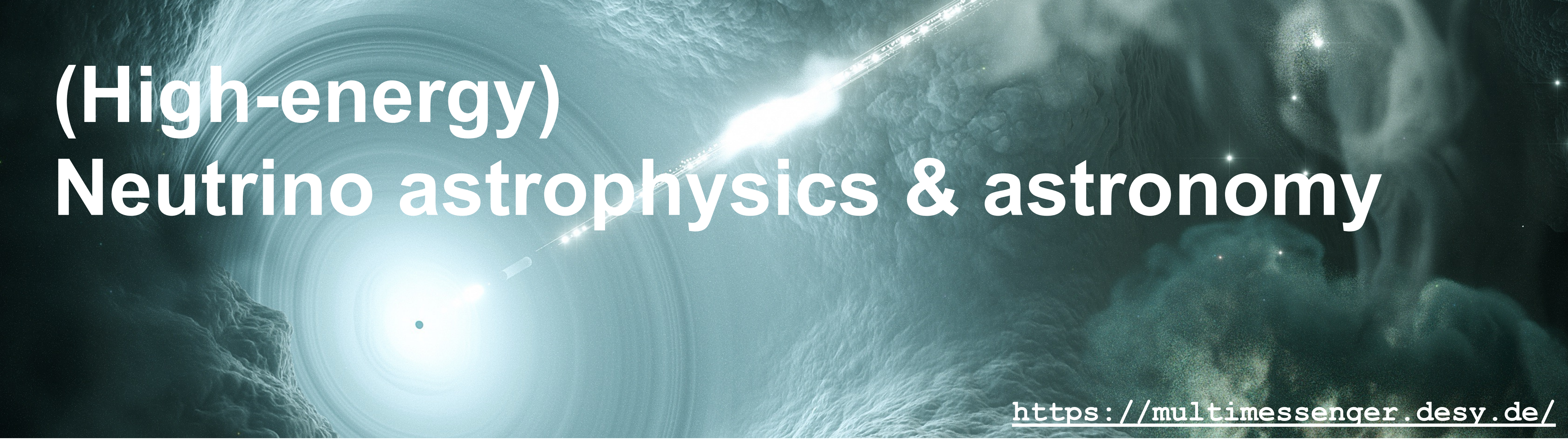


(High-energy) Neutrino astrophysics & astronomy

https://multimessenger.desy.de/

Winter, Walter
DESY, Zeuthen, Germany

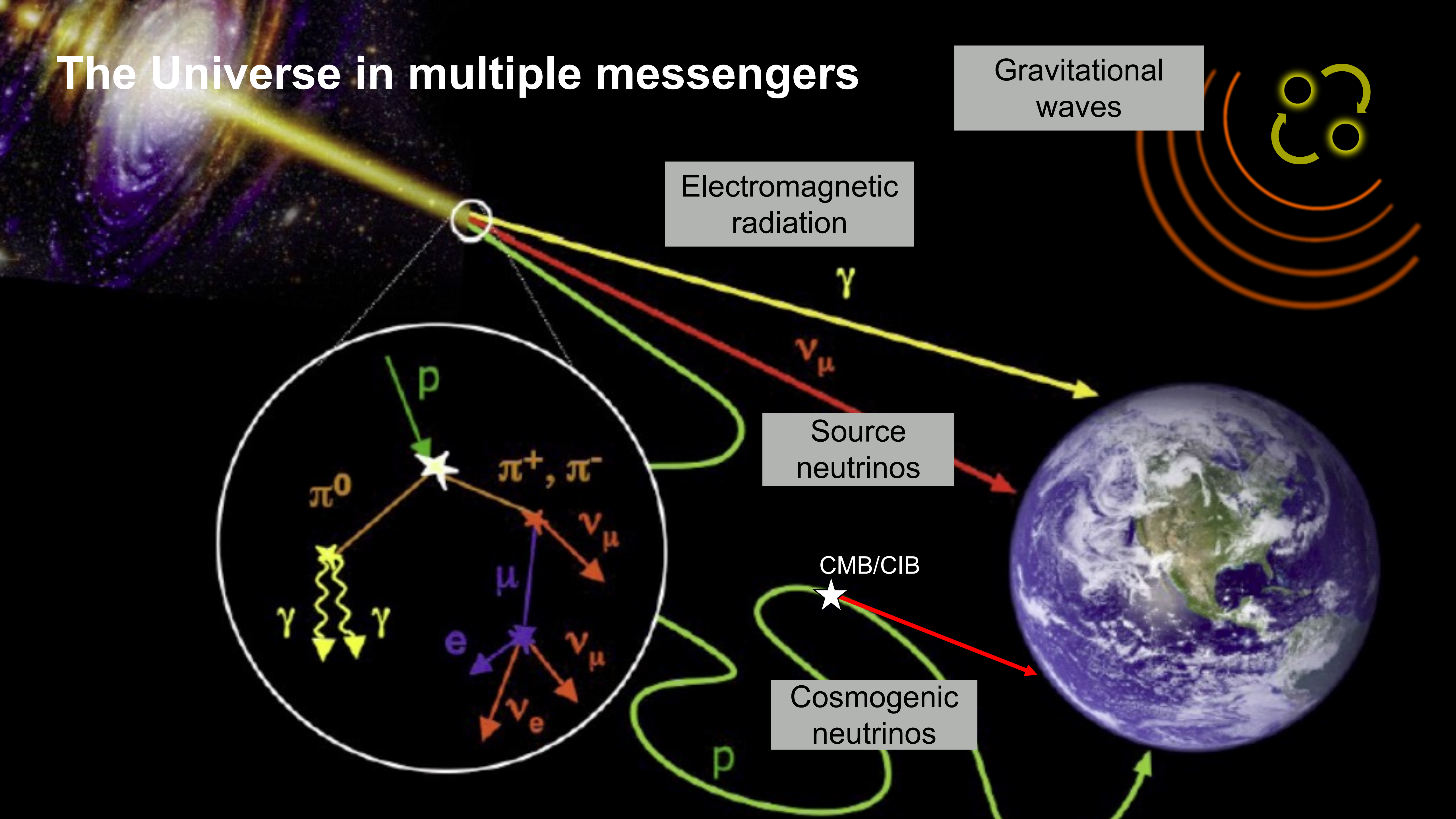
DESY summer students
August 2025

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Contents

- Observations of TeV-PeV neutrinos (overview of selected results)
- Physics of neutrino production (theory)
- Multi-messenger follow-ups / astrophysical objects:
  Neutrinos from AGN blazars

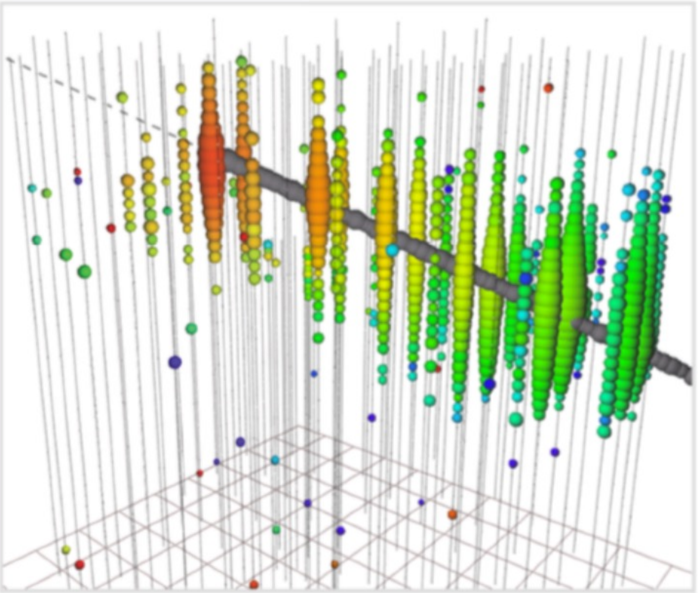
The Universe in multiple messengers



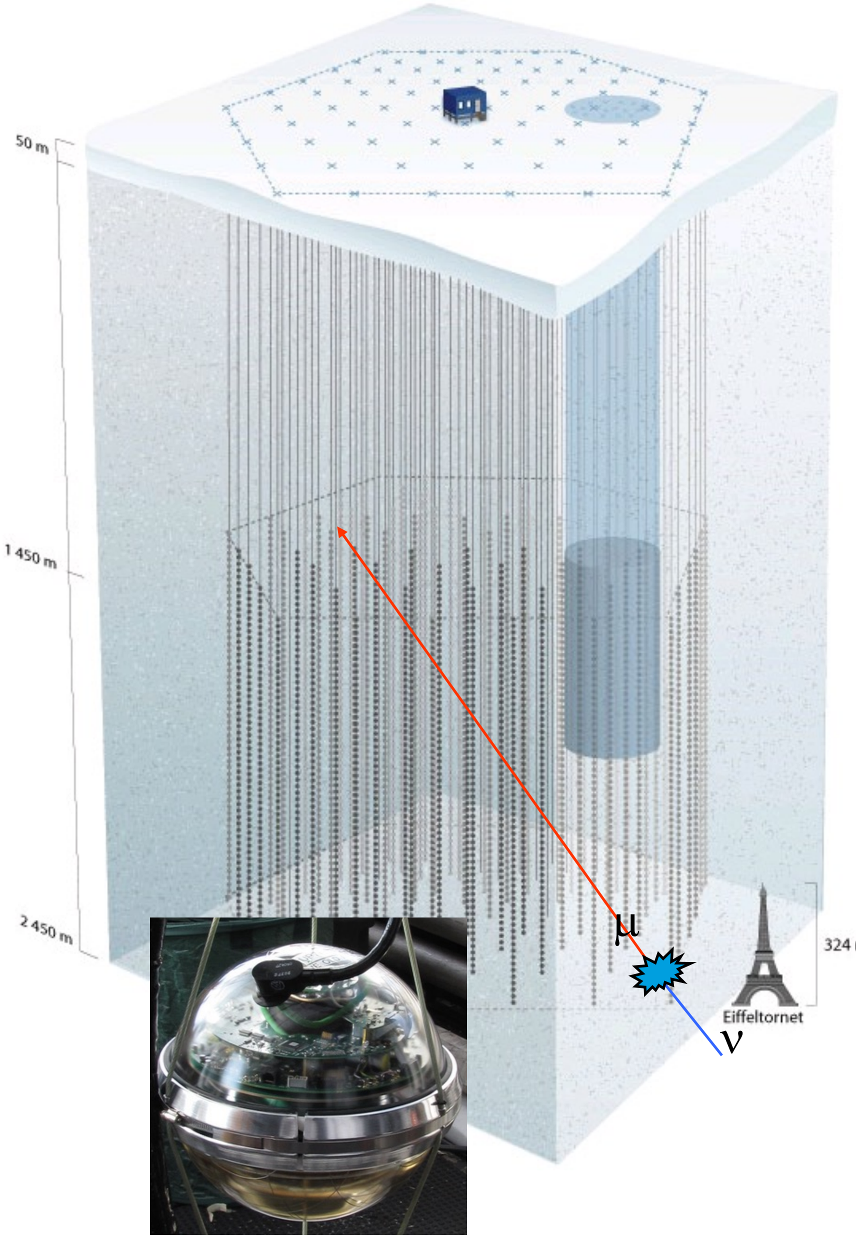
Observations of TeV-PeV neutrinos (overview)

Observing TeV-PeV neutrinos with IceCube

Muon track:
- From ν_μ
- From ν_τ (17 %)

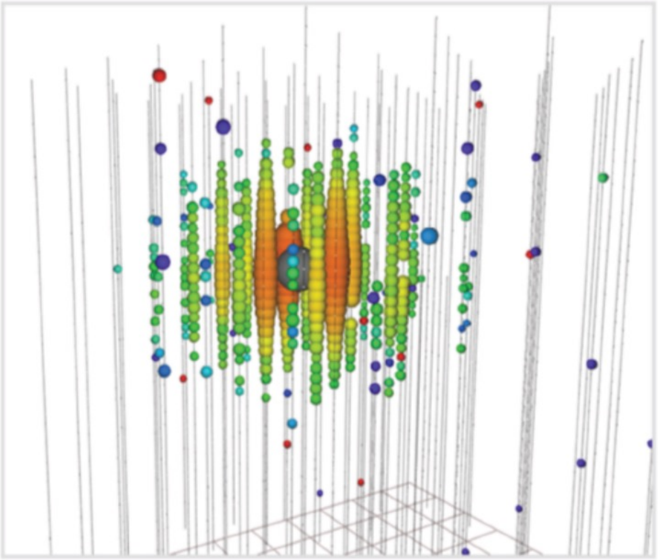


Better directional info



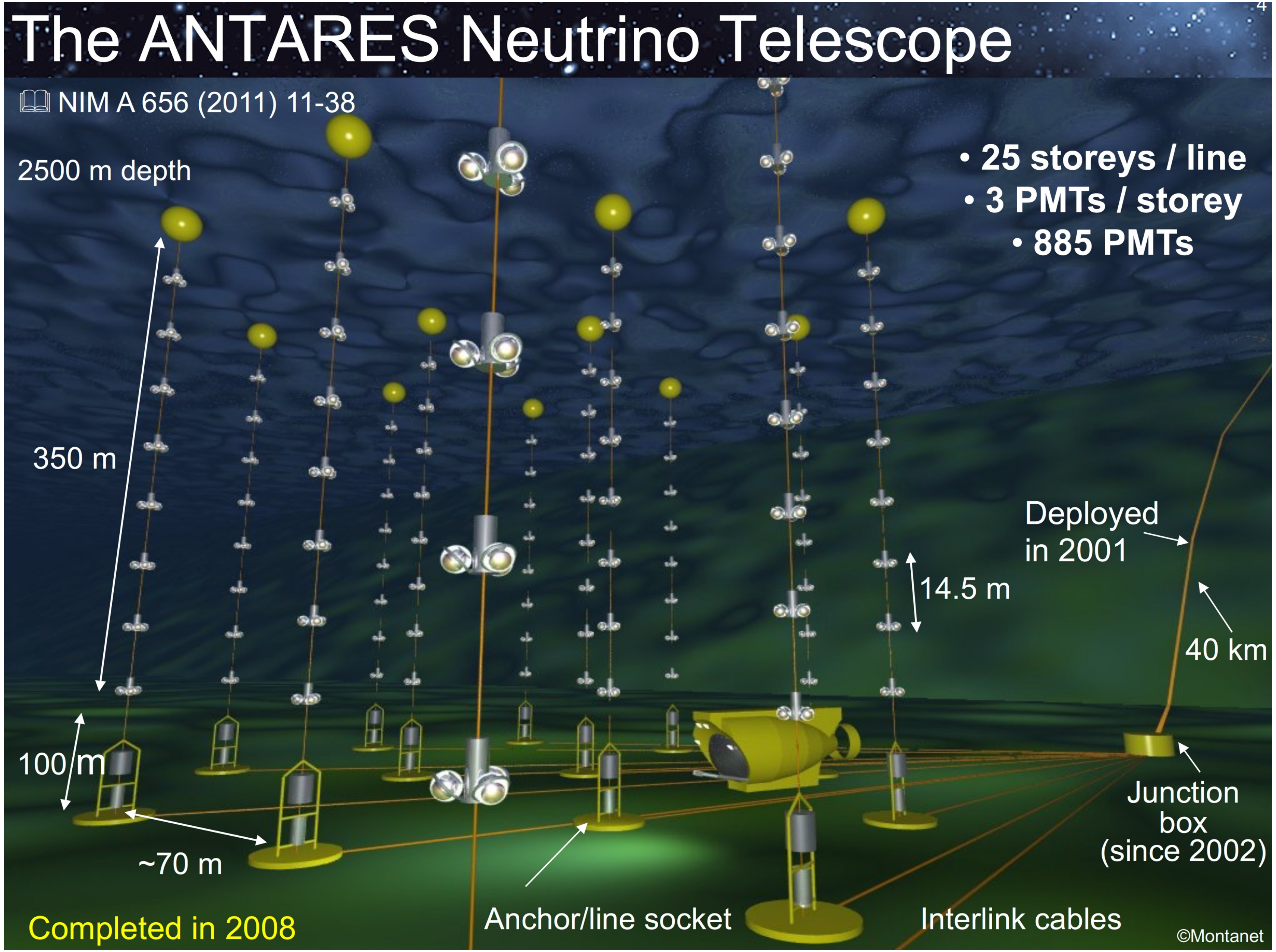
IceCube http://icecube.wisc.edu/

Cascade (shower):
- From ν_e
- From ν_τ
- From ν_e, ν_μ, ν_τ NC interactions



Better energy info

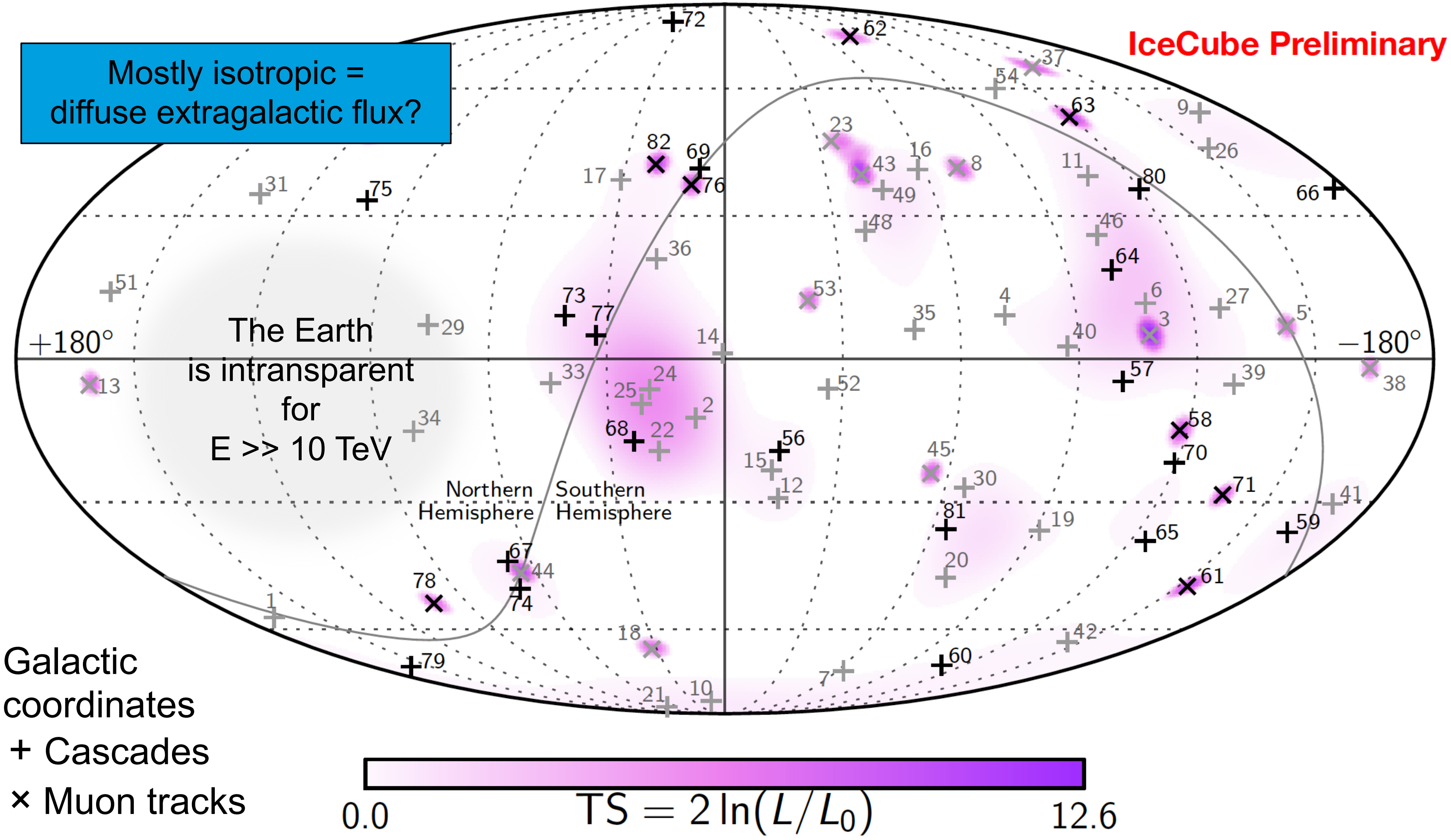
ANTARES



A. Kouchner

A flux of high-energy cosmic neutrinos

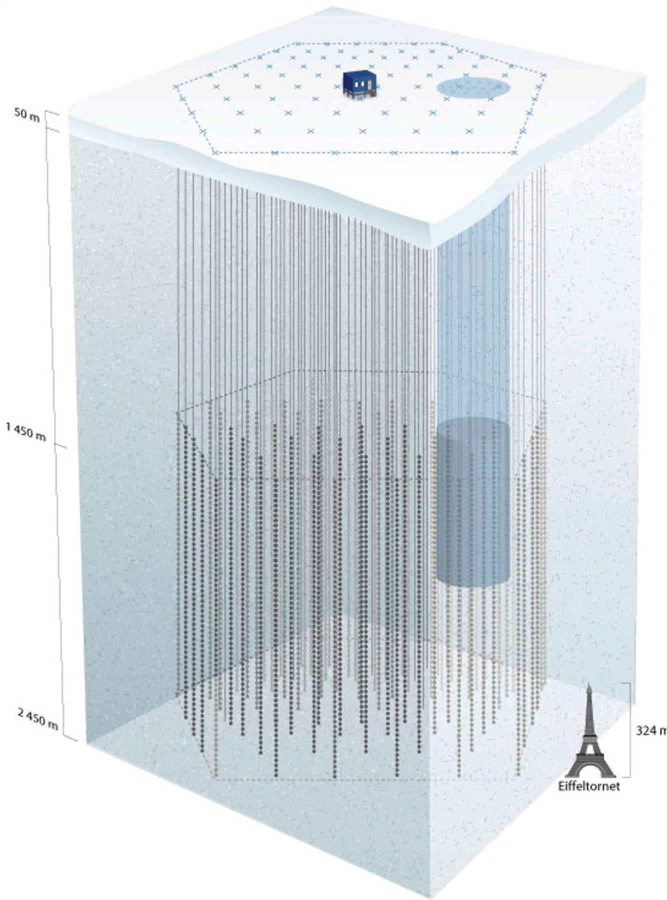
Mostly isotropic = diffuse extragalactic flux?



