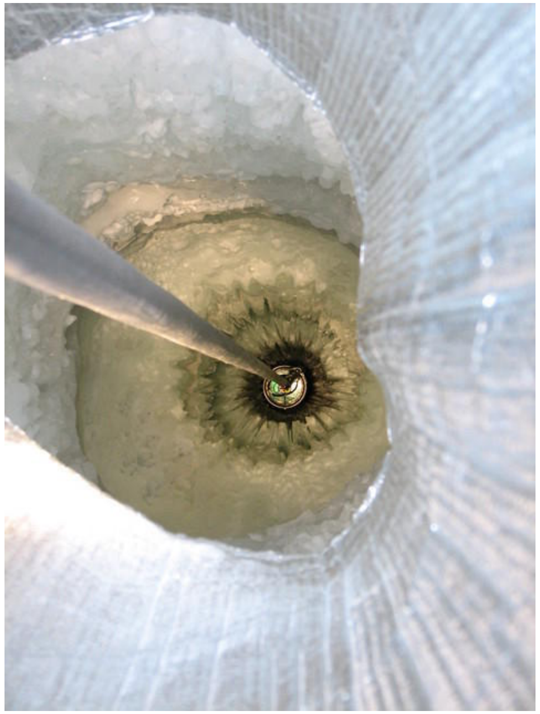
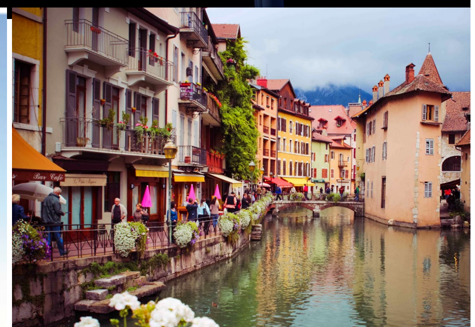
IceCube Observations on the cosmos

Teresa Montaruli
University of Geneva

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

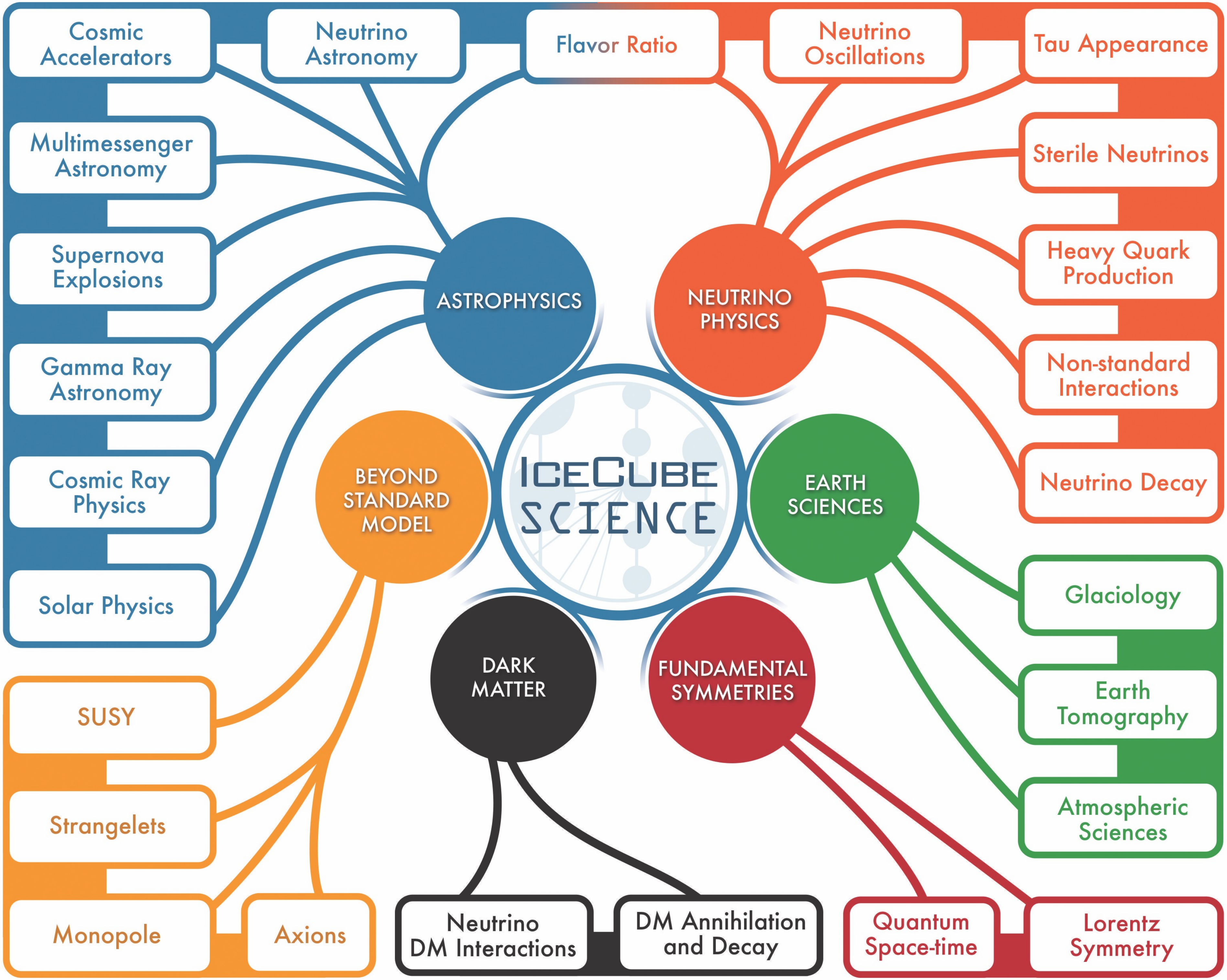




ICECUBE COLLABORATION

LAYOUT

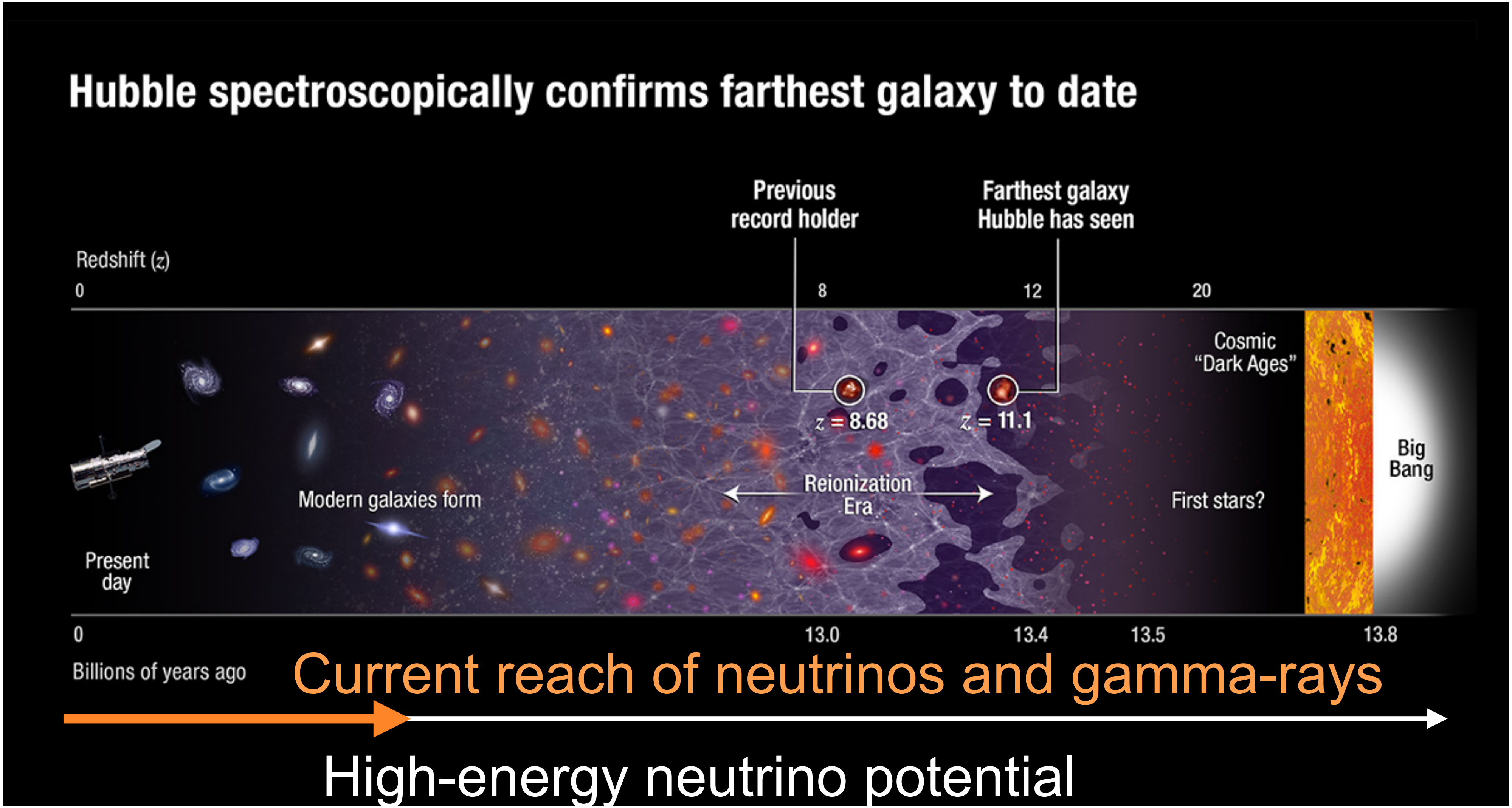
- IceCube
- High Energy Astrophysics: the search for cosmic ray sources
    - Diffuse flux searches
    - Source searches
    - Multi-messenger programs:
- Dark Matter
- Neutrino properties


Cosmic Accelerators
Neutrino Astronomy
Flavor Ratio
Neutrino Oscillations
Tau Appearance
Multimessenger Astronomy
Sterile Neutrinos
Supernova Explosions
Heavy Quark Production
ASTROPHYSICS
NEUTRINO PHYSICS
Gamma Ray Astronomy
Non-standard Interactions
Cosmic Ray Physics
Neutrino Decay
BEYOND STANDARD MODEL
ICECUBE SCIENCE
EARTH SCIENCES
Solar Physics
Glaciology
DARK MATTER
FUNDAMENTAL SYMMETRIES
SUSY
Earth Tomography
Strangelets
Atmospheric Sciences
Monopole
Axions
Neutrino DM Interactions
DM Annihilation and Decay
Quantum Space-time
Lorentz Symmetry

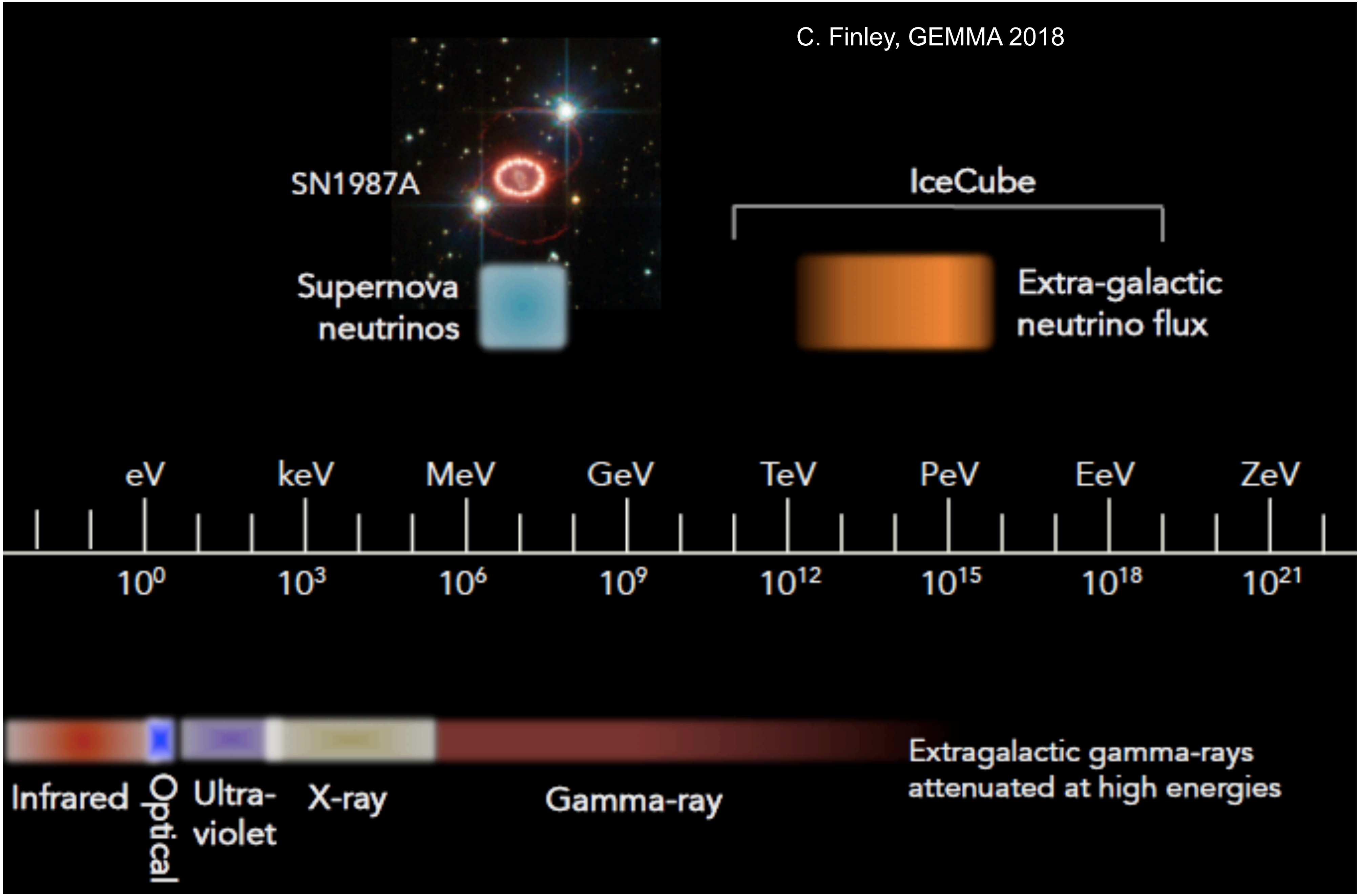
Observation of the cosmos with IceCube neutrinos

- High-energy Multi-Messenger Astrophysics is one of the MOST FASCINATING fields
- Allows to test the Laws of Physics in extreme conditions not reproducible in the lab
- Gamma-rays are currently the messenger providing most precise information on the >100 GeV sky
- Cosmic rays are still observed at >>100 TeV, when gamma-rays begin to be absorbed on the way to us
- Neutrinos can be used since they reach us from well beyond z = 2, but sensitivity of instruments is limited

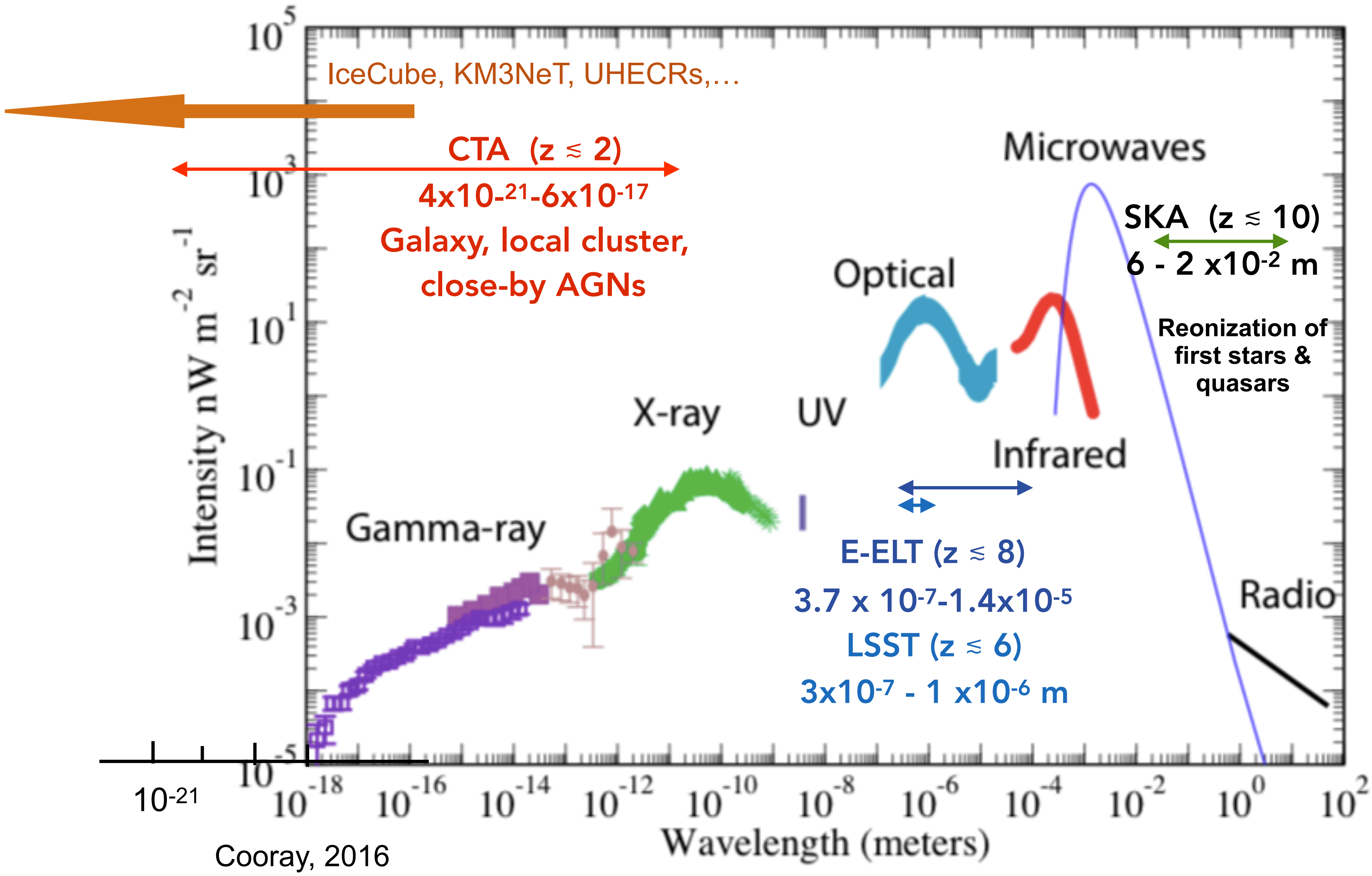
https://www.nasa.gov/feature/goddard/2016/hubble-team-breaks-cosmic-distance-record



The high-energy frontier



FLUXES FROM THE HEAVENS (Z=0)

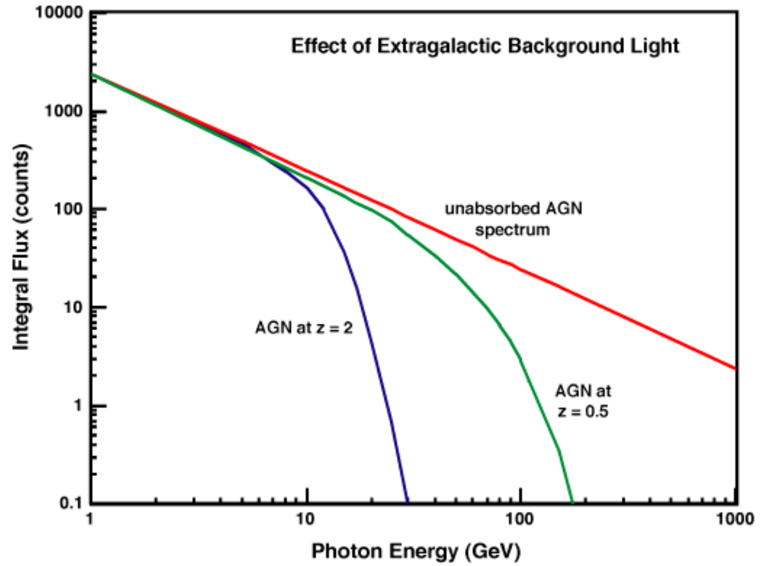


20 decades in the wavelength of the extragalactic diffuse radiation

Gamma-ray exploration by Fermi: up to z ~ 4.3

$\gamma_{VHE}\,\gamma_{EBL} \rightarrow e^{+} + e^{-}$

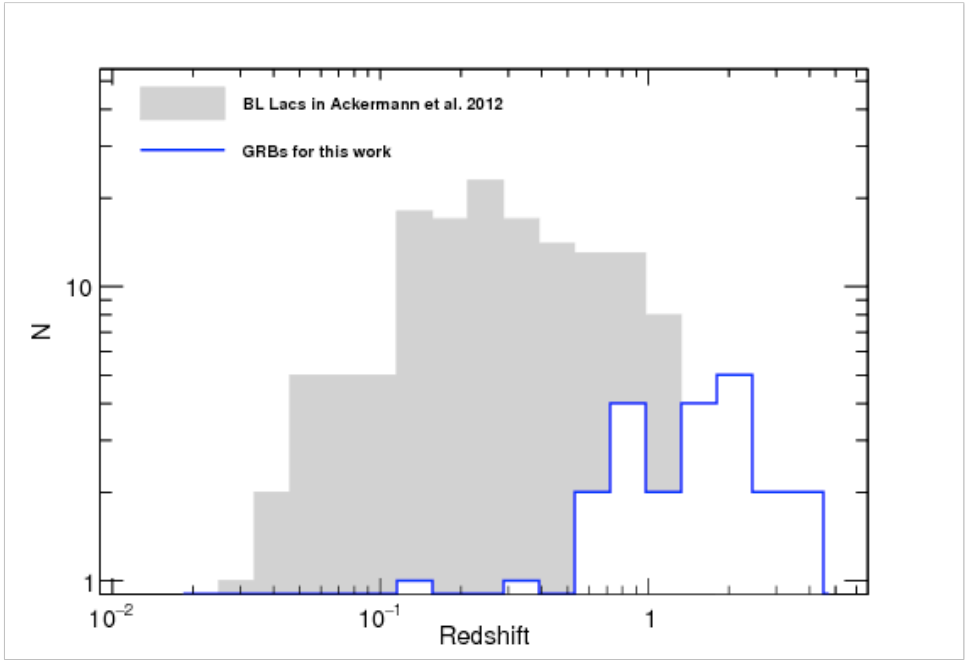
$E\gamma_{VHE} \cdot E\gamma_{EBL} > (m_e c^2)^2$

