Advances in Astroparticle Physics and Cosmology

(AAPCOS-2023)

High-energy neutrinos from the Sun as a discovery tool for dark matter - electron scattering

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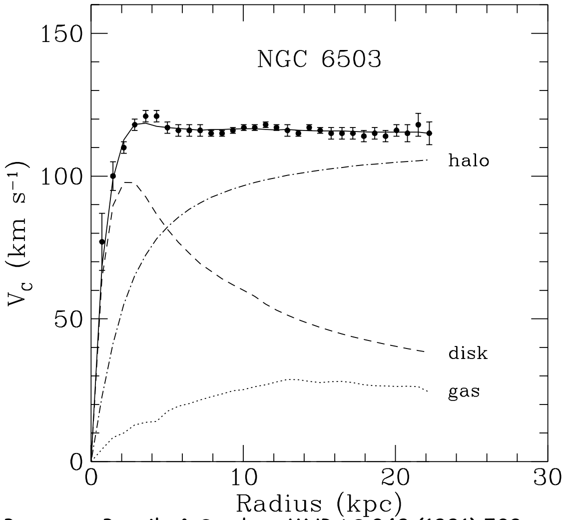
Thanks to my collaborators: Tarak Nath Maity, Akash Kumar Saha, and Sagnik Mondal

(work in preparation)

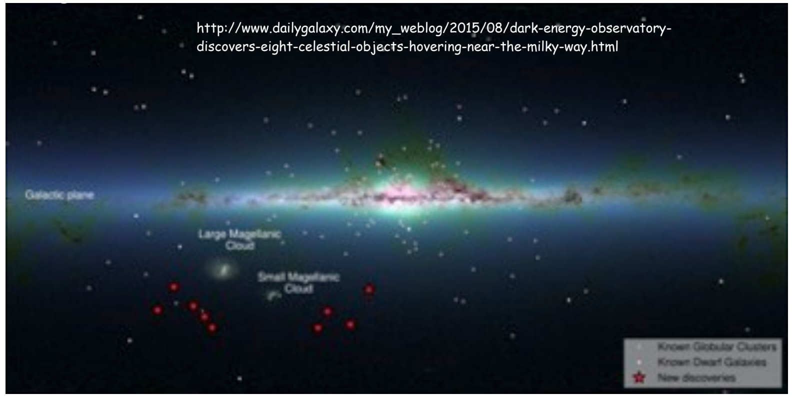
Contents

- Dark matter introduction
- Dark matter - electron coupling
- Capture of dark matter in the Sun
- Search for dark matter - electron interactions via high-energy neutrino observations of the Sun
- Conclusions

Gravitational detection of dark matter



Begeman, Broeils & Sanders MNRAS 249 (1991) 523

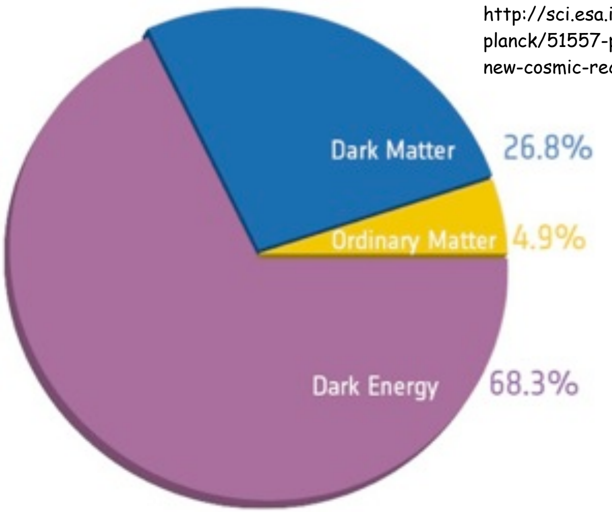


Bullet cluster

https://en.wikipedia.org/wiki/File:1e0657_scale.jpg

ESA website

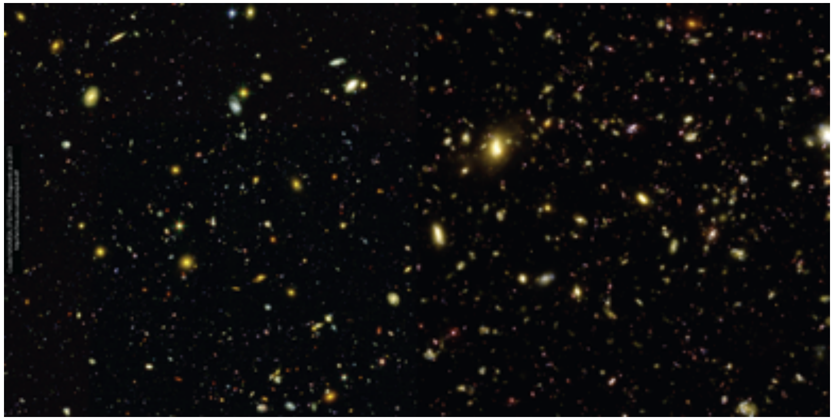
http://sci.esa.int/planck/51557-planck-new-cosmic-recipe/



Real observation from Hubble eXtreme Deep Field Observations: left side

Mock observation from Illustris: right side

Illustris website



Dark matter candidates

10^{-22} eV ~ 100 $M_{\odot}$

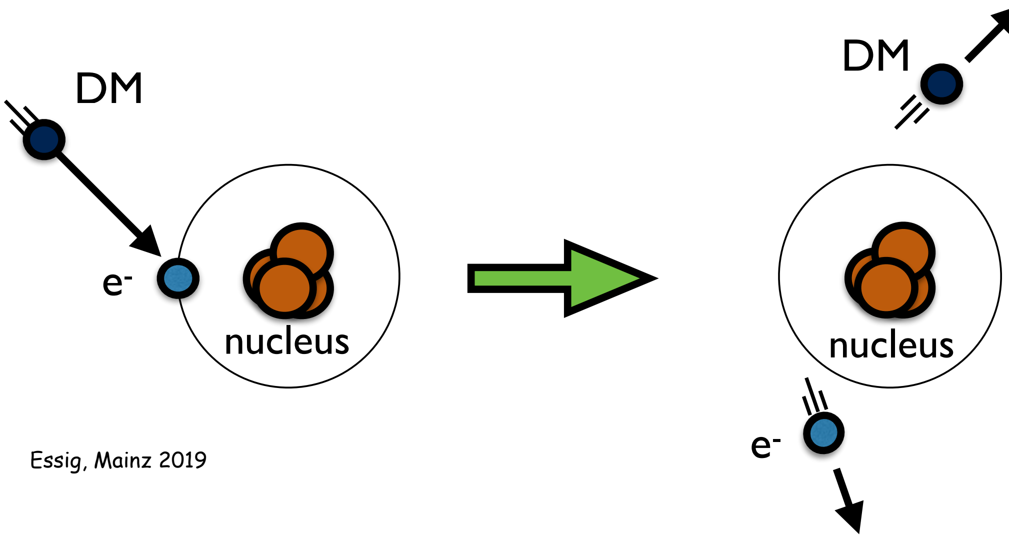
Wide range in dark matter candidate masses

We need to thoroughly test all well-motivated candidates

It is important to test all regions of the dark matter mass parameter space and all different couplings of dark matter - Standard Model particles

Dark matter - electron coupling

Dark matter - electron scattering



Essig, Mainz 2019

Sensitive to dark matter - electron coupling

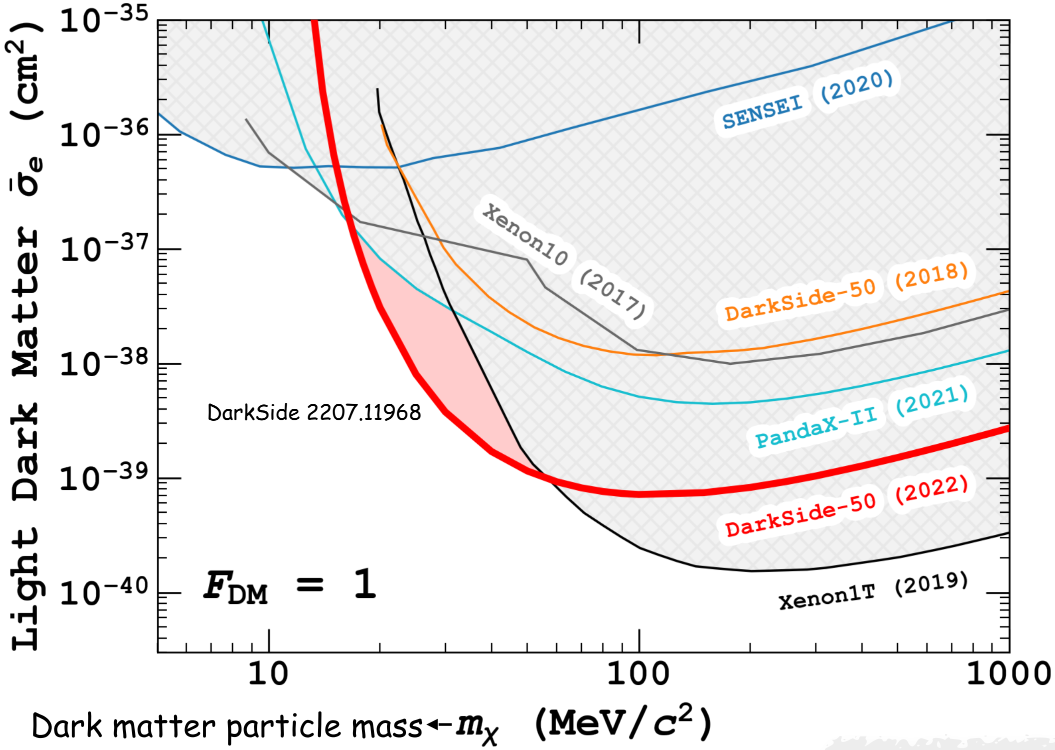
Search for the electron recoil in underground experiments (experiments are situated underground to suppress various backgrounds)

