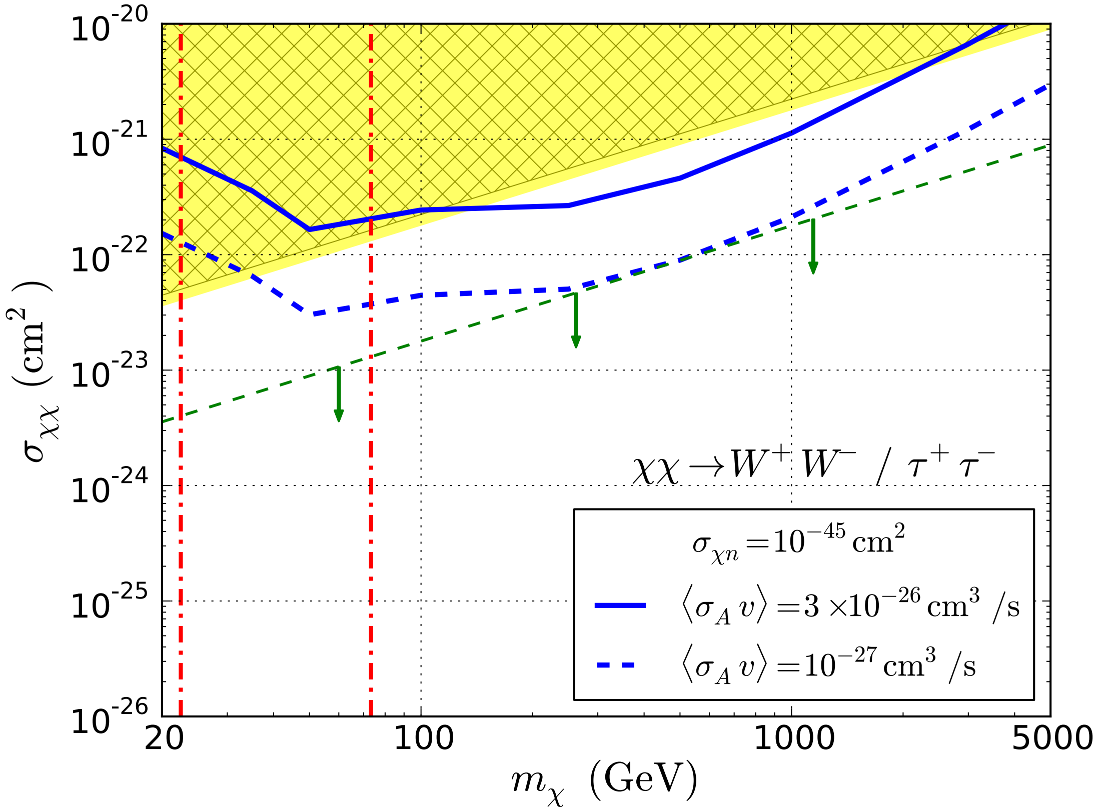
Independently probe SI interesting $\sigma_{\chi\chi}/m_{\chi\chi}$ region

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

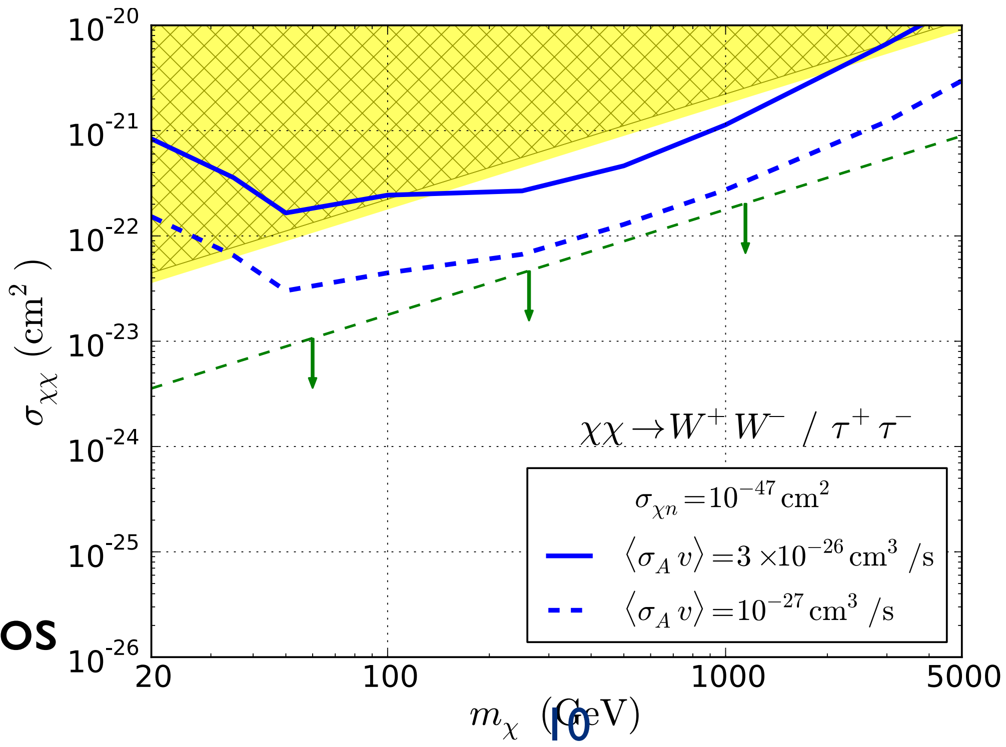
Probing SIDM models

$W^+ W^- / \tau^+\tau^-$ - 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)

