Halo VDF independent constraints on spin dependent DM-nucleon scattering, by combining IceCube and PICO results

M. Rameez for IceCube and PICO

CARLSBERGFONDET

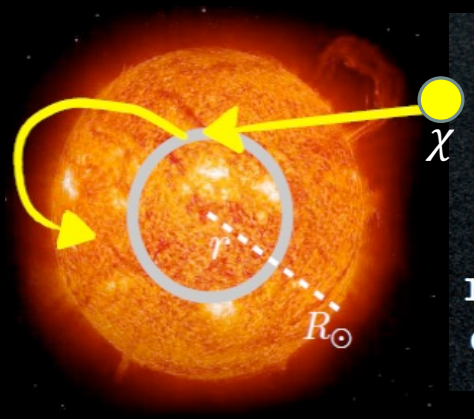
The Niels Bohr International Academy

IceCube

PICO

Dark Ghosts 2018

DM Capture and Annihilation in the Sun



$$\Gamma_{\rm capt} = \frac{\rho_{\rm DM}}{M_{\rm DM}} \sum_i \sigma_i \int_0^{R_\odot} dr\, 4\pi r^2\, n_i(r) \int_0^{\infty} dv\, 4\pi v^2\, f_\odot(v)\, \frac{v^2 + v_{\odot\rm esc}^2}{v}\, \wp_i(v, v_{\odot\rm esc})$$

- DM number density
- Scattering Cross Section: $\sigma_{SD} \propto J(J+1)$, $\sigma_{SI} \propto A^2$
- Number density of element i -> Solar Model
- velocity distribution (in solar frame, without Sun's gravity)
- effect of solar gravity

Capture

Equilibrium $\Rightarrow$ $\Gamma_A^{equi} = \frac{1}{2} C_c$

Annihilation

Spin Dependent scattering

- Only the hydrogen in the Sun contributes significantly.
- Lower event rates in direct detection experiments
- More interesting for IceCube

Spin Independent scattering

- Heavier nuclei contribute more due to $\propto A^2$ enhancement.
- Better sensitivity using direct detection experiments such as LUX, XENON etc

The secondary annihilation products can interact in the dense baryonic environment inside the Sun

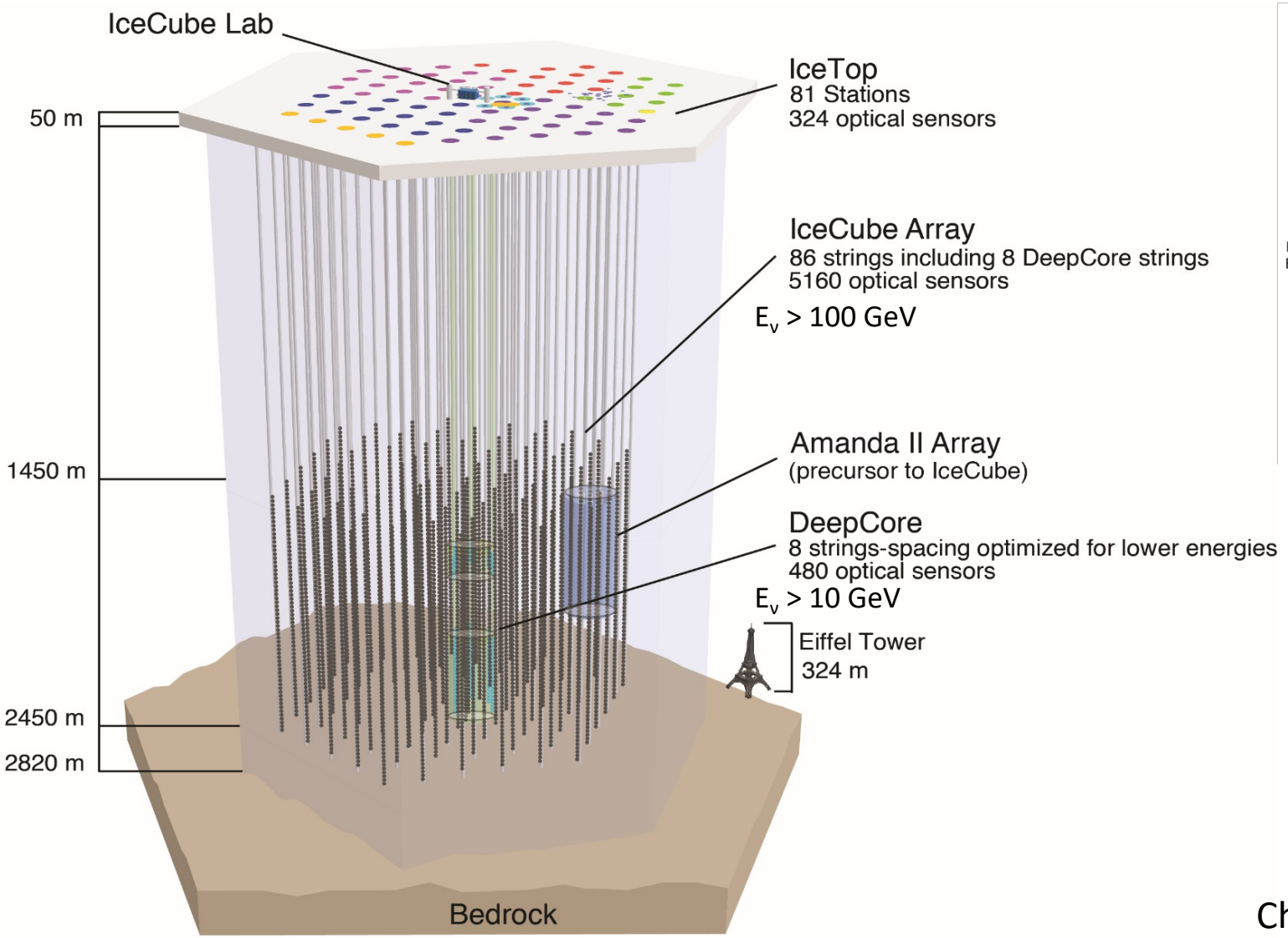
Neutrinos are the only messengers that can get out

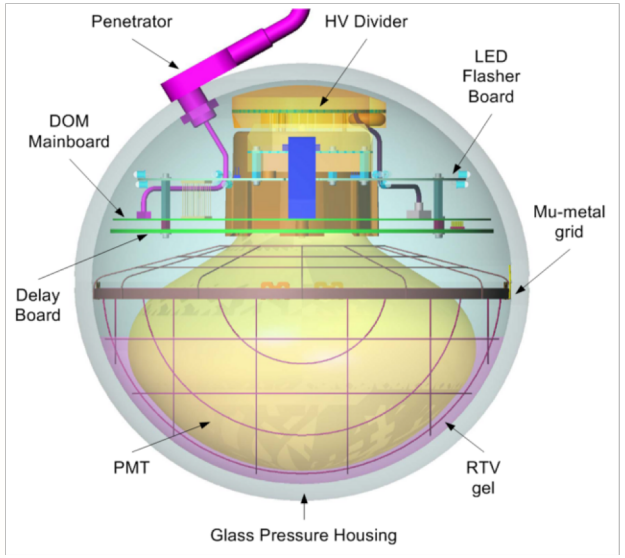
GeV neutrinos from the Sun- Smoking gun for DM

Sun opaque to neutrinos above ~1 TeV (Exercise)

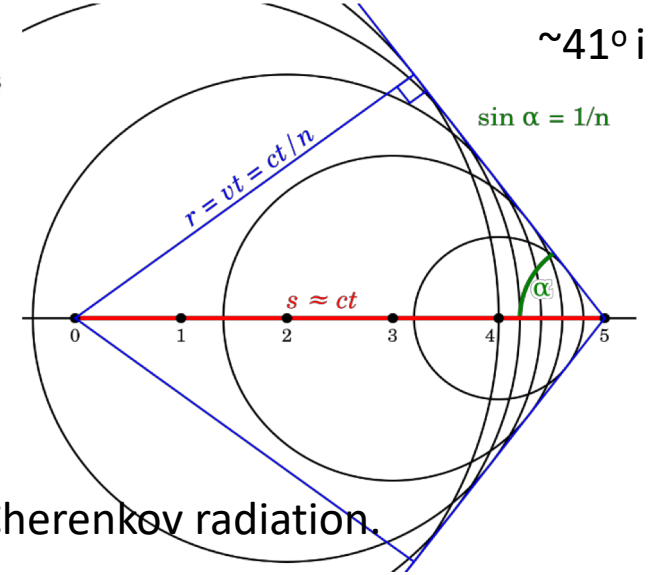
Slide credits: M. Cirelli

The IceCube Neutrino Observatory

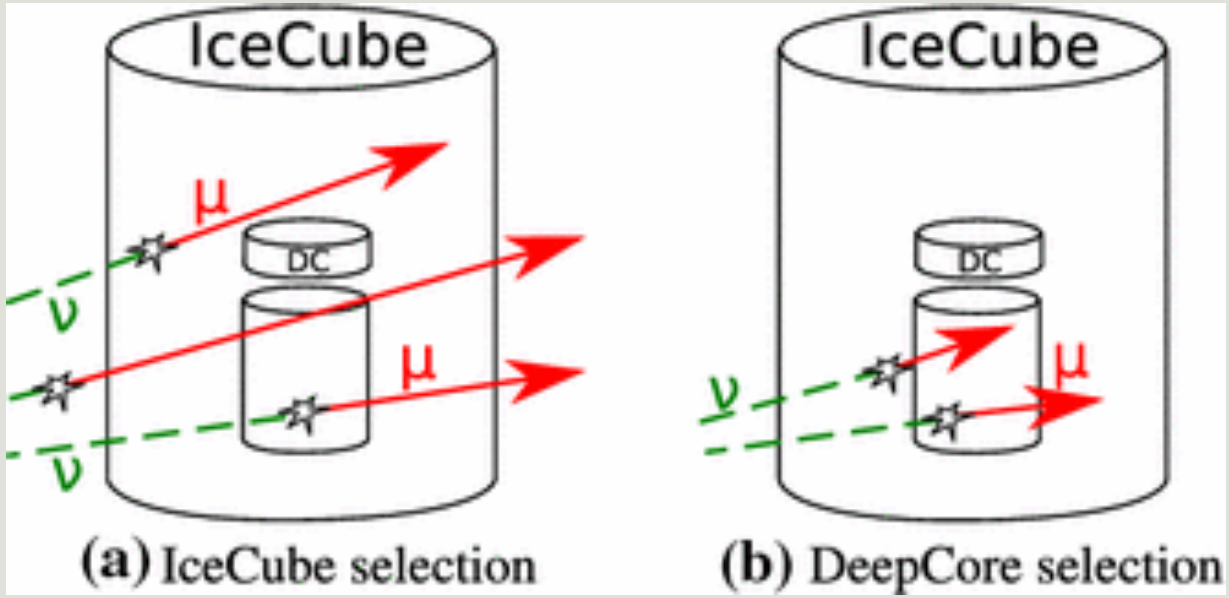




~41° in ice

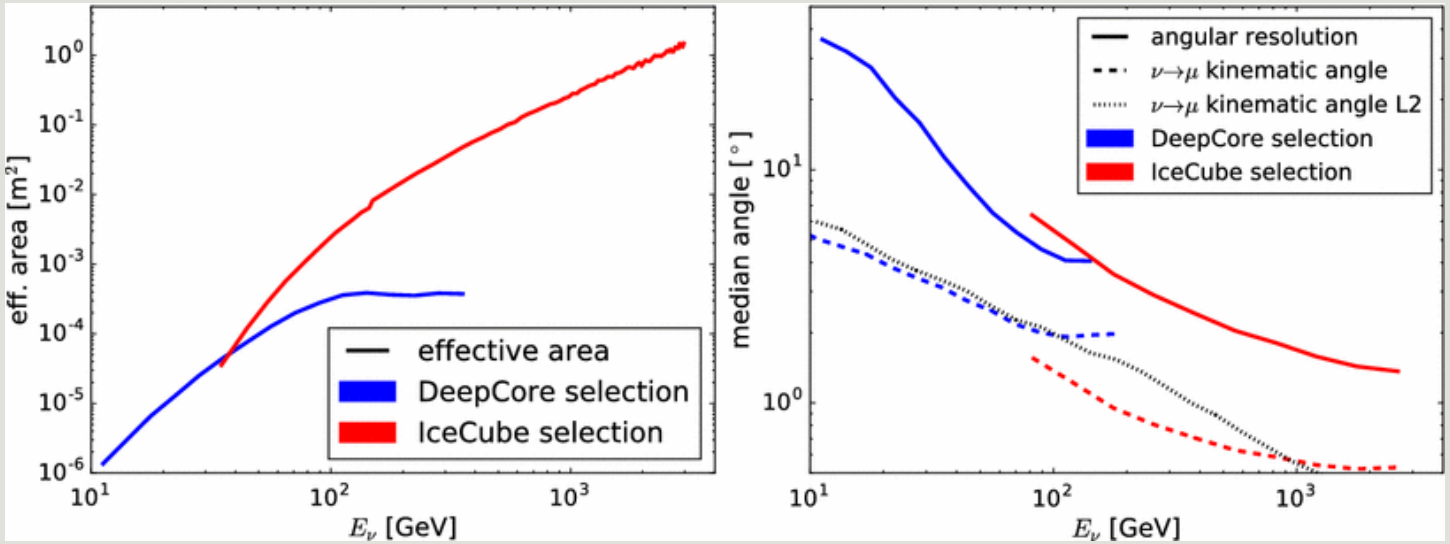


Cherenkov radiation.