Generally sensitive to lower dark matter masses as compared to nuclear scattering

Many on-going and near future laboratory experiments are pursuing this search strategy, e.g., SENSEI, XENON (various versions), DarkSide-50, CDMS, EDELWEISS, and DAMIC

Tremendous progress during the last few years

Dark matter - electron scattering



Target materials: silicon

⇓

(Smallest target mass, however lowest DM mass threshold)

⇓

most sensitive to DM masses ~ 10 MeV

Target materials: xenon

⇓

(Largest target mass and heaviest DM mass threshold)

⇓

most sensitive to DM masses ~ 200 MeV

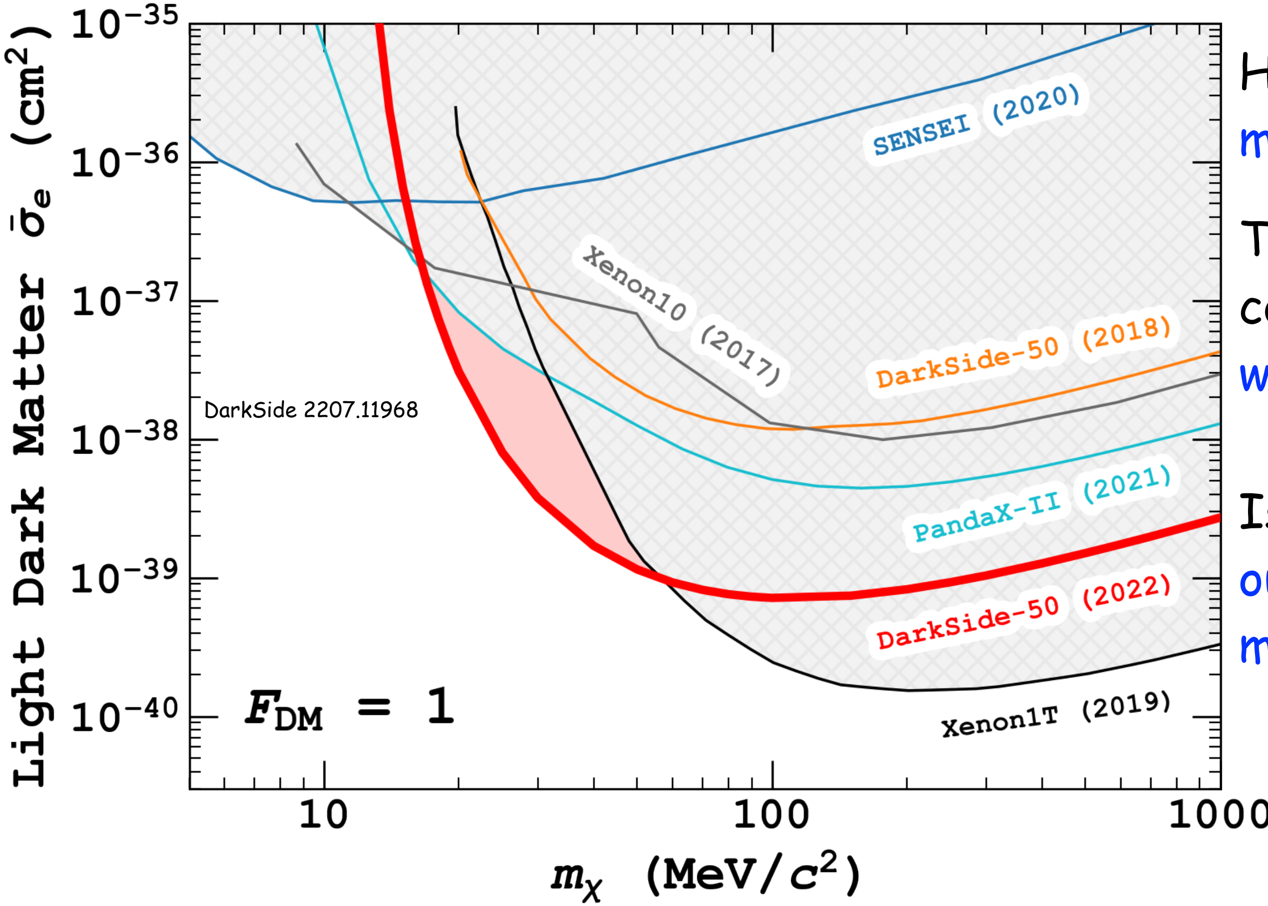
argon ⇒ (Mid-range target mass mid-range DM mass threshold)

⇓

most sensitive to DM masses ~ 50 MeV

These upper limits assume the Standard Halo Model. See Maity and Laha 2208.14471 for effects of dark matter substructures for xenon-based detectors; Maity et al 2011.12896 for effects due to modifications in halo velocity distributions; and many others

Dark matter - electron scattering



How to probe heavier DM masses?

These laboratory limits continue at heavier masses with $1/m_\chi$ scaling

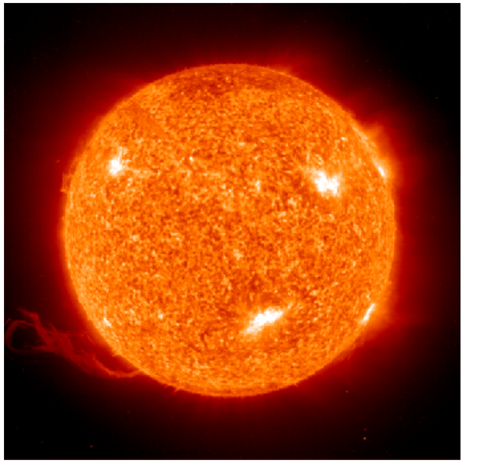
Is there a way to improve our sensitivity at higher masses?

Yes! Increase the exposure, i.e., build a bigger detector and run it for a longer time

Exposures:- DarkSide-50: (12306 ± 184) kg-days; SENSEI ~ 20 g-days;
XENON1T: (22 ± 3) tonne-day

Is there a dark matter detector with a larger exposure?

Yes, the Sun! The Sun as a dark matter detector has orders of magnitude larger exposure! It has been moving through the dark matter halo during its whole life-time: total exposure $\approx 4.6\,\mathrm{M_\odot}\,\mathrm{Gyr}$, target mass X lifetime



