DARK MATTER SEARCHES IN

IceCube

J. A. Aguilar on behalf of IceCube

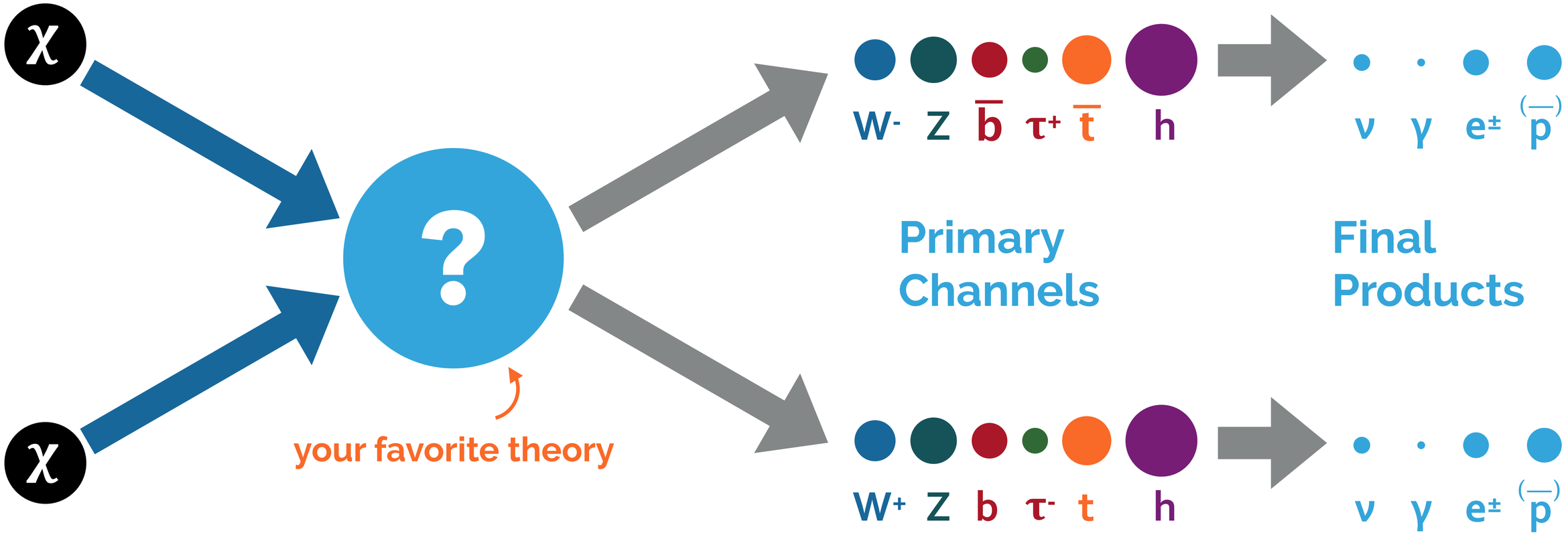
Photo: Ian Reese

ULB

31st Rencontres de Blois 2019

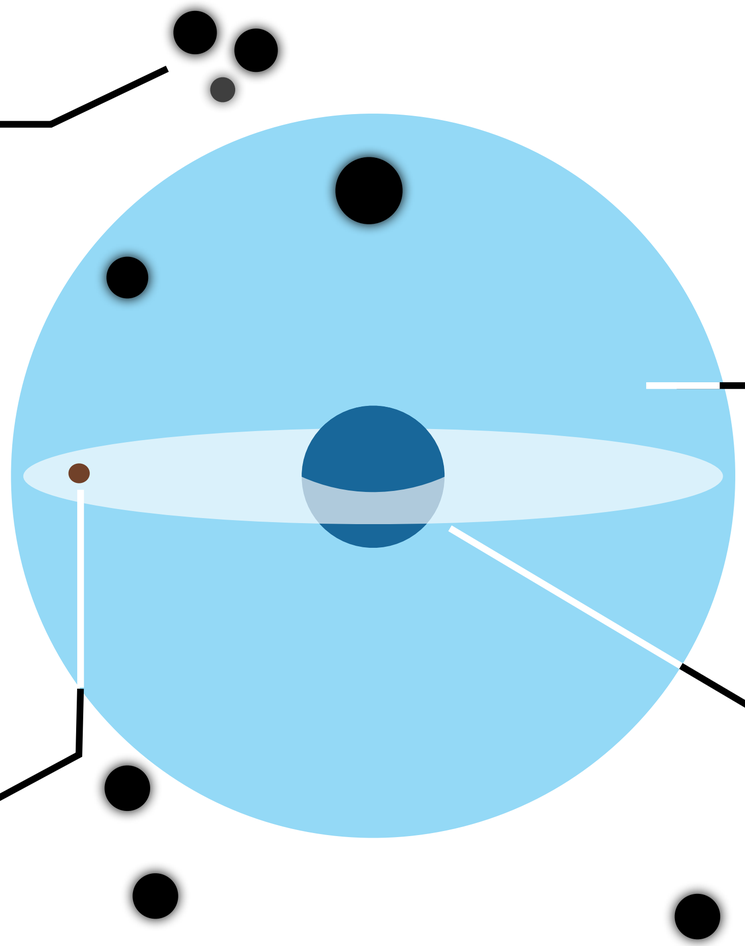
iihe

Indirect Detection of Dark Matter



- No need of specialized detectors: **Gamma-ray telescopes, neutrino detectors, CR-experiments**
- Search for products of dark matter annhilation processes: **Focus on large reservoirs of dark matter**

Dark Matter Searches Where to Look?



Dwarf spheroidal Galaxies
Cluster of Galaxies

Probe velocity-averaged DM annihilation cross section $\langle v\sigma_A \rangle$

Galactic Halo

Probe velocity-averaged DM annihilation cross section $\langle v\sigma_A \rangle$

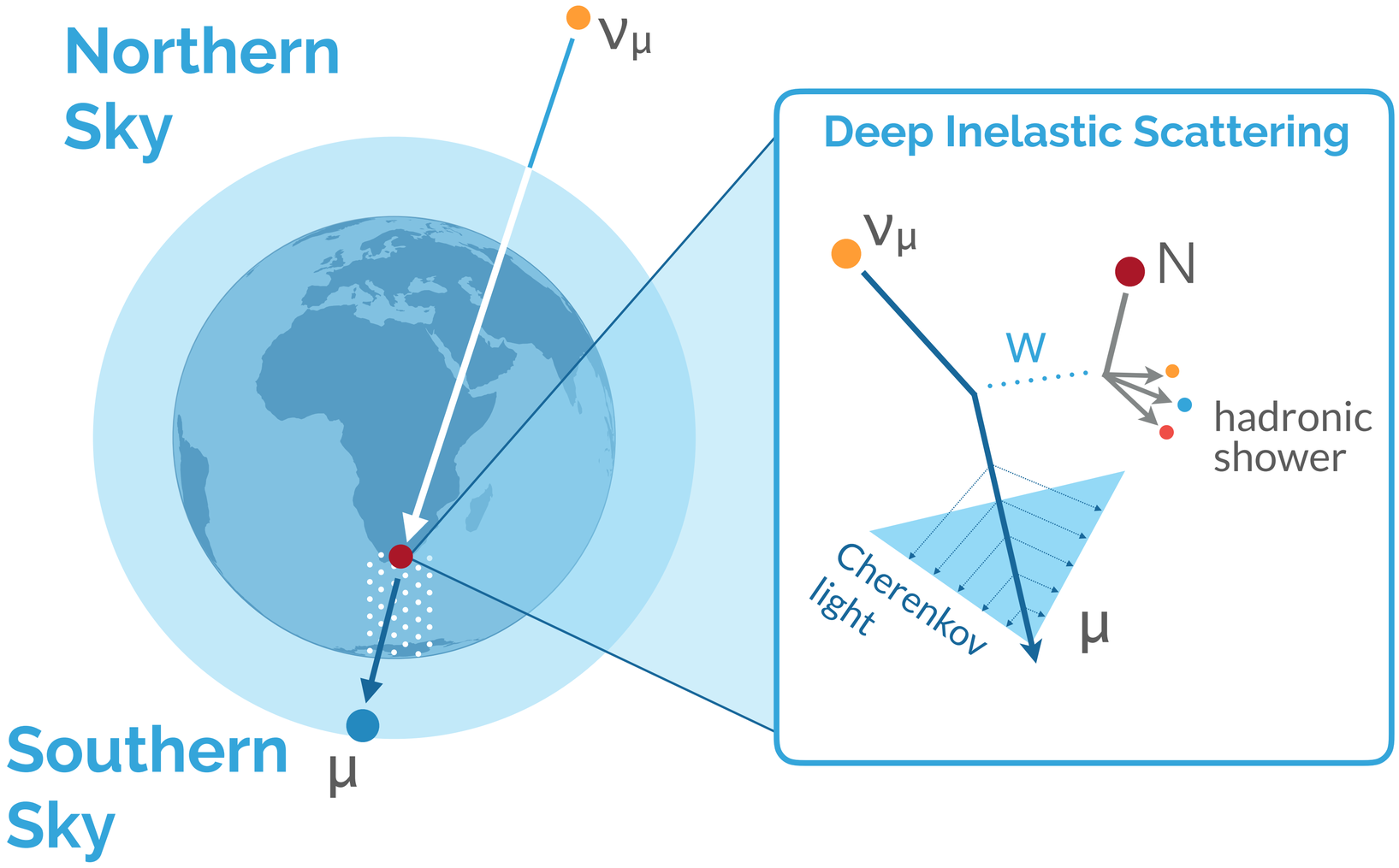
Galactic Center

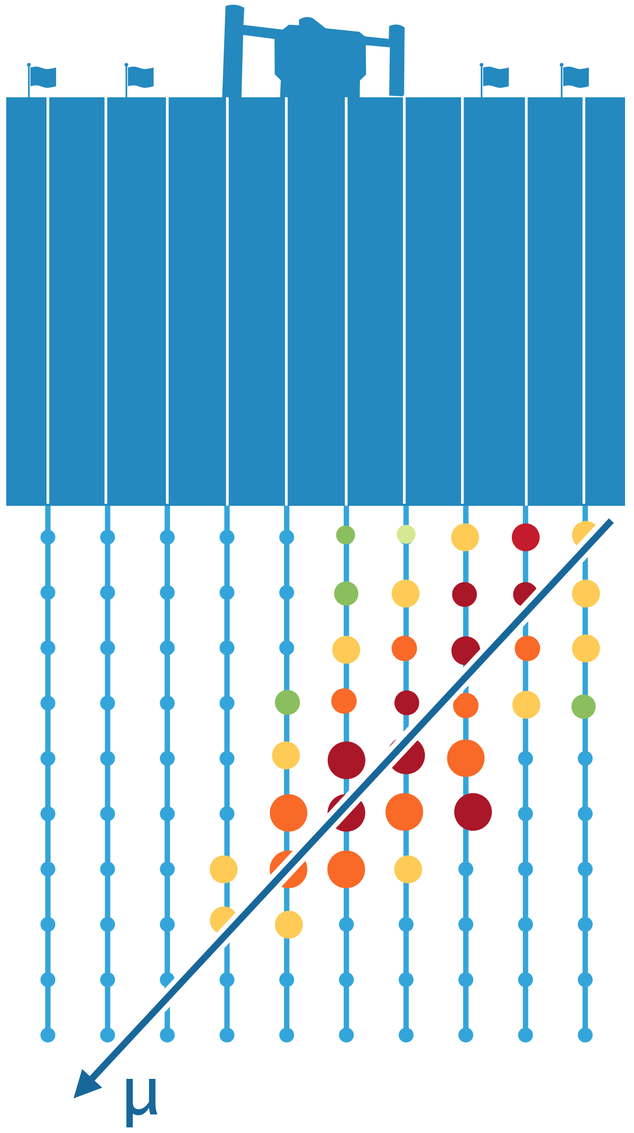
Probe velocity-averaged DM annihilation cross section $\langle v\sigma_A \rangle$

Local Sources (Sun, Earth)

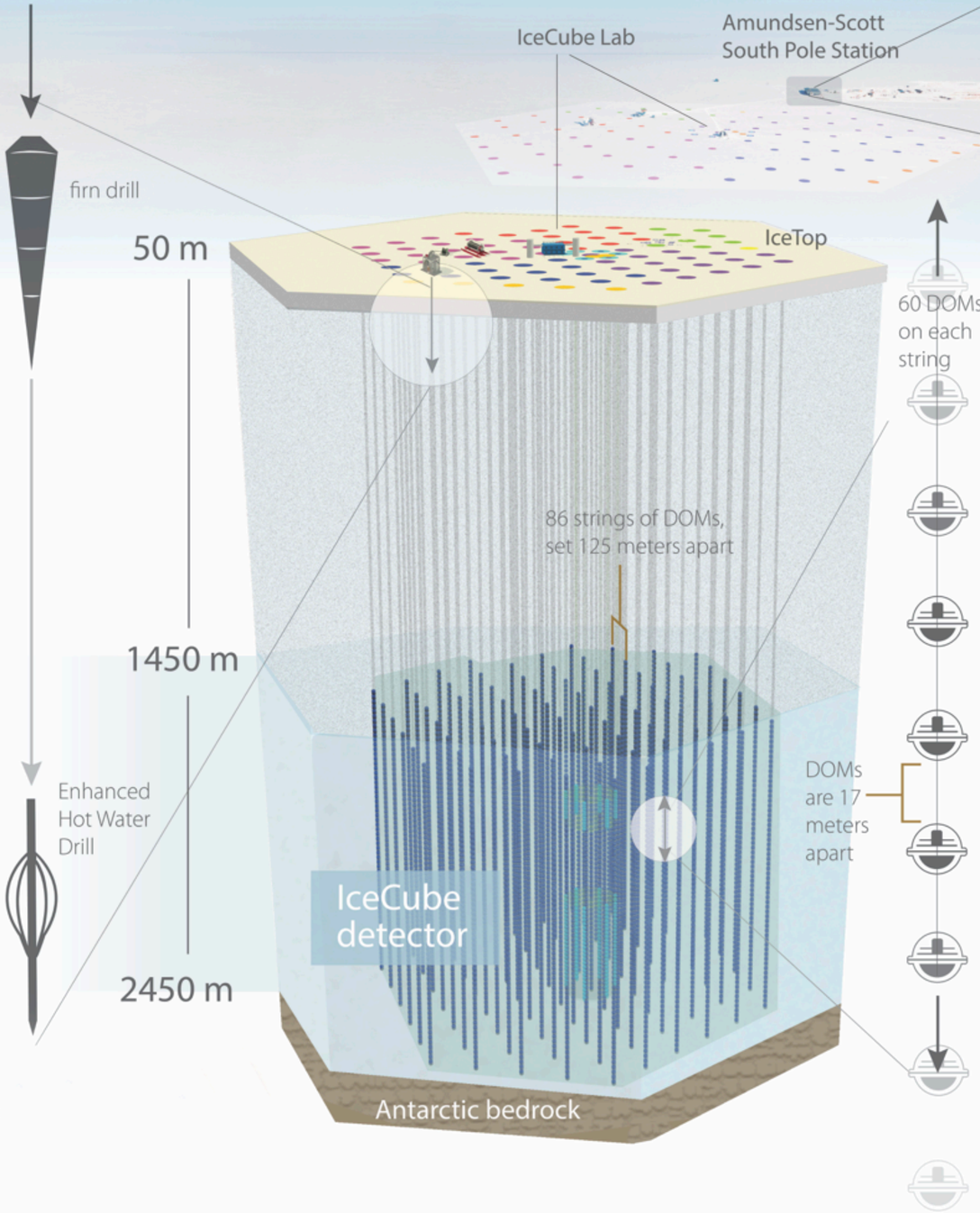
Only accessible with neutrinos
Under equilibrium they can probe σ_{SI} and σ_{SD}

Detection Principle How Do We Detect Neutrinos?

