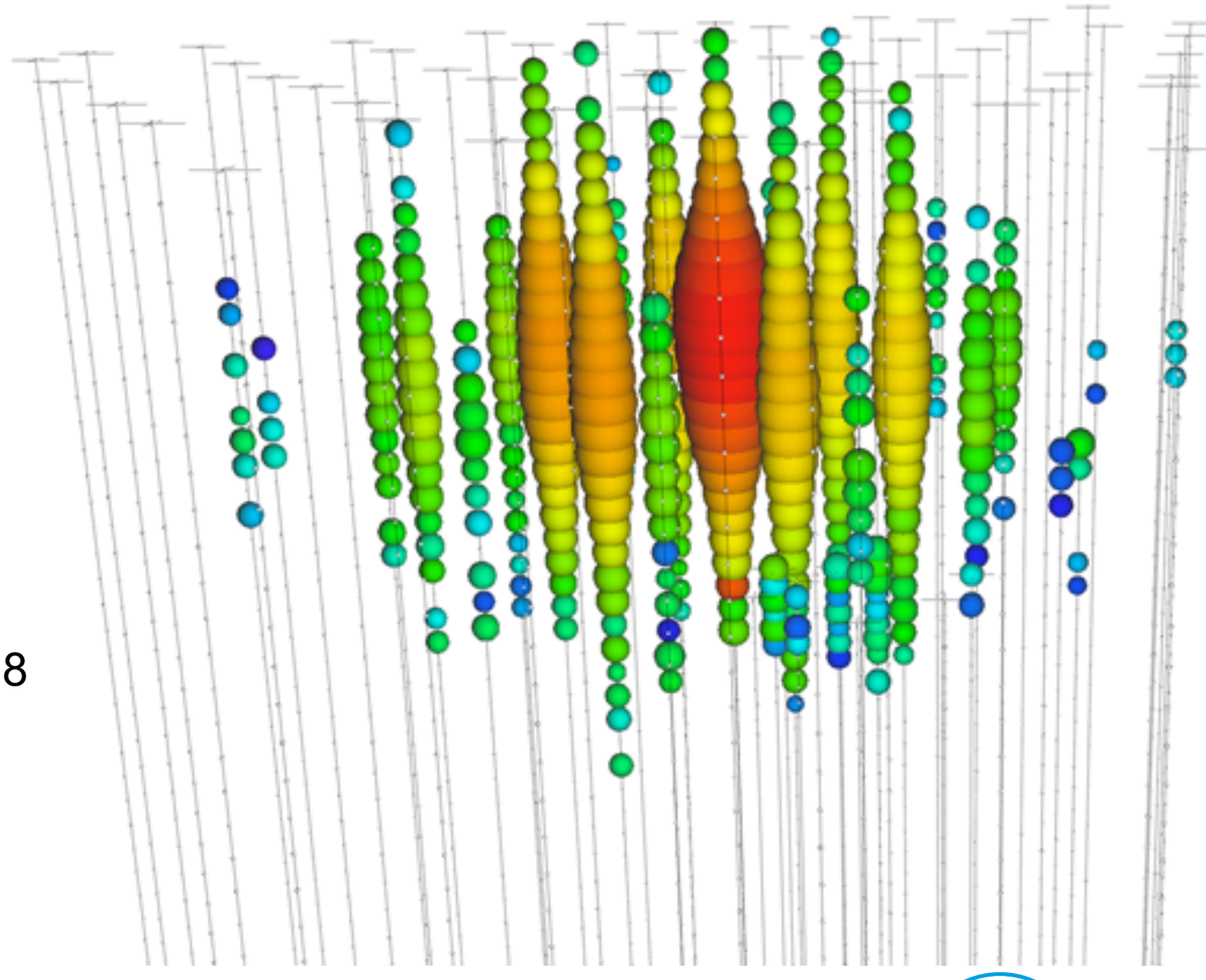
Cosmic neutrinos

and what they tell us about the sources of cosmic rays.



Markus Ackermann, DESY

ISVHECRI, May 21 - May 26, 2018

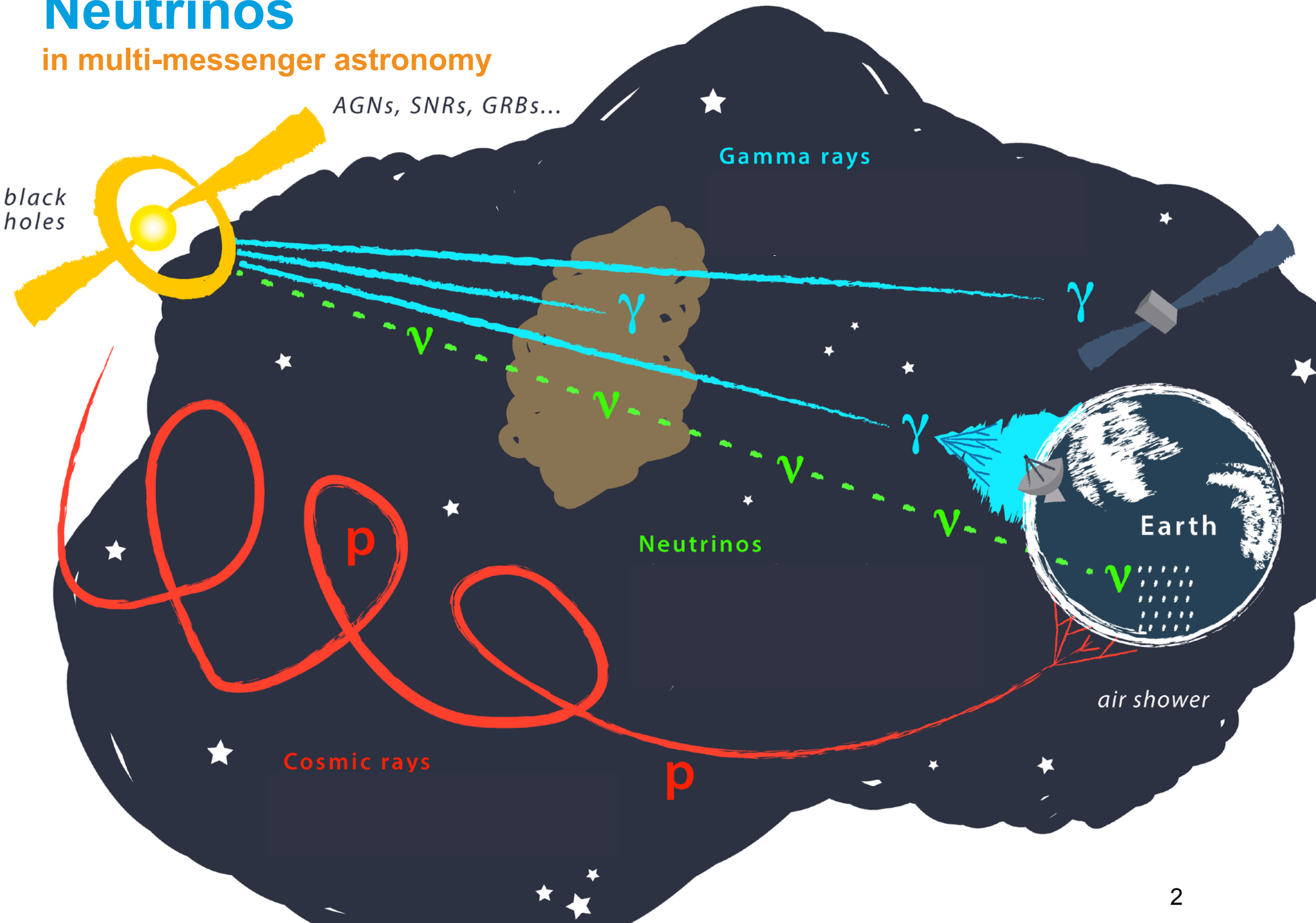
Nagoya, Japan

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

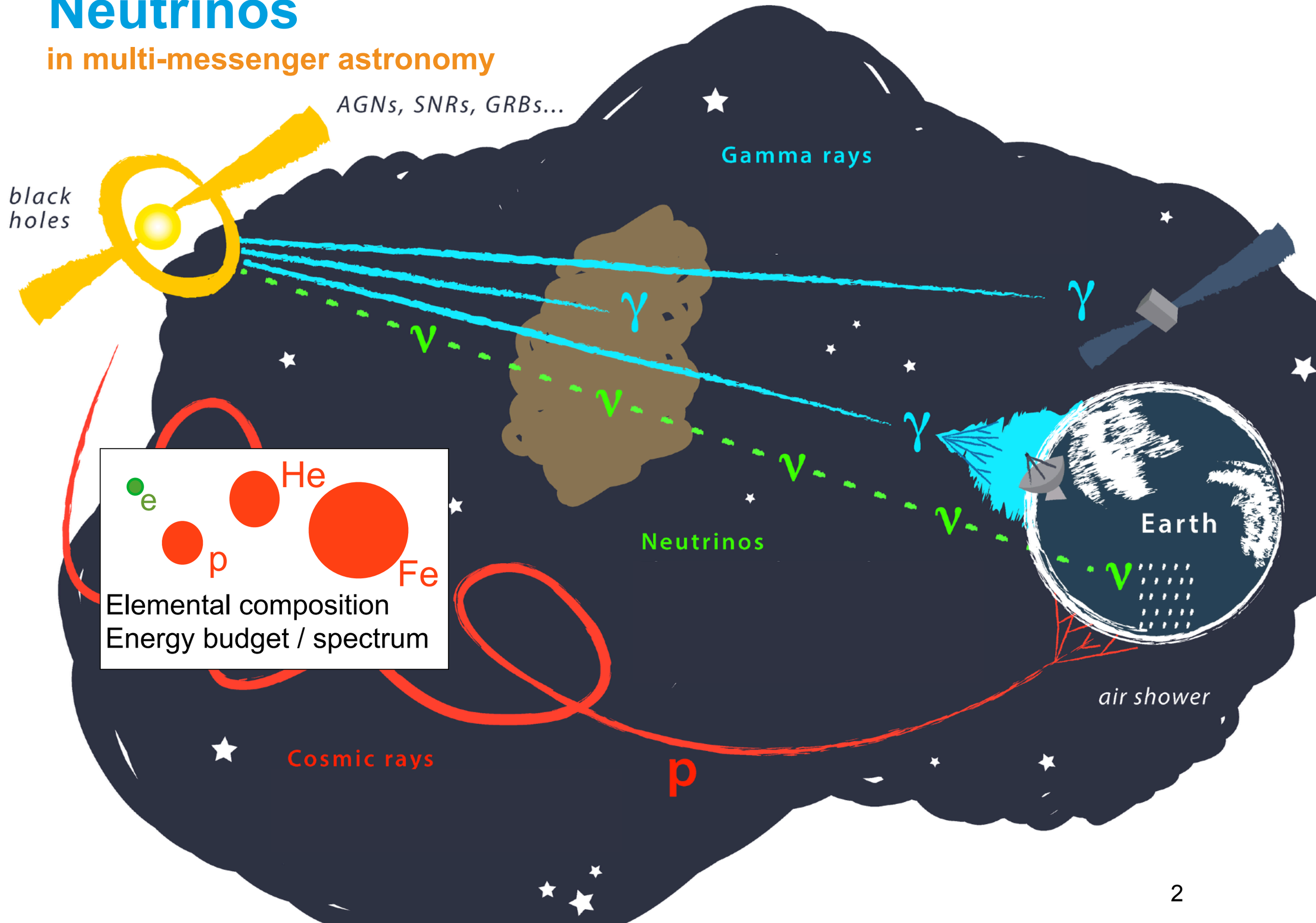
Neutrinos

in multi-messenger astronomy



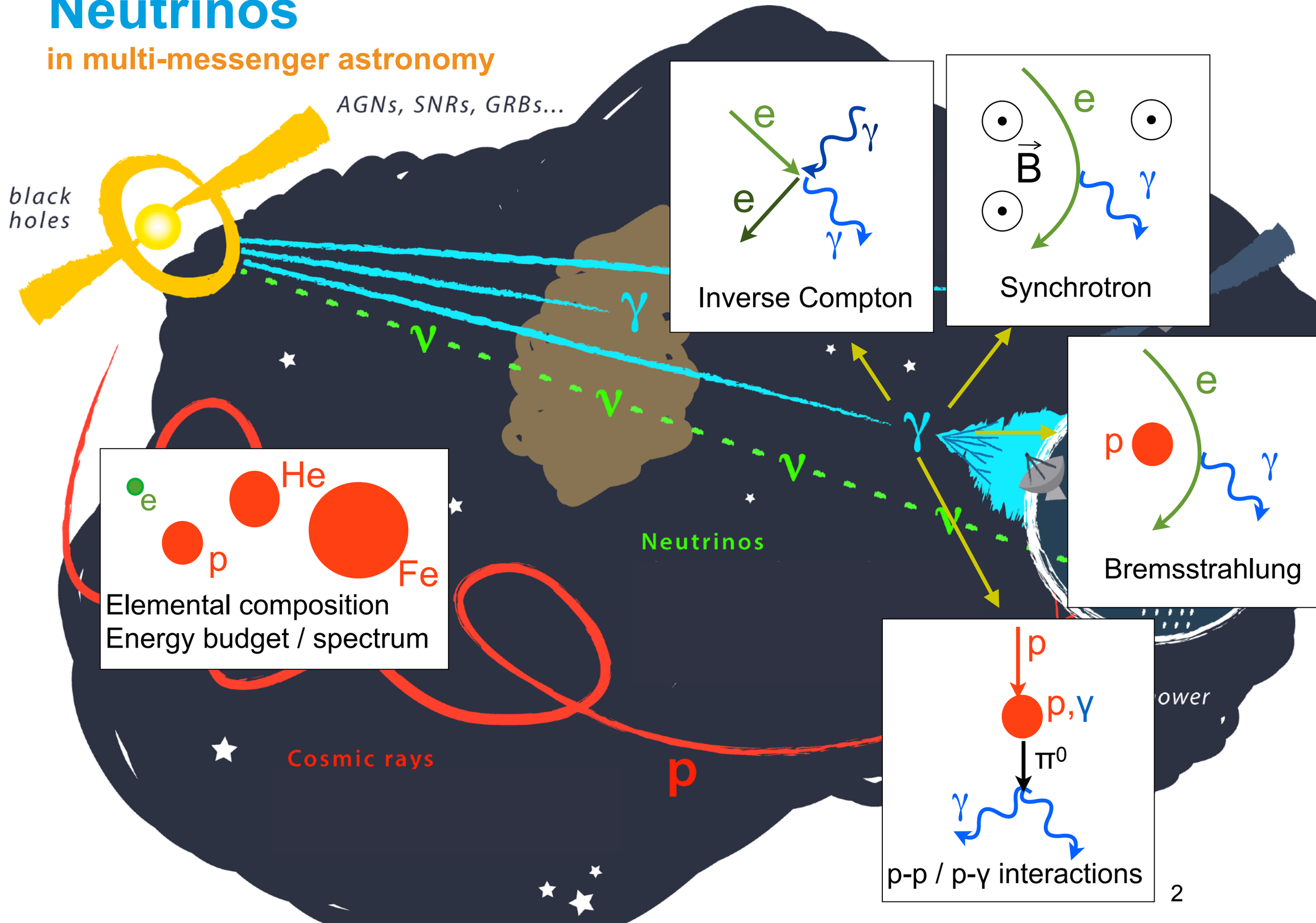
Neutrinos

in multi-messenger astronomy



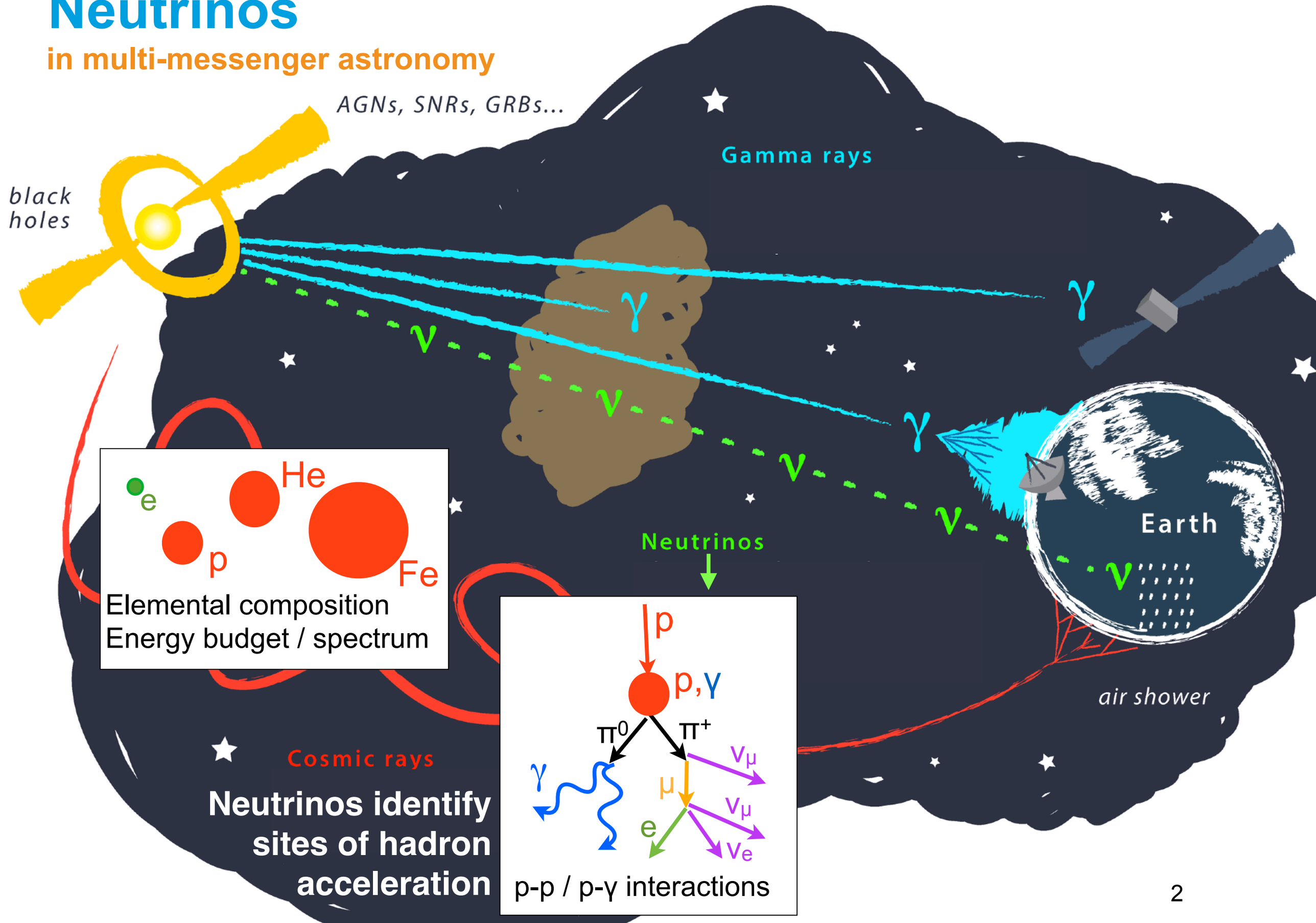
Neutrinos

in multi-messenger astronomy

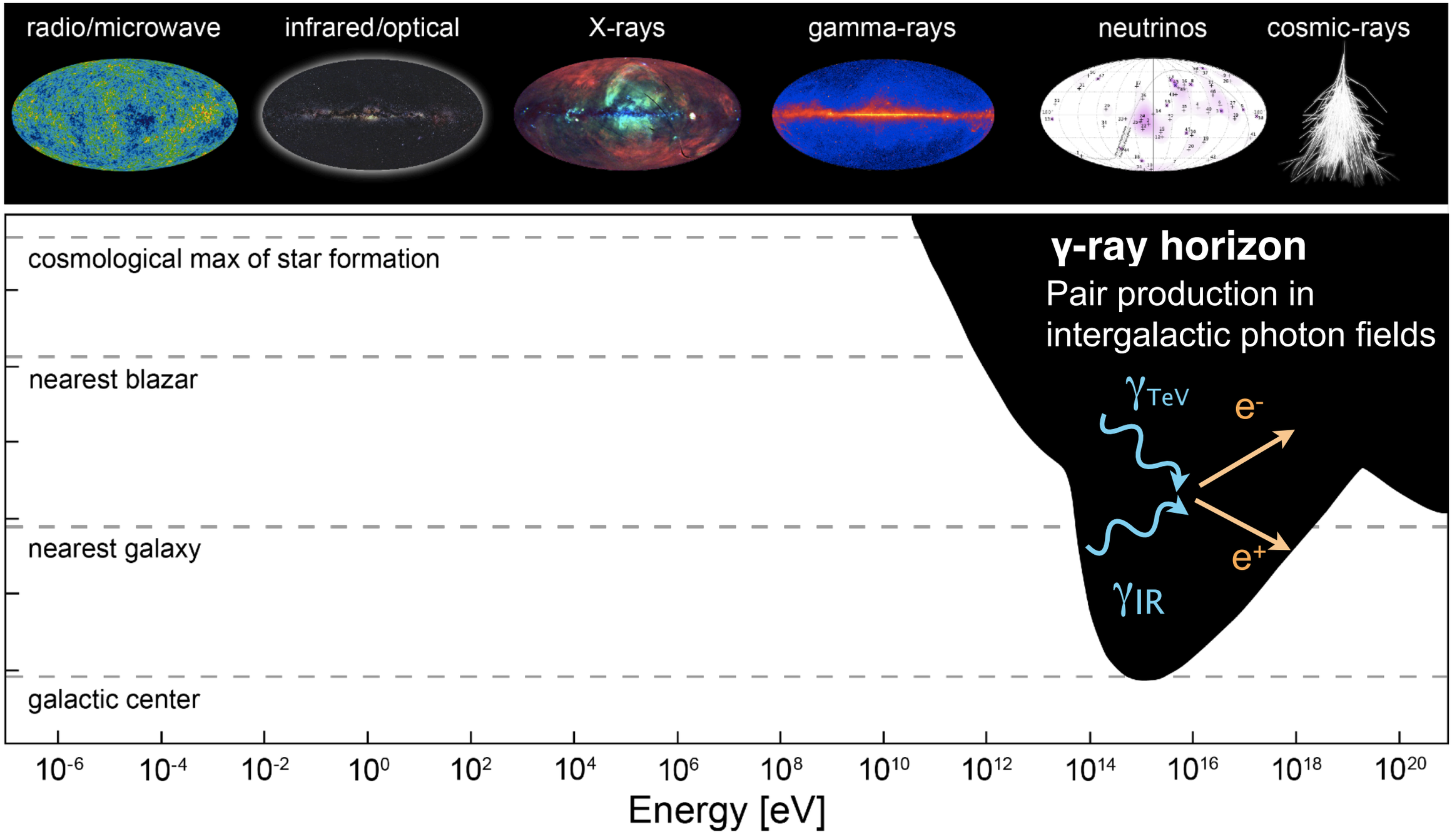


Neutrinos

in multi-messenger astronomy

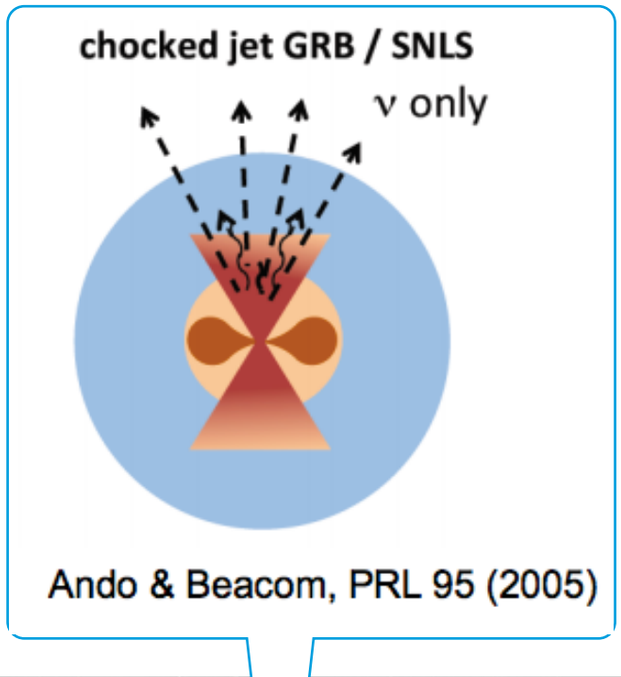


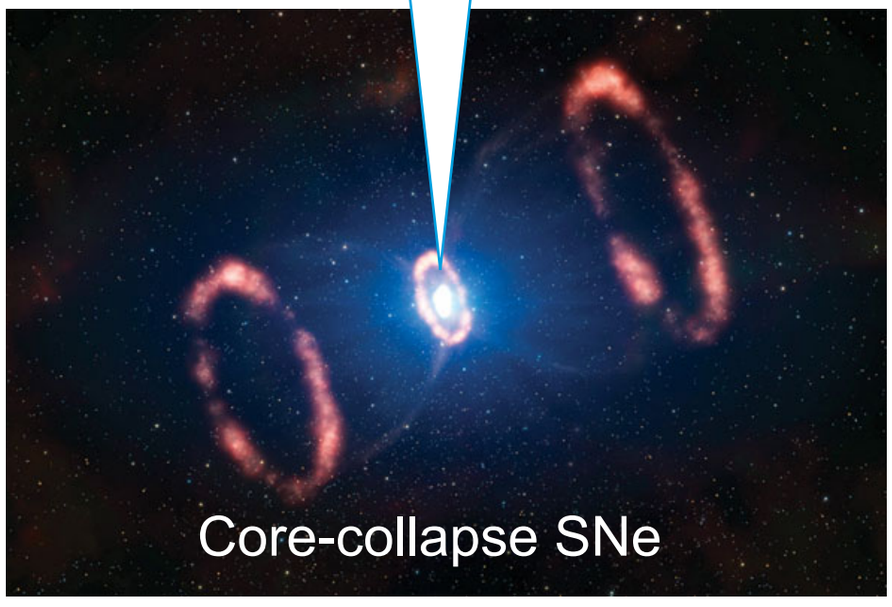
PeV astronomy with neutrinos



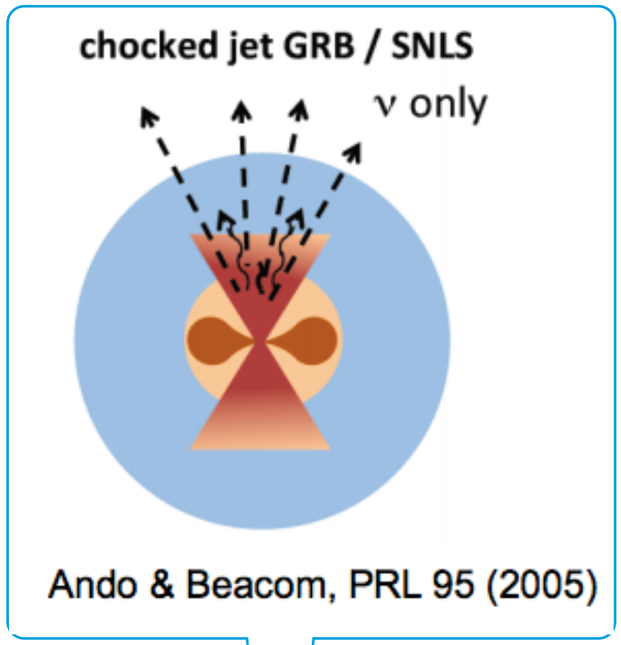
- Neutrinos allow us to **peek beyond** the gamma-ray horizon…

