Multi-Messenger signals from Seyfert galaxies

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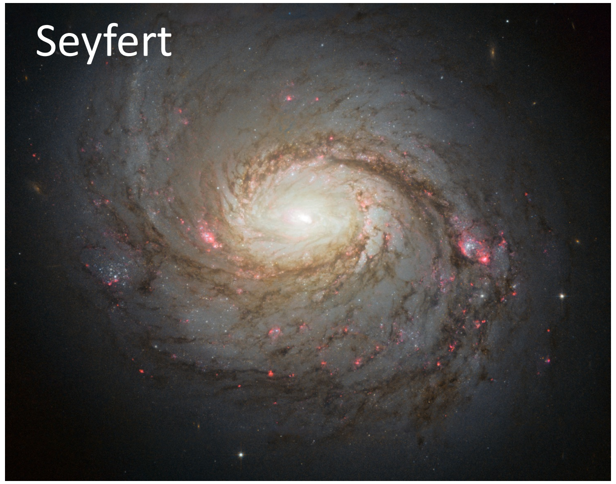
Outline

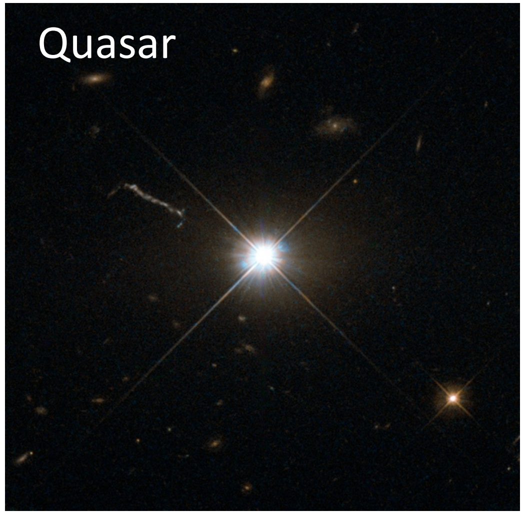
- AGN outflows: observations, properties, and physics
- AGN outflows as particle accelerators and gamma-ray and neutrino sources
- Multi-messenger emission from galactic and ultra fast outflows
- Application to NGC 1068 and multi-messenger implications

Two main classes: non-jetted and jetted AGN

Non-jetted AGN

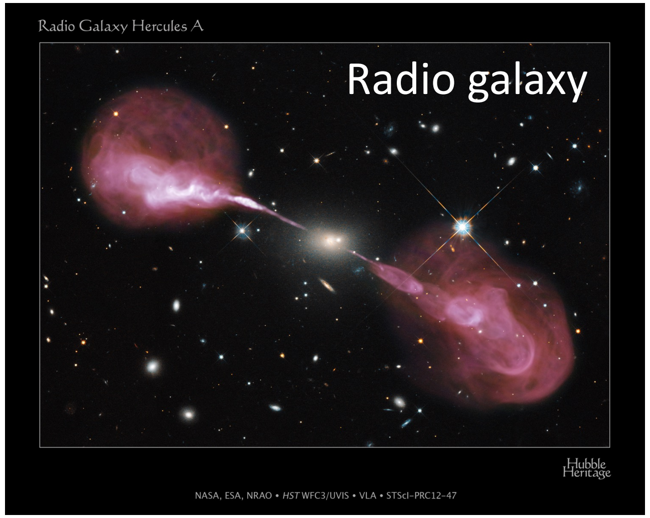
- Bulk of the AGN population (Seyfert, QSO).
- Multi-phase and multi-scale wide angle winds with velocities from a few thousands km/s up to mildly relativistic values.
- Electromagnetic emission dominated by UV-optical emission from the accretion disk and by X-ray emission from the corona.

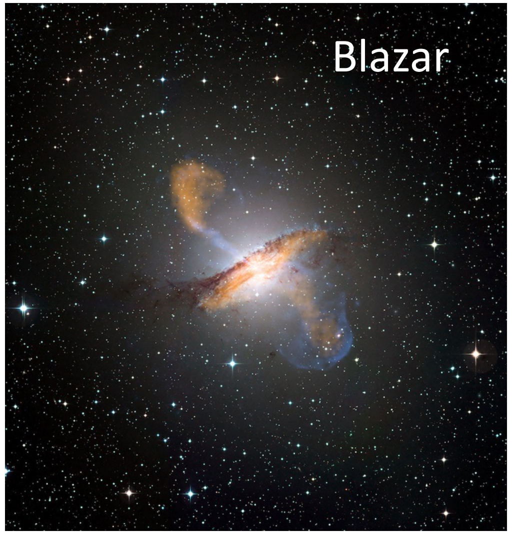




Jetted AGN

- ~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.

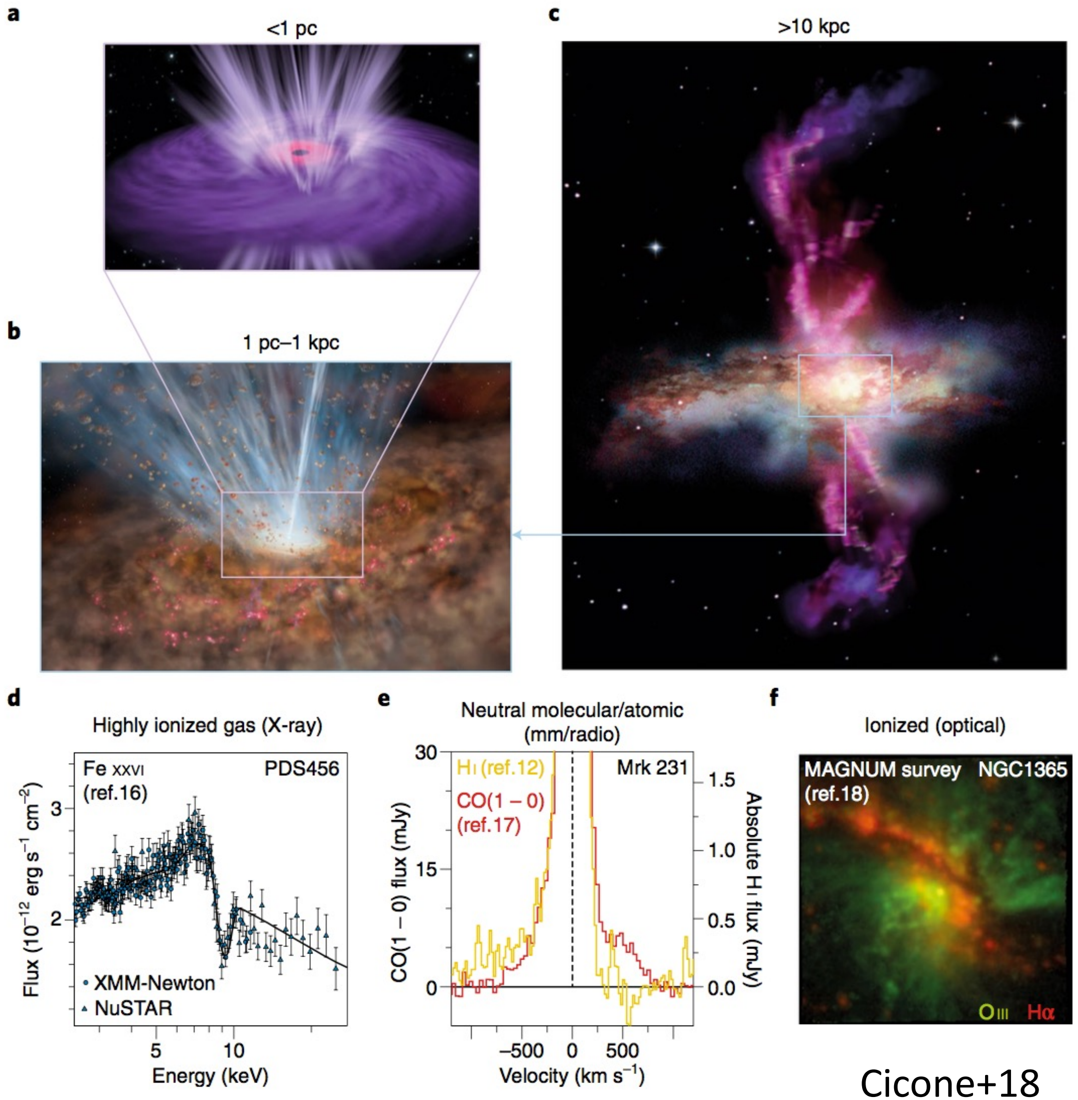




AGN outflows are multi-phase & multi-scale

AGN winds launched from the accretion disk by thermal, radiative, and magnetic processes

Winds from the central AGN propagate into the host galaxy



Winds are seen across the electromagnetic spectrum

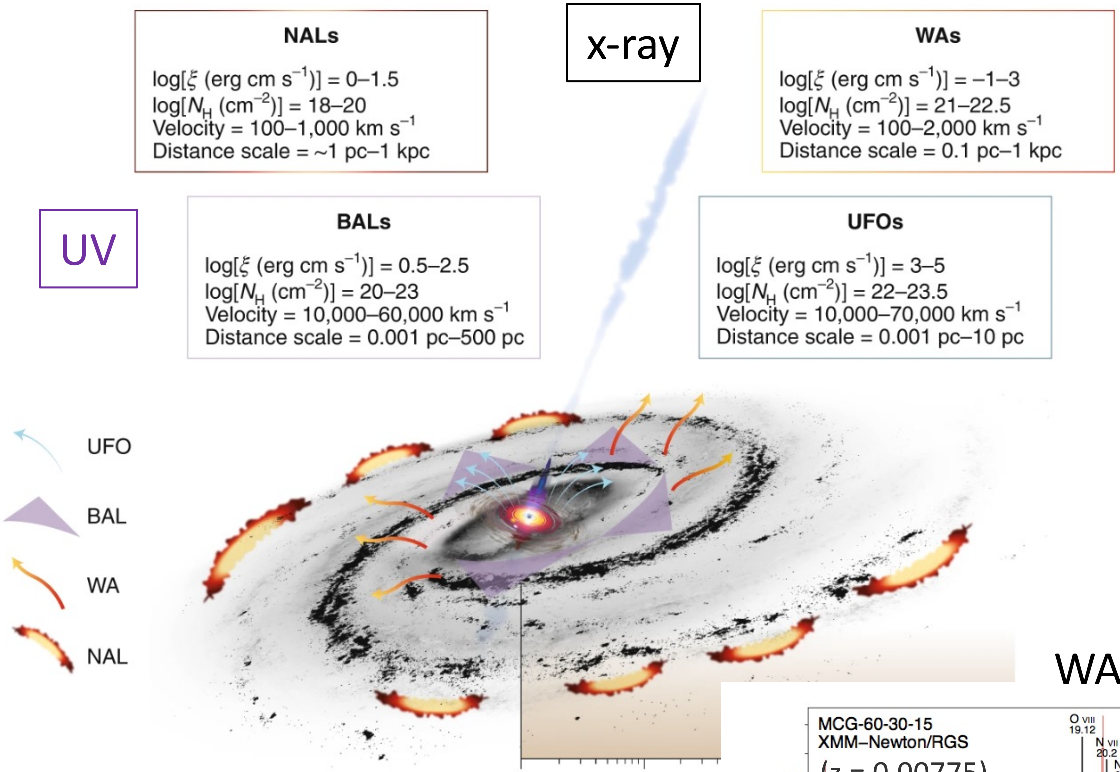
Different tracers probe different phases and different scales

