UNIVERSITÉ DE GENÈVE

ICECUBE

Joint Annual Meeting of SPS and ÖPG,
26-30 August 2019, Zürich

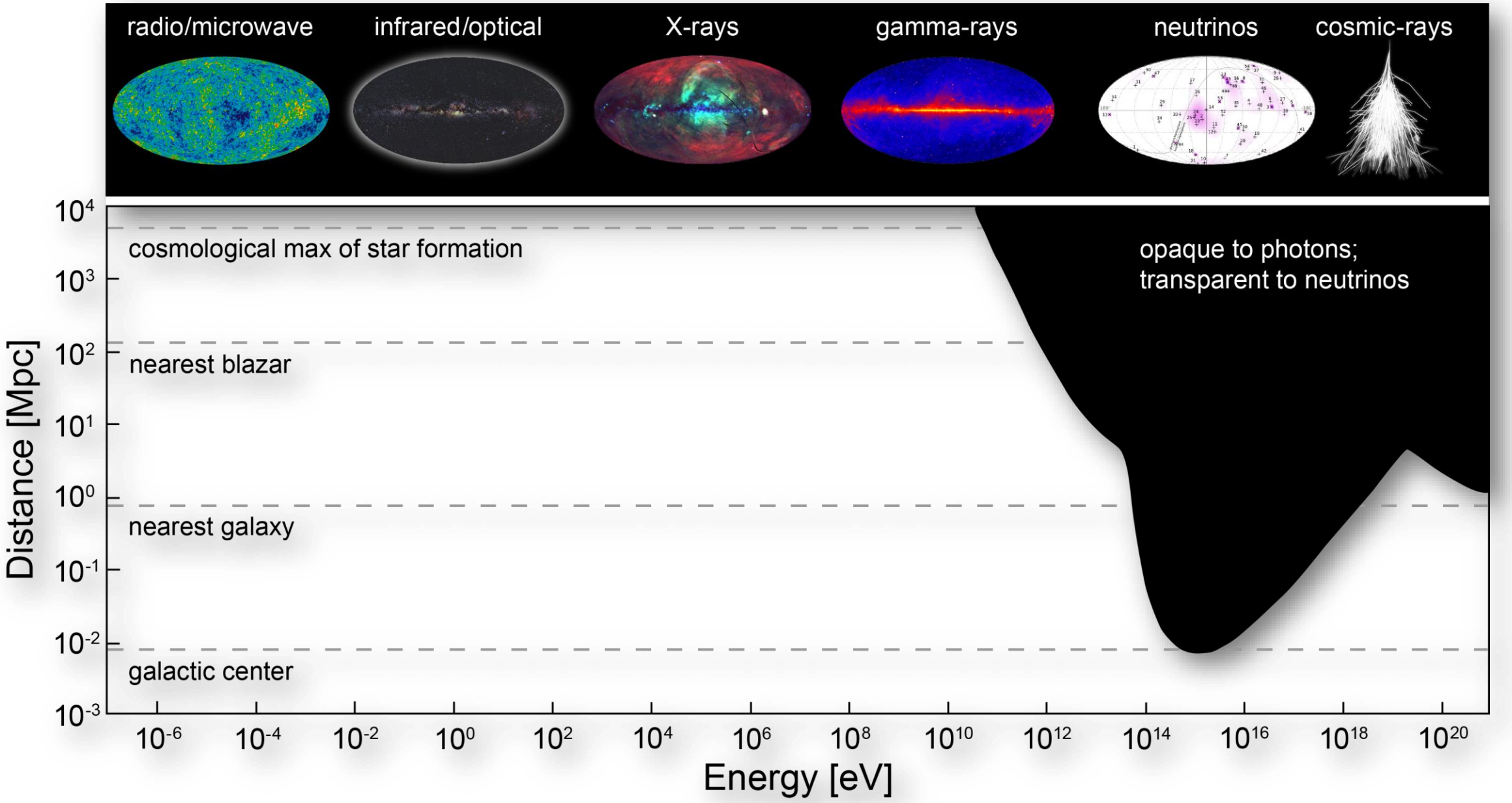
Neutrino point-source searches for multi-messenger astronomy with IceCube

Anastasia Barbano, Francesco Lucarelli, Teresa Montaruli
DPNC, University of Geneva

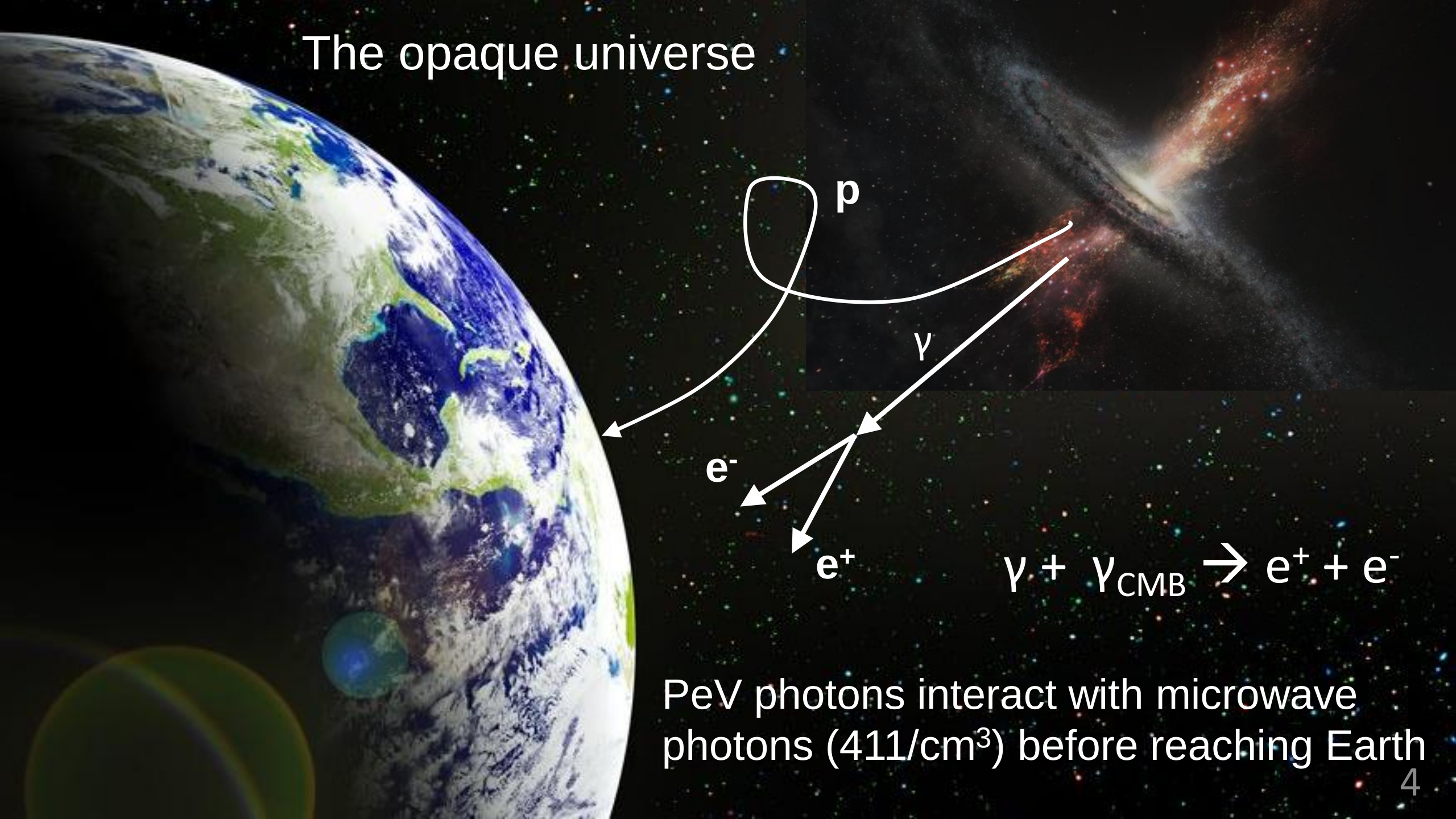
Contents

- Neutrinos as messengers
- The IceCube neutrino telescope
- The discovery of cosmic neutrinos
- Where do they come from?

Exploring the extreme universe



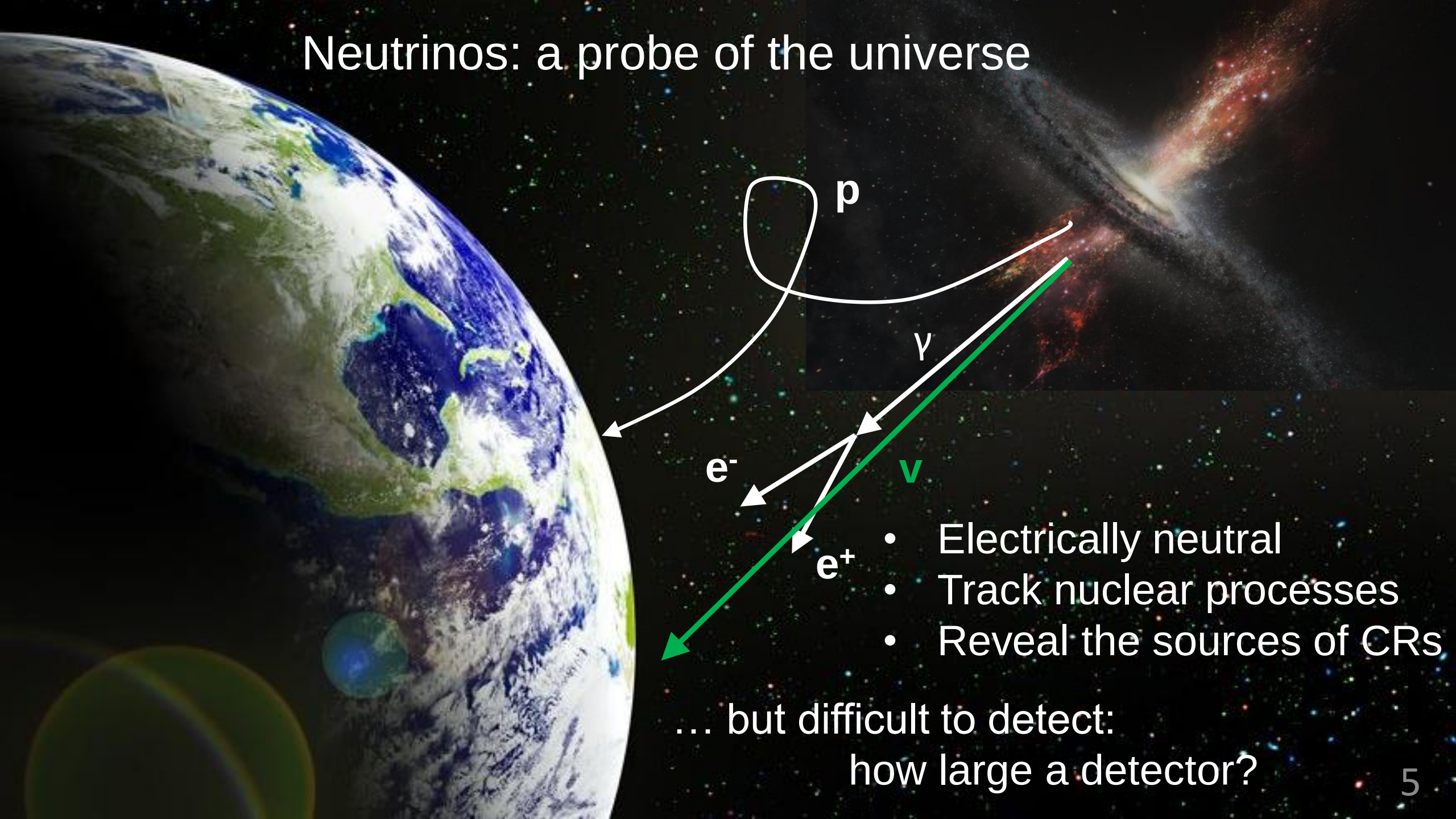
The opaque universe



$$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$$

PeV photons interact with microwave photons (411/cm³) before reaching Earth

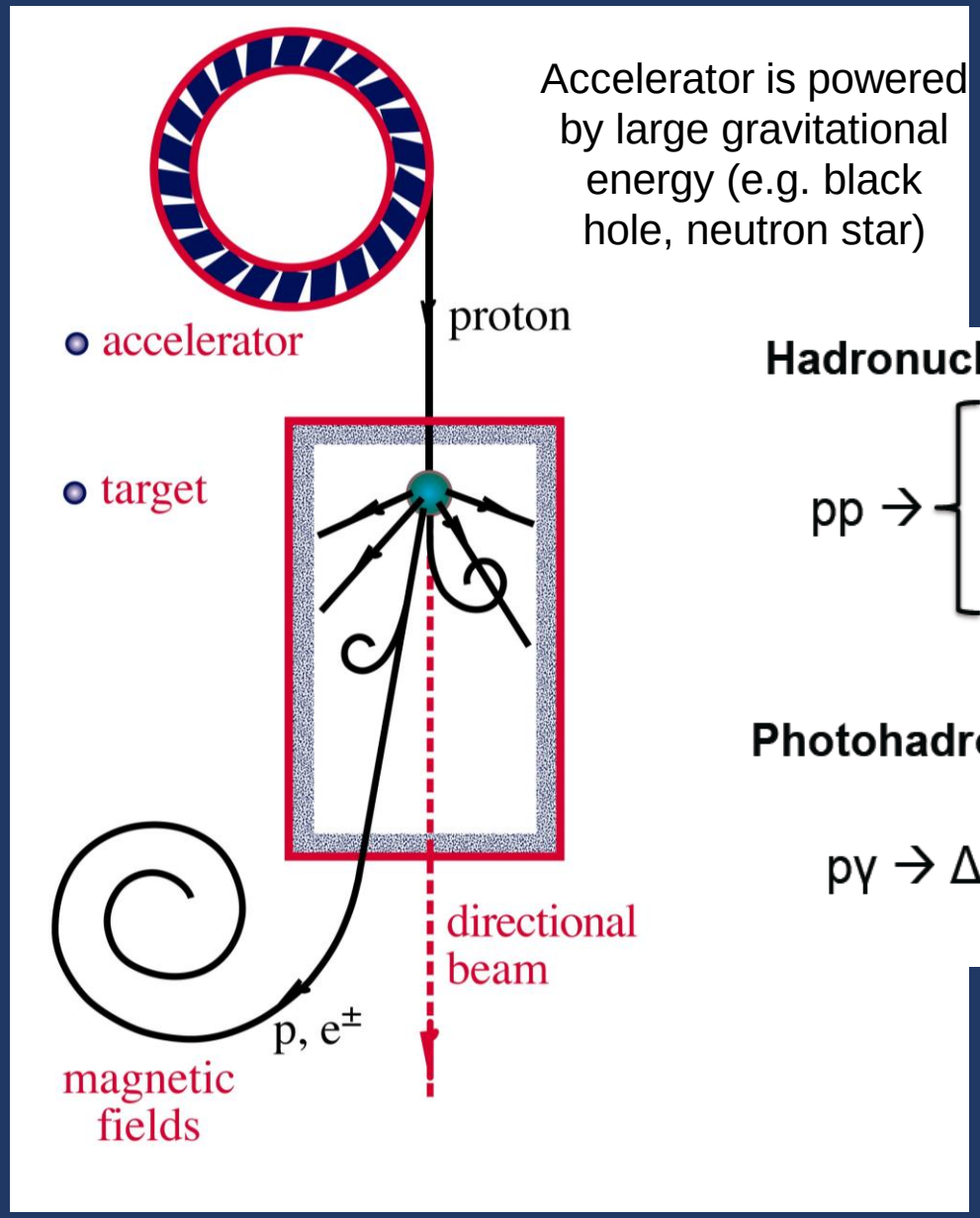
Neutrinos: a probe of the universe



- Electrically neutral
- Track nuclear processes
- Reveal the sources of CRs

… but difficult to detect:
how large a detector?

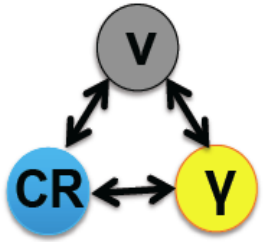
The generic messenger Source: the Cosmic Beam Dump



Accelerator is powered by large gravitational energy (e.g. black hole, neutron star)

Hadronuclear (e.g. star burst galaxies and galaxy clusters)

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$



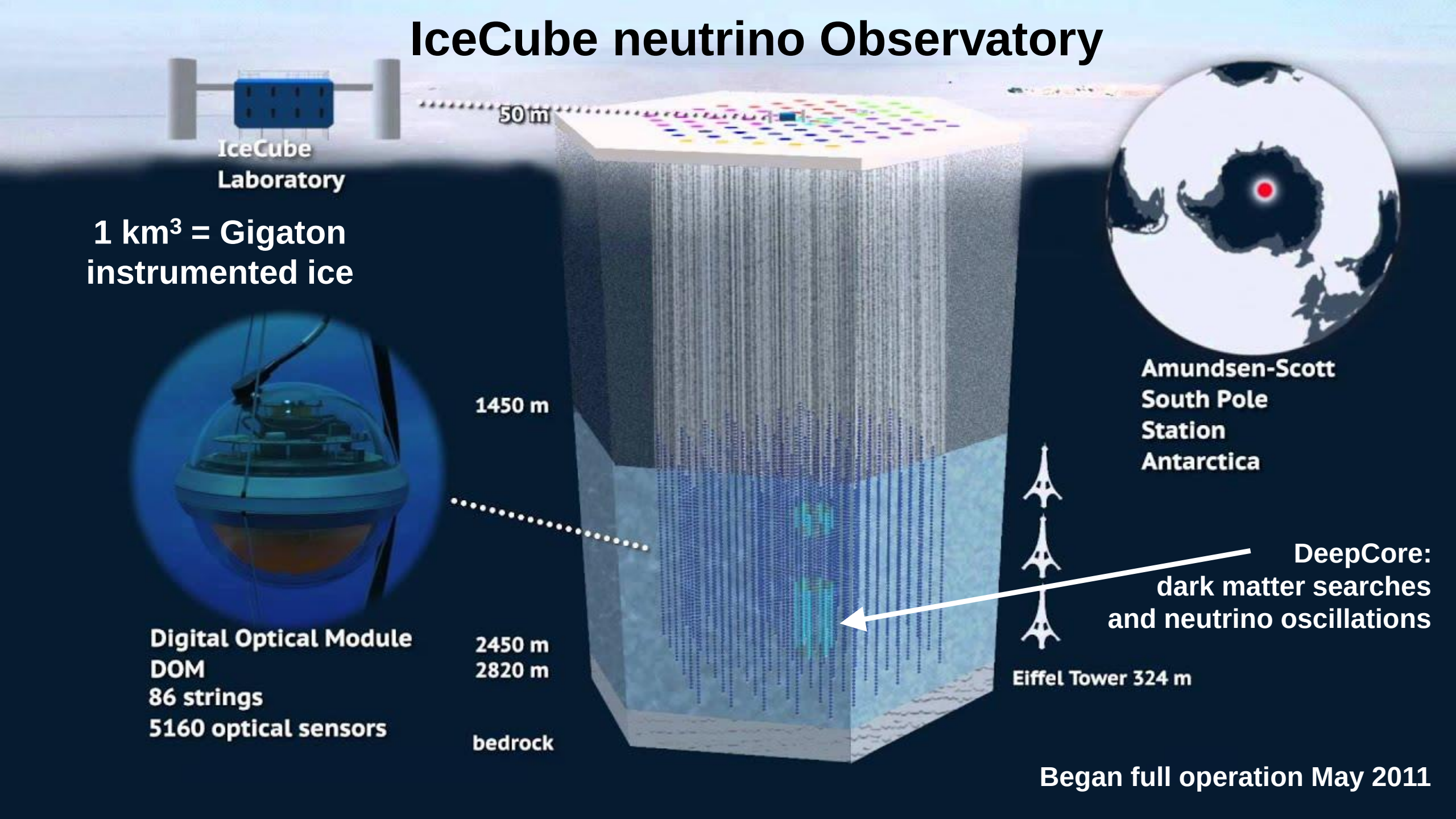
Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

