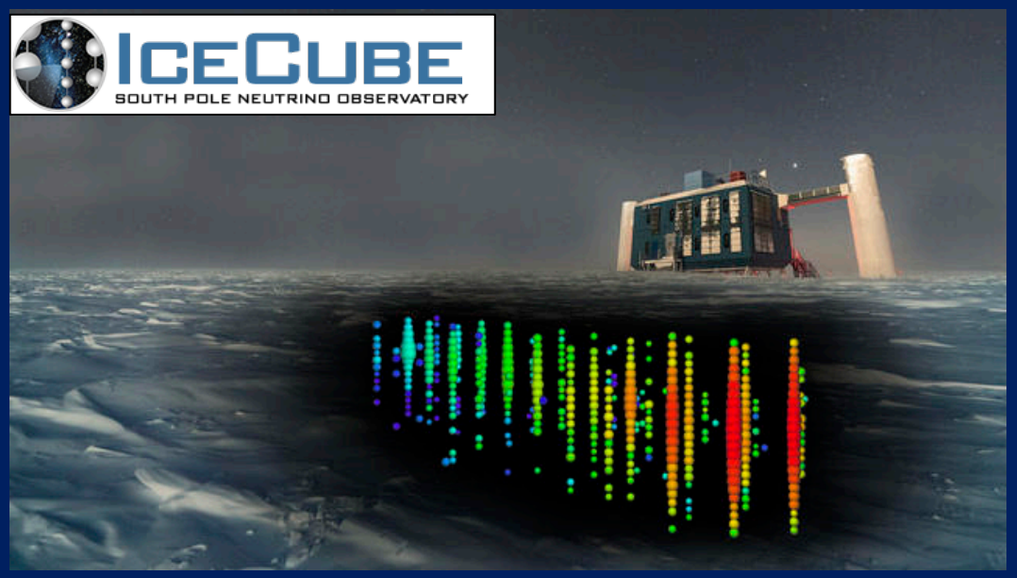
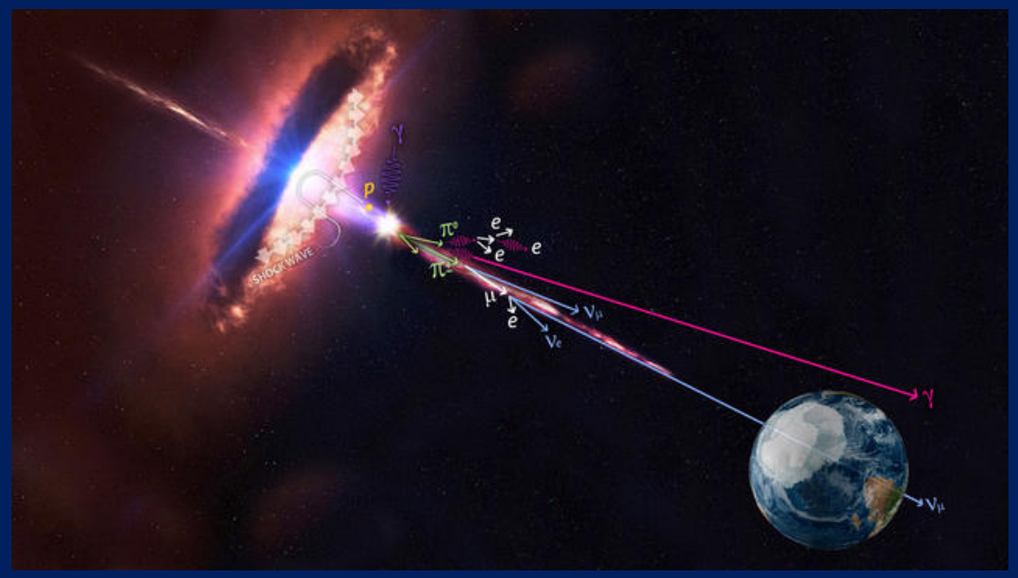




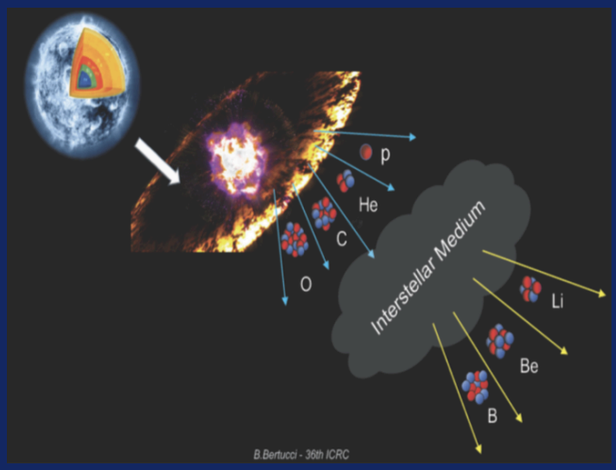
Astronomical Neutrino Sources
- (selected) Latest IceCube High Energy ν Results

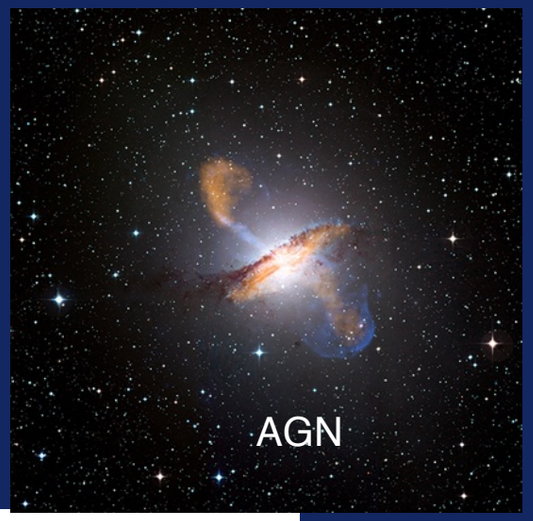
Joanna Kiryluk
Stony Brook University

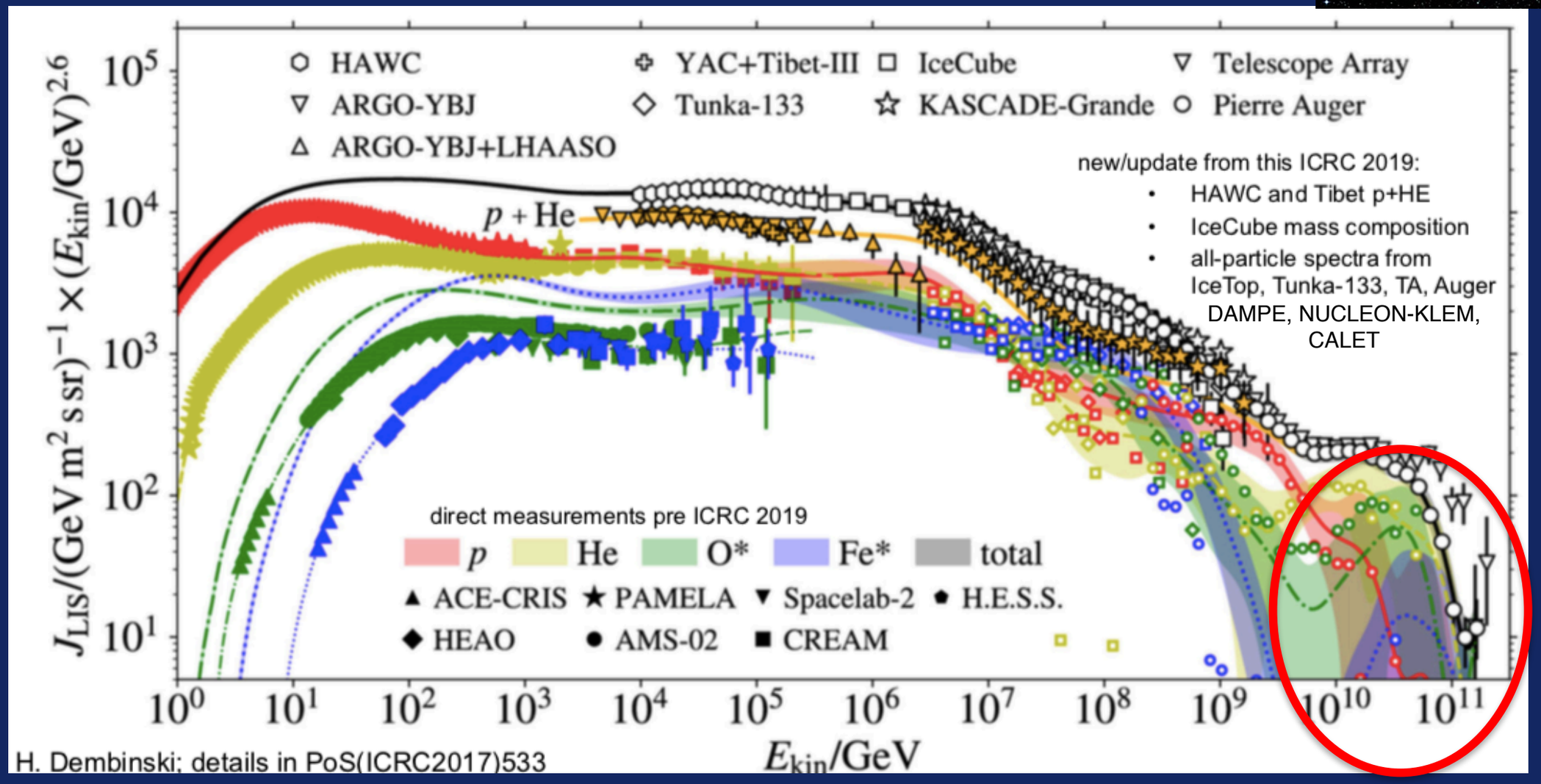
for the IceCube Collaboration

29th International Symposium on Lepton Photon Interactions at High Energies (LP20019)
5-10 August 2019, Toronto (Canada)

Open Question: Origin of Cosmic rays at Ultra-High Energies

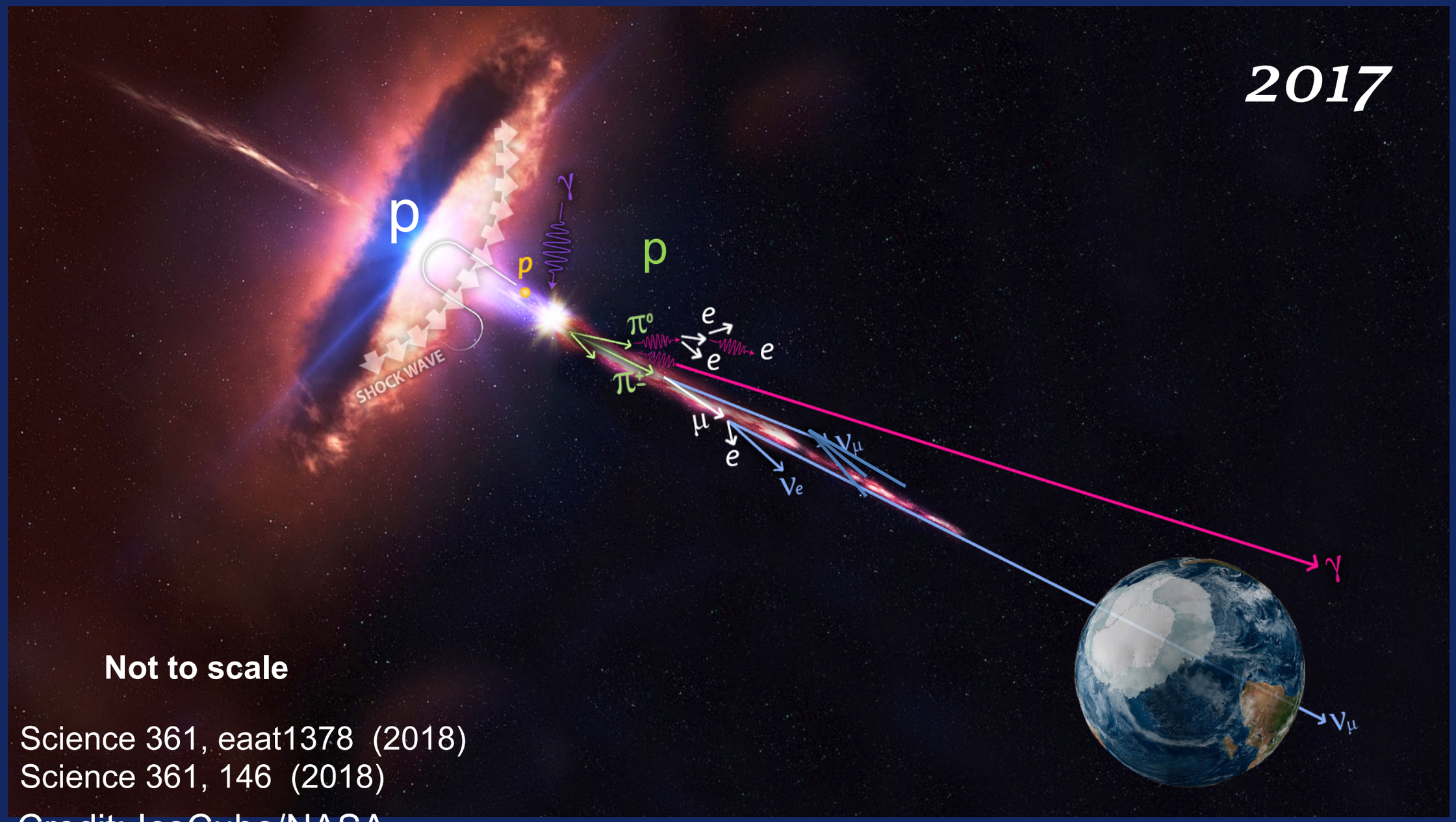






H. Dembinski; details in PoS(ICRC2017)533

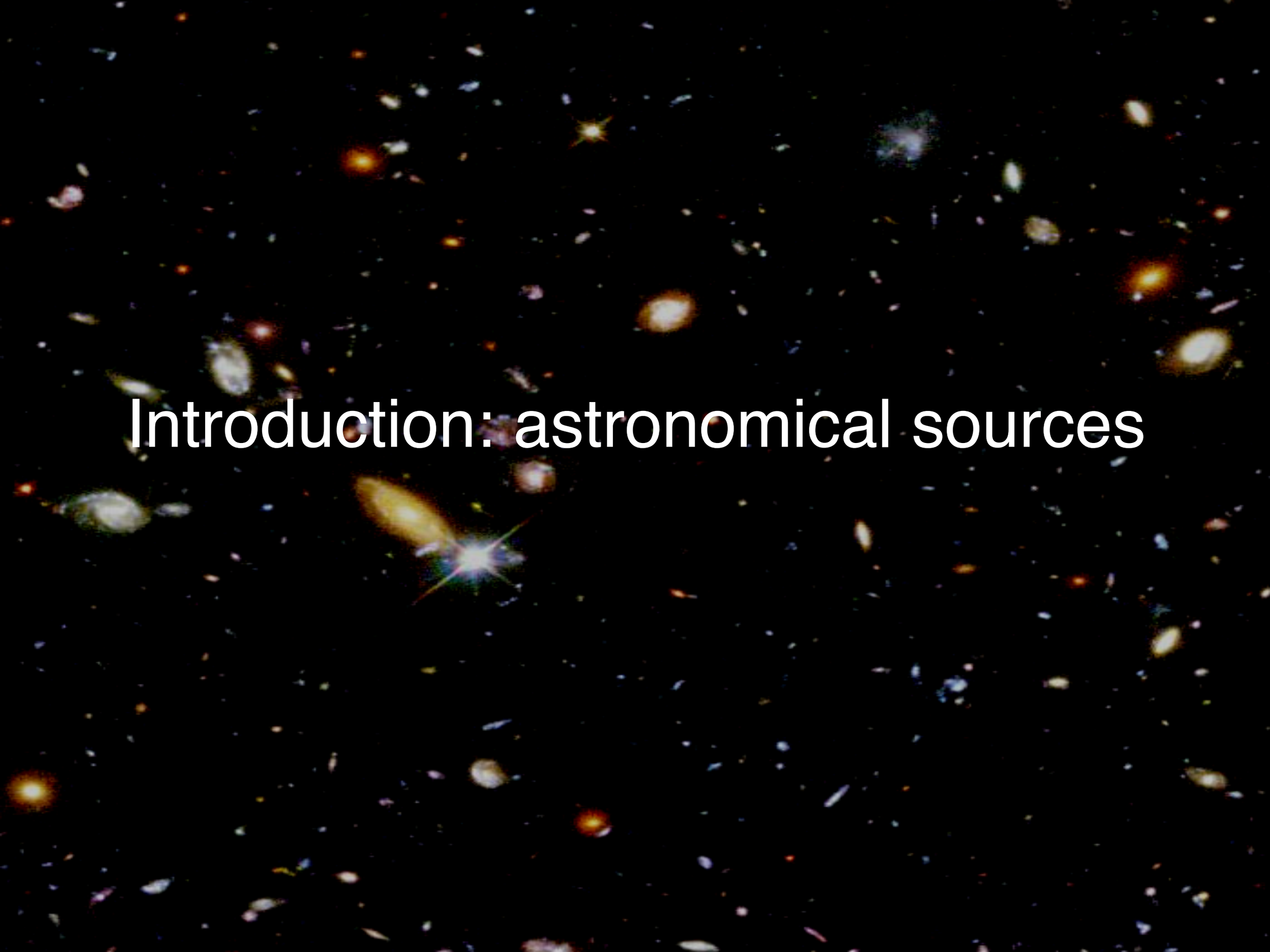
Breakthrough in Multi-Messenger Astronomy: IceCube Neutrinos Point to Long-Sought Cosmic Ray Accelerator



