Indirect Searches for Dark Matter in the Centre of the Milky Way with the IceCube Neutrino Telescope

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Overview

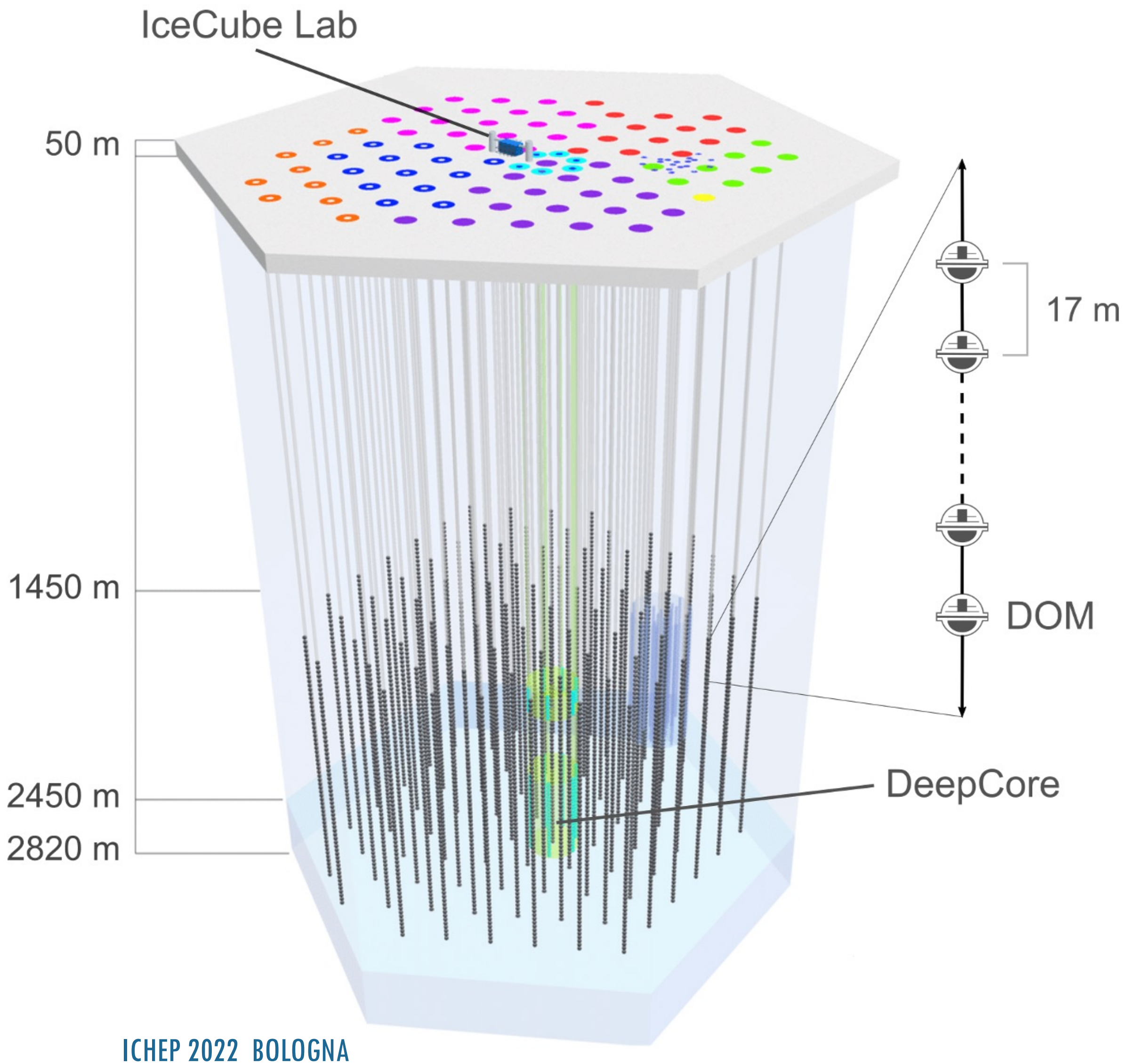
- **Search for neutrino lines from dark matter annihilation and decay with IceCube**

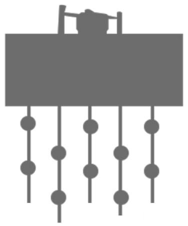
  Juan Antonio Aguilar, Chaïmae EL AISATI, Thomas Hambye and Michael Gustafsson

- **Low energy dark matter search with eight years of IceCube data**

  Nadege Iovine and Juan Antonio Aguilar

IceCube Neutrino Observatory

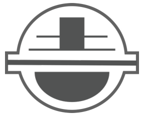




Detector located at the South Pole

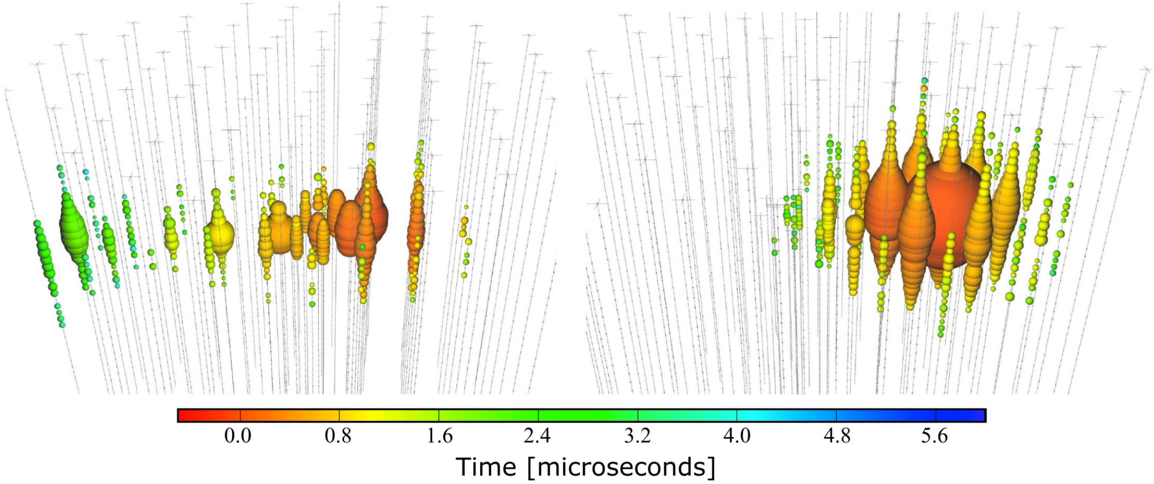
86 strings covering 1 km^3

→ Including 8 strings forming DeepCore



5,160 Digital Optical Modules DOMs

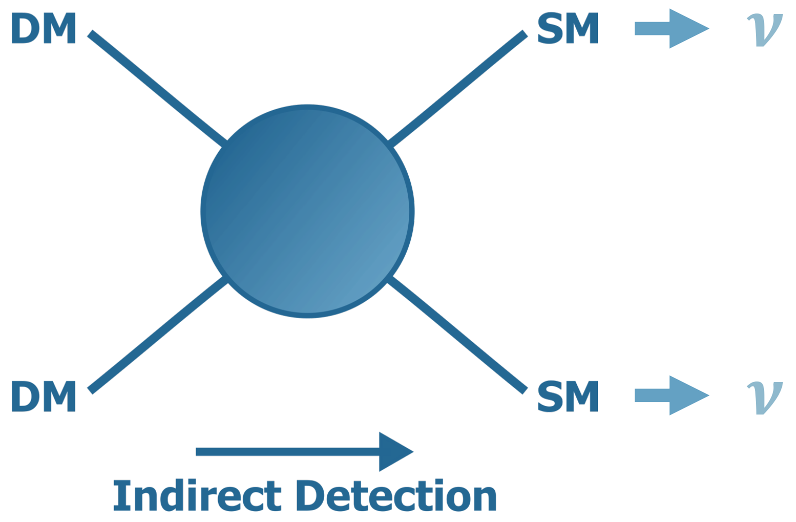
Track **Cascade**



Indirect Dark Matter Searches

Indirect search

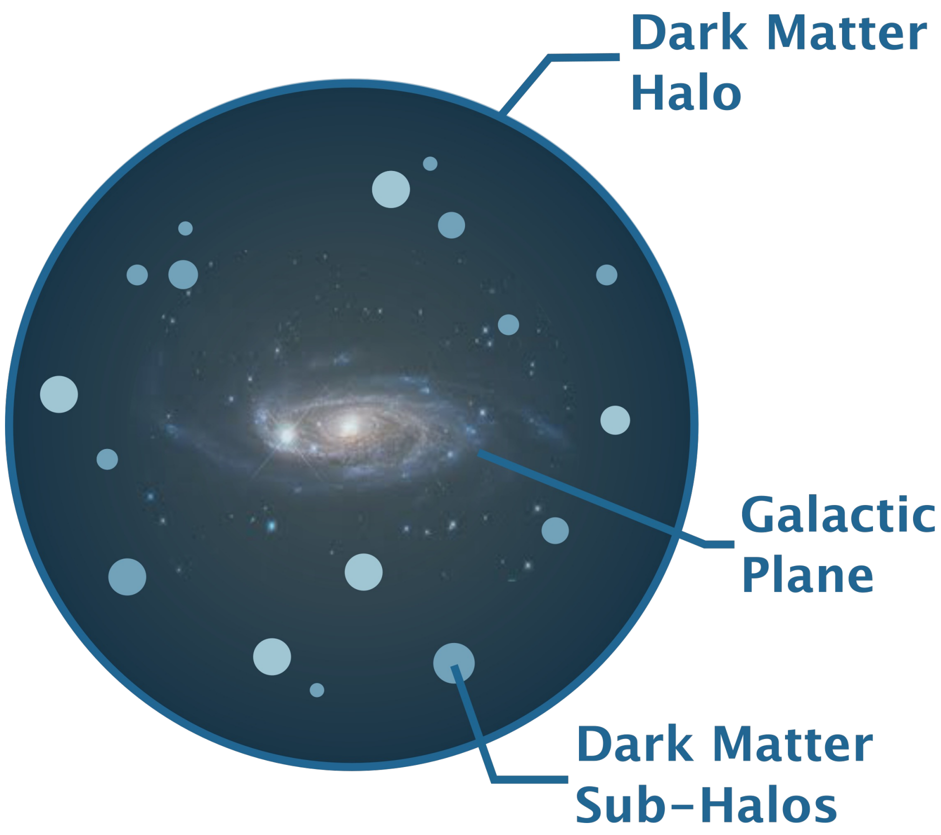
Look for SM particles from annihilation of dark matter particles



Dark matter halo

Milky Way immersed in dark matter halo

→ Highest DM density towards the Galactic Centre



Signal Expectations

Annihilation: $$\frac{\mathrm{d}\phi_\nu}{dE_\nu} = \frac{1}{4\pi}\,\frac{\langle\sigma_A v\rangle}{2\,m_\chi^2}\,\frac{dN_\nu}{dE_\nu}\int_0^{\Delta\Omega} d\Omega \int_{l.o.s}\rho_\chi^2(r(s,\Psi,\theta))ds$$

Decay: $$\frac{\mathrm{d}\phi_\nu}{dE_\nu} = \frac{1}{4\pi}\,\frac{1}{\tau_\chi m_\chi}\,\frac{dN_\nu}{dE_\nu}\int_0^{\Delta\Omega} d\Omega \int_{l.o.s}\rho_\chi(r(s,\Psi,\theta))ds$$

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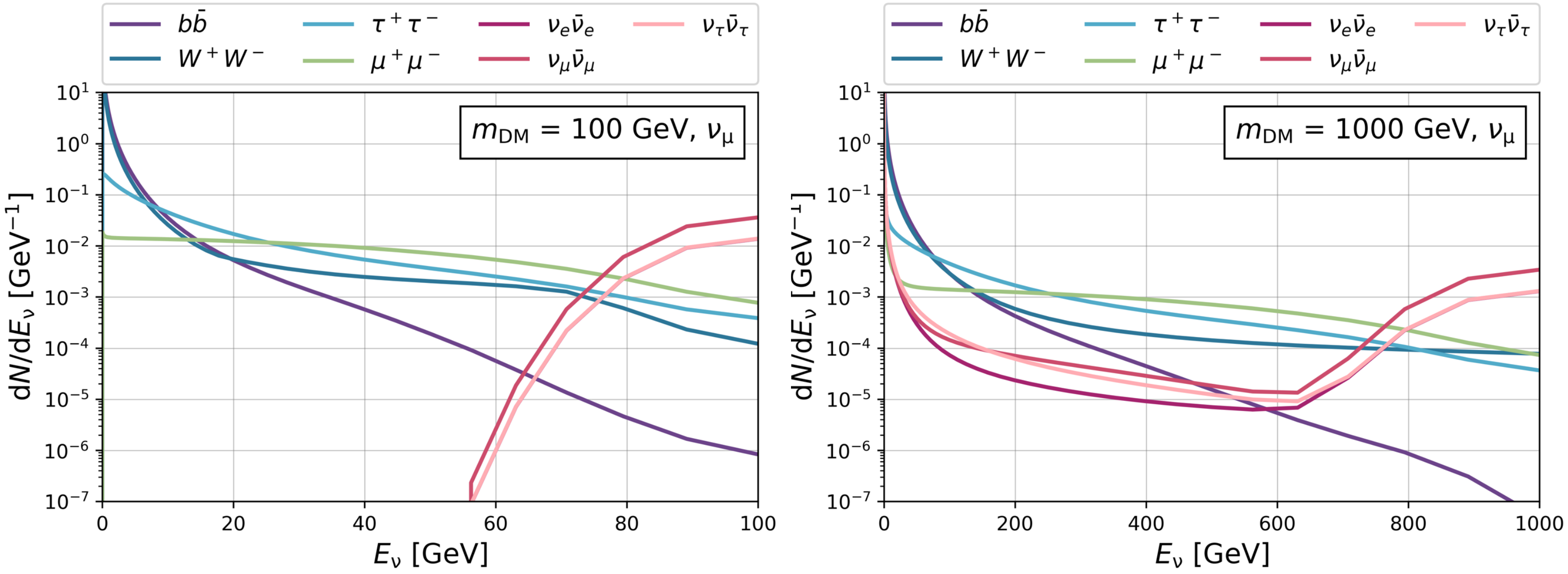
Particle physics inputs