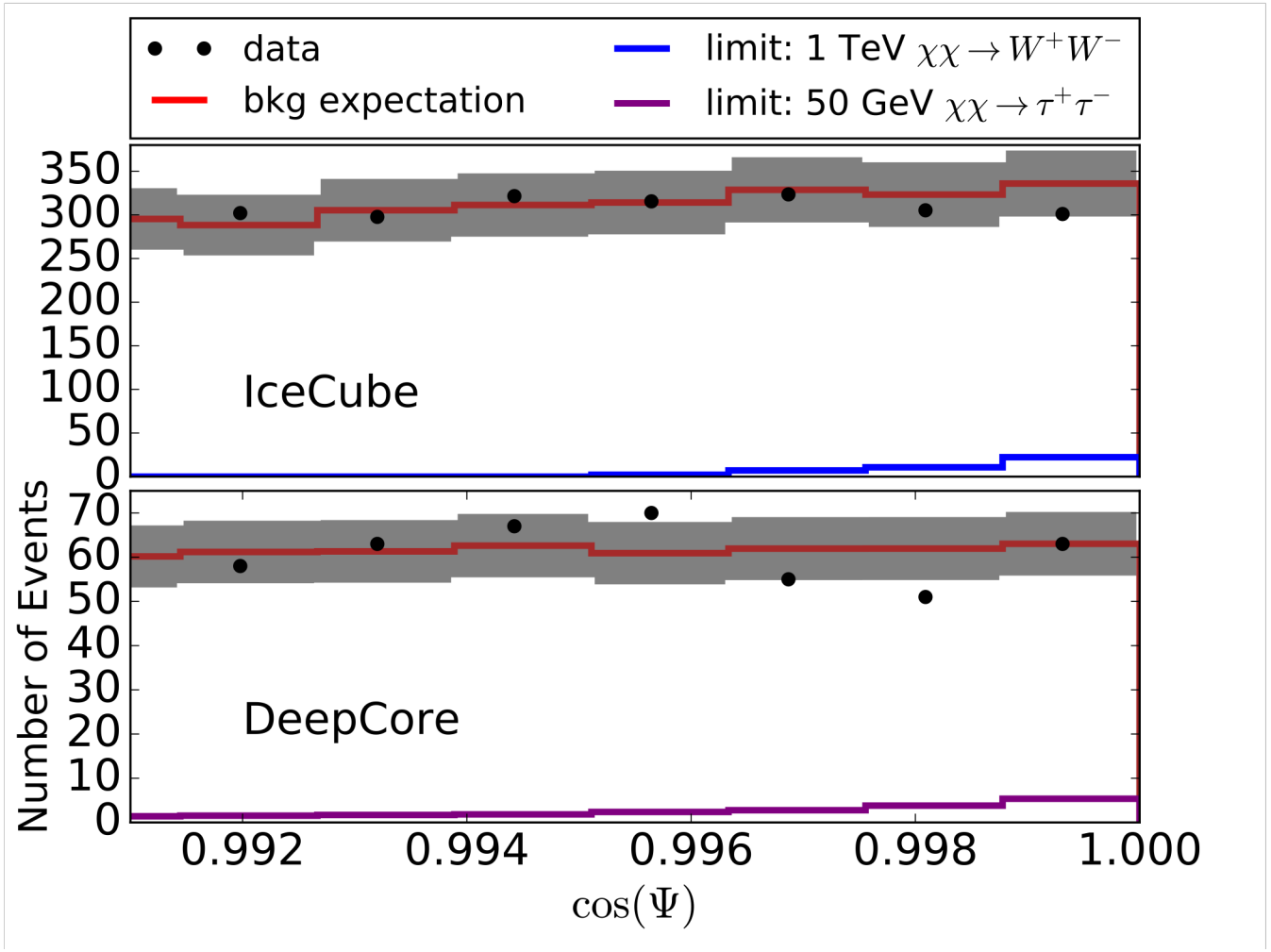


Unbinned maximum likelihood ratio method

Event by event angular resolution



Results

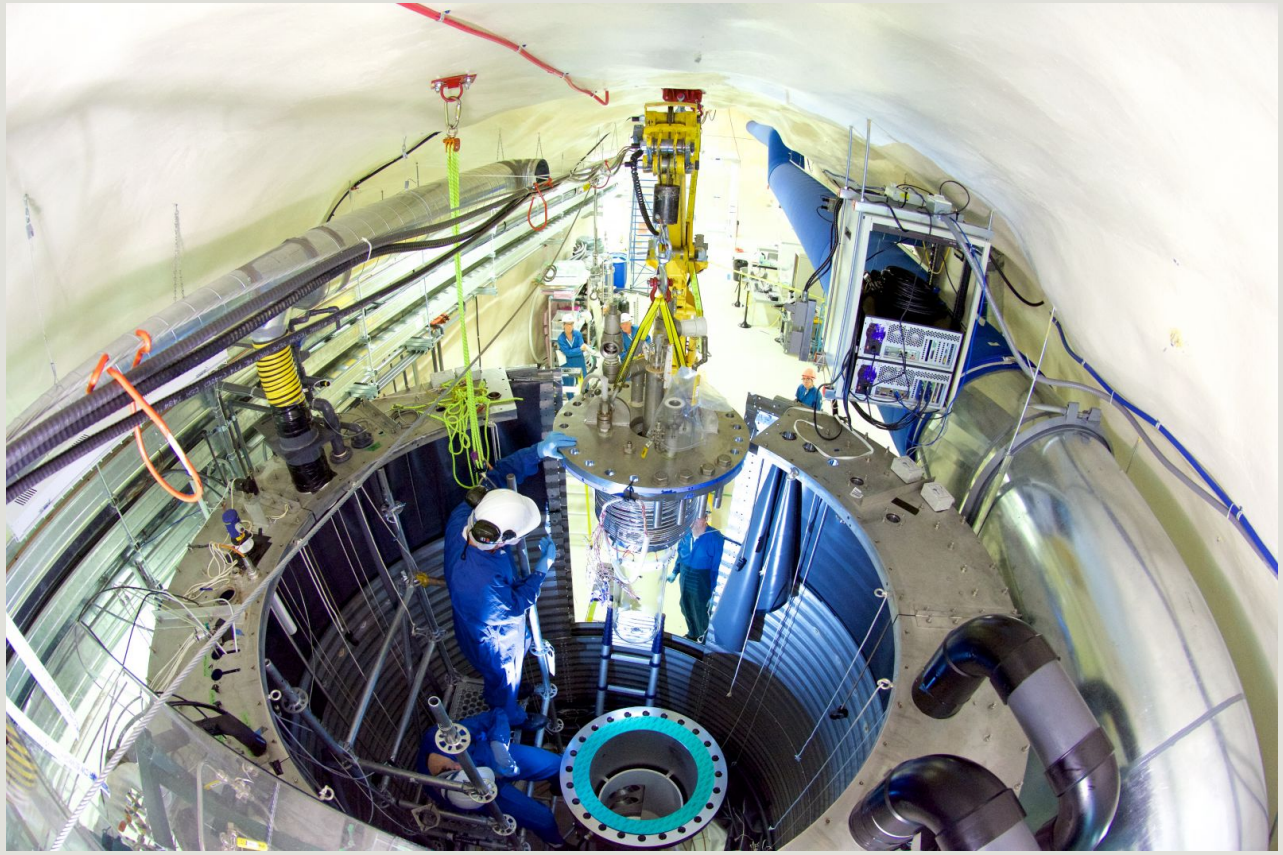


- No statistically significant excess
- Unbinned maximum likelihood ratio method
- 532 days of livetime : 3 years of IC86 austral winters only
- Best p – value ~28.2%
  250 GeV $\chi\chi \to b\bar{b}$

Eur.Phys.J. C77 (2017) no.3, 146

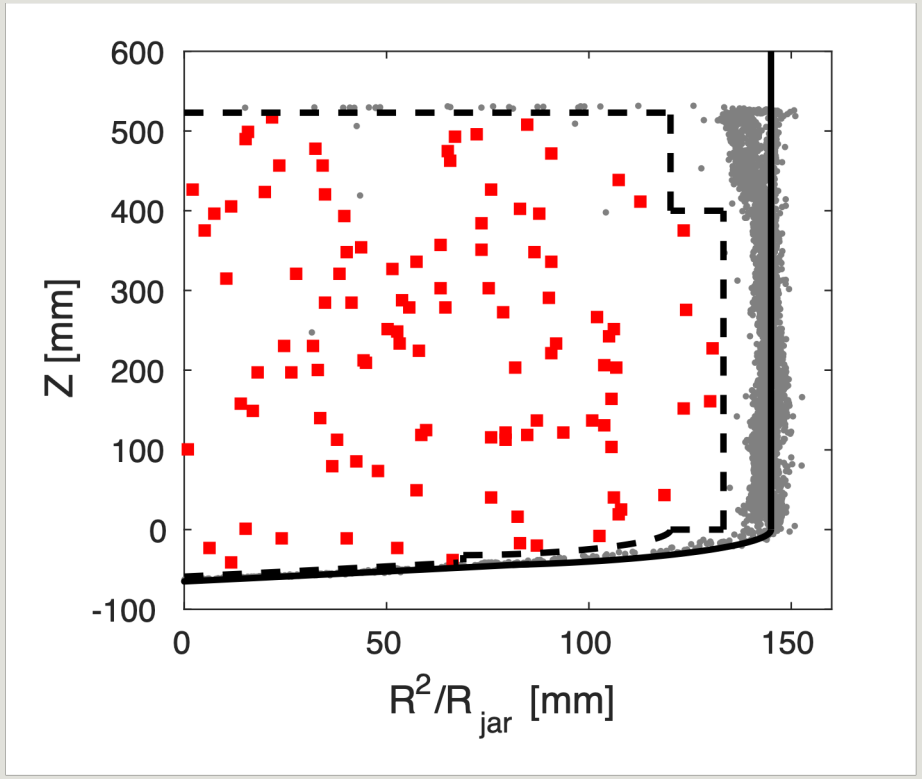
The PICO 60 Superheated Bubble Chamber

Phys. Rev. Lett. 118, 251301 (2017)



Phys.Rev.Lett. 118 (2017) no.25, 251301

52.2 $\pm$ 0.5 kg C_3F_8
November 2016 to January 2017
1167 kg days of effective exposure



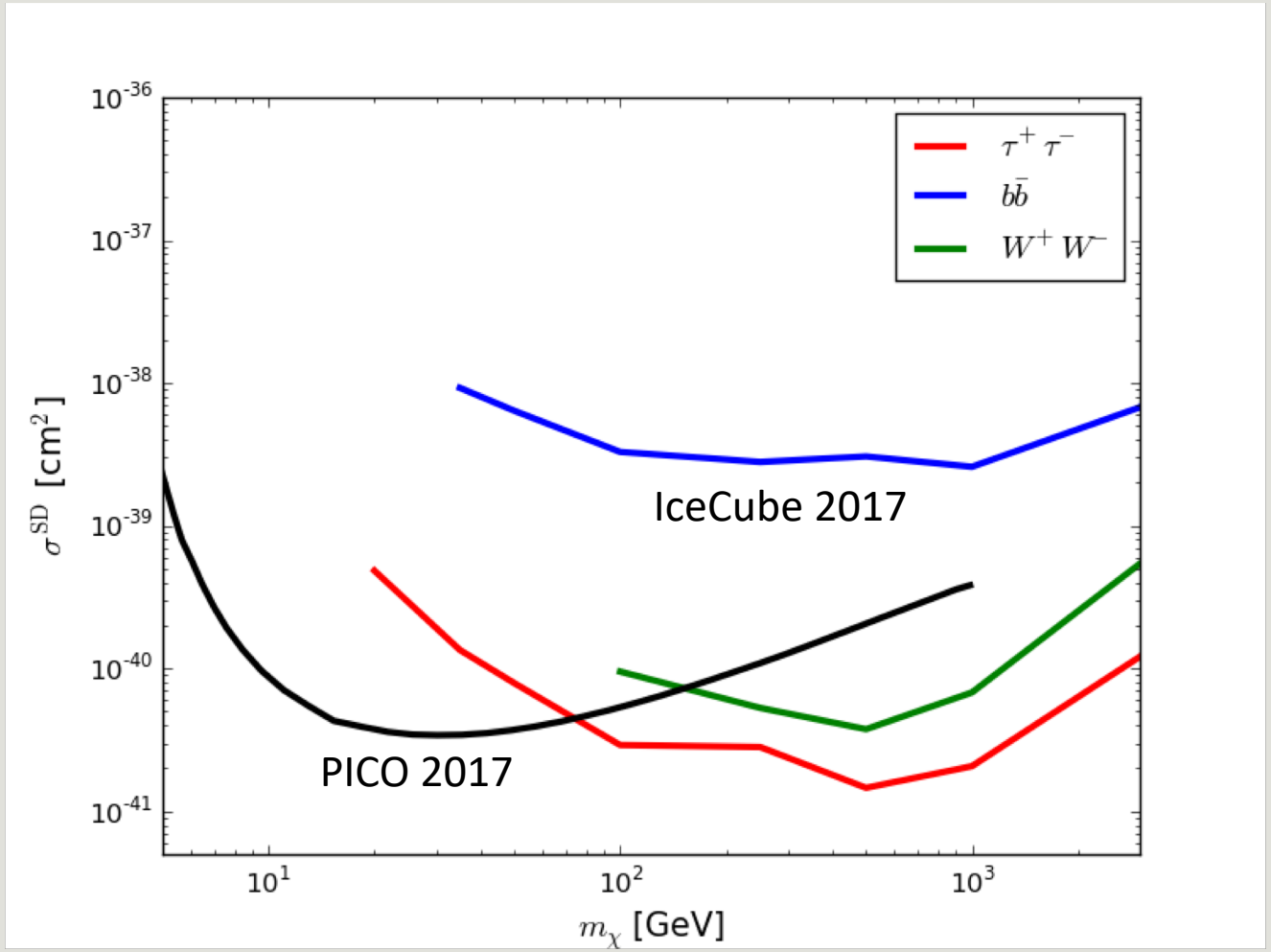
IceCube + PICO together have the most stringent constraints on σ_{SD}