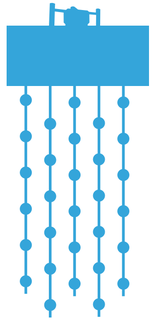




IceCube Neutrino Observatory



5,160 Digital Optical Modules (DOMs)



86 string with 60 DOMs each

6 denser strings called **DeepCore**

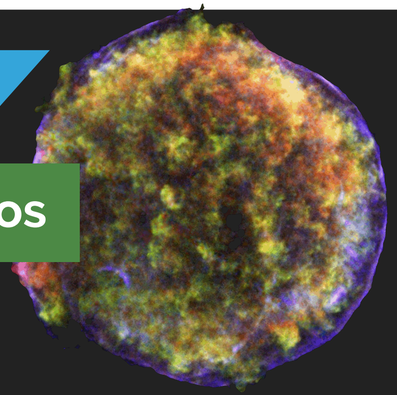
1 km^2 surface array with 324 DOMs: **IceTop**

Completion in December 2010

Neutrino Detectors Scientific Scope

And Cosmic Rays

SN Neutrinos



Astrophysical

MeV

GeV-TeV

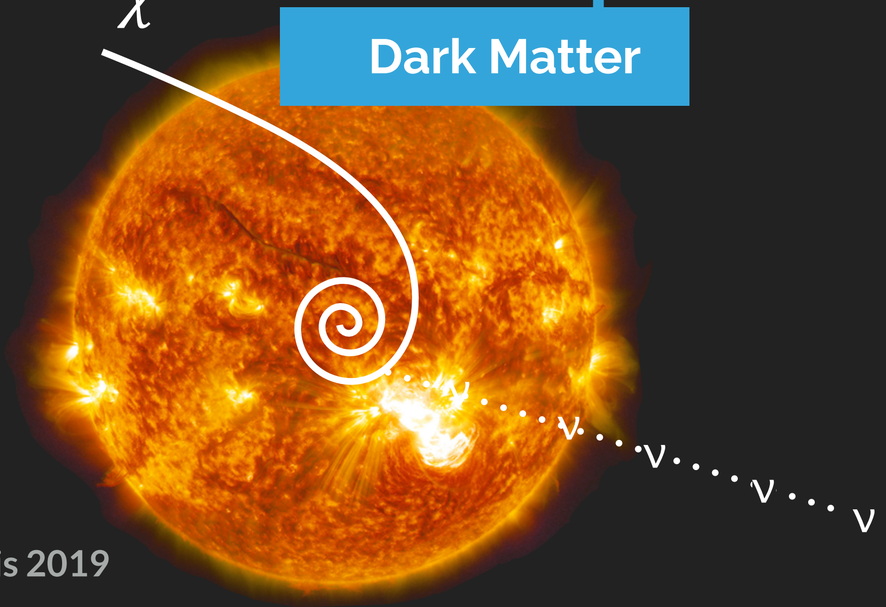
<100 TeV

>100TeV

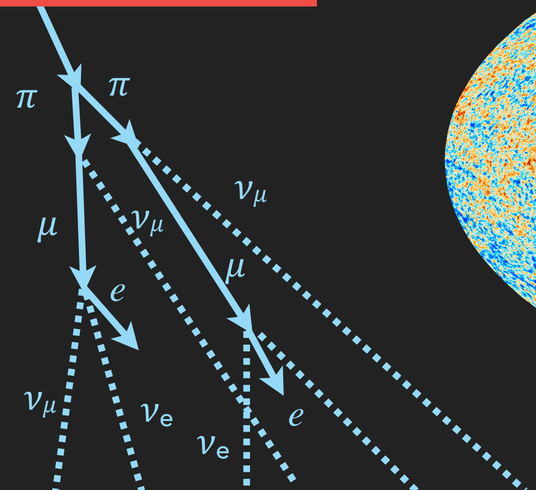
> 10^6 TeV

χ

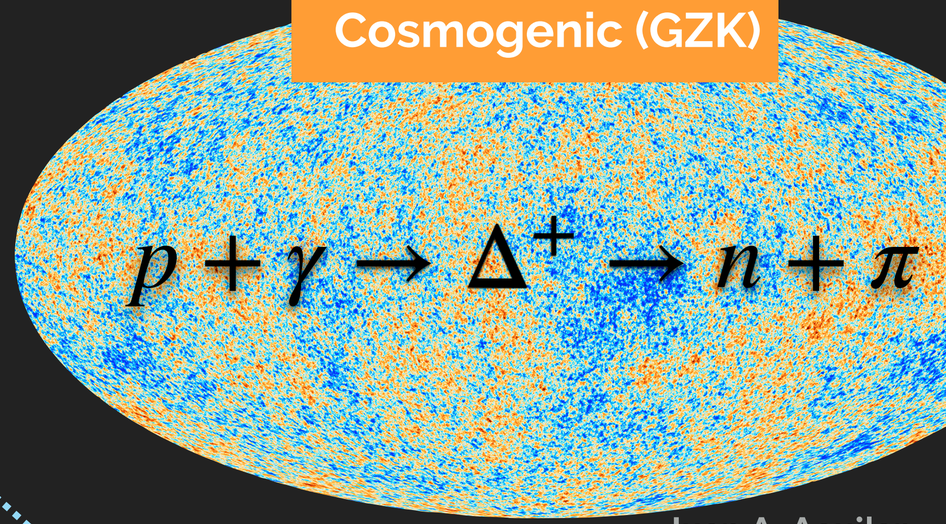
Dark Matter



Atmos: Oscillations, sterile ν , Prompt



Cosmogenic (GZK)



Neutrino Detectors Scientific Scope

And Cosmic Rays

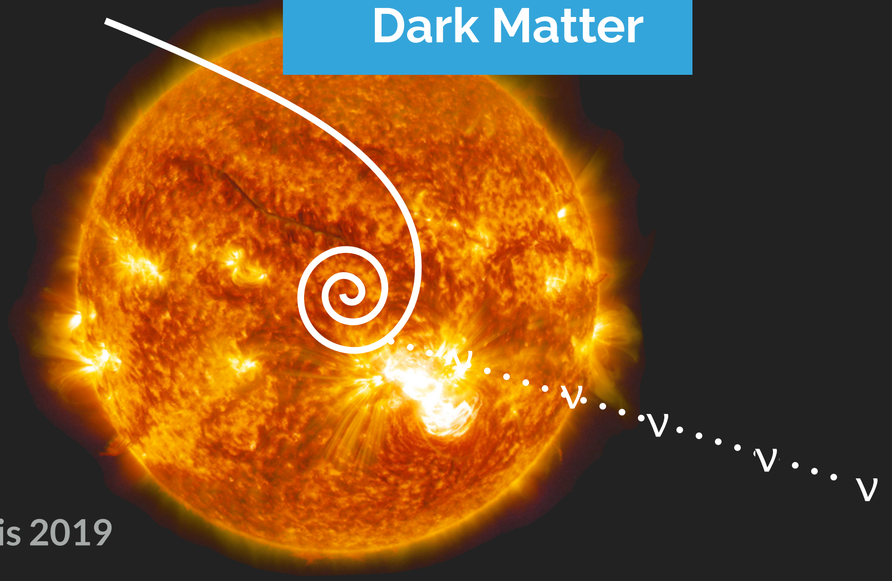
SN Neutrinos

Astrophysical

MeV | GeV-TeV | <100 TeV | >100TeV | > 10^6 TeV

Dark Matter

χ



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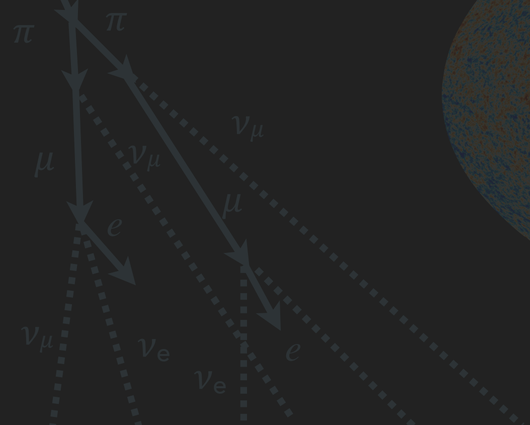

Cosmogenic (GZK)

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi$$

Dark Matter Searches In a Nutshell

$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\int_0^{\Delta\Omega}\mathrm{d}\Omega\int_{l.o.s}\rho_\chi^2(r(s,\Psi,\theta))\mathrm{d}s$$

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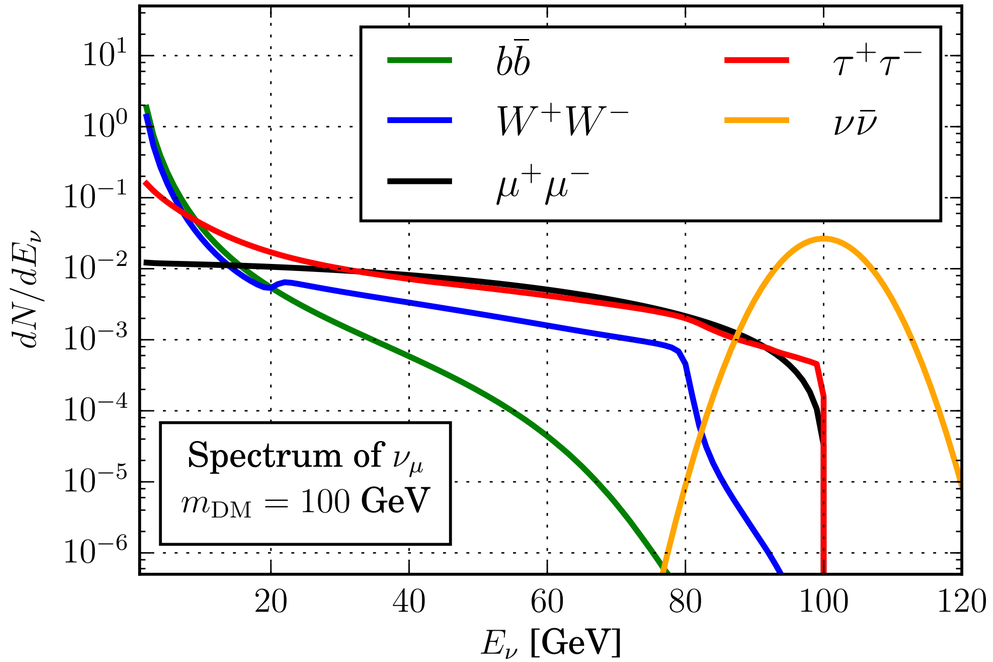
Theory input: SUSY?



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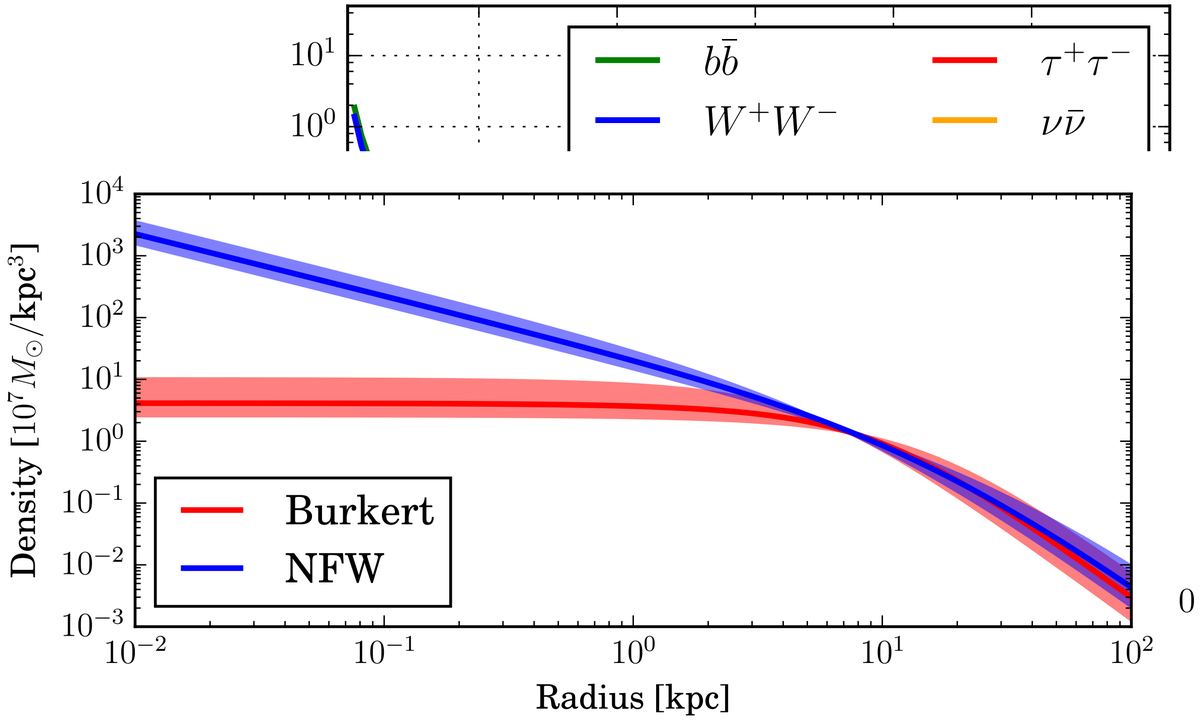

