Multimessenger astronomy

with high-energy neutrinos

Markus Ackermann, DESY

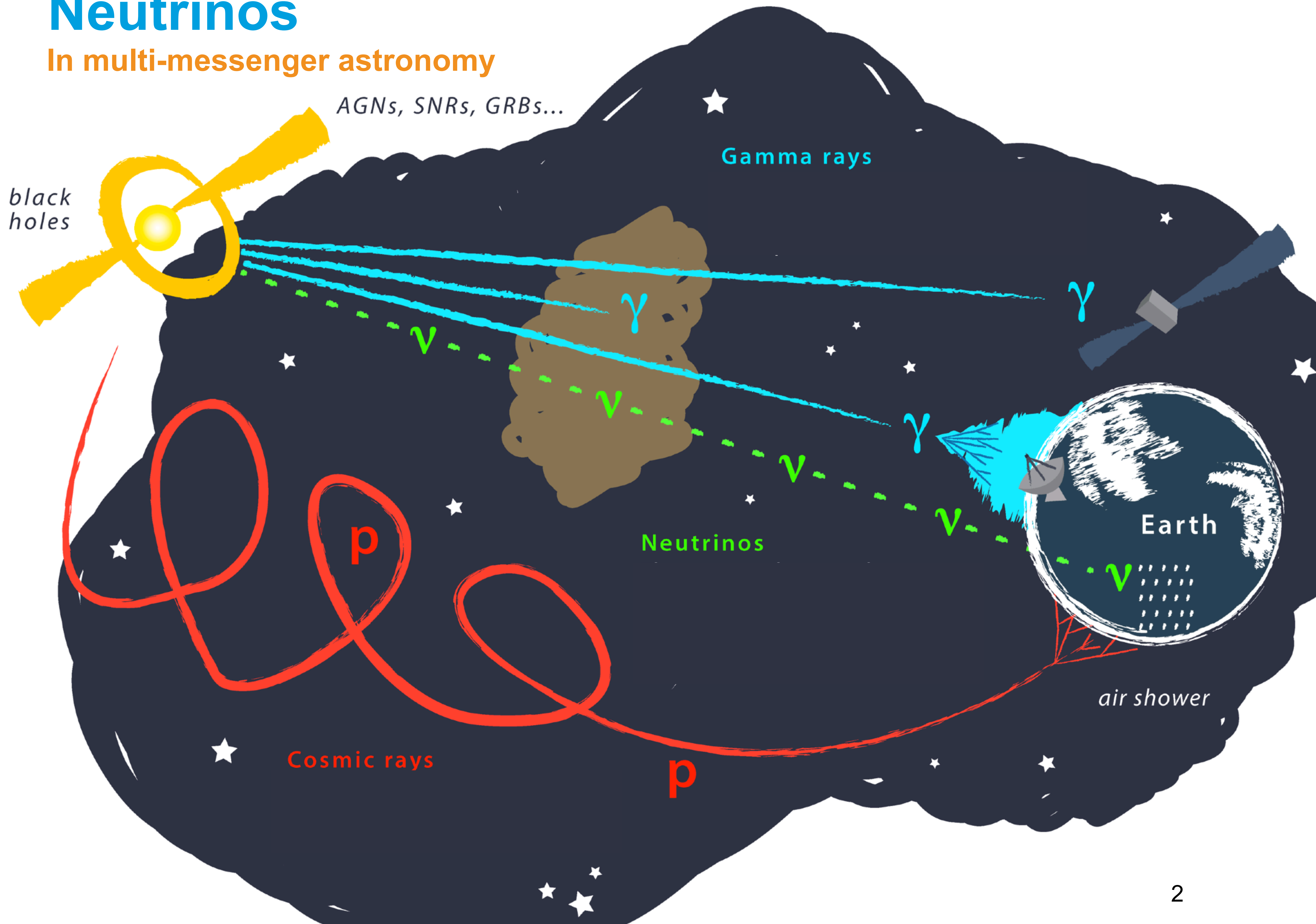
CTA Japan workshop

Feb 21, 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

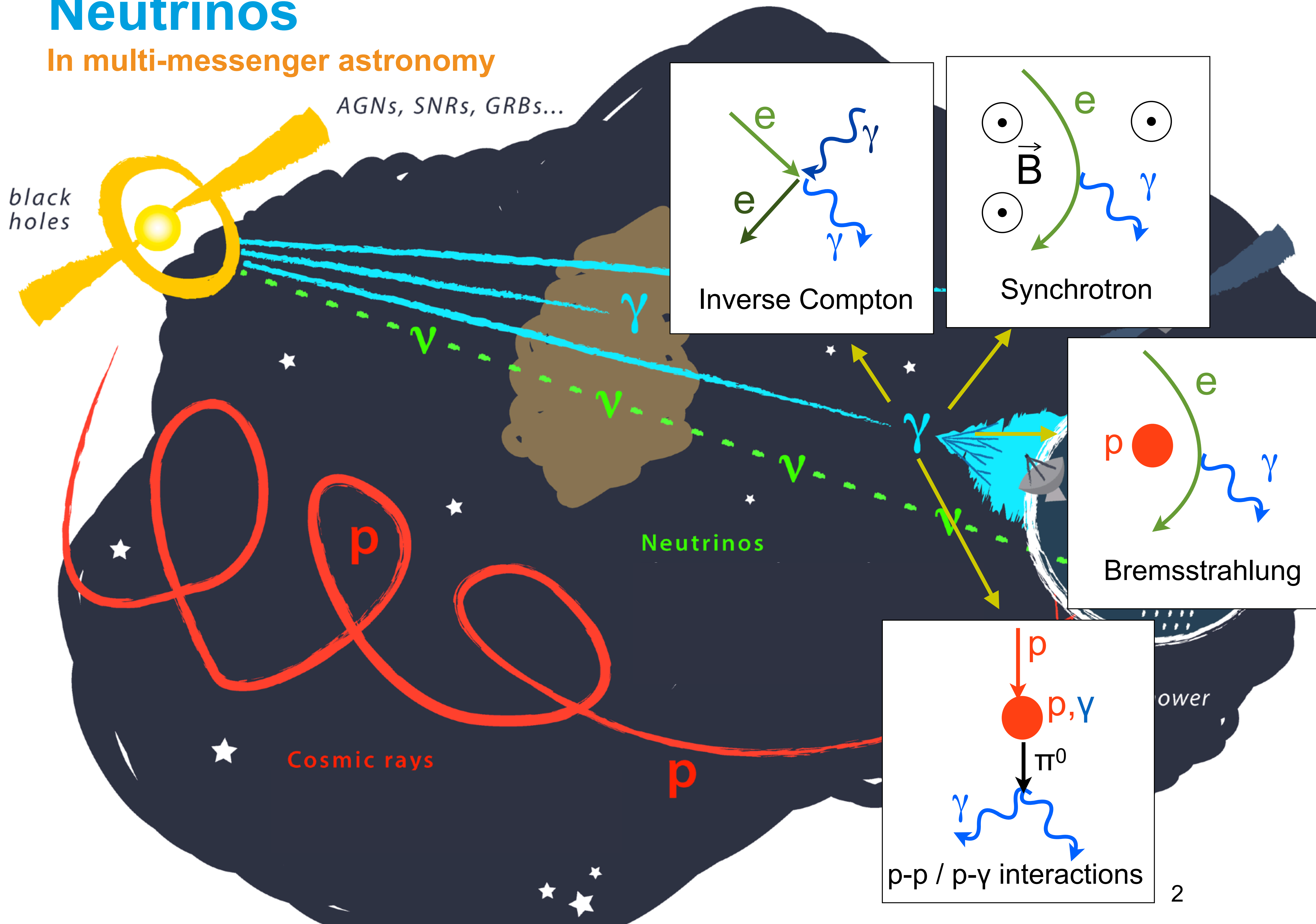
Neutrinos

In multi-messenger astronomy



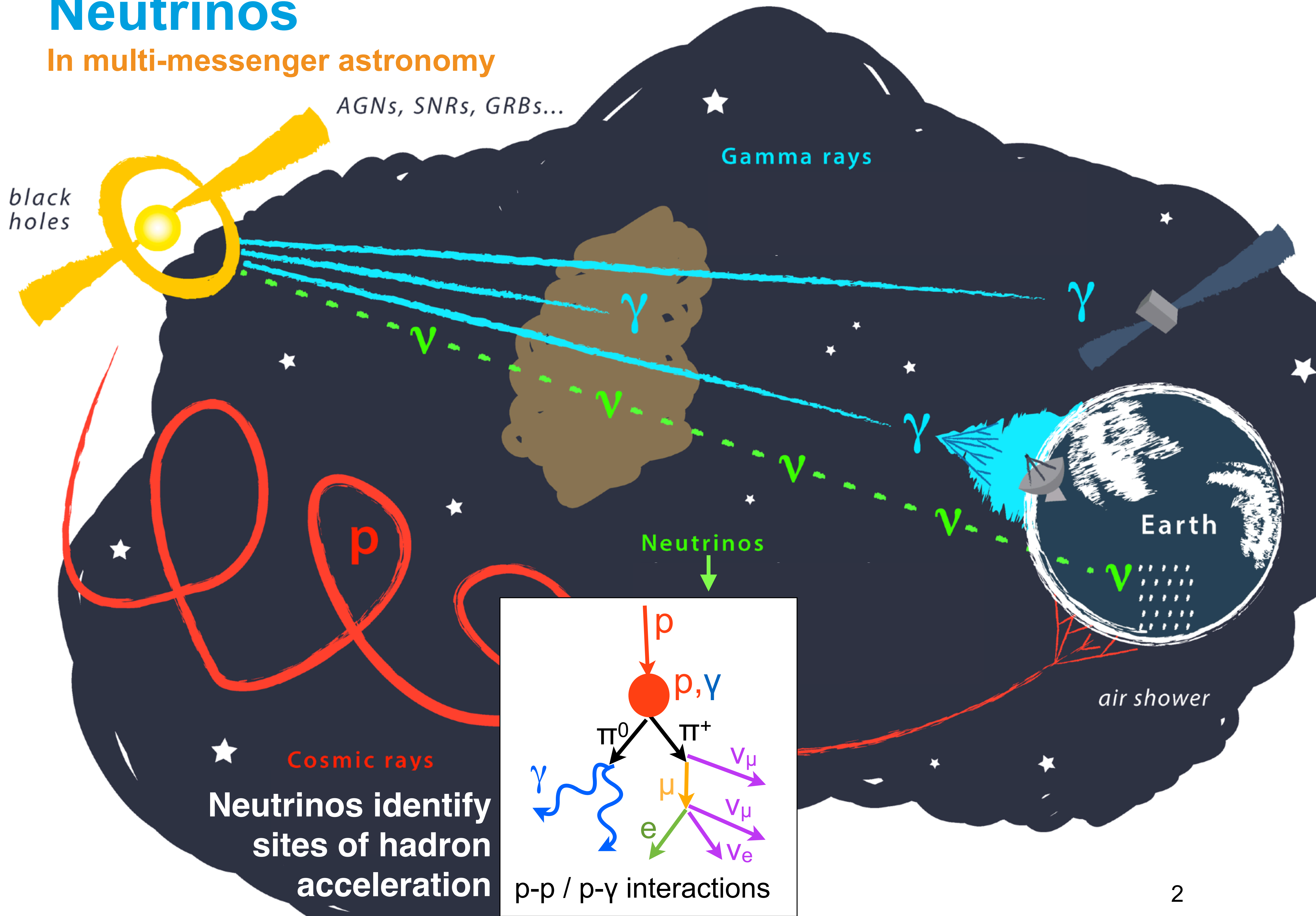
Neutrinos

In multi-messenger astronomy



Neutrinos

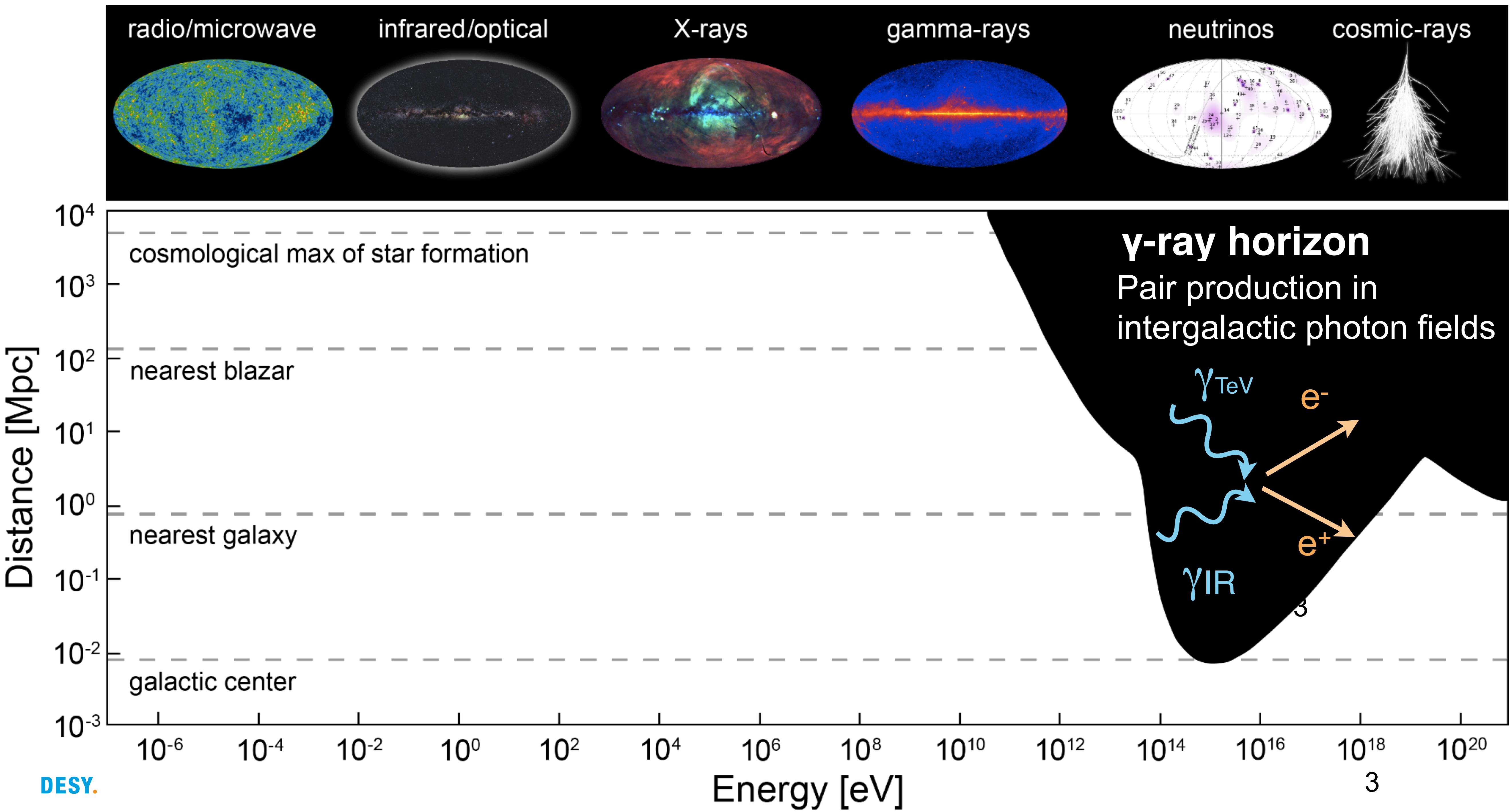
In multi-messenger astronomy



Neutrinos identify sites of hadron acceleration

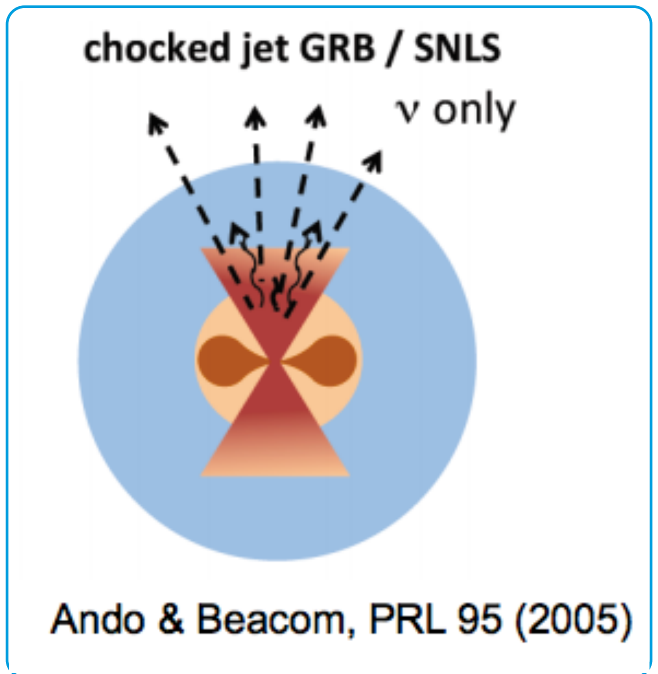
The domain of neutrino astronomy

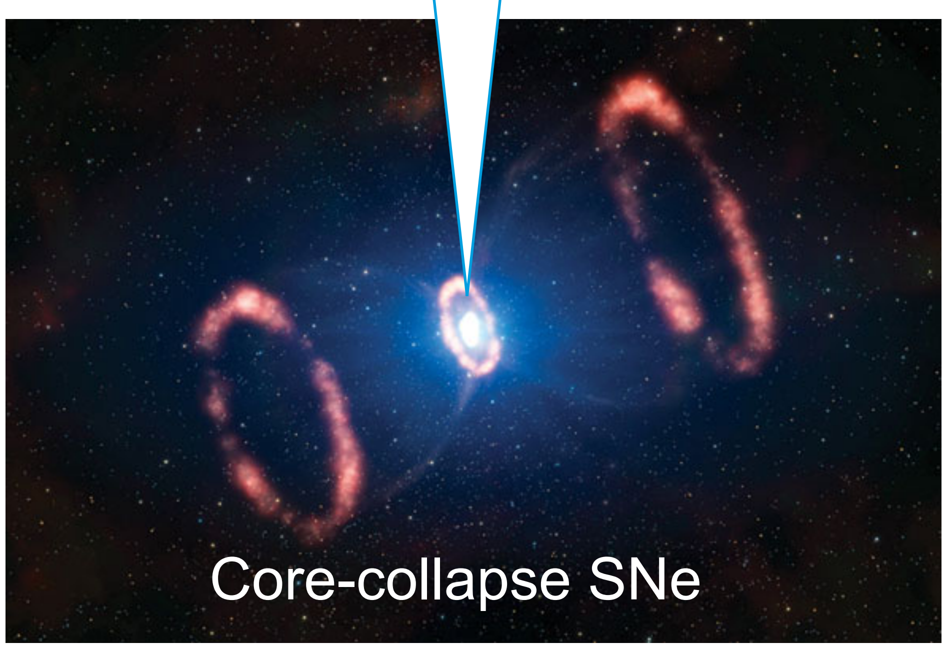
- **Neutrinos** allow us to observe the universe that is opaque to electromagnetic radiation.
- **Astronomy at PeV energies** can only be done with neutrinos !