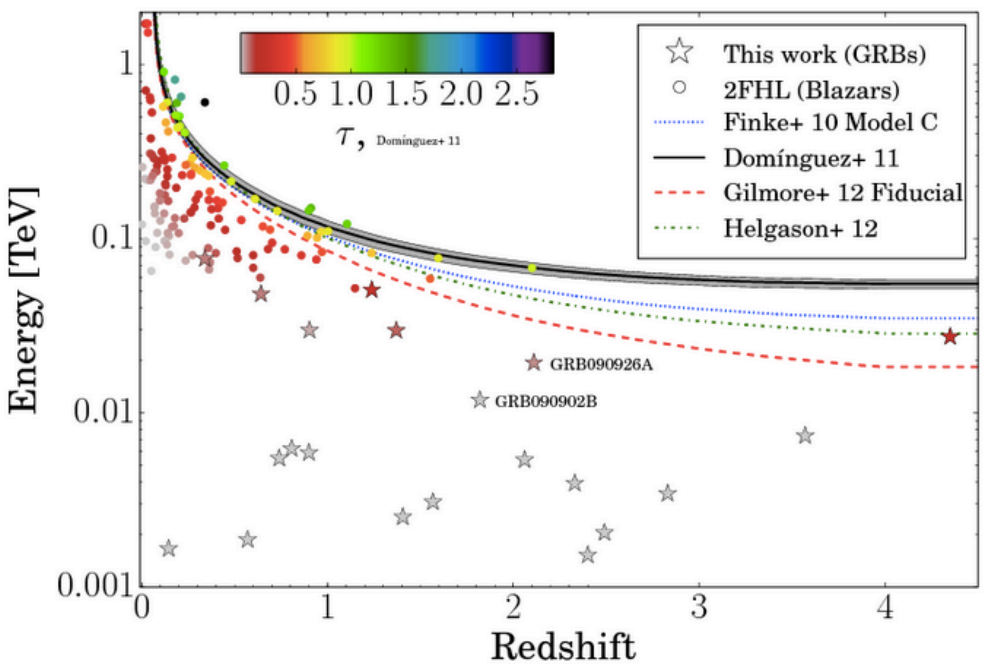


$\Phi_{obs}(E_\gamma, z) = e^{-\tau(E\gamma, z)} \times \Phi_{int}(E_\gamma).$

22 Fermi GRBs 65-550 GeV

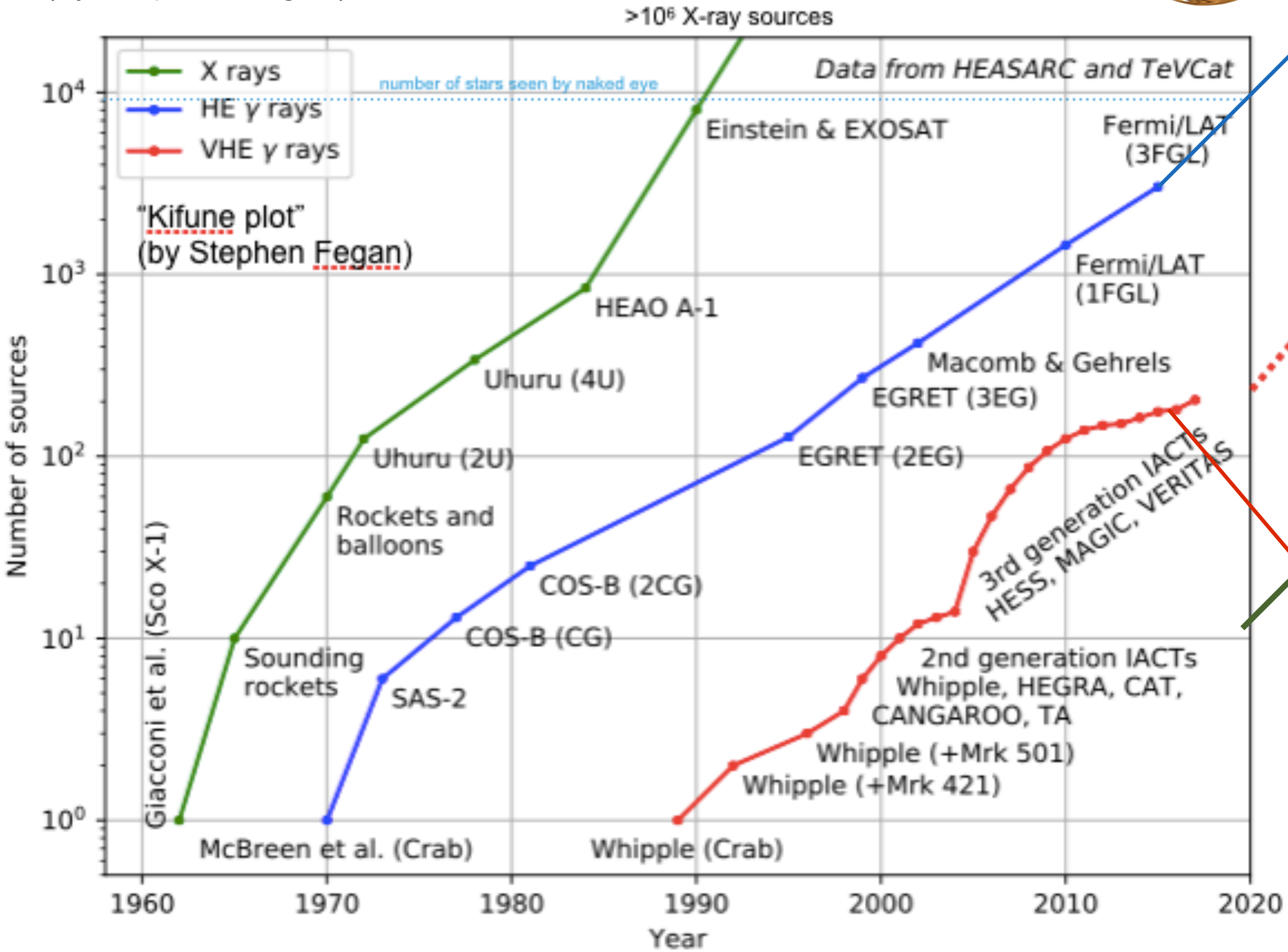
~80% of the 3rd Fermi-LAT Catalog of Hard Sources are blazars. Highest redshifts z~4.31

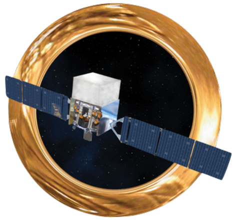


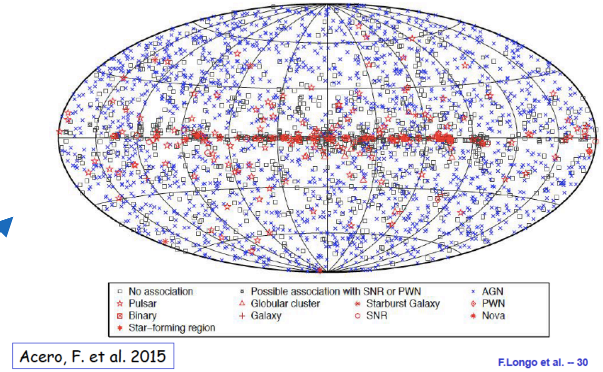


Gamma-ray Sources & Detection Technique Advancement

"Kifune plot"
(by Stephen Fegan)



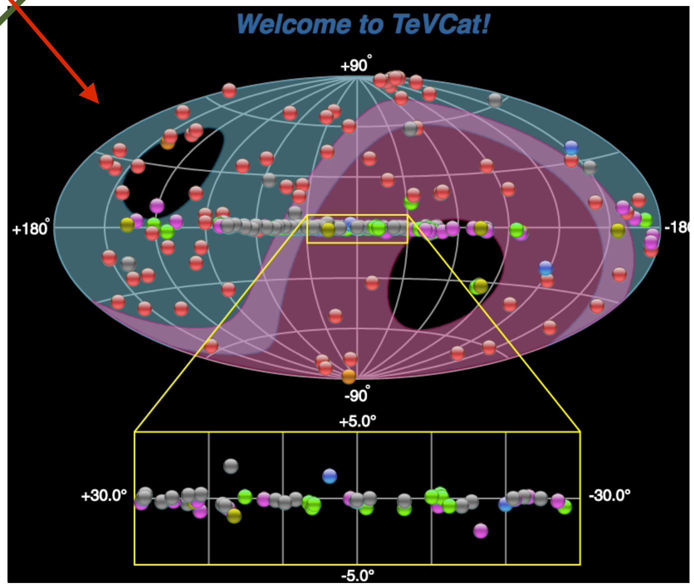




3FGL 3034 sources > 100 MeV
95% extragalactic!
21% BL Lacs
16% FSRQ
19% unclassified blazars +
22% unassociated high lat

CTA

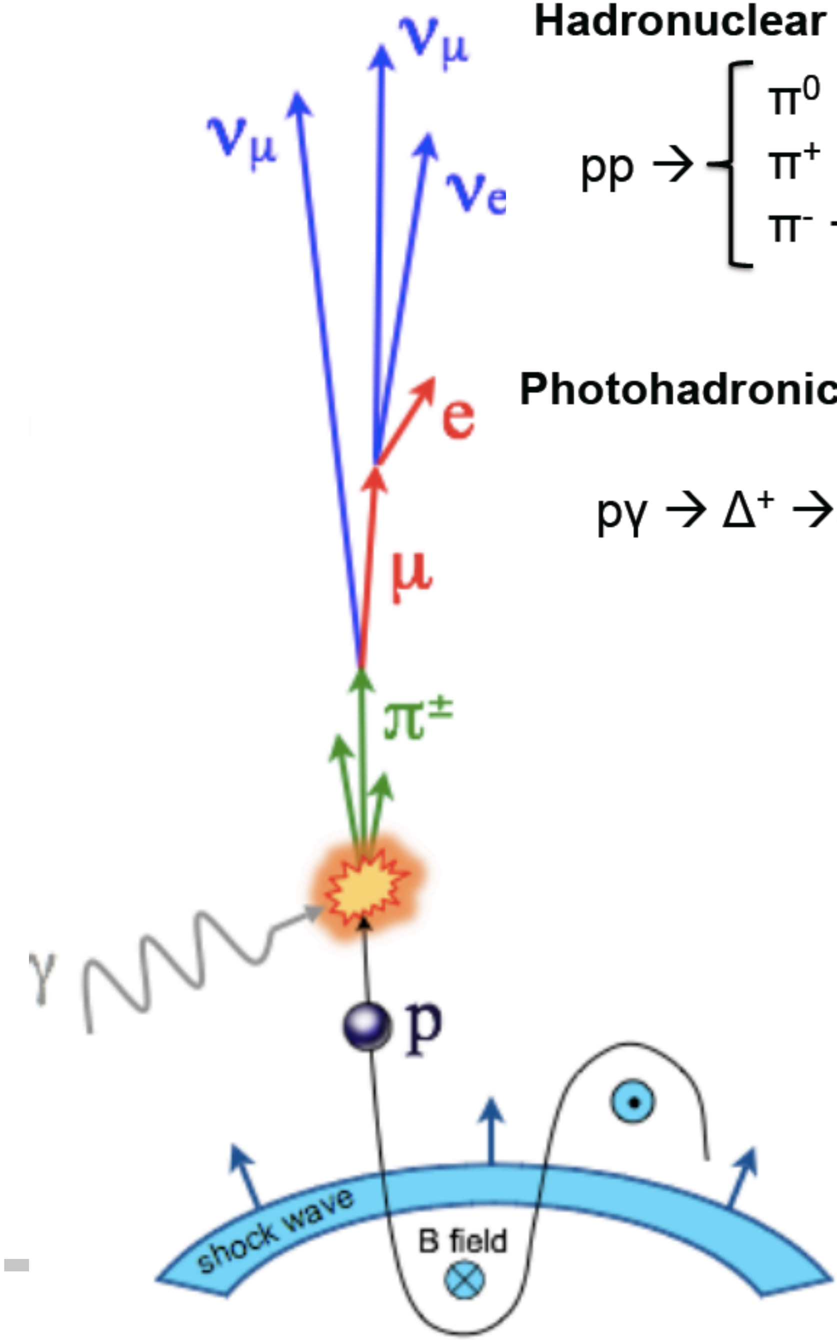
Neutrino sauces



About 210 TeV sources > 100 GeV
~37% discovered day H.E.S.S.
(exposure to the Galaxy matters!)

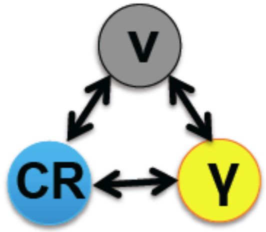
tevcat.uchicago.edu

COSMIC NEUTRINO SOURCE MODEL



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

Neutrino flavour ratio at source:

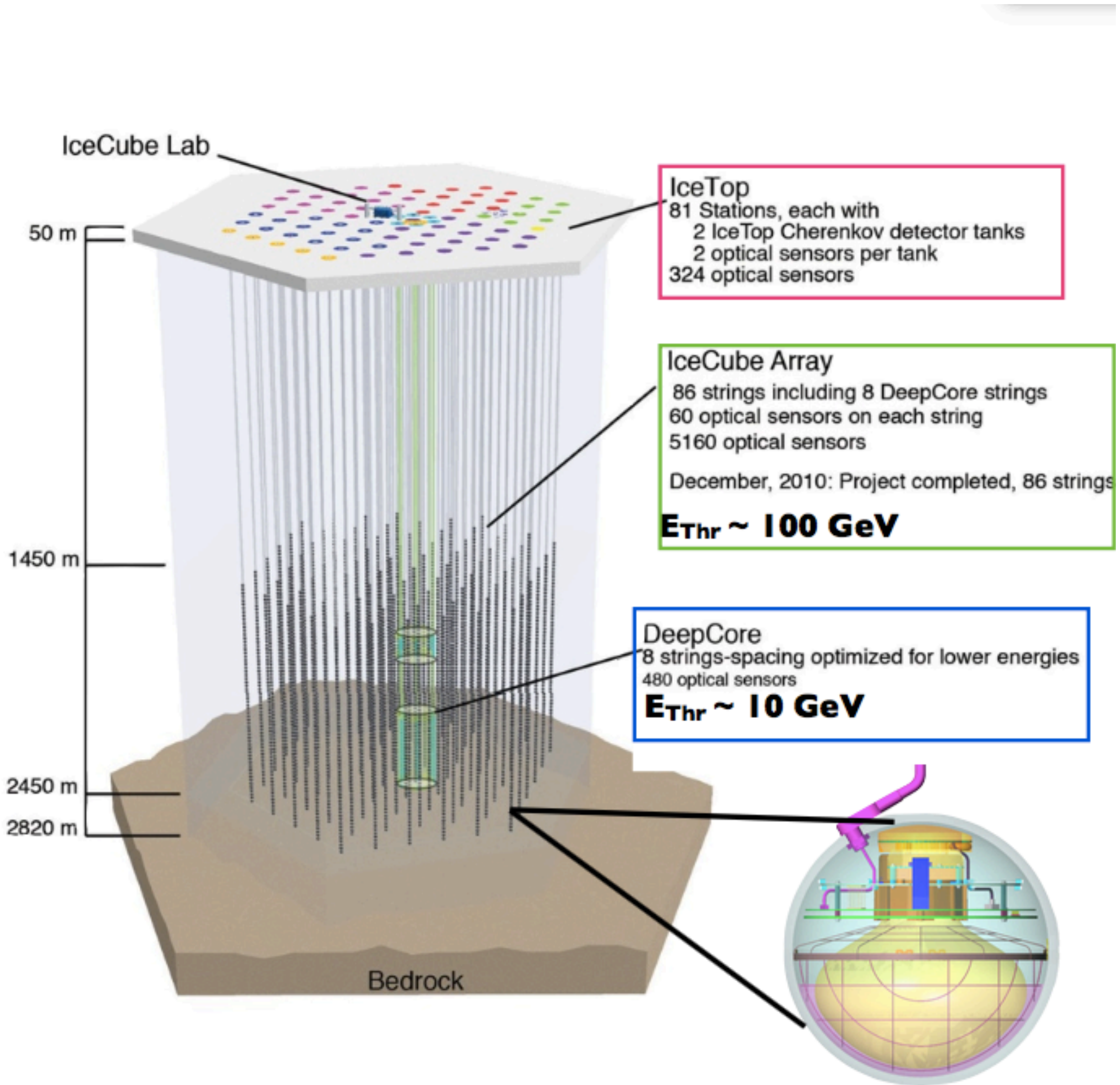
pion-muon decay

$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 2 : 0$$

Oscillations average out over cosmic baselines

$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$$

THE ICECUBE OBSERVATORY



Gigaton Detector at the South Pole

86 strings with 60 Digital (DOMs) Optical Modules each = 5160 DOMs in Ice

Began operations in full configuration (IC86) in May 2011

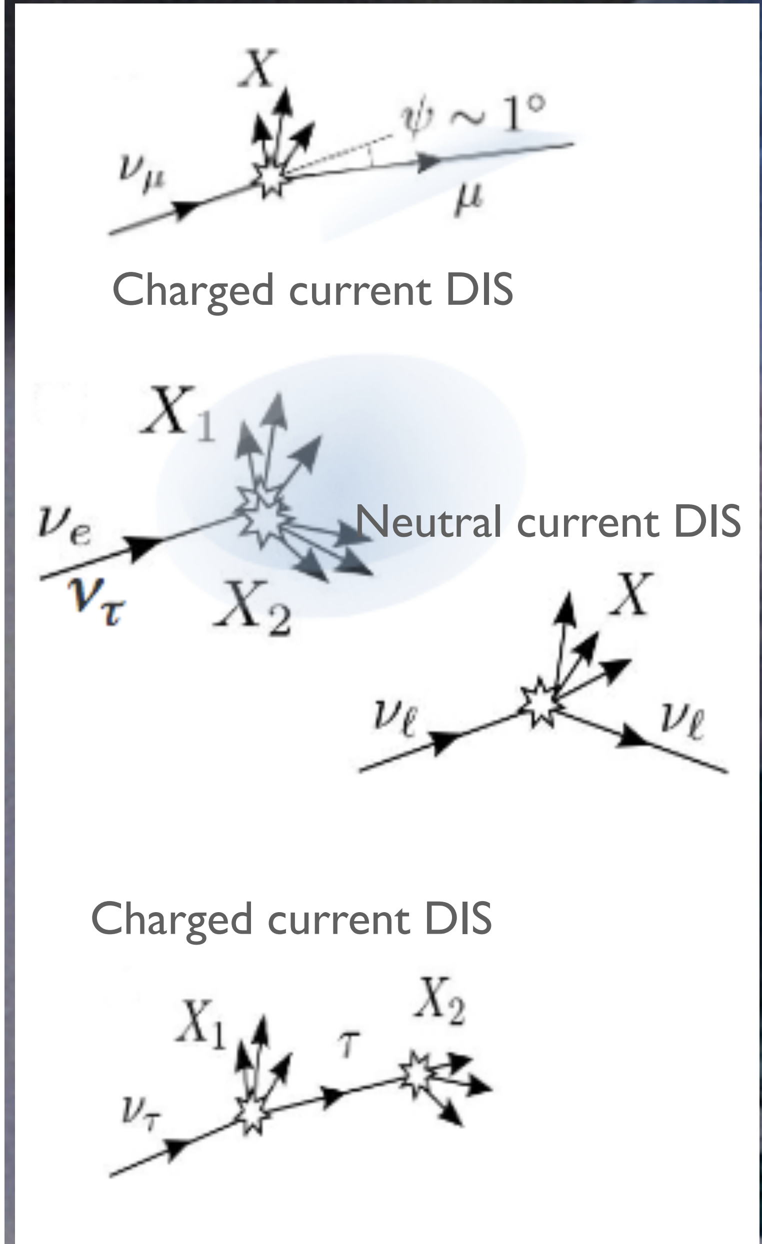
Livetime > 99% (since 2014)

