Numerical modelling of sources of astrophysical neutrinos

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HELMHOLTZ

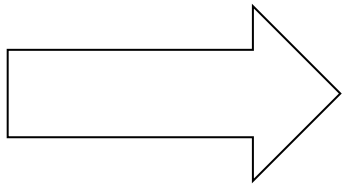
DESY.

Neutrinos from the cosmos

Messengers of Cosmic Ray interactions

High-Energy Cosmic Rays (CRs) + target

p (or *nucleus*) $\Rightarrow$ p, γ



High energy gamma rays and neutrinos!

$\dots$,

$\pi^{\pm} \Longrightarrow \dots + \nu$,

$\pi^{0} \Longrightarrow \gamma\gamma$,

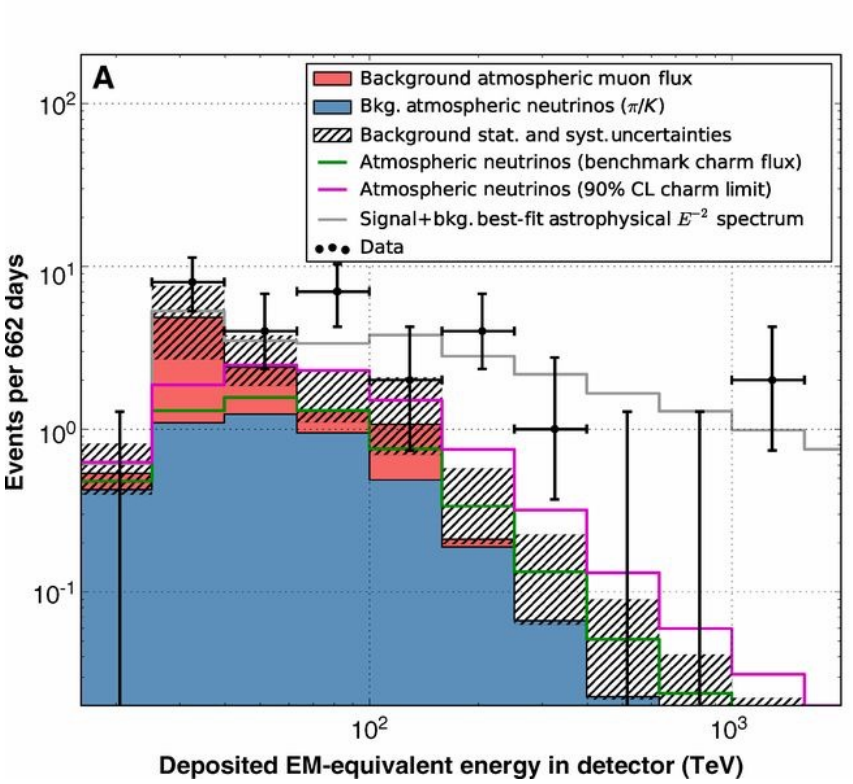
$n \Longrightarrow \dots + \nu$.

Can interact in the *source of CRs*
or *during their propagation*

"Astrophysical" neutrinos

We saw them!

…and we observe them "regularly"