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

Credit: IceCube/NASA

A blazar emitting very high energy neutrinos and gamma rays

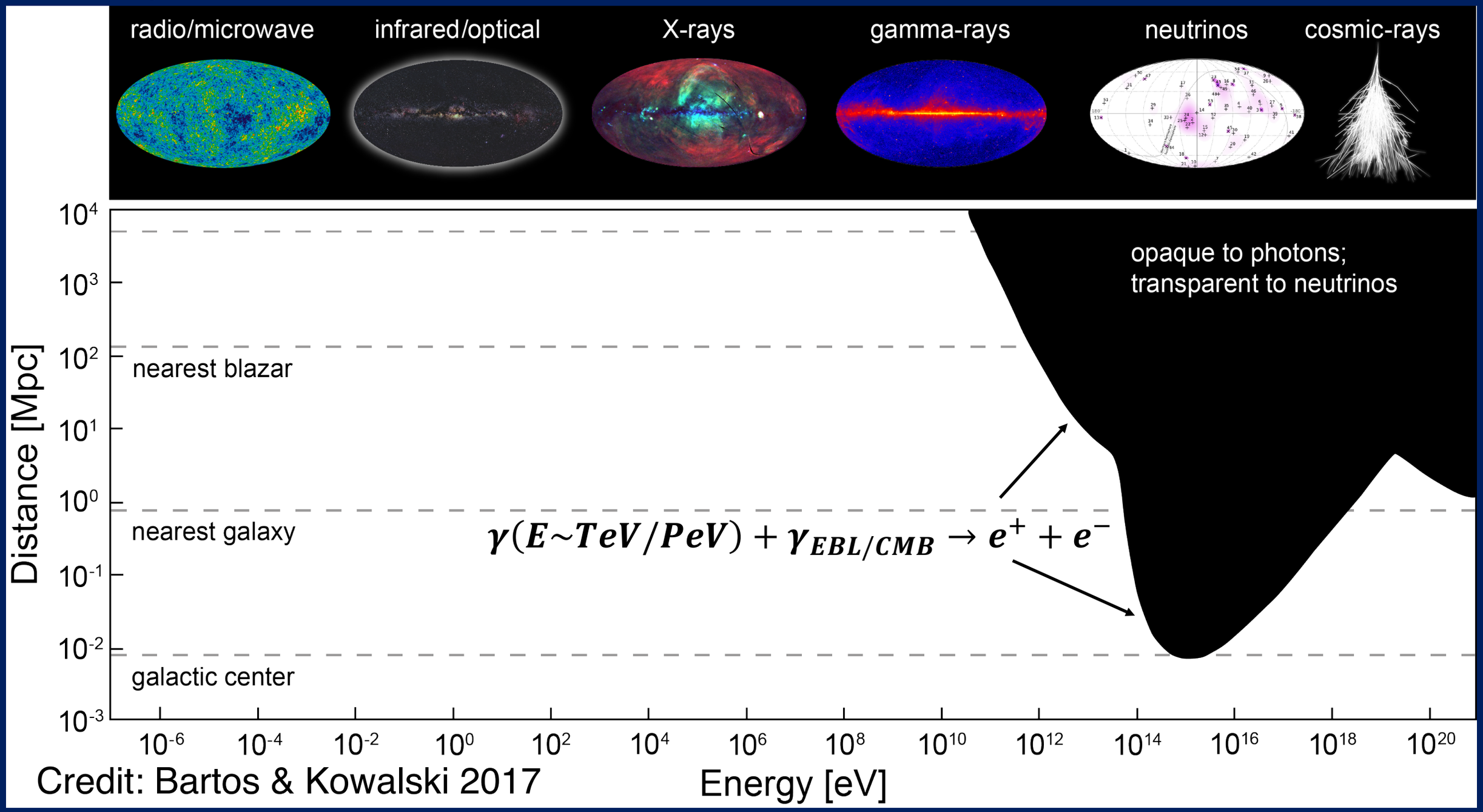


Introduction: astronomical sources

Multi-messenger Astronomy

- opening a new window to the Universe

1pc ~ 3 lyr

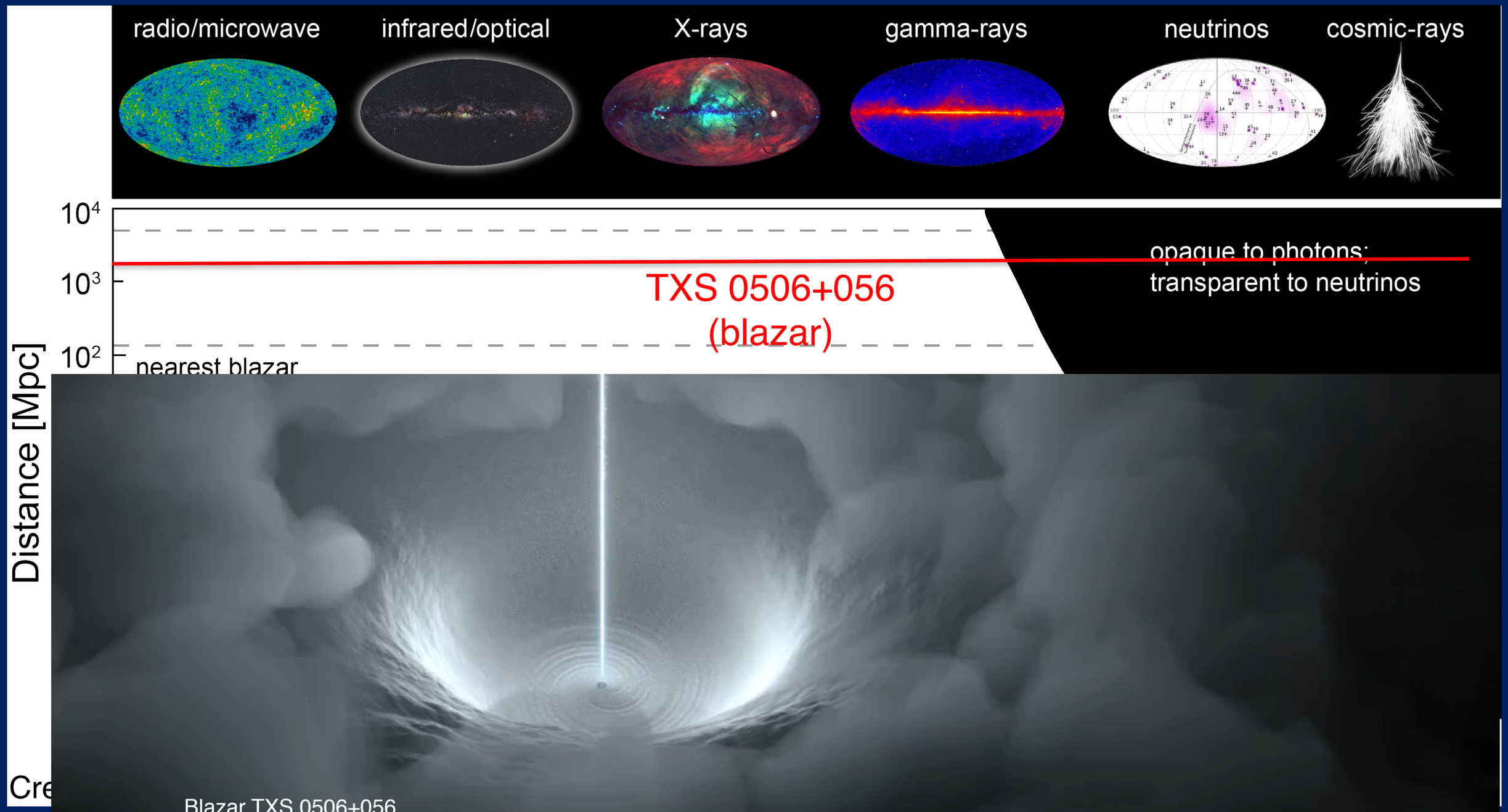


Credit: Bartos & Kowalski 2017

Multi-messenger Astronomy

- opening a new window to the Universe

1pc ~ 3 lyr



Blazar TXS 0506+056
Credit: DESY/Science lab

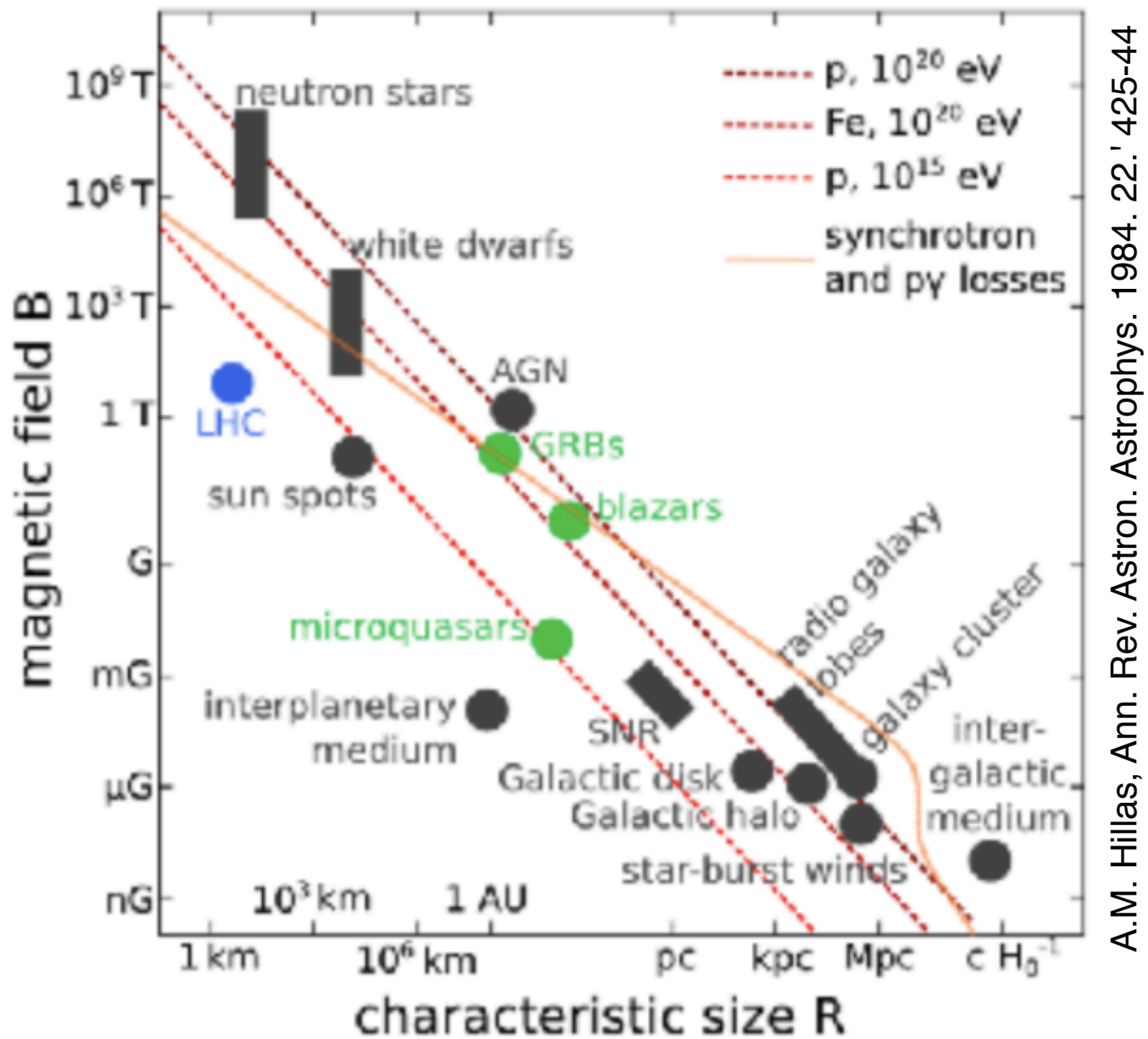
Possible Sources of Accelerated Cosmic Rays

[Observed by EM telescopes/detectors]

$$E_{max} = 10^{18} eVZ\beta \left(\frac{R}{kpc}\right)\left(\frac{B}{\mu G}\right)$$

Hillas plot

Source classes as function of the magnetic field strength B and their characteristic size R



A.M. Hillas, Ann. Rev. Astron. Astrophys. 1984. 22.' 425-44

Credit: E. Bernardini (HEP-EPS, 2019)

Possible Sources of Accelerated Cosmic Rays

[Observed by EM telescopes/detectors]

$$E_{max} = 10^{18} eVZ\beta \left(\frac{R}{kpc}\right)\left(\frac{B}{\mu G}\right)$$

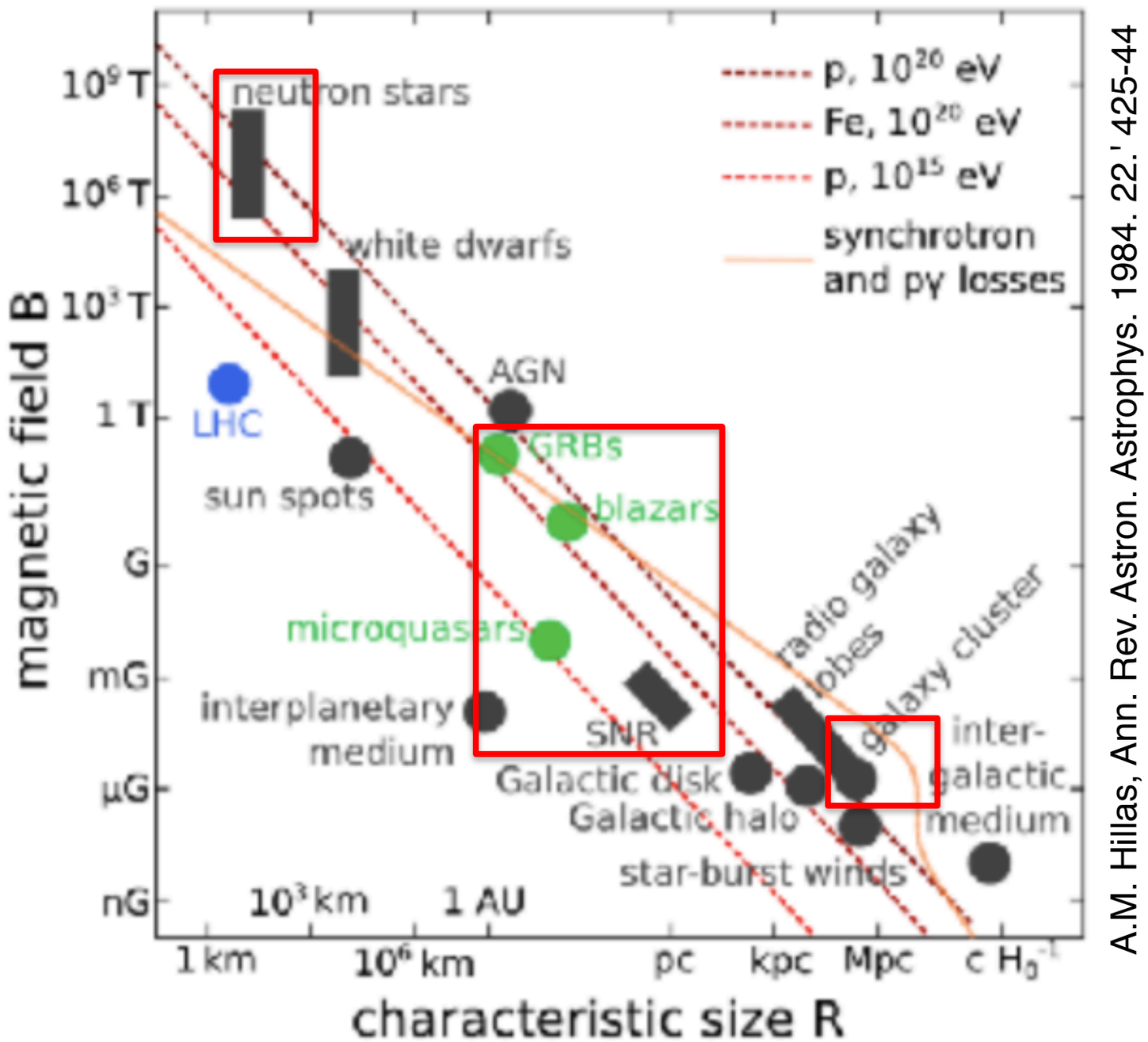
- Galactic
- Extra-Galactic

  z dependence

- Steady
- Transient

- Compact
- Extended

Hillas plot



A.M. Hillas, Ann. Rev. Astron. Astrophys. 1984. 22.' 425-44

Credit: E. Bernardini (HEP-EPS, 2019)

EM energy spectrum and corresponding physics processes

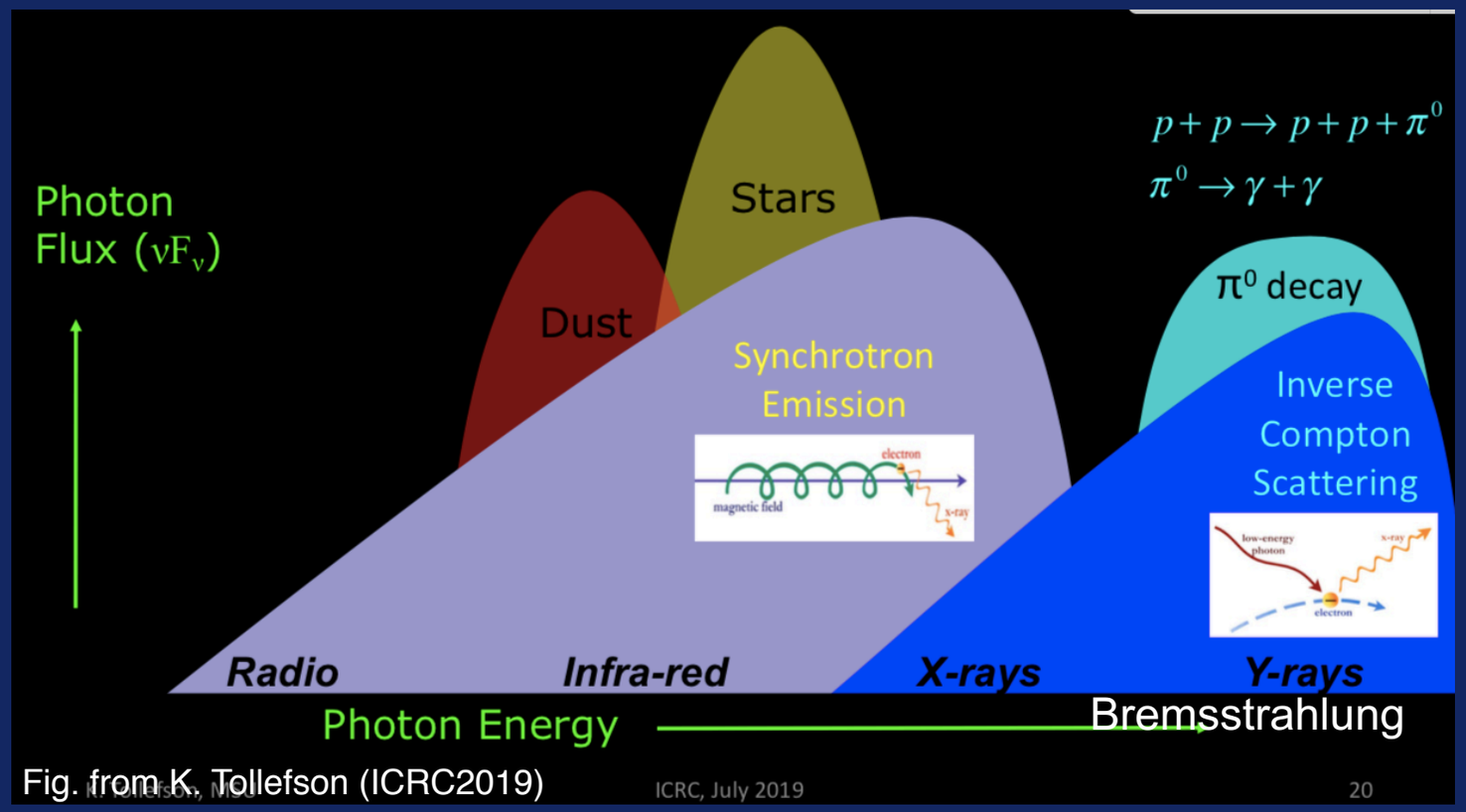


Fig. from K. Tollefson (ICRC2019)

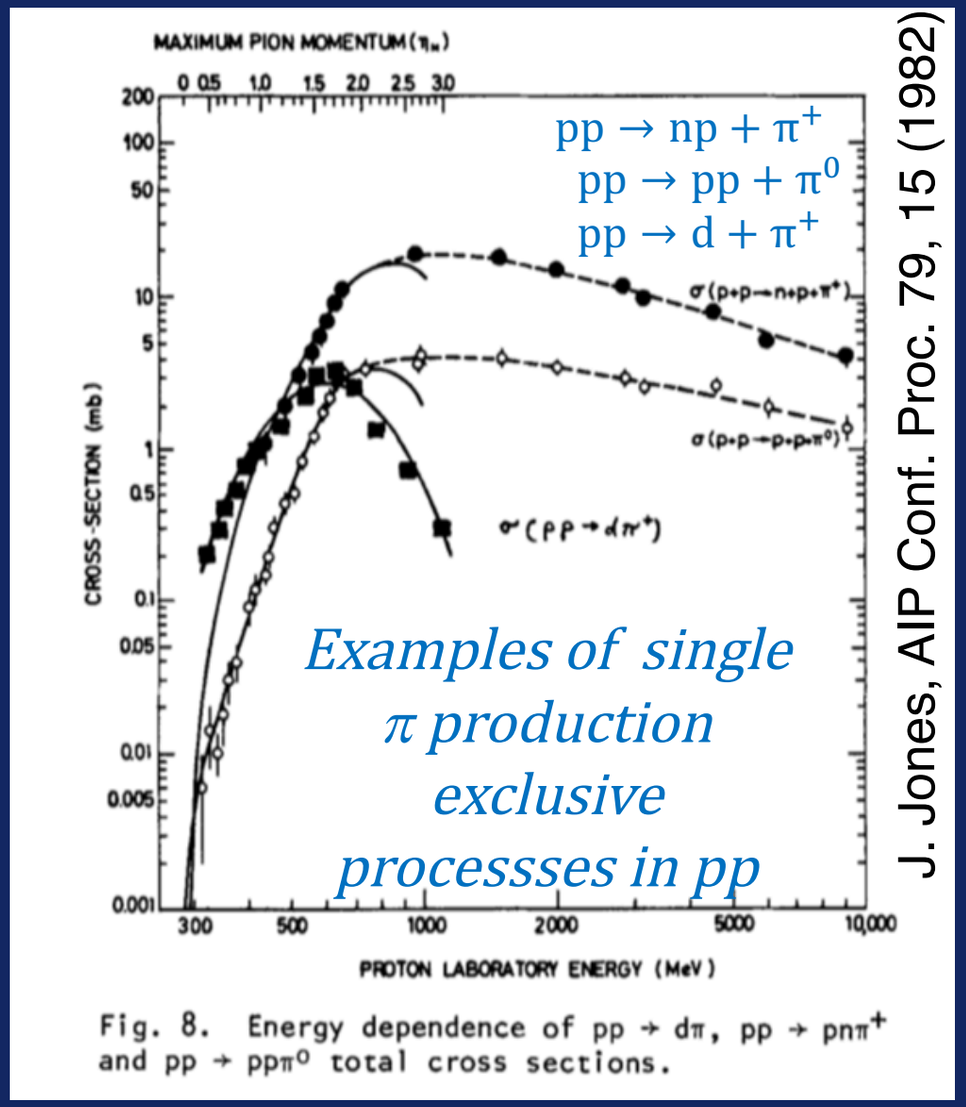
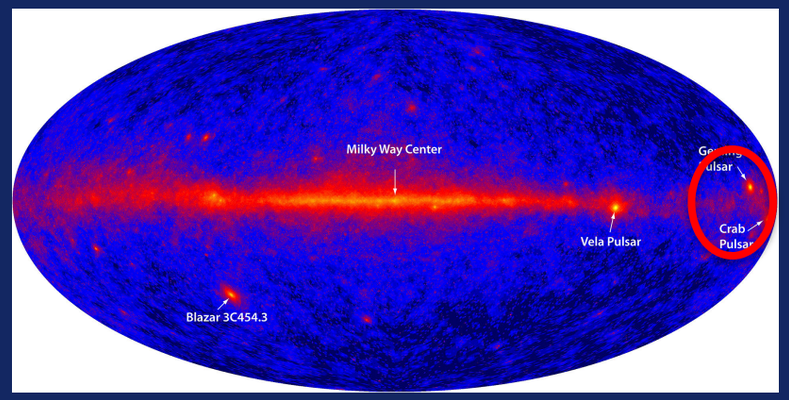
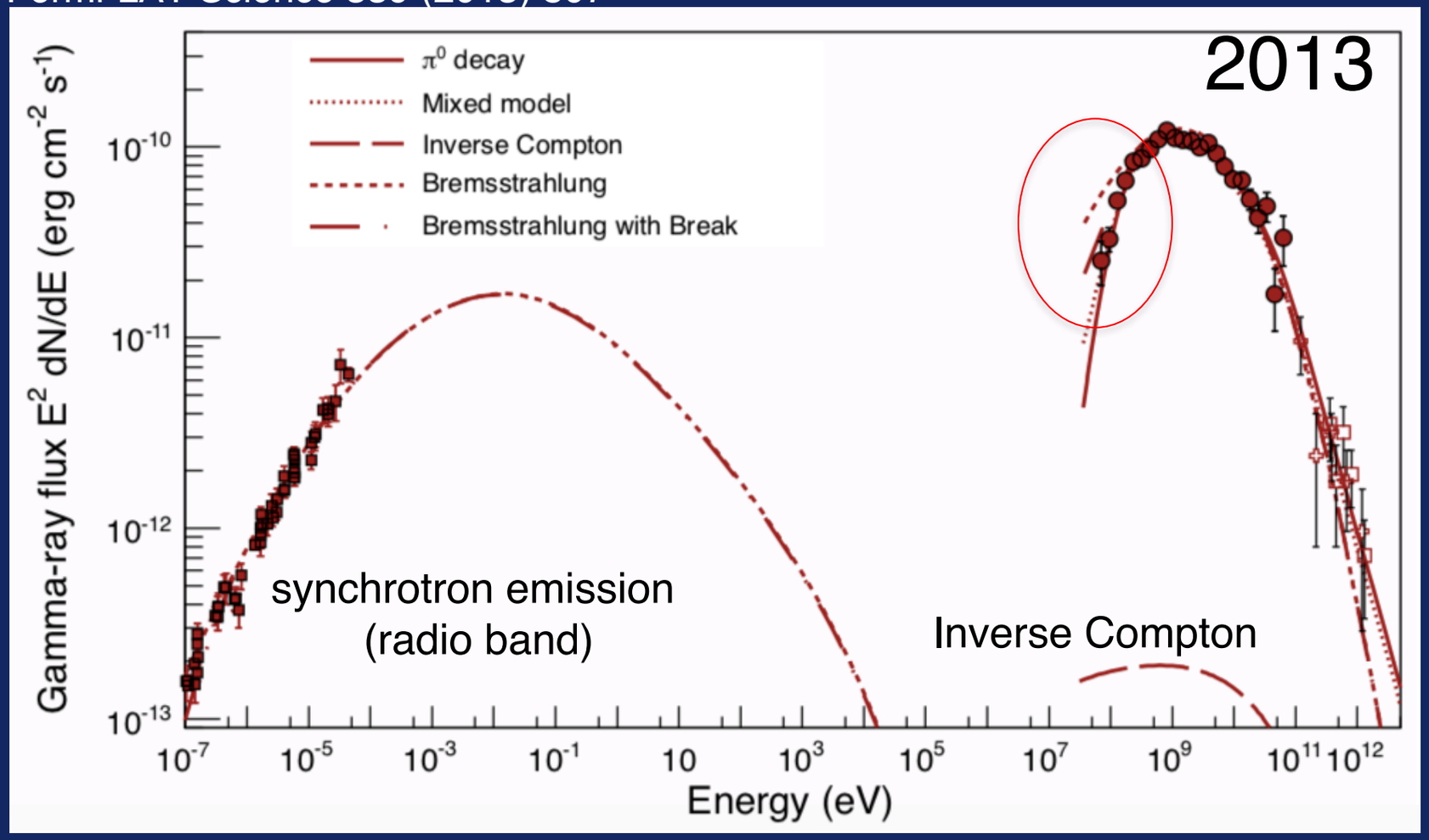


Fig. 8. Energy dependence of $pp \rightarrow d\pi$, $pp \rightarrow pn\pi^+$ and $pp \rightarrow pp\pi^0$ total cross sections.



