Searches for Dark Matter in the Galactic Halo and extragalactic sources with IceCube

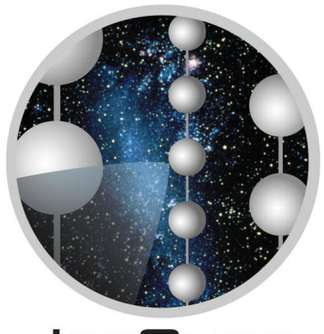
Minjin Jeong for the IceCube collaboration

Sungkyunkwan University (SKKU)

NuFact 2022

Working Group 5

August 5, 2022

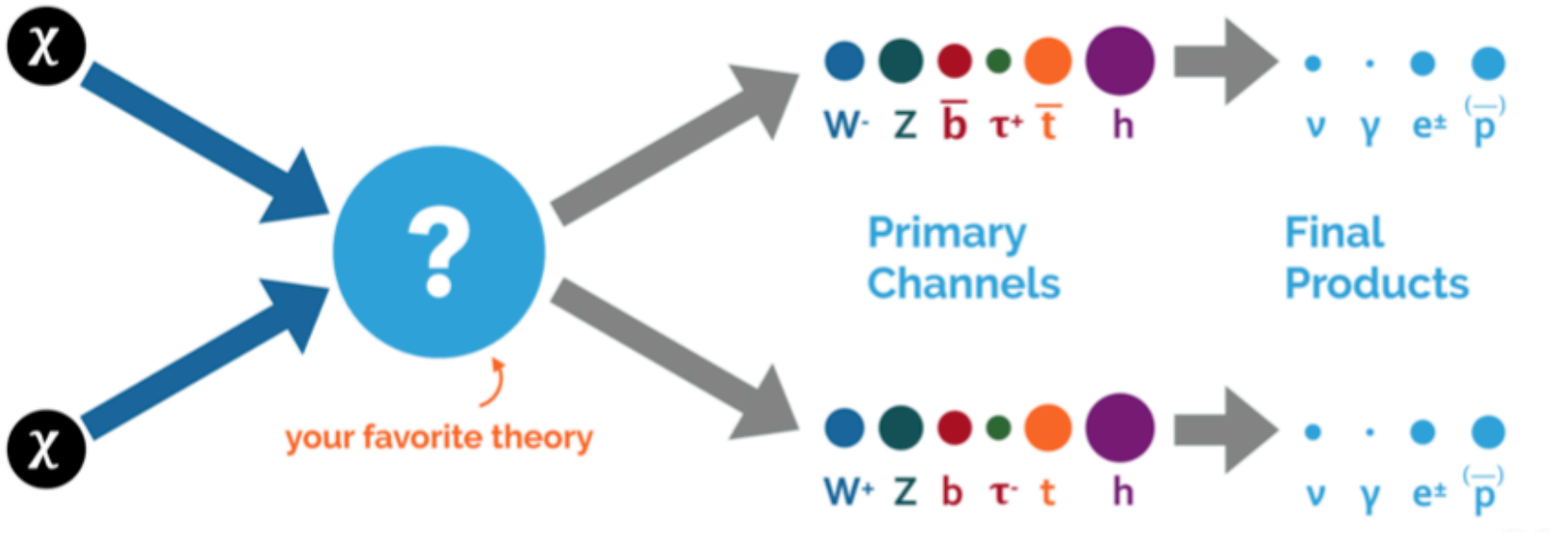


Outline

- Indirect detection of dark matter
- The IceCube Neutrino Observatory
- Recent Dark Matter Searches with IceCube
  - 7.5-year HESE data analyses
  - Neutrino line search
  - 8-year oscNext data analysis
  - Search for DM in galaxy clusters and galaxies
- Conclusions

Indirect detection of dark matter

Indirect detection of dark matter

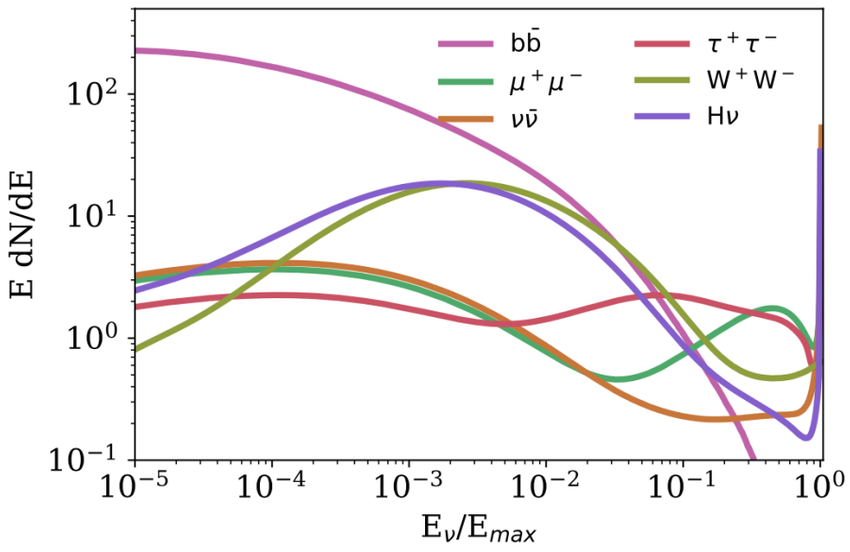


Annihilating DM ($\chi + \chi \rightarrow SM + SM$)

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

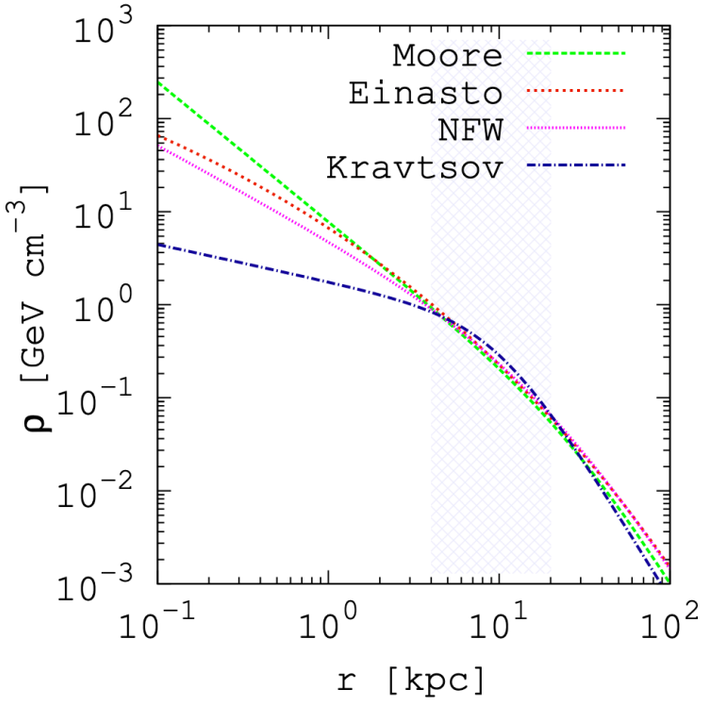
Decaying DM ($\chi \rightarrow SM + SM$)

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



simulated neutrino spectra

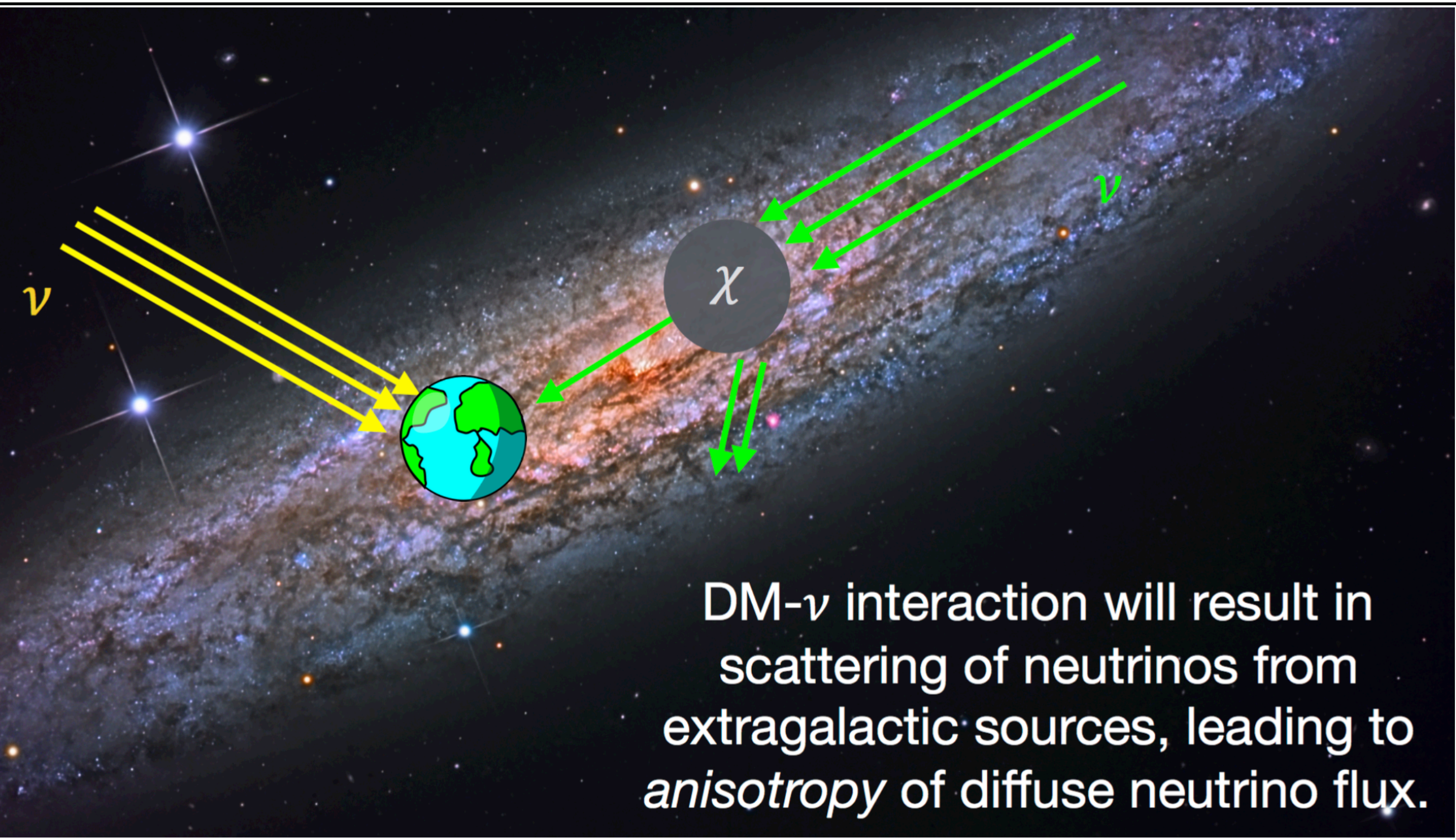
R. Abbasi *et al.* (IceCube Collaboration)
arXiv:2205.12950



DM halo models of the Milky Way

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

Indirect detection of dark matter

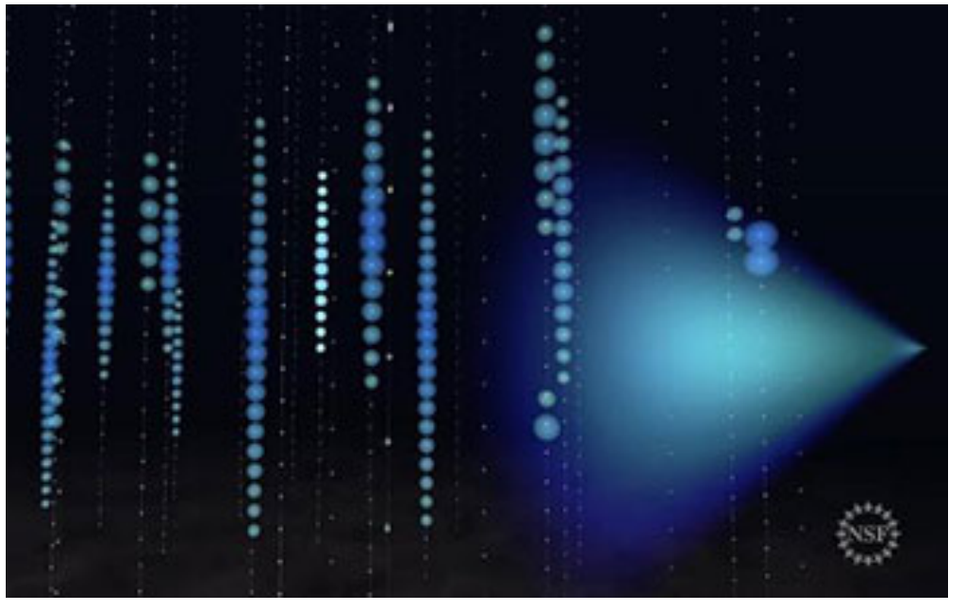


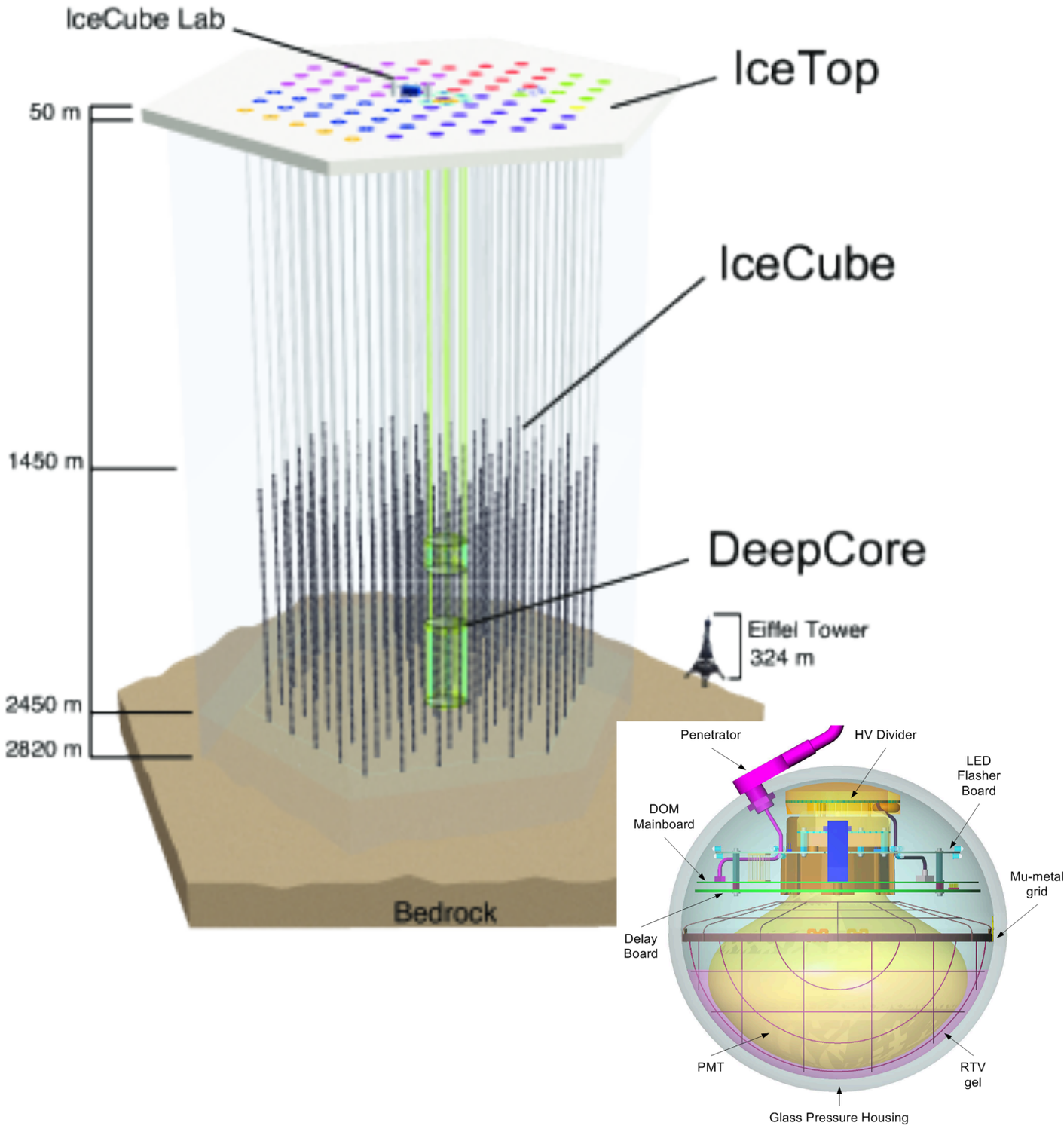
CA, A. Kheirandish & A. Vincent Phys. Rev. Lett. **119**, 201801

The IceCube Neutrino Observatory

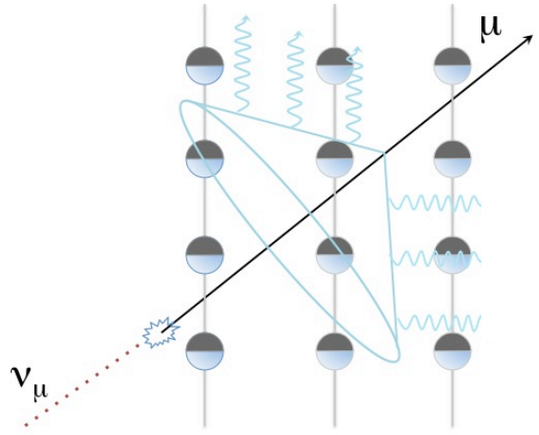
The IceCube Neutrino Observatory

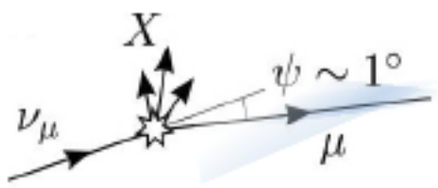
- Deployed in deep glacial ice in the Antarctica
- 5,160 digital optical modules on 86 vertical strings (~1 km^3)
- Detects Cherenkov radiation from neutrino interactions in the ice
- Ultra-transparent ice formed via compaction over ~100,000 years