97-98% of data

97-98% (analysis-ready, full-detector configuration data)

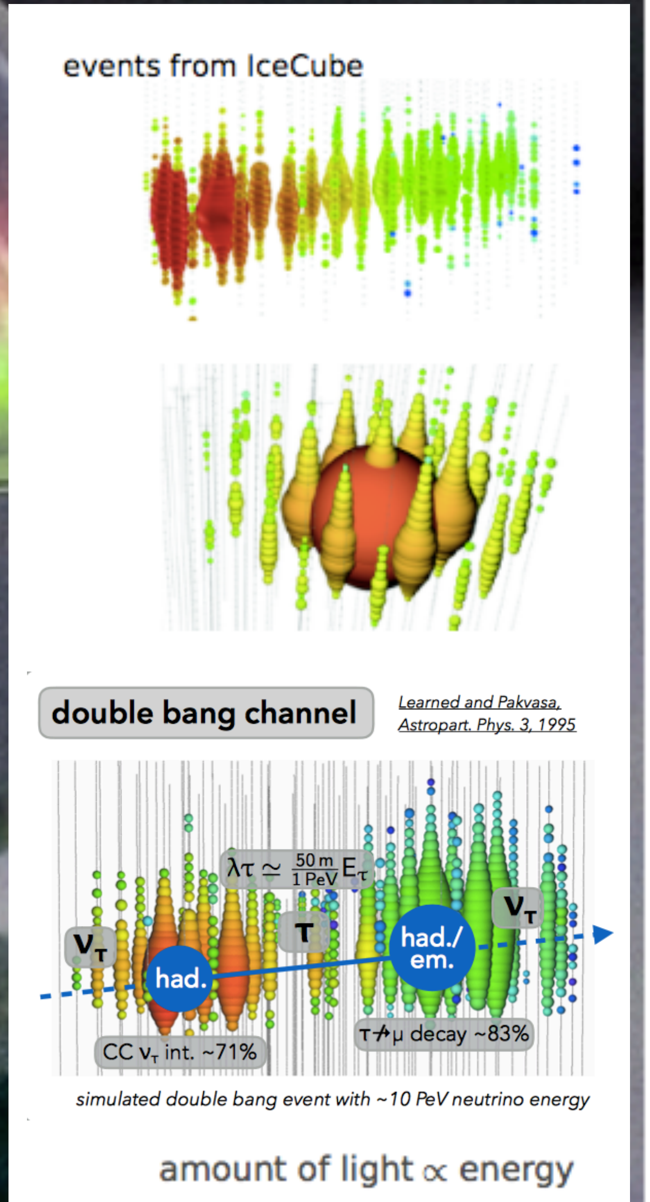
>98% sensor modules full functional

NEUTRINO EVENTS (IN ICECUBE)

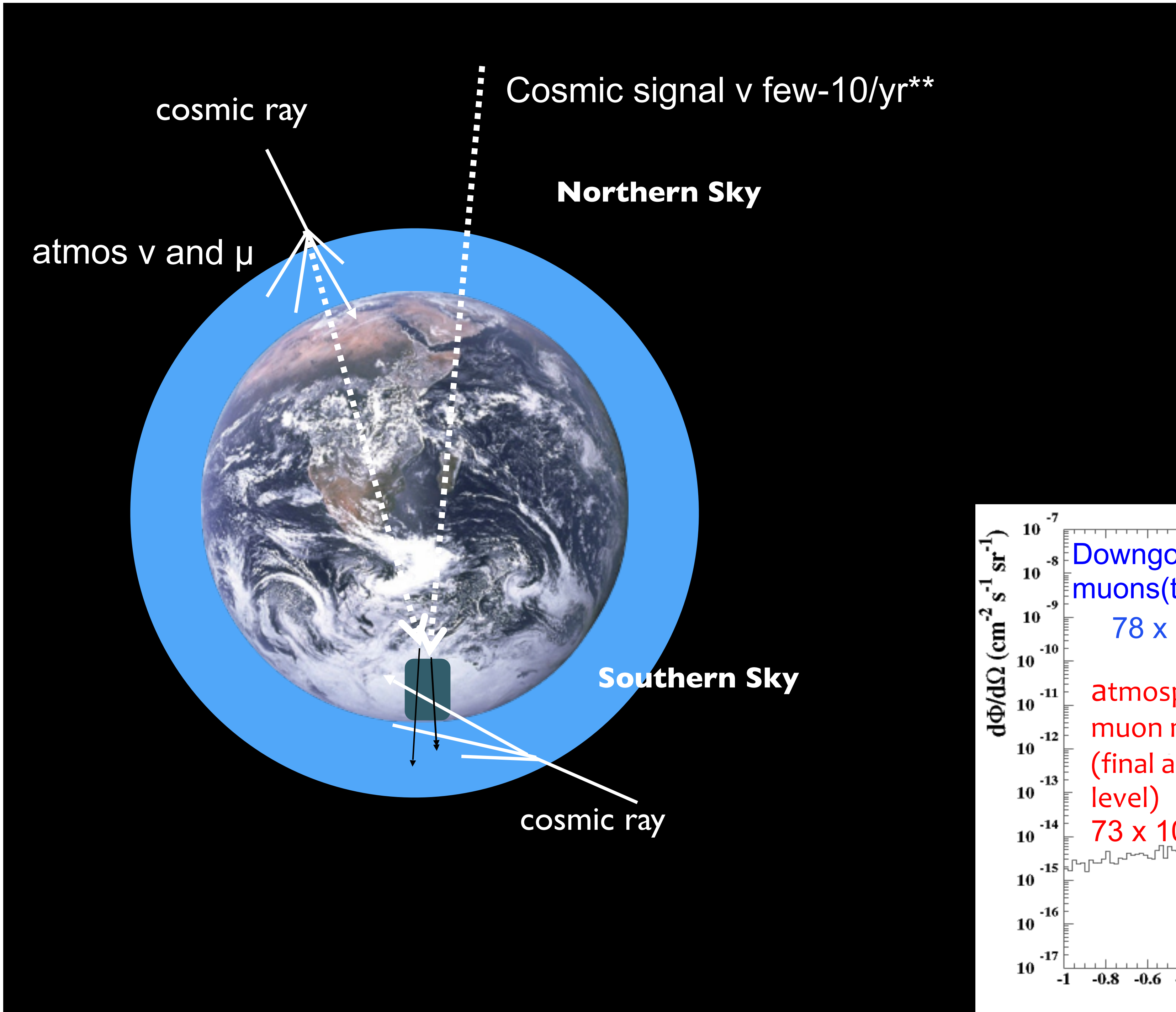


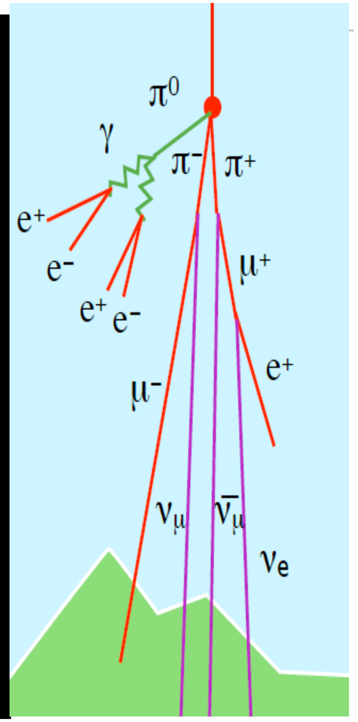
Track
Standard reconstruction;
about x2 energy resolution
Angular resolution < 1°

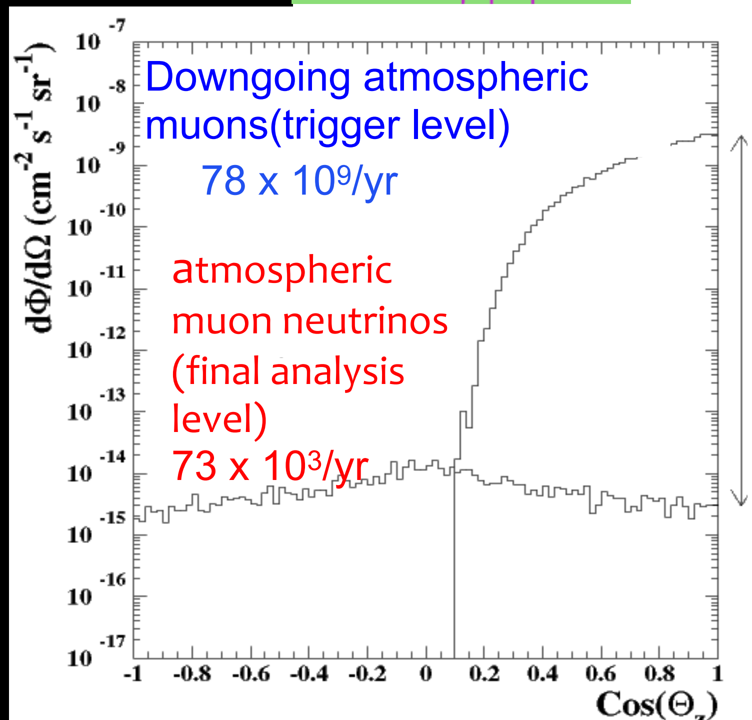
Cascade
15% energy resolution
Angular resolution O(10°)



SIGNAL AND BACKGROUND





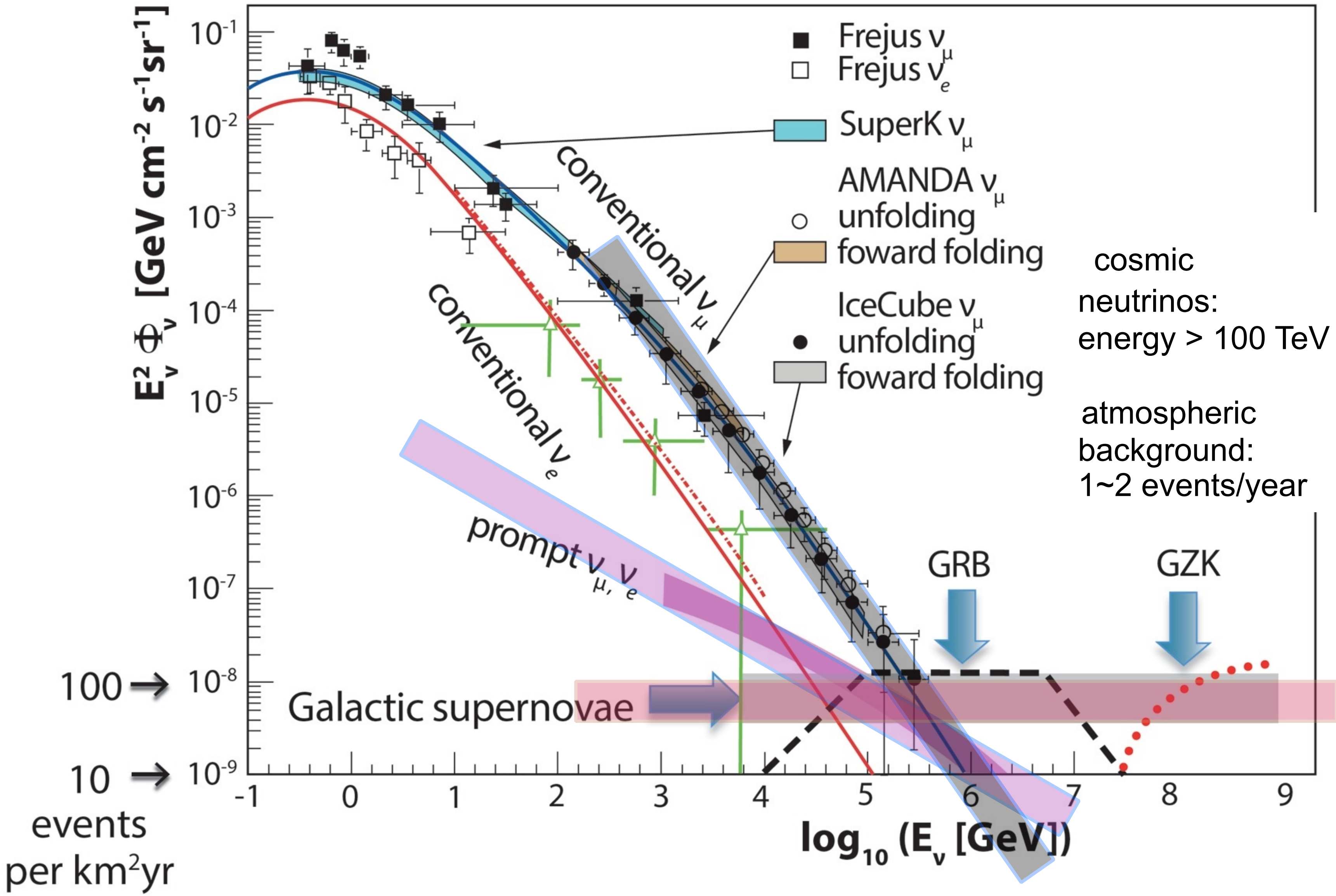


COSMIC DIFFUSE MUON NEUTRINO FLUXES

arXiv:1510.0812

Upgoing events

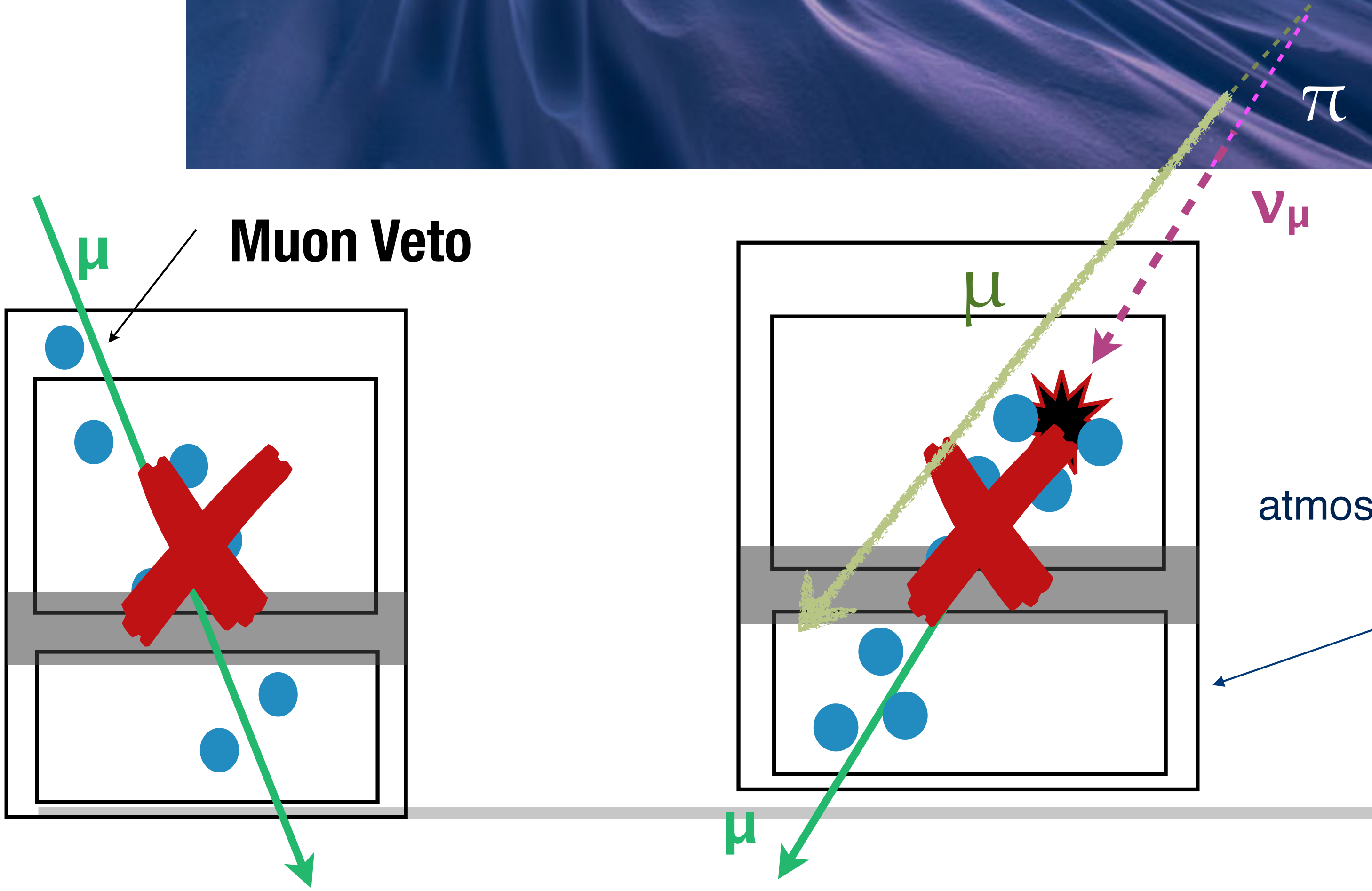
IceCube Collaboration Phys. Rev. Lett. 110 (2013) 151105 /1212.4760v2



cosmic neutrinos: energy > 100 TeV

atmospheric background: 1~2 events/year

Starting events



Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

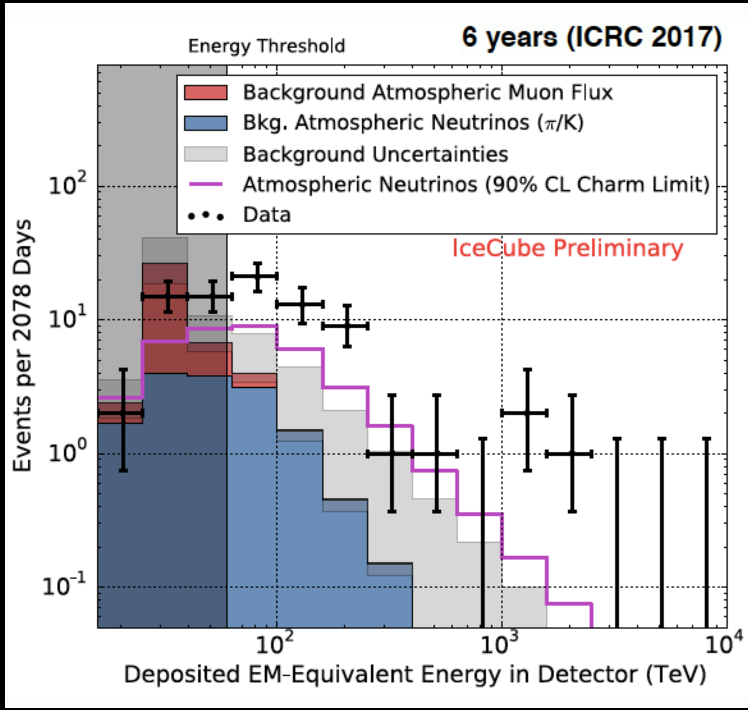
atmospheric neutrino tag

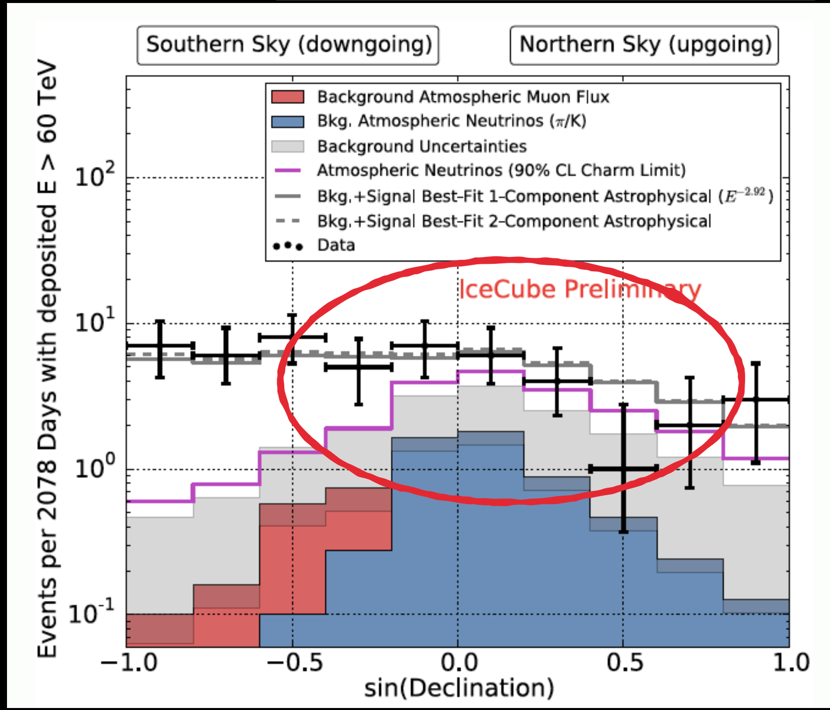
Signal from the heavens

80(+2) events/6 yrs (2010-2015)