Galactic coordinates

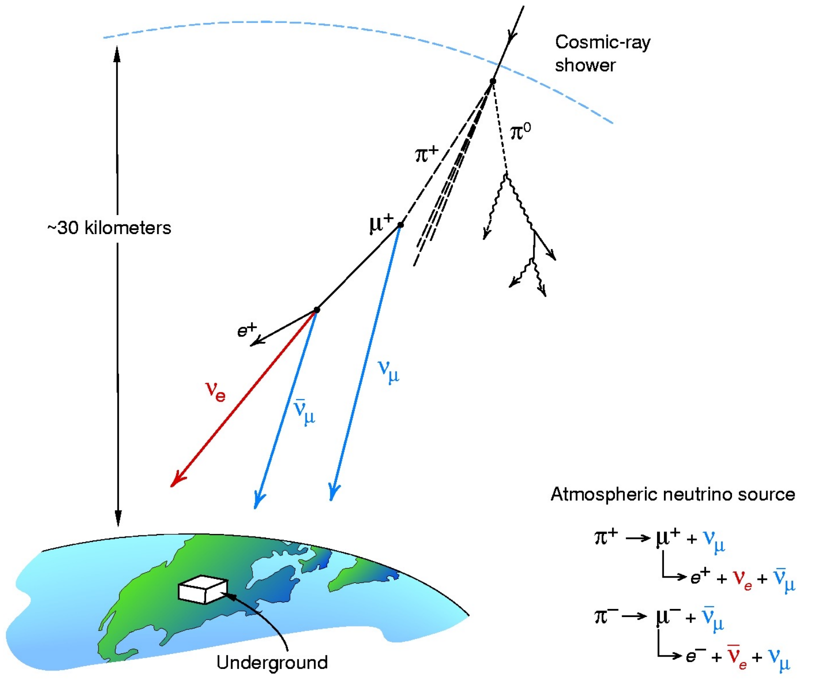
+ Cascades

× Muon tracks



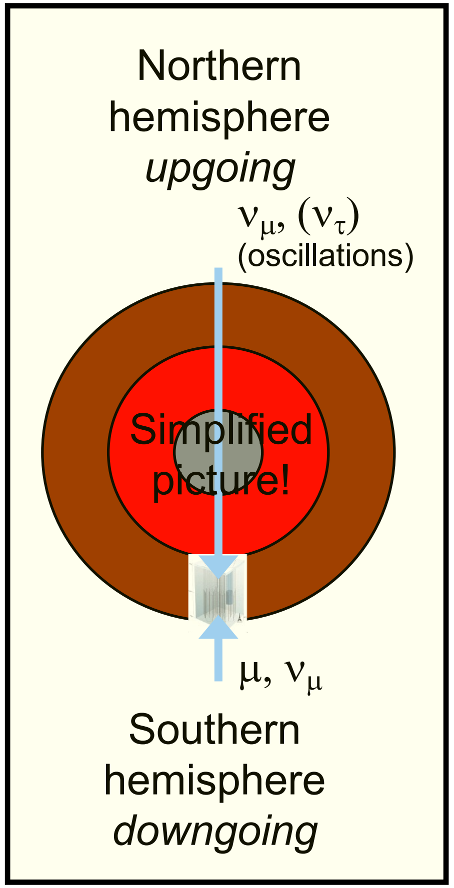
IceCube: Science 342 (2013) 1242856; Phys. Rev. Lett. 113, 101101 (2014); update from Kopper at ICRC 2017

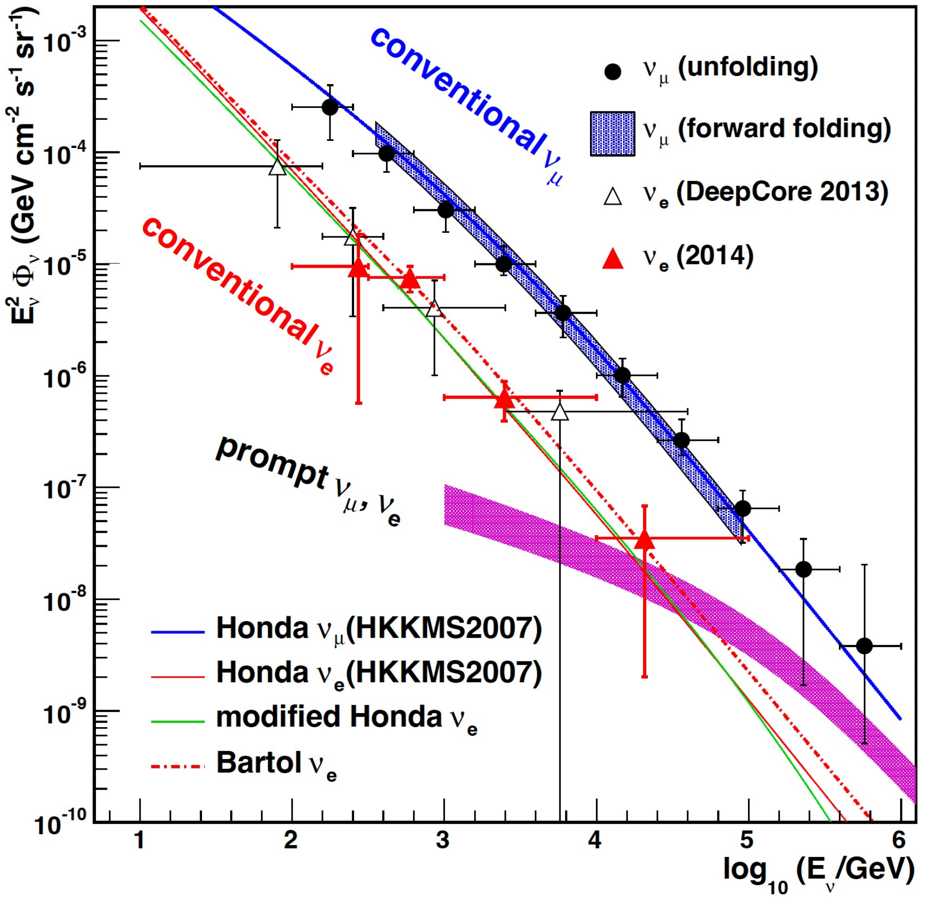
Backgrounds: Neutrinos and muons from the atmosphere



Muon lifetime: 2 10^{-6} s (~ 600 m) x E/m_0.
In addition: muons lose energy.

Consequence: Atmospheric neutrino and muon backgrounds at Earth





For transport computations, see Gaisser, Engel, Resconi: Cosmic rays and particle physics, Cambridge, 2016

IceCube, Phys. Rev.D 91 (2015) 122004

Diffuse neutrino flux – observed in different event samples

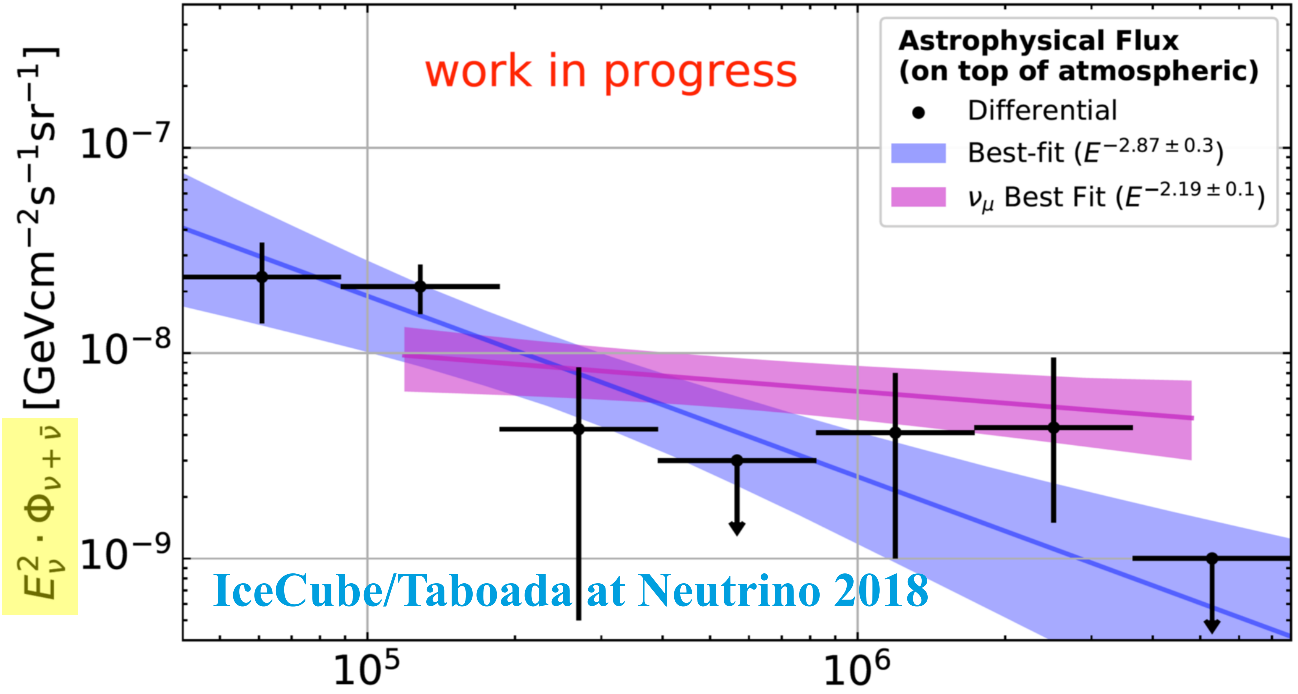
HESE = High Energy Starting Events

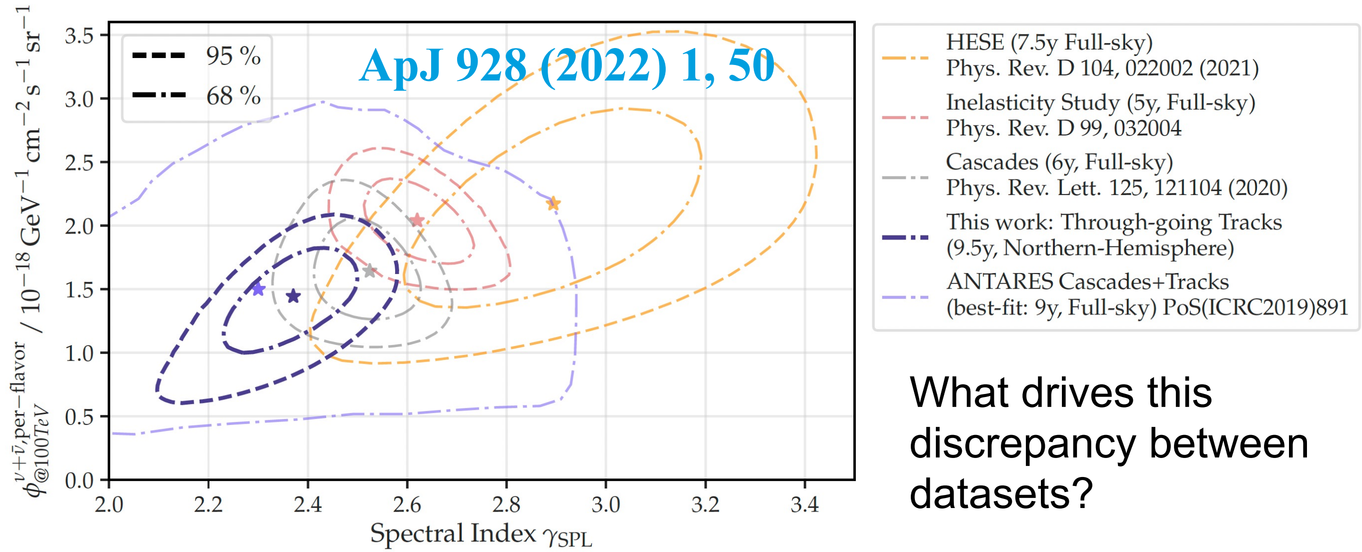
Interaction within detection volume

Outer layer of detector used as veto (atm. muons)

Sensitive to both hermispheres, all flavors

Lower energies = contained events





What drives this discrepancy between datasets?

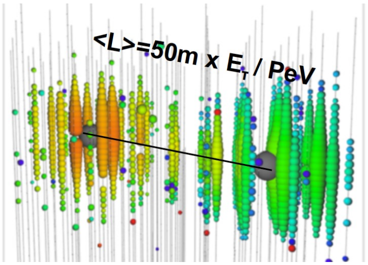
Through-going muon tracks

Sensitive to ν_μ only from Northern hemisphere

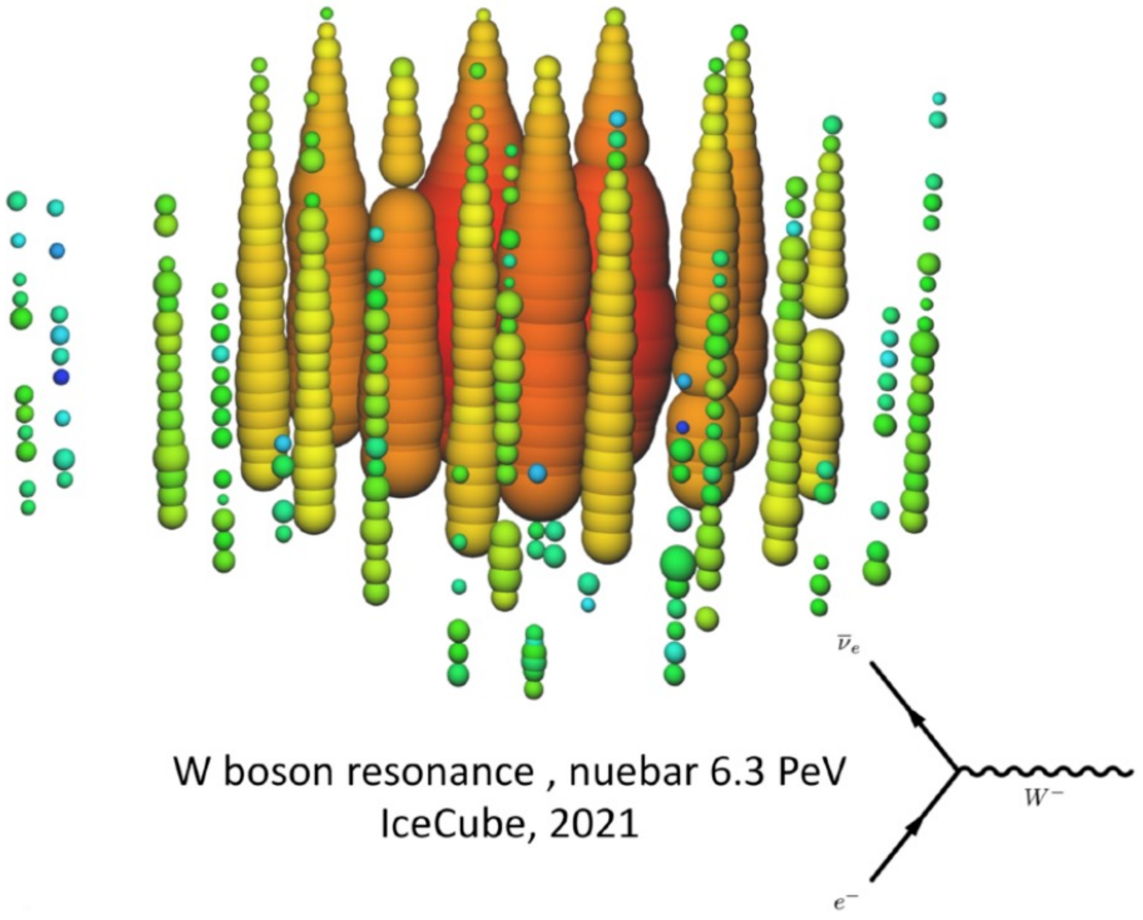
Large effective volume (interaction may be outside detector)