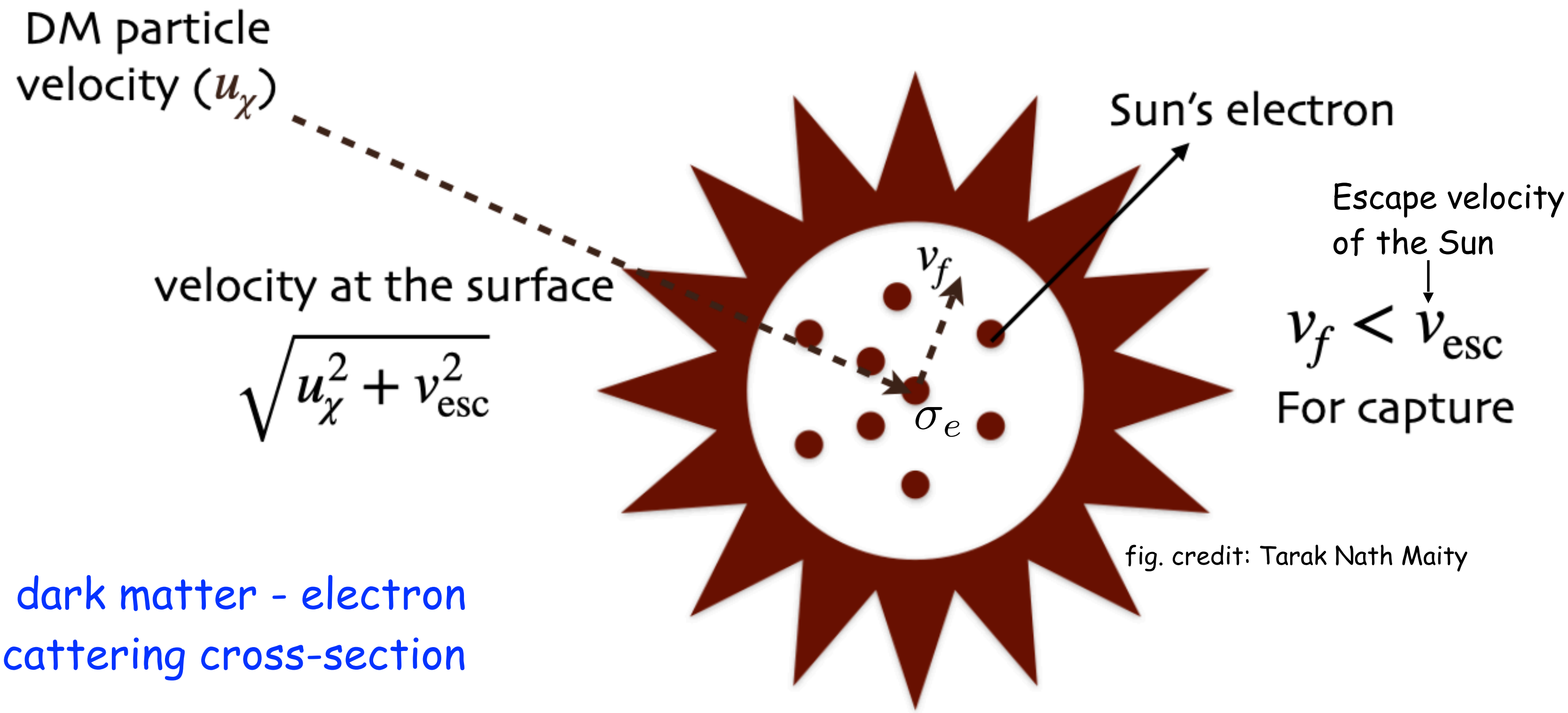
Can we use the Sun as a dark matter detector? This talk!

Do dark matter particles interact with the Sun?

Can we detect the signature of dark matter in the Sun?

Do dark matter particles interact with the Sun?

Do dark matter particles interact with the Sun?



σ_e = dark matter - electron scattering cross-section

1. Dark matter particles are gravitationally accelerated towards the Sun

2. A small fraction of these dark matter particles scatter with Solar electrons

3. Some fraction of the scattered dark matter particle get captured inside the Sun

Do dark matter particles interact with the Sun?

$$C = \underbrace{\int_0^{R_\odot} 4\pi r^2 n_e(r) dr}_{\text{total number of Solar electrons}} \underbrace{\int_0^\infty du_\chi \underbrace{\frac{\rho_\chi}{m_\chi}}_{\text{number density of the local dark matter}} \frac{f_{v_\odot}(u_\chi)}{u_\chi} \sqrt{u_\chi^2 + v_{\rm esc}(r)^2}\, g(w)\sigma_e}_{\text{incident dark matter flux}}$$

C ← total Solar capture rate of dark matter

$g(w)$ ← capture probability

See Kopp et al. 0907.3159; Garani and Palomares-Ruiz 1702.02768; Liang et al. 1802.01005; Maity et al. 2112.08286

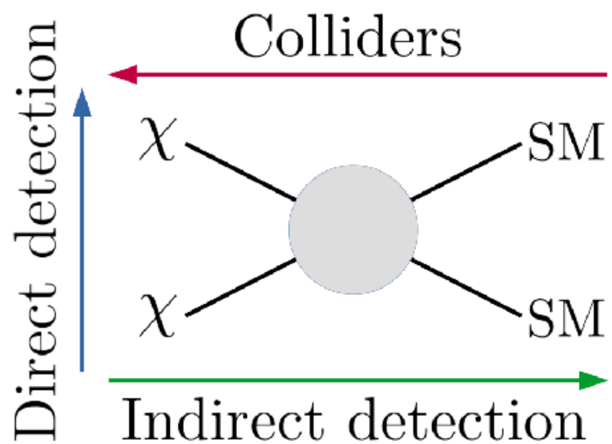
$n_e(r)$ = number density of Solar electrons as a function of radius

ρ_χ = local dark matter density at the Solar position

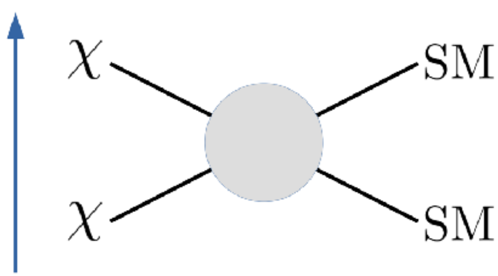
$f_{v_\odot}(u_\chi)$ = dark matter velocity distribution at the Solar position

A large amount of dark matter is captured inside the Sun. Assuming $m_\chi = 100\,\mathrm{GeV}$ and $\sigma_e = 10^{-39}\,\mathrm{cm}^2$, the total mass of dark matter particles captured is $\approx 4 \times 10^{-17}\,\mathrm{M}_\odot$, similar to mass of some asteroids

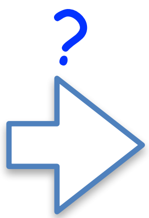
Is there a signature of dark matter inside the Sun?

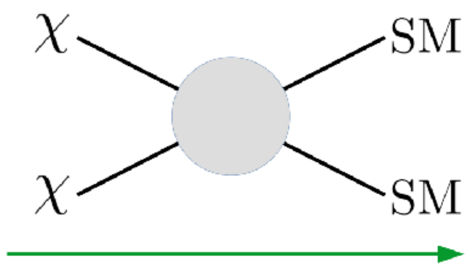


2104.11488



Solar capture





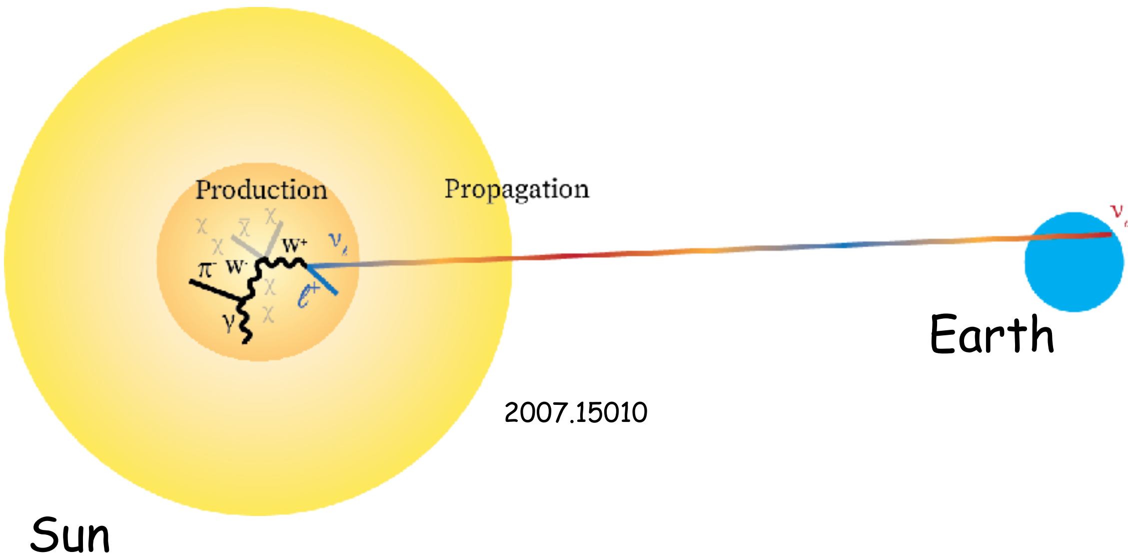
Annihilation signature

This process can be used to capture a lot of dark matter inside the Sun

Is there a measurable effect of these captured dark matter particles?

Can we detect the signature of dark matter in the Sun?

