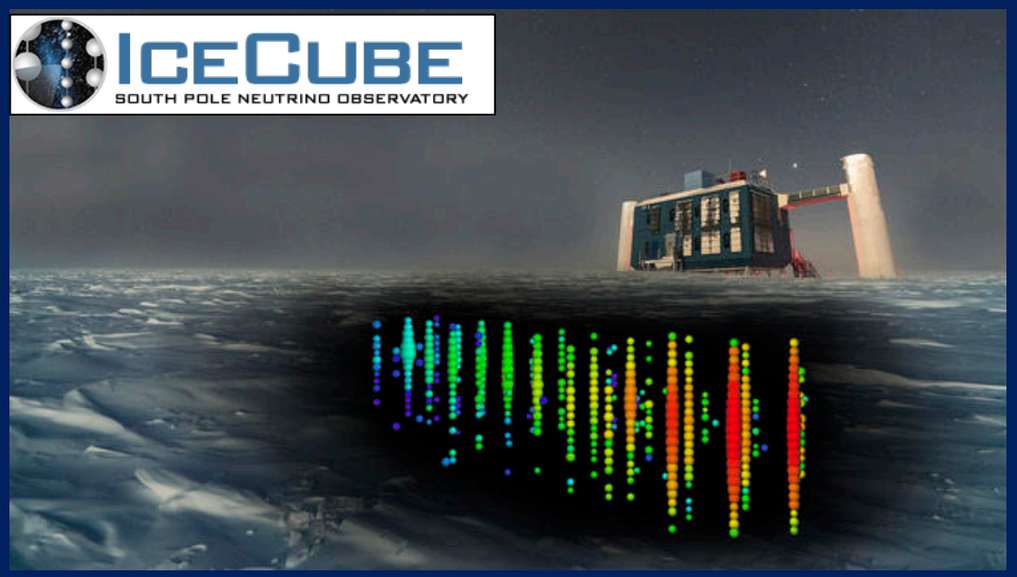
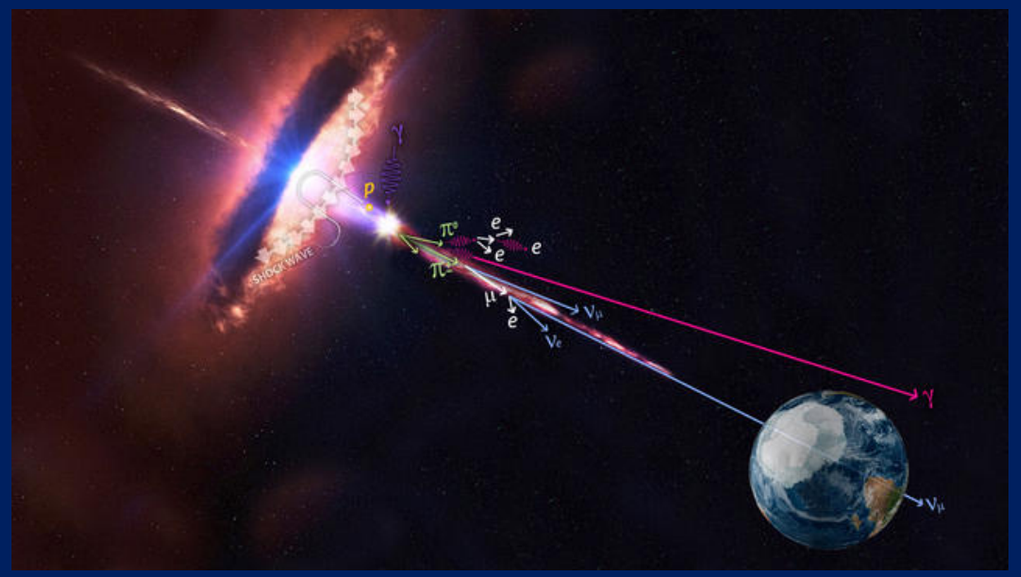




Latest Results from IceCube

Joanna Kiryluk
Stony Brook University
for the IceCube Collaboration

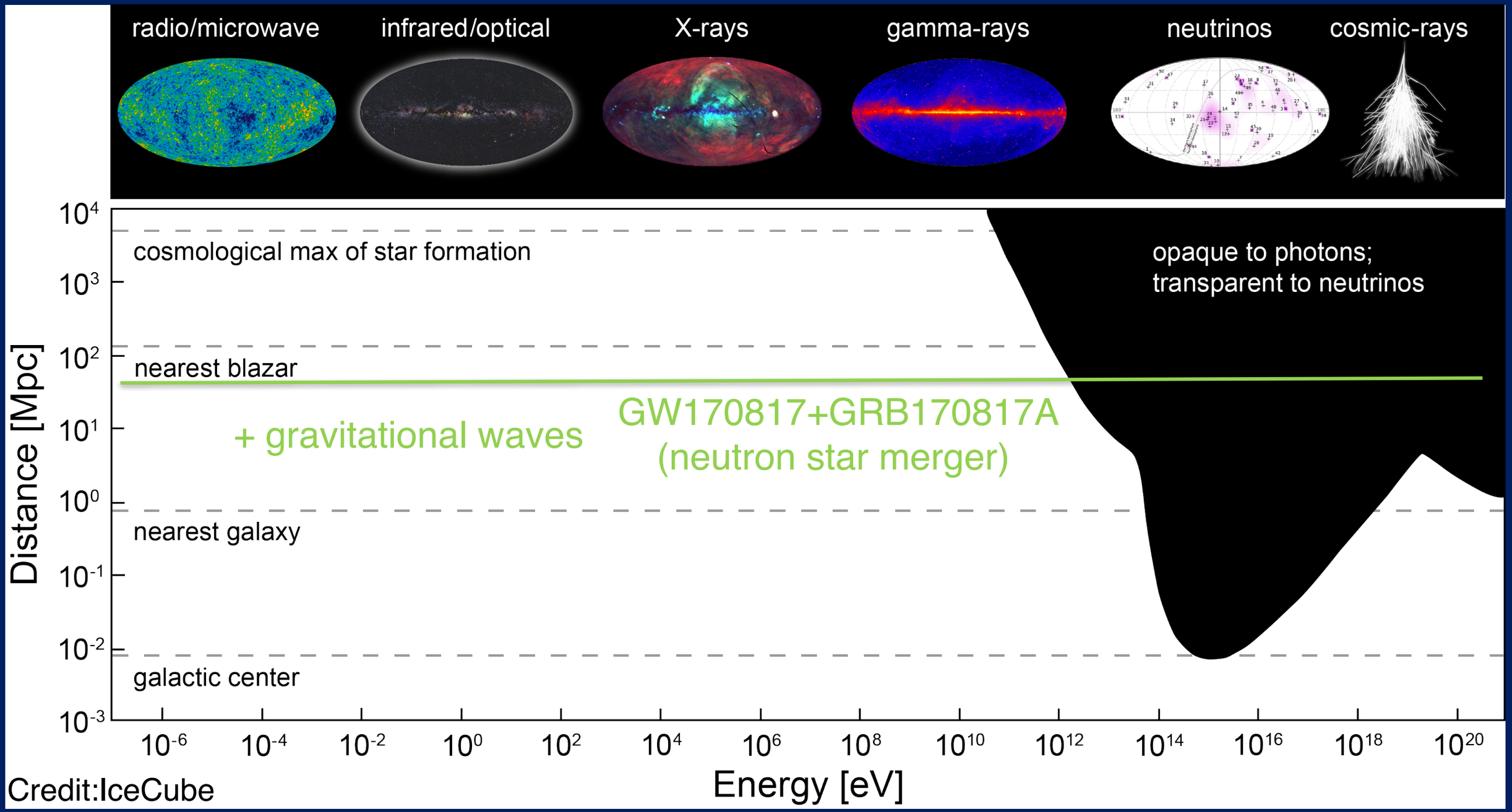
The International Workshop on Next Generation Nucleon Decay and Neutrino Detectors (NNN2018)

1-3 November 2018, Vancouver (BC, Canada)

Introduction: Multi-messenger Astronomy

- opening a new window to the Universe

1pc ~ 3 lyr



Introduction: Multi-messenger Astronomy

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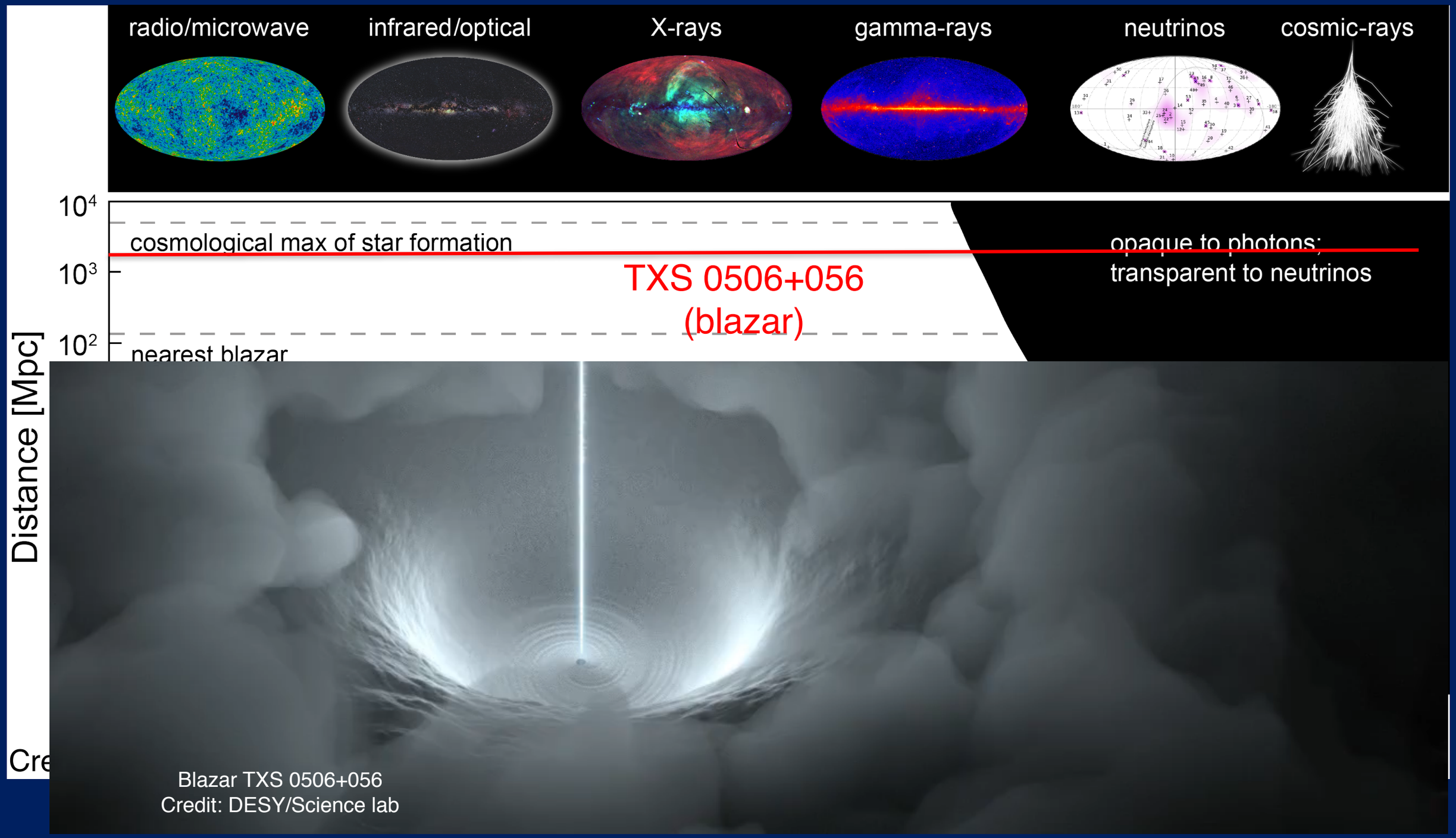
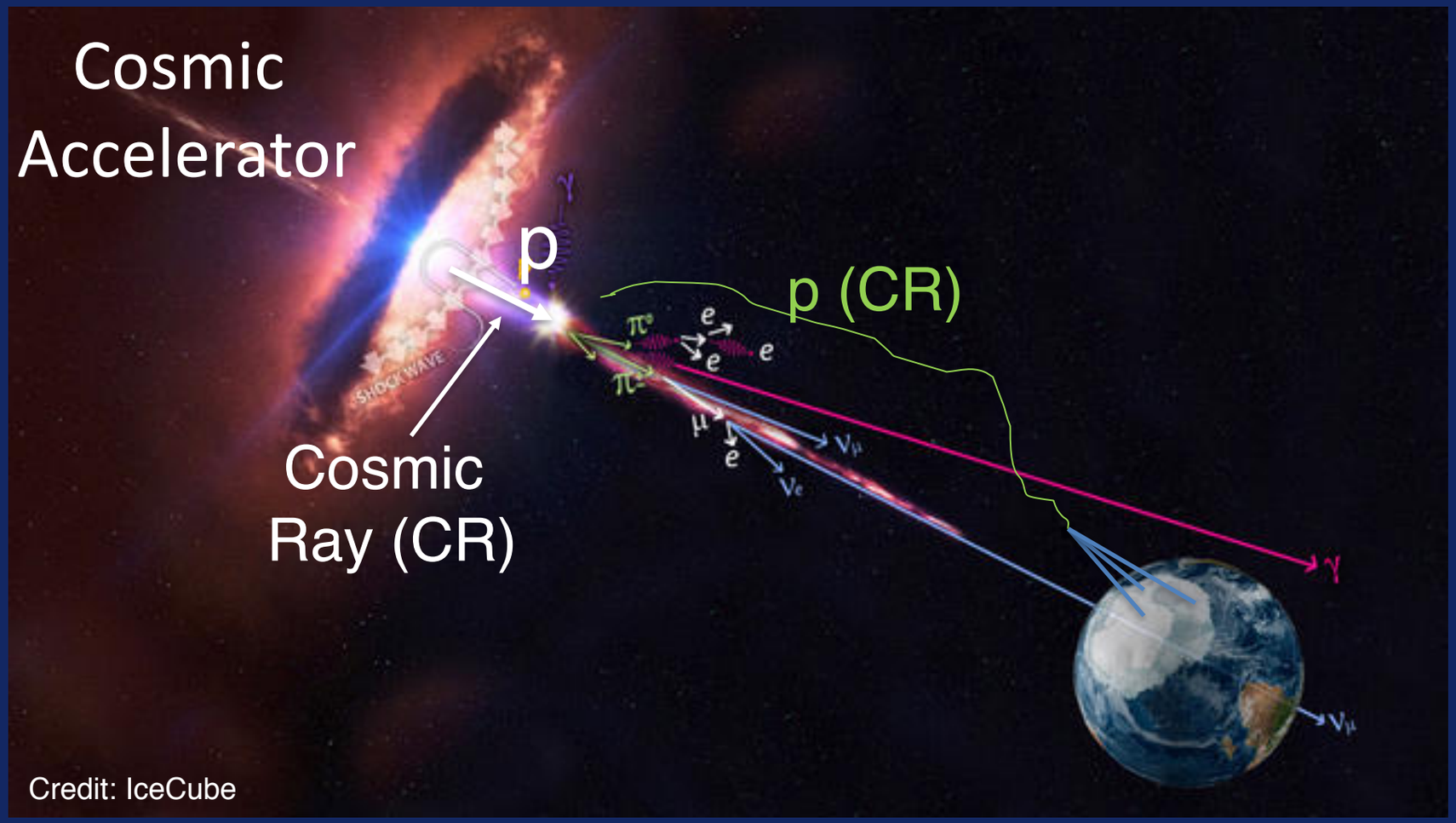
1pc ~ 3 lyr



Introduction: Multi-messenger Astronomy

- opening a new window to the Universe



Astrophysical neutrino production

$$p + p \rightarrow \pi + \ldots \rightarrow \nu + \ldots$$

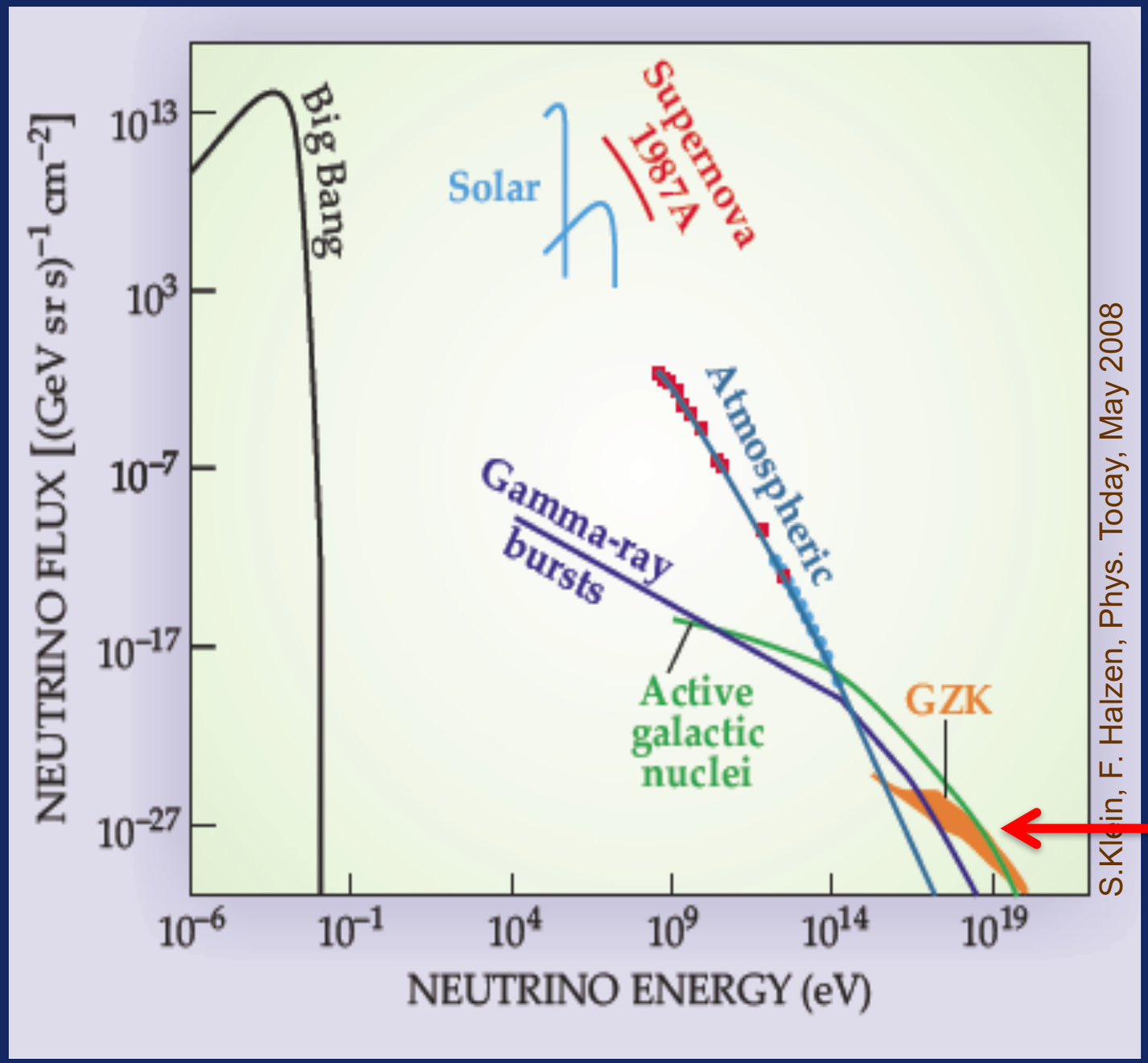
hadro production

$$p + \gamma \rightarrow \Delta \rightarrow \left(p + \pi \rightarrow p + \gamma\gamma\right) \rightarrow n + \pi \rightarrow n + \nu + \ldots$$

photo production

$E_\nu \sim E_p/20 \sim E_\gamma/2$

Introduction: Neutrinos Fluxes



- CR spectrum formation
- CR acceleration
  - Fermi mechanism: $\gamma_{CR} \sim 2$
- CR propagation

$$\Phi_{CR} \sim E_{CR}^{-\gamma_{CR}}$$

- ν benchmark model: $\gamma_\nu \sim 2$

$$\Phi_\nu \sim E_\nu^{-\gamma_\nu}$$

[Fermi acceleration at shock fronts]

