Dark matter searches in the Galactic Center with IceCube DeepCore and IceCube Upgrade
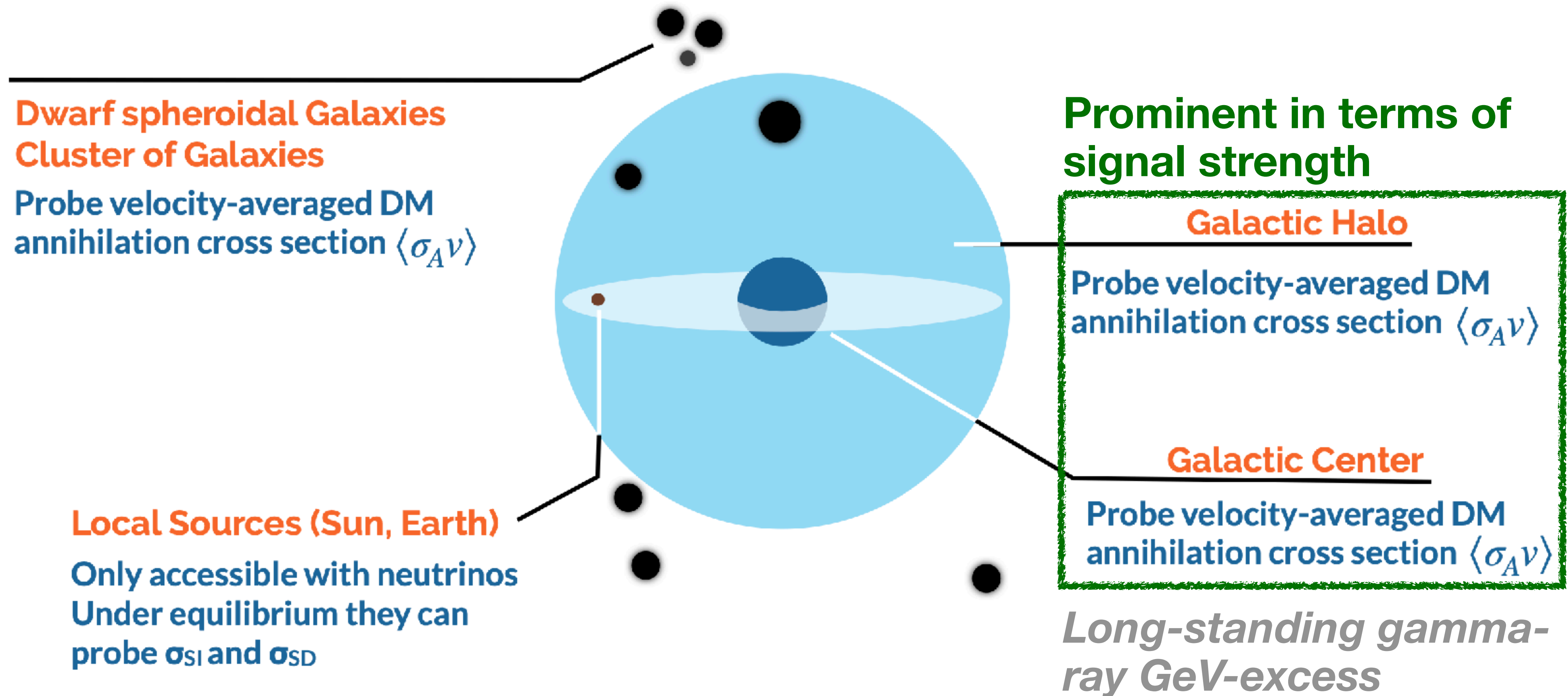
Nhân Châu
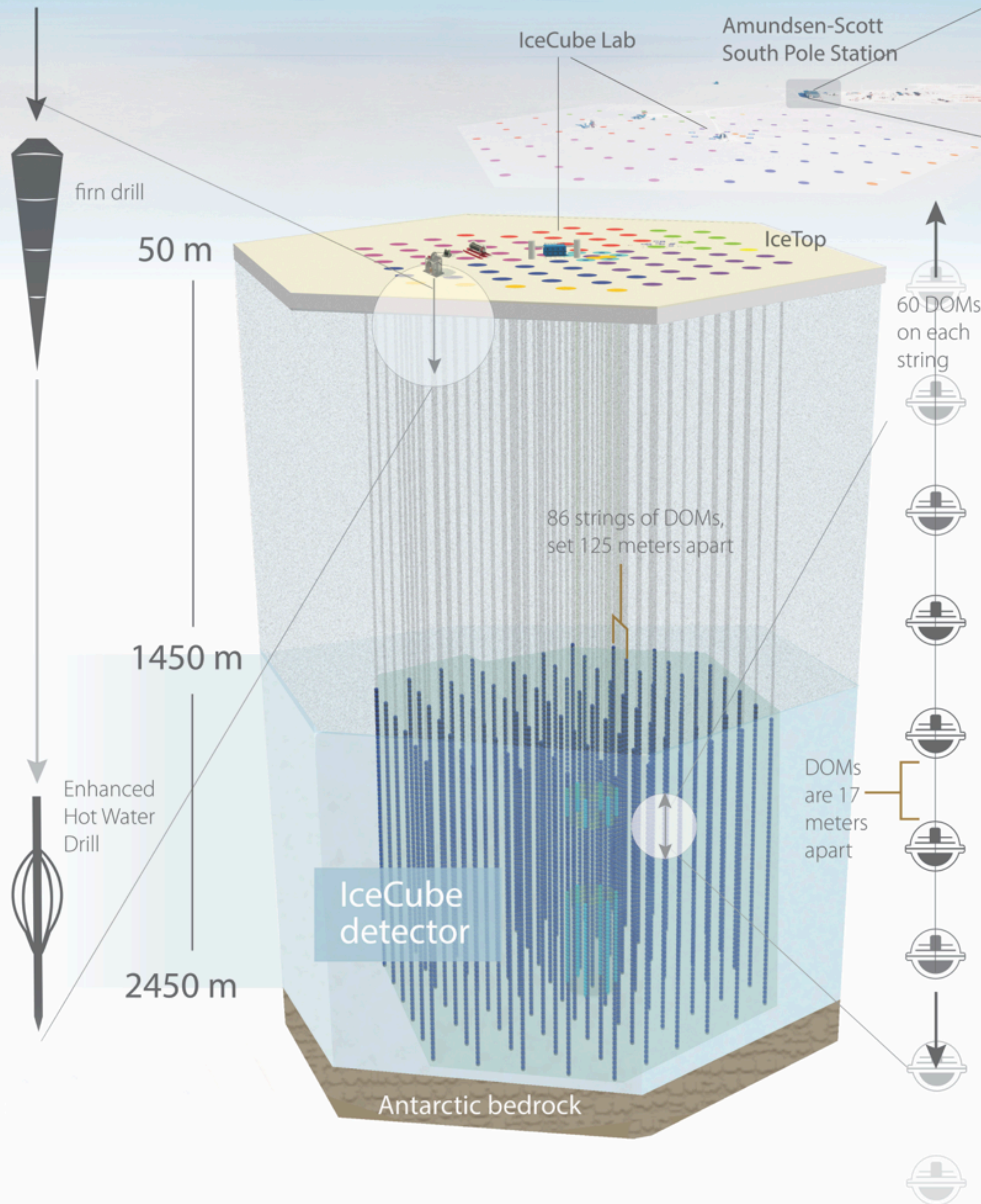*on behalf of the IceCube Collaboration*

Indirect Detection of Dark Matter

- Looking for **anomalous SM flux** from **large reservoir of Dark Matter.**
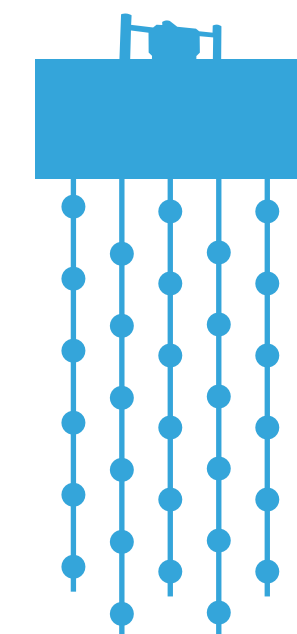- Astrophysical objects as potential sources- make use of **the existing telescopes.**

Dwarf spheroidal Galaxies
Cluster of Galaxies
Probe velocity-averaged DM annihilation cross section $\langle \sigma_A v \rangle$

Prominent in terms of signal strength

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

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

Long-standing gamma-ray GeV-excess

Local Sources (Sun, Earth)
Only accessible with neutrinos
Under equilibrium they can probe σ_{SI} and σ_{SD}

IceCube Neutrino Observatory

IceCube Lab

Amundsen-Scott South Pole Station

firn drill

50 m

IceTop

60 DOMs on each string

86 strings of DOMs, set 125 meters apart

1450 m

Enhanced Hot Water Drill

IceCube detector
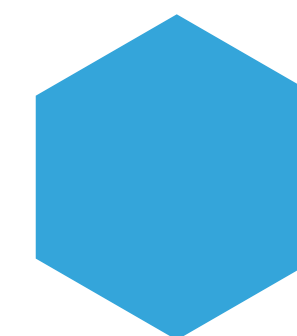
DOMs are 17 meters apart

2450 m

Antarctic bedrock

5,160 Digital Optical Modules (DOMs)

86 string with 60 DOMs each

6 denser strings called **DeepCore**
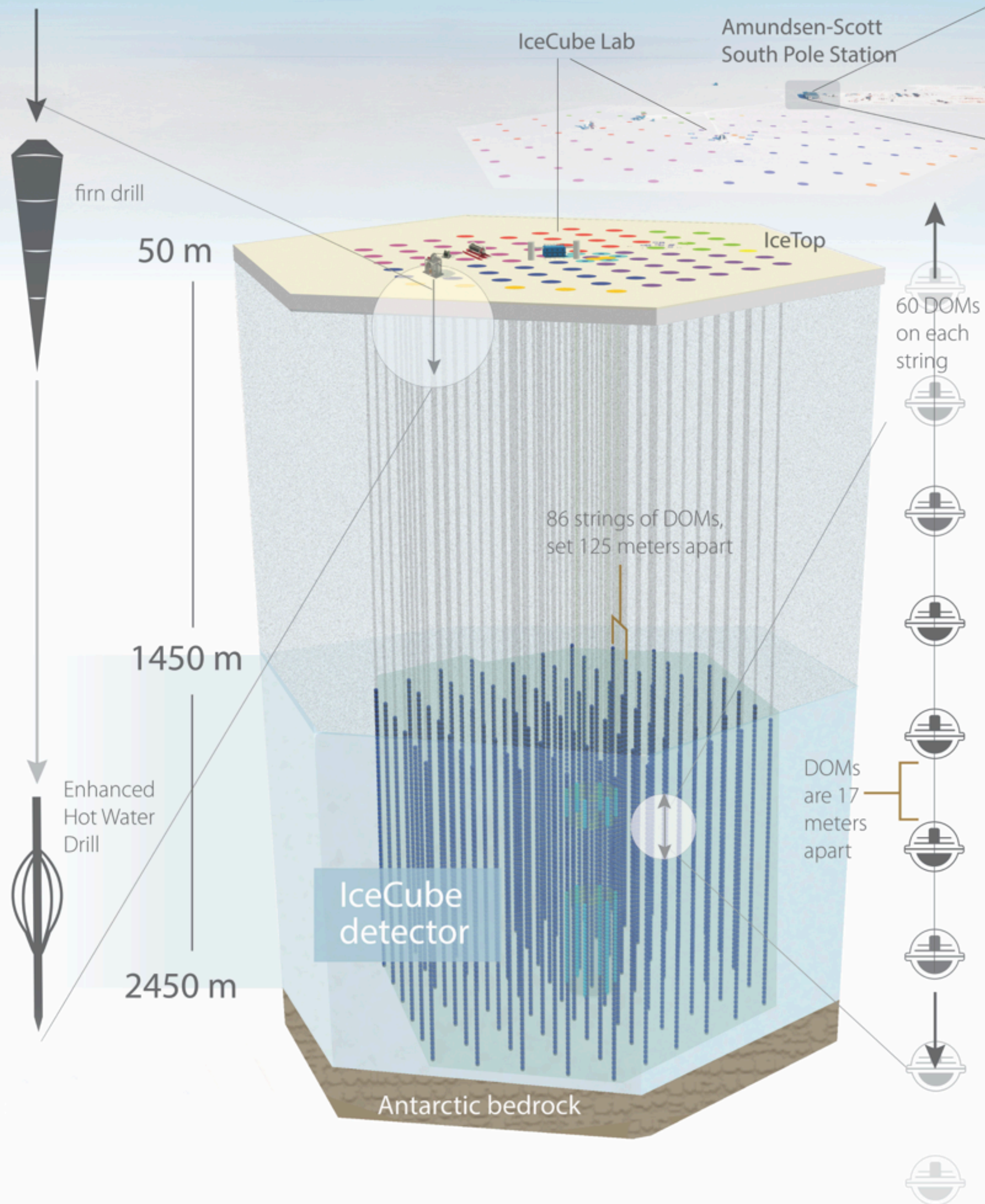
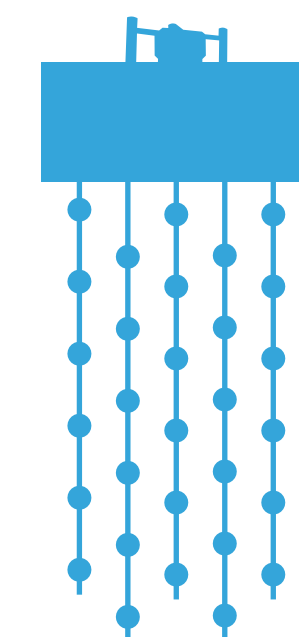**1 km² surface array with 324 DOMs: IceTop**

Completion in December 2010

IceCube Neutrino Observatory

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50 m

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TeV-peV

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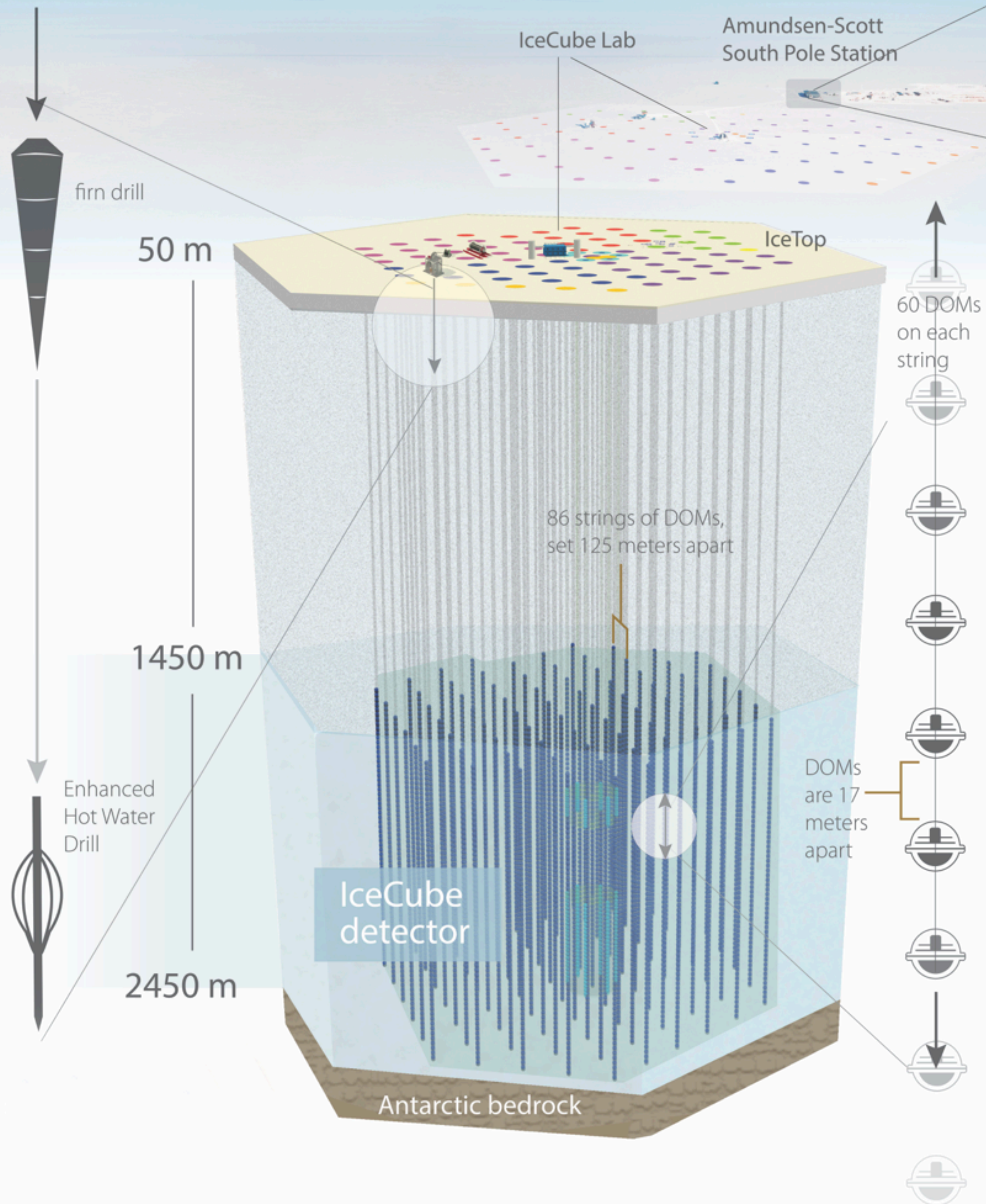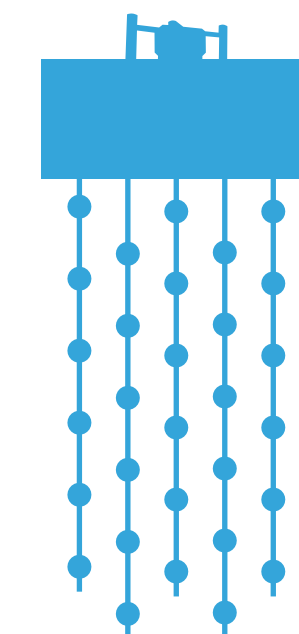
1 km² surface array with 324 DOMs: IceTop

Completion in December 2010

IceCube Neutrino Observatory

firn drill

50 m

IceCube Lab

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60 DOMs
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86 strings of DOMs,
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DOMs
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5,160 Digital Optical Modules (DOMs)

