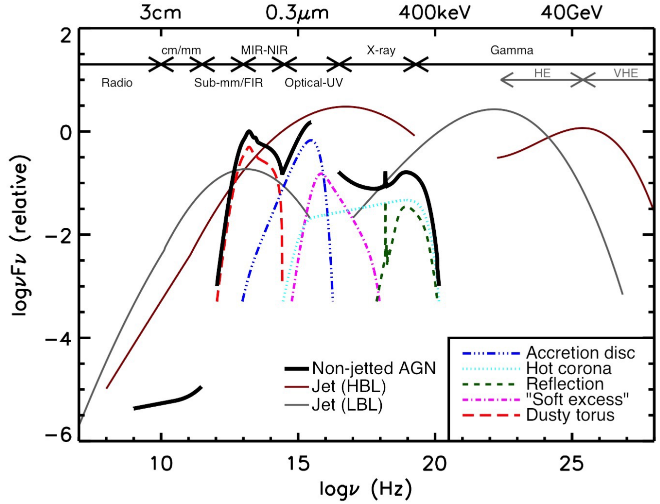
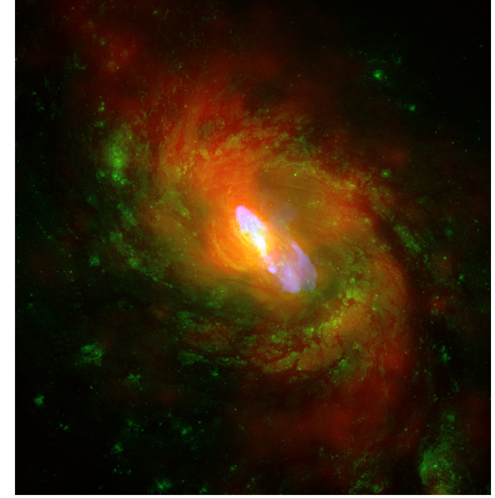




A multi-messenger view of NGC 1068*

Paolo Padovani, European Southern Observatory, Garching bei München, Germany

- Main properties of the prototype Seyfert II galaxy
- From the radio to the γ-ray bands: the various relevant components
- Putting it all together: the possible source of neutrino emission

*partly based on PP et al., Nature Astronomy, in prep.

NGC 1068: the prototype Seyfert II

NUCLEAR EMISSION IN SPIRAL NEBULAE*

CARL K. SEYFERT†

ABSTRACT

Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest spirals observed, NGC 1068 and NGC 4151.

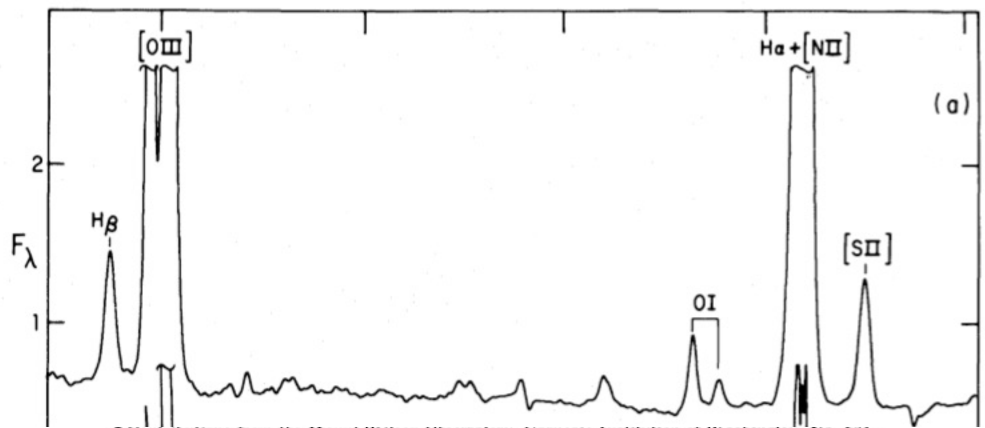
tensities. Color temperatures of the continua of each spiral were determined for this purpose.

The observed relative intensities of the emission lines exhibit large variations from nebula to nebula. Profiles of the emission lines show that all the lines are broadened, presumably by Doppler motion, by amounts varying up to 8500 km/sec for the total width of the hydrogen lines in NGC 3516 and NGC 7469. The hydrogen lines in NGC 4151 have relatively narrow cores with wide wings, 7500 km/sec in total breadth. Similar wings are found for the Balmer lines in NGC 7469. The lines of the other ions show no evidence of wide wings. Some of the lines exhibit strong asymmetries, usually in the sense that the violet side of the line is stronger than the red.

In NGC 7469 the absorption K line of *Ca* II is shallow and 50 A wide, at least twice as wide as in normal spirals.

Absorption minima are found in six of the stronger emission lines in NGC 1068, in one line in NGC 4151, and one in NGC 7469. Evidence from measures of wave length and equivalent widths suggests that these absorption minima arise from the G-type spectra on which the emissions are superposed.

The maximum width of the Balmer emission lines seems to increase with the absolute magnitude of the nucleus and with the ratio of the light in the nucleus to the total light of the nebula. The emission lines in the brightest diffuse nebulae in other extragalactic objects do not appear to have wide emission lines similar to those found in the nuclei of emission spirals.



* *Contributions from the Mount Wilson Observatory, Carnegie Institution of Washington*, No. 671.

† Fellow of the National Research Council.

[1] *Lick Obs. Bull.*, **19**, 33, 1939.

[2] NGC 1068, 1275, 2782, 3077, 3227, 3516, 4051, 4151, 4258, 5548, 6814, and 7469.

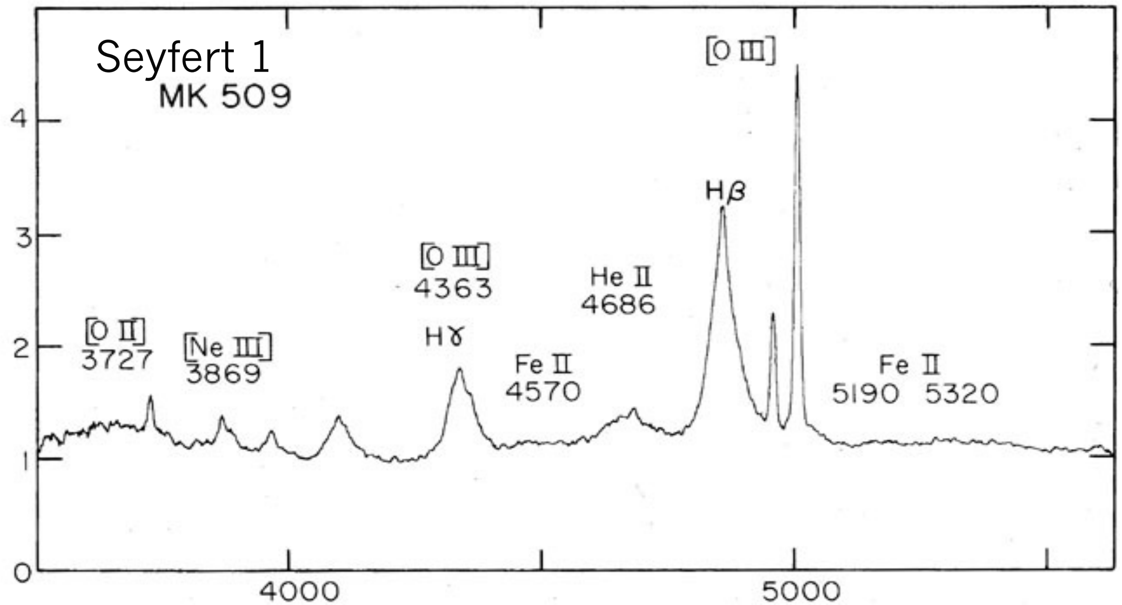
[3] *Lick Obs. Bull.*, **5**, 71, 1908.

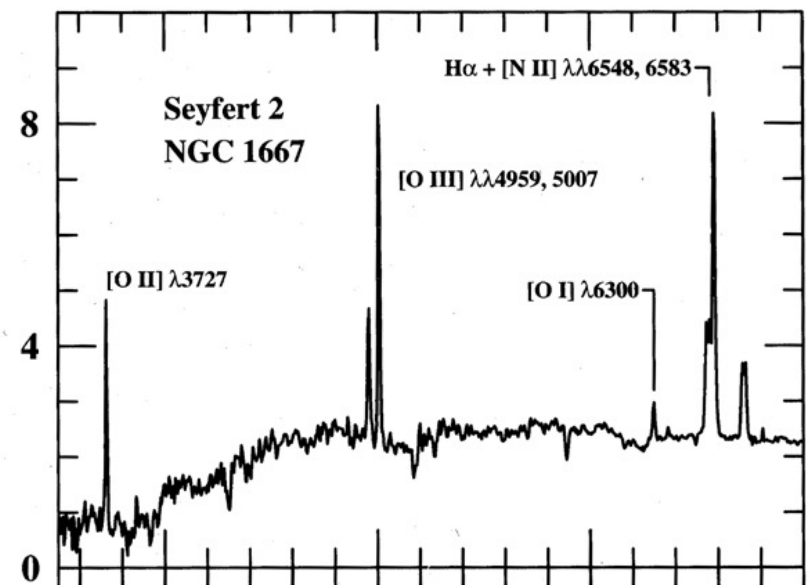
[4] *Pop. Astr.*, **25**, 36, 1917; *Proc. Amer. Phil. Soc.*, **56**, 403, 1917.

[5] *Lowell Obs. Bull.*, **3**, 59, 1917. [6] *Lick Obs. Pub.*, **13**, 88, 1918.