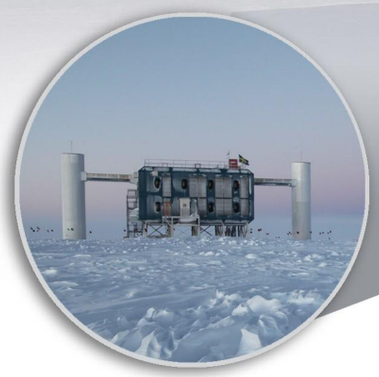
- Waxman-Bahcall bound

$$E_\nu^2 \Phi_{\mathrm{WB}} \approx 3.4 \times 10^{-8}\,\mathrm{GeV/cm^2 sr\,s}$$

IceCube

South Pole Neutrino Observatory

See talks by J. Kelly (IceCube Detector) and J. Highnight (Gen2 upgrade)

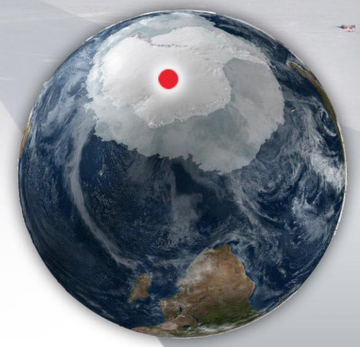


IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW–Madison

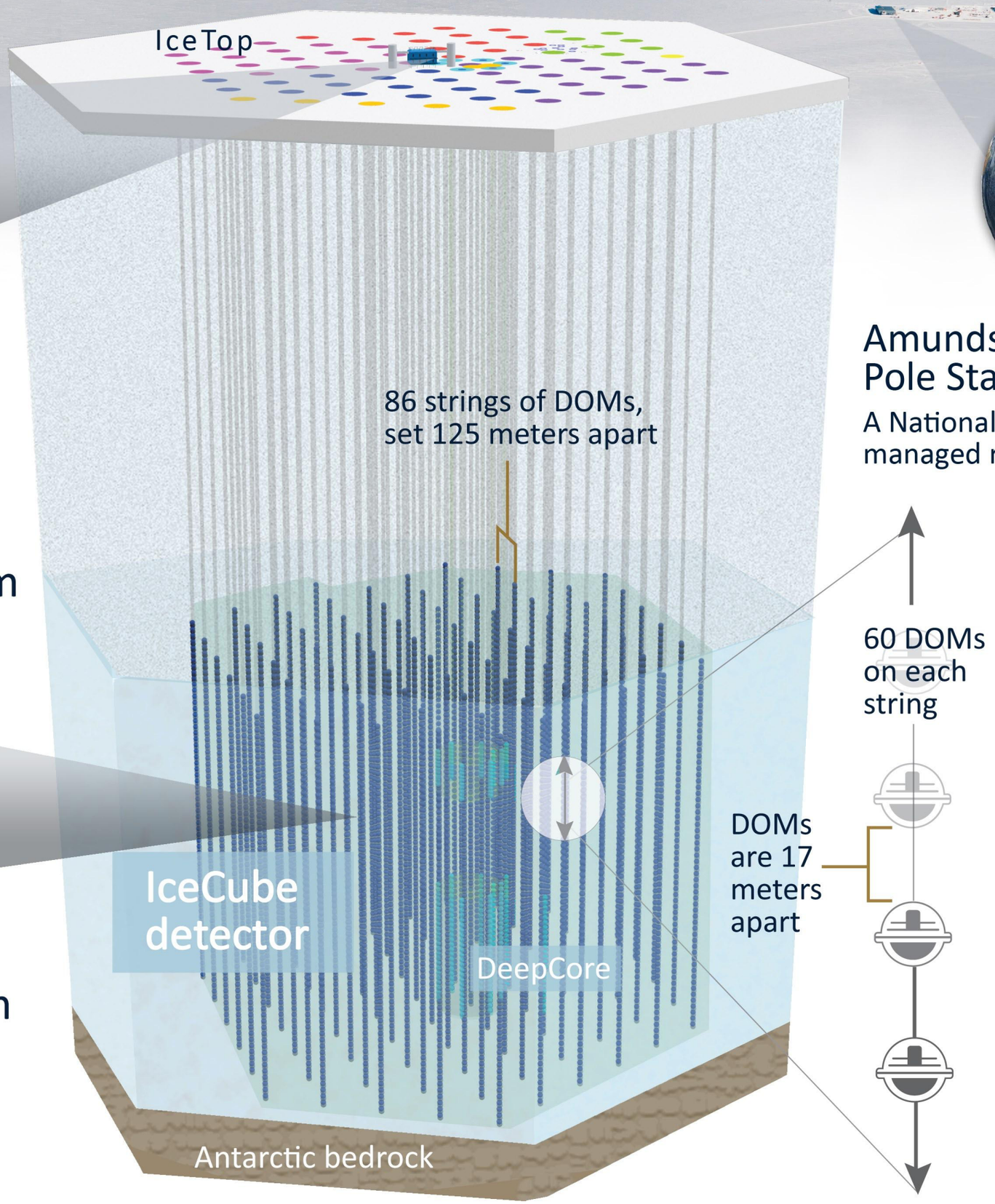
Digital Optical Module (DOM)

5,160 DOMs deployed in the ice



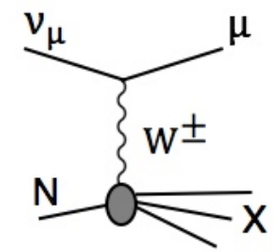
Amundsen–Scott South Pole Station, Antarctica

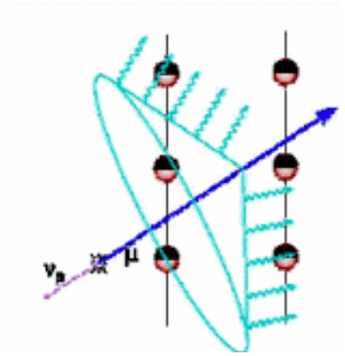
A National Science Foundation-managed research facility

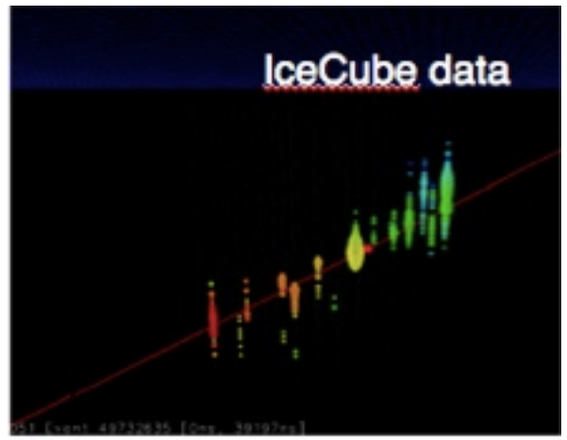


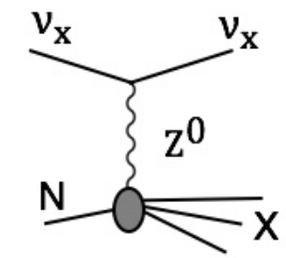
Credit: IceCube

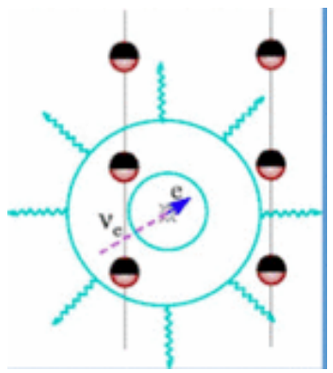
IceCube: Event Signatures

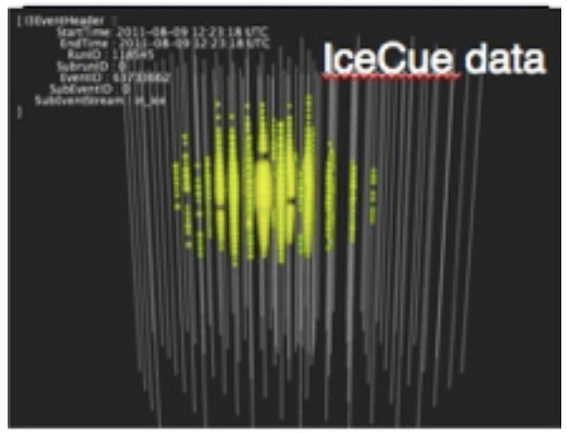


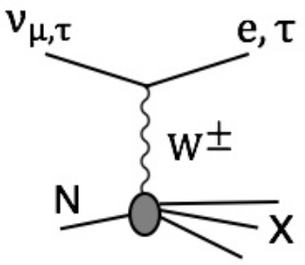


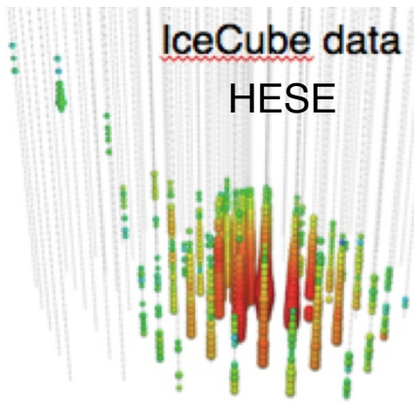


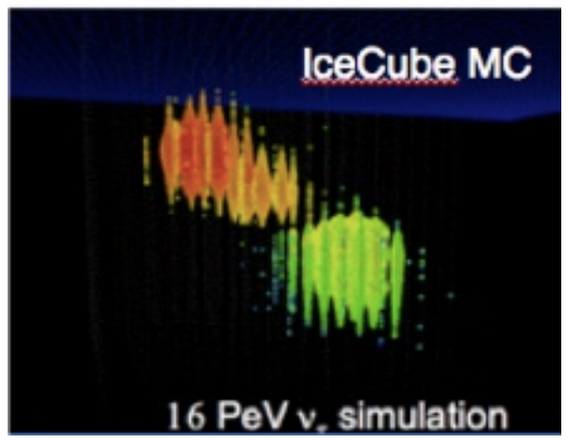












Tracks:

- through-going muons
- energy resolution ~ factor of 2
- pointing resolution <1°

Cascades:

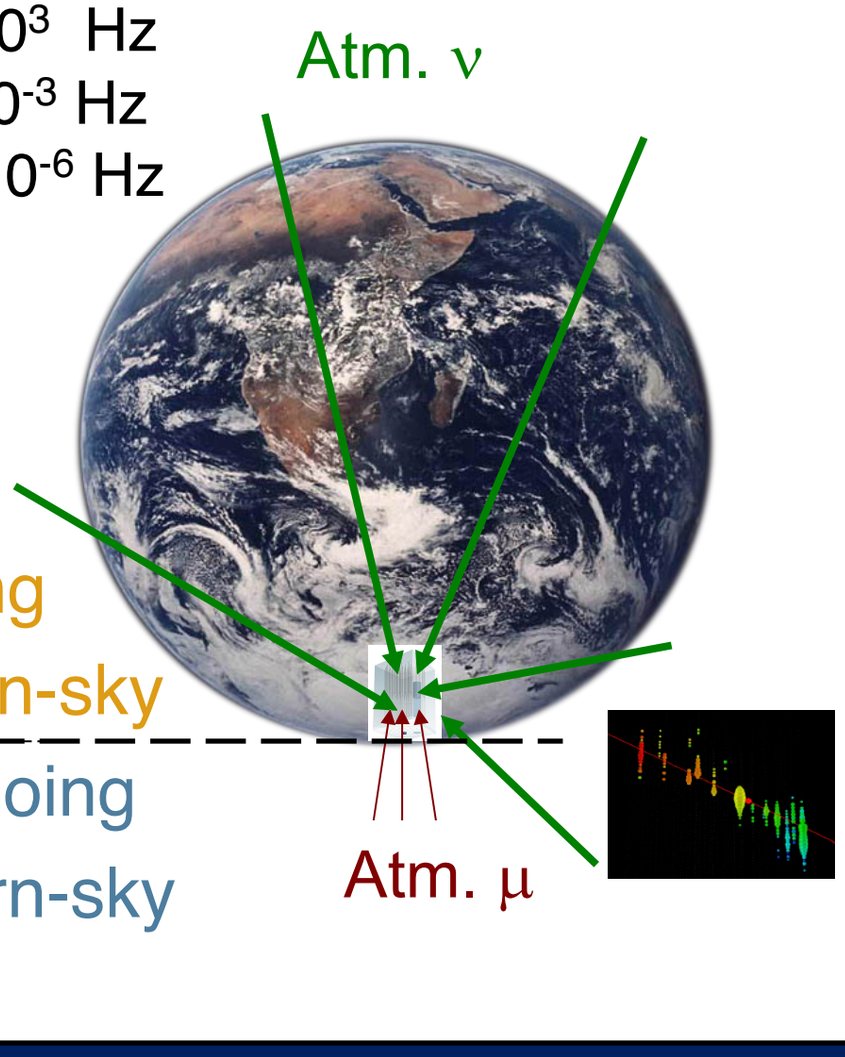
- e-m and/or hadronic cascades
- cascades contained in detector, resolutions:
  - visible energy ~ 10%
  - angular ~ 10°- 40°

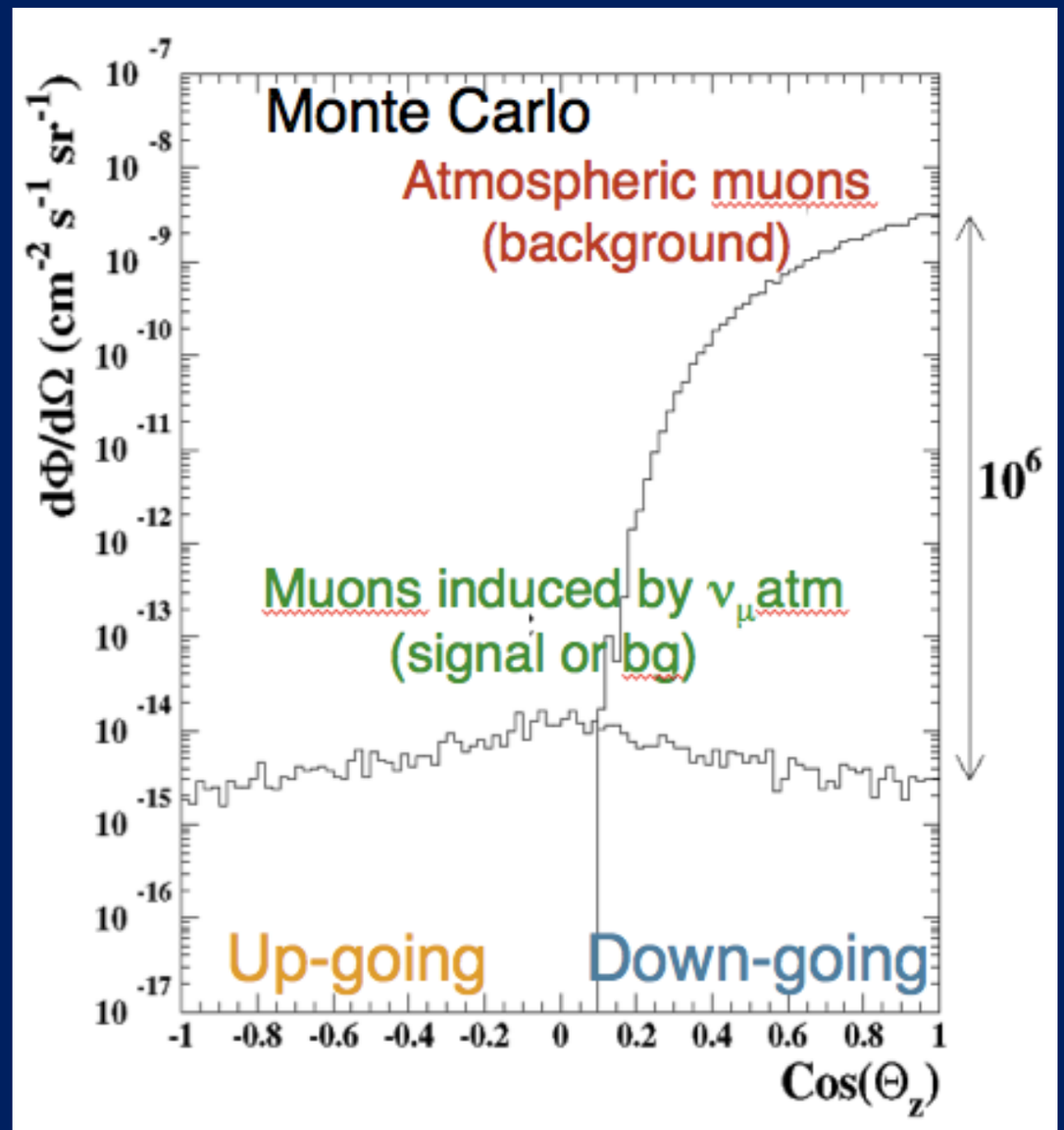
Composites

- starting events (“HESE”,”MESE”)
- tau “double bangs” (E_ν ~ 10’s of PeV)

IceCube: Muon Neutrinos (Tracks)

