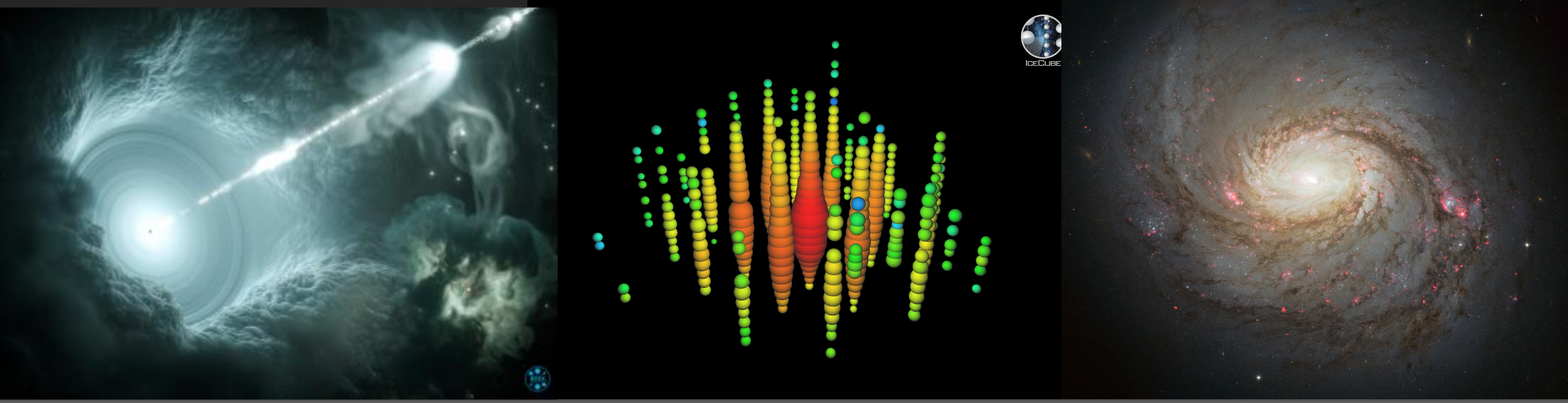


Models of neutrino sources

Alessandra Lamastra

INAF – Osservatorio Astronomico di Roma

Isola d'Elba - Vulcano Workshop 2022

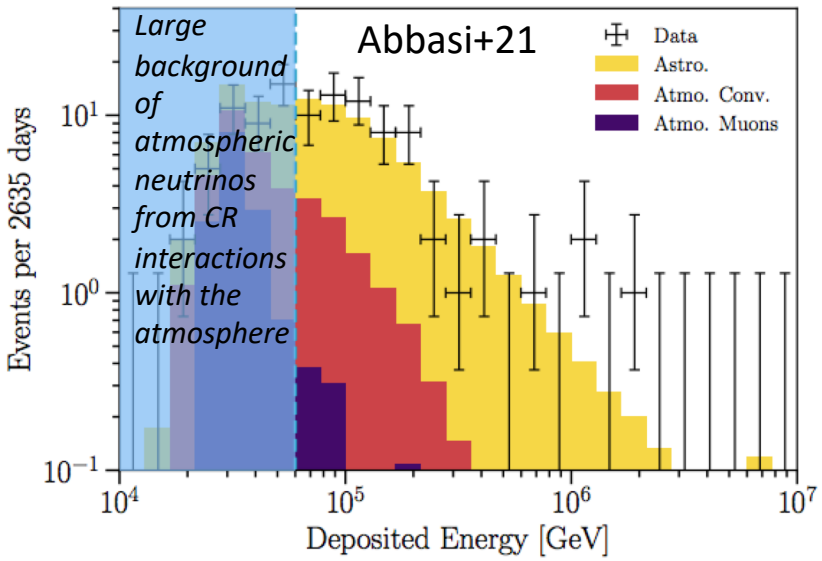
Outline

- Astrophysical neutrino flux
- Neutrino source candidates
- HE neutrino production
- HE neutrinos from Active Galactic Nuclei
  - NGC 1068
  - TXS 0506+056

Astrophysical neutrino flux

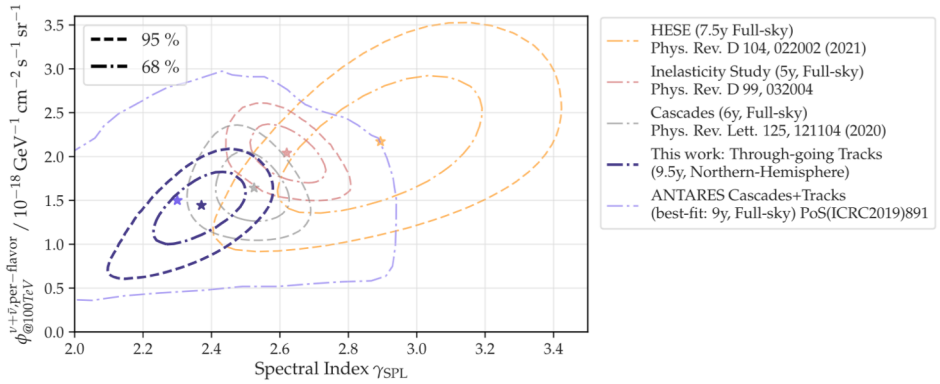
2013: Discovery of a diffuse flux of astrophysical neutrinos (IceCube+13)

