Status delle osservazioni: IceCube

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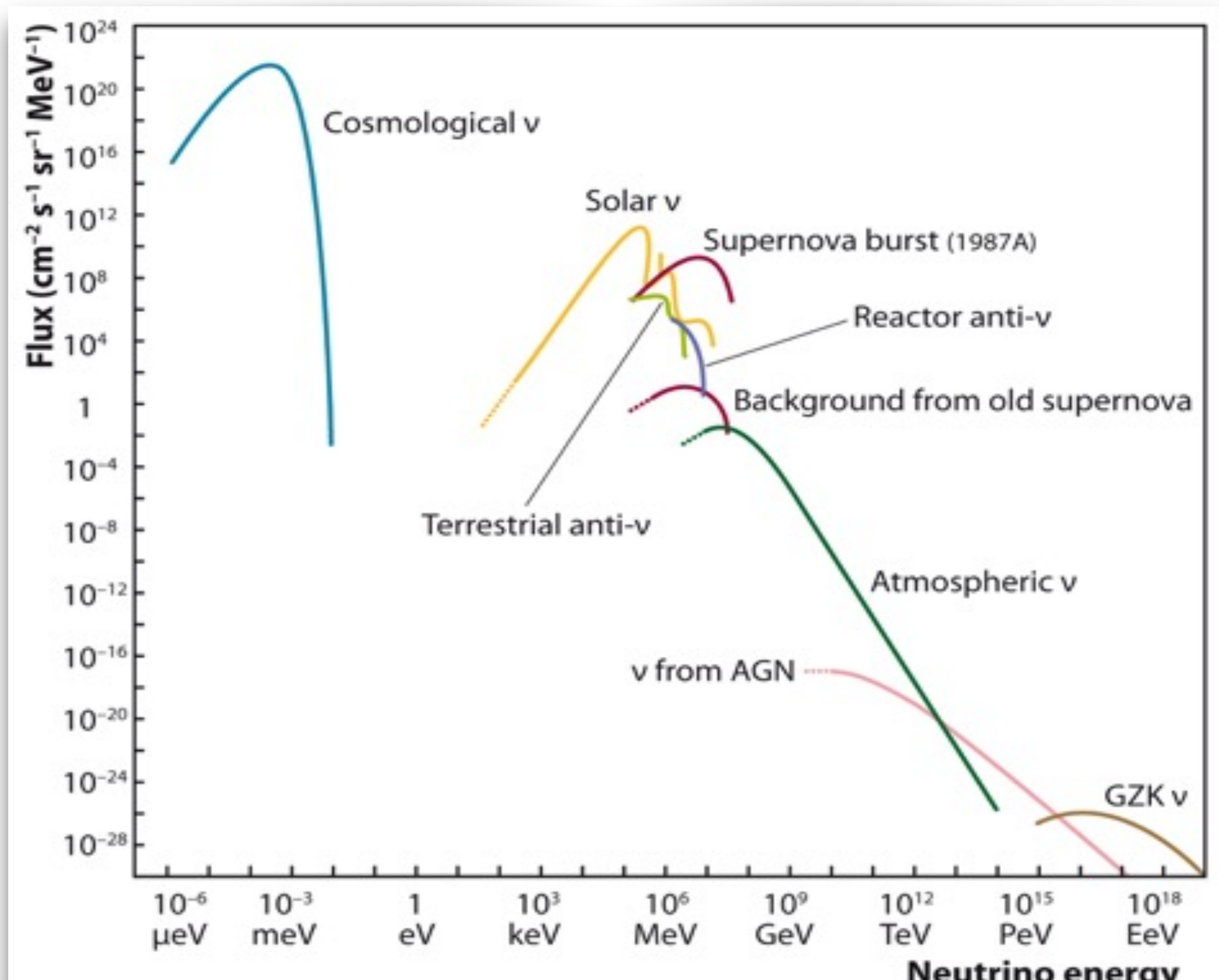
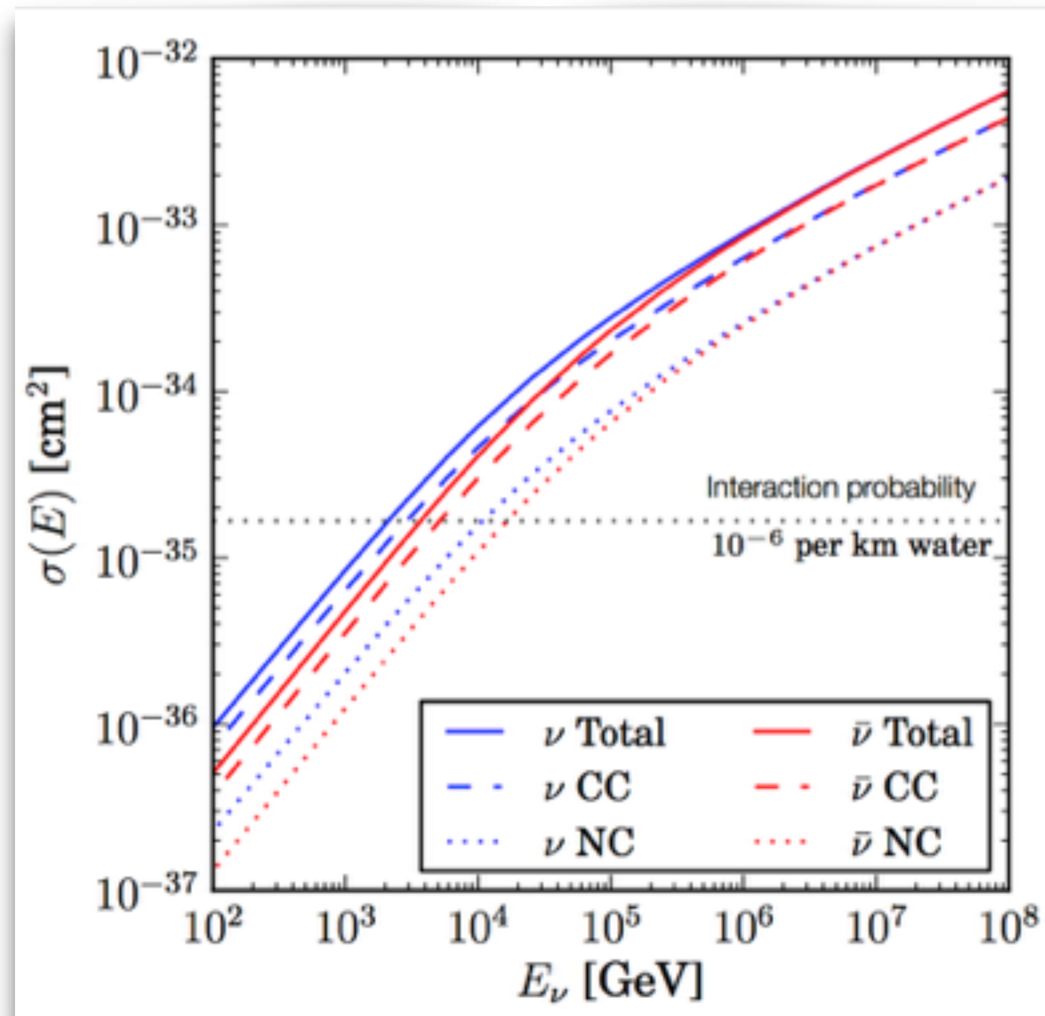
How to detect neutrinos

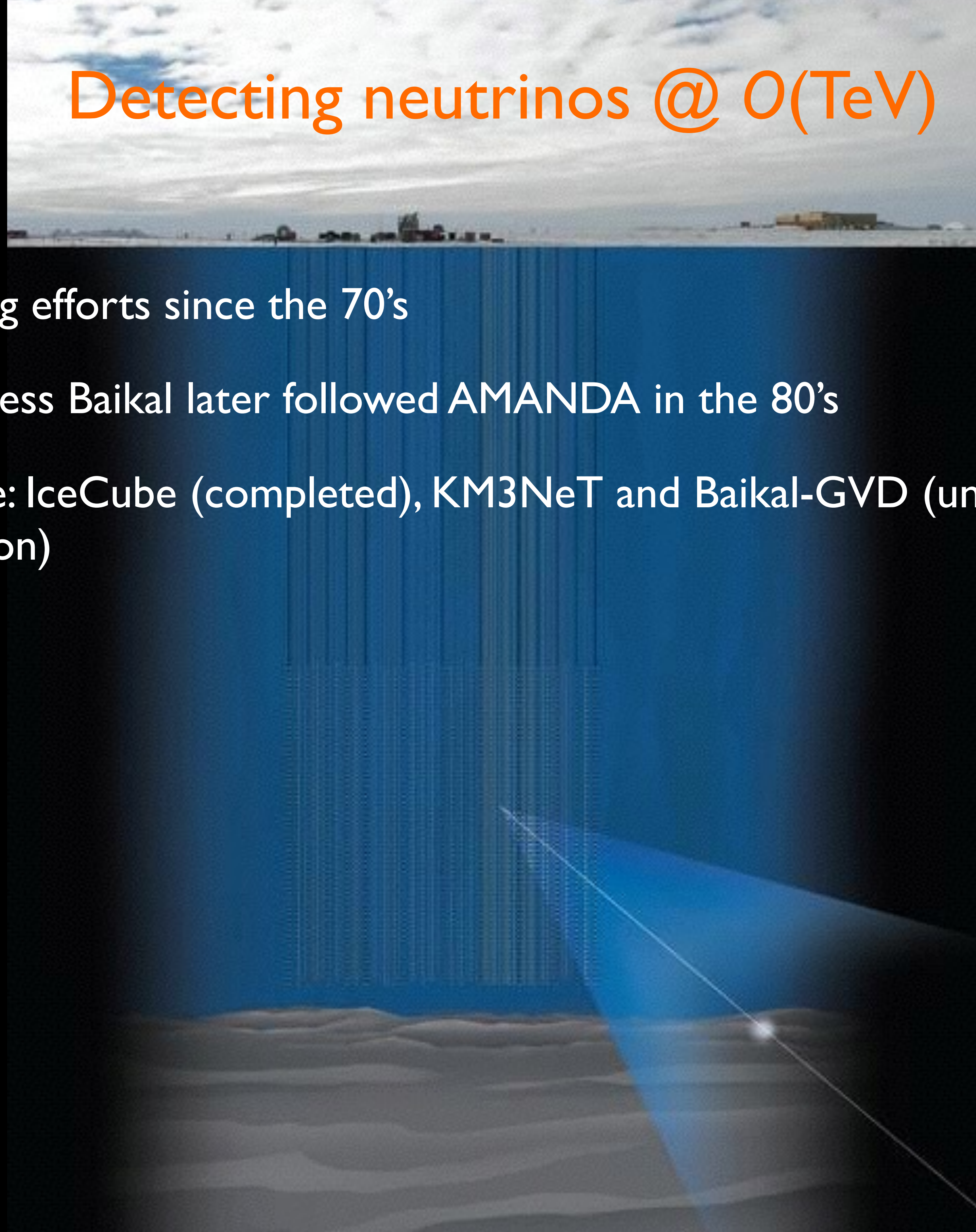
- Benchmark astrophysical flux: $O(10^5)$ per km^2 per year above 100 TeV
- Need km^3-scale detectors!
- Large volumes, use natural water or ice



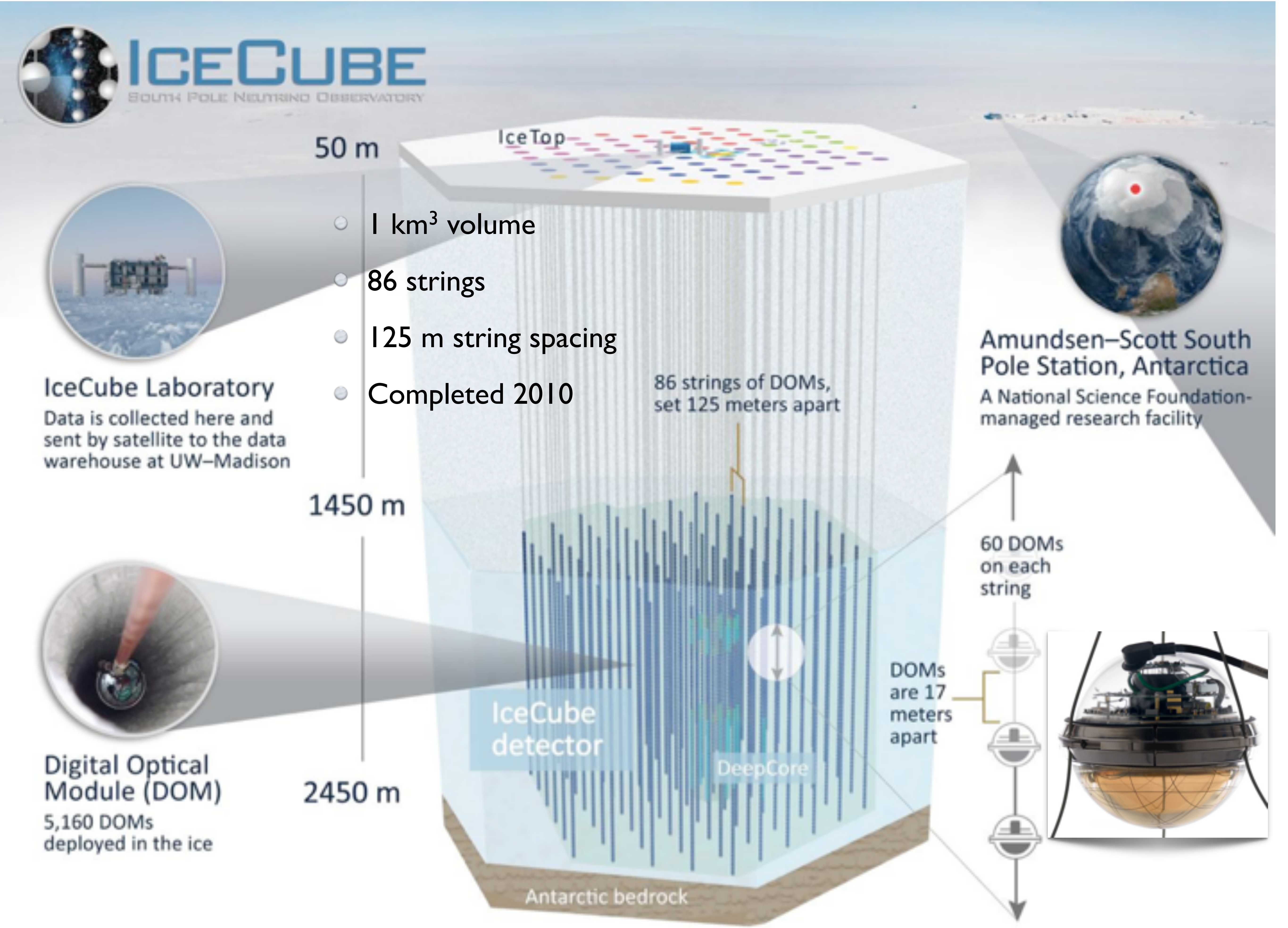


Detecting neutrinos @ O(TeV)

- Pioneering efforts since the 70's
- First success Baikal later followed AMANDA in the 80's
- Km^3-scale: IceCube (completed), KM3NeT and Baikal-GVD (under construction/ preparation)

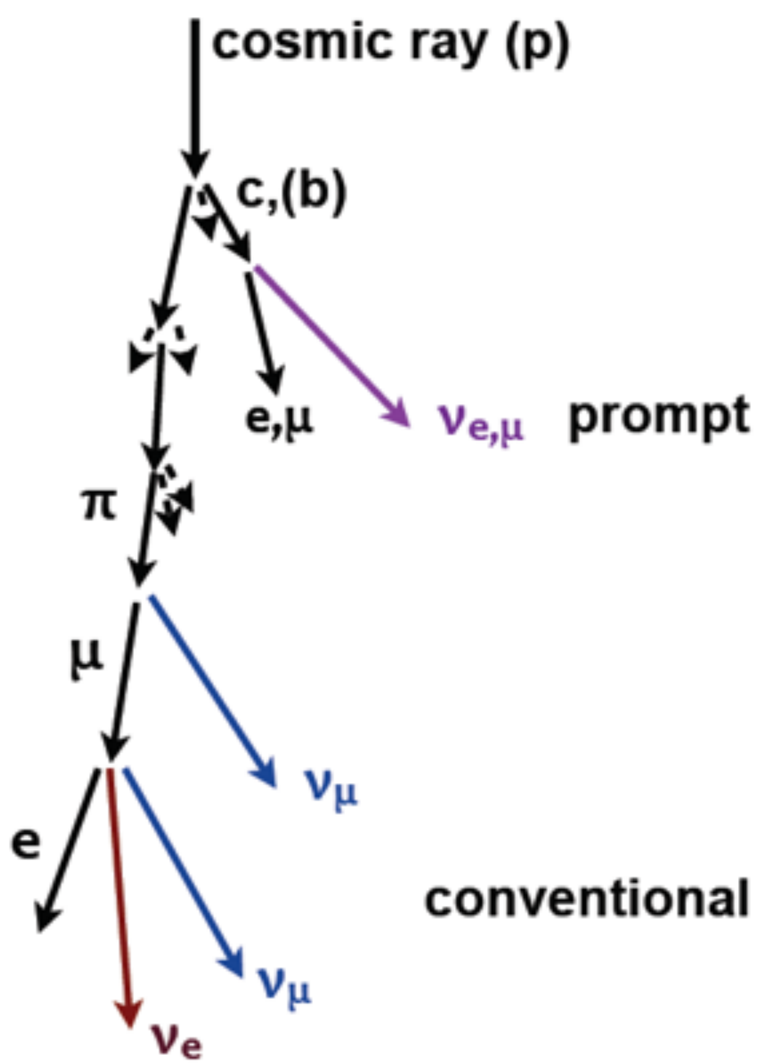


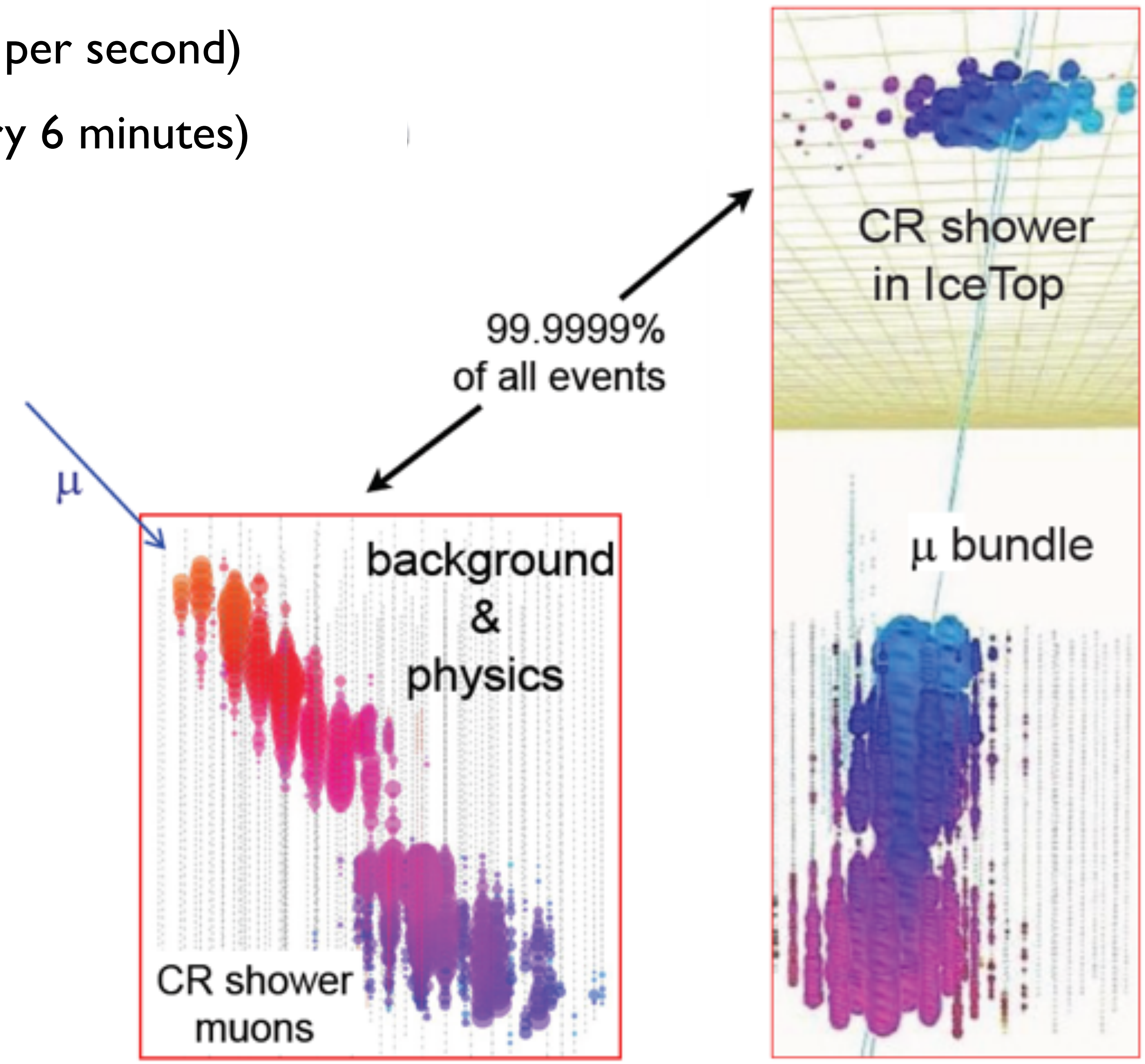
- 1 km^3 volume
- 86 strings
- 125 m string spacing
- Completed 2010



Challenge: Signal and background(s)

- Expected signals are weak and mimicked by irreducible backgrounds
- Event rates in IceCube (year^{-1}):
  - atmospheric muons 7 x 10^{10} (2000 per second)
  - atmospheric neutrinos 5 x 10^{4} (1 every 6 minutes)
  - astrophysical $O(10)$





