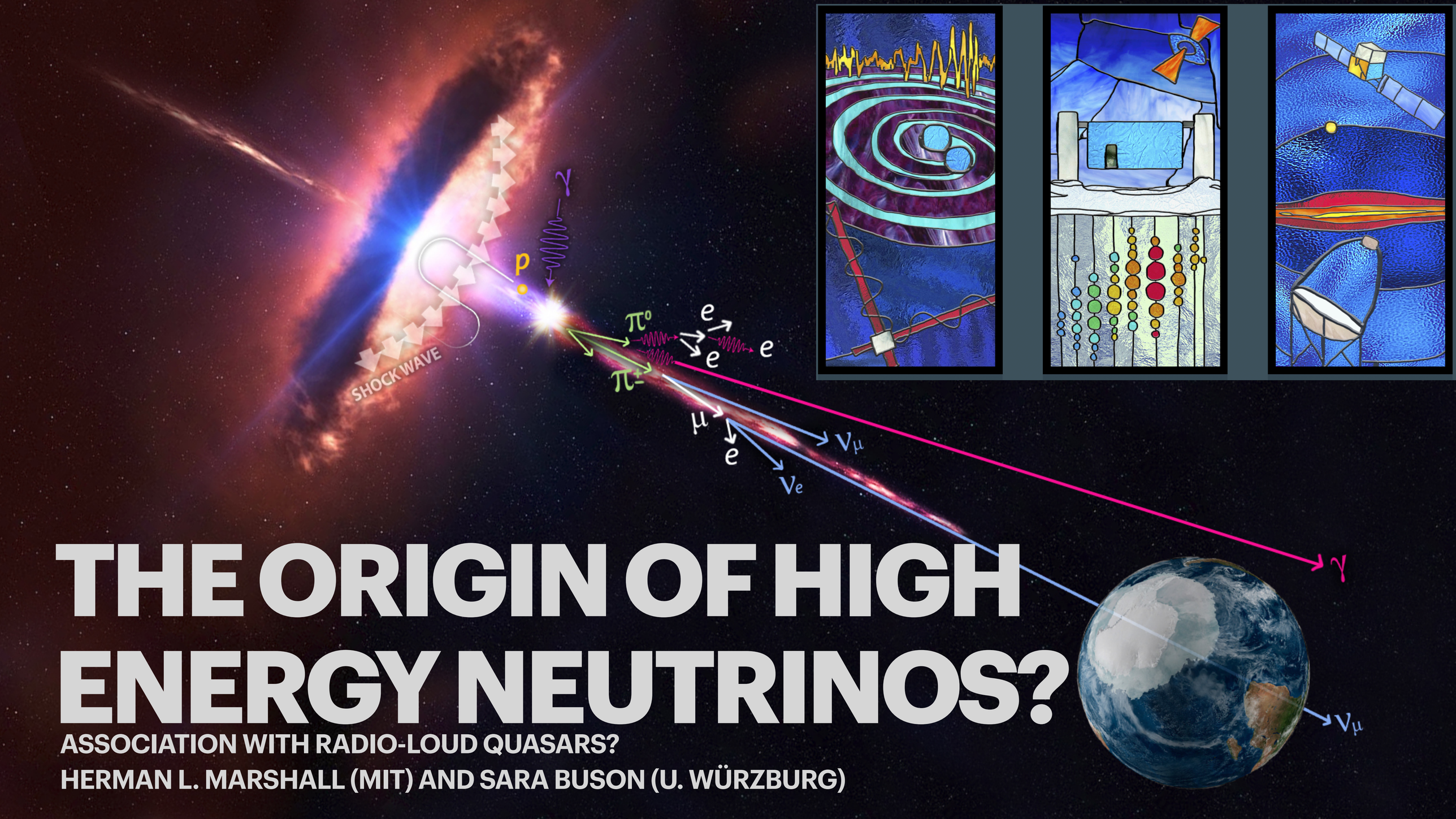


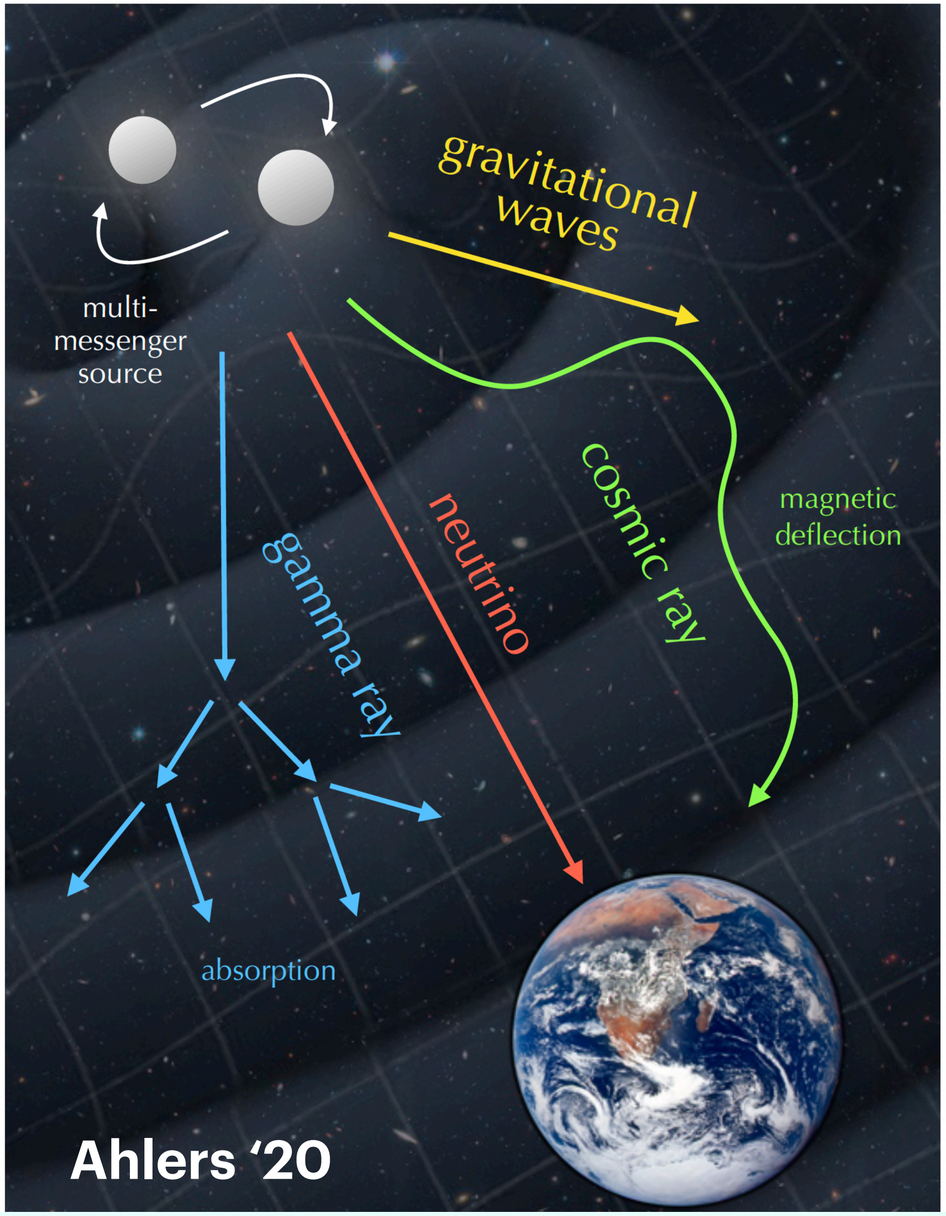
THE ORIGIN OF HIGH ENERGY NEUTRINOS?

