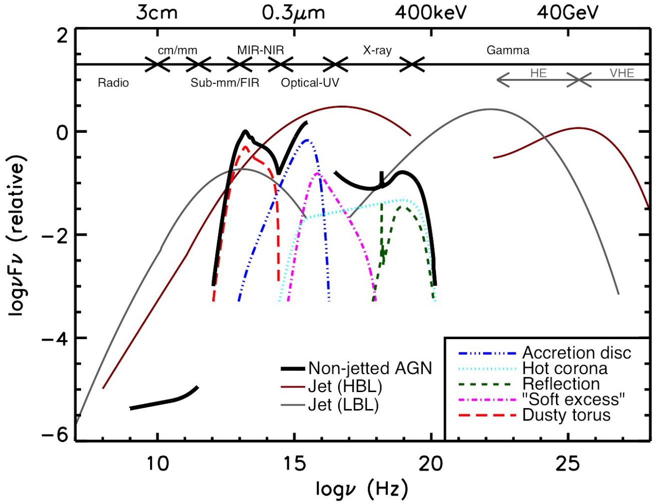
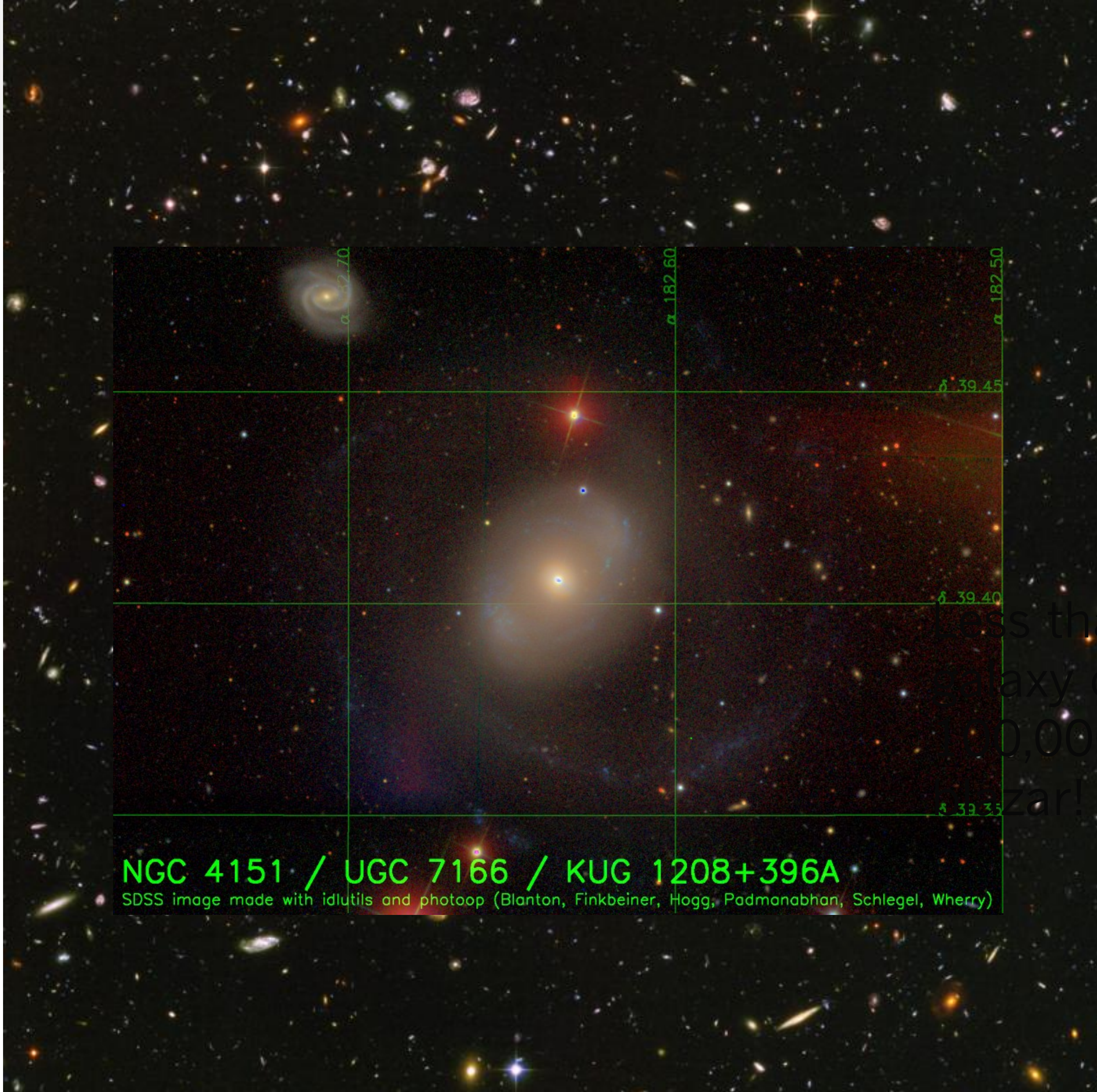


A multi-wavelength view of Active Galactic Nuclei with an emphasis on γ-rays

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

- A broad look at AGN
- Blazars as (almost) the only γ-ray emitting AGN
- A multi-wavelength (and multi-messenger!) view of γ-ray AGN
- Open issues and the near future

*partly based of PP et al., Astr. & Astroph. Review, 2017, 25 and PP, Astr. & Astroph. Review, 2016, 24, 13



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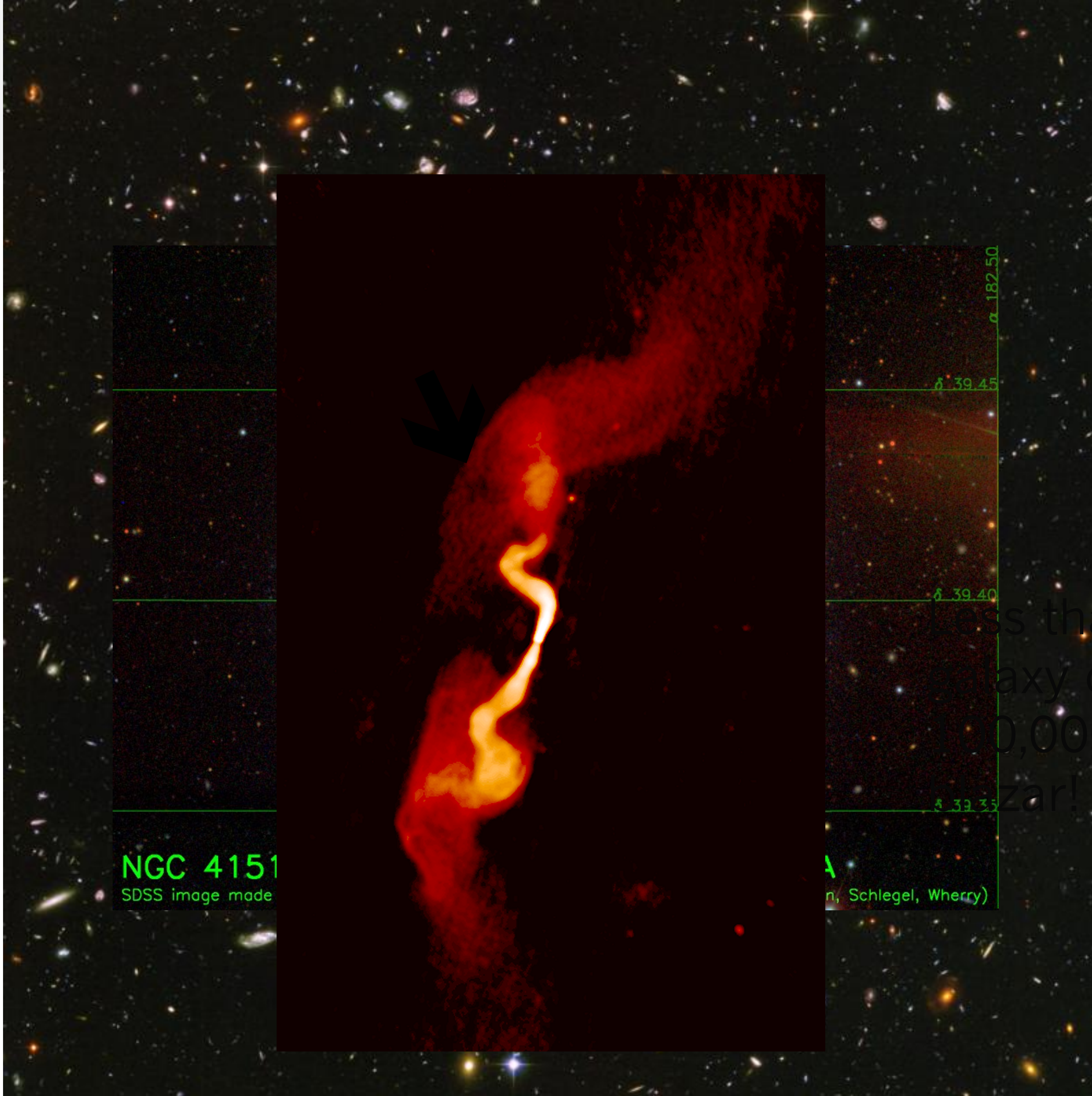

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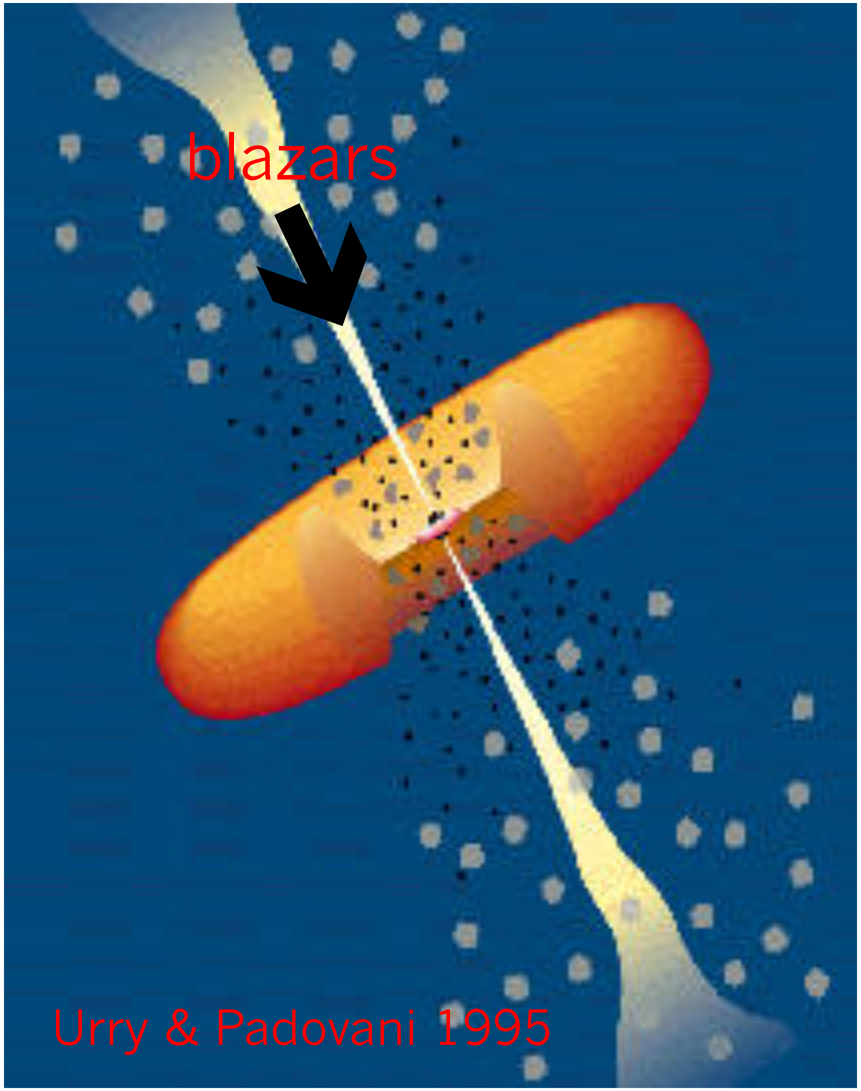
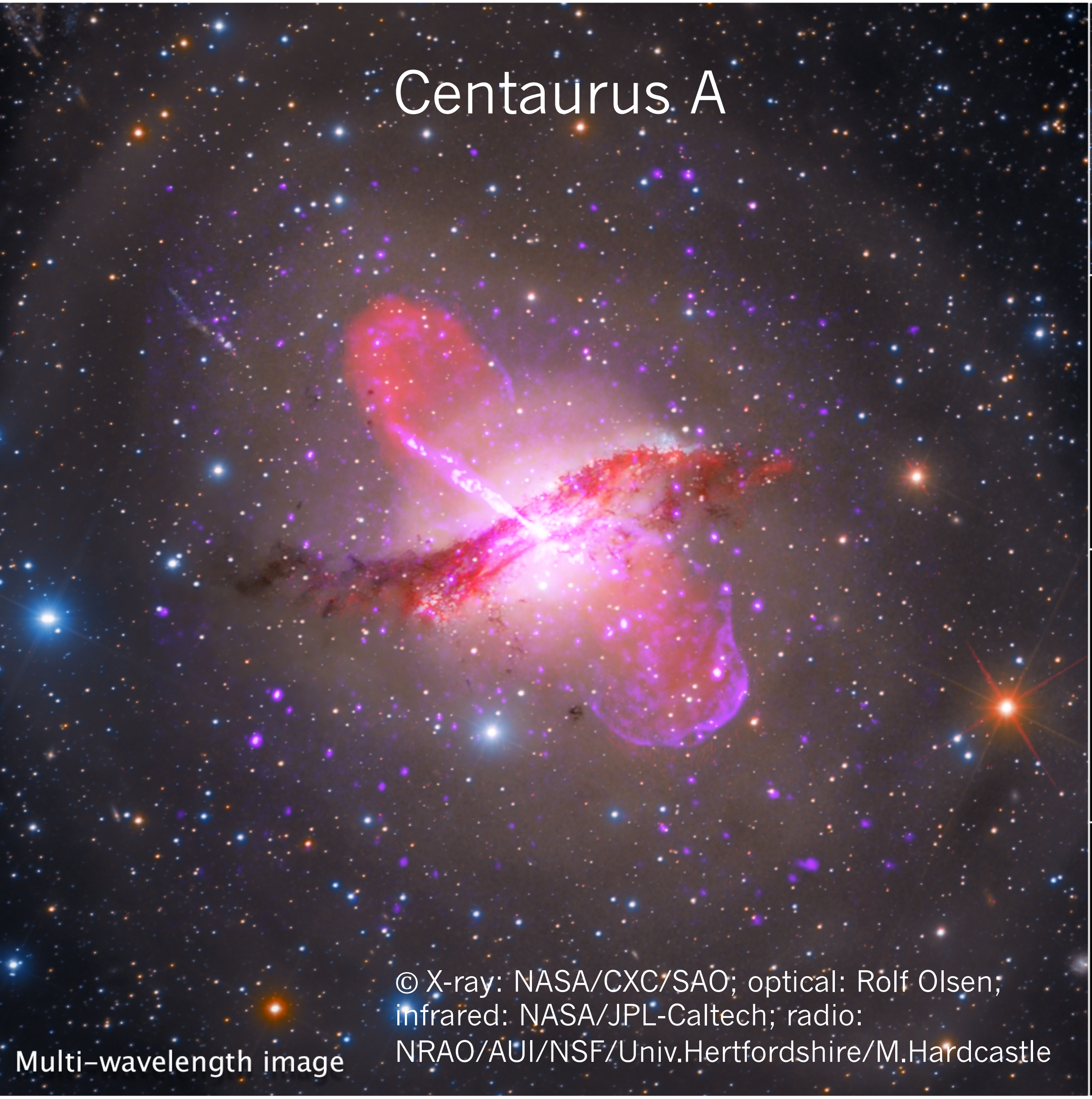
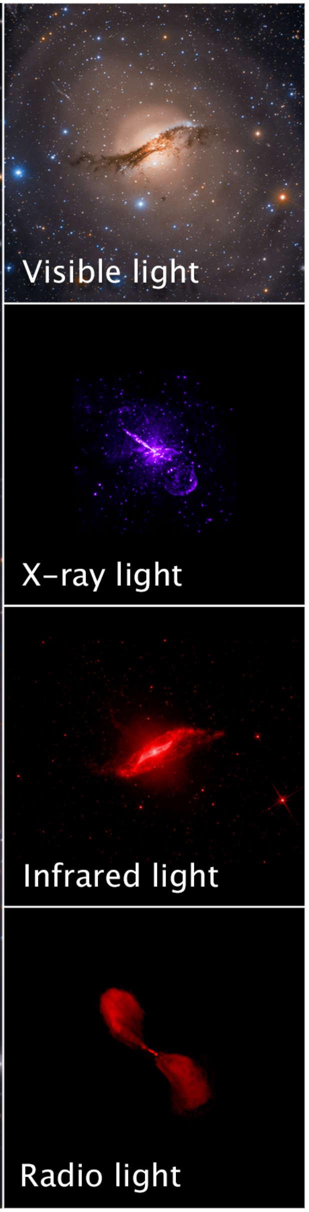
What are AGN?

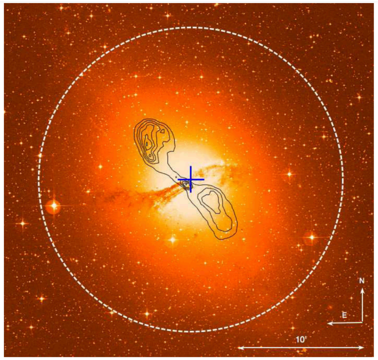


Less than 1 galaxy out of 100,000 is a blazar!

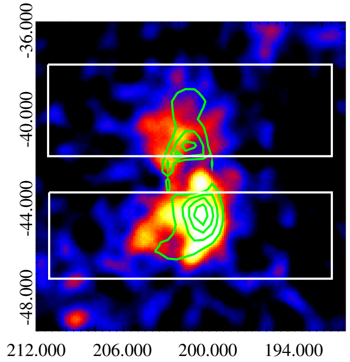
Why multi-wavelength?