Challenge: Neutrino fluxes

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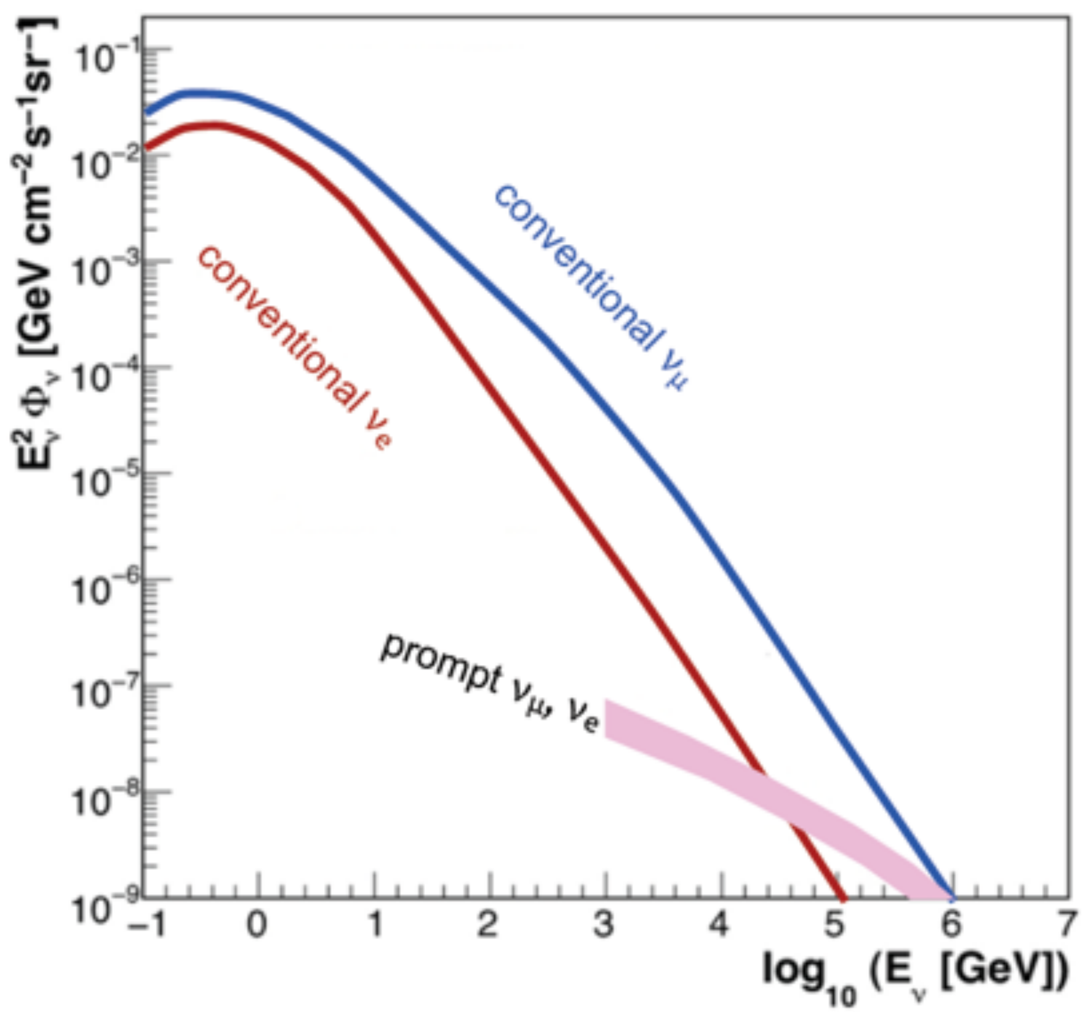
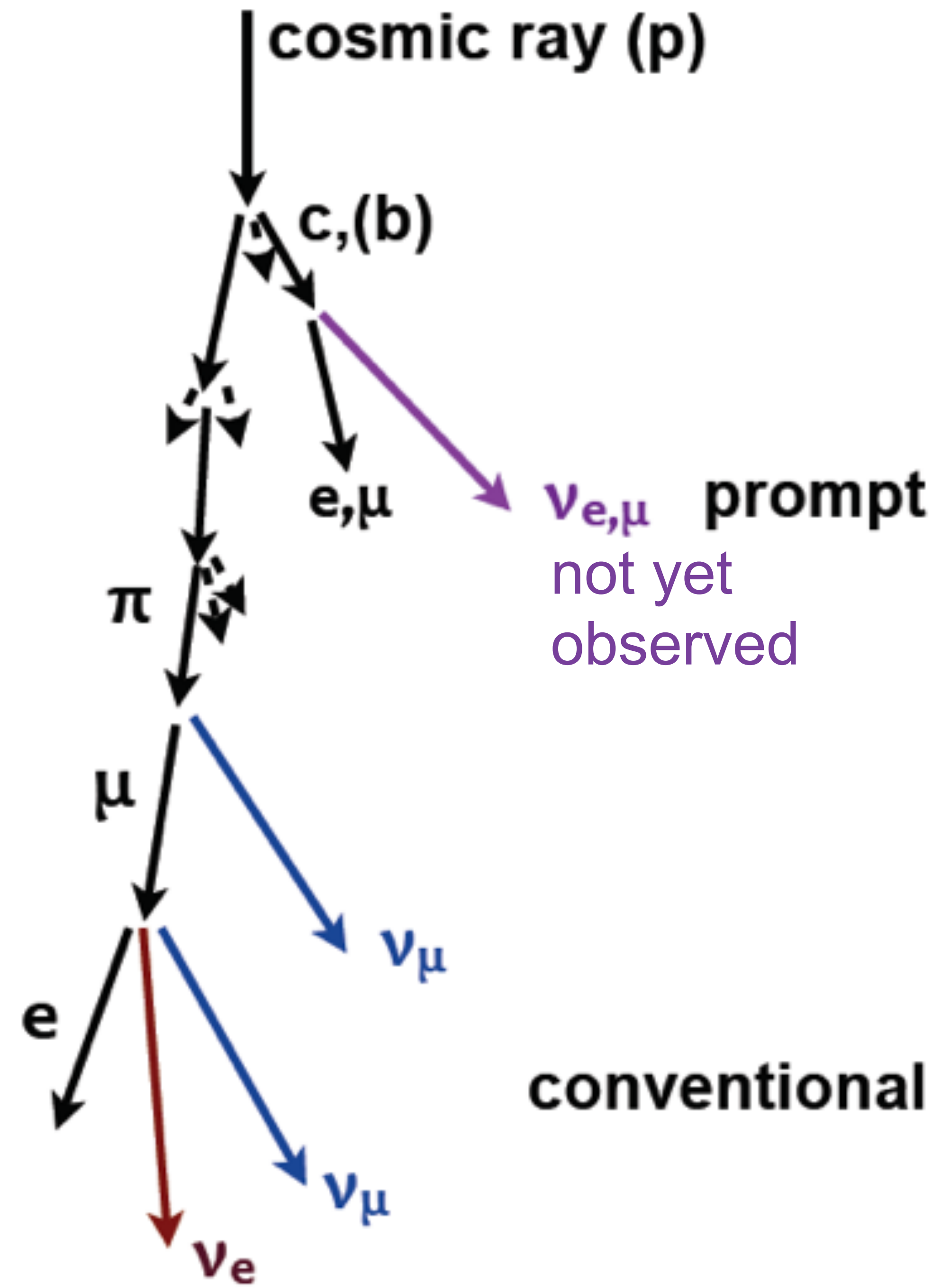
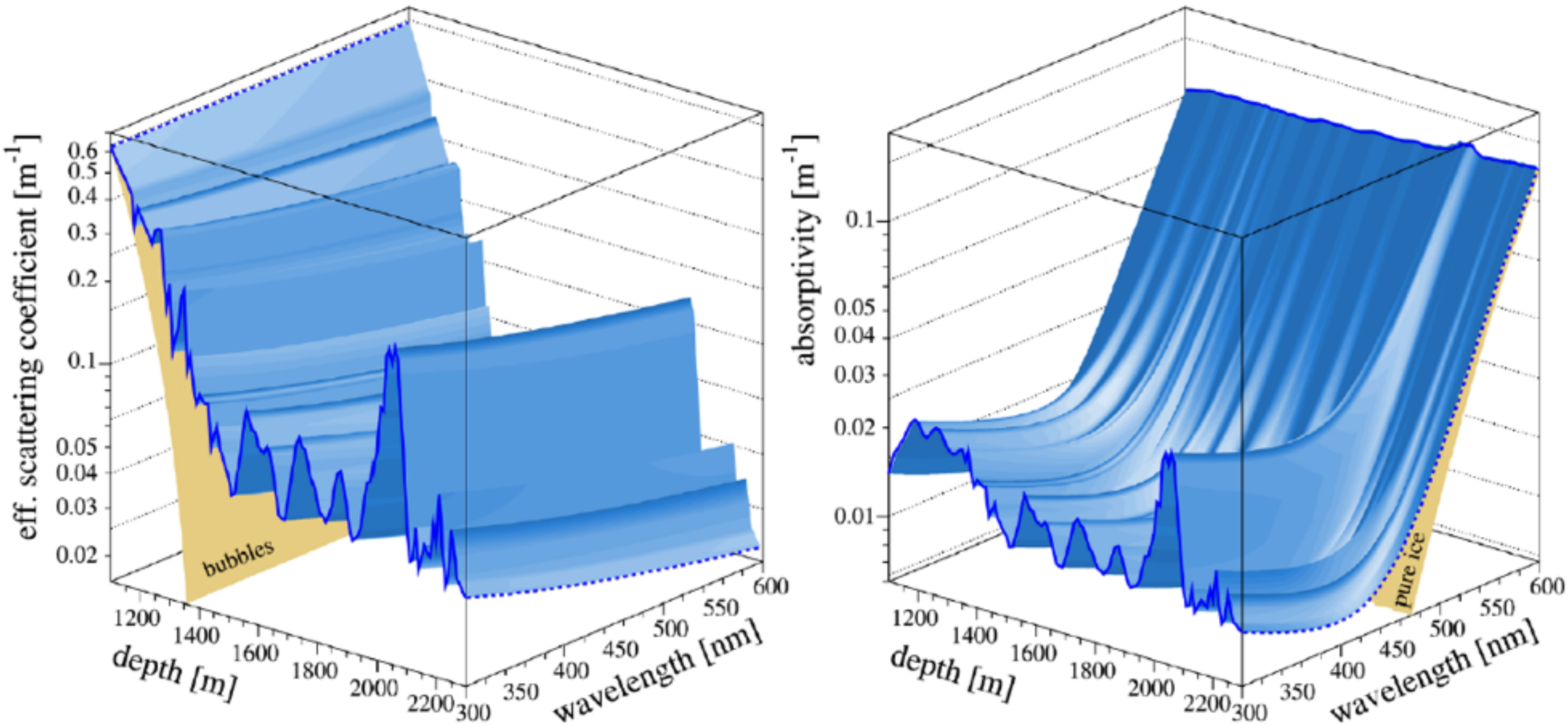




Challenge: Ice optical properties



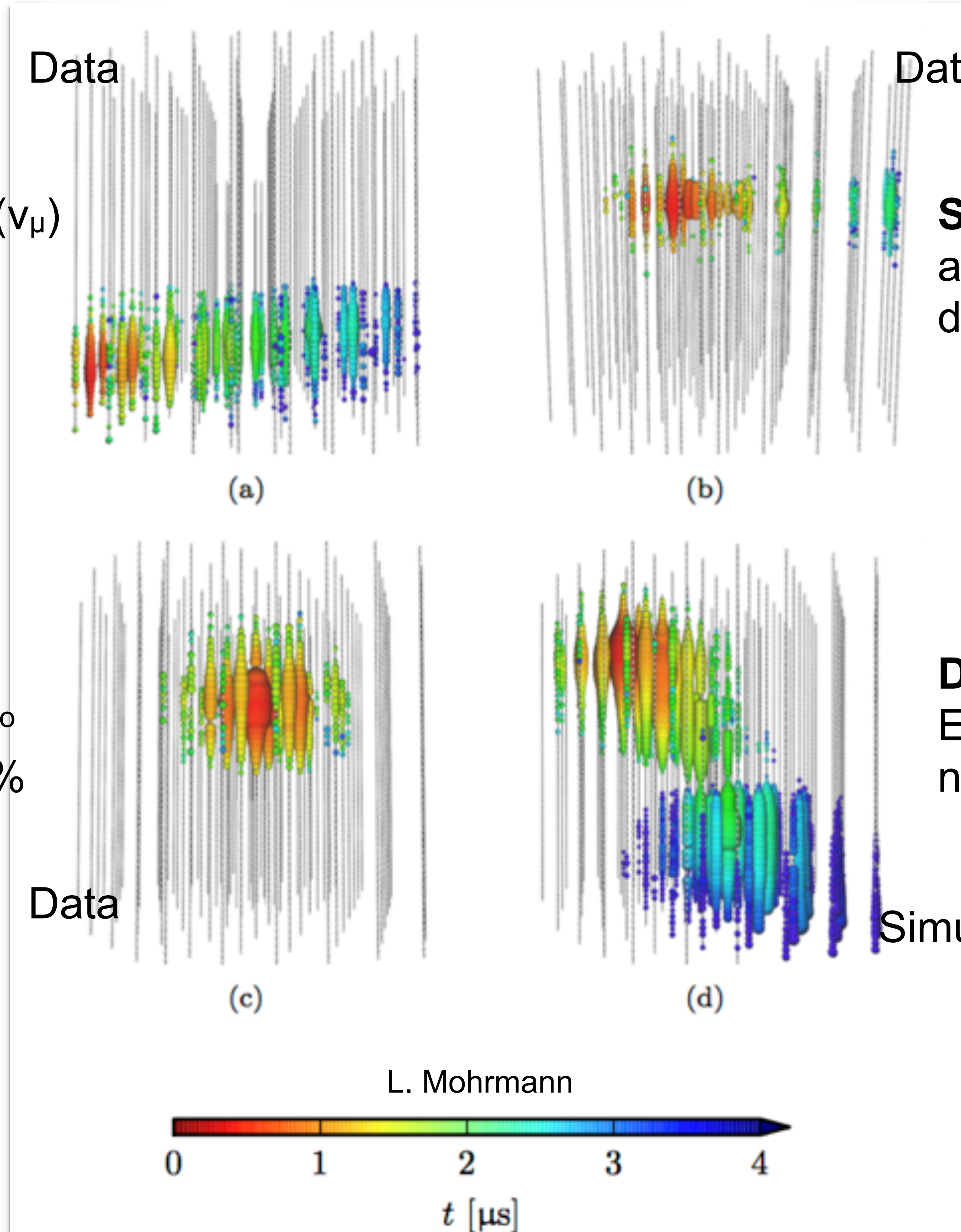
Neutrino signatures in ice

Through-going track (ν_μ)
angular resolution < 1^o
only dE/dx

Starting track (ν_μ)
angular resolution < 1^o
dE/dx + energy at vertex

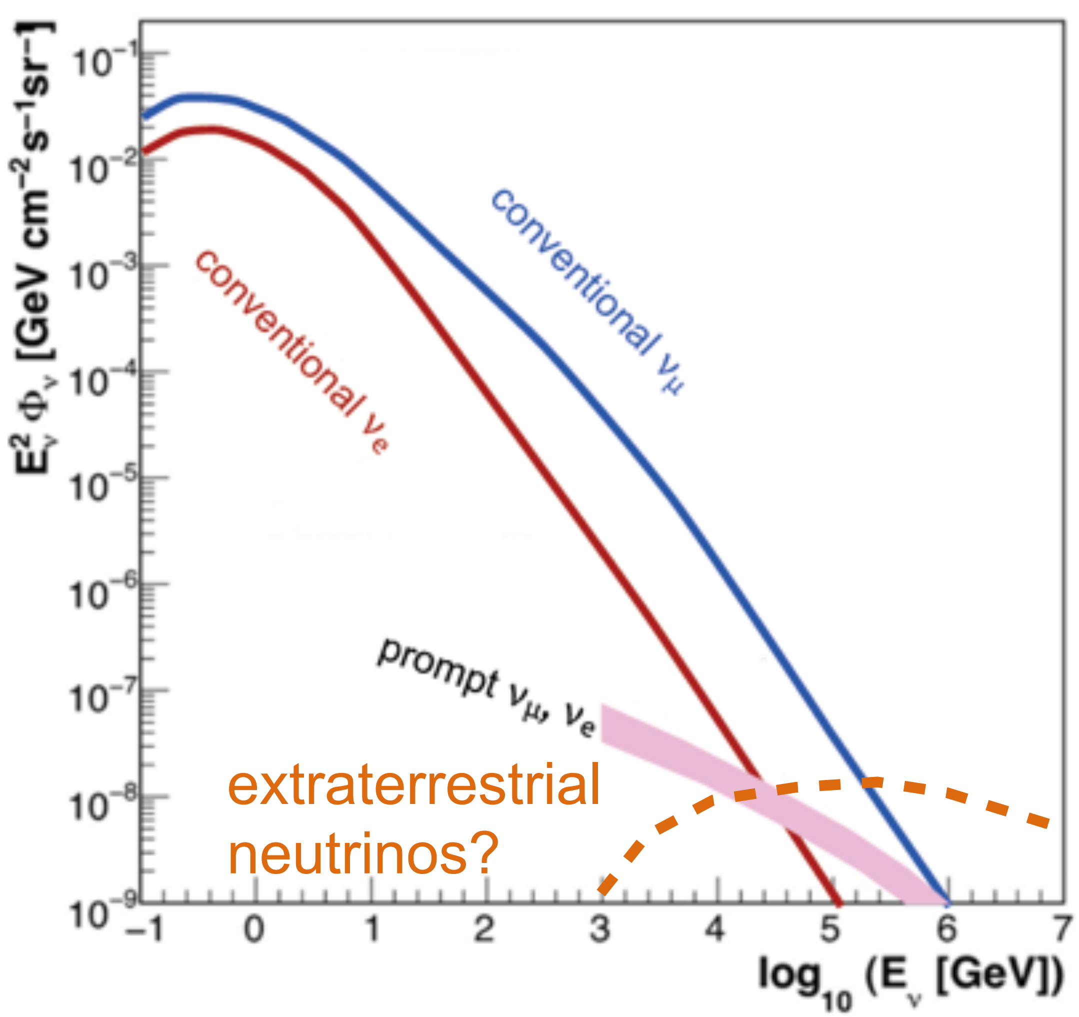
Cascade (ν_e, ν_μ, ν_τ)
angular resolution > 10^o
energy resolution ~ 15%

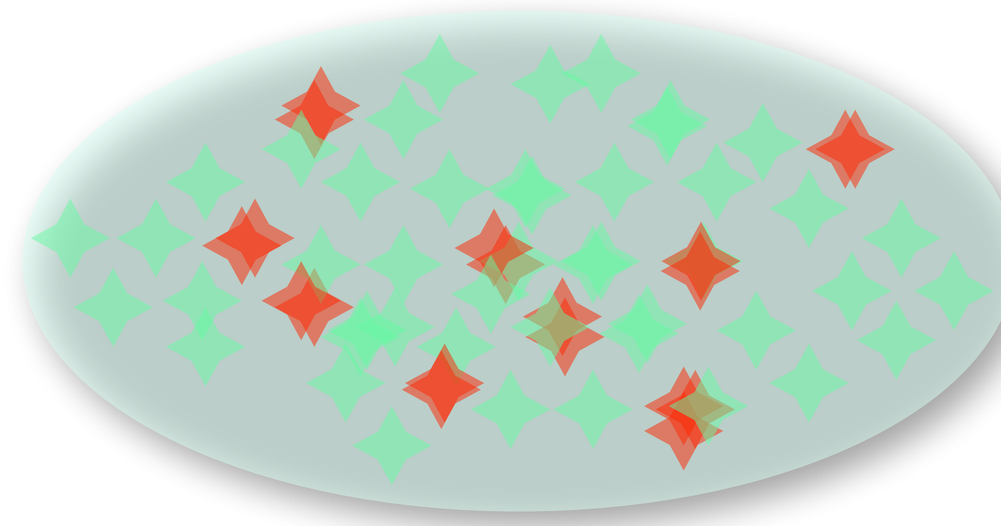
Double-Bang (ν_τ)
E > O(PeV)
not observed yet!



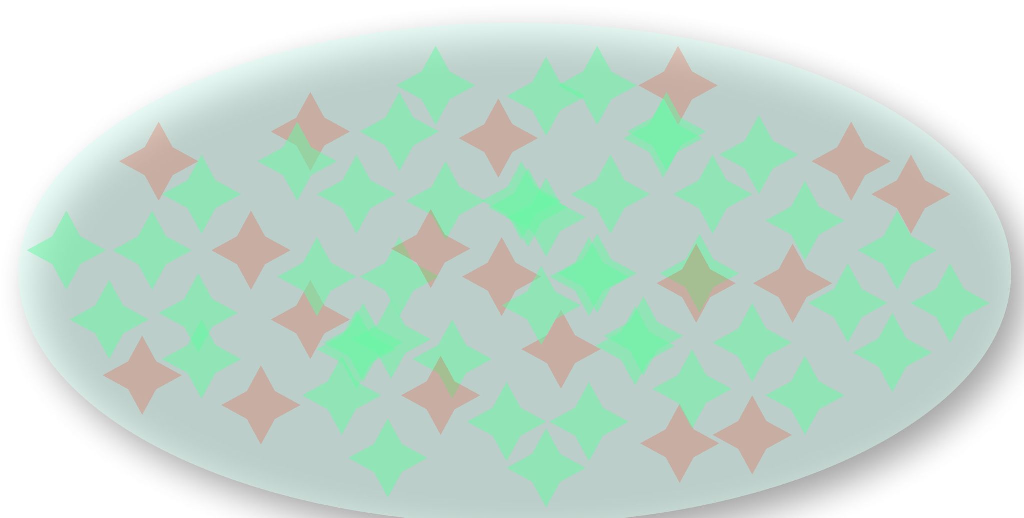
Searching for cosmic neutrinos

- The signal is expected to exhibit a differed spectrum
- Search for deviations from background
  - in energy (diffuse-like searches)
  - in energy and direction (look for individual sources)





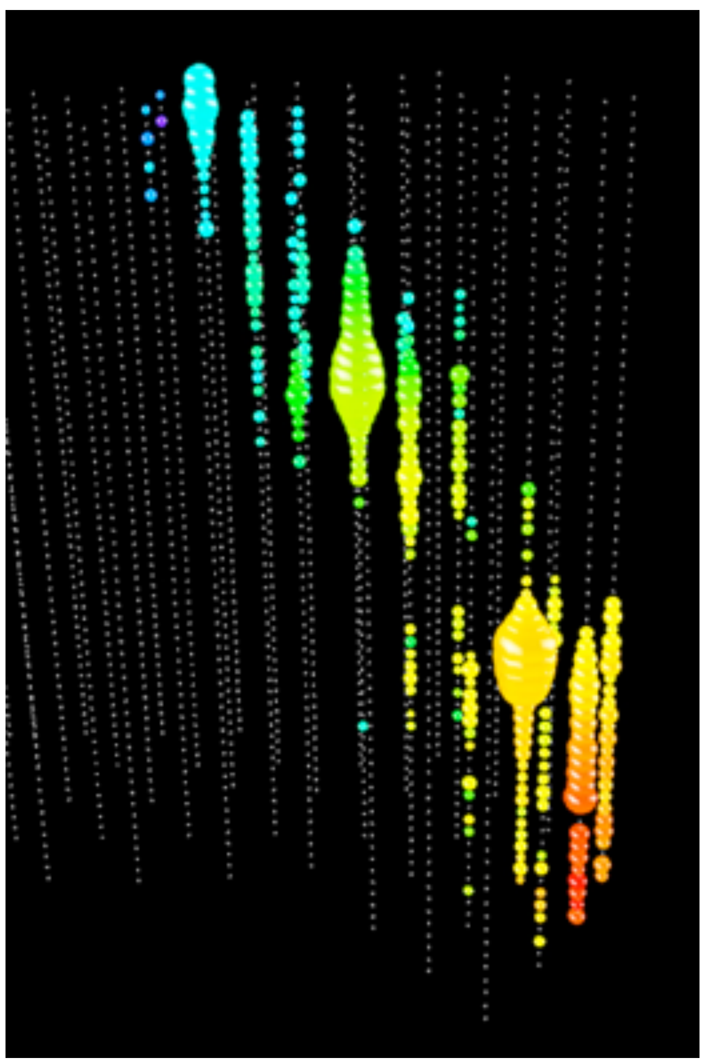
Individual sources: search for excesses from few strong objects. Localised (in space and/or time)

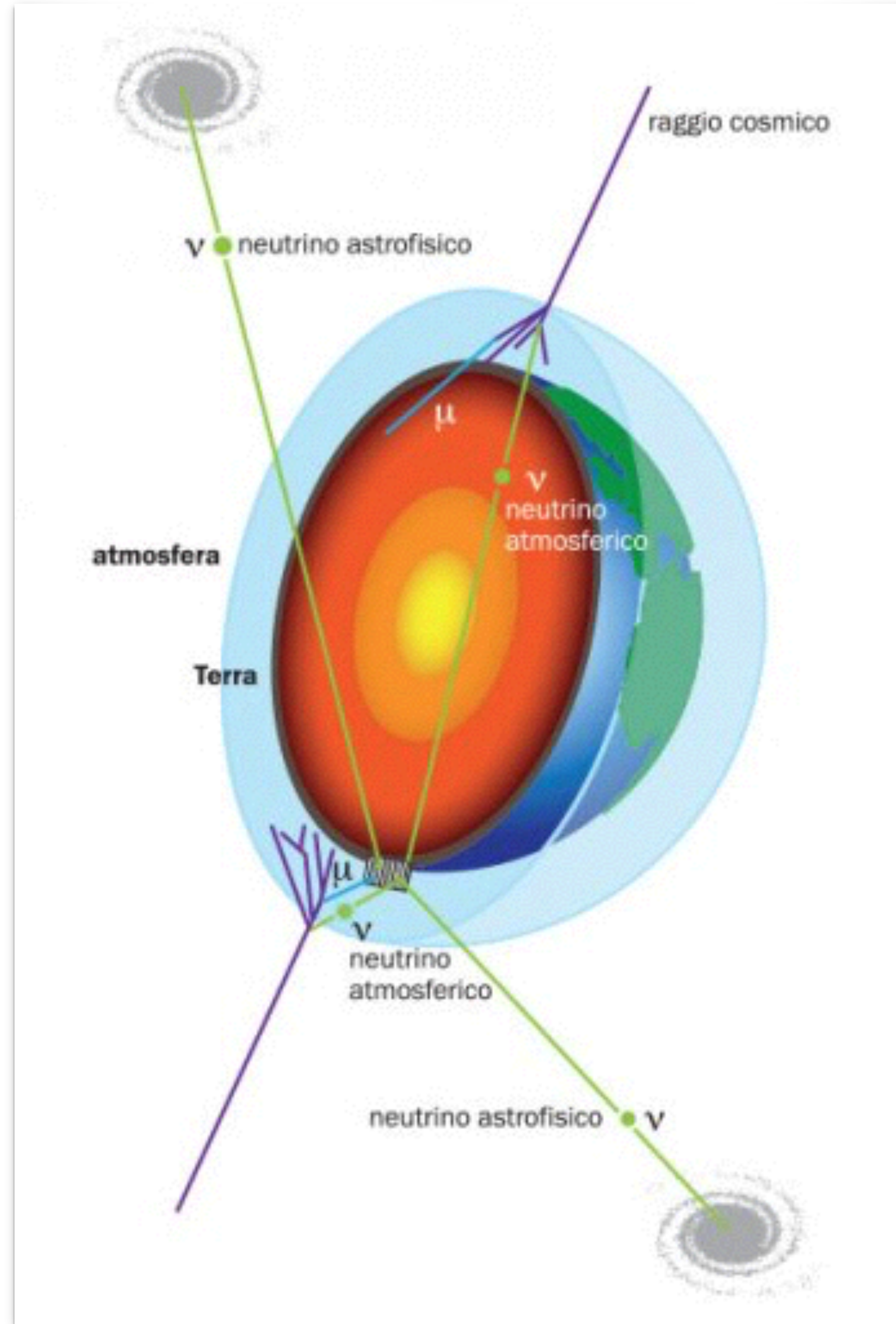


Diffuse searches: search for an overall excess from an ensemble of many weak sources. Deviation in energy spectrum