Muon energy gives a lower limit for neutrino energy

New event classes

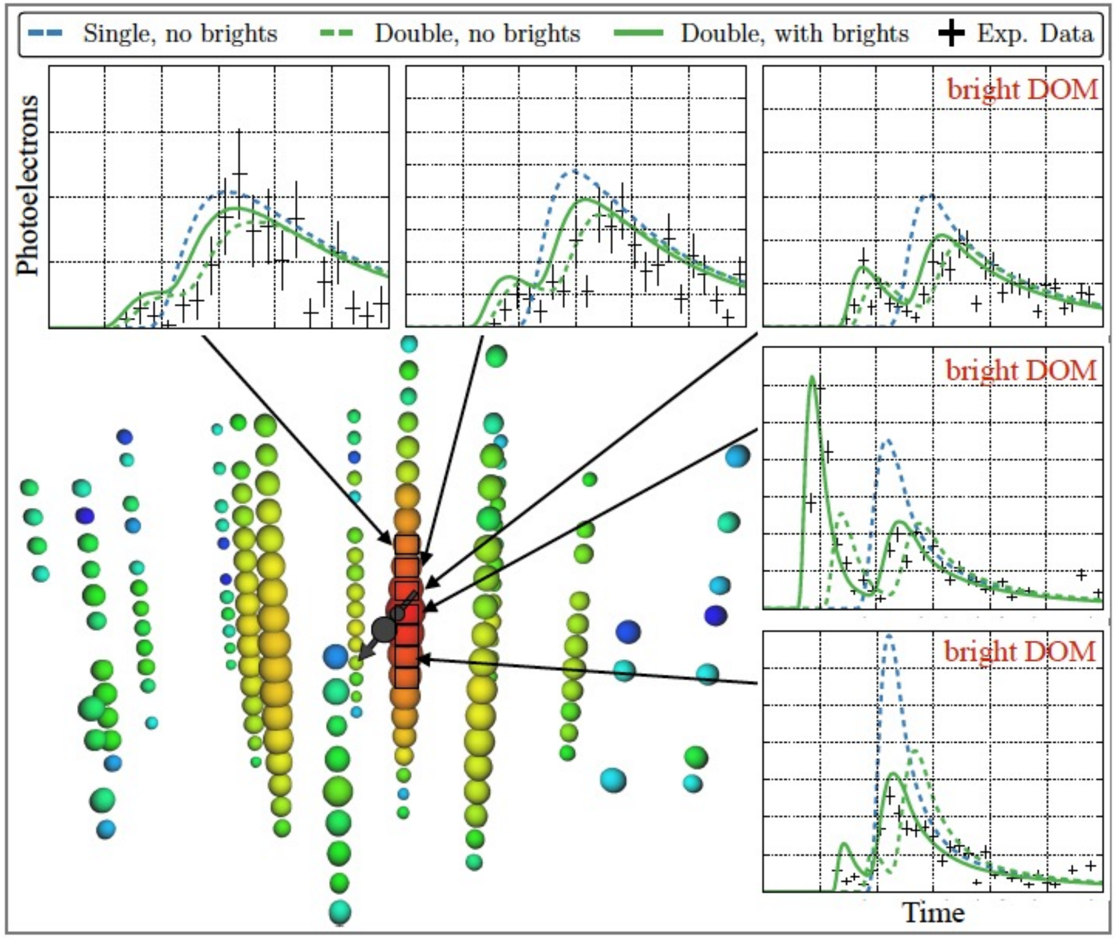


Glashow resonance



IceCube, Nature 591 (2021) 7849, 220

Double bang (ν_τ) candidates

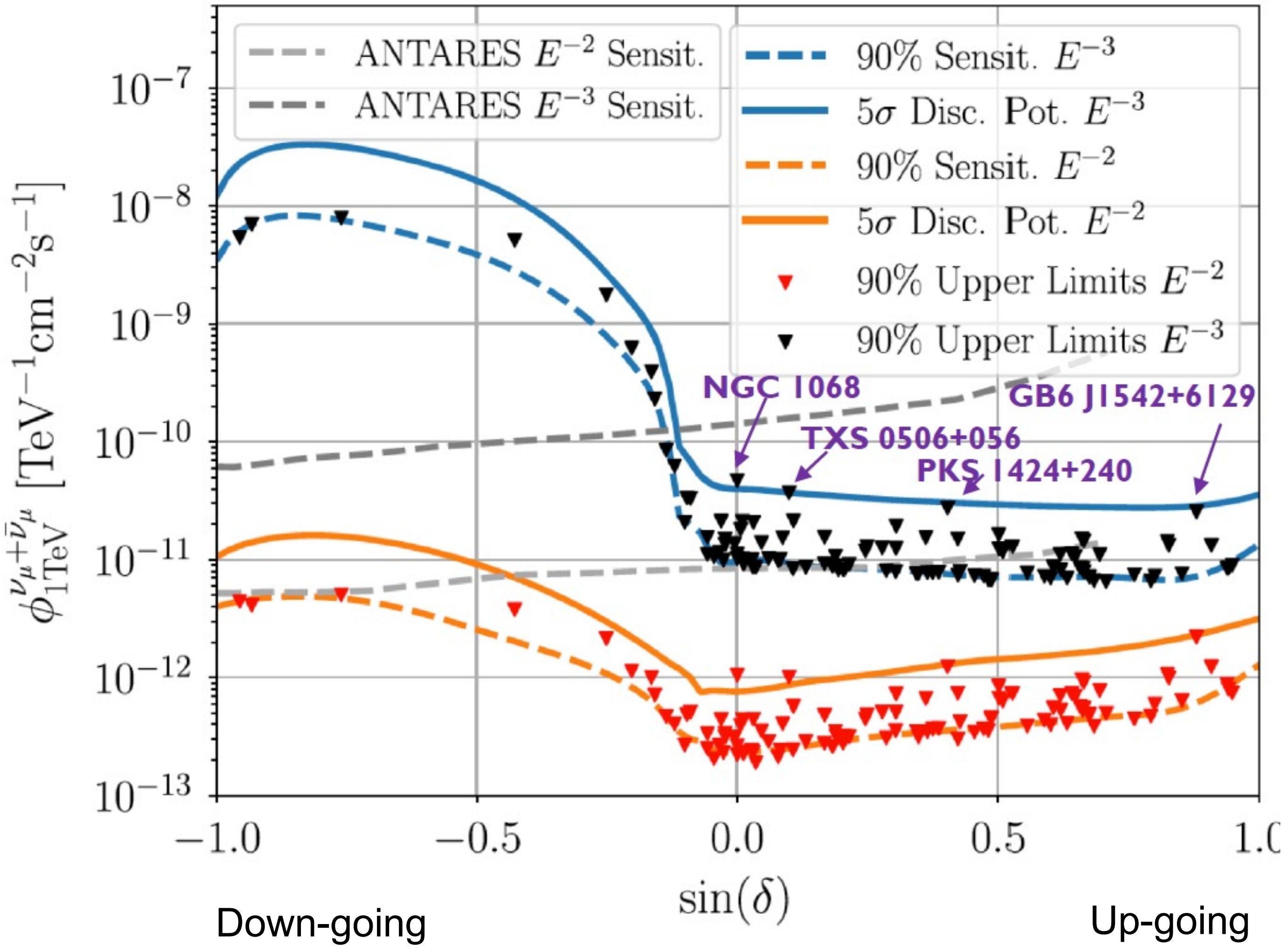


IceCube, arXiv:2011.03561 and PRL 125 (2020) 12, 121104

Time-integrated 10 year point source searches

- Most significant:
  NGC 1068 (3σ post-trial)
  Active galaxy, Seyfert 2, starburst

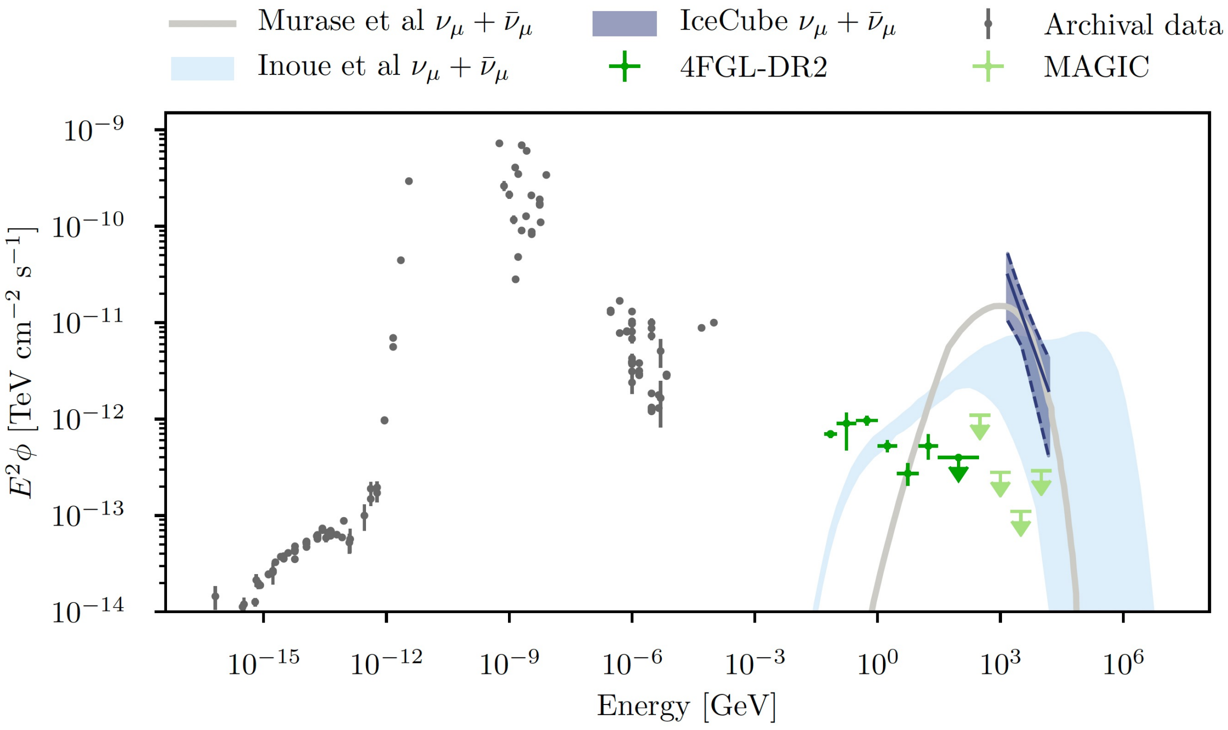
- The other three are AGN blazars
- TXS 0506+056 is prominent because it was found earlier through a multi-messenger follow-up

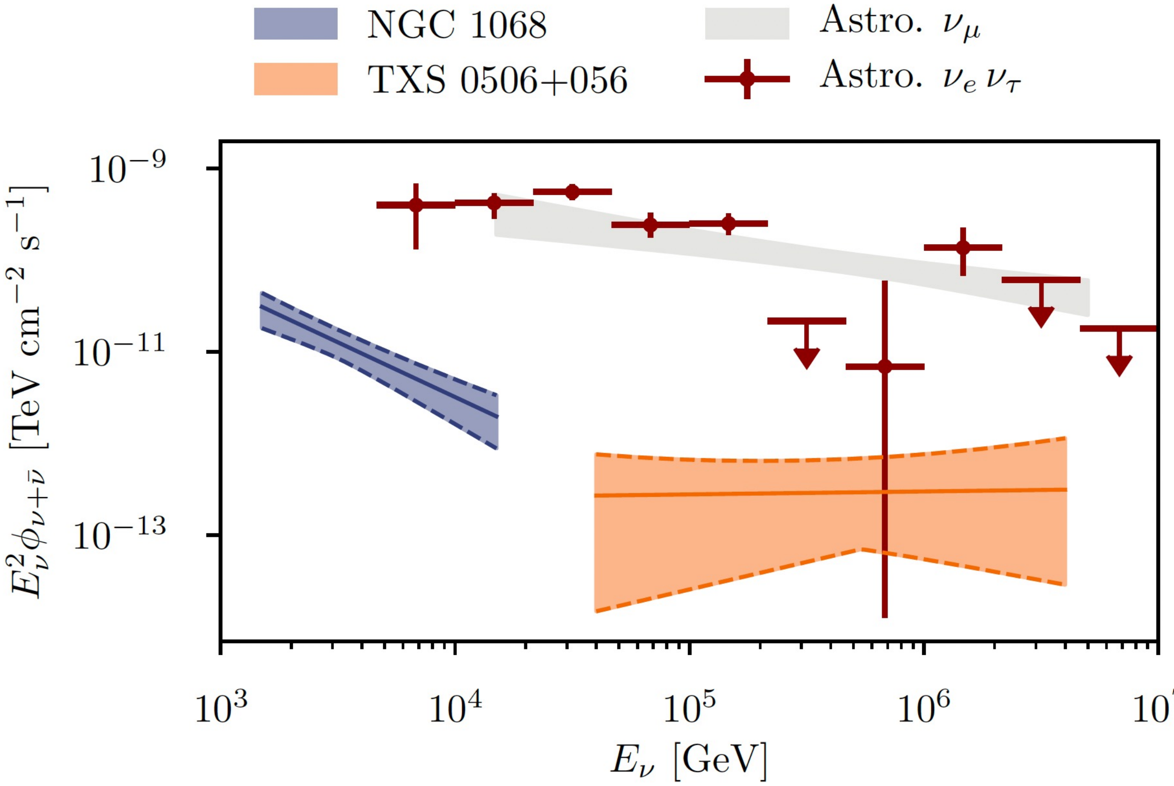


IceCube, PRL 124 (2020) 5, 051103;
from G. Illuminati @ Paris 2020

Neutrinos from NGC 1068

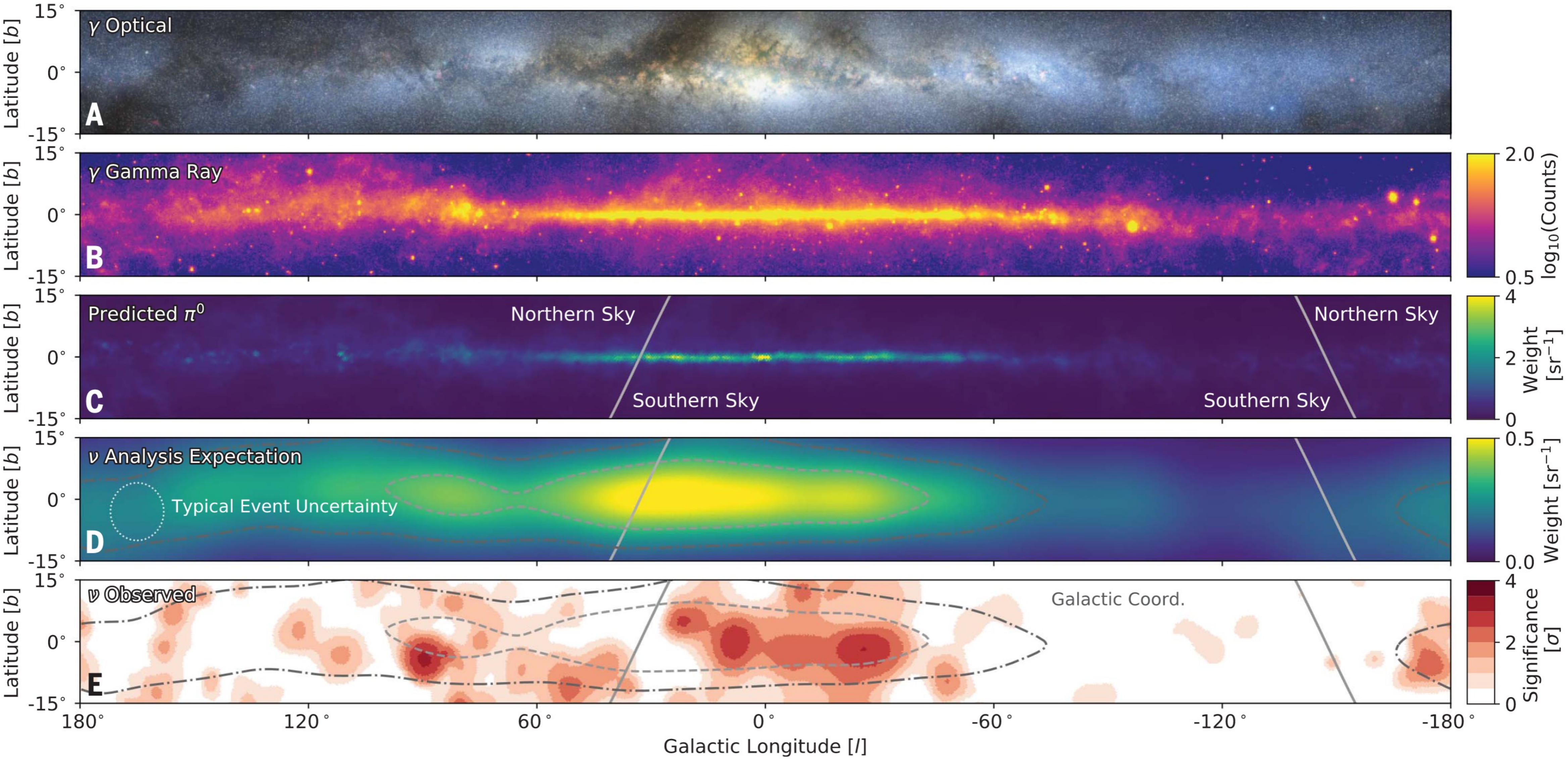
- Excess of 79 (+22 -20) events, leading to 4.2σ significance
- Strongest point source, soft spectrum, z=0.004
- Obscured in very-high energy gamma-rays; kind-of expected if neutrino production is efficient, e.g. Murase, Guetta, Ahlers, PRL 116 (2016) 071101





IceCube, Science 378 (2022) 6619, 538

Galactic plane seen in neutrinos at 4.5σ



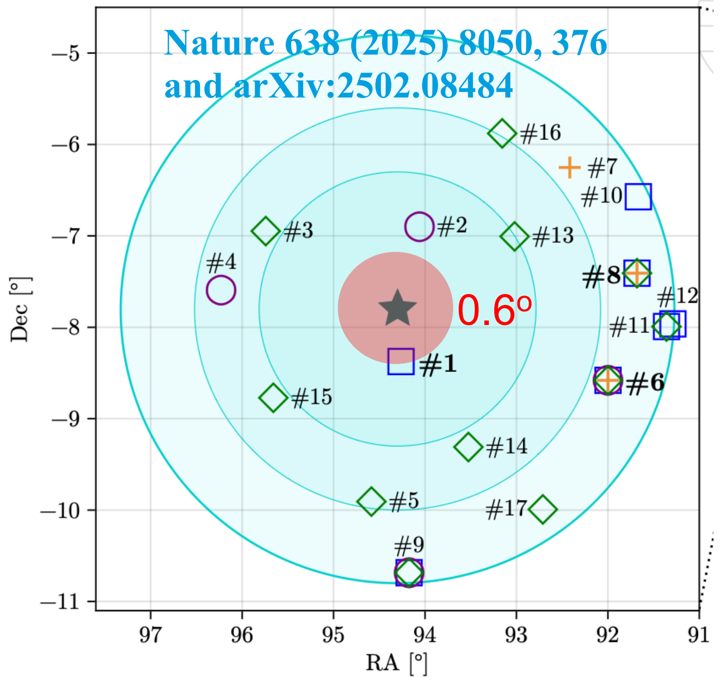
IceCube, Science 380 (2023) 1338;
see also ANTARES, Phys. Lett. B 841 (2023) 137951

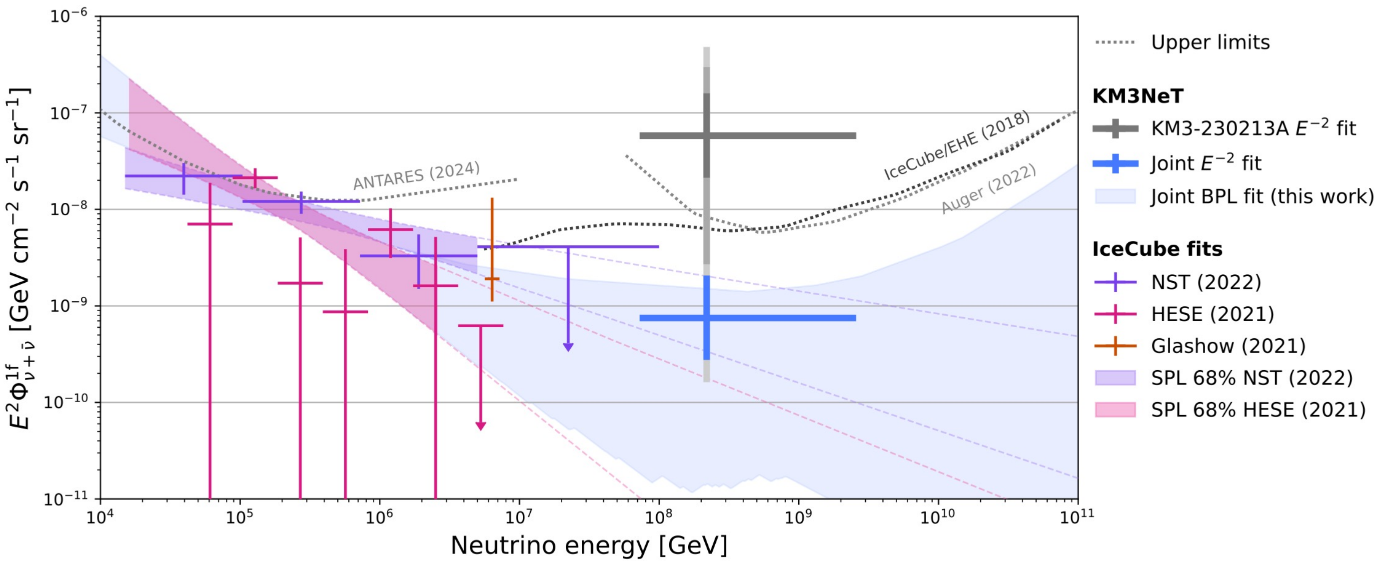
KM3-230213A

A high-energy neutrino of unknown origin

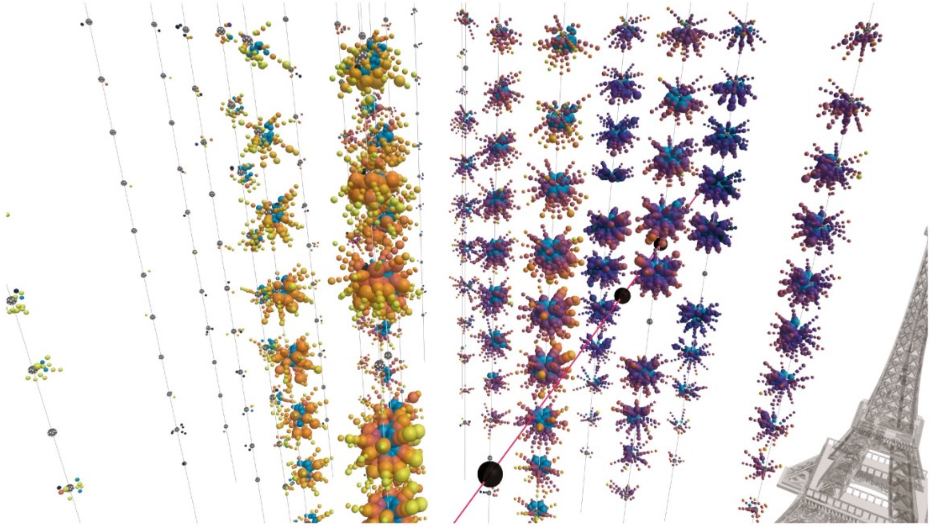
Finding its origin would be direct evidence for UHECRs!