ASSOCIATION WITH RADIO-LOUD QUASARS?

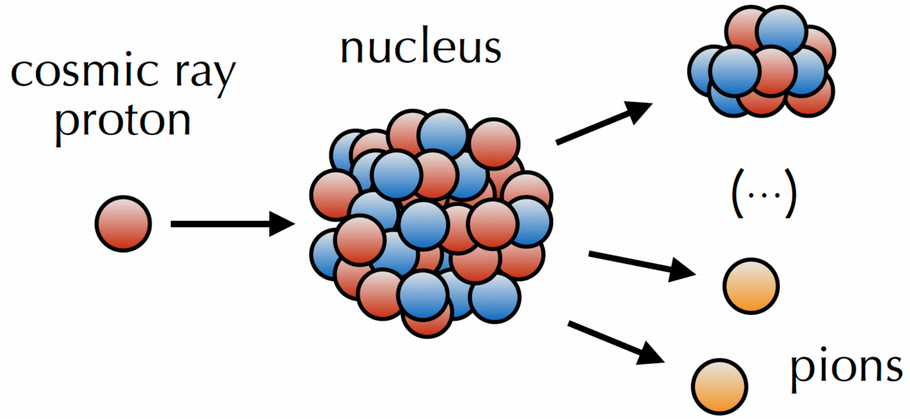
HERMAN L. MARSHALL (MIT) AND SARA BUSON (U. WÜRZBURG)

OVERVIEW

- What is a neutrino (ν) in astrophysical context
- Detecting a ν (tough!) and the extragalactic ν background
- Association with one γ-ray quasar in 2017, others?
- Are most/all high E neutrinos associated with quasars?
  - Statistics!
  - Validation?



Acceleration of charged nuclei (**cosmic rays**) - especially in the aftermath of cataclysmic events, sometimes visible in **gravitational waves**.

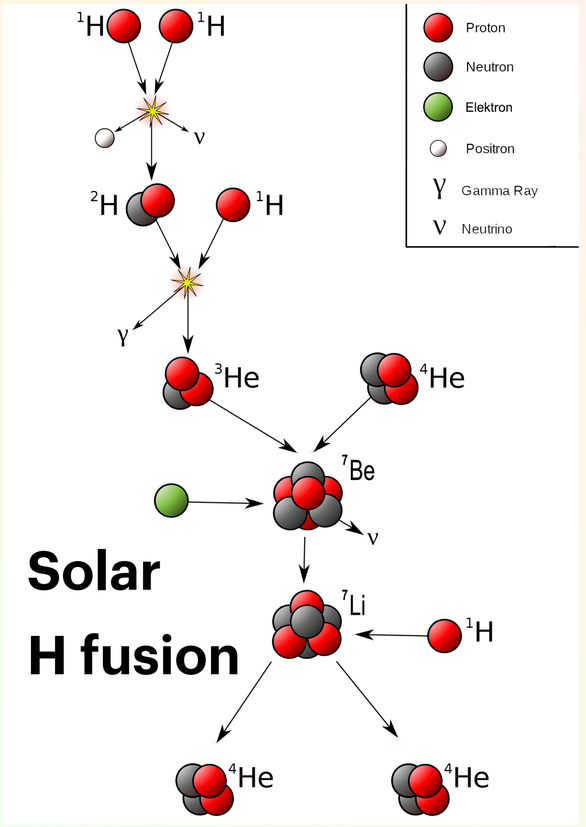


Secondary **neutrinos** and **gamma-rays** from pion decays:

$$\pi^+ \to \mu^+ + \nu_\mu \qquad \pi^0 \to \gamma + \gamma$$
$$\hookrightarrow e^+ + \nu_e + \nu_\mu$$