86 string with 60 DOMs each

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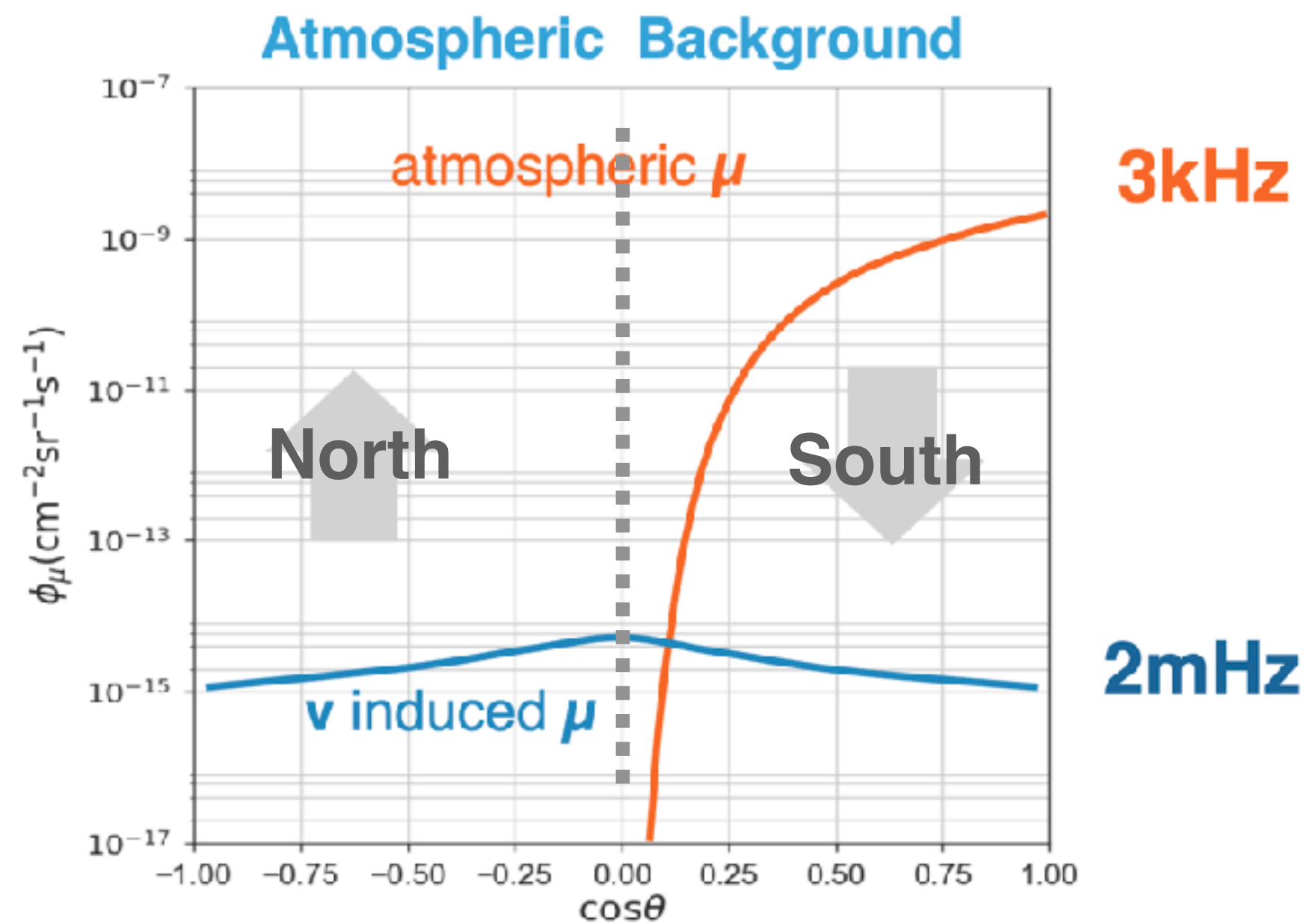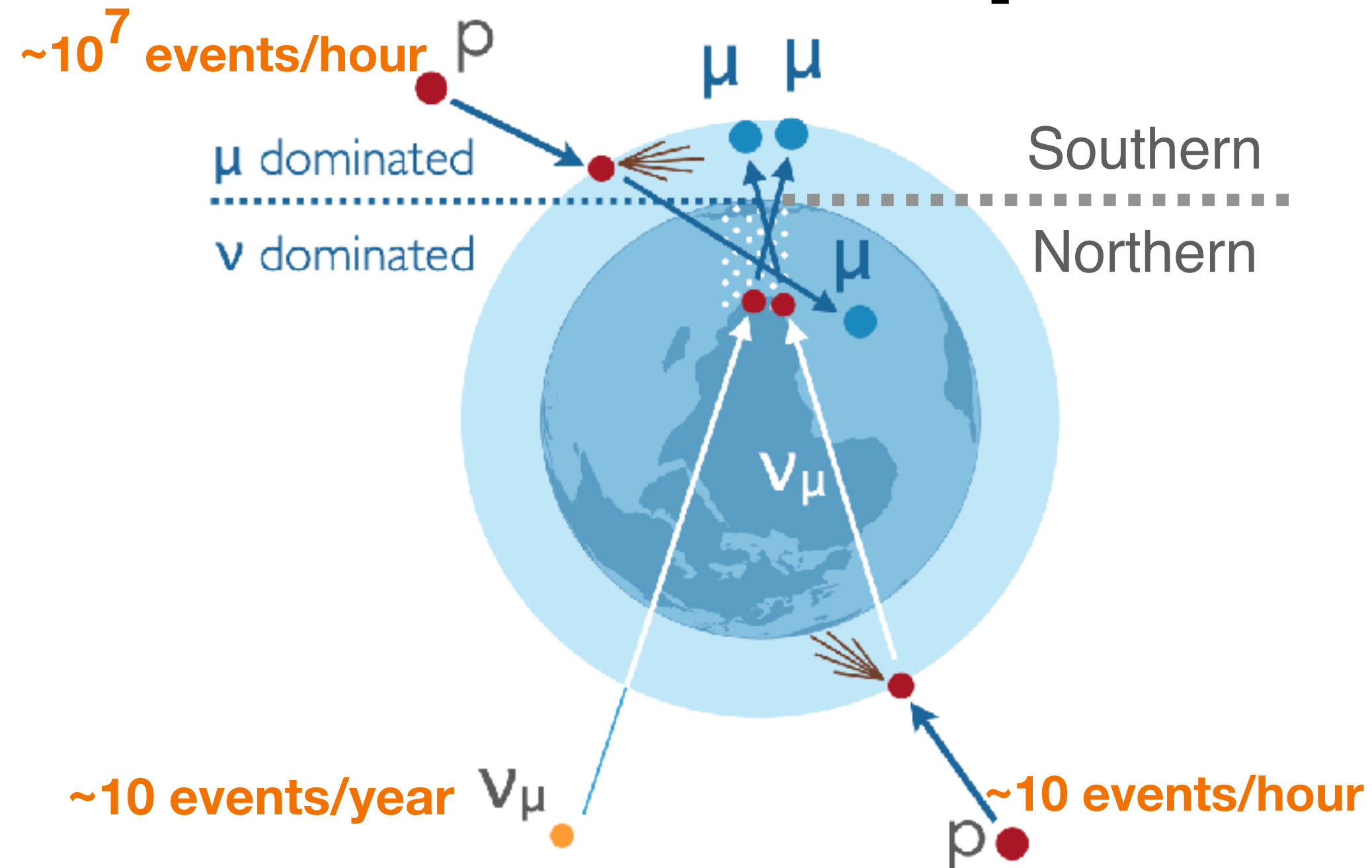*Down to GeV-scale*

1 km² surface array with 324 DOMs: IceTop

Completion in December 2010

# Detection Principle - background rejection

~10^7 events/hour

μ dominated

ν dominated

Southern

Northern

μ μ

μ

ν_μ

~10 events/year ν_μ

~10 events/hour

p

Atmospheric Background

North

South

atmospheric *μ*

3kHz

ν induced *μ*

2mHz

- **In Northern sky**: Earth acts as the natural filter for atm. muons - making use of **up-going events.**

- **In Southern sky**: using outer layer as an active veto for selecting **starting events.**

μ **Veto**

ν_μ

ν_μ

μ
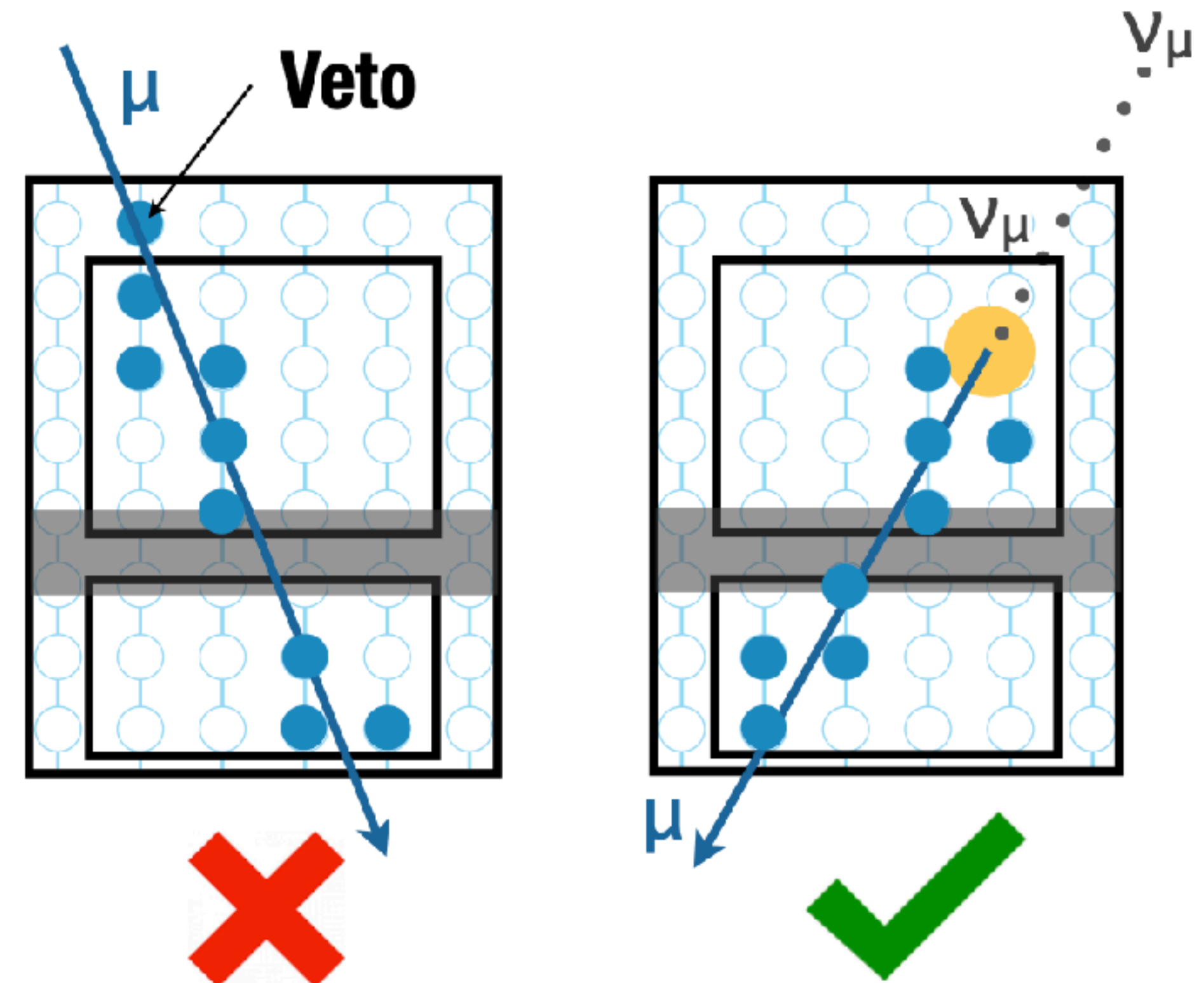
Indirect Search for Dark Matter with IceCube
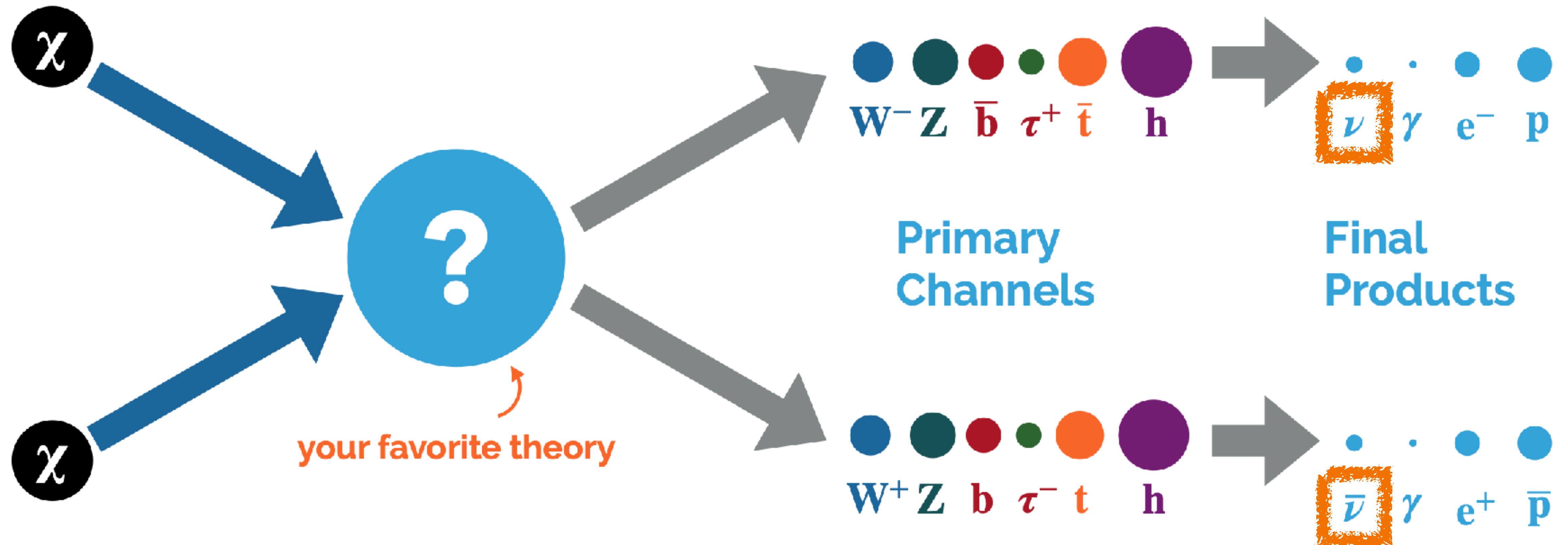
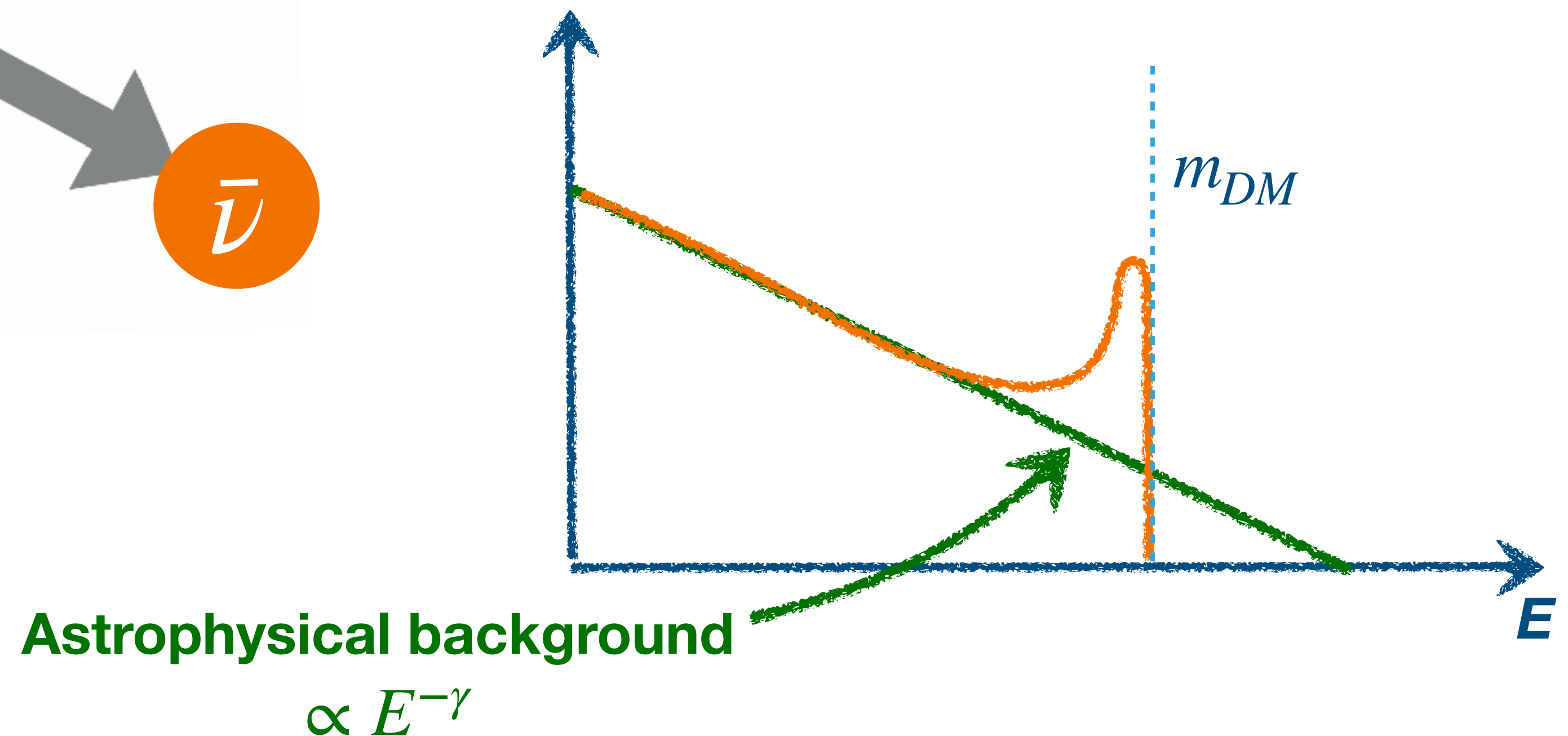- Look for **anomalous neutrino flux** from **large reservoir of Dark Matter.**

