Dark matter capture, neutrino observatories, and subdominant WIMPs

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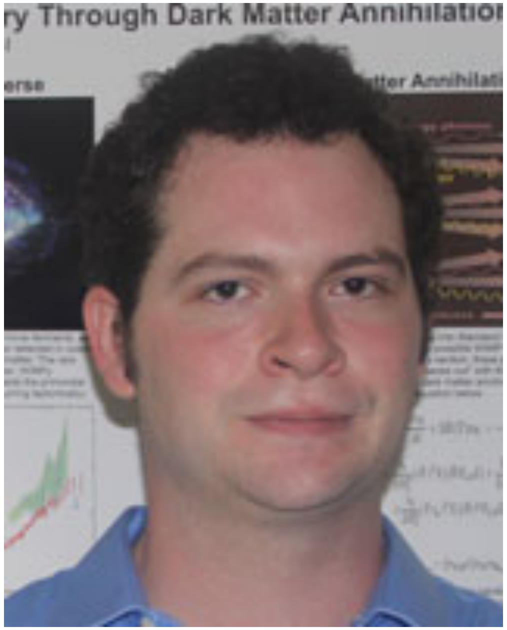
Work done with:



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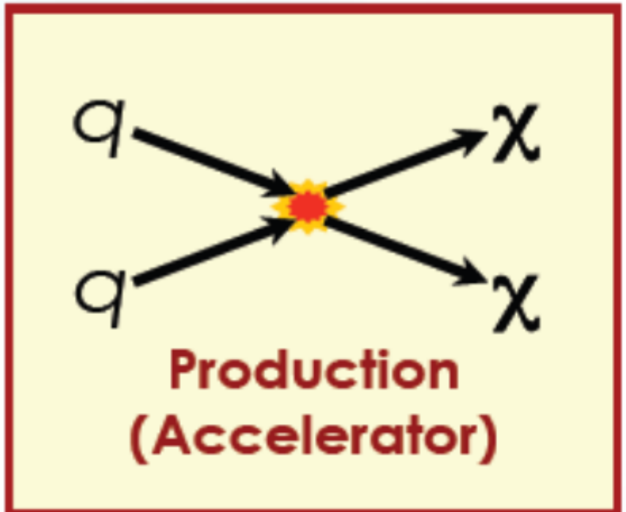
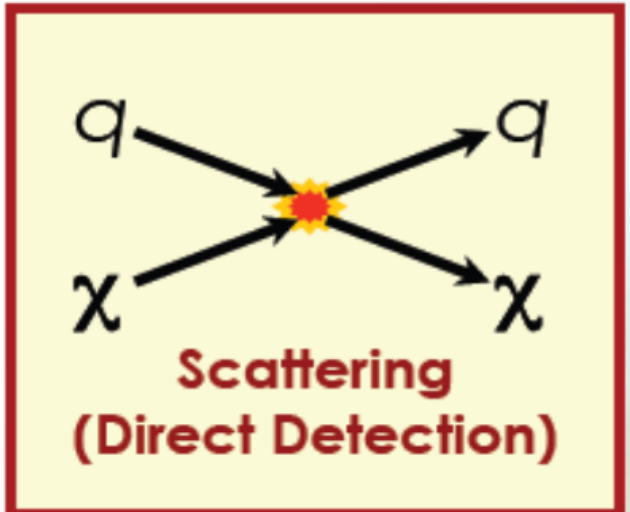
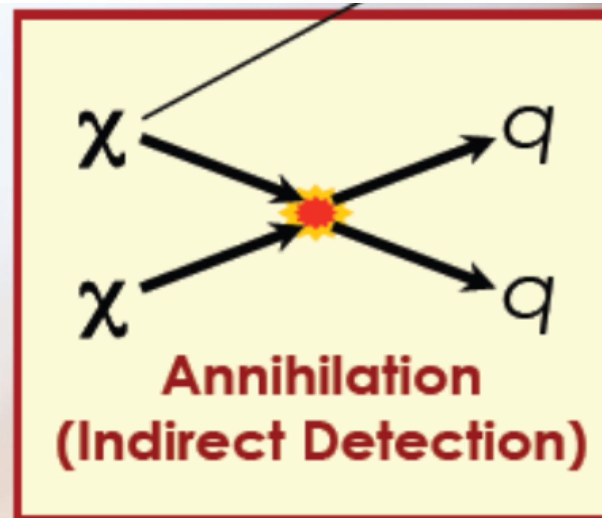
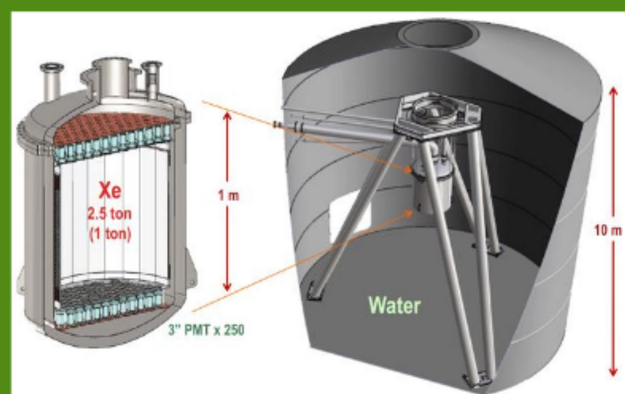
Ways to look for WIMP Dark Matter

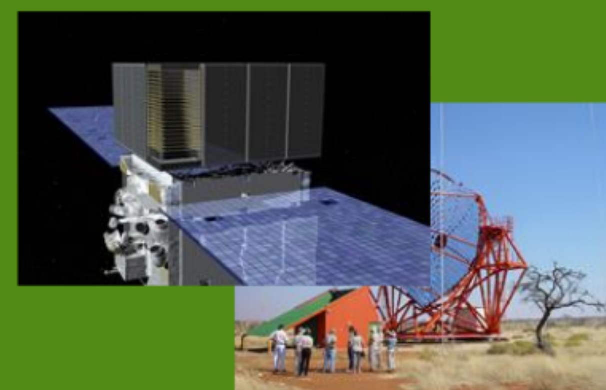
Fig. from J. Conrad











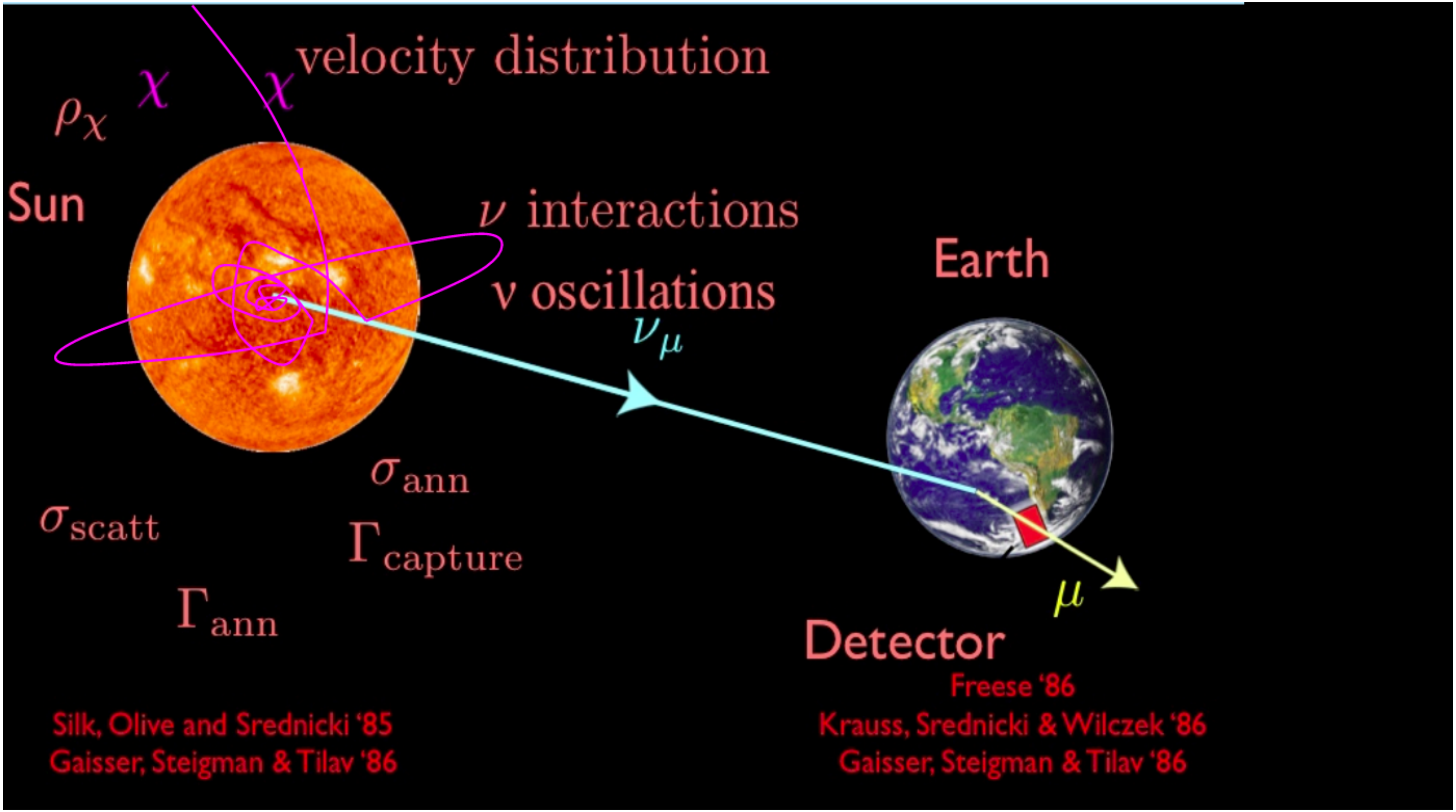
Large Hadron Collider

Deep underground detectors (e.g based on Xenon)