- Dark matter mass
- Neutrino spectra

PPPC4 spectra
from [arXiv:1012.4515]



Signal Expectations

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Astrophysics inputs

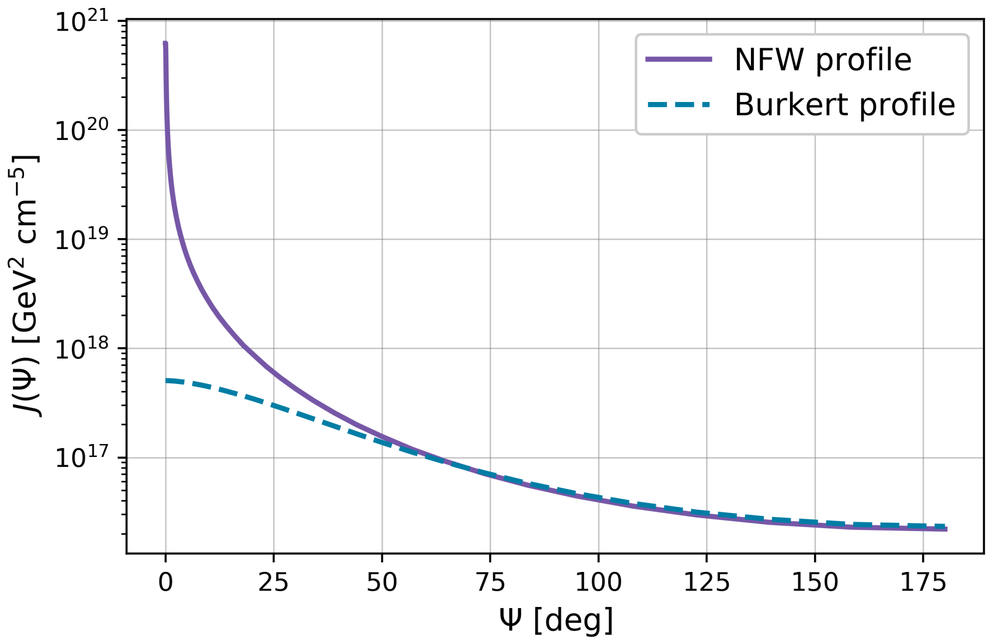
J-factor (DM annihilation) and **D-factor** (DM decay)

→ 2 density profiles evaluated: NFW and Burkert

→ Parameters values taken from [arxiv:1304.5127]

$$\rho_{NFW}(r) = \frac{\rho_0}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

$$\rho_{Burkert}(r) = \frac{\rho_0}{\left(1+\frac{r}{r_s}\right)\left(1+\left(\frac{r}{r_s}\right)^2\right)}$$



Search for neutrino lines from dark matter annihilation and decay with IceCube

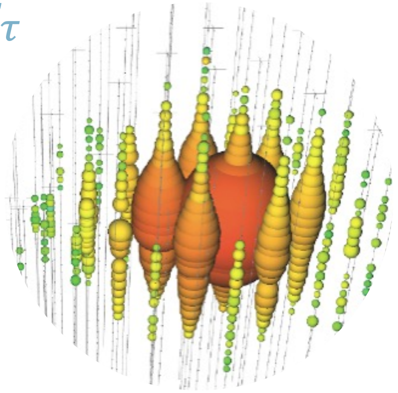
Event Selection

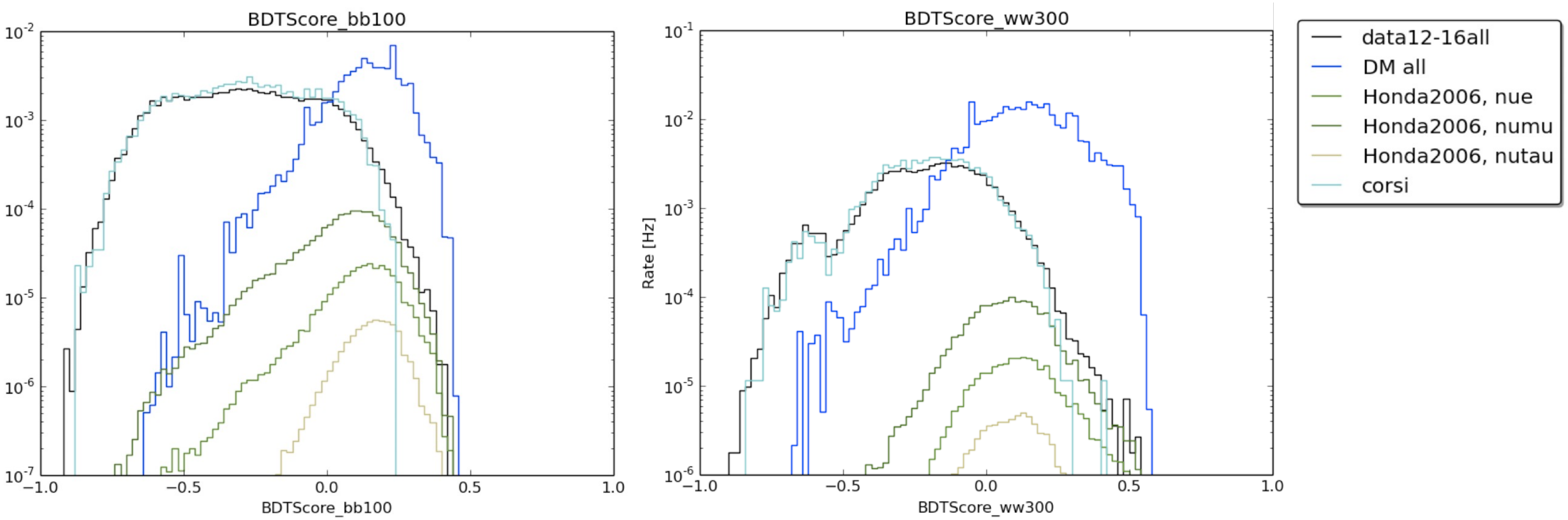
- **5 years** of **IceCube data** from 2012 to 2016
  → **DeepCore data** focusing on **cascade events**
- **Boosted Decision Trees** used to optimise selection
  - **LE sample:** soft spectra - $b\bar{b}$ 100 GeV
  - **HE sample:** harder spectra - W^+W^- 300 GeV

Cascade Events

CC ν_e & ν_τ

NC all ν

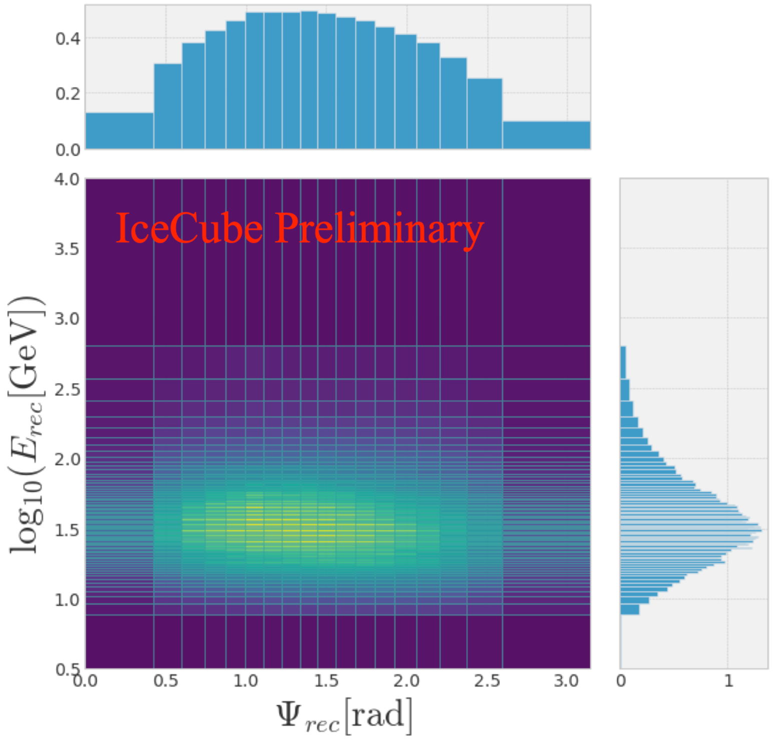




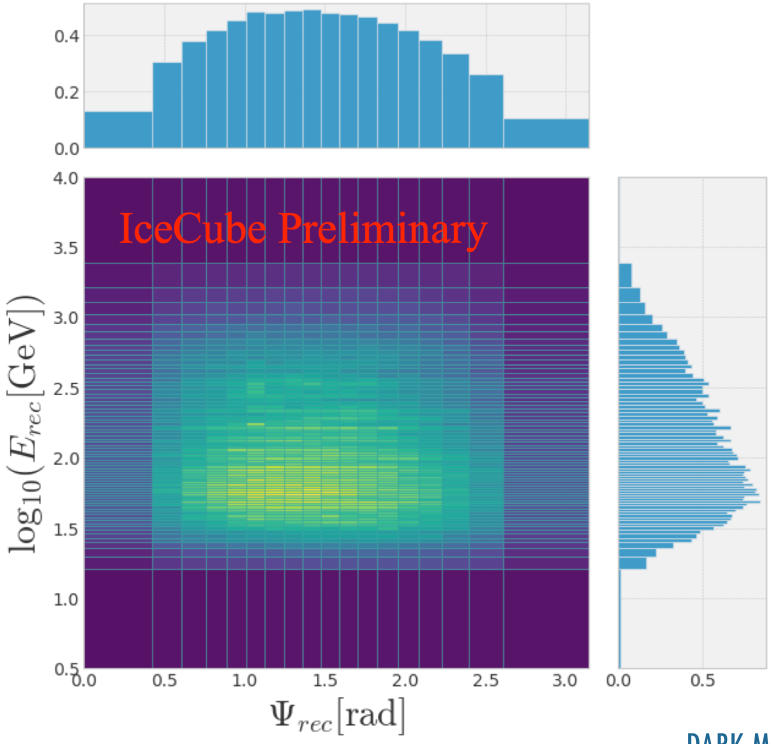
Background PDFs

- PDF built from **data scrambled in right ascension (RA)**
- Histogram built with **irregular binning**
  → **Quantile binning** [physt]

LE sample



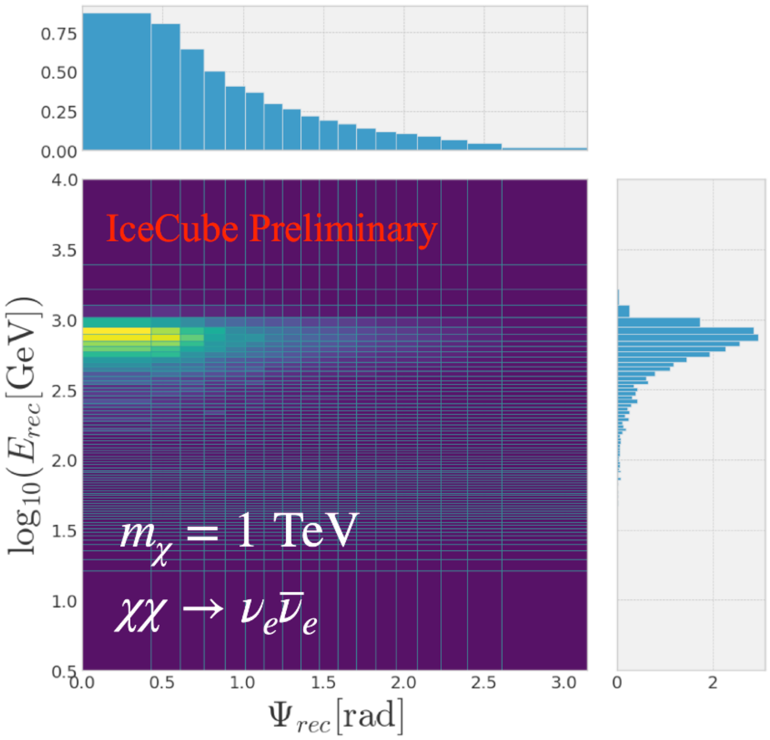
HE sample



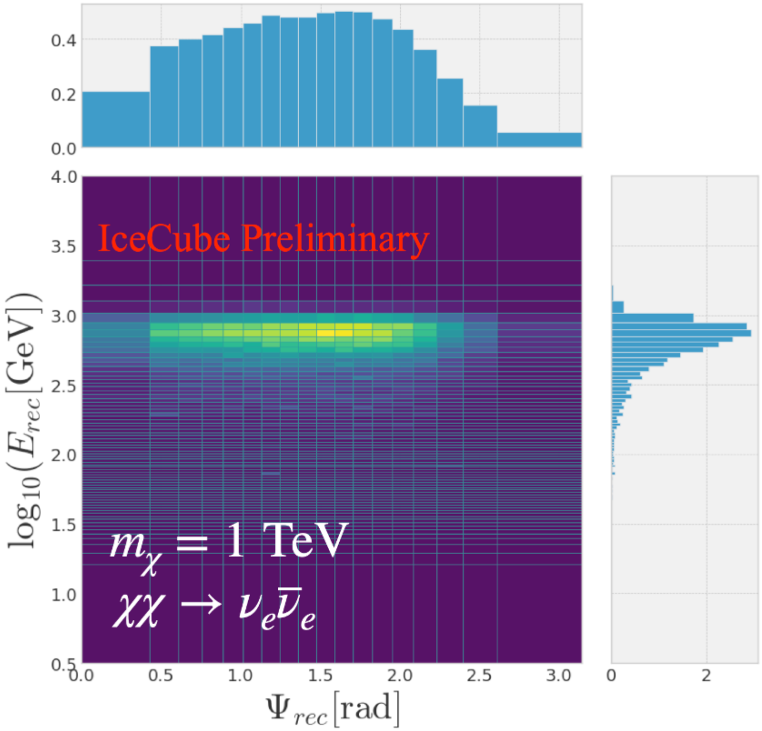
Signal PDFs

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

HE sample



Scrambled



Binned Likelihood Method

Likelihood formulations

$$\mathcal{L}_{\text{Poisson}}(\mu) = \prod_i \text{Poisson}\left(\text{n}^i_{\text{obs}}\,;\text{n}_{\text{tot}}\,f(\text{i};\mu)\right)$$