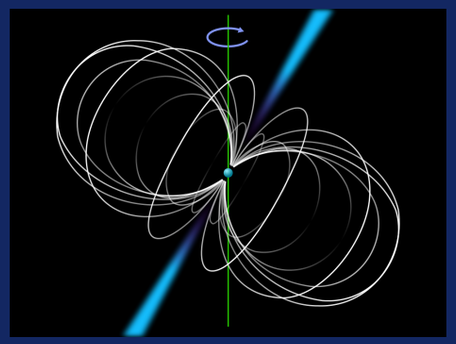
IC443 Supernova Remnants (SNR) : Galactic & Extended Source of (VHE) γ's (and CR)

Fermi-LAT Science 339 (2013) 807



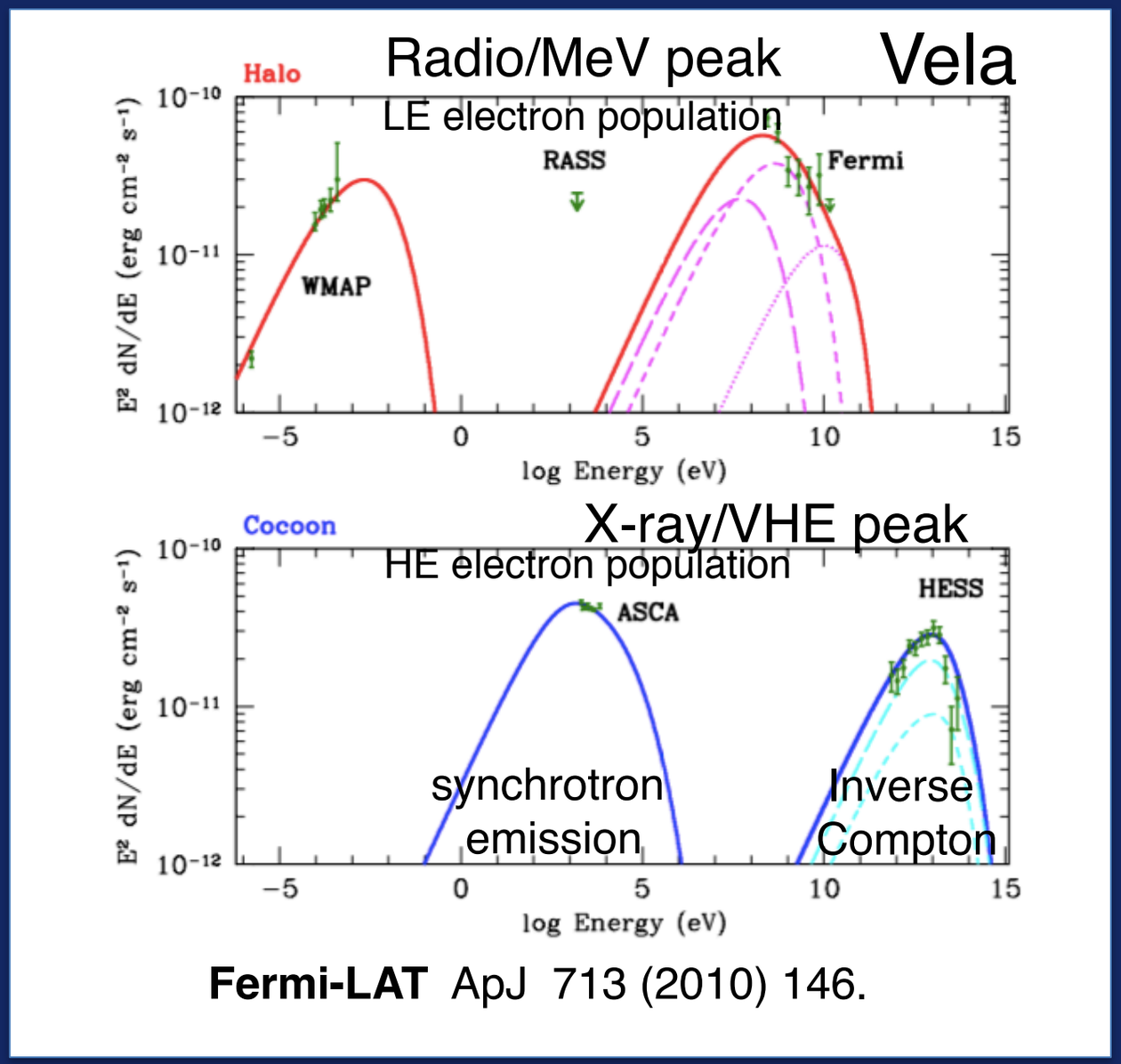
The first detection of π^0 decay feature in γ-ray spectra of IC443 by **Fermi-LAT** provides direct evidence that cosmic-ray protons are accelerated in SNRs. Should be neutrino (galactic) sources

Pulsars and surrounding Pulsar Wind Nebula (PWN) : (Galactic & Extended Source) of VHE γ's

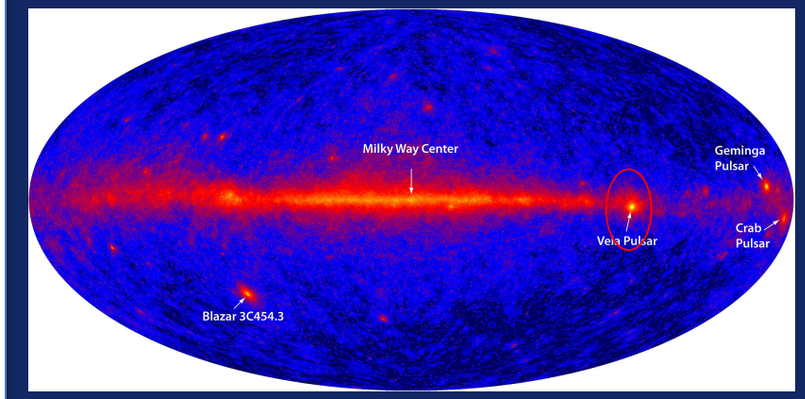


Pulsar:

- a highly magnetized rotating neutron star. Emits a beam of em radiation.
- generates pulsar winds (charged particles/plasmas accelerated to relativistic speeds by rapidly rotating B fields of 10^8 T) which power surrounding Supernova Remnants = PWN



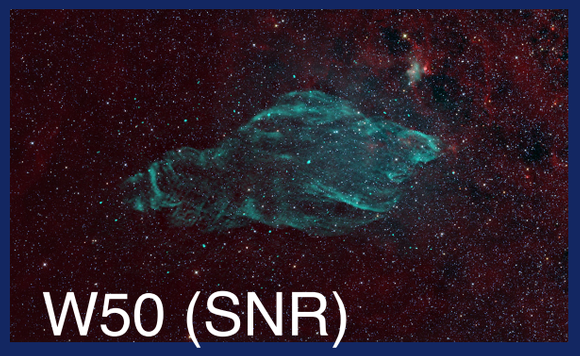
Fermi-LAT ApJ 713 (2010) 146.

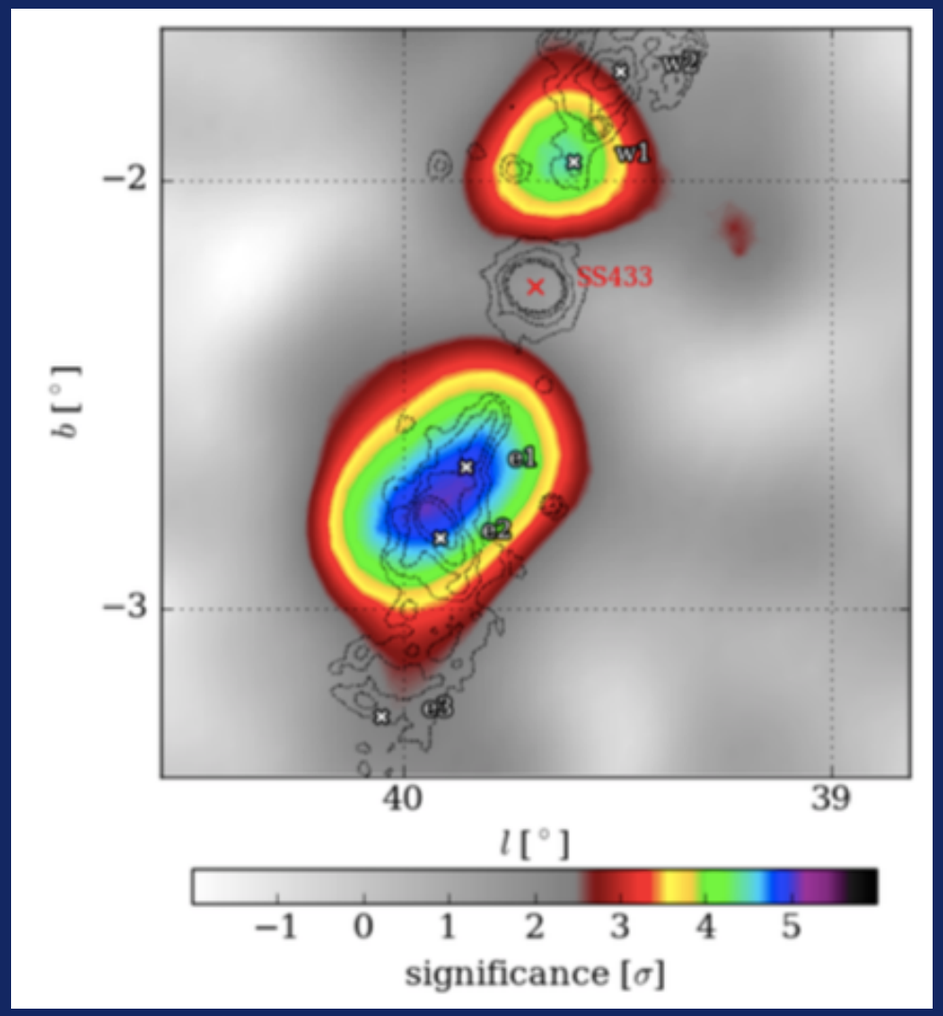


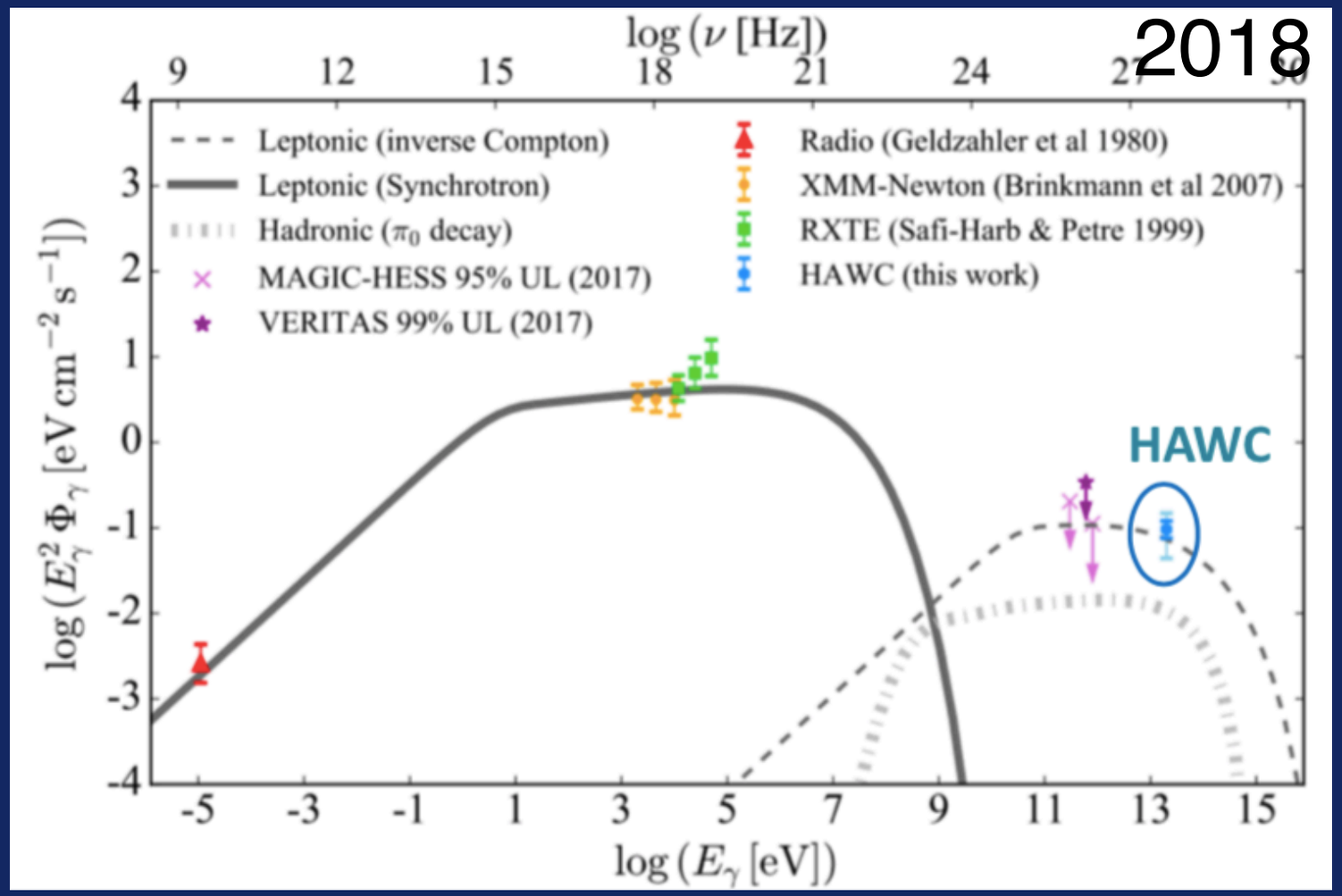
Chandra X-rays

- Vela: Spectral Energy Distribution strongly favors a two-component leptonic model
- Hadronic model is disfavored

Microquasar SS 433 and its Jets: (Galactic) Source of VHE γ rays $E_\gamma > 100$ TeV

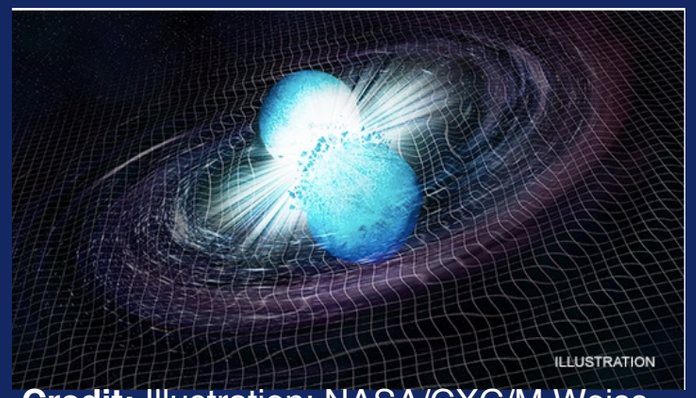






HAWC Collab. , Nature, 562: 82-85 (2018)

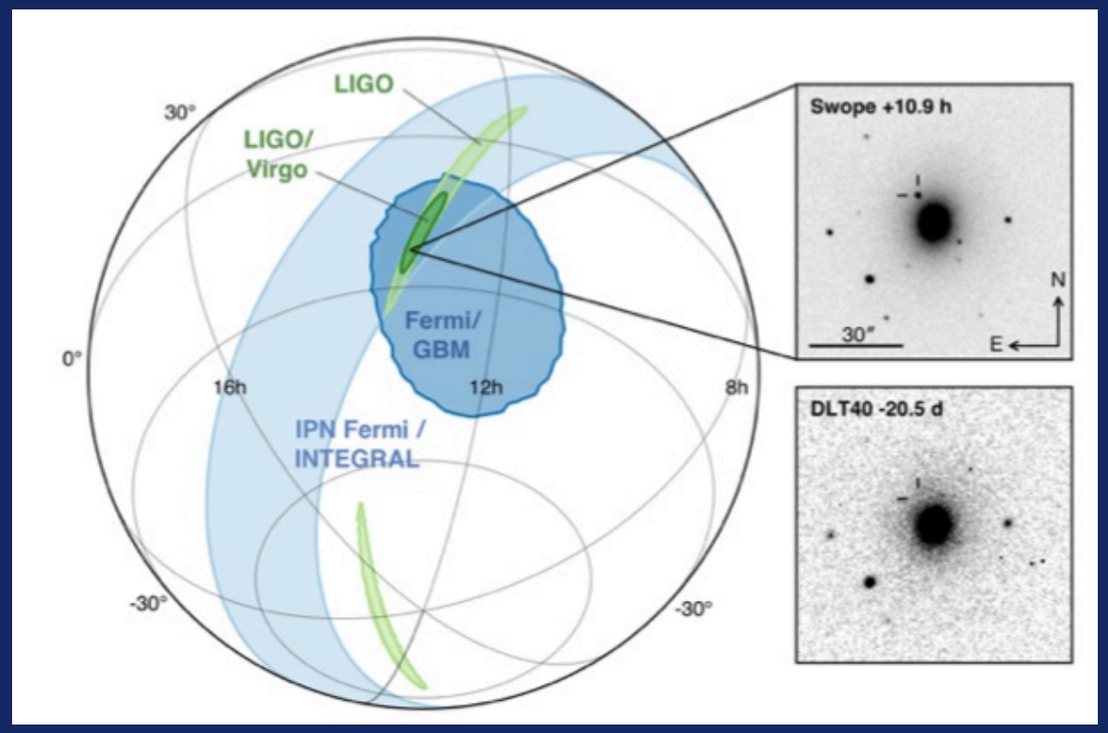
- SS433 : its jets distort the SNR shell
- First direct observation of particle acceleration in jets
- γ rays are not Doppler boosted, origin in lobes, not central Black Hole
- Model of PeV <u>electrons</u> + B of 16 mG matches the data



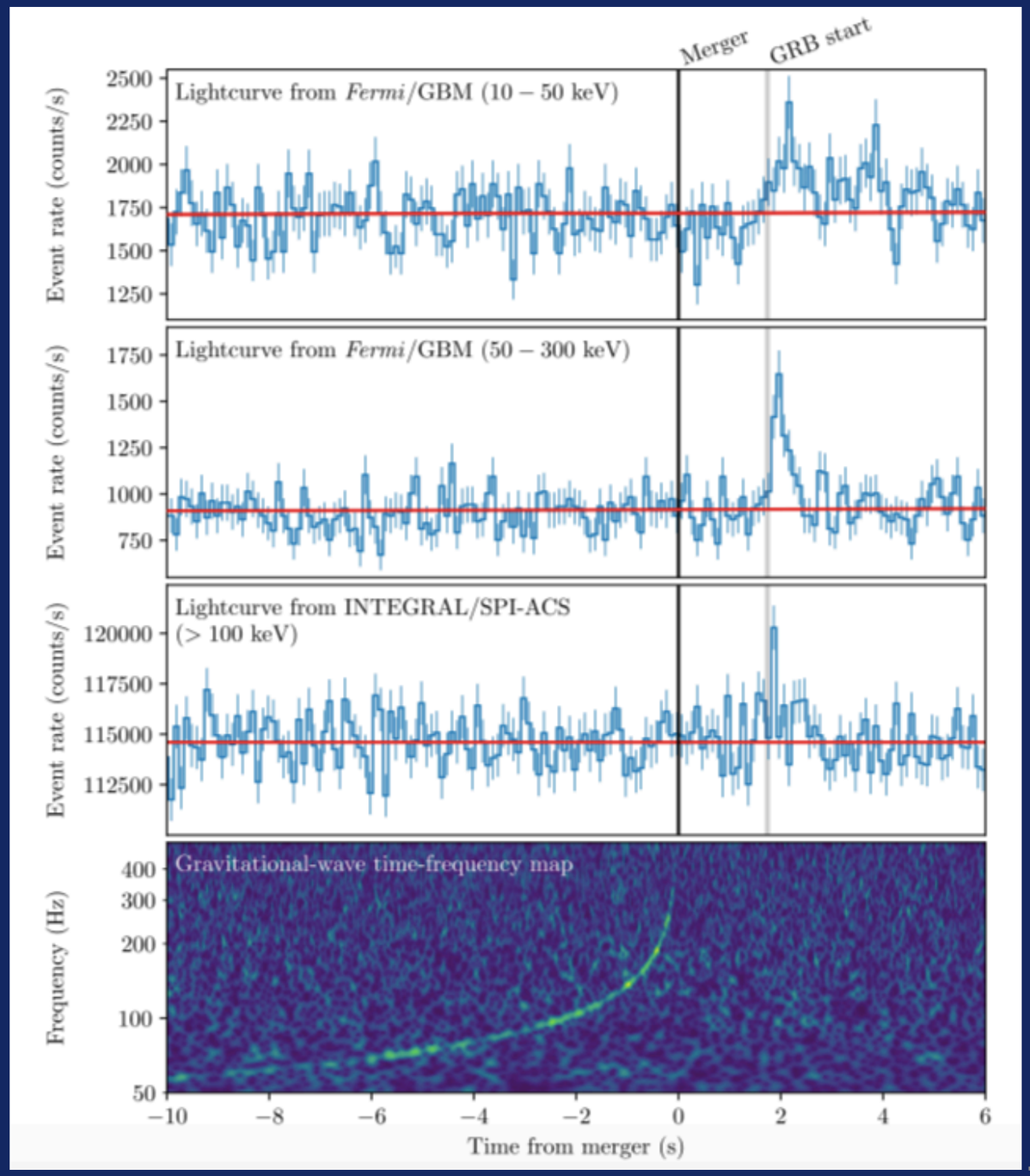
Credit: Illustration: NASA/CXC/M.Weiss

Neutron Stars Merger

Confirmed Source (Transient & Compact) of gravitational waves GW170817 and (short) gamma ray bursts GRB 170817A



Astrophys.J. 848 (2017) no.2, L12

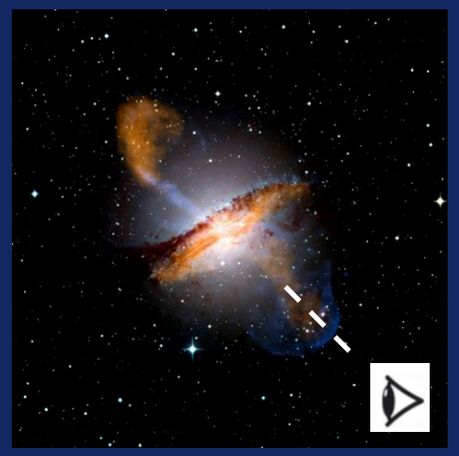


Astrophys.J. 848 (2017) no.2, L13

NS-merger: possible neutrino production source

No ν observed so far.