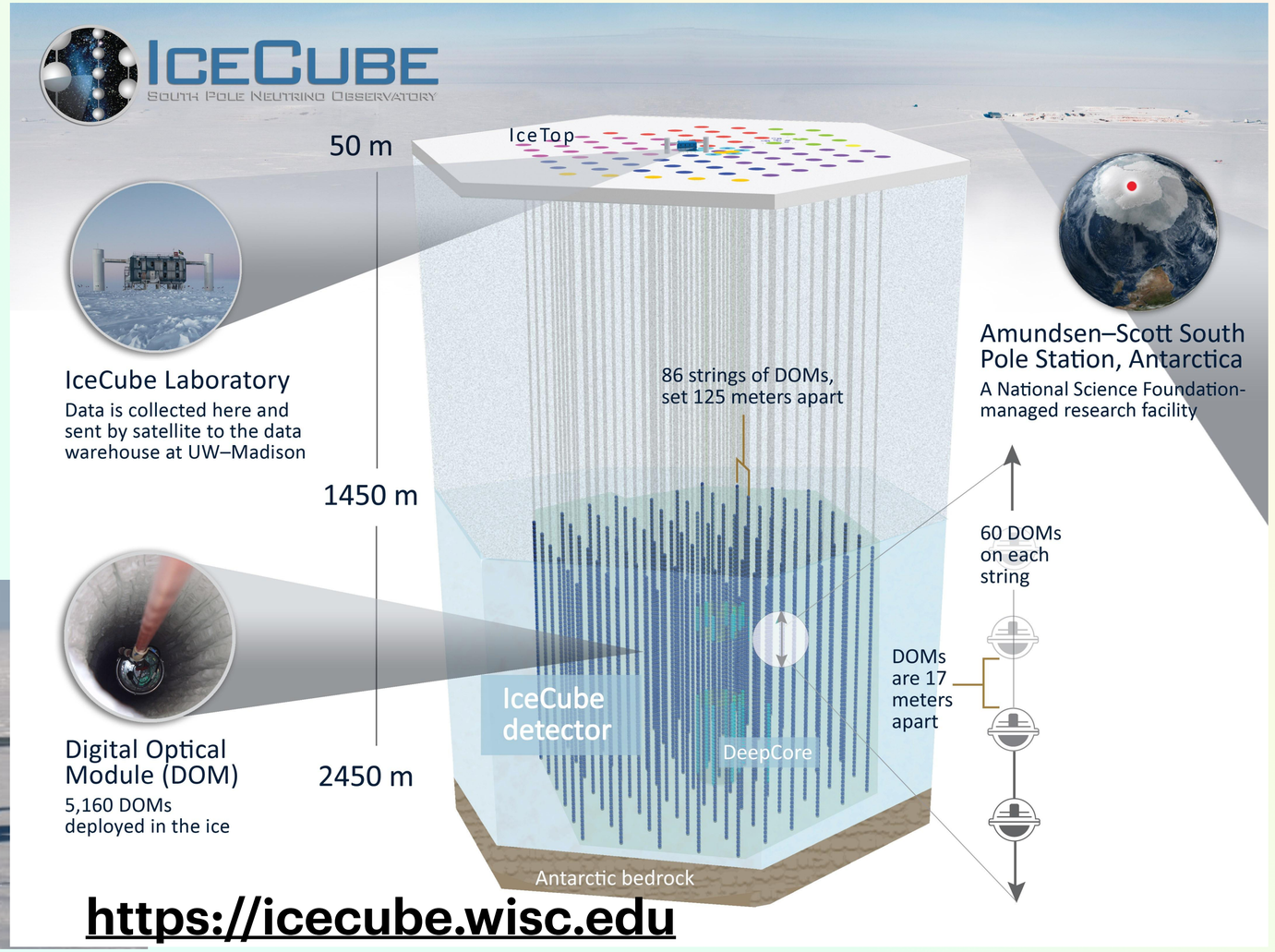
NEUTRINOS

- Postulated in 1930 by W. Pauli, named by E. Fermi
- Needed to explain beta decay of nuclei, detected directly in 1956
- Neutral, very light (< 0.12 eV), weak interactions, three “flavors”
- At Earth, most are from the Sun (0.4-18 MeV each)
- Detected from SN 1987A
  - >99% of energy release is in neutrinos (10-20 MeV each)
  - multi-messenger astronomy (part of TDAMM)!
- Has 99.95% chance of going through Earth w/o interaction
- Detectors must be BIG and scientists must be CAREFUL and PATIENT!