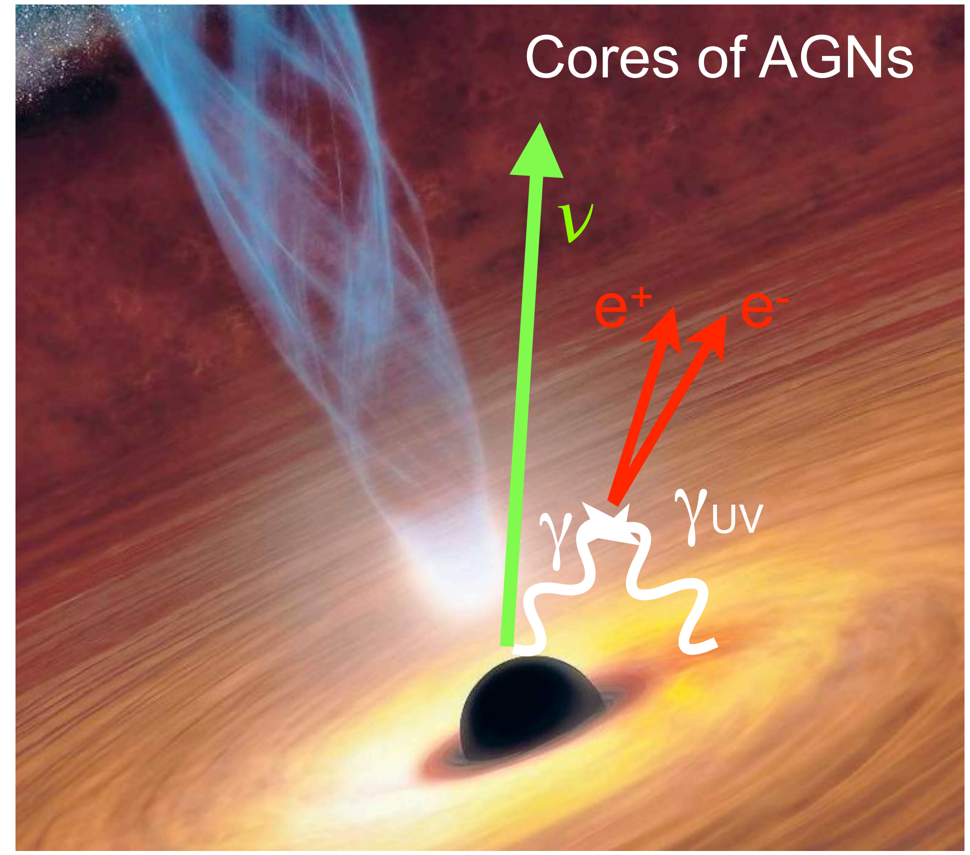


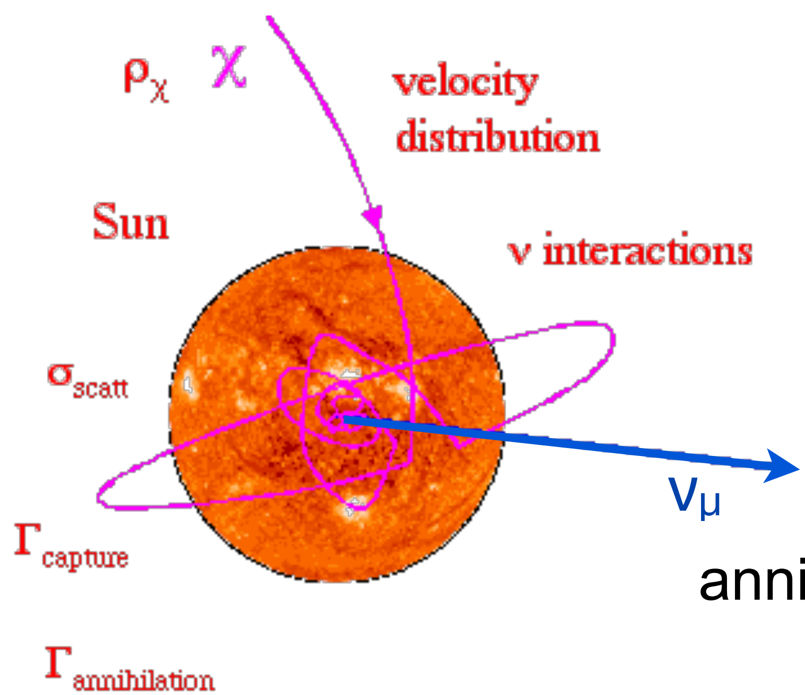
Astrophysical environments opaque to EM radiation

…can only be observed in neutrinos







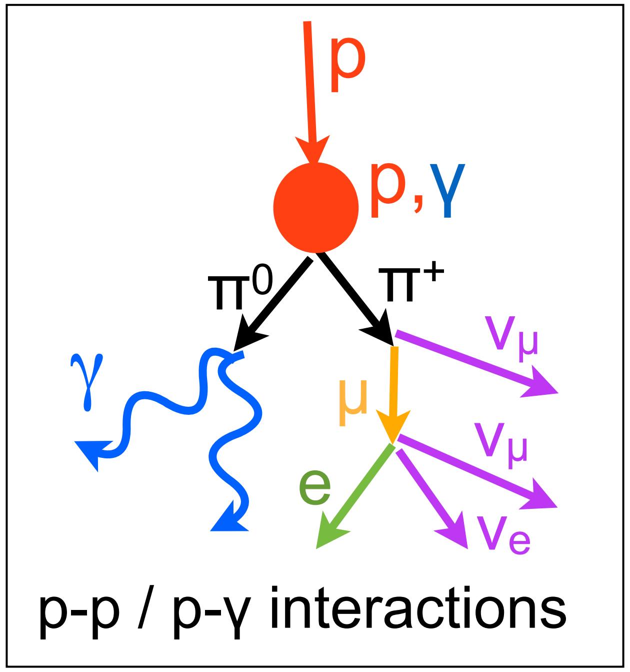


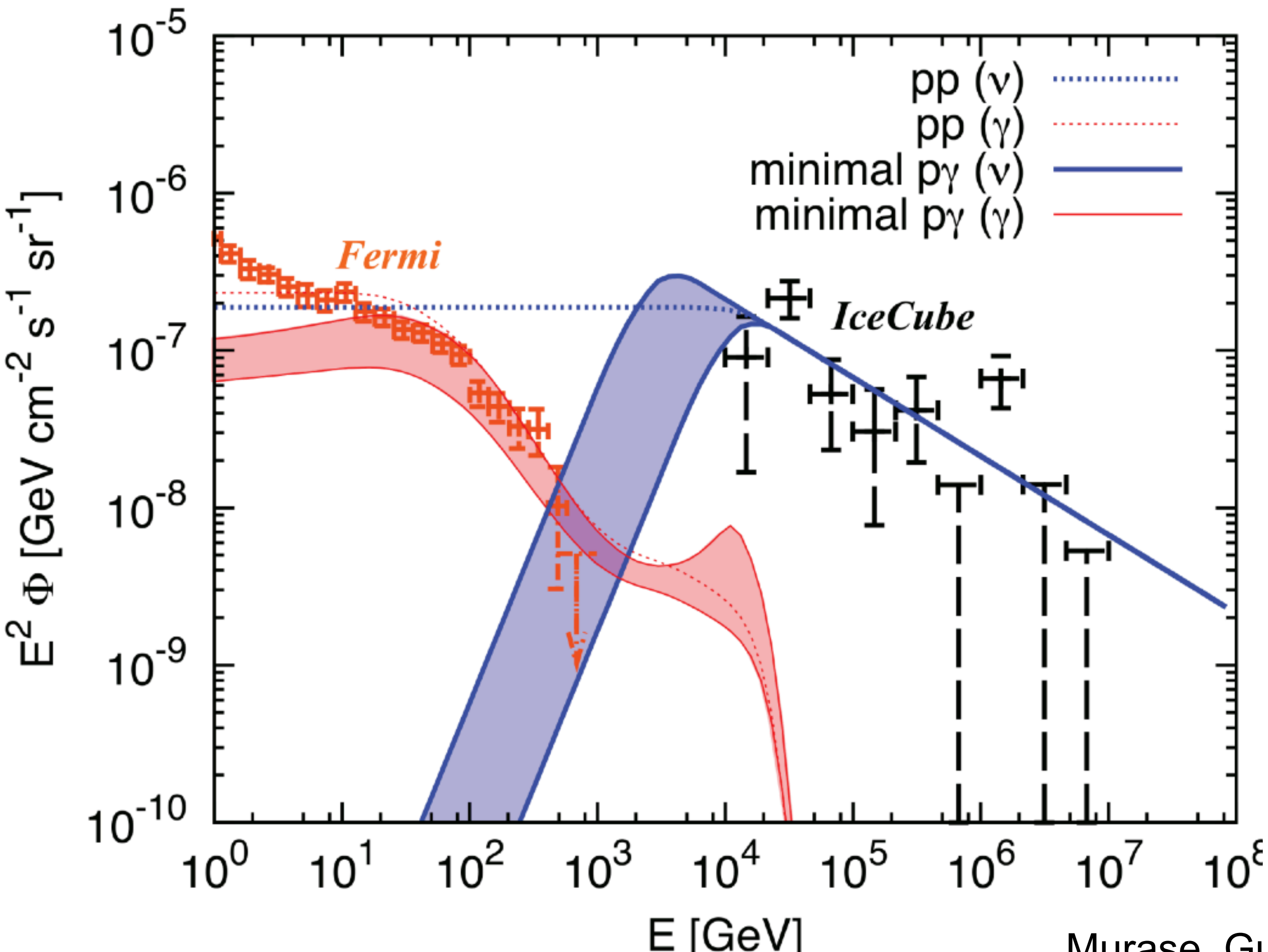
Dark Matter annihilation in the sun

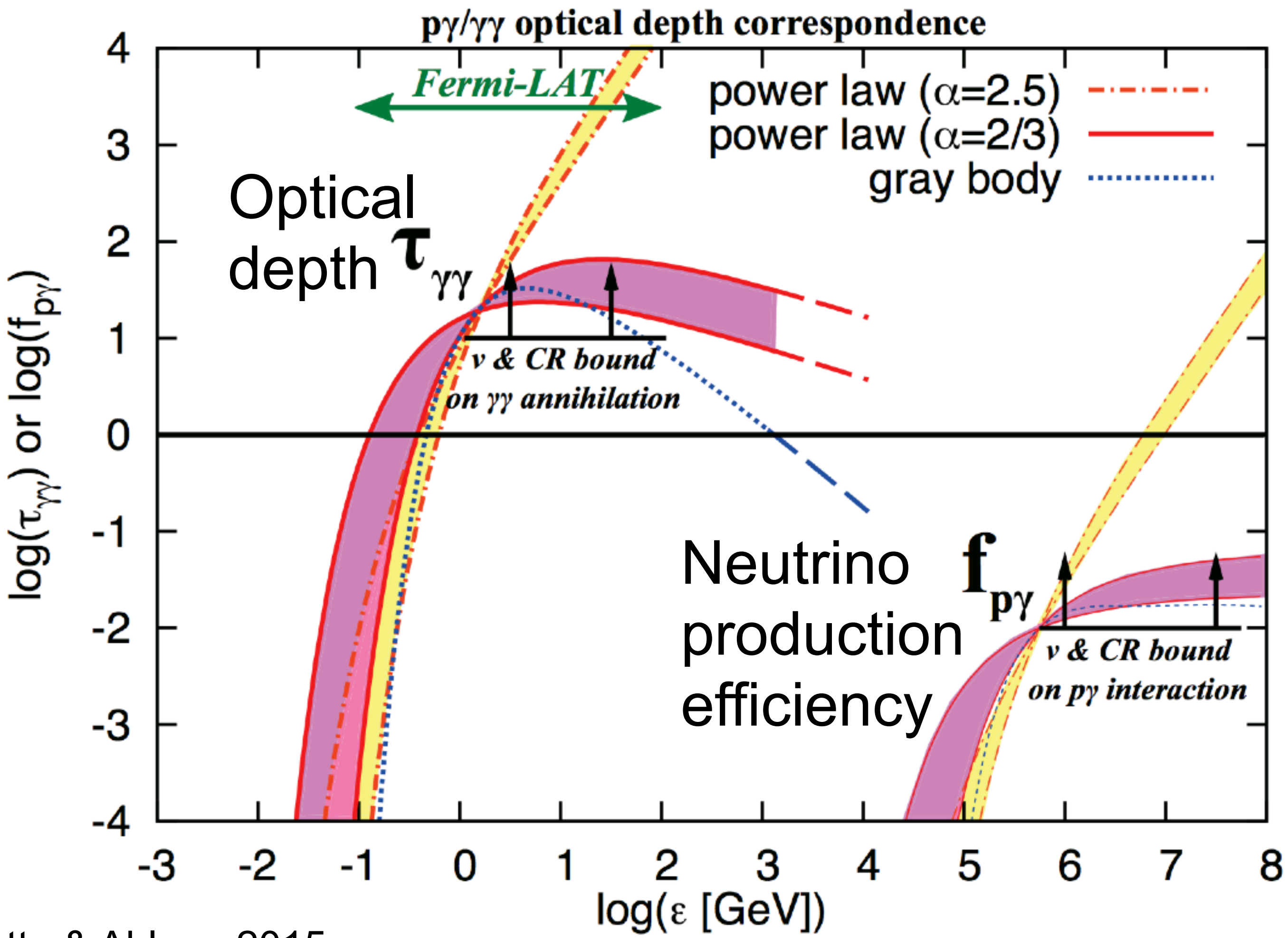
Constraints from gamma rays

The case for gamma-ray opaque neutrino sources

- **Gamma rays and neutrinos** produced simultaneously in pp and pγ interactions
- **Gamma rays** are reprocessed to **GeV energies** in EBL
- **Strong constraints** from observed extragalactic gamma-ray background

