Recent results on indirect Dark Matter Searches with IceCube

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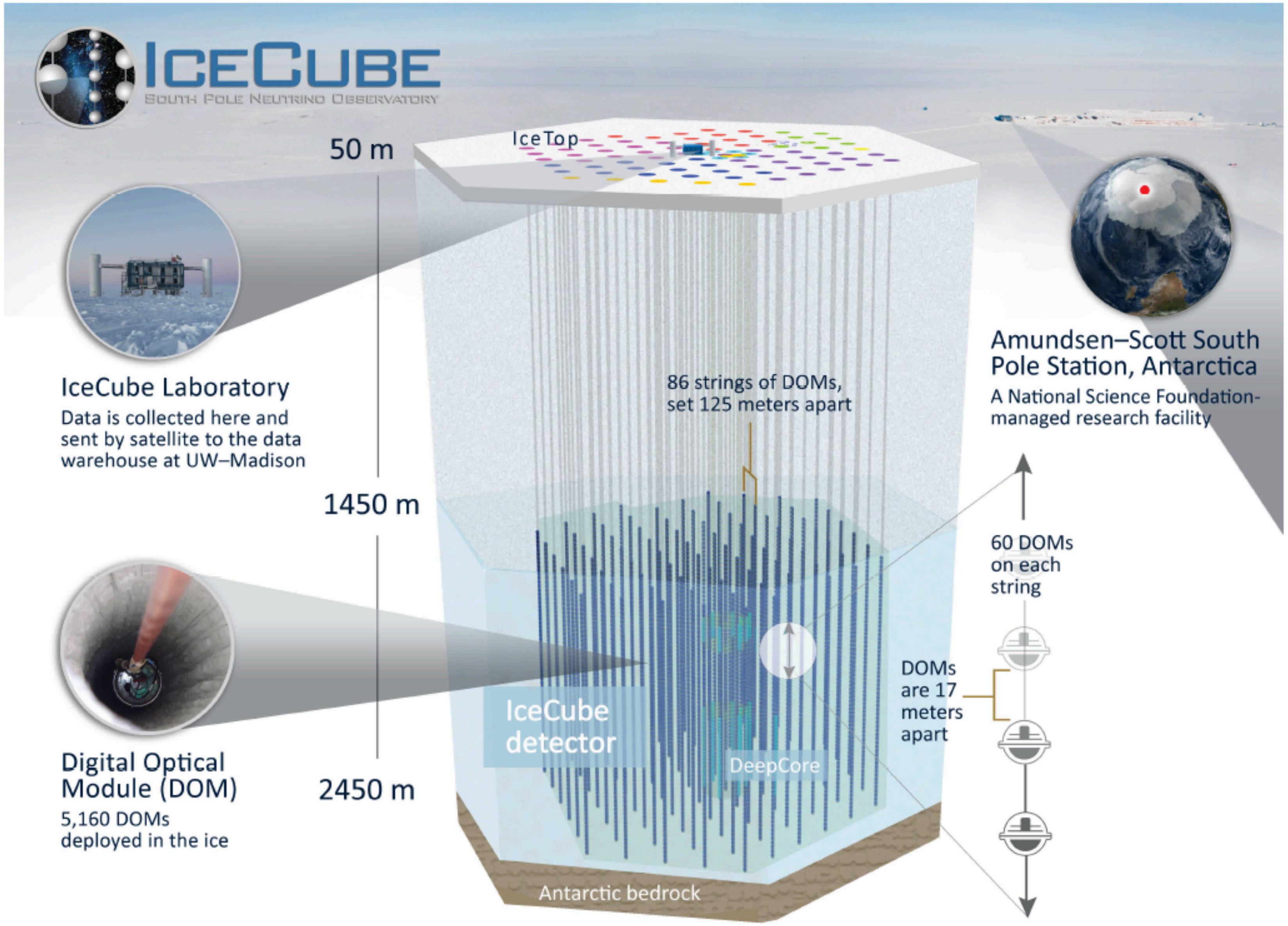
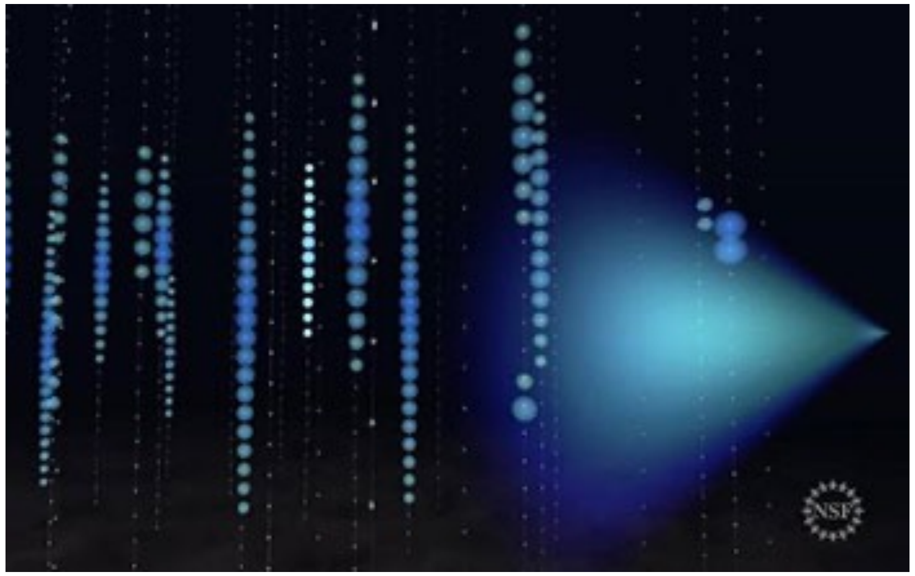
Outline

- Overview of indirect dark matter (DM) search with IceCube
- Results from recent IceCube analyses
  - Wearing interacting massive particles (WIMPs)
  - Secluded DM
  - Heavy DM (TeV-PeV scale)
- Conclusions

The IceCube Neutrino Observatory

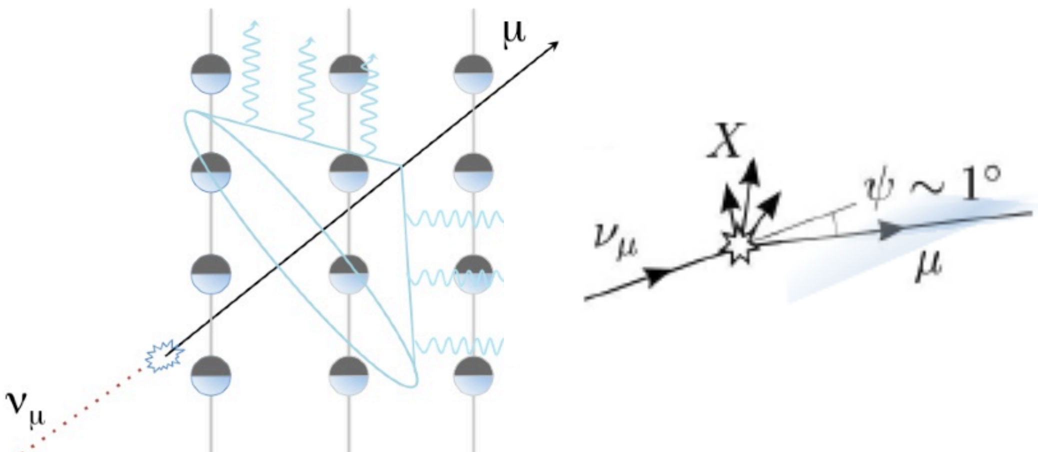


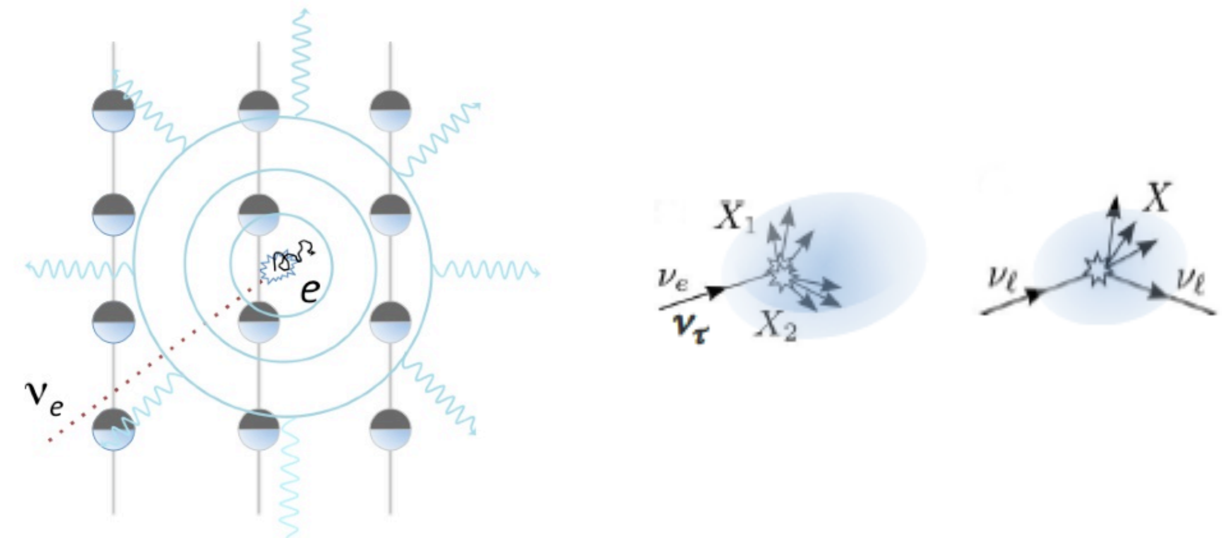
Digital Optical Module
(PMT & electronics)

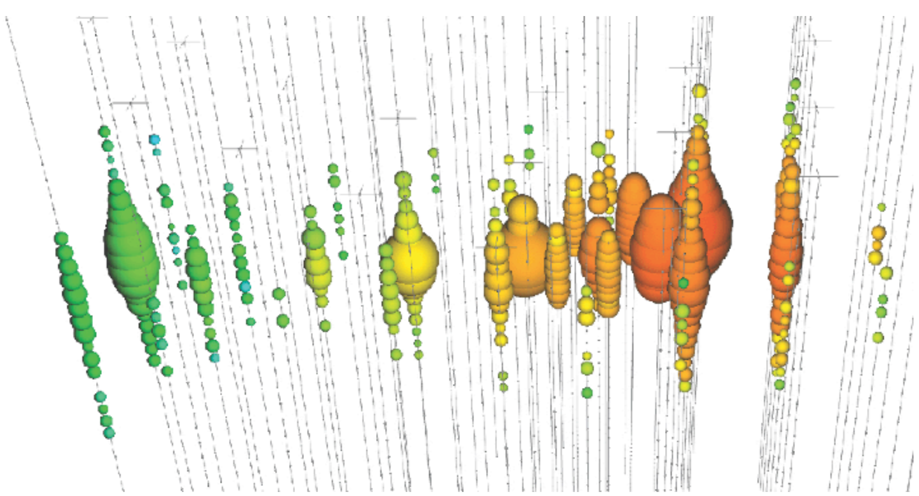


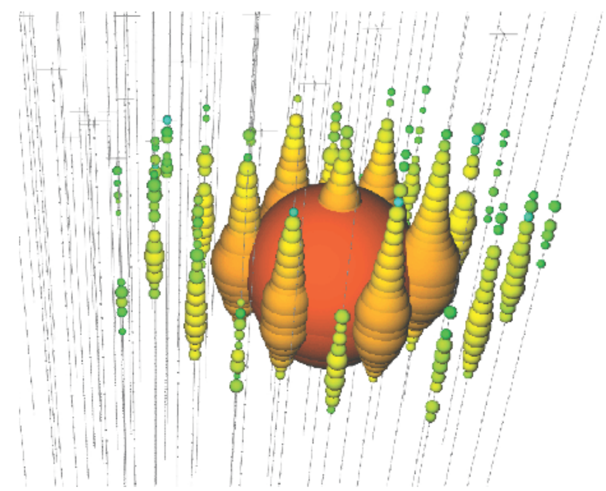
- Ice Cherenkov detector at the geographic South Pole.
- 5,160 digital optical modules deployed.
- Fully constructed in 2010.
- Energy threshold: ~10 GeV.

Event Topologies in IceCube









ν_μ CC interaction

Angular resolution < 1°

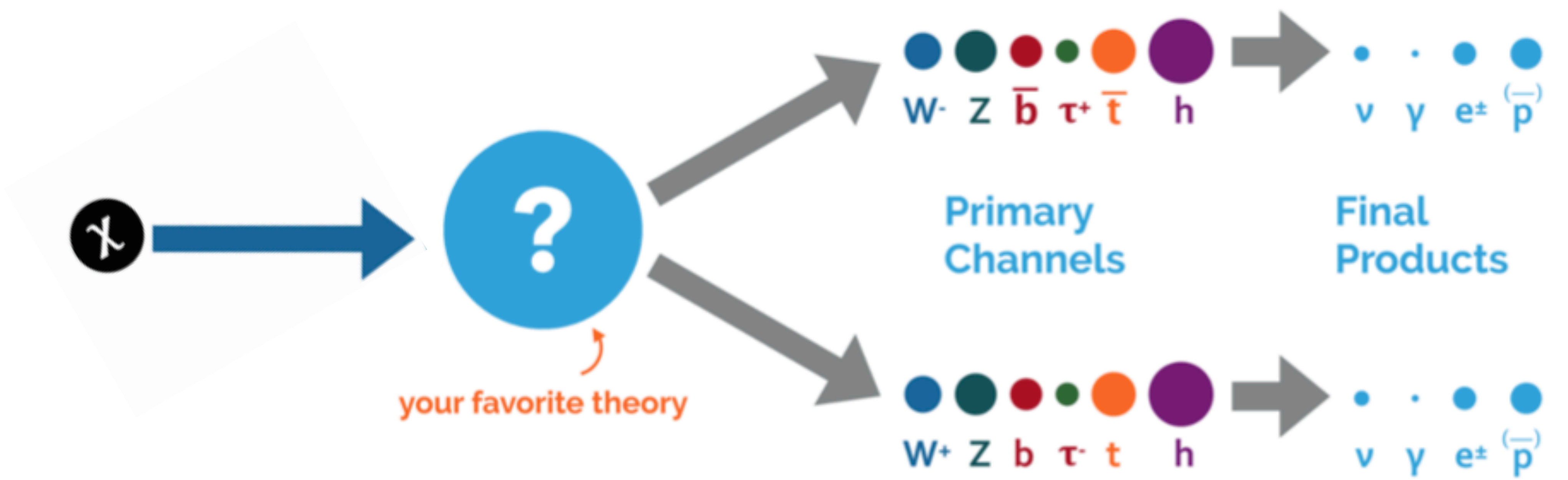
Large uncertainties in energy reconstruction

ν_{all} NC, ν_e/ν_τ CC interaction

Angular resolution : 15° to 20°

Energy resolution ~15%

Indirect DM search with neutrinos

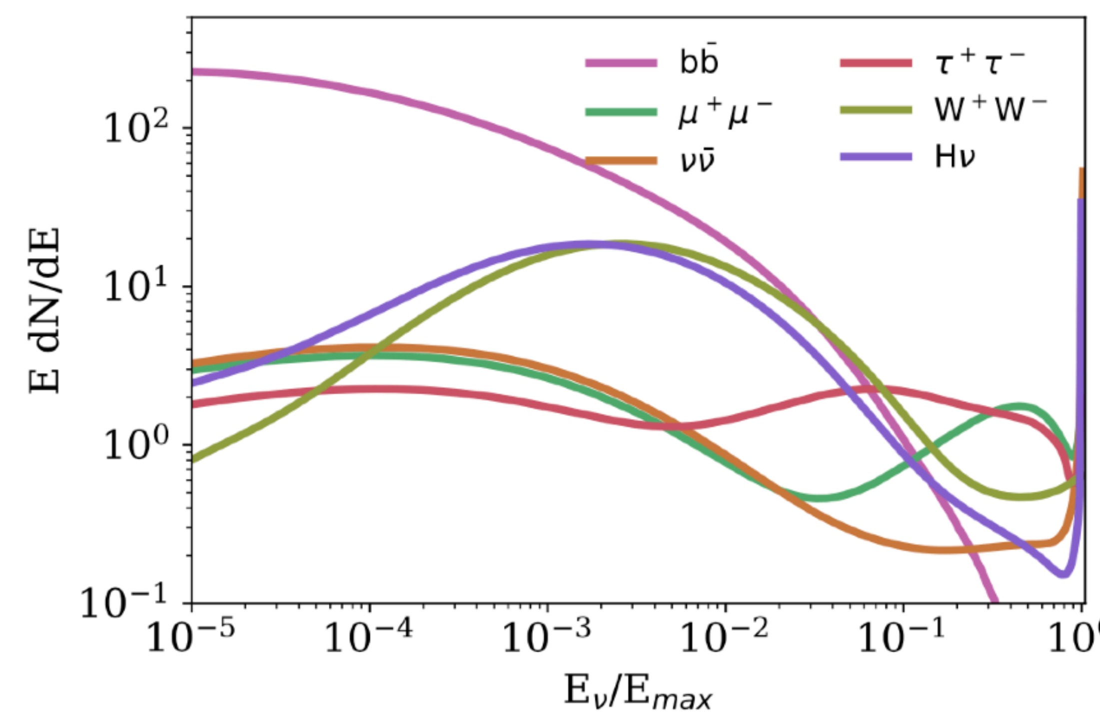


(The figure is adopted from Juan. A. Aguilar, “Searches for Dark Matter with IceCube”, NuDM2022.)

- A neutrino flux is expected from DM decay in a massive astronomical object.