Neutrinos from the centre of the Sun



Neutrinos can travel from the centre of the Sun

Solar core density $\approx$ 150 g cm^{-3}

Solar core radius $\approx$ 1.5 $\times$ 10^{10} cm (~ 20% of the Solar radius)

$$\lambda \approx 1.6 \times 10^{10} \left(\frac{100\,\mathrm{GeV}}{E_\nu} \right) \mathrm{cm}$$

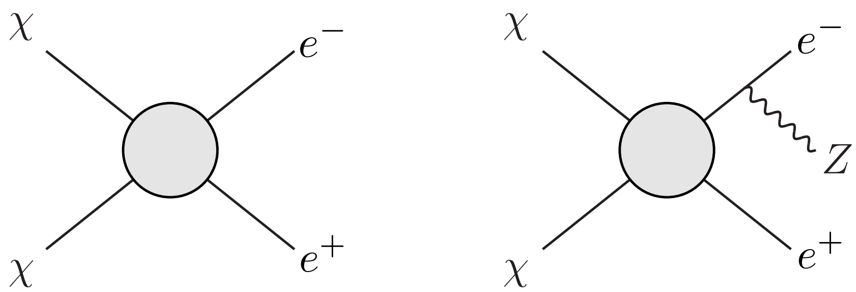
Mean free path inside Solar core of a neutrino

$$\lambda \approx 3.3 \times 10^{10} \left(\frac{100\,\mathrm{GeV}}{E_{\bar{\nu}}} \right) \mathrm{cm}$$

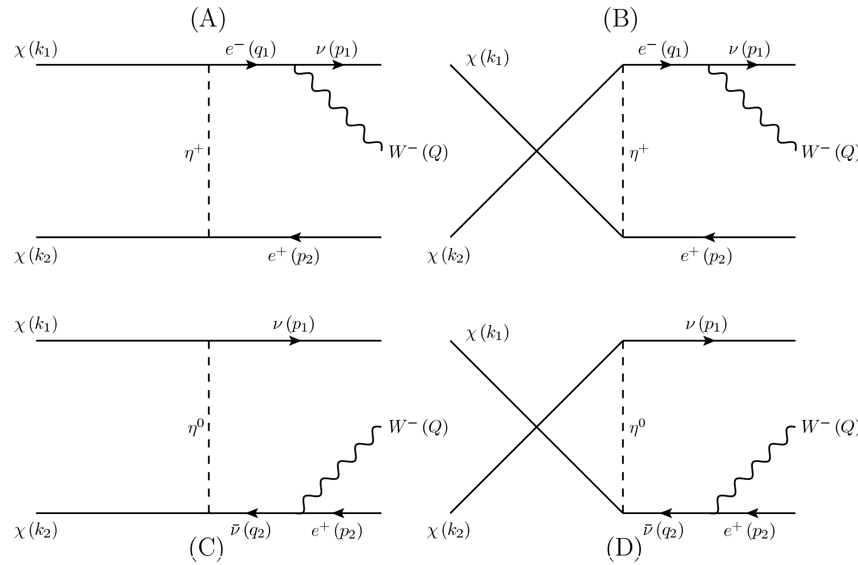
Mean free path inside Solar core of an anti-neutrino

Neutrinos and anti-neutrinos are the only particles which can inform us about the dark matter annihilation signature inside the Solar core

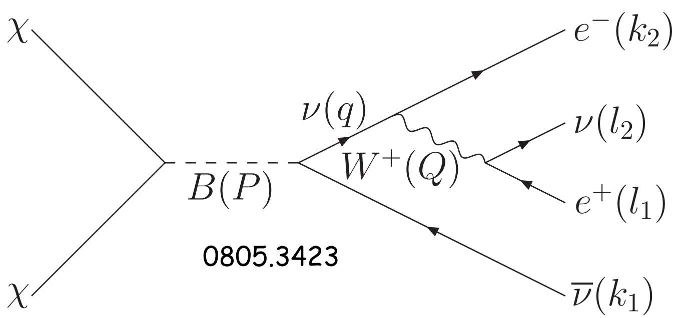
Where will the neutrinos come from?



(a) modified from 0805.3423 (b)



1009.2584



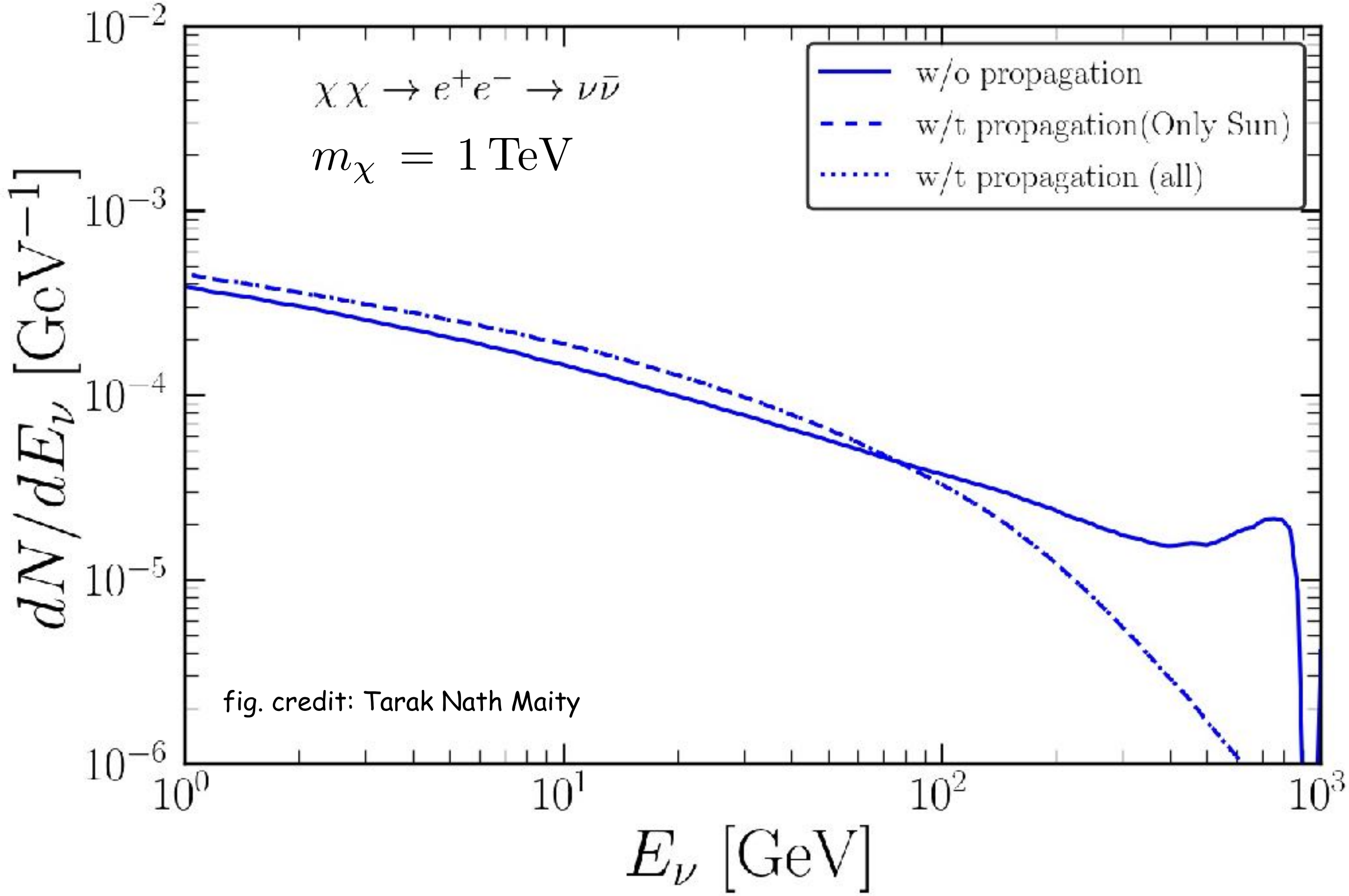
0805.3423

Due to electroweak corrections, large number of neutrinos and anti-neutrinos of all flavours are produced from every final state

Electroweak corrections are relevant for dark matter masses $\gtrsim 500\,\mathrm{GeV}$

A large amount of literature dedicated to studying these electroweak corrections for various dark matter annihilation channels Cirelli et al PPPC4DM ID, Bauer etal HDMSpectra 2007.15001

Neutrino spectrum from the Sun



High-energy neutrino + anti-neutrino spectrum emitted from the Sun due to annihilation of the accumulated dark matter

Dramatic effect on the spectrum due to propagation effects inside the Sun (propagation effects using 2007.15010)

Capture rate (C) and annihilation rate ($\Gamma_{\rm ann}$) are in equilibrium: $\Gamma_{\rm ann} = \frac{C}{2}$

Neutrino + anti-neutrino flux: $\frac{d\phi}{dE_\nu} = \frac{\Gamma_{\rm ann}}{4\pi d_\odot^2}\frac{dN}{dE_\nu}$

How to detect these neutrinos?

