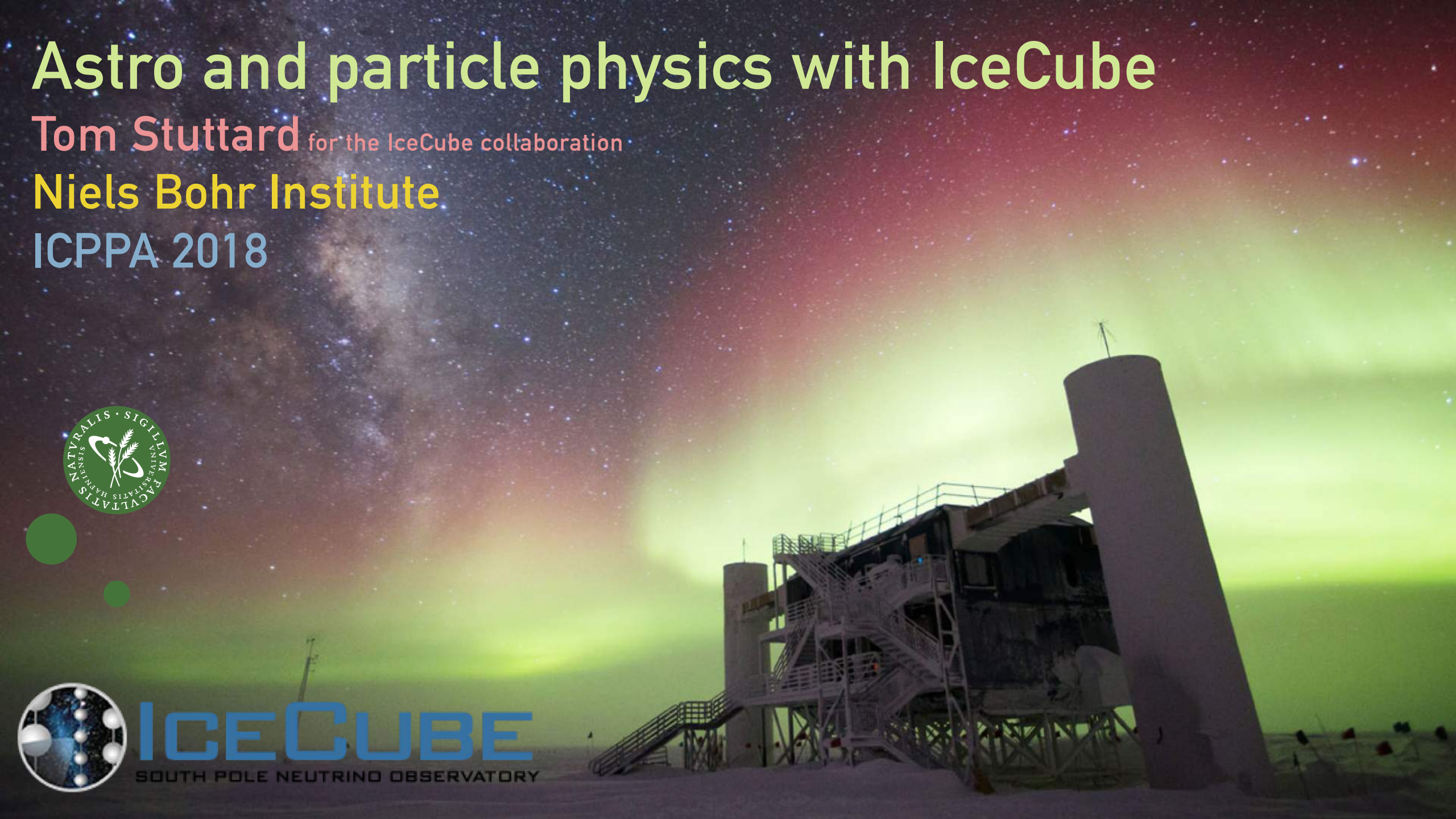
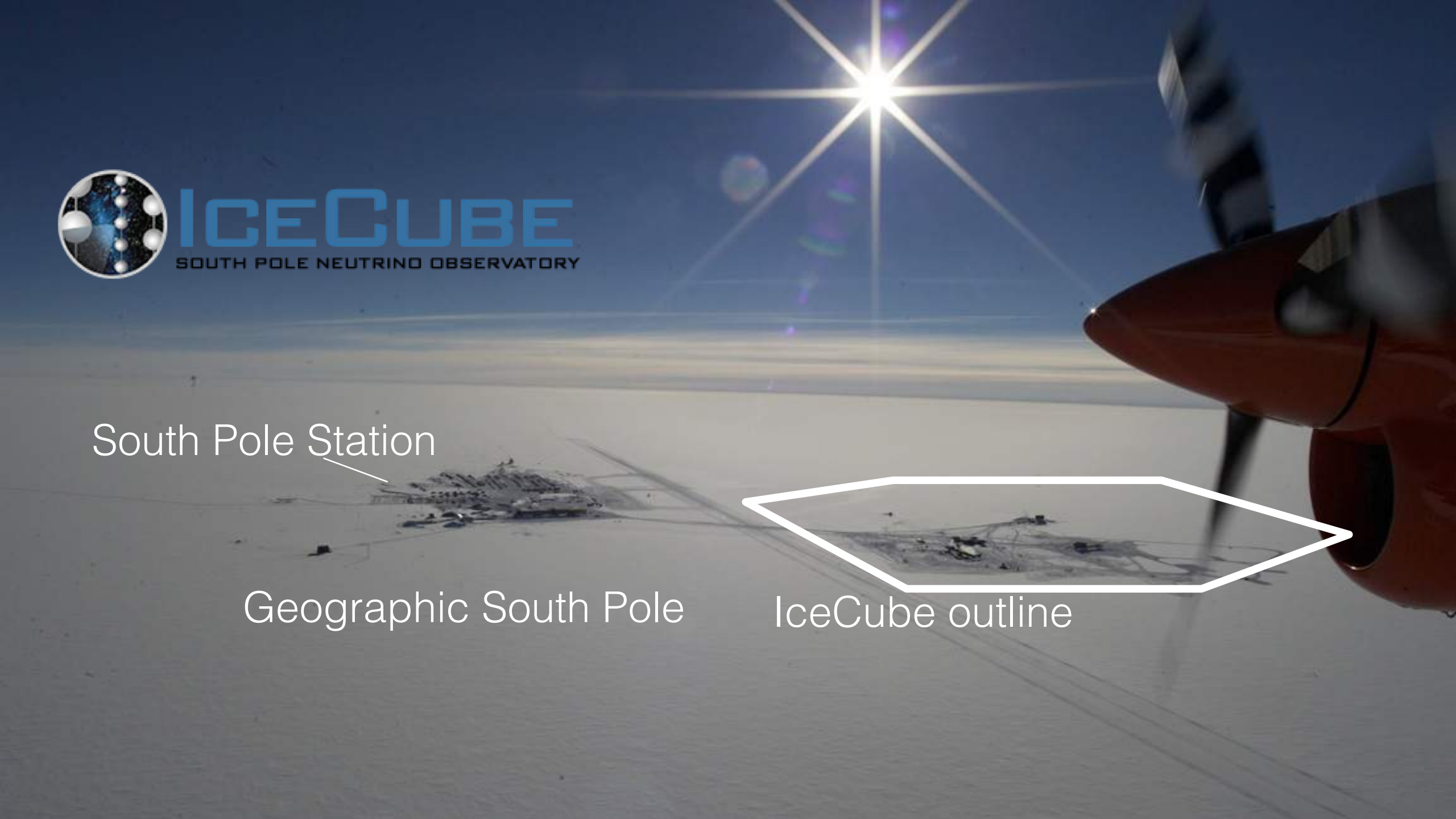
Astro and particle physics with IceCube

Tom Stuttard for the IceCube collaboration
Niels Bohr Institute

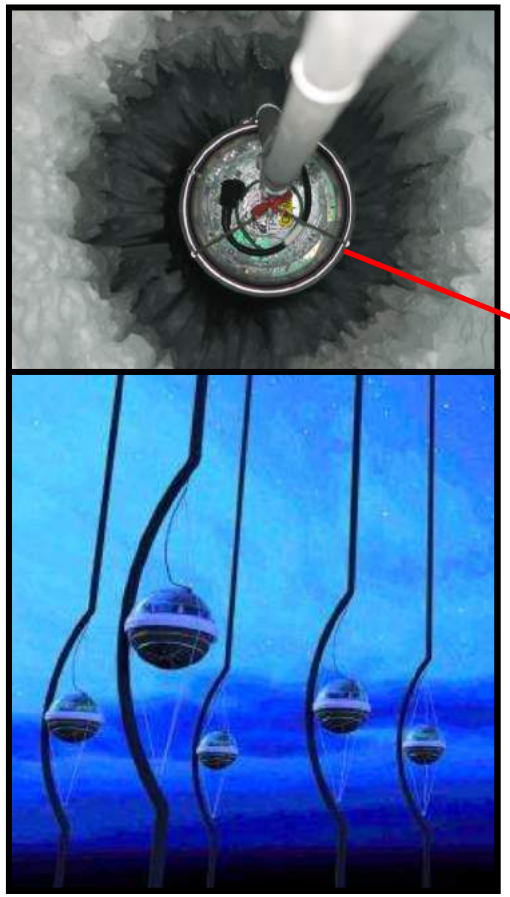
ICPPA 2018

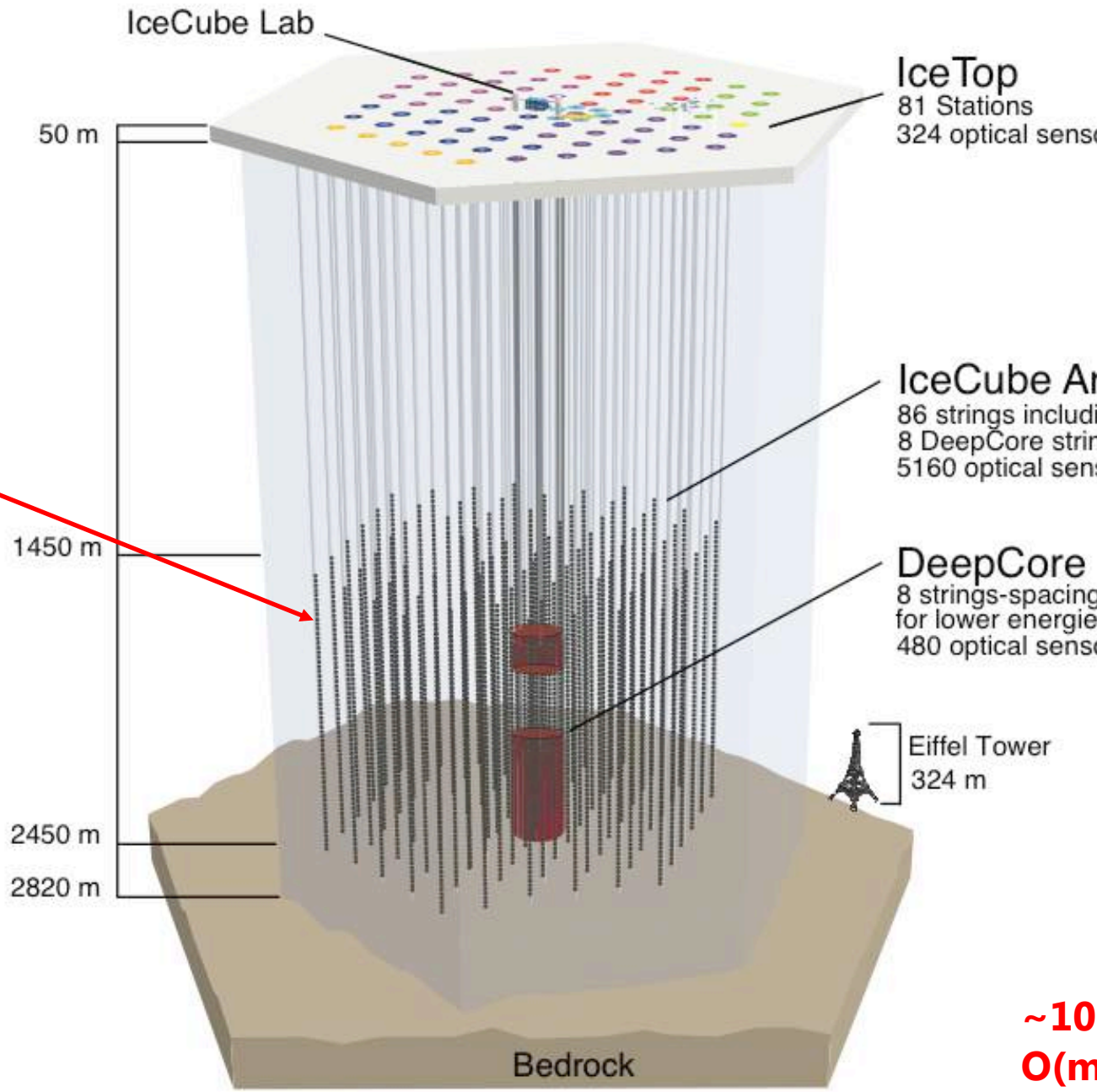



IceCube
SOUTH POLE NEUTRINO OBSERVATORY
South Pole Station
Geographic South Pole
IceCube outline