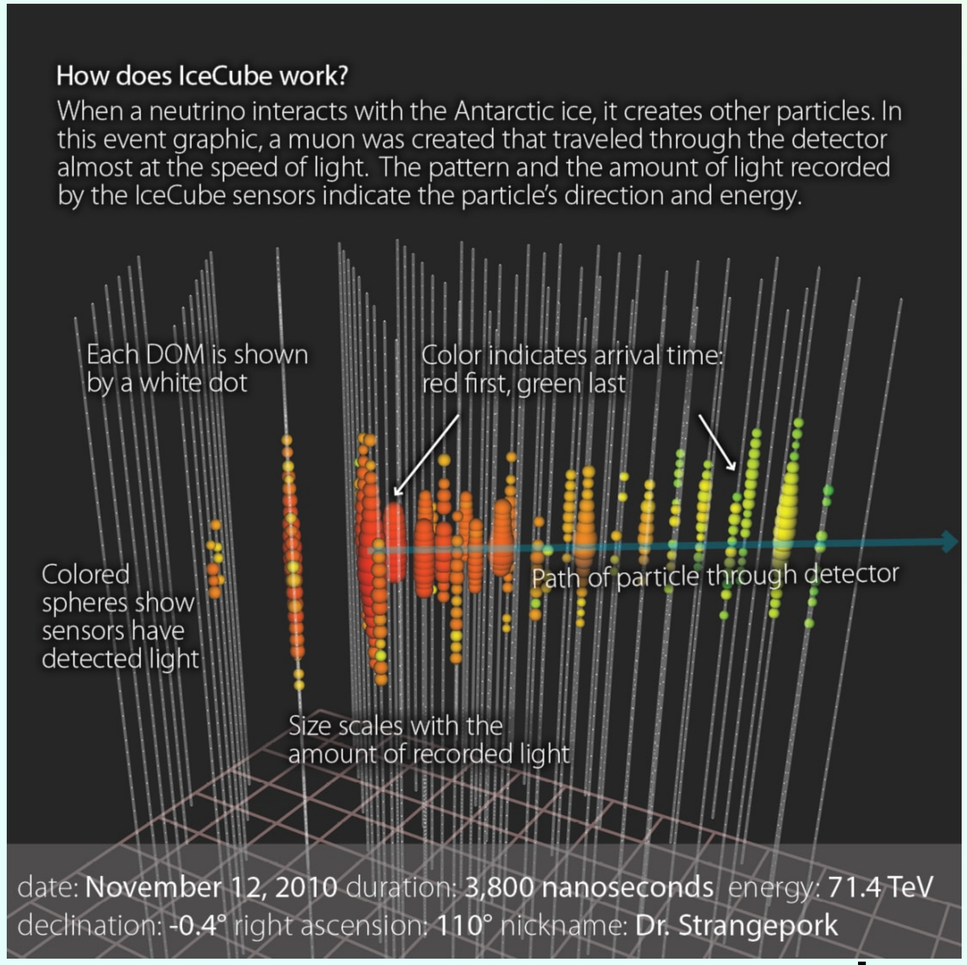
ICE-CUBE — AN OBSERVATORY

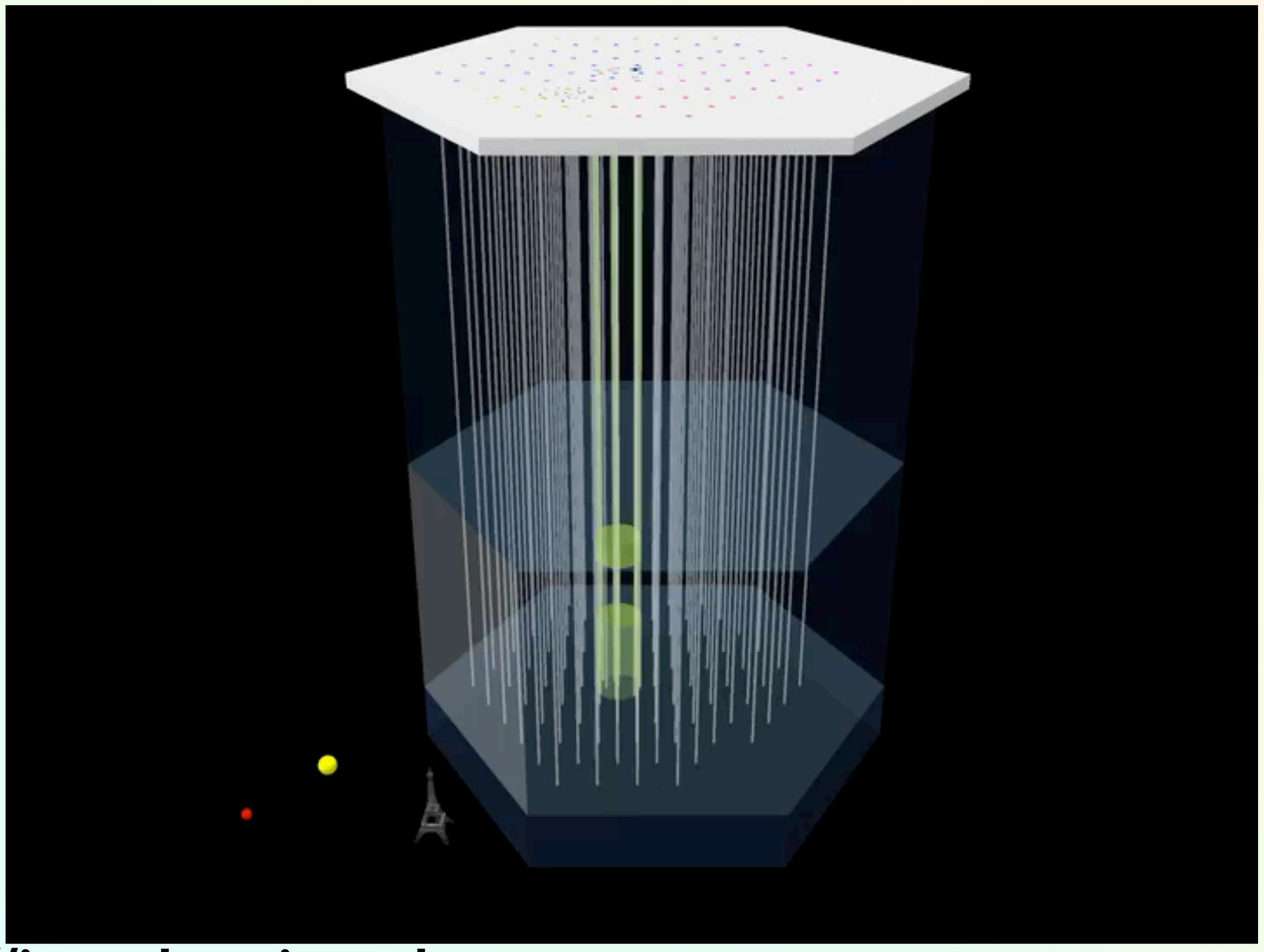
- At the South Pole!
- 1 km across, 2.5 km deep
- 86 holes in ice for strings of DOMs
- DOMs detect light to 2 ns
- Energies of neutrinos: 300 TeV to 1 EeV (10^{18} eV!)