Cicone+18

Nuclear disk winds

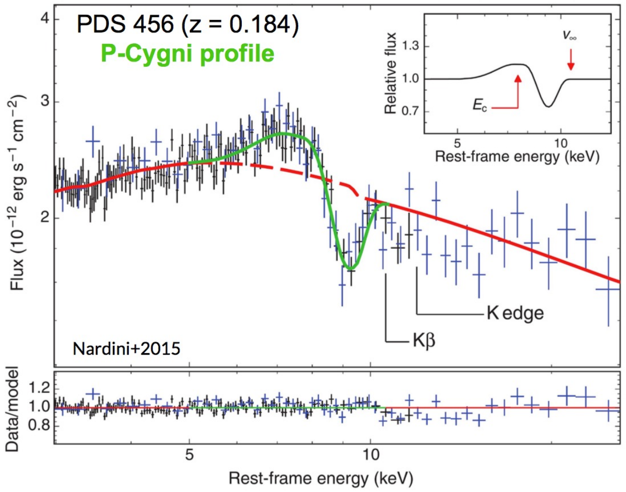
Inner to outer

1. UFO, WA
2. BAL, NAL

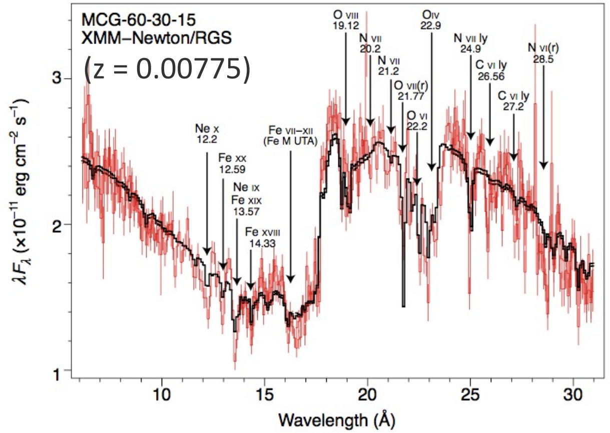


Laha 2021

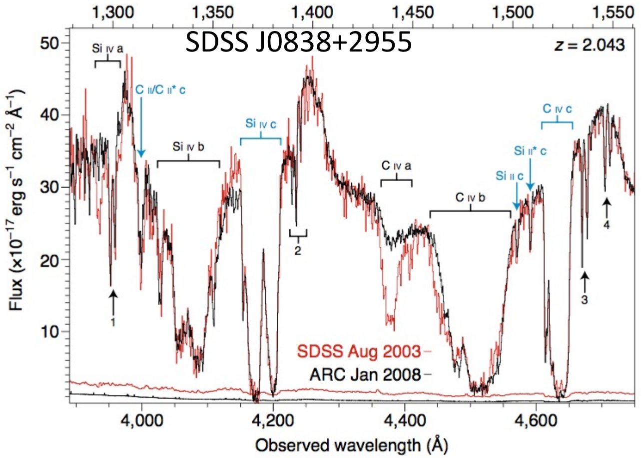
UFO



WA



BAL

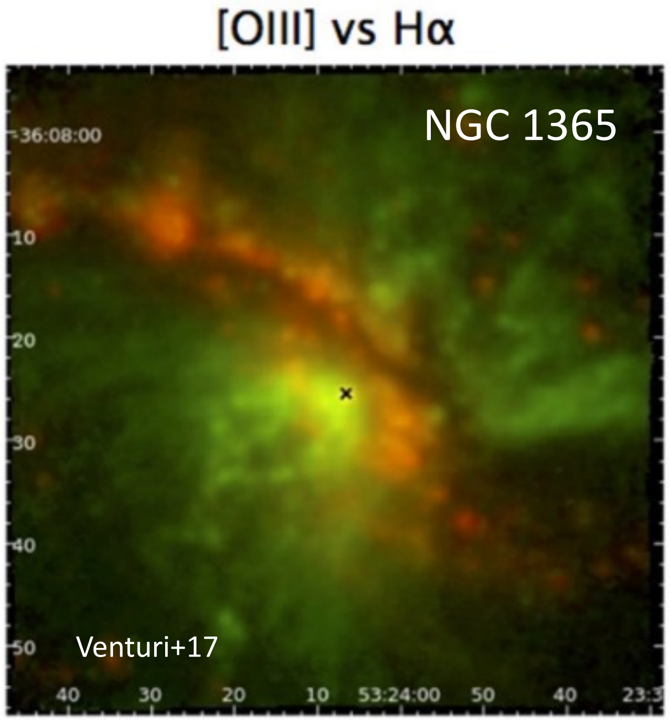


Galaxy scale outflows

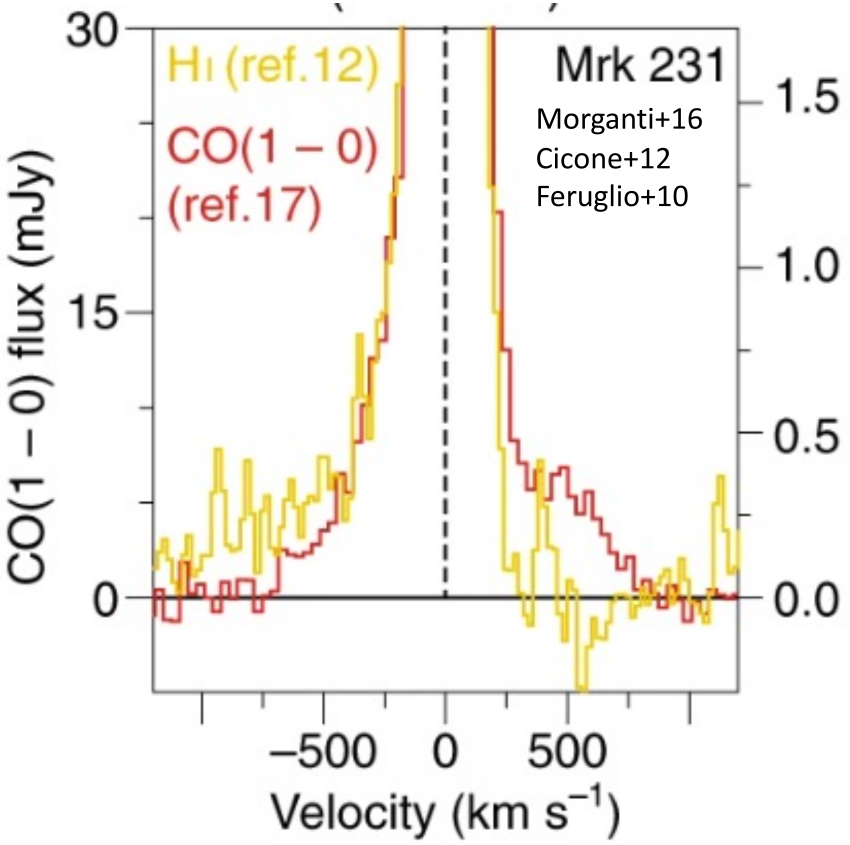
Inner to outer

1. UFO, WA
2. BAL, NAL
3. Ionized outflows ($v \simeq 10^3$ km/s)
4. Molecular/atomic gas outflows ($v \simeq 10^2$-10^3 km/s)