$15.6^{+11.4}_{-3.9}$ atm. neutrinos

25.2±7.3 atm. muons



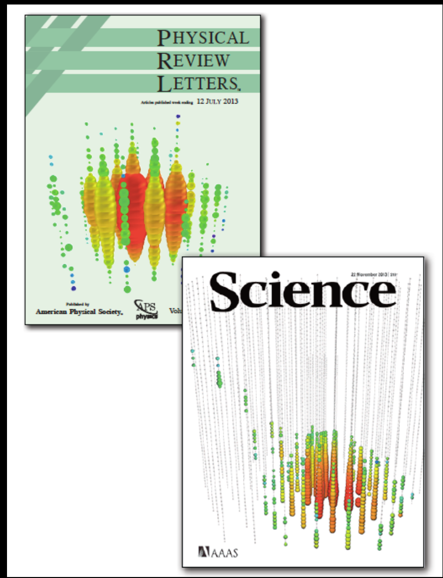


Best fit spectral index ($E^{-\gamma}$):

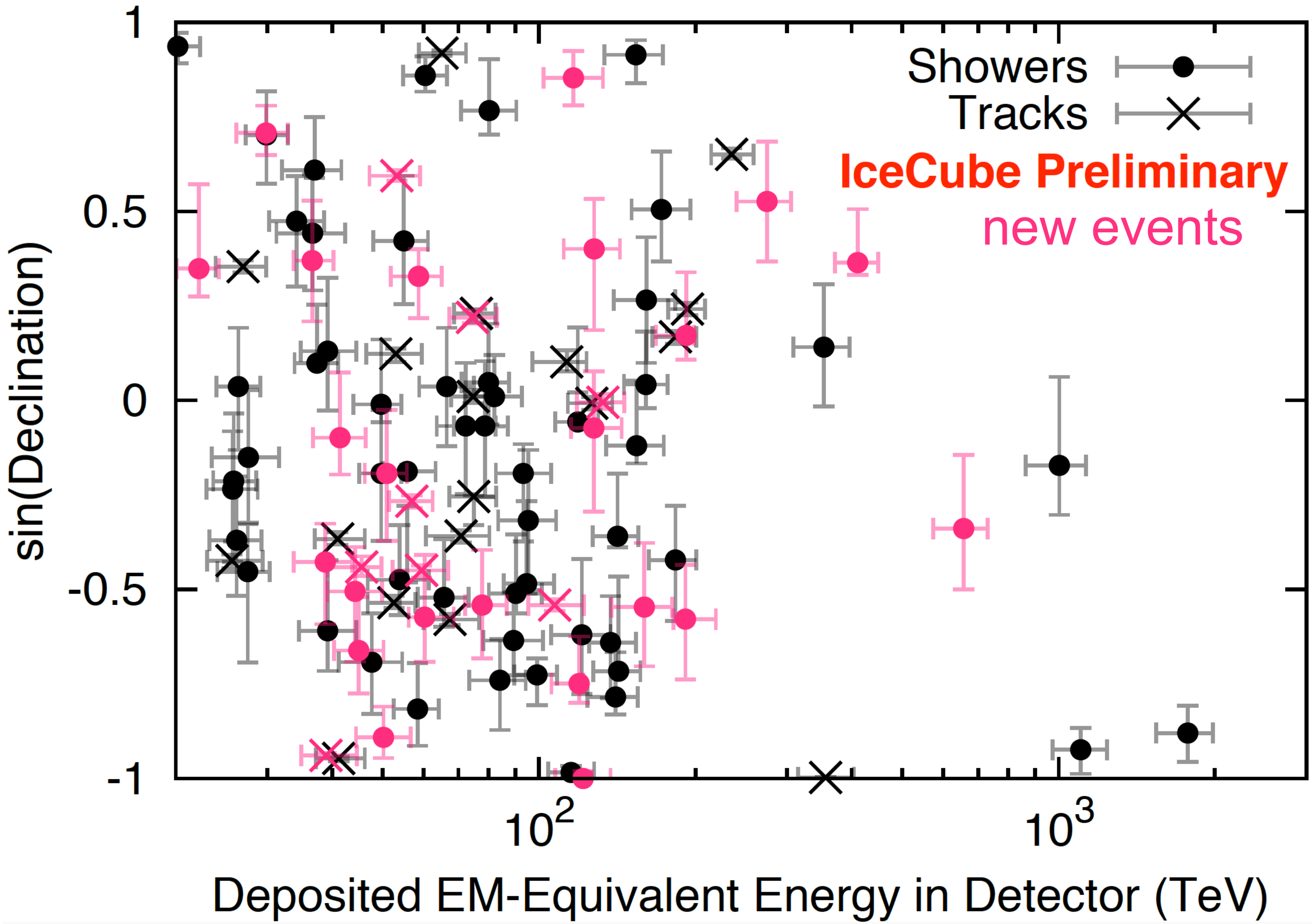
$\gamma=-2.92^{+0.33}_{-0.29}$

Background only hypothesis rejected at ~8 σ

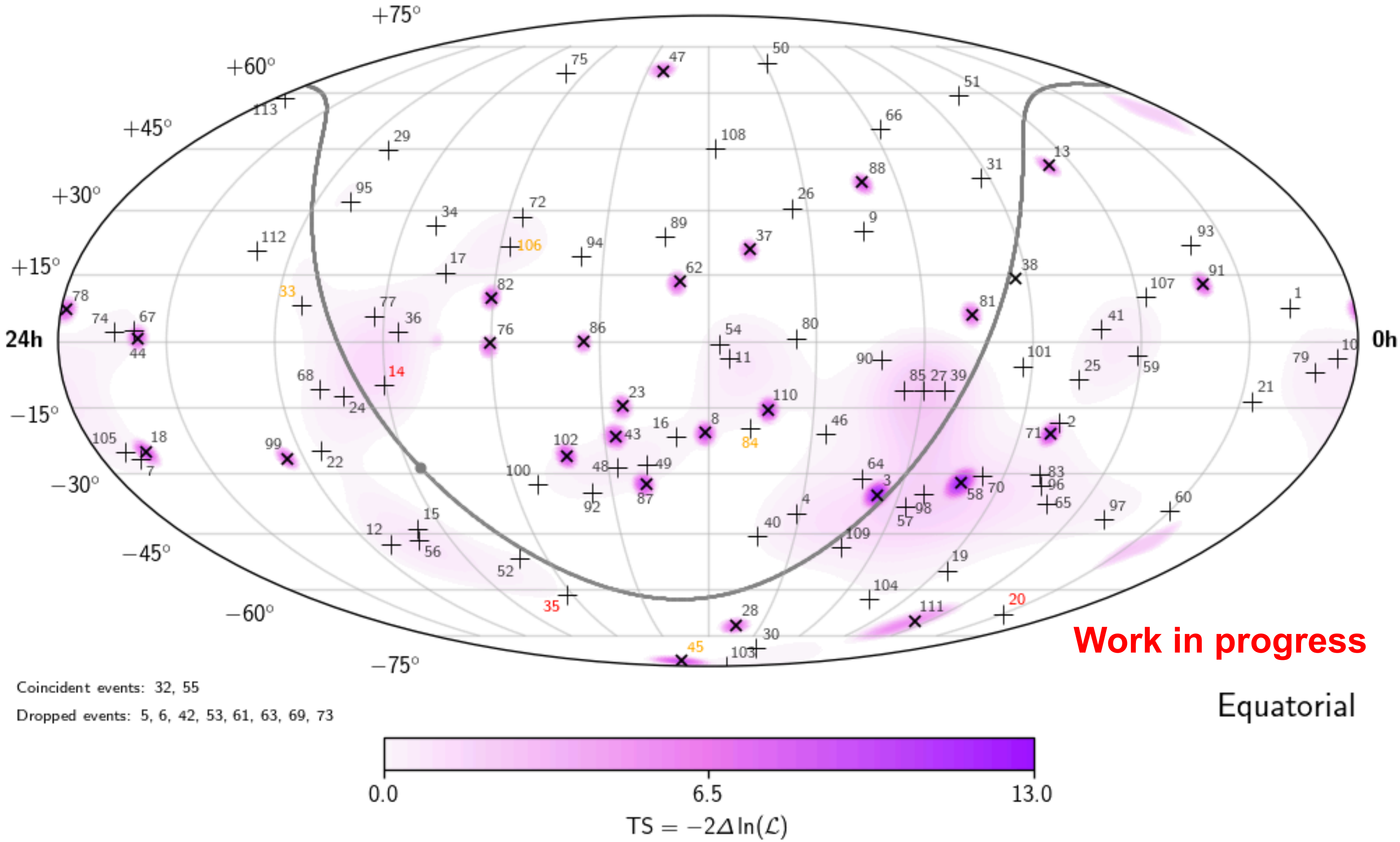
Yet it is not possible to distinguish single power law or more components



HIGH ENERGY STARTING EVENTS (HESE) 7.5 YR



High-energy starting events (HESE) 7.5 yr



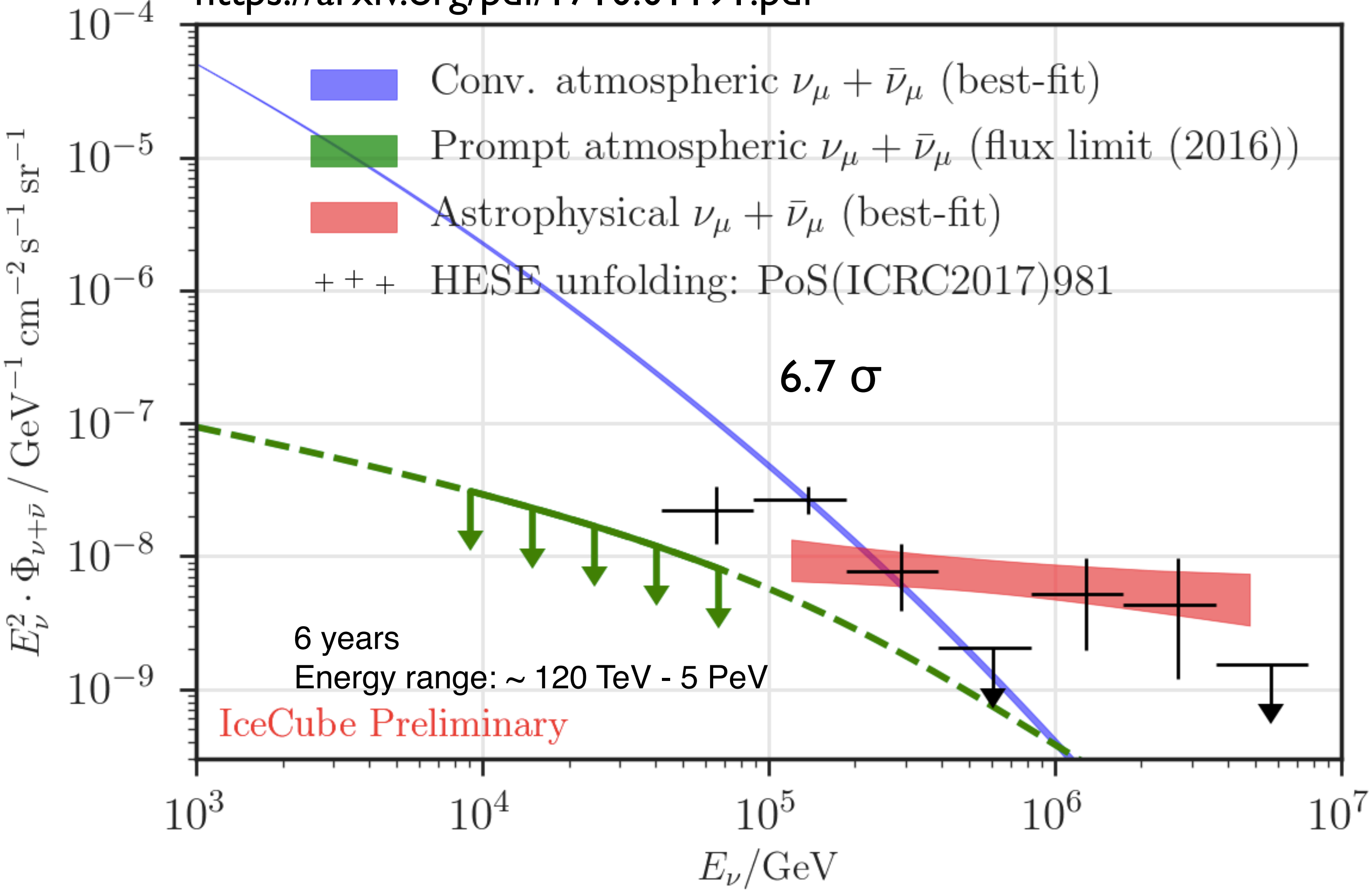
$E < 300\,\mathrm{TeV}$ $\quad 300\,\mathrm{TeV} < E < 1\,\mathrm{PeV}$ $\quad 1\,\mathrm{PeV} < E$

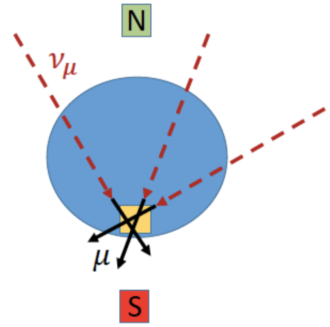
>8 sigma detection of astrophysical neutrinos

No significant clustering observed (103 events)

THE MEASURED DIFFUSE NEUTRINO FLUXES: UPGOING NEUTRINO-INDUCED MUON TRACKS

https://arxiv.org/pdf/1710.01191.pdf



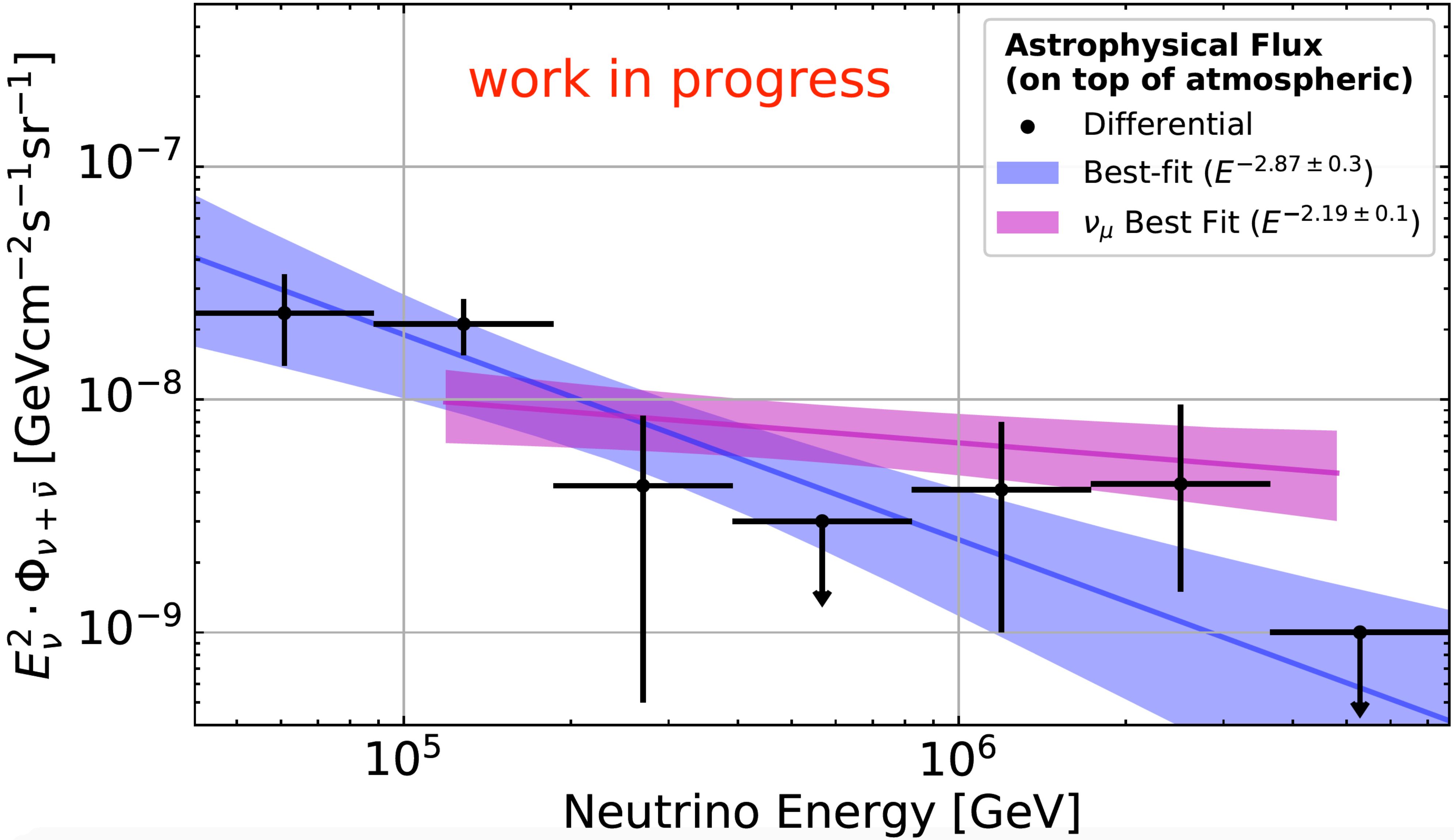


IceCube, ApJ, 2016

Best fit cosmic flux

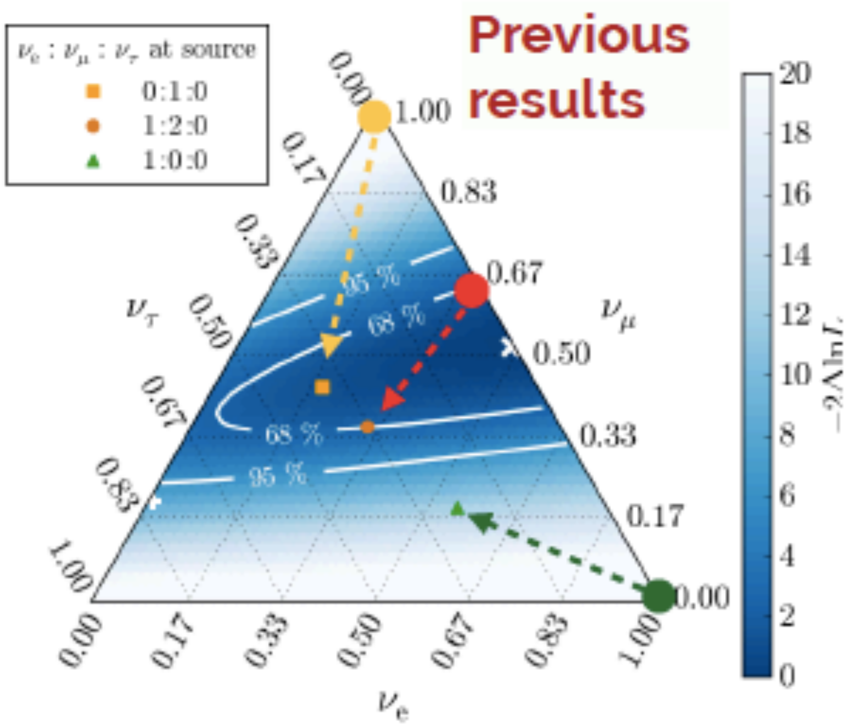
$$\frac{d\Phi_{\nu+\bar{\nu}}}{dE} = (1.01\pm^{0.26}_{0.23})\left(\frac{E}{100\,\text{TeV}}\right)^{-2.19\pm0.10} \cdot 10^{-18}\text{GeV}^{-1}cm^{-2}s^{-1}sr^{-1}$$