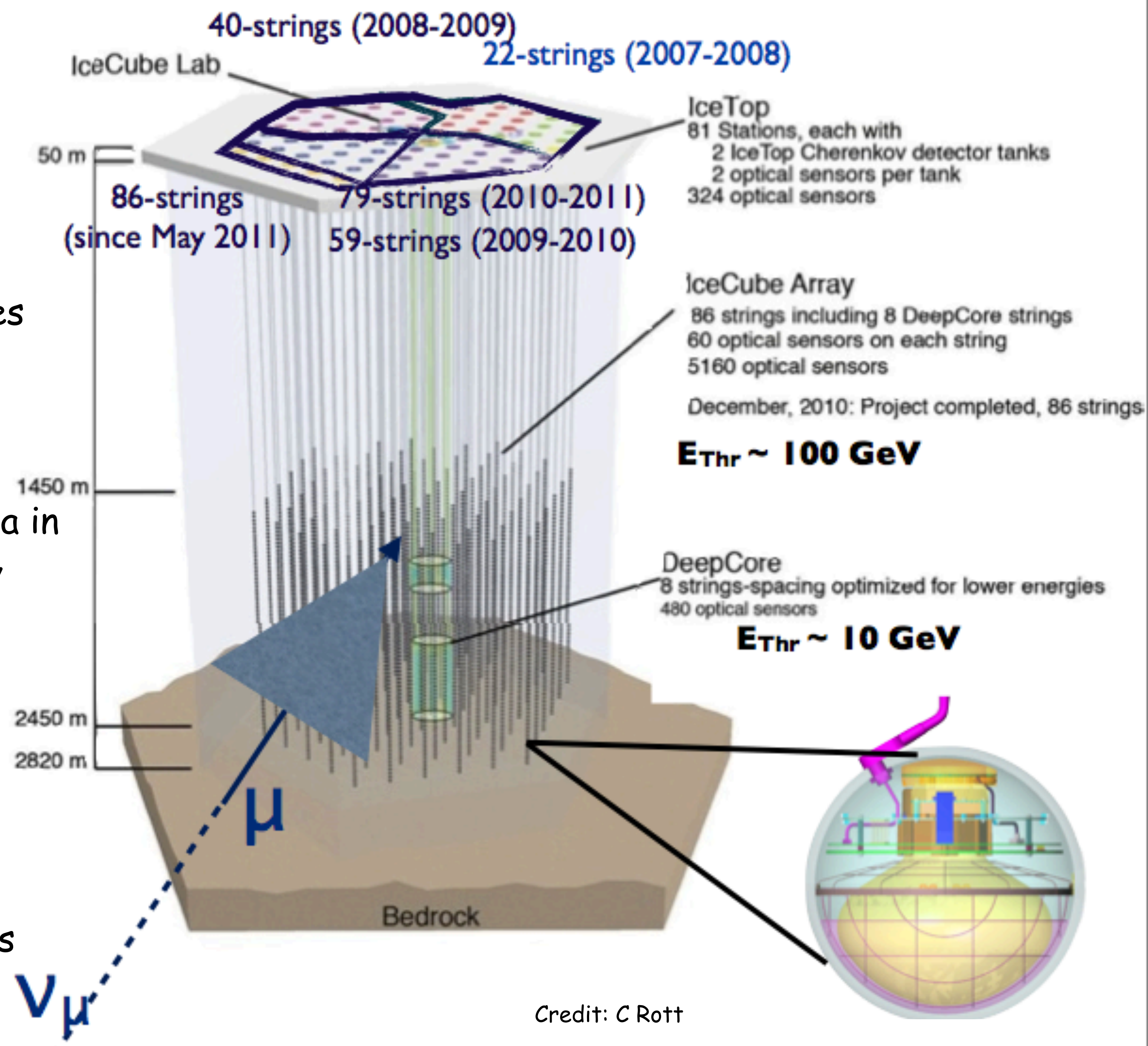
How to detect these neutrinos? IceCube neutrino telescope

Gigaton effective volume neutrino detector at South Pole

5160 Digital Optical Modules distributed over 86 strings

Completed in Dec 2010; data in full configuration from May 2011

Neutrino detected through Cherenkov light emission from charged particles produced due to neutrino CC/NC interactions



Credit: C Rott

Look at the Sun: muon neutrino + anti-neutrino interaction on nucleons and detection morphology

Factor of $\lesssim 2$ energy resolution

$\lesssim 5^\circ$ angular resolution (worsens at energies $\lesssim$ 200 GeV)

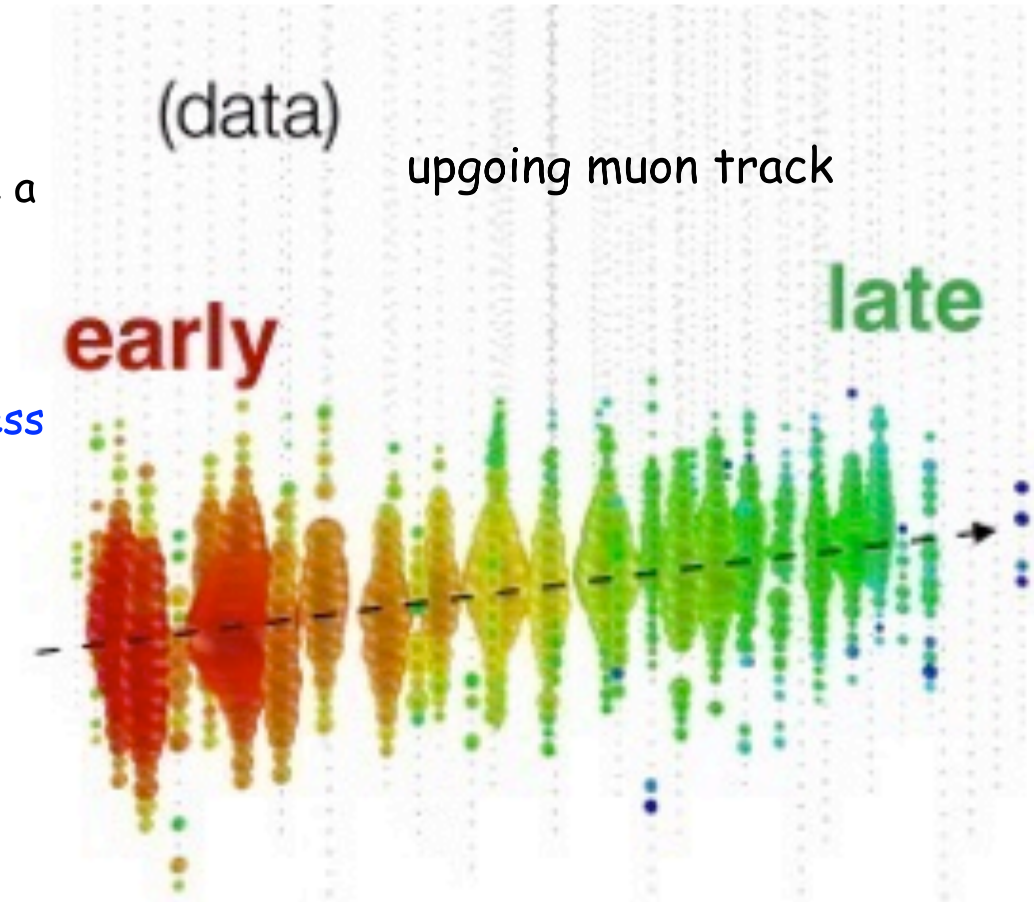
Atmospheric neutrinos all over the sky are a major background for this search

Using muon tracks (induced by neutrino interactions) to look at the Sun can suppress this background/ use starting events

Atmospheric muons are also a major background for this search

(i) Observation of the Sun when below the horizon or (ii) using only starting events/ DeepCore to mitigate these two backgrounds

$\nu_\mu + N \to \mu^- + N'$ and the corresponding interaction by $\overline{\nu}_\mu$