28

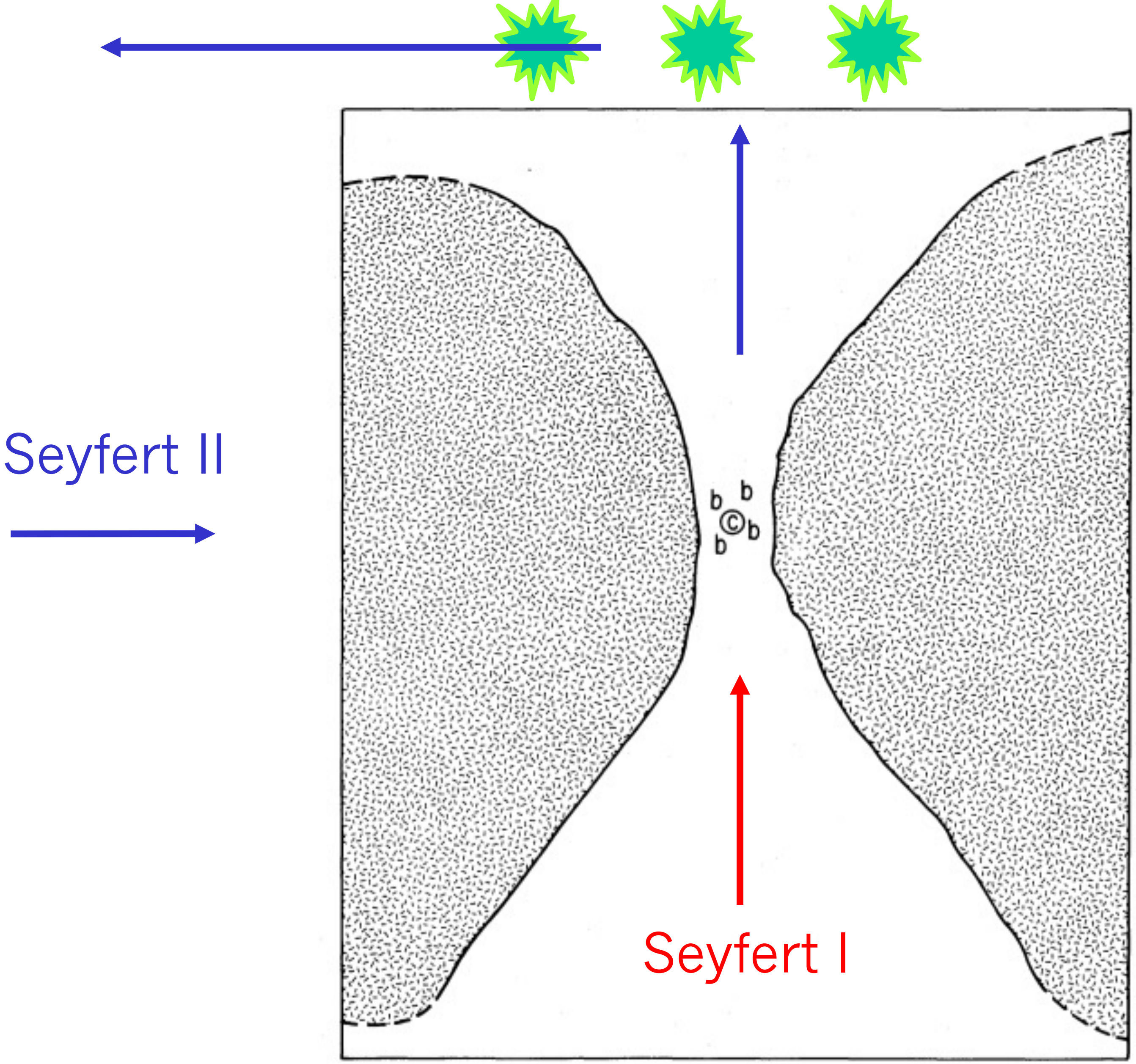
Seyfert I's and II's



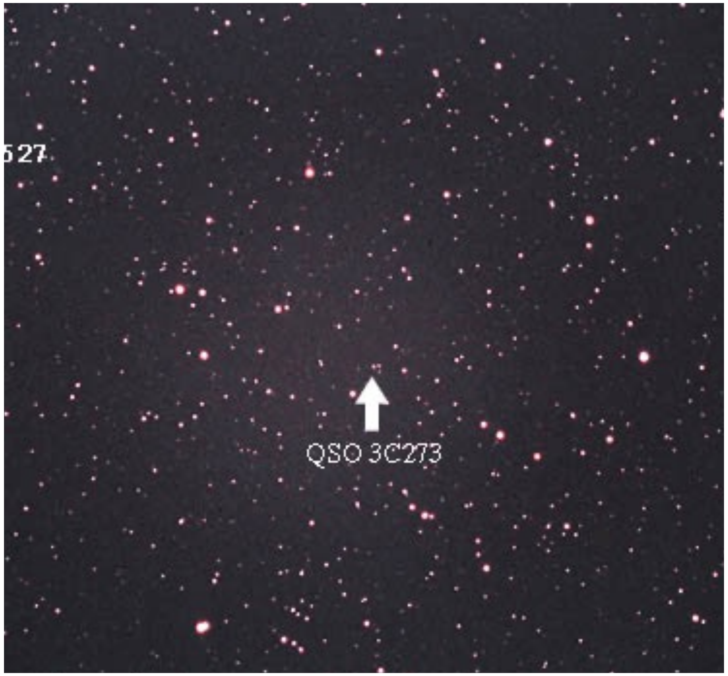


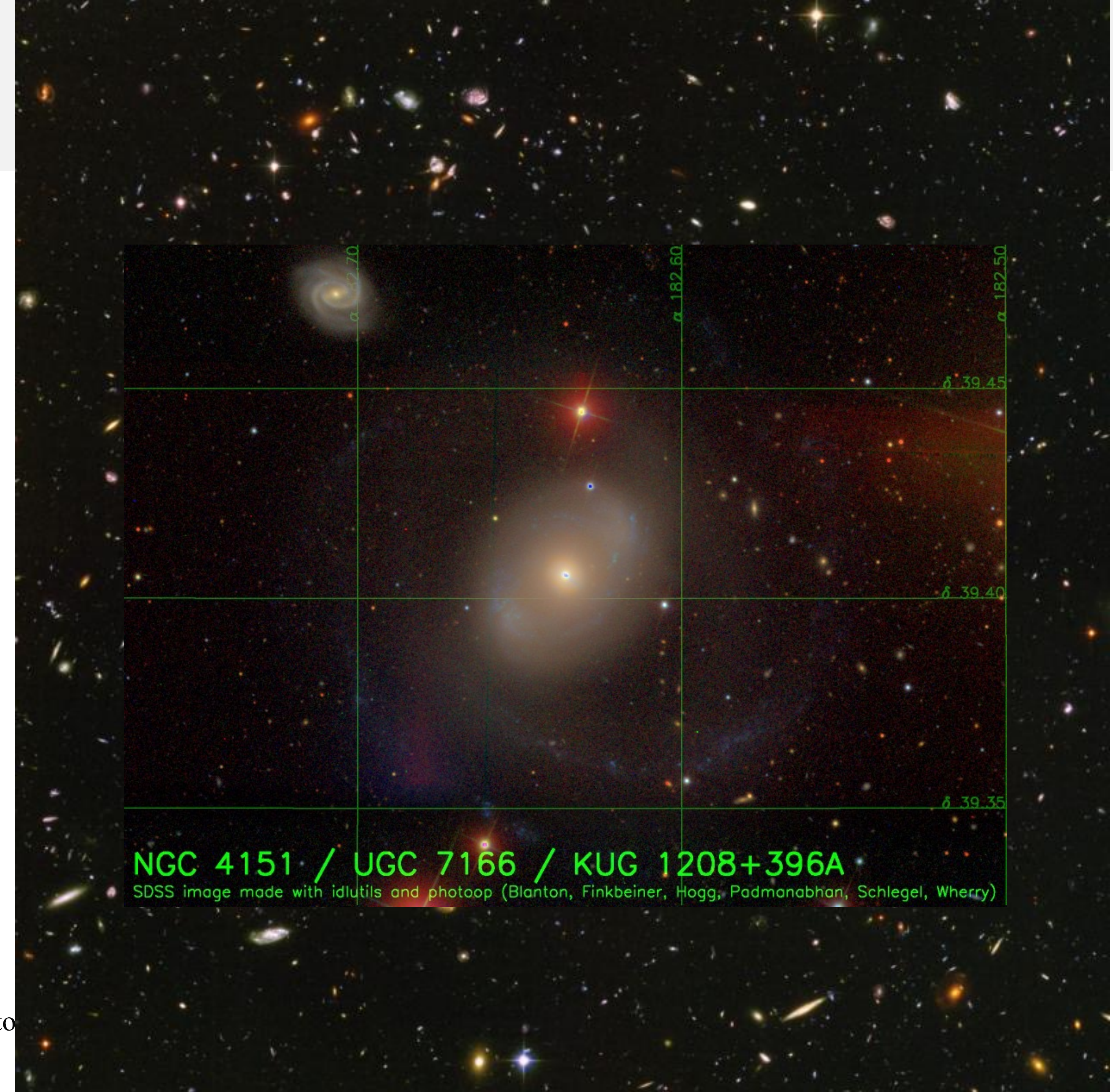
Narrow lines:
full width at half maximum
< 1,000 km/s

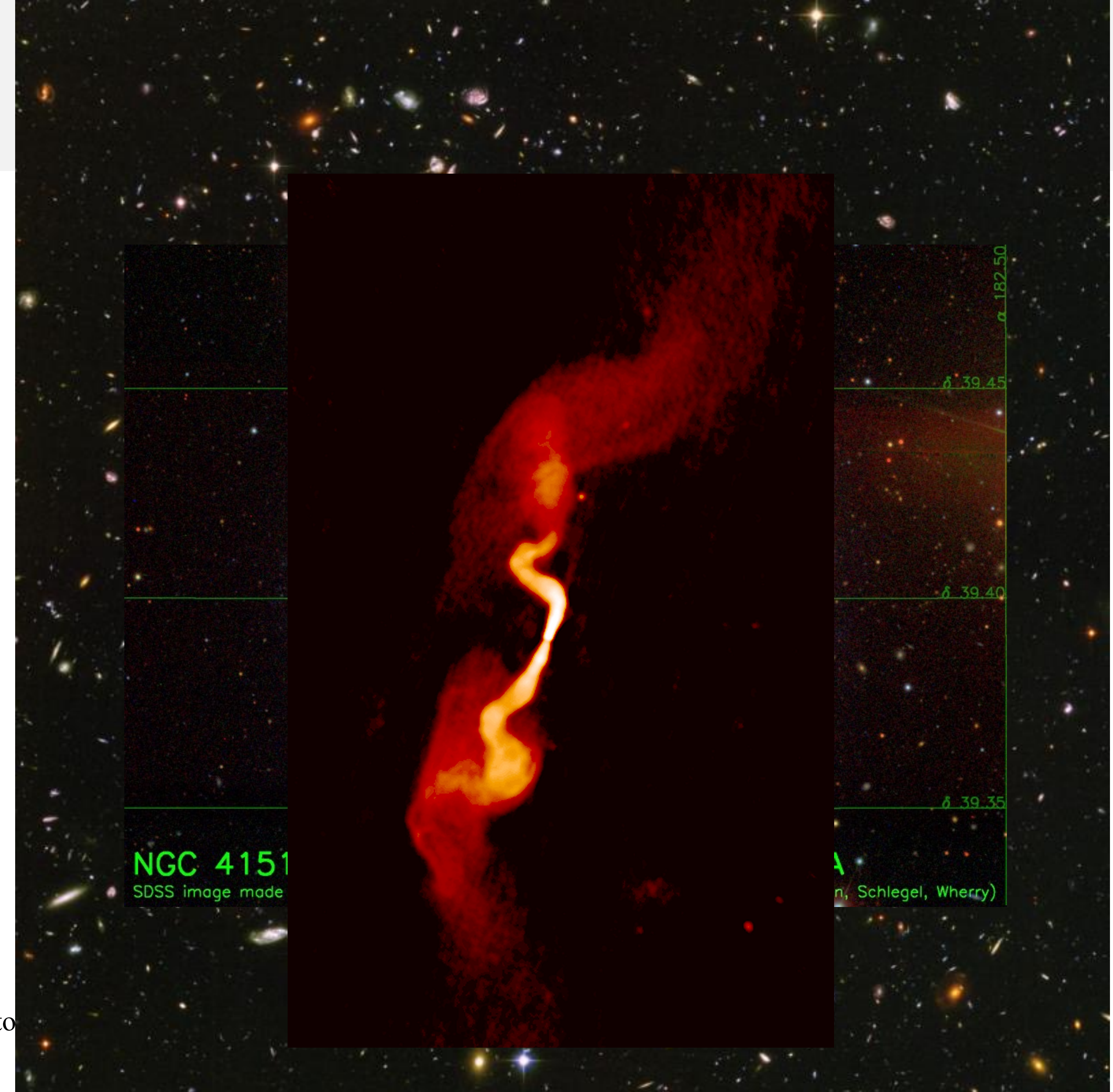
Antonucci & Miller (1985)



Quasars and Seyferts belong to the same class of sources: AGN



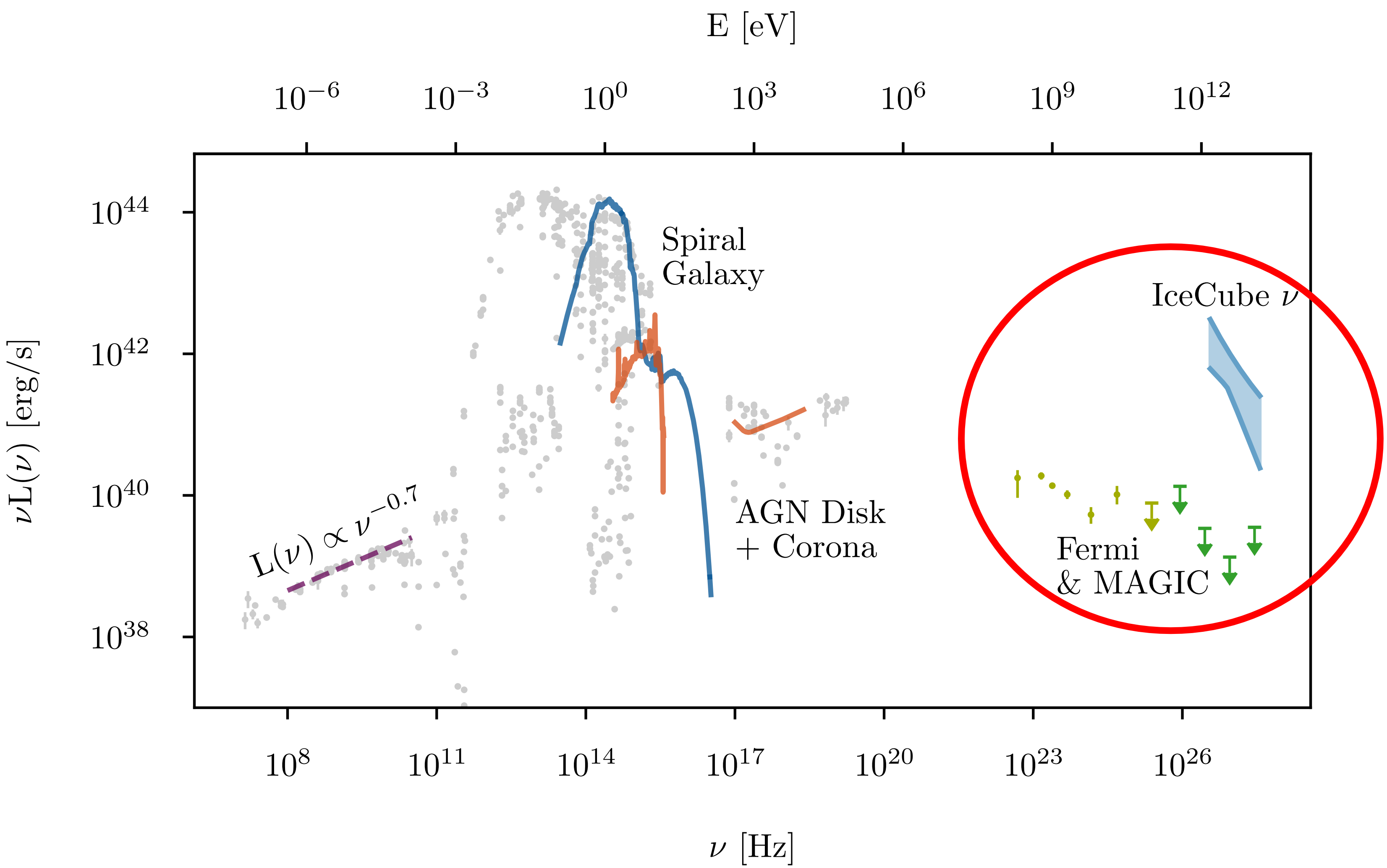

α 182.70
α 182.60
α 182.50
δ 39.45
δ 39.40
δ 39.35
NGC 4151 / UGC 7166 / KUG 1208+396A
SDSS image made with idlutils and photoop (Blanton, Finkbeiner, Hogg, Padmanabhan, Schlegel, Wherry)


α 182.50
δ 39.45
δ 39.40
δ 39.35
NGC 4151
SDSS image made
n, Schlegel, Wherry)

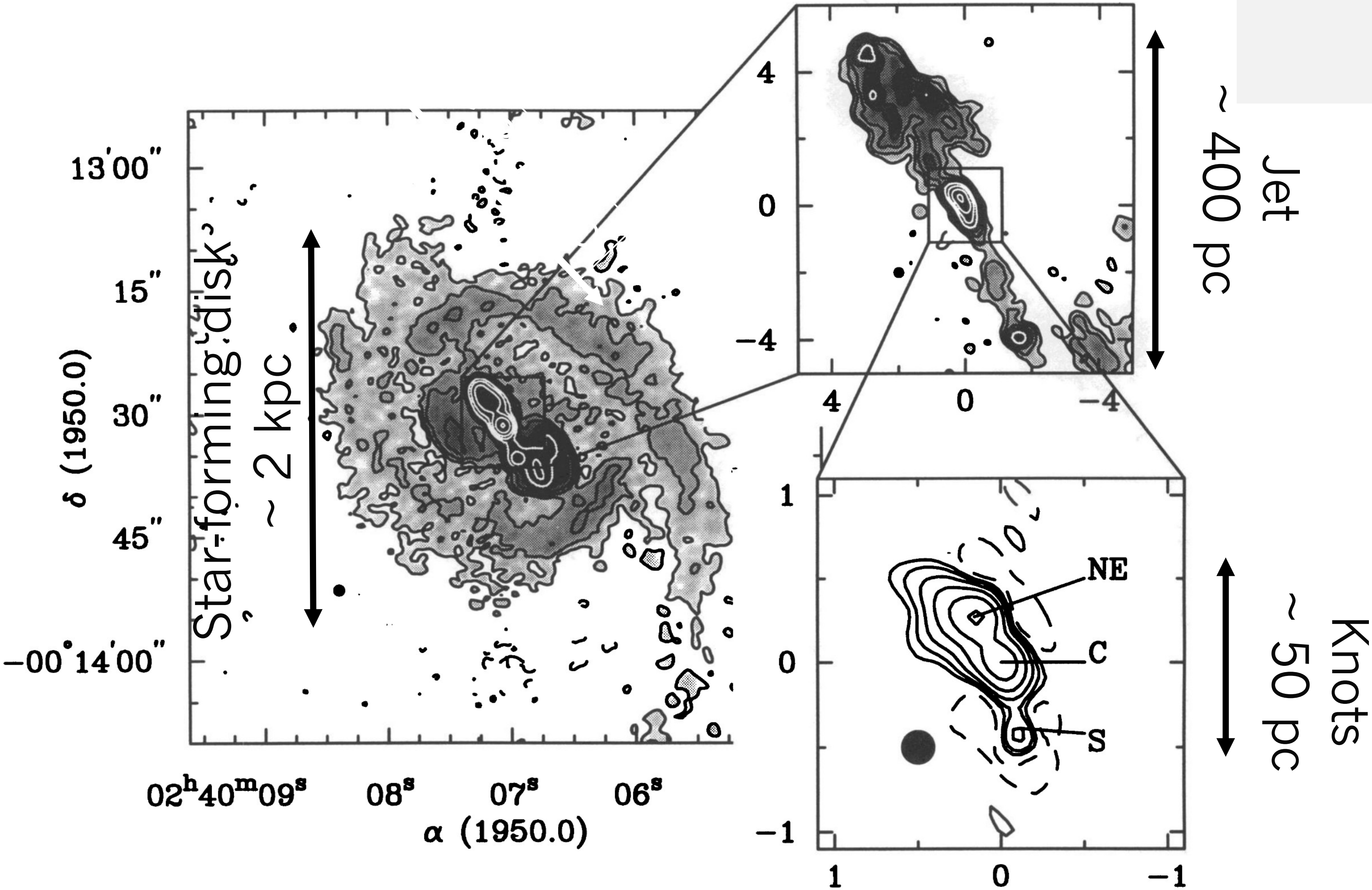
The distance to NGC 1068

- Value commonly used: D_L = 14.4 Mpc
- If one uses z = 0.00379 and standard cosmology (assuming Hubble flow) then D_L = 16.3 Mpc
- Most likely value is **D_L = 10.1±1.8 Mpc**
- 1″ ≡ 48.9 pc (1 kpc ≡ 20.4″)

