Neutrinos as a signal for dark matter

Joakim Edsjö
Oskar Klein Centre for Cosmoparticle Physics
Stockholm University

edsjo@fysik.su.se

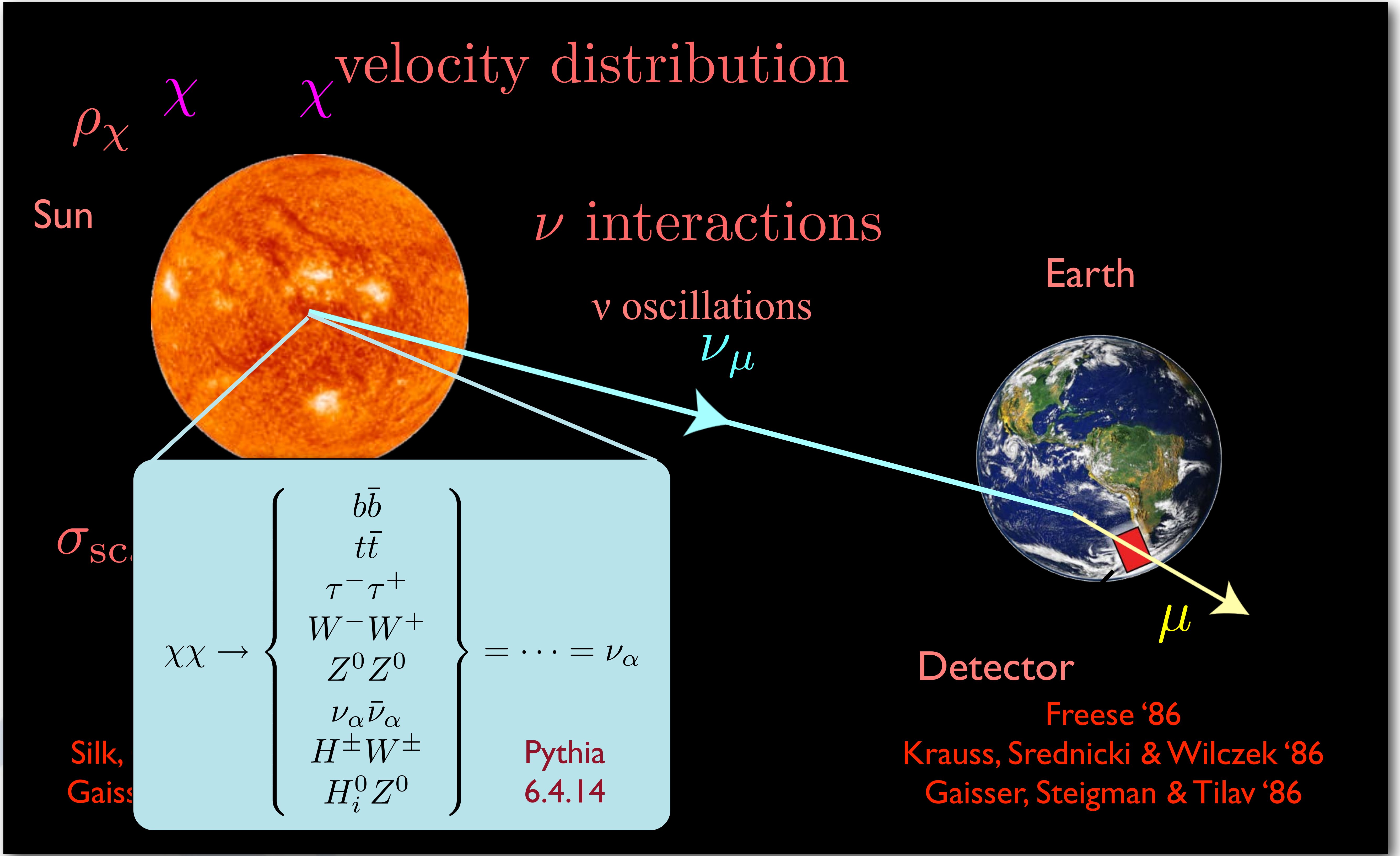
Bethe Forum
November 15, 2011

Neutrinos from dark matter

- Neutrinos from dark matter annihilation in the Sun
- Neutrinos from dark matter annihilations in the Earth
- Neutrinos from dark matter annihilations in the galactic halo

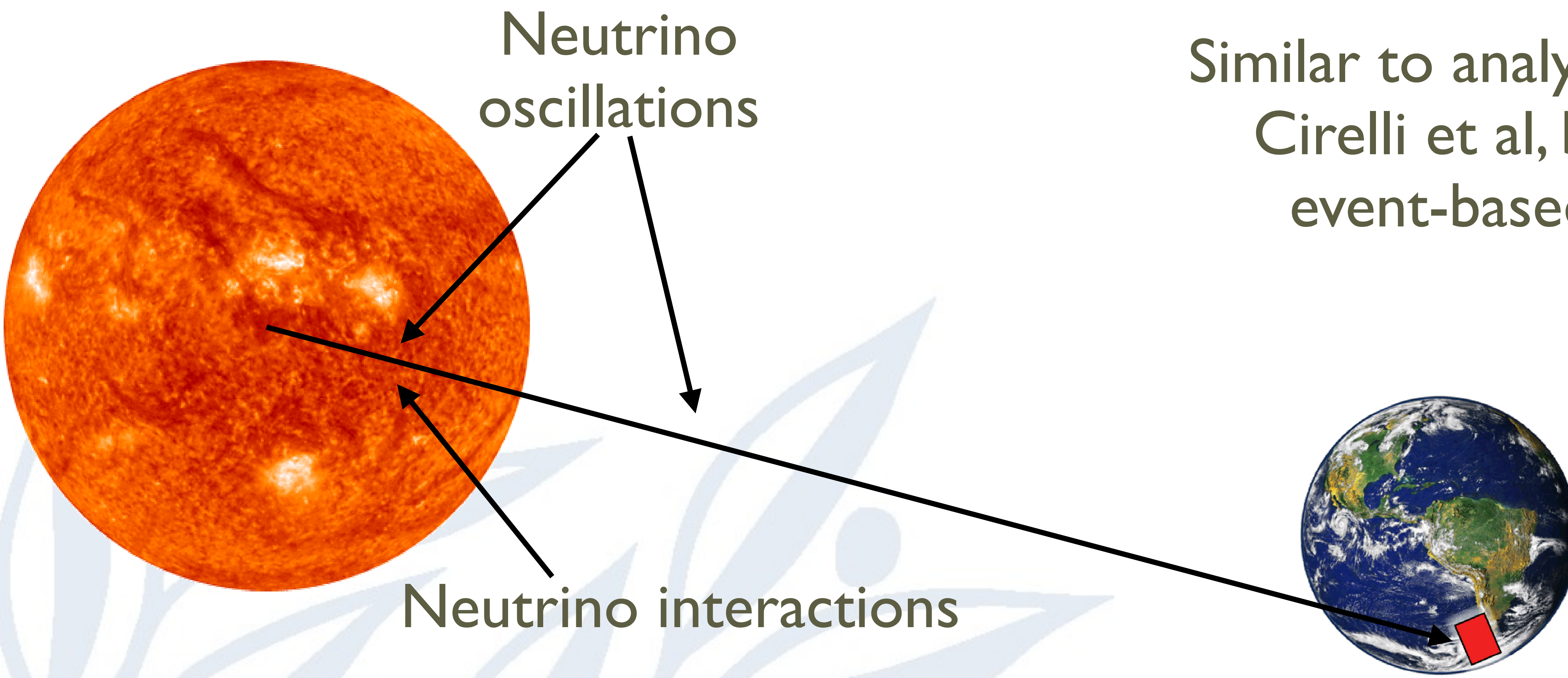
Will focus mostly on the first two

WIMP Capture



M. Blennow, J. Edsjö and
T. Ohlsson, JCAP01 (2008) 021

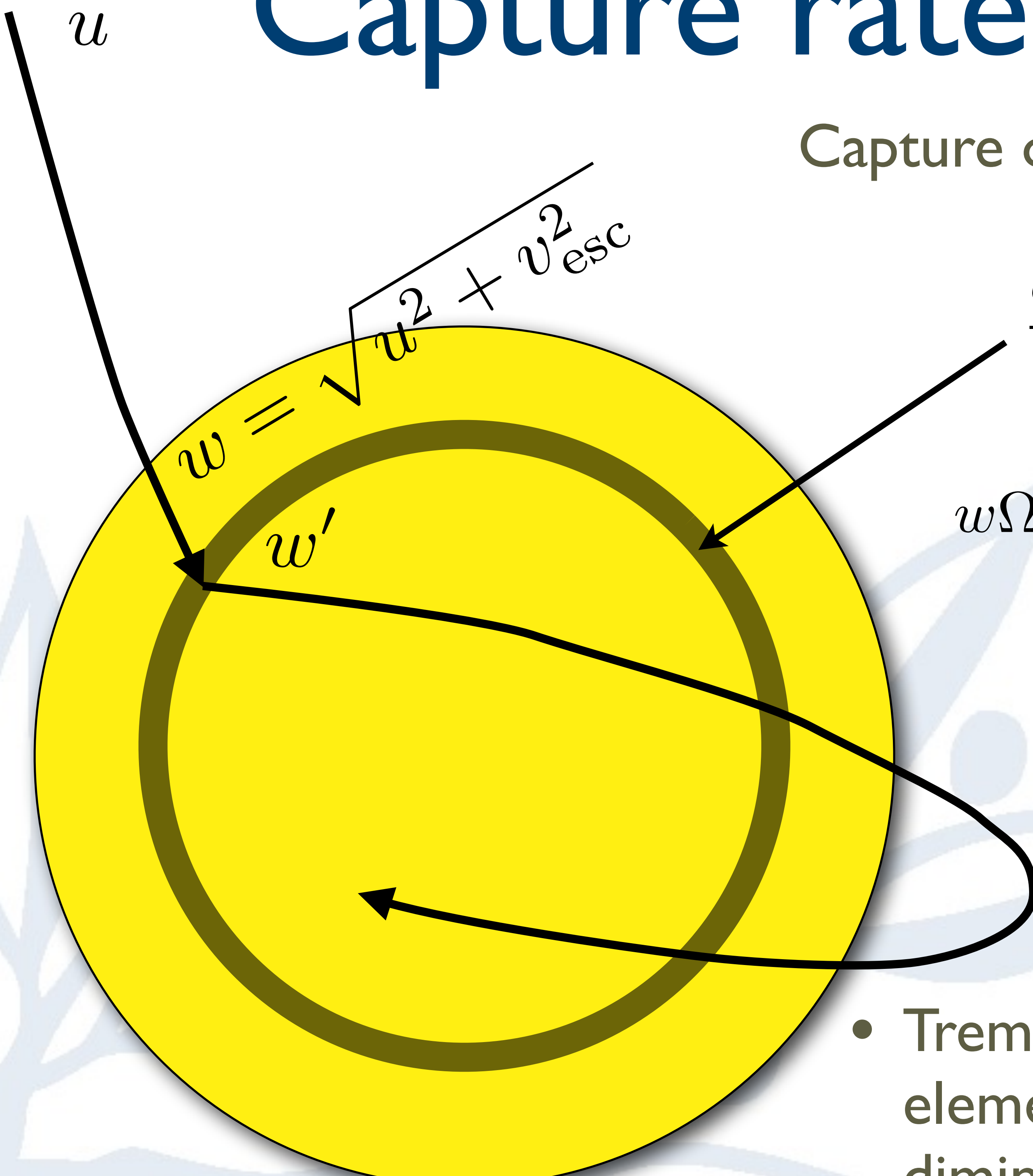
Neutrino oscillations



Similar to analysis of Cirelli et al, but event-based.

- New numerical calculation of interactions and oscillations in a fully three-flavour scenario. Regeneration from tau leptons also included.
- **Publicly available code:** WimpSim: WimpAnn + WimpEvent suitable for event Monte Carlo codes: www.physto.se/~edsjo/wimpsim
- Main results are included in DarkSUSY.

Capture rate calculation



Capture on element i in volume element

$$\frac{dC_i}{dV} = \int_0^{u_{max}} \mathrm{d}u \frac{f(u)}{u} w\Omega_{v,i}(w),$$

$$w\Omega_{v,i} \propto \sigma_{\chi i} n_i(r) P(w' < v_{\rm esc})[\text{FF suppr.}]$$

~A^2 ~A^2

~A^4

- Tremendous enhancements for heavy elements in the Sun. The form factor diminishes it somewhat though by reducing the first A^2.
- Low velocity WIMPs are easier to capture.

Neutrino Telescopes

Capture and annihilation

Evolution equation

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

Solution

$$\Gamma_A = \frac{1}{2} C \tanh^2 \frac{t}{\tau}$$

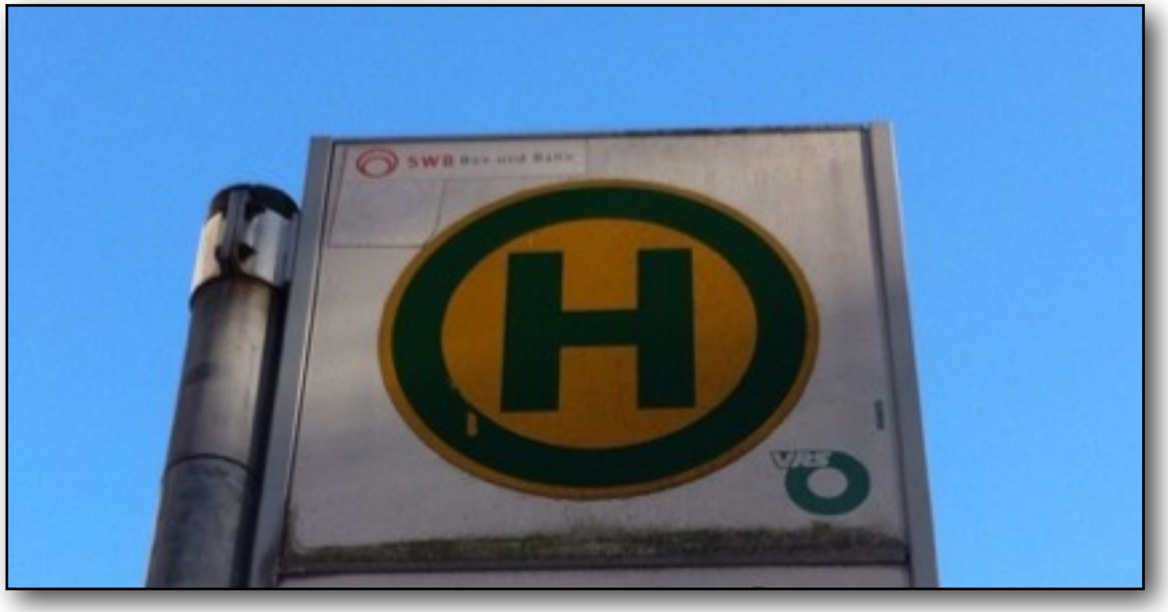
$$\tau = \frac{1}{\sqrt{C C_A}}$$

Dependencies

$$C \quad \sim \quad \begin{cases} f(v), \rho_\chi, \sigma_{\rm scatt}, \\ \text{composition of Earth/Sun} \end{cases}$$

$$C_A \quad \sim \quad \sigma_{\rm ann}, \rho(r) \text{ in Earth/Sun}$$

Capture details



- Traditionally, these type of calculations were carried out as if the Earth and the Sun was in free space ignoring effects of the planets, but for precise calculations,
  - We need to include the effects of the planets for solar capture
  - We need to include the effects of the Sun and the planets for Earth capture