IceCube
SOUTH POLE NEUTRINO OBSERVATORY

>5000 PMTs

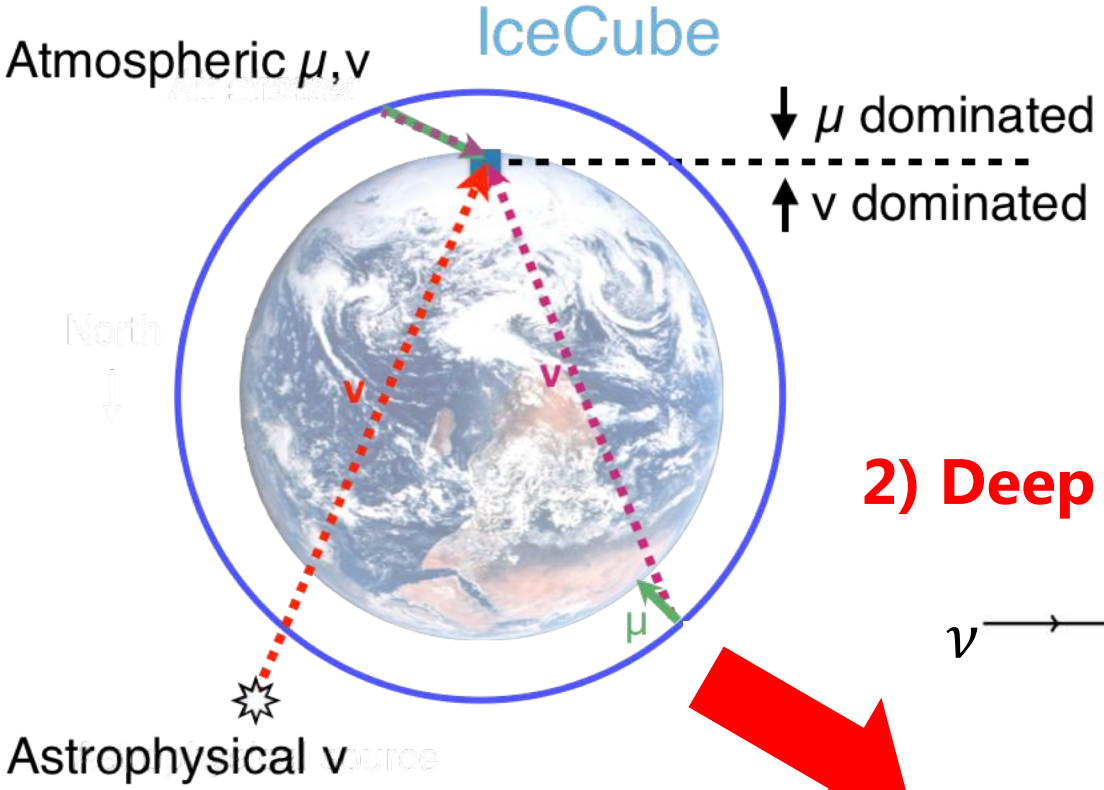




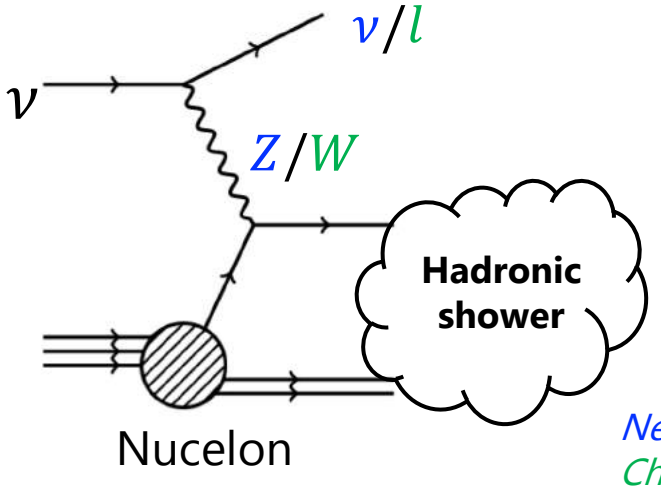
~100% uptime
O(mHz) atmospheric ν rate

Detecting neutrinos in ice

1) Neutrinos interact in ice

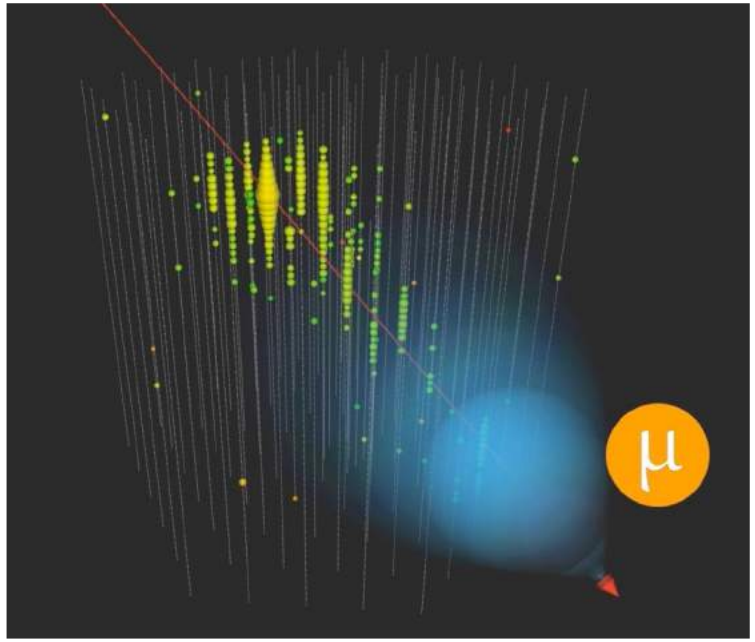


2) Deep Inelastic Scattering



Neutral current (NC)
Charged current (CC)

3) Detect Cherenkov light in PMTs

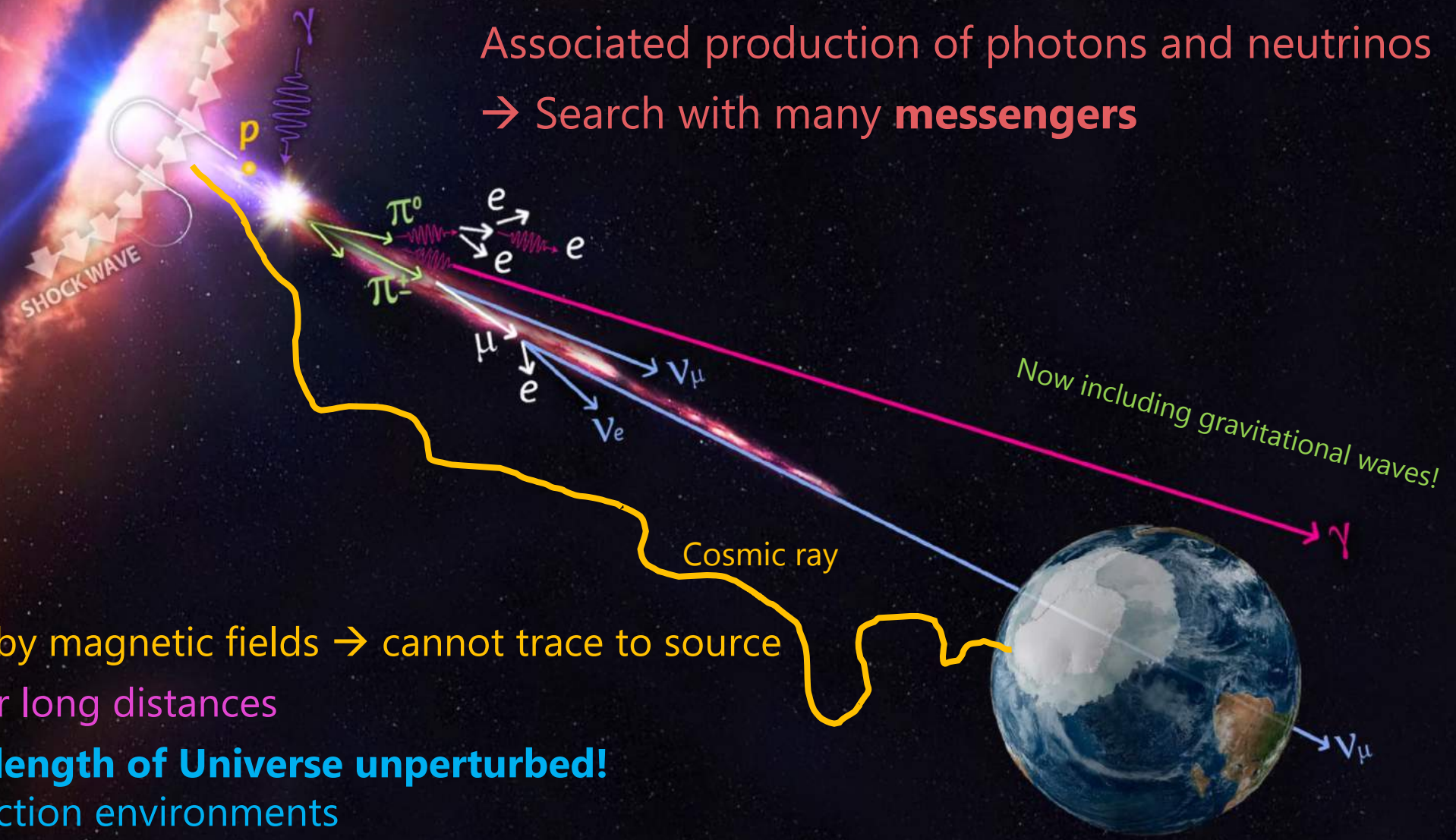


Multimessenger Astronomy

Source of high energy cosmic rays unknown

Associated production of photons and neutrinos

→ Search with many **messengers**



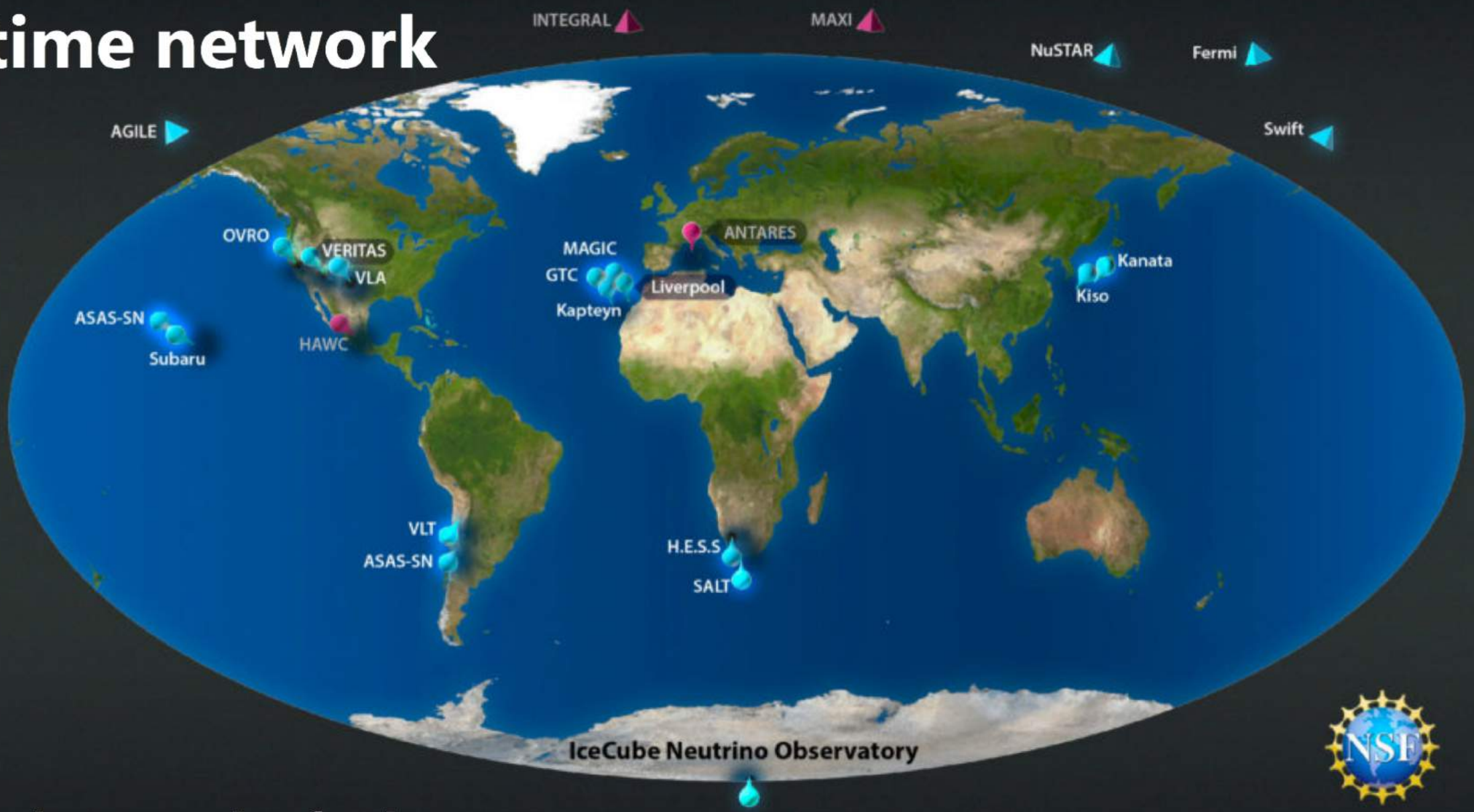
Cosmic rays deflected by magnetic fields → cannot trace to source

Photons absorbed over long distances

Neutrinos can travel length of Universe unperturbed!

+ escape dense production environments

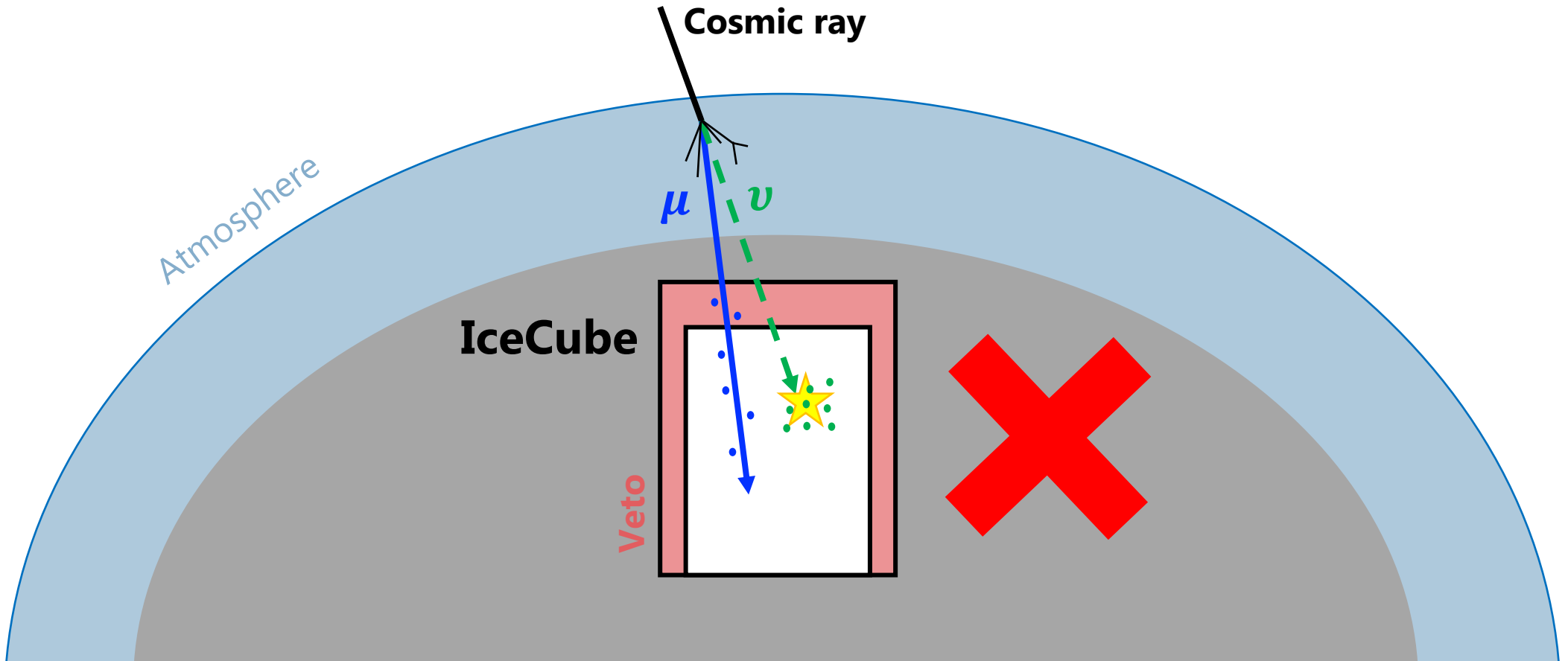
Realtime network



- Global network of telescopes
- Alerts sent during astrophysical event → global follow-up

