



ICECUBE

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ULB

Indirect searches for dark matter in the Galactic Center with IceCube-DeepCore and IceCube-Upgrade

Nhân Châu
on behalf of the IceCube Collaboration

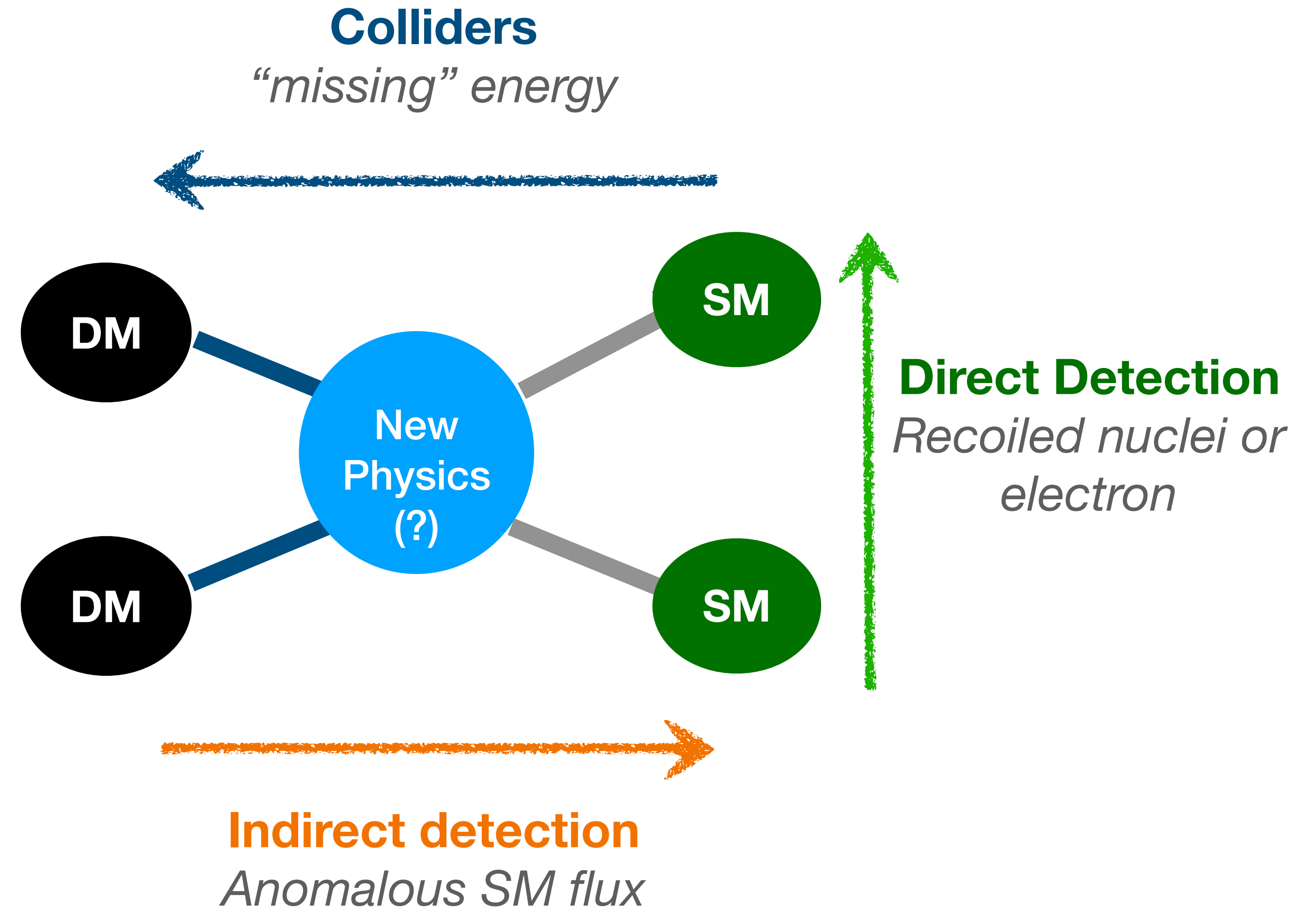
35th Rencontres de Blois - October 21-25, 2024

Detection of Dark Matter

Assumptions:

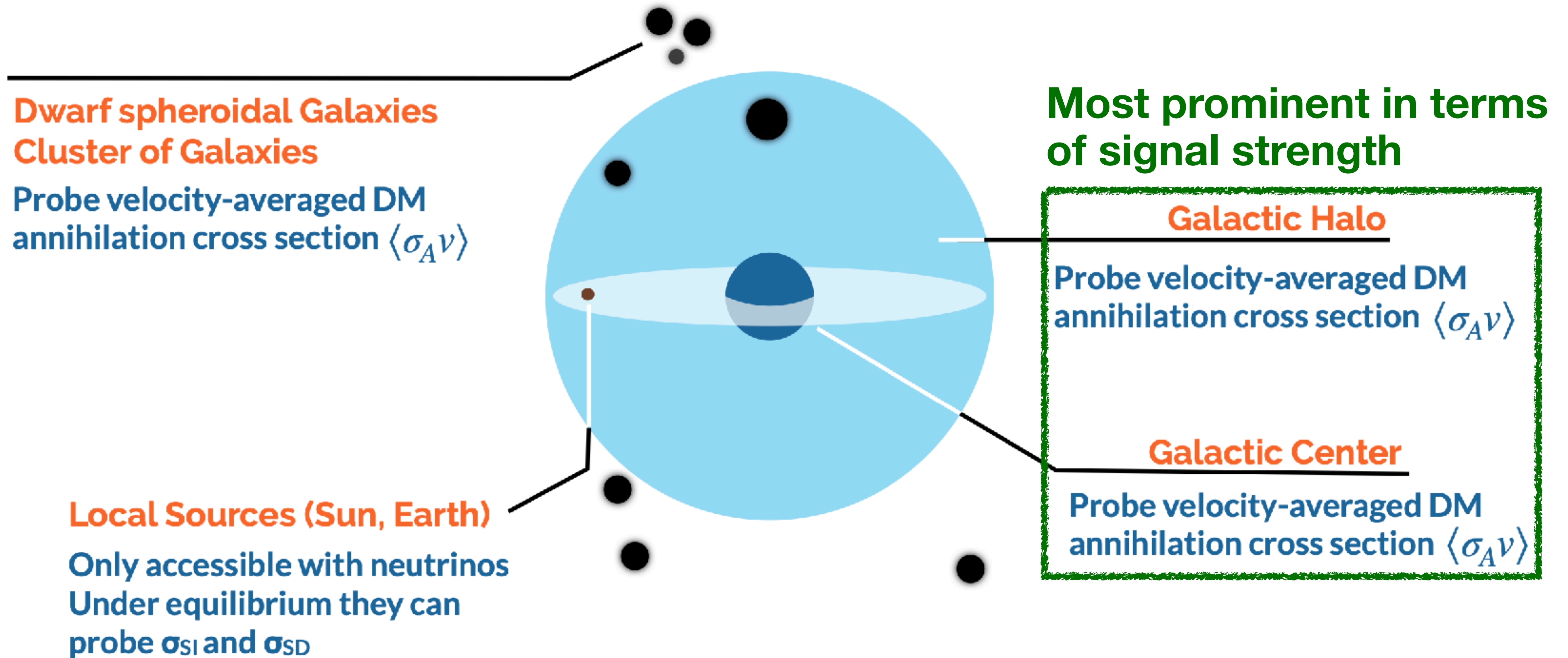
- The **particle solution** to the dark matter problem
- **Can interact (weakly) with Standard Model Particles (ordinary matter)**
- Cold and stable

 Wide class of candidates and interaction ranges

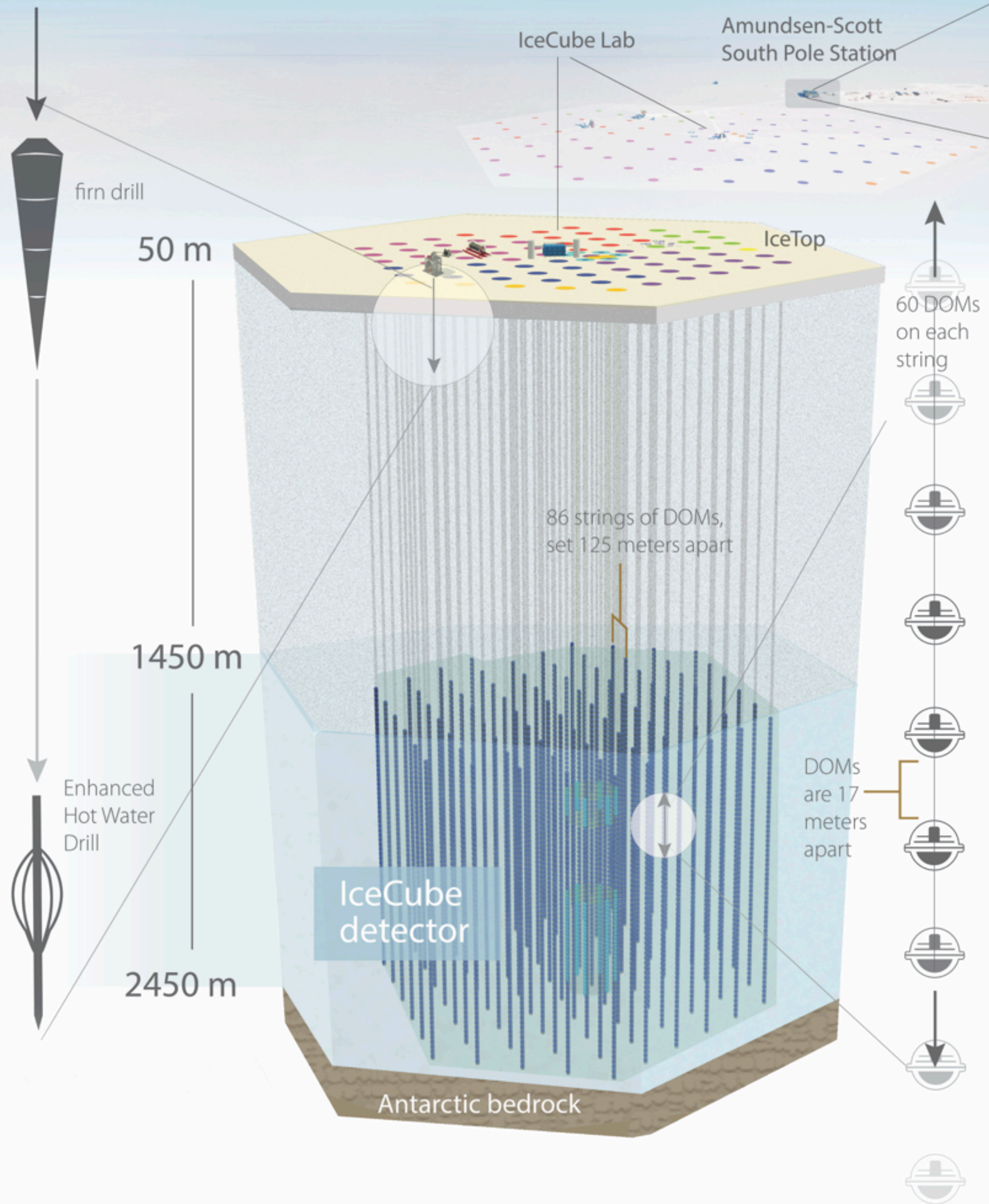


Indirect Detection of Dark Matter

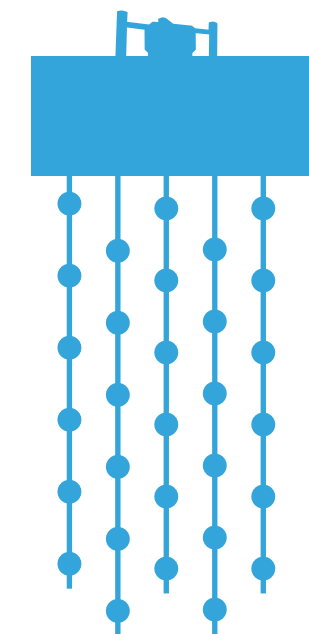
- Looking for **anomalous SM flux** from **large reservoir of Dark Matter**.
- Astrophysical objects as potential sources- make use of **the existing telescopes**.



IceCube Neutrino Observatory



5,160 Digital Optical Modules (DOMs)



86 string with 60 DOMs each
6 denser strings called **DeepCore**



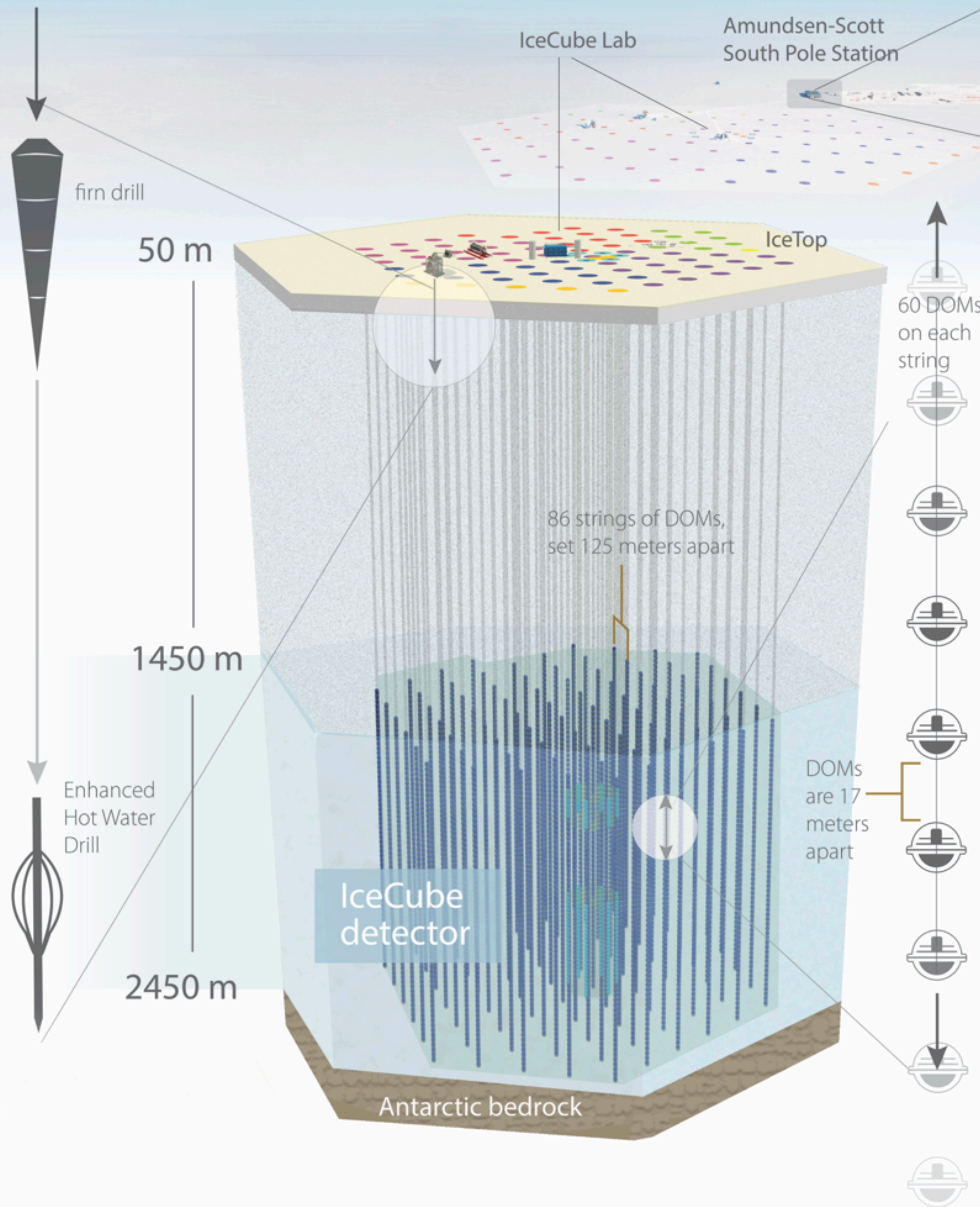
1 km² surface array with 324 DOMs: **IceTop**



Completion in December 2010

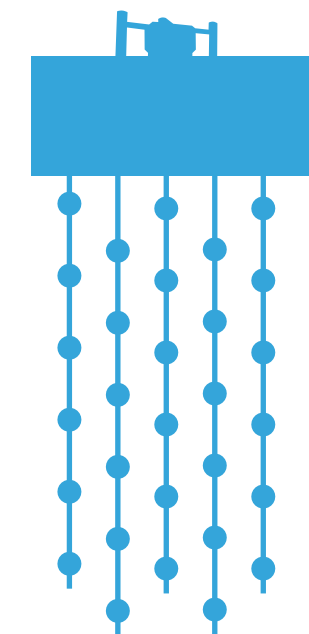


IceCube Neutrino Observatory

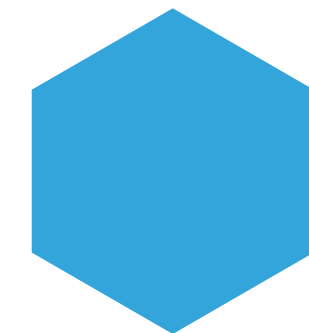


5,160 Digital Optical Modules (DOMs)

TeV-peV
86 string with 60 DOMs each



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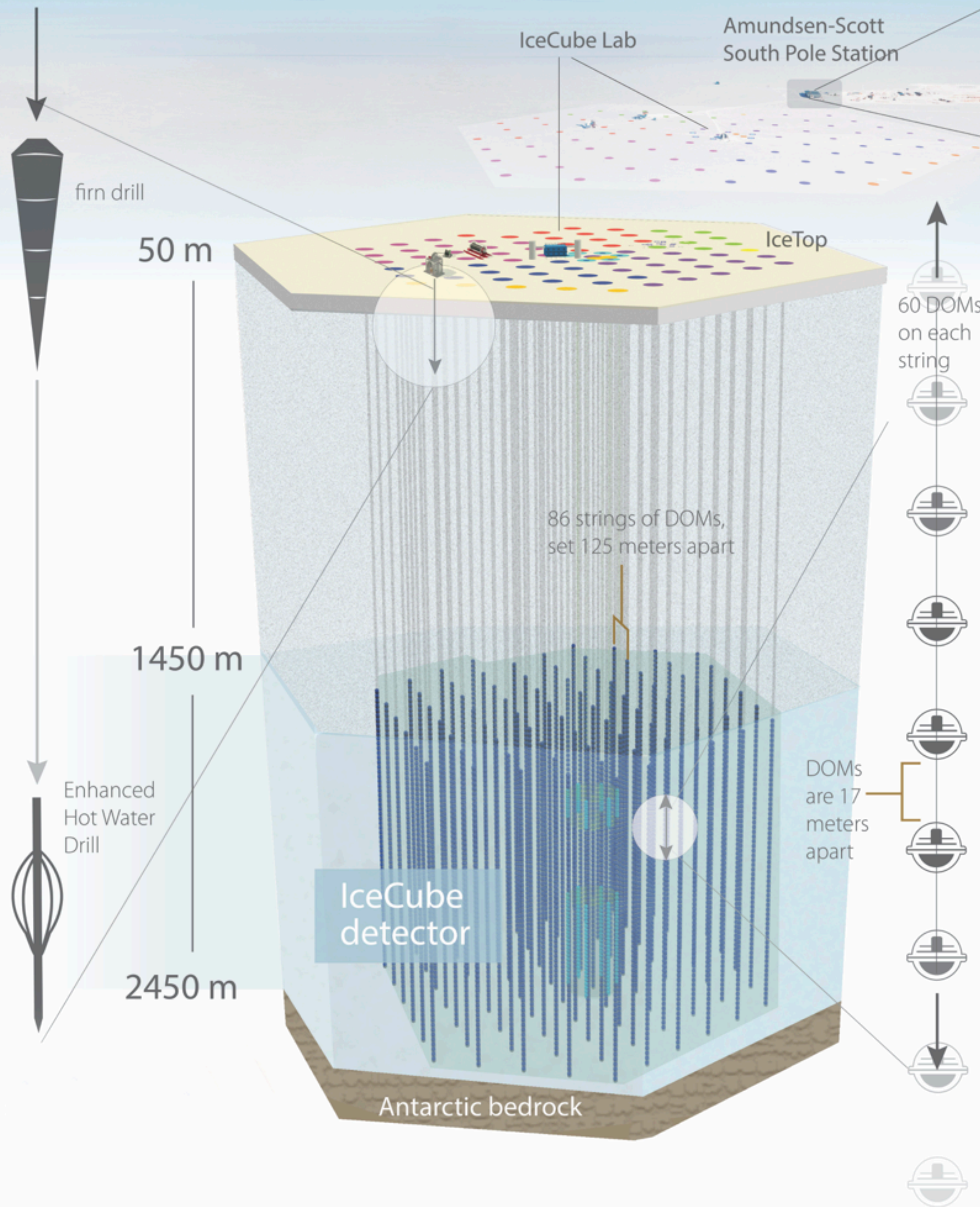
1 km² surface array with 324 DOMs: IceTop