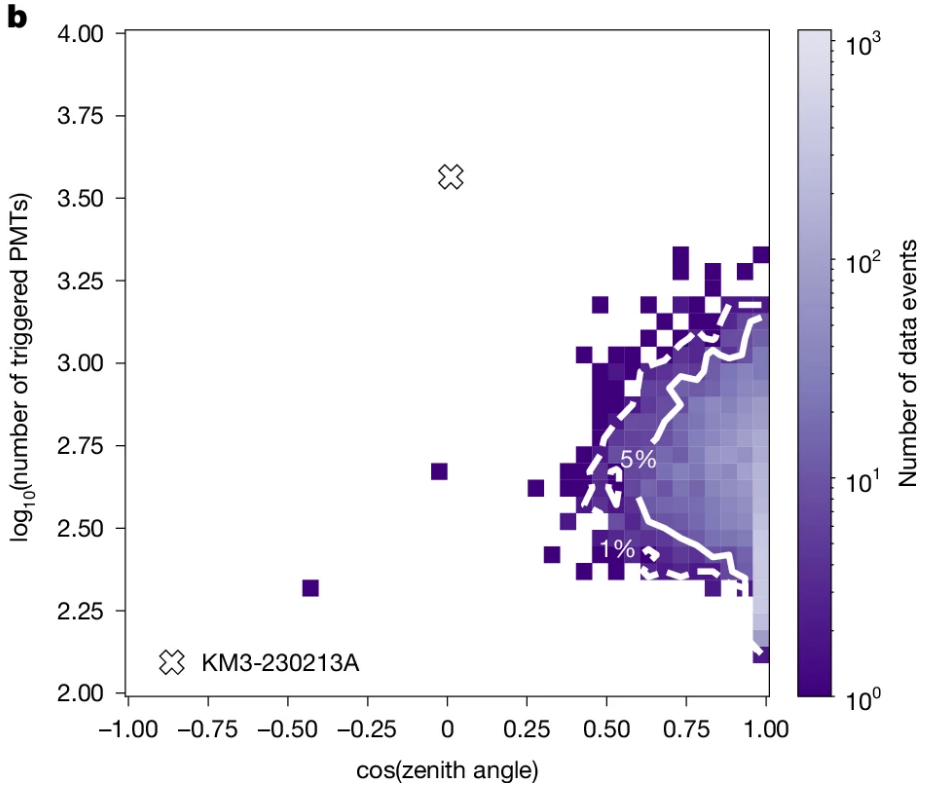


[IceCube collaboration, Science 342 (2013)]

2013:
IceCube discovers
astrophysical neutrinos

…

2025
KM3Net observes a
neutrino with O(100 PeV)



[KM3NeT collaboration, Nature 638 (2025)]

Where are they from?

Candidate sources of astrophysical neutrinos

What makes the observed neutrinos?

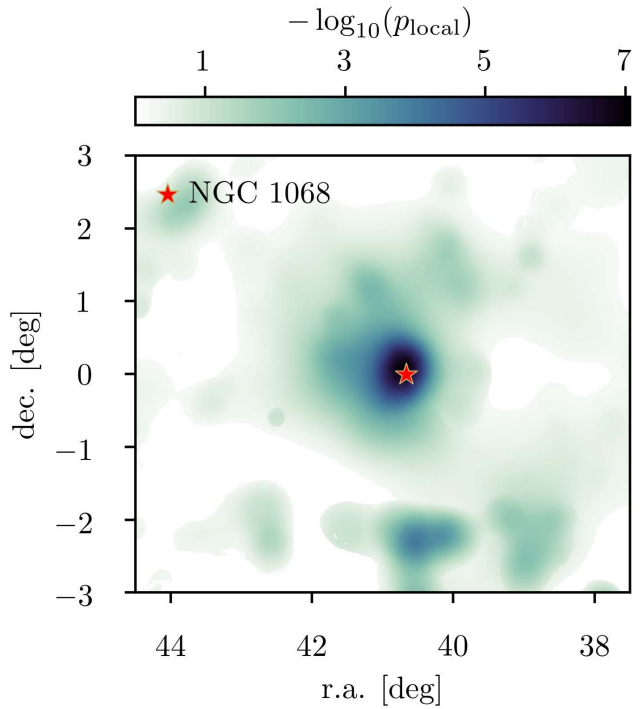
If it can accelerate hadrons and offer a target, then can make neutrinos (AGN, GRB, TDE, ...)

NOT SO EASY... ONLY 3 SOURCES SO FAR!

TXS 0506+056 (blazar)