Detecting astrophysical neutrinos

- Overwhelming atmospheric neutrino background
- Suppress using **self-veto**



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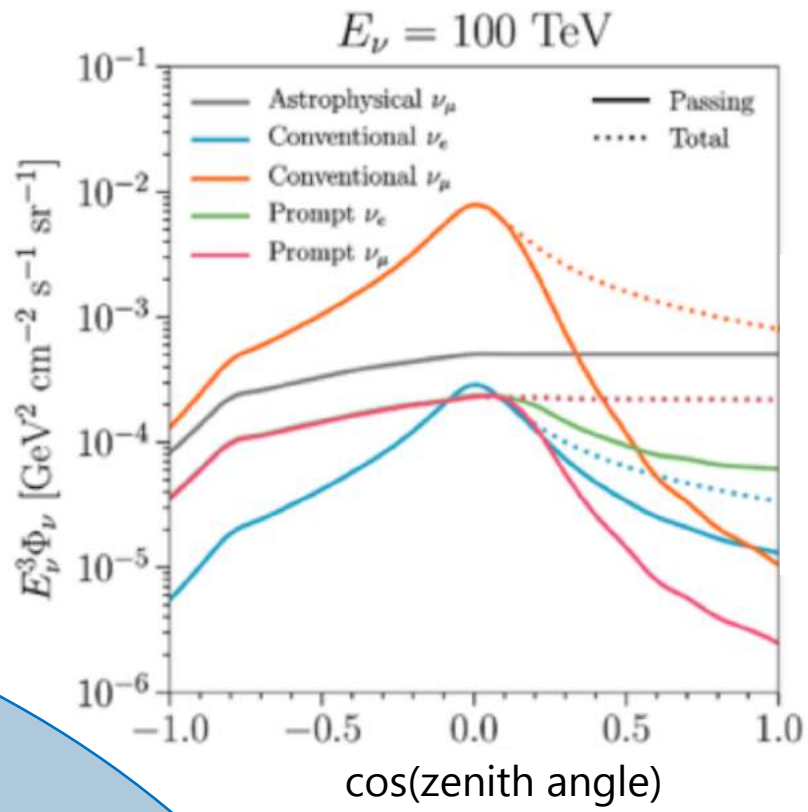
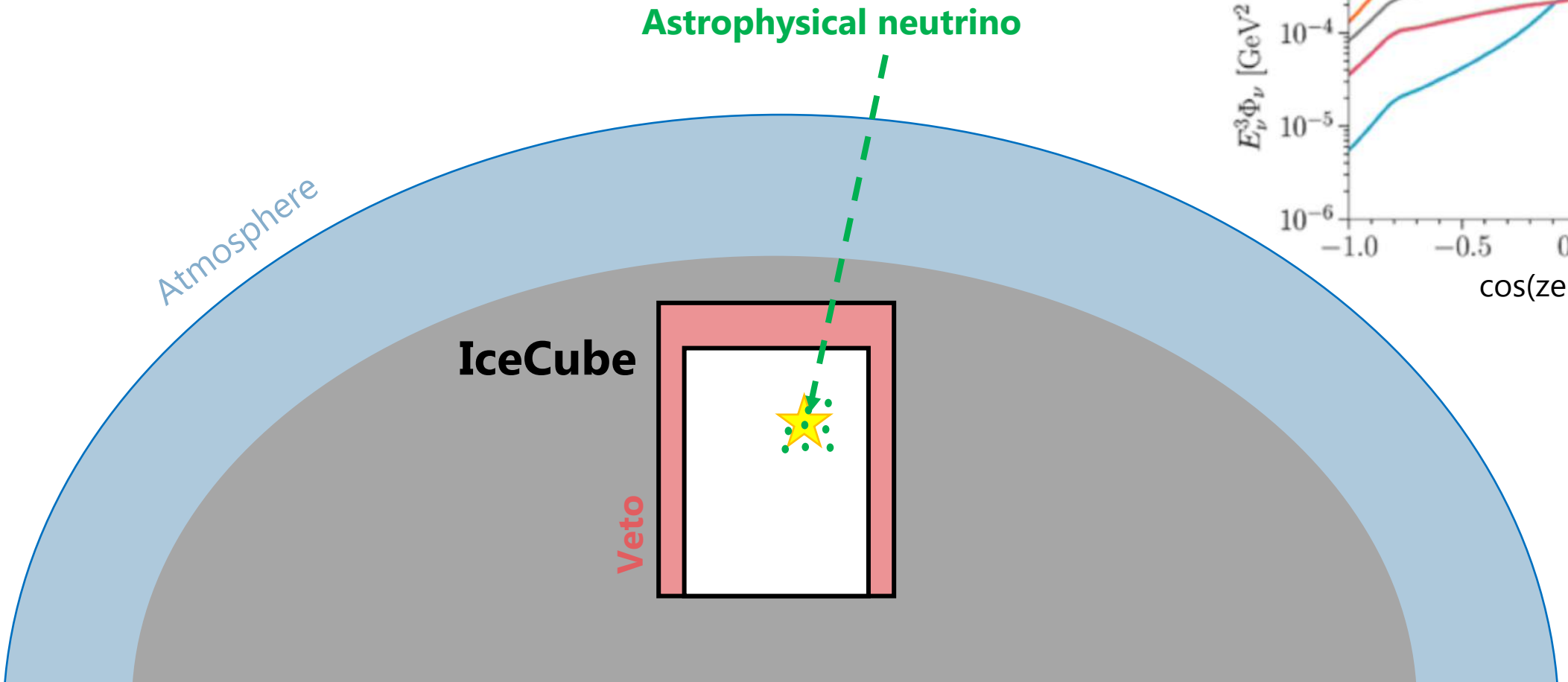
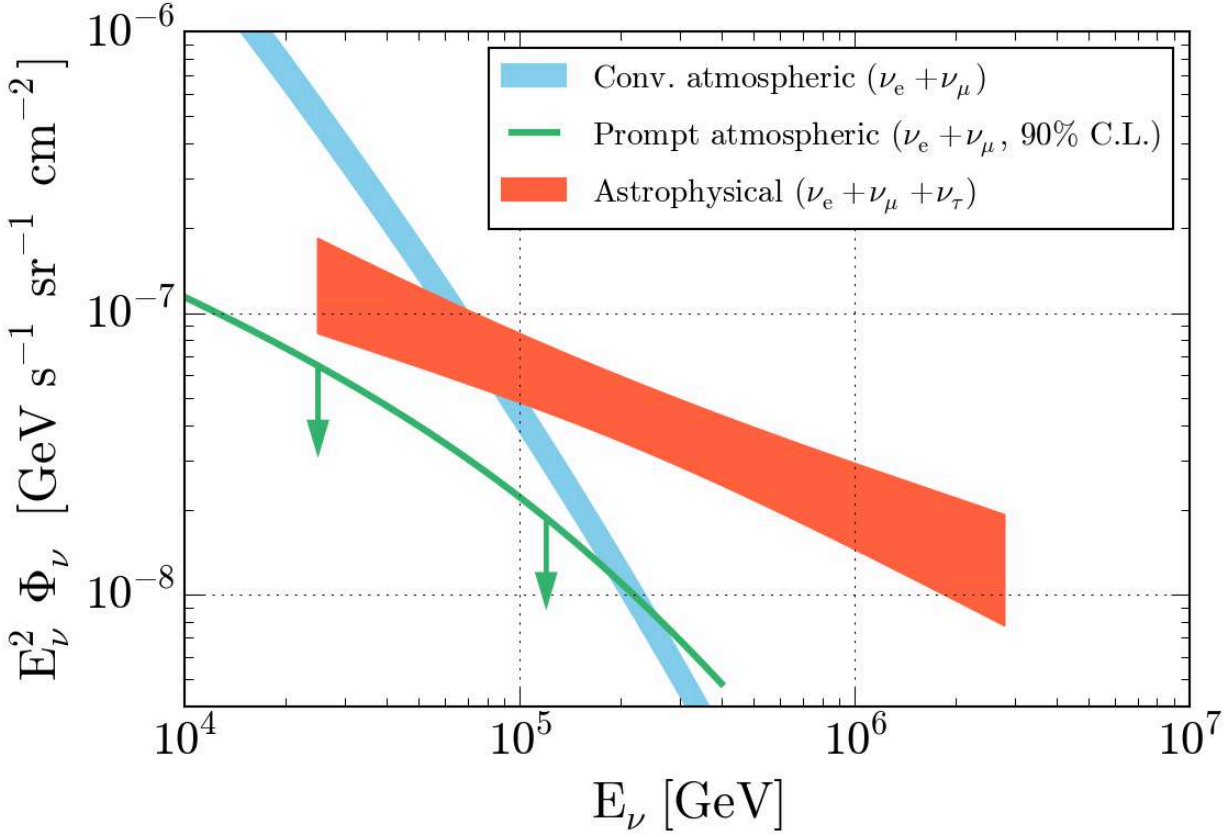




Astrophysical neutrino flux

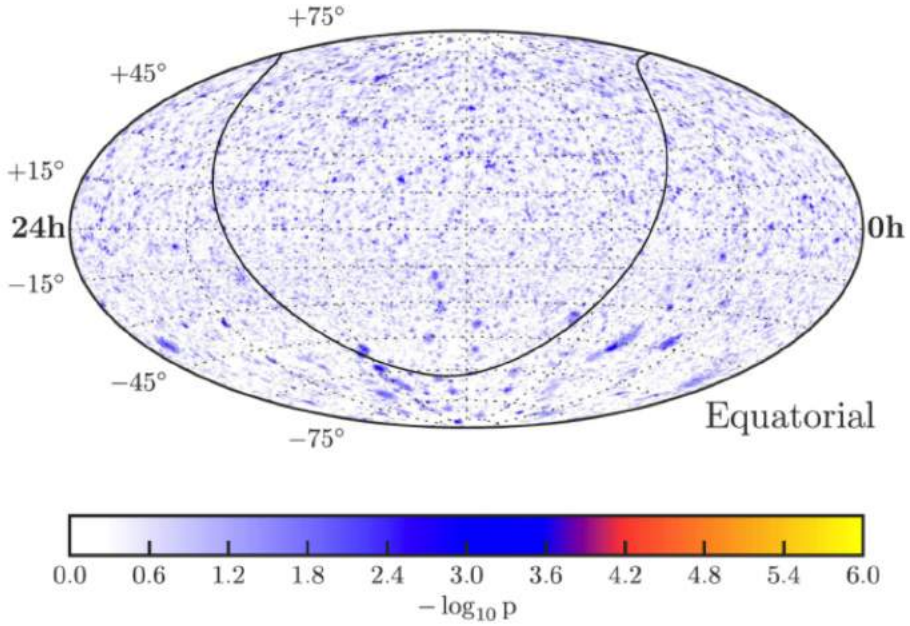
- IceCube discovered high-energy **astrophysical** neutrino flux (2013)
- **TeV-PeV** → dominates above 100 TeV



- 7.5 year High Energy Starting Event (HESE) results coming soon

Searching for neutrino sources

- What is the source of these high-energy astrophysical neutrinos?
  - Blazars? Gamma ray bursts? Decaying dark matter?
  - Isotropic flux → dominated by extragalactic sources
- Search for clustering in neutrino direction/time



8 year neutrino source hot spots

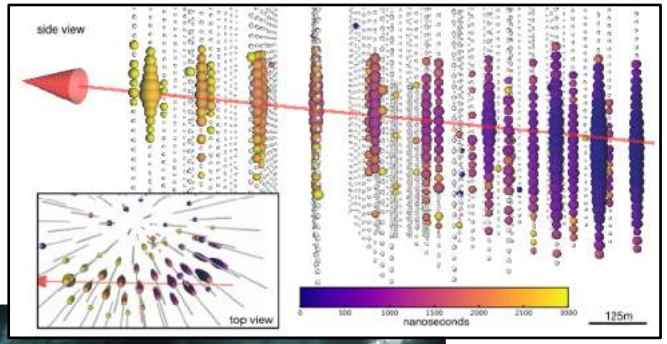
- **No source found until…**

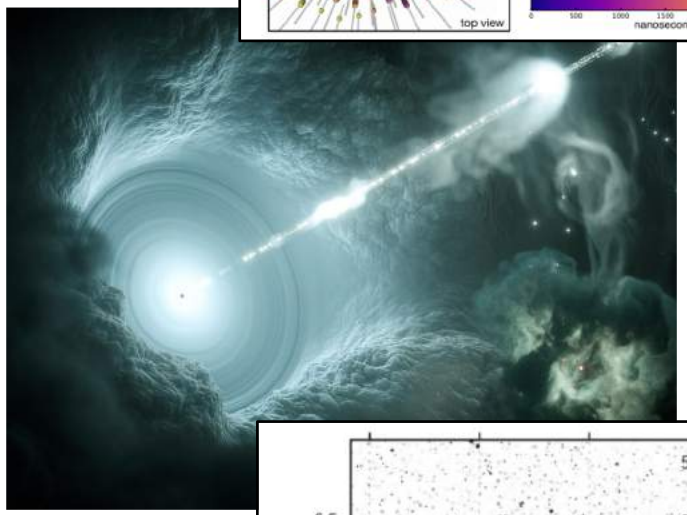
Observation of ν emission from flaring blazar

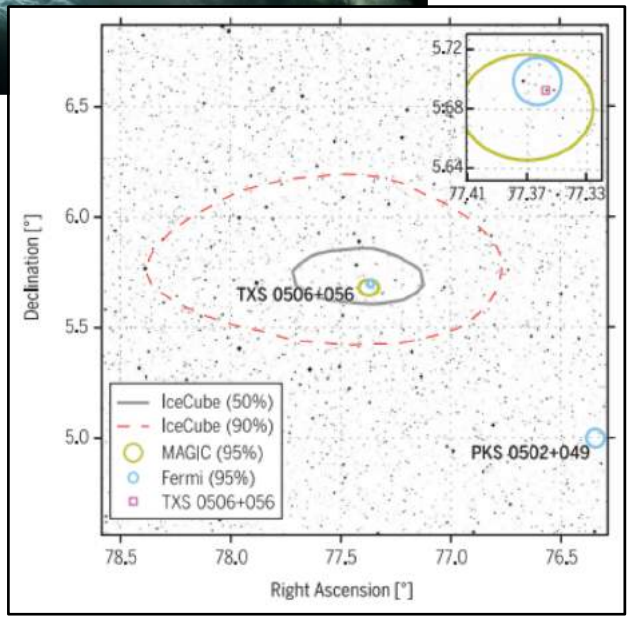
- September 22nd 2017:
  - 300 TeV neutrino detected by IceCube
  - Alert triggered to multimessenger partners after 43s
  - >20 observatories make follow up observations (γ-ray, X-ray, optical, radio)

- **Blazar TXS 0506+056** identified as being within 0.1° of neutrino direction

- **Fermi** and **MAGIC** observe coincident high energy gamma ray flaring from blazar
  - **Chance coincidence rejected at 3σ!**