Aharonian et al. (2009), E > 0.1 TeV [H.E.S.S.] (**nucleus**)

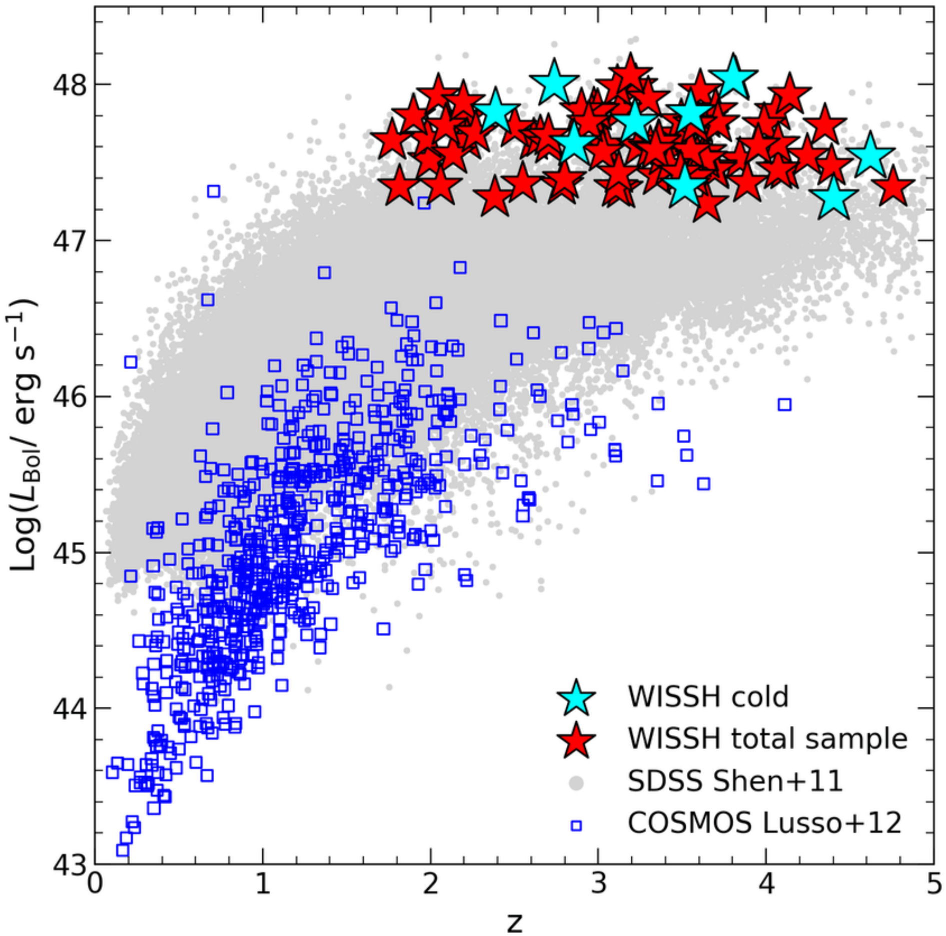


Yang et al. (2012), E < 3 GeV [*Fermi*] (**lobes**)

AGN overview

AGN main characteristics include:

1. High powers: most powerful "non-explosive" sources in the Univ … bright AGN (~ 10^{47} e … t galaxies!
   - ✓ visible … ecord z = 7.642 (Wan… 670 Myr old



Bischetti et al. 2021

AGN overview

AGN main characteristics include:

1. High powers: most powerful "non-explosive" sources in the Universe (up to 10^{48} erg/s) → bright AGN ($\sim 10^{47}$ erg/s) equivalent to $\simeq$ 1,000 bright galaxies!
   - ✓ visible up to large distances: current record z = 7.642 (Wang et al. 2021); Universe was only 670 Myr old
2. Small emitting regions: ≈ a few light days (1 lt-day = 2.6 10^{15} cm ≈ 1 millipc); $R \lesssim c\, t_{var}/(1+z)$
   - ✓ extremely large energy densities (= L/Volume)
3. Strong evolution: higher powers/numbers in the past, with peak at z ≈ 2

AGN overview

AGN main characteristics include:

1. High powers: most powerful "non-explosive" sources in the Universe (up to 10^{48} erg/s) → bright AGN (~ 10^{47} erg/s) equivalent to ≃ 1,000 bright galaxies!
   - ✓ visible up to large distances: current record z = 7.642 (Wang et al. 2021); Universe was only 670 Myr old
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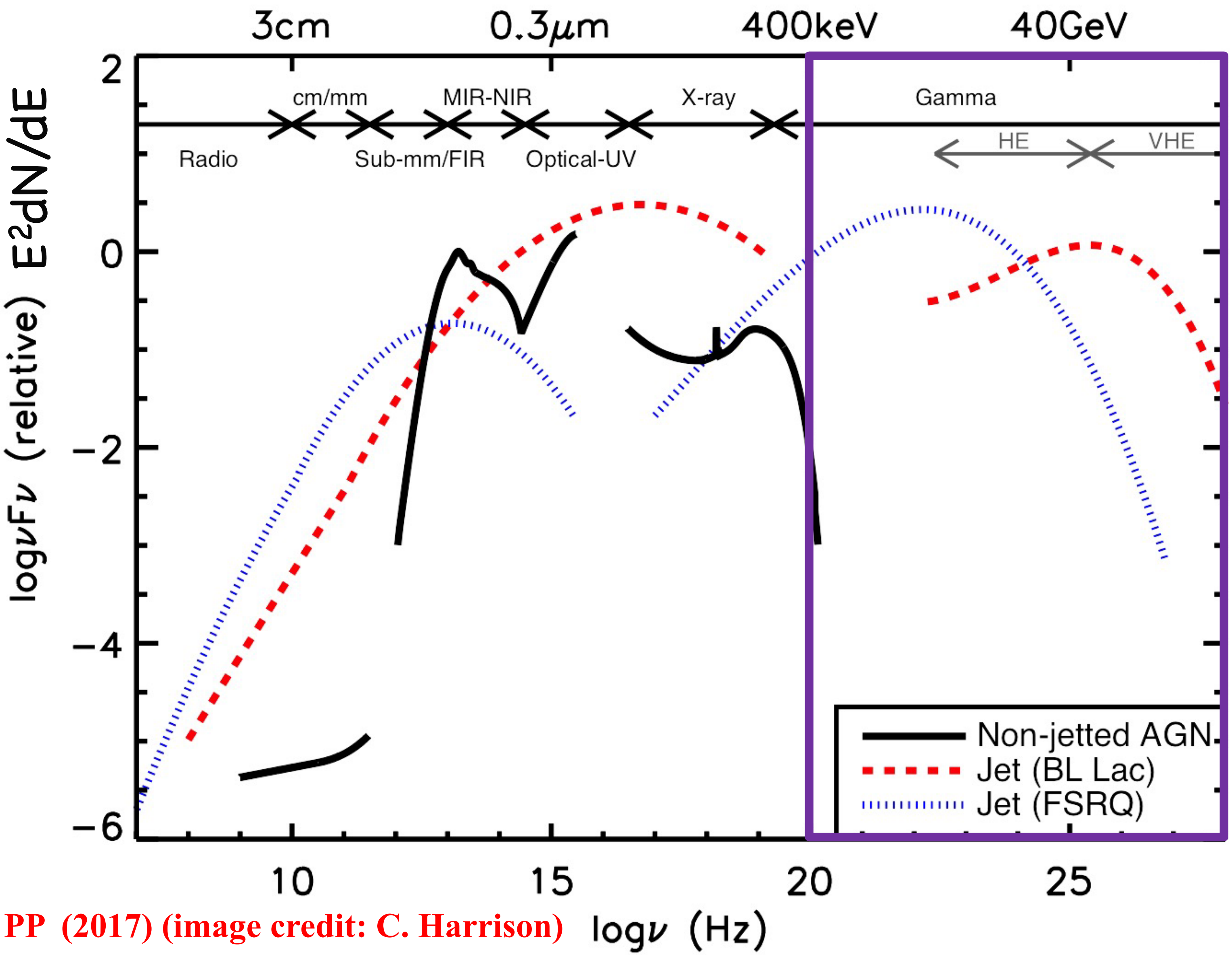
   - ✓ extremely large energy densities (= L/Volume)
3. Strong evolution: higher powers/numbers in the past, with peak at z ≈ 2
4. Broad-band emission: from the radio- to the γ-ray band (and more, into multi-messenger territory)

AGN overview



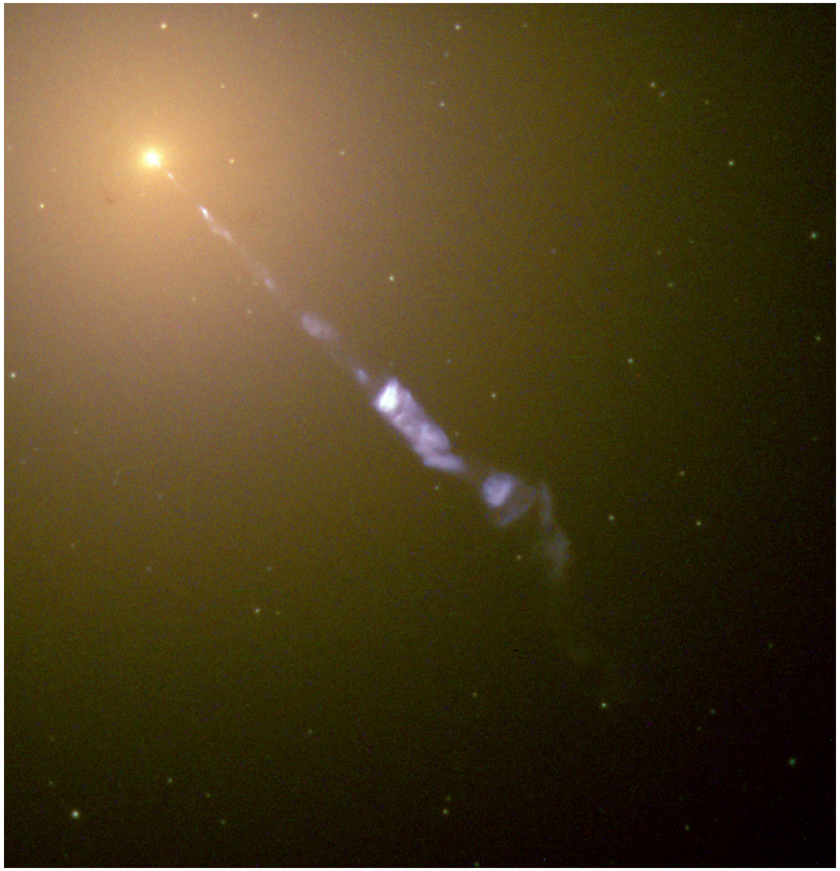
PP (2017) (image credit: C. Harrison)

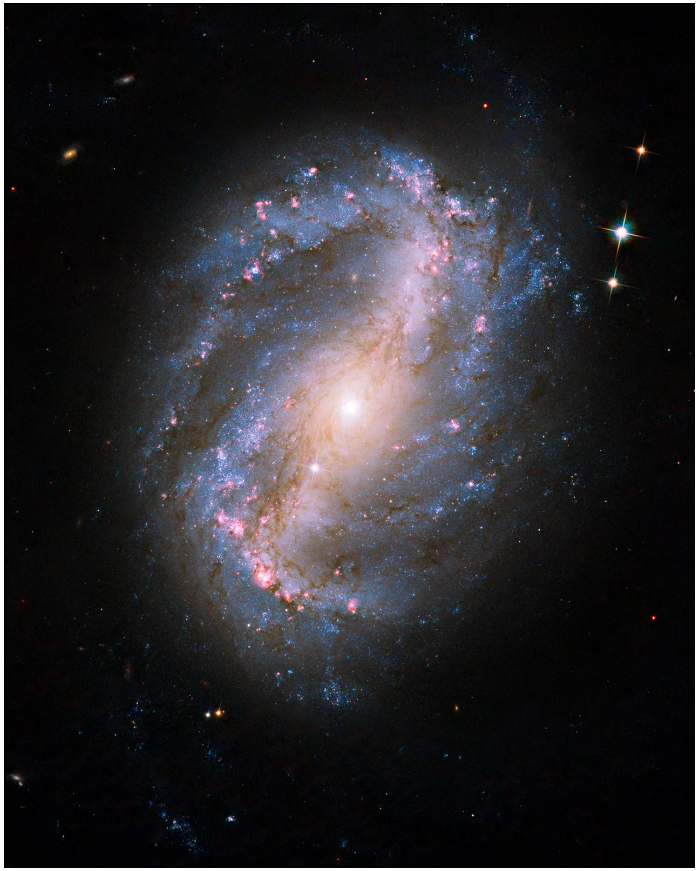
Table 1 The AGN zoo: list of AGN classes

Class/Acronym	Meaning	Main properties/reference
Quasar	Quasi-stellar radio source (originally)	Radio detection no longer required
Sey1	Seyfert 1	FWHM $\gtrsim 1,000$ km s^{-1}
Sey2	Seyfert 2	FWHM $\lesssim 1,000$ km s^{-1}
QSO	Quasi-stellar object	Quasar-like, non-radio source
QSO2	Quasi-stellar object 2	High power Sey2
RQ AGN	Radio-quiet AGN	see ref. 1
RL AGN	Radio-loud AGN	see ref. 1
Jetted AGN		with strong relativistic jets; see ref. 1
Non-jetted AGN		without strong relativistic jets; see ref. 1
Type 1		Sey1 and quasars
Type 2		Sey2 and QSO2
FR I	Fanaroff-Riley class I radio source	radio core-brightened (ref. 2)
FR II	Fanaroff-Riley class II radio source	radio edge-brightened (ref. 2)
BL Lac	BL Lacertae object	see ref. 3
Blazar	BL Lac and quasar	BL Lacs and FSRQs
BAL	Broad absorption line (quasar)	ref. 4
BLO	Broad-line object	FWHM $\gtrsim 1,000$ km s^{-1}
BLAGN	Broad-line AGN	FWHM $\gtrsim 1,000$ km s^{-1}
BLRG	Broad-line radio galaxy	RL Sey1
CDQ	Core-dominated quasar	RL AGN, $f_{core} \geq f_{ext}$ (same as FSRQ)
CSS	Compact steep spectrum radio source	core dominated, $\alpha_r > 0.5$
CT	Compton-thick	$N_H \geq 1.5 \times 10^{24}$ cm^{-2}
FR 0	Fanaroff-Riley class 0 radio source	ref. 5
FSRQ	Flat-spectrum radio quasar	RL AGN, $\alpha_r \leq 0.5$
GPS	Gigahertz-peaked radio source	see ref. 6
HBL/HSP	High-energy cutoff BL Lac/blazar	$\nu_{synch\ peak} \geq 10^{15}$ Hz (ref. 7)
HEG	High-excitation galaxy	ref. 8
HPQ	High polarization quasar	$P_{opt} \geq 3\%$ (same as FSRQ)
Jet-mode		$L_{kin} \gg L_{rad}$ (same as LERG); see ref. 9
IBL/ISP	Intermediate-energy cutoff BL Lac/blazar	$10^{14} \leq \nu_{synch\ peak} \leq 10^{15}$ Hz (ref. 7)
LINER	Low-ionization nuclear emission-line regions	see ref. 9
LLAGN	Low-luminosity AGN	see ref. 10
LBL/LSP	Low-energy cutoff BL Lac/blazar	$\nu_{synch\ peak} < 10^{14}$ Hz (ref. 7)
LDQ	Lobe-dominated quasar	RL AGN, $f_{core} < f_{ext}$
LEG	Low-excitation galaxy	ref. 8
LPQ	Low polarization quasar	$P_{opt} < 3\%$
NLAGN	Narrow-line AGN	FWHM $\lesssim 1,000$ km s^{-1}
NLRG	Narrow-line radio galaxy	RL Sey2
NLS1	Narrow-line Seyfert 1	ref. 11
OVV	Optically violently variable (quasar)	(same as FSRQ)
Population A		ref. 12
Population B		ref. 12
Radiative-mode		Seyferts and quasars; see ref. 9
RBL	Radio-selected BL Lac	BL Lac selected in the radio band
Sey1.5	Seyfert 1.5	ref. 13
Sey1.8	Seyfert 1.8	ref. 13
Sey1.9	Seyfert 1.9	ref. 13
SSRQ	Steep-spectrum radio quasar	RL AGN, $\alpha_r > 0.5$
USS	Ultra-steep spectrum source	RL AGN, $\alpha_r > 1.0$
XBL	X-ray-selected BL Lac	BL Lac selected in the X-ray band
XBONG	X-ray bright optically normal galaxy	AGN only in the X-ray band/weak lined AGN

PP et al. (2017)

Jetted vs. non-jetted AGN





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

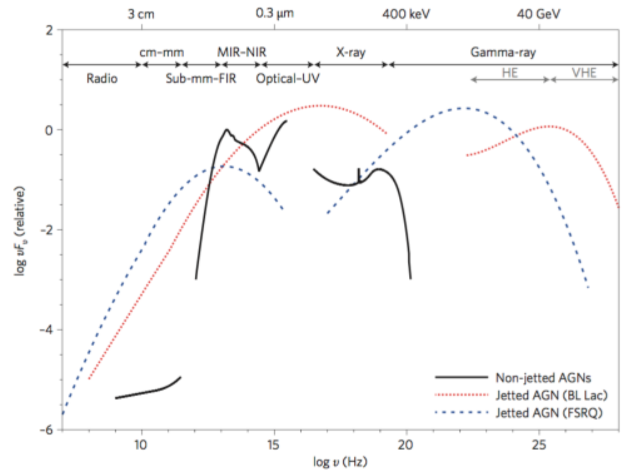
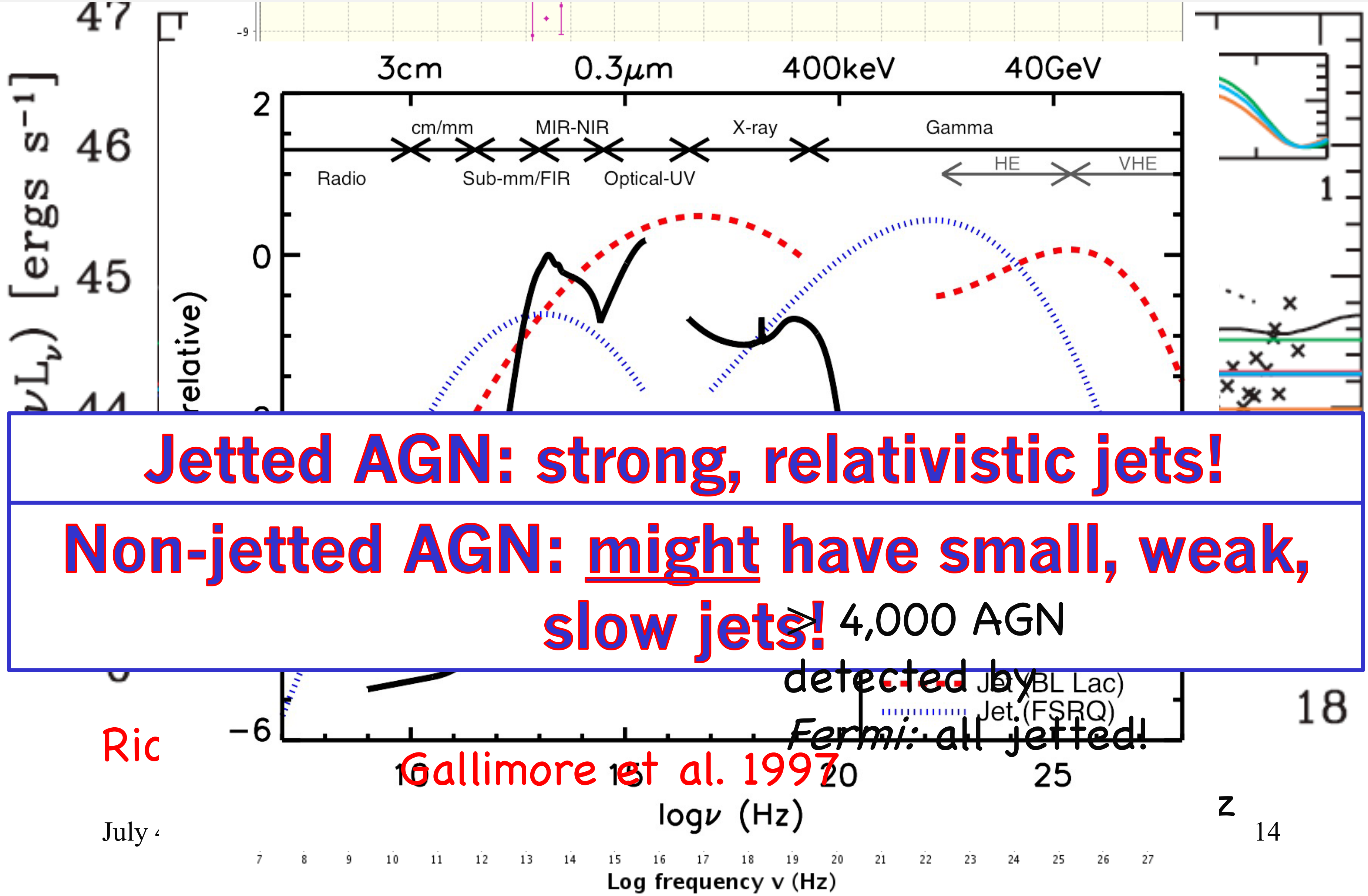


Figure 1 | A schematic representation of the SEDs of AGNs. The black solid curve represents the typical SED of non-jetted AGNs, while the dotted red and dashed blue lines refer to two jetted AGNs, a BL Lac (based on the SED of Mrk 421) and a flat-spectrum radio quasar (based on the SED of 3C 454.3), 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 jetted – non-jetted AGN dichotomy

- Two main classes:
  - ✓ jetted AGN emit a *large fraction* of their energy non-thermally and in association with powerful relativistic jets
  - ✓ the multi-wavelength emission of non-jetted AGN is *dominated* by thermal emission, directly or indirectly related to the accretion disk
- Strongest argument comes from hard X-rays–γ-rays