Isolating neutrino events: direction

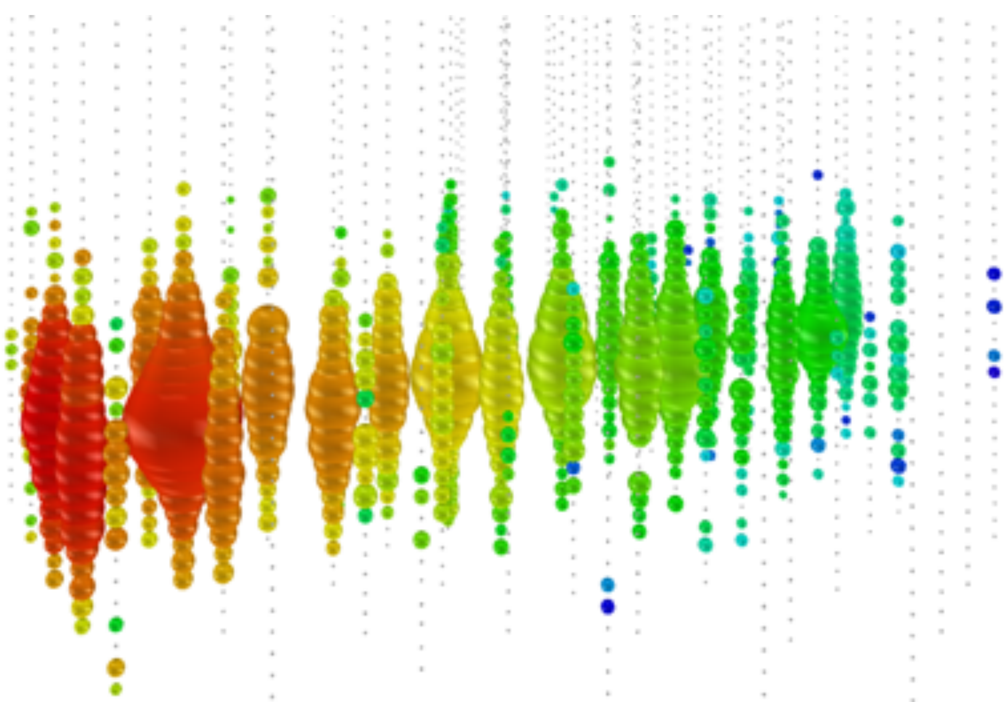
- Earth stops penetrating muons from below
- Apply direction cuts (select up-going)
  - Effective volume larger than detector
  - E > O(100 GeV)
  - Sensitive to ν_μ only
  - Sensitive to "half" the sky (the North)



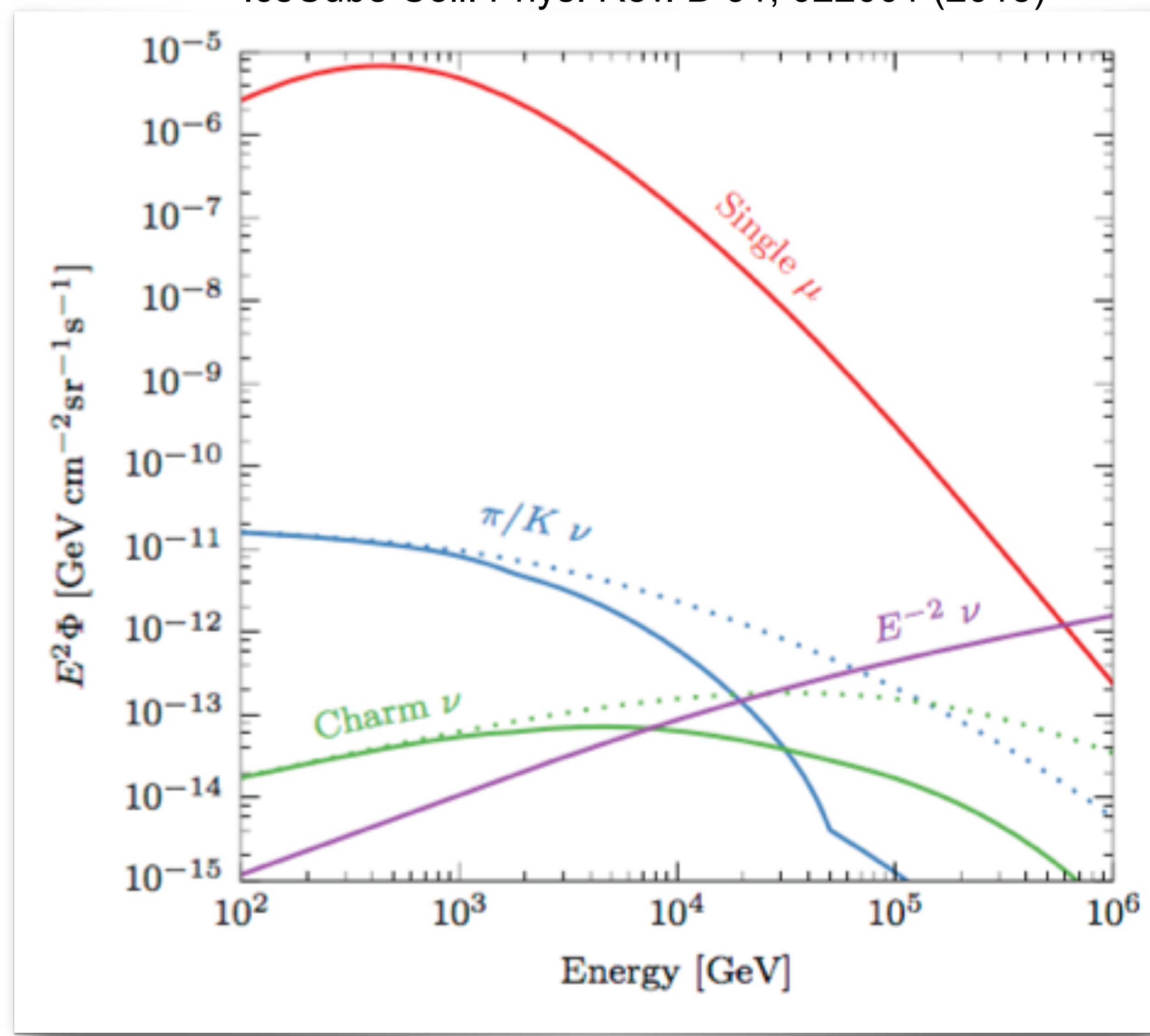


Isolating neutrino events: energy

- Energy spectrum looks different for background and signal
- Select high-energy events
  - reject atmospheric μ
  - reject atmospheric ν_μ
  - requires strong energy cuts
  - mostly sensitive to the horizon

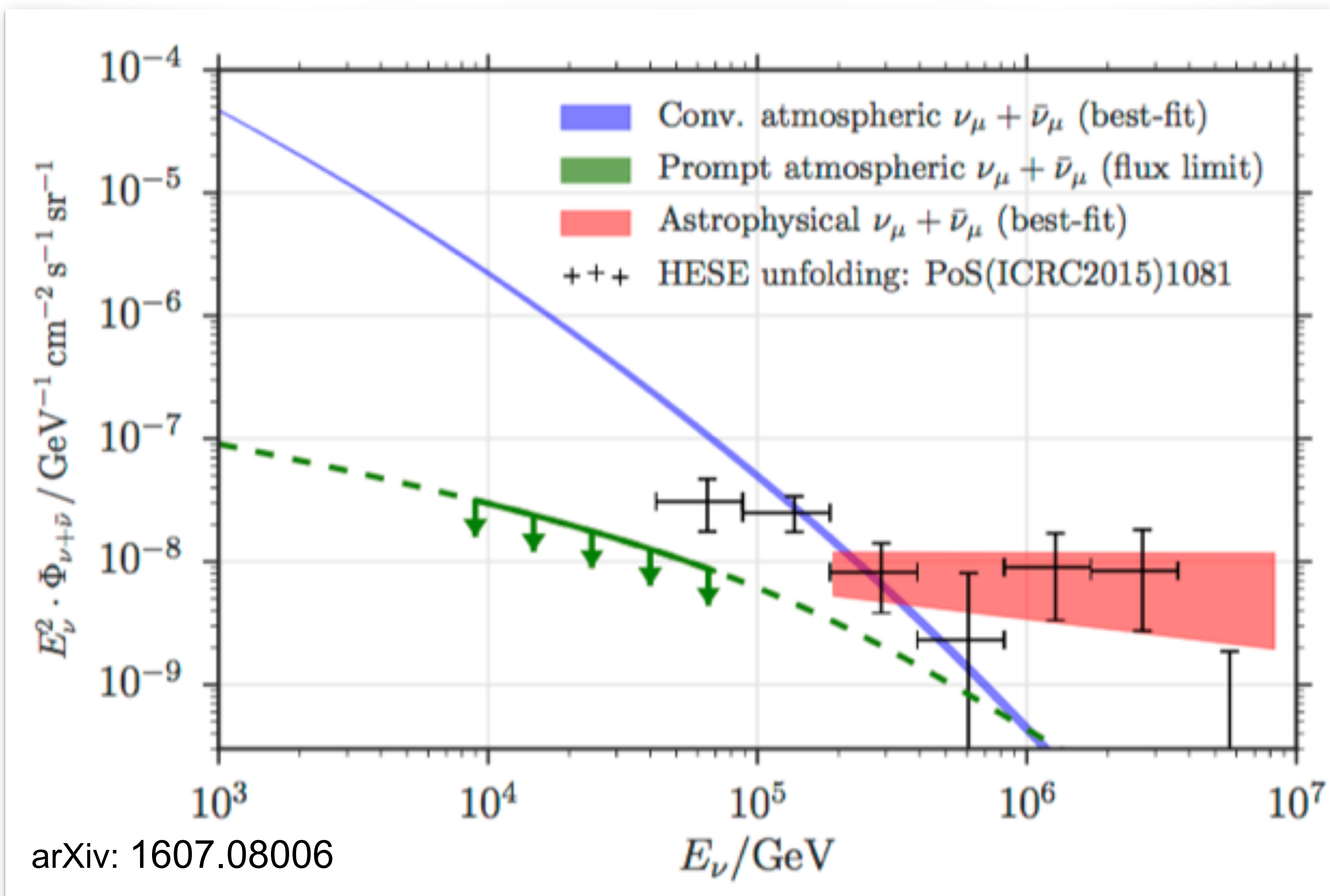


IceCube Coll. Phys. Rev. D 91, 022001 (2015)



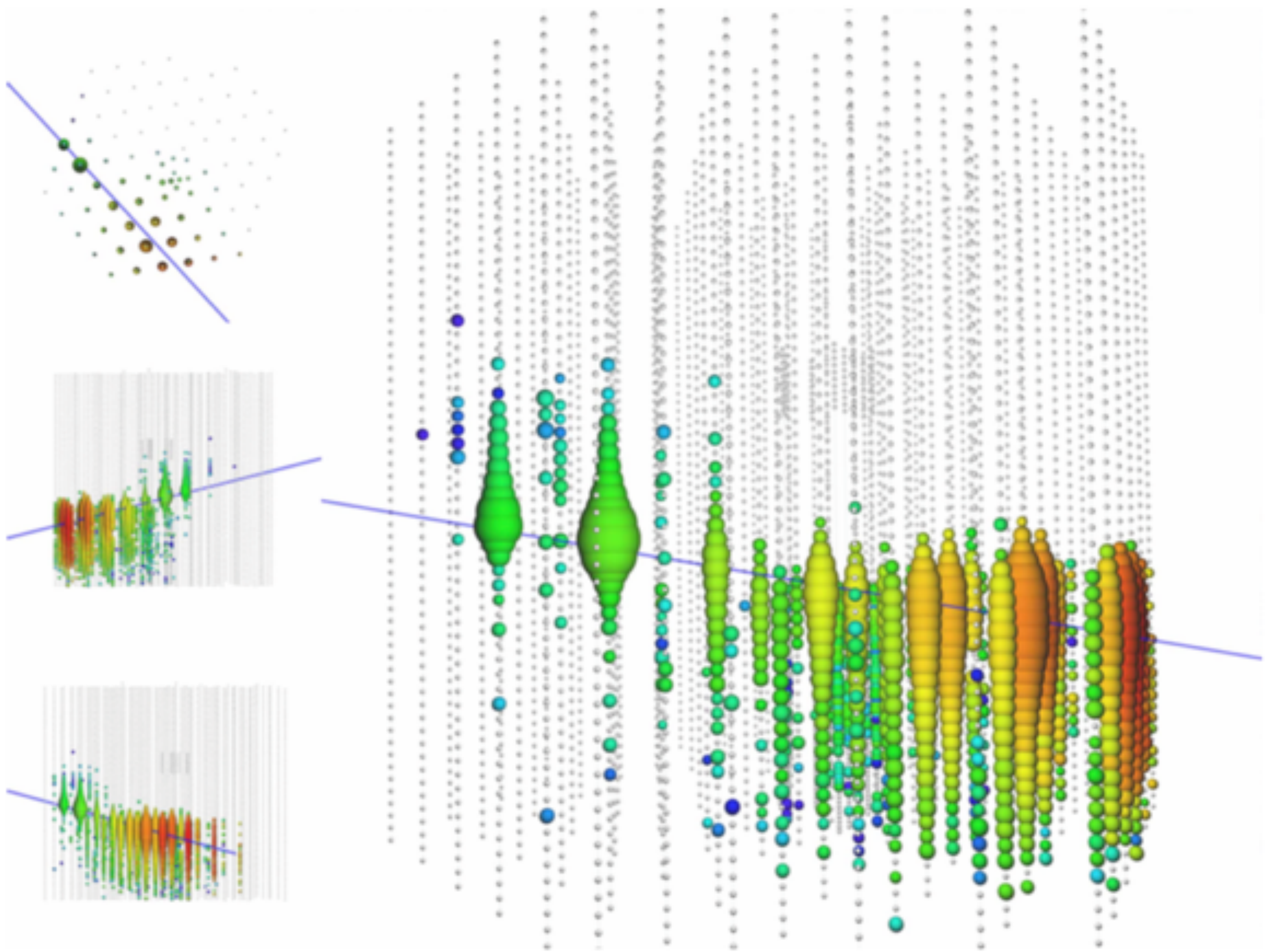
Diffuse searches with up-going muons

- Between 191 TeV and 8.3 PeV a significant astrophysical contribution is observed, excluding a purely atmospheric origin at 5.6 σ significance
- Data well described by an isotropic, unbroken power law flux with
  - normalisation at 100 TeV neutrino energy of $0.90^{+0.30}_{-0.27} \times 10^{-18}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1} and a hard spectral index of $\gamma = 2.13 \pm 0.13$



The (so far) highest energy event

- The highest energy event observed has a reconstructed muon energy of (4.5 ± 1.2) PeV
  - probability of less than 0.005% for this event to be of atmospheric origin

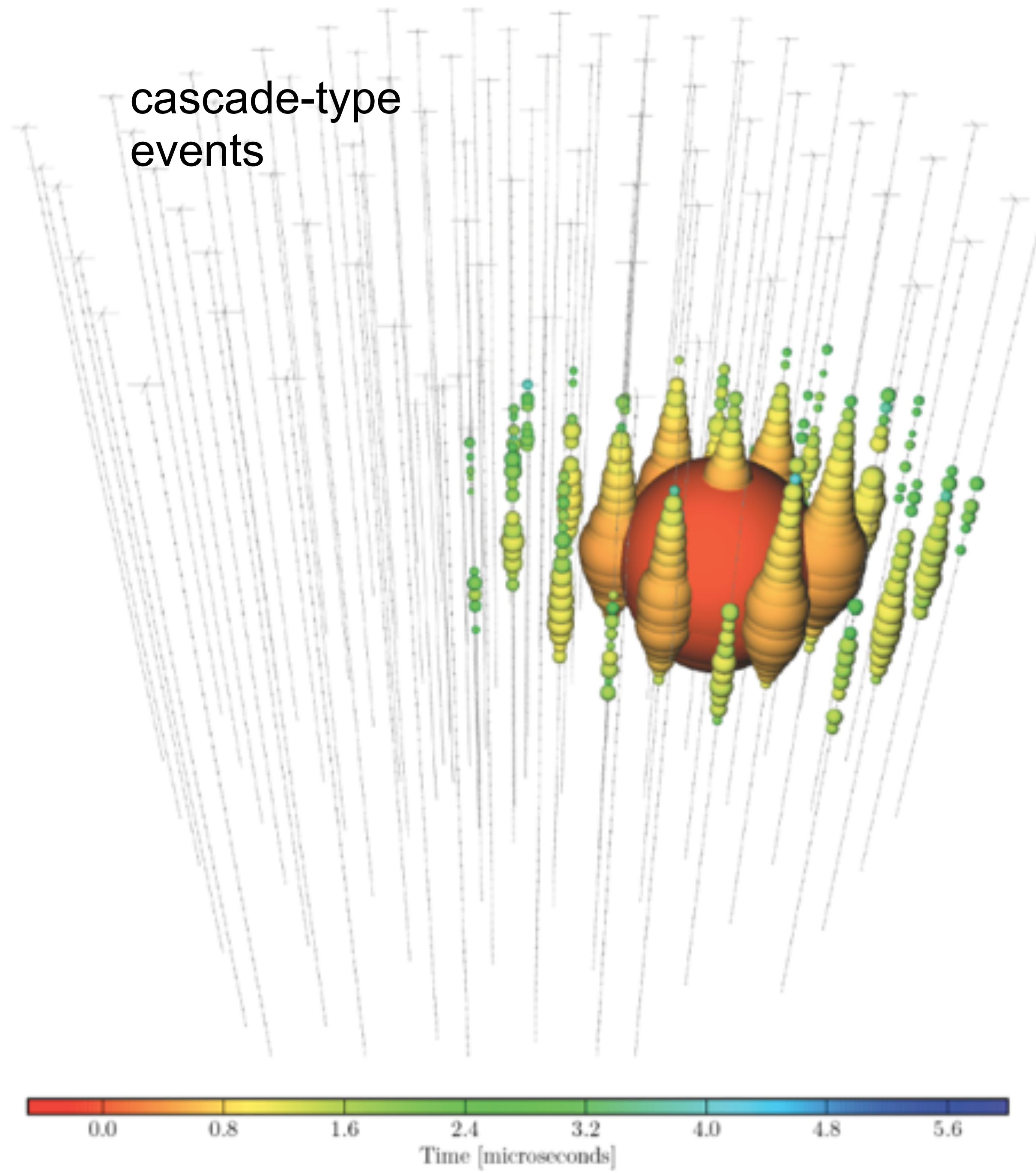


arXiv: 1607.08006

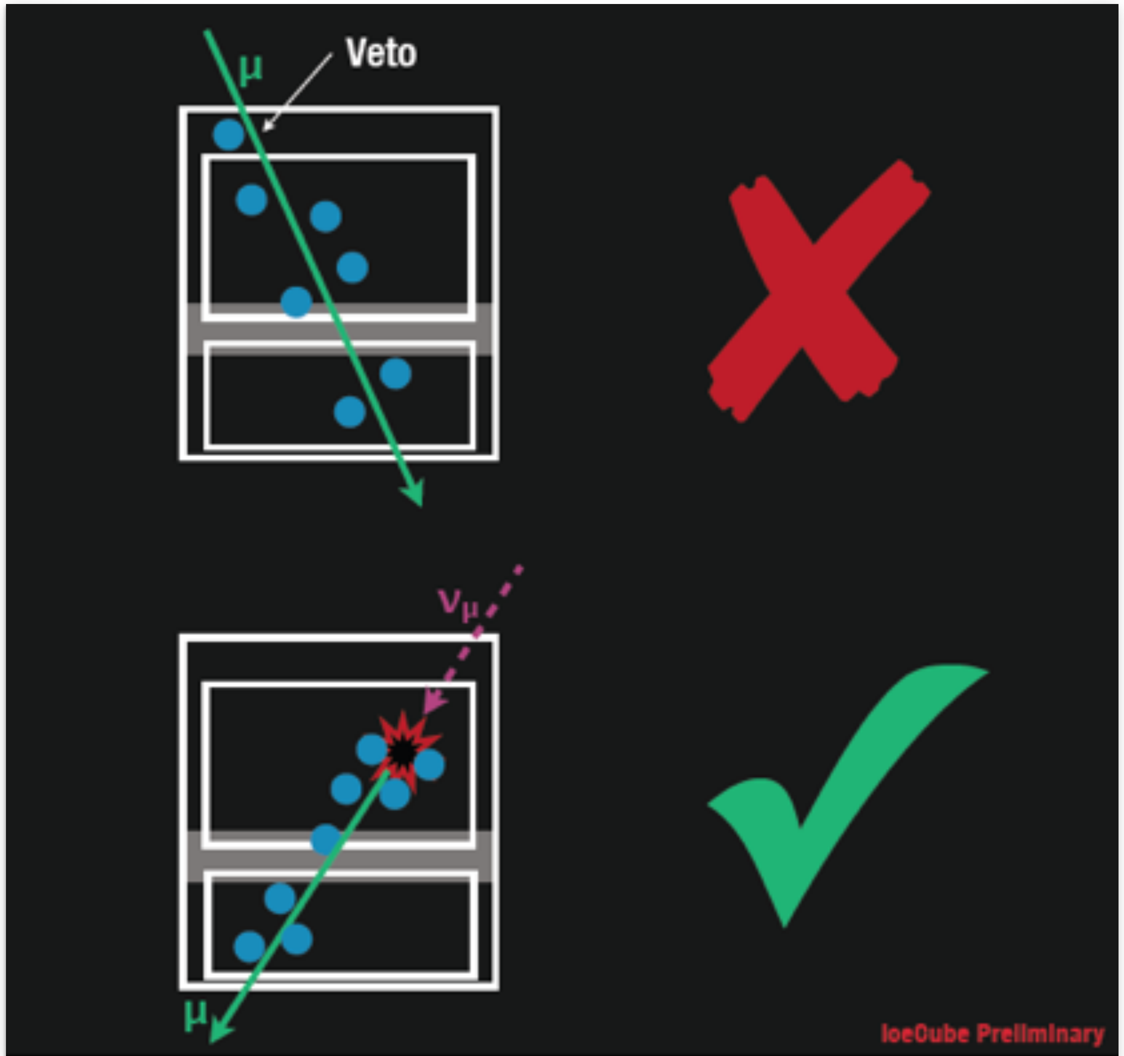
Isolating neutrino events: interaction type

- Looking for cascades
  - Effective volume smaller than detector
  - E > *O*(30 TeV)
  - Sensitive to all flavours
  - Sensitive to full sky
  - almost background-free!