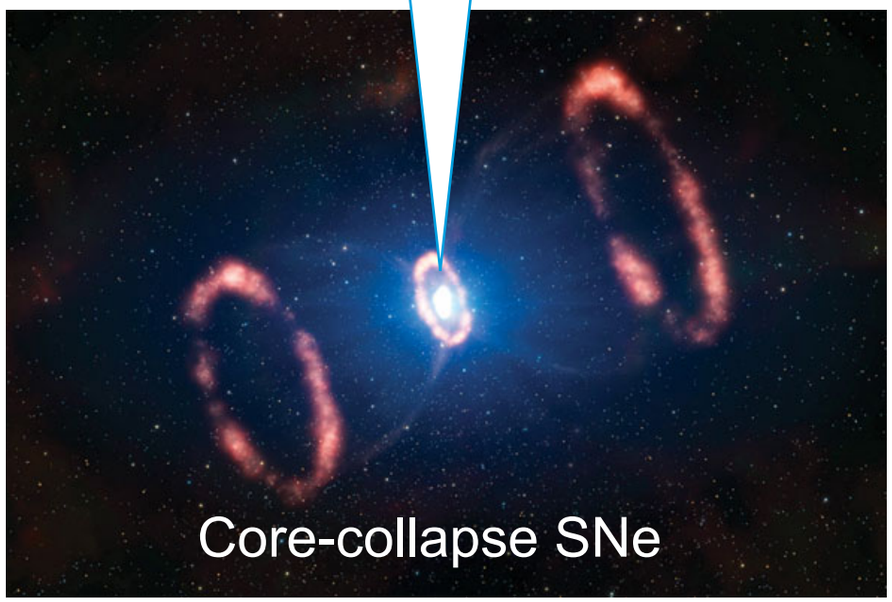
Environments opaque to EM radiation

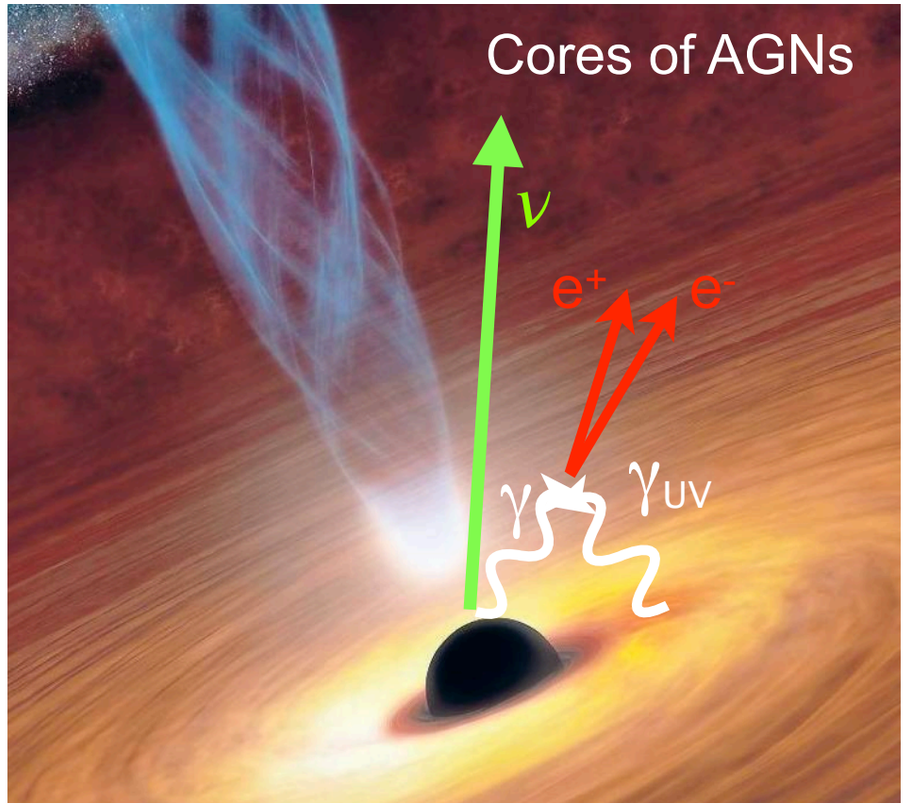




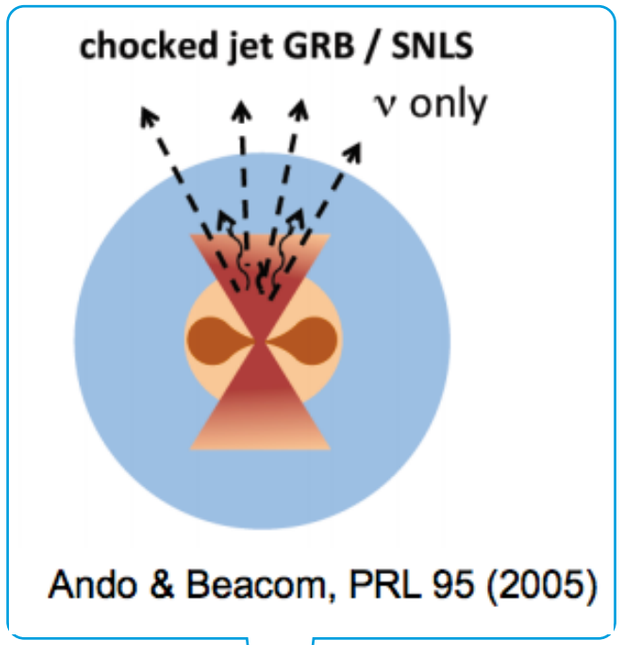
Environments opaque to EM radiation

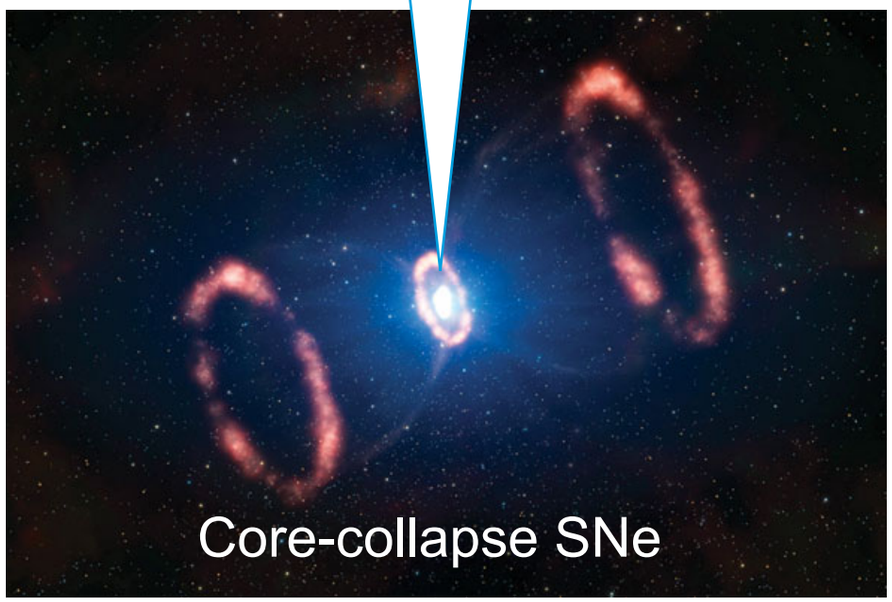


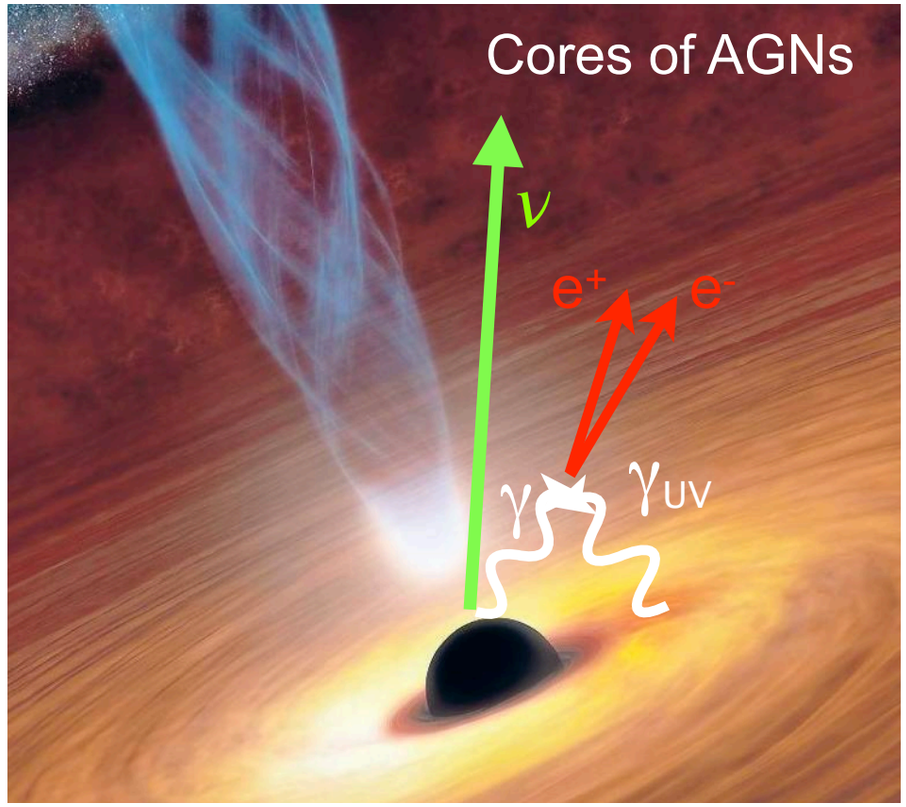


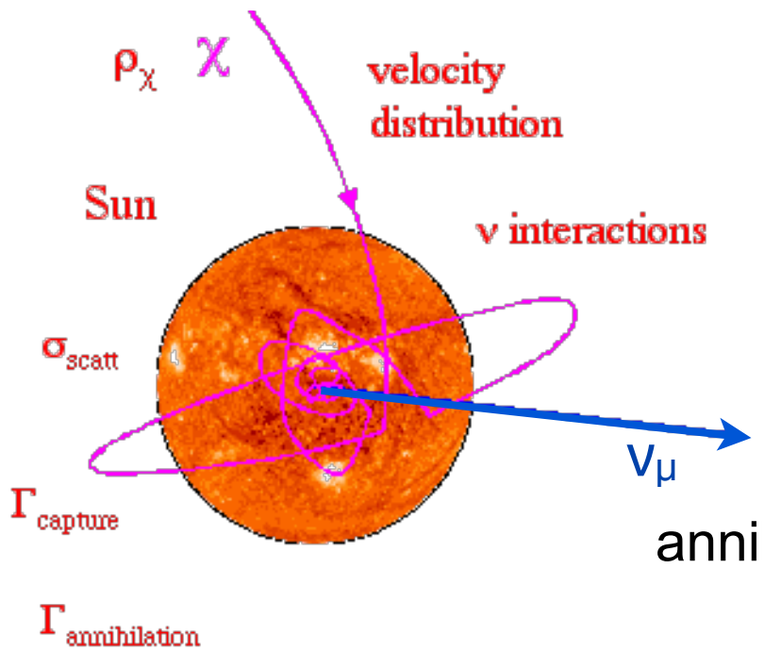


Environments opaque to EM radiation



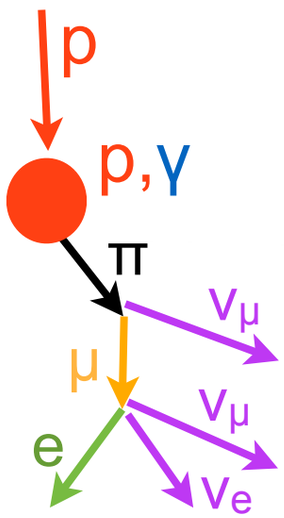




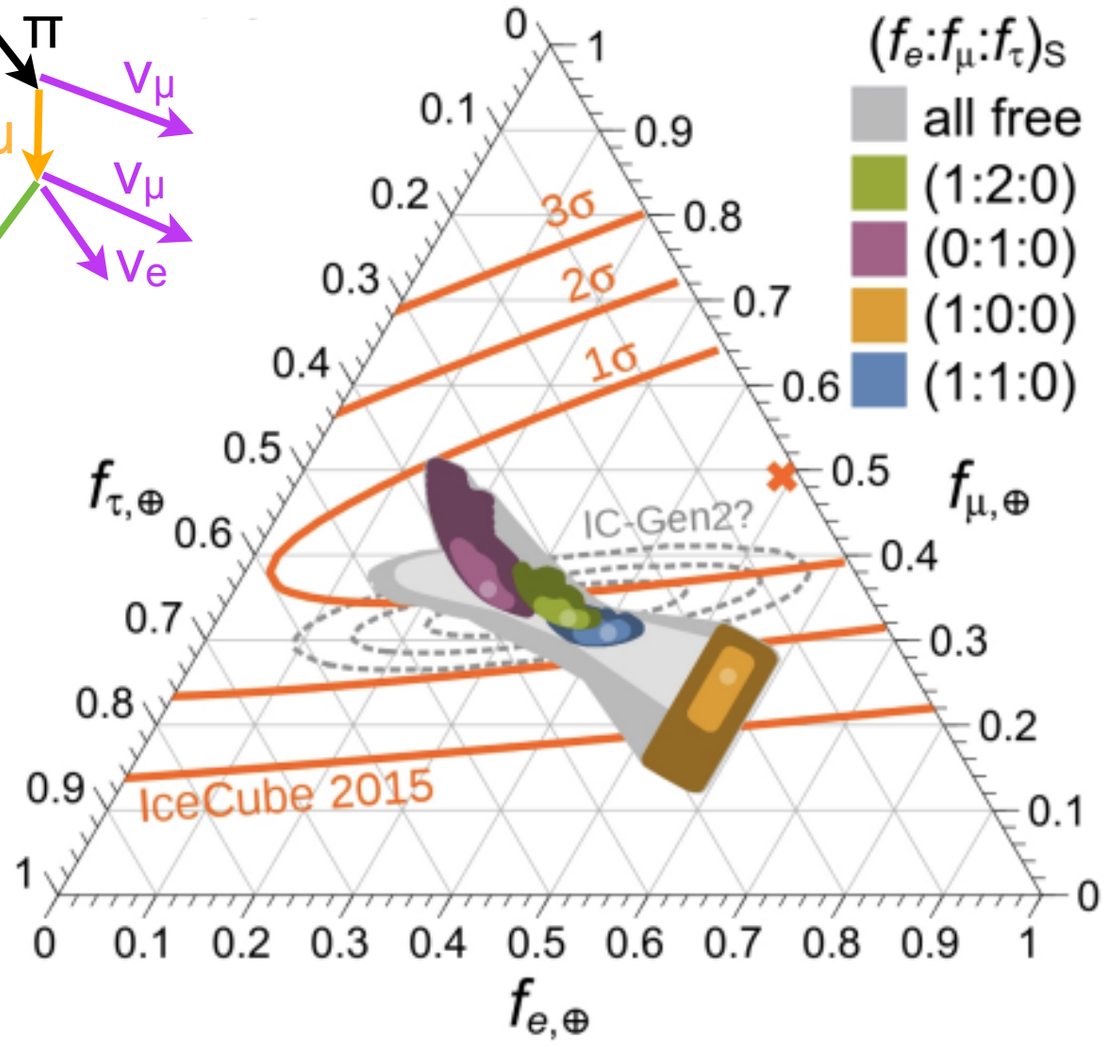


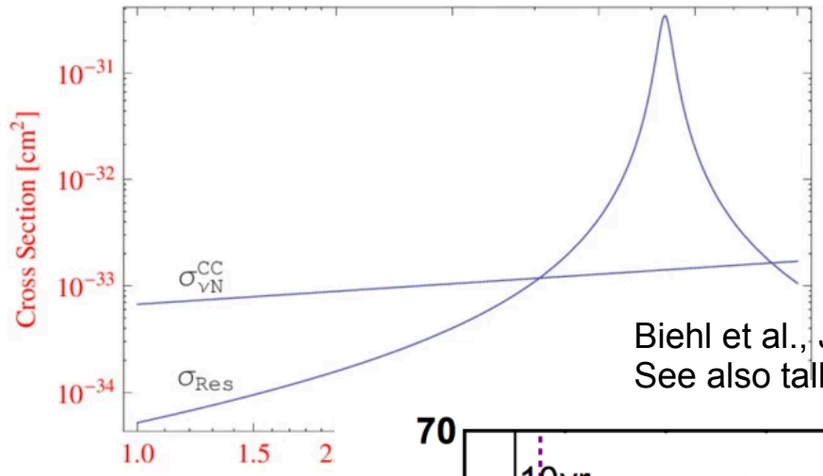
Dark Matter annihilation in the sun

Interaction processes and environments

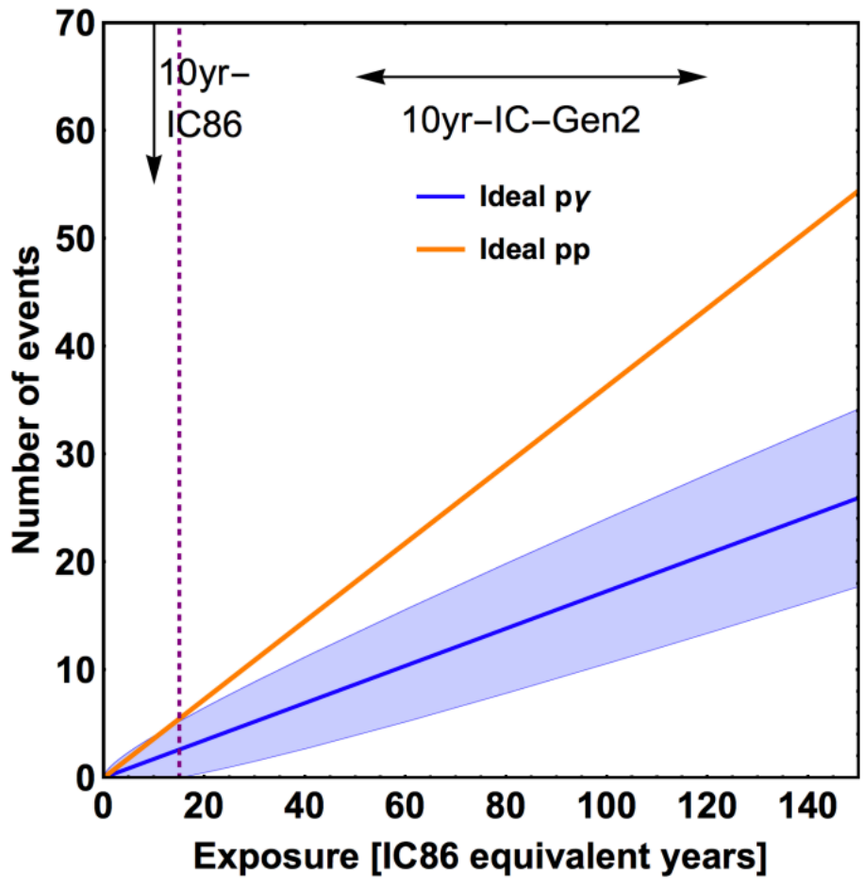


Bustamante, Beacom & Winter, PRL 2015



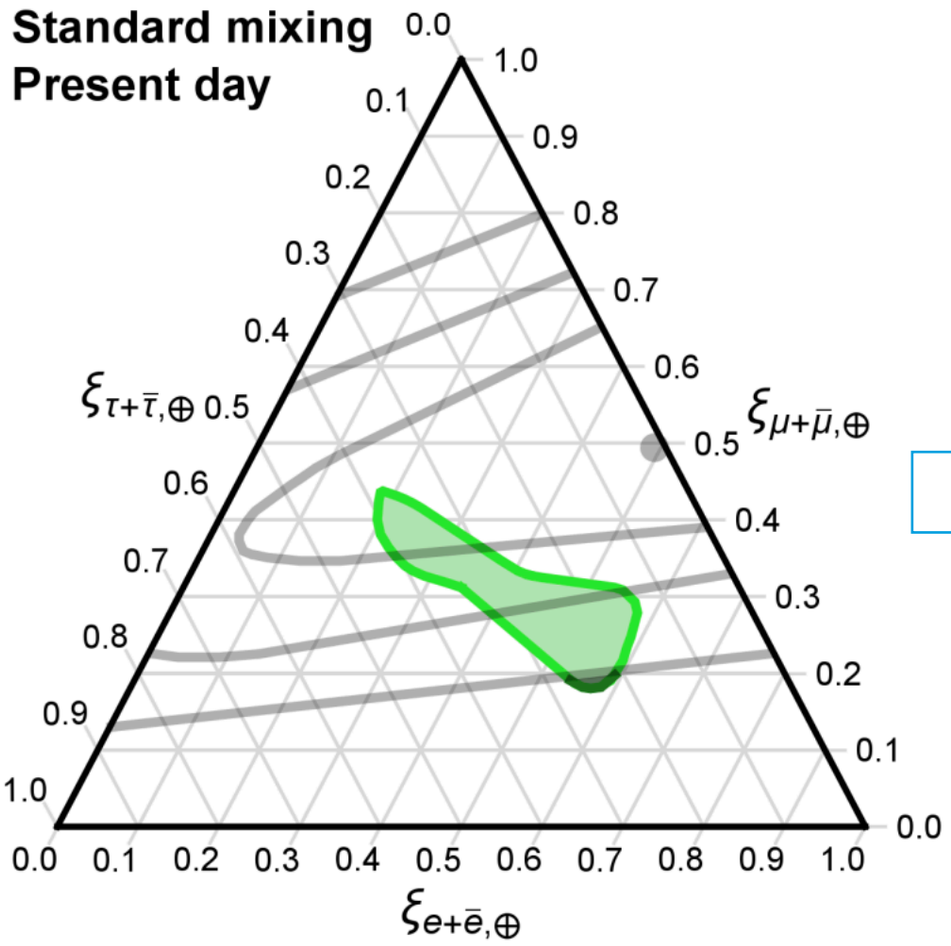


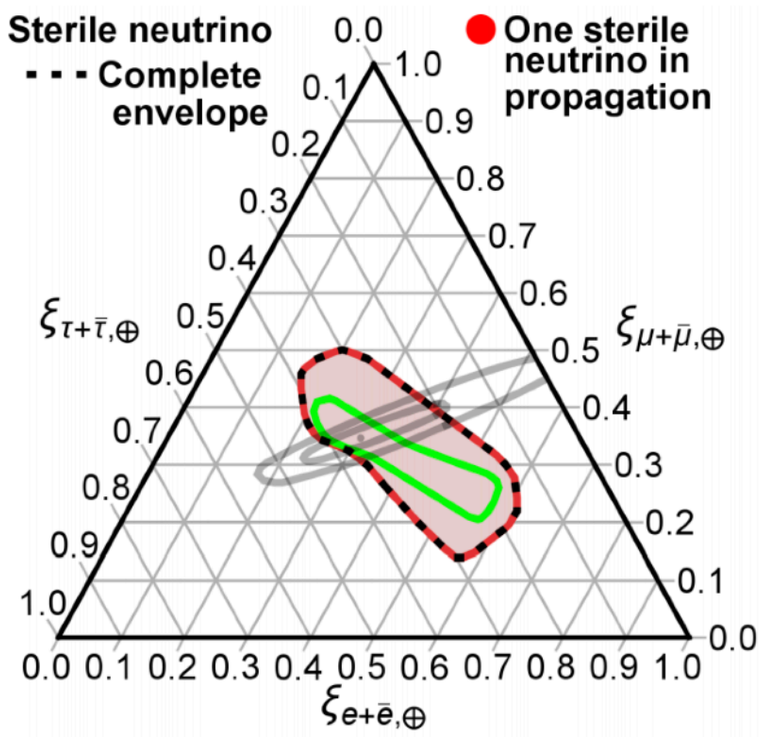
Biehl et al., JCAP 2017
See also talk on Monday



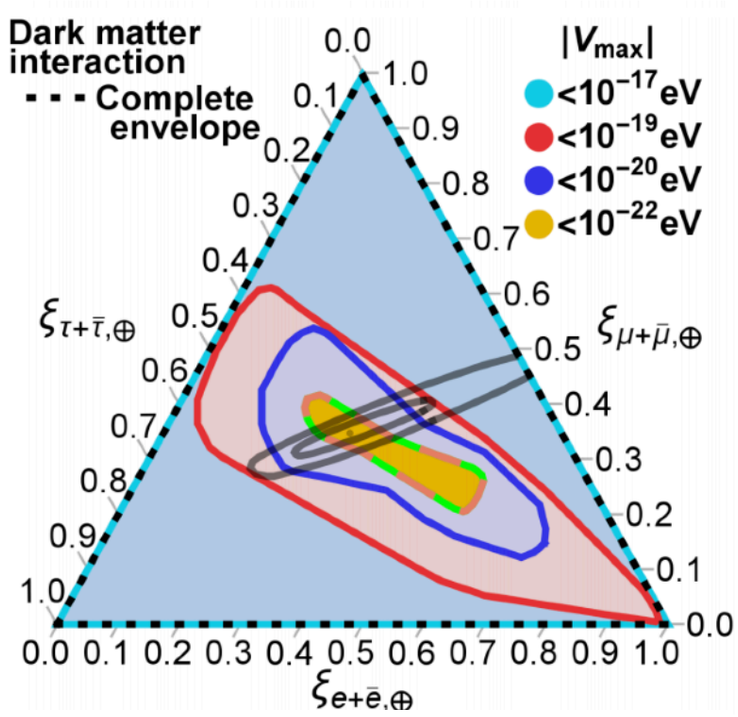
- **Flavor ratio** depends on production mechanism / source environment.
- **Glashow resonance** events might allow to distinguish interaction processes.