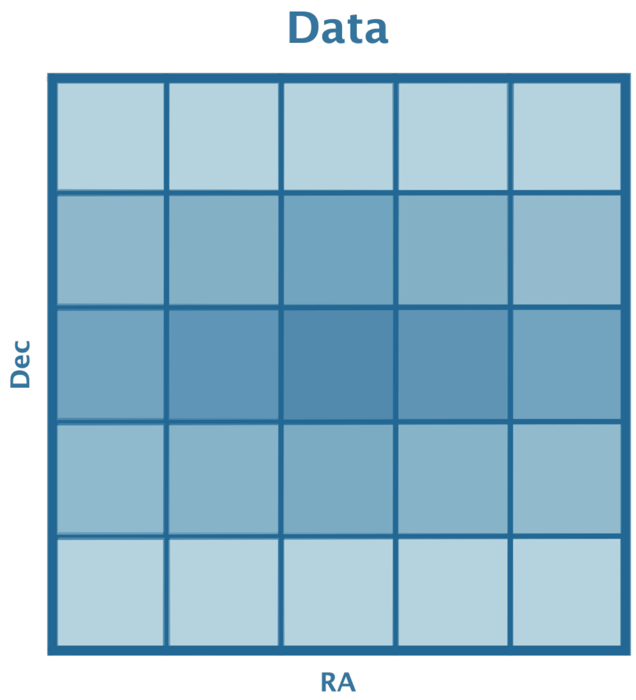
where $\mu = n_{\text{sig}}/n_{\text{tot}}$ is the **signal fraction** and

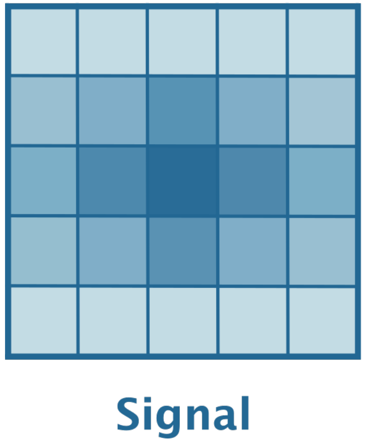
$$f(i\,;\mu) = \mu\,f_{sig}(i) + (1-\mu)\,f_{BG}(i)$$

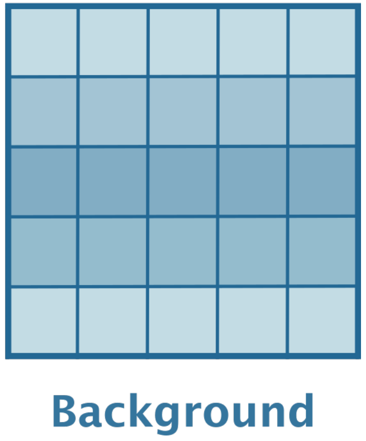
Signal subtraction

$$f_{BG} = \frac{1}{(1-\mu)}\left(f_{scr.data} - \mu\,f_{scr.\,sig}\right)$$

$$\Rightarrow\; f(i\,;\mu) = \mu\,f_{sig}(i) + f_{scr.data}(i) - \mu\,f_{scr.\,sig}(i)$$



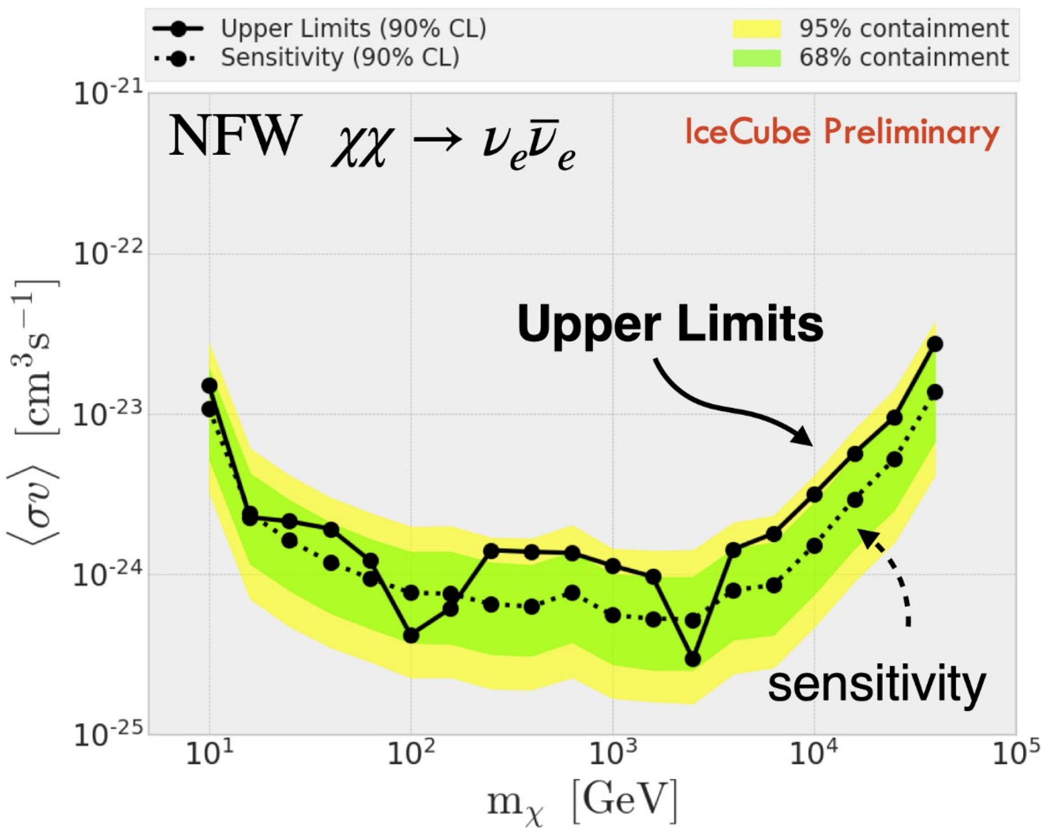


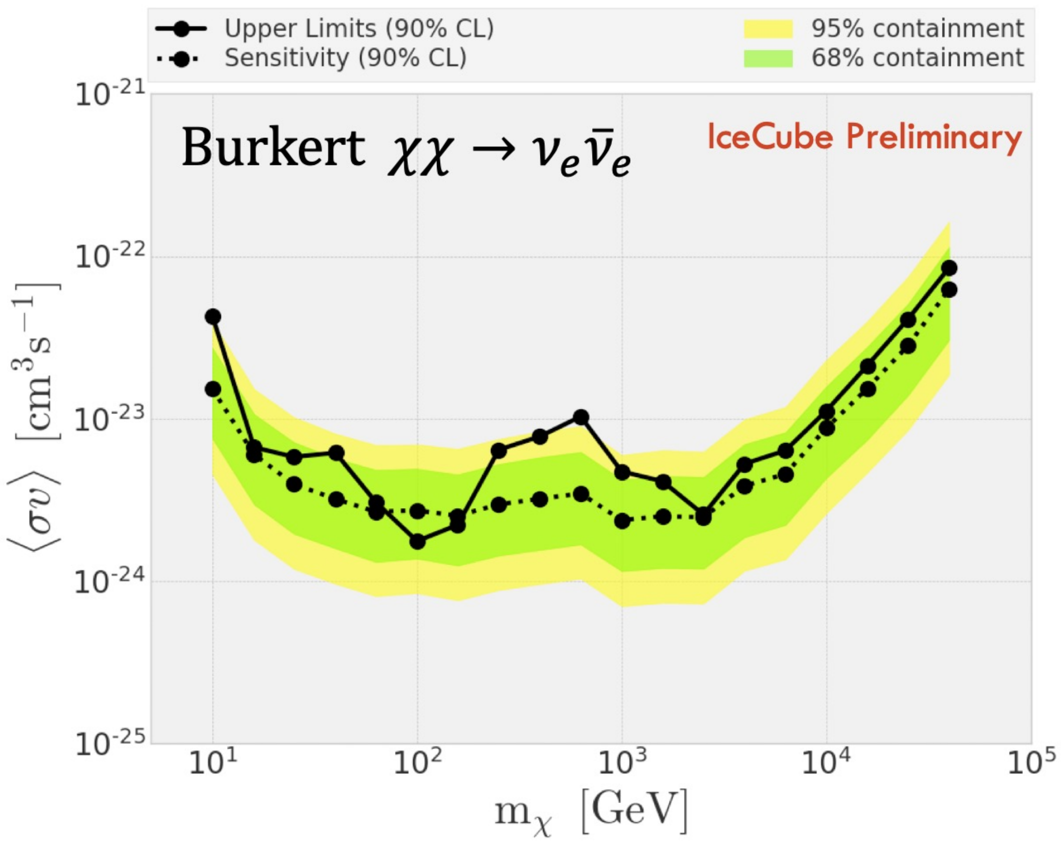


Results: DM Annihilation

90% CL limit (solid) and **90% CL median limit** (dotted) in terms of $\langle \sigma_A v \rangle$

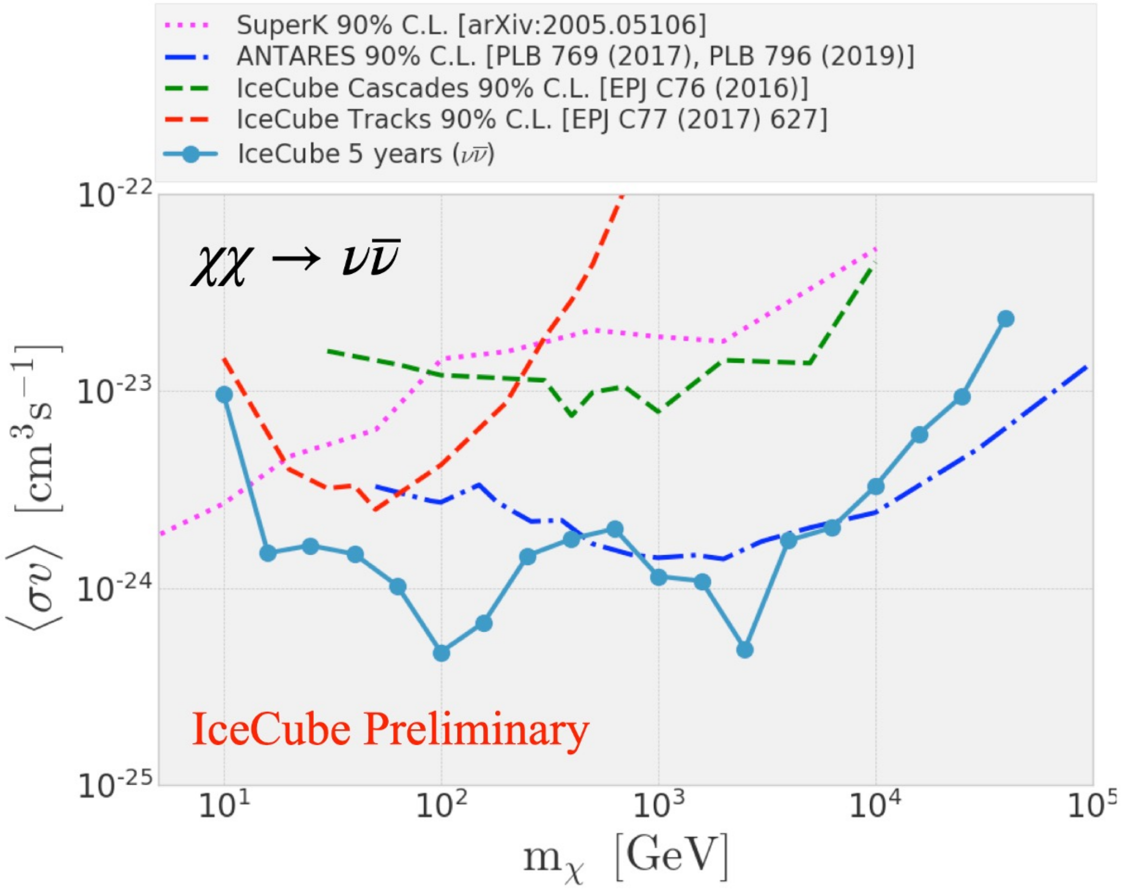
→ For DM annihilation into the $\nu_e \bar{\nu}_e$ channel