- Energy 220 PeV; 72 PeV – 2.6 EeV 90% CL interval
  Nature 638 (2025) 8050, 376 (corresponds to primary rigidity R ~ 1 – 100 EV!!!)
- 17 blazars within 99%CL region, #1 (MRC 0614-083) is closest source →
- Tension with IceCube favors "year-long transient"
  Neronov, Oikonomou, Semikoz, 2025; Li et al 2025.
  → Tidal Disruption Event? AGN accretion flare?
- Combined fit with IceCube: arXiv:2502.08173





b



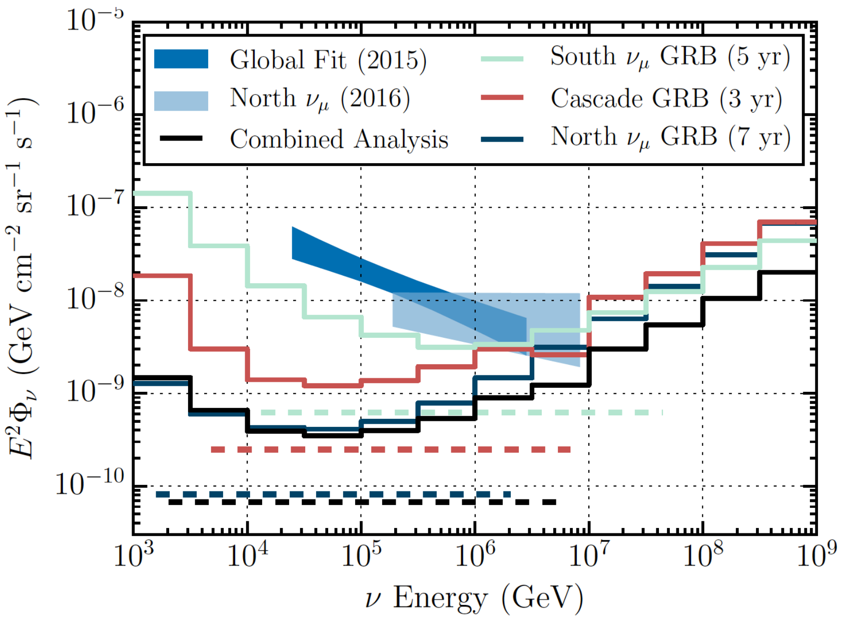
Nature 638 (2025) 8050, 376

Stacking limits ...

... for the most energetic sources classes

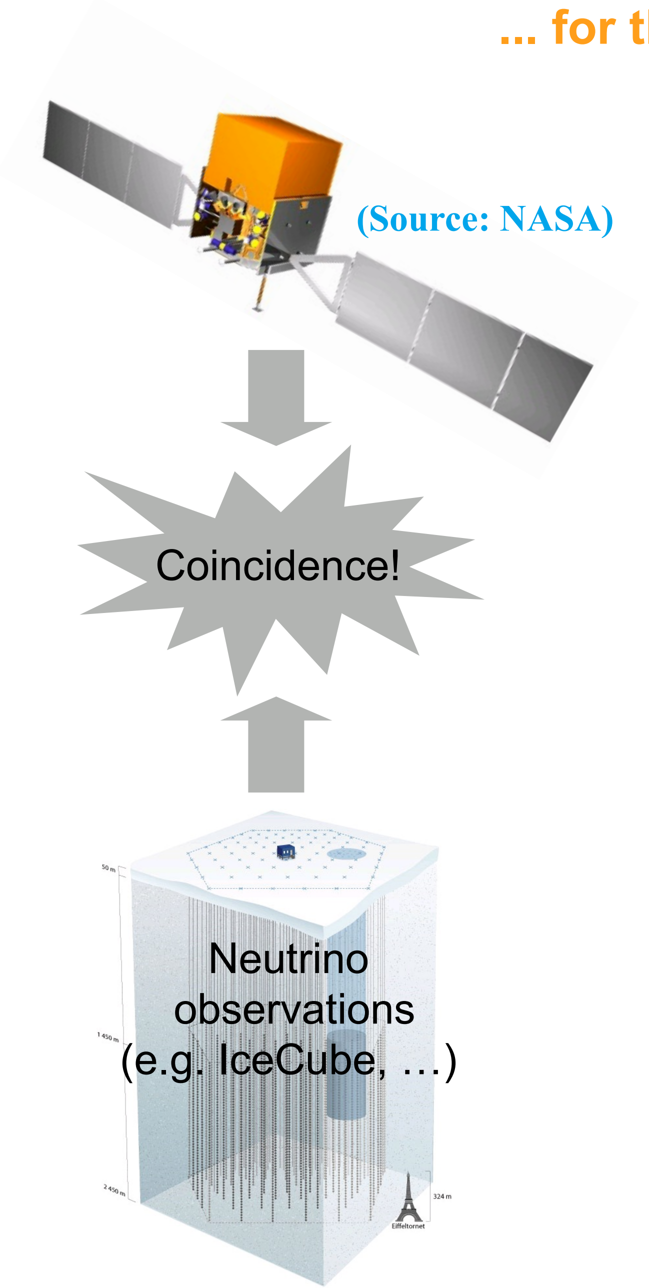
Gamma-Ray Bursts (GRBs)

- Transients, time variability
- High luminosity over short time



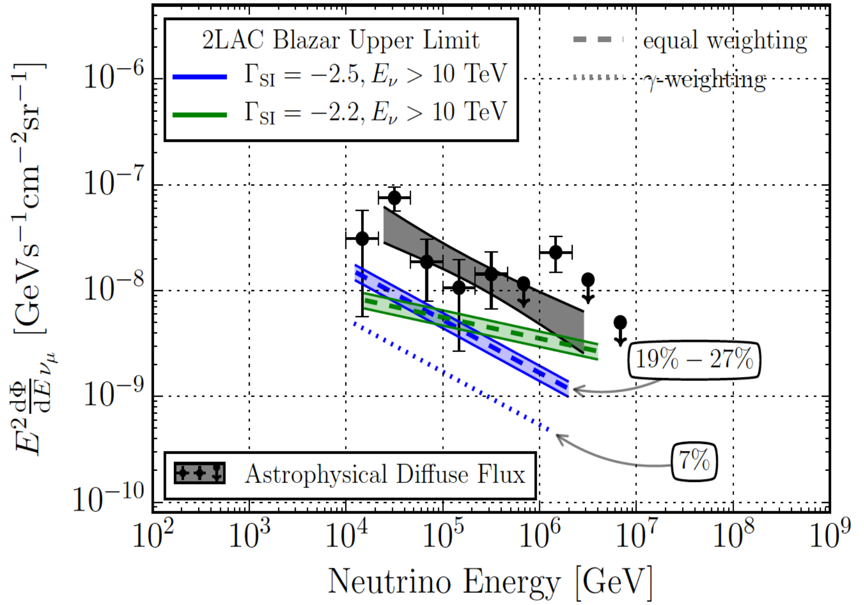
- Less than ~1% of observed ν flux

IceCube, Nature 484 (2012) 351;
Newer version: arXiv:1702.06868



Active Galactic Nuclei (AGN) blazars

- Steady emission with flares
- Lower luminosity, longer duration

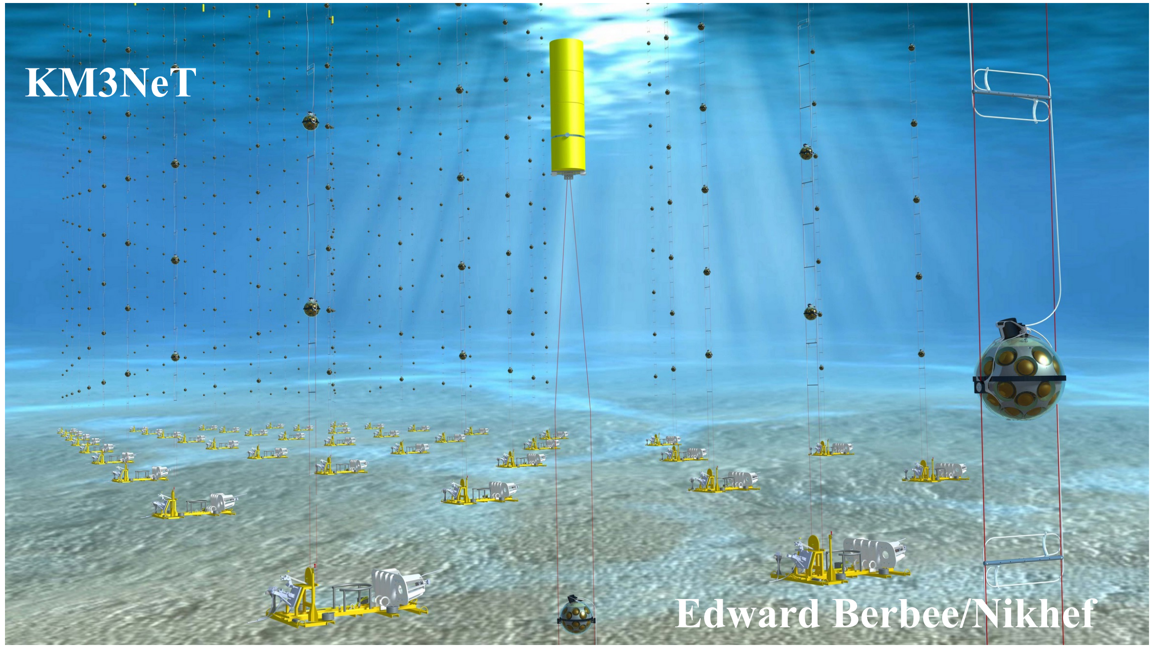


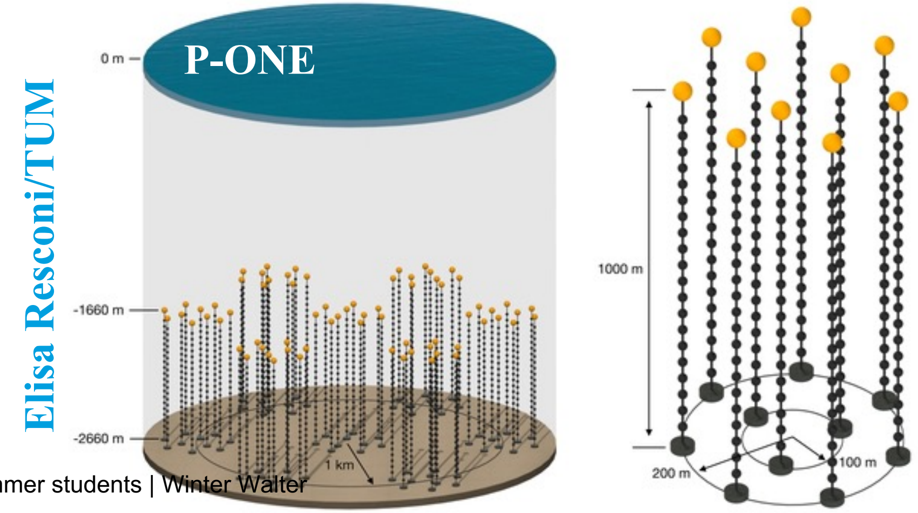
- Less than ~25% of observed ν flux?

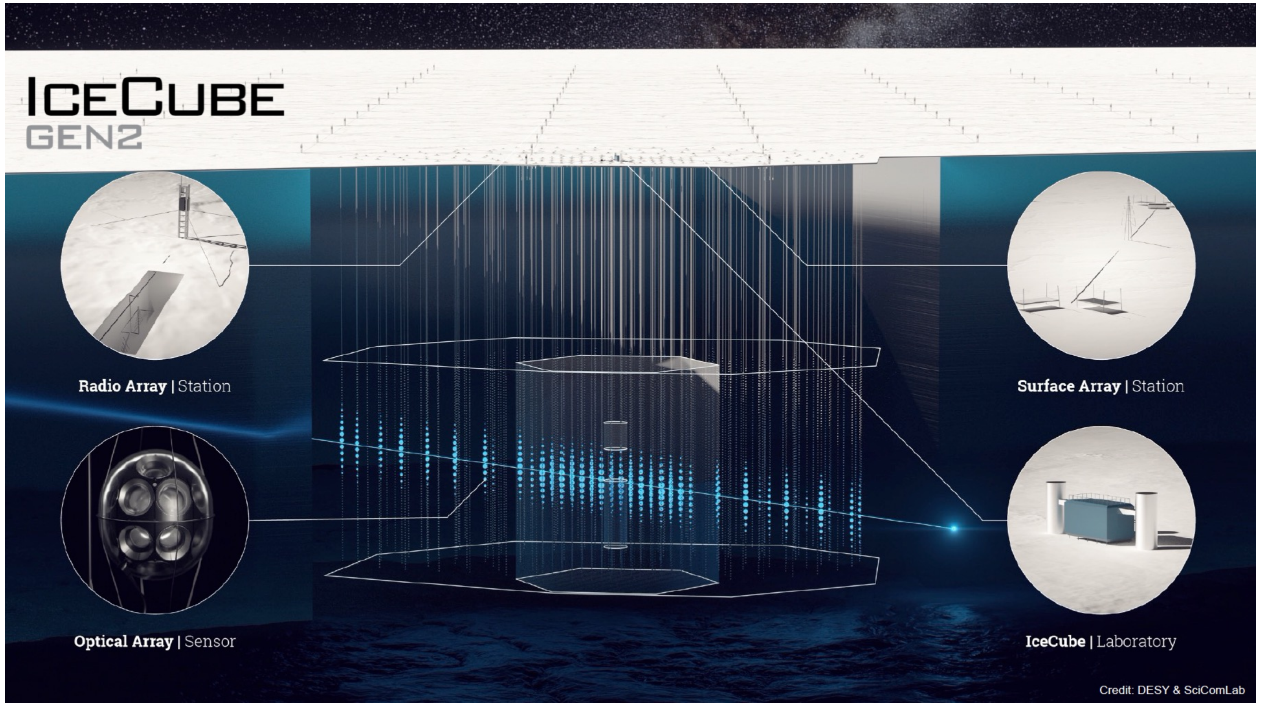
IceCube, Astrophys. J. 835 (2017) 45

Future neutrino telescopes: PeV neutrinos

... towards a global neutrino observatory?



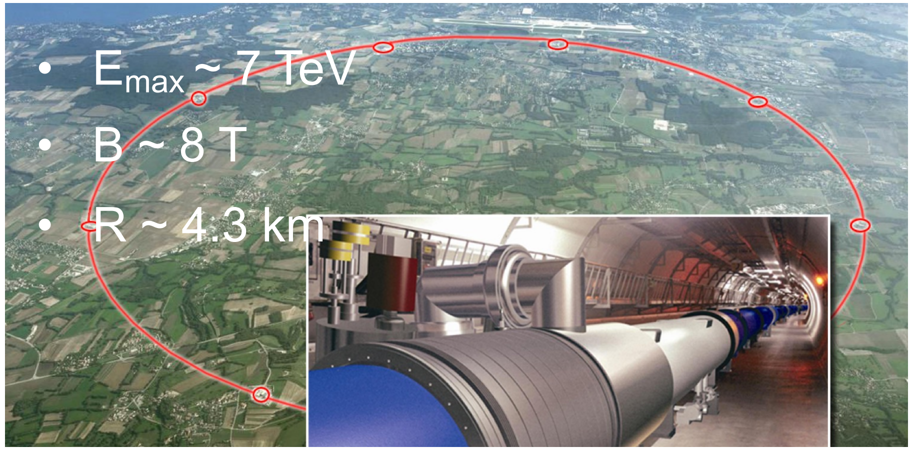




Physics of neutrino production

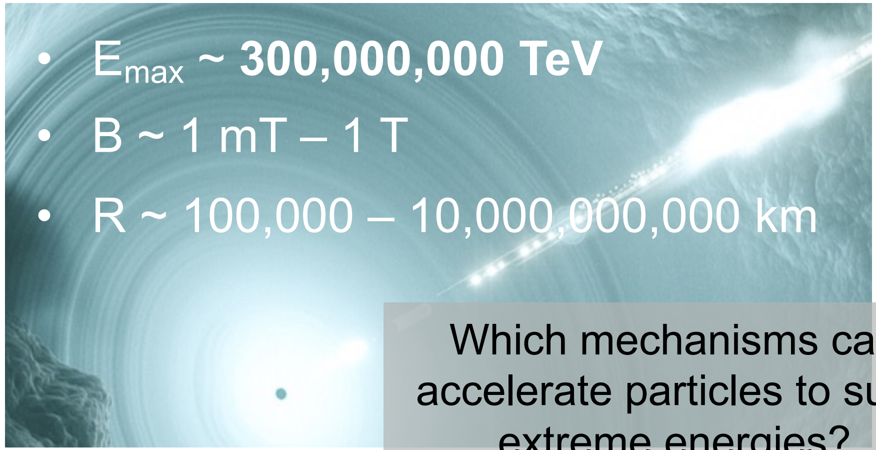
(theoretical background)

Particle acceleration ... a pragmatic perspective



- E_{max} ~ 7 TeV
- B ~ 8 T
- R ~ 4.3 km

Lorentz force
= centrifugal force
➔ E_{max} ~ Z c B R

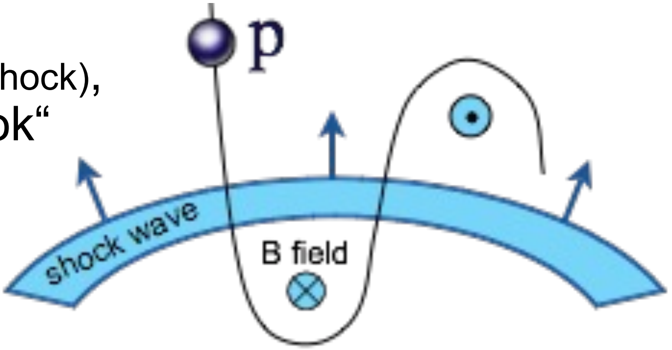


- E_{max} ~ **300,000,000 TeV**
- B ~ 1 mT – 1 T
- R ~ 100,000 – 10,000,000,000 km

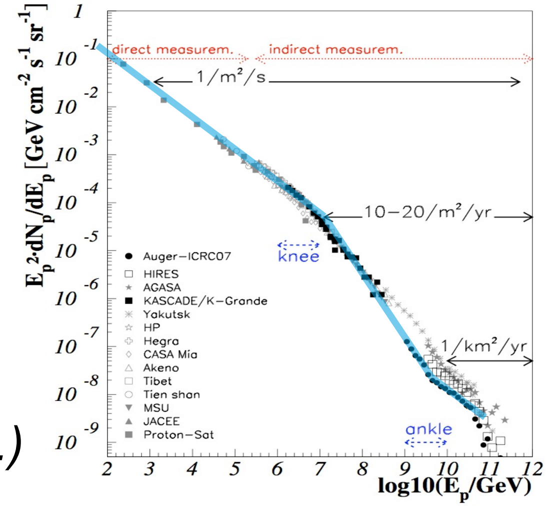
Which mechanisms can accelerate particles to such extreme energies?

Example: *Fermi shock acceleration*

- Energy gain per cycle: E ➔ η E
- Escape probability per cycle: P_{esc}
- Yields a **power law** spectrum ~ $E^{\frac{\ln P_{esc}}{\ln \eta}-1}$
- ln P_{esc}/ln η ~ -1
  (from compression ratio of a strong shock), and $\mathbf{E^{-2}}$ is the typical “textbook“ spectrum

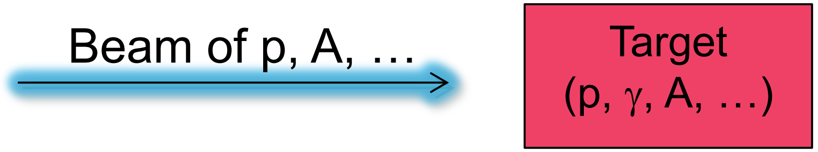


- Theory of acceleration challenging, but we **do observe** power law (= non-thermal) spectra in Nature
- For multi-messenger perspective: adopt pragmatic point of view! *(we know that it works, somehow ...)*



Secondary production: Particle physics 101?