IceCube

No excess of GeV neutrinos from the Sun

Standard Maxwellian Halo (SMH)
+
Capture Annihilation equilibrium
+ (Other assumptions)

constraint on σ_{SD}



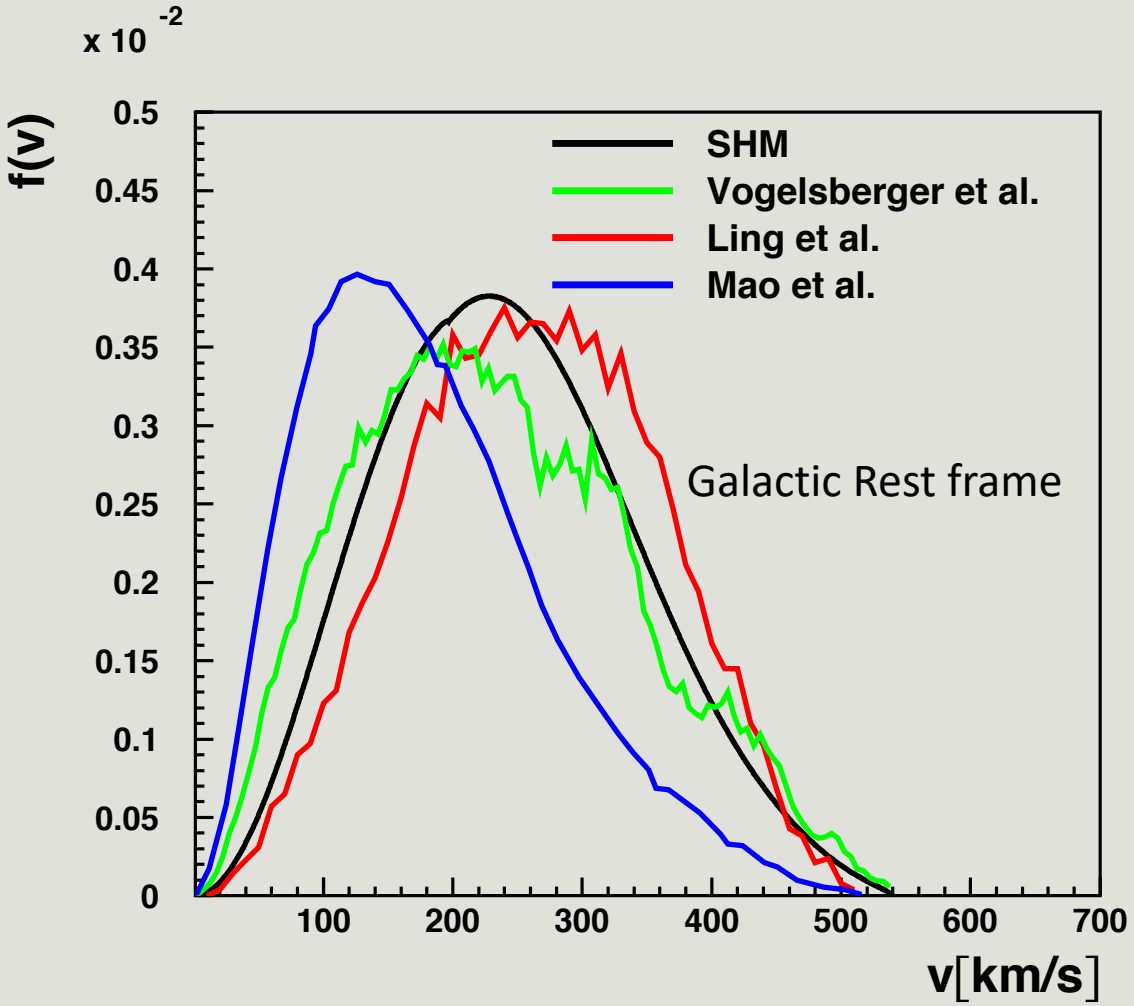
PICO

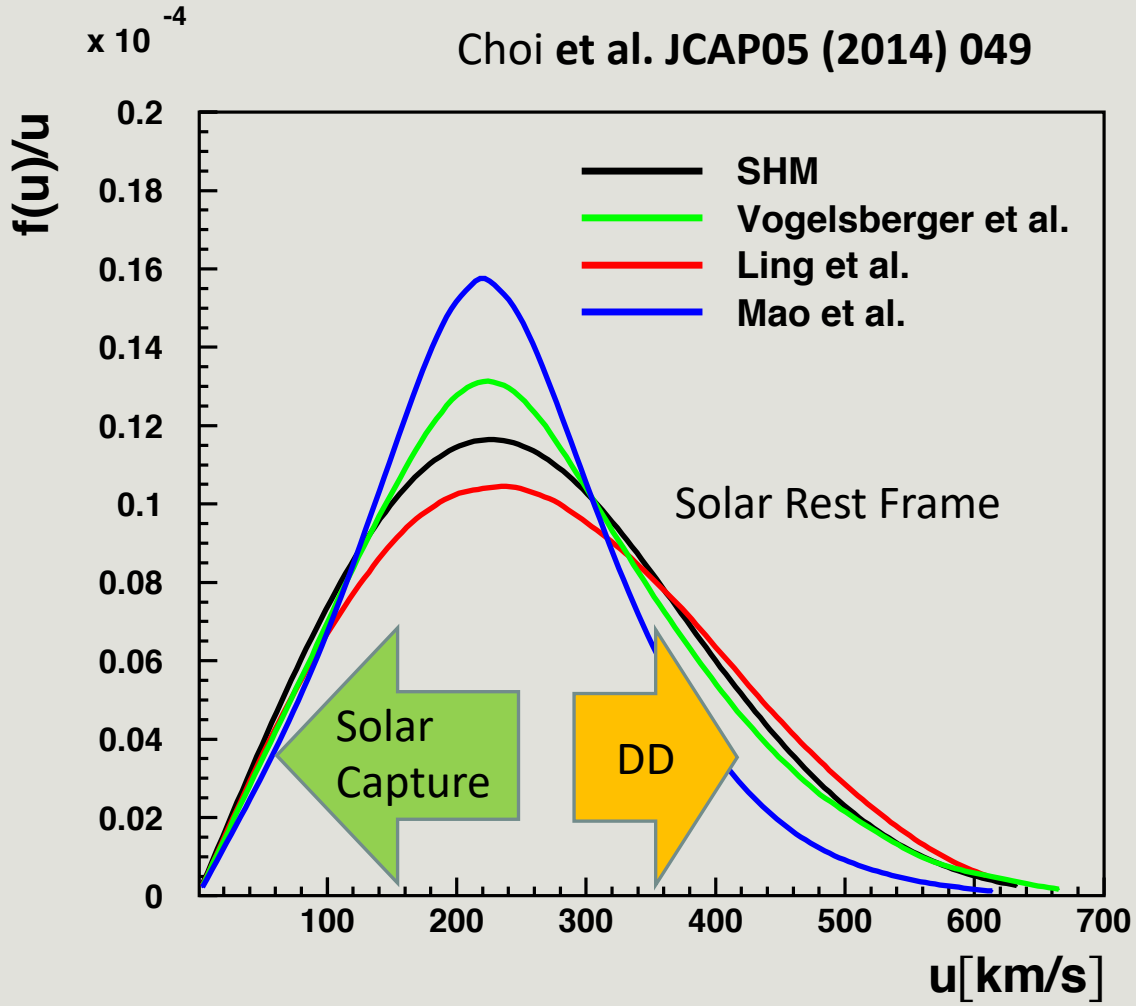
No excess of nuclear recoil events within the detector

Standard Maxwellian Halo (SMH)
+ (Other assumptions)
+
Detector Response

constraint on σ_{SD}

The Standard Maxwellian Halo Velocity distribution function

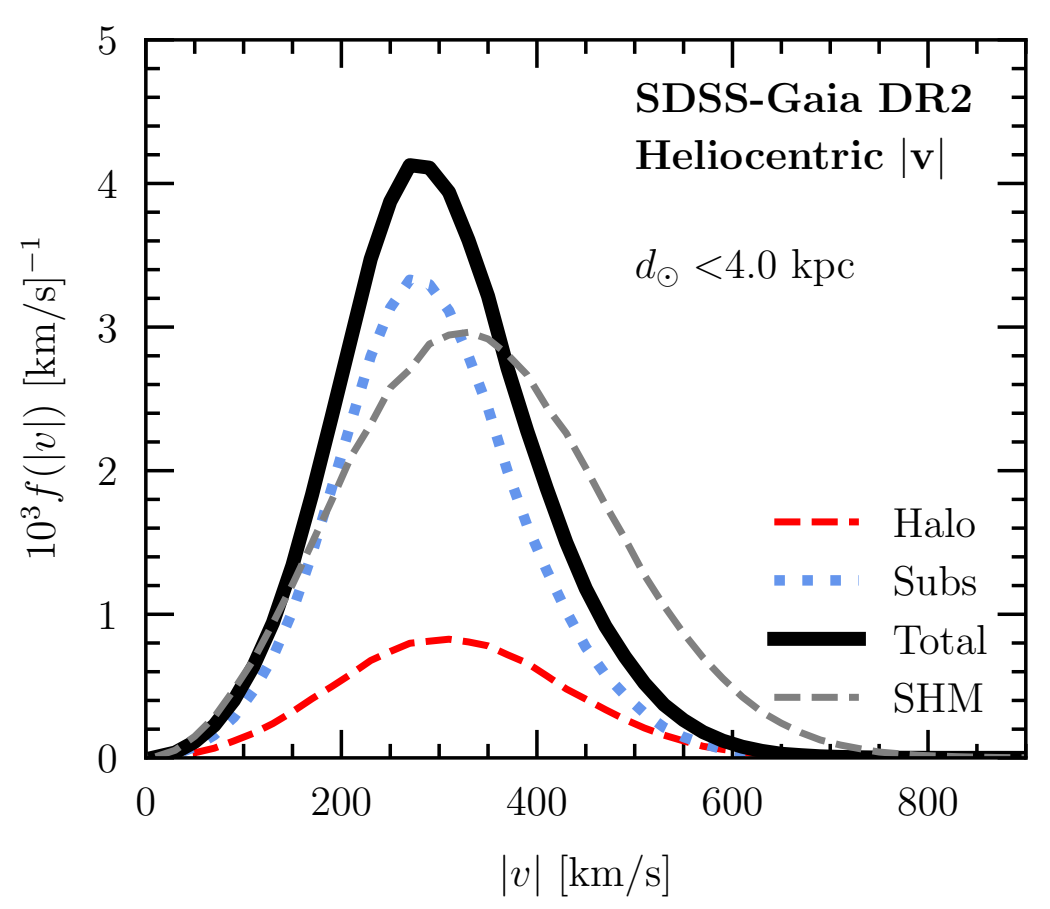




Choi **et al. JCAP05 (2014) 049**

Slower DM particles are more likely to get captured in the Sun
Faster DM particles are more likely to recoil off nuclei in PICO
Deviations from SMH will affect the constraints from the different searches differently