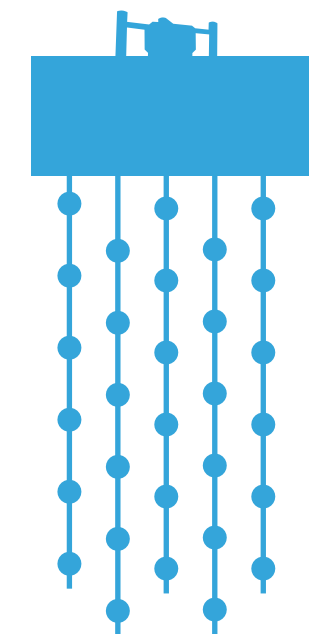
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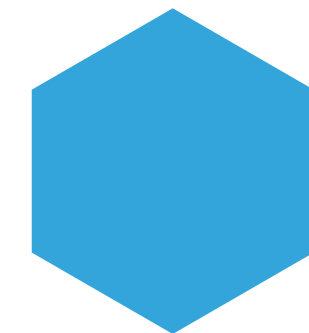
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Down to GeV-scale



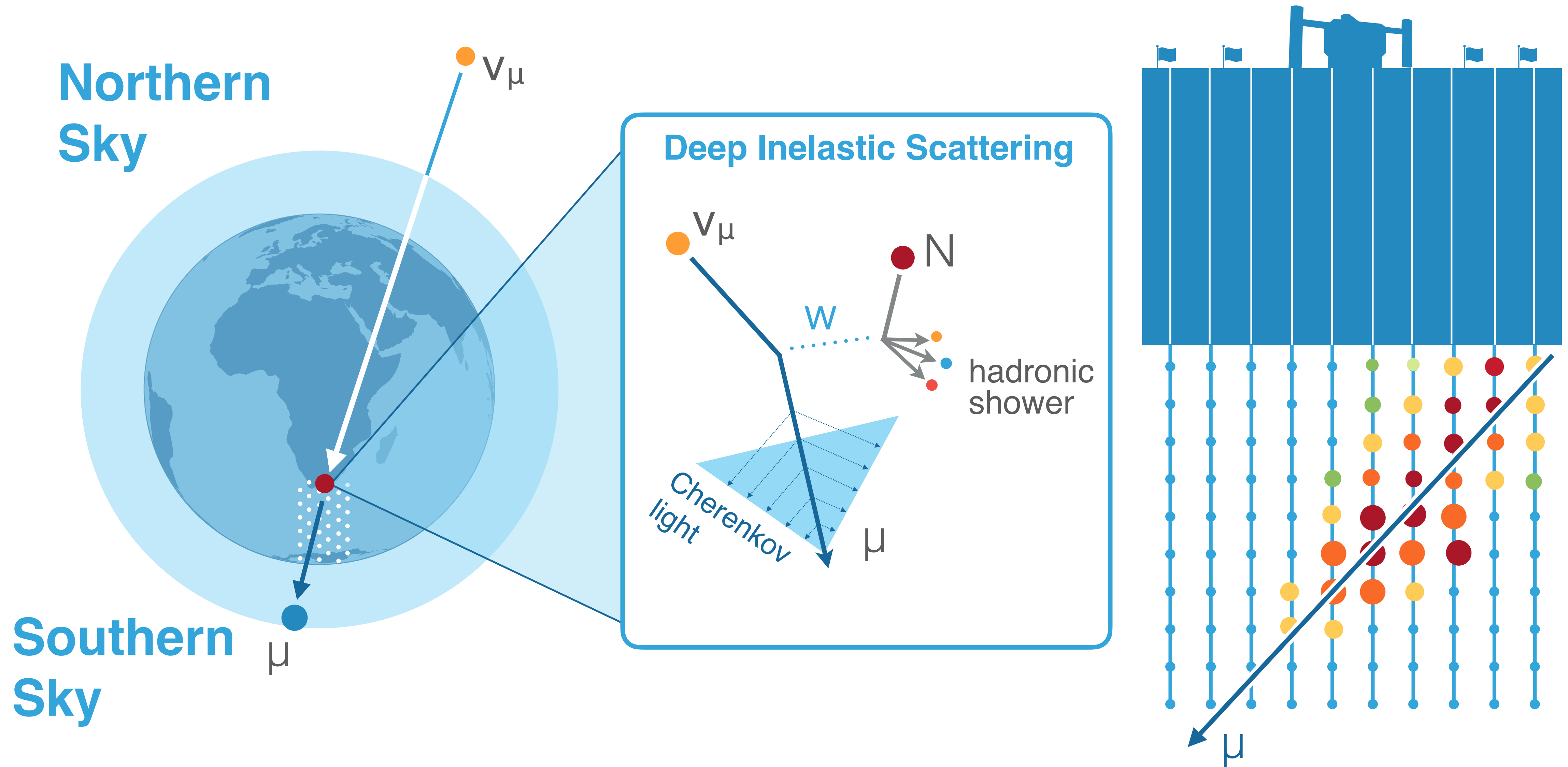
1 km² surface array with 324 DOMs: IceTop



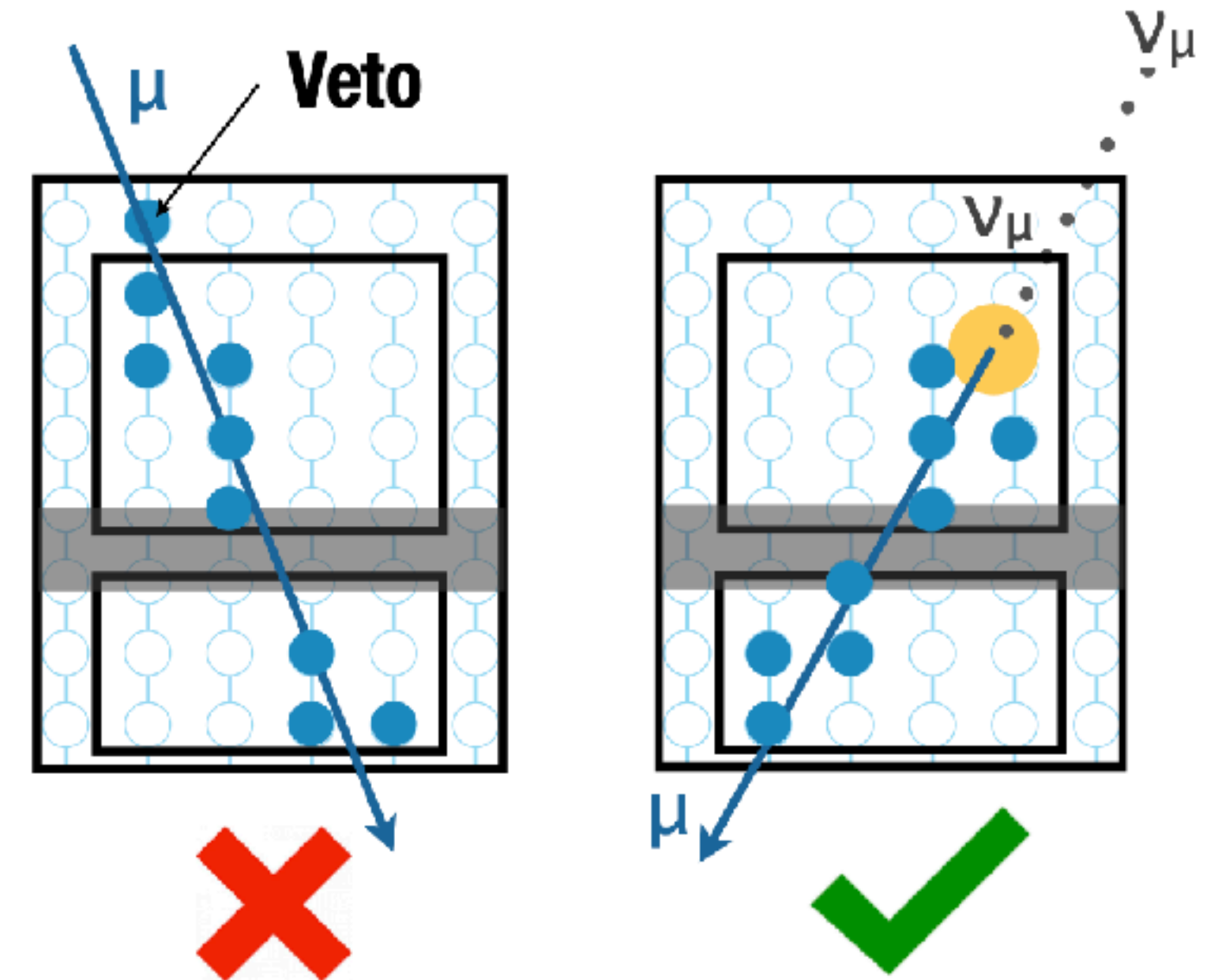
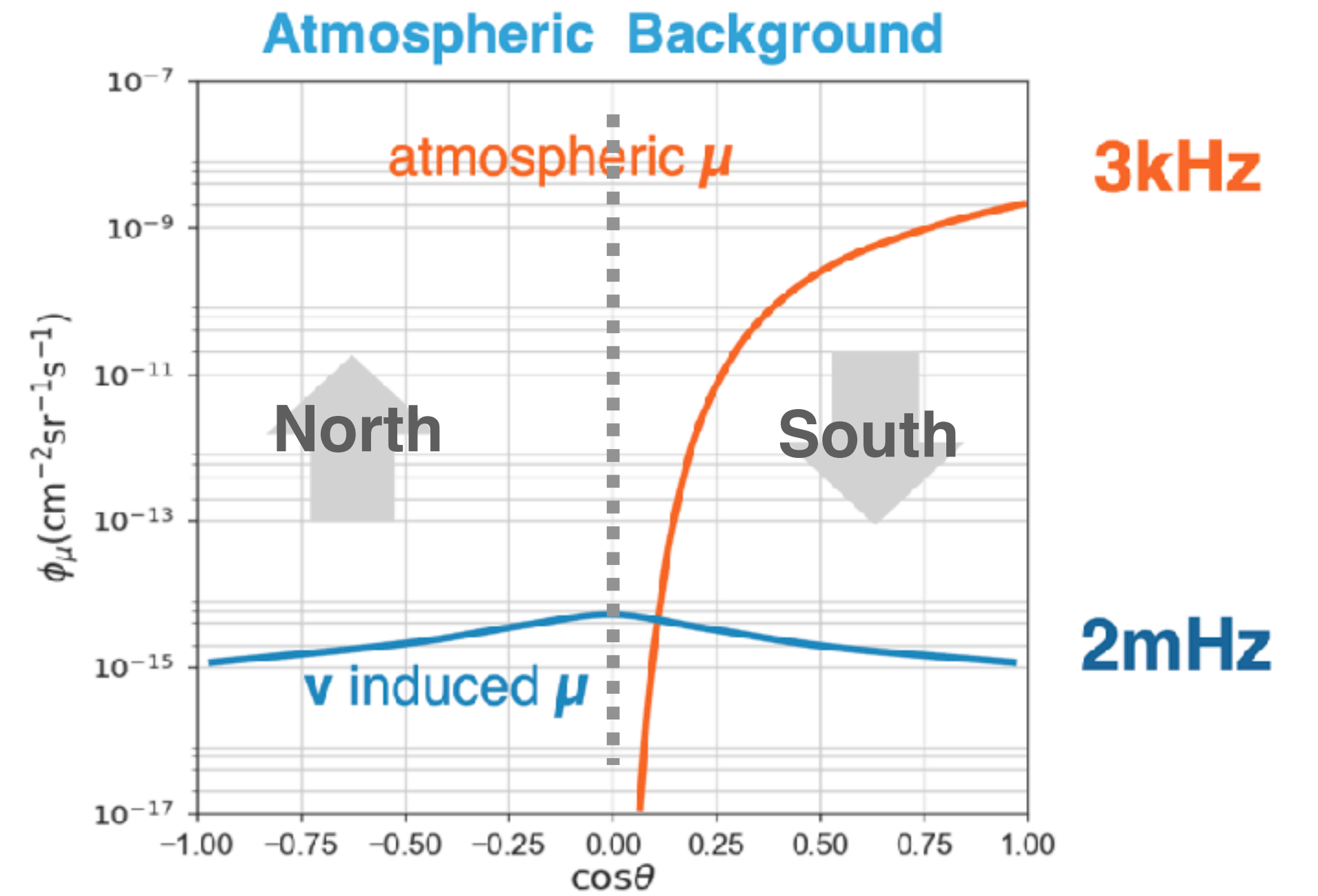
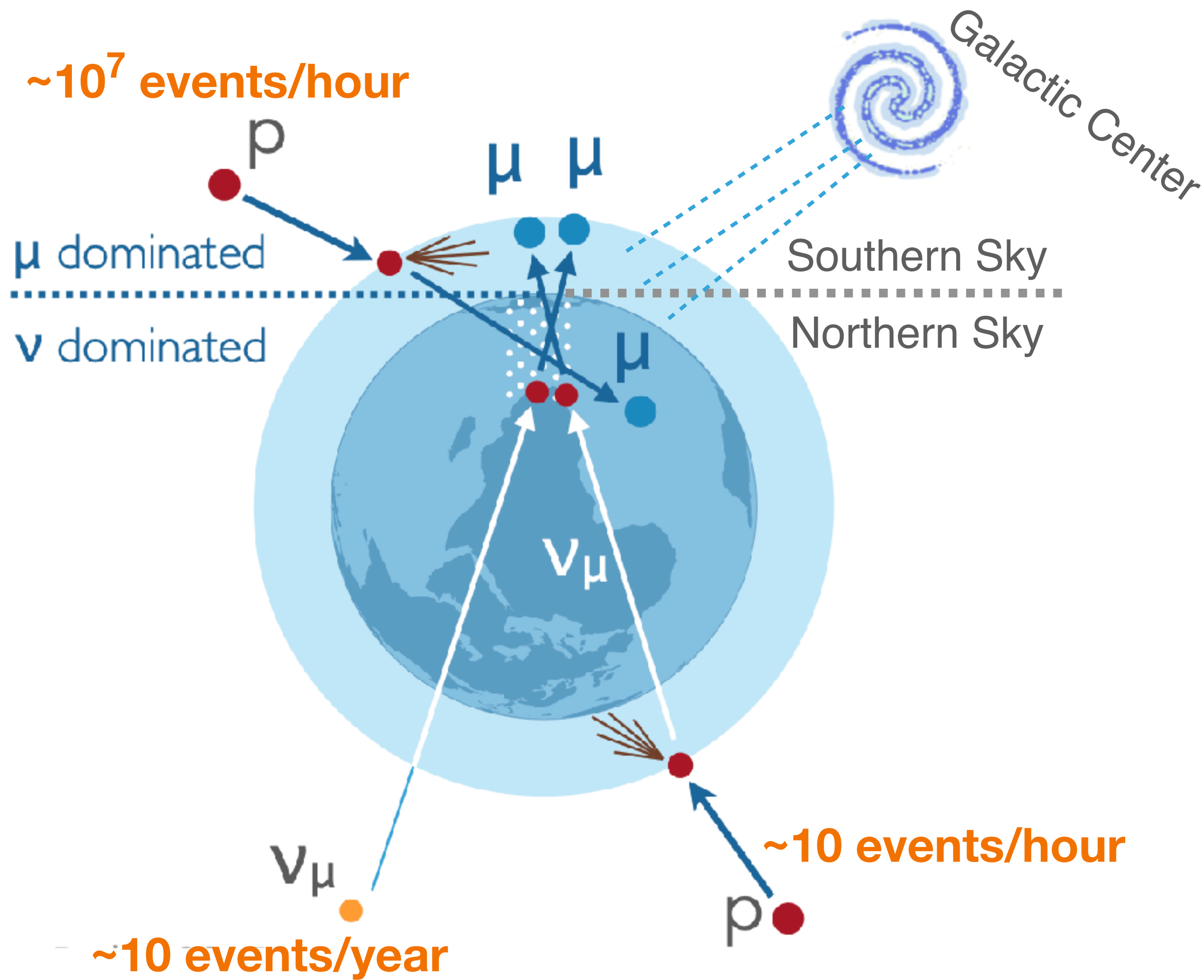
Completion in December 2010