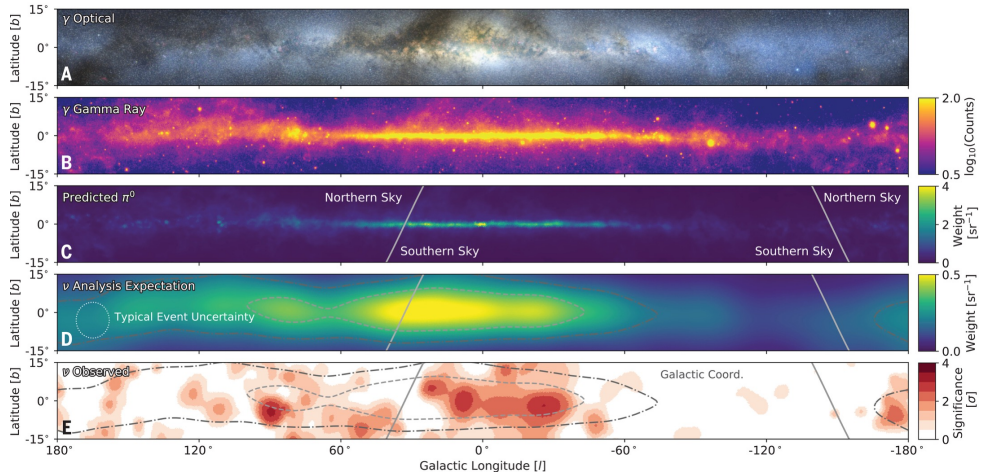
[IceCube collaboration, Science 361 (2018)]

NGC 1068 (Seyfert galaxy)



[IceCube collaboration, Science 378 (2022)]

OUR GALAXY



[IceCube collaboration, Science 380 (2023)]

My job!

Numerical modelling of sources of astrophysical neutrinos

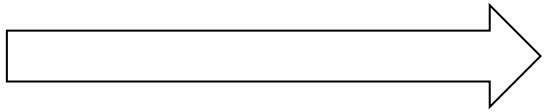
Imagine a radiation zone where accelerated particles are injected...

THEORY:

Input parameters

- **Magnetic field**
- **Radius**
- **Spectrum of leptons**
- **Spectrum of hadrons**

Simulate interactions in the source (numerical methods: $\boldsymbol{AM^3}$)



Density of each particle species

Flux of photons

(Flux of neutrinos, if hadronic model)

The main tool: AM^3

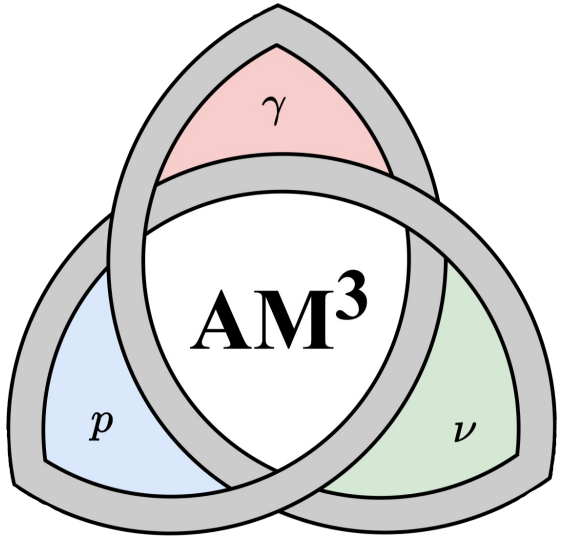
Simulating particle interactions in a radiation zone

Solve the kinetic equation (source, advection, sink) for each species I

Network of coupled PDEs

$$\partial_t n_i(E,t) = Q_i(E,t) - \partial_E[\dot{E}(E,t) n_i(E,t)] - k(E,t) n_i(E,t)$$

Time dependent: solves for $n_i(t)$



Info and installation: here

[Klinger et al., APJ Suppl. (2024)]

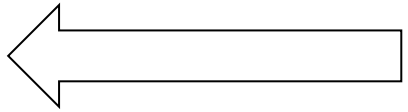
My job!

Numerical modelling of sources of astrophysical neutrinos

Imagine a radiation zone where accelerated particles are injected...

Best-fit inputs:

Understand what's going on in the source!



Multi-messenger picture of source

- observed multiwavelength spectrum of photons
- flux of neutrinos, where available

MODELLING:

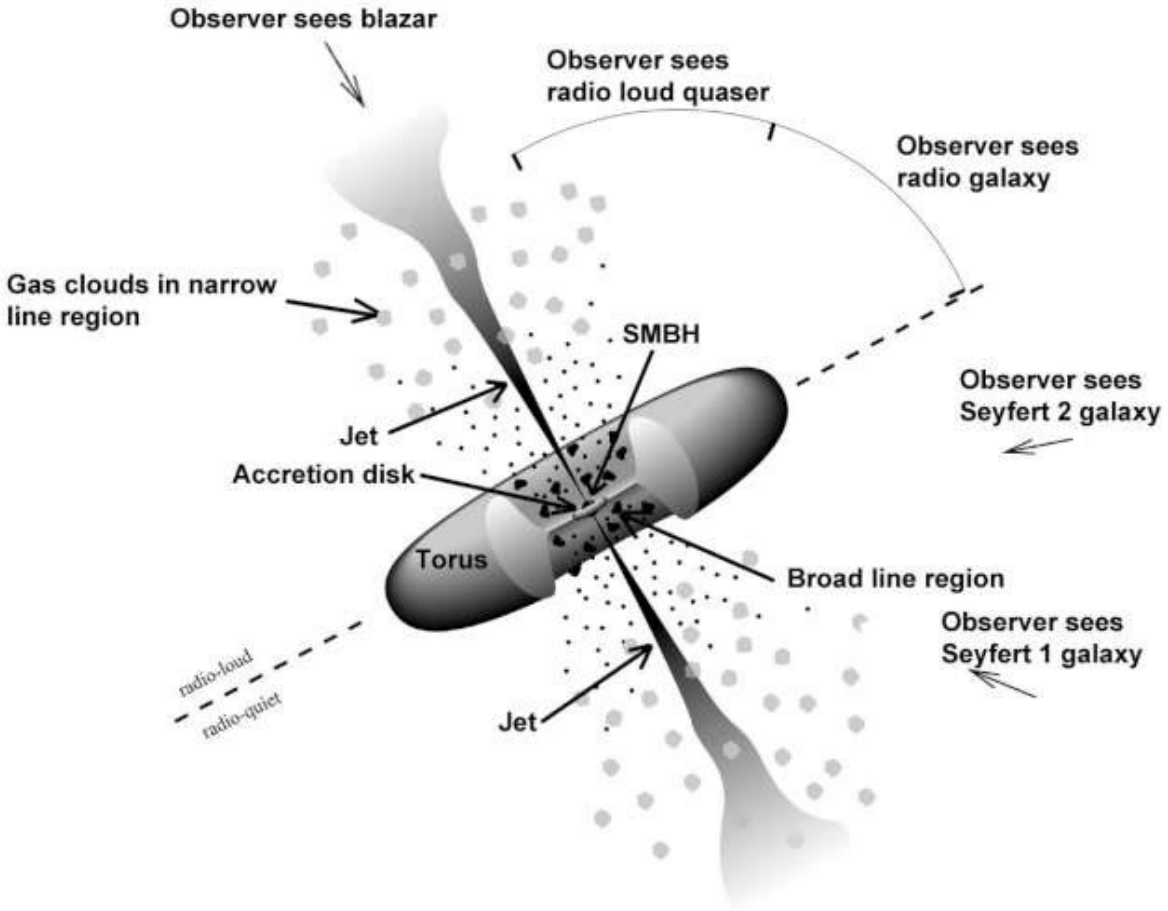
Find input parameters
that best describe the data

So far…

Focus on AGN and first results

Neutrinos observed:

from blazar (TXS 0506+056)
from Seyfert galaxy (NGC 1068)