All's not well with the SMH

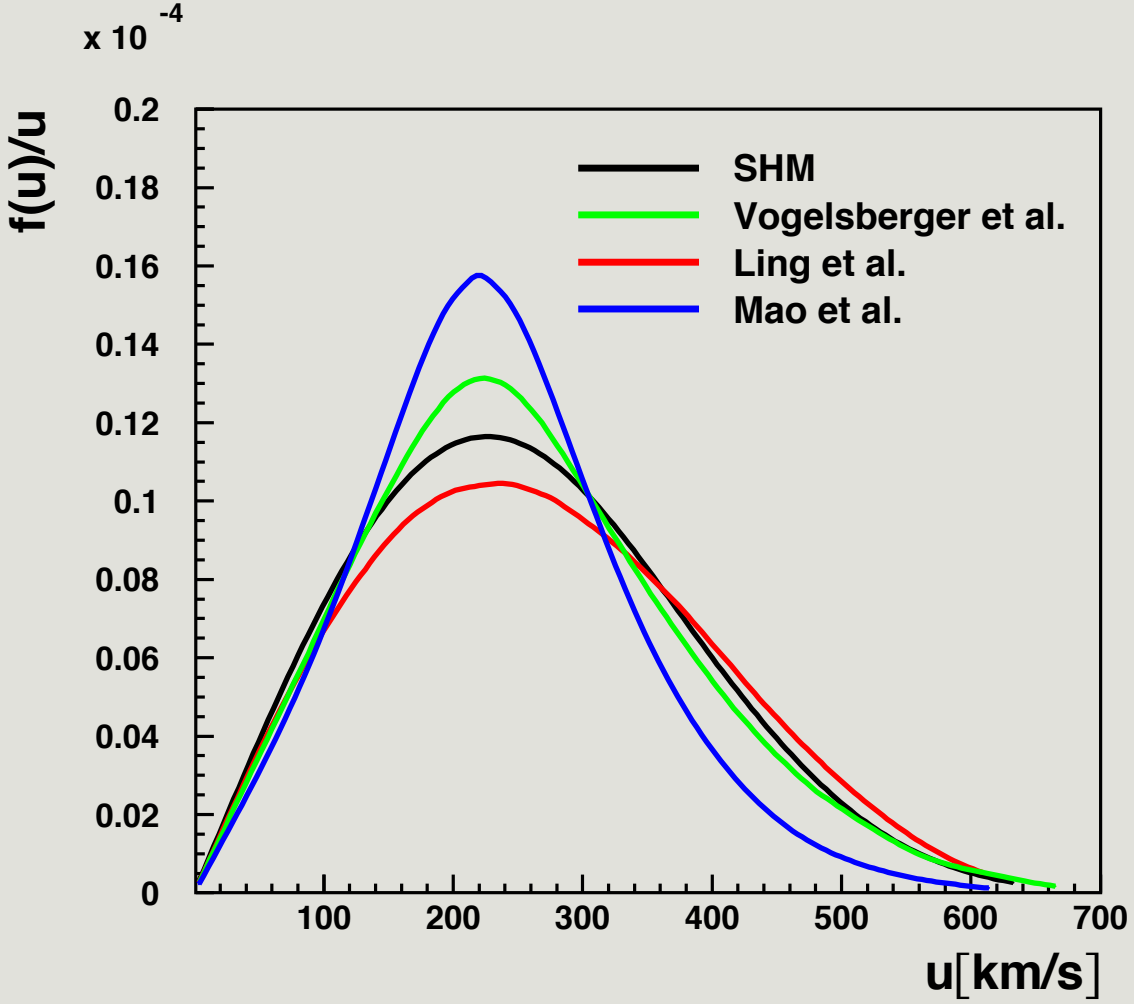


Necib, Lisanti and Belokurov 1807.02519
|Z coord| < 2.5 kpc
4 kpc sphere around the Sun

"the debris from the youngest mergers may be in position and velocity substructure. Referred to as tidal streams, these cold phase-space features tend to trace fragments of a progenitor's orbit (Zemp et al. 2009; Vo- gelsberger et al. 2009; Diemand et al. 2008; Kuhlen et al. 2010; Maciejewski et al. 2011; Vogelsberger & White 2011; Elahi et al. 2011). "

The Method of Ferrer, Ibarra and Wild

http://iopscience.iop.org/article/10.1088/1475-7516/2015/09/052/meta



$$f(\vec{v}) = \int_{|\vec{v}| \leq v_{max}} d^3 v_0 \delta^{(3)}(\vec{v} - \vec{v}_0) f(v_0)$$

Any VDF can be expressed as a superposition of hypothetical streams with fixed velocity v_0 w.r.t. the solar system.

Derive DD and IC Solar WIMP constraints separately for each stream, report the worst allowed by both.

How the calculations are done

PICO Event Rate

$$R = \mathcal{E} \cdot \sum_i \int_0^\infty \mathrm{d}E_R \, \epsilon(E_R) \frac{\xi_i \rho_{\mathrm{loc}}}{m_{A_i} m_{\mathrm{DM}}} \int_{v \geq v_{\mathrm{min},i}^{(\mathrm{DD})}(E_R)} \mathrm{d}^3 v \, v f(\vec{v} + \vec{v}_{\mathrm{obs}}(t)) \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_R} \, .$$

DMDD
https://dmdd.readthedocs.io/en/latest/
Gluscevic et al 2015, Anand et al 2013

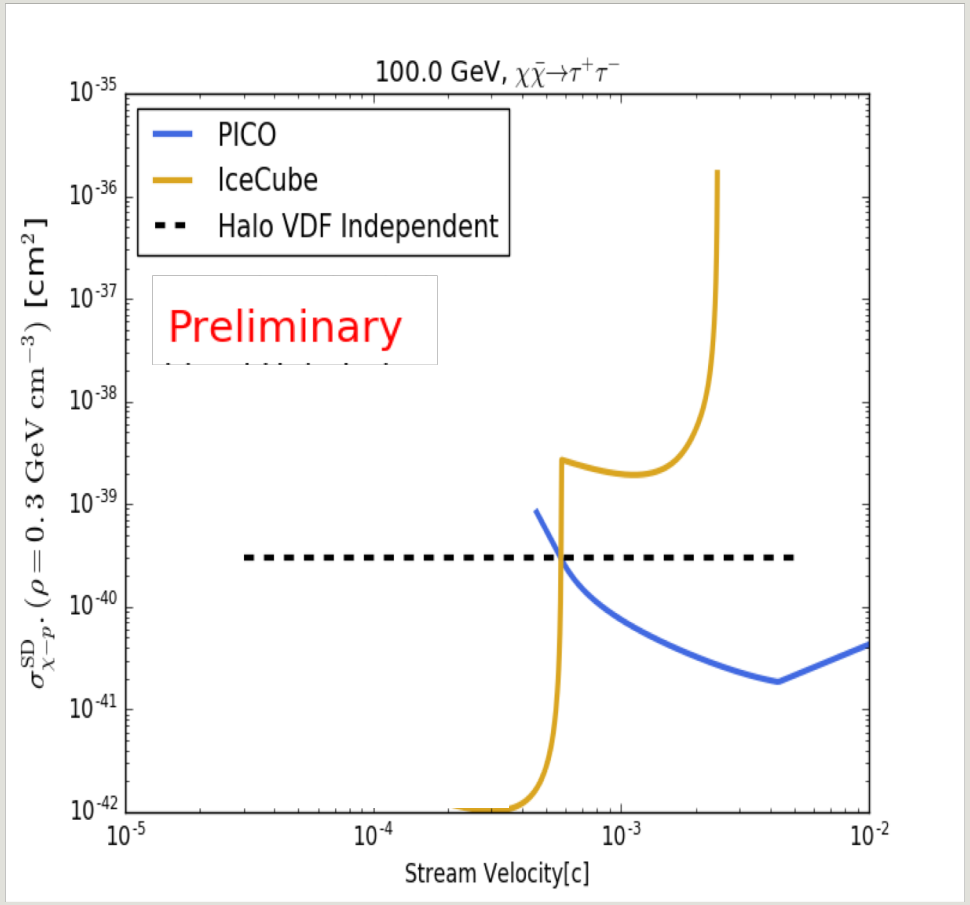
Solar Capture Rate

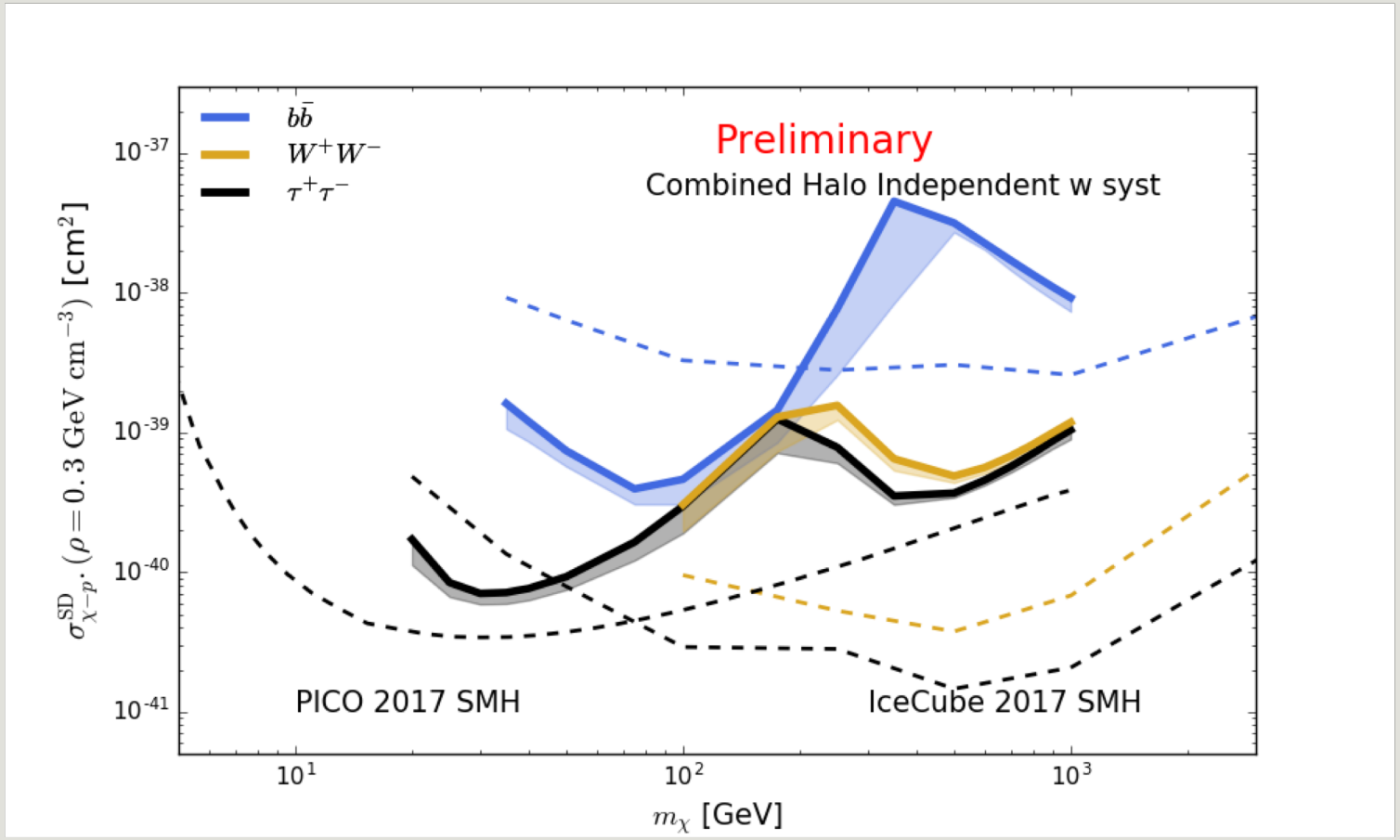
$$C = \sum_i \int_0^{R_\odot} 4\pi r^2 \mathrm{d}r \, \eta_i(r) \frac{\rho_{\mathrm{loc}}}{m_{\mathrm{DM}}} \int_{v \leq v_{\mathrm{max},i}^{(\mathrm{Sun})}(r)} \mathrm{d}^3 v \, \frac{f(\vec{v})}{v} \left(v^2 + [v_{\mathrm{esc}}(r)]^2 \right) \times$$

$$\int_{m_{\mathrm{DM}} v^2/2}^{2\mu_{A_i}^2 \left(v^2 + [v_{\mathrm{esc}}(r)]^2 \right)/m_{A_i}} \mathrm{d}E_R \frac{\mathrm{d}\sigma_i}{\mathrm{d}E_R} \, ,$$

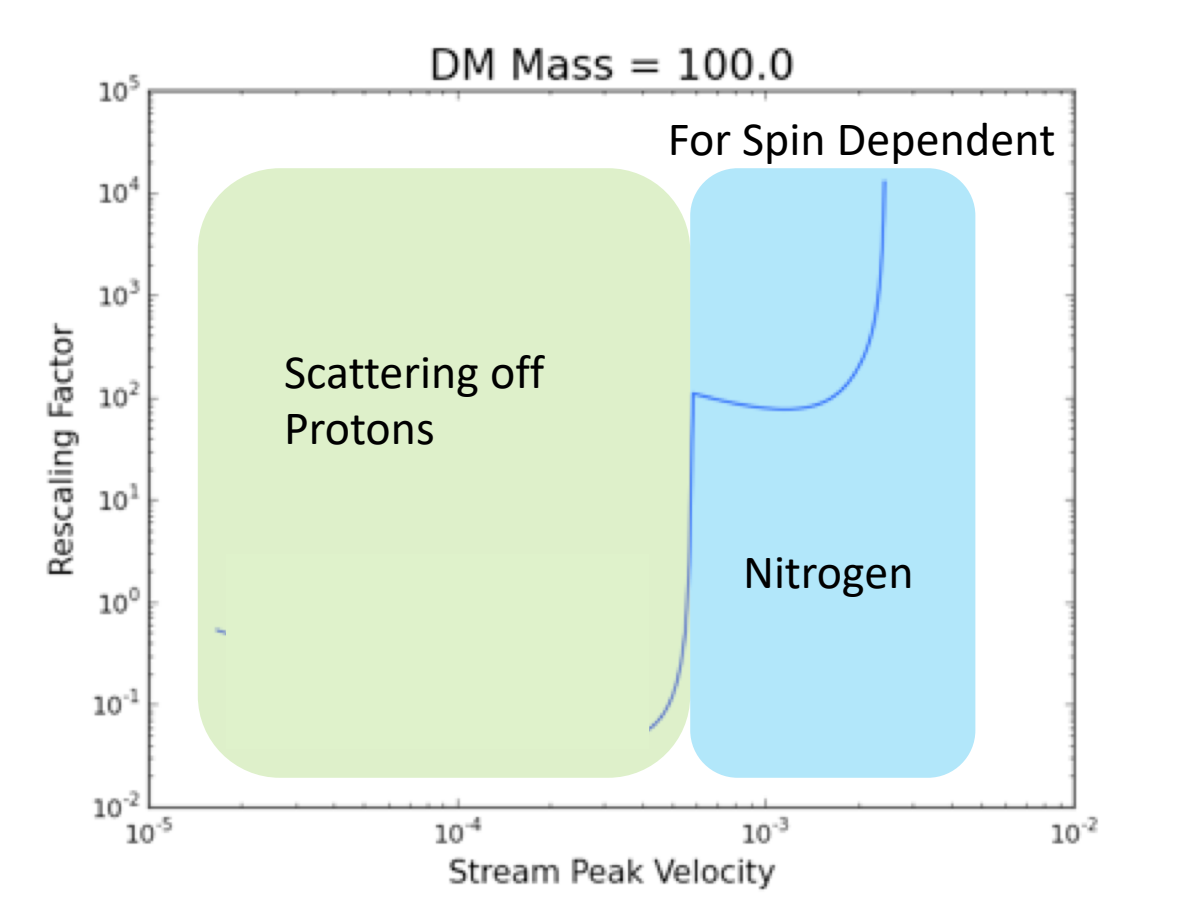
https://github.com/rameez3333/SolarCaptureRates
/data/ana/BSM/IceCubePicoJoinedAnalysis/
Code tested and verified by Carlos Arguelles