Ionized outflow

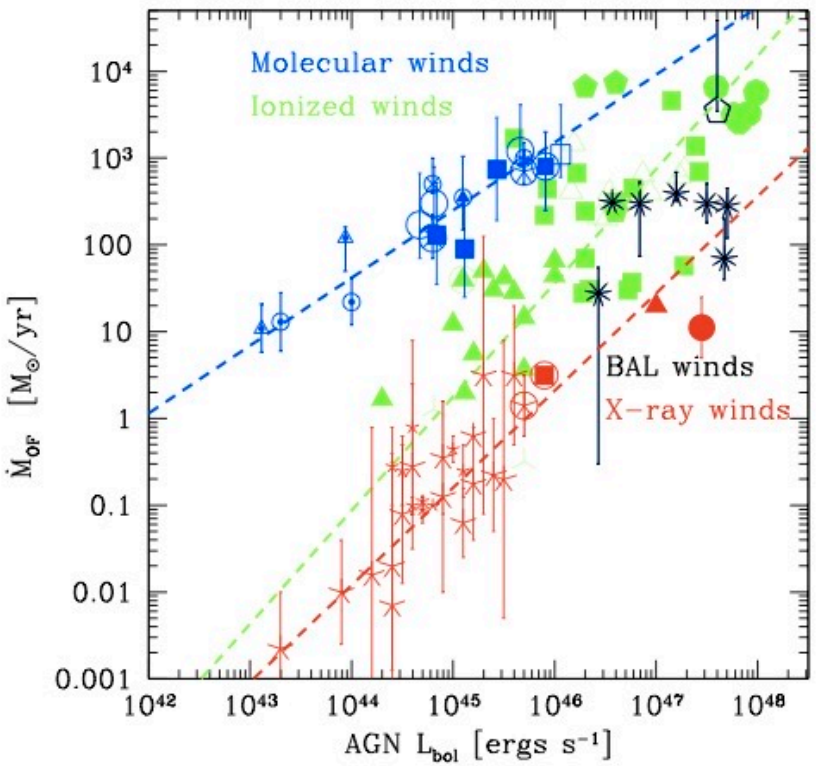


Neutral molecular/atomic outflow



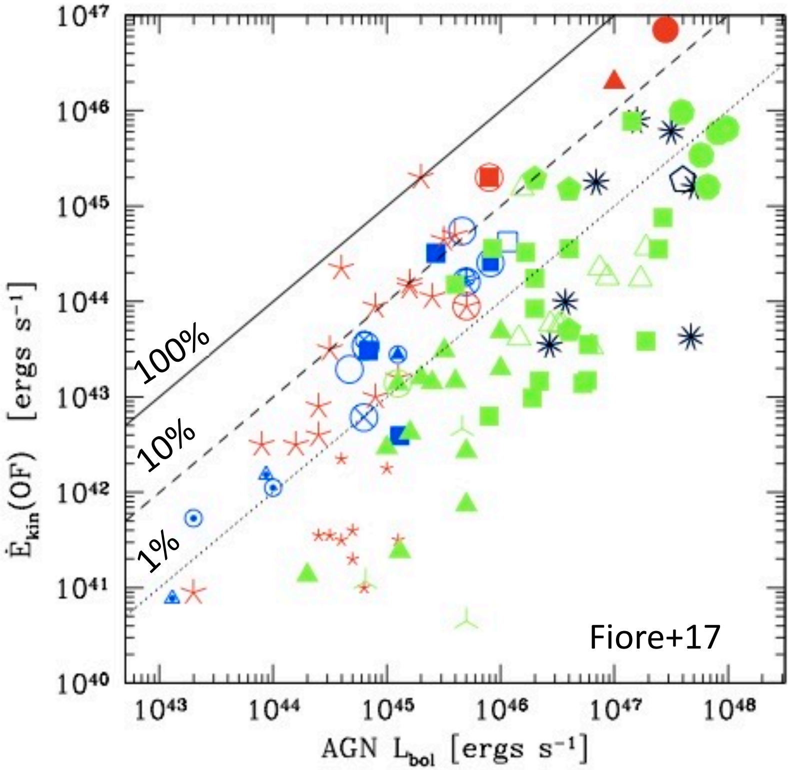
AGN outflow properties

Mass outflows rate
$\dot{M}_{OF} \propto M_{OF}V_{OF}/R$



All wind components correlate with L_{AGN}

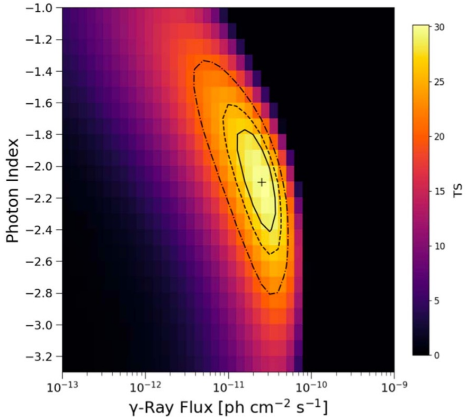
Kinetic power
$\dot{E}kin \propto \dot{M}_{OF}V^2_{OF}$



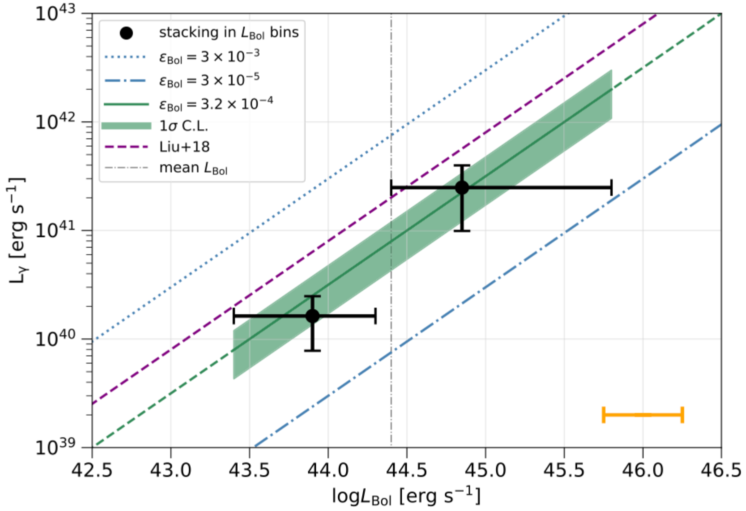
Outflow kinetic power consistent with prediction in AGN feedback models (few % of L_{AGN})

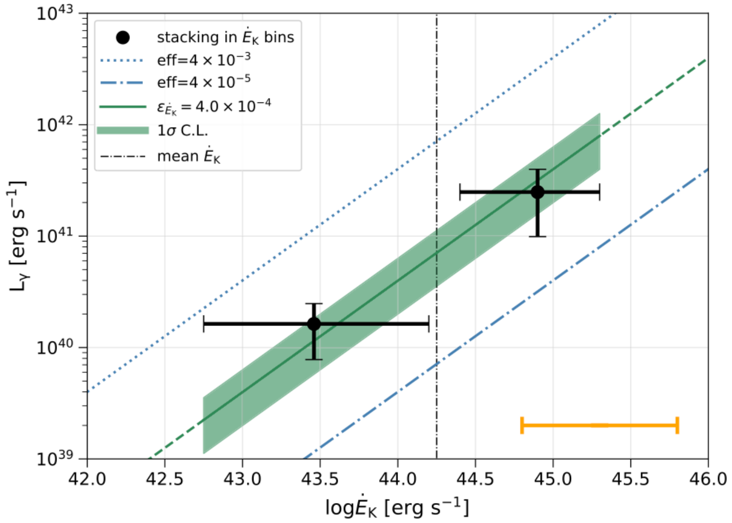
Gamma-rays from AGN outflows

Stacked Fermi-LAT analysis of 11 nearby (z<0.1) AGN with UFOs (Ajello+23)



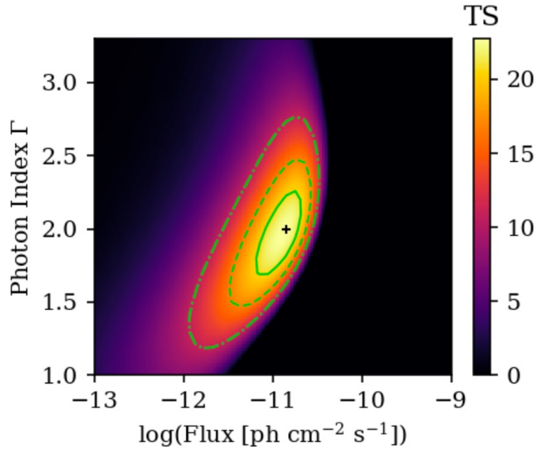
emission detected at 5.2 **σ**





The gamma-ray luminosity scales with the AGN bolometric luminosity and the UFO kinetic power

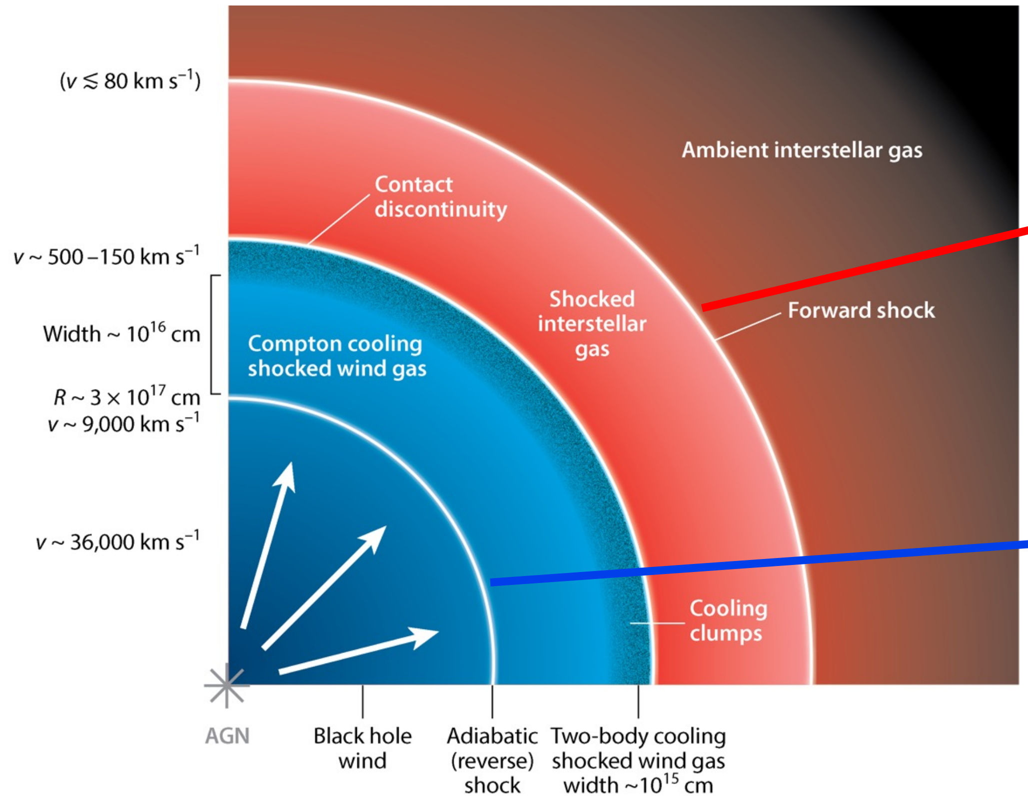
Stacked Fermi-LAT analysis of 45 nearby (z<0.2) galaxies with a molecular outflows (McDaniel+23)



emission detected at 4.4 **σ**

No correlation between the gamma-ray emission and the properties of the molecular outflow

Particle acceleration in AGN outflows



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

Particle acceleration at the forward shock (DSA)

- Rapid fall of acceleration efficiency in time
- Mach number dependent on the external medium

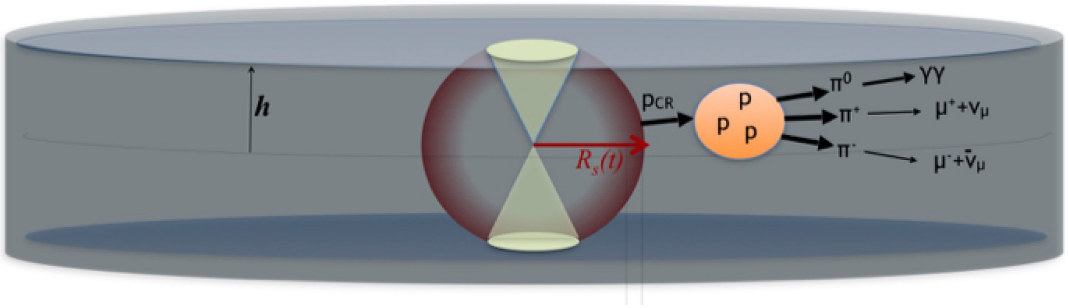
(Wang & Loeb 2016, Lamastra+16,17, Liu+18, Ajello+21)

Particle acceleration at the wind termination shock (DSA)

- fast cool plasma at the wind termination shock
- High Mach number and acceleration efficiency