https://icecube.wisc.edu

ICE-CUBE — NOT “DIRECT” DETECTION





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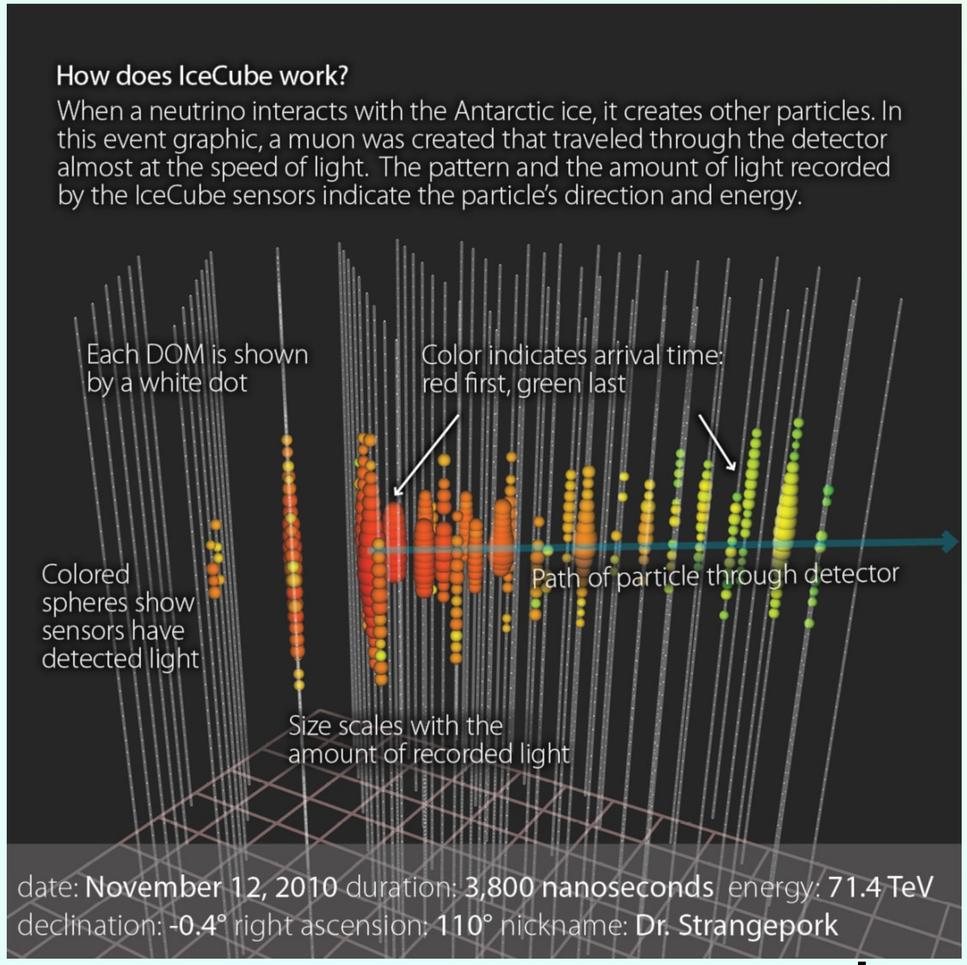
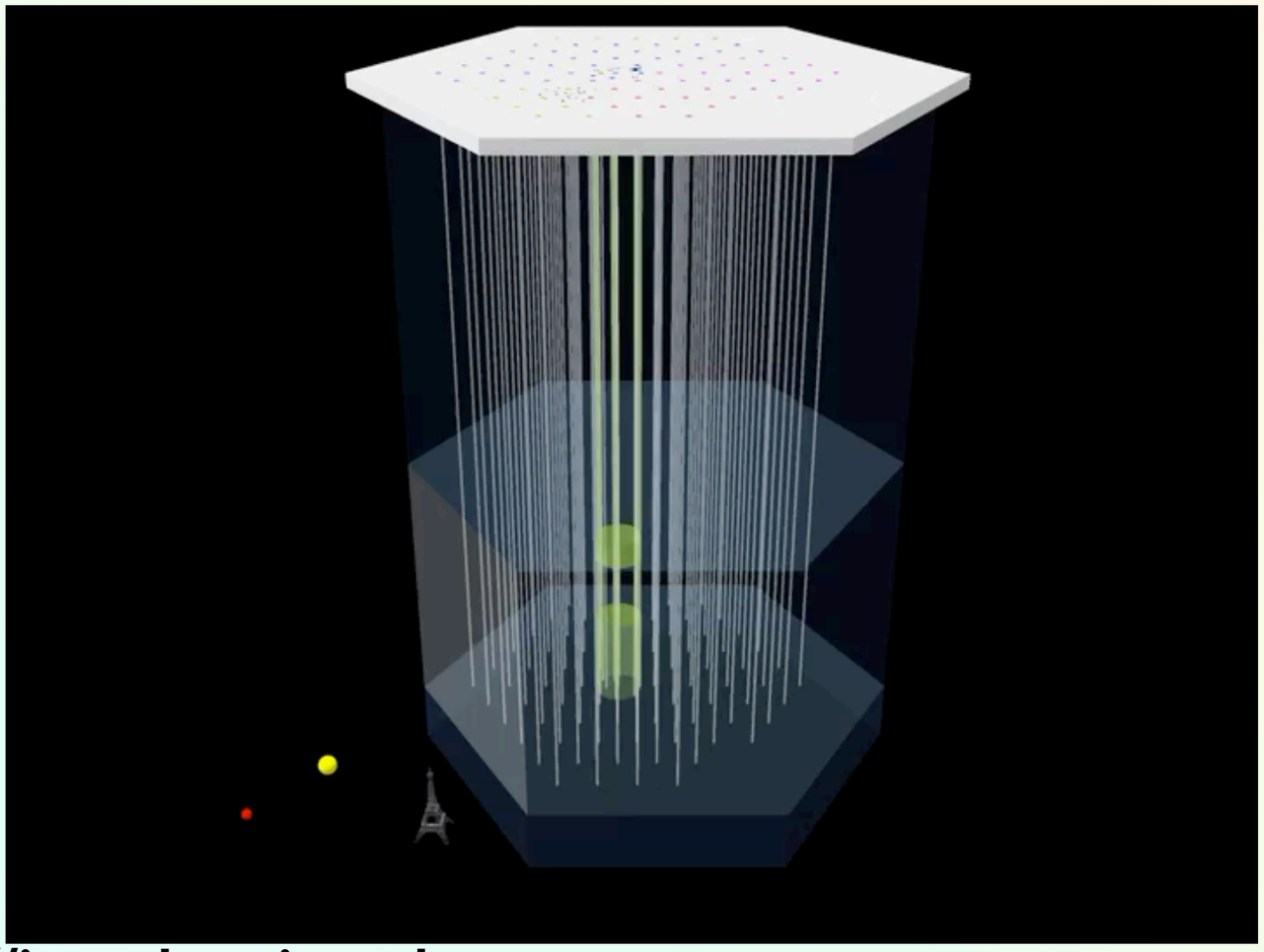
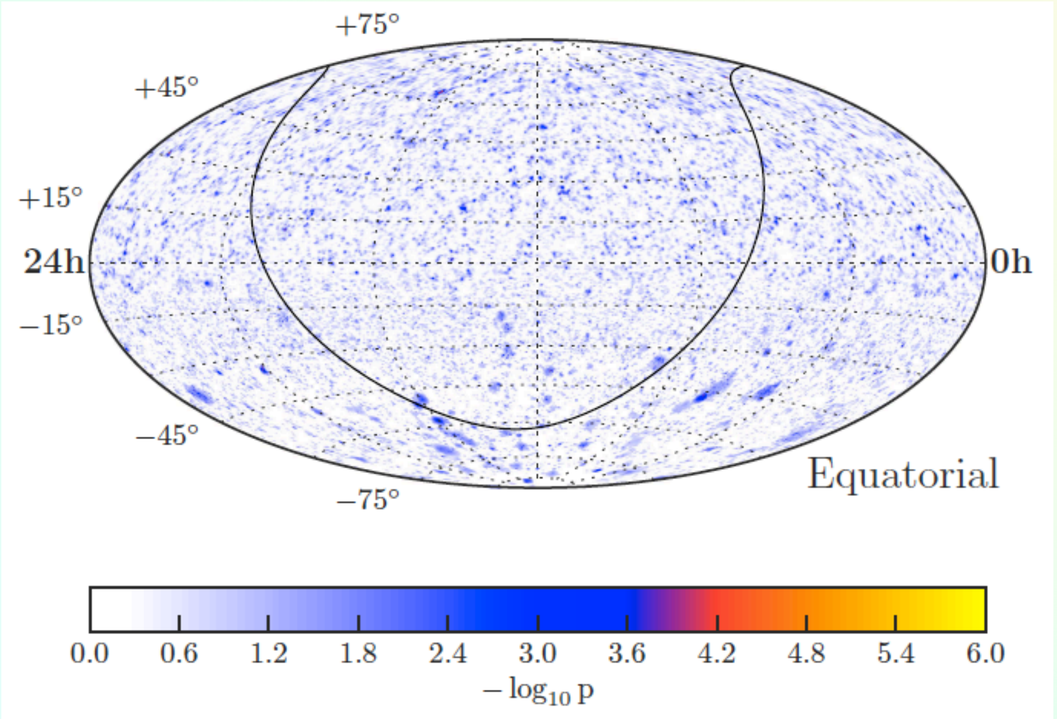




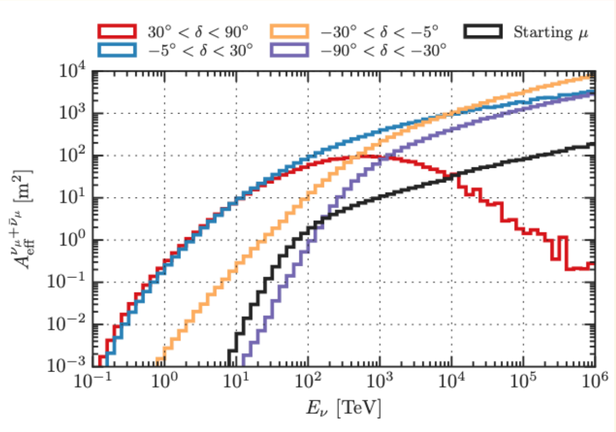
https://icecube.wisc.edu

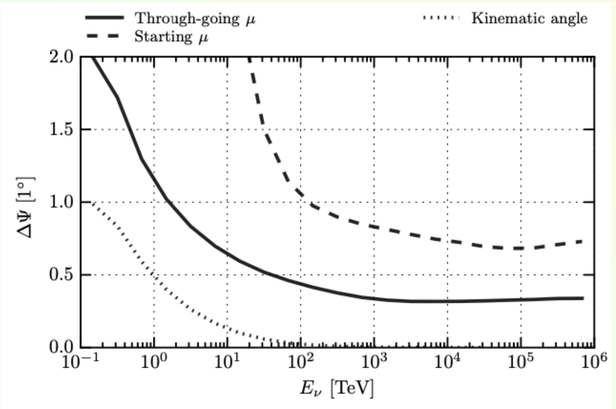
ALL-SKY ICECUBE RESULTS

- 7 years of IceCube data
- TS = 2 log(L[n_s]/L[0]), n_s = estimated signal
  - also depends on γ
  - γ is fitted for events
  - unbinned likelihood L
- Make TS map
  - 190,000 independent positions
  - Need pre-trial TS > 5.67σ for 3σ significance
- Conclude: no individual sources — consistent with uniform sky background