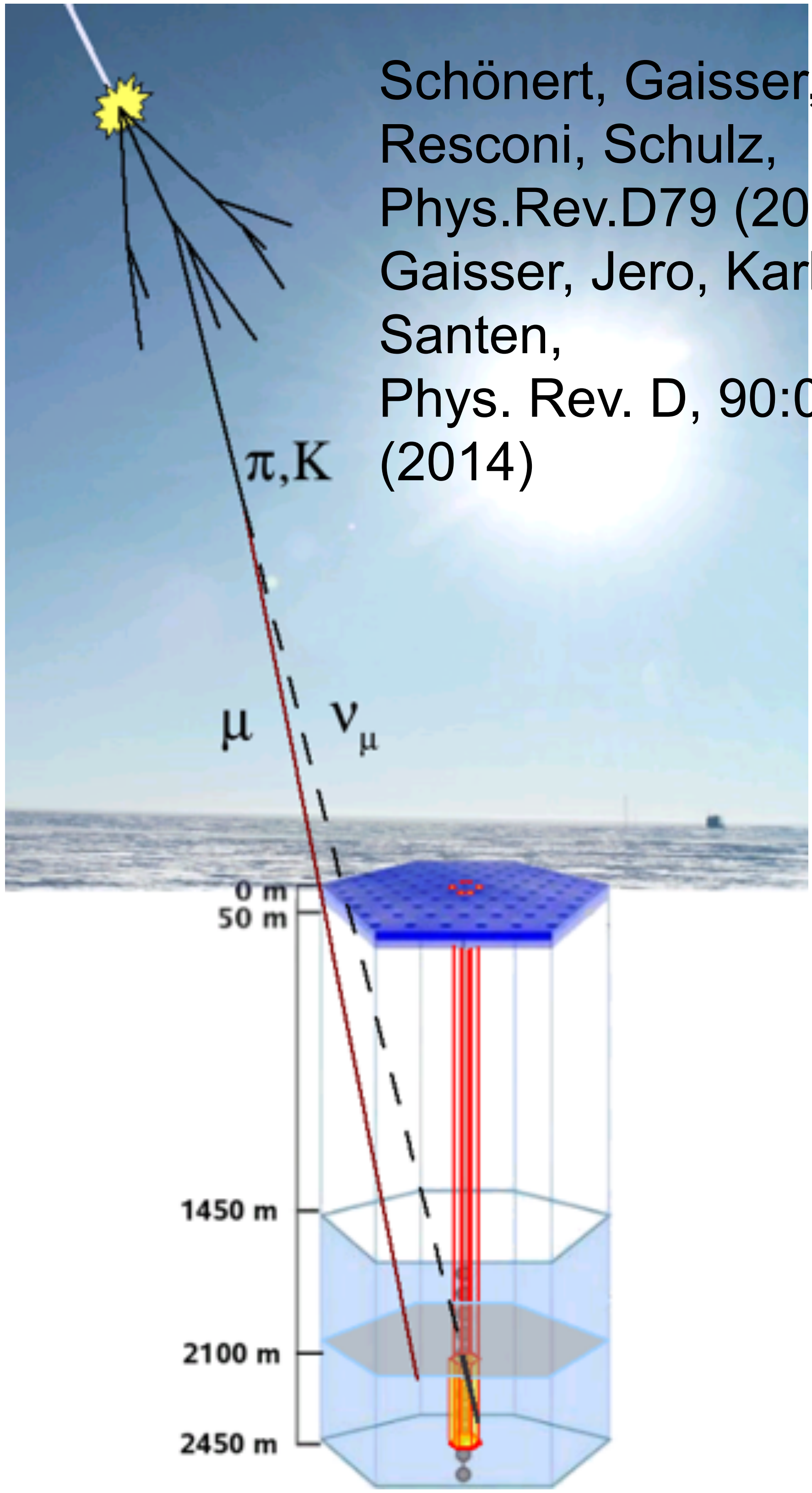
cascade-type
events



How to veto down-going atmospheric neutrinos

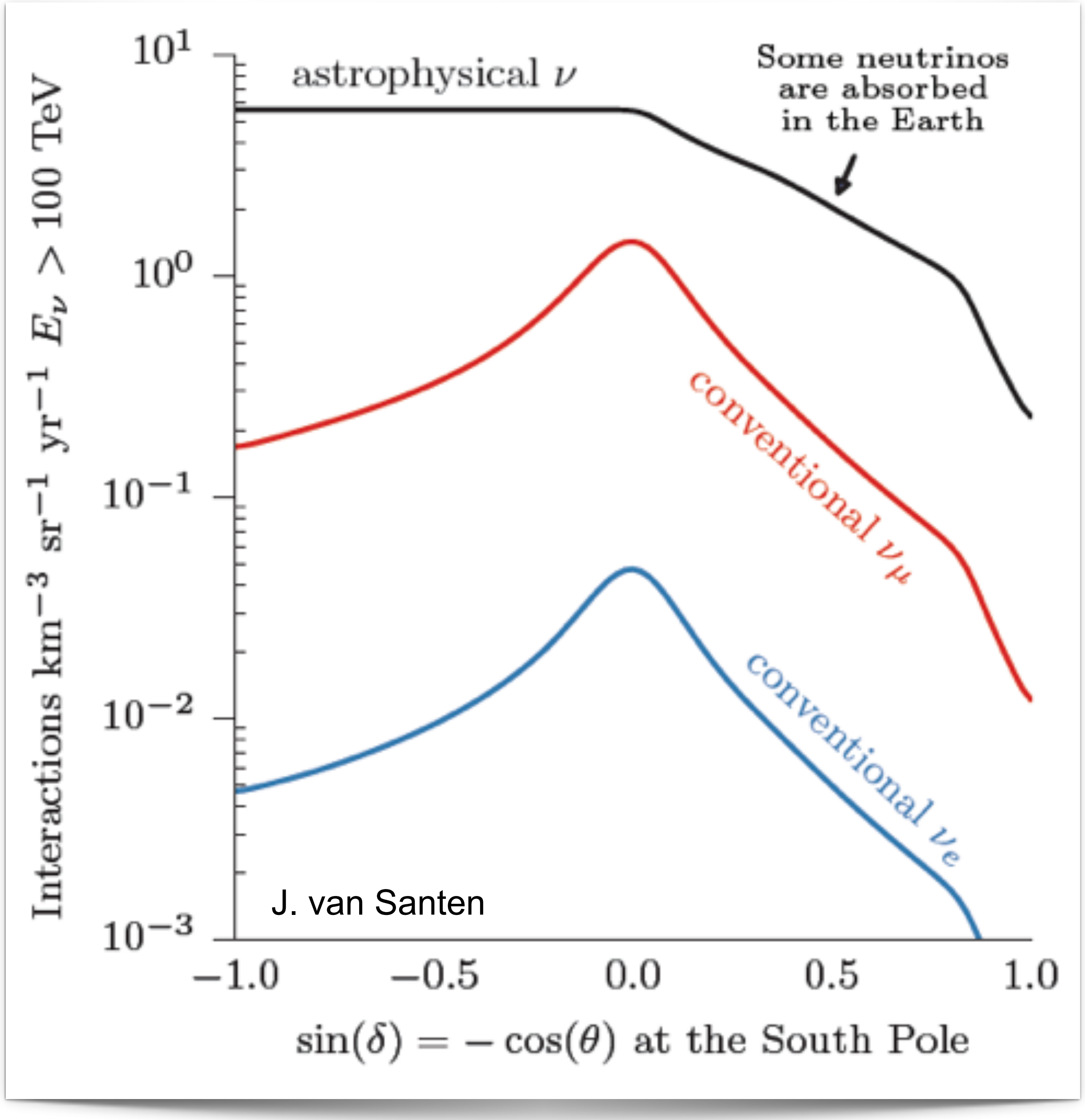


- Atmospheric neutrinos will, in general, be accompanied by muons produced in the same parent air shower
- Golden channel: "down-going starting events"



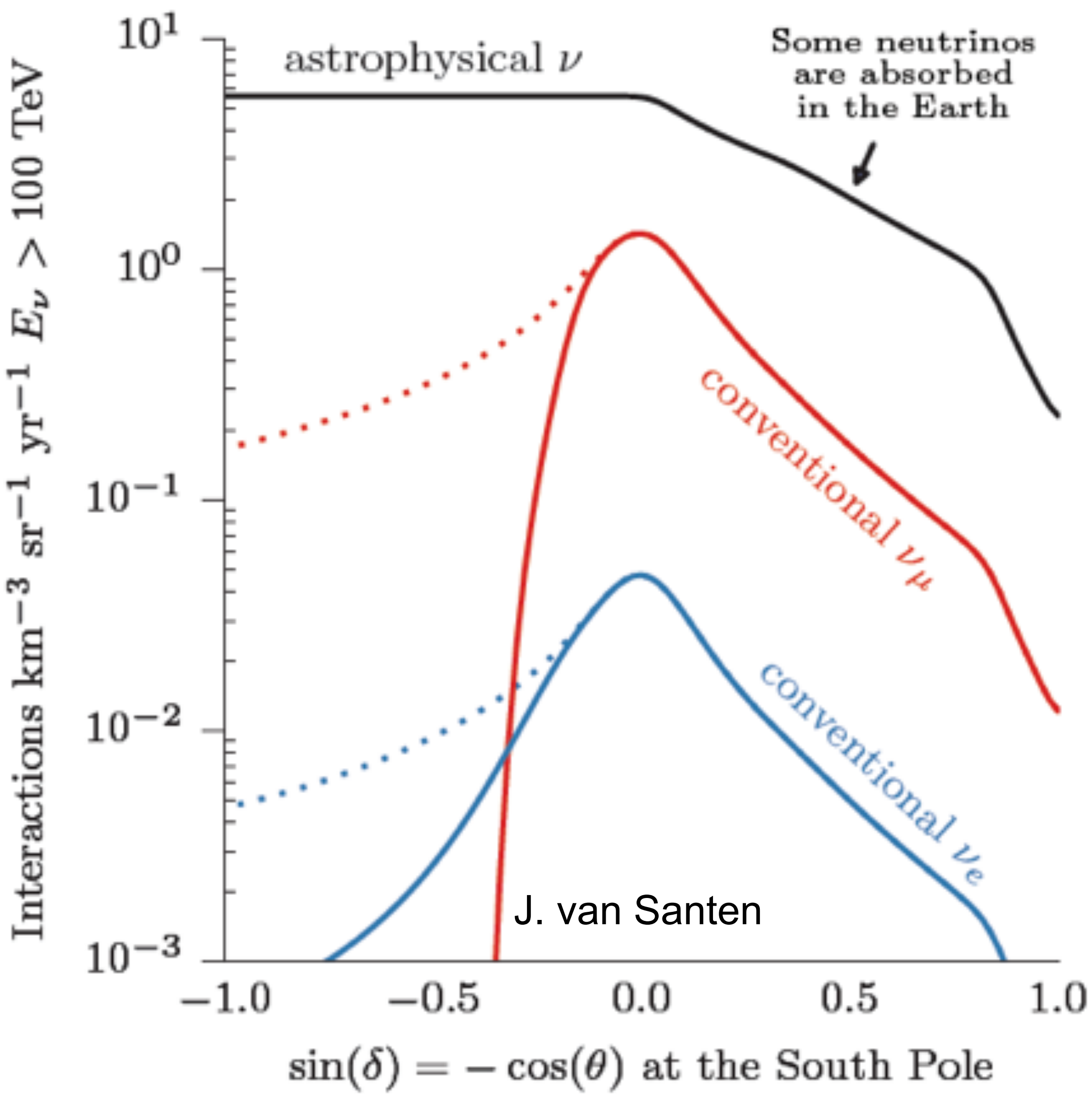
Schönert, Gaisser, Resconi, Schulz, Phys.Rev.D79 (2009)
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

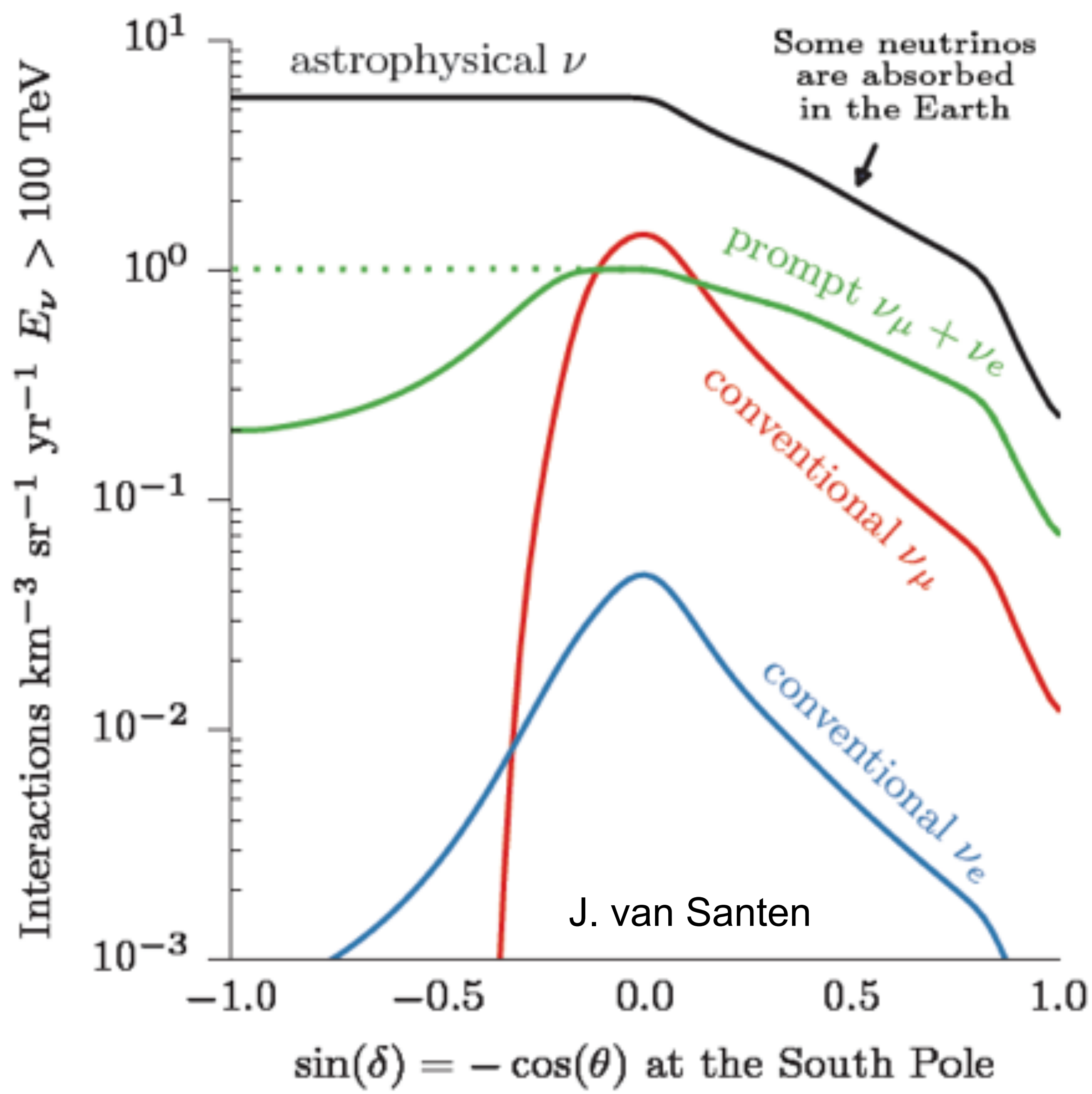
Atmospheric versus astrophysical neutrinos



Vetoing atmospheric neutrinos

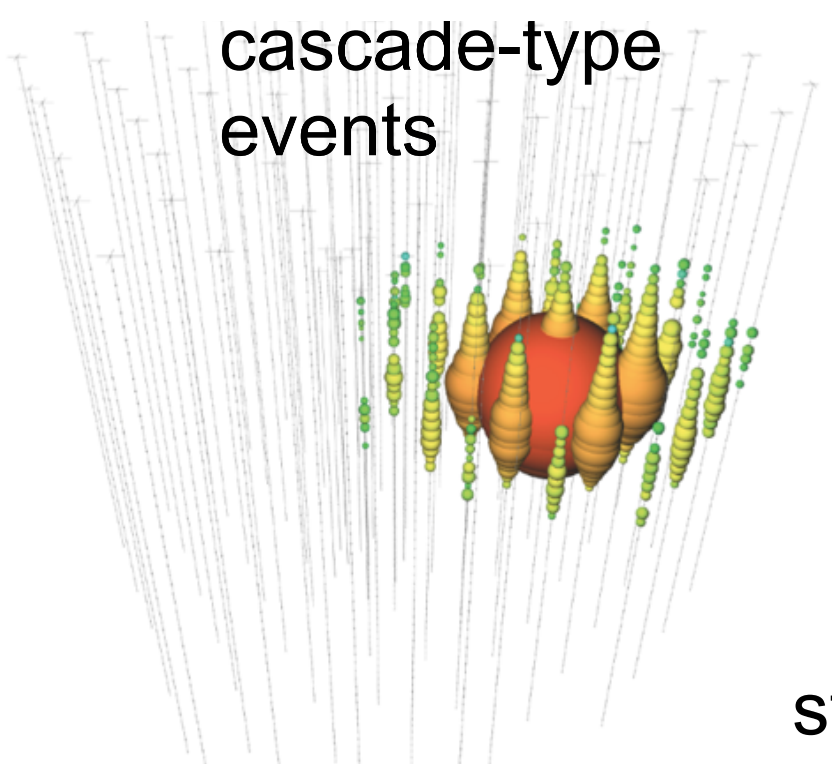
- The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different

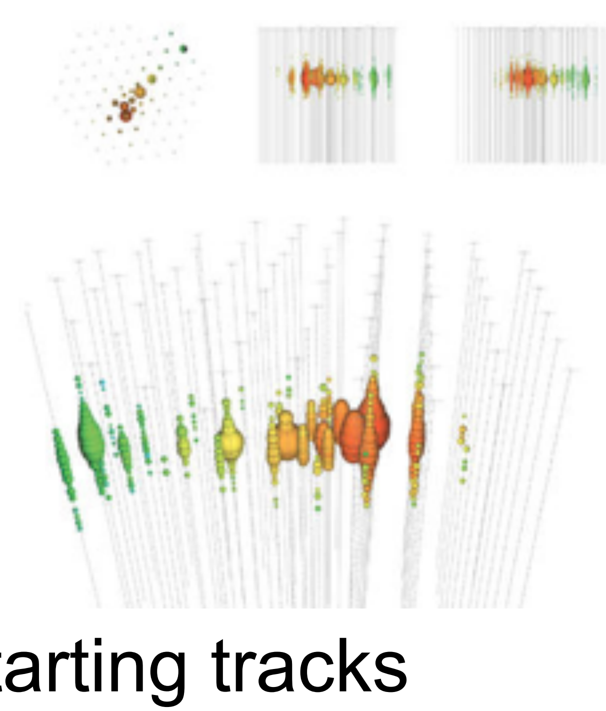


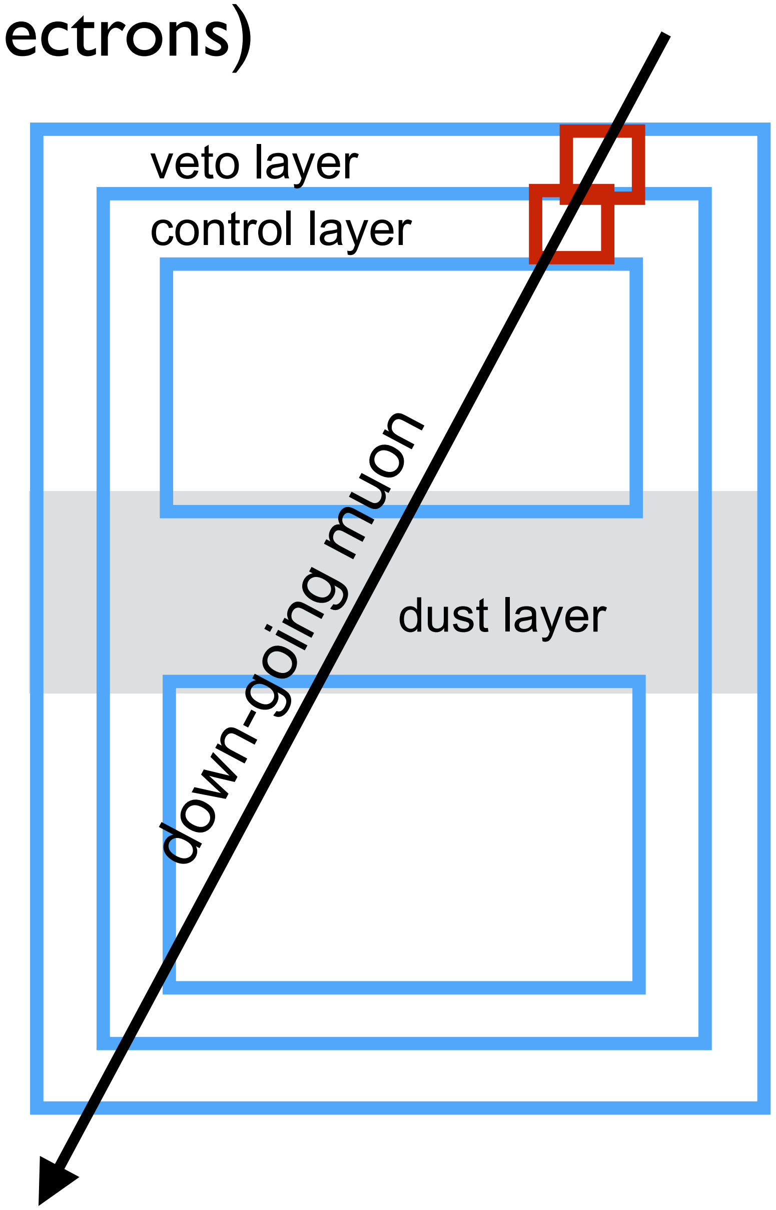


The breakthrough

- Search for well reconstructed contained and semi-contained events
- Veto atmospheric muons and neutrinos
- Use data to measure muon background (inner veto layer)
- Only study very high energies (> 4000 photo-electrons)
- Energy threshold: ~ 30 TeV

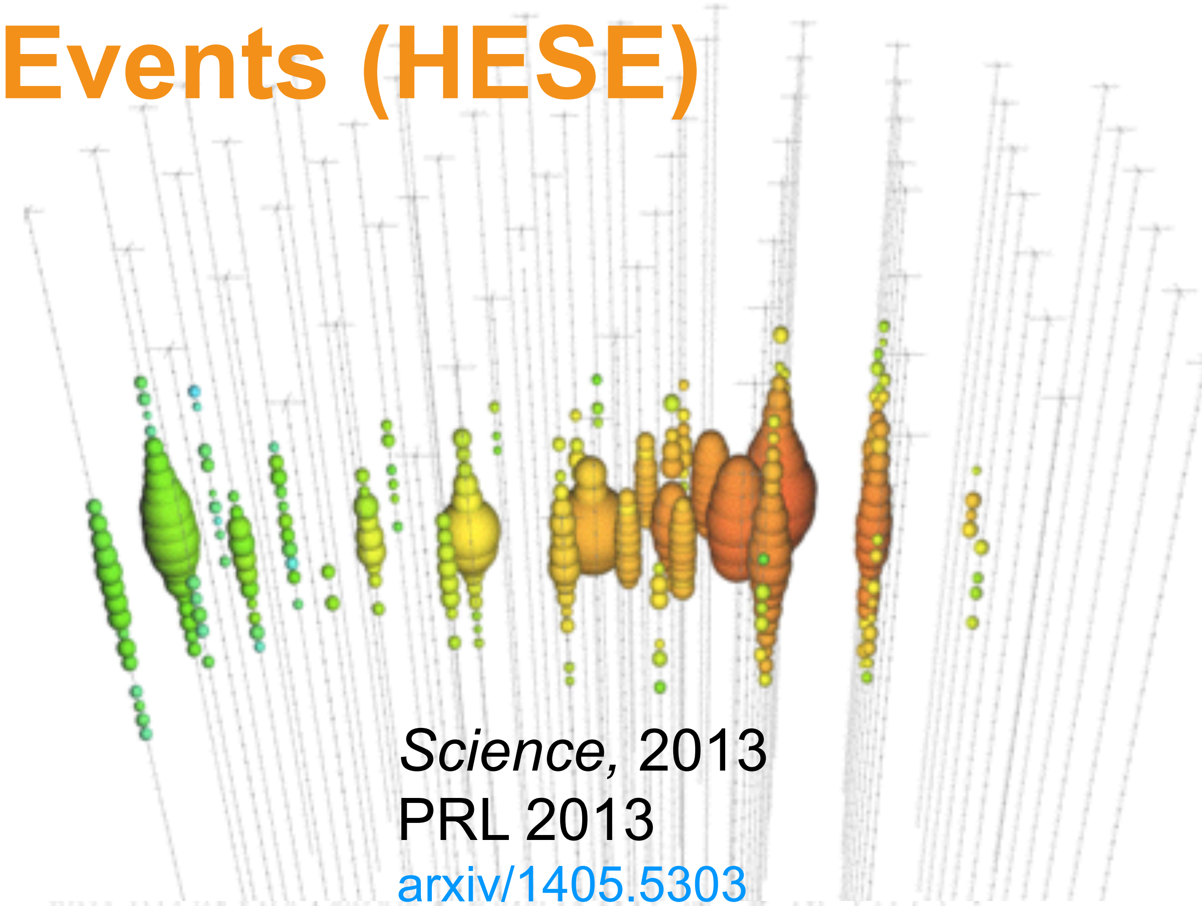




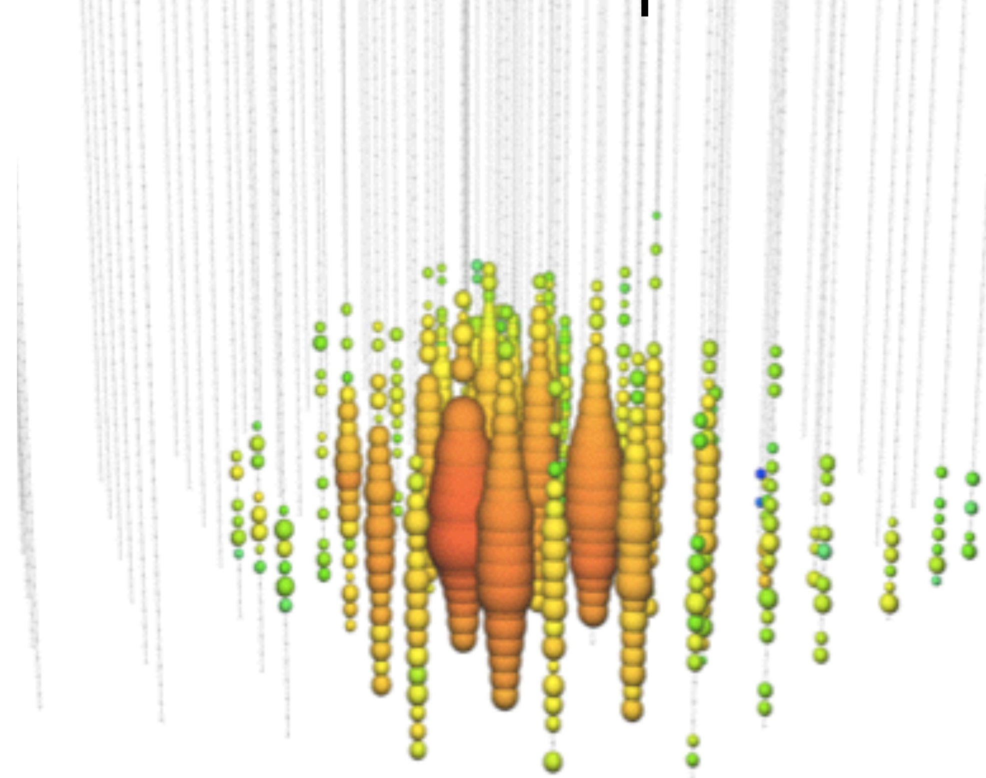


High Energy Starting Events (HESE)

- Track-like events
  - ~1° angular resolution
  - Muon takes some energy away
- Cascade-like events
  - ~10°-45° angular resolution
  - 15% visible energy resolution
- Residual background: atmospheric muons and atmospheric neutrinos