cosmic ray + gamma

cosmic ray + neutrinos

IceCube neutrino Observatory



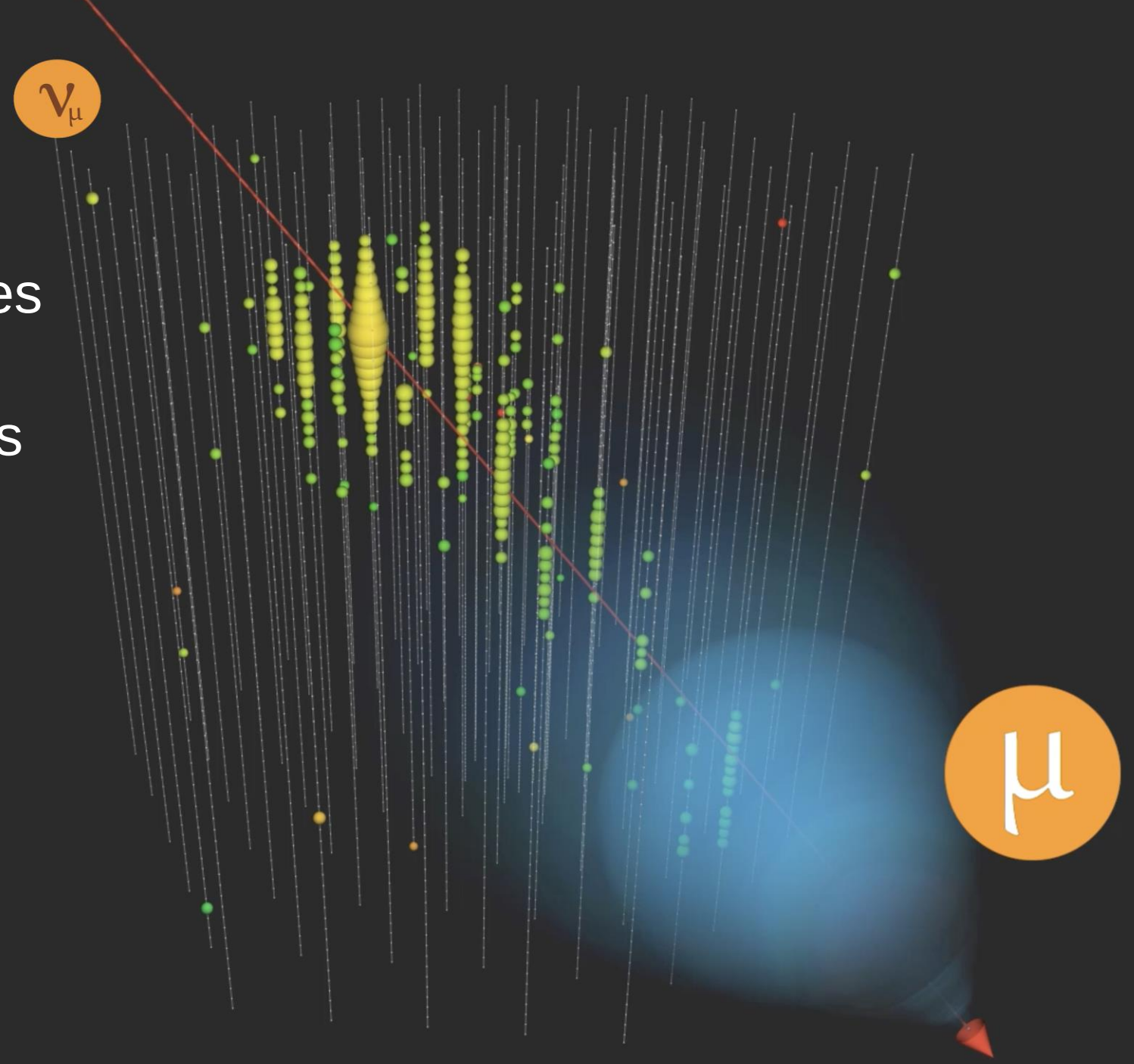
1 km^3 = Gigaton instrumented ice

DeepCore:
dark matter searches
and neutrino oscillations

Began full operation May 2011

Principle of detection

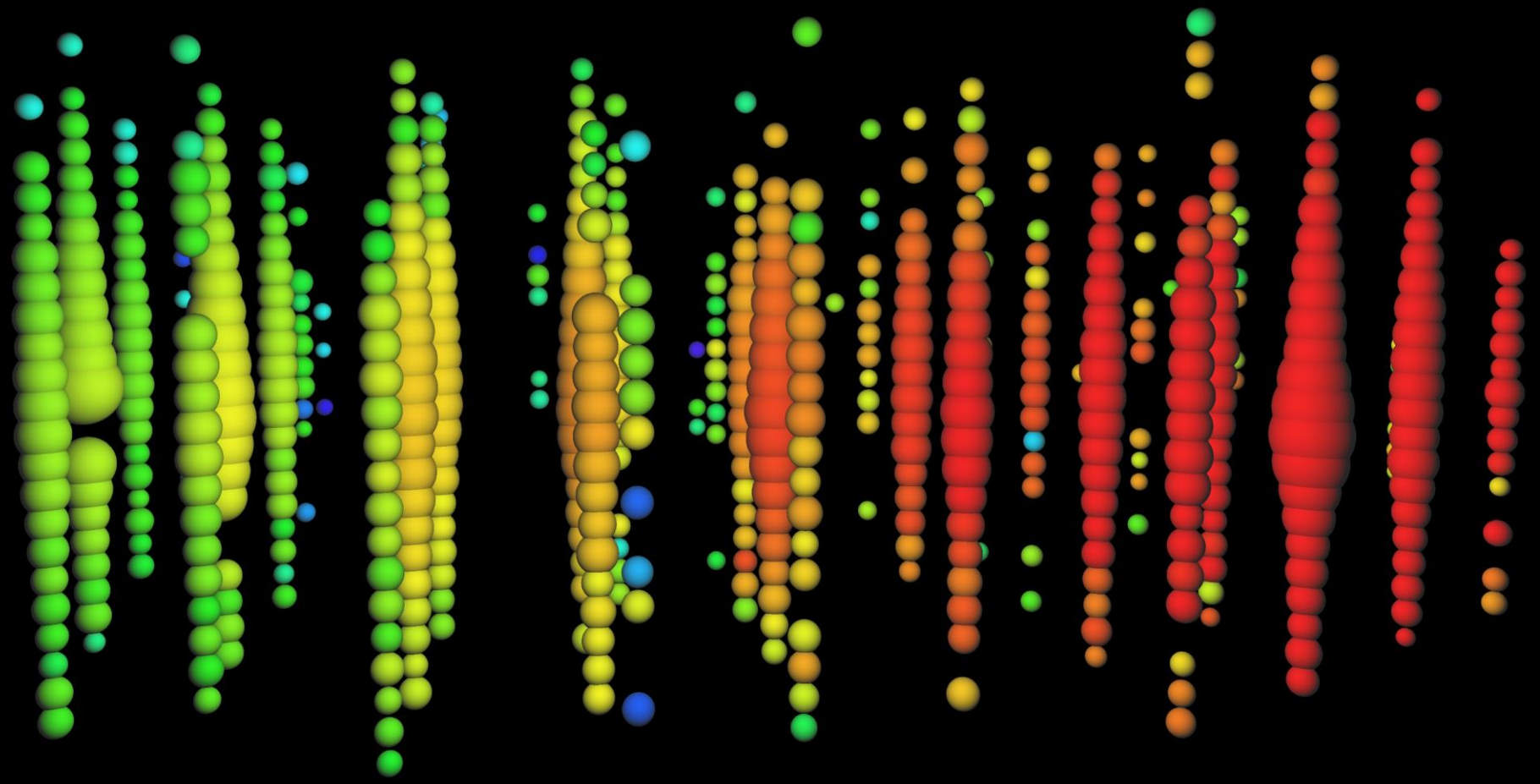
- A muon neutrino produces a muon
- Lattice of photomultipliers to detect cone of Cherenkov light



Track-like event

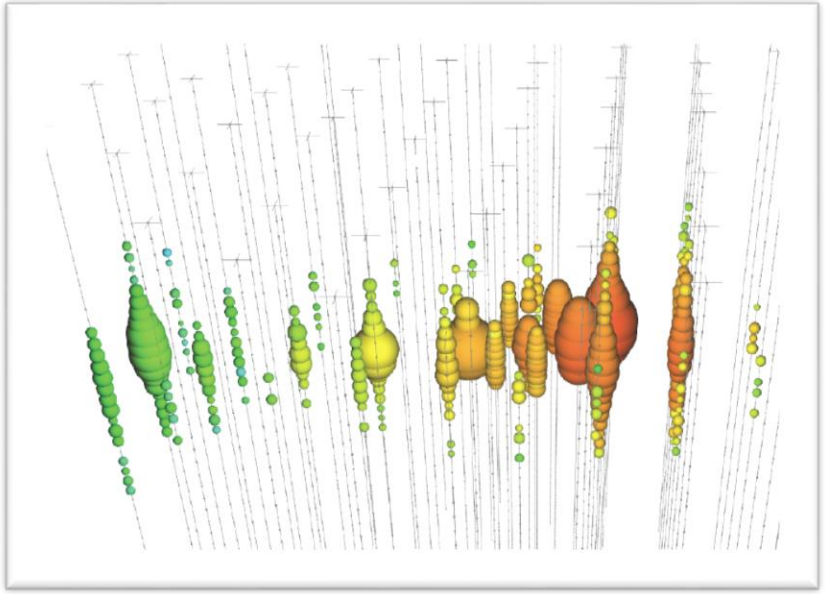
(28 Oct 2010)

Muon energy: ~604 TeV
Neutrino energy: ~880 TeV
Radius ~ number of photons
Time: red → purple



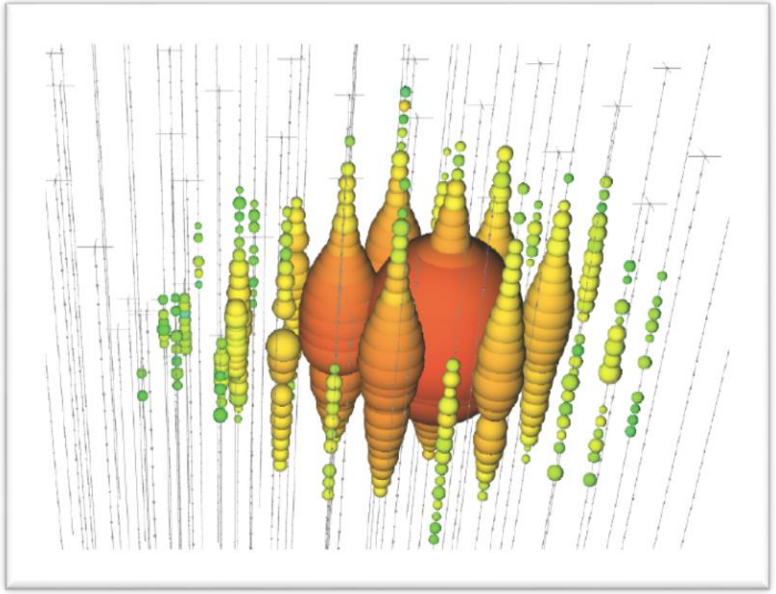
Event topologies

Tracks



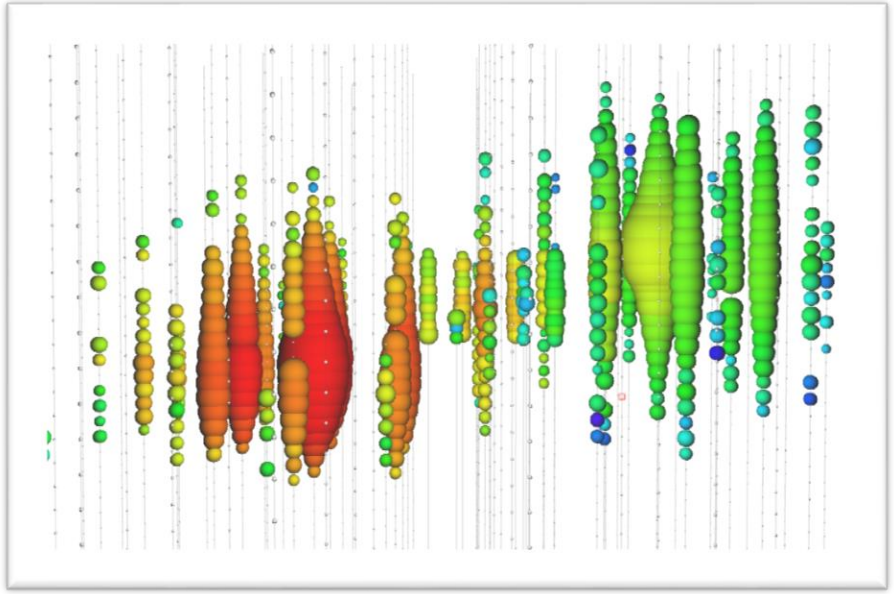
- ν_μ charged-current (CC) interactions
- Atmospheric μ
- ν_τ CC interactions with muonic tau decay
- Good angular resolution: < 0.3° (>100 TeV)
- Energy resolution: x2

Cascades



- All neutral-current (NC) interactions
- ν_e, ν_τ CC interactions
- Angular resolution: ~10° (> 100 TeV)
- Good energy resolution: ~15%

Double-cascades



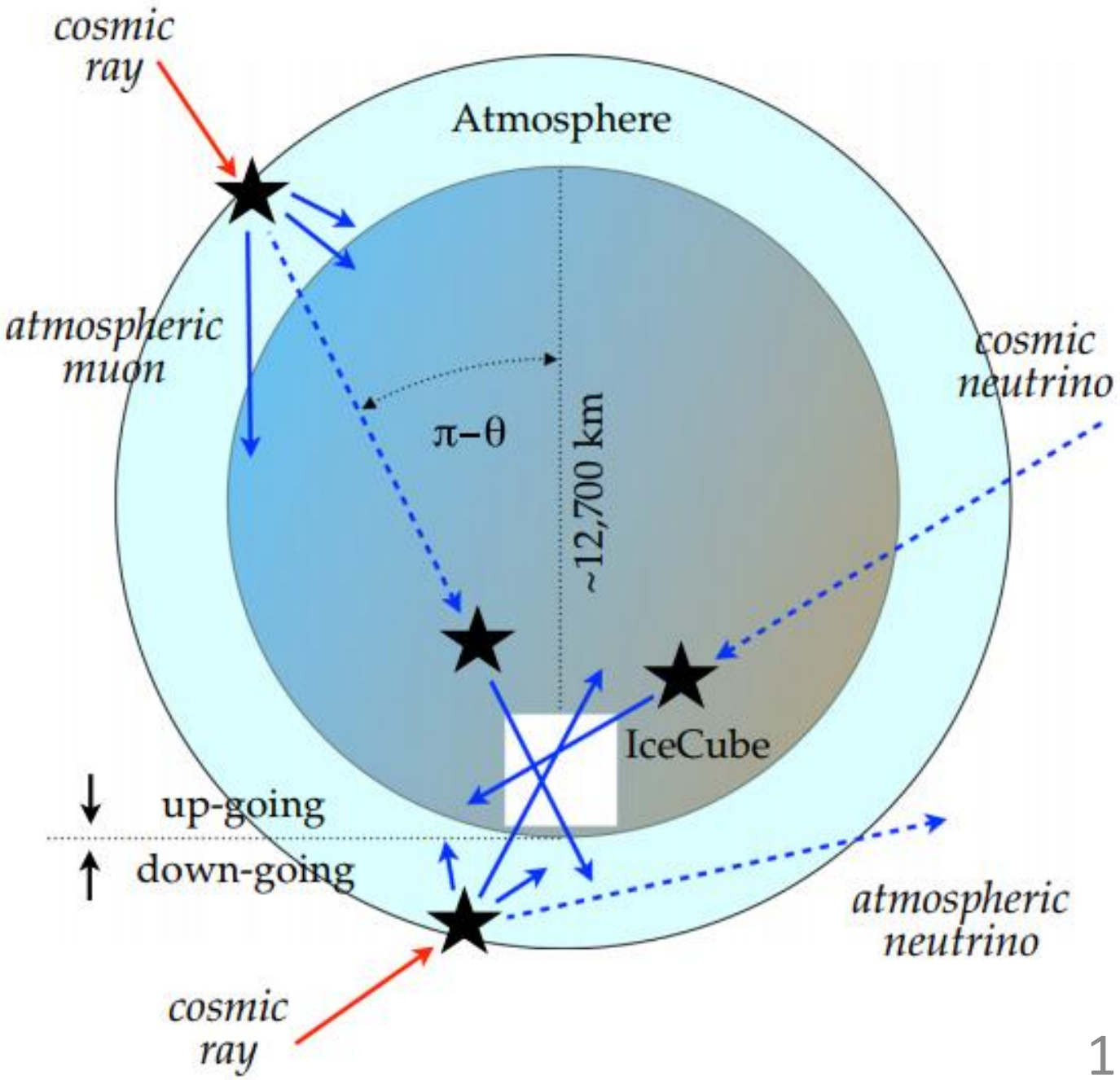
- Very high-energy (>2 PeV) ν_τ CC interactions with hadronic/electronic tau decay
- ~2 expected in 6 years

Signal and background

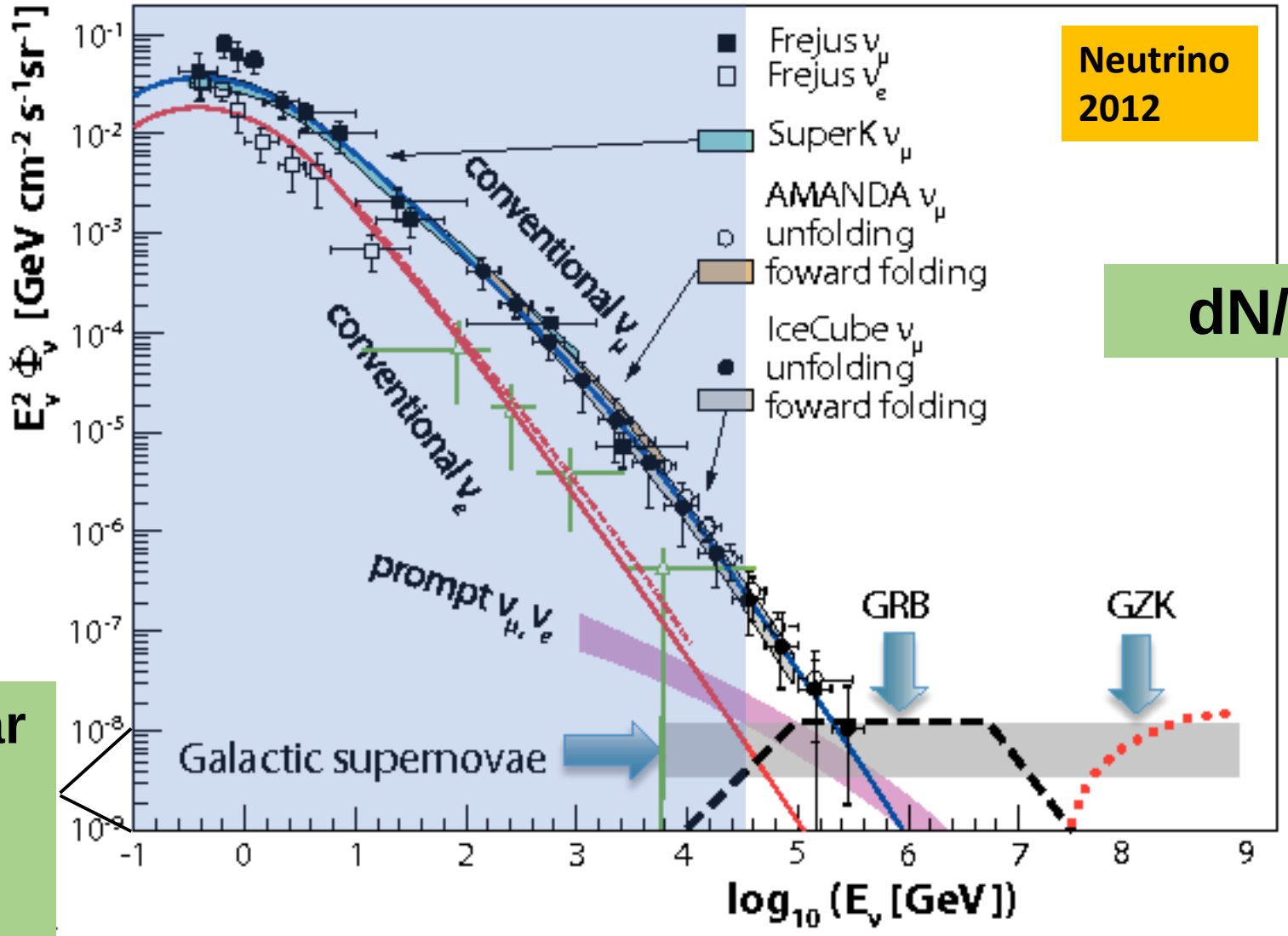
- 2 kinds of backgrounds:
  - Atmospheric μ
  - Atmospheric ν

- 3 components in neutrino flux:
  - Conventional atmospheric **ν** from K/Pi decays in air-showers
  - Prompt atmospheric **ν** from decays of charmed hadrons in air-showers
  - Astrophysical **ν**, power-law energy spectrum

- Muons detected per year:
  - Atmospheric μ ~ 10^{11} (3000 per second)
  - Atmospheric ν → μ ~ 10^{5} (1 every 6 minutes)
  - Cosmic ν → μ ~ 1-10 (> 50 TeV)