High Energy Starting Events (HESE) 7.5 years

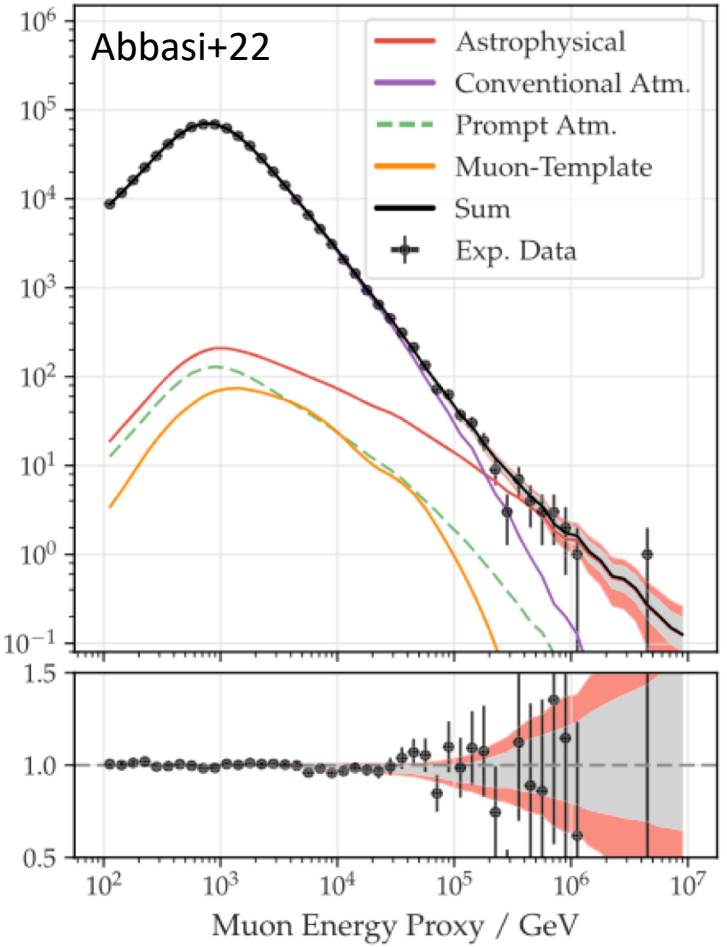


E>100 TeV excess of astrophysical neutrinos above the atmospheric components

$\phi = \phi_* (E_\nu/100\ \text{TeV})^{\gamma_{SPL}}$

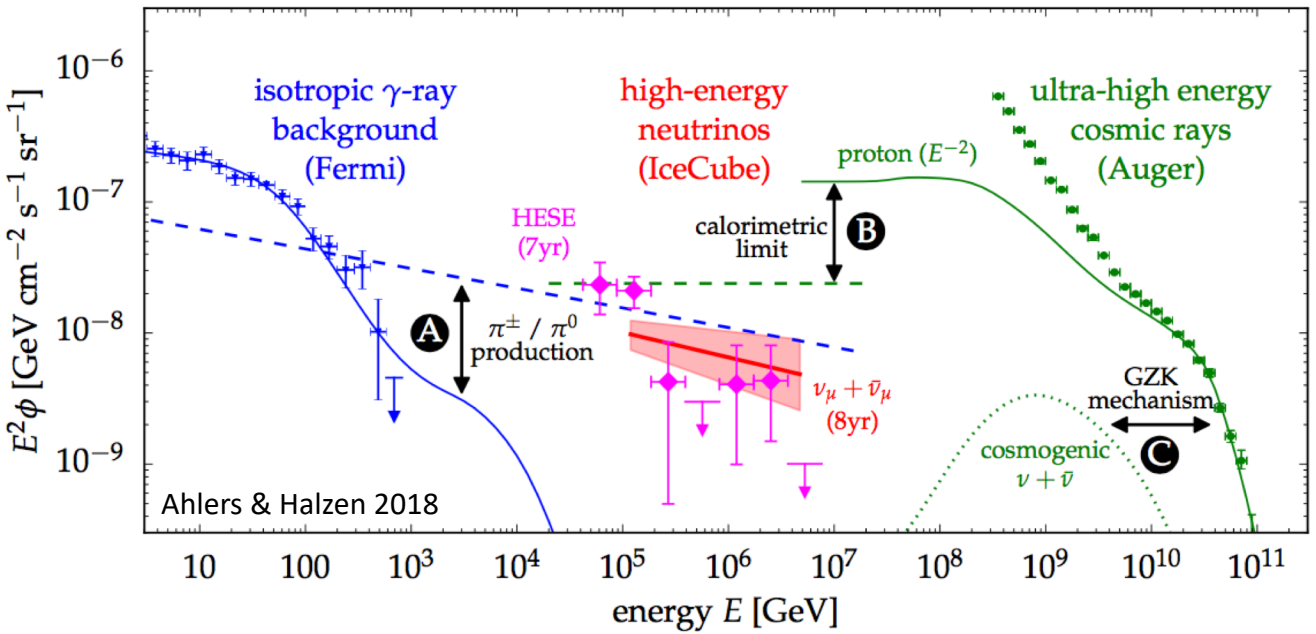


Through going muon tracks 9.5 years



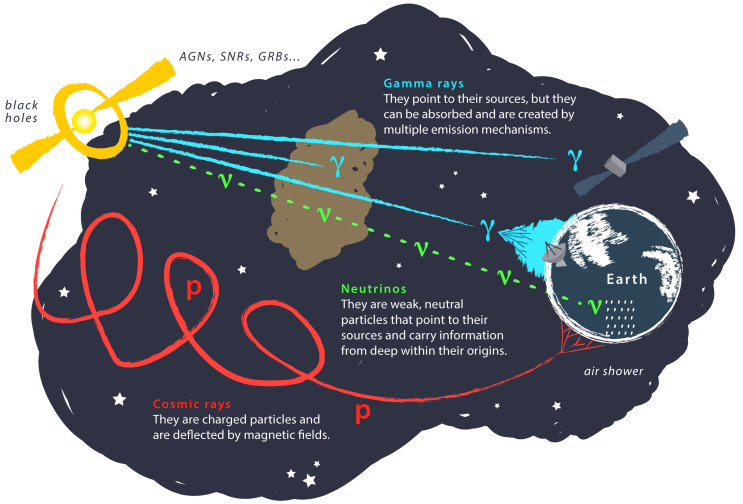
The multi-messenger picture

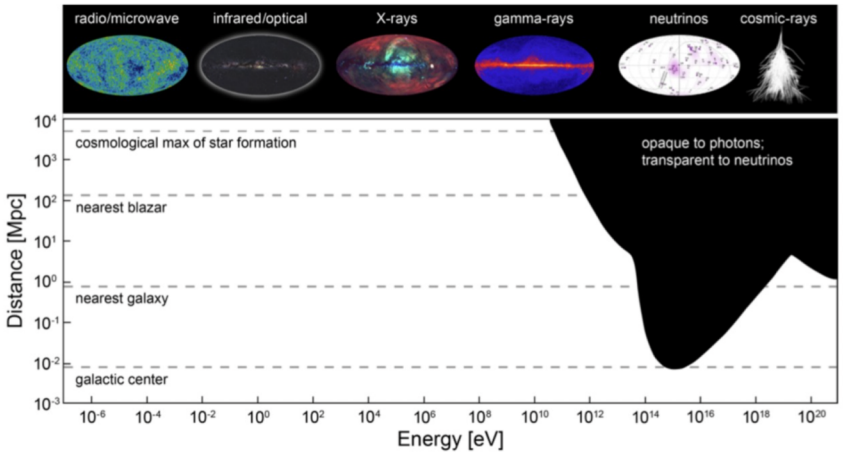
Neutrino production is closely related to the production of cosmic rays and γ-rays



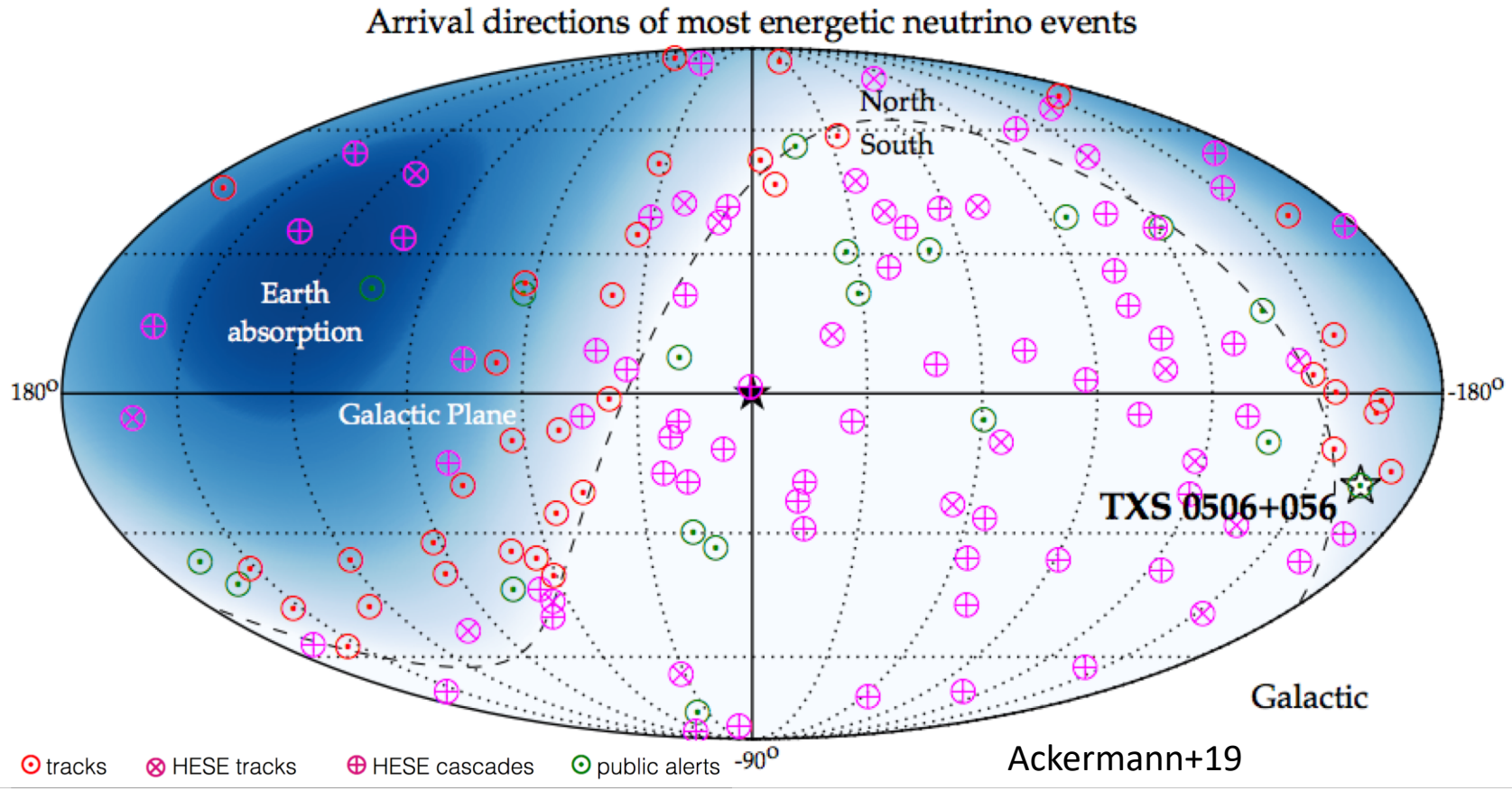
Neutrinos as messengers of CR accelerators

Neutrinos can reach Earth undeflected and unabsorbed from cosmological distances





Arrival directions of cosmic neutrinos



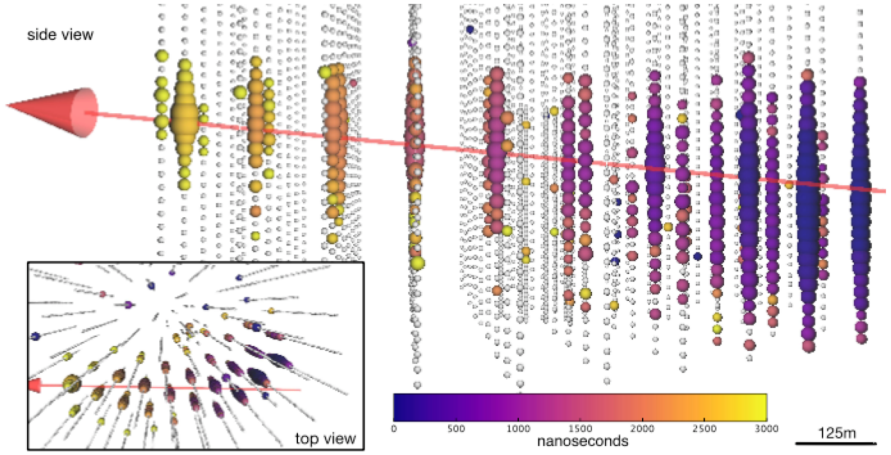
Ackermann+19

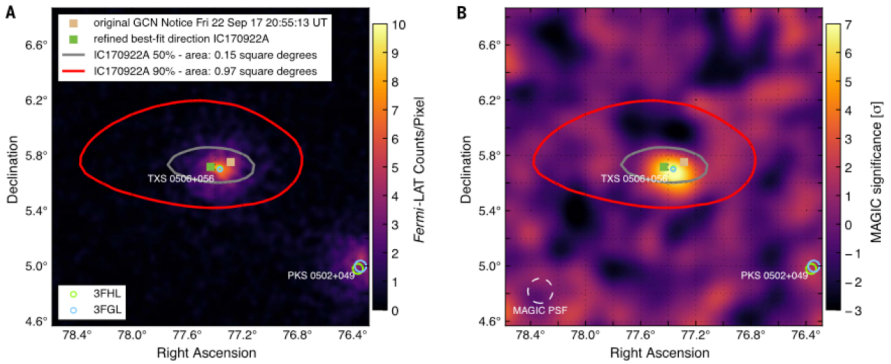
Mostly extragalactic sources but 10% galactic contribution cannot be excluded