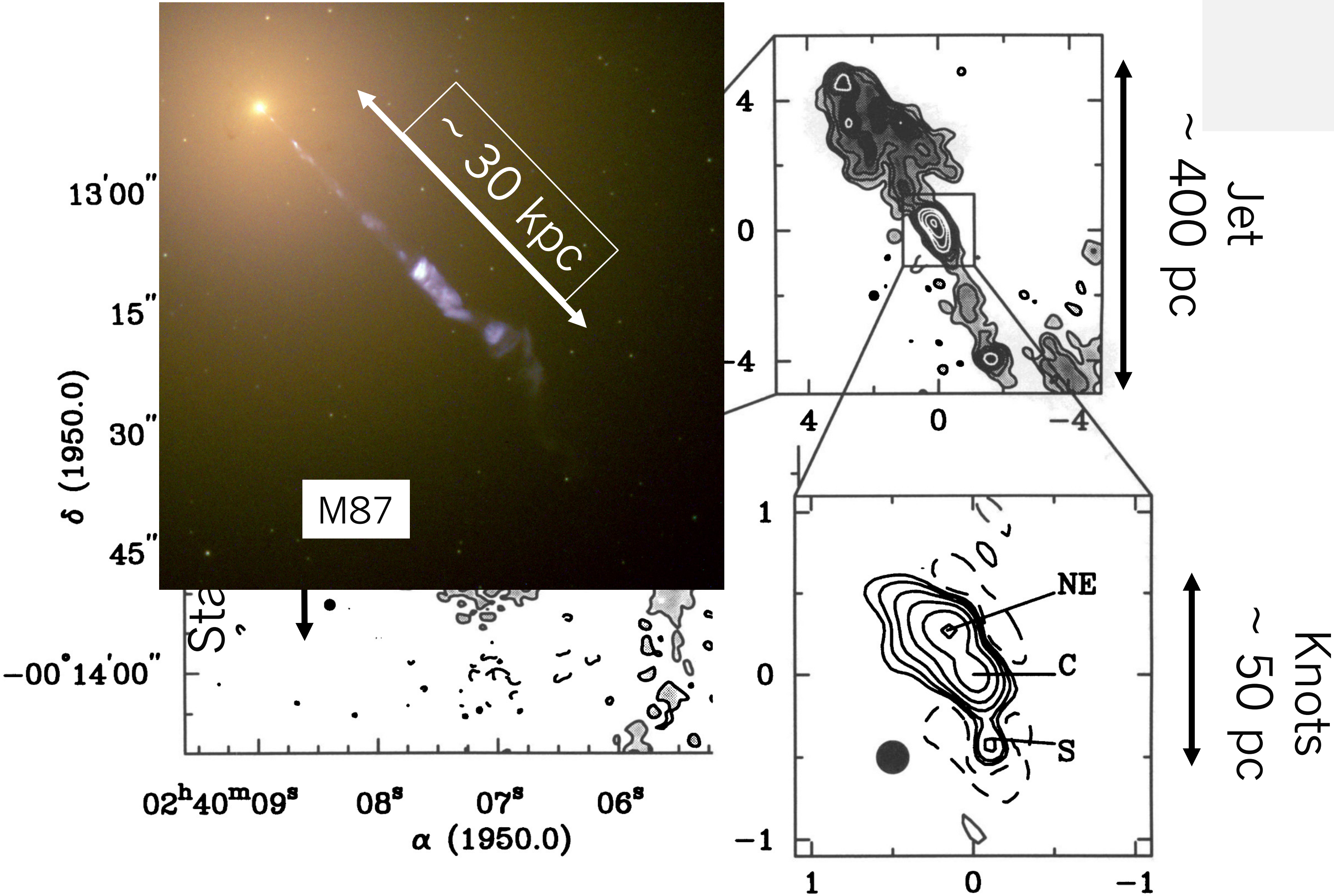
NGC 1068: the global SED



PP et al. in prep.



Gallimore et al. 1996 (1.7 GHz)



Gallimore et al. 1996 (1.7 GHz)

Jet N

PUBLISHED: 24 JULY 2017 | VOLUME: 1 | ARTICLE NUMBER: 0194

comment

On the two main classes of active galactic nuclei

Paolo Padovani

Active galactic nuclei (AGNs) are empirically divided into 'radio-loud' and 'radio-quiet'. These 50-year-old labels are obsolete, misleading and wrong. I argue that AGNs should be classified as 'jetted' and 'non-jetted' based on a physical difference — the presence (or lack) of strong relativistic jets.

It is widely accepted that AGNs are powered by supermassive black holes. And it is (almost) equally widely accepted that there are two main classes of AGNs: the radio-loud (RL) and the radio-quiet (RQ). These classifications go all the way back to the work of Sandage[1], who realized soon after the discovery of the first quasar — 3C 273, a very strong radio source — that there were many similar sources in the sky that were however undetected by the radio telescopes of the time. It was later understood that these quasars were only radio-faint, but the name radio-quiet stuck. Indeed, for the same optical power, the radio powers of RQ quasars are a few orders of magnitude smaller than those of their RL counterparts. This is, in fact, how RQ quasars are characterized: relatively low radio-to-optical flux density ratios (radio loudness, $R \lesssim 10$) and low radio powers ($P_{1.4GHz} \lesssim 10^{24}$ W Hz^{-1} locally[2]). We know now that RQ AGNs are the norm, not the exception, as they make up the large majority (>90%) of the AGN population[3]. We also know that, despite what the odd labels might suggest, the differences between the two classes are not restricted to the radio band; far from it. And they are not simply taxonomic either, as the two classes represent intrinsically different objects. Most RL AGNs emit a large fraction of their energy non-thermally over the whole electromagnetic spectrum. In contrast, the multiwavelength emission of RQ AGNs is dominated by thermal emission, directly or indirectly related to the accretion disk around the supermassive black hole.

The most striking difference is in the hard X-ray to gamma-ray band: while many (likely all, but see below) RL sources emit all the way up to GeV (2.4×10^{23} Hz) and sometimes TeV (2.4×10^{26} Hz) energies, nearby (RQ) bright Seyfert galaxies have a sharp cut-off at energies $\lesssim 1$ MeV (ref. [4]). This cut-off has to apply to the whole RQ AGN population in order to not violate the constraint provided by the X-ray background above these energies[5]. Moreover, no RQ AGN has ever been detected in gamma-rays[6] with the exception of NGC 1068 and NGC 4945, two Seyfert 2 galaxies in which the gamma-ray emission is thought to be related to their starburst component[7]. This means that, while RQ AGNs are actually not radio-quiet, they are gamma-ray-quiet.

Due to what are the differences between the two classes? One simple thing: the presence (or absence) of a strong relativistic jet. The relative (and absolute) strength of the radio emission in the two classes is just a consequence of this fundamental physical difference. Hence the need for the new and better names, jetted and non-jetted AGNs[2]. This is illustrated in Fig. 1, which compares the spectral energy distributions (SEDs) of typical non-jetted AGNs with those of two jetted ones, a BL Lac and a flat-spectrum radio quasar (FSRQ). Both of these belong to the blazar class, which

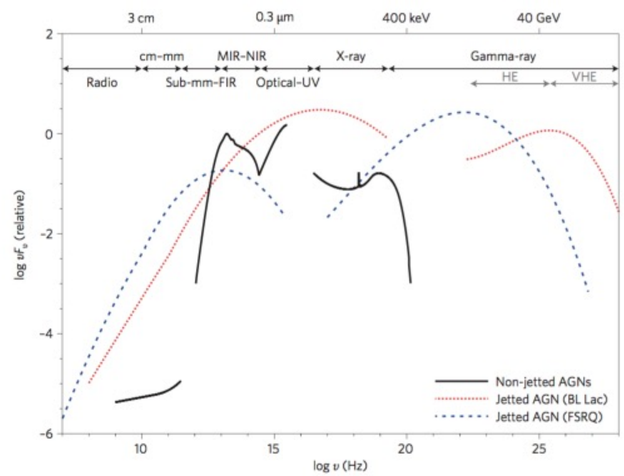
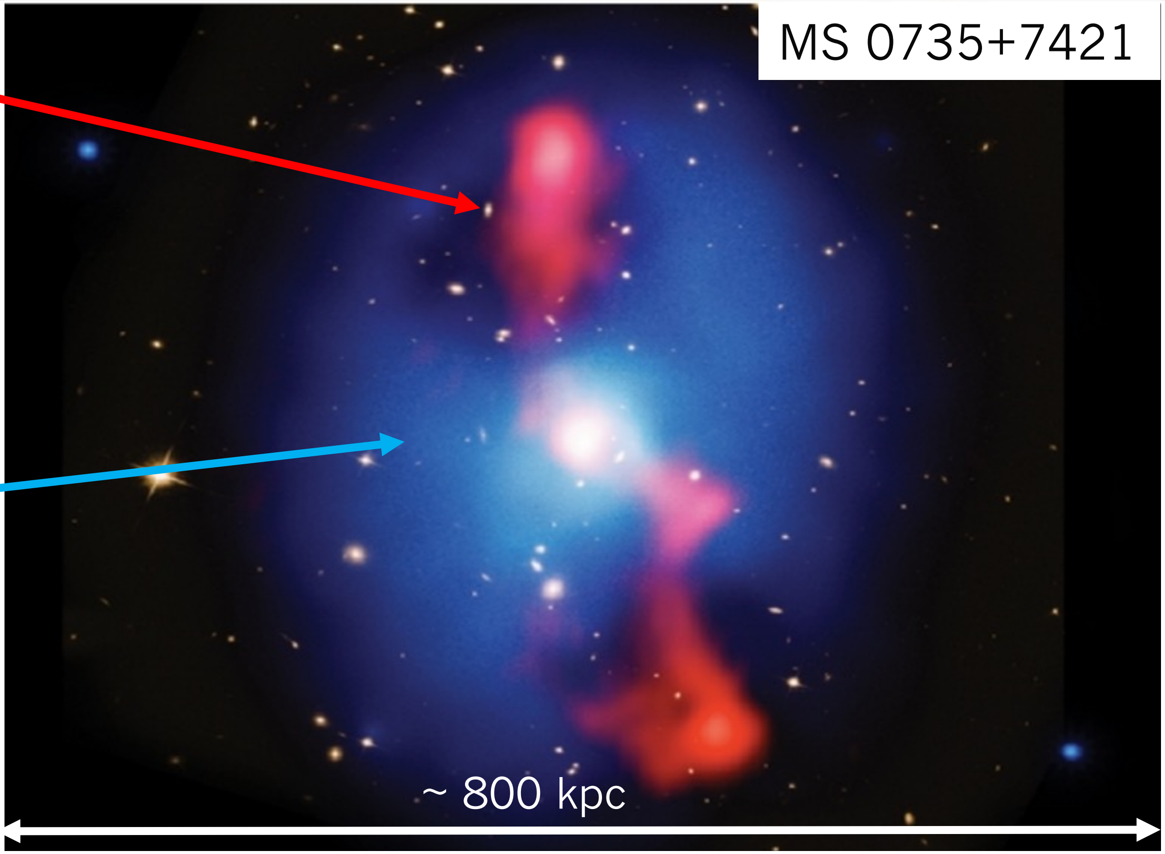


Figure 1 | A schematic representation of the SEDs of AGNs. The black solid curve represents the typical SED of non-jetted AGNs, while the dotted red and dashed blue lines refer to two jetted AGNs, a BL Lac (based on the SED of Mrk 421) and a flat-spectrum radio quasar (based on the SED of 3C 454.3), respectively. The plot is adapted from ref. 17 and Padovani *et al.*, manuscript in preparation. ν, frequency; F_ν, flux; FIR, far-infrared; MIR, mid-infrared; NIR, near-infrared; HE, high energy; VHE, very-high energy. Image credit: C. M. Harrison.

The radio band: jet power

Radio jet
(VLA)

X-ray
(Chandra)



$P_{1.4\ GHz}$ (jet)
~ 3.2 10^{22} W/Hz =
4.4 10^{38} erg/s

Log P_{cav} (1e42 erg/s) = 0.75 log $P_{1.4\ GHz}$ (1e40 erg/s) + 1.91 [σ ~ 0.8]
(Cavagnolo et al. 2010) → **P_{jet} ~ 7.8 10^{42} erg/s ~ $10^{42.9 \pm 1.0}$ erg/s**

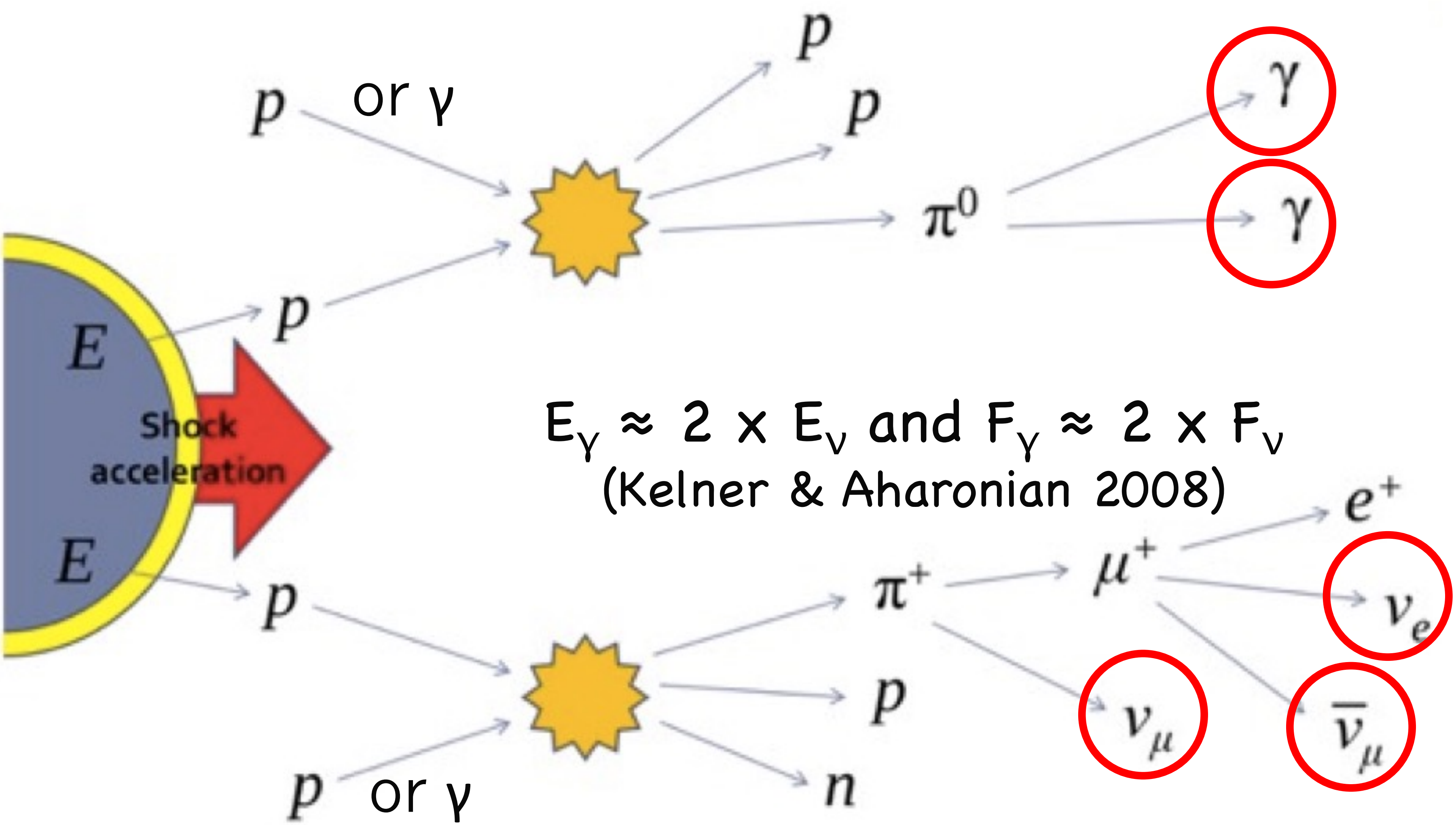
P (jet) [TXS 0506+056] ~ 10^{45} – 10^{46} erg/s