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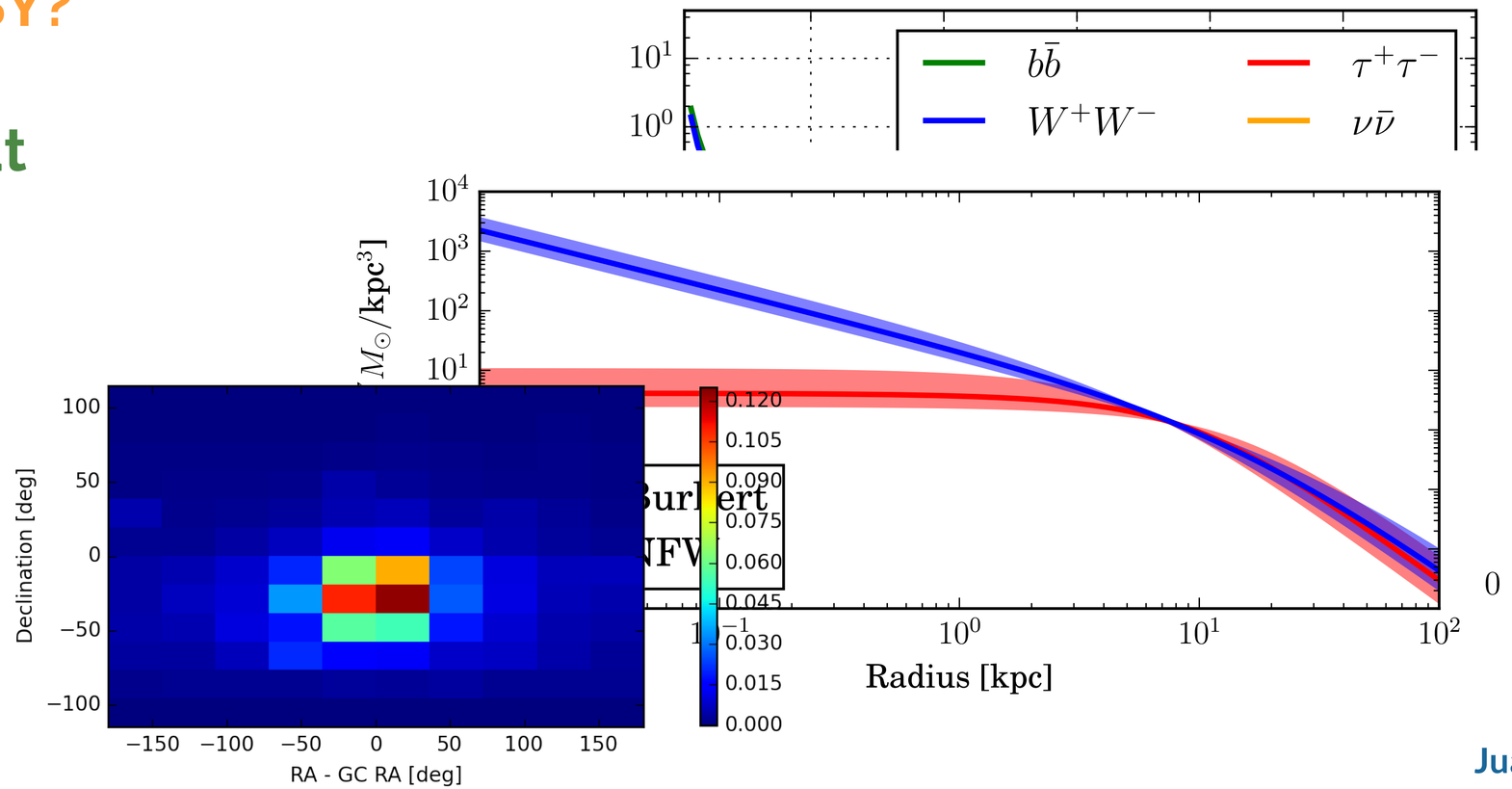
Astrophysics input

Measurement



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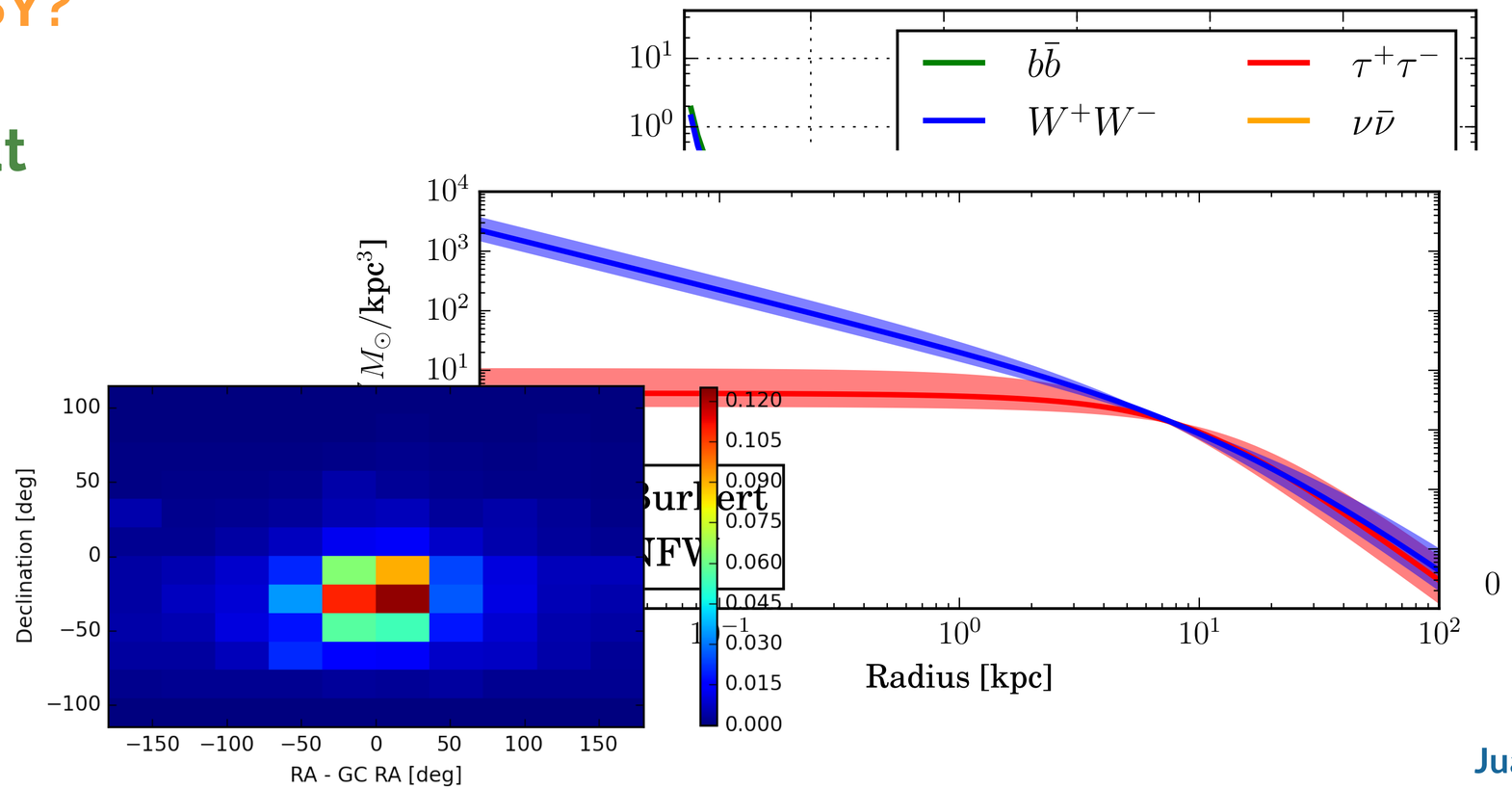
Theory input: SUSY?

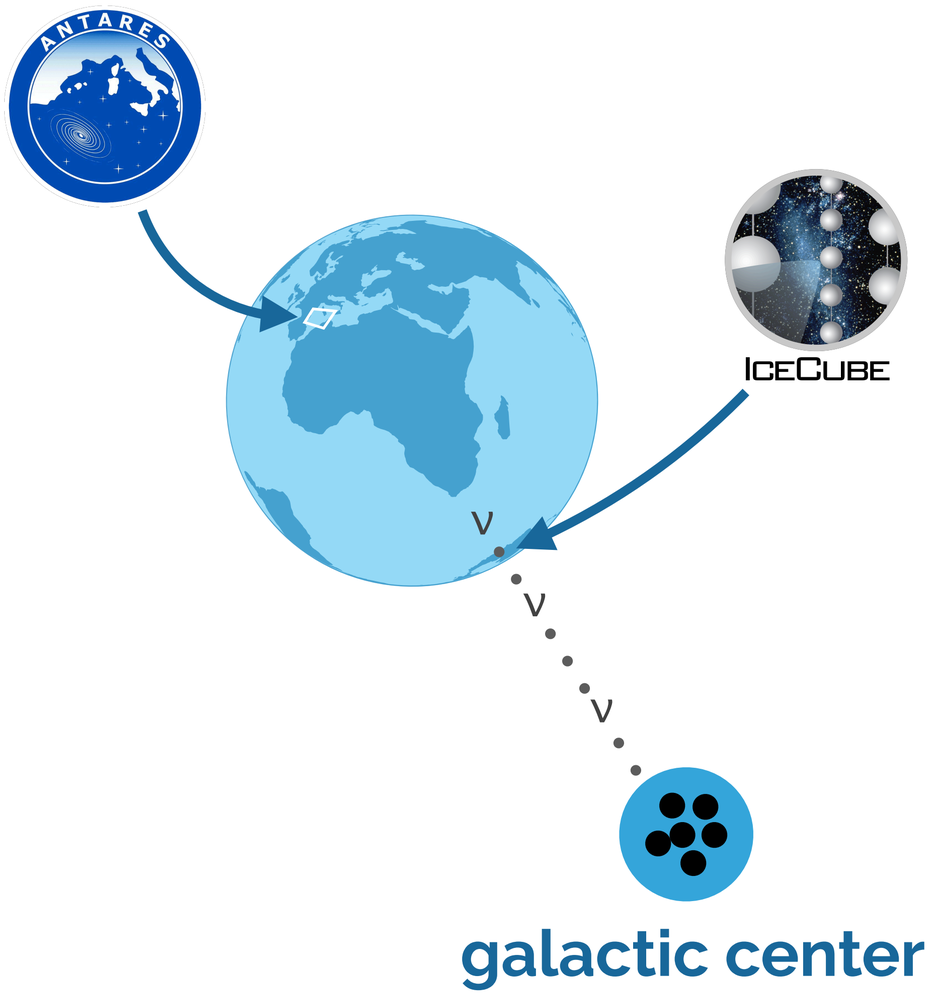
Astrophysics input

Measurement

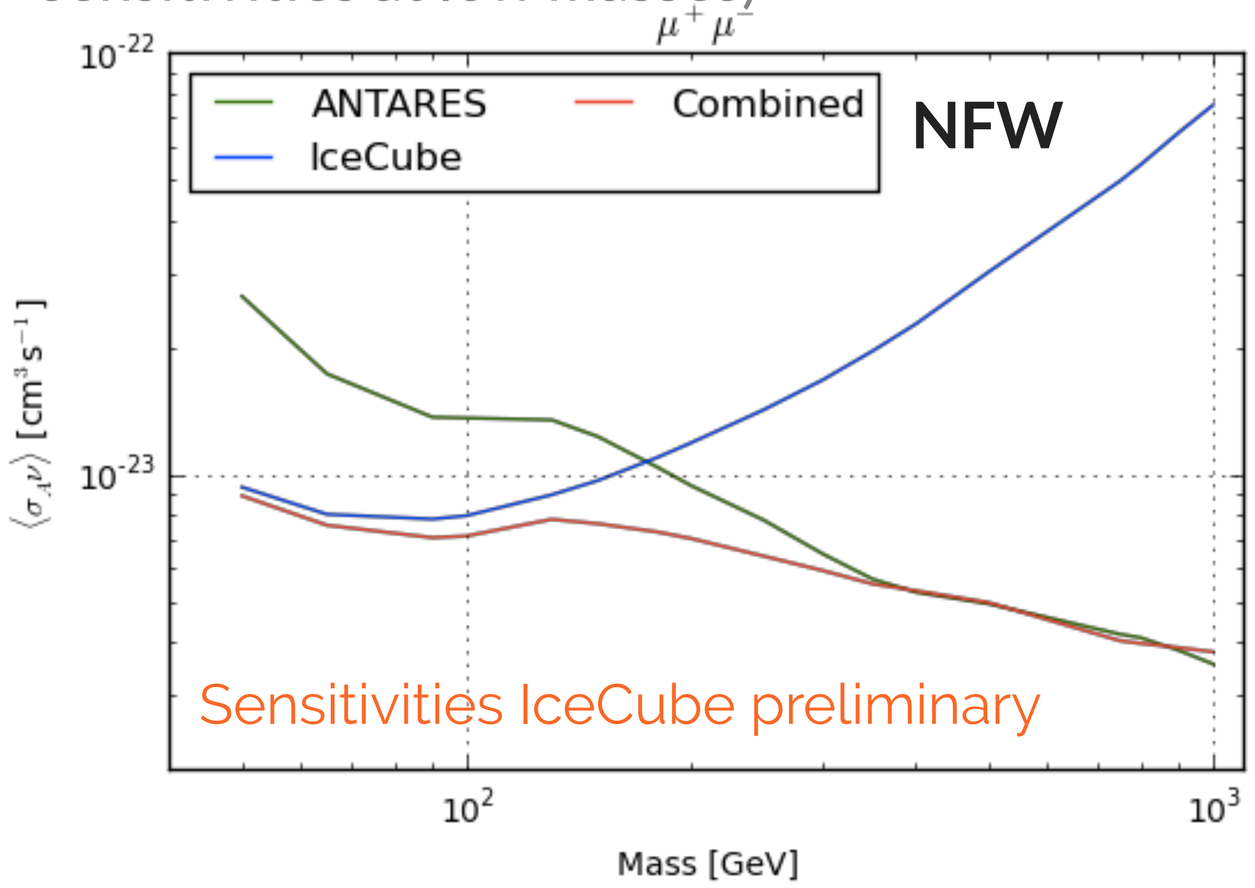
Constrain!



