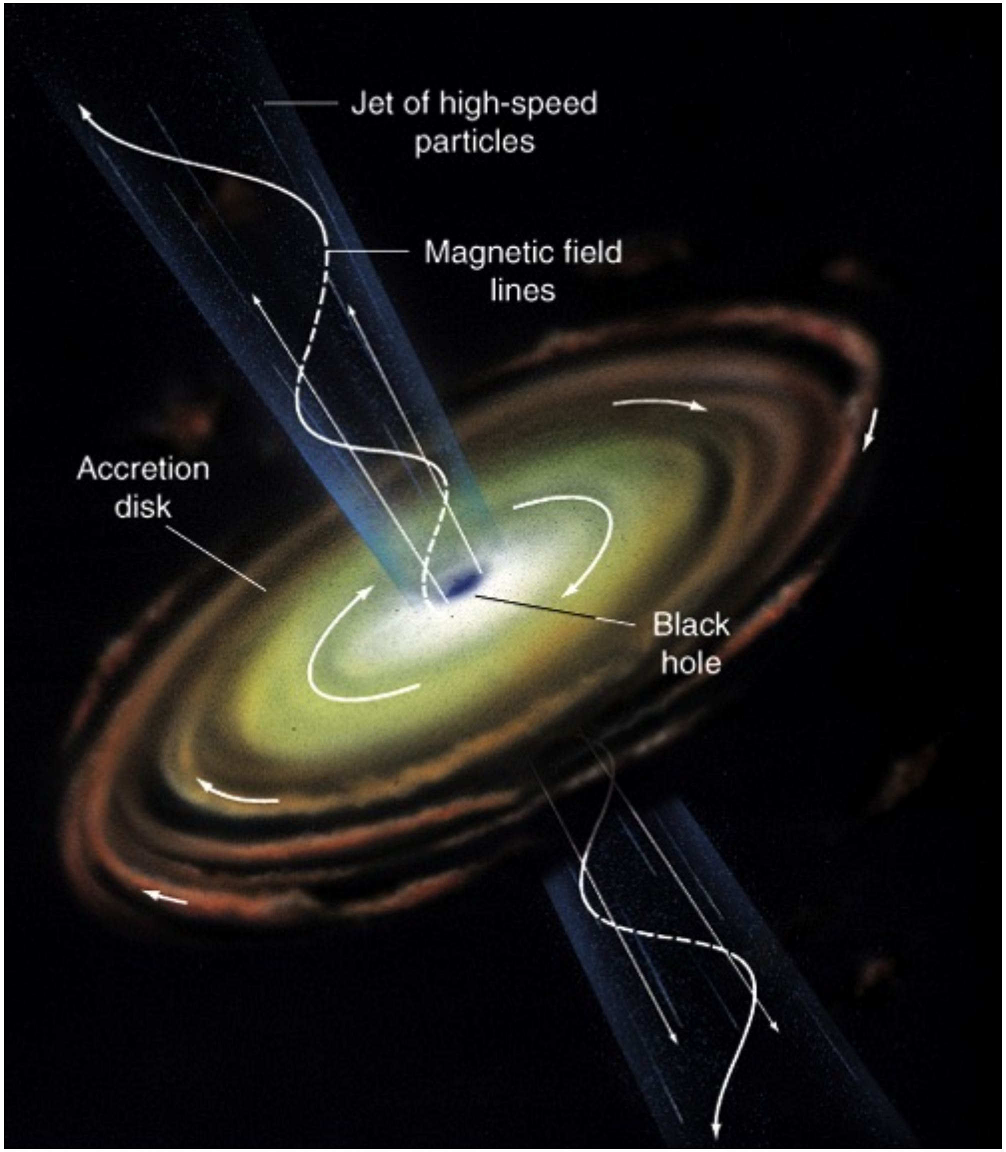
AGN: Classification and Unification Model

Powering AGN



(1) A compact central source provides a very intense gravitational field. For active galaxies, the black hole has $M_{BH} = 10^6 - 10^9\ M_{sun}$

(2) Infalling gas forms an accretion disk around the black hole.

(3) As the gas spirals inward, friction heats it to extremely high temperatures; emission from the accretion disk at different radii ($T > 10^4$ K) accounts for optical through soft X-ray continuum.

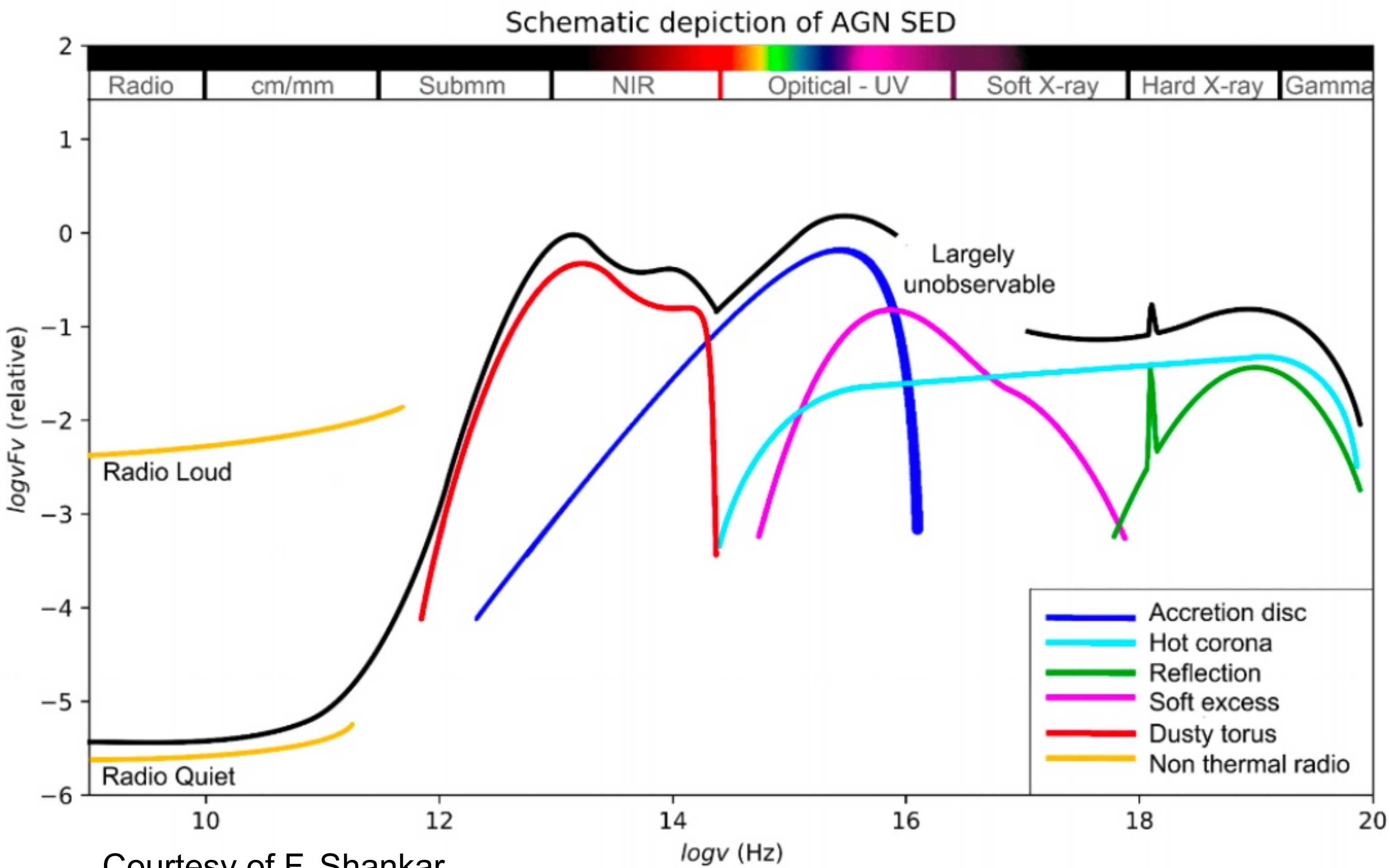
(4) Some of the gas is driven out into jets, focused by magnetic fields.

AGN global properties

- Active Galactic Nuclei (AGN) are powerful sources of radiation which exist in the centre of ≈1-10% of all galaxies (linked to duty cycle)
- Galaxies which host an AGN are known as active galaxies
- The span of observed AGN bolometric luminosities is huge, $L \approx 10^{40}$–10^{48} erg/s
- AGN are not always active (duty cycle)
- Large variety of properties → sub-classes
- Broad-band continuum and wide range in emission-line ionization
- Variability on short timescale → inner regions of the AGN implied
- The most luminous AGN outshine their host galaxies by factors >1000
- AGN are the most luminous long-lived objects in the Universe

AGN as broad-band emitters

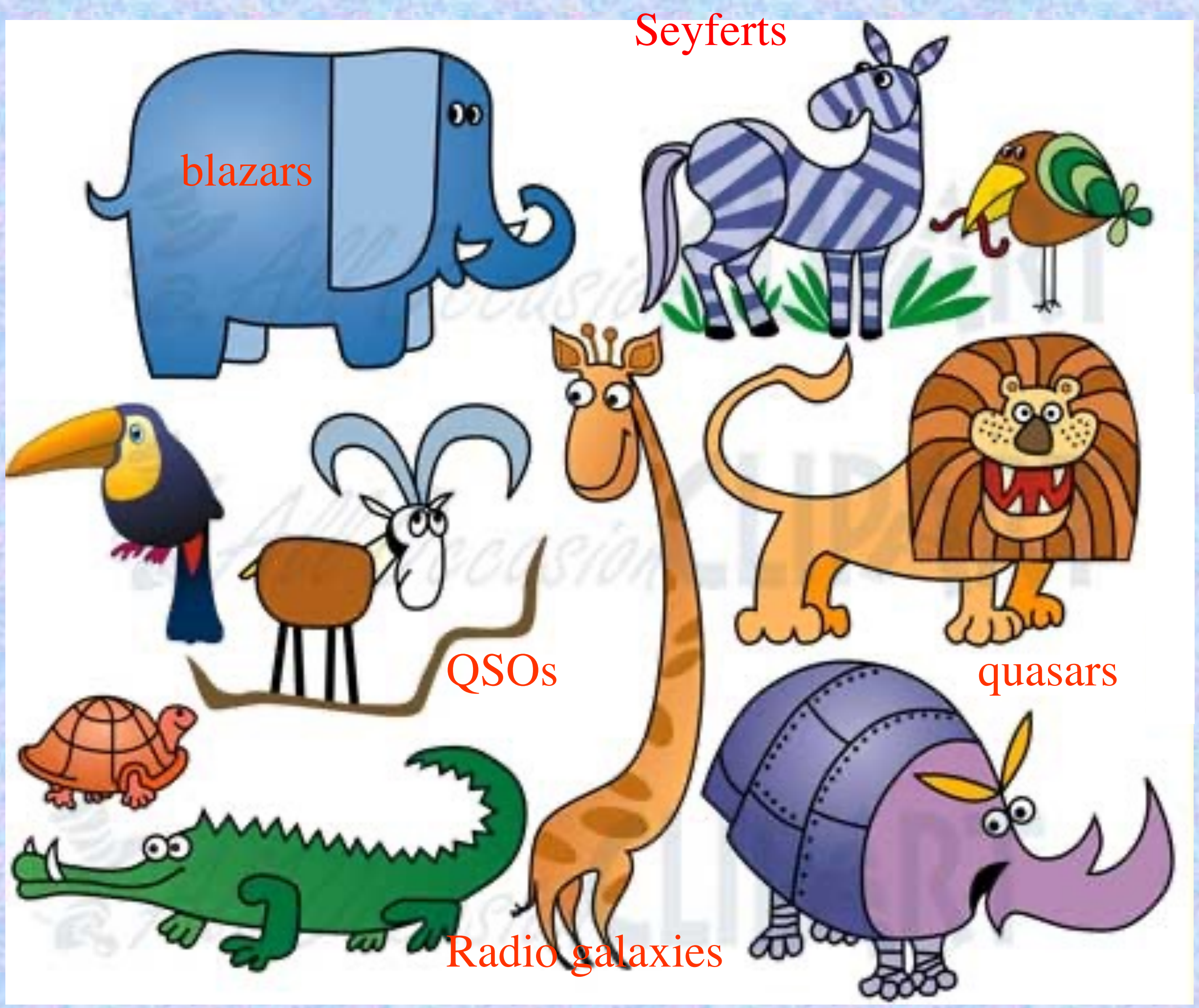
The νF_ν vs. Energy (frequency) representation [erg/s] allows to see where most of the AGN radiation is emitted



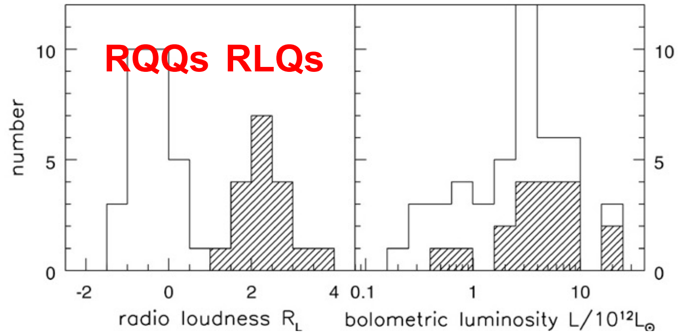
Courtesy of F. Shankar

Radio-loud (jetted-) AGN widely discussed in another lesson of the course

AGN taxonomy: the AGN zoo



AGN classification: RQ vs. RL



Radio-quiet

Radio-loud

Definition based on the relevance of the radio emission wrt. e.g. the optical emission [~10% of luminous AGNs are radio loud − R=F(5GHz)/F(opt)>10 (core emission)]

Seyfert Galaxies ($M_B>-23$ class.)

