AGN outflows as accelerator of CRs and neutrinos

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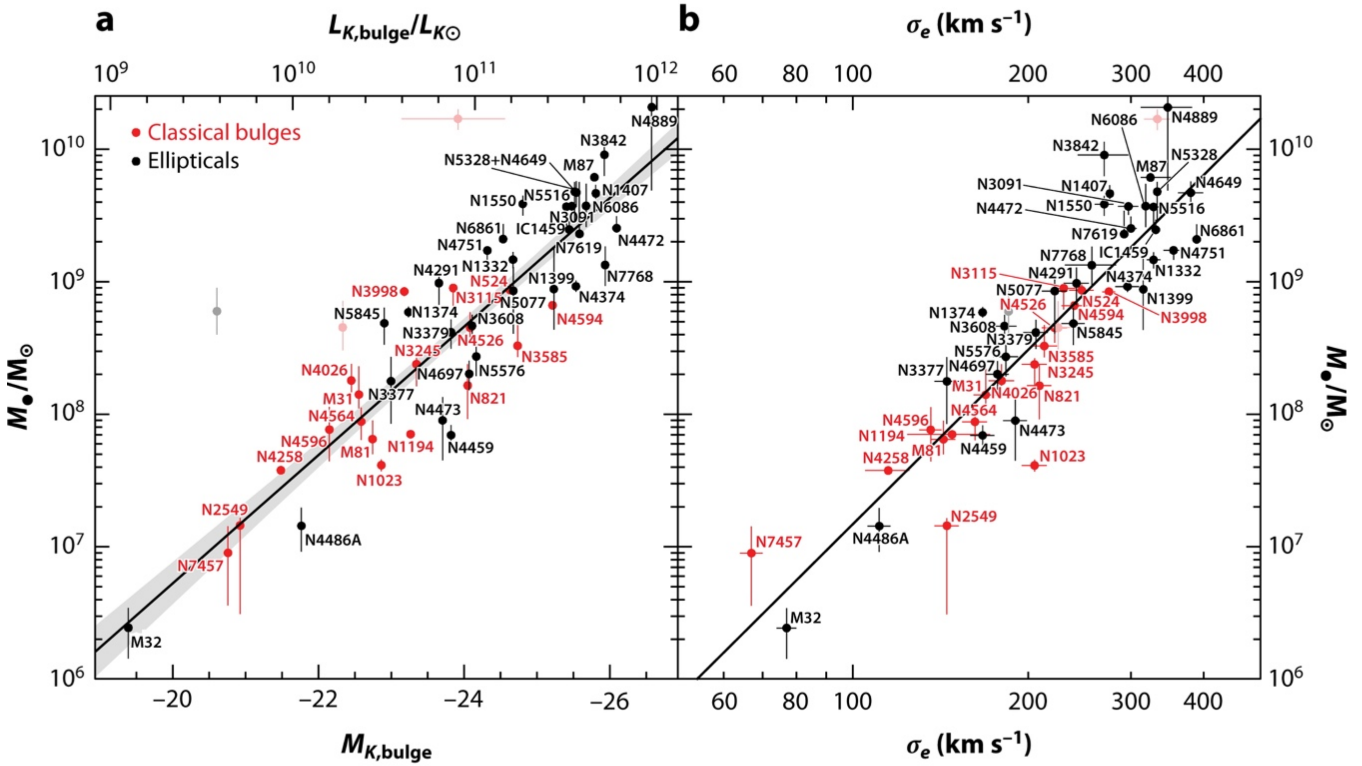
Outline

- Observations and physics of AGN winds
- AGN winds as particle accelerators and non-thermal emitters
- Gamma-ray and neutrino emission from AGN winds: the case study of NGC 1068
- Extragalactic gamma-ray and neutrino backgrounds from AGN winds in cosmological galaxy formation models

AGN winds and galaxy evolution

The evolution of galaxies and nuclear black holes are linked



Kormendy J, Ho LC. 2013.
Annu. Rev. Astron. Astrophys. 51:511–653

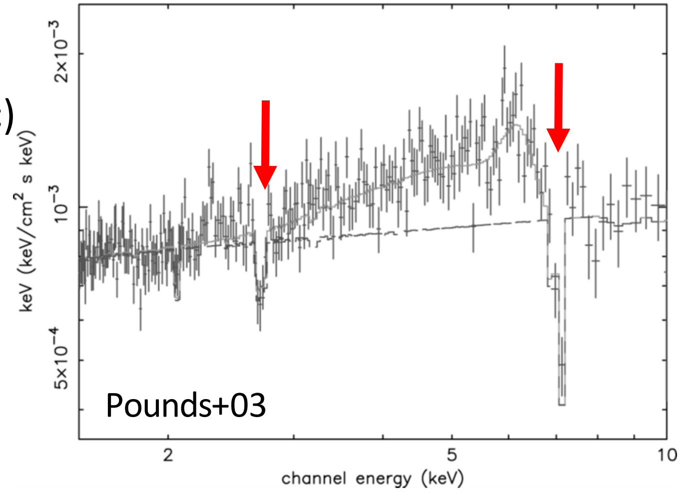
$$E_{BH} \approx \eta M_{BH} c^2 \approx 2\times10^{61}\ (M_{BH}/10^8 M_\odot)\ \mathrm{erg}$$

$$E_b \approx M_b \sigma^2 \approx 8\times10^{58} (M_{BH}/10^8 M_\odot)(\sigma/200\ \mathrm{km/s})\ \mathrm{erg}$$

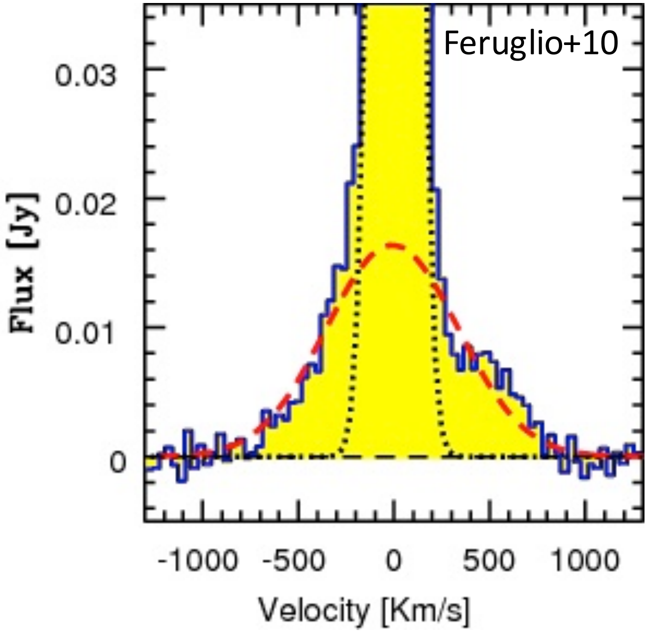
AGN wind observations

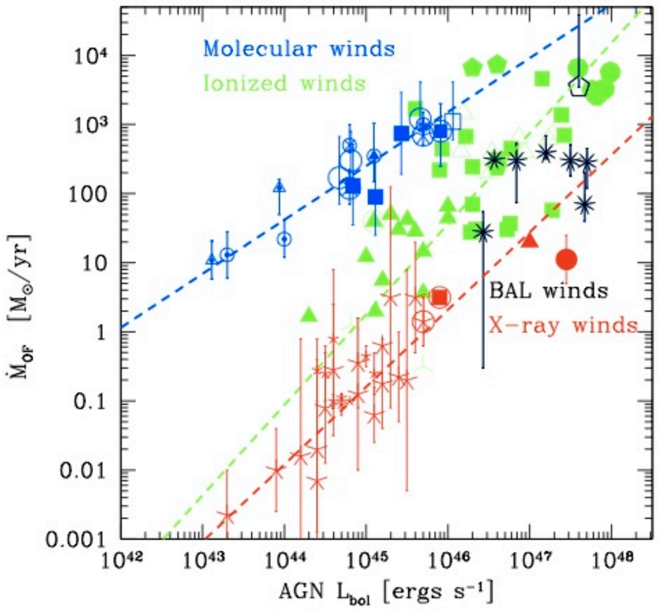
- Radio jets (relativistic)
- X-ray winds (WA thousands km/s, UFO semi-relativistic)
- ionized gas outflows (v=1000-3000 km/s)
- atomic gas outflows (v=100-1000 km/s)
- molecular gas outflows (100-2000 km/s)

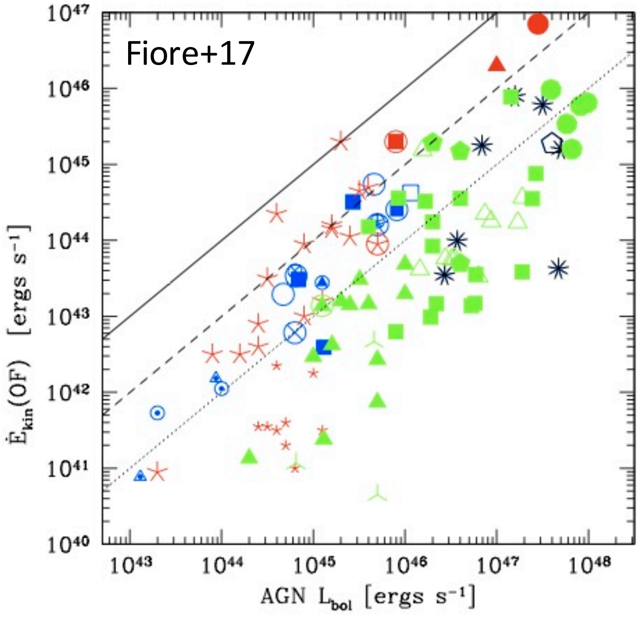
PG1211+143 (z=0.08) v≃0.1 c



Mrk 231 (z=0.04) v≃1000 km/s





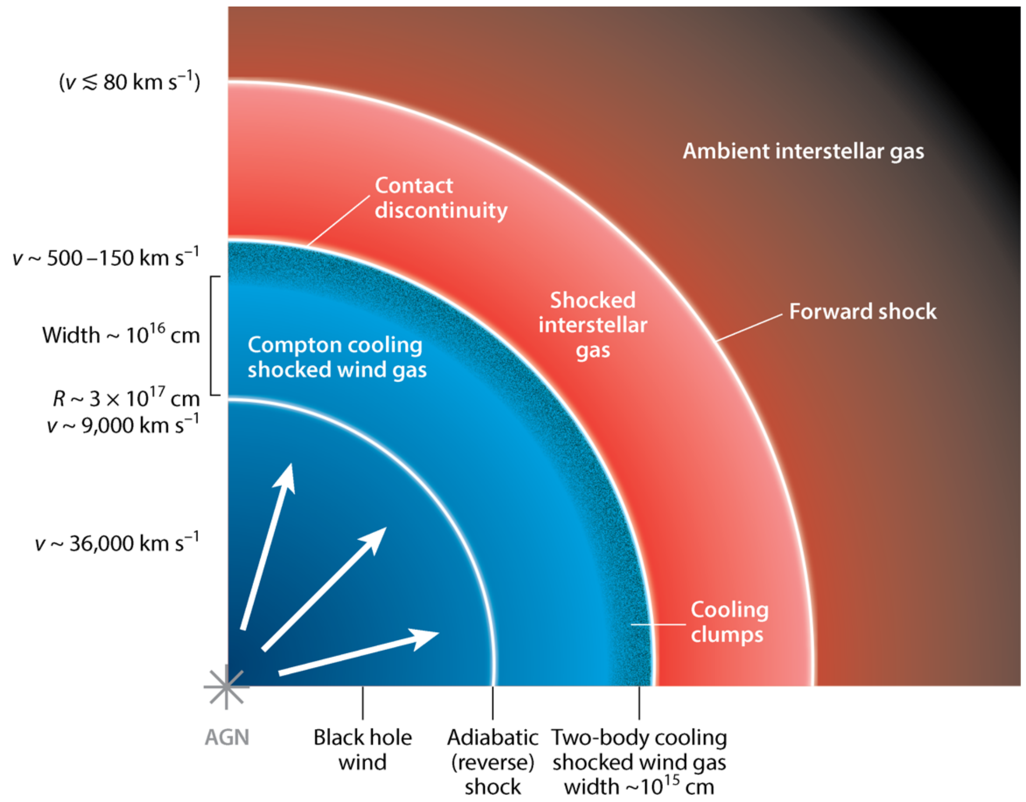


- 18 molecular outflows
- 36 ionized gas outflows
- 6 BAL
- 30 X-ray winds

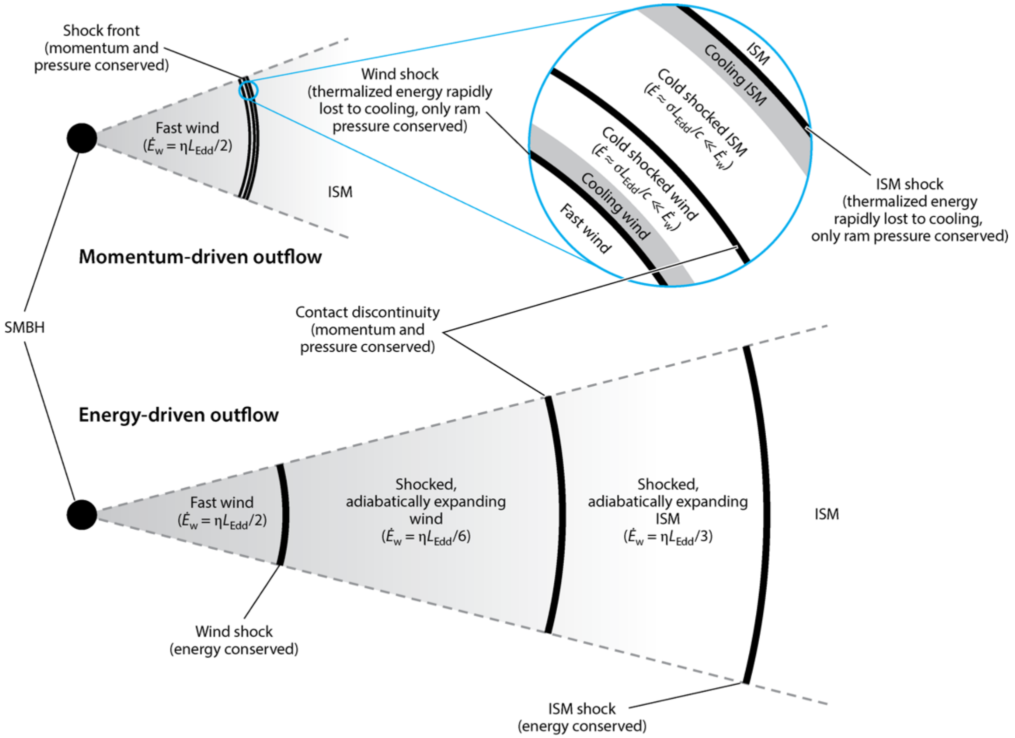
$$\frac{L_{kin}}{L_{AGN}} \approx (0.1-10)\%$$