Gitti et al. 2012

The first (extragalactic) neutrino source

TXS 0506+056,
a blazar in γ-ray outburst
(a BL Lac) at z = 0.3365;
p—value (post-trial)
~ 3 – 3.5σ [E ~ 290 TeV]

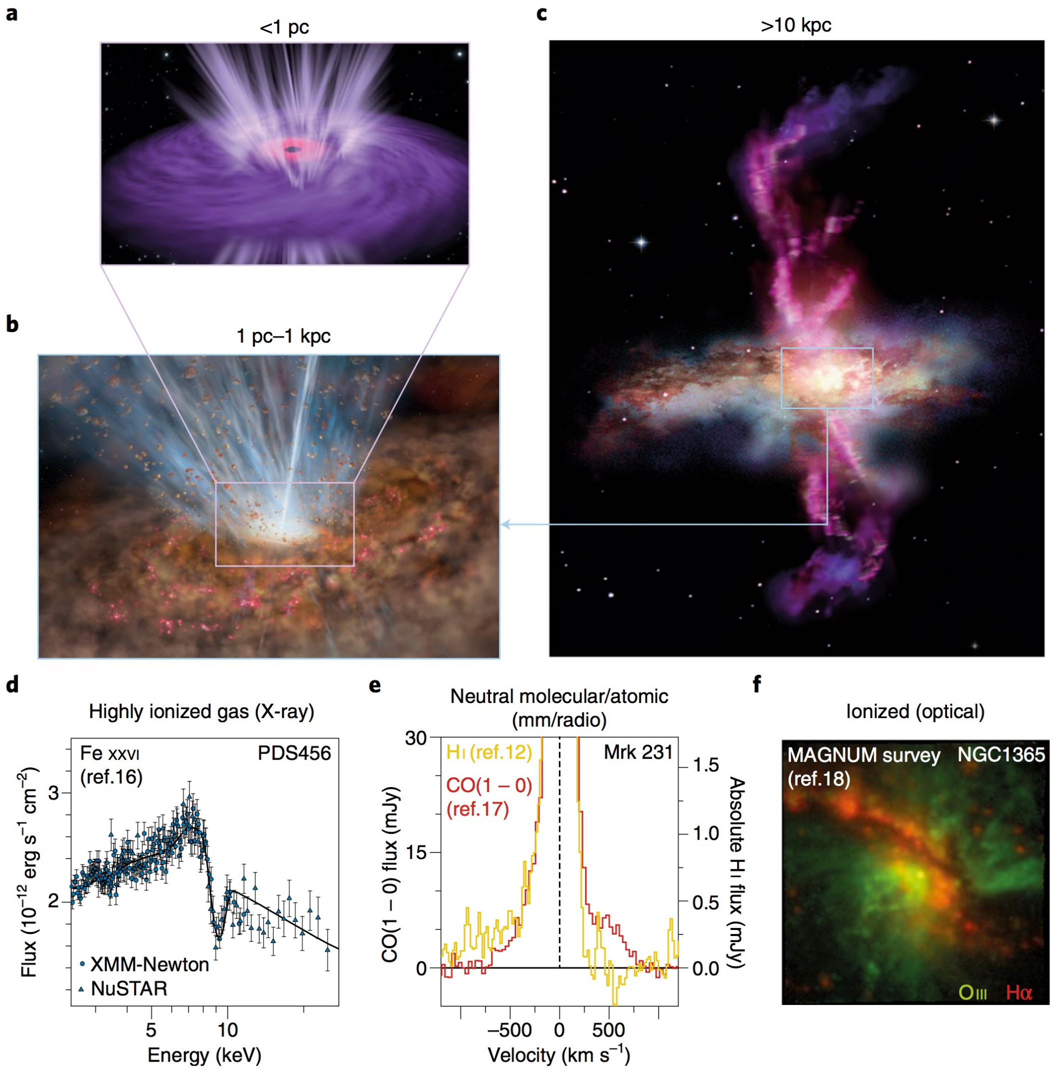
Neutrino relevance



$E_\gamma \approx 2 \times E_\nu$ and $F_\gamma \approx 2 \times F_\nu$
(Kelner & Aharonian 2008)

Outflows in AGN

ultrafast outflows (UFOs)



proton – proton collisions can produce low-level γ-rays and neutrinos

Cicone et al. 2018

The sub-mm band (ALMA data)

A&A 567, A125 (2014)
DOI: 10.1051/0004-6361/201423843

Astronomy & Astrophysics

Molecular line emission in NGC 1068 imaged with ALMA⋆

I. An AGN-driven outflow in the dense molecular gas

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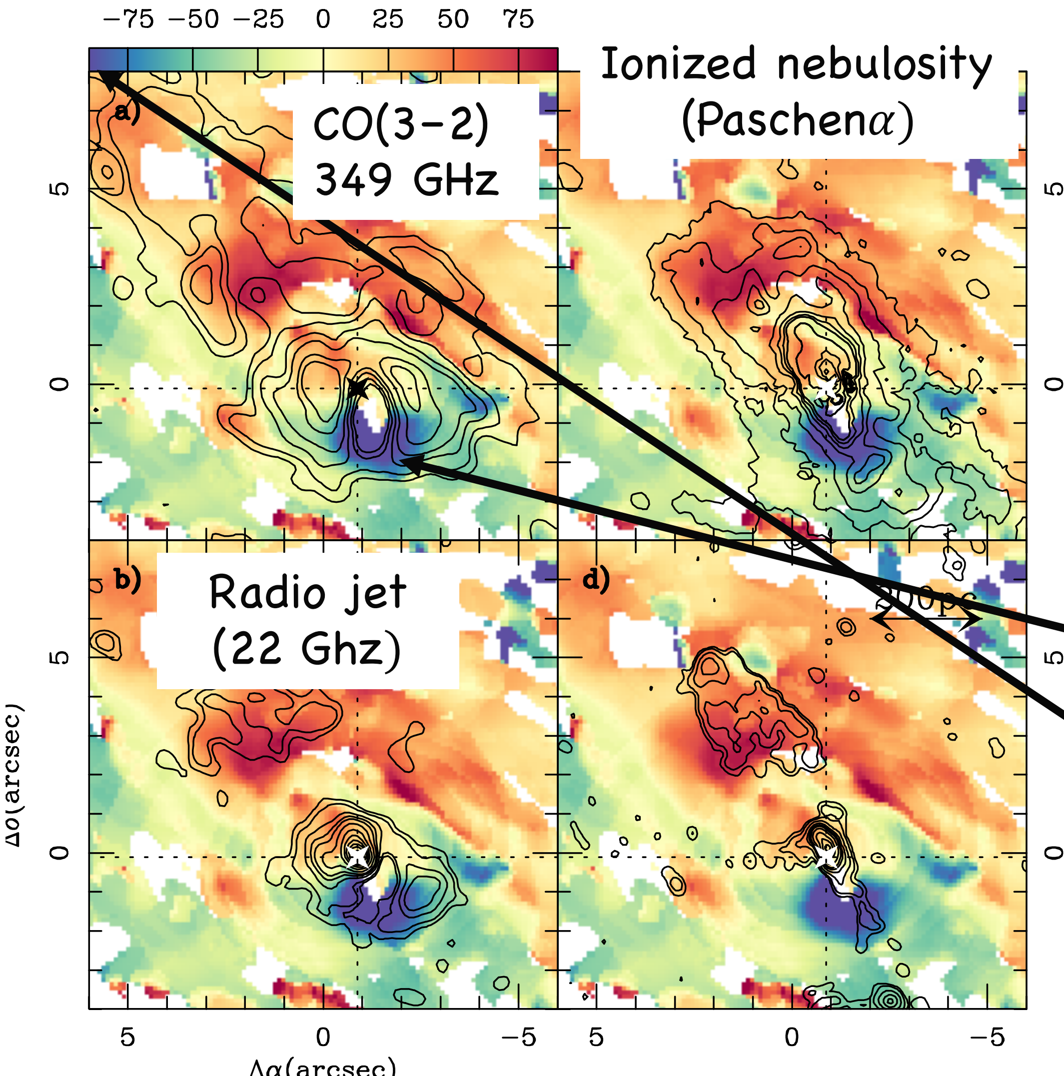
ABSTRACT

Aims. We investigate the fueling and the feedback of star formation and nuclear activity in NGC 1068, a nearby (D = 14 Mpc) Seyfert 2 barred galaxy, by analyzing the distribution and kinematics of the molecular gas in the disk. We aim to understand if and how gas accretion can self-regulate.
Methods. We have used the Atacama Large Millimeter Array (ALMA) to map the emission of a set of dense molecular gas ($n(H_2) \simeq 10^{5-6}$ cm^{-3}) tracers (CO(3–2), CO(6–5), HCN(4–3), HCO^+(4–3), and CS(7–6)) and their underlying continuum emission in the central $r \sim 2$ kpc of NGC 1068 with spatial resolutions ~0.3″–0.5″ (~20–35 pc for the assumed distance of D = 14 Mpc).
Results. The sensitivity and spatial resolution of ALMA give an unprecedented detailed view of the distribution and kinematics of the dense molecular gas ($n(H_2) \geq 10^{5-6}$cm^{-3}) in NGC 1068. Molecular line and dust continuum emissions are detected from a $r \sim 200$ pc off-centered circumnuclear disk (CND), from the 2.6 kpc-diameter bar region, and from the $r \sim 1.3$ kpc starburst (SB) ring. Most of the emission in HCO^+, HCN, and CS stems from the CND. Molecular line ratios show dramatic order-of-magnitude changes inside the CND that are correlated with the UV/X-ray illumination by the active galactic nucleus (AGN), betraying ongoing feedback. We used the dust continuum fluxes measured by ALMA together with NIR/MIR data to constrain the properties of the putative torus using CLUMPY models and found a torus radius of 20^{+6}_{-10} pc. The Fourier decomposition of the gas velocity field indicates that rotation is perturbed by an inward radial flow in the SB ring and the bar region. However, the gas kinematics from $r \sim 50$ pc out to $r \sim 400$ pc reveal a massive ($M_{mol} \sim 2.7^{+0.9}_{-1.2} \times 10^7$ $M_\odot$) outflow in all molecular tracers. The tight correlation between the ionized gas outflow, the radio jet, and the [illegible] of outward motions in the disk suggests that the outflow is AGN driven.
Conclusions. The molecular outflow is likely launched when the ionization cone of the narrow line region sweeps the nuclear disk. The outflow rate estimated in the CND, $dM/dt \sim 63^{+21}_{-37}$ $M_\odot$ yr^{-1}, is an order of magnitude higher than the star formation rate at these radii, confirming that the outflow is AGN driven. The power of the AGN is able to account for the estimated momentum and kinetic luminosity of the outflow. The CND mass load rate of the CND outflow implies a very short gas depletion timescale of ≤1 Myr. The CND gas reservoir is likely replenished on longer timescales by efficient gas inflow from the outer disk.

Key words. galaxies: individual: NGC 1068 – galaxies: ISM – galaxies: kinematics and dynamics – galaxies: nuclei – galaxies: Seyfert – [illegible] galaxies

The sub-mm band: molecular outflow power



$1'' \equiv 48.9$ pc

Most molecular gas in the Universe is in H_2 form

$M_{outflow}$ from (outflow-related) CO(3-2) line emission (assuming CO luminosity to H_2 mass conversion factor)

$R_{outflow} \sim 1.5''$ (75 pc)

v ~ 100 km/s

$\dot{E}_{kin} \sim 4.0^{+0.3}_{-2.4}\ 10^{41}$ erg/s

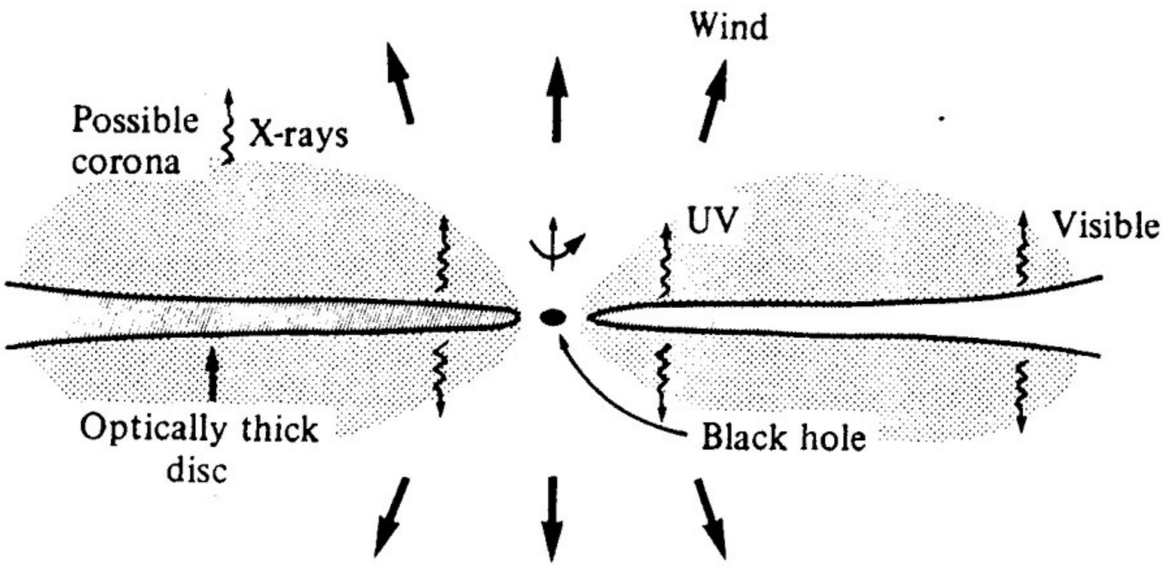
(errors only from $M_{outflow}$)