Galactic Center ANTARES & IceCube

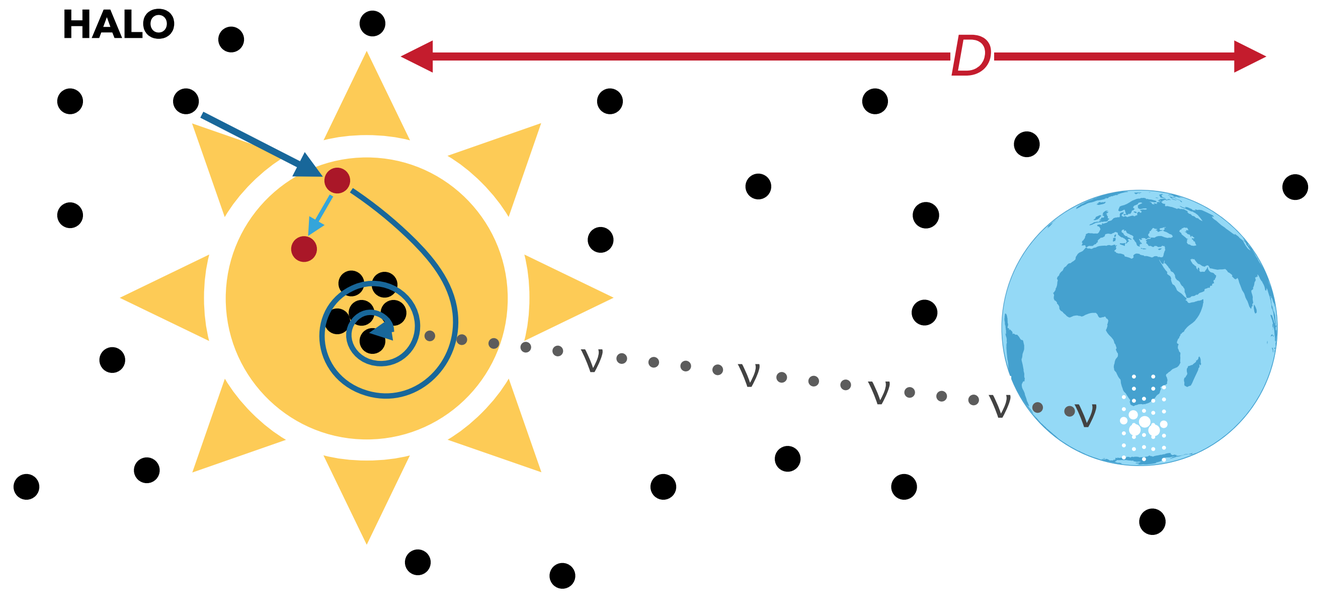


- ANTARES can use the Earth as a shield to observe the Galactic Center.
- IceCube needs a self-veto technique (better sensitivities at low masses)



[Neutrino 2018, doi:10.5281/zenodo.1300924]

Dark Matter from Celestial Bodies

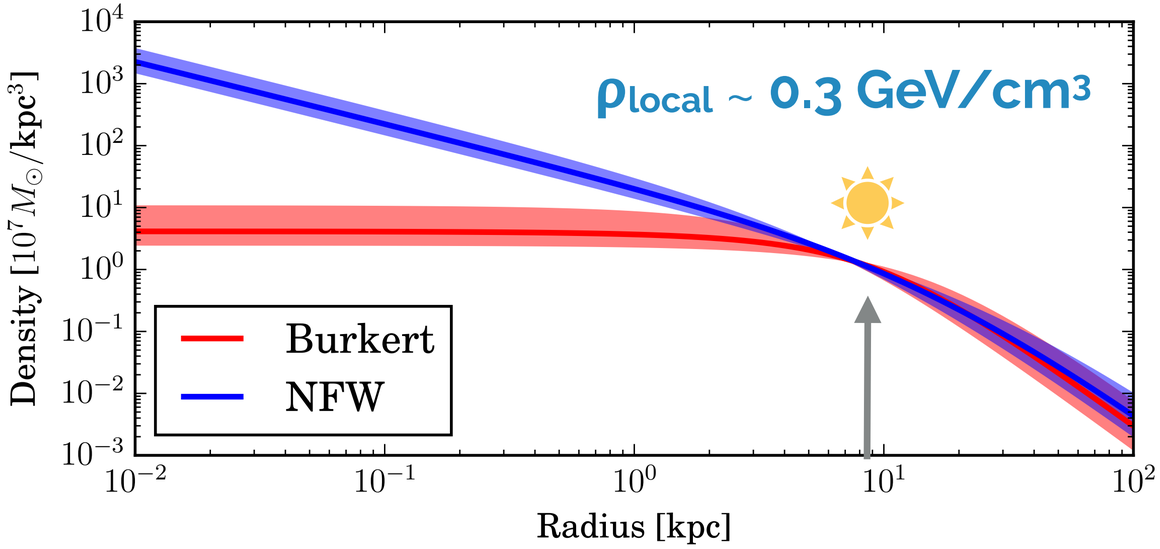


$$\frac{\mathrm{d}N}{\mathrm{d}t} = C_c - C_A N^2 - C_E N$$

annihilation σ_A

capture $\sigma_{\chi-N}$

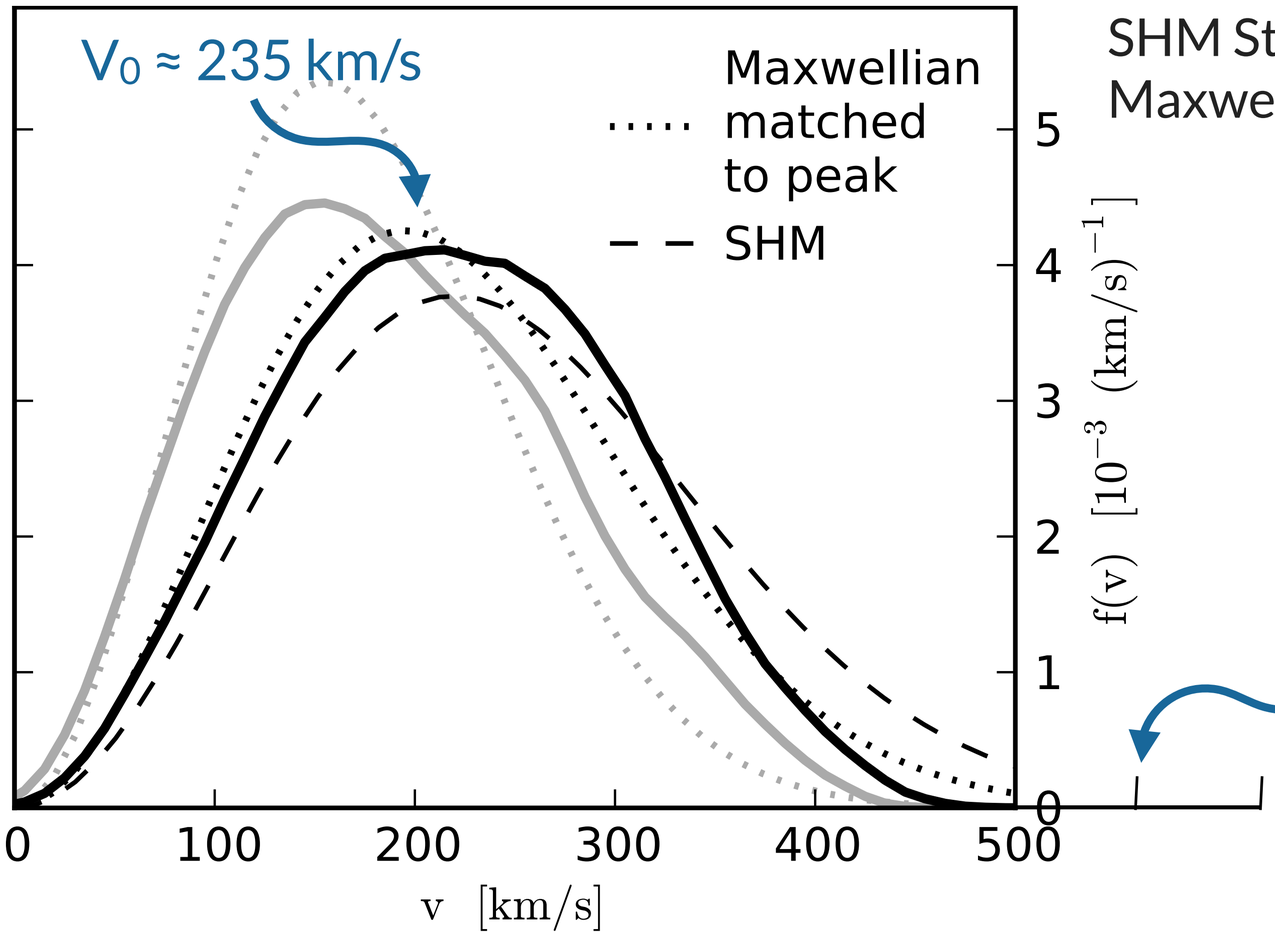
- Signal from the Sun or Earth in neutrinos cannot be mis-interpreted as an astrophysical source.
- Halo models agree in the Solar System.
- **Equilibrium** (dN/dt = 0) assumed for the Sun, not for Earth!



Celestial Bodies Velocity Distribution

Heavy dark matter particles can only be captured at low velocities

Figure from https://arxiv.org/pdf/1308.1703.pdf



SHM Standard Halo Model = Maxwellian with v_{esc}

$V_{esc} \approx 544$ km/s

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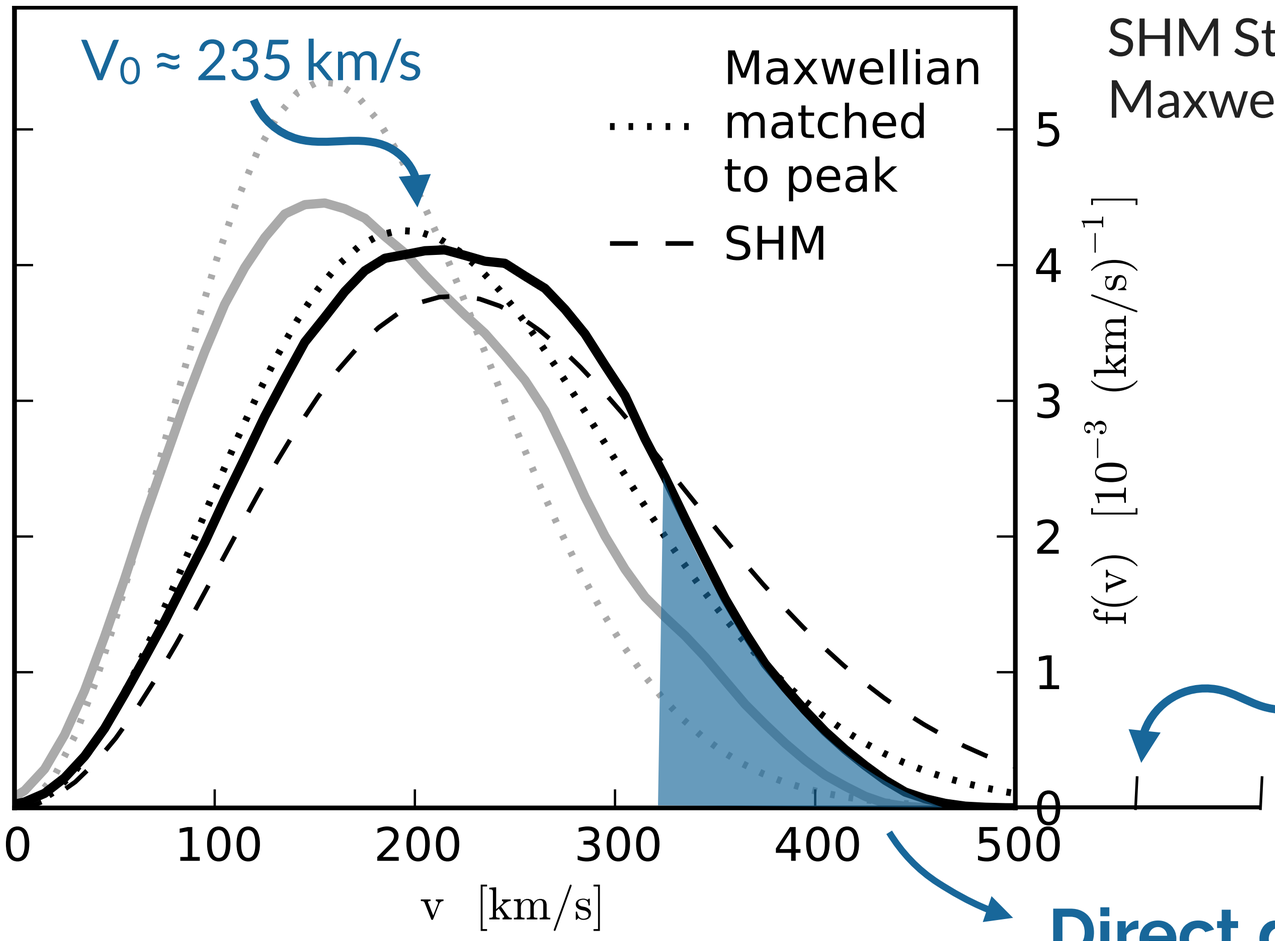

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Direct detection

Celestial Bodies Velocity Distribution

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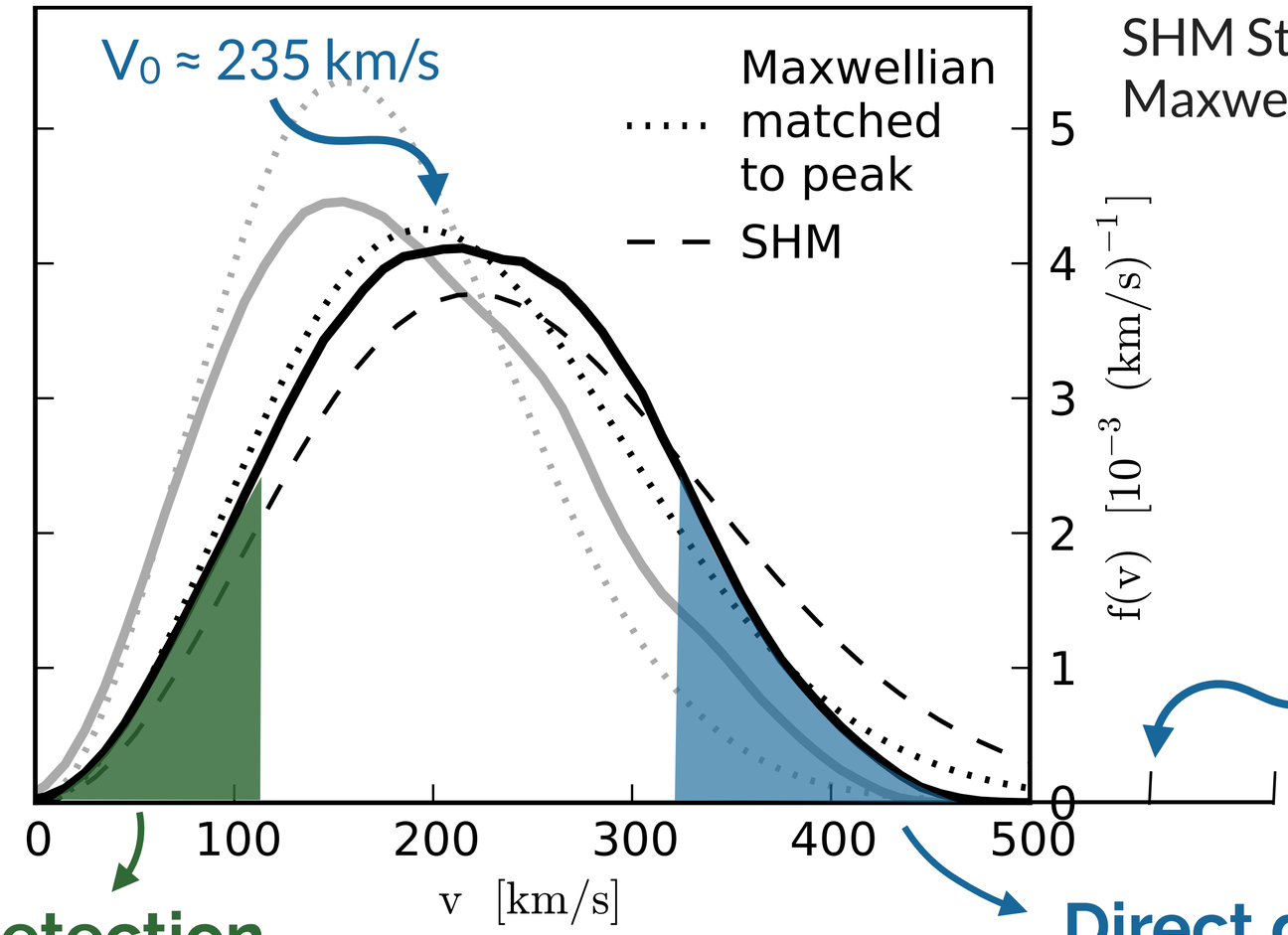