Gamma ray telescopes, neutrino telescopes, Charged cosmic ray detectors

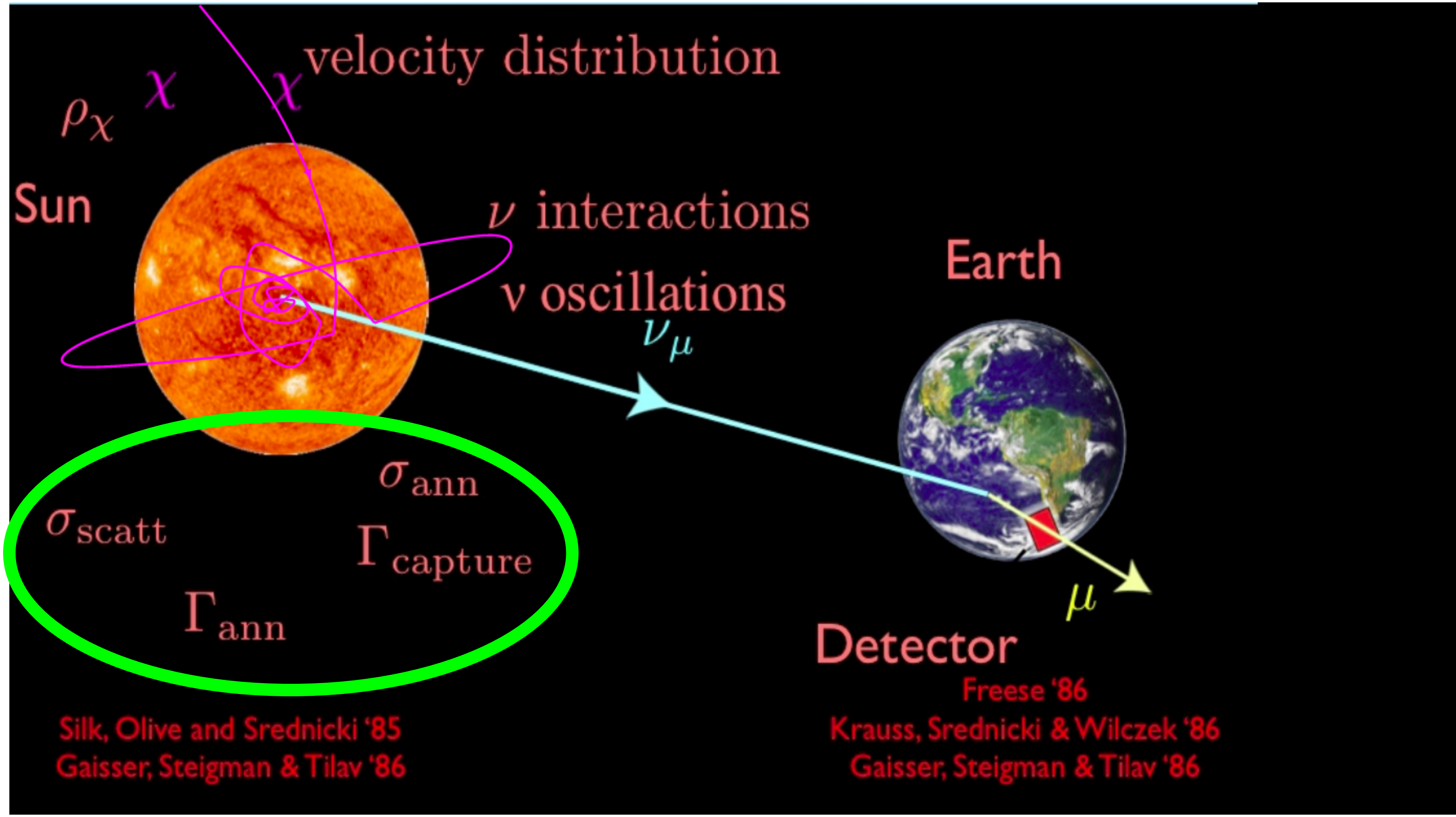
Capture in Massive Bodies

Fig. from J. Edsjö



Capture in Massive Bodies

Fig. from J. Edsjö



Number of captured particles

WIMP annihilation rate:

$$\Gamma_A = \langle \sigma v \rangle_{\rm ann} \int d^3r\, n^2(\vec{r}, t)$$

WIMP number density

The number of captured WIMP at time *t* obeys

$$\frac{dN}{dt} = -C_A N^2 - C_E N + C$$

Number of WIMPs captured

$$N(t) = \int d^3r\, n(\vec{r}, t)$$

Annihilation

$$C_A = \frac{2\Gamma_A}{N^2(t)}$$

Evaporation.

$m_\chi \lesssim 5\,{\rm GeV}$,

$C_E N \ll C_A N^2$

Capture Rate

$$C = K^s(m_\chi)\sigma_p^s \rho_\chi^{\rm loc}$$

Number of captured particles

WIMP annihilation rate:

$$\Gamma_A = \langle \sigma v \rangle_{\rm ann} \int d^3r\, n^2(\vec{r}, t)$$

WIMP number density

The number of captured WIMP at time *t* obeys

$$\frac{dN}{dt} = -C_A N^2 - C_E N + C$$

Capture Rate

This is where all the details are hidden away…

- interaction details, e.g. nuclear form factors
- chemical composition of the capturing body
- WIMP velocity distribution
- ...

$$C = K^s(m_\chi)\sigma_p^s \rho_\chi^{\rm loc}$$

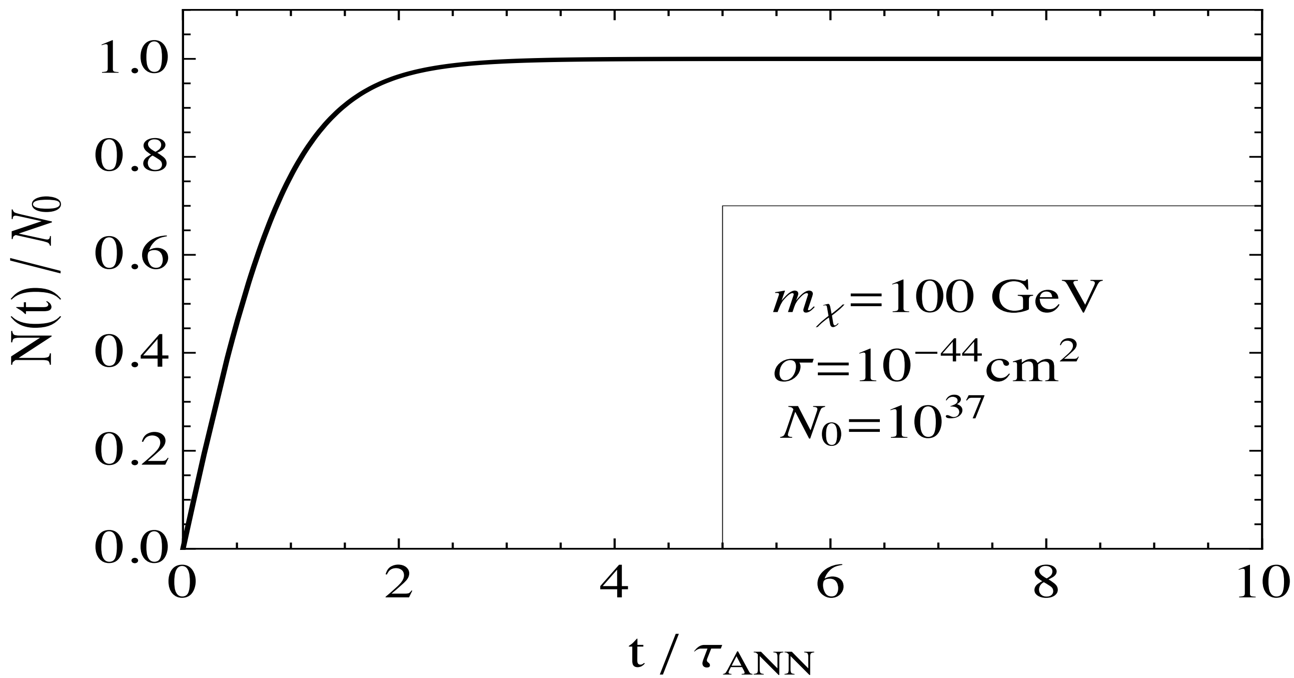
WIMP-proton scattering cross-section for *s* = SI/SD