$\dot{E}_{kin} \sim 10^{41.6 \pm 1.0}$ erg/s

García-Burillo et al. 2014

The X-ray band

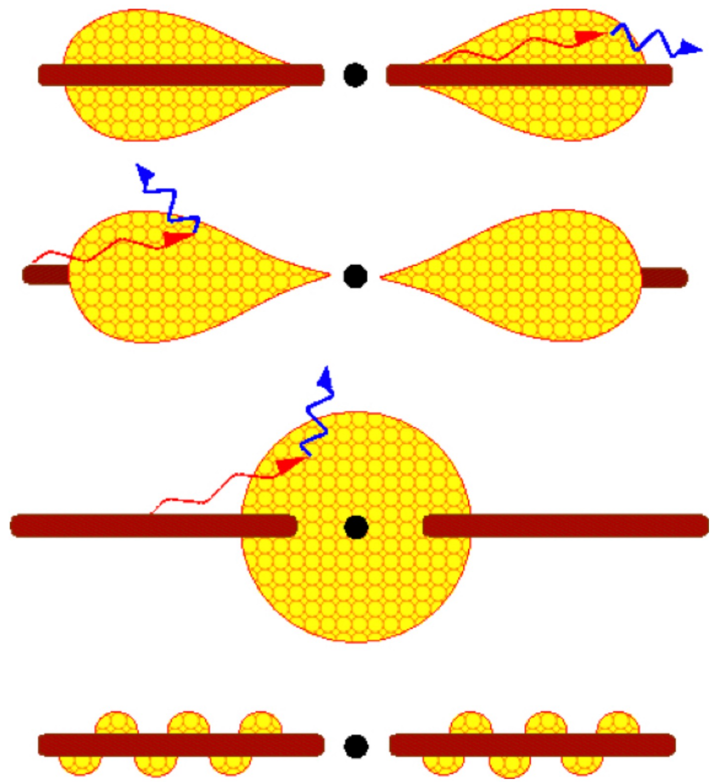
UV photons + Inverse Compton from relativistic electrons ($T \approx 10^9$ K) → X-ray photons ("corona")



Wiita 1991

The X-ray band

UV photons + Inverse Compton from relativistic electrons ($T \approx 10^9$ K) → X-ray photons (“corona”)



Figu
‘corona”
is the

Figure 10: Various possible (in principle) disc-coronal structures. [*Courtesy: Chris Done.*]

Lasota 2023

The X-ray band

UV photons + Inverse Compton from relativistic electrons ($T \approx 10^9$ K) → X-ray photons ("corona")

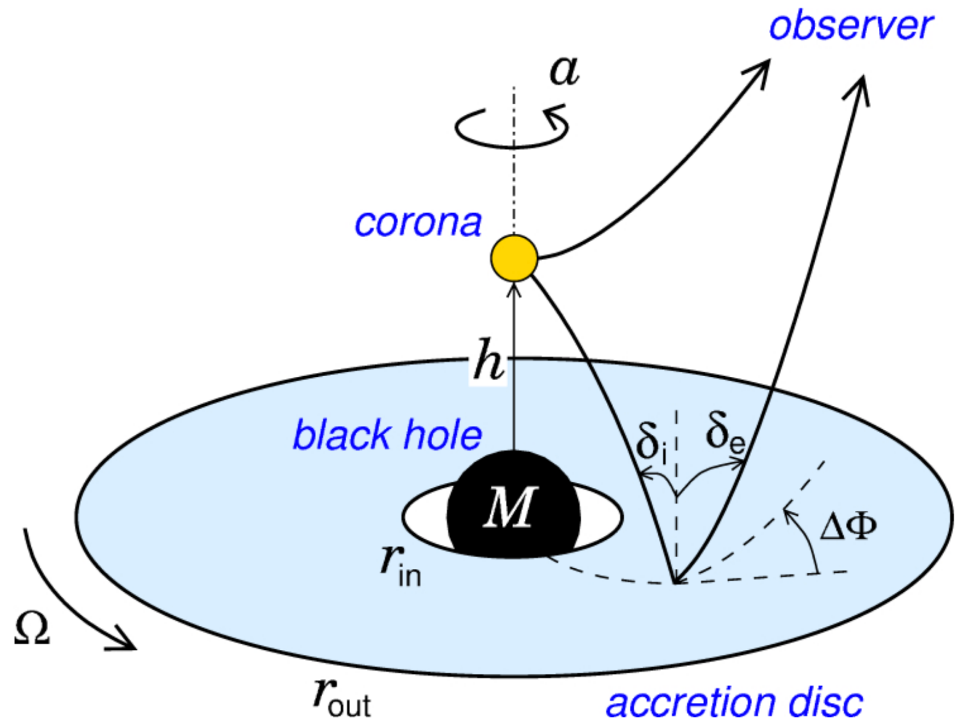


Figure 11: A scheme representing the lamppost "coronal" model. The feature called "corona" is the lamppost in question. [*From Caballero-Garcia et al. (2019)*.]

Lasota 2023

The X-ray corona

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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Uncovering the geometry of the hot X-ray corona in the Seyfert galaxy NGC 4151 with IXPE

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Affiliations are listed at the end of the paper

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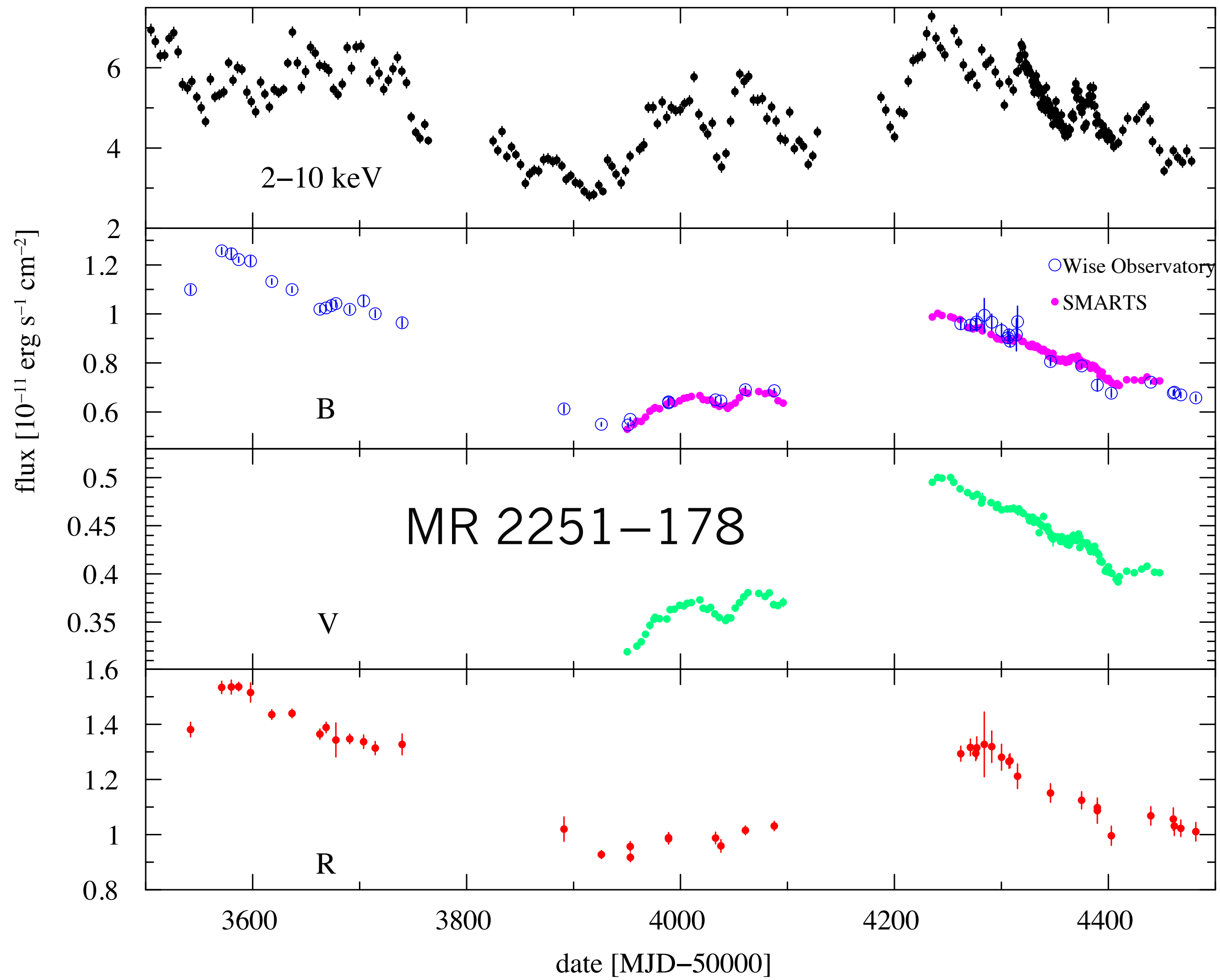
ABSTRACT

We present an X-ray spectropolarimetric analysis of the bright Seyfert galaxy NGC 4151. The source has been observed with the *Imaging X-ray Polarimetry Explorer* (*IXPE*) for 700 ks, complemented with simultaneous *XMM–Newton* (50 ks) and *NuSTAR* (100 ks) pointings. A polarization degree $\Pi = 4.9 \pm 1.1$ per cent and angle $\Psi = 86° \pm 7°$ east of north (68 per cent confidence level) are measured in the 2–8 keV energy range. The spectropolarimetric analysis shows that the polarization could be entirely due to reflection. Given the low reflection flux in the *IXPE* band, this requires, however, a reflection with a very large (>38 per cent) polarization degree. Assuming more reasonable values, a polarization degree of the hot corona ranging from ~4 to ~8 per cent is found. The observed polarization degree excludes a 'spherical' lamppost geometry for the corona, suggesting instead a *slab*-like geometry, possibly a *wedge*, as determined via Monte Carlo simulations. This is further confirmed by the X-ray polarization angle, which coincides with the direction of the extended radio emission in this source, supposed to match the disc axis. NGC 4151 is the first active galactic nucleus with an X-ray polarization measure for the corona, illustrating the capabilities of X-ray polarimetry and *IXPE* in unveiling its geometry.

Key words: polarization – galaxies: active – galaxies: individual: NGC 4151 – galaxies: Seyfert.

Same story for Cygnus X-1 (Galactic BH) and possibly IC 4329 and MCG-05-23-16 (Sey Is)

The X-ray band



PP et al. 2017

The X-ray band: AGN power

- $L_{2\text{-}10\ keV}$ (i … cci et al. 2016) [D_L …
- $L_{bol,X}$ = 3. … s et al. 2020)
- $L_{bol,IR}$ = 6 … the [O IV] 25.89 μm …
- Logarithm … ± 0.5 erg/s]
- Consisten … dusty torus: $L_{bol,ALMA}$ = … 2014) and GRAVITY …

L_{Bol}/L_X =

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **456,** L94–L98 (2016) doi:10.1093/mnrasl/slv178

NuSTAR catches the unveiling nucleus of NGC 1068

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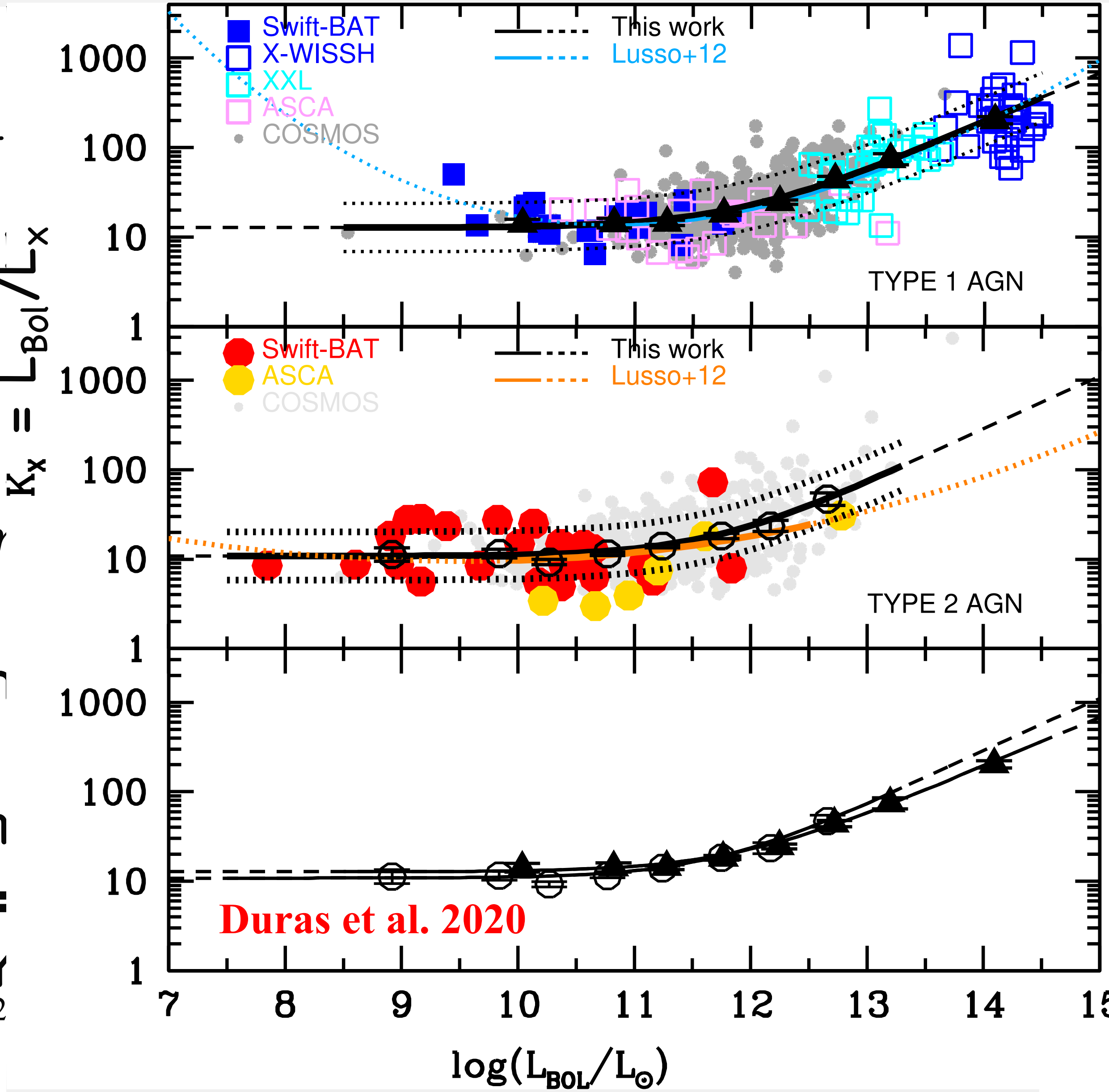
ABSTRACT

We present a *NuSTAR* and *XMM–Newton* monitoring campaign in 2014/2015 of the Compton-thick Seyfert 2 galaxy, NGC 1068. During the 2014 August observation, we detect with *NuSTAR* a flux excess above 20 keV (32 ± 6 per cent) with respect to the 2012 December observation and to a later observation performed in 2015 February. We do not detect any spectral variation below 10 keV in the *XMM–Newton* data. The transient excess can be explained by a temporary decrease of the column density of the obscuring material along the line of sight (from $N_H \simeq 10^{25}$ cm^{-2} to $N_H = 6.7 \pm 1.0 \times 10^{24}$ cm^{-2}), which allows us for the first time to unveil the direct nuclear radiation of the buried active galactic nucleus in NGC 1068 and to infer an intrinsic 2–10 keV luminosity $L_X = 7^{+7}_{-4} \times 10^{43}$ erg s^{-1}.