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi m_\chi \tau_\chi} \frac{dN_\nu}{dE_\nu} \int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_\chi(s) ds$$

Particle Physics Factor



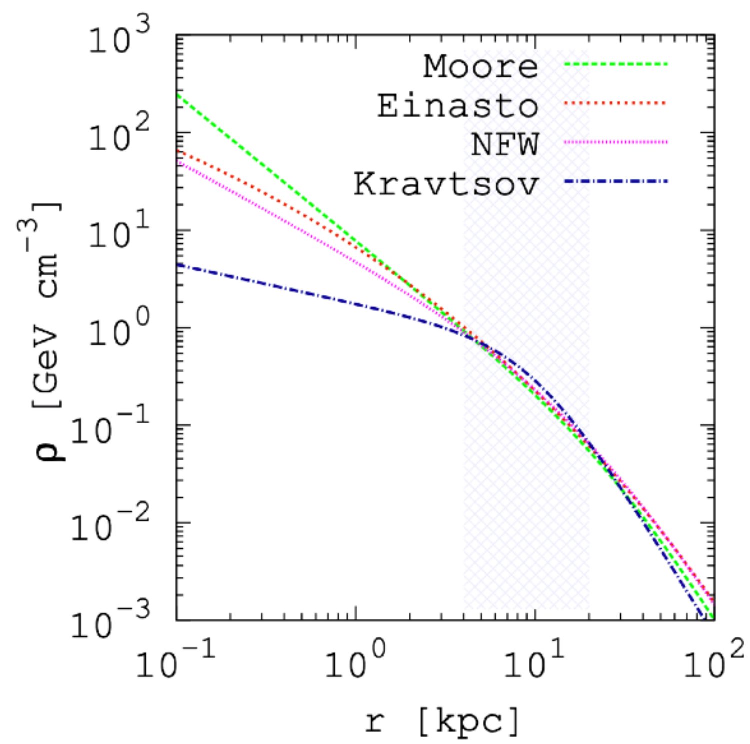
R. Abbasi *et al.* arXiv:2205.12950

Indirect DM search with neutrinos

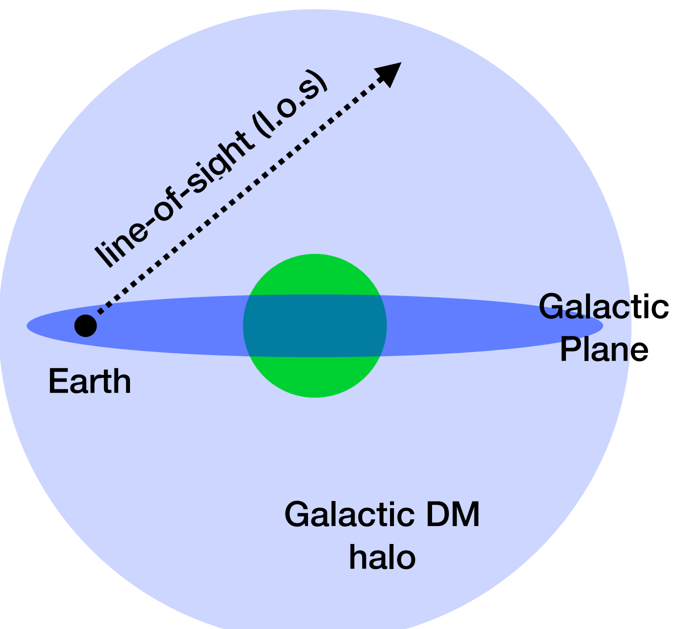
$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi m_\chi \tau_\chi} \frac{dN_\nu}{dE_\nu} \int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_\chi(s) ds$$

Astrophysical Factor (D-factor)

- The astrophysical factor depends on the DM mass density distribution only.
- This factor has a significant impact on the analysis sensitivity.
  - The signal flux is proportional to it.

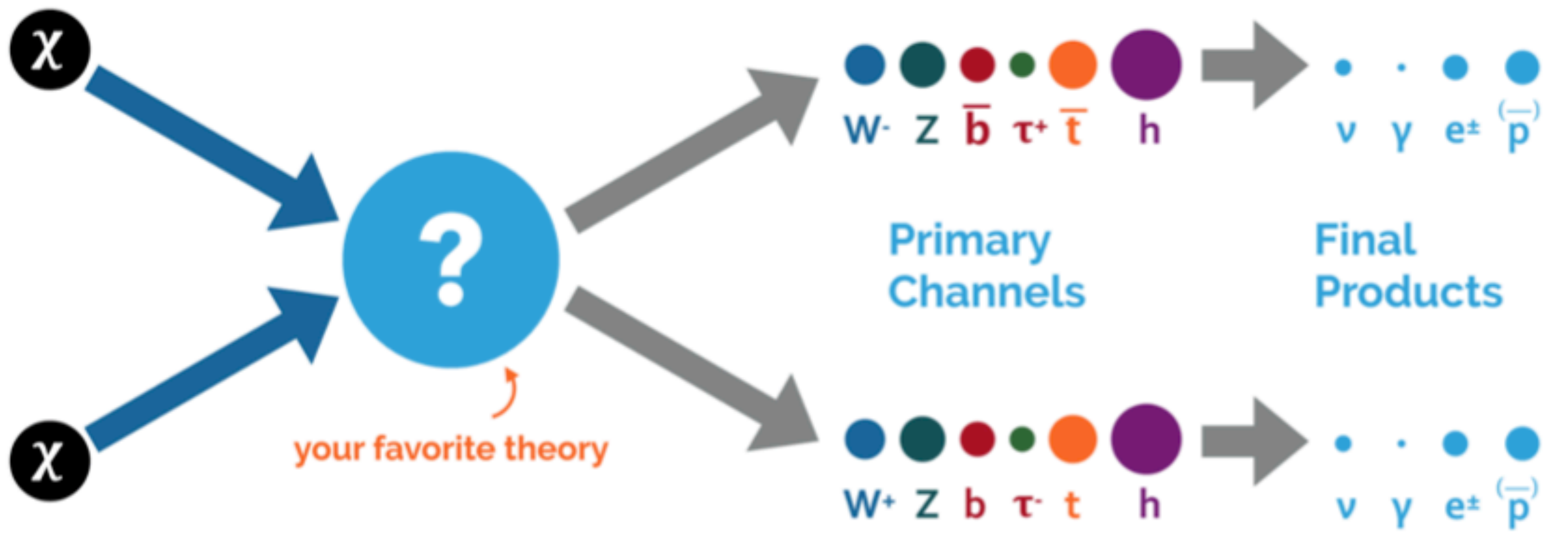


DM halo models of the Milky Way



R. Abbasi *et al.* (IceCube Collaboration)
Phys. Rev. D **84**, 022004

Indirect DM search with neutrinos



(The figure is adopted from Juan. A. Aguilar, "Searches for Dark Matter with IceCube", NuDM2022.)

- Flux from DM annihilation:

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN_\nu}{dE_\nu} \int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_\chi^2(s) ds$$

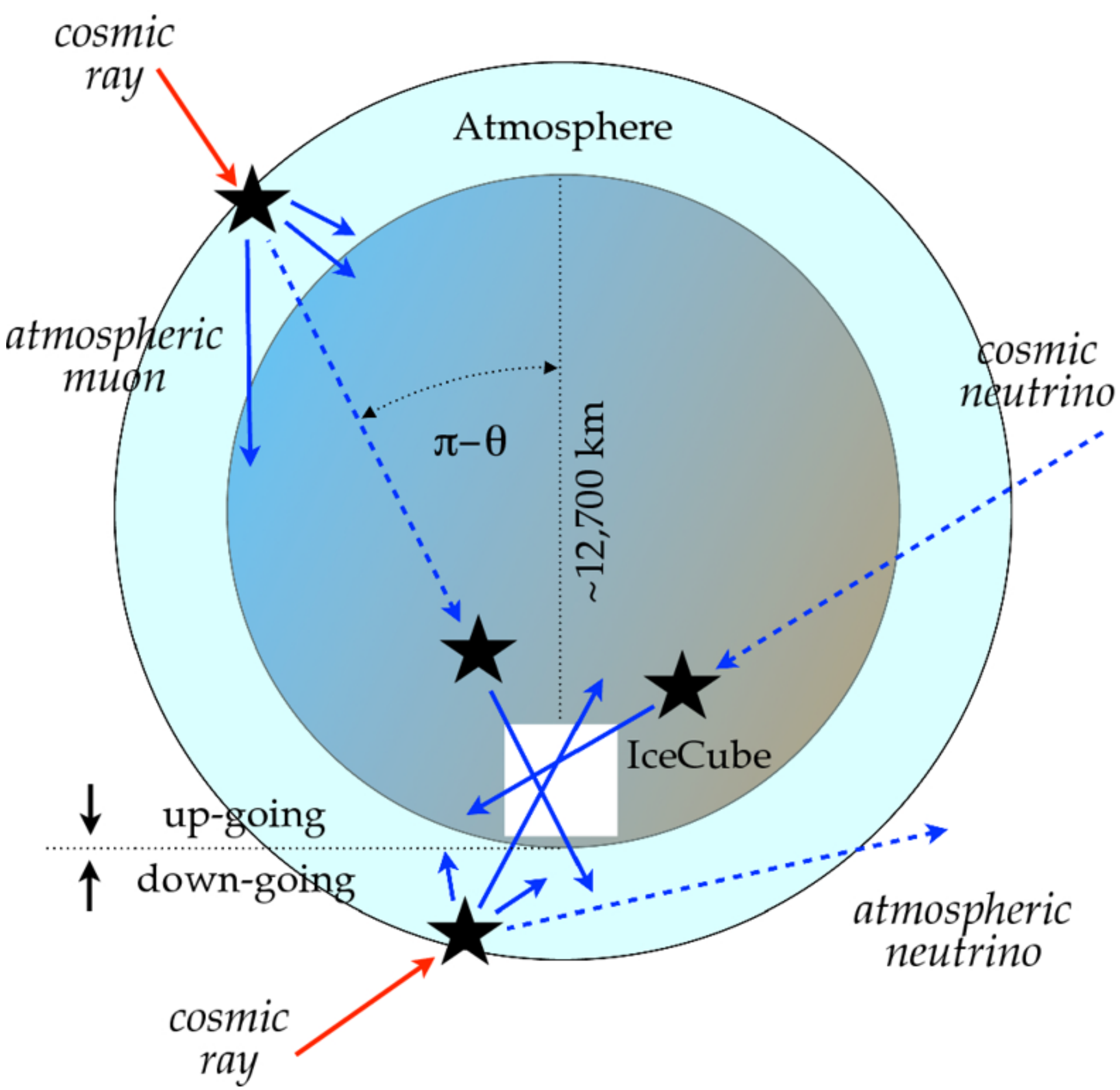
Particle Physics Factor

Astrophysical Factor (J-factor)

Common backgrounds for DM searches

- Atmospheric muons and neutrinos produced by cosmic-ray interactions with atmospheric molecules

- Diffuse astrophysical neutrinos from baryonic matter
    - Relevant for heavy decaying/annihilating DM searches



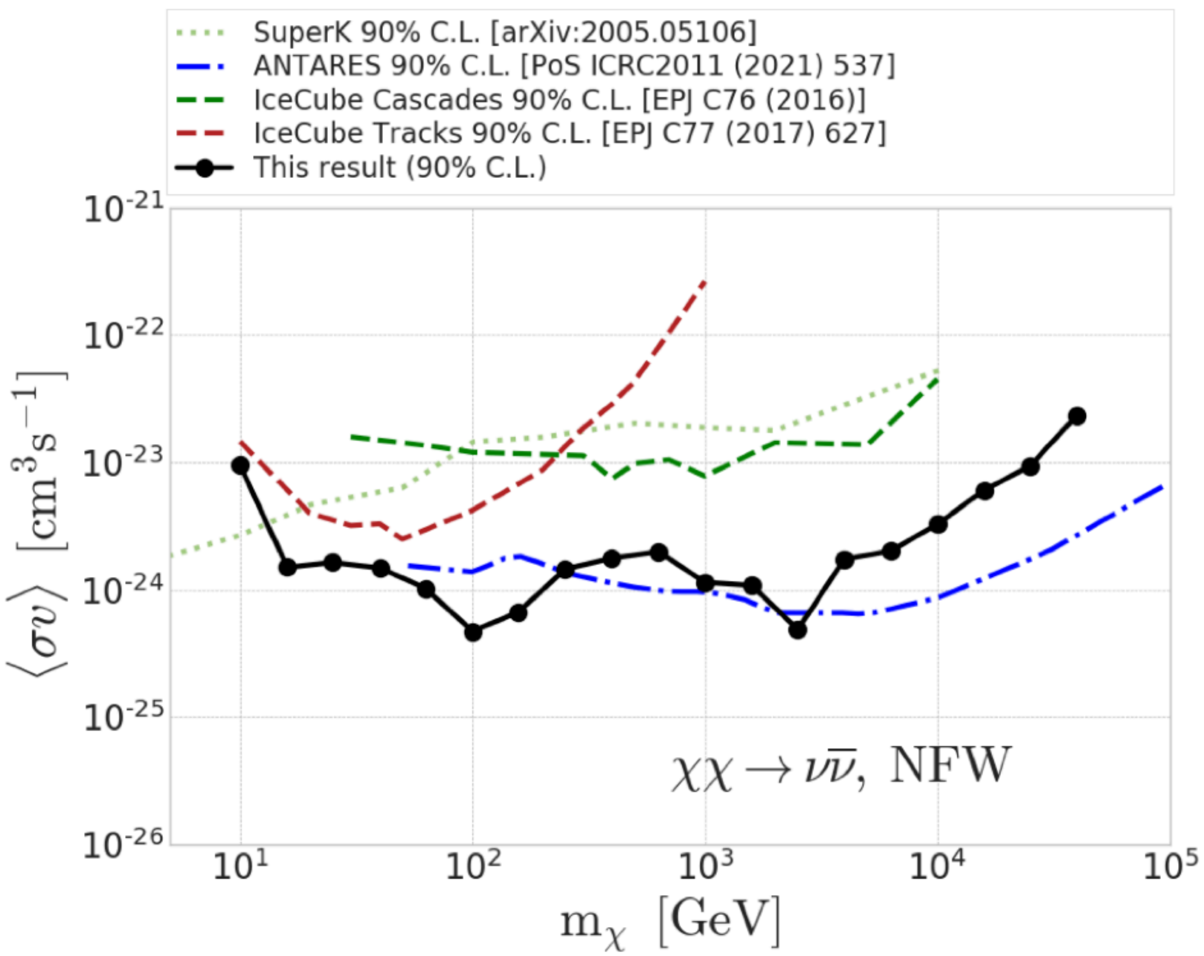
Eur. Phys. J. C (2018) 78:924

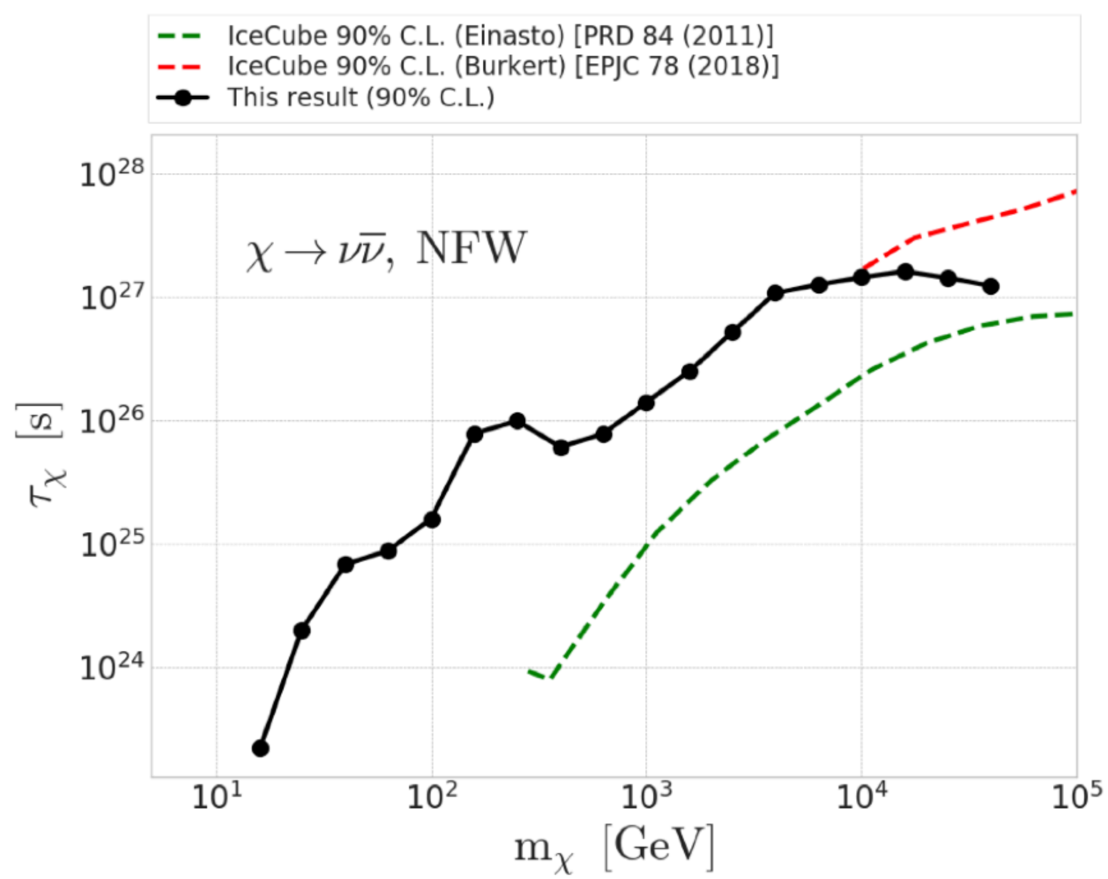
Searches for weakly interacting massive particles (WIMPs)

Galactic WIMP annihilation / decay

- Optimized to probe the $\nu\bar{\nu}$ channel.
  - Focusing on detecting the monochromatic line in the neutrino spectrum.
- Using 5 years of cascades contained in the DeepCore subarray.
- Significantly improved limits with respect to previous Galactic WIMP searches with IceCube.