The jetted – non-jetted AGN dichotomy

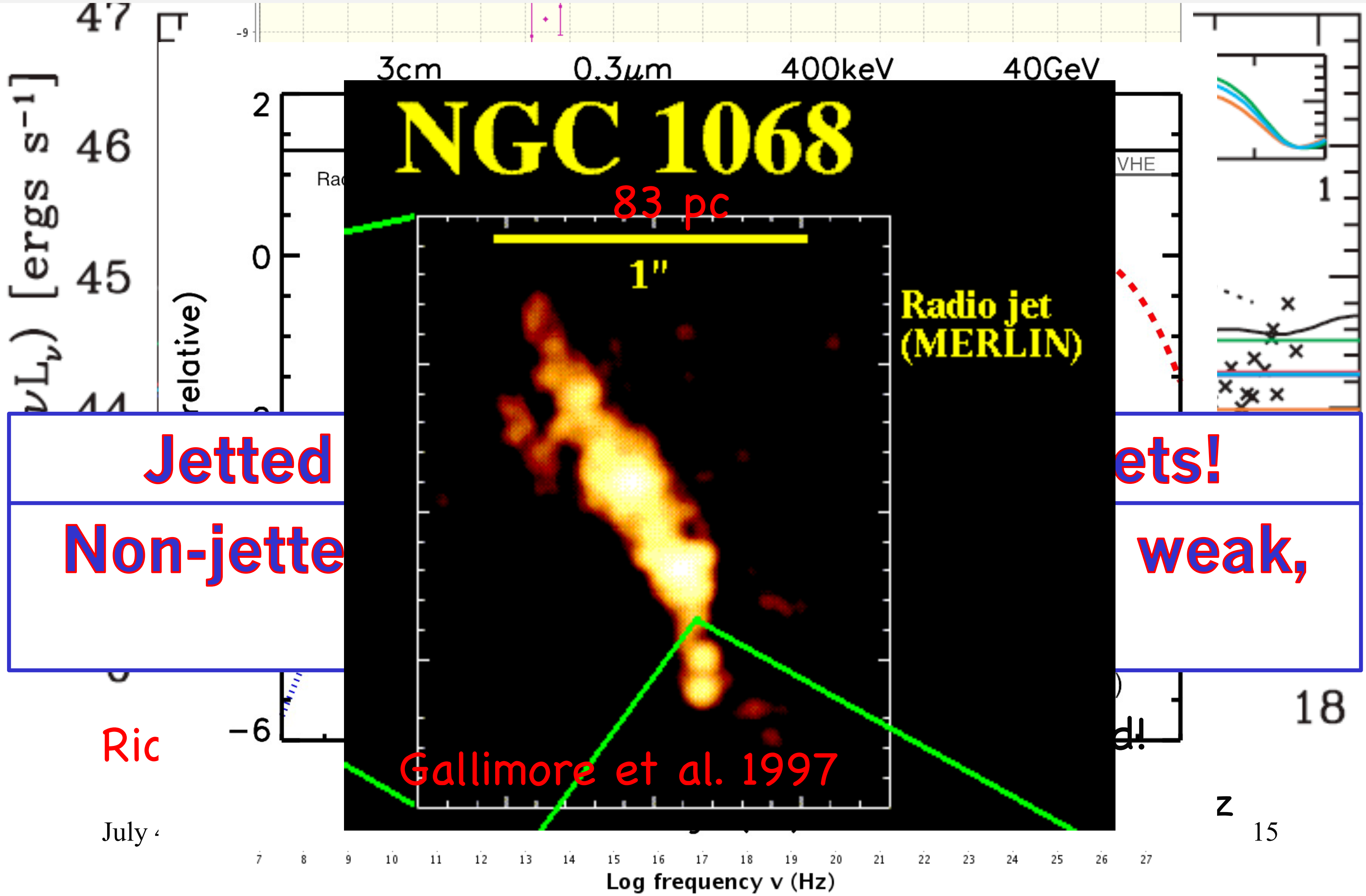


Jetted AGN: strong, relativistic jets!

Non-jetted AGN: <u>might</u> have small, weak, slow jets!

Ric

The jetted – non-jetted AGN dichotomy

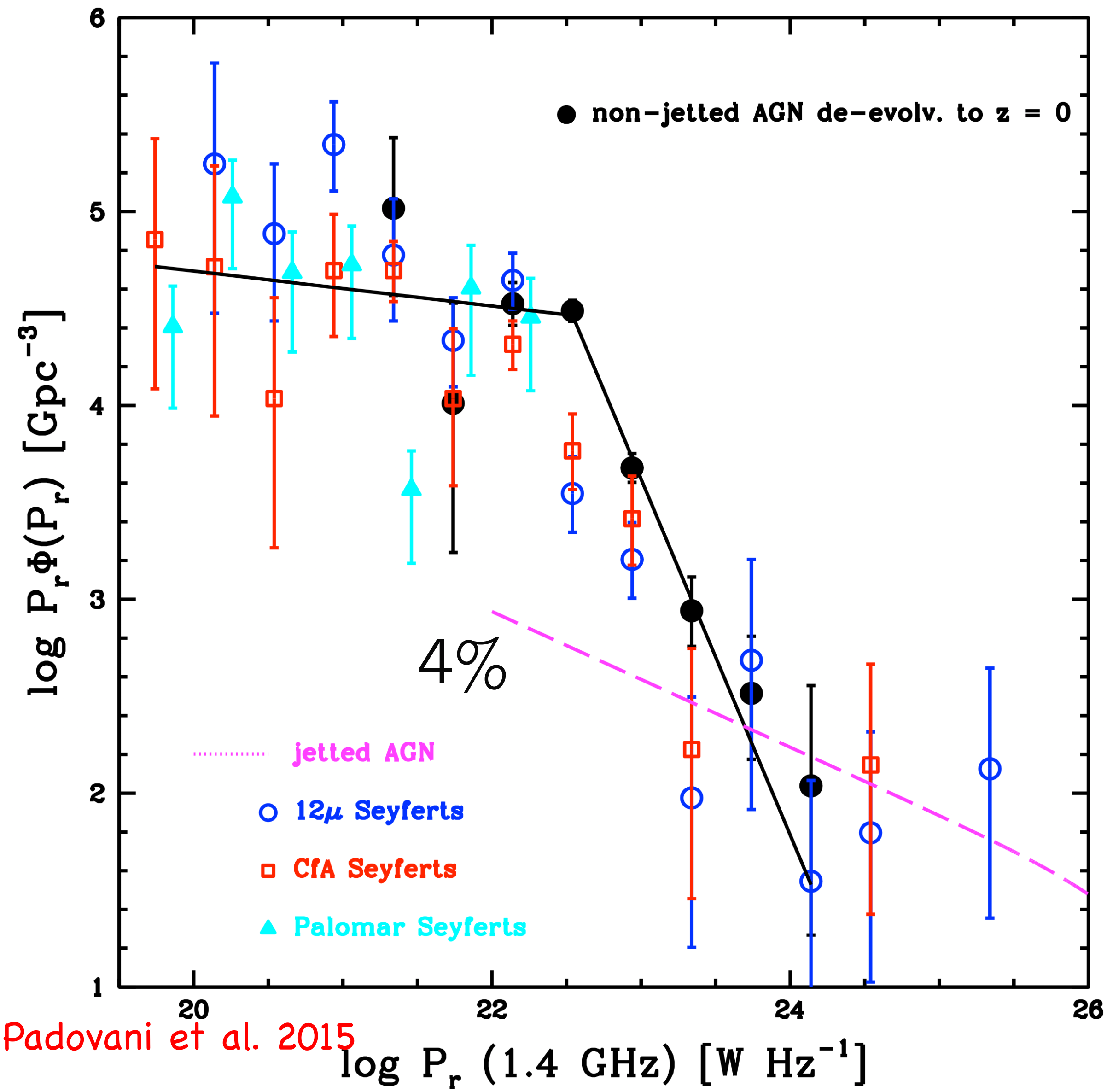


Jetted AGN are the exception

- "Classic" fraction of jetted (~~radio-loud~~) AGN is ≈ 10% (Kellermann et al. 1989)
  - ✓ based on Palomar-Green sample (UV-selected quasars)
  - ✓ biased as jetted AGN more powerful than non-jetted ones in optical band
- Real value more likely $\lesssim$ 1% (Padovani 2011; Padovani et al. 2015)

Jetted AGN are the exception

- "Clas GN is ≈ 10%
  - ✓ -selected
  - ✓ than
- Real l1; Padc



adapted from Padovani et al. 2015

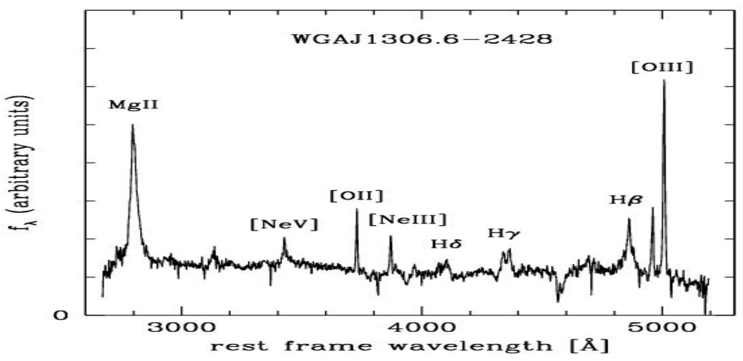
The importance of being a blazar (especially for this meeting)

- Blazars make up > 55% (and likely $\lesssim$ 90%) of the *Fermi* (50 MeV – 1 TeV) sky

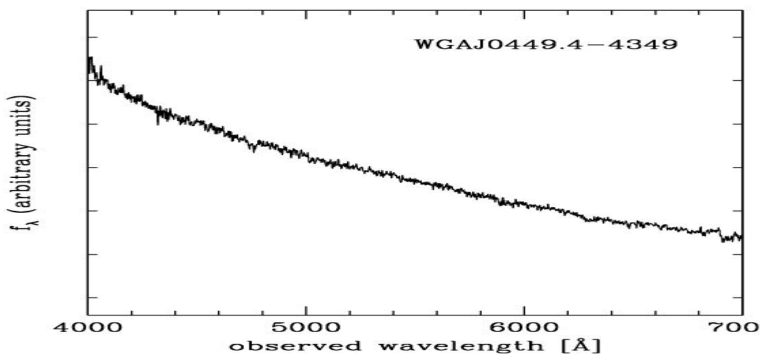
- About 90% of extragalactic sources with E > 1 TeV are blazars

The two main flavours of blazars

Flat-Spectrum Radio Quasars

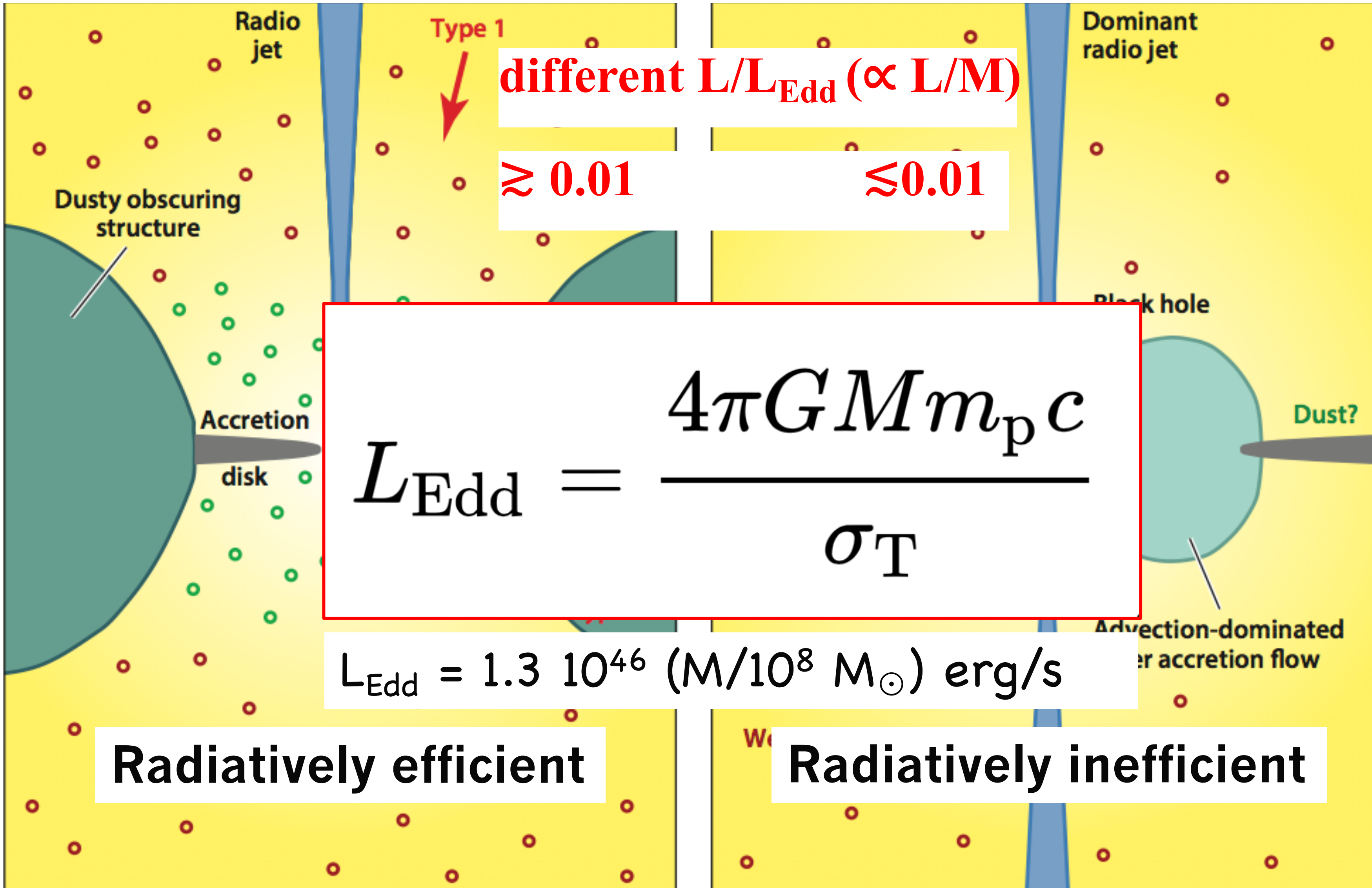


BL Lacertae objects



Accretion efficiency

Heckman & Best 2014



different L/L_{Edd} ($\propto$ L/M)

$\gtrsim 0.01$ $\lesssim 0.01$

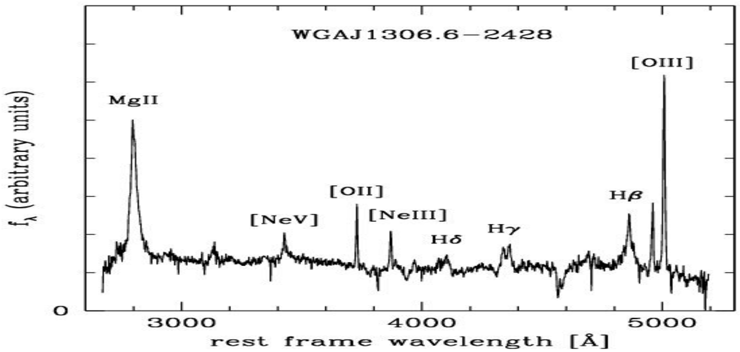
$$L_{\rm Edd} = \frac{4\pi G M m_{\rm p} c}{\sigma_{\rm T}}$$