<u>Rates:</u> IceCube
Atm. μ 10^{3} Hz
Atm. ν 10^{-3} Hz
Astro. ν 10^{-6} Hz

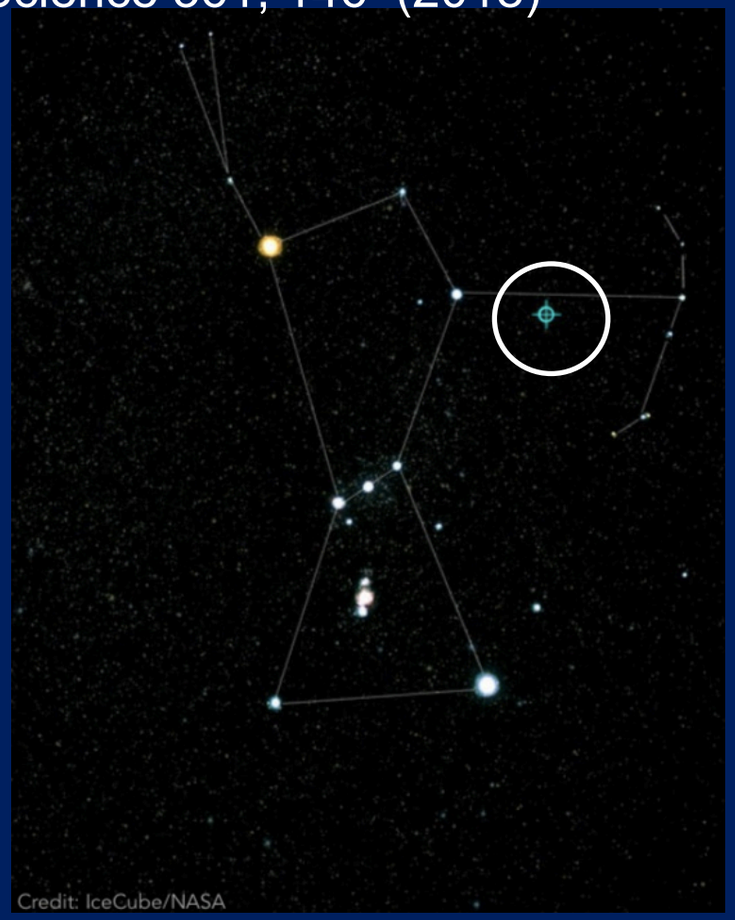




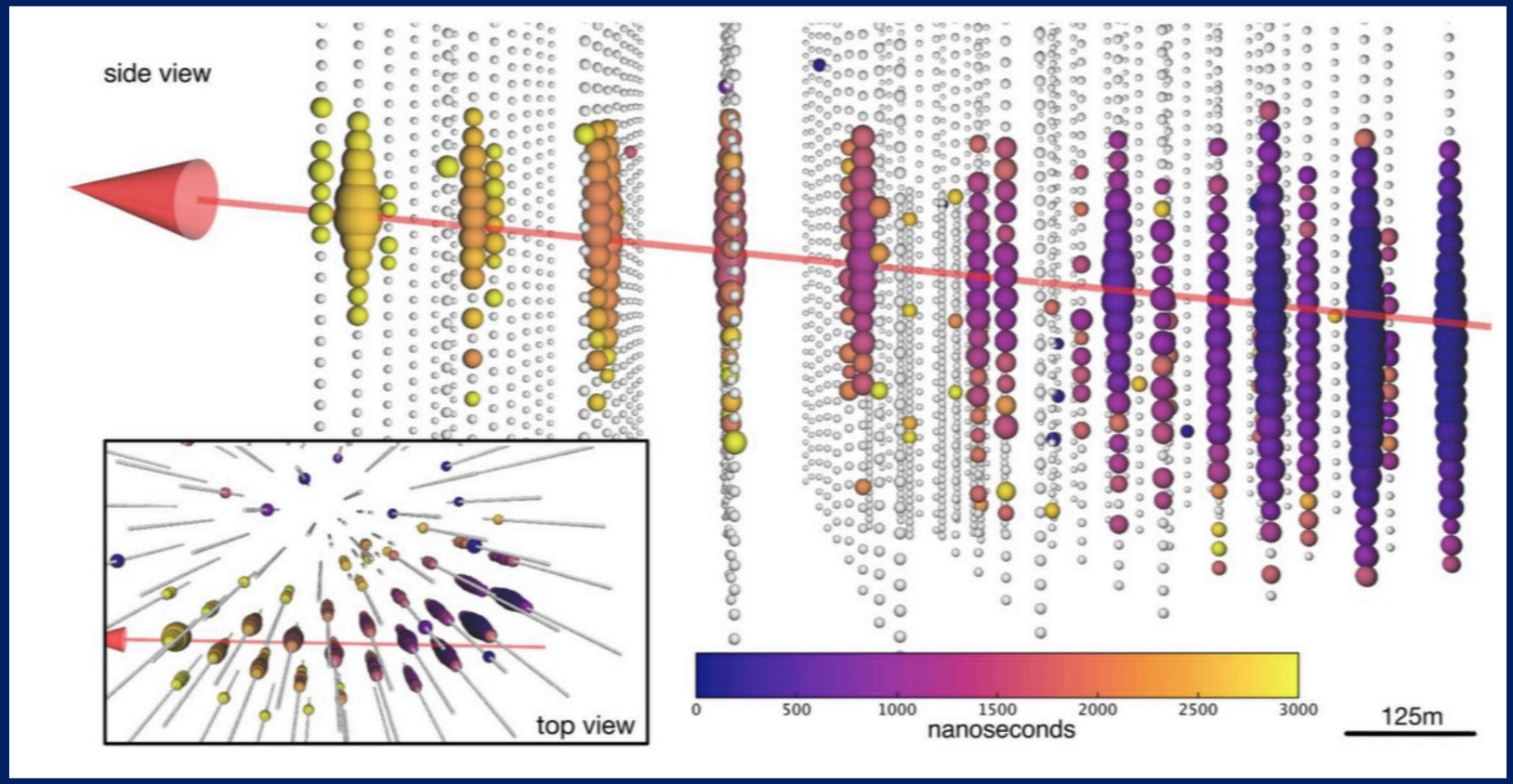
ν_μ - from the Northern sky ("up-going" μ only): atmospheric or astrophysical origin

Evidence of the first ν source: TXS 0506+056

Science 361, eaat1378 (2018)
Science 361, 146 (2018)



IceCube-170922: IceCube neutrino EHE alert

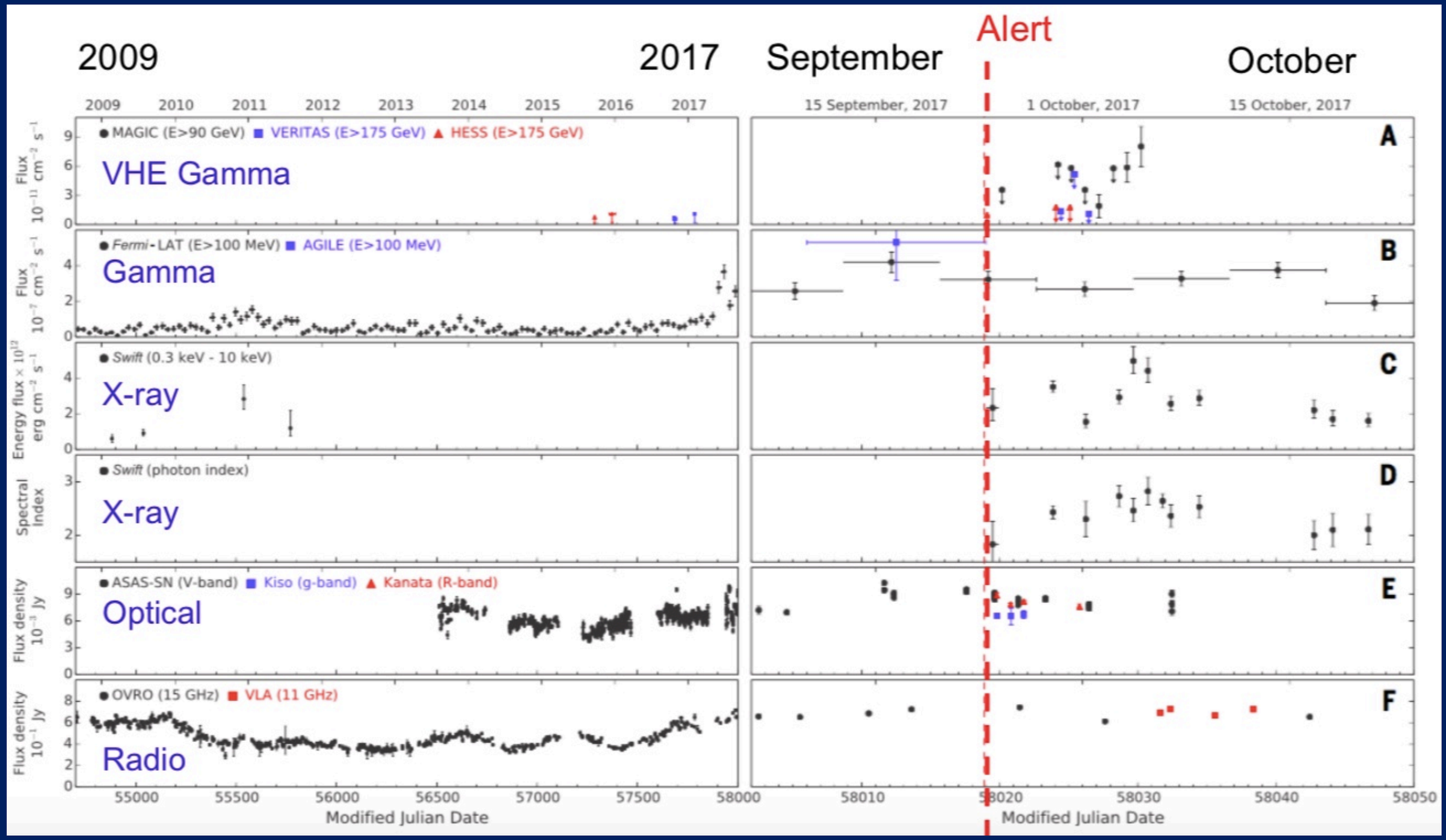


On 22 September 2017 IceCube detected a ~290-TeV neutrino from a direction , as reported by Fermi-LAT on September 28 2017, consistent with the flaring γ-ray blazar TXS 0506+056.

Evidence of the first ν source: TXS 0506+056

Science 361, eaat1378 (2018)
Science 361, 146 (2018)

IceCube-170922: IceCube neutrino EHE alert



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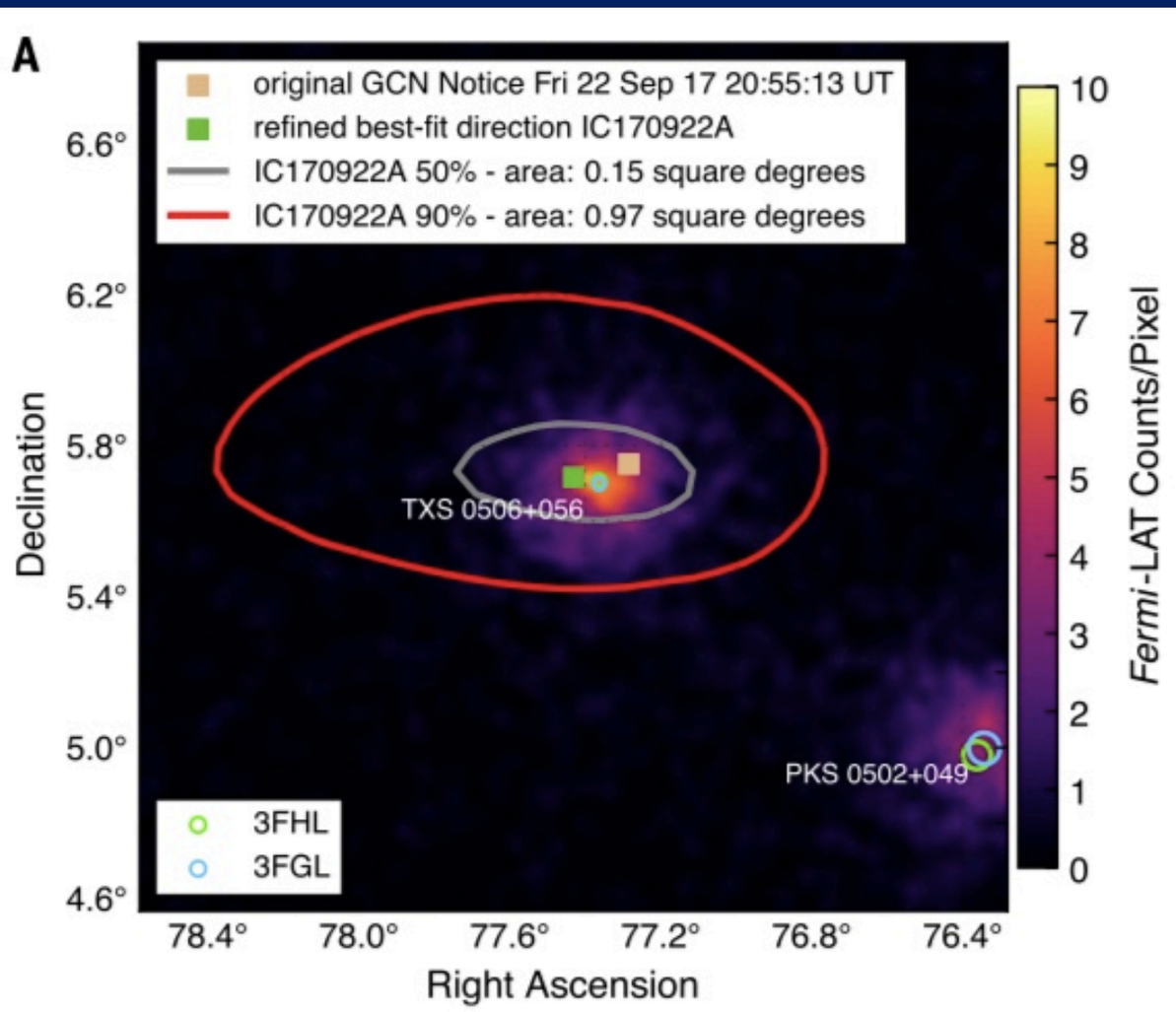
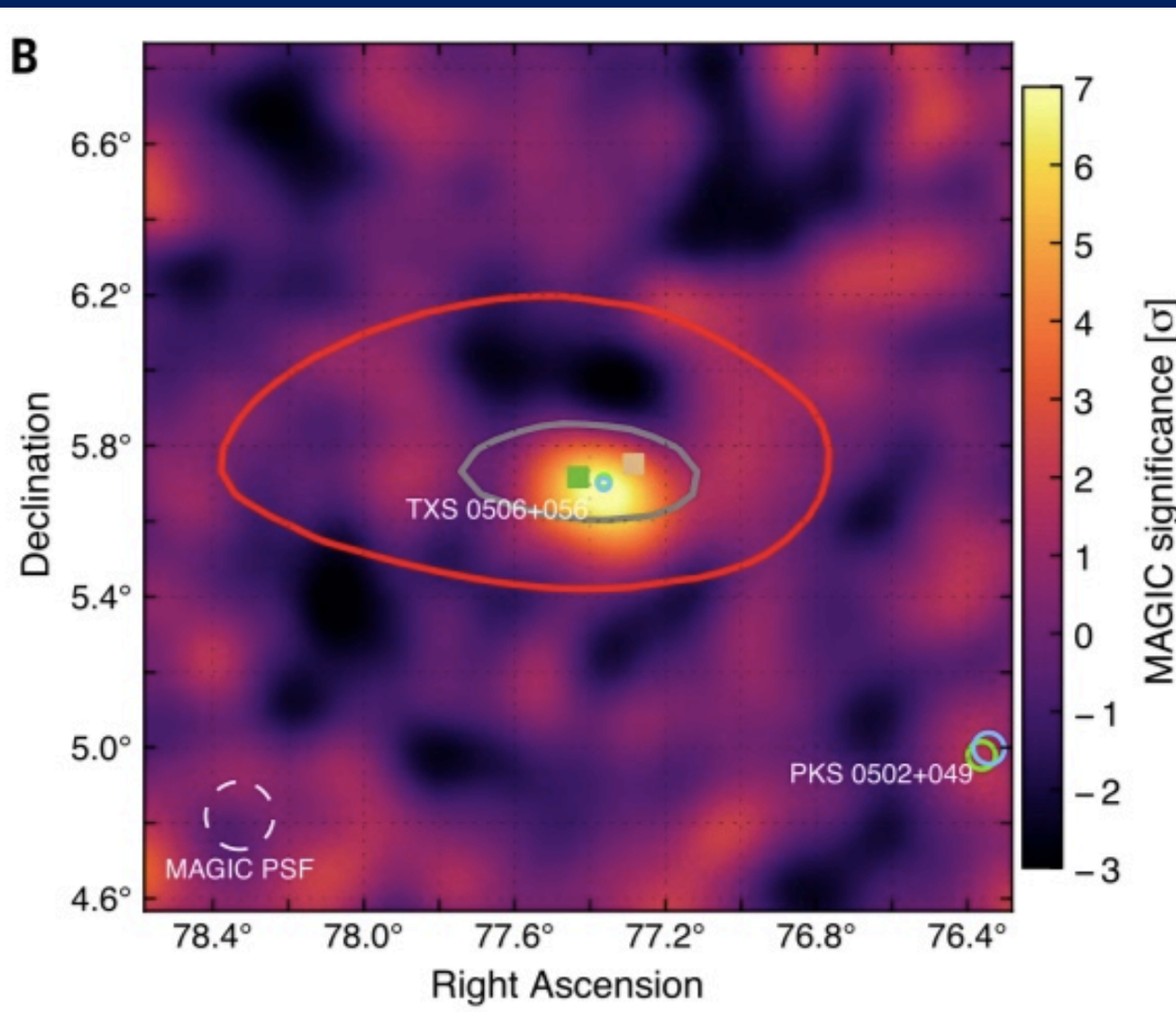


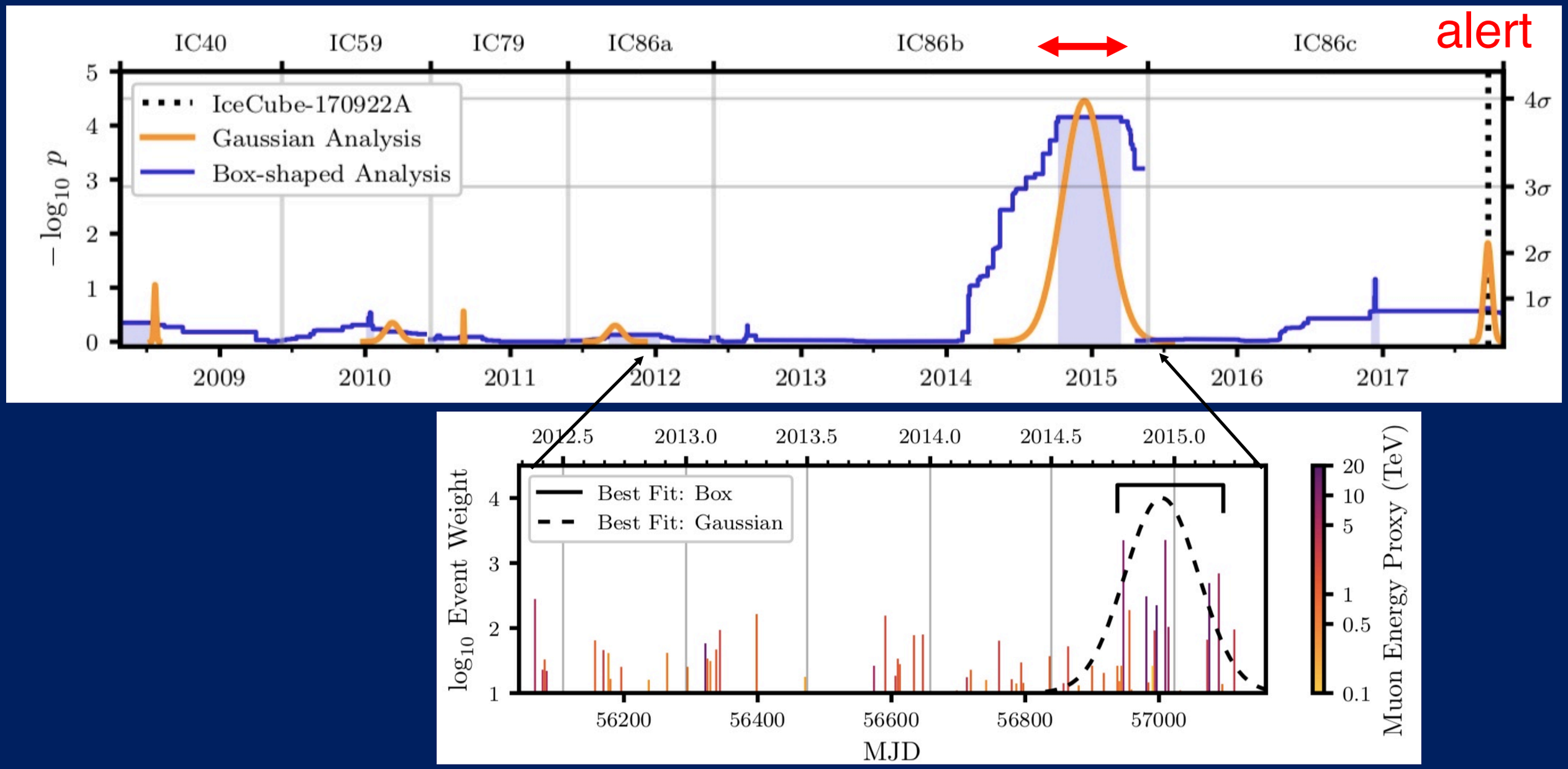


Flaring blazar TXS 0506+056 identification by Fermi & Magic

Evidence of the first ν source: TXS 0506+056

Science 361, eaat1378 (2018)
Science 361, 146 (2018)