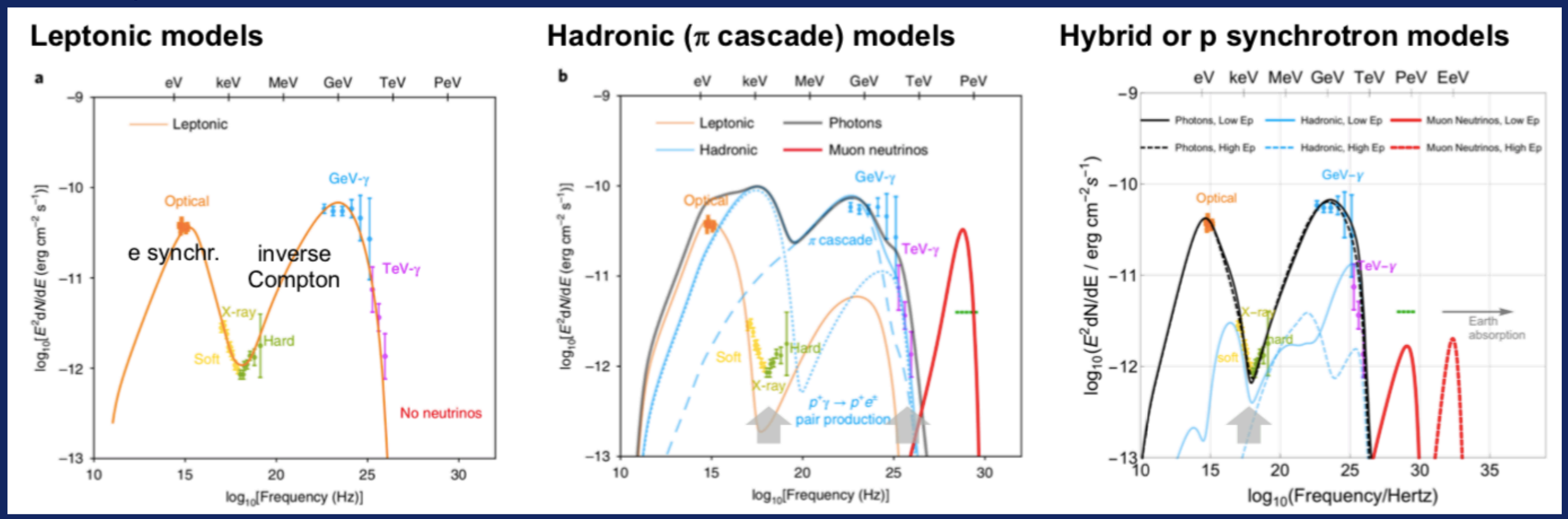
Astrophys.J. 850 (2017) no.2, L35
R. Hussain et al (ICRC2019)



TXS 0506+56 blazar (AGN+Jets)
(Extra Galactic) Source of (VHE) γ's and ν's

Example Model:

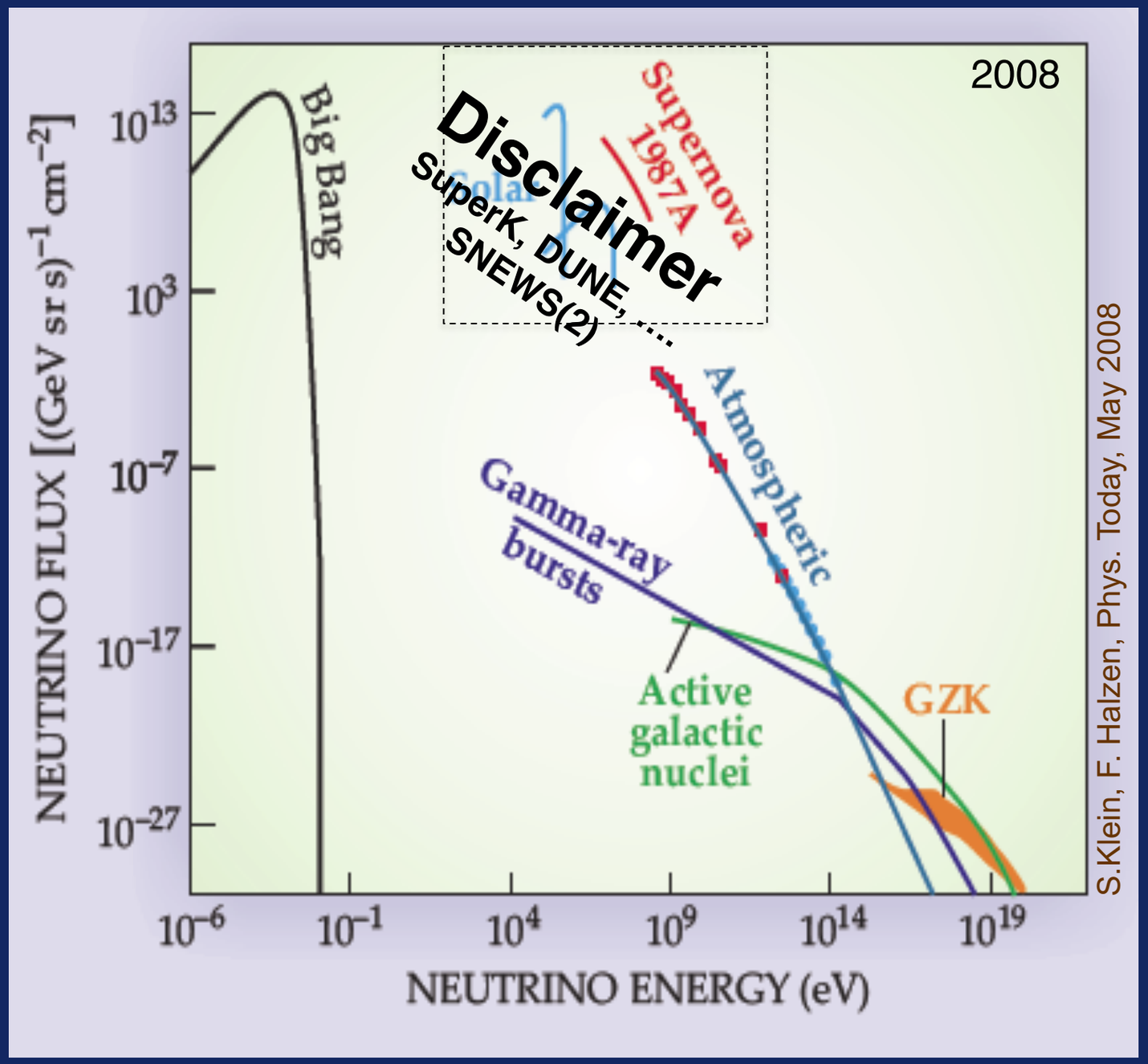
- One spherical radiation zone model



Gao et al, Nature Astronomy 3 (2019) 88
W. Winter et al (ICRC2019)

X-ray and VHE γ-ray data sensitive to (sub-dominant) hadronic contributions

Neutrino 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

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

Two neutrino production mechanisms at source:

- pp (hadro-production)
- pγ (photo-production)

Benchmark "model": pion and muon decays, e.g.

$$\pi^+ \to \mu^+ + \nu_\mu \to \left(e^+ + \nu_e + \overline{\nu_\mu}\right) + \nu_\mu$$

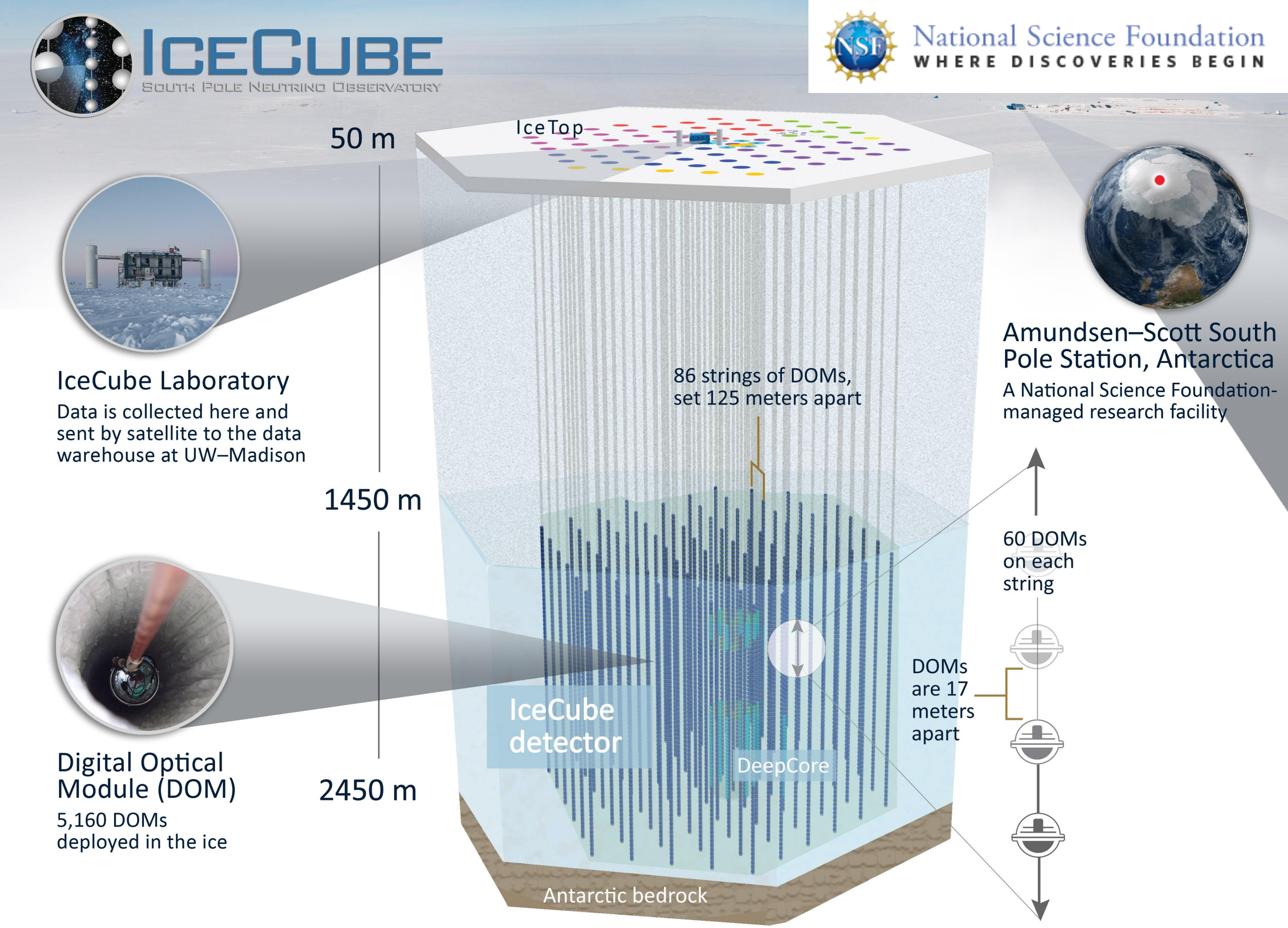
Resulting ν flux flavor composition:

At Source $(f_e : f_\mu : f_\tau)_S = (1:2:0)_S$

At Earth $(f_e : f_\mu : f_\tau)_E = (1:1:1)_E$

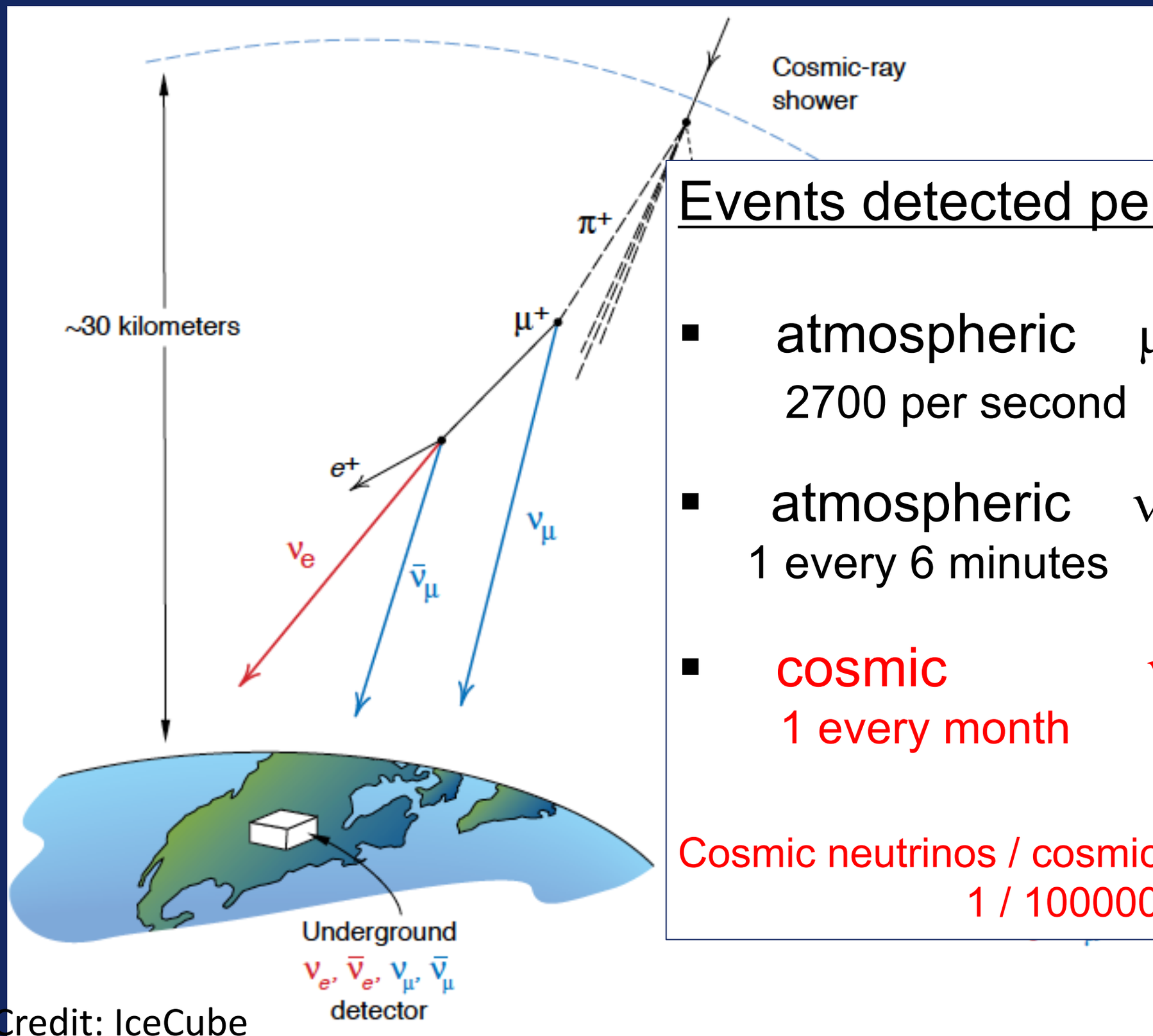
Require large detection volumes: ~ 1 km^3 or more

IceCube ν telescope



Credit: IceCube

Atmospheric muons and neutrinos: how many?



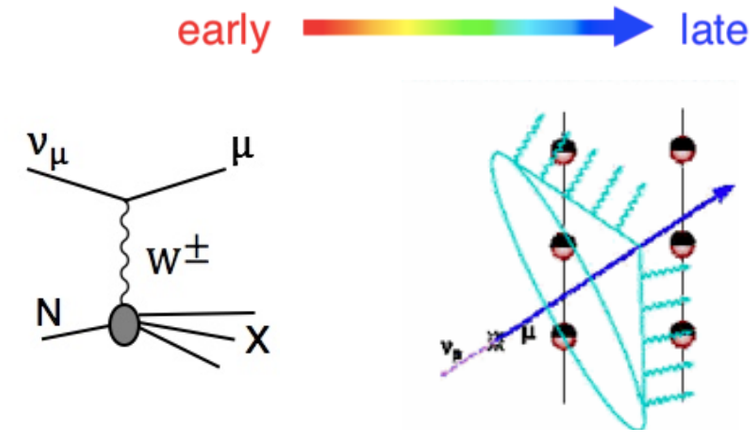
Credit: IceCube

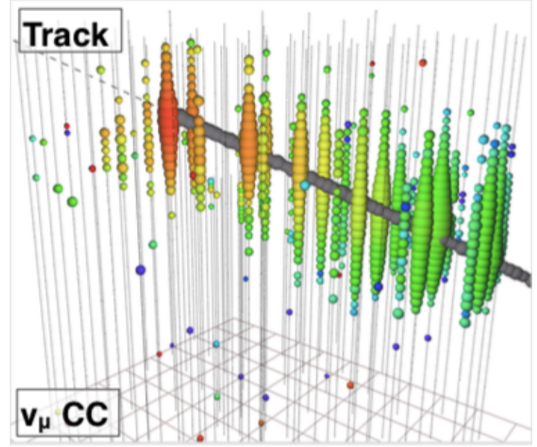
<u>Events detected per year:</u>

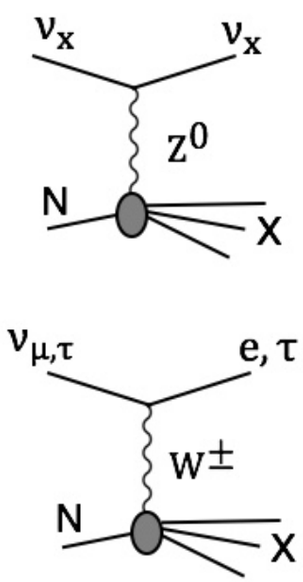
- atmospheric $\mu \sim 10^{11}$
  2700 per second
- atmospheric $\nu \sim 10^5$
  1 every 6 minutes
- cosmic $\nu \sim 10$
  1 every month

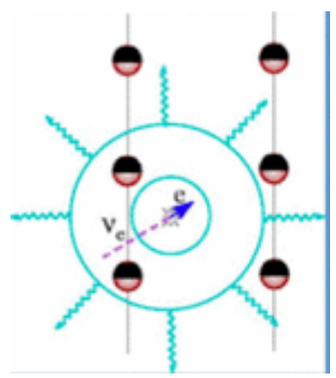
Cosmic neutrinos / cosmic rays background:
1 / 10000000000

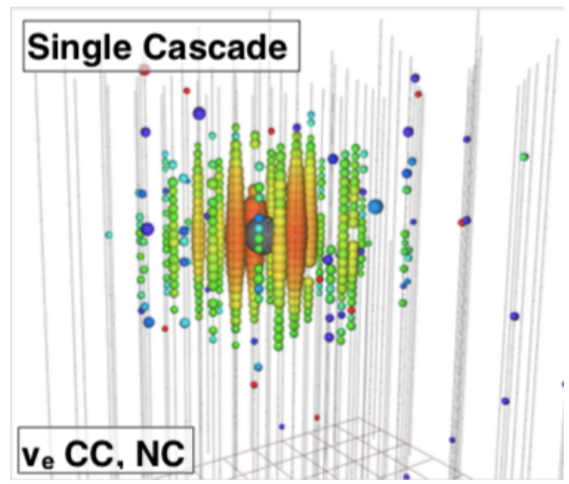
IceCube: Event Signatures

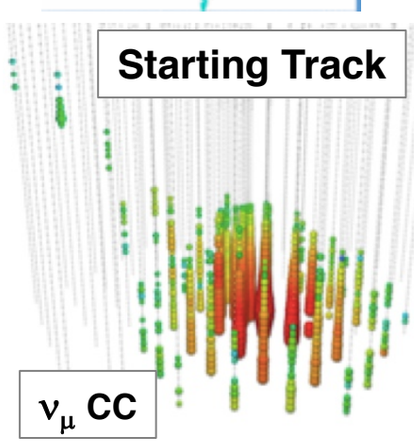


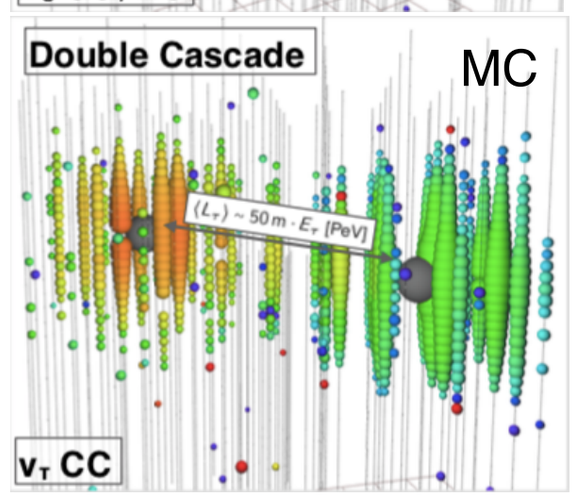












Tracks:

- 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

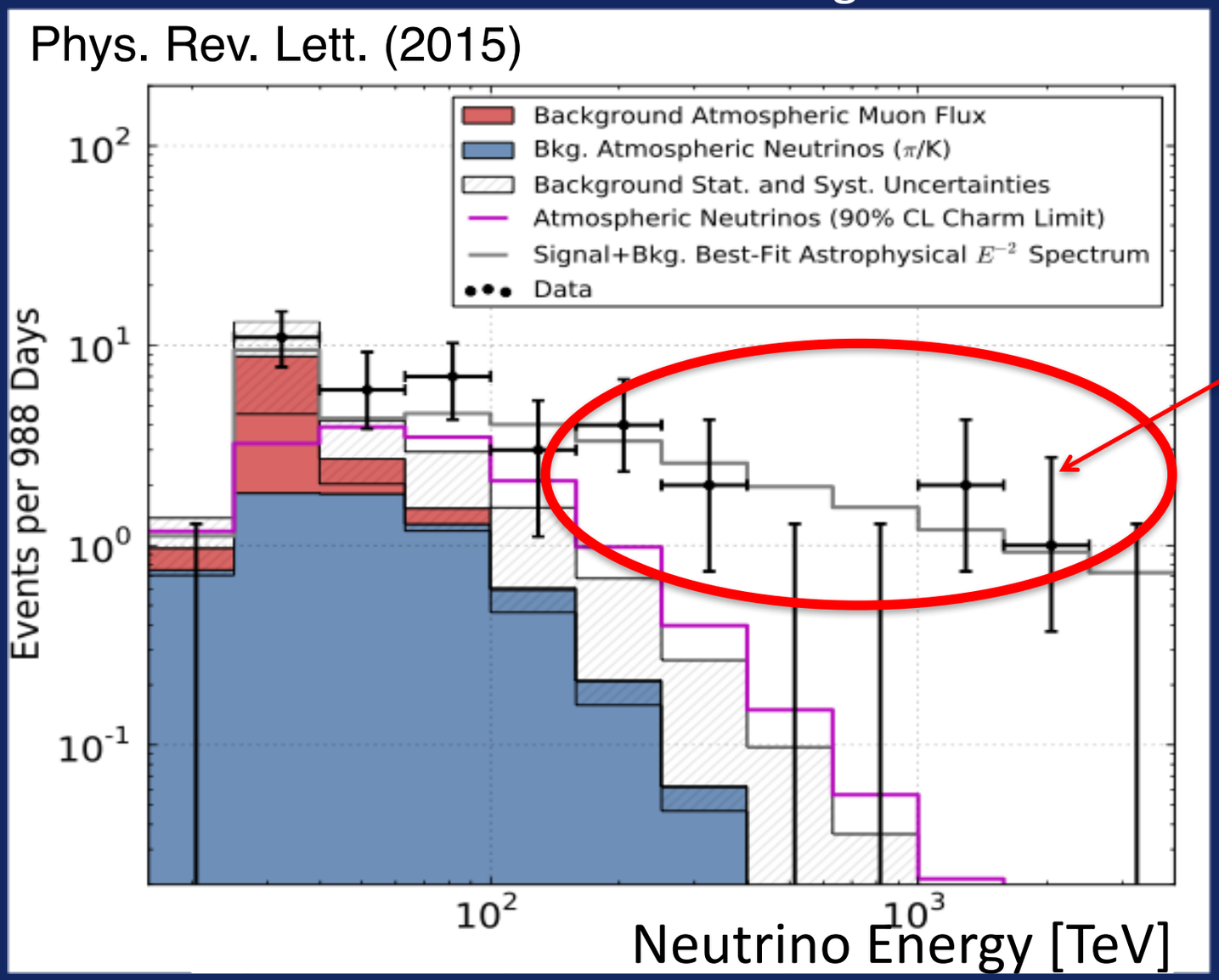
- starting tracks
- tau "double cascades" (τ hadronic decay)

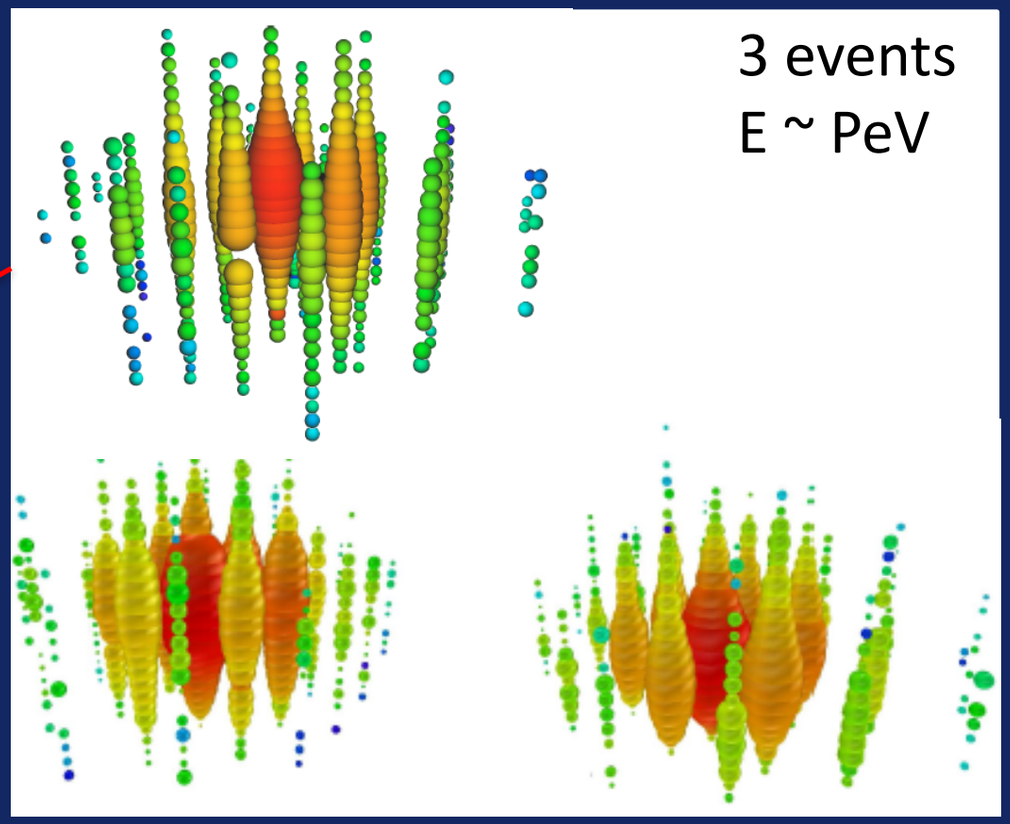
Cosmic Neutrino (diffuse) Flux

Discovery of Cosmic Neutrinos with IceCube

"$\nu_\mu + \nu_e + \nu_\tau$ All-Sky High Energy Starting Events" (HESE) analysis

Contained Cascades + Starting Tracks



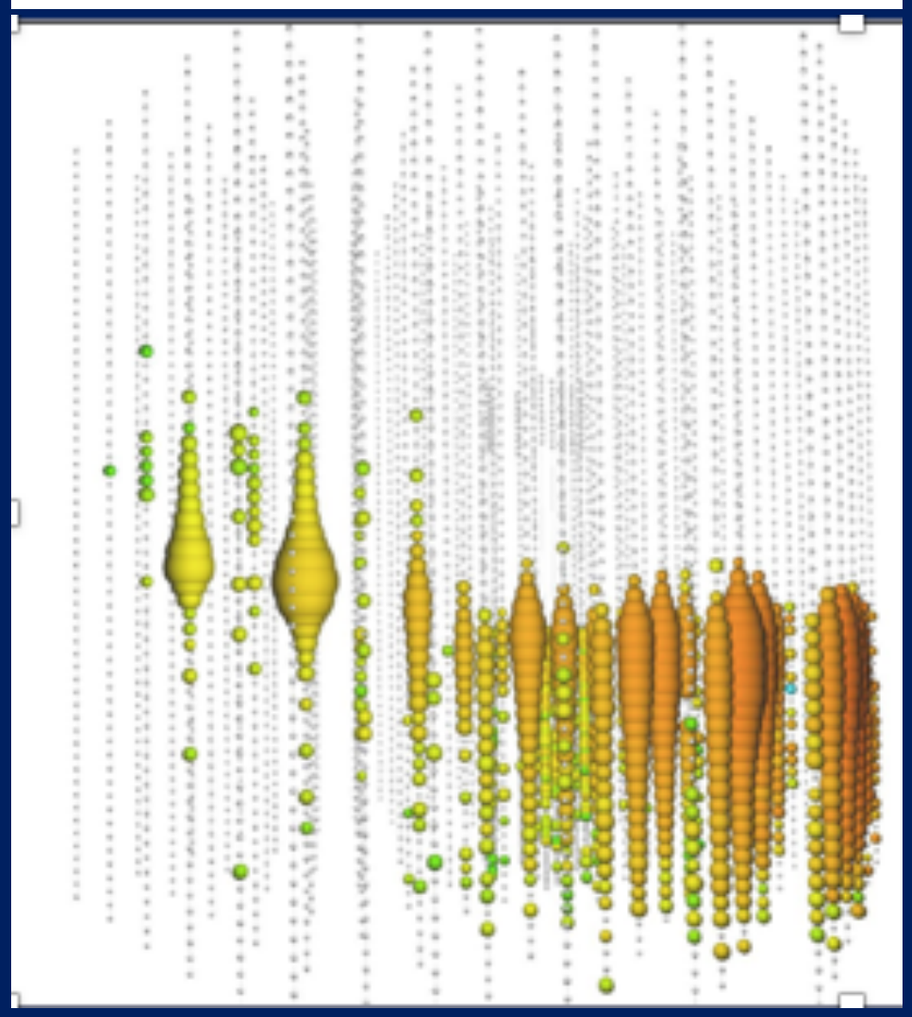


IceCube Highest Energy PeV Neutrinos

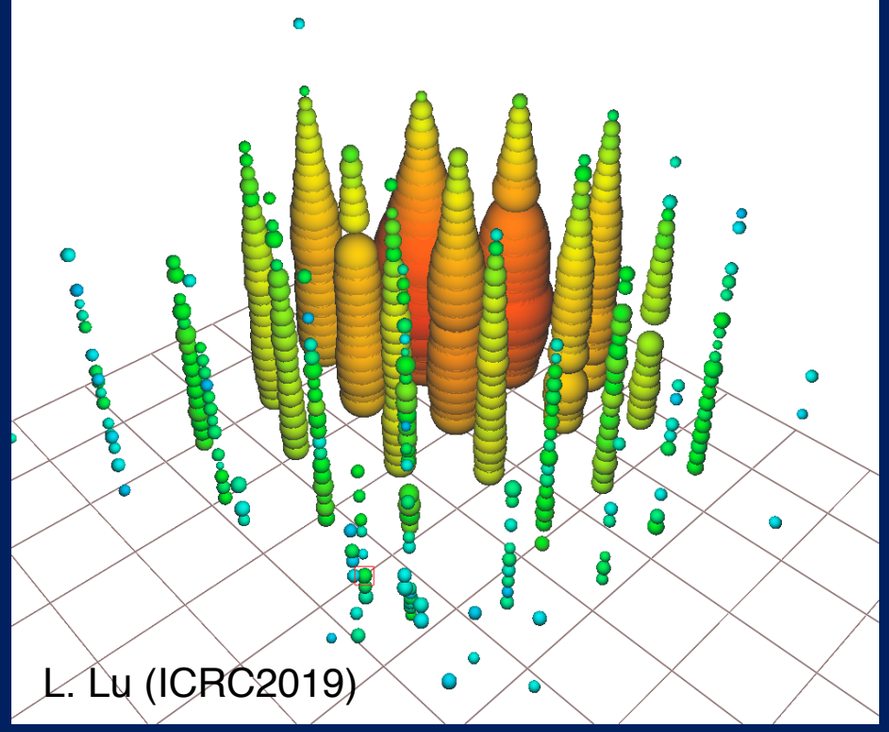
Muon Neutrino (track) PoS(ICRC2015) 1079

June 2014
deposited energy:
2.6 ± 0.3 PeV
DEC=11.42° RA=110.63°

Median muon energy: 4.5 ± 1.2 PeV
Median ν energy: 8.7 PeV

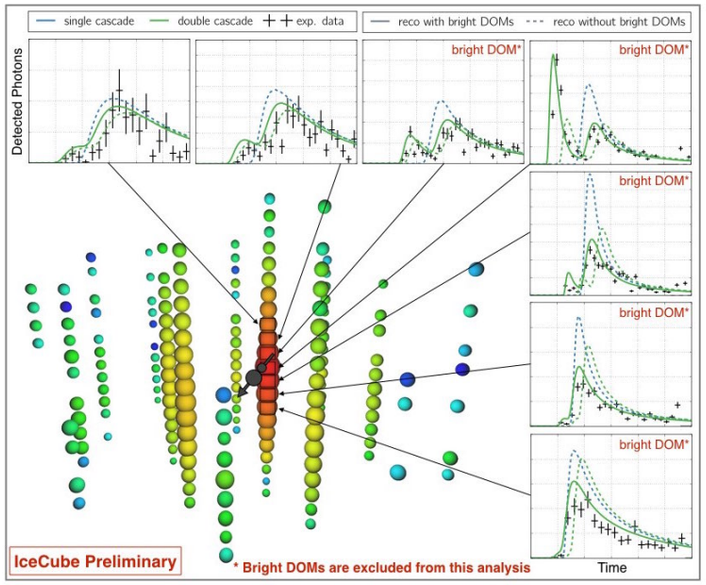


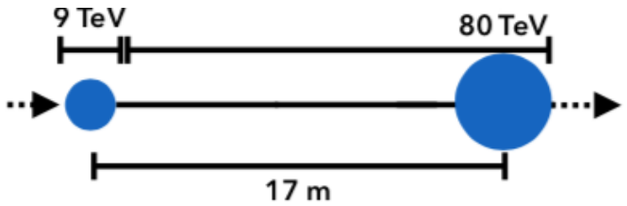
partially contained Cascade
deposited energy: 5.9±0.18 PeV



L. Lu (ICRC2019)

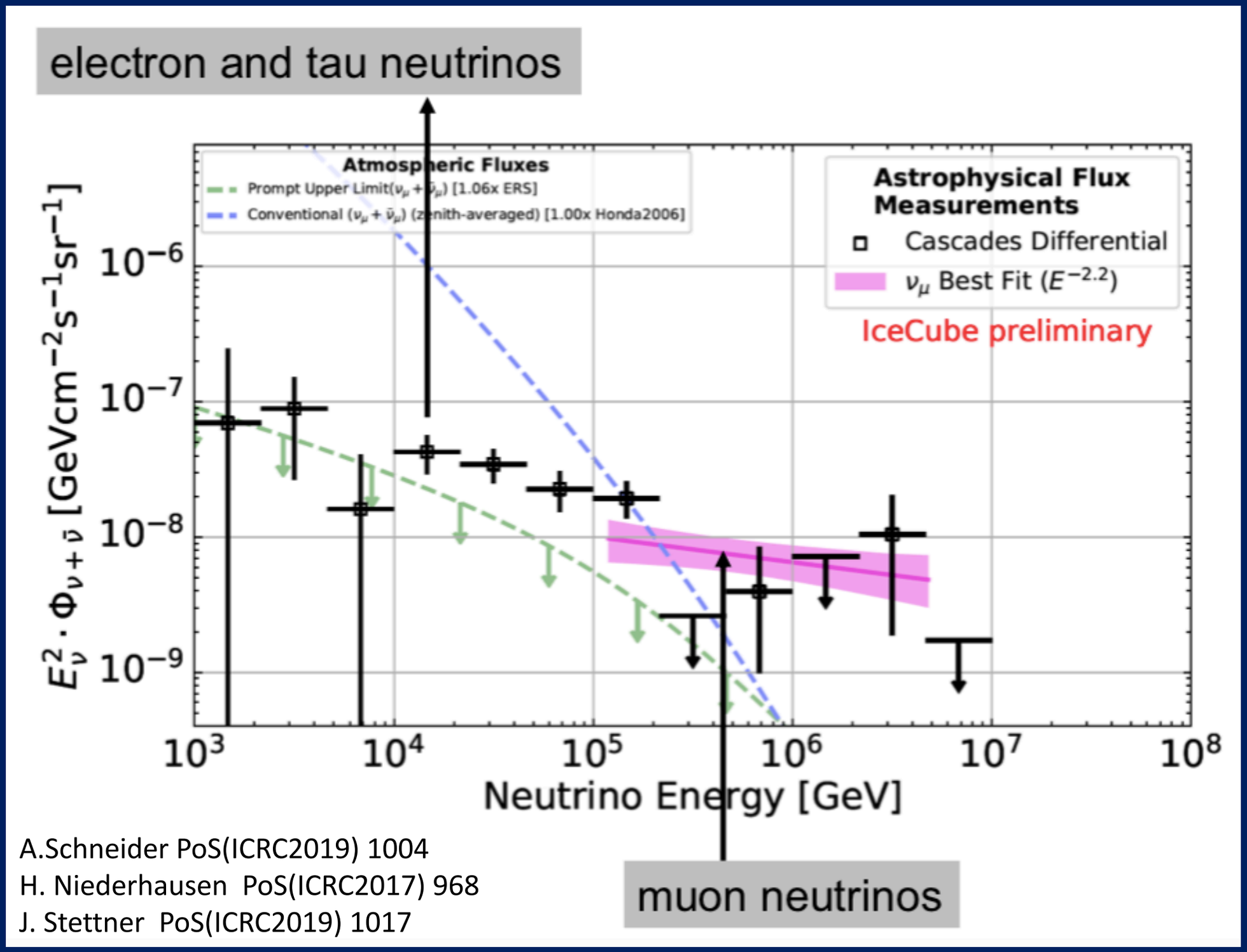
Double cascade & double pulse, tau neutrino candidate
deposited energy 90 TeV





J. Stachurska (ICRC2019)
J. Soedingrekso, L. Wille (ICRC2019)

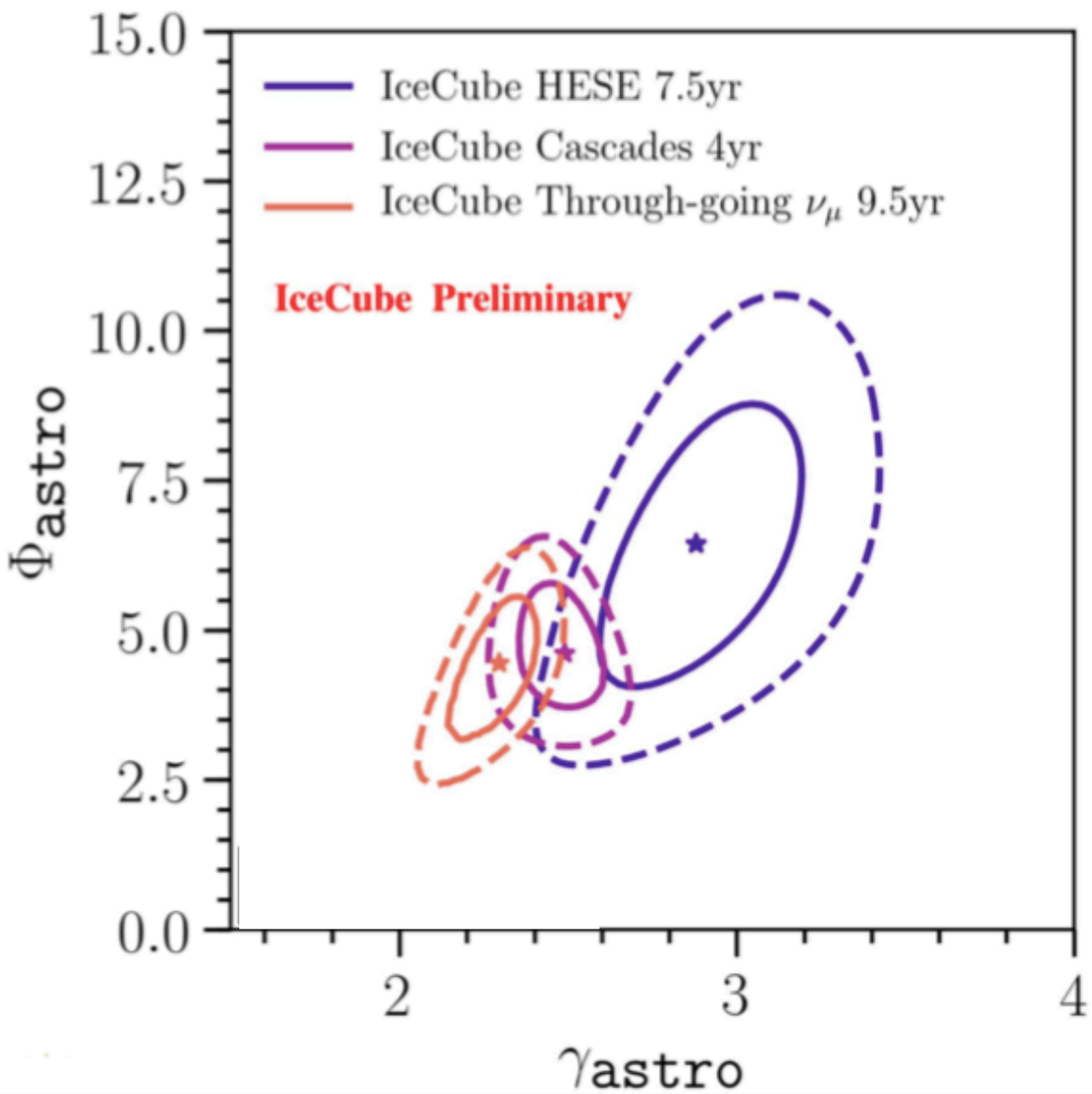
IceCube Diffuse Neutrino flux
Measurements and characteristics



A.Schneider PoS(ICRC2019) 1004
H. Niederhausen PoS(ICRC2017) 968
J. Stettner PoS(ICRC2019) 1017

Fig. From F. Halzen (ICRC2019)

IceCube Diffuse Neutrino flux Measurements and characteristics



$$\frac{d\Phi_{6\nu}}{dE} = \Phi_{astro}\left(\frac{E_\nu}{100\text{TeV}}\right)^{-\gamma_{astro}} \cdot 10^{-18}\ [\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]$$

Name	Approx. Neutrino Energy	Direction	Dominant Flavor	Unbroken Spectral Index
HESE	50 TeV - 5 PeV	All-sky	e, μ, τ	2.89
Cascades	5 TeV - 5 Pev	All-sky	e, τ	2.48
NuMu	50 TeV - 10 PeV	Northern sky	μ	2.28