Indirect Search for Dark Matter with IceCube
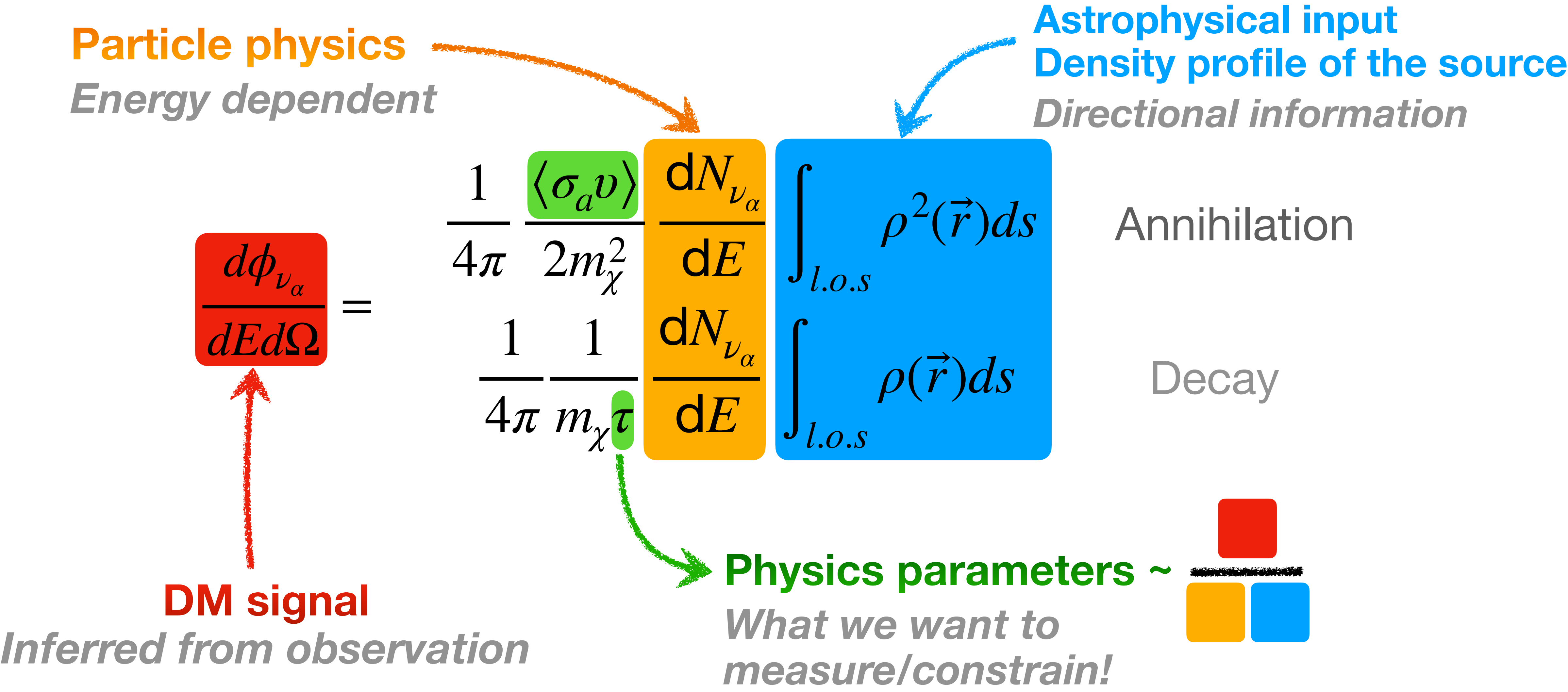## Neutrino lines
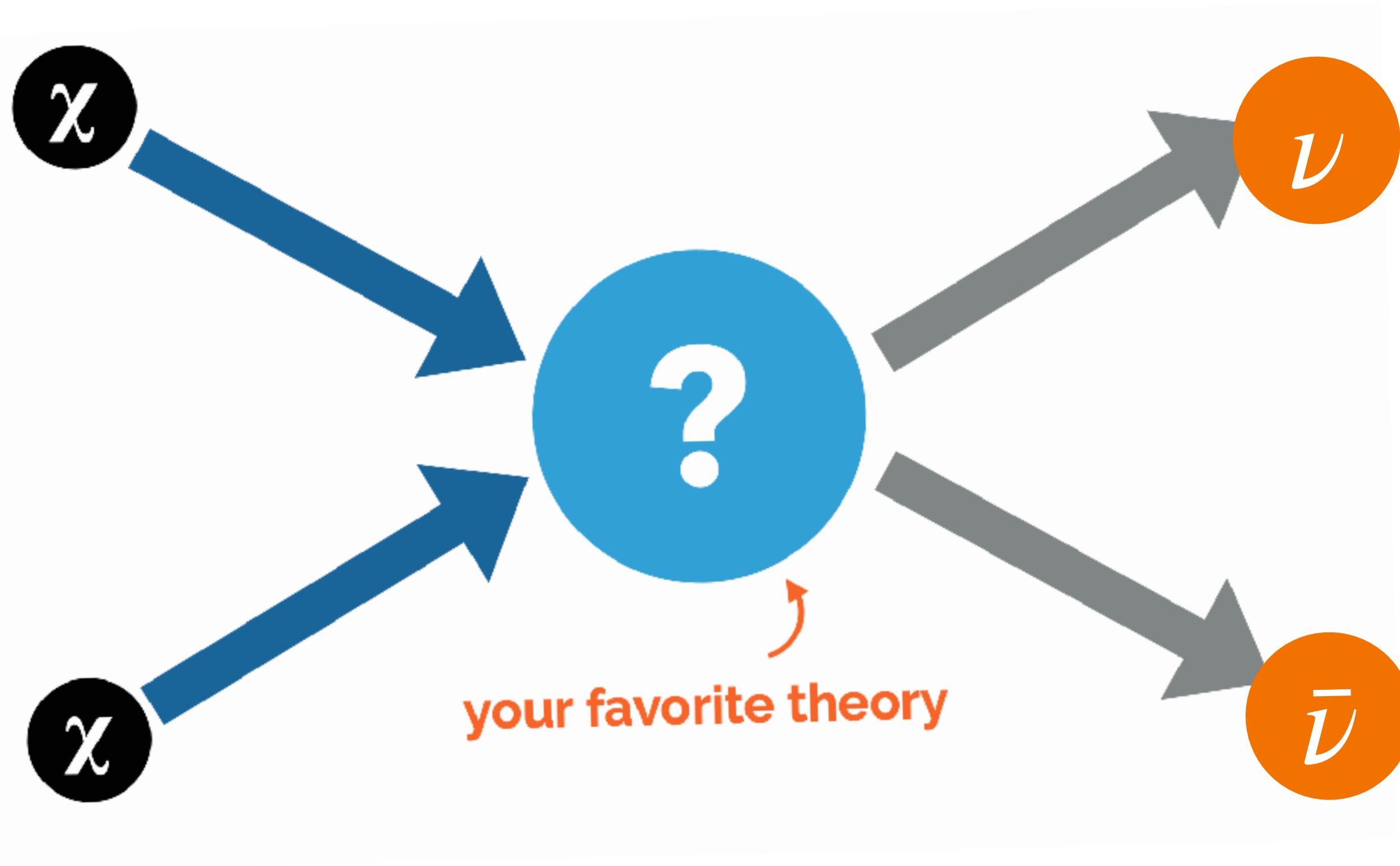
- Direct annihilation/decay into neutrino pairs.

- **Monochromatic peak in energy at DM mass.**

- **Distinctive from astrophysical background, smoking gun DM signature.**

- Rely on energy resolution!

Astrophysical background
$\propto E^{-\gamma}$

Particle physics
Energy dependent

**Astrophysical input
Density profile of the source**
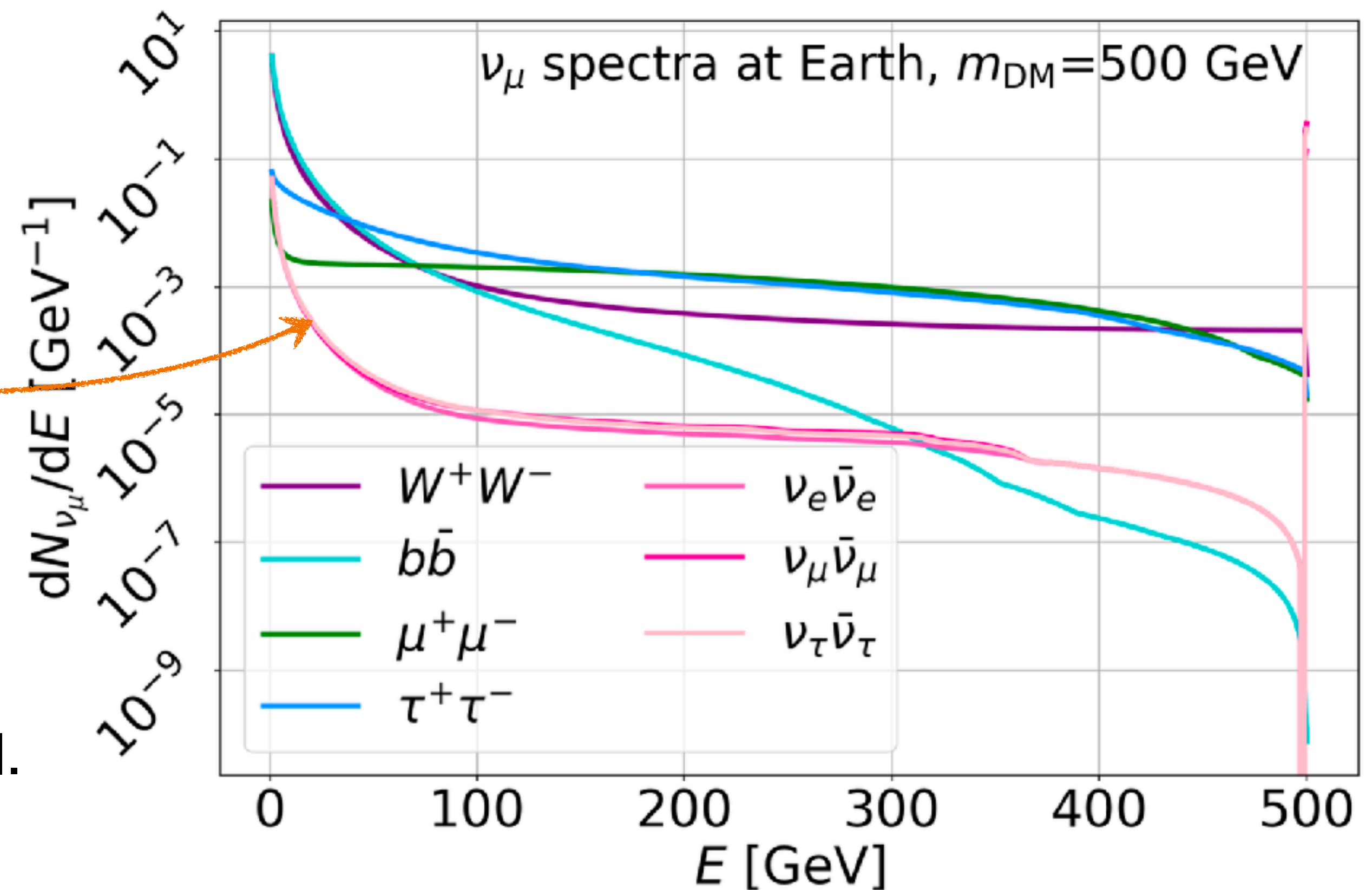*Directional information*

$$\frac{d\phi_{\nu_\alpha}}{dEd\Omega} = \frac{1}{4\pi}\frac{\langle\sigma_a v\rangle}{2m_\chi^2}\frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E}\int_{l.o.s}\rho^2(\vec{r})ds \qquad \text{Annihilation}$$

$$\frac{1}{4\pi}\frac{1}{m_\chi\tau}\frac{\mathrm{d}N_{\nu_\alpha}}{\mathrm{d}E}\int_{l.o.s}\rho(\vec{r})ds \qquad \text{Decay}$$

DM signal

Inferred from observation

Physics parameters ~

*What we want to
measure/constrain!*
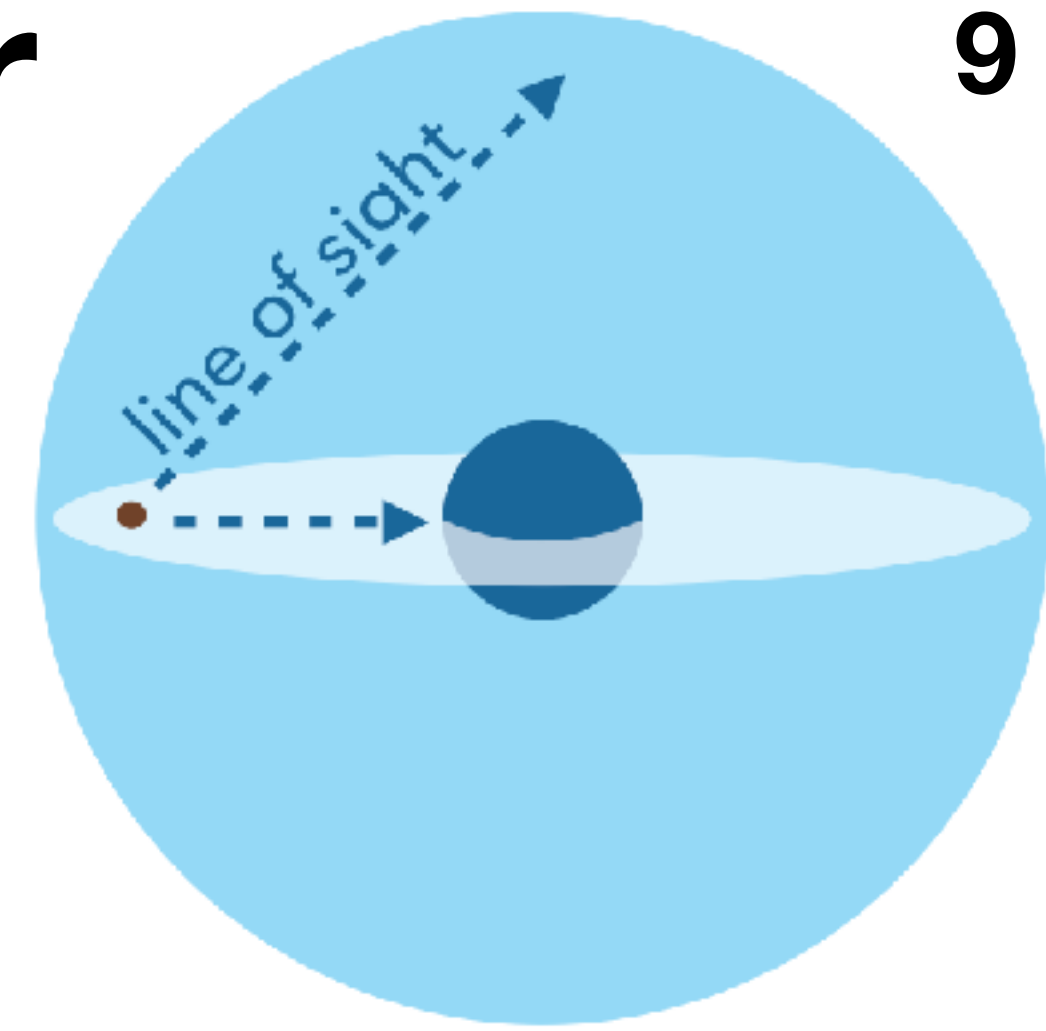
Dark Matter Signal from Galactic Center

$$\frac{d\phi_{\nu_\alpha}}{dEd\Omega} = \frac{1}{4\pi} \frac{\langle\sigma_a v\rangle}{2m_{\text{DM}}^2} \boxed{\frac{\text{d}N_{\nu_\alpha}}{\text{d}E}} \int_{l.o.s} \rho^2(\vec{r})ds$$

- Spectra computed with $\chi\alpha\rho\nu$
  arXiv:2007.15010v2

➡ Couple Pythia with the state-of-the-art EW correction - JHEP 06 (2021) 121

- Assuming 100% BR for each primary channel.