Type 1 and Type 2

Quasars ($M_B<-23$)

Type 1 and Type 2

Low-ionization nuclear emission-line region galaxies (LINERS)

Radio Galaxies

Broad-line radio galaxies (BLRGs)

Narrow-line radio-galaxies (NLRGs)

Blazars

BL Lacs

Optically violently variable quasars (OVVs)

Radio-loud Quasars

More complete AGN taxonomy

3-dimensional classification: spectral type,
radio properties, and AGN luminosity (still open issues)

Name	Spectral Type?	Radio Loud?	Luminosity?
Seyferts	1, 1.2, 1.5, 1.8, 1.9, 2.0	No	Moderate
Quasars	1, 2	No	High
LINERS	1, 2	Yes and No	Low
Broad-line Radio Galaxies (BLRGs)	1	Yes	Moderate
Narrow-line Radio Galaxies (NLRGs)	2	Yes	Moderate
Radio-loud quasars	1, 2	Yes	High
FRIs	1	Yes	Low
FRIIs	1, 2	Yes	Low-High
Blazars	0!!!	Yes	Low-High

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

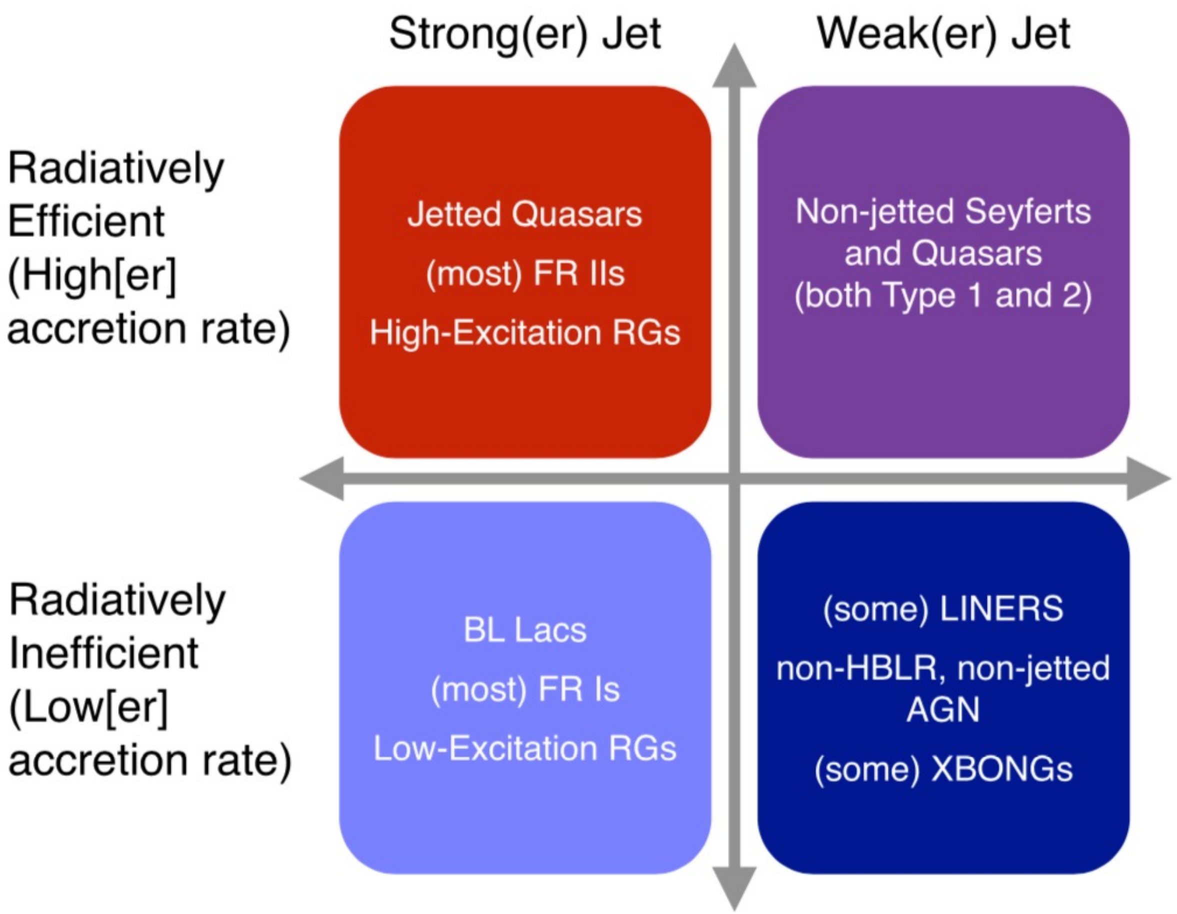
main

additional 'sub-classes'

Padovani et al. (2017)

A recent definition: jetted vs. non-jetted AGN

[see Padovani+2017 review on AGN]



RADIO-LOUD AGN: emission dominated by non-thermal processes (jet-related)
RADIO-QUIET AGN: multi-band emission dominated by thermal processes (and radio emission can be related to star formation – see studies in the CDF-S, Bonzini et al. 2013)

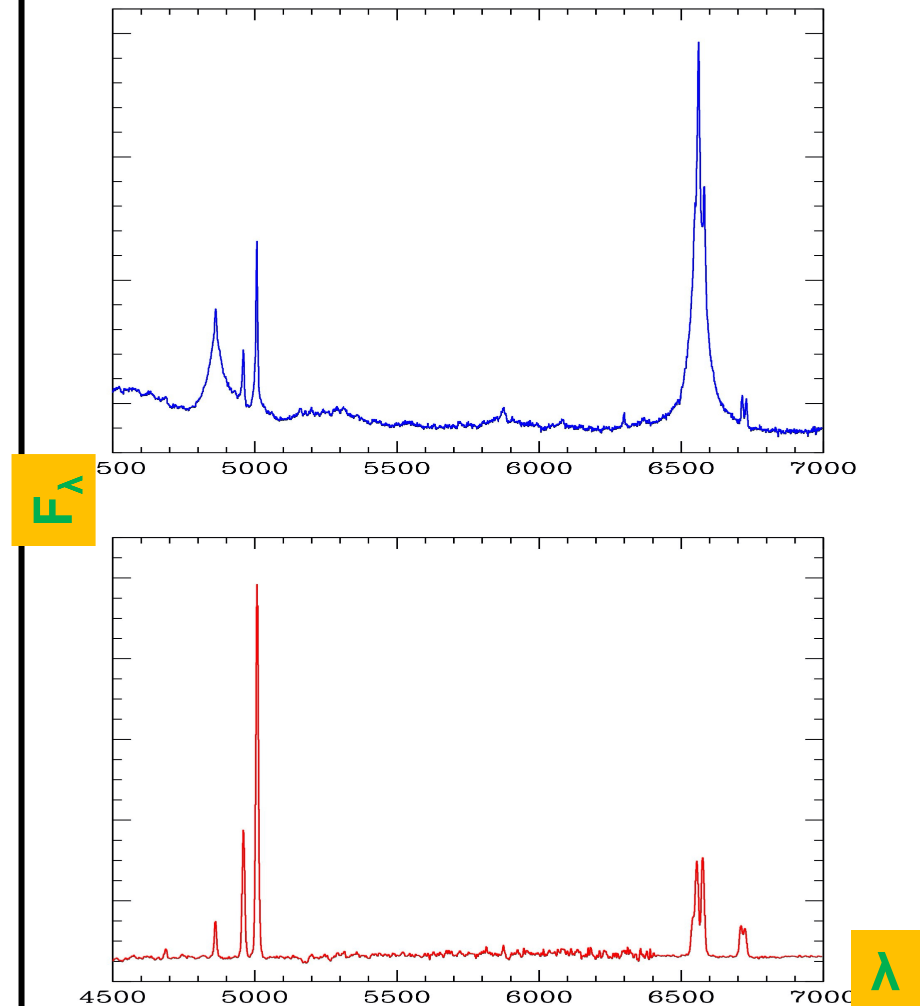
Seyfert galaxies

➢ Type 1 AGN:

- broad optical/UV permitted emission lines (FWHM~1500-15000 km/s)
- narrow (FWHM~500-1000 km/s) forbidden lines
- Width due to rotational motion around the BH ➔ BH mass
- $n \approx 10^{9-10}$ cm^{-3} (photo-ionized clouds with small volume filling factor)
- Collisional de-excitation dominates over forbidden line emission

➢ Type 2 AGN:

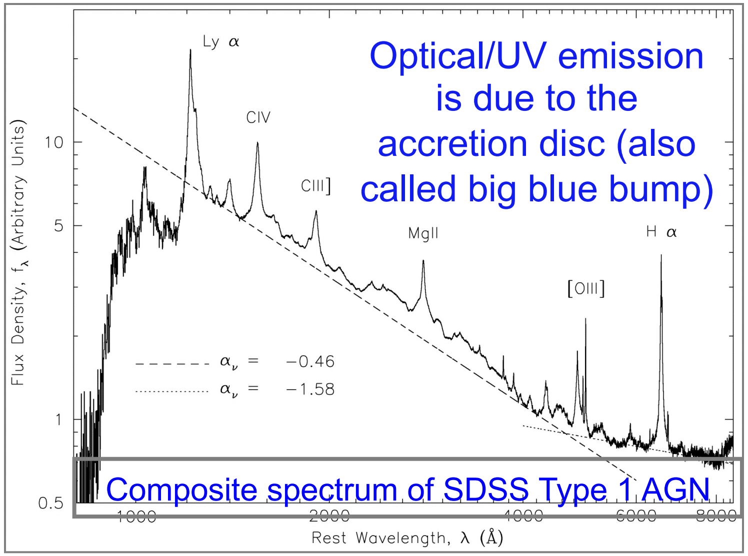
- FWHM permitted and forbidden lines almost the same
- The forbidden lines, while narrower than the permitted ones, are usually broader than the emission lines in most starburst galaxies
- $n \approx 10^{3-5}$ cm^{-3} (lower density allows forbidden transitions, otherwise electron, while moving to a lower state, would pass its energy to the e^-/atom responsible for the collision, hence no energy radiated)

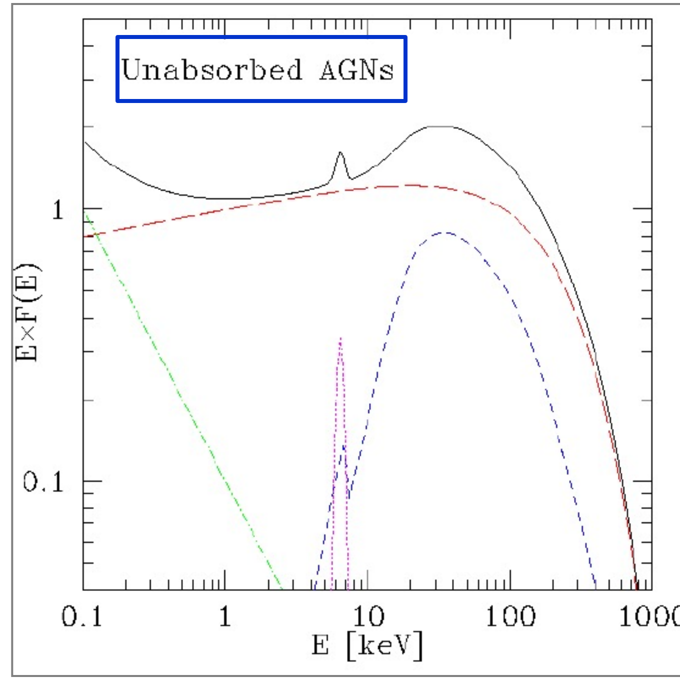


Classification (Type 1, Type 2) valid for most AGN and vastly related to Unification Scheme