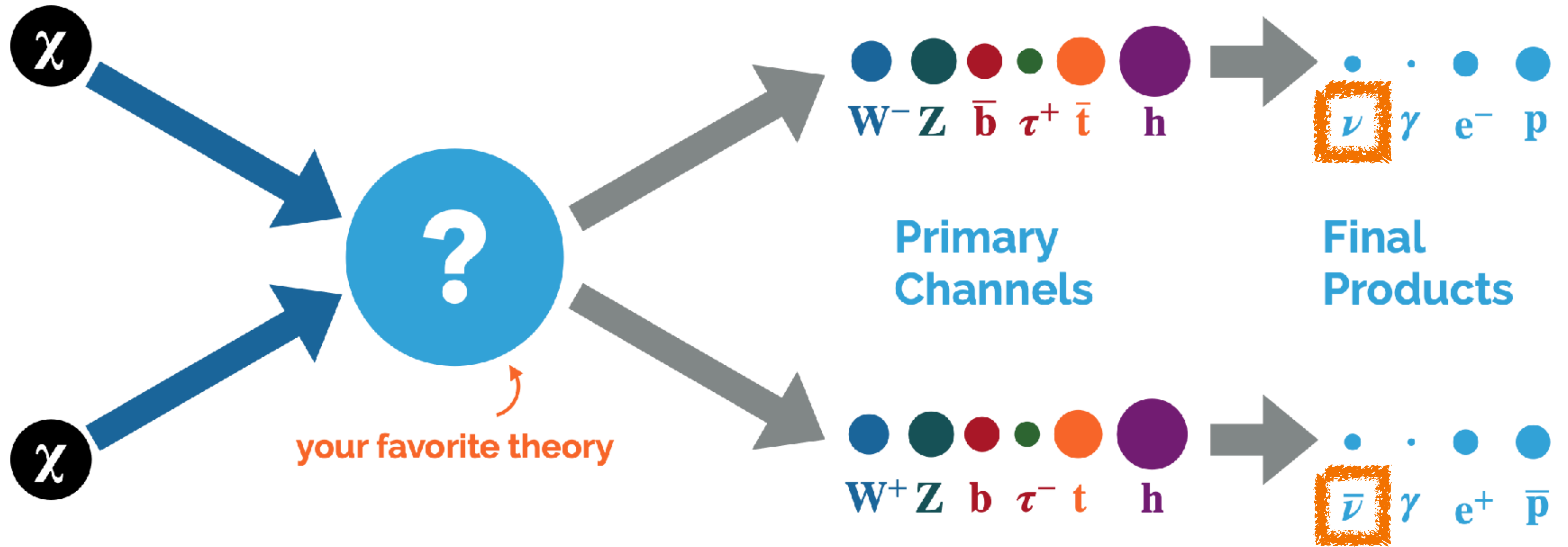
Detection Principle



Detection Principle - background rejection



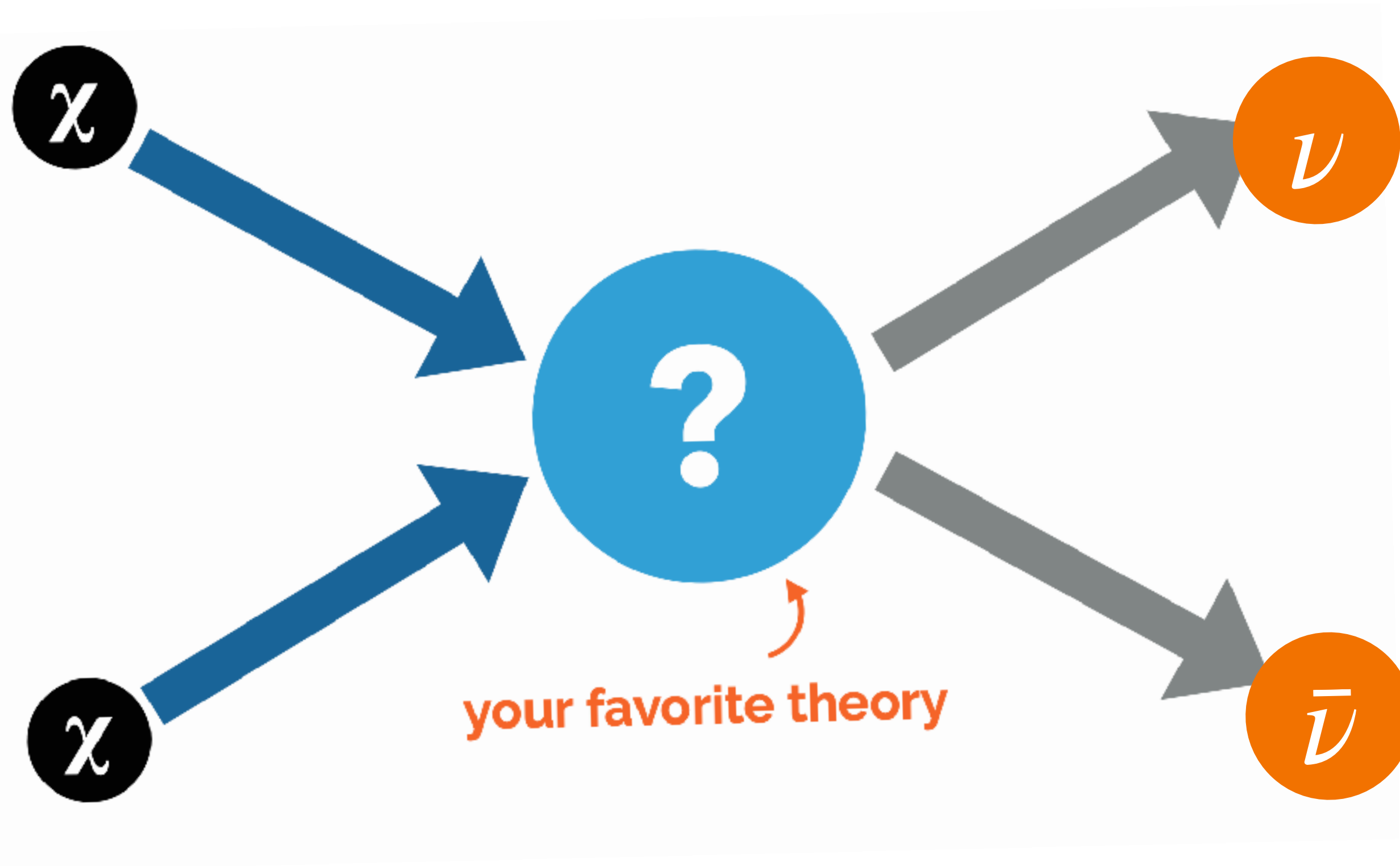
Indirect Search for Dark Matter with IceCube



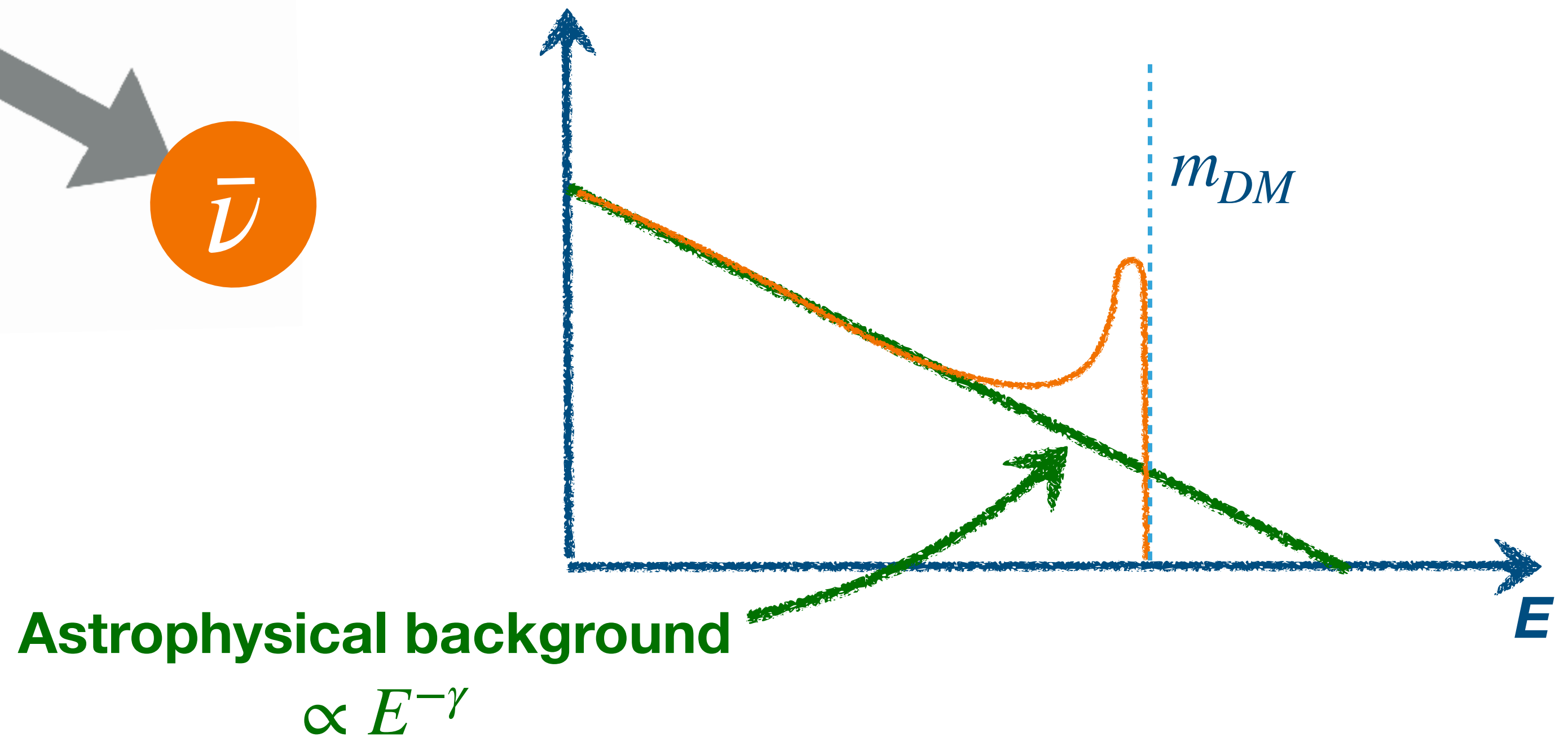
- Look for **anomalous neutrino flux** from **large reservoir of Dark Matter**

Indirect Search for Dark Matter with IceCube

Neutrino lines



- ▶ Direct annihilation/decay into neutrino pairs.
- ▶ Sharp peak in energy at DM mass.
- ▶ Distinctive from astrophysical background, smoking gun DM signature.
- ▶ Rely on energy resolution!



Dark Matter Signal from Galactic Center

Particle physics
Energy dependent

Astrophysical input
Density profile of the source
Directional information

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

$$\frac{1}{4\pi} \frac{1}{m_\chi \tau} \frac{dN_{\nu_\alpha}}{dE} \int_{l.o.s} \rho(\vec{r}) ds$$

Annihilation

Decay

DM signal
Inferred from observation

Physics parameters ~
What we want to measure/constrain!

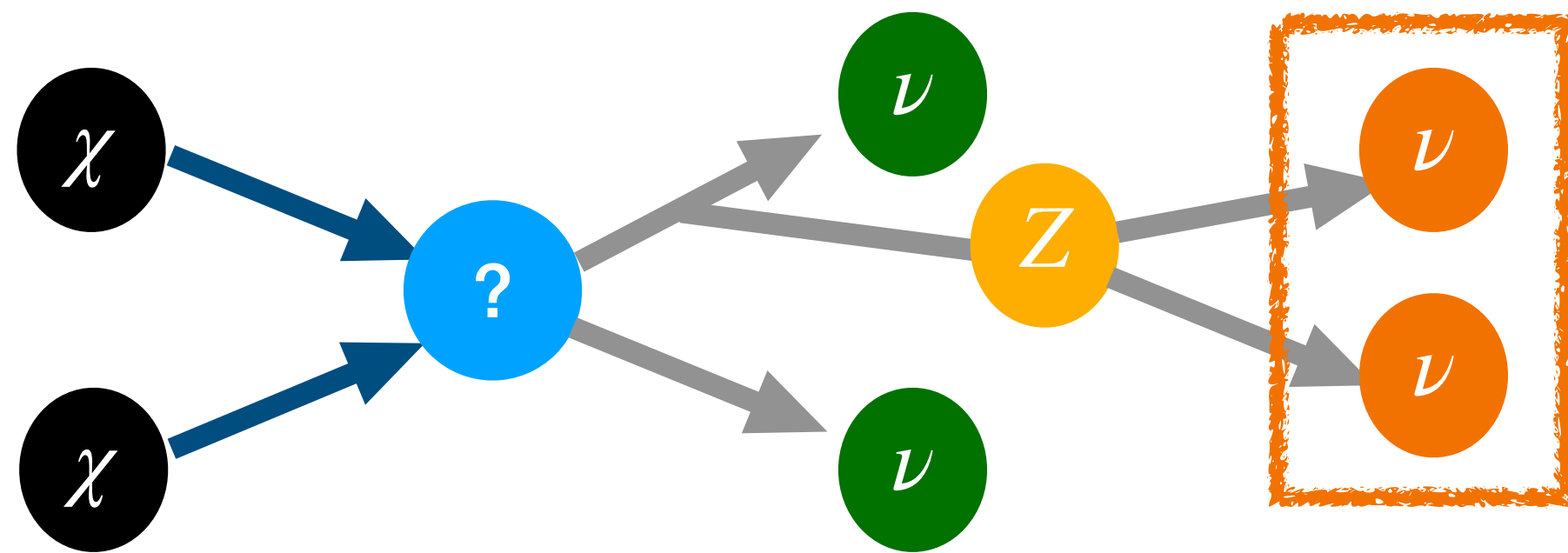


Dark Matter Signal from Galactic Center

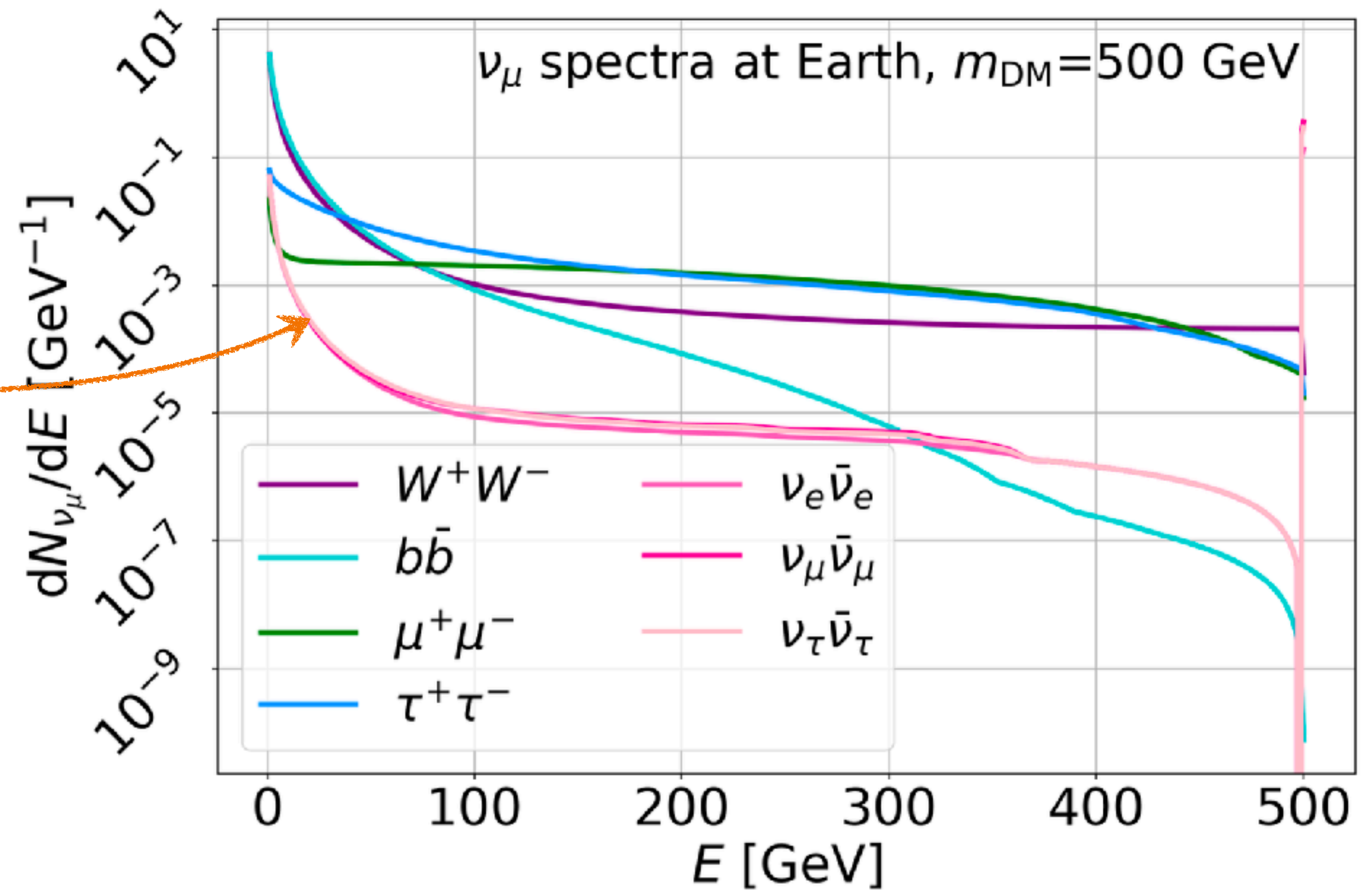
$$\frac{d\phi_{\nu_\alpha}}{dEd\Omega} = \frac{1}{4\pi} \frac{\langle \sigma_a v \rangle}{2m_{\text{DM}}^2} \frac{dN_{\nu_\alpha}}{dE} \int_{l.o.s} \rho^2(\vec{r}) ds$$

- Spectra computed with *χarou*
[arXiv:2007.15010v2](https://arxiv.org/abs/2007.15010v2)

➔ Couple Pythia with the state-of-the-art EW correction - [JHEP 06 \(2021\) 121](https://arxiv.org/abs/2007.15010v2)



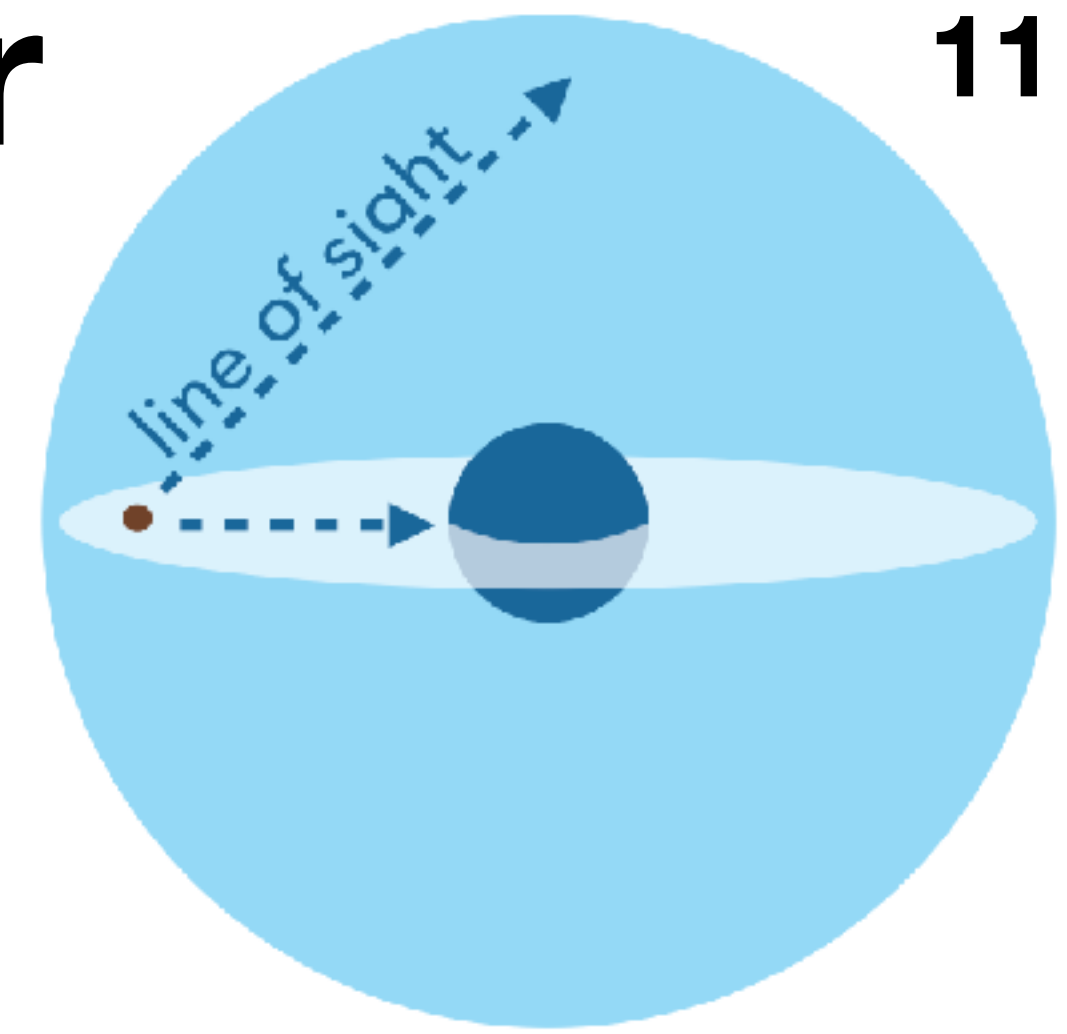
- Assuming 100% BR for each primary channel
- Propagation to the Earth assuming averaged oscillation