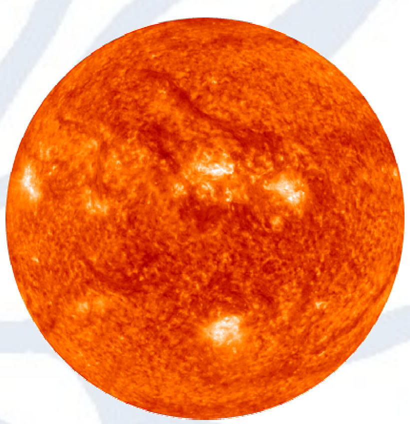
DM diffusion in the solar system

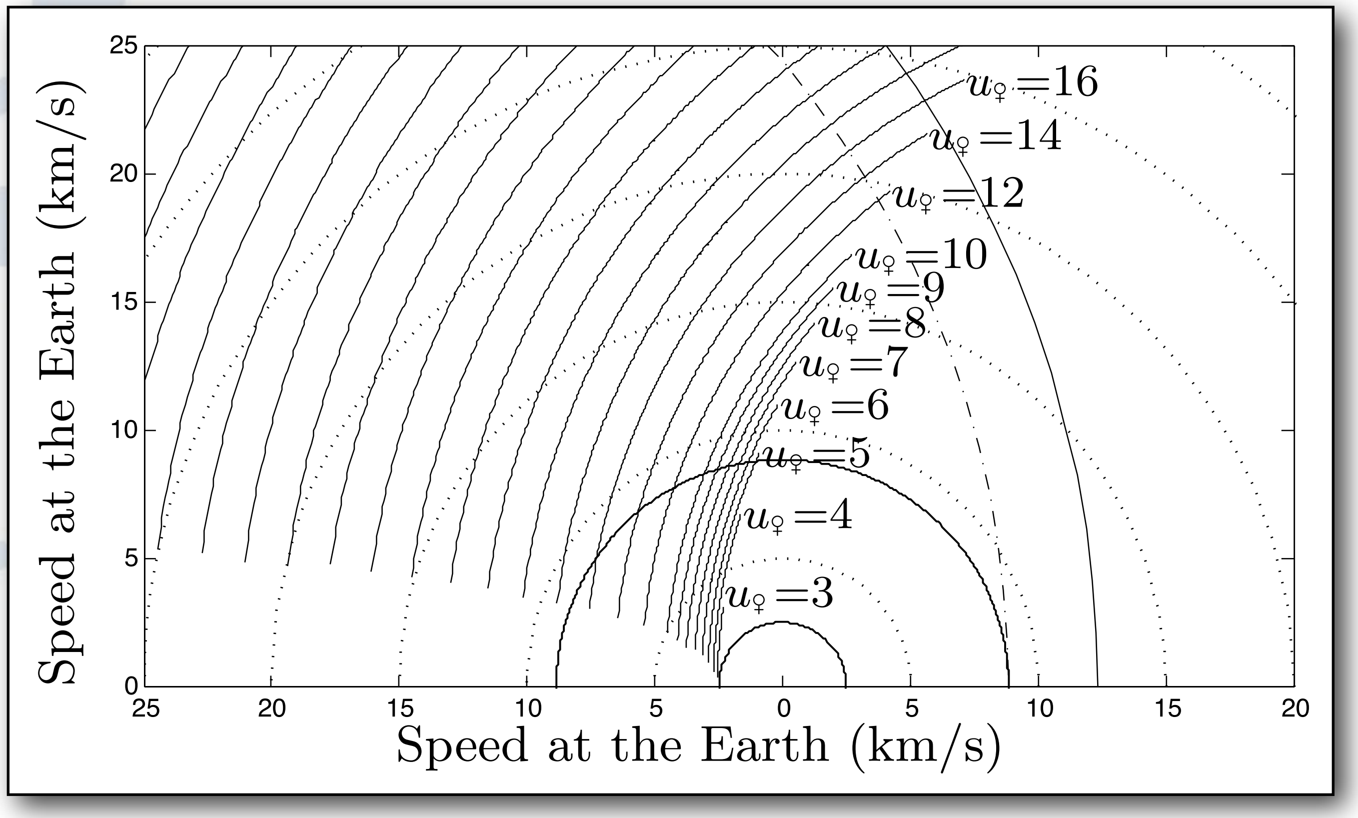
- DM particles are affected by the Sun and the planets (gravitational diffusion) in the course of being captured.
- See Gould '91, Lundberg & Edsjö '04 and Peter '09 for more details

Diffusion by planets, e.g. Jupiter

- In **Jupiter**'s frame of reference: w=w'

- In the **Sun**'s frame of reference, w'≠w (since Jupiter is moving) and it could happen that w'<$v_{esc, solar\ system}$, i.e. that the WIMP is now gravitationally bound to the solar system.





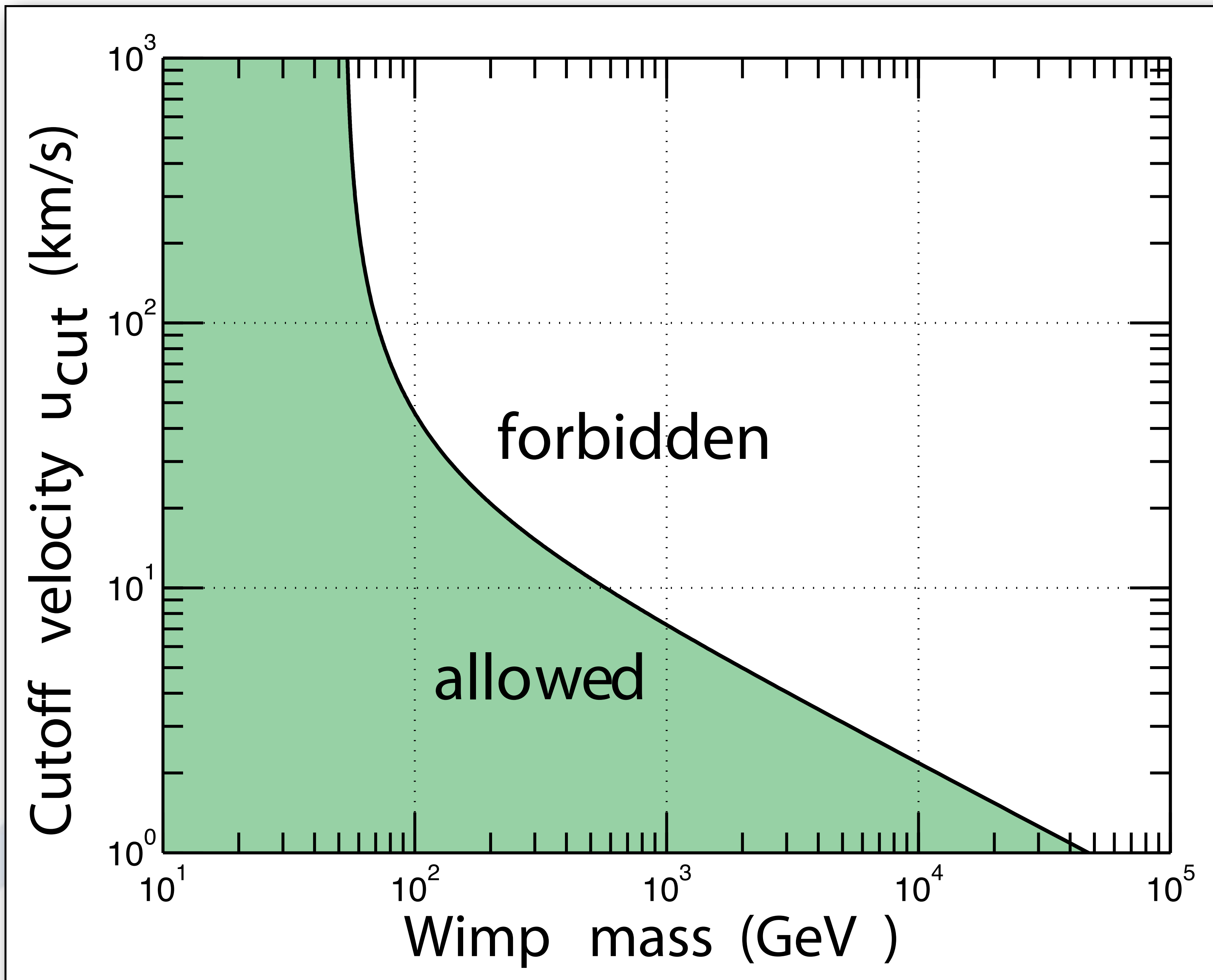
Main ingredients in Lundberg & Edsjö (2004) gravitational diffusion

- Numerical simulations of WIMP diffusion in the solar system
- Included diffusion with Earth and Jupiter and added Venus by hand.
- Included effects of solar depletion (big effect)

Earth Capture

Why are low velocities needed?

- Capture can only occur when a WIMP scatters off a nucleus to a velocity less than the escape velocity

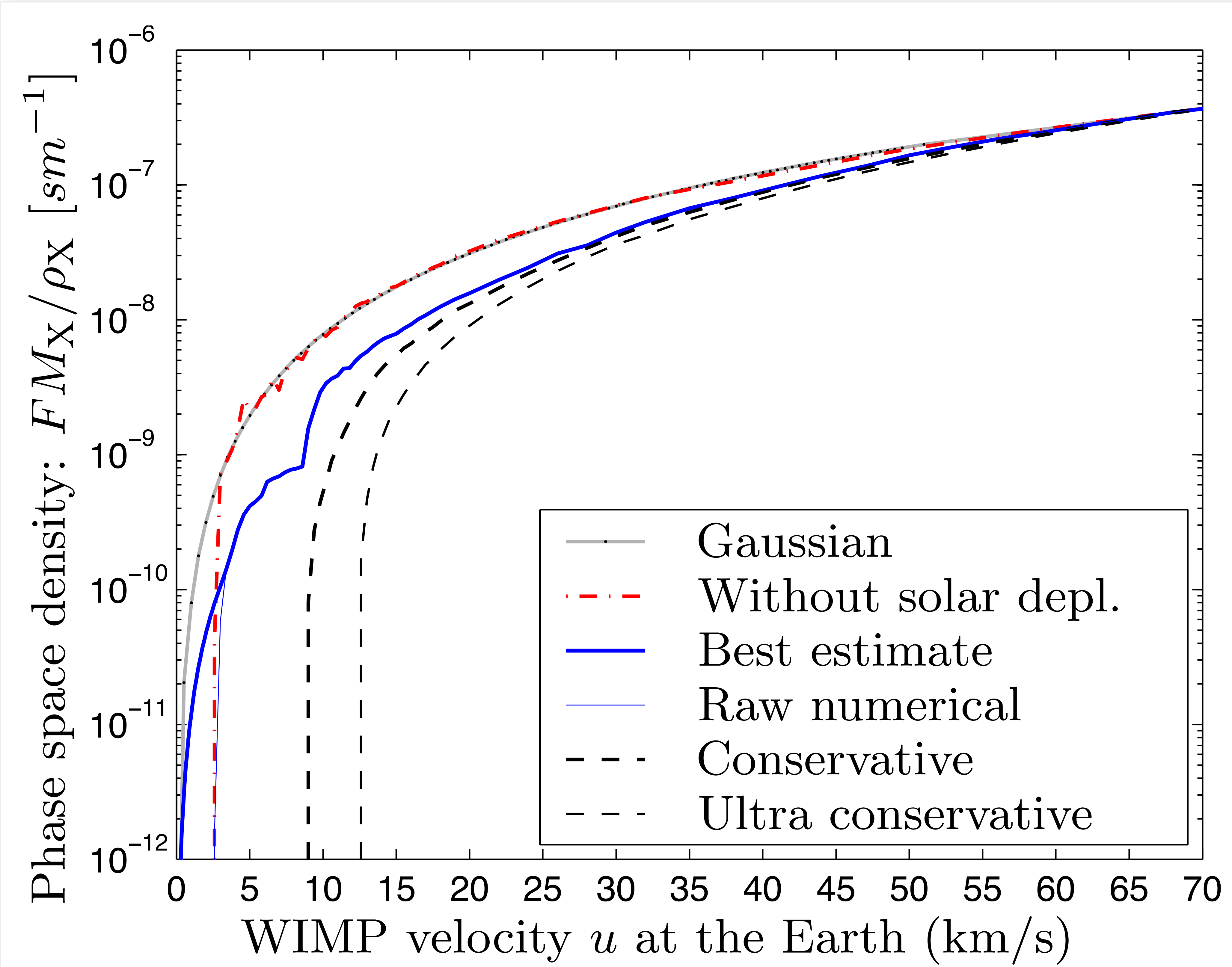


For capture on Fe, we can only capture WIMPs if the velocity is lower than

$$u_{\rm cut} = 2\frac{\sqrt{M_\chi M_{Fe}}}{M_\chi - M_{Fe}} v_{\rm esc}$$

or, alternatively, for a given lowest velocity, we can only capture WIMPs up to a maximal mass.