The physics of AGN winds

The galactic non-relativistic outflows are produced when wide angle fast winds (v≈0.1-0.3 c) shock against the galaxy ISM (e.g. King+03,+11,+15,Faucher-Giguere+12, Zubovas+12,+14)



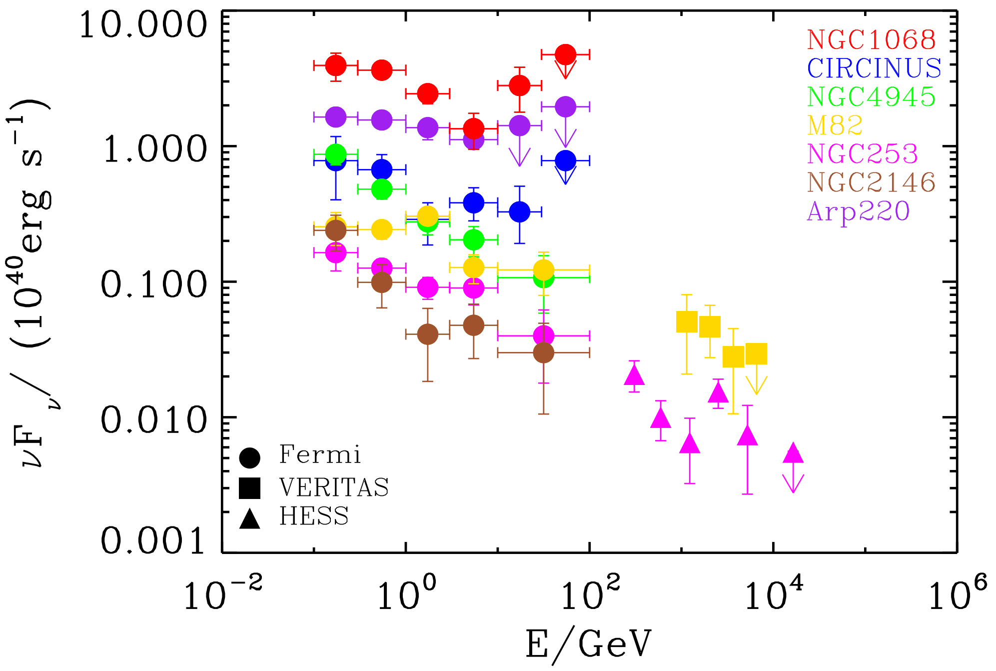
King A, Pounds K. 2015.
Annu. Rev. Astron. Astrophys. 53:115–54



King A, Pounds K. 2015.
Annu. Rev. Astron. Astrophys. 53:115–54

AGN winds as particle accelerators

Adapted from Ackermann+12



Diffusive shock acceleration

$$N_p(E) = A_p E^{-p} \exp\left[-\left(\frac{E}{E_{\max,p}}\right)\right] \qquad p \approx 2$$

CR protons

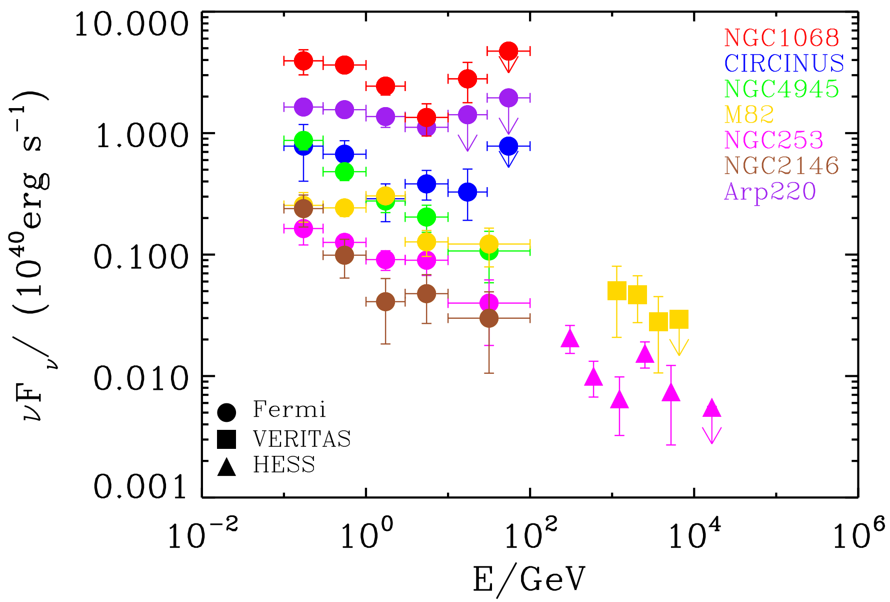
jet $\varepsilon_p^{\max} \approx (3/20) e B_j R \simeq 1.6 \text{ EeV } \epsilon_{B,-2}^{1/2} L_{j,43}^{1/2} \theta_{j,-1}^{-1}$

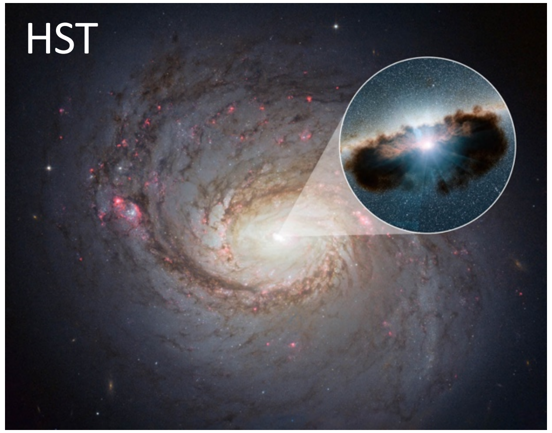
wind $\varepsilon_p^{\max} \approx (3/20)(V_w/c) e B_w R \simeq 21 \text{ PeV } \epsilon_{B,-2}^{1/2} L_{w,44}^{1/2} (V_w/1000 \text{ km s}^{-1})^{1/2}$

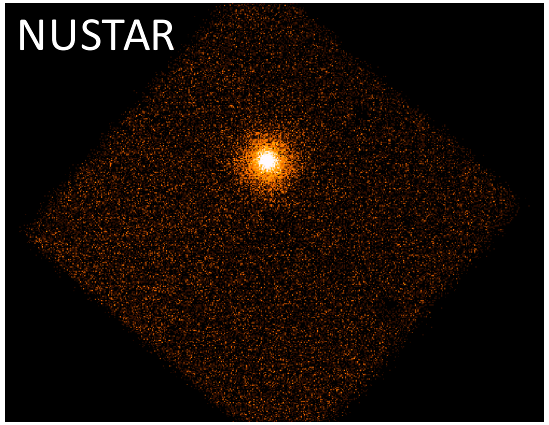
10-100 PeV protons may be produced => AGN winds could be sources of Pev neutrinos

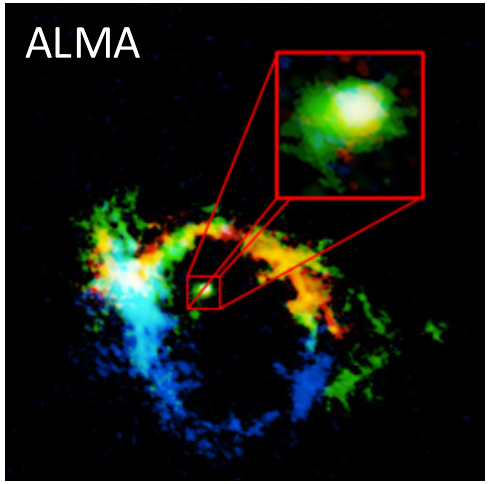
NGC 1068 – prototypical Seyfert 2 galaxy

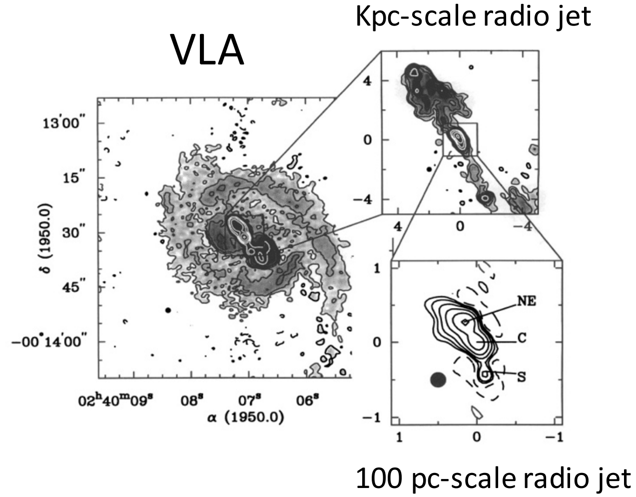
- distance D=14.4 Mpc
- composite starburst/AGN galaxy ($M_{BH} \approx 10^7 M_\odot$)
- Luminous infrared galaxy $L_{IR}=2.8\times10^{11} L_\odot$
- High luminosity ($L_{AGN}=10^{44}$-10^{45} erg/s)
  high obscured ($N_H>10^{24}$ cm^{-2}) AGN



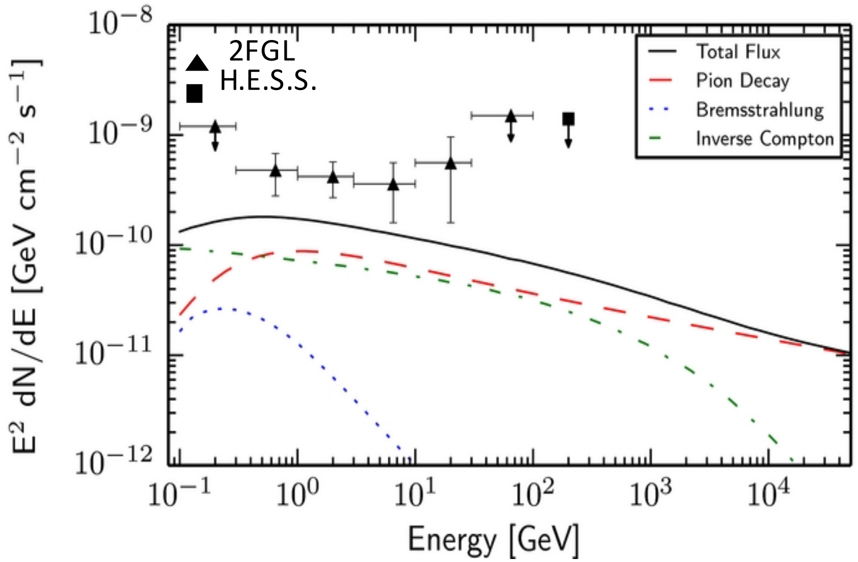


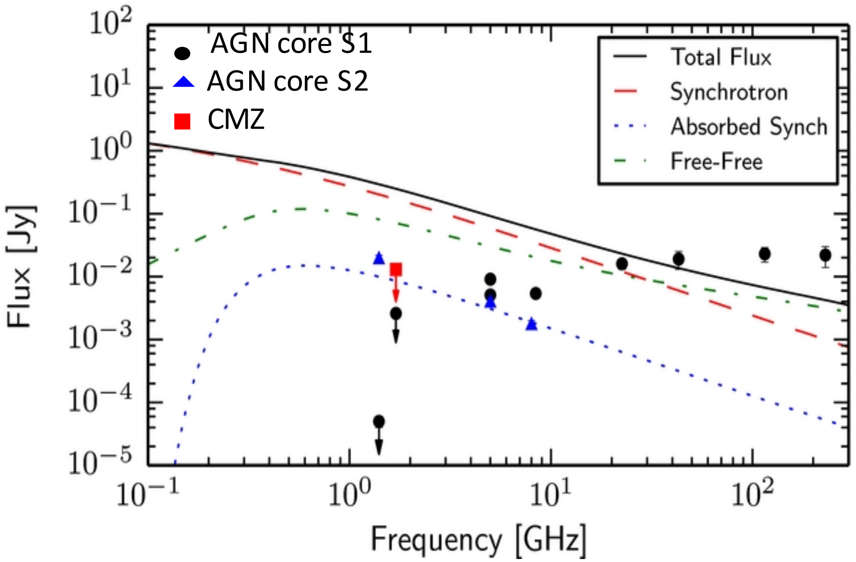




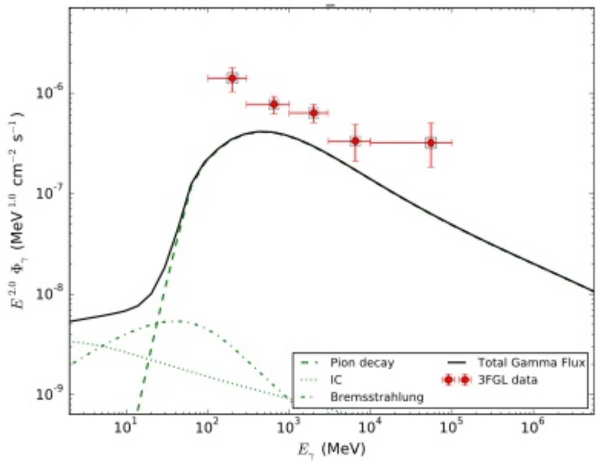


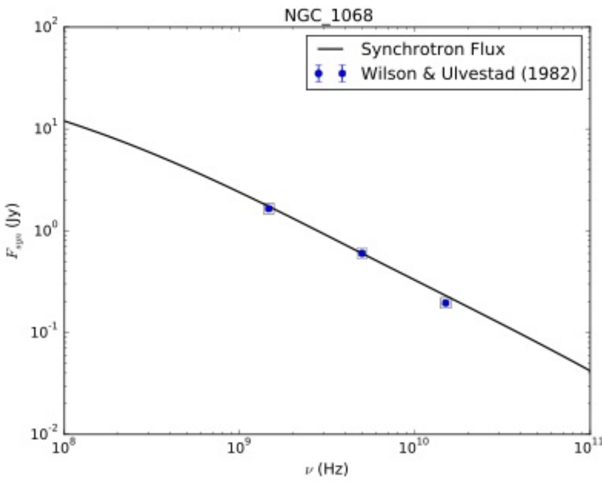
NGC 1068 gamma-ray and radio emissions: problems with the starburst interpretation