Optical band

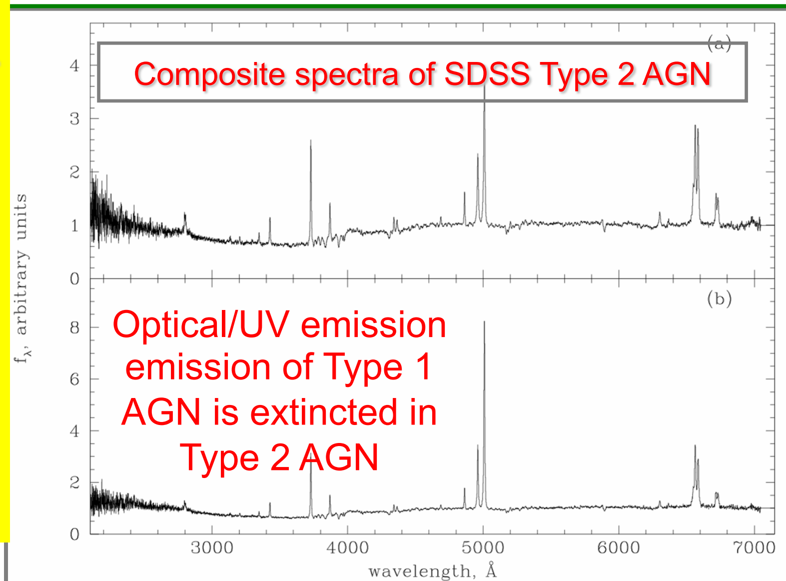
Type 1 AGN

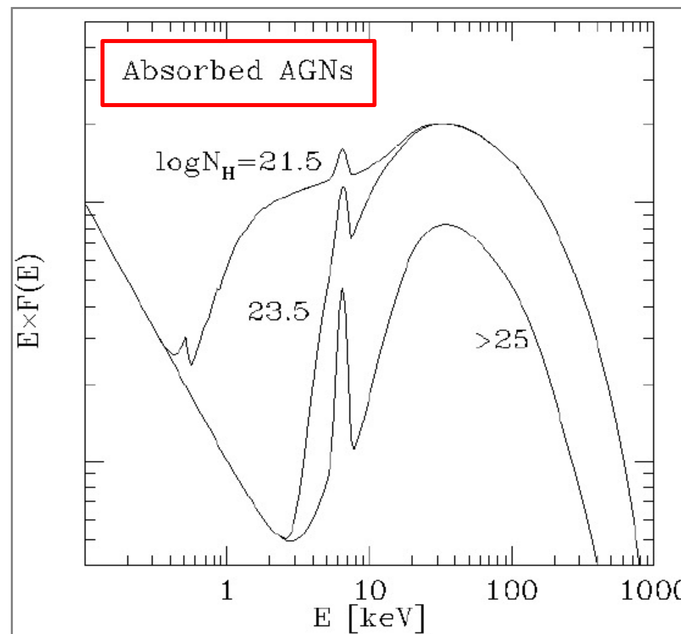




Type 2 AGN easily missed in optical and partly in X-ray surveys

Type 2 AGN



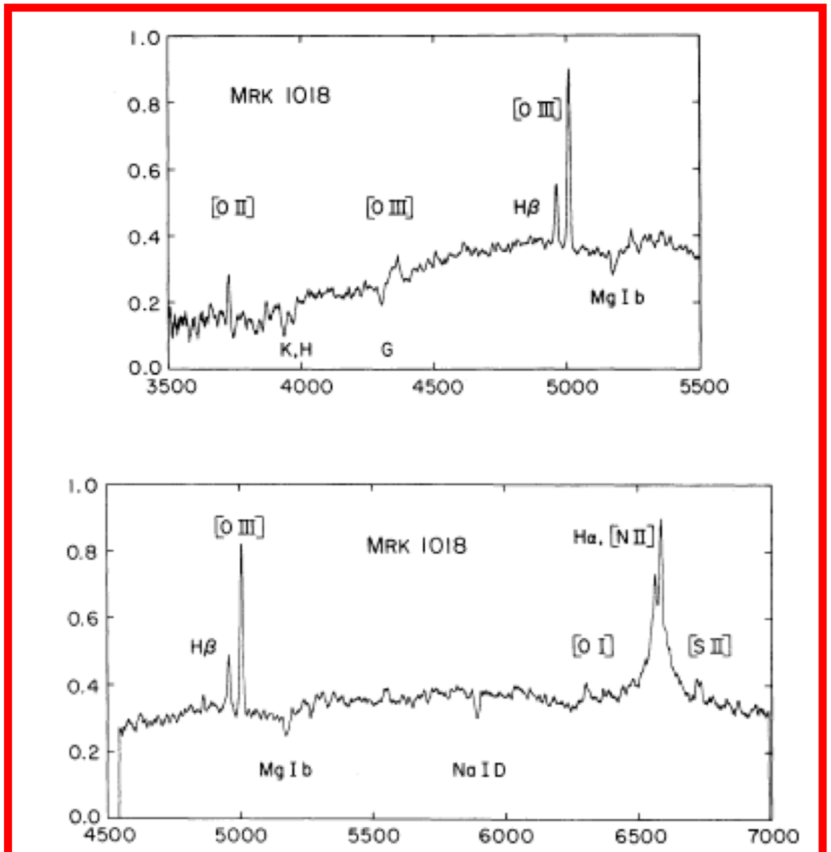


X-ray band

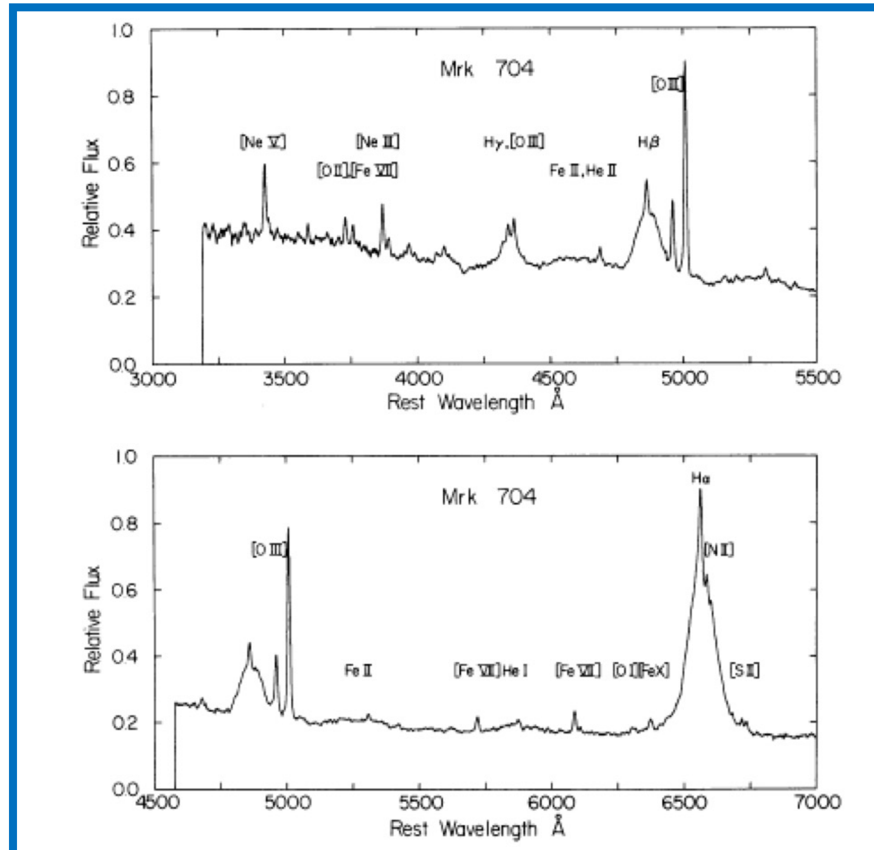
Intermediate-type Seyfert galaxies

References: Osterbrock (1977, 1981; Winkler 1992)

Type 1.9



Type 1.5



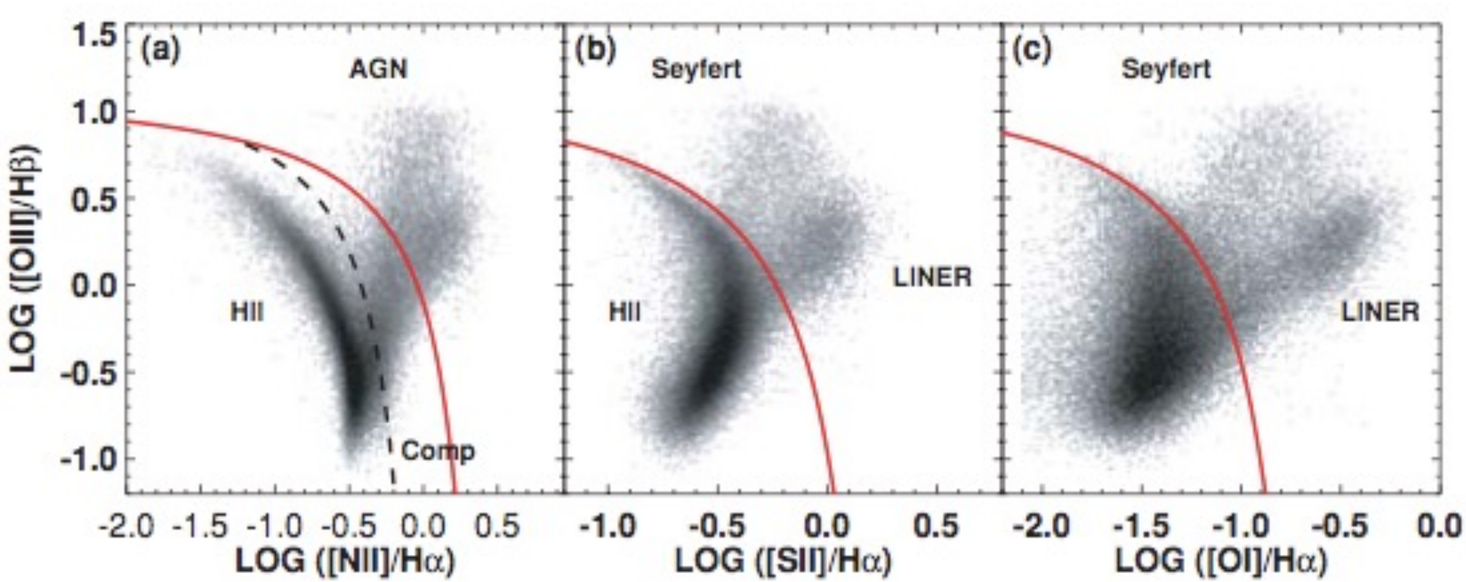
Type 1.9: broad component visible in Hα but not in Hβ

Type 1.5: F(Hβ)/F[OIII]=0.33−2.0

Seyfert 2 galaxies (narrow-line AGN)

• Seyfert galaxies can be differentiated from normal emission-line galaxies through the flux ratios of certain narrow emission lines (only narrow-line components are considered)

• The shape of the underlying ionizing source determines how many photons are available to produce particular emission lines



BPT diagnosctic diagrams

Kewley et al. (2006) – red line shows extreme starburst, dashed line is classification line

Quasars

• Higher luminosity “cousins” of Seyfert galaxies

• Thanks to X-ray surveys, also the narrow-line counterparts of local Sey 2 galaxies (Type 2 quasars) have been detected and studied over the last decade

• Hosts are typically elliptical galaxies

RADIO-LOUD QUASARS: similar optical properties but strong radio emission

Broad-line Seyferts (QSOs): blue continuum

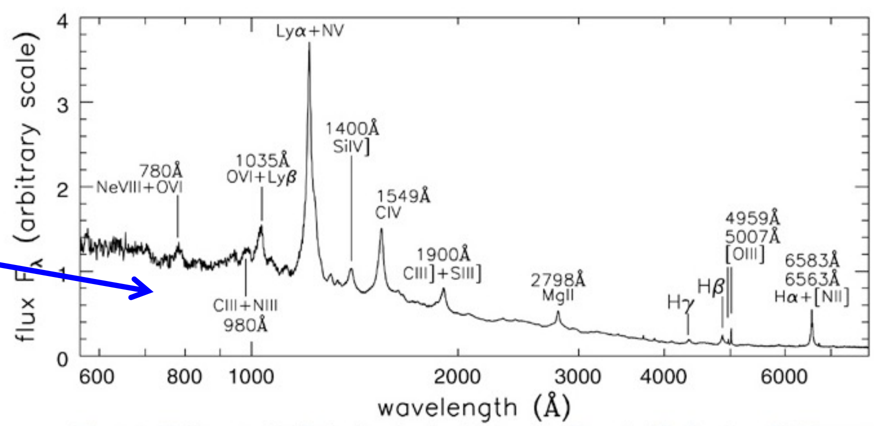


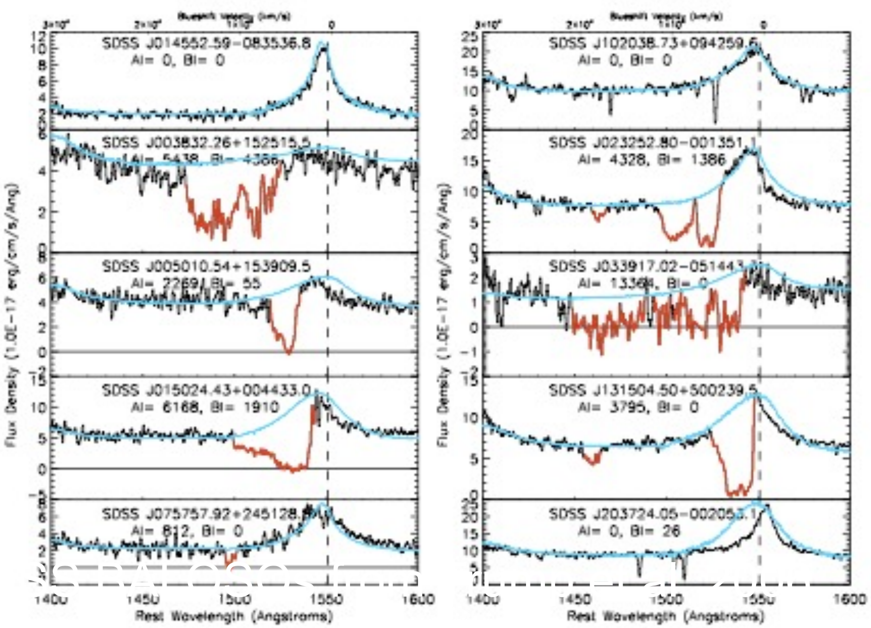
Fig 9.1 (Telfer et al.) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Broad-absorption line quasars (BALQSOs)

Normal quasars viewed at angle along the l.o.s. of intervening, fast-moving material (radiatively-driven wind from the accretion disc?)
➔ Winds providing feedback on the environment surrounding the AGN?