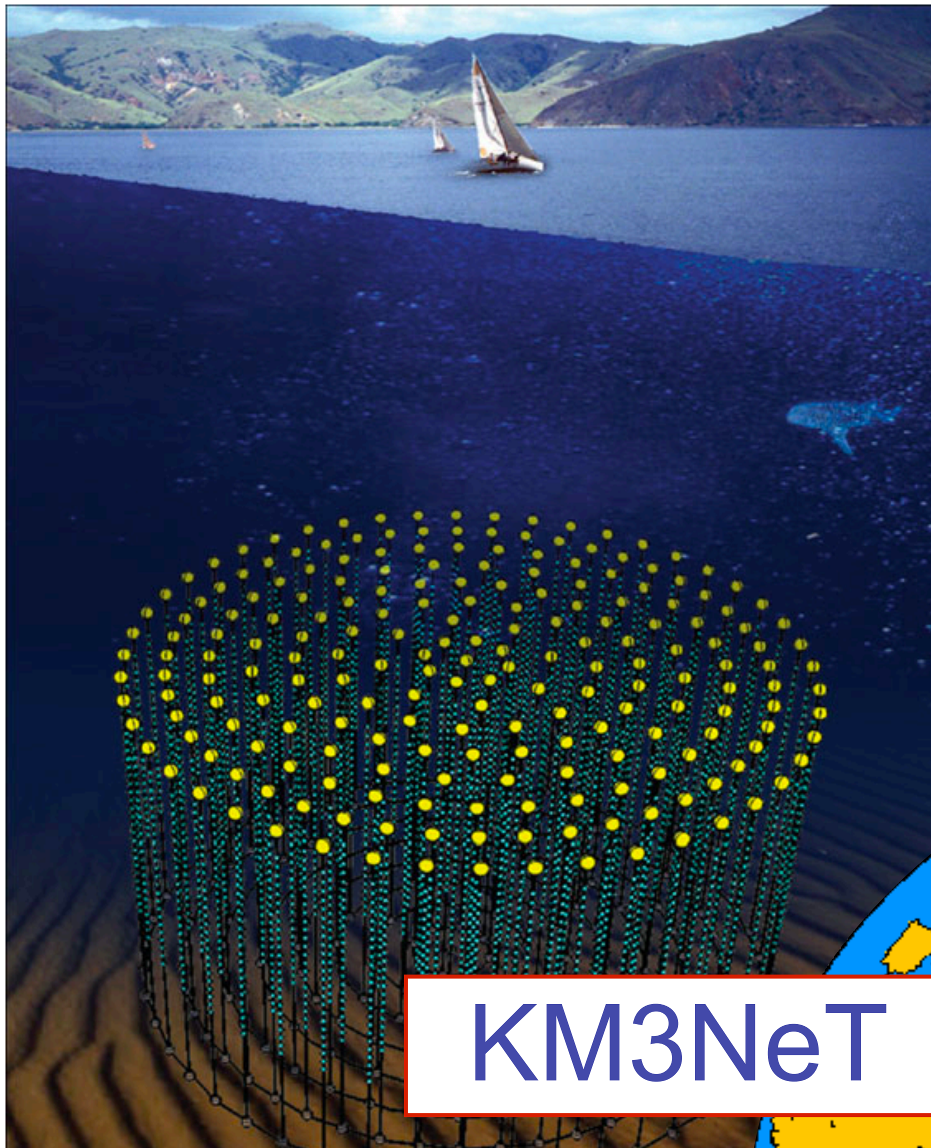


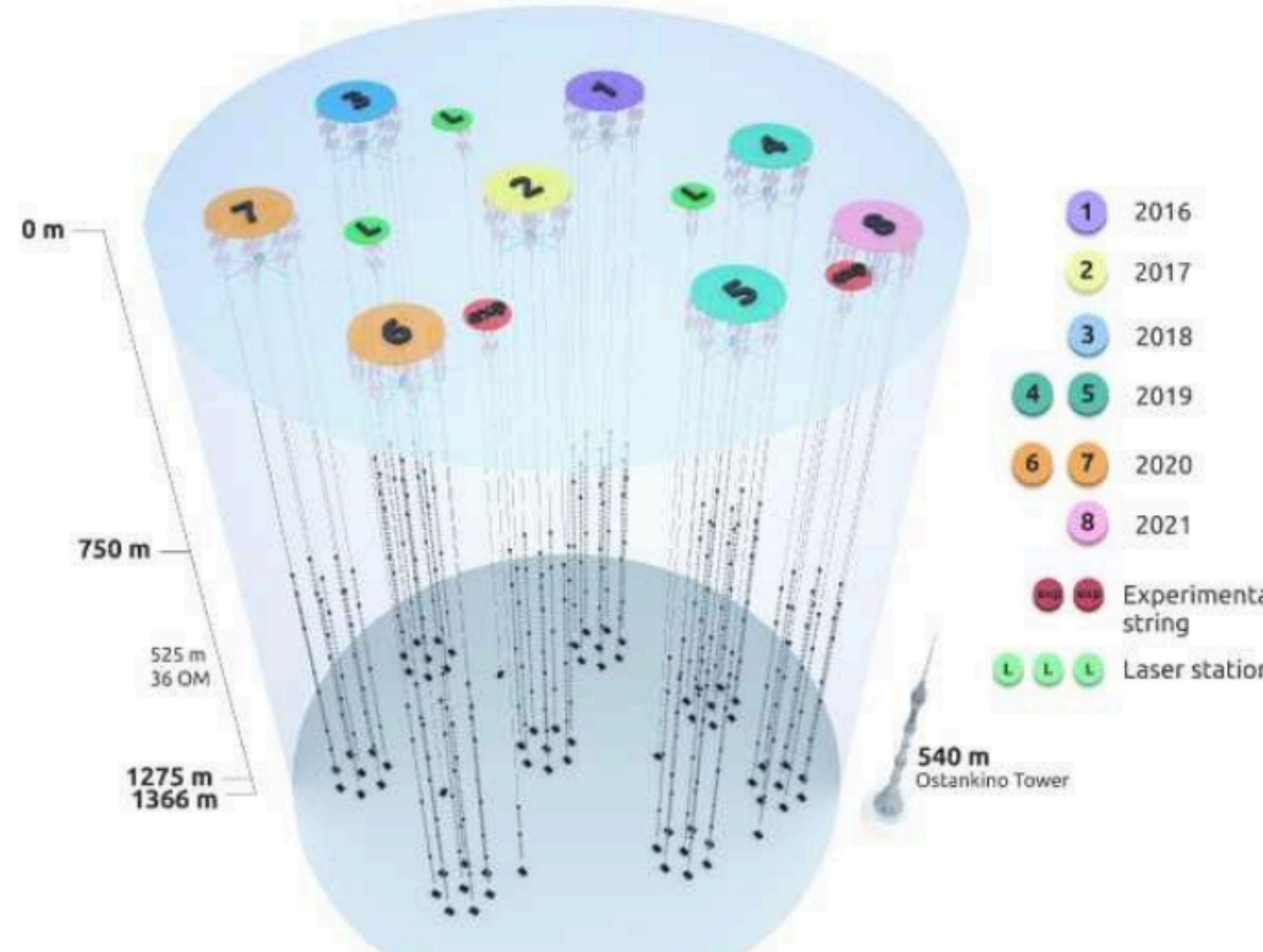


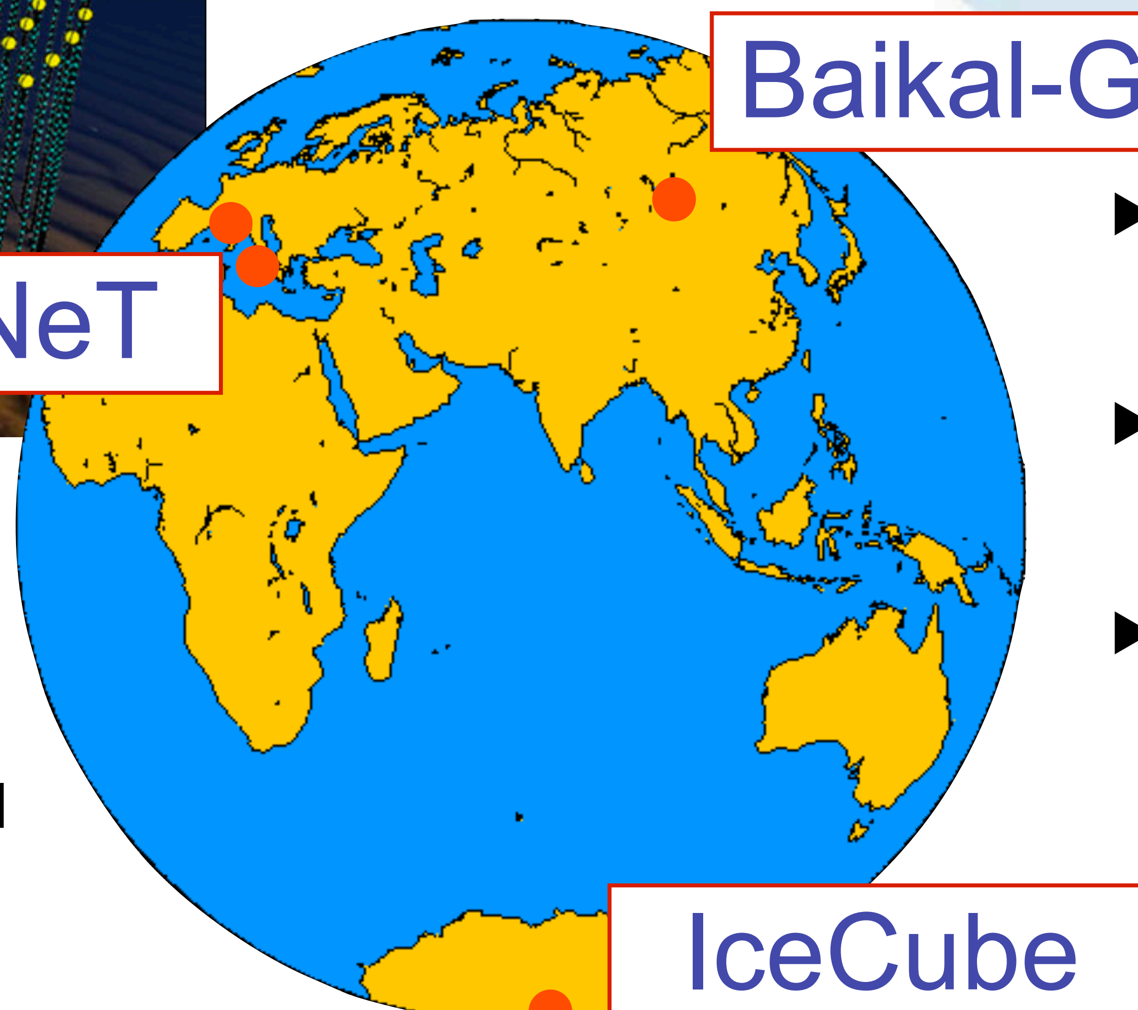


Murase, Guetta & Ahlers, 2015

Neutrino telescopes



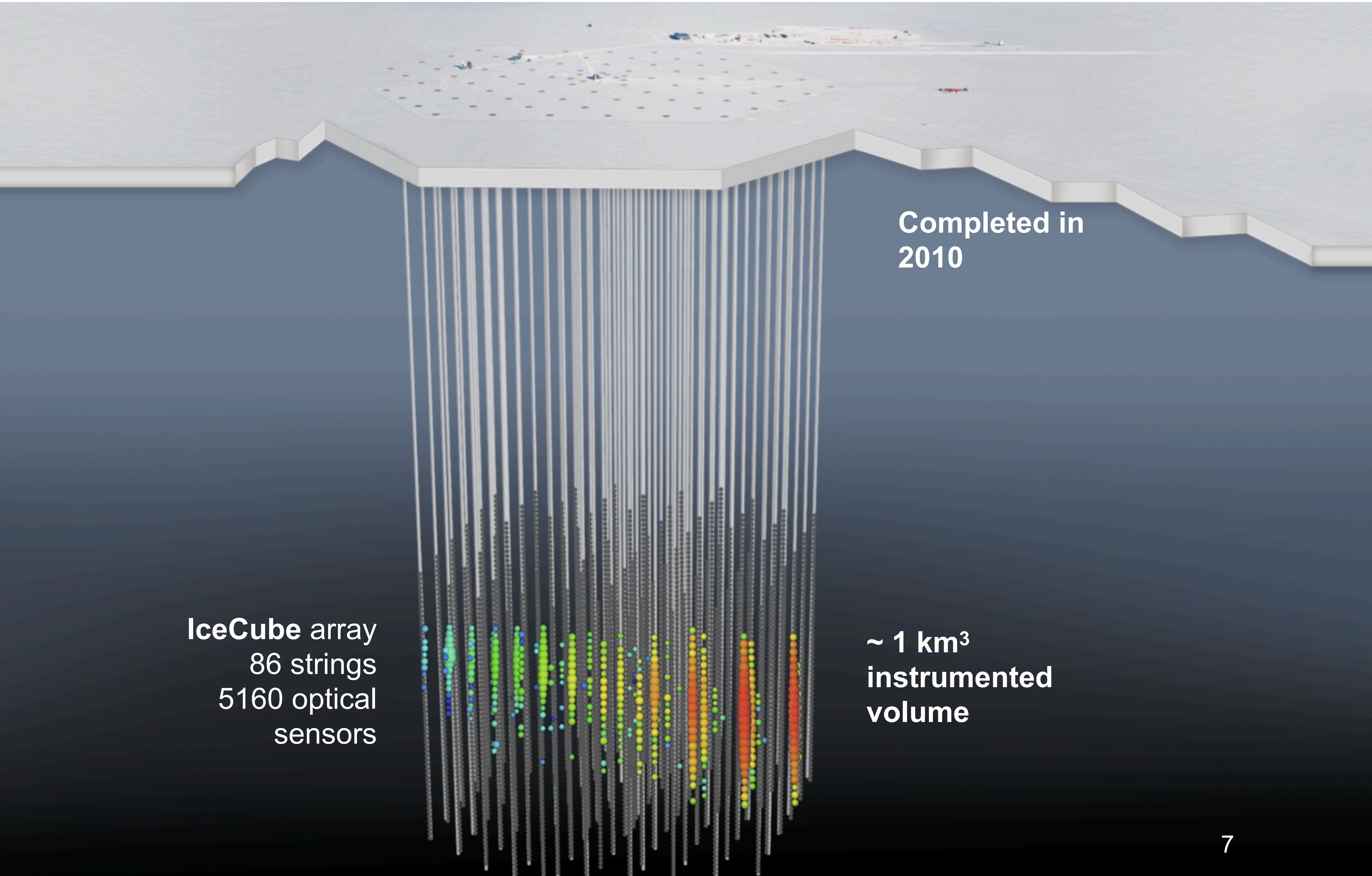




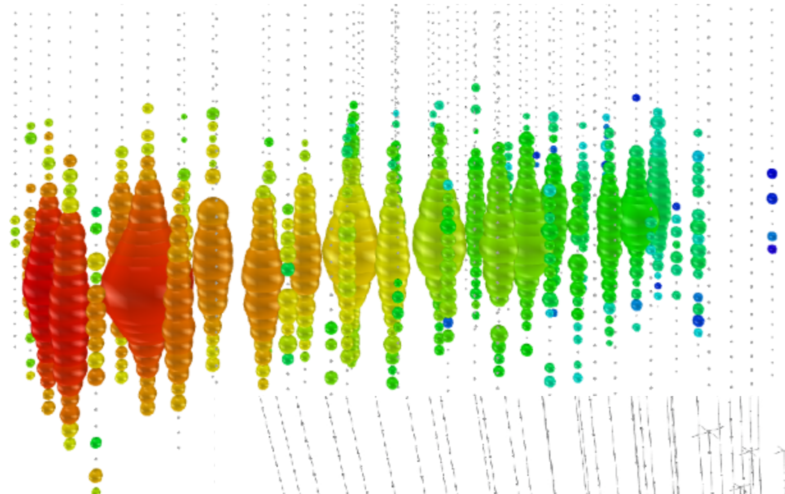
- Under construction
- 10 strings deployed (ARCA)
- O(1 km³) instrumented volume in two-block configuration

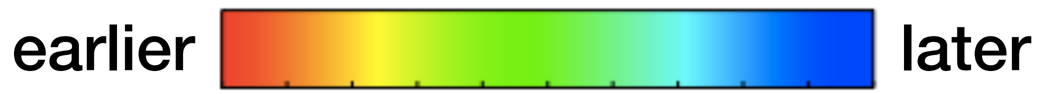
- Completed in 2021 in GVD-I configuration
- 0.5 km³ instrumented volume
- Extension to 1 km³ planned

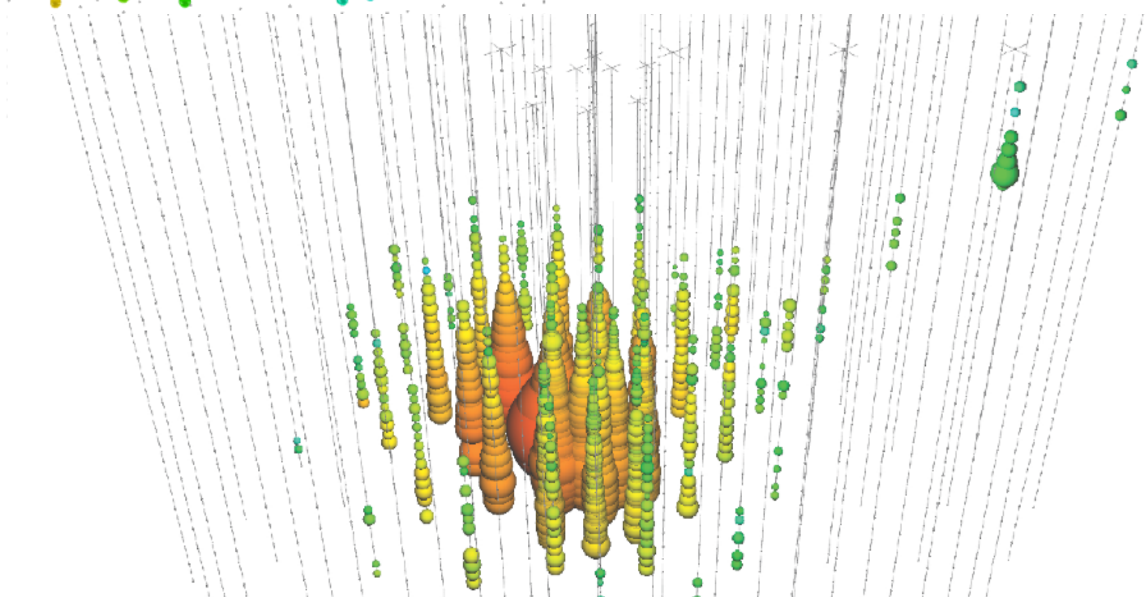
IceCube


Completed in 2010
IceCube array
86 strings
5160 optical sensors
~ 1 km³ instrumented volume

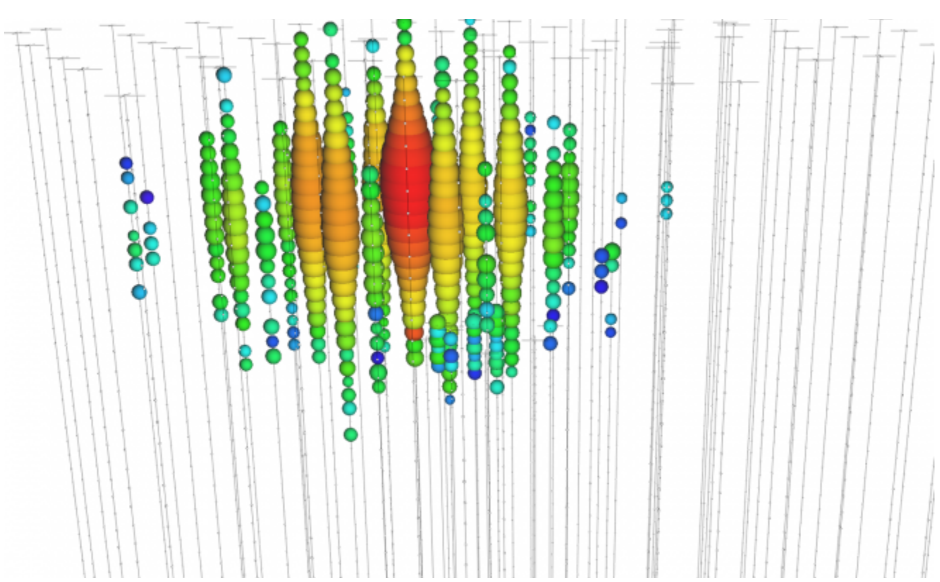
Signatures of neutrinos







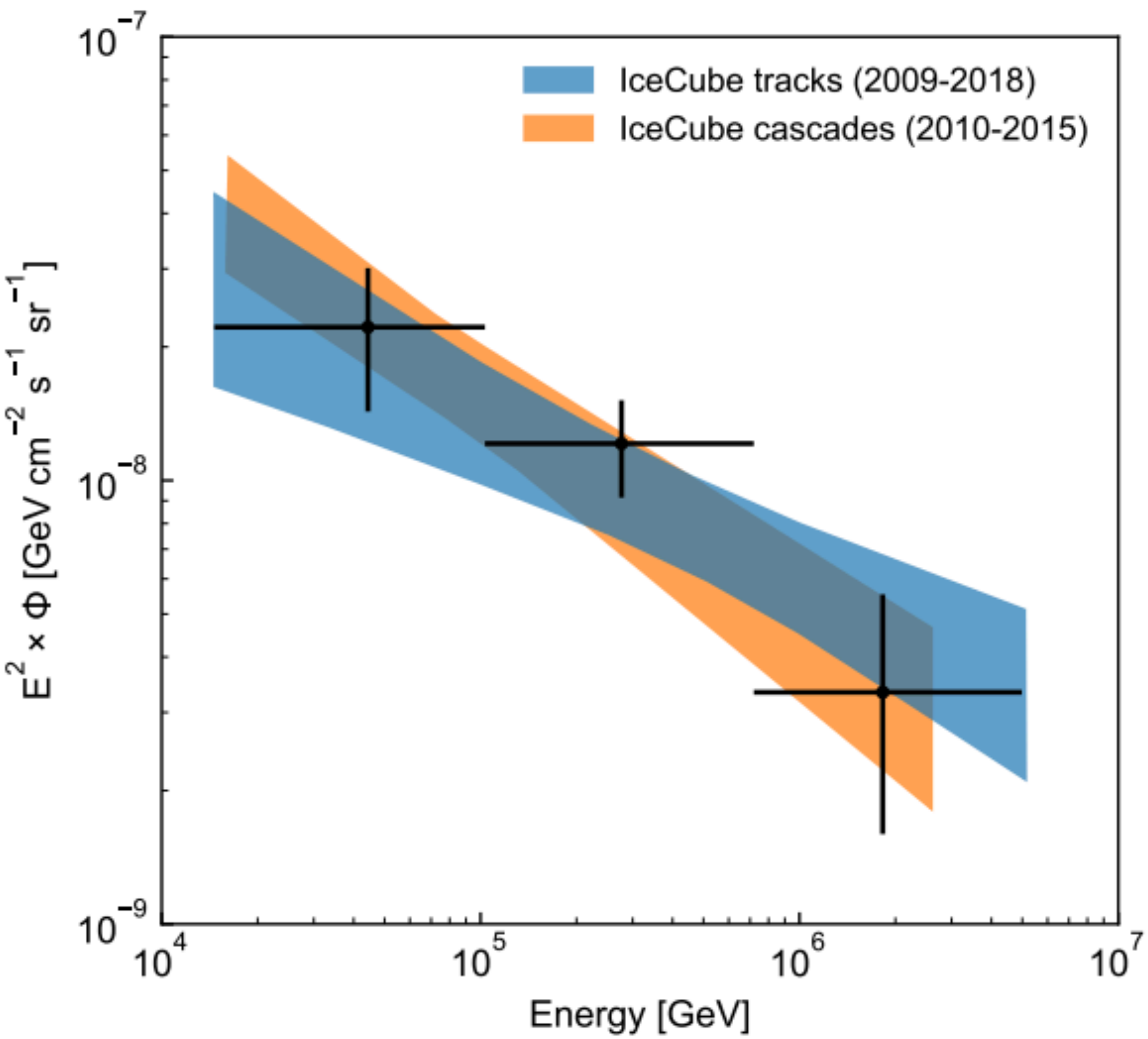
- **Track-like events**
  - ν_μ - CC interaction
  - Good angular resolution (< 1º)
  - Only lower bound on energy