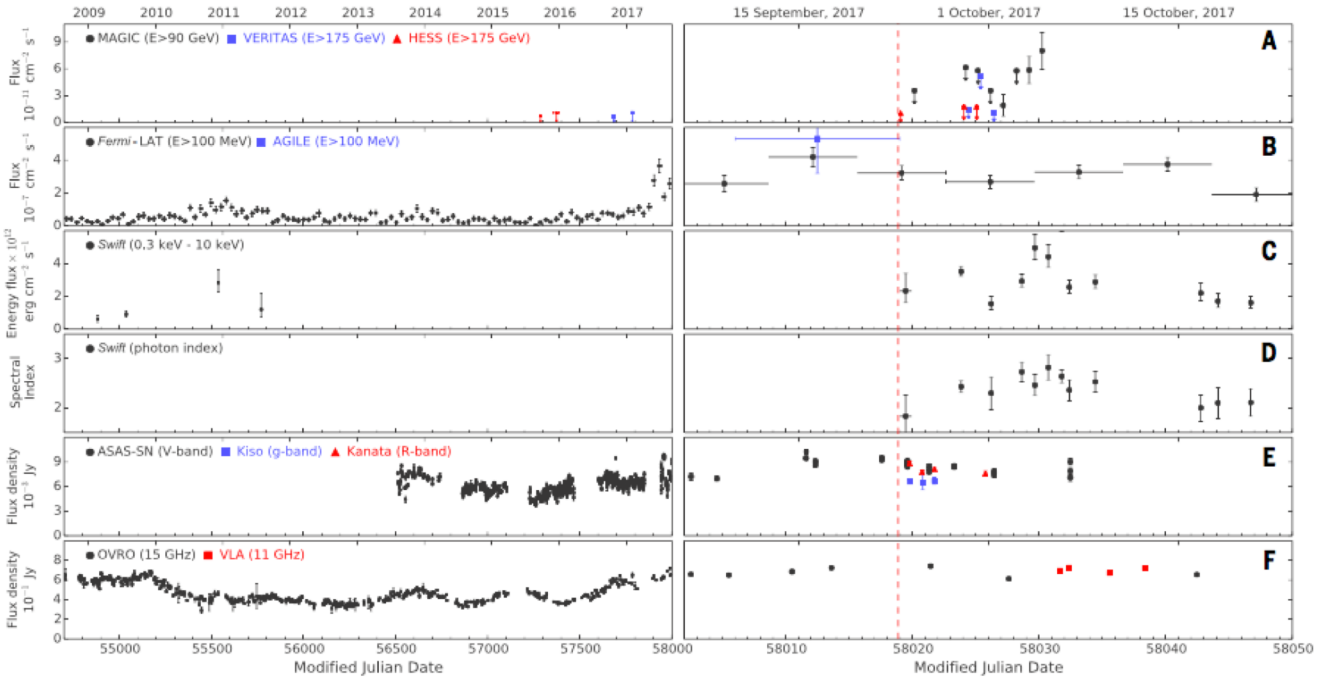
No significant correlation of diffuse flux with known sources

Realtime neutrino alert: IceCube-170922A / TXS 0506+056

Most significant association (3σ) of a high-energy (290 TeV) neutrino with an astrophysical source: the blazar TXS 0506+056 (z=0.34)

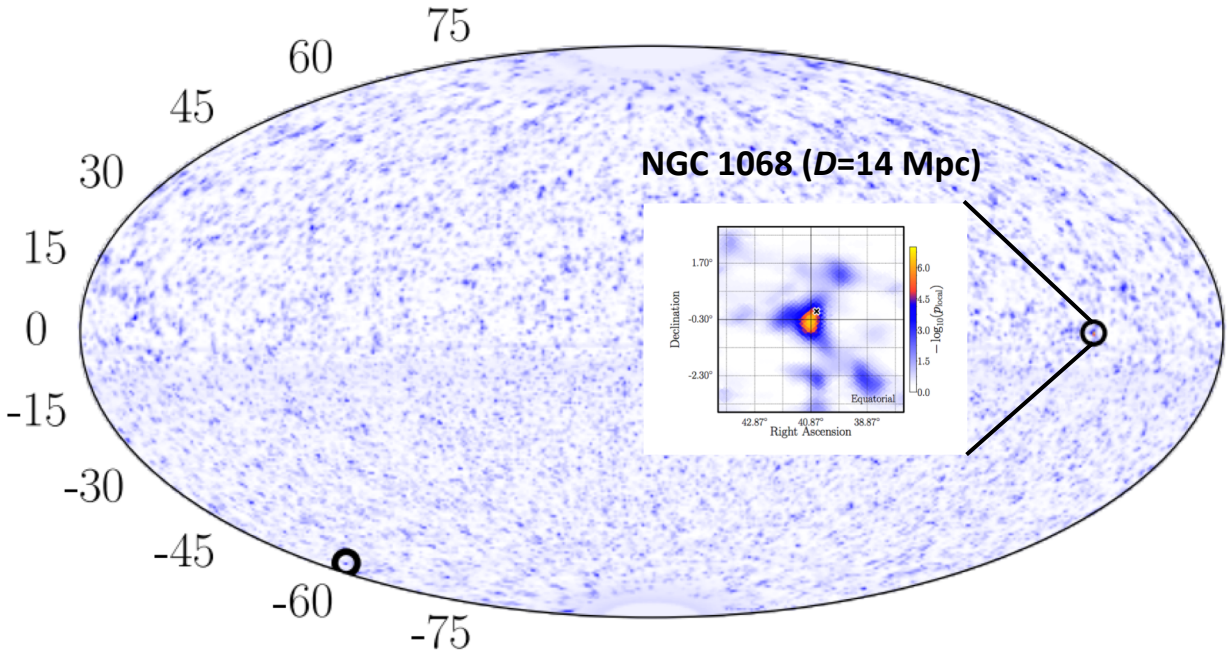




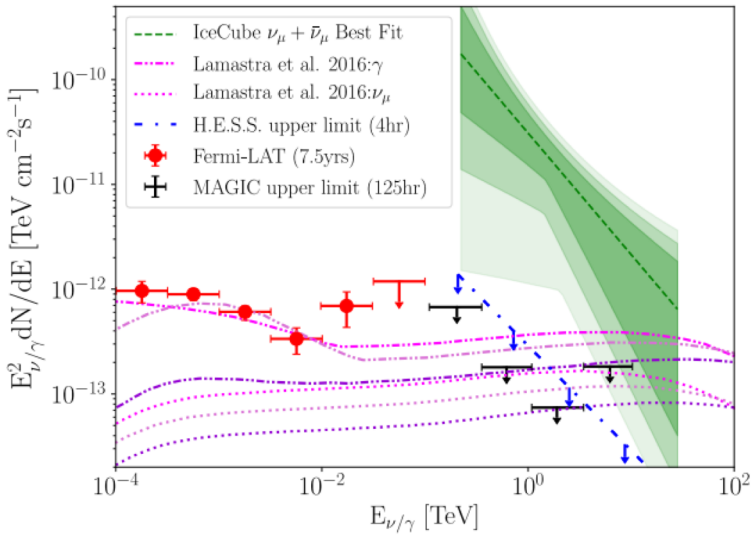


IceCube+18

Point-like neutrino source searches



IceCube+20

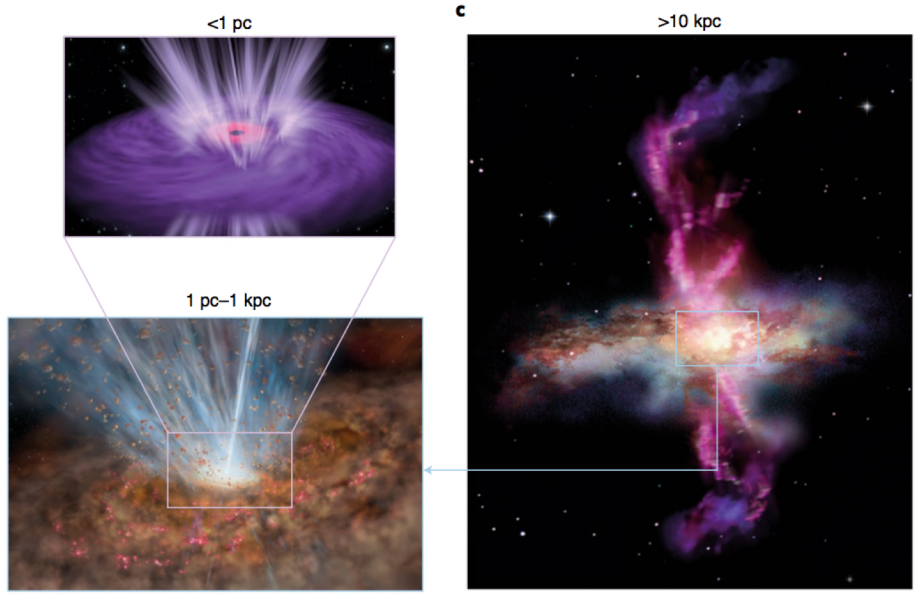


The neutrino flux outshines the measured gamma-ray emission

Hottest spot in the IceCube all-sky scan at position 0.35 deg away from the direction of the nearby starburst/Seyfert galaxy NGC 1068 (2.9σ post trial)

Active Galactic Nuclei

Most powerful sources in the Universe (up to 10^{48} erg/s). Energy is generated by conversion of gravitational energy of the infalling material onto SMBH ($M_{BH}=10^6$-10^9 $M_\odot$) into radiation and outflows.