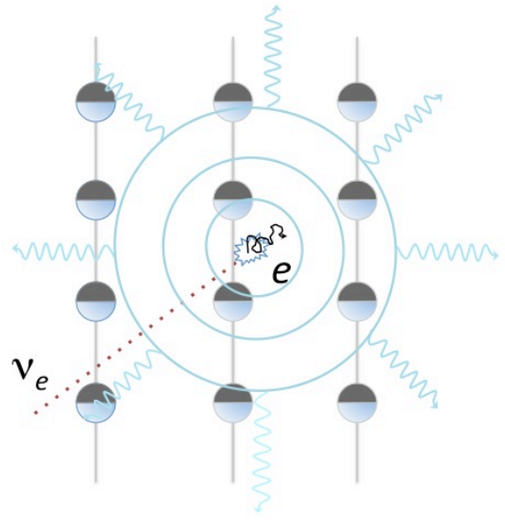


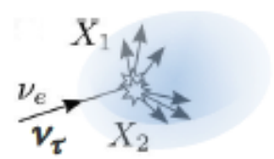


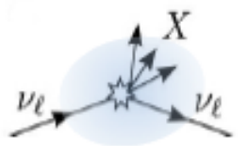
Event Topologies in IceCube

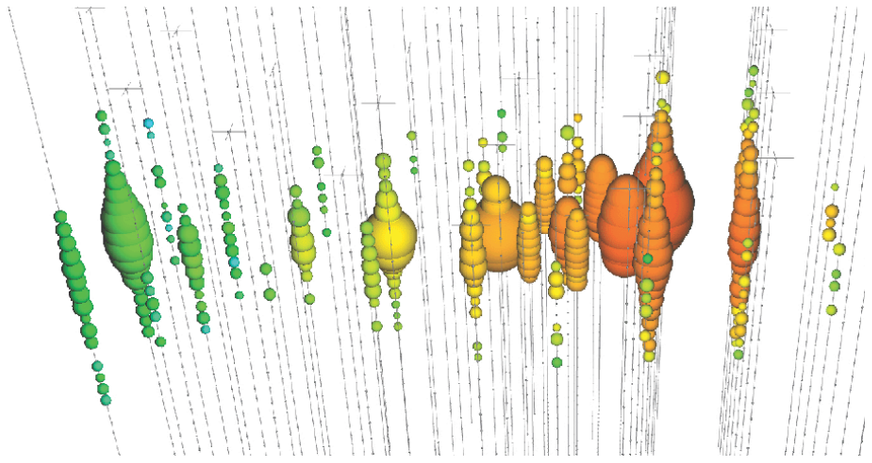








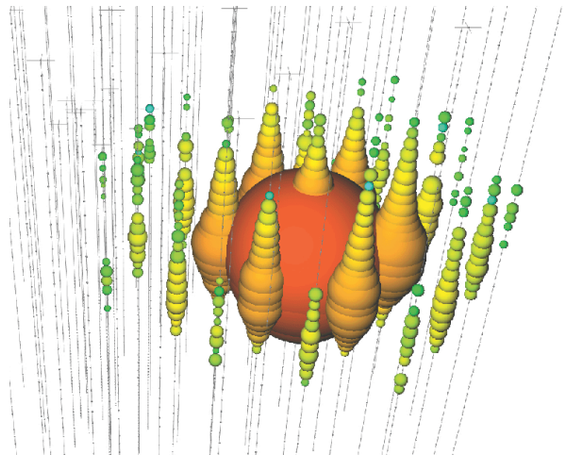




ν_μ CC interaction

Angular resolution < 1°

Large uncertainties in energy reconstruction



ν_{all} NC, ν_e/ν_τ CC interaction

Angular resolution : 15° to 20°

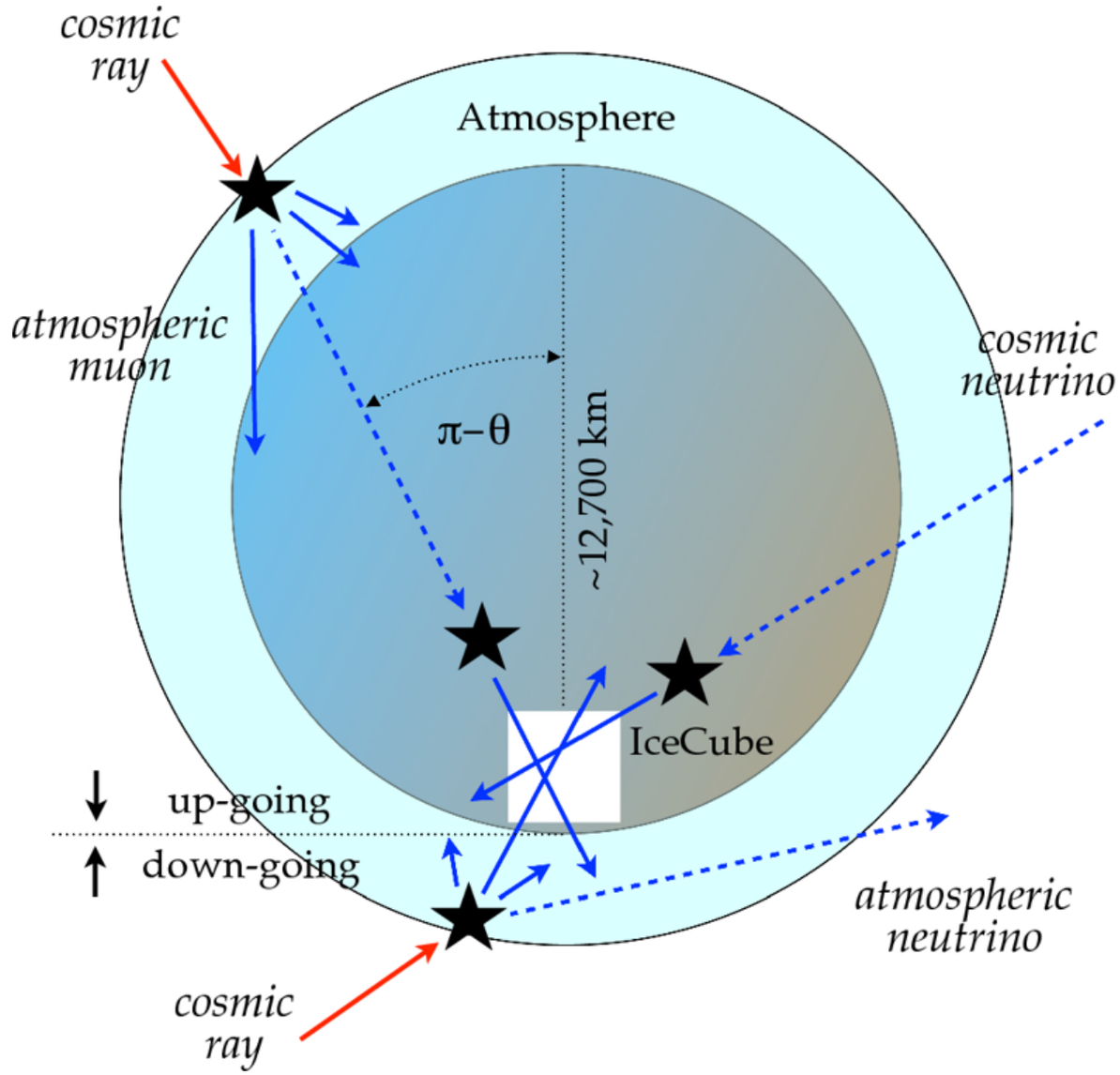
Energy resolution ~15%

Backgrounds for DM searches

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

- Diffuse astrophysical neutrinos from baryonic matter (isotropic)

  - Relevant for heavy decaying/annihilating DM searches



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

Searches for dark matter using 7.5 years of HESE data

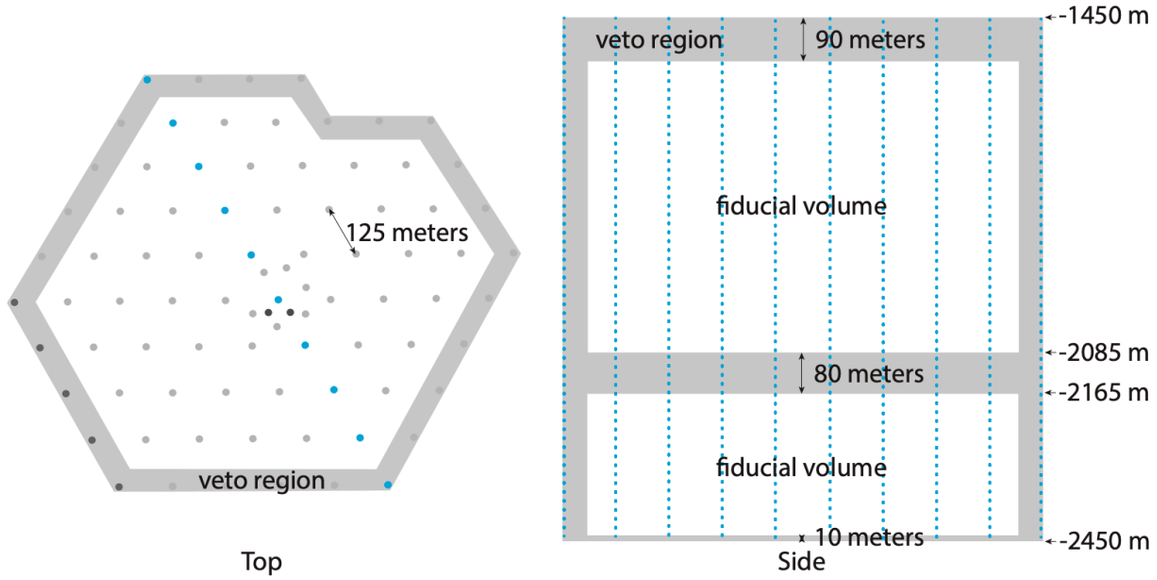
High-Energy Starting Events (HESE)

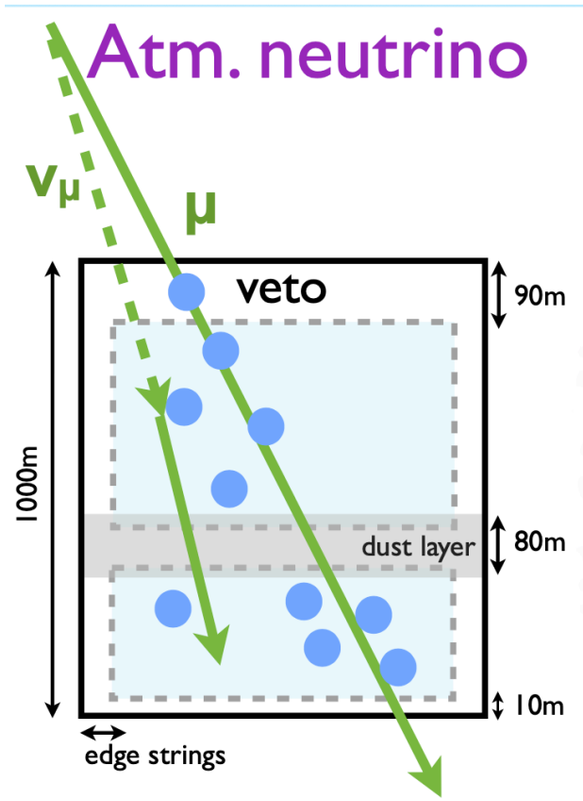
- Select events with a contained interaction vertex.
- Events are also required to deposit more than 6,000 PE in the detector.

⇨ 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.





Decaying DM search

Two flux contributions considered

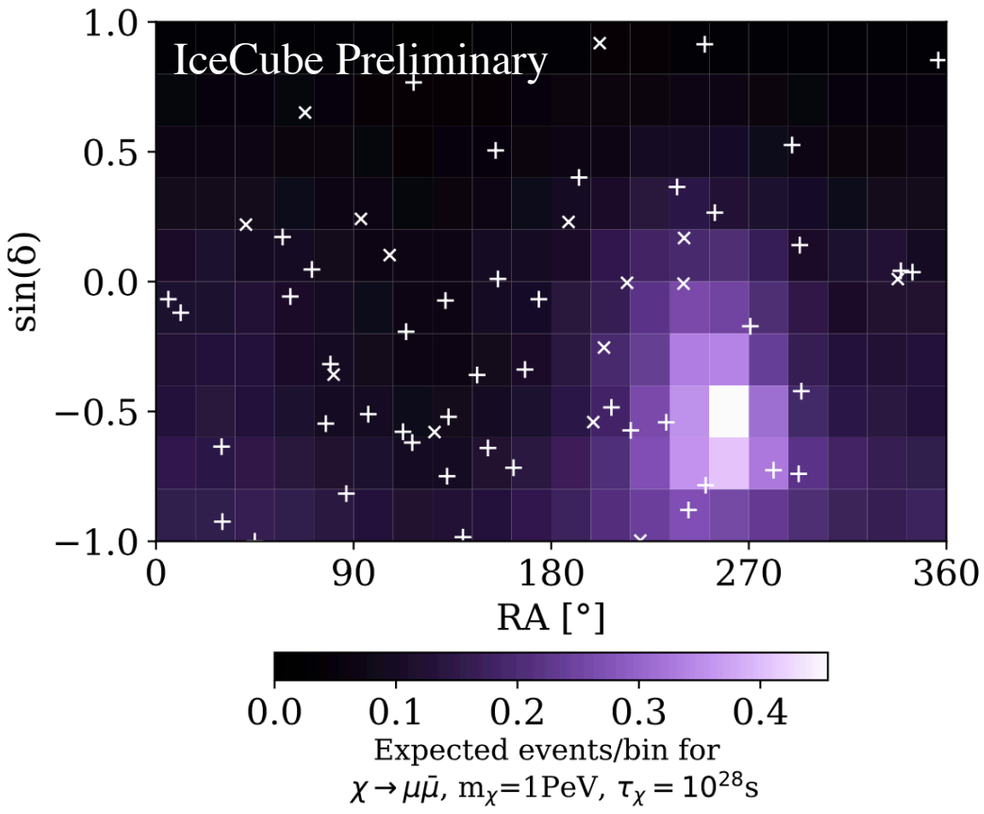
$$\frac{d\Phi_\nu}{dE_\nu} = \frac{d\Phi_\nu^{Gal}}{dE_\nu} + \frac{d\Phi_\nu^{Cos}}{dE_\nu}$$

(1) DM decay in the Galactic Halo (anisotropic flux)

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

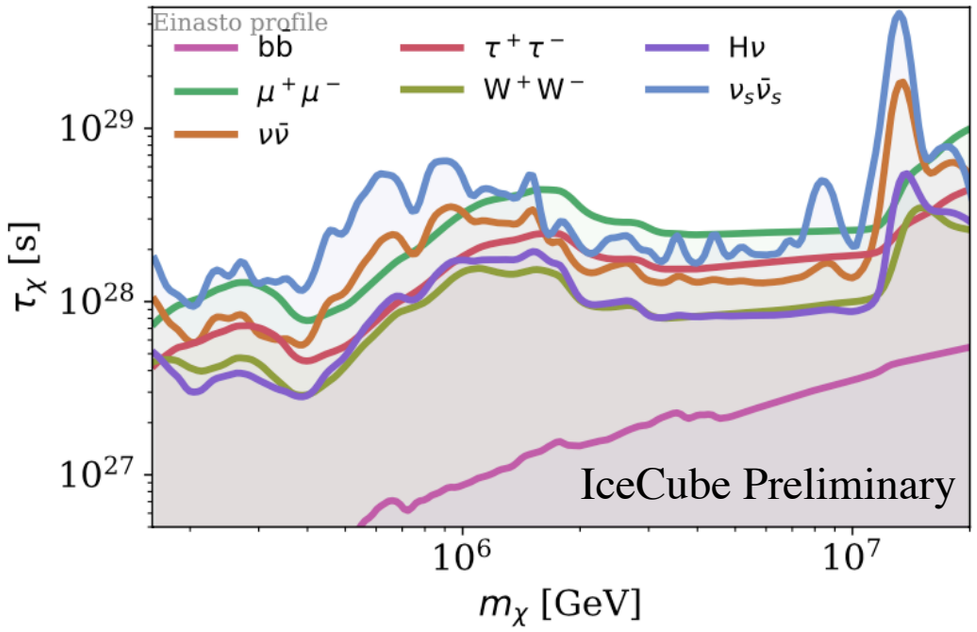
(2) DM decay at cosmological distances (red-shifted spectrum, isotropic flux)

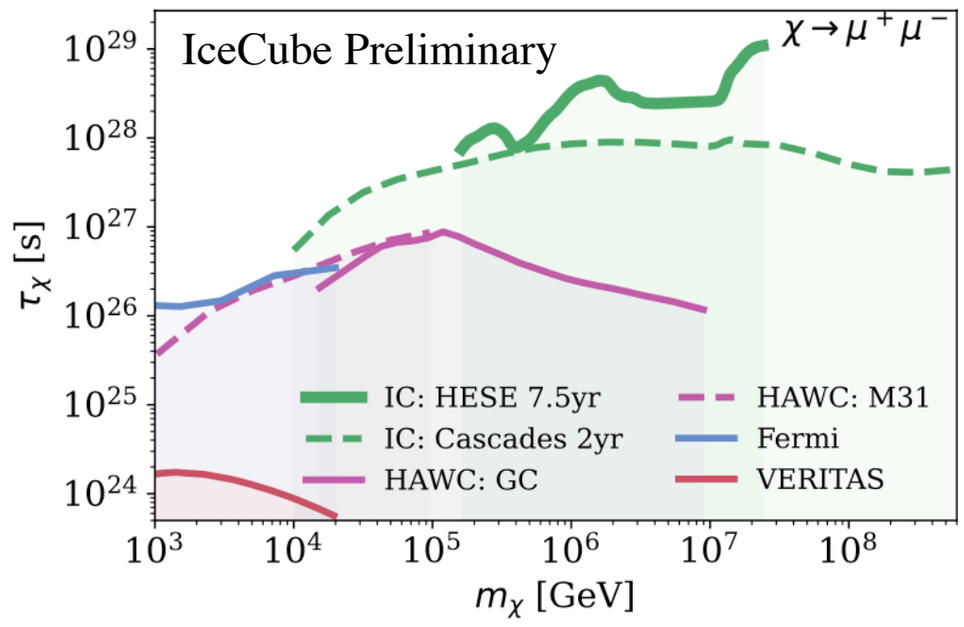
$$\frac{d\Phi_\nu^{Cos}}{dE_\nu} = \frac{\Omega_\chi \rho_c}{4\pi m_\chi \tau_\chi H_0} \int_0^\infty \frac{dN_\nu}{E_\nu(1+z)} \frac{dz}{\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}}$$