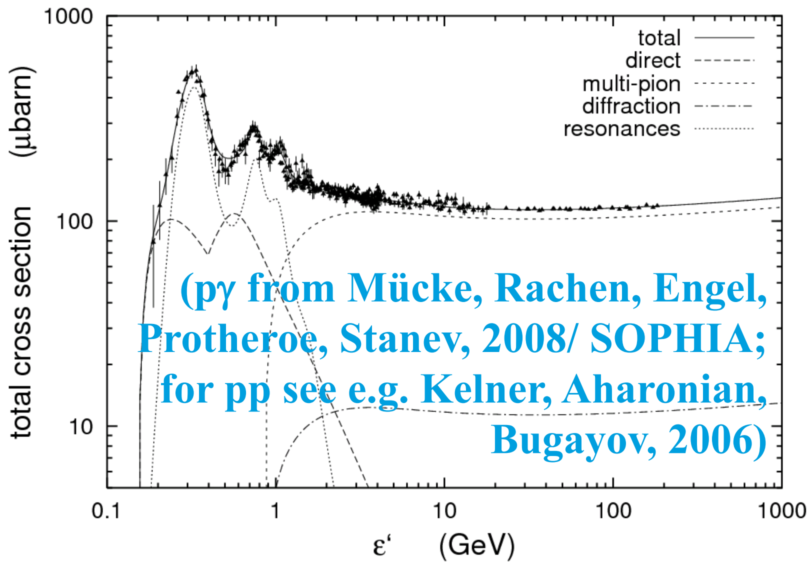
- **Beam dump picture (particle physics)**



- Interaction rate $\Gamma \sim c\ \ N\ [\mathrm{cm}^{-3}]\ \ \sigma\ [\mathrm{cm}^2]$

Target density (e.g. N_γ) critical for production!

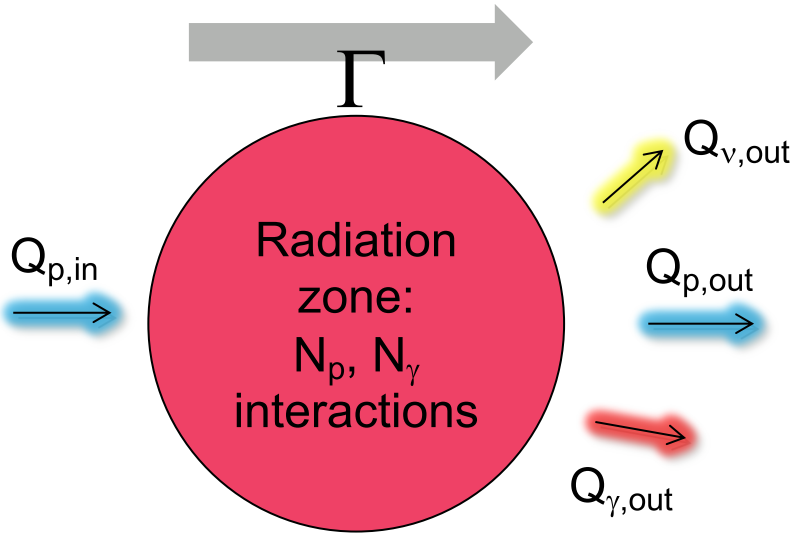
Key challenge: Need volume



(pγ from Mücke, Rachen, Engel, Protheroe, Stanev, 2008/ SOPHIA; for pp see e.g. Kelner, Aharonian, Bugayov, 2006)

(Photon energy in nucleon rest frame)

- **Astrophysical challenges:**
  - Feedback between beam and target (e.g. photons from π^0 decays)
  - Need self-consistent description called **radiation model**
  - Density *in* source, in general, **not** *what you get* from the source



Here: typically a spherical blob in relativistically moving frame

Global radiation models (theory)

- Time-dependent PDE system, one PDE per **particle species *i***

$$\frac{\partial N_i}{\partial t} = \frac{\partial}{\partial E}\left(-b(E)N_i(E)\right) - \frac{N_i(E)}{t_{\mathrm{esc}}} + Q(E)$$

Cooling (continuous) | Escape | Injection

$b(E)=-E\, t^{-1}_{\mathrm{loss}}$

“radiation processes”

$Q(E,t)$ [$\mathrm{GeV}^{-1}\ \mathrm{cm}^{-3}\ \mathrm{s}^{-1}$]

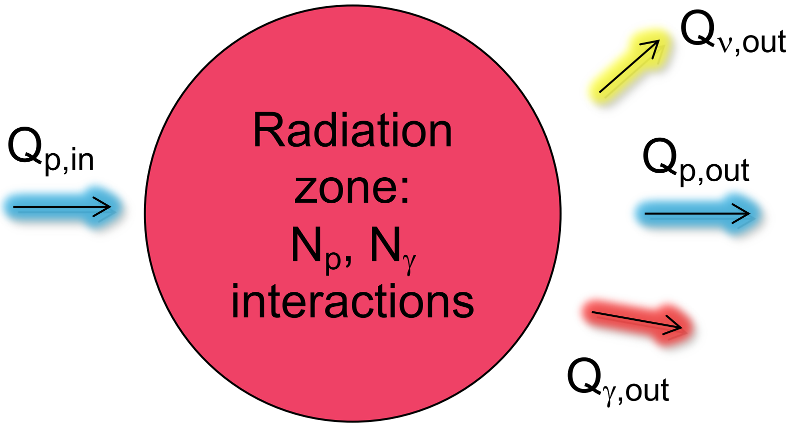
$N(E,t)$ [$\mathrm{GeV}^{-1}\ \mathrm{cm}^{-3}$] particle spectrum including spectral effects

- Injection: species *i* from acceleration zone, and from other species *j*:

$$Q(E) = Q_i(E) + Q_{ji}(E)$$

$$Q_{ji}(E_i) = \int dE_j\, N_j(E_j)\, \Gamma_j^{\mathrm{IT}}(E_j)\, \frac{dn^{\mathrm{IT}}_{j\to i}}{dE_i}(E_j, E_i)$$

Density other species	Inter-action rate	Re-distribution function +secondary multiplicity



Strongly forward peaked spectra in interaction frame (e.g. blob frame)

→ Re-distribution function narrow + peaked

E.g. $E_\nu \sim 0.25\ E_\pi$
$\sim 0.25 \times 0.2 \times E_p = 0.05\ E_p$

Radiation processes

Examples for e and p

- These processes lead to cooling, escape (→ leave species), and re-injection terms
- Other processes relevant for neutrinos: synchroton cooling of muons, pions

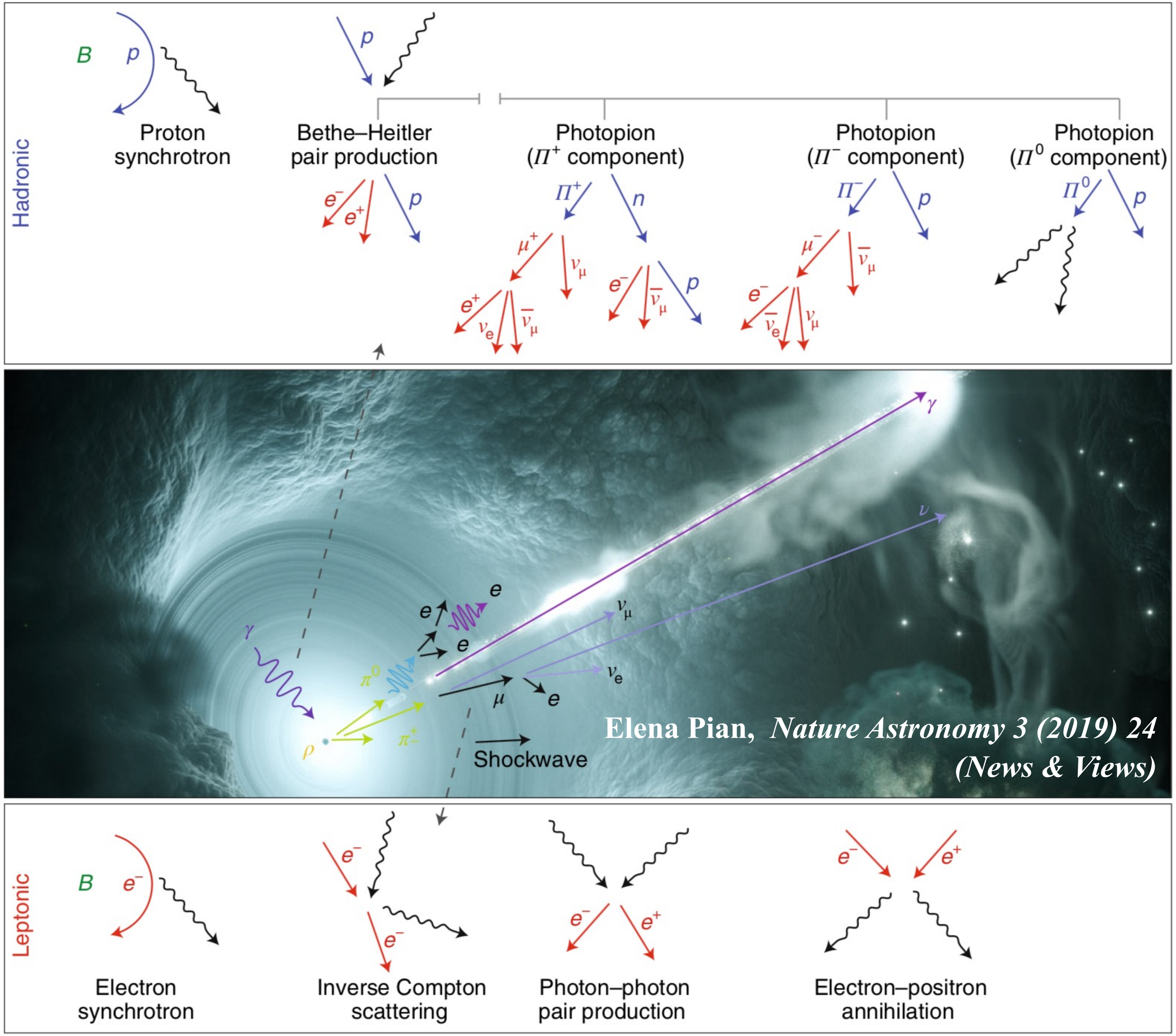
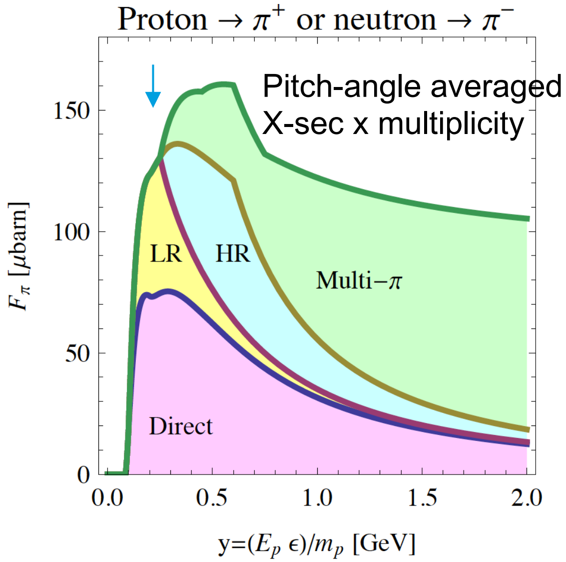


Photo-pion production in the multi-messenger context

- Neutrino peak determined by maximal cosmic ray energy
  [conditions apply: for target photons steeper (softer) than ε^{-1} (and low enough ε_{min})]
- Interaction with target photons
  (Δ-resonance approximation for C.O.M. energy):

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ & \rightarrow \nu \\ p + \pi^0 & \rightarrow \gamma \end{cases}$$

E_γ [keV] ~ 0.01 Γ^2/E_ν [PeV]
keV energies interesting!
(computed for Δ-res, yellow) →

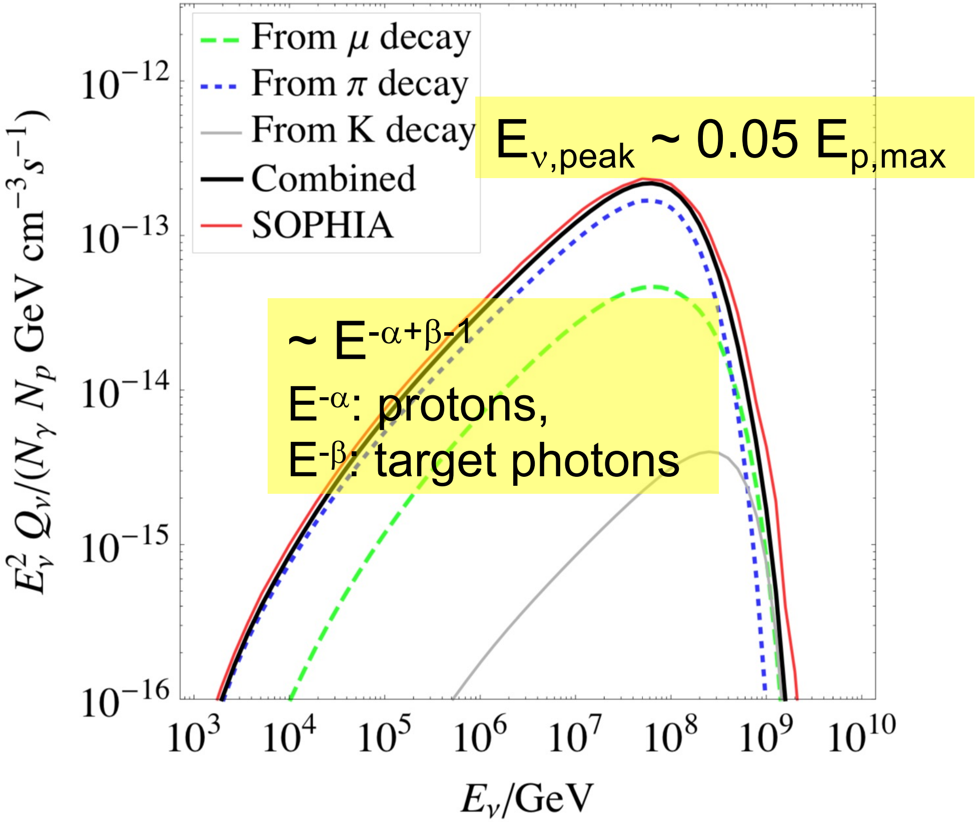


- Photons from pion decay:

$$\pi^0 \rightarrow \gamma + \gamma$$

Injected at $E_{\gamma,peak}$ ~ 0.1 $E_{p,max}$
TeV–PeV energies interesting!
(but: electromagnetic cascade in source – later!)

AGN neutrino spectrum (example)



From: Hümmer et al, Astrophys. J. 721 (2010) 630;
for a more complete view of possible cases, see
Fiorillo et al, JCAP 07 (2021) 028

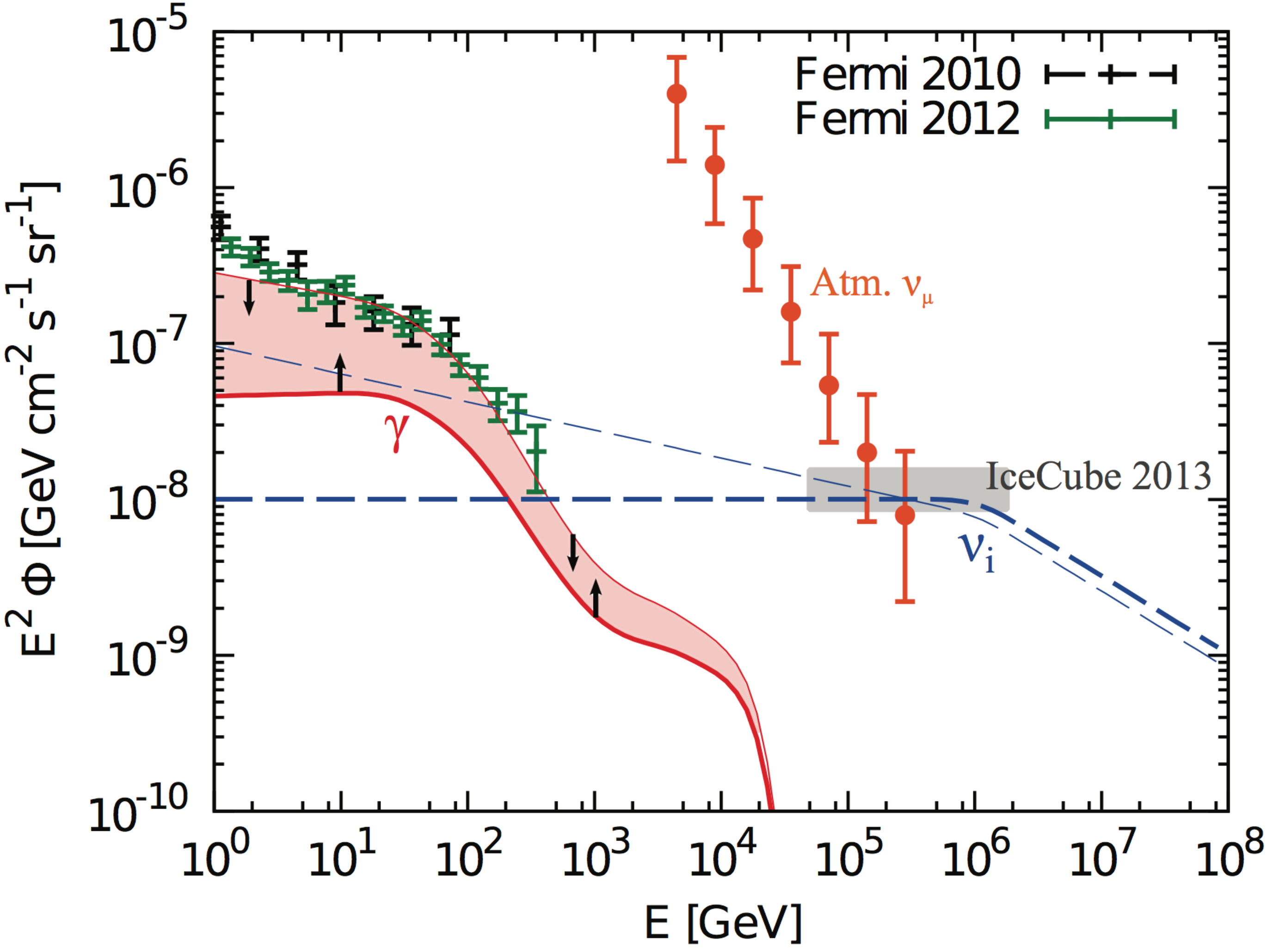
Application for pp interactions: Starburst galaxies

Gamma-ray diffuse flux

$$p + p \rightarrow \begin{cases} \left.\begin{matrix}\pi^+ \\ \pi^-\end{matrix}\right\} \nu \\ \pi^0 \quad \gamma \end{cases}$$

- Neutrinos and gamma-rays follow primary E^{-2} spectrum
- Diffuse gamma-ray background dominated by AGN; non-AGN contributions sub-leading
- Constrains spectral index for non-AGN contributions (starburst galaxies, ...)