SHM Standard Halo Model = Maxwellian with v_{esc}

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Indirect detection

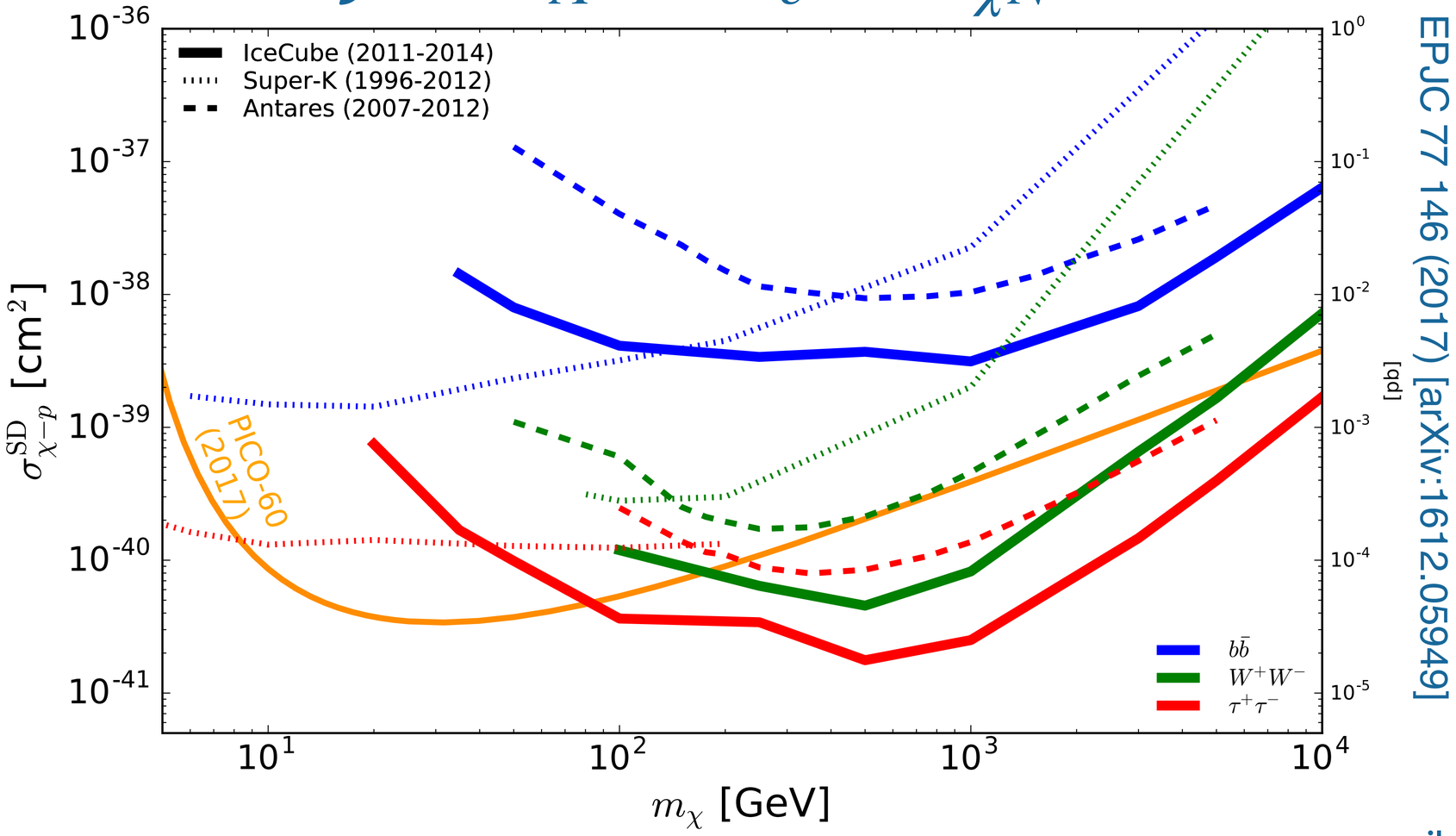
Direct detection

Celestial Bodies Results from the Sun

- Only events when Sun is below the horizon: **532 days of livetime**
- The mean free path of TeV neutrinos smaller than the Sun radius: **Low energy analysis**
- Best limits $m_\chi > 80$ **GeV**

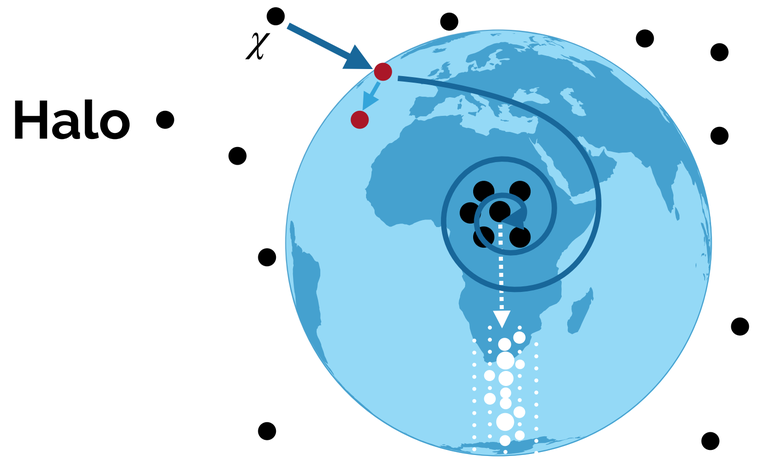
equilibrium!

$$\Phi_\nu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{\chi N}$$

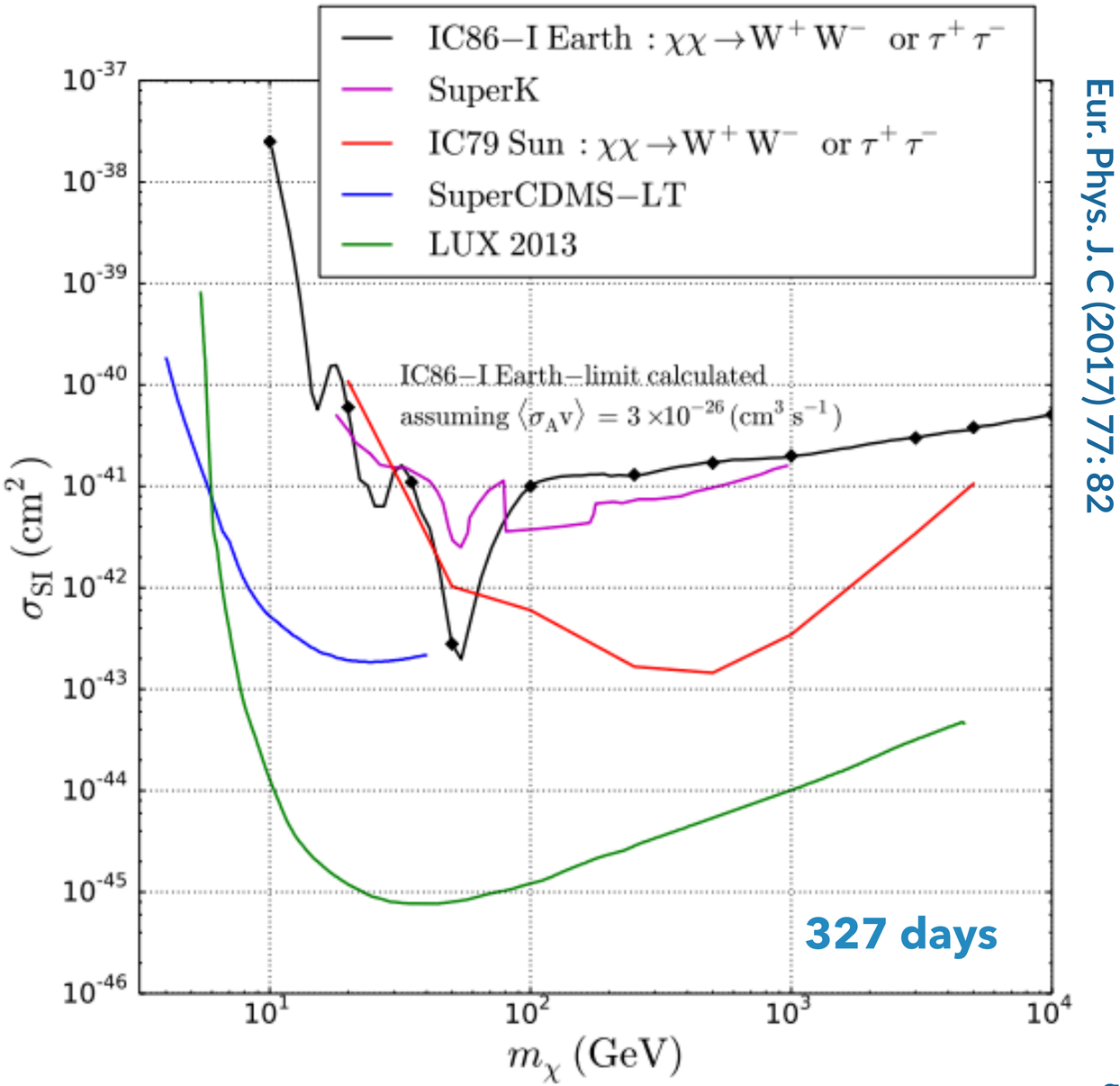


EPJC 77 146 (2017) [arXiv:1612.05949]

Celestial Bodies Results from the Earth

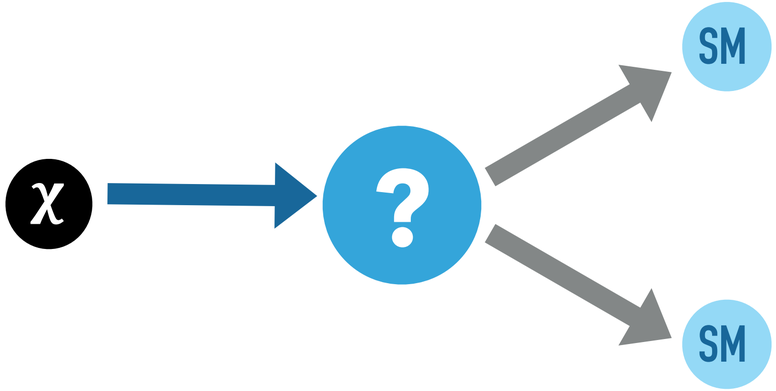


- **No thermal equilibrium**
- Analysis very senstive to astrophysical uncertainties (dark disc, velocity distribution)
- More years of data currently being analyzed



Eur. Phys. J. C (2017) 77: 82

Decaying Dark Matter Lifetime



If dark matter is unstable its lifetime must exceed the age of the Universe

Not factor 2, no so pronounced in the direction of the GC

Galactic

$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \frac{1}{4\pi}\frac{1}{m_\chi \tau_\chi}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\int_0^{\Delta\Omega}\mathrm{d}\Omega\int_{l.o.s}\rho_\chi(r(s,\Psi,\theta))\mathrm{d}s$$

constrain

Extra-galactic component can be ignored for Ψ < 10deg.