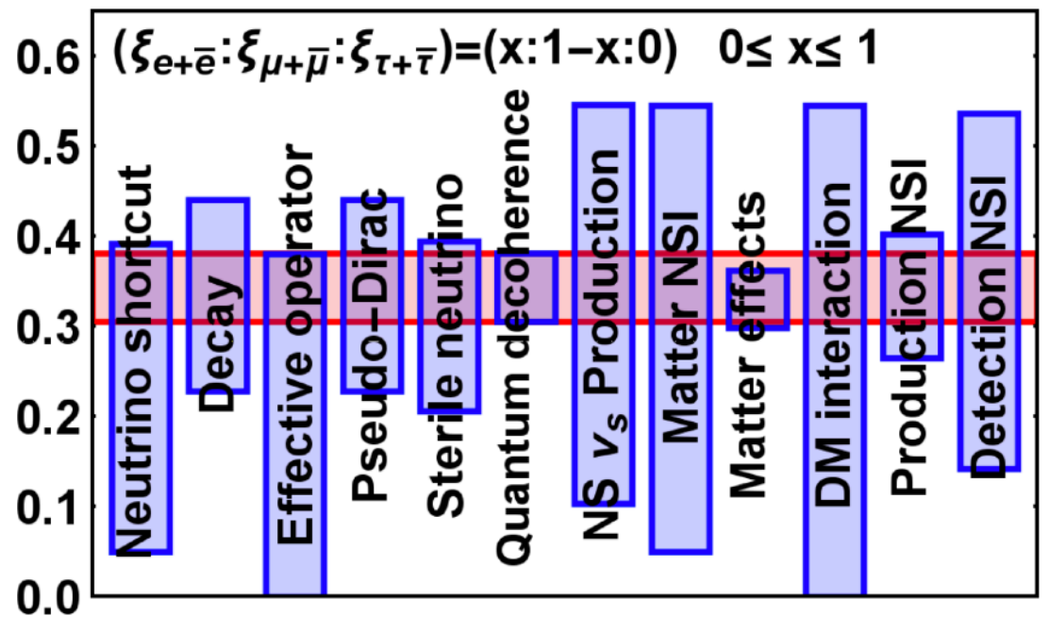
New physics





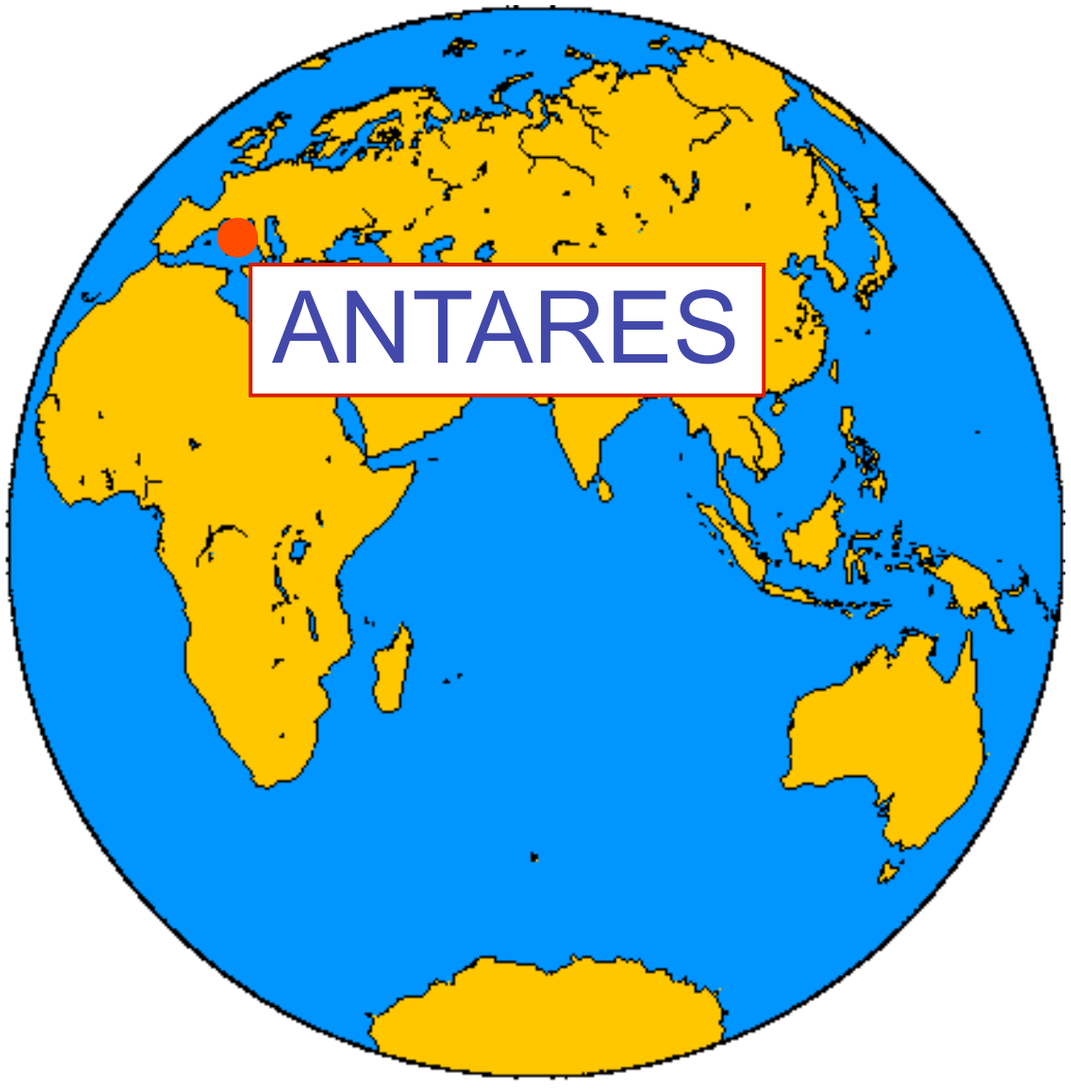
Rassmusen et al., 2017

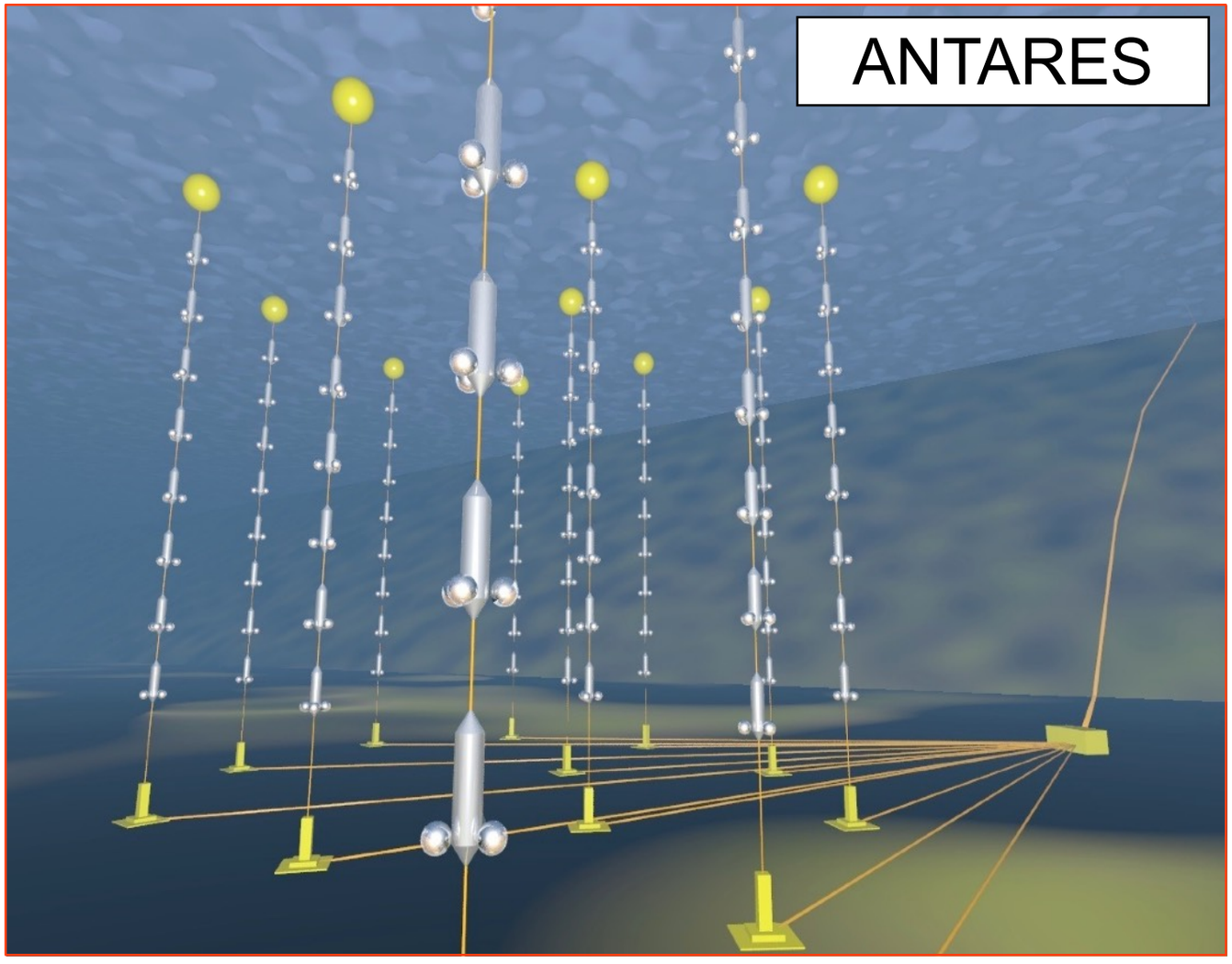




- Observations of an **unexpected flavor ratio** could identify new physics
- ν_τ **fraction** important observable

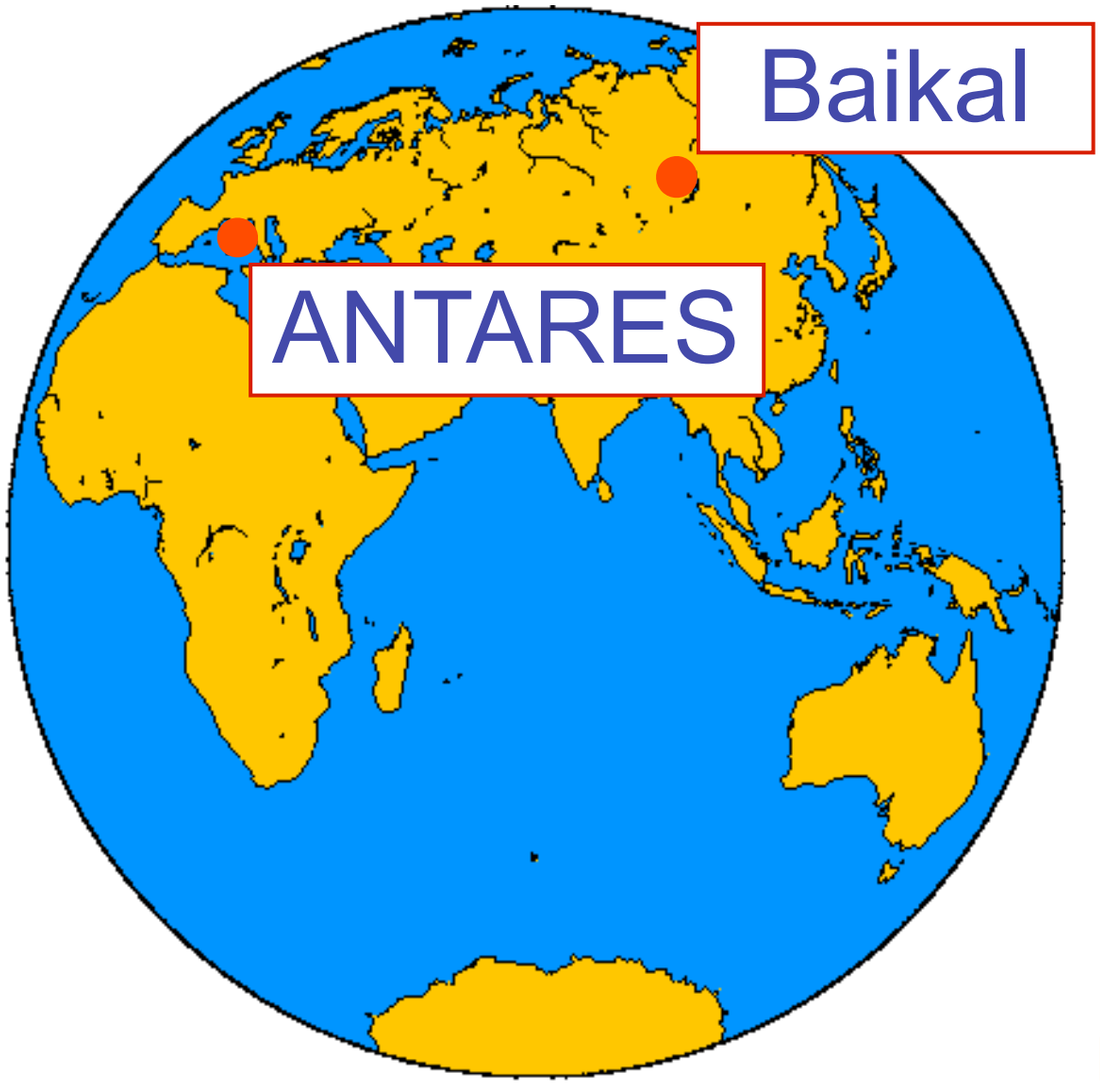
Neutrino telescopes: ANTARES

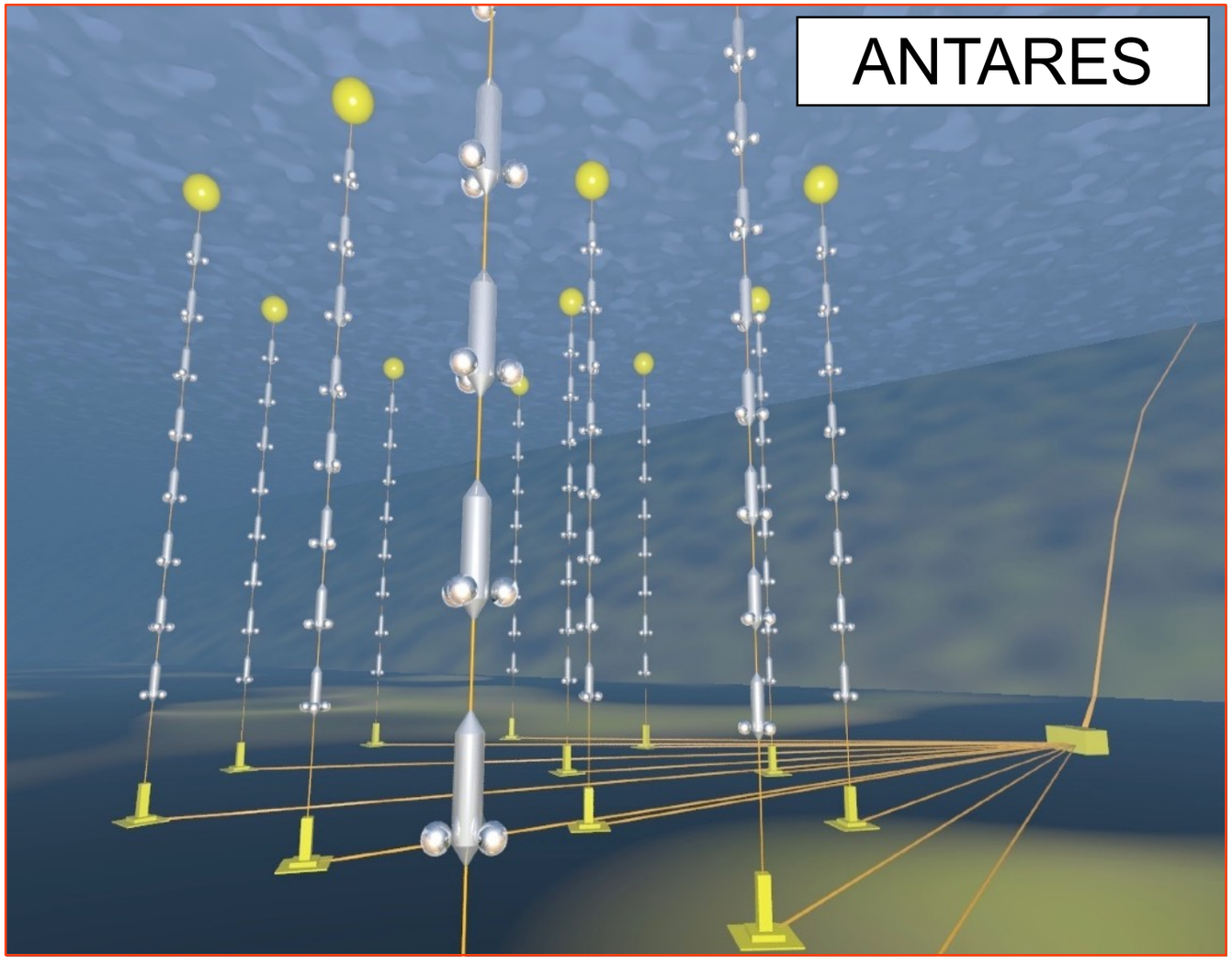




- Mediterranean sea, off **Toulon, France**
- **Operating since 2008** in final configuration
- 885 PMTs on 12 strings (~**10^{-2} km^3** instrumented volume)

Neutrino telescopes: ANTARES





- Mediterranean sea, off **Toulon, France**
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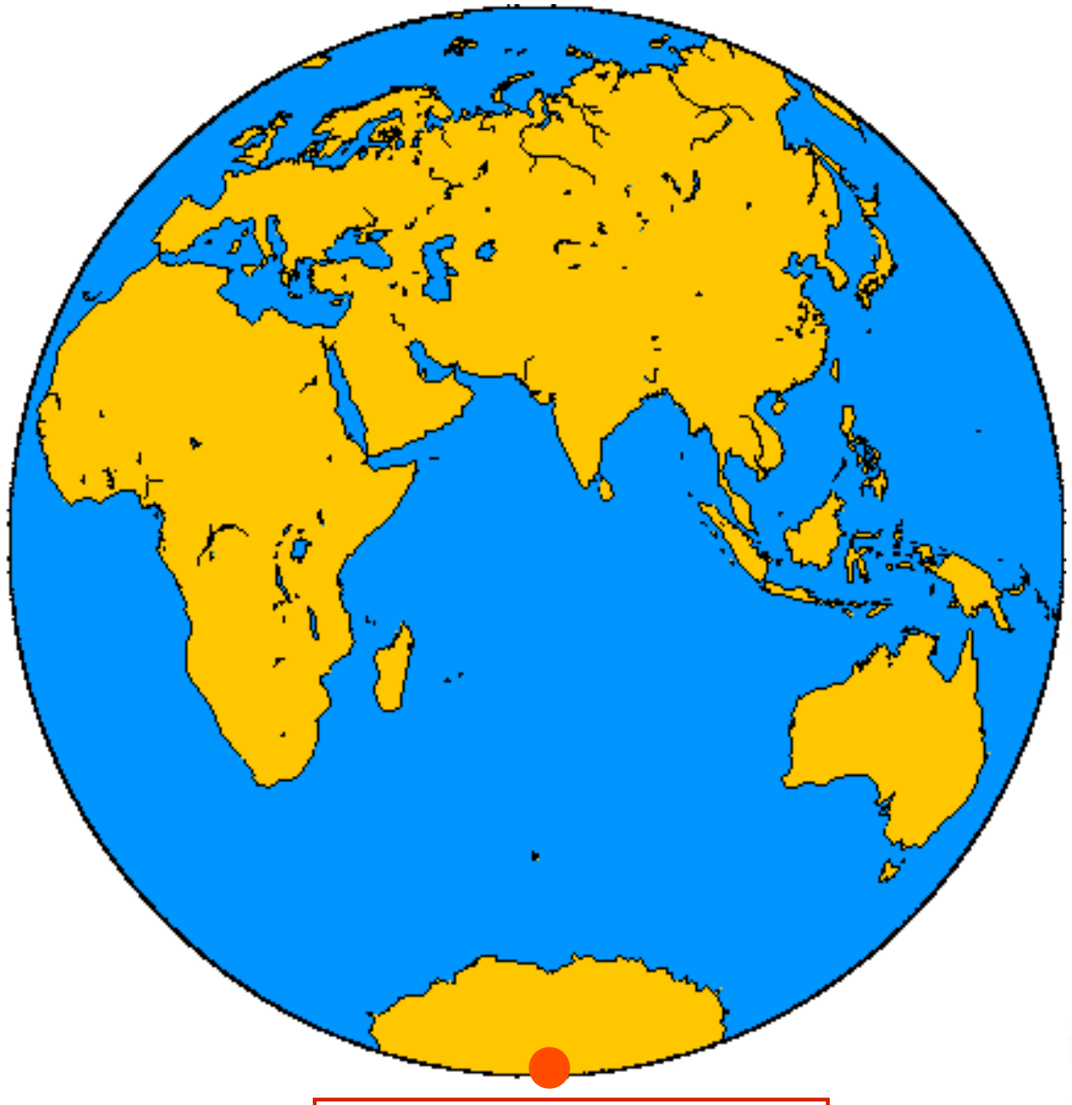
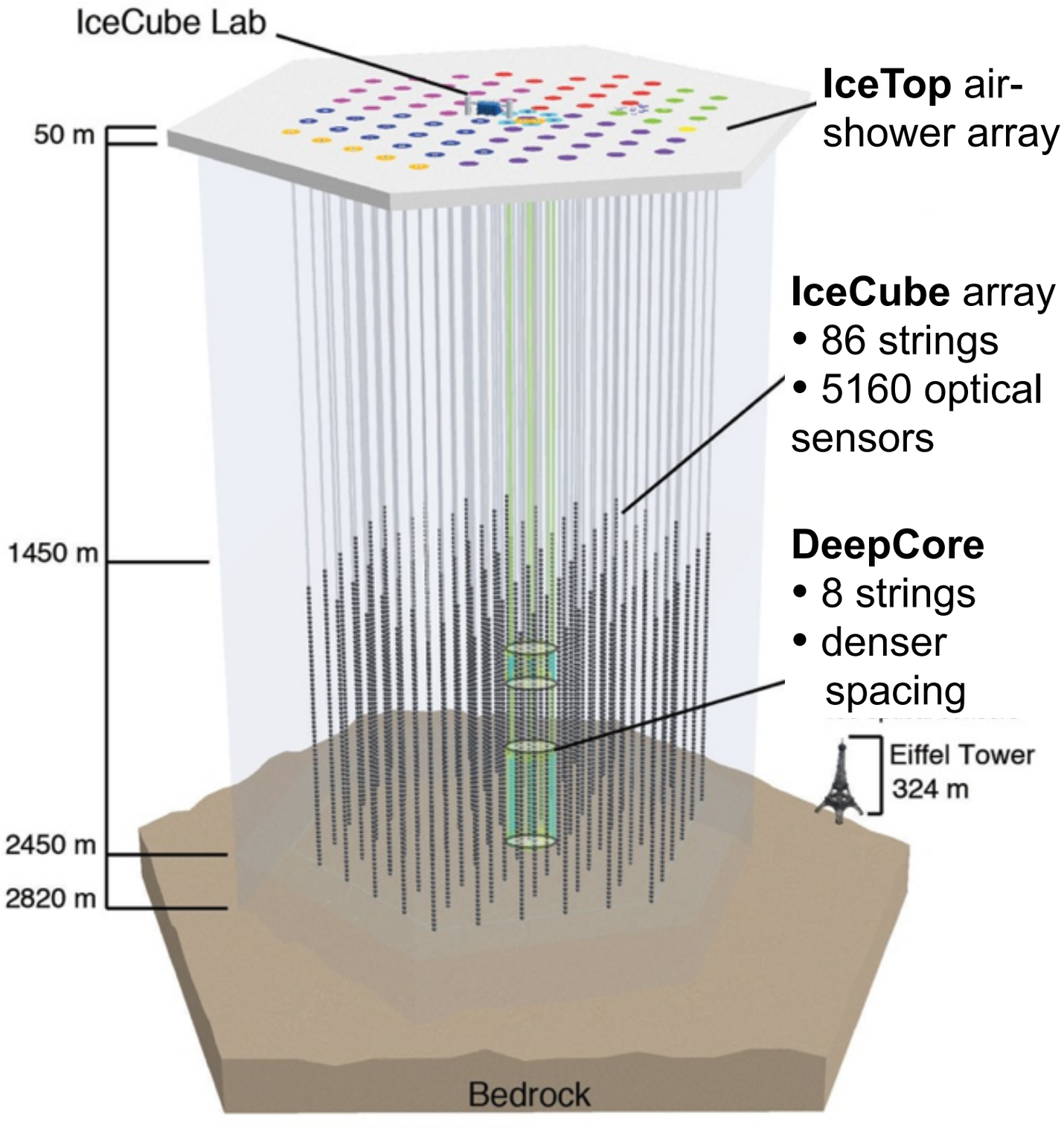
Neutrino telescopes: IceCube

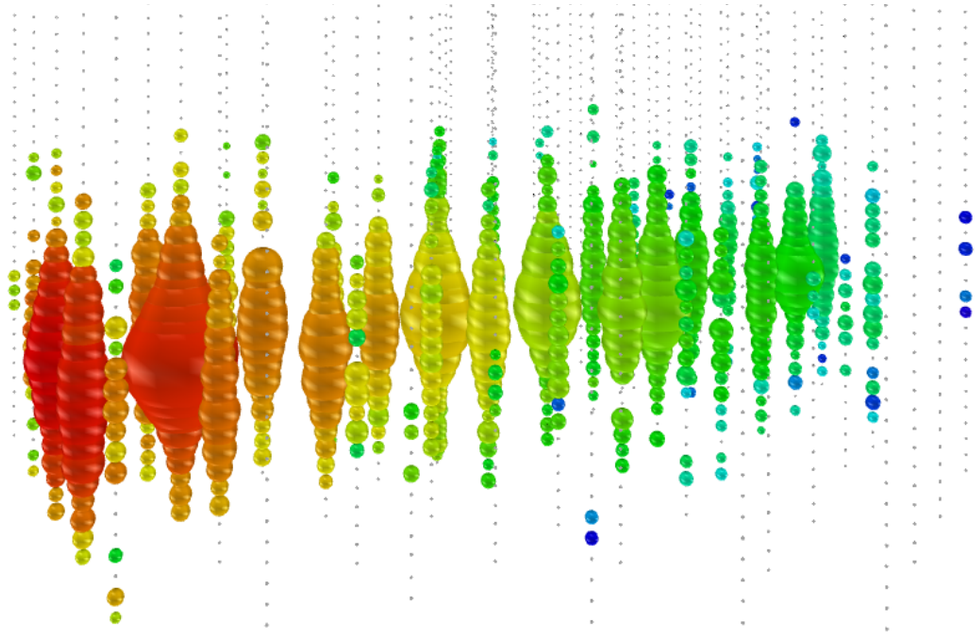


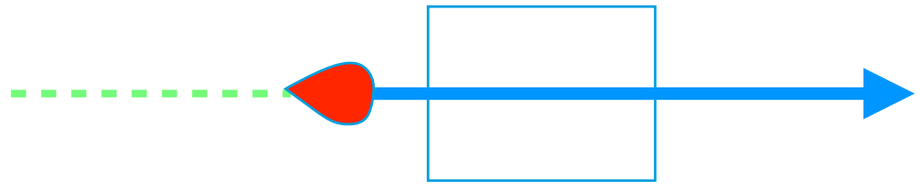
IceCube

- **Completed** in Dec **2010**.
- Instrumented volume: **~ 1km^3**

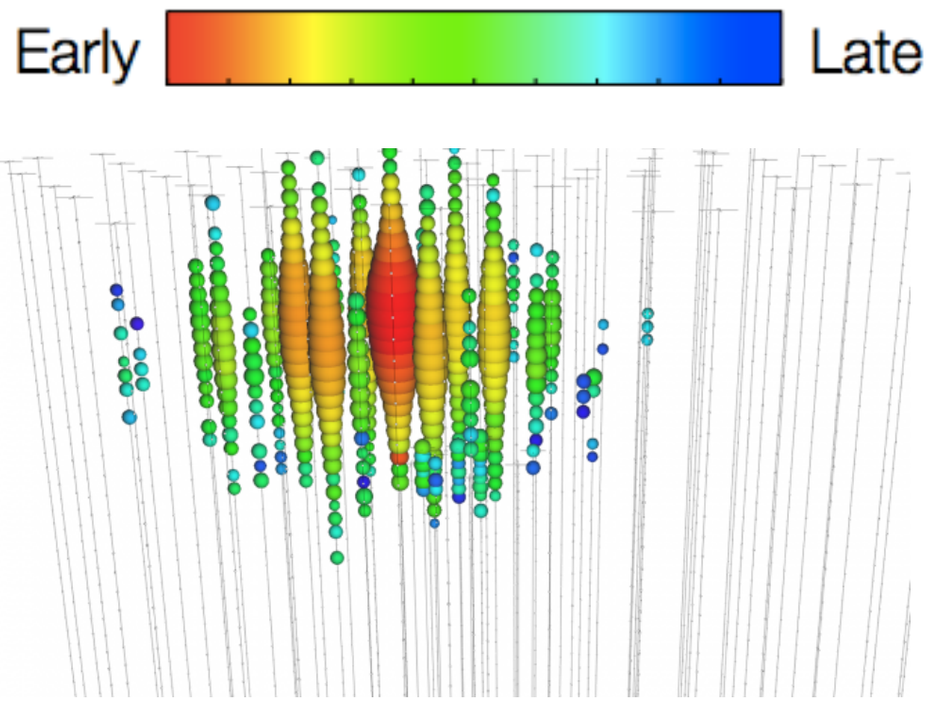


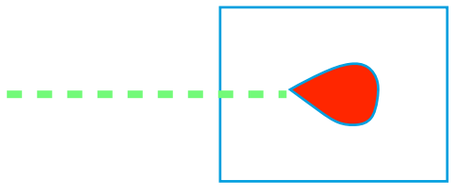
Signatures of neutrino interactions





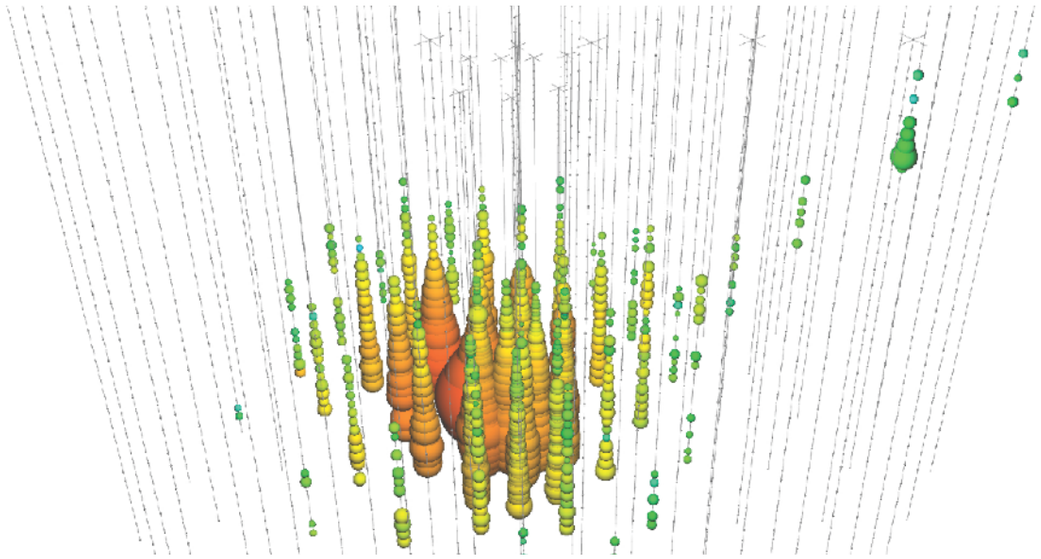
- **Track-like event** signatures
  (CC interactions of ν_μ)
  - **Angular** resolution: < 1°
  - **Effective volume:** up to tens of km³.
  - **Energy** resolution: only indirect measure of μ energy.

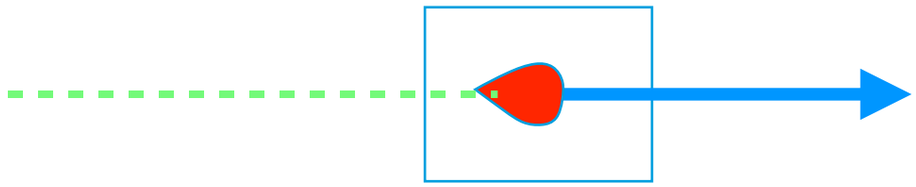




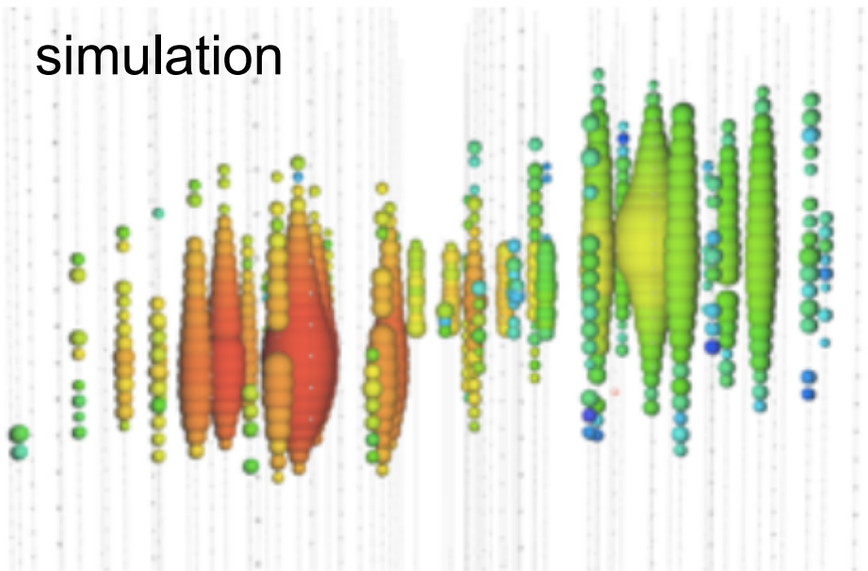
- **Shower-like event** signatures
  (CC interactions of ν_e,ν_τ, NC interactions)
  - **Angular** resolution: > 10°
  - **Effective volume:** ~ 1 km³.
  - **Energy** resolution: ~15% of deposited energy.