Other neutrino flavours are also utilised in this search strategy

Our results

Look towards the Sun

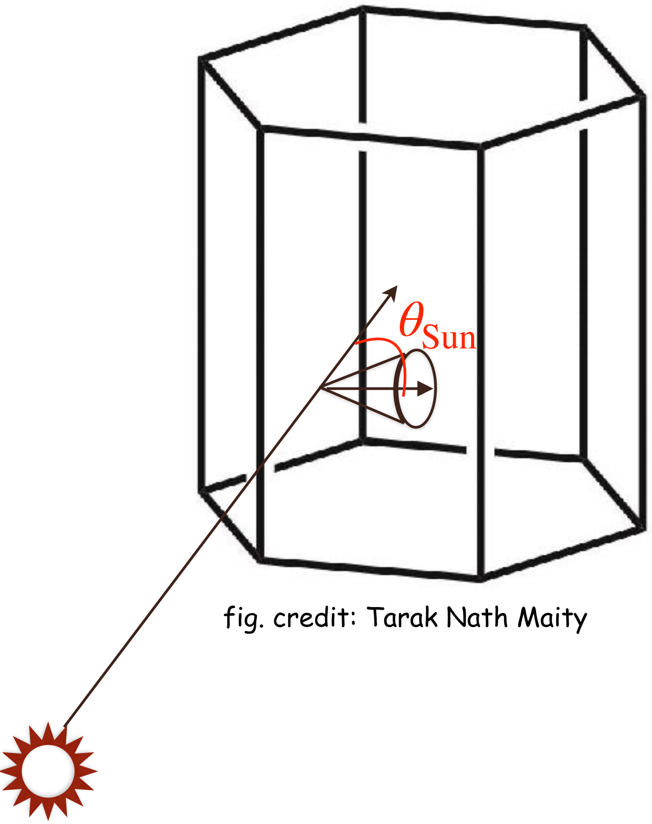
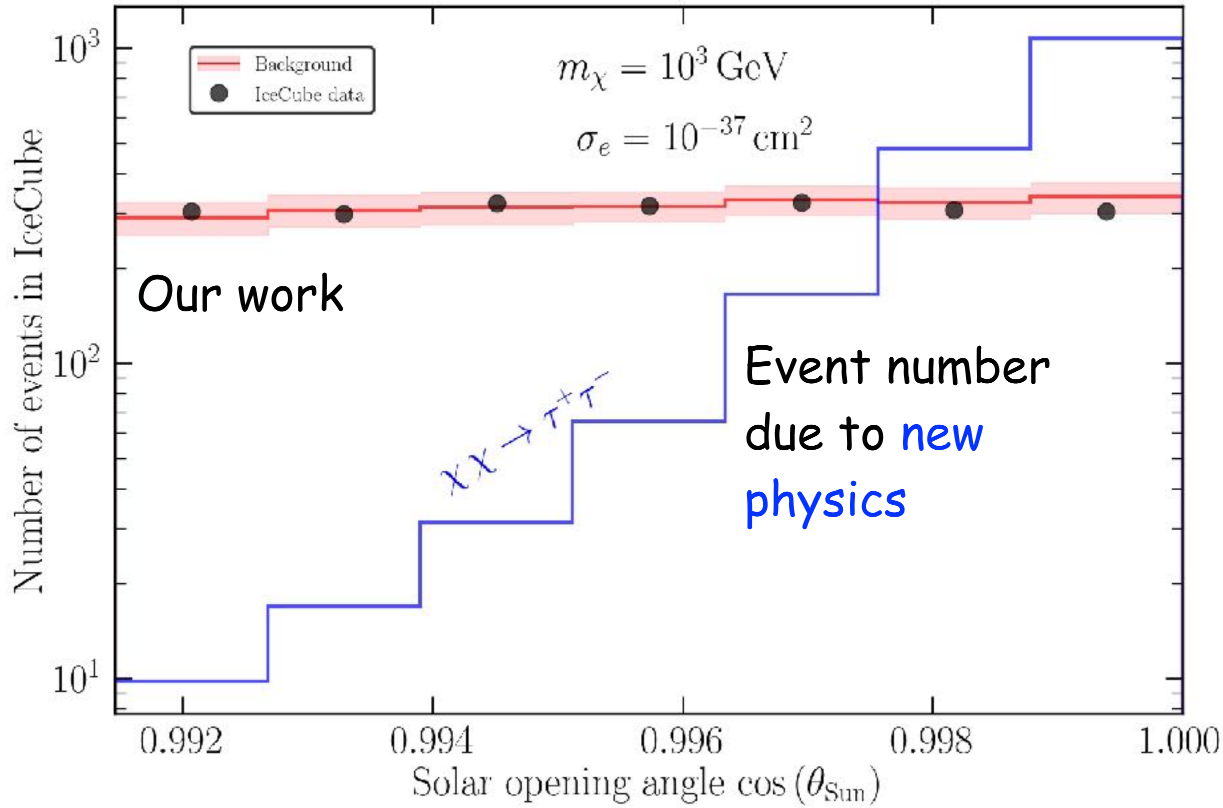
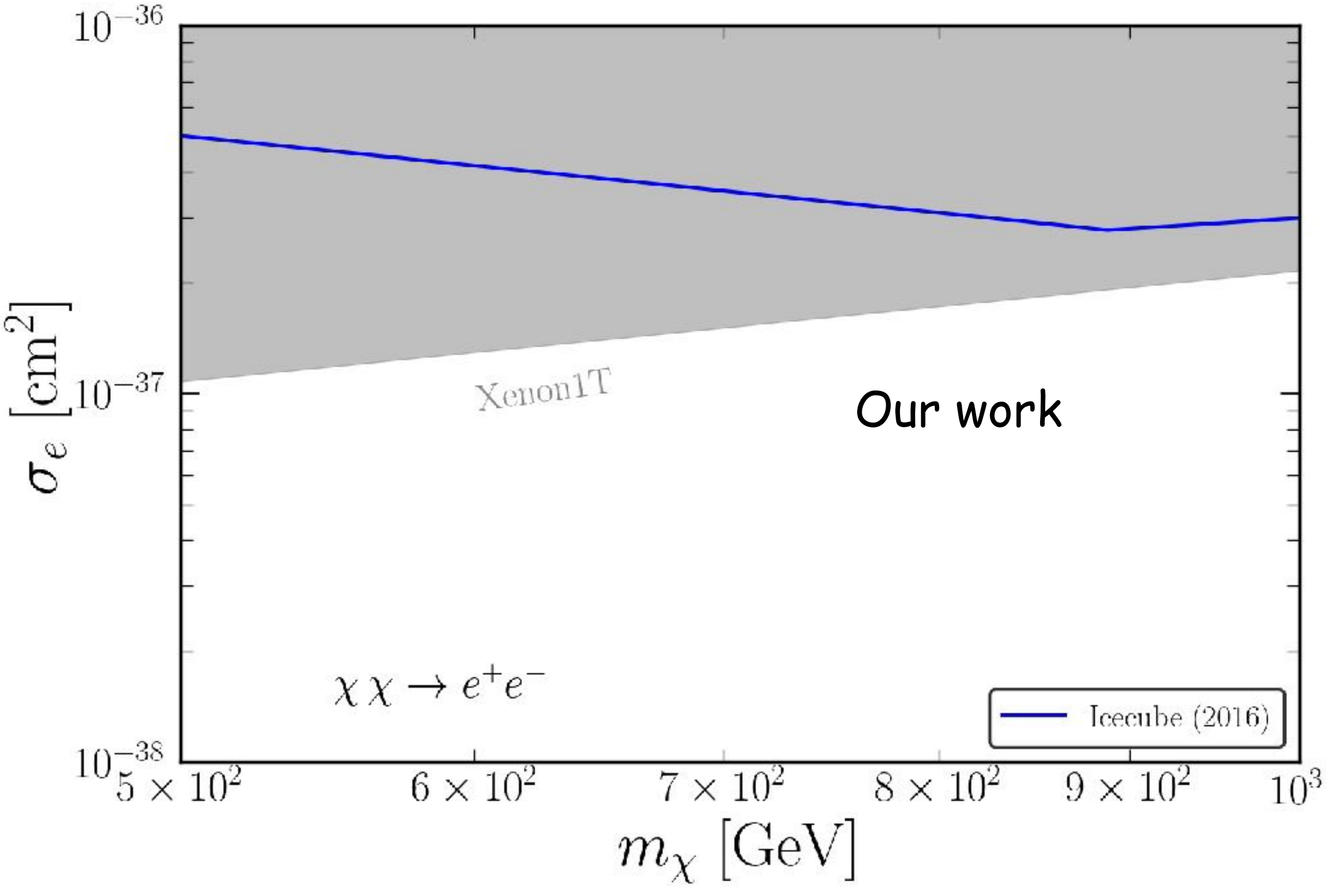


fig. credit: Tarak Nath Maity



Event number due to new physics exceeds the observed data $\Longrightarrow$ constraints on new physics