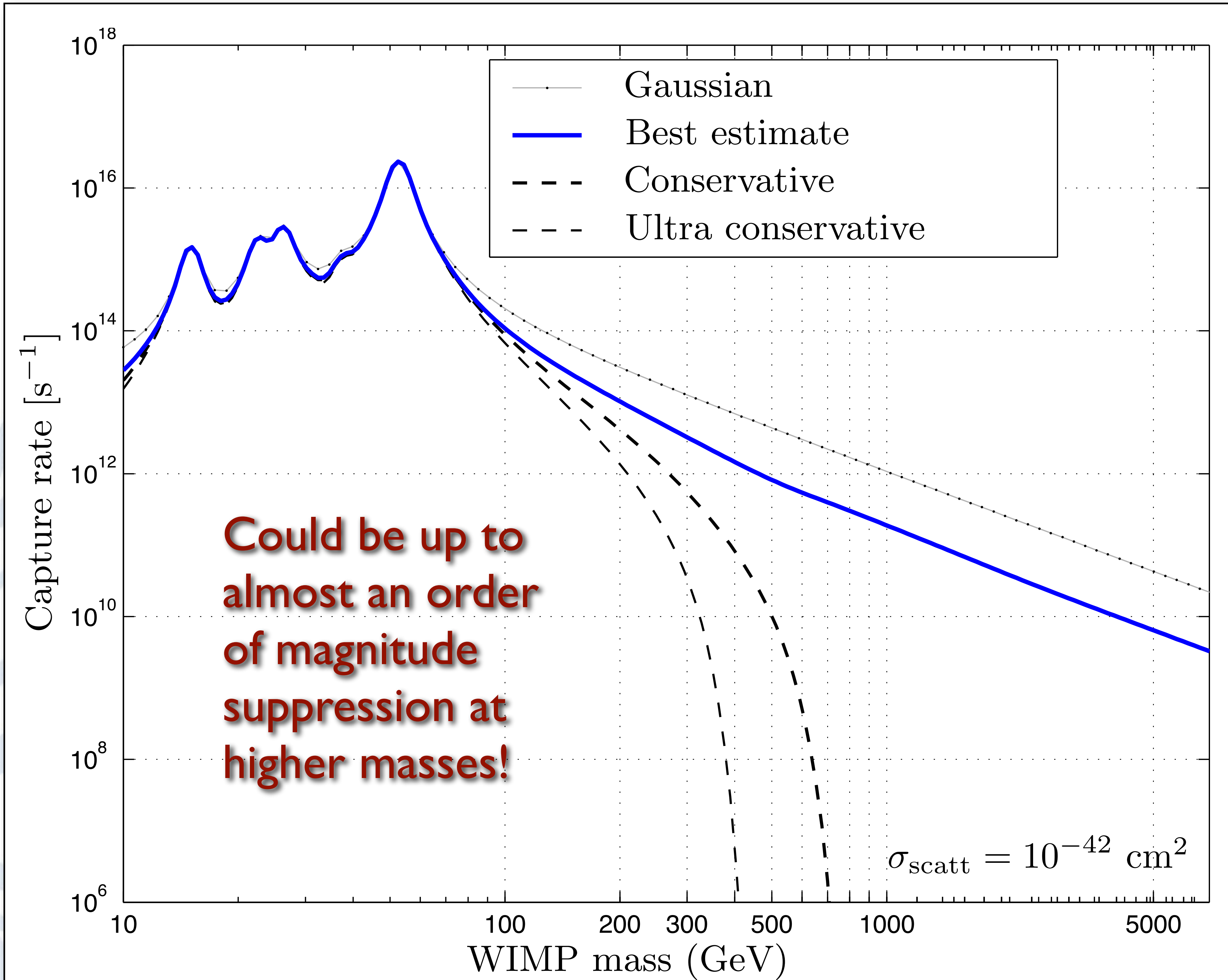
Velocity distribution at Earth



- Without solar capture, Gould's results of 'capture as in free space' are confirmed.
- Including solar capture, we get a significant suppression at low velocities, not as bad as initially thought, but still significant

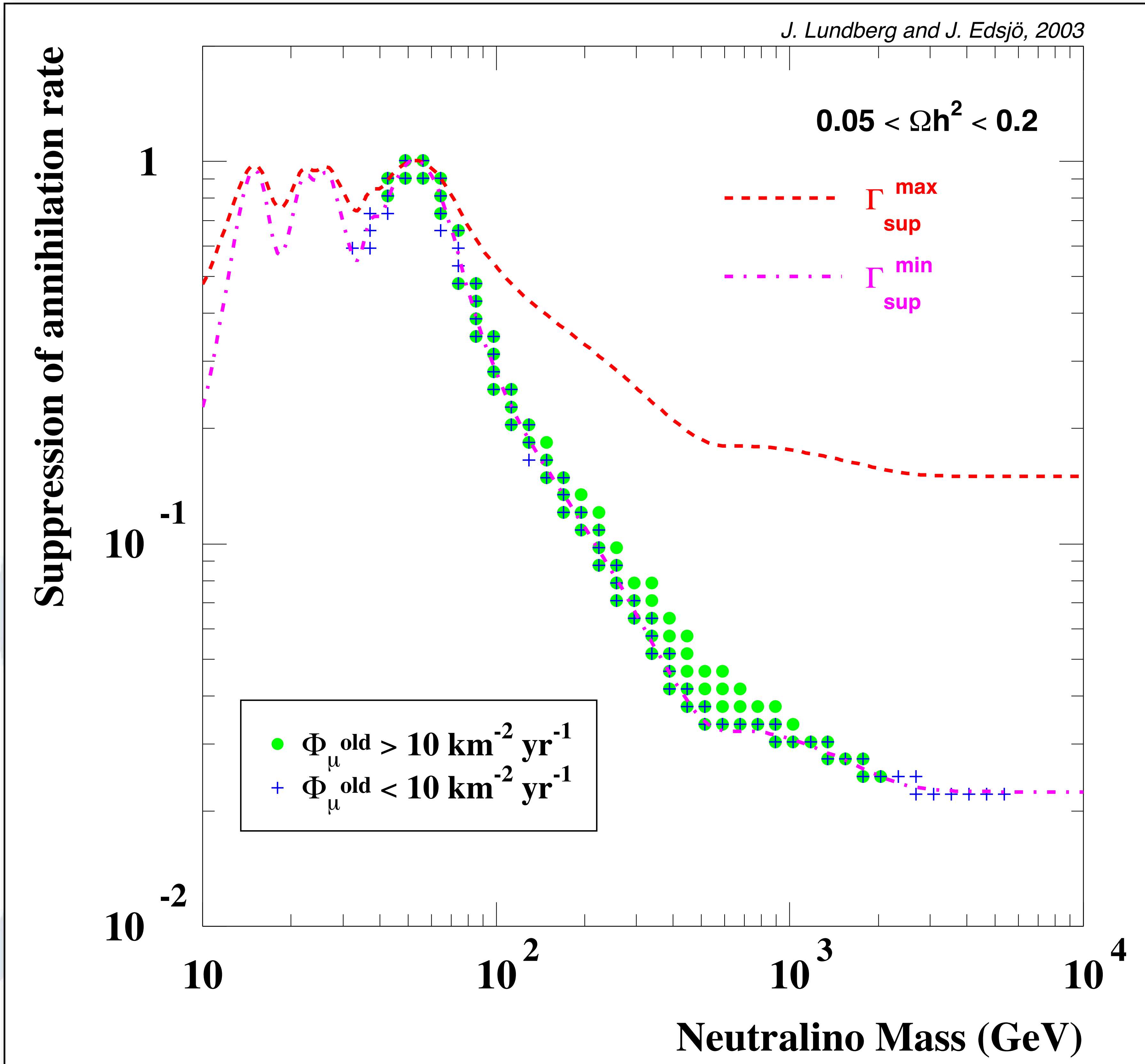
Lundberg & Edsjö, '04

Earth capture rates



Lundberg & Edsjö, '04

Earth annihilation rates



$$\Gamma_A = \frac{1}{2} C \tanh^2 \frac{t}{\tau}$$

Annihilation and capture is not in equilibrium in the Earth

⇩

The annihilation rates may be suppressed by up to almost two orders of magnitude!

Diffusion work by Peter & Tremaine arXiv: 0806.2133 and later

- Full numerical simulations, but only including Jupiter.
- Included effects of Jupiter on WIMPs in the process of being captured by the Sun. This could cause a large reduction in the solar capture for heavy WIMPs.

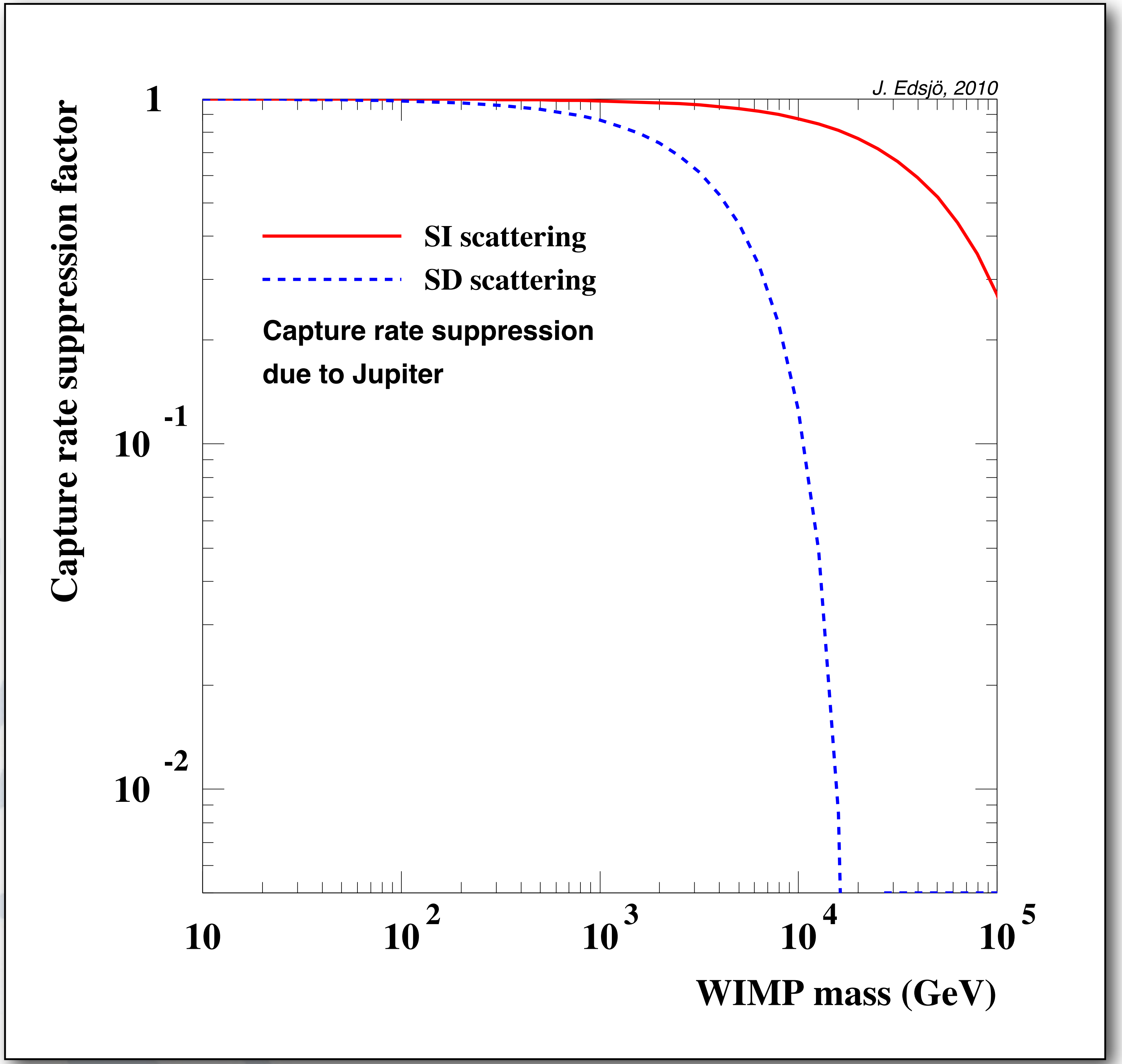
Jupiter effects on solar capture

- Traditionally, if a WIMP scatters to below the escape velocity (at that point in the Sun), it is considered captured.
- Peter & Tremaine showed that if the WIMP after its first scatter reaches out to Jupiter, Jupiter can disturb the orbit so that it no longer passes through the Sun and eventually gets thrown out of the solar system.
- This can reduce the solar capture rate, especially for heavy WIMPs

Jupiter effects - simple approximation

- For typical neutralino WIMPs, a simple approximate method is OK (see Peter, arXiv:0902.1347 for more accurate setups).
  - if a WIMP after its first scatter has a velocity that would not take it out to Jupiter (instead of the escape velocity), we consider it captured.

Jupiter suppression for the Sun



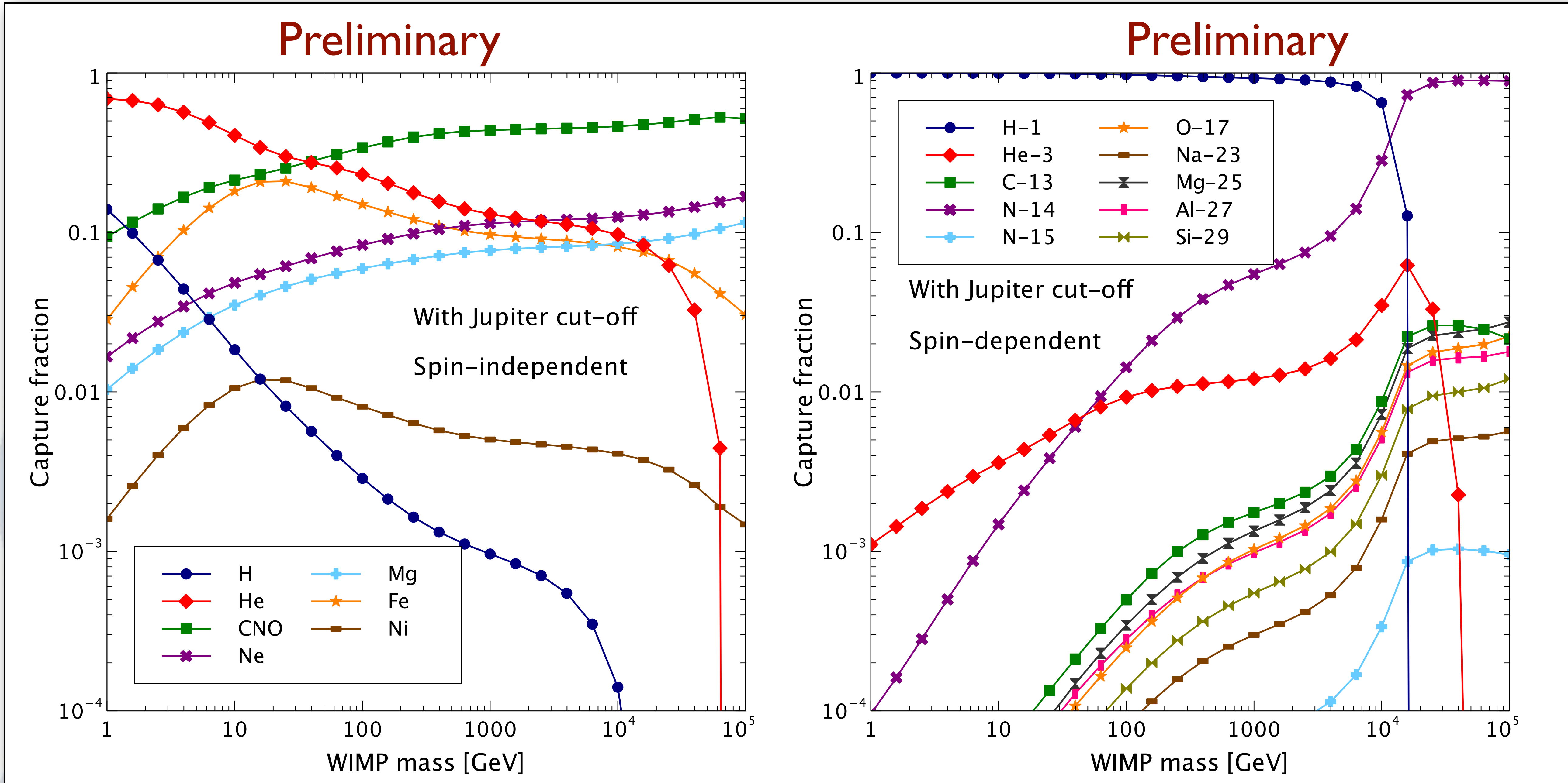
In this figure, for SD scattering only Hydrogen is included.