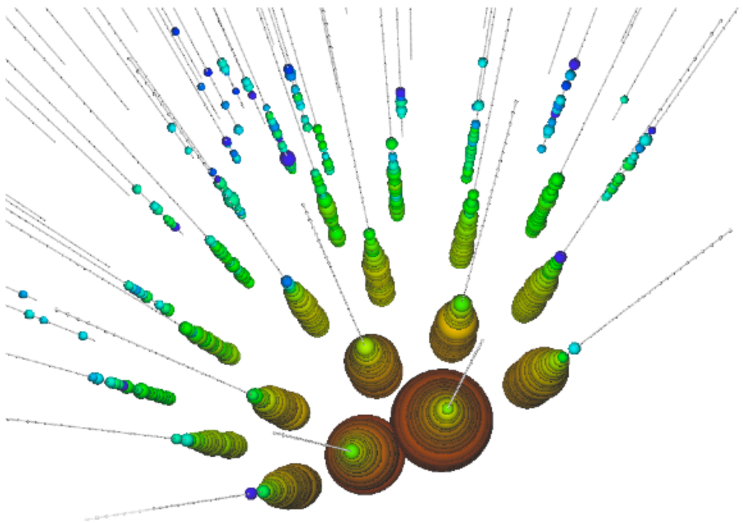


- **Shower-like events**
  - ν_e, ν_τ - CC, and all NC interactions
  - Limited angular resolution (~10º)
  - Calorimetric energy measurement (~15% energy resolution)

Cosmic neutrinos

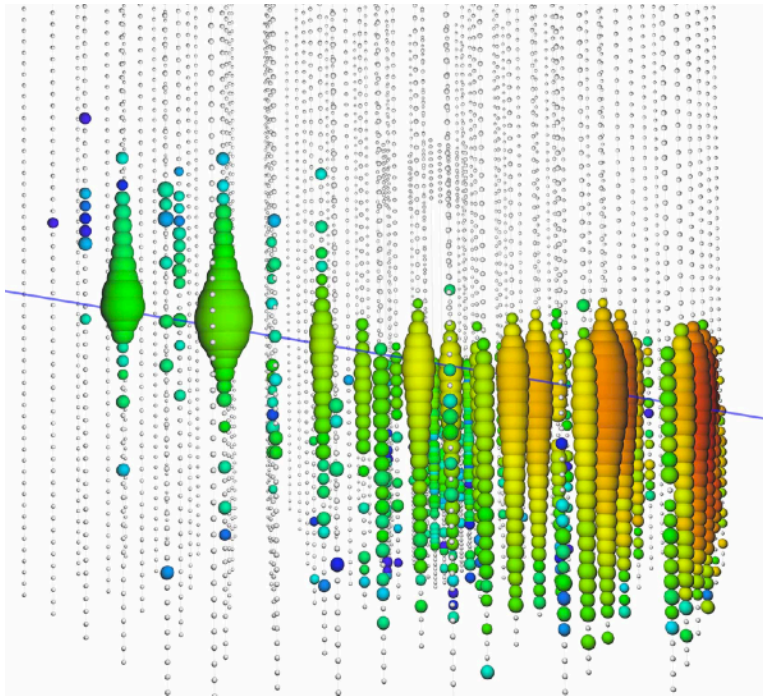
The spectrum of cosmic neutrinos





~ 6 PeV (shower-like)

>2.6 PeV (track-like)



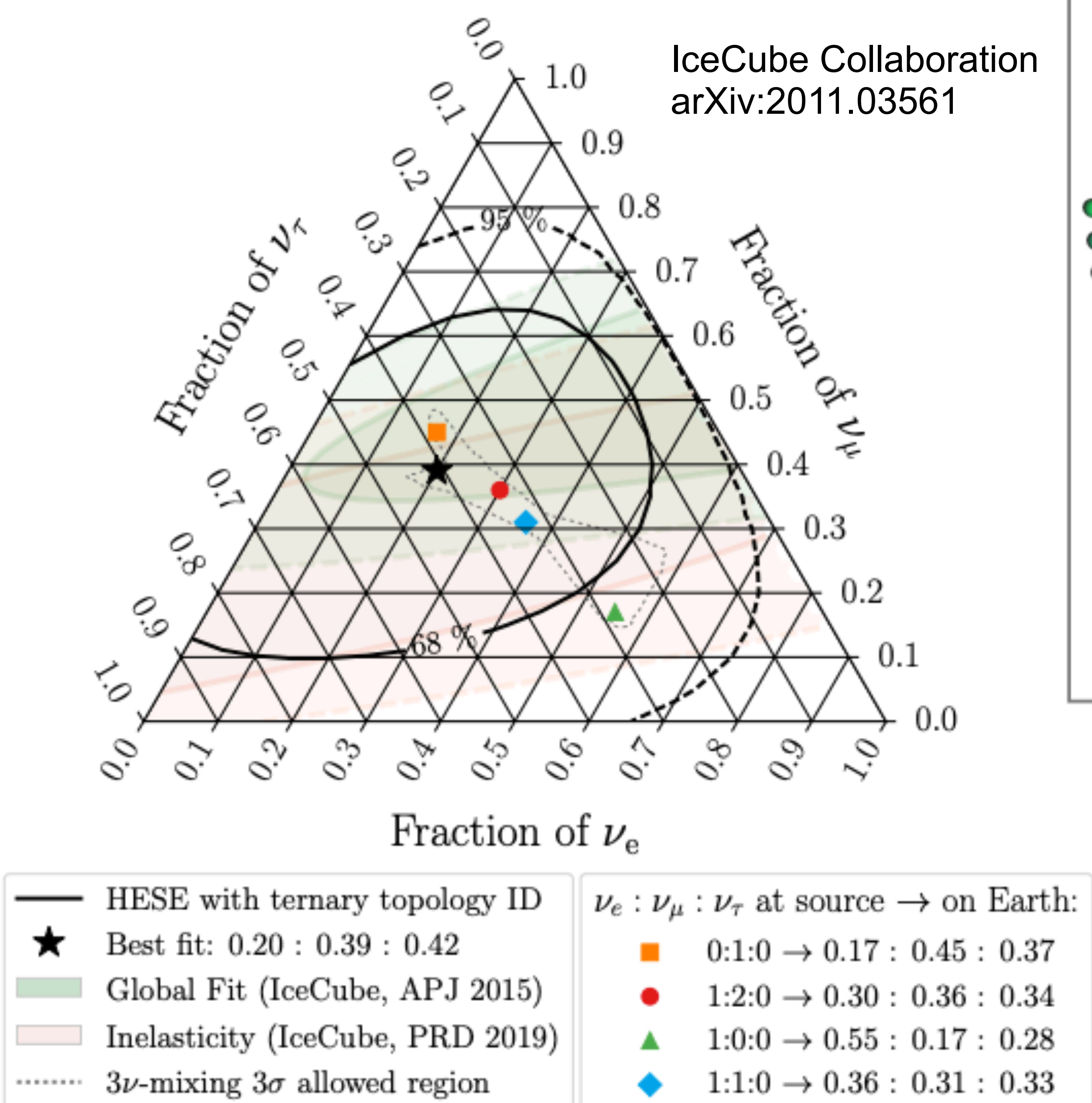
- Independent results from shower-like and track-like events:
  - Showers (6 yr) : γ = -2.53 ± 0.07 (IceCube Collaboration, PRL, 2020)
  - Tracks (10 yr) : γ = -2.37 ± 0.09 (IceCube Collaboration, arXiv:2111.10299)
- Spatial distribution of events consistent with isotropic distribution

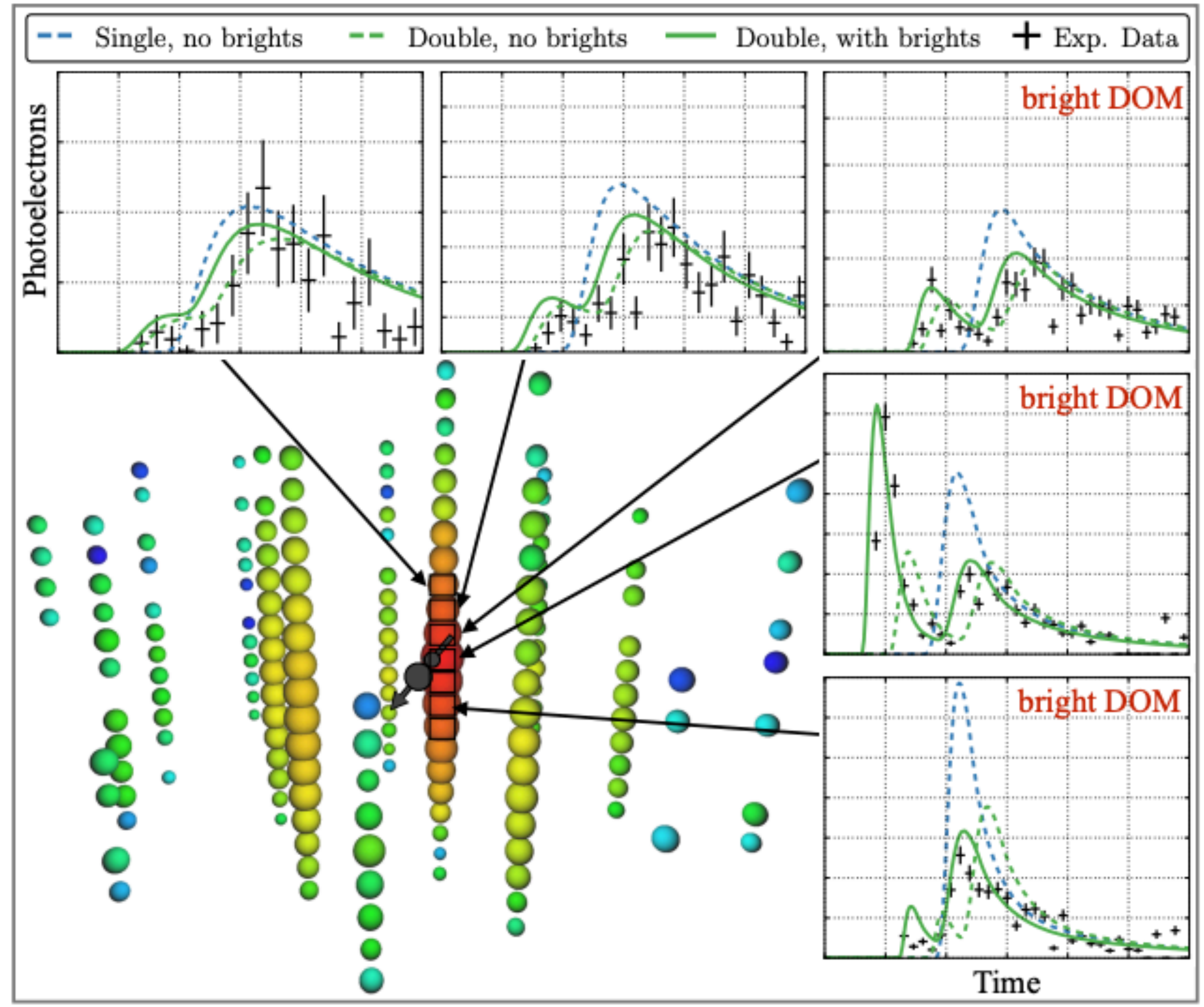
The flavor composition of cosmic neutrinos

First ν_τ candidates

- Non-observation of tau neutrinos rejected at 2.8σ significance

IceCube Collaboration
arXiv:2011.03561



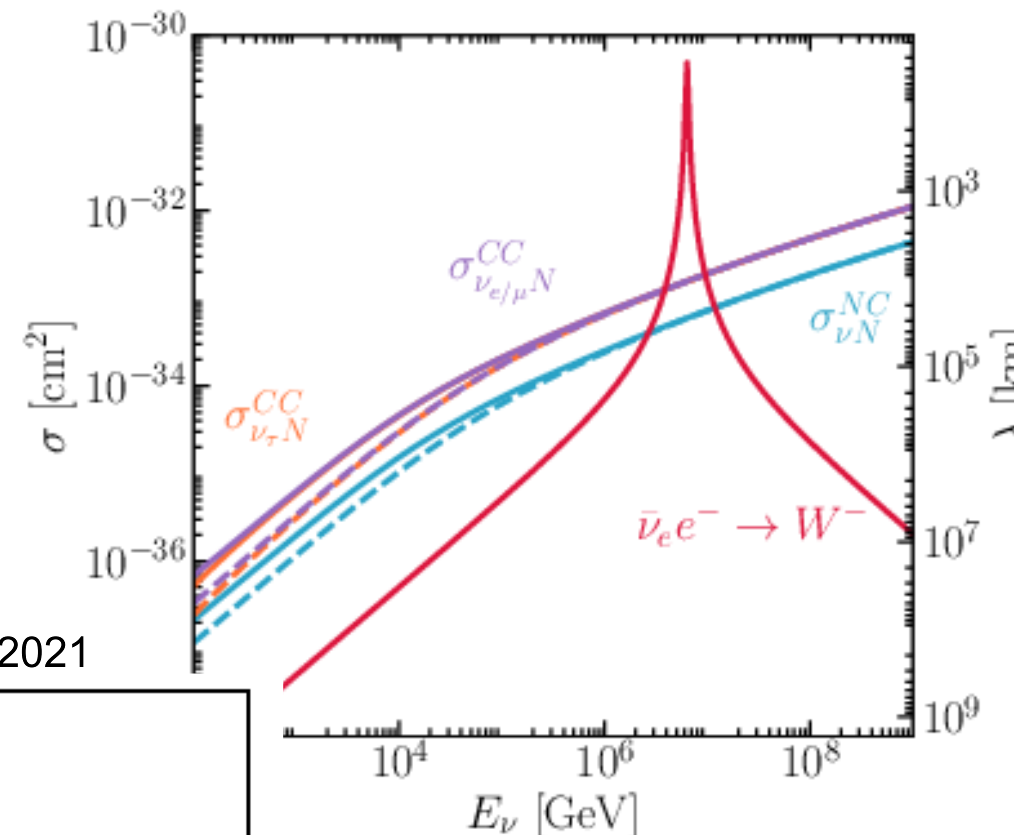


Source flavor ratios:
- **0:1:0 :** μ cooling in strong magnetic fields
- **1:2:0 :** π / μ decay without cooling effects
- **1:0:0 :** neutrinos from β decay
- **1:1:0** : neutrinos from K mesons

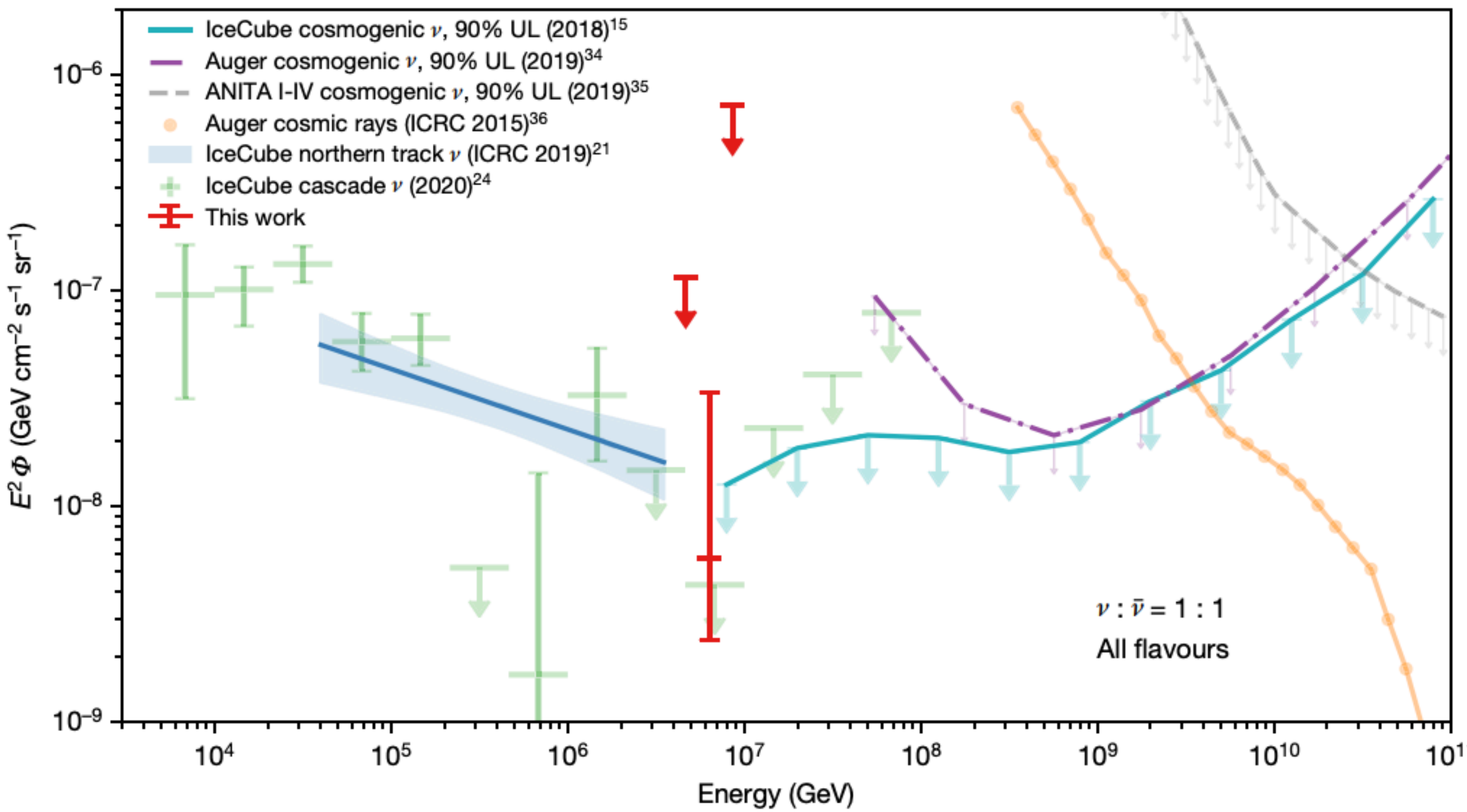
Neutrinos at the Glashow resonance

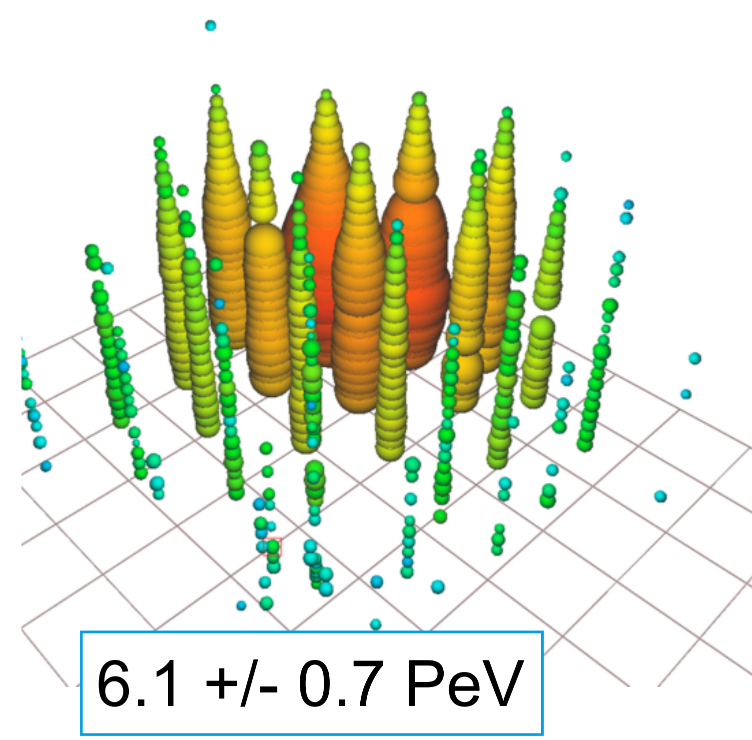
Detection of first likely Glashow resonance neutrino