Dark Matter Signal from Galactic Center

11

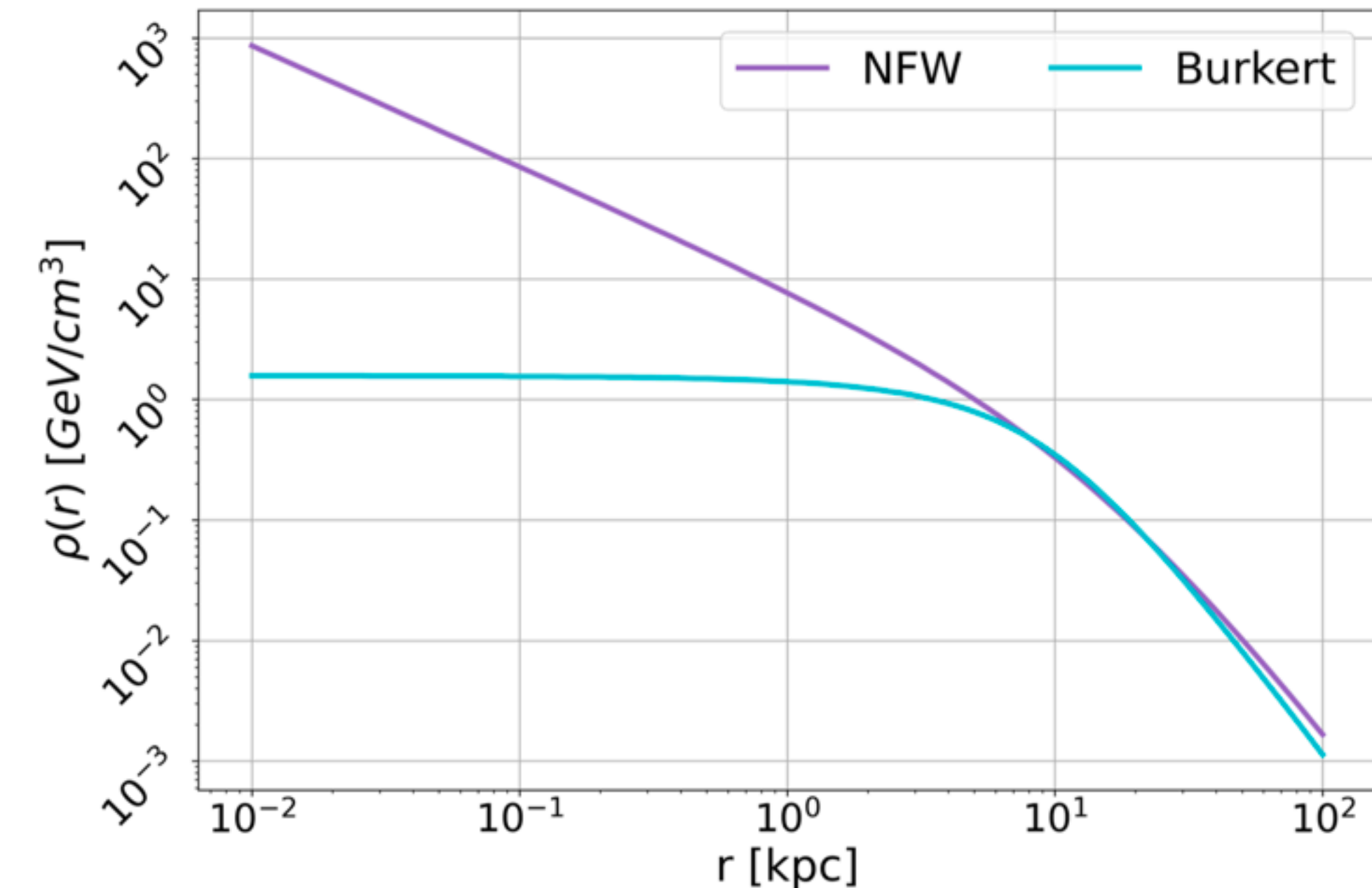
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- **J-factor**: Integration of DM profile along the line-of-sight

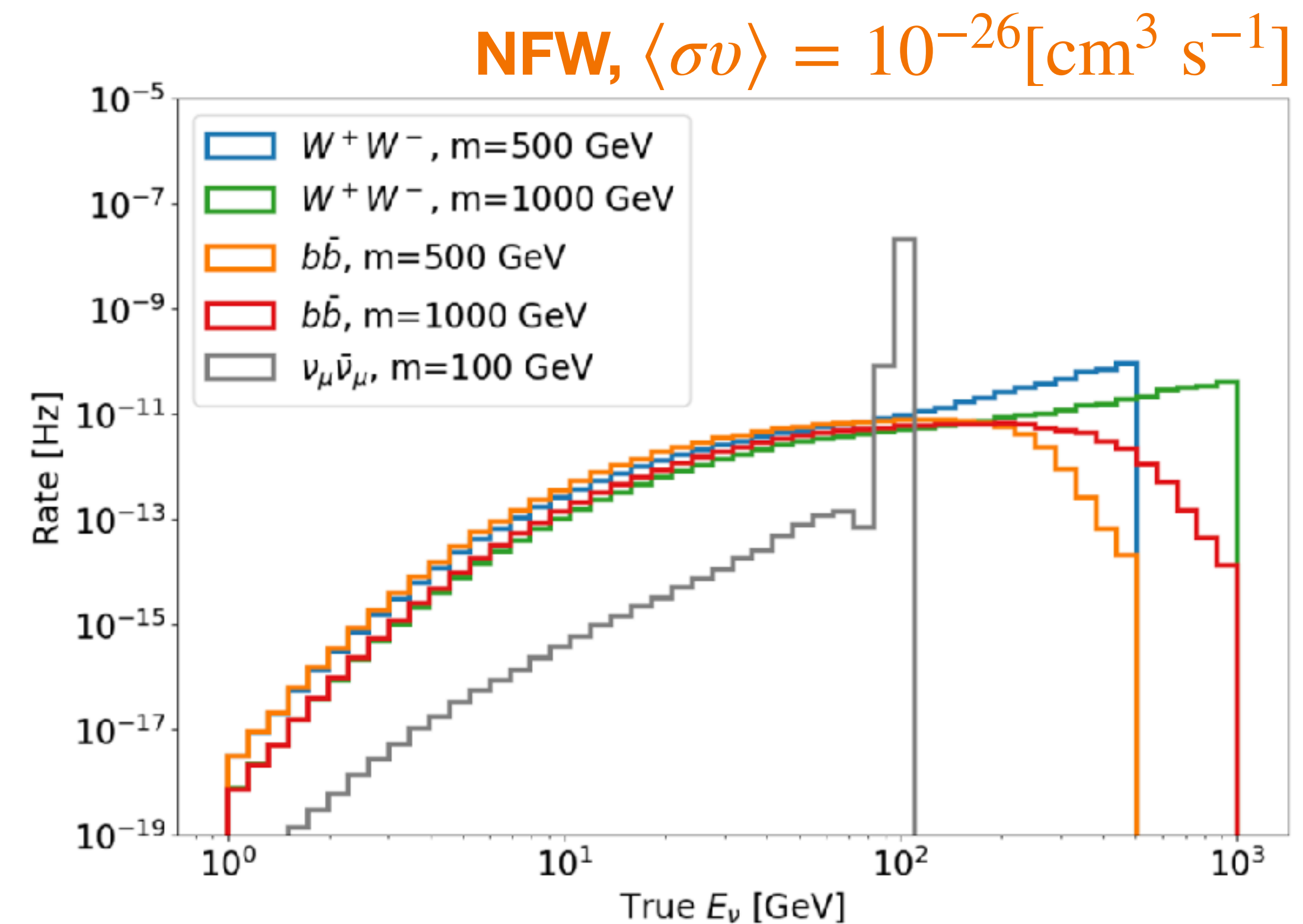
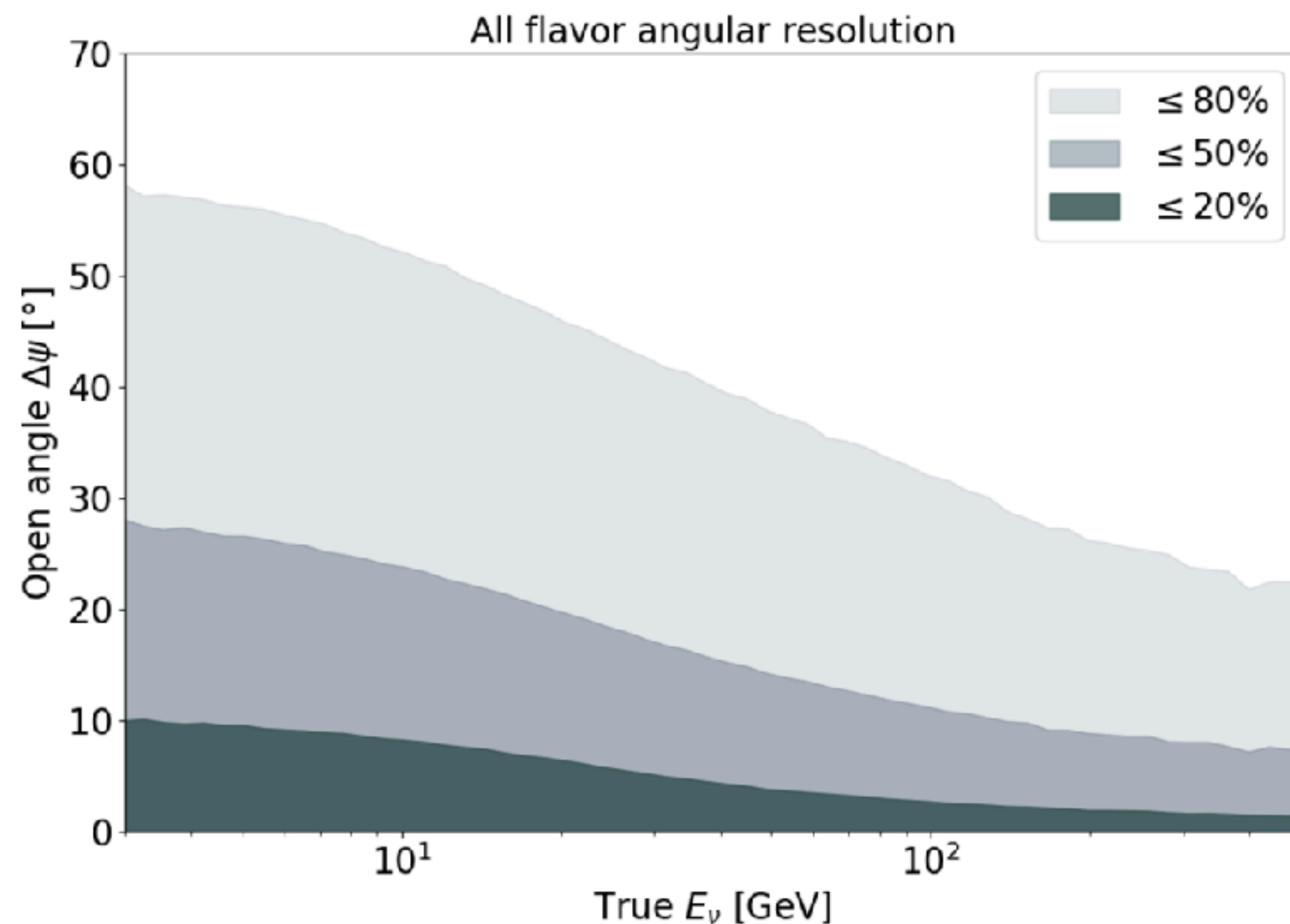
$$J(\Psi) = \int_{\Delta\Omega} d\Omega(\Psi) \int_0^{l_{max}} \rho_{\text{DM}}^2(r(l, \Psi)) dl$$

- Computed with **Clumpy** ([arXiv:1806.08639](https://arxiv.org/abs/1806.08639)) for 2 parametric profiles:
NFW and **Burkert**
- Parameter values for the Milky Way taken from Nesti&Salucci ([arXiv:1304.5127](https://arxiv.org/abs/1304.5127))



Dark Matter search in the Galactic Center

- Search for signal of dark matter annihilation/decay in the Galactic Center using IceCube.
- Using most up-to-date data sample of IceCube/DeepCore (9.3 years 2012-2022).
 - Targeting low energy dark matter mass (GeV up to \sim TeV).
 - Multiple advancement in understanding the detector lead to the optimisation for the detection of GeV neutrinos.

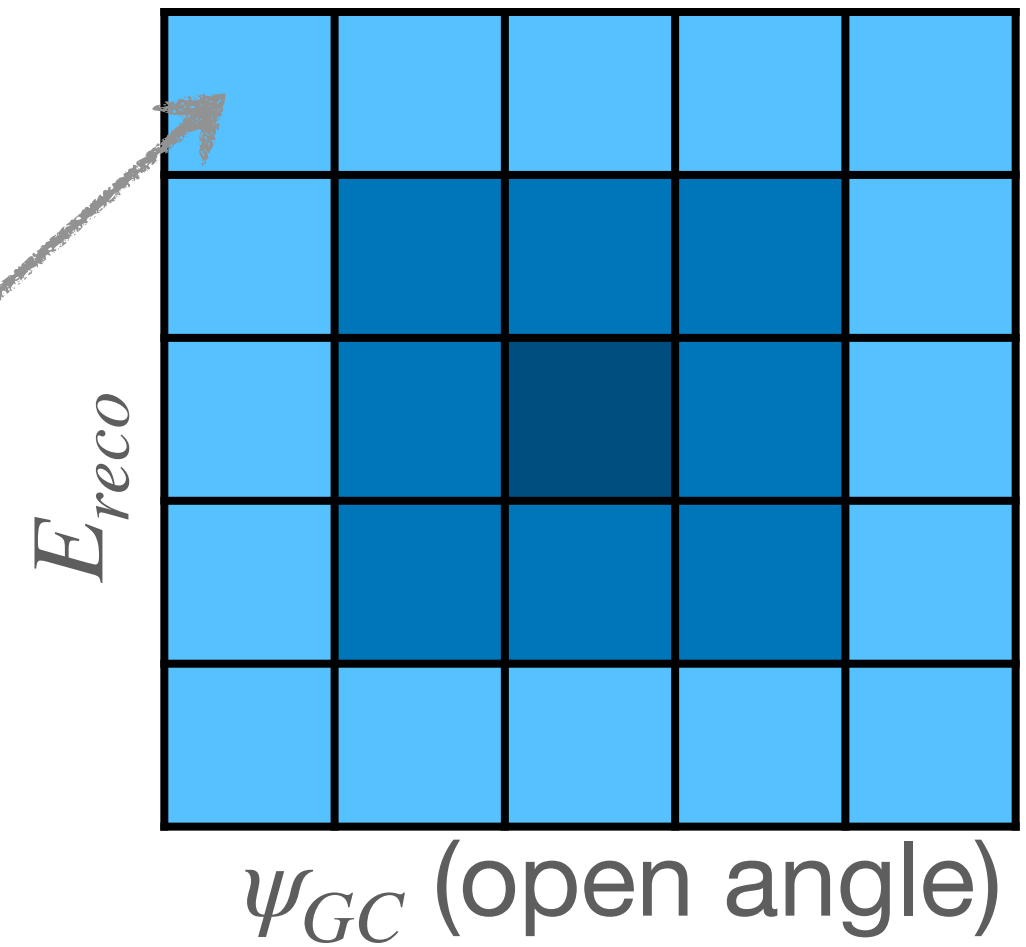


Analysis method

- Binned Poisson Likelihood**

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

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



$$f(i; \xi) = \xi \mathcal{S}_i + (1 - \xi) \mathcal{B}_i,$$

Signal PDF (MC)

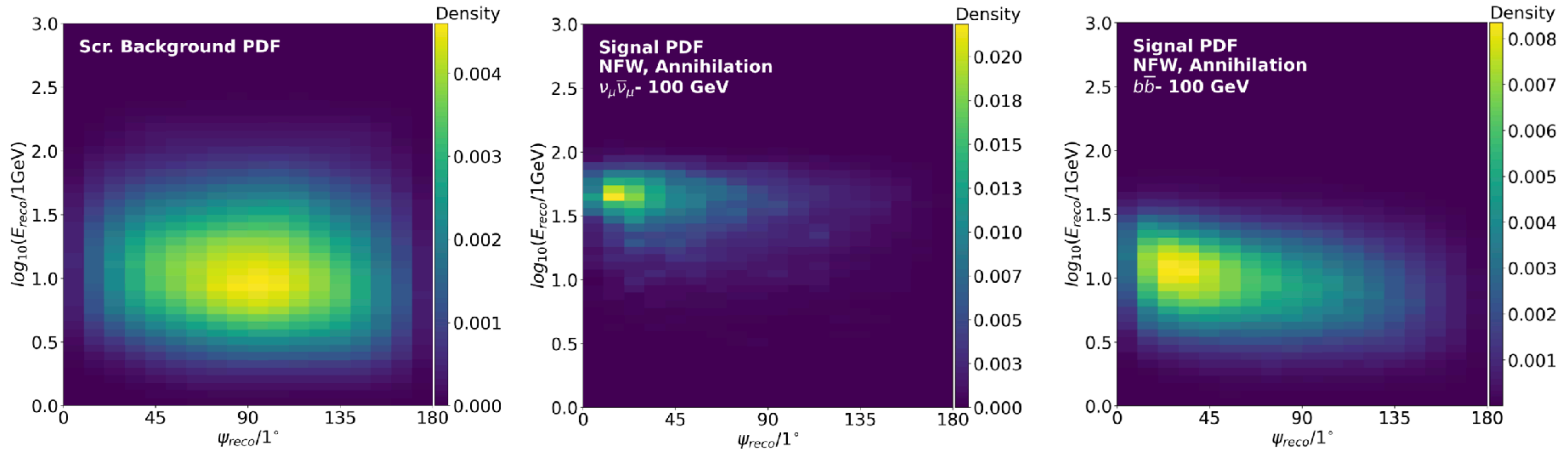
$$\mathcal{B}_i = \frac{1}{1 - \xi} (\mathcal{B}_i^{scr} - \xi \mathcal{S}_i^{scr})$$

Background PDF as RA Scrambled data
Signal subtraction for correction of signal contamination