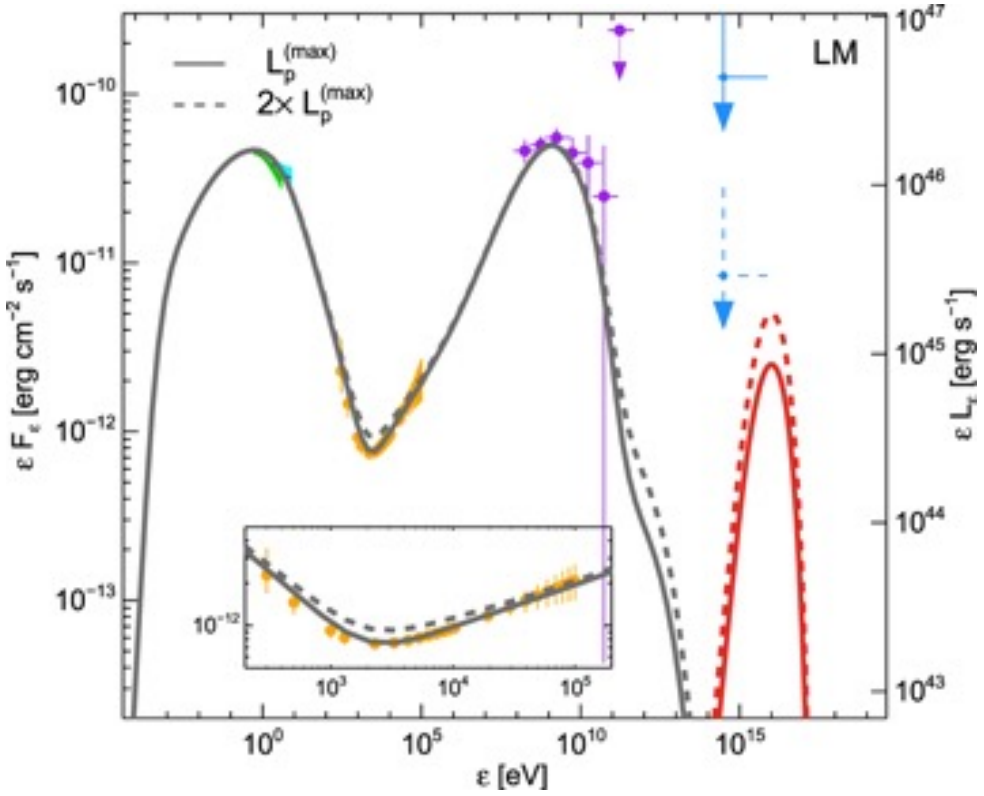
Both are AGNs
BUT WHERE ARE NEUTRINOS PRODUCED?

So far…

Focus on AGN and first results

Neutrinos observed:

from blazar (TXS 0506+056) → expected production in the jet



Leptons and protons are accelerated and injected

Relativistic boosting of jet emission
→ explains high luminosity

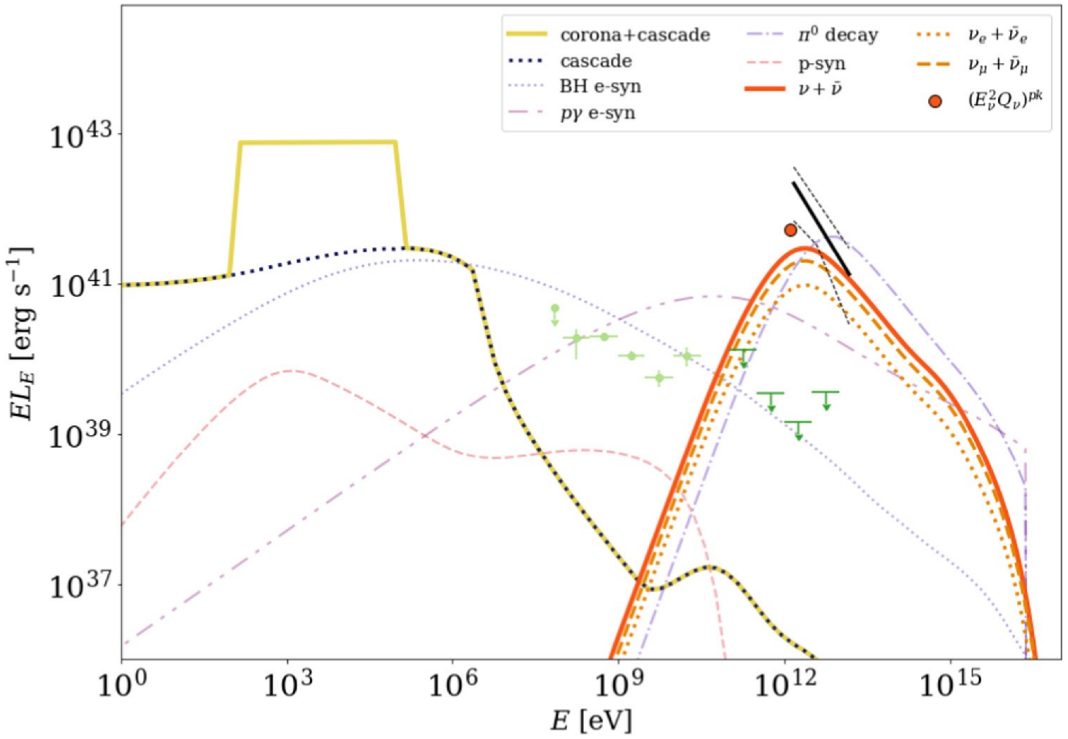
[Keivani et al., APJ. (2018)]