- 1% chance probability that event is charged/neutral current
- Glashow resonance events probe anti-νe flux
- Rate of Glashow neutrinos can probe photohadronic production



IceCube Collaboration, Nature, 2021



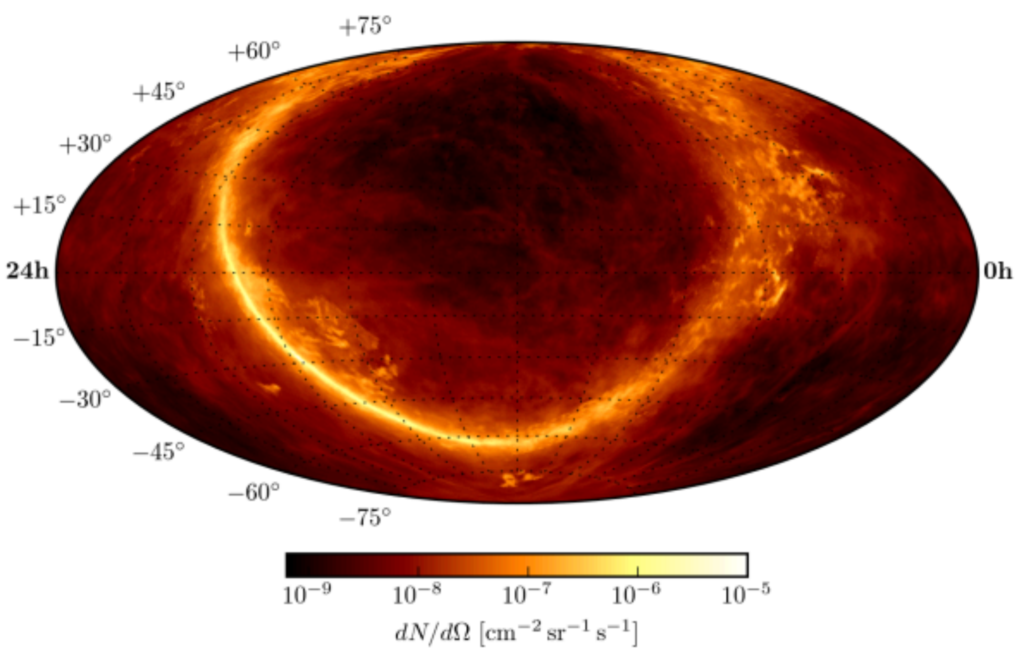


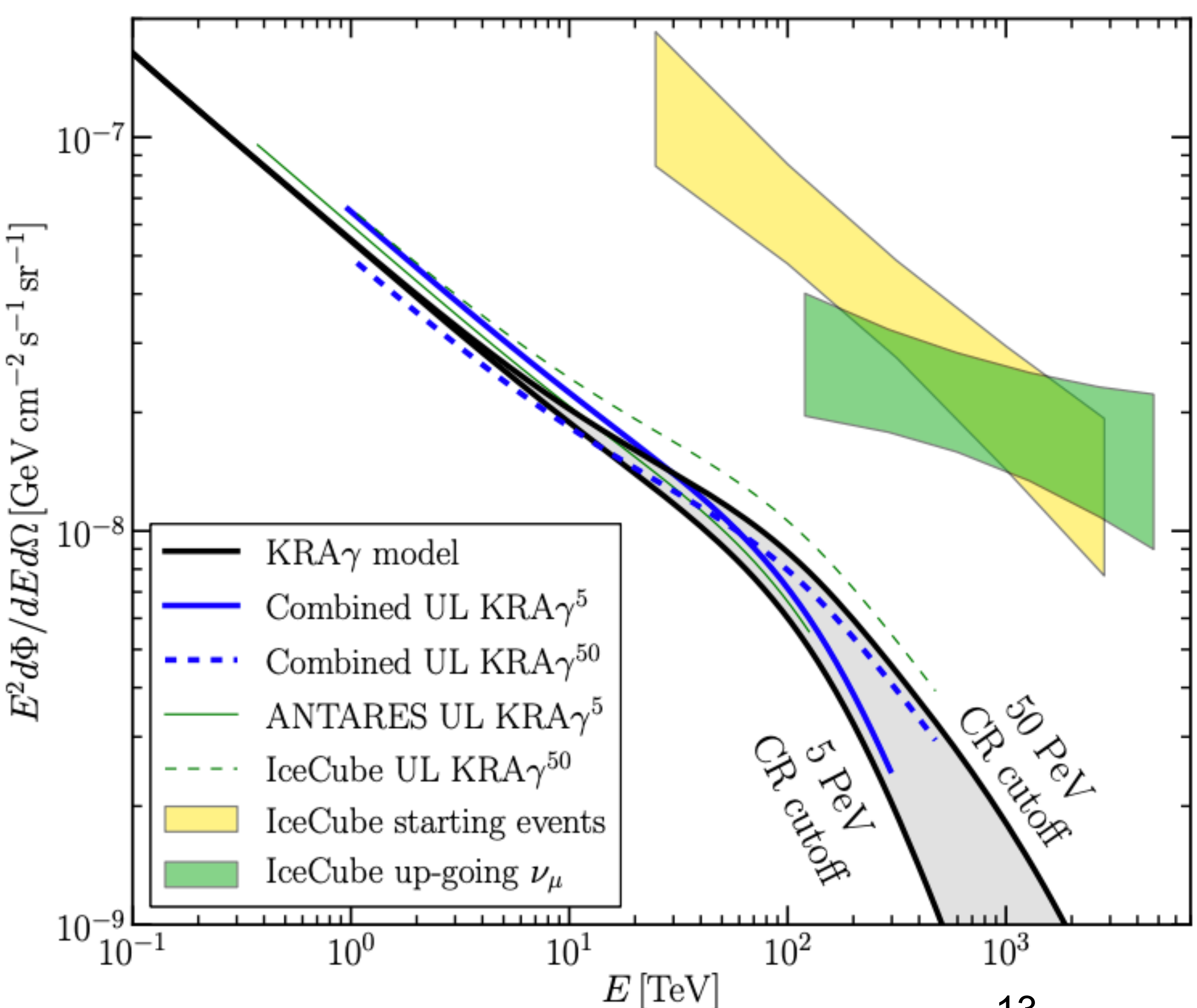
Galactic contribution to the neutrino flux

Probing Galactic cosmic-ray interactions in the TeV regime

- No galactic contribution found so far.
- Most stringent constraints from combined ANTARES/IceCube analysis
- Starts to constrain models that predict a harder CR spectrum in the inner Galaxy
- Complementary to gamma-ray observations

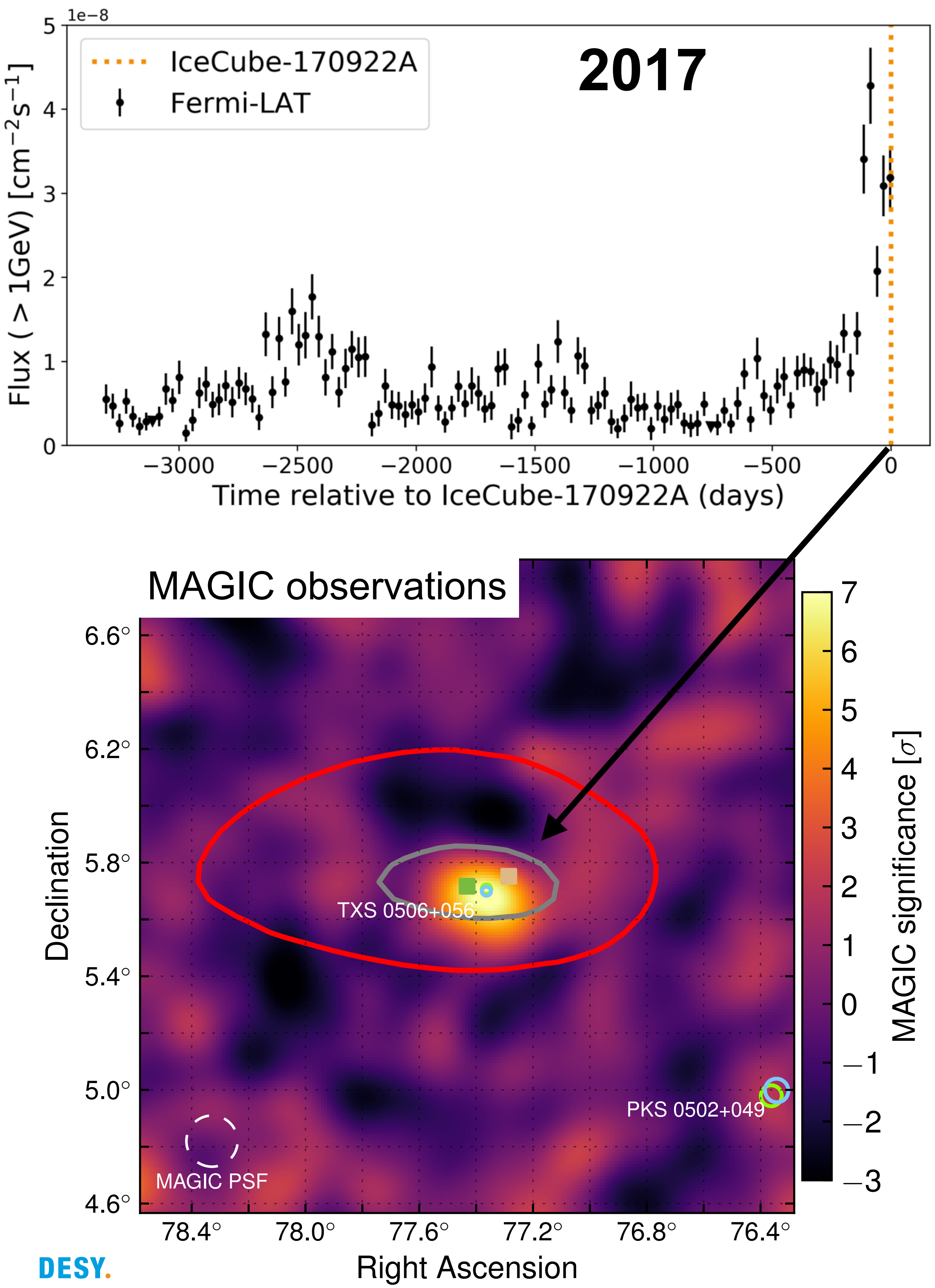
ANTARES & IceCube collaborations, ApJL 2018

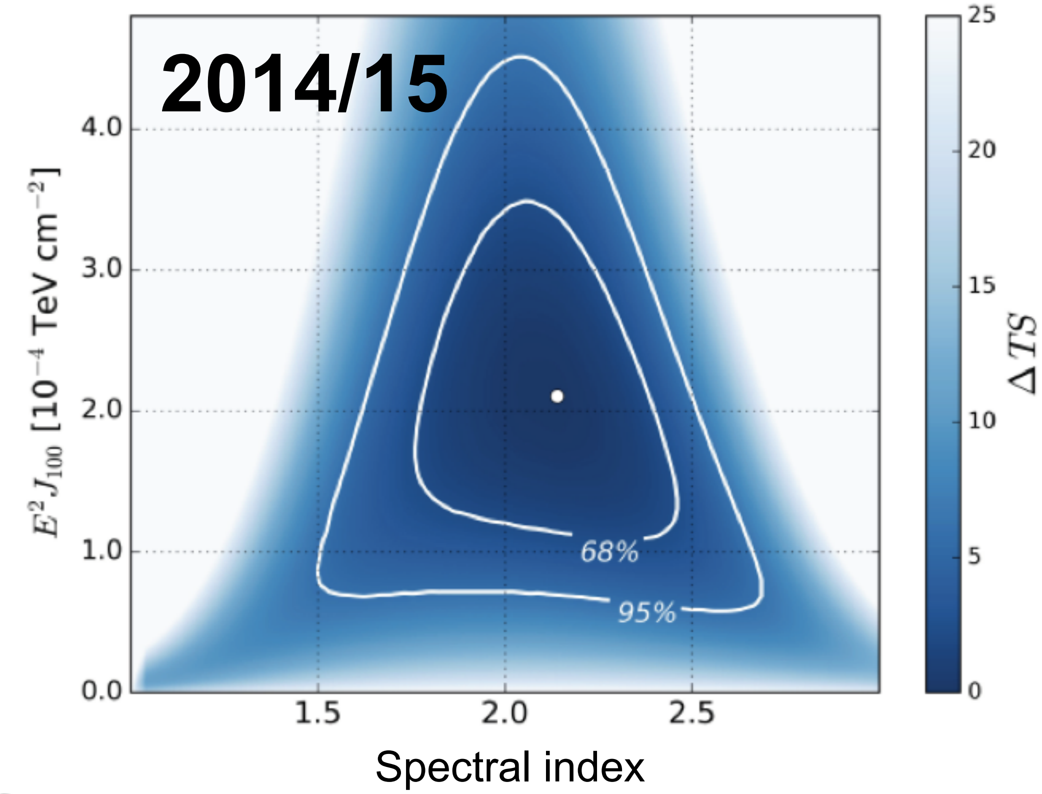


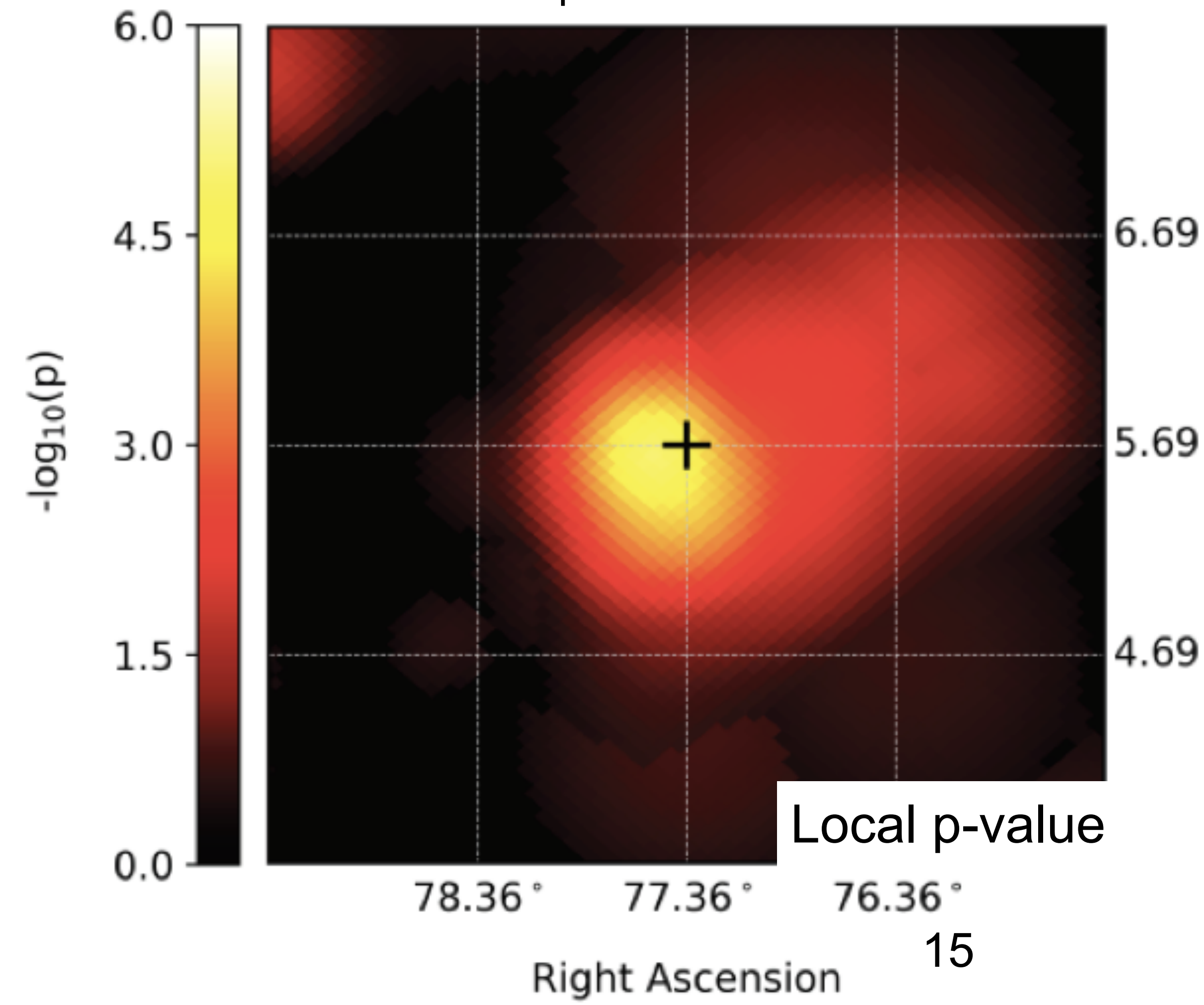


Multi-messenger observations

Neutrinos from the direction of TXS 0506+056





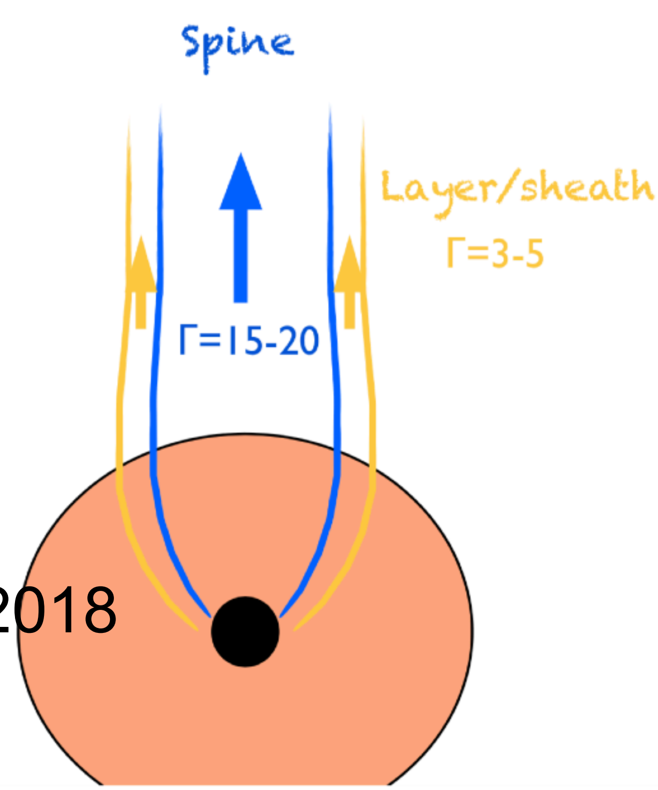


DESY.