$L_{Edd} = 1.3\ 10^{46}\ (M/10^{8}\ M_{\odot})$ erg/s

Radiatively efficient **Radiatively inefficient**

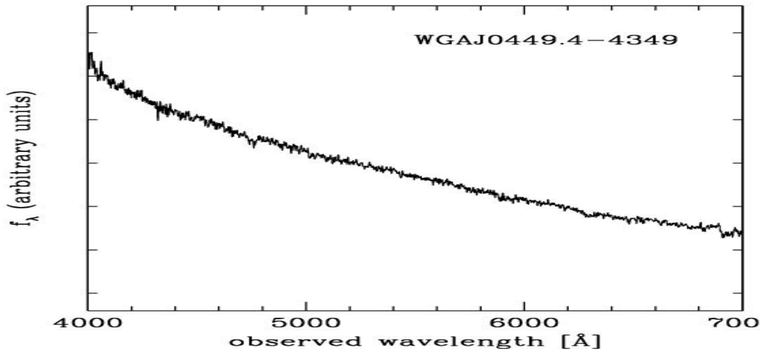
The two main flavours of blazars

Flat-Spectrum Radio Quasars



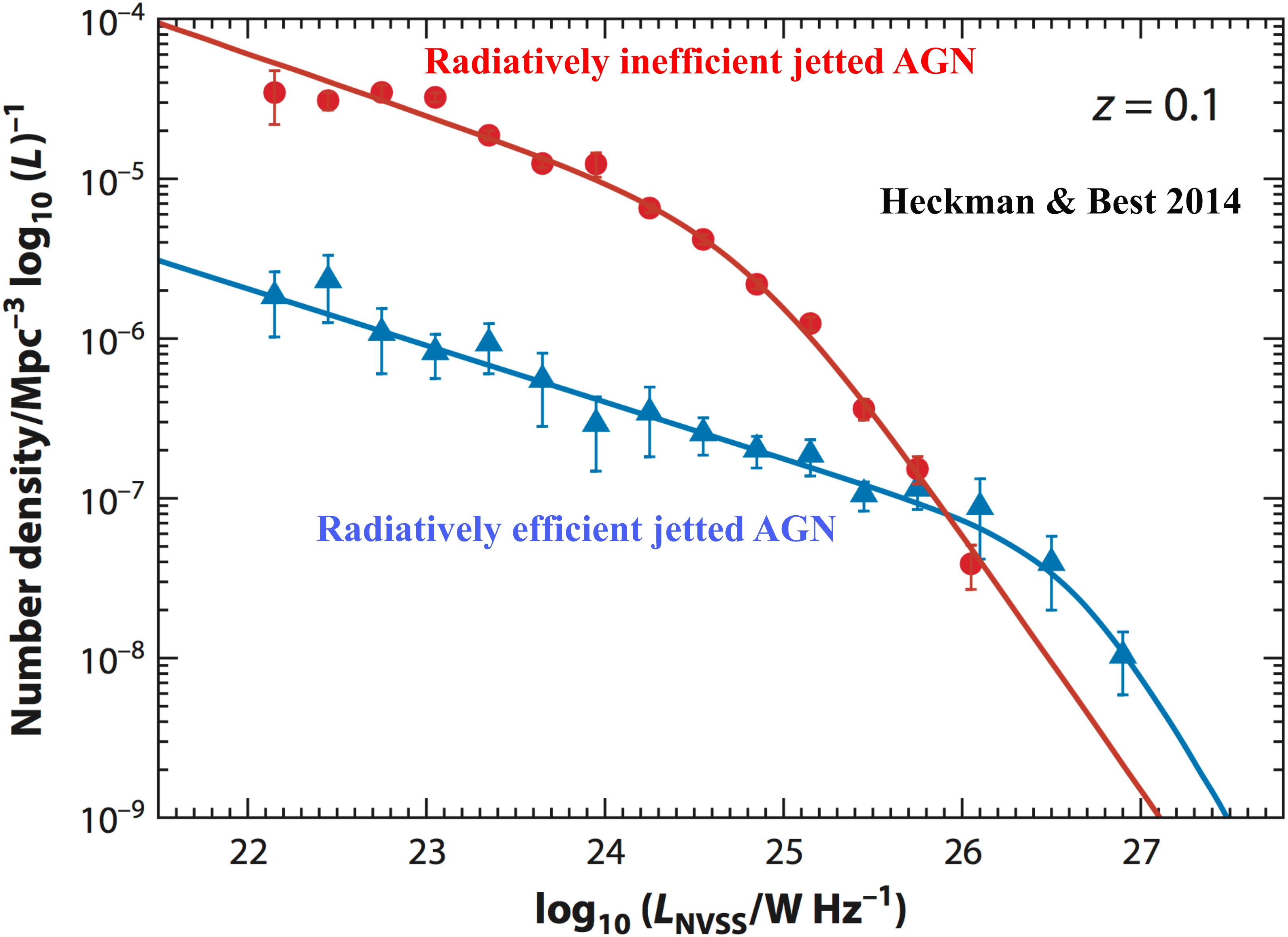
High-excitation galaxies

BL Lacertae objects



Low-excitation galaxies

Radiatively efficient AGN are the exception

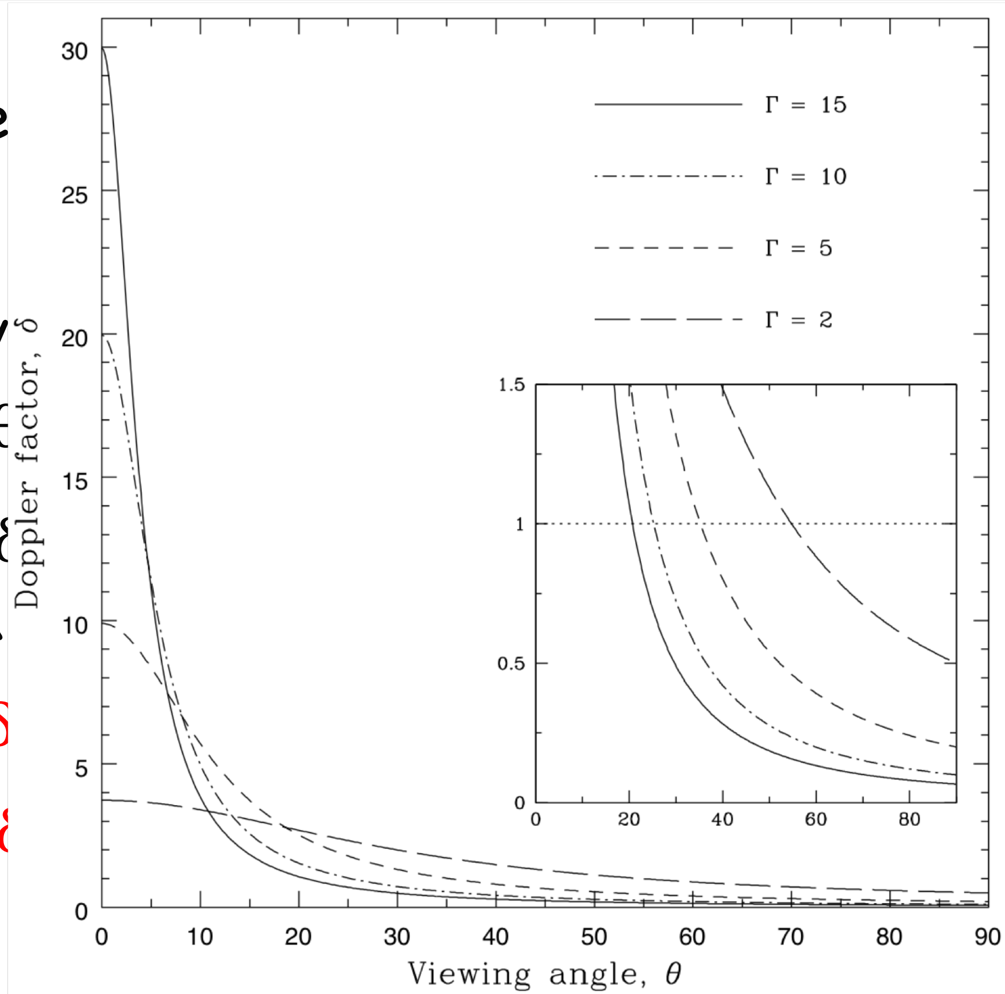


What about radio galaxies?

- Blazars are relativistically beamed (Doppler boosted)
  - ✓ $\Gamma = (1 - \beta^2)^{-1/2}$ (Lorentz factor), $\beta = v/c$
  - ✓ $\delta = 1/[\Gamma(1 - \beta\cos\theta)]$ (Doppler factor): small θ, $\delta \sim 2\Gamma$
  - ✓ $\nu_{obs} = \delta\nu_{em}$ + I_ν/ν^3 (I_ν = specific intensity) relativistic invariant → $L_{obs} = \delta^3 L_{em}$ ($L_{obs} = \delta^{p+\alpha} L_{em}$, $p \sim 2 - 3$)
- $\Gamma = 10$ → $\delta \sim 20$, $L_{obs} \sim 400 - 8{,}000\ L_{em}$;
- $\Gamma = 30$ → $\delta \sim 60$, $L_{obs} \sim 4{,}000 - 200{,}000\ L_{em}$

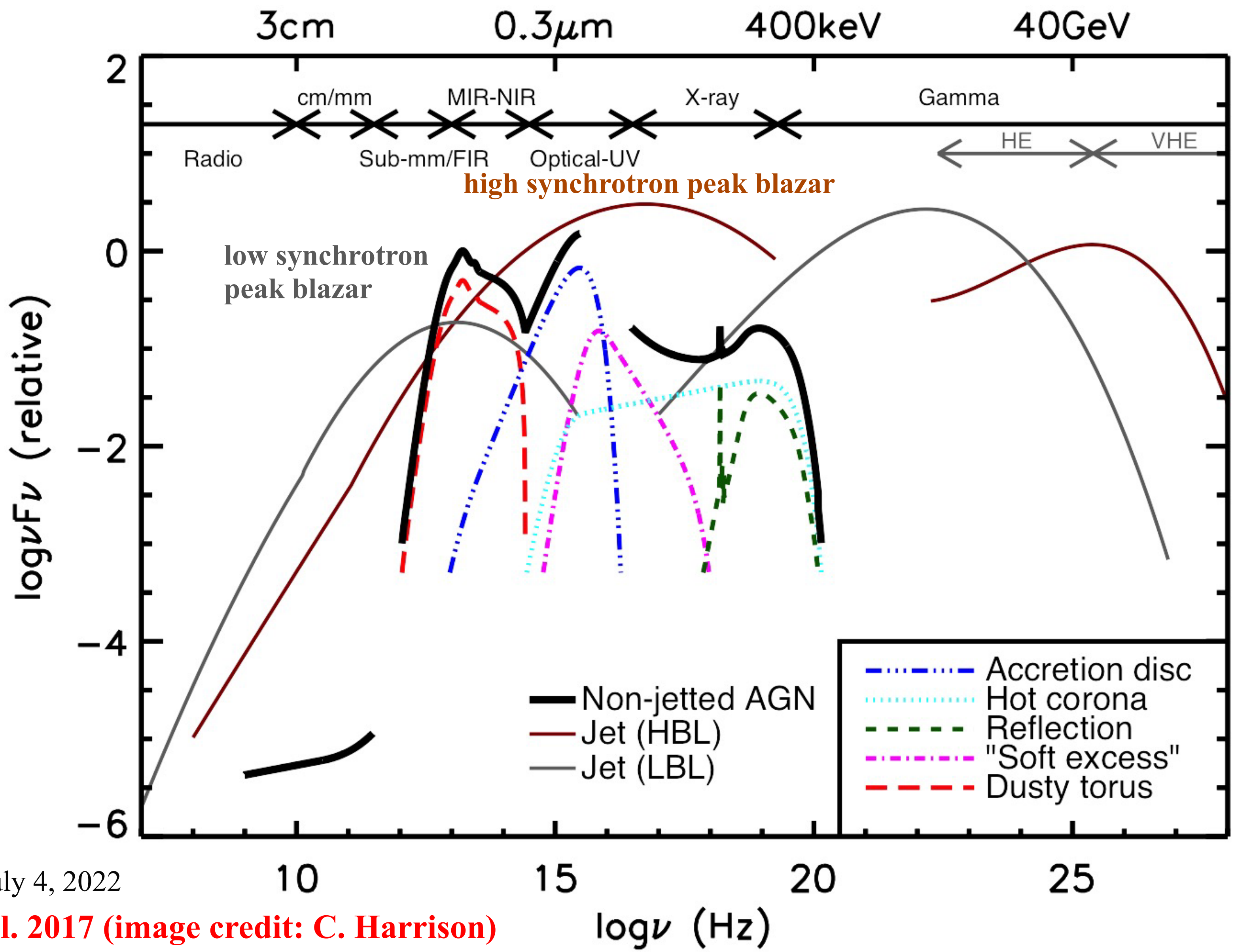
What about radio galaxies?

- Blazars are … oosted)
  - ✓ Γ = (1
  - ✓ δ = 1/ … small θ
  - ✓ ν_{obs} = δ … relativistic invaria … ~ 2 – 3)
- Γ = 10 → δ
- Γ = 30 → δ … m



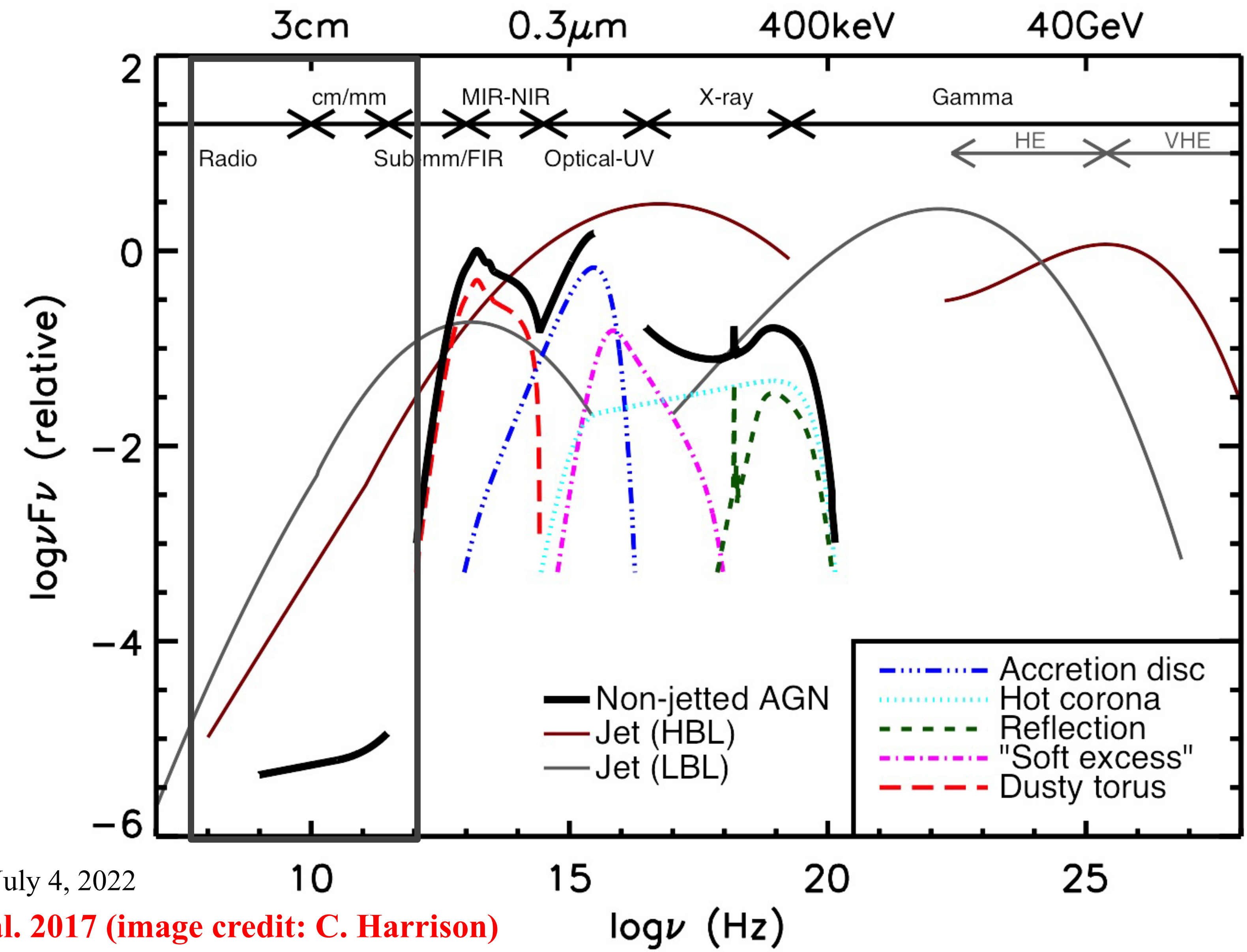
(Urry & Padovani 1995)

The AGN SED



PP et al. 2017 (image credit: C. Harrison)

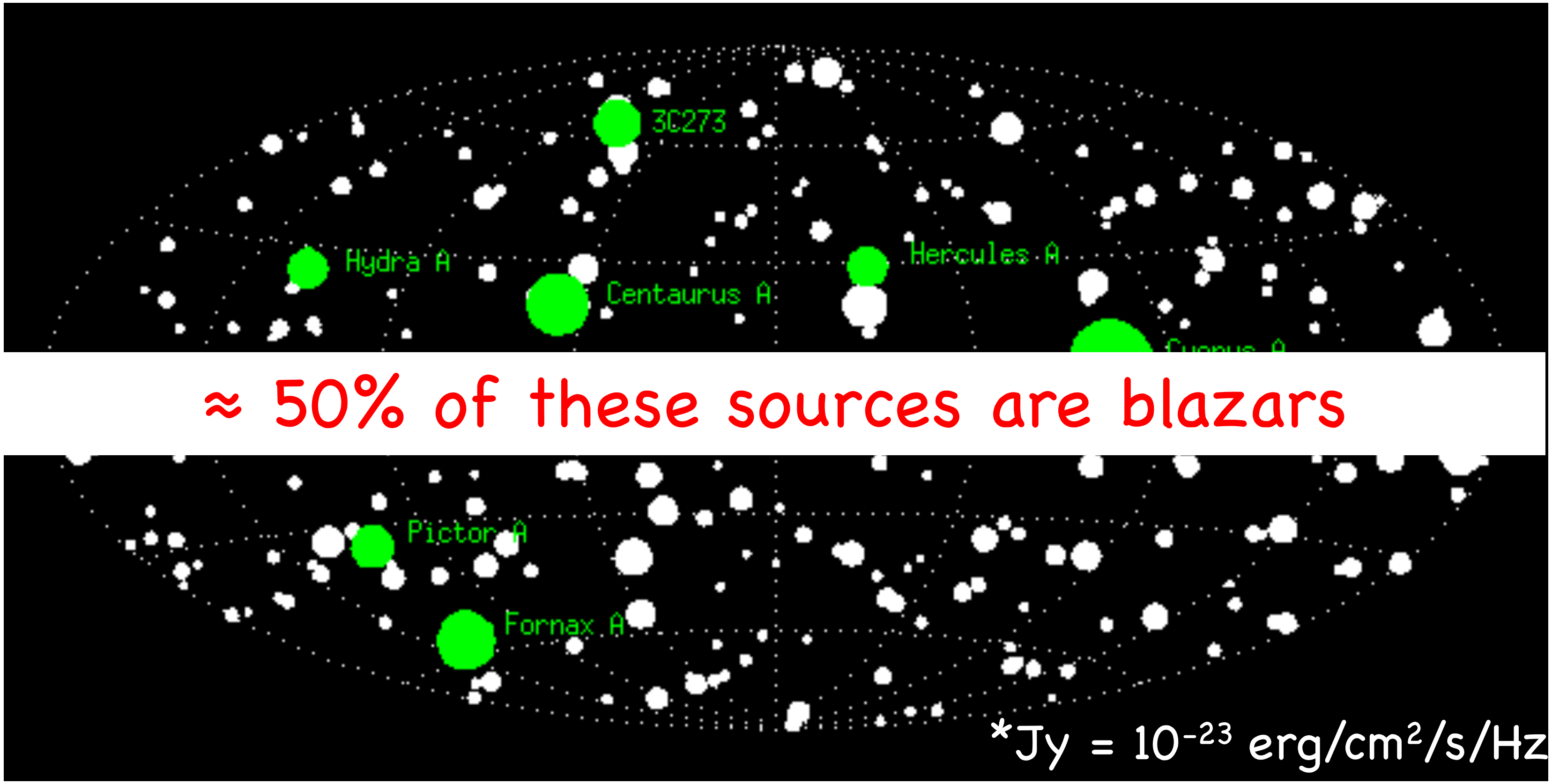
The AGN SED: the radio band



PP et al. 2017 (image credit: C. Harrison)

Radio-selected AGN

Brightest extragalactic radio sources (> 2 Jy* @ 2.7 GHz: Wall & Peacock 1985)



≈ 50% of these sources are blazars

*Jy = 10^{-23} erg/cm²/s/Hz

The radio band (@ ≈ 1 GHz)

- Flux densities $\gtrsim$ **1 mJy**:
  - ✓ sources: **jetted AGN** [mostly blazars (both flavours) and radio-galaxies]
  - ✓ selection done by just observing the sky as AGN are (basically) the only sources (only band; stars are weak radio emitters)
  - ✓ physics: **jet** (synchrotron emission)

The radio band (@ ≈ 1 GHz)

- Flux densities $\lesssim$ **1 mJy**:
  ✓ sources: both **non-jetted AGN** [dominant type] and (a decreasing fraction of) **jetted AGN**
  ✓ selection done by using multi-wavelength data to separate AGN (especially non-jetted ones) from star-forming galaxies (optical counterparts faint)
  ✓ physics: **jet** (jetted AGN) and **star formation** [Supernova Remnants] plus possibly **corona, mini-jets and winds** (non-jetted AGN)

The radio band (@ ≈ 1 GHz)