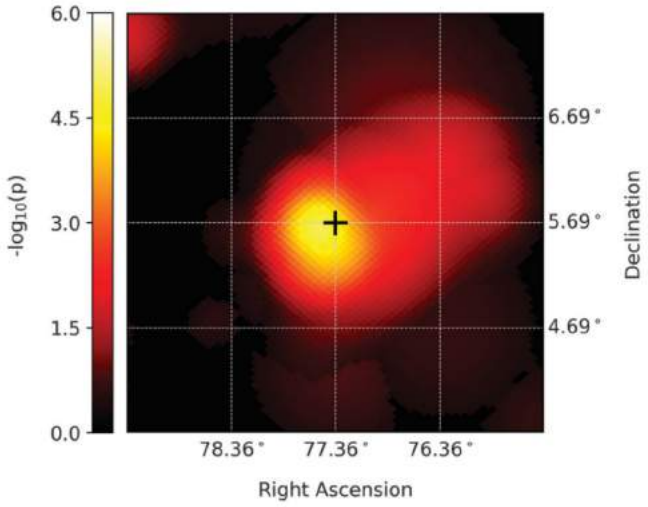
arXiv:1807.08816

Paper link

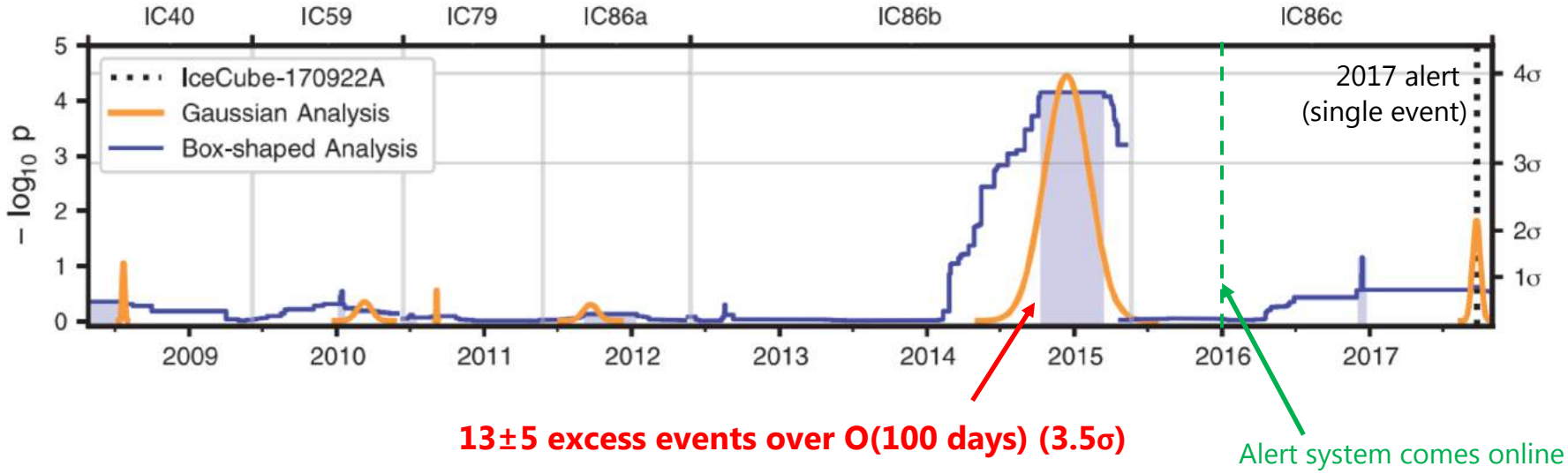
Archival examination of blazar

- Following alert → search for ν emission from this blazar across all 9.5 years of IceCube data
- **3.5σ excess** observed in for O(100 days) in 2014/15
  - Neutrino-only observation, does not depend on e.g. gamma ray emission observations

Sky map during 2014/15 emission



Time-dependent neutrino search in direction of blazar

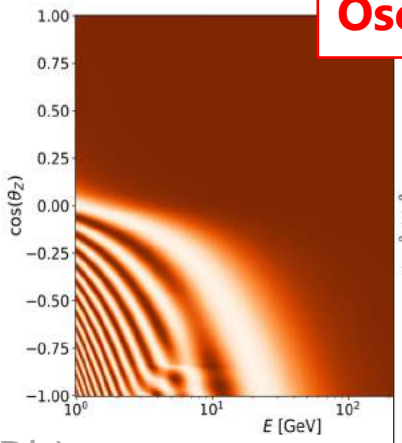


- **Two independent ≥3σ observations indicate blazar as source of high energy ν!**
  - But, stacking analyses show blazars can only account for part of the observed astrophysical flux
  - **More types of sources must be out there!**

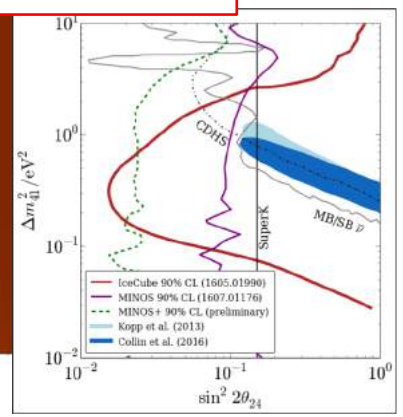
Particle physics

- High energies, range of neutrino propagation distances and high statistics neutrino samples → **IceCube has a broad particle physics scope**

Oscillations



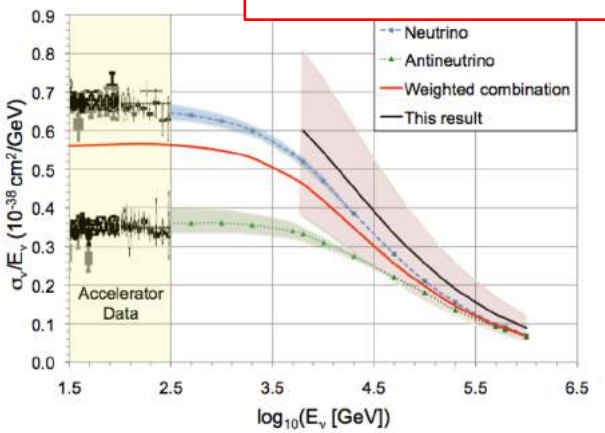
(Dis)appearance



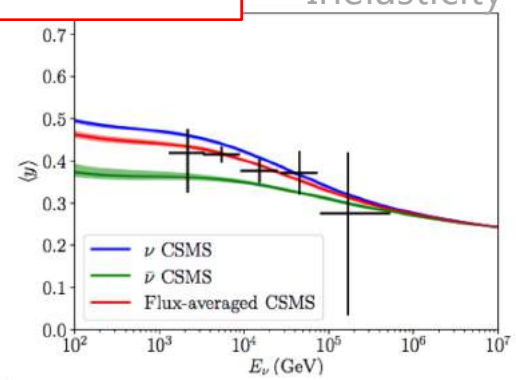
Sterile neutrinos

Interactions with matter

Cross section

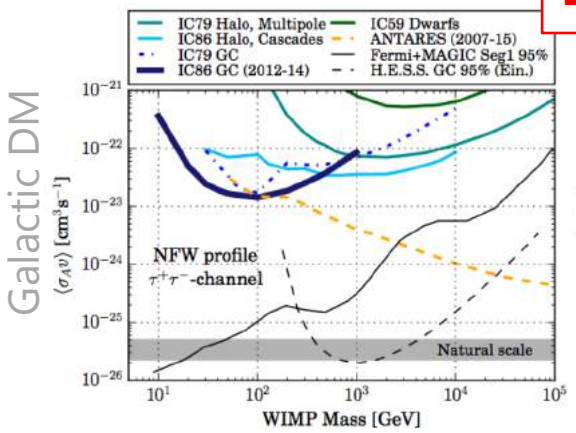


Inelasticity

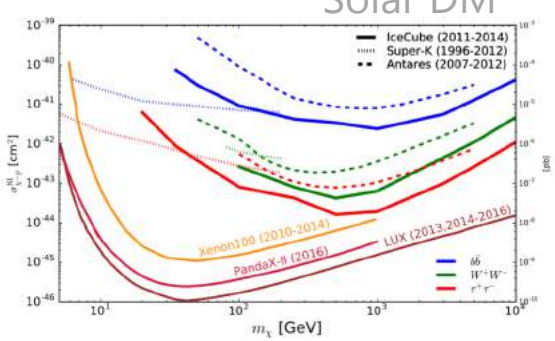


Dark Matter

Galactic DM

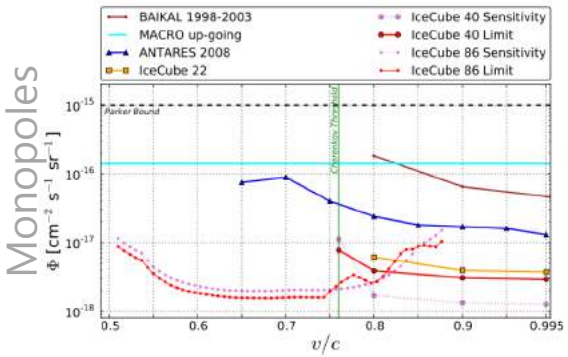


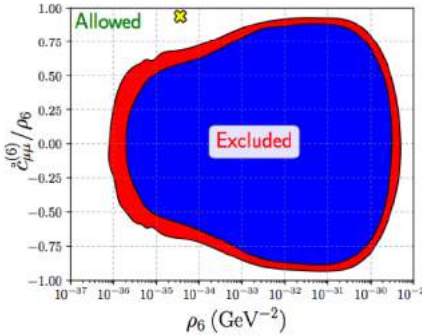
Solar DM



Beyond Standard Model

Monopoles

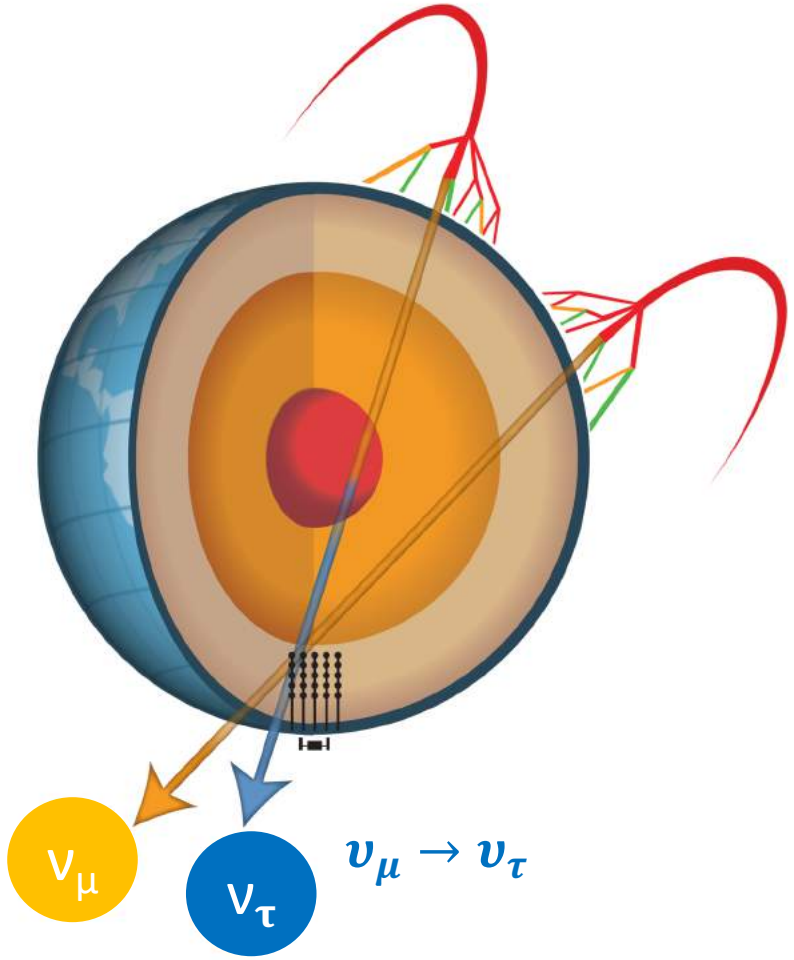


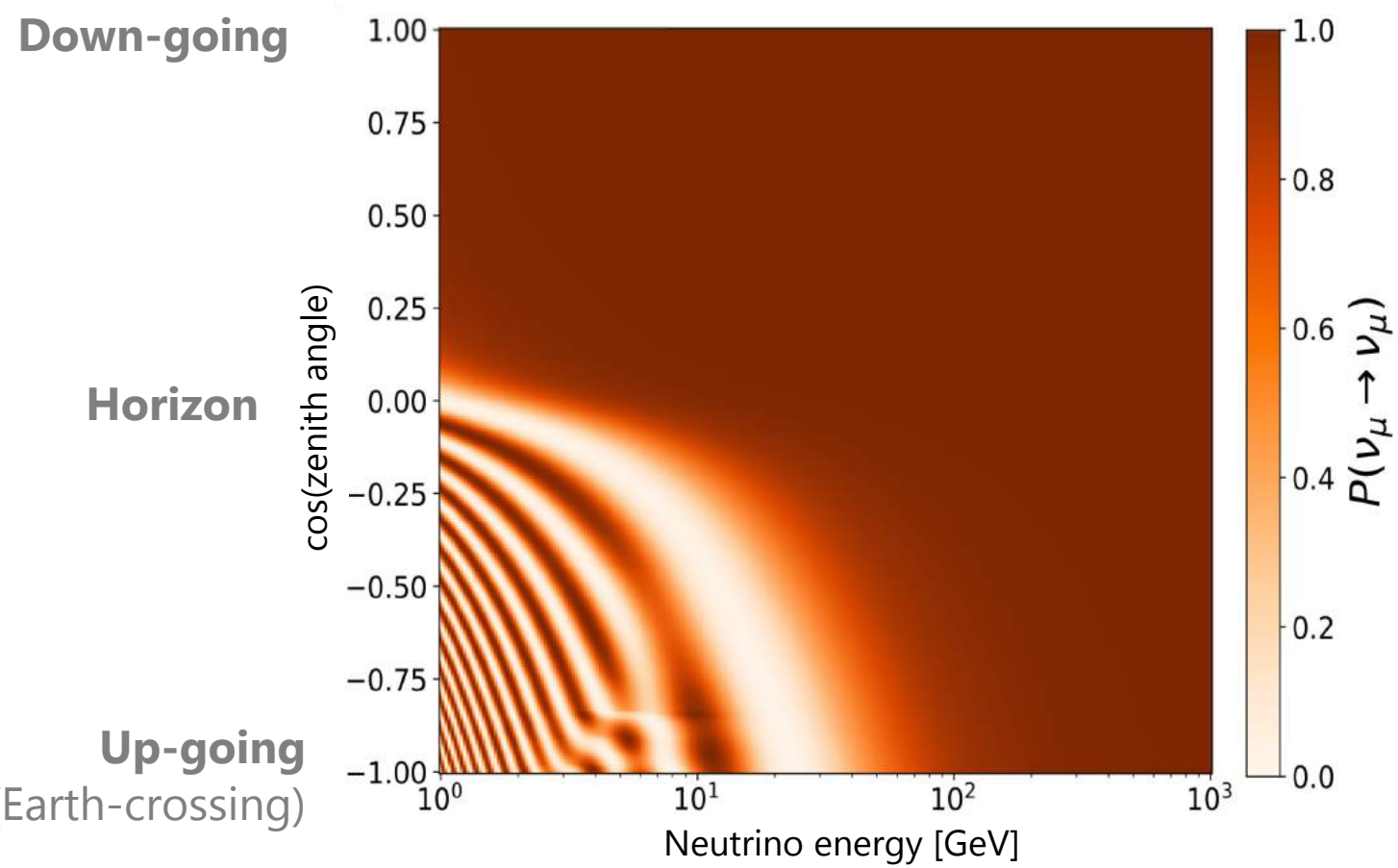


Lorentz violation

Oscillations in DeepCore

- **Atmospheric neutrino** oscillations observed in DeepCore @ ~20 GeV
- Search for 3D distortions in event rates: $[\boldsymbol{E}, \boldsymbol{cos}(\boldsymbol{\theta}_{\boldsymbol{zenith}}), \boldsymbol{particle\ ID}]$