Cosmic neutrino fluxes

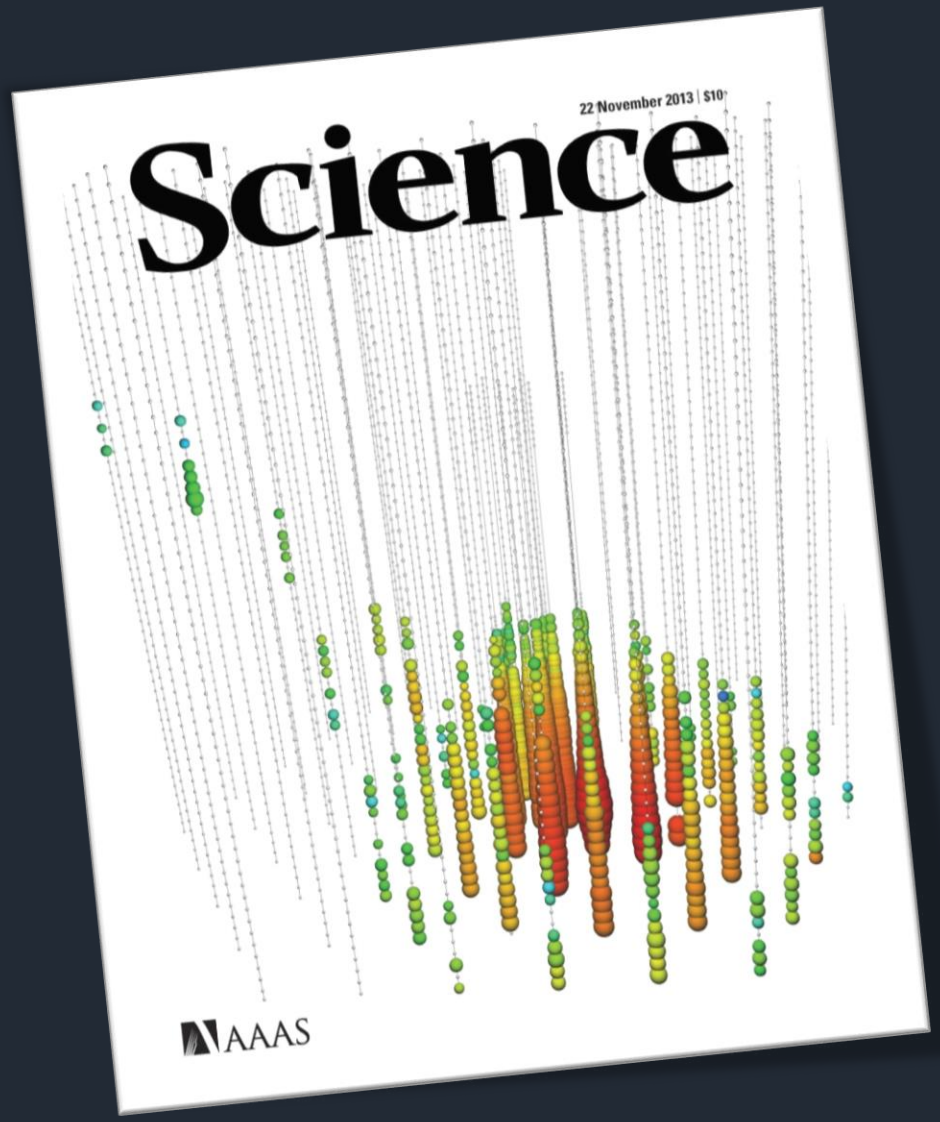


dN/dE ~ E^{-2}

1-10 events/year > 50 TeV for a fully efficient km³ detector

Atmospheric **50 TeV** **Cosmic**

The discovery of cosmic neutrinos

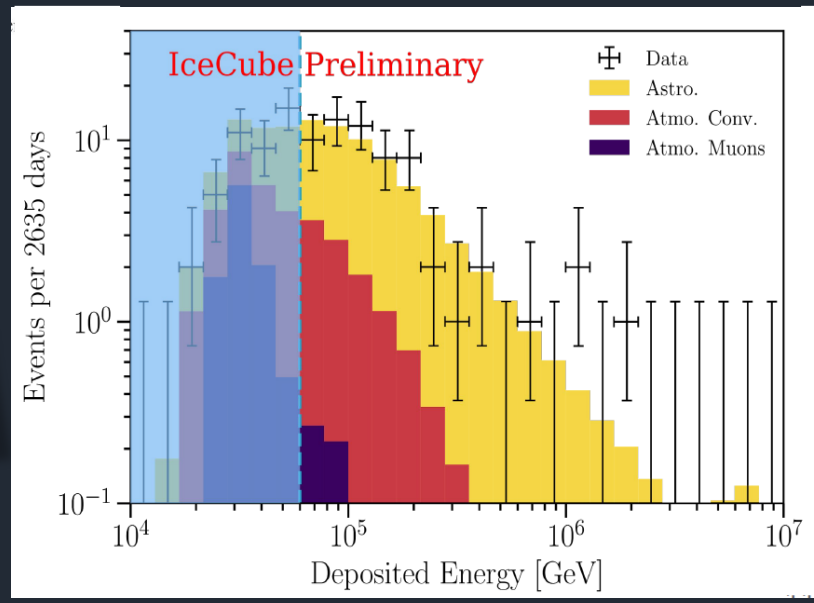


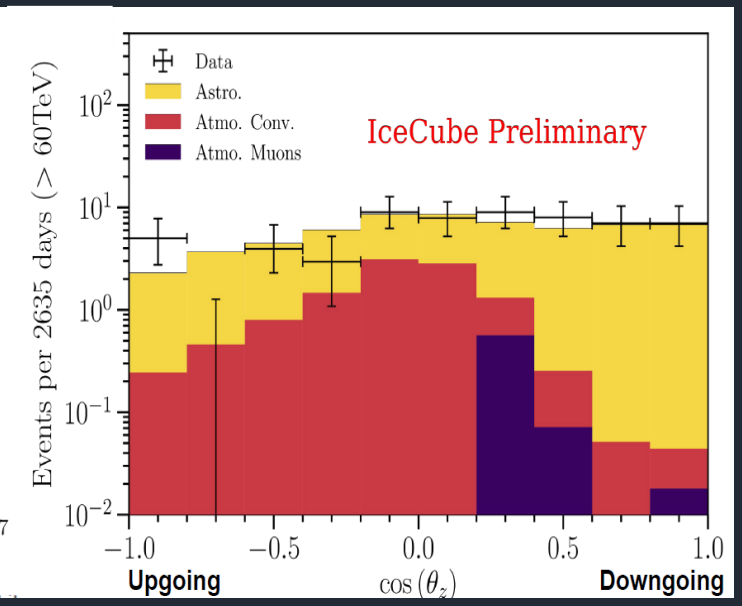
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector

IceCube Collaboration*

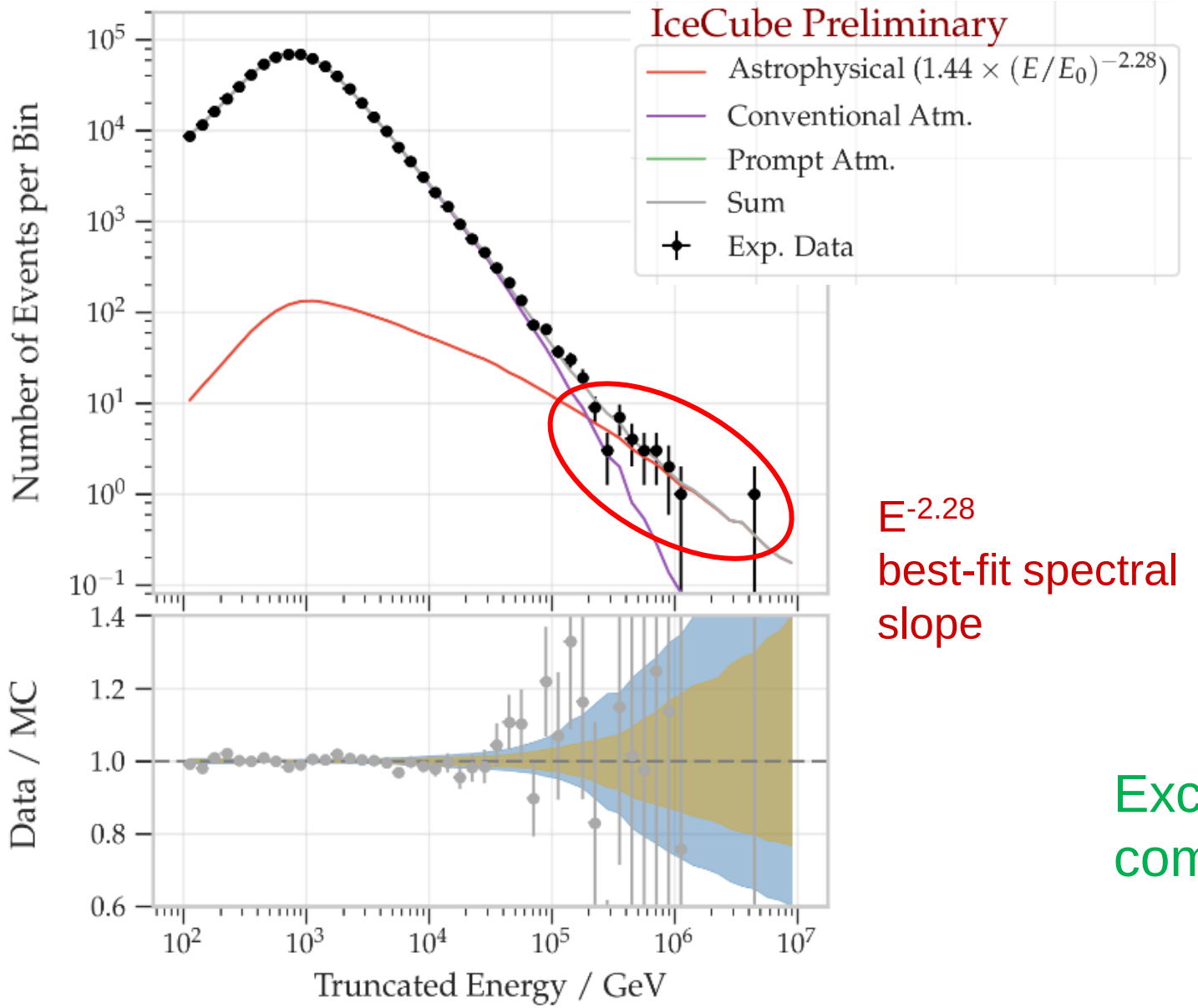
- 2-year dataset (May 2010 to May 2012)
- 28 neutrino events detected
- expected atmospheric background: $10.6^{+5.0}_{-3.6}$
- 30 < E < 1200 TeV

Latest results (ICRC19)

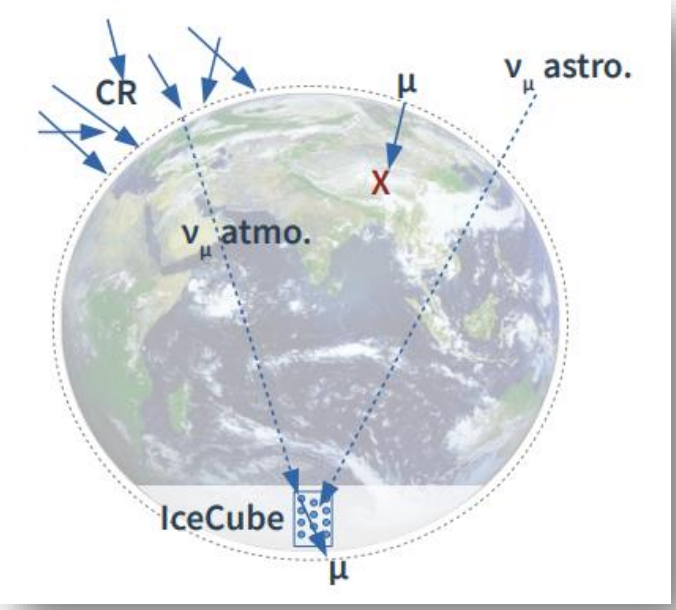




Astrophysical neutrinos, 9 years of data



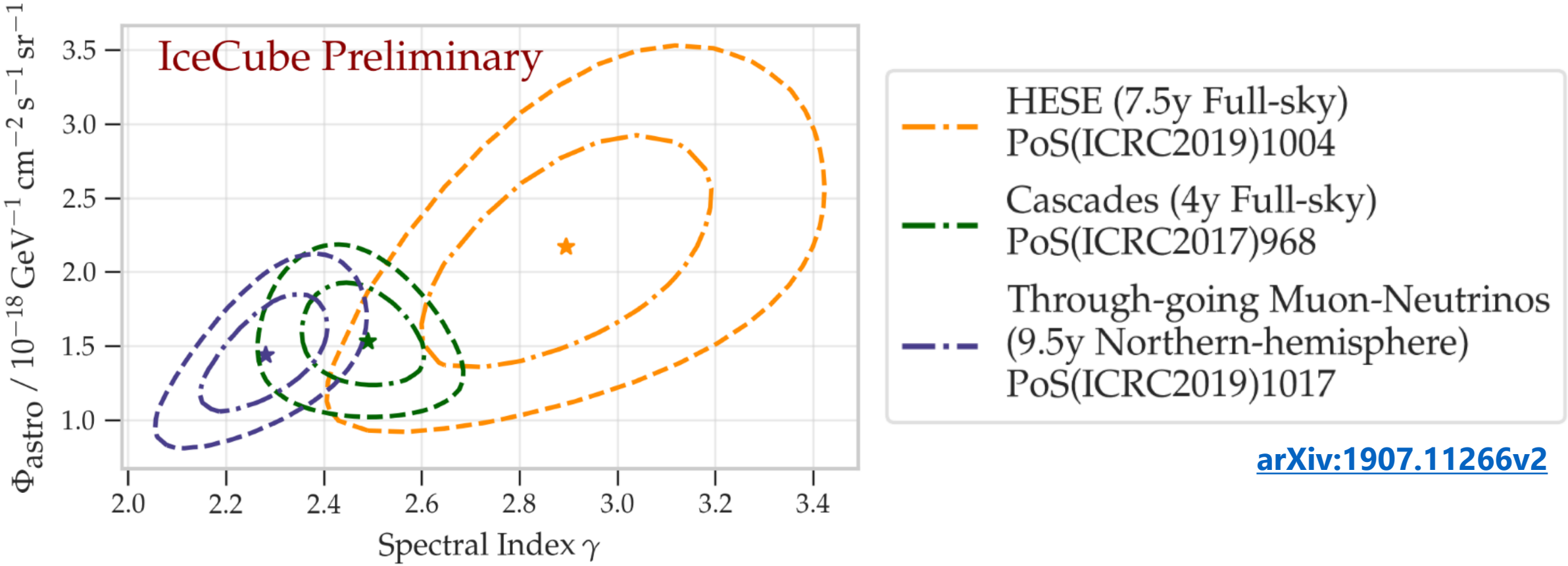
$E^{-2.28}$
best-fit spectral slope



- Independent analysis using thorough-going muon events from the Northern Hemisphere

Excess of a high-energy component clearly visible

Single power law astrophysical neutrino spectra



arXiv:1907.11266v2

- Single power law may not be possible, e.g. contribution of sources of different nature to fluxes?

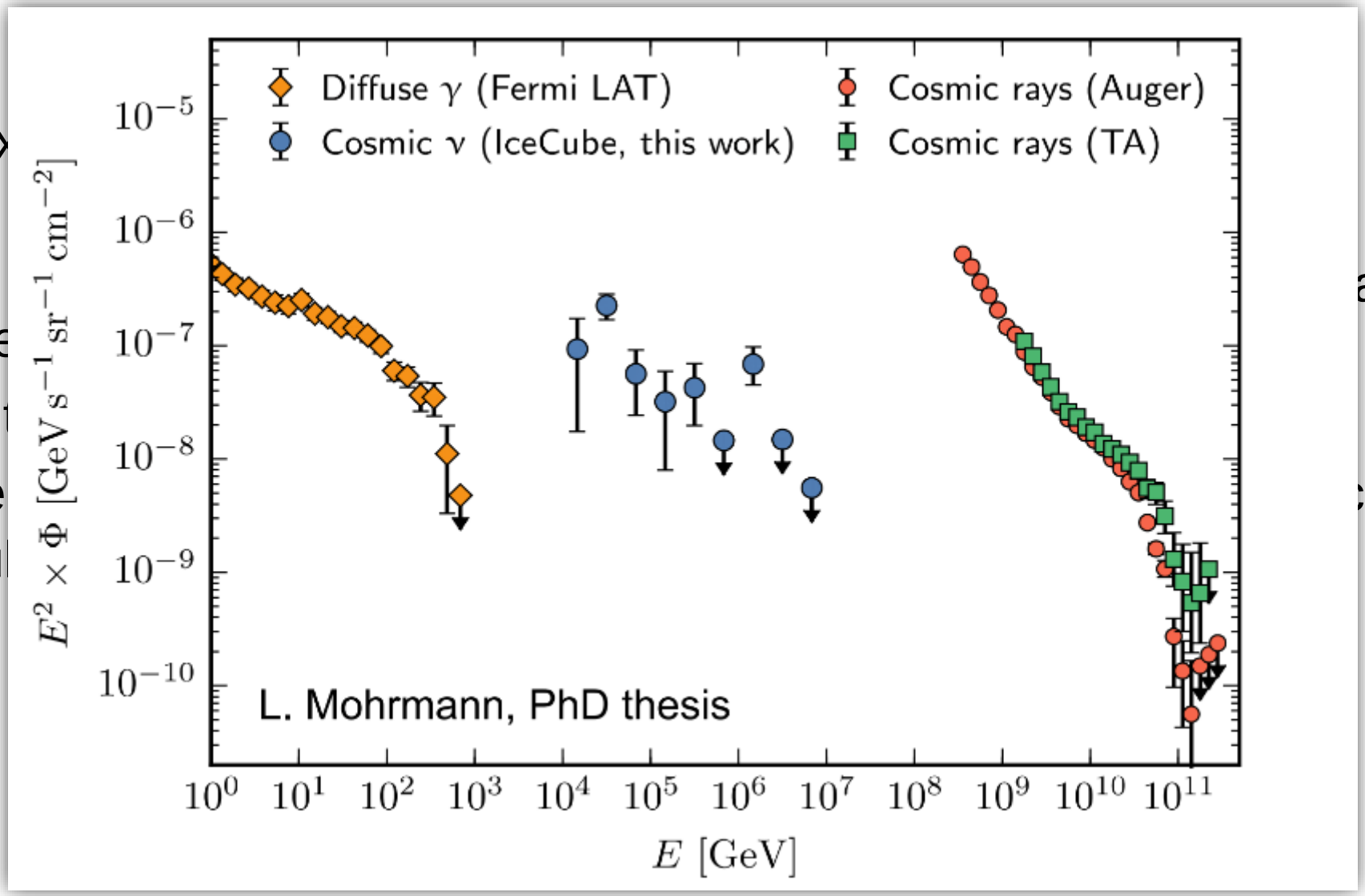
Lessons so far

- Diffuse flux of neutrinos of astrophysical origin
- A Galactic component cannot be excluded
    - But galactic neutrino searches for emission from the Galactic plane revealed no significant correlations so far
- Where do they come from?
- Where are the gammas counterpart of PeV neutrinos from same sources?

  →multi-messenger searches

Lessons so far

- Diffuse flux
- A Galactic
  - But
    reve
- Where do
- Where are
  →mul



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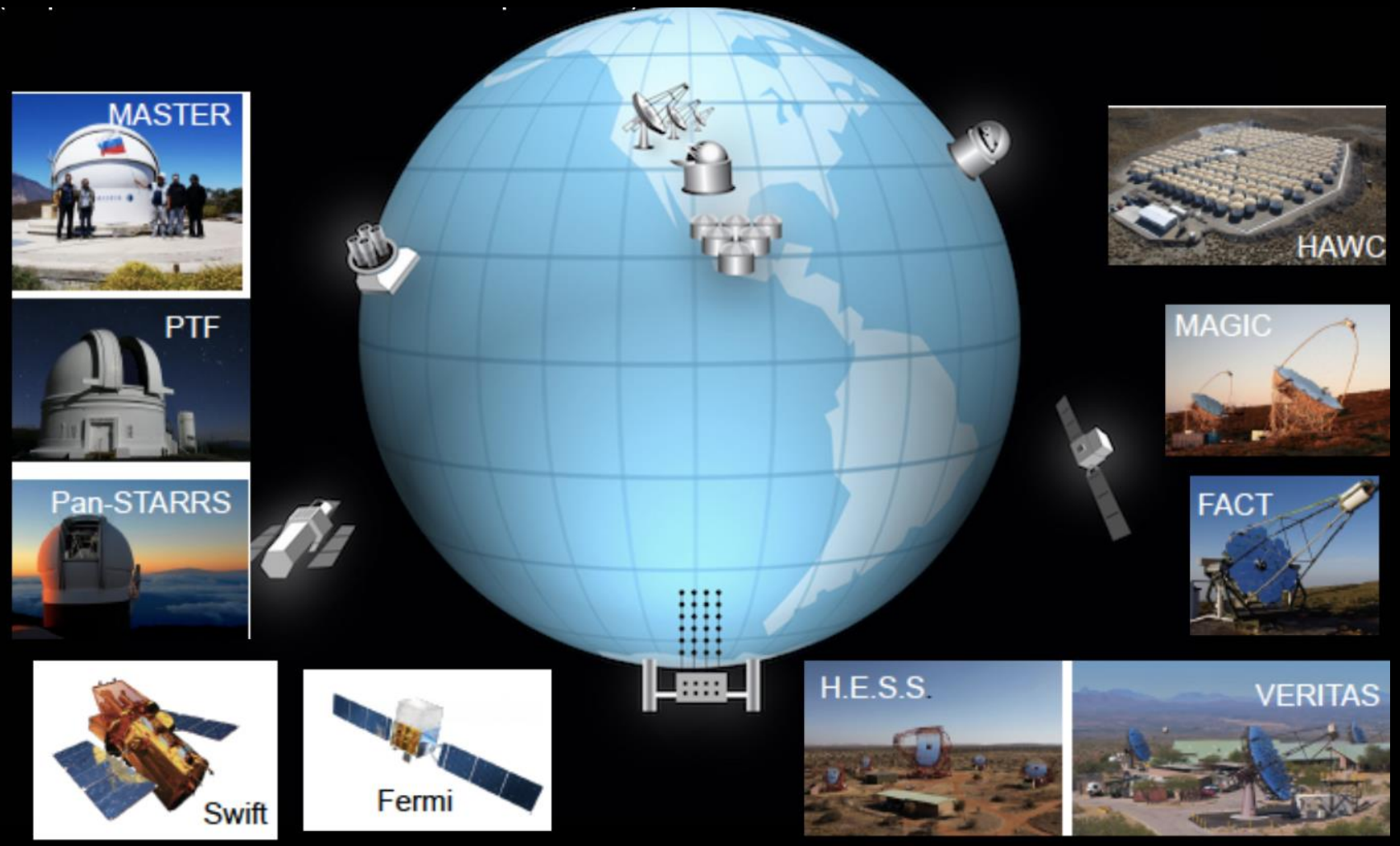
ces?