- Averaged oscillation over large distance.

$$\frac{d\phi_{\nu_\alpha}}{dEd\Omega} = \frac{1}{4\pi} \frac{\langle\sigma_a v\rangle}{2m_{\text{DM}}^2} \frac{\text{d}N_{\nu_\alpha}}{\text{d}E} \int_{l.o.s} \rho^2(\vec{r})ds$$

- **J-factor**: Integration of DM profile along the line-of-sight:

$$J(\Psi) = \int_{\Delta\Omega} \text{d}\Omega(\Psi) \int_0^{l_{max}} \rho_{\text{DM}}^2(r(l,\Psi))\, dl$$

- Computed with **Clumpy** ([arXiv:1806.08639](#)) for 2 parametric profiles:
  NFW and **Burkert.**

- Parameter values for the Milky Way taken from Nesti&Salucci ([arXiv:1304.5127](#)).
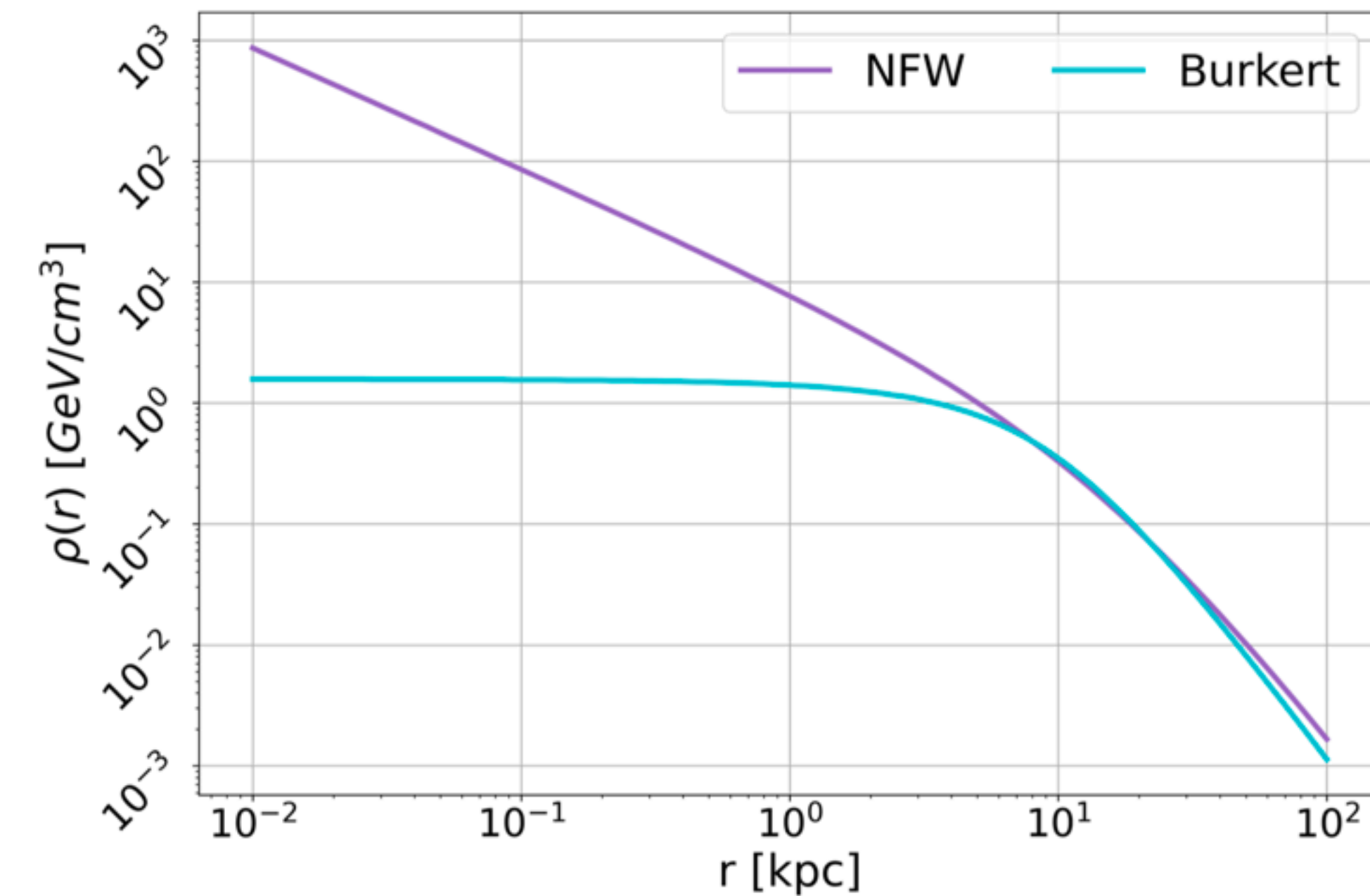
Analysis method

- **Binned Poisson Likelihood.**

$f(i; \xi)$: event fraction

$$\mathscr{L}(\xi) = \prod_i Poisson(n_{obs}^i; n_{obs}^{tot} f(i, \xi))$$

E_{reco}

ψ_{GC} (open angle)
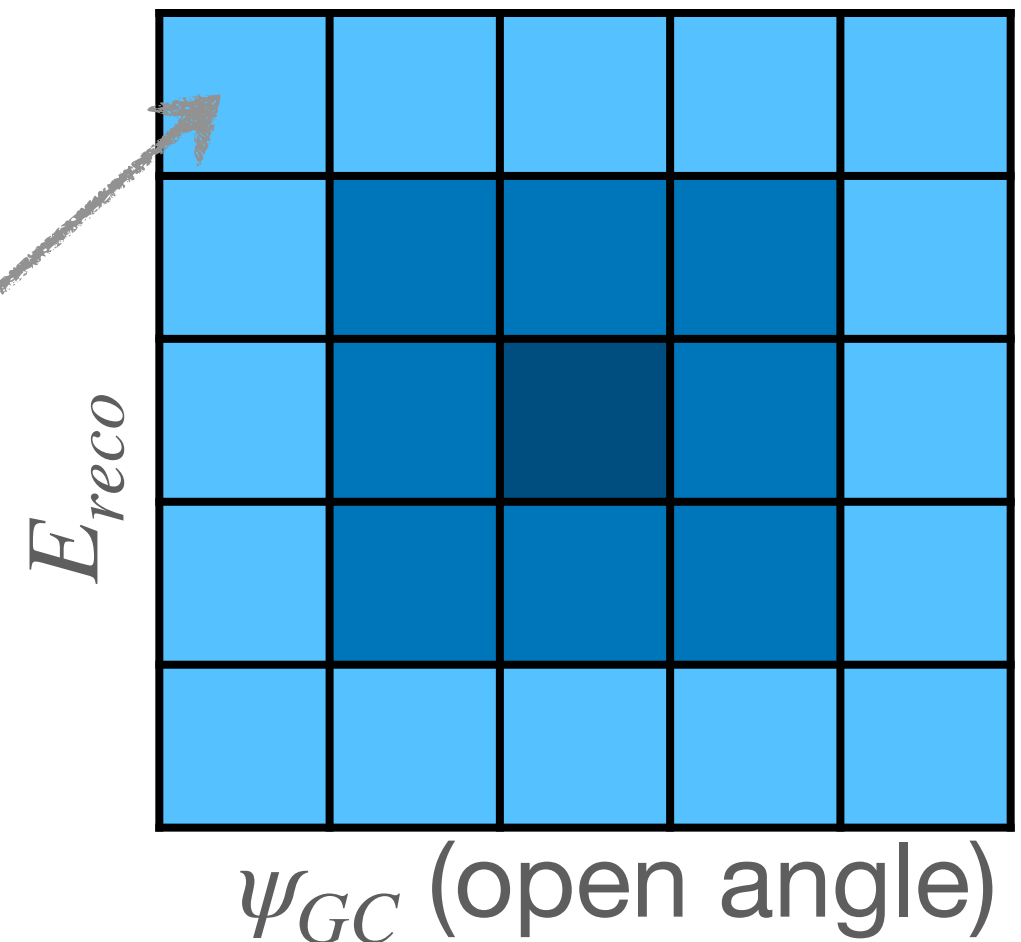
$$f(i\,;\,\xi) = \xi \boxed{\mathscr{S}_i} + (1-\xi)\mathscr{B}_i, \qquad \mathscr{B}_i = \frac{1}{1-\xi}(\boxed{\mathscr{B}_i^{scr}} - \boxed{\xi \mathscr{S}_i^{scr}})$$

Signal PDF (MC)

Background PDF as RA Scrambled data

Signal subtraction for correction of signal contamination

- **One parameter to fit: signal fraction** $\xi = \dfrac{n_{signal}^{tot}}{n_{obs}^{tot}}$ (→translated to physics parameters).

DM Search with IceCube DeepCore

- Search for signal of **dark matter annihilation/decay in the Galactic Center.**

- Using most up-to-date **IceCube/DeepCore data (9.3 years 2012-2022).**

  ‣ Targeting **dark matter mass of GeVs up to ∼ TeV.**

  ‣ Multiple advancement in understanding the detector lead to the **optimisation for the detection of GeV neutrinos.**
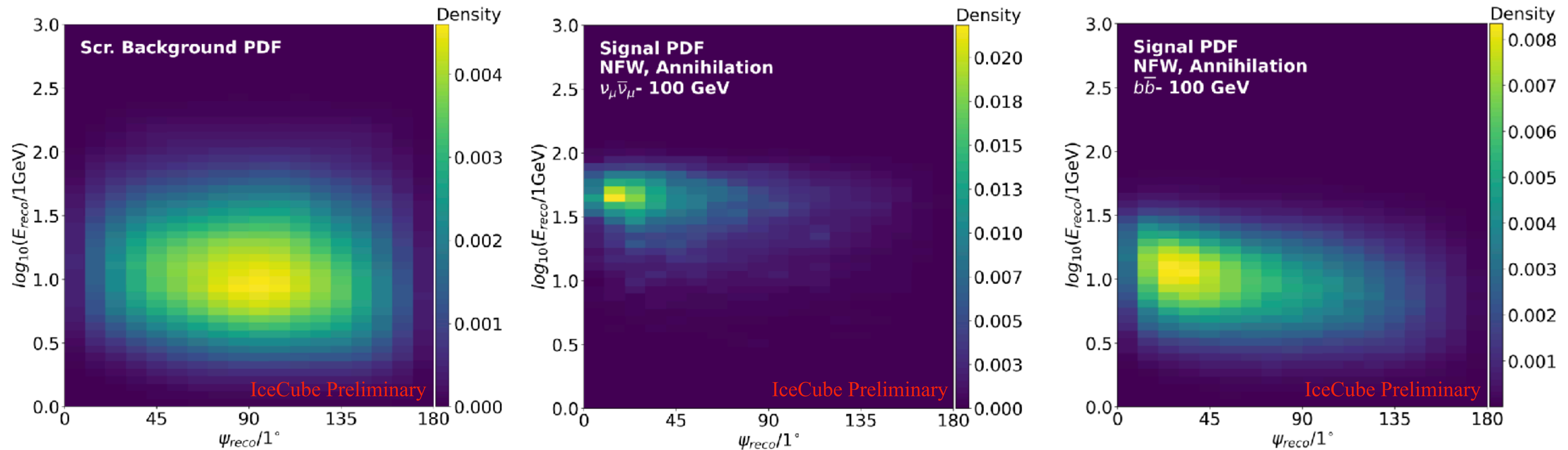

NFW, $\langle \sigma v \rangle = 10^{-26}[\text{cm}^3 \text{ s}^{-1}]$
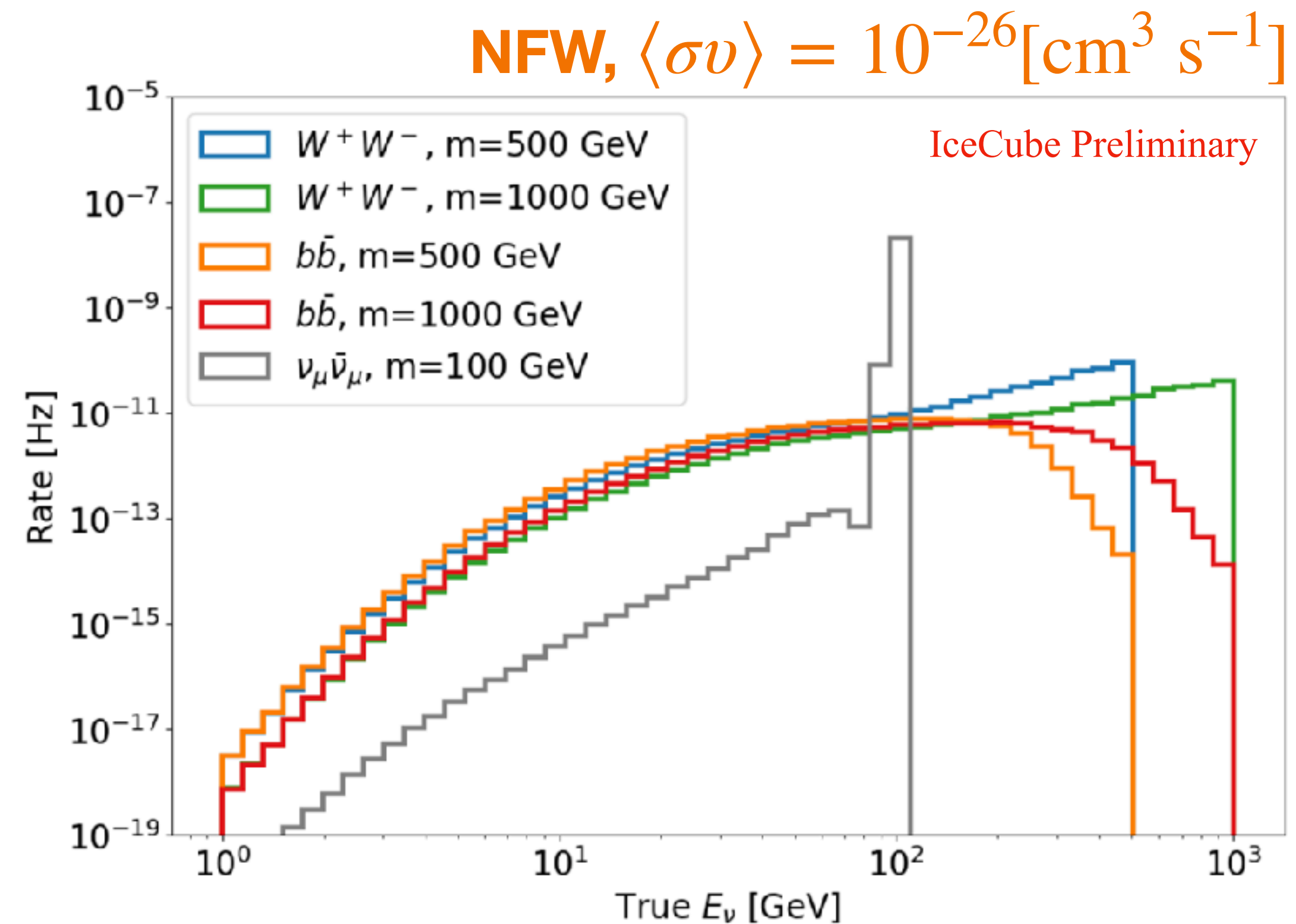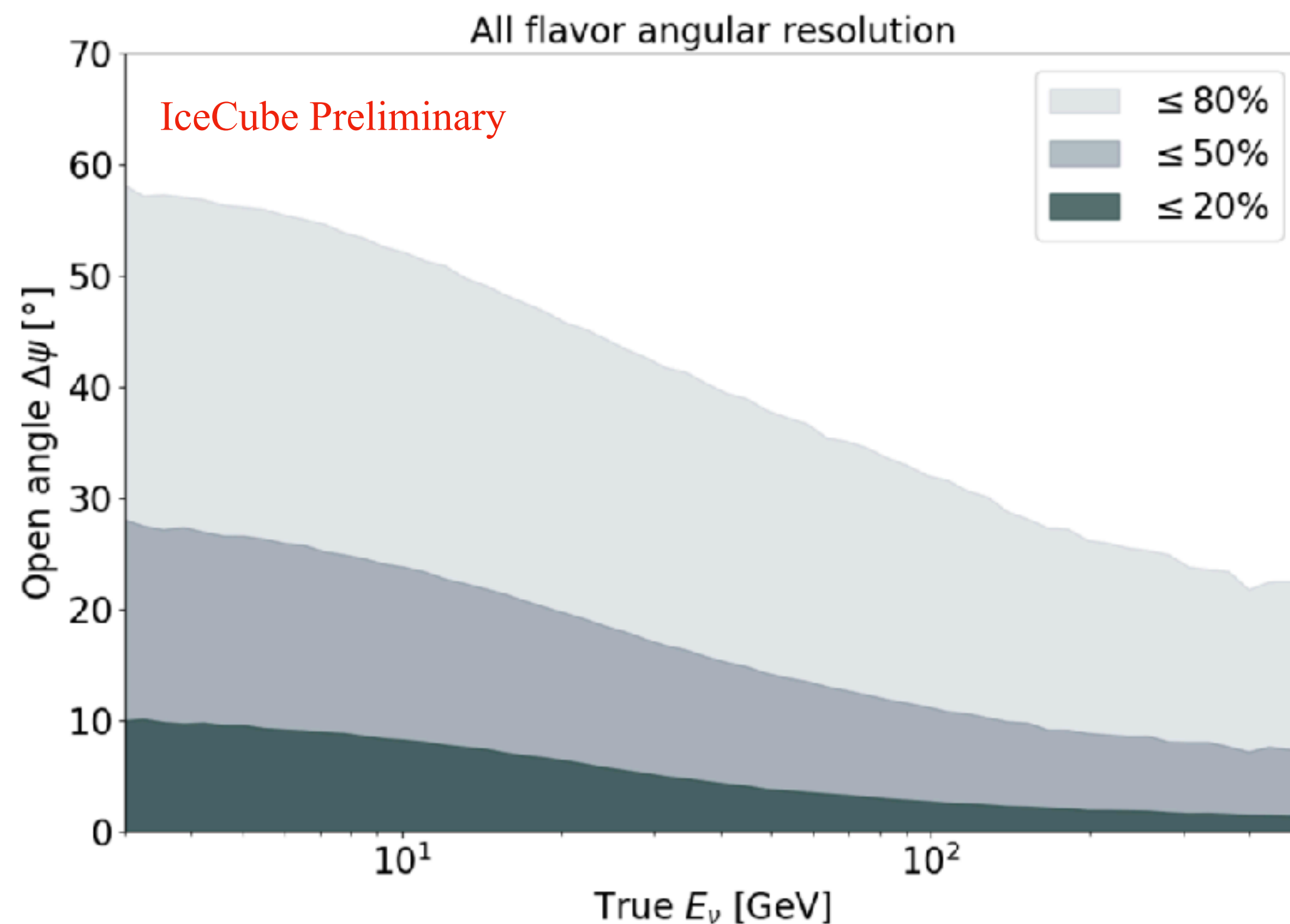
Expected distributions

- PDF on **two observables**: **energy and opening angle** to the Galactic Center.