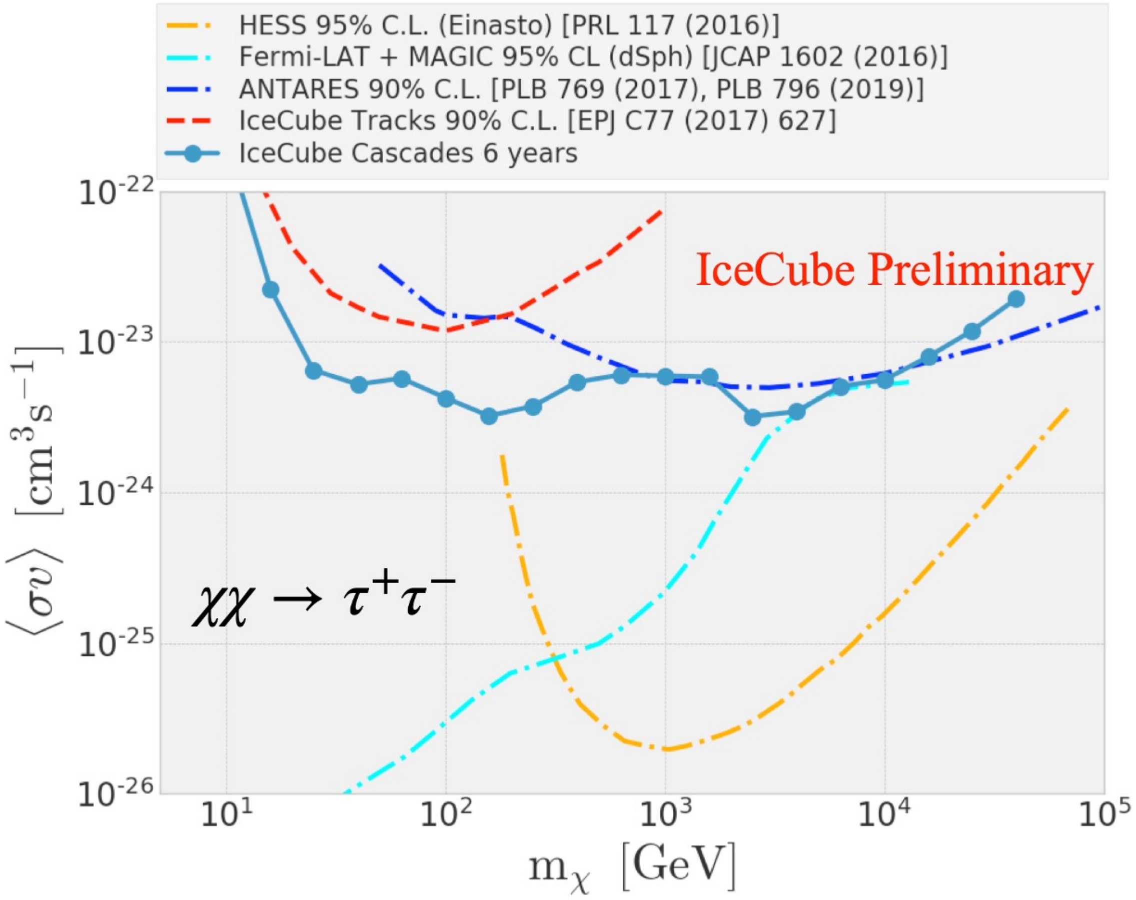




Comparison: DM Annihilation

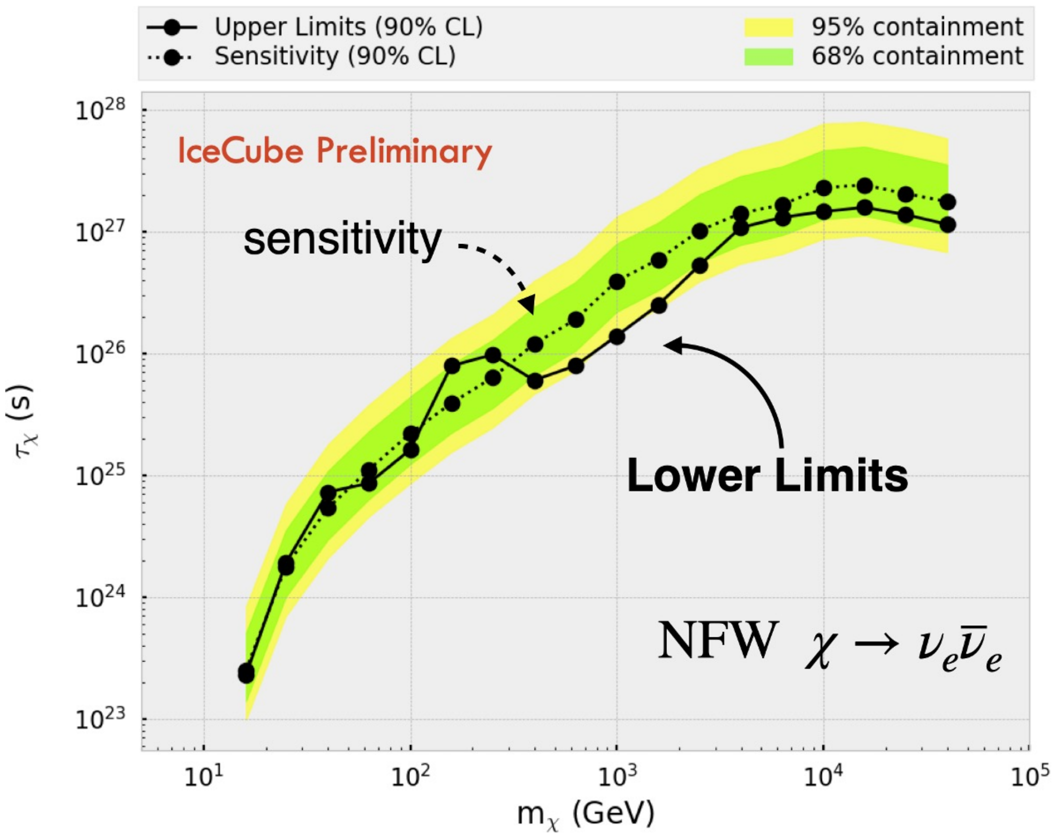
Comparison of **90% CL limits** in terms of $\langle \sigma_A v \rangle$ for $\nu\bar{\nu}$ and $\tau^+\tau^-$

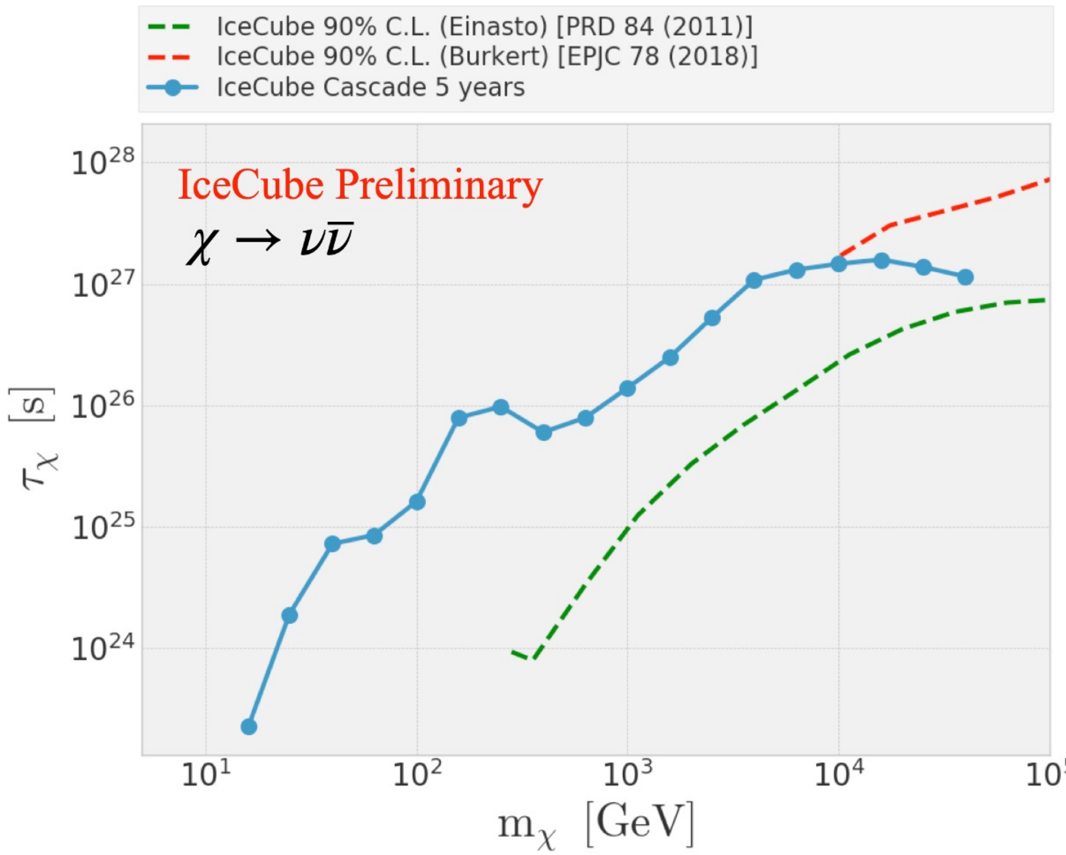




Results: DM Decay

90% CL limit (solid) and **90% CL median limit** (dotted) in terms of τ_χ





Low energy dark matter search with eight years of IceCube data

Event Selection

Low energy event selection (oscNext)

- **8.03 years** of IceCube data from 2012 to 2020
- **DeepCore data** with **all three neutrino flavours**