IceCube Realtime Public Alerts

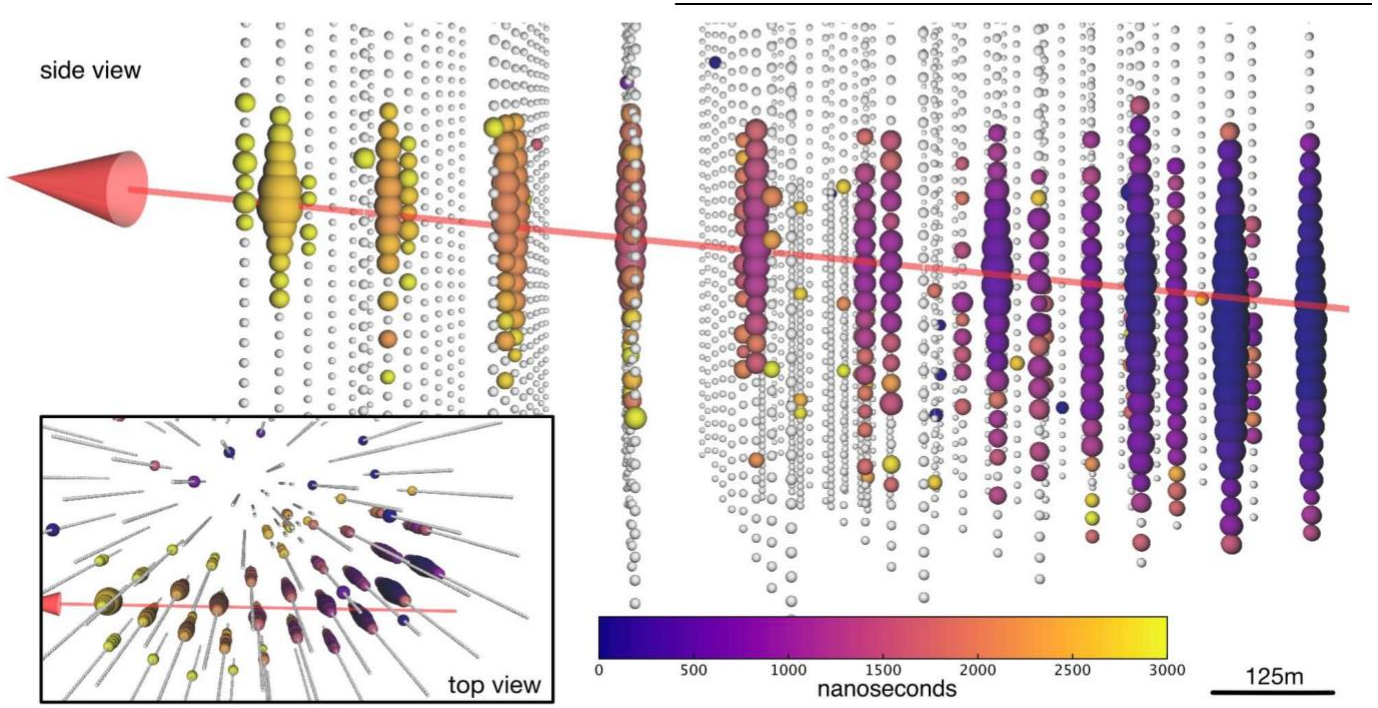
- Operating since 2016
- ~ 8 public track alerts per year with $E>10^{14}$ eV
- ~ 3 have probability of being of cosmic origin > 50% (depends on assumed cosmic spectrum)
- Alerts transmitted via satellite to GCN (Gamma-ray Coordination Network) in < 1 min



2017 September 22: Alert event IceCube-170922A

- 23.7 ± 2.8 TeV muon energy loss in the detector
  → most probable neutrino energy ~ 290 TeV
  (upper limit at 90% CL is 4.5 (7.5) PeV for a spectral index of -2.13 (-2))
- Signalness: 56.5 %