A.Schneider PoS(ICRC2019) 1004
H. Niederhausen PoS(ICRC2017) 968
J. Stettner PoS(ICRC2019) 1017
+ Starting tracks only: Phys. Rev. D99, 032004 (2019)

A. Kappes, D. Williams (ICRC2019)

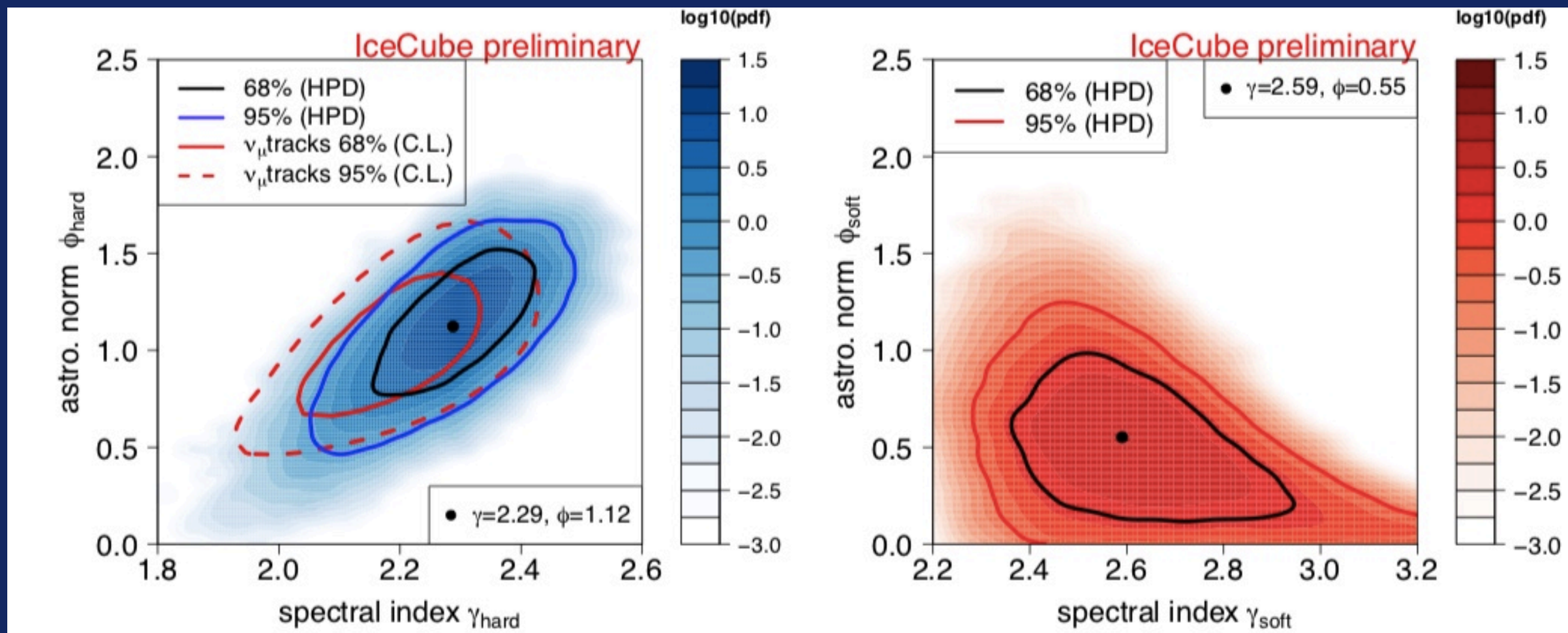
Single power law (unbroken) describes data well,
IceCube continue to observe PeV ν events

Cascades diffuse flux measurement and characteristics

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

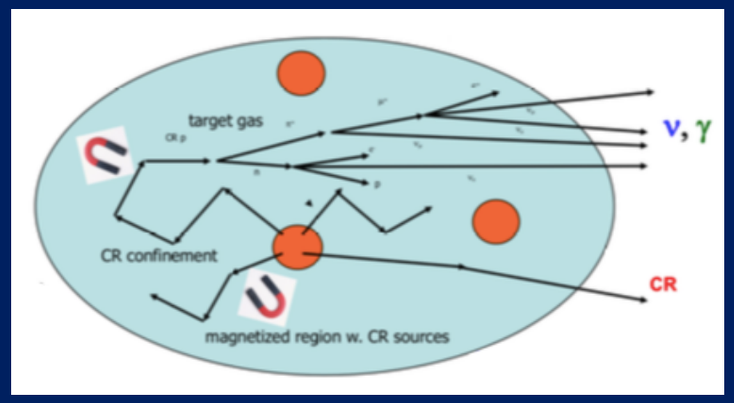
Beyond single power-law

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

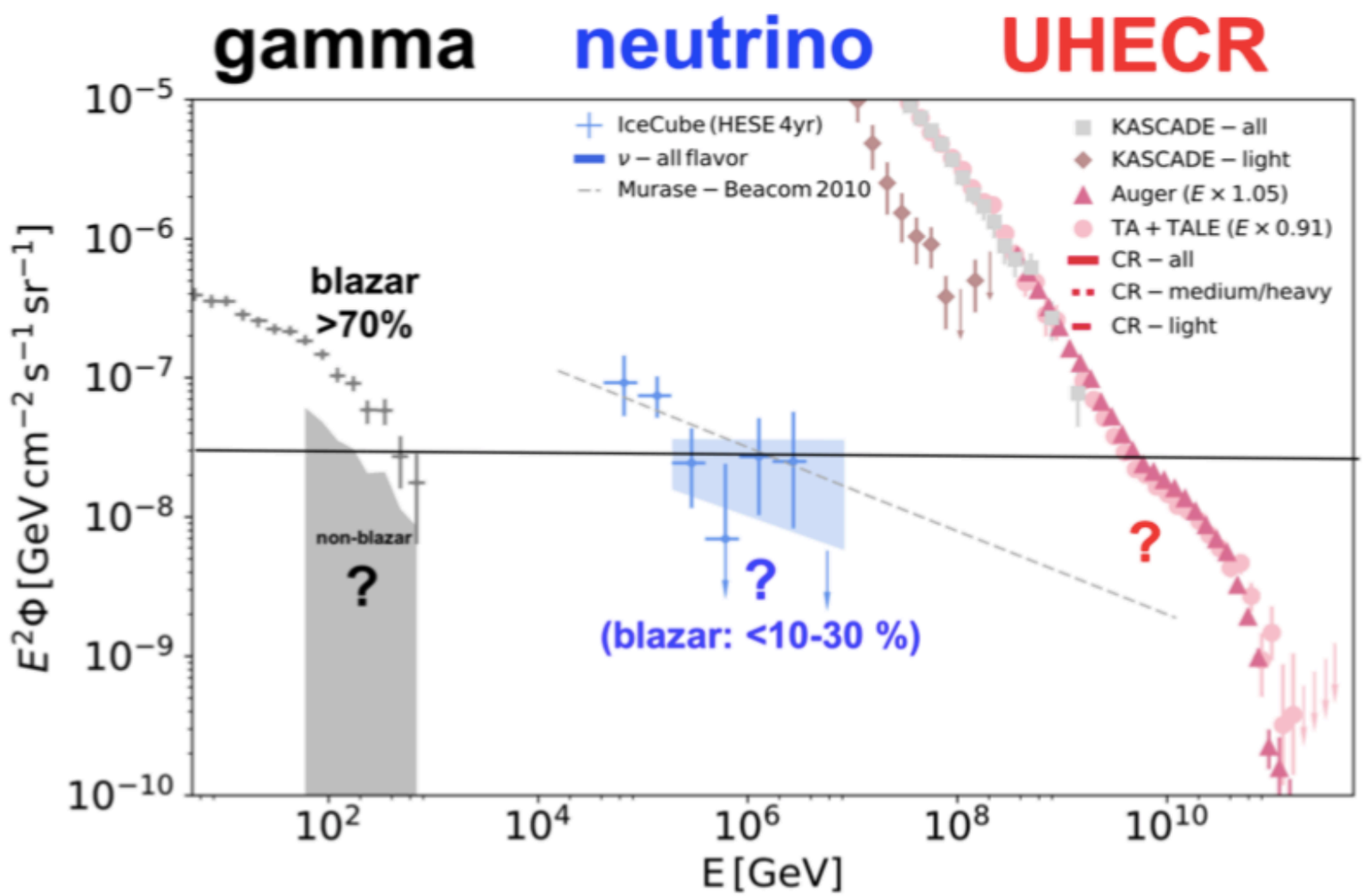


Fit with two component flux model describes cascade data well, however fit with single power law flux is preferred.

Neutrino, γ-rays and cosmic rays connection



Cosmic Rays "reservoirs":
Starburst galaxies (SN, GRB's,)
Galaxy clusters



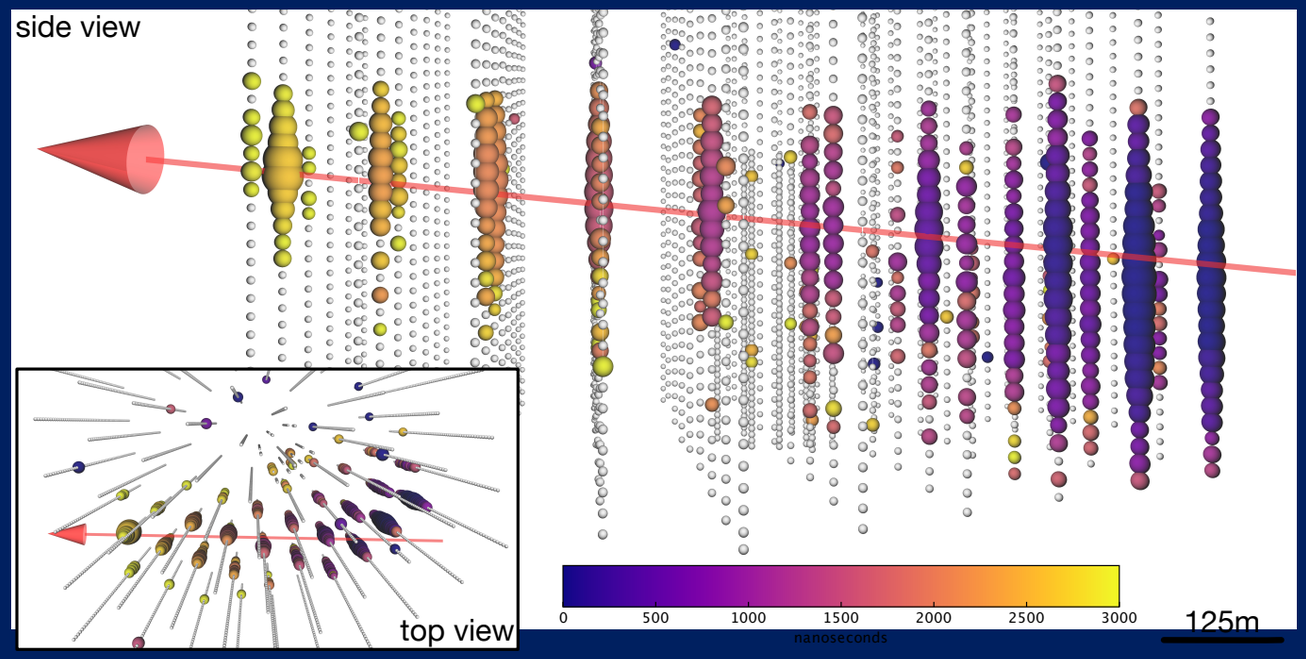
Particle energy budgets are roughly comparable (10^{43} -10^{44} erg Mpc^{-3} yr^{-1})

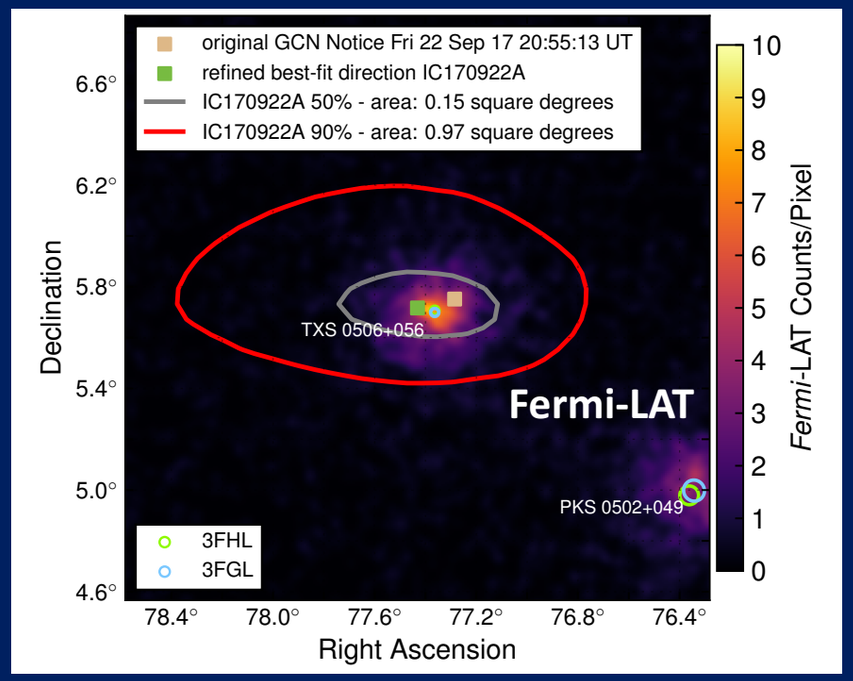
Figs from: A.Kappes, K. Murase (ICRC2019)

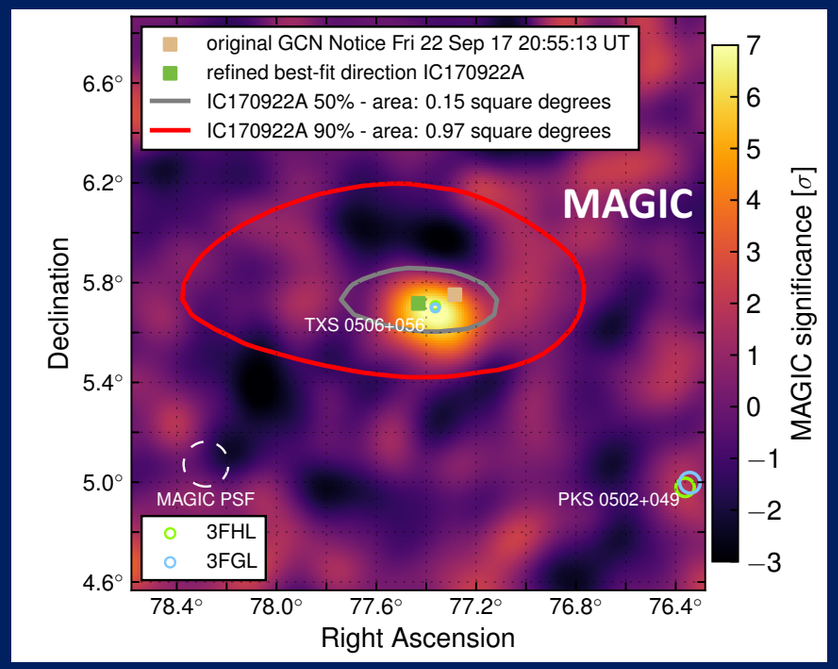
Cosmic Neutrino (Point) Sources

Evidence of the first ν source: TXS 0506+056

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







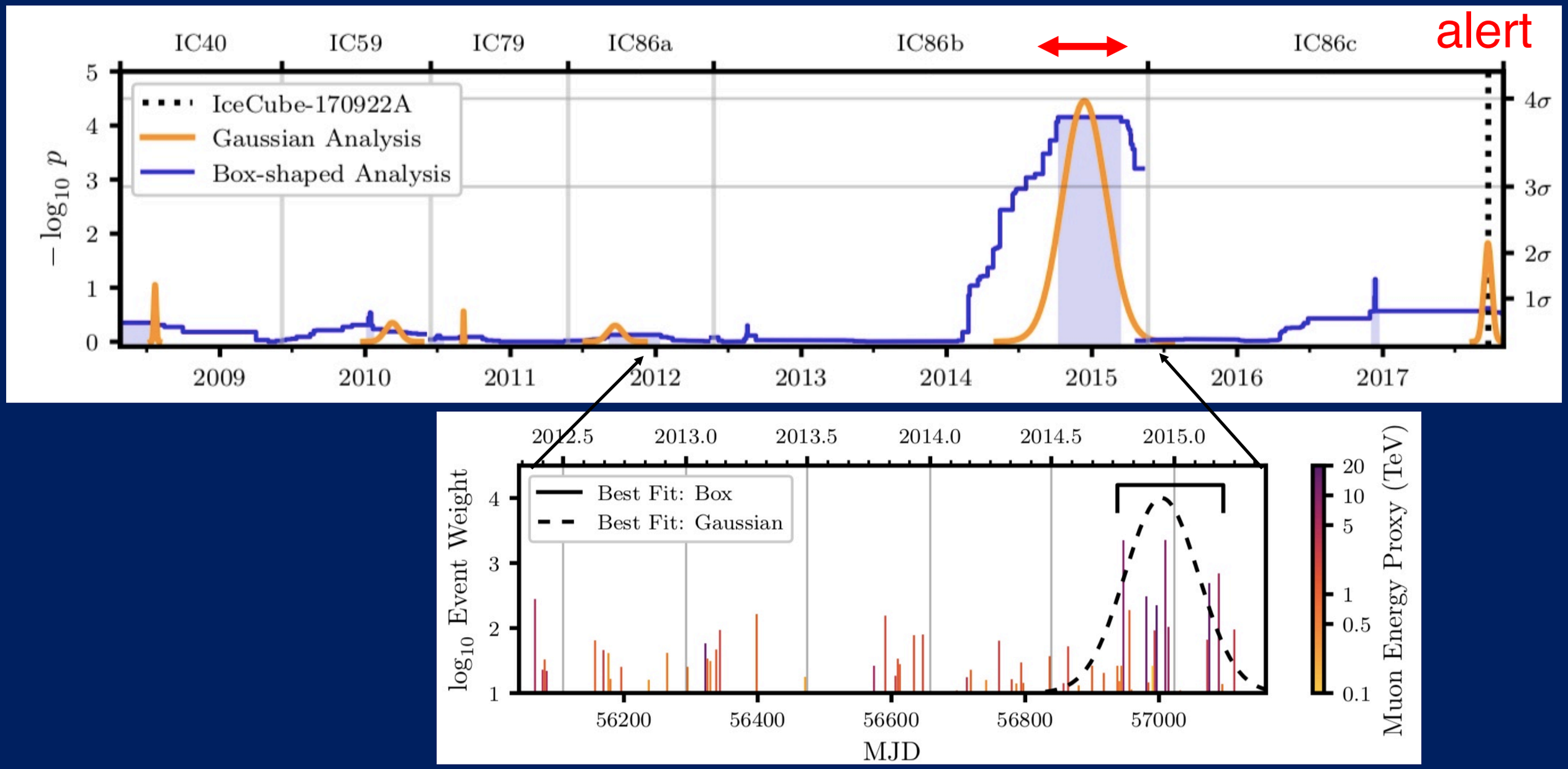
On 22 September 2017 IceCube detected a ~290-TeV neutrino from a direction , as reported by Fermi-LAT on September 28 2017, consistent with the flaring γ-ray blazar TXS 0506+056.