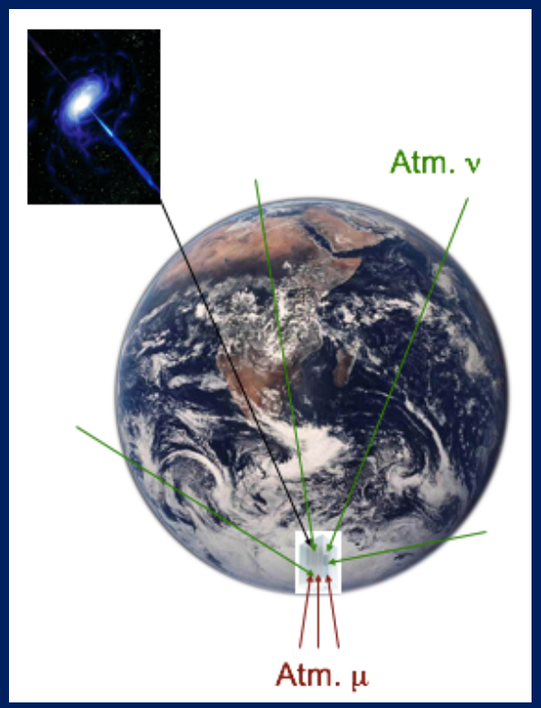
- **ν_μ-flare found in archival IceCube data 10/2014- 03/2015**

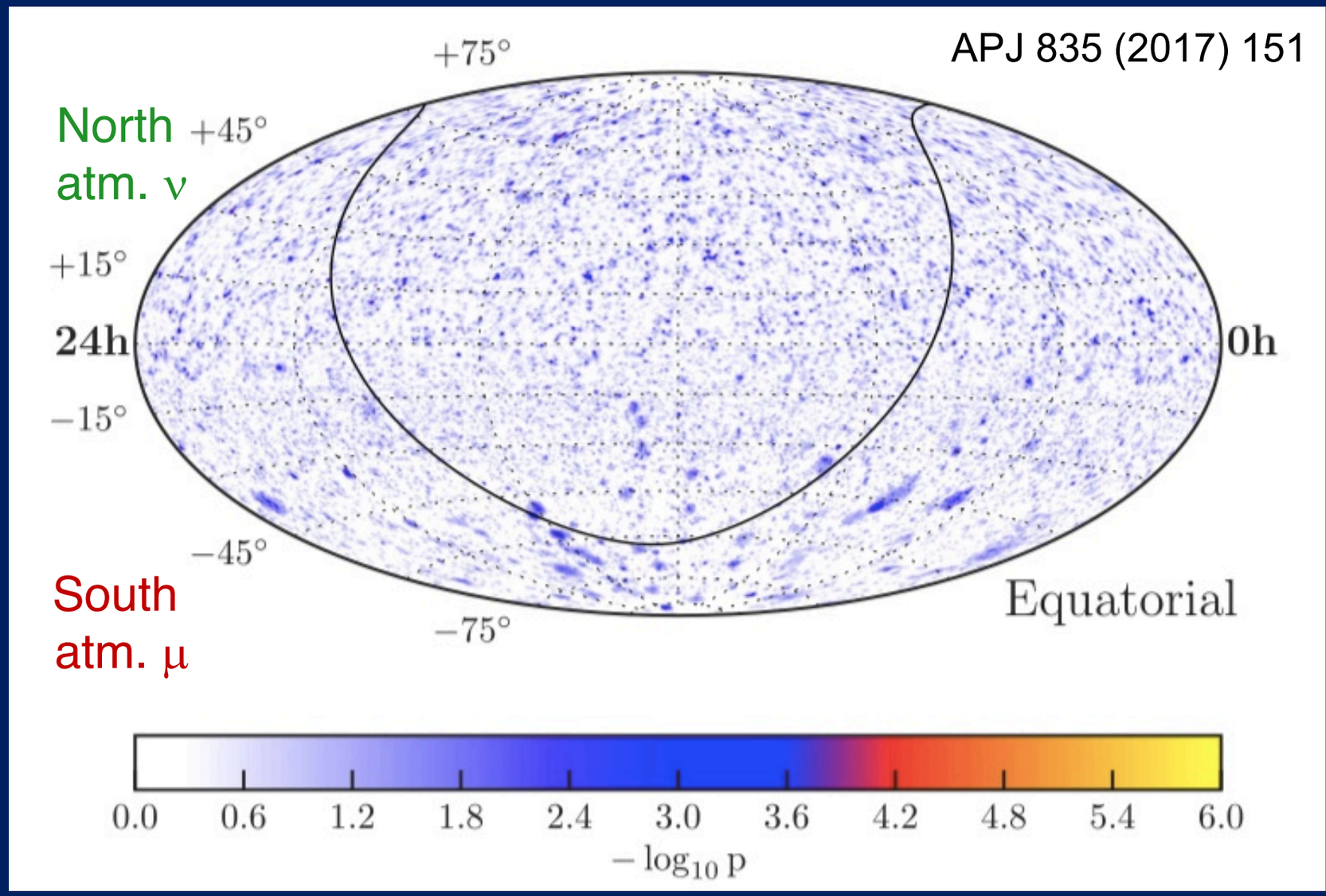


Identification of a blazar as a source of HE ν's and CR's
Significance: 3.5 sigma (2 / 10000)

Point Source Search: 7yr (2008-2015)

- All-Sky search: Search for excess of astrophysical ν from a common direction over the background of atm. ν (Northern Sky) or μ / ν (Southern Sky).
- Assumed time integrated emission of ν's, unbroken energy spectrum $E^{-\gamma}$

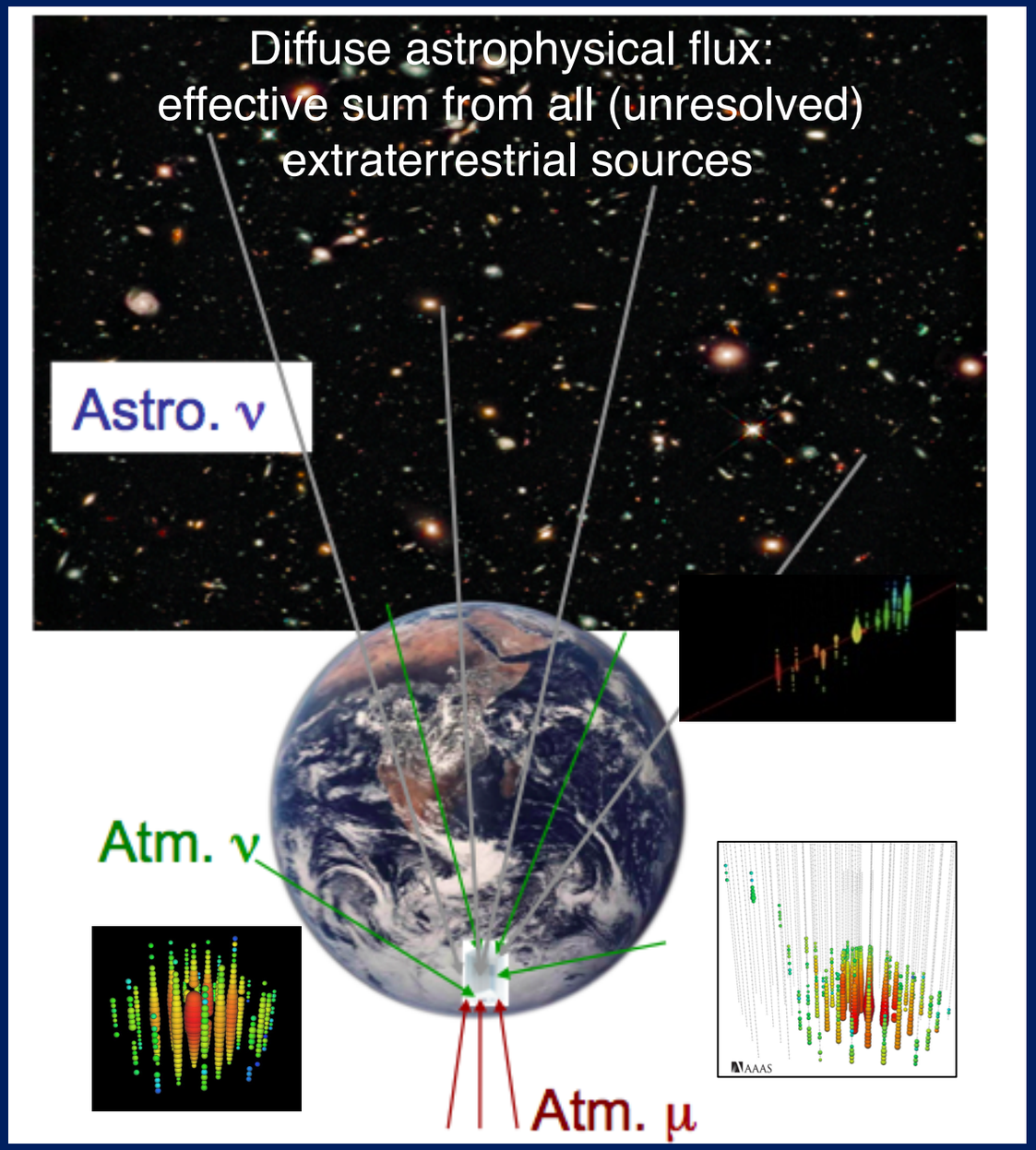




No significant observation of a point source
No correlation with a known list of galactic and extragalactic sources.

Neutrino diffuse flux measurement and characteristics

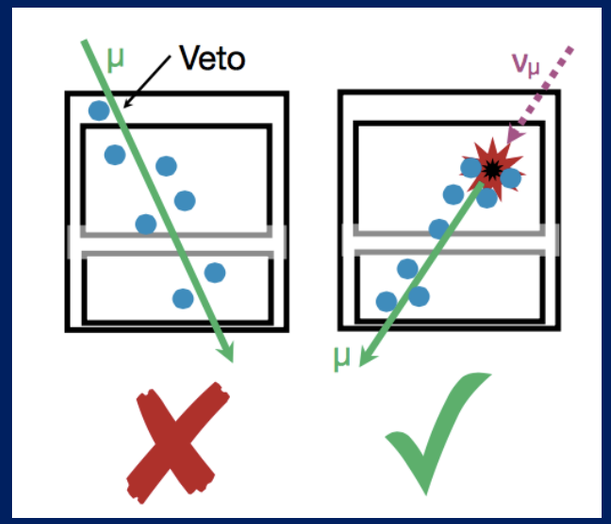
IceCube (ICRC2017), arXiv:1710.01191 [astro-ph.HE]

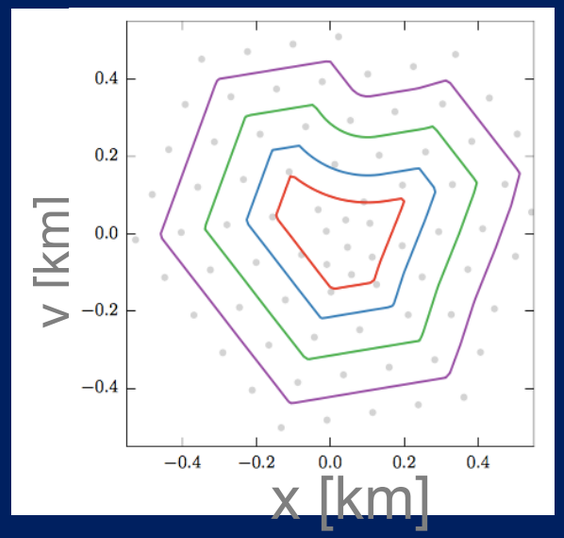


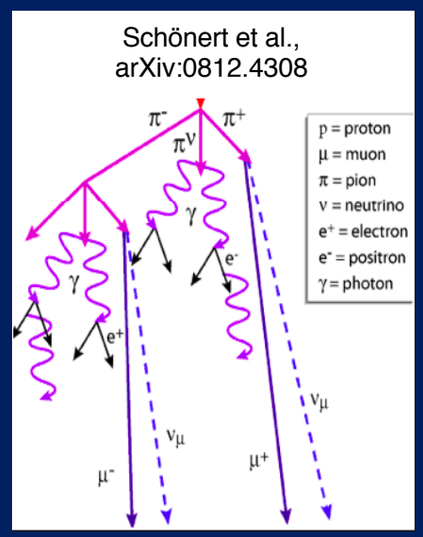
- Base line astrophysical neutrinos flux model:

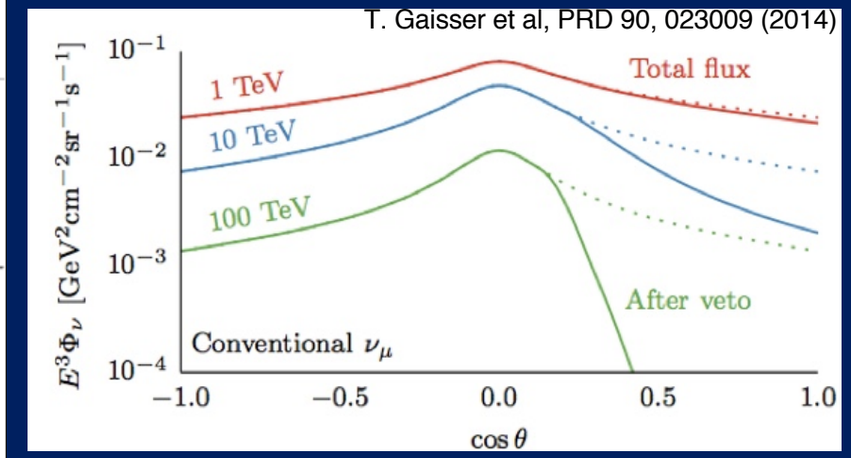
$$\Phi = \Phi_0 \times E^{-\gamma}$$

- Detection & analysis channels:
  - Muon tracks (northern sky, ν_μ)
  - Starting events (all-sky, $\nu_\mu + \nu_e + \nu_\tau$)
  - Cascades (all-sky, $\nu_e + \nu_\tau$)





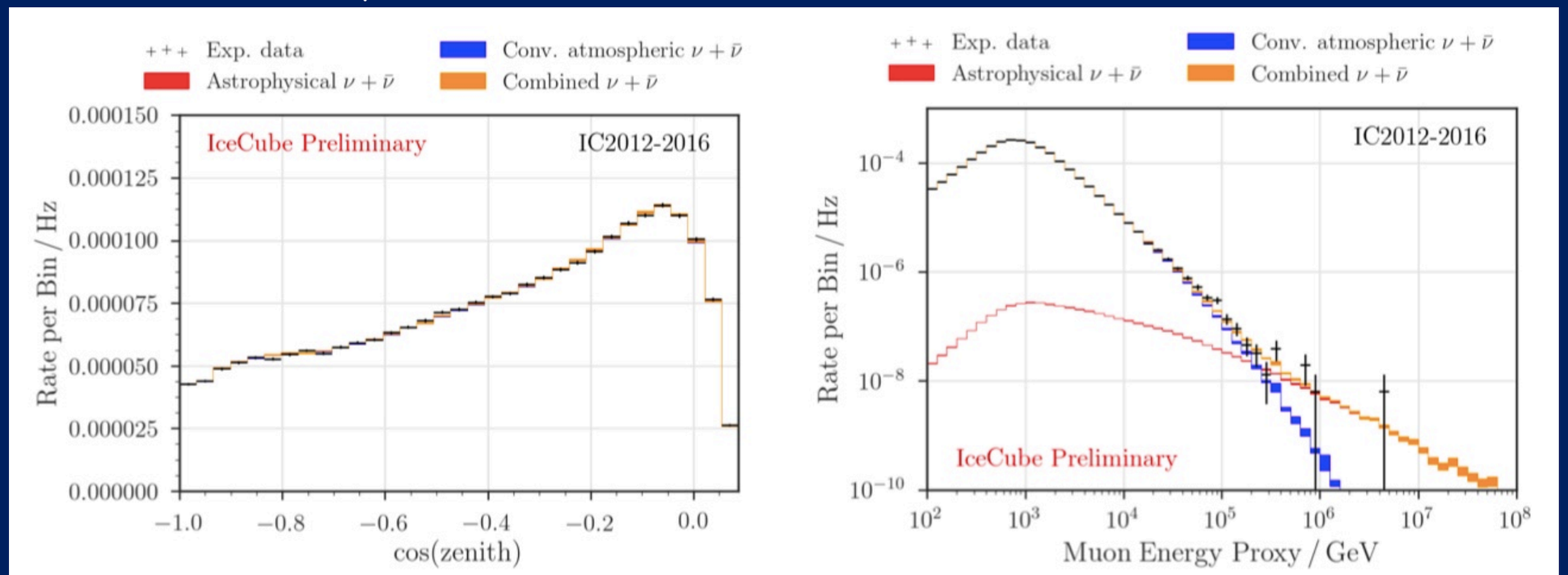


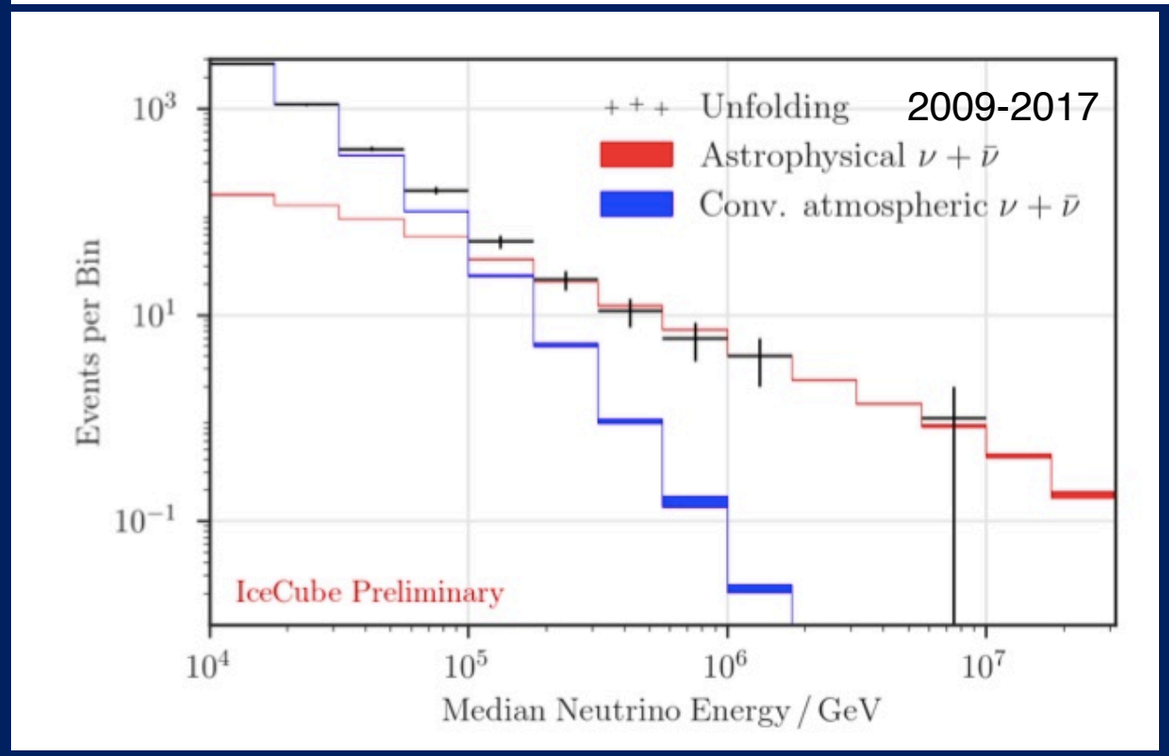


Neutrino diffuse flux measurement and characteristics

IceCube (ICRC2017), arXiv:1710.01191 [astro-ph.HE]