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

Expected distributions

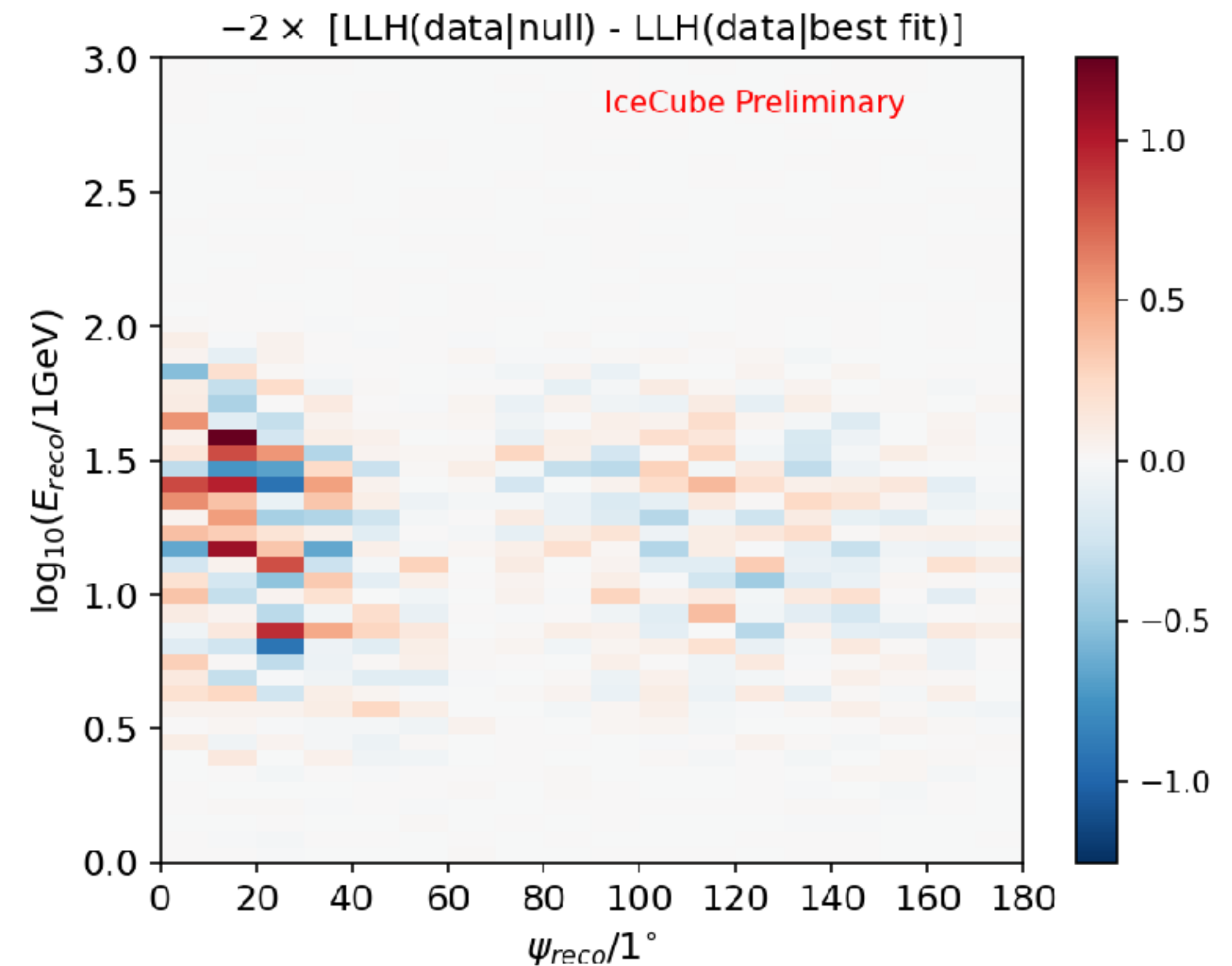
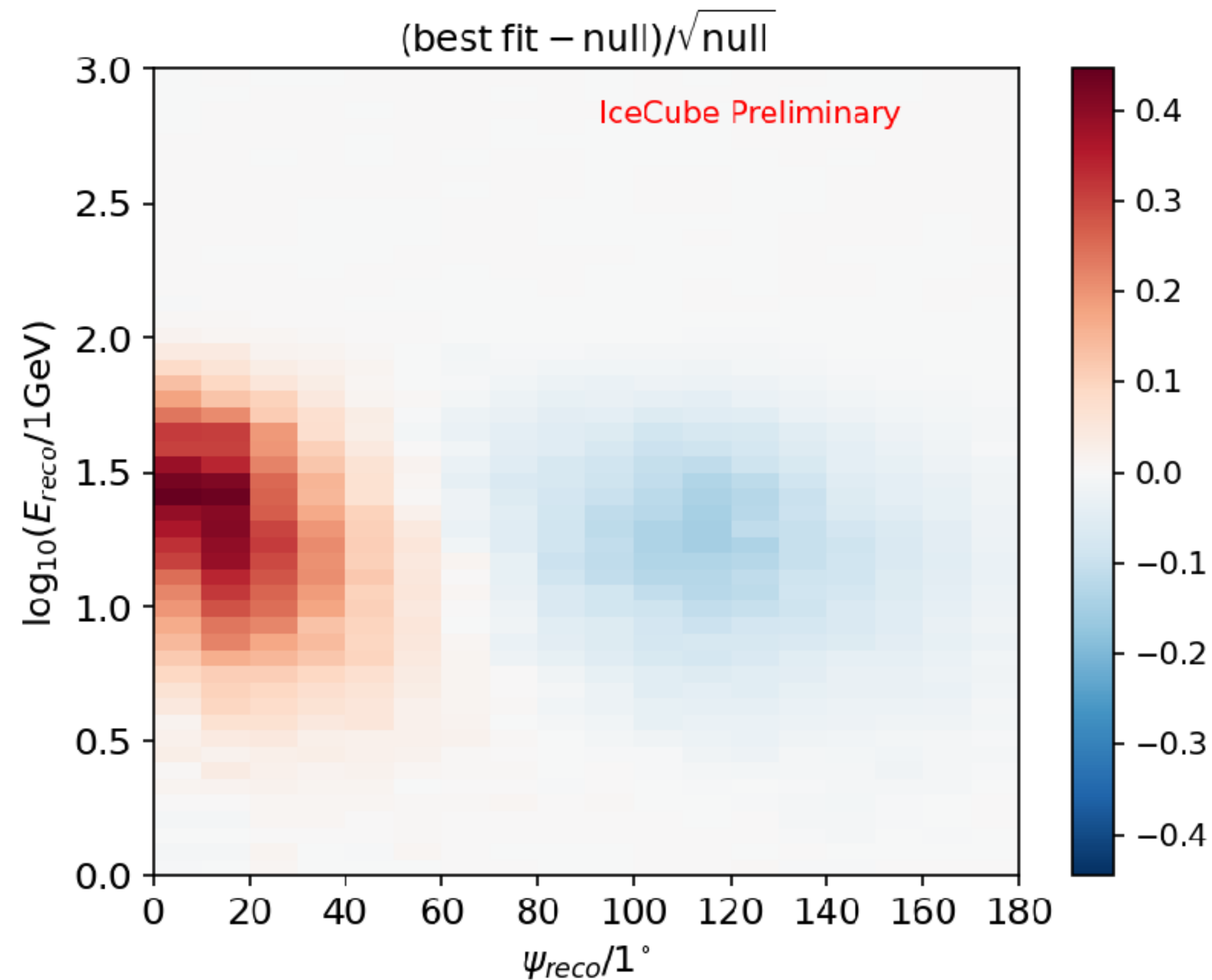
- PDF on two observables: energy and open angle to the Galactic Center



- Search for **spherical excess of neutrino events pronounced to the Galactic Center.**

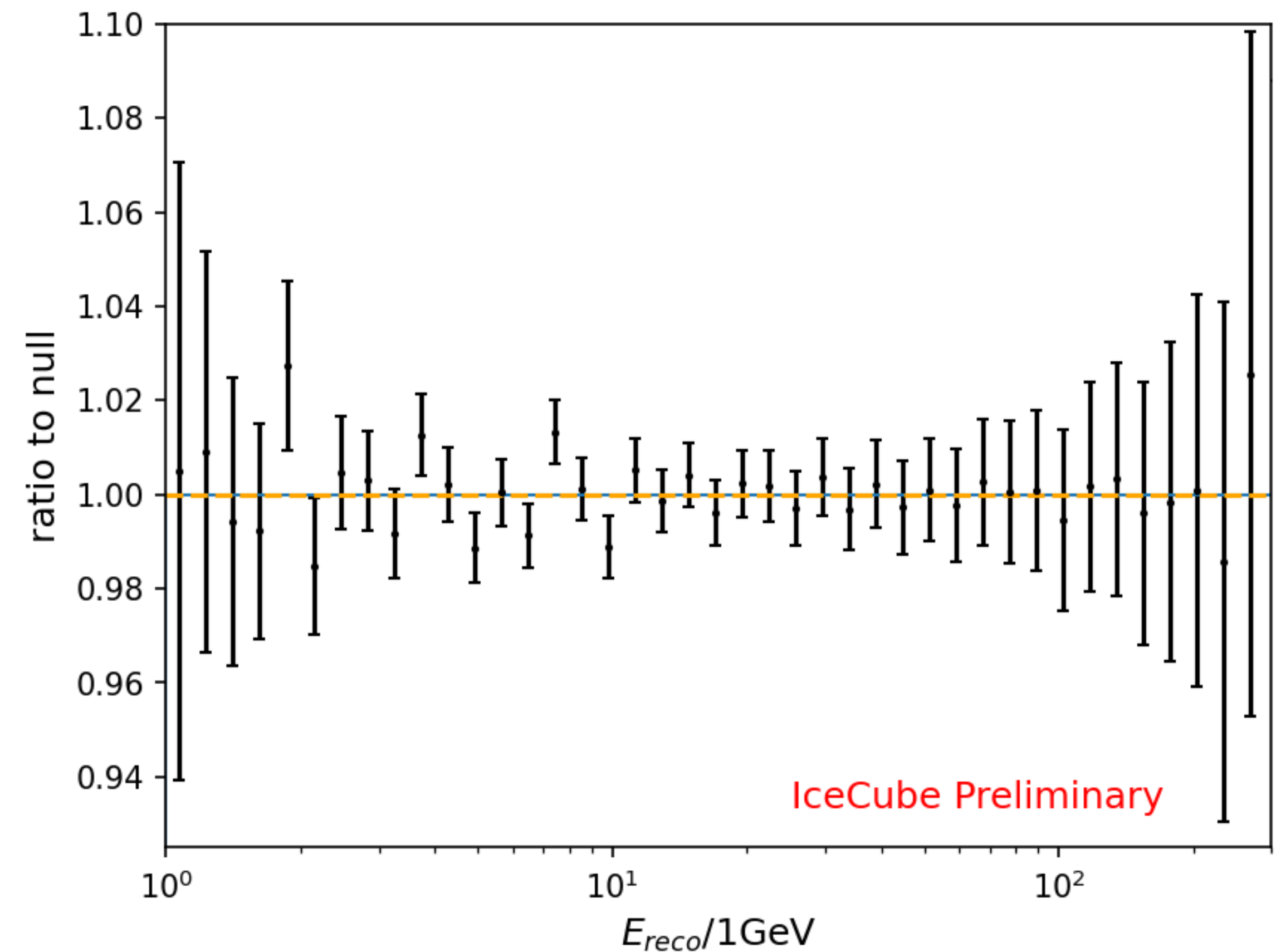
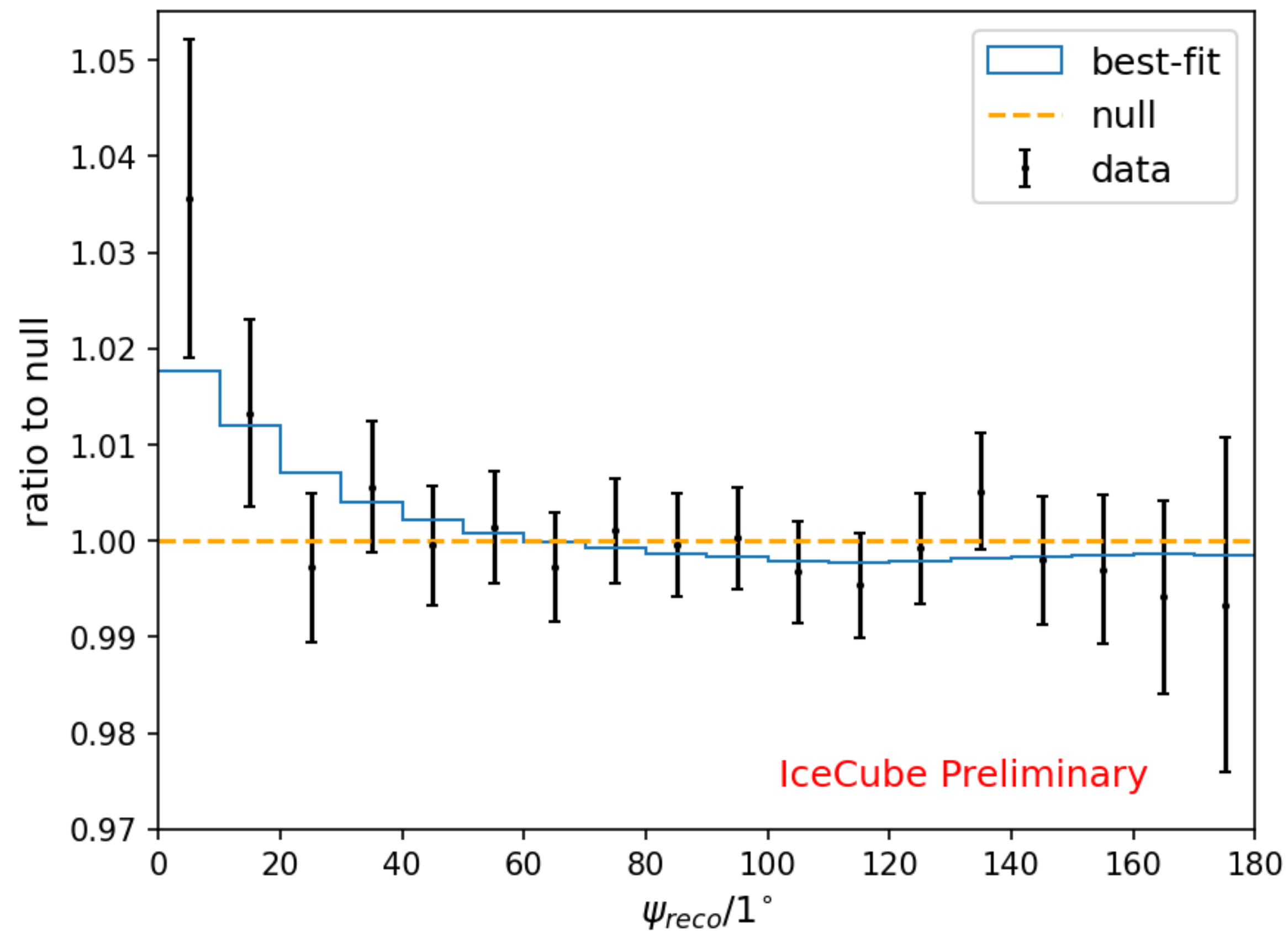
Results - Expectation vs Data

- **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)