+ : cascade
x : track-like

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



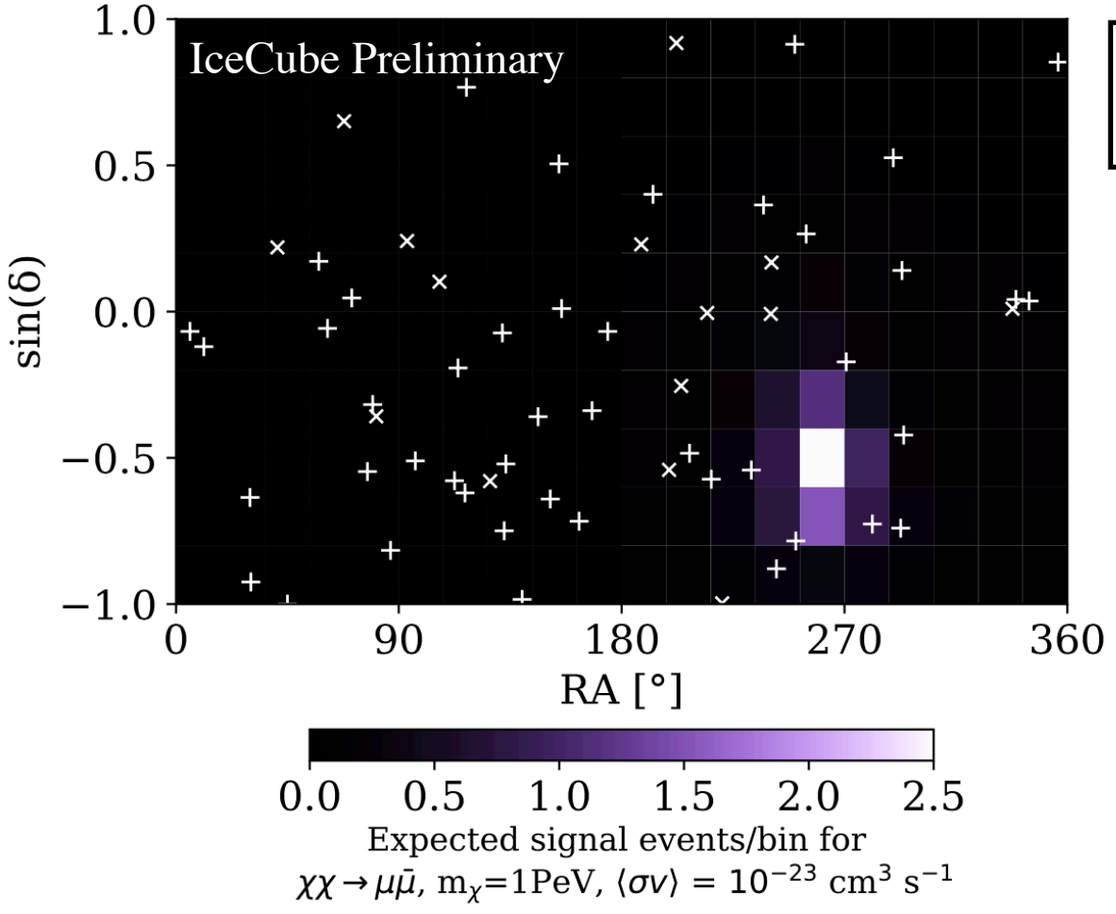


Annihilating DM Search

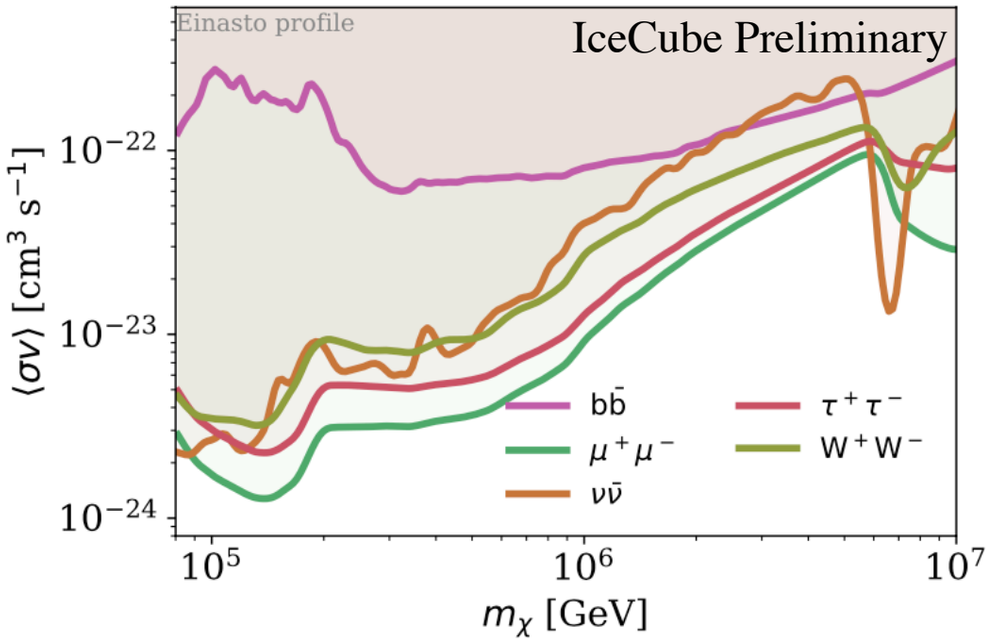
- Flux from dark matter annihilation

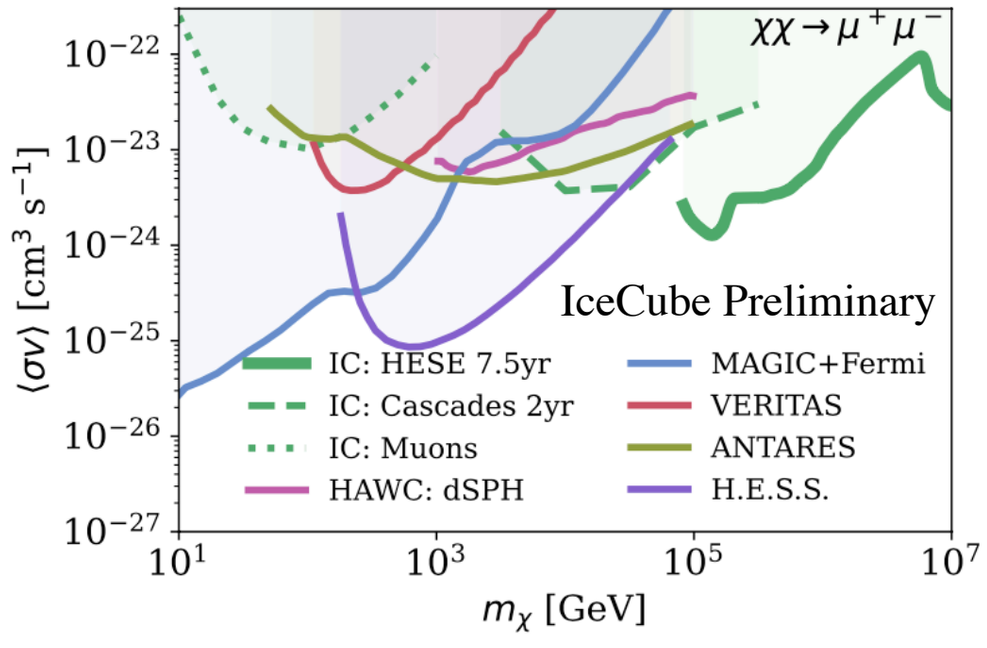
$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \frac{dN_\nu}{dE_\nu} \int_{l.o.s.} \rho_\chi^2(s) ds$$

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



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





Search for DM—ν scattering

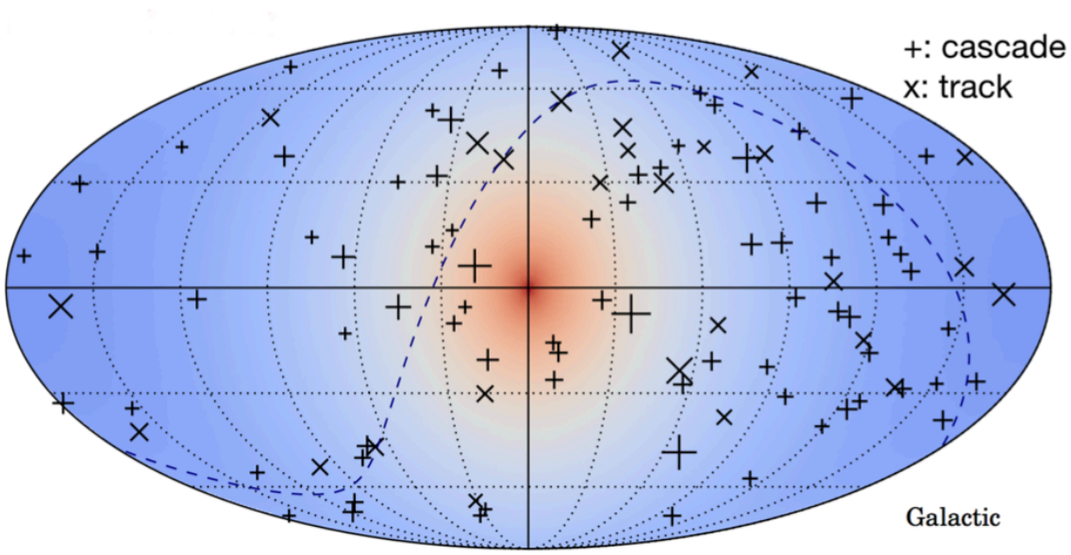
- Scattering of high-energy cosmic neutrinos on DM in the Galactic Halo

  ⇨ Signatures in energy and angular distribution of high-energy neutrinos expected

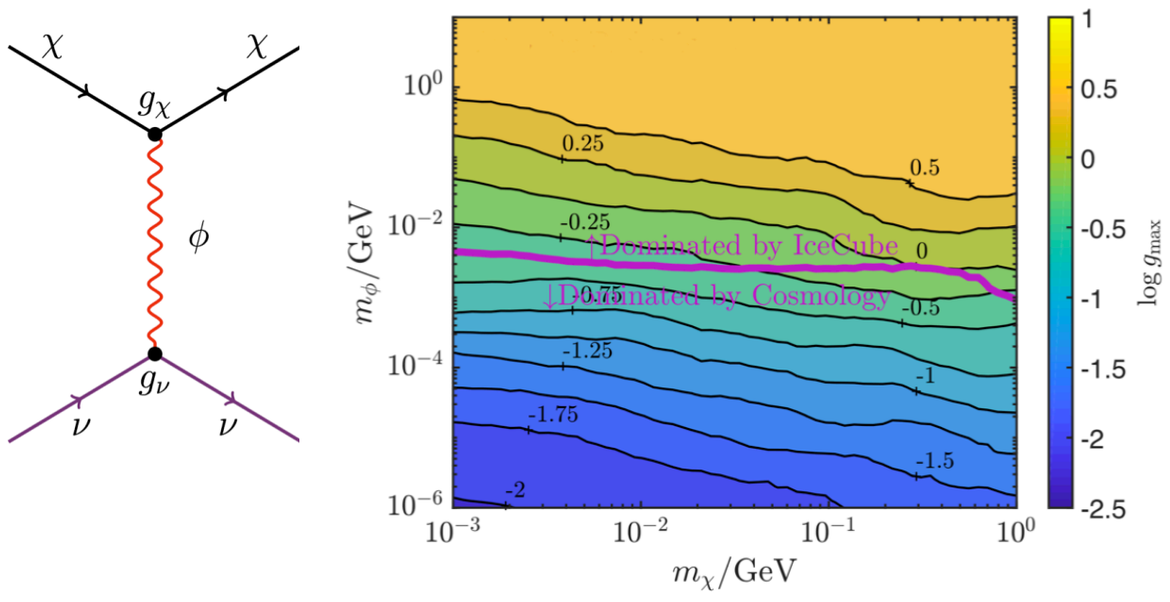
- Focusing on high-energy neutrinos (cross-section increases with energy)

- Very stringent limits on the maximum coupling, g_{max}, derived

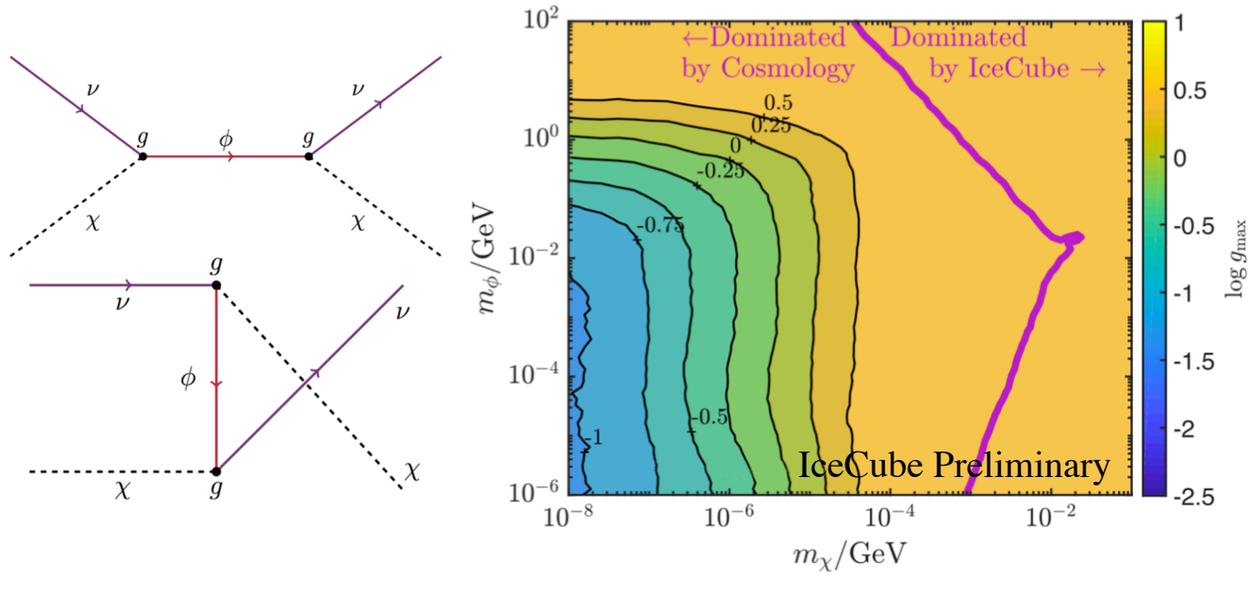
DM column density and observed events



fermionic DM & vector mediator



scalar DM & fermionic mediator

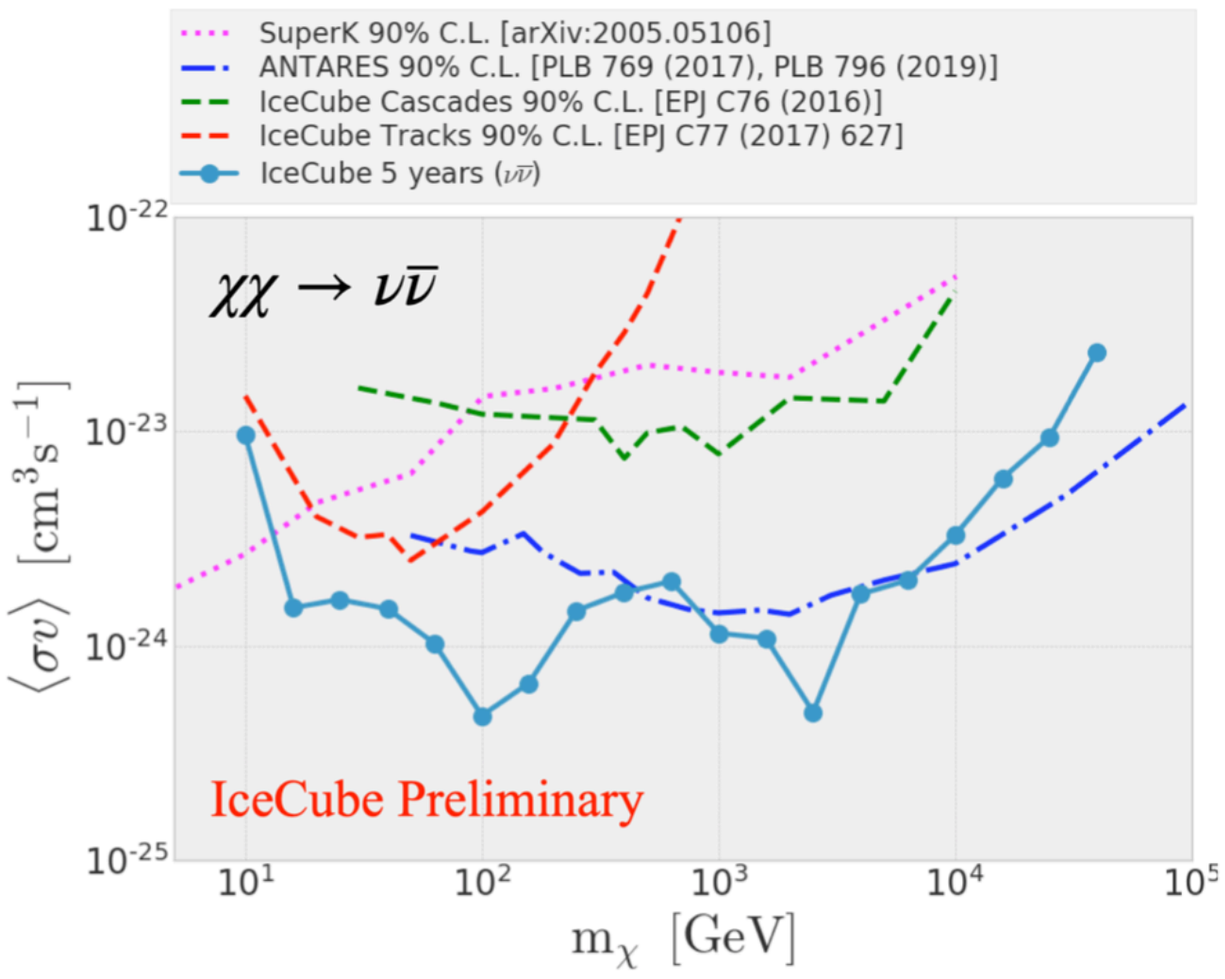


Search for neutrino lines using 5 years of IceCube data

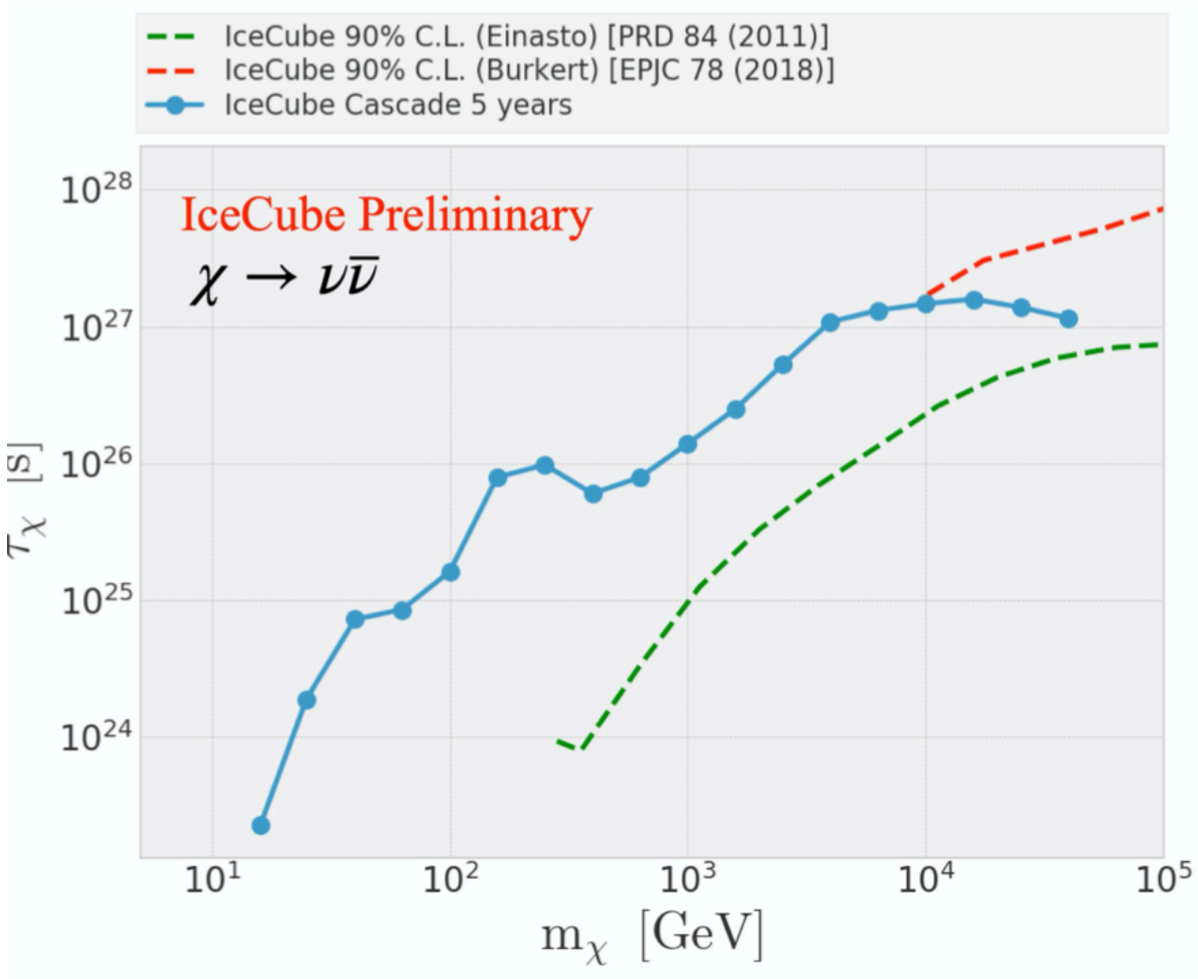
Neutrino Line analysis

- Aimed primarily at finding signals from $\chi \to \nu\bar{\nu}$ and $\chi\chi \to \nu\bar{\nu}$ in the Galactic Center
  - A line feature in the neutrino spectra expected
- Event selection optimized to achieve a good energy resolution
  - Focusing on cascade events
  - Events contained in the DeepCore
- Two subsamples optimized for different DM mass ranges
  - LE sample for 10 GeV < m_χ < 1 TeV
  - HE sample for 1 TeV < m_χ < 40 TeV
- Energy resolution of ~15%
- 5 years of data (from 2012 to 2016)