R. Abbasi et al, arXiv:2303.13663

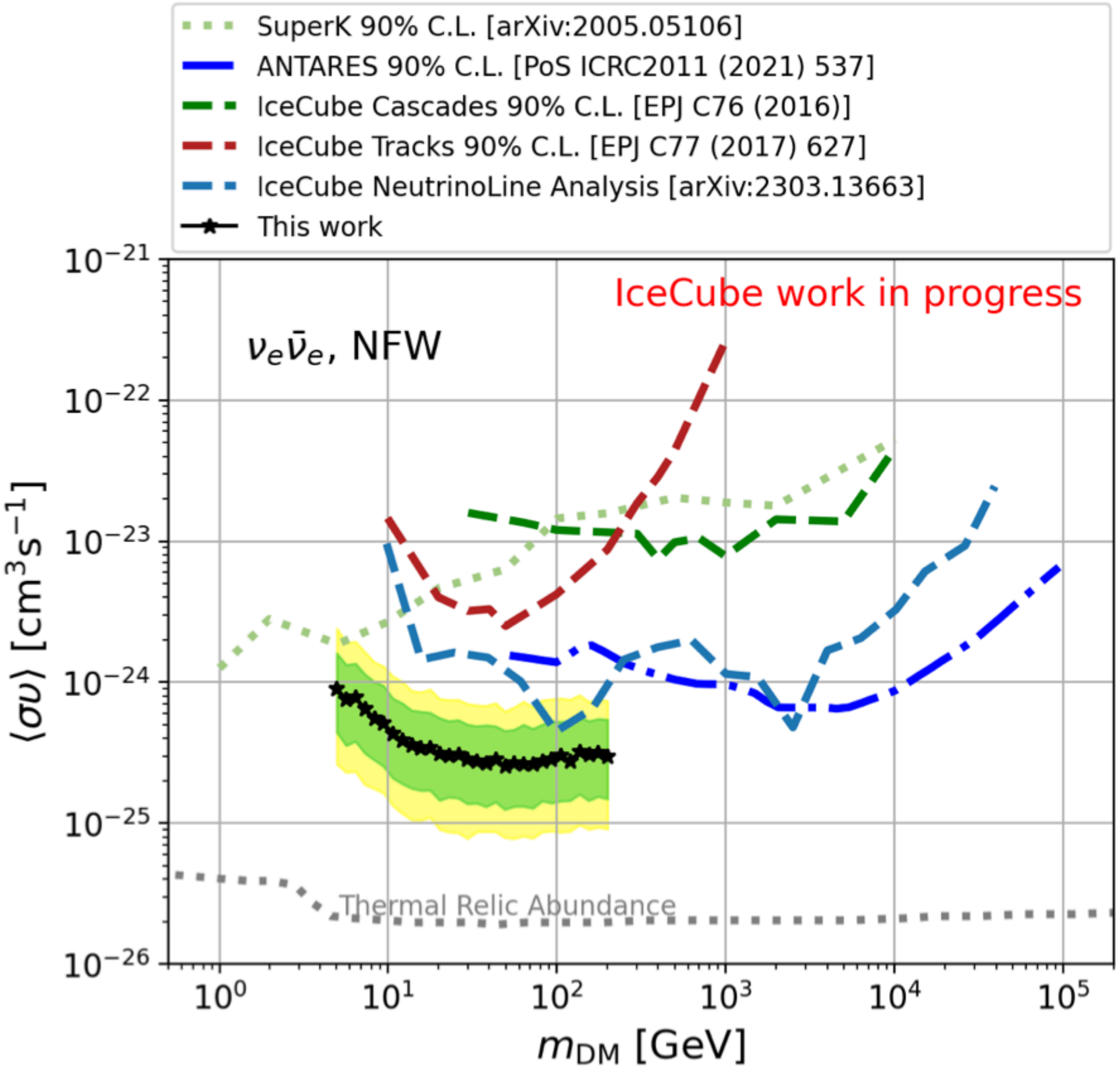




Galactic WIMP annihilation

- A next-generation analysis in progress.
- Using 9.3 years of low energy events (oscNext sample) .
  - Established for atmospheric neutrino measurements.
- Sensitivity considerably improved for low DM masses.

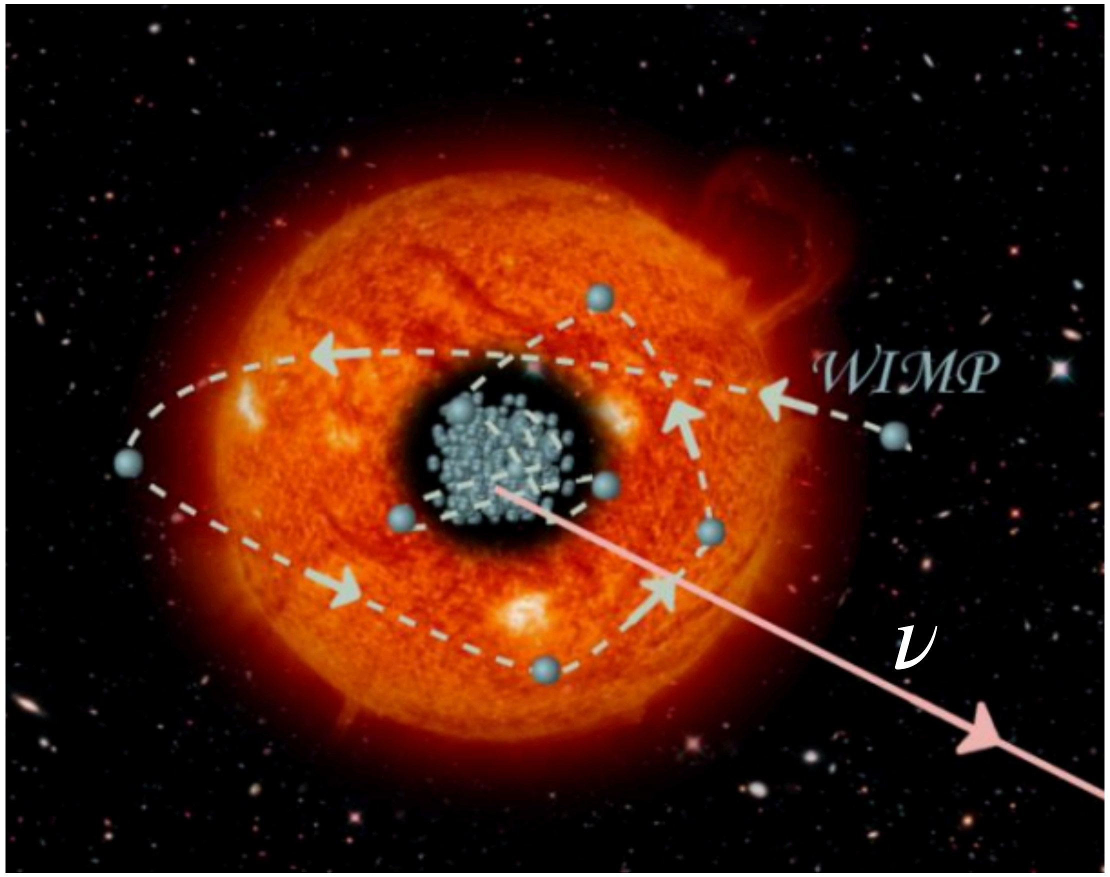
R. Abbasi et al, PoS(ICRC2023)1394



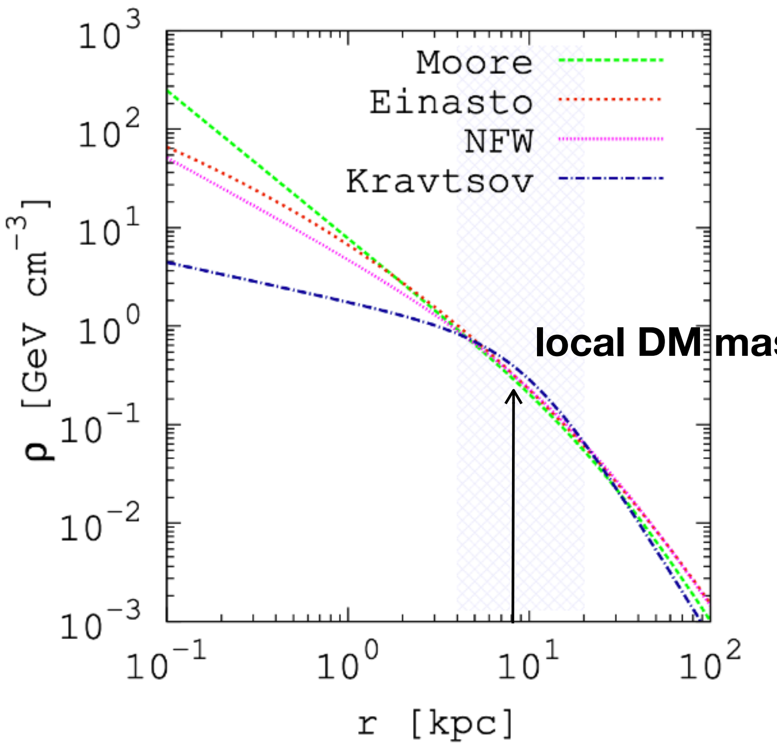
Sensitivity to the thermally-averaged WIMP annihilation cross section

Neutrinos from WIMP annihilation in the Sun

- The solar system travels through the Galactic Halo.
- WIMPs could scatter off nuclei in the Sun, loose their kinetic energy and become **gravitationally trapped** in the center of the Sun.
- **The trapped WIMPs could self-annihilate** to produce neutrinos directly or indirectly.
  - The neutrinos can escape the Sun and could be detected at Earth.



The figure is taken from J. Kunen's talk at Darkattack-2012.



DM halo models of the Milky Way

R. Abbasi *et al.* (IceCube Collaboration)
Phys. Rev. D **84**, 022004

Limits on WIMP-nucleus scattering

- The capture rate and annihilation rates are expected to be in equilibrium.

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

capture rate $\propto \sigma_{\chi N}$

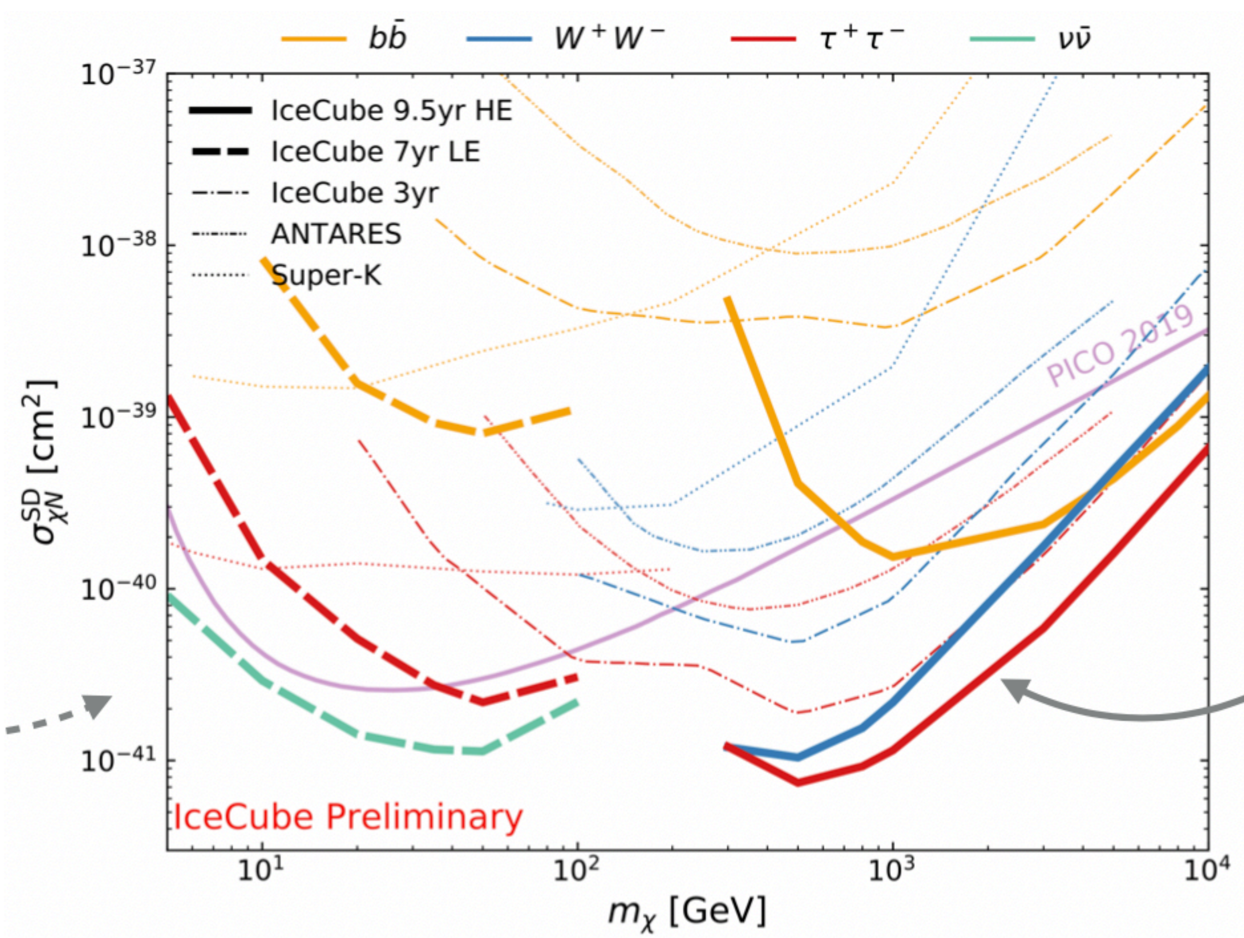
annihilation rate

evaporation rate (negligible above a few GeV)

Limits from the LE analysis

- 7 years of DeepCore data (mostly cascades).

Phys. Rev. D 105, 062004



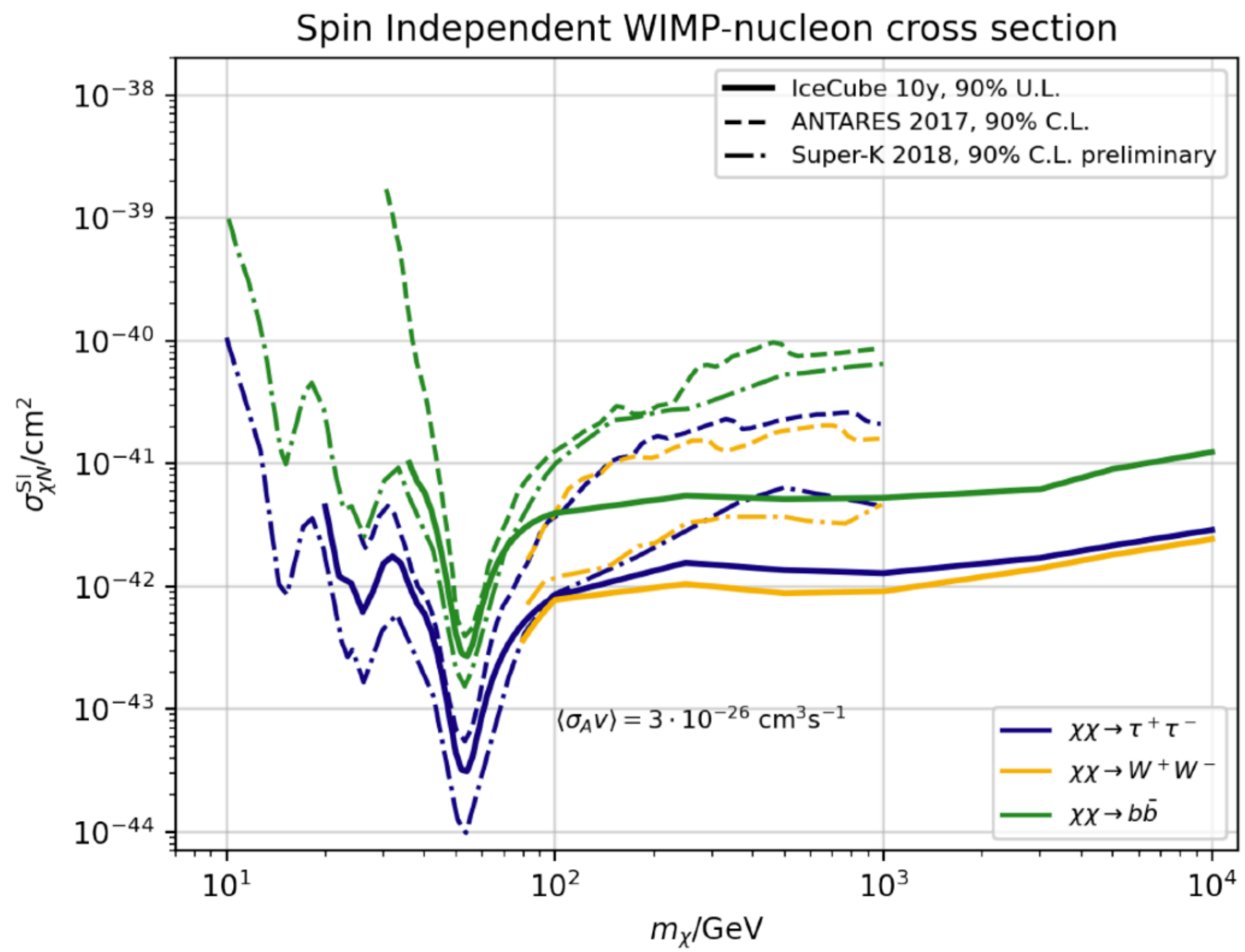
Limits from the HE analysis

- 9.5 years of track events

PoS(ICRC2021)020

WIMP annihilation in the Earth

- WIMPs can be accumulated and annihilate in the center of the Earth, similar to the solar WIMPs.
  - Among the annihilation products **only neutrinos can reach Earth's surface**.
- The **angular and energy distribution of the neutrino flux** would be distinctive from the atmospheric backgrounds.
- Our latest results use 10 years of IceCue data and derive the world-best limits for DM masses above 100 GeV.
  - PoS(ICRC2023)1393