Yoast-Hull+10

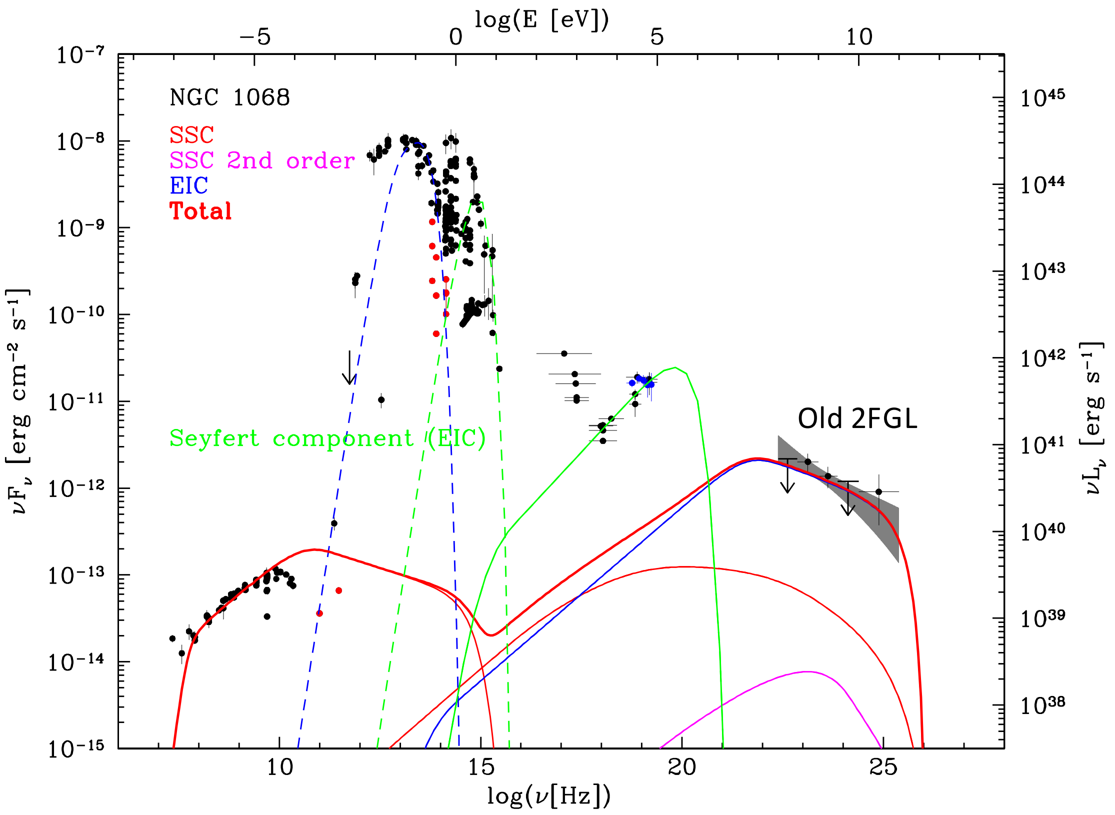




Eichmann+16

NGC 1068 gamma-ray and radio emissions: AGN jet model

CR electrons accelerated in the misaligned relativistic jet



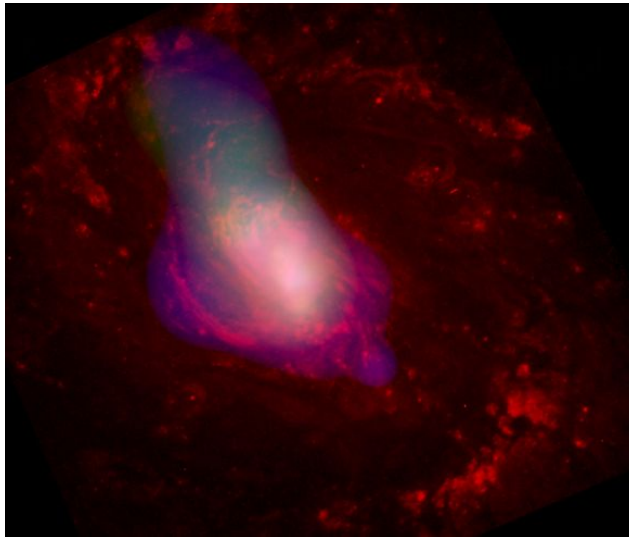
Lenain+10

Gamma-ray emission: IC scattering of IR photons

Radio emission: Synchrotron Self Compton

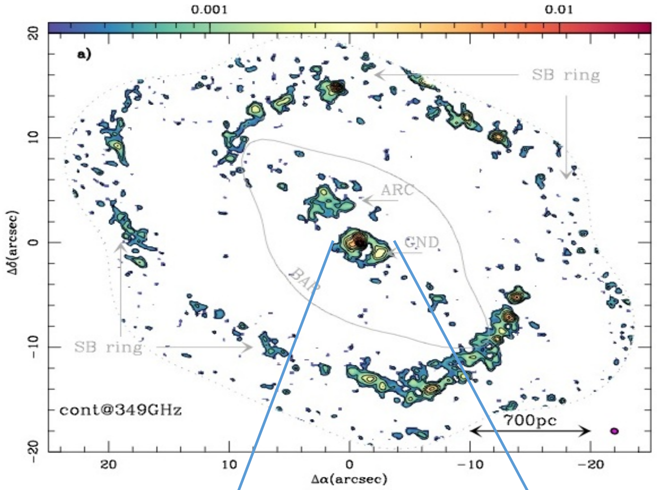
NGC 1068 gamma-ray and radio emissions: AGN wind model

CR electrons and protons accelerated in the non-relativistic AGN wind



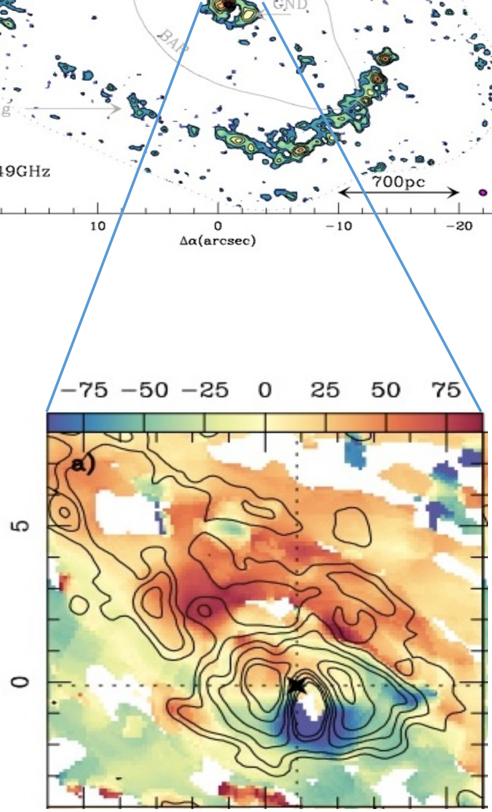
Optical (red) HST observation (Capetti+97)

X-ray (blue, green) Chandra observation (Ogle+03)



ALMA observation

Garcia-Burillo+14



Color scale: residual mean-velocity field obtained after subtraction of the rotation component

Black contours: integrated intensity of CO (3-2)

CND

370 pc x 200 pc

$h \approx 10$ pc

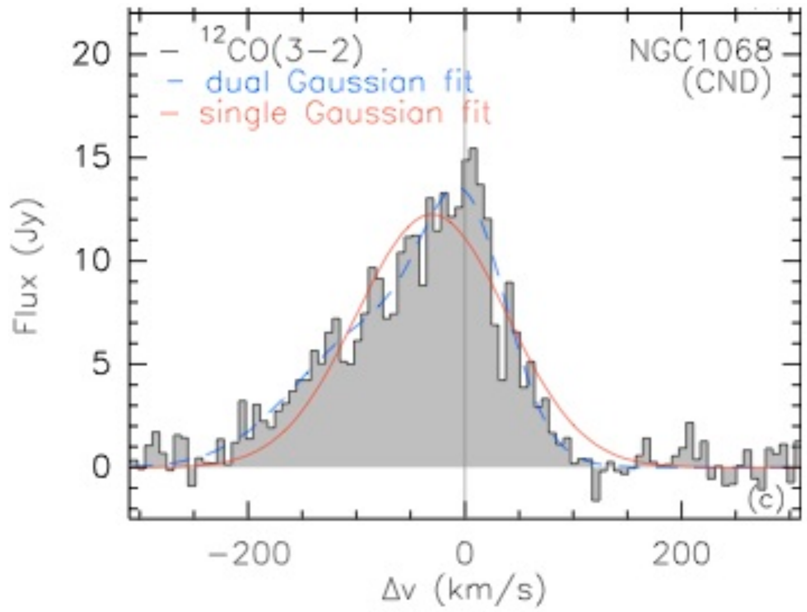
$M_{gas} \approx 5 \times 10^7\ M_\odot$

$\Sigma_{gas} \approx (0.01\text{-}0.05)$ g cm^{-2}

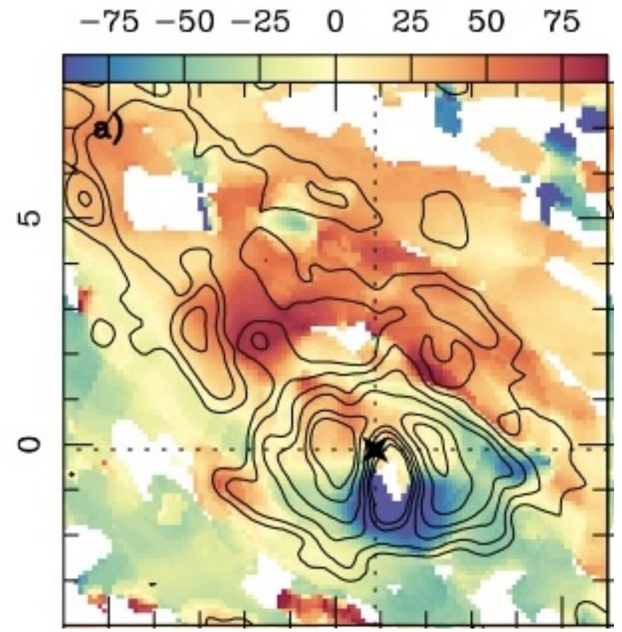
$n_H \approx (110\text{-}460)$ cm^{-3}

molecular outflow: observations & properties

SMA observation (Krips+11)



ALMA observation (Garcia-Burillo+14)



outflow velocity: $v_{out} \approx (100\text{-}200)$ km/s

outflow size: $R_{out} \approx 100$ pc

outflowing gas mass: $M_{out} \approx 1.8 \times 10^7\ M_\odot$

mass outflow rate: $dM_{out}/dt = 3 \times v_{out} \times (M_{out}/R_{out}) \approx 108\ M_\odot/yr$

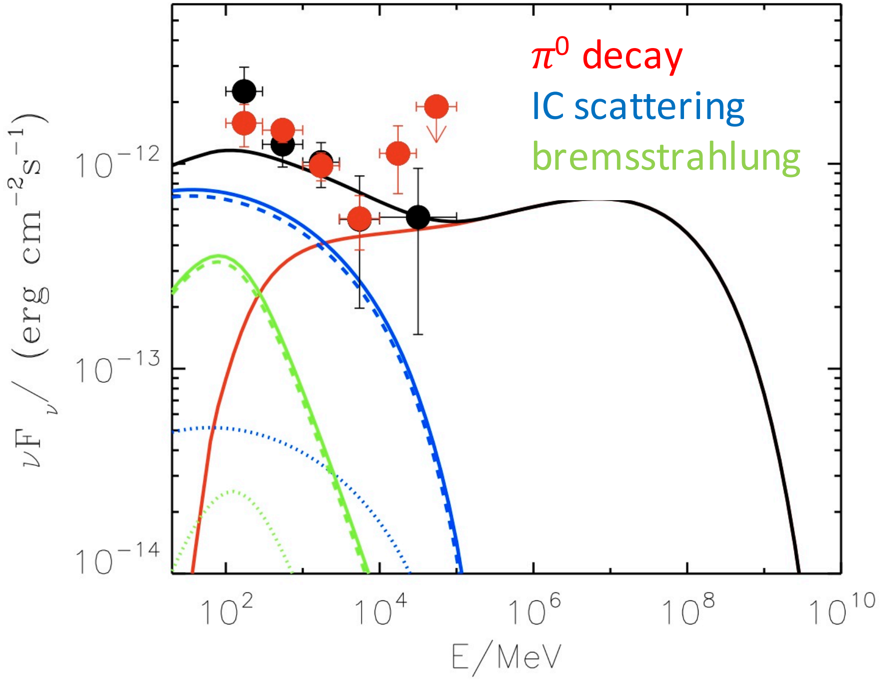
kinetic luminosity: $L_{kin} = 0.5 \times (dM_{out}/dt) \times v^2_{out} \approx 1.5 \times 10^{42}$ erg/s

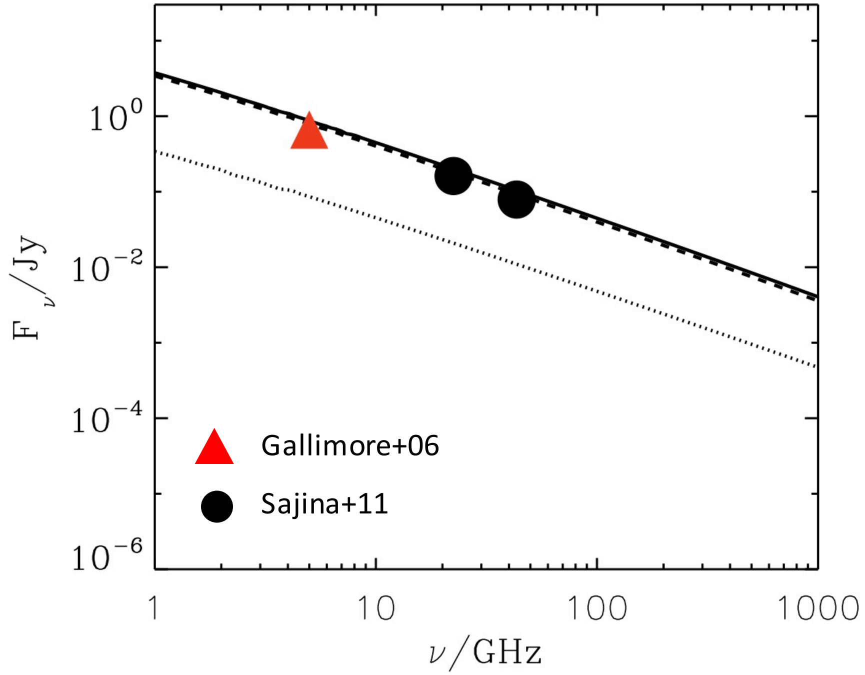
Star formation: $SFR_{CND} \approx 1\ M_\odot/yr$ $\quad L_{kin,SF} \leq L_{kin}$

AGN luminosity: $L_{bol} \approx (10^{44}\text{-}10^{45})$ erg/s $\quad L_{bol} \approx (100\text{-}1000) \times L_{kin}$