Key words: galaxies: active – galaxies: individual: NGC 1068 – galaxies: Seyfert.

The X-ray band: AGN power

- $L_{2\text{-}10\ keV}$ (i … et al. 2016) [D_L
- $L_{bol,X}$ = 3. … t al. 2020)
- $L_{bol,IR}$ = 6 … e [O IV] 25.89 μm
- Logarithn … erg/s]
- Consisten … ty torus: $L_{bol,ALMA}$ = … 14) and GRAVITY



The X-ray band: AGN power

- $L_{2\text{-}10\ keV}$ (intrinsic) = $2.7^{+2.7}_{-1.5}\ 10^{43}$ erg/s (Marinucci et al. 2016) [D_L = 10.1 Mpc]

- $L_{bol,X} = 3.5\ 10^{44}$ erg/s [$10^{44.5\pm0.4\pm0.3}$ erg/s] (Duras et al. 2020)

- $L_{bol,IR} = 6.1\ 10^{44}$ erg/s, IR-based, computed from the [O IV] 25.89 μm line luminosity (Spinoglio et al. 2022)

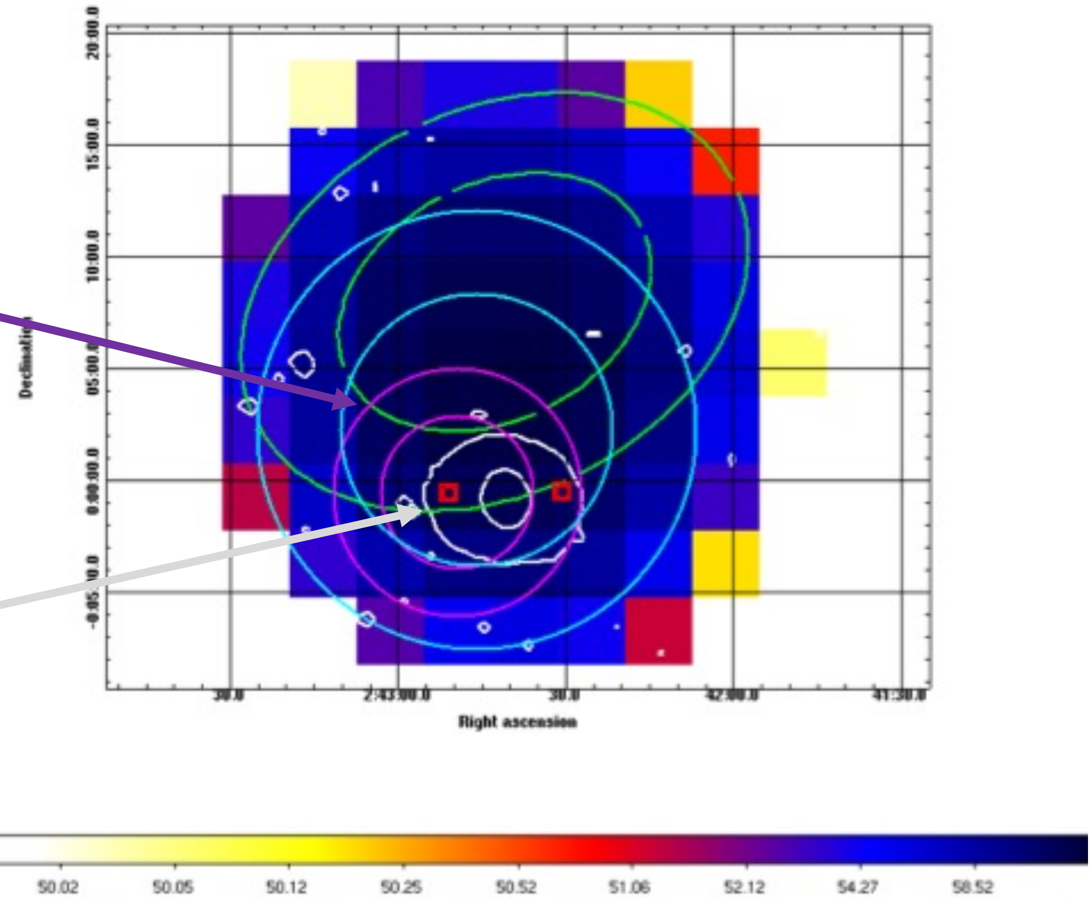
- Logarithmic mean: **$L_{bol} = 4.6\ 10^{44}$ erg/s [$10^{44.7\pm0.5}$ erg/s]**

- Consistent with ALMA model-dependent fit to dusty torus: **$L_{bol,ALMA} = 10^{44.3\pm0.1}$** erg/s (García-Burillo et al. 2014) and GRAVITY Collaboration (2020): **$10^{44.8\pm0.5}$** erg/s

The γ-ray band

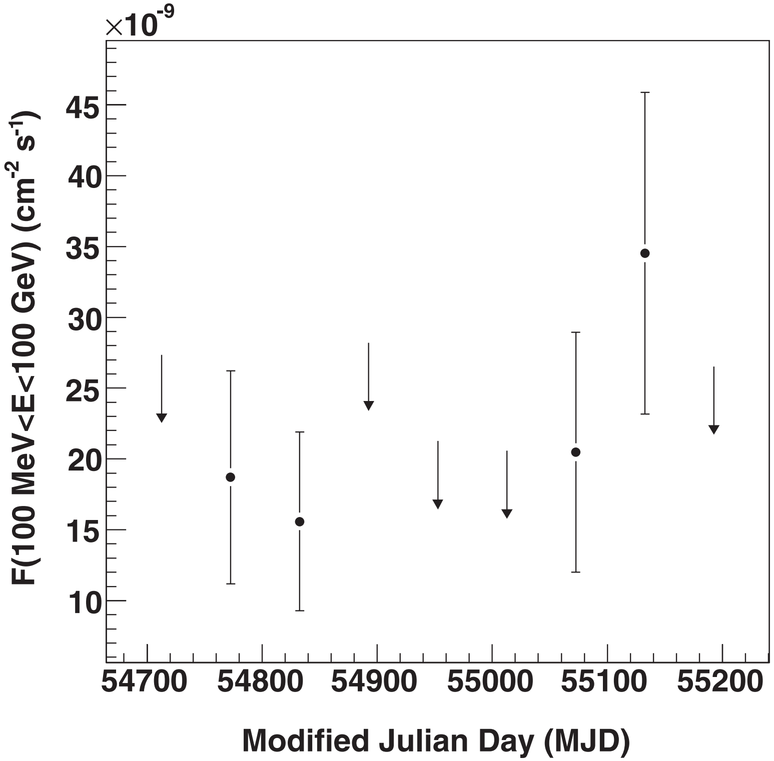
Fermi 68% and 95% error circles

Optical galaxy

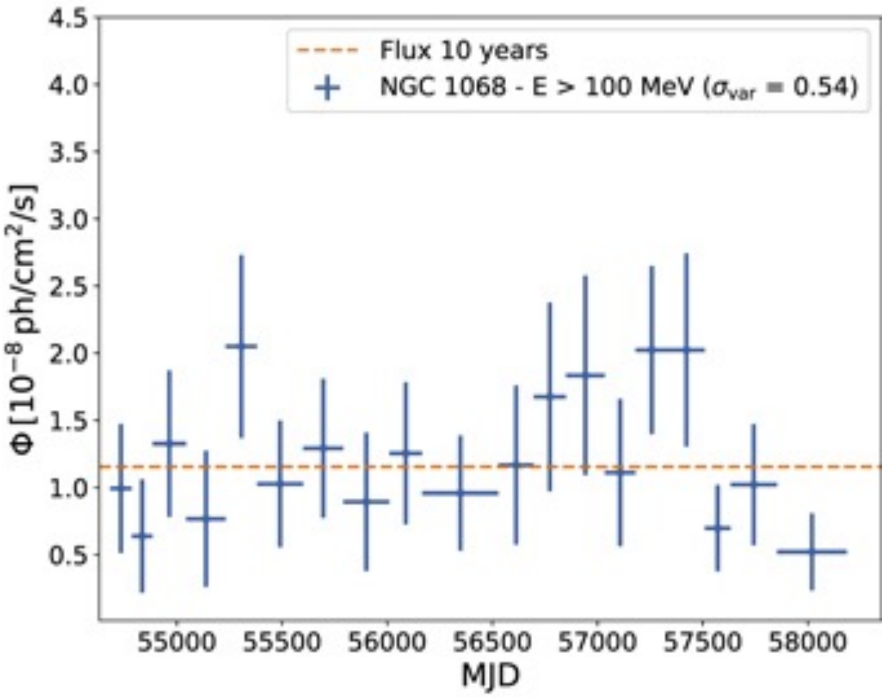


Lenain et al. (2010)

γ-ray (non-)variability

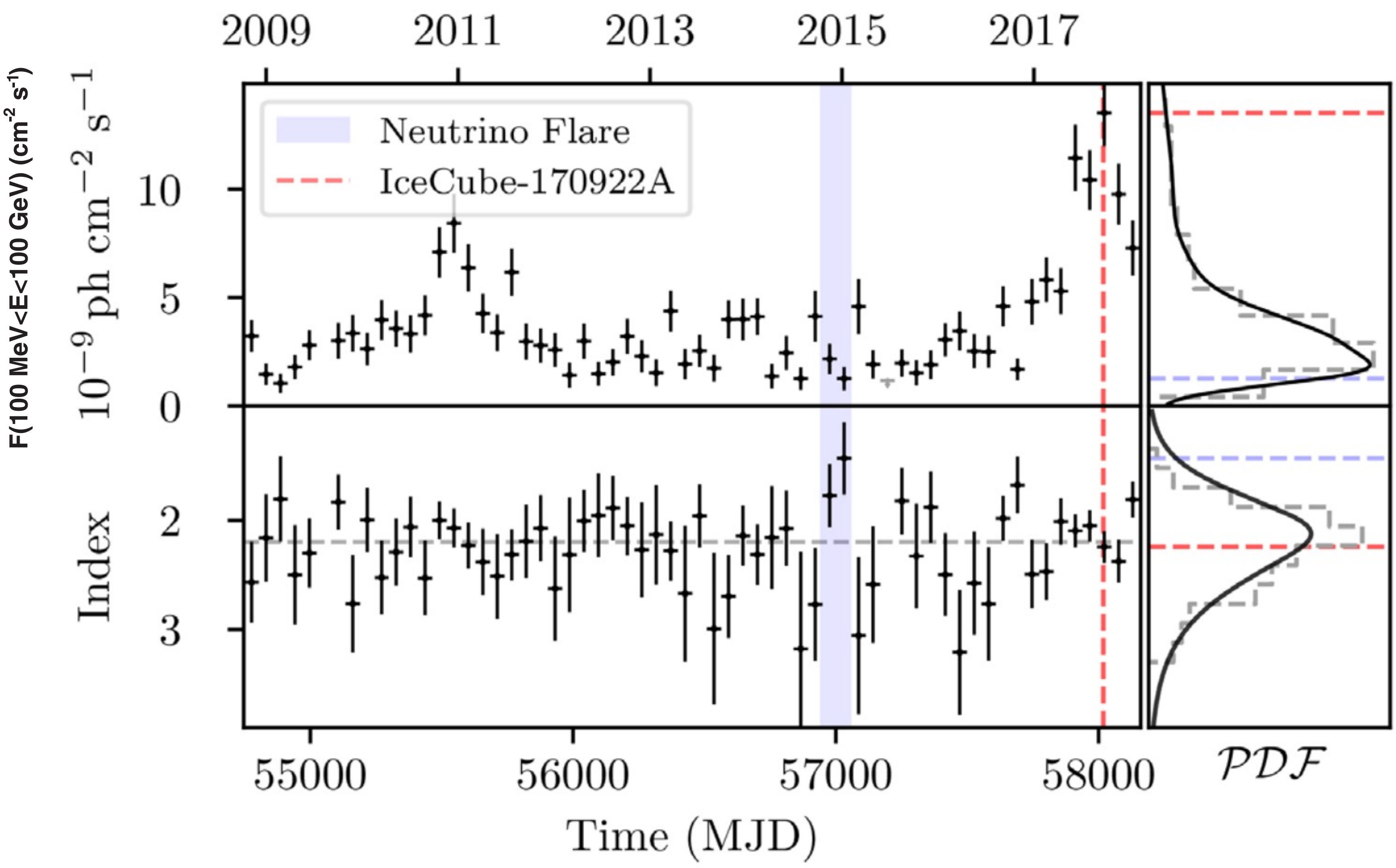


Lenain et al. (2010)



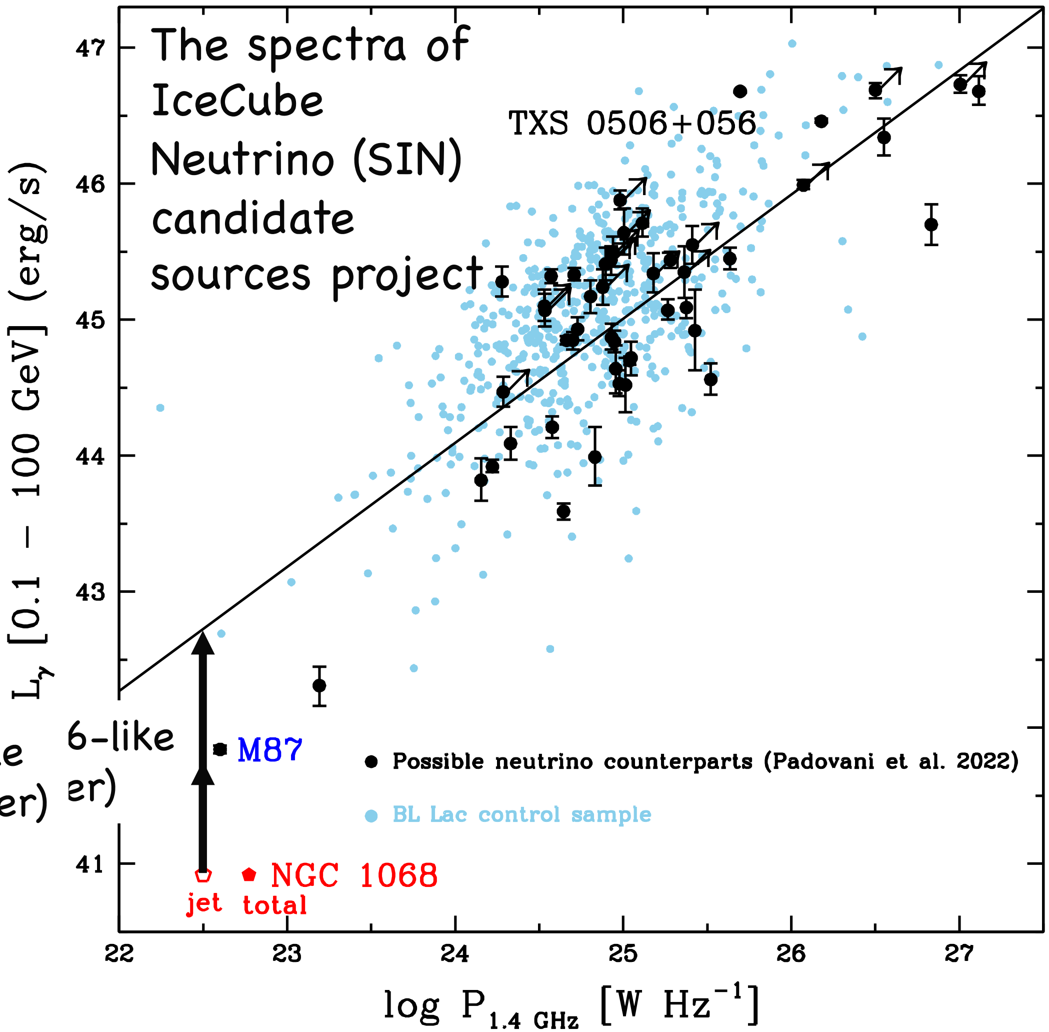
Ajello et al. (2020)