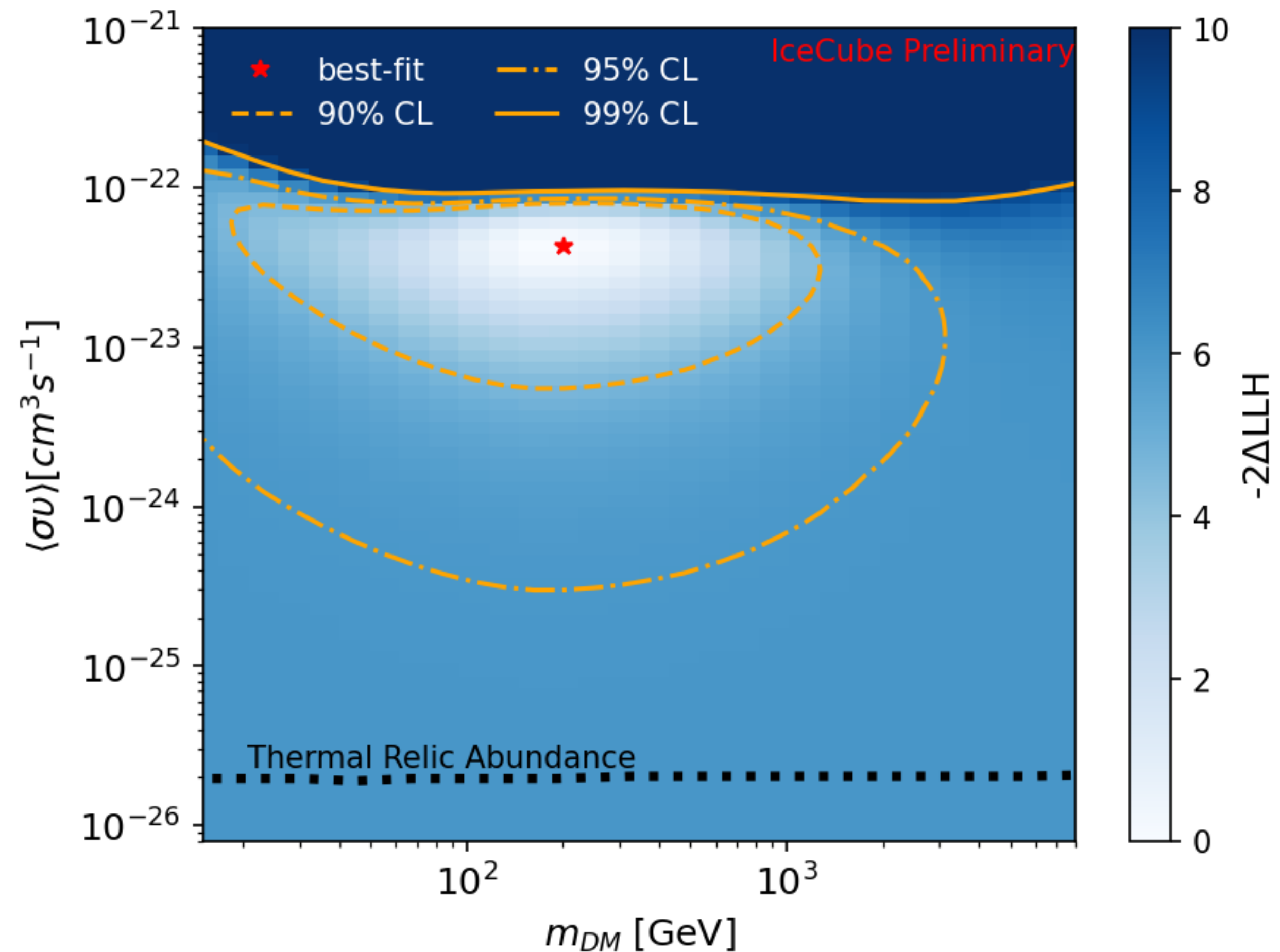
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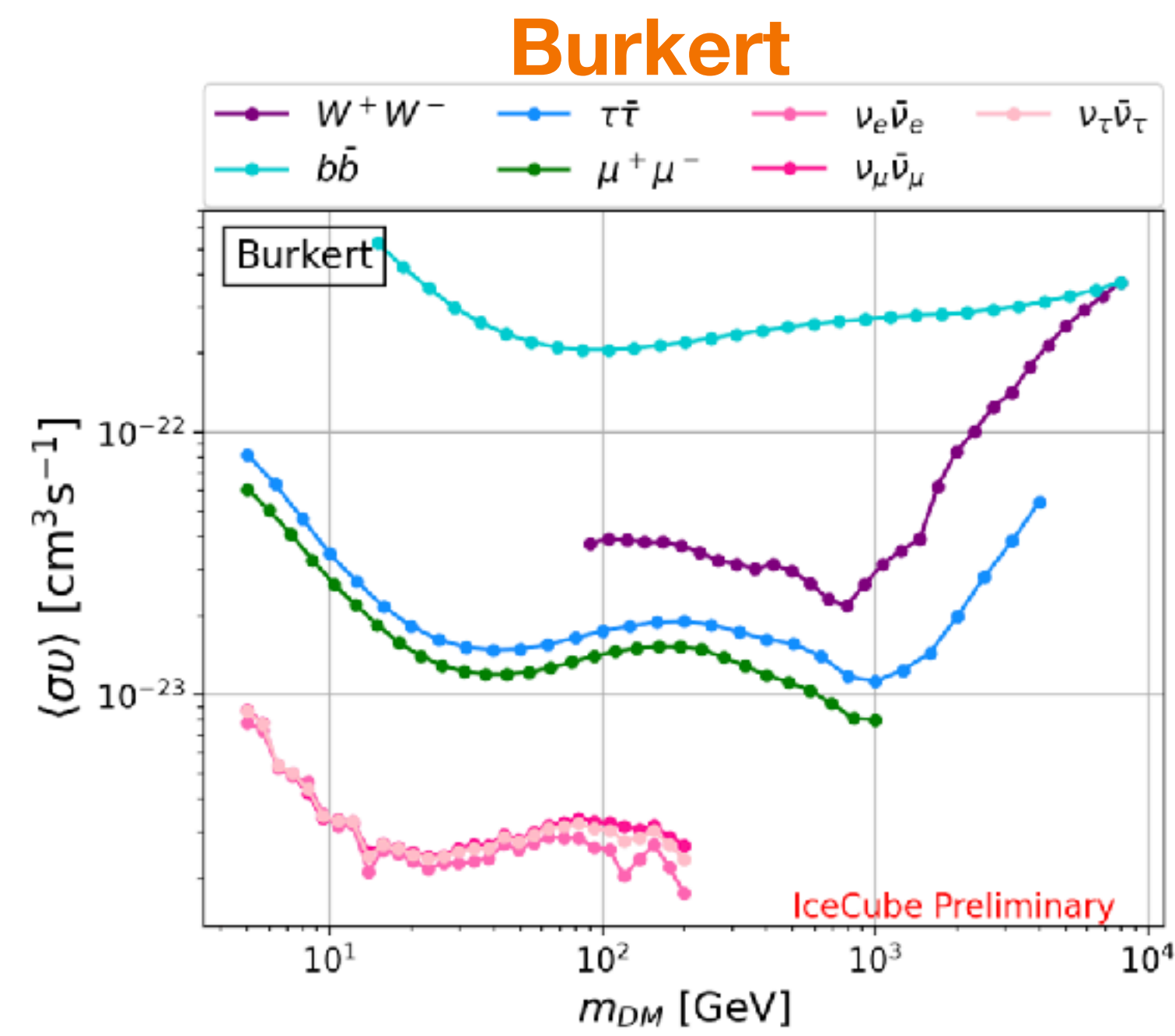
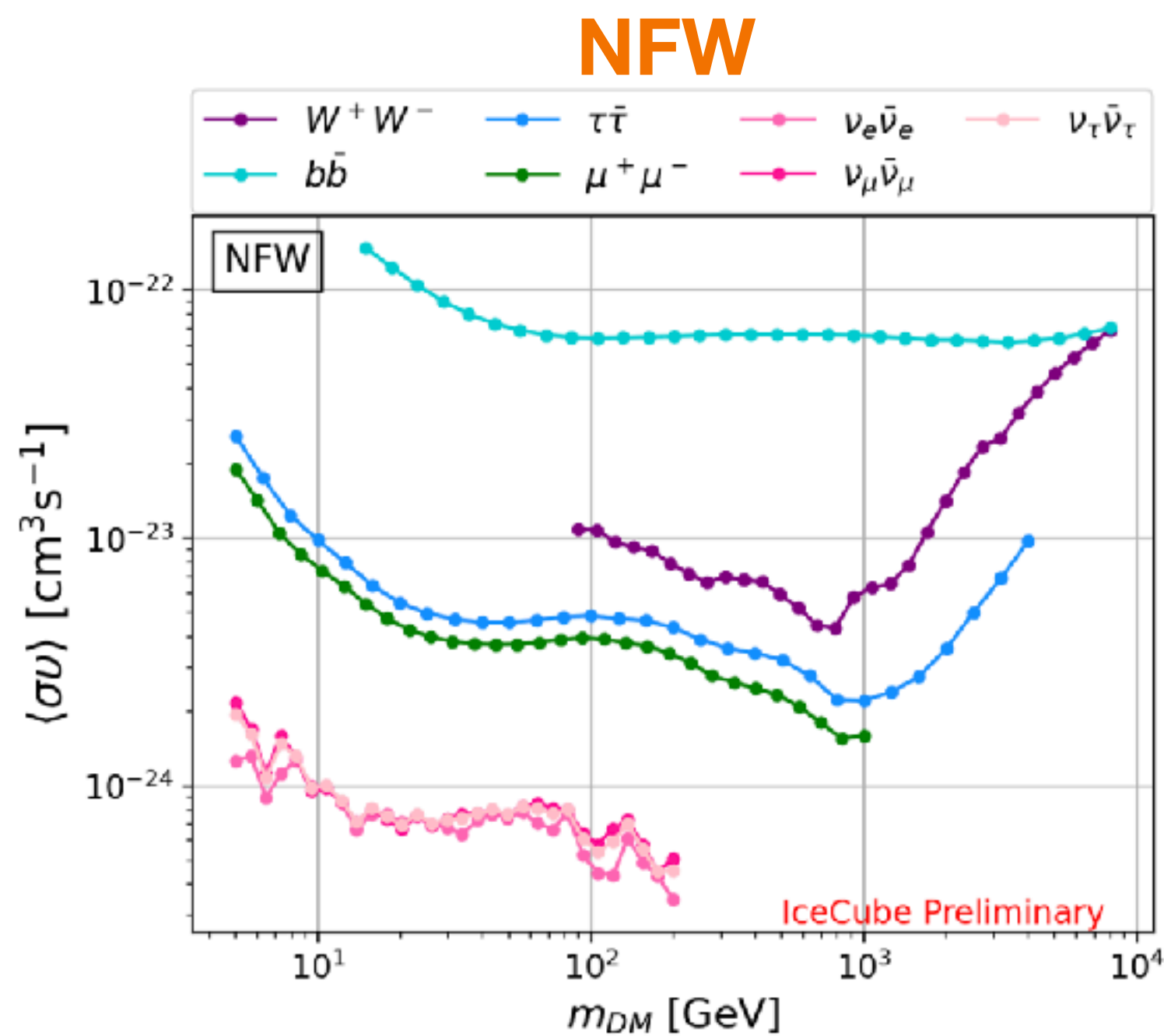
Results - LLH scan

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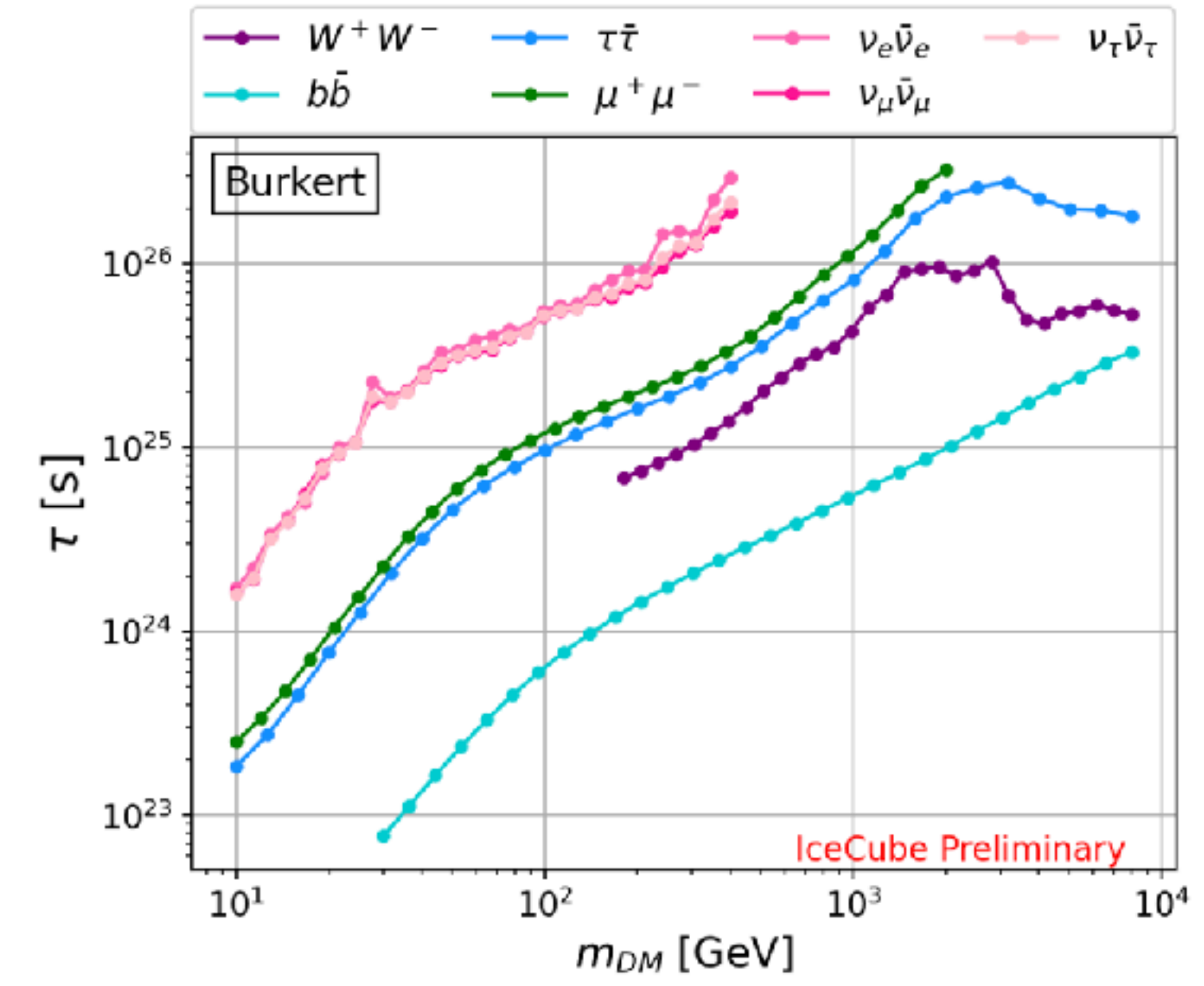
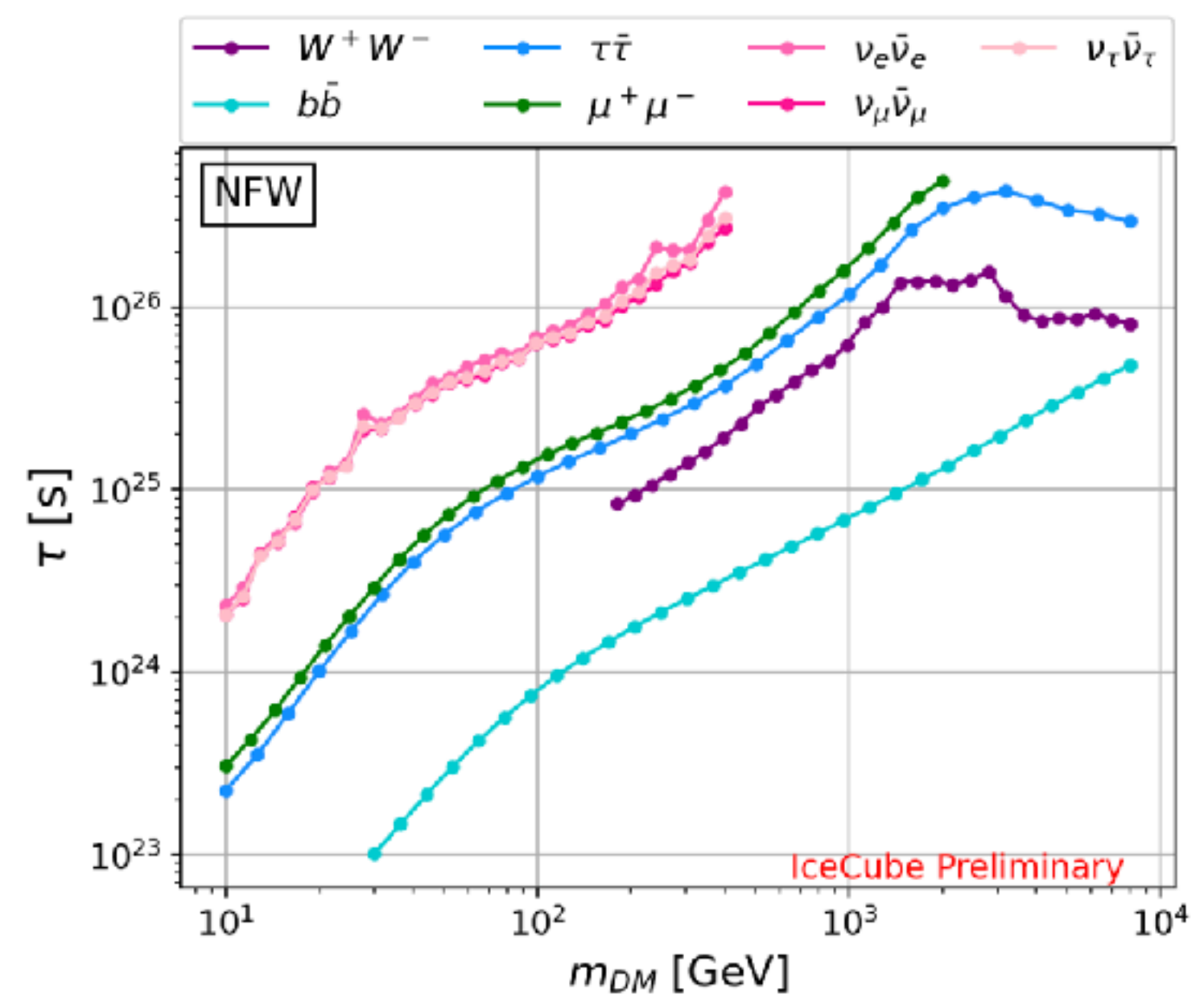
Results - Limits

Annihilation
(Upper limit)

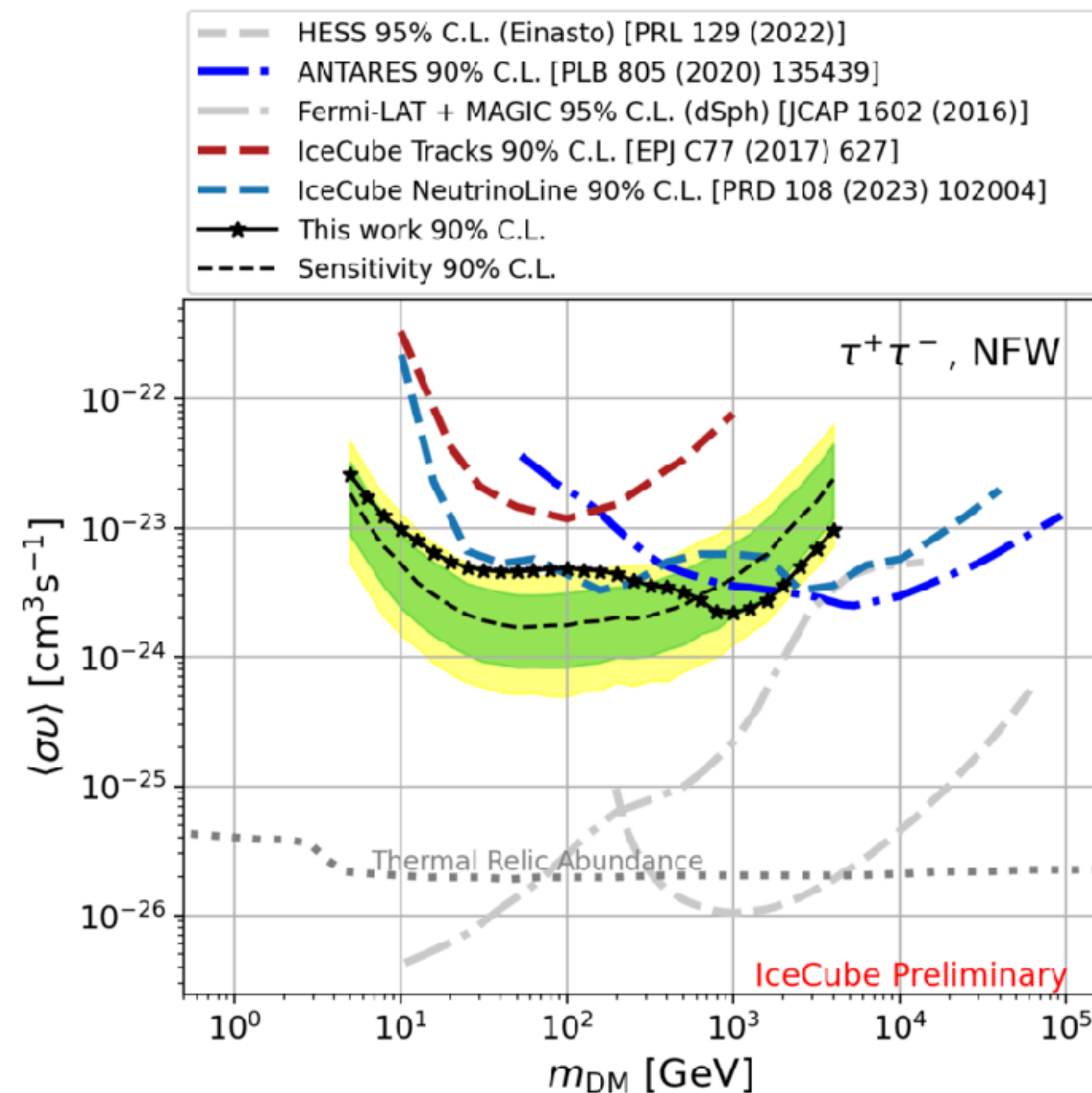
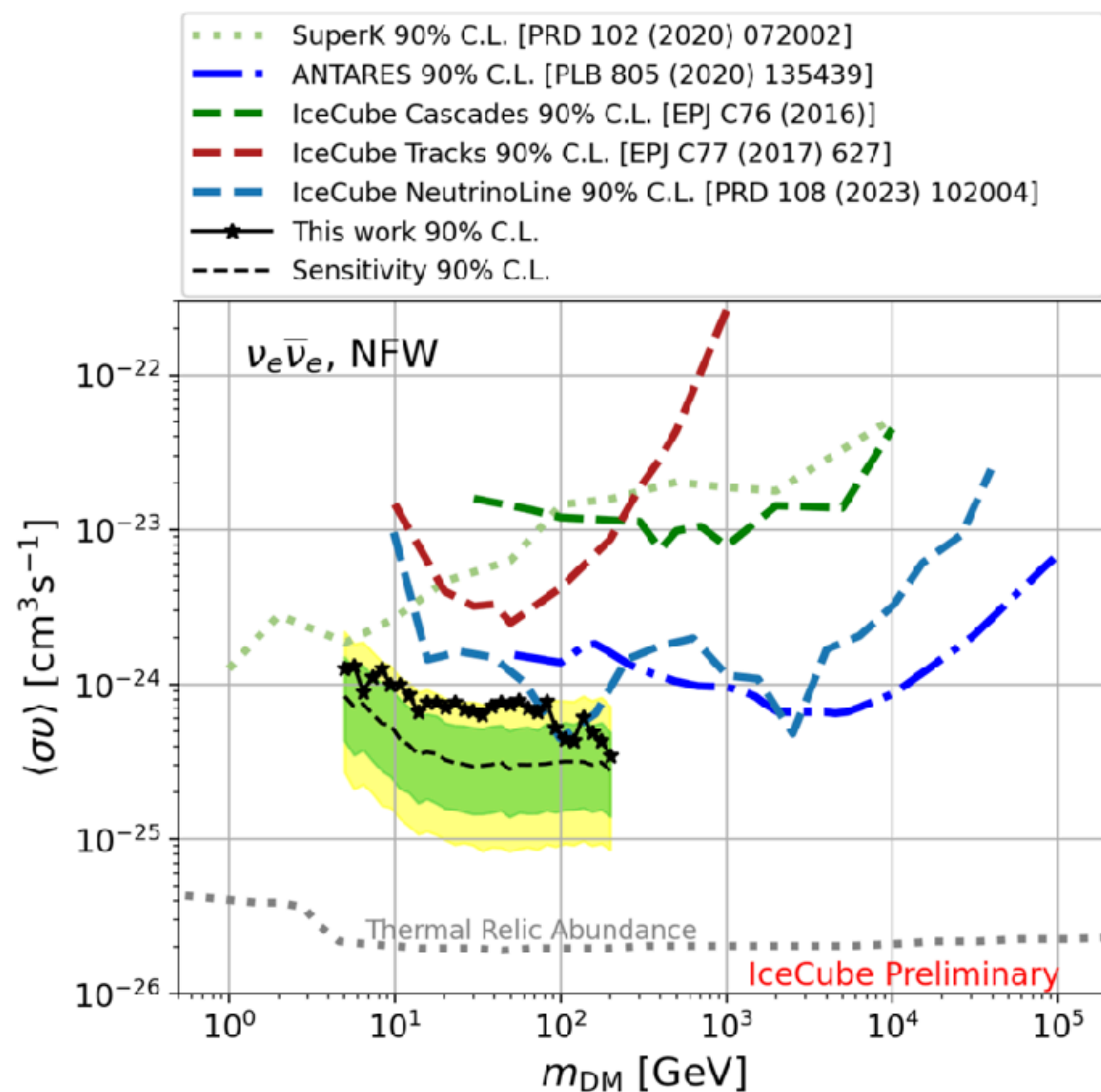