Radio jet: $L_{jet} = 10^{43}$ erg/s $\quad L_{jet} \approx 10 \times L_{kin}$

NGC 1068 - gamma-ray and radio spectra





R_{out}=100 pc v_{out}=200 Km/s L_{kin}=1.5x10^{42} erg/s

η_p=0.1-0.5 η_e=0.01-0.2

n_H=10^2-10^4 cm^{-3}

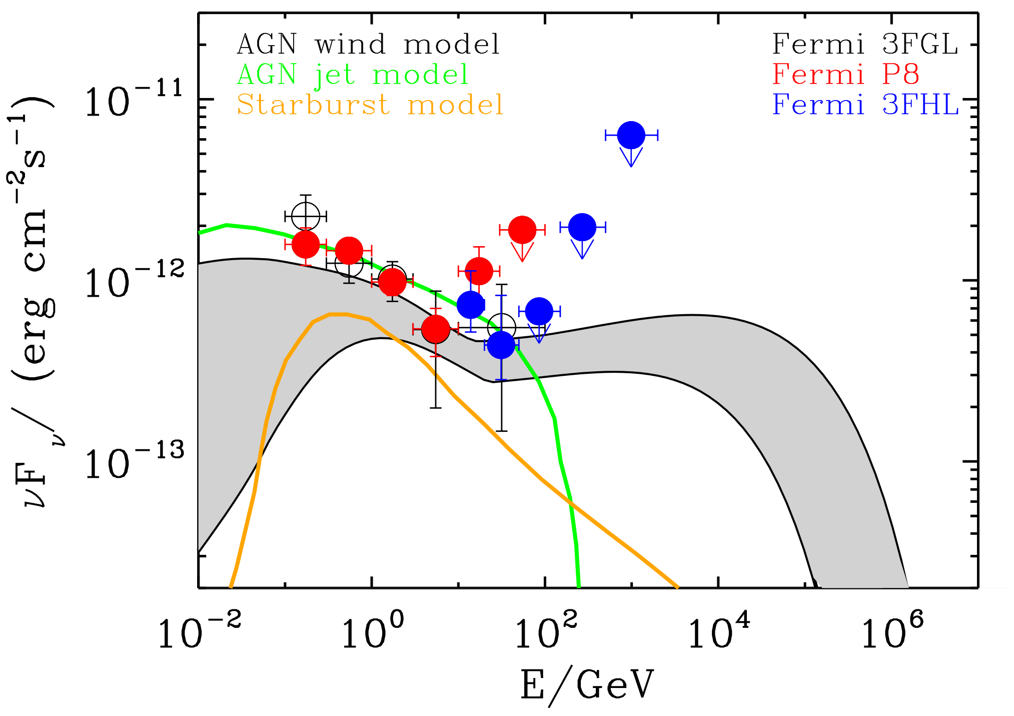
B_{ISM}=30-1000 μG

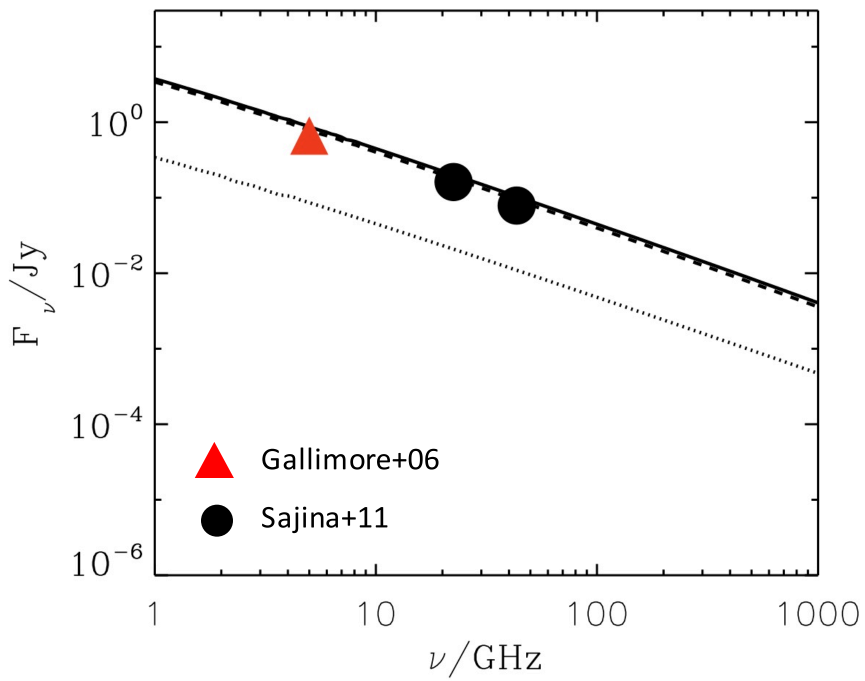
dashed: primary electrons

dotted: secondary electrons/positrons from charged pion decays

Lamastra+16

NGC 1068 - gamma-ray and radio spectra





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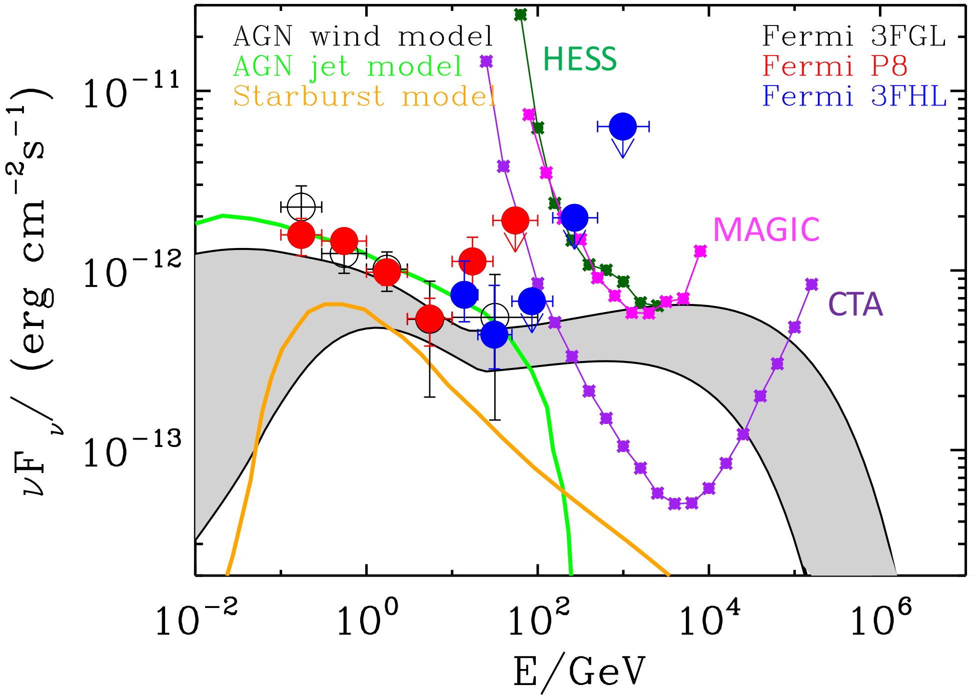
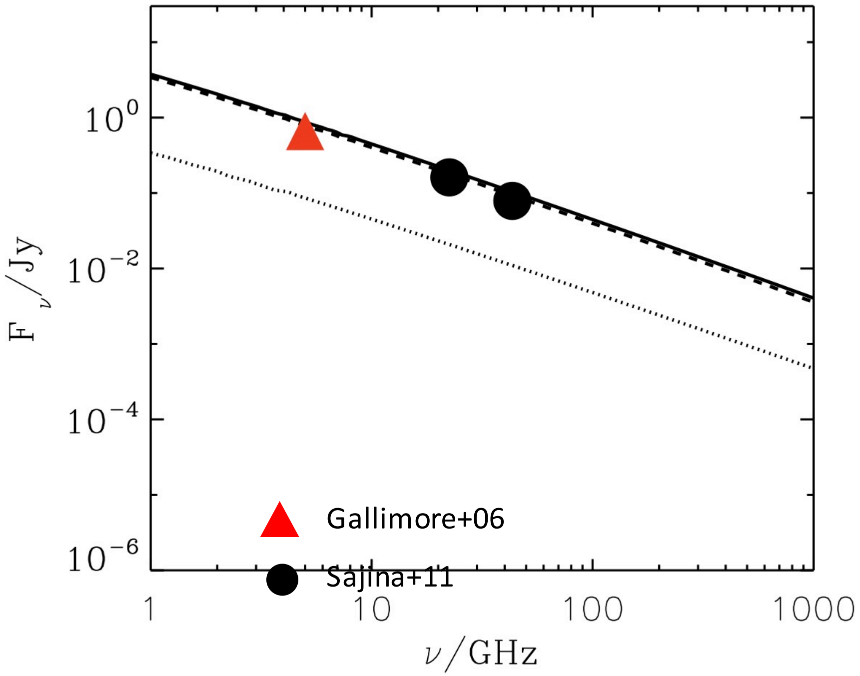
Lamastra+16

NGC 1068 - gamma-ray and radio spectra

sensitivity 5$\boldsymbol{\sigma}$ in 50 hours





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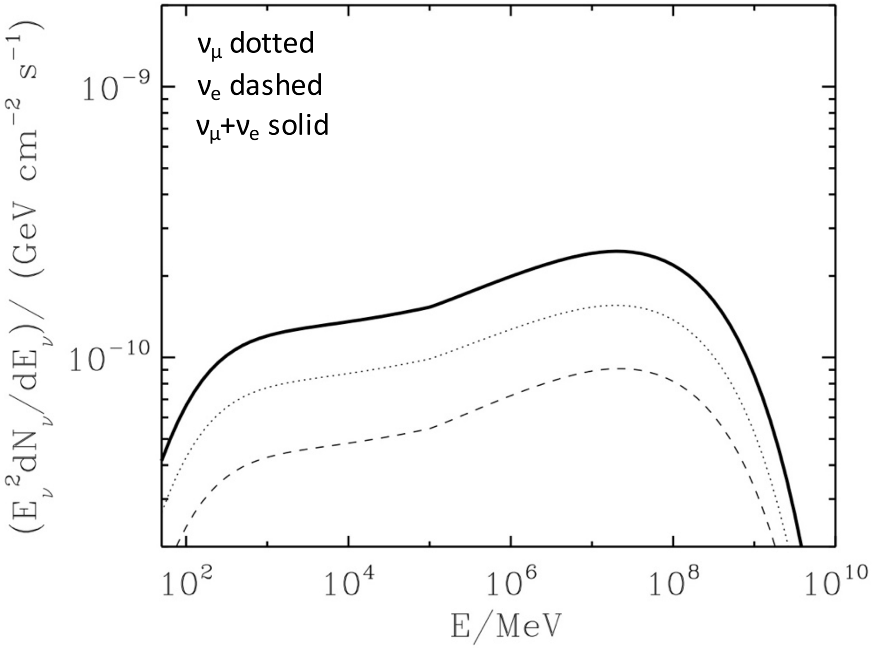
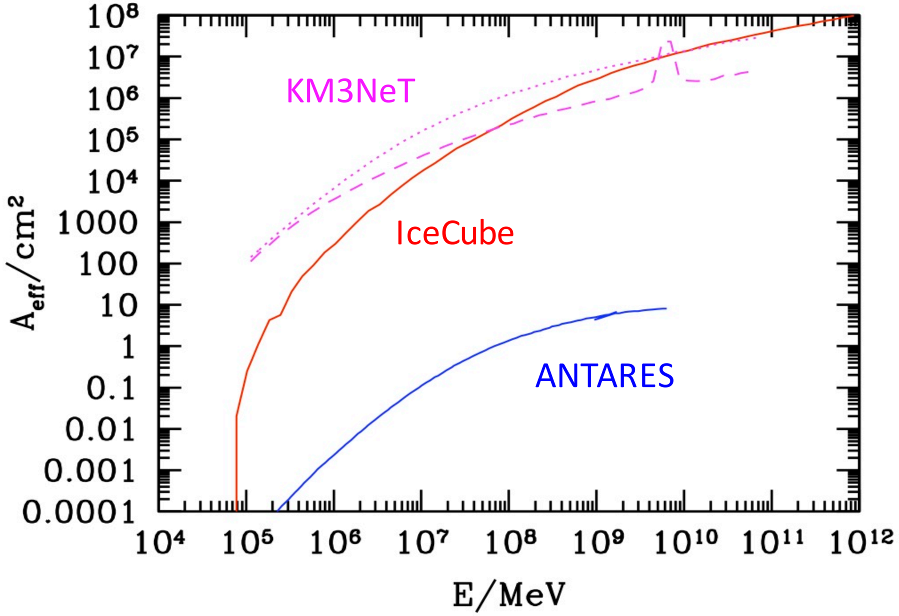
NGC 1068 – neutrino spectrum





$$p + p \rightarrow \pi^0 + \pi^\pm + \ldots$$

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

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

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

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

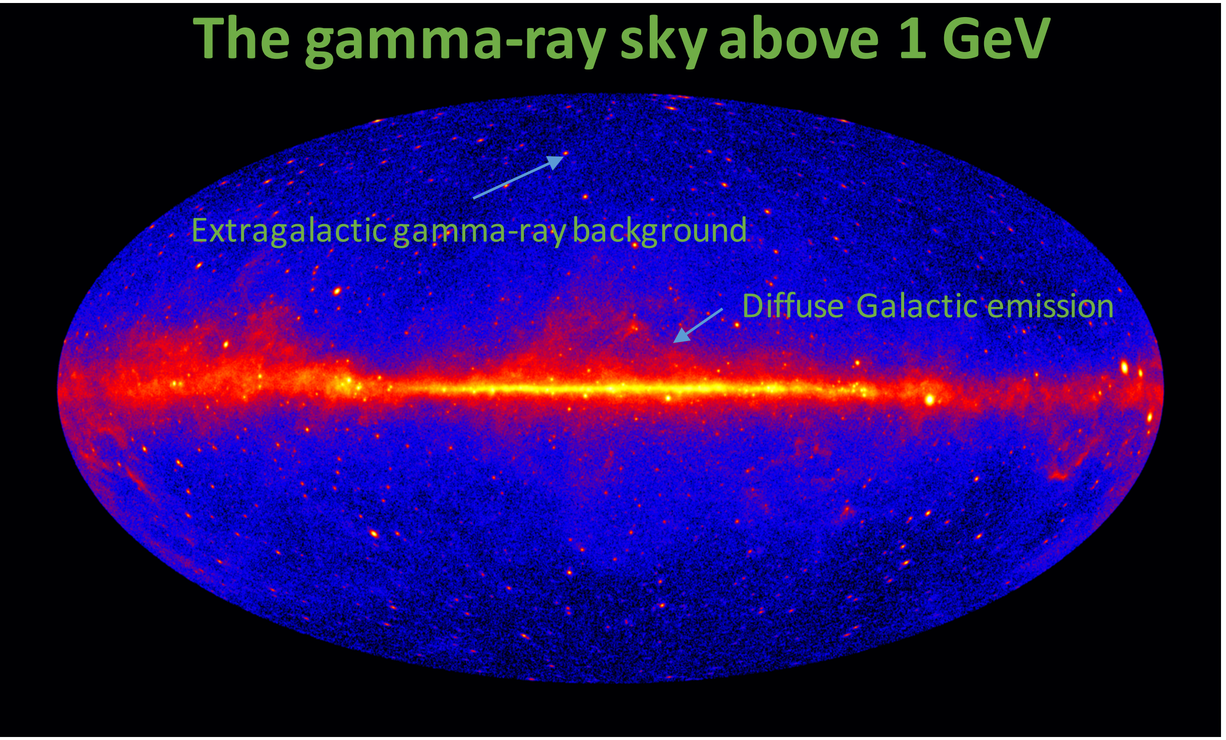
$$\mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