More elements for SI.

Elements in the Sun

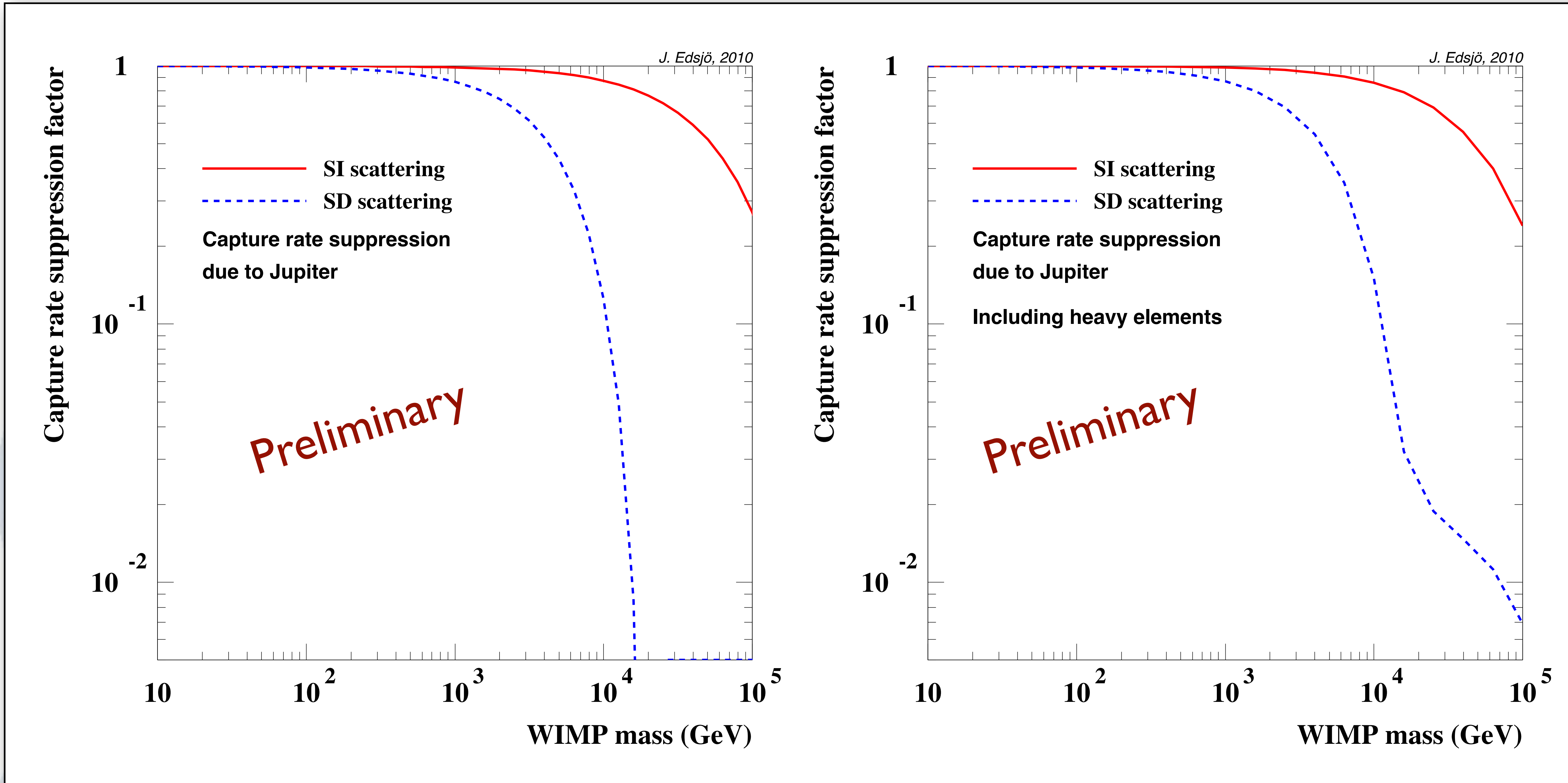
- Traditionally
  - only Hydrogen has been included for SD scattering in the Sun.
  - for SI scattering, the 16 most relevant elements have been included (up to Ni), in some calculations even fewer
- We now use new more accurate abundances of elements (and their isotopes) from Asplund et al and include
  - 112 isotopes up to ^{235}U for SD scattering
  - 289 isotopes up to ^{238}U for SI scattering

More accurate solar abundances



Work in progress to include a "complete" set of elements by Edsjö, Savage, Scott & Serenelli, based on solar models in Asplund et al, 2009

New capture rate suppressions



Work in progress to include a "complete" set of elements by Edsjö, Savage, Scott & Serenelli, based on solar models in Asplund et al, 2009

Current status of WIMP diffusion

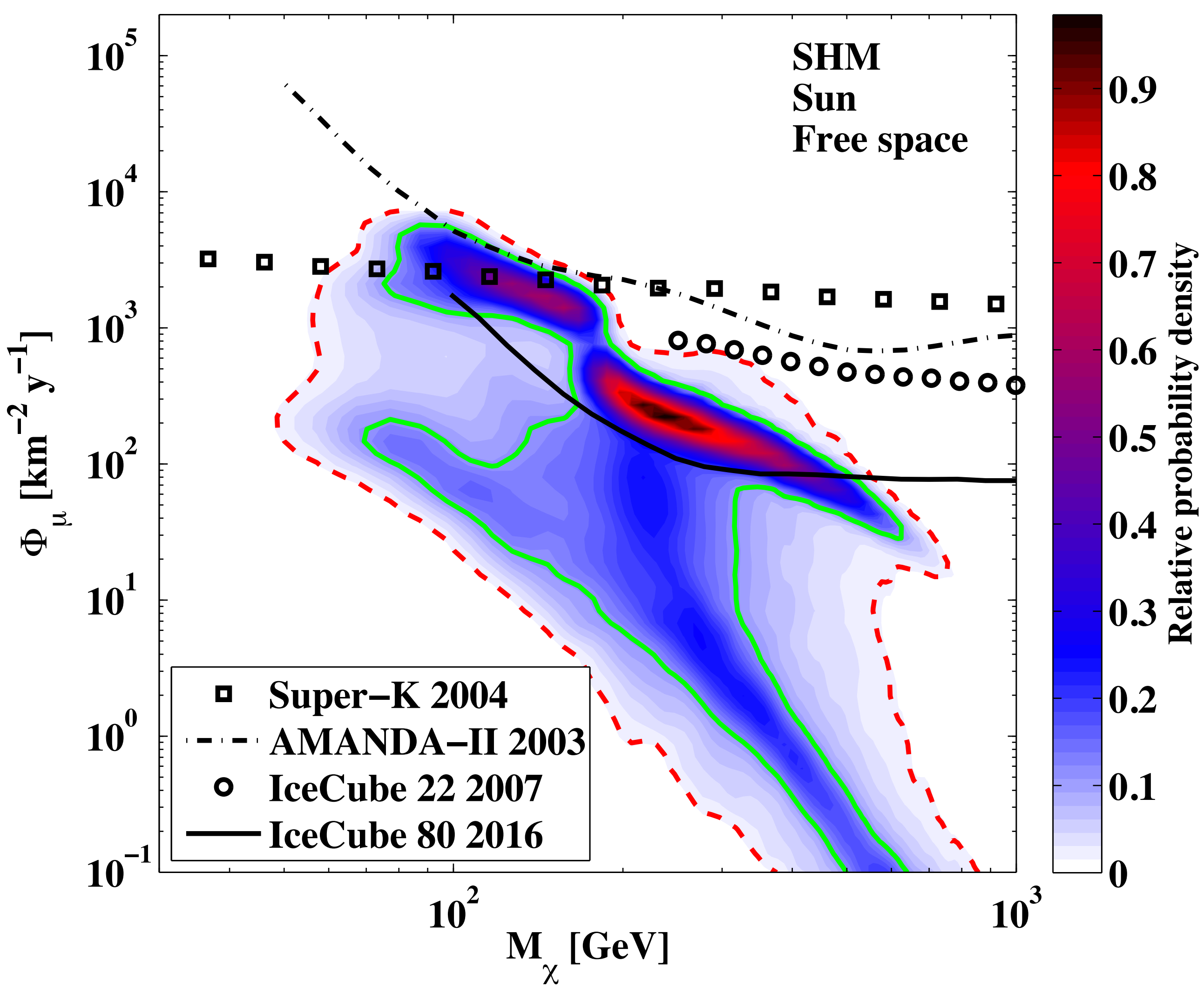
- Best available simulations so far by Annika Peter ('09).
- Compared to Lundberg & Edsjö ('04), she
  - only includes Jupiter, but
  - does a more sophisticated treatment of solar depletion (does not see an as large effect as in Lundberg & Edsjö)
- More accurate simulations needed that take more planets into account (really hard!)

Effects of dark disk

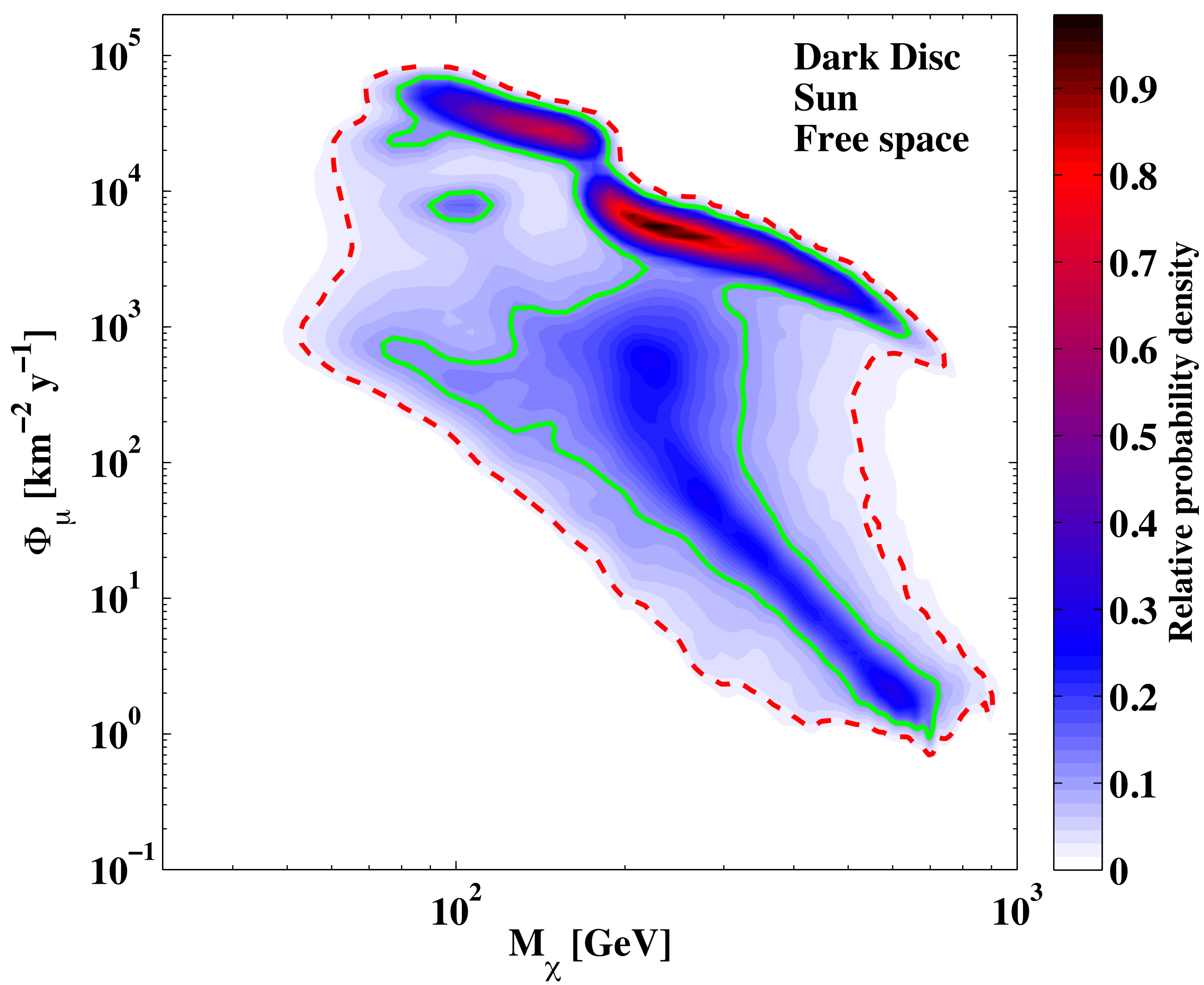
- It has been suggested (Read et al, '08) that as massive satellites fall into the Milky Way, their dark matter preferentially ends up in a dark disk, co-rotating with the stars
- If so, these dark matter particles move slowly with respect to the solar system, and are easier to capture (both by the Sun and by the solar system via gravitational diffusion) than regular halo dark matter