• High-ionization (HIBAL): Lyα, NV, SiIV, CIV
• Low-ionization (LOBAL): AlIII, MgII

Velocity outflows of thousands km/s up to ≈50,000 km/s

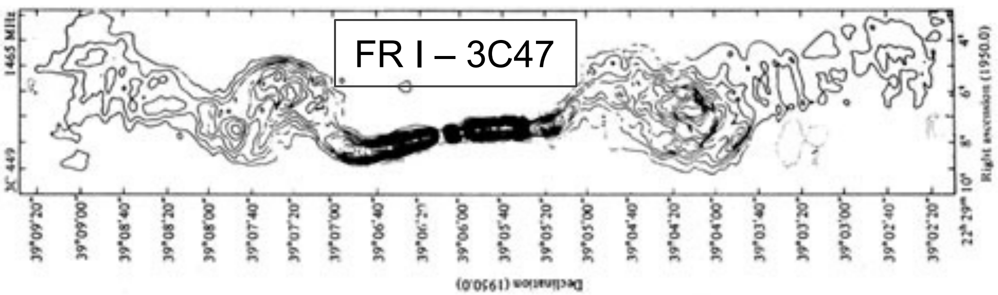


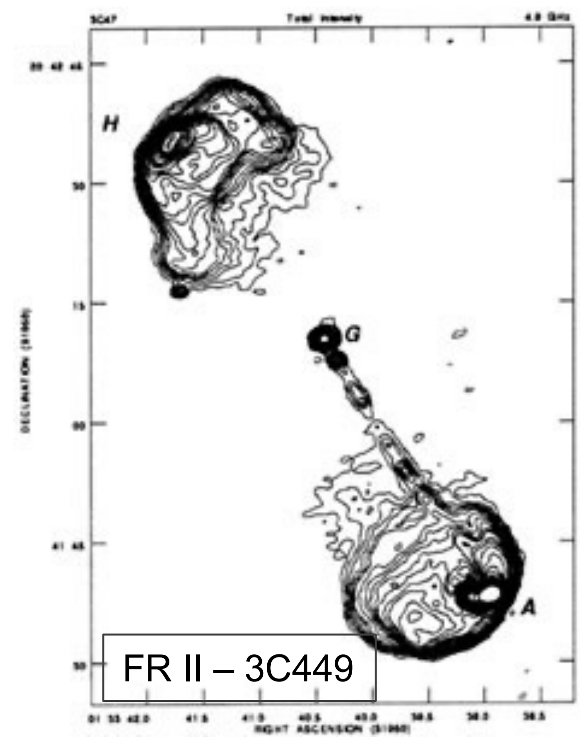
Trump+06

Radio galaxies: classification basef on radio power and morphology

Expanded discussion on RGs later in the course

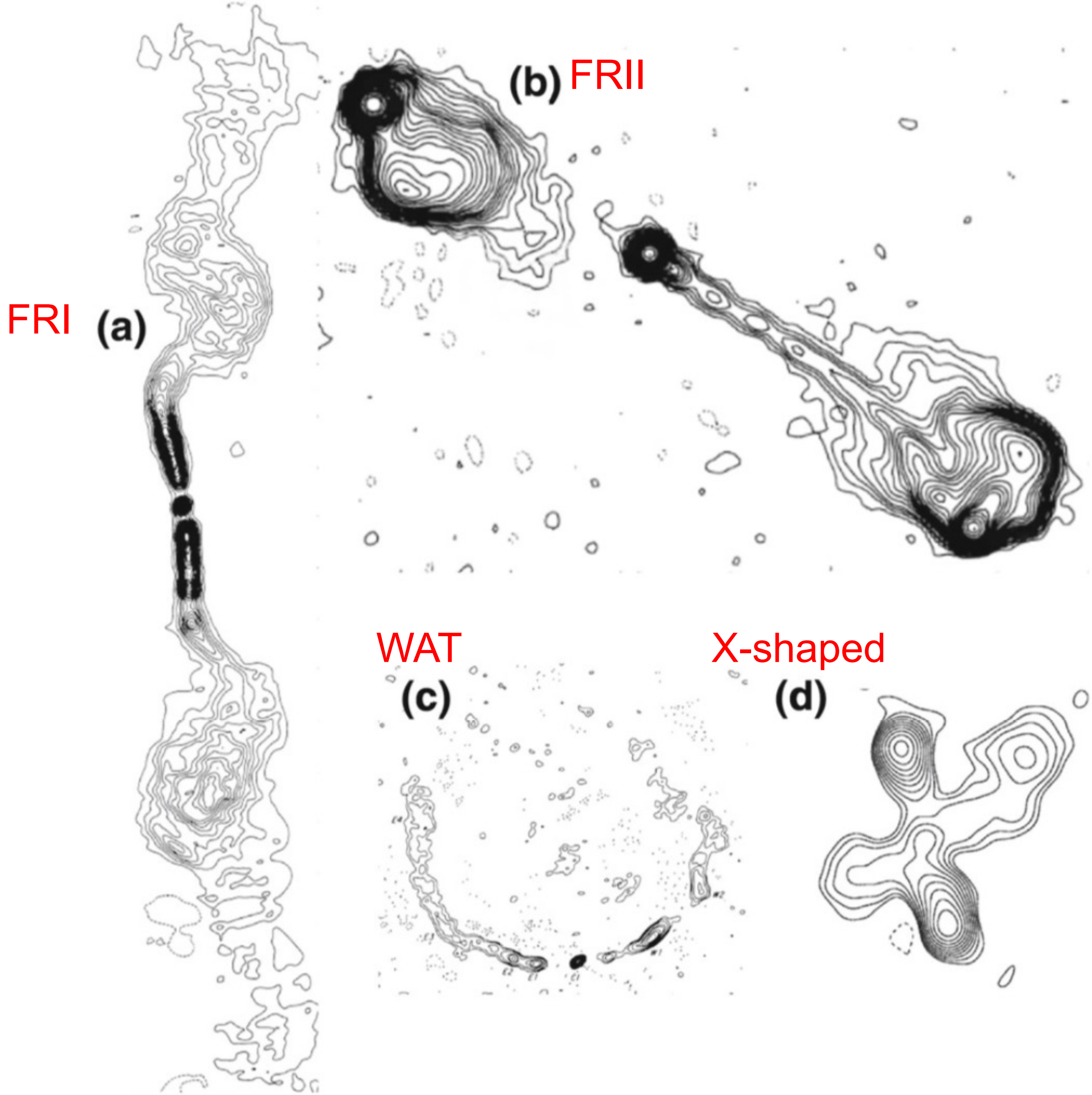
- Fanaroff & Riley (1974) – FR I
  - Less luminous, 2-sided jets dominate over radio lobes
- FR II
  - More luminous, edge-brightened radio lobes dominated over 1-sided jet (Doppler boosting of approaching jet and de-boosting of receding jet)
  - Efficient to transport energy up to the hot spots, where shocks are produced by the relativistic jet,





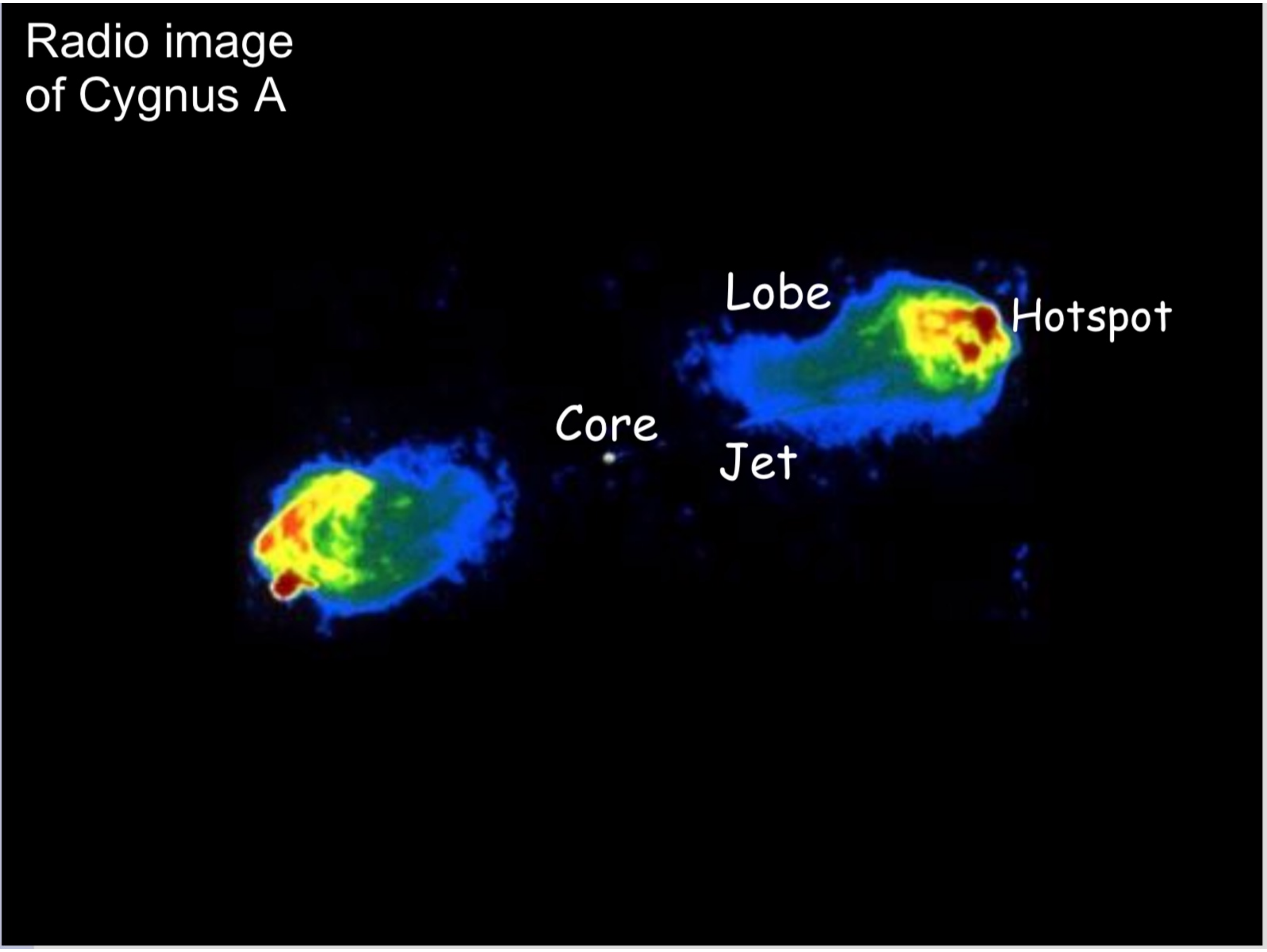
Ratio of the separation of the highest surface brightness regions on opposite sides of the central galaxy and the extent of the source measured from the lowest surface brightness contour (sort of "contrast" parameter): R<0.5: FRI R>0.5: FRII

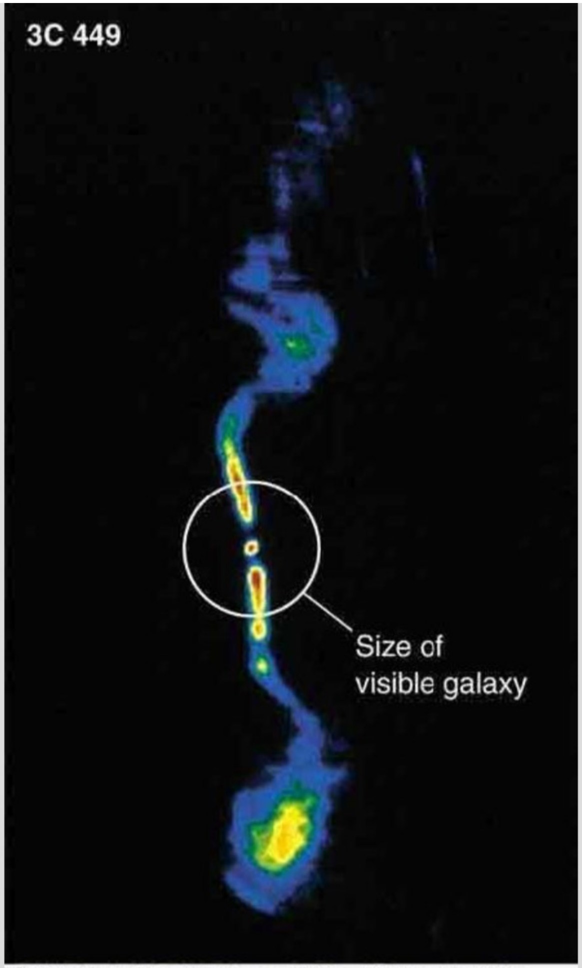
"Dividing line" L[178 MHz]≈10^{25} W/Hz/ster (FR1974)



Environment and mergers have a role in shaping radio galaxies

Extension well beyond the size of the galaxy





Radio galaxies: the new class of FR0

Compact radio galaxies (<10kpc), often unresolved at JVLA resolutions down to ~0.3” (Baldi et al. 2015, 1018; see also Ghisellini and Capetti works).