Signatures of neutrino interactions





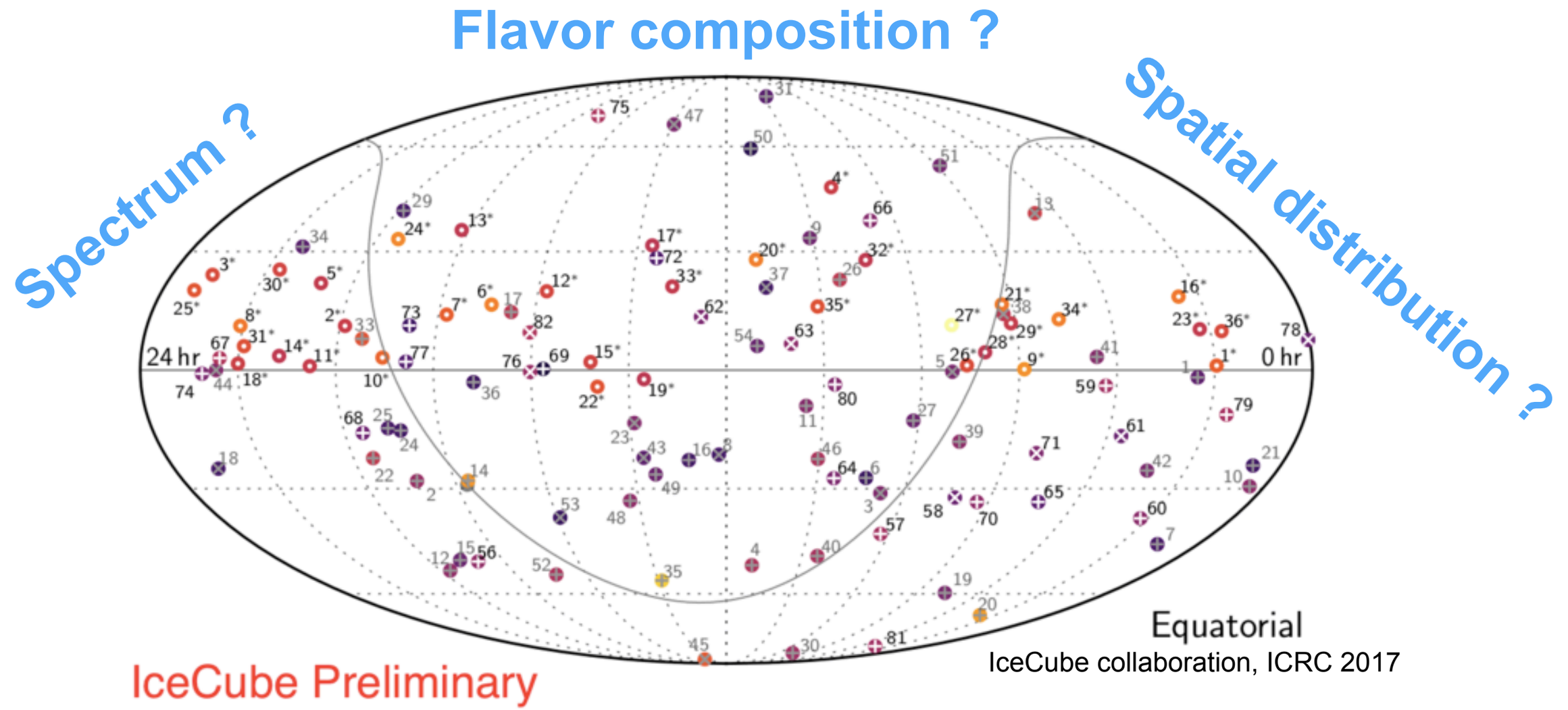
- **Starting events**
  (all flavors)
  - **Angular** resolution: < 1° - 15°
  - **Effective volume:** <~ 0.5 km³
  - **Energy** resolution: ~15% of deposited energy.



- **High-energy ν_τ events**
  (CC interactions ν_τ)
  - ν_τ at PeV energies
  - unique signatures that can identify a ν_τ interaction.

High-energy cosmic neutrinos

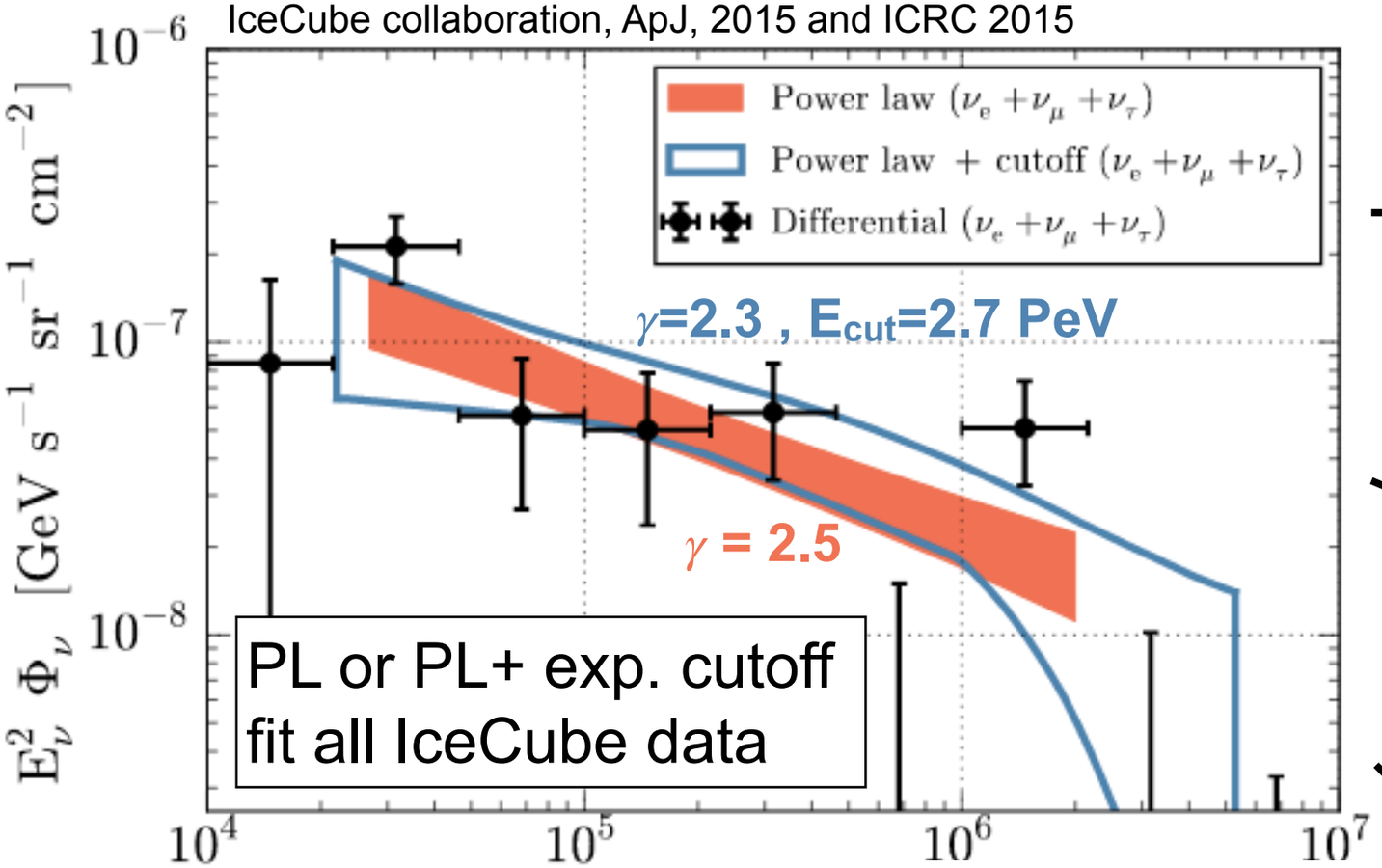
What did we learn in the 5 years since their discovery ?

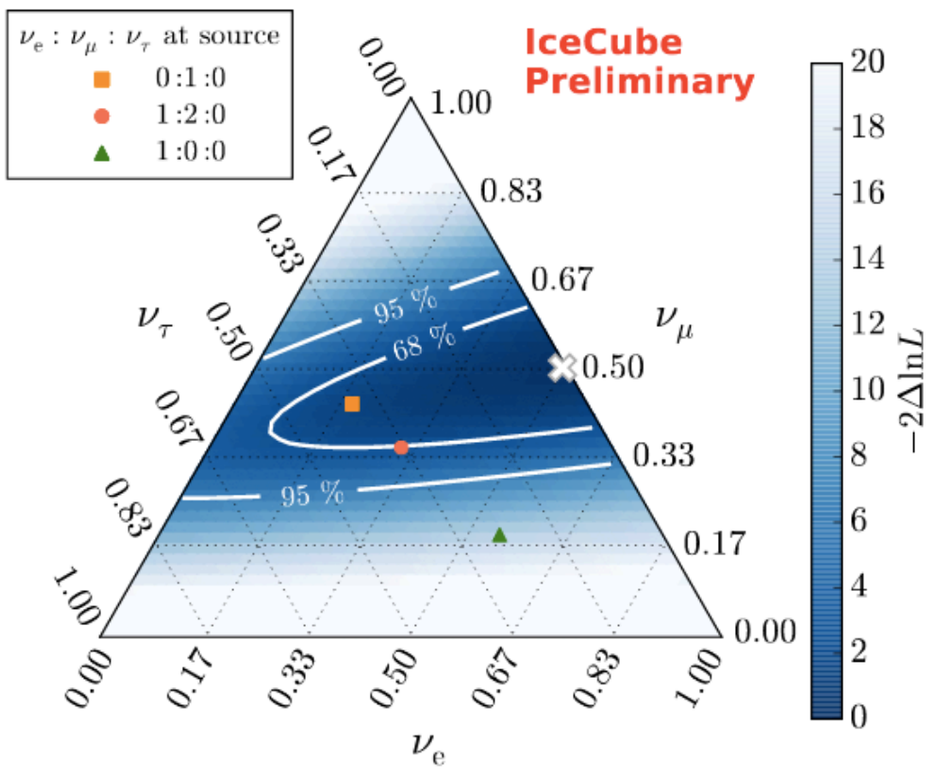


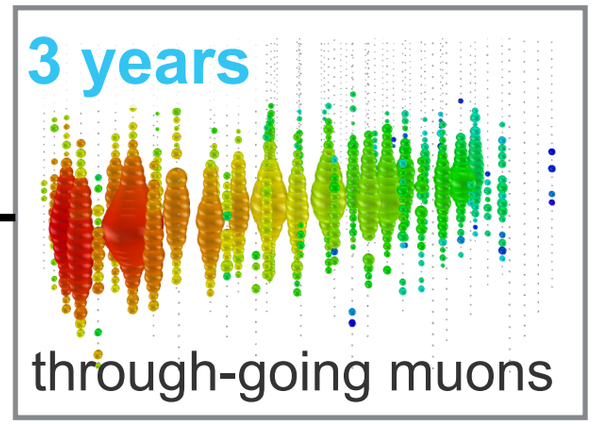
IceCube high-energy events > 30 TeV (2010 - 2016)

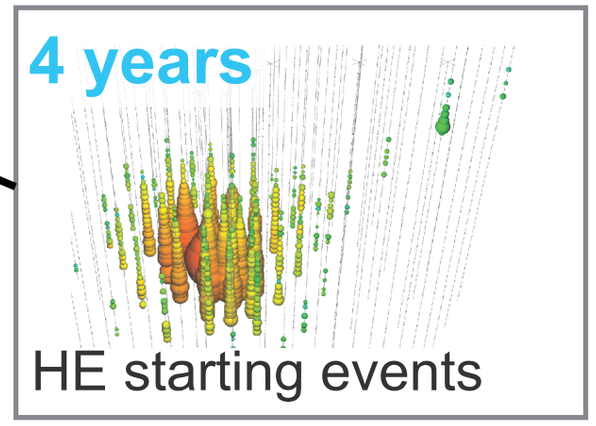
Astrophysical neutrinos in 2015

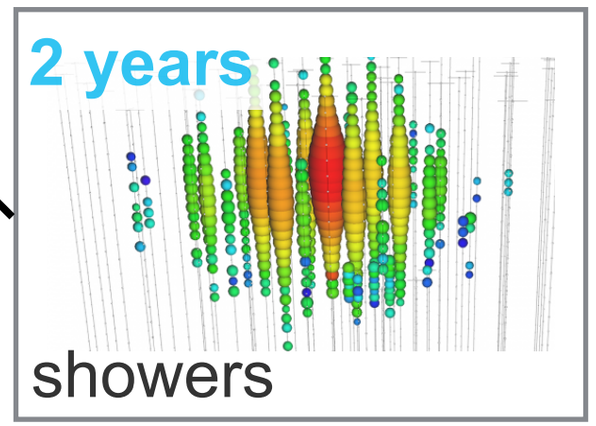
IceCube collaboration, ApJ, 2015 and ICRC 2015





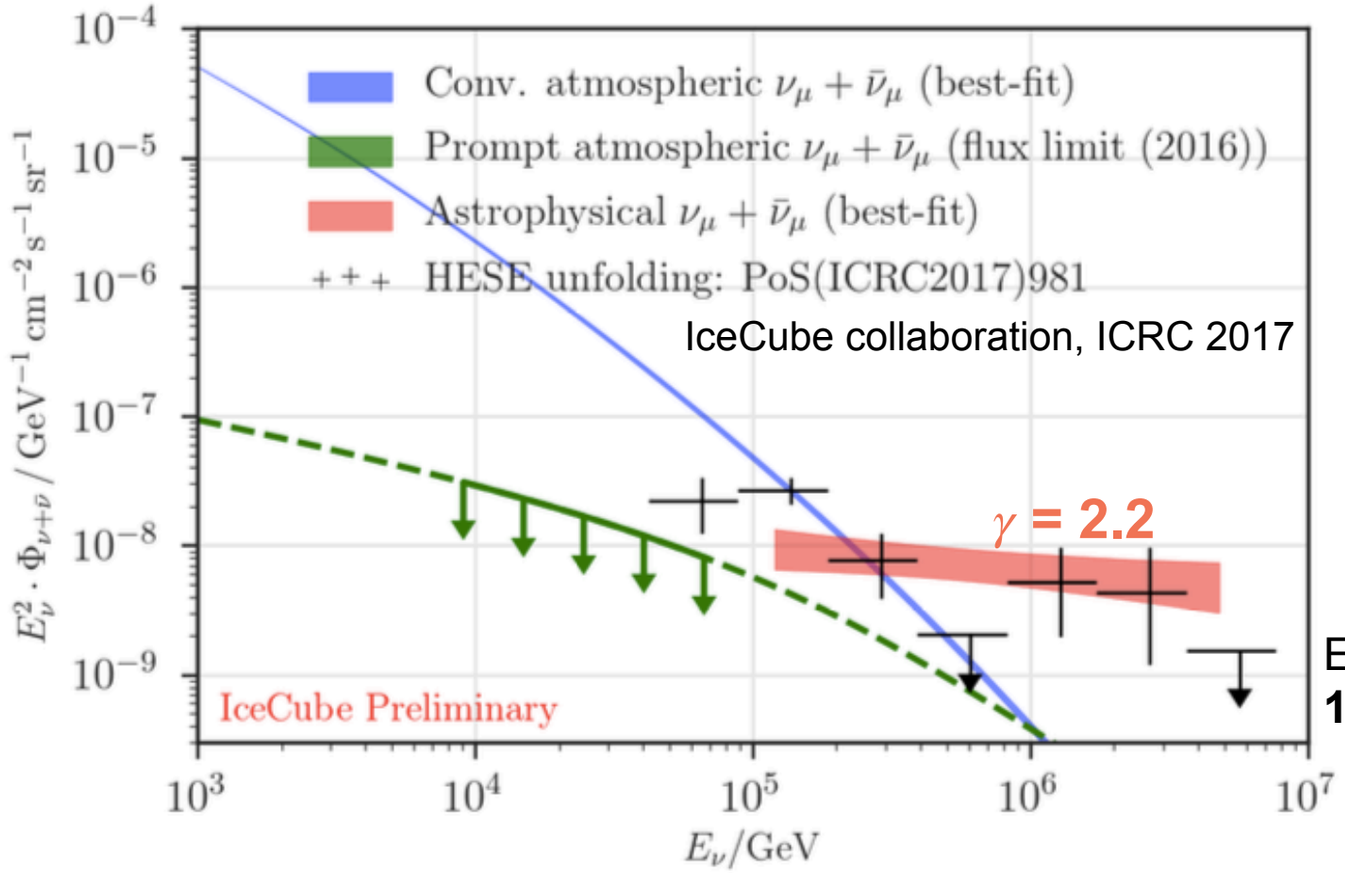




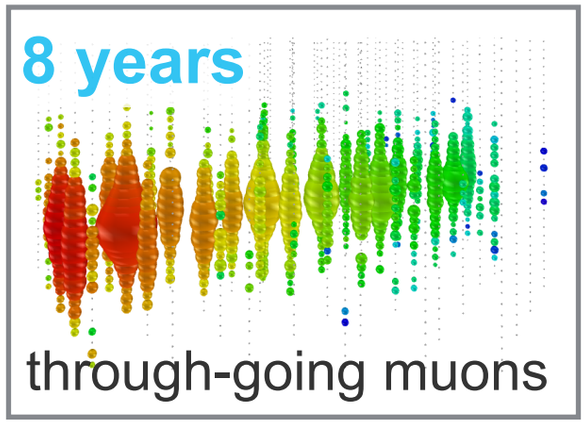


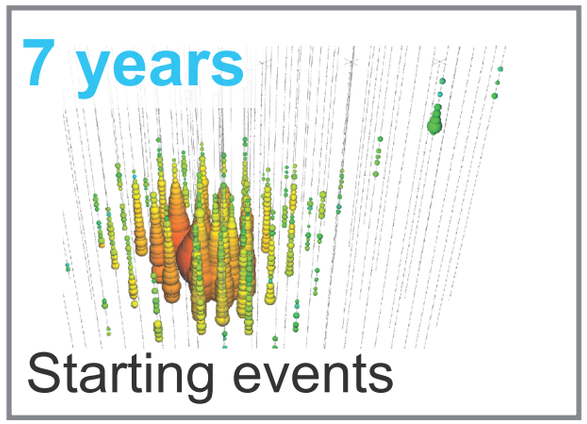
- **Global analysis** of multiple event samples from IceCube.

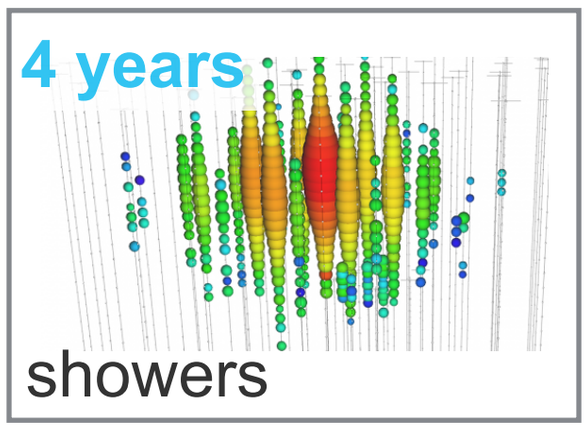
Updated measurements



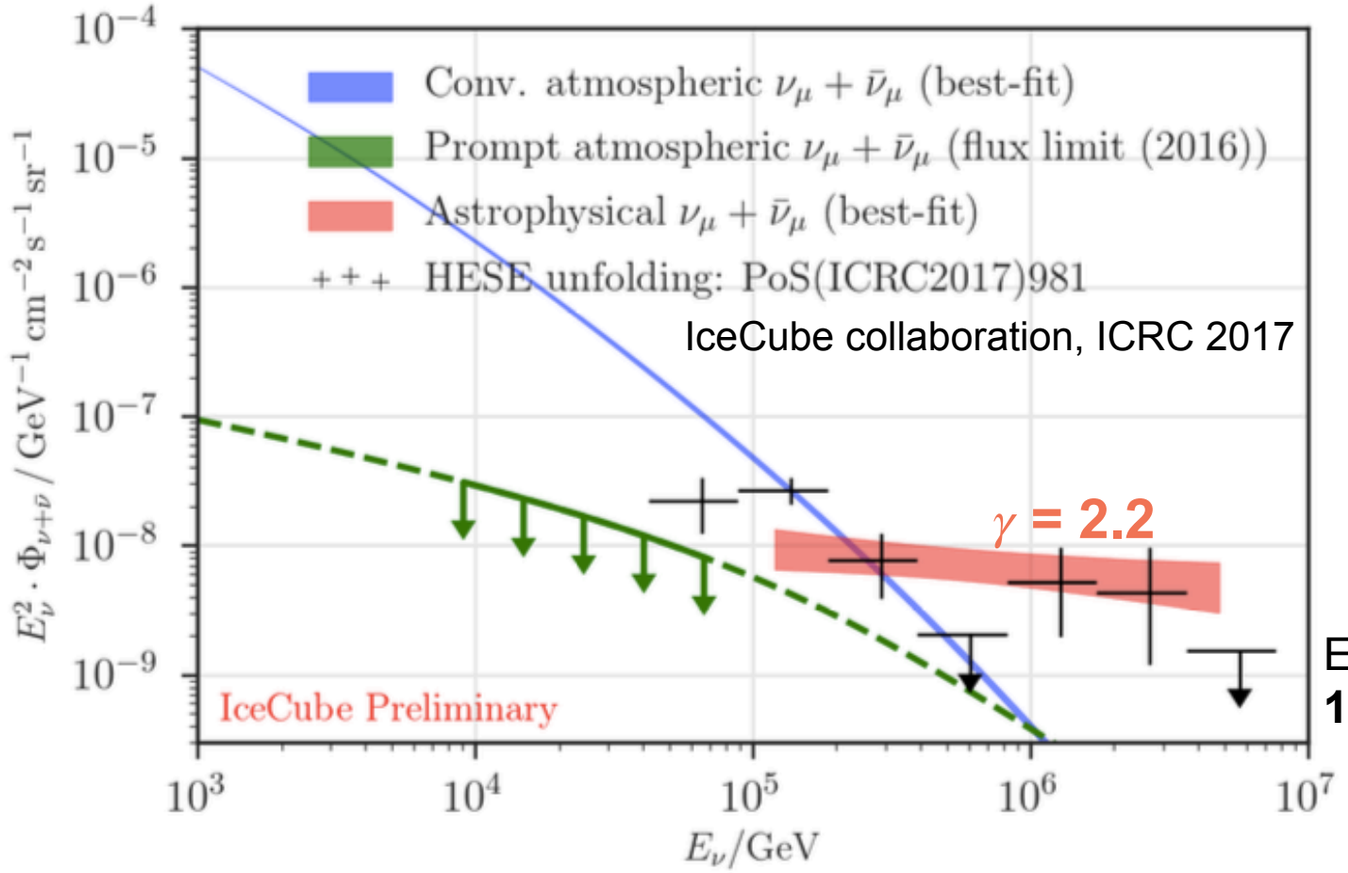
Energy range:
120 TeV - 5 PeV

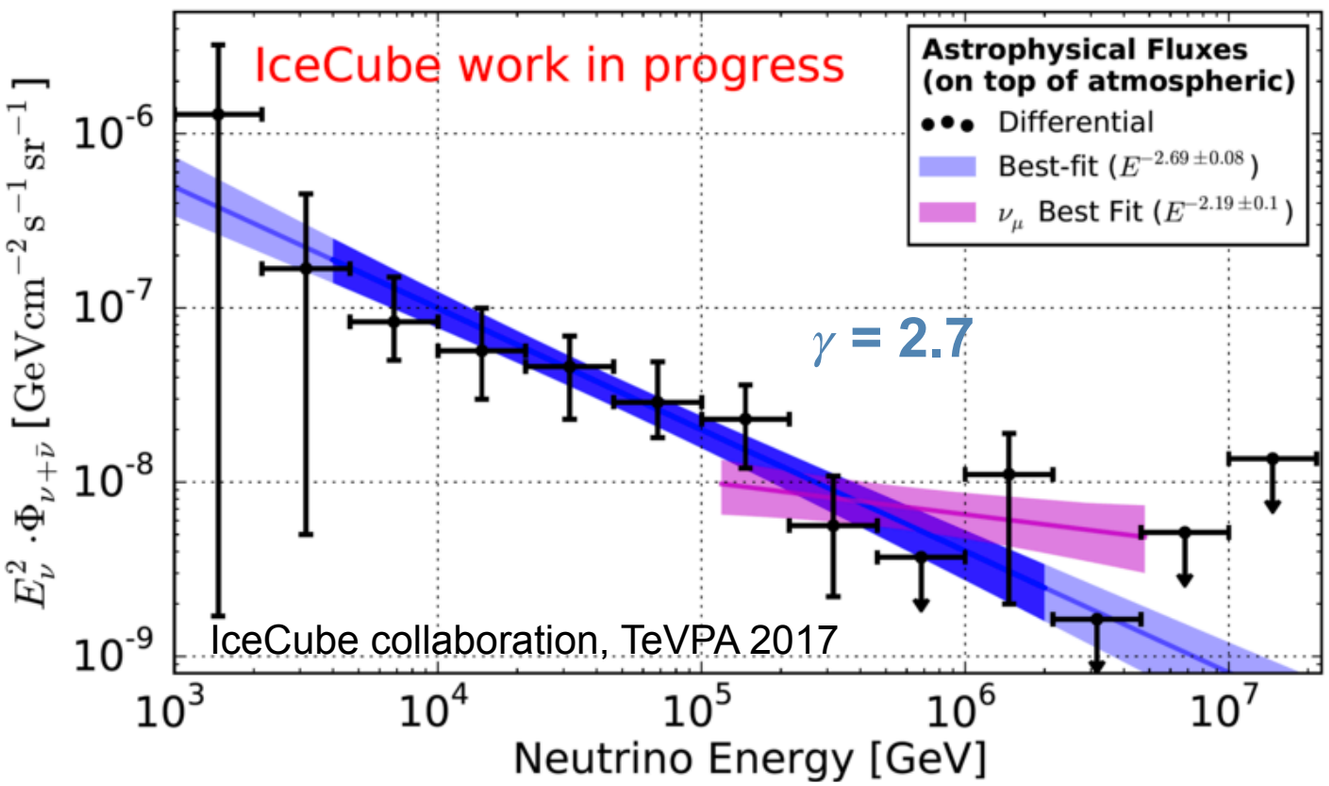






Updated measurements





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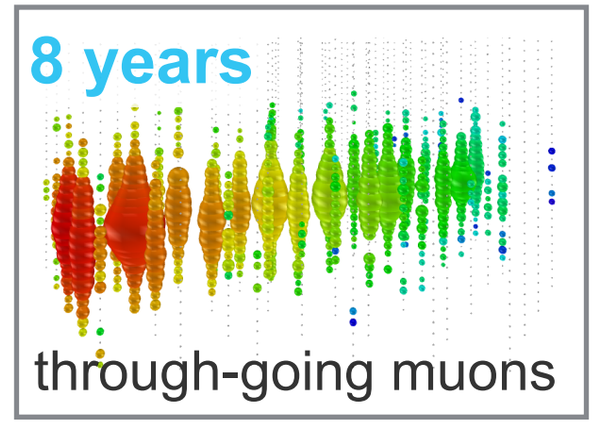
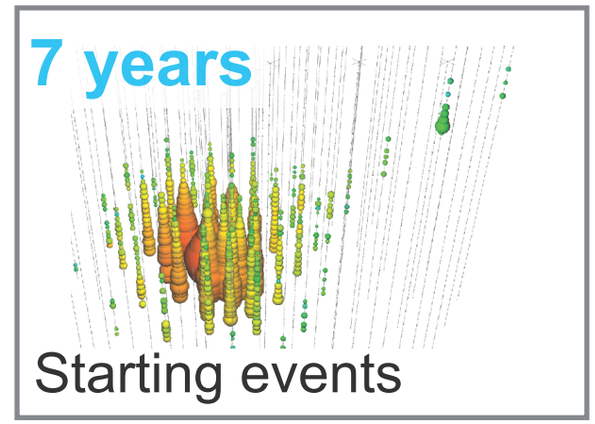
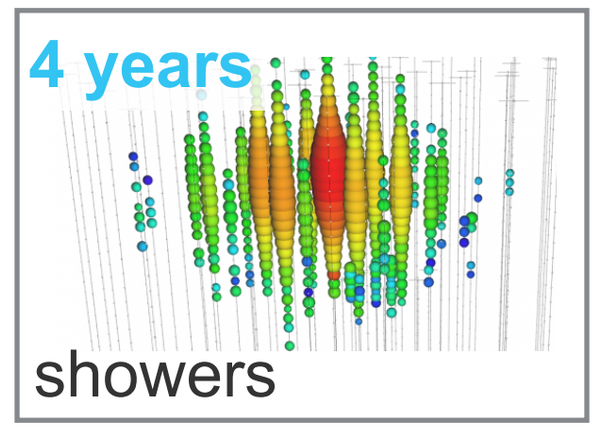