Effects on solar fluxes

Without dark disk



With dark disk

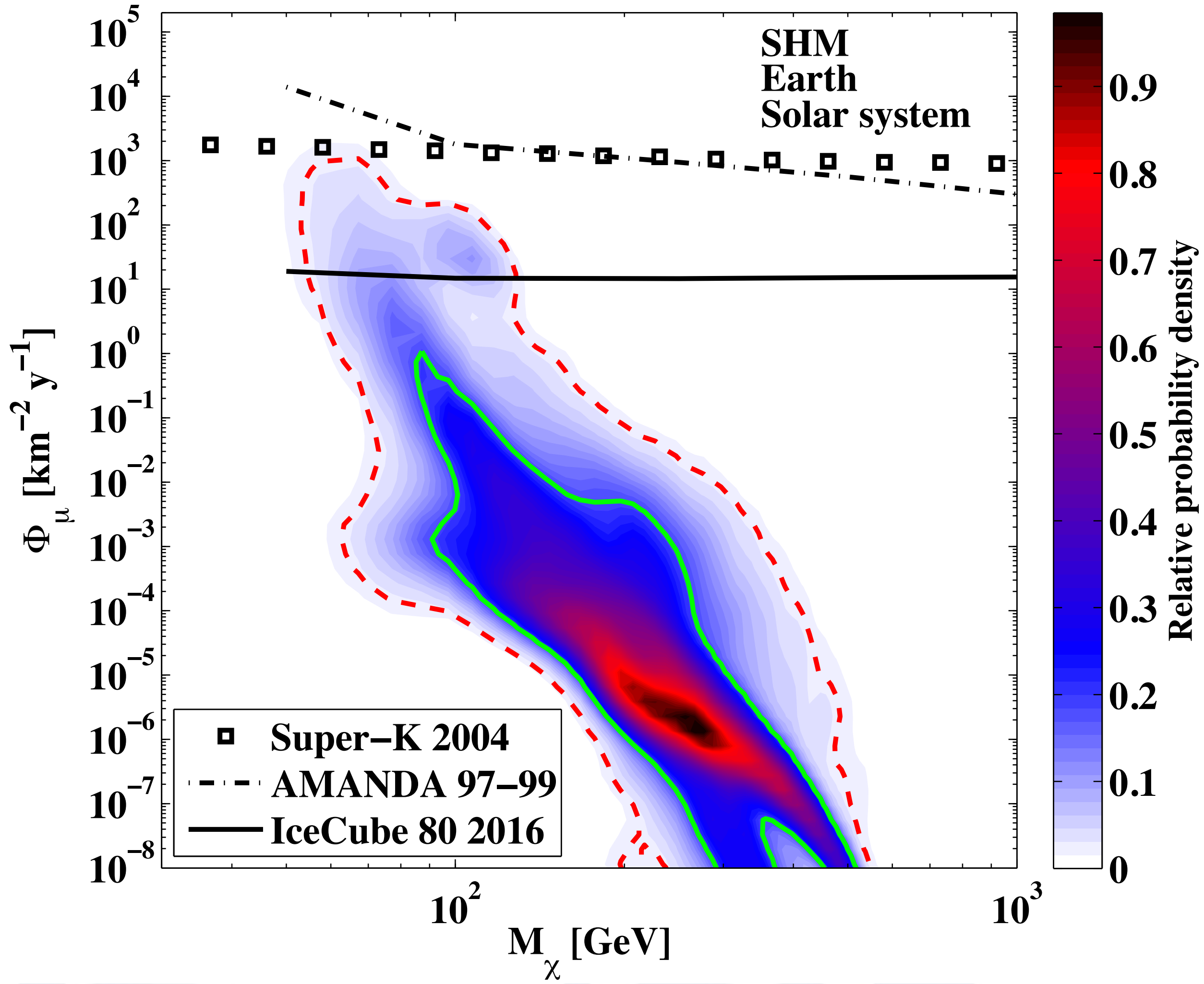


Fluxes from the Sun can be enhanced by up to one order of magnitude

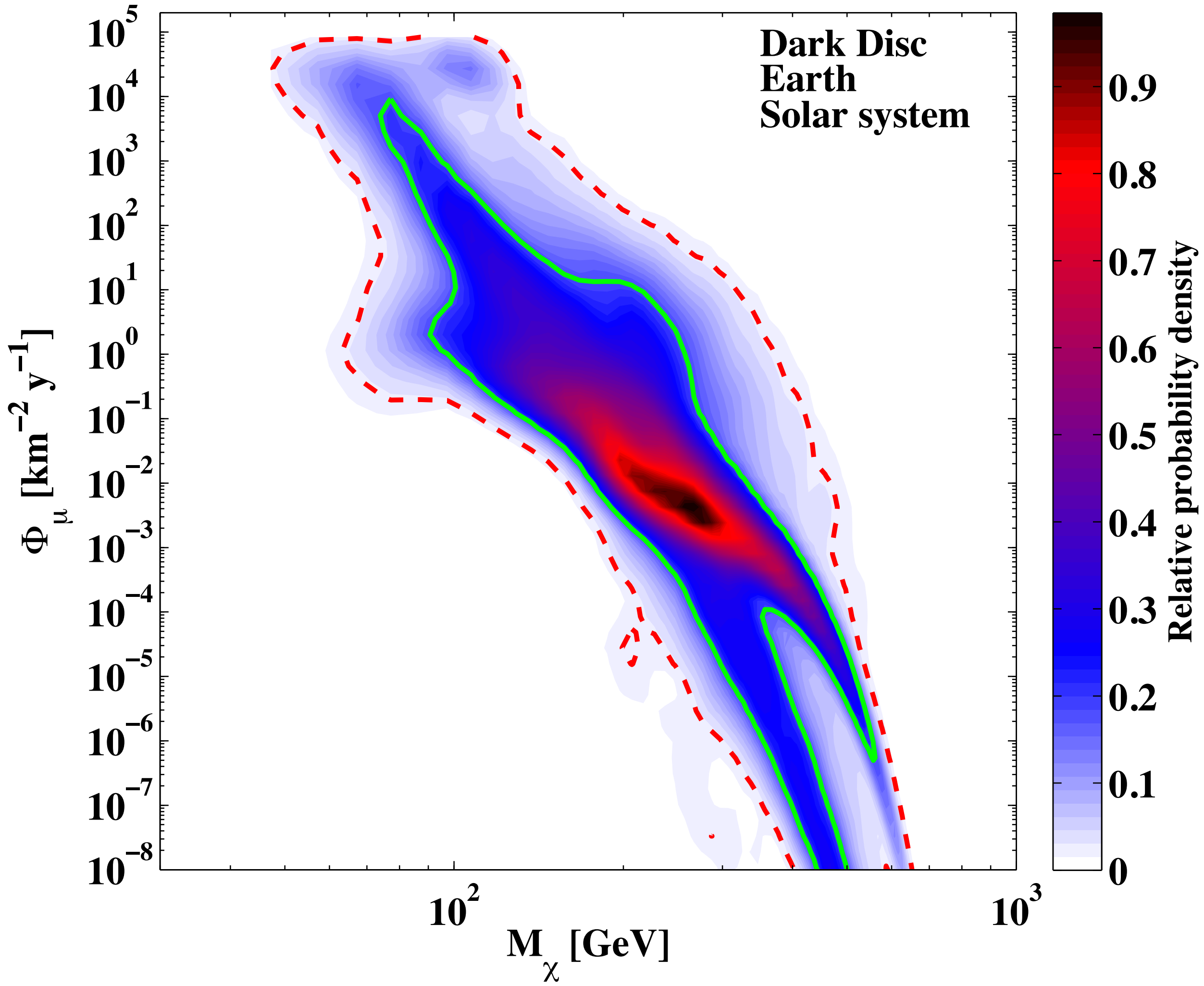
Bruch et al, arXiv:0902.4001

Effects on Earth fluxes

Without dark disk



With dark disk



Fluxes from the Earth can be enhanced by up to three orders of magnitude

Bruch et al, arXiv:0902.4001

Dark disk comments

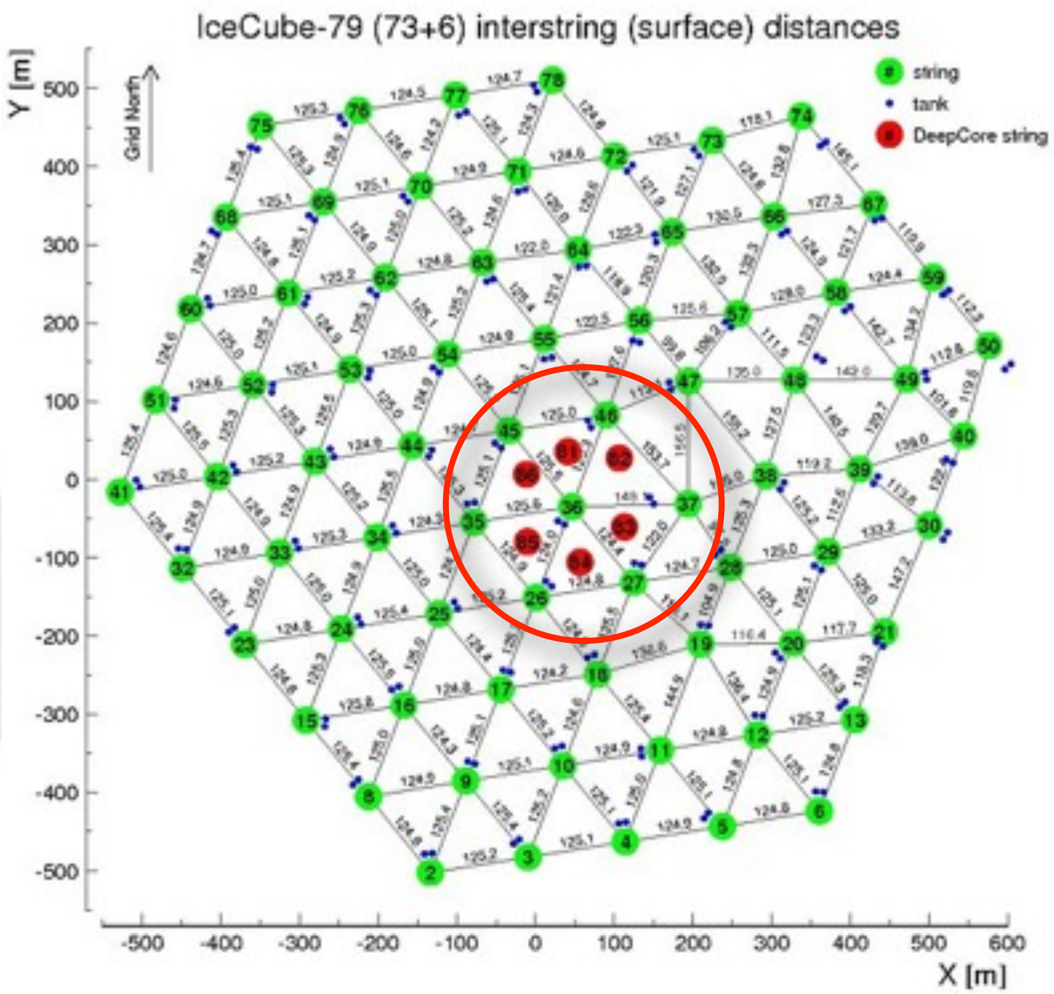
- Could give dramatic enhancements for neutrino rates from the Sun (x10) and the Earth (x1000).
- However, these enhancements depend crucially on the unknown properties of the dark disk
- Direct detection rates are not affected as much, as the dark disk gives low recoil energies, buried in the background
- Halo stars constrain the density of the disk and it seems that the density cannot be too high. (Pestaña & Eckhart, arXiv:1009.0925, Bidin et al, arXiv:1011.1289, Sanchez-Salcedo et al, 1103.4356)

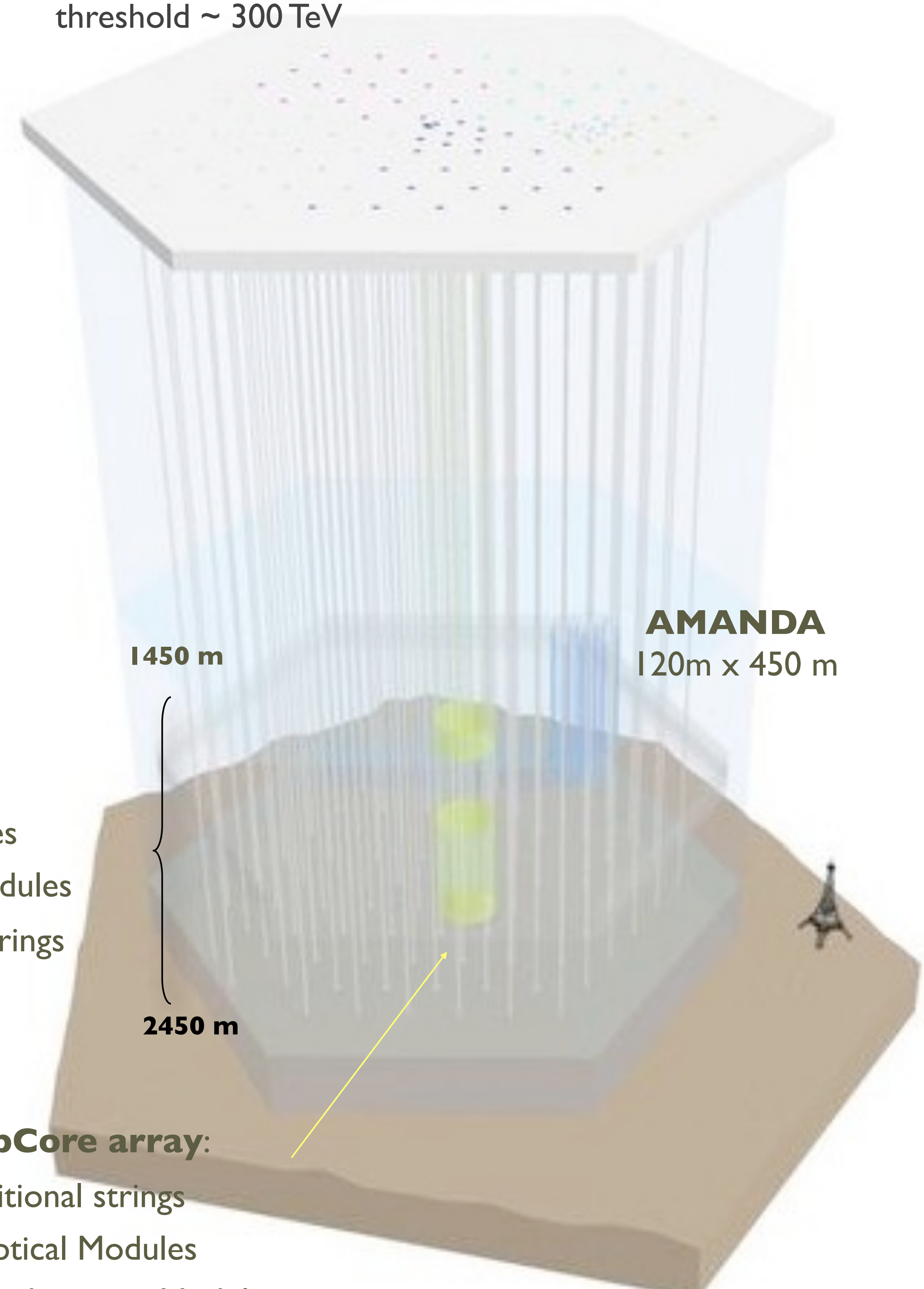
The IceCube Detector

IceTop: Air shower detector

80 stations/2 tanks each

threshold ~ 300 TeV





InIce array:

80 Strings

60 Optical Modules

17 m between Modules

125 m between Strings

DeepCore array:

6 additional strings

60 Optical Modules

7/10 m between Modules

72 m between Strings

IceCube complete - Dec 18 2010

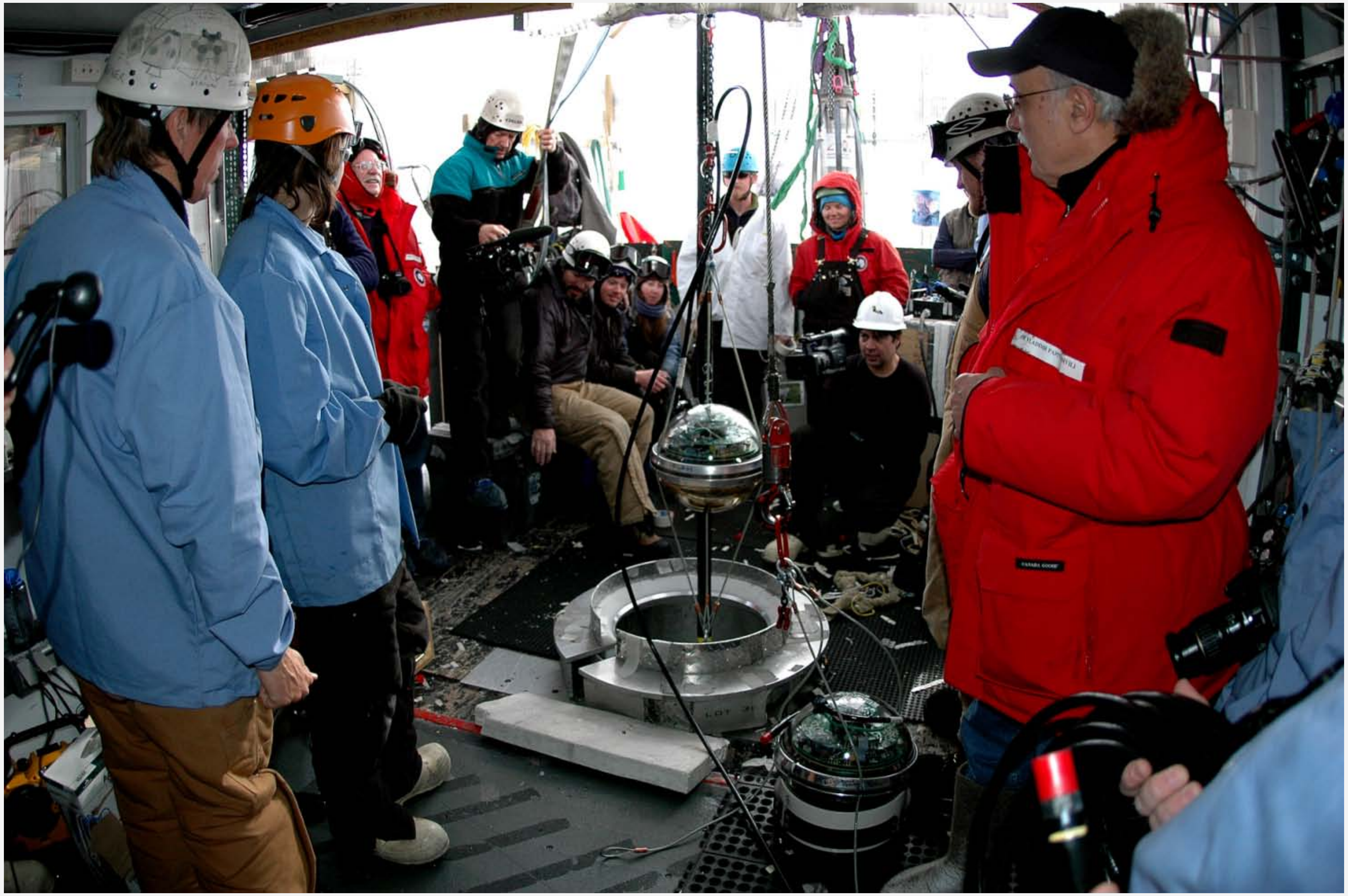
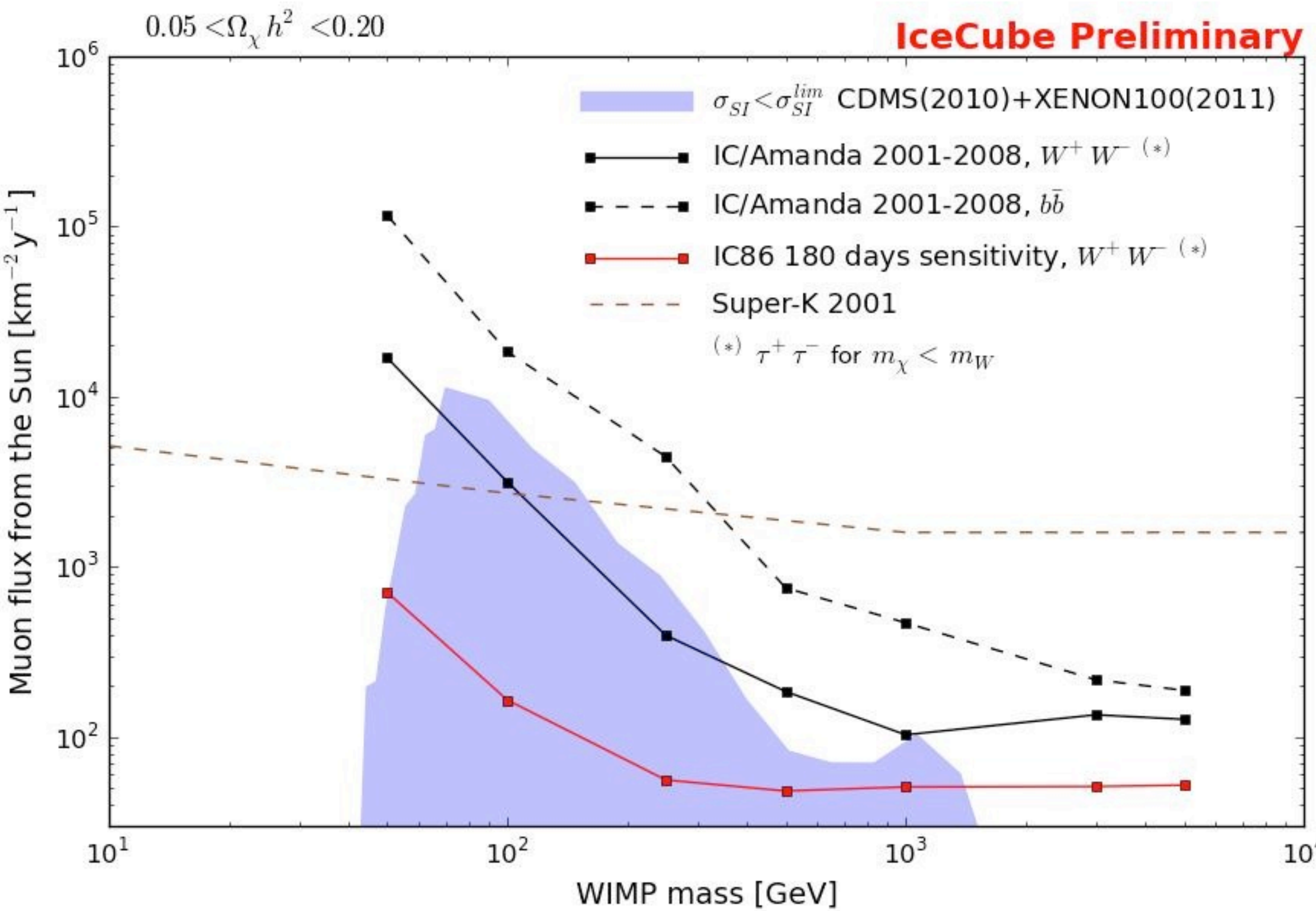


Photo: P. Rejcek, NSF

IceCube collaboration 33 institutions worldwide w. ~250 scientists

IceCube 2001-2008 limits



Spin-dependent direct detection

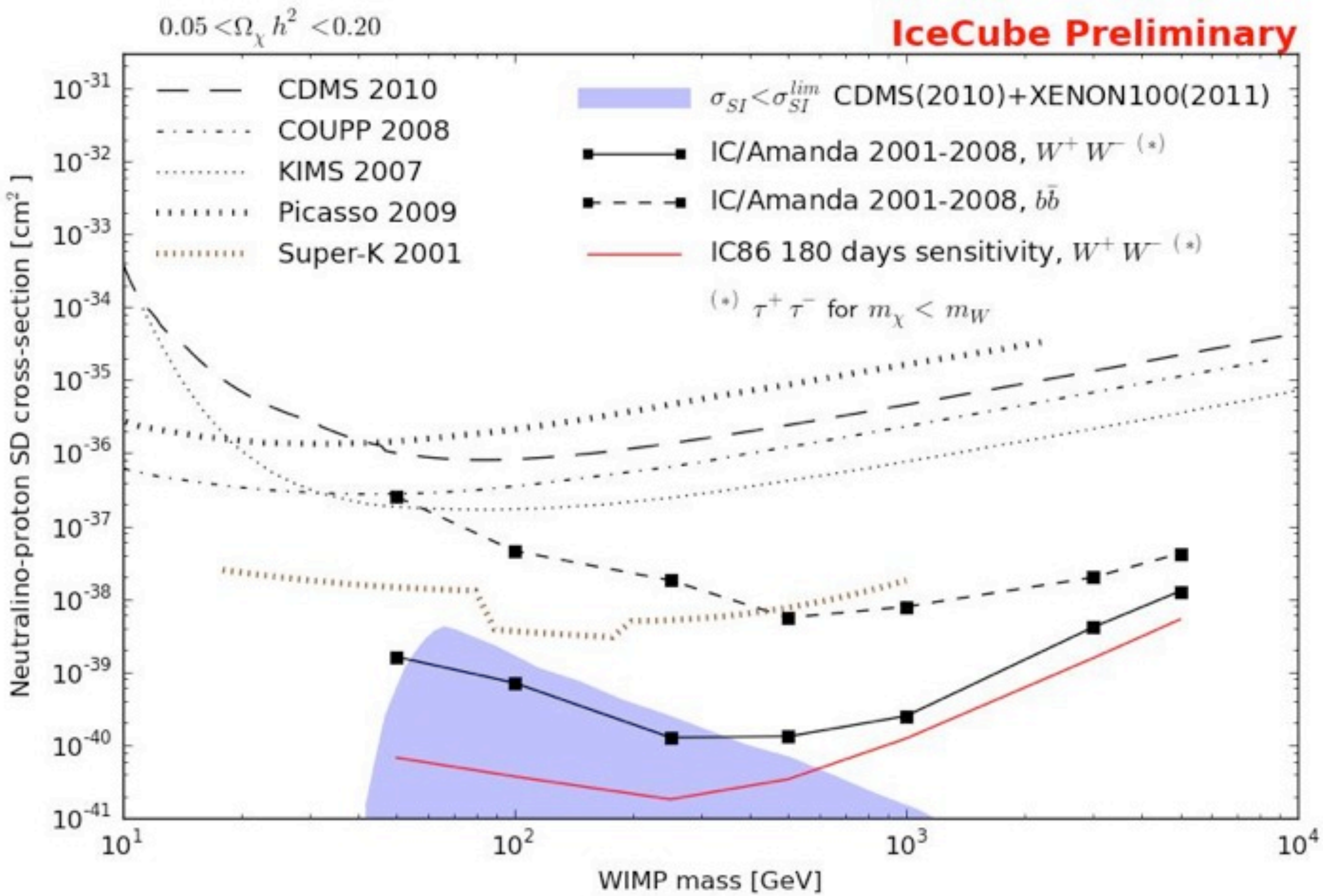
Lab experiments

- COUPP
- PICASSO
- XENON10/100/1T ...
- ...
- Mass: ~ 10 – 1000 kg

Astrophysical experiments

- Neutrinos from the Sun with e.g. IceCube
- Mass (of the Sun): $2 \cdot 10^{30}$ kg

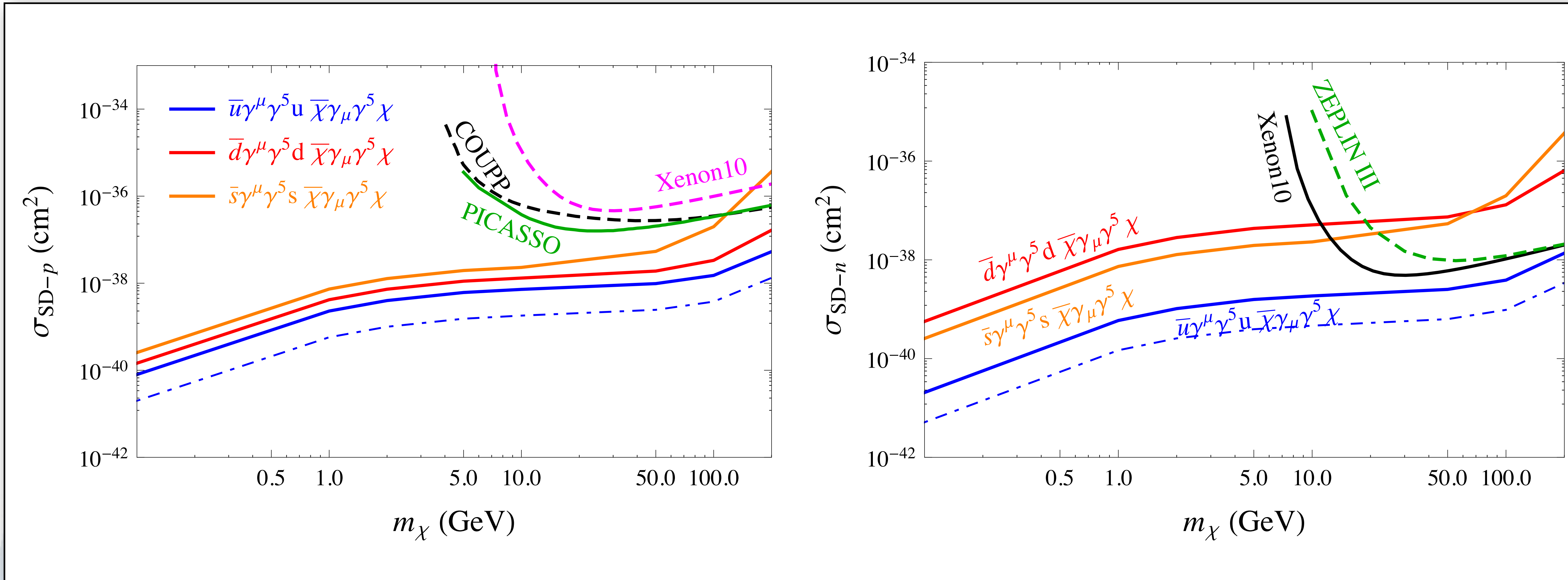
Complementarity between neutrino detectors and direct detection



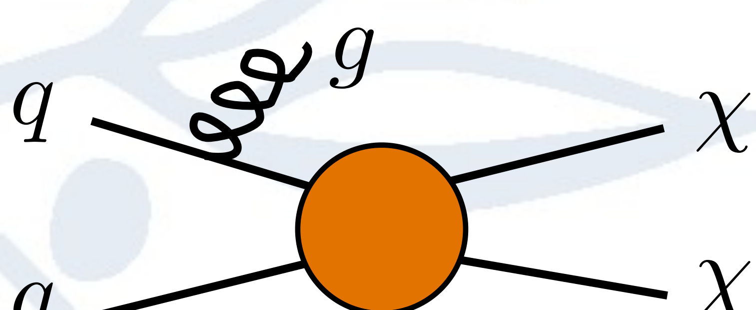
Wikström & Edsjö, arXiv:0903.2986,
see also Serpico & Bertone, arXiv:1006.3268, where relative uncertainties are studied (~factor of two)