Results


100.0 GeV, $\chi\bar{\chi}\to\tau^+\tau^-$
PICO
IceCube
Halo VDF Independent
Preliminary
$\sigma^{SD}_{\chi-p}$, ($\rho = 0.3$ GeV cm^{-3}) [cm^2]
Stream Velocity[c]


$b\bar{b}$
W^+W^-
$\tau^+\tau^-$
Preliminary
Combined Halo Independent w syst
PICO 2017 SMH
IceCube 2017 SMH
$\sigma^{SD}_{\chi-p}$, ($\rho = 0.3$ GeV cm^{-3}) [cm^2]
m_χ [GeV]

Common question



$$v_{max,i}^{(sun)}(r) = 2 * v_{esc}(r) * \frac{\sqrt{M_{DM} M_{A_i}}}{|M_{DM} - M_{A_i}|}$$

Uses solar density profile, nuclear abundances and form factors exactly as in DarkSuSy

$$\text{Rescaling Factor} = \frac{\Gamma_{capt}(SMH)}{\Gamma_{capt}(stream,v)}$$

Conclusions

Recent observations and simulations suggest significant deviations from SMH velocity distribution

Individually, DD and IC constraints can be significantly worse

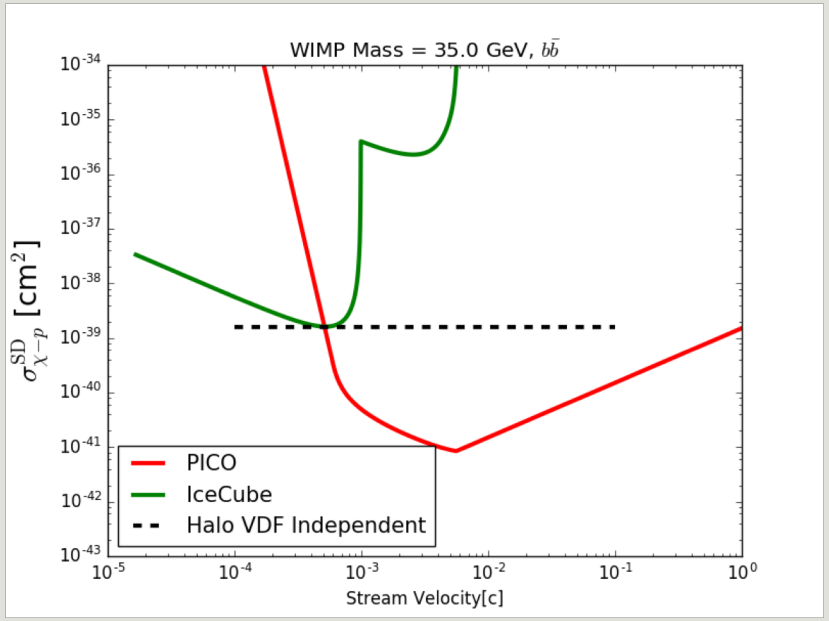
However, Solar searches and direct detection are complementary in the velocity dependence of their constraints.

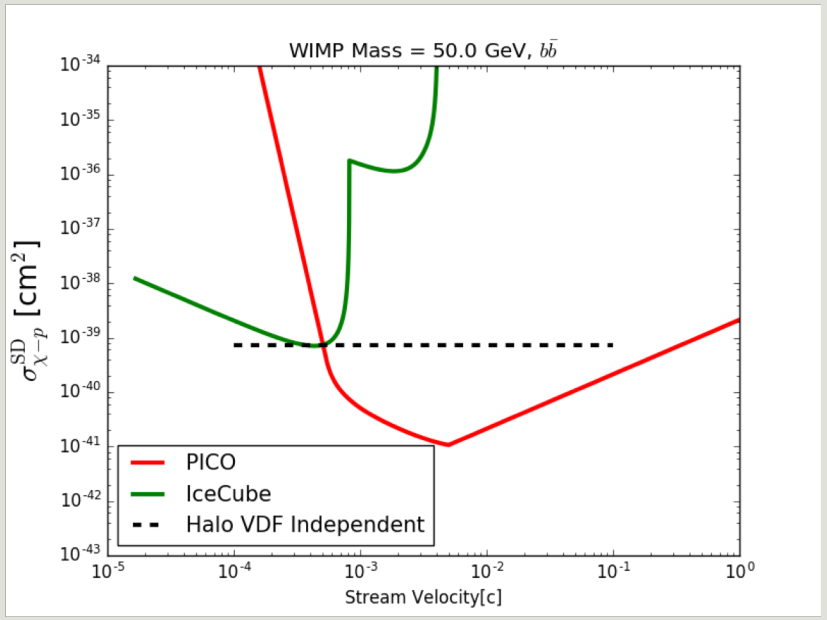
Combined Halo Independent bound is still quite stringent

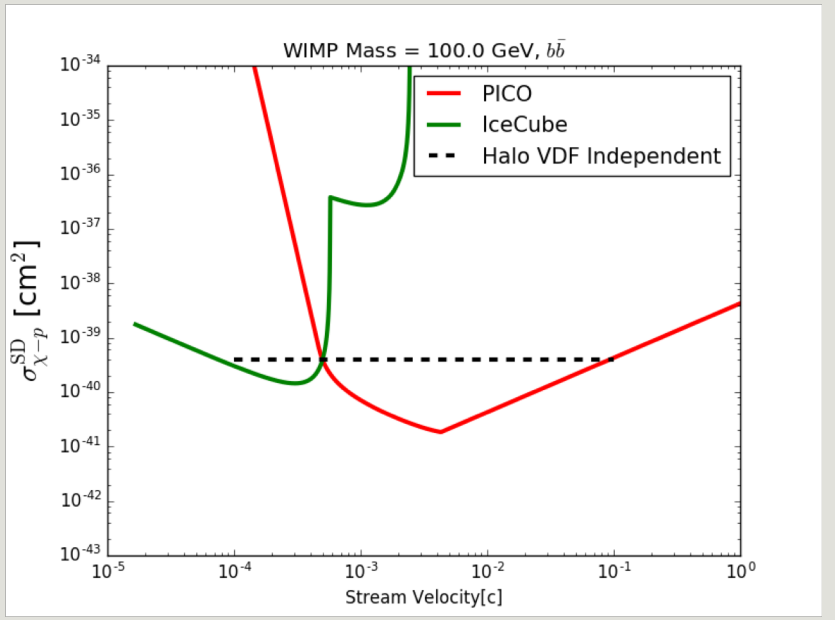
$\sigma_{SD} < 10^{-39} cm^2 \, (10^{-38} cm^2) for \, a \, 1 \, TeV \, DM \rightarrow \tau^+\tau^- \, (b\bar{b})$ for $\rho = 0.3 \, GeV/cm^3$

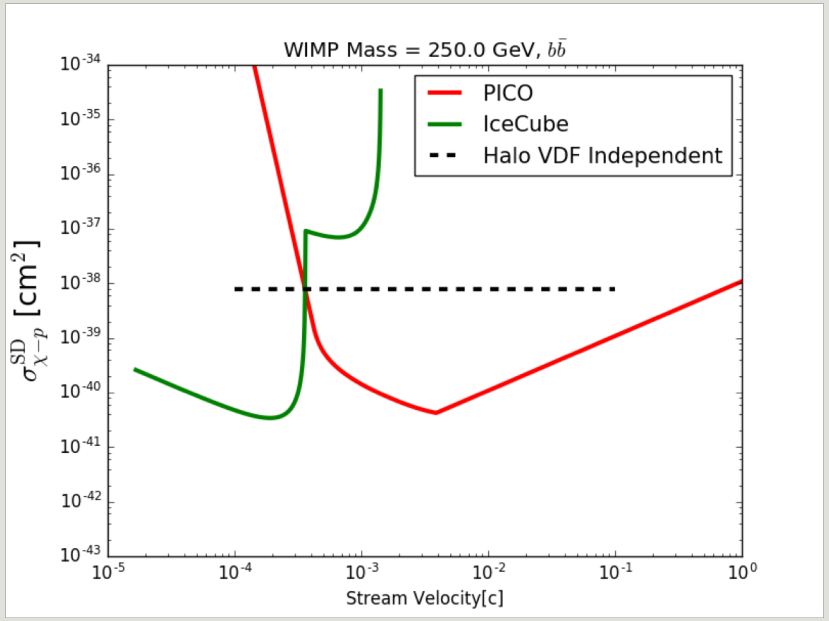
Conservative and robust w.r.t. any uncertainties in the VDF

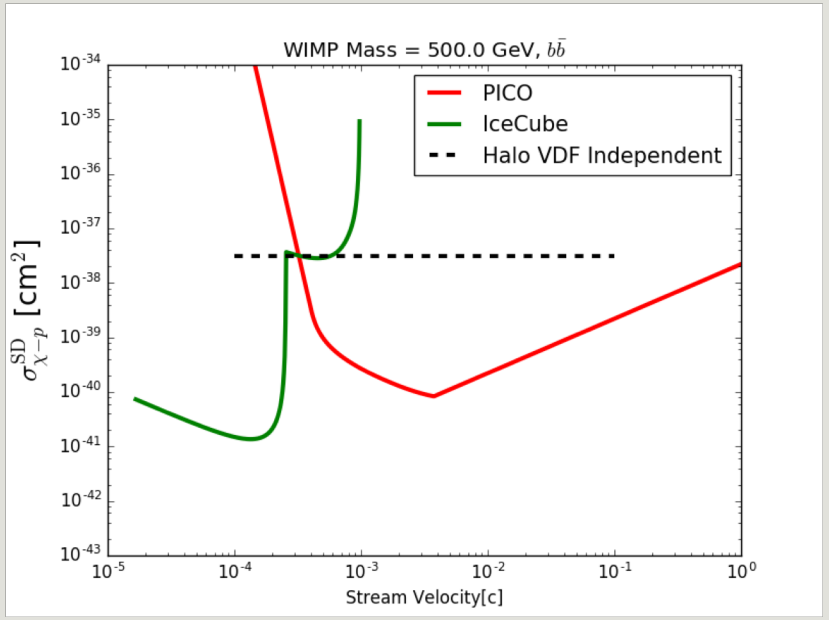
Unfortunately, still susceptible to uncertainties/local fluctuations in ρ

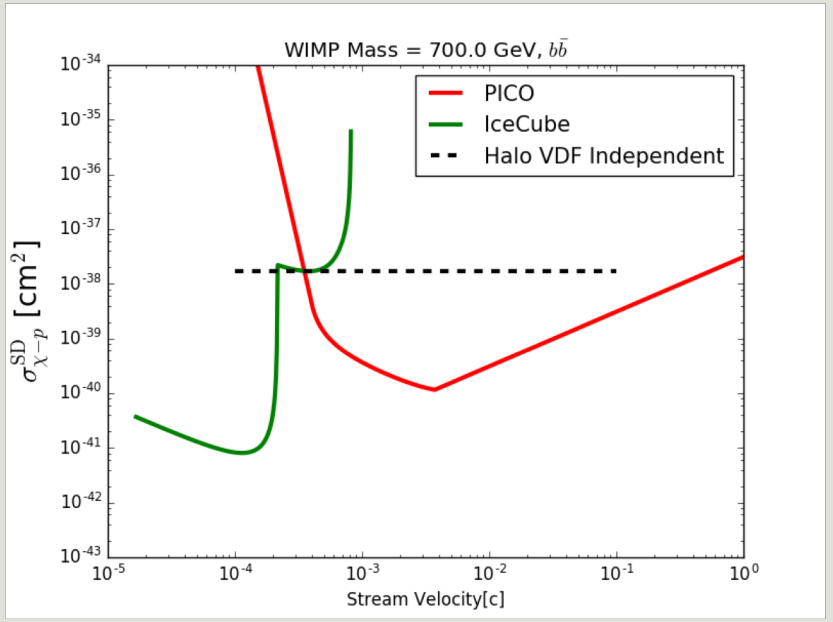

WIMP Mass = 35.0 GeV, $b\bar{b}$
$\sigma^{SD}_{\chi-p}$ [cm^2]
Stream Velocity[c]
PICO
IceCube
Halo VDF Independent


WIMP Mass = 50.0 GeV, $b\bar{b}$
$\sigma^{SD}_{\chi-p}$ [cm^2]
Stream Velocity[c]
PICO
IceCube
Halo VDF Independent


WIMP Mass = 100.0 GeV, $b\bar{b}$
$\sigma^{SD}_{\chi-p}$ [cm^2]
Stream Velocity[c]
PICO
IceCube
Halo VDF Independent


WIMP Mass = 250.0 GeV, $b\bar{b}$
$\sigma^{SD}_{\chi-p}$ [cm^2]
Stream Velocity[c]
PICO
IceCube
Halo VDF Independent


WIMP Mass = 500.0 GeV, $b\bar{b}$
$\sigma^{SD}_{\chi-p}$ [cm^2]
Stream Velocity[c]
PICO
IceCube
Halo VDF Independent


WIMP Mass = 700.0 GeV, $b\bar{b}$
$\sigma^{SD}_{\chi-p}$ [cm^2]
Stream Velocity[c]
PICO
IceCube
Halo VDF Independent

Summary & Outlook

All comments from IceCube reviewers have been implemented.