Expected number of neutrino events in one year of integration time

	N_ν	N_{ν_μ}	N_{ν_e}
ANTARES	7×10^{-7}	-	-
IceCube	0.1	-	-
KM3NeT	-	0.6	0.1

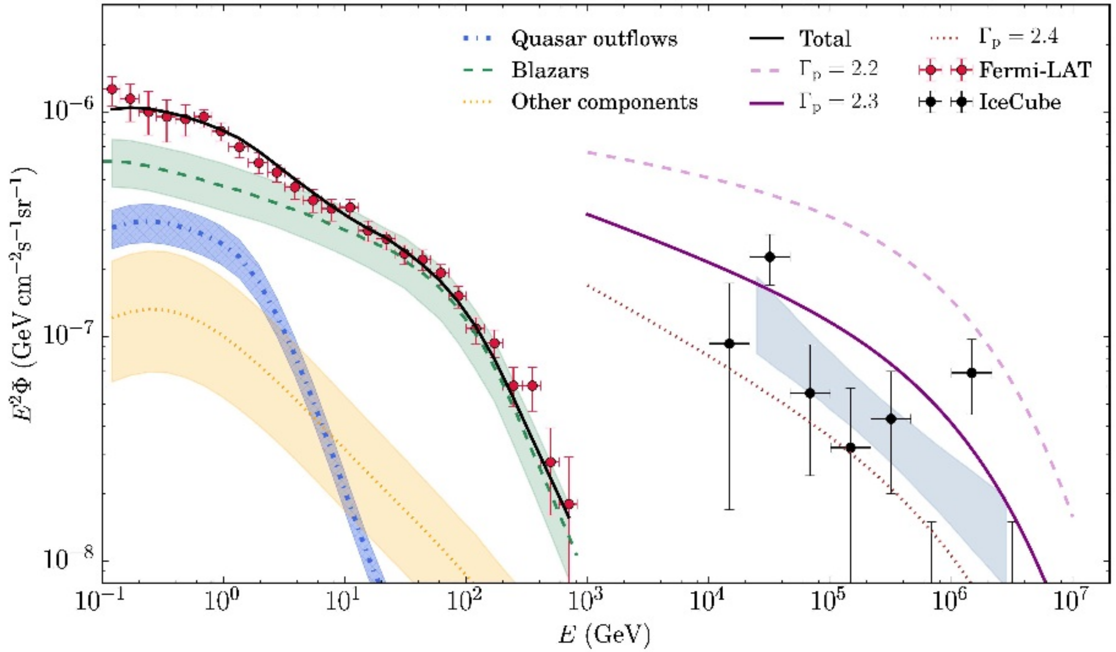
Lamastra+16

The extragalactic gamma-ray and neutrino backgrounds



5 years of Fermi-LAT data

Wang & Loeb 2016



Blazars: 50% of the EGB @ E< 10 GeV

SF galaxies: 13% of the EGB @ E<10 GeV

Radio galaxies: 7% of the EGB @ E<10 GeV

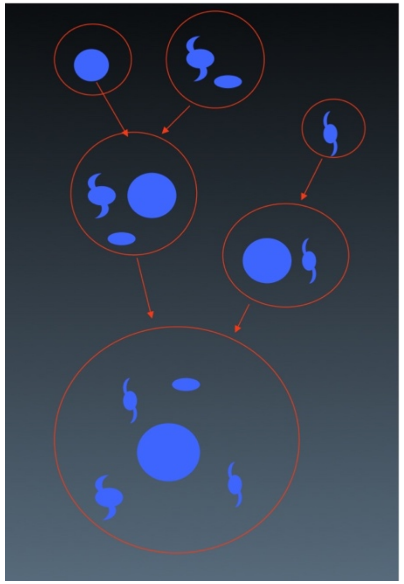
AGN winds: 20%-40% of the EGB @ E<10 GeV

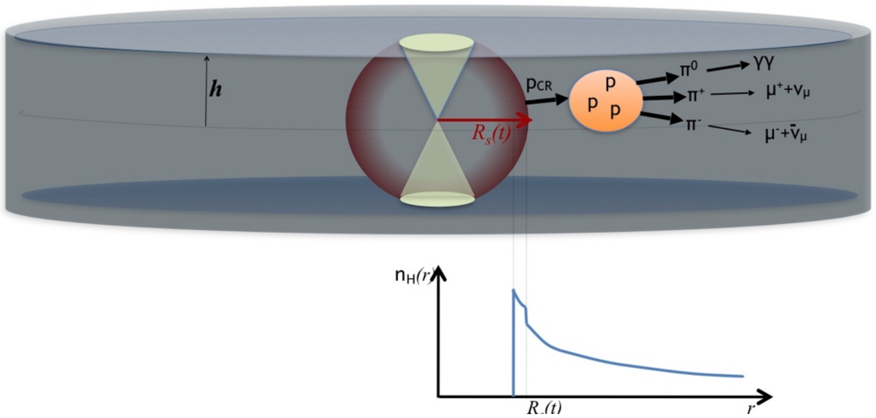
Semi-analytic models for galaxy formation

Kauffmann+93
Cole+94
Monaco+00
Granato+04
Bower+06
Croton+06
Menci+06,14
Lamastra+10,13

Three main ingredients:

- Hierarchical merging of DM haloes and of substructures: higher density perturbation collapse first, larger scale perturbation later.
- Galaxy interactions to fuel both star formation and AGN (Cavaliere & Vittorini 2000).
- A physical model for AGN feedback (Lapi+05).





Halo properties

Density profiles
Virial temperature
Virial radius

Gas properties

Profiles
Cooling-heating processes
Collapse, disk formation

Col-mag rel.

Star formation

Quiescent
Starburst

Evolution of stellar pop.

Growth of BHs
evolution of AGNs

Gas heating (feedback)

SNae
UV background
AGN

M_{BH}-M_* rel.

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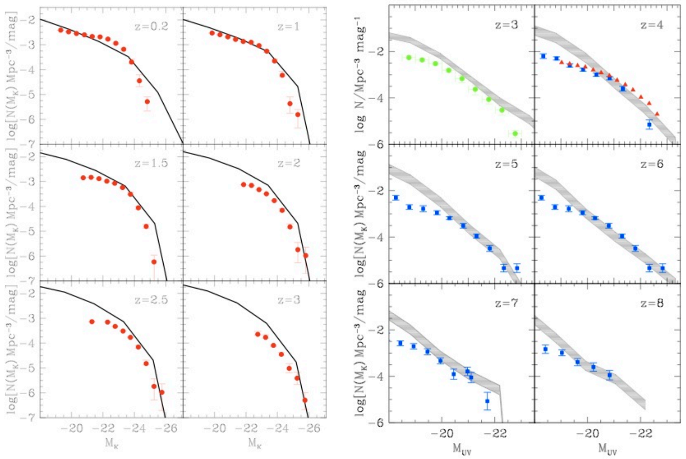
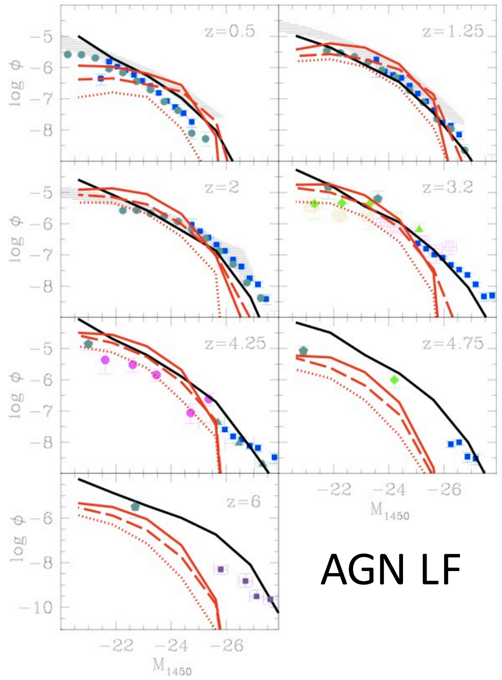
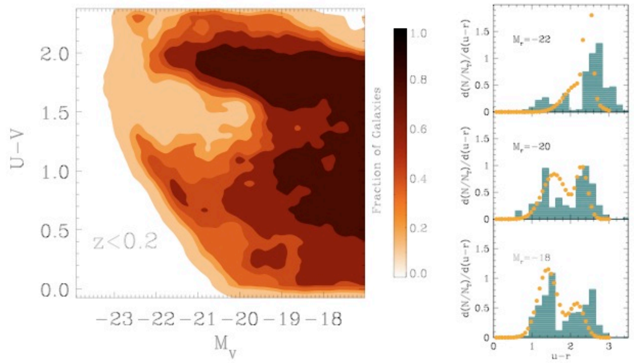


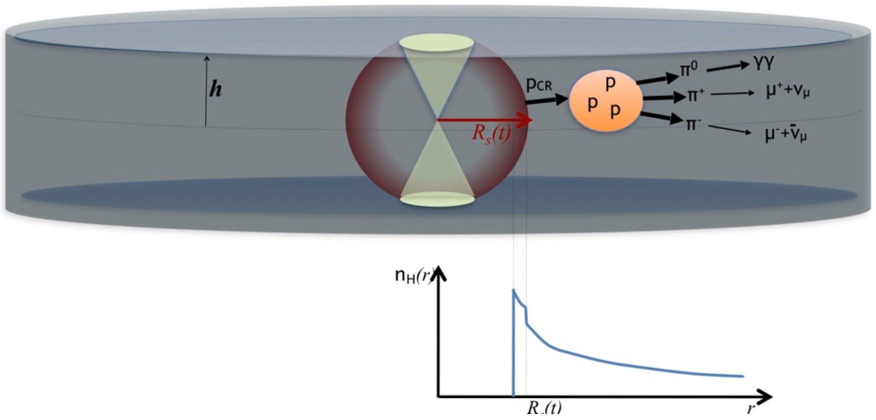
Gal. LF in K and UV band

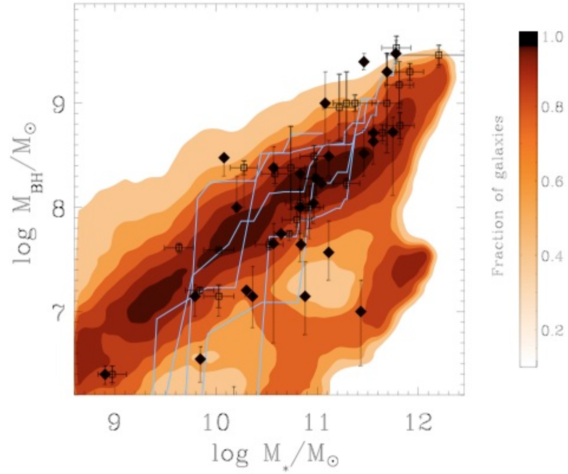


AGN LF



Col-mag rel.





M_{BH}-M_* rel.

Extragalactic gamma-ray background from AGN winds and SF galaxies

$$E^2\frac{dN}{dE} = \int_0^{z_{max}}\int_{L_{\gamma,min}}^{L_{\gamma,max}} \phi(L_\gamma,z)\frac{I(E'_\gamma,L_\gamma,z)}{4\pi D_L^2(z)} exp[-\tau_{\gamma\gamma}(E'_\gamma,z)]\frac{d^2V}{dzd\Omega}dL_\gamma dz$$

- ✓ AGN-driven winds

$$L_{kin}^{AGN} = \varepsilon_{AGN} L_{AGN}$$

$$\varepsilon_{AGN} = 0.01$$ Fiore+17

- ✓ SN-driven winds

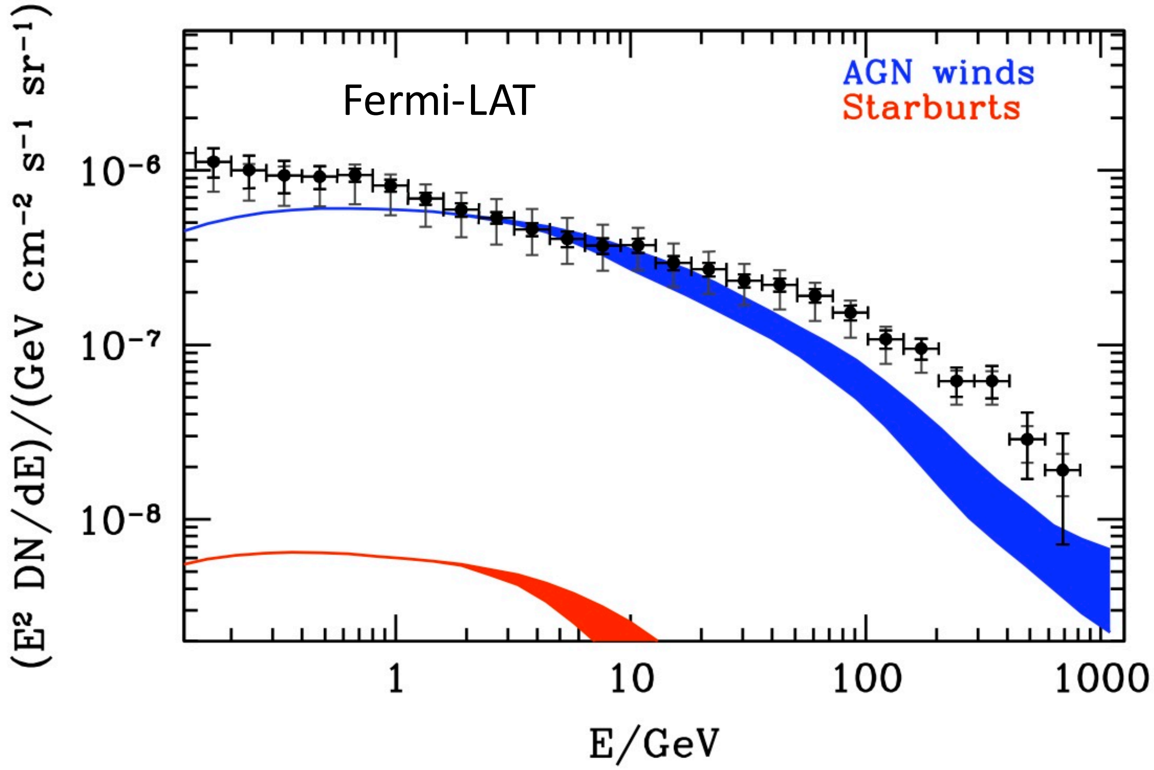
$$L_{kin}^{SB} = \varepsilon_{SN}\nu_{SN}E_{SN}$$

$$\varepsilon_{SN} = 0.1$$

$$\nu_{SN} \propto SFR$$

$$E_{SN} = 10^{51} erg$$

- ✓ Calorimetric regime => advective and diffusive escape of accelerated protons are negletcted