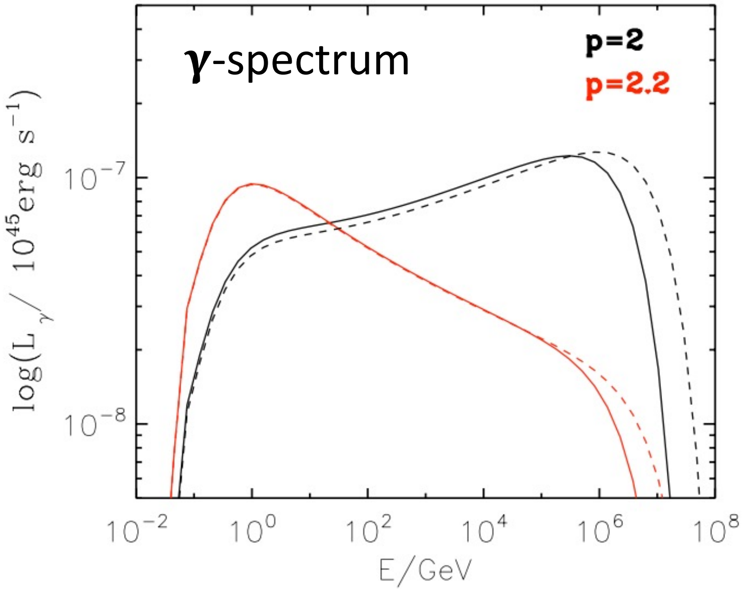
(Peretti, AL+23)

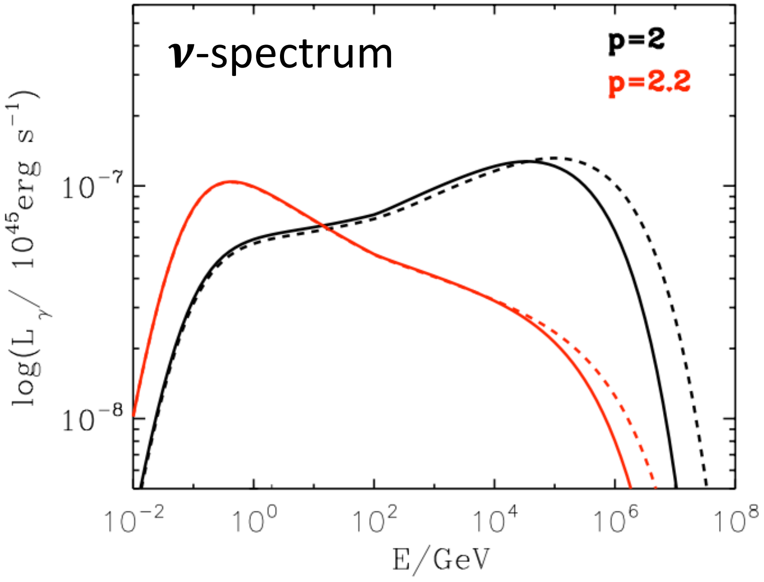
Forward shock model



wind shock (wind + host galaxy gas)

gamma-ray and neutrino emissions from pp interactions



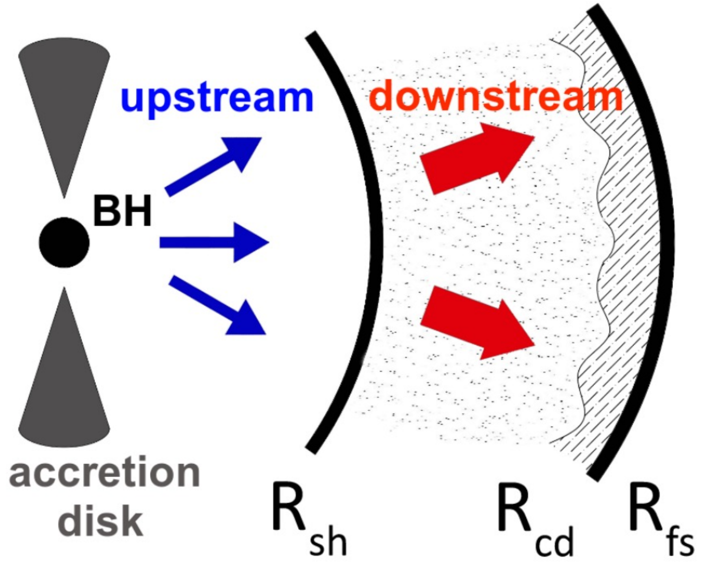


Molecular outflow parameters:
R_{fs} = 100 pc
v_{sh} = 200 Km/s
dM_{out}/dt=100 $M_\odot$/yr

AGN wind forward shocks predicted to be weak gamma-ray and neutrino emitters

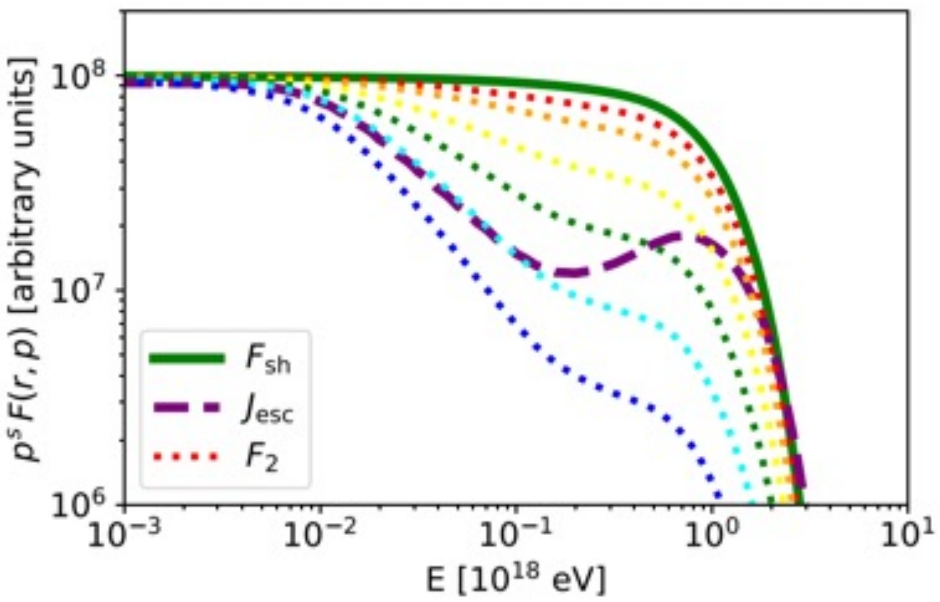
(Wang & Loeb 2016, Lamastra+16,17, Liu+18, Ajello+21)

Termination shock model



UFO parameters:
R_{sh} = 0.8 pc
v_{sh} = 6x10^4 km/s
dM_{out}/dt=0.1 $M_\odot$/yr

Particle spectrum



Acceleration-transport model

$$r^2 u(r)\partial_r f = \partial_r[r^2 D(r,p)\partial_r f] + \frac{1}{3}\partial_r[r^2 u(r)]p\partial_p f + r^2 Q(r,p) - r^2\Lambda(r,p)$$

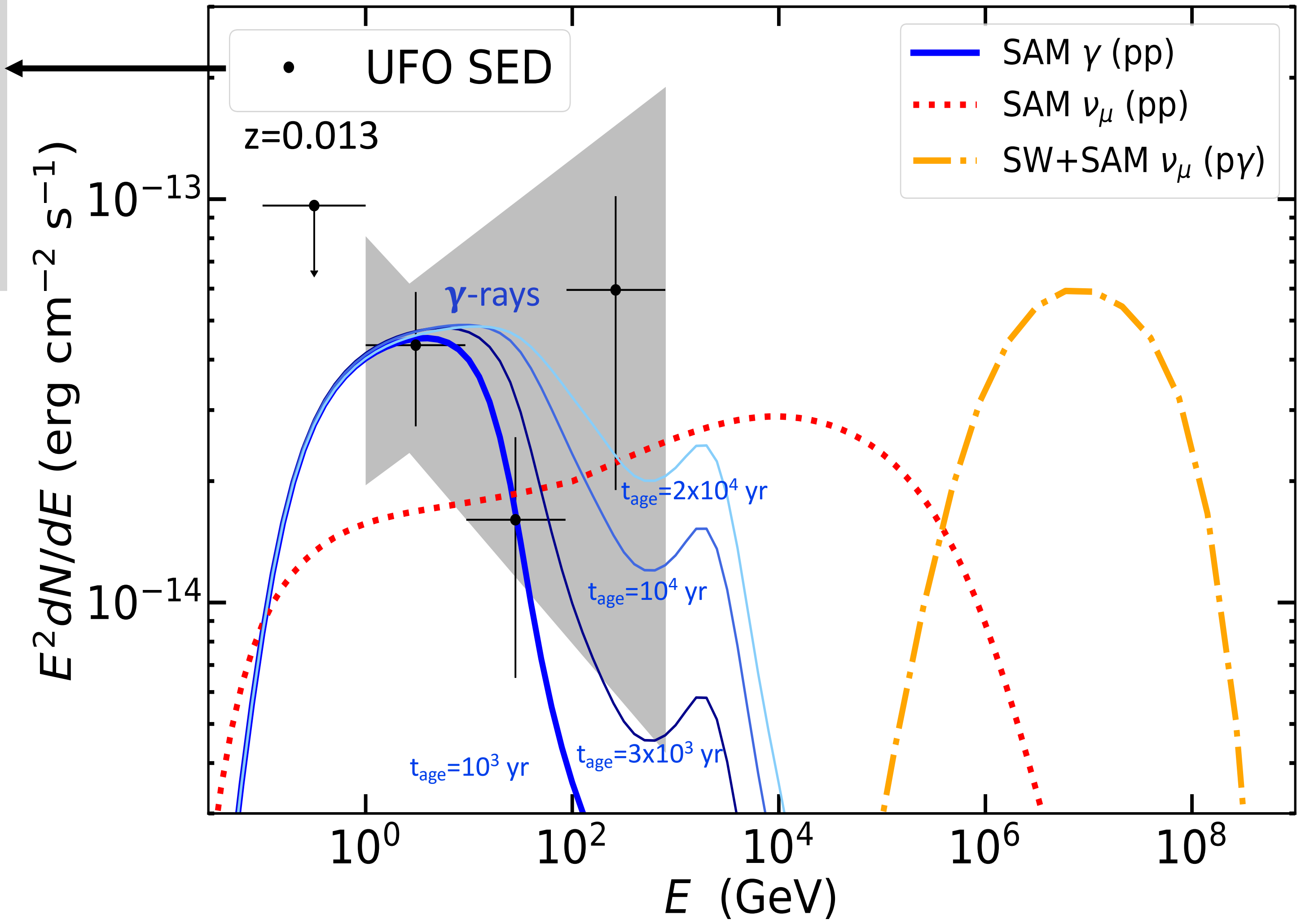
advection diffusion adiabatic losses injection pp and p$\boldsymbol{\gamma}$ losses

UFOs are potential accelerators of UHECRs in the EeV region

Multi-messenger emission from prototype UFO

Average gamma-ray UFO SED from stacking analysis of Fermi-LAT data of 11 nearby AGN with UFOs (Ajello+21)