Bechtol et al, 2017;
Palladino et al, arXiv:1812.04685;
Peretti et al, 2020; …



Murase, Ahlers, Lacki, 2013

Flavor composition in terms of *flavor triangles*

Theoretical expectations

- Standard model expectation for flavor mixing (averaged neutrino oscillations):

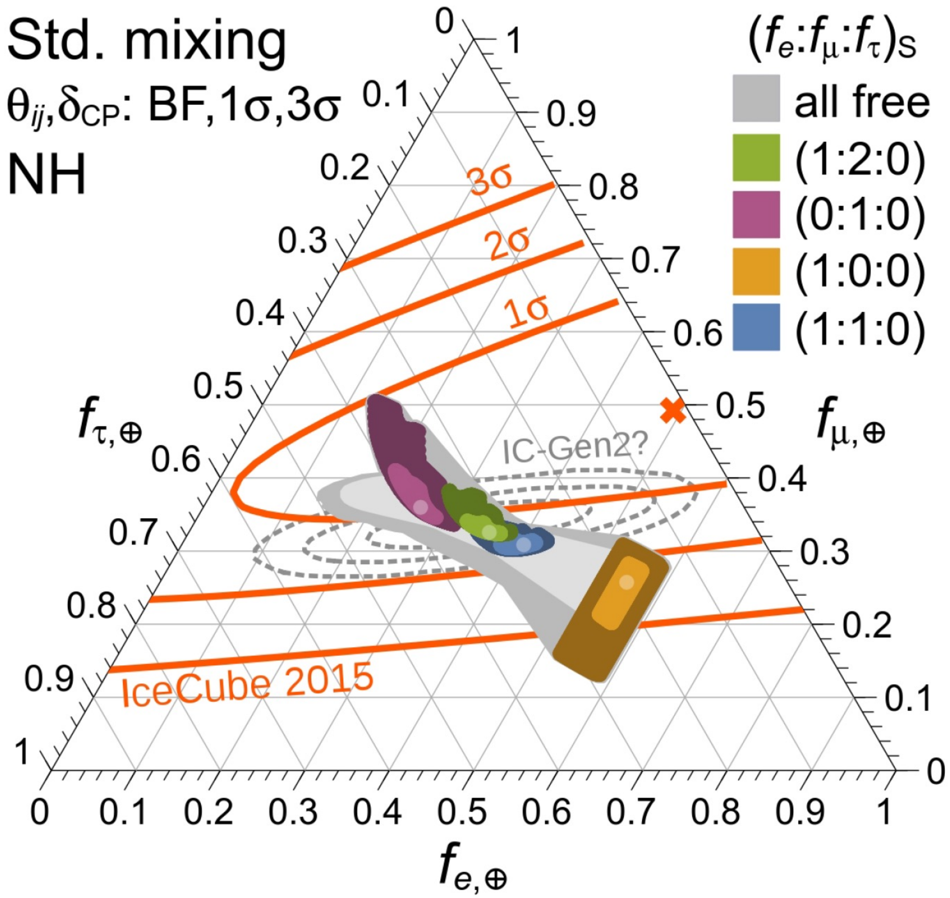
$$P_{\alpha\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

- Flavor compositons at source $(f_e:f_\mu:f_\tau)_S$:
  - Pion decay chain: (1:2:0)
  - Muon damped source: (0:1:0) – previous slide
  - Neutron decays: (1:0:0)
  - Charmed meson decays or muon pile-up: (1:1:0)

for a comprehensive picture of energy-dependent flavor compositions, see Hümmer et al, Astropart. Phys. 34 (2010) 205

- Small region of flavor triangle occupied by SM physics, but BSM may cause deviations! →

Physics potential



IceCube measurement Astrophys. J. 809 (2015) 1, 98; updates: Eur. Phys. J. C 82 (2022) 11, 1031, ICRC 2025

Bustamante, Beacom, Winter, PRL 115 (2015) 16, 161302; Arguelles, Katori, Salvado, PRL 115 (2015) 161303;

dates back to: Barenboim, Quigg, 2003

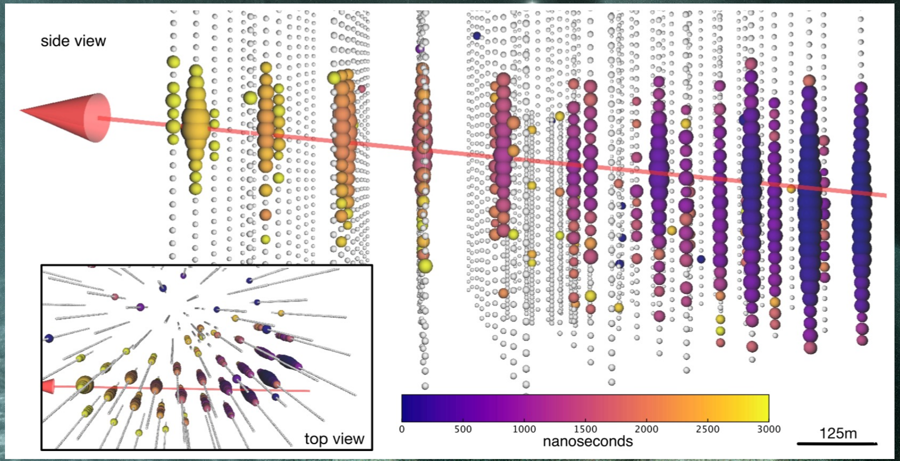
(shaded regions: current 3σ range for mixing params)

Multi-messenger follow-ups

Example: AGN blazars

AGN blazar

Science 361 (2018) no. 6398, eaat1378



https://multimessenger.desy.de/

What is an AGN blazar?
(AGN = Active Galactic Nucleus)

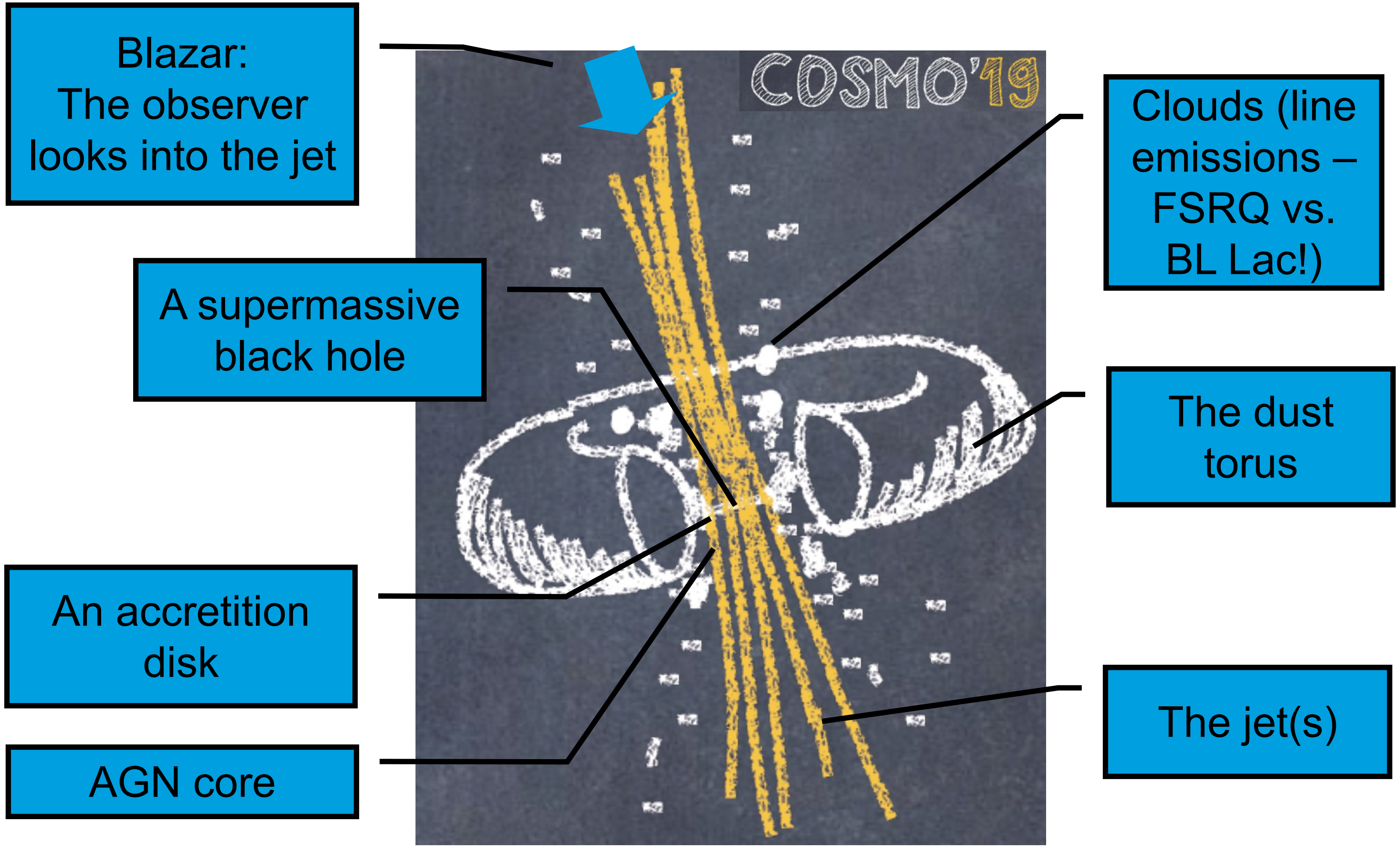
Theory basics:

1

Angular momentum determines geometry

2

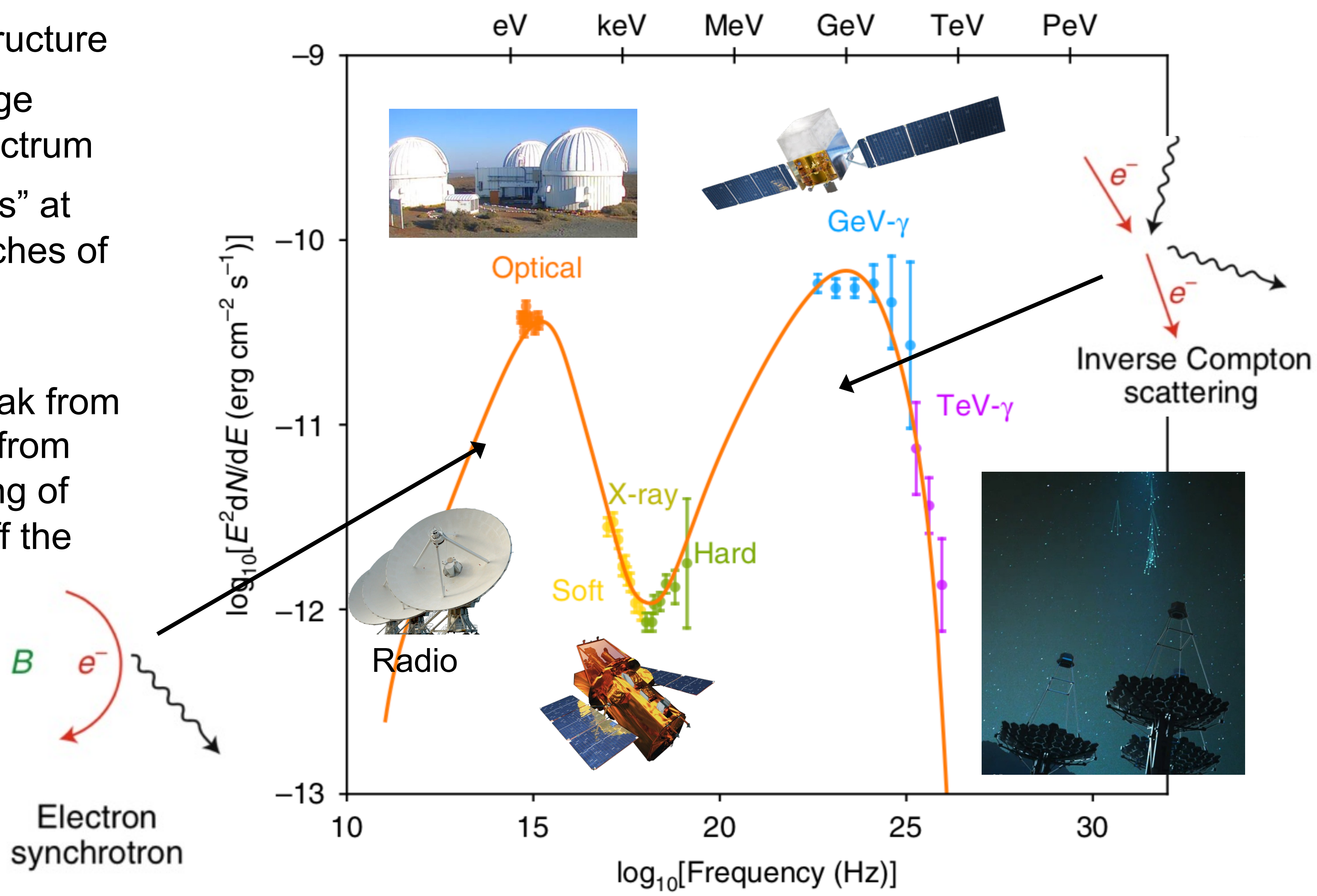
Estimate for accretion power:
Eddington luminosity
$L_{edd} \sim 10^{47}$ erg s^{-1}
$\times M_{BH}/(10^9 M_{sun})$



Electromagnetic picture of blazars

- Exhibit a typical two-hump structure
- Measured over extremely large range of electromagnetic spectrum
- Often observation “campaigns” at same time, or follow-up searches of neutrinos

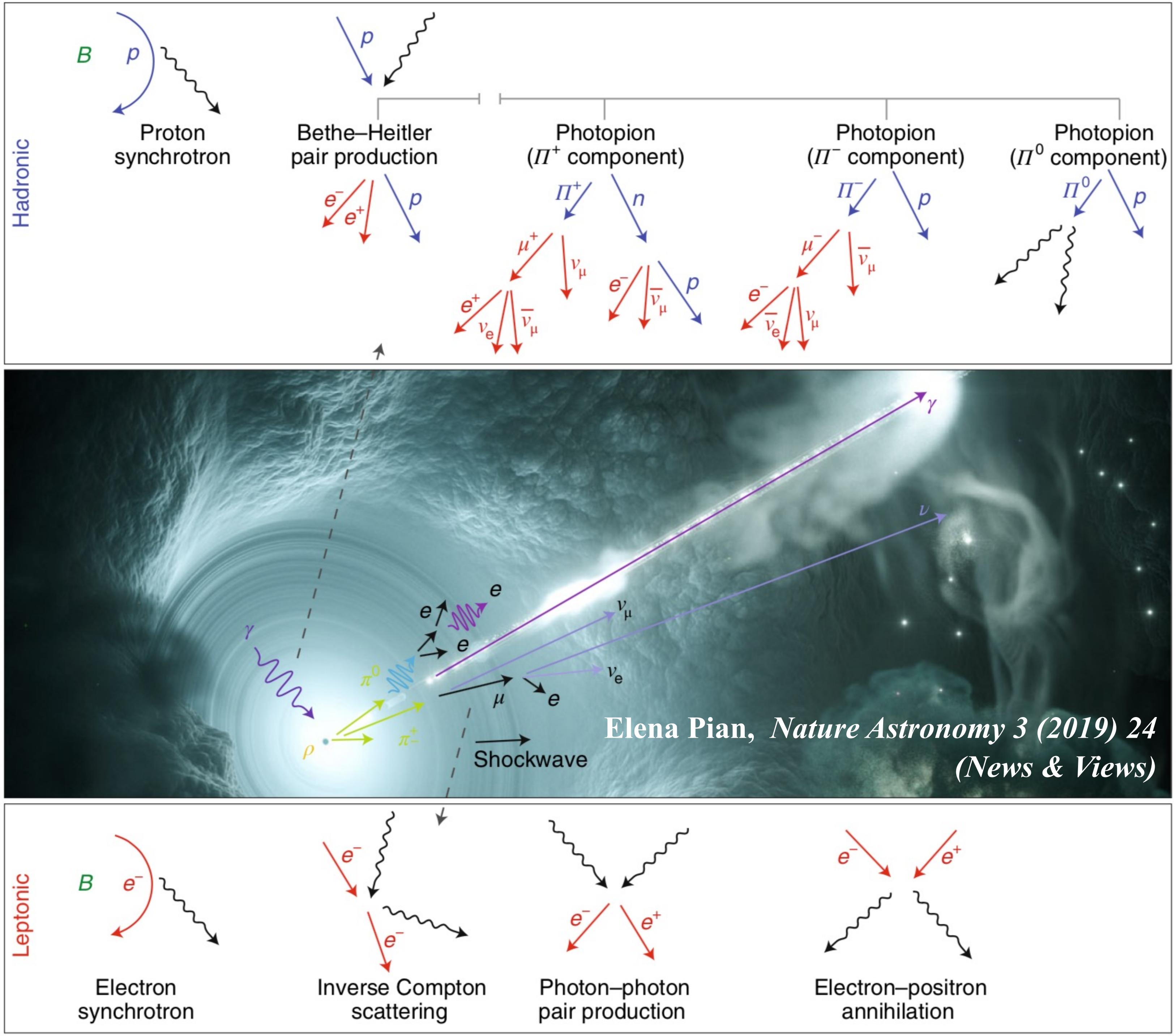
- Simplest explanation: first peak from electron synchrotron, second from inverse Compton up-scattering of these synchrotron photons off the same electrons
(= SSC – “synchrotron self-Compton model”)



Credits: VLA, ASAS-SN, Swift, Fermi, MAGIC, DESY science comm. lab., Pian 2019, Gao et al, 2019

Radiation processes

Examples for e and p - recap



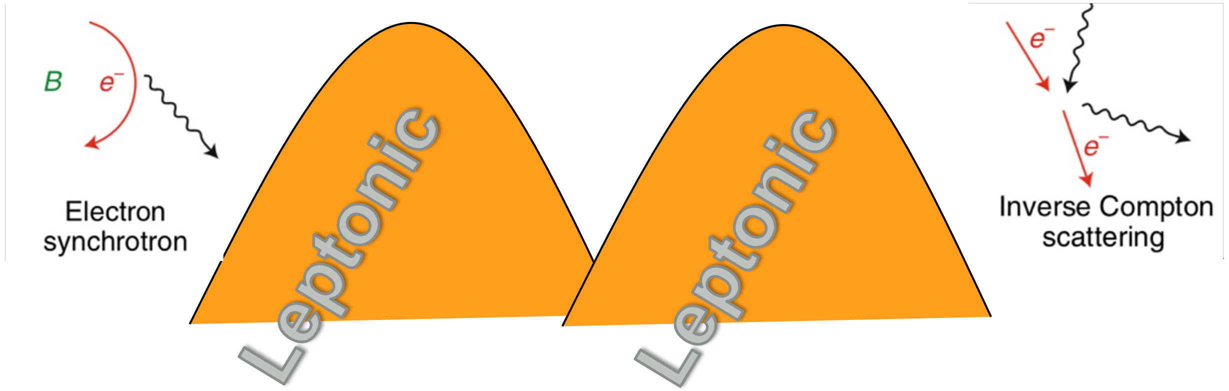
Elena Pian, *Nature Astronomy 3 (2019) 24 (News & Views)*

Typical SED models (qualitatively)

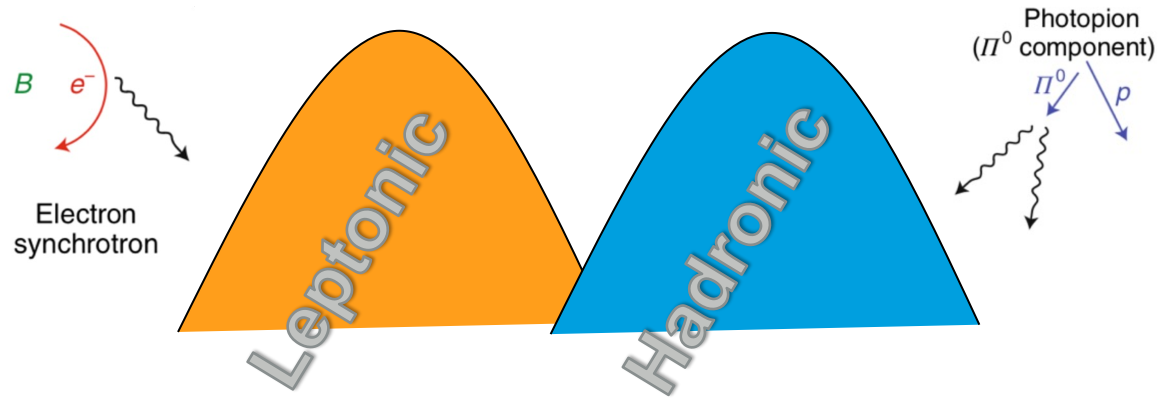
One spherical radiation zone
Fewest assumptions

R'

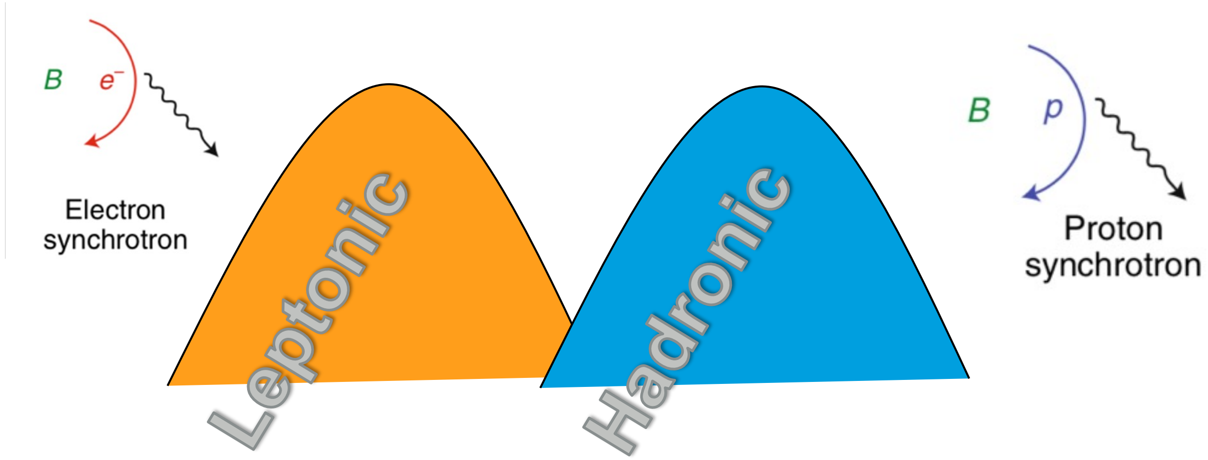
- Synchrotron self-Compton (SSC) or external Compton (EC) models