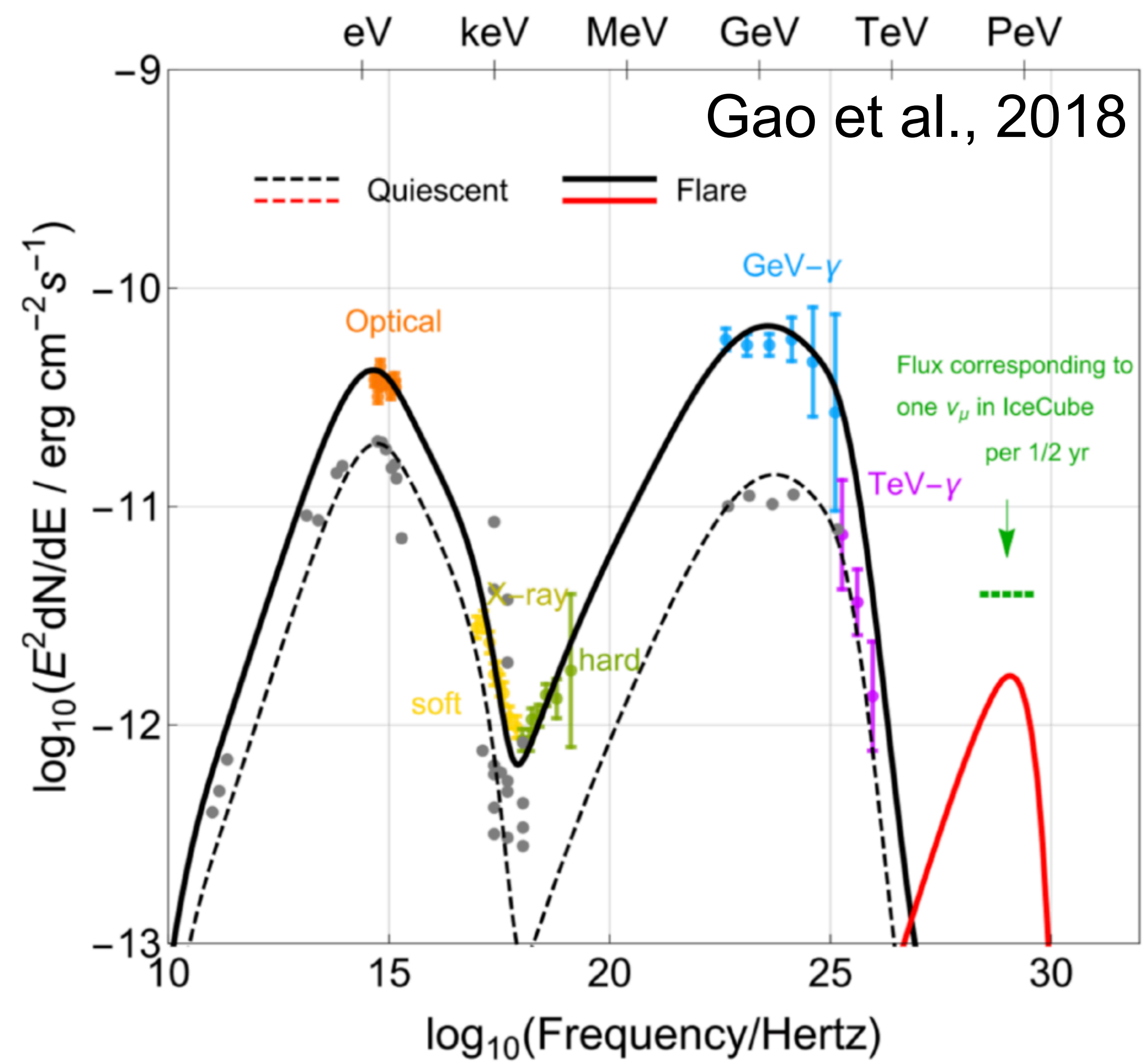
Blazars as neutrino sources

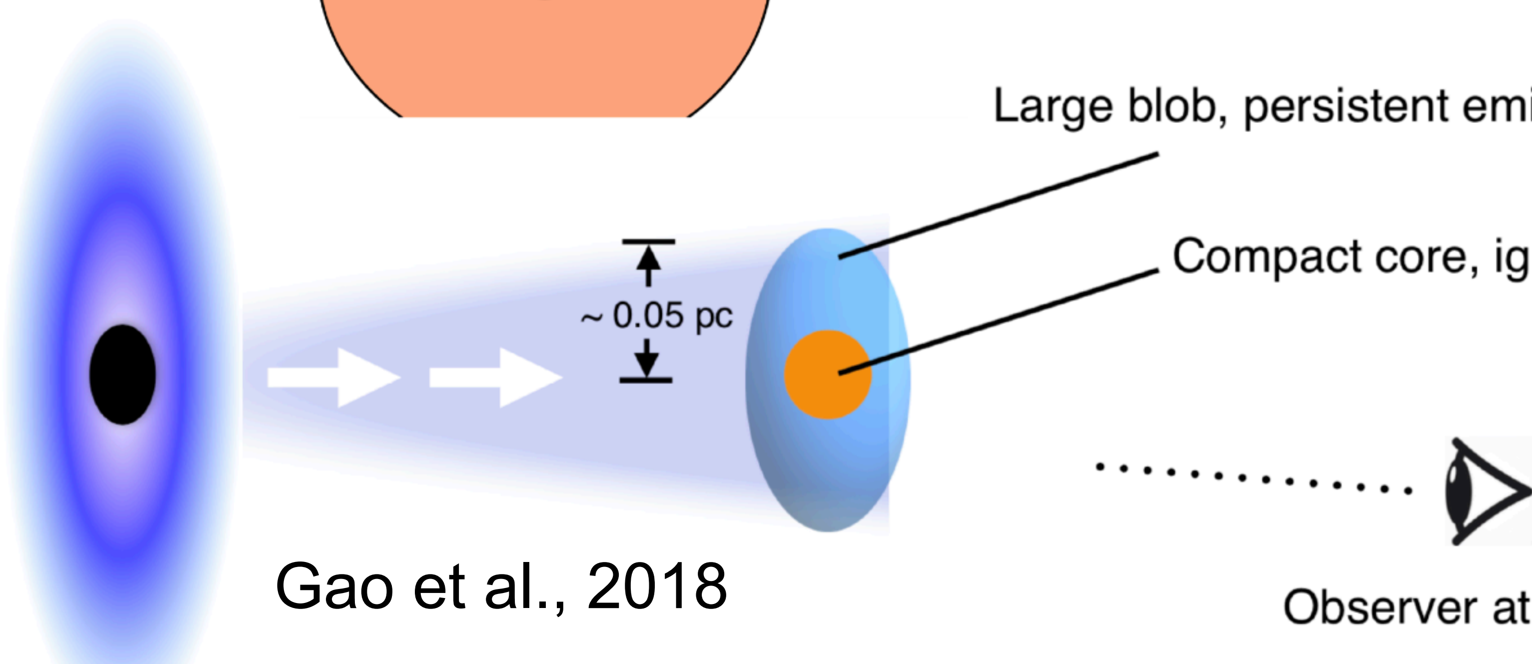
Simple one-zone models not consistent with X-ray emission

- Two emission zones help to reconcile observations



Tavecchio, 2018



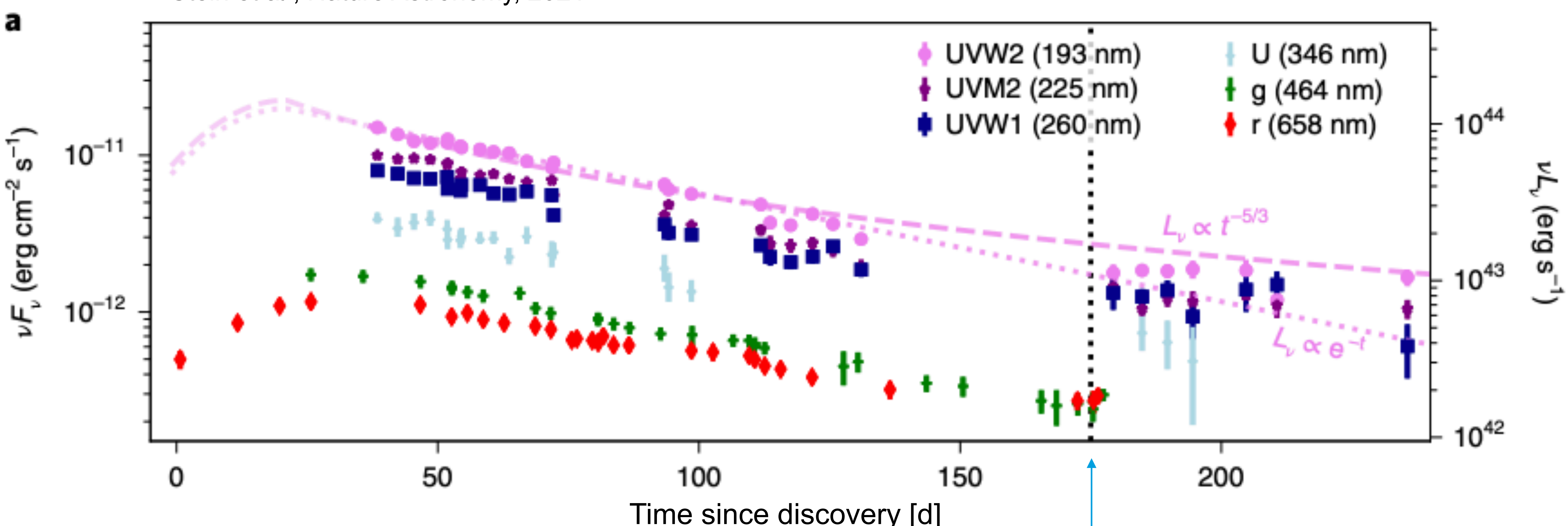


Gao et al., 2018

Tidal disruption events

- IceCube high-energy neutrino observed in spatial coincidence with TDE AT2019dsg
- Neutrino observation consistent with TDE energetics

Stein et al., Nature Astronomy, 2021

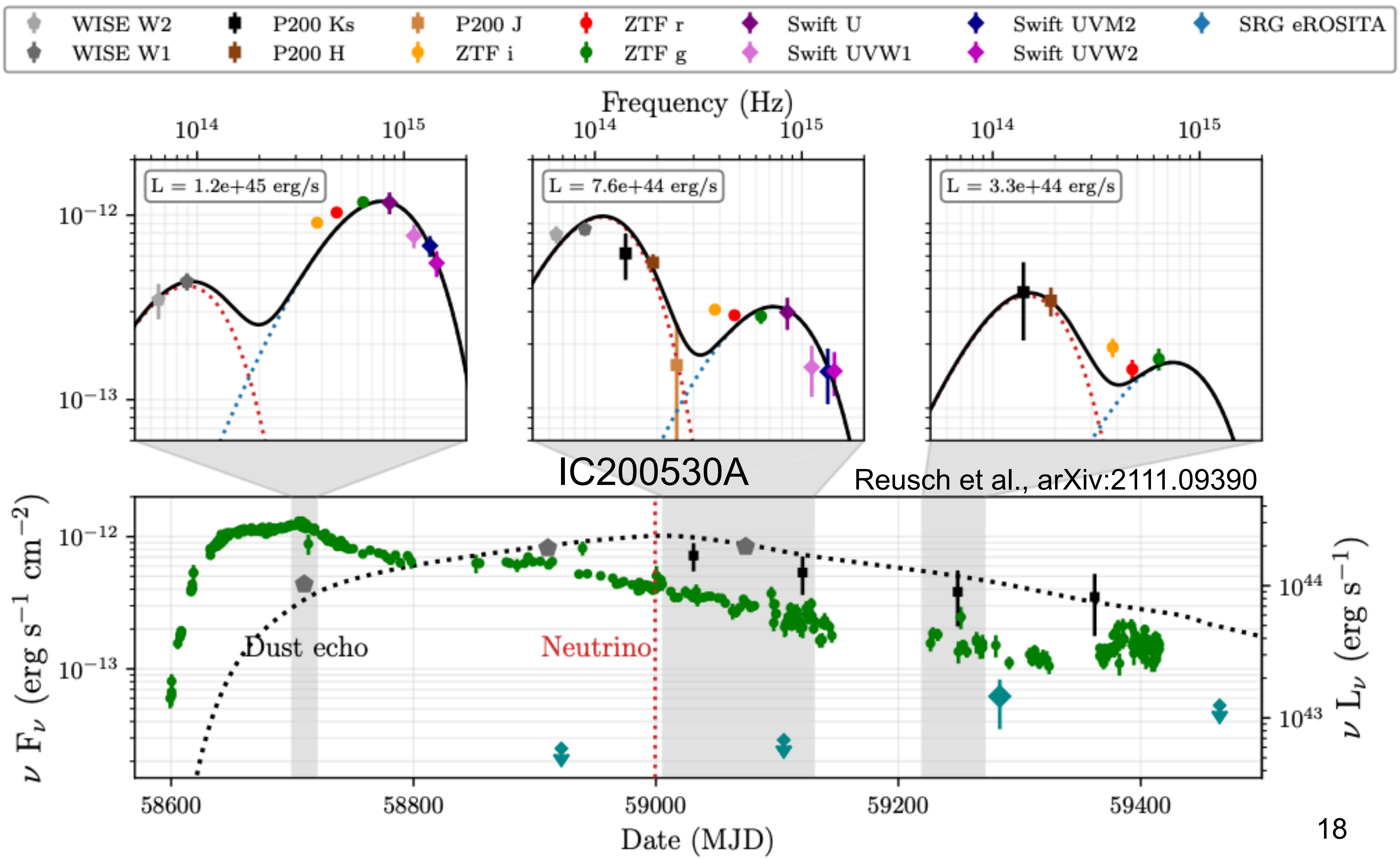


IC191001A
~ 200 TeV
0.2% chance probability

Tidal disruption events

A second coincidence

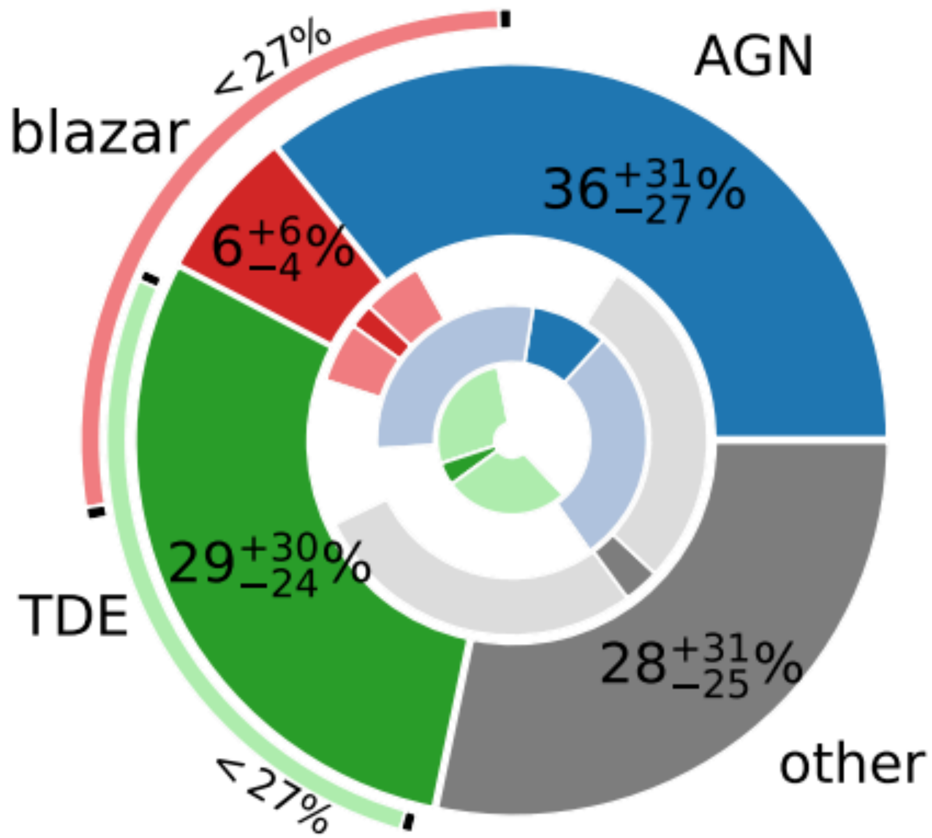
- Coincidence with TDE candidate AT2019fdr
- “Dust echo” observed for both coincidences



Reusch et al., arXiv:2111.09390

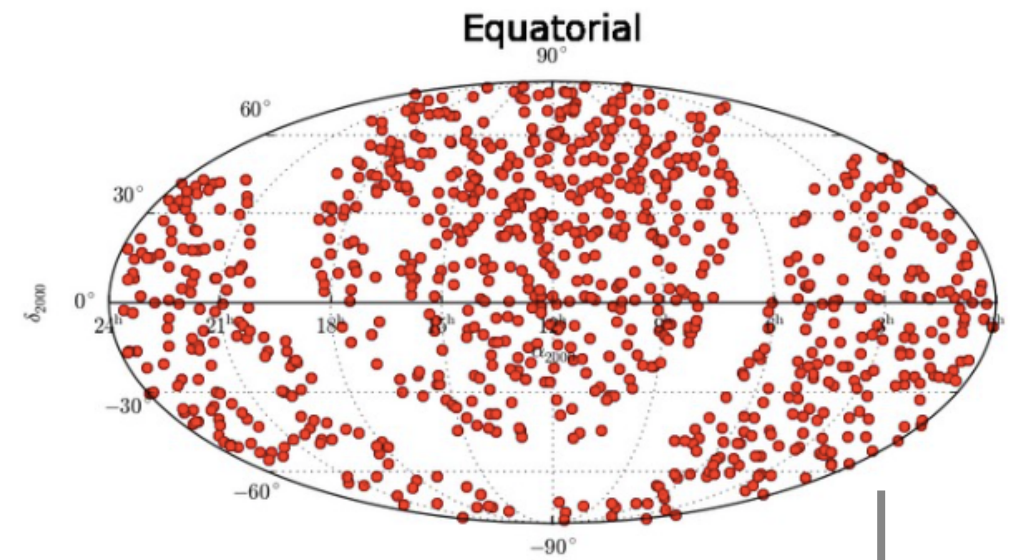
A census of the neutrino sky

"The IceCube Pie Chart"