Results



90% C.L. limits on the thermally averaged DM annihilation cross section

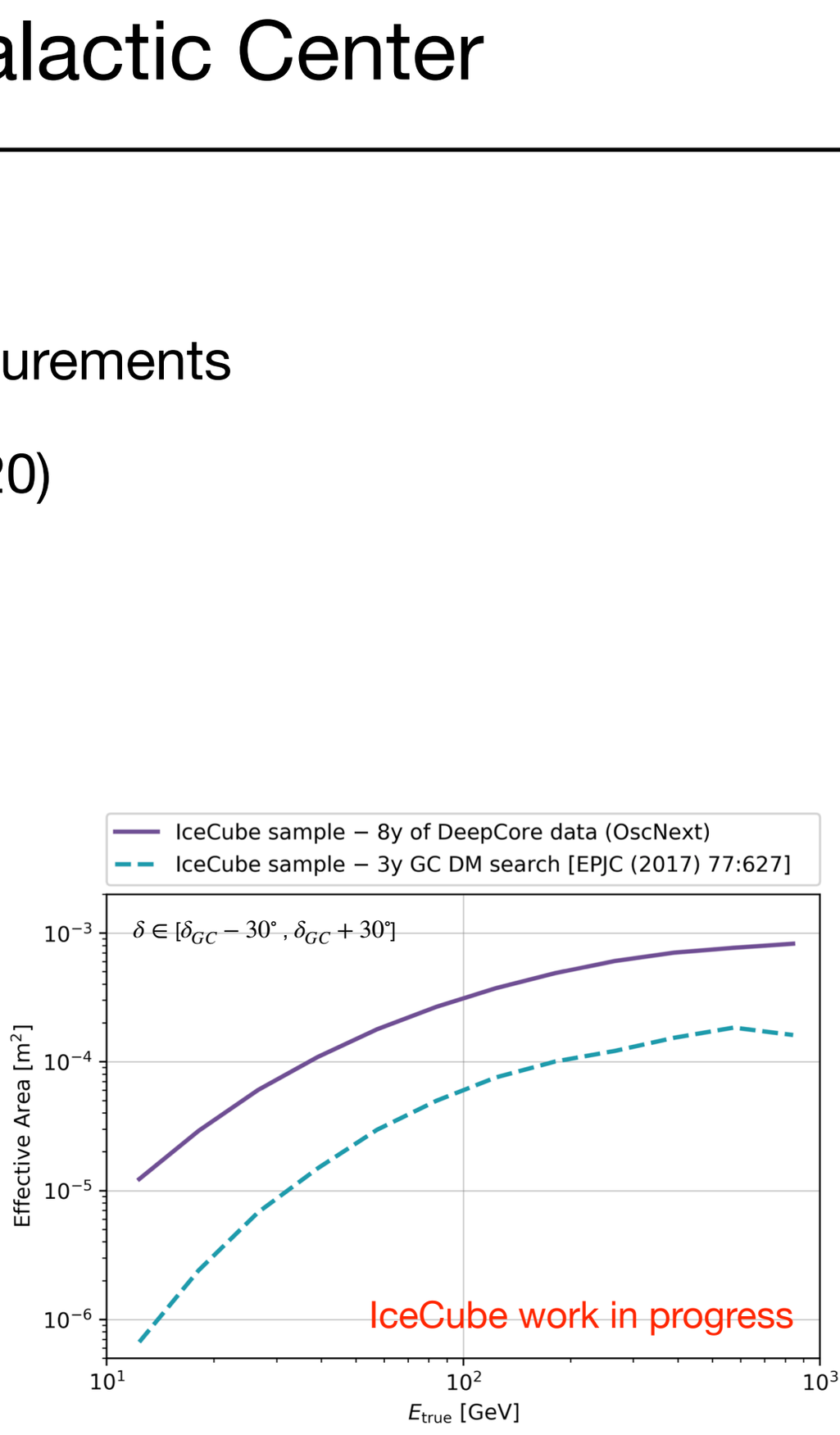


90% C.L. limits on the dark matter decay lifetime

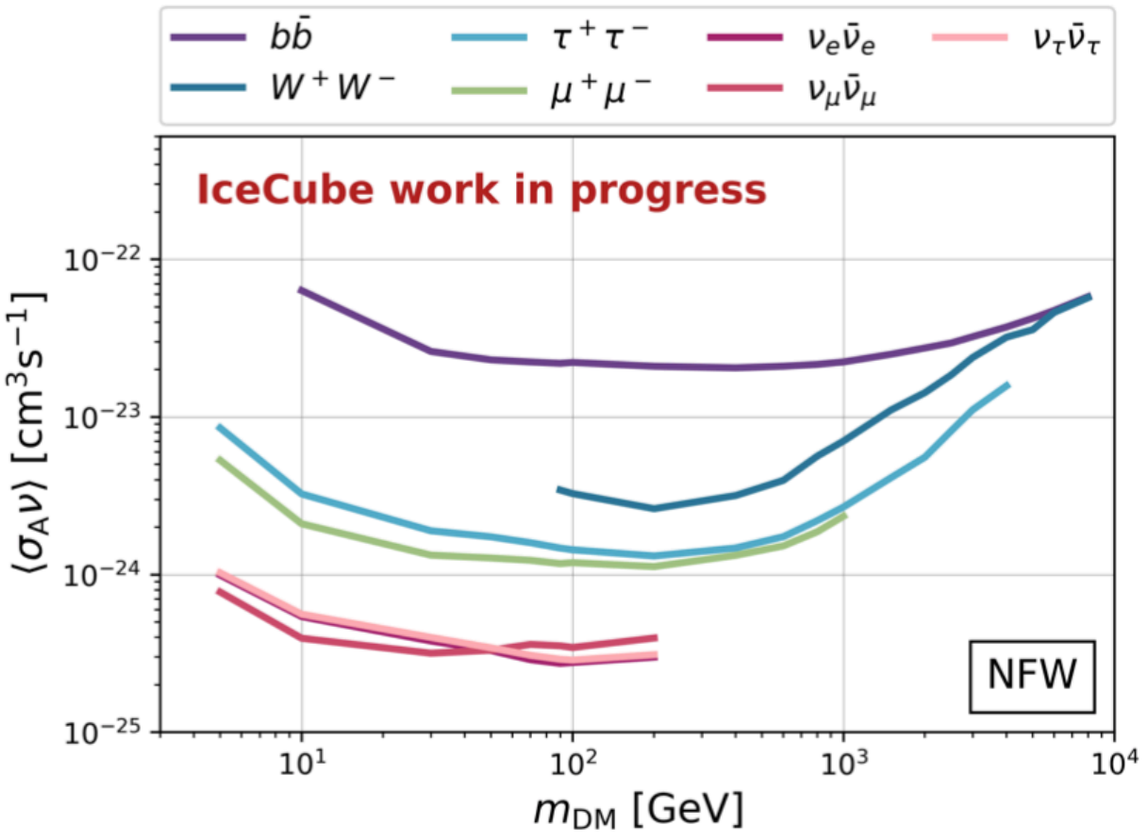
Search for dark matter annihilation in the Galactic Center using 8 years of oscNext data

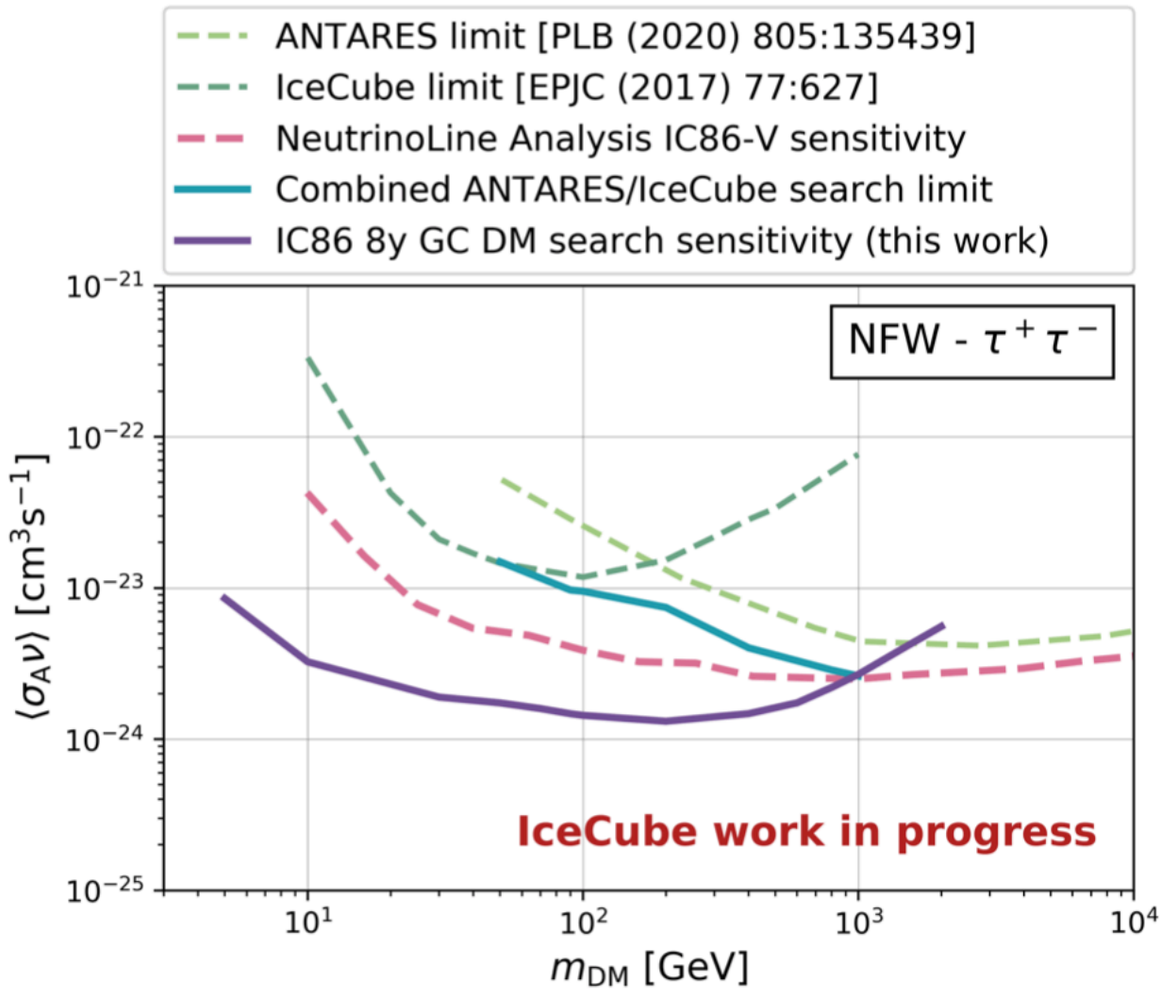
Search for DM annihilation in Galactic Center

- Low energy event selection (OscNext)
  - Developed for atmospheric neutrino measurements
  - 8 years of IceCube data (from 2012 to 2020)
  - Containing all three neutrino flavors
- Changes in the event selection
  - Energy cut and zenith angle cut released
- Observables : arrival direction, energy, topology of events
- Considerable improvements compared to the previous GC analysis using 3-year DeepCore data



Sensitivities





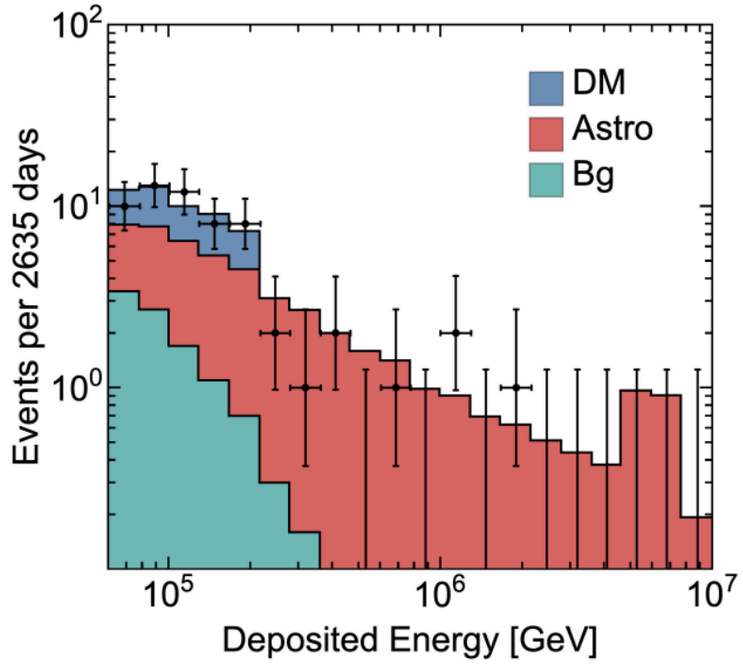
- Significant improvement in sensitivities compared to the combined ANTARES/IceCube analysis
- Leading sensitivities for $m_\chi < 1$ TeV with neutrino telescopes

Search for dark matter decay in Galaxy Clusters and Galaxies

Motivation

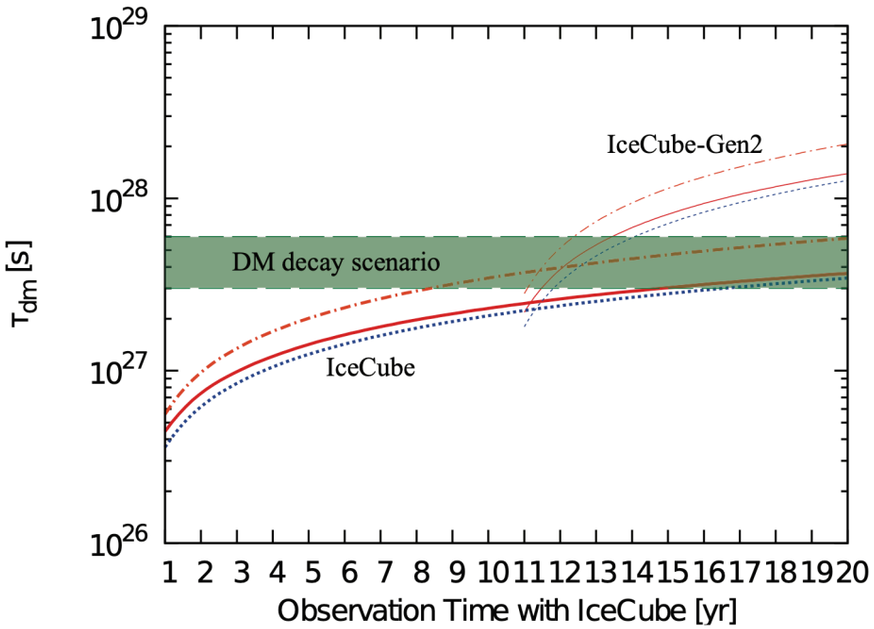
- Theoretical works suggest that some of the IceCube events could be explained by heavy decaying dark matter.

- IceCube is highly sensitive to heavy dark matter hypotheses, as proven by previous analyses.



Marco Chianese *et al* JCAP11(2019)046

- Galaxy clusters and galaxies, relatively close to the Milky Way, are good targets to look for dark matter.
  - Previous IceCube analyses searched for annihilating dark matter in these targets but not decaying dark matter.



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

DM Decay in Galaxy Clusters and Galaxies

- Searching for dark matter decay in galaxy clusters, dwarf galaxies, and Andromeda
- DM masses : 10 TeV to 1 EeV
- DM decay channels : $\chi \to b\bar{b}, \chi \to \tau^+\tau^-, \chi \to W^+W^-, \chi \to \nu\bar{\nu}$
- 9 years of up-going track event sample (2011 to 2019)
- Targets with large astrophysical factors and positive declinations selected
- An unbinned maximum likelihood analysis performed

Source	Type	RA[°]	Dec [°]	θ_{max} [°]	D_{max} $[GeV/cm^2]$
Virgo	galaxy cluster	186.63	12.72	6.11	2.54×10^{20}
Coma	galaxy cluster	194.95	27.94	1.30	1.49×10^{19}
Perseus	galaxy cluster	49.94	41.51	1.35	1.44×10^{19}
Andromeda	galaxy	10.68	41.27	8.00	1.70×10^{20}
Draco	dwarf galaxy	260.05	57.92	1.30	9.35×10^{18}
Ursa Major II	dwarf galaxy	132.87	63.13	0.53	2.48×10^{18}
Ursa Minor	dwarf galaxy	227.28	67.23	1.32	1.35×10^{18}
Segue 1	dwarf galaxy	151.77	16.08	0.34	9.75×10^{17}
Coma Berenices	dwarf galaxy	186.74	23.9	0.34	9.15×10^{17}
Leo I	dwarf galaxy	152.12	12.3	0.45	8.22×10^{17}
Boötes I	dwarf galaxy	210.03	14.5	0.53	7.97×10^{17}

Conclusions

- Indirect detection of Dark Matter with neutrino telescopes provides complementarity to other techniques due to different backgrounds and systematics.

- IceCube provides strong constraints on dark matter decay, annihilation, and dark matter - neutrino interaction.