RA: 77.43° (-0.65°/+0.95° 90% CL)
Dec: 5.72° (-0.30°/+0.50° 90% CL)




```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy
neutrino candidate event
DATE:    17/09/23 01:09:26 GMT
FROM:    Erik Blaufuss at U. Maryland/IceCube
<blaufuss@icecube.umd.edu>

Claudio Kopper (University of Alberta) and Erik Blaufuss
(University of  Maryland) report on behalf of the IceCube
Collaboration (http://icecube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy
event with a high probability of being of astrophysical origin.
The event was identified by the  Extremely High Energy (EHE)
track event selection. The IceCube detector was in a normal
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interaction vertex that is outside the detector, produce a muon
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28 Sept 2017, Fermi-LAT gamma-ray observations

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

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on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

4 Oct 2017, MAGIC VHE gamma-ray observations

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

> 400 GeV γ-rays from the blazar

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

Looking at neutrinos from TXS 0506+056 back in time

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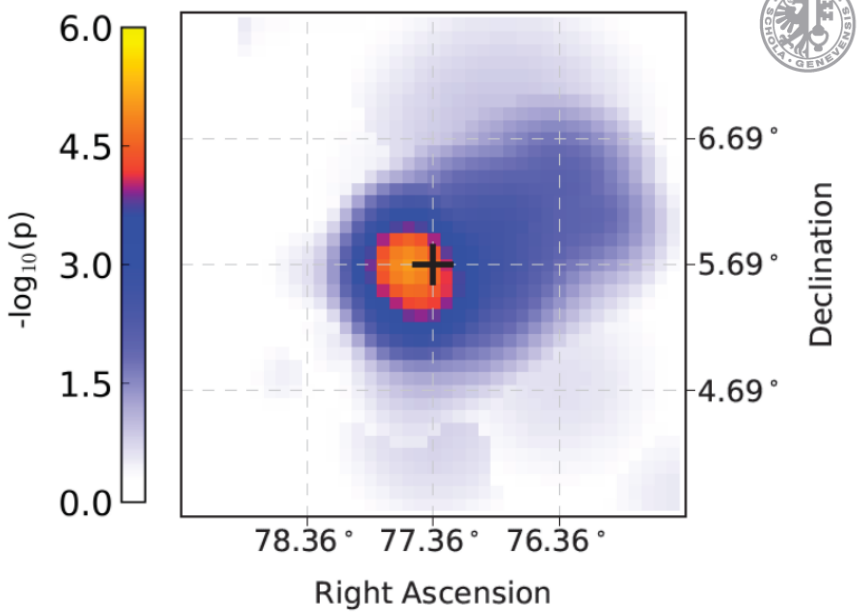
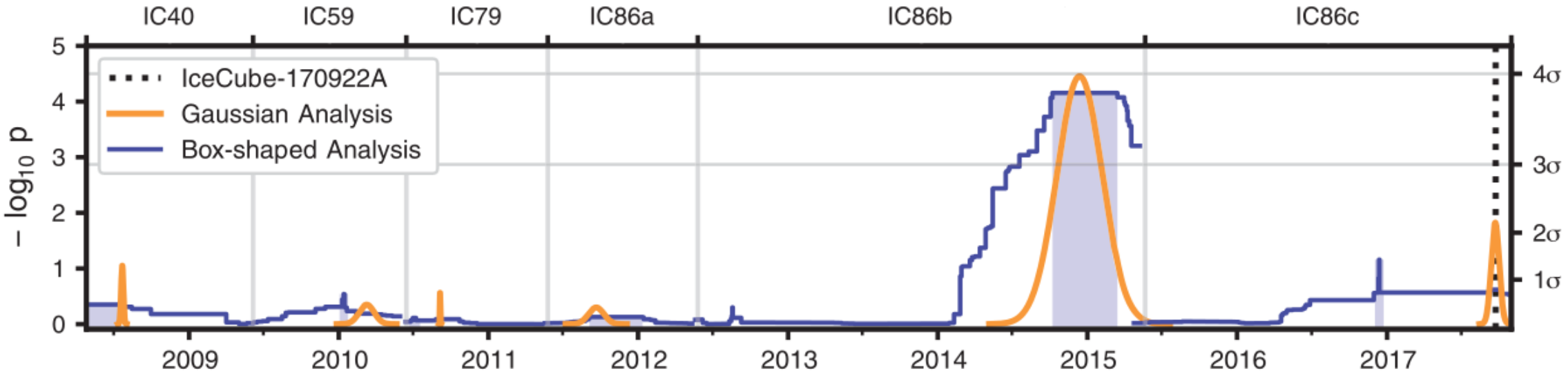
A. Christov,
I. Al Samarai,
T. Montaruli

- Analysis of 9.5 yr in 6 independent periods
- 150 day flare in Dec 2014 of 19 events
- Inconsistent with background at 3.5σ
- Spectrum $E^{-2.1}$



Science 361 (2018)
no.6398, 147-151



… so where do they come from?

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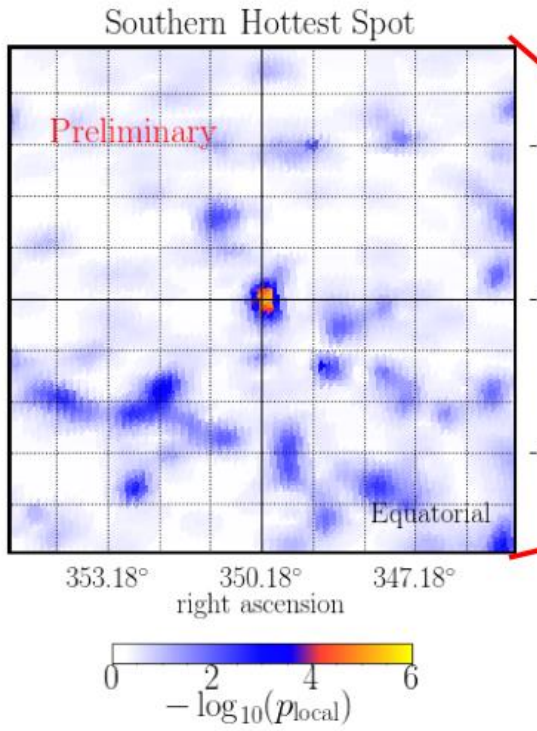
T. Carver, T. Montaruli

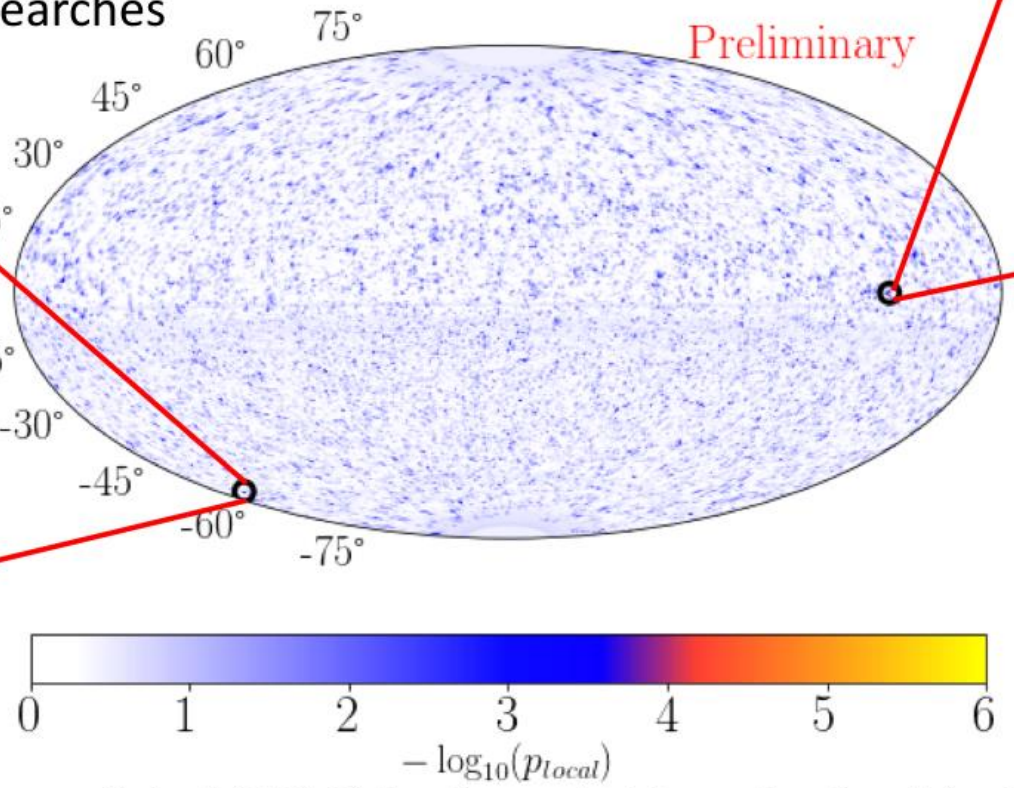
To be submitted to PRL

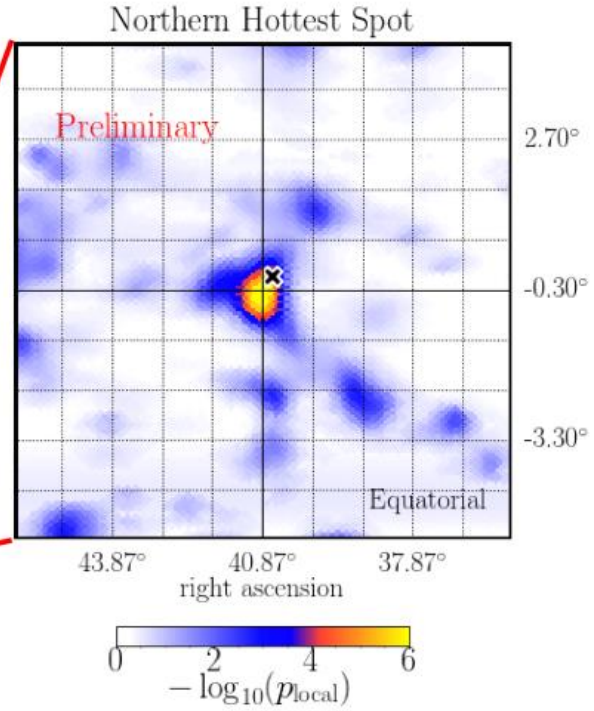
All sky combined 10 year search

- 1.1M neutrino events
- ~1-10 cosmic neutrino/year expected above 50 TeV

Using high energy through-going tracks and tracks optimized for point source searches







Hottest spot in Northern Hemisphere coincides with 2.9sigma excess at the position of NGC 1068 → evidence of non-uniform map

arXiv:1908.05993v1

… so where do they come from?

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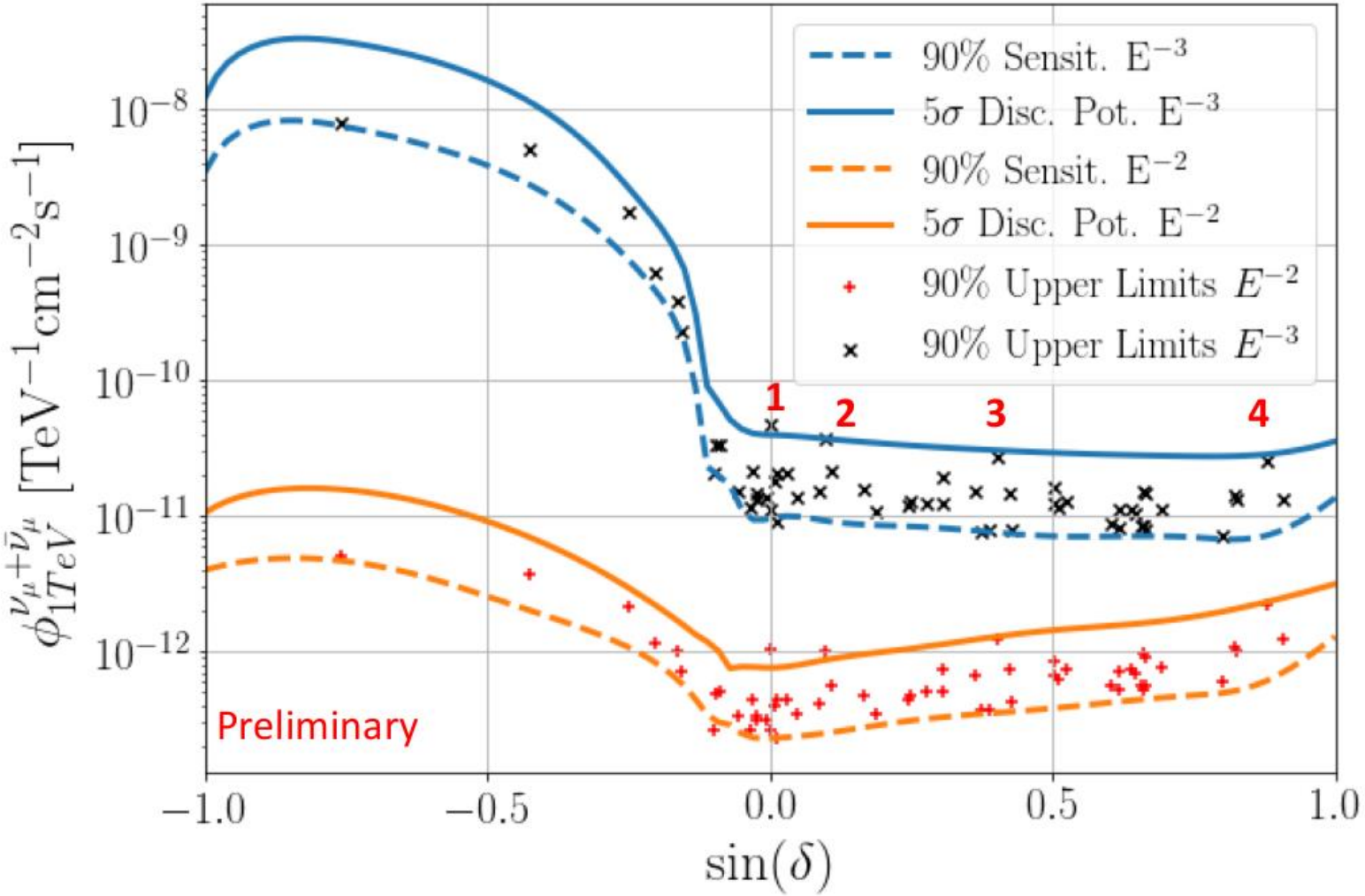
T. Carver,
T. Montaruli

To be submitted to PRL

All sky combined 10 year search