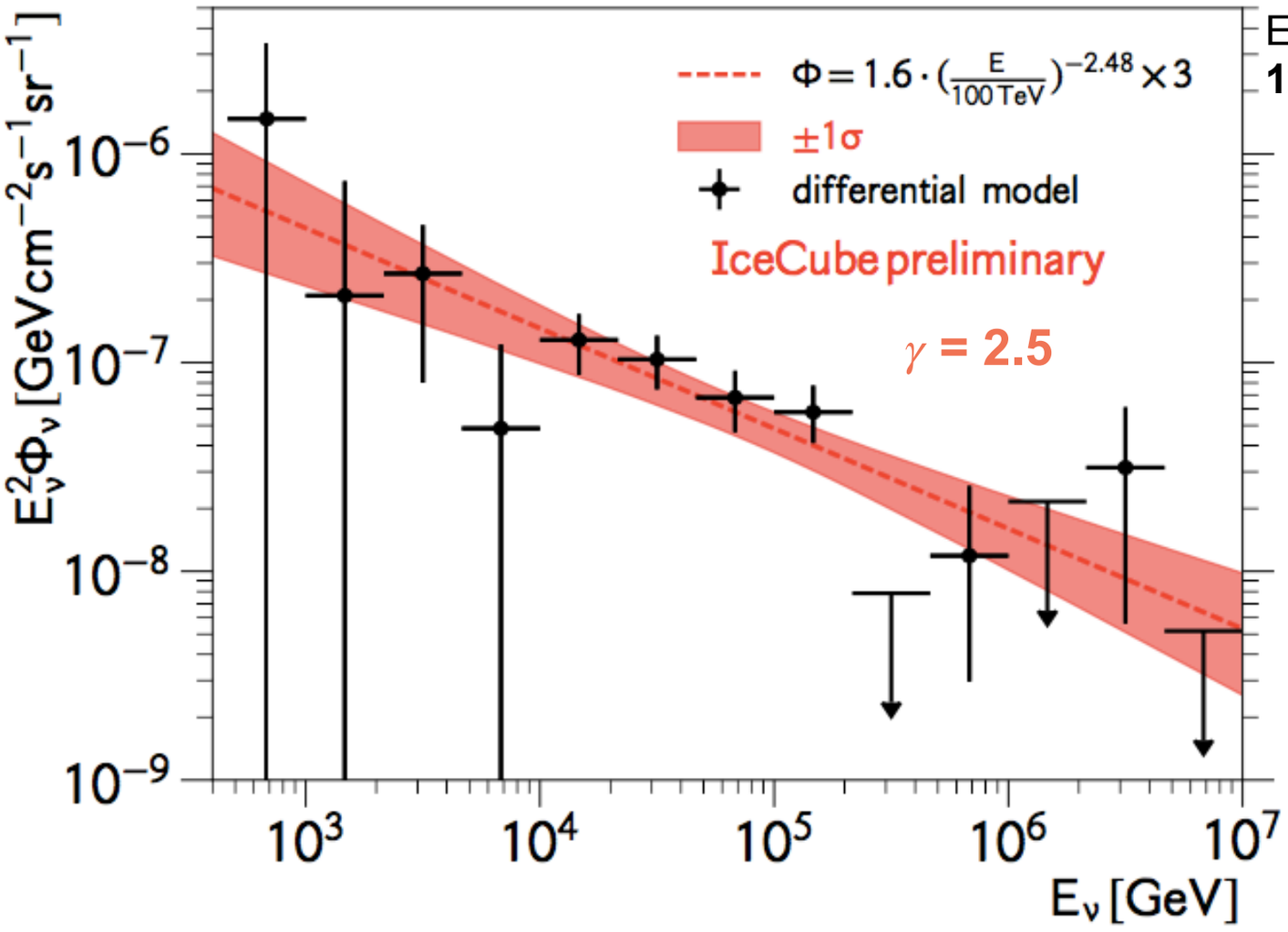




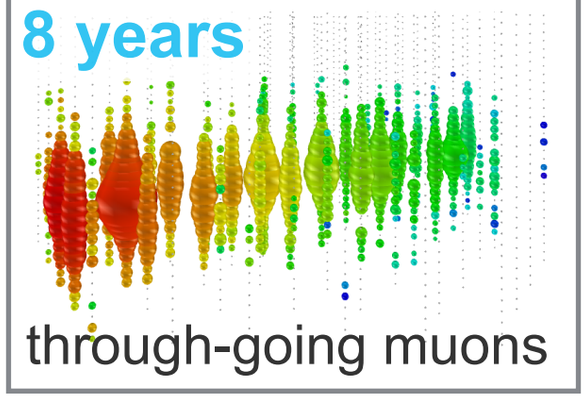
Energy range:
<10 TeV - 2 PeV

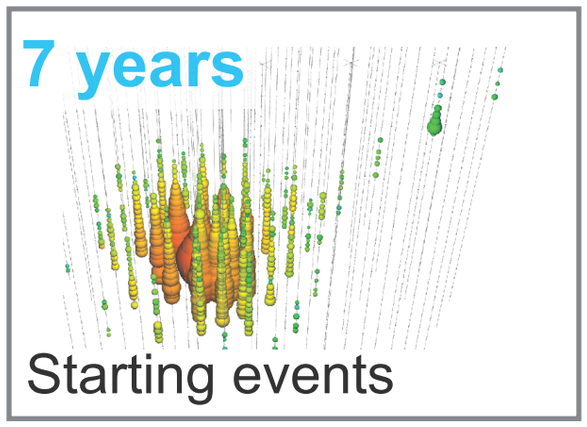
Updated measurements

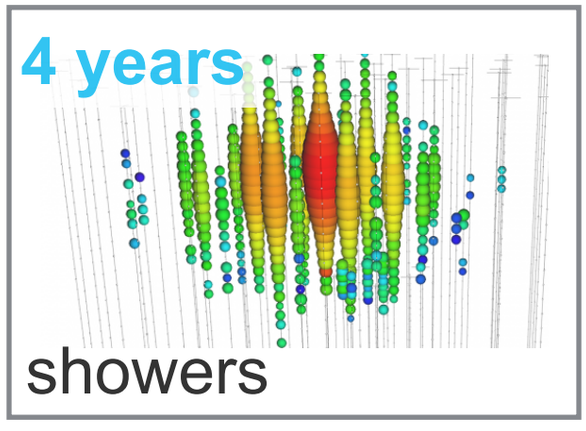
IceCube collaboration, ICRC 2017



Energy range:
12 TeV - 2.1 PeV



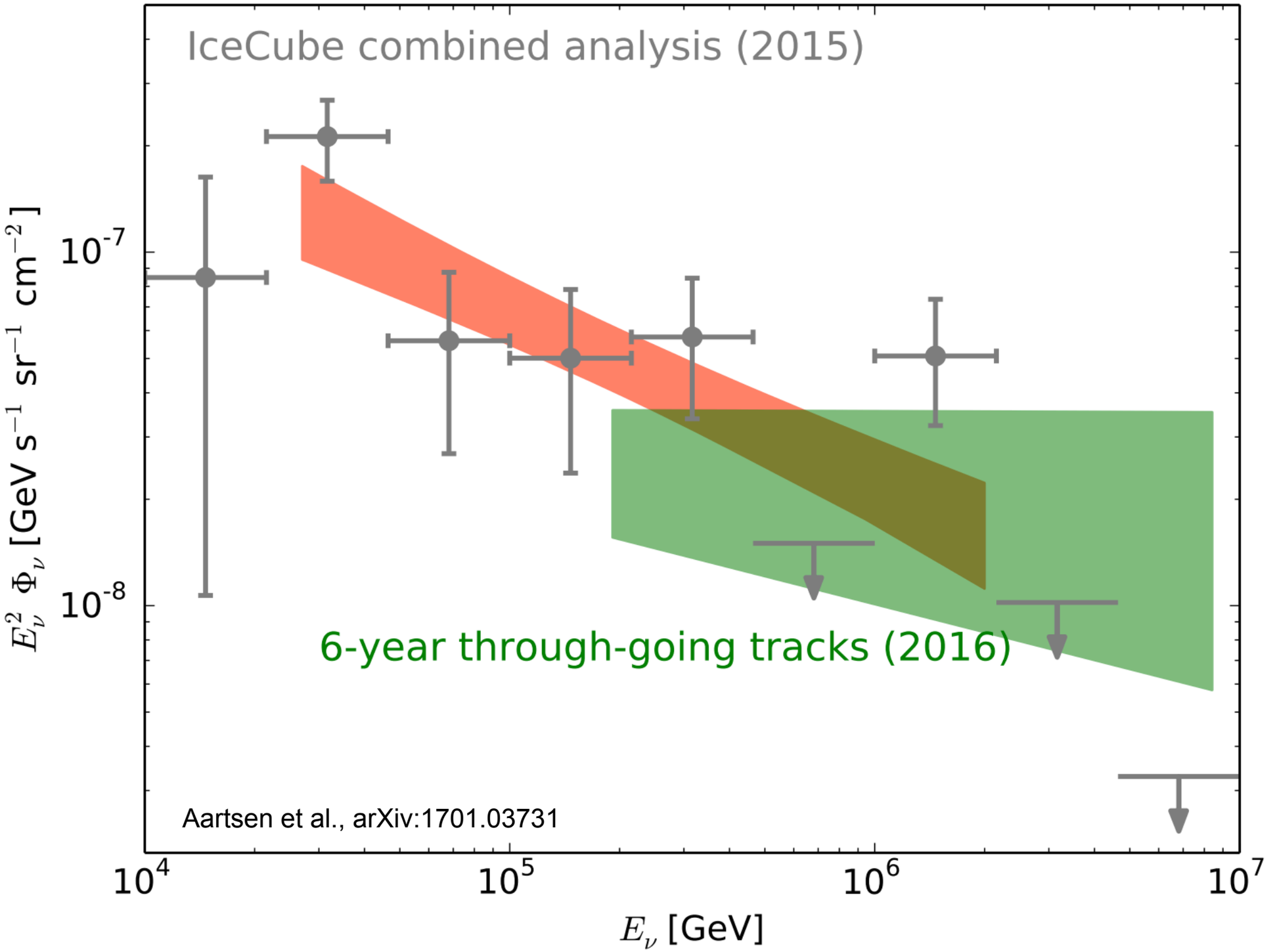




- **Spectral index** for through-going tracks **harder** than for showers / starting events
  - Sensitive to different energy ranges
- Potential **spectral hardening** above 100 TeV.

The cosmic neutrino spectrum

… could be more complex than a simple power law.



The cosmic neutrino spectrum

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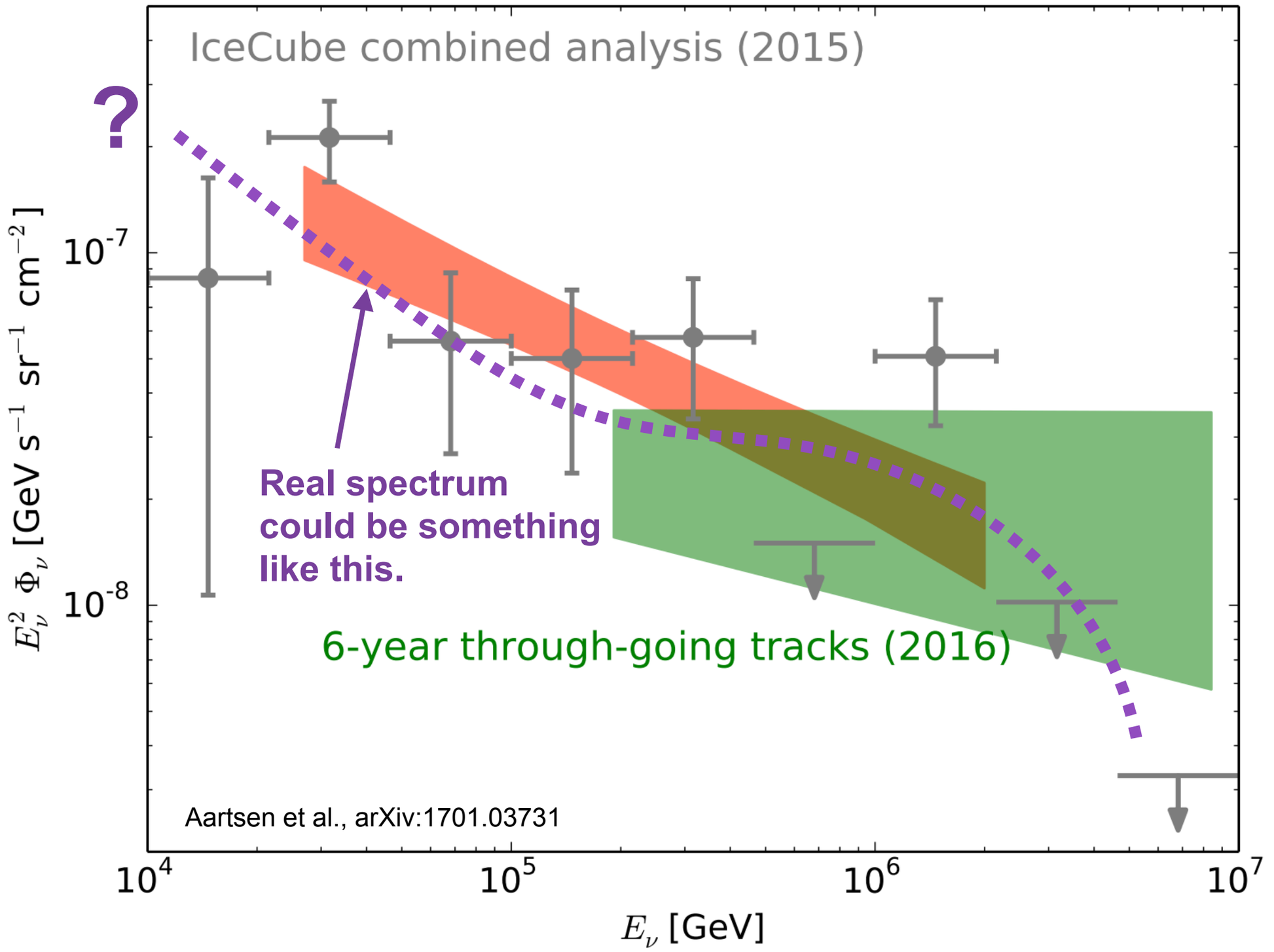
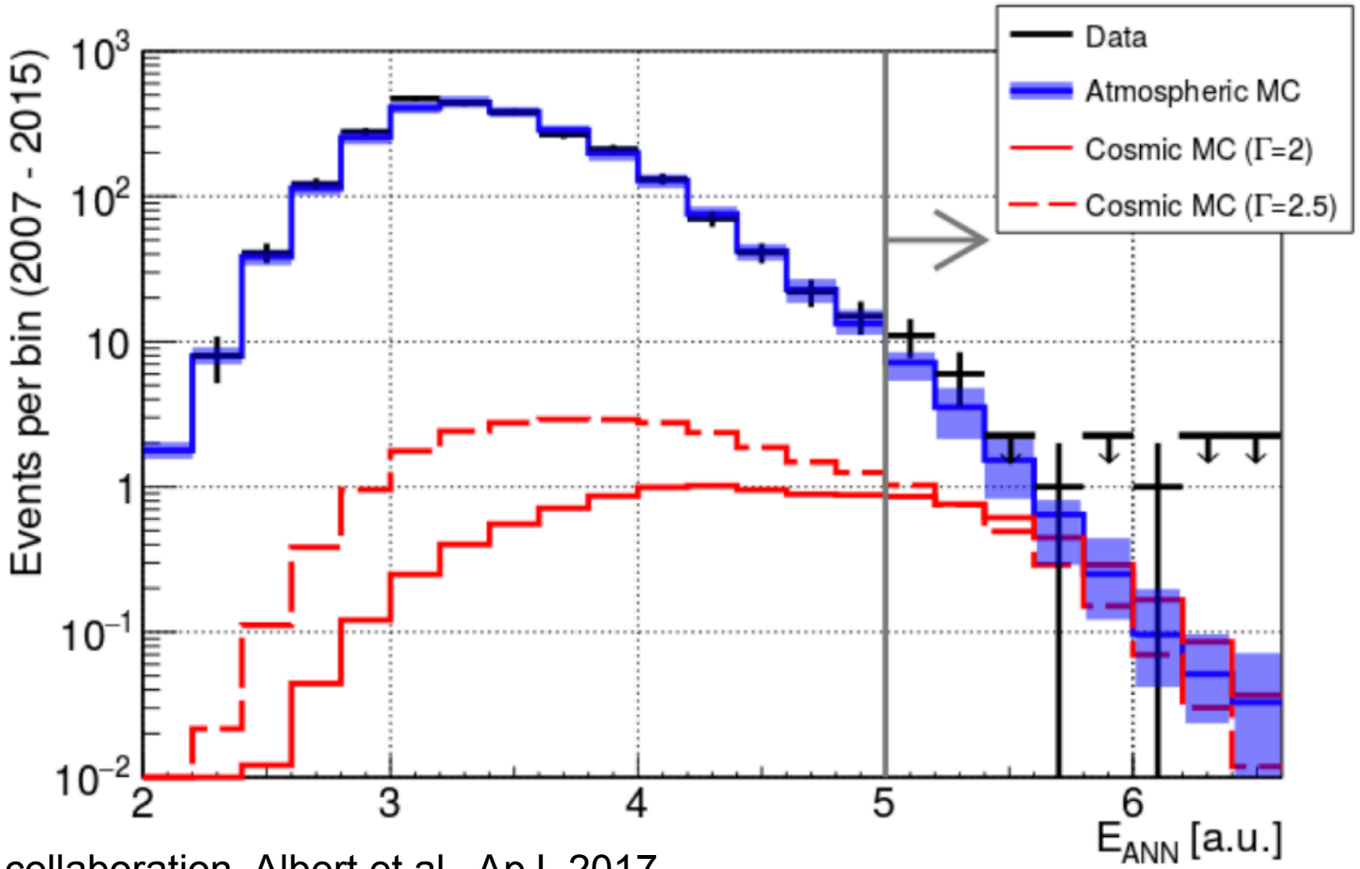


Diffuse neutrinos

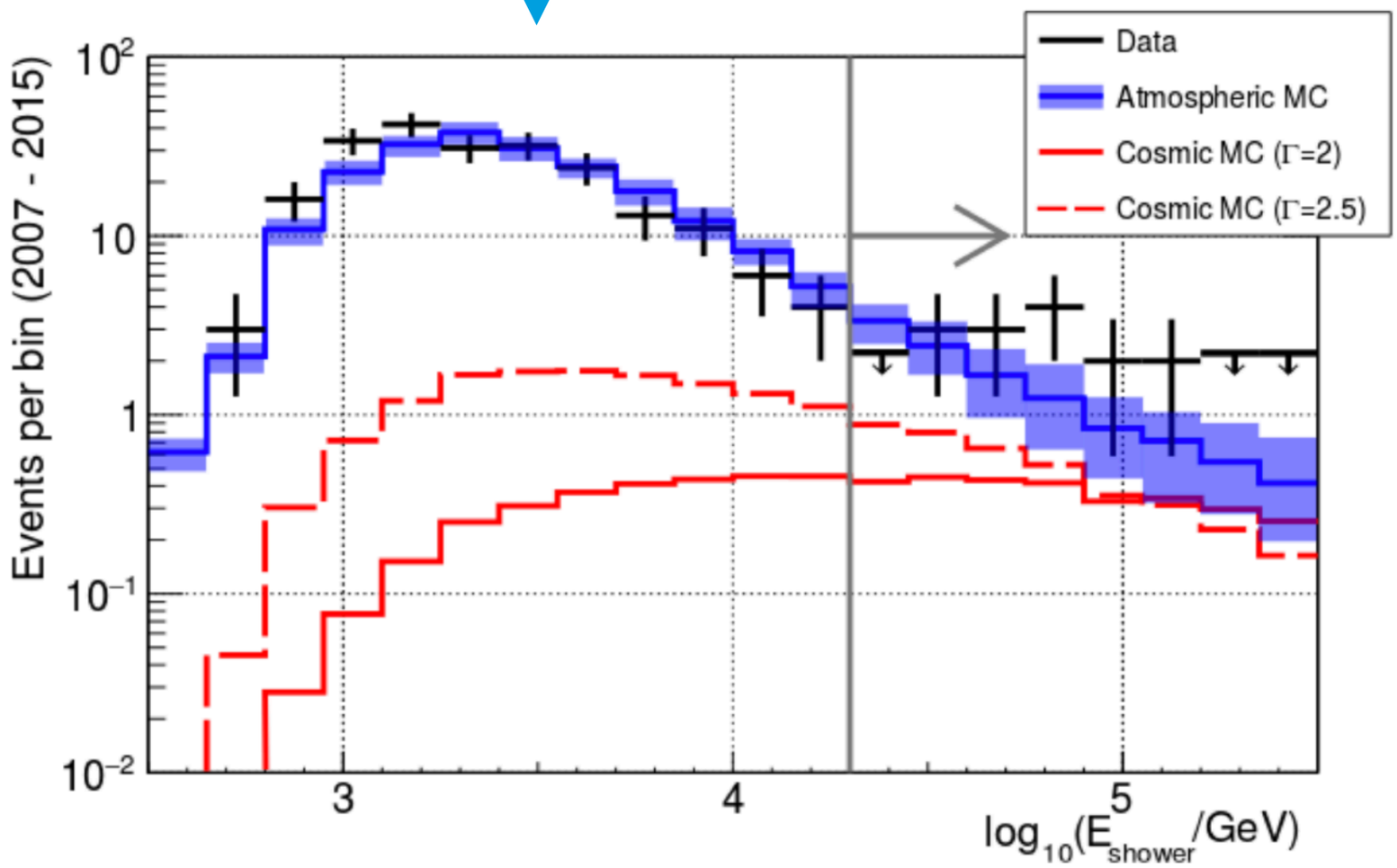
Observed by ANTARES

track-like events



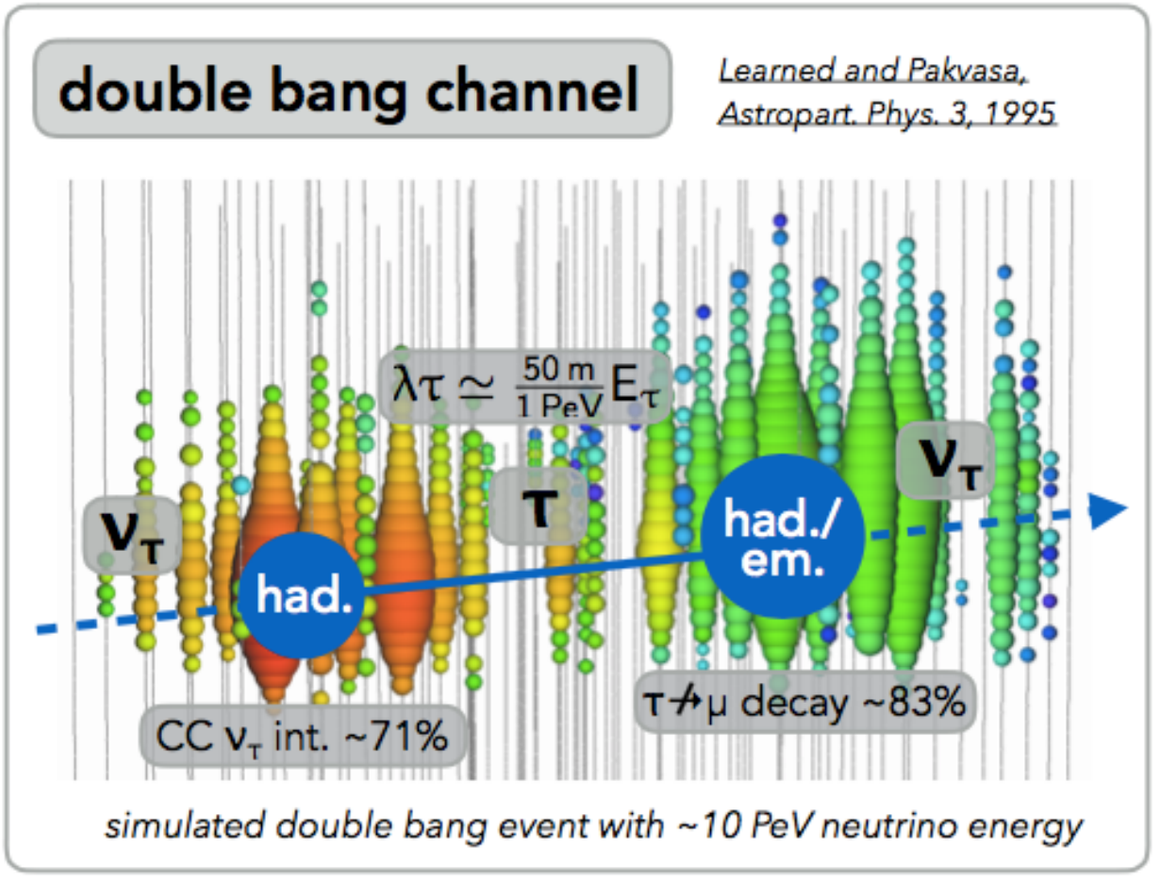
ANTARES collaboration, Albert et al., ApJ, 2017

shower-like events

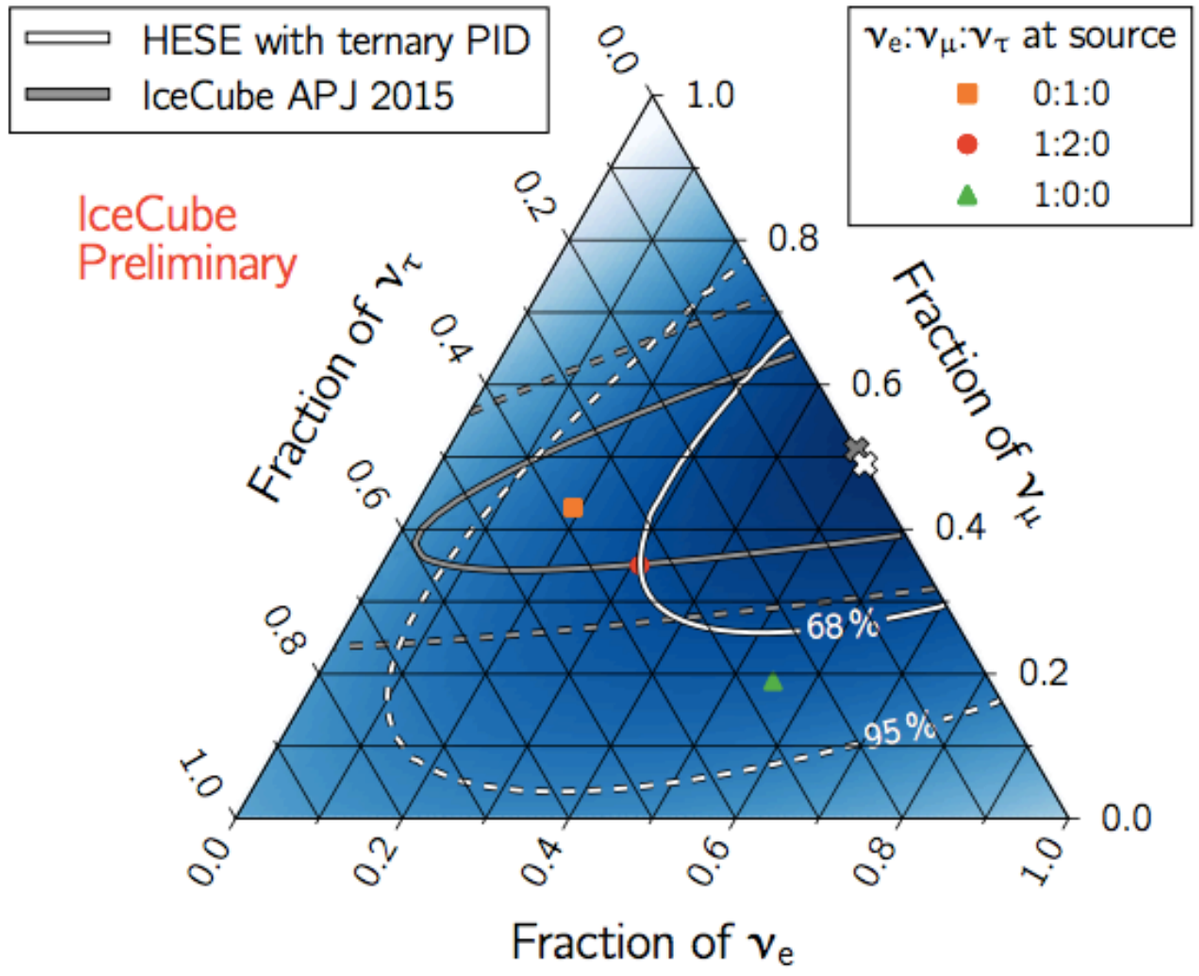


- **1.6σ excess** over background
- **Spectrum consistent** with IceCube measurements

Identification of tau neutrinos



IceCube collaboration, ICRC 2017



ν_e:ν_μ:ν_τ = 1:1:1

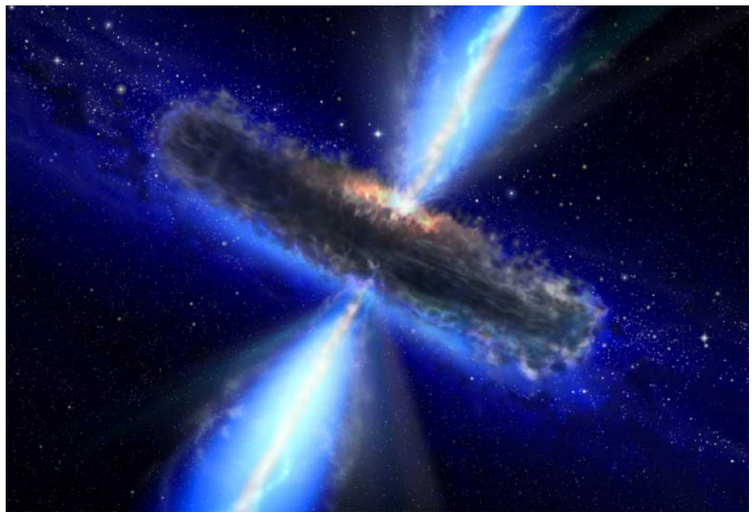
Φ(E) diff. unfolding

$N_{sig} = 1.441^{+0.024}_{-0.018}$

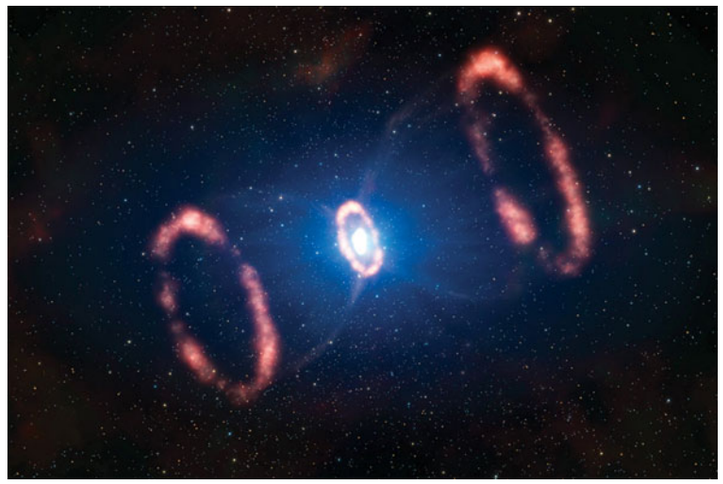
$N_{bg} = 0.938^{+0.219}_{-0.092}$

- Search for **characteristic ν_τ signature**.
- Sensitive to ν_τ **with E > 100 TeV**.
- **No ν_τ candidate** found in high-energy starting event sample. Consistent with fluctuation.