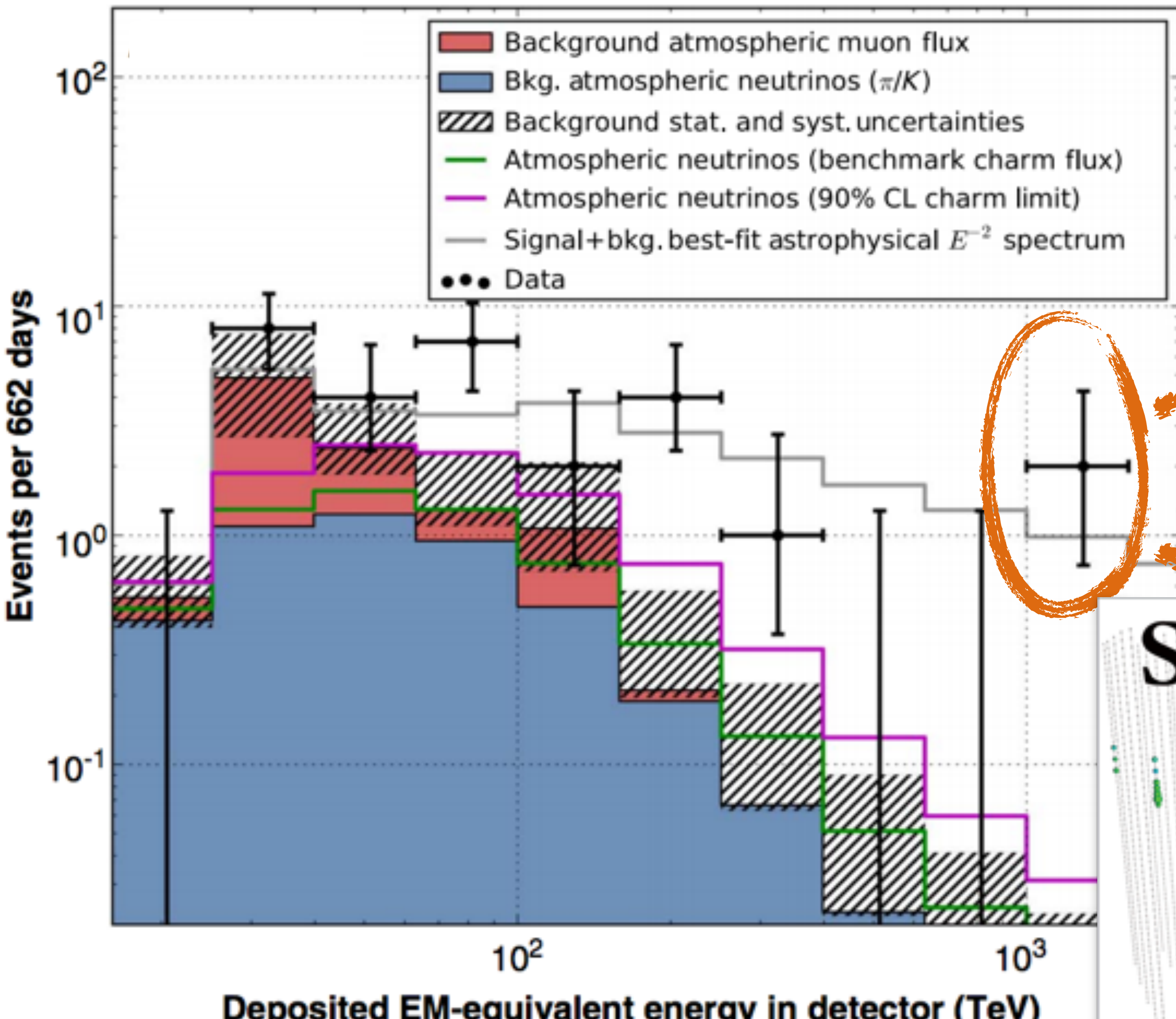


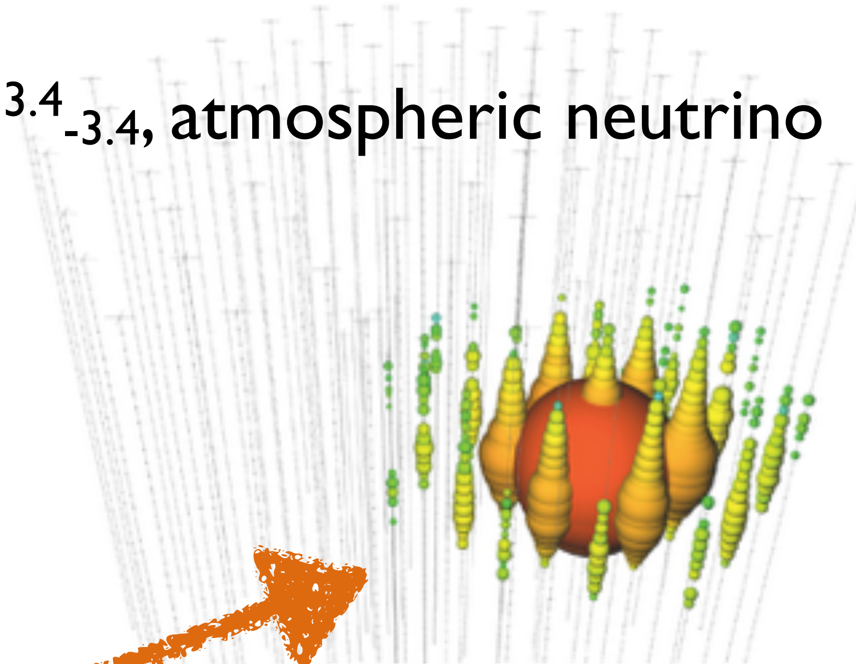
Science, 2013
PRL 2013
arxiv/1405.5303



First clear evidence for extraterrestrial neutrinos

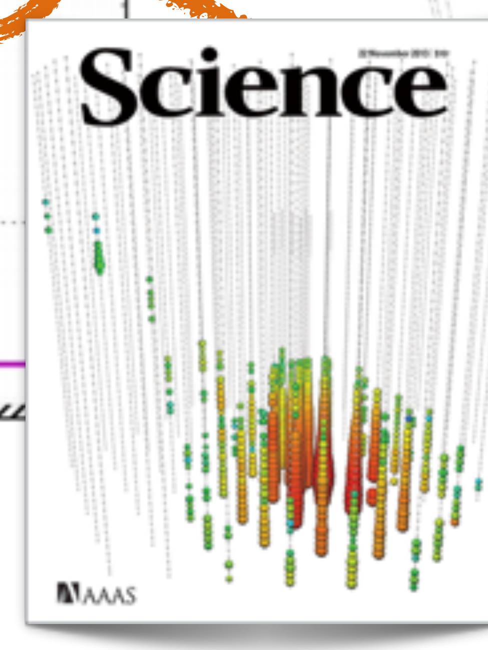
- 28 events found above 30 TeV, muon background $6.0^{+3.4}_{-3.4}$, atmospheric neutrino background $4.6^{+3.7}_{-1.2}$, significance 4.1 σ

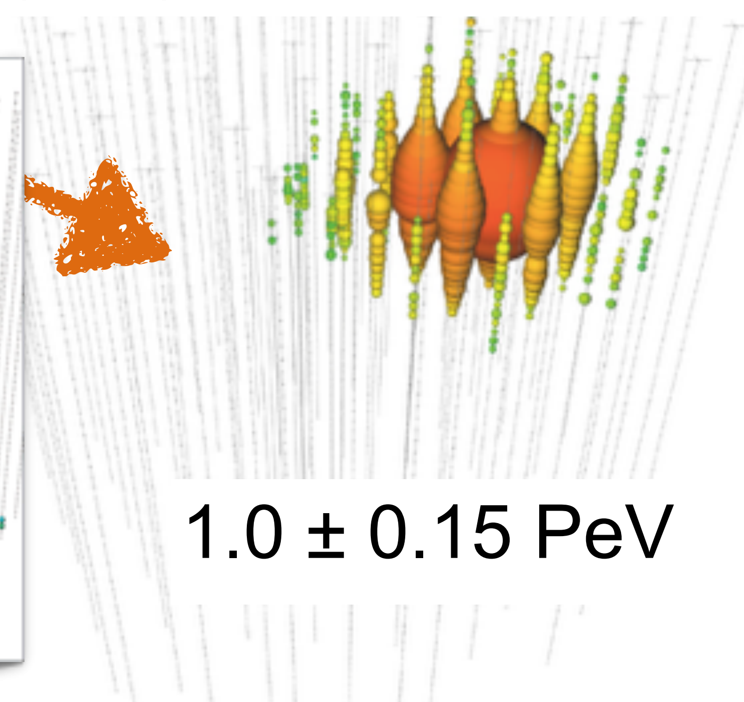




1.1 ± 0.17 PeV

IceCube Collaboration: M. G. Aartsen et al
Science 342 (2013) 1242856

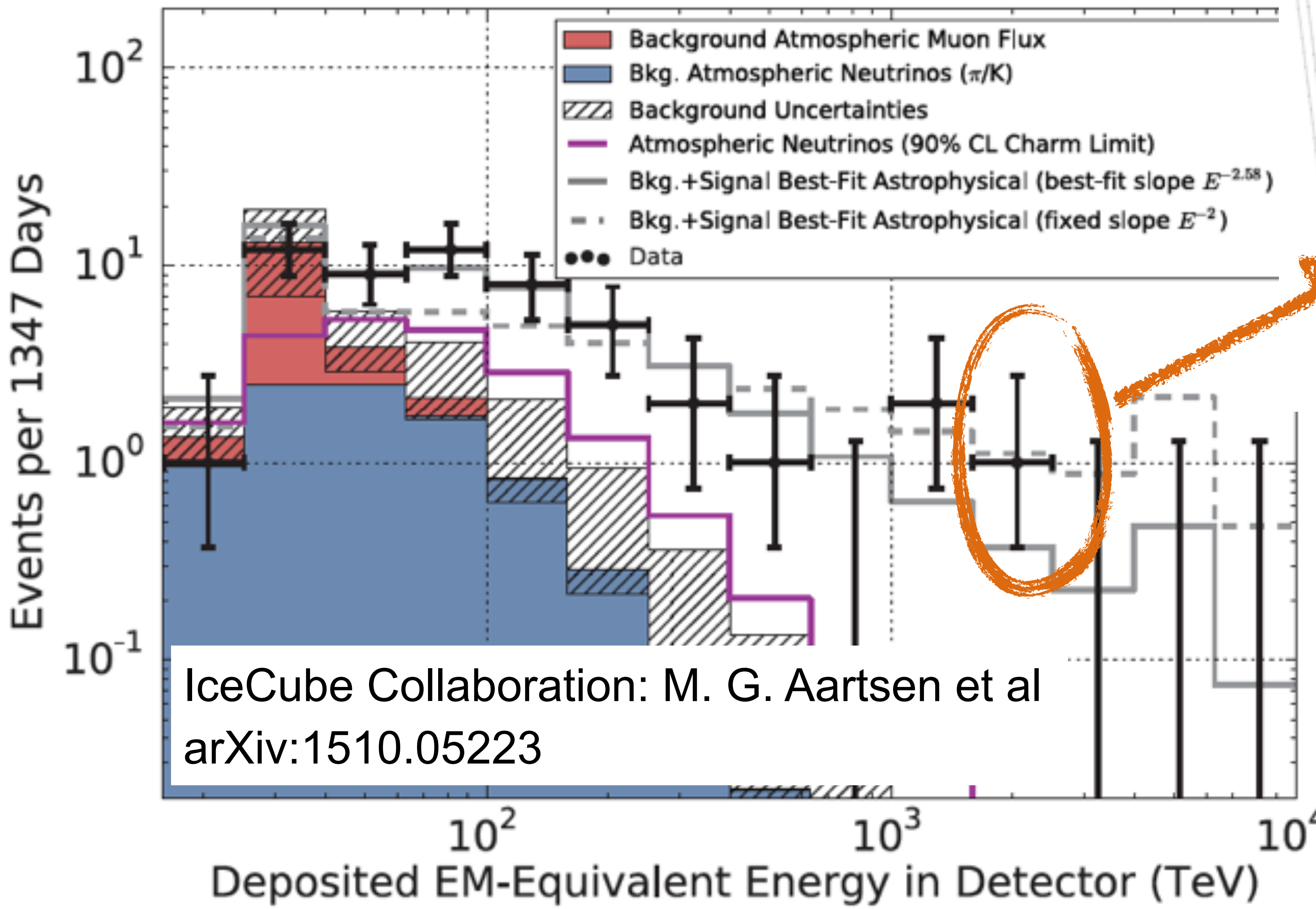


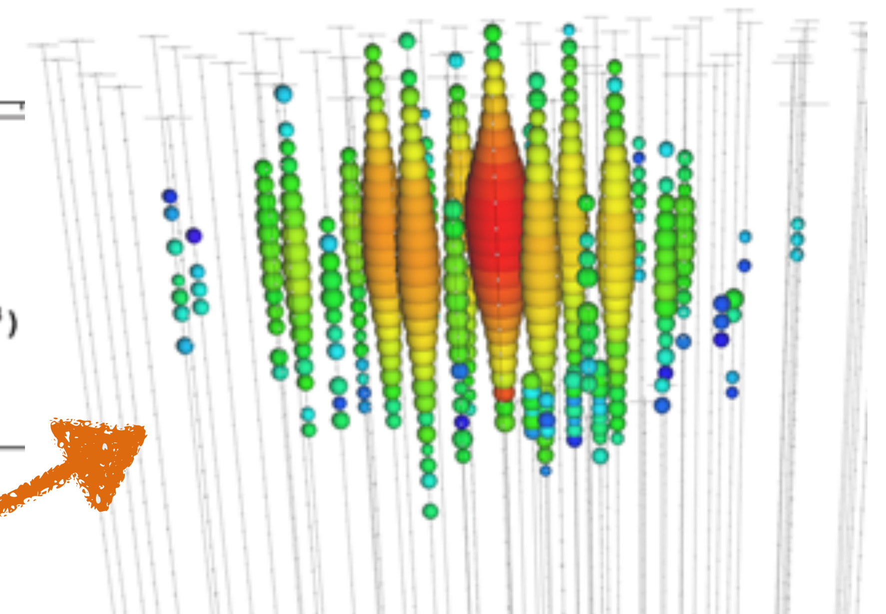


1.0 ± 0.15 PeV

Four years of IceCube data

- 54 events found, muon background $12.6^{+5.1}_{-5.1}$, atmospheric neutrino background $9.0^{+8.0}_{-1=2.2}$
- 39 cascades, 13 tracks, 2 likely background

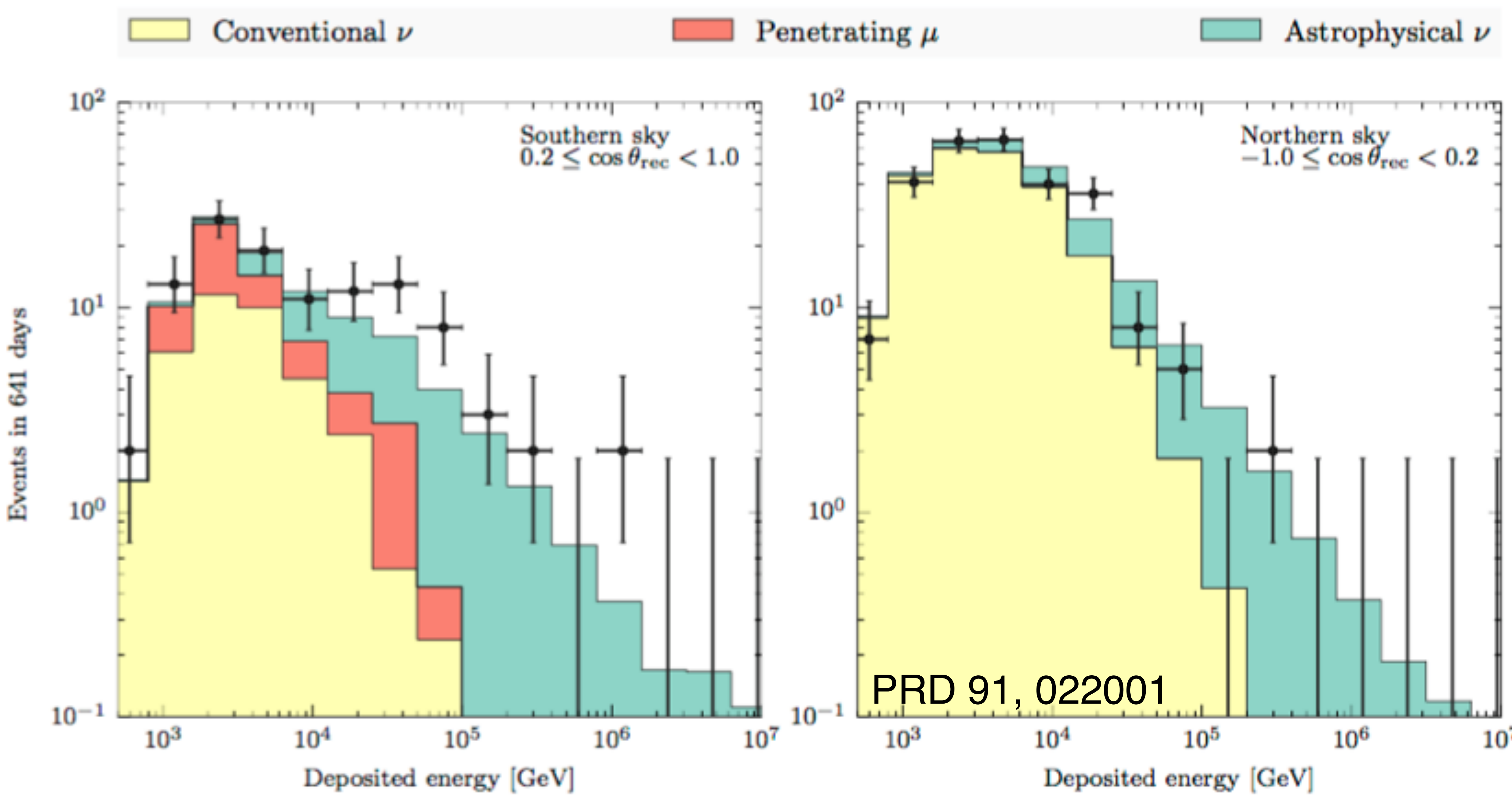




$2.0^{+0.26}_{-0.24}$ PeV

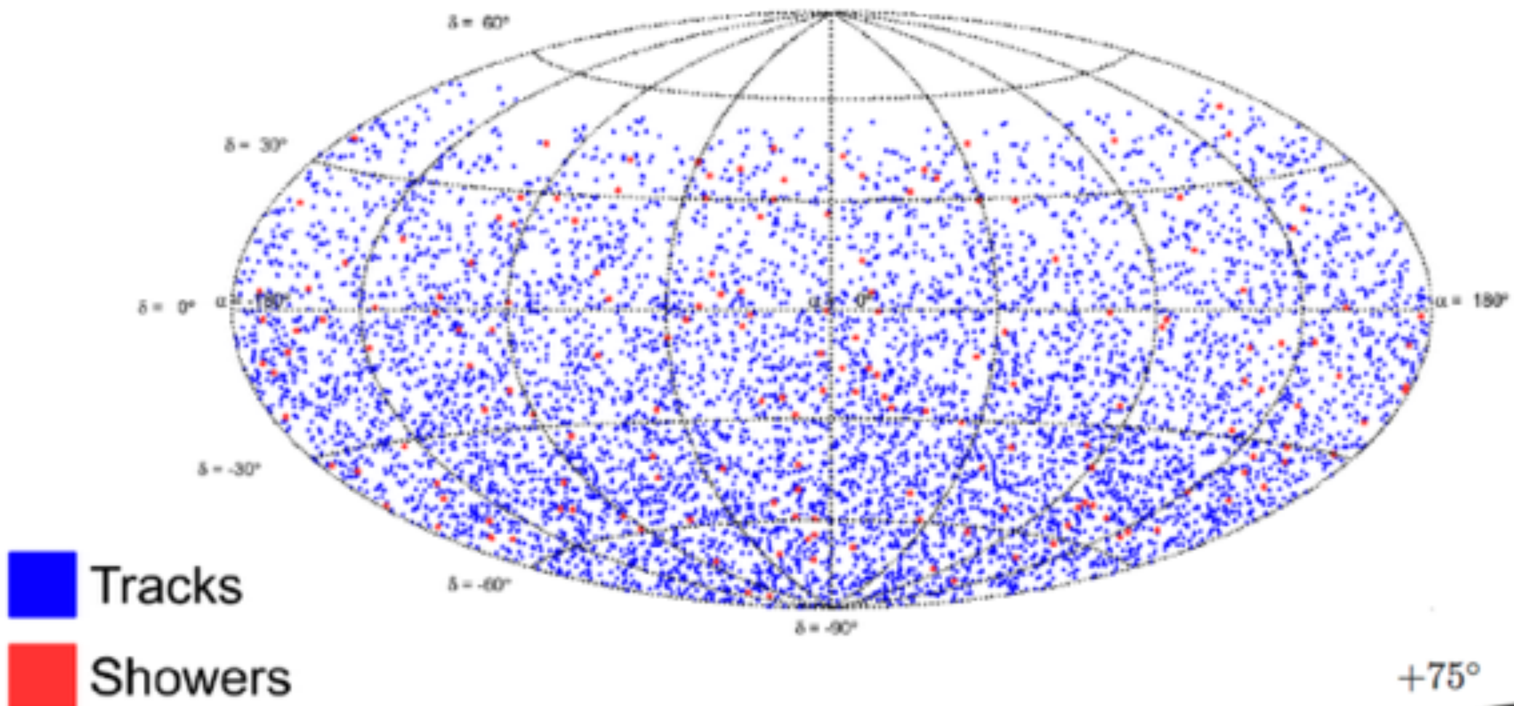
Lowering the energy threshold

- Thicker veto at low energies suppresses penetrating muons without sacrificing high-energy neutrino acceptance
- Best fit spectral index: 2.46 ± 0.12



Search for point sources of neutrinos

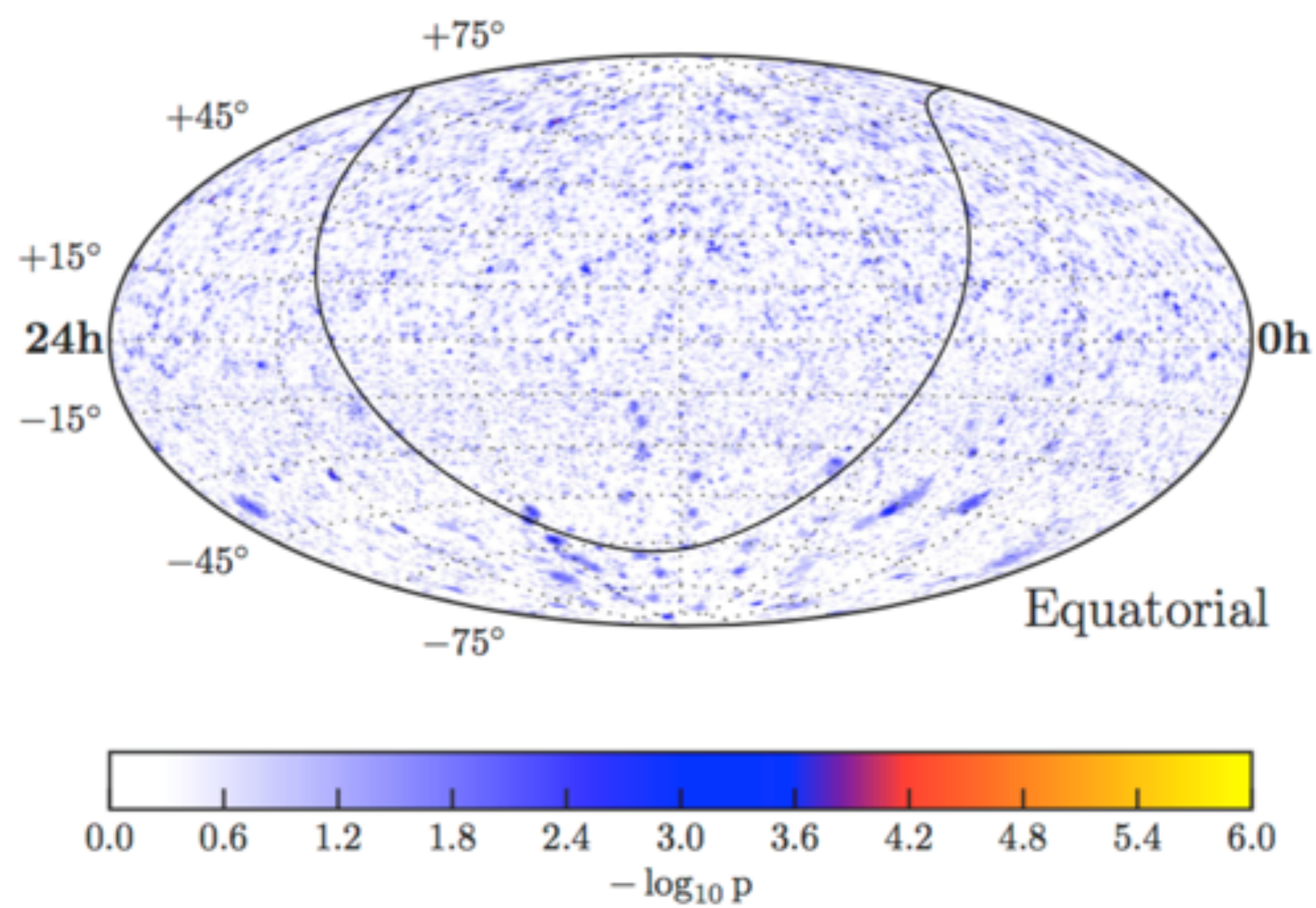
- Neutrinos alone do not (yet) reveal a source