Lamastra+17

Extragalactic gamma-ray background from AGN winds and SF galaxies

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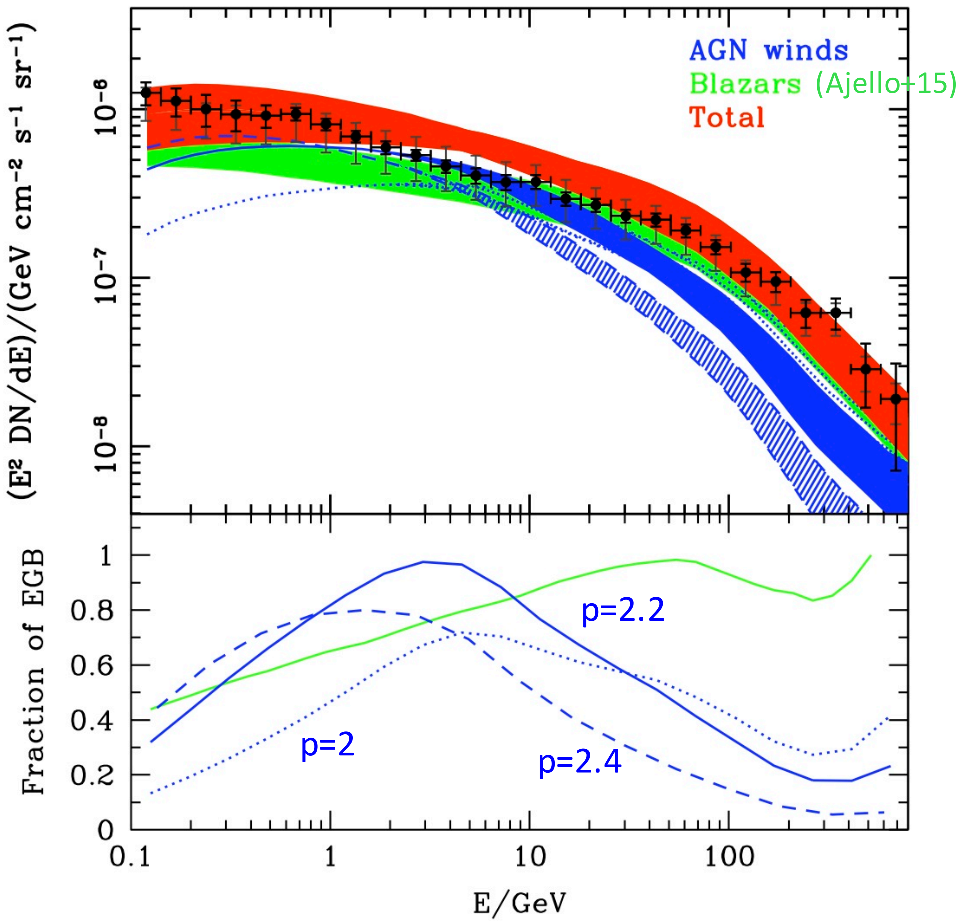
The cumulative gamma-ray emission from AGN winds and blazars could account for the amplitude and spectral shape of the EGB



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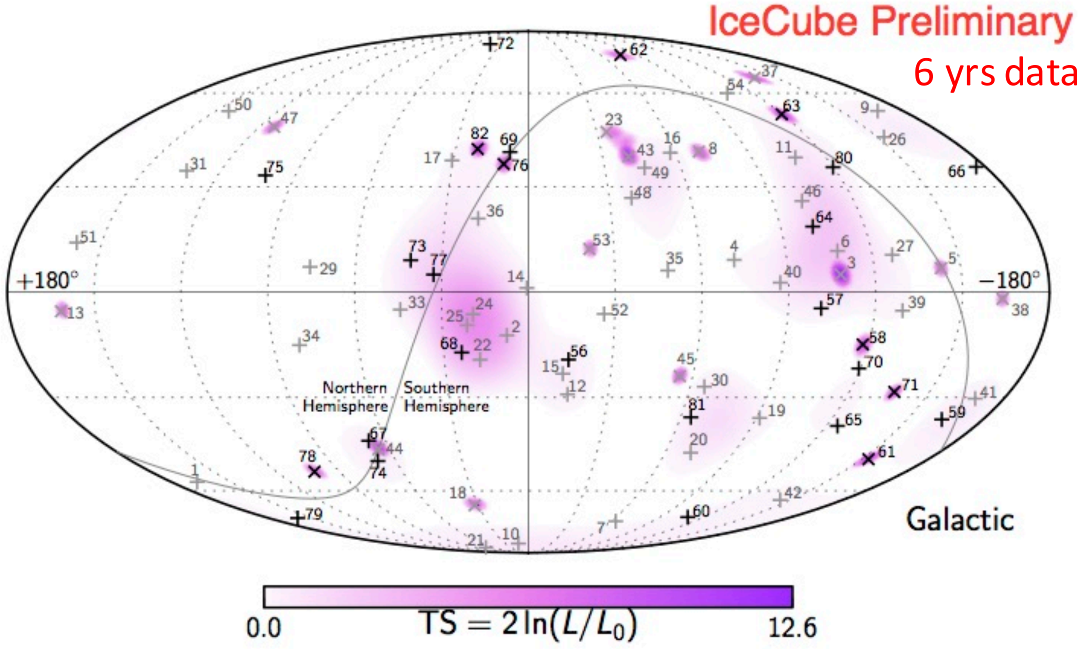
IceCube Neutrino



- **Active galactic nuclei**

  (e.g. Stecker+91, Mannheim 95, Stecker 13, Murase+14, Dermer+14, Tavecchio+14, Padovani+15, Wang & Loeb 26, Lamastra+17)

- **Starburst galaxies**

  (e.g. Loeb & Waxman 06, Thompson+07, Murase+13, Tamborra+14, Anchordoqui+14)

- **Gamma-ray burst**

  (e.g. Waxman & Bahcall 97, Murase+16, Liu & Wang 13)

- **Galaxy groups/clusters**

  (e.g. Berezinsky+97, Murase+08, Ahlers & Lacki 13, Zandanel+14)

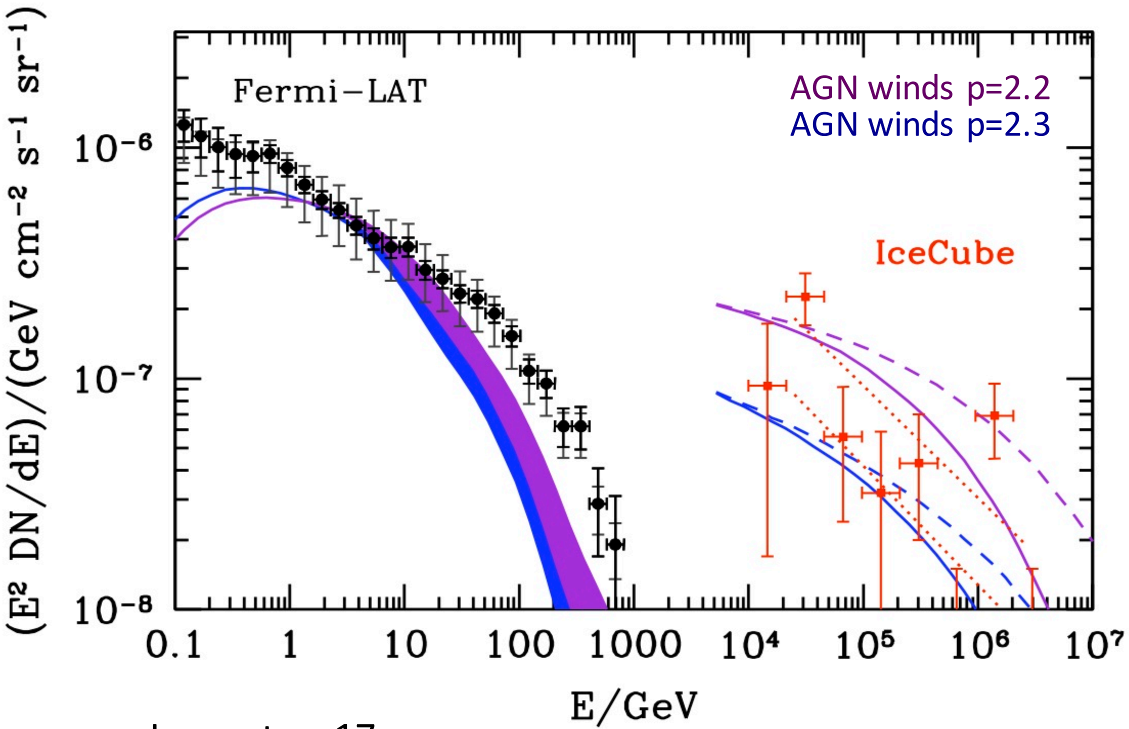
Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

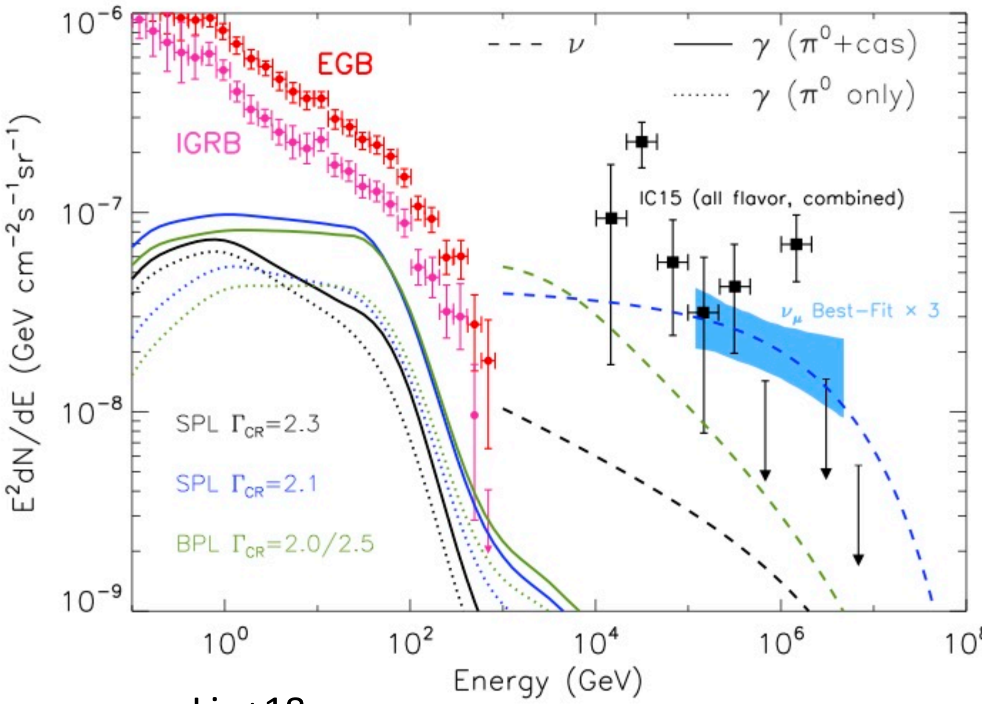
First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Neutrino background from AGN winds