What is the origin of the astrophysical neutrinos?

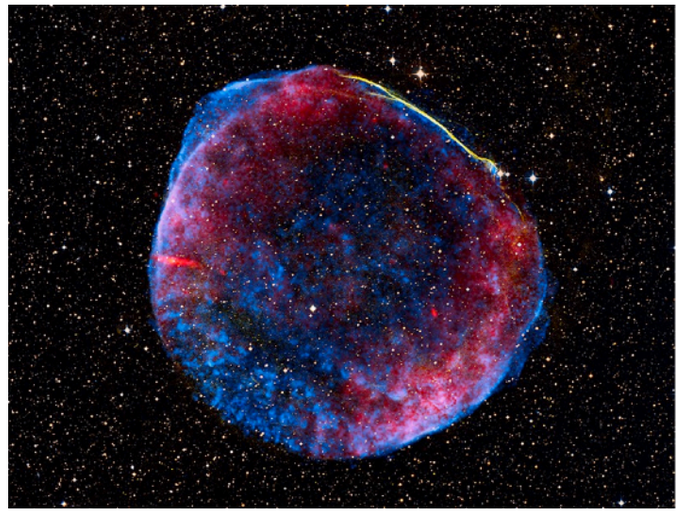


Active Galaxies ?



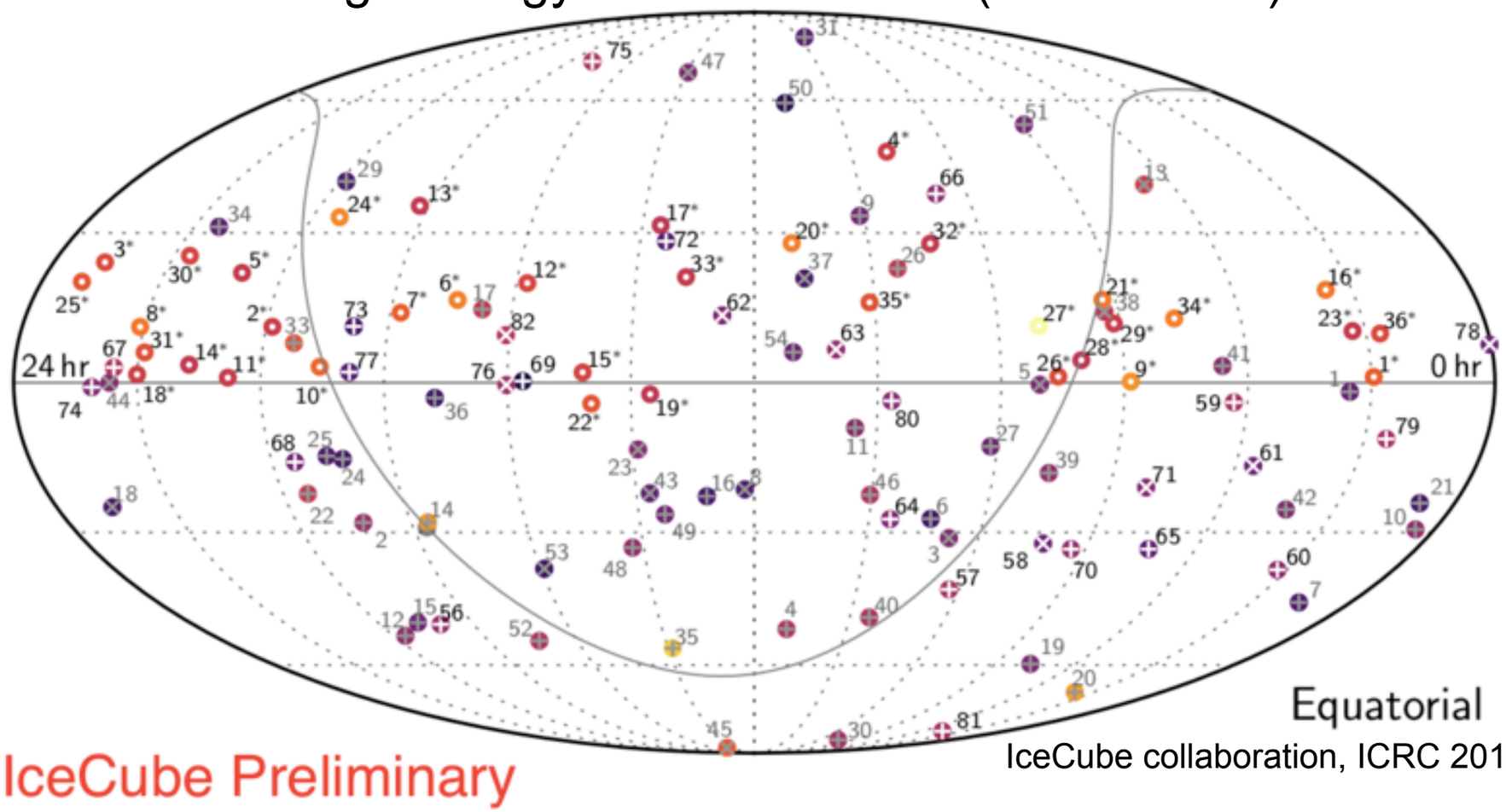
SNe ?

GRBs ?



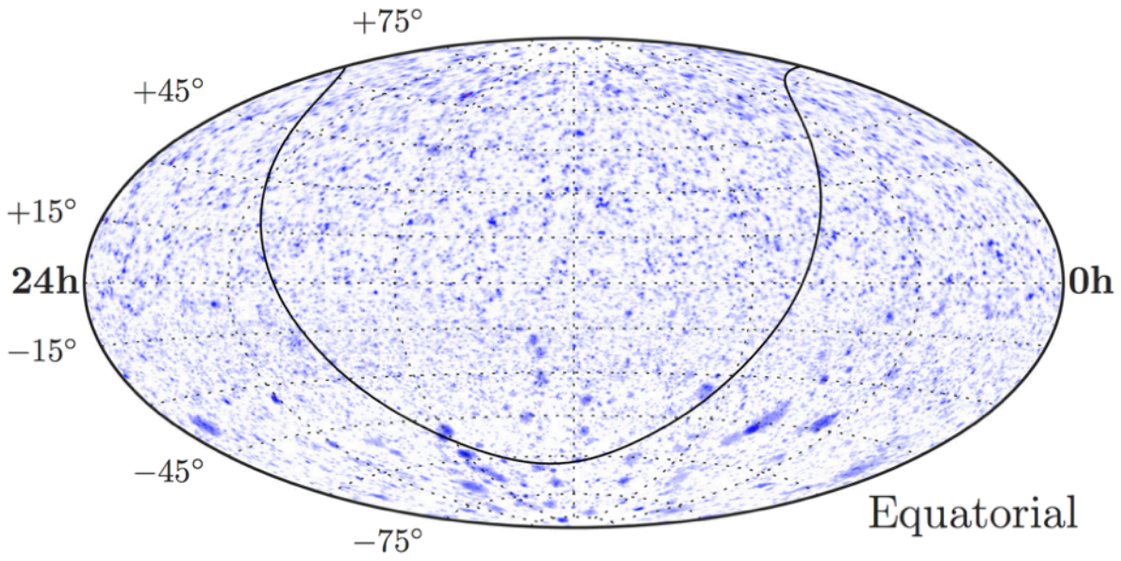
Supernova remnants ?

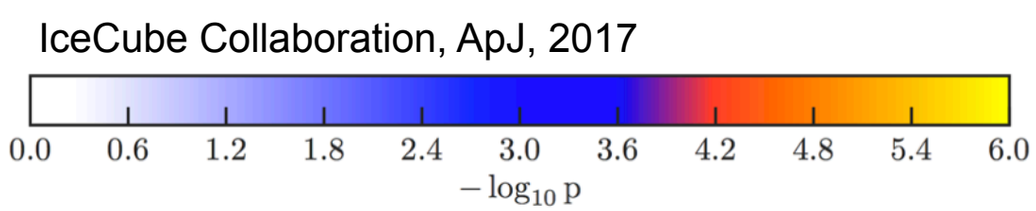
IceCube's high-energy neutrinos



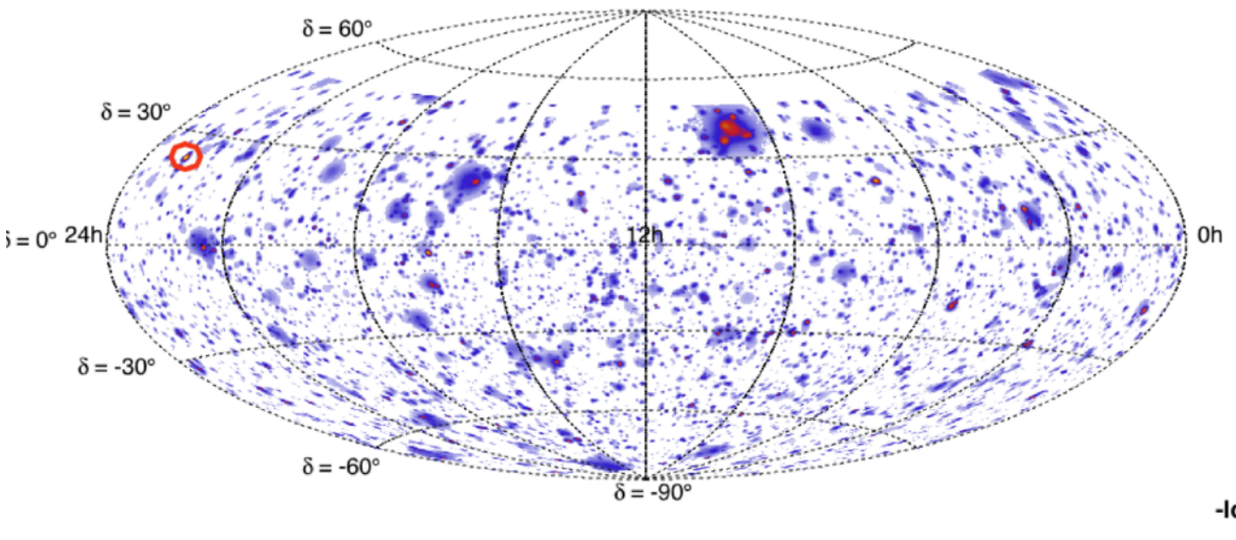
- **Compatible** with an **isotropic** distribution
  - points to extragalactic origin of cosmic neutrinos
- **No significant clustering** of high-energy events

Searches for individual sources of neutrinos



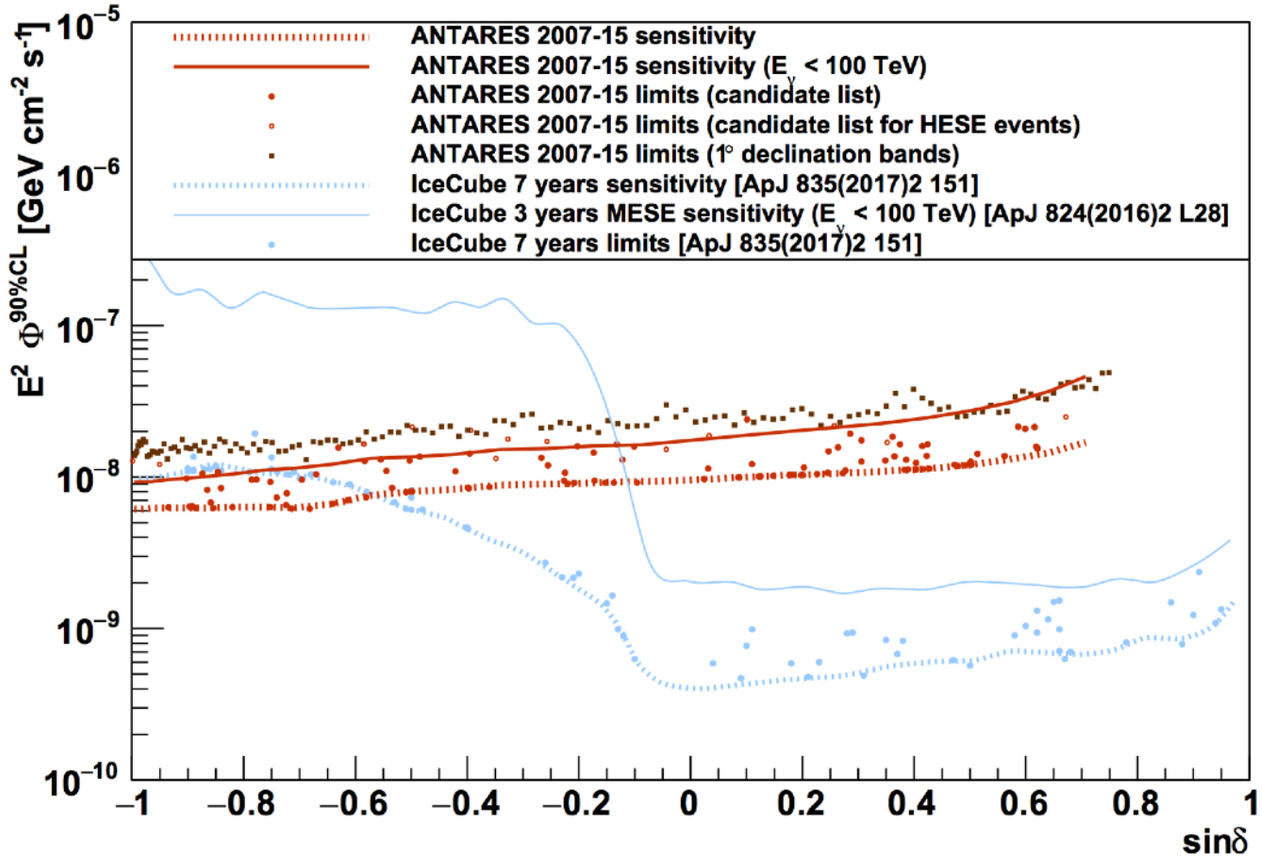


IceCube Collaboration, ApJ, 2017



ANTARES collaboration, PRD, 2017

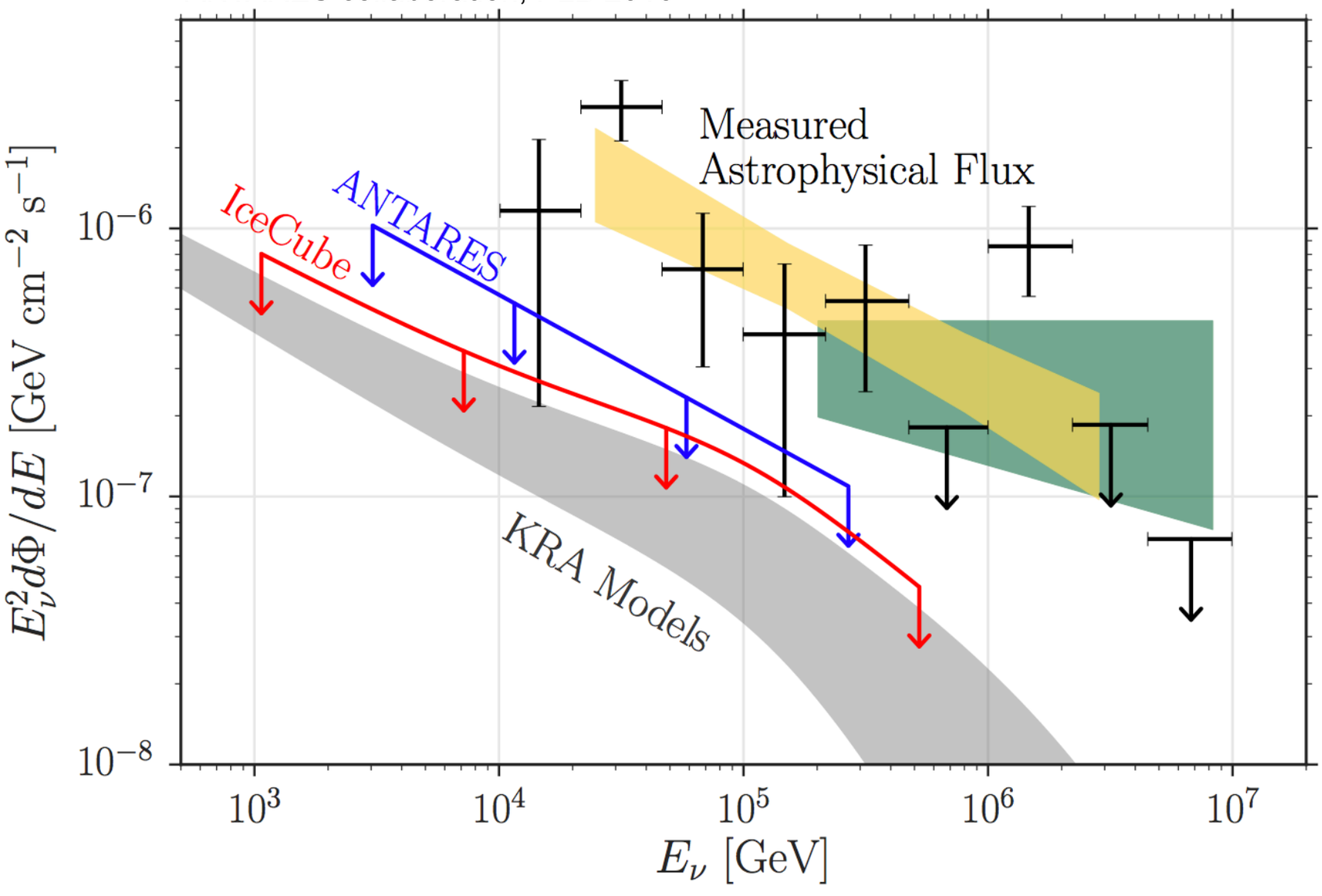
- Search for neutrino sources on **large event samples** dominated by atmospheric background
  - **Search for a local excess** of events.
- **No point source** found.
- **No extended source** found.



Neutrinos from the Galaxy

- Neutrinos from the **interactions of cosmic rays** with interstellar gas.
- Expected spatial distribution **well understood** from gamma-ray data.
- Intensity above 10 TeV uncertain.

IceCube collaboration, ApJ 2017
ANTARES collaboration, PLB 2016

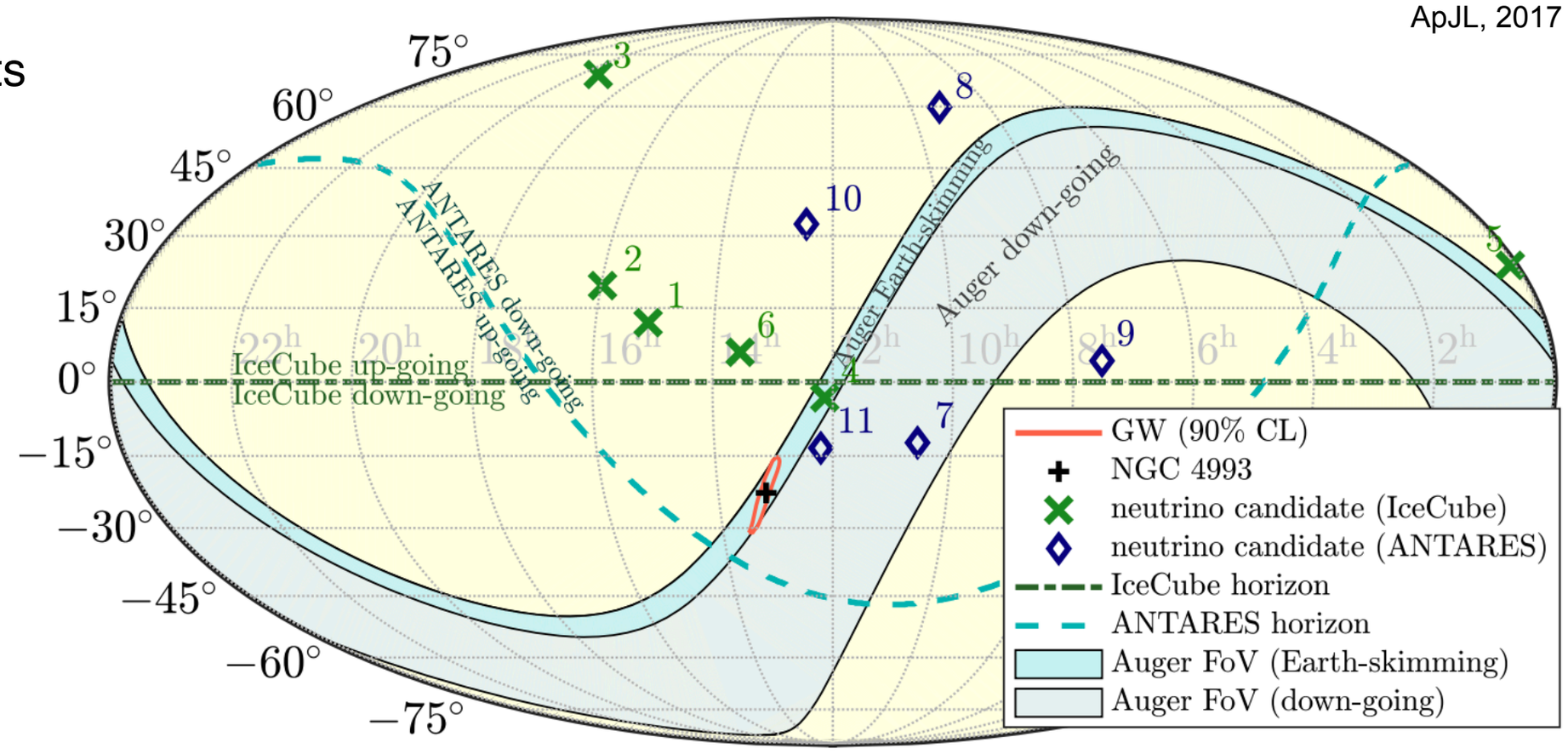


- **No correlation** found.
- Only **small fraction** of signal can **originate from CR interactions** in the Galaxy.