ANTARES ApJ 786 2014

North: post-trial 29%

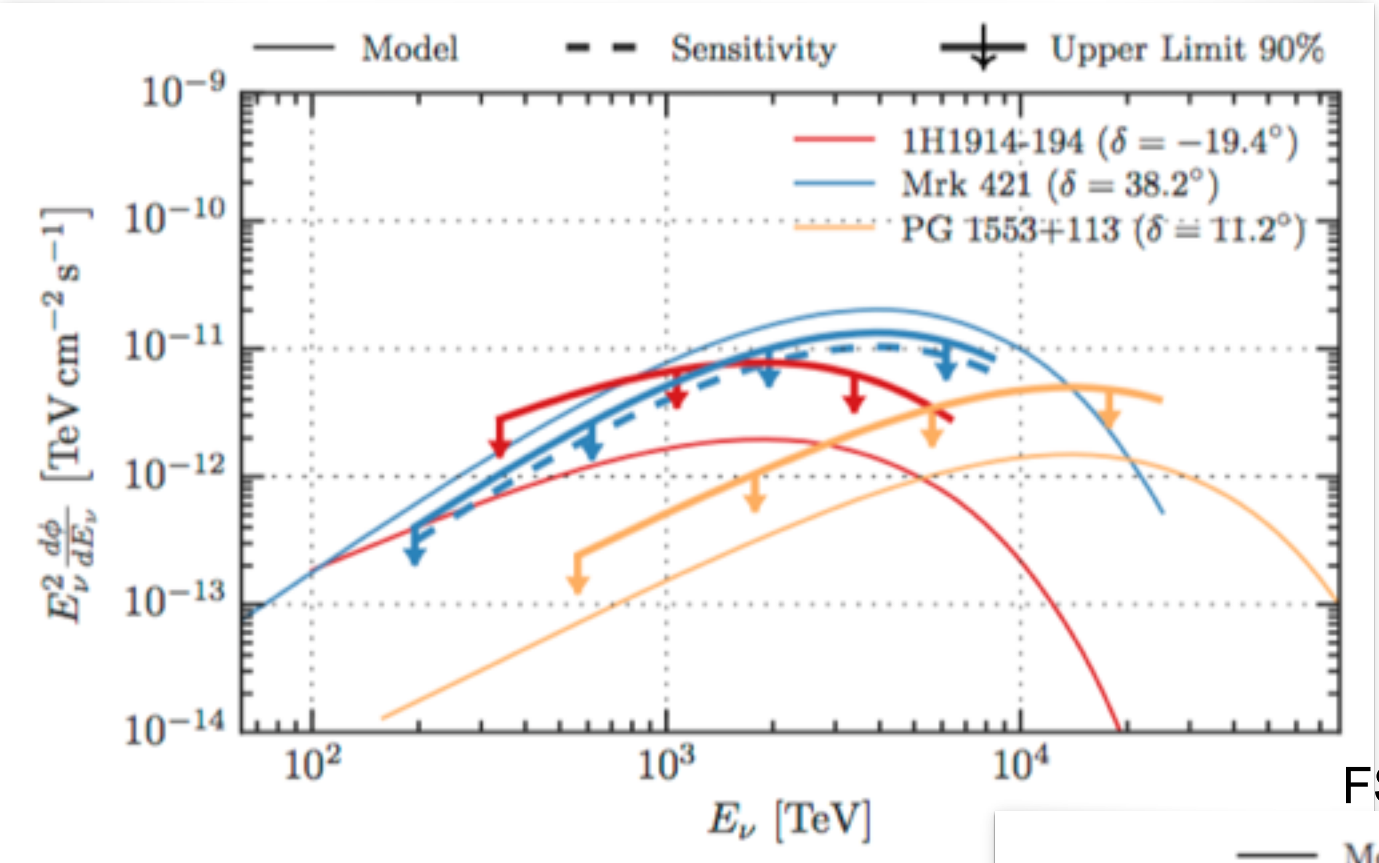
South: post-trial 17%



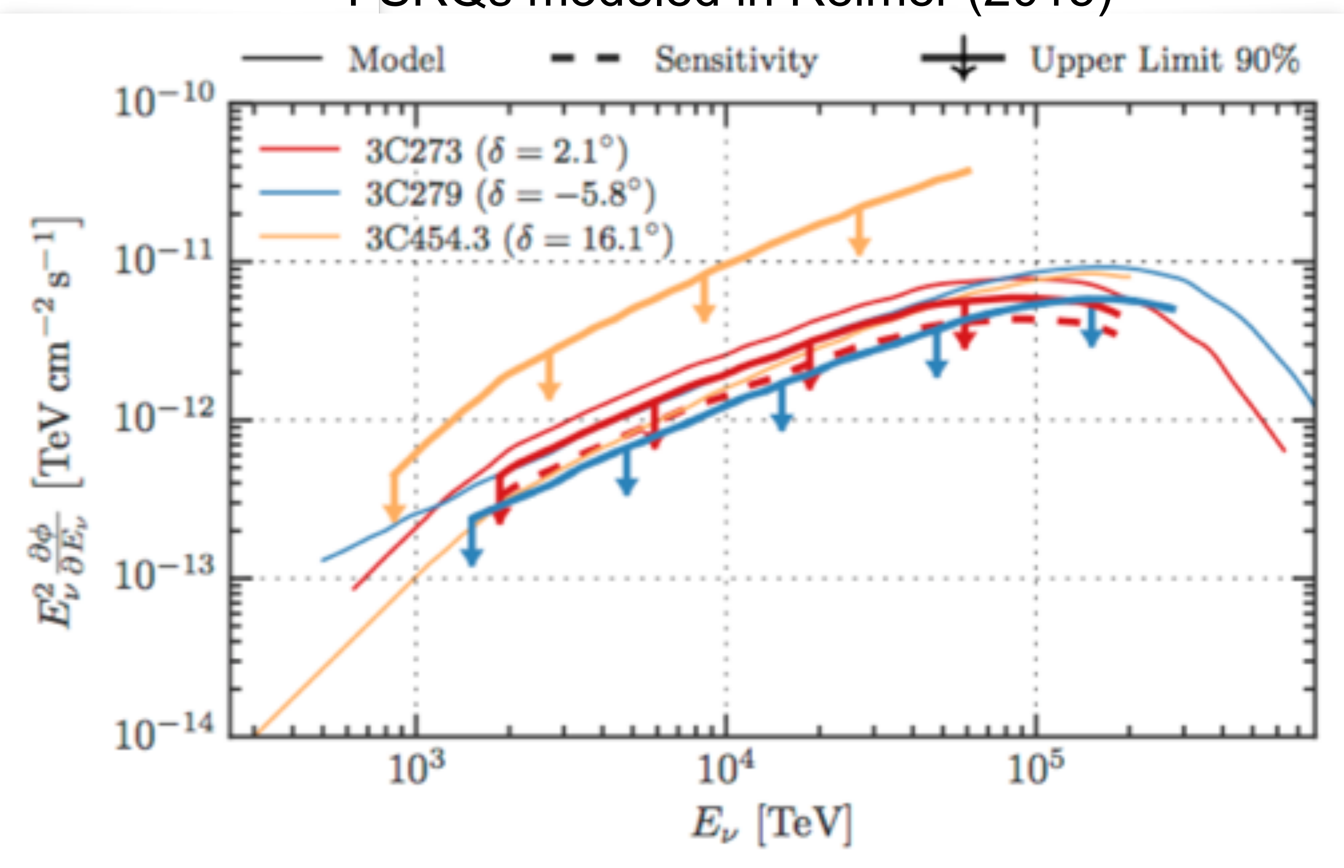
IceCube, arXiv:1609.04981

Constraints from time integrated limits

BL-Lacs modeled in Petropoulou et al. (2015)

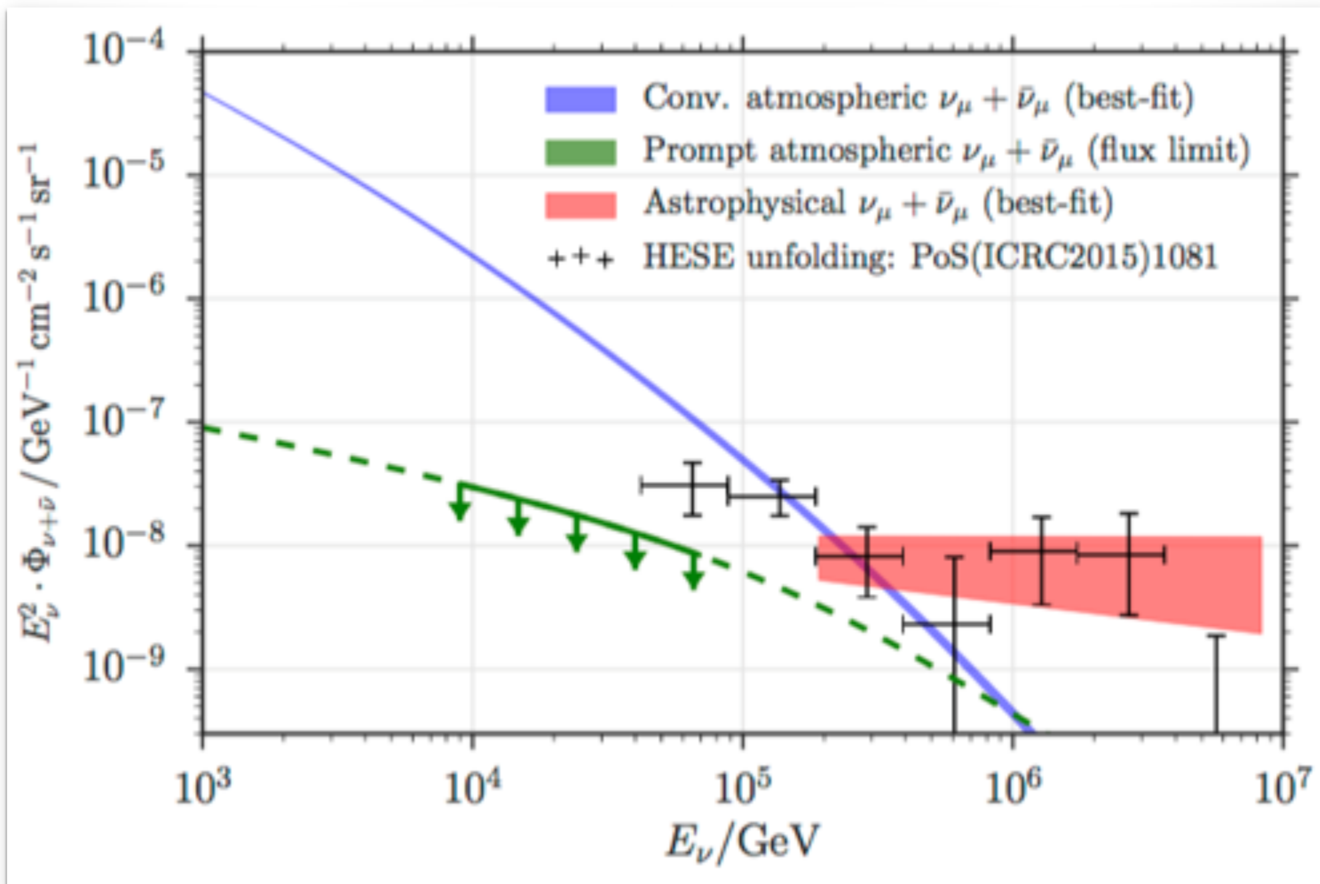


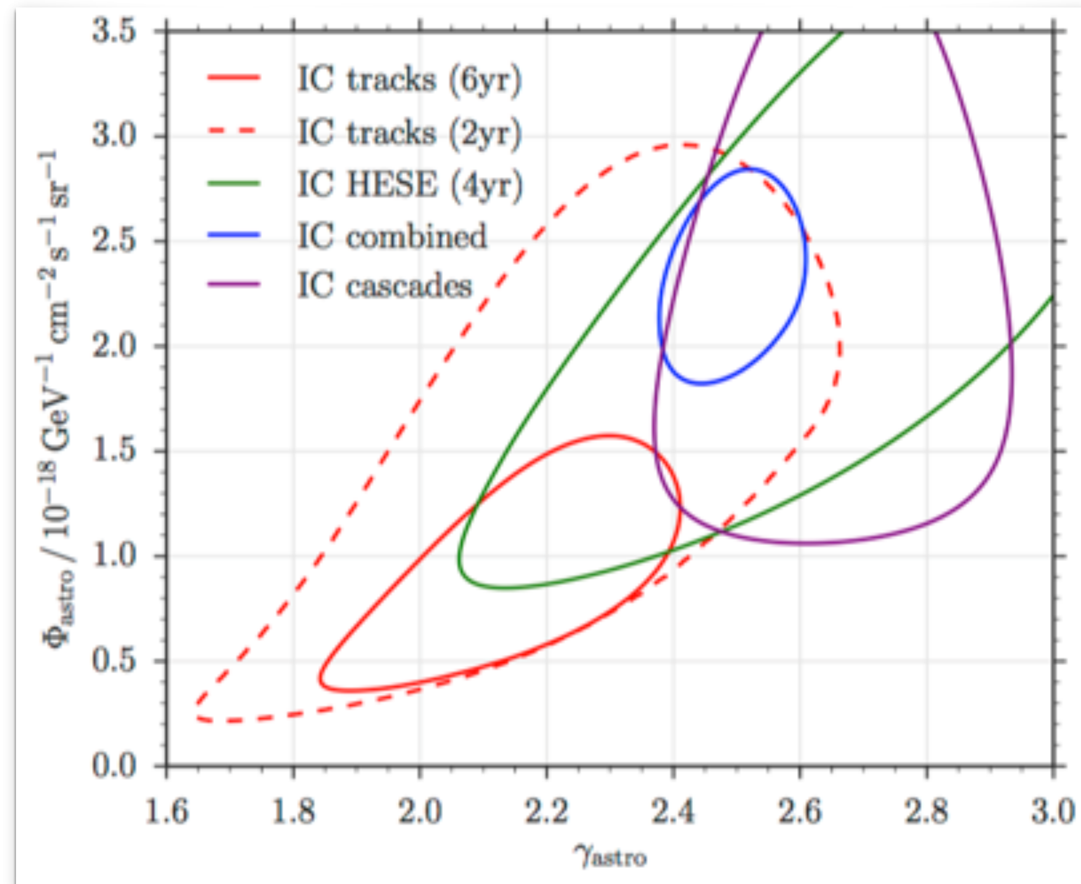
FSRQs modeled in Reimer (2015)



IceCube, arXiv:1609.04981

Tension between IceCube analyses if power law





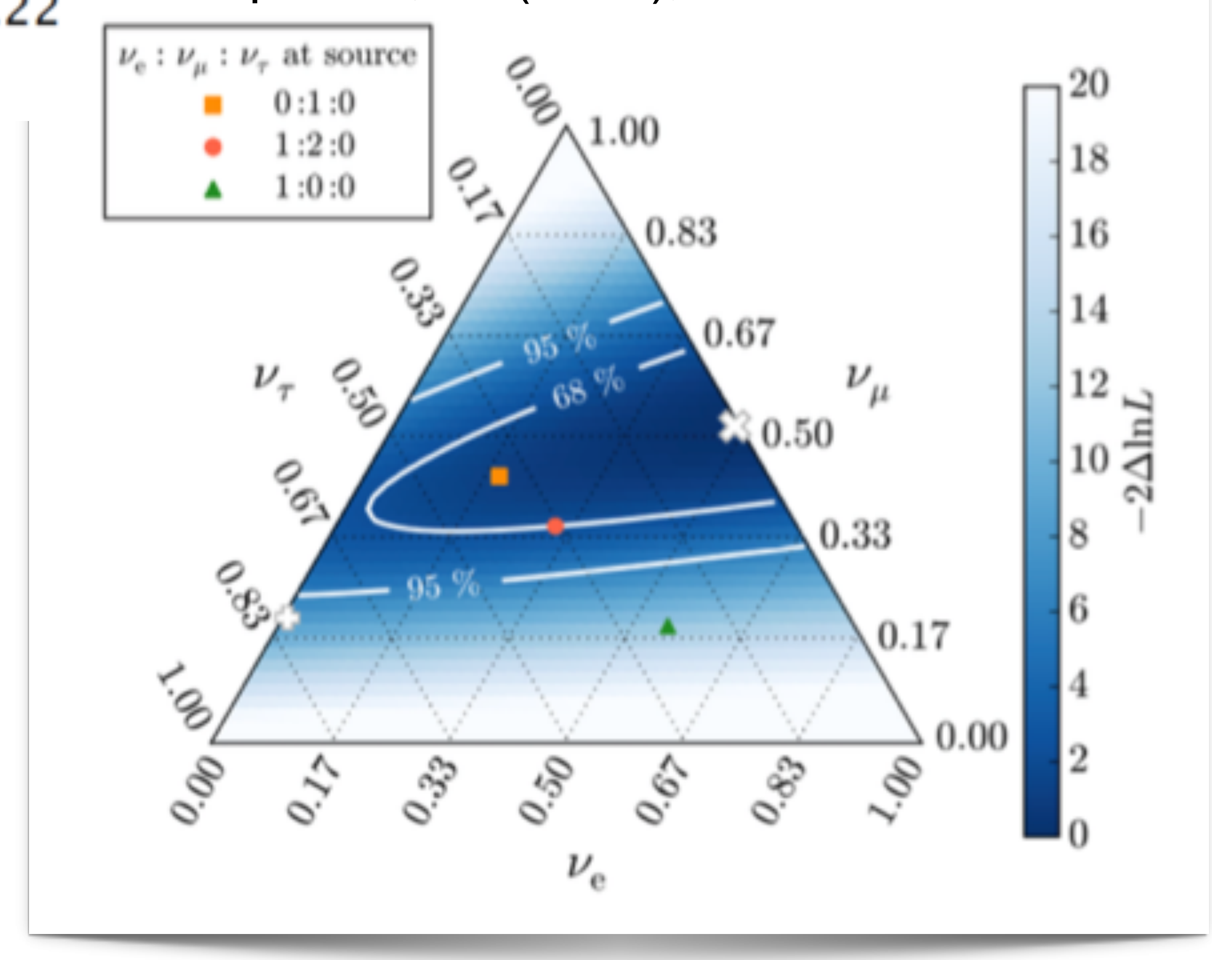
arXiv: 1607.08006

Flavours

Sources → Earth

	ν_e	ν_μ	ν_τ	ν_e	ν_μ	ν_τ
Pion Decay	1	2	0	1	1	1
Muon damped	0	1	0	0.2	0.39	0.39
Neutron decay	1	0	0	0.56	0.22	0.22

ApJ 809, 98 (2015), arXiv:1507.03991

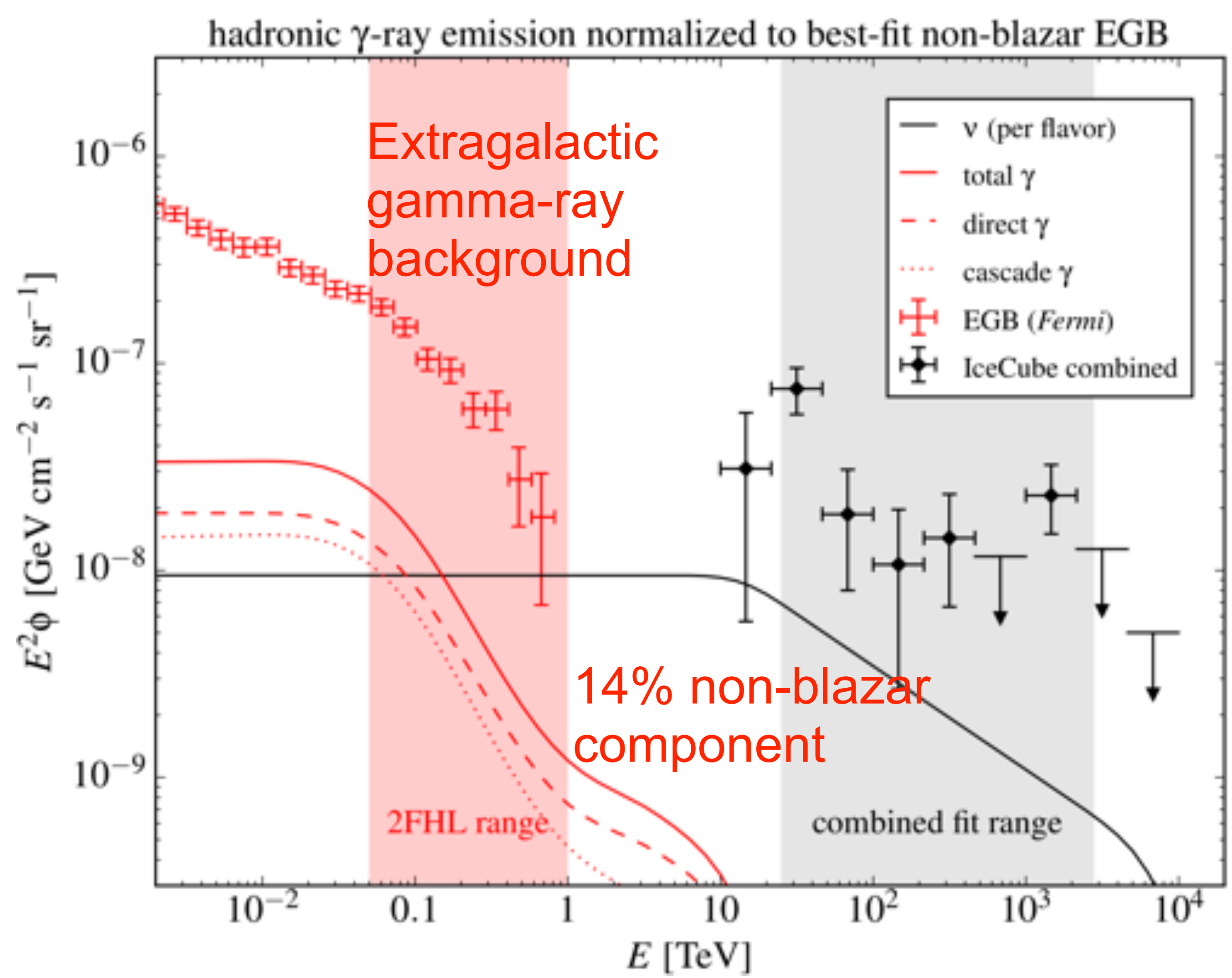


What do we know

- Astrophysical neutrinos: spectrum, declination, flavour admixture
- Data shows some extra-galactic component
- Data deviates from an unbroken E^{-2} spectrum
- Few bright sources are disfavoured by point source searches
- FERMI Blazars disfavoured by point source searches
- Star forming galaxies disfavoured by diffuse FERMI extragalactic flux
- Gamma-ray bursts also also disfavoured by dedicated searches

Looking for counterparts of IceCube events

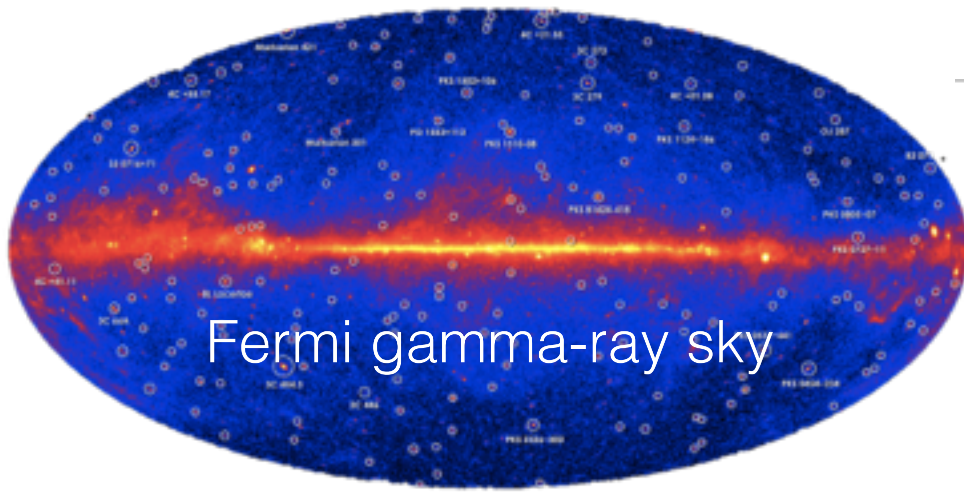
- Star-forming galaxies
  - contribute at most ~15% of extragalactic gamma-ray background (EGB)
  - proposed as the dominant source of HESE (arxiv/1306.3417)
  - evidence against star-forming galaxies as dominant source of HESE (arxiv/1511.00688)