PICO review will come with the paper.

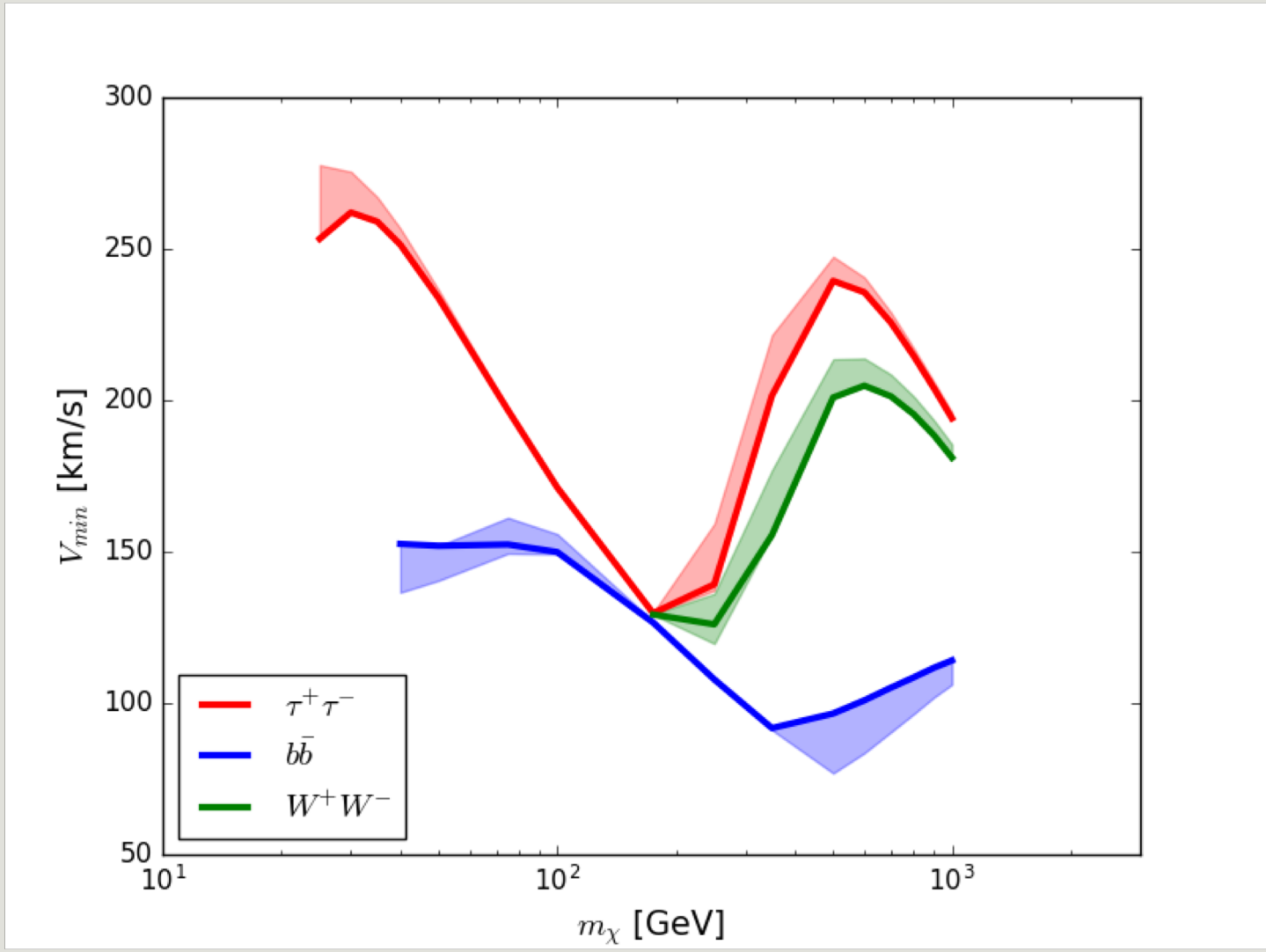
Not a blinded analysis, write paper soon.

Review from the PICO side will come at the stage of the paper draft.

Paper outline in discussion in the WG

Thanks to my reviewers.

How fast should you drive your dark matter particle to escape IceCube and PICO

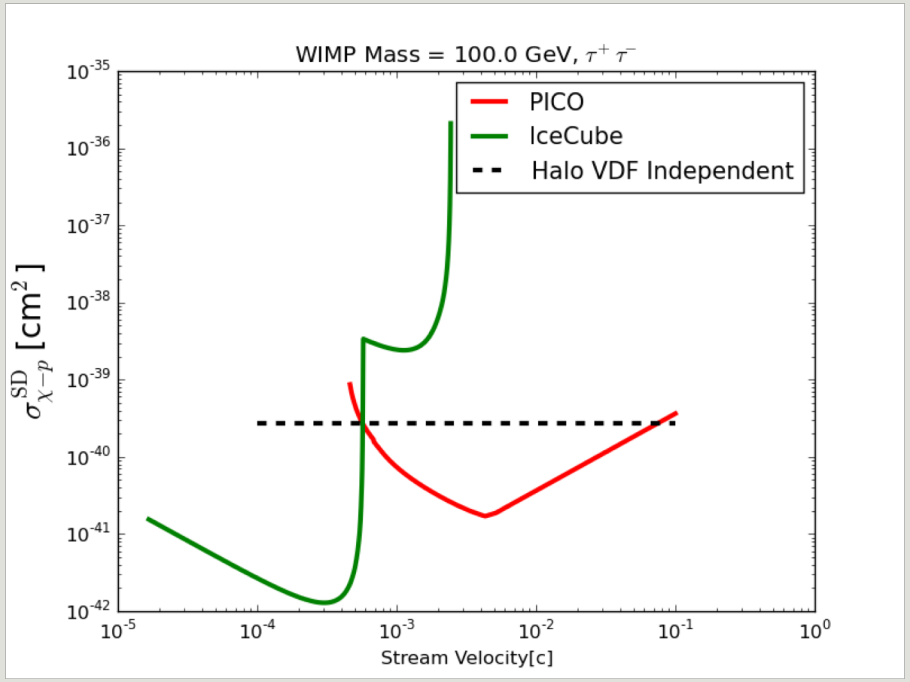


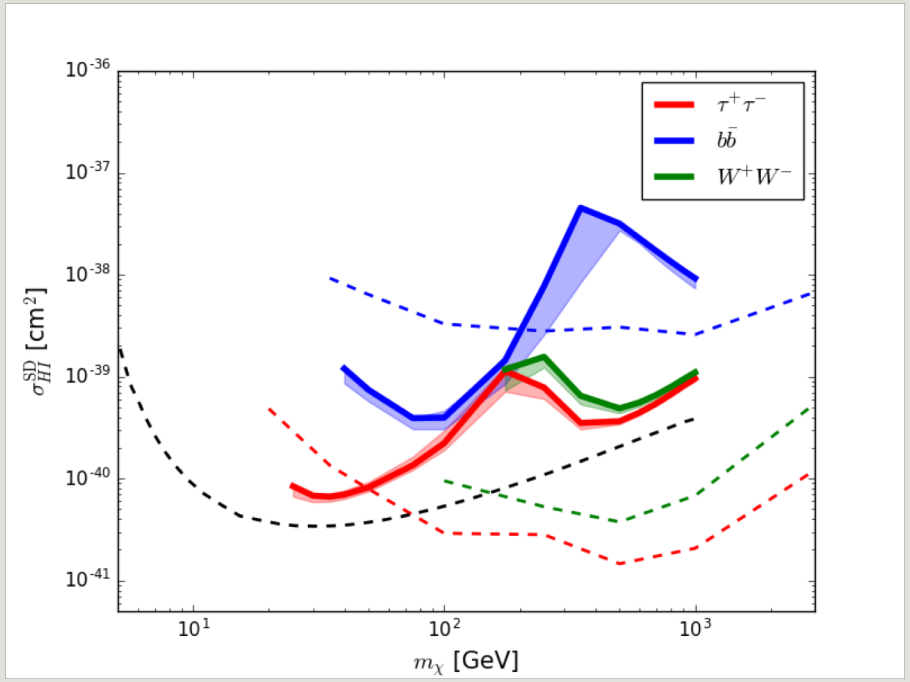
Preliminary Paper Outline

Proposed Journal: EPJC Letters?

Proposed Title : “Halo Velocity Distribution Independent constraints on Spin-Dependent DM-Nucleon interactions”
Authors : PICO and IceCube collaborations

Figures to show :



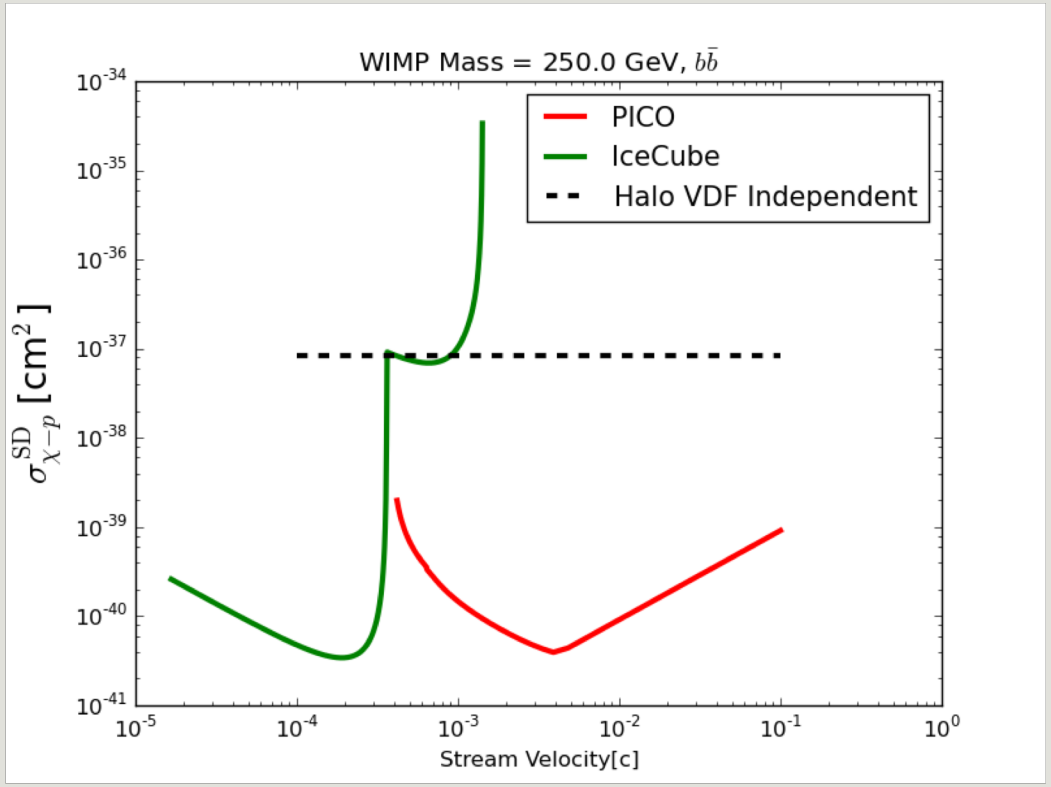


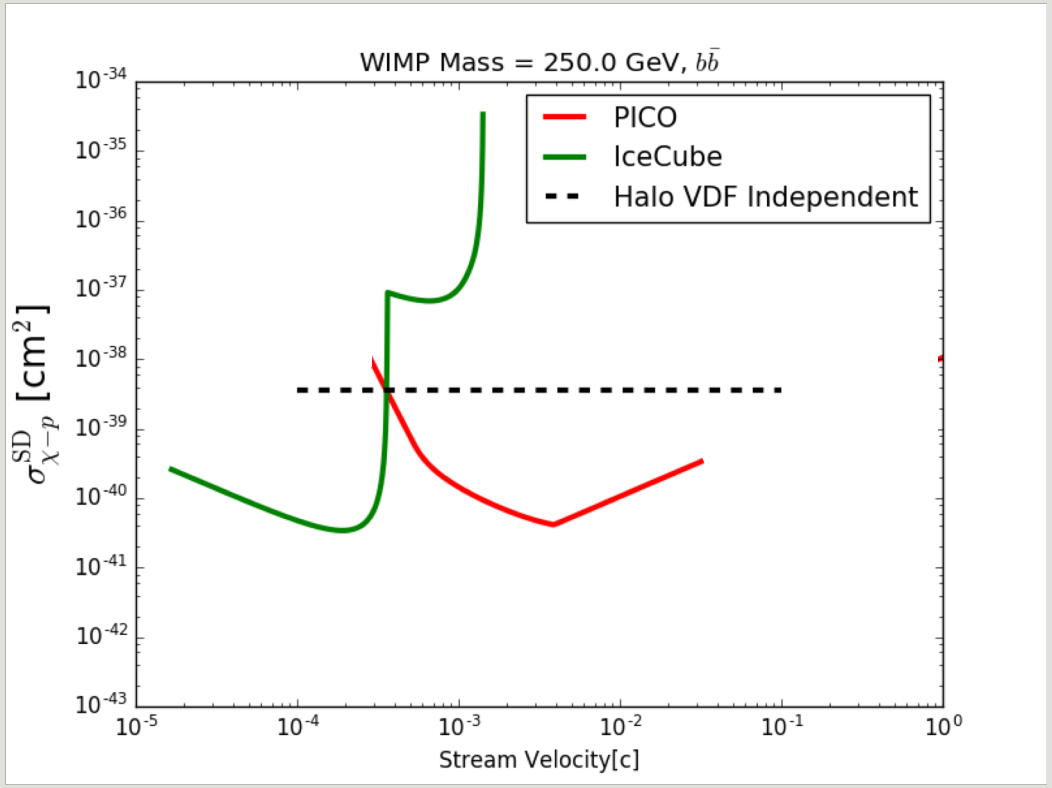
What has changed?