So far…

Focus on AGN and first results

Neutrinos observed:

from Seyfert galaxy (NGC 1068) → the jet points elsewhere: production in the core



Protons are accelerated in the core region

Dense target of coronal X-rays
→ production of neutrinos
→ absorption of HE gammas

[Fiorillo et al., APJL (2024)]

So far…

Focus on AGN and first results

Neutrinos observed:

from blazar (TXS 0506+056) → expected production in the jet
from Seyfert galaxy (NGC 1068) → the jet points elsewhere: production in the core

Both are AGNs, but only TXS has the powerful jet..
What if also in TXS neutrinos are produced in the core region?

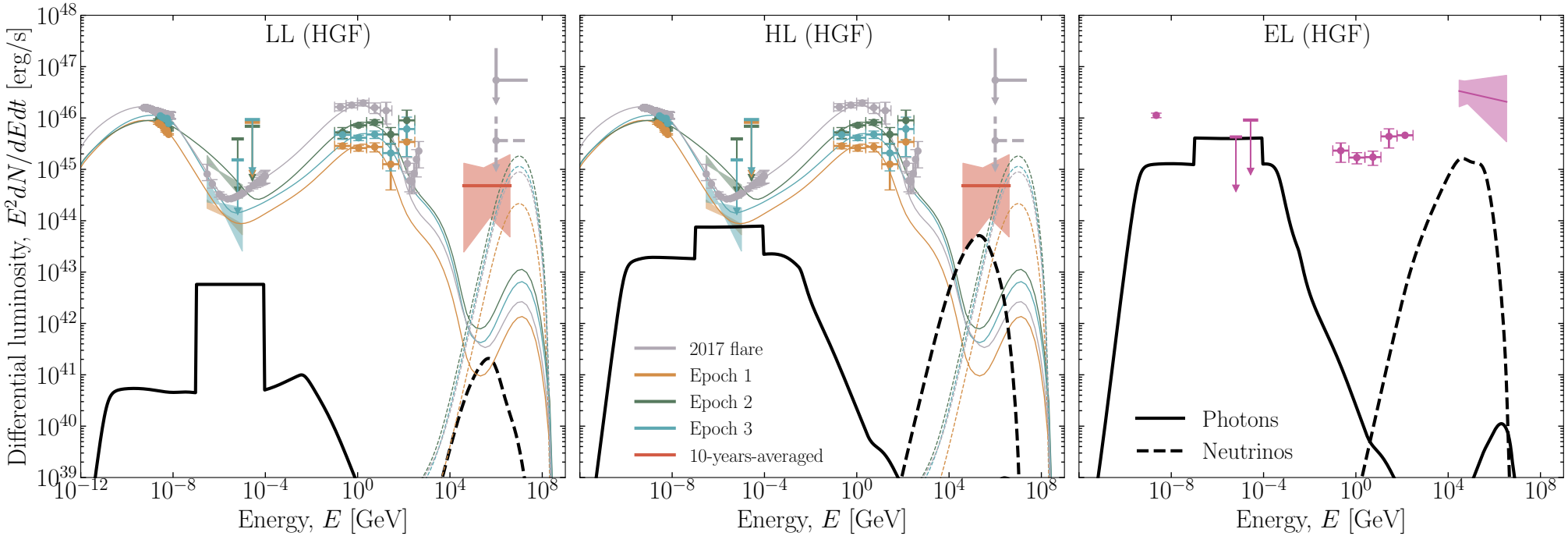
Can the neutrinos from TXS 0506+056 have a coronal origin?
[Fiorillo, **FT**, Petropoulou, Winter, APJ (in press)]

So far…

Focus on AGN and first results

Can the neutrinos from TXS 0506+056 have a coronal origin?
[Fiorillo, **FT**, Petropoulou, Winter, APJ (in press)]

Simulating multi-messenger emission from the core of TXS 0506+056...



Neutrino emission from the core is too low to explain the IceCube observations.

Blazar jet remains the preferred location for neutrino production