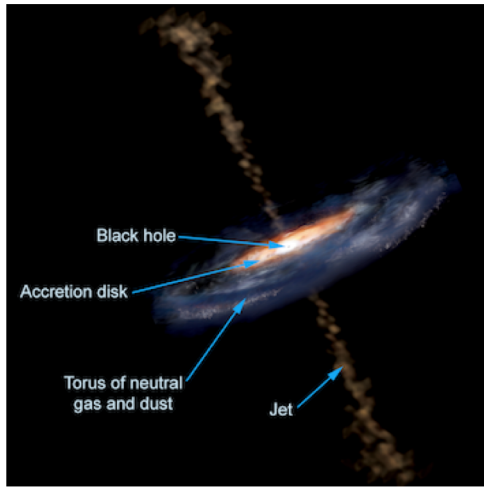


Non-jetted AGN

- Bulk of the AGN population (Seyfert, QSO).
- Multi-phase (neutral, ionized, and molecular gas) and multi-scale wide angle winds with velocities from a few thousands km/s up to mildly relativistic values.
- Electromagnetic emission dominated by UV-optical emission from the accretion disk and by X-ray emission from the corona.

Jetted AGN

- ~10% of the AGN population (blazar, radio galaxies).
- Highly collimated relativistic outflows.
- Electromagnetic emission dominated by jet non-thermal emission in the radio and gamma-ray band.

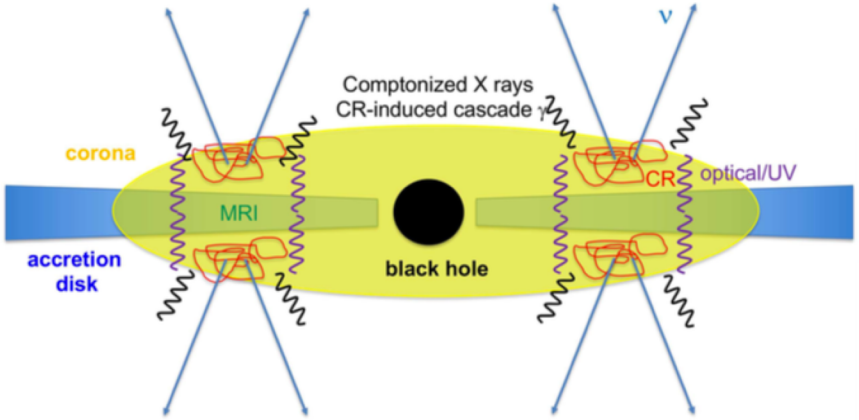


Possible sites of neutrino production in AGN

Accretion of surrounding matter onto a SMBH creates an ideal environment for acceleration and interaction of cosmic particles.
Possible acceleration mechanisms are diffusive shock acceleration, magnetic reconnections, and stochastic acceleration in plasma turbulence.

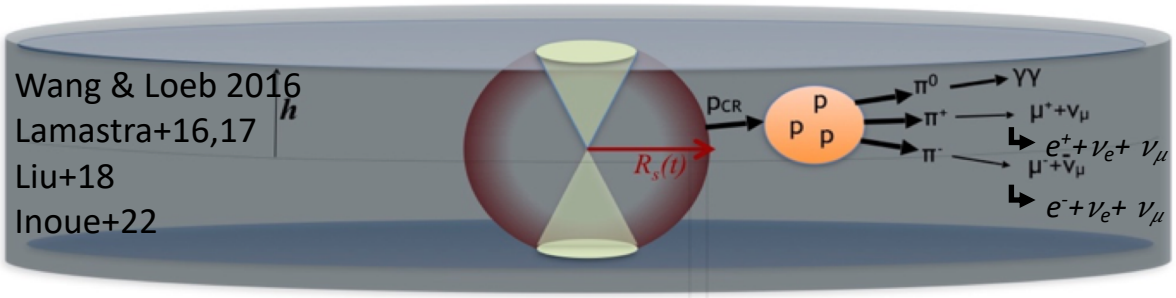
AGN core (disk-corona)

Inoue+19
Murase+20
Anchordoqui+21



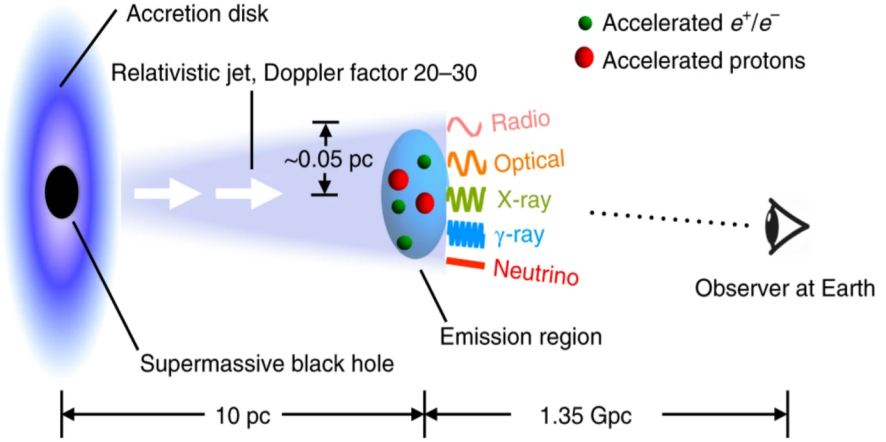
AGN wind

Wang & Loeb 2016
Lamastra+16,17
Liu+18
Inoue+22

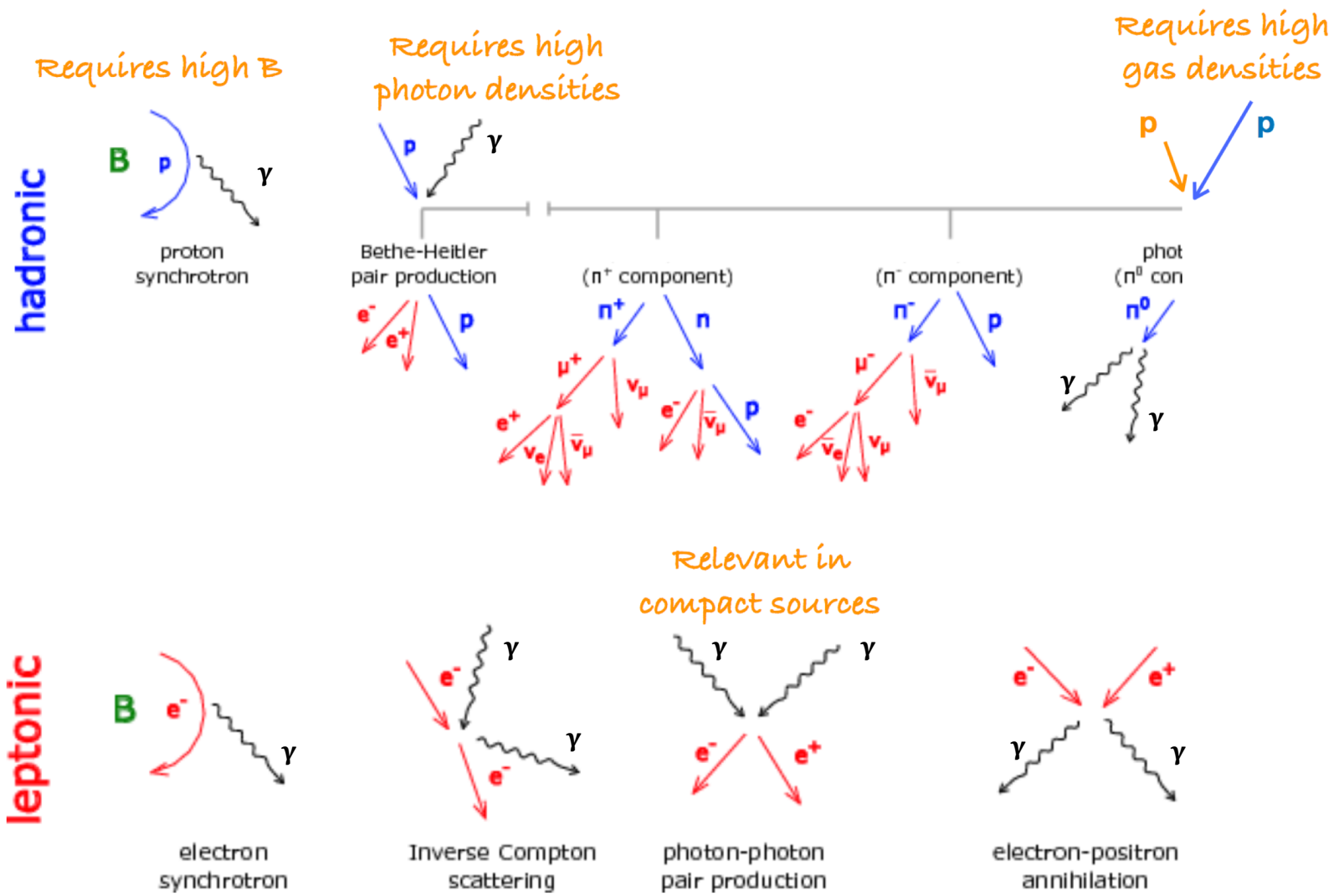


AGN jet

Gao+18
MAGIC+18
Keivani+18
Cerruti+19



Interaction processes in a nutshell



Neutrinos only from hadronic processes

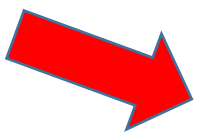
Gamma-ray and neutrino production in hadronic interactions