Searching for transient sources

- **Search for correlations** of neutrinos
  - with observed light curves in various electromagnetic (EM) wave bands.
  - with interesting EM or gravitational-wave transients
- IceCube and ANTARES **high-energy neutrinos trigger** EM follow-up observations.
- **No significant correlation found** with:
  - Gamma-ray bursts
  - Fast radio bursts
  - Gravitational wave events
  - Supernovae

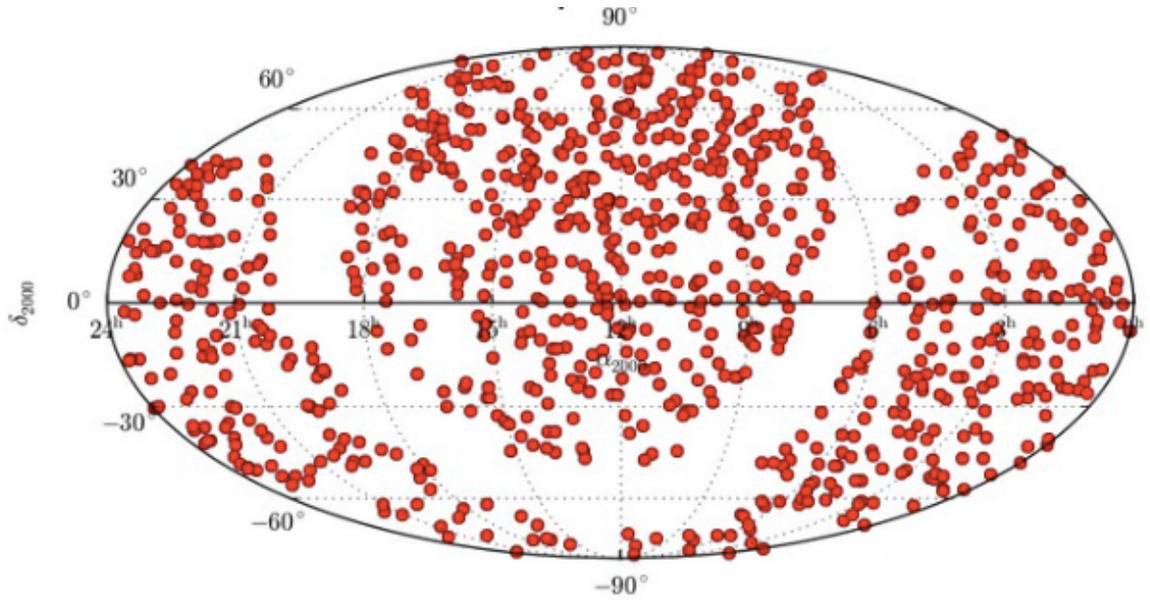
ANTARES+IceCube+PAO+LIGO+VIRGO
ApJL, 2017



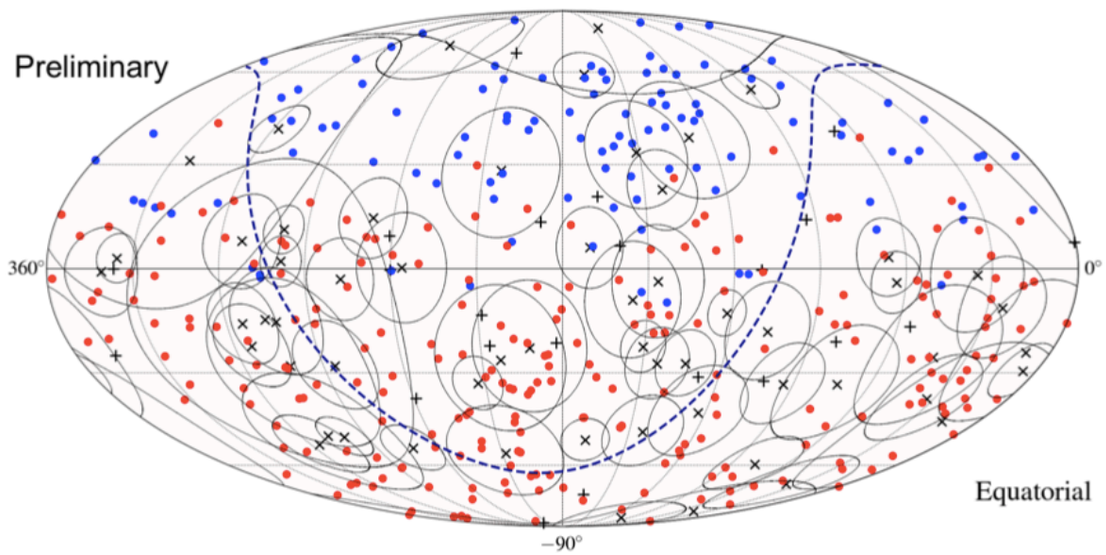
Auto- and cross-correlation searches

Finding sources below the detection threshold

Fermi LAT Blazars - 2LAC catalog



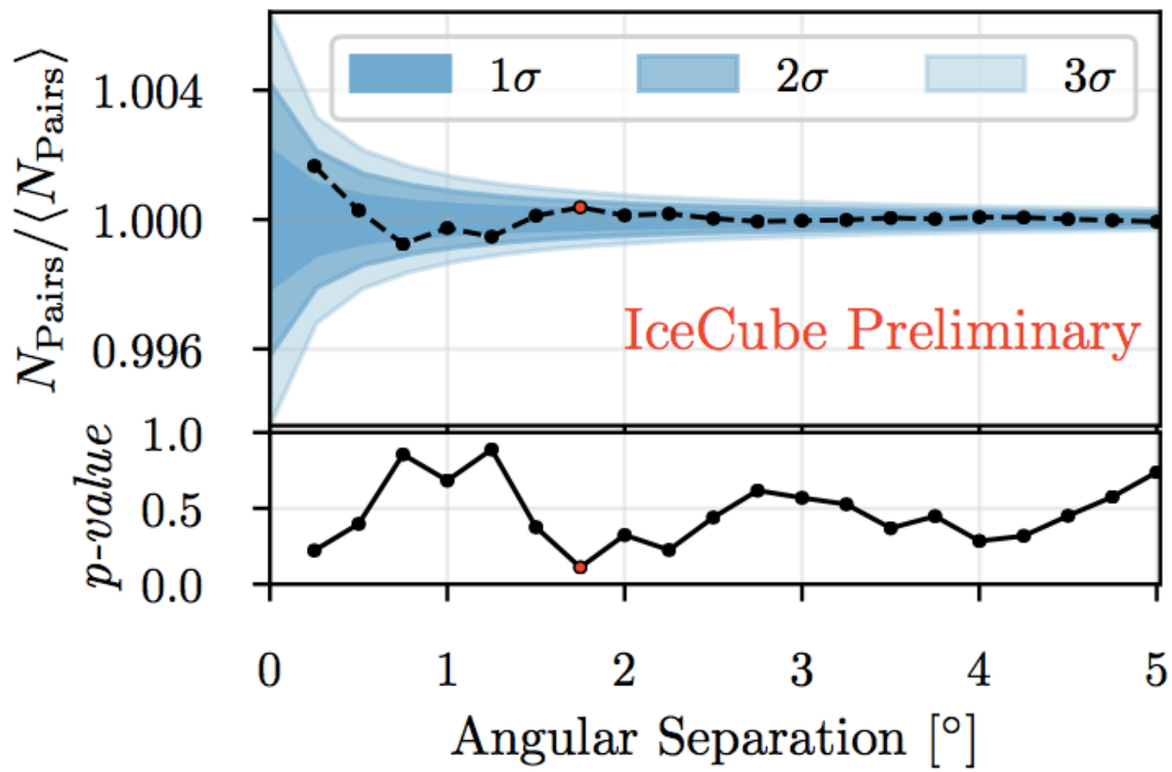
UHECR - TA & Auger



IceCube collaboration, ICRC 2017

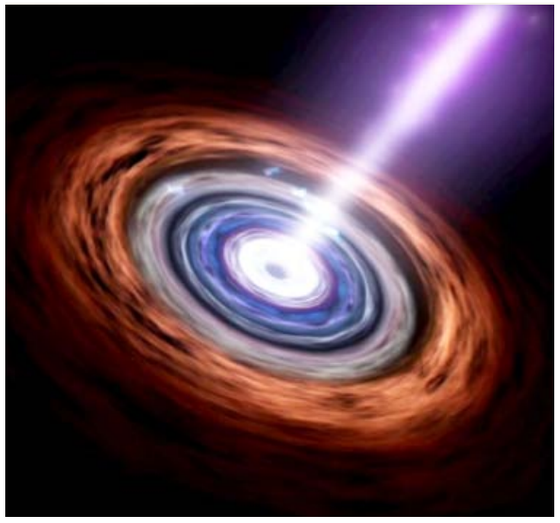
IceCube collaboration, ICRC 2017

2pt-autocorrelation

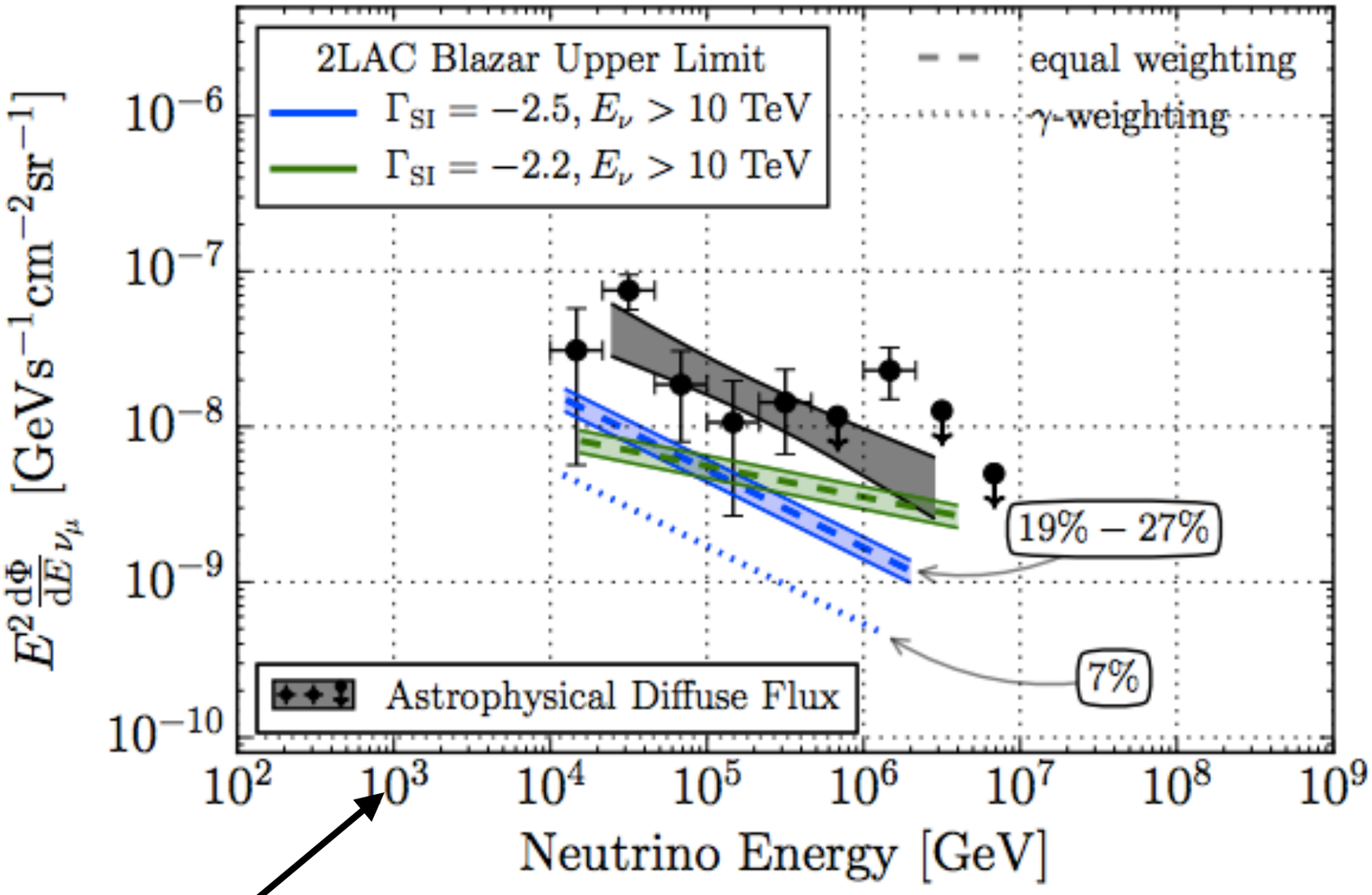


- **None of the performed searches** finds a significant correlation with IceCube neutrinos
- Similar searches are performed with ANTARES

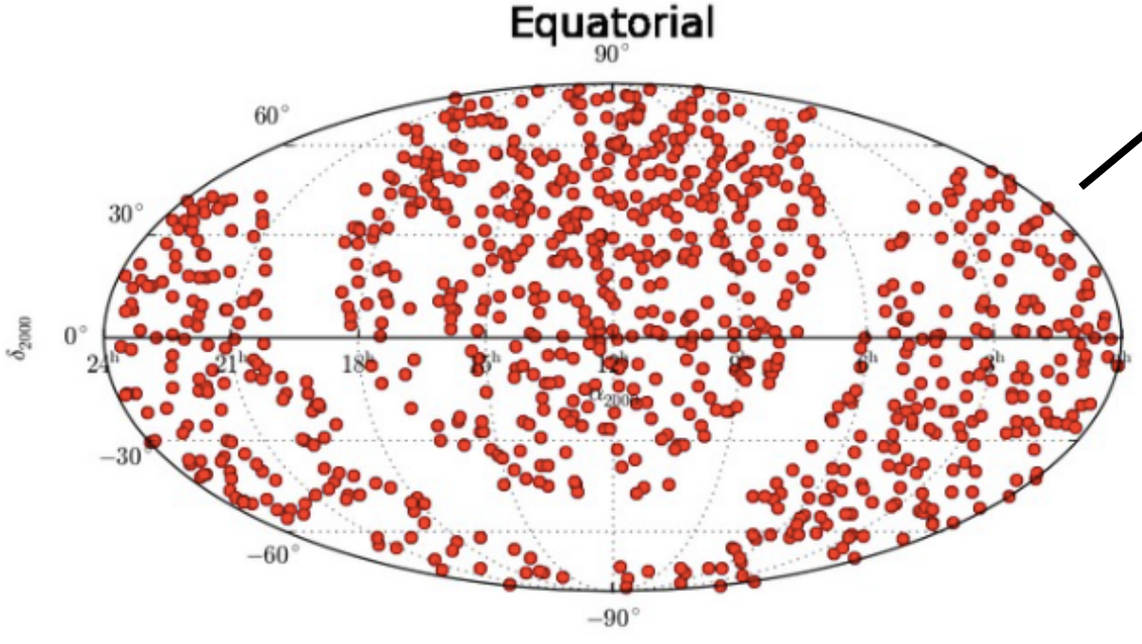
Neutrinos from Blazars



IceCube collaboration, ApJ, 2017



All blazars from *2-LAC* – 862 objec

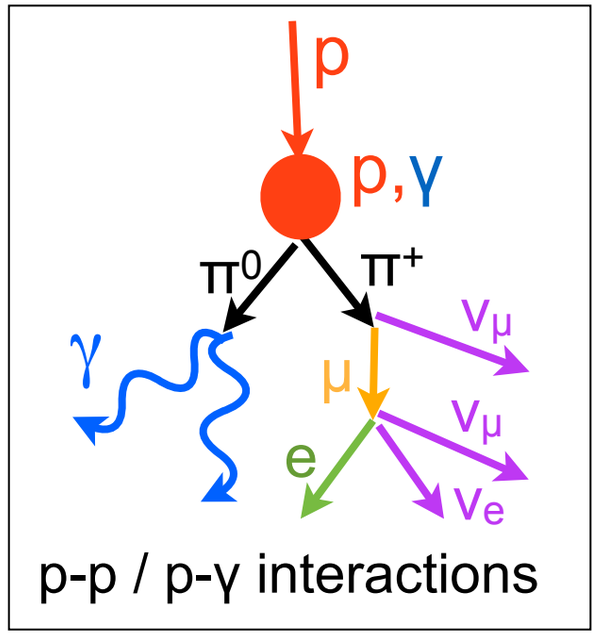


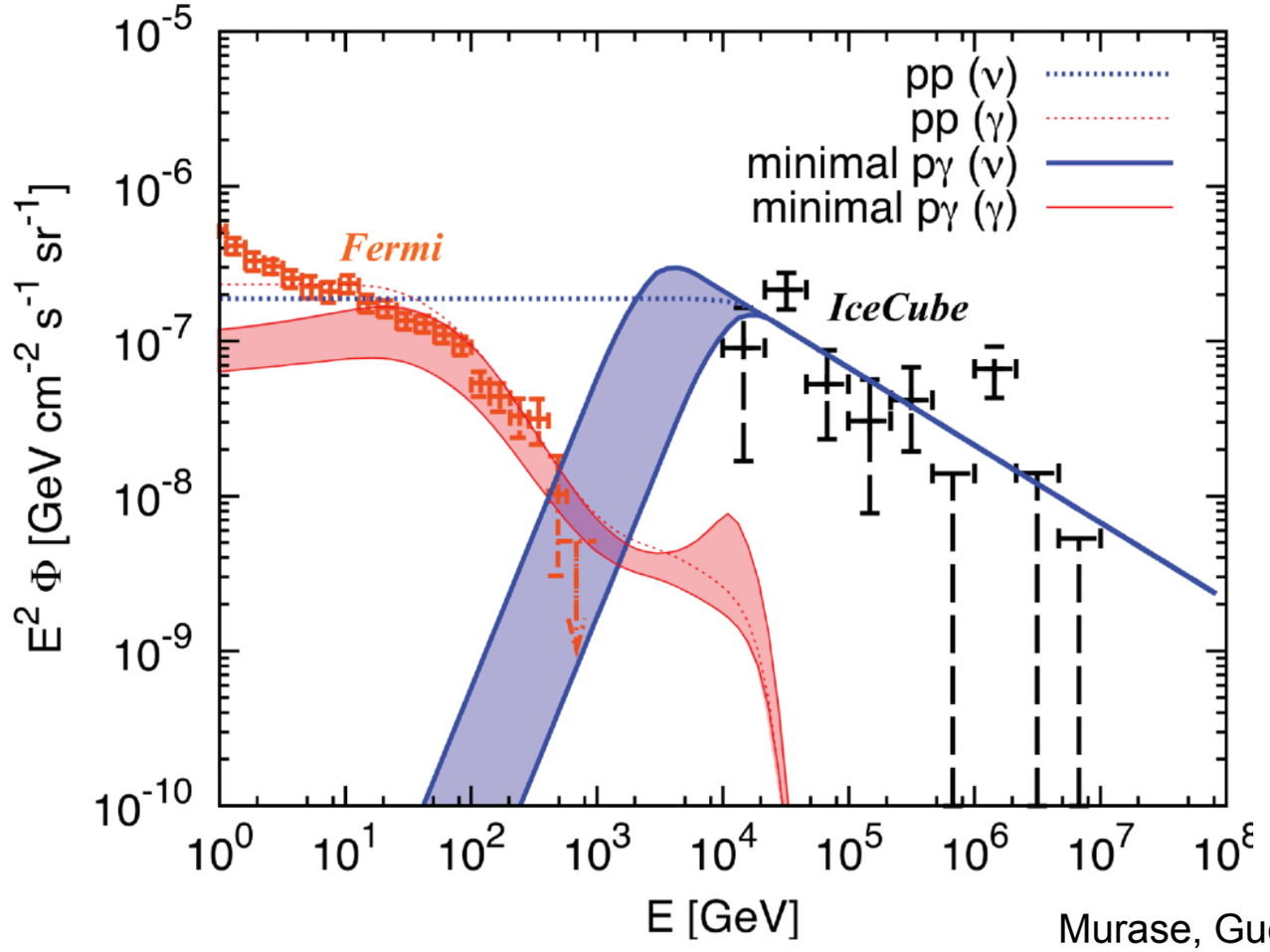
- **Blazars dominate** the **extragalactic gamma-ray** emission above 10 GeV
- **Fermi LAT blazars** can only be responsible for a **small fraction** of the observed ν's.

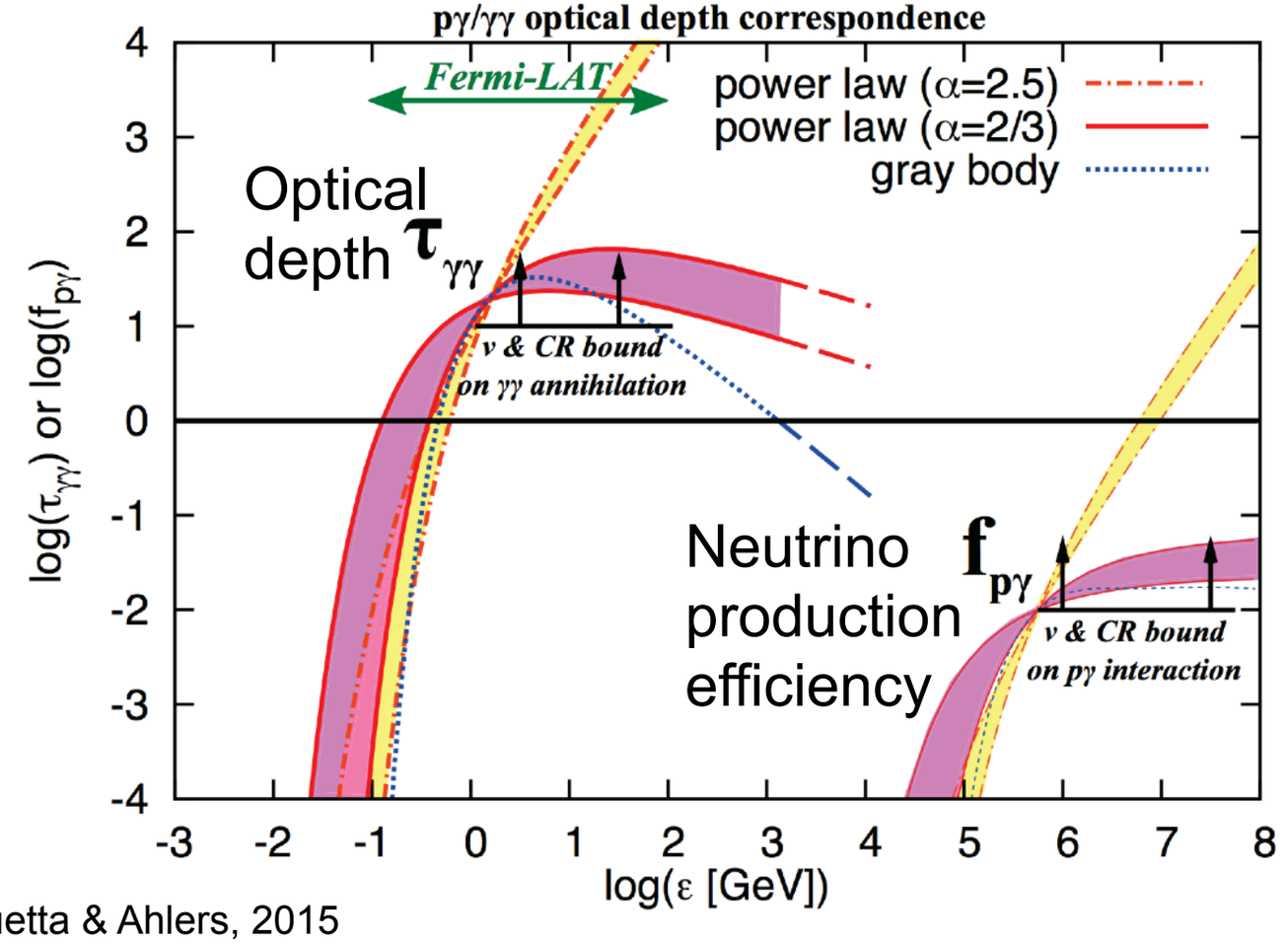
Constraints from gamma rays

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



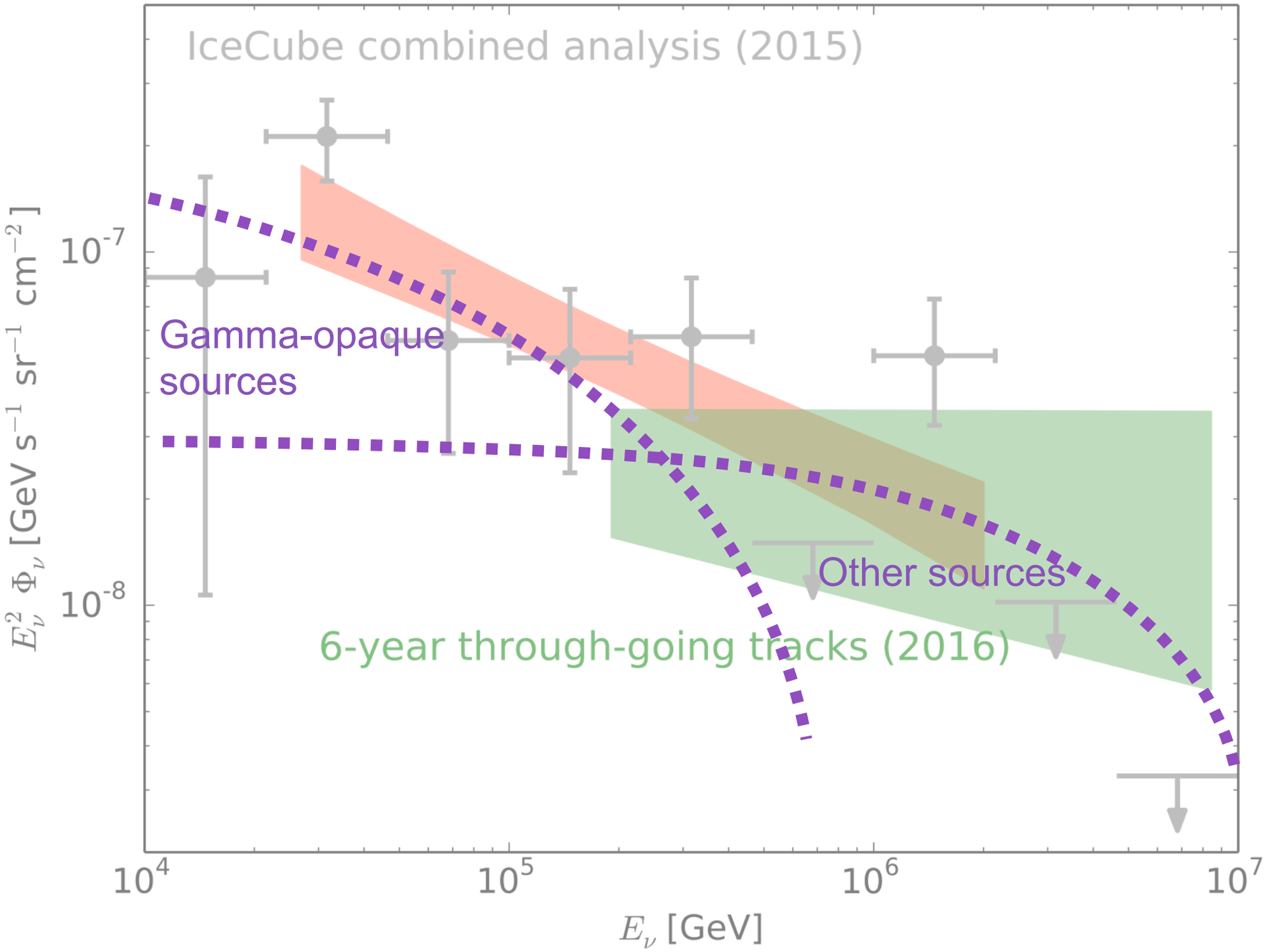




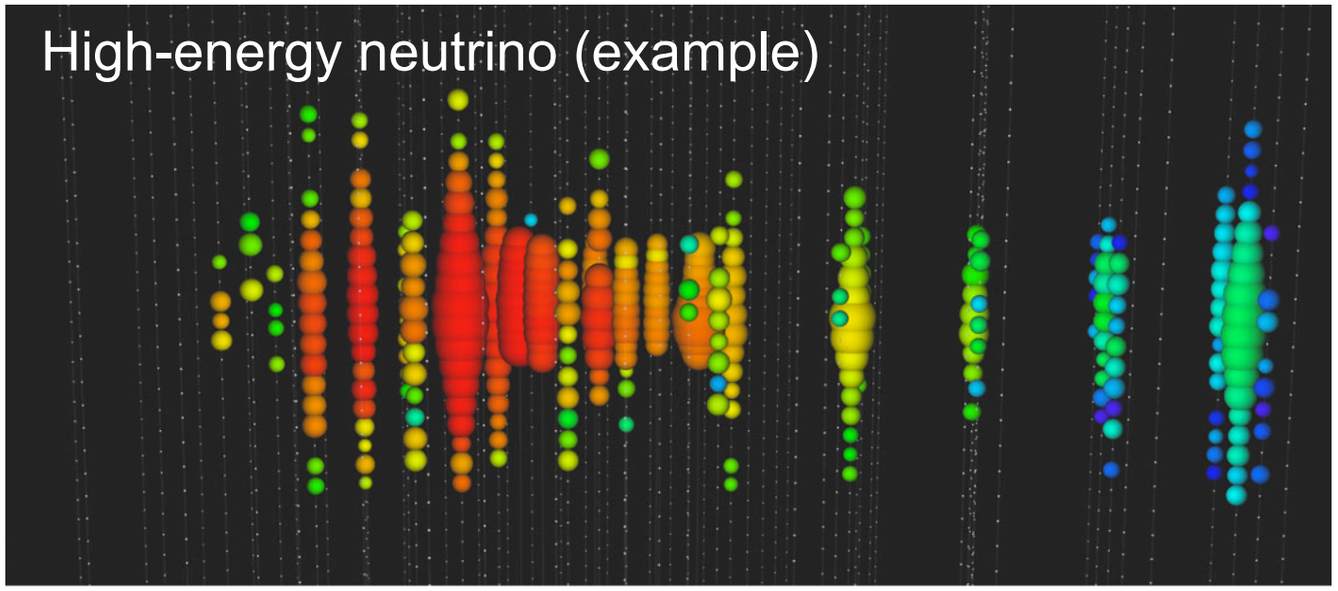
Murase, Guetta & Ahlers, 2015

A possible scenario

Multiple populations of neutrino sources



A very interesting coincidence



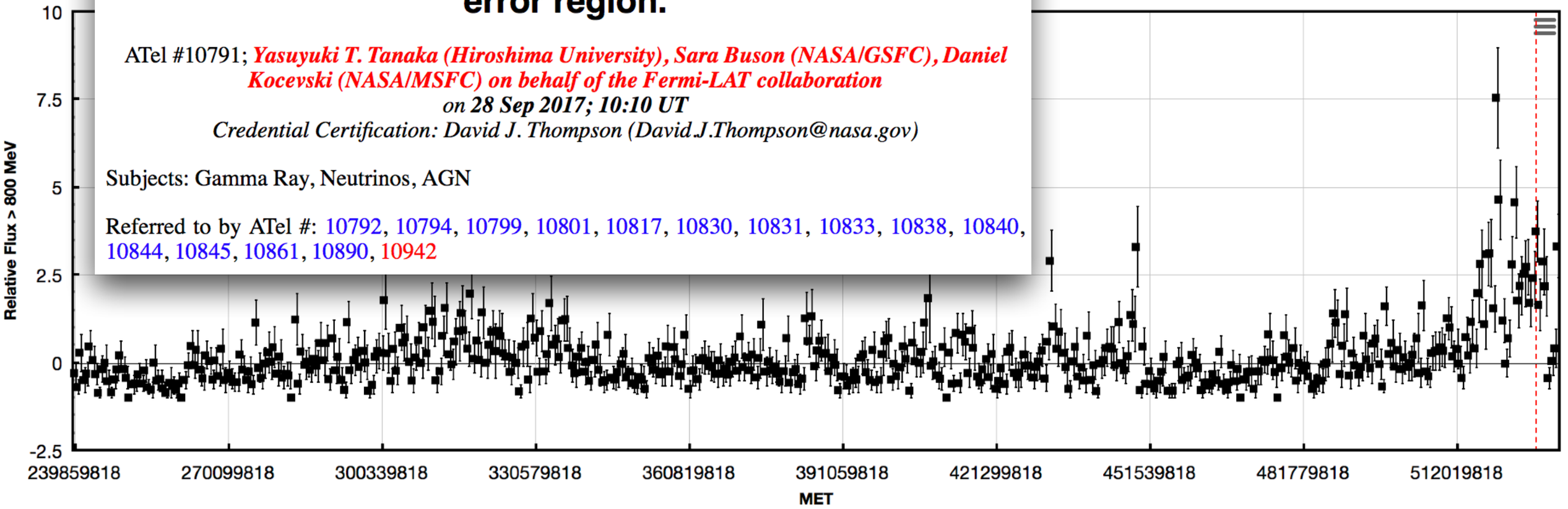
- **Blazars** are highly variable neutrino sources
- **> 100 TeV neutrino** arrived from within 0.1 deg of the source direction
- Arrival during an 6 month period with up to **6 x higher than average gamma-ray flux**

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942



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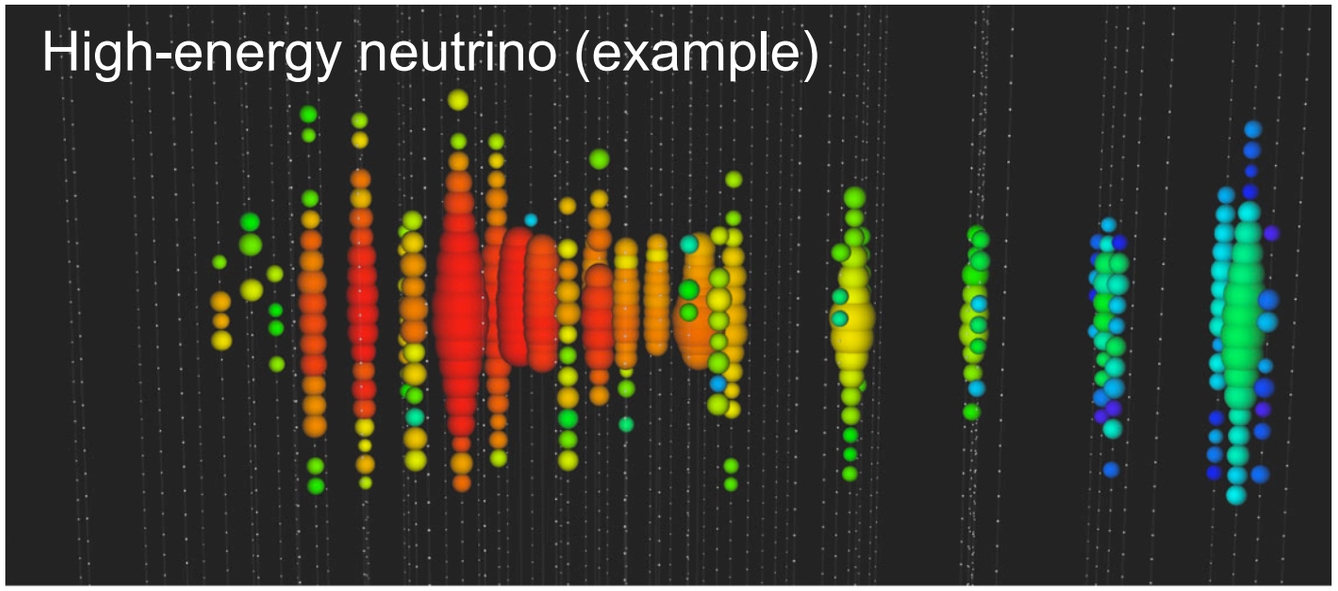

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Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located
erro

ATel #10791; *Yasuyuki T. Tanaka (Hiroshi*
Kocevski (NASA/MSFC) on b
on 28 Sep
Credential Certification: David J.