Local WIMP density

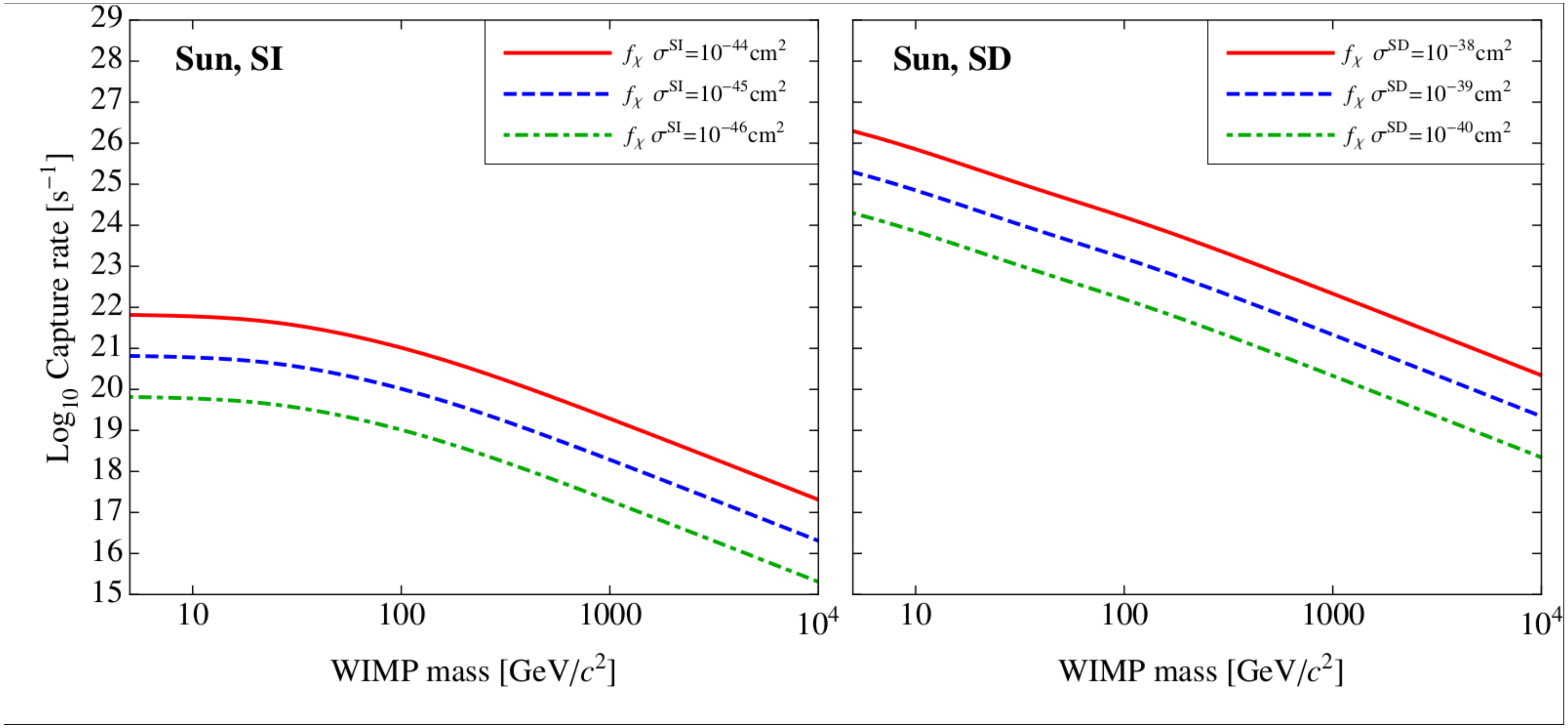
$$\frac{dN}{dt} = -C_A N^2 - C_E N + C$$

with the time scale at which annihilation & capture rates equate

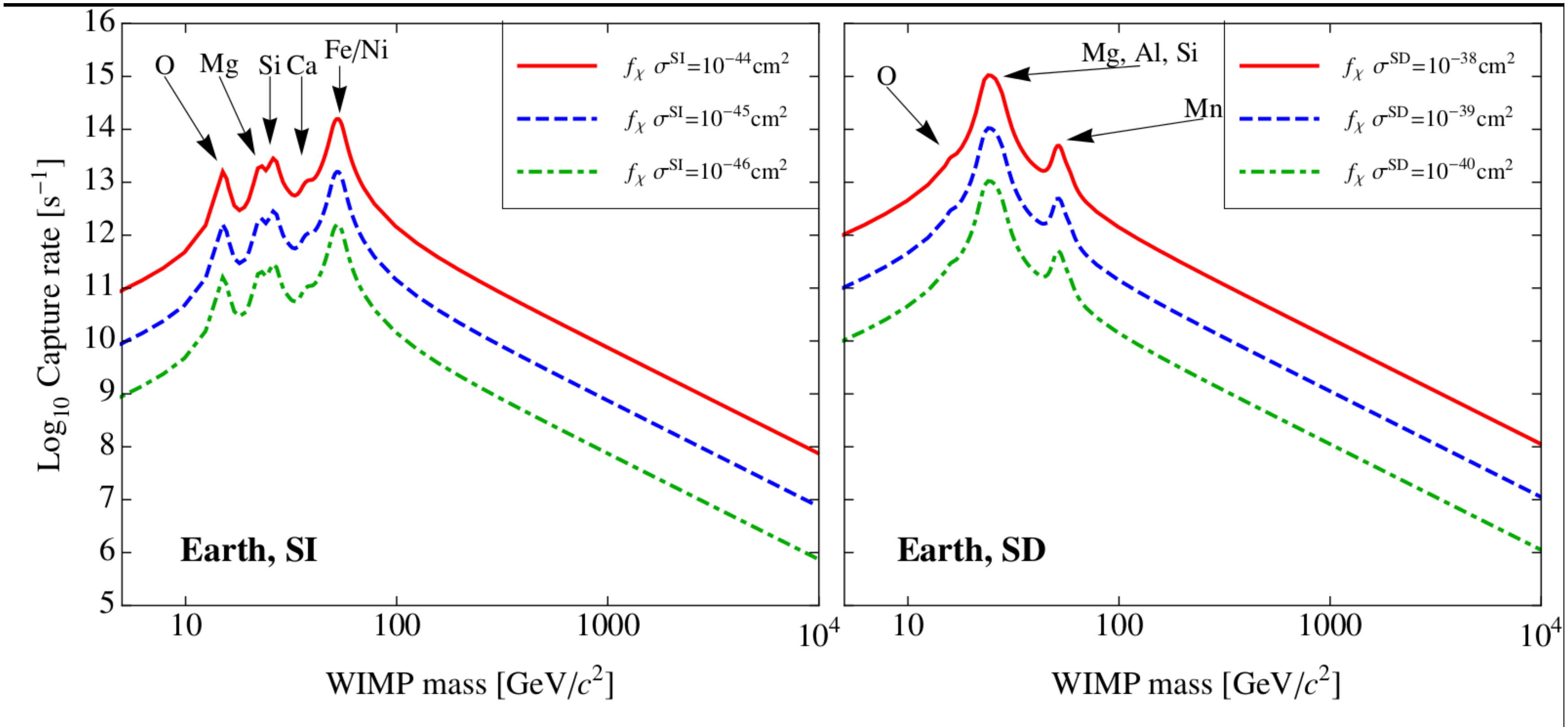
$$\tau_{\rm ann} = 1/\sqrt{CC_A}$$



Capture Rate, Sun



Capture Rate, Earth

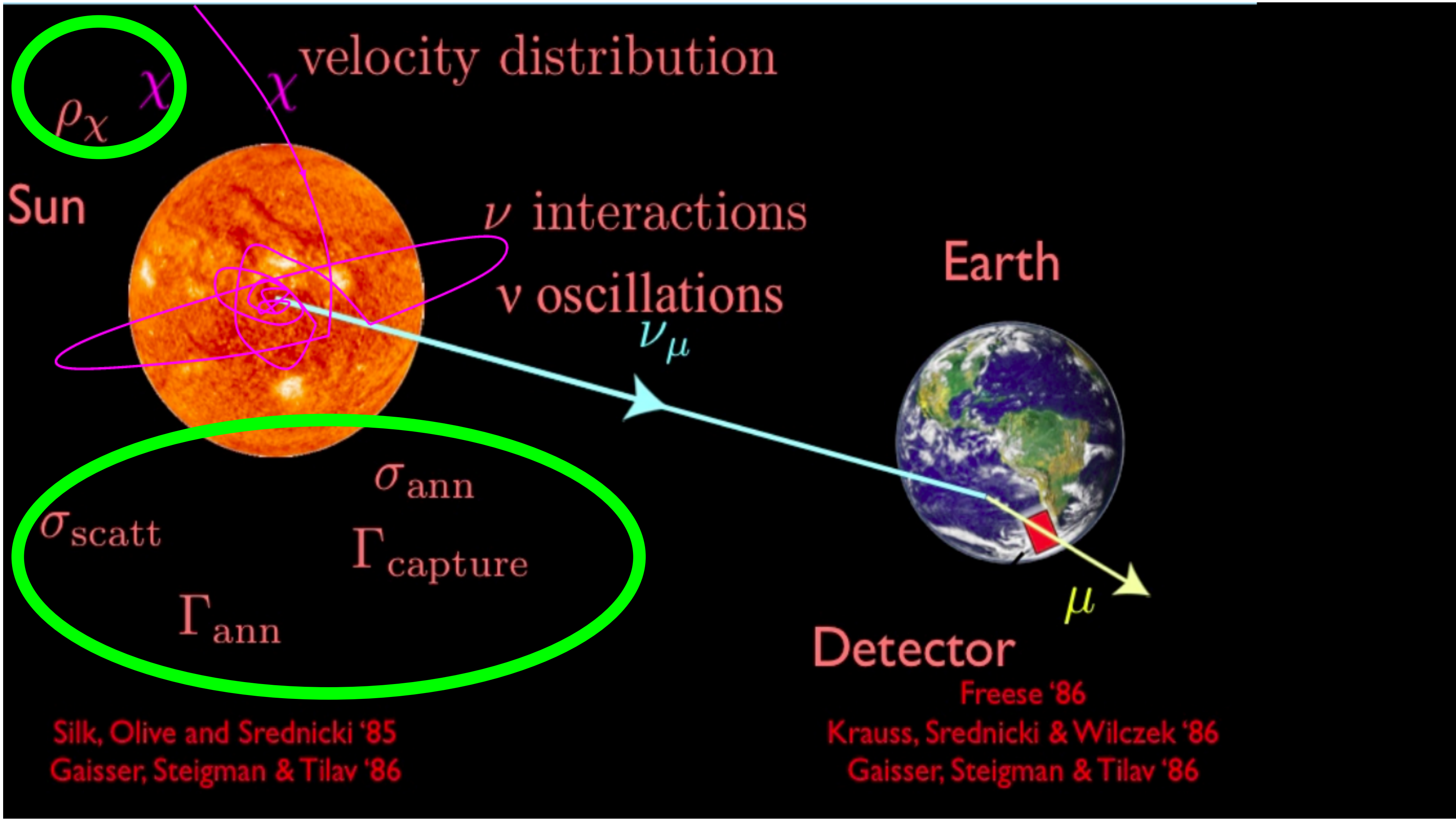


Chemical Composition of the Earth used

Isotope i	Mass Fraction x_i (%)			Potential ϕ_i
	Mantle	Core	Total	
Fe	6.26	85.5	32.0	1.59
O	44.0	0.0	29.7	1.28
Si	21.0	6.0	16.1	1.33
Mg	22.8	0.0	15.4	1.28
Ni	0.20	5.2	1.82	1.63
Ca	2.53	0.0	1.71	1.28
Al	2.35	0.0	1.59	1.28
S	0.03	1.9	0.64	1.62
Cr	0.26	0.9	0.47	1.50
Na	0.27	0.0	0.18	1.30
P	0.009	0.2	0.07	1.63
Mn	0.10	0.30	0.08	1.54
C	0.01	0.20	0.07	1.64
H	0.01	0.06	0.03	1.35