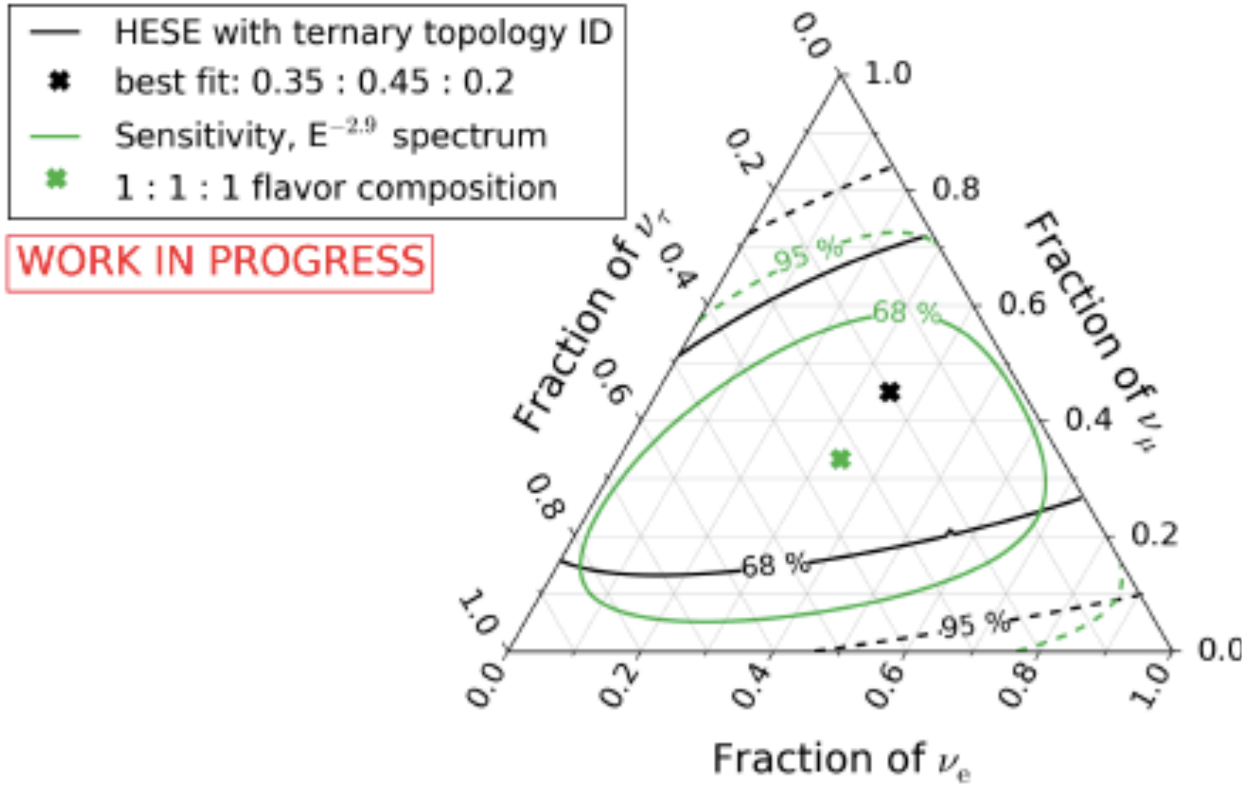
THE DIFFUSE ASTROPHYSICAL NEUTRINO SPECTRUM



$$E^2\Phi_\nu = 1.86^{+0.75}_{-0.65} \cdot 10^{-8} \cdot \left(\frac{E}{100\,\mathrm{TeV}}\right)^{-0.87^{+0.31}_{-0.22}} \mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$$

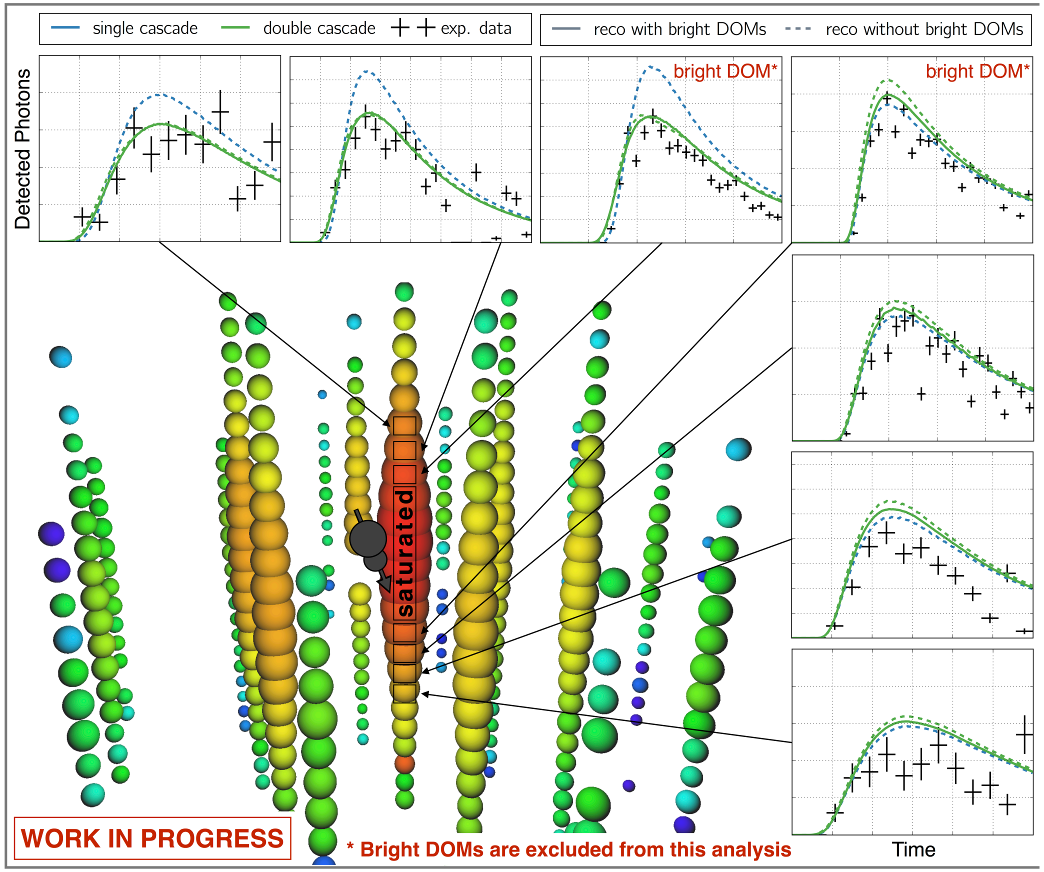
THE HIGH-ENERGY NEUTRINO



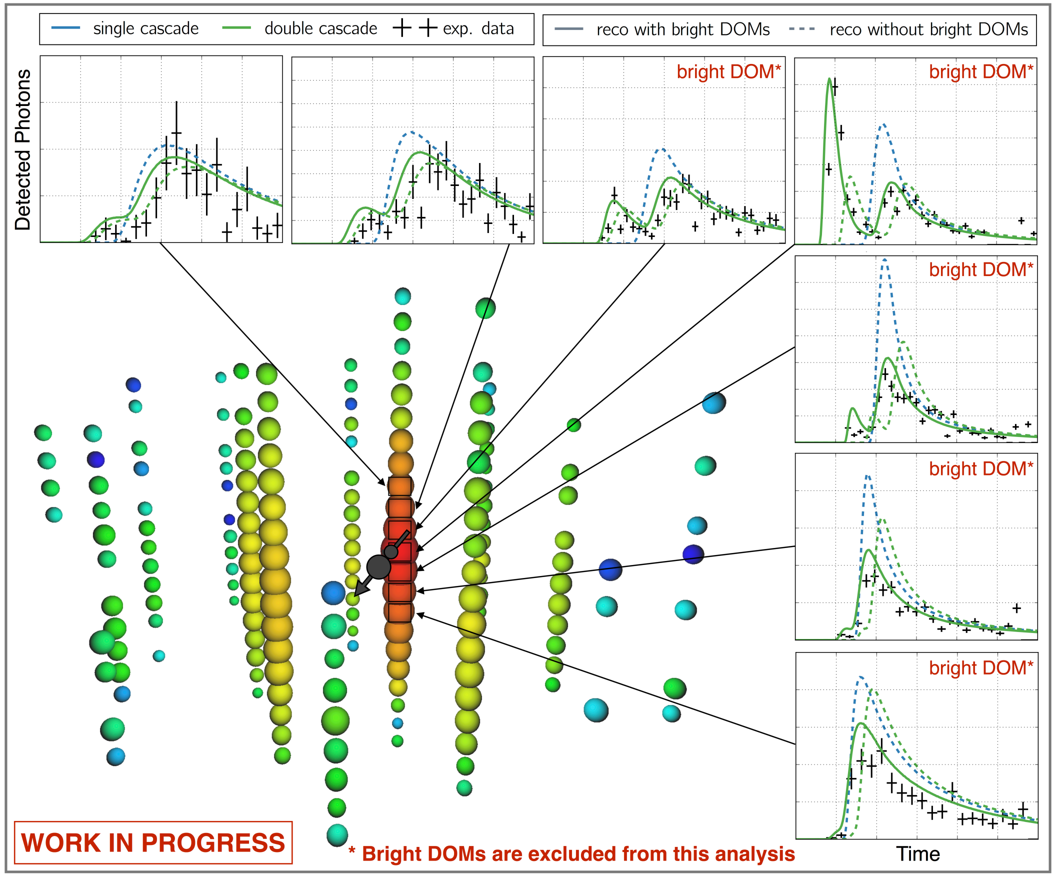


Tau neutrinos can arise from prompt neutrinos produced in the decay of heavy mesons in the atmosphere or from oscillations of cosmic neutrinos. Background expectation is ~0.7 events. Best fit flavor composition is ν_e: ν_μ:ν_τ = 0.35:0.45:0.20. No tau neutrino cannot be currently excluded.

High-energy starting events (7.5 years): Identification of two double-cascade events



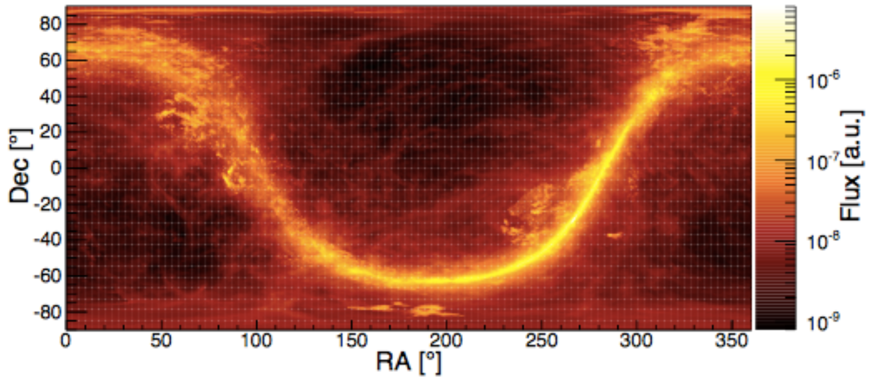
Event 1



Event 2

- Background expectation: ~0.7 events
- Detailed study of waveforms and background probability in progress

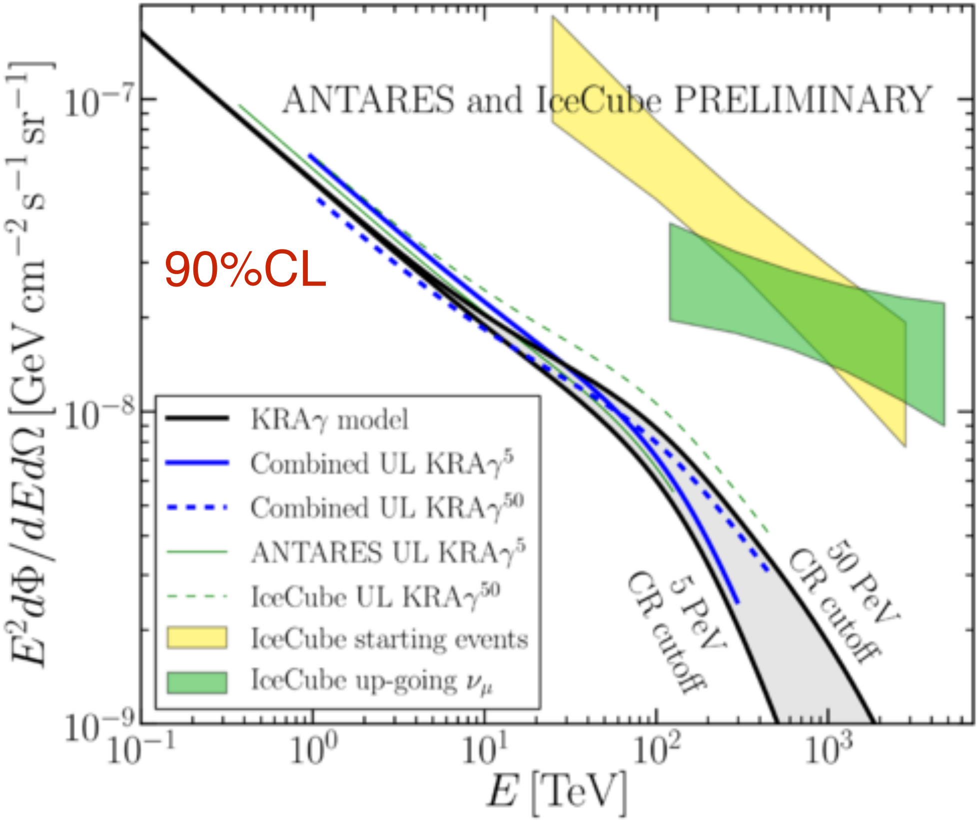
NEUTRINOS FROM THE GALACTIC PLANE ?



(a) KRA-γ (50 PeV cutoff) template

▶ Analysis of correlation with template map derived from interstellar gas distribution reproducing Fermi-LAT data
▶ Only small fraction of signal can originate from CR interactions in the Galaxy.

IceCube, ApJ 849:67 (2017): <14% of diffuse ν flux is Galactic

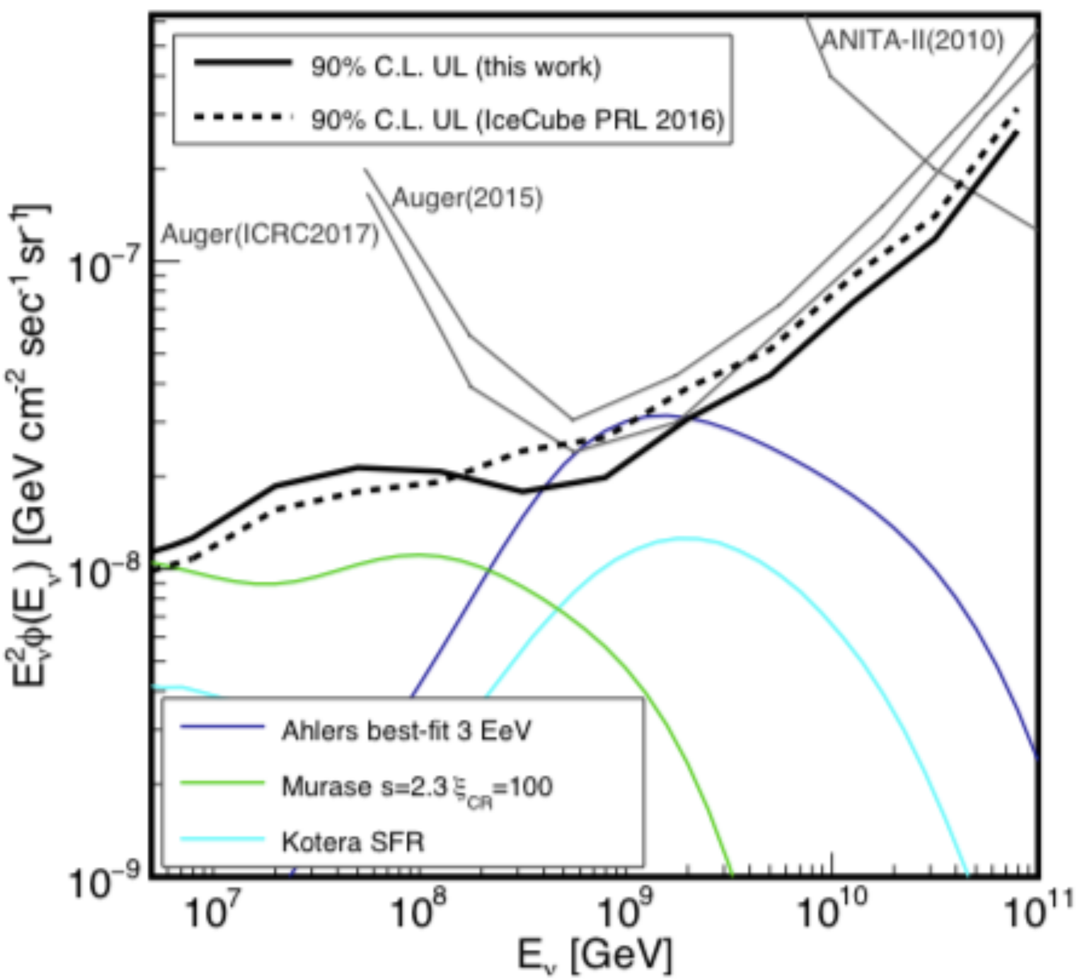


ANTARES arXiv:1602.03036

Models in Gaggero et al, arXiv:1504.00227

COSMOGENIC NEUTRINOS?

9 yr EHE analysis of 5 - 5 x 10^4 PeV - neutrinos (paper draft). 2 PeV events selected not compatible with cosmogenic nature.