- Search for **spherical excess of neutrino events pronounced to the Galactic Center.**
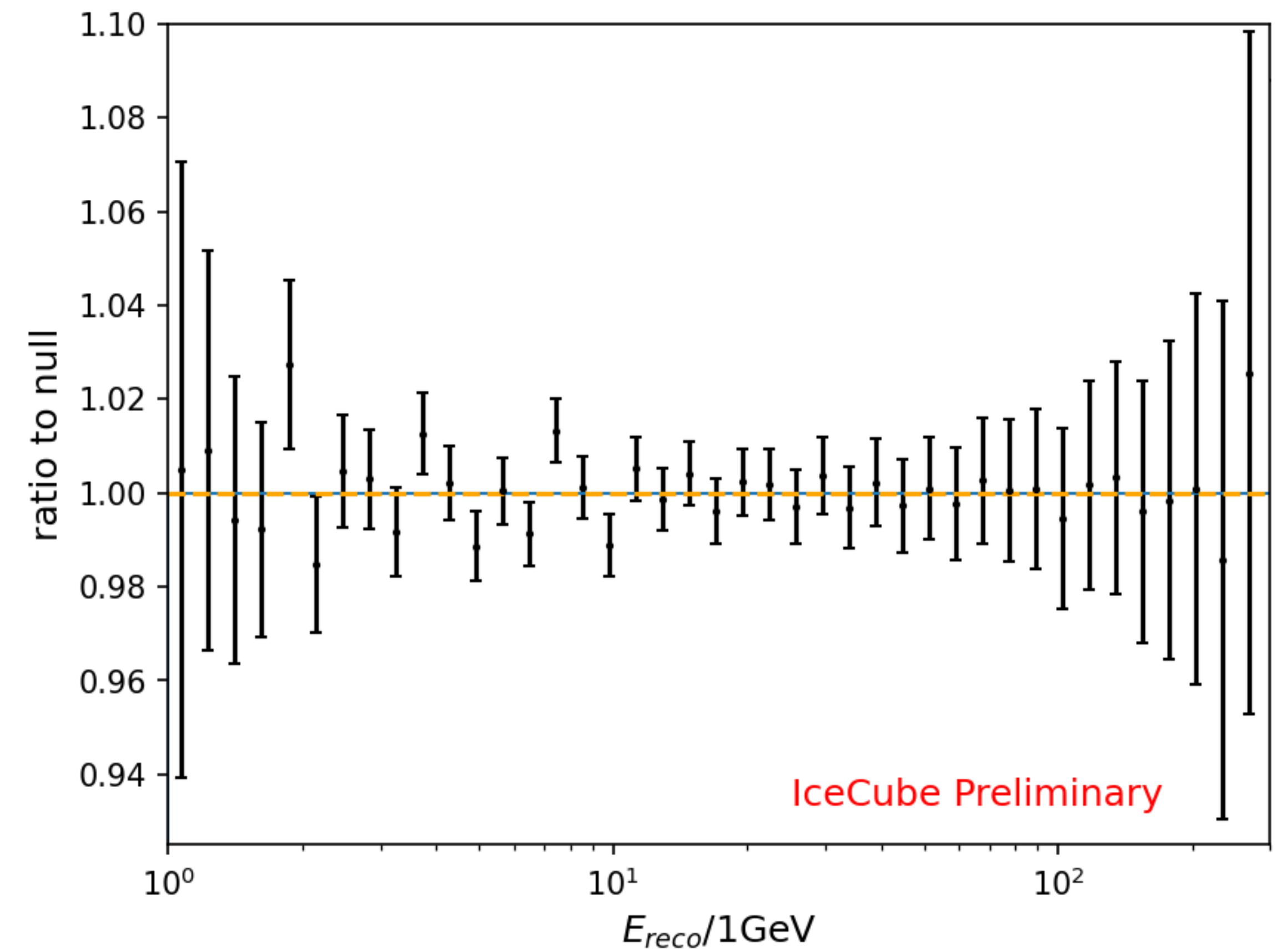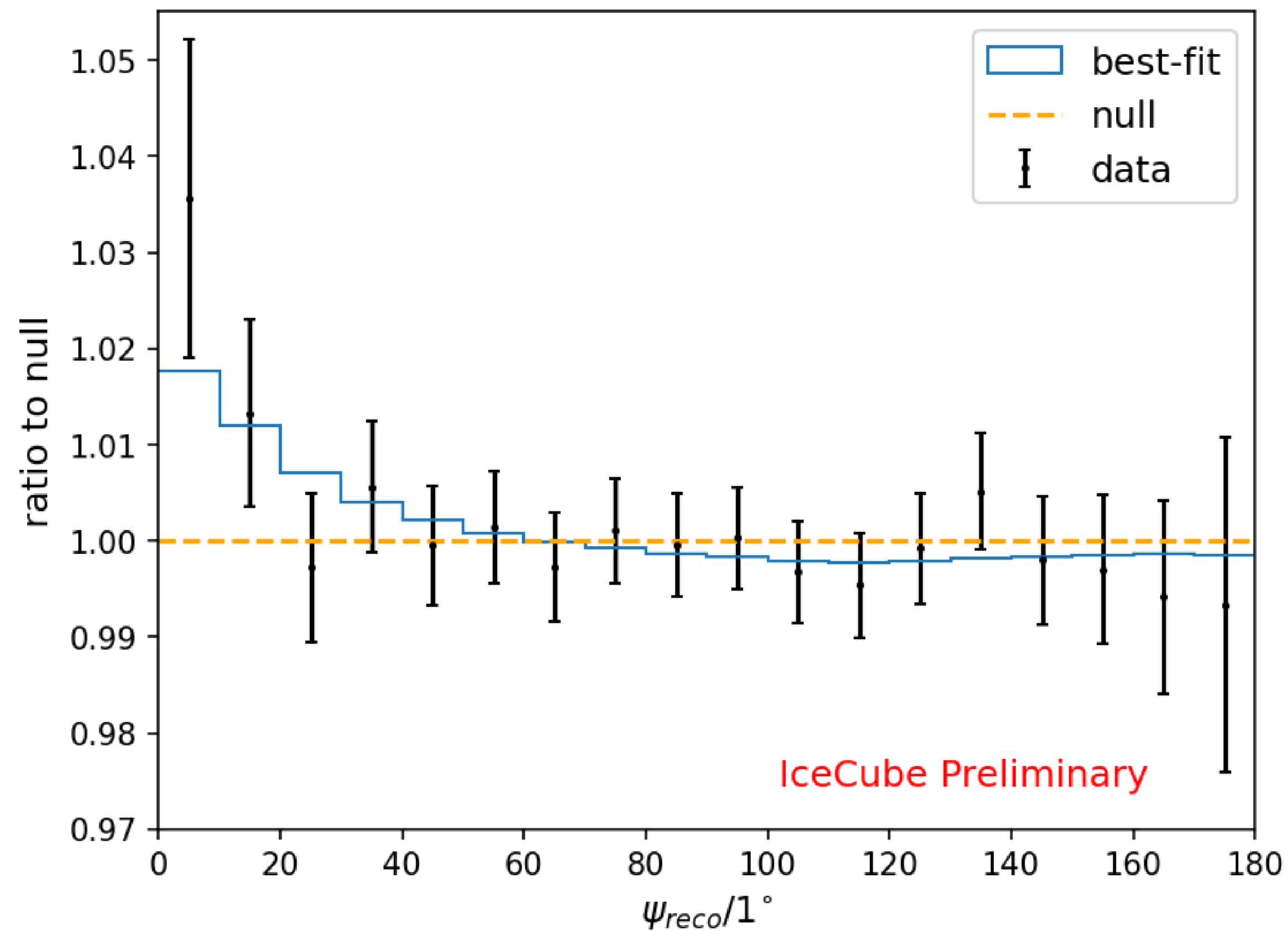
Results - Expectation vs Data

- **No significance excess** above 3σ level i.e **no DM found.**

- **Most significance**: **2.47/1.08** σ **(pre/post-trial) at m=201.6 GeV,** $b\bar{b}$, **NFW, annihilation** (best-fit signal).
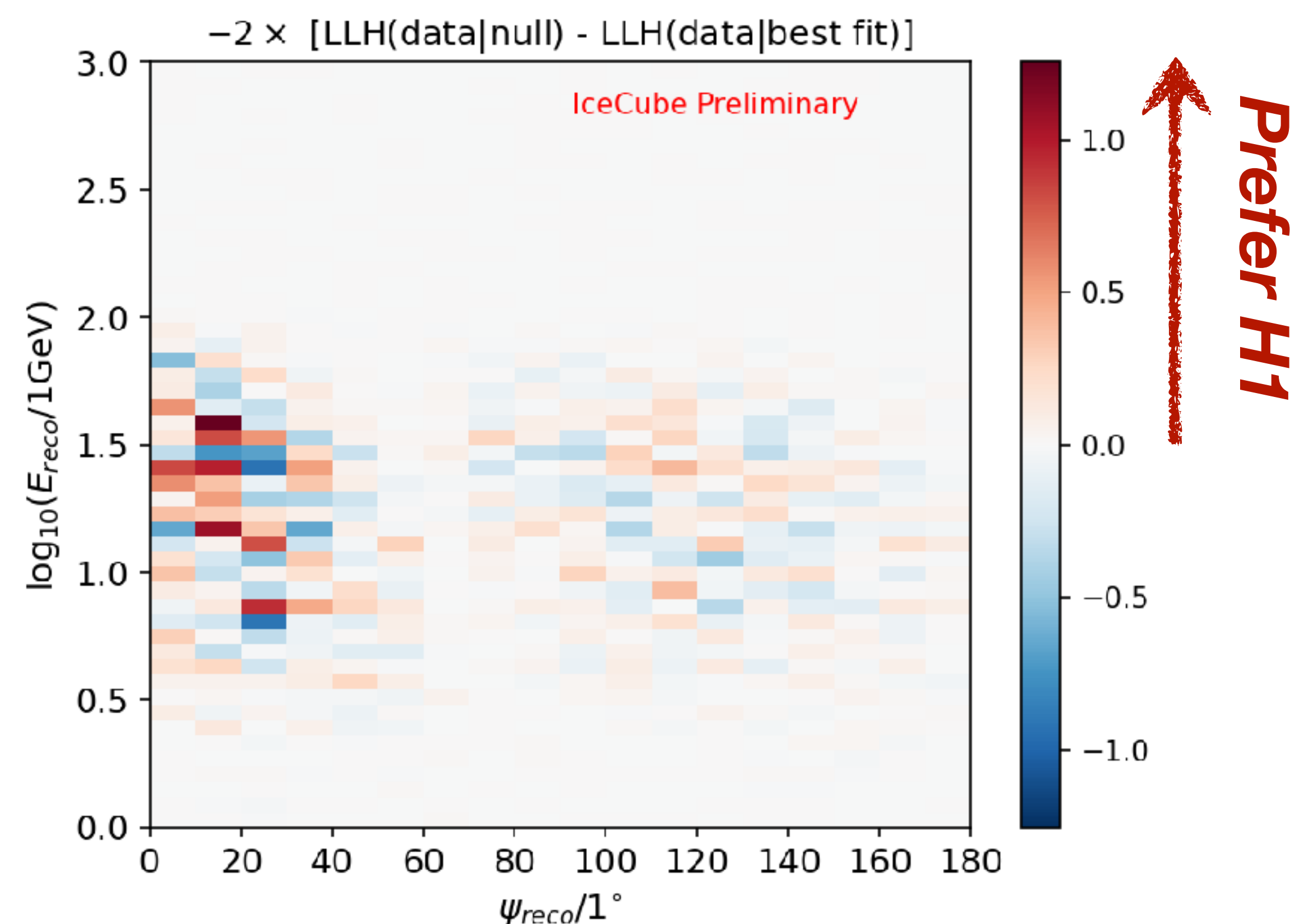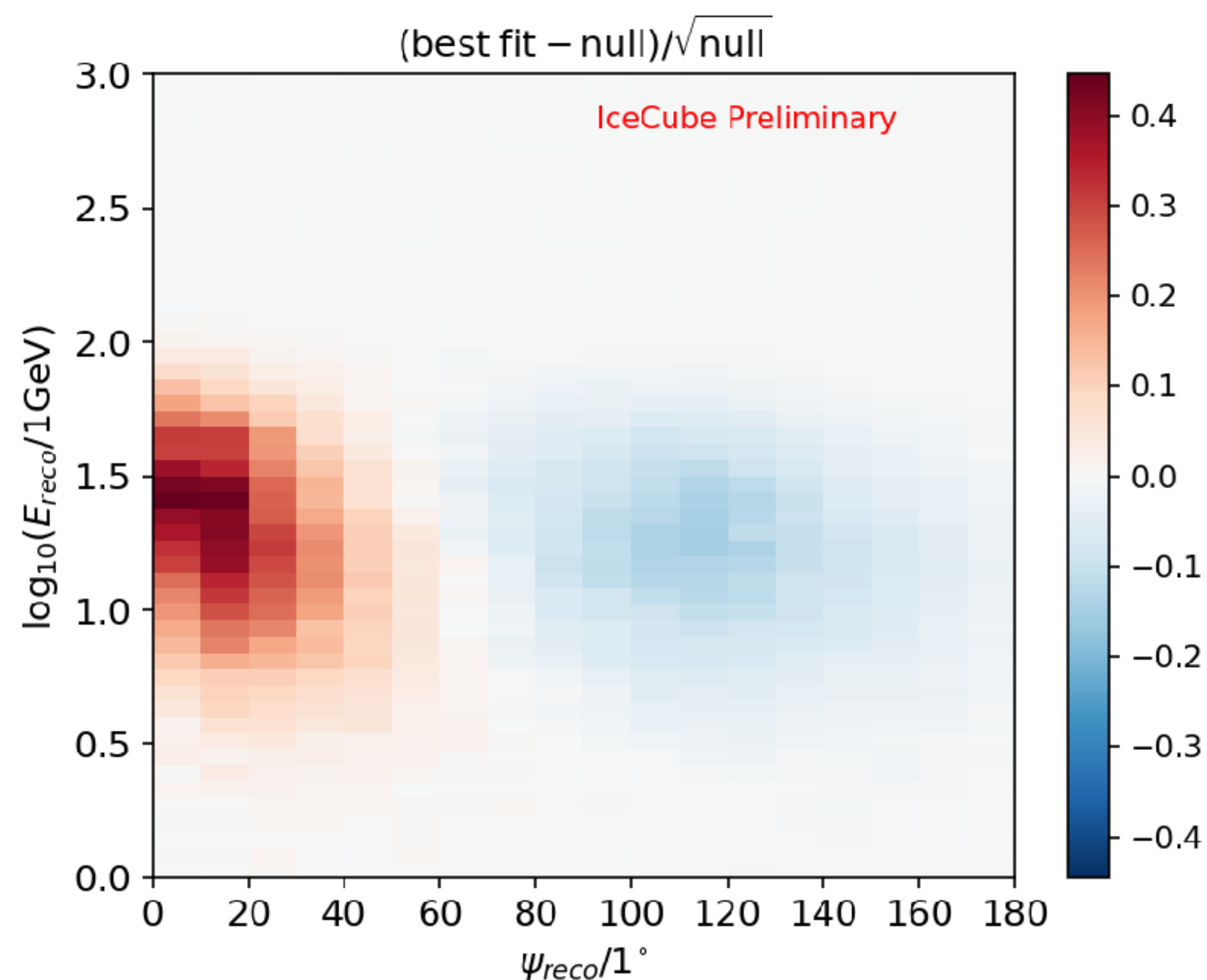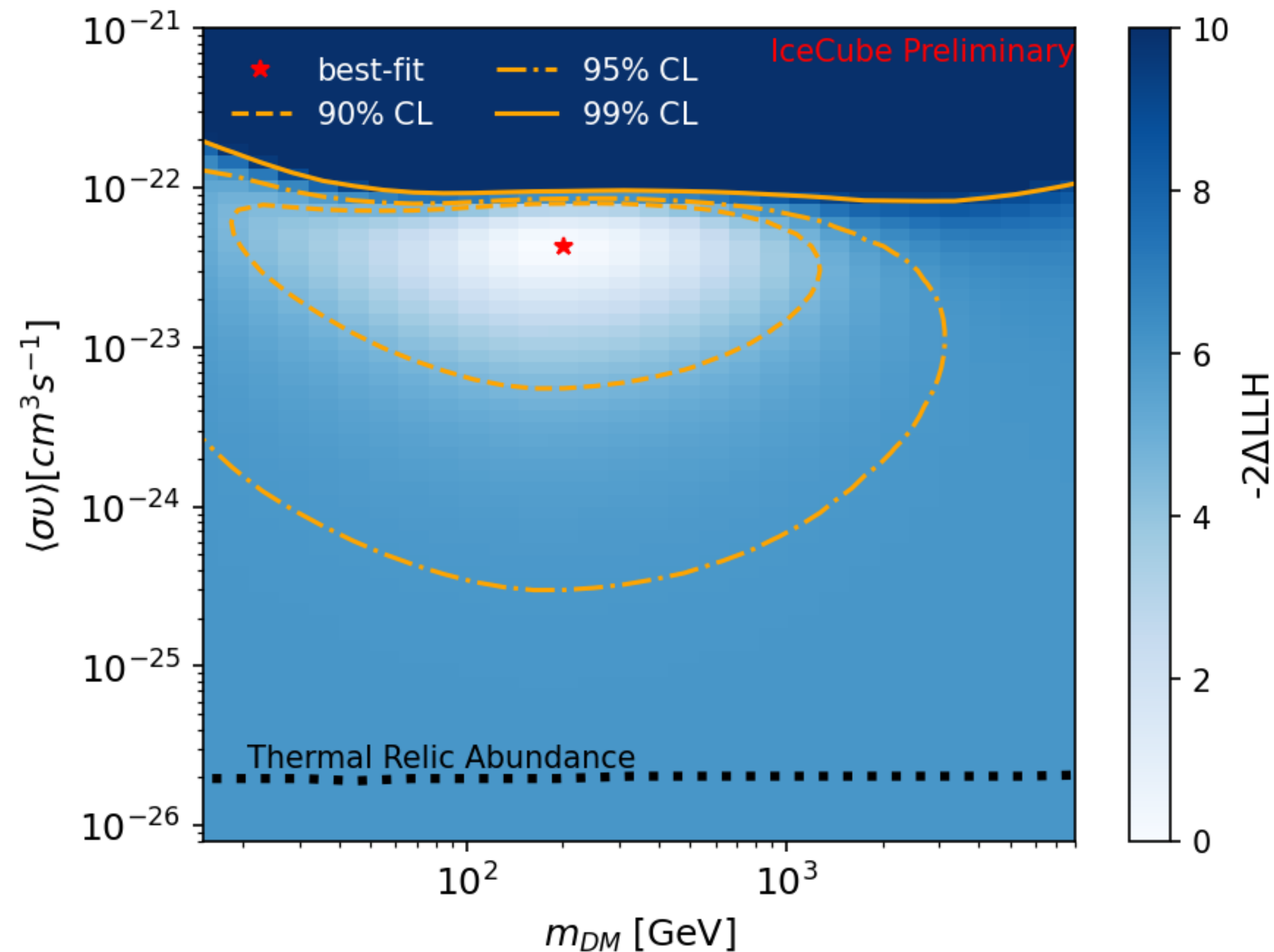
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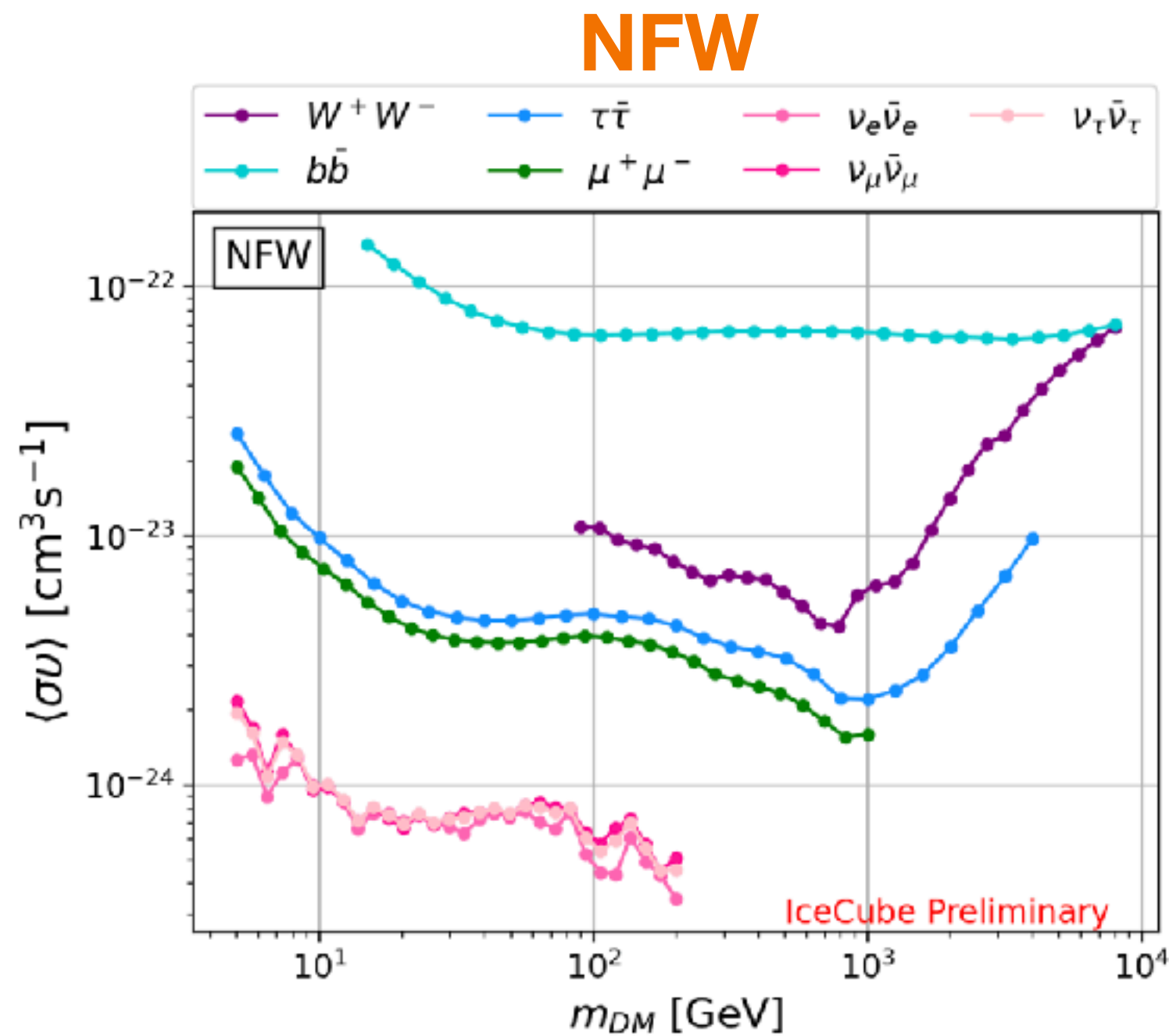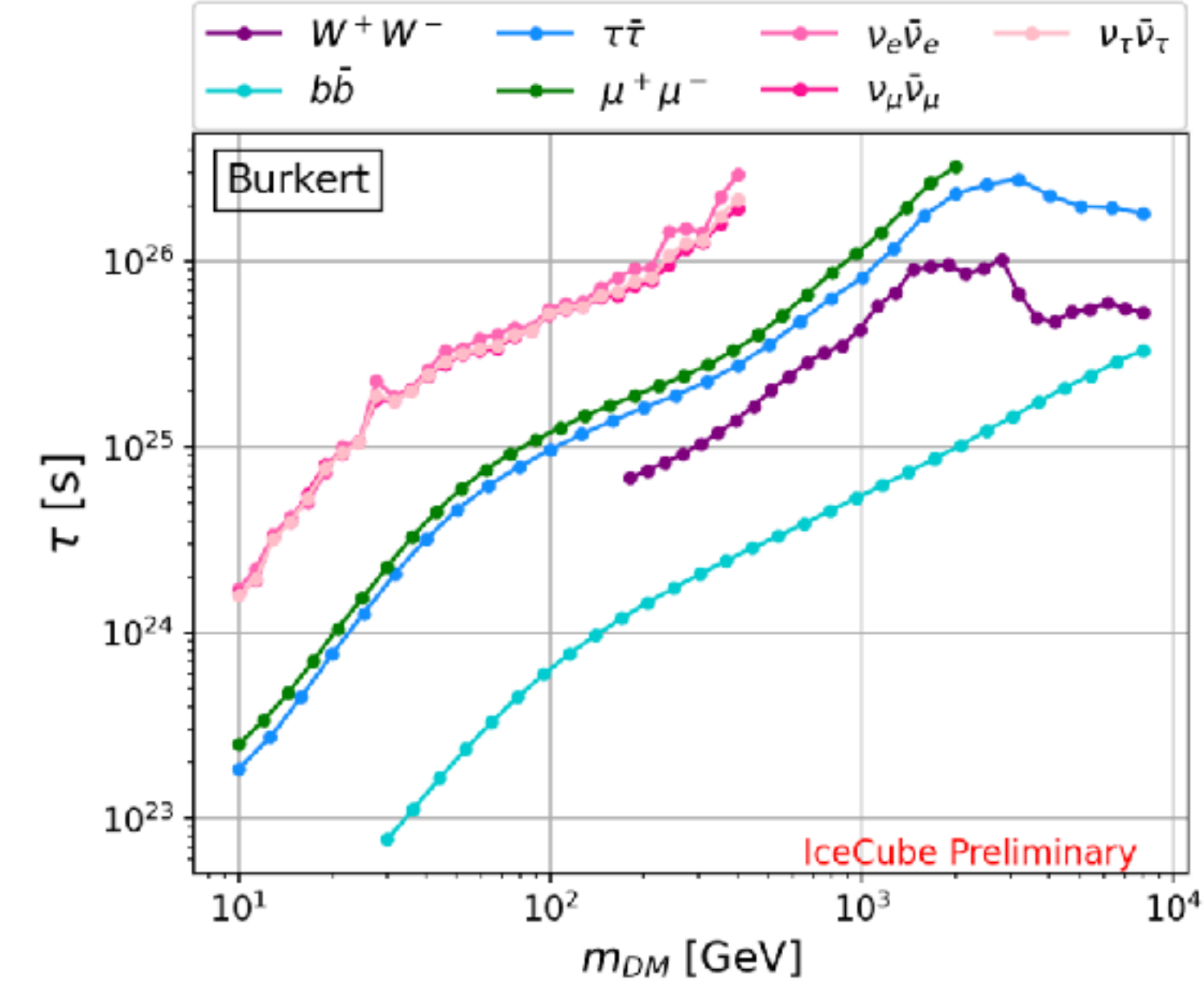
Results - LLH scan