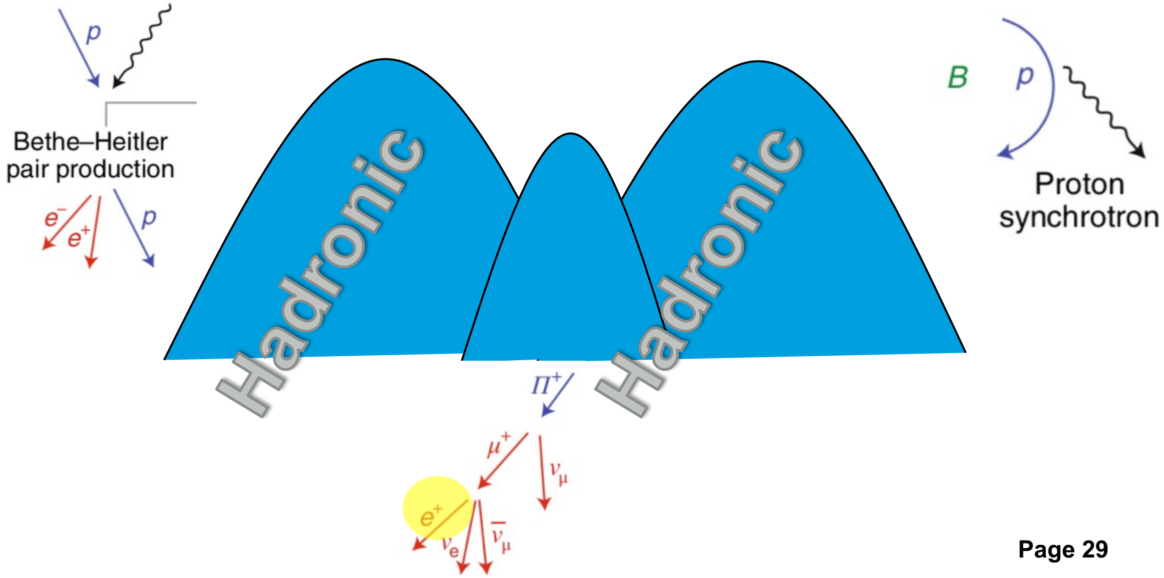
- Pion cascade models



- Proton synchrotron models (require large B')

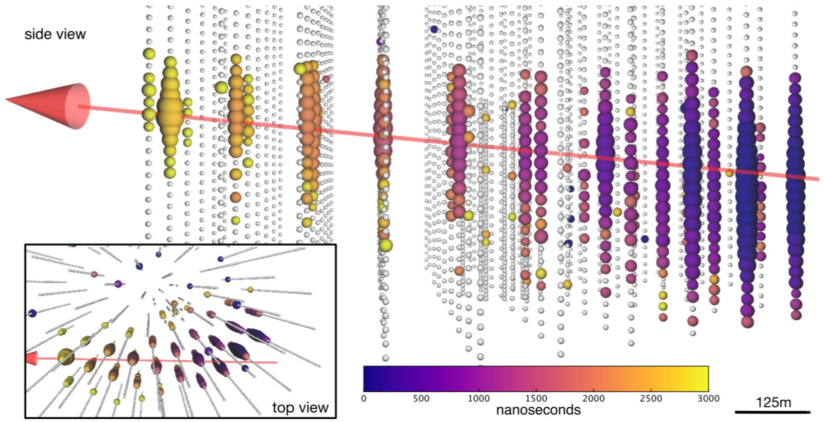


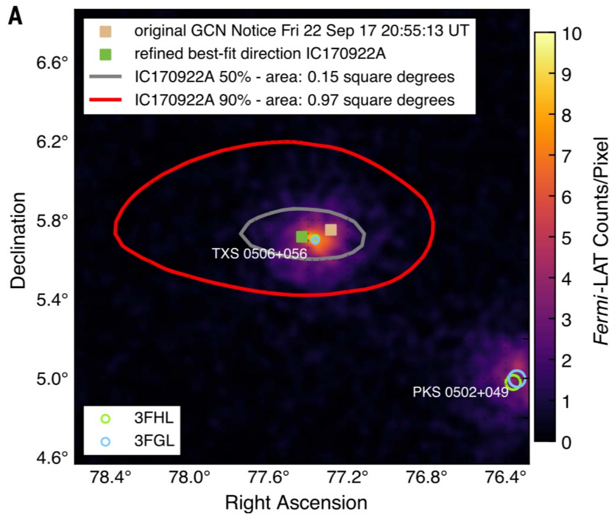
- More exotic hadronic models, for example:



A neutrino from the flaring AGN blazar TXS 0506+056

Sept. 22, 2017:
A neutrino in coincidence with a blazar flare



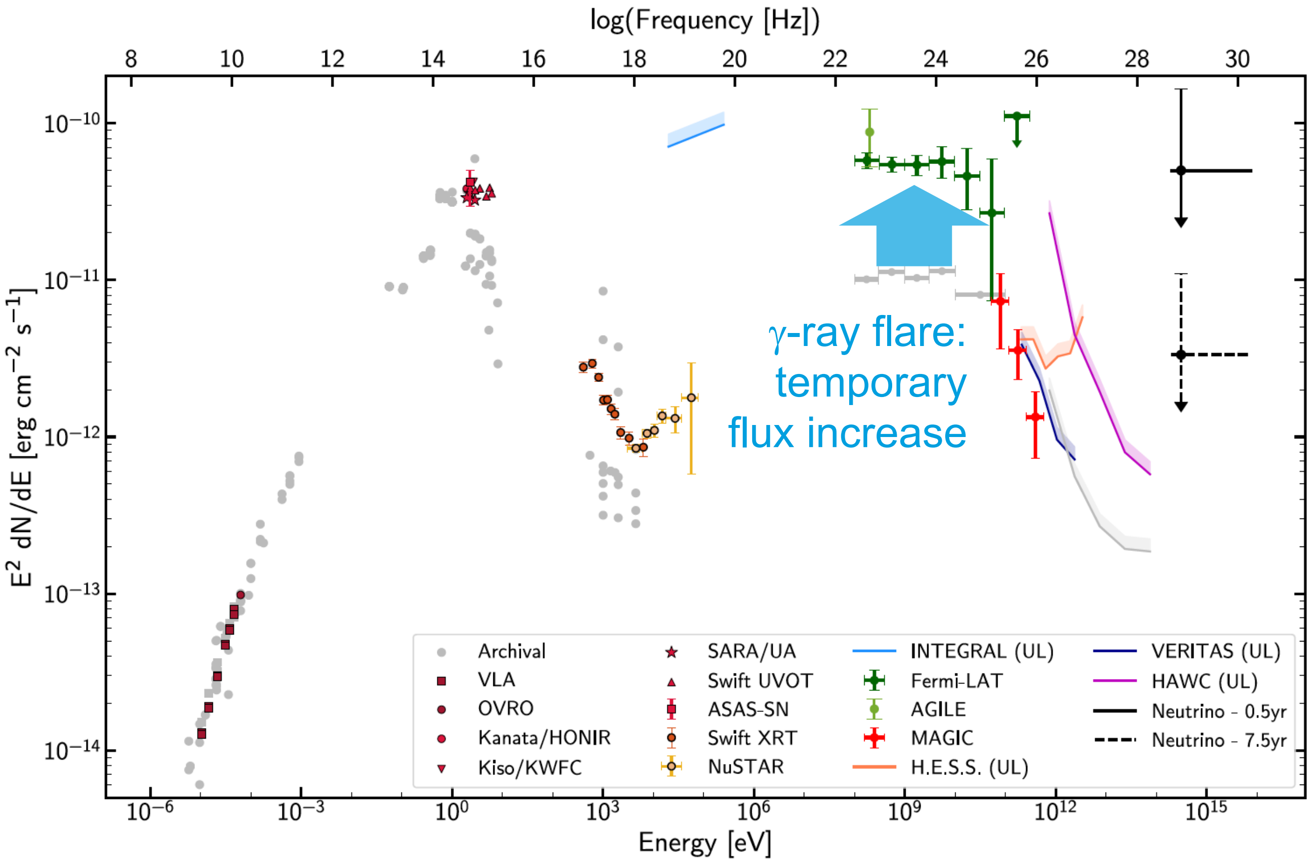


Observed by Fermi-*LAT* and MAGIC (blazar flare)

Significance for correlation: 3σ

z = 0.3365 ± 0.0010
Paiano et al, 2018

SED from a multi-wavelength campaign

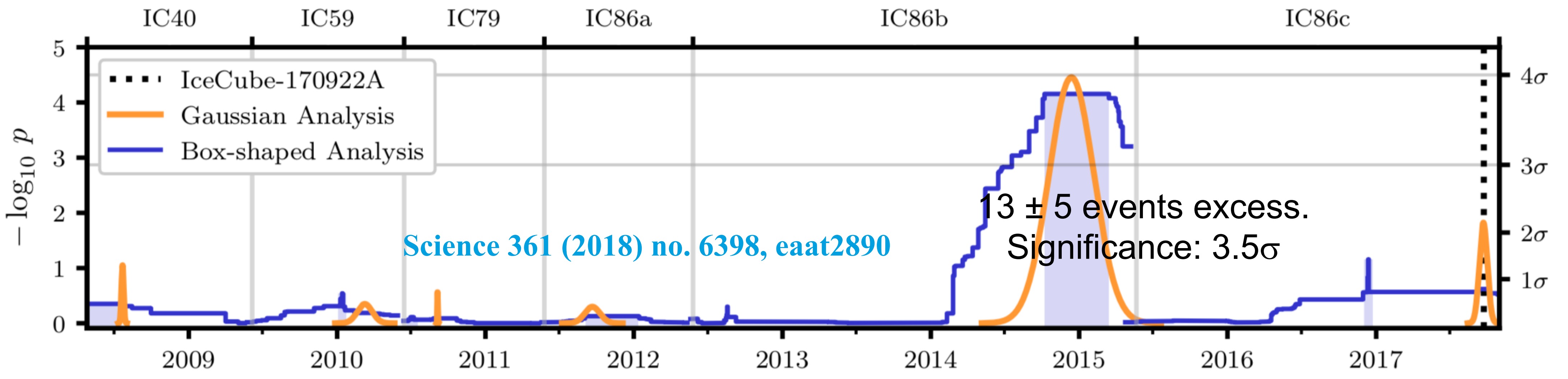


Color: coincident with neutrino; gray: archival data

Science 361 (2018) no. 6398, eaat1378

Analysis of archival neutrino (IceCube)

A (orphan) neutrino flare (2014-15) found from the same object in archival neutrino data

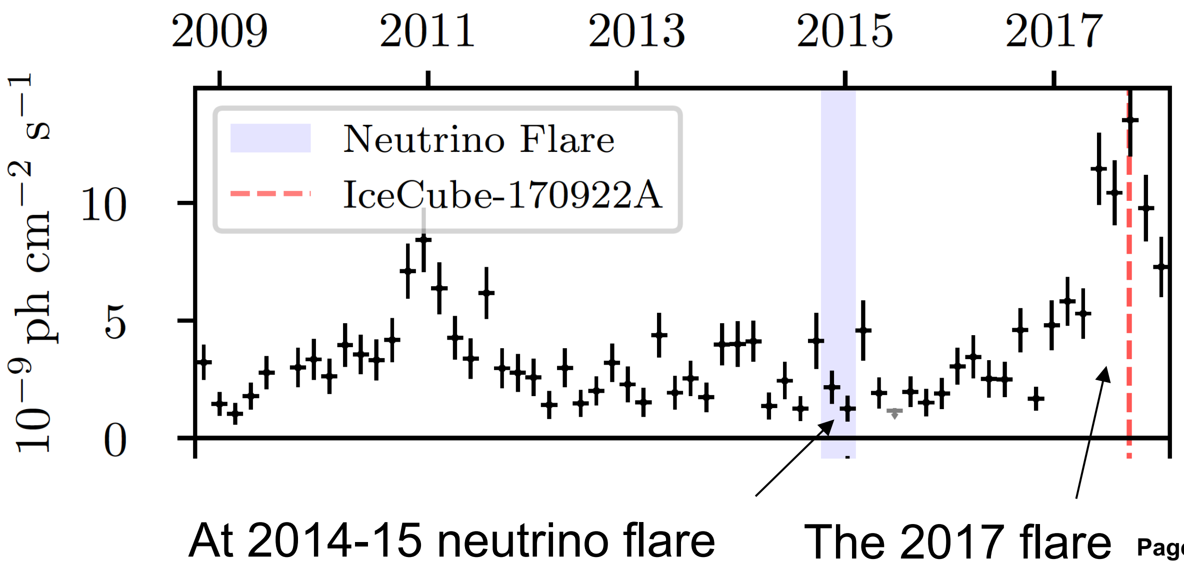


Science 361 (2018) no. 6398, eaat2890

During that historical flare:

- Coincident data sparse (since no dedicated follow-up campaign)
- No significant gamma-ray activity

Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192



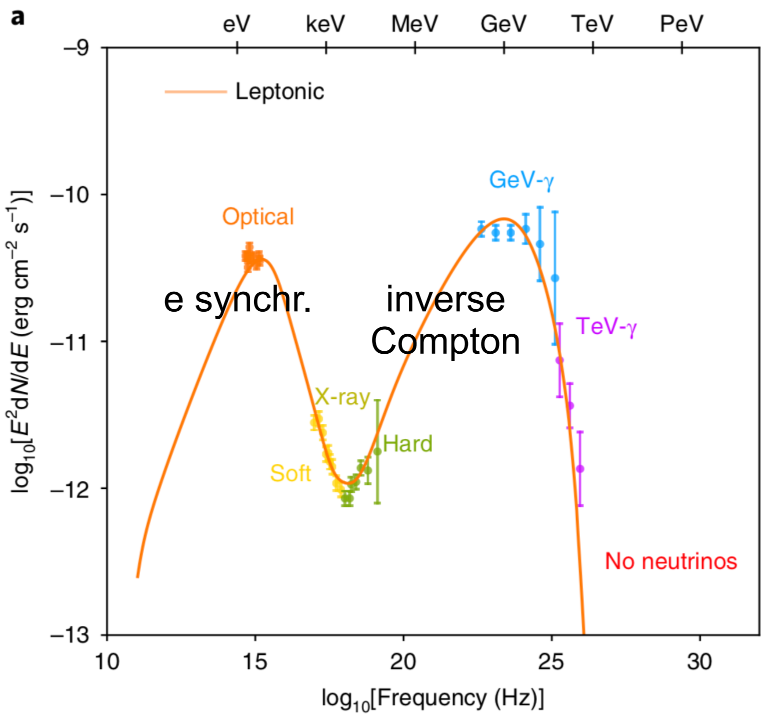
Multi-messenger interpretation of TXS 0506+056

One zone model results (2017 flare)

One spherical radiation zone
Fewest assumptions

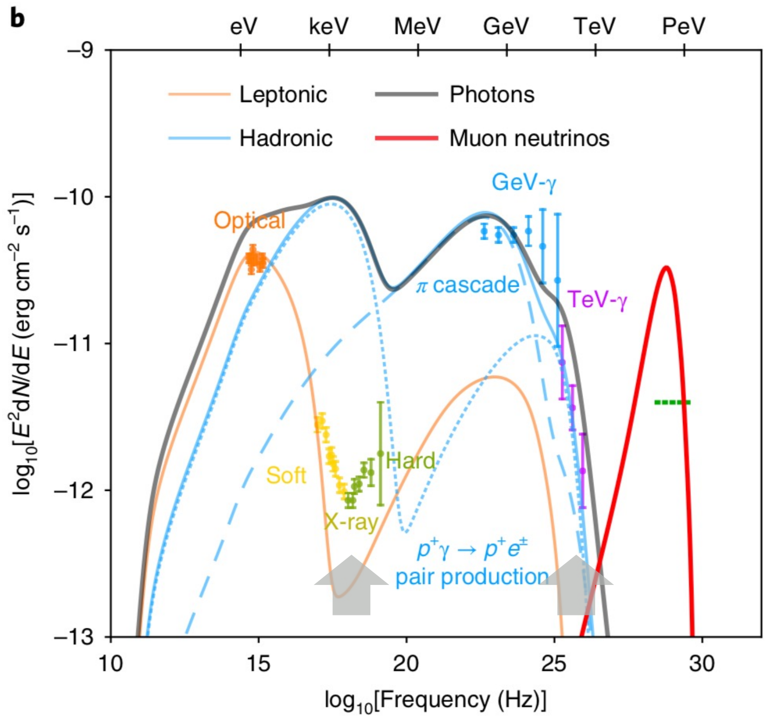
R'

Leptonic models



- No neutrinos

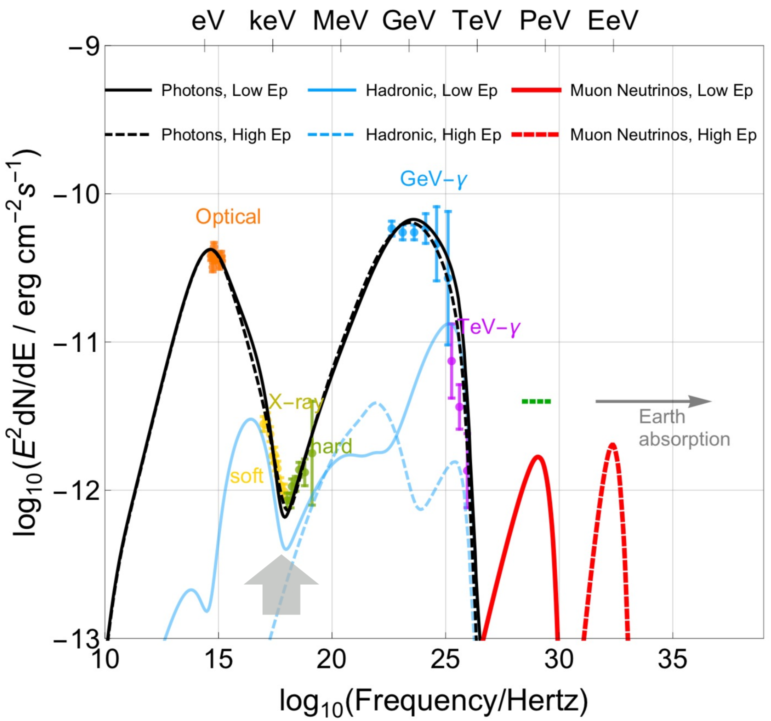
Hadronic (π cascade) models



- Violate X-ray data

X-ray (and TeV γ-ray) data indicative for hadronic origin

Hybrid or p synchrotron models



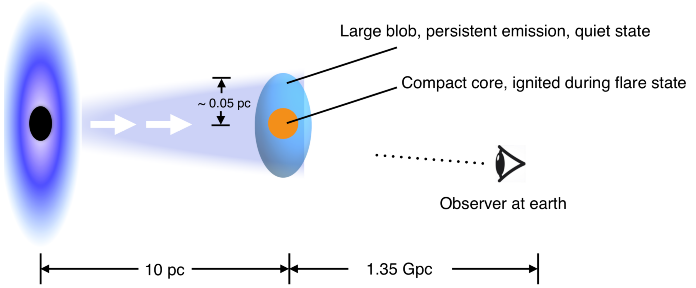
- **Violate energetics (L_{edd}) by a factor of a few hundred or significantly exceed ν energy**

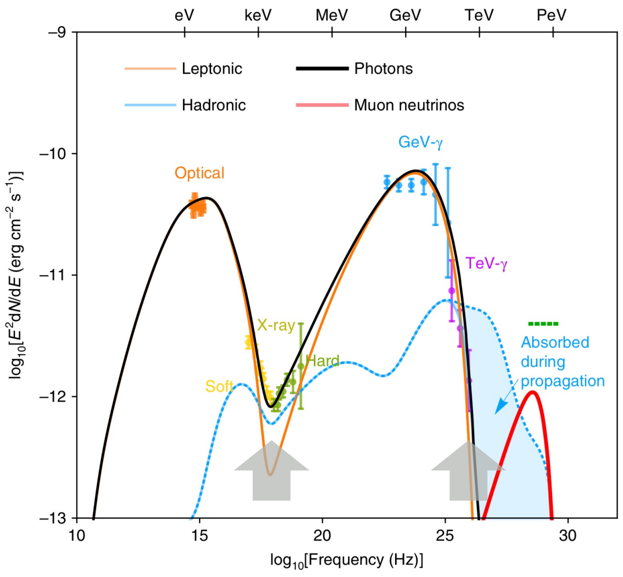
Gao, Fedynitch, Winter, Pohl, *Nature Astronomy 3 (2019) 88;*
see also Cerutti et al, 2018; Sahakyan, 2018; Gokus et at, 2018; Keivani et al, 2018

More freedom through multiple radiation zones

... to solve energetics problem (examples). At the expense of more parameters.