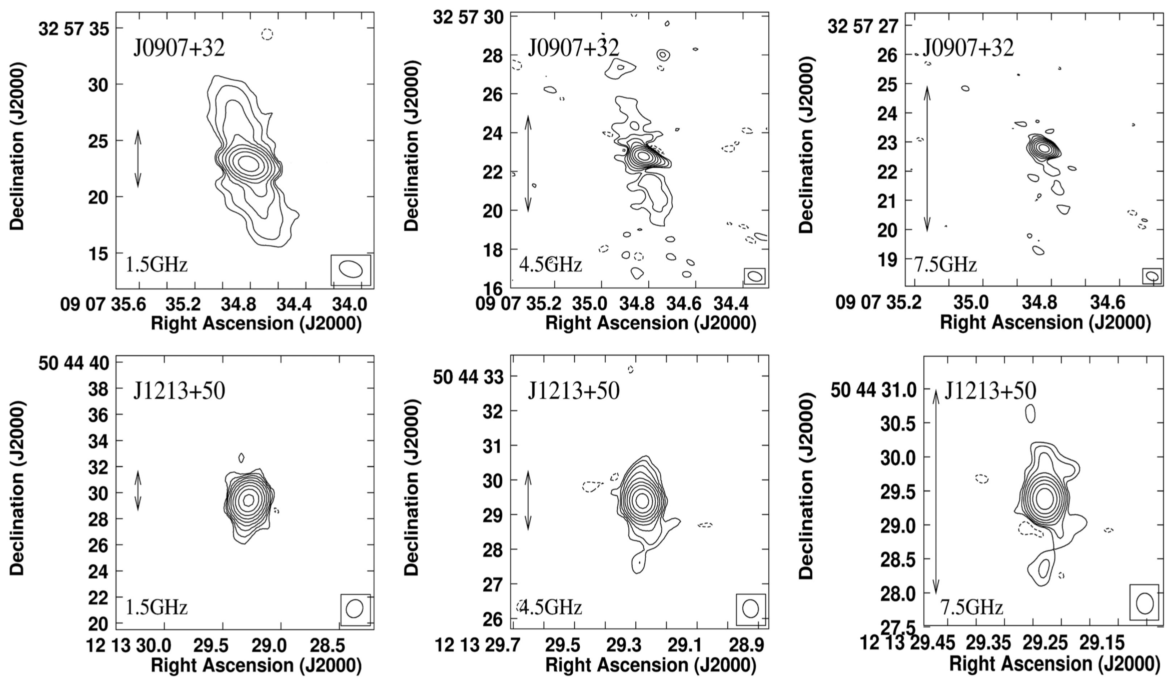
[1] The ratio between the core and total emission in FR0s is ~30 times higher than that in FRIs.

[2] FR0s have the same properties as FRIs from the nuclear and host points of view.

FR0s differ from FRIs only in the paucity of extended radio emission

Possible physical explanations

(1) Young radio galaxies?
(2) A variation of accretion or jet launching prevents the formation of large-scale radio structures
(3) Mildly relativistic jets?



Baldi et al. (2018)

Radio galaxies: flat and steep spectrum sources

$$S_\nu \propto \nu^{-\alpha}$$

$\alpha \geq 0.5$ Steep spectrum sources ~ extended sources

$\alpha \leq 0.5$ Flat spectrum sources ~ compact sources (CSS, GPS)

Blazars = BL LACs + FSRQs (see following slides) are flat-spectrum radio sources (i.e., jet oriented at θ<15 deg wrt. the line of sight)
FSRQs have also strong and broad emission lines, while BL LACs have weak emission lines, absorption lines from their host galaxy, often featureless

This LEG/HEG definition applies also to radio-quiet AGN (e.g., Seyfert galaxies are HEGs, LINERs and low-luminosity AGN are LEGs)

OPTICAL:

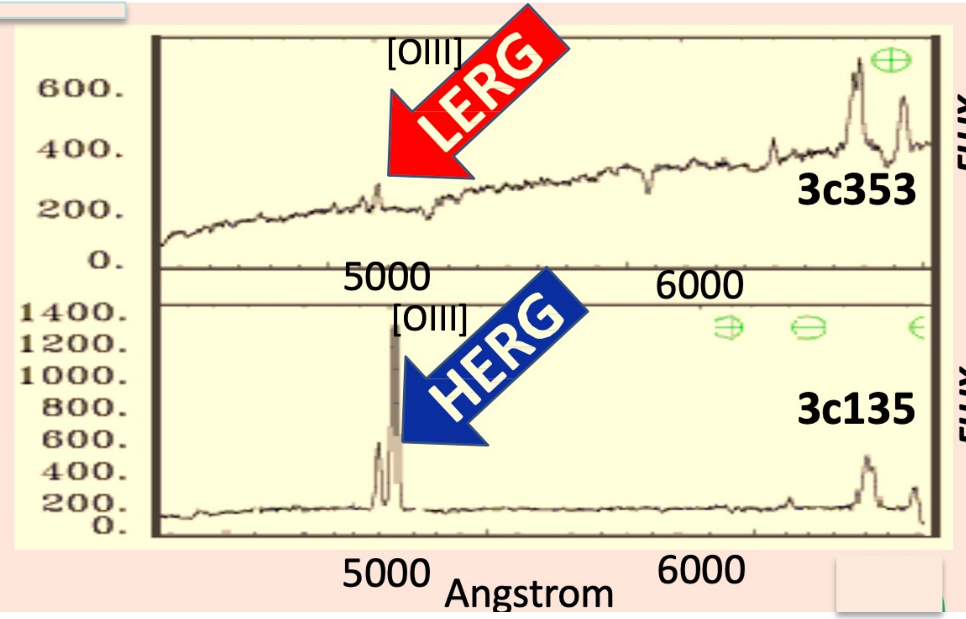
EI = excitation index → proxy of the radiative efficiency

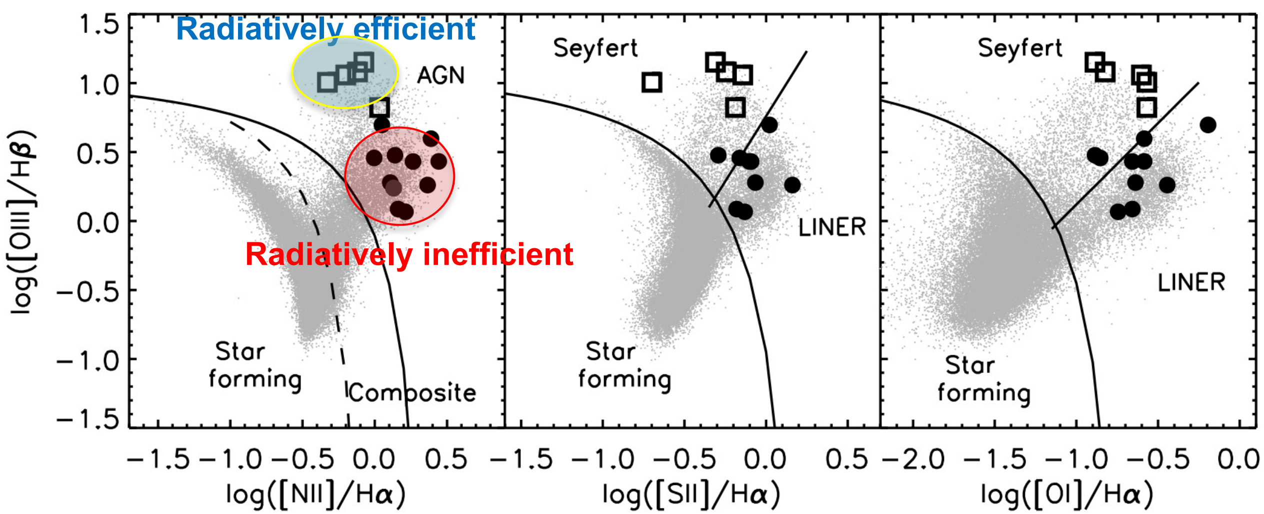
EI<0.95 LEG

EI>0.95 HEG

$$EI = \log\left(\frac{[OIII]}{H\beta}\right) - \frac{1}{3} \times \left[\log\left(\frac{[NII]}{H\alpha}\right) + \log\left(\frac{[SII]}{H\alpha}\right) + \log\left(\frac{[OI]}{H\alpha}\right)\right]$$

Buttiglione et al. (2010→12 papers)

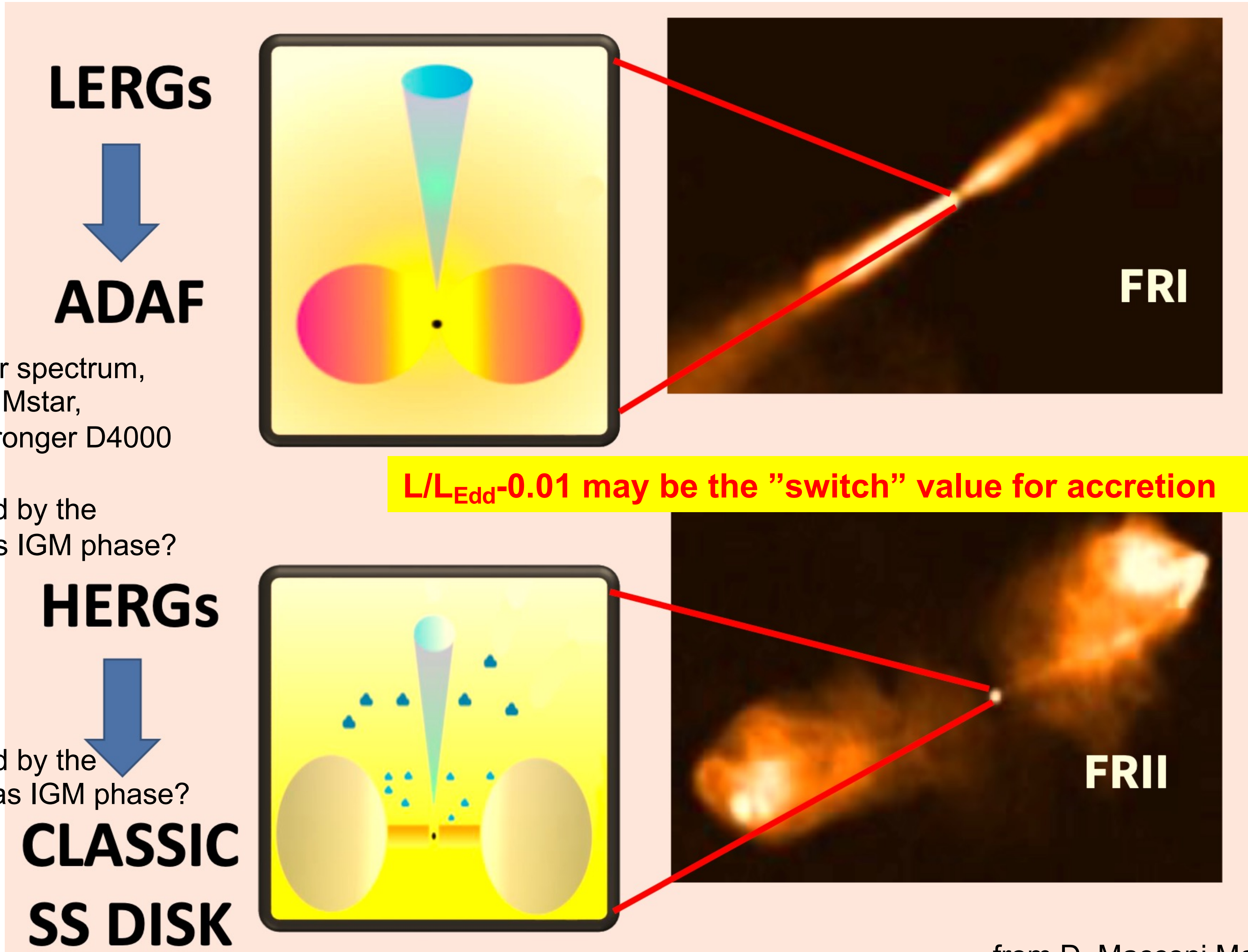




BPT diagnosctic diagrams

Smolcic et al. (2009)

Radio galaxies: low- and high-excitation RGs



Redder spectrum,
higher Mstar,
and stronger D4000 break
Fuelled by the
hot gas IGM phase?