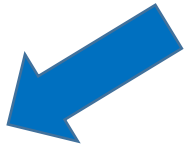
proton-proton (pp)

$p+p \rightarrow \pi + X$

Relevant in sources with large gas densities

γ and ν spectra follow spectrum of protons





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

$\pi^+ \rightarrow \mu^+ + \nu_\mu$

$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$

$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$

$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$

$E_\nu \simeq E_p/20$

$E_\gamma \simeq E_p/10$

$L_\gamma \simeq L_\nu$

proton-photon (pγ)

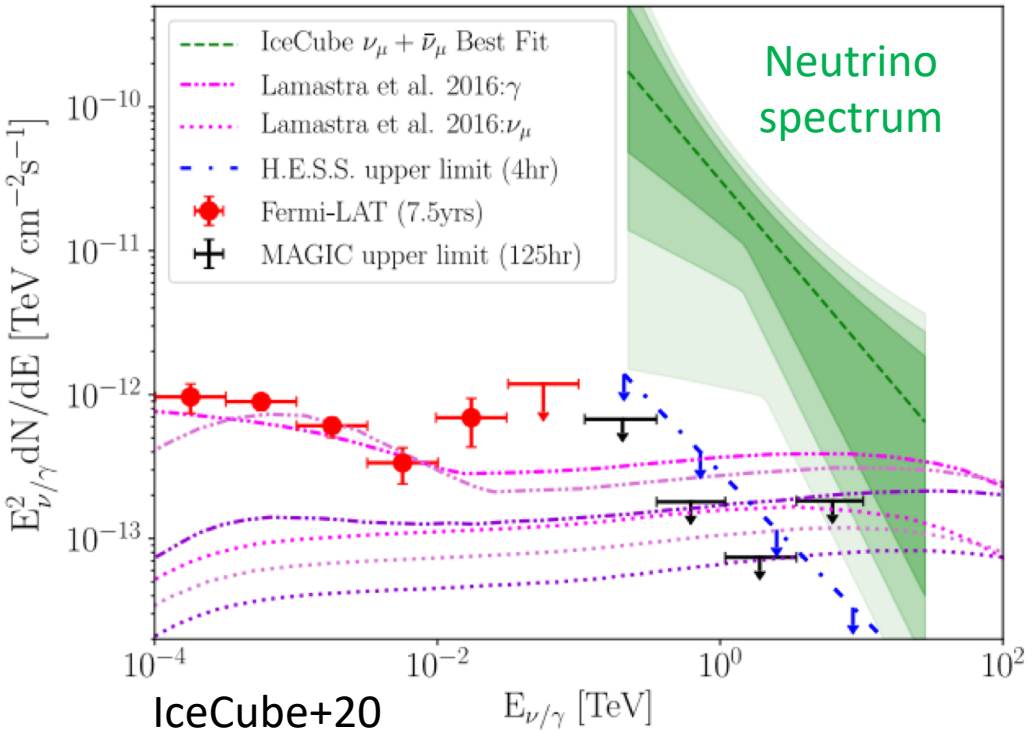
$p+\gamma \rightarrow \pi + X$

Relevant in sources with large photon densities

γ and ν spectra depend on target photon fields

High-energy threshold for process:
$E_p \gtrsim 7\times10^{16}$ eV $(E_\gamma/\text{eV})^{-1}$

HE neutrinos from non- jetted AGN: the case of NGC 1068



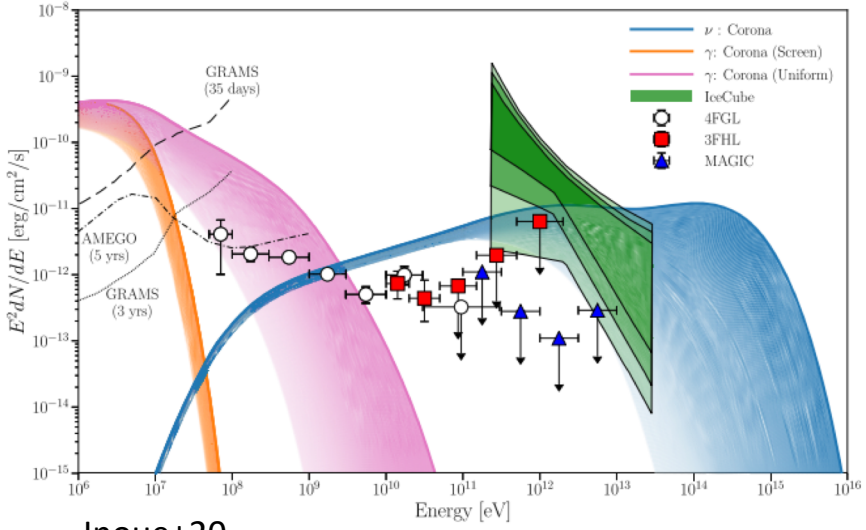
IceCube+20

The neutrino flux $\phi_\nu = 3\times10^{-8}\,(E_\nu/\mathrm{TeV})^{-3.2}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ much higher than the observed gamma-ray flux.

Attenuation necessary to absorb the gamma-ray emission accompanying neutrinos.

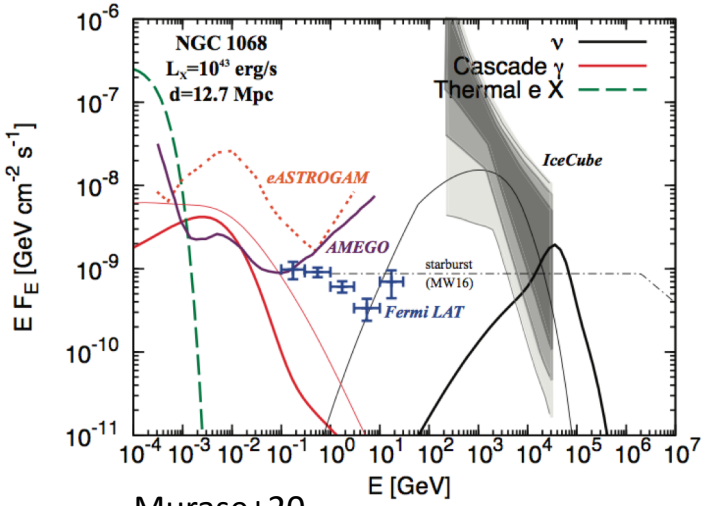
AGN core models

AGN corona (pp+pγ)



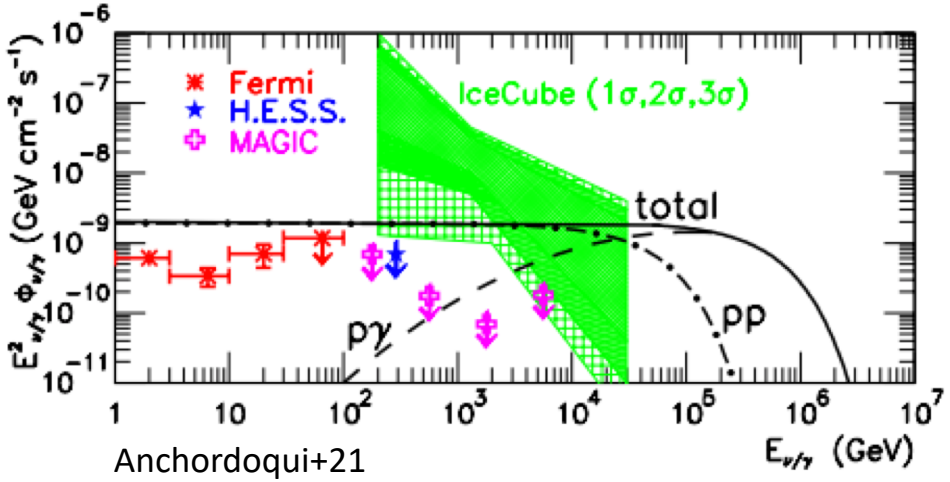
Inoue+20

Magnetized AGN corona (pp+pγ)



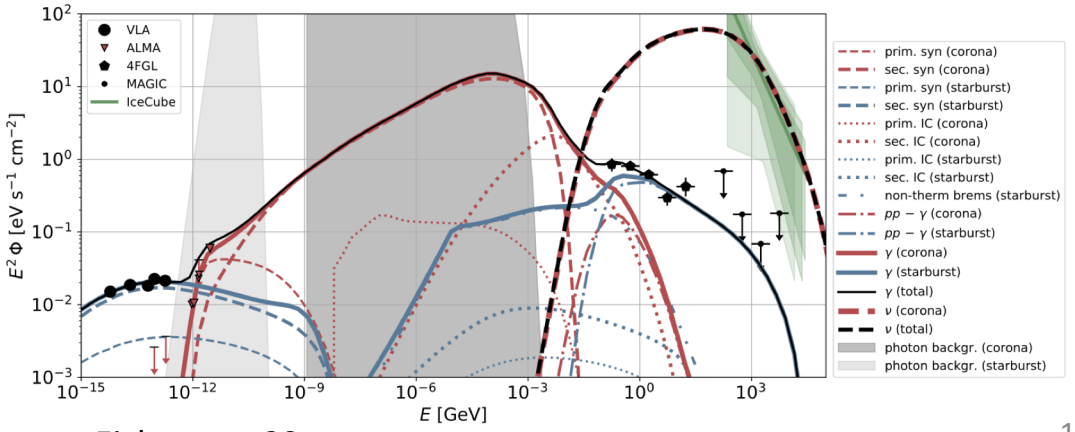
Murase+20

Accretion shock (pp+pγ)