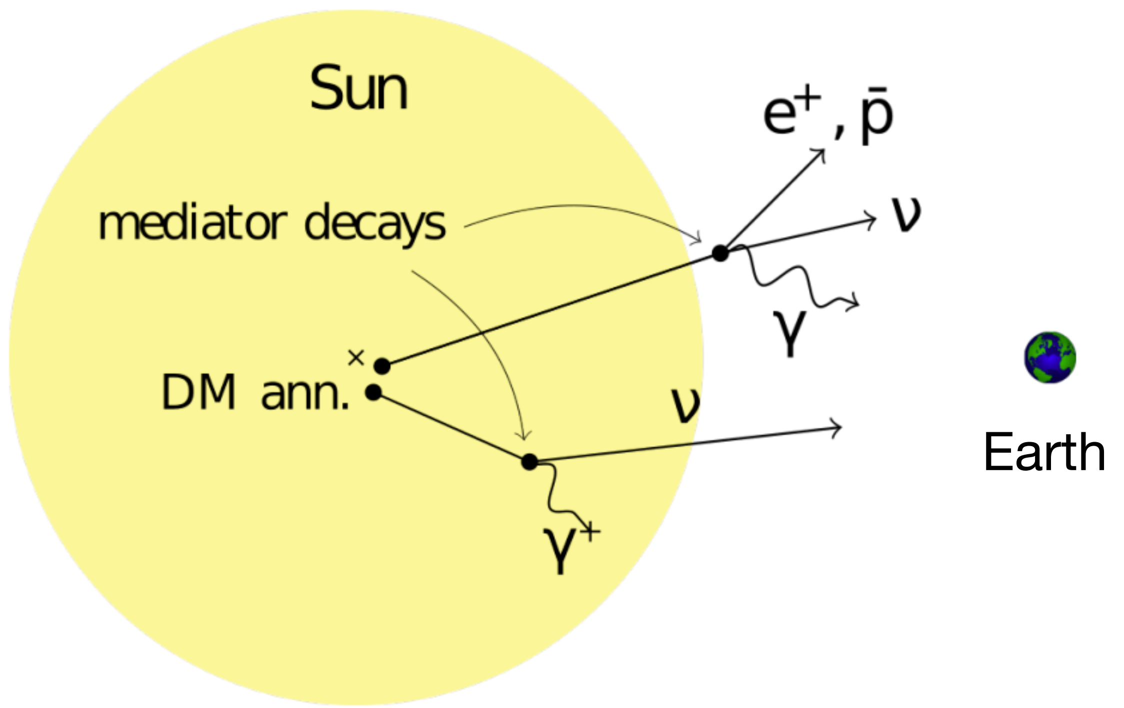


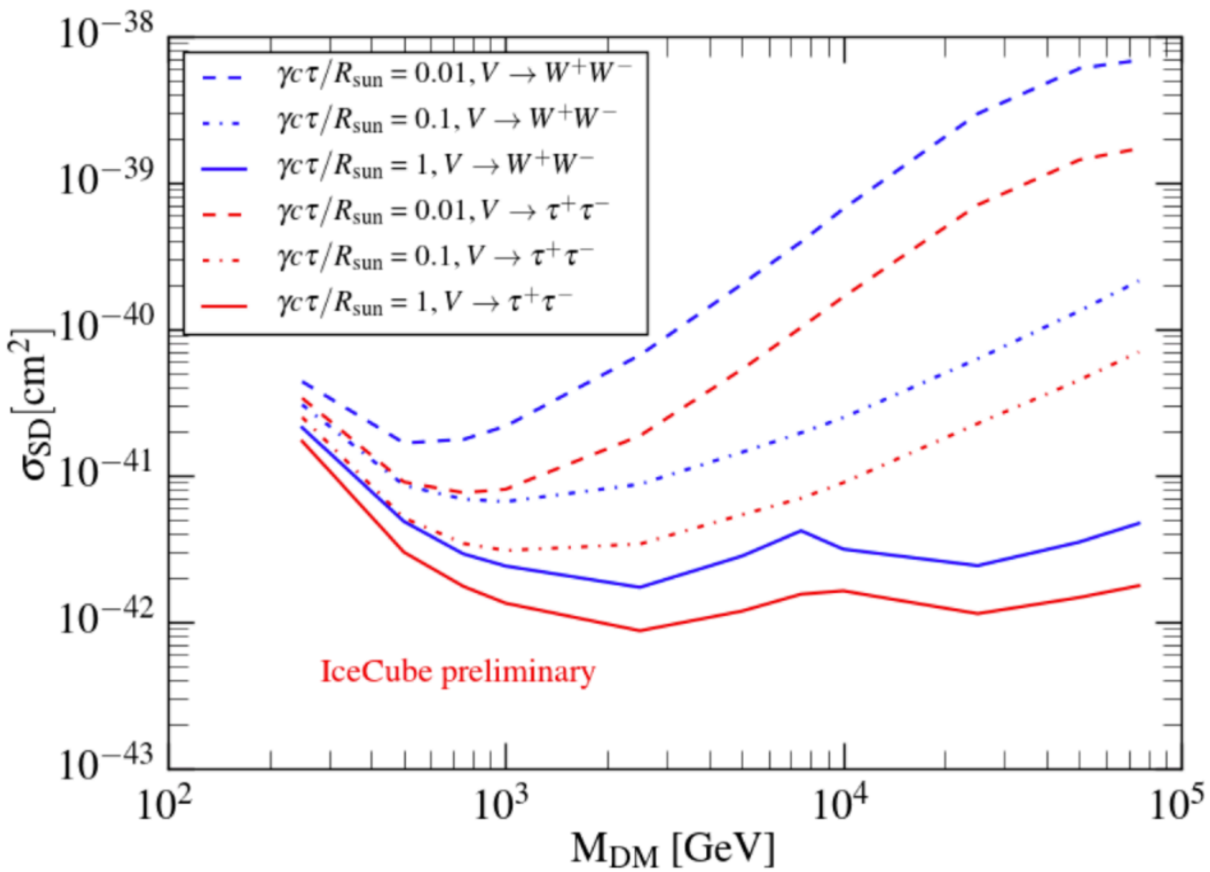
(An annihilation cross section is assumed, because the WIMP capture and annihilation rates in the Earth would not be in equilibrium.)

Search for secluded dark matter

Secluded DM in the Sun

- Secluded DM is expected to annihilate into **metastable mediators**, such as dark photons or Z'.
- In these models, mediators can decay to produce SM particles inside or outside the Sun, depending on their lifetime.
- When they decay inside the Sun, **only neutrinos with energies below ~1 TeV can escape the solar plasma** and arrive at Earth.
- We used 6 years of track events to look for neutrinos from secluded DM in the Sun.
  - PoS(ICRC2021)521

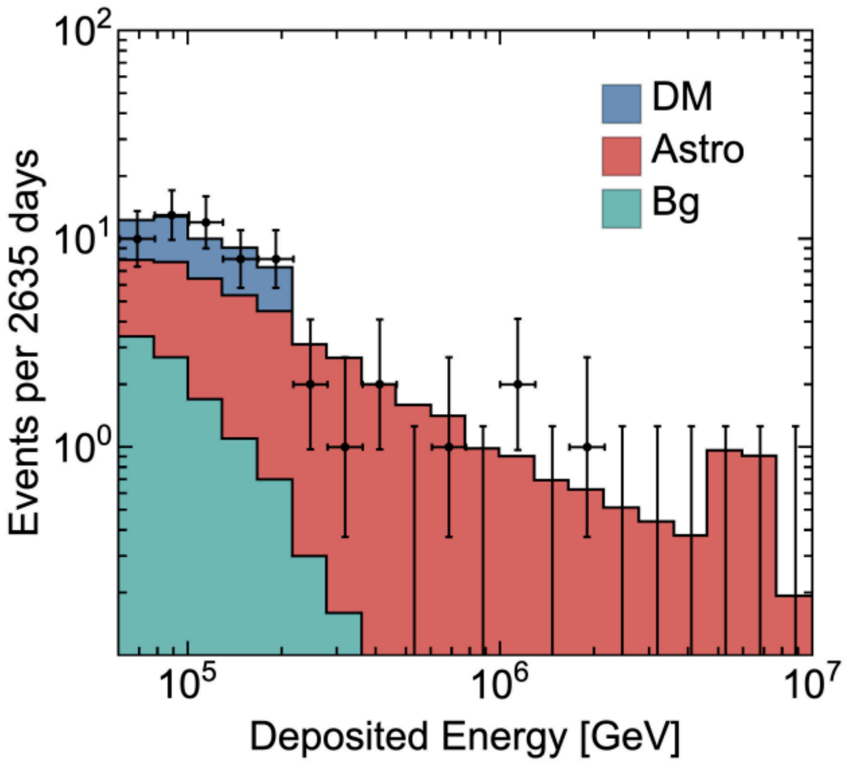




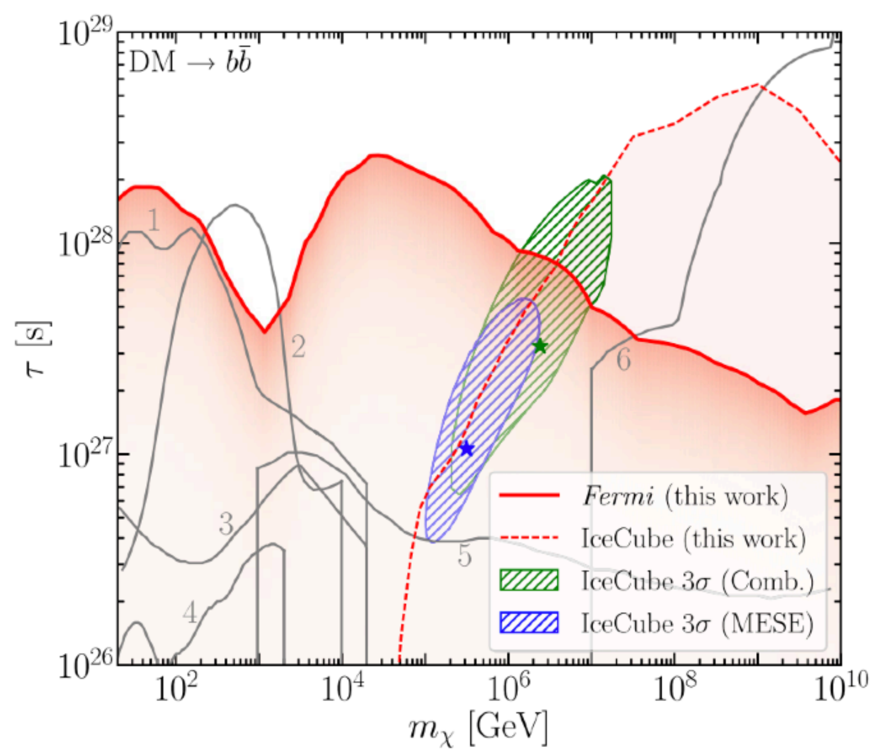
Searches for heavy (TeV-PeV) dark matter

TeV-PeV dark matter

- Modern neutrino and gamma-ray experiments allow us to test physics on the PeV scale.
  - This possibility inspired extensive discussions on heavy dark matter.
- It was speculated that the high-energy astrophysical neutrinos observed at IceCube could hint at signals from decaying heavy DM.



M. Chianese *et al*, JCAP11(2019)046



T. Cohen *et al,* Phys. Rev. Lett. 119, 021102

A. Esmaili *et al*, JCAP 11 (2012) 034

K. Murase *et al,* Phys. Rev. Lett. 115, (2015) 071301

C. Rott *et al*, Phys. Rev. D 92, 023529 (2015)

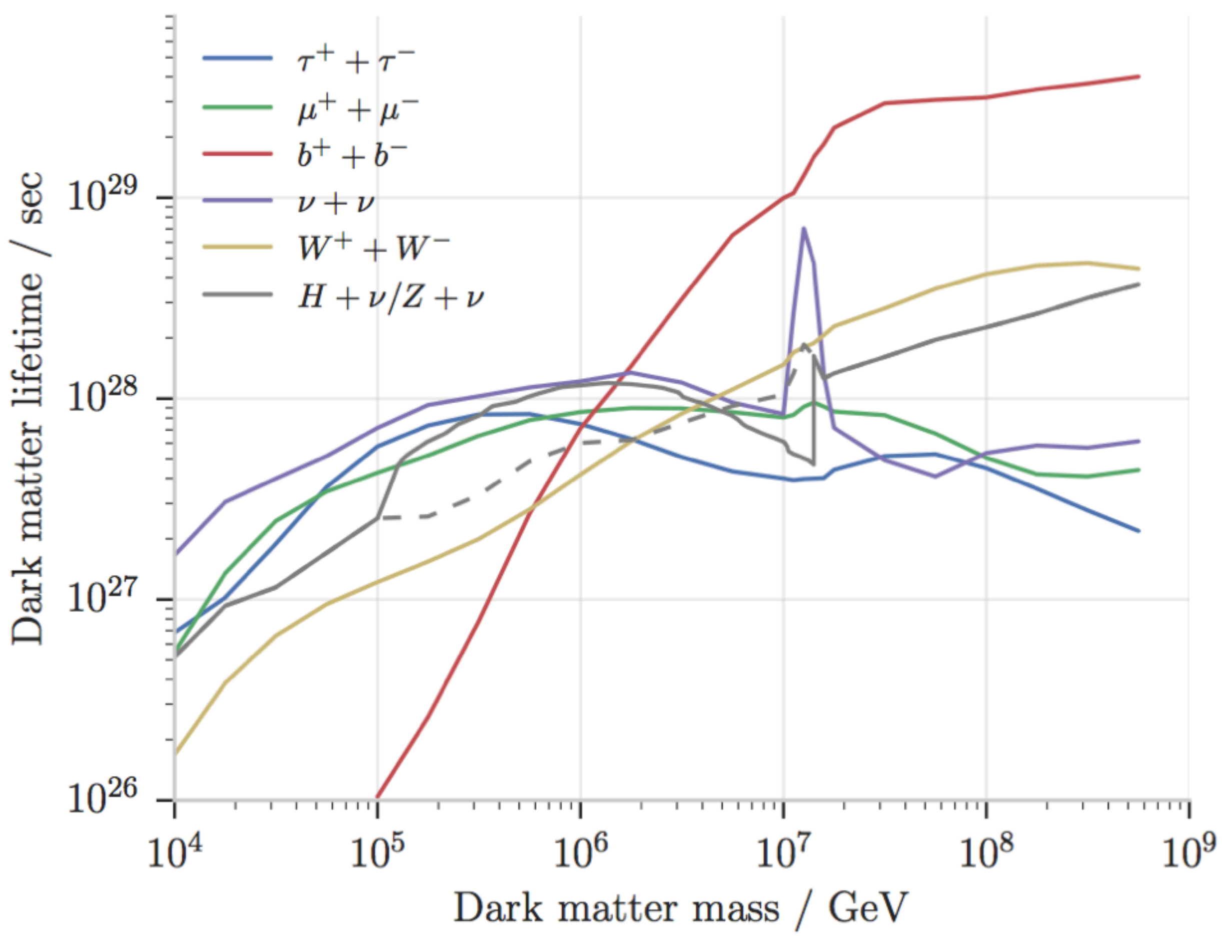
M. Kachelrieß *et al*, Phys. Rev. D 98, 083016 (2018).

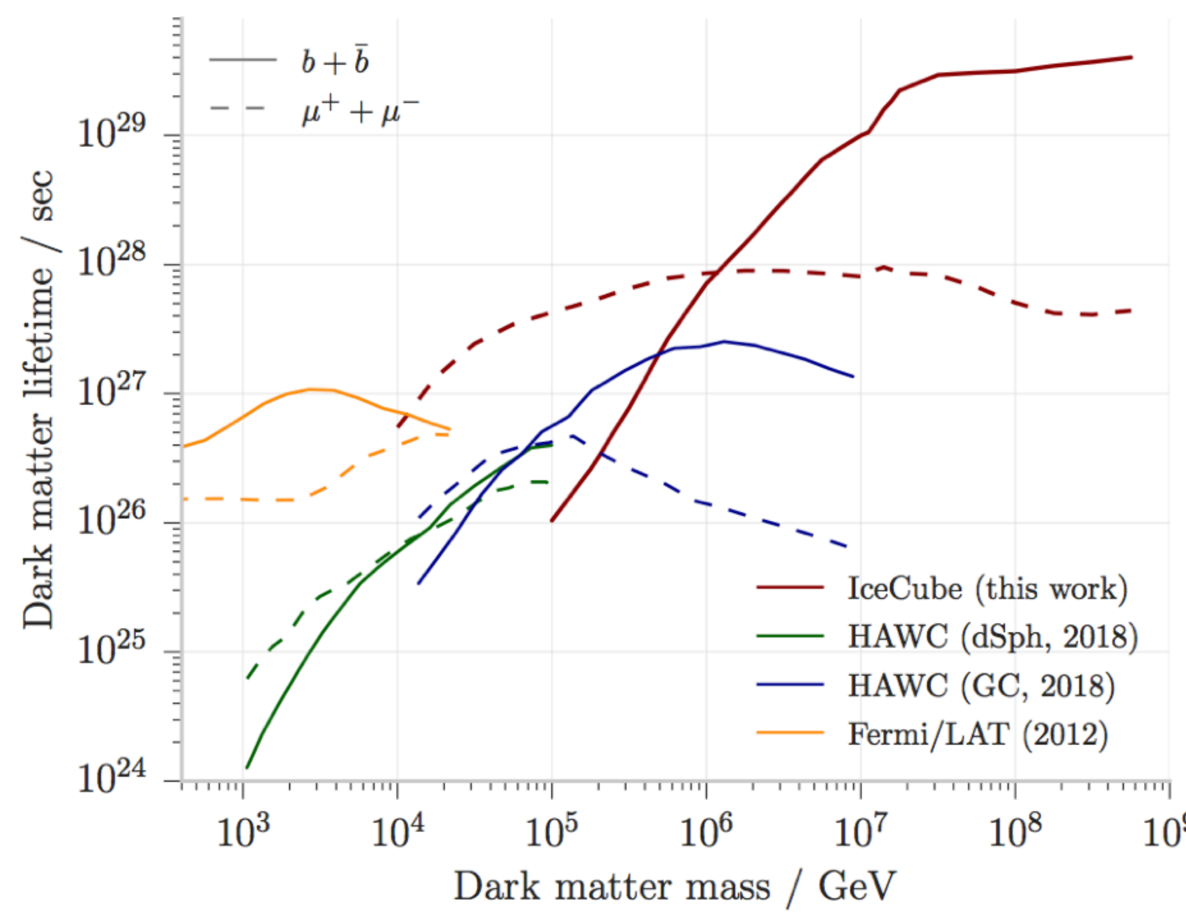
G. Lambiase *et al,* EPJC 78 (2018) 350

G. Chakravarty *et al*, Adv.High Energy Phys. 2020 (2020) 2478190

Previous search for decaying DM with IceCube

- IceCube has been proven to be highly sensitive to TeV-PeV DM decay models.
  - A previous IceCube analysis looked for neutrinos from **Galactic and cosmological DM decays**. This work resulted in some of the most stringent limits on the DM lifetime.