Peretti, AL+23



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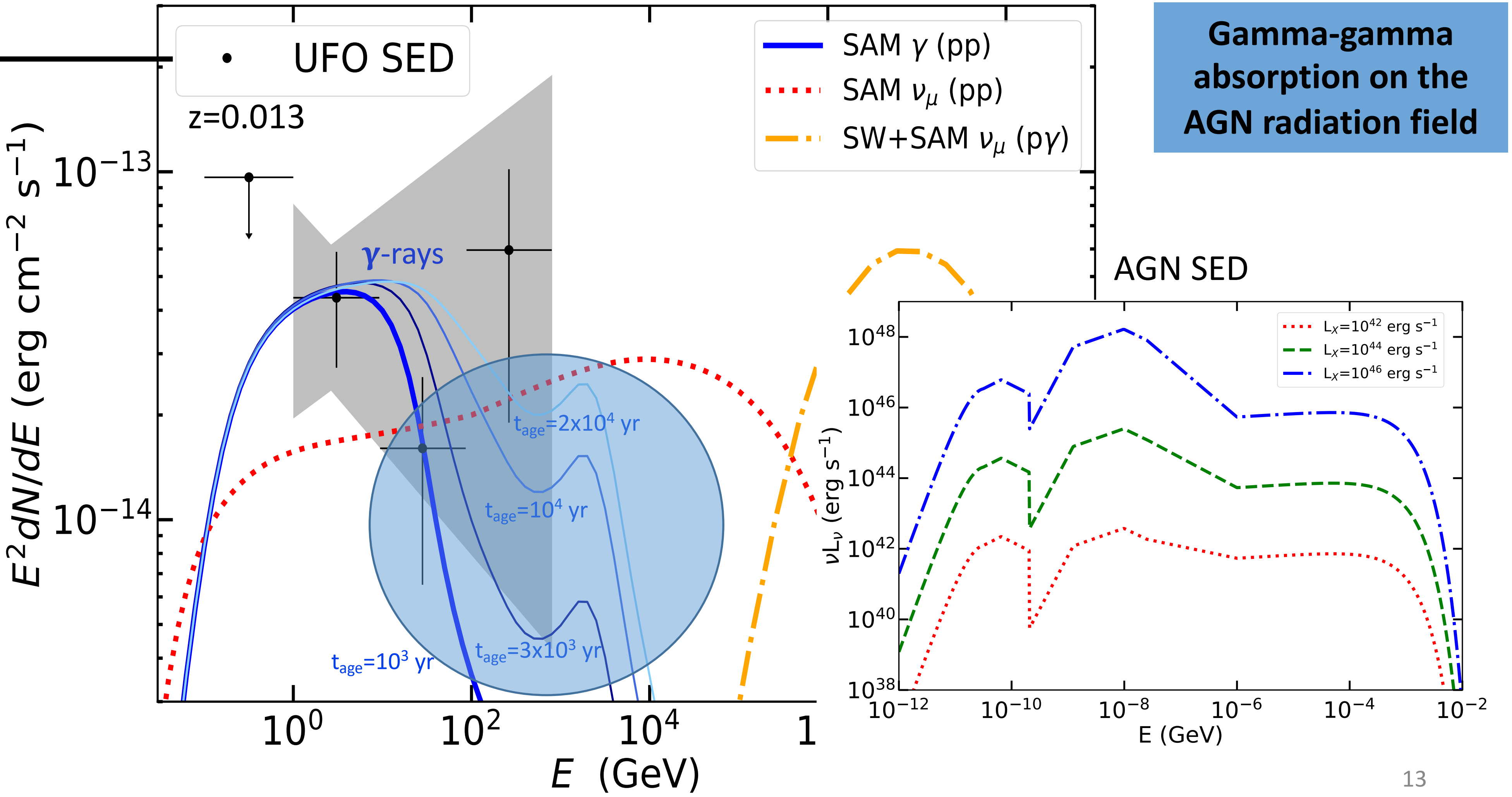
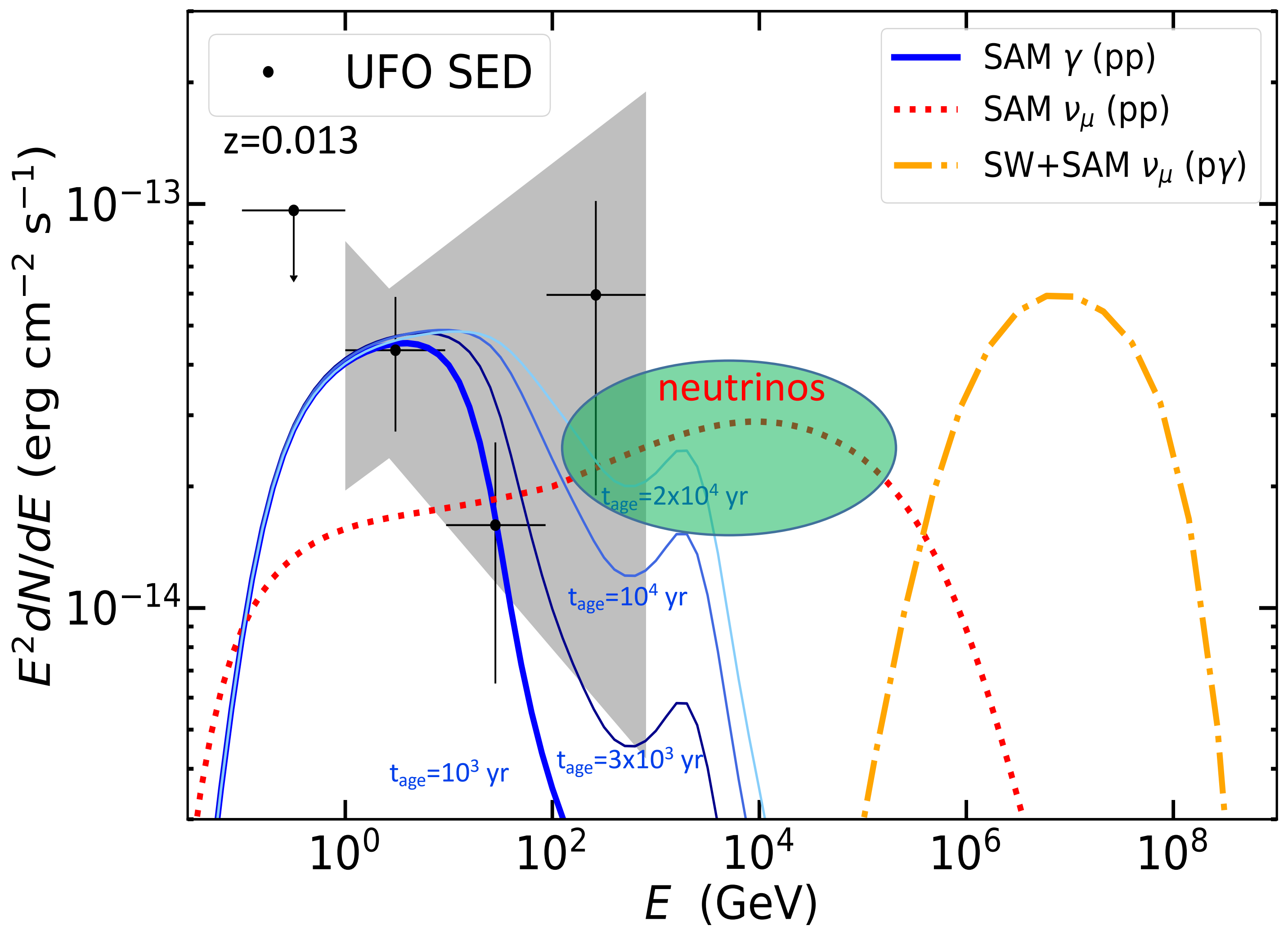