- **No significance excess** above 3σ level i.e **no DM found.**

- **Most significance**: **2.47/1.08 σ (pre/post-trial) at m=201.6 GeV, $b\bar{b}$, NFW, annihilation** **(best-fit signal).**
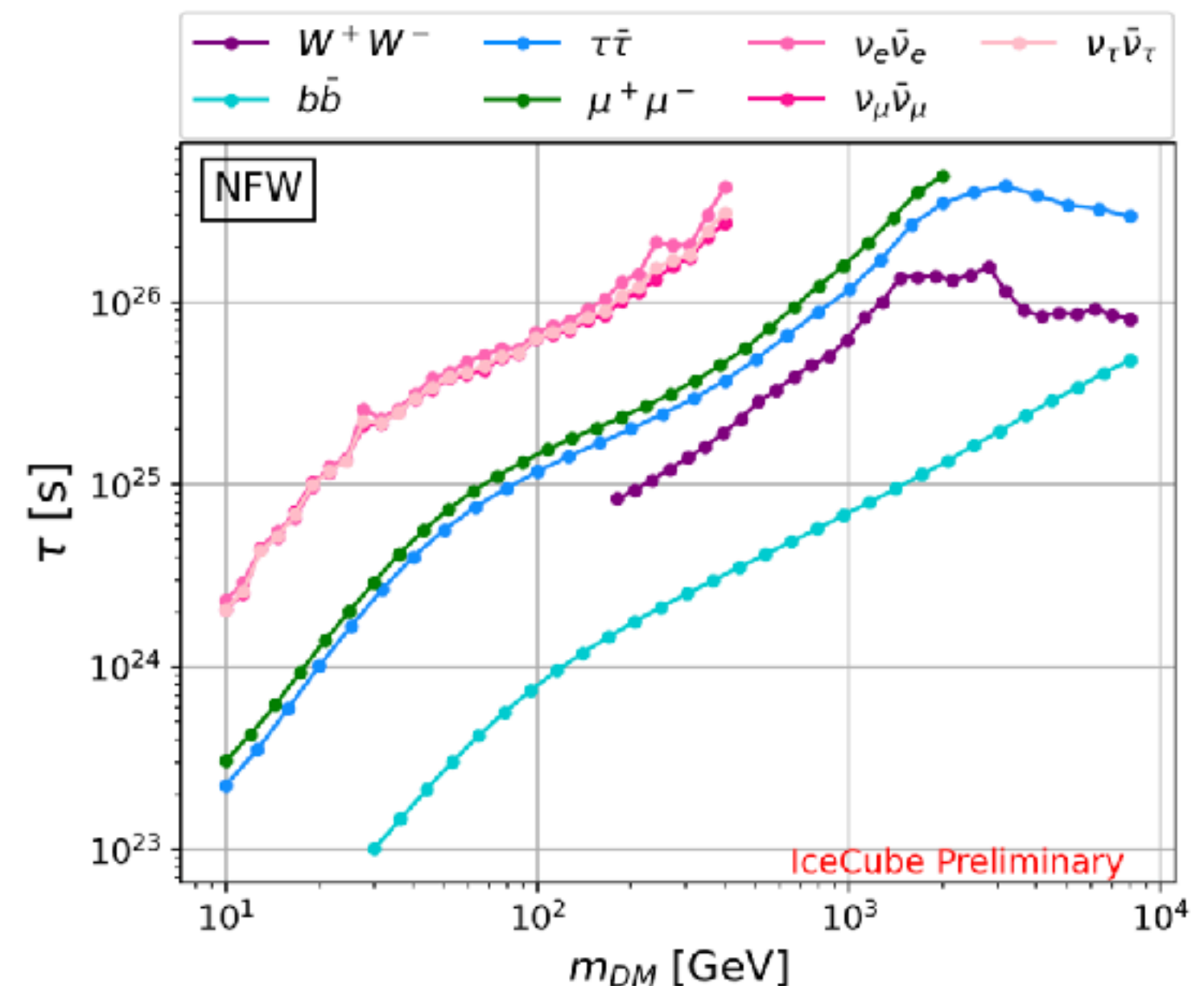
Results - Limits

NFW

Burkert

Annihilation (Upper limit)
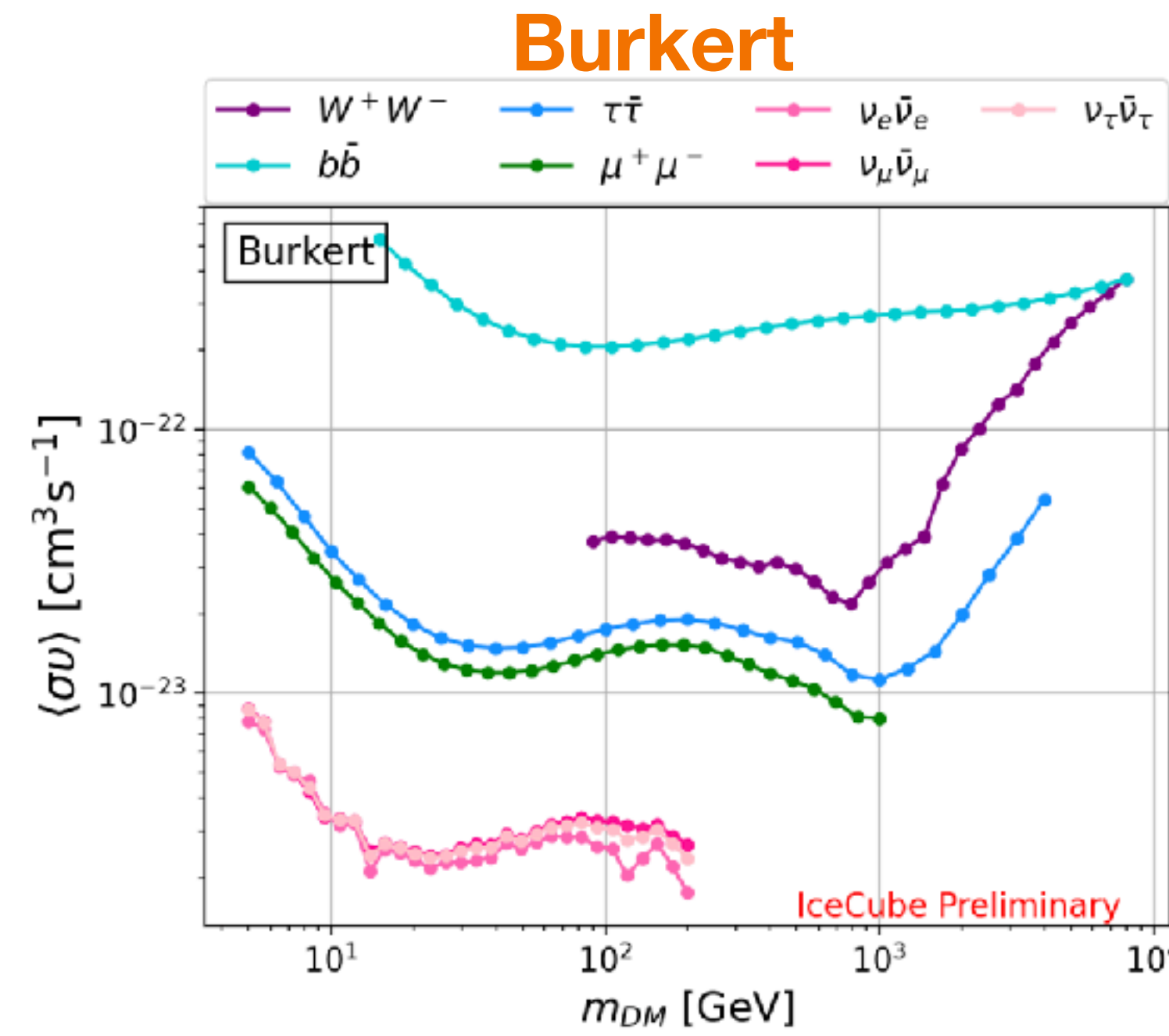
Decay (Lower limit)