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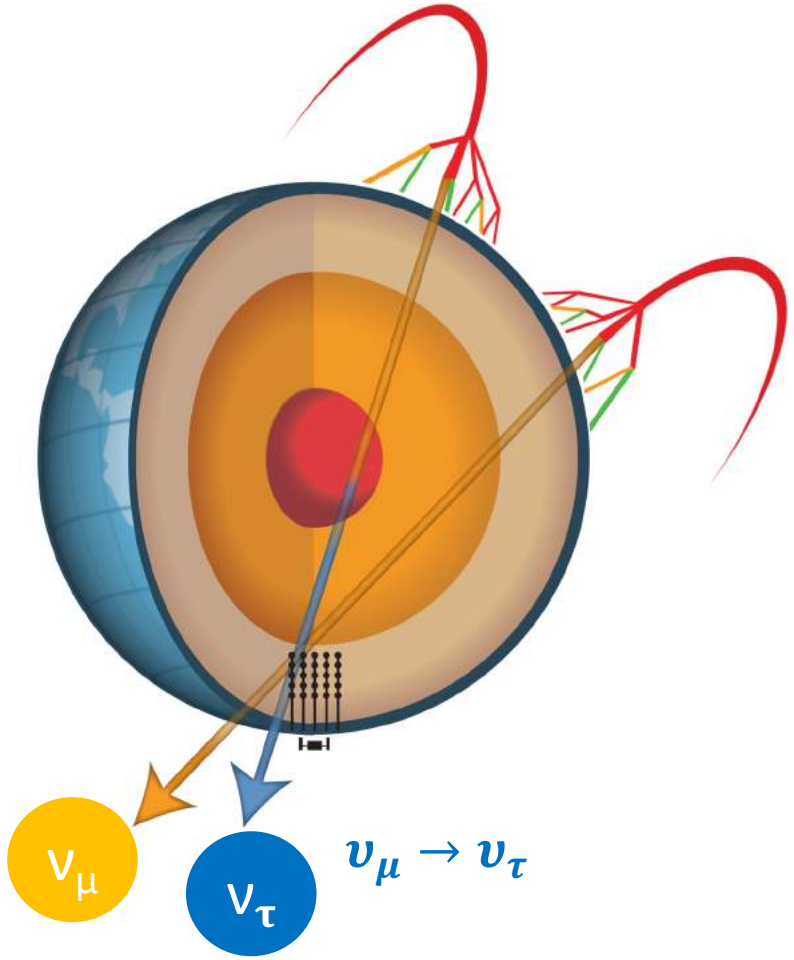
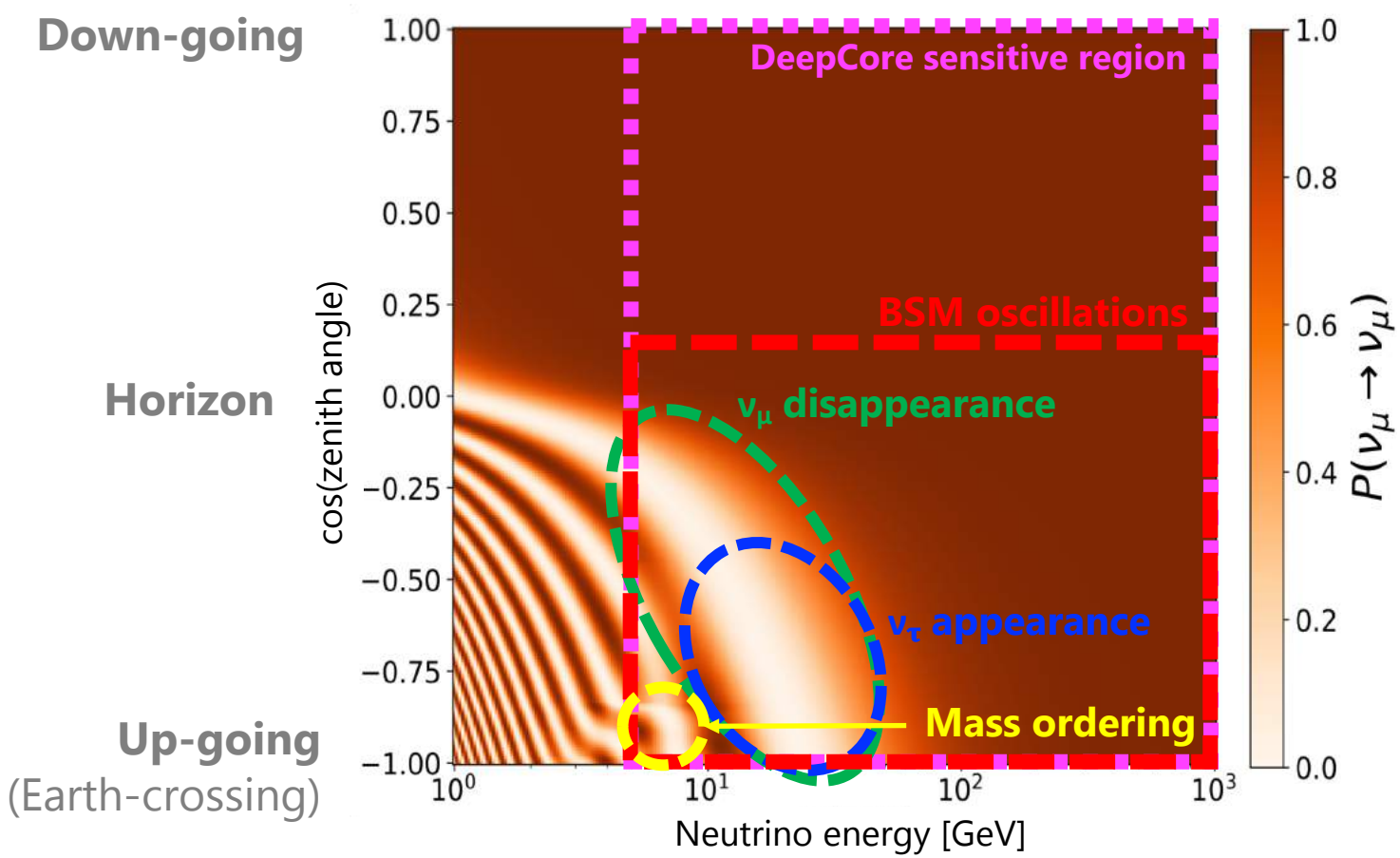
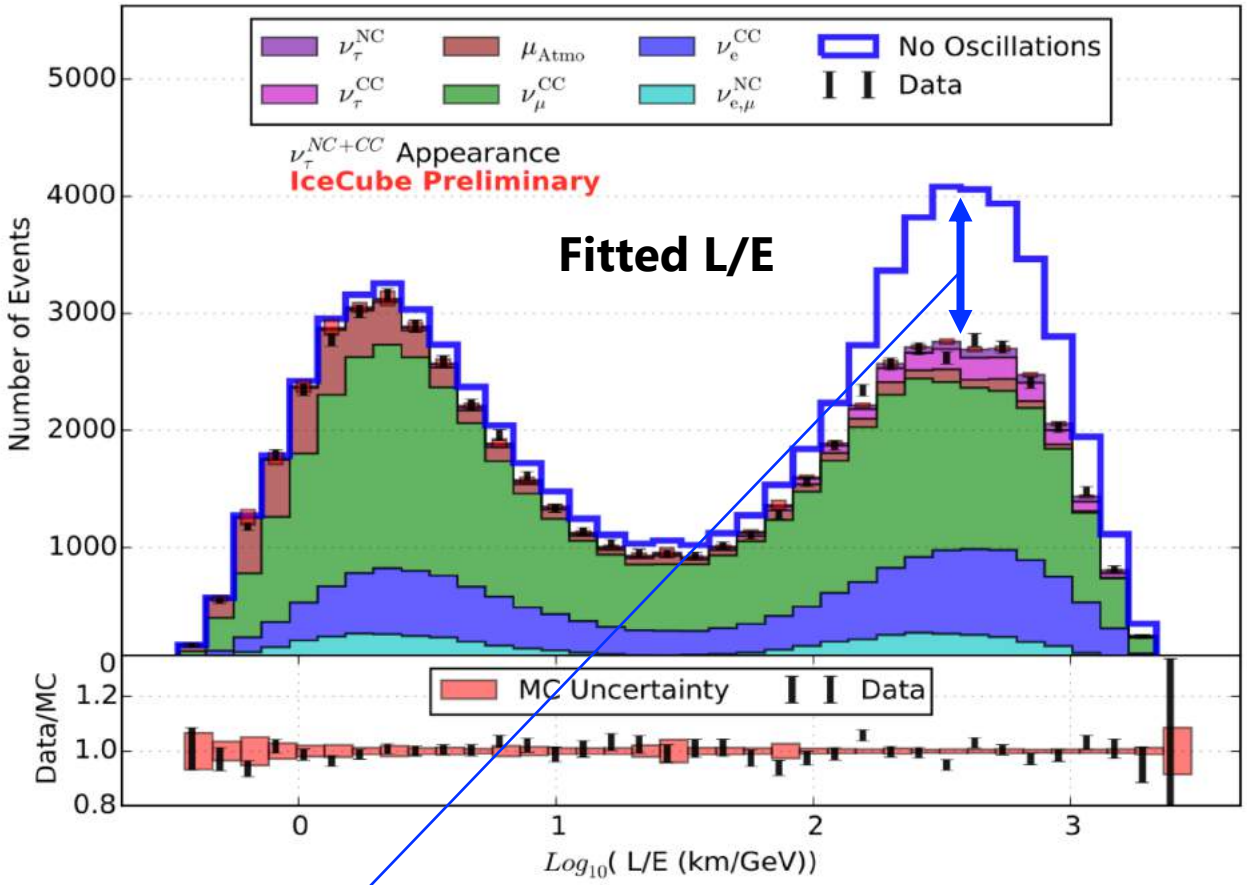




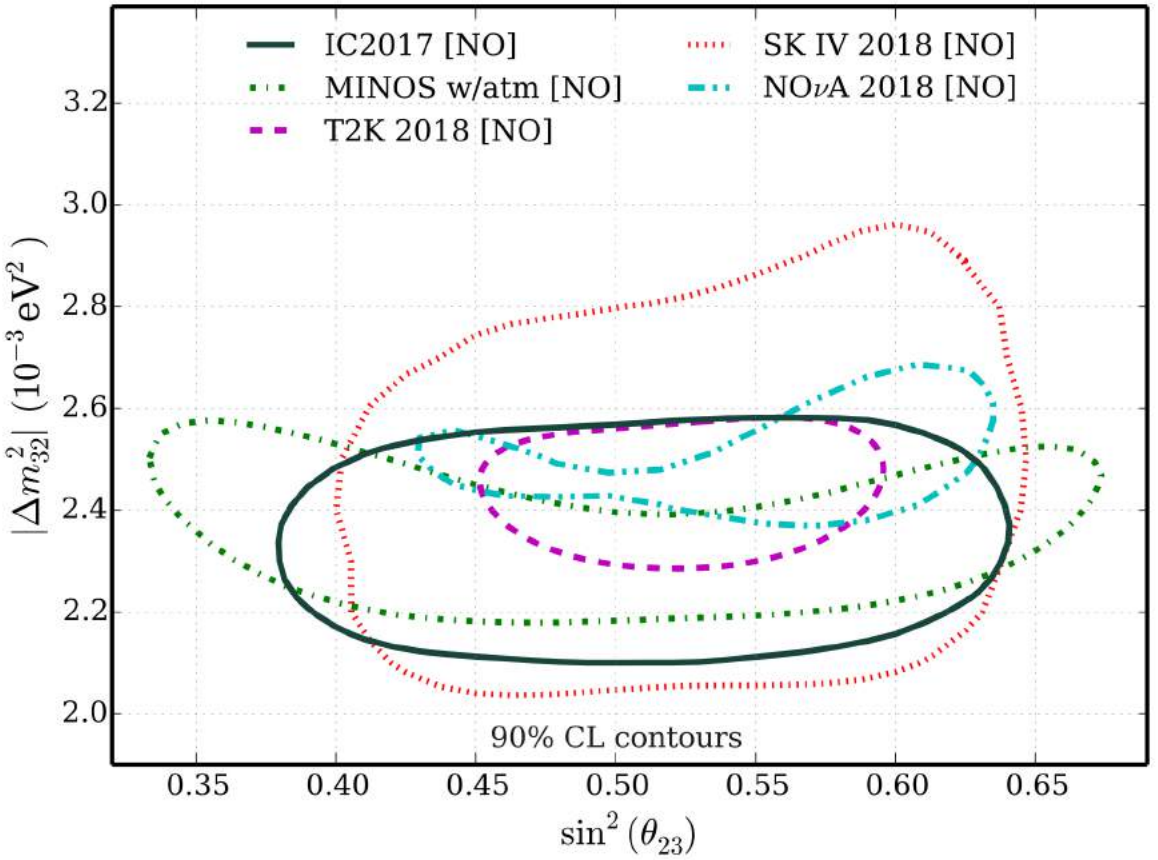
arXiv:1707.07081

ν_μ disappearance

- ν_μ disappearance measured using 3 years of DeepCore data



Disappearance signal

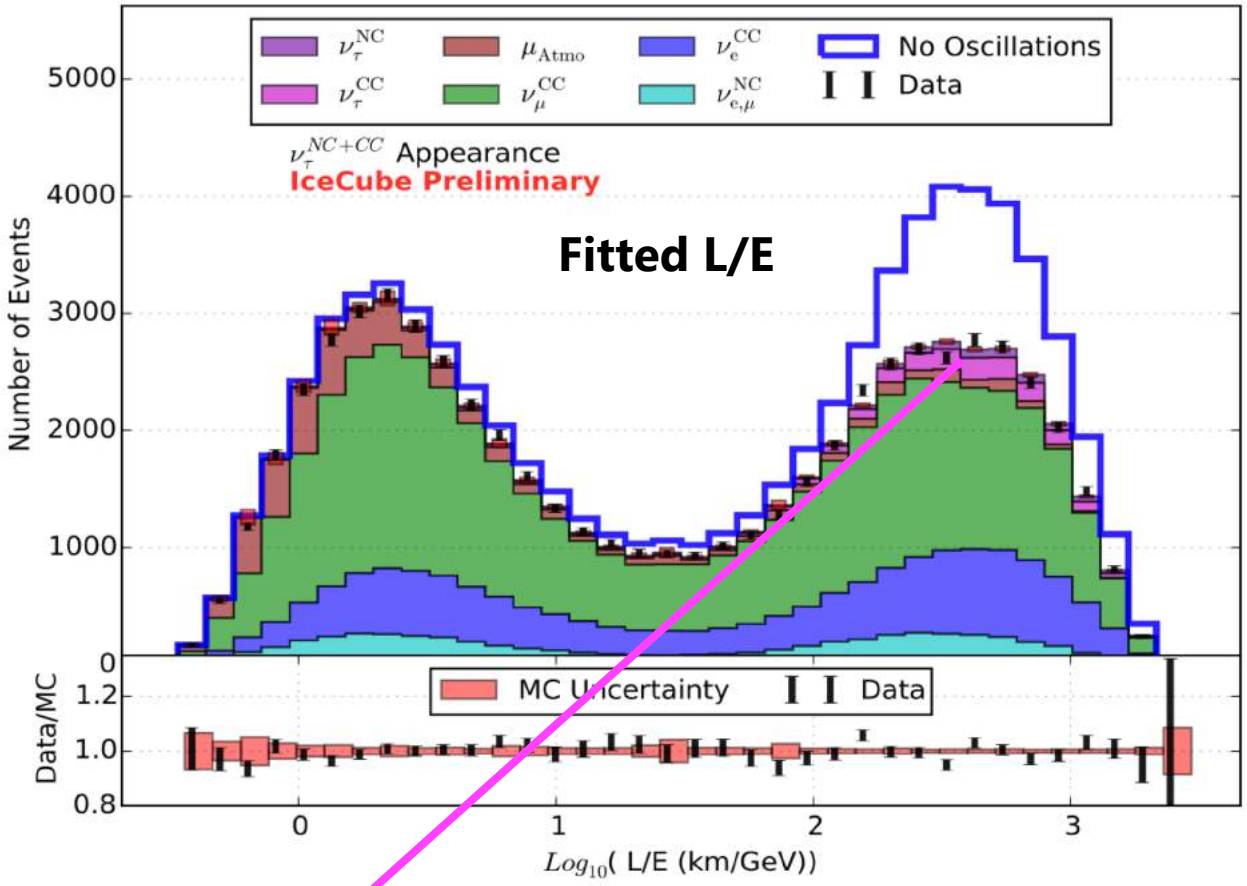


→ **Results consistent with long baseline accelerators**
→ **Order of magnitude higher E_ν**