Source list of 110 Galactic and Extragalactic objects

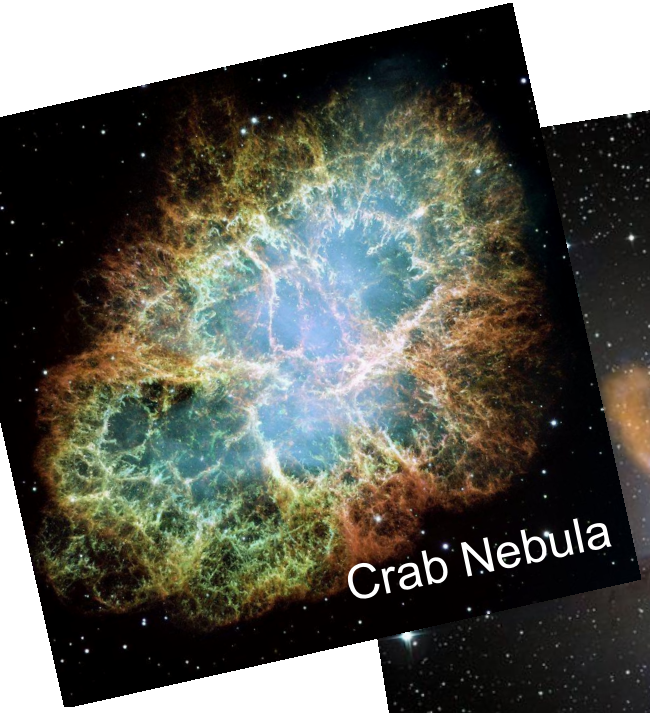


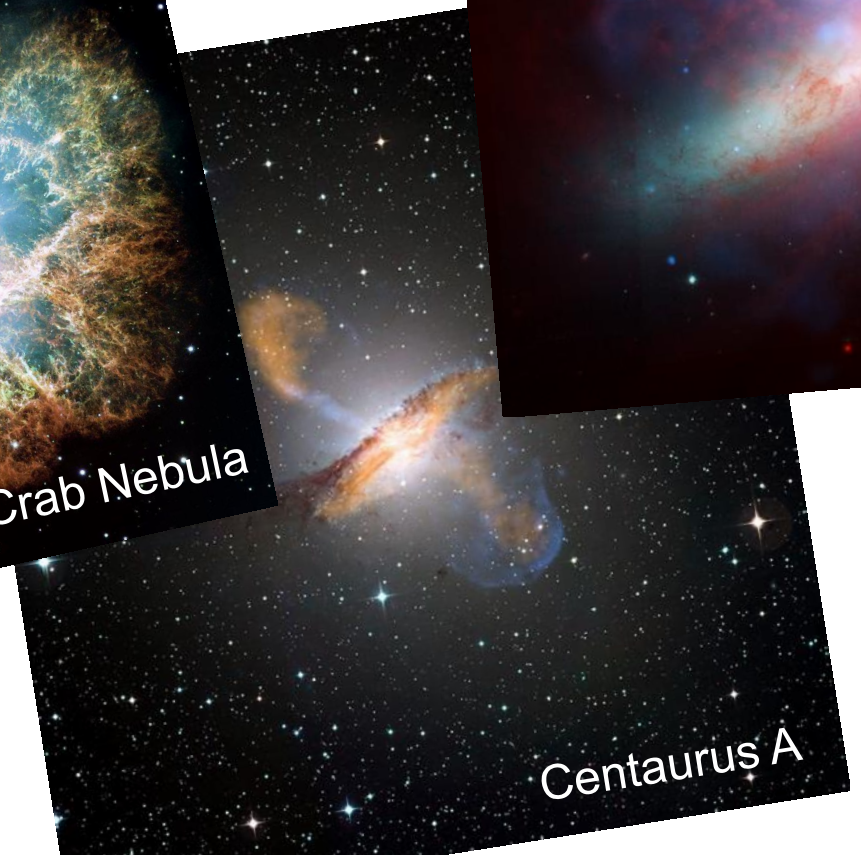
1. NGC 1068
2. TXS 0506 + 056
3. PKS 1424 + 240
4. GB6 J1542+6129

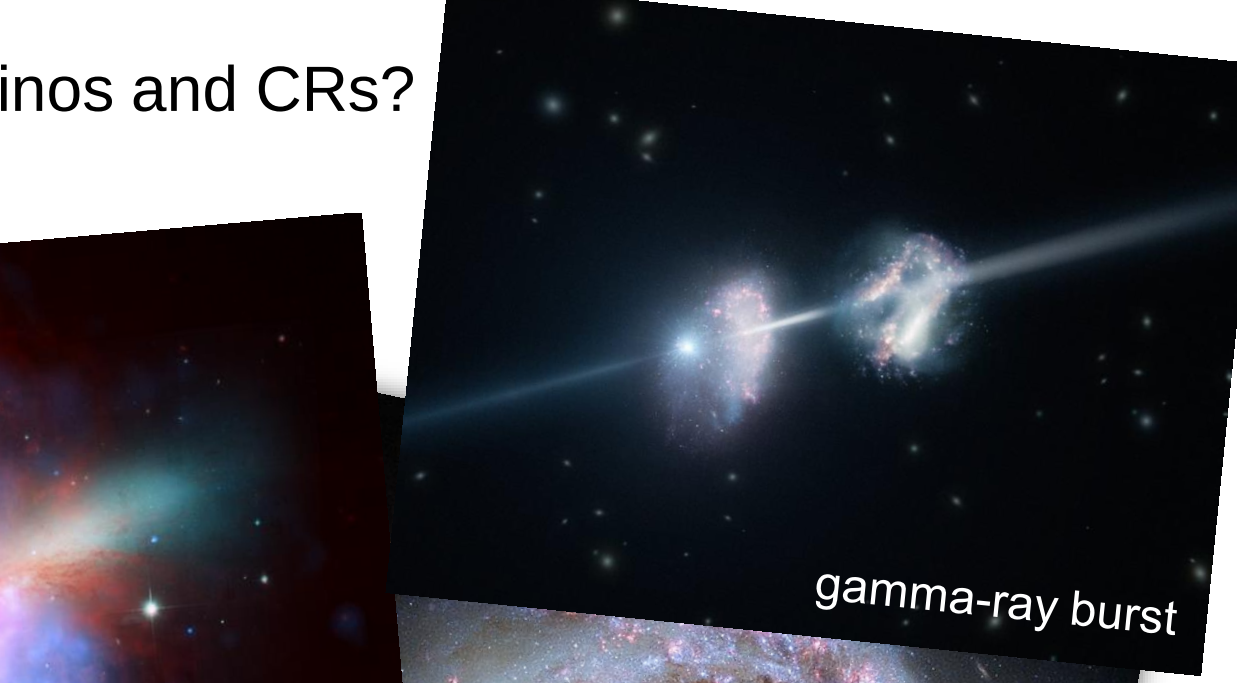
Source list search is incompatible with background at 3.3σ (2.25σ without TXS 0506)

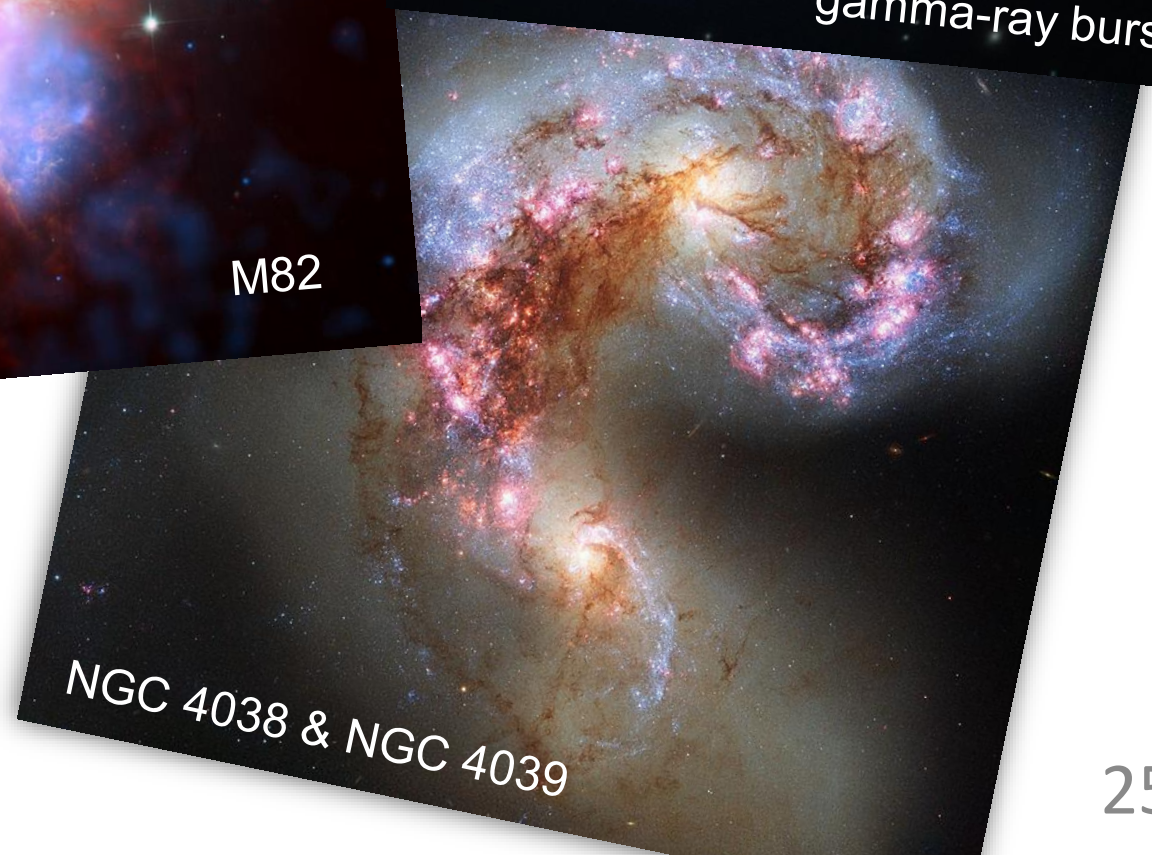
arXiv:1908.05993v1

- Are blazars the sources of the diffuse neutrinos and CRs?
- Or galaxy mergers?
- Starbust galaxies?
- Gamma ray bursts?
- Neutron stars?









Many other point-source searches

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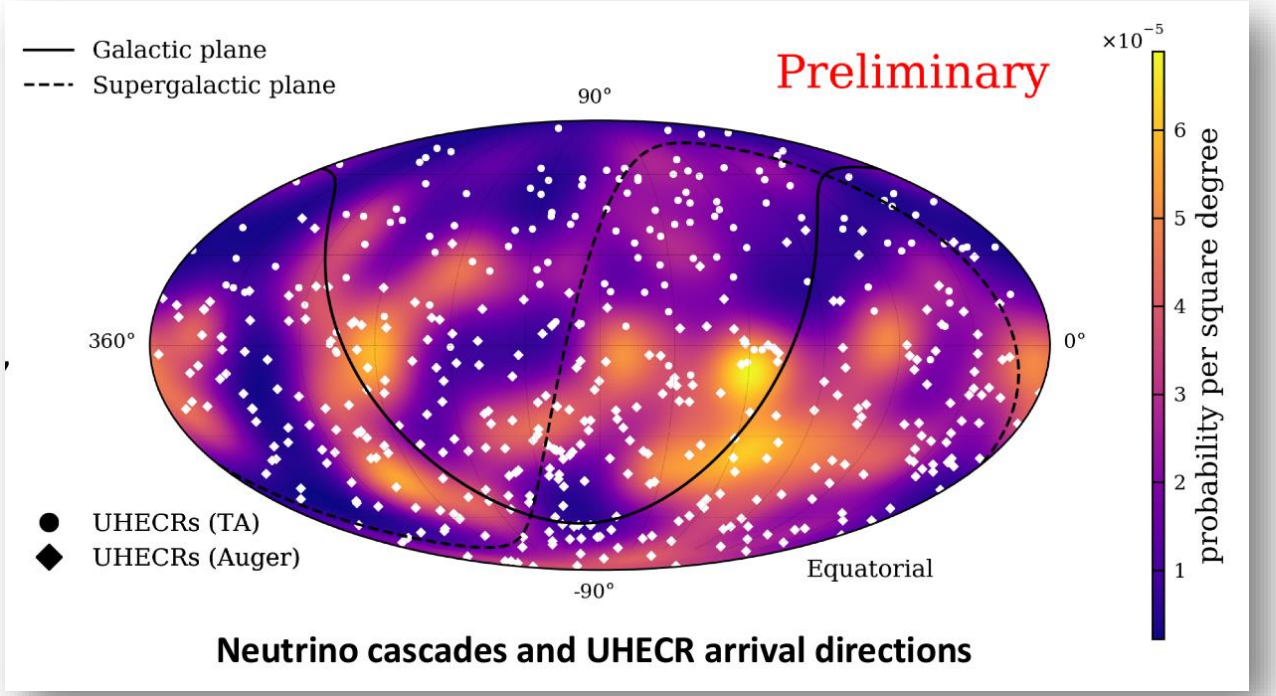
C. Alispach,
A. Barbano,
T. Montaruli

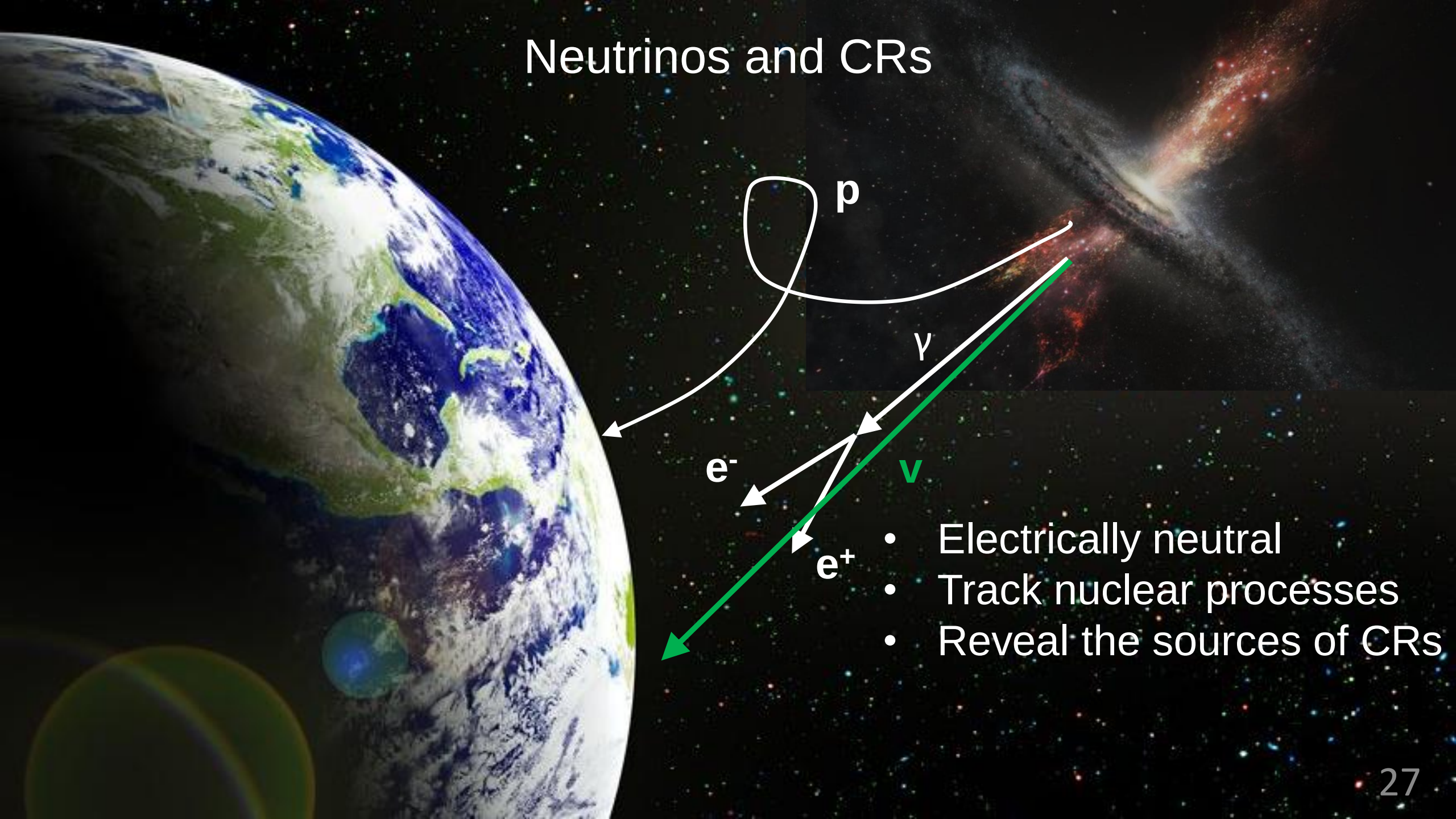
ICRC 2019

- Combined ANTARES, IceCube, Auger and Telescope Array search for common origin of ultra-high energy CRs and high-energy neutrinos



Neutrino cascades and UHECR arrival directions

Neutrinos and CRs



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- Track nuclear processes
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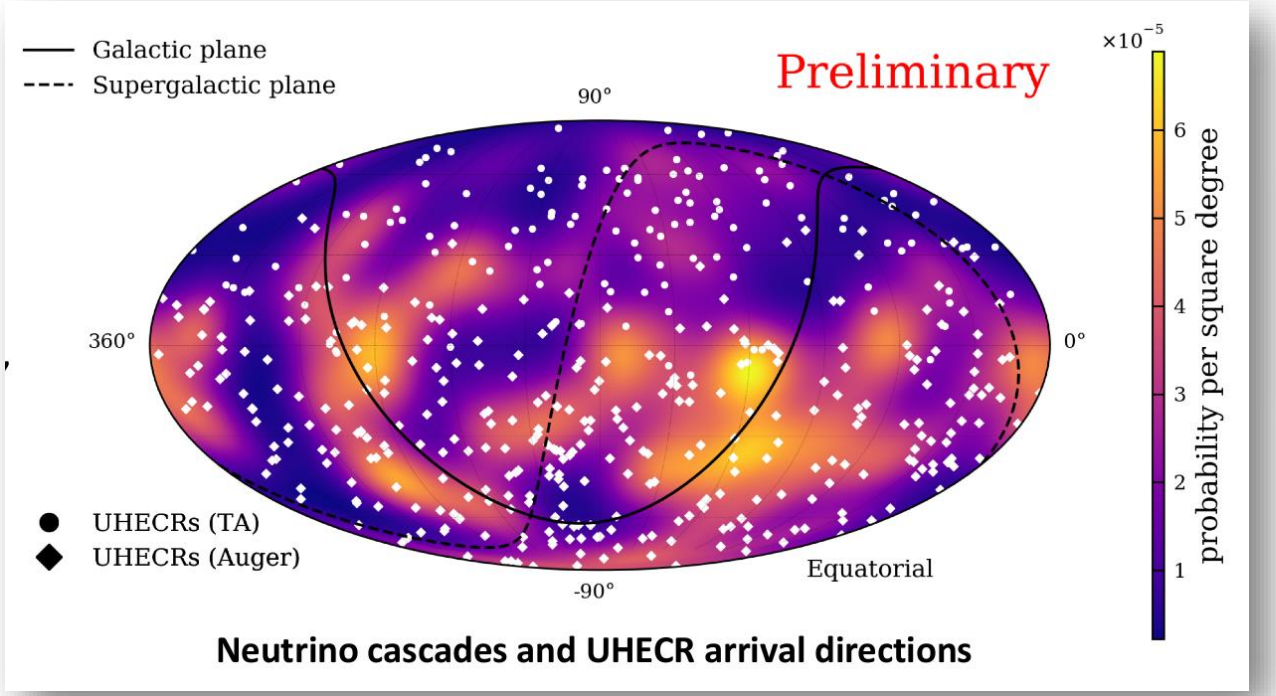
- Combined ANTARES, IceCube, Auger and Telescope Array search for common origin of ultra-high energy CRs and high-energy neutrinos

Method: stacked unbinned likelihood:

$$\ln \mathscr{L}(n_s) = \sum_{i=1}^{N_{\mathrm{Auger}}} \ln\left(\frac{n_s}{N_{\mathrm{CR}}} S^i_{\mathrm{Auger}} + \frac{N_{\mathrm{CR}} - n_s}{N_{\mathrm{CR}}} B^i_{\mathrm{Auger}}\right) + \sum_{i=1}^{N_{\mathrm{TA}}} \ln\left(\frac{n_s}{N_{\mathrm{CR}}} S^i_{\mathrm{TA}} + \frac{N_{\mathrm{CR}} - n_s}{N_{\mathrm{CR}}} B^i_{\mathrm{TA}}\right),$$

n_s = number of UHECR signal event (free parameter)
N_{CR} = total number of CR events
$S^i_{\text{CR experiment}}$ = signal PDF
$B^i_{\text{CR experiment}}$ = background PDF



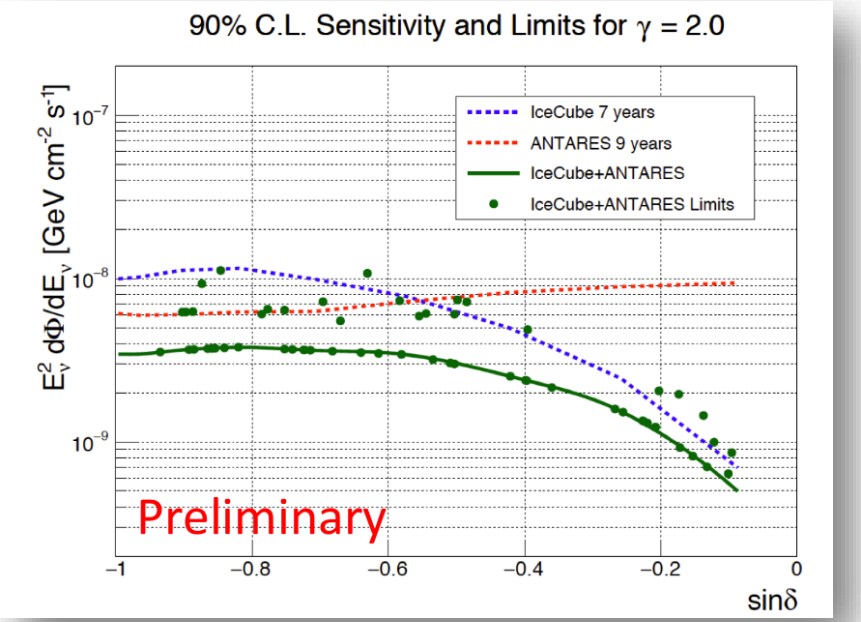
Neutrino cascades and UHECR arrival directions

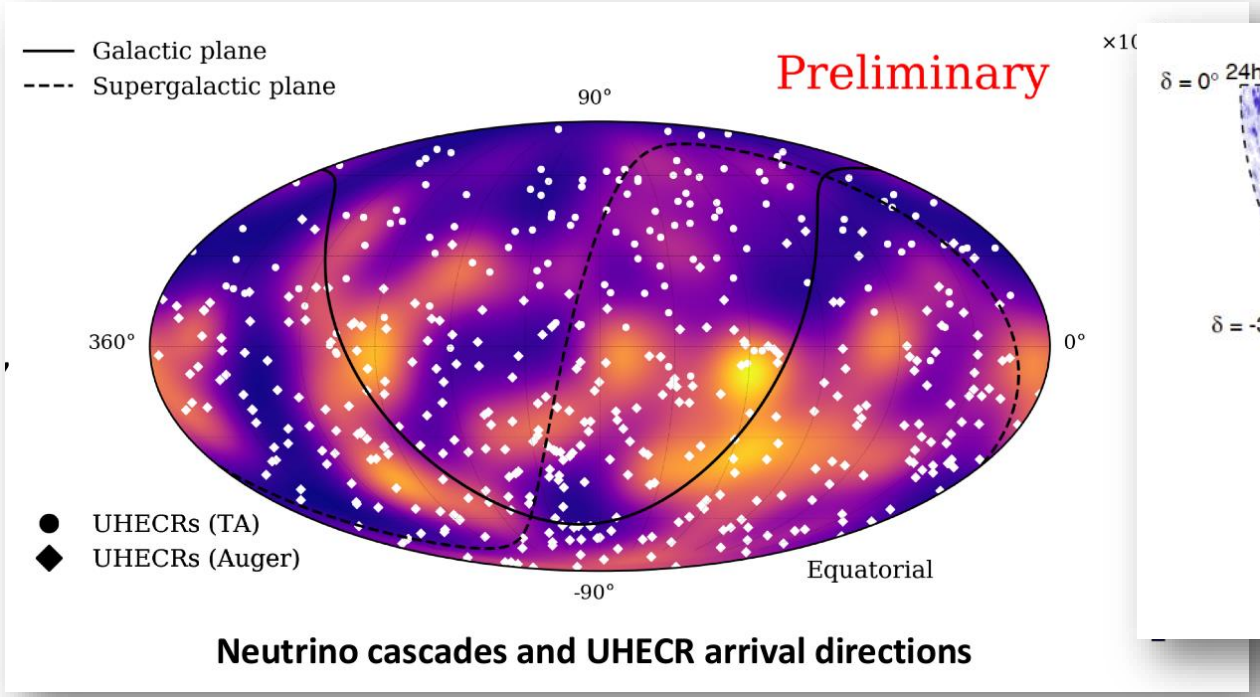
Gal. magnetic deflection	(2.4°, 3.7°)	(4.8°,7.4°)	(7.2°,11.1°)
p-values (tracks)	underfluctuation	underfluctuation	underfluctuation
p-values (cascades)	underfluctuation	0.41	0.29

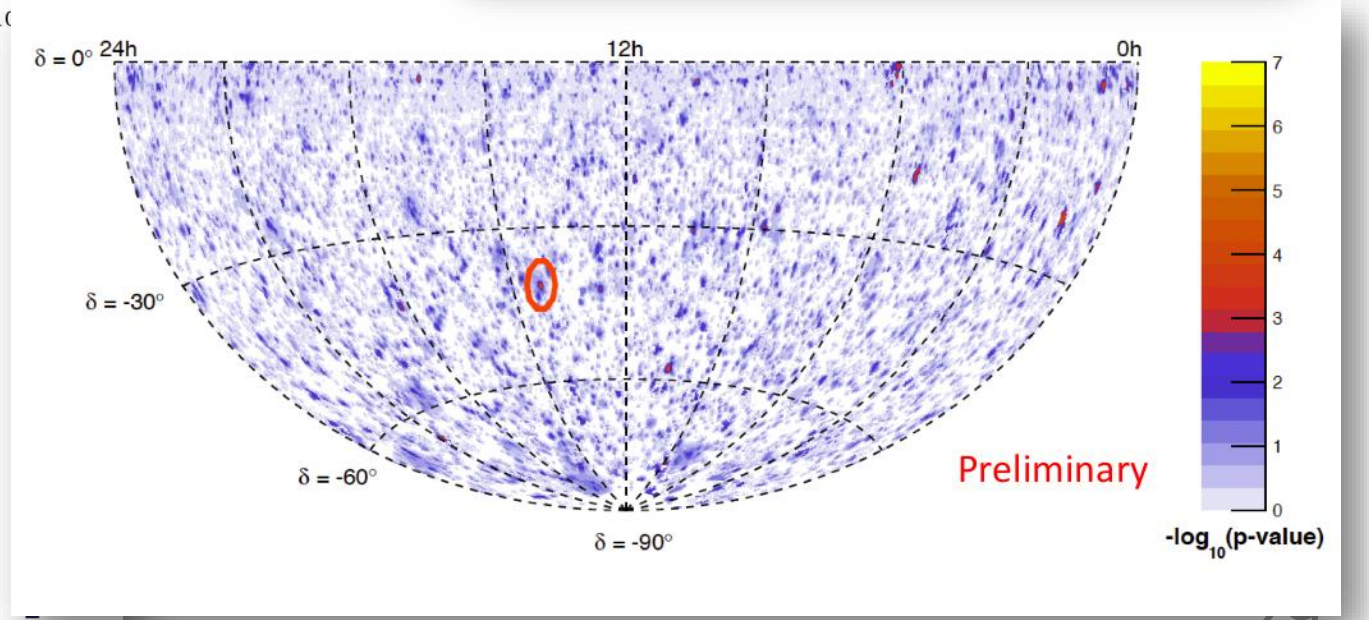
0.90 post-trial

Many other point-source searches

- Combined ANTARES, IceCube, Auger and Telescope Array search for common origin of ultra-high energy CRs and high-energy neutrinos
- Joint Southern sky search with ANTARES







Many other point-source searches