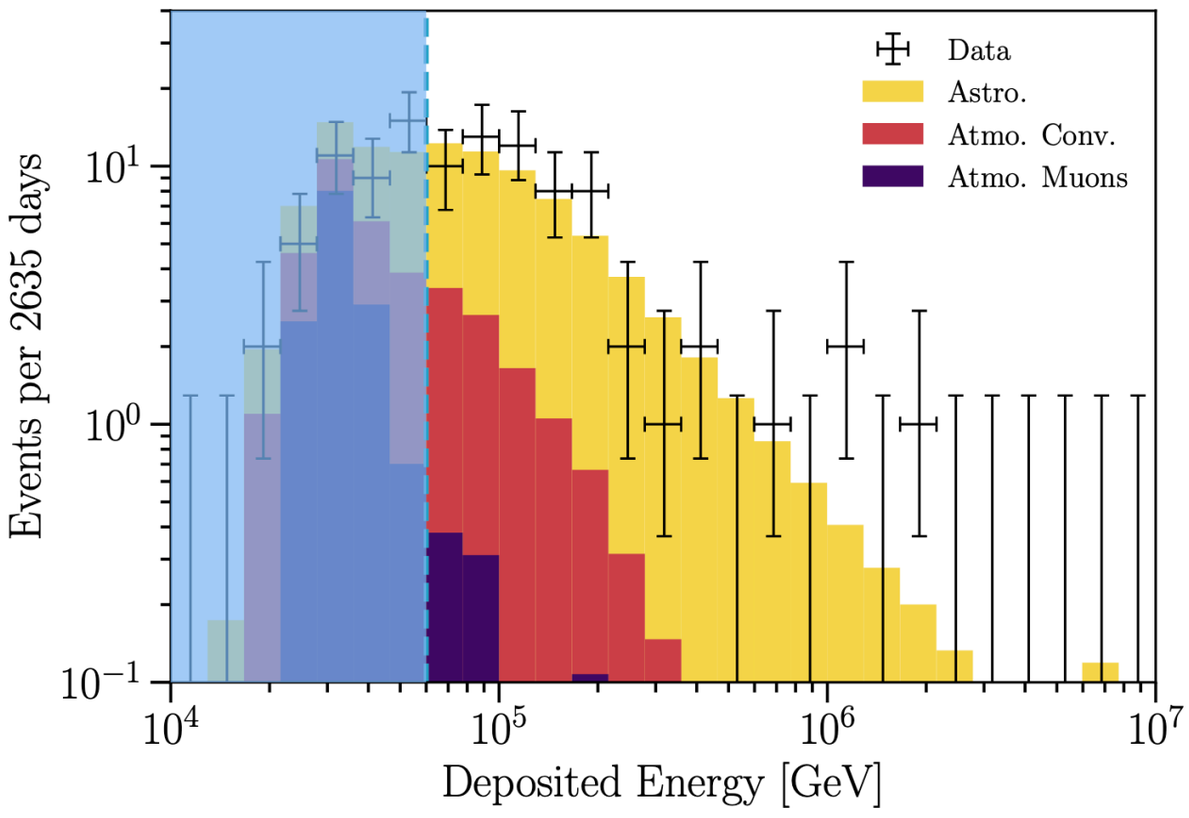
- Analyses are on-going with more data and improved analysis techniques. Two of them are shown here.
  - Search for DM annihilation in the GC with OscNext
  - Search for DM decay in galaxy clusters and galaxies

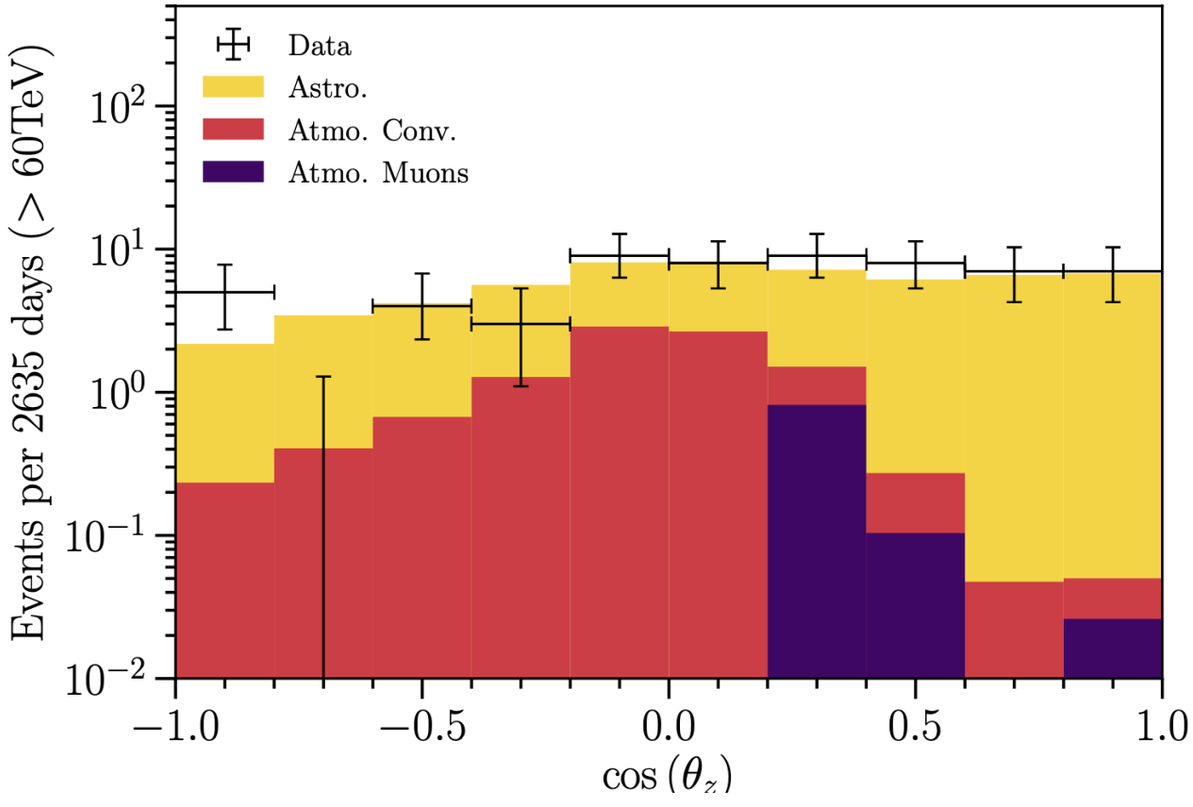
- Very strong bounds on WIMP nucleon scattering have been achieved. (See talk by C. Tönnis.)

Backups

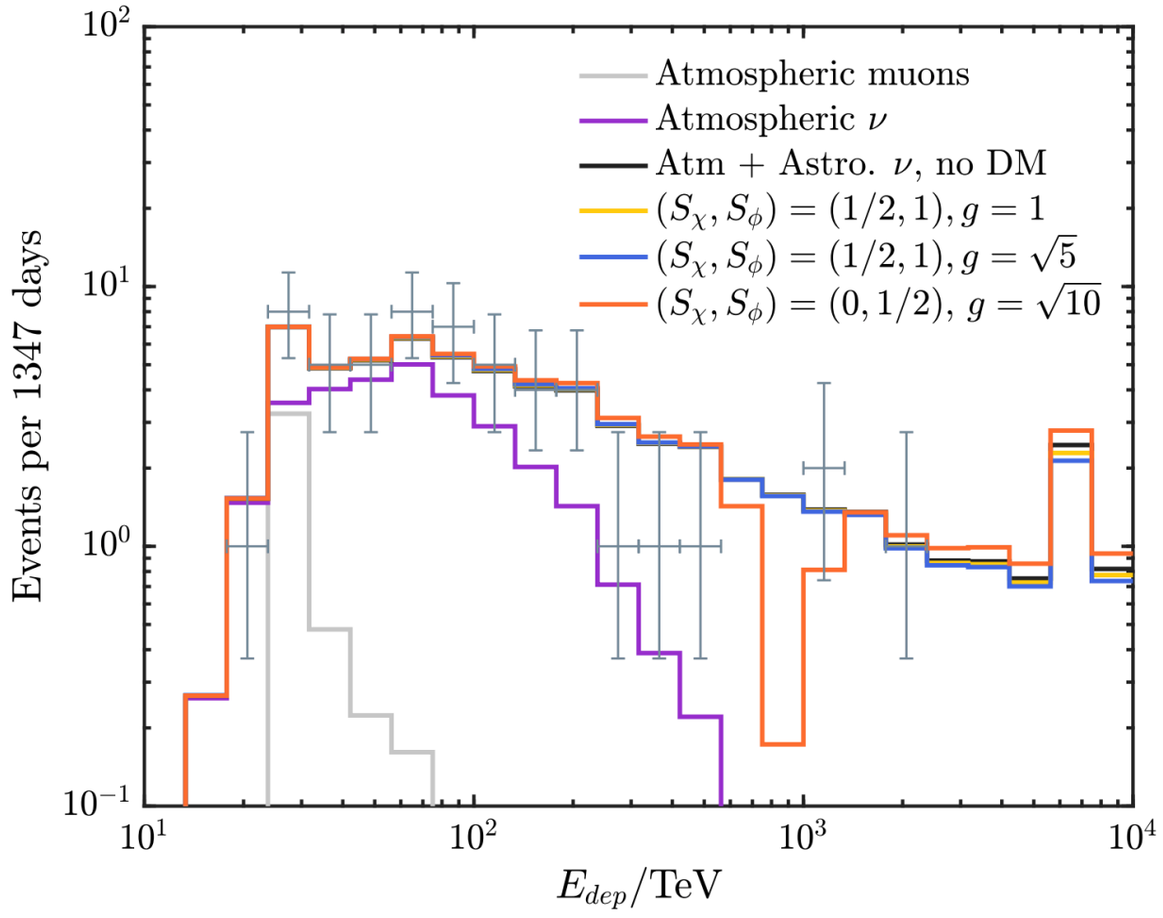
Backups : 7.5-year HESE analyses

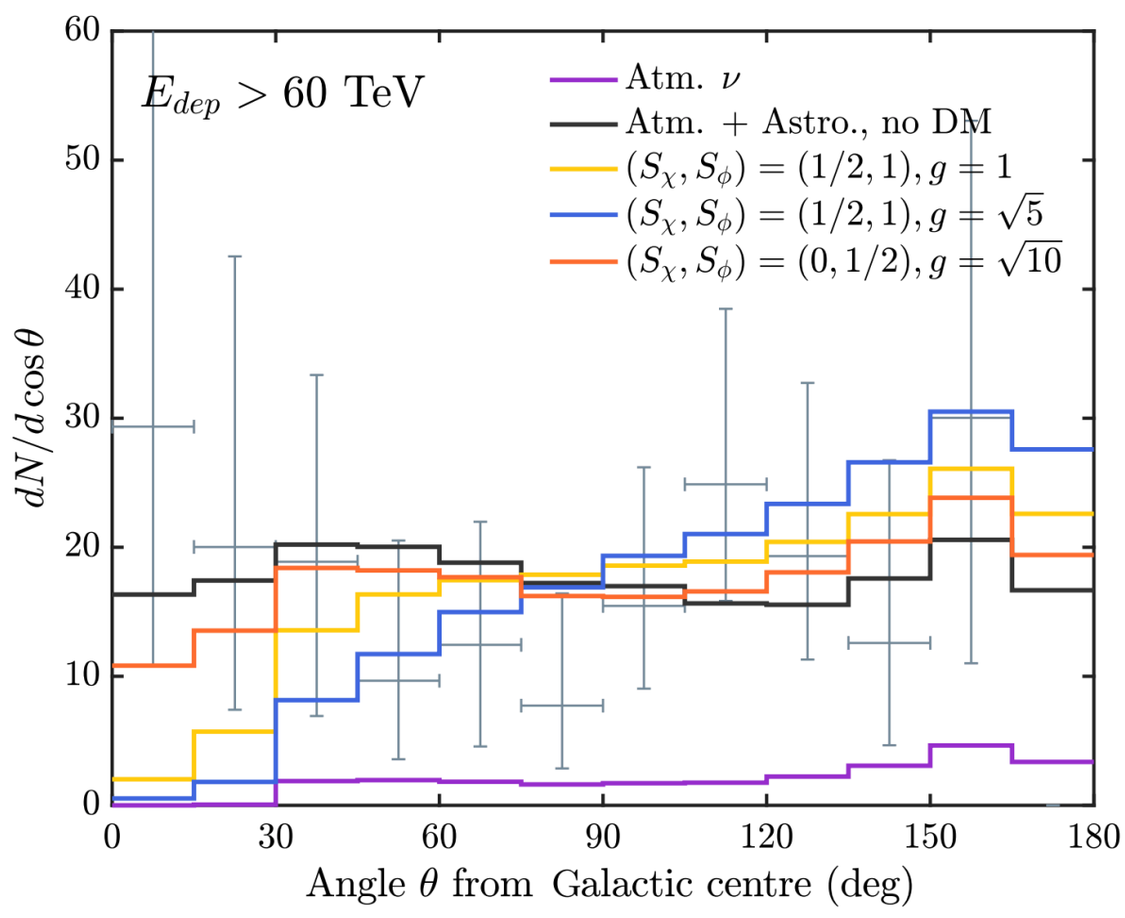
High-Energy Starting Events (HESE)





Expected signatures of DM — ν scattering



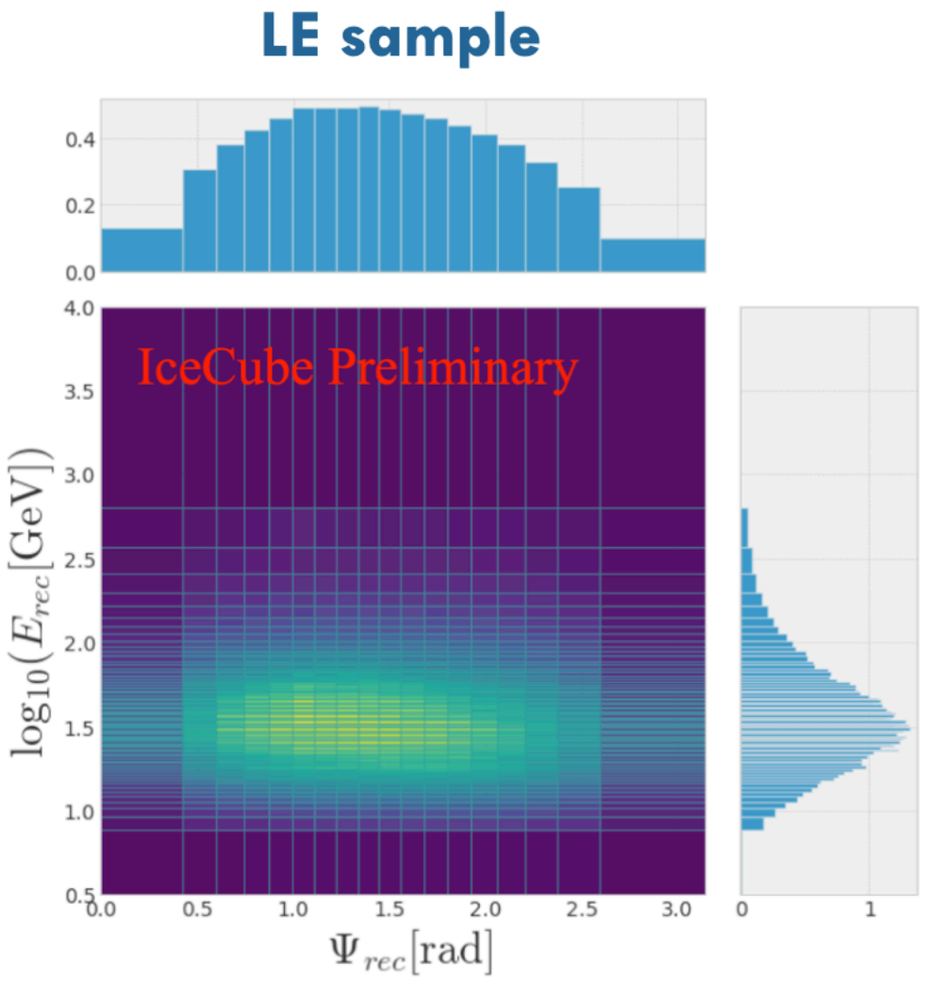


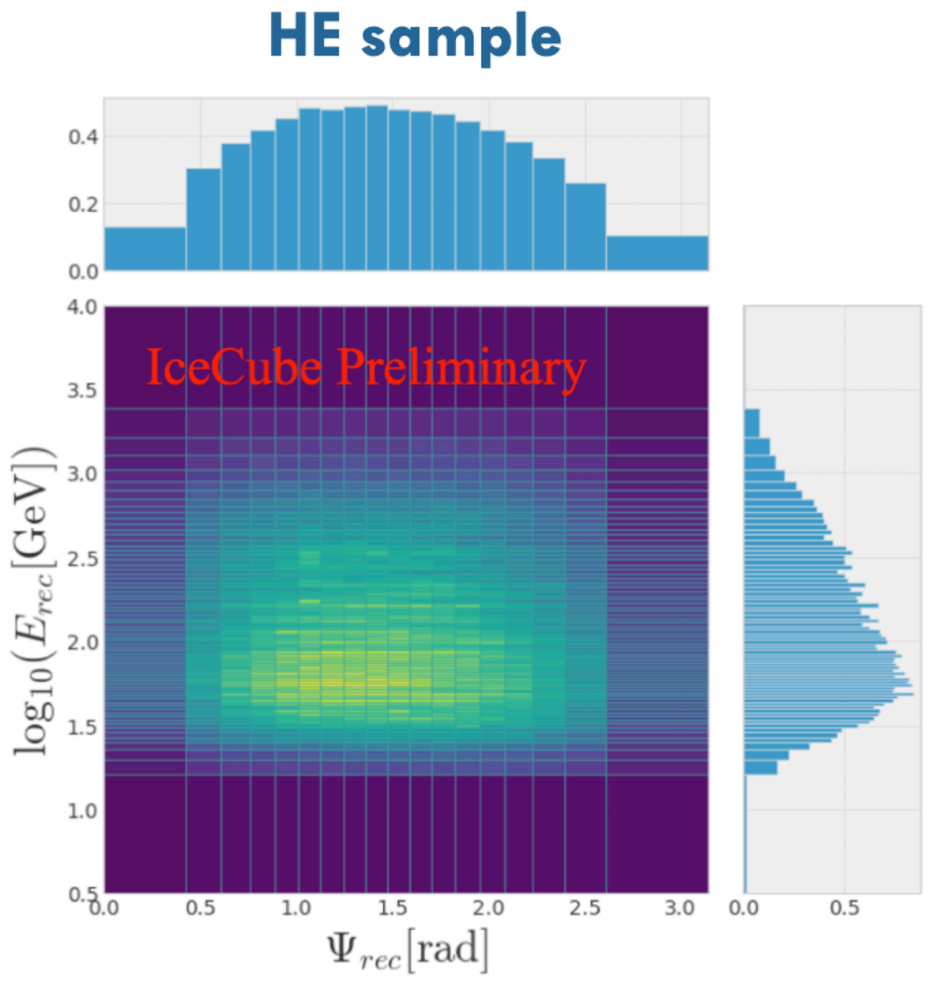
CA, A. Kheirandish & A. Vincent Phys. Rev. Lett. **119**, 201801