- As neutralino capture in the Sun is very efficient for SD scattering, we can place a limit on the SD scattering cross section with neutrino telescopes
- The limits are very competitive compared to direct searches

Tevatron limits

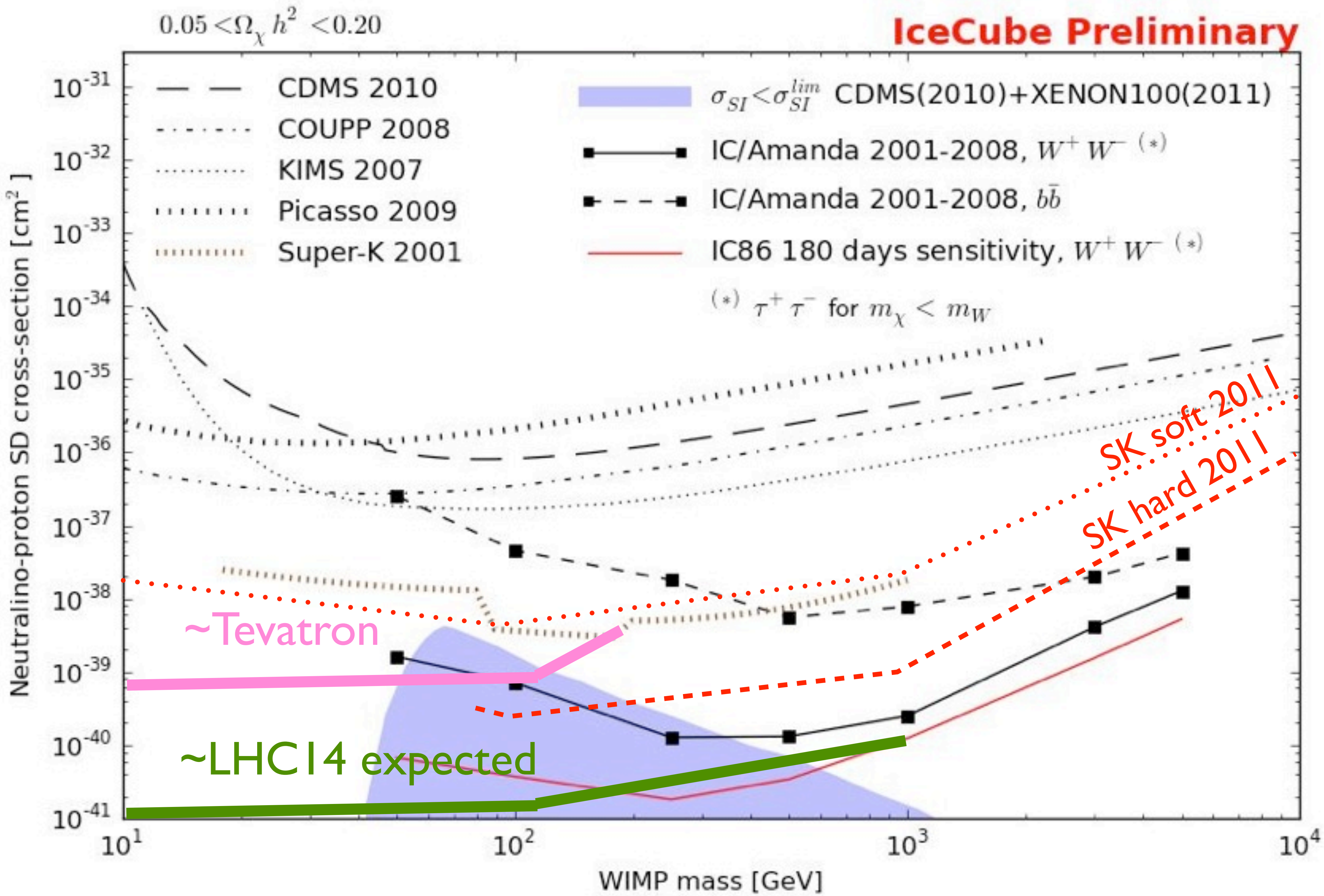


- SD scattering probes WIMP-proton(neutron) coupling. This is the same coupling that appears in p-p-colliders, for WIMP production. The experimental signature is a monojet, arising from initial state radiation



Bai, Fox & Harnik, arXiv:1005.3797.
See also Goodman et al, arXiv:1005.1286
Rajaraman et al, arXiv:1108.1196
Fox et al, arXiv:1109.4398

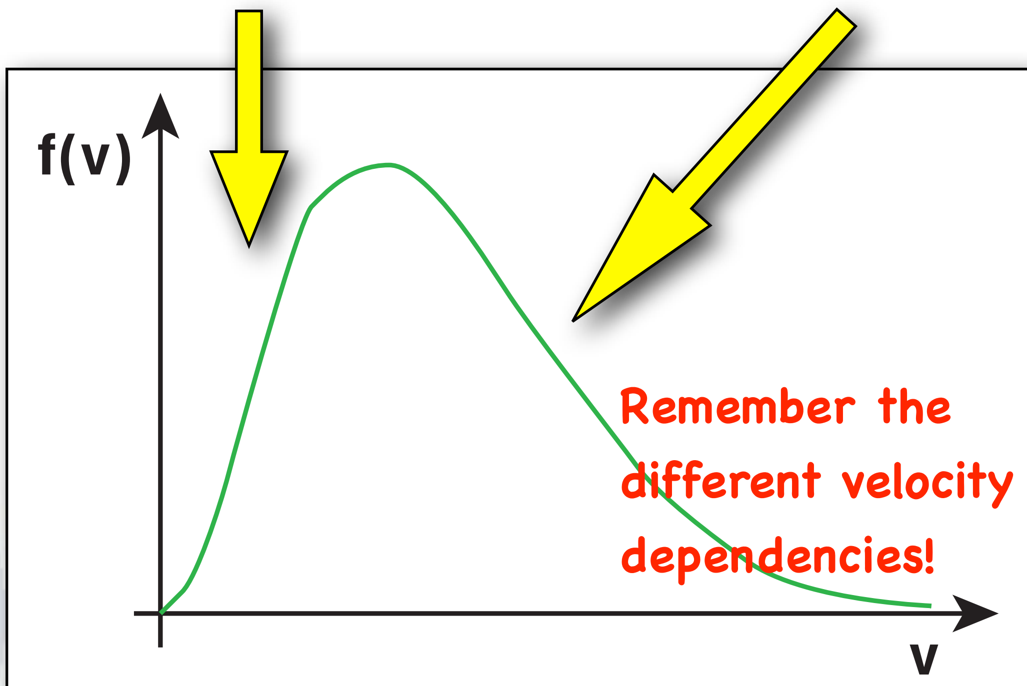
Complementarity between neutrino detectors, direct detection and Tevatron

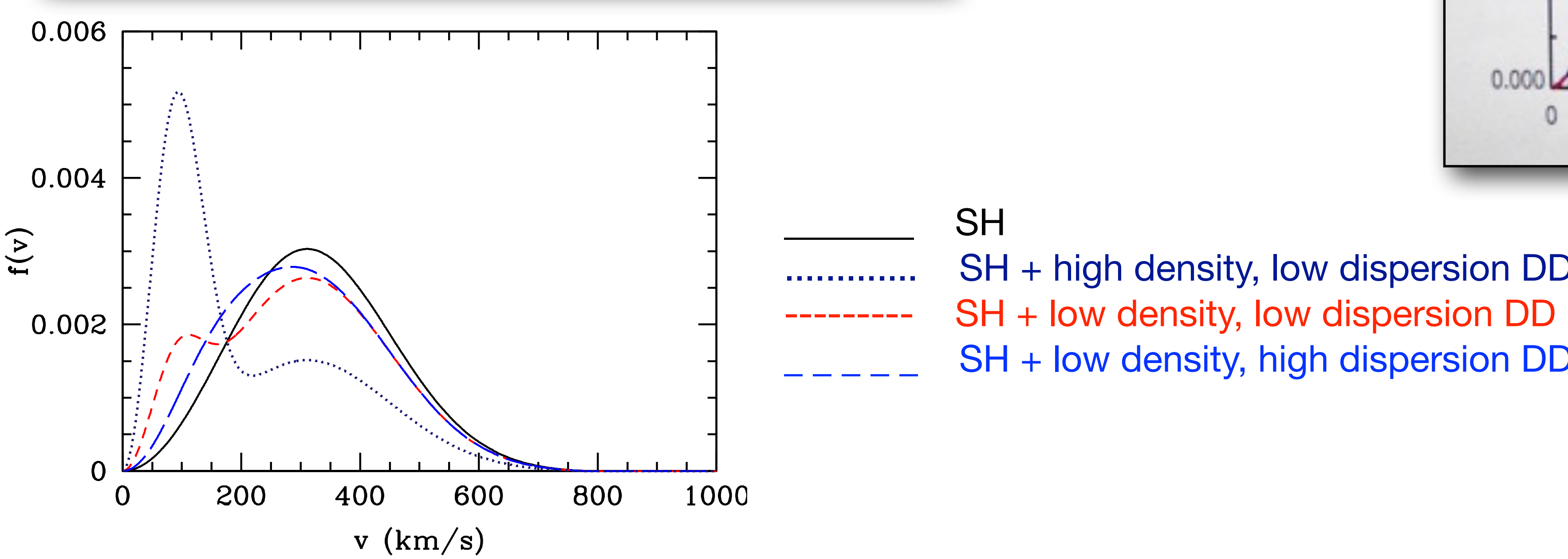


A note about velocity distributions

Capture sensitive to the low-velocity region

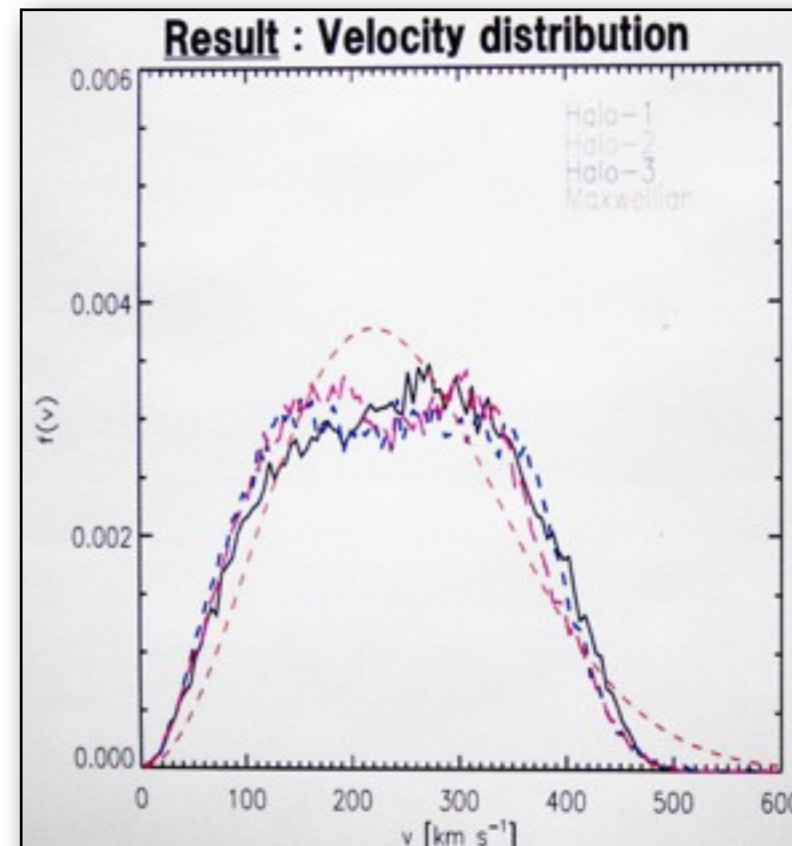
Direct detection sensitive to higher velocities