↑
Excluded

Decay
(Lower limit)



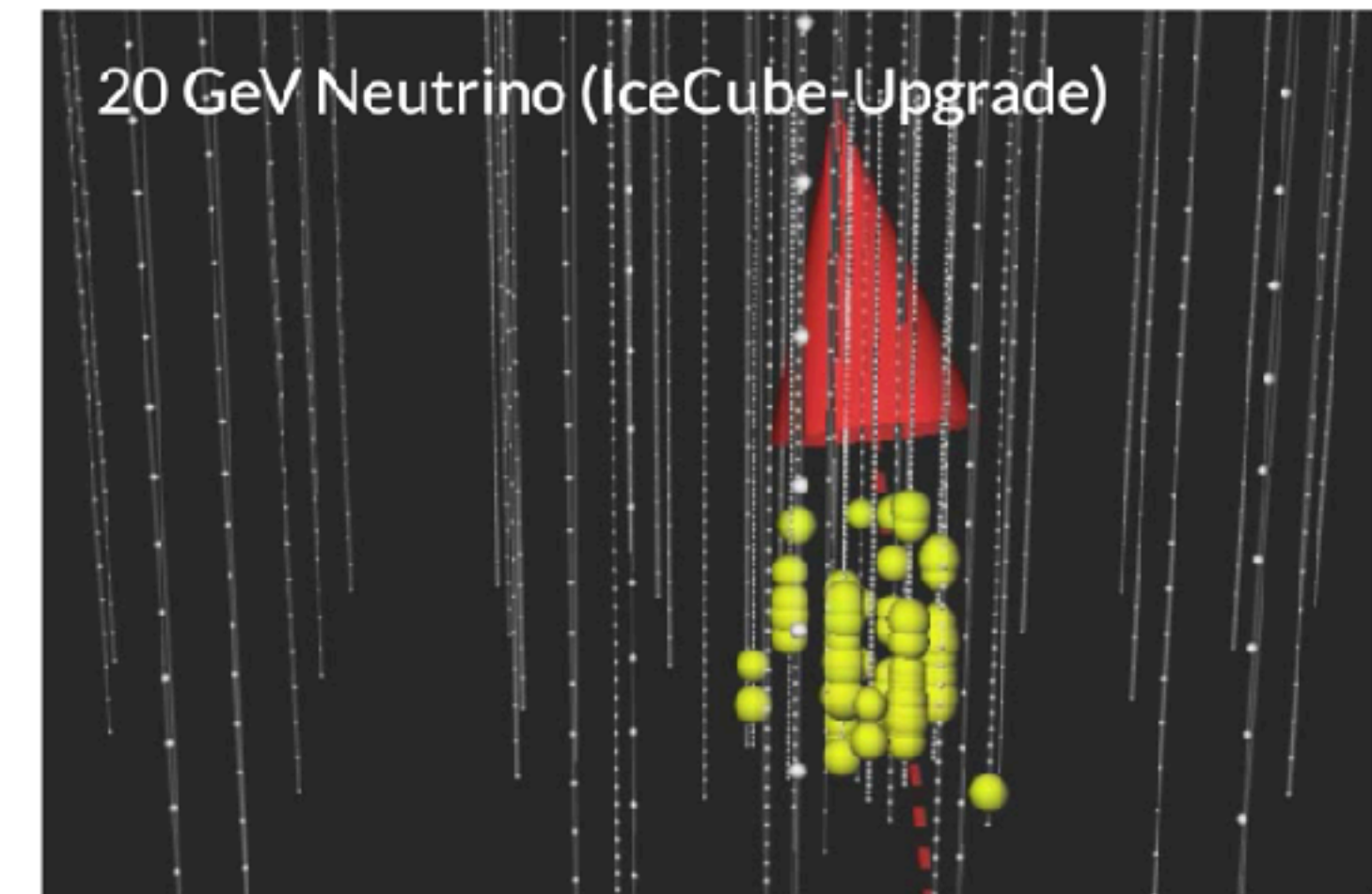
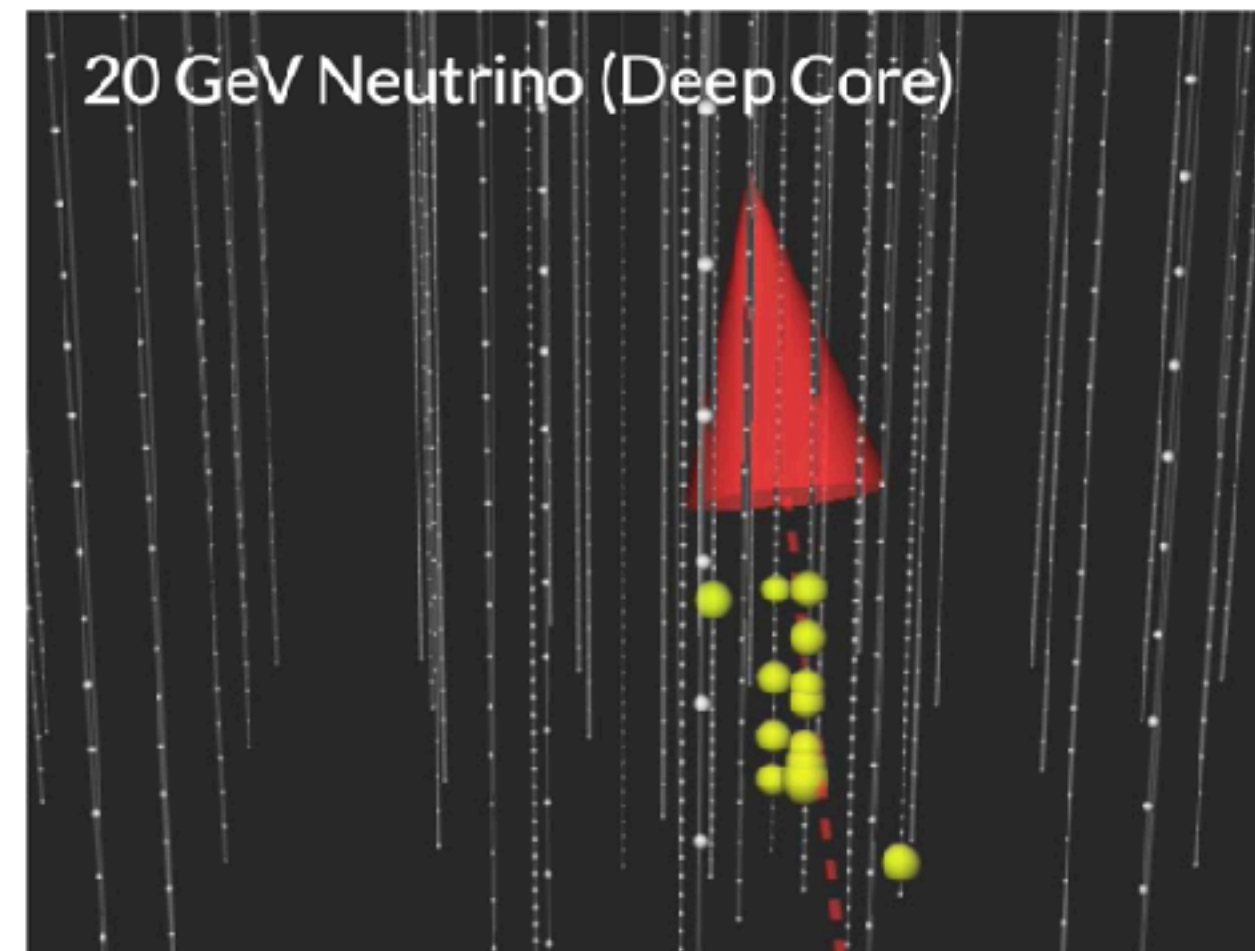
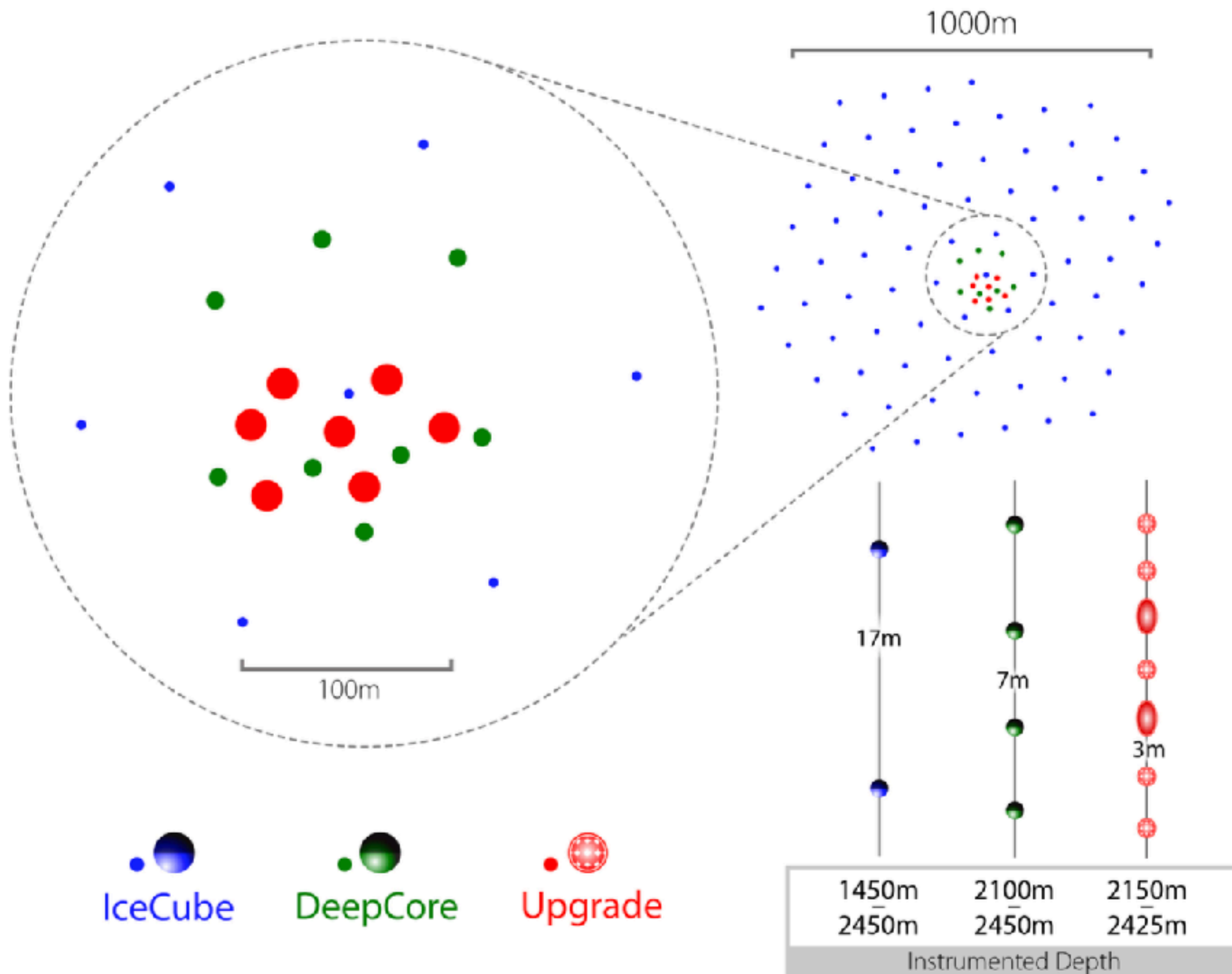
↓
Excluded



- **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

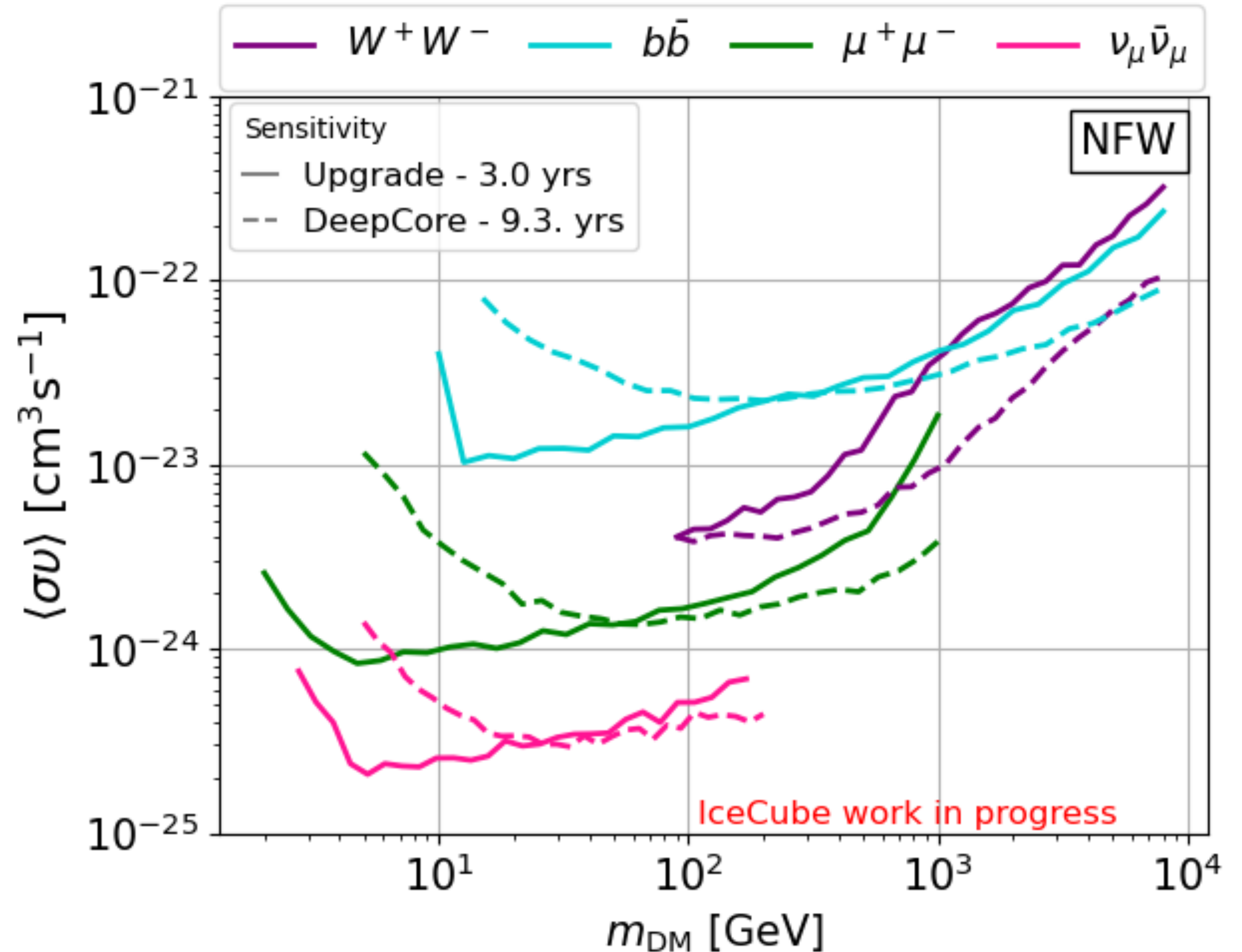
- Deployment planned for 2025-2026
- Extend sensitivity at lower energy
- Ice calibration, better control of the systematics. Improved energy and angular reconstruction
- Reprocess of existing data with new calibration/ice model/reconstruction!
- Precision measurement of atmospheric neutrino oscillations.