Muon tracks ν_μ Northern Sky (8yrs 2009-2017)





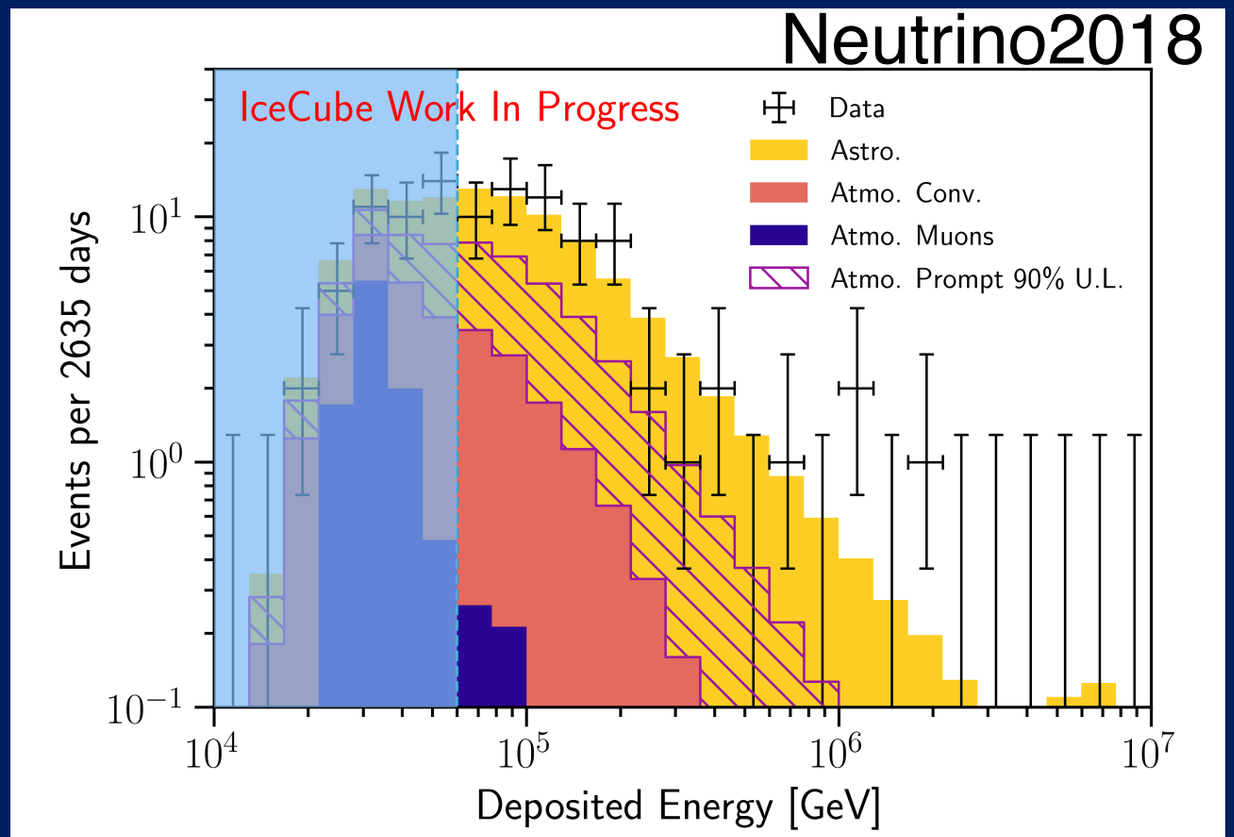
- The atmospheric-only hypothesis is excluded by 6.7σ
- Astrophysical flux $\Phi = \Phi_0 \times E^{-\gamma}$

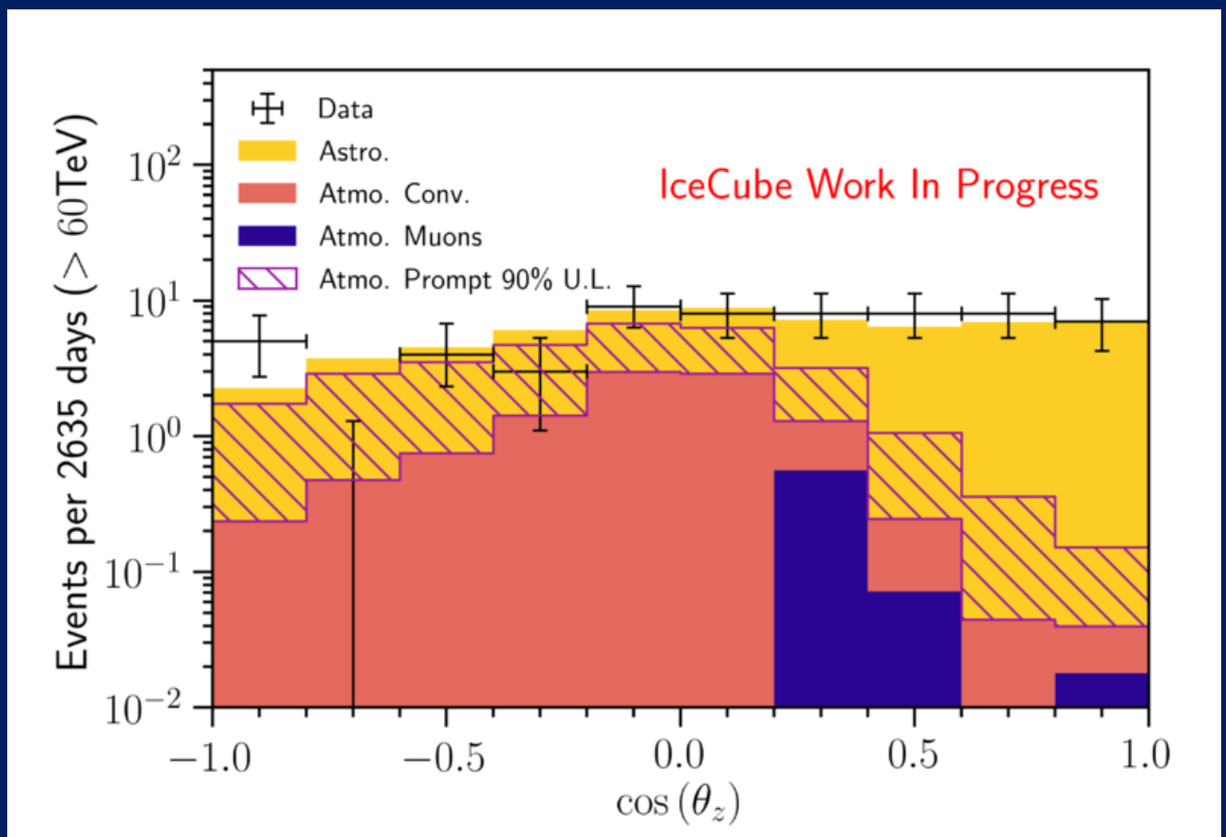
$\gamma = 2.19 +/- 0.10$

Neutrino diffuse flux measurement and characteristics

HESE all-sky all-flavor neutrinos
2010-2017 (7.5yrs)

Astrophysical neutrino flux discovery:
Science 342, 1242856 (2013)
PRL 113 (2014) 101101



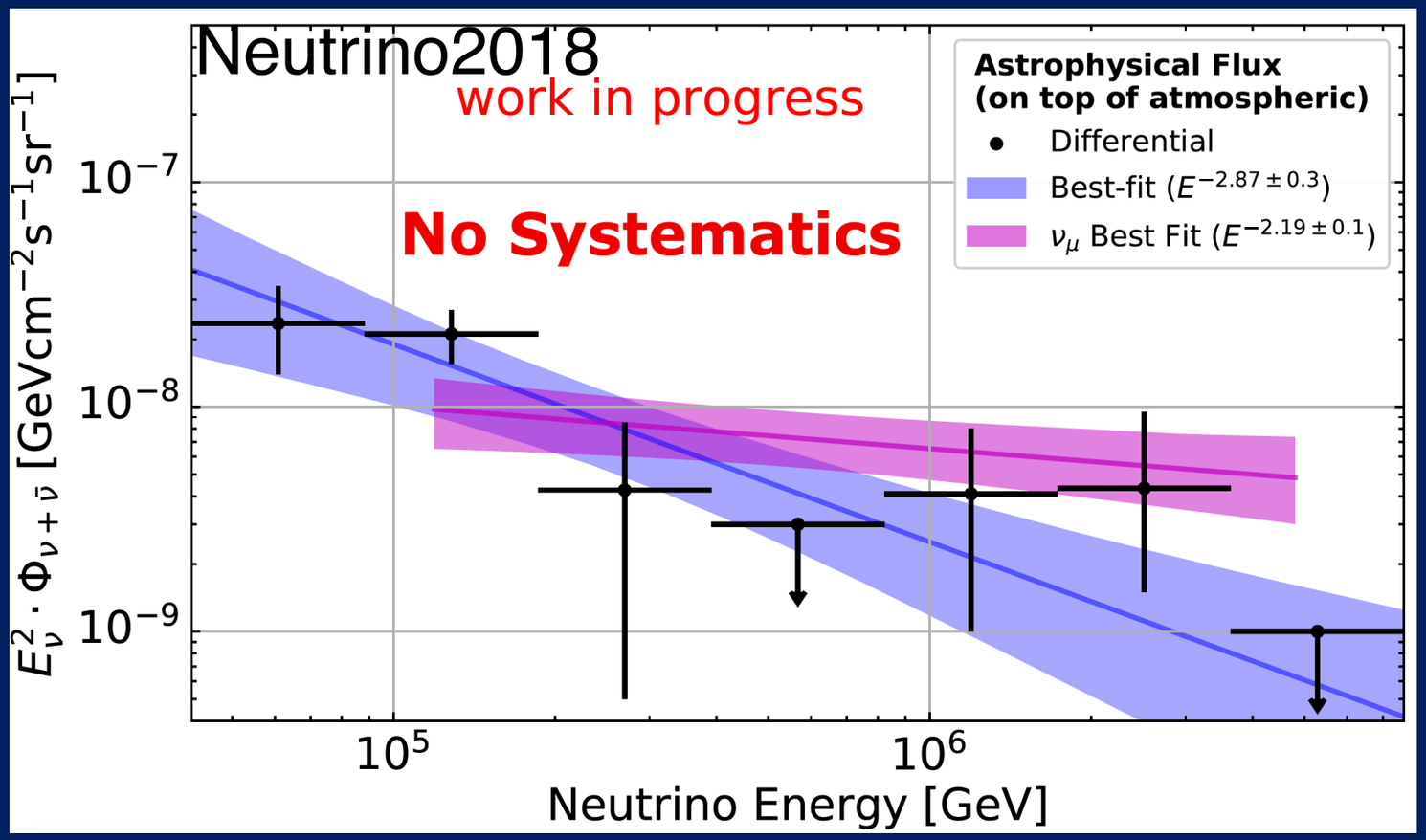


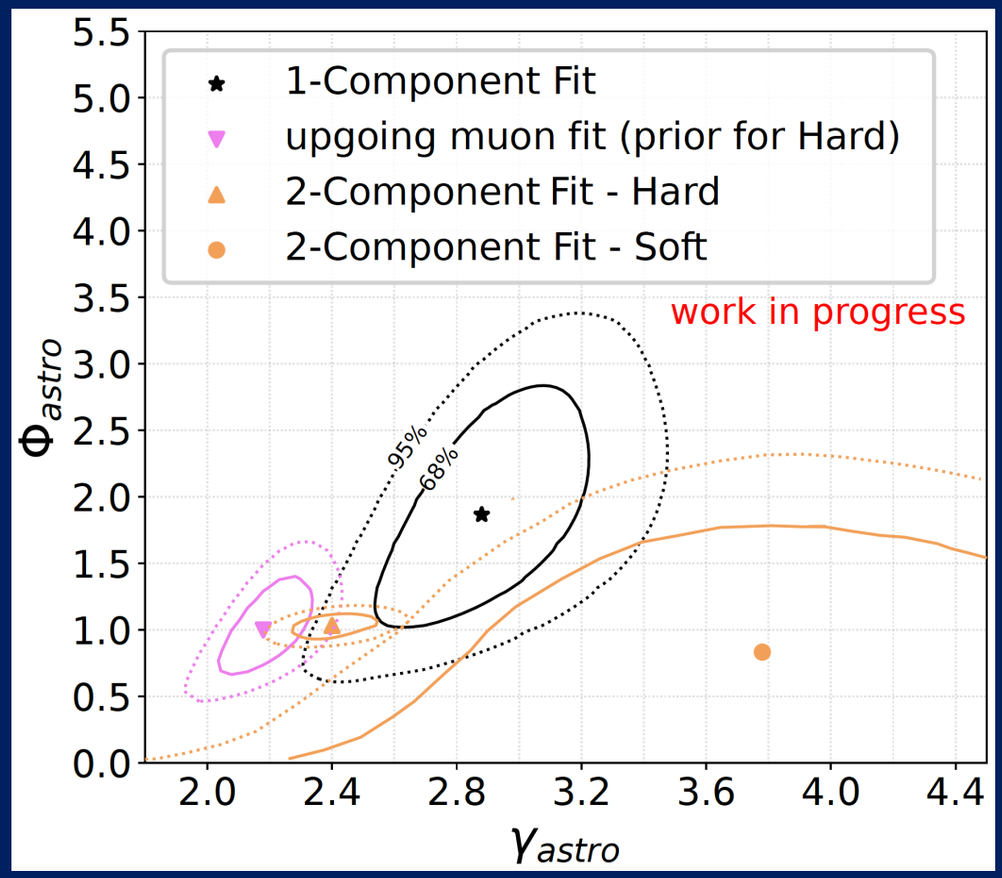
Astrophysical flux: $\Phi = \Phi_0 \times E^{-\gamma}$

γ = 2.9 +/- 0.3

Neutrino diffuse flux measurement and characteristics

HESE & Muon track results comparison:





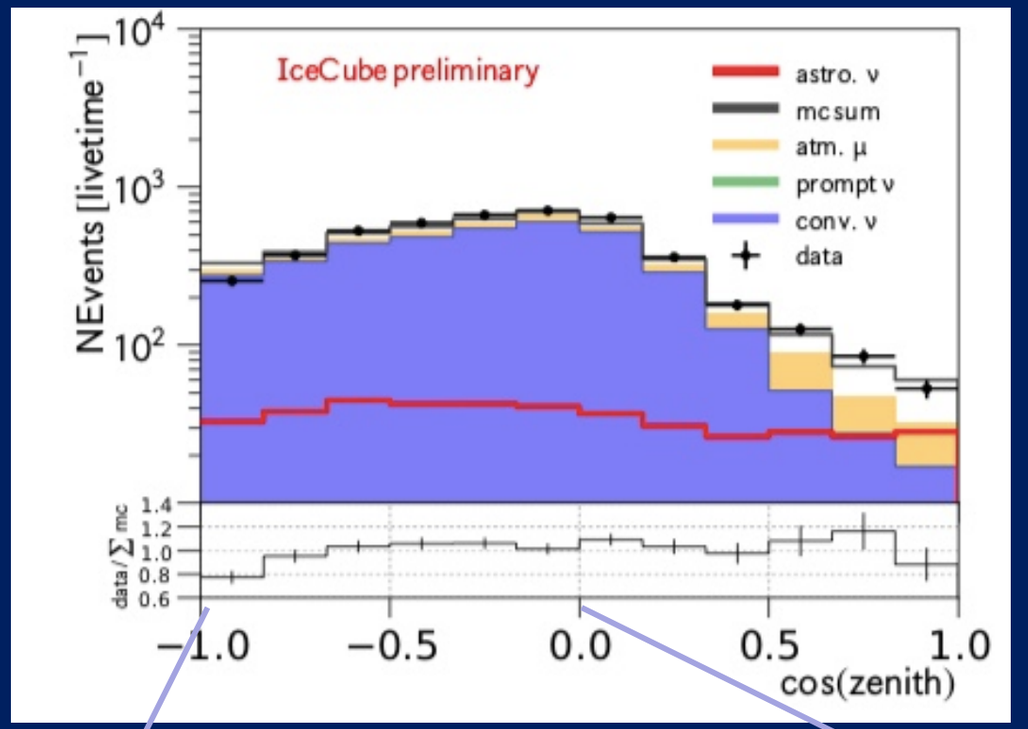
Muon and HESE single power-law fit result consistent