- Combined ANTARES, IceCube, Auger and Telescope Array search for common origin of ultra-high energy CRs and high-energy neutrinos
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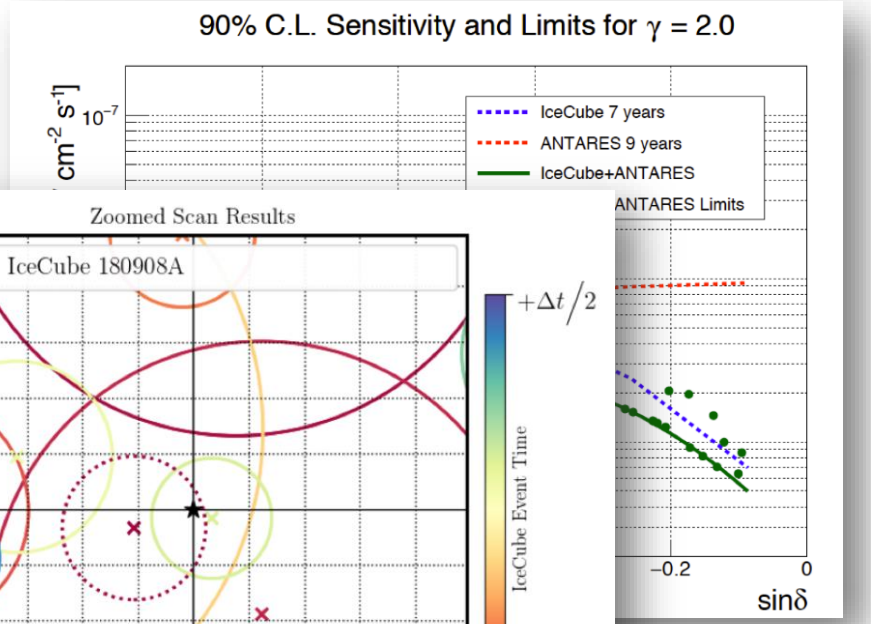
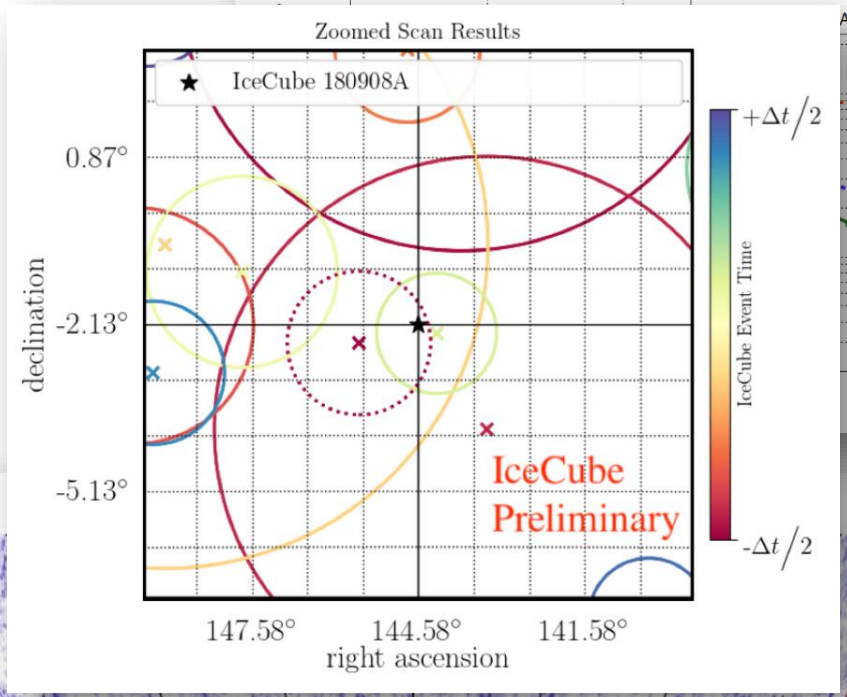
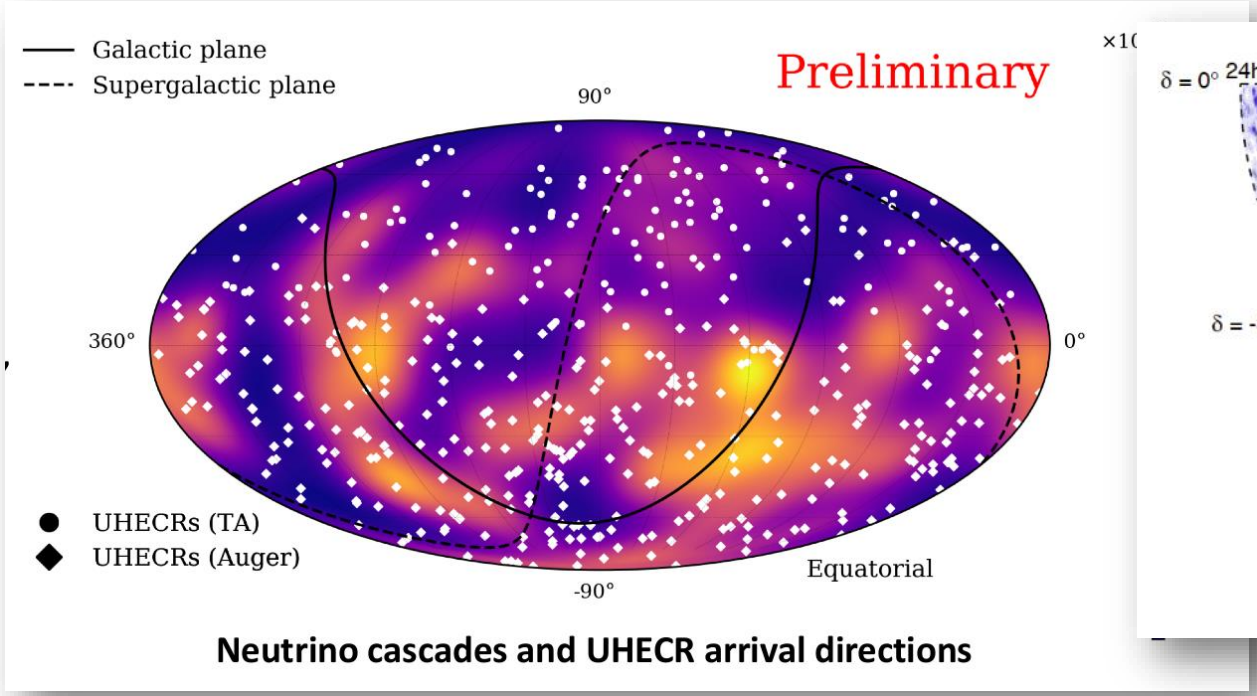
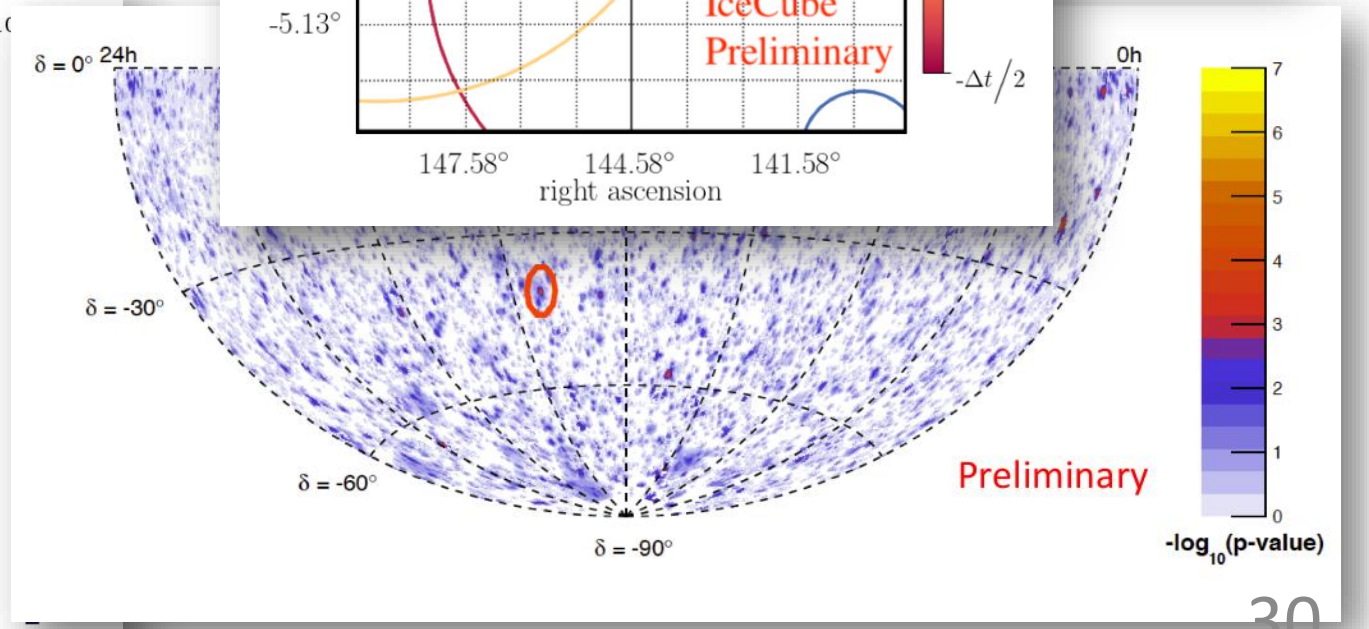
- IceCube follow up on internal and external triggers



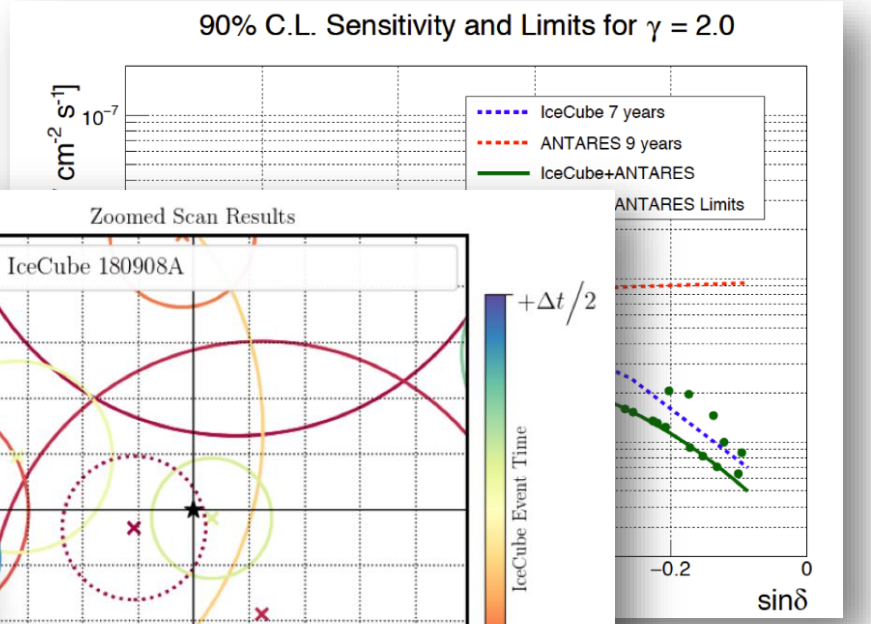


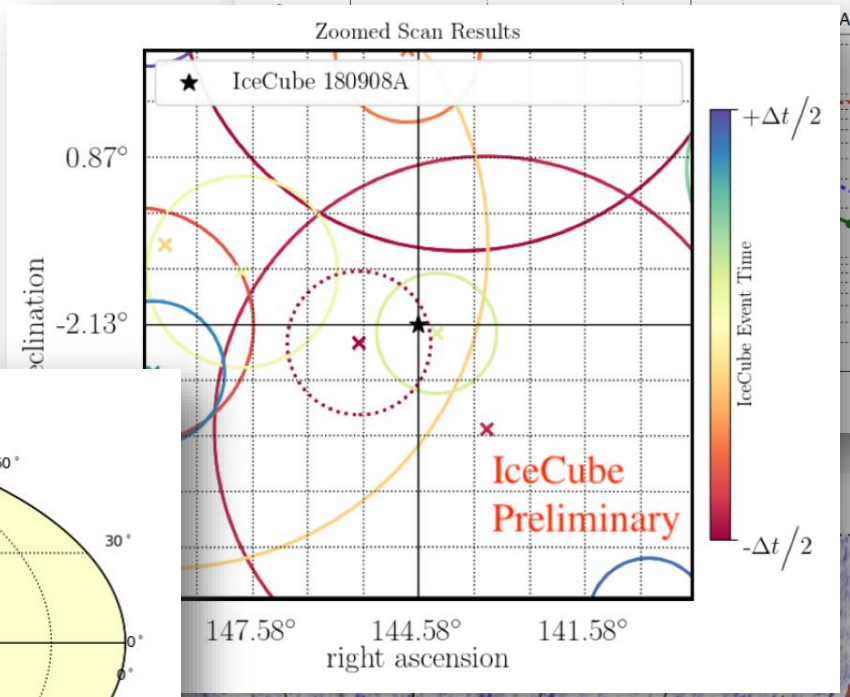


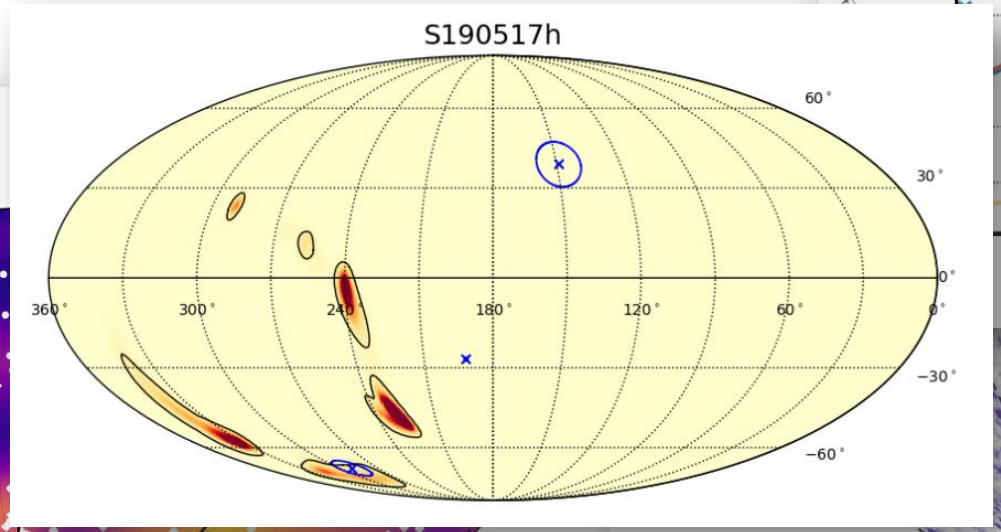


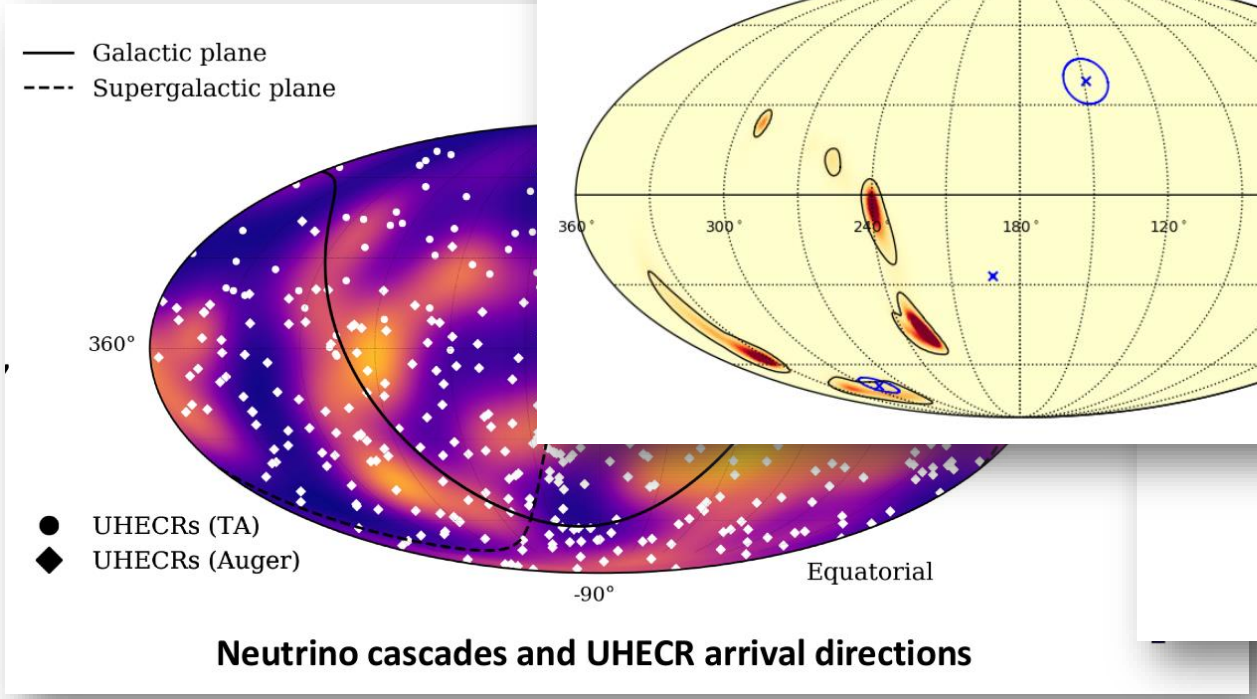
Many other point-source searches

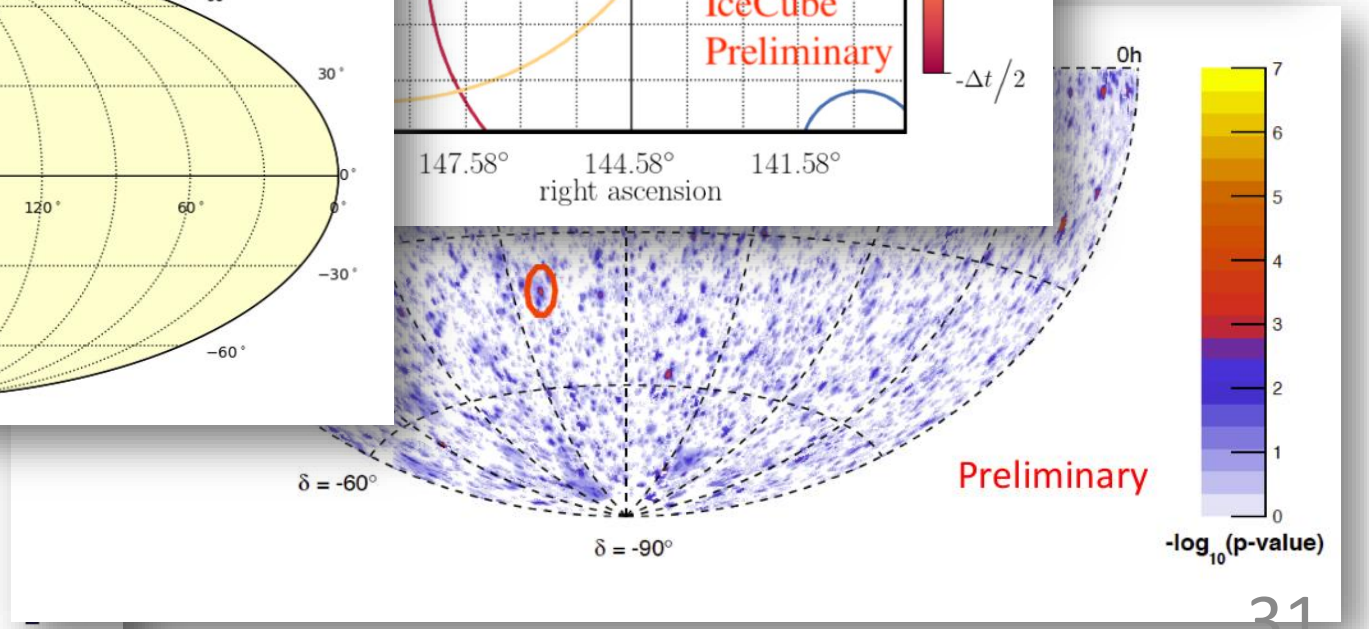
- Combined ANTARES, IceCube, Auger and Telescope Array search for common origin of ultra-high energy CRs and high-energy neutrinos
- Joint Southern sky search with ANTARES
- IceCube follow up on internal and external triggers
- IceCube follow up of Gravitational Wave events











Many other point-source searches

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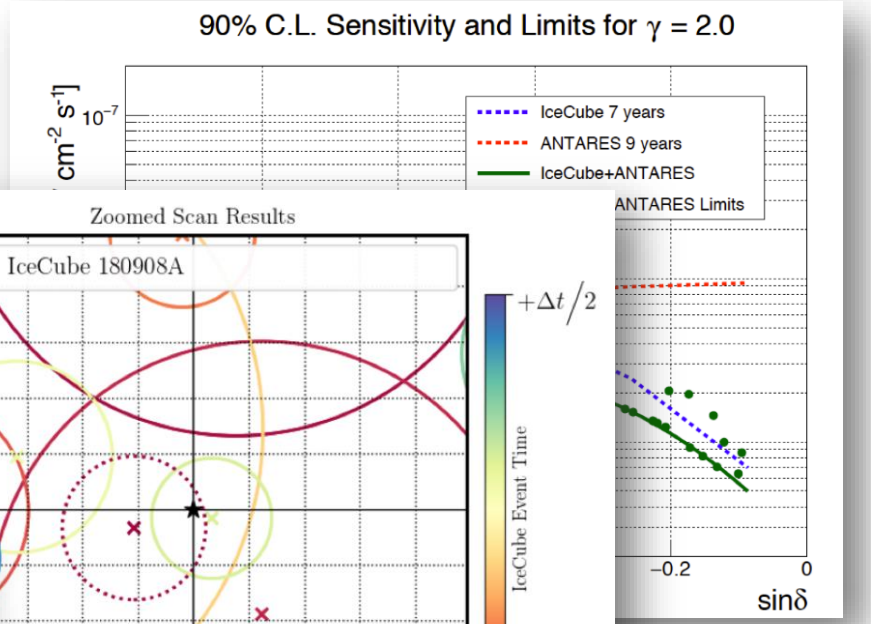
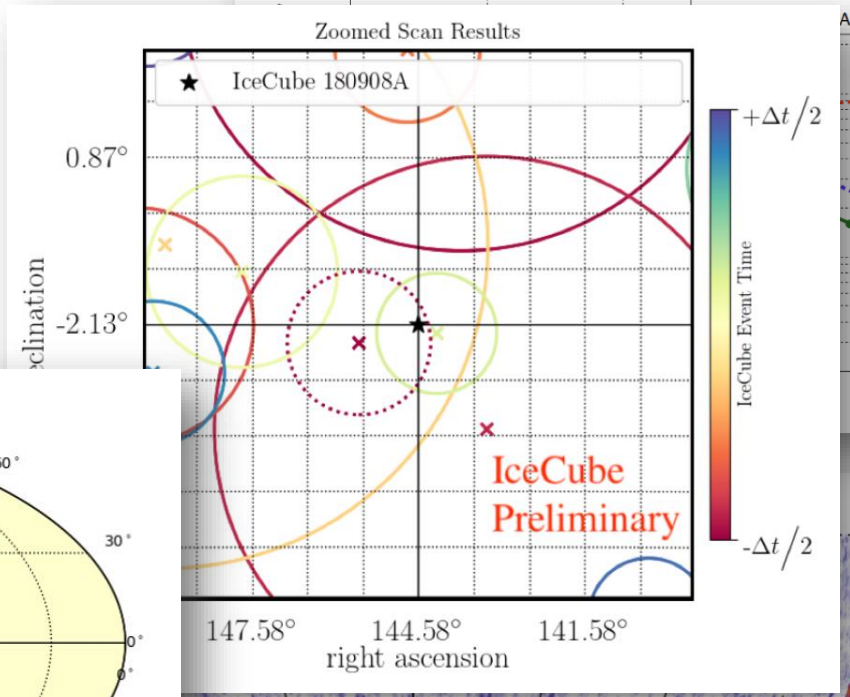
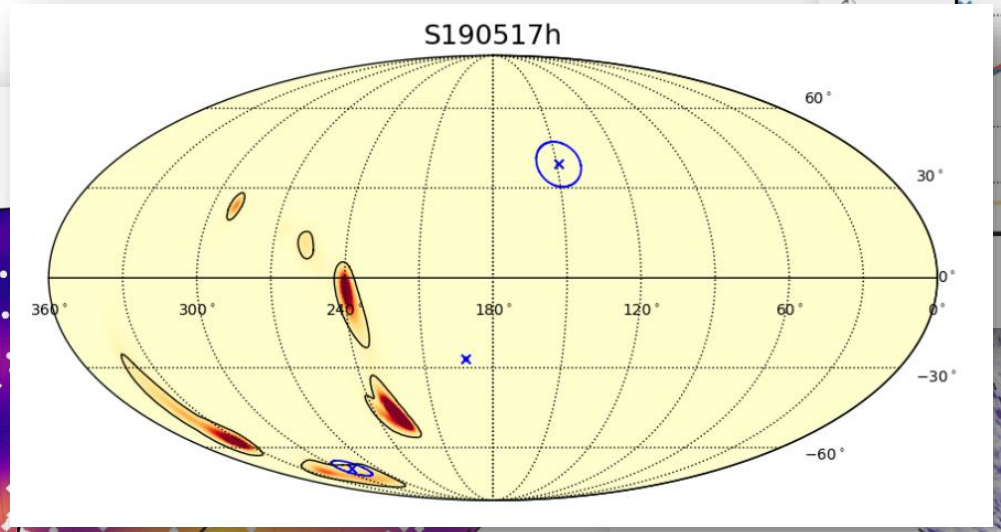
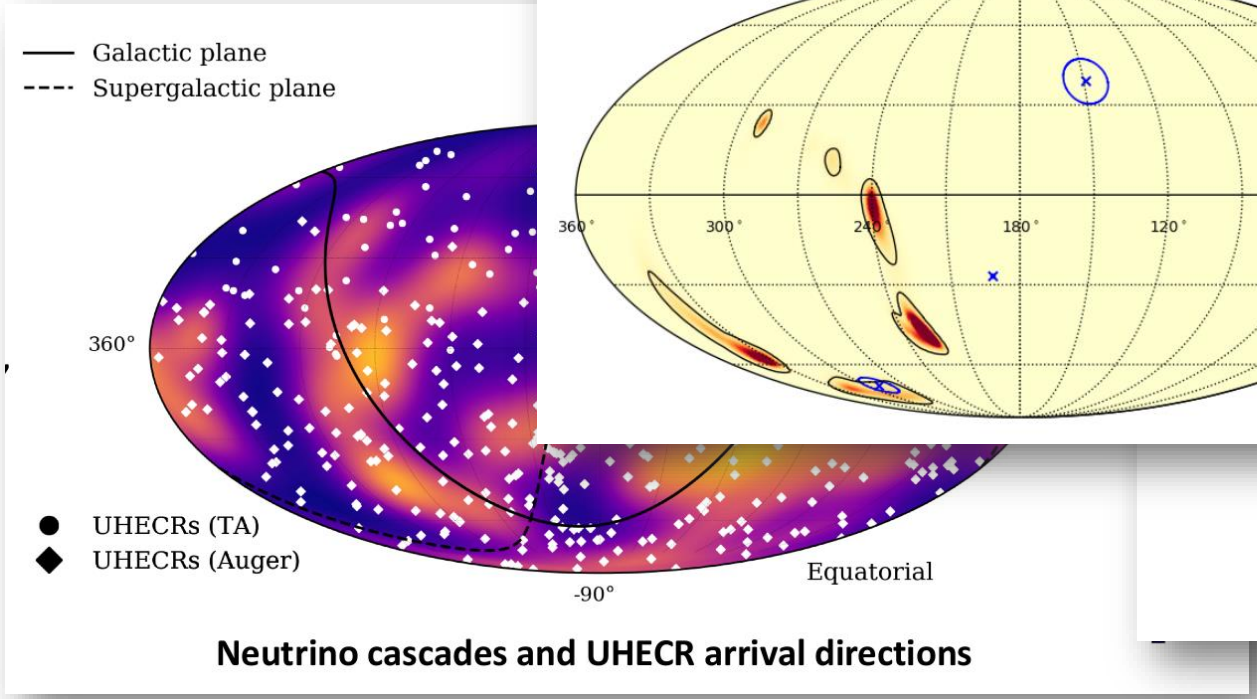
- Joint Southern sky search with ANTARES
- IceCube follow up on internal and external triggers
- IceCube follow up of Gravitational Wave events
- Searches for time-dependent neutrino emissions from blazars
- …

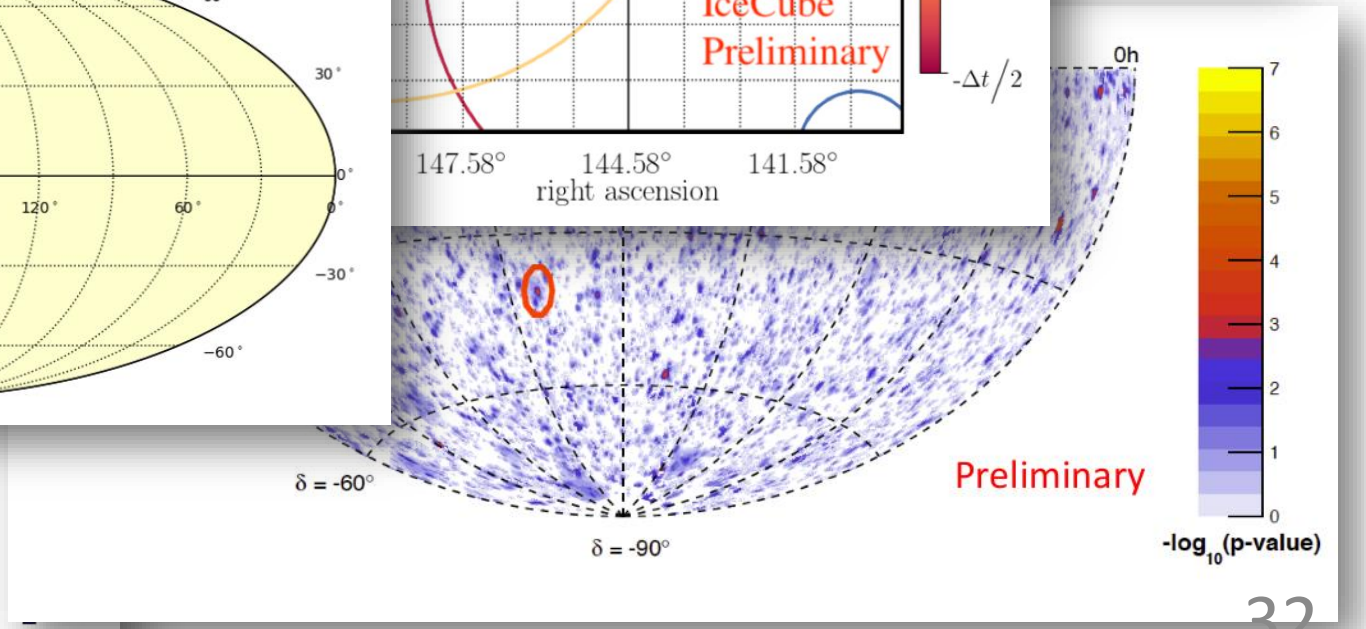






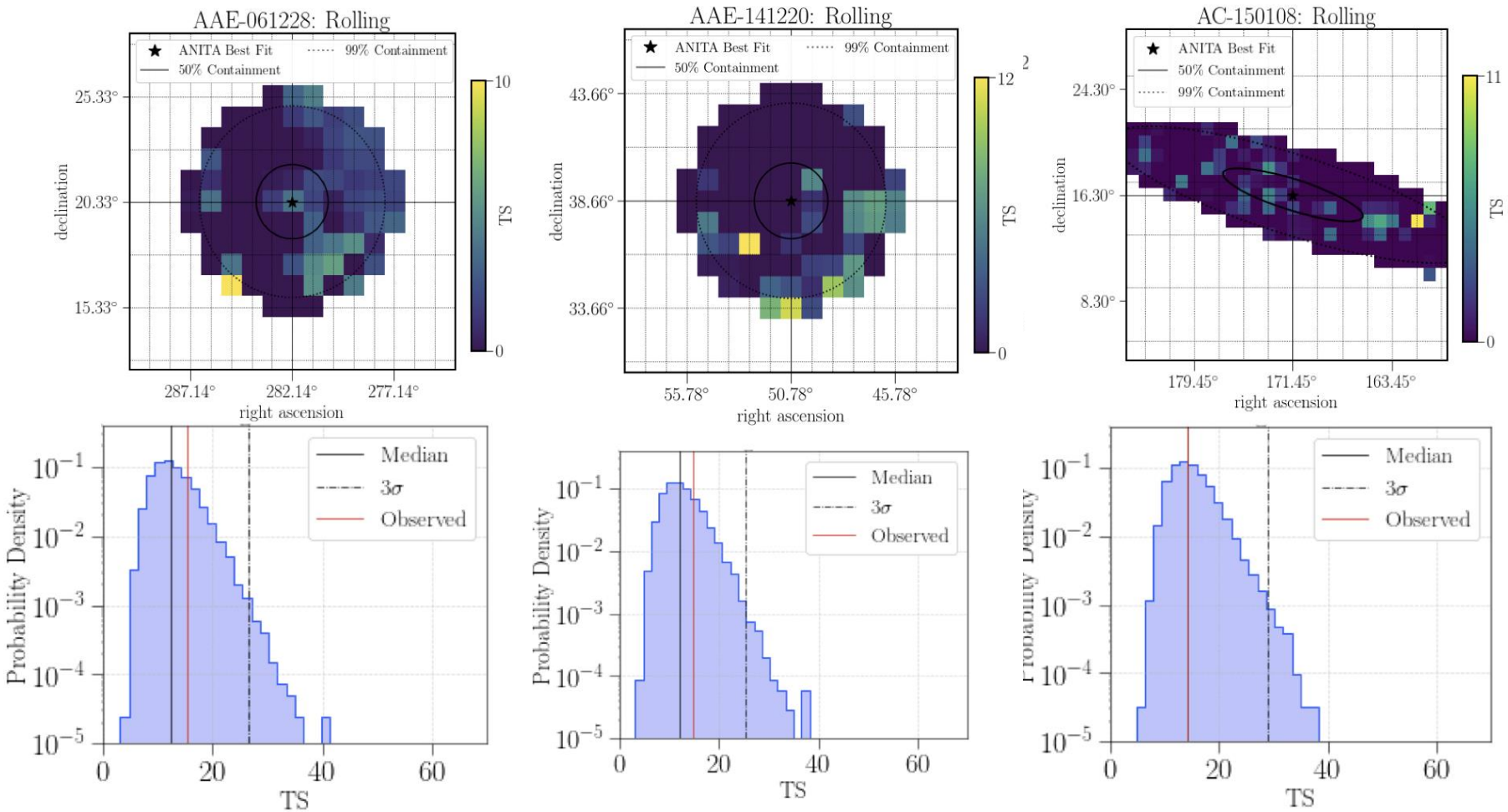


Neutrino cascades and UHECR arrival directions



Search for IceCube events in the direction of ANITA neutrino candidates

- ANITA detected 2 events consistent (with caveats) with upgoing astrophysical ν_τ and 1 neutrino candidate from Askaryan emission searches
- Are the events originating from astrophysical point sources?
- Search for lower energy neutrino counterparts in IceCube: search for spatial and temporal clustering in IceCube data



Results consistent with background

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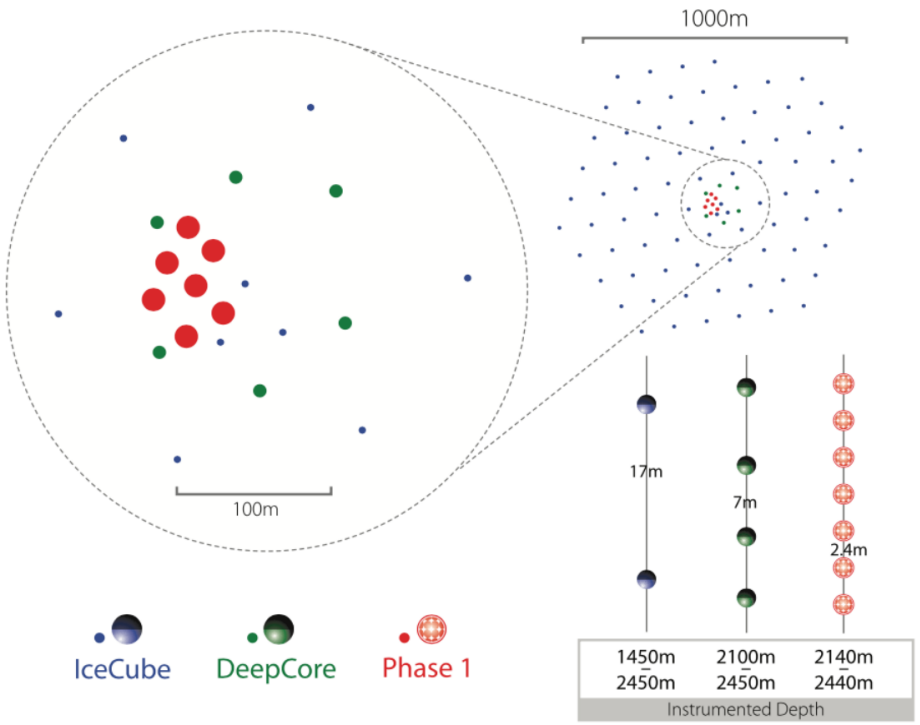
A. Barbano,
T. Montaruli

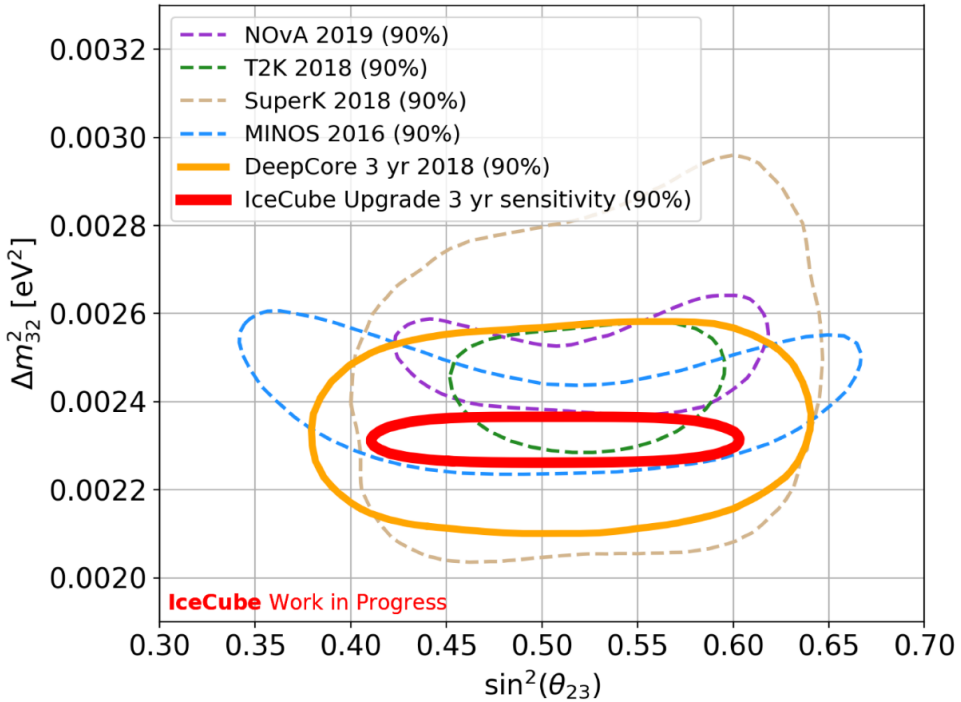
arXiv:1908.08060v1

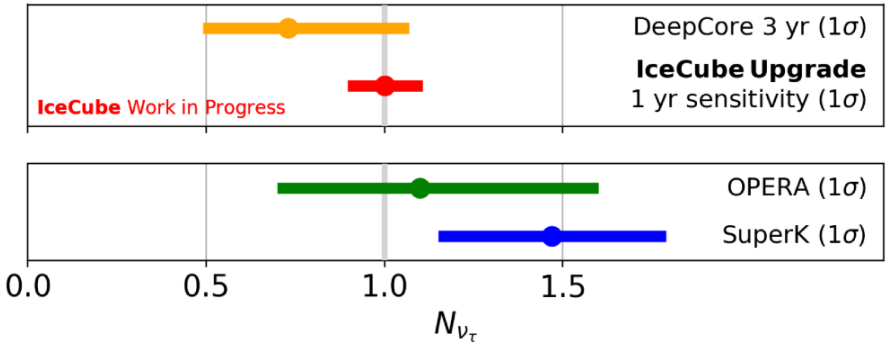
Outlook: IceCube upgrade

- 7 new strings in the DeepCore region (~20m inner-string spacing)
- Planned to deploy in 2022-2023
- New multi-PMT sensors
- New calibration devices
- Precision measurement of atmospheric neutrino oscillation



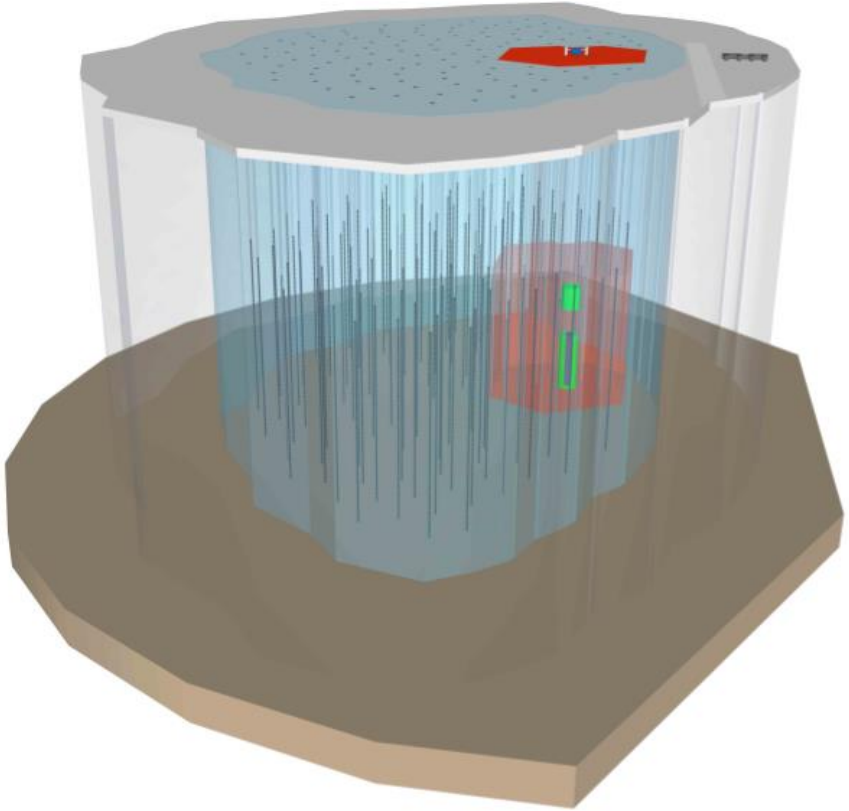