Backups : neutrino line analysis

Background PDFs

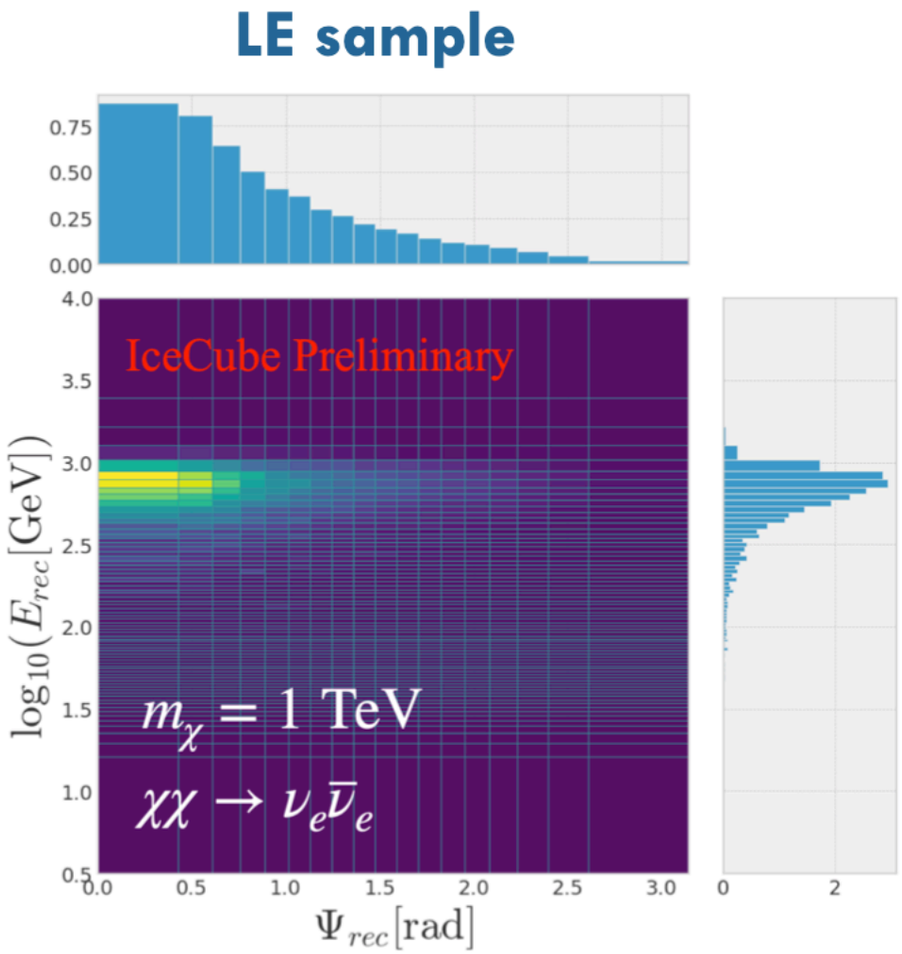
- PDF built from data scrambled in RA
- Histogram built with irregular binning
  - Quantile binning [https://github.com/janpipek/physt]

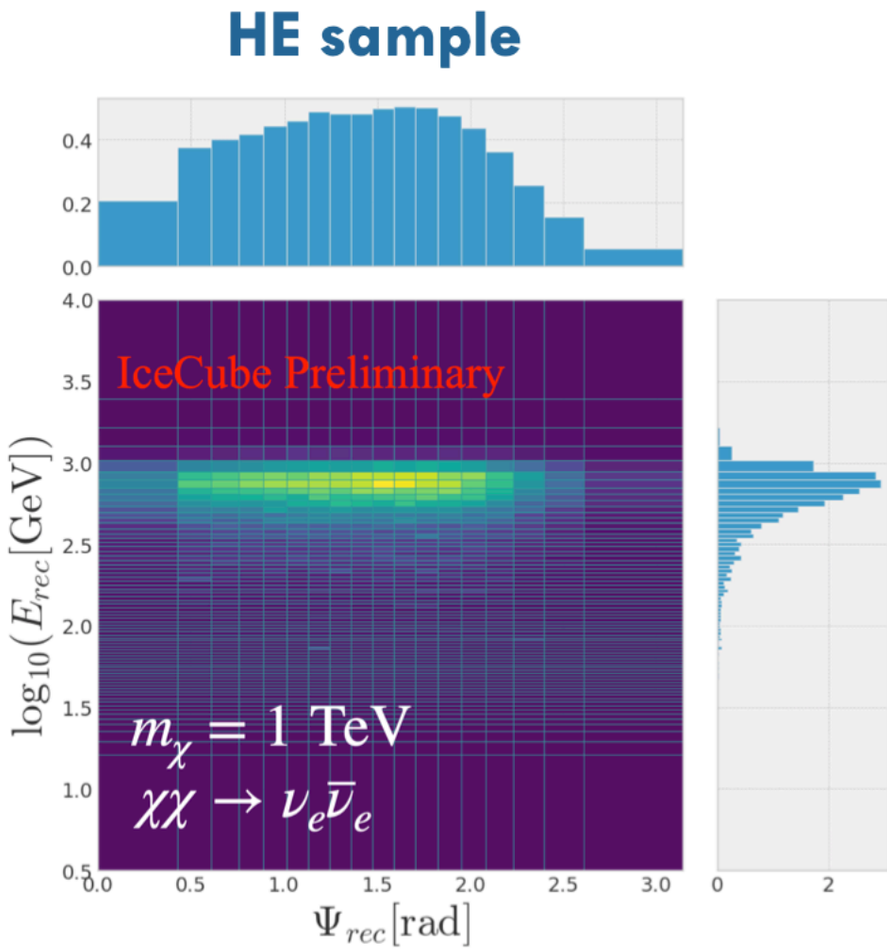




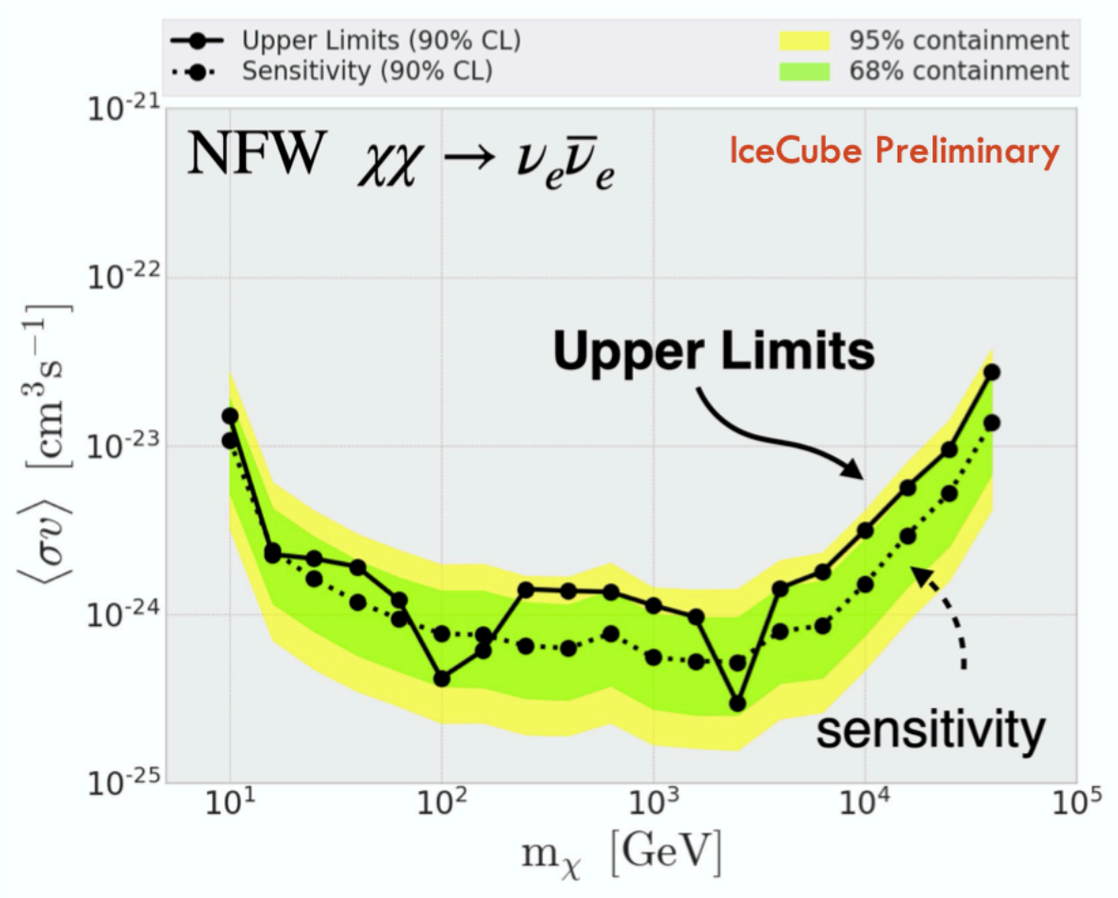
Signal PDFs

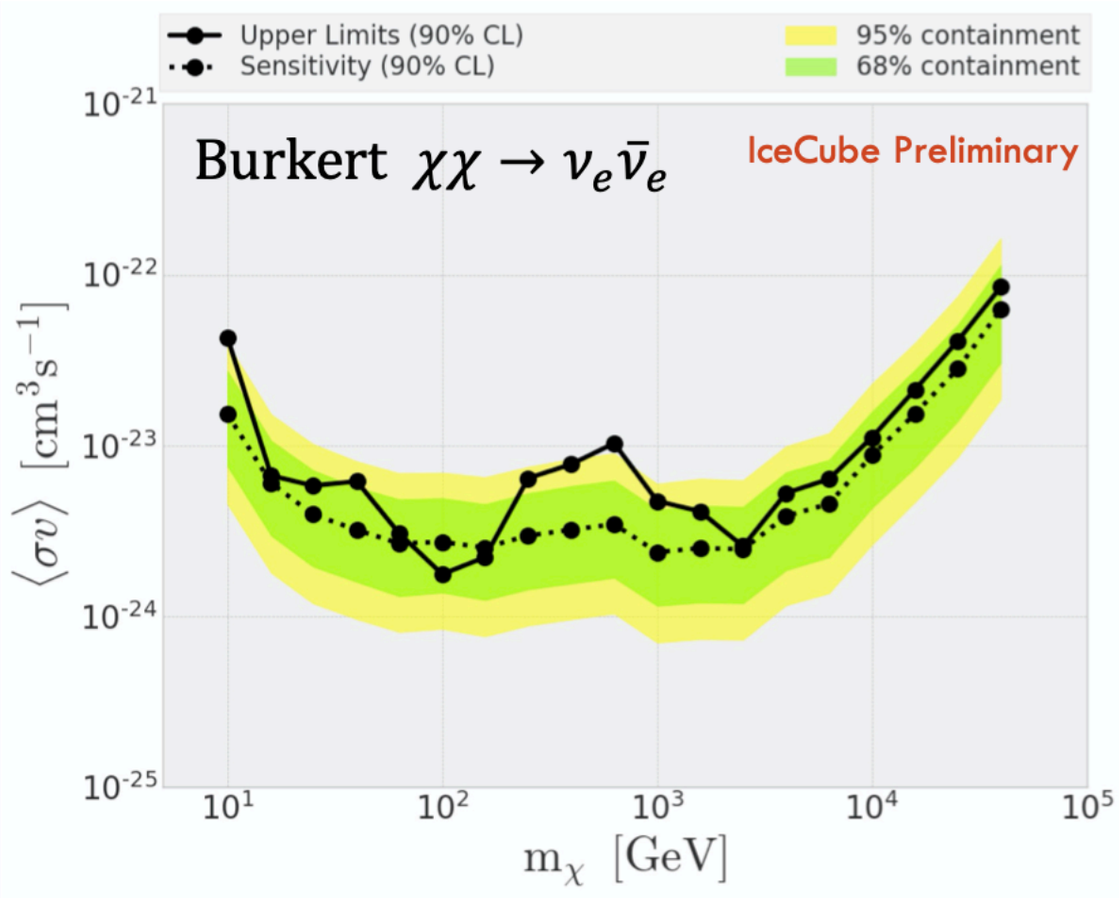
- PDF built from Monte Carlo neutrino simulations weighted with
  - Spectra: PPPC4 spectra
  - Source morphology: NFW and Burkert halo profiles