Capture in Massive Bodies

Fig. from J. Edsjö



Subdominant WIMPs

WIMPs could make up all or a fraction $f_\chi = \rho_\chi^{\rm loc}/\rho_{\rm DM}^{\rm loc}$ of the observed DM

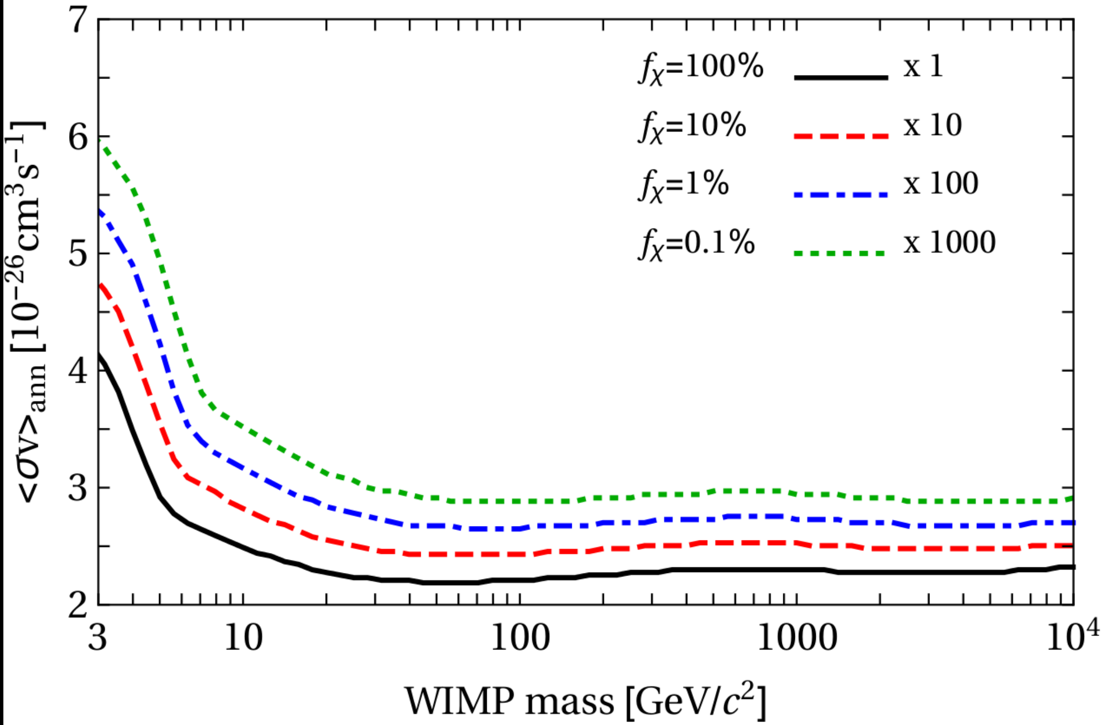
Assumptions:

Standard 'freeze-out' scenario

S-wave annihilation

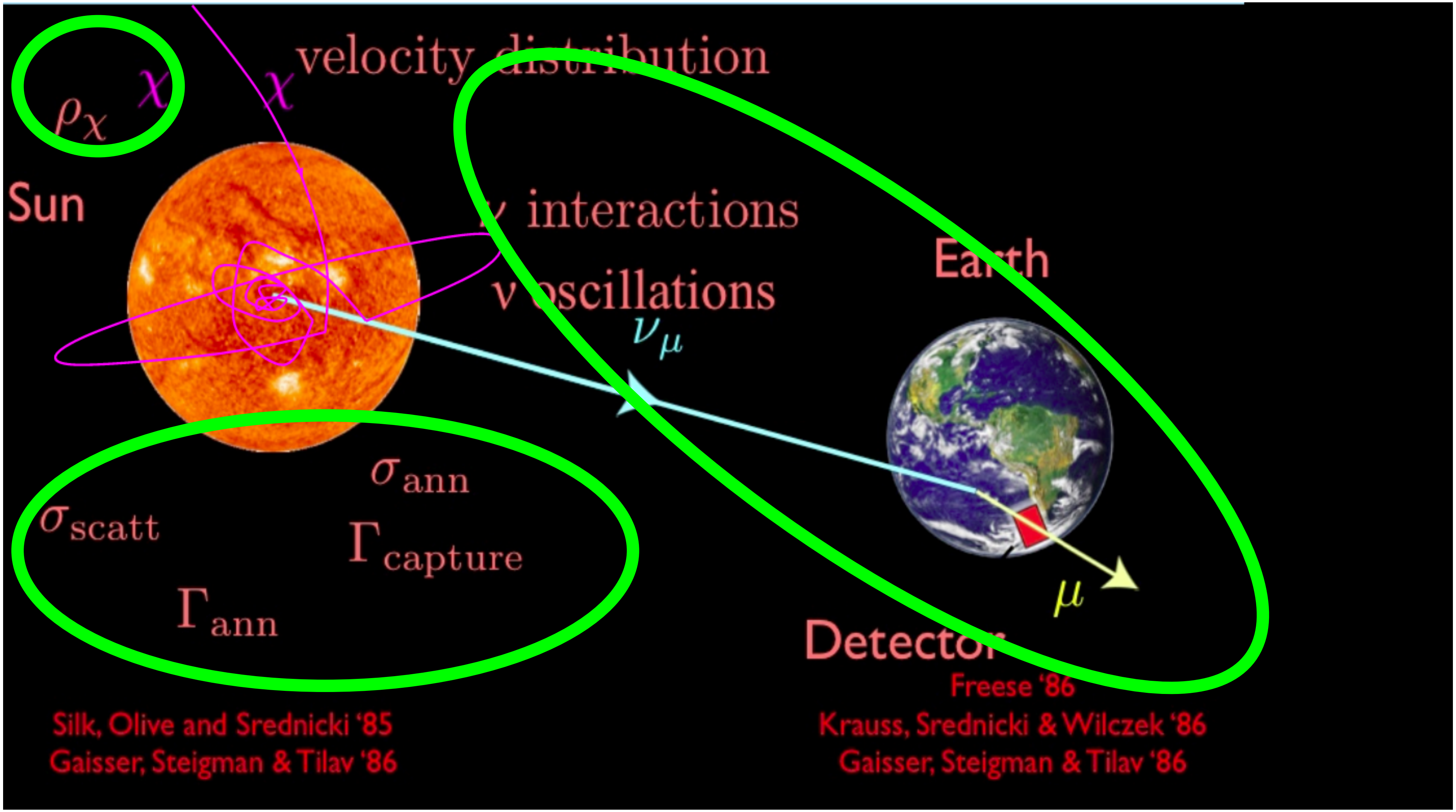
No significant contribution from co-annihilation