Switched to dmdd (https://pypi.org/project/dmdd/) instead of exponential form factors. (very small difference)

Switched to 1 sigma pessimistic efficiency curves for PICO

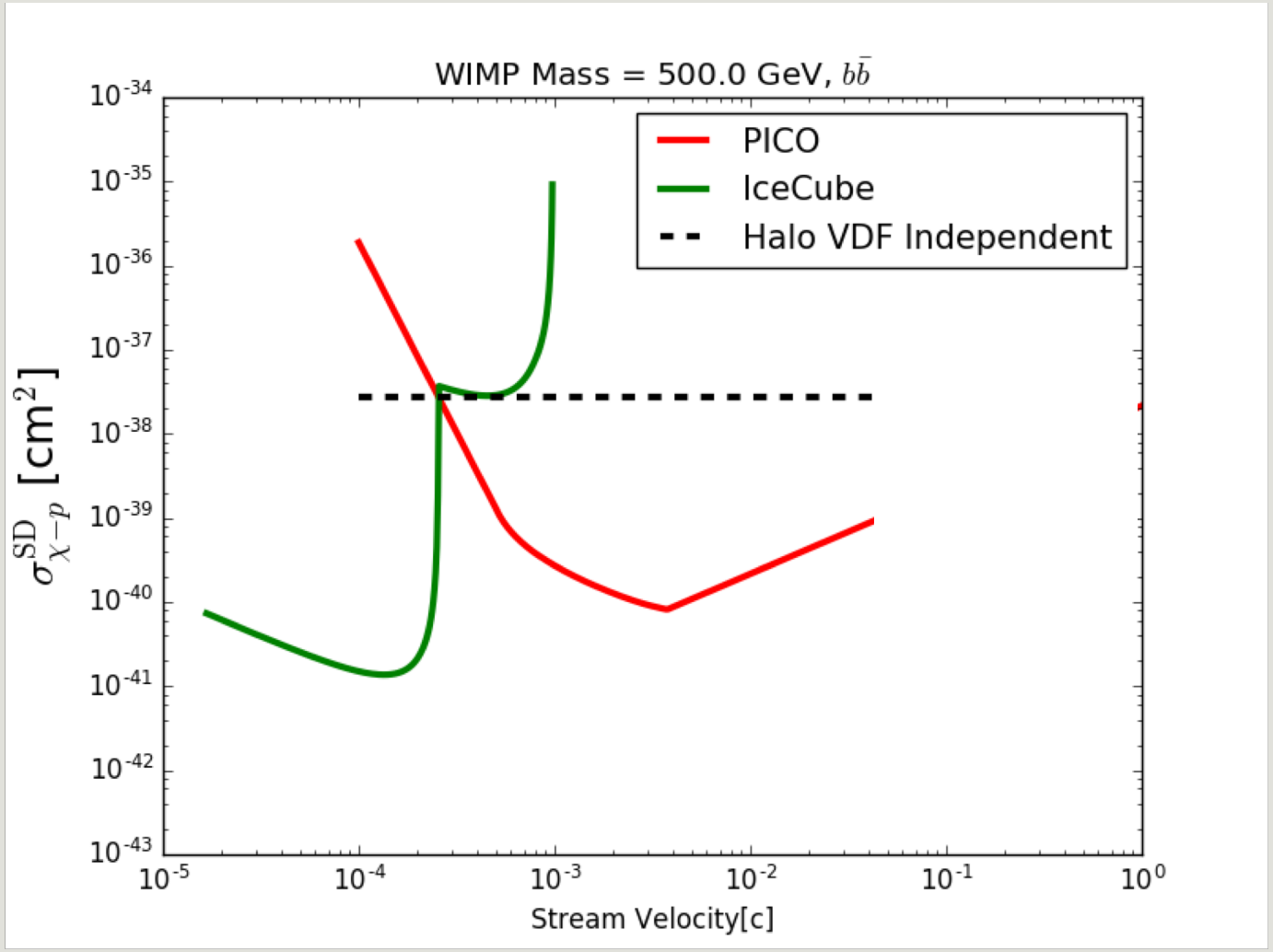
Finer scan near threshold to more precisely find the intersection





Why is 500 GeV bbar so bad

Sun : Kinematic threshold for scattering off Protons, beyond this only Nitrogen contributes
PICO – maximum recoil energy just at efficiency threshold



Systematics

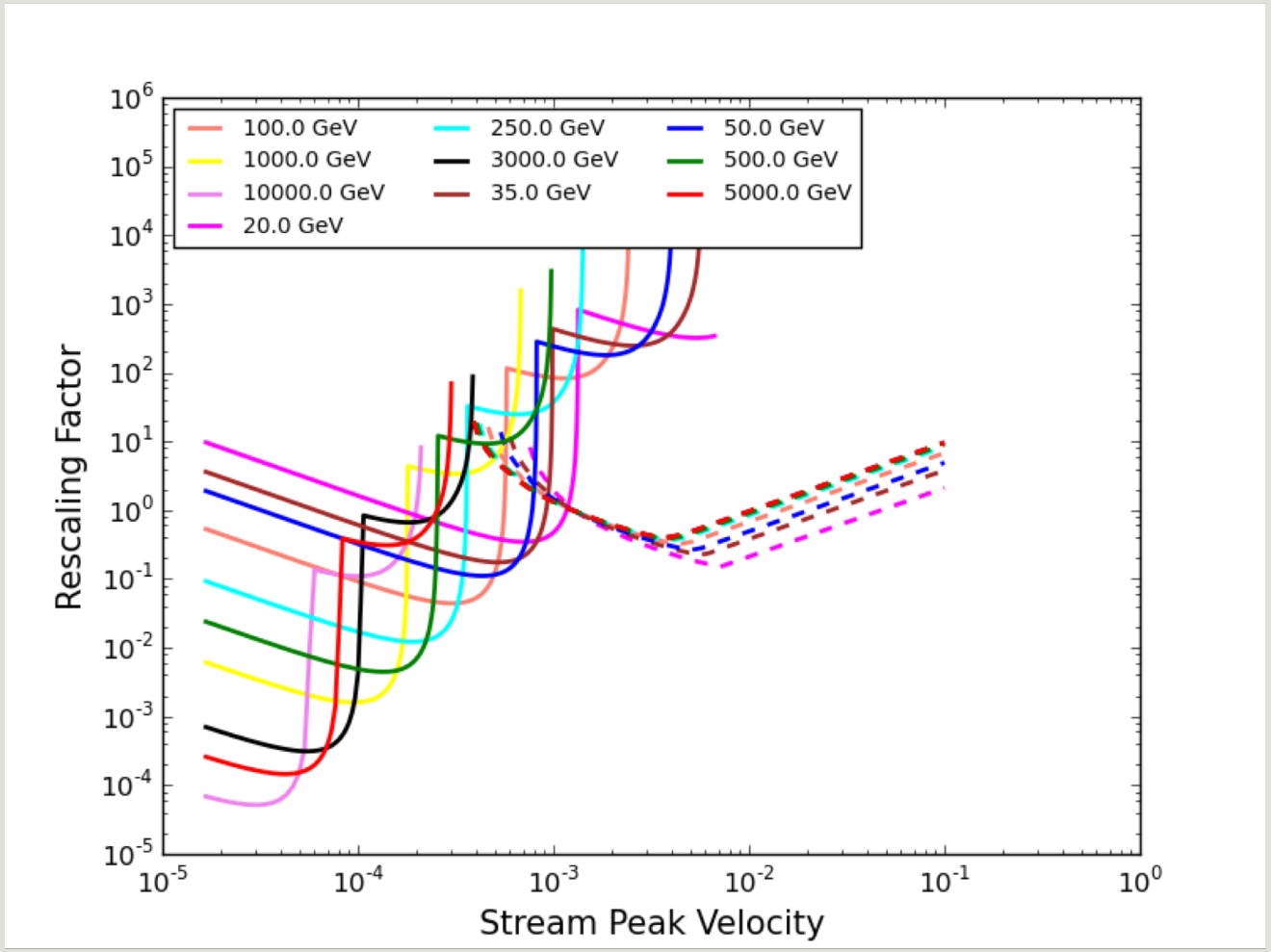
IceCube curves are already scaled up to IceCube systematics pessimistic

PICO curves are obtained from 1 sigma pessimistic efficiencies.

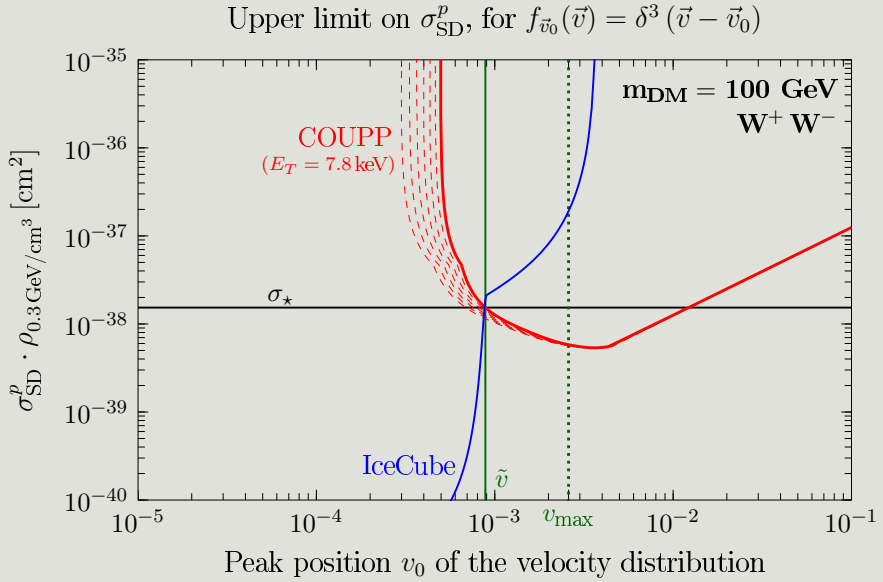
Sufficient? Derive same results with optimistic curves from both experiment and draw a band?