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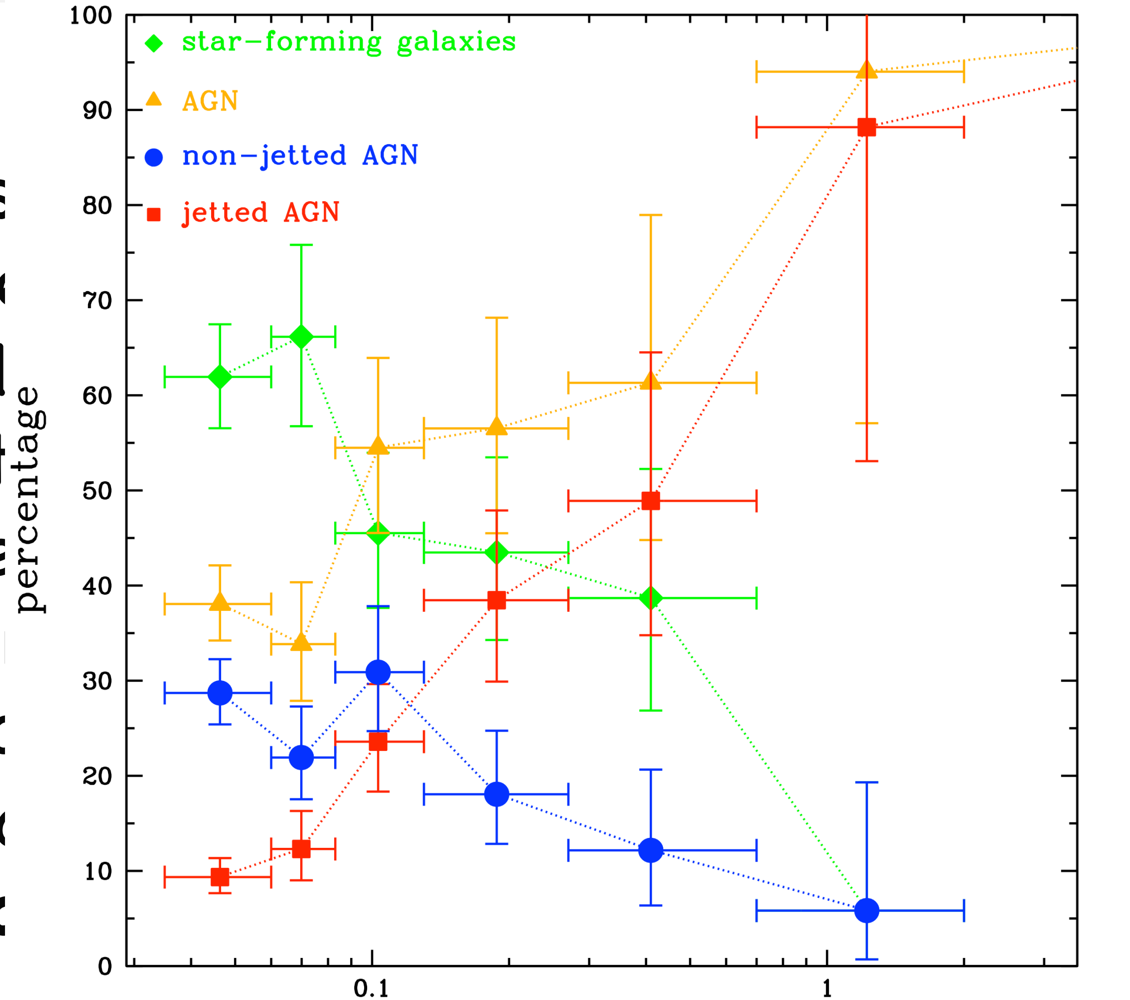

nt type]
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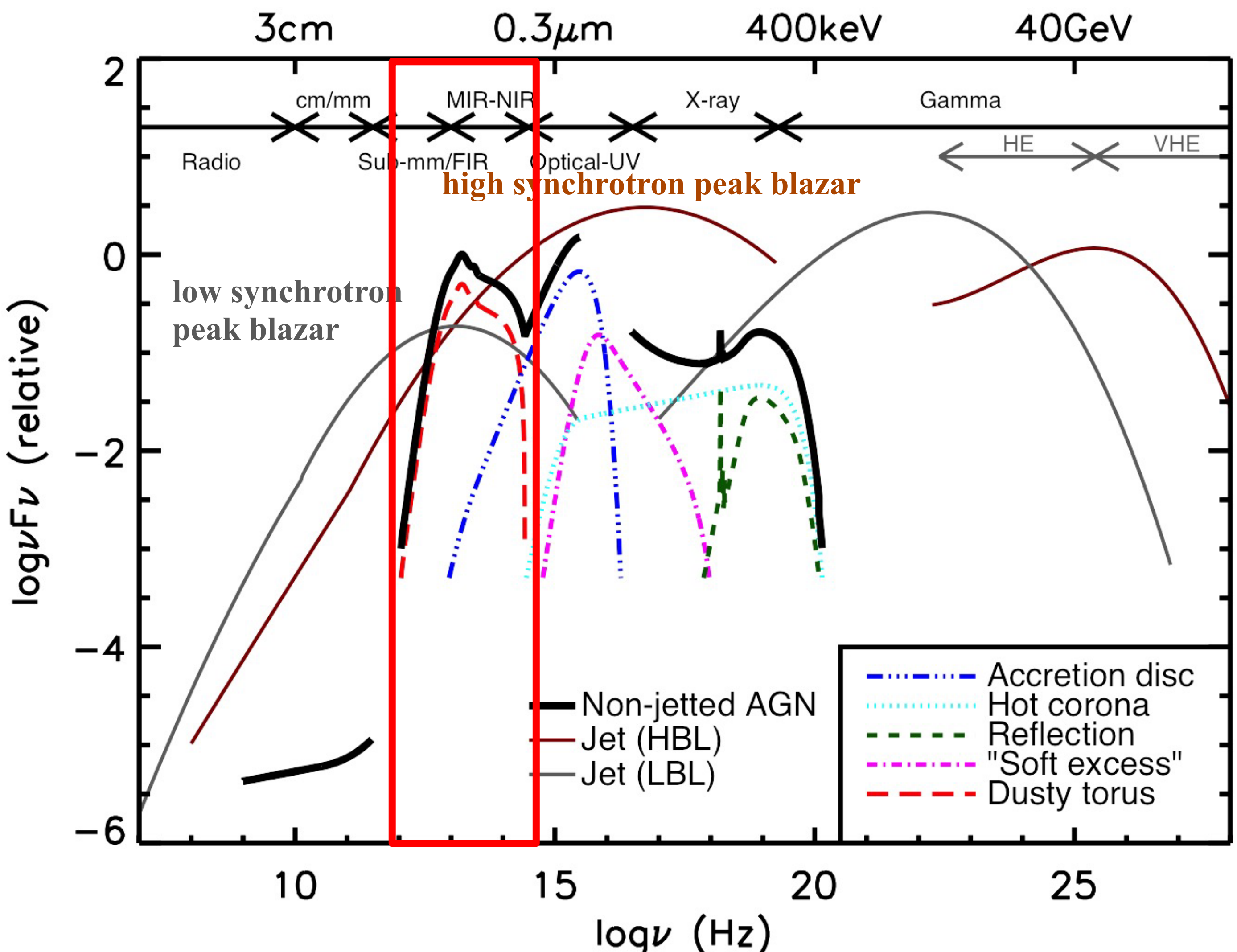
[mJy] PP (2016)

Below 0.1 mJy the radio sky is dominated by star-formation-related processes!

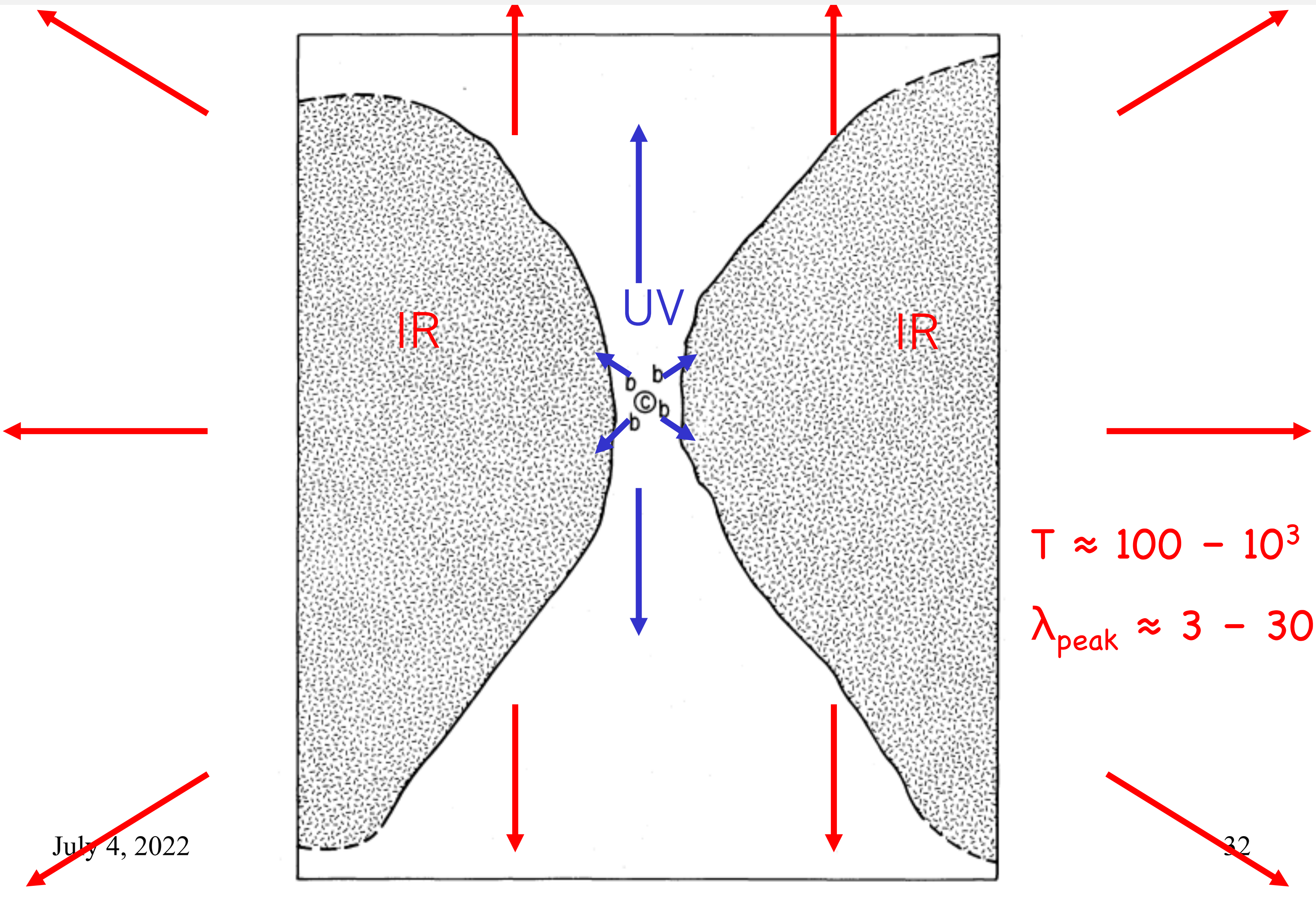
The AGN SED: the infrared band



PP et al. 2017 (image credit: C. Harrison)

AGN dust emission

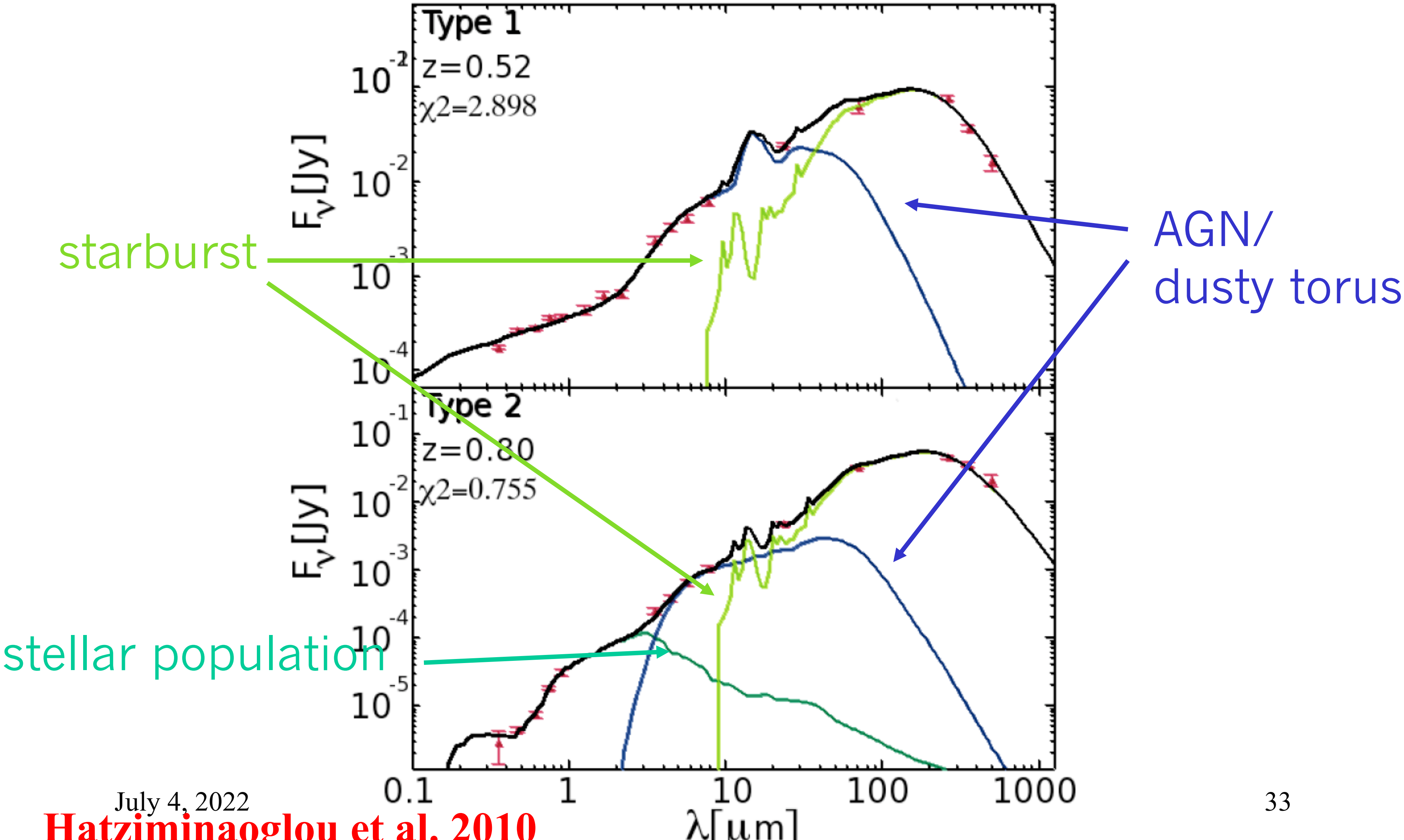
Antonucci & Miller (1985)



$T \approx 100 - 10^3$ K

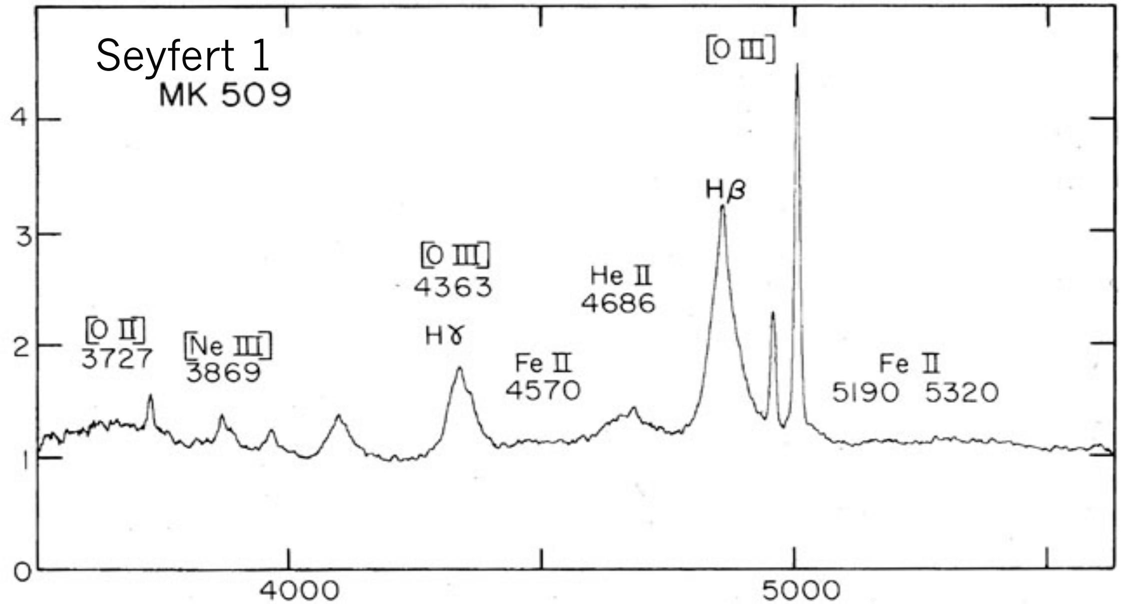
$\lambda_{peak} \approx 3 - 30\mu m$

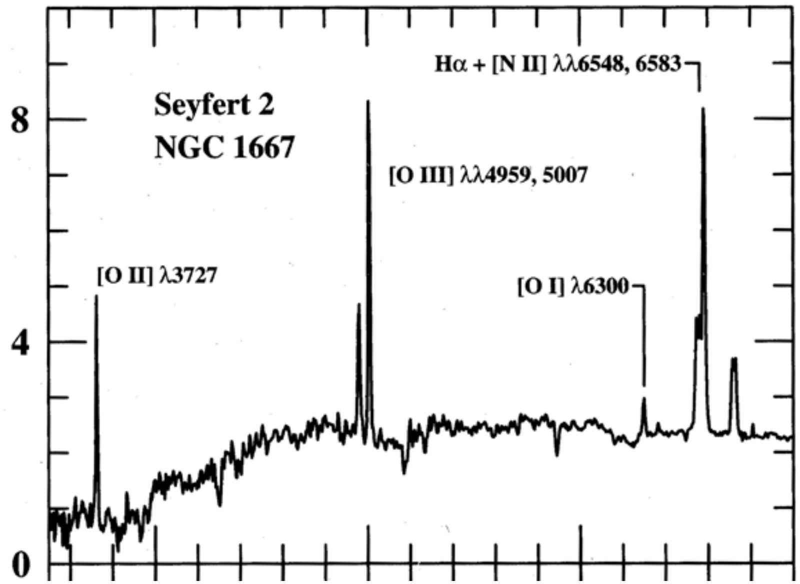
AGN and host galaxy IR emission



Hatziminaoglou et al. 2010

Seyfert 1's and 2's

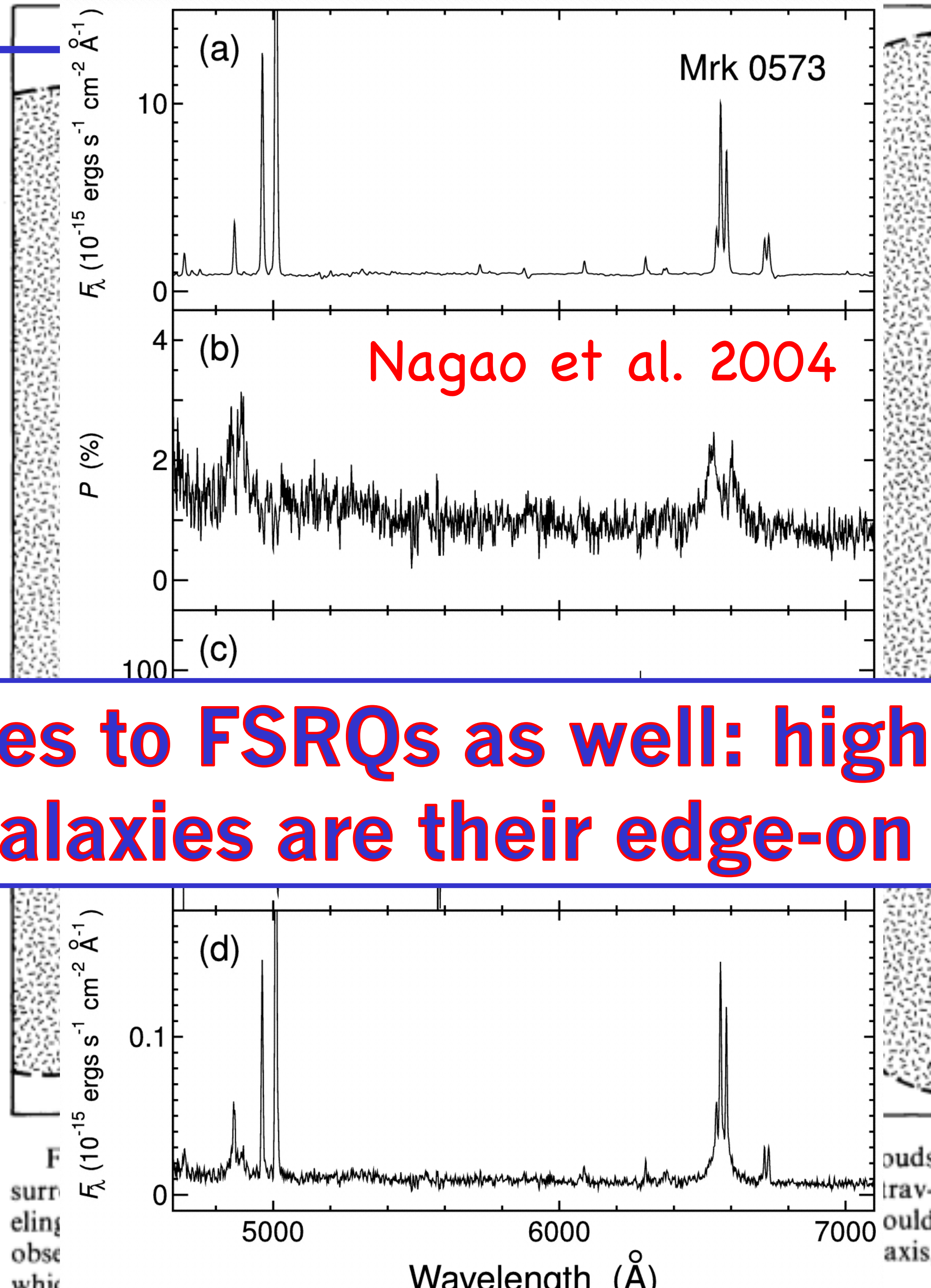




Narrow lines: full width at half maximum < 1,000 km/s

Antonucci & Miller (1985)