Gamma-gamma absorption on the AGN radiation field

Multi-messenger emission from prototype UFO

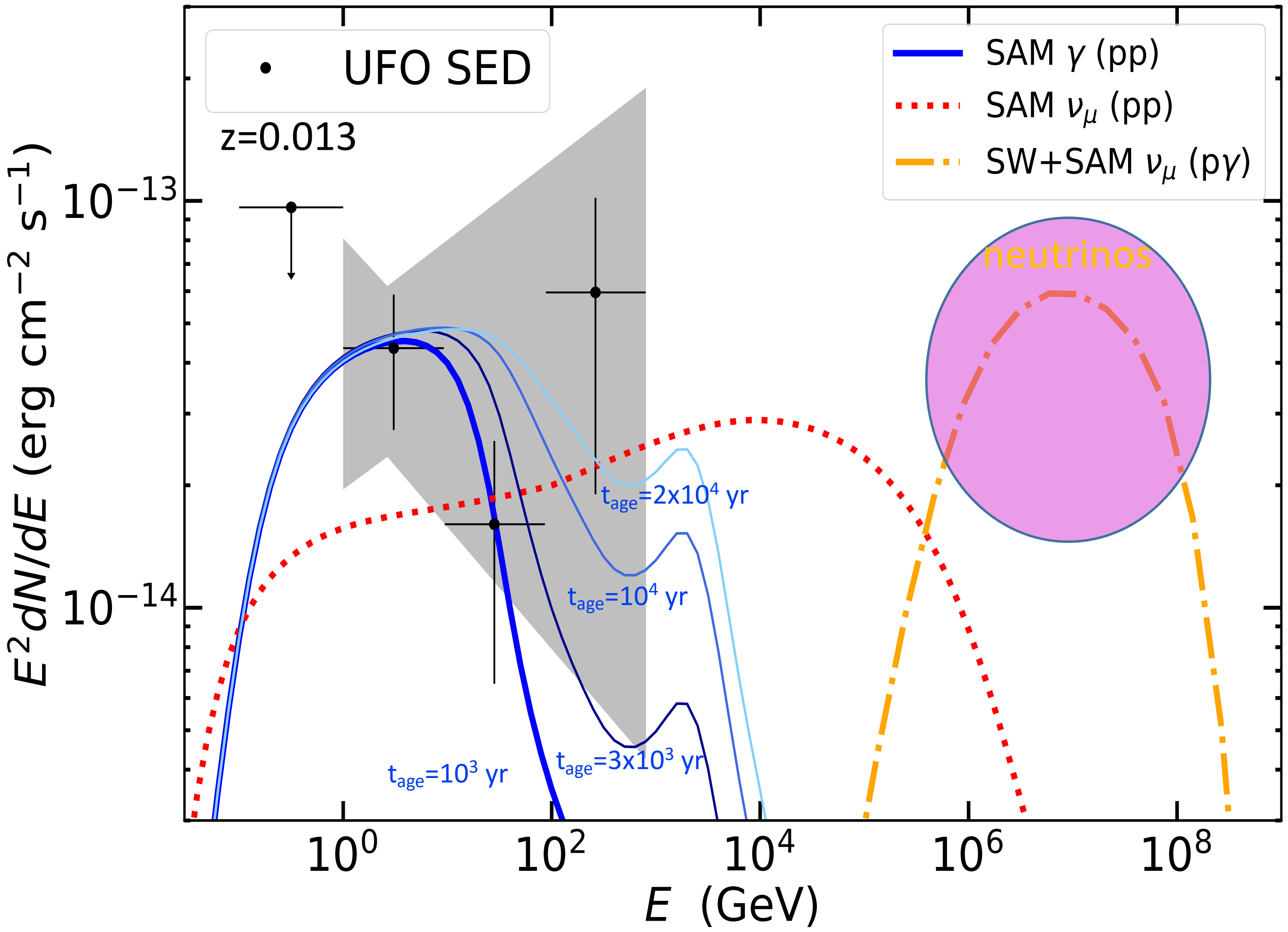
Peretti, AL+23



Tev neutrinos (pp) with partially absorbed gamma-ray counterpart

Multi-messenger emission from prototype UFO

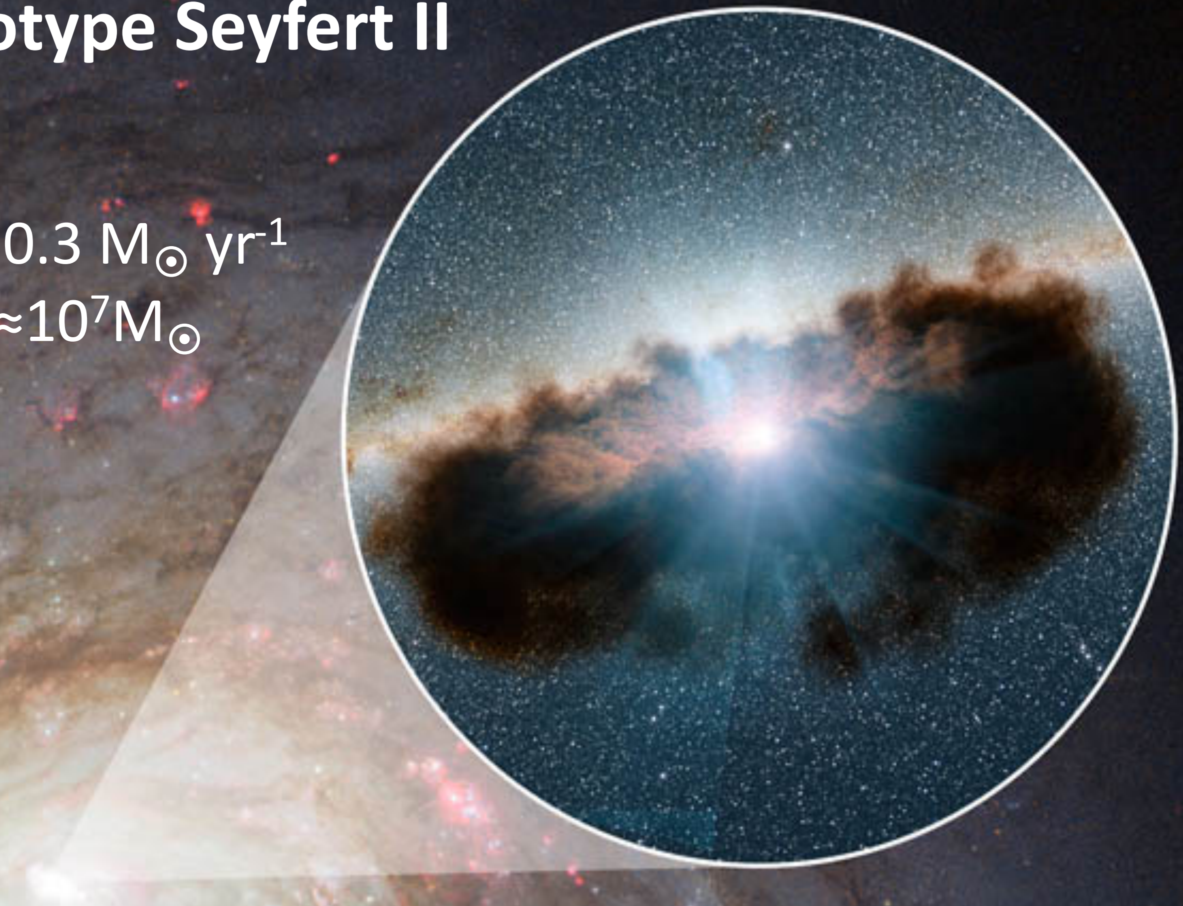
Peretti, AL+23



100 TeV - 100 PeV neutrinos (pγ) without gamma-ray counterpart

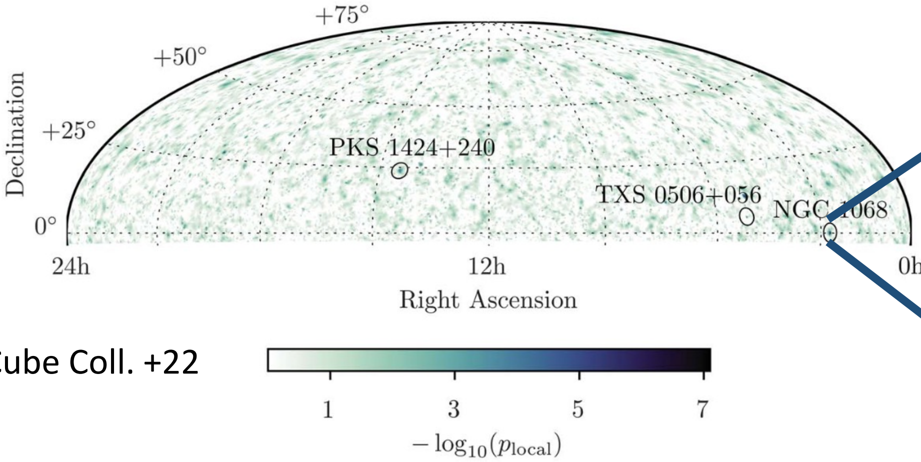
NGC 1068: The prototype Seyfert II

- Spiral galaxy at distance D=10.1±1.8 Mpc
- Star forming disk and starburst ring SFR=10.3 $M_\odot$ yr^{-1}
- Active nucleus powered by a SMBH of $M_{BH} \approx 10^7 M_\odot$
- 500 pc-scale weak jet (v<0.05 c)
- 200 pc-scale AGN-driven wind (molecular)
- Highly obscured AGN

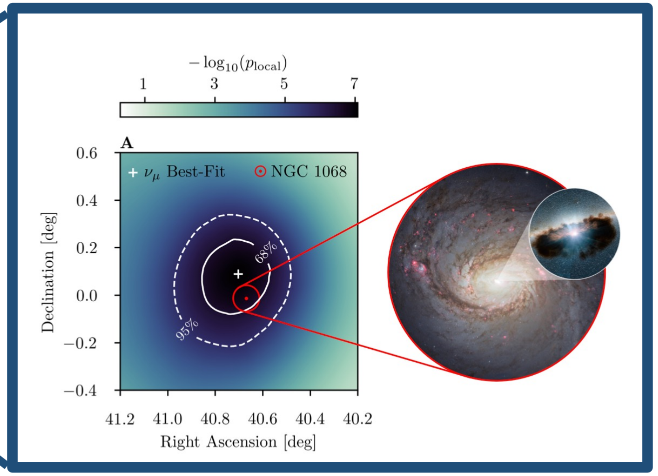


Credit: NASA, ESA & A. van der Hoeve

Evidence of neutrino emission from NGC 1068



IceCube Coll. +22



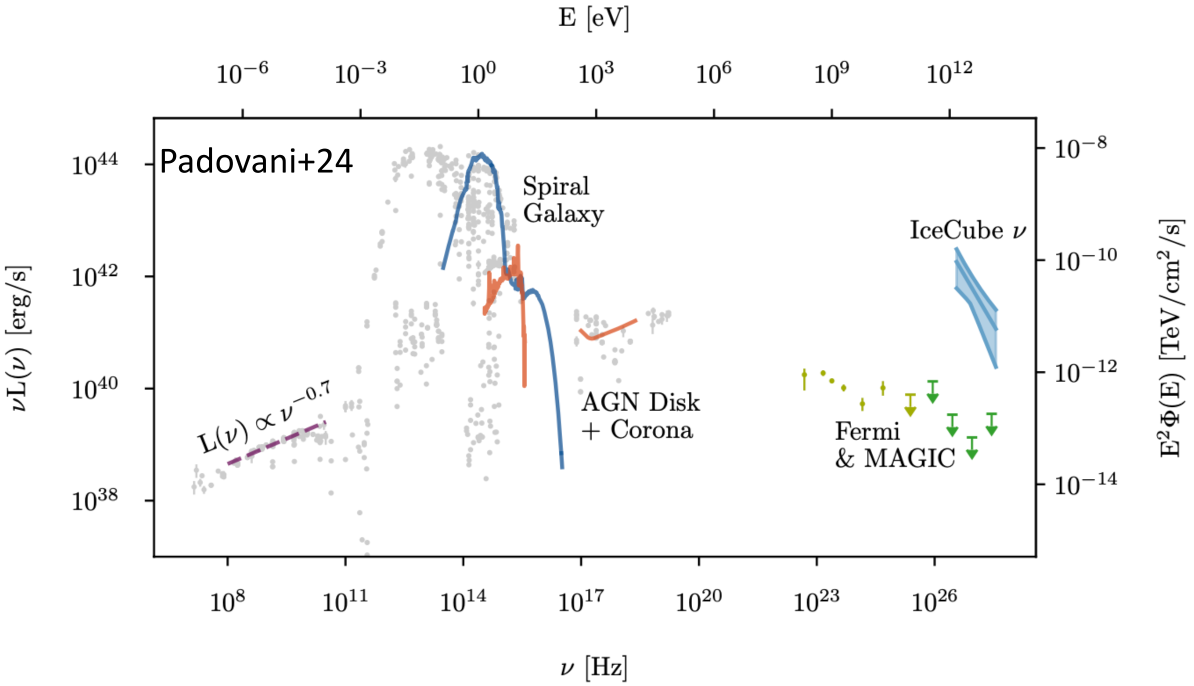
Global IceCube significance 4.2 **σ**

Astrophysical neutrino events = 79^{+22}_{-20}

Energy: (1.5 - 15.0) TeV

Flux: $\Phi_\nu = 5 \times 10^{-11} (E_\nu/\mathrm{TeV})^{-3.2}\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