3-dimensional PDFs

→ Angular information: Ψ_{reco}

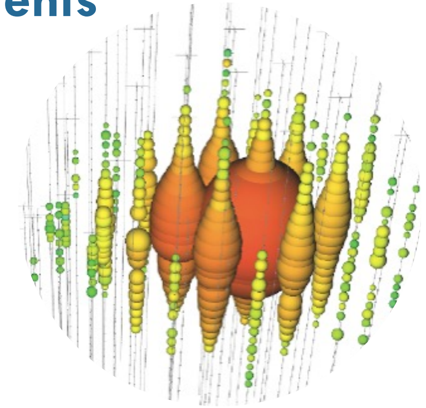
→ Energy: $\log_{10}(E_{reco})$

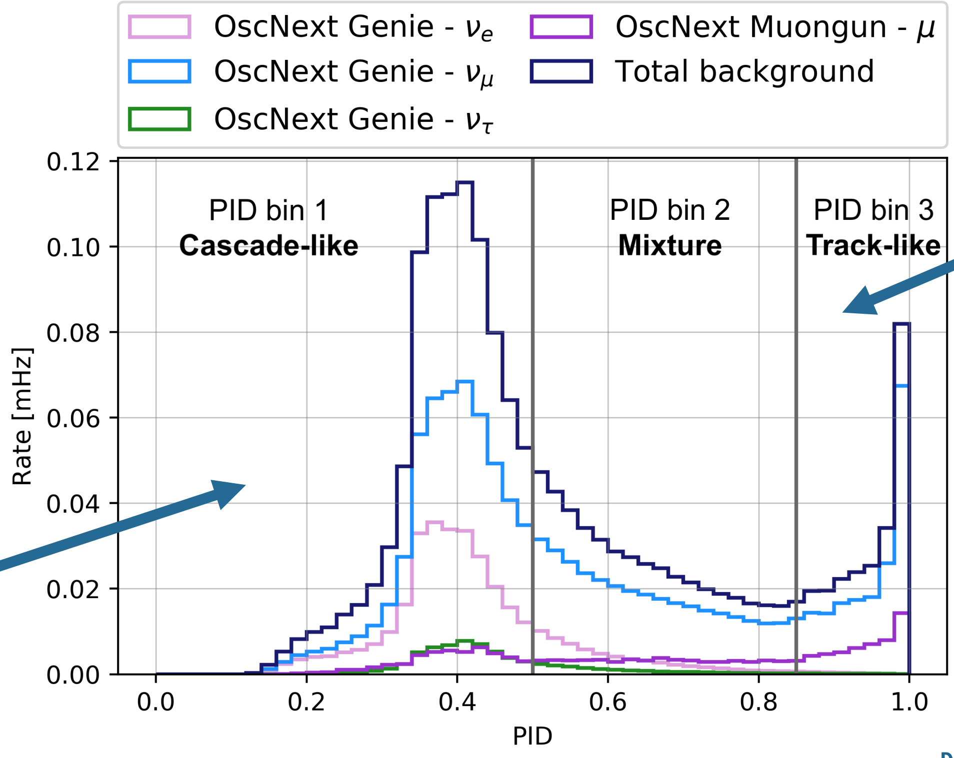
→ Event topology: **Particle ID (PID)**

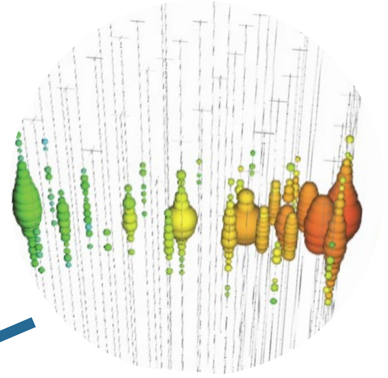
Cascade Events

CC ν_e & ν_τ

NC all ν







Track events

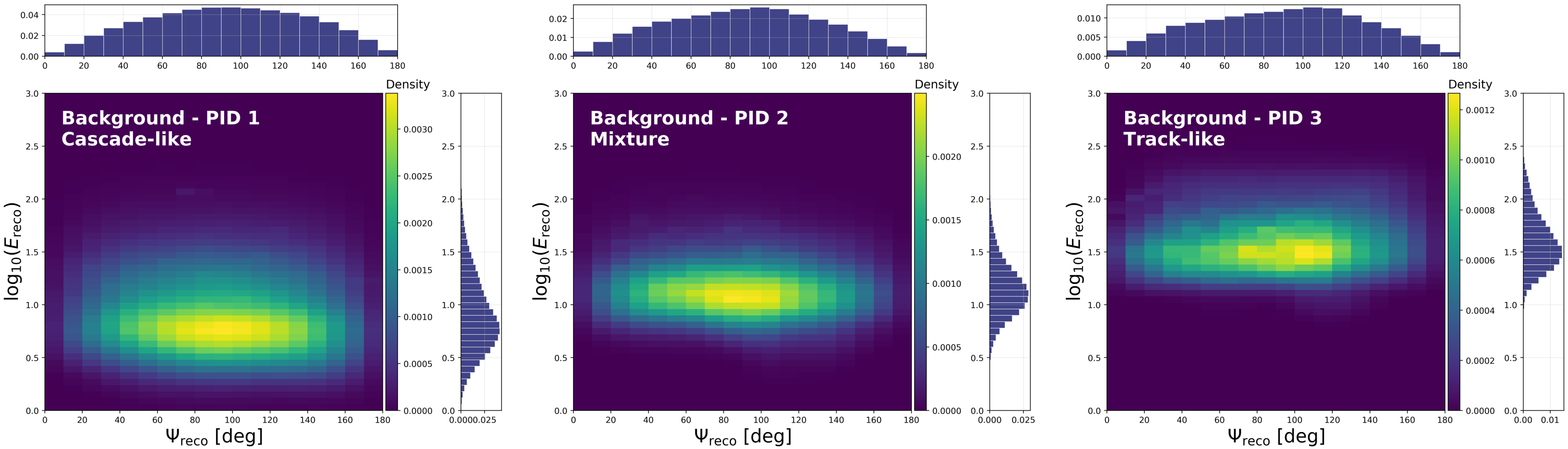
CC ν_μ

Background PDF

- PDF built from **MC neutrino and muon simulations**

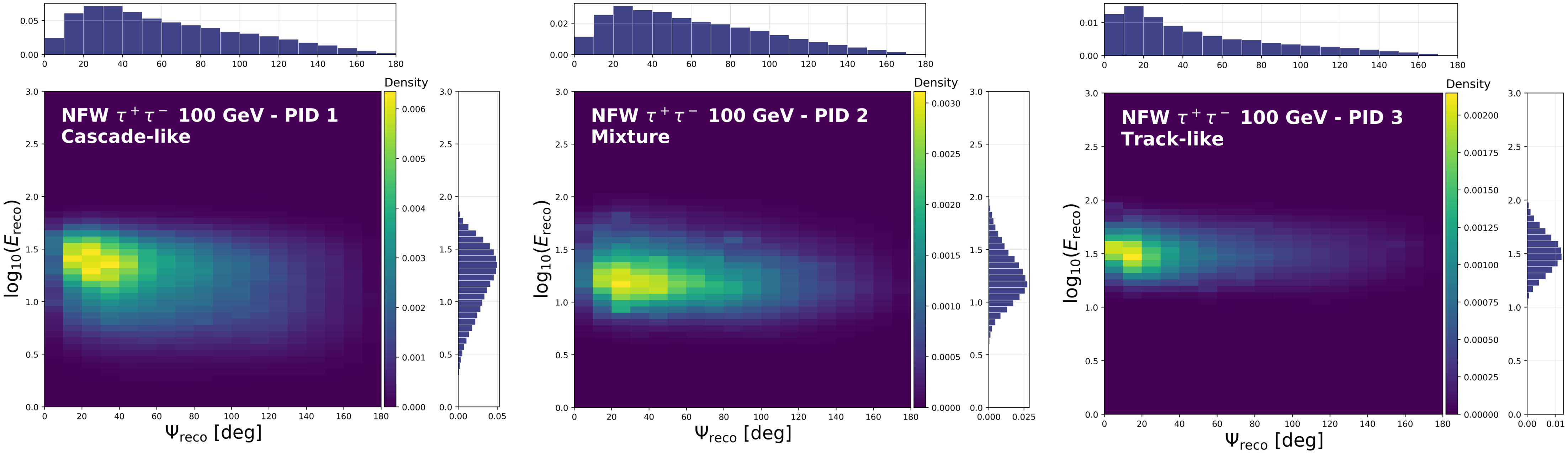
  → Weighted according to **atmospheric flux**

- PDF smoothed using **Kernel Density Estimation (KDE)**



Signal PDFs

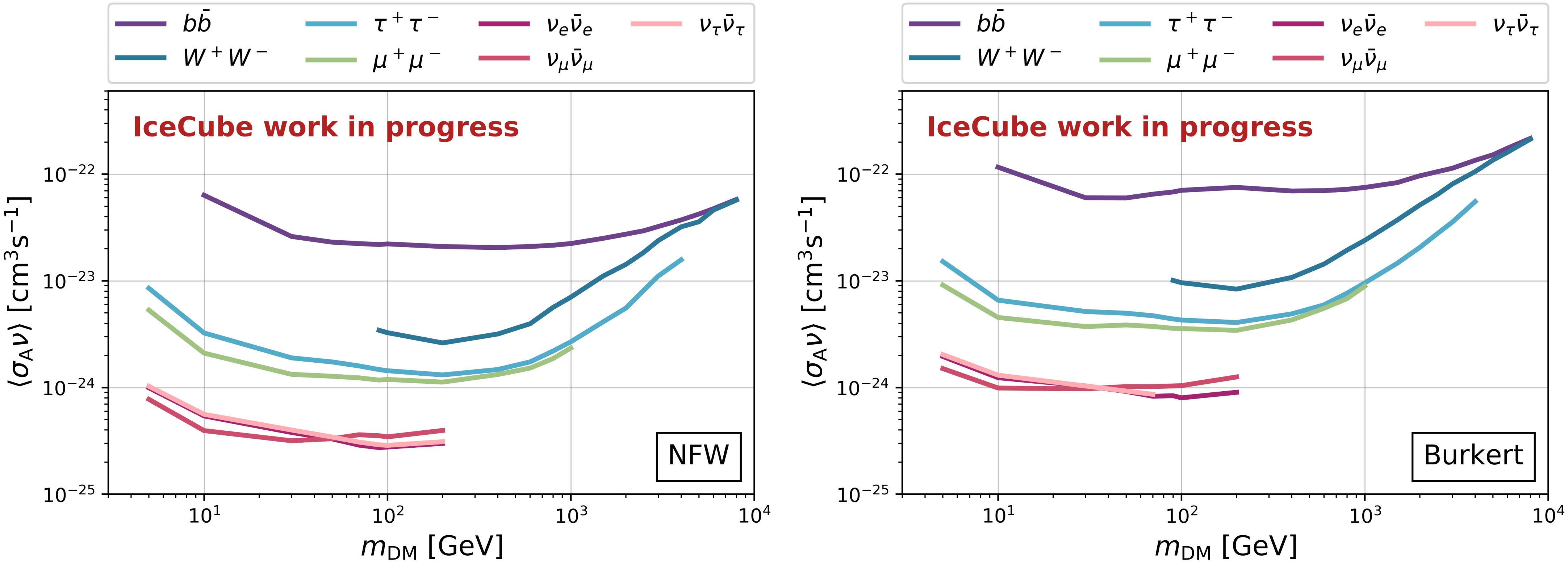
- Monte Carlo neutrino simulations weighted with
  - **PPPC4 spectra:** DM masses beteween 5 GeV and 8 TeV
    DM annihilation through $\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, W^+W^-, \tau^+\tau^-, \mu^+\mu^-, b\bar{b}$
  - **Source morphology:** NFW and Burkert halo profiles



Sensitivities

90% CL median limit on the thermally-averaged self-annihilation cross section $\langle \sigma_A v \rangle$

→ For all considered combinations of DM mass, annihilation channel and halo profile



Comparison to previous results

- **Orders of magnitude improvement** with respect to the previous published IceCube search [arXiv:1908.07300]

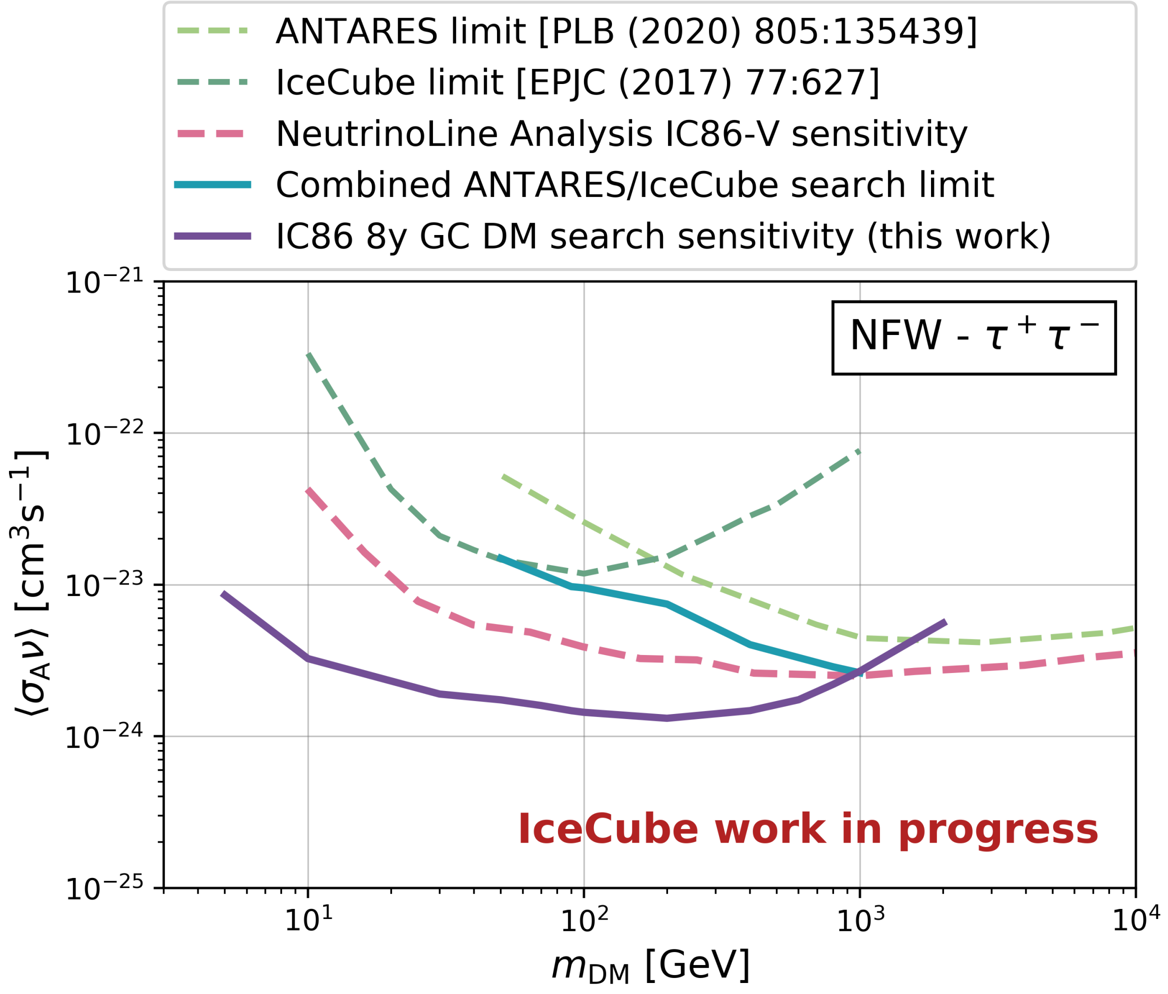
  → Up to factor 102.9 at 10 GeV

- **Leading sensitivities** from **neutrino experiments** for dark matter masses below **1 TeV**

Outlooks:

- **Unblinding** in the near future

  → Analysis taken over by **Nhan Chau**



Conclusion and outlooks

Conclusion

Neutrino-line dark matter search

- Direct annihilation/decay to neutrinos can provide a smoking gun signature
  → No astrophysical background
- No evidence of dark matter from the 5 years DM search
- Best upper limit on $\langle \sigma_A v \rangle$ for the $\nu\bar{\nu}$ channel for masses $<$ 1TeV and best lower limits on the decay lifetime τ_χ