Constraints on dark matter - electron scattering

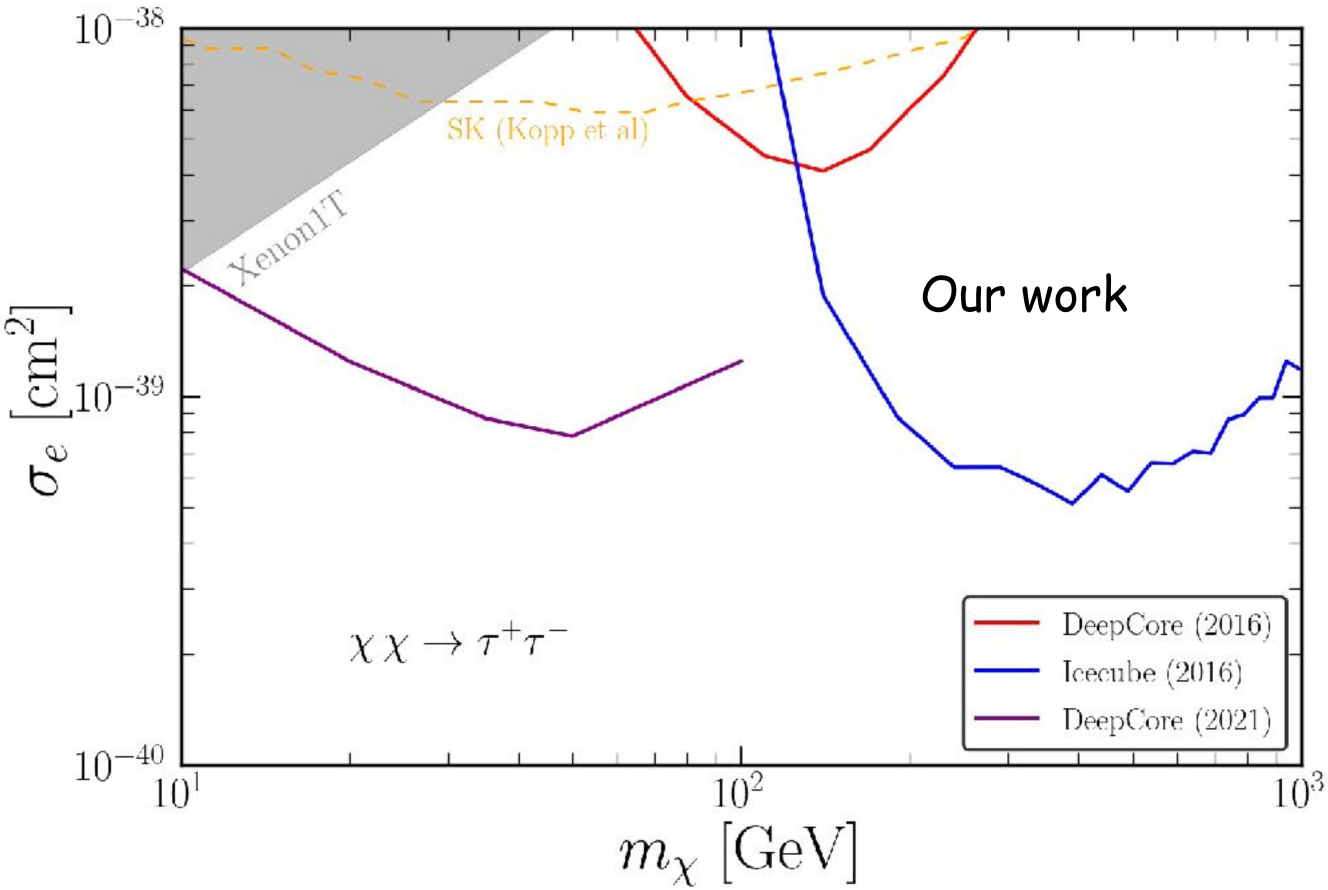


Using results of IceCube data, we derive stringent constraints on dark matter - electron scattering cross-section

Our derived limits are competitive with Xenon1T assuming e^+e^- dark matter annihilation final state

These limits will improve with near-future data from various IceCube upgrades, KM3NeT, and other neutrino telescope data — tremendous discovery potential of this technique using guaranteed data-set

Constraints on dark matter - electron scattering



Using results of IceCube data, we derive stringent constraints on dark matter - electron scattering cross-section

Our derived limits are orders of magnitude more stringent than Xenon1T assuming $\tau^+\tau^-$ dark matter annihilation final state

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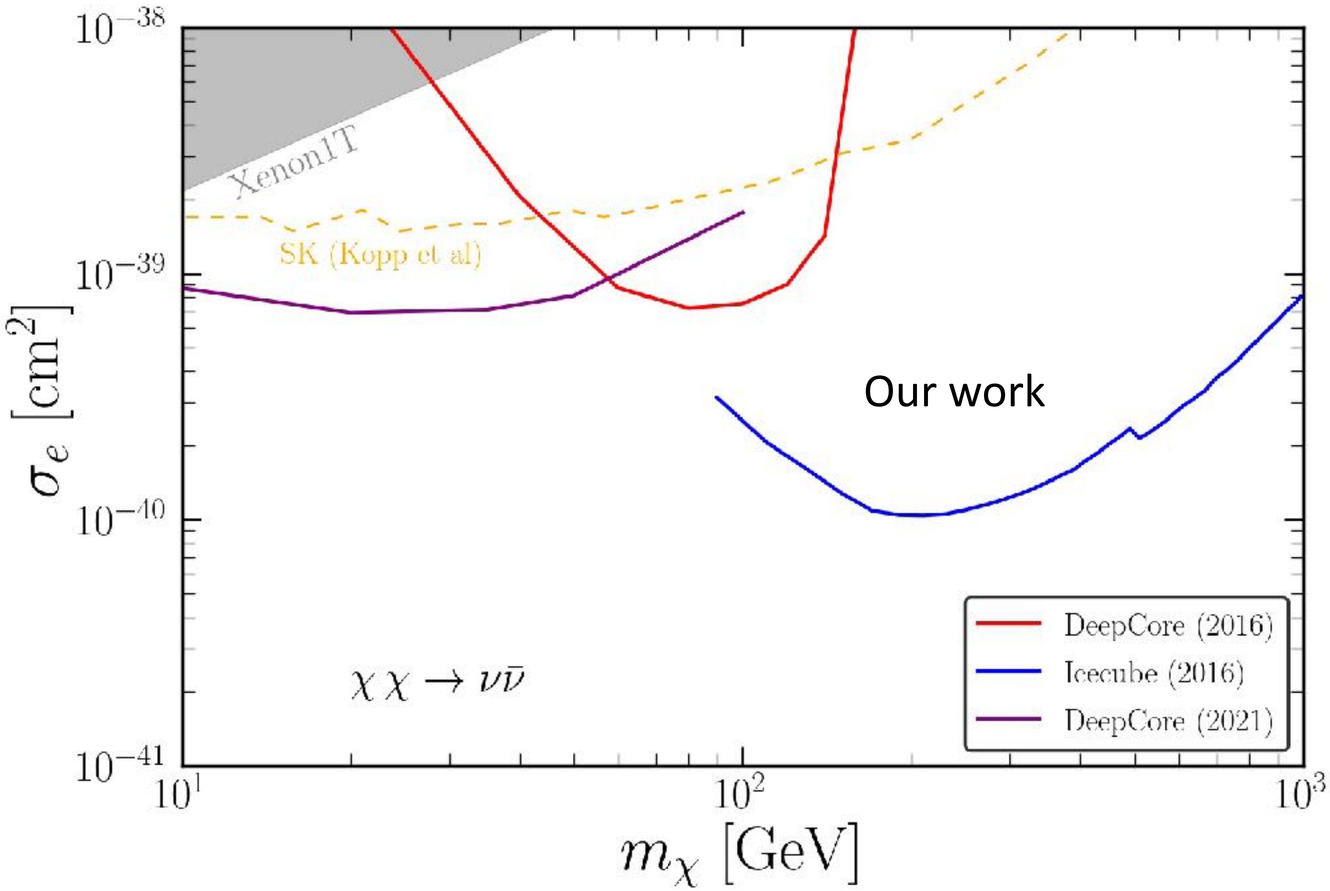
Constraints on dark matter - electron scattering



Using results of IceCube data, we derive stringent constraints on dark matter - electron scattering cross-section

Our derived limits are orders of magnitude more stringent than Xenon1T assuming $\nu\bar{\nu}$ dark matter annihilation final state

These limits will improve with near-future data from various IceCube upgrades, KM3NeT, and other neutrino telescope data — tremendous discovery potential of this technique using guaranteed data-set

Conclusions

We must probe all regions of the dark matter parameter space and all different couplings of dark matter - Standard Model particles

We probe dark matter captured in the Sun via electron scattering using the neutrinos produced from various dark matter annihilation final states

For various final states, we derive the most stringent bound on dark matter - electron scattering cross-section for heavy dark matter

Near future guaranteed data set from various different neutrino telescopes (either currently running or under construction) have the potential to discover dark matter interaction using this technique