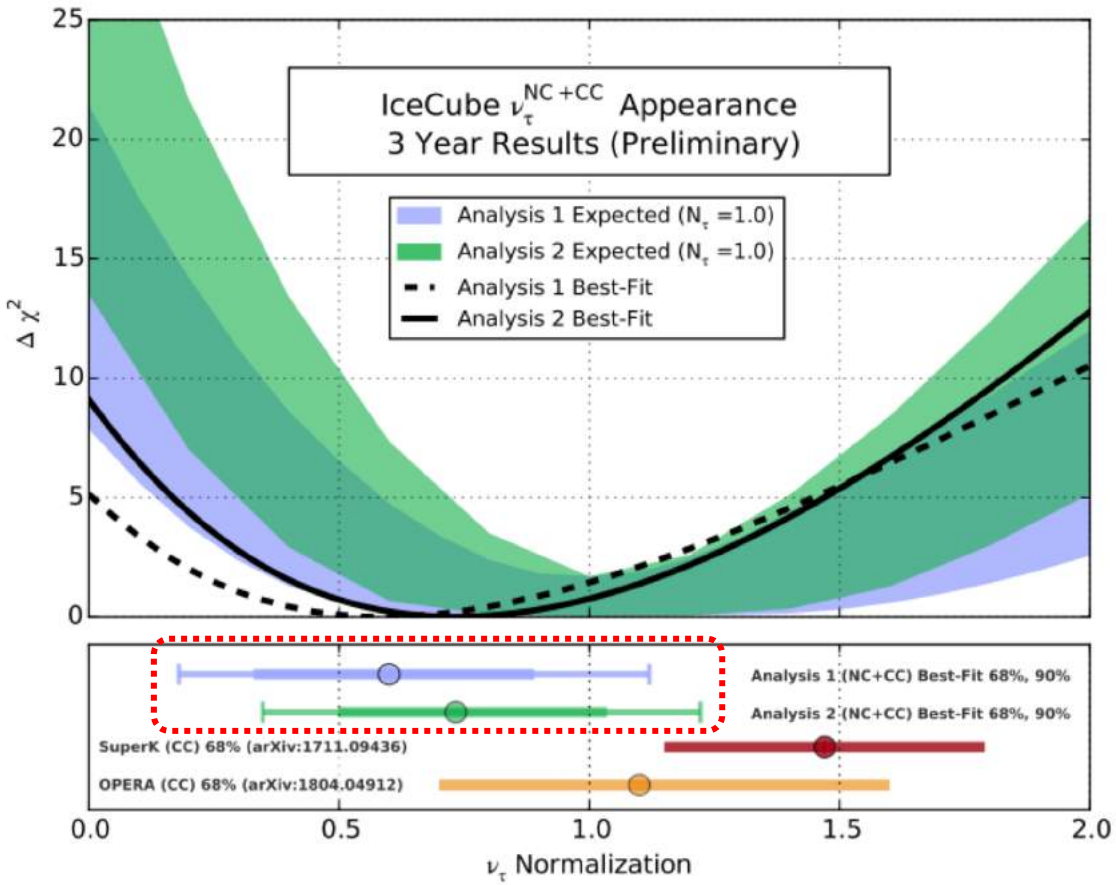
ν_τ appearance

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \vdots \end{pmatrix} = \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \\ \vdots & & \ddots & \end{pmatrix}}^{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \vdots \end{pmatrix}$$

- ν_τ appearance measured using 3 years of DeepCore data



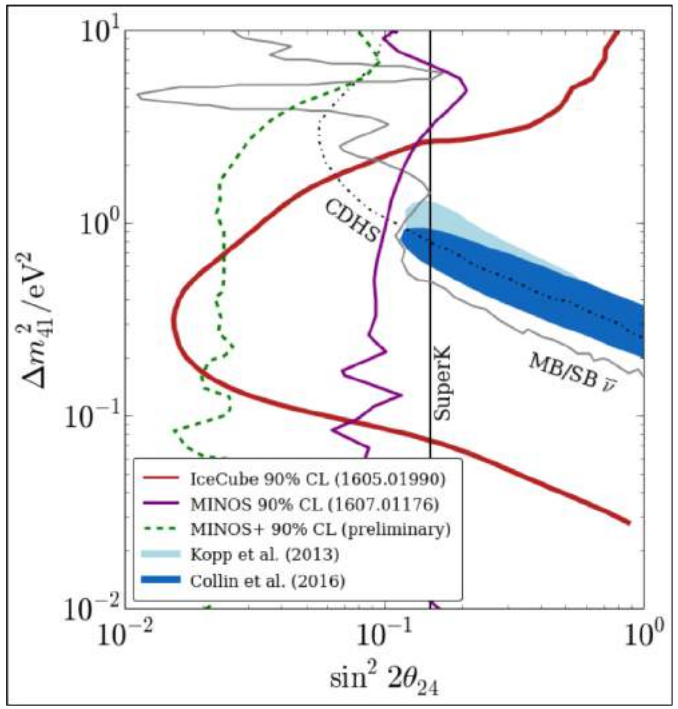
Appearance signal (suppressed cross section)



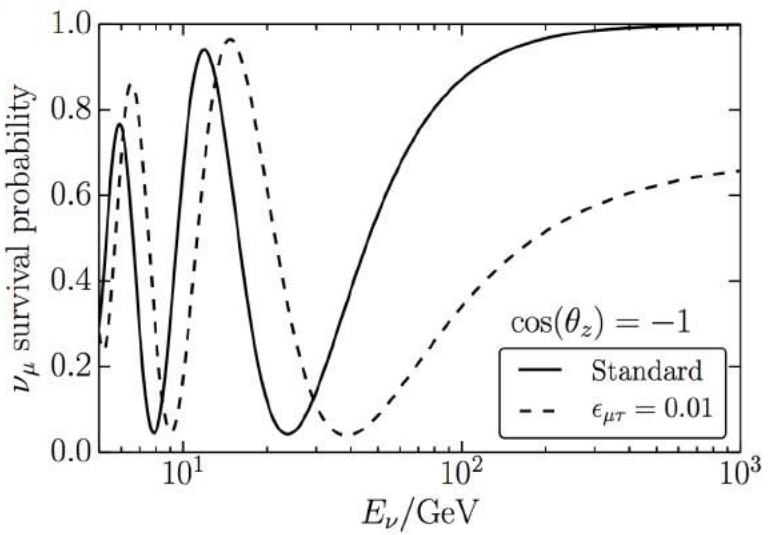
→ **World best measurement**
→ **Consistent with 3 flavour PMNS unitarity**

Many other oscillation results published/underway…

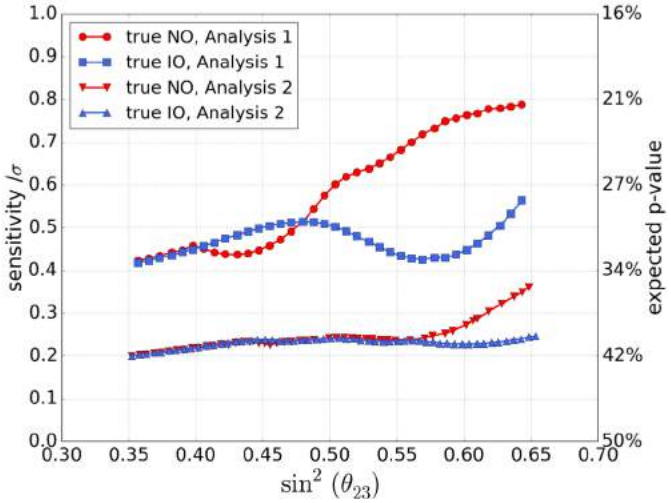
1 eV sterile neutrinos



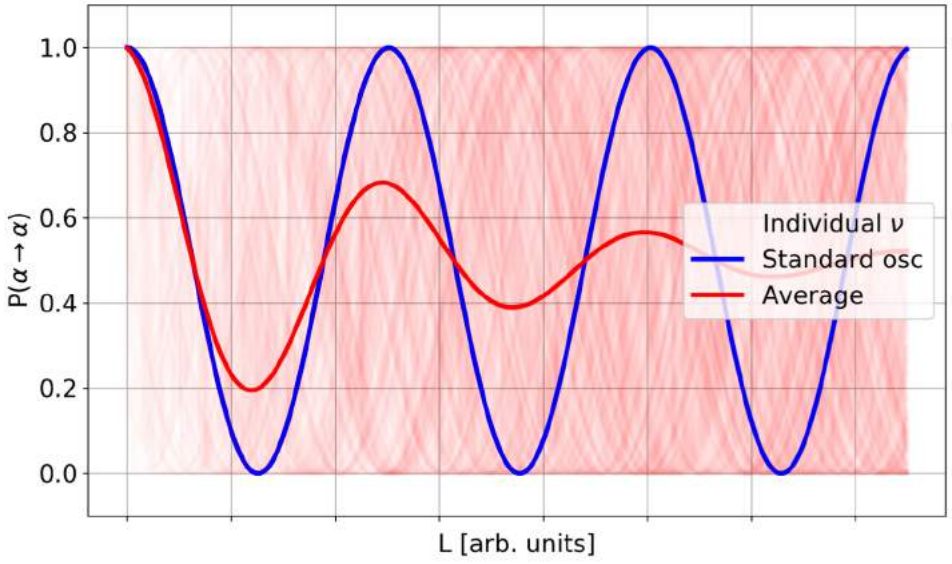
Non-Standard Interactions NSI)