Multi-wavelength photon follow up observations

Evidence of the first ν source: TXS 0506+056

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

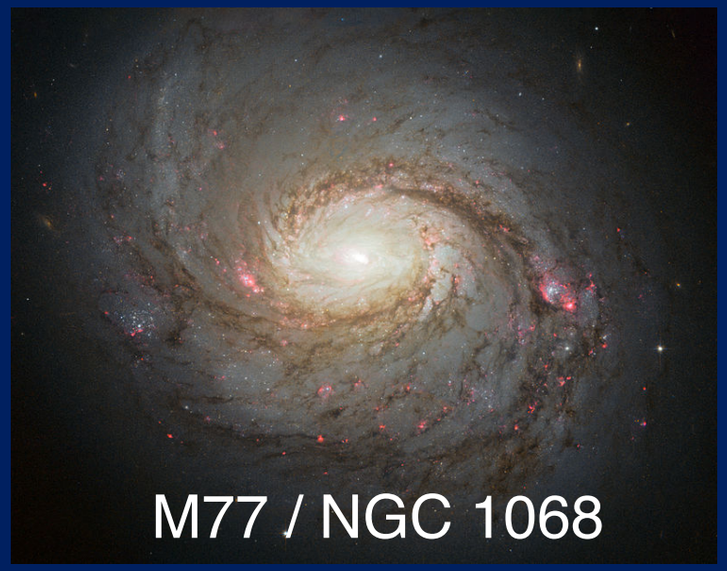
- **ν_μ-flare found in archival IceCube data 10/2014- 03/2015**

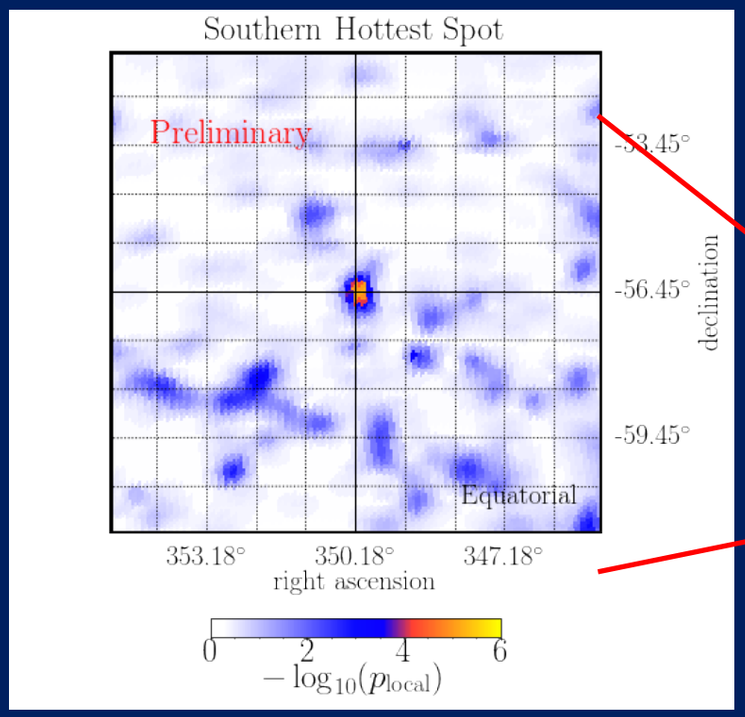


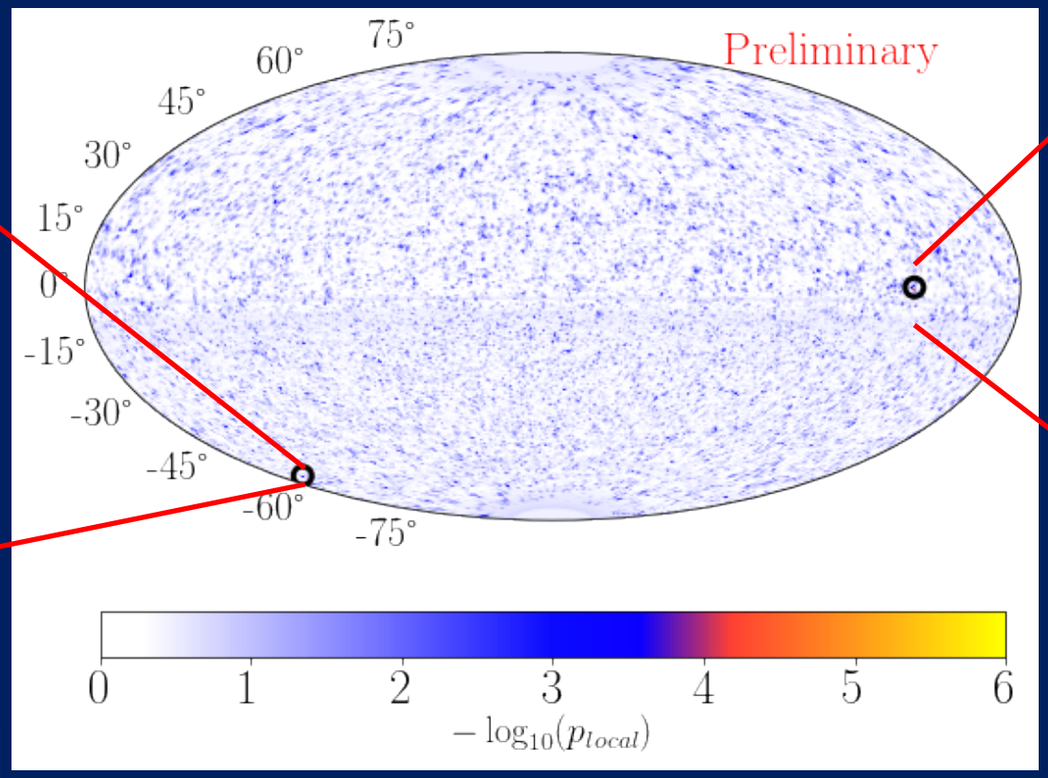
Identification of a blazar as a source of HE ν's and CR's
Significance: 3.5 sigma (2 / 10000)

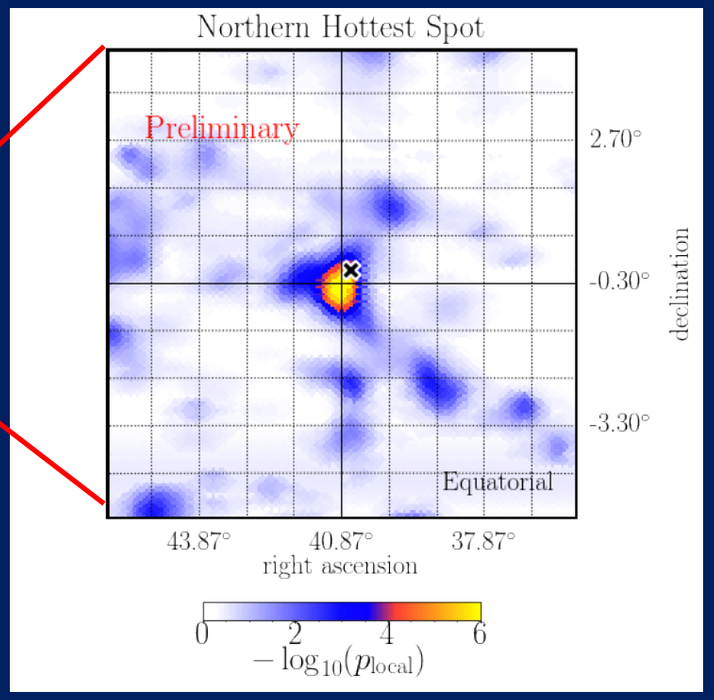
IceCube All-Sky Point Source Search

- All-Sky search (10yrs): Search for excess of astro ν from a common direction over the bg of atm. ν (Northern Sky) or μ / ν (Southern Sky).
- Assumed time integrated emission of ν's and $E^{-\gamma}$ energy spectrum.









Hottest Point in South : δ< -5°

RA = 350.18° , Dec -56.45°

n_{signal} =17.8, γ = 3.3, TS= 20.0

-log10(pval) =5.37 ⇒ 75% post-trial

Hottest Point in North : δ ≥ -5°

RA = 40.87° , Dec = -0.30°

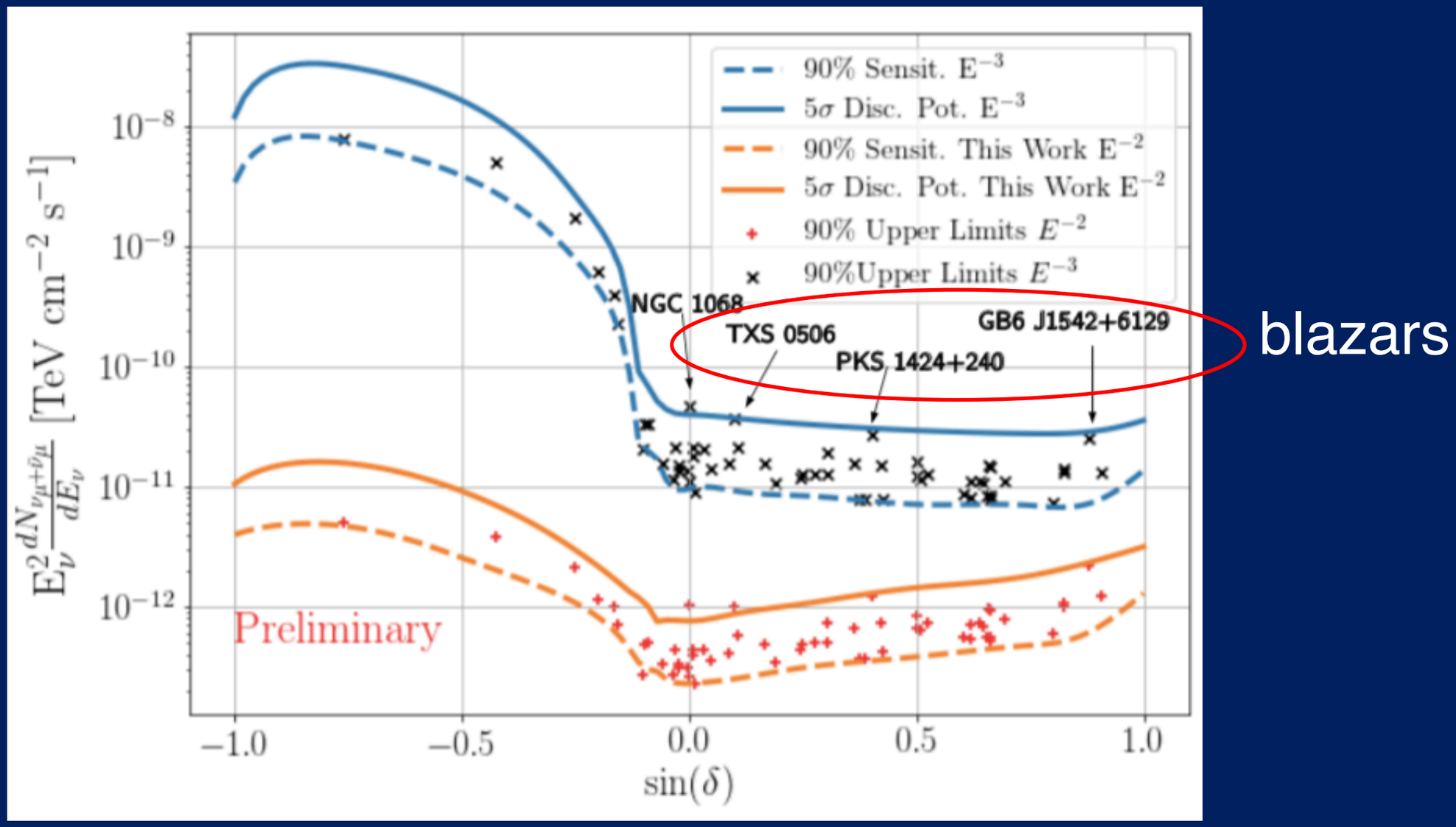
n_{signal} = 61.5 , γ= 3.4, TS = 25.3

-log10(pval)= 6.45 ⇒ 9.9% post-trial

T. Carver et al (ICRC2019)

IceCube All-Sky Point Source: Catalog List Search

- New source candidates list of 110 Galactic & Extra-galactic sources
- Results: Northern Sources (87 extra-galactic, 10 Galactic)
  Southern Sources (11 extra-galactic, 2 Galactic)



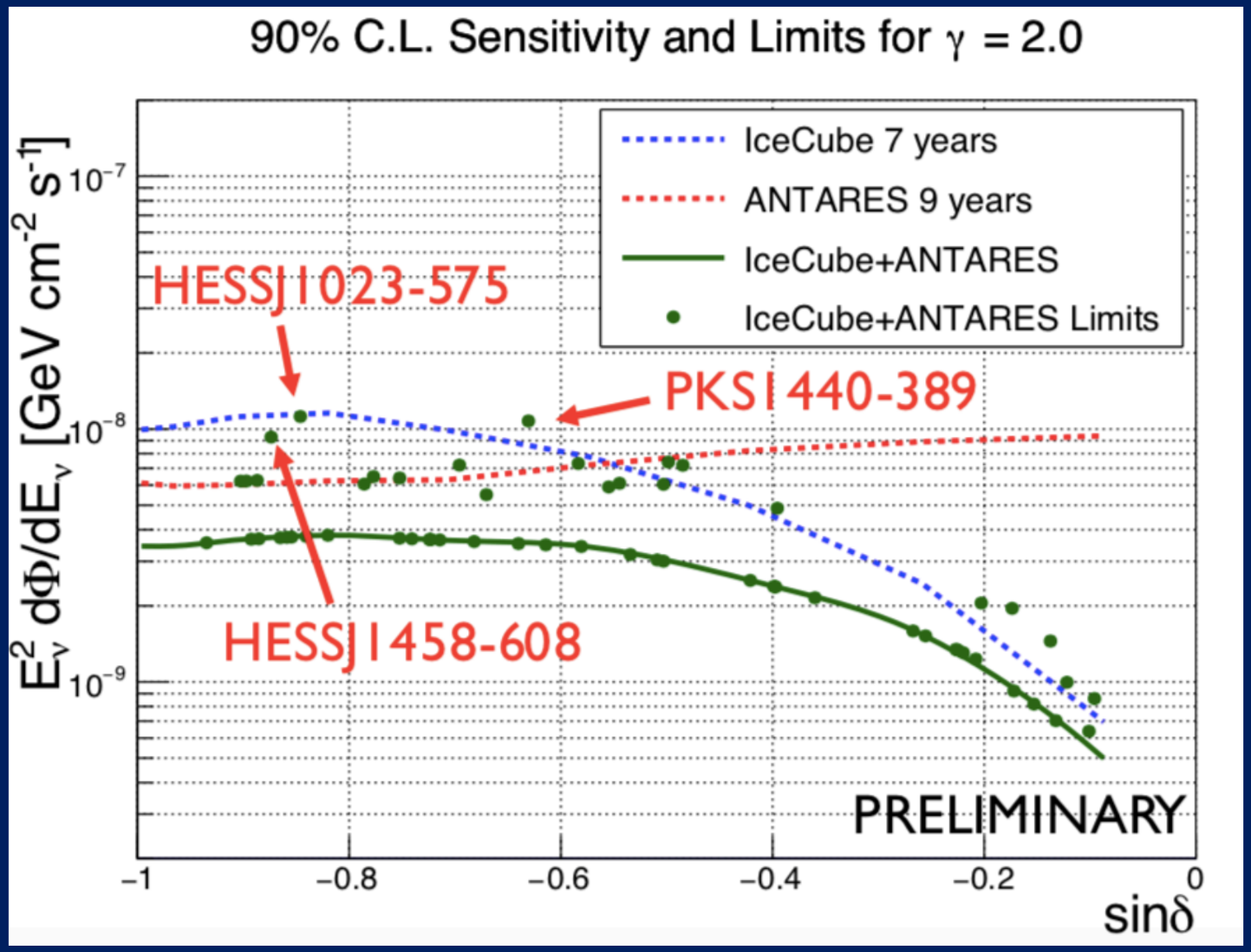
blazars

- Most significant source from list NGC1068 (2.9σ post trial)
- 4 most significant sources 3.3σ post trial (2.2σ without TXS 0506)

T. Carver et al (ICRC2019)

IceCube+Antares: Southern-Sky Point Source Catalog List Search

- New source candidates list of 57 Galactic & Extra-galactic sources
- 7yrs IceCube data + 9years Antares data



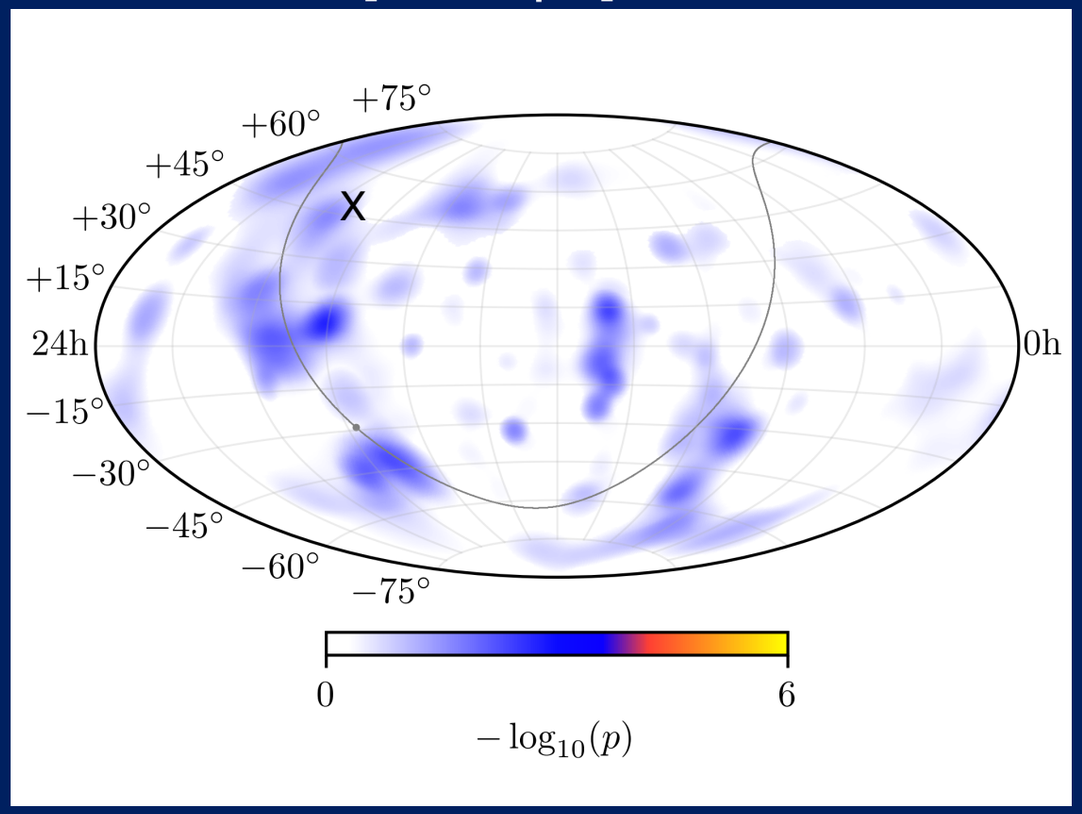
No significant evidence of cosmic neutrino sources has been found

Source name	δ	$\hat{n}_s$	$\hat{\gamma}$	pre-trial p-value	$\Phi_{E^{-2.0}}^{90\%C.L.}$ [10^{-9} GeV cm^{-2} s^{-1}]	$\Phi_{E^{-2.5}}^{90\%C.L.}$ [10^{-6} GeV$^{1.5}$ cm^{-2} s^{-1}]
HESSJ1023-575	-57.76°	6.4	3.5	0.0079	11.2	2.5
PKS1440-389	-39.14°	3.0	2.4	0.0085	10.8	3.0
HESSJ1458-608	-60.88°	3.7	3.6	0.036	9.3	2.0

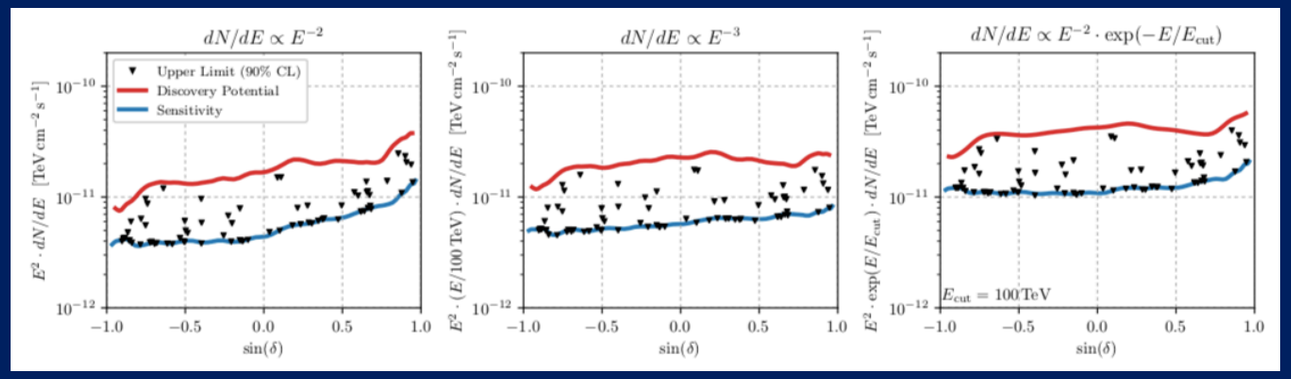
G. Illuminati et al (ICRC2019)

IceCube All-Sky Source Search with Cascades (7yrs)

1907.06714 [astro-ph]



- Median cascade resolution < 10^0 above 40 TeV with deep learning
- The most significant source was RX J1713.7-3946 (Supernova Remnant, SNR)



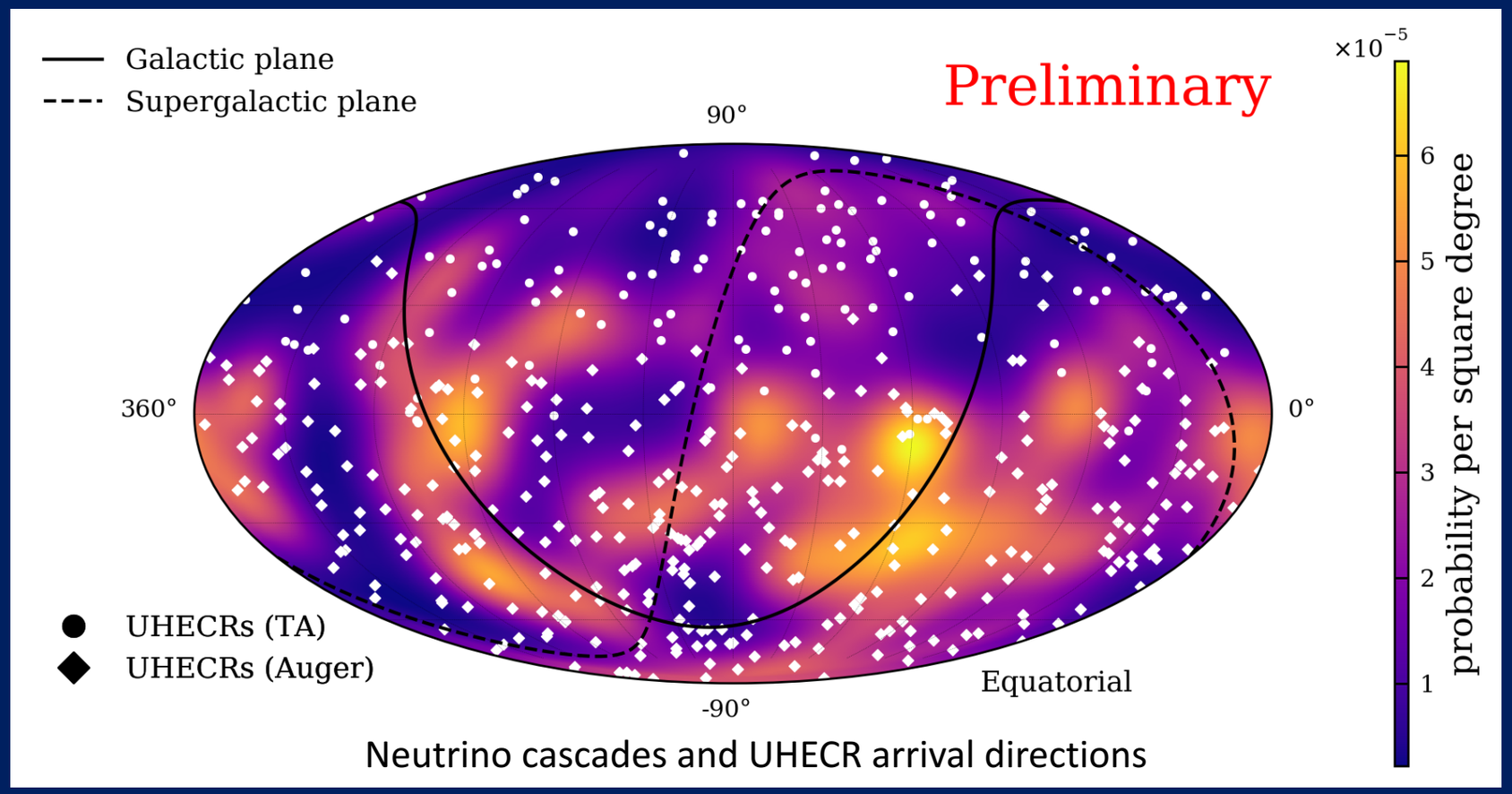
SNR stacking analysis results

	7yr Cascades					7yr Tracks			
Catalog	Sensitivity	p-value	n_s	γ	UL	p-value	n_s	γ	UL
SNR with mol. cloud	9.9	0.12	17.2	3.76	24	0.25	16.5	3.95	2.23
SNR with PWN	6.3	1	0	—	6.3	0.34	9.36	3.95	11.7
SNR alone	7.5	0.082	8.2	2.42	15	0.42	3.82	2.25	2.06

Table 1. Sensitivity and results of the SNR stacking analyses, compared to the previous analysis with tracks (Aartsen et al. 2017b). Sensitivity and ULs are given as $E^2 \cdot (E/100\,\mathrm{TeV})^{0.5} \cdot dN/dE$ in units 10^{-12} TeV cm^{-2} s.