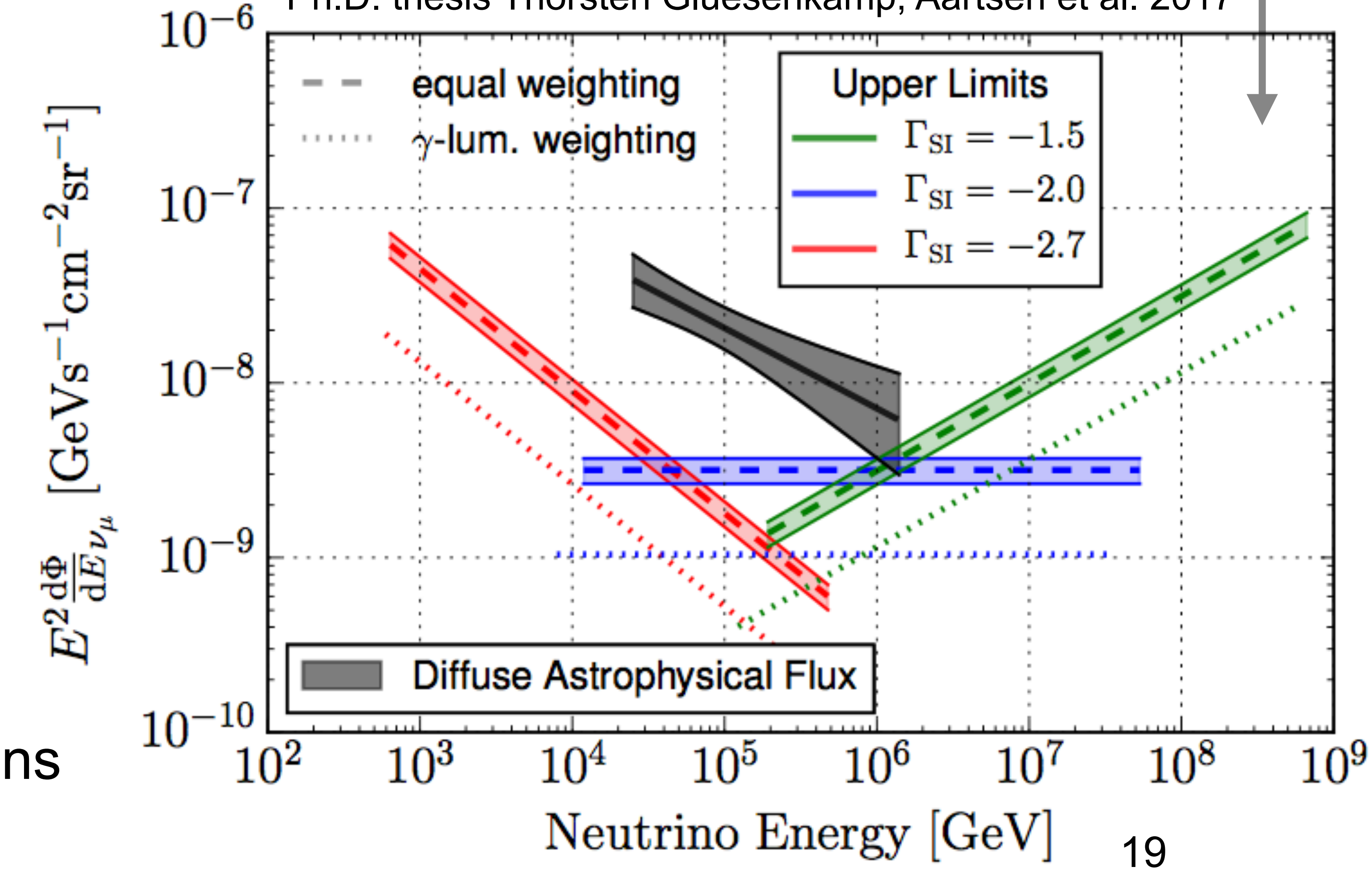
Bartos et al., arXiv 2105.03792

All blazars from *2-LAC* – 862 objects



Total blazar contribution to cosmic neutrinos

Ph.D. thesis Thorsten Gluesenkamp, Aartsen et al. 2017



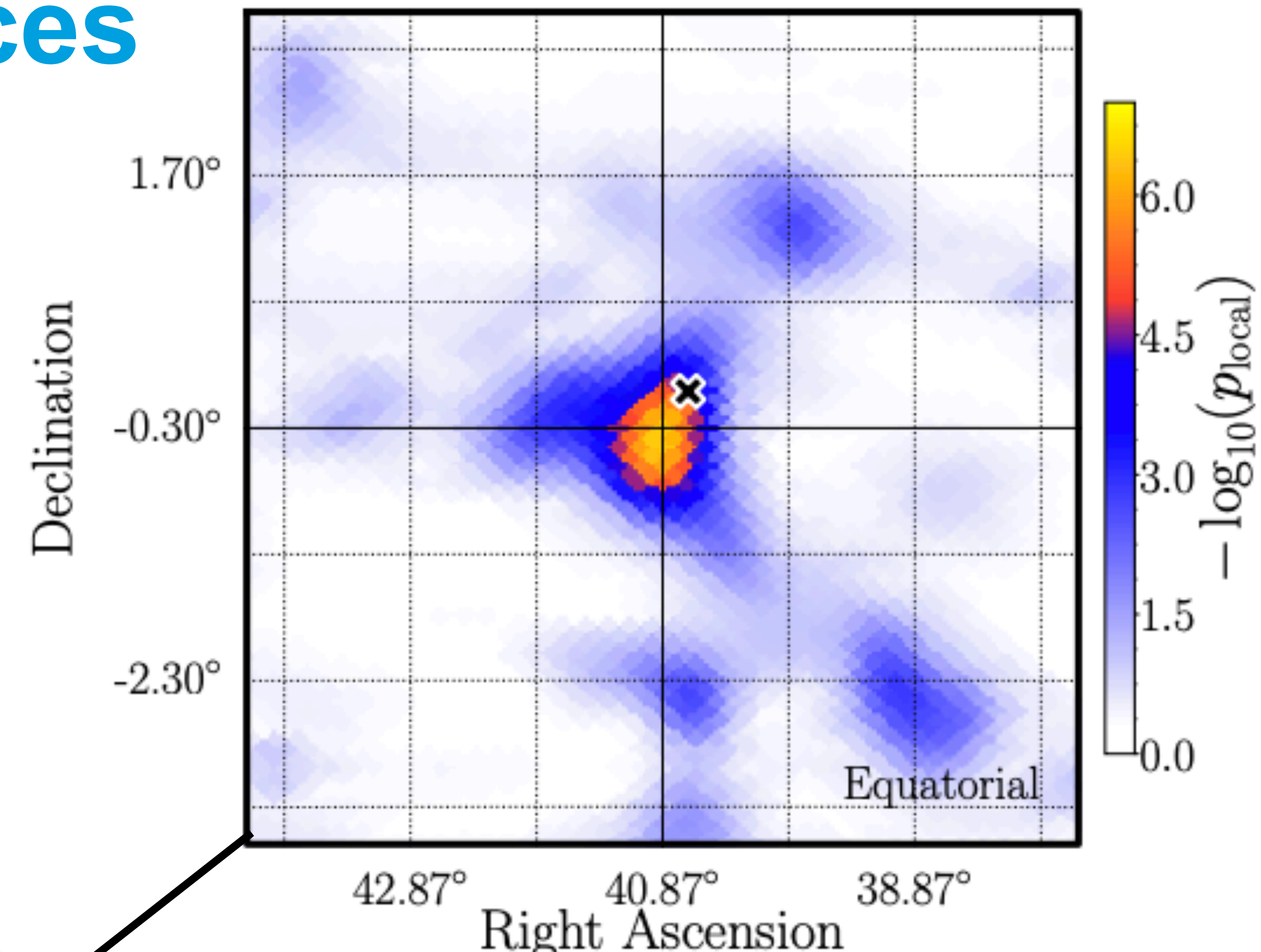
- Even Blazars and TDE together could not explain the observed diffuse neutrino emission.
- Neutrino sky is likely complex with several important source populations

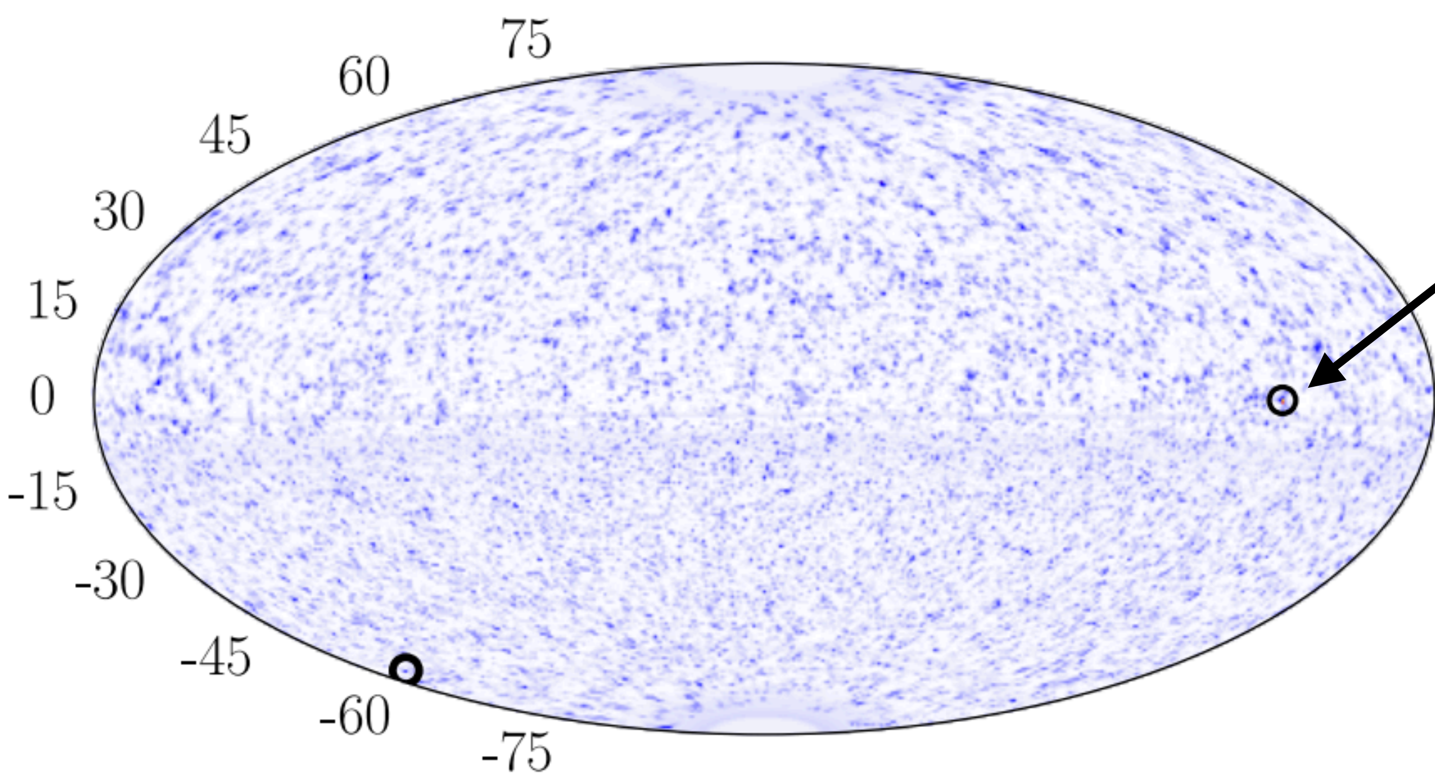
Neutrino sources

Searches for point sources

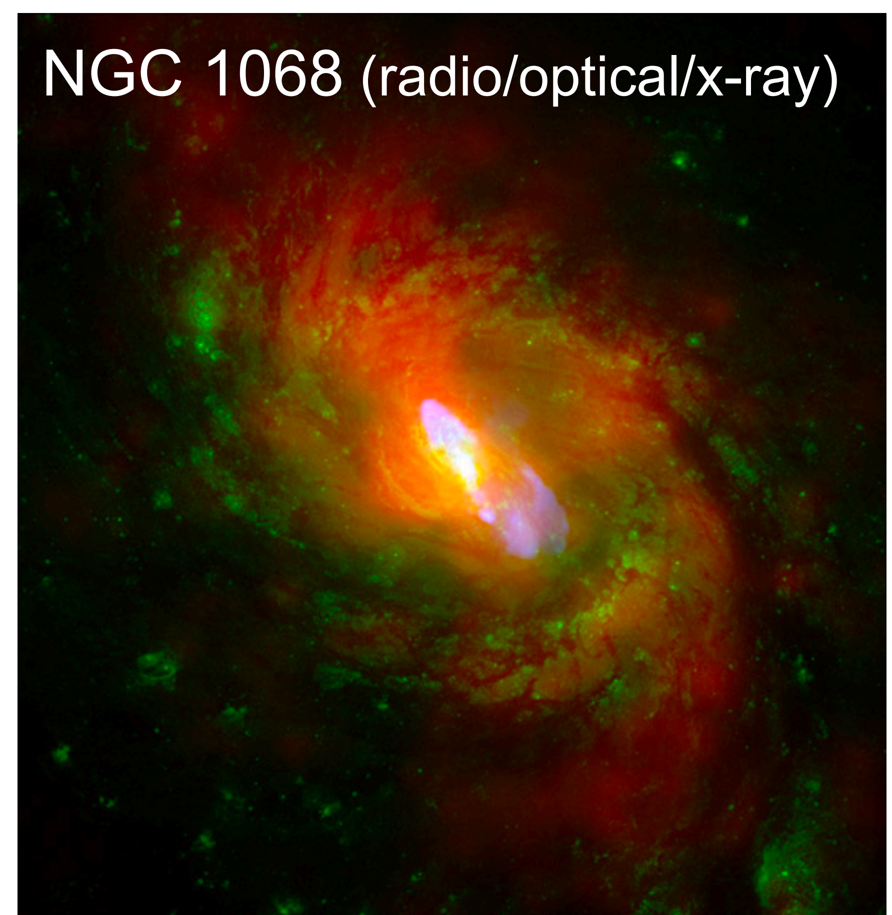
NGC 1068

- No significant detection of a point source in 10 years of IceCube data
- Most significant spot on northern hemisphere is in the direction of NGC1068 (2.9 σ, trial-corrected)





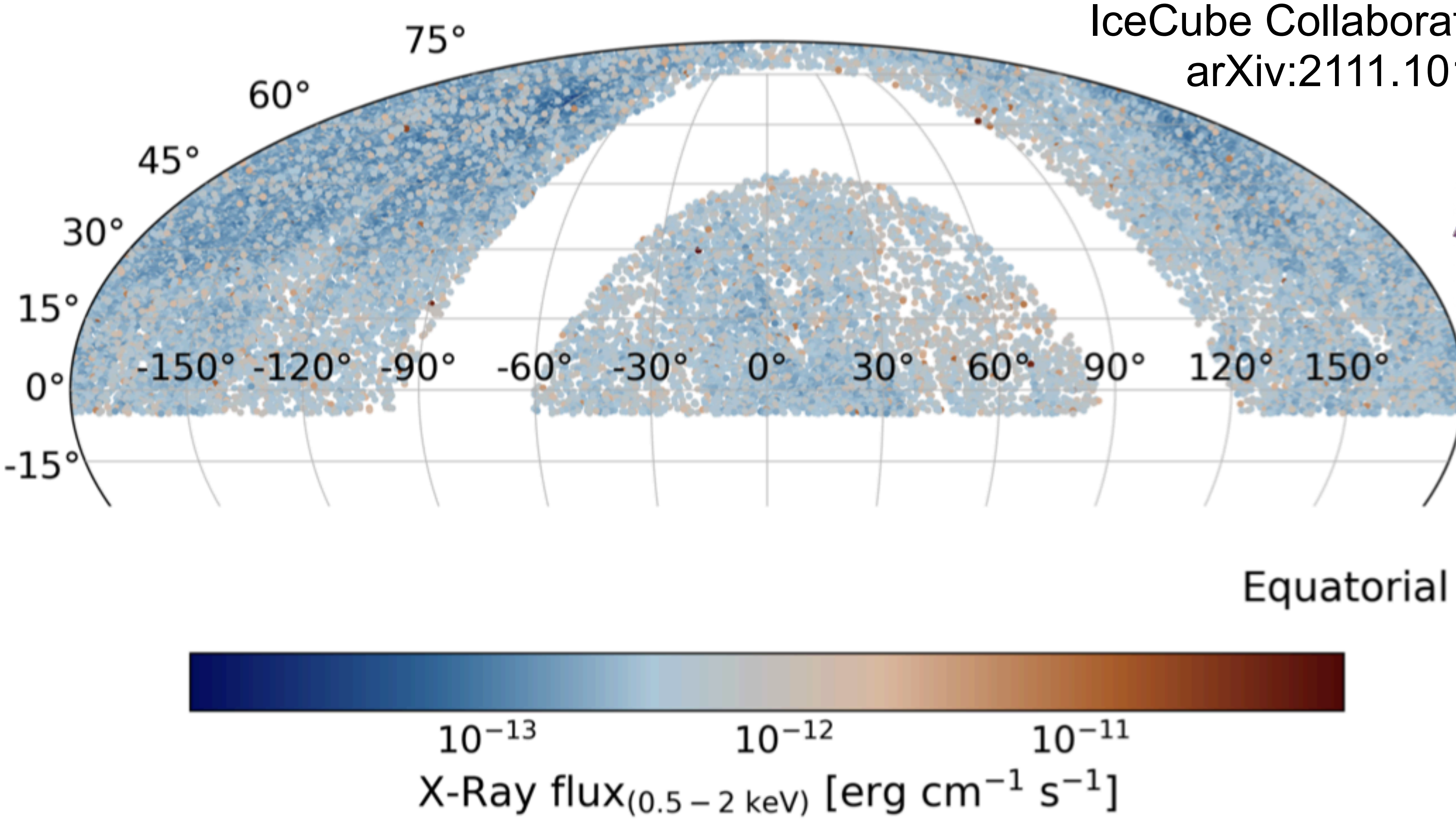
IceCube Collaboration, PRL, 2020



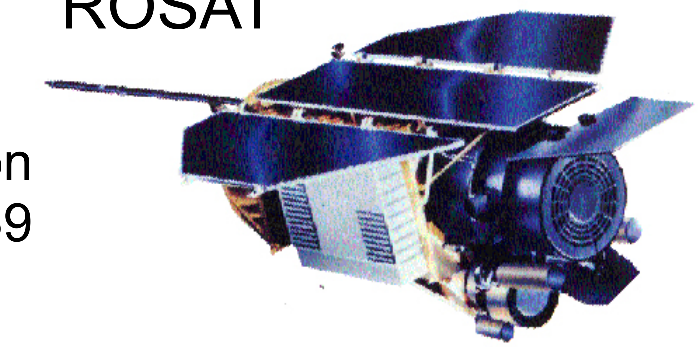
Neutrino/AGN correlation

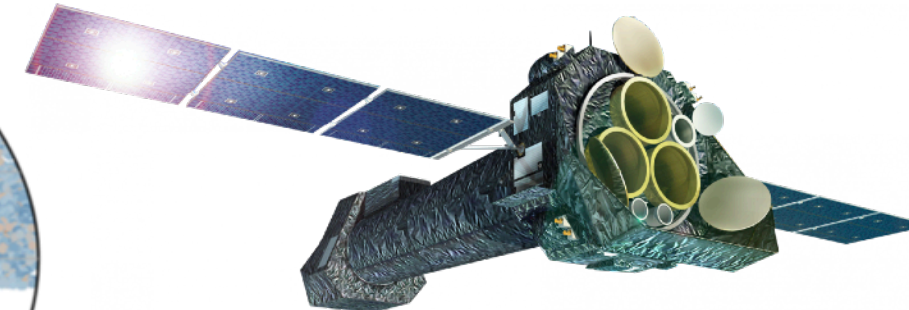
Search for neutrino emission from AGN cores