M. G. Aartsen *et al*, Eur. Phys. J. C (2018) 78 831

Search for DM decay using 7.5 years of HESE data

Analysis summary

- Similar to the previous analysis, we searched for **neutrinos from Galactic and cosmological DM decay**.

$$\frac{d\Phi_\nu}{dE_\nu d\Omega} = \frac{d\Phi_\nu^{Gal}}{dE_\nu d\Omega} + \frac{d\Phi_\nu^{Cos}}{dE_\nu d\Omega}$$

1) Contribution from Galactic DM decay:

$$\frac{d\Phi_\nu^{Gal}}{dE_\nu d\Omega} = \frac{1}{4\pi m_\chi \tau_\chi} \frac{dN_\nu}{dE_\nu} \int_{l.o.s.} \rho_\chi(s) ds$$

(DM sub-halos were neglected, as the total flux is not sensitive to sub-halos.)

2) Contribution from cosmological DM decay:

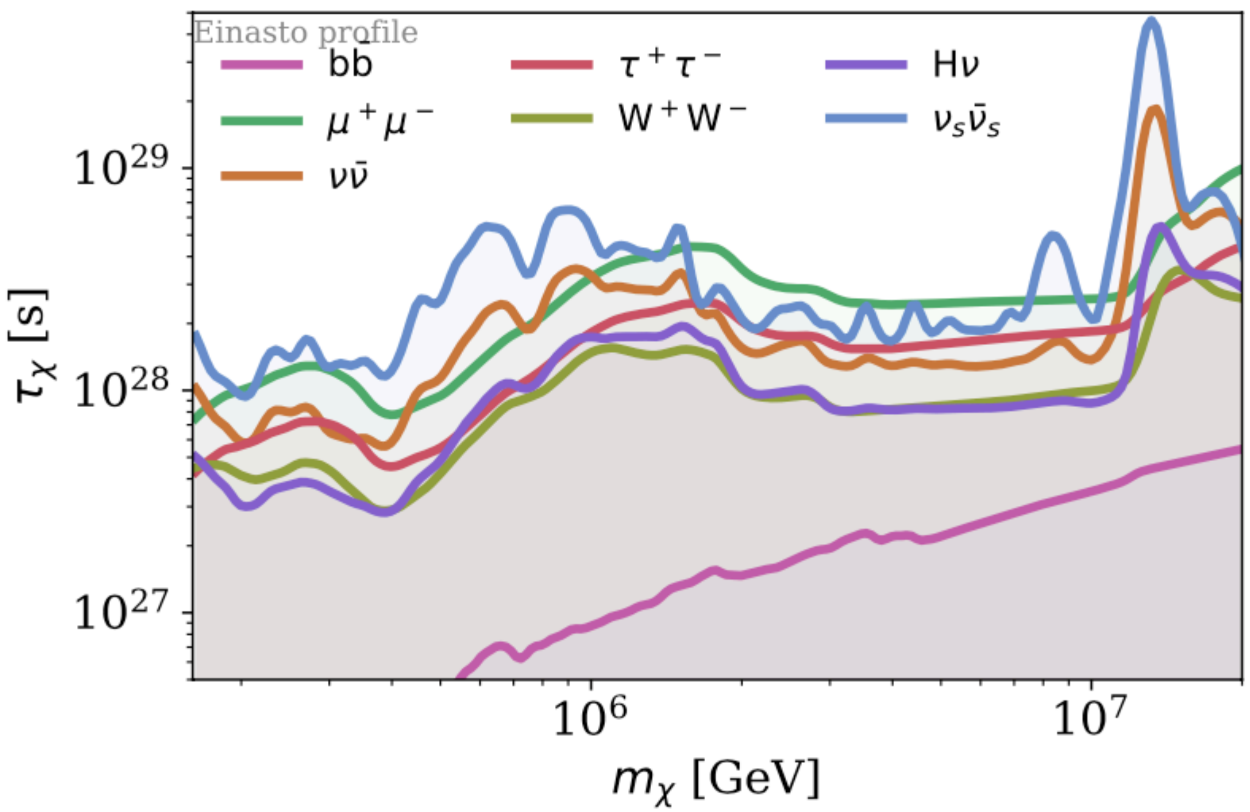
$$\frac{d\Phi_\nu^{Cos}}{dE_\nu d\Omega} = \frac{\Omega_\chi \rho_c}{4\pi m_\chi \tau_\chi H_0} \int_0^\infty \frac{dN_\nu}{E_\nu(1+z)} \frac{dz}{\sqrt{\Omega_\Lambda + \Omega_m (1+z)^3}}$$

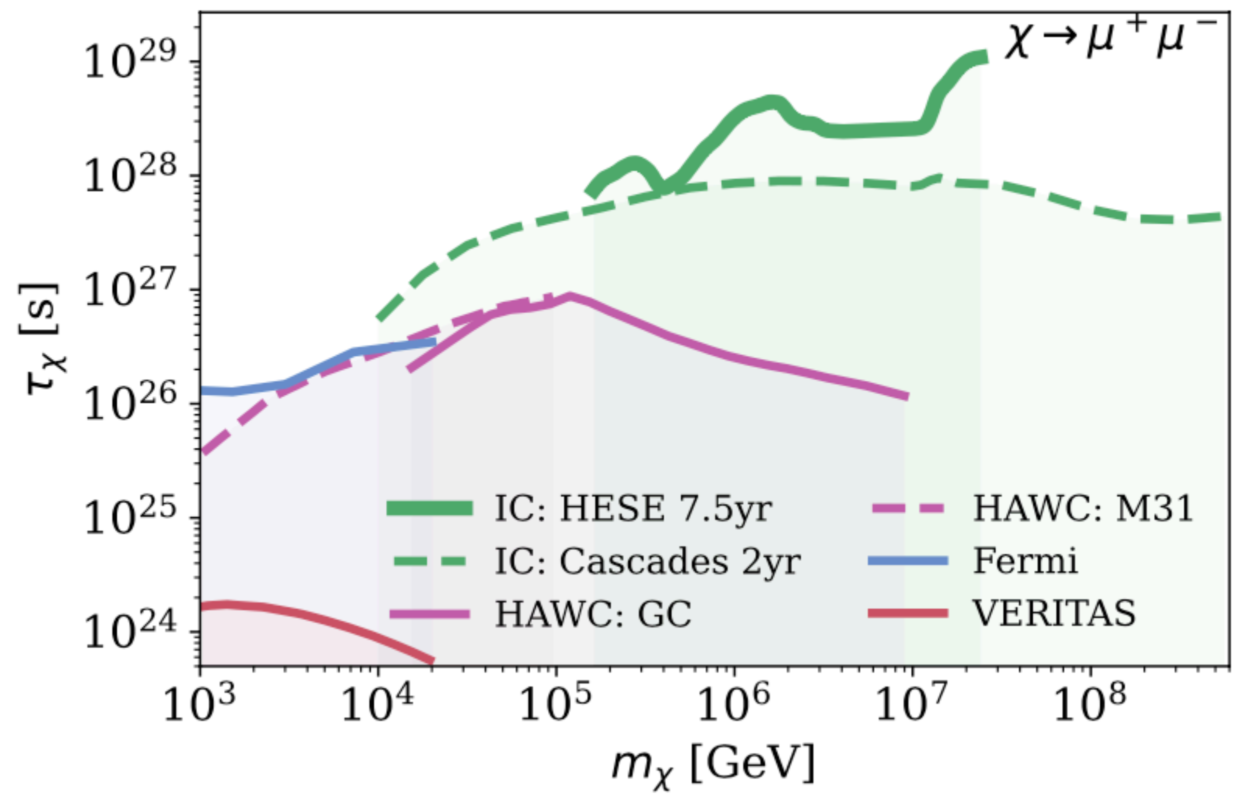
(As a conservative approach, we also neglected extragalactic DM clumps.)

Analysis summary

- Considering DM masses from 160 TeV to 20 PeV.
- Data sample: 7.5 years of High Energy Starting Events (HESE).
  - Containing both tracks and cascades.
  - High purity of astrophysical neutrinos above 60 TeV.
- Expected backgrounds:
  - Astrophysical neutrinos from luminous matter (assuming an isotropic flux with an unbroken power-law spectrum).
  - Atmospheric neutrinos and muons.

Analysis results





R. Abbasi et al, arXiv:2205.12950

The results improve upon the previous IceCube limits and are highly competitive.

Search for DM decay in galaxy clusters and galaxies

Analysis summary

- The first search for neutrinos from **DM decay in nearby galaxy clusters and galaxies.**
- DM masses: **10 TeV to 1 EeV**.
- Data sample: 10.4 years of upward-going tracks.
  - Mostly **muon neutrinos from the Northern Sky** (Sub-degree angular resolution above ~1 TeV).
- Using 3 galaxy clusters, 7 dwarf spheroidal galaxies, and Andromeda as targets.
  - Selection criteria: high signal strength (large D-factor) & located in the Northern Sky.
  - Assuming Zhao profiles for the dwarf galaxies and NFW profiles for the others.
  - Sources stacked within the same source class.

Source	Type	$\alpha[°]$	δ [°]	θ_{ROI} [°]	$\log_{10}(D_{ROI}/GeV/cm^2)$
Virgo	galaxy cluster	186.63	12.72	6.11	20.40
Coma		194.95	27.94	1.30	19.17
Perseus		49.94	41.51	1.35	19.15
Andromeda	galaxy	10.68	41.27	8.00	20.23
Draco	dwarf galaxy	260.05	57.92	1.30	18.97
Ursa Major II		132.87	63.13	0.53	18.39
Ursa Minor		227.28	67.23	1.32	18.13
Segue 1		151.77	16.08	0.34	17.99
Coma Berenices		186.74	23.9	0.34	17.96
Leo I		152.12	12.3	0.45	17.92
Boötes I		210.03	14.5	0.53	17.90

α : right ascension

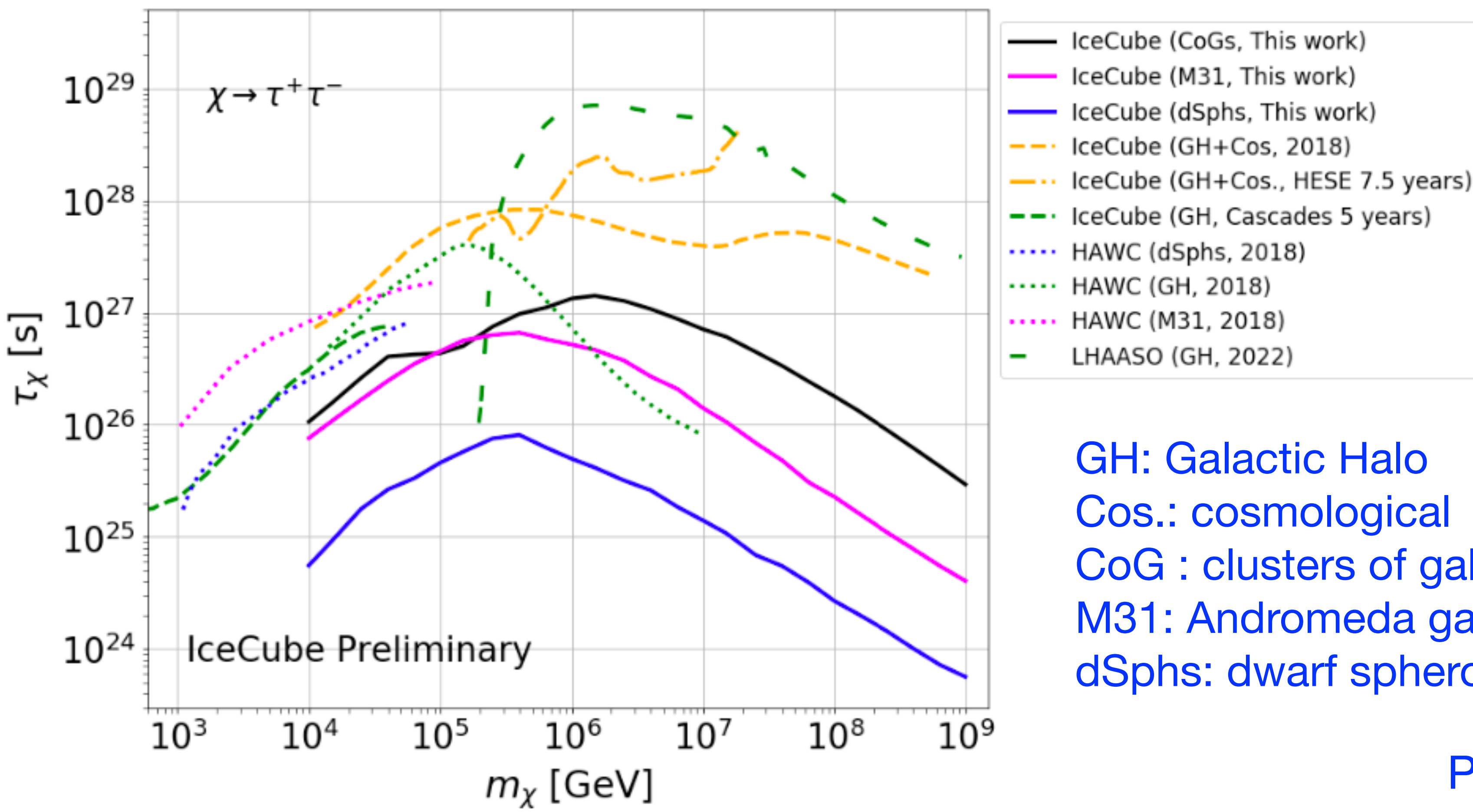
δ : declination

θ_{ROI} : size of ROI (angular distance to the center of the target)

D_{ROI} : D-factor integrated for the ROI

Pos(ICRC2023)1378

Analysis results



GH: Galactic Halo
Cos.: cosmological
CoG : clusters of galaxies
M31: Andromeda galaxy
dSphs: dwarf spheroidal galaxies

Pos(ICRC2023)1378

- The D-factor for the Galactic Halo is more than an order of magnitude larger compared to the targets for this work.
- Below 100 TeV the HAWC analyses of M31 and dSphs provide more stringent limits than this work.
  - HAWC has a superior angular resolution and effective area than IceCube.
  - On the PeV scale, gamma rays from extragalactic sources would be attenuated due to the galactic and extragalactic background light.
  - Neutrinos are a good complementary tool to search for PeV-scale DM in extragalactic sources.