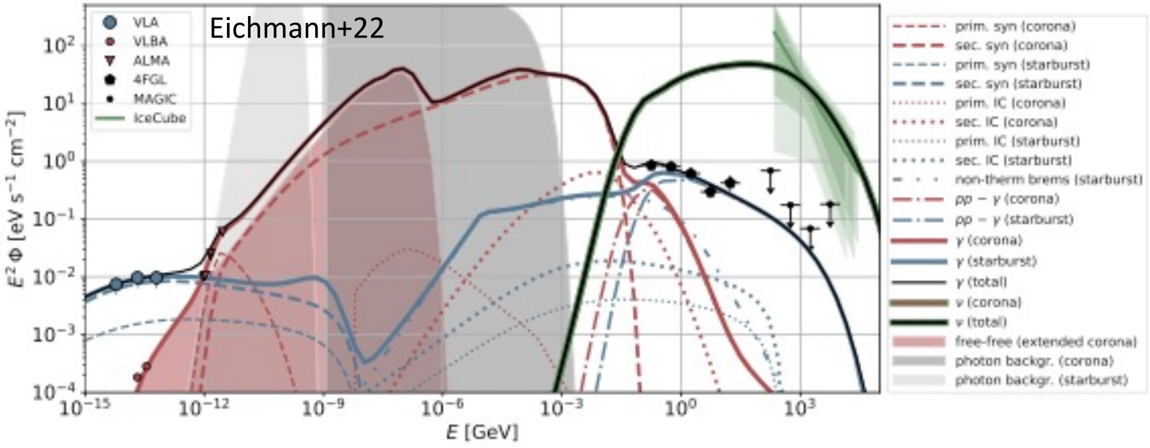
IceCube can't resolve the region of the neutrino production

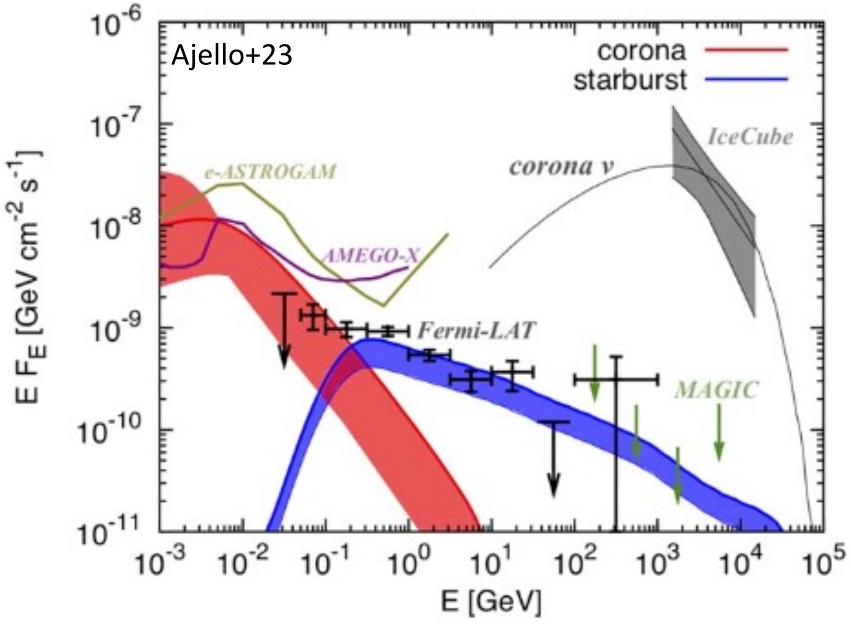


gamma-ray flux << neutrino flux => neutrino production site opaque to gamma-rays

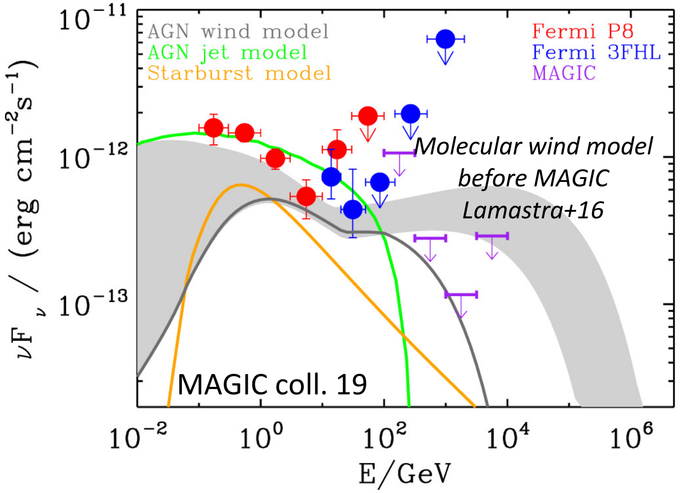
Gamma-rays from NGC 1068

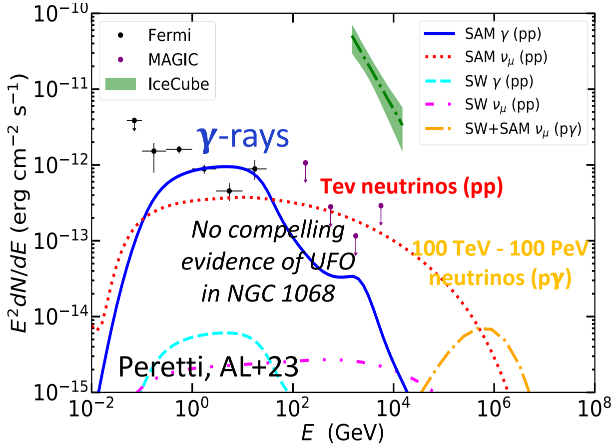
Starburst



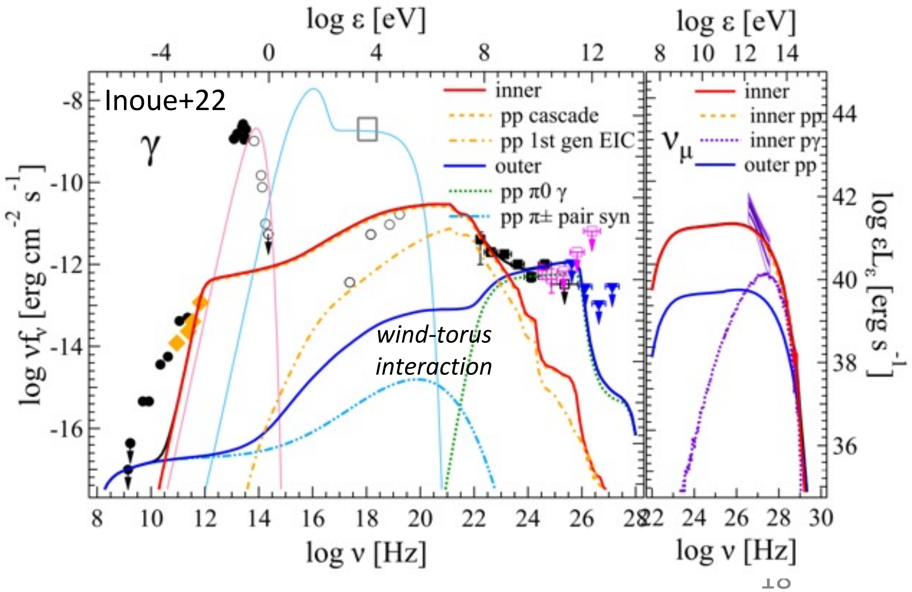


AGN outflow



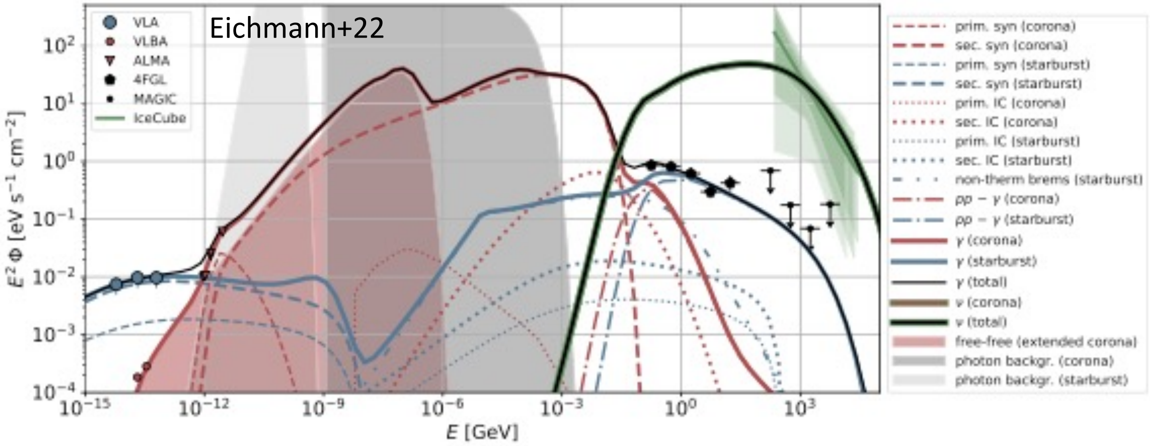


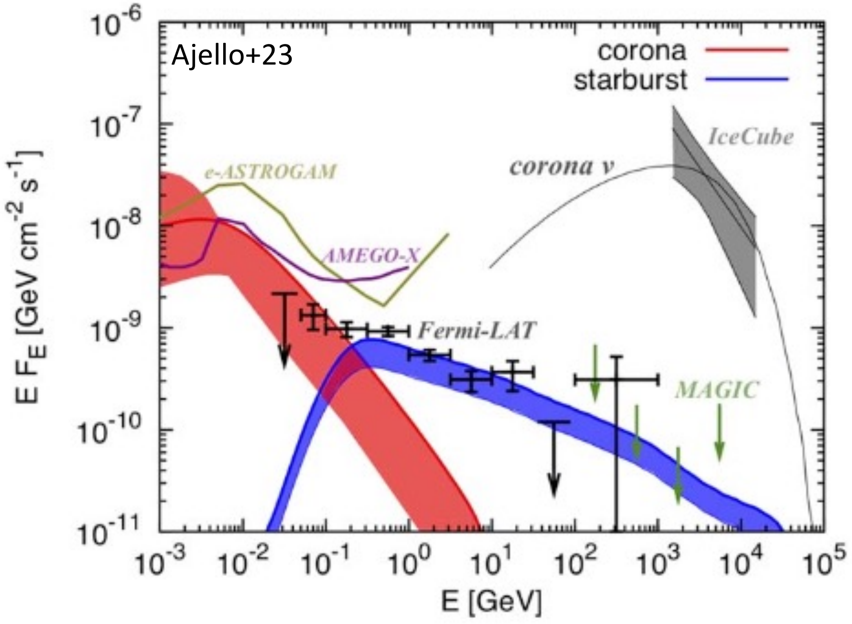
The starburst activity in the CND and in the SB ring appears as the most plausible regions for the production of gamma rays.
However, AGN-driven winds could contribute to the gamma-ray luminosity