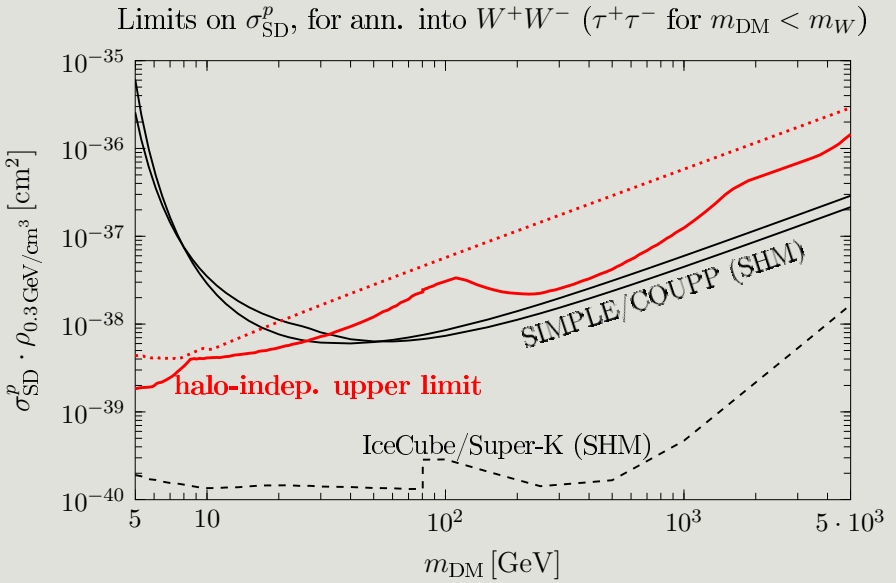
Backups

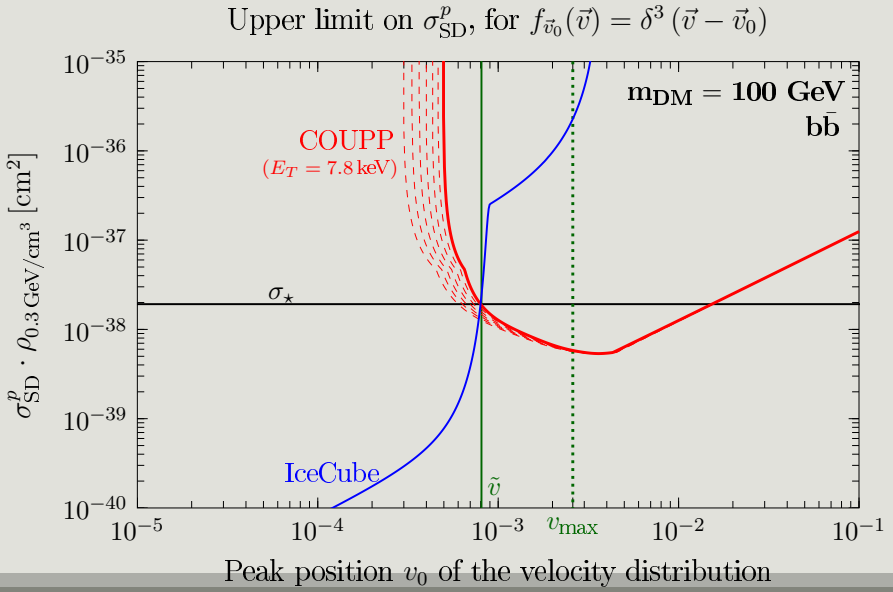
Rescaling Factors

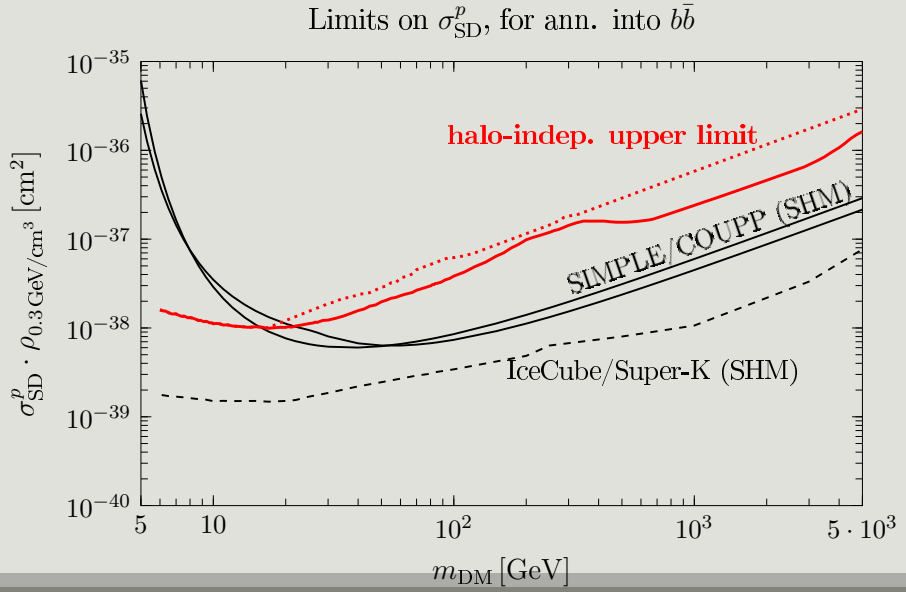


Ferrer, Ibarra and Wild - Results









Paper from 2015: Authors used simplified solar model, form factors and older IC results

We can do better:

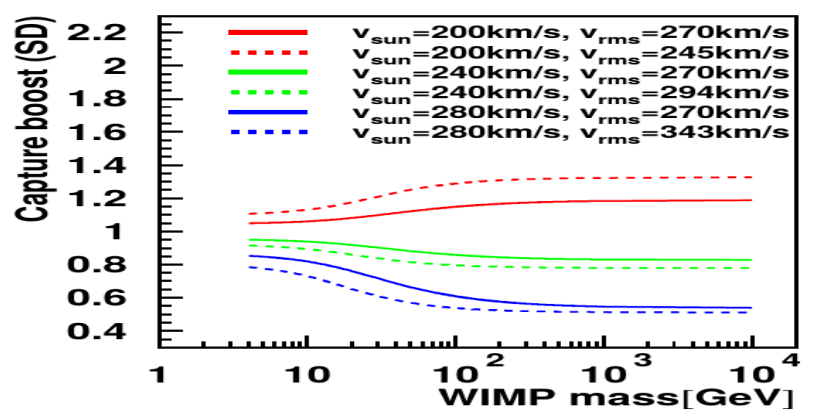
Newer IC Solar DM limits - 3 year Combined

PICO is orders of magnitude better than COUPP

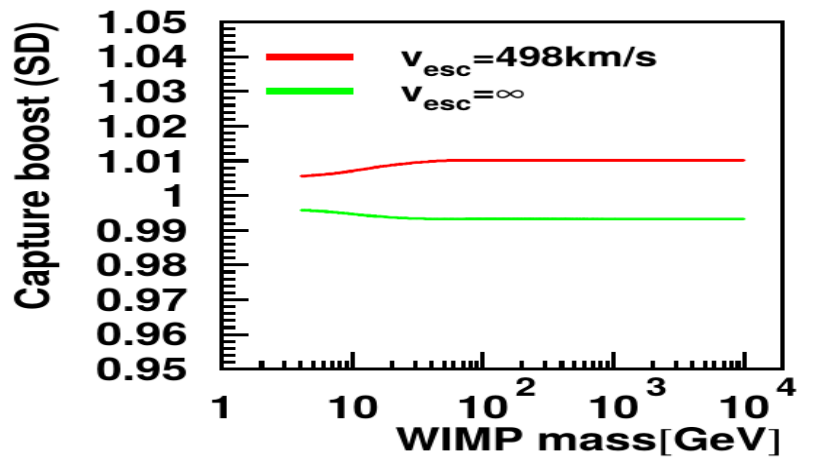
Astrophysical Uncertainties

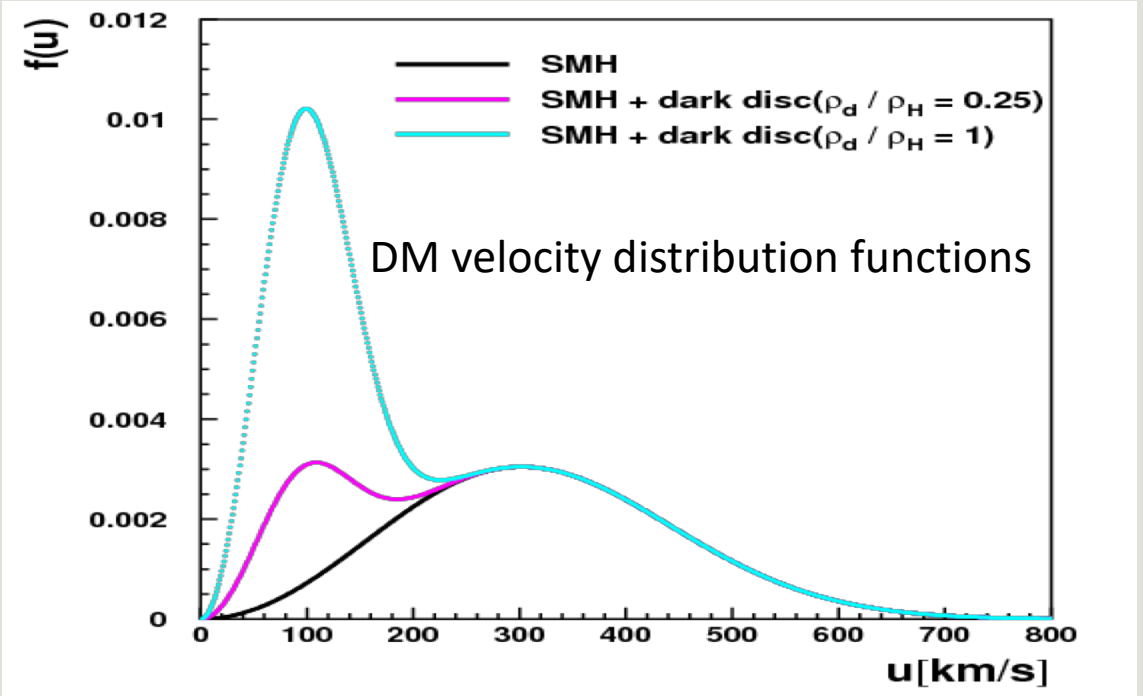
There are uncertainties on:

- The velocity of the Sun w.r.t the halo



- The fraction of DM in a co-rotating dark disk
- The galactic escape velocity





C. Rott et al. JCAP05 (2014) 049

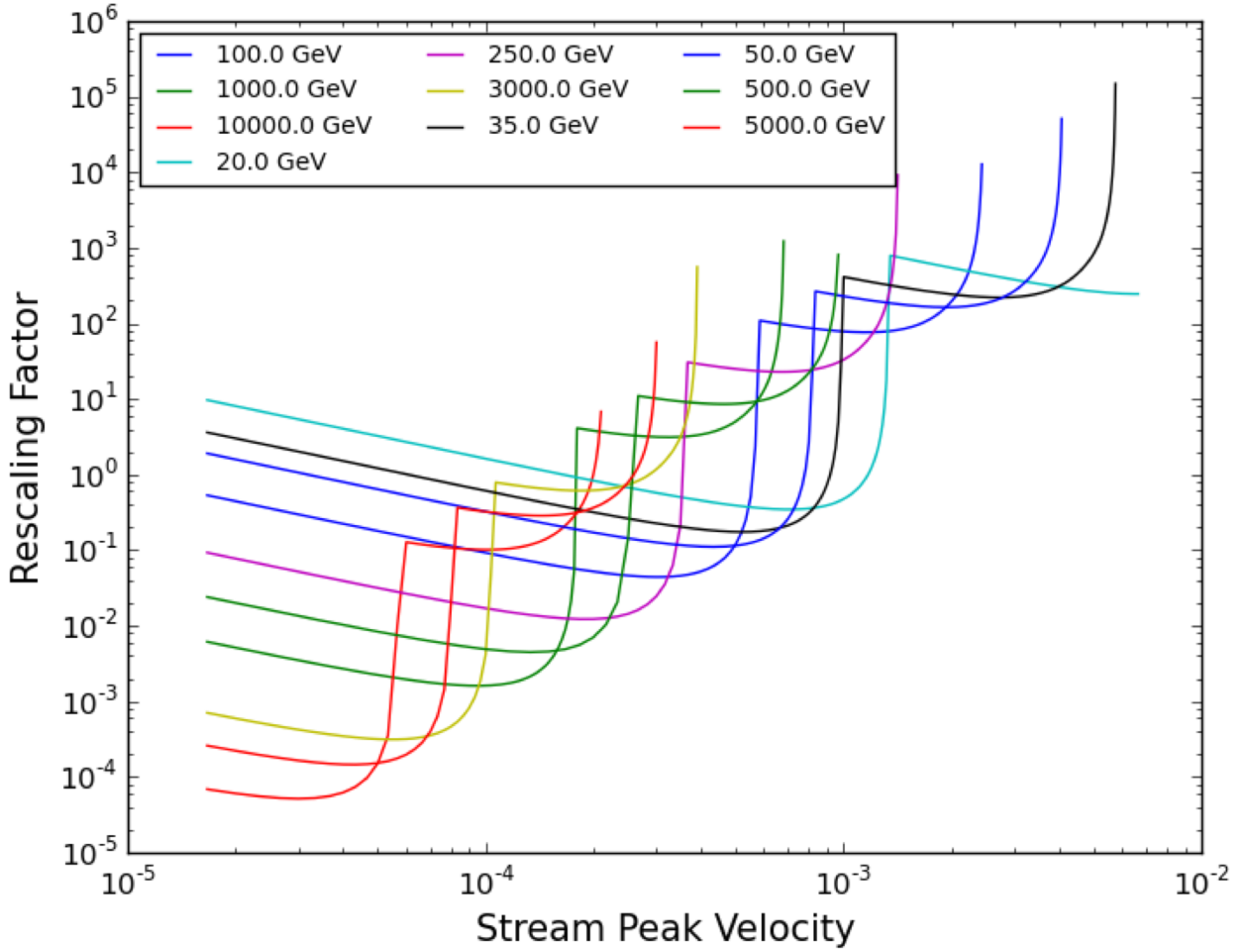
The uncertainties are **20% (50%) at low (high) WIMP masses**

Our results are conservative w.r.t. the dark disk fraction.

Largest uncertainties come from the VDF and the local DM density

Preliminary Results (contd)

https://github.com/rameez3333/SolarCaptureRates



Currently waiting for the PICO lines from Ken Clark

The plan is to derive IceCube-PICO combined VDF independent SD limits and

IceCube-LUX combined VDF independent SI limits.

Ferrer, Ibarra and Wild - Results