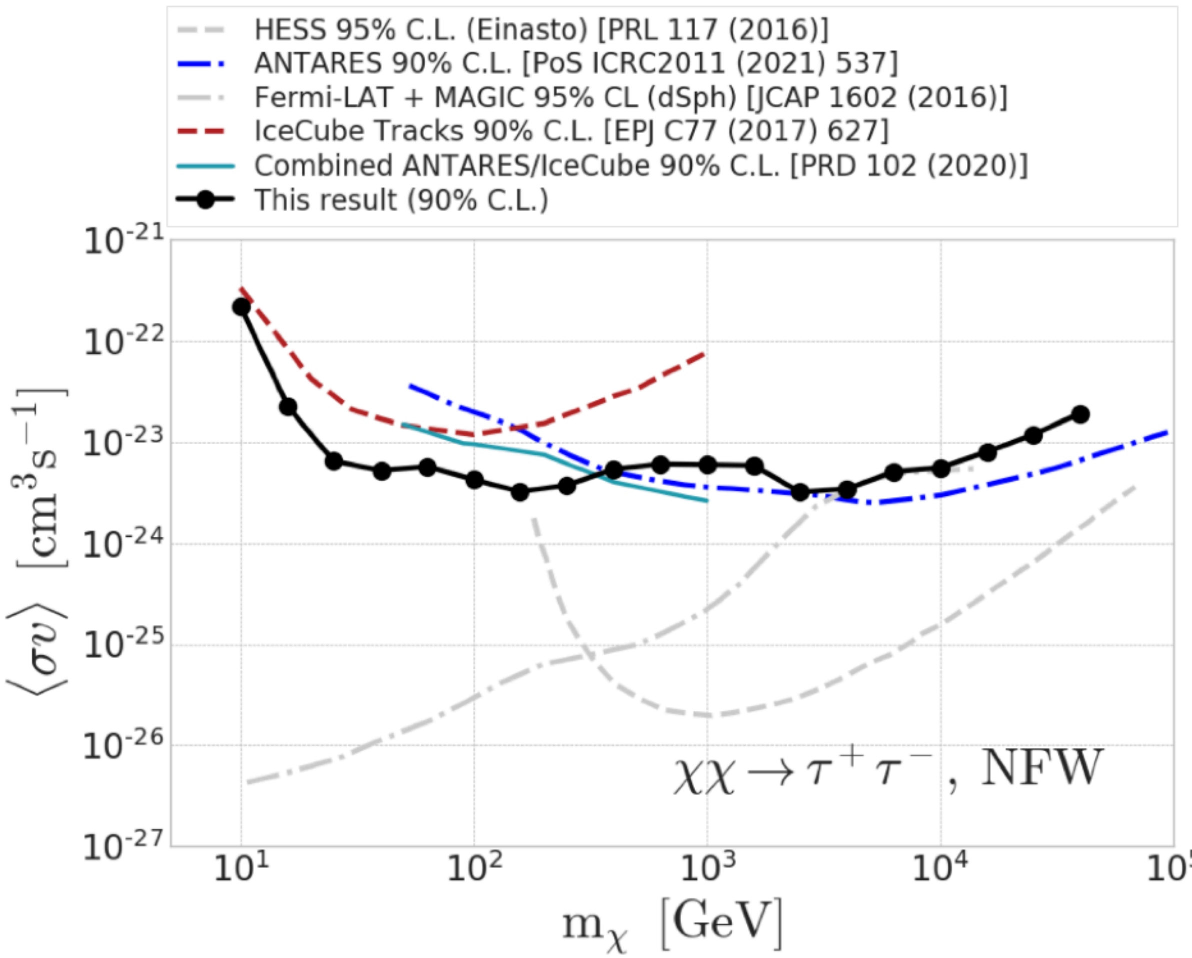
Conclusions

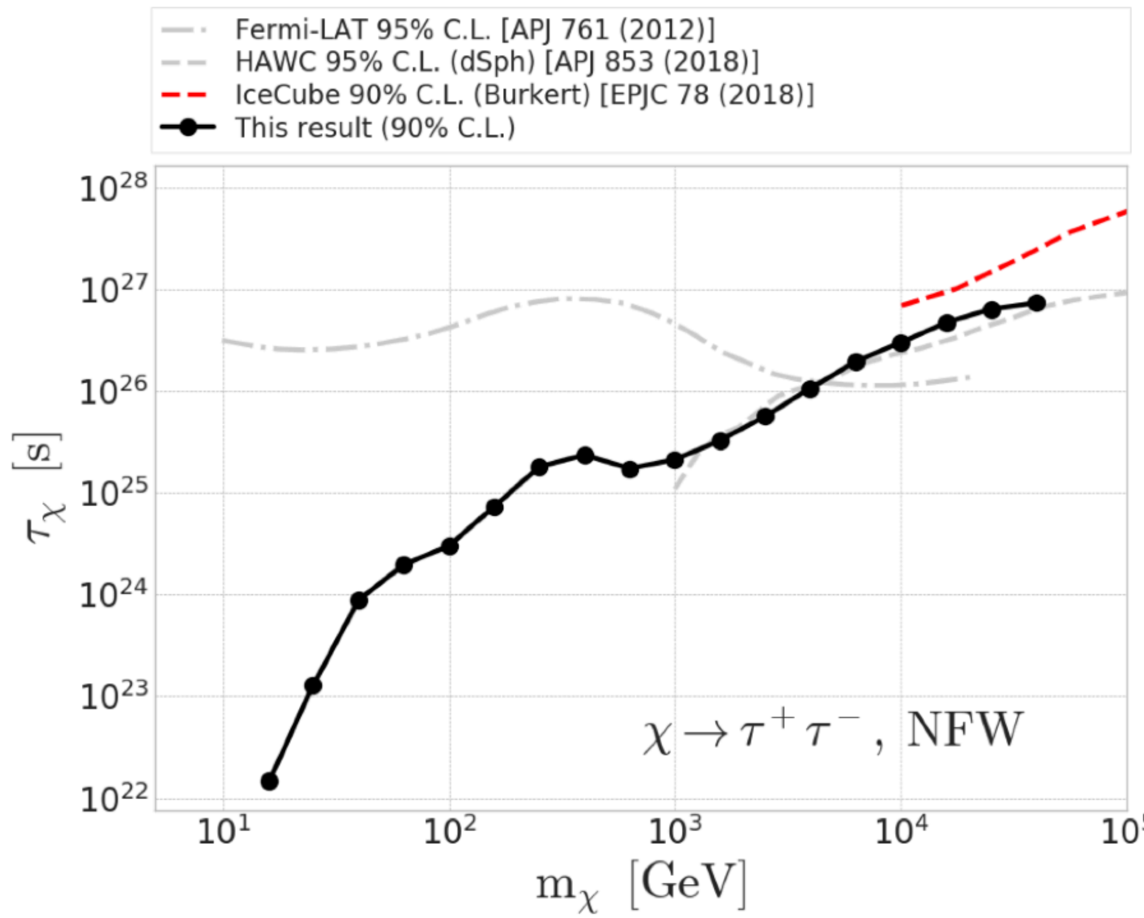
- Indirect search for dark matter provides complementarity to other techniques due to different backgrounds and systematics.
- Neutrinos also provide unique ways to search for DM in the Sun and Earth.
- The IceCube Collaboration has an active program of DM searches with competitive limits on DM annihilation, decay, and scattering.
- For the first time, we searched for neutrinos from DM decay in galaxy clusters and galaxies.

Thank You

Backups

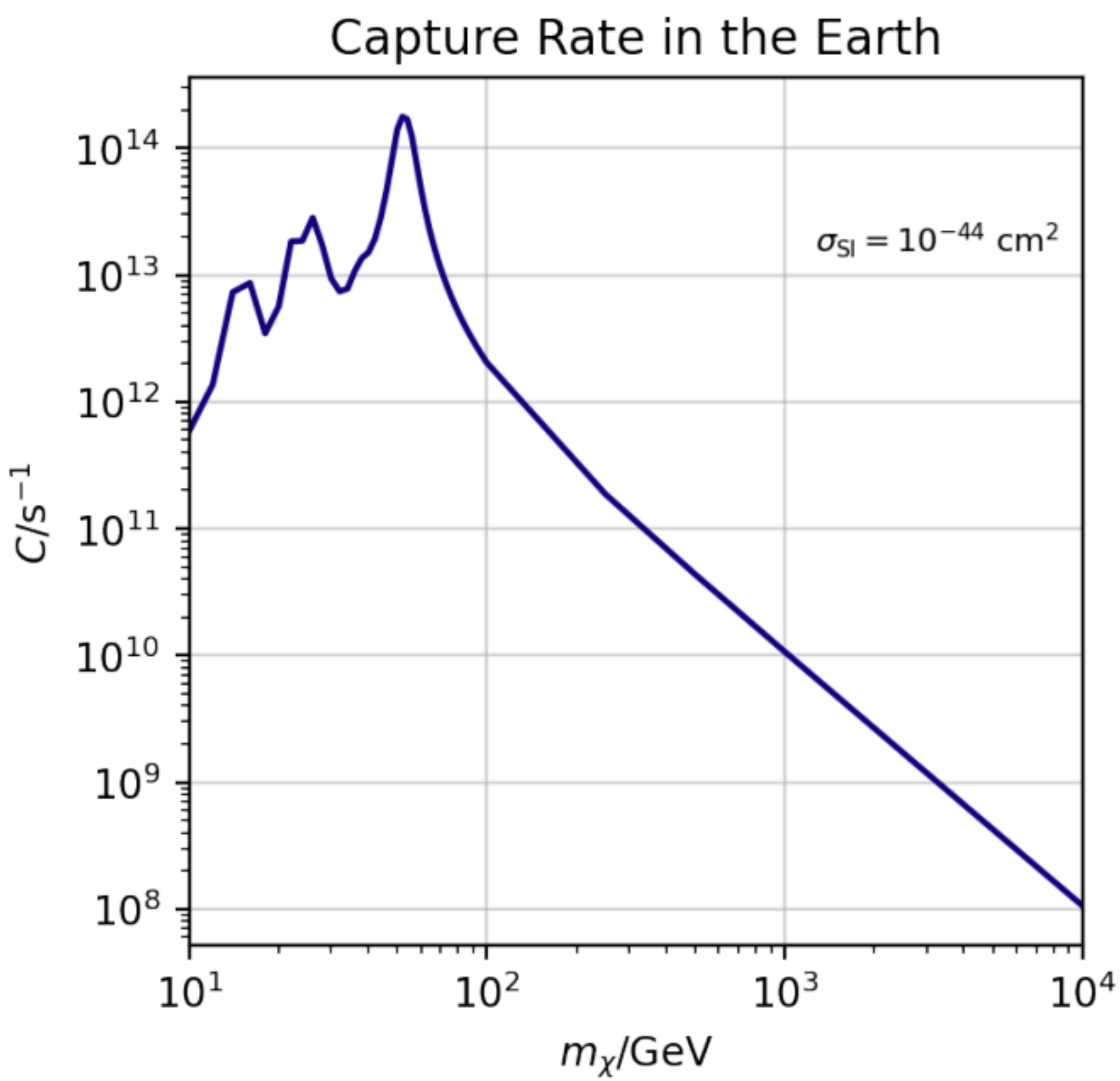
Backups : Search for Galactic WIMP annihilation with 5 years of cascade events


HESS 95% C.L. (Einasto) [PRL 117 (2016)]
ANTARES 90% C.L. [PoS ICRC2011 (2021) 537]
Fermi-LAT + MAGIC 95% CL (dSph) [JCAP 1602 (2016)]
IceCube Tracks 90% C.L. [EPJ C77 (2017) 627]
Combined ANTARES/IceCube 90% C.L. [PRD 102 (2020)]
This result (90% C.L.)
$\langle \sigma v \rangle$ [cm^{3}s^{-1}]
m_χ [GeV]
$\chi\chi \to \tau^+\tau^-$, NFW


Fermi-LAT 95% C.L. [APJ 761 (2012)]
HAWC 95% C.L. (dSph) [APJ 853 (2018)]
IceCube 90% C.L. (Burkert) [EPJC 78 (2018)]
This result (90% C.L.)
τ_χ [s]
m_χ [GeV]
$\chi \to \tau^+\tau^-$, NFW

Backups : Search for Earth WIMP

WIMP capture rate



PoS(ICRC2023)1393

Backups : The HESE analysis

Analysis summary

- DM masses: 160 TeV to 20 PeV.
- DM decay channels: $b\bar{b}, W^+W^-, \tau^+\tau^-, \mu\mu^+, H\nu, \nu\bar{\nu}, \nu_s\bar{\nu}_s$.
- PYTHIA 8.1 used to calculate the neutrino spectra.
  - Partially taking into account electroweak corrections.
- Data sample: 7.5 years of High Energy Starting Events (HESE).
- Backgrounds:
  - Atmospheric neutrinos
  - Astrophysical neutrinos from luminous matter (assuming an isotropic flux with an unbroken power-law spectrum).
- A binned maximum likelihood analysis performed.

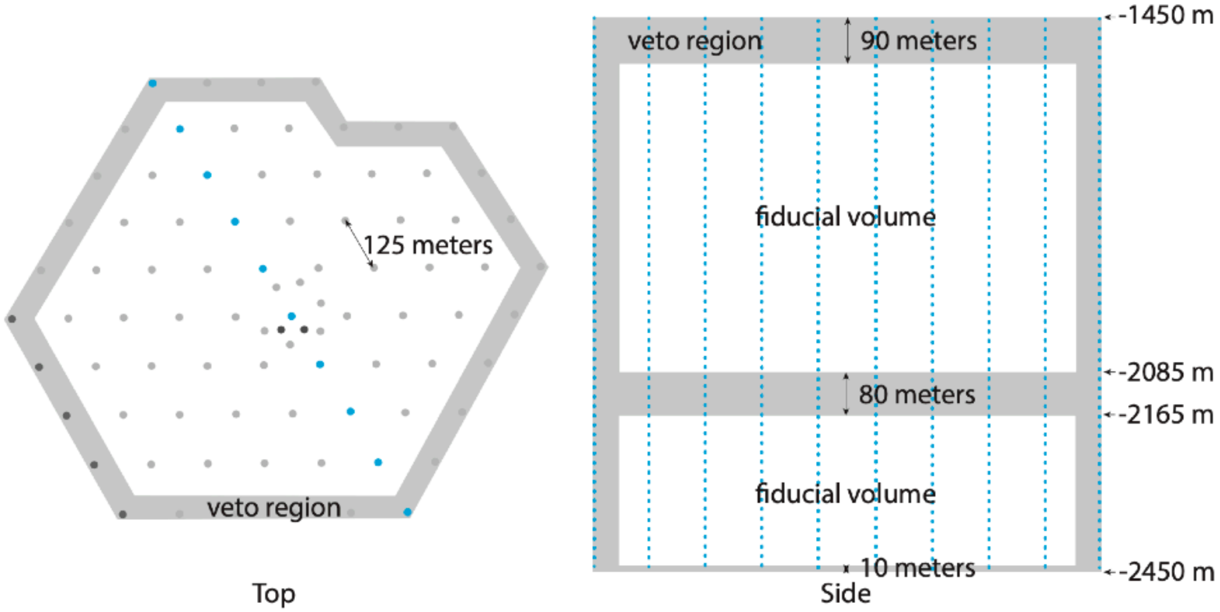
The HESE event selection

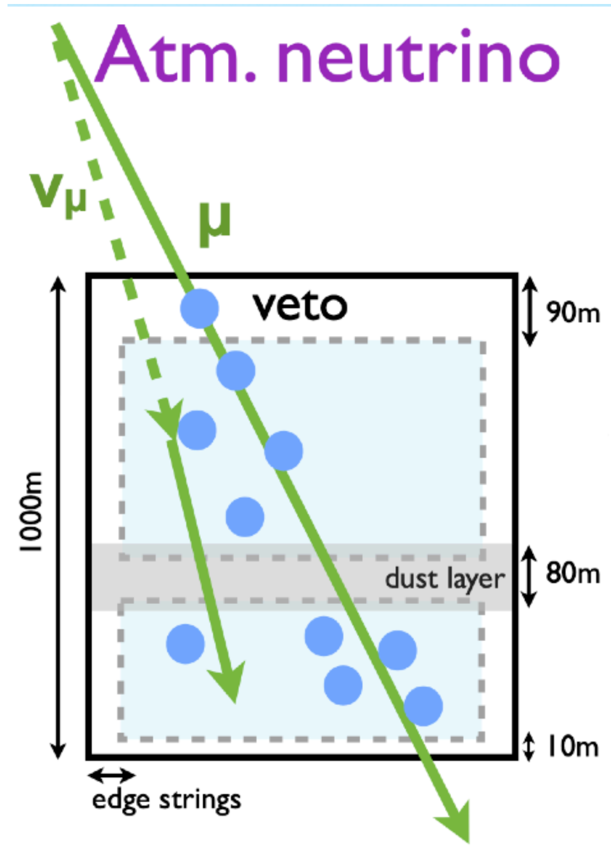
- We select events with a containe[d]
interaction vertex.
- Events are also required to deposit more than 6,000 photoelectrons in the detector.

⇨ The sample contains cascades and tracks from all directions.

⇨ The outer layer also acts as veto of down-going atmospheric neutrinos that accompany muons.