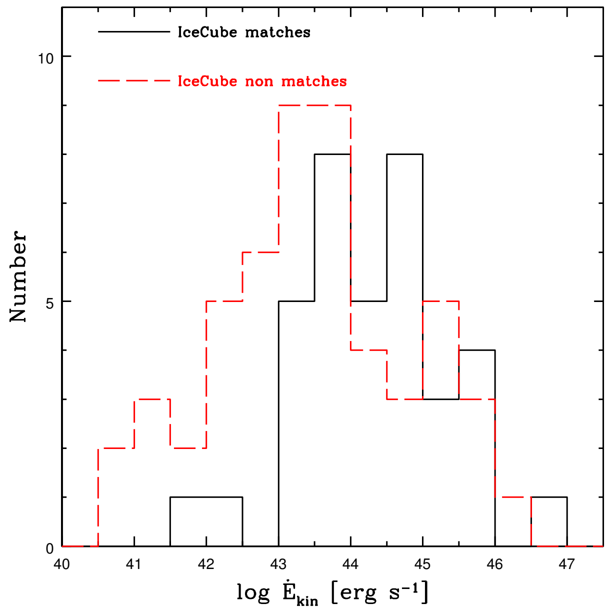


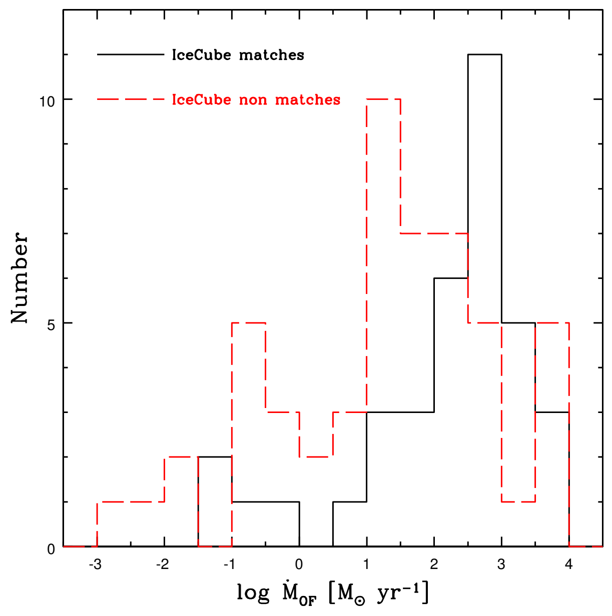
Lamastra+17

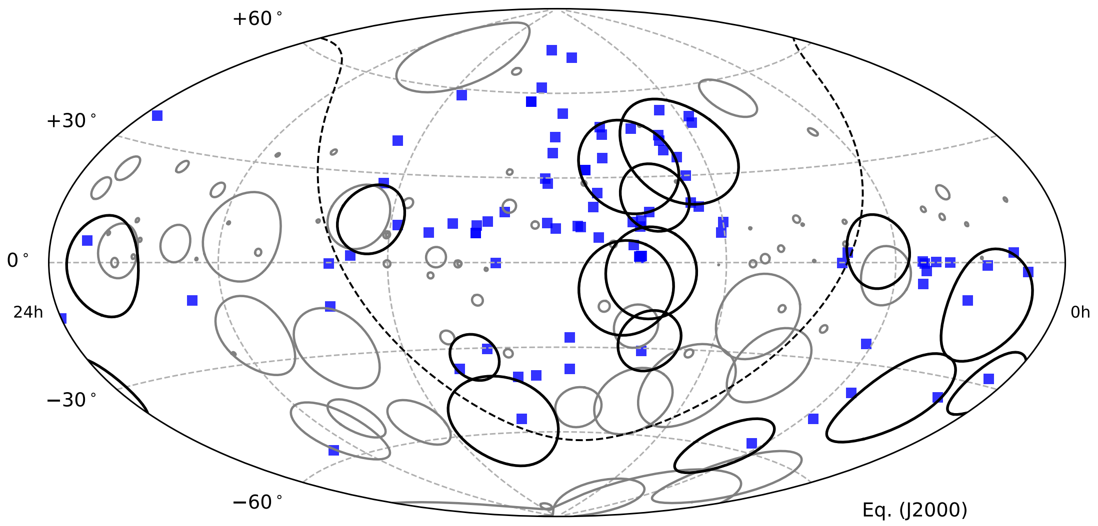


Liu+18

Observational test







36 AGN winds associated with an IceCube neutrino

52 AGN winds not associated with an IceCube neutrino

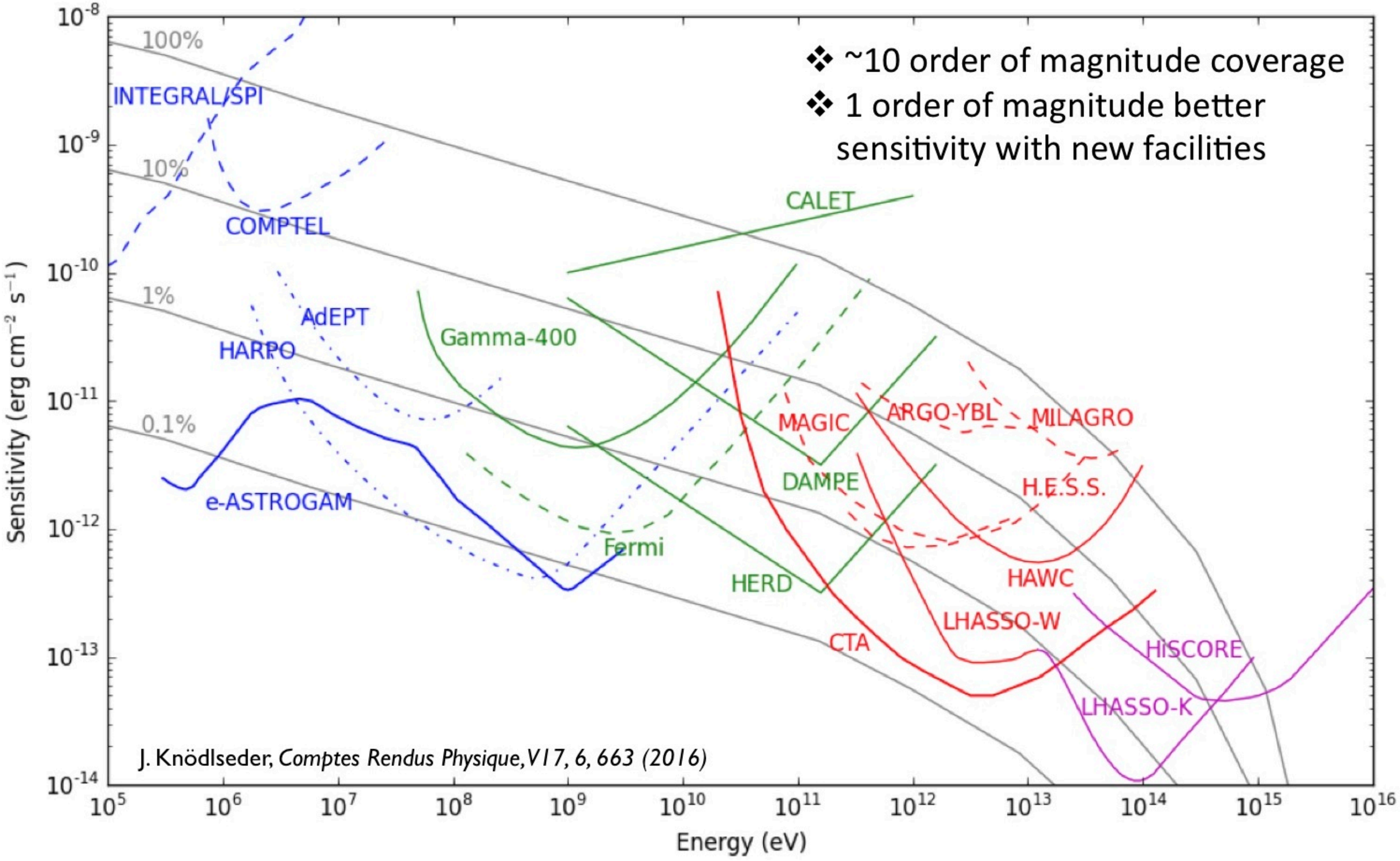
Padovani+18

Summary

- AGN winds are predicted to be particle accelerators and neutrino sources.
- The cumulative gamma-ray emission from AGN winds could account from 30% to 80% of the EGB flux around 10 GeV.
- AGN winds could account for a large fraction of the neutrino background detected by IceCube for spectral indices $p<2.2$. For softer spectral indices ($p>2.2$) the EGB data rules out the possibility that the dominant fraction of IceCube neutrinos is accounted for AGN winds.
- Further progress in this topic requires better AGN winds and neutrino statistics.
  In the next future, the improved sensitivity and angular resolution of next generation Cherenkov telescopes (CTA) and neutrino detectors (KM3net, IceCube-Gen2) will allow us to constrain effectively the possible astrophysical sources of neutrino events, and will provide a direct test of gamma-ray and neutrino background models.

Backup slides

Gamma-ray instruments



Theoretical modelling

$$Q_p(E) = A_p E^{-p} \exp\left[-\left(\frac{E}{E_{\max,p}}\right)\right] \qquad E_{\max,p} = 0.5\left(\frac{v_s}{10^8\,cm/s}\right)^2\left(\frac{\tau_{age}}{10^3\,yr}\right)\left(\frac{B}{\mu G}\right) TeV$$

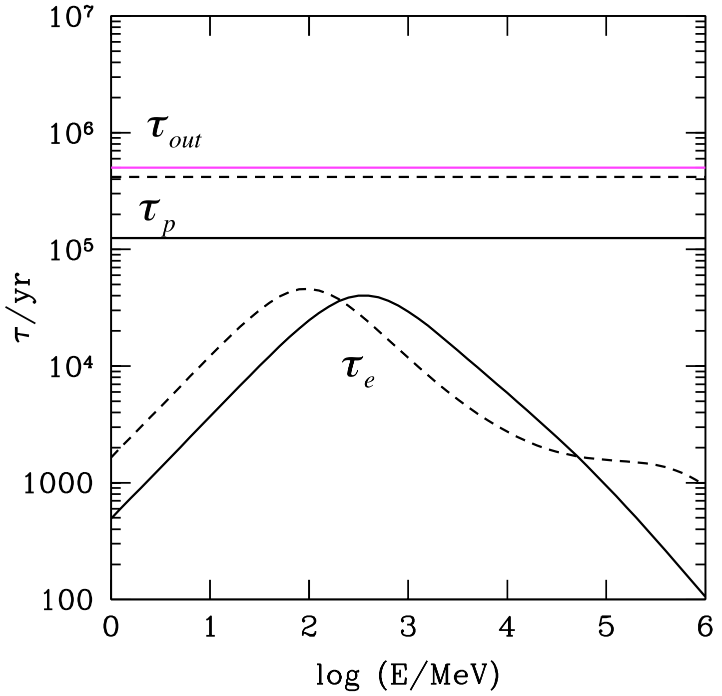
$$Q_e(E) = A_e E^{-p} \exp\left[-\left(\frac{E}{E_{\max,e}}\right)\right] \qquad E_{\max,e} = 100\left(\frac{v_s}{10^8\,cm/s}\right)\left(\frac{B}{\mu G}\right)^{-0.5} TeV$$

$$\frac{N(E)}{\tau_{life}} - \frac{d}{dE}[b(E)N(E)] - Q(E) = 0 \qquad \int_{E_{min}}^{E_{max}} N(E)E\,dE = \eta E kin$$

CR protons $\tau_p \approx 5\times 10^7\,yr\left(\frac{n_H}{cm^{-3}}\right)^{-1}$

CR electrons $\tau_e = (\tau_{syn}^{-1} + \tau_{IC}^{-1} + \tau_{brem}^{-1} + \tau_{ion}^{-1})^{-1}$

Outflow time scale $\tau_{out} \approx 10^6\,yr\left(\frac{R_{out}}{kpc}\right)\left(\frac{v_{out}}{10^8\,cm/s}\right)^{-1}$



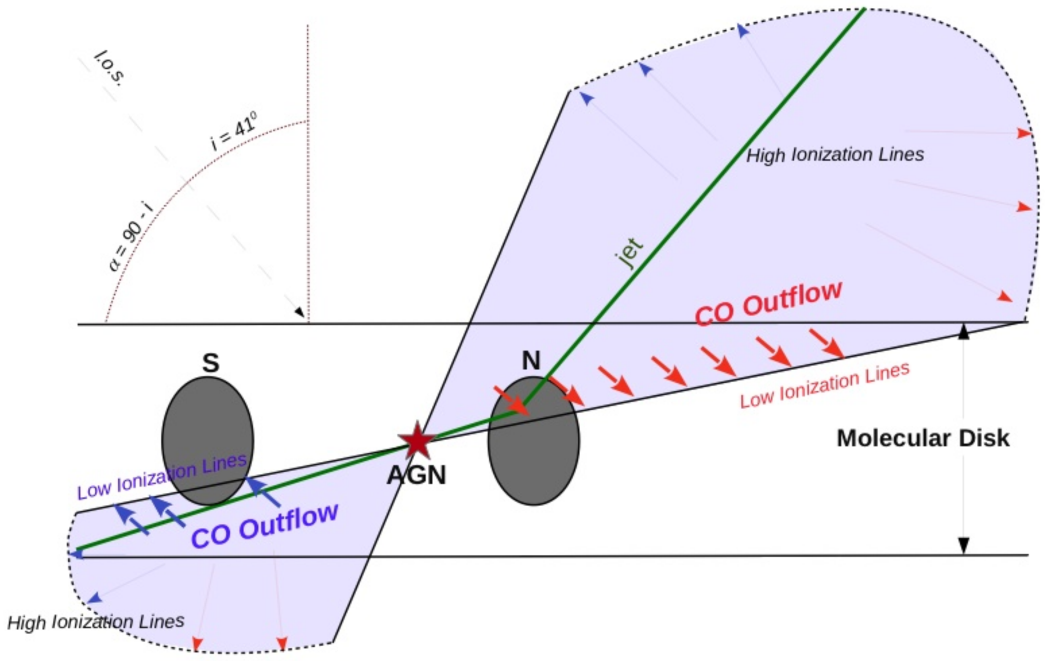
Solid: n_H=120 cm^{-3}
B_{ISM}=100 µG
L_{AGN}=2.1×10^{45} erg/s

Dashed: n_H=400 cm^{-3}
B_{ISM}=350 µG
L_{AGN}=4.2×10^{44} erg/s

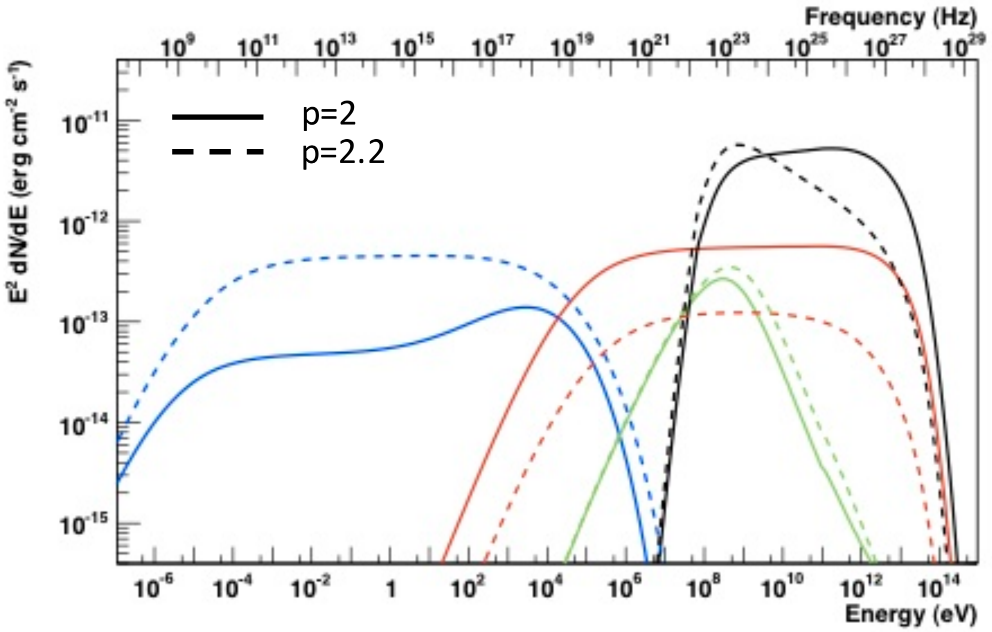
Molecular outflow – the powering source and structure

1. Star formation: $SFR_{CND} \approx 1\ M_{\odot}/yr$ $L_{kin,SF} \leq L_{kin}$
2. AGN luminosity: $L_{bol} \approx (10^{44}\text{-}10^{45})$ erg/s $L_{bol} \approx (100\text{-}1000) x L_{kin}$
3. Radio jet: $L_{jet} = 10^{43}$ erg/s $L_{jet} \approx 10 x L_{kin}$