SIDM Constraints from IceCube

- SIDM is severely constrained if annihilates into WW

$$\frac{\sigma_{\chi\chi}}{m_\chi} < 0.6\ \mathrm{cm^2/g} \quad \text{if} \quad \langle\sigma v\rangle = 3\times10^{-26}\mathrm{cm^3/s}$$

$$\frac{\sigma_{\chi\chi}}{m_\chi} < 0.1\ \mathrm{cm^2/g} \quad \text{if} \quad \langle\sigma v\rangle = 1\times10^{-27}\mathrm{cm^3/s}$$

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

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

$$\mathbf{\Gamma}_{\chi\chi} \;\propto\; \mathbf{n}_\chi^{\mathrm{halo}}\, \mathbf{N}_\chi\, \sigma_{\chi\chi}(\mathbf{v}_{\mathrm{rel}})\, \mathbf{v}_{\mathrm{rel}}$$

$$\sigma_{\chi\chi}(\mathbf{v}_{\mathrm{rel}}) \;\rightarrow \text{possible} \quad \text{Sommerfeld} \quad \text{enhanced}$$

$$\mathbf{\Gamma}_{\mathrm{A}} \quad \rightarrow \qquad ||$$

Equilibrium among capture and annihilation rates

=> maximum annihilation rate

vdSIDM Model

Tulin, Yu & Zurek

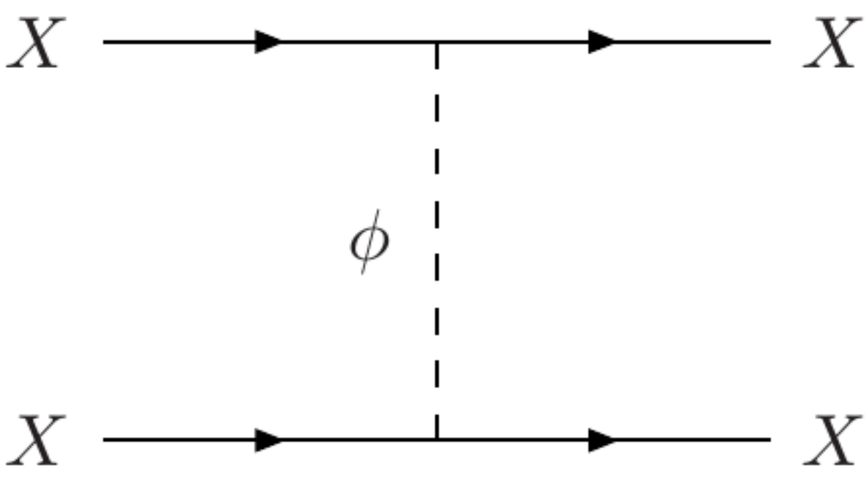
PRD **87** (2013)

DM Elastic Scattering

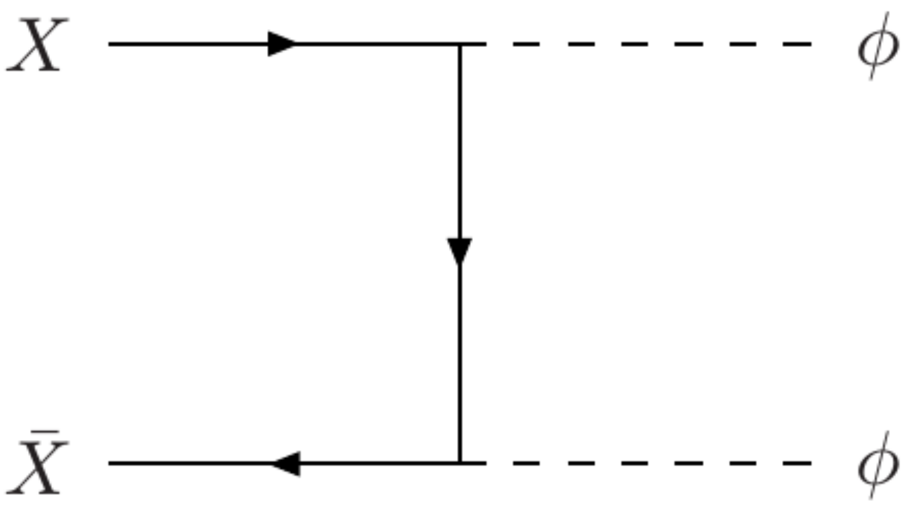
$$\mathcal{L}_{\mathbf{int}} = \mathbf{g}_{\chi}\,\overline{\chi}\,\gamma^{\mu}\,\chi\,\phi_{\mu}$$