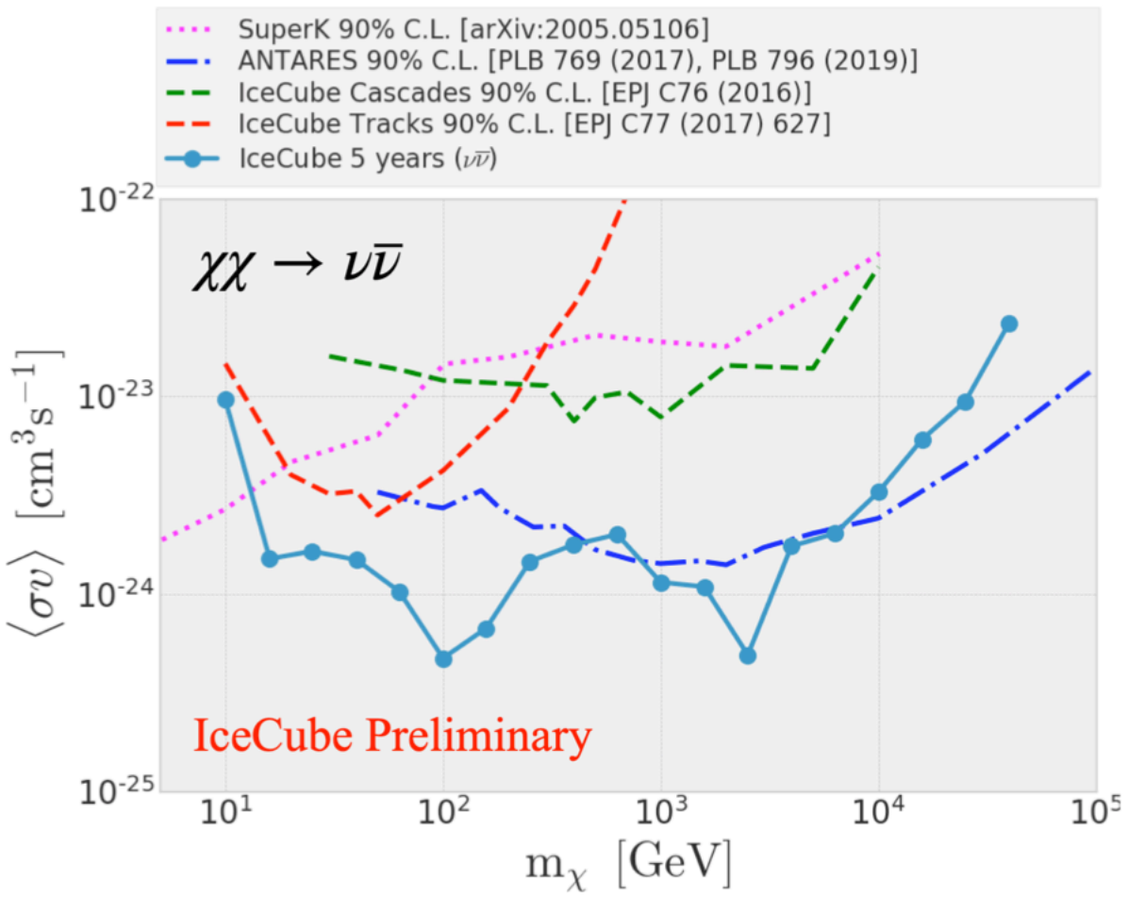


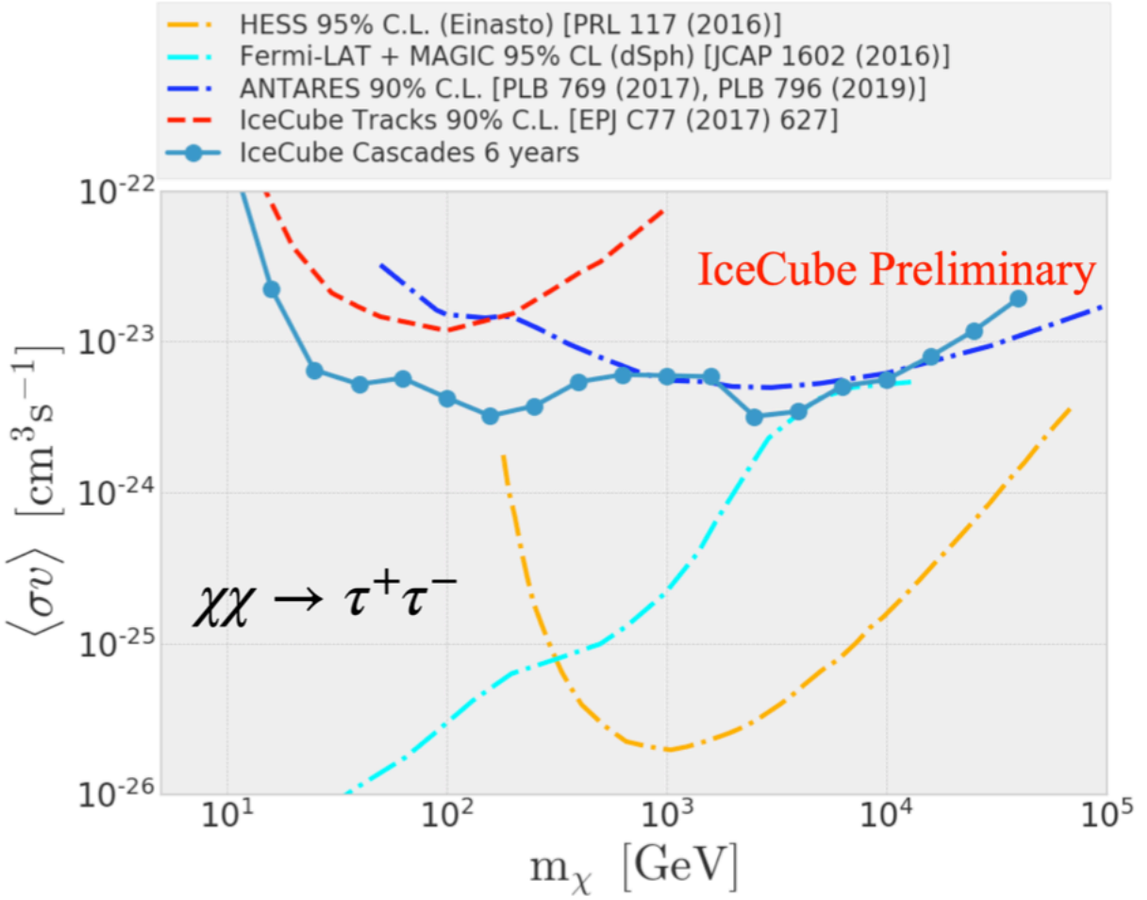
Sensitivities and limits



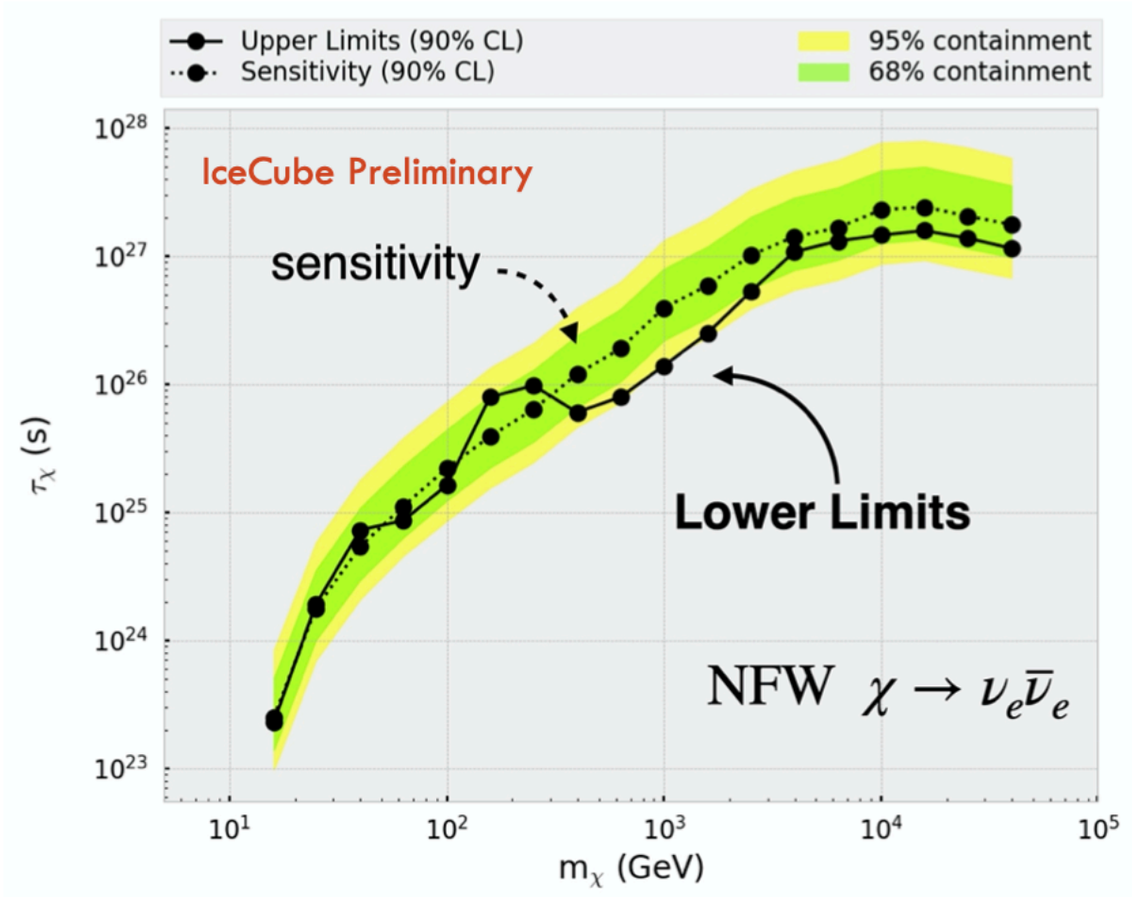


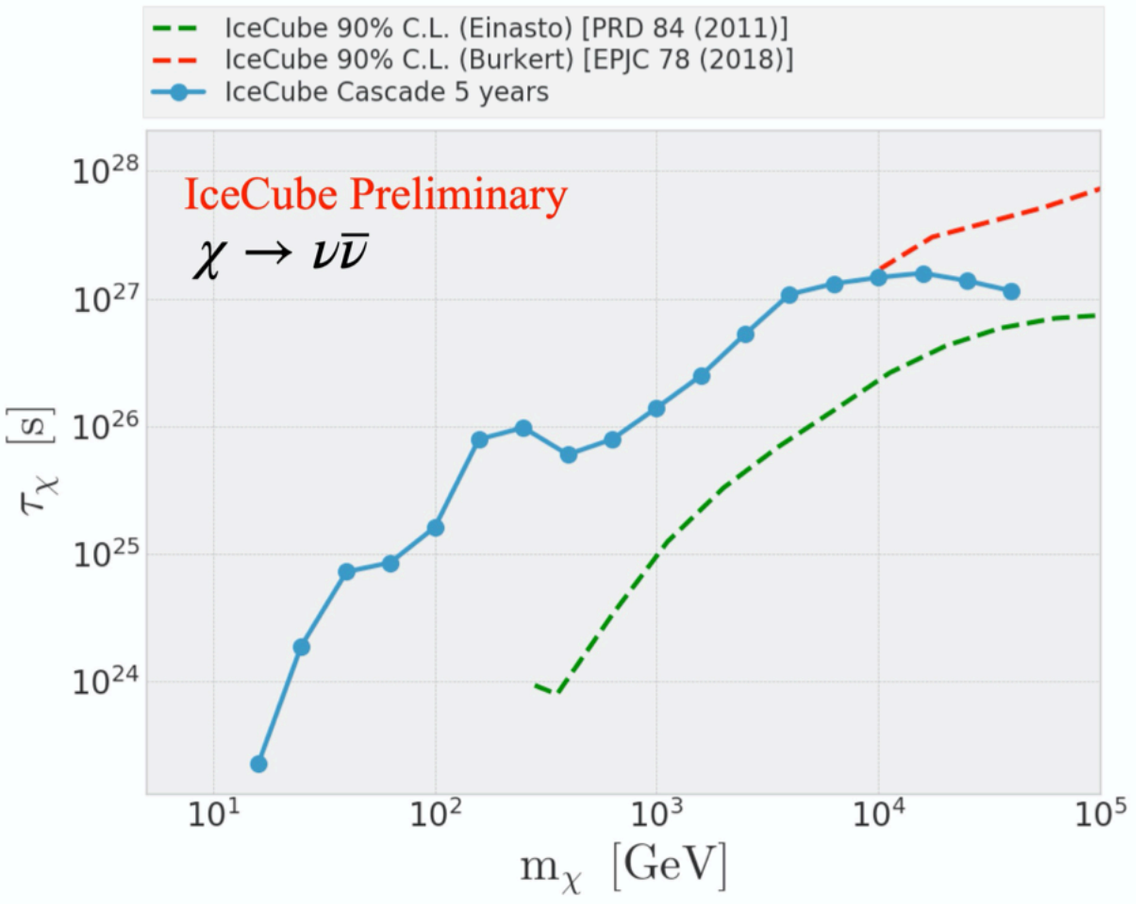
Sensitivities and limits





Sensitivities and limits



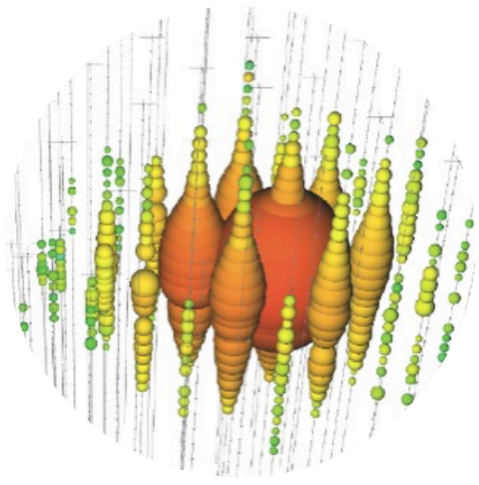


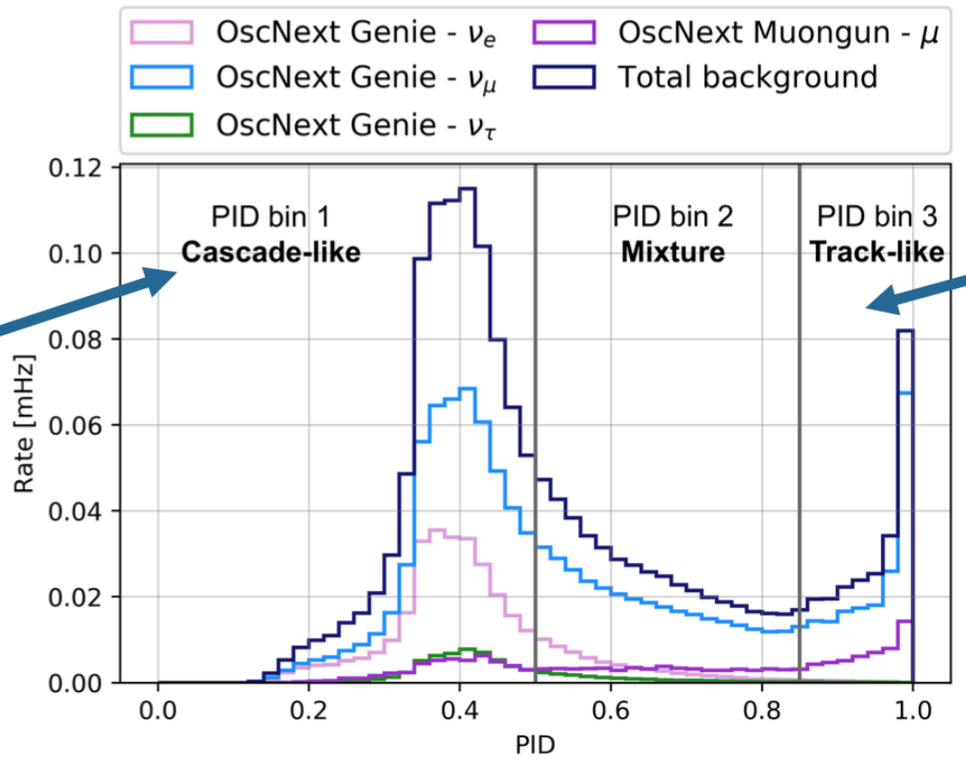
Backups : low mass DM in GC

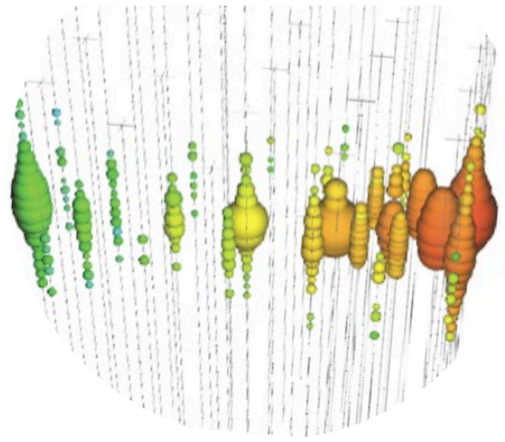
PID

Cascade Events

NC ν – CC ν_e & ν_τ





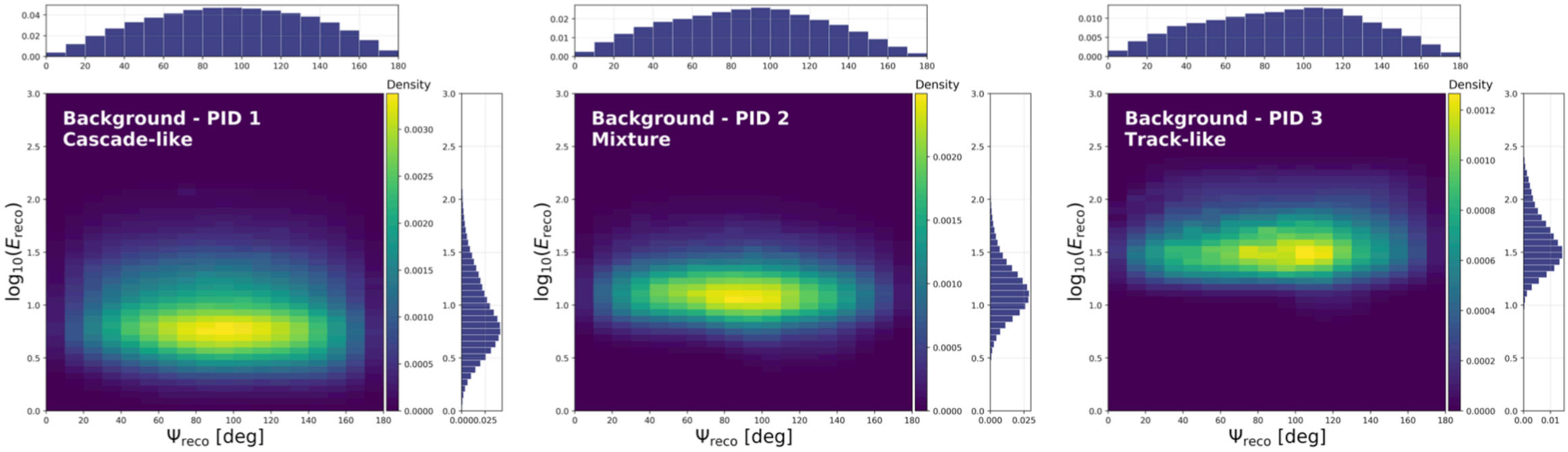


Track events

CC ν_μ

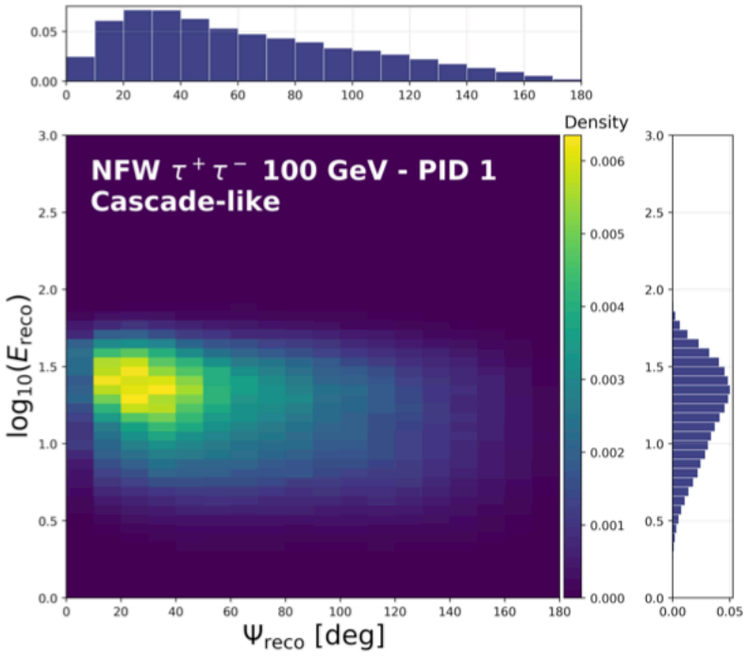
Background PDFs

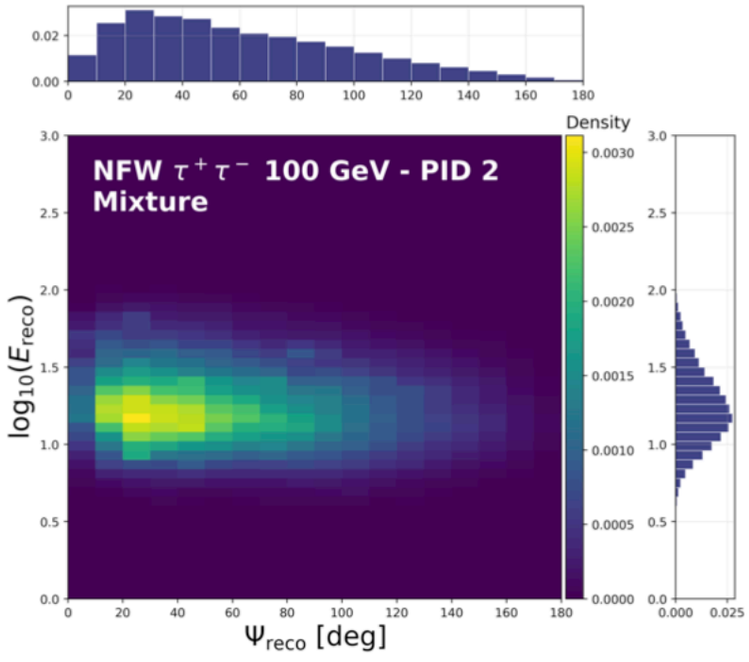
- PDF built from MC neutrino and muon simulations
  - Weighted according to atmospheric flux
- PDF smoothed using Kernel Density Estimation (KDE)

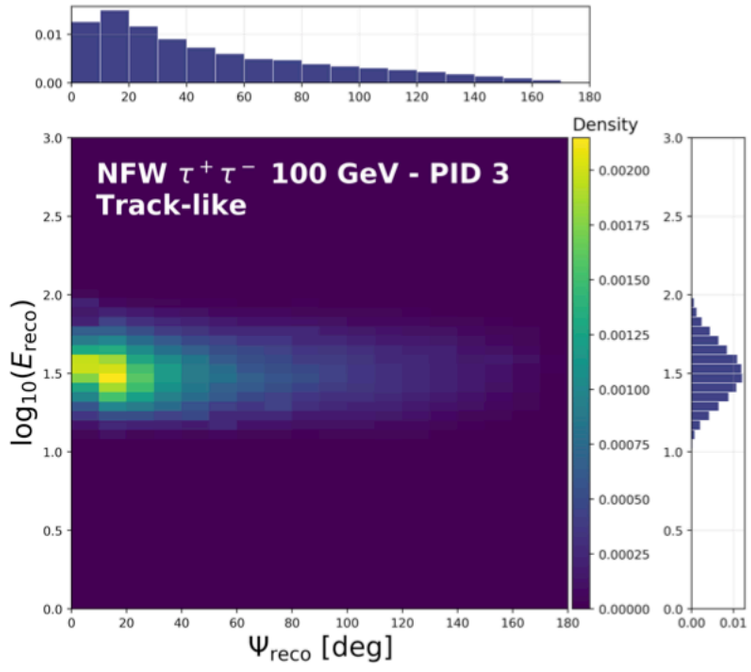


Signal PDFs

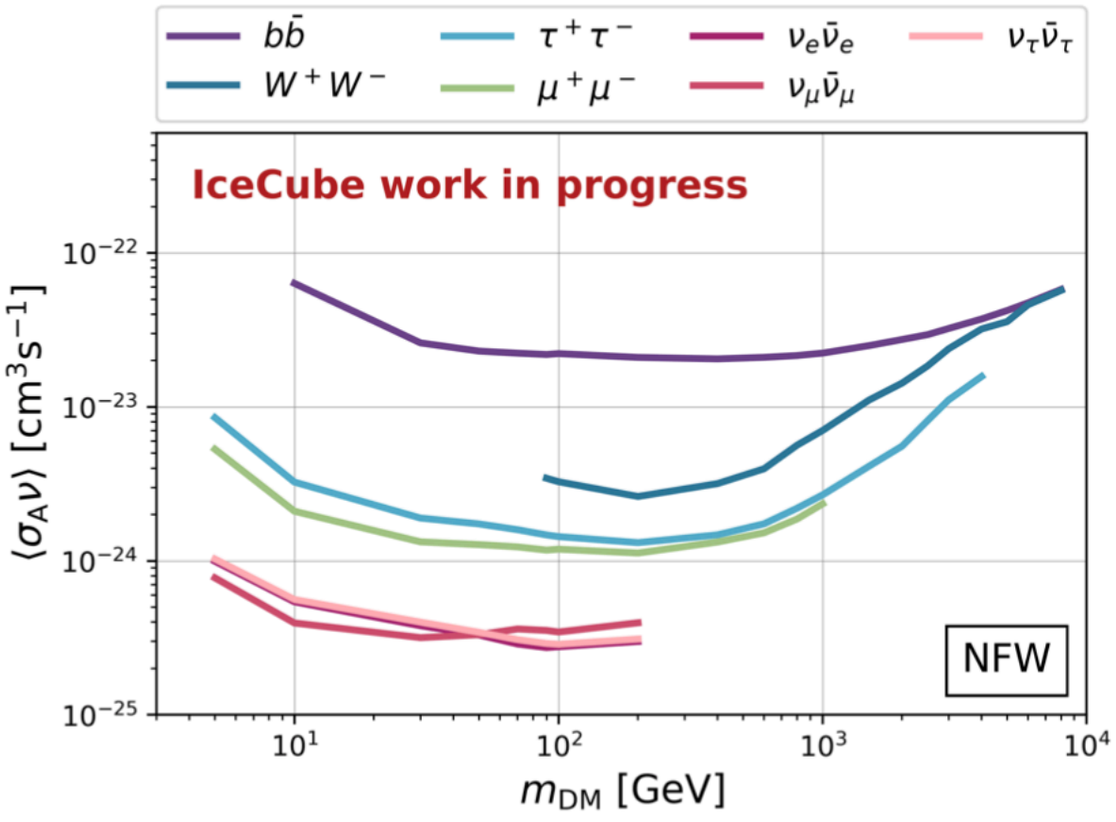
- Monte Carlo neutrino simulations weighted with PPPC4 spectra
  - DM masses between 5 GeV and 8 TeV
  - DM annihilation through $\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, W^+W^-, \tau^+\tau^-, \mu^+\mu^-, b\bar{b}$
- Source morphology: NFW and Burkert halo profiles