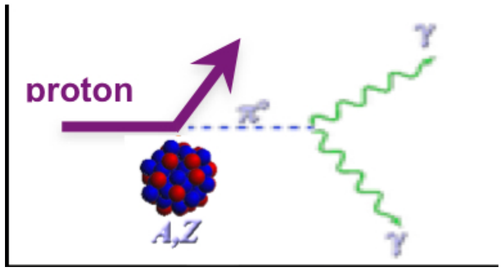
AGN-driven outflow



AGN winds as emitters in the gamma-ray and radio bands



Pion decay



$$p+p\to\pi^0+\pi^\pm+\ldots$$

$$\pi^0\to\gamma+\gamma$$

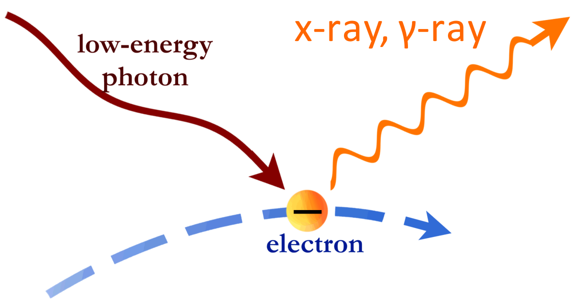
$$\pi^+\to\mu^++\nu_\mu$$

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

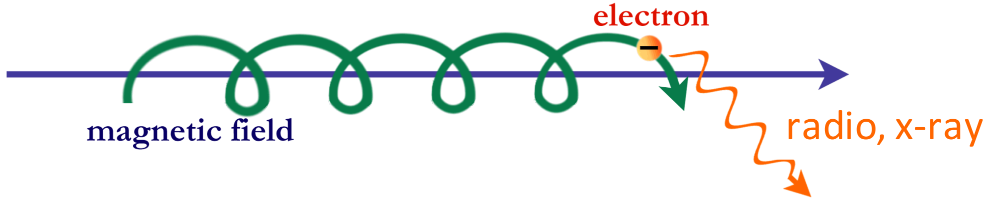
$$\pi^-\to\mu^-+\bar{\nu}_\mu$$

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

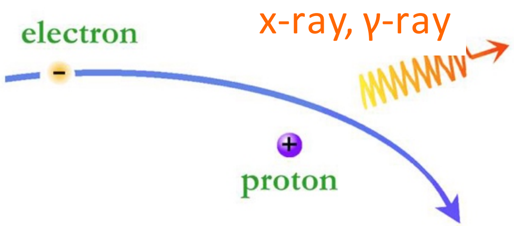
Inverse Compton



Synchrotron

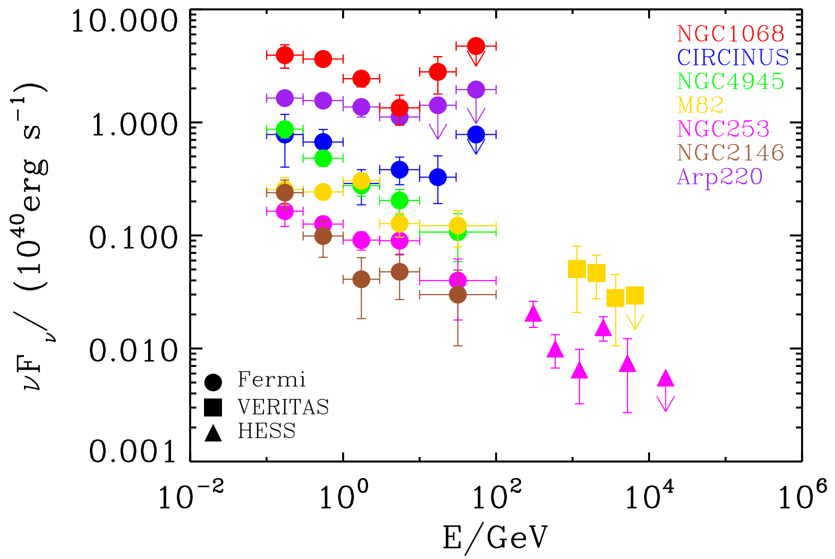


Bremsstrahlung

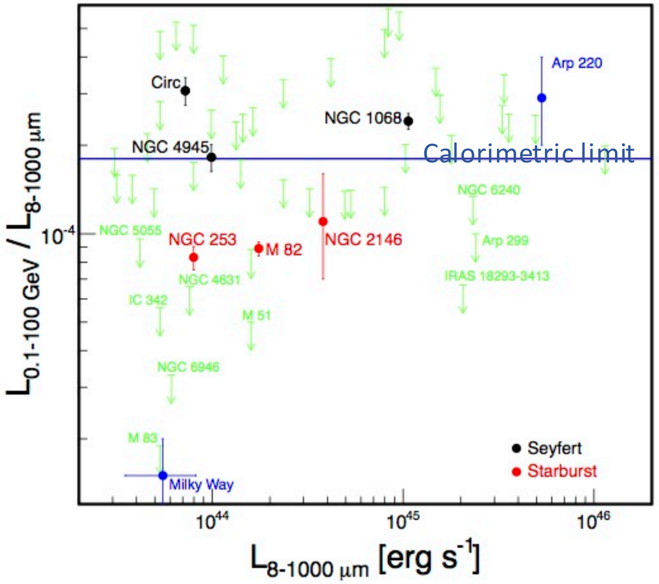


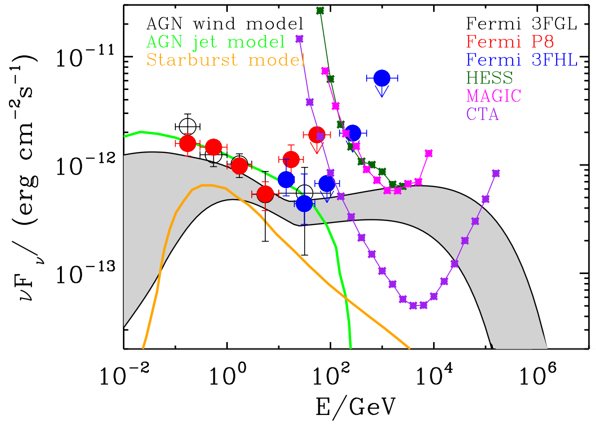
GeV-TeV observations of SF and active galaxies

Adapted from Ackermann+12

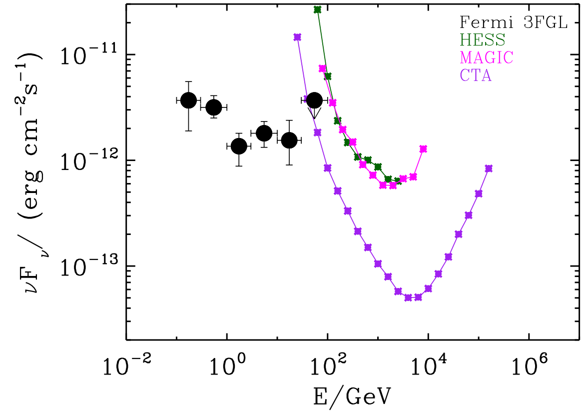


Wojaczynski+17

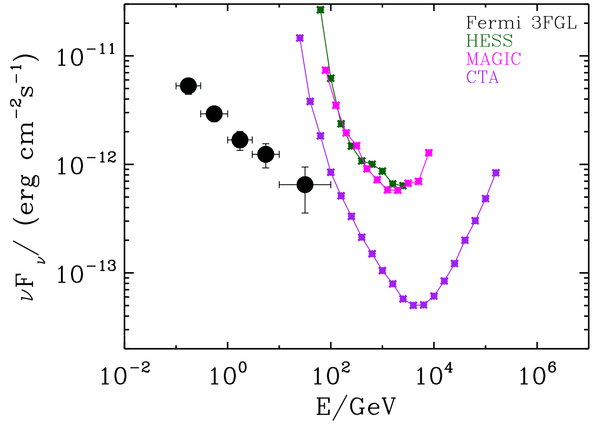




NGC 1068



CIRCINUS

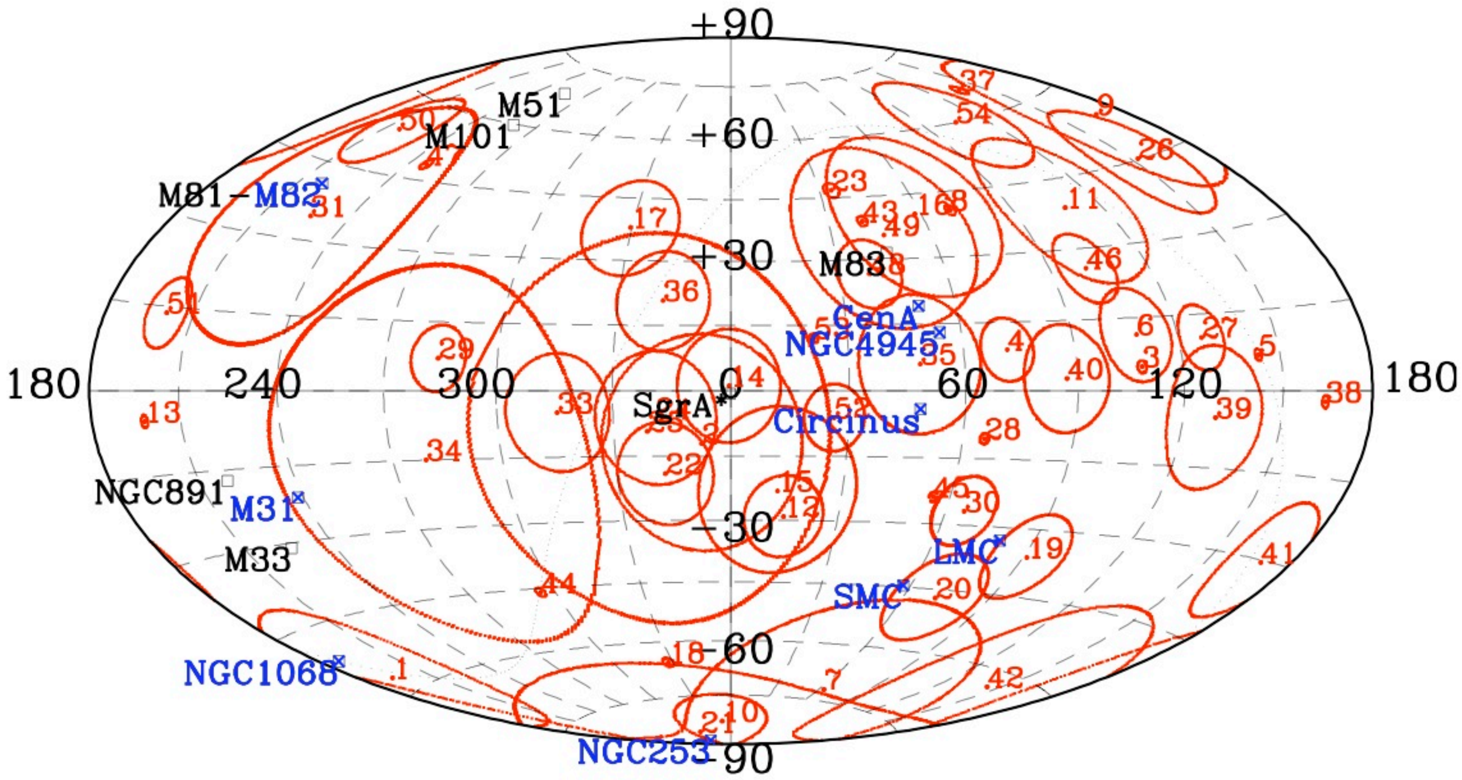


NGC4945

sensitivity 5**σ** in 50 hours

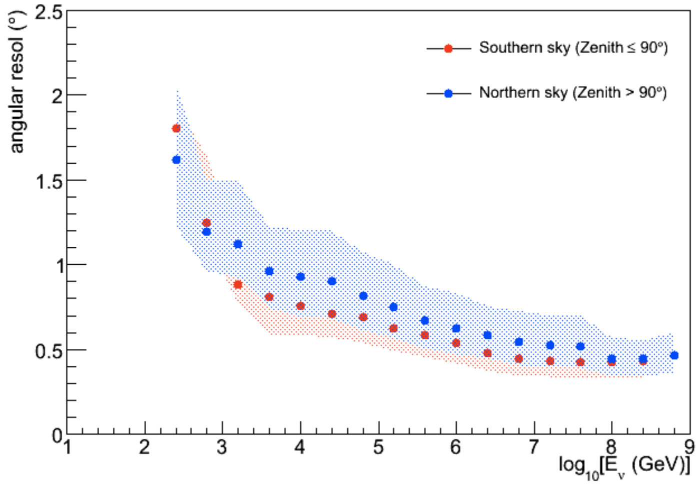
IceCube neutrinos and AGN/starburst galaxies

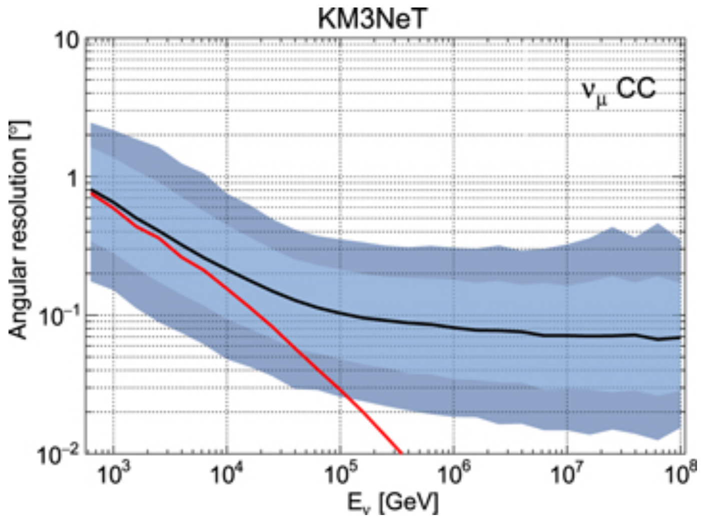
IceCube data 54 events (4 yrs data)



Local galaxies with v<1200 Km/s and $F_{100\mu m(IRAS)}$>50 Jy

Galaxies in the 3FGL catalogue





Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on *28 Sep 2017; 10:10 UT*
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430, 11489

We searched for Fermi-LAT sources inside the extremely high-energy (EHE) IceCube-170922A neutrino event error region (https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3, see also ATels 10773, 10787) with all-sky survey data from the Large Area Telescope (LAT), on board the Fermi Gamma-ray Space Telescope. We found that one Fermi-LAT source, TXS 0506+056 (3FGL J0509.4+0541 and also included in the 3FHL catalog, Ajello et al., arXiv:1702.00664, as 3FHL J0509.4+0542), is located inside the IceCube error region. The FAVA (Fermi All-sky Variability Analysis) light curve at energies above 800 MeV shows a flaring state recently (https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27). Indeed, the LAT 0.1--300 GeV flux during 2018 September 15 to 27 was (3.6+/-0.5)E-7 photons cm-2 s-1 (errors are statistical only), increased by a factor of ~6 compared to the 3FGL flux, with nearly the same power-law index of 2.0+/-0.1. We strongly encourage multiwavelength observations of this source. We also encourage optical spectroscopy for this source, because the redshift is still unknown. According to NED, the R-band magnitude is reported as 15.1 (Healey et al. 2008, ApJS 175, 97). Radio observations show that this blazar has had increasing flux during the past year: http://www.astro.caltech.edu/ovroblazars/data.php?page=data_query, http://www.physics.purdue.edu/astro/MOJAVE/sourcepages/0506+056.shtml.

Because Fermi operates in an all-sky scanning mode, regular gamma-ray monitoring of this source region will continue. For this source the Fermi-LAT contact person is Yasuyuki T. Tanaka (ytanaka@astro.hiroshima-u.ac.jp). The Fermi-LAT is a pair conversion telescope designed to cover the energy band from 20 MeV to greater than 300 GeV. It is the product of an international collaboration between NASA and DOE in the U.S. and many scientific institutions across France, Italy, Japan and Sweden.

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on *4 Oct 2017; 17:17 UT*
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.