⇨ **A high purity of astrophysical neutrinos is achieved above 60 TeV.**



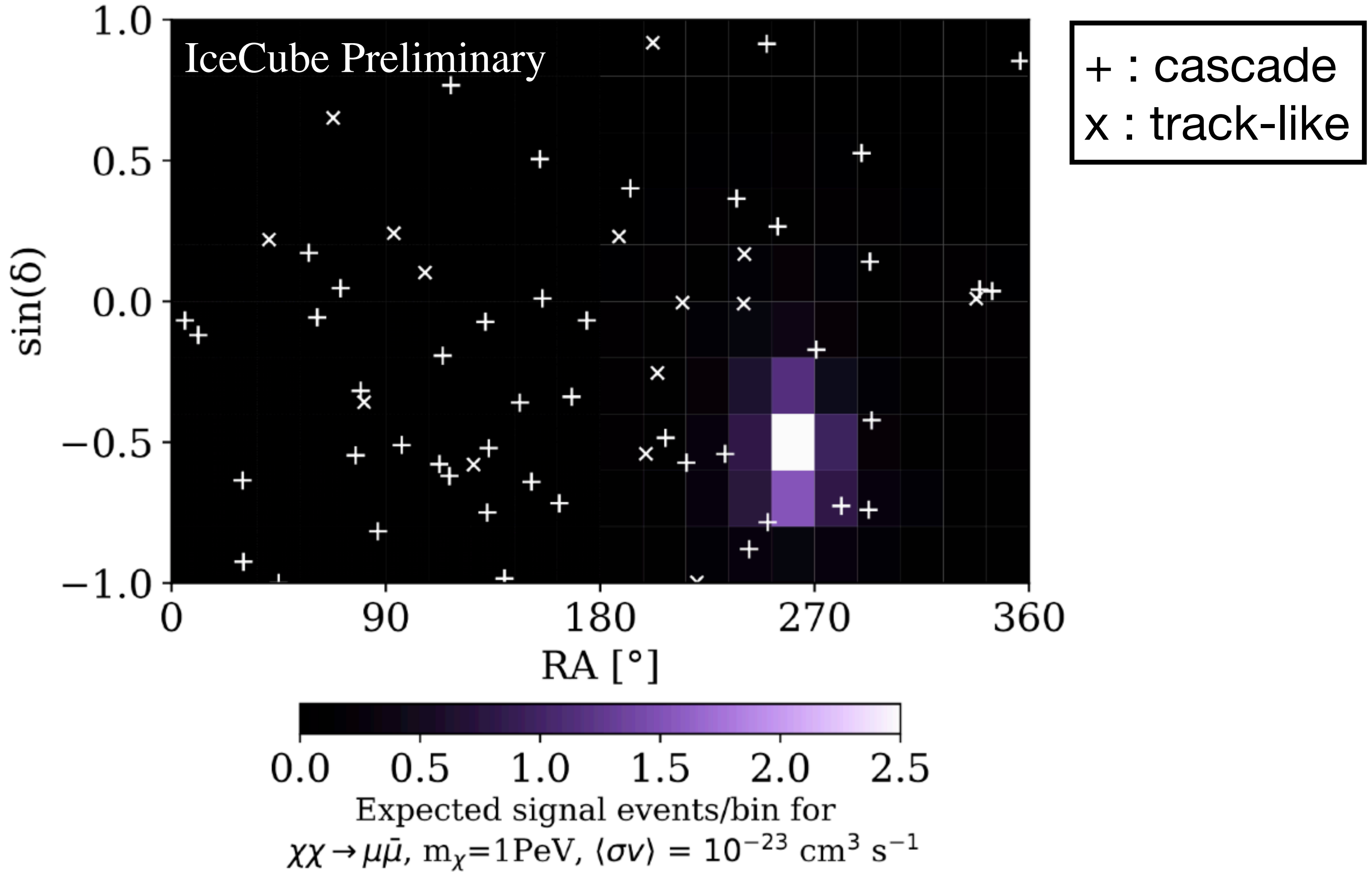


Annihilating DM search

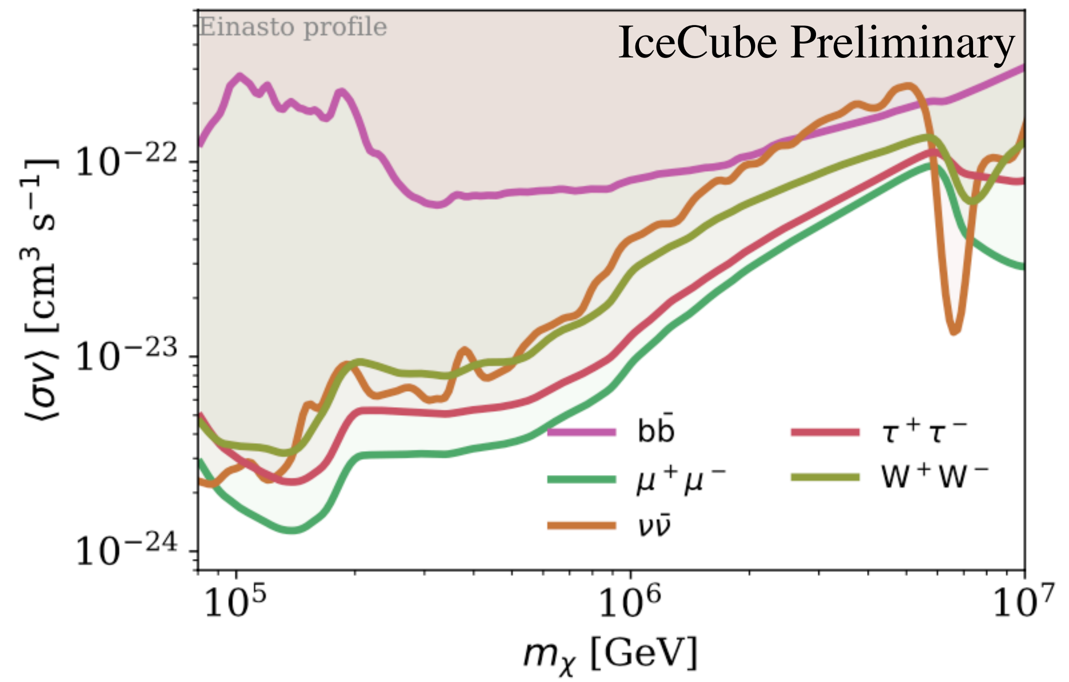
- Flux from dark matter annihilation

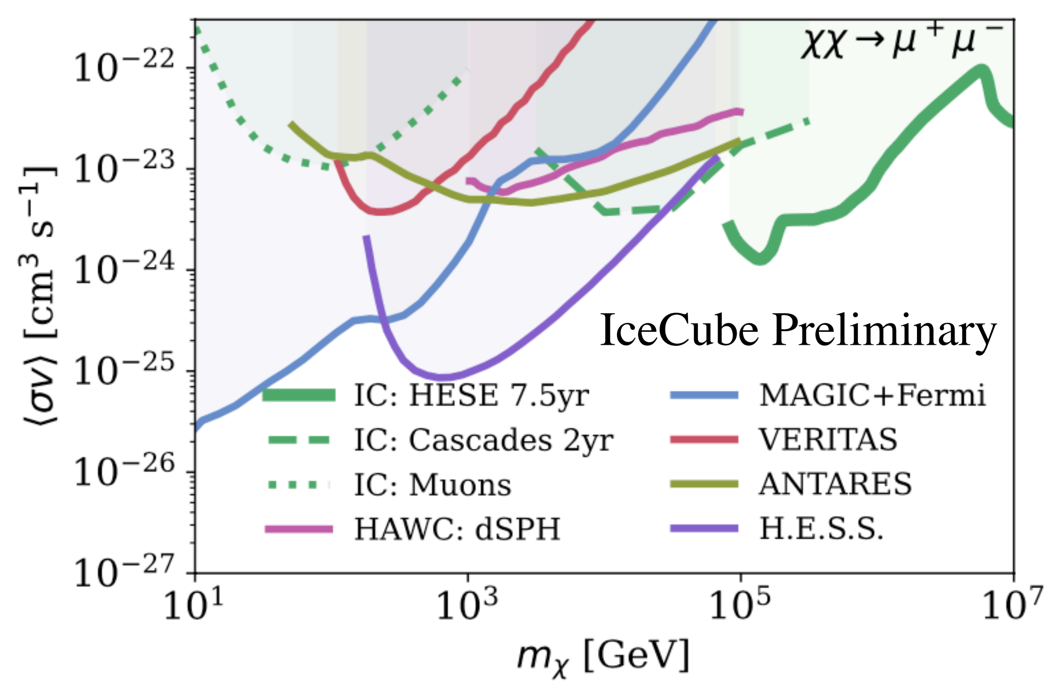
$$\frac{d\Phi_\nu}{dE_\nu d\Omega} = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN_\nu}{dE_\nu} \int_{l.o.s.} \rho_\chi^2(s) ds$$

(The galactic component dominates due to ρ_χ^2.)

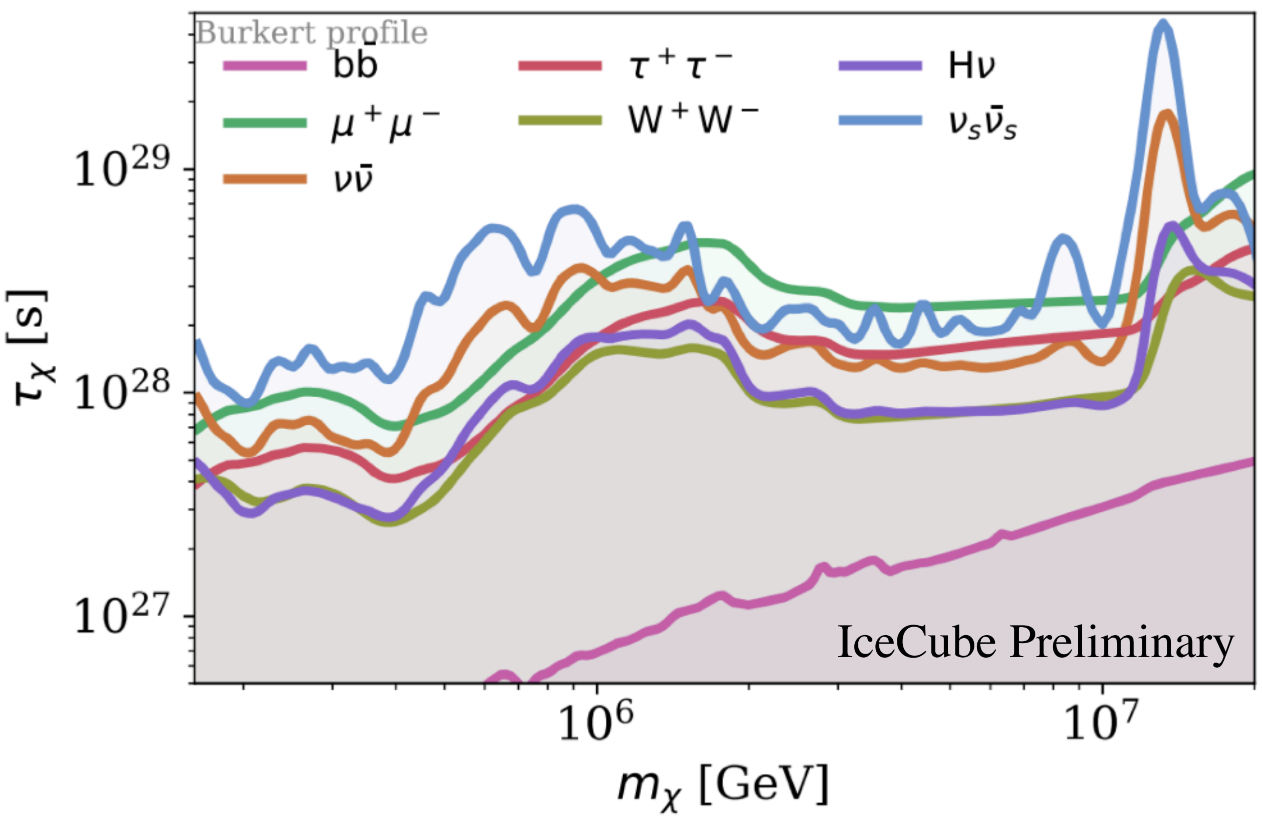


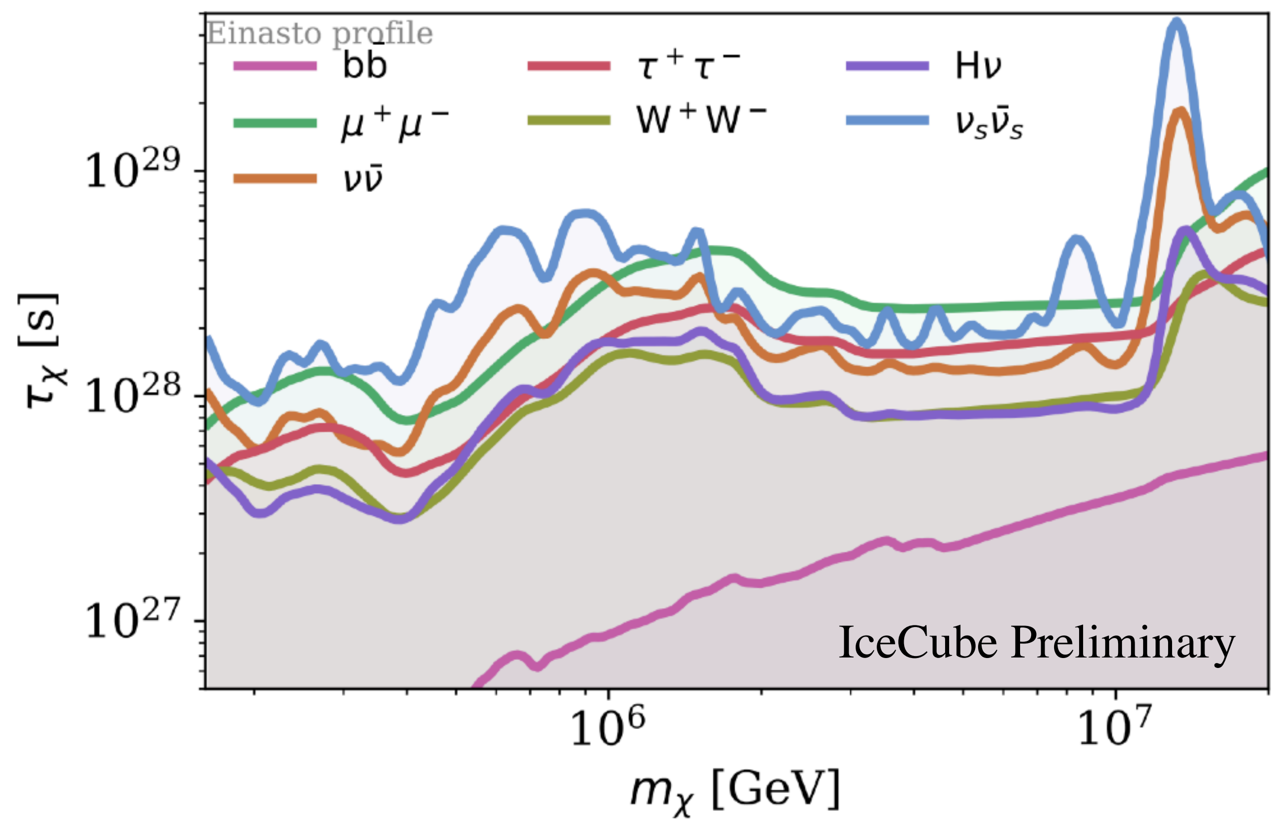
Most competitive limits over 100 TeV for a large number of channels



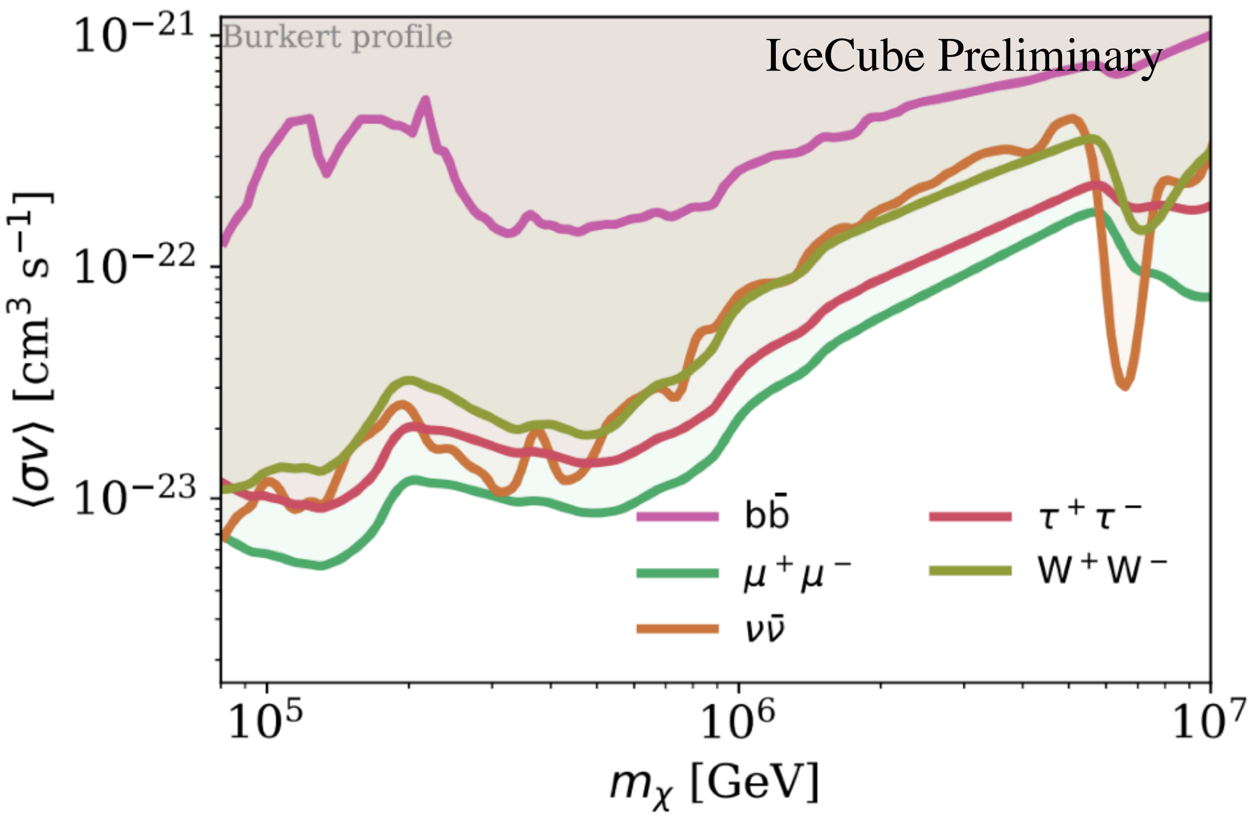


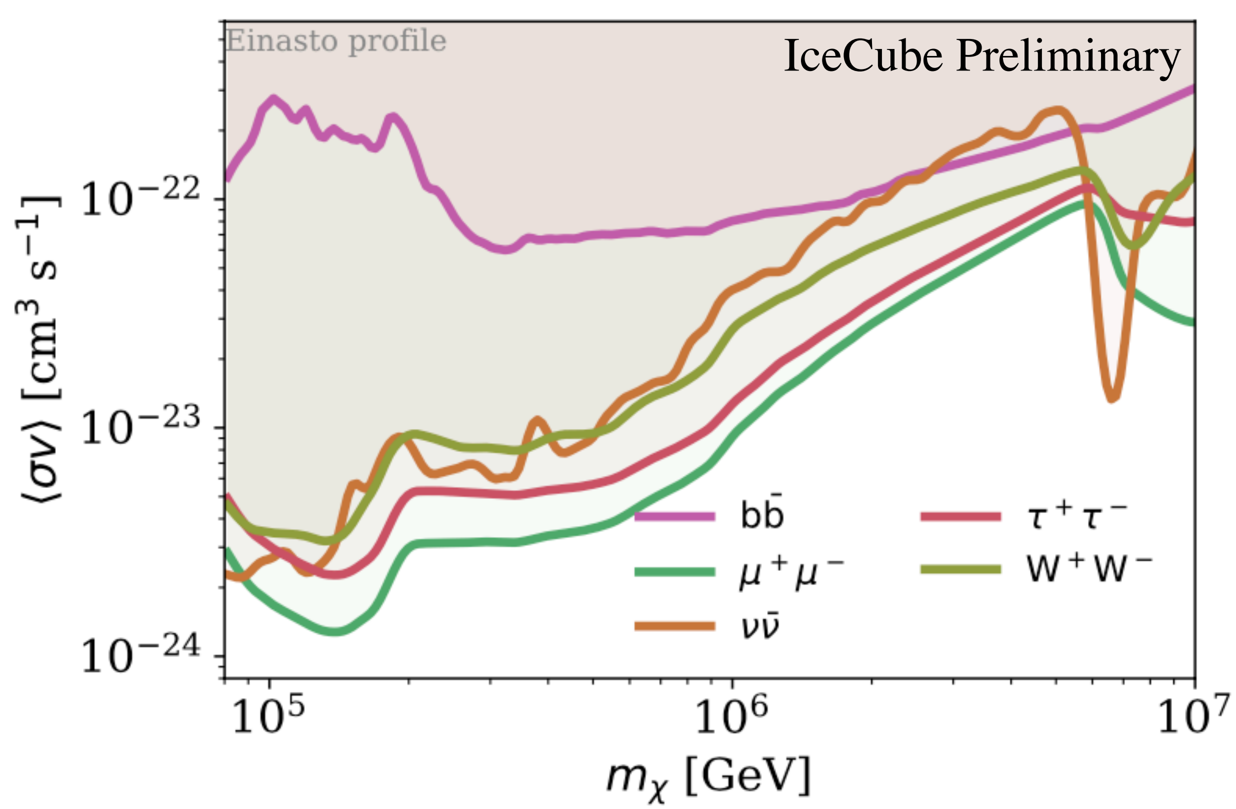
DM decay limits with the Burkert profile