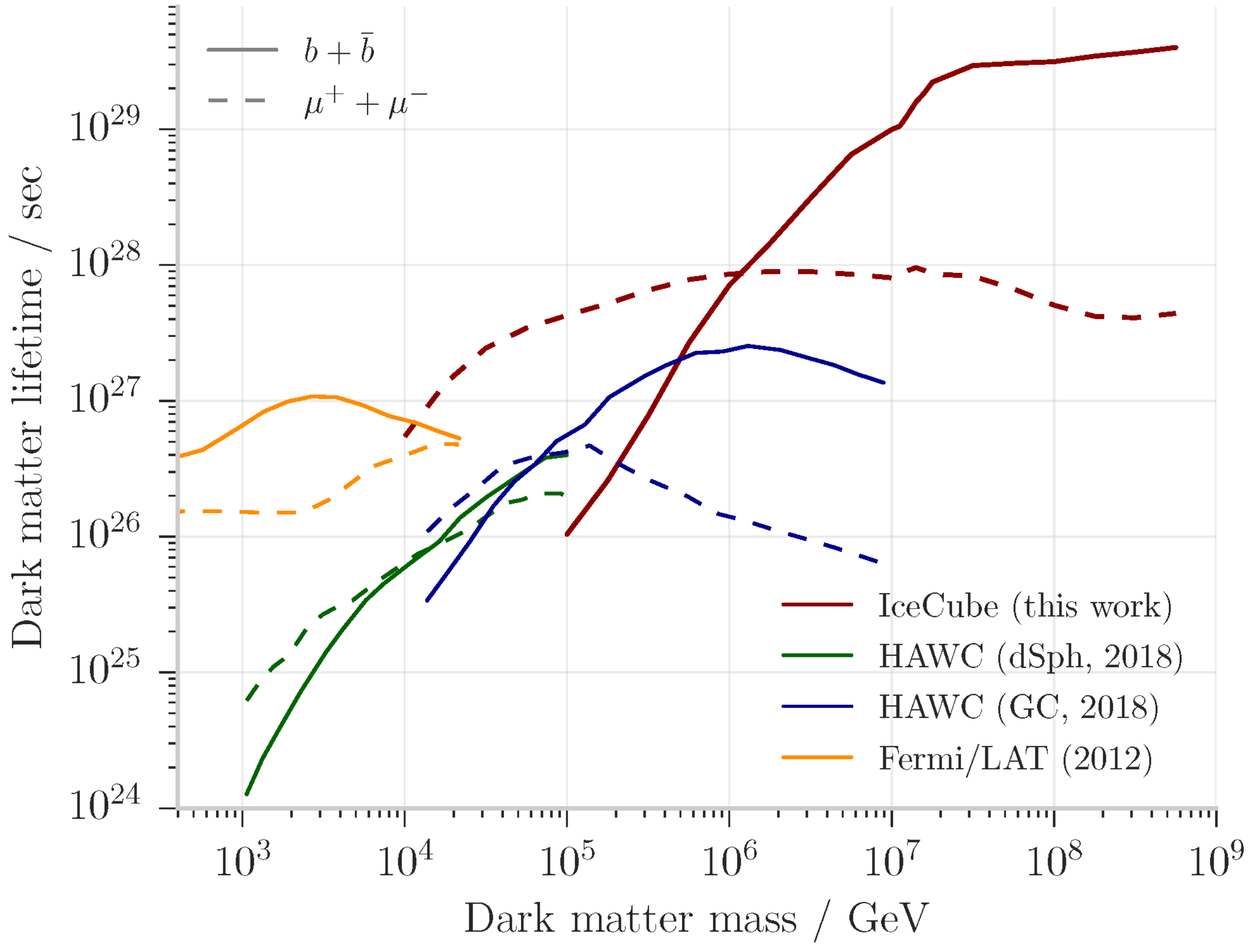
Extra-Galactic

$$\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu} = \frac{1}{4\pi}\frac{\Omega_\chi \rho_c}{m_\chi \tau_\chi}\int_0^{\infty}\mathrm{d}z\,\frac{c}{H(z)}\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu}\Bigg|_{E=E_\nu(1+z)}$$

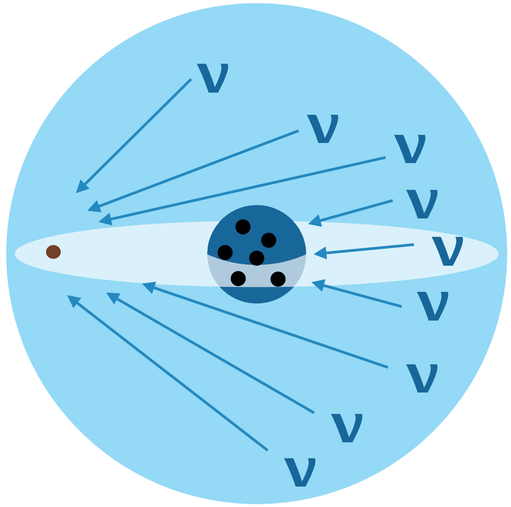
Decaying Dark Matter Lifetime

- Two IceCube independent data samples:
  - Track-like with six years of data
  - Cascade-like with two years of data
- Dark Matter alone cannot explain IceCube neutrino flux.
- Best limits > 10 TeV

Eur. Phys. J. C (2018) 78: 831

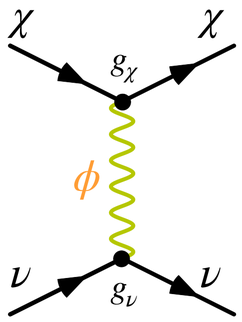


Neutrino Dark Matter Scattering

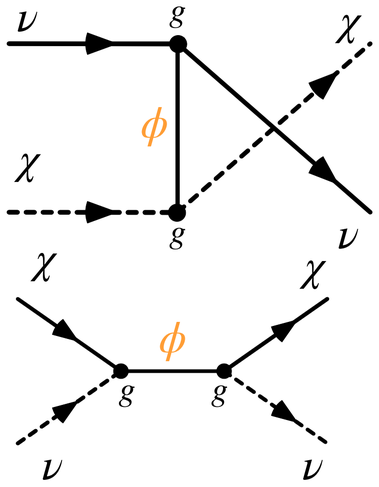


- Scattering of high energy cosmic neutrinos on DM in the halo can lead to a **deficit of high energy neutrinos** from the GC
- Focusing on HE neutrinos (cross-section increases with energy)

Fermion—vector



Scalar—Fermion



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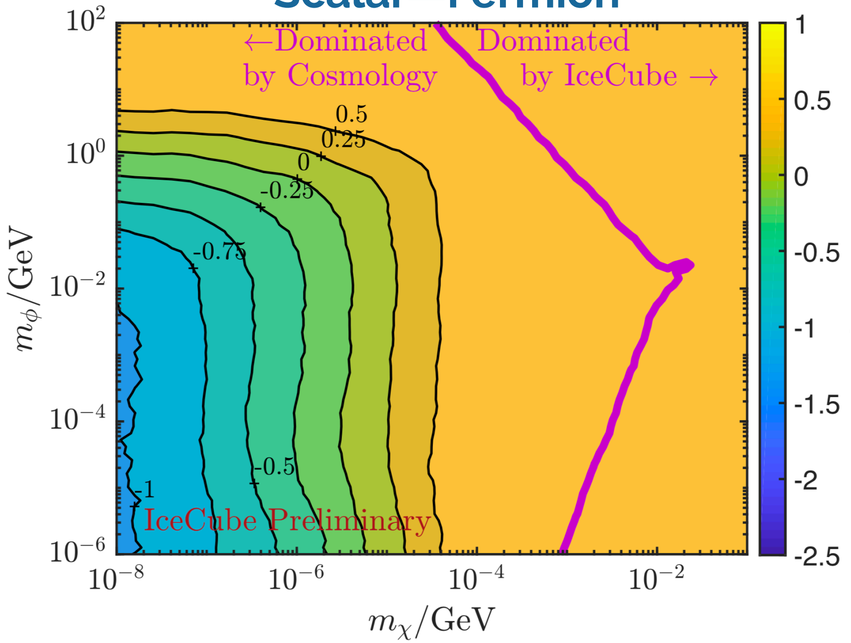
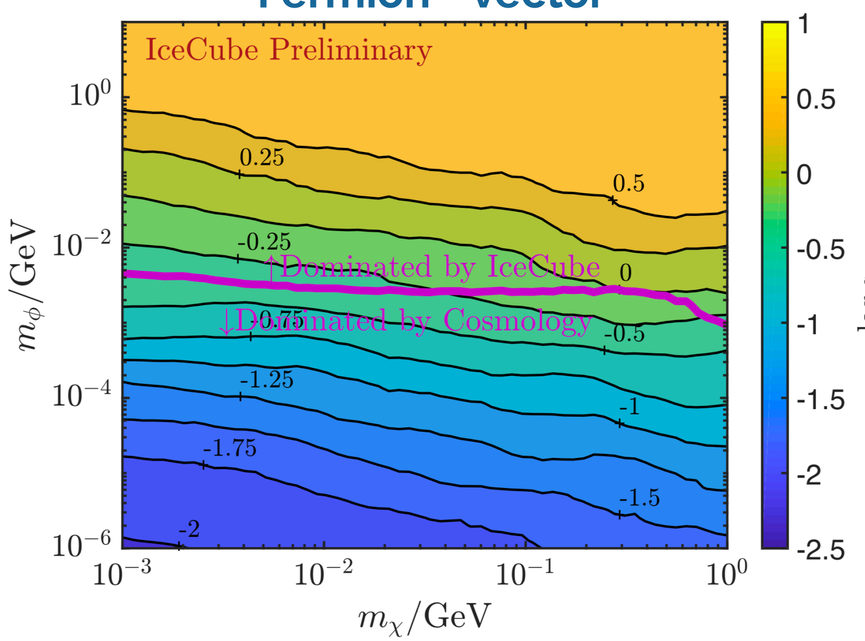


Fermion—vector



[Neutrino 2012, doi:10.5281/zenodo.1300506]

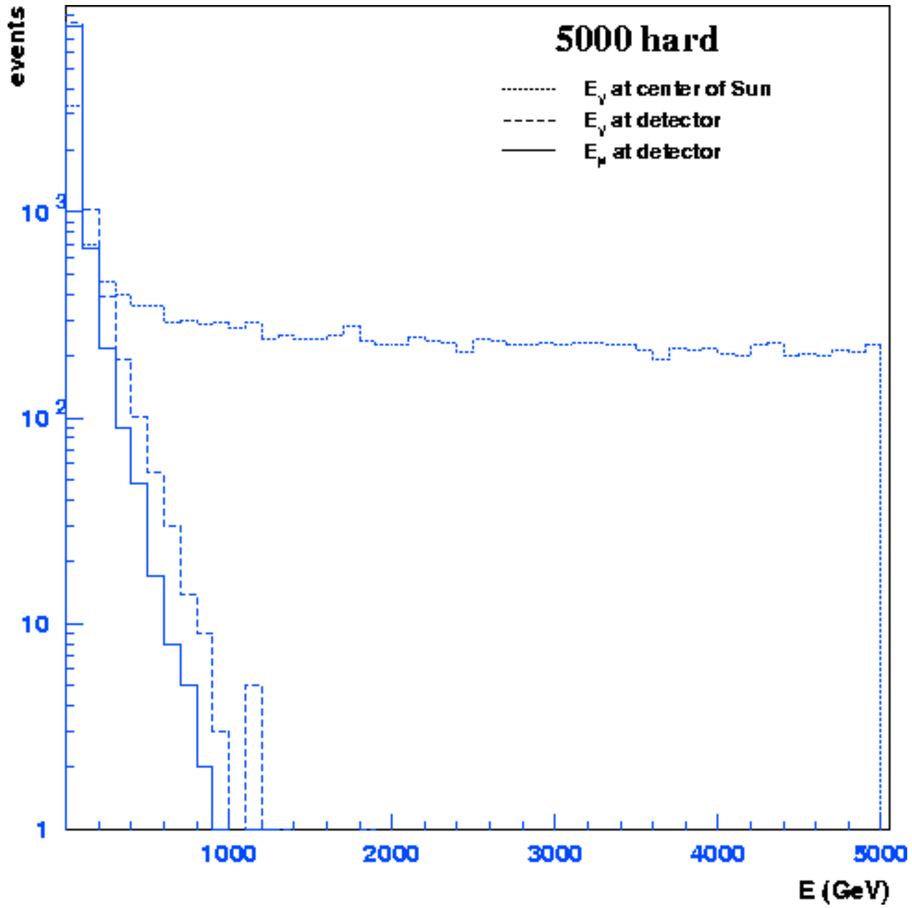
Conclusions

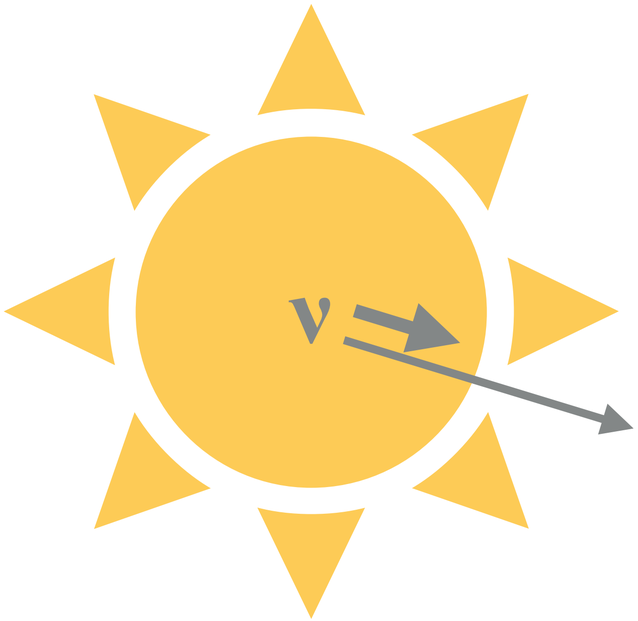
- **Indirect detection of Dark Matter** with neutrino telescopes provides complementarity to other techniques due to different backgrounds and systematics.
- Many astrophysical signals can be interpreted as Dark Matter. We need **strong corroboration** from all searching strategies.
- IceCube has a **lively program of Dark Matter searches,** with very competitive results.

backups

CELESTIAL BODIES: NEUTRINOS FROM THE SUN

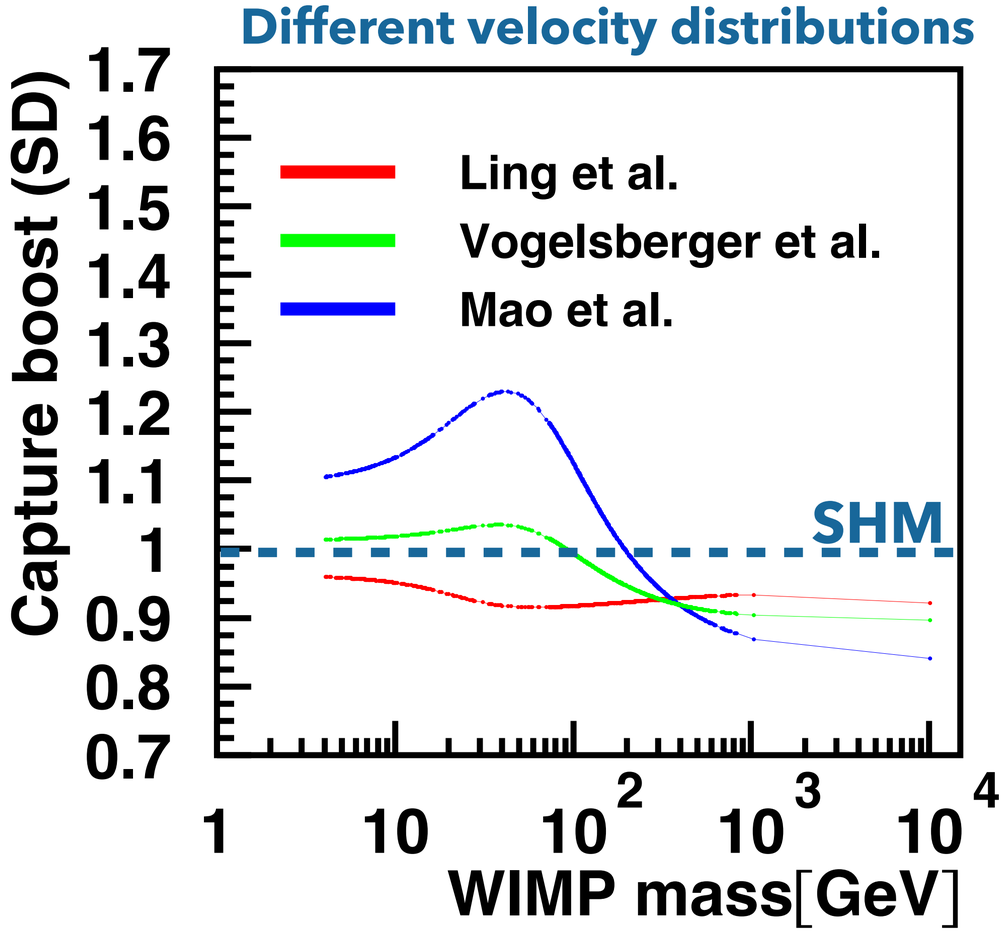
- The mean free path of neutrinos of 5000 GeV is smaller than the Sun radius
- Indirect searches from the Sun are **low-energy analysis** even for the highest dark matter masses.