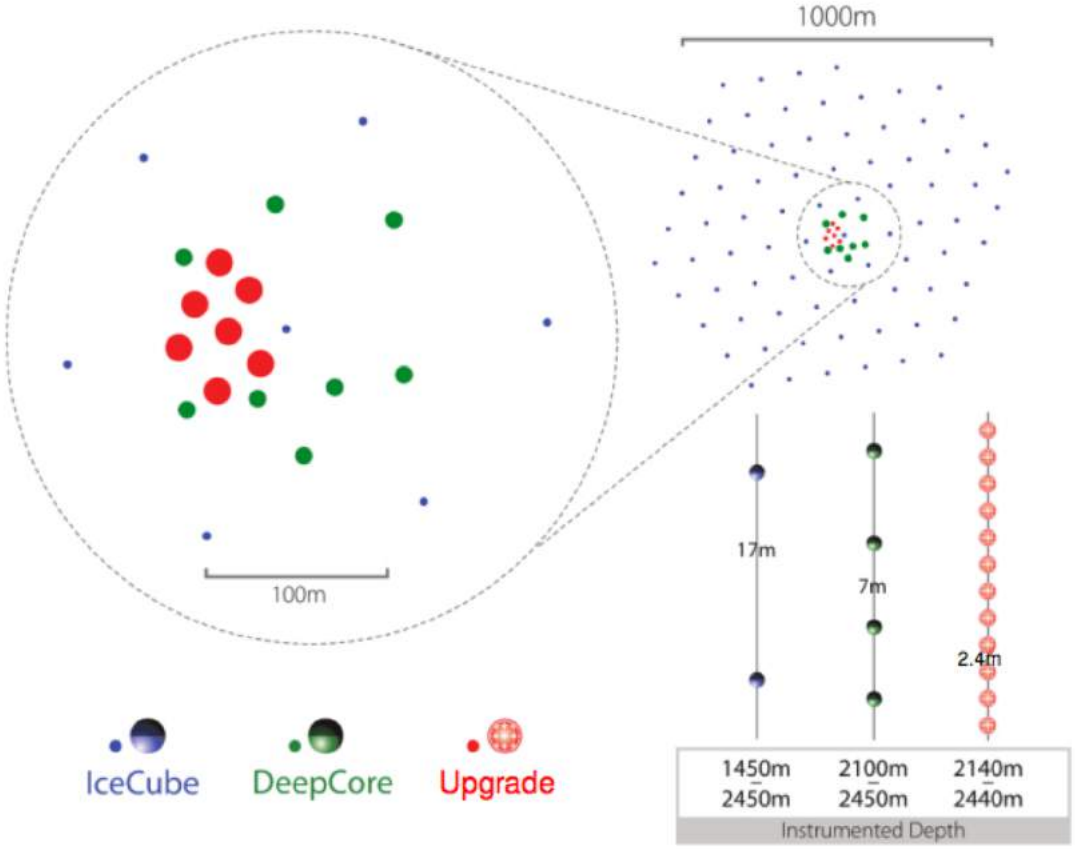
Neutrino mass ordering



Neutrino decoherence



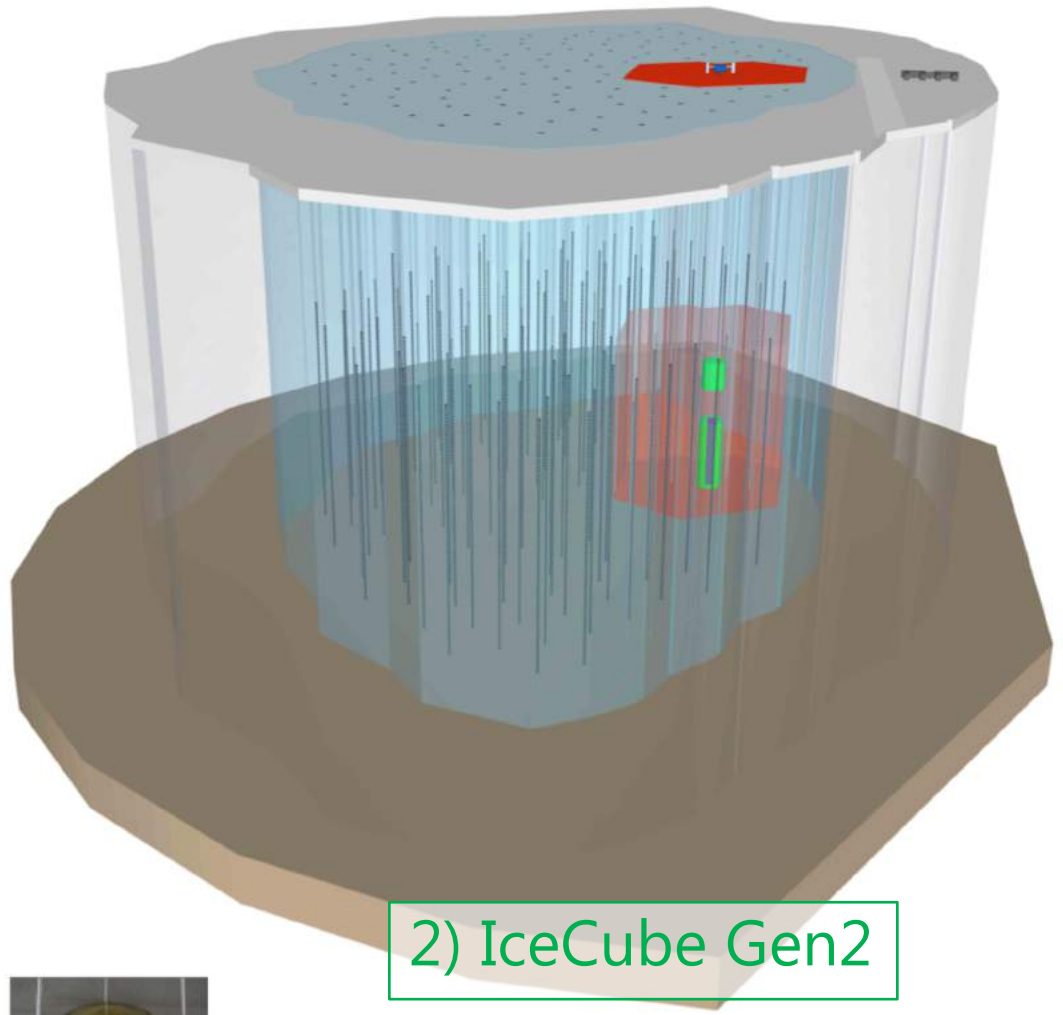
The future



1) IceCube Upgrade

Denser low energy array
Improved calibration

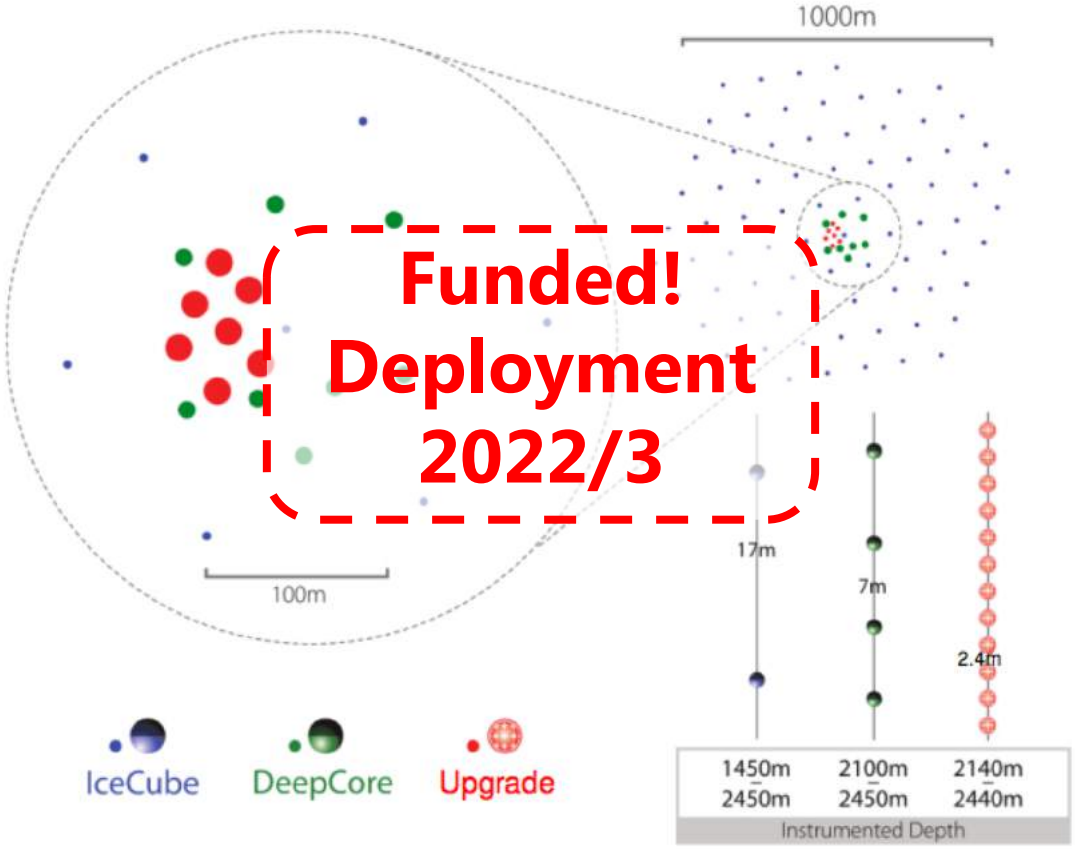
New optical modules



2) IceCube Gen2

10 km^3 high energy array
Expanded surface array

The future



Funded!
Deployment
2022/3

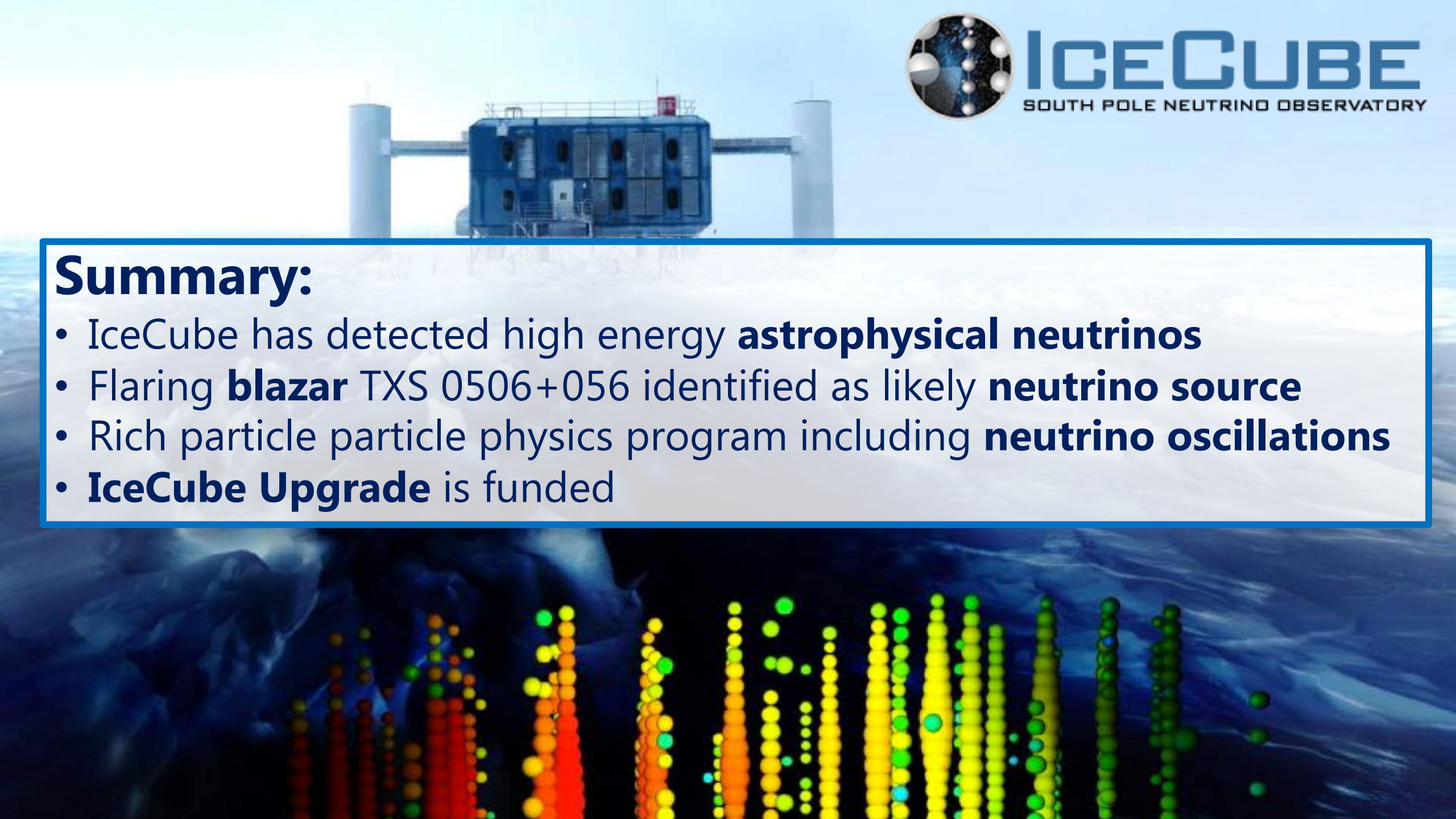
1) IceCube Upgrade

Denser low energy array
Improved calibration

New optical modules

2) IceCube Gen2

10 km^3 high energy array
Expanded surface array



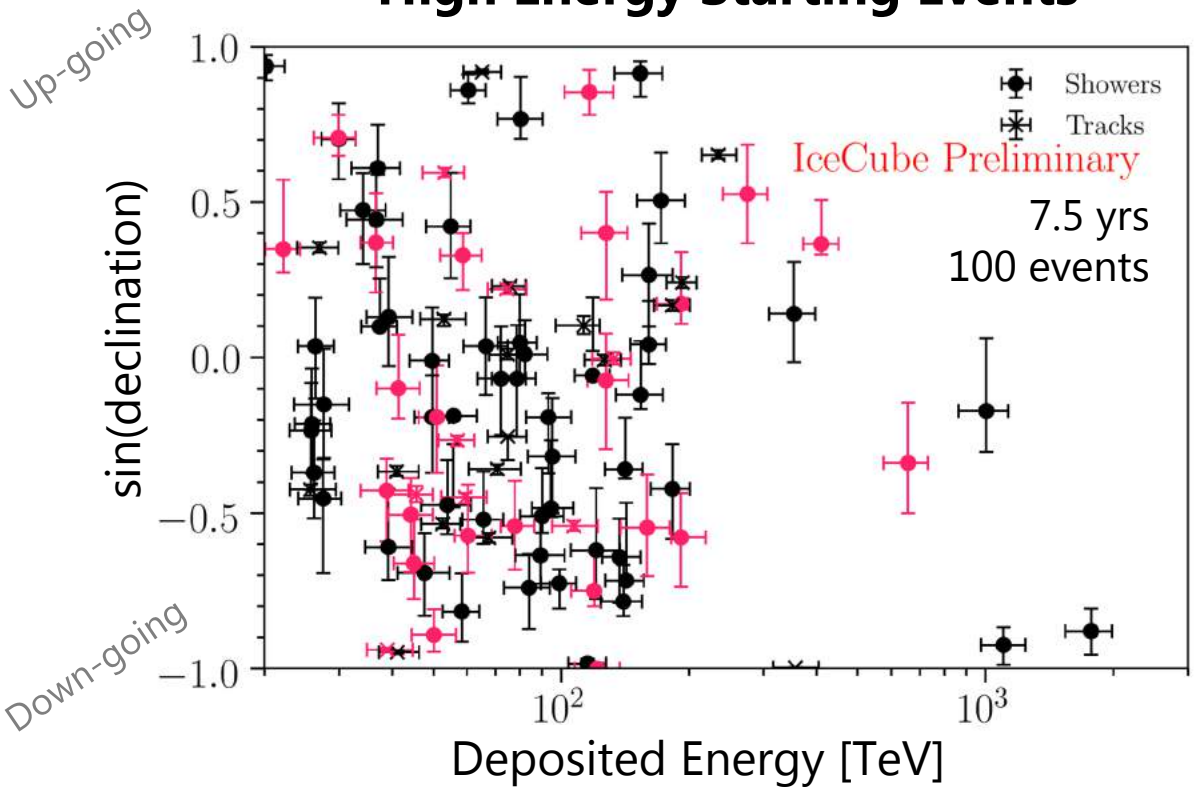
Summary:

- IceCube has detected high energy **astrophysical neutrinos**
- Flaring **blazar** TXS 0506+056 identified as likely **neutrino source**
- Rich particle particle physics program including **neutrino oscillations**
- **IceCube Upgrade** is funded