DM annihilation limits with Burkert profile





Backups : Search for DM decay in galaxy clusters and galaxies

Analysis overview

- We search for neutrinos from **DM decay in nearby galaxy clusters and galaxies.**
- We consider DM masses ranging from **10 TeV to 1 EeV**.
  - Twenty six mass values evenly spaced on a logarithmic scale are considered.
- Representative decay channels are chosen: $b\bar{b}, W^+W^-, \tau^+\tau^-, \nu\bar{\nu}$.
  - Distinctive neutrino spectra are expected.
- The neutrino spectra for the different DM masses and channels are calculated using the χarov package.
  - Q. Liu et al, JCAP 10 (2020), 043.
  - C.W. Bauer et al, J. High Energ. Phys. 2021, 121 (2021) (latest implementation of electroweak corrections).
- A well-established IceCube data sample is used.
  - The sample contains mostly **muon neutrinos from the Northern Sky**.
  - The angular resolution is better than a degree for neutrino energies above a few TeV.
  - The data was collected from 2011 to 2022 (livetime of **10.4 years**).

Target selection and D-factors

Source	Type	$\alpha[^\circ]$	$\delta\ [^\circ]$	$\theta_{ROI}\ [^\circ]$	$\log_{10}(D_{ROI}/GeV/cm^2)$
Virgo	galaxy cluster	186.63	12.72	6.11	20.40
Coma		194.95	27.94	1.30	19.17
Perseus		49.94	41.51	1.35	19.15
Andromeda	galaxy	10.68	41.27	8.00	20.23
Draco	dwarf galaxy	260.05	57.92	1.30	18.97
Ursa Major II		132.87	63.13	0.53	18.39
Ursa Minor		227.28	67.23	1.32	18.13
Segue 1		151.77	16.08	0.34	17.99
Coma Berenices		186.74	23.9	0.34	17.96
Leo I		152.12	12.3	0.45	17.92
Boötes I		210.03	14.5	0.53	17.90

α: right ascension

δ: declination

(In equatorial coordinates for J2000)

[1] A. Tamm *et al, Astron. Astrophys.* **546** (2012) A4.

[2] A. Geringer-Sameth *et al, Astrophys. J.* **801** no. 2, (2015) 74.

[3] M. A. Sanchez-Conde *et al, JCAP* **12** (2011) 011.

- DM halo models for candidate targets are adopted from [1-3].
  - We adopt Zhao profiles for the dwarf galaxies and NFW profiles for the others.
- Sources with relatively large D-factors and positive declinations are selected.
- In the table, the D-factors are calculated up to their saturation angles.
  - An exception is the Andromeda galaxy for which we limit θ_{ROI} to 8° to well separate its ROI from the Galactic Plane.
- We stack the sources within the same source type.

Statistical methods

- We perform an unbinned maximum likelihood analysis.
- Likelihood Function:

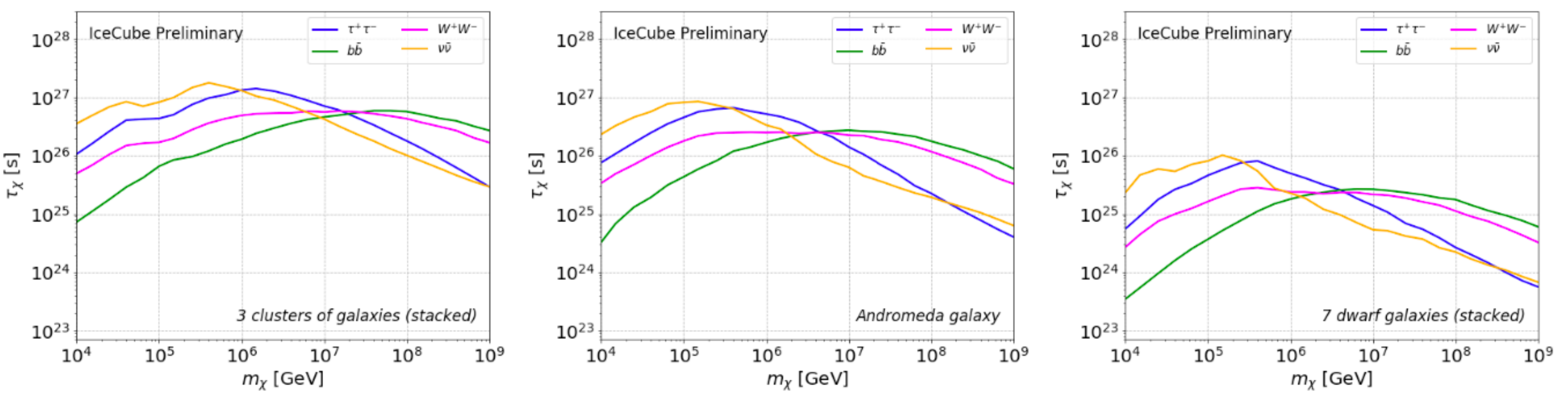
$$\mathcal{L}(n_s) = \prod_{i=1}^{N} \left[\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right]$$

- The function is maximized with respect to the number of signal events (n_s).
- The signal and background PDFs (S_i, B_i) depend on the reconstructed direction and energy of event i.
- The signal PDF accounts for the signal neutrino flux as well as the detector response.
- The background PDF is estimated by scrambling events in right ascension.
- Test Statistic

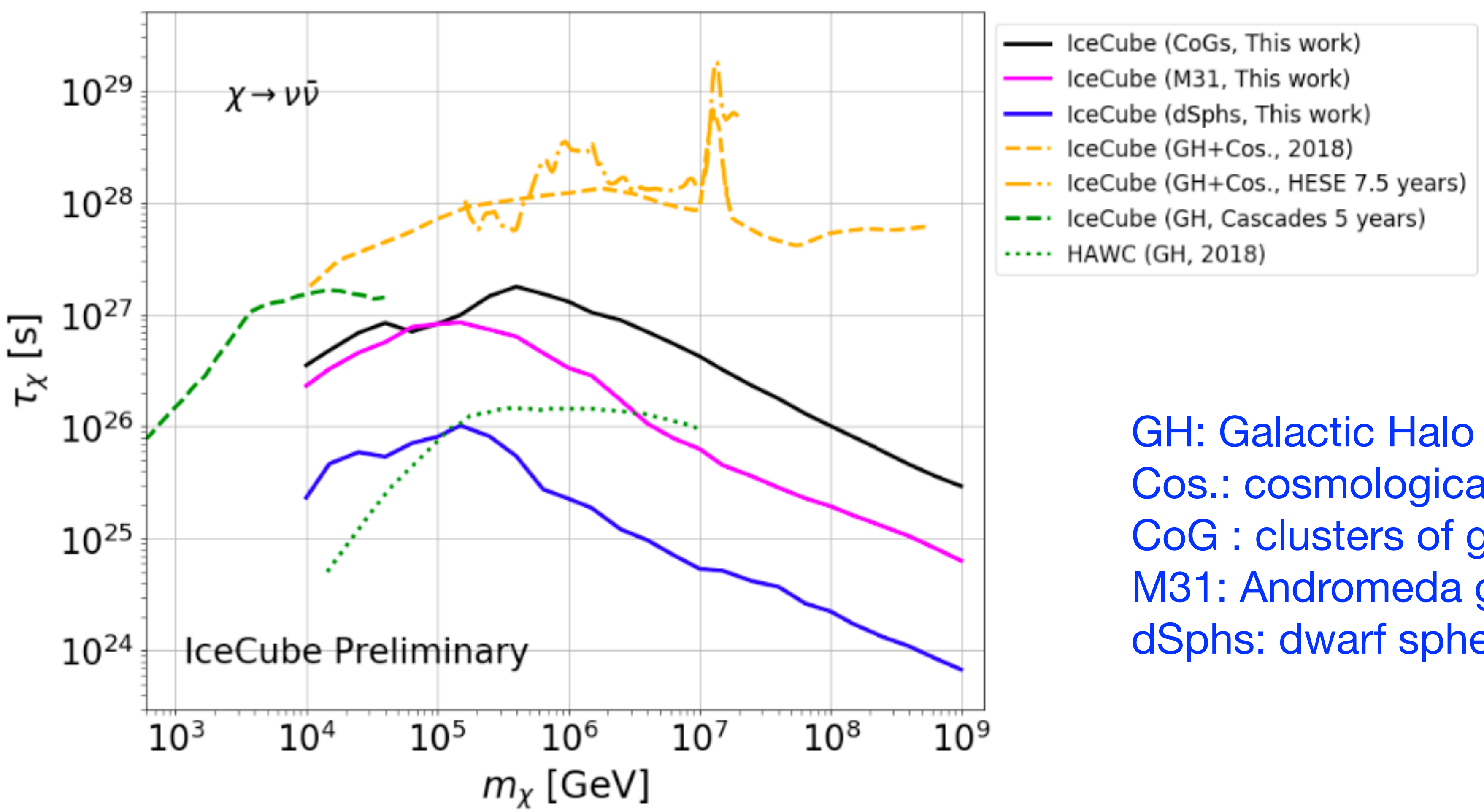
$$TS = -2 \ln \frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(\hat{n}_s)}$$

Analysis results

- We found no signal from DM decay in the targets.
  - The most significant local p-value is 0.013 (2.2σ).
  - The global significance should be smaller than 2.2σ, since tests were repeated for different DM masses, decay channels, and source groups.
- We derived lower limits on the DM lifetime at 90% C.L..



Comparison to recent DM searches

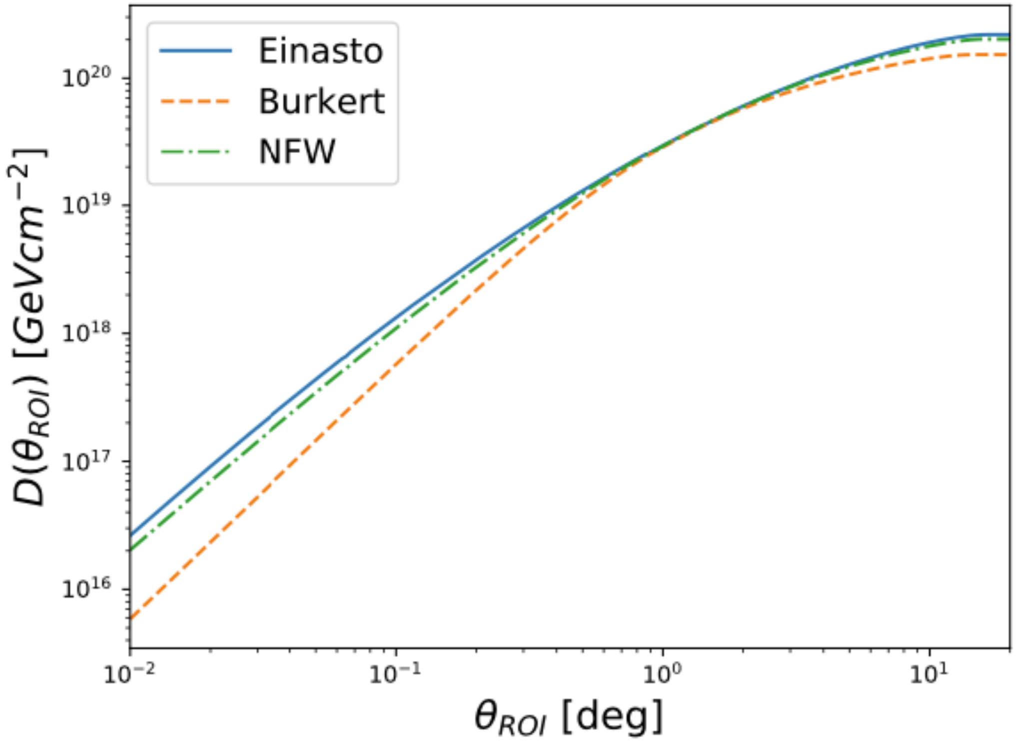


GH: Galactic Halo
Cos.: cosmological
CoG : clusters of galaxies
M31: Andromeda galaxy
dSphs: dwarf spheroidal galaxies

- The analysis complements the recent IceCube analyses.
- The D-factor for the Galactic Halo is more than an order of magnitude larger compared to the targets for this work.
- The presented analysis is the first IceCube analysis of its kind.
- Confidence levels: 90% for IceCube, 95% for HAWC

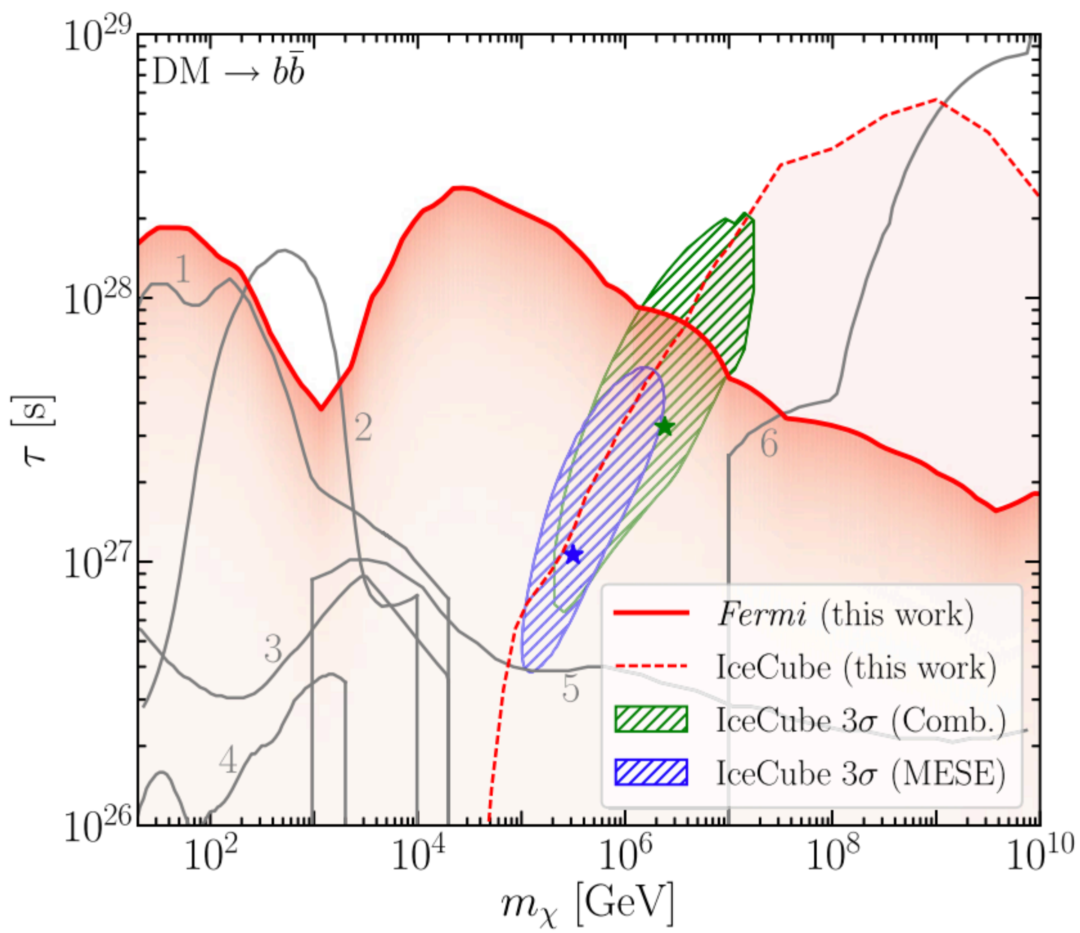
D-factor profiles for Andromeda

- The D-factor for the Andromeda galaxy is calculated for different ROI size settings.
  - For the calculation, we use the CLUMPY package.
- Three different halo models are compared.
  - The models are taken from A. Tamm et al, Astron. Astrophys. 546 (2012) A4.
  - The NFW profile is chosen for the main analysis.
- For large θ_{ROI} values, the halo models agree well.
  - This indicates that the halo model uncertainty has a relatively small impact on the analysis.



IceCube event excess and DM decay

Decaying DM interpretation of IceCub event excess



T. Cohen *et al*, Phys. Rev. Lett. 119, 021102