Aartsen+ ‘17



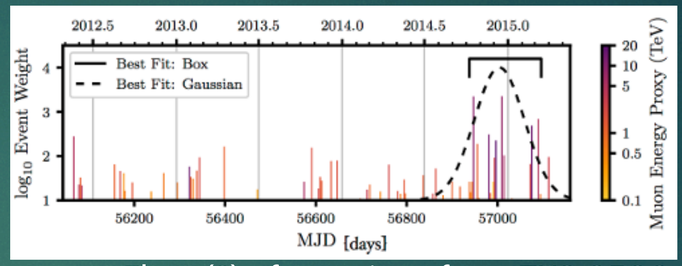


Cosmic neutrinos may originate in blazars

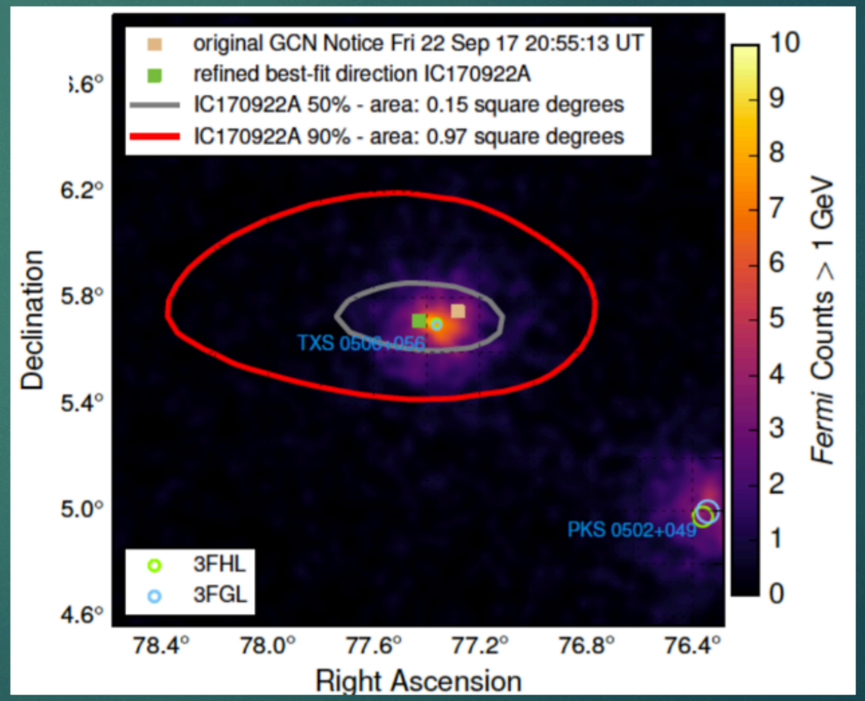
- Intriguing high-energy *Neutrino/Blazar* Association
- IC 170922A & TXS 0506+056
  - High-Energy neutrino (>183TeV)
  - Flaring γ–ray blazar (Tanaka, SB+ Atel #10791)
  - ~3σ post-trial chance coincidence correlation