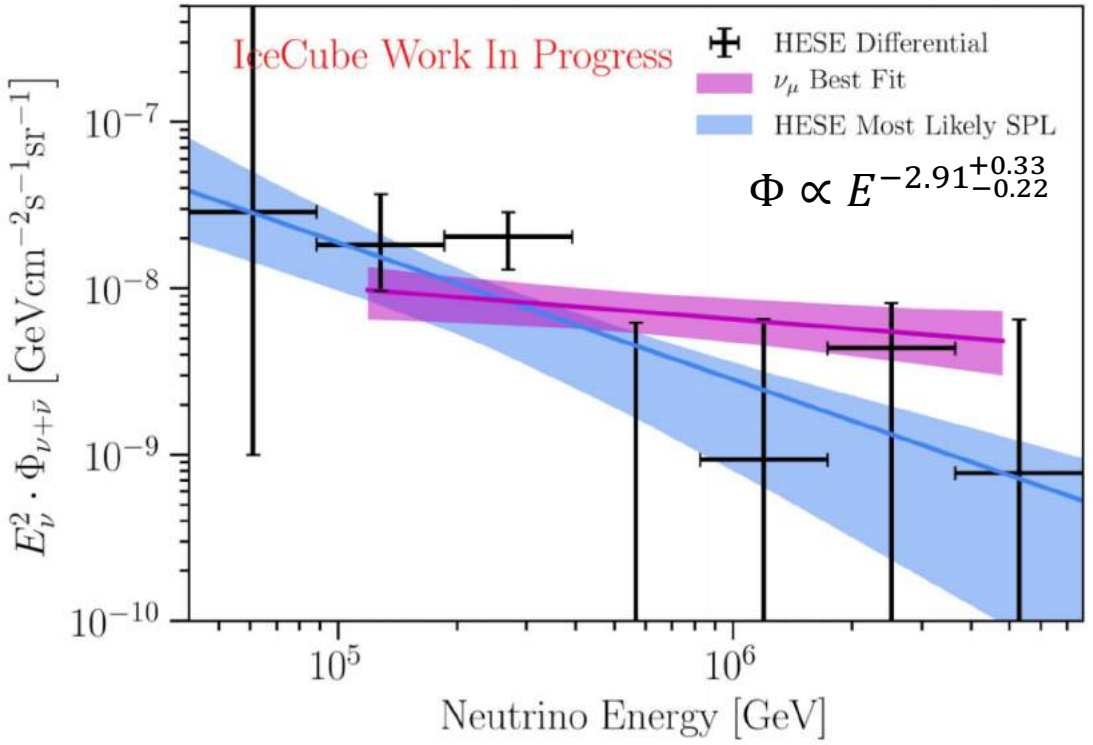
Backup

HESE 7.5 year results

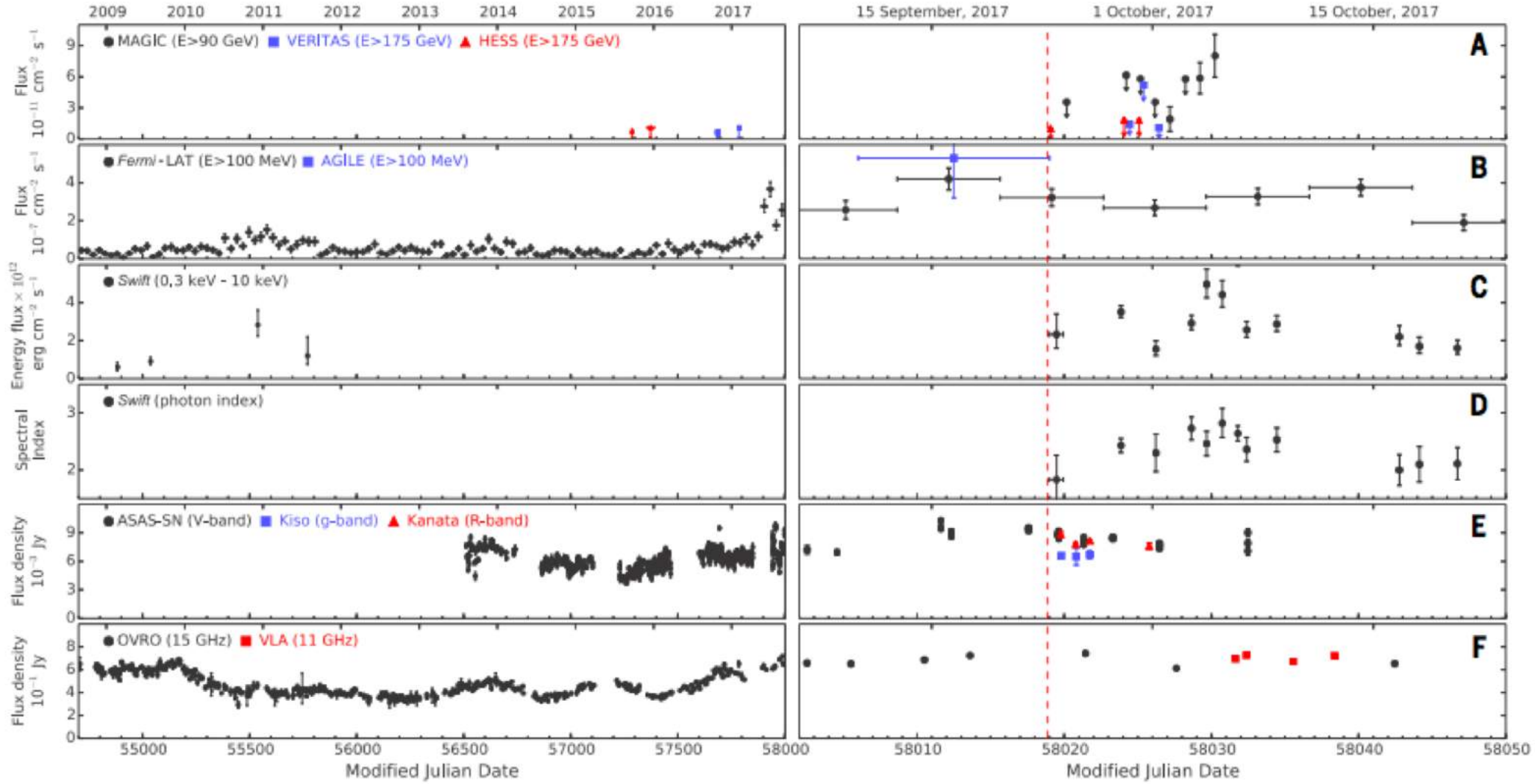
High Energy Starting Events



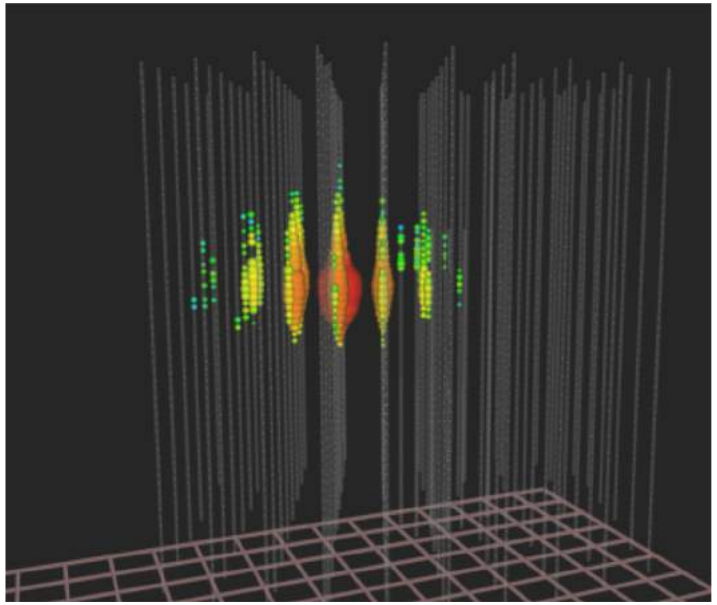
Astrophysical neutrino flux



TXS 0506+056 alert multimessenger observation



Event topologies

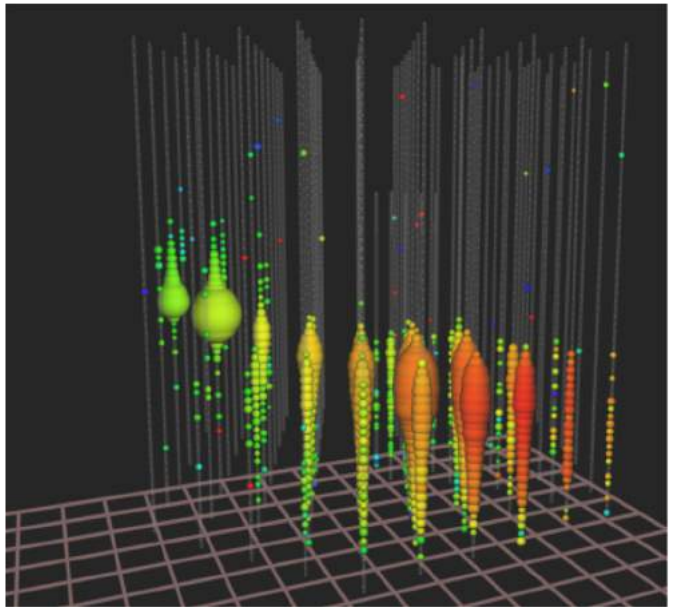


Cascade

$\upsilon_{e,CC}$

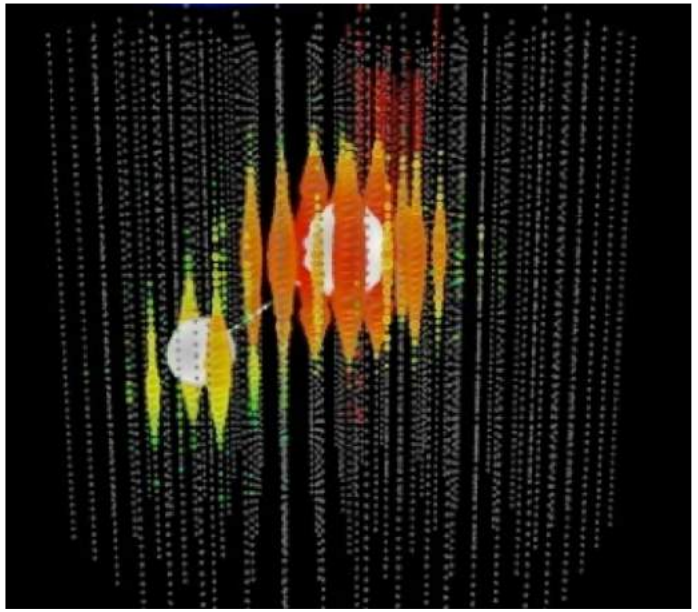
υ_{NC}

$\upsilon_{\tau,CC}$ (low energy)



Track

$\upsilon_{\mu,CC}$

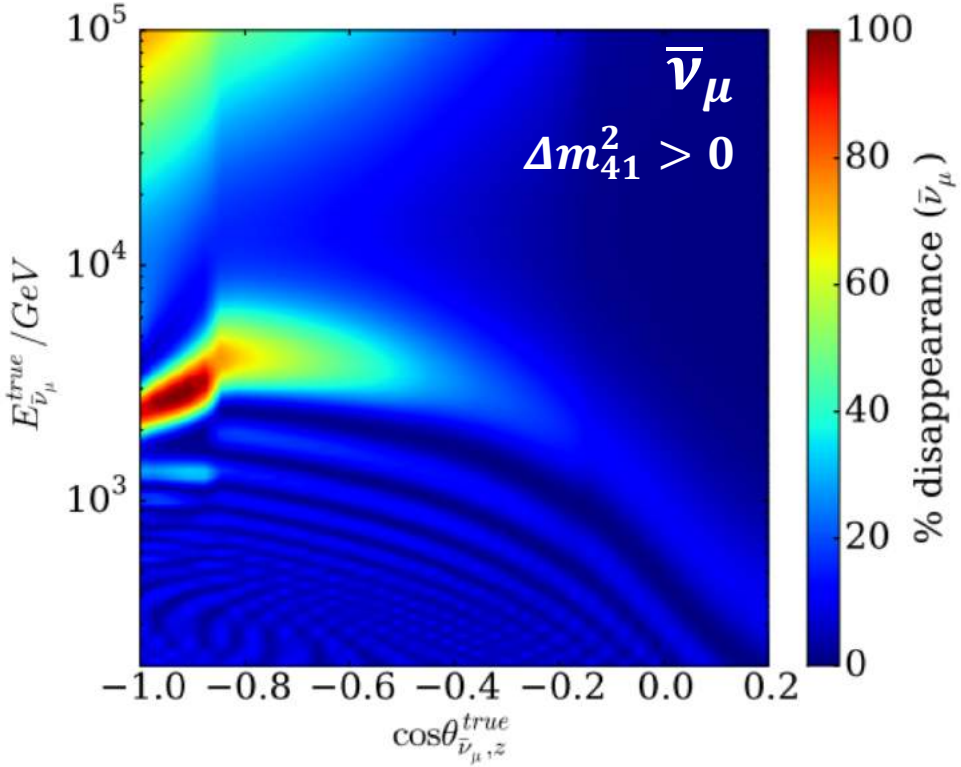


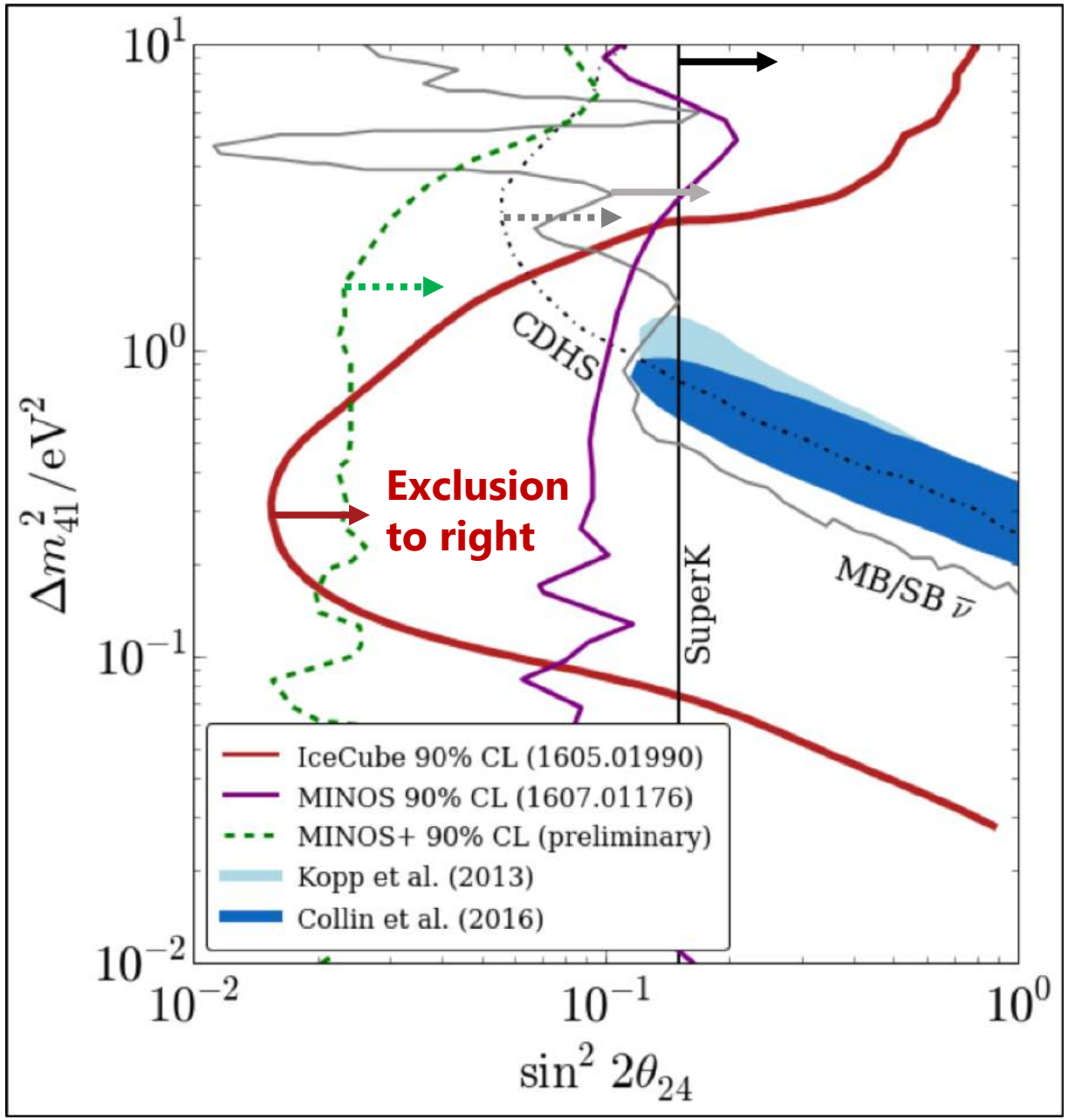
Double bang

$\upsilon_{\tau,CC}$ (high energy)

High energy steriles

- Sensitive to 1 eV sterile neutrino via matter resonance
- Not observed → tension with short baseline anomalies





Other sterile mixing parameters = 0 (conservative)

Ice properties