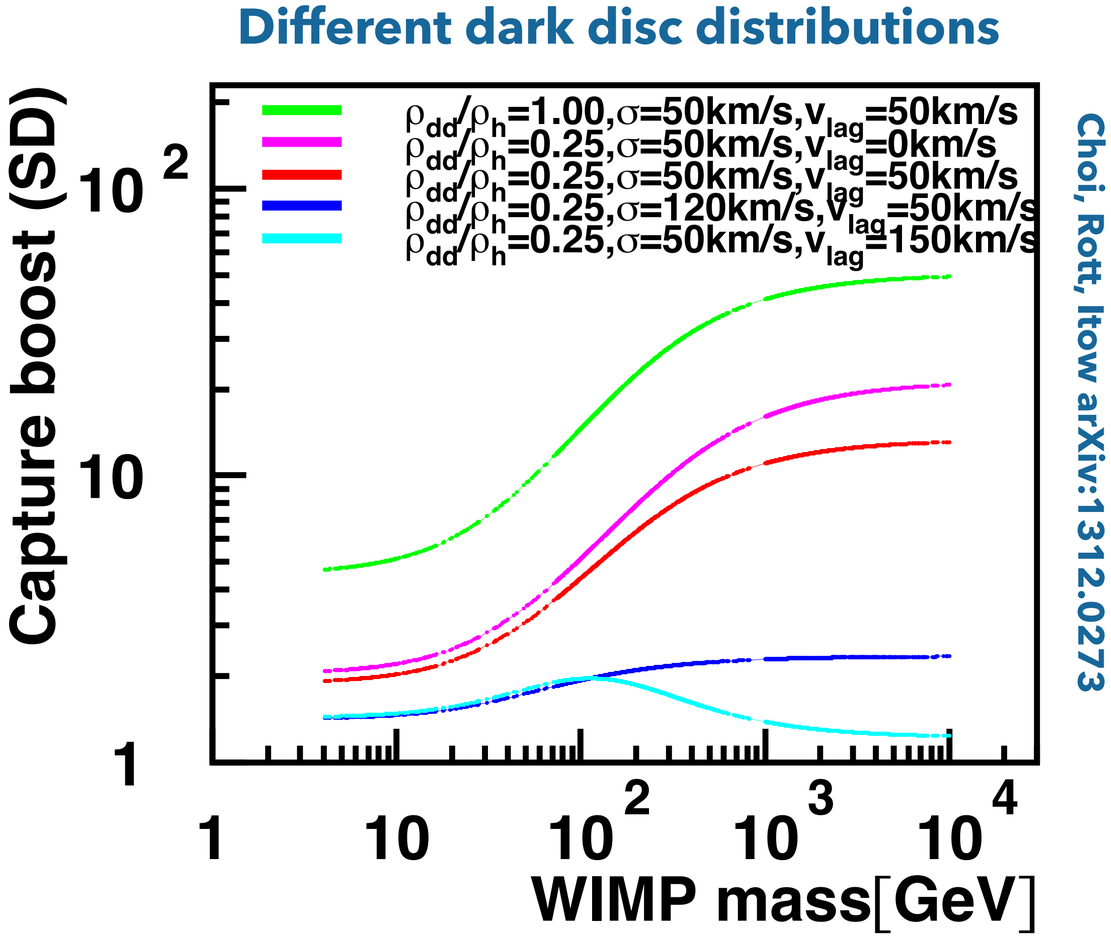




CELESTIAL BODIES: ASTROPHYSICAL INPUT

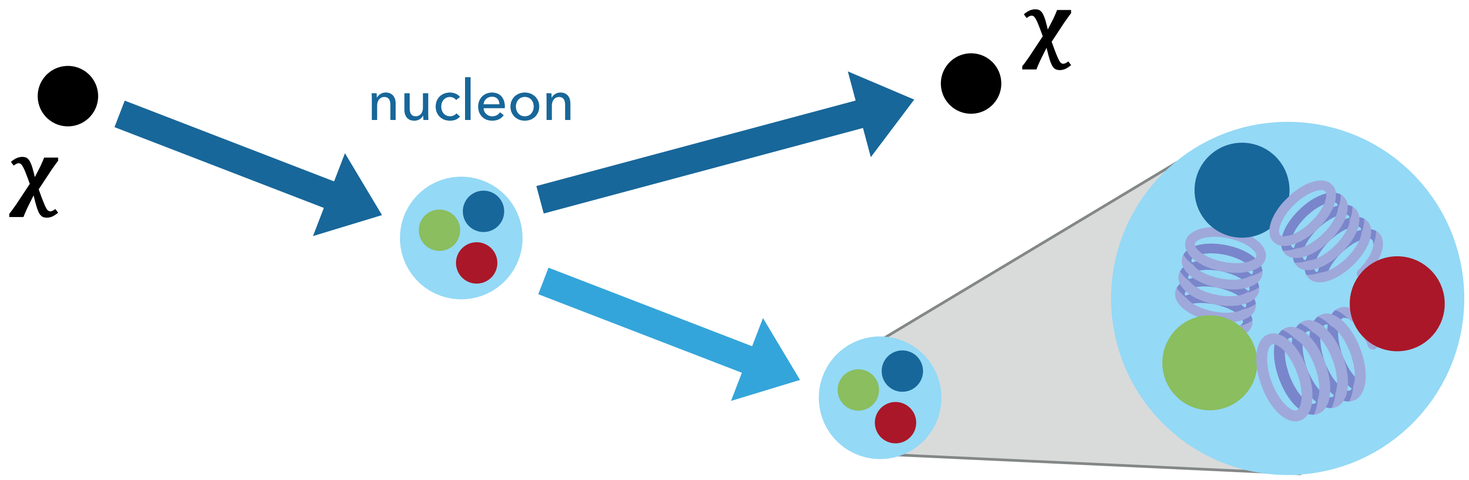
Effect of uncertainties in velocity distributions for Sun results:





A **dark matter disc** will have a significant (good) impact on the capture rate for the Sun/Earh

CELESTIAL BODIES: PARTICLE PHYSICS INPUT



Both direct detection and indirect detection (gravitational capture) depend on the WIMP-nucleon cross-section.

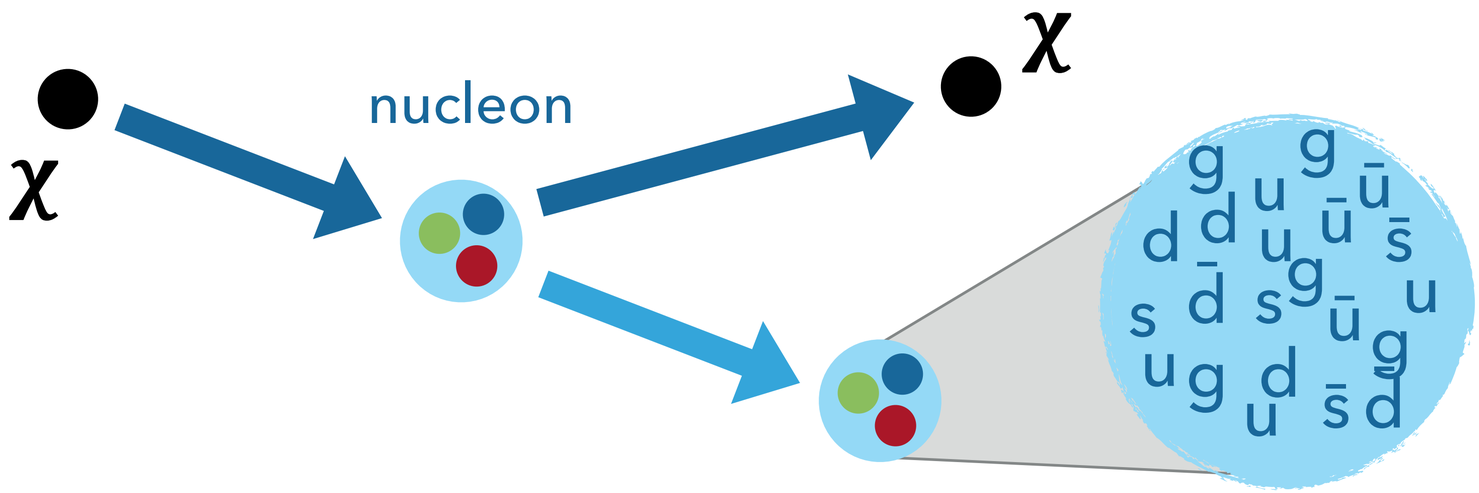
$$\sigma_{SI} \propto A^2$$

Spin independent → **Use heavy nuclei as target: Direct detection**

$$\sigma_{SD} \propto (a_p \langle S_p \rangle + a_n \langle S_n \rangle) \frac{J+1}{J} \frac{S(|\vec{q}|)}{S(0)}$$

Spin dependent → **Sun is full of protons: Indirect detection**

CELESTIAL BODIES: PARTICLE PHYSICS INPUT



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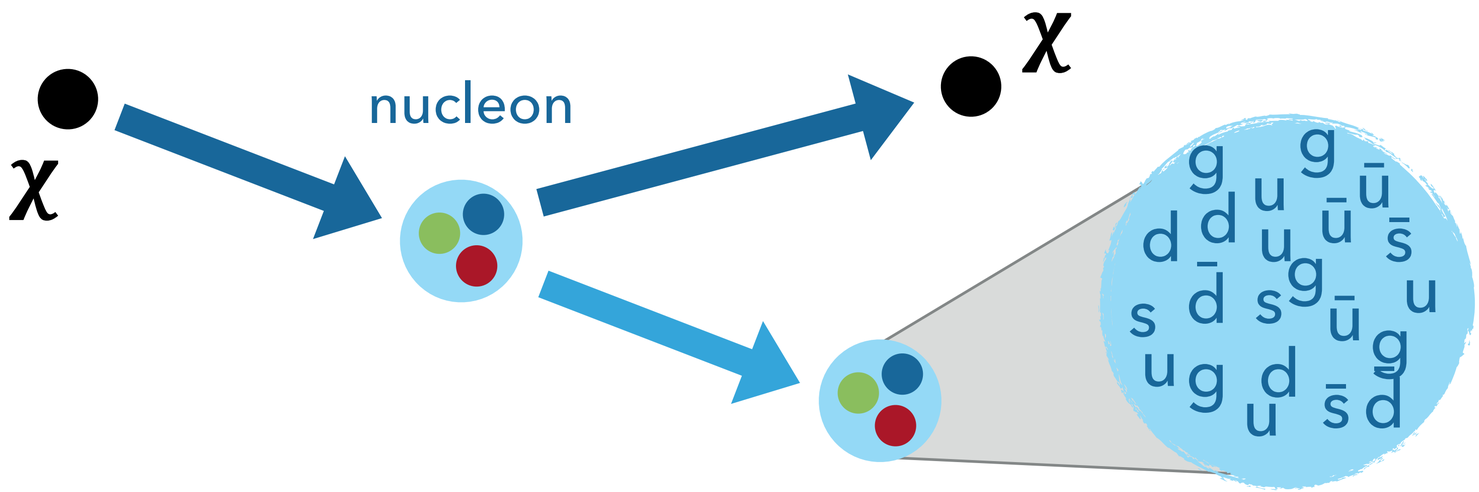

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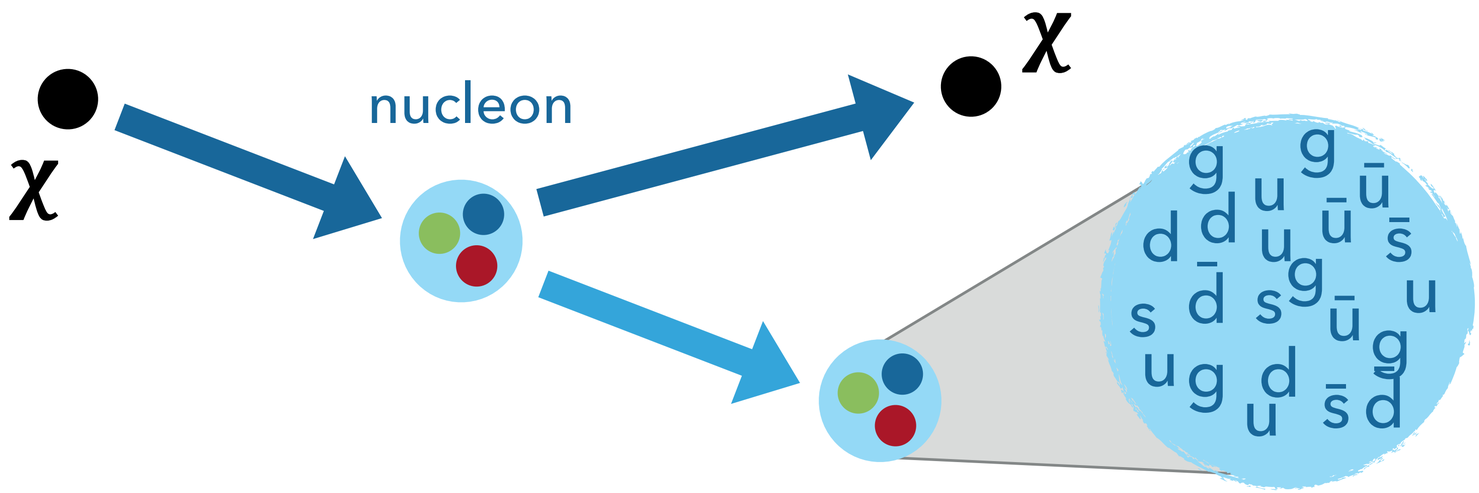
The nucleon structure plays an essential role in calculating observables

CELESTIAL BODIES: PARTICLE PHYSICS INPUT



Both direct detection and indirect detection (gravitational capture) depend on the WIMP-nucleon cross-section.

$$\sigma_{SI} \propto A^2$$

Spin independent → **Use heavy nuclei as target: Direct detection**

$$\sigma_{SD} \propto (a_p \langle S_p \rangle + a_n \langle S_n \rangle) \frac{J+1}{J} \frac{S(|\vec{q}|)}{S(0)}$$