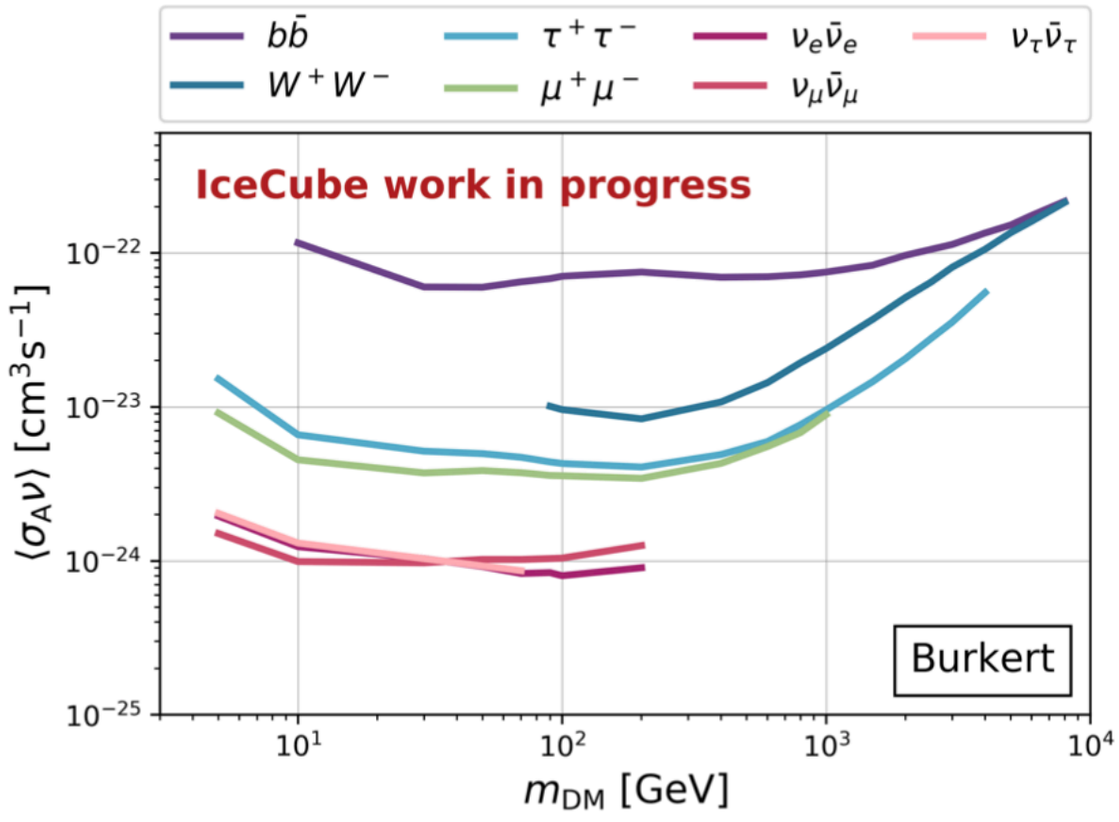




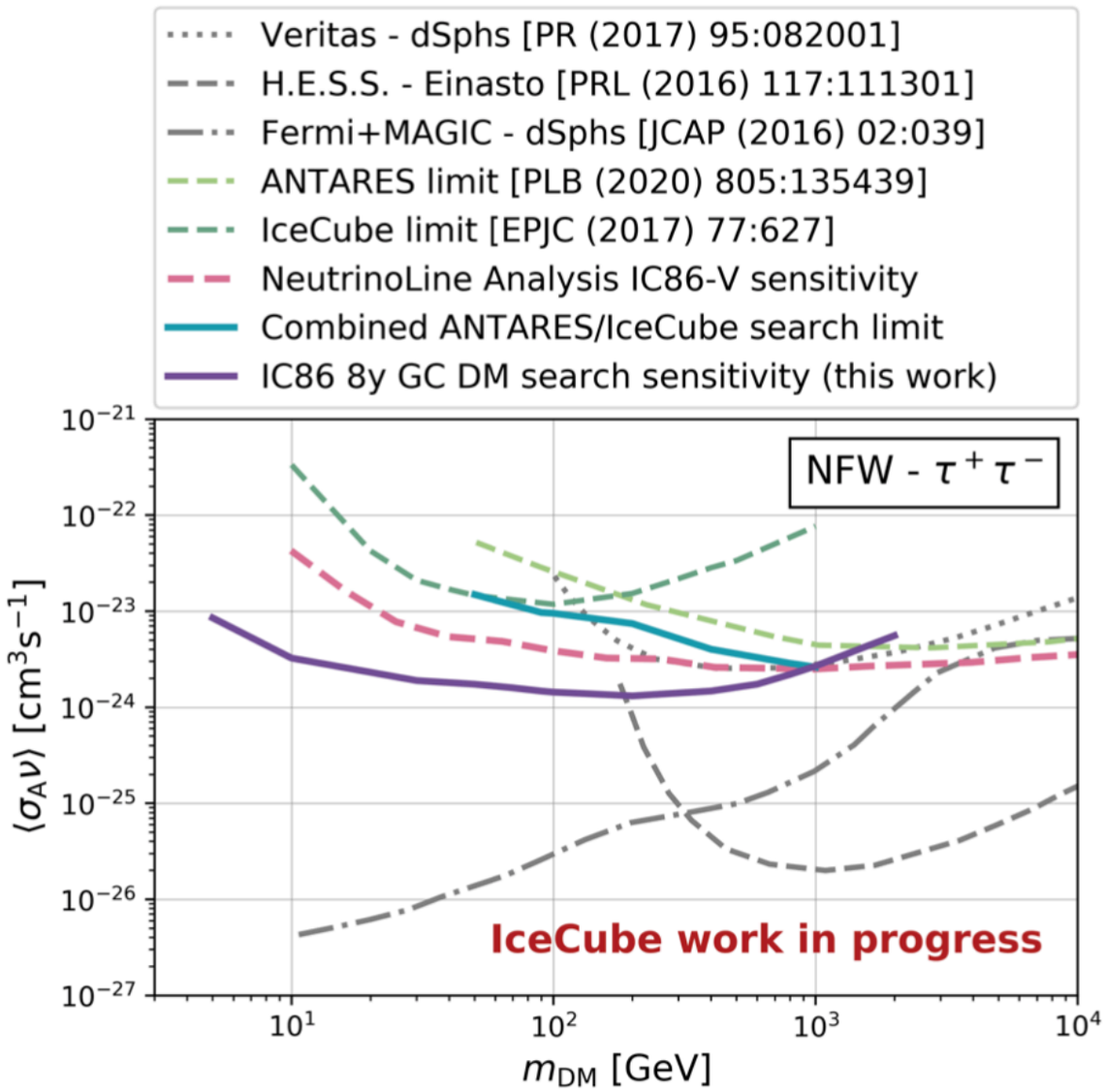


Sensitivities





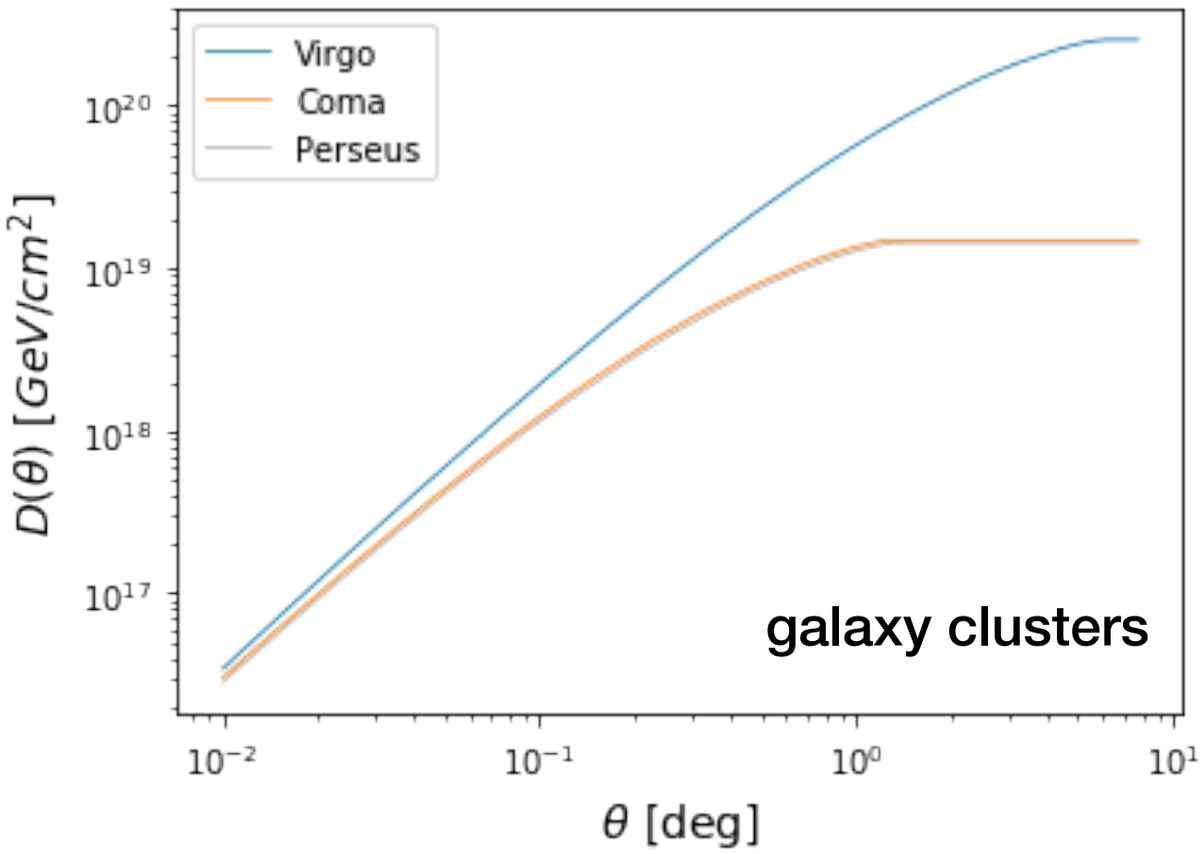
Sensitivities



Backups : extragalactic DM search

DM halo models

- DM halo models of the targets were adopted from [1-3].
  - For M31, the NFW model is used.
- Then the astrophysical factors were calculated up to the saturation angles.
  - The ROi for M31 is an exception. The ROI is smaller than the saturation angle. But this choice leads to as good sensitivity as using the saturation angle.



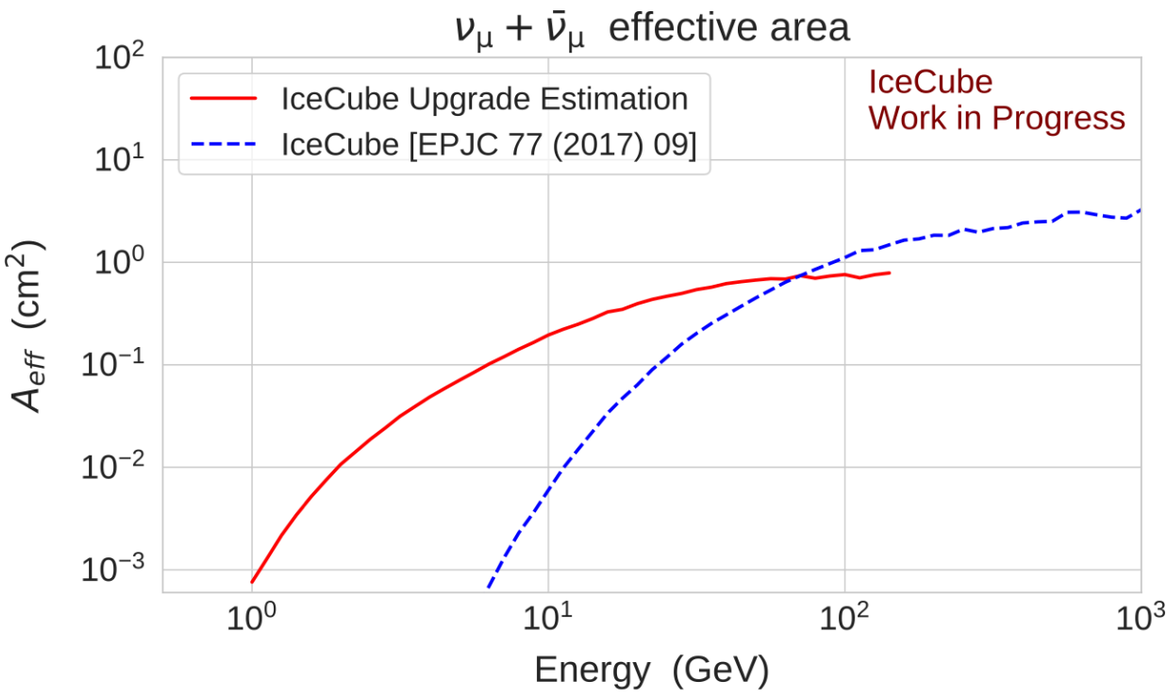
[1] A. Geringer-Sameth et al, *Astrophys. J.* **801** no. 2, (2015) 74.

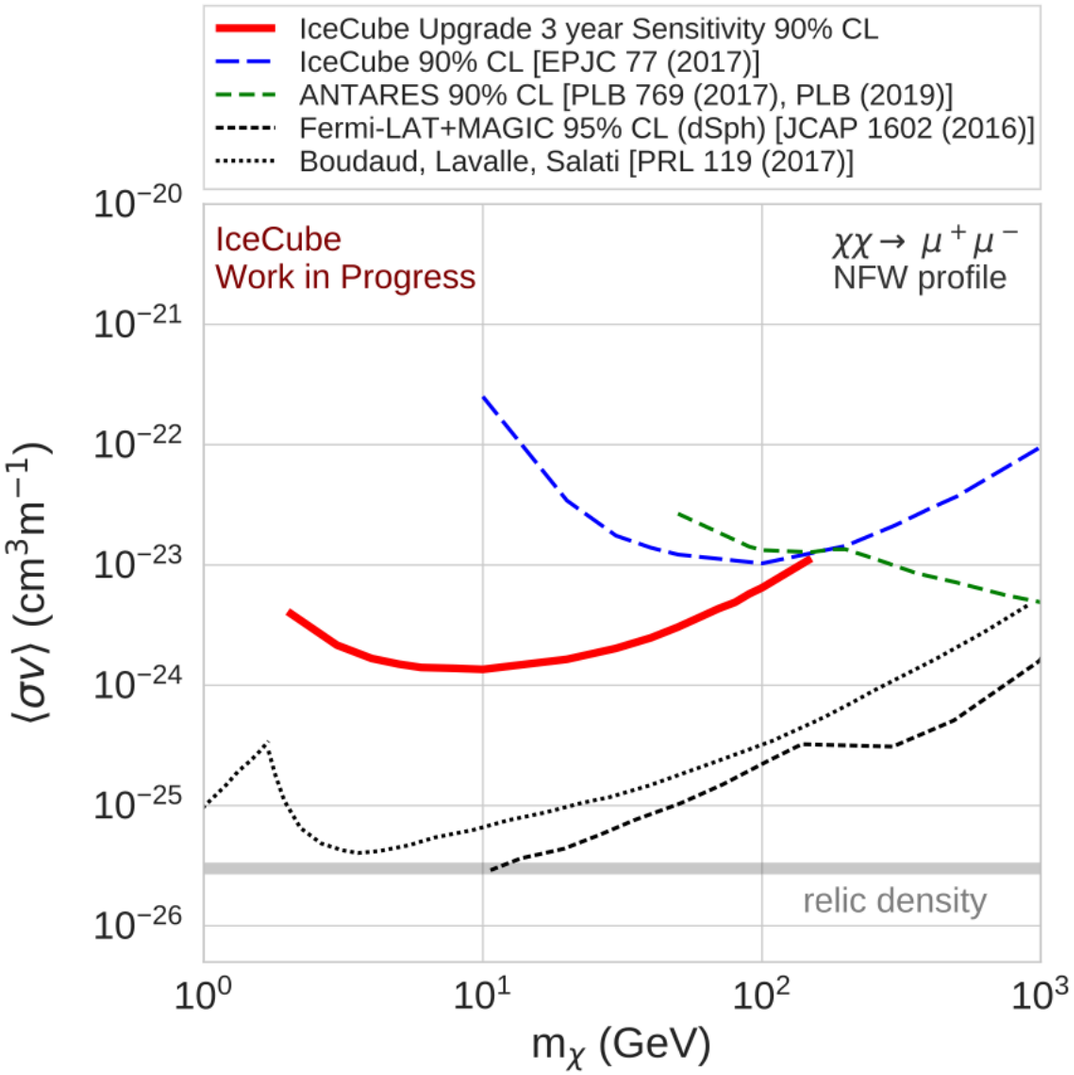
[2] M. A. Sanchez-Conde, *JCAP* **12** (2011) 011.

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

Sensitivities for IceCube-Upgrade

Sensitivities for IceCube-Upgrade





The IceCuba collaboration, PoS(ICRC2019)506