Following Steigman+ 1204.3622

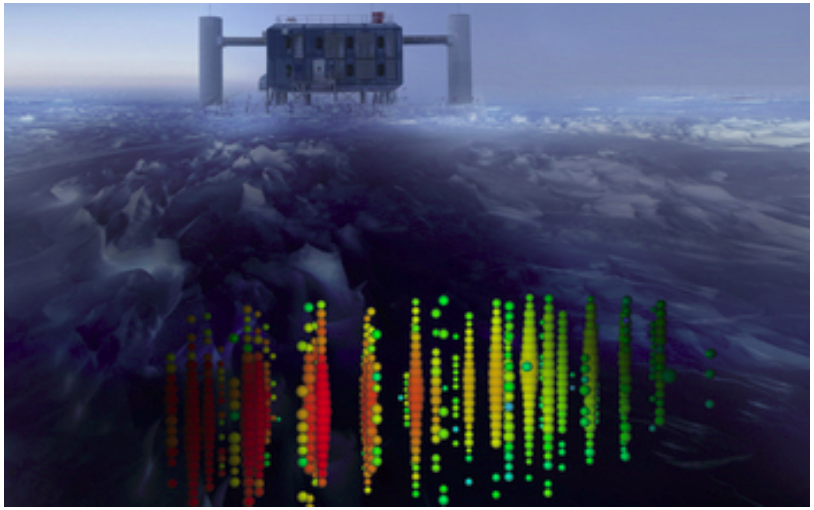


Capture in Massive Bodies

Fig. from J. Edsjö



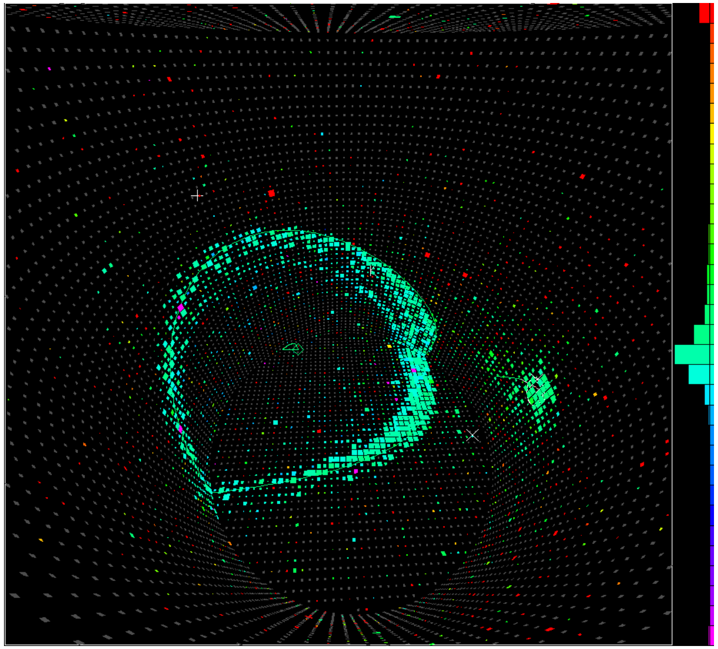
Signals at neutrino observatories



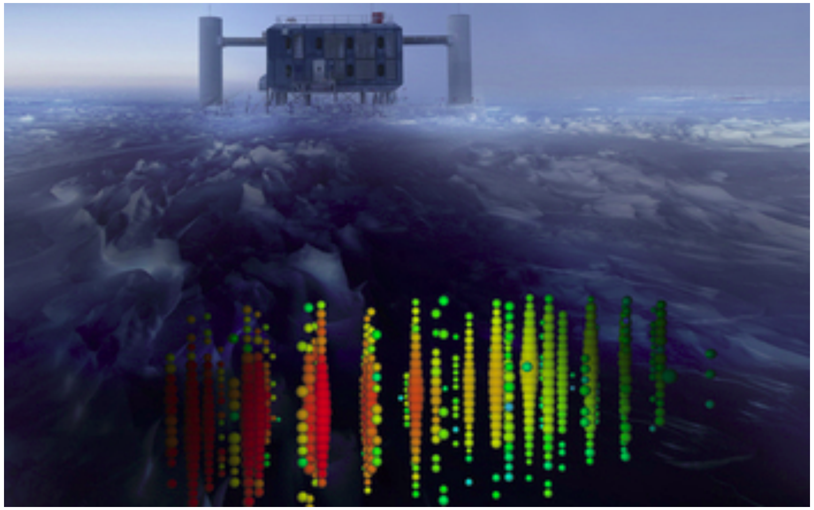
Neutrino observatories (mainly) detect Cherenkov light from muons

Muon flux at detector:

$$\Phi_\mu^{\rm DM} = \Gamma_A \times Y(m_\chi, \mathcal{B}_\chi^X)$$



Signals at neutrino observatories



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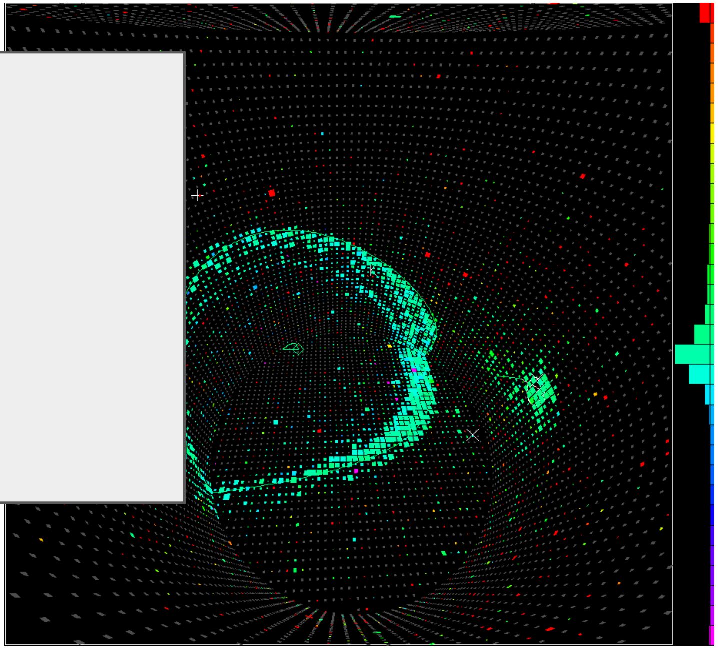
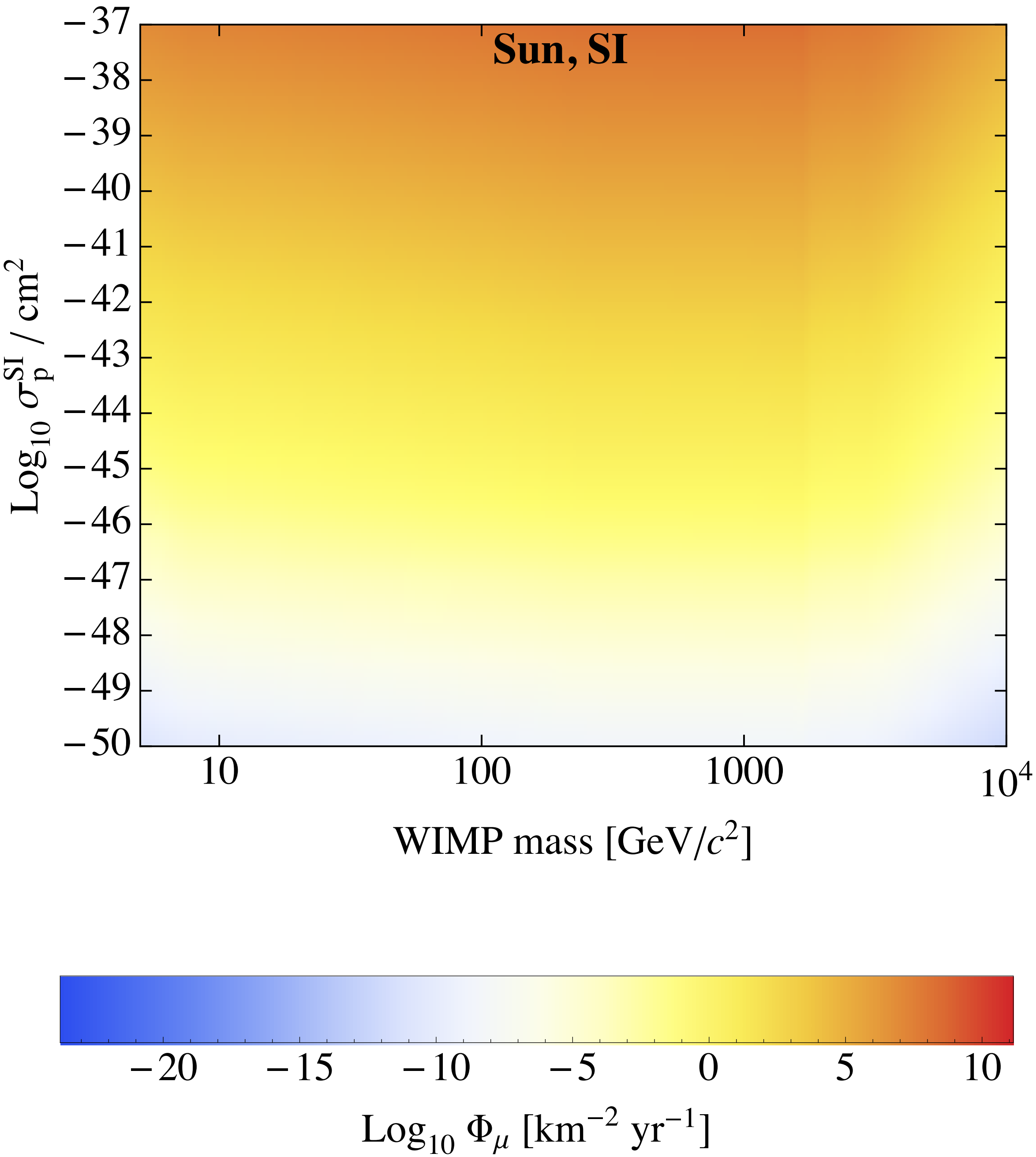
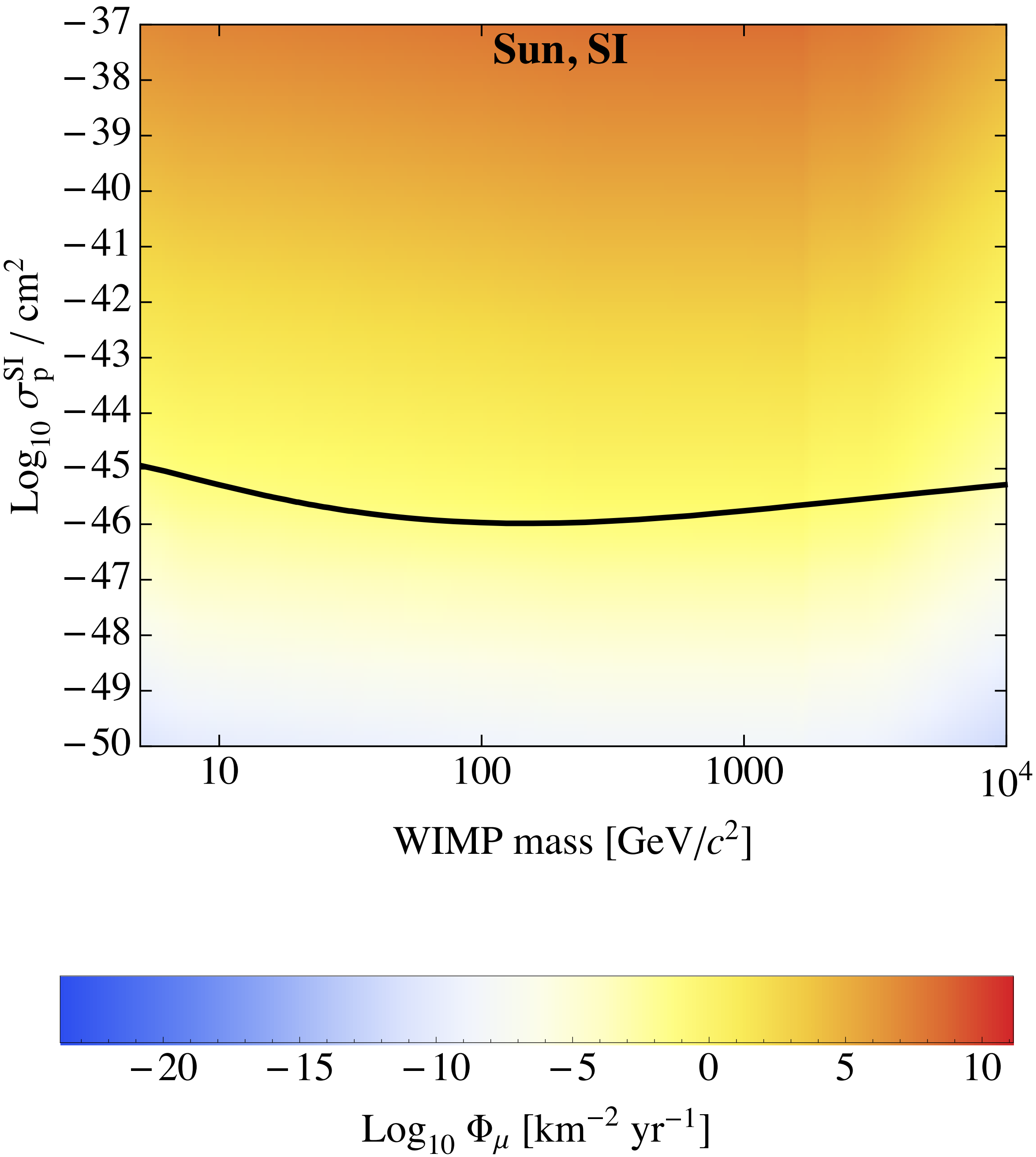