Neutrino diffuse flux measurement and characteristics

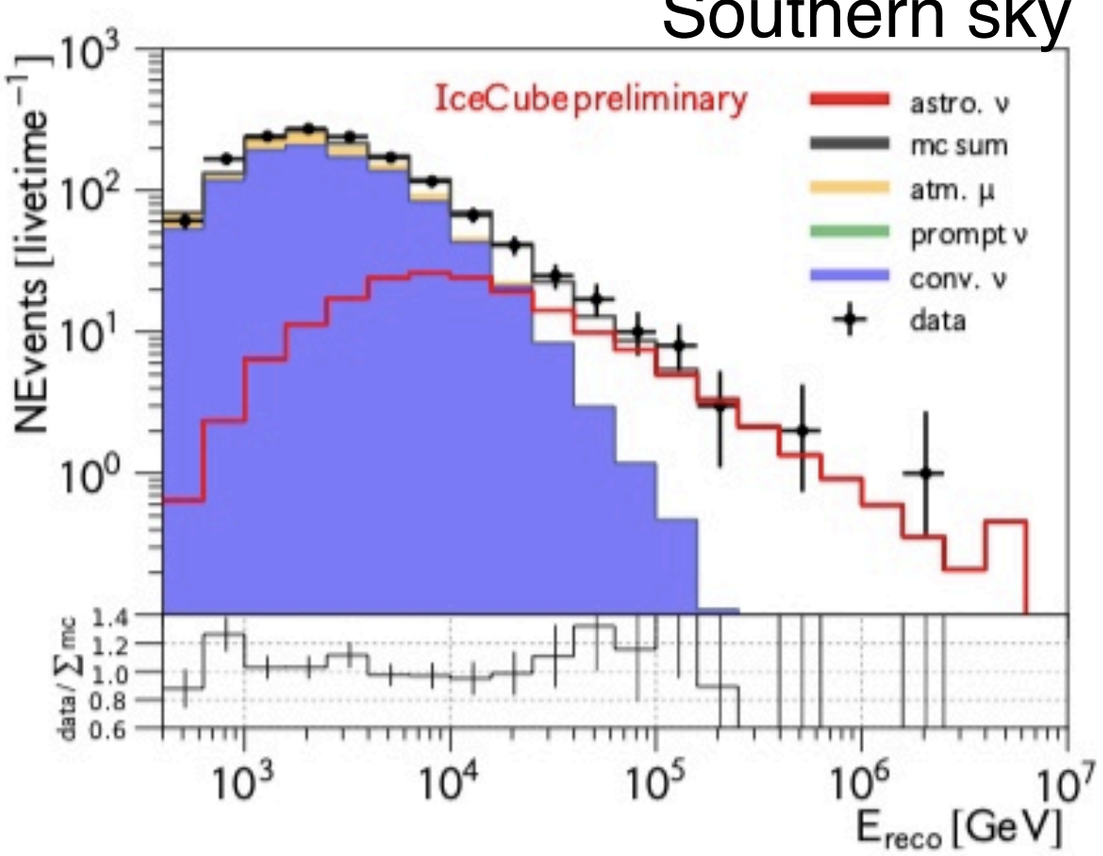
IceCube (ICRC2017), arXiv:1710.01191 [astro-ph.HE]

Contained Cascades
all-sky $\nu_e+\nu_\tau$ neutrinos
2012-2015 (4yrs)

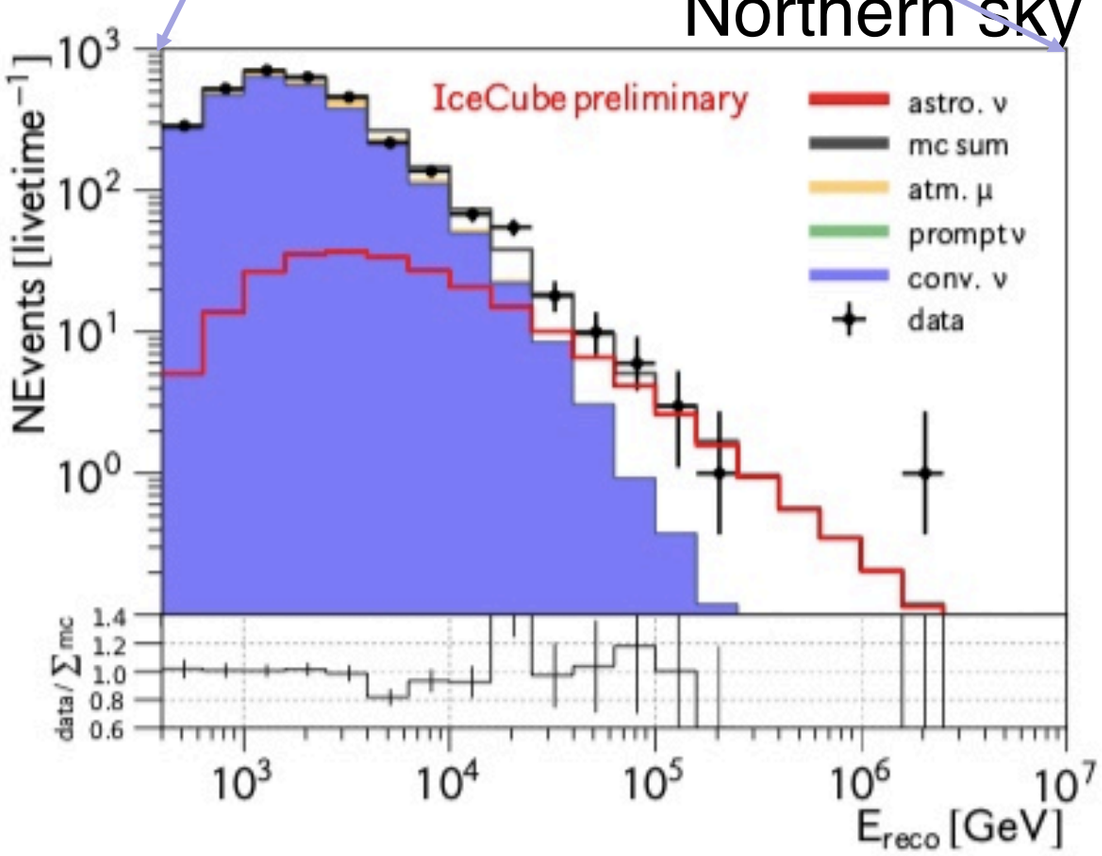
Astrophysical flux $\Phi = \Phi_0 \times E^{-\gamma}$
γ = 2.48 +/- 0.08



Southern sky



Northern sky

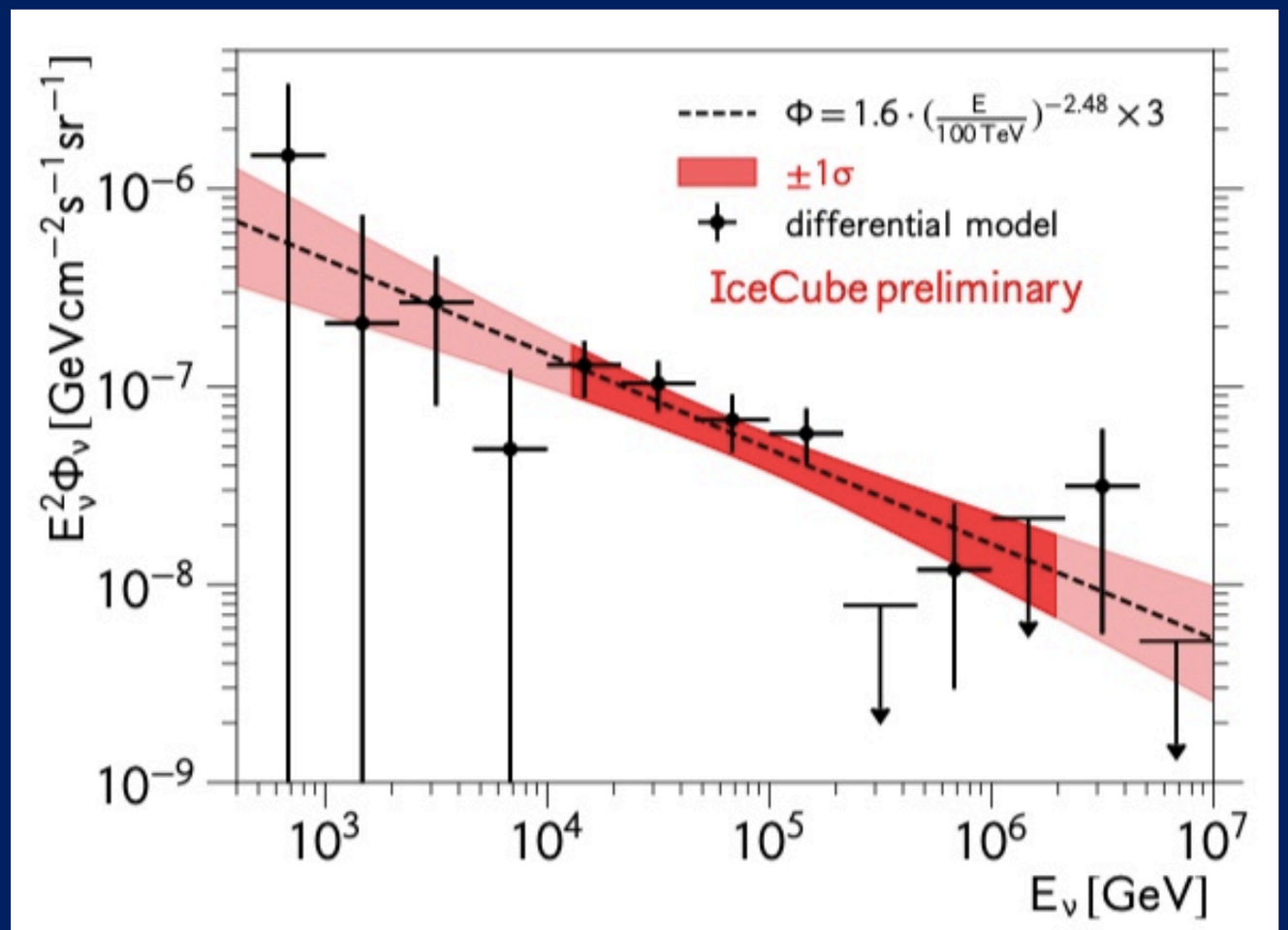


J. Kiryluk (Stony Brook University), NNN2018

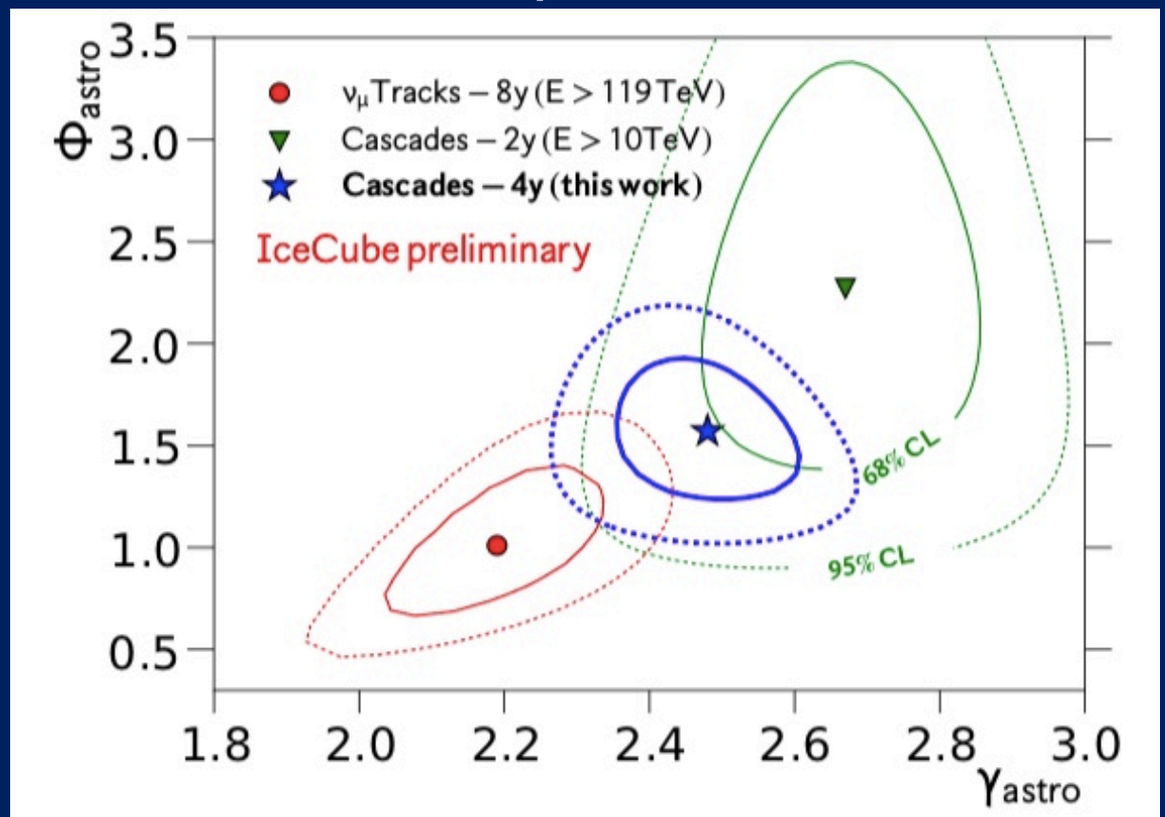
Neutrino diffuse flux measurement and characteristics

IceCube (ICRC2017), arXiv:1710.01191 [astro-ph.HE]

Contained Cascades all-sky $\nu_e+\nu_\tau$ neutrinos 2012-2015 (4yrs)



Cascades & Muon track results comparison:



Parameter		Prior	Result
spectral index	γ	-	$\mathbf{2.48 \pm 0.08}$
norm astro	ϕ	-	$(\mathbf{1.57^{+0.23}_{-0.22}})$ c.u.
norm conv	ϕ_{conv}	1.00 ± 0.30	$(1.12 \pm 0.10) \cdot \Phi_{HKKMS06}$
norm prompt	ϕ_{prompt}	$0.0^{+1.8}_{-0.0} \cdot \Phi_{BERSS}$	$< X \cdot \Phi_{BERSS}(^{**})$
norm muon	ϕ_{muon}	-	1.40 ± 0.04
scattering scale	ε_{scat}	$1.00 \pm 0.10(^*)$	1.07 ± 0.02
absorption scale	ε_{abs}	$1.00 \pm 0.10(^*)$	0.99 ± 0.03
dom efficiency	ε_{eff}	0.99 ± 0.10	1.00 ± 0.06

Table 1: Single power-law fit results. (1 c.u. $\equiv 10^{-18}$ GeV^{-1}s^{-1}sr^{-1}cm^{-2}). (*) This prior us

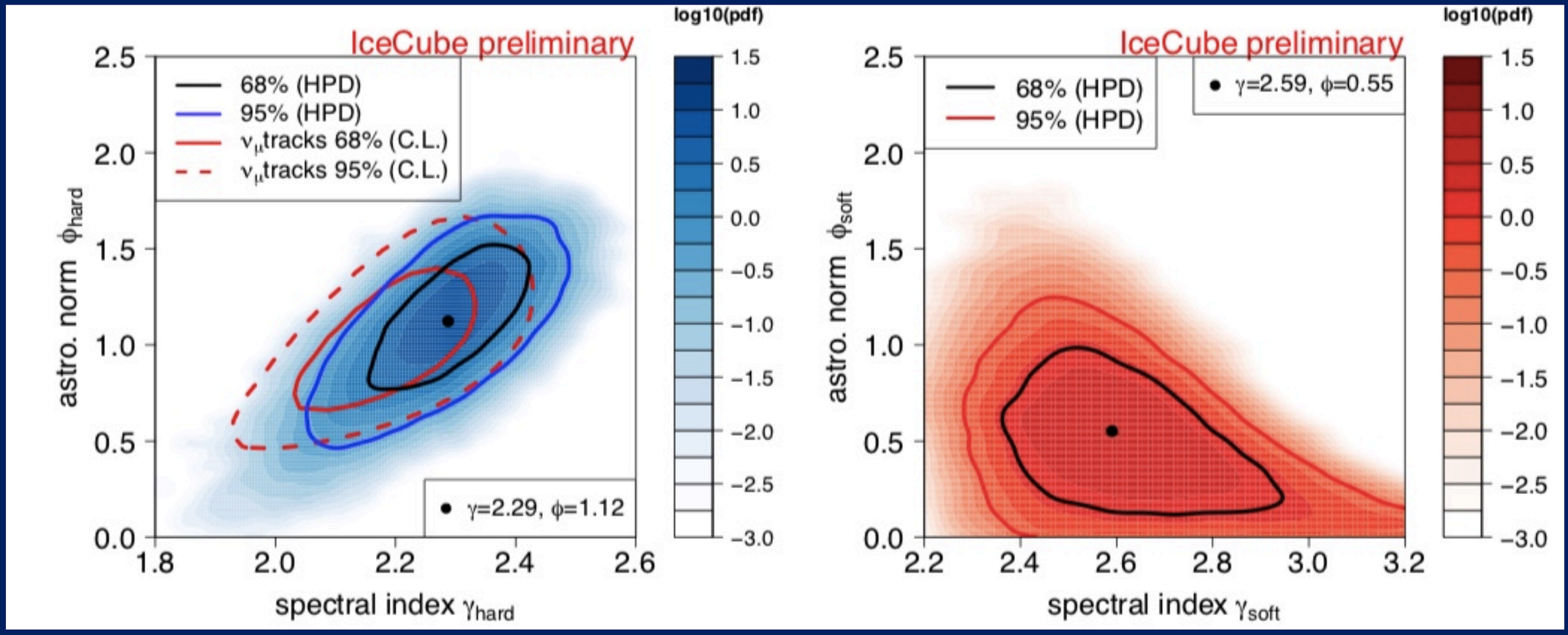
Cascade & Muon track single power-law fit result consistent at p=4%

Neutrino diffuse flux measurement and characteristics

IceCube (ICRC2017), arXiv:1710.01191 [astro-ph.HE]

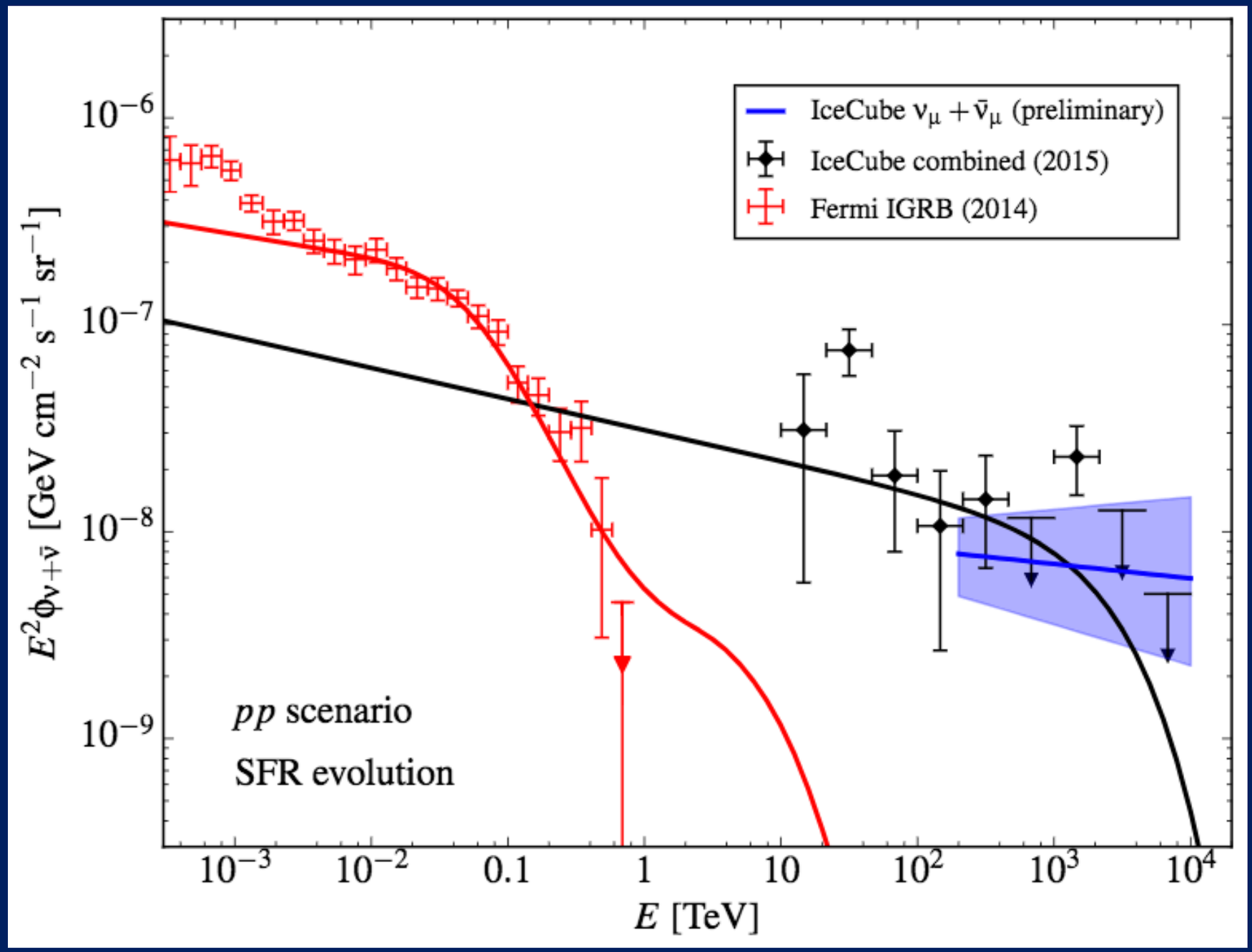
Beyond single power-law

$$\Phi(E_\nu) = \Phi_0 \times 10^{-18} \left\{ (1-\alpha) \left[\frac{E_\nu}{10^5\, GeV} \right]^{-\gamma_{\text{soft}}} + \alpha \left[\frac{E_\nu}{10^5\, GeV} \right]^{-\gamma_{\text{hard}}} \right\}$$



Fit with two component flux model describes cascade data well, however fit with single power law flux is preferred.