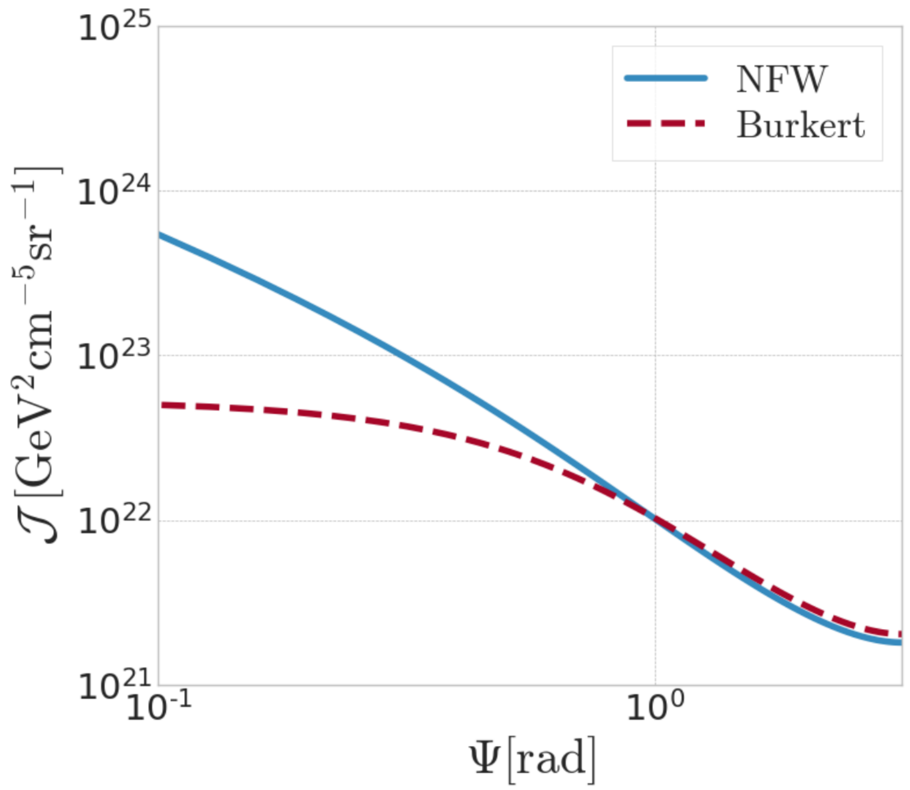
Low energy dark matter search with eight years of IceCube data

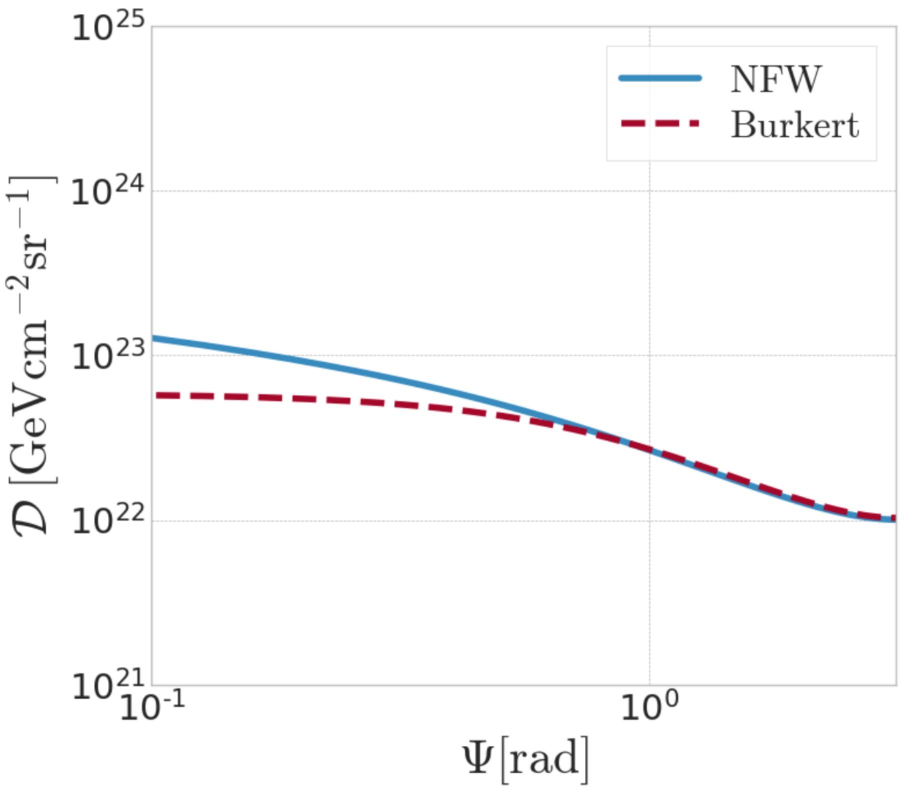
- Considerable improvement of the sensitivities with respect to previous IceCube results
- Leading sensitivities from neutrino experiments for dark matter masses $<$ 1 TeV

Backup Slides

J-factor and D-factor

$$\rho_{NFW}(r) = \frac{\rho_0}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2} \qquad \rho_{Burkert}(r) = \frac{\rho_0}{\left(1+\frac{r}{r_s}\right)\left(1+\left(\frac{r}{r_s}\right)^2\right)}$$



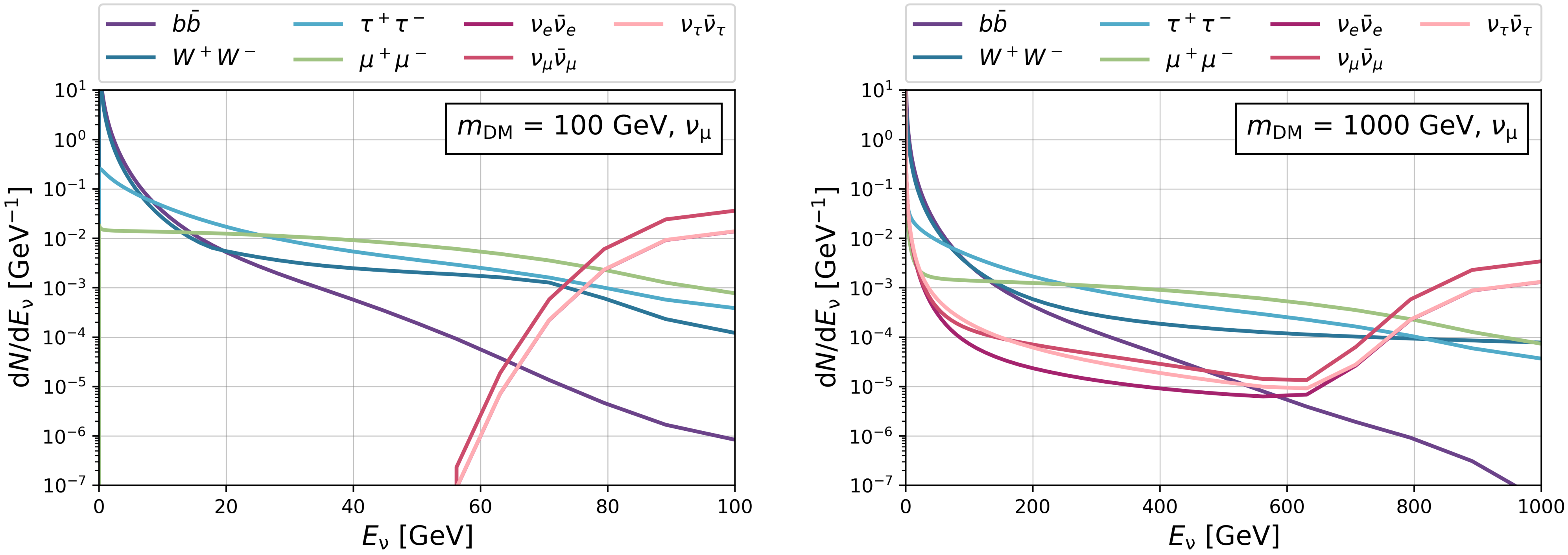


Neutrino spectra at Earth

PPPC4 spectra taken from [5]

DM channels: $\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, W^+W^-, \tau^+\tau^-, \mu^+\mu^-, b\bar{b}$