IceCube Collaboration
arXiv:2111.10169



ROSAT

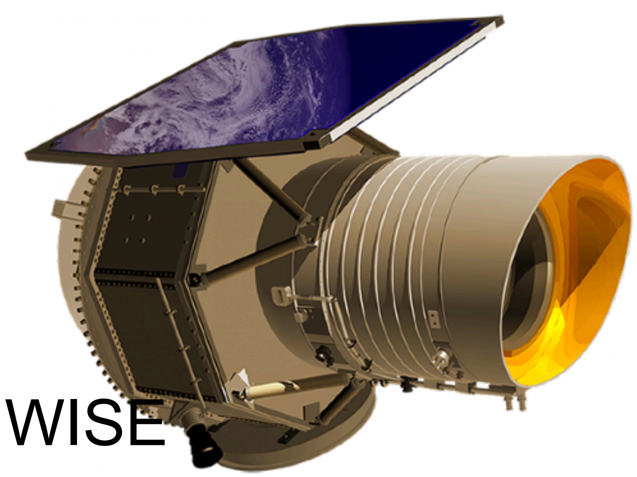




XMM Newton

X-ray flux from ROSAT and XMMSL2 surveys:

- proxy for neutrino flux
- weights in source stacking analysis

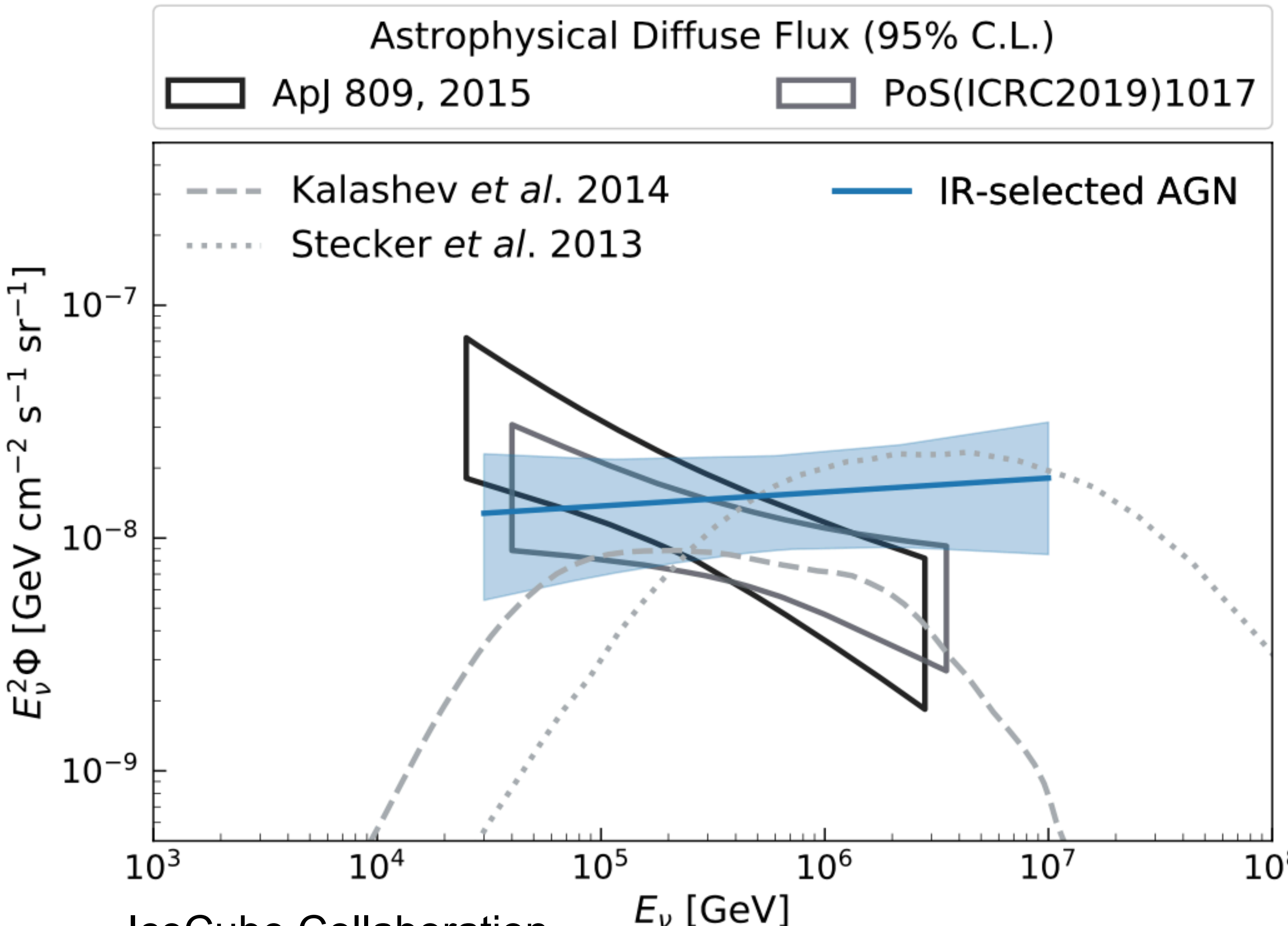


WISE

32249 AGN candidates
on northern hemisphere selected
from WISE color data

Search for neutrino emission from AGN cores

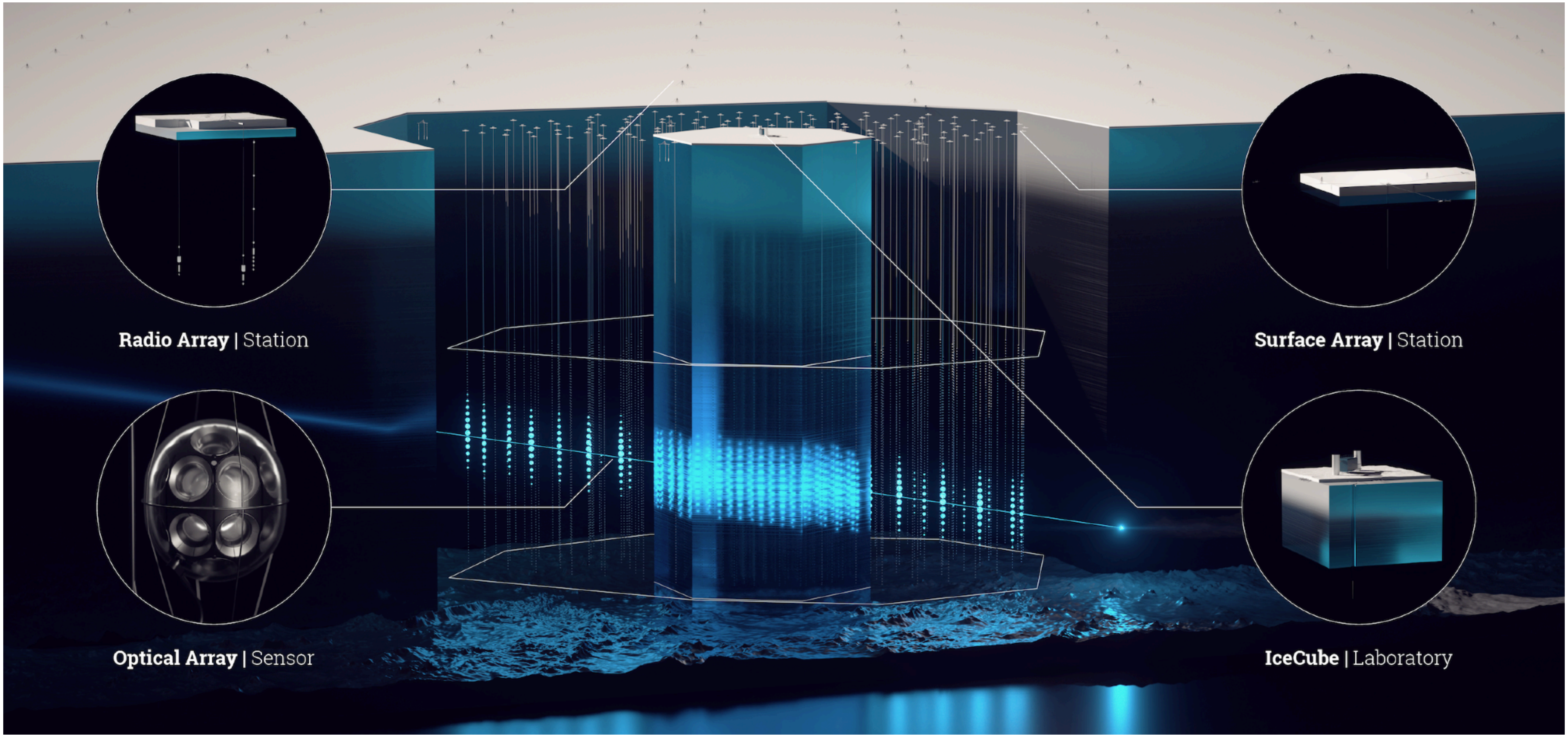
- Correlation tested on 8 year IceCube data
- Most sensitive analysis to constrain the AGN contribution to the cosmic neutrino flux
- **Best fit shows a 2.6σ statistical excess** for correlation with AGN sample.
- If real, would imply a 27% — 100% contribution of AGN to the total cosmic neutrino flux at 100 TeV
- AGN cores are opaque to gamma rays
- Significant detection of AGN as neutrino sources in reach of current neutrino observatories



IceCube Collaboration
arXiv:2111.10169

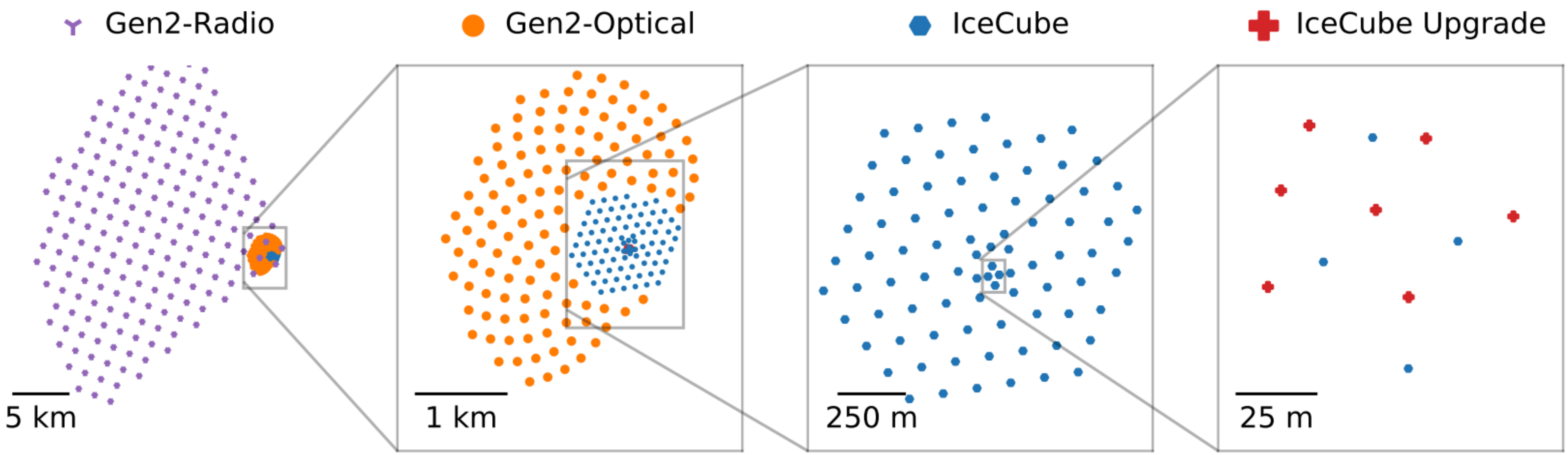
IceCube-Gen2

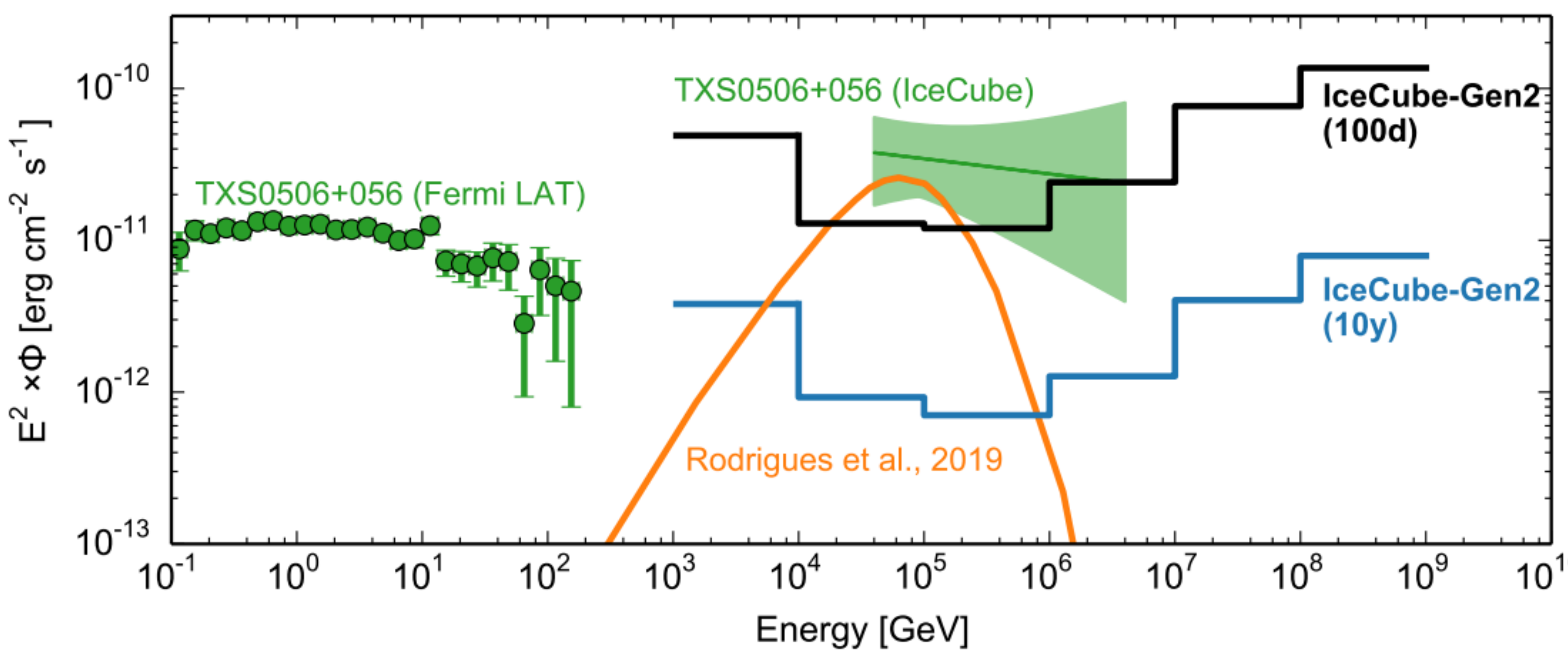
The IceCube-Gen2 neutrino telescope



- 5 x sensitivity and 8 x instrumented volume of IceCube
- Combination of optical detector with a large radio array for coverage up to EeV energies

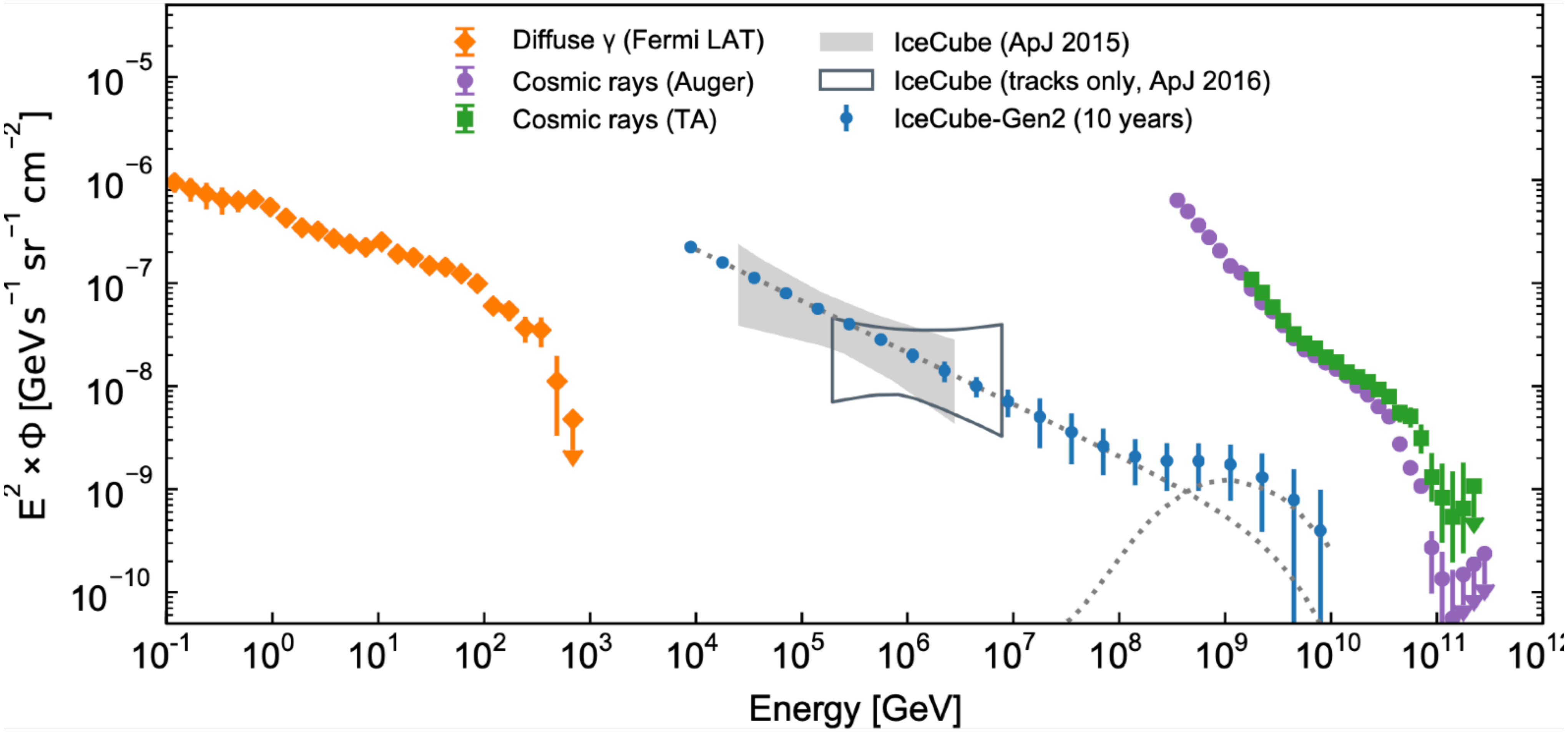
The IceCube-Gen2 observatory





Neutrino astronomy with IceCube-Gen2

- Precision measurement of the spectrum from 10 TeV - 10 EeV



- Brightest neutrino sources from several populations detectable as individual sources
- > 1 high-energy neutrinos from gamma-ray blazars / year
- Flavor composition measurement differential in energy
- Glashow resonance as a diagnostic for the interaction target
- etc…

Summary

- Measurements of the diffuse neutrino spectrum and flavor composition continue to improve
- First tau neutrino and Glashow resonance candidates detected
- After blazars, TDE emerge as a second potential candidate for neutrino sources
- Neutrinos produced in AGN cores could contribute a large fraction of the observed neutrino flux and they are gamma-opaque sources. More statistics needed for confirmation.
- With KM3NeT and Baikal-GVD two km3-class neutrino telescopes on the Northern hemisphere are under construction that can complement IceCube observations in the near future
- IceCube-Gen2 is planned as a next generation neutrino telescopes which will allow precision studies of the neutrino sky and routine source detections.