χ $\equiv$ DM Fermion

ϕ $\equiv$ vector mediator



Self Interaction



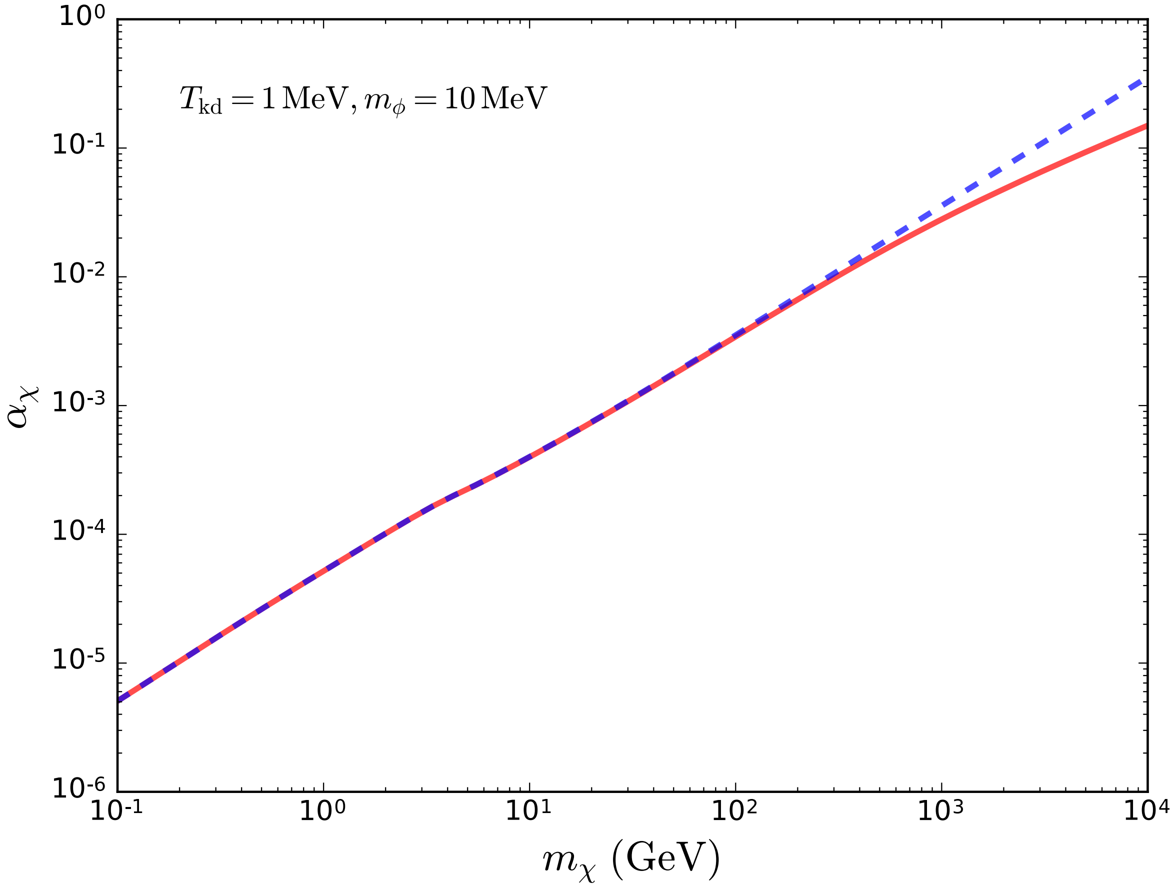
DM Annihilation

vdSIDM Model

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

$\mathbf{m}_\phi \sim \mathbf{1} - \mathbf{100\,MeV}$ 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

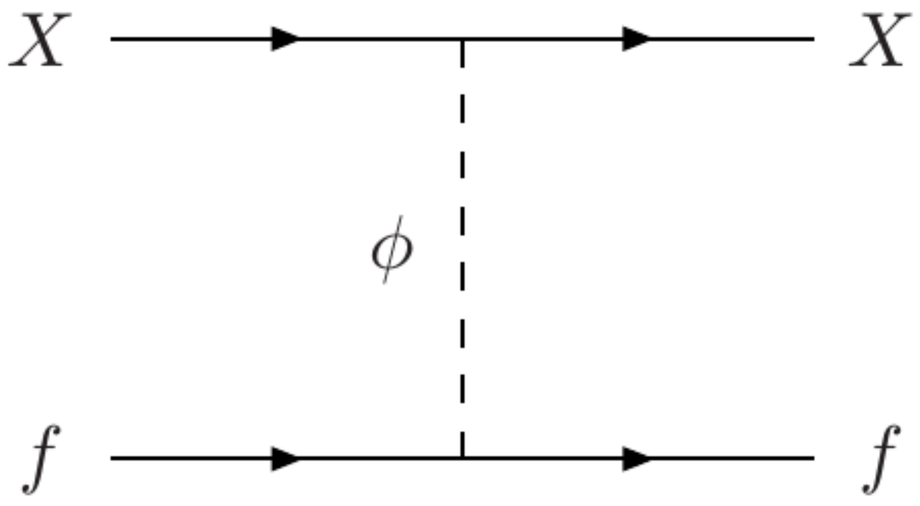
$$\mathcal{L}_{\mathbf{mix}} = \frac{\epsilon_\gamma}{\mathbf{2}}\phi_{\nu\mu}\mathbf{F}^{\mu\nu} + \mathbf{m_Z^2}\epsilon_{\mathbf{Z}}\phi_\mu\mathbf{Z}^\mu$$

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

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

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

ϵ_γ and $\epsilon_{\mathbf{Z}} << \mathbf{1}$



DM - nucleon scattering

Capture in the Sun

Scattering with Sun's Nuclei

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

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

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

suppression factor:

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

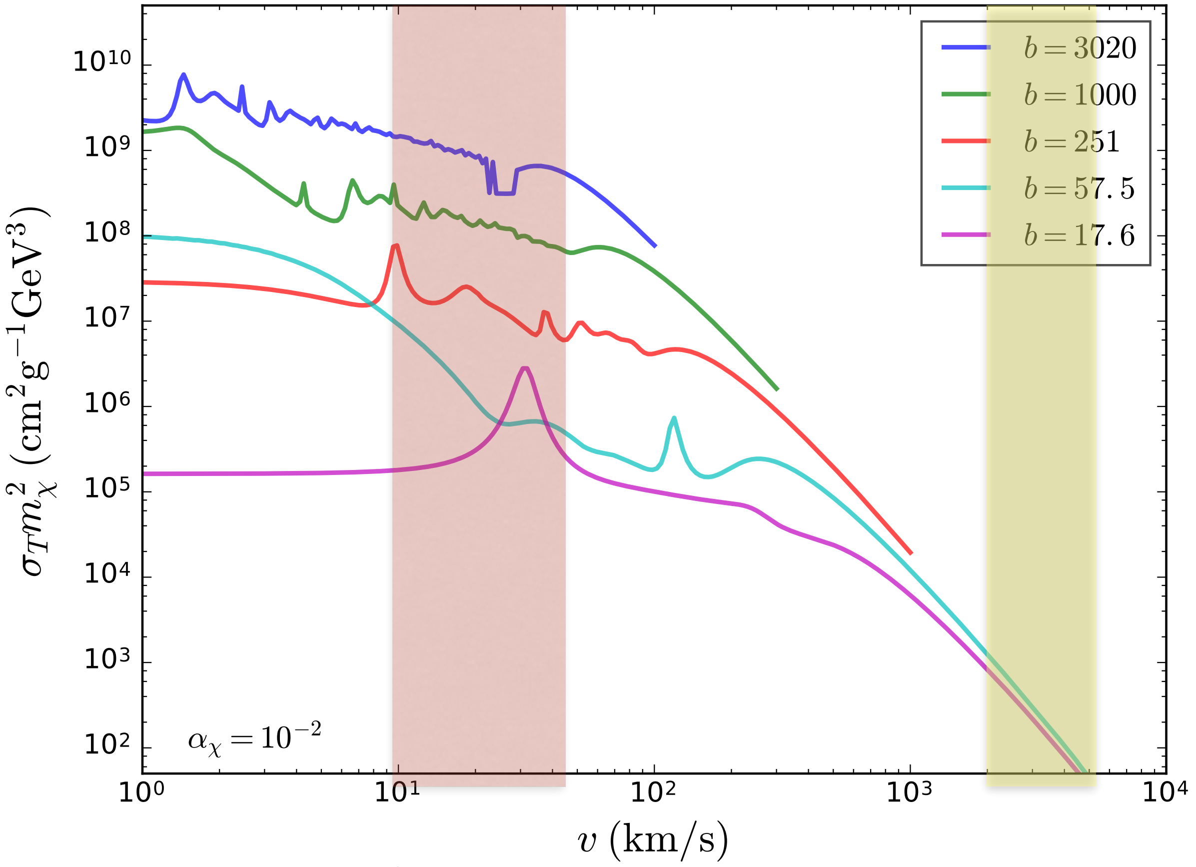
Capture in the Sun

DM Self Scattering

non relativistic limit => Yukawa potential

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

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



$$\mathbf{b} = \alpha_\chi \mathbf{m}_\chi / \mathbf{m}_\phi$$

Self Interacting σ:
partial wave method

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