Excluded

Excluded

Results - Limits
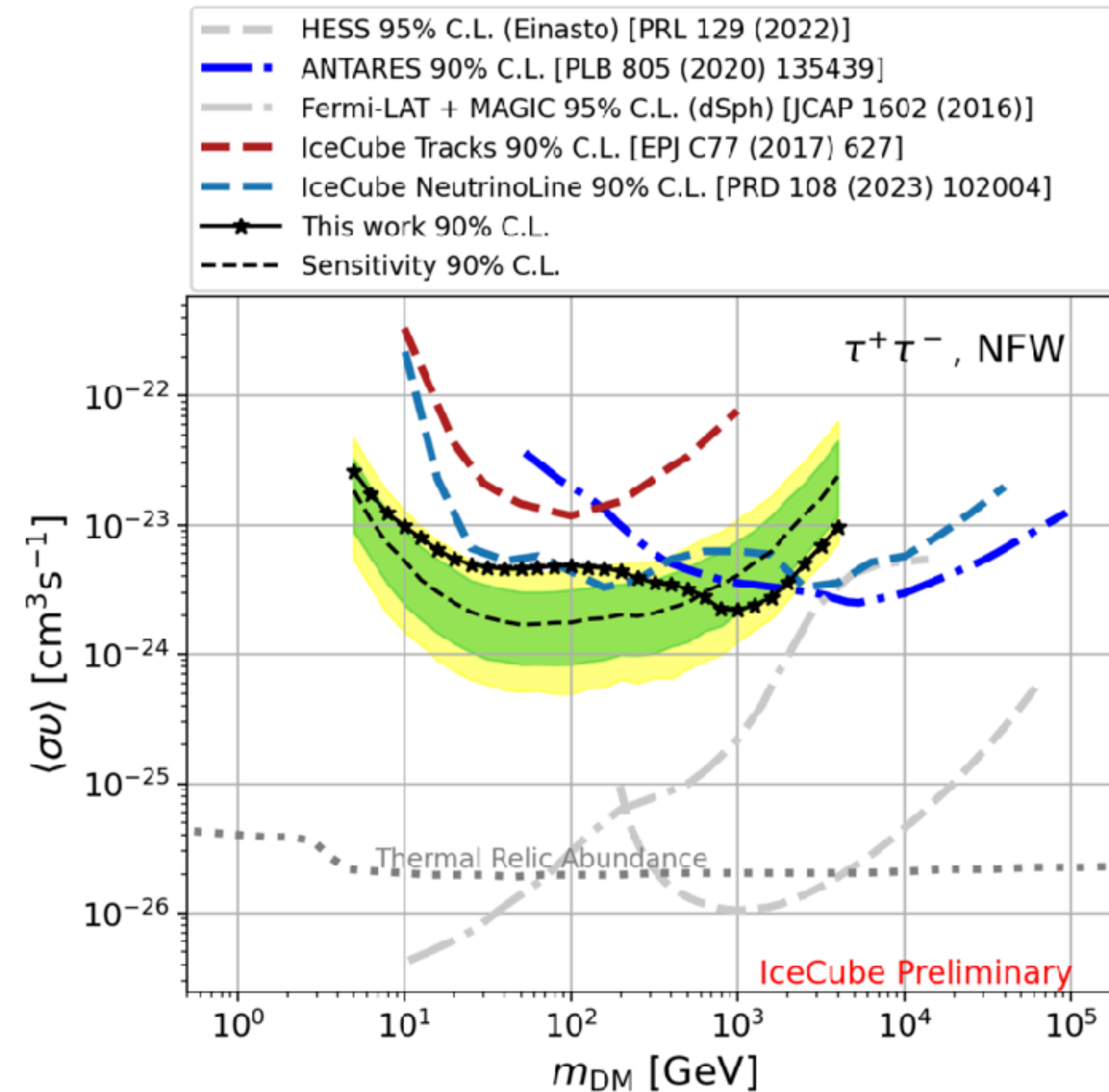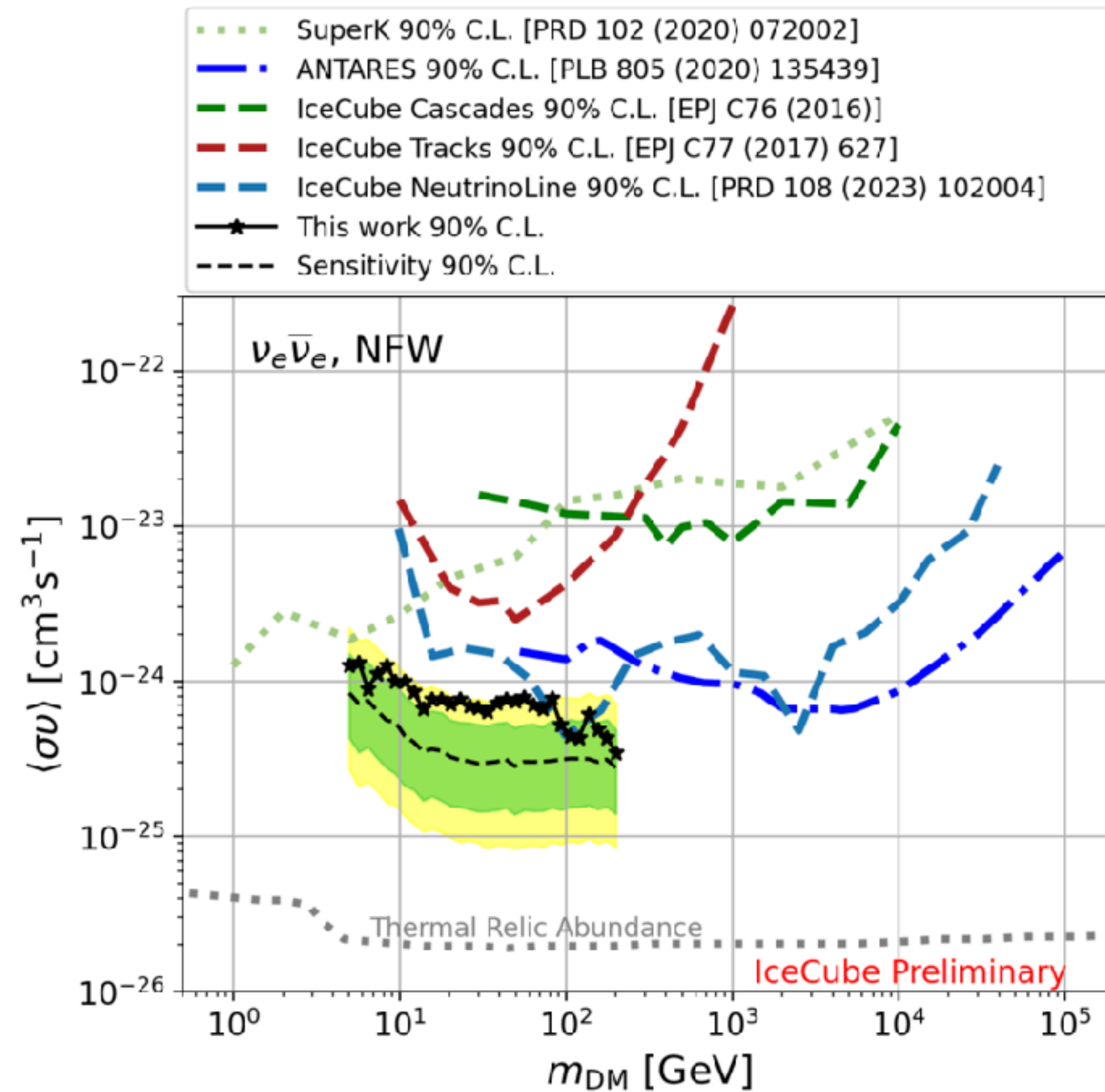
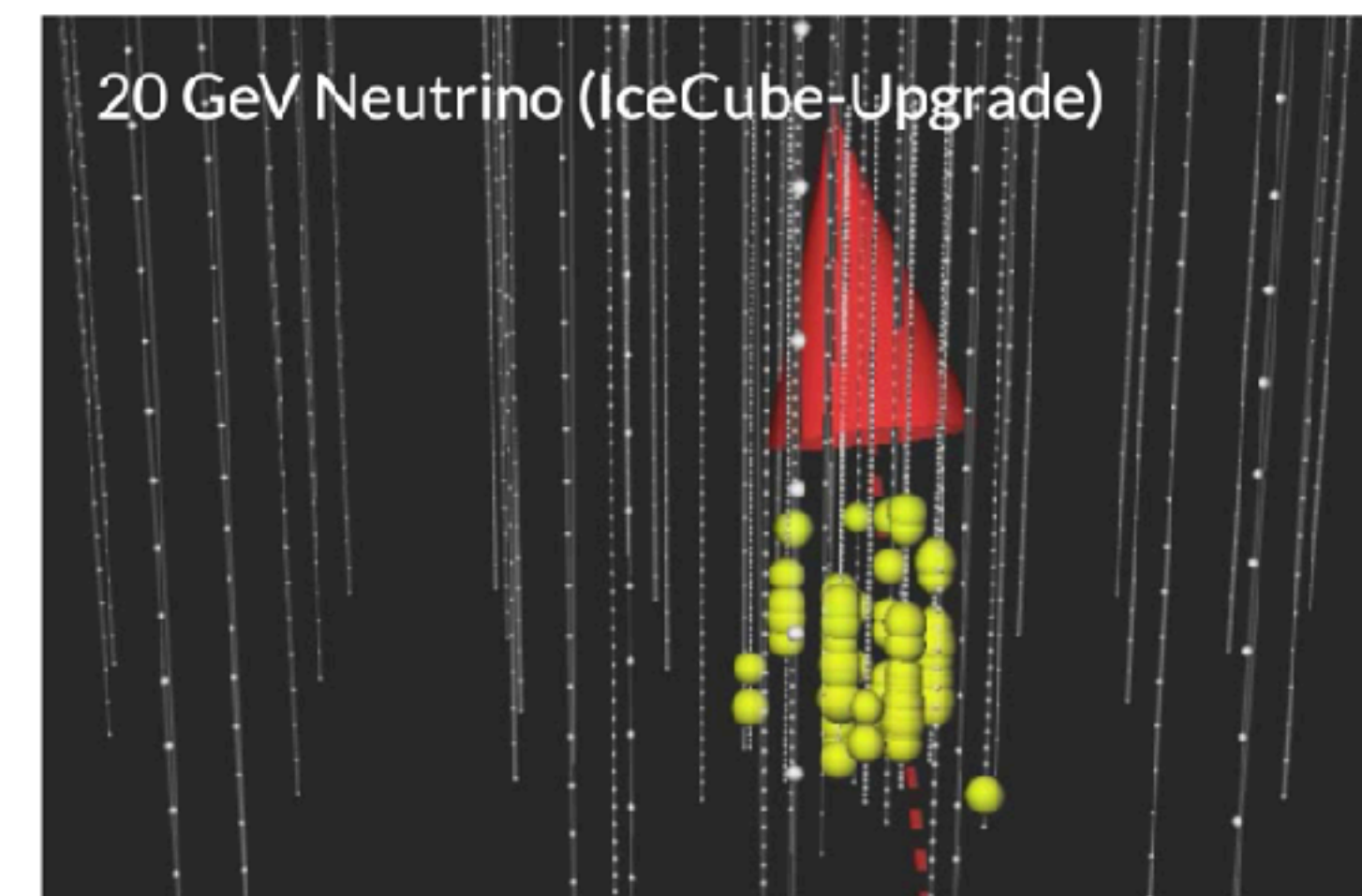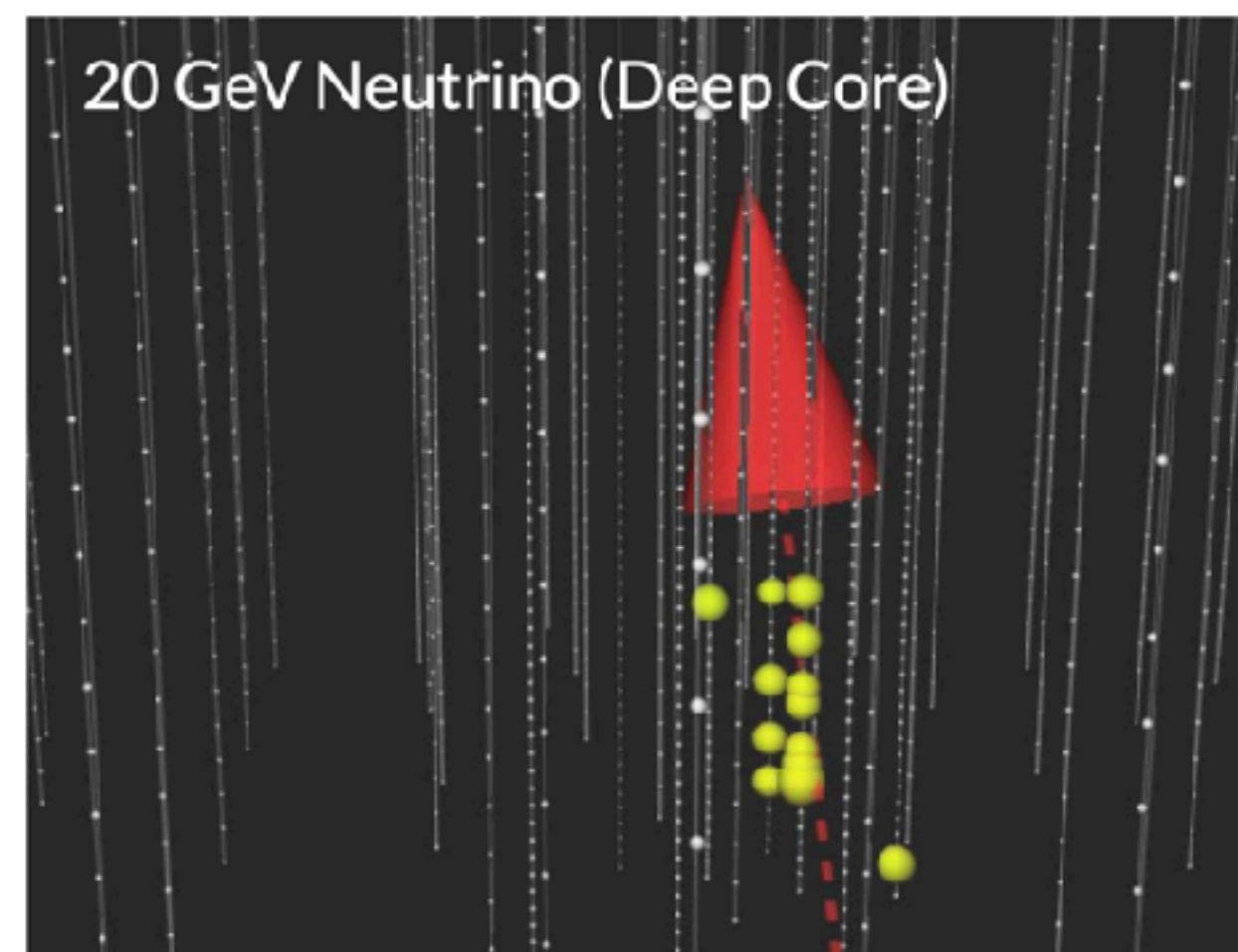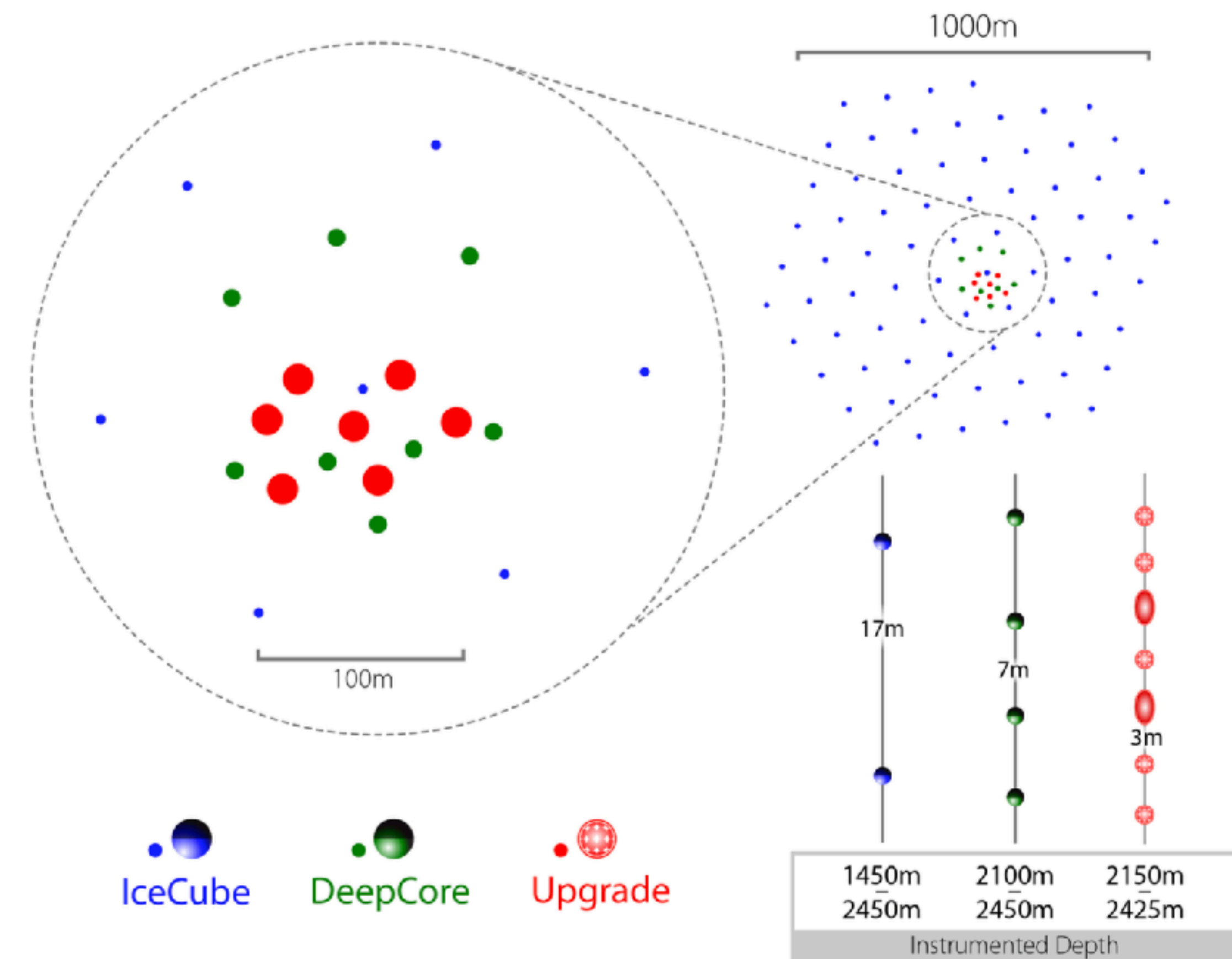
- **Improve the current IC limit** mainly in the **energy range 5 - 100 GeV.**
- **1 order of magnitude** improvement at ~ 10 GeV.
- **Best limit** in **neutrino line channel.**

IceCube Upgrade

- Deployment planed for 2025-2026!

- Extend sensitivity at lower energy.

- Ice calibration, better control of the systematics.

  ‣ Improved energy and angular reconstruction.

- **Objectives:**

  ‣ **Reprocess of existing data** with new calibration/ice model/reconstruction.