June 2019: NSF gave 20M for icecube upgrade

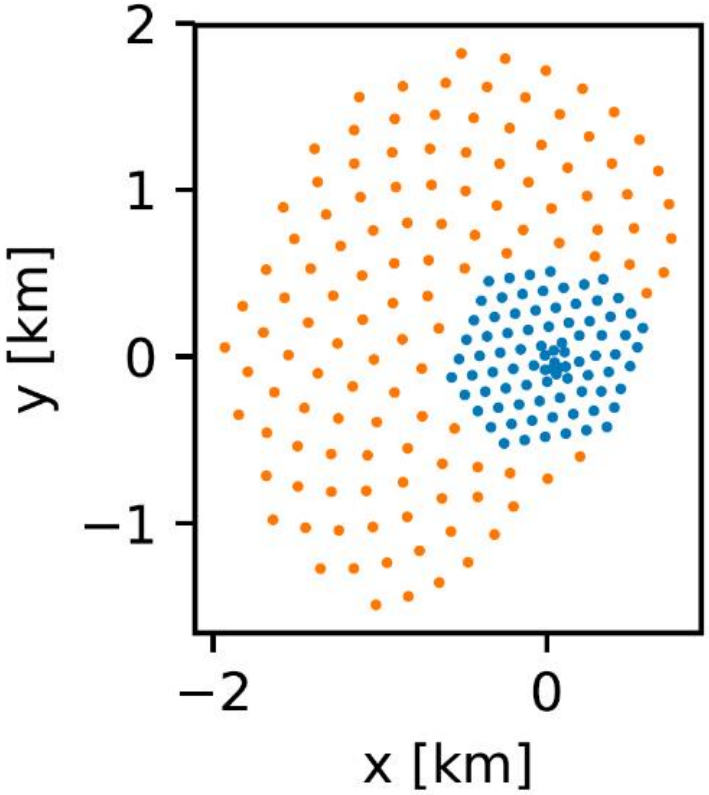




The upgrade will have world-leading sensitivity to tau neutrino appearance

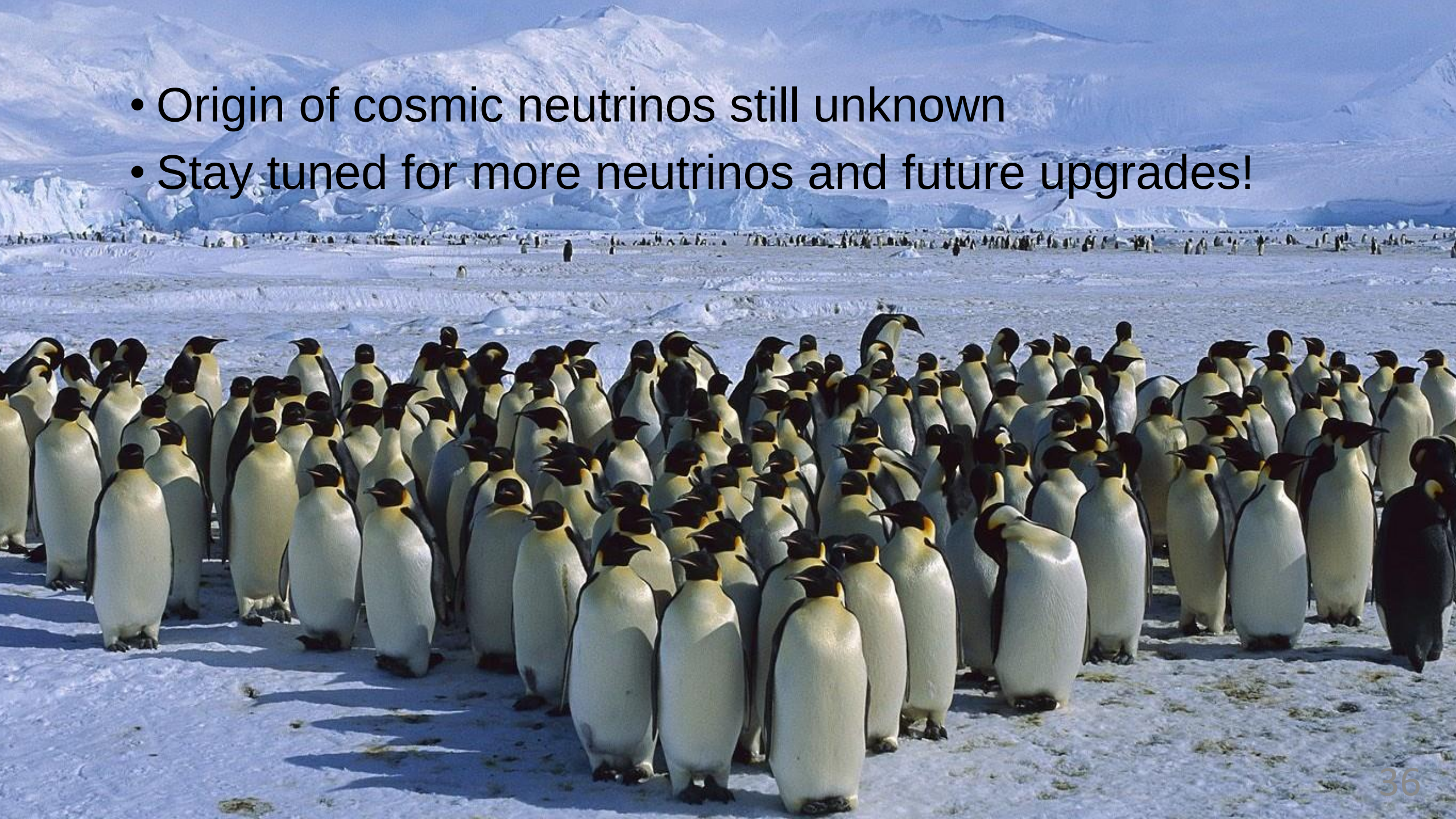
The future: IceCube-Gen2





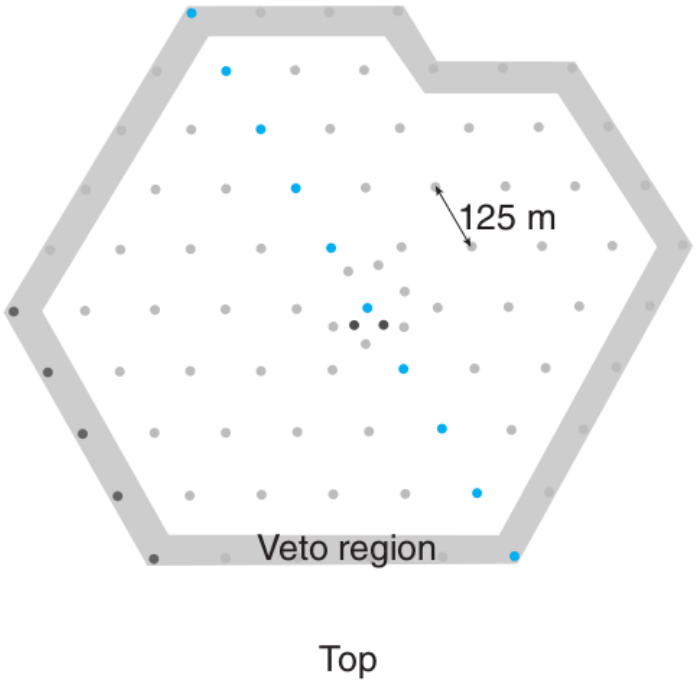
- Multi-component facility (low- and high-energy and multi-messenger)
- In-ice high-energy Cherenkov array with 6-10 km^3 volume
- Will be sensitive to 5x fainter sources
- Wide-band neutrino observatory with optical and radio detectors, surface array

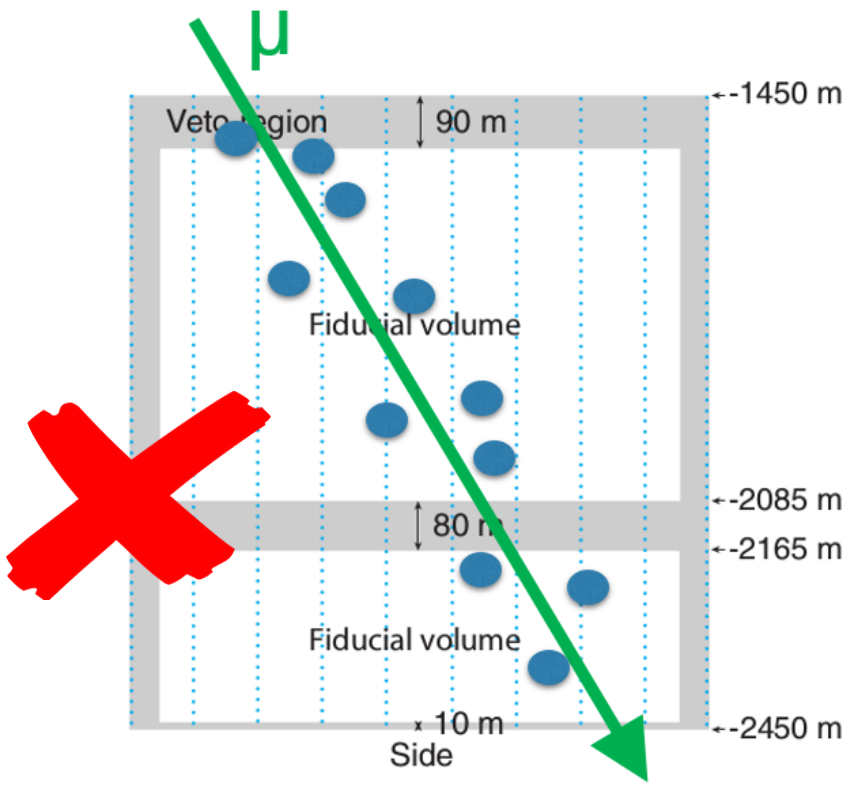
- Origin of cosmic neutrinos still unknown
- Stay tuned for more neutrinos and future upgrades!

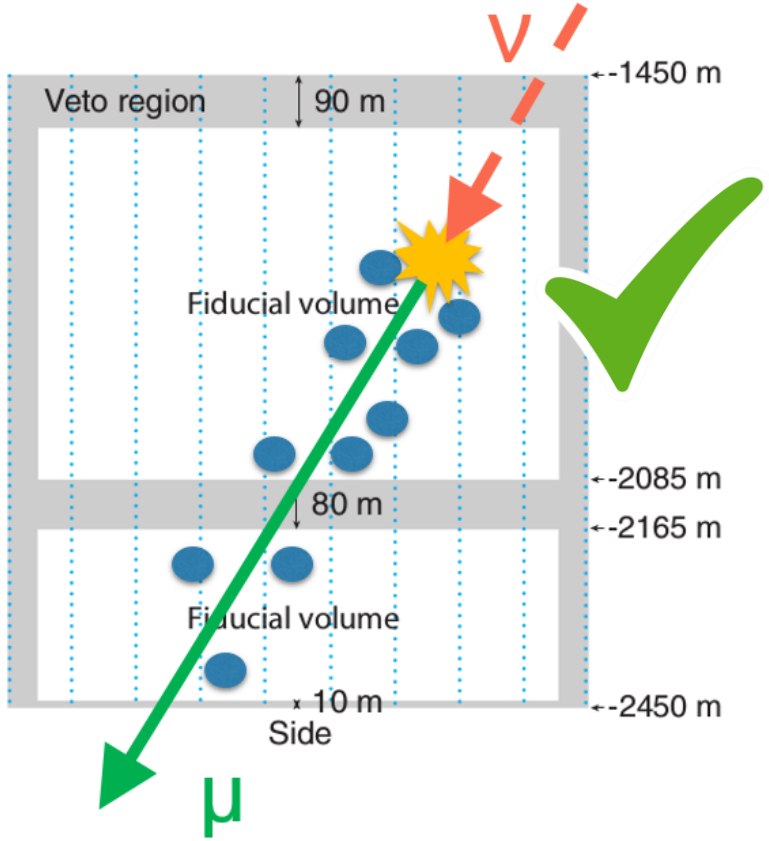


Backup

High-Energy Starting Events (HESE)



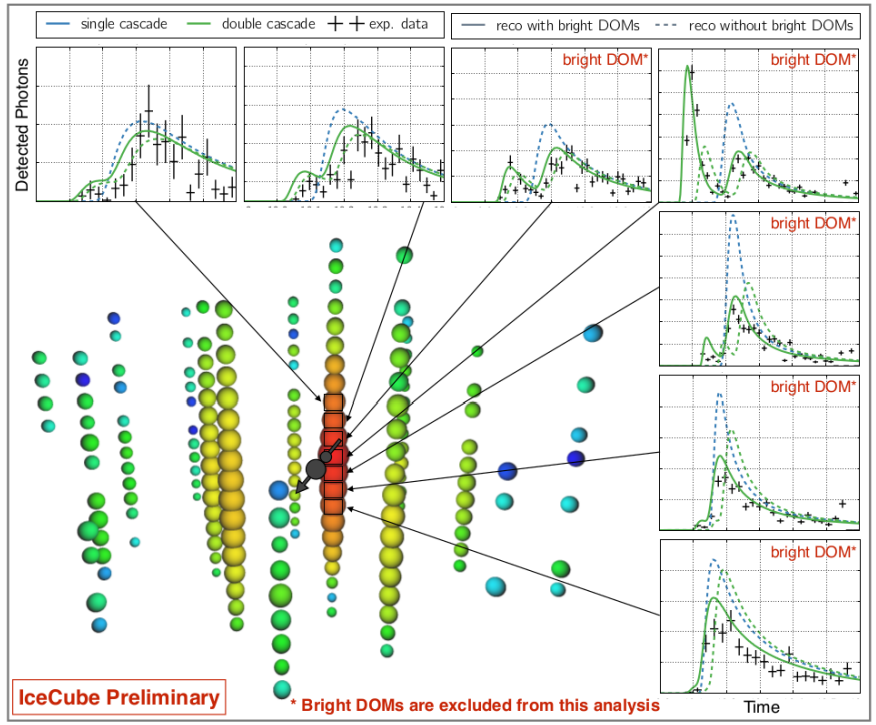


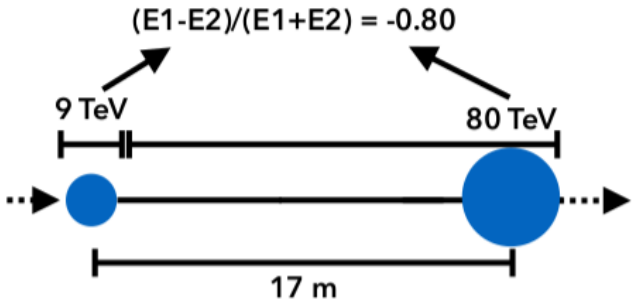


- No light in the veto region
- Active veto for atmospheric μ entering from outside the detector
- Indirect veto for atmospheric ν that are typically accompanied by muons
- All sky, all flavors
- Selection on Q_{tot} > 6000 p.e.
- Sensitive above 60 TeV

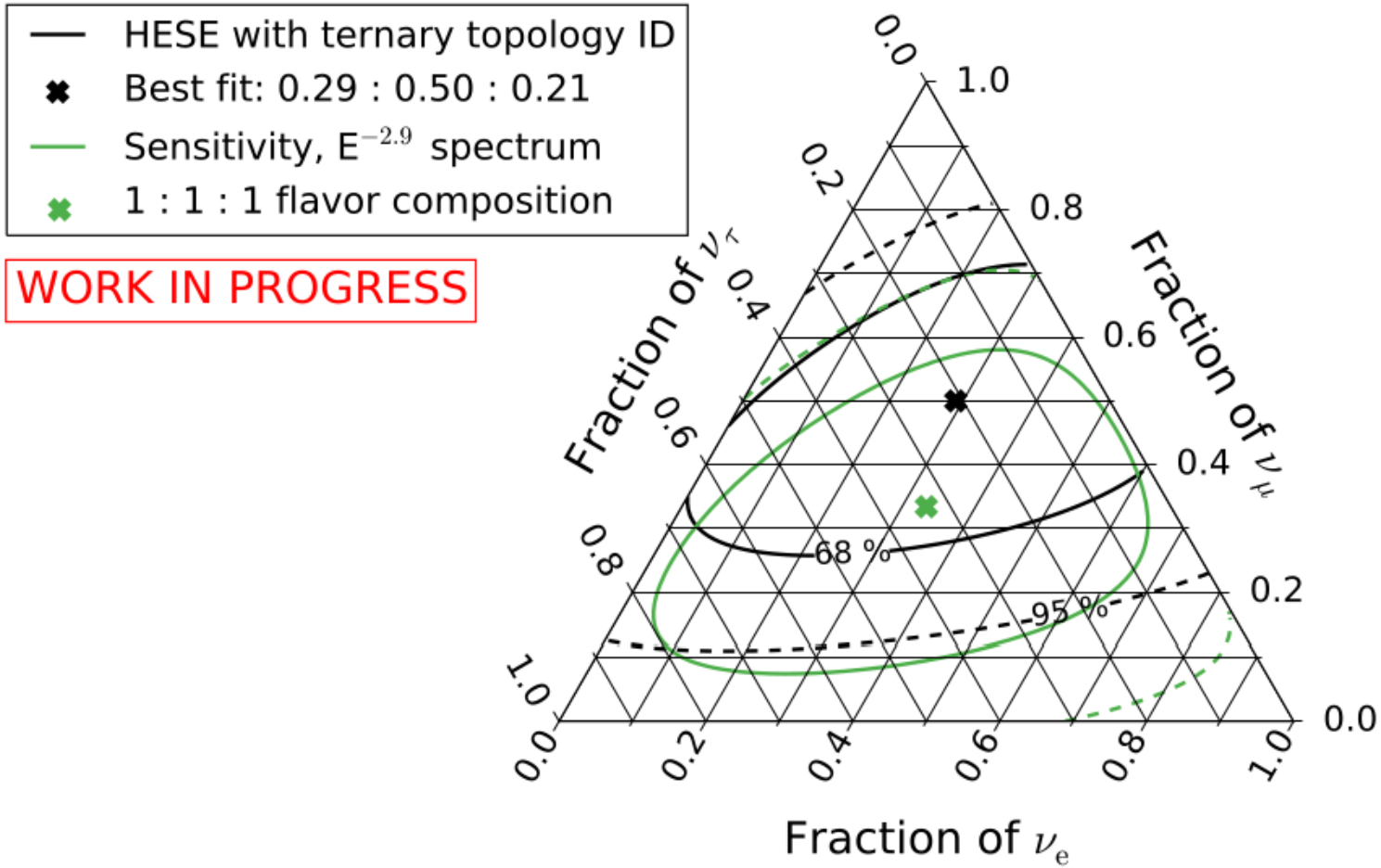
Flavor composition

"Double-double"
Observed 2014





Best-fit $\nu_e:\nu_\mu:\nu_\tau = 0.29:0.50:0.21$



- First best-fit non zero in each flavor component!
- First probe of neutrino oscillations over cosmological baselines and at TeV energies
- Consistent with previous measurement and expectation of 1:1:1 for astrophysical neutrinos

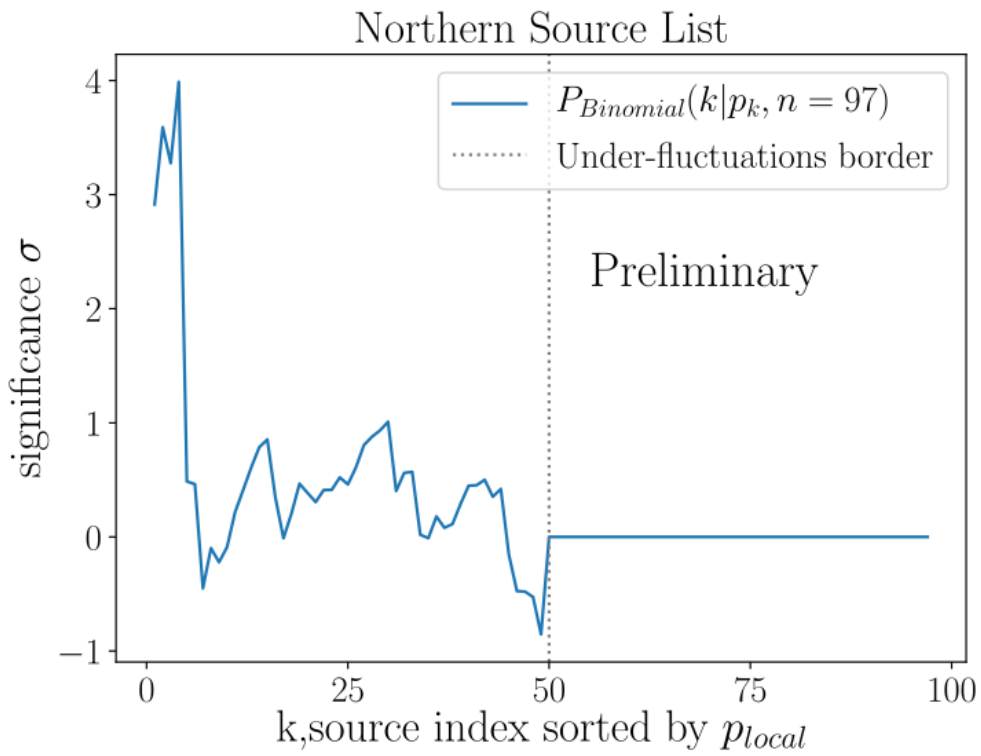
… so where do they come from?

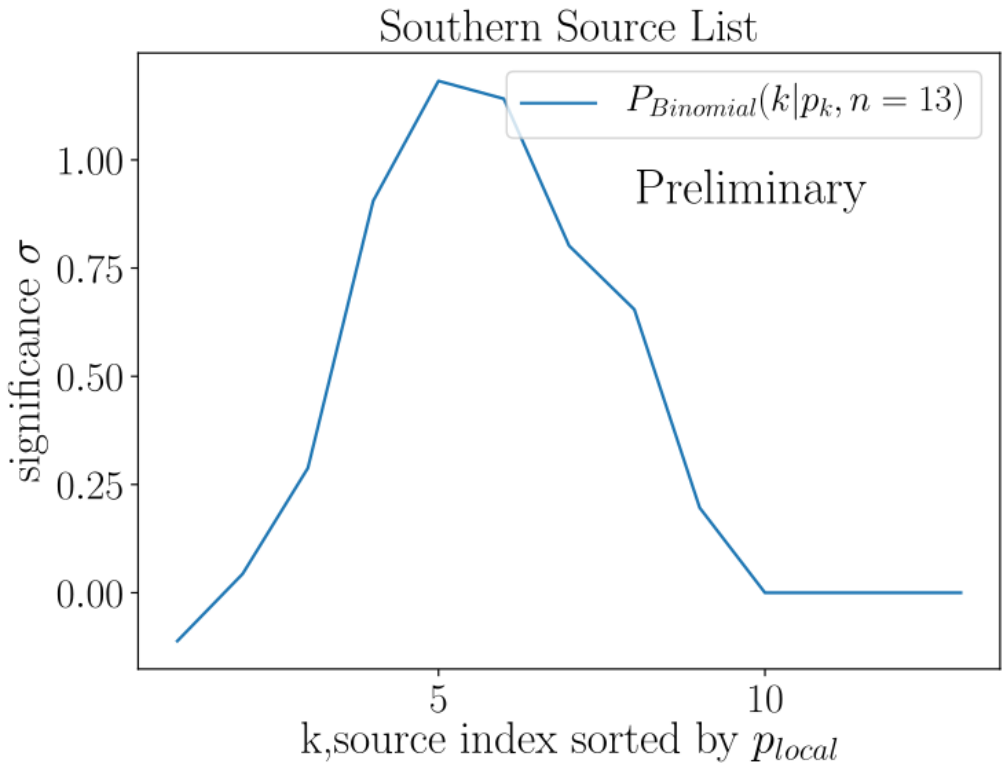
UNIVERSITÉ DE GENÈVE
T. Carver,
T. Montaruli

To be submitted to PRL

All sky combined 10 year search: source population results

Search for excess of hotspots → A significant p-value demonstrates inconsistency with background-only for entire catalog.





- Probability of k or more sources passing a threshold out of a catalog of N
- 4σ pre-trial where k = 4 in Northern Catalog → 3.3 σ post-trial (2.25 σ w/o TXS 0506+056) to account for N other possible excesses
- Includes NGC 1068, TXS 0506+056, PKS 1424+240,GB6 J1542+6129

Is there a Galactic component?

- Stacked search for IceCube neutrino emission from HAWC TeV gamma-ray sources in 2HWC catalog
- Template analysis for neutrino emission from Galactic plane including morphology of gamma-ray emission
- More significant result for J1857+027 (p-value 0.02 before trial correction)