Seyfert 2

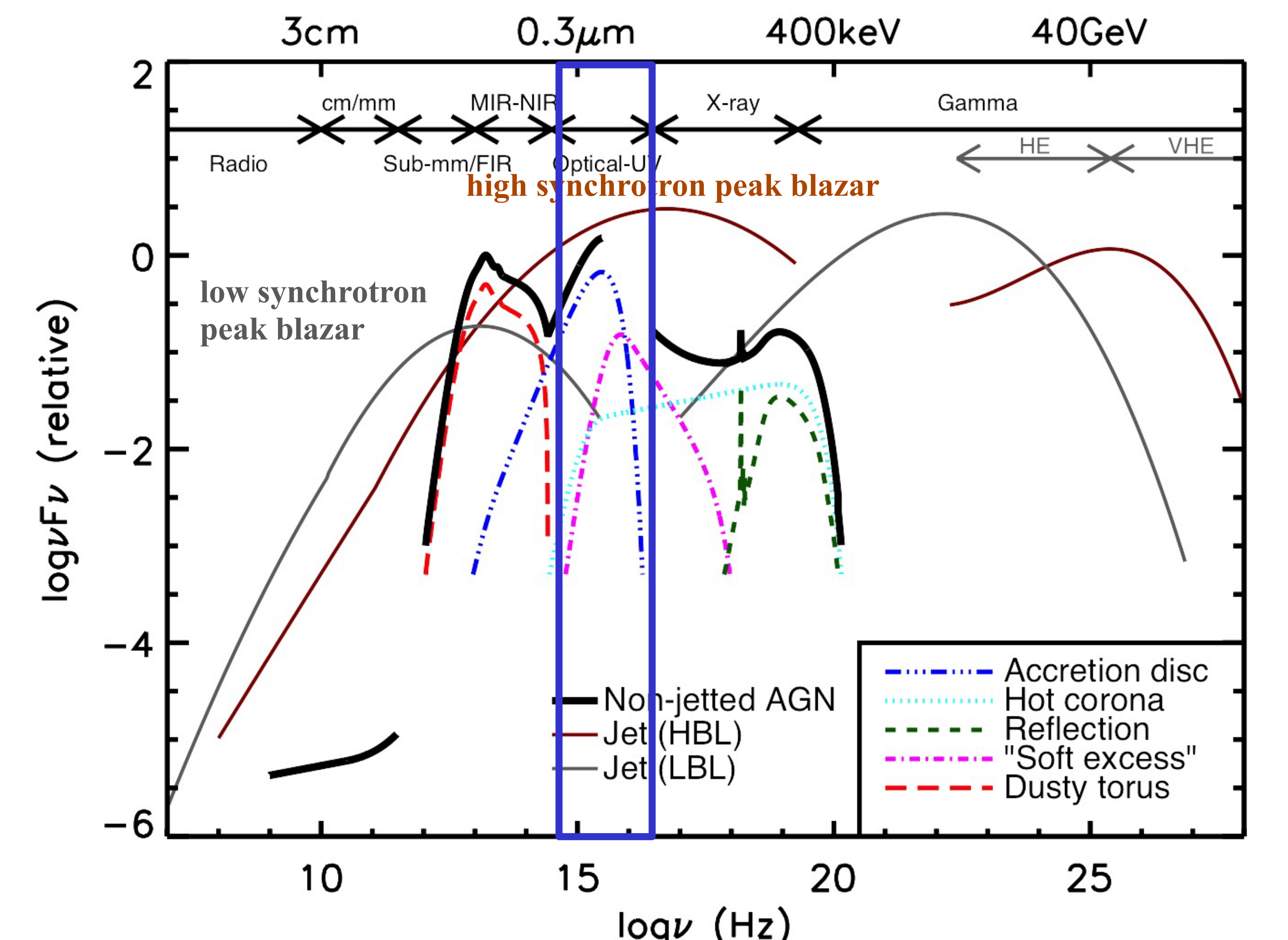


This applies to FSRQs as well: high-excitation radio galaxies are their edge-on version

The (near-)infrared band

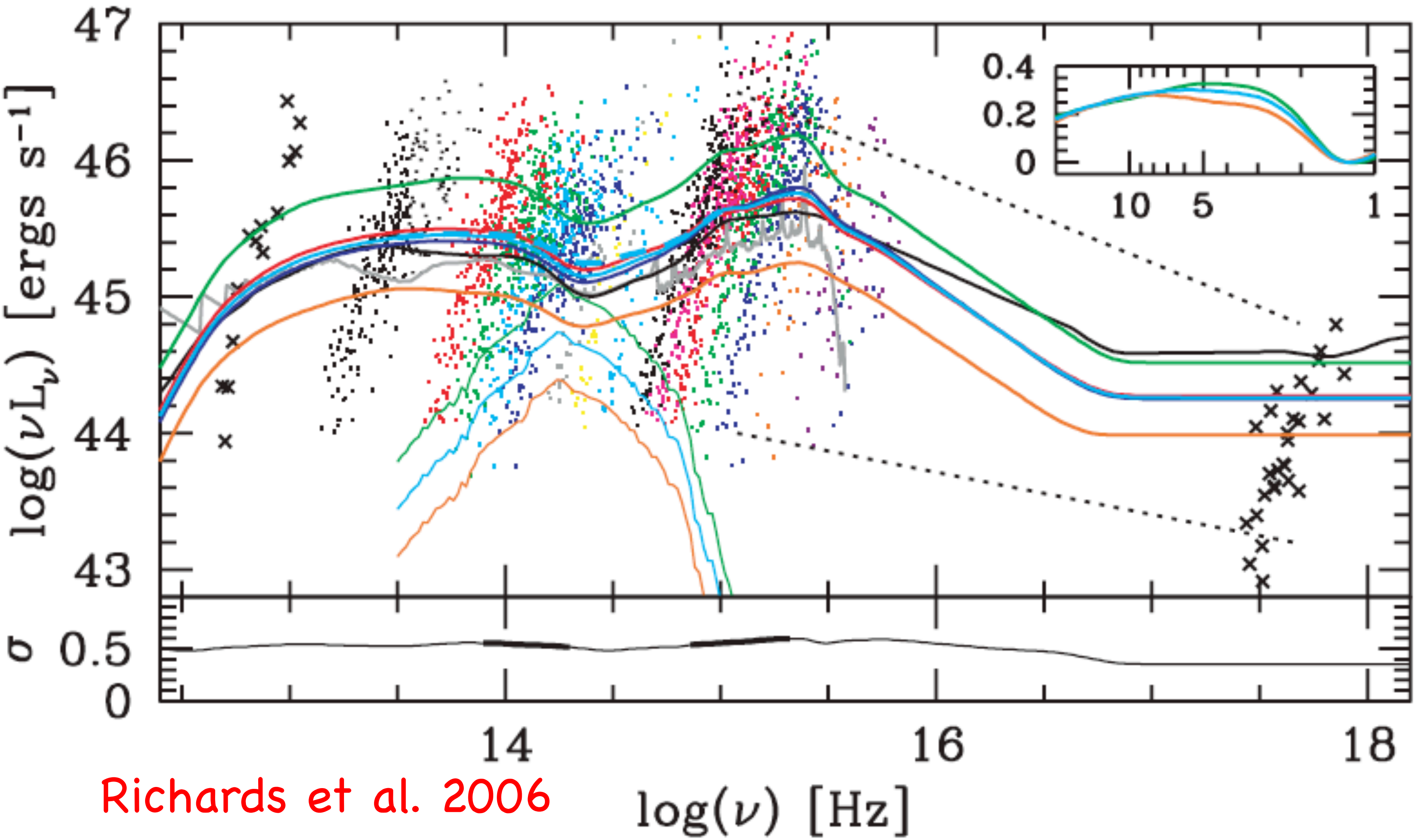
- Sources: mostly non-jetted & radiatively efficient AGN (*FSRQs but not BL Lacs*). Sensitive to both obscured and unobscured AGN (almost isotropic selection); also extremely obscured AGN (missed by optical and soft X-ray surveys)
- Physics: obscuring dust
- Biases:
  - ✓ low reliability: selects also non-AGN: e.g., $z > 1$ massive galaxies)
  - ✓ low completeness (particularly for deep surveys; misses AGN above the flux limit, particularly low-power sources)
  - ✓ **does not select AGN without dust:** $L \lesssim 10^{42}$ erg/s – $L/L_{Edd} \lesssim 0.01$; all jetted AGN of the radiatively inefficient type (hosted in E's, low L/L_{Edd}: e.g., low-excitation radio galaxies like M87; no obscuring torus)

The AGN SED: the optical/UV band



PP et al. 2017 (image credit: C. Harrison)

AGN optical/UV emission



Richards et al. 2006

$T \approx 10^5$ K → $\lambda_{peak} \approx 300$ Å

The optical/UV band

- Source ... g most of their ... picks broad-li...
- Physic ... versity
- Biases
  - ✓ mi ... ugh m ... s) and ev...
  - ✓ mi ... > AGN +
  - ✓ mi ... ally at z
- Make ... ues

Spectral Type	Example(s)	Temperature Range	Key Absorption Line Features	Brightest Wavelength (color)
O	Stars of Orion's Belt	>30,000	Lines of ionized helium, weak hydrogen lines	<97 nm (ultraviolet)*
B	Rigel	30,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines	97–290 nm (ultraviolet)*
A	Sirius	10,000 K–7,500 K	Very strong hydrogen lines	290–390 nm (violet)*
F	Polaris	7,500 K–6,000 K	Moderate hydrogen lines, moderate lines of ionized calcium	390–480 nm (blue)*
G	Sun, Alpha Centauri A	6,000 K–5,000 K	Weak hydrogen lines, strong lines of ionized calcium	480–580 nm (yellow)
K	Arcturus	5,000 K–3,500 K	Lines of neutral and singly ionized metals, some molecules	580–830 nm (red)
M	Betelgeuse, Proxima Centauri	<3,500 K	Molecular lines strong	>830 nm (infrared)

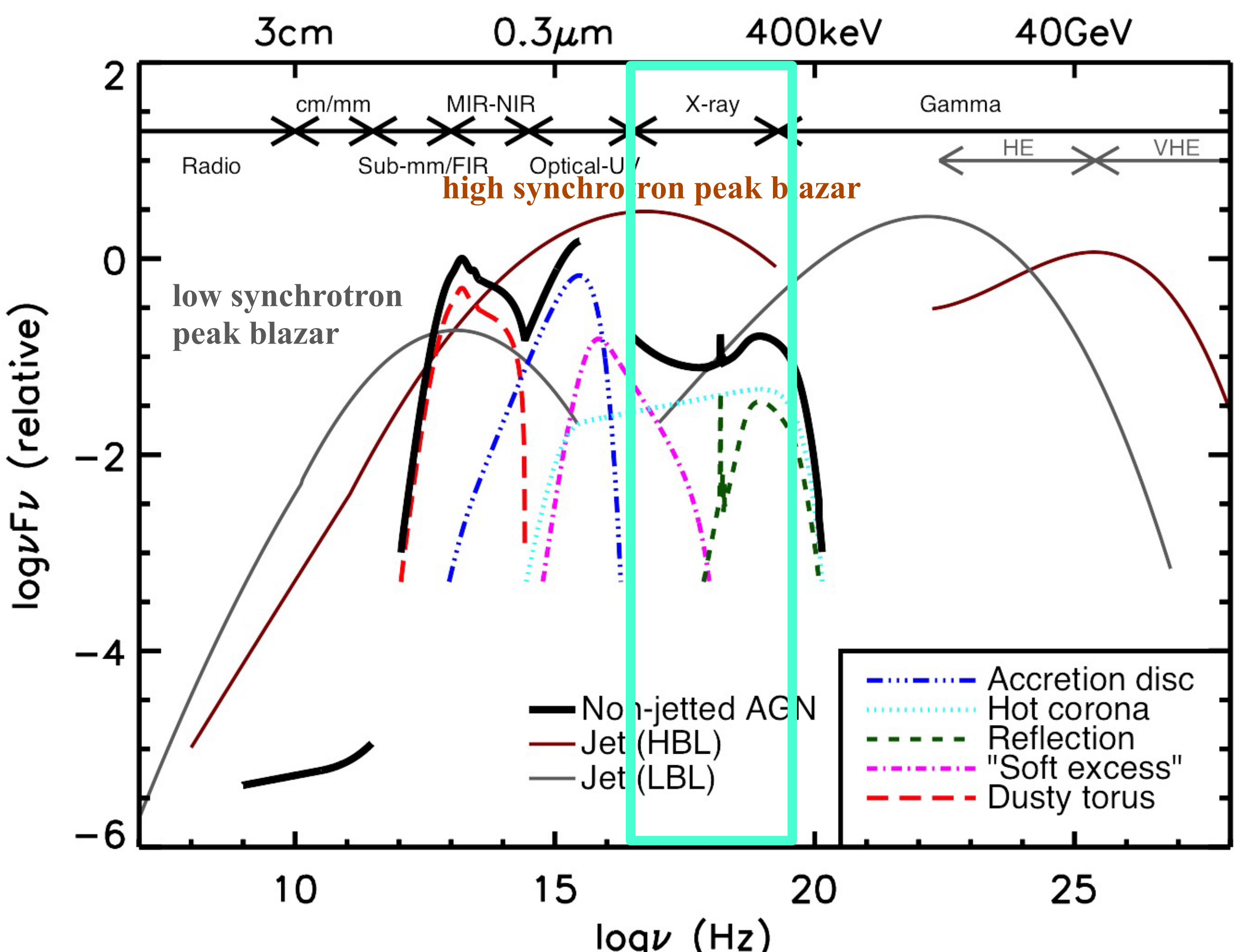
The optical/UV band

- Sources: unobscured (mostly) non-jetted AGN (emitting most of their energy in the UV band) → optical/UV selection picks broad-line sources (*FSRQs but not BL Lacs)*
- Physics: accretion disk, M_{BH}; good to study spectral diversity
- Biases:
  - ✓ misses LOTS of obscured (narrow-line) AGN (although many are still selected through their emission lines) and even moderately obscured ones
  - ✓ misses many low-luminosity AGN; host galaxy light > AGN + $L \lesssim 10^{42}$ erg/s - $L/L_{Edd} \lesssim 0.01$
- Makes up for this with numbers: huge optical catalogues

Population

Population

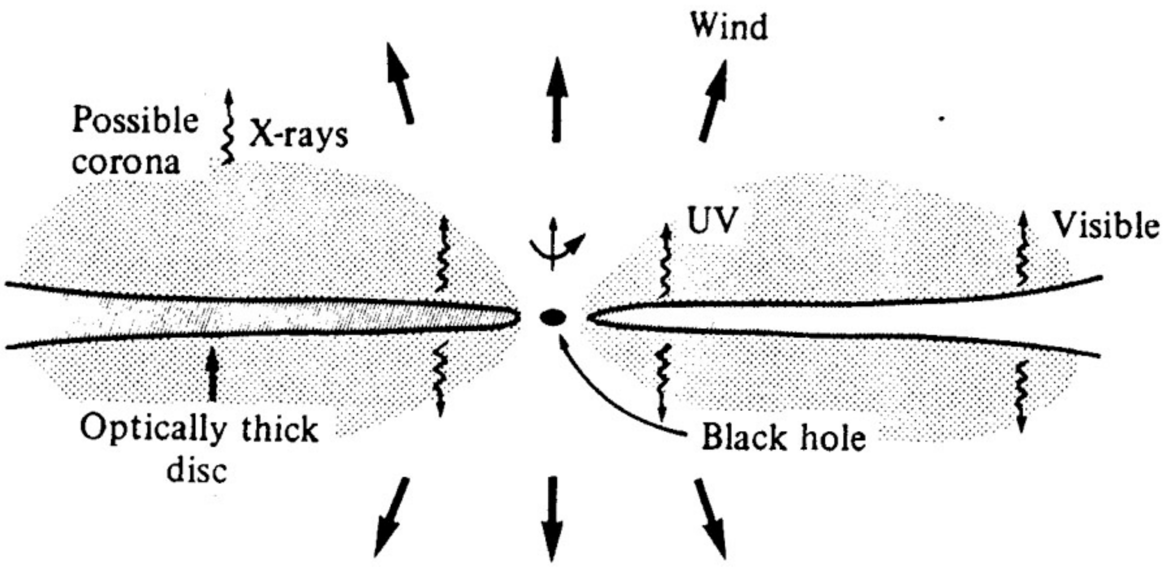
The AGN SED: the X-ray band



PP et al. 2017 (image credit: C. Harrison)