Subjects: Gamma Ray, Neutrinos, AGN

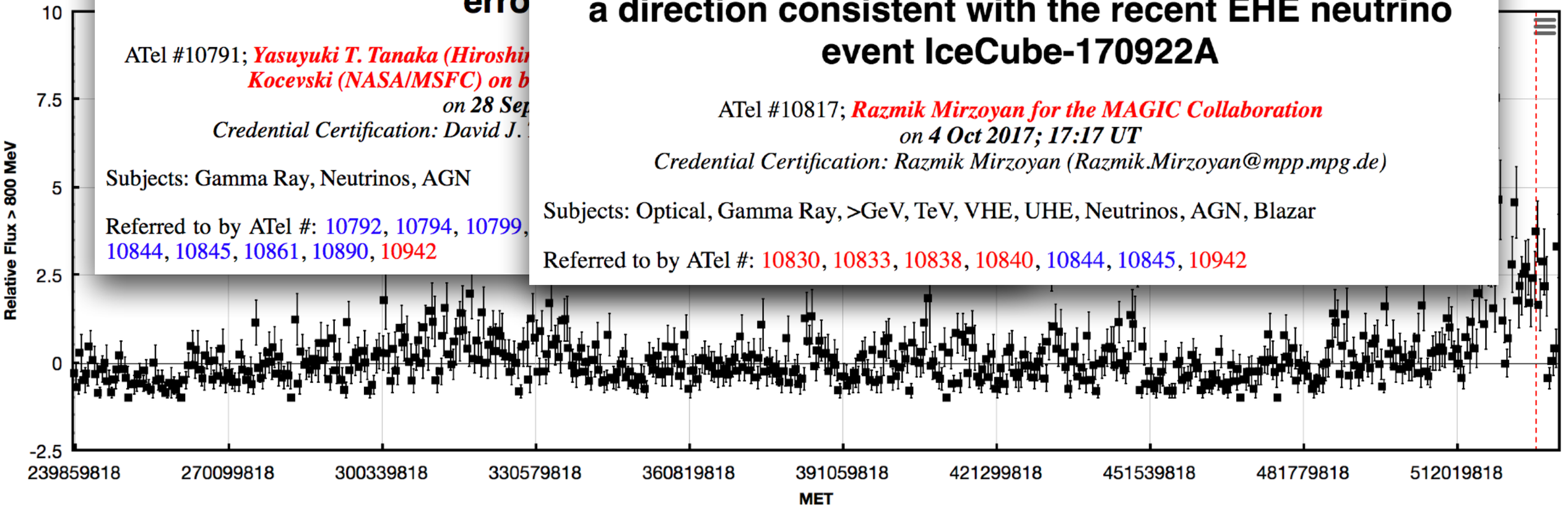
Referred to by ATel #: 10792, 10794, 10799, 10844, 10845, 10861, 10890, 10942

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

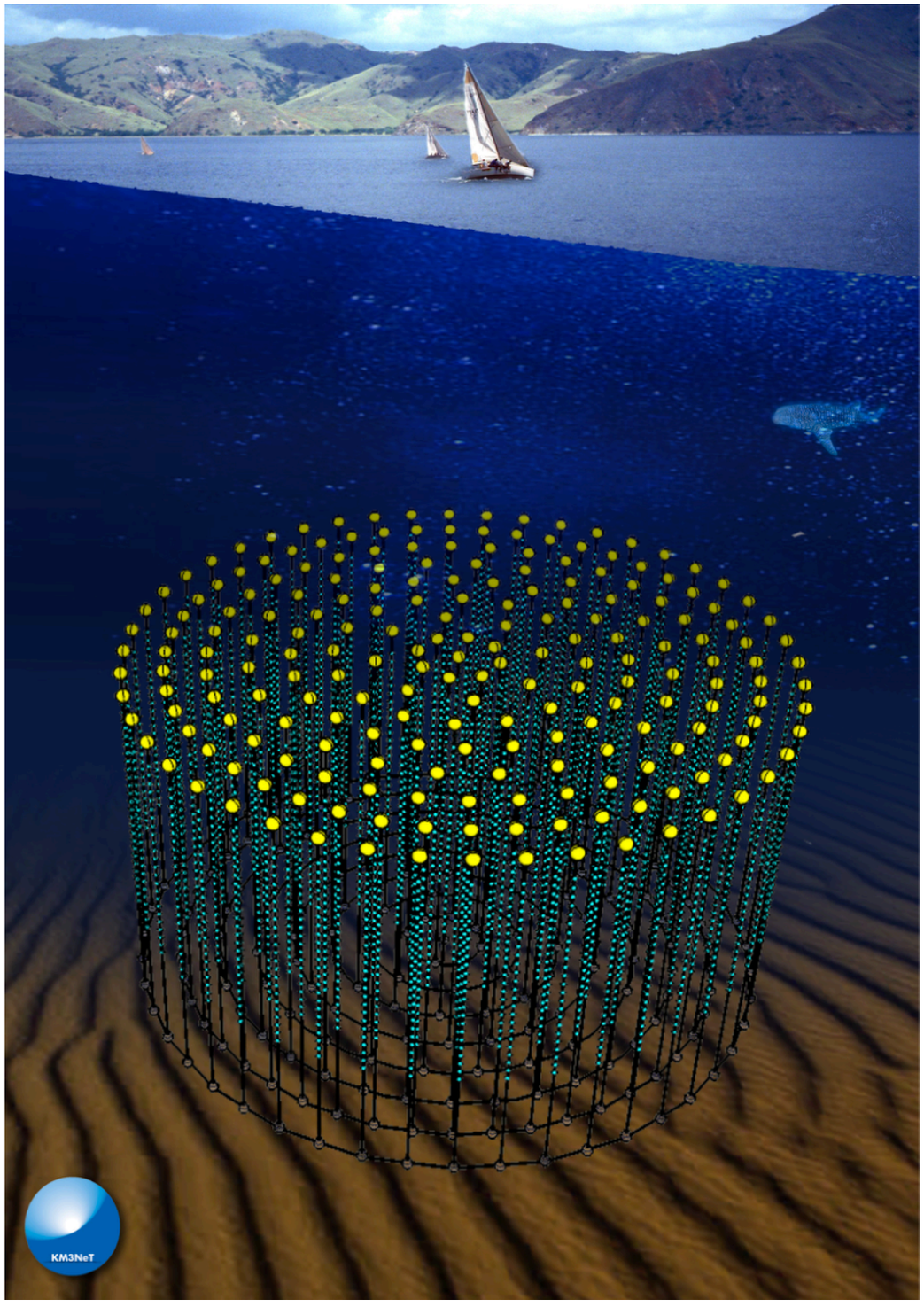
Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

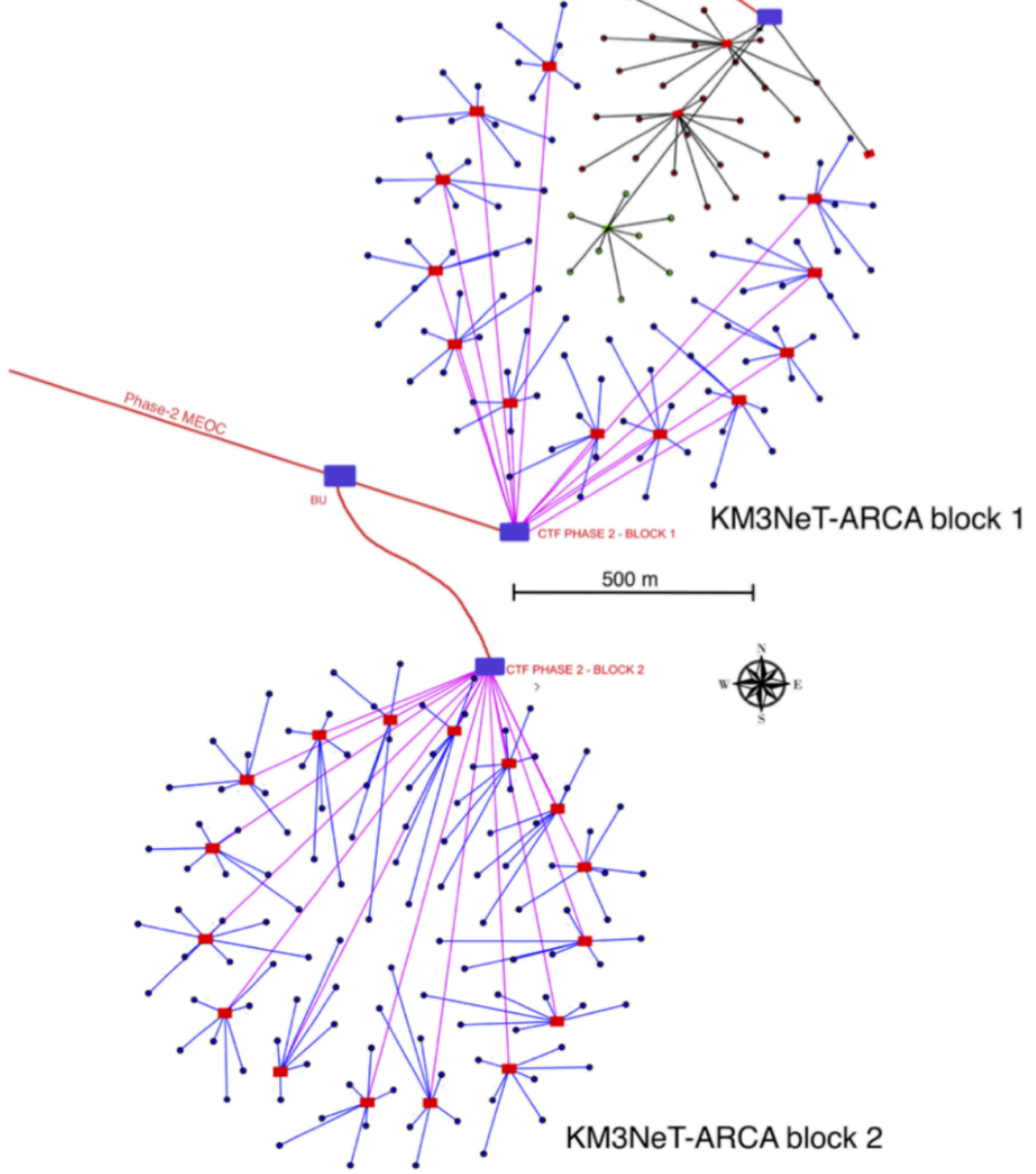
Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942



Where to go from here ?

The next generation of neutrino telescopes

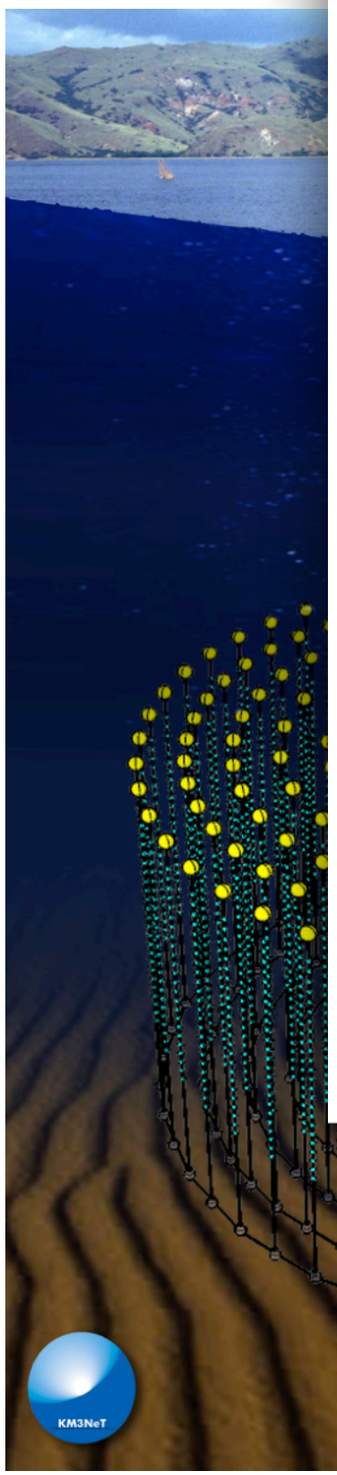


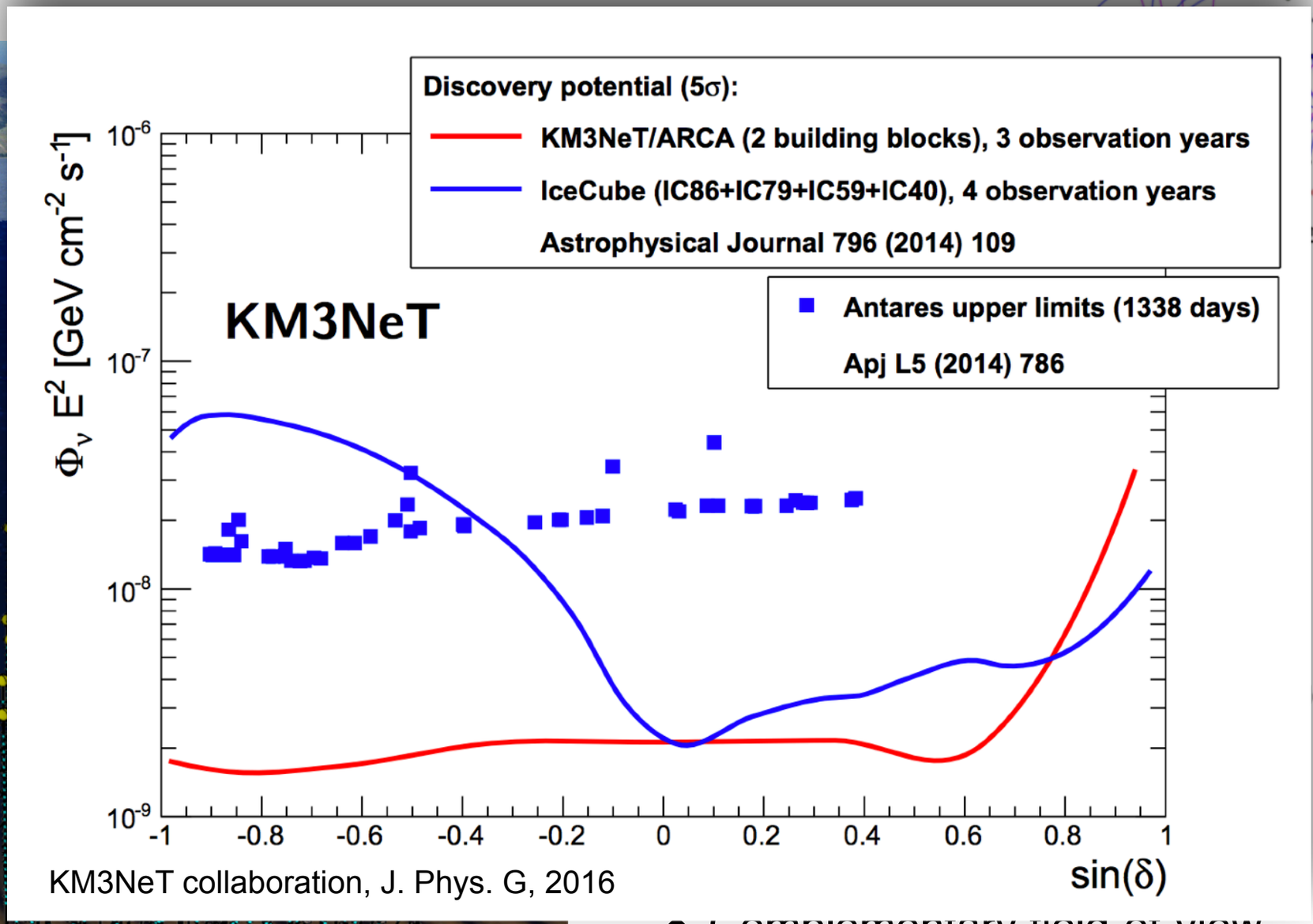


- **KM3NeT - ARCA**
  - Similar instrumented volume to IceCube
  - Complementary field-of-view
  - Better angular resolution than IceCube
- Construction has started

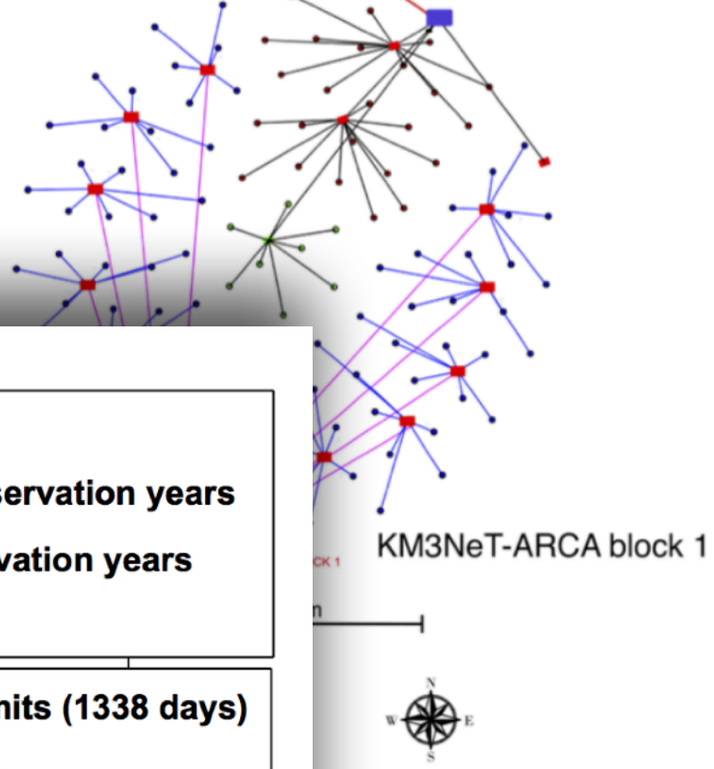
Where to go from here ?

The next generation of neutrino telescopes





KM3NeT collaboration, J. Phys. G, 2016



eT-ARCA block 2

IceCube

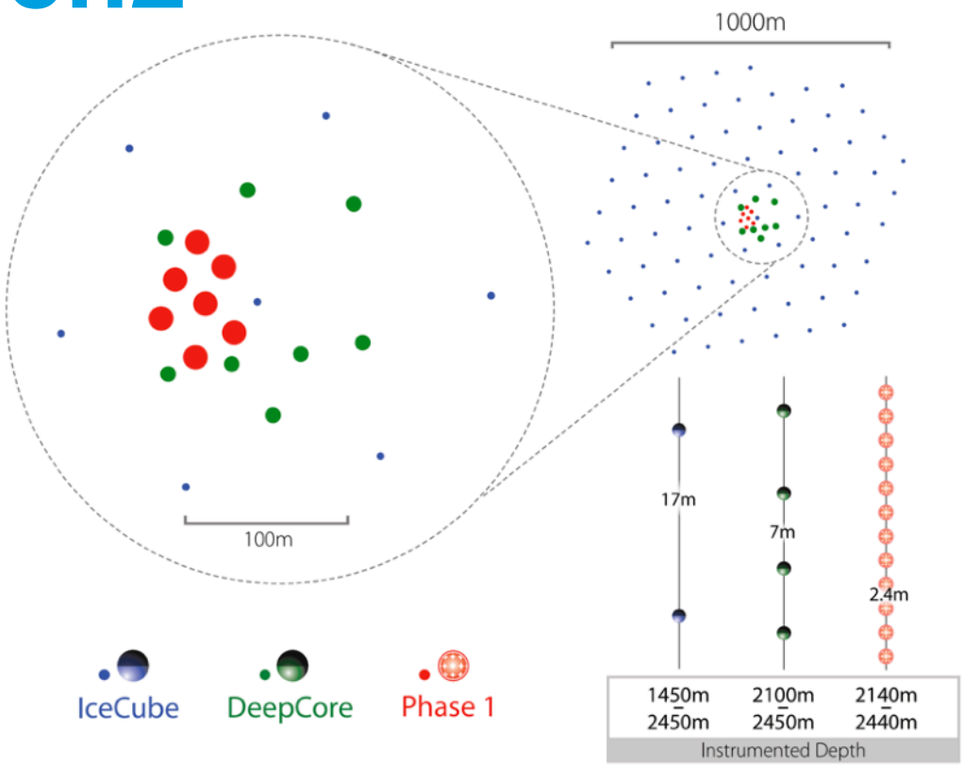
- Complementary field-of-view
- Better angular resolution than IceCube

- Construction has started

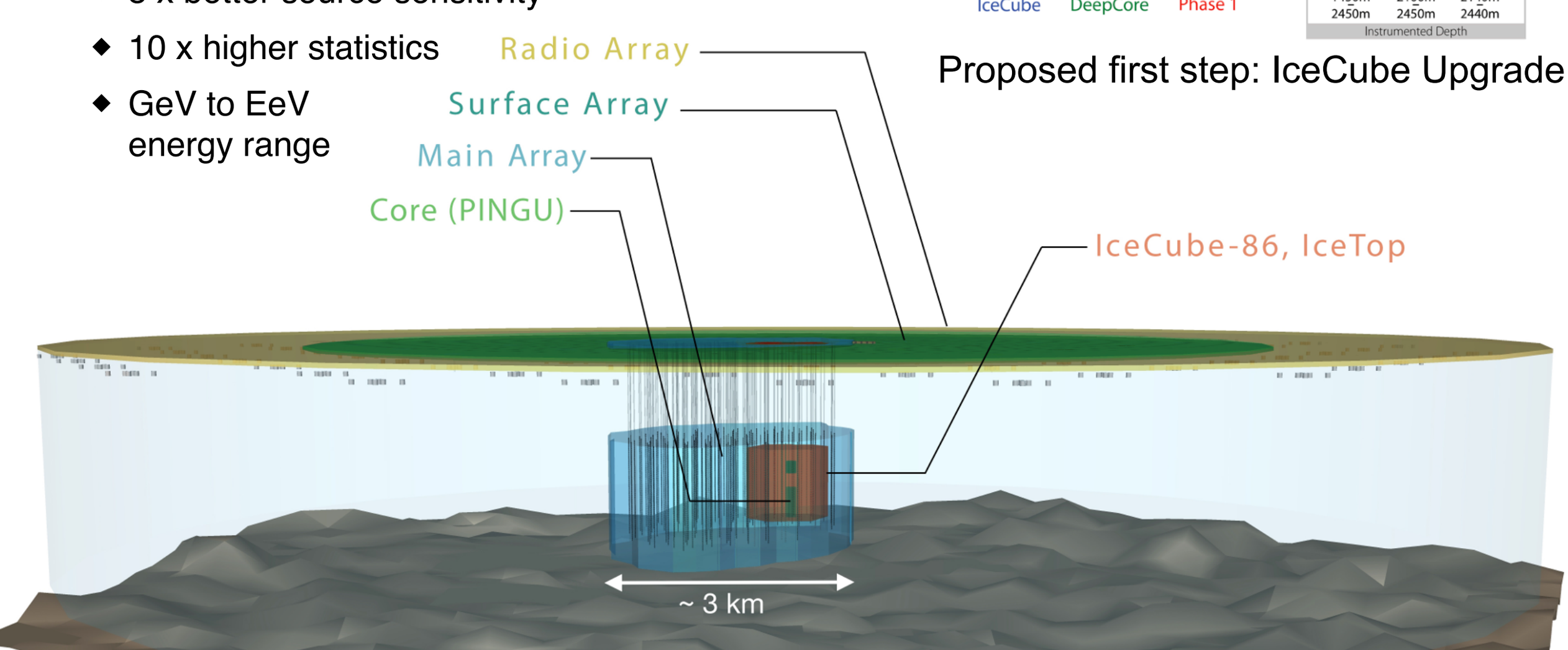
From IceCube to IceCube-Gen2

- **IceCube Upgrade** proposal
  - 7 new strings in center of IceCube
  - New calibration devices

- Future IceCube-Gen2 will allow **precision studies** of cosmic neutrinos.
  - 5 x better source sensitivity
  - 10 x higher statistics
  - GeV to EeV energy range



Proposed first step: IceCube Upgrade



Summary

- We are measuring the **spectrum and flavor composition** of the astrophysical neutrino flux with increasing precision
- Its **origin remains elusive**, but many constraints can be found
  - Not dominated by a few individual sources
  - No apparent correlation with the Galactic plane
  - Blazars (and GRB) can only contribute a relatively small fraction
  - At least some fraction of the neutrino flux has to come from hidden/gamma-ray dark sources
- There is an **interesting coincidence** between a >100 TeV neutrino and the Blazar TXS 0506+056
- The **next generations** of neutrino telescopes are under construction (KM3NeT) or in an advanced design stage (IceCube-Gen2)