γ-ray (non-)variability



TXS 0506+056: Padovani et al. (2018)

γ-ray emission: comparison with blazars

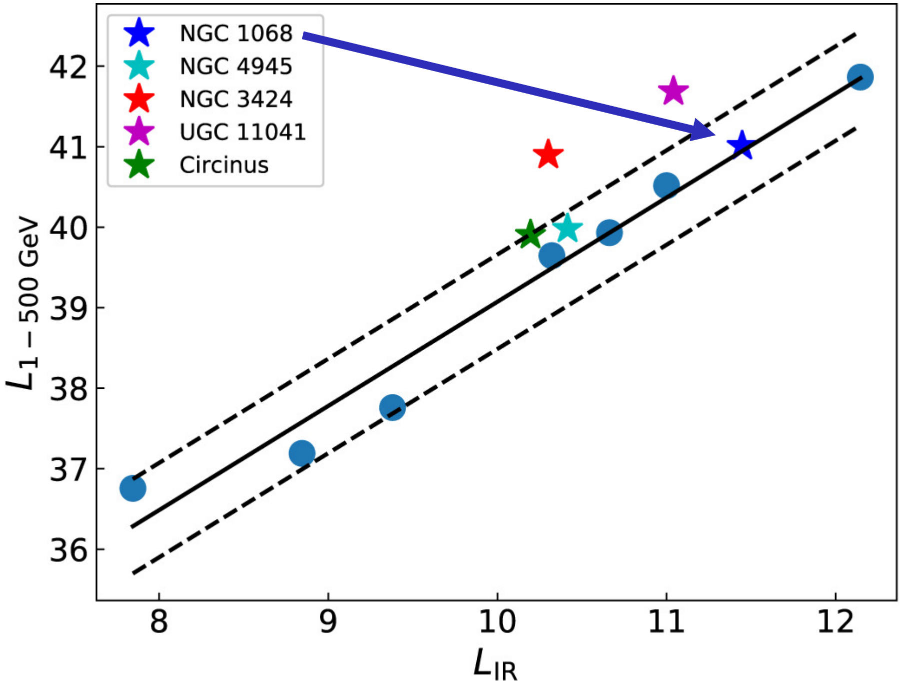


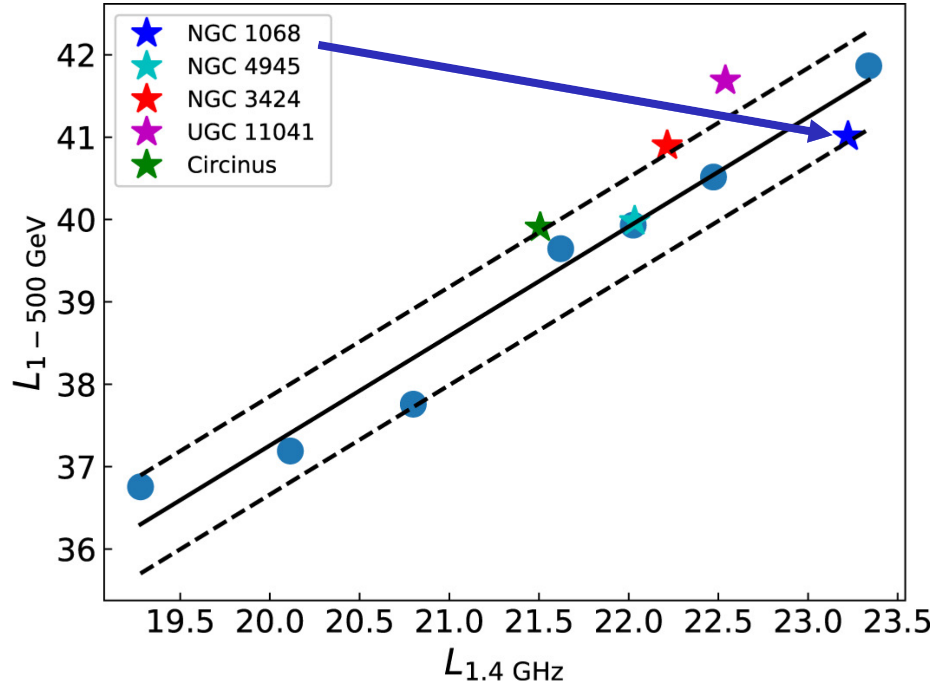
M 87-like
(7 x higher)

Adapted from Paiano, Falomo, Treves, PP et al. (2023)

γ-ray band: the starburst power

Star-forming and starburst (blue points) galaxies

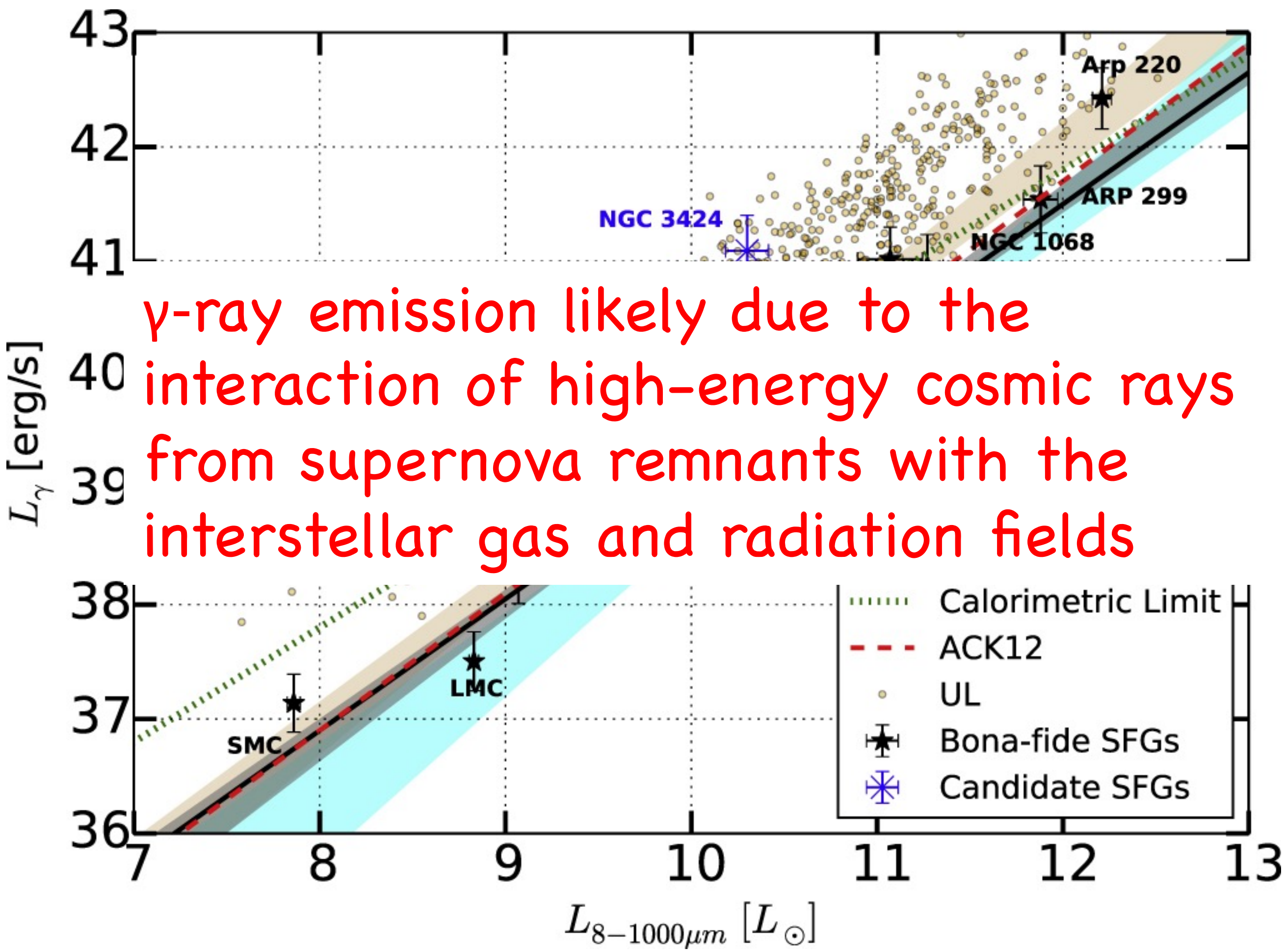




Peng et al. (2019)

γ-ray emission process

Star-forming galaxies



γ-ray emission likely due to the interaction of high-energy cosmic rays from supernova remnants with the interstellar gas and radiation fields

Ajello et al. (2020)

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5.1σ stacking detection

Gamma Rays from Fast Black-hole Winds

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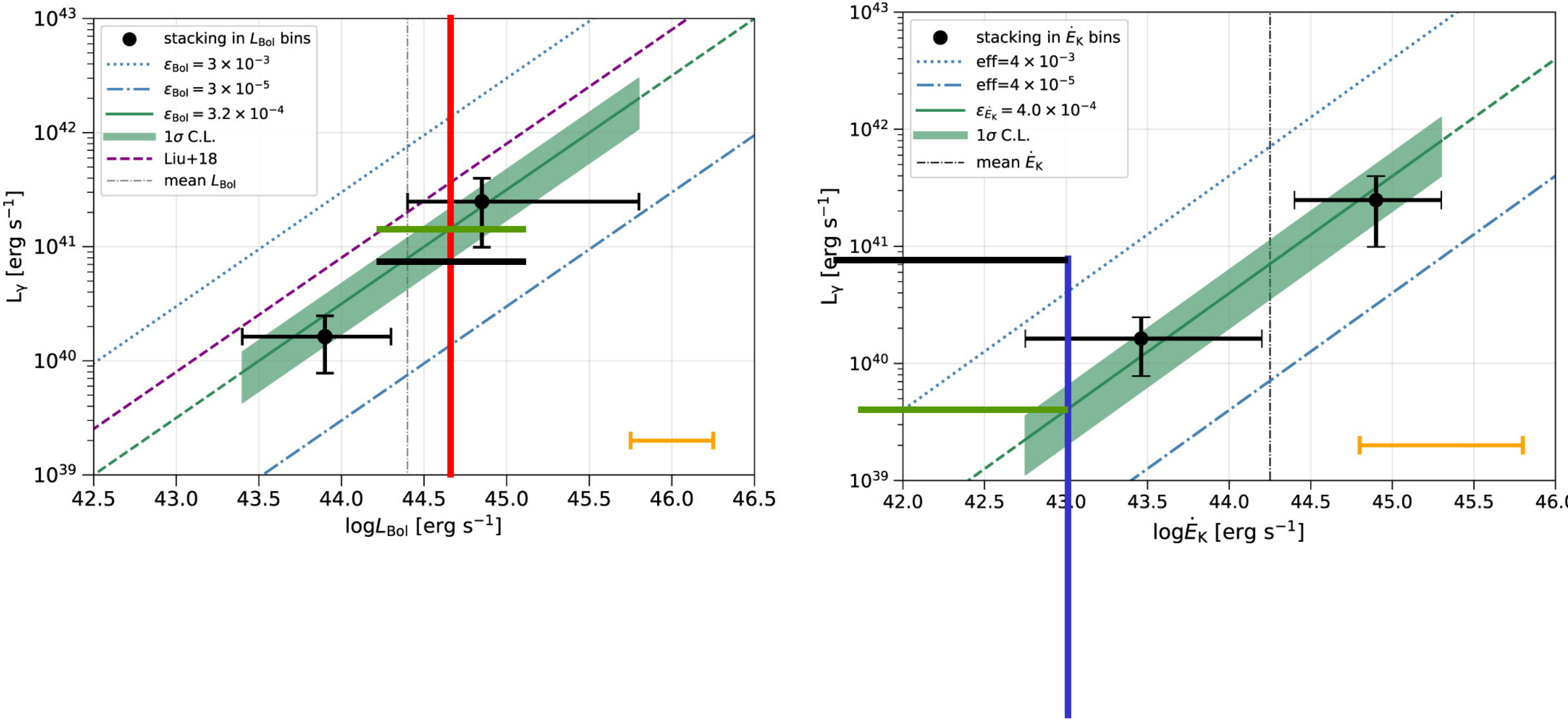
Abstract

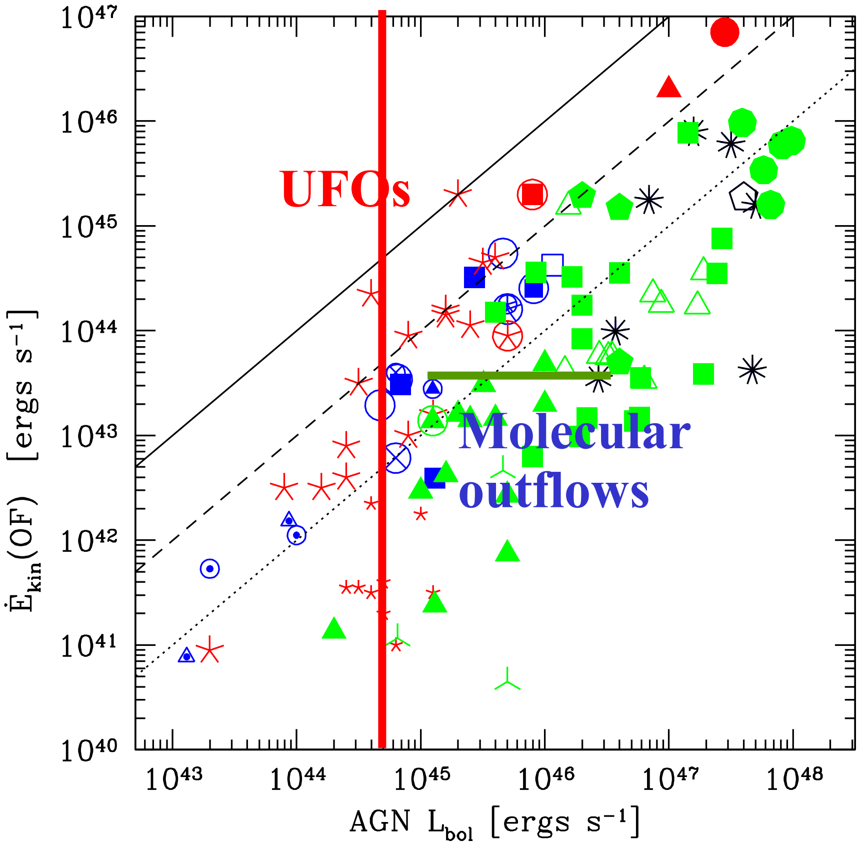
Massive black holes at the centers of galaxies can launch powerful wide-angle winds that, if sustained over time, can unbind the gas from the stellar bulges of galaxies. These winds may be responsible for the observed scaling relation between the masses of the central black holes and the velocity dispersion of stars in galactic bulges. Propagating through the galaxy, the wind should interact with the interstellar medium creating a strong shock, similar to those observed in supernovae explosions, which is able to accelerate charged particles to high energies. In this work we use data from the Fermi Large Area Telescope to search for the γ-ray emission from galaxies with an ultrafast outflow (UFO): a fast ($v \sim 0.1$ c), highly ionized outflow, detected in absorption at hard X-rays in several nearby active galactic nuclei (AGN). Adopting a sensitive stacking analysis we are able to detect the average γ-ray emission from these galaxies and exclude that it is due to processes other than UFOs. Moreover, our analysis shows that the γ-ray luminosity scales with the AGN bolometric luminosity and that these outflows transfer ∼0.04% of their mechanical power to γ-rays. Interpreting the observed γ-ray emission as produced by cosmic rays (CRs) accelerated at the shock front, we find that the γ-ray emission may attest to the onset of the wind–host interaction and that these outflows can energize charged particles up to the transition region between galactic and extragalactic CRs.