X-ray band

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

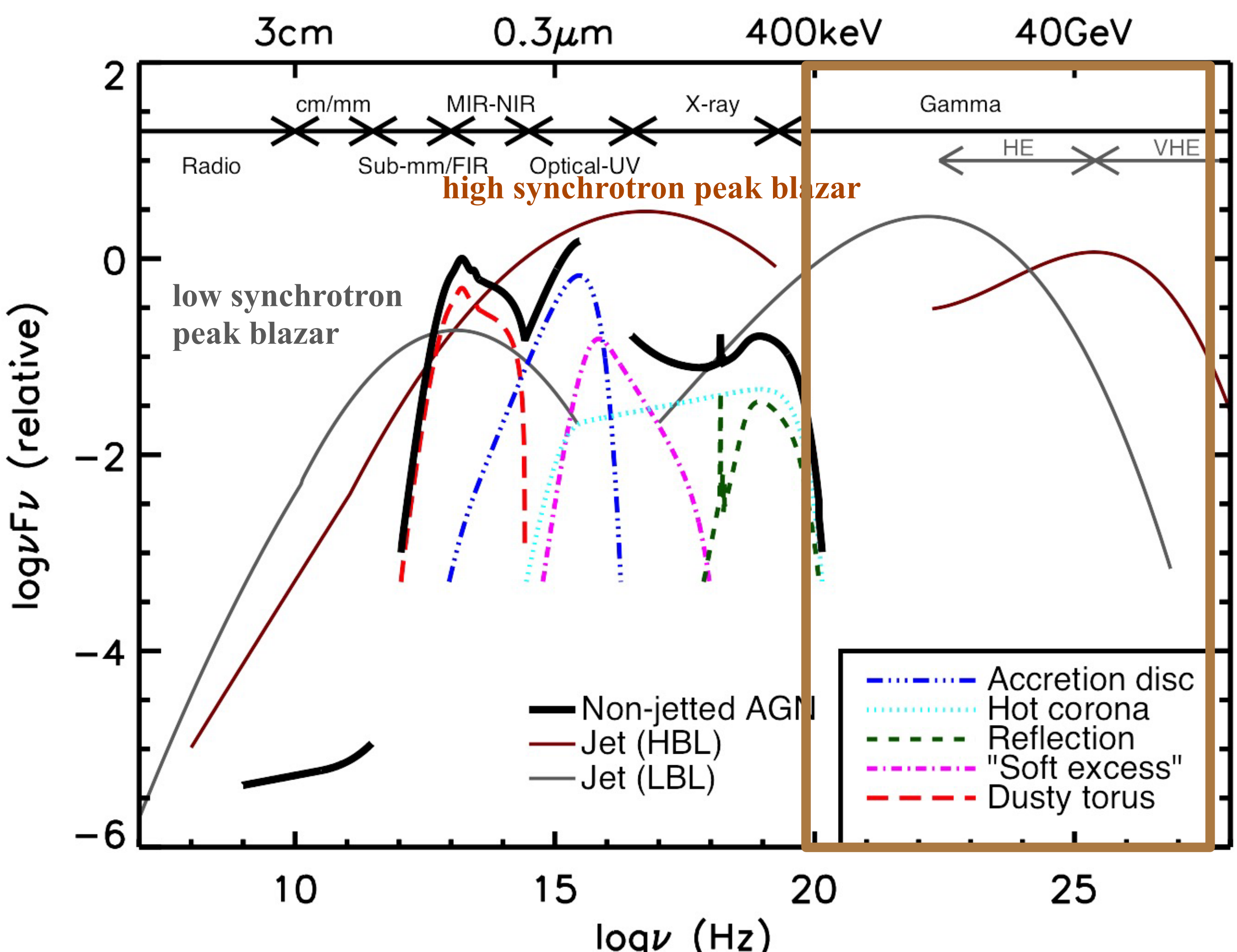


Wiita 1991

The X-ray band

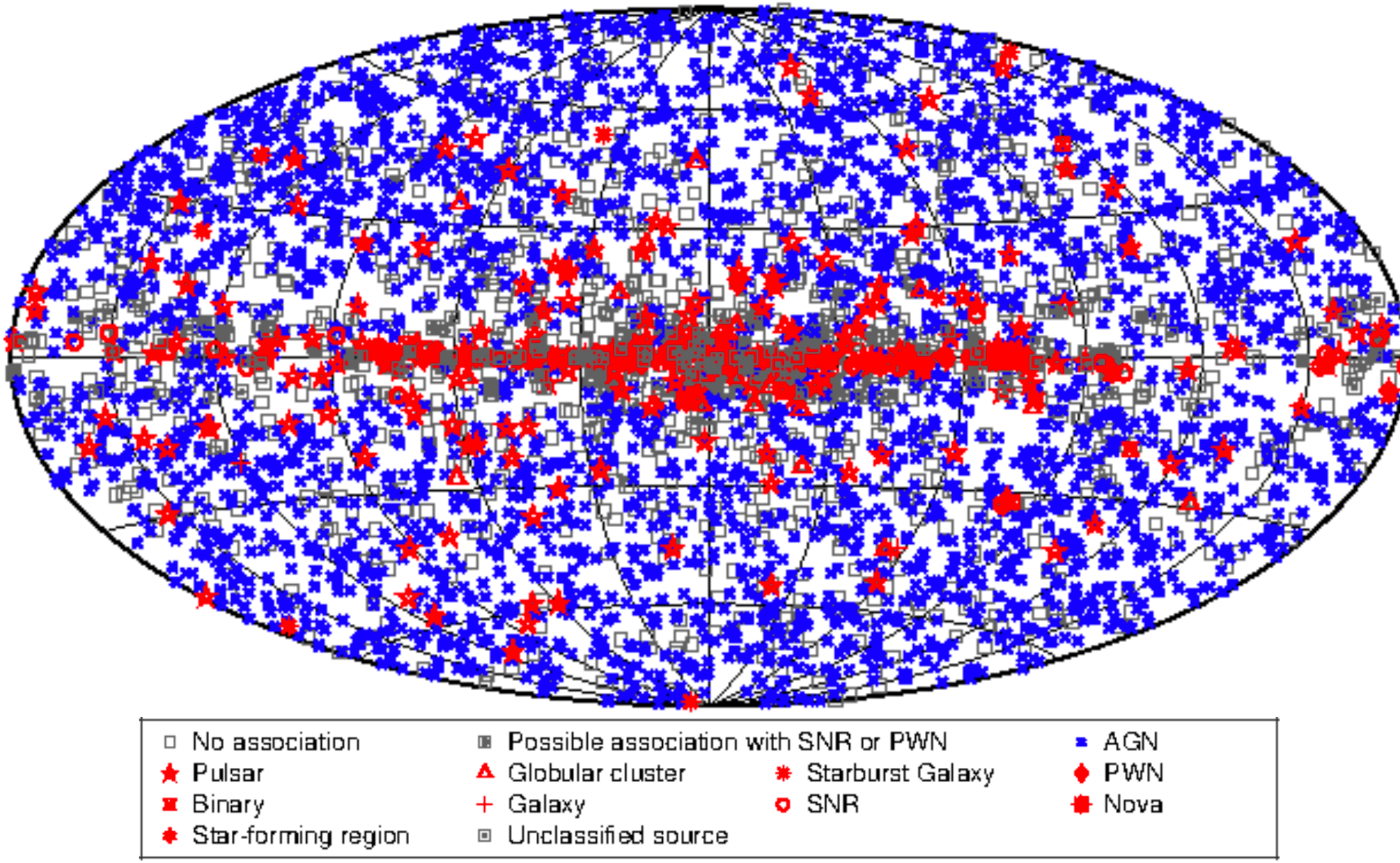
- Sources: essentially **all** (**no "X-ray quiet" AGN**; but see biases)
- Physics: **corona**, reflection, scattering, absorption by disk and torus, jet emission (in jetted AGN)
- Biases:
  - ✓ absorption at low energies (typically $\lesssim$ 10 keV, N_H dependent)
  - ✓ misses low-luminosity AGN ($L_X < 10^{42}$ erg/s: host galaxy contamination; but see Lambrides et al. 2020), including many **low-power jetted AGN** (i.e. low-excitation radio galaxies)

The AGN SED: the γ-ray band



PP et al. 2017 (image credit: C. Harrison)

The high-energy γ-ray sky



The high-energy γ-ray sky

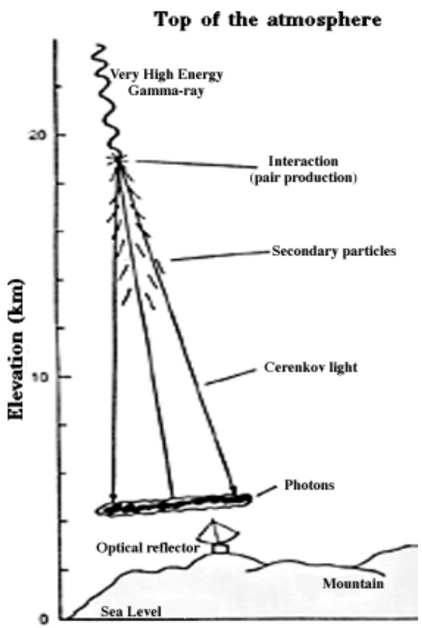
- 6658 sources detected all-sky in the 50 MeV – 1 TeV range ($1.2\ 10^{22}$ – $2.4\ 10^{26}$ Hz) (4th *Fermi* source catalogue – DR3, 2022)

Galactic sources (pulsars, supernova remnants, etc.)	539	8.1%
Blazars	2,226	33.4%
Blazar candidates of uncertain type	1,517	22.8%
Other extra-galactic sources (radio galaxies, starbursts, etc.)	85	1.3%
Unclassified	2,291	34.4%

- AGN (blazars) make up ≈ 56% (< 91%) of the MeV – GeV γ-ray sky
- γ-ray AGN sky ≈ radio-bright AGN sky (same non-thermal sources)!

The very high-energy γ-ray sky

- 250 sources detected above 1 TeV (> 2.4 10^{26} Hz) by Cherenkov telescopes [from the ground] (TeVCat)



- AGN (blazars) make up > 1/3 of the TeV sky and 89% of the extragalactic sky

The γ-ray band

- Sources: (basically) only **jetted AGN, mostly blazars;** non-jetted AGN cores very unlikely γ-ray emitters but AGN outflows are [at very low levels: e.g., Wang & Loeb 2016, Lamastra et al. 2017]: Ajello et al. (2021)

The γ-ray band

The Astrophysical Journal, 921:144 (14pp), 2021 November 10 https://doi.org/10.3847/1538-4357/ac1bb2

5.1σ stacking detection

Gamma Rays from Fast Black-hole Winds

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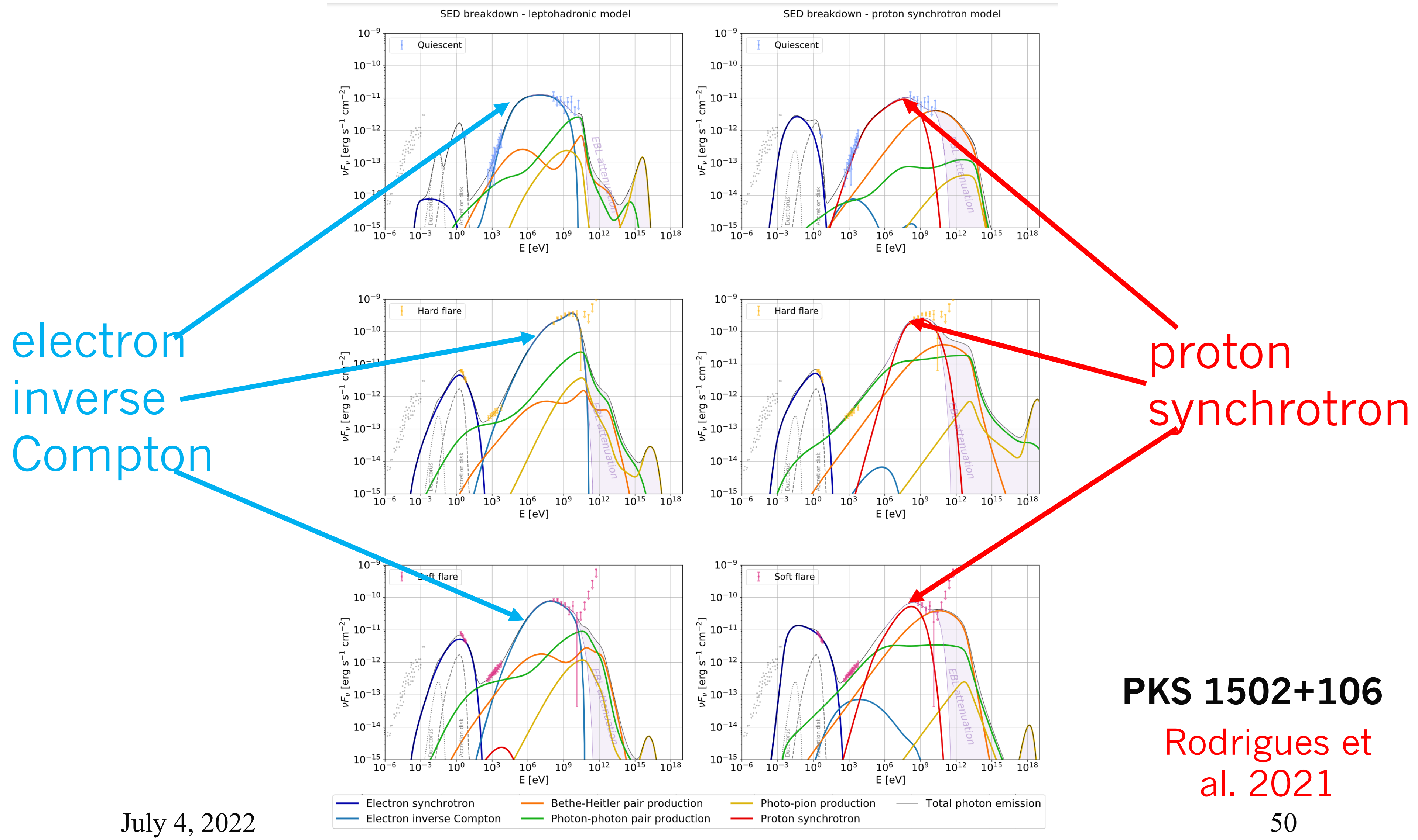
Abstract

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.

Leptonic vs. hadronic emission



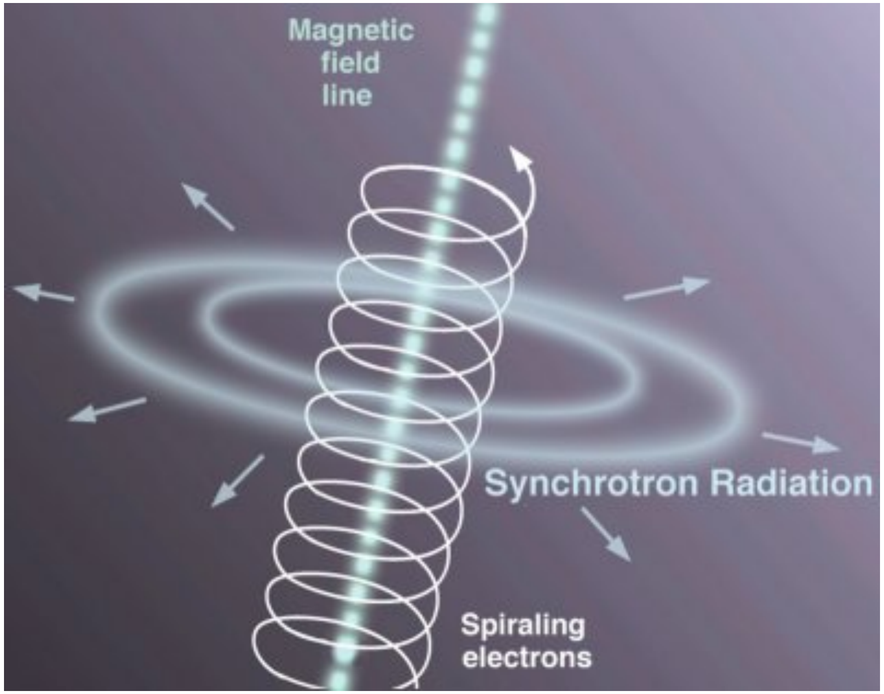
PKS 1502+106

Rodrigues et al. 2021

The γ-ray band

- Sources: (basically) only **jetted AGN, mostly blazars;** non-jetted AGN cores very unlikely γ-ray emitters but AGN outflows are [at very low levels: e.g., Wang & Loeb 2016, Lamastra et al. 2017]: Ajello et al. (2021)
- Physics: **jet** (extremely high-energy processes); but process still not clear (leptonic [inverse Compton] or hadronic [pion decay])
- **Multi-messenger link: neutrinos (and maybe ultra high-energy cosmic rays)**

The mystery of gamma-ray photons

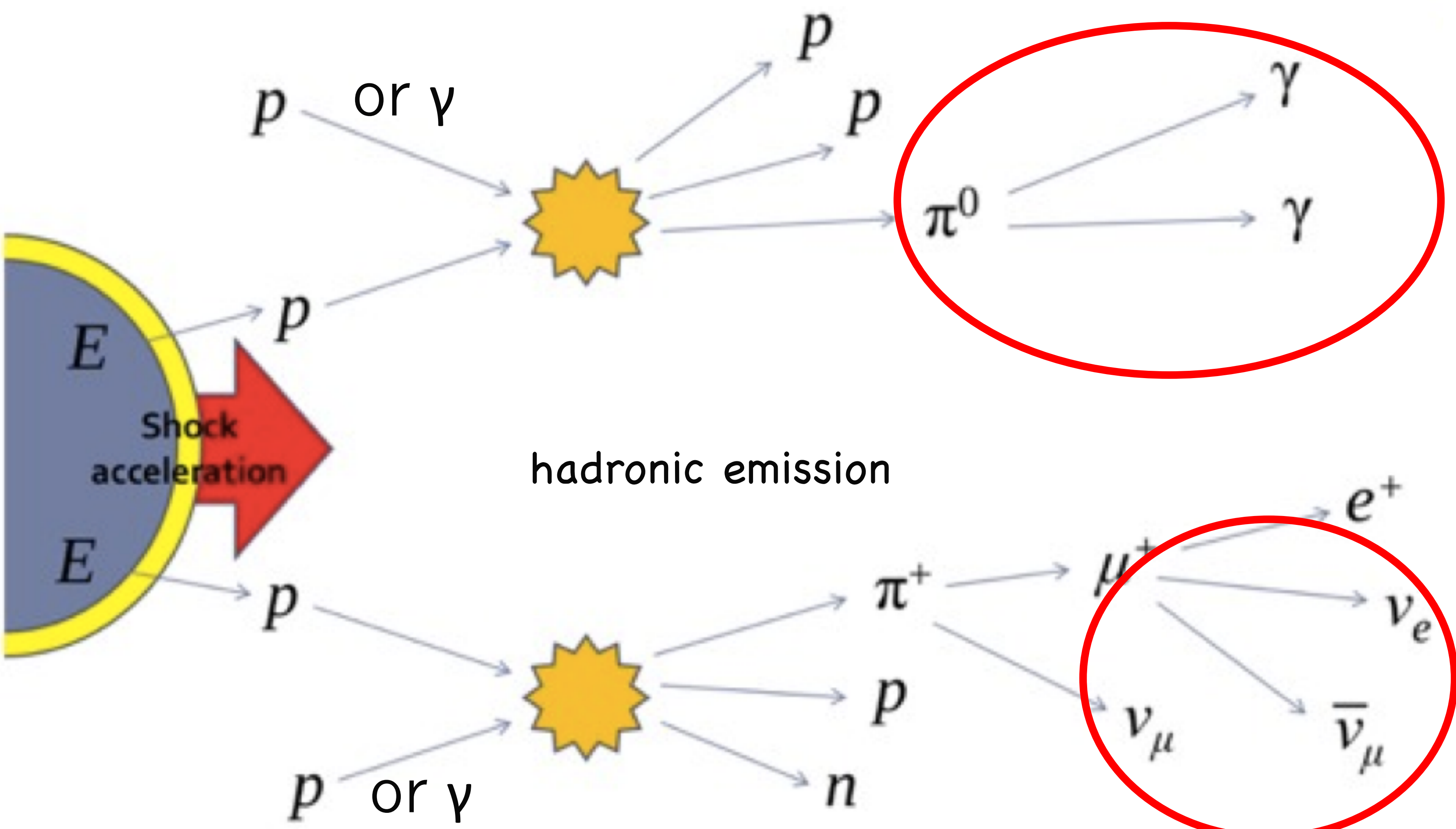


$e^- + \gamma_{\text{low-energy}} \rightarrow \gamma_{\text{high-energy}}$

leptonic emission

- ✓ Synchrotron self-Compton
- ✓ External Compton (accretion disk, broad line region, molecular torus) [valid only for FSRQs!]

The mystery of gamma-ray photons



The first (extragalactic) neutrino source

TXS 0506+056,
a blazar at z = 0.3365

Multi-wavelength overview

Table 3 A multi-wavelength overview of AGN highlighting the different selection biases (weaknesses) and key capabilities (strengths)

Band	Type	Physics	Selection biases/weaknesses	Key capabilities/strengths
Radio, $f_r \gtrsim 1$ mJy	Jetted	Jet	Non-jetted sources	High efficiency, no obscuration bias
Radio, $f_r \lesssim 1$ mJy	Jetted and non-jetted	Jet and SF	Host contamination	Completeness, no obscuration bias
IR	Type 1 and 2	Hot dust and SF	Completeness, reliability, host contamination, no dust	Weak obscuration bias, high efficiency
Optical	Type 1	Disk	Completeness, low-luminosity, obscured sources, host contamination	High efficiency, detailed physics from lines
X-ray	Type 1 and (most) 2	Corona	Very low-luminosity, heavy obscuration	Completeness, low host contamination
γ-ray	Jetted	Jet	Non-jetted, unbeamed sources	High reliability
Variability	All (in principle)	Corona, disk, jet	Host contamination, obscuration, cadence and depth of observations	Low-luminosity

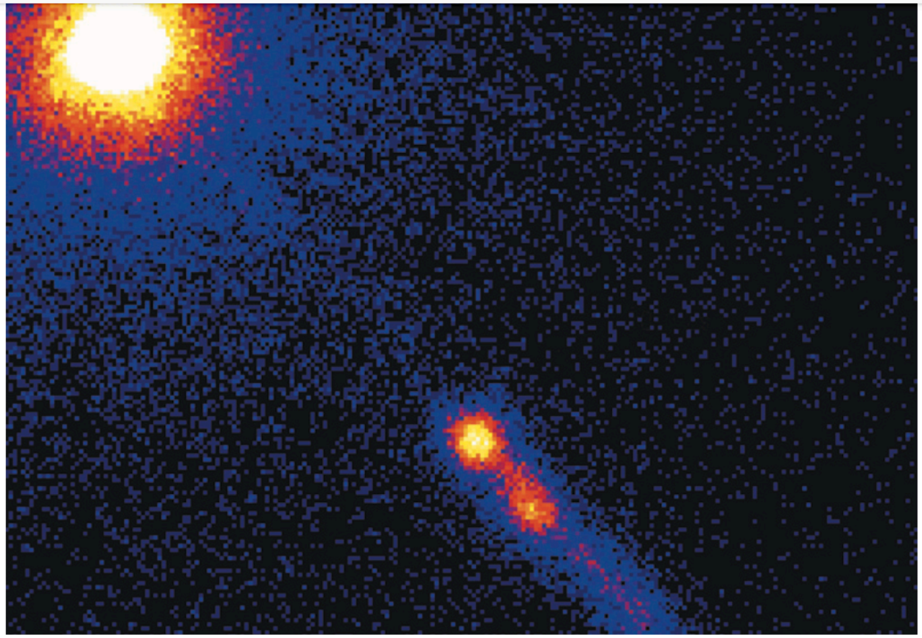
The definitions of some of the terms used in the bias and capability columns are as follows: *Efficiency*: ability to identify a large number of AGN with relative small total exposure times (this is thus a combination of the nature of AGN emission and the capabilities of current telescopes in a given band). *Reliability*: the fraction of sources that are identified as AGN using typical criteria that are truly AGN. *Completeness*: the ability to detect as much as possible of the full underlying population of AGN

PP et al. 2017

Open ... ction)

- Why ... s?
- Wh ... ts?
- Why ... mes
- Com ... gy of the

NASA/CXC/SAO/H.MARSHALL ET A



X-ray observations show that quasar 3C273 shoots out a jet of plasma blobs that seem to move faster than light.