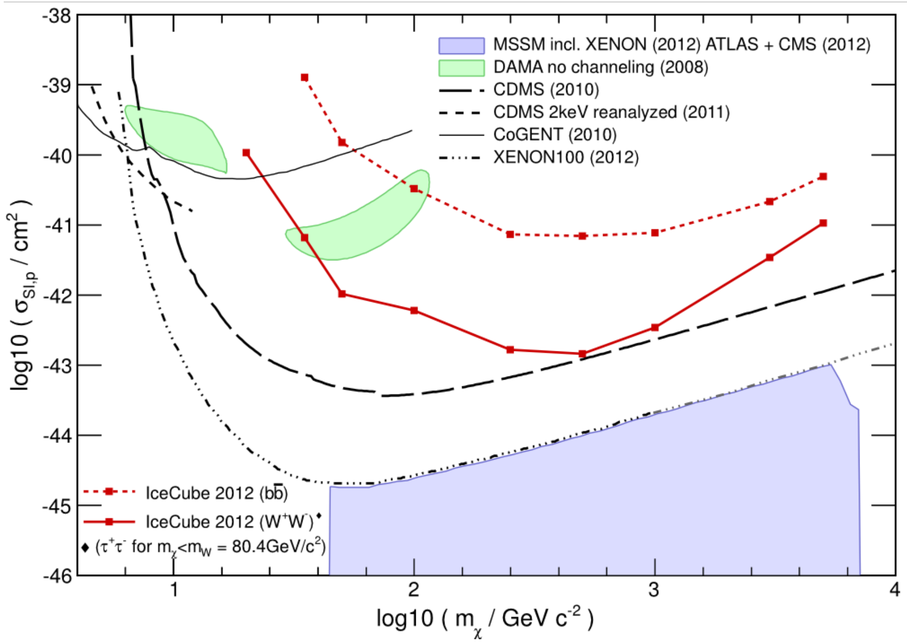
Spin dependent → **Sun is full of protons: Indirect detection**

The nucleon structure plays an essential role in calculating observables

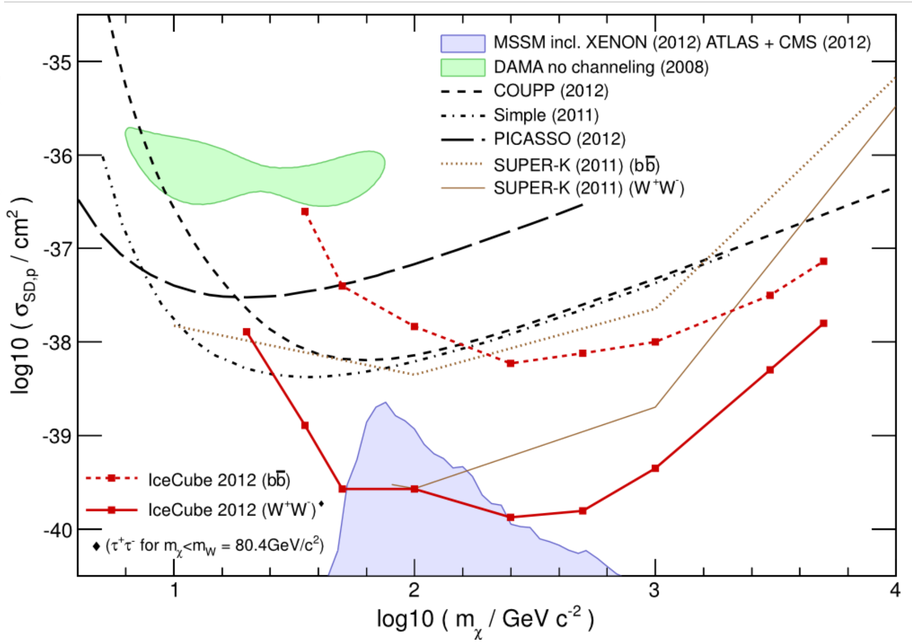
But it seems to affect more σ^{SI} than σ^{SD}

R. Ruiz, C. de los Heros arXiv:1307.6668

WIMP Searches From the Sun



90% CL χ-p cross-section (spin-independent)



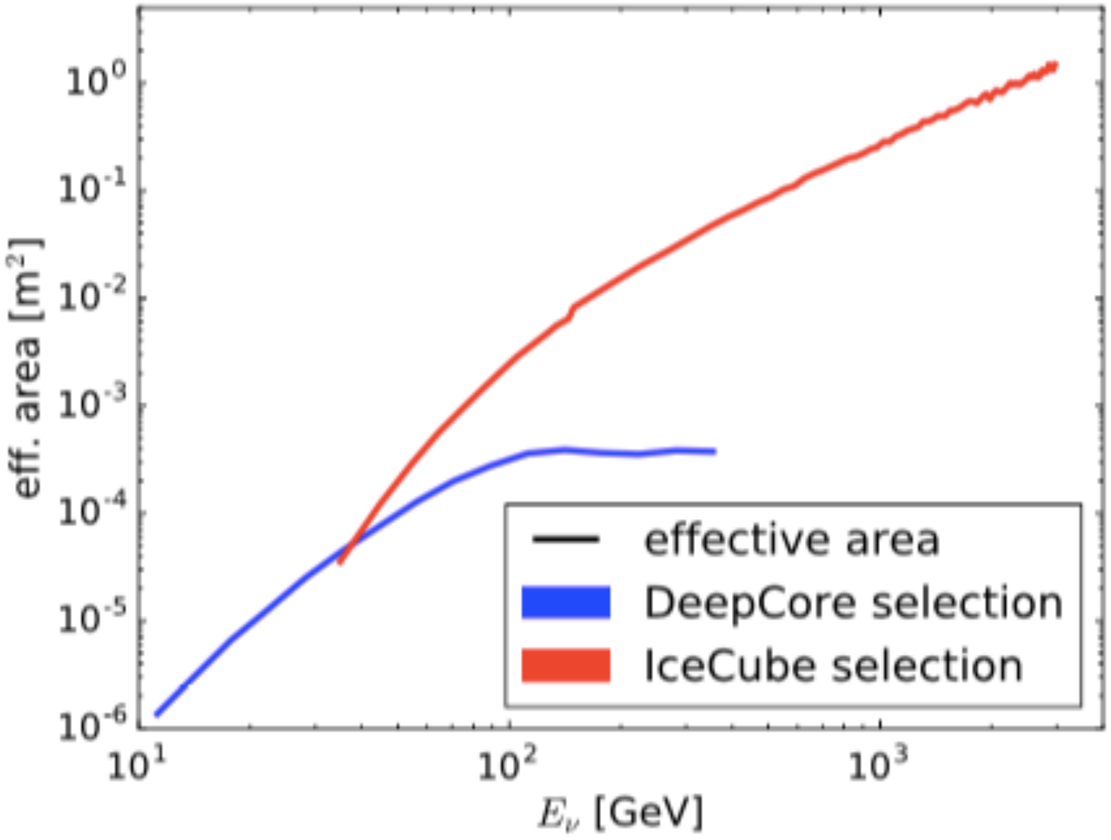
90% CL χ-p cross-section (spin-dependent)

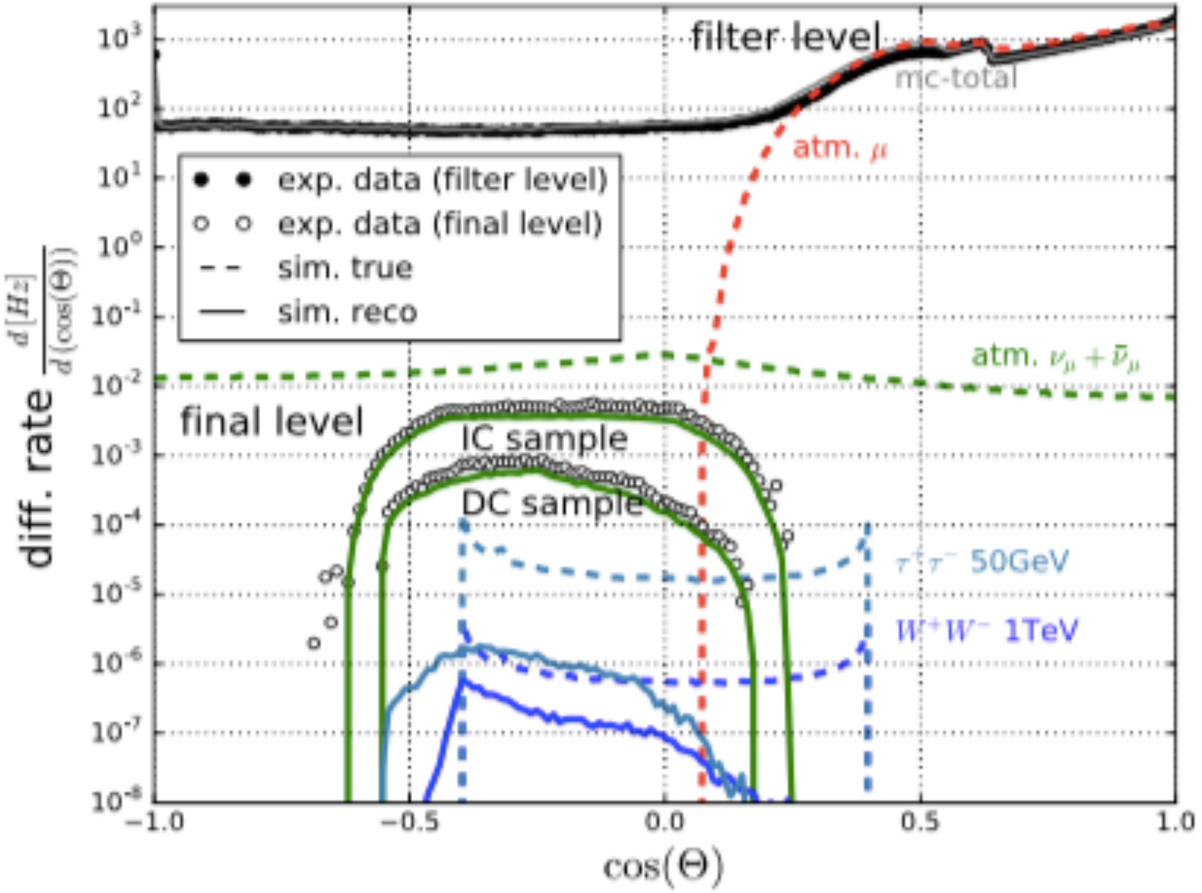
Complementary to direct detection search efforts

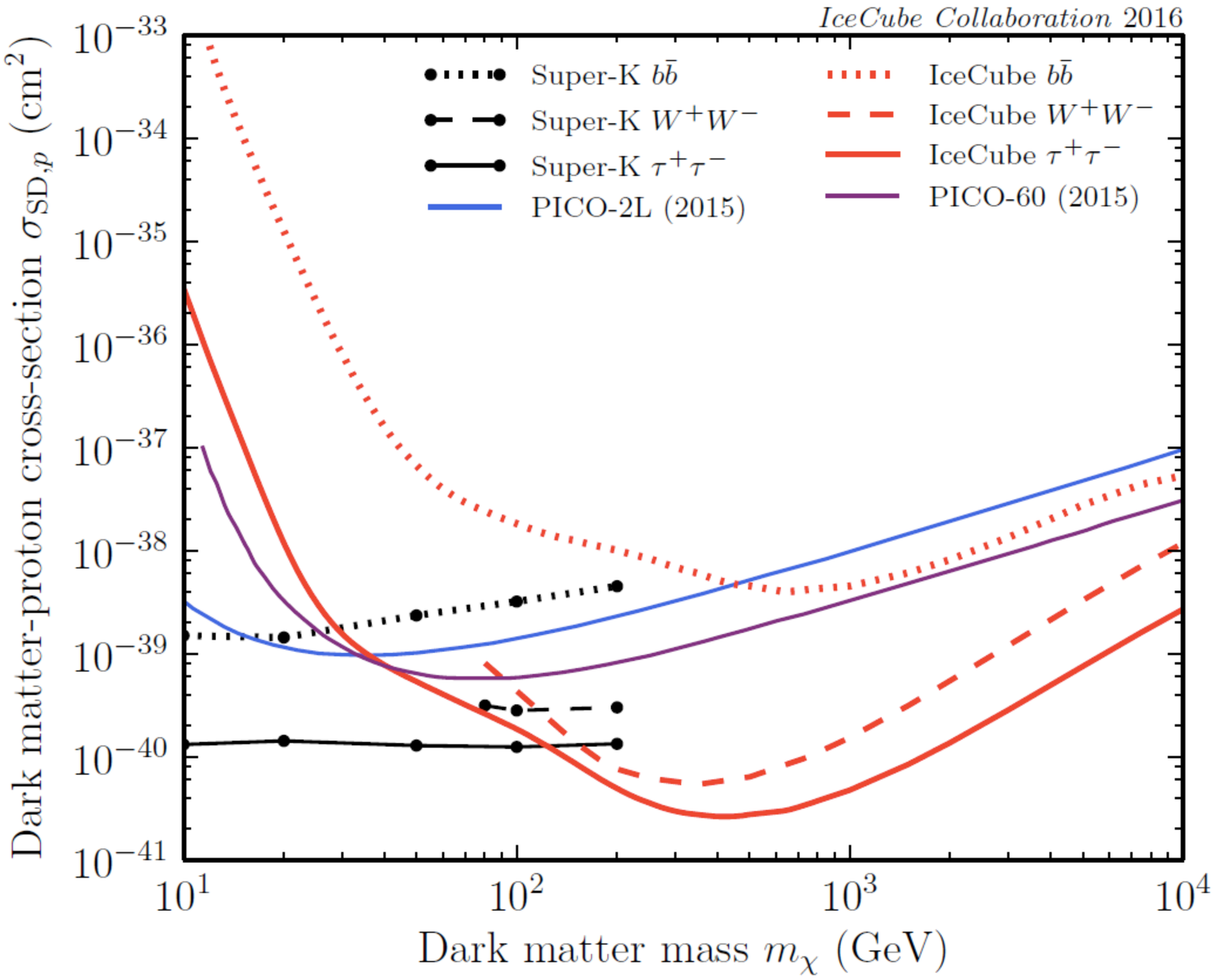
fills out WIMP picture by testing other properties

Most stringent SD cross-section limit for most models

Effective Areas Sun






IceCube Collaboration 2016
Super-K $b\bar{b}$
Super-K W^+W^-
Super-K $\tau^+\tau^-$
PICO-2L (2015)
IceCube $b\bar{b}$
IceCube W^+W^-
IceCube $\tau^+\tau^-$
PICO-60 (2015)
Dark matter-proton cross-section $\sigma_{SD,p}$ (cm^2)
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^1
10^2
10^3
10^4
Dark matter mass m_χ (GeV)

EARTH WIMP Spin independent