Evidence for a connection between TXS 0506+056 and IC170922A

IceCube, Fermi, MAGIC+ Science 361, 146 2018



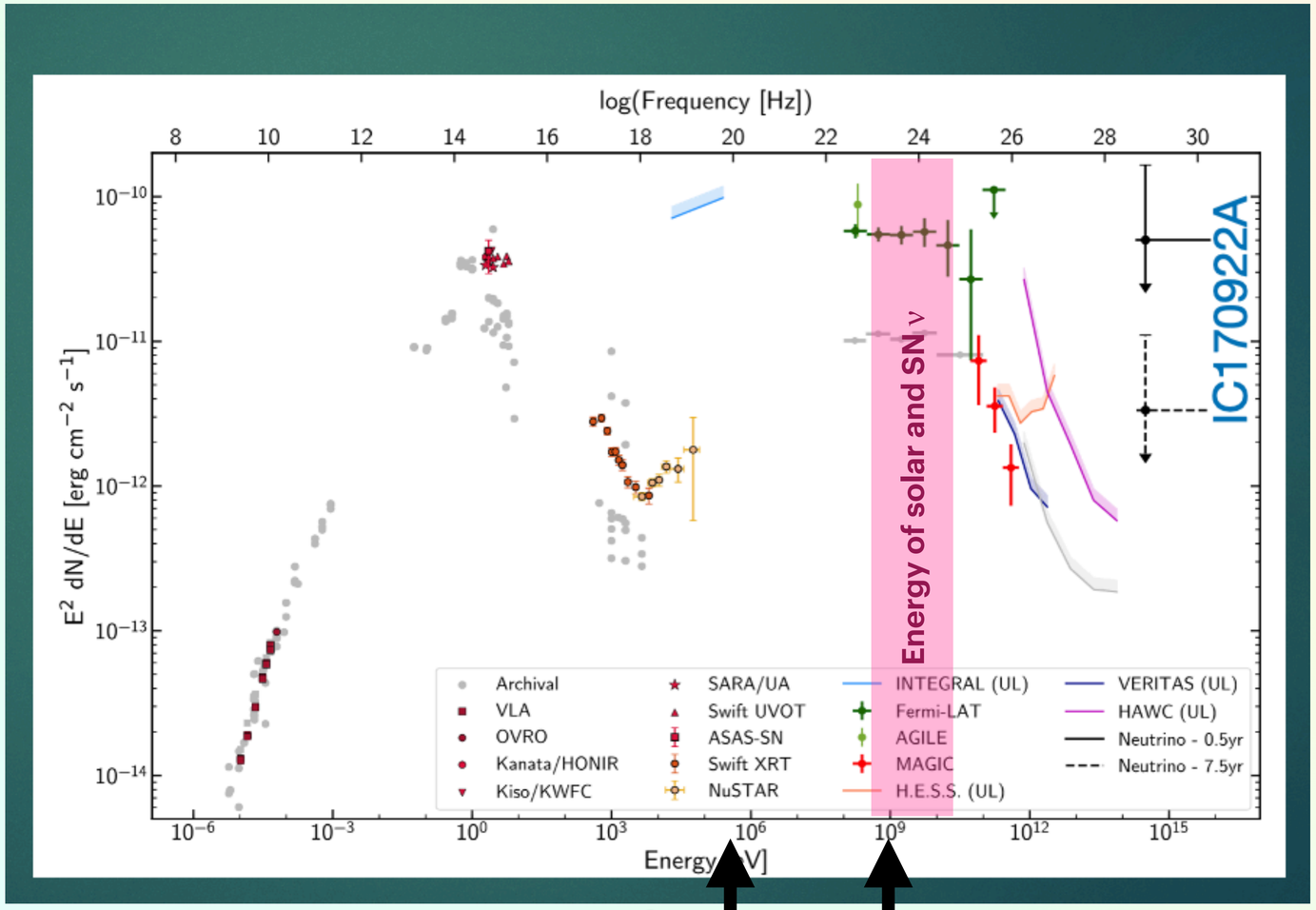
Flare (?) of neutrinos from TXS 0506



S. Buson, 2020

PHYSICAL IMPLICATIONS

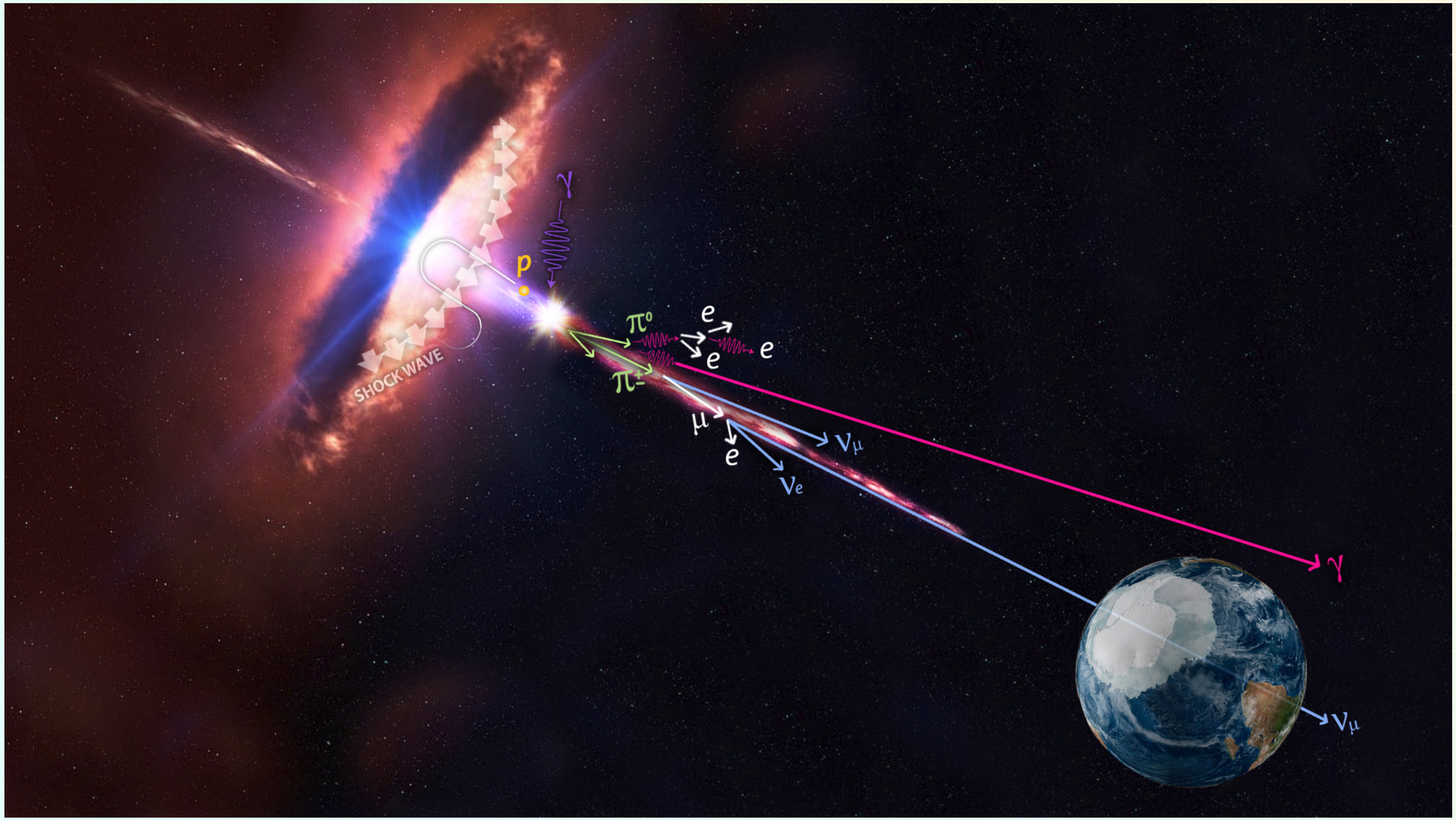
- High E neutrinos are not from “normal” nuclear processes
- Energy density comparable to that of AGN core!
- Physics:
  - Upscattering by high E protons in quasar jet?
  - Scattering by high E protons in gas of host galaxy?
  - High E protons require jet with speed of > 0.999 c!