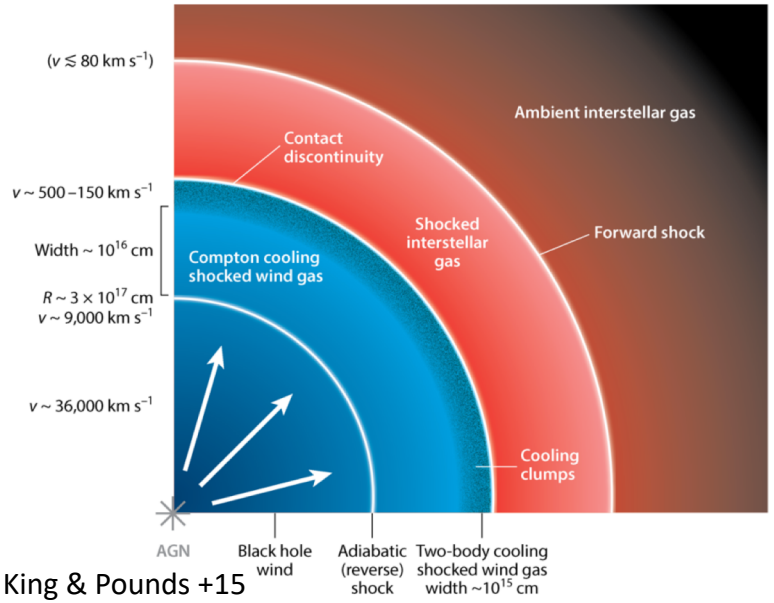
Anchordoqui+21

AGN corona (pp) + starburst (pp)



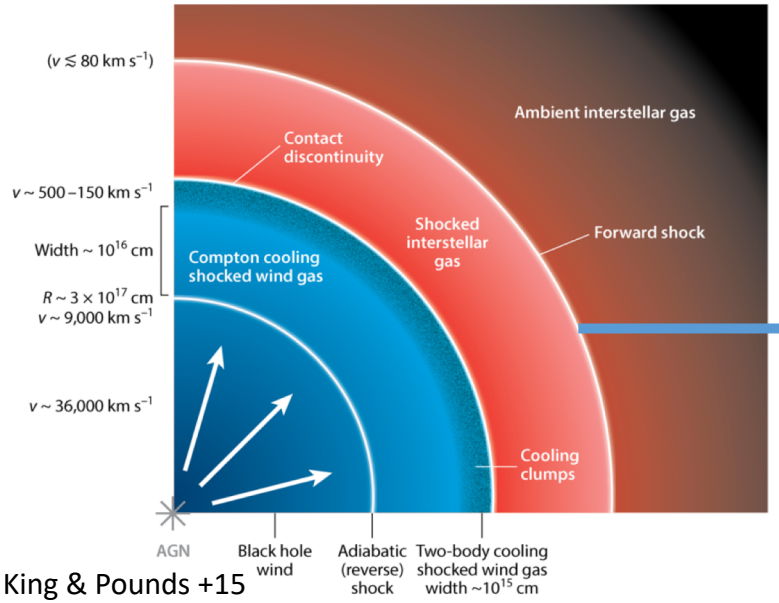
Eichmann+22

AGN wind models



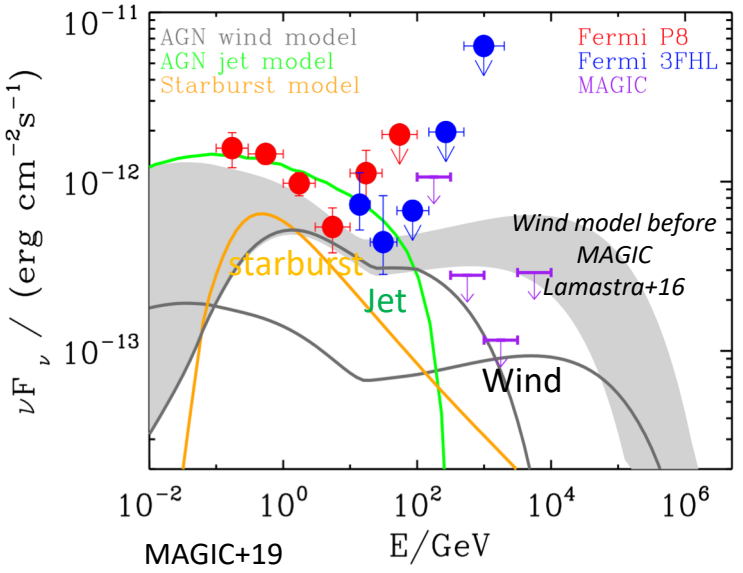
King & Pounds +15

AGN wind models

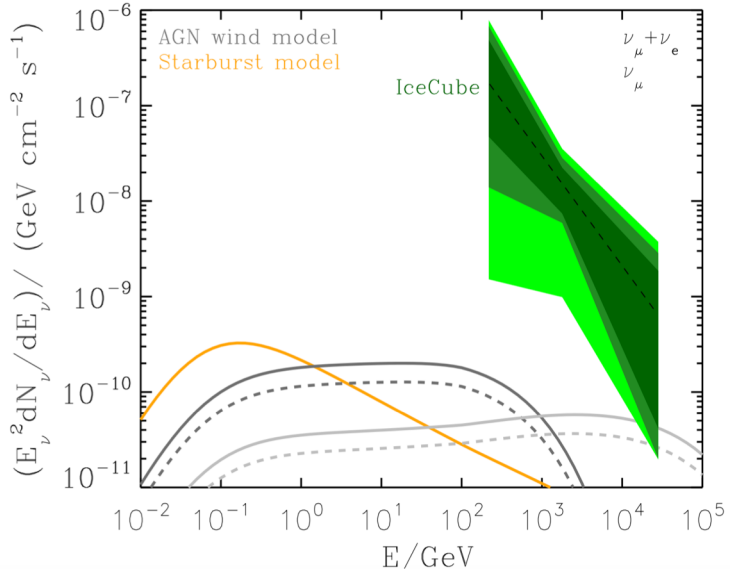


King & Pounds +15

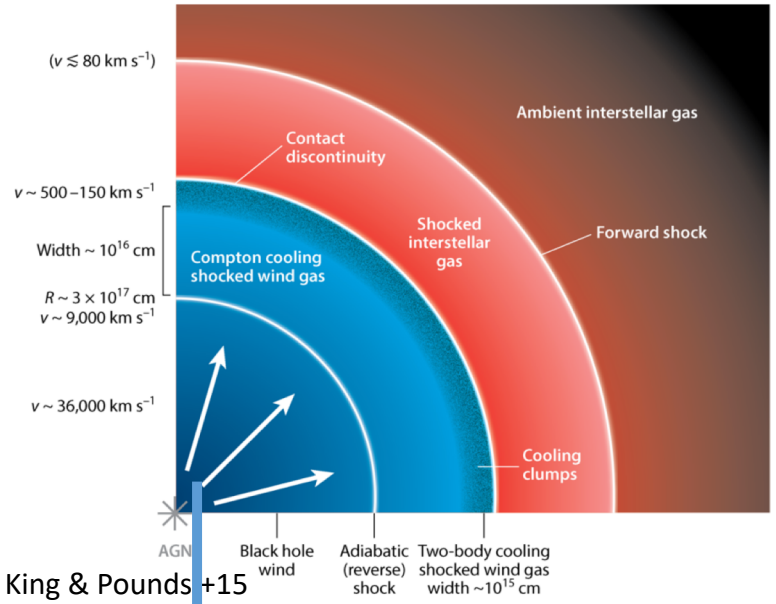
Galactic molecular wind (pp)