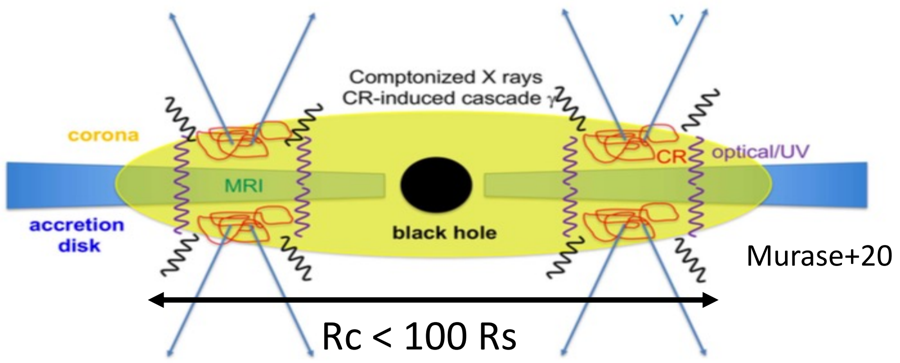


Gamma-rays and neutrinos from NGC 1068

Starburst + AGN corona







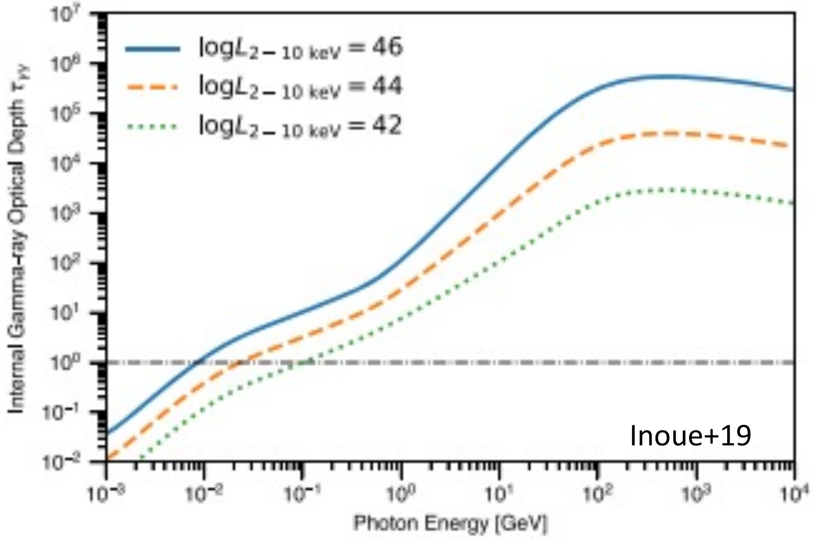
Region of hot ($T \simeq 10^9$ K) electrons which inverse Compton scatter the UV photons from the accretion disk and produce X-rays

p-γ (but also p-p) interaction

e.g., Ep ~ 100 TeV

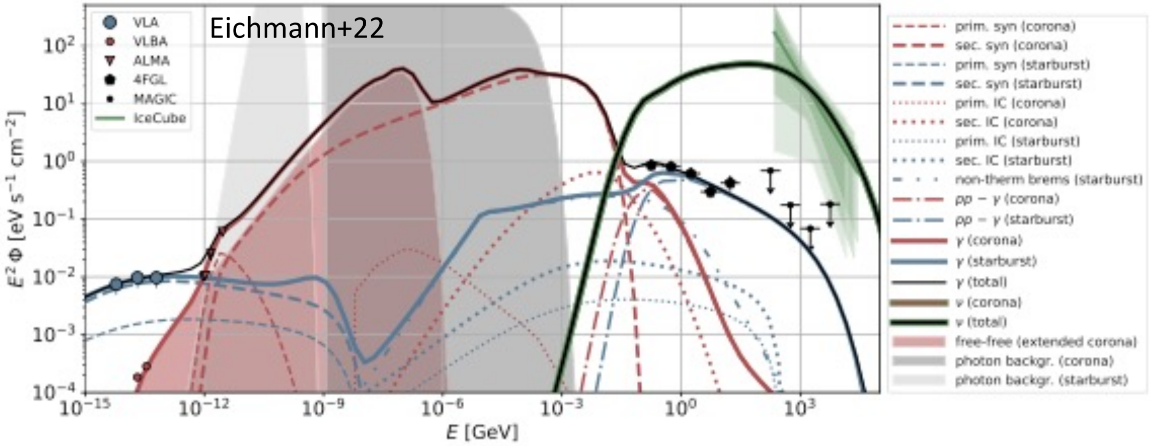
target γ ~ X-ray domain

γγ→e^+e^- optical depth

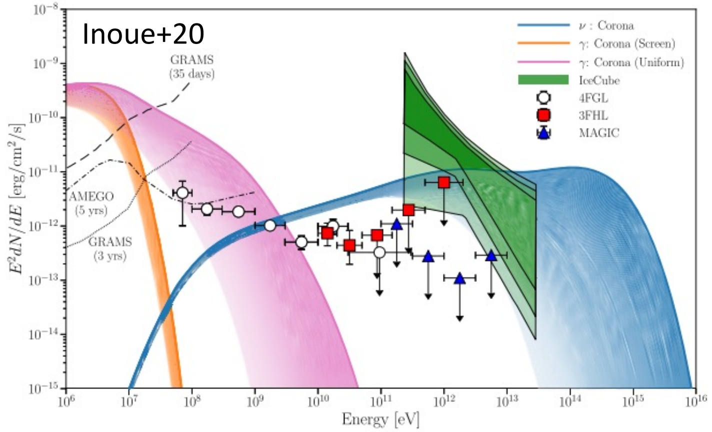


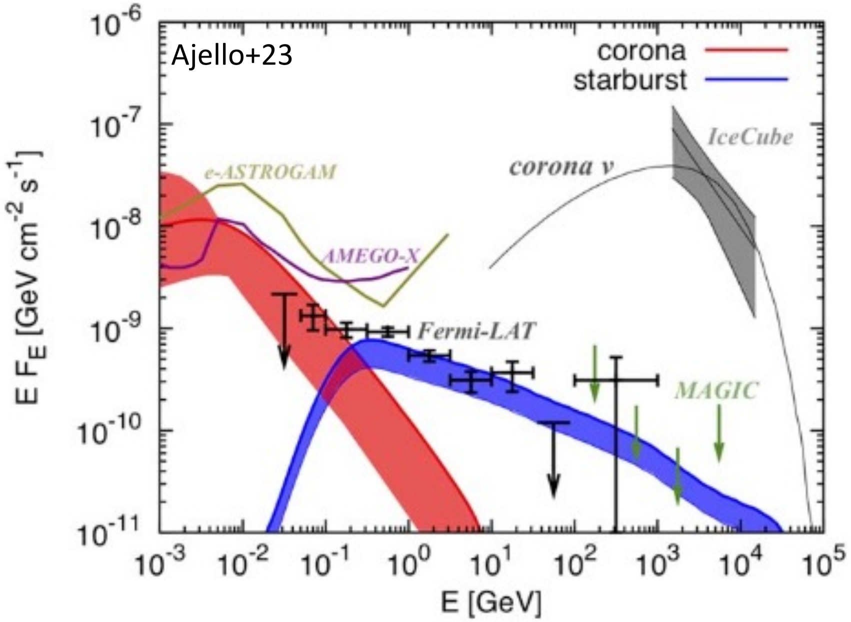
Gamma-rays and neutrinos from NGC 1068

Starburst + AGN corona

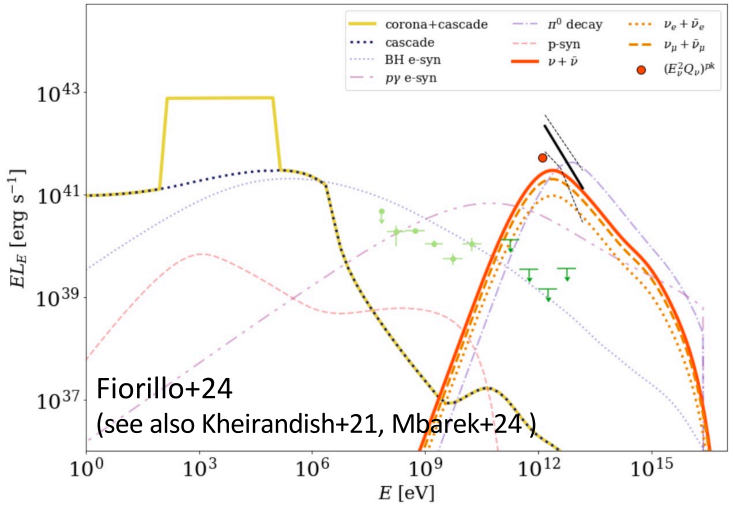


Diffusive shock acceleration

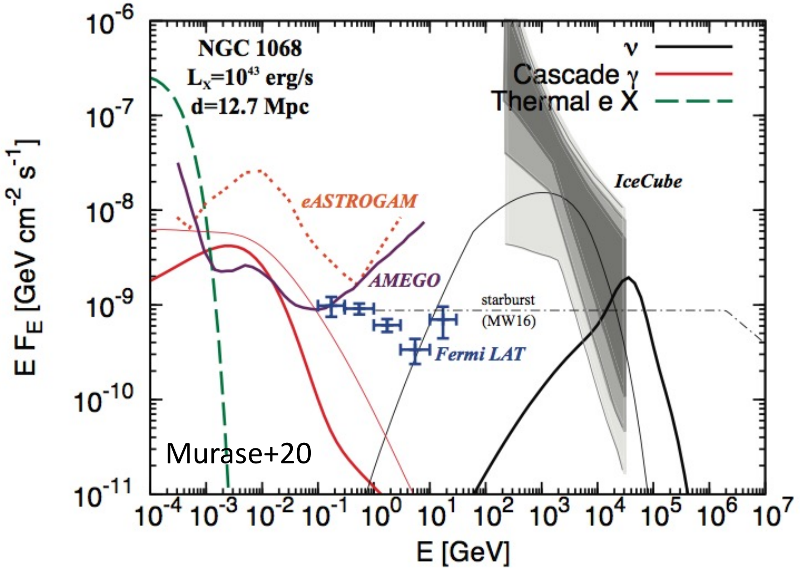




Magnetic reconnection



Stochastic acceleration in turbulence



The electromagnetic counterpart of the neutrino emission is in the MeV band

Summary

- Outflows in non-jetted AGN are potential particle accelerators (up to EeV in UFO) and gamma-ray and neutrino sources.
- Multi-messenger observations of NGC 1068 point to the region near the SMBH (possibly the AGN corona) as the environment where IceCube neutrinos are produced. The neutrino emission is not related to the gamma-ray emission. In order to reveal the sites and mechanisms of GeV-TeV gamma-rays, observations with lower energy threshold and higher sensitivity are necessary (**CTAO**).
- The electromagenic counterpart of the neutrino emission is predicted in the MeV band. Future MeV missions are of paramount importance to test the AGN corona scenario.

➢ We need to search for and study other neutrino-Seyfert candidates with current and next generation neutrino and gamma-ray telescopes. Promising targets: NGC 4151, NGC 3079, CGCG 420-015 *(Neronov+24, Abbasi+24).*

Thanks for your attention!