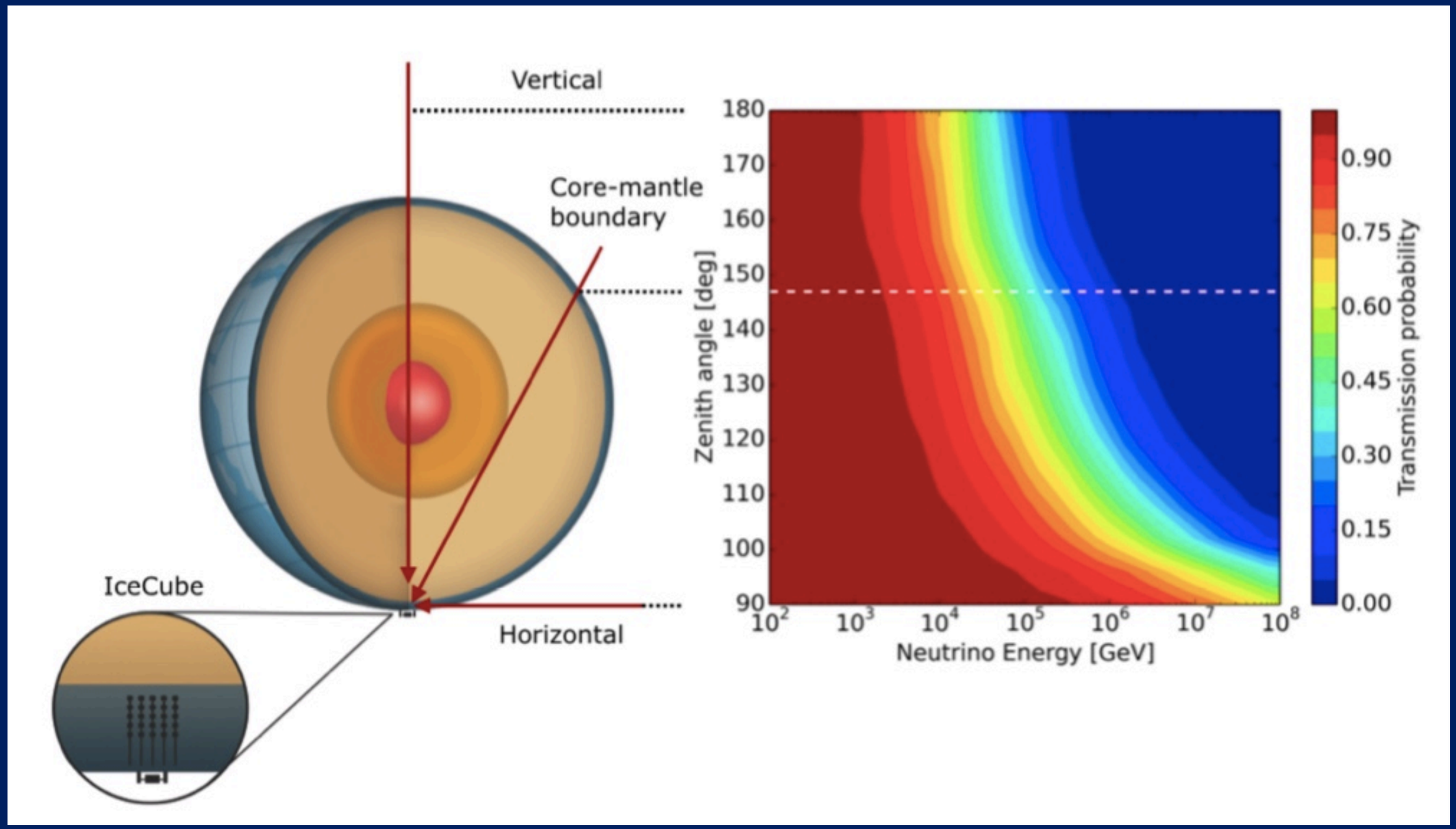
Diffuse flux: neutrinos and photons



The large neutrino flux implies that a significant fraction of the energy in the non-thermal universe is generated in hadronic (pp) accelerators
Neutrinos from blazar(s) cannot explain (majority) of the diffuse flux

Neutrino- Nucleon Cross Section Measurements

IceCube: Nature 551 (2017) 596



TeV-PeV Neutrino absorption in Earth

Neutrino- Nucleon Cross Section Measurements

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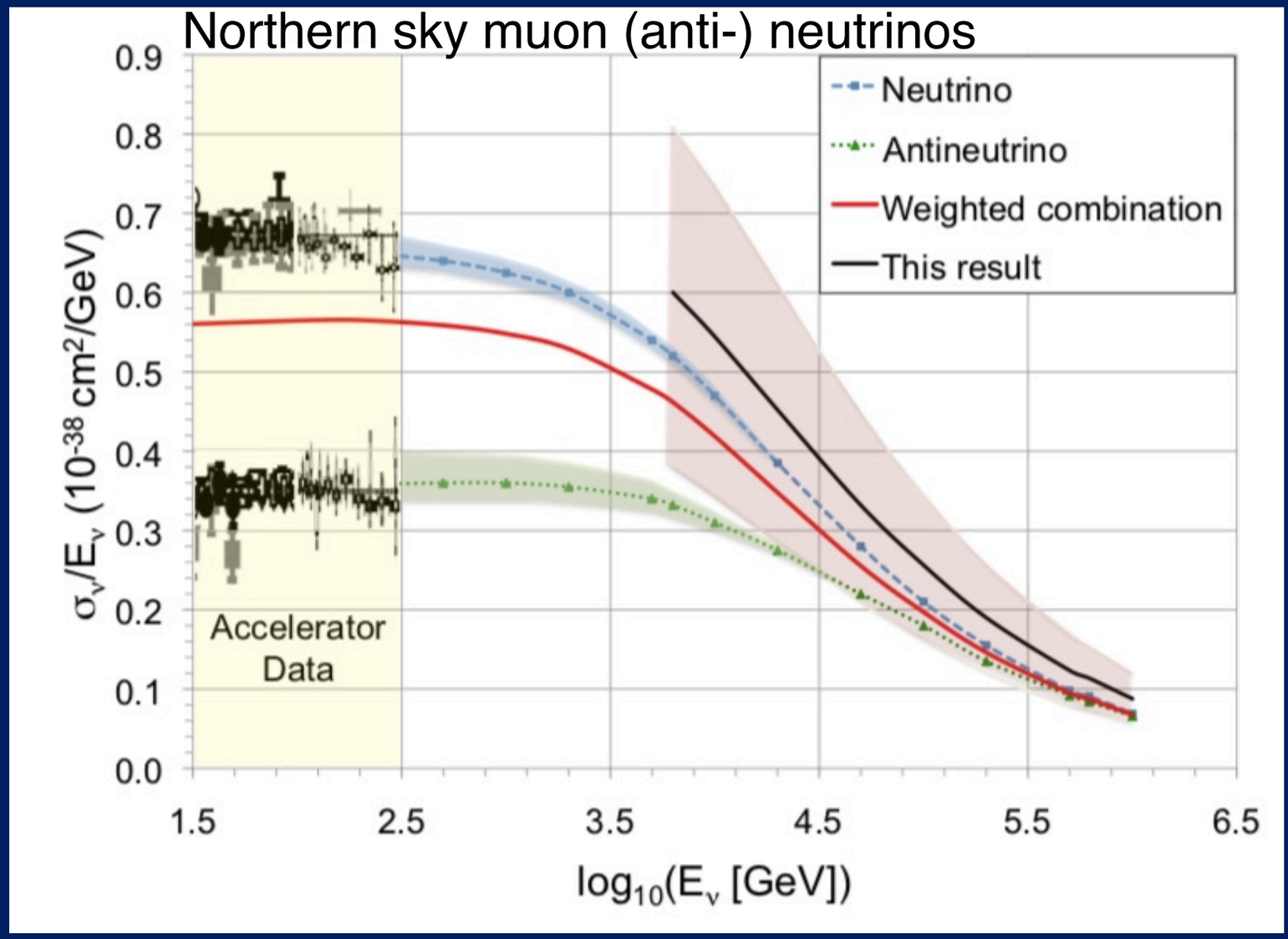
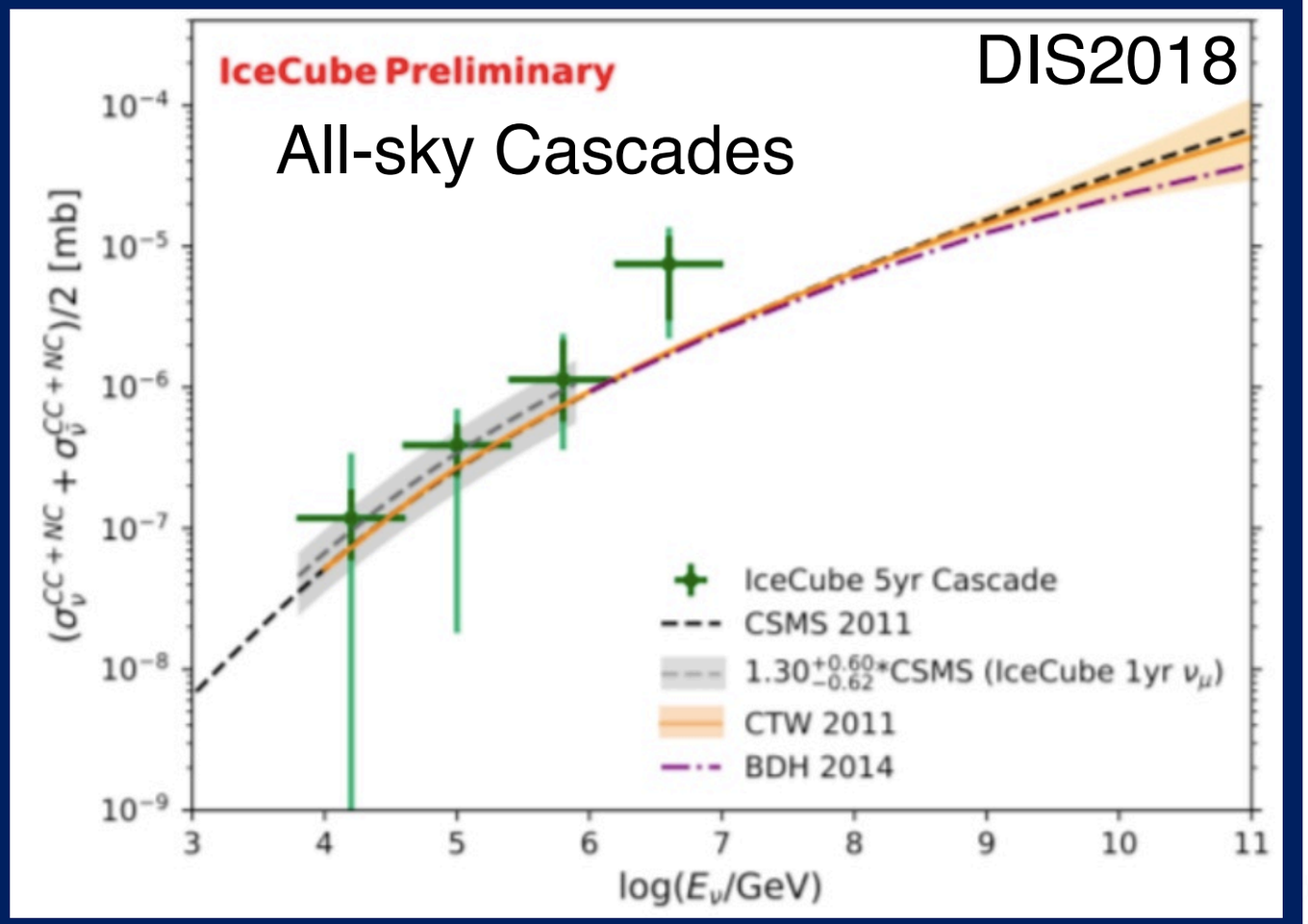


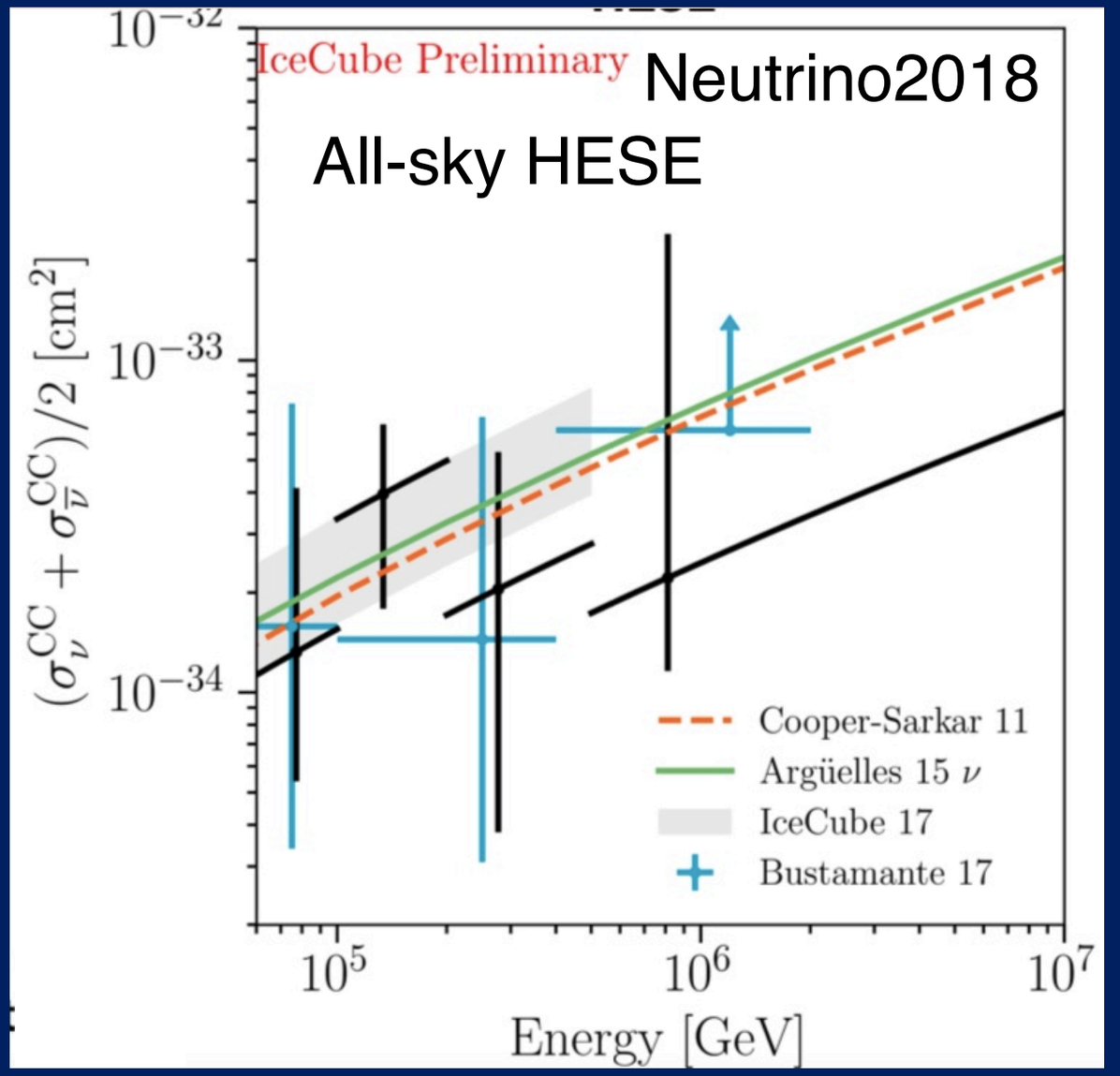
Standard Model ν_μ-N cross section scales by κ factor (fit parameter)

$$\kappa = 1.30^{+0.21}_{-0.19}\ (\text{stat.})\ ^{+0.39}_{-0.43}\ (\text{syst.})$$