IceCube-Upgrade

Galactic Center DM sensitivity

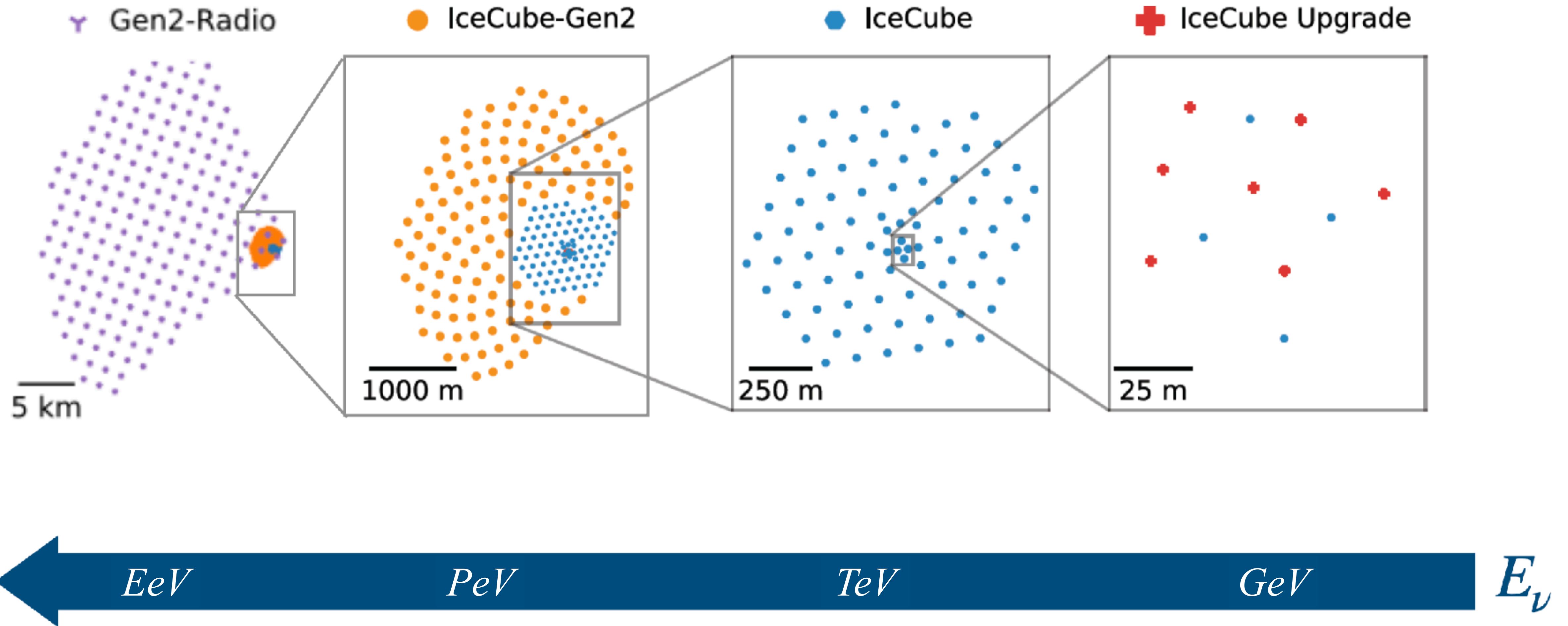
- Reach to the current level of DeepCore within 3 years
- 1 order of magnitude improvement below ~ 50 GeV



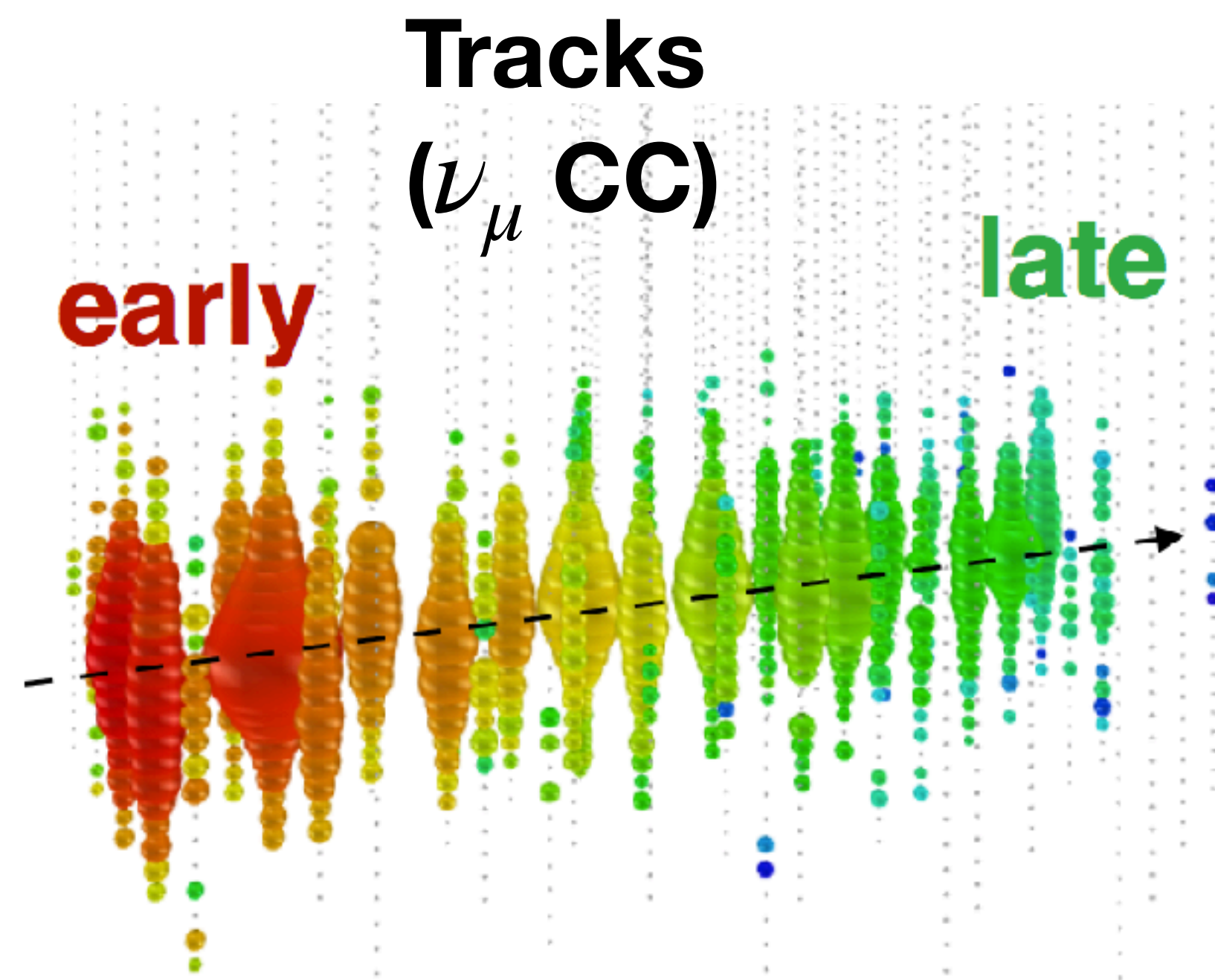
- **IceCube** can perform **indirect dark matter detection** with **competitive results** and provide **complementary to other techniques**.
- The presented work yields **world-leading limits on neutrino line signal** of DM and **best limit among neutrino telescopes** at GeV-scale DM mass.
- Improvement thanks to advancement in understanding the detector.
- **IceCube-Upgrade** will come soon and enhance the capabilities of the current IceCube detector.

Back up

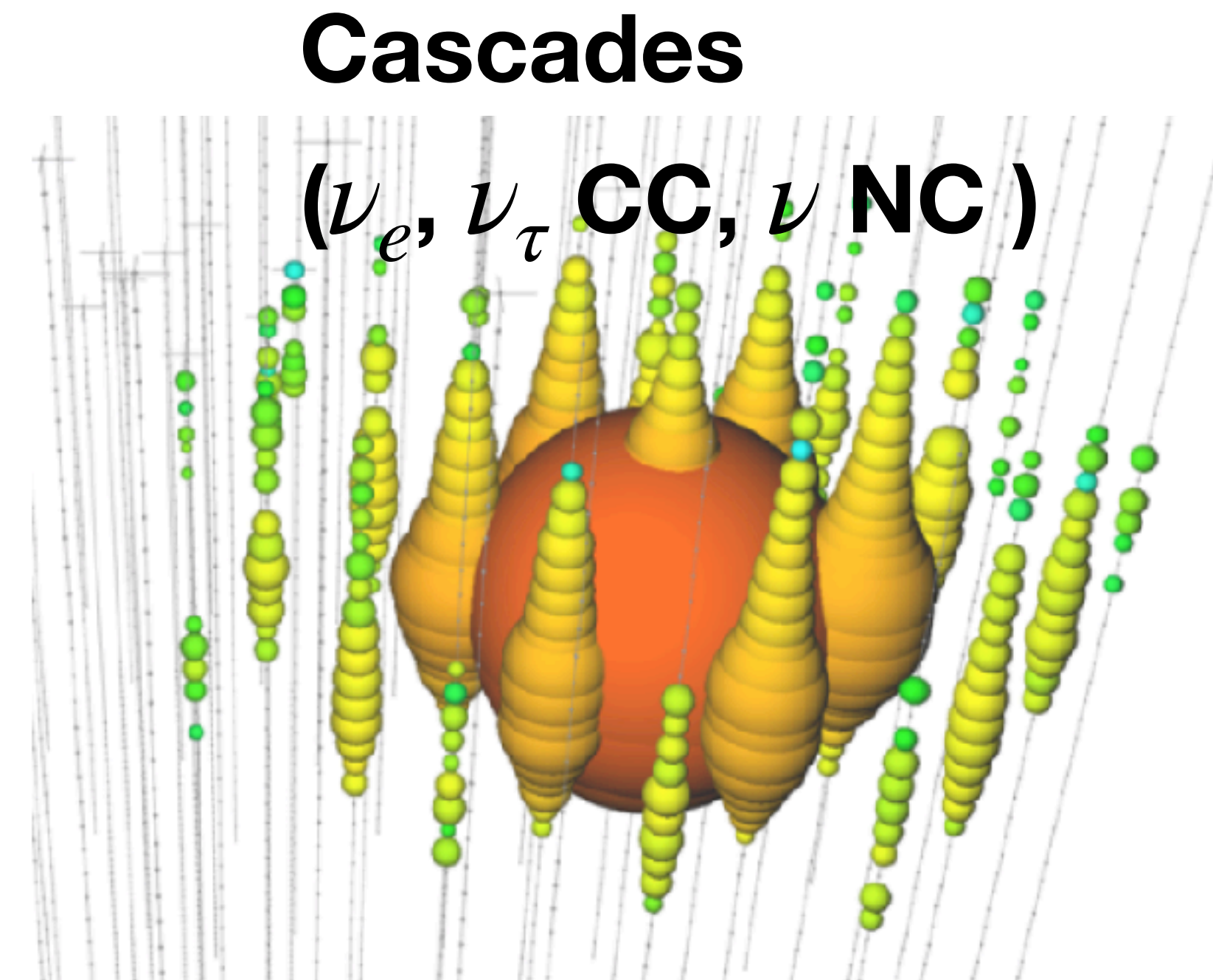
The future of IceCube: Upgrade and Gen2



Detection Principle - event signatures

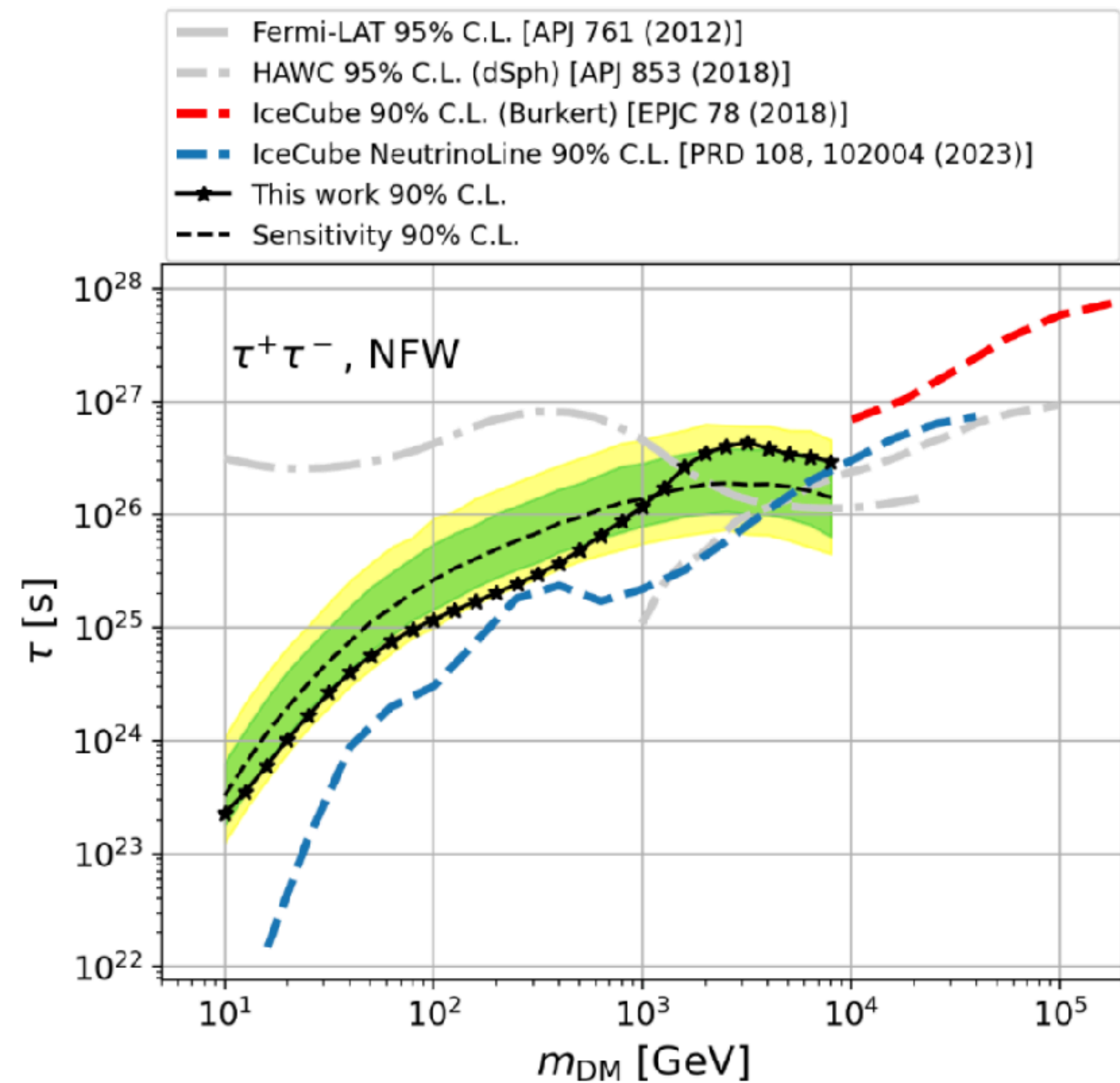
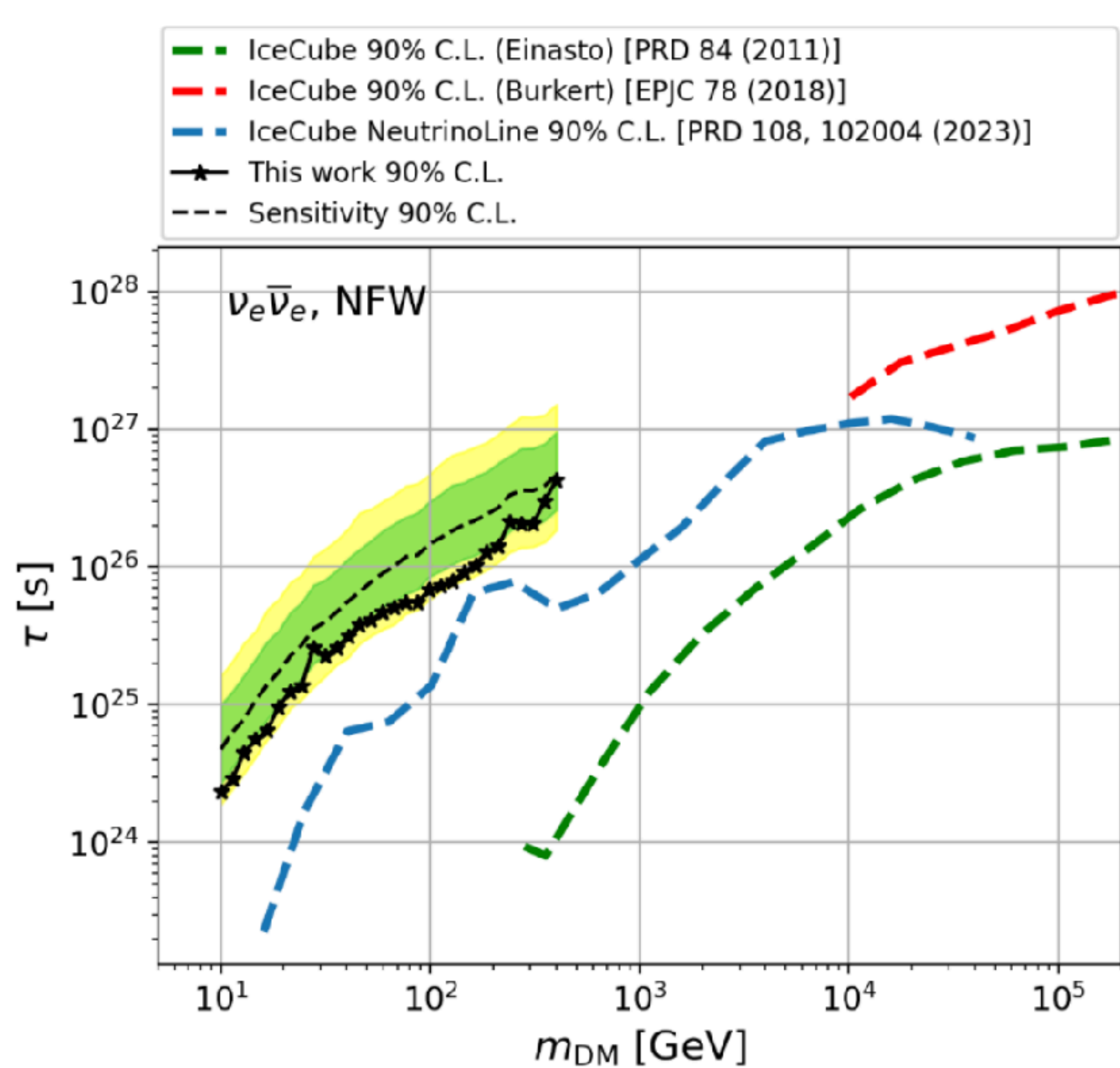


- Good angular resolution.
- Challenge in energy reconstruction



- Large angular resolution.
- Good energy resolution

Results - Limits





ICECUBE UPGRADE OPTICAL SENSORS

1600 m

calibration



PDOM

1 x 10" PMT



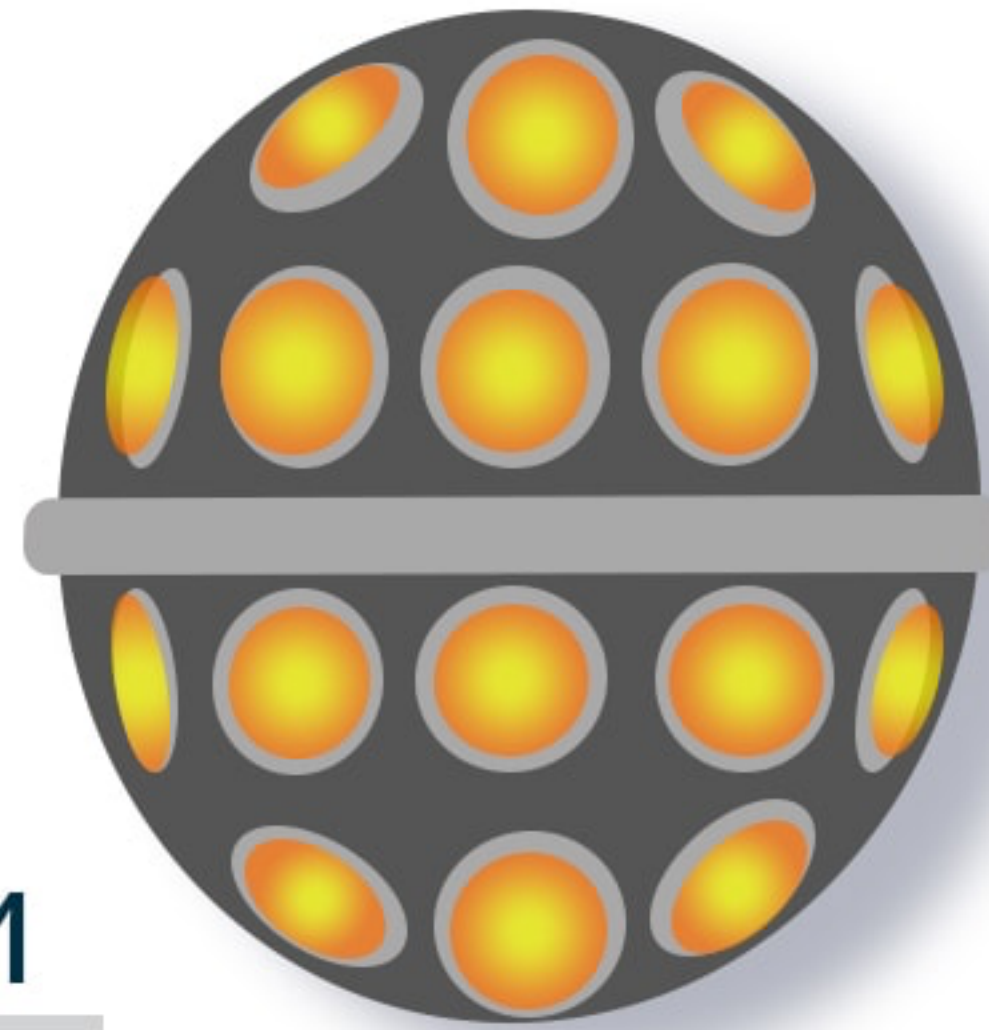
2150 m

neutrino physics



MDOM

24 x 3" PMT



2425 m

deep ice



D-EGG

2 x 8" PMT



2600 m