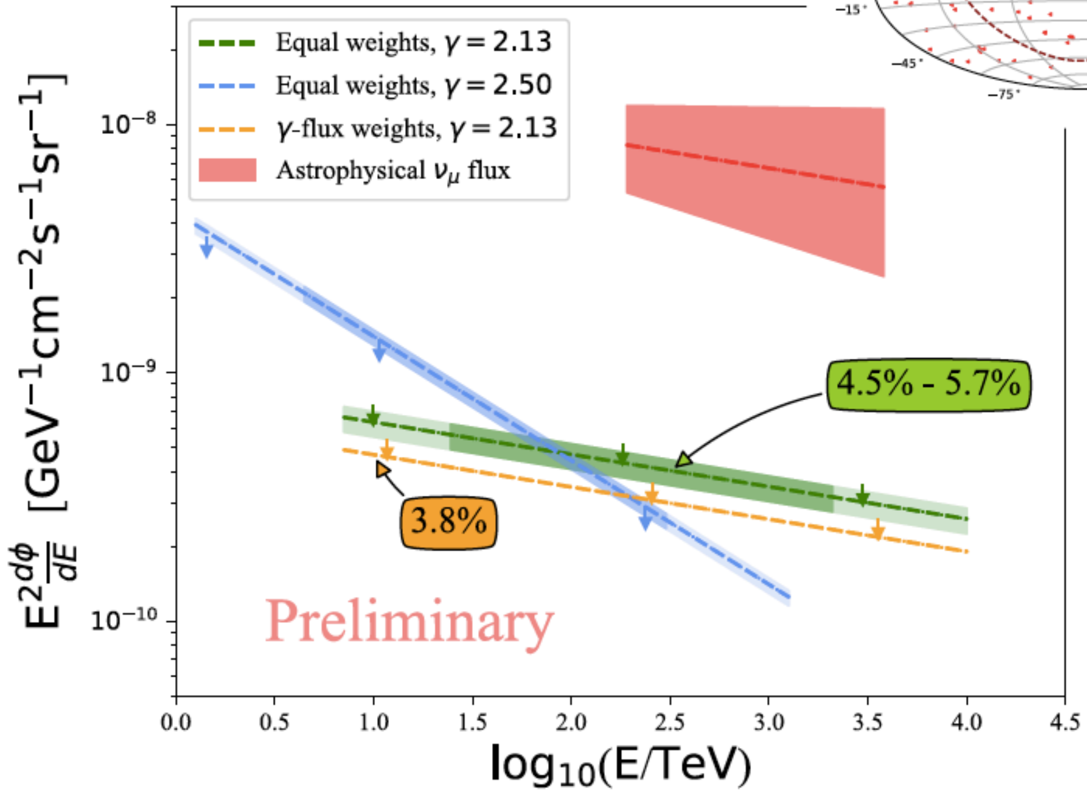


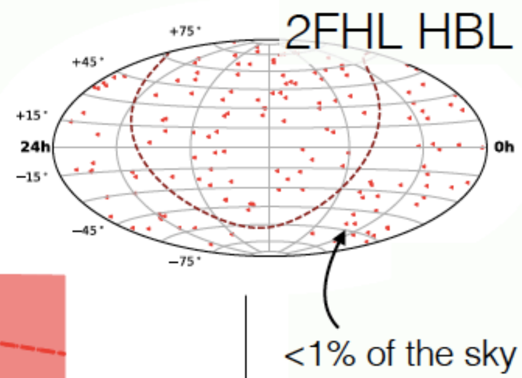
Phys. Rev. Lett. 117 (2016)

DISTRIBUTION OF HIGH ENERGY NEUTRINOS

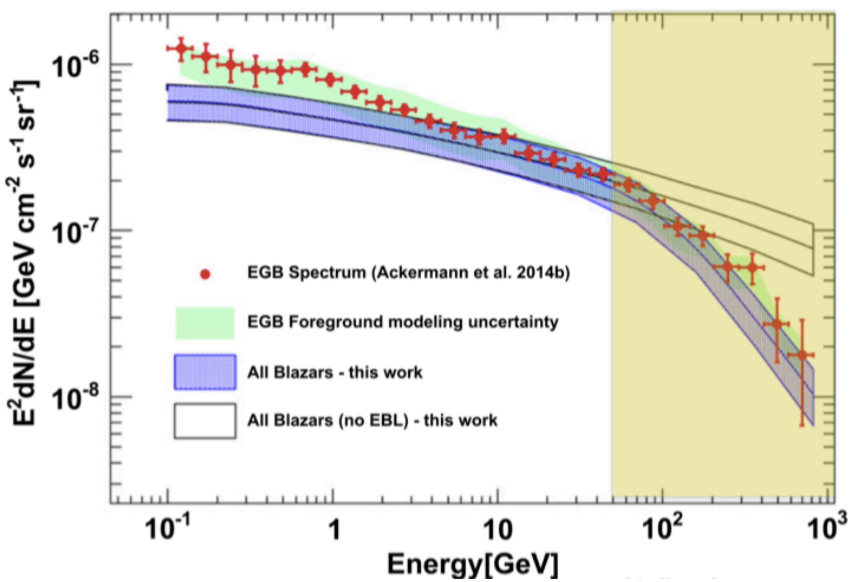
Neutrinos from Fermi 2LAC 862 blazar directions

Blazars account for:
85% of extragalactic γ background
< 6% of the IceCube neutrino flux





EGB: Ackermann et al. 2015, Models: Ajello+2015, Di Mauro+2015



IceCube-170922A - Fermi-AGILE-GBM - MAGIC

Date: 22 Sept 2017

RA: 77.43° (-0.80°/+1.30° 90% CL)
Dec: 5.72° (-0.40°/+0.70° 90% CL)

Energy (prelim. reported est.): > 120 TeV

```
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
operating state. EHE events typically have a neutrino
interaction vertex that is outside the detector, produce a muon
```

Date: 28 Sept 2017

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

Date: 4 Oct 2017

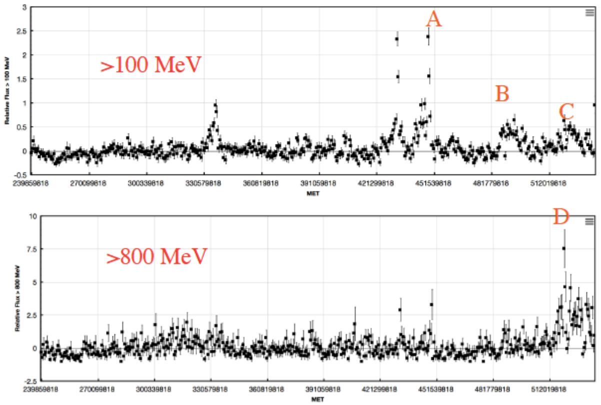
First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

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

FAVA TXS 0506+056

`Fermi All-sky Variability Analysis' (Abdollahi+17)



Related

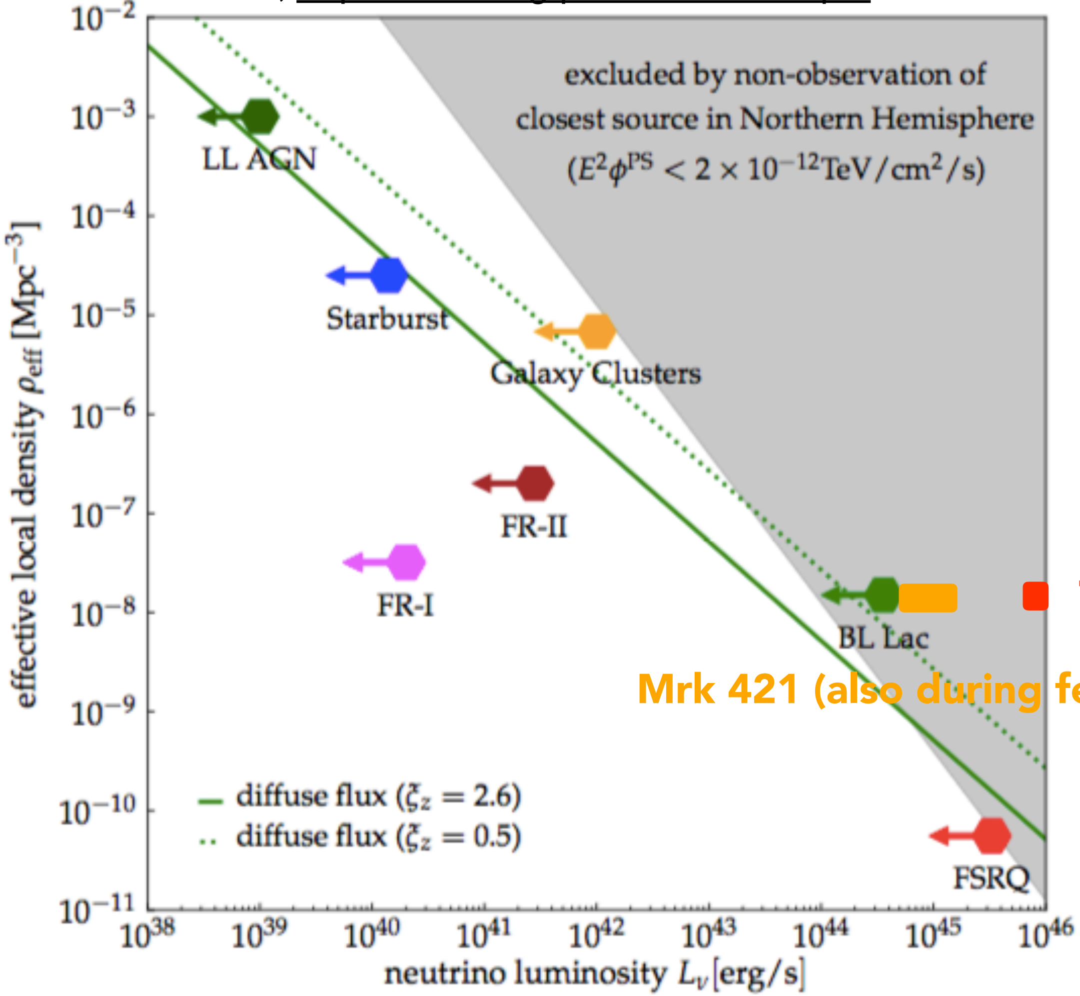
10845	Joint Swift XRT and NuSTAR Observations of TXS 0506+056
10844	Kanata optical imaging and polarimetric follow-ups for possible IceCube counterpart TXS 0506+056
10840	VLT/X-Shooter spectrum of the blazar TXS 0506+056 (located inside the IceCube-170922A error box)
10838	MAXI/GSC observations of IceCube-170922A and TXS 0506+056
10833	VERITAS follow-up observations of IceCube neutrino event 170922A
10831	Optical photometry of TX0506+056
10830	SALT-HRS observation of the blazar TXS 0506+056 associated with IceCube-170922A
10817	First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A
10802	HAWC gamma ray data prior to IceCube-170922A
10801	AGILE confirmation of gamma-ray activity from the IceCube-170922A error region
10799	Optical Spectrum of TXS 0506+056 (possible counterpart to IceCube-170922A)
10794	ASAS-SN optical light-curve of blazar TXS 0506+056, located inside the IceCube-170922A error region, shows increased optical activity
10792	Further Swift-XRT observations of IceCube 170922A
10791	Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.
10787	H.E.S.S. follow-up of IceCube-170922A
10773	Search for counterpart to IceCube-170922A with ANTARES

Z = 0.3365 ±0.0010
(Paiano+ 2018 ApJ, 854)

https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon

The updated Kowalski's (after Hillas') plot

Ahlers & Halzen, https://arxiv.org/pdf/1805.11112.pdf & 2014



Is there a special class of bright BL Lac (baryon loading changing with time?flares?) given that constraints from?Caveat: the observed flux spectral index is still uncertain

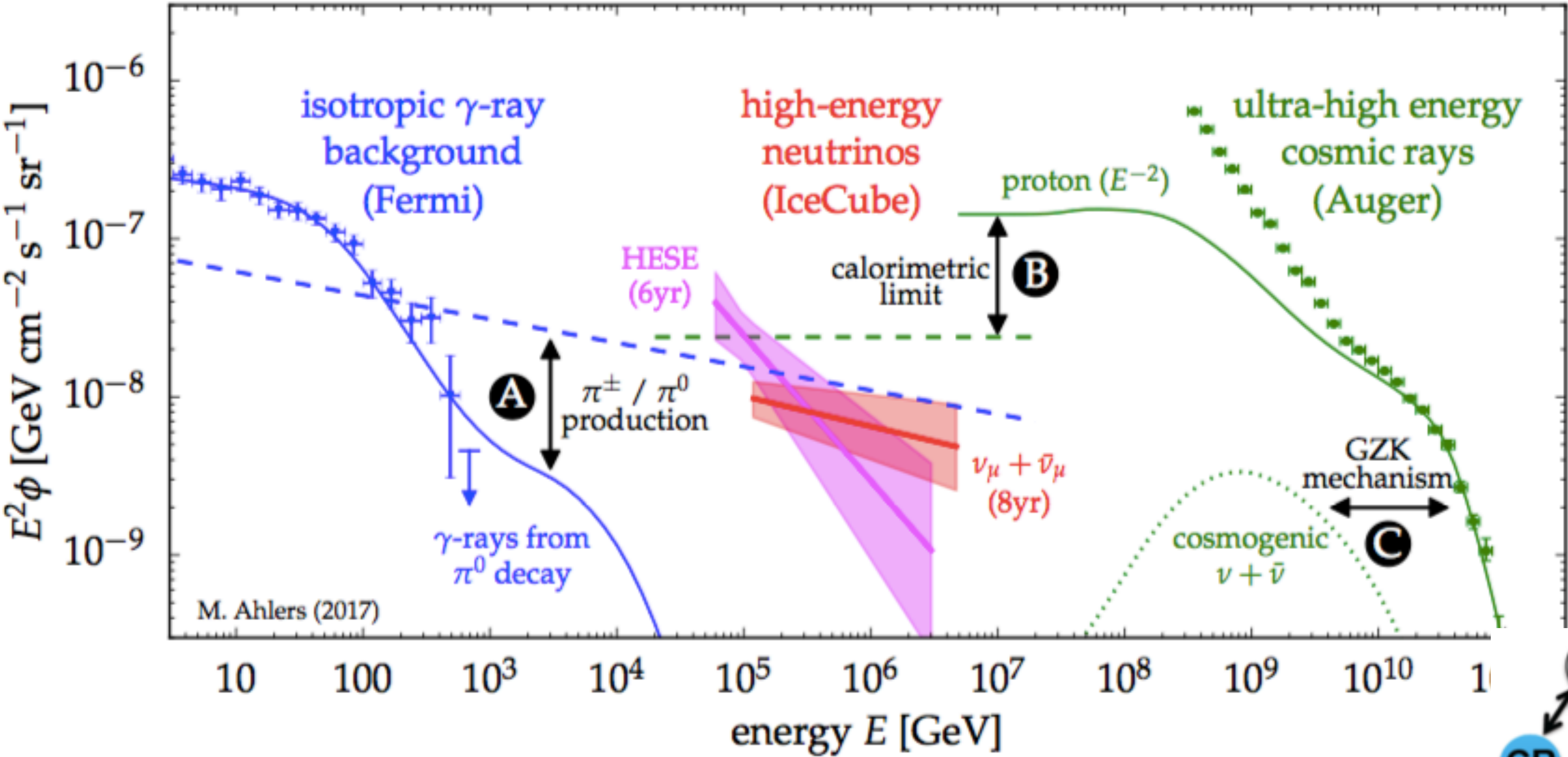
https://arxiv.org/pdf/1806.04769.pdf

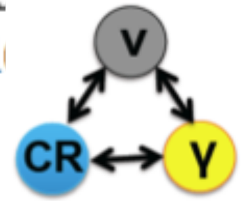
Kowalski, 2014; Murase, Waxman, 2016

Green line: the neutrino emissivity for the sources producing the IceCube neutrino flux (muon up-going tracks) with E^{-2} power law, normalisation ~ 10^{-8} GeV cm^{-2} s^{-1} sr^{-1}, and for no evolution in the local universe (z<2) (dotted green line) and for star formation rate (SFR) ns∝ $(1 + z)^3$ fr z < 1.5 (solid green line). They gray region indicates the region at the level of the discovery potential of IceCube in point source searches with 2032 d (Reimann et al, ICRC 2017).

Energy balance in diffuse fluxes

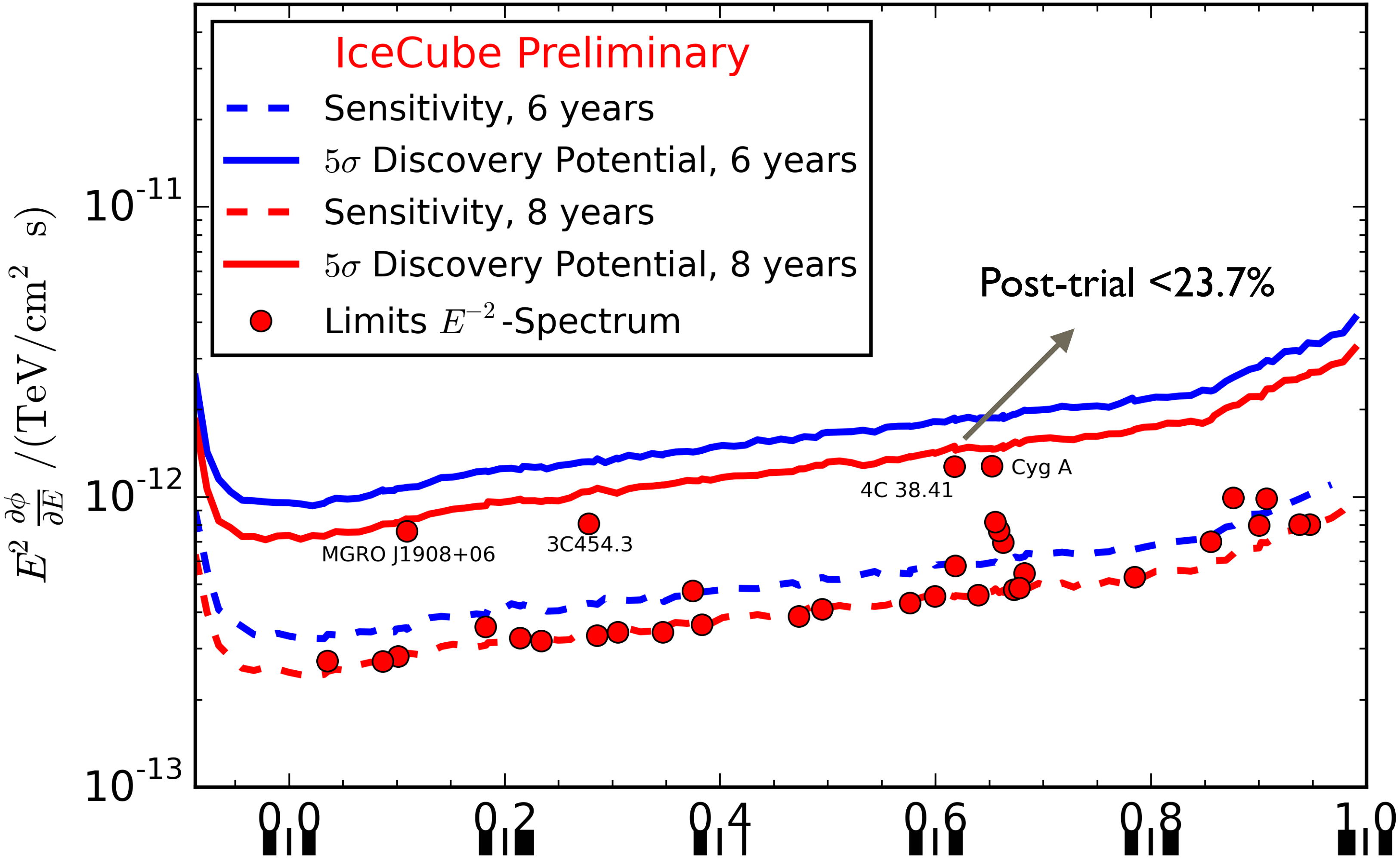
A: The production of π± and neutral pions π0 in cosmic-ray interactions (pp)leads to the emission of neutrinos (dashed blue) and γ-rays (solid blue).
B: Cosmic ray emission models (solid green) of the most energetic cosmic rays imply a maximal flux (calorimetric limit) of neutrinos from the same sources (green dashed).
C: The same cosmic ray model predicts the emission of cosmogenic neutrinos from the collision with cosmic background photons (GZK mechanism)



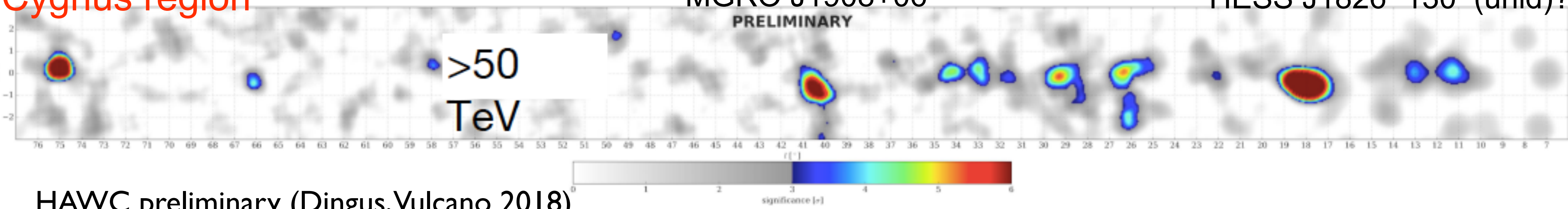


https://arxiv.org/pdf/1805.11112.pdf

POINT SOURCE SEARCHES 8 YR



Cygnus region MGRO J1908+06 HESS J1826−130 (unid)?