Rest-mass energy of e-

Rest-mass energy of p

NEUTRINOS FROM A QUASAR JET

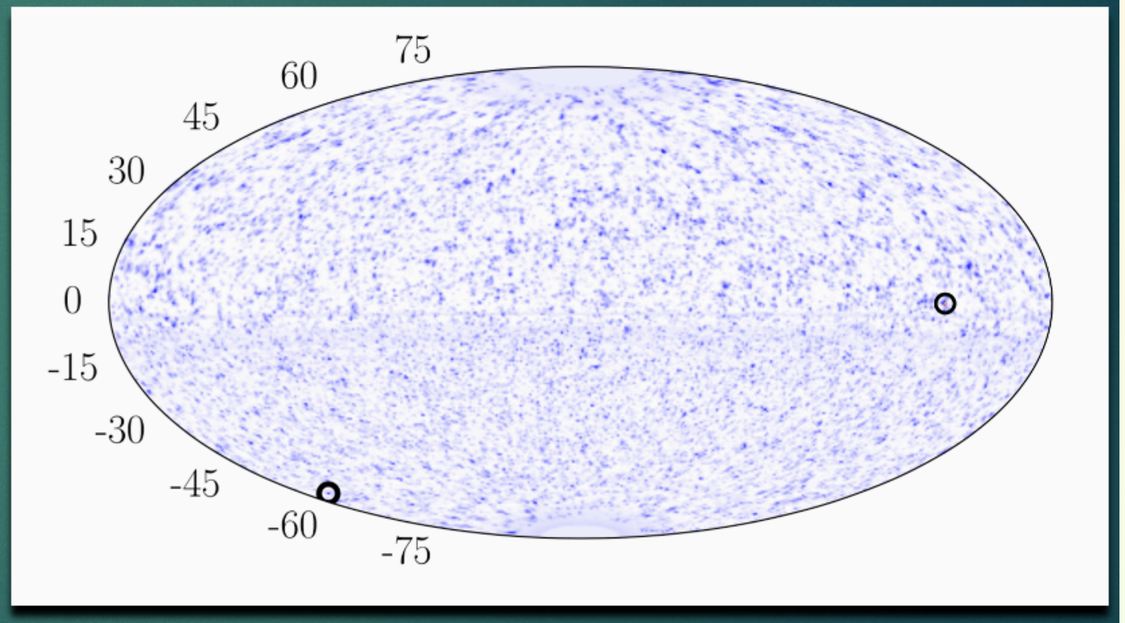


MORE SOURCES…

Neutrino Sky

- Blind all-sky search (10-years IC data)
- Tested a list of extragalactic candidates. Most significant spots :
  - NGC 1068 (level of 2.9σ)
  - PKS 1424+240, GB6 J1542+6129, TXS 0506+056
- Correlations with tested sources (northern catalog, level of 3.3σ)

Latest studies (IceCube, ANTARES)



See e.g. F. Halzen talk, G. Illuminati talk

- Neither individual neutrino-source detected at high confidence, nor source classes
- Events isotropically distributed (favoring extragalactic origin)

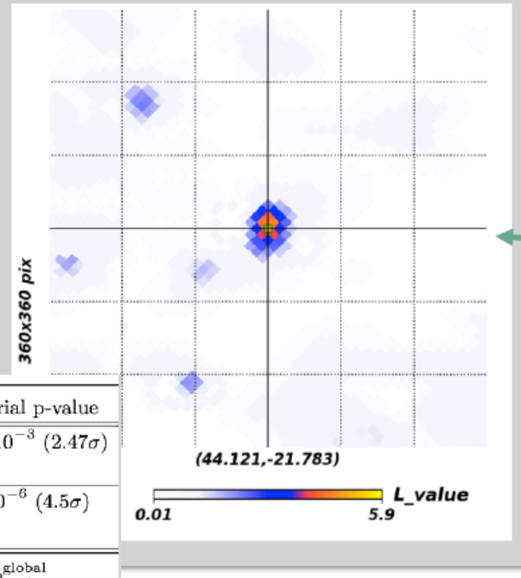
S. Buson, 2020

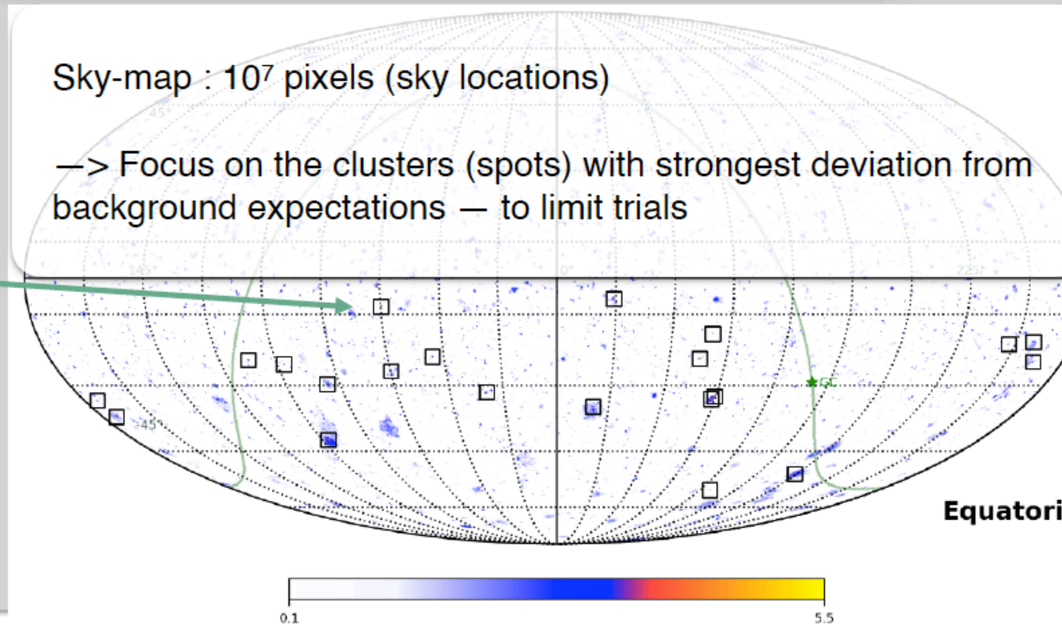
MORE ASSOCIATIONS?

- IceCube: L_ν = -log(p-val) assumes ν cluster is a source
- Overplot with 1177 known γ-ray quasar positions
- Assoc. by L_ν and angle from "hotspot" (L_ν > 4, or 3.5σ)
- 10 new candidates
- Validated with MC catalogs

Skymap: Cross-correlation analysis

Northern and southern hemispheres treated separately





Sky region	Dataset (energies)	5BZCat	Hotspots	Matches	Pre-trial p-value	Post-trial p-value
North ($-3^\circ \leq \delta \leq 81^\circ$)	9 yr data (∼TeV/$\lesssim$ 0.1 PeV)	2130	66	42	5.12×10^{-4} (3.28σ)	6.79×10^{-3} (2.47σ)
South ($-85^\circ < \delta < -5^\circ$)	7 yr data ($\gtrsim$ 0.1 PeV)	1177	19	10	3×10^{-7} (4.99σ)	2×10^{-6} (4.5σ)
					$p^{\text{global}}_{\text{pre}}$	$p^{\text{global}}_{\text{post}}$
North + South		–	–	–	3.62×10^{-9} (5.78σ)	2.59×10^{-7} (5.02σ)

Buson+ '23

STATISTICS QUESTIONS!

- Confusion about choice of L_{min}
  - They tried L_{min} = [3.5, 4.0, 4.5] but use 4.0, with best post-trial p of 2e-6
  - They actually quote -$\log_{10}$(p-value), not -ln(p-value) [Also x2?]
  - They say L_ν = 4.5 corresponds with 2σ pre-trial signif.
- Independent ν maps? 0.1° bins but 0.5° IceCube resolution?
  - 0.5° resolution gives ~60,000 independent positions in southern sky
  - Expect 6 “hotspots” at L_{min} = 4.0 if 60,000 positions on sky?
- “Optimization” of signal by varying association distance (0.4° to 0.7°)
  - Why not set at 0.5°?
  - 0.55° circle = 4.7e-5 of sky —> 0.056 chance of 1 of 1177 blazars —> expect 1 “hit”?
- Validation OK?
  - Buson+: Shift blazars 1e8 times, drawn from U(0,10) — get post-trial p = 1.5e-5
- Other test statistics include blazar flux levels, different samples, etc.