Yield obtained from Monte Carlo simulations

We use results from WimpSim (Blennow+ 0709.3898)



Sun, SI
−37
−38
−39
−40
−41
−42
−43
−44
−45
−46
−47
−48
−49
−50
$\mathrm{Log}_{10}\,\sigma_p^{SI}$ / cm^2
10
100
1000
10^4
WIMP mass [GeV/c^2]
−20
−15
−10
−5
0
5
10
$\mathrm{Log}_{10}\,\Phi_\mu$ [km^{-2} yr^{-1}]



Sun, SI
−37
−38
−39
−40
−41
−42
−43
−44
−45
−46
−47
−48
−49
−50
$\mathrm{Log}_{10}\,\sigma_p^{SI}$ / cm^2
10
100
1000
10^4
WIMP mass [GeV/c^2]
−20
−15
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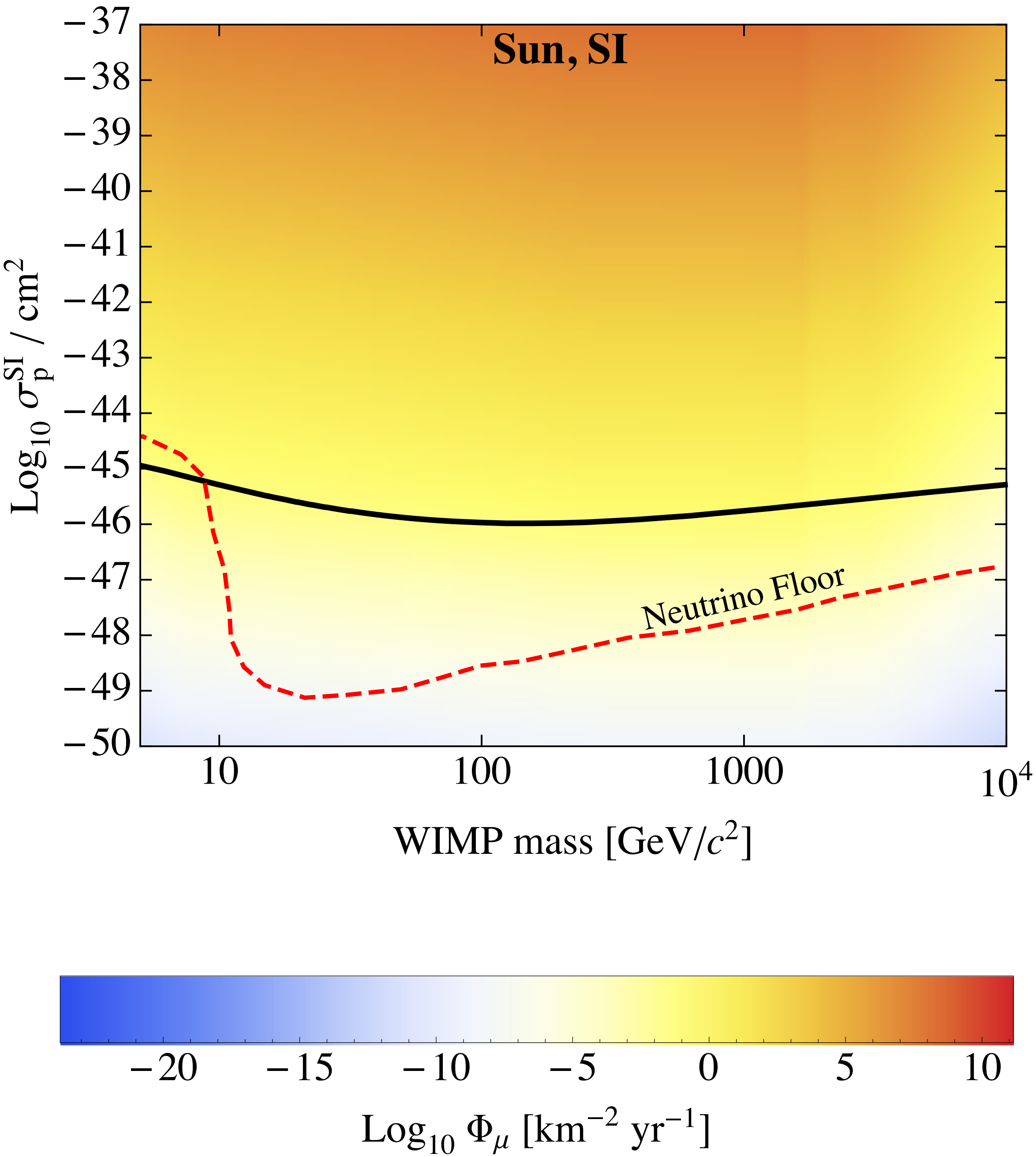
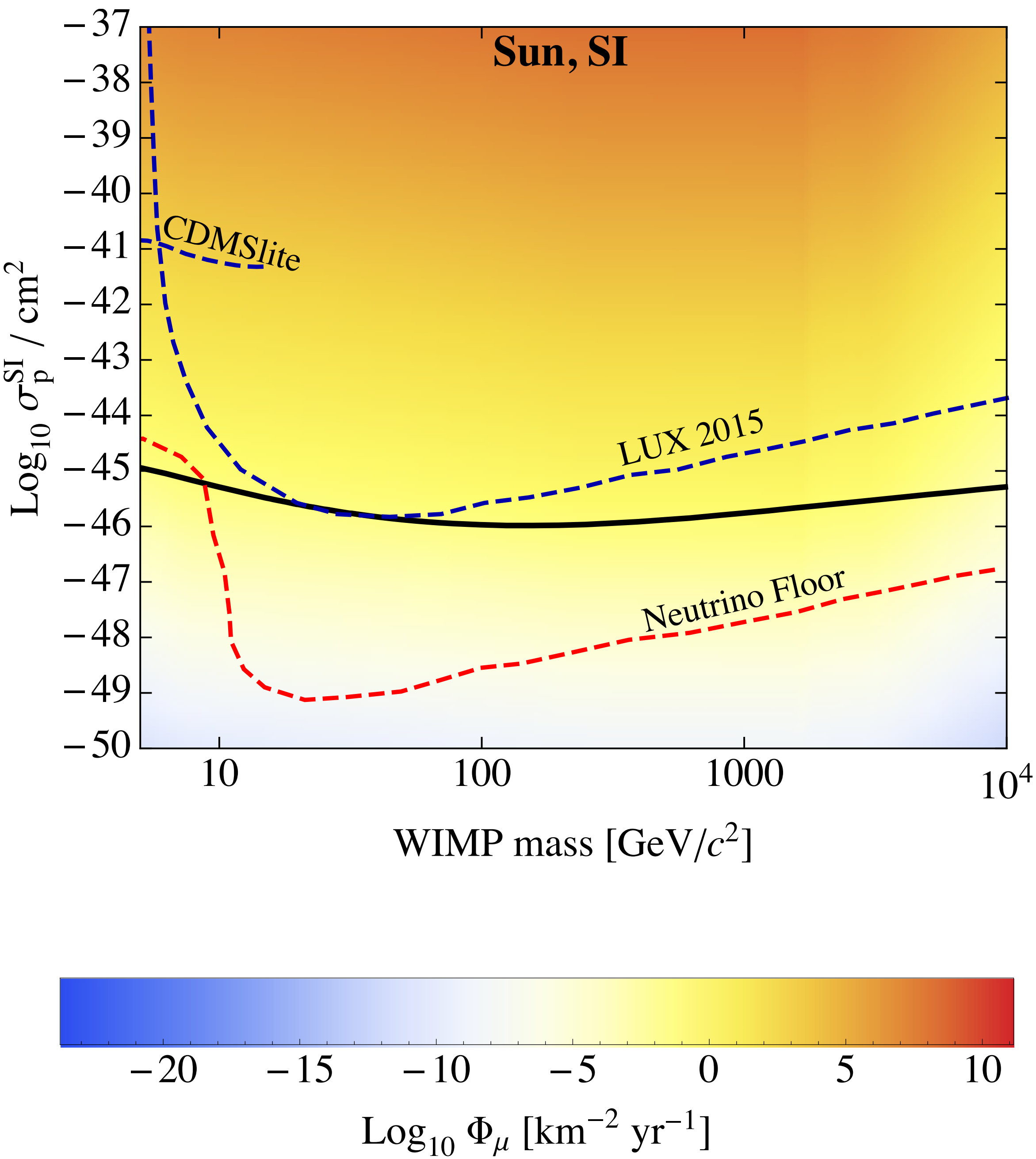
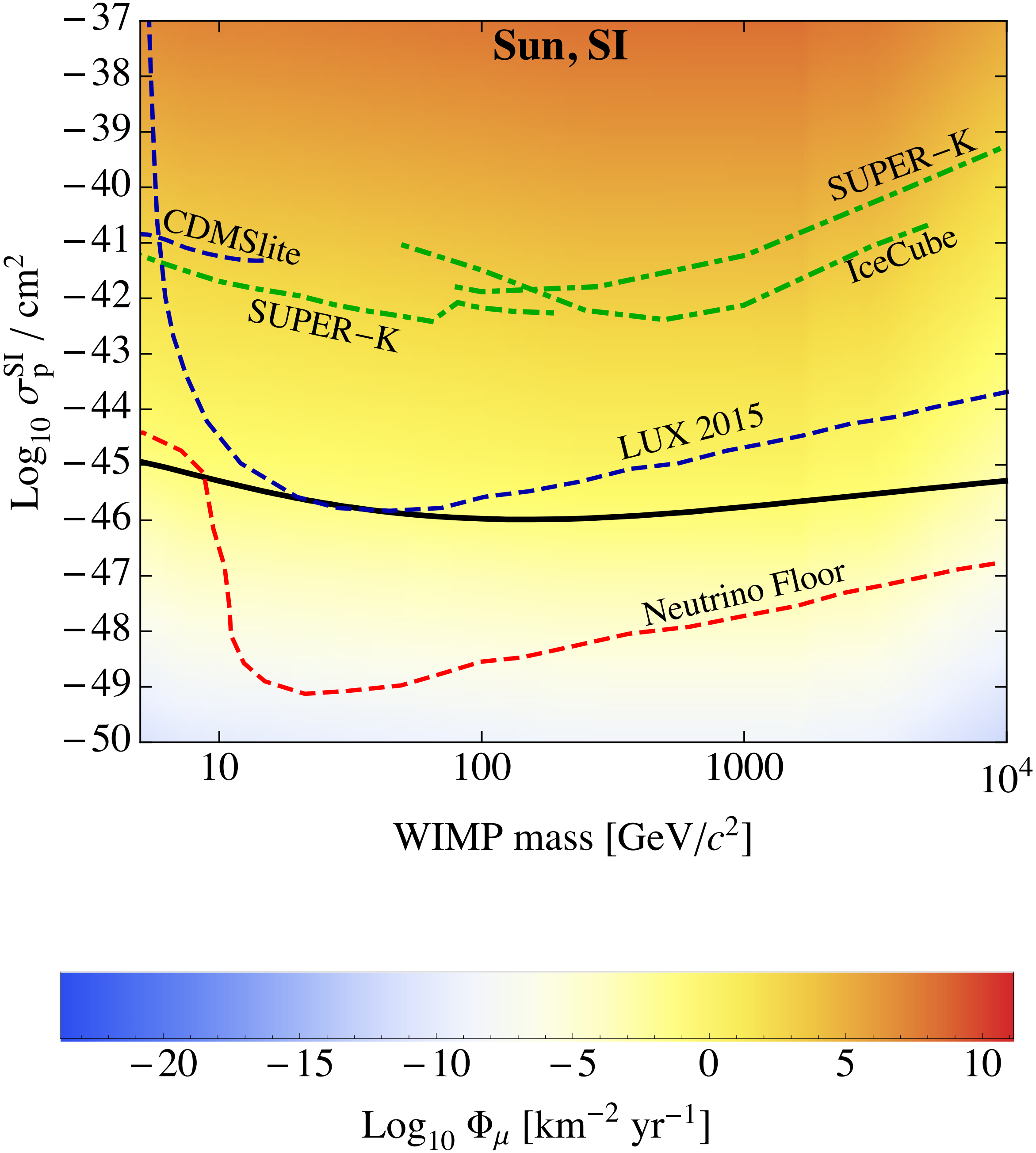
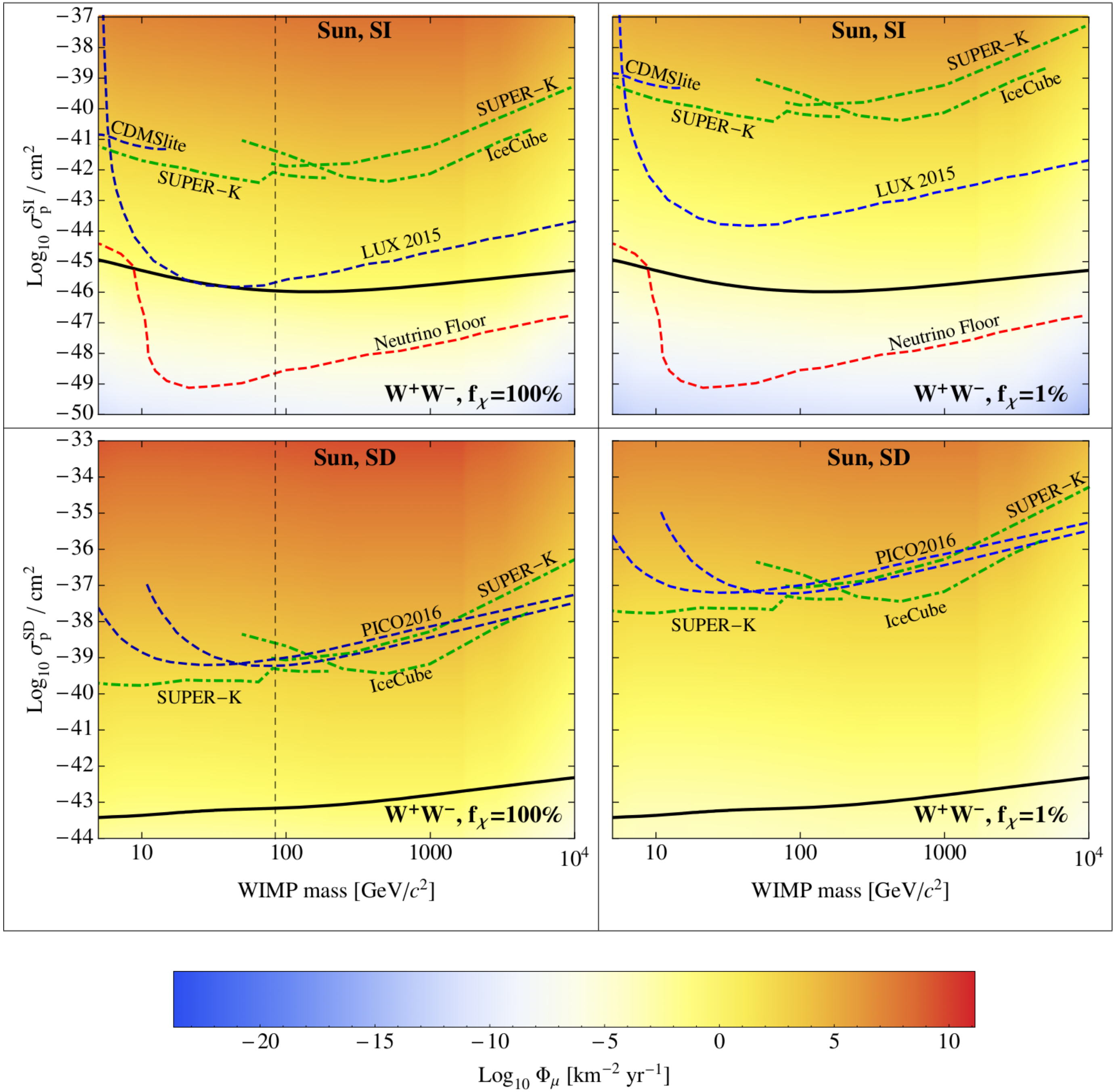
0
5
10
$\mathrm{Log}_{10}\,\Phi_\mu$ [km^{-2} yr^{-1}]


Sun, SI
Neutrino Floor
Log$_{10}$ σ_p^{SI} / cm^2
WIMP mass [GeV/c^2]
−37
−38
−39
−40
−41
−42
−43
−44
−45
−46
−47
−48
−49
−50
10
100
1000
10^4
−20
−15
−10
−5
0
5
10
Log$_{10}$ Φ_μ [km^{-2} yr^{-1}]