Fuelled by the
cold gas IGM phase?

from D. Macconi Master thesis

Blazars

• Sources of high-energy emission (up to TeV), luminous over the entire electromagnetic spectrum

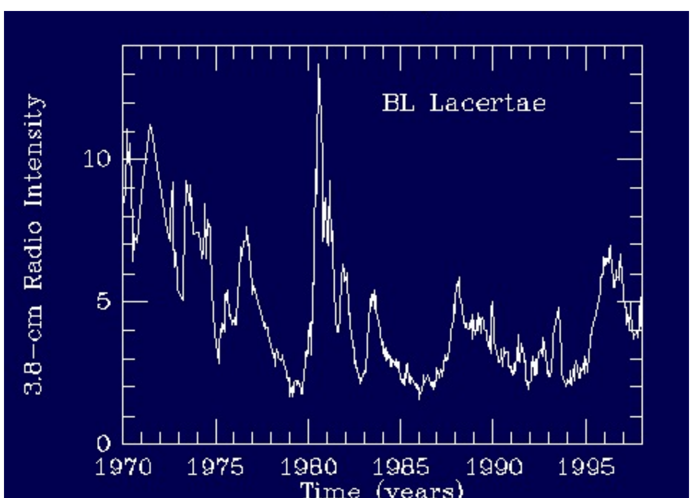
• Hosts are typically giant elliptical galaxies

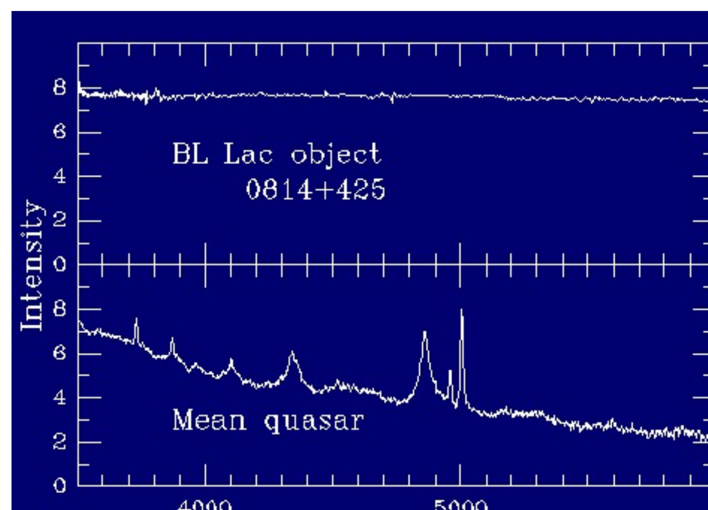
BL LACs: flat and usually featureless (EW<5Å) optical spectrum

Highly polarized, strong and fast variability

OVVs: optical spectrum with features

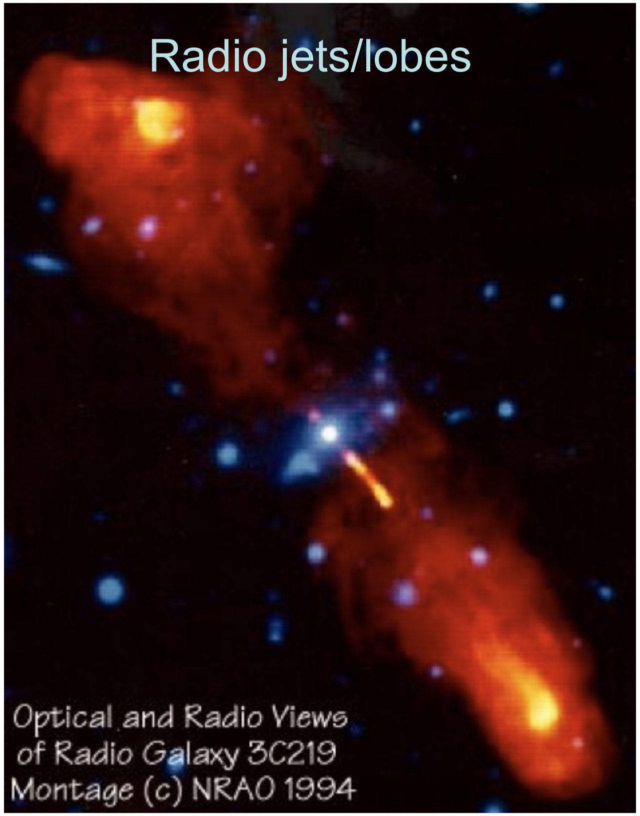
Even stronger variability than BL Lacs, but lower polarization

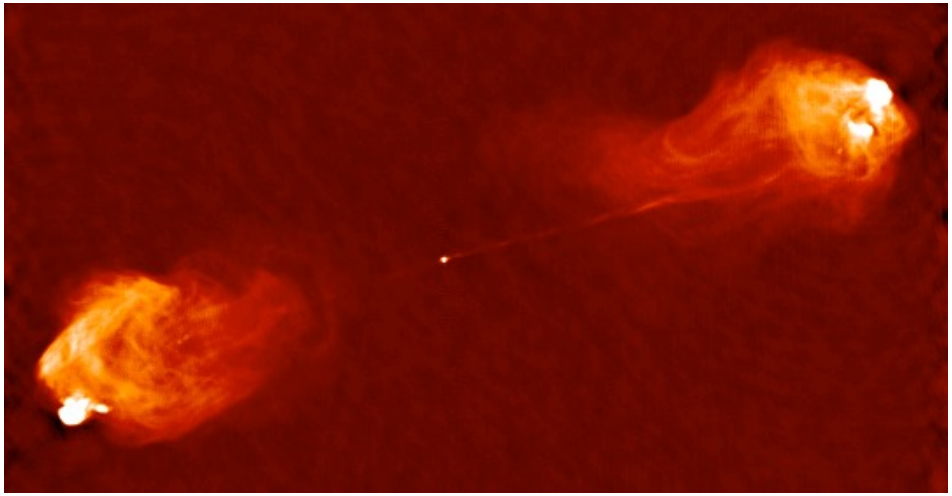




Radio galaxies: optical spec. classification

- Broad Line Radio Galaxies:
  - Emission line widths similar to those in a Seyfert Type 1
- Narrow Line Radio Galaxies:
  - Emission line widths similar to those in a Seyfert Type 2





LINERs

• Sources characterized by narrow, low-ionization emission lines

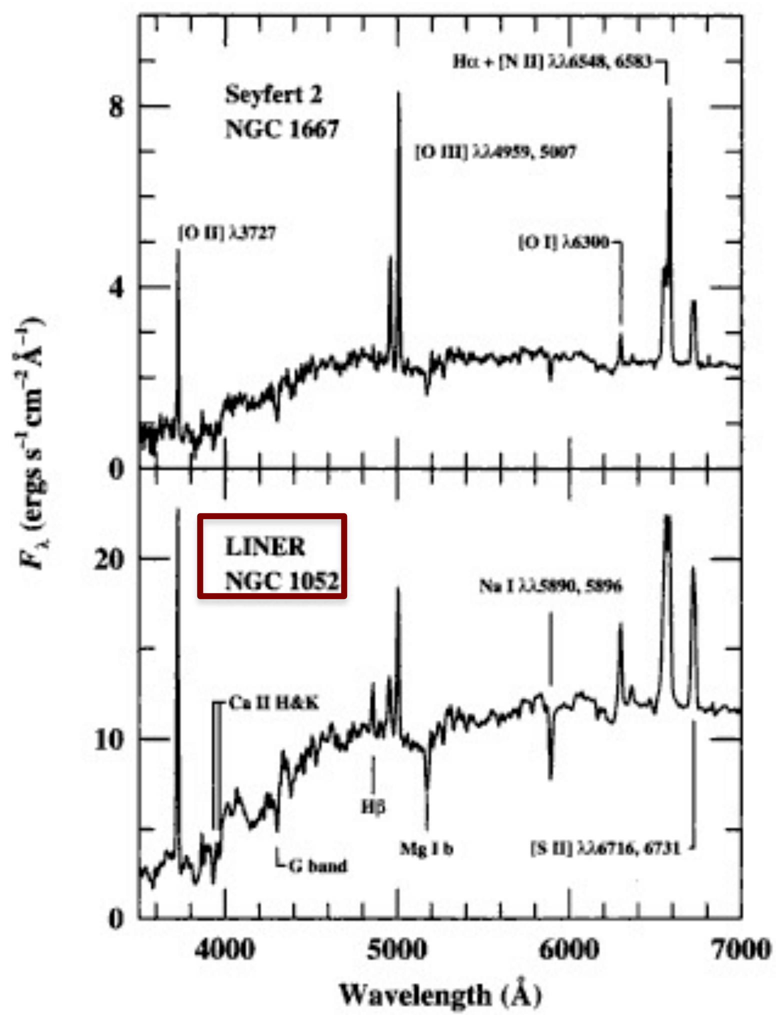
• Weak non-thermal continuum

• Emission due to either AGN (of low luminosity) or shocks/winds from a starburst

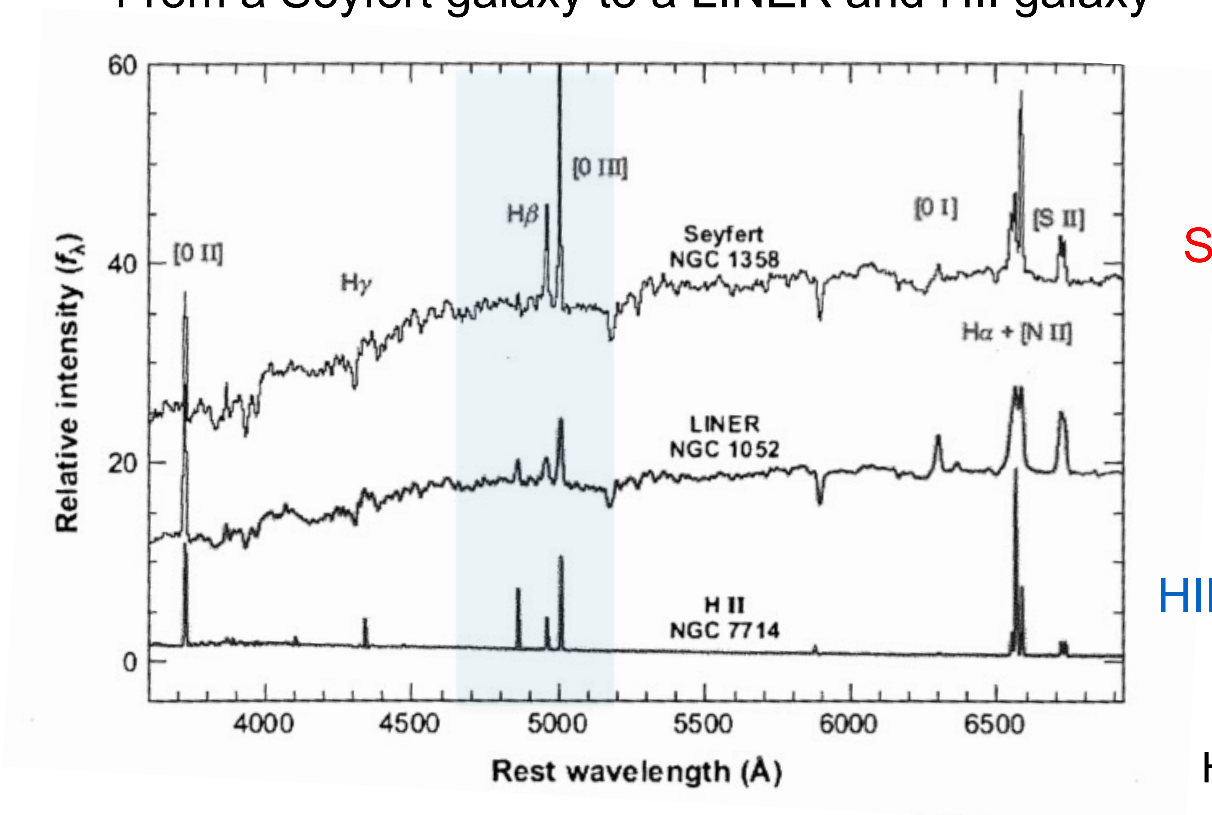
• Hosts are typically spirals

LINER: [OIII]/Hβ less prominent than in Sey 2
Strong [OI]6300Å and [NII]6548,6583Å