Quasars still defy explanation

Fifty years after finding that these cosmic beacons lie far away, astronomers need to think harder about how they radiate so much energy, says **Robert Antonucci**.

Arthur C. Clarke posed one explanation for why no extraterrestrial life forms have been in touch in his 1953 novel, *Childhood's End*. The book describes a Galactic club of advanced civilizations that have a policy not to interfere in cultures at a primitive stage of evolution, such as our own. But once a society masters nuclear weapons and interstellar travel and becomes dangerous, the Galactic authorities introduce themselves and their rules, which include a ban on wars.

Astronomy's childhood ended 50 years ago with a discovery that made us full citizens of the Universe. In 1963, the first measurement of the distance to a quasar — a radio source that looks like a star in visible light — showed it to be an enormously powerful beacon lying billions of light years away[1]. Until then, astronomy had been limited to exploring our local patch of space time, in which everything looks familiar. Before quasars, the distant Universe was tantalizingly out of reach.

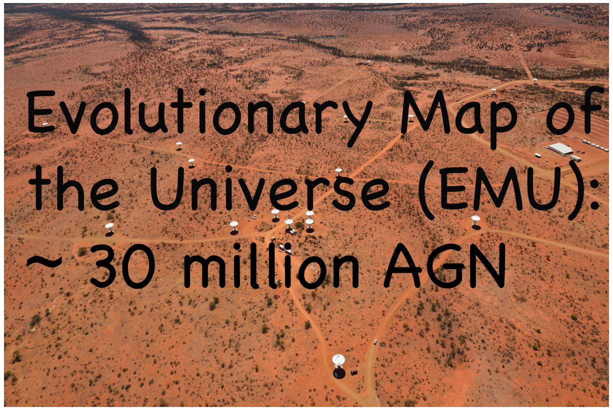
Quasars are immensely bright. From the central point in a galaxy, they emit as much energy as thousands of giant galaxies from a region as tiny as the Solar System. They radiate energy across the electromagnetic spectrum, from radio waves to γ-rays. Many expel jets of particles at near-light speed, which inflate vast particle clouds or 'lobes' that measure millions of light years across and emit radio waves.

Light that has travelled from distant quasars offers us a glimpse back in time. Since the discovery in the 1920s that the Universe is expanding, cosmologists have known that the cosmos has a finite age of about 13.7 billion years. Astronomers have ▶

Open issues (a small/biased selection)

- Why do only a minority of AGN have jets?
- What accelerates particles in AGN jets?
- Are (some) blazars neutrino emitters? Strong link to γ-ray emission
- Composition, geometry, and morphology of the obscuring dust. Link to external Compton emission in FSRQs

The (near) future: radio

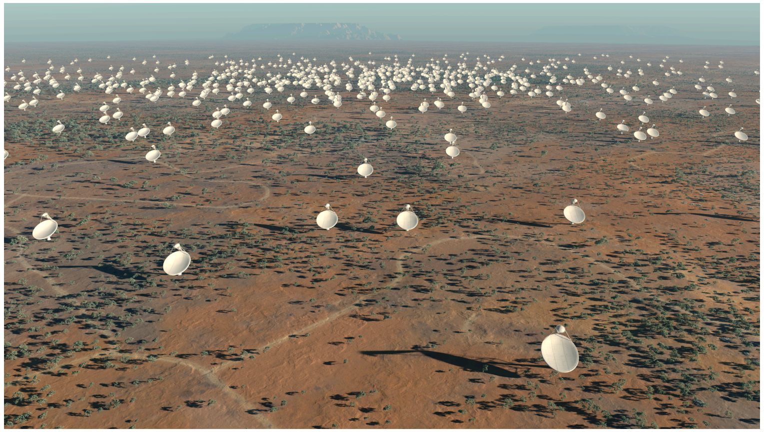


Australian SKA Pathfinder (ASKAP; Australia)

MeerKAT (South Africa)

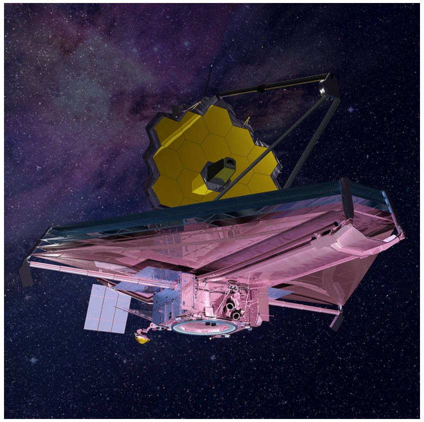
e-MERLIN (UK)

APERTIF (The Netherlands)

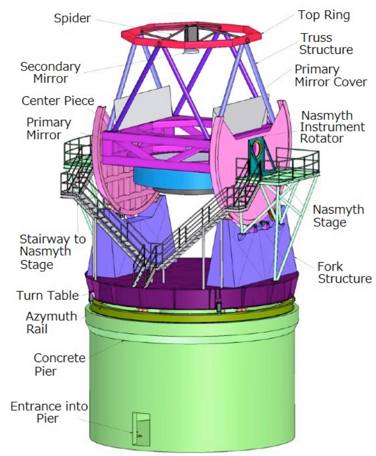


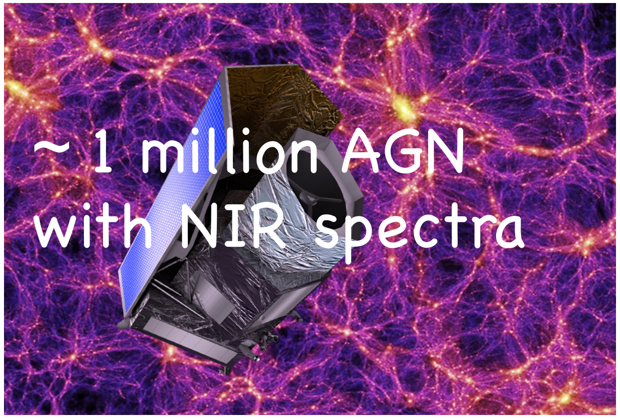
Square Kilometre Array (2023+)

The (near) future: IR



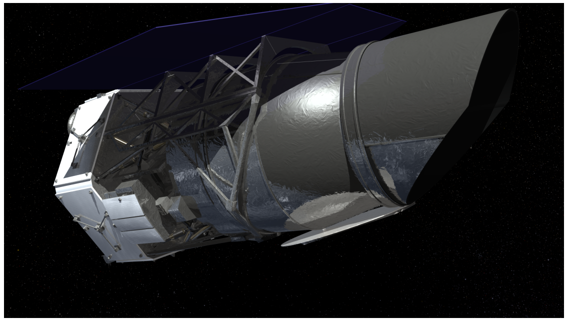
JWST (NASA/ESA)





Euclid (ESA/NASA; 2022)

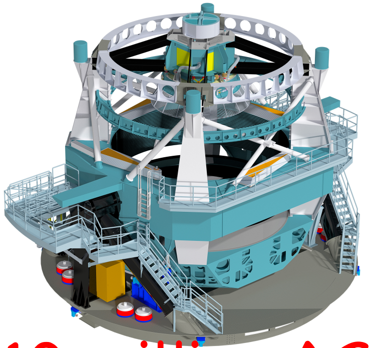
Tokyo Atacama Observatory (Japan; 2022+)



Nancy Grace Roman Space Telescope [previously know as Wide Field Infrared Survey Telescope] (NGRST, NASA; late 2020s)

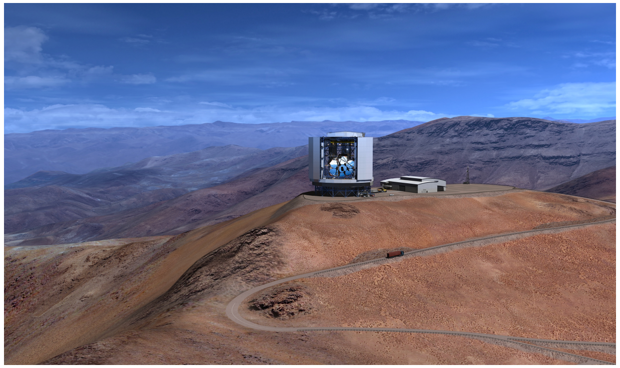
The (near) future: optical (NIR)

Zwicky Transient Facility (2017)



> 10 million AGN

Vera C. Rubin Observatory [LSST] (2023)



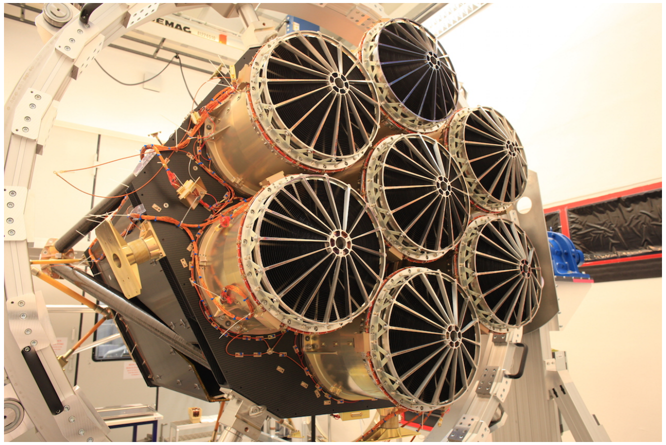
GMT (USA; 2029)

ELT (ESO; 2027)

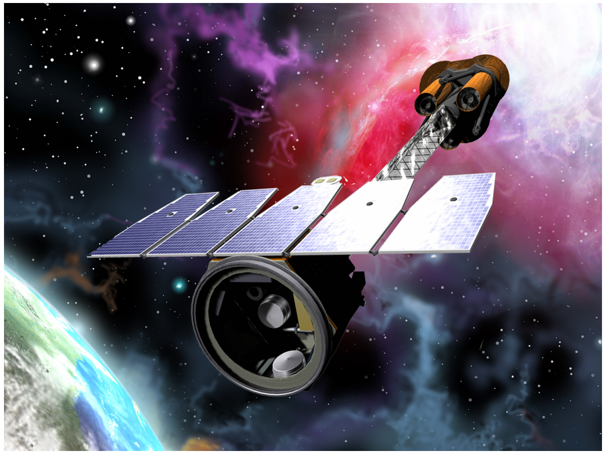
TMT (USA; 2030)

The (near) future: X-ray

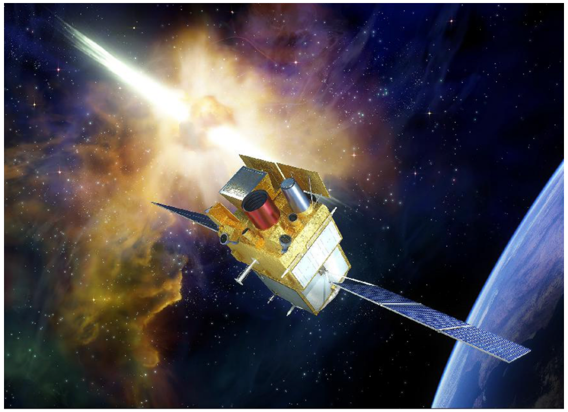
~ 3 million AGN



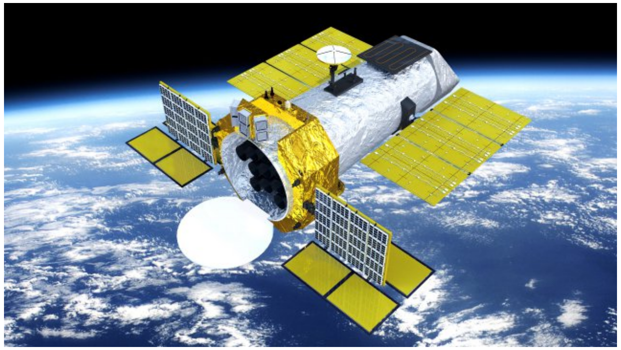
eROSITA (MPE/Russia)



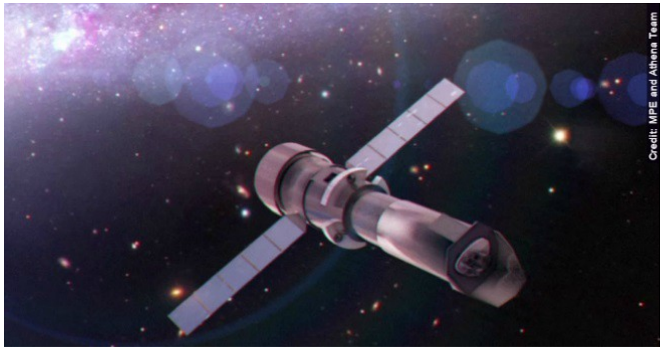
IXPE (NASA+)



SVOM (China/France; mid 2023)



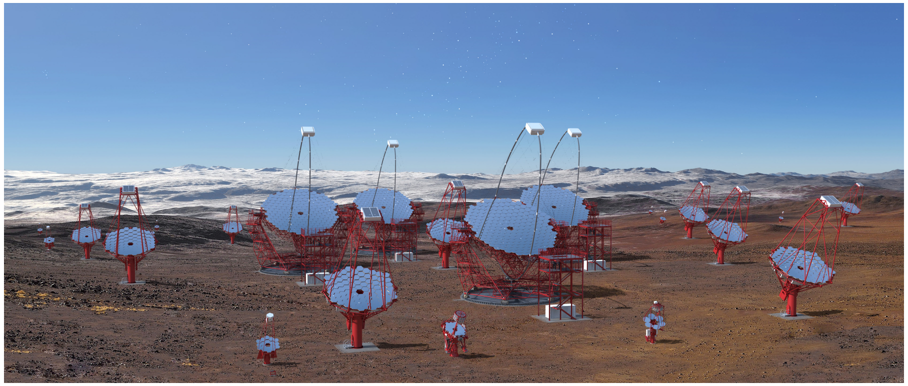
eXTP (China+; 2027)



Athena (ESA; 2031?)

The (near) future: γ-ray

Large High Altitude Air Shower Observatory (LHAASO, China)



Cherenkov Telescope Array (CTA; 2023)

~ 10x more TeV blazars

Main messages

- Different bands give us very different perspectives on the physics and different AGN types
- Jetted AGN are rare but (almost) the only γ-ray emitters; blazars rule the γ-ray sky because of Doppler boosting
- AGN have gone multi-messenger: TXS 0506+056, a blazar at z = 0.3365, has been associated with IceCube neutrinos → important for γ-ray emission
- There are a still number of open issues; in the next few years we'll be flooded (even more) with AGN data

Astron Astrophys Rev (2017) 25:2
DOI 10.1007/s00159-017-0102-9

CrossMark

REVIEW ARTICLE

Active galactic nuclei: what's in a name?

P. Padovani[1] · D. M. Alexander[2] · R. J. Assef[3] · B. De Marco[4,5] · P. Giommi[6] · R. C. Hickox[7] · G. T. Richards[8] · V. Smolčić[9] · E. Hatziminaoglou[1] · V. Mainieri[1] · M. Salvato[4]

Received: 12 June 2017

Abstract Active galactic nuclei (AGN) are energetic astrophysical sources powered by accretion onto supermassive black holes in galaxies, and present unique observational signatures that cover the full electromagnetic spectrum over more than twenty orders of magnitude in frequency. The rich phenomenology of AGN has resulted in a large number of different "flavours" in the literature that now comprise a complex and confusing AGN "zoo". It is increasingly clear that these classifications are only partially related to intrinsic differences between AGN and primarily reflect variations in a relatively small number of astrophysical parameters as well the method by which each class of AGN is selected. Taken together, observations in different electromagnetic bands as well as variations over time provide complementary windows on the physics of different sub-structures in the AGN. In this review, we present an overview of AGN multi-wavelength properties with the aim of painting their "big picture" through observations in each electromagnetic band from radio to γ-rays as well as AGN variability. We address what we can learn from each observational method, the impact of selection effects, the physics behind the emission at each wavelength, and the potential for future studies. To conclude, we use these observations to piece together the basic architecture of AGN, discuss our current understanding of unification models, and highlight some open questions that present opportunities for future observational and theoretical progress.

Astron Astrophys Rev (2016) 24:13
DOI 10.1007/s00159-016-0098-6

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REVIEW

The faint radio sky: radio astronomy becomes mainstream

Paolo Padovani[1]

Received: 9 June 2016

Abstract Radio astronomy has changed. For years it studied relatively rare sources, which emit mostly non-thermal radiation across the entire electromagnetic spectrum, i.e. radio quasars and radio galaxies. Now, it is reaching such faint flux densities that it detects mainly star-forming galaxies and the more common radio-quiet active galactic nuclei. These sources make up the bulk of the extragalactic sky, which has been studied for decades in the infrared, optical, and X-ray bands. I follow the transformation of radio astronomy by reviewing the main components of the radio sky at the bright and faint ends, the issue of their proper classification, their number counts, luminosity functions, and evolution. The overall "big picture" astrophysical implications of these results, and their relevance for a number of hot topics in extragalactic astronomy, are also discussed. The future prospects of the faint radio sky are very bright, as we will soon be flooded with survey data. This review should be useful to all extragalactic astronomers, irrespective of their favourite electromagnetic band(s), and even stellar astronomers might find it somewhat gratifying.

Keywords Radio continuum: galaxies · Galaxies: active · Galaxies: starburst · Quasars: general · Galaxies: statistics · Surveys

Abbreviations

6dFGS	6 Degree field galaxy survey
AGN	Active galactic nuclei

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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

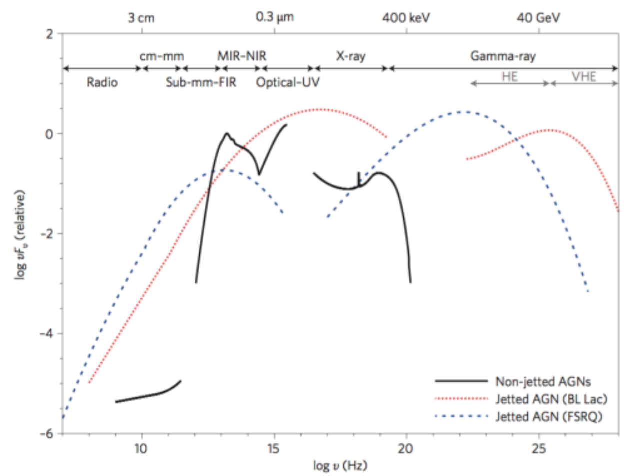

Figure 1 | A schematic representation of the SEDs of AGNs. The black solid curve represents the typical SED of non-jetted AGNs, while the dotted red and dashed blue lines refer to two jetted AGNs, a BL Lac (based on the SED of Mrk 421) and a flat-spectrum radio quasar (based on the SED of 3C 454.3), 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.