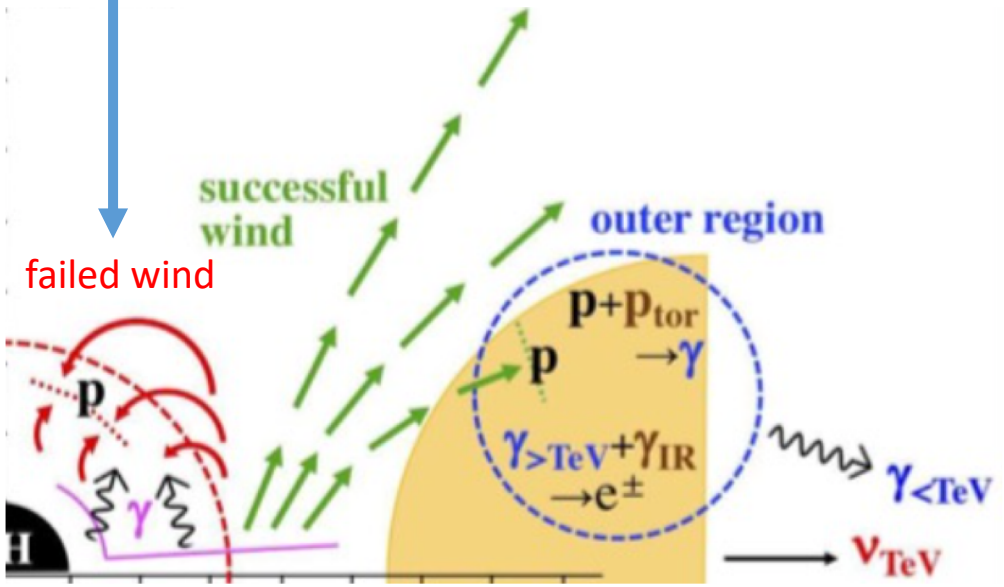
MAGIC+19



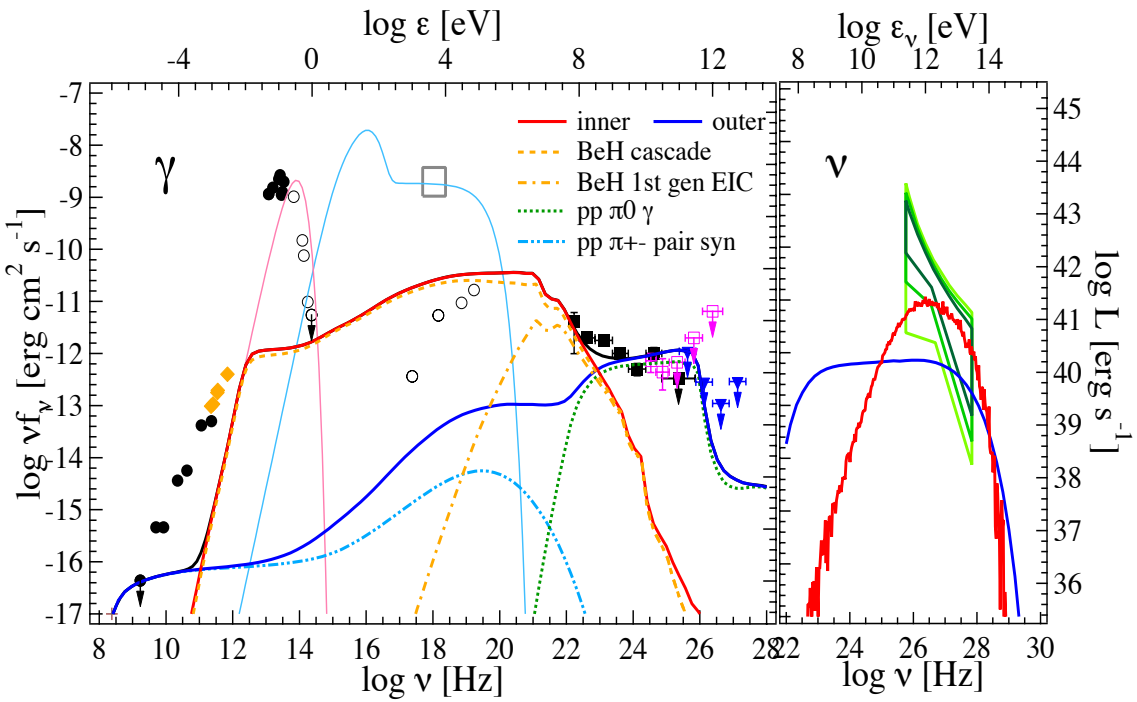
AGN wind models



King & Pounds +15

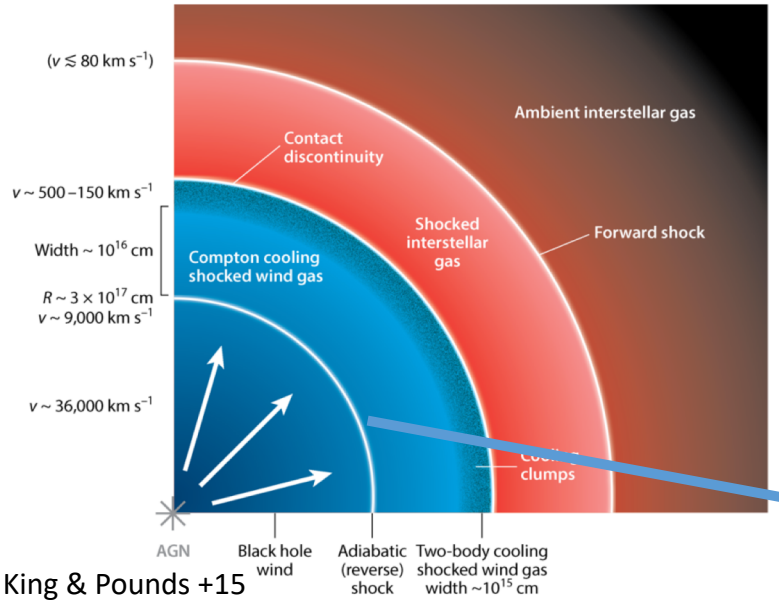


Inner failed wind (pγ) + outer wind-torus (pp)



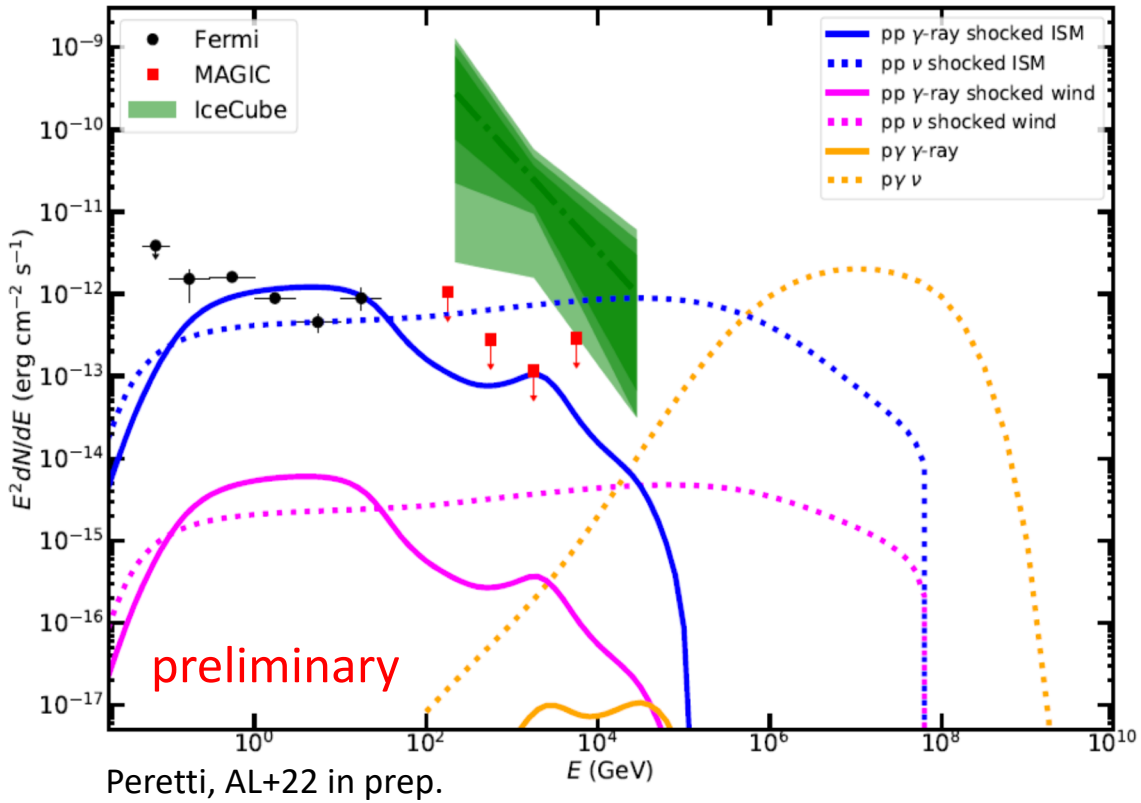
Inoue+22

AGN wind models



King & Pounds +15

Ultra fast outflows (pp+pγ)



Peretti, AL+22 in prep.

HE neutrinos from jetted AGN: the case of TXS 0506+056 (2017 flare)