Host galaxy may contribute significantly in the optical band in both



From a Seyfert galaxy to a LINER and HII galaxy



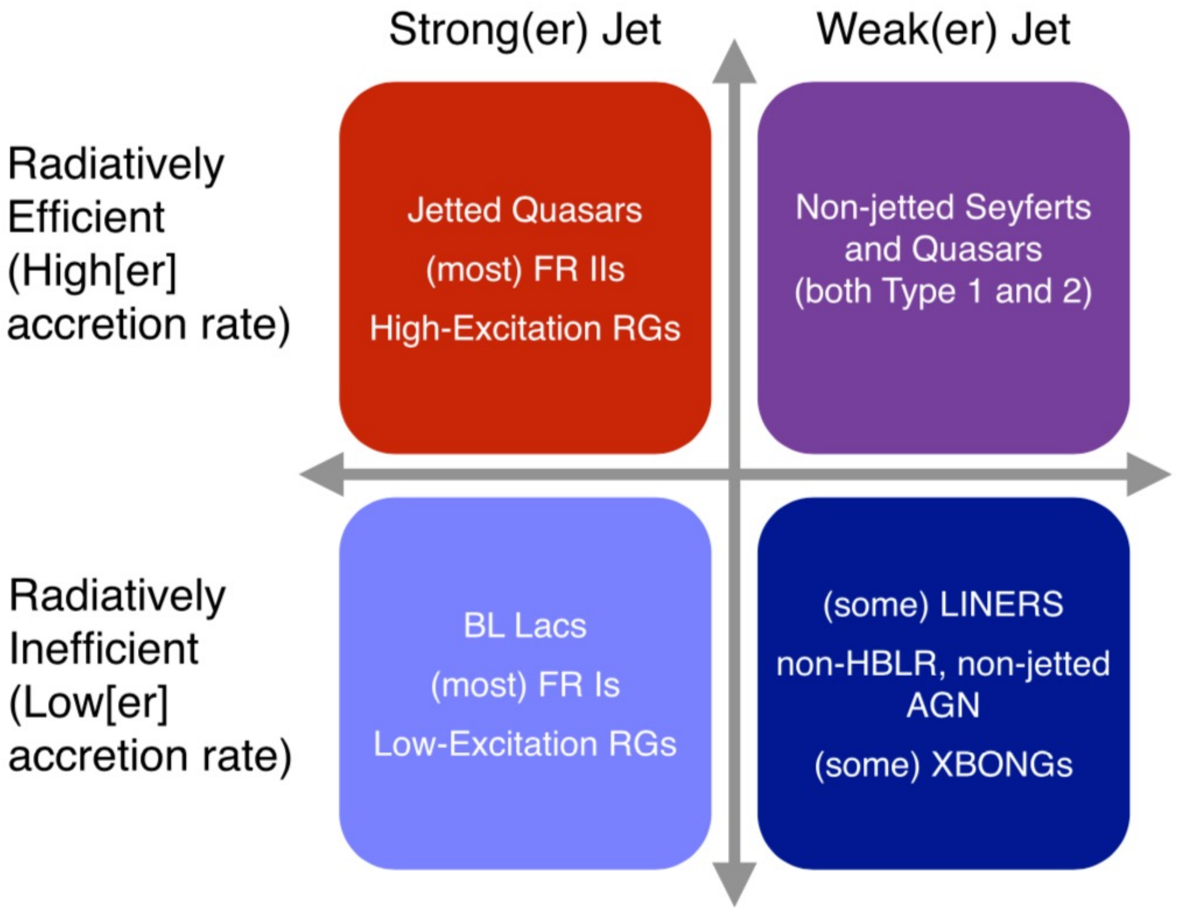
Seyfert galaxy

LINER

HII=star-forming galaxy

Ho et al. (2008)

[see Padovani+2017 review on AGN]

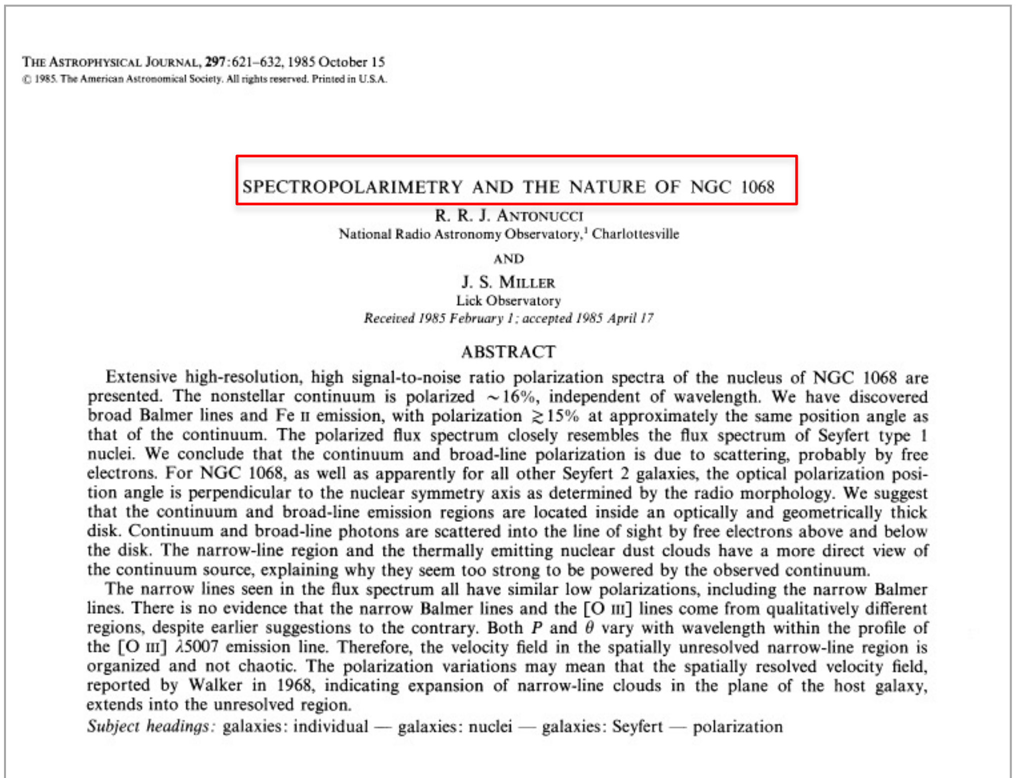


AGN Unification

After numerous attempts to provide a unification model for the RL AGN population…

A milestone in AGN unification. I

A classical Sey 2 galaxy (NGC1068) observed in polarized light showed a Sy1-like polarized spectrum, a featureless continuum with high polarization and position angle perpendicular to the radio jet. The observed properties could be explained by reflection of an hidden BLR into the line of sight, the scattering source being composed of hot electrons rather than dust grains.



THE ASTROPHYSICAL JOURNAL, 297:621–632, 1985 October 15

SPECTROPOLARIMETRY AND THE NATURE OF NGC 1068

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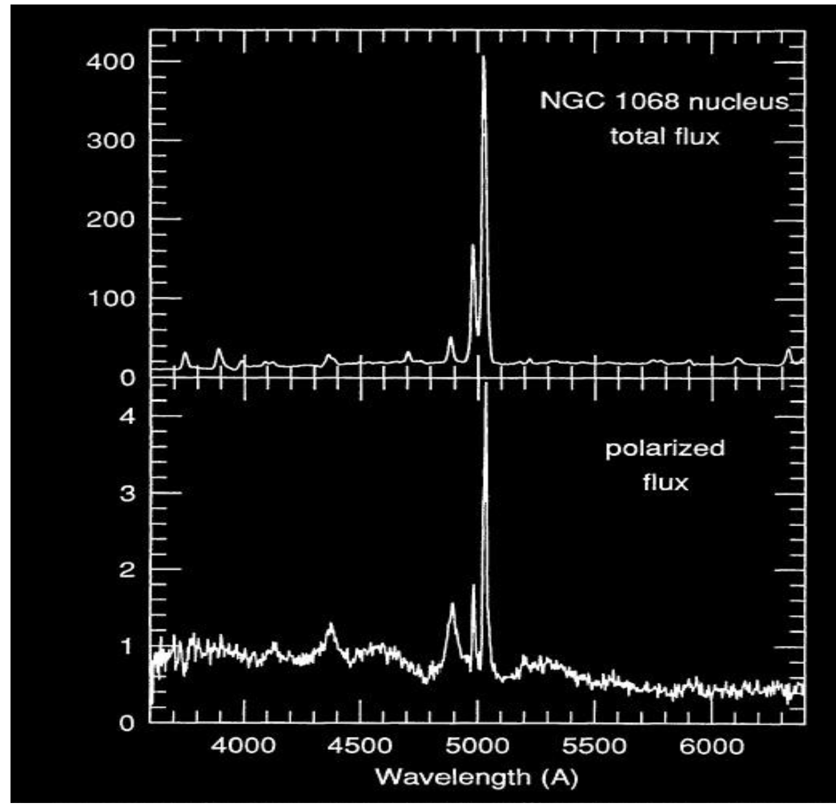
Received 1985 February 1; accepted 1985 April 17

ABSTRACT

Extensive high-resolution, high signal-to-noise ratio polarization spectra of the nucleus of NGC 1068 are presented. The nonstellar continuum is polarized ~16%, independent of wavelength. We have discovered broad Balmer lines and Fe II emission, with polarization ≳15% at approximately the same position angle as that of the continuum. The polarized flux spectrum closely resembles the flux spectrum of Seyfert type 1 nuclei. We conclude that the continuum and broad-line polarization is due to scattering, probably by free electrons. For NGC 1068, as well as apparently for all other Seyfert 2 galaxies, the optical polarization position angle is perpendicular to the nuclear symmetry axis as determined by the radio morphology. We suggest that the continuum and broad-line emission regions are located inside an optically and geometrically thick disk. Continuum and broad-line photons are scattered into the line of sight by free electrons above and below the disk. The narrow-line region and the thermally emitting nuclear dust clouds have a more direct view of the continuum source, explaining why they seem too strong to be powered by the observed continuum.

The narrow lines seen in the flux spectrum all have similar low polarizations, including the narrow Balmer lines. There is no evidence that the narrow Balmer lines and the [O III] lines come from qualitatively different regions, despite earlier suggestions to the contrary. Both P and θ vary with wavelength within the profile of the [O III] λ5007 emission line. Therefore, the velocity field in the spatially unresolved narrow-line region is organized and not chaotic. The polarization variations may mean that the spatially resolved velocity field, reported by Walker in 1968, indicating expansion of narrow-line clouds in the plane of the host galaxy, extends into the unresolved region.
Subject headings: galaxies: individual — galaxies: nuclei — galaxies: Seyfert — polarization



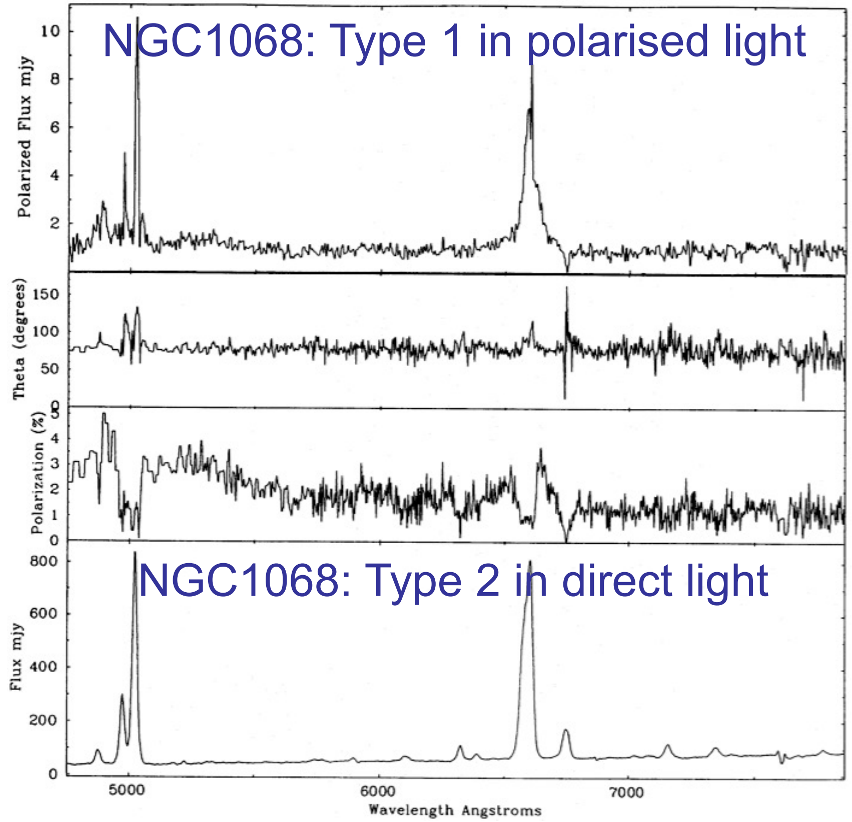
Antonucci & Miller 1985

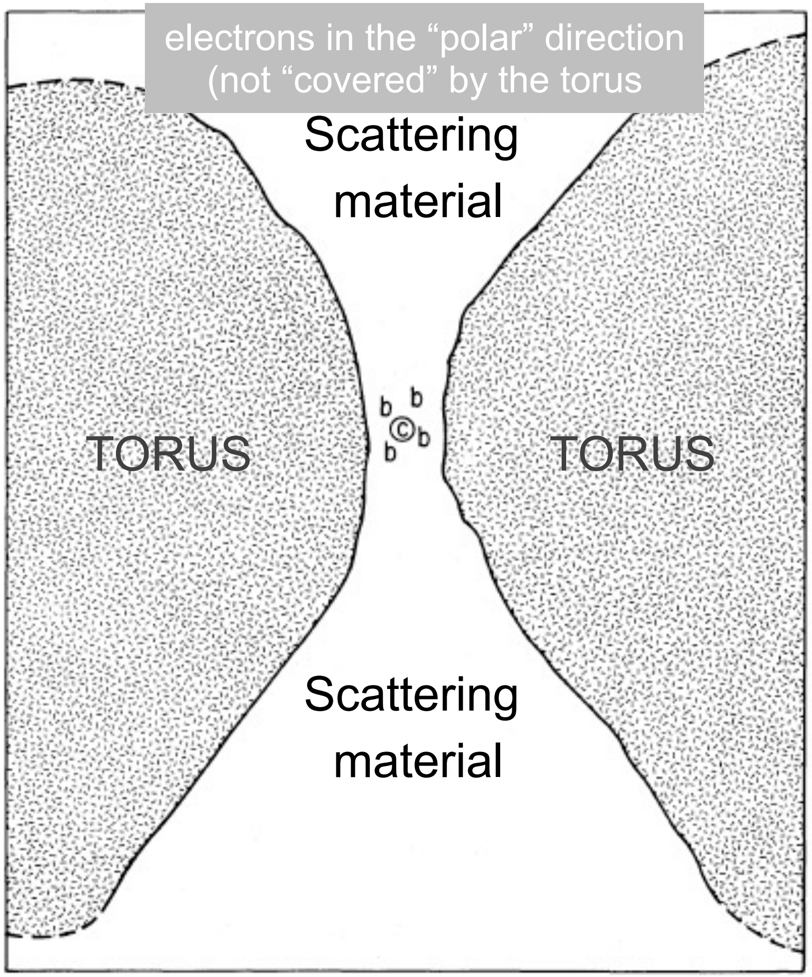
A milestone in AGN unification. II

Hidden Type 1 AGNs in Type 2 AGN (but not in all)