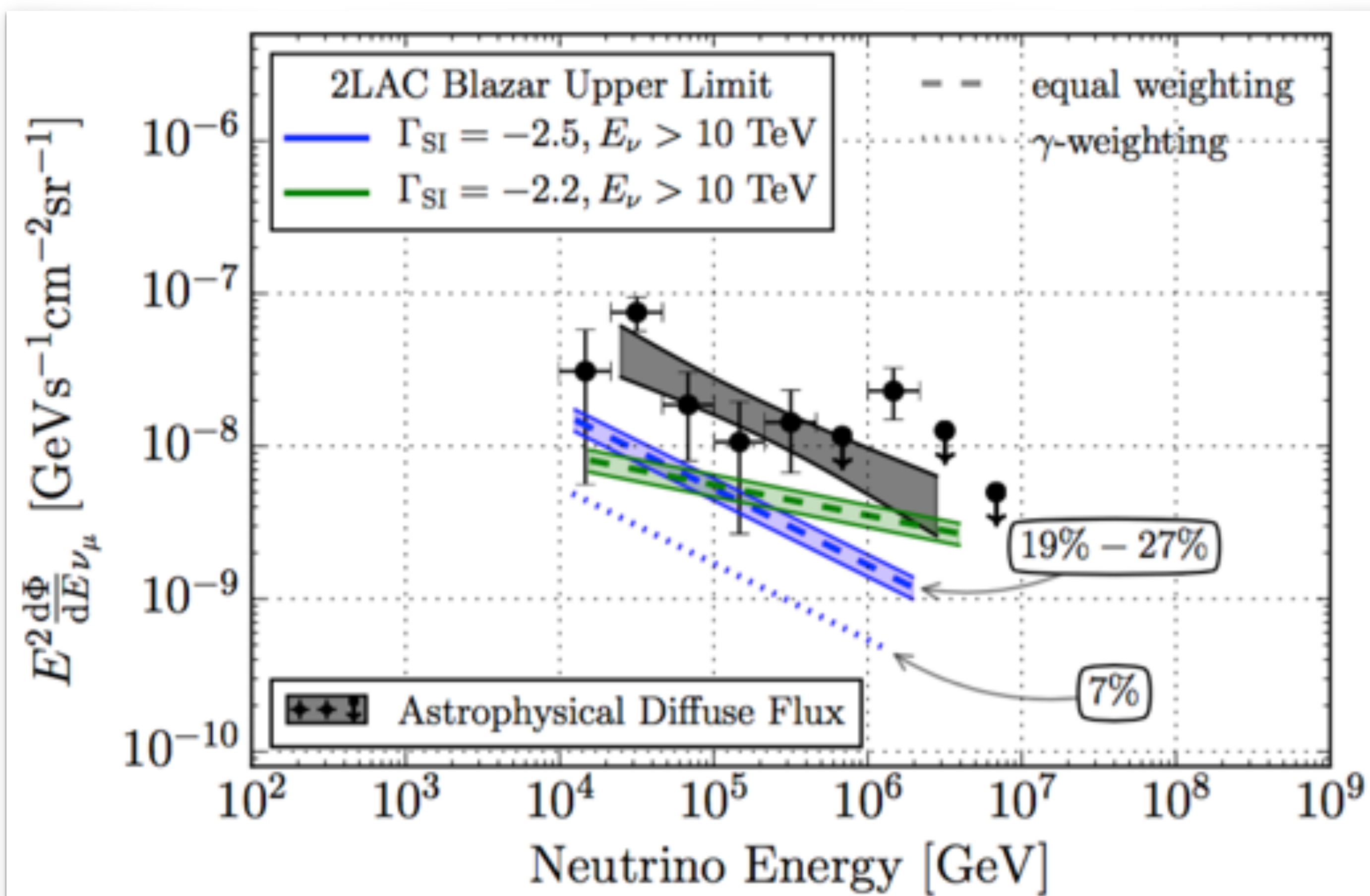


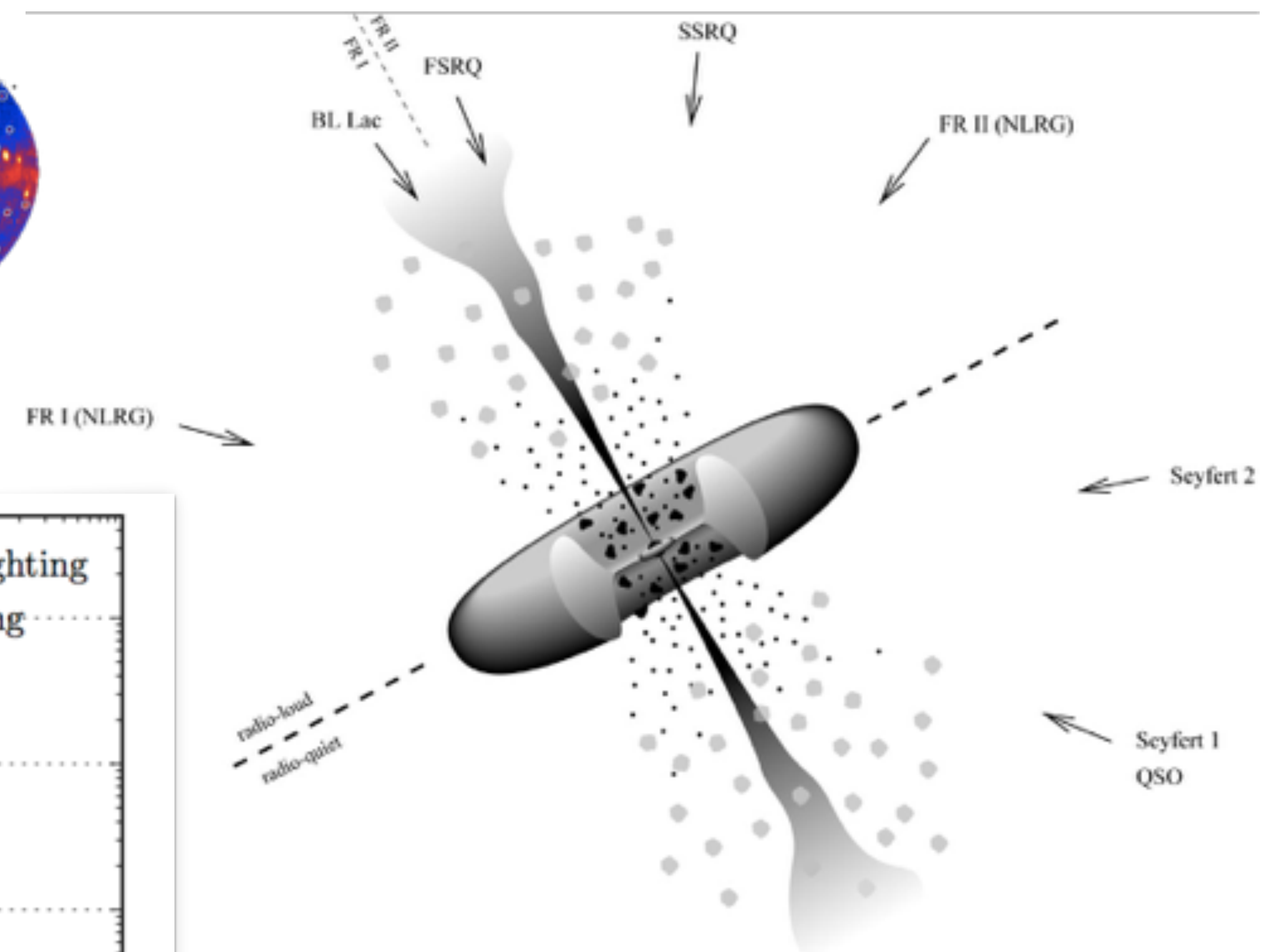
Bechtol et al. arXiv:1511.00688

Looking for counterparts of IceCube events

- Correlation study of 3 years of IceCube data and 862 Fermi- LAT Blazars





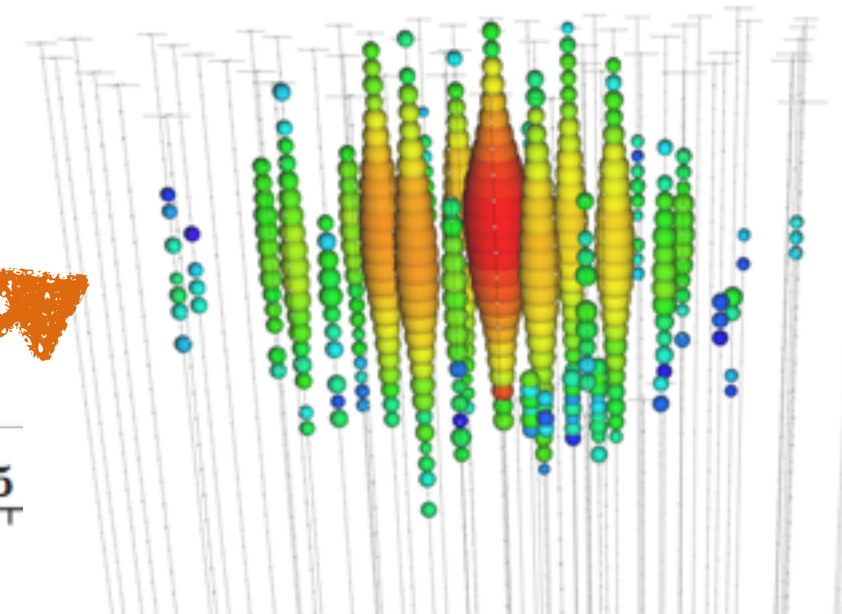


IceCube Coll.,

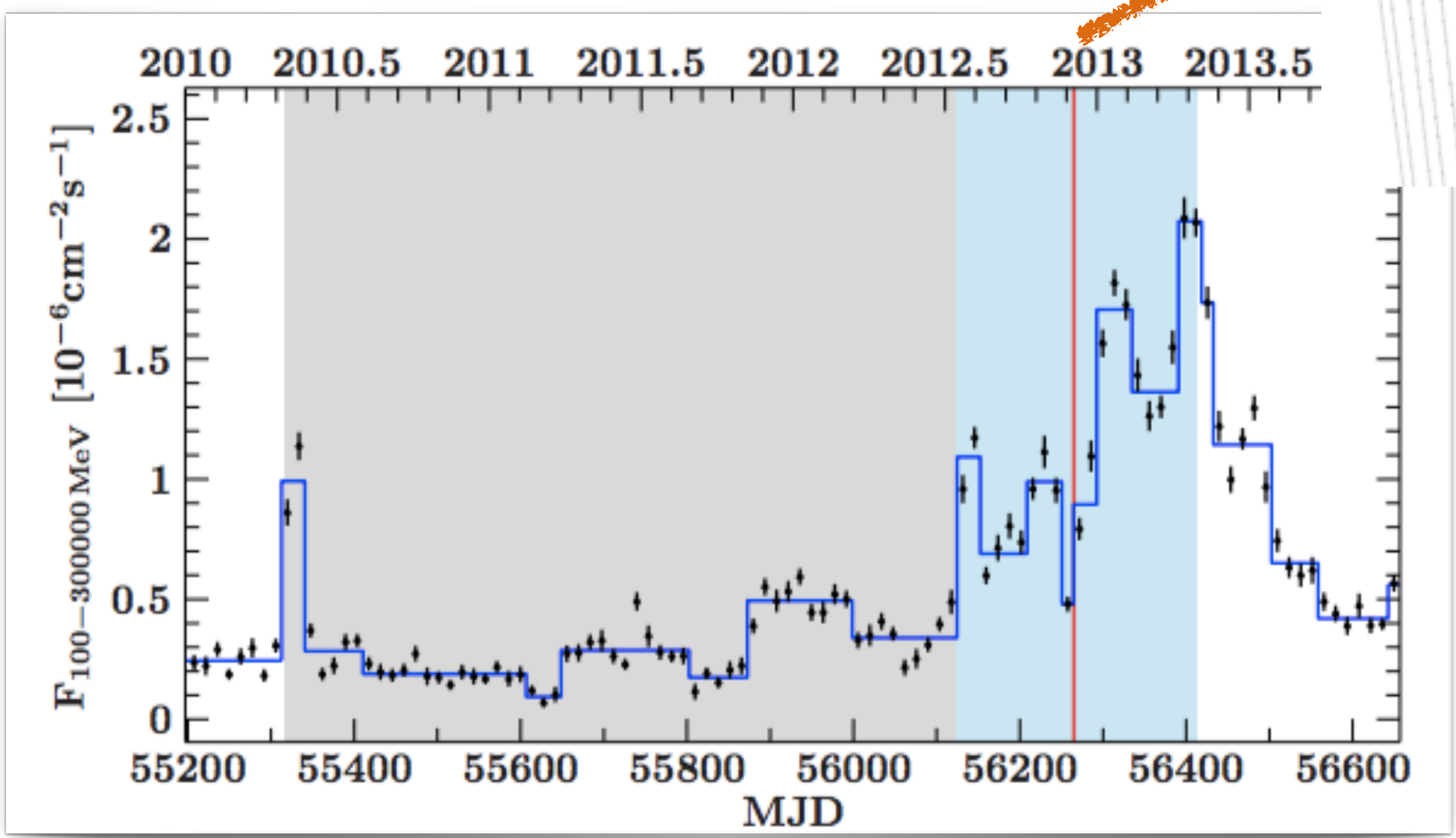
arXiv:1502.03104

Looking for counterparts of IceCube events

- Major outburst of FSRQ PKS B1424−418 occurred in temporal and positional coincidence PeV neutrino (Big Bird)
- 5% chance coincidence



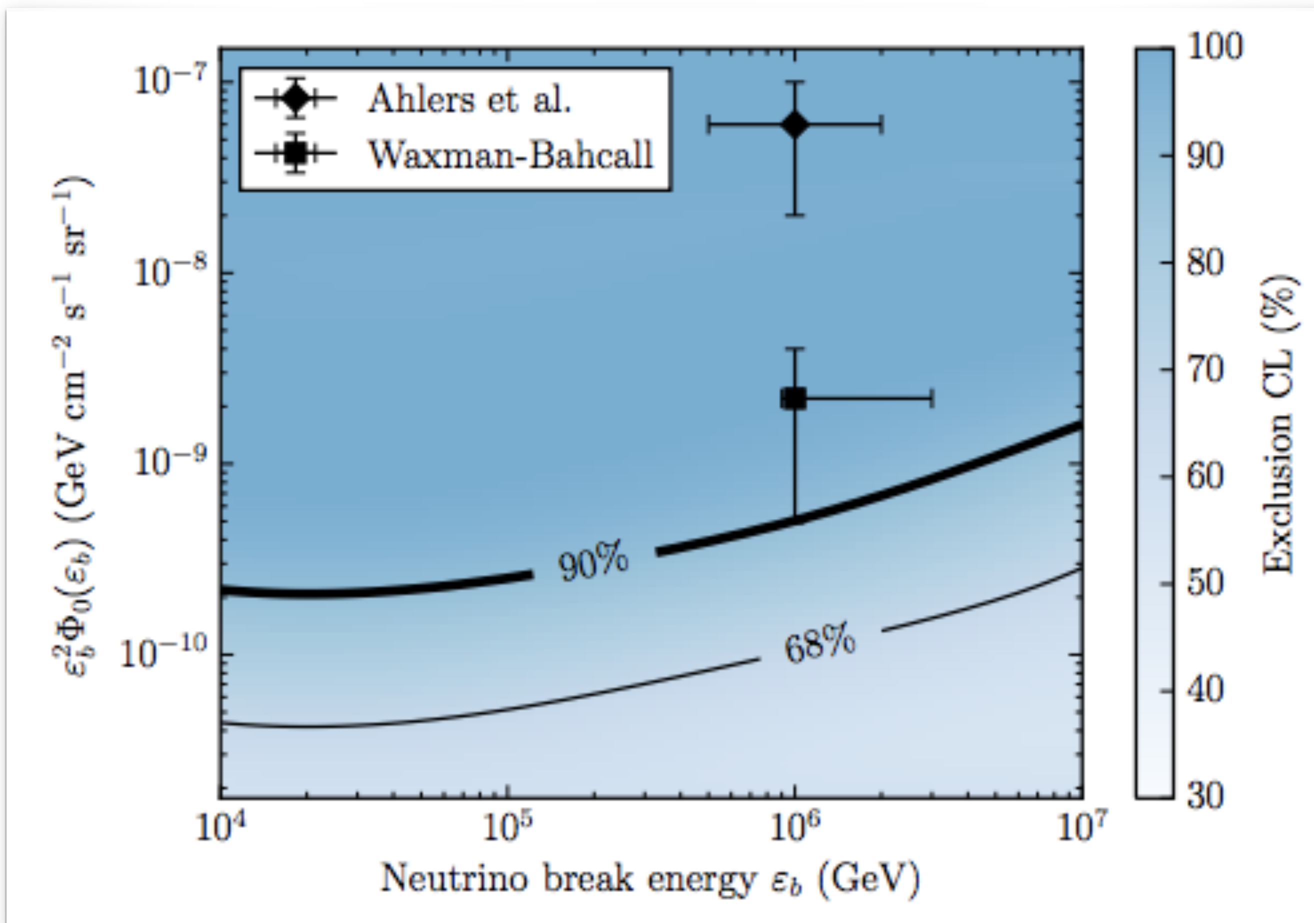
$2.0^{+0.26}_{-0.24}$ PeV



Kadler et al., Nature 520, 266 (2016)

Looking for counterparts of IceCube events

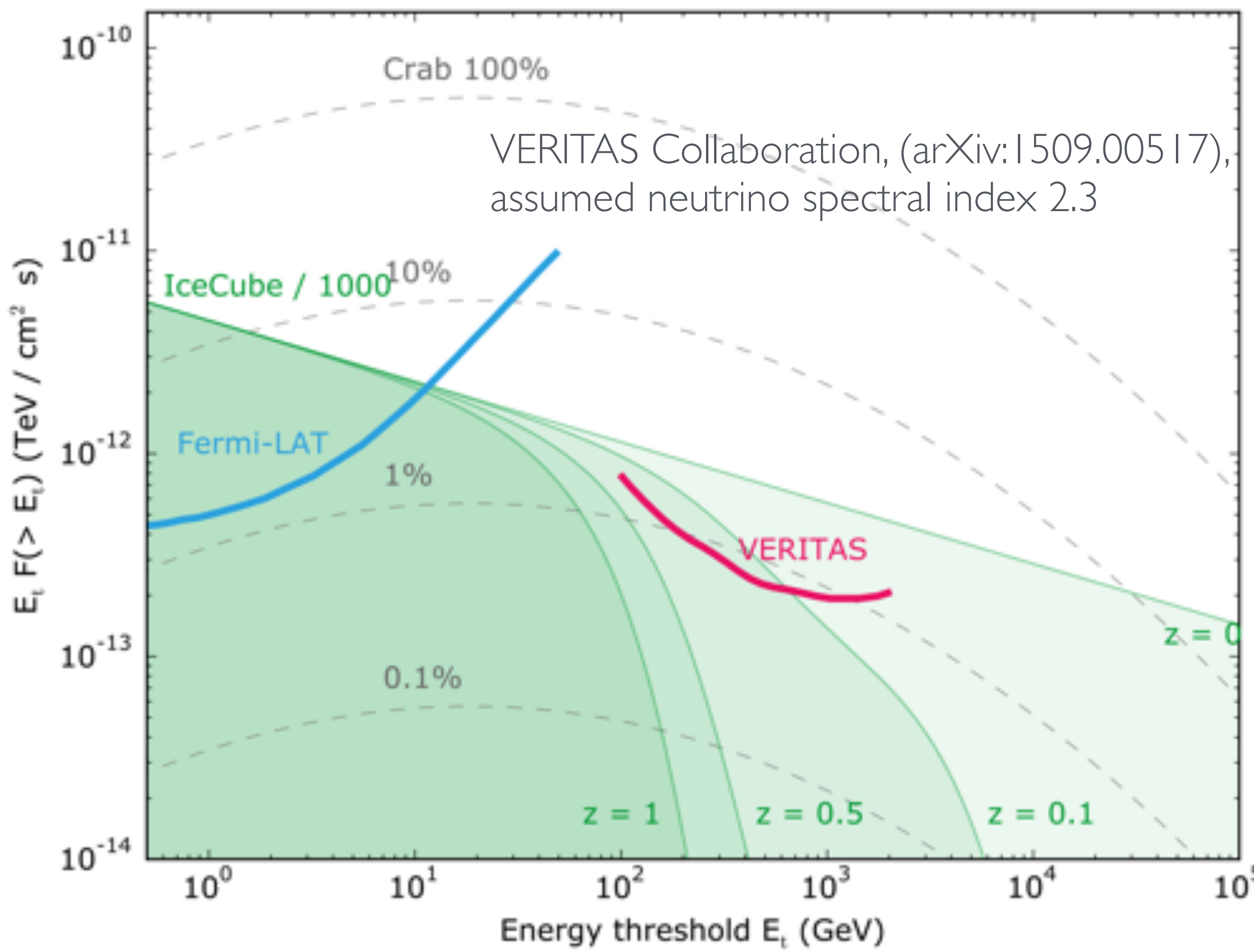
- > 800 GRBs correlated with IceCube data
- GRBs contribute less than 1% to observed diffuse neutrino flux. Potential large population of nearby low-luminosity GRBs not constrained.



IceCube Coll., ApJ 805, 2015 arXiv:1601.06484

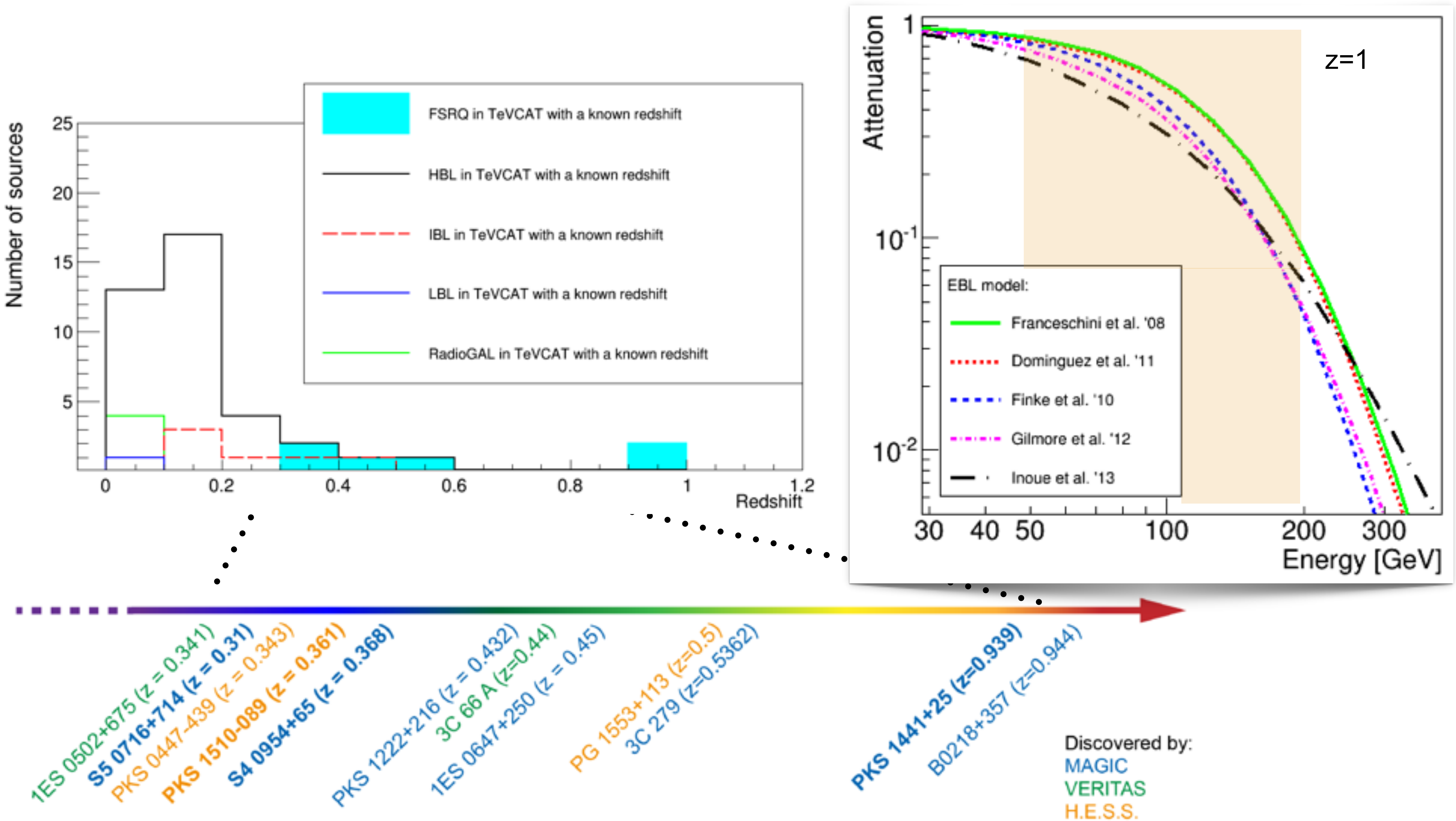
Looking for gamma-ray counterparts

- No significant correlation between contained tracks and Fermi sources (arxiv/1505.00935)
- Steady sources seem to be ruled out (z<0.2)
- If neutrinos are extragalactic, counterparts in gamma-ray are hard to find!