  ‣ **Precision measurement of atmospheric neutrino oscillations.**

1000m

17m

7m

3m

| 1450m | 2100m | 2150m |
| 2450m | 2450m | 2425m |

Instrumented Depth

100m

IceCube   DeepCore   Upgrade

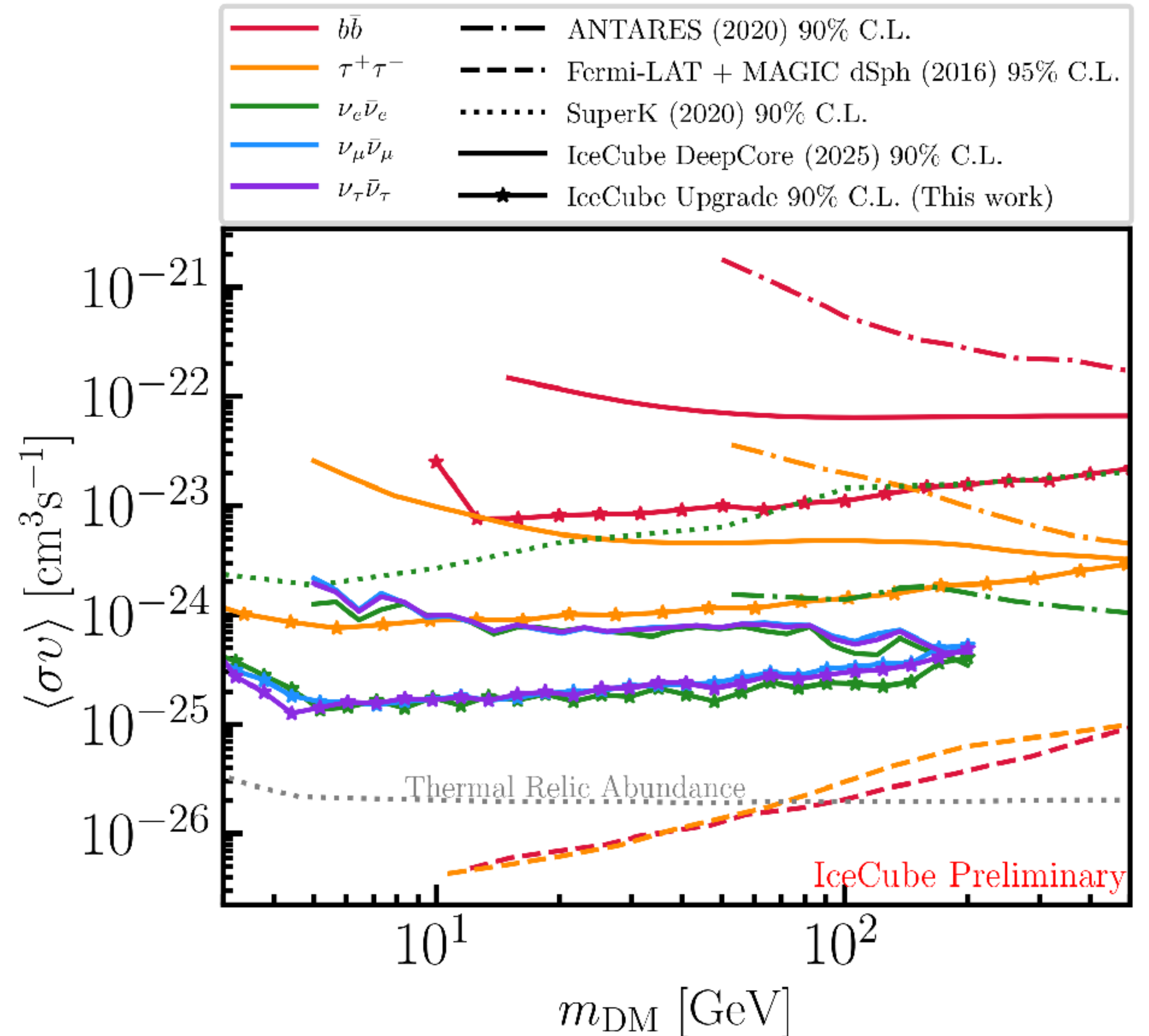20 GeV Neutrino (Deep Core)

20 GeV Neutrino (IceCube-Upgrade)

IceCube Upgrade
Galactic Center DM sensitivity

- Reach to the current level of DeepCore (9 years) within 3 years

- **1 order of magnitude improvement below ~50 GeV**

- **World leading constrains for neutrino lines.**

Conclusions

- **IceCube** can perform **indirect dark matter detection with competitive results** and provide **complementary to other techniques.**

- **IceCube DeepCore** yields **world-leading limits on DM neutrino line signal** and **best limit among neutrino telescopes at GeV-scale DM masses.**

- **Improvement thanks to advancement in understanding the detector.**

- **IceCube Upgrade will come soon and enhance the capabilities of the current IceCube detector.**

Back up

Galactic Plane as a background

- Checking the GP's impact by modifying the likelihood:

$$\mathcal{L}(\xi) = \prod_i Poisson(n_{obs}^i; n_{obs}^{tot} f(i, \xi))$$

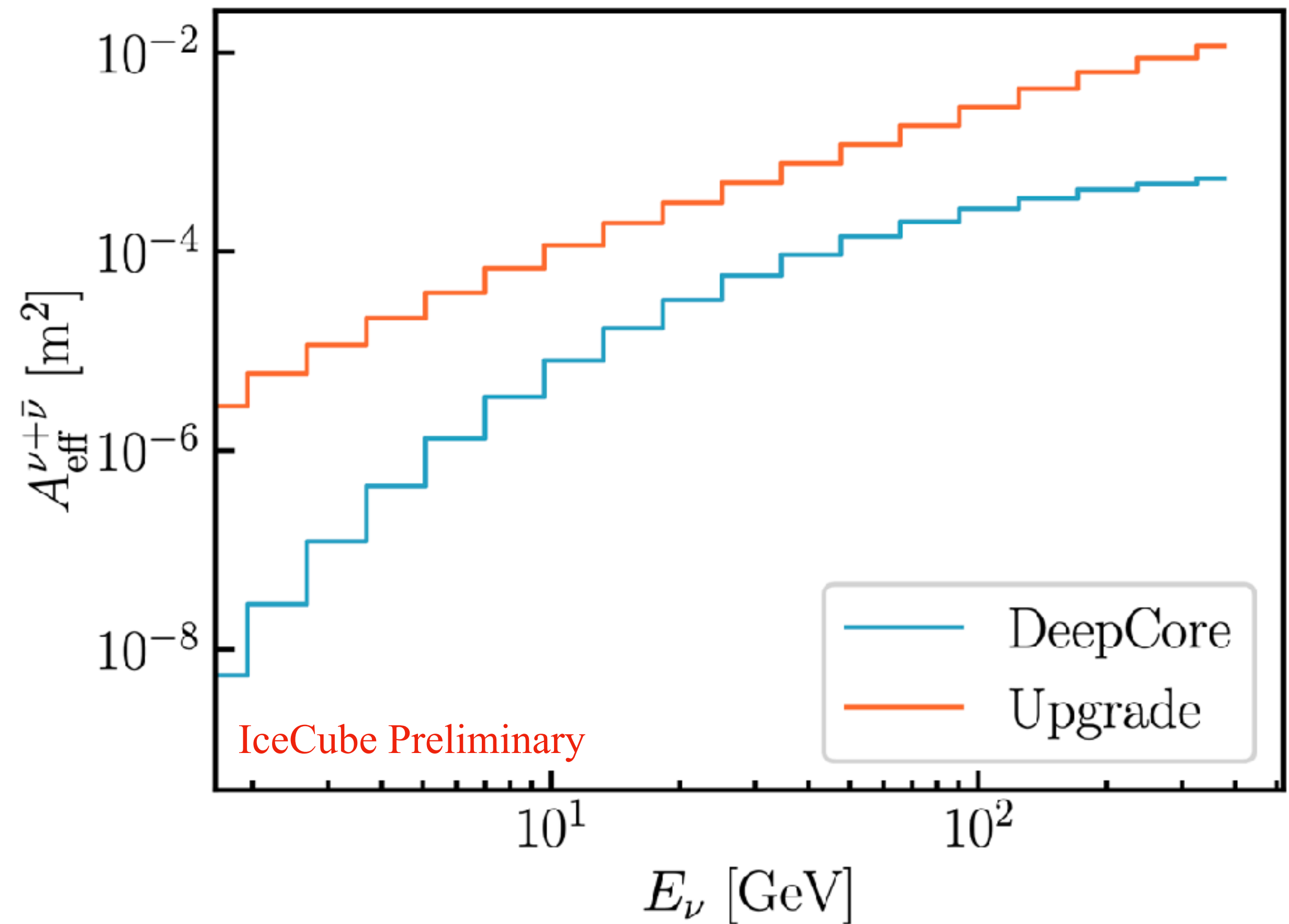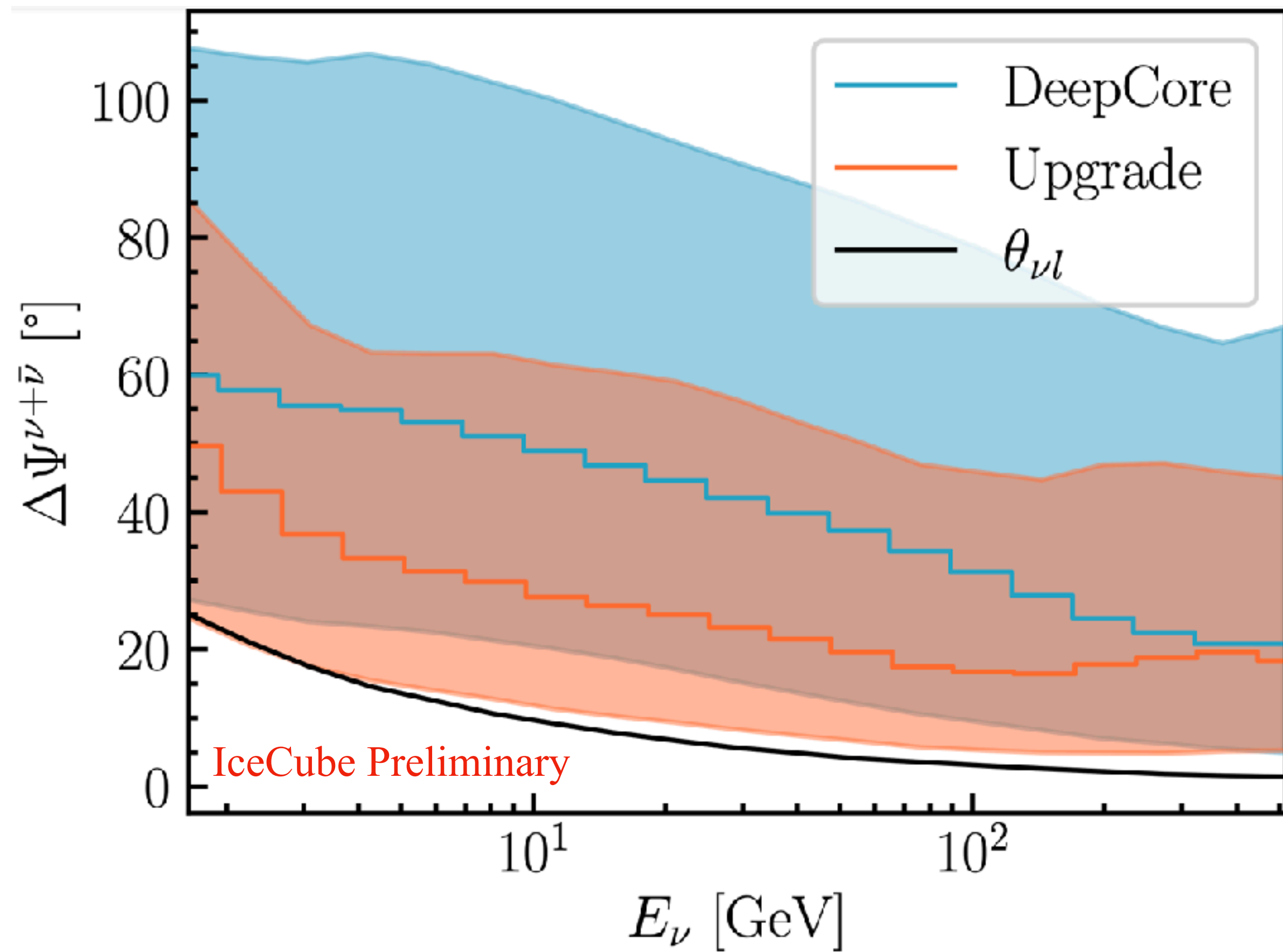$$f(i; \xi) = \xi f_s(i) + n_{GP} f_{GP}(i) + f_{BG}^{scr} - \xi f_s^{scr}(i) - n_{GP} f_{GP}^{scr}(i)$$

- Assuming π_0 and KRA_γ templates and power-law extrapolation from TeVs down to GeVs

  ‣ ~ 0.01% contribution, well below 90% C.L DM sensitivity

- No feasible impacts on sensitivity at GeV range compare to stat. fluctuation!

  ‣ Unblind without GP

  ‣ post-unblinding checks with GP also show no feasible impacts

✳ GP emission will need to be included for DM searches in TeV energies

Results - Limits
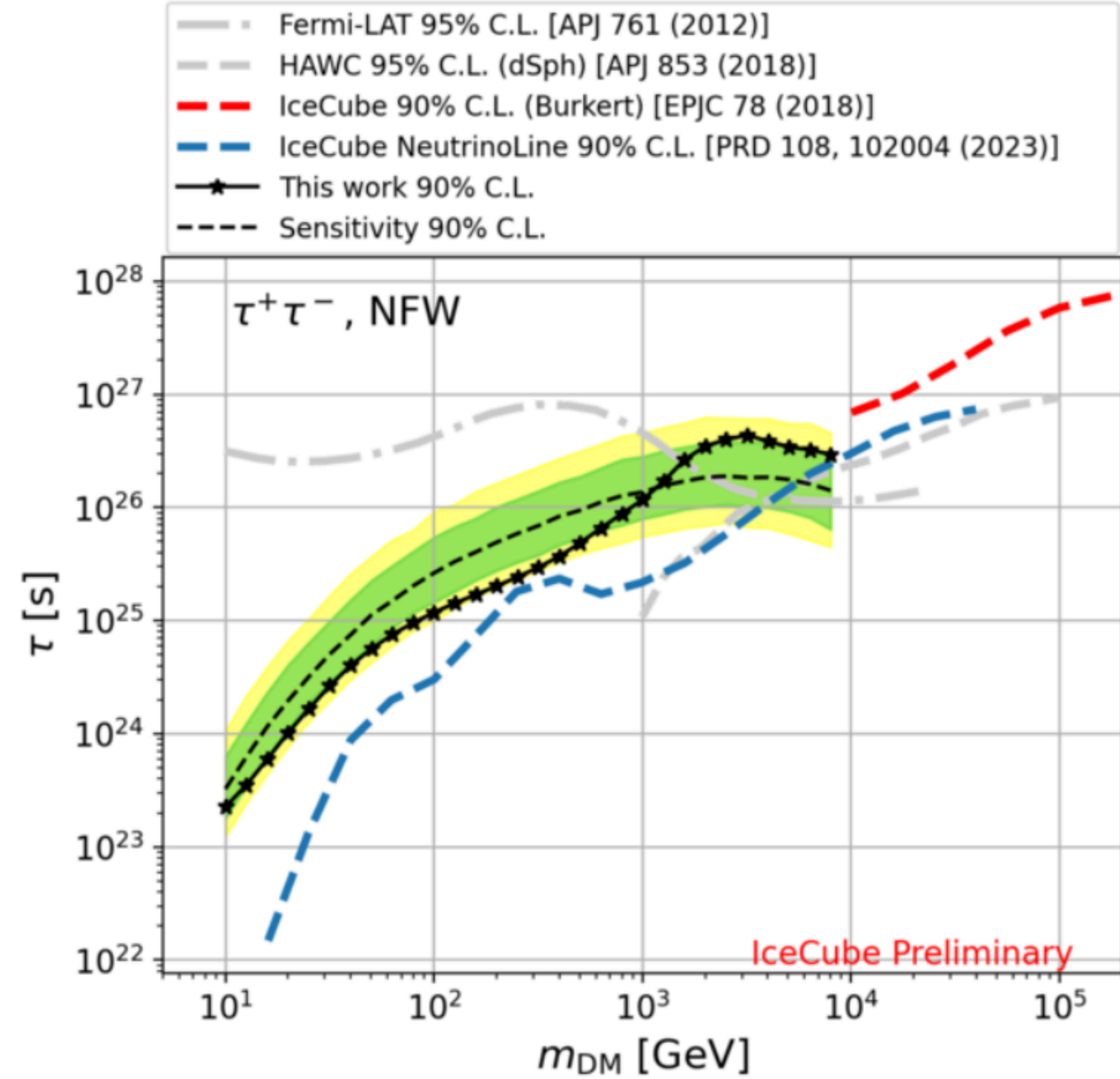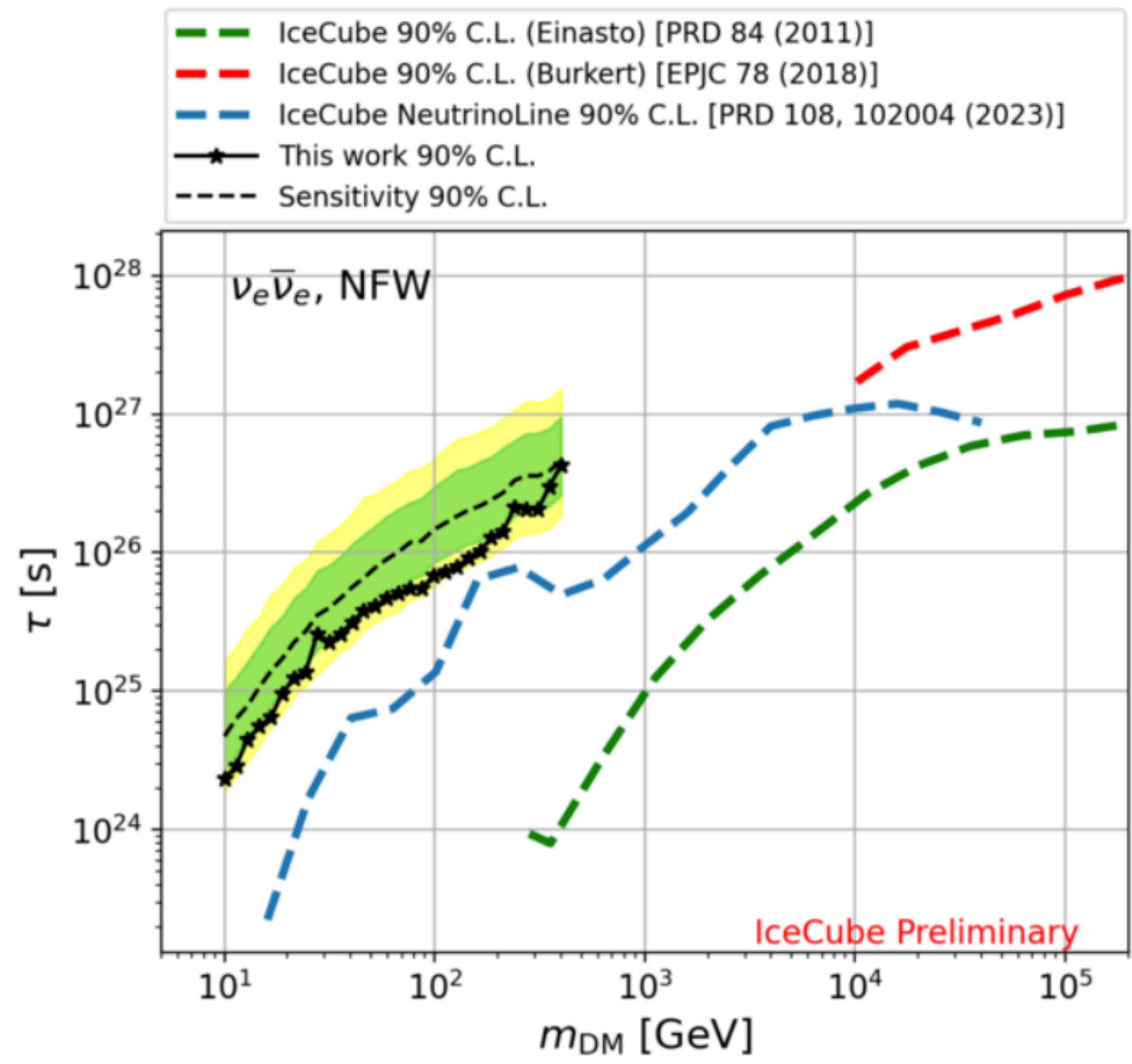
Upgrade vs DeepCore

Upgrade Analysis