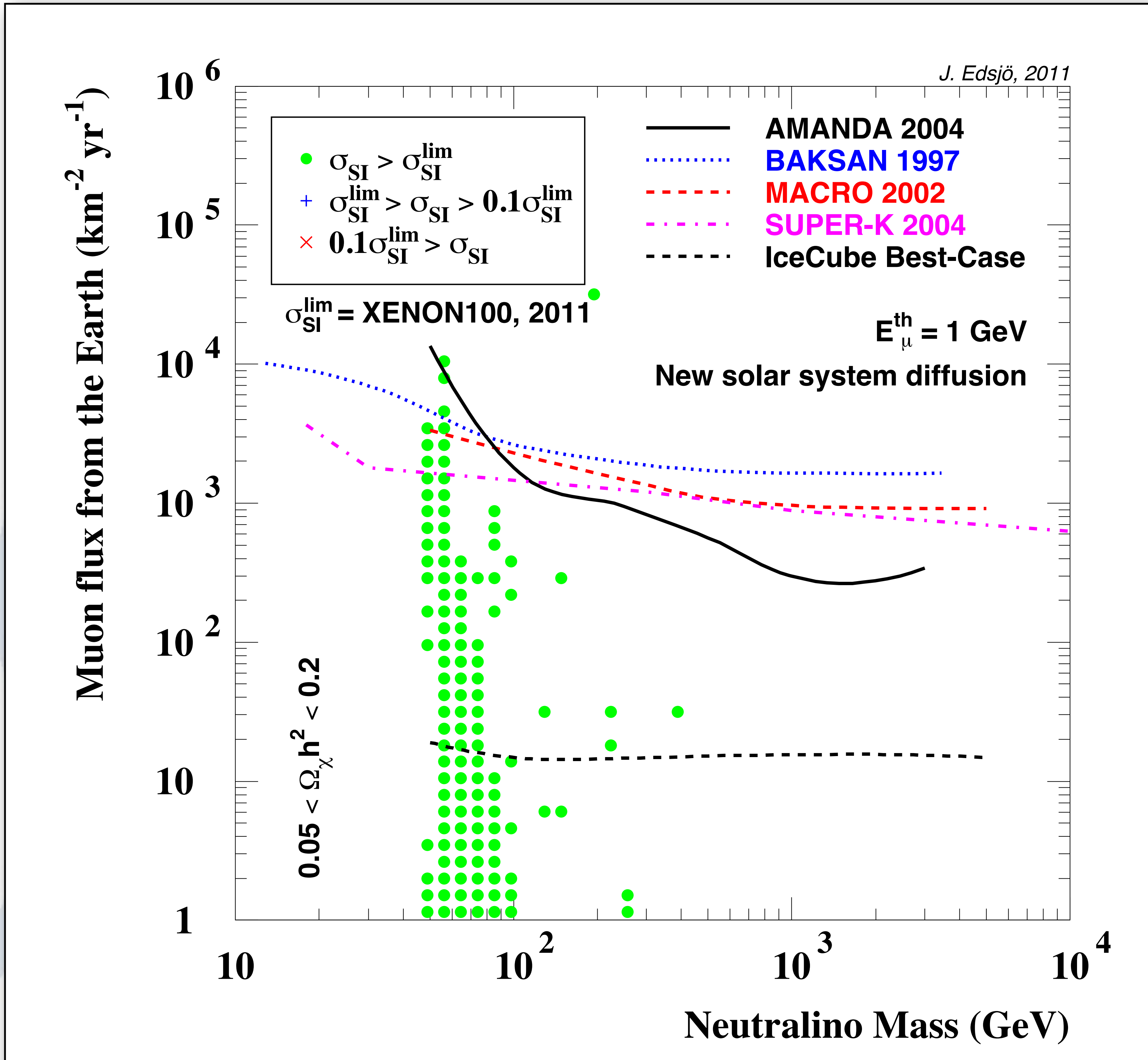
Dark disk, fig. from Anne Green

Also, velocity distribution in the galaxy most likely not Maxwellian



Preliminary results from Shogo Masaki

Neutrino-induced muon fluxes from the Earth

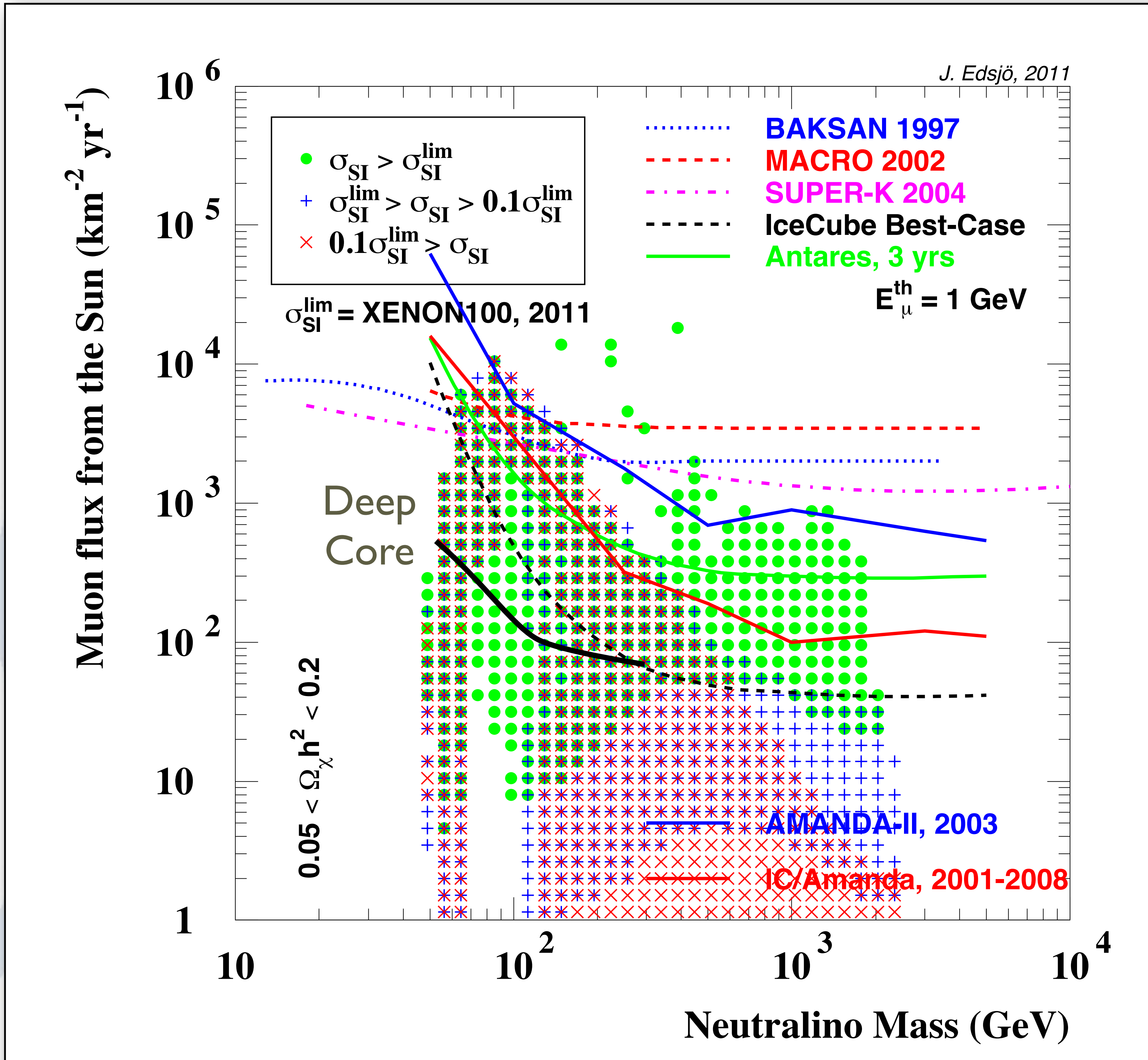


- Direct detection and the neutrino signal from the Earth are both sensitive to the spin-independent scattering cross section

- Large correlation

Suppression from solar capture included. Dark disk not included

Neutrino-induced muon fluxes from the Sun

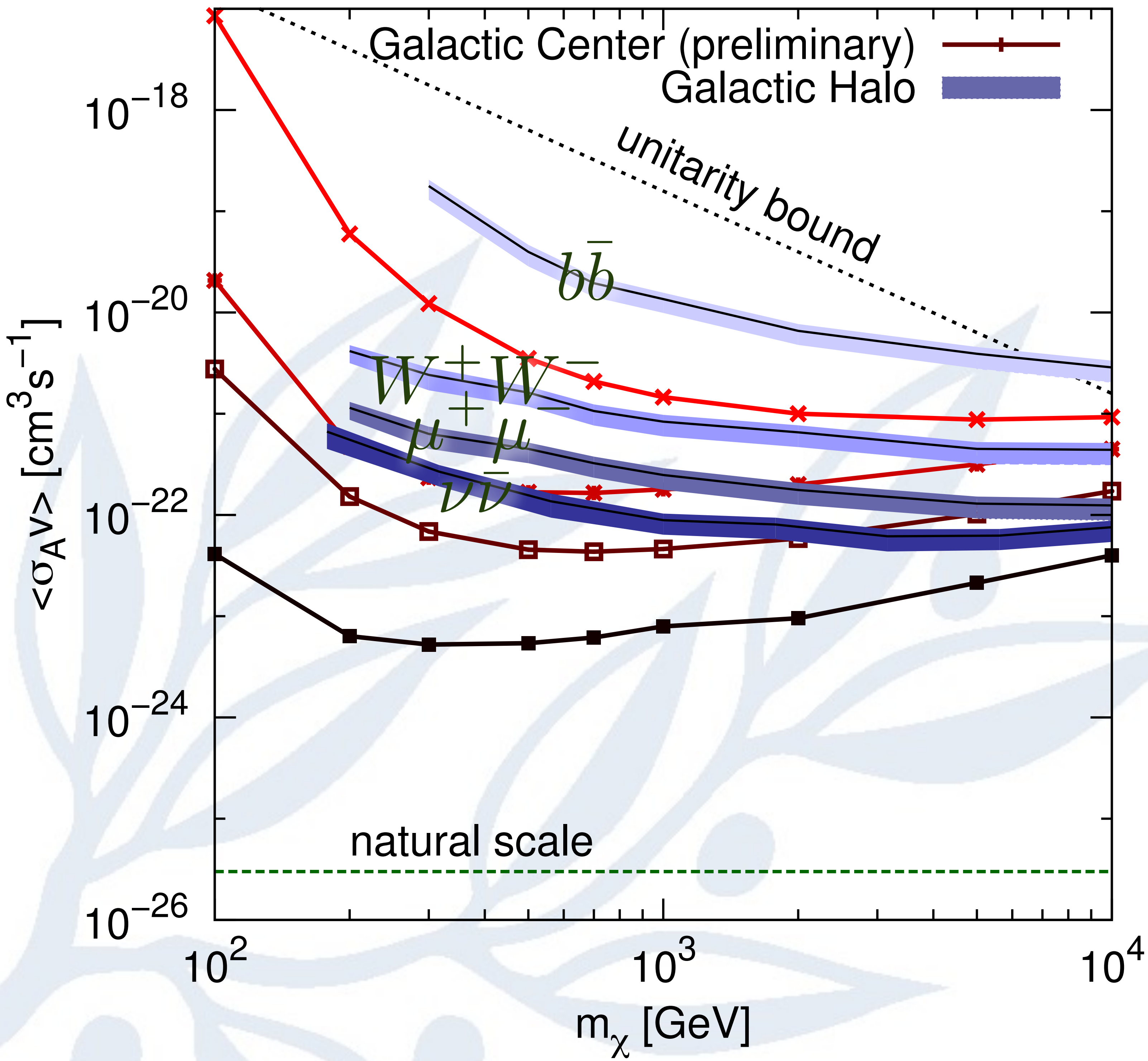


- Compared to the Earth, much better complementarity due to spin-dependent capture in the Sun.

Uncertainties with respect to direct detection

Input	Direct detection	Neutrinos from Sun	Neutrinos from Earth
Velocity distribution, f(u)	"All" velocities, for low-masses, high-velocity tail	Low velocities, some solar diffusion effects, especially for heavy WIMPs	Very low velocities, large solar diffusion effects
Form factor	Velocities ~200 km/s => low momentum transfer	Velocities ~1500 km/s => high momentum transfer	Velocities ~200 km/s => low momentum transfer
Local density	Sensitive to it now	Sensitive to average over last $\sim 10^8$ years	Sensitive to average over last $\sim 10^9$ years

IceCube and dark matter from the galactic halo



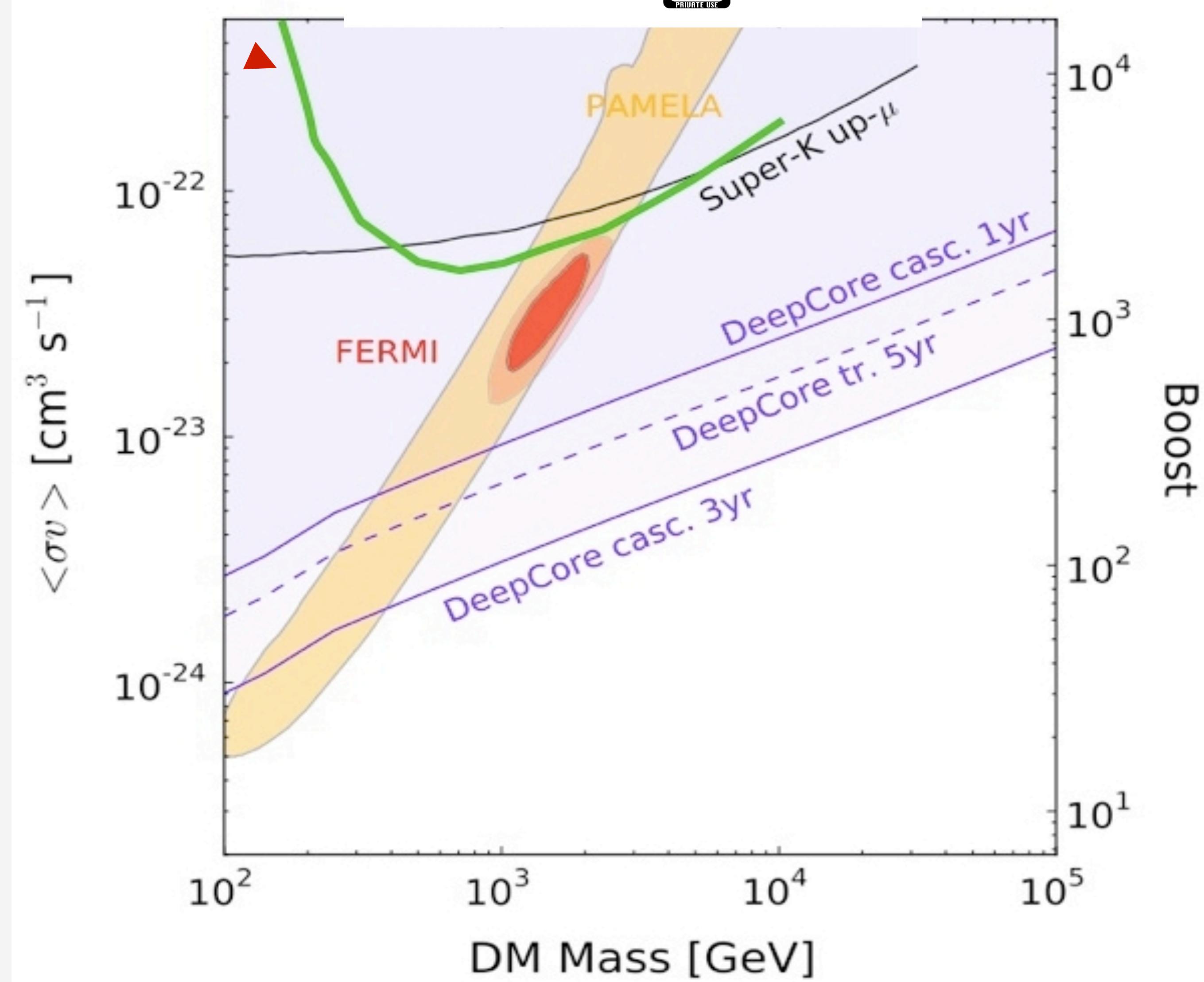
- Halo analysis uses IceCube-22 data. Not very sensitive to halo profile
- Galactic centre analysis uses IceCube-40 and an NFW halo profile

arXiv: 1111.2738

IceCube/DeepCore and cascades from the halo

IC40 PRELIMINARY

DM+DM m^+m^-



- NFW assumed here, but cascades have a pointing accuracy of about 50°, so the results are not very sensitive to the halo profile

Sensitivity from Mandal et al, PRD 81, 043508 (2010)
IC40 limits from Olga Botner's talk in Madison, April 2011

DarkSUSY

DarkSUSY 6 in progress

- DarkSUSY 5.0.5 is available at darksusy.org
- Long paper, describing DarkSUSY available as JCAP 06 (2004) 004 [astro-ph/0406204]
- Manual (pdf and html) available

WimpSim
for WIMP annihilations
in the Sun/Earth also
available.

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

DarkSUSY: computing supersymmetric dark-matter properties numerically

P Gondolo[1], J Edsjö[2], P Ullio[3], L Bergström[2], M Schelke[2] and E A Baltz[4]

DarkSUSY 6

- DarkSUSY 6 will contain
  - new more modular design, not as SUSY focused
  - new propagation routines
  - new simulation tables with larger mass ranges
  - interfaces to more codes
  - kinetic decoupling (smallest dark matter halos)
  - DLHA?
  - ...

not public yet, but soon...

Conclusions

- Heavier elements will influence capture of WIMPs in the Sun.
- Neutrino fluxes from the Sun/Earth are affected by solar system diffusion. Sun fluxes may be reduced for DM masses above 1 TeV due to Jupiter.
- A dark disk can enhance the neutrino-fluxes from the Sun (x10) and the Earth (x1000). However, the existence and properties of this dark disk are quite uncertain.
- IceCube has started to cut into the MSSM parameter space