→ Spectropolarimetry revealing Type 1 AGN in at least some Type 2 AGNs

→ Polarised emission is scattered light that is hidden from direct view

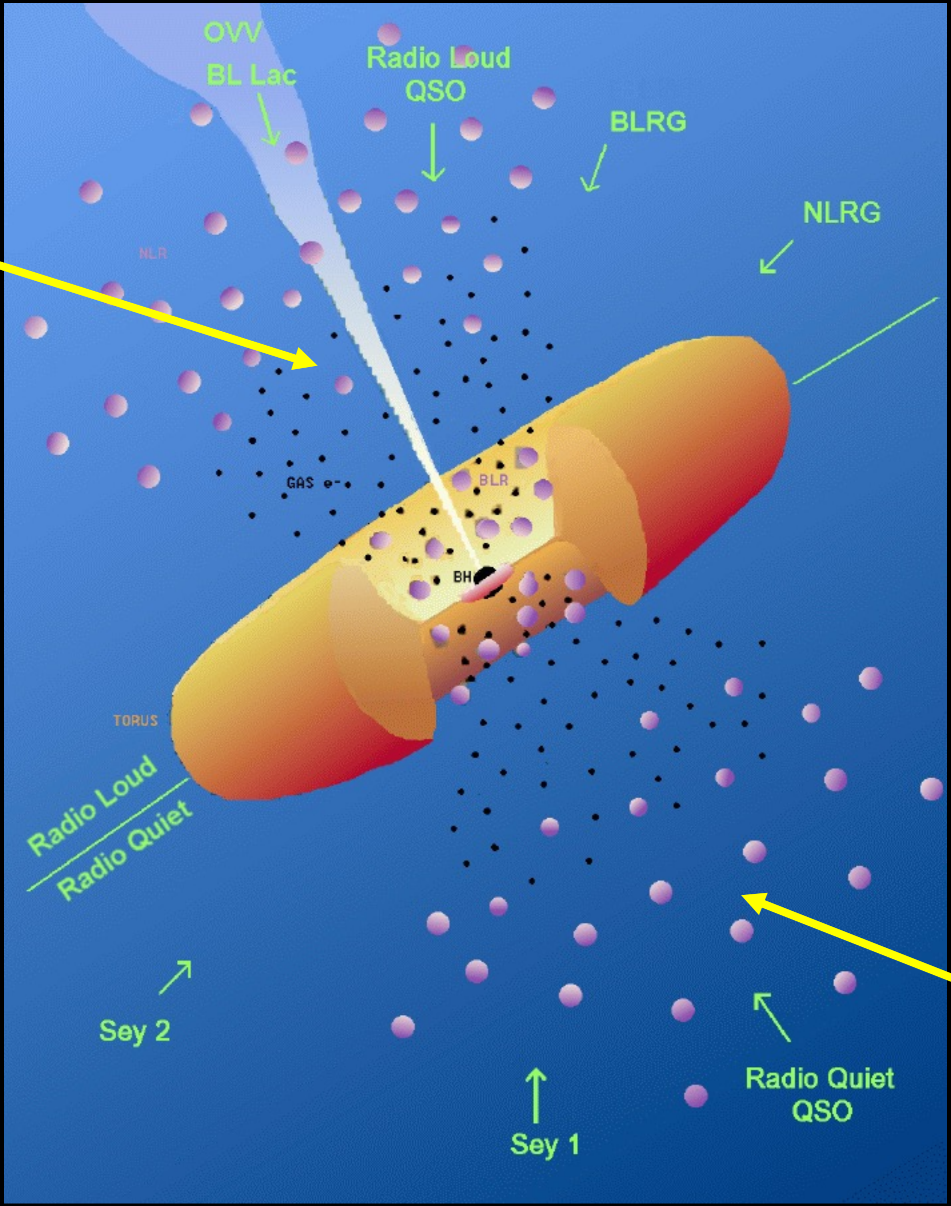




Antonucci & Miller 1985; Antonucci 1993, ARA&A

AGN taxonomy/classification

Unification scheme for radio-loud (jetted) AGN
(top part of the cartoon)



Remember: only a limited fraction of AGN (~10%) has jets

Unification scheme for radio-quiet (not-jetted) AGN
(bottom part of the cartoon)

adapted from Urry & Padovani 1995

A logarithmic view of an AGN

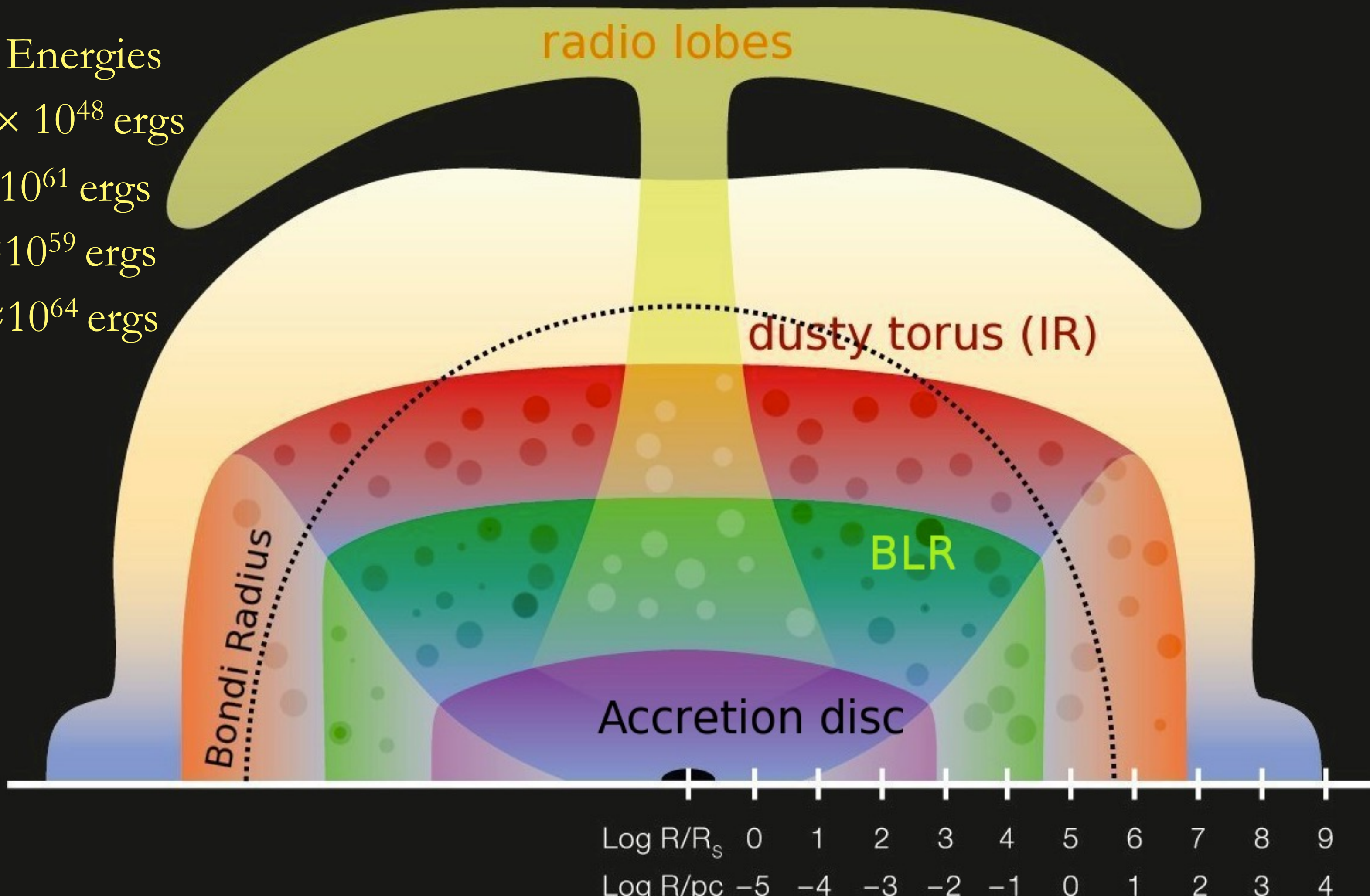
Binding Energies

$E_{b,\odot} \approx 4 \times 10^{48}$ ergs

$E_{b,BH,8} \approx 10^{61}$ ergs

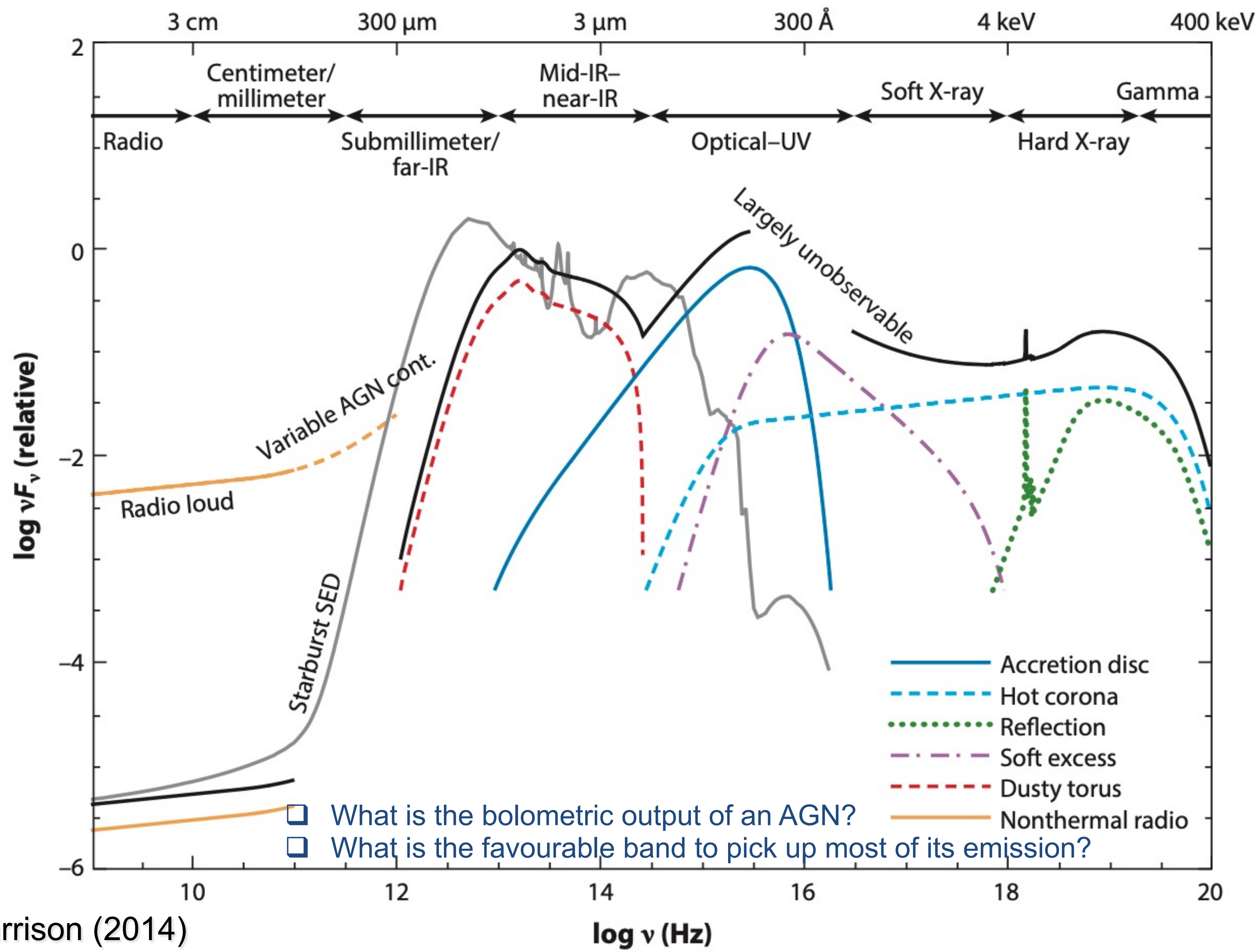
$E_{b,gal,11} \approx 10^{59}$ ergs

$E_{b,Coma} \approx 10^{64}$ ergs