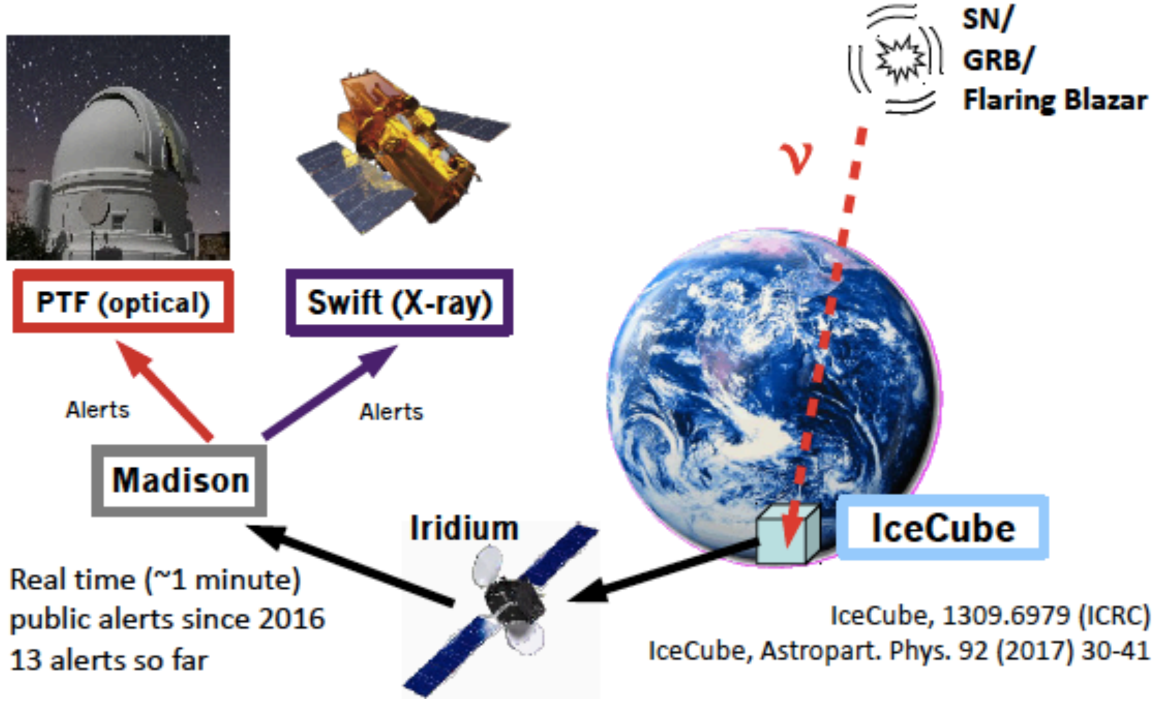


HAWC preliminary (Dingus, Vulcano 2018)

First map with E>50 TeV! Looking for the PeVatrons producing the galactic CR knee

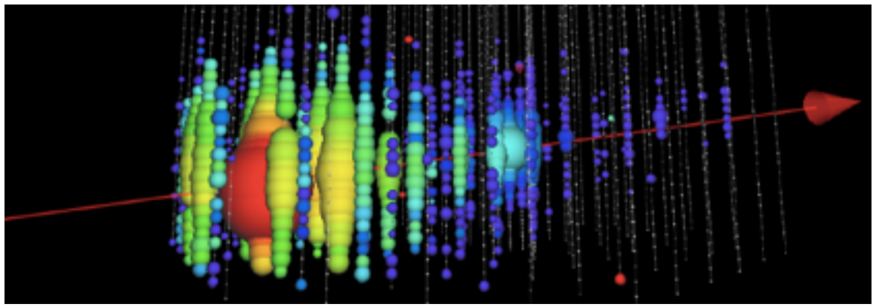
AMON
Astrophysical Multimessenger Observatory Network

IceCube alerts



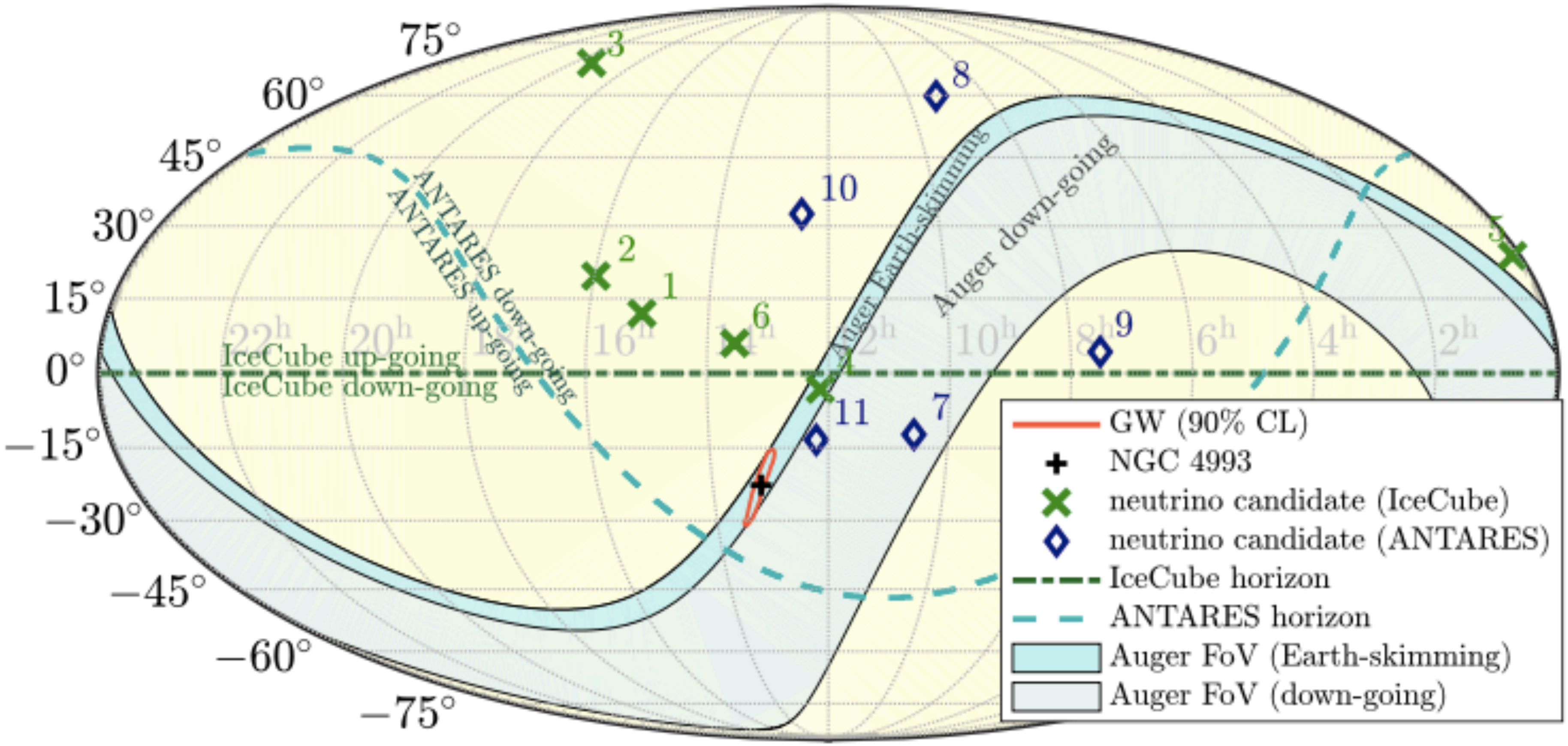
Prompt emission from GRBs can produce < 1% of observed neutrino flux

arXiv:1702.06868



Neutrinos from GW170817? coalescence of binary n-star

ANTARES/IceCube/LigoSC/Virgo. Phys.Rev. D93 (2016), 122010, Phys.Rev. D96 (2017), 022005, arXiv:1710.05839

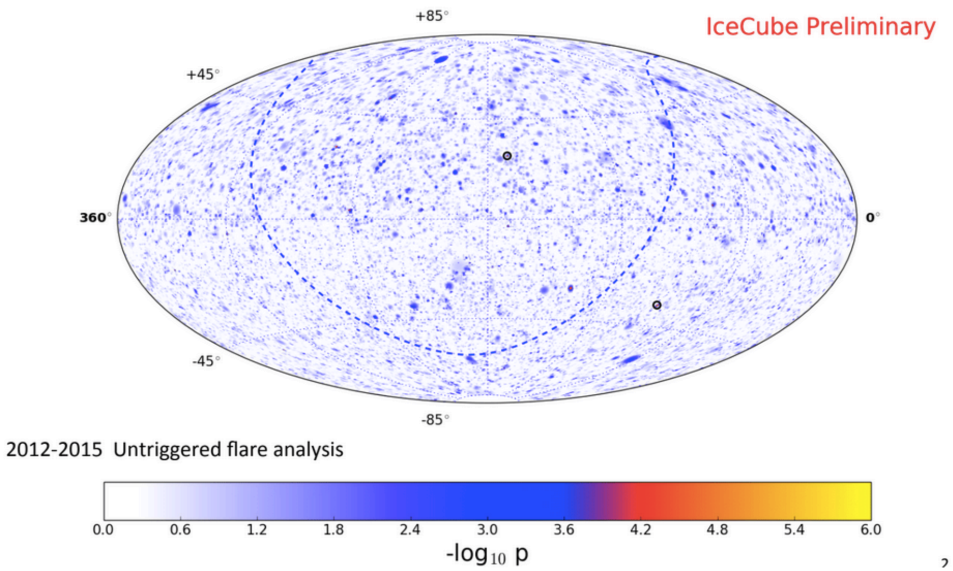


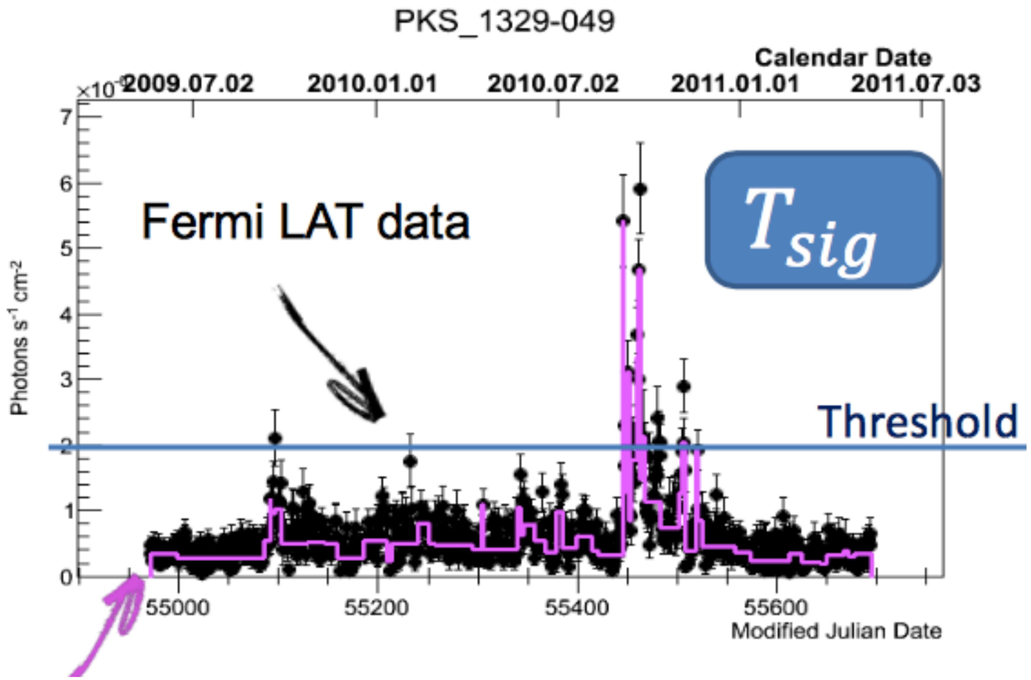
This non-detection is consistent with our expectations from a typical GRB observed off-axis, or with a low-luminosity GRB.

SEARCHES IN THE TIME DOMAIN

Untriggered searches within IceCube

Triggered searches by multi-messenger partners and by IceCube to them online and offline, target of opportunity with MM partners





A. Christov, TeVPA2017

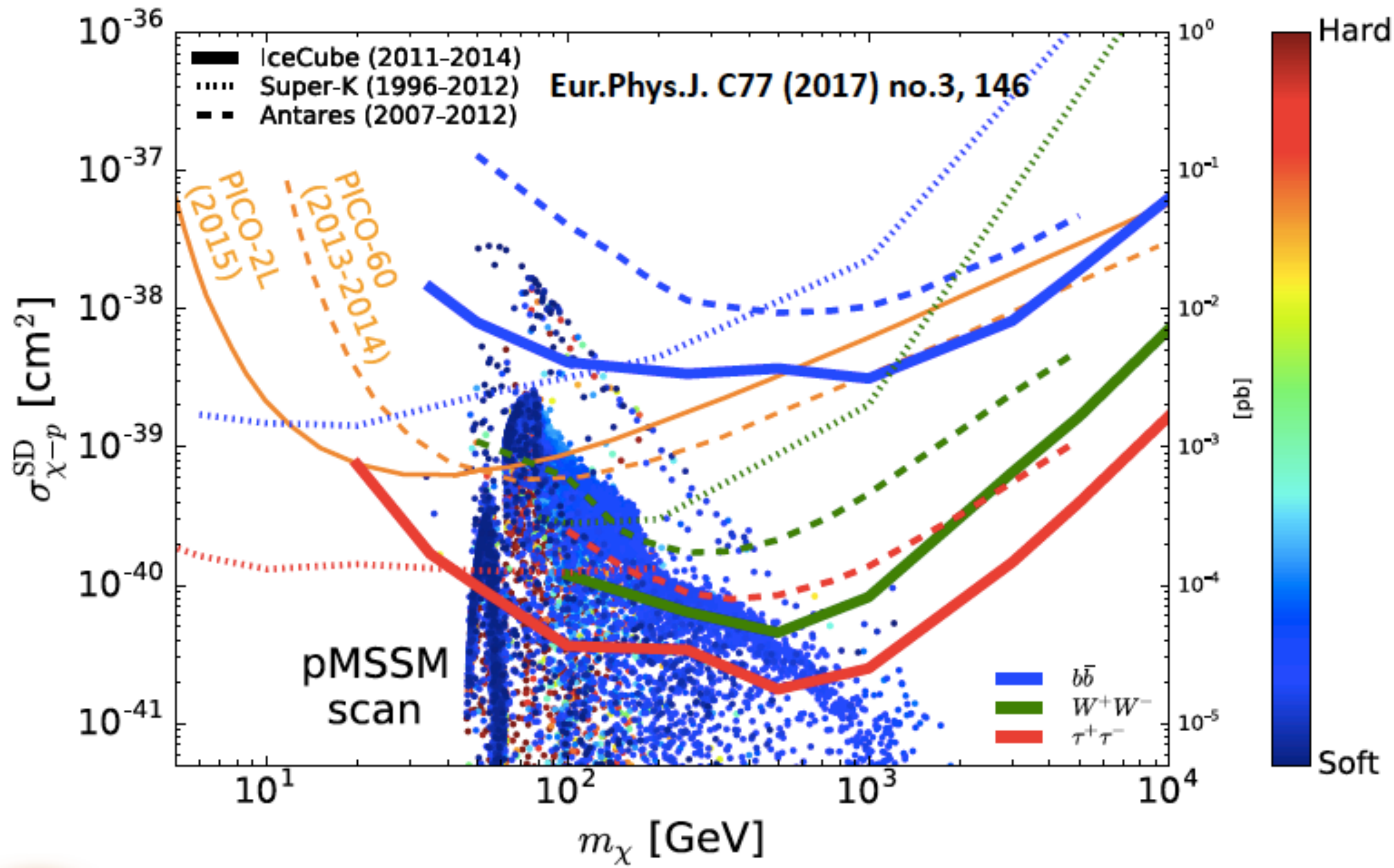
NOT ONLY ASTROPHYSICS…

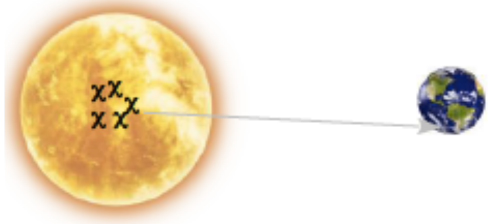
Dark Matter

Fundamental properties of neutrinos:

- Neutrino cross section (Nature, Nov. 22, 2017, 10.1038/nature24459)
- Neutrino mass
- Neutrino Hierarchy
-

DARK MATTER IN THE SUN (532 DAYS)

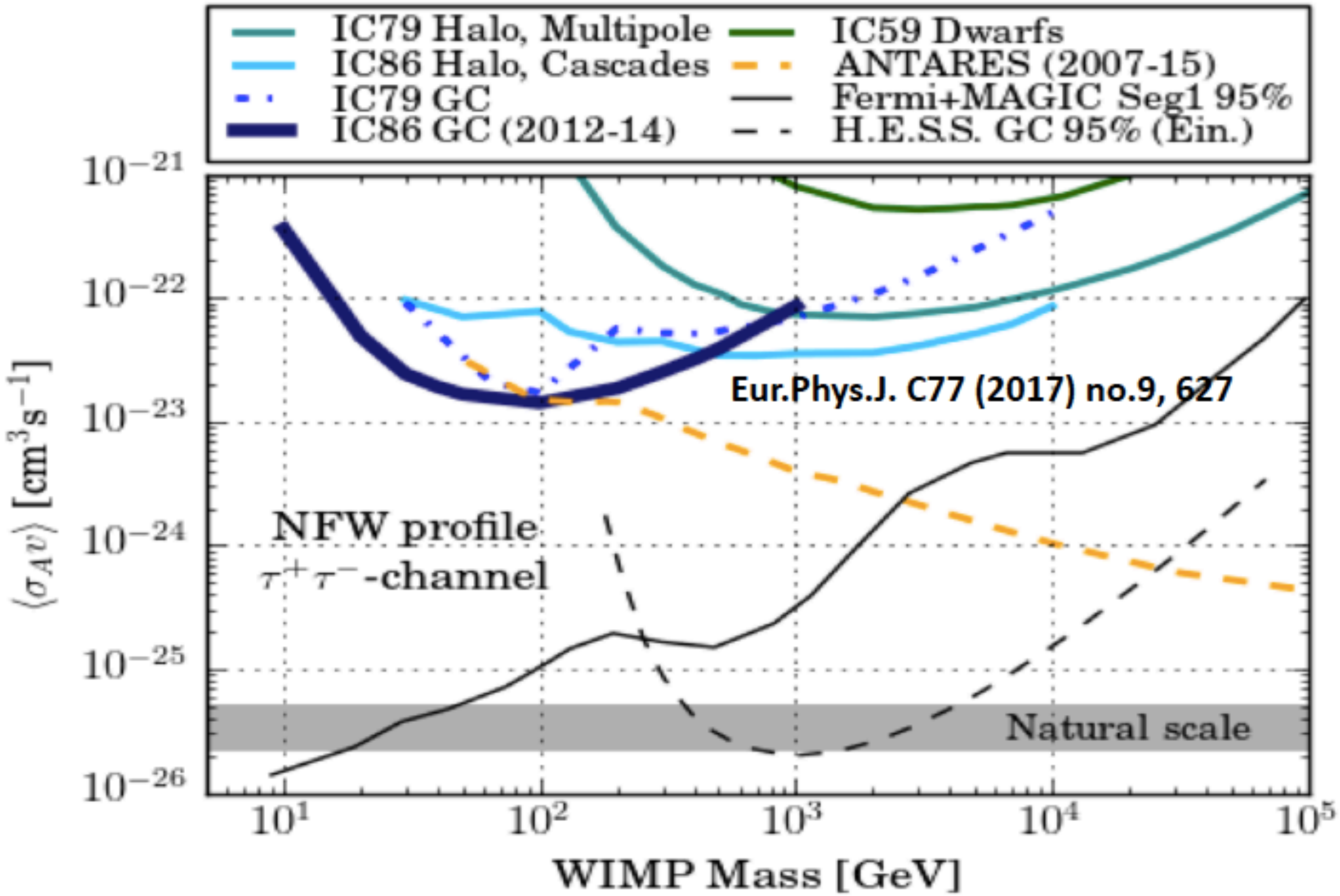




equilibrium!