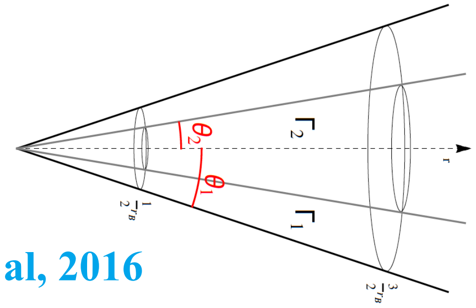
Formation of a compact core



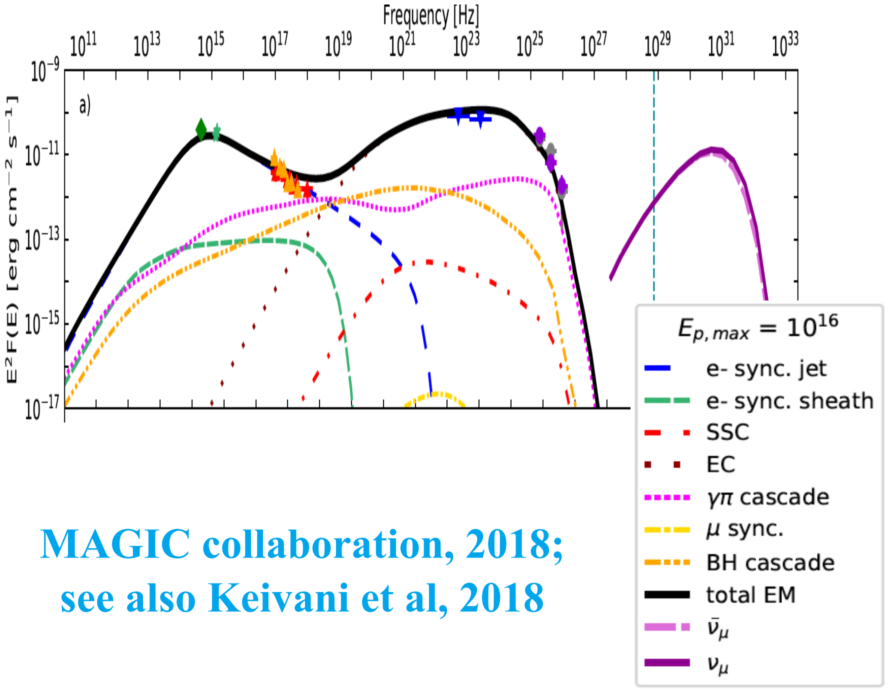


Gao et al, *Nature Astronomy 3 (2019) 88*

External radiation fields

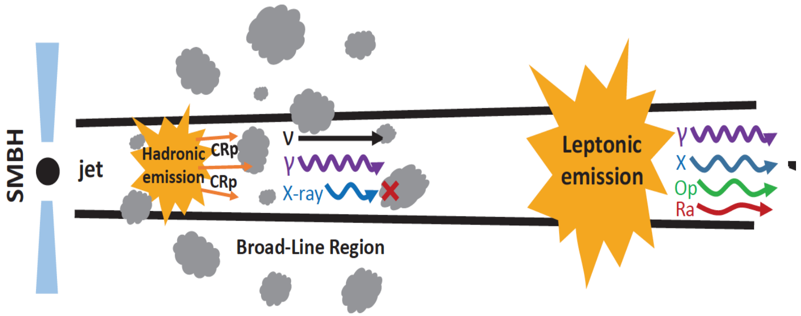


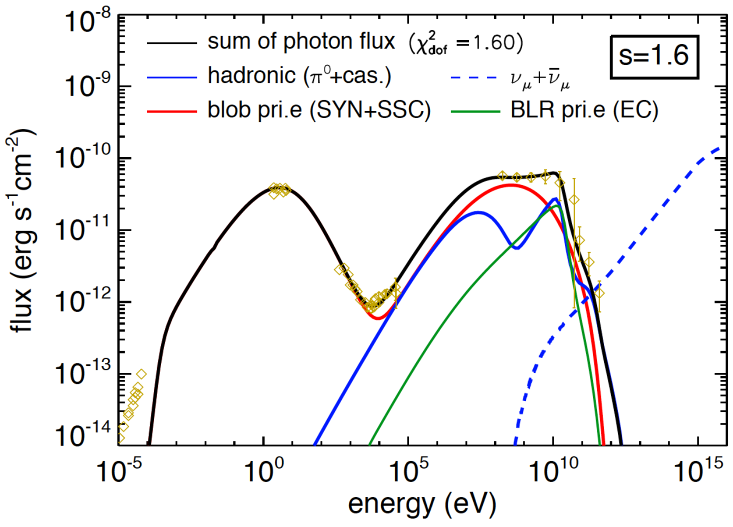
Sikora et al, 2016



MAGIC collaboration, 2018;
see also Keivani et al, 2018

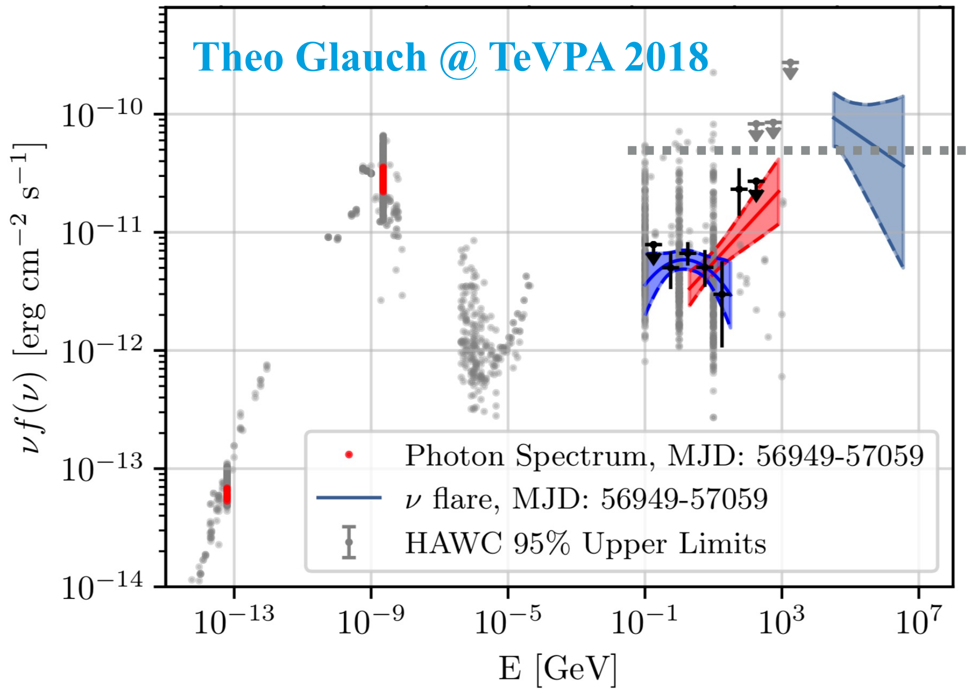
Jet-cloud interactions/ several emission zones





Liu et et al, 2018;
see also Xue et al, 2019

The archival (2014-15) neutrino flare of TXS 0506+056



- Electromagnetic data during neutrino flare sparse (colored)
- Hardening in gamma-rays? (red shaded region)

Padovani et al, 2018; Garrappa et al, arXiv:1901.10806

Theoretical challenge: Where did all the energy go to?

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} n + \pi^+ \Rightarrow \nu \\ p + \pi^0 \Rightarrow \gamma \end{cases}$$

Comparable amounts of energy

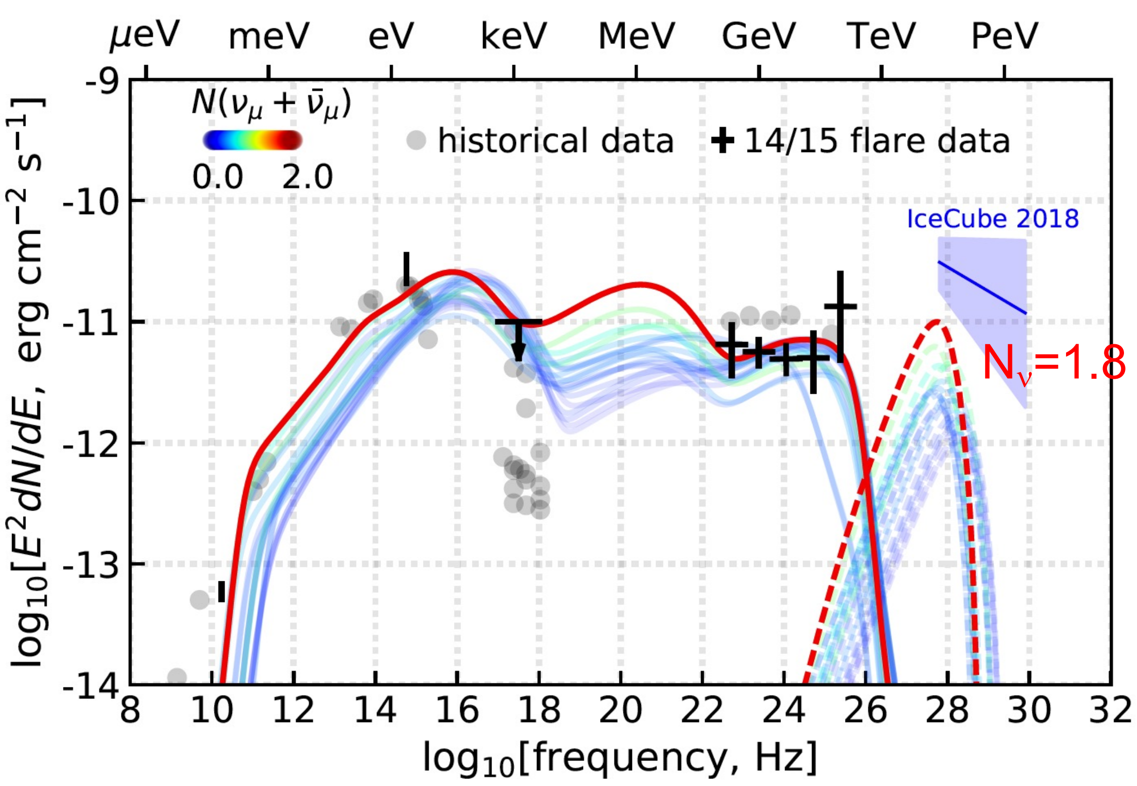
Options for hiding the gamma-rays (+electrons):

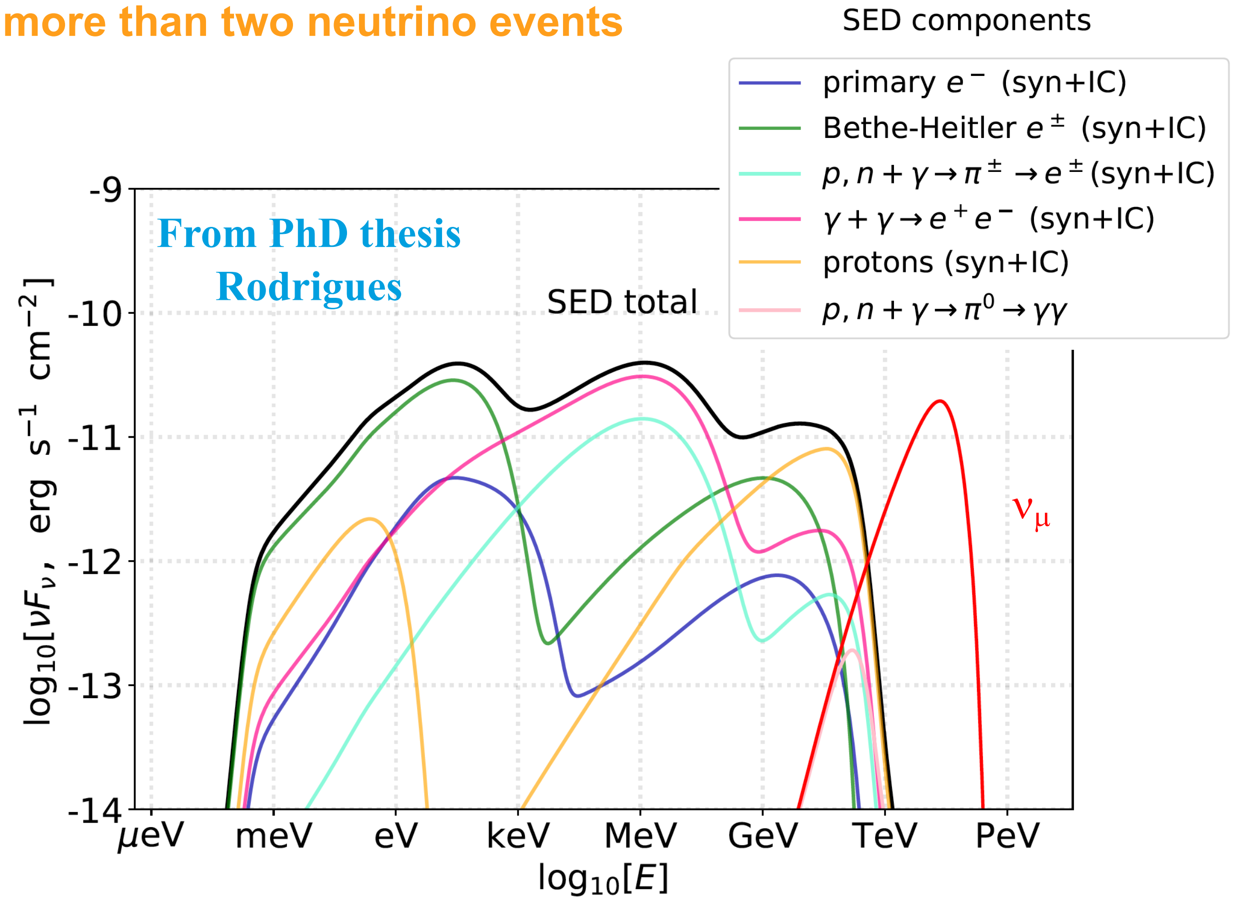
- **Reprocessed** and "parked" in E ranges without data during flare? (e.g. MeV range, sub-eV range)
  - → Can this be accommodated in a self-consistent model (next slide)? Fine-tuned during flare?
  - → Requires monitoring in all wavelength bands
- Leave source + **dumped** into the **background light**?
  - → Implies low radiation density to have gamma-rays escape
  - → Difficult to accommodate energetics if sole solution (low neutrino production efficiency!)
- **Absorbed or scattered** in some **opaque region**, e.g. dust/gas/radiation?
  - → Requires additional model ingredients

    see e.g. Wang et al, 2018; Murase et al, 2018

One zone description of spectral energy distribution

.... can describe SED (with significant excess of L_{edd}), but no more than two neutrino events





Energy deposited in MeV range and absorbed in EBL (here about 80% absorbed, 20% re-processed for E_γ > TeV)

Primary electron processes (synchrotron and inverse Compton) dominate *nowhere* in this model!

From: Rodrigues, Gao, Fedynitch, Palladino, Winter, ApJL 874 (2019) L29; see also Halzen, et al, ApJL 874 (2019) 1, L9; Petropoulou et al, ApJ 891 (2020) 115

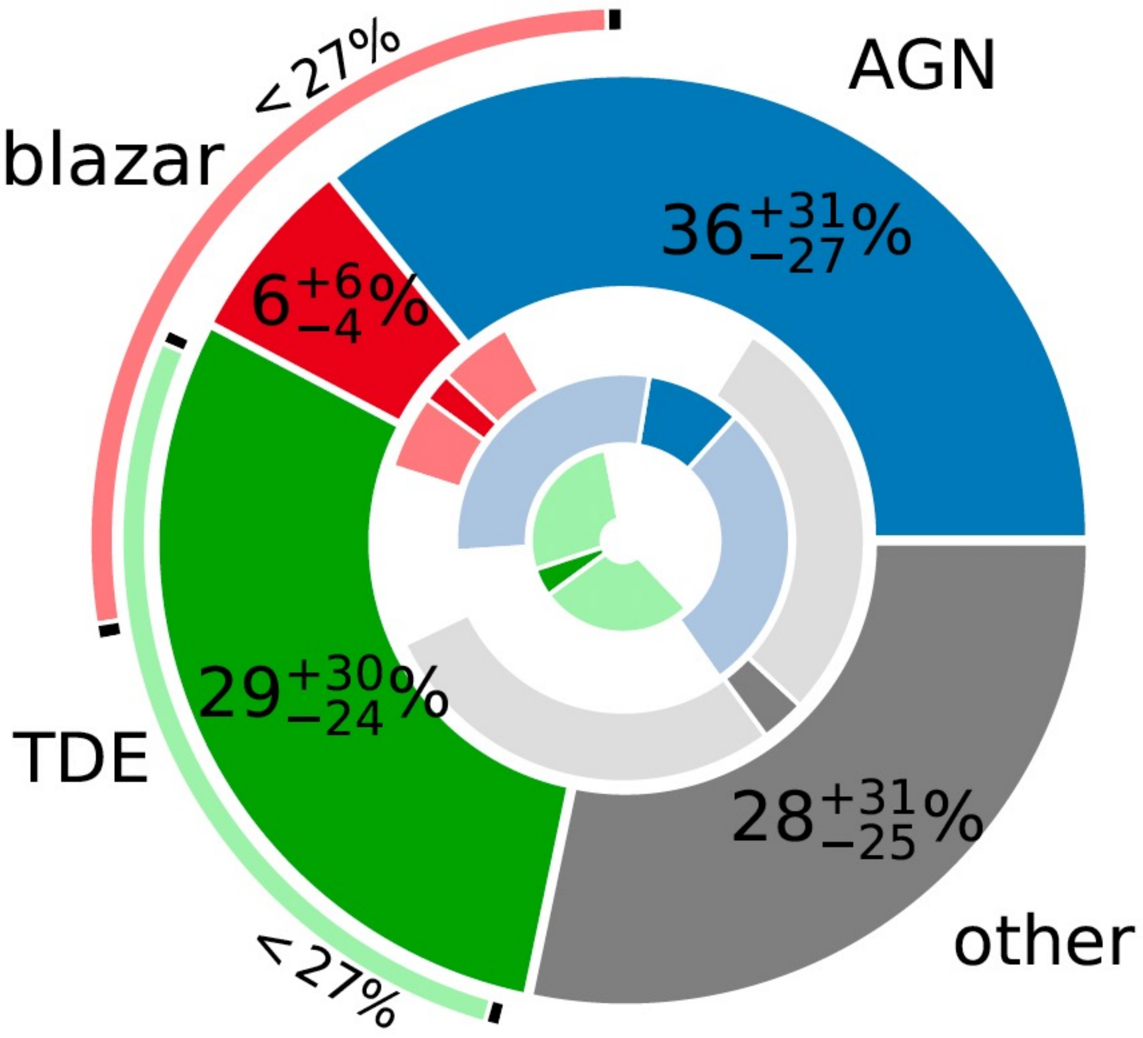
Summary and outlook

Evidence for multiple individual neutrino source populations emerging

- AGN blazars
- AGN cores
- TDE?
- Galactic
- Other

Neutrino production

- The neutrinos spectrum typically peaks at the primary energy $E_{\nu,peak} \sim 0.05\ E_{p,max}$. Exception: strong B (secondary cooling)
- The neutrino spectrum follows the primary spectrum for pp interactions and thermal targets with high C.O.M. energies
- Neutrinos can be only seen from very nearby or very luminous individual sources



Bartos et al, arXiv:2105.03792