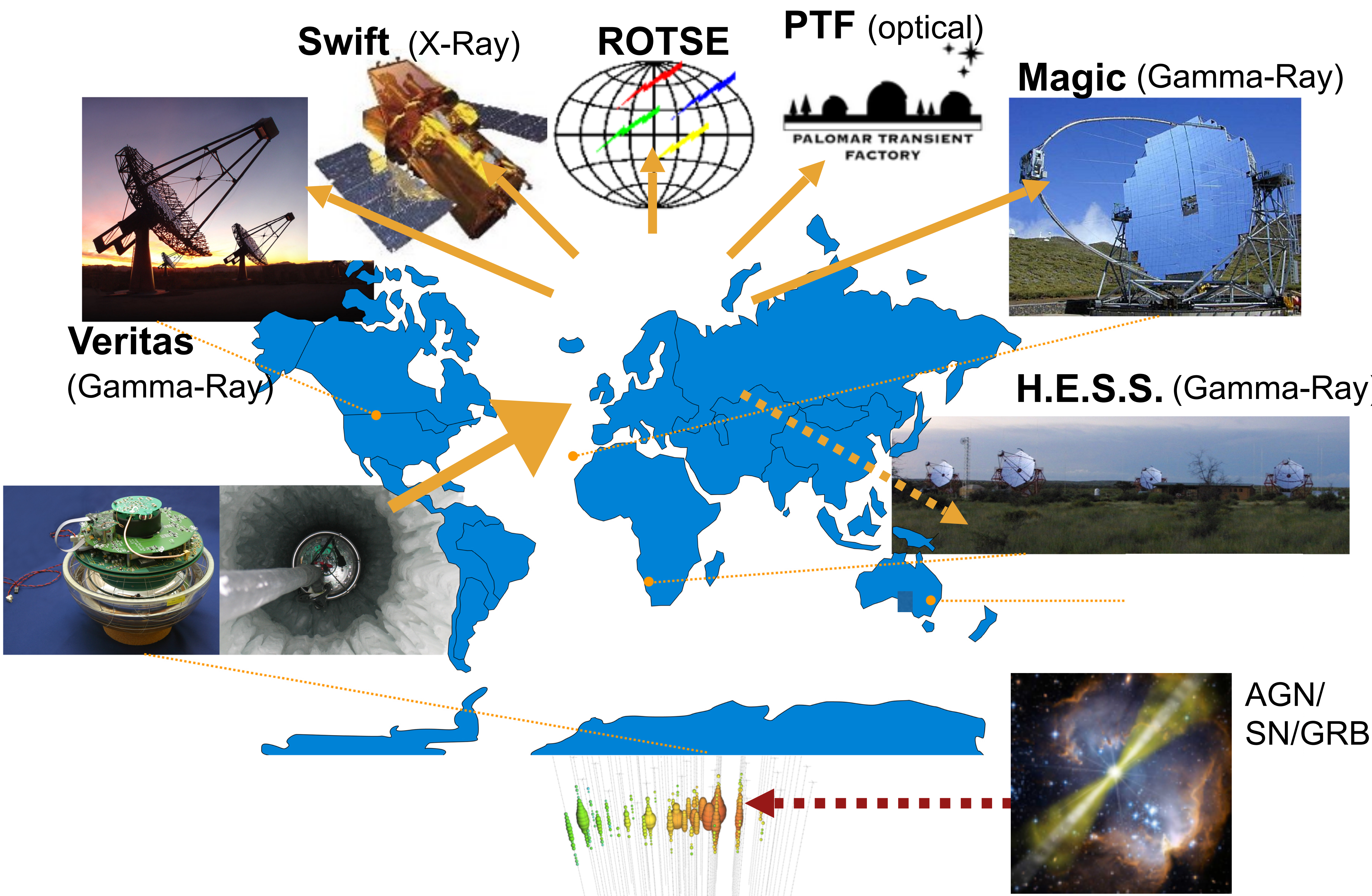


Extending the (gamma-ray) horizon?

- Look at lowest energies with IACTs (E<200 GeV)



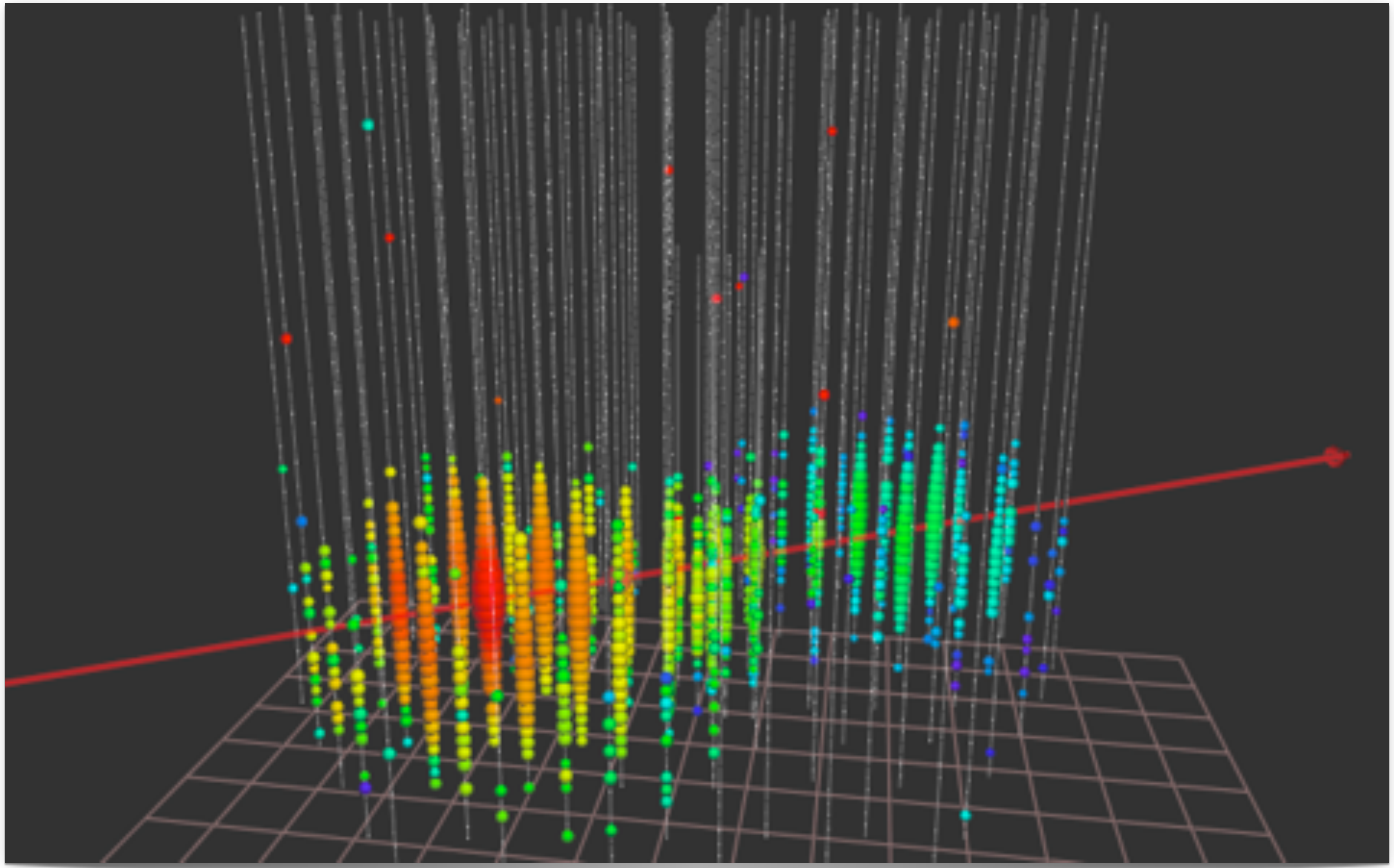
Gamma-ray, optical & X-Ray follow-up program



EB @ THE MULTI-MESSENGER APPROACH TO HIGH-ENERGY GAMMA-RAY SOURCES, Barcelona (2006)
Ackermann et al. arXiv:0709.2640 IceCube A&A 539, A60 (2012) IceCube arXiv: 1610.01814

IceCube public alerts

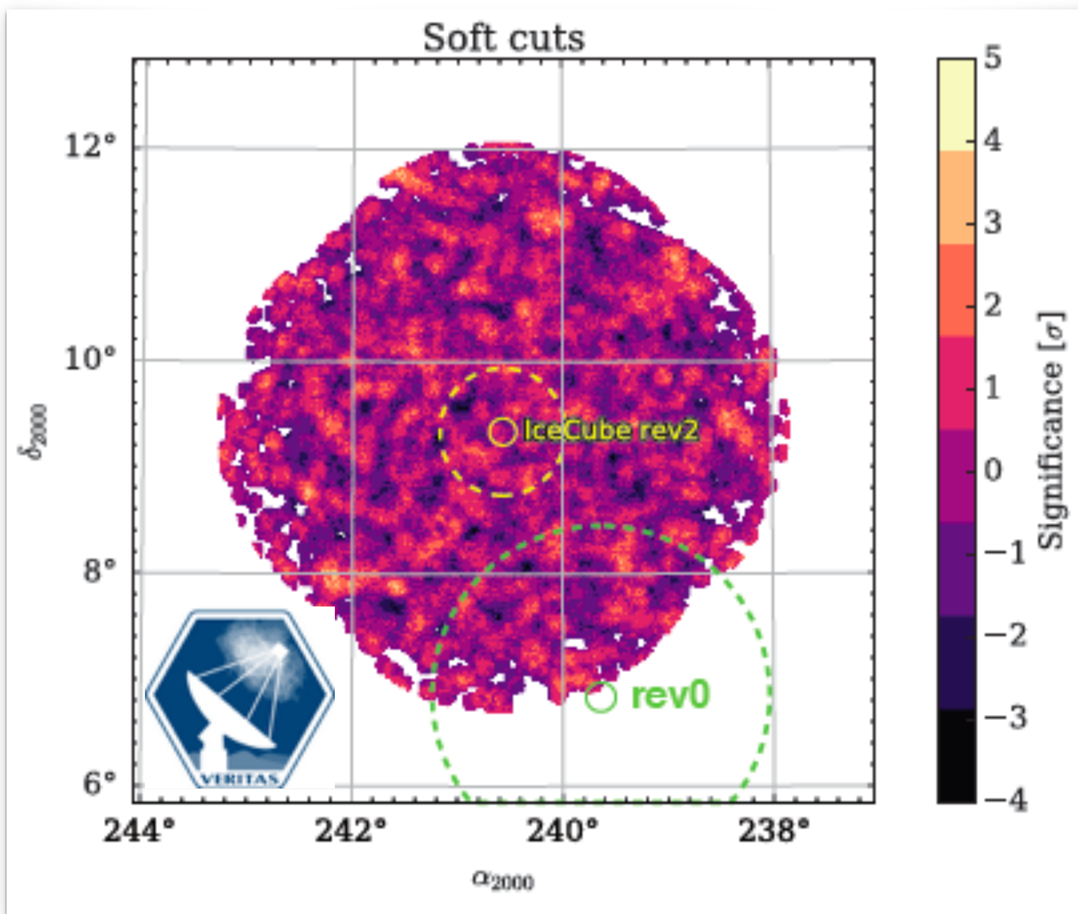
- 8 high-energy track events per year
  - ~50% signal purity
  - Since April 2016
  - Delay of < 1min



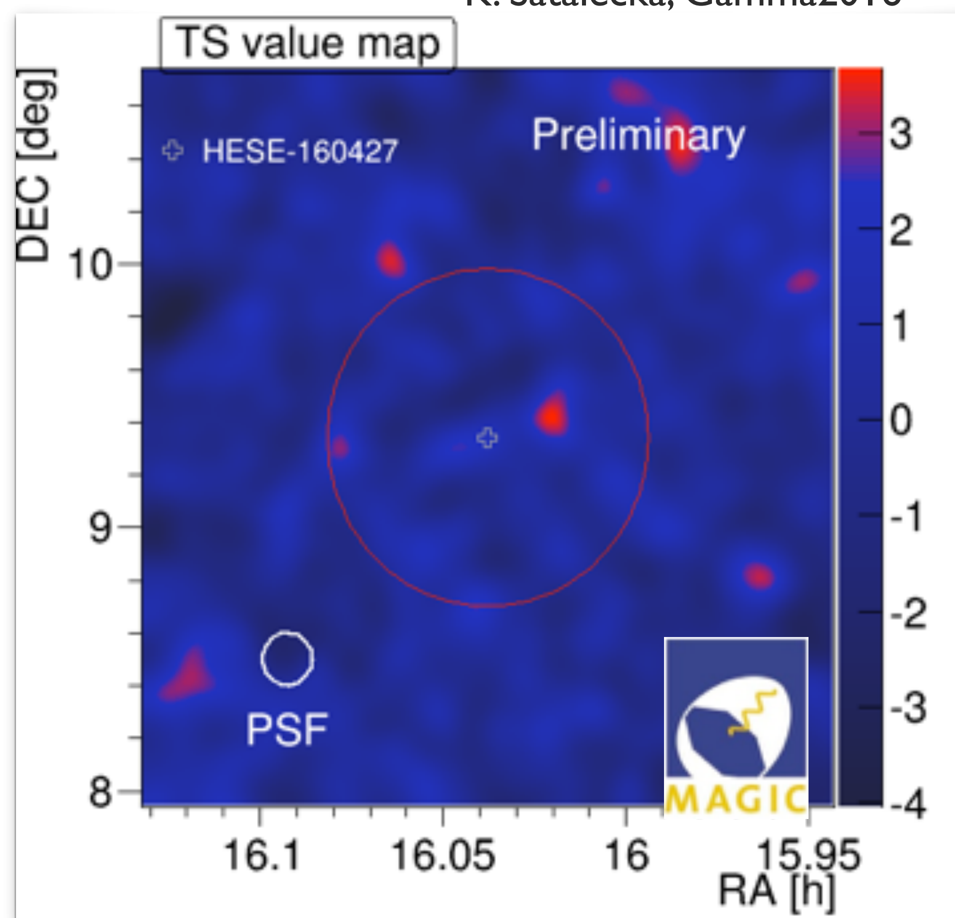
HESE-160427A in gamma-rays

- Observed by FACT, H.E.S.S., MAGIC & VERITAS
  - No signal found

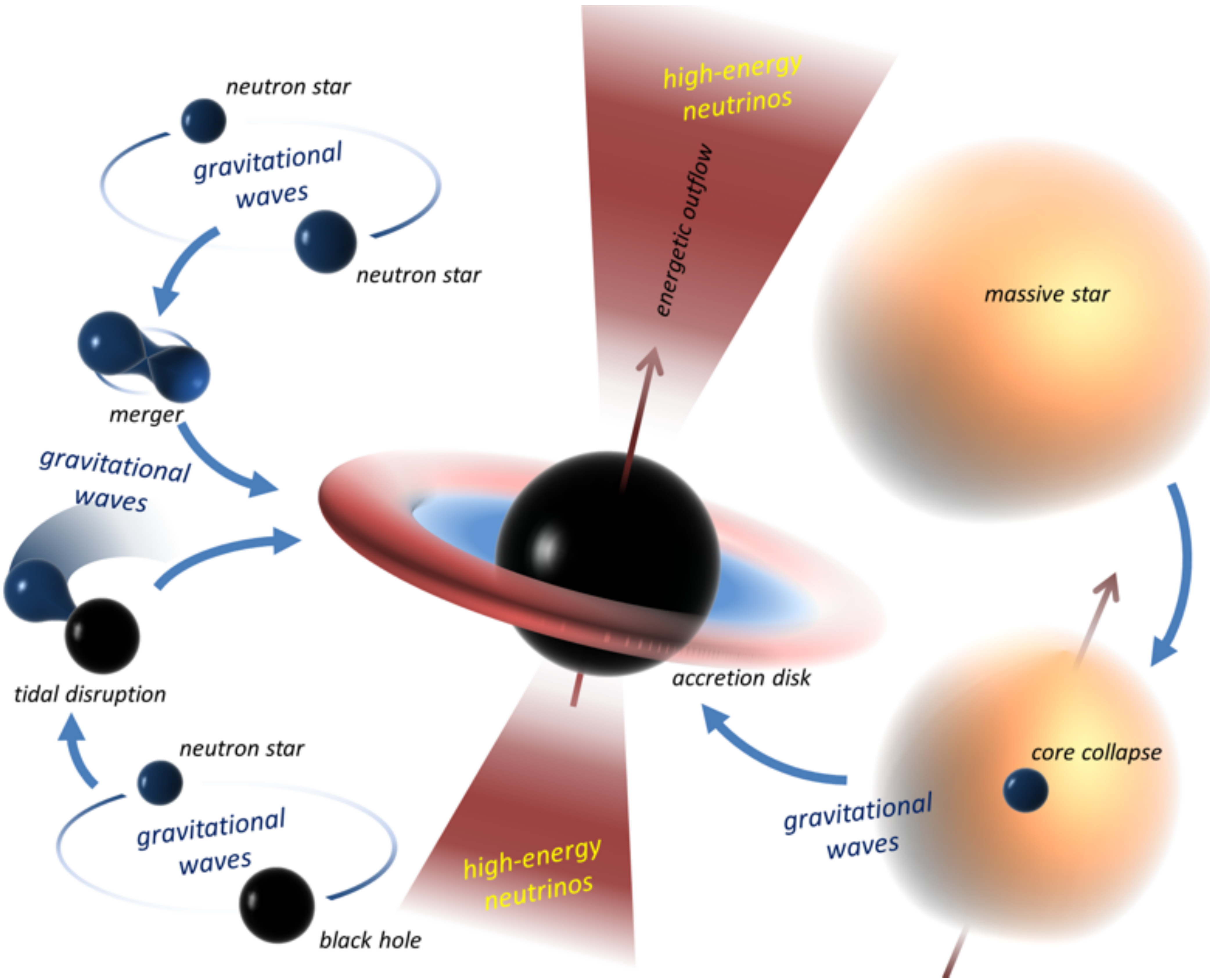
M. Santander, ICHEP 2016



D. Gora, Neutrino 2016
K. Satalecka, Gamma2016



Gravitational Waves and High-Energy Neutrinos

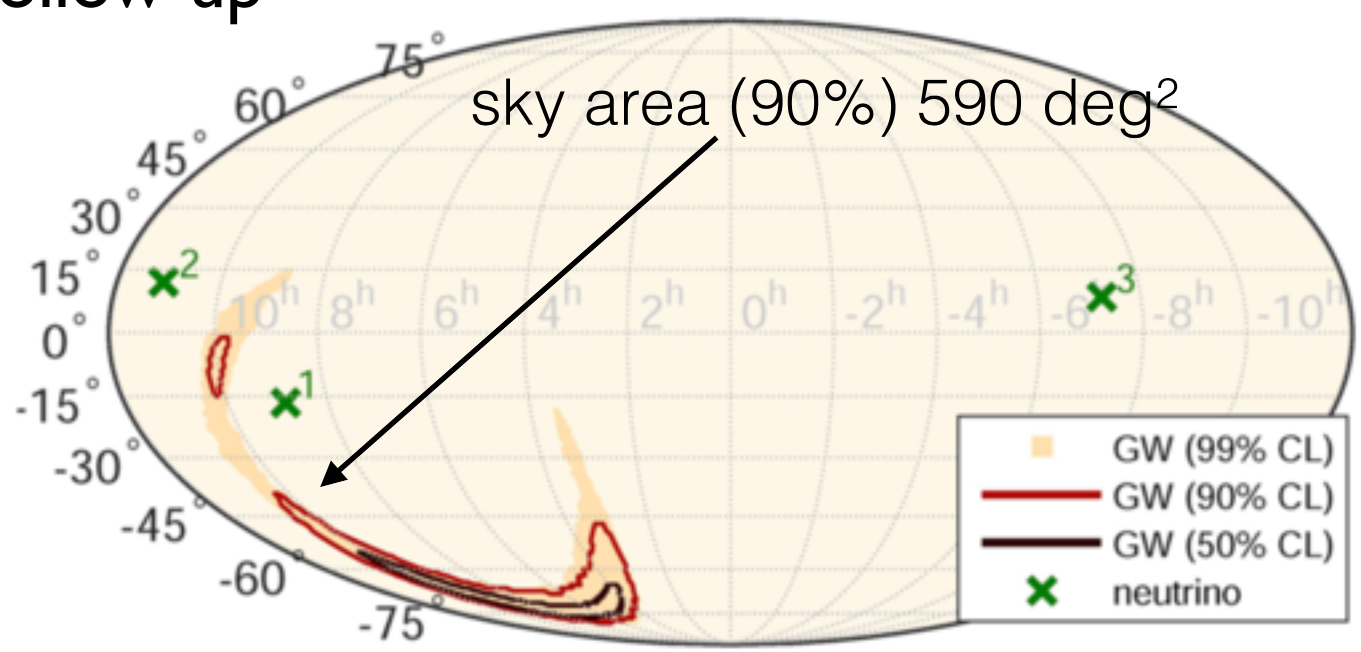


http://ligo.org

IceCube, LIGO and Virg, Phys. Rev. D 90, 102002 (2014)

Any neutrino in coincidence with Gravitational Waves?

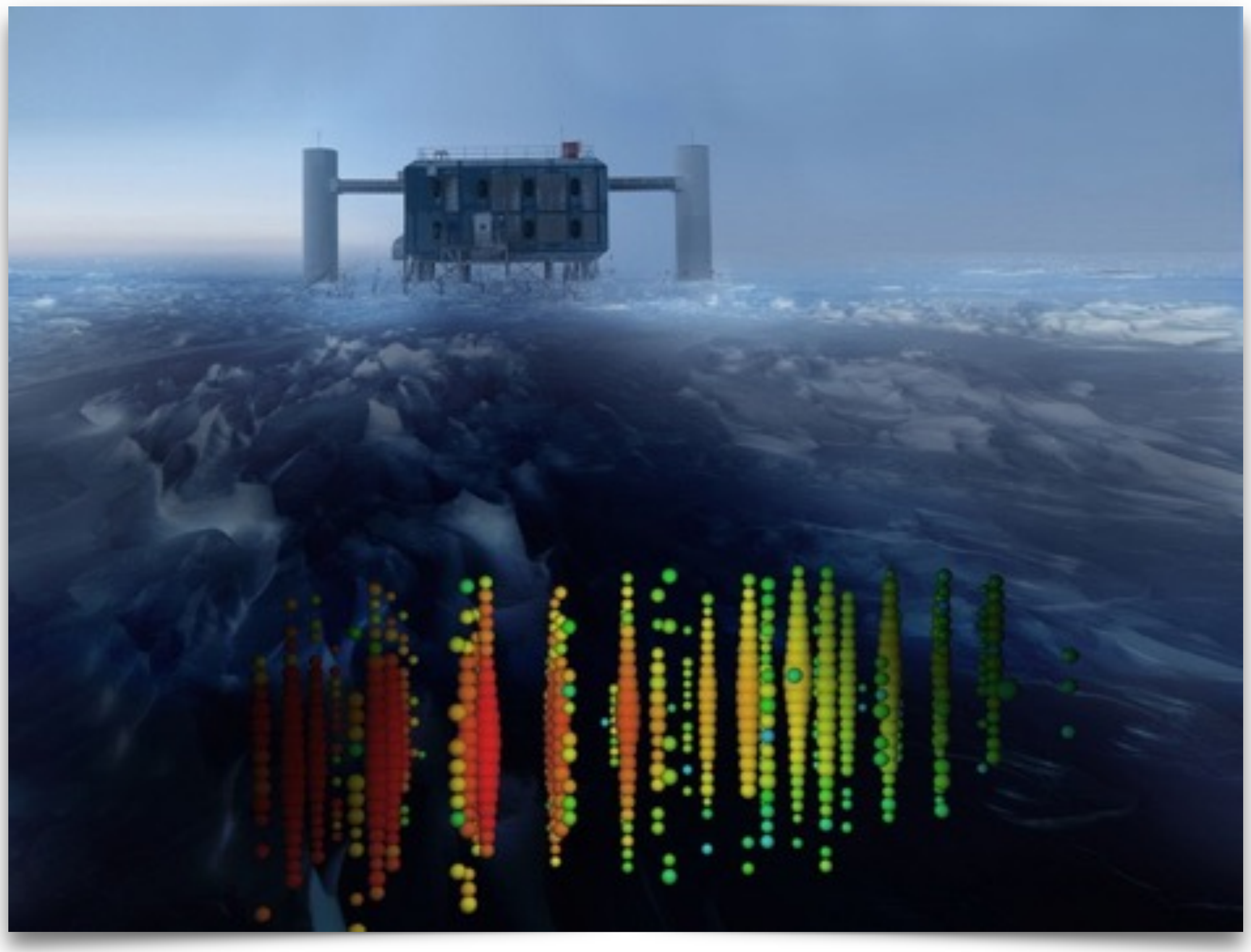
- **GW 150914 (D=410 Mpc, 5x10^{54} erg/s)** [B. Abbott et al (2016)] **could have had associated high energy neutrinos**
- Within ± 500 s of GW 150914 ANTARES found 0 events and IceCube 3 events from online pipelines
  - Rates compatible with expected background
  - IceCube event energies are not significant (p-value 33%)
  - Directional coincidence not significant (probability of at least one neutrino to be accidentally coincident would have been 4%)
- If positive coincidences will be observed it can improve the efficiency of electromagnetic follow-up



ANTARES, IceCube, LIGO and Virgo arXiv: 1602.05411

The dawn of Neutrino Astronomy

- IceCube has paved the road for neutrino astrophysics!
- No evidence yet of neutrino point and extended sources
- The sources of IceCube neutrinos are not readily traced by extragalactic gamma-ray emitters
- Large number of weak sources or transients?



IceCube-Gen2

A wide band neutrino observatory (MeV – EeV) using several detection technologies – optical, radio, and surface veto – to maximize the science

Multi-component observatory:
- Surface air shower detector
- Gen2 High-Energy Array
- Sub-surface radio detector
- PINGU