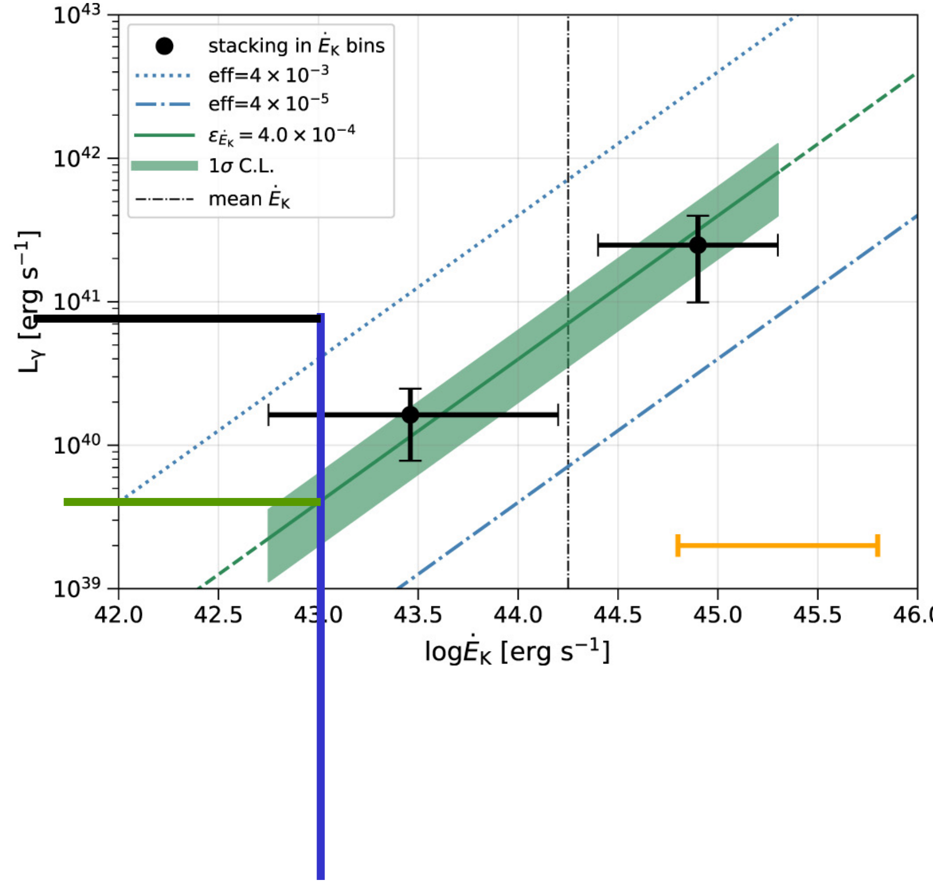
γ-rays from ultrafast outflows



Ajello et al. (2020)

γ-rays from ultrafast outflows





Fiore et al. (2017)

Ajello et al. (2020)

γ-rays from molecular outflows

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4.4σ stacking detection

Gamma-Ray Emission from Galaxies Hosting Molecular Outflows

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Abstract

Many star-forming galaxies and those hosting active galactic nuclei show evidence of massive outflows of material in a variety of phases including ionized, neutral atomic, and molecular. Molecular outflows in particular have been the focus of recent interest as they may be responsible for removing gas from the galaxy, thereby suppressing star formation. As material is ejected from the cores of galaxies, interactions of the outflowing material with the interstellar medium can accelerate cosmic rays and produce high-energy gamma rays. In this work, we search for gamma-ray emission from a sample of local galaxies known to host molecular outflows using data collected by the Fermi Large Area Telescope. We employ a stacking technique in order to search for and characterize the average gamma-ray emission properties of the sample. Gamma-ray emission is detected from the galaxies in our sample at the 4.4σ level with a power-law photon index of $\Gamma \approx 2$ in the 1–800 GeV energy range. The emission is found to correlate with tracers of star formation activity, namely the 8–1000 μm infrared luminosity. We also find that the observed signal can be predominantly attributed to H II galaxies hosting energy-driven outflows. While we do not find evidence suggesting that the outflows are accelerating charged particles directly, galaxies with molecular outflows may produce more gamma rays than galaxies without outflows. In particular, the set consisting of gamma-ray-detected galaxies with molecular outflows are nearly perfect calorimeters and may be future targets for searches of high-energy neutrinos.

Unified Astronomy Thesaurus concepts: Gamma-rays (637); Particle astrophysics (96); High energy astrophysics (739); Cosmic rays (329); AGN host galaxies (2017); Galactic winds (572)

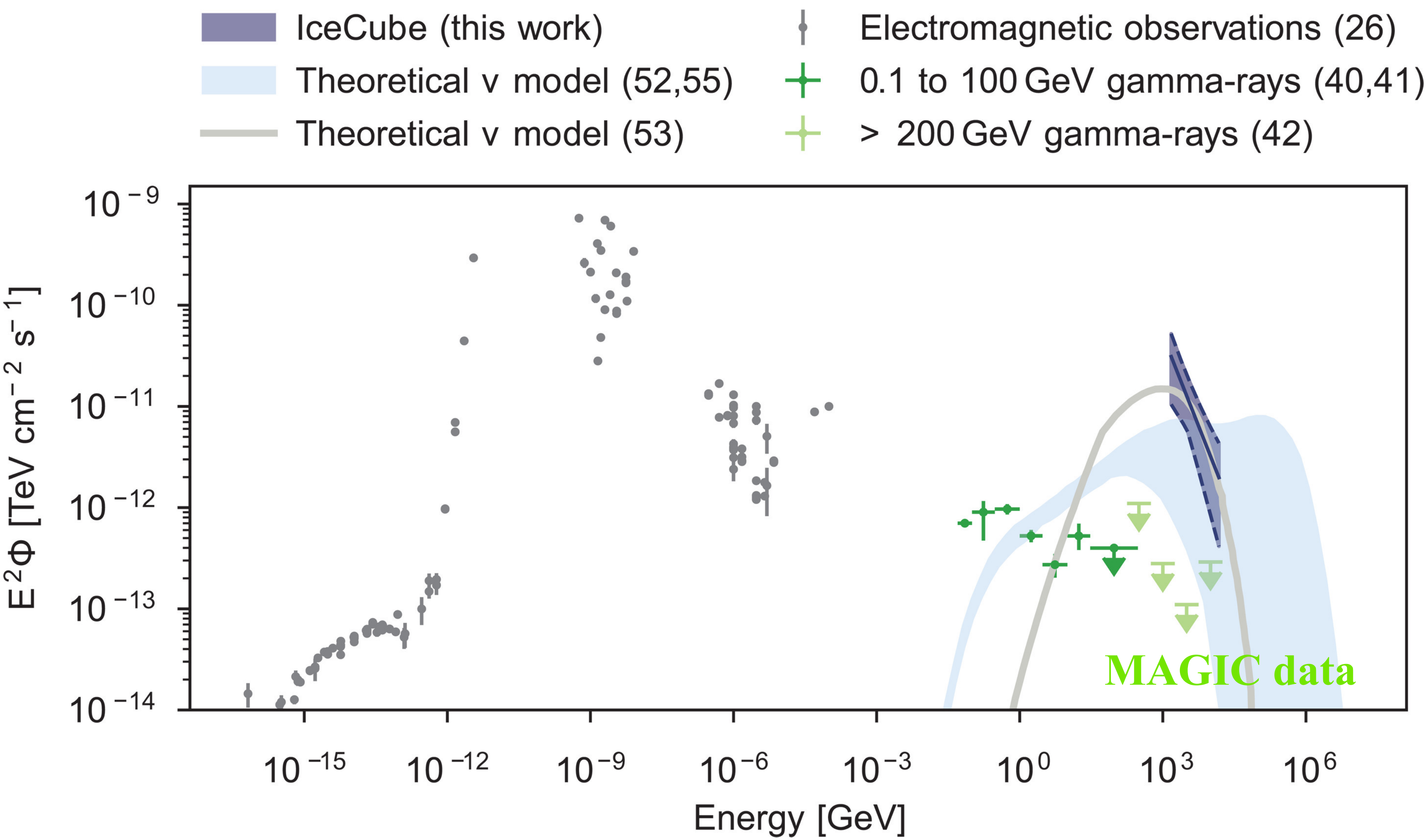
γ-rays from molecular outflows

- Signal only from non-AGN sources (star-forming galaxies)
- No correlation between $\dot{E}_{kin}$ and L_γ (unlike for UFOs)

γ-ray and neutrino powers

- L_γ (0.1 – 100 GeV) = 8.3 10^{40} erg/s [$10^{40.92\pm0.03}$ erg/s], Γ= 2.34$\pm$0.05 (4FGL-DR3)
- L_ν (1.5 – 15 TeV) = $10^{42.1\pm0.2}$ erg/s, Γ= 3.2$\pm$0.2$\pm$0.07 (IceCube Collaboration 2022)
- $L_\nu \sim$ 15 x L_γ. **If hadronic interactions** were producing both, **without γ-ray absorption,** then energy range and powers are expected to be the same (within 2 x: Kelner & Aharonian 2008)

γ-ray and neutrino powers



IceCube Collaboration (2022)

Emission powers (erg/s)

Measured powers

L_{radio}	L_{FIR}	L_X	L_γ	L_ν
[1.4 GHz]	[8 – 1000 μm]	[2–10 keV]	[0.1 – 100 GeV]	[1.5 – 15 TeV]
$10^{38.9}$	$10^{44.6\pm0.1}$	$10^{43.4\pm0.3}$	$10^{40.92\pm0.03}$	$10^{42.1\pm0.2}$

Derived powers

$\dot{E}_{kin}$	P_{jet}	L_{bol}	L_{Edd}	L_{bol}/L_{Edd}
$10^{41.6\pm1.0}$ (mol.)	$10^{42.9\pm1.0}$	$10^{44.7\pm0.5}$	$10^{44.9\pm0.3}$	$10^{-0.3\pm0.6}$

Emission powers (erg/s)

$L_\nu \approx L_\gamma/2$ + band conversion → $L_\nu \approx L_\gamma/6$

Component	Scale	Power (erg/s)	L_γ (erg/s) (0.1 – 100 GeV)	L_ν (erg/s) (1.5 – 15 TeV)
Star formation	> Kpc	$10^{44.6}$	$\sim 10^{40.9}$	$\sim 10^{40.1}$
Jet	~ Kpc	$10^{42.9\pm1}$	$< 10^{41.7}$? (M87-like) [absorbed!]	$< 10^{40.9}$
Outflow	~ 100 pc	$10^{41.6\pm1.0}$	$< 10^{41.2}$ (UFO-like)	$< 10^{40.4}$
BH vicinity	~ 0.03 millipc (~ 50 R_S)	$10^{44.7\pm0.5}$	?	?

Total: $\lesssim 10^{41.9}$ $\ll 10^{41.1}$

Observed: $10^{40.92\pm0.03}$ $10^{42.1\pm0.2}$

Main points

- Various components and physical processes at work in NGC 1068:
  1. star-forming region
  2. small jet
  3. outflow
  4. AGN core
- Robust power estimates for all of them were derived
- 1-3 appear to be ruled out as relevant for the IceCube association
- We are then left with the AGN core (various papers published on this topic)

Main points

- Various components and physical processes at work in NGC 1068:

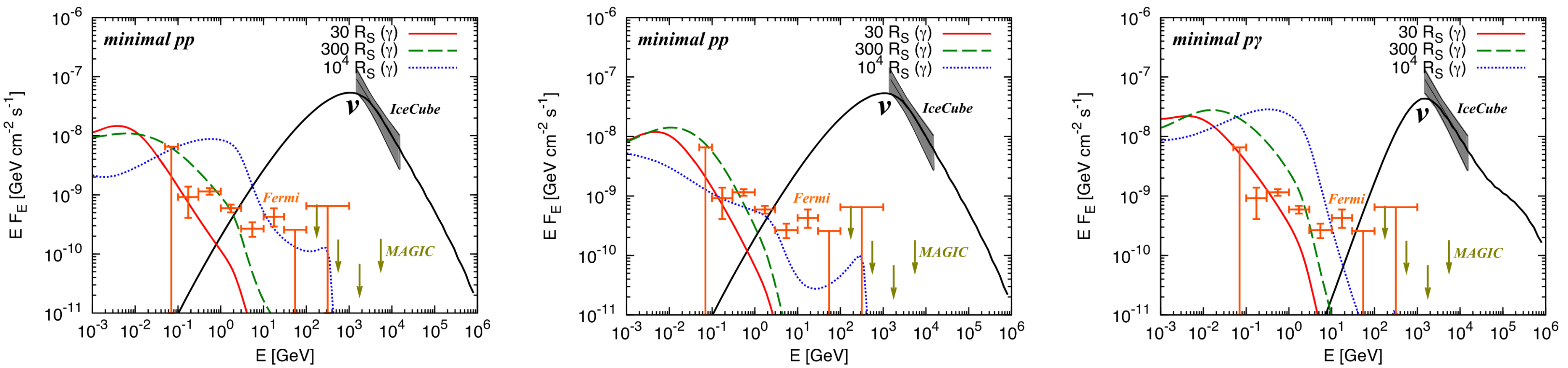


Figure 3. Left: neutrino and cascaded gamma-ray spectra in the minimal *pp* scenario with $\xi_B = 0.01$, where the IC cascade contribution is significant. Middle: same as the left panel but for $\xi_B = 1$, where the synchrotron cascade dominates. Right: neutrino and cascaded gamma-ray spectra in the minimal $p\gamma$ scenario with $\xi_B = 1$, where the Bethe–Heitler pair production enhances the cascade flux.

- 1-3 appear to be ruled out as relevant for the IceCube association
- We are then left with the AGN core (various papers published on this topic)

Murase (2022)

NGC 1068 as a cosmic laboratory

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(Dated: September 27, 2023)

ABSTRACT

We present a comprehensive multi-messenger study of NGC 1068, the prototype Seyfert II galaxy recently associated with high-energy IceCube neutrinos. Various aspects of the source, including its nuclear activity, jet, outflow, the starburst region, are analised in detail using a multi-wavelength approach. We also explore its γ-ray and neutrino emissions and investigate potential mechanisms underlying these phenomena and their relations with the different astrophysical components to try to understand which one is responsible for the IceCube neutrinos. Specific theoretical models are also discussed.