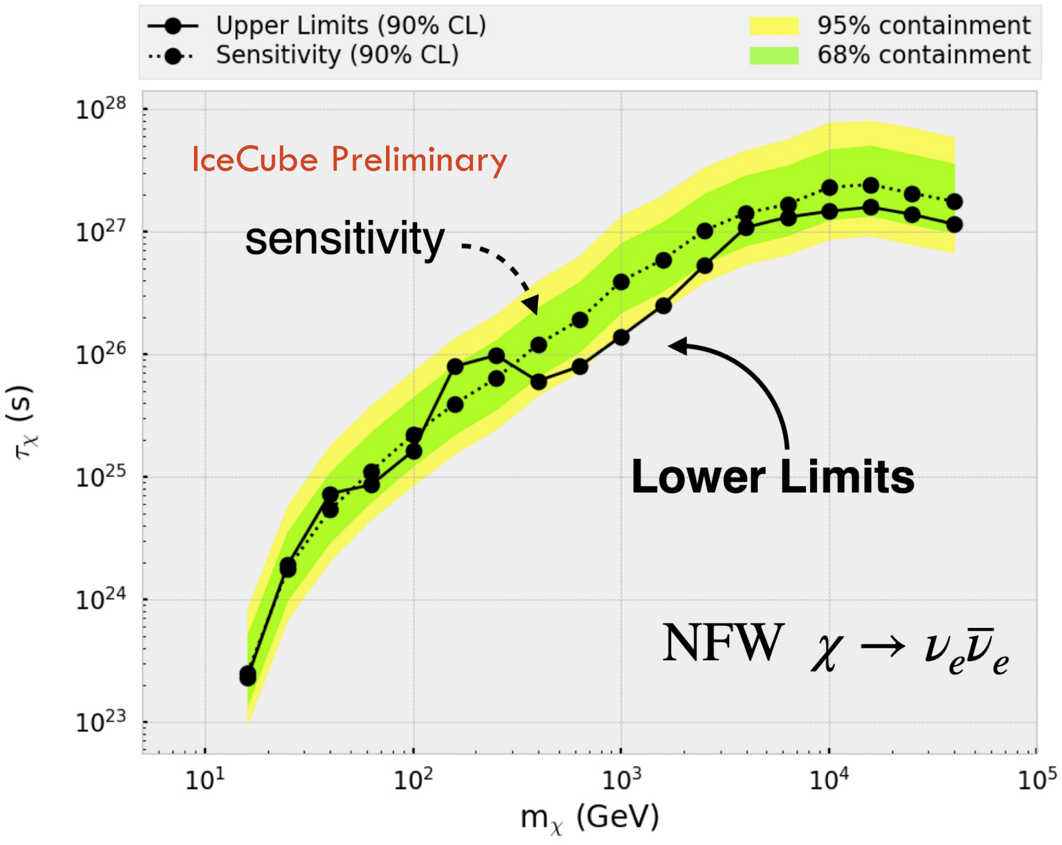
DM masses: Masses from 5 GeV to 8 TeV

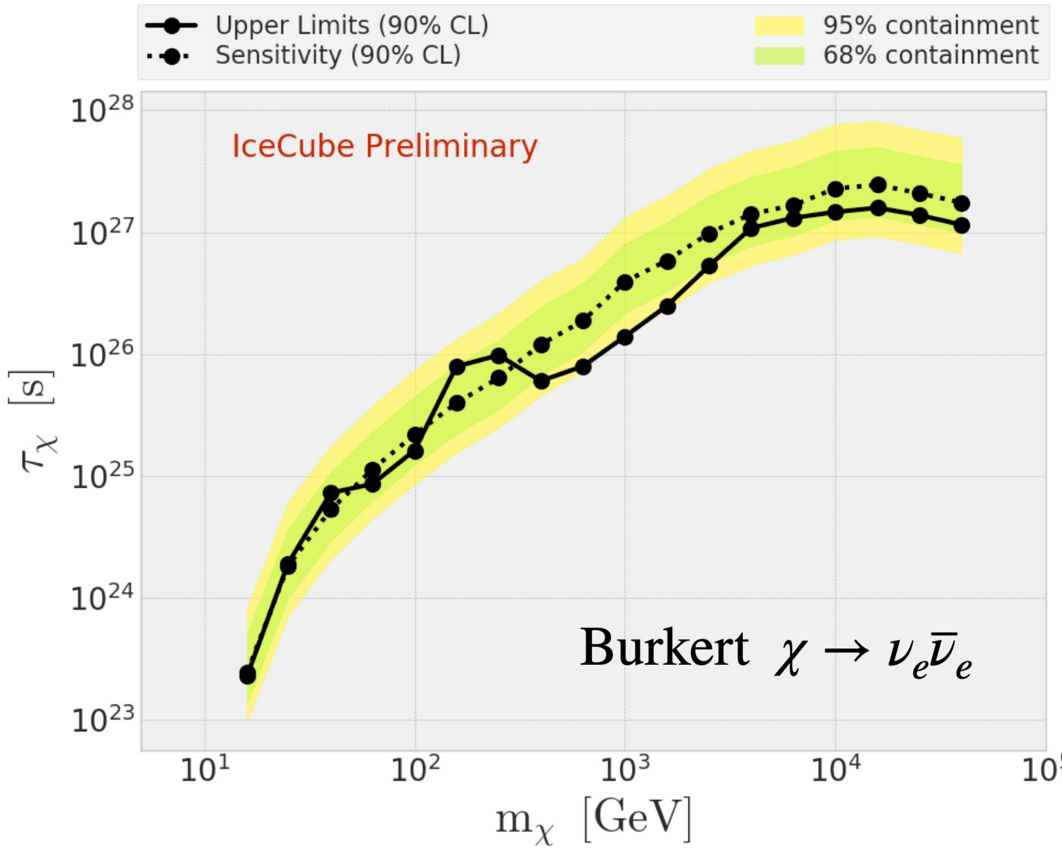


Results: DM Decay

90% CL limit (solid) and **90% CL median limit** (dotted) in terms of τ_χ

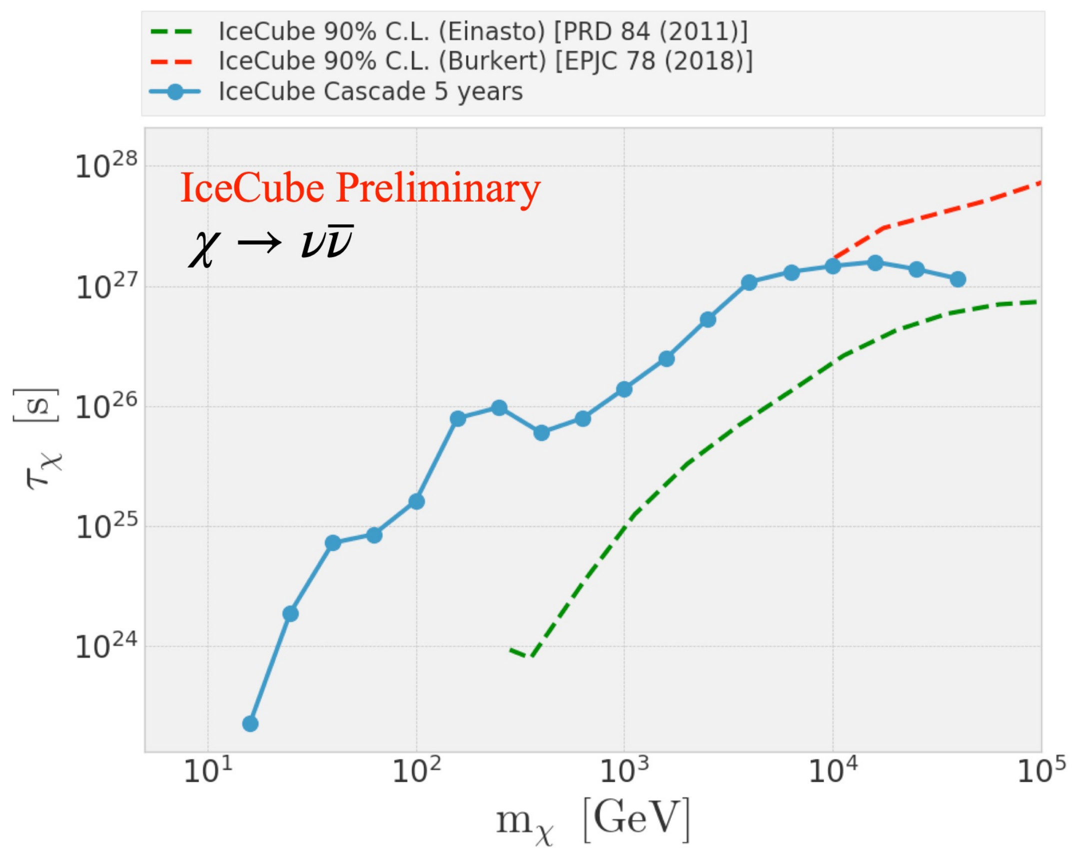
→ For DM annihilation into the $\nu_e \bar{\nu}_e$ channel

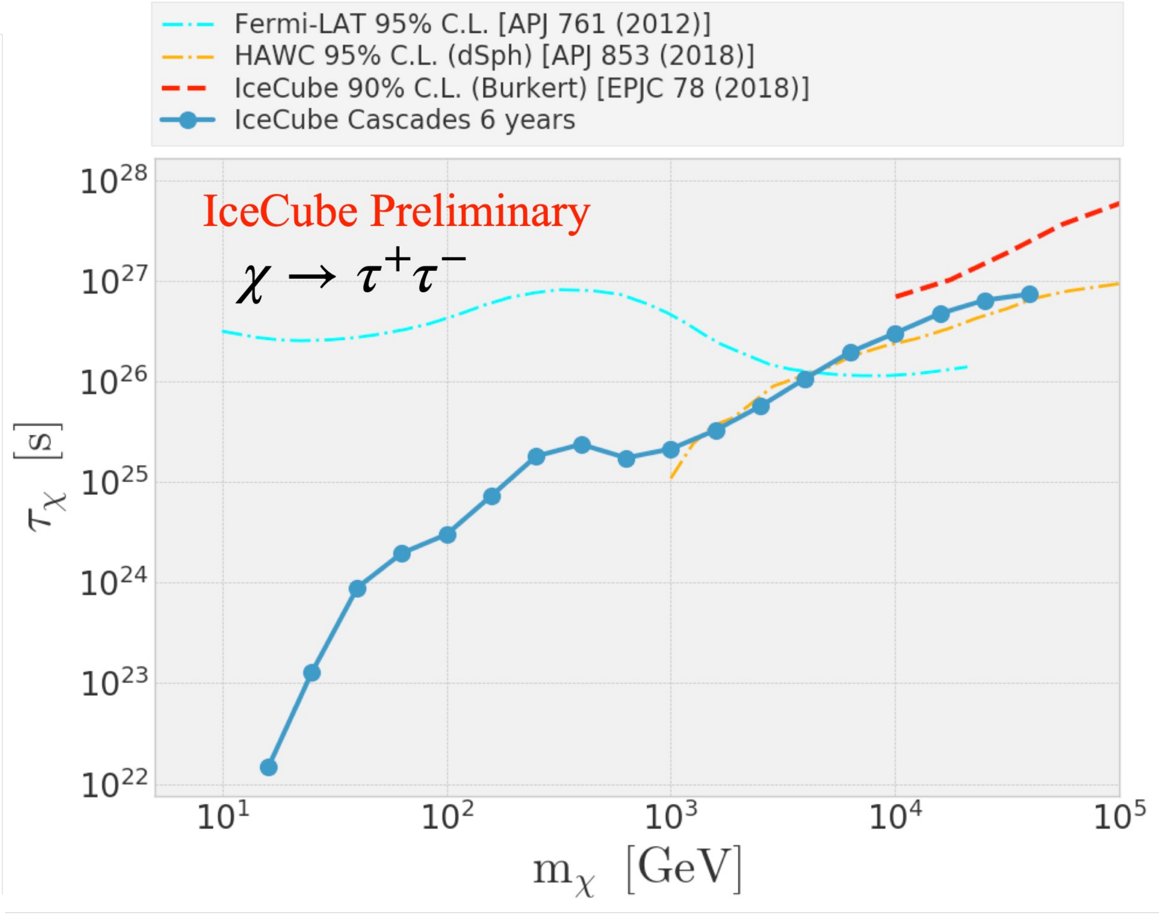




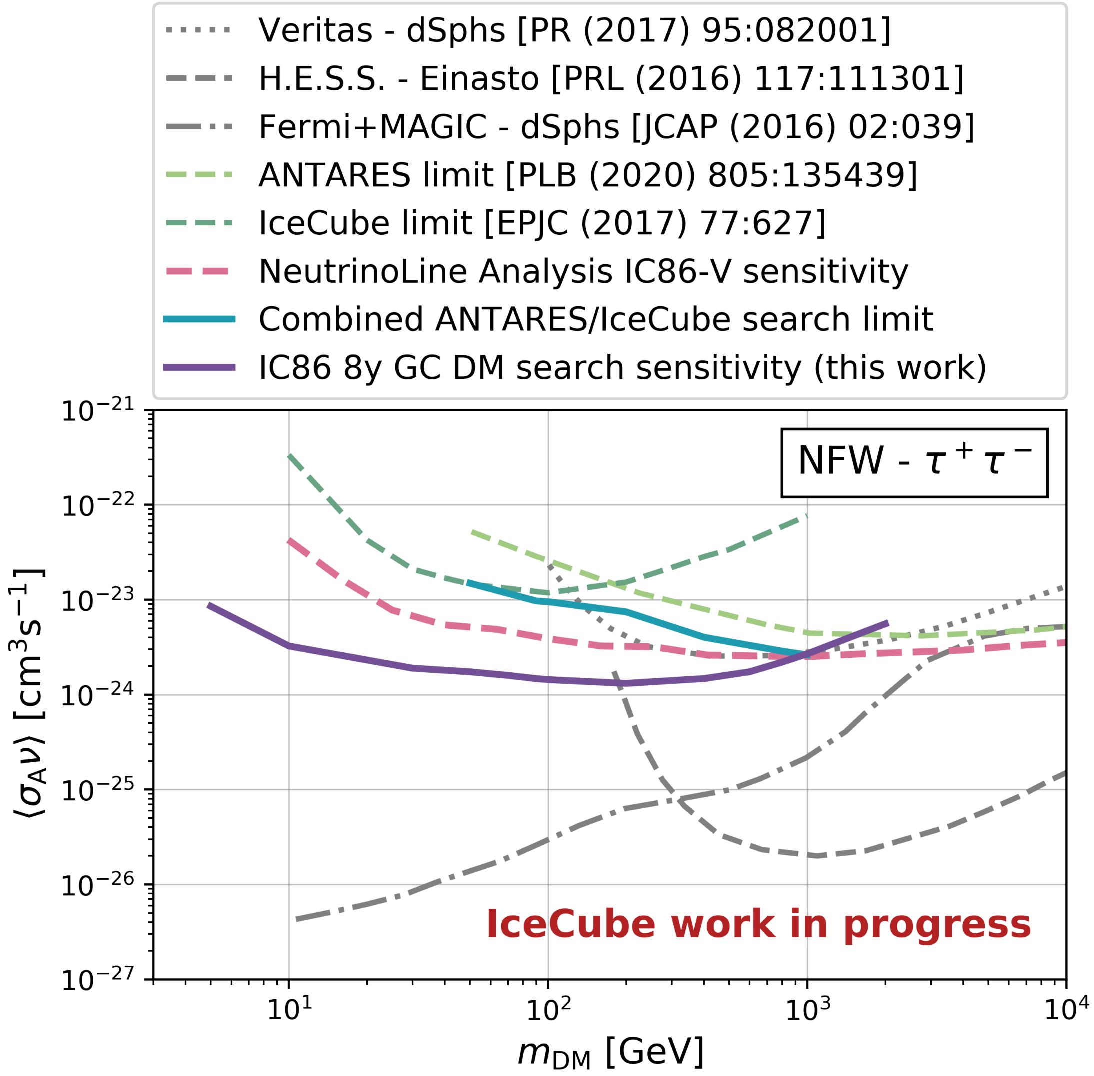
Comparison: DM Decay

90% CL limits in terms of the thermally-averaged self-annihilation cross-section τ_χ