Blazar emission models

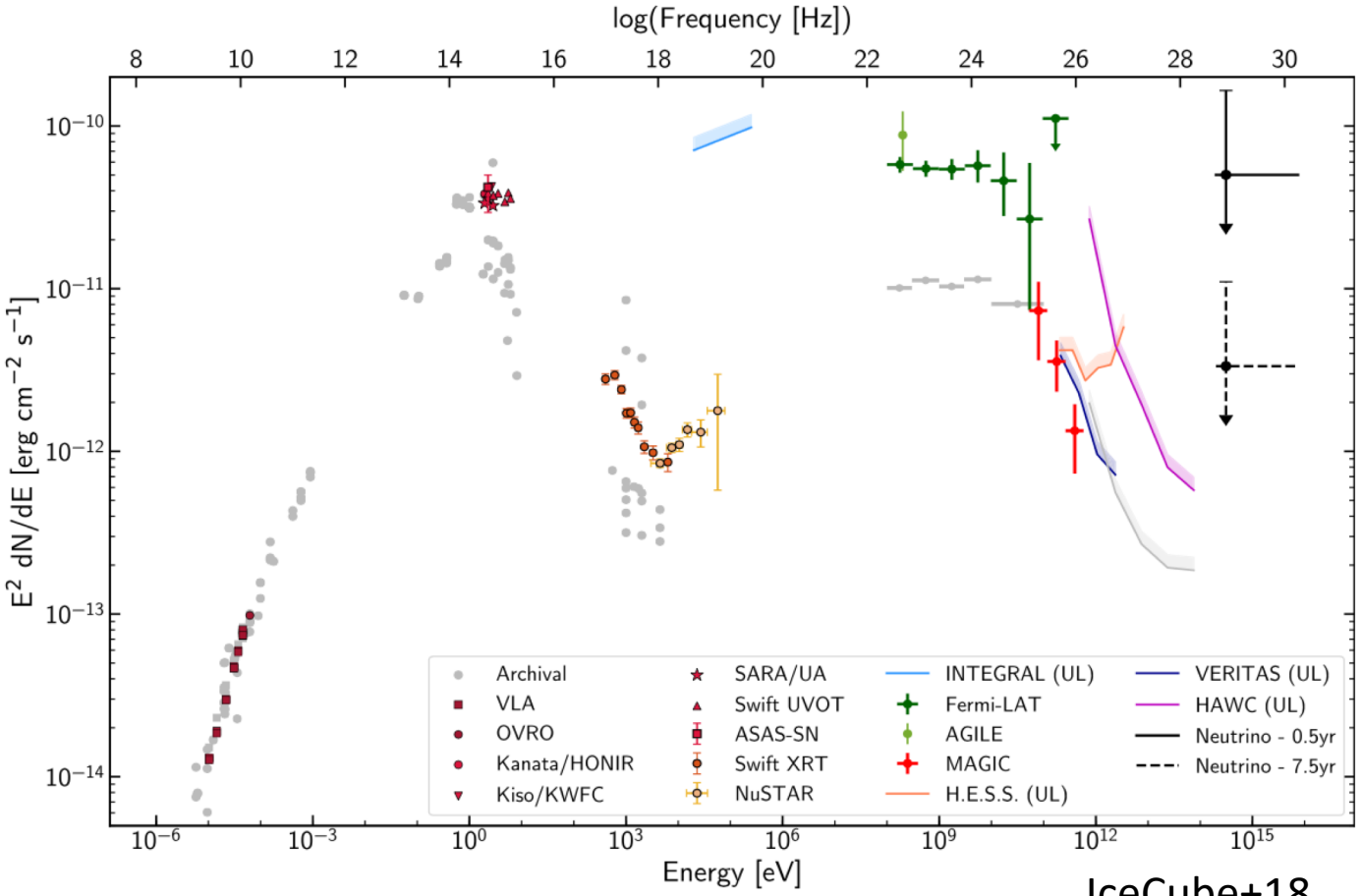
Leptonic scenario

Low-energy SED component => synchrotron emission by electrons accelerated in the jet.

High-energy SED component => IC emission from accelerated electrons and seed photons. Seed photons are synchrotron photons (SSC), or external photon fields (EIC).

Hadronic scenario

The neutrino emission is associated with the decay of pions produced in hadronic interactions in the jet.



IceCube+18

UL producing one detection as IC170922A in 0.5 yr

UL producing a detection as IC170922A in 7.5 yr

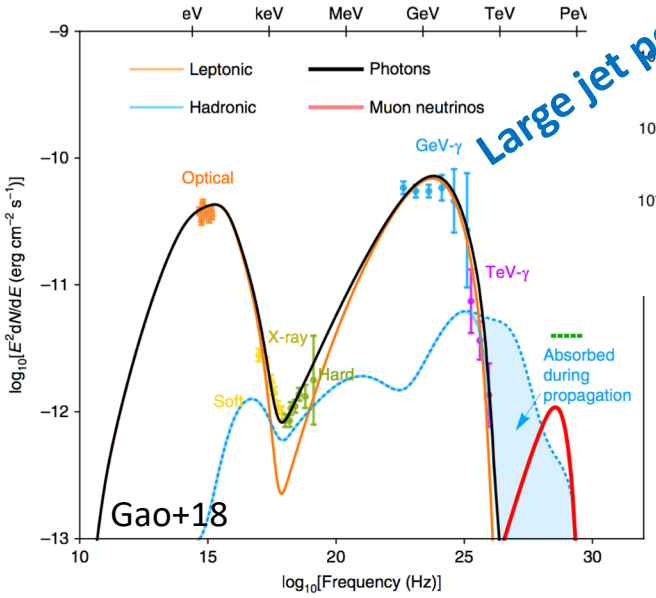
Blazar lepto-hadroinc models

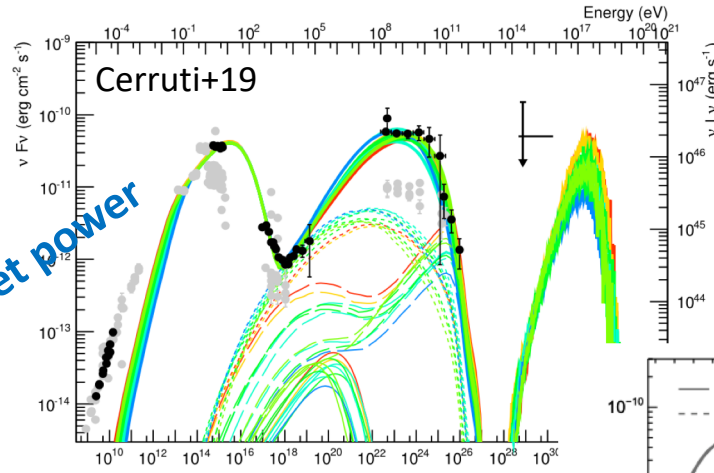
Blazar one–zone models

- Leptonic electromagnetic emission with subdominant hadronic component.
- Neutrino emission from pγ interactions constrained by cascade flux in the X-ray band. Neutrino rates 0.01 -1 / yr.
- They require large jet power ($L_{jet} > L_{Edd}$) or external target photon fields.

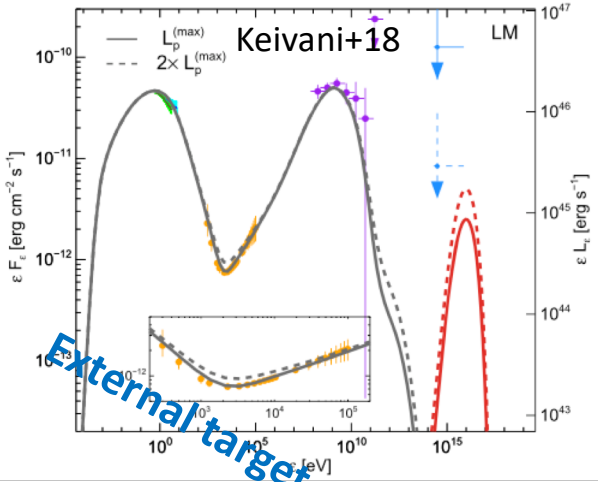
Blazar two –zone models

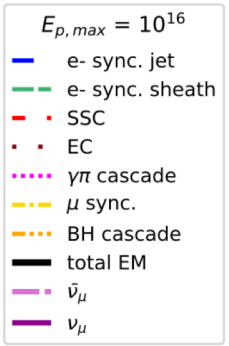
- Electromagnetic and neutrino emission from two physically distinct emission zones in the jet.
- Several model parameters not stronlgy constrained by current observations

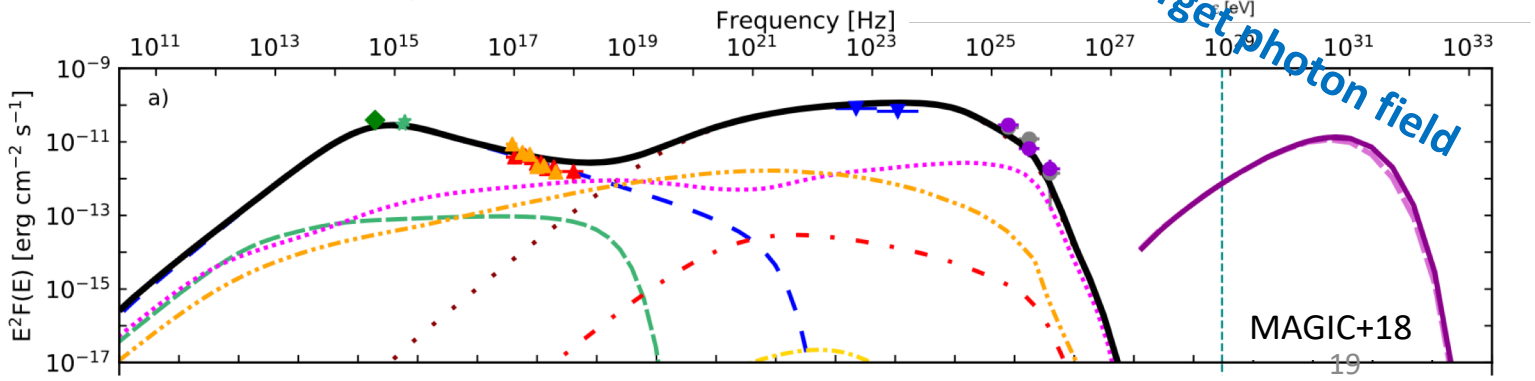




one-zone models







Summary

- IceCube has identified a diffuse flux of astrophysical neutrinos in the TeV-PeV energy range of unknown origin.
- Galactic and extragalactic sources are candidate sources, but absence of anisotropies favours the latter.
- Jetted and non-jetted AGN are promising neutrino sources.
- Neutrino astronomy is now a reality and a key component of multi-messenger astrophysics.

Thanks for your attention!