Questions & comments: ranjanlaha@iisc.ac.in

Capture rate differential equation

$$\frac{dN_\chi}{dt} = C_c - C_a N_\chi^2$$

$$N_\chi(t) = \sqrt{\frac{C_c}{C_a}} \tanh\left(\sqrt{C_c C_a}\, t\right)$$

$$\tau_{\text{eq}} = \frac{1}{\sqrt{C_c C_a}}$$

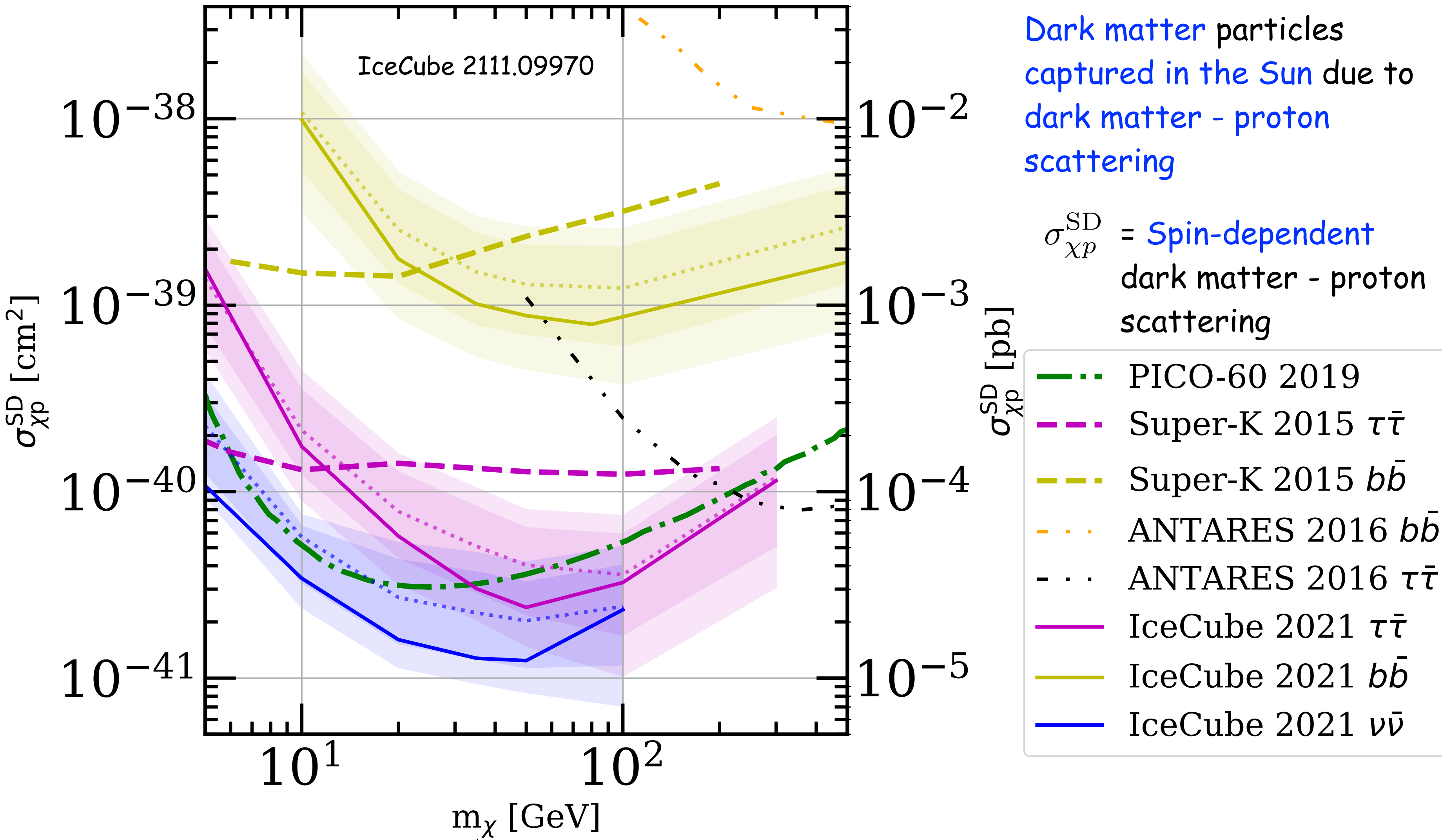
$$\tau_{\text{eq}} \lll \tau_\odot$$

$$N_{\chi,\text{eq}} = \sqrt{\frac{C_c}{C_a}}$$

$$\Gamma_a = \frac{1}{2} C_a (N_{\chi,\text{eq}})^2 = \frac{1}{2} C_c$$

Has this strategy been used before?

Neutrino telescopes and dark matter -proton scattering cross-section

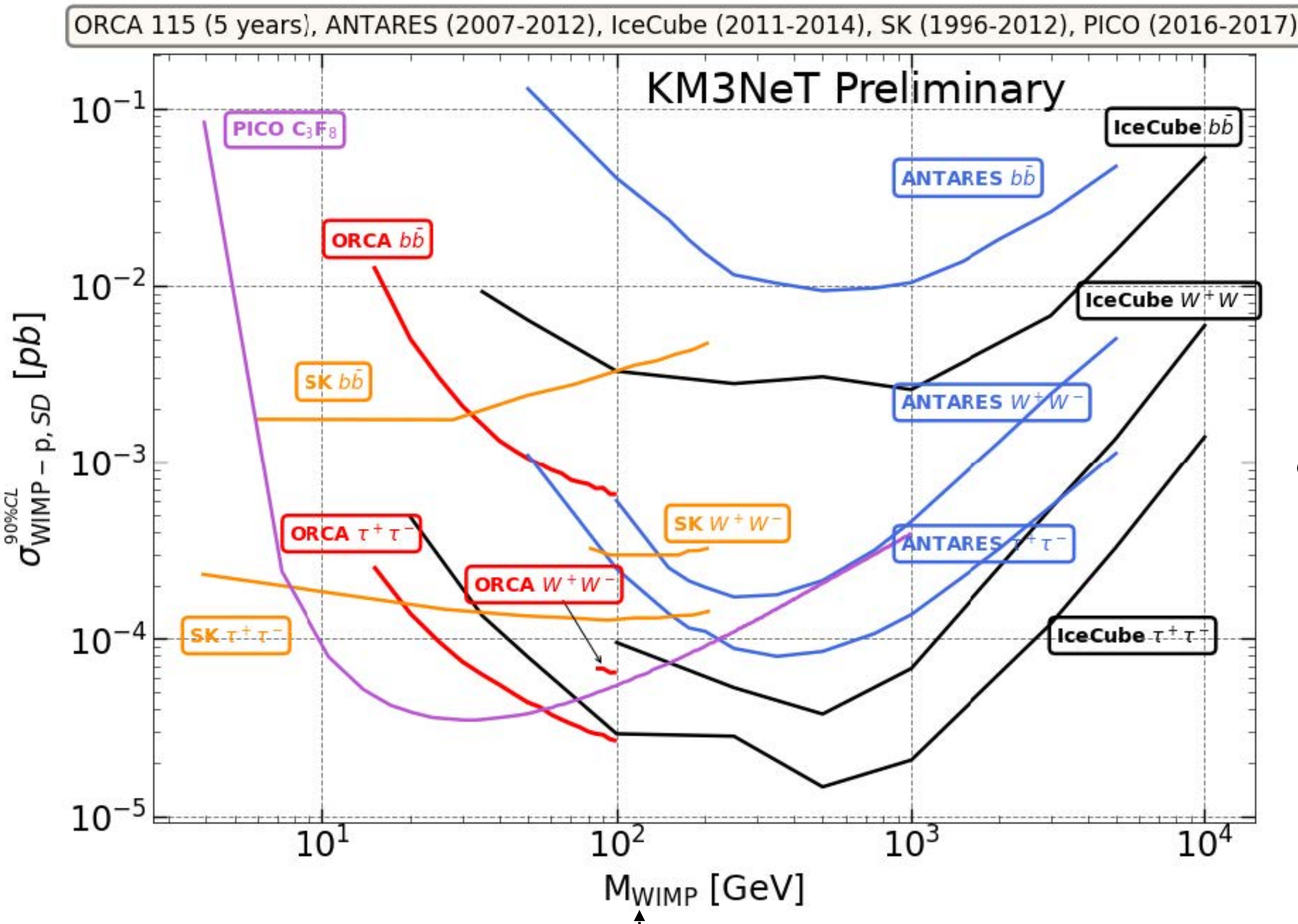


Dark matter particle mass

Dark matter particles captured in the Sun due to dark matter - proton scattering

$\sigma_{\chi p}^{SD}$ = Spin-dependent dark matter - proton scattering

Neutrino telescopes and dark matter -proton scattering cross-section



Dark matter particle mass

Zornoza 2021 review

Various neutrino telescopes set the most stringent constraints on dark matter - proton scattering

$\sigma^{90\%\mathrm{CL}}_{\mathrm{WIMP}-p,\mathrm{SD}}\,[pb]$ = Spin-dependent dark matter - proton scattering cross-section