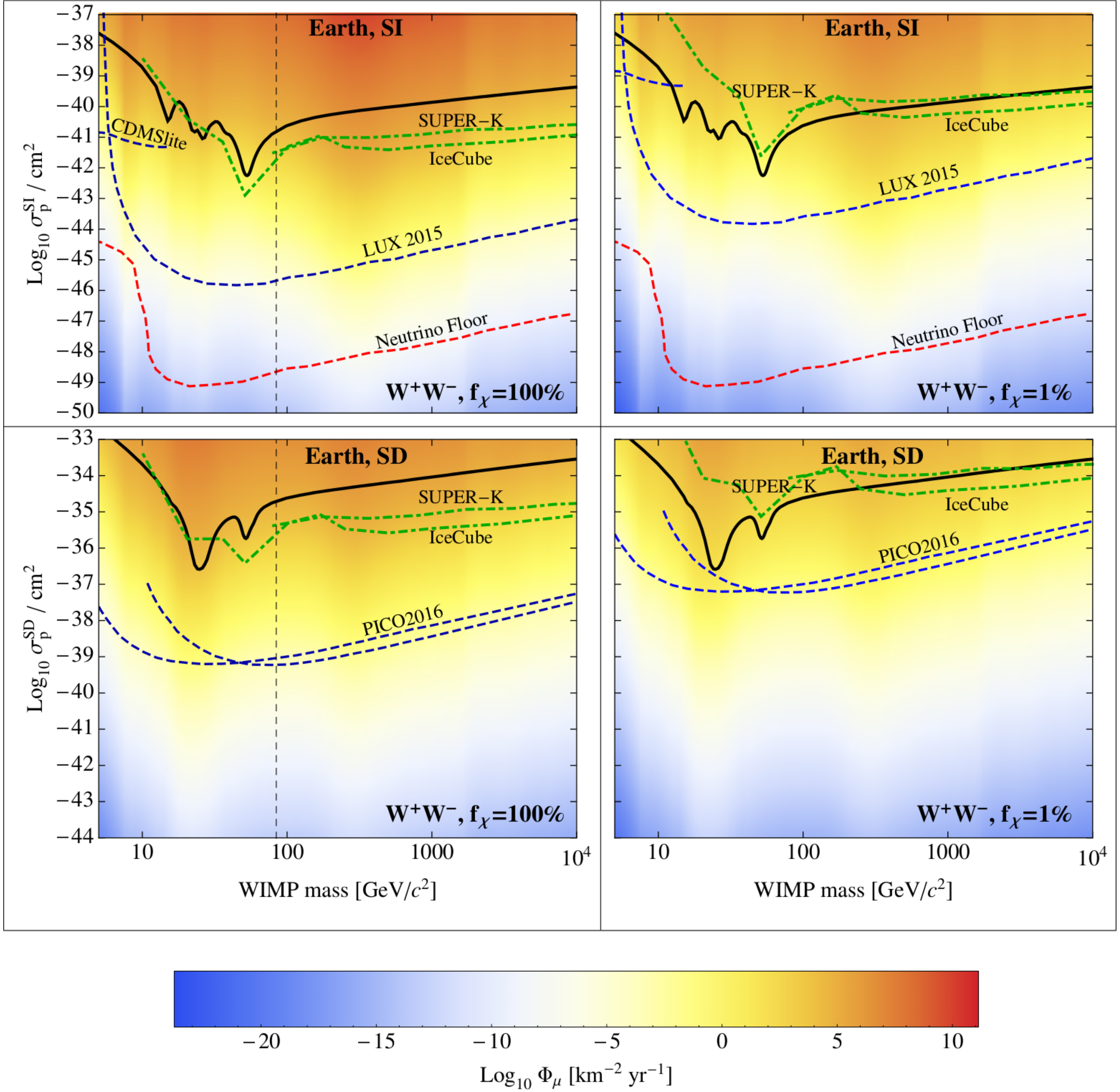


Sun, SI
CDMSlite
LUX 2015
Neutrino Floor
−37
−38
−39
−40
−41
−42
−43
−44
−45
−46
−47
−48
−49
−50
$\mathrm{Log}_{10}\,\sigma_p^{SI}$ / cm^2
10
100
1000
10^4
WIMP mass [GeV/c^2]
−20
−15
−10
−5
0
5
10
$\mathrm{Log}_{10}\,\Phi_\mu$ [km^{-2} yr^{-1}]


Sun, SI
CDMSlite
SUPER−K
SUPER−K
IceCube
LUX 2015
Neutrino Floor
$\mathrm{Log}_{10}\,\sigma_p^{SI}$ / cm^2
WIMP mass [GeV/c^2]
$\mathrm{Log}_{10}\,\Phi_\mu$ [km^{-2} yr^{-1}]



Sun, SI
Sun, SI
CDMSlite
SUPER−K
IceCube
LUX 2015
Neutrino Floor
W⁺W⁻, fχ=100%
W⁺W⁻, fχ=1%
Sun, SD
Sun, SD
PICO2016
$\mathrm{Log}_{10}\,\sigma_p^{SI}$ / cm^2
$\mathrm{Log}_{10}\,\sigma_p^{SD}$ / cm^2
WIMP mass [GeV/c^2]
$\mathrm{Log}_{10}\,\Phi_\mu$ [km^{-2} yr^{-1}]


Earth, SI
Earth, SI
Earth, SD
Earth, SD
CDMSlite
SUPER−K
IceCube
LUX 2015
Neutrino Floor
PICO2016
W+W−, fχ=100%
W+W−, fχ=1%
Log10 σp^SI / cm^2
Log10 σp^SD / cm^2
WIMP mass [GeV/c^2]
Log10 Φμ [km^−2 yr^−1]

What's new?

Effect of subdominant WIMP DM on WIMP capture and annihilation (bounds on indirect detection cross section)

$$\Phi_\mu \propto \begin{cases} \langle \sigma\, v\rangle_{\rm ann} \left(\sigma_p^s\right)^2 f_\chi^2 \propto \left(\sigma_p^s\right)^2 f_\chi & \text{for } t_\odot \lesssim \tau_{\rm ann}, \\ \sigma_p^s\, f_\chi & \text{for } t_\odot \gtrsim \tau_{\rm ann}. \end{cases}$$

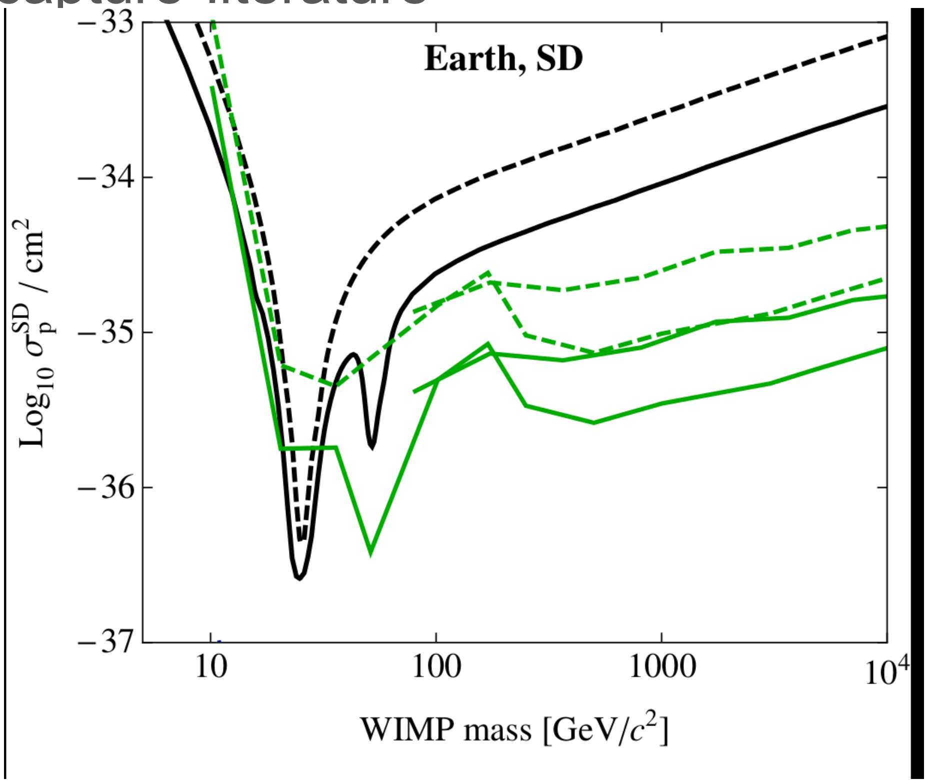
$$\sigma_p^s \propto \begin{cases} f_\chi^{-1/2} & \text{for } t_\odot \lesssim \tau_{\rm ann}, \\ f_\chi^{-1} & \text{for } t_\odot \gtrsim \tau_{\rm ann}, \end{cases}$$

Bounds on direct detection cross section scale as $\sigma_p^s \propto f_\chi^{-1}$

What's new?

Effect of subdominant WIMP DM on WIMP capture and annihilation

Updated chemical composition of the Earth w.r.t. previous capture literature



Main effect from inclusion of ^{55}Mn, ^{25}Mg, and ^{29}Si

Bounds roughly factor three stronger than with 'old' composition

Results shown are valid for:

Vanilla freeze-out production with s-wave annihilation and no significant contribution from co-annihilation

Isospin conserving WIMP-proton interactions

Nuclear Form Factors used: Helm for SI, thin-shell approximation for SD (other form-factor models lead to ~10 % changes)

Maxwellian WIMP velocity distribution boosted to the Solar System frame

WIMP thermalization time-scales much shorter than the capture time-scales

Conclusions

WIMP capture and annihilation in massive bodies may yield detectable neutrino signals

Yields strongest current bounds on SD interactions from capture and annihilation in the Sun

Complimentary search channel to direct detection, collider searches and other indirect detection methods (different systematics!)

Bounds from capture in the Earth on SD scattering cross-section improved by ~factor 3

Interesting channel for sub-dominant WIMP DM. Scaling behaviour is as simple (but different) as for direct & other indirect detection techniques