Sommerfeld effect does not play significant role

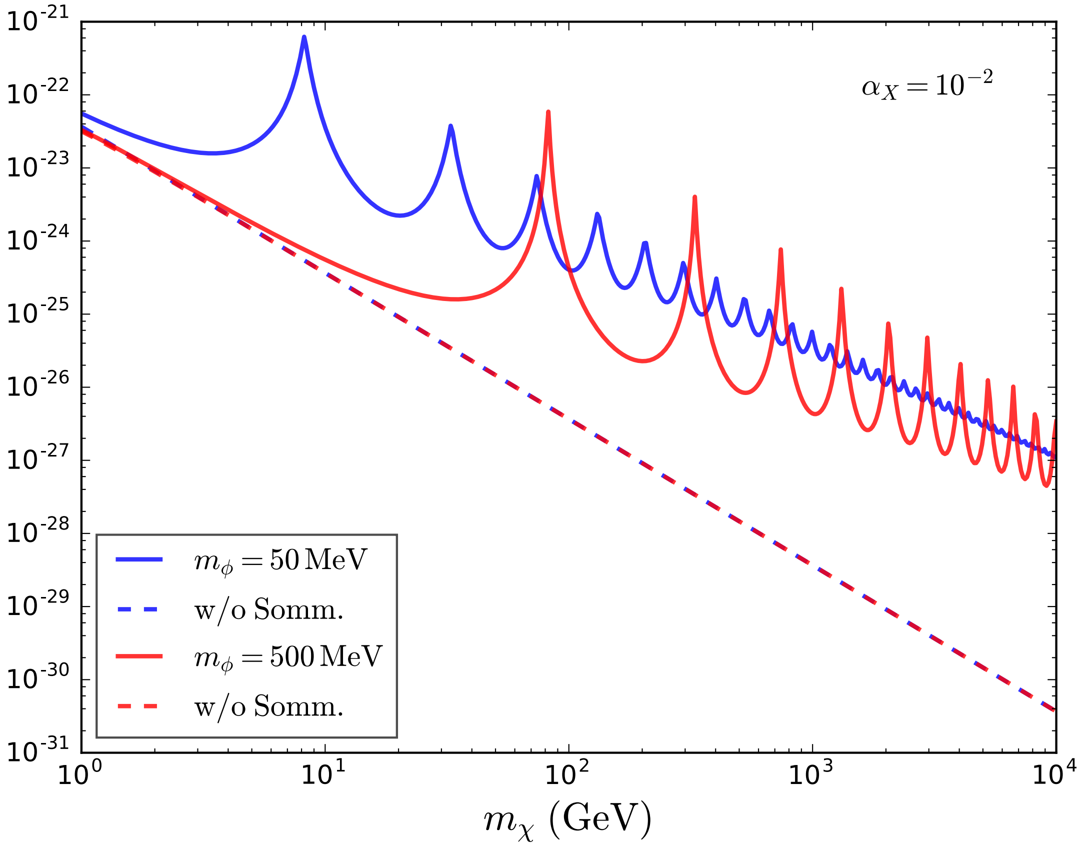
Annihilation in the Sun

$$\mathbf{\Gamma_A = \frac{1}{2}\langle \sigma_A v\rangle V_{eff}}$$

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

S ≡ Sommerfeld factor

Annihilation XS



Annihilation Channel:

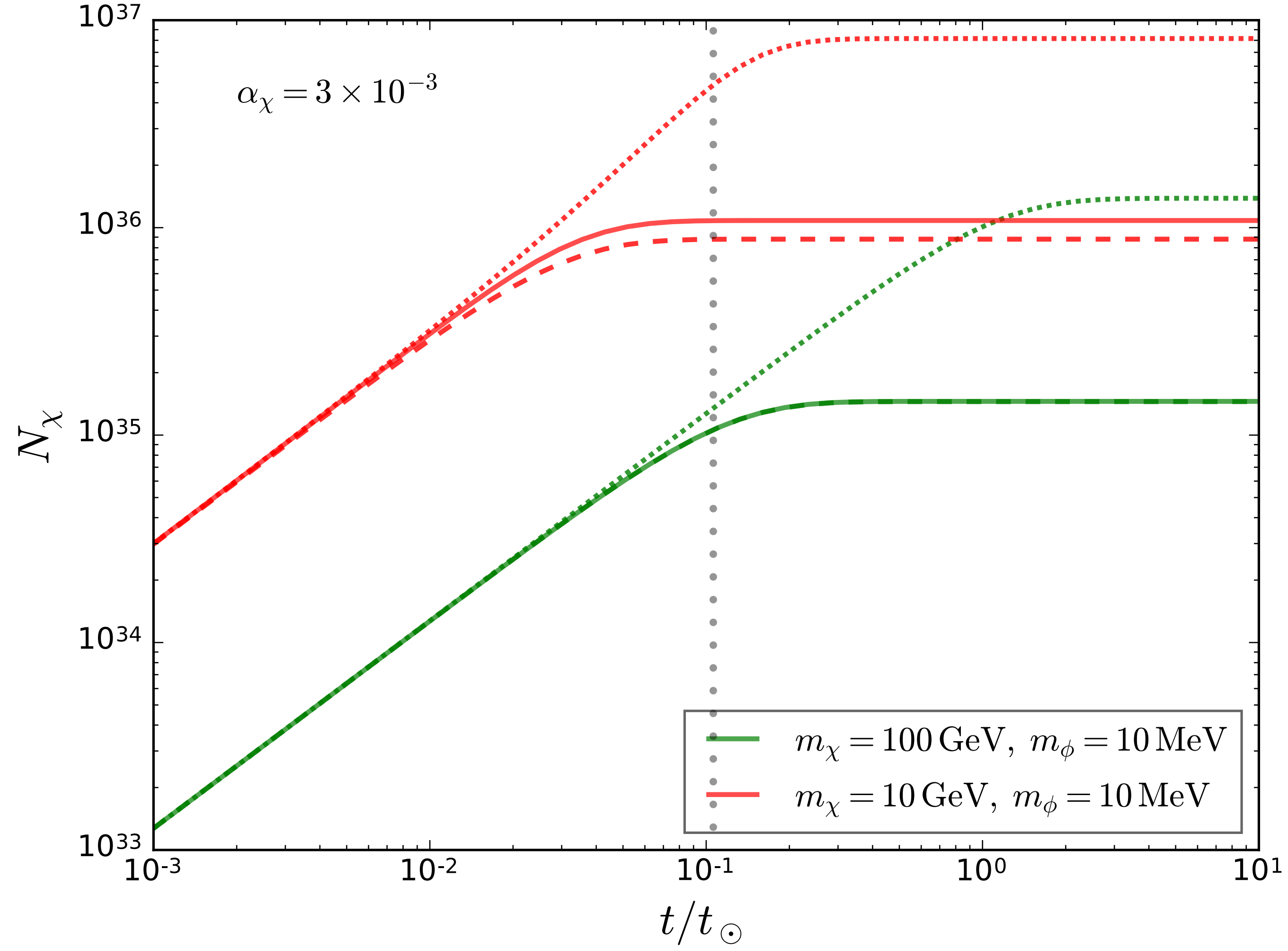
$$\chi\,\overline{\chi} \rightarrow \phi\,\phi \rightarrow 2\nu_l\,2\overline{\nu_l}$$