$$\Phi_\nu \rightarrow \Gamma_A \rightarrow C_c \rightarrow \sigma_{\chi N}$$

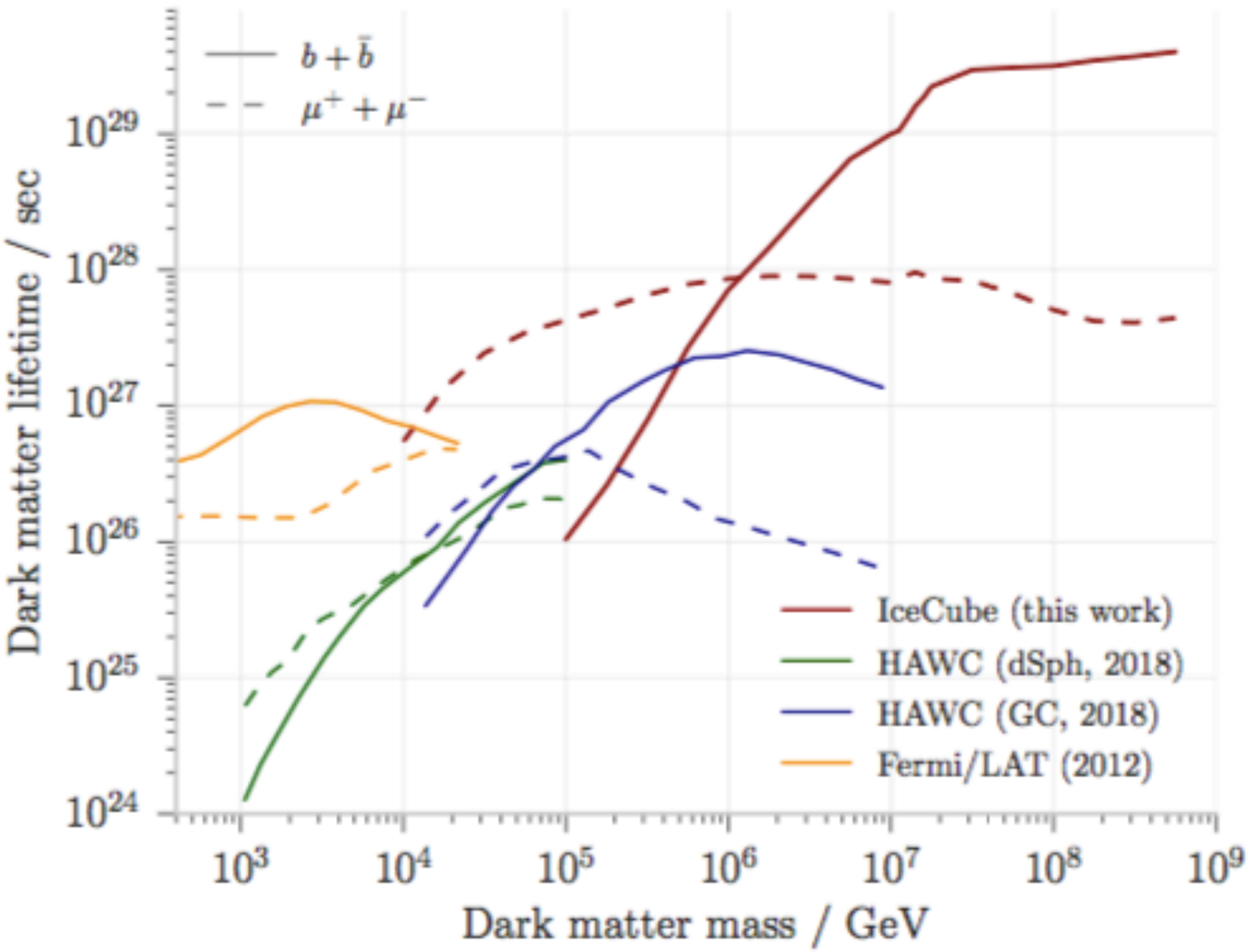
DM IN THE GALAXY

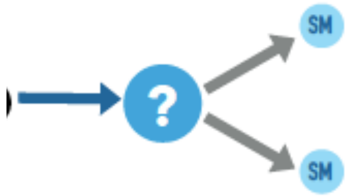


$$\frac{d\Phi_\nu}{dE_\nu} = \frac{1}{4\pi}\frac{\langle\sigma_A v\rangle}{2m_\chi^2}\frac{dN_\nu}{dE_\nu}\int_0^{\Delta\Omega} d\Omega \int_{l.o.s} \rho_\chi^2(r(s,\Psi,\theta))ds$$

DECAYING DM (6 YR)

airXiv:1804.03848

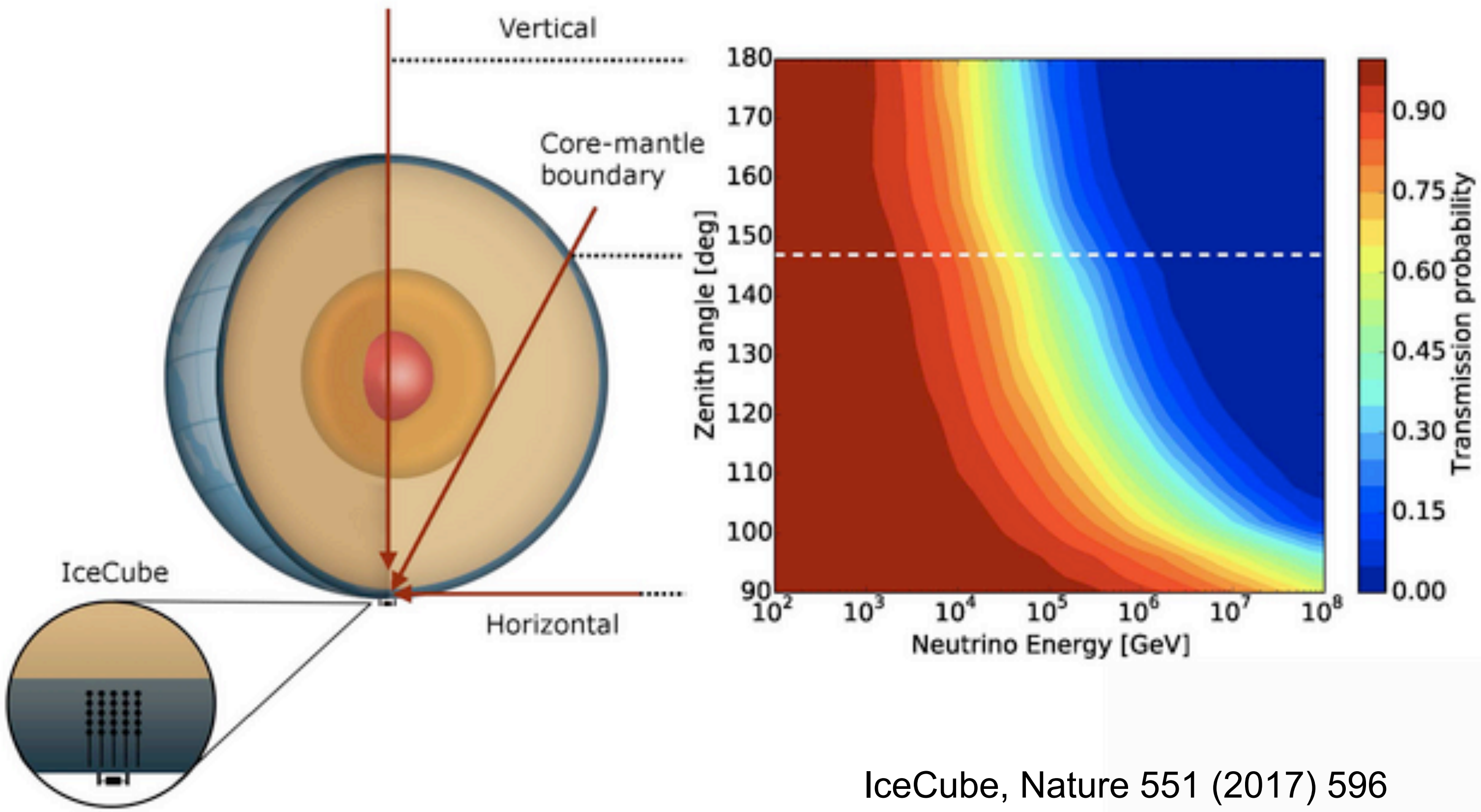




τ_χ > age of universe

NEUTRINO INTERACTION IN THE EARTH

- Neutrino beam crosses 20-12700 km in the Earth where it interacts
- Absorption is measured from neutrino spectral changes with zenith



IceCube, Nature 551 (2017) 596

https://www.youtube.com/watch?v=OdWZA5UxmOk&feature=youtu.be

NEUTRINO CROSS SECTION

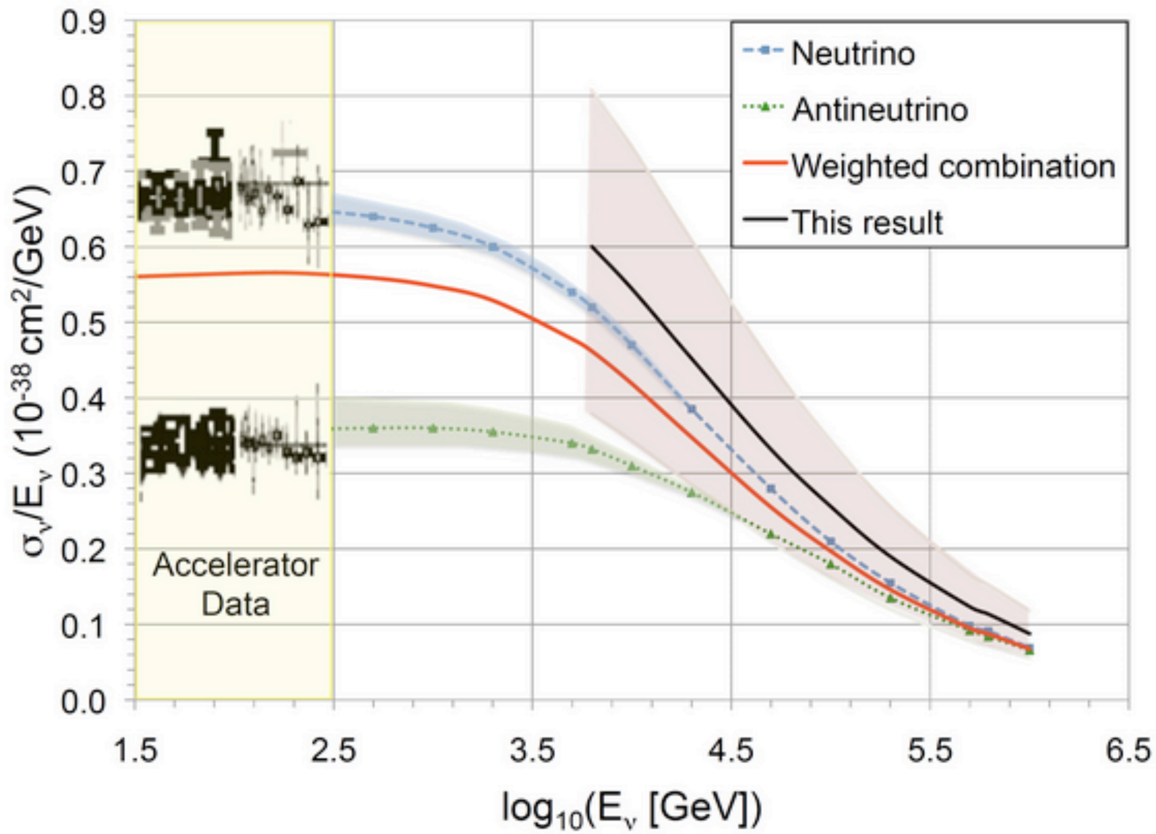
- First cross-section measurement for a neutrino energy range 10^3 higher than particle accelerators where DIS cross section is no longer linear
- Measurement reflects a flux-weighted sum of ν_μ and anti-ν_μ

Blue and green lines : SM DIS cross sections for ν_μ and anti-ν_μ with uncertainties.

Red line : mixture of ν_μ and anti-ν_μ as in IceCube sample.

Black line: result (assuming CC/NC cross section as in data). Pink band : 1σ (stat+sys) uncertainty.

Systematic uncertainties:
- density distribution of the Earth (1-2%),
- atmospheric pressure variations (4%),
- angular acceptance of DOMs (4%),
- atmospheric neutrino spectral slope (10%).

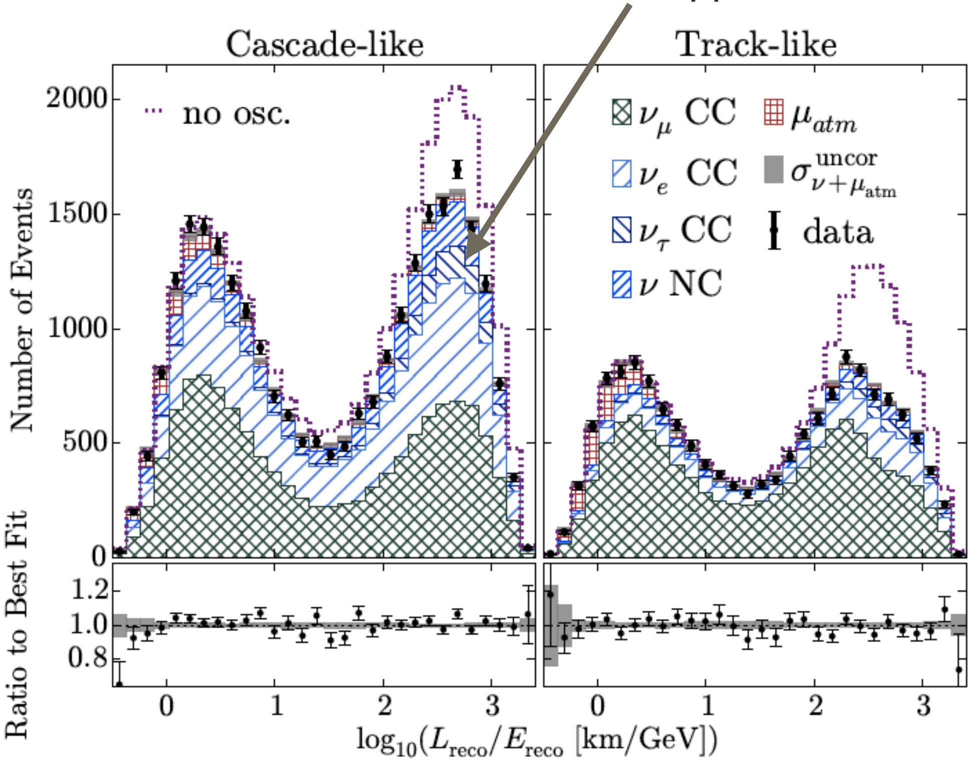


https://www.nature.com/articles/nature24459
and http://arxiv.org/abs/1711.08119

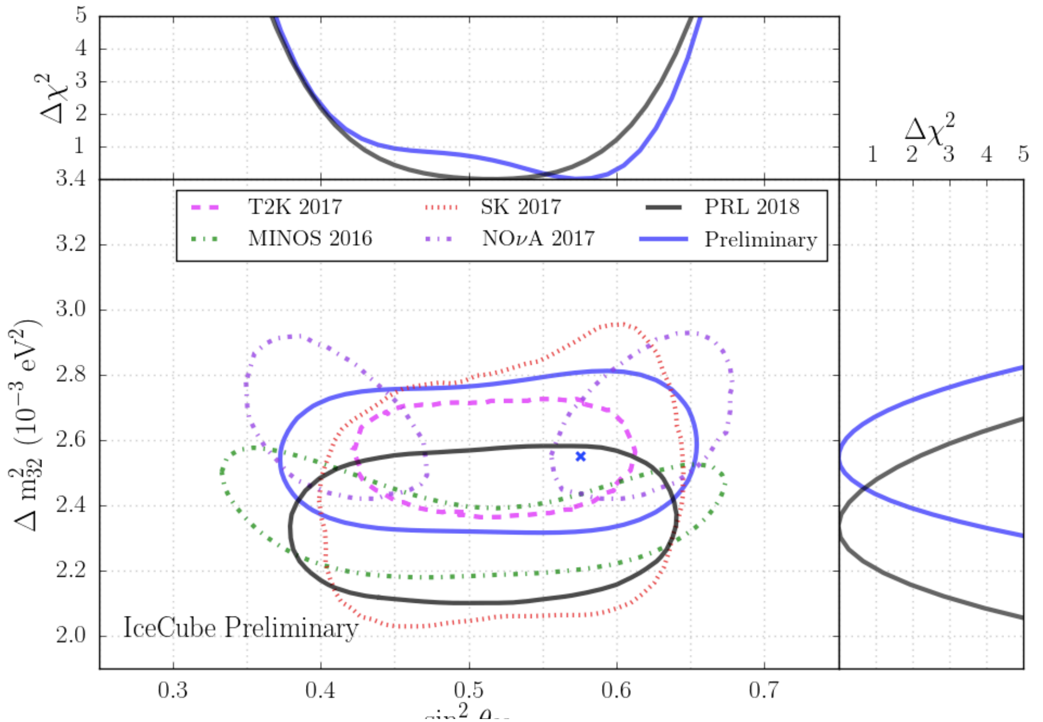
NEUTRINO MASSES WITH OSCILLATIONS

νμ Disappearance

Appearance of ντ compatible with SK and OPERA



Preliminary updated results



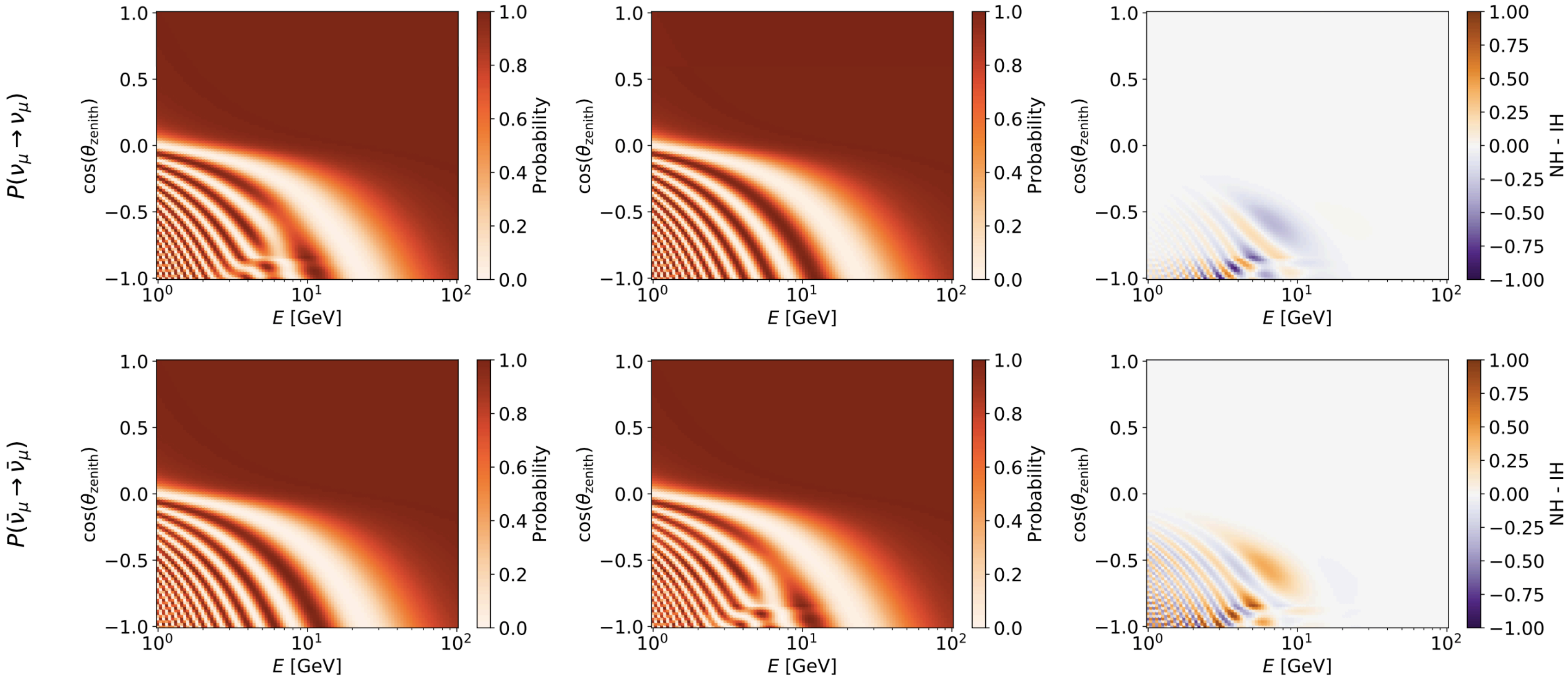
PRL 120, 071801 (2018): 41’599 Low Energy starting events (tracks and cascades) in 1’022 d with E_ν ~5.6 - 56 GeV

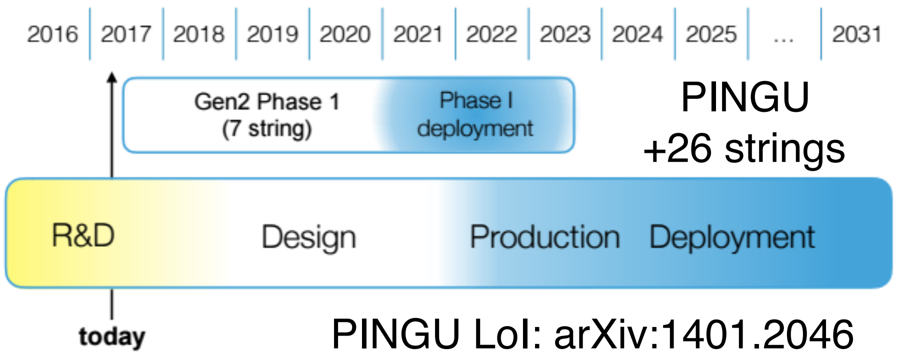
Best fit $\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$,

$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}$ eV^2

MASS ORDERING

NMO leads to matter effects for neutrinos (NO) or anti-neutrinos (IO) - no nu-nubar discrimination capability in IceCube and effects at curent energy threshold.





PINGU LoI: arXiv:1401.2046
update: arXiv:1607.02671

IceCube-Gen2: ~10 km^3 with ~120 new stringsIceCube, arXiv:1412.5106 (LOI)
IceCube, 1510.05228 (ICRC)

CONCLUSIONS AND OUTLOOK

- Neutrino astronomy has been a long journey
- But the new astronomy is not a solitary journey and is seing bright times!