Search for Sources of Neutrinos and UHECR

Combined ANTARES, IceCube, PAO and TA search for common origin between high energy neutrinos and cosmic rays



Three searches:

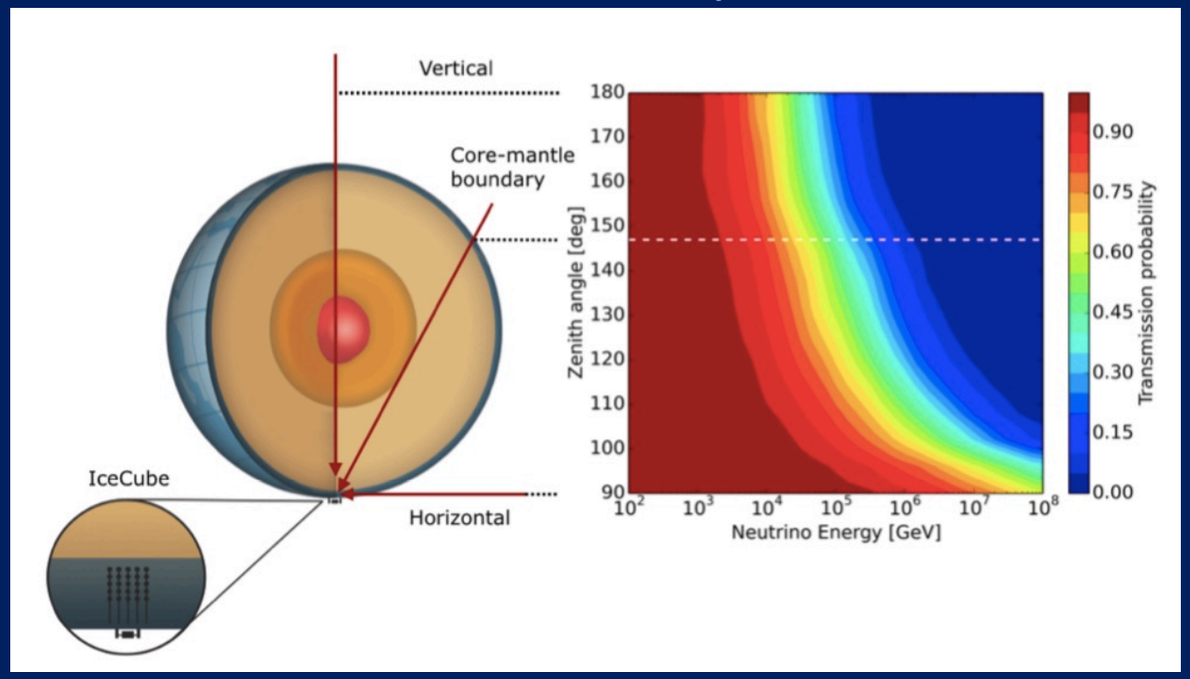
1. Neutrino/UHECR cross-correlation
2. Search for neutrino clusters in direction of UHECR
3. Search for UHECR clusters in direction of neutrinos

No significant correlation seen

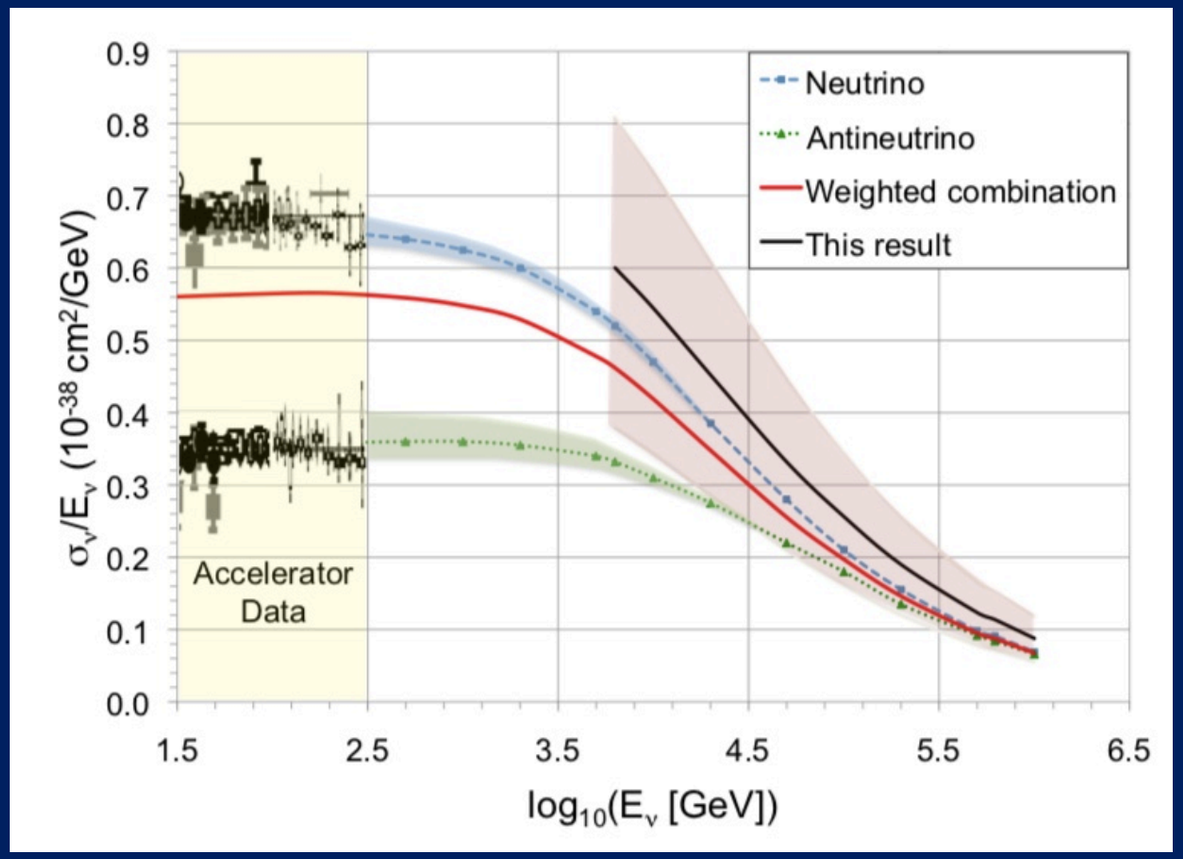
A. Barbano, D. Williams (ICRC2019)

Neutrino- Nucleon Cross Section Measurements

TeV-PeV Neutrino absorption in Earth



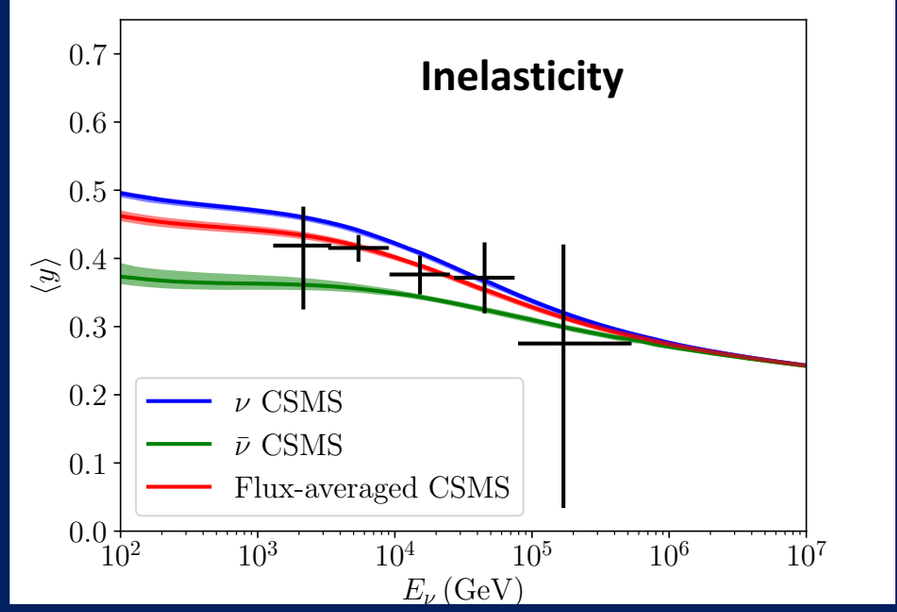
IceCube: Nature 551 (2017) 596



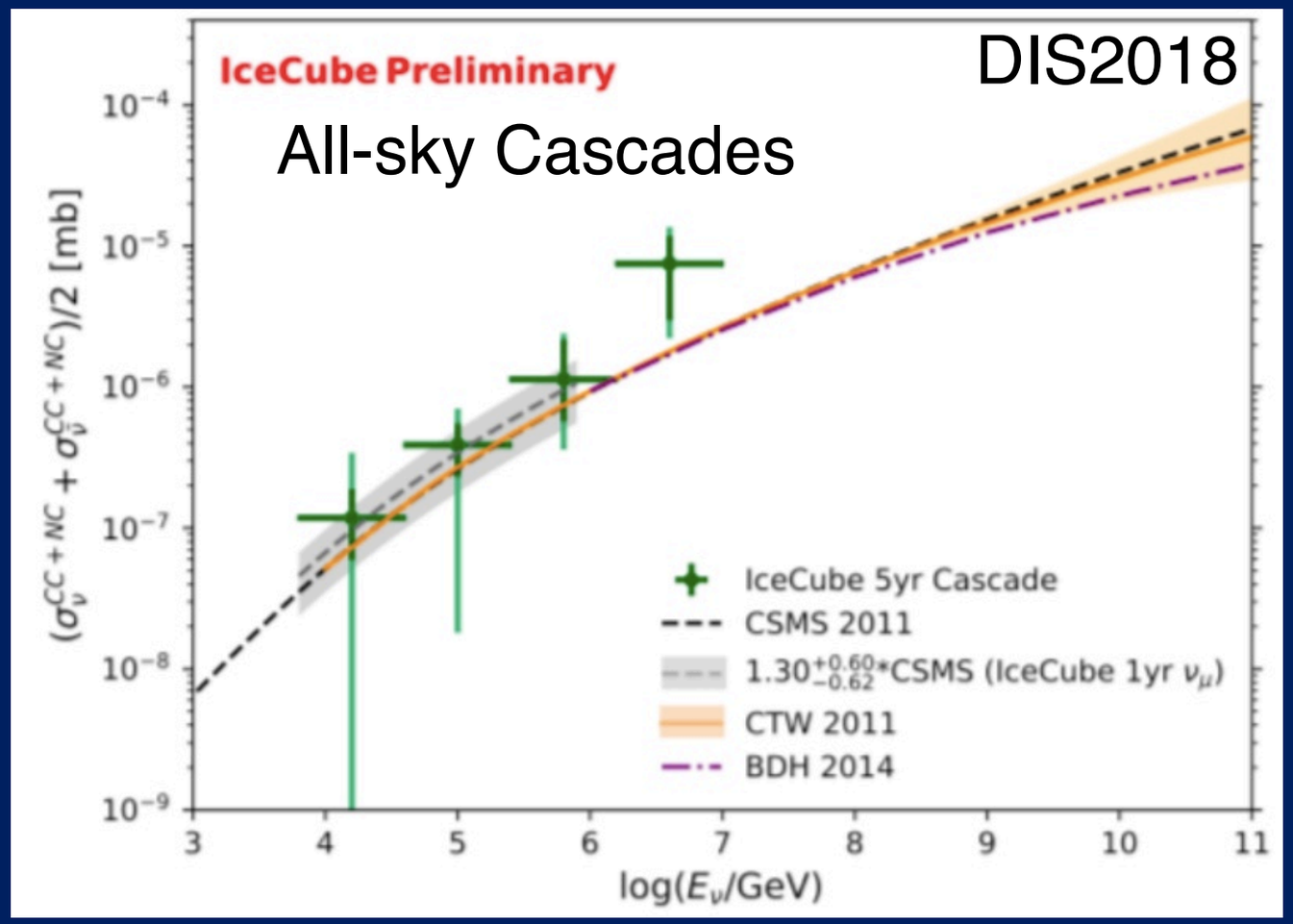
SM ν_μ-N cross section scales by κ factor

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

IceCube, Phys. Rev. D 99, 032004 (2019)

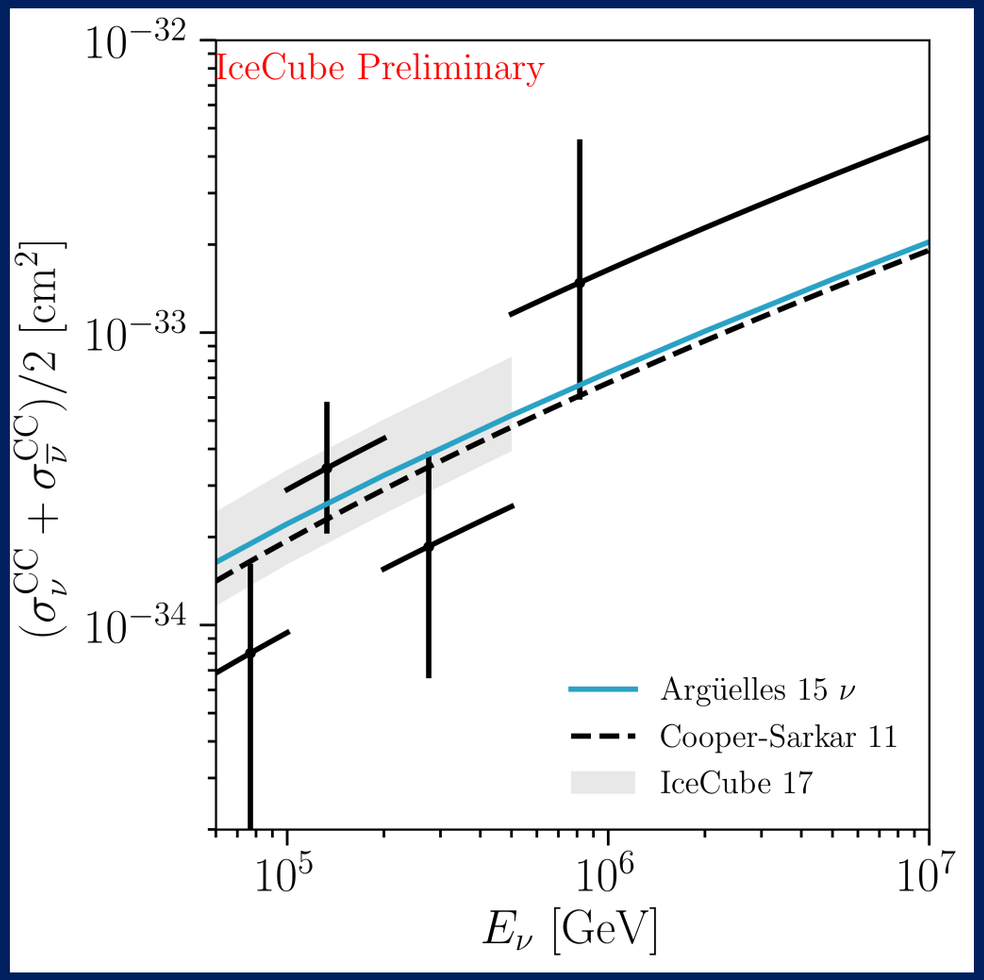


HE Neutrino- Nucleon Cross Section Measurements



arXiv:1809.06782 [hep-ex]

7.5 year HESE

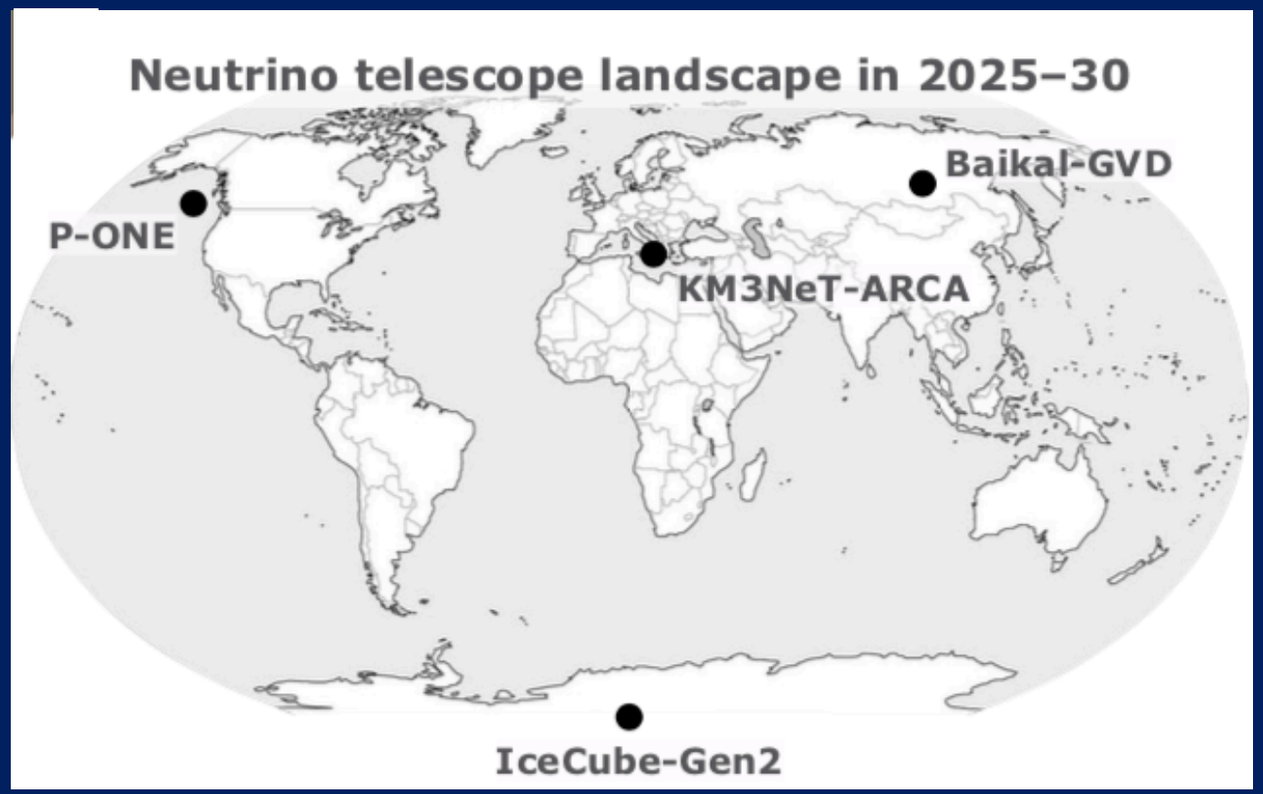


T. Yuan (ICRC2019)

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

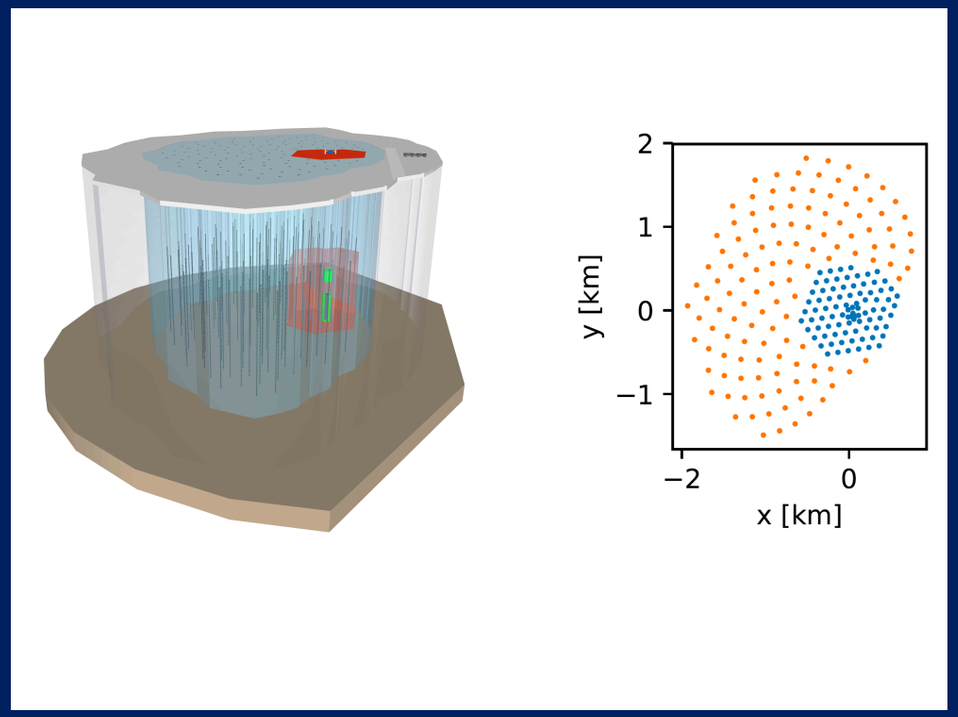
(Optical) Neutrino Observatories: Future

to address the unresolved origin of astrophysical neurinos



- Baikal-GVD, Km3Net – ARCA
under construction
coming online
ICRC2019 first results

- P-ONE Ocean Network Canada
conceptual phase



- IceCube-Gen2: proposed multi-cubic-kilometer neutrino detector
- Designed to be sensitive to 5x fainter sources
- Wide-band neutrino observatory with optical and radio detectors, surface array

Era of km^3 neutrino astronomy has begun

IceCube Discovery → *Measurements* → *Models testing*

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

Astrophysical neutrinos have been discovered
Diffuse flux characteristics - unbroken power law
Interpretation challenging
Evidence of neutrino source: flaring blazar
M77/NG1068 stands out in the latest source search (catalog and all sky search)
Cosmic accelerator source searches continue ….

Large(r) detectors needed on BOTH Northern and Southern hemisphere

Other complementary techniques (not covered here): ν's radio detection

Stay tuned!

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

National Science Foundation
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