Branching Ratio:

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

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

Nχ Time Evolution in the Sun



- - - Sommerfeld (NO Self Capture)

— Sommerfeld + Self Capture

…… Only Self Capture

Enhancements on Γ_A:

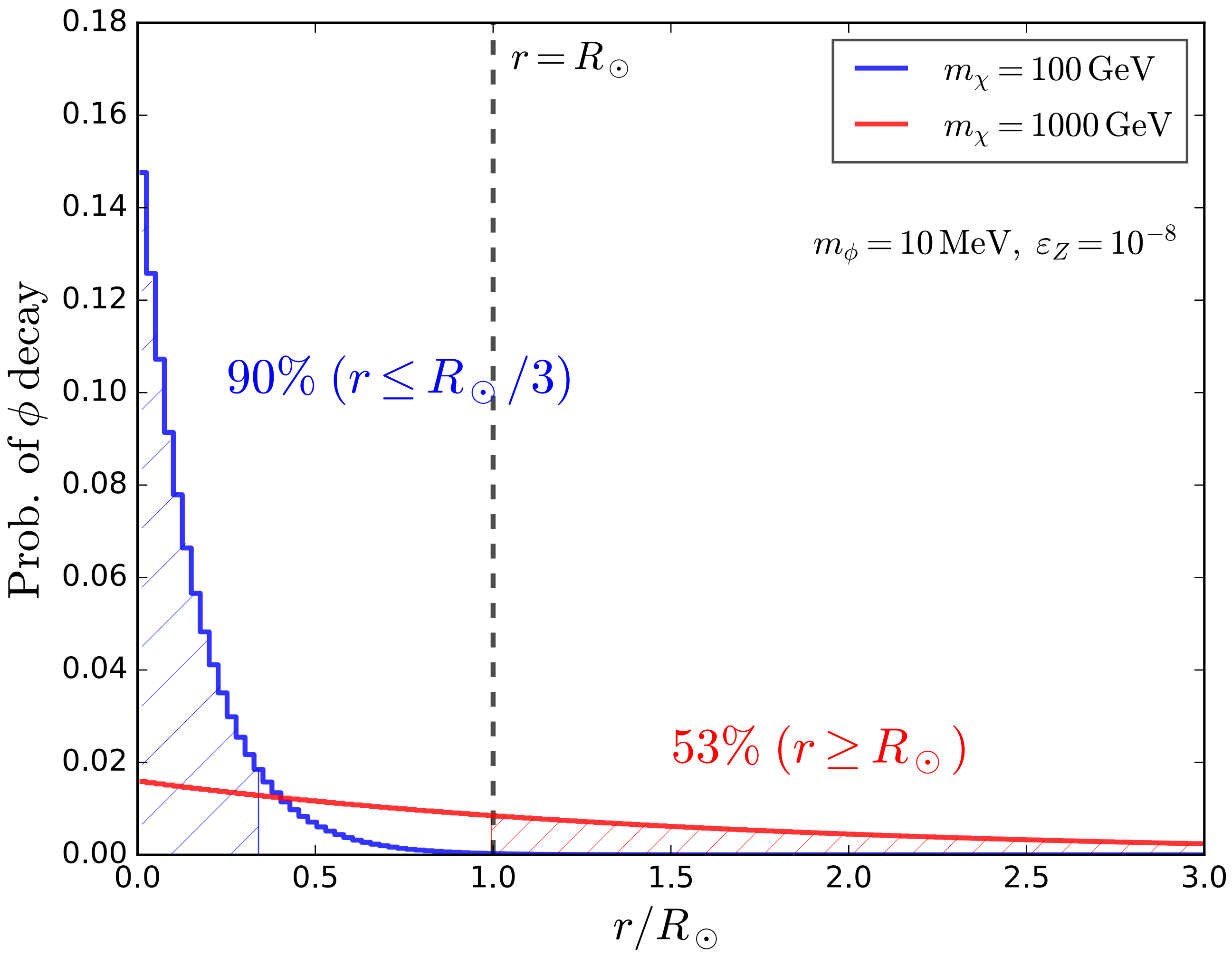
- Self Capture
- Sommerfeld effect on annihilation

Suppression on Γ_A:

- momentum transfer suppression $\sigma_{\chi N}$

ν Production and Propagation

ϕ lifetime is important

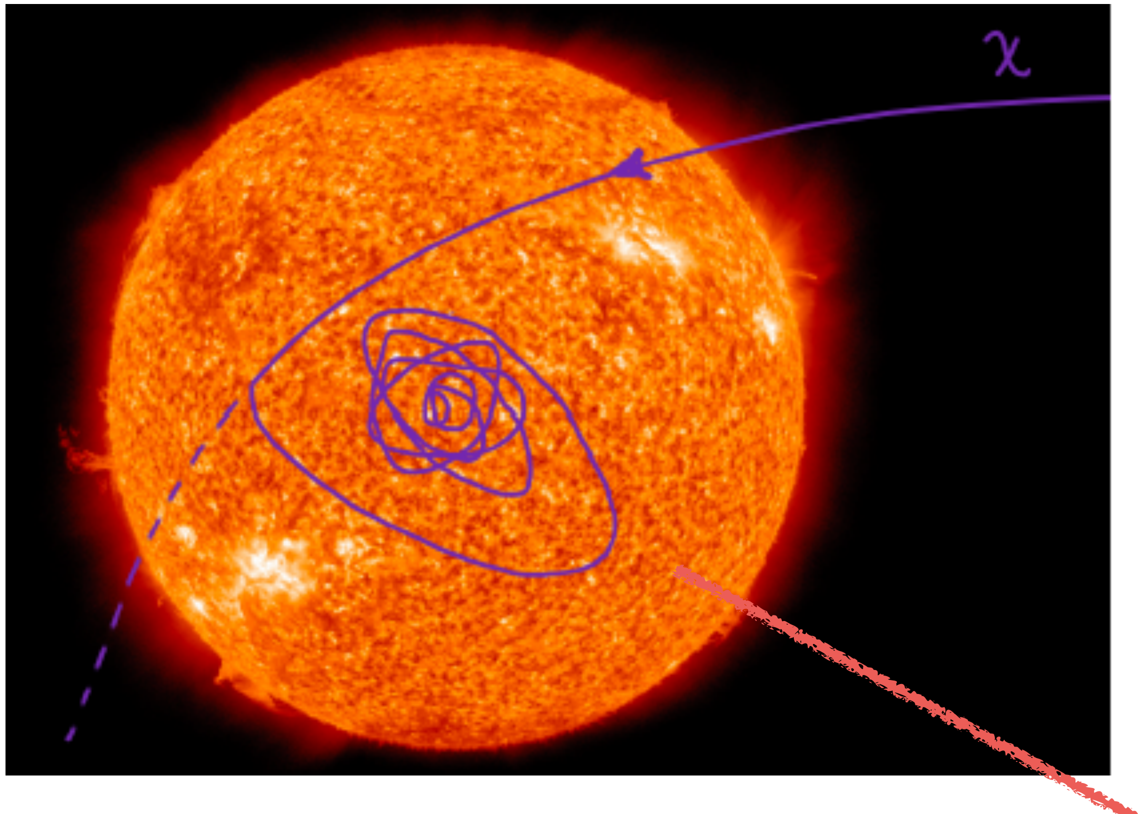


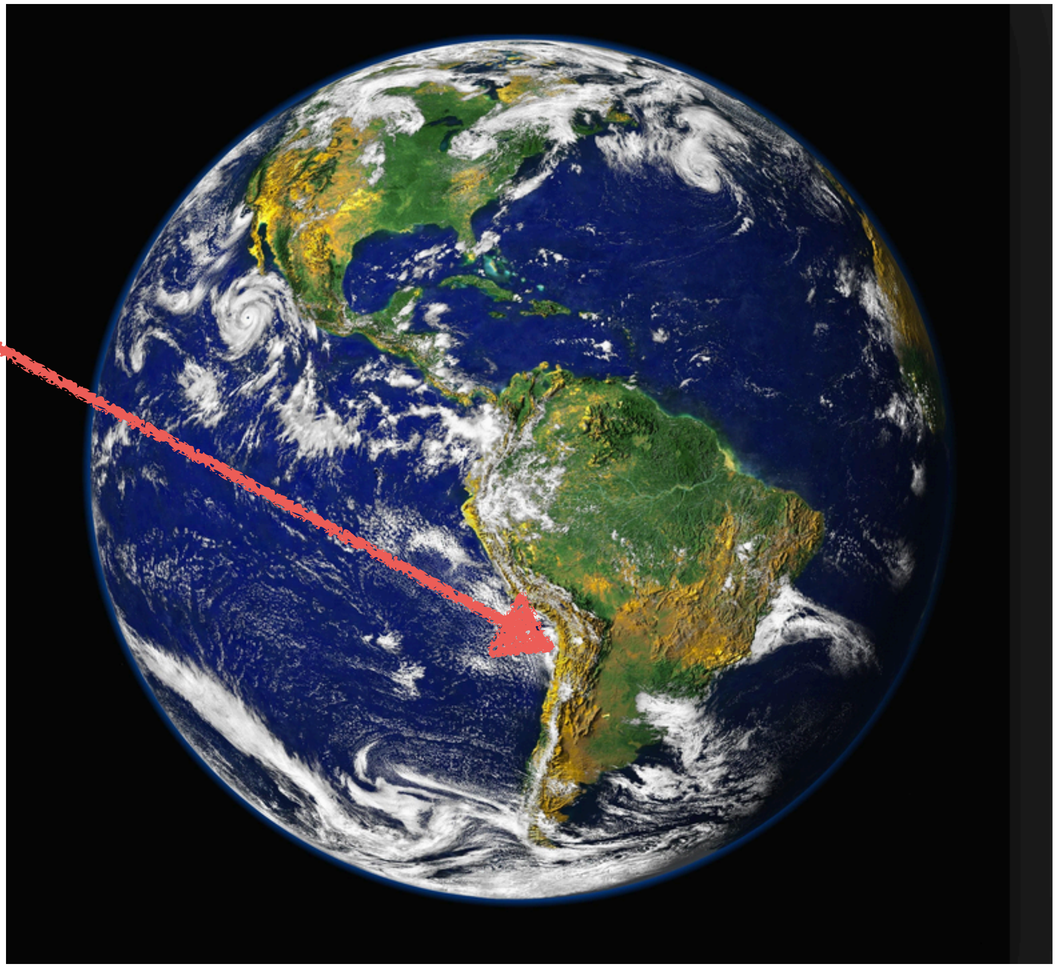
Standard Wimp: ν production in Sun's core

vdSIDMS: ν production beyond 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





Results: arXiv:1711.02052
IA, D.S.Robertson

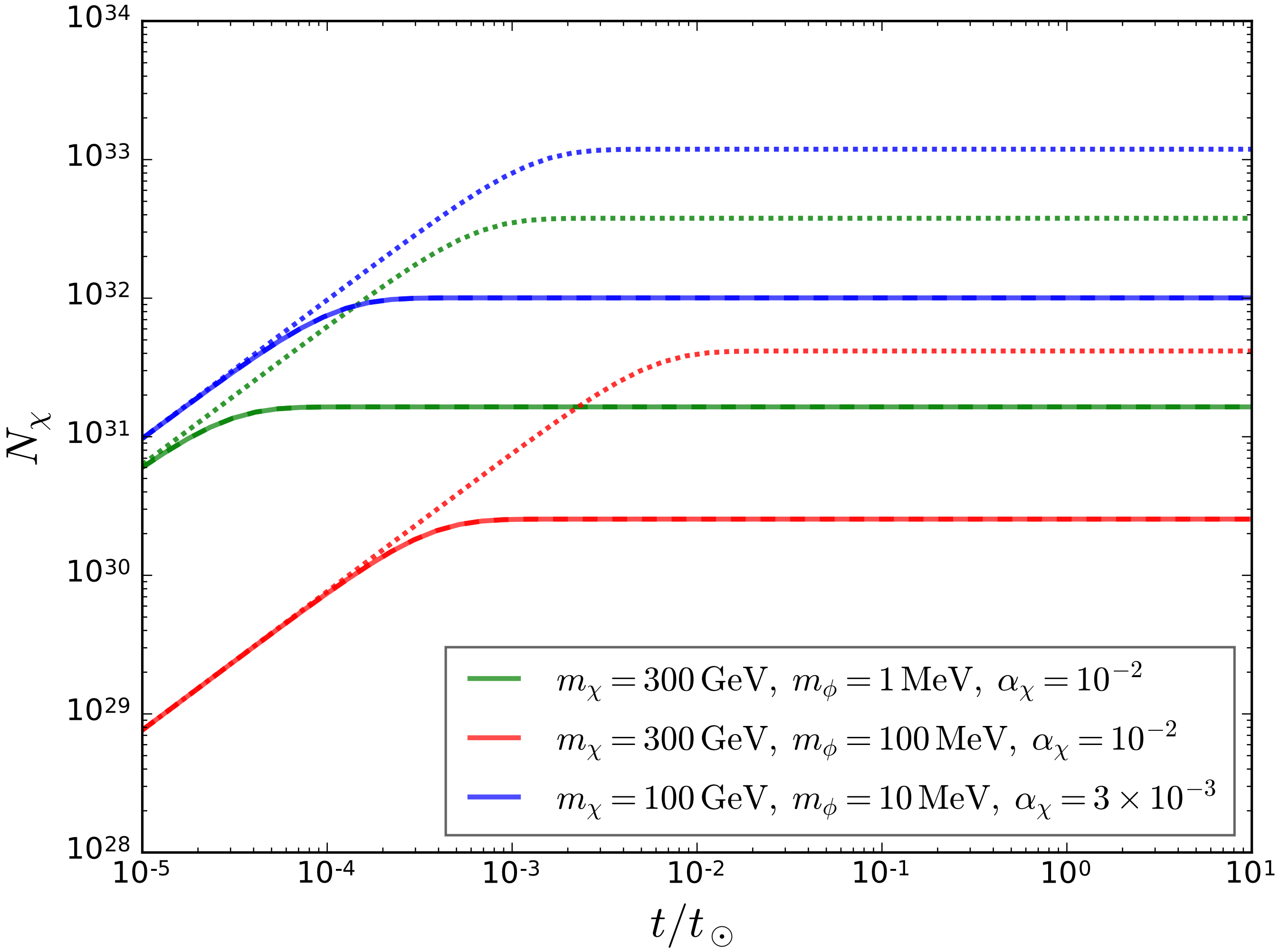
Conclusions

- 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

- if $\sigma_{\chi\chi}$ is velocity dependent, there will be enhancements on annihilation rate and a significant enhancement on the neutrino production

stay tuned:
arXiv:1706.XXXXX
IA, D.S.Robertson


10^{34}
10^{33}
10^{32}
10^{31}
10^{30}
10^{29}
10^{28}
N_χ
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
$t/t_\odot$
$m_\chi = 300\,\mathrm{GeV},\ m_\phi = 1\,\mathrm{MeV},\ \alpha_\chi = 10^{-2}$
$m_\chi = 300\,\mathrm{GeV},\ m_\phi = 100\,\mathrm{MeV},\ \alpha_\chi = 10^{-2}$
$m_\chi = 100\,\mathrm{GeV},\ m_\phi = 10\,\mathrm{MeV},\ \alpha_\chi = 3\times 10^{-3}$