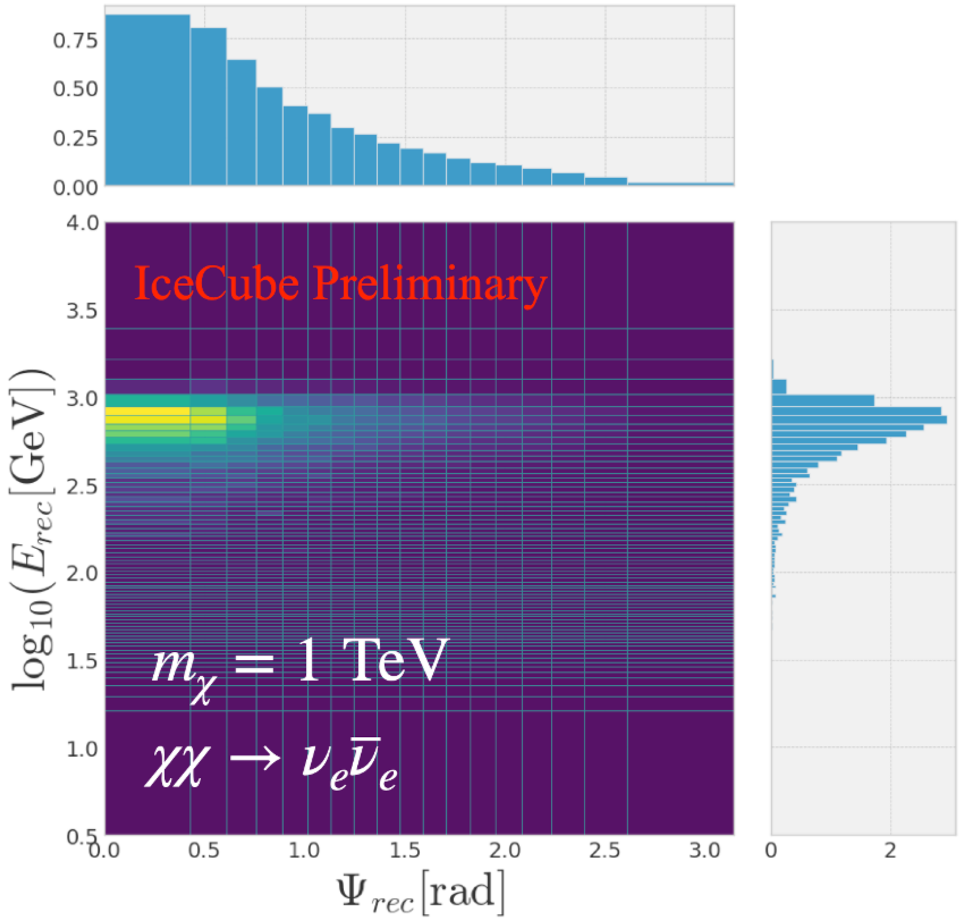


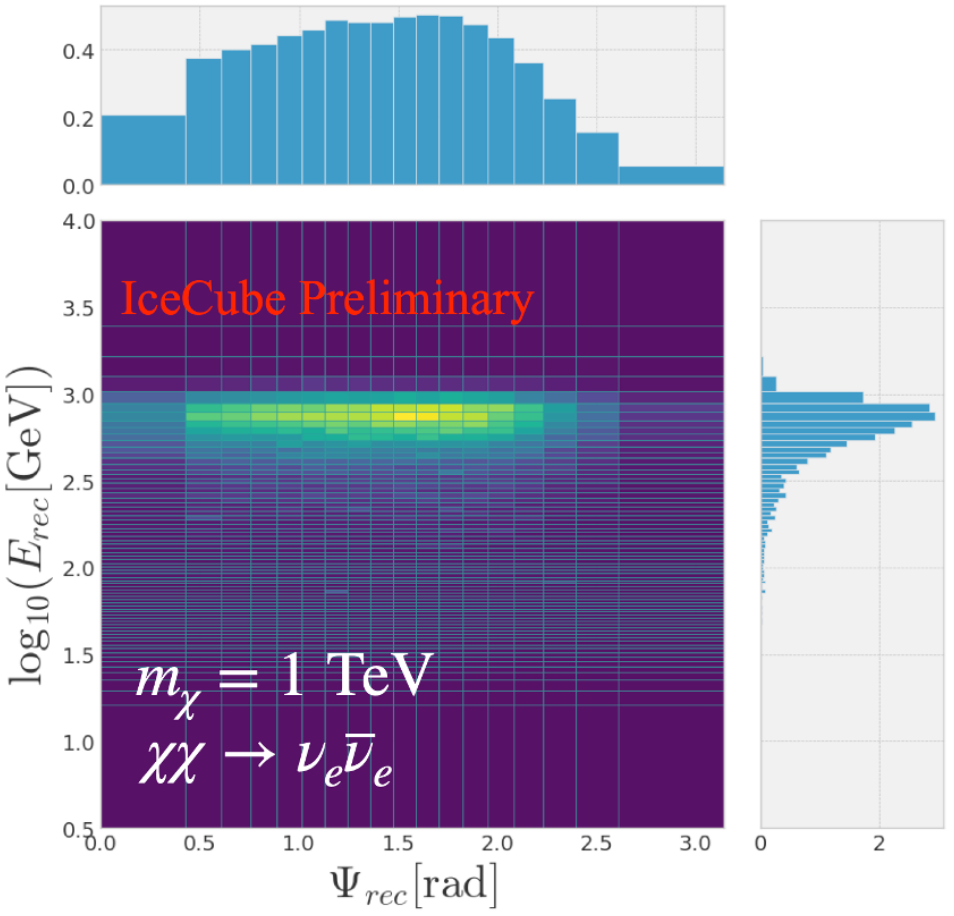


Comparison with γ-ray experiment limits



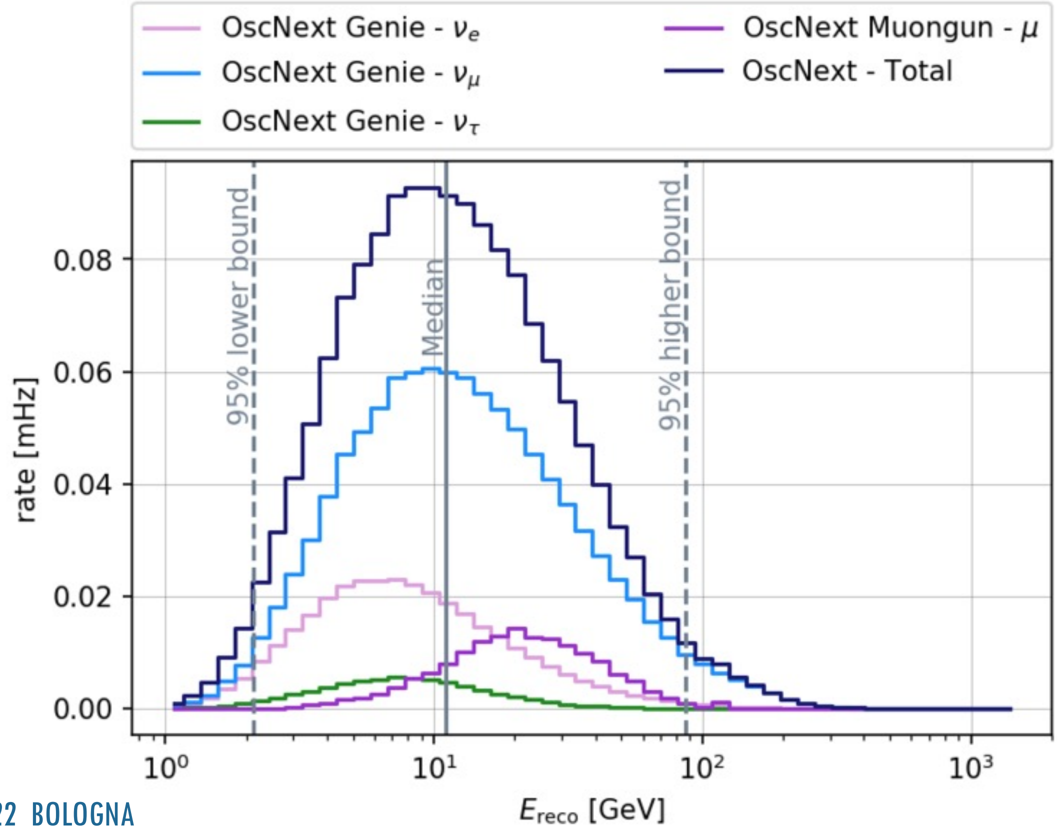
Scrambled Signal

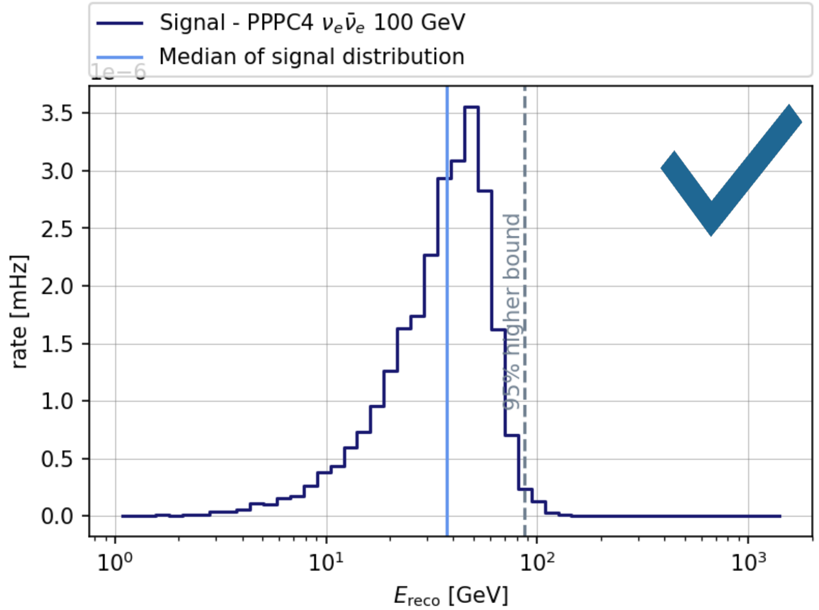


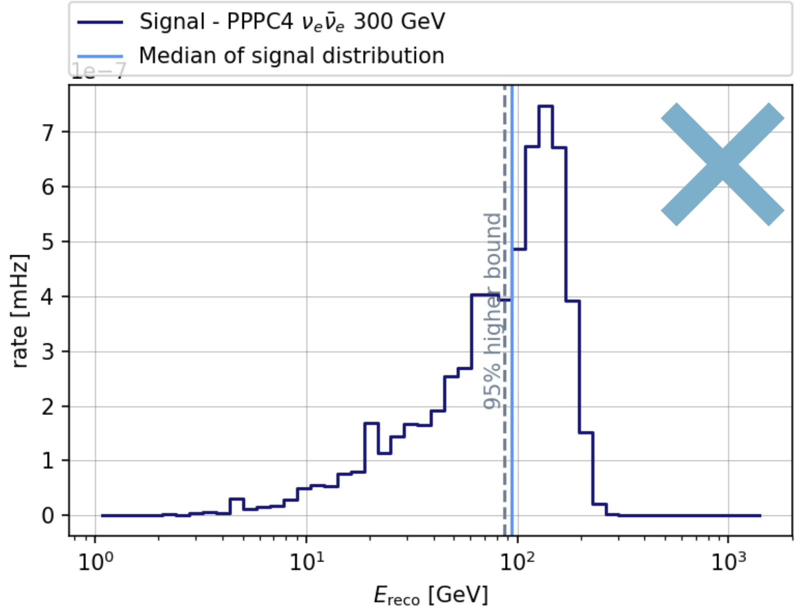


Scanned Masses

Only select masses where the **median** of the **signal expectation** is in the **95%** of the **energy response** of the detector.







Kernel Density Estimation

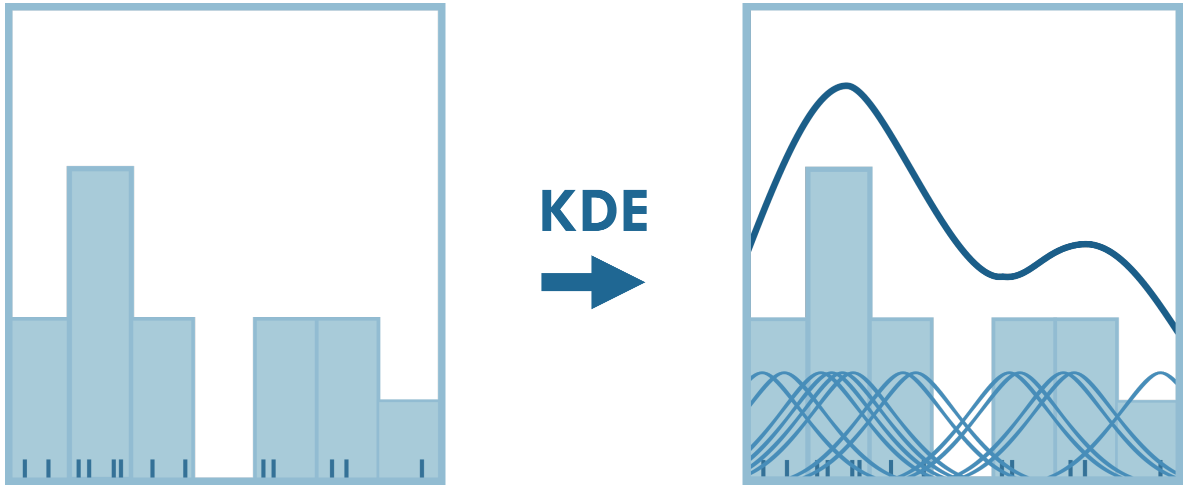
Kernel Density Estimation (KDE)

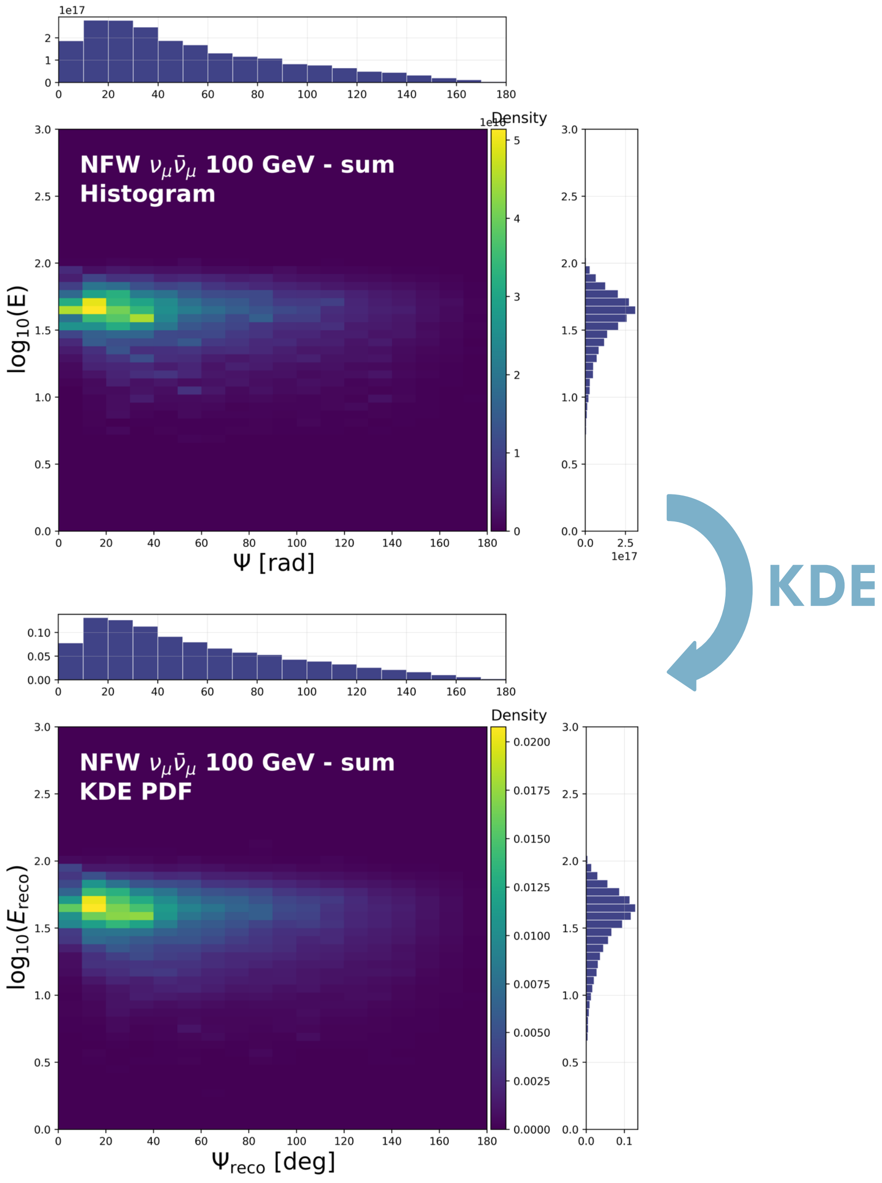
- Gaussian kernel
- **Bandwidth** selected with **cross-validation** method

KDE method built from **2D distributions**

→ Applied on $\log(\Psi_{reco})$- $\log_{10}(E_{reco})$ distributions

→ Done for **each PID bin**





Kernel Selection