Neutrino- Nucleon Cross Section Measurements

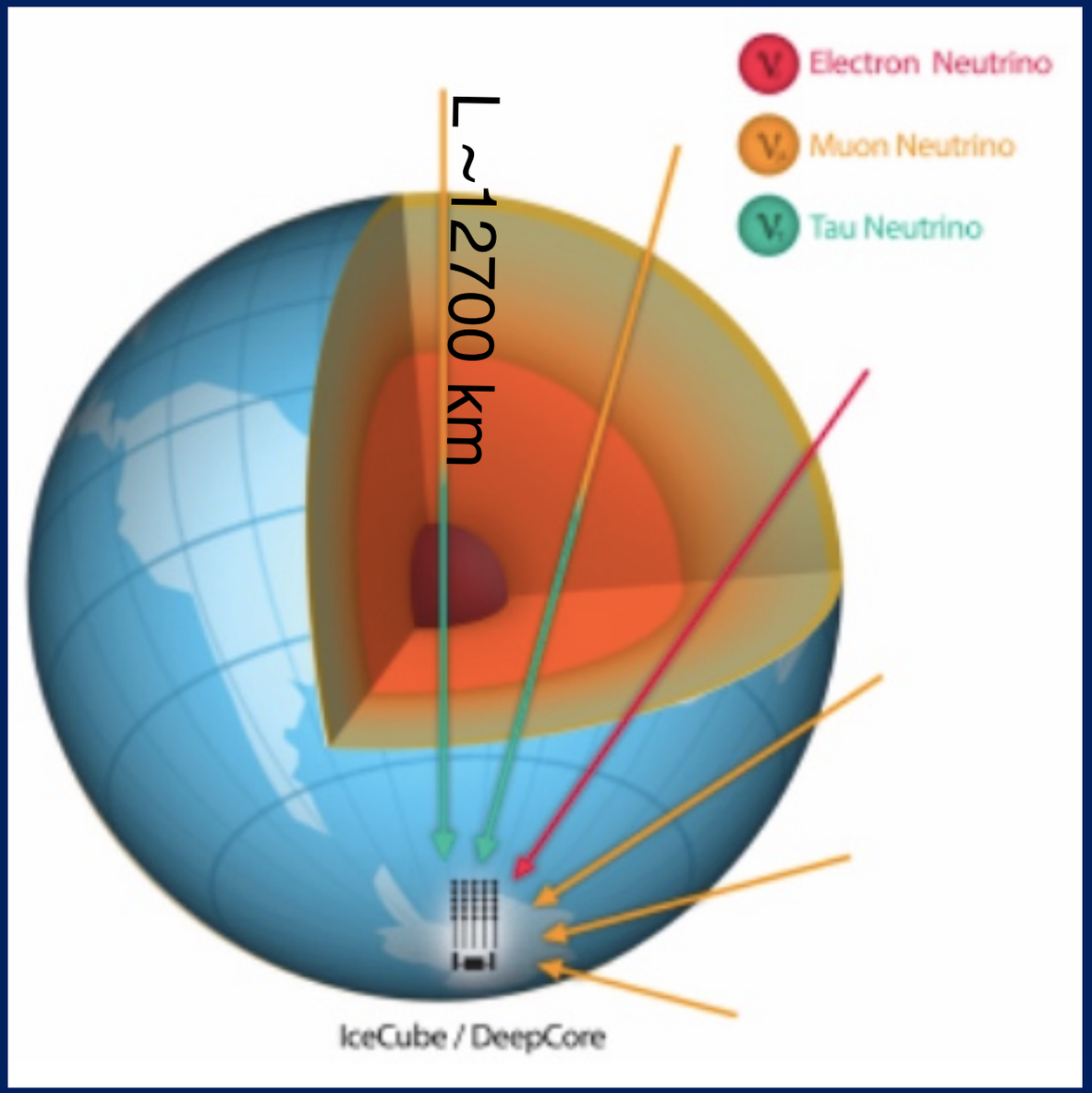


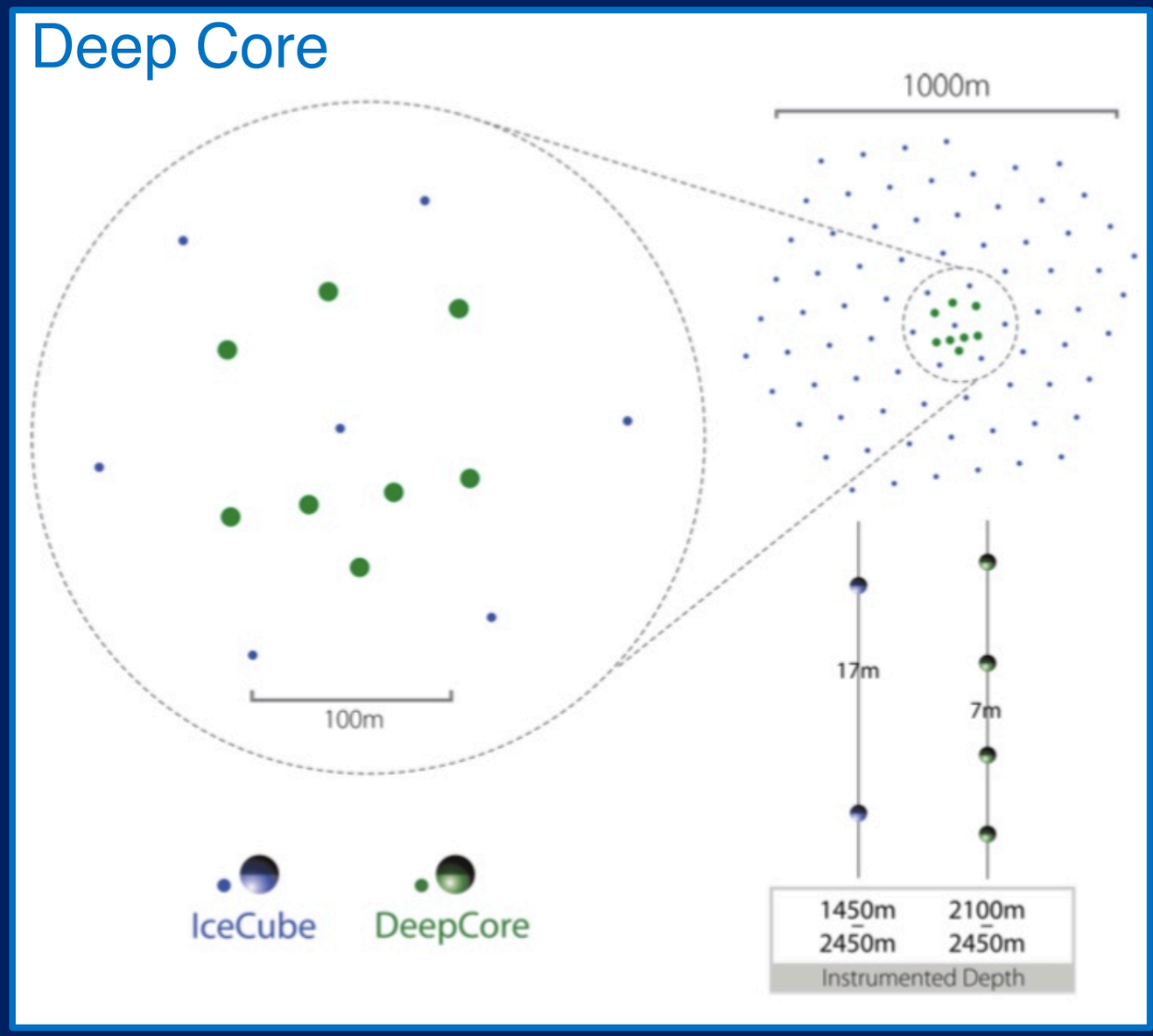
arXiv:1809.06782 [hep-ex]



TeV-PeV neutrinos of all flavors
Cross section consistent with Standard Model

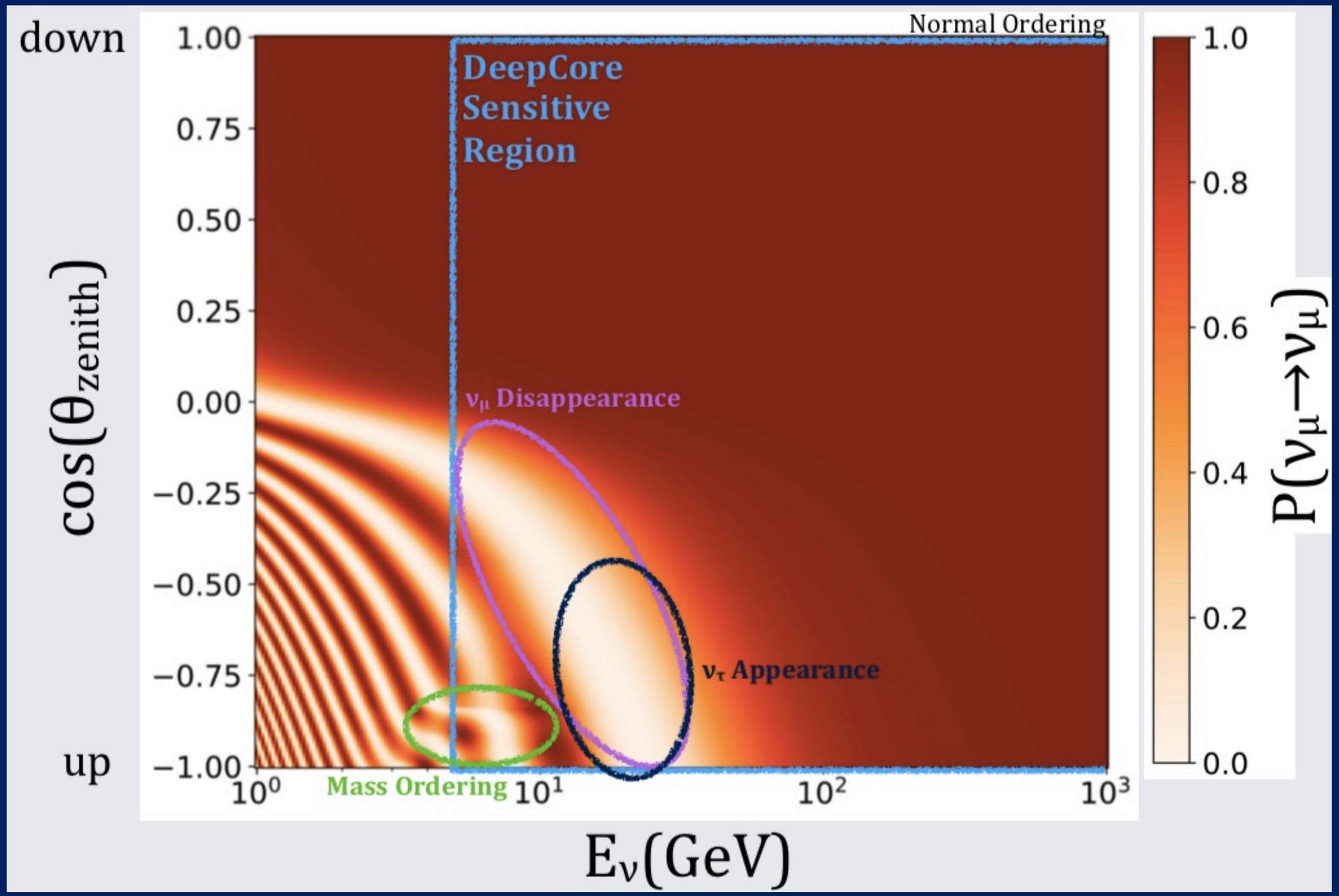
Neutrino oscillations with Deep Core and atmospheric neutrinos





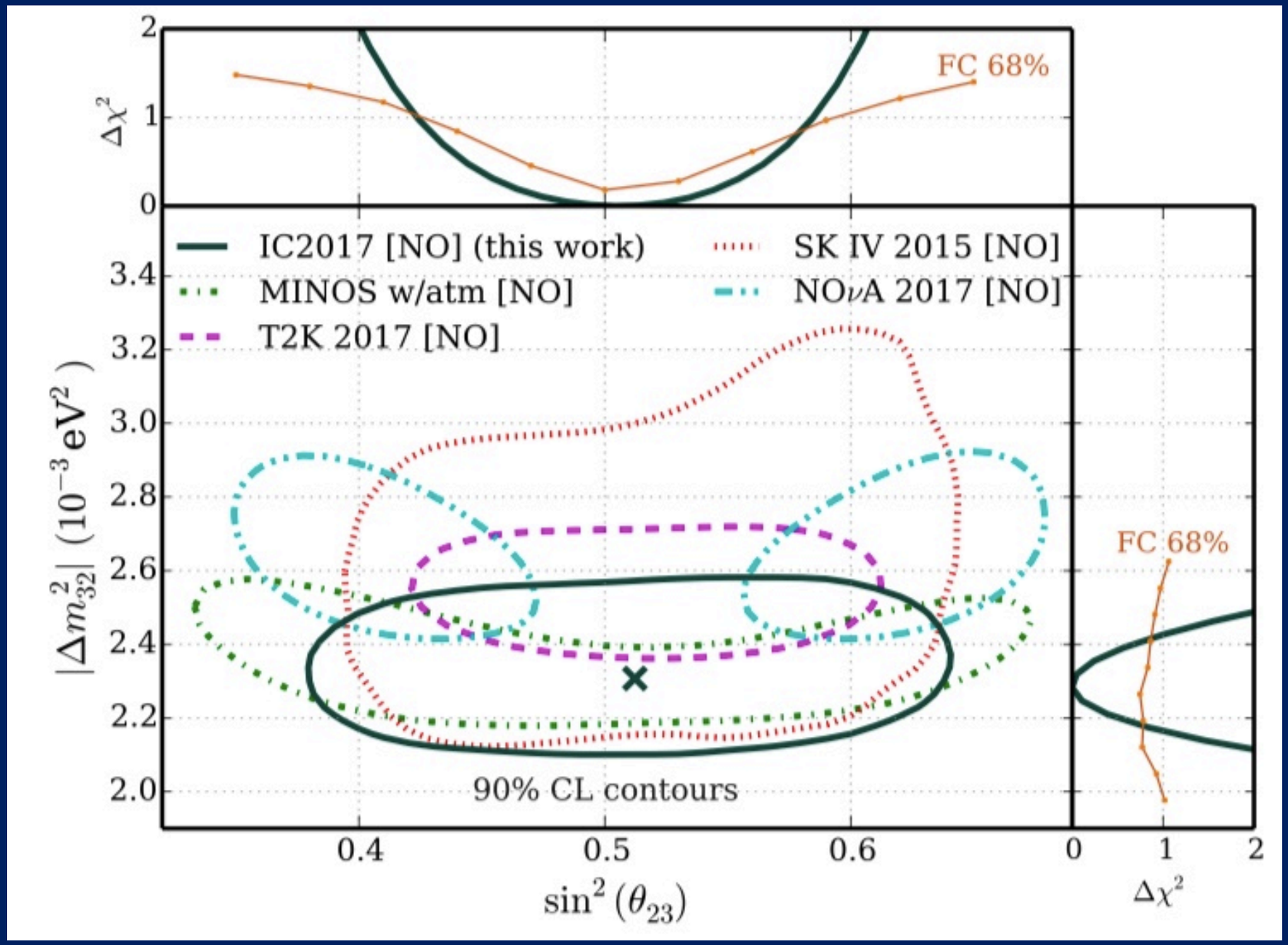
Wide range of energy and baselines:
E_ν ~ a few GeV – 100's TeV

Neutrino oscillations with Deep Core and atmospheric neutrinos



Neutrino oscillations with Deep Core and atmospheric neutrinos: ν_μ disappearance

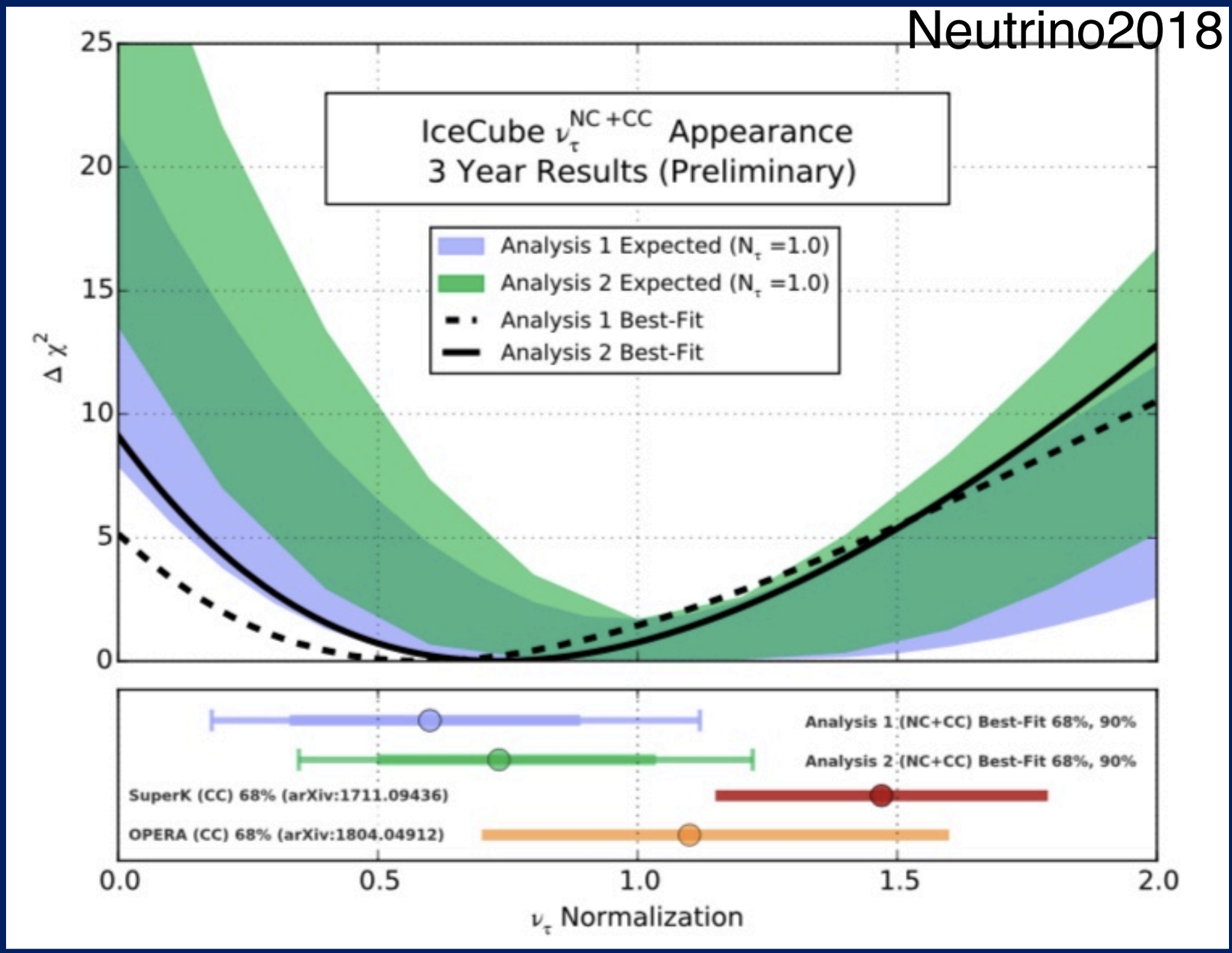
Phys. Rev. Lett. 120, 071801 (2018)



Standard oscillation parameters measurement

Neutrino oscillations with Deep Core and atmospheric neutrinos: ν_τ appearance search

Neutrino2018



Result consistent with Super-K and OPERA,
Consistent with unitary PMNS at 90% CL

Era of km^3 neutrino & multimessanger astronomy has begun

Discovery → ***Measurements*** → ***Models testing***

Diffuse signal → ***First source*** → ***Catalog!***

Astrophysical neutrinos have been discovered
Diffuse flux characteristics started
Interpretation challenging
Evidence of neutrino source: flaring blazar
Cosmic accelerator source searches continue …..

Neutrino oscillation physics

Measure oscillation parameters
Test PMNS unitarity with tau neutrinos

Stay tuned!

IceCube
SOUTH POLE NEUTRINO OBSERVATORY

National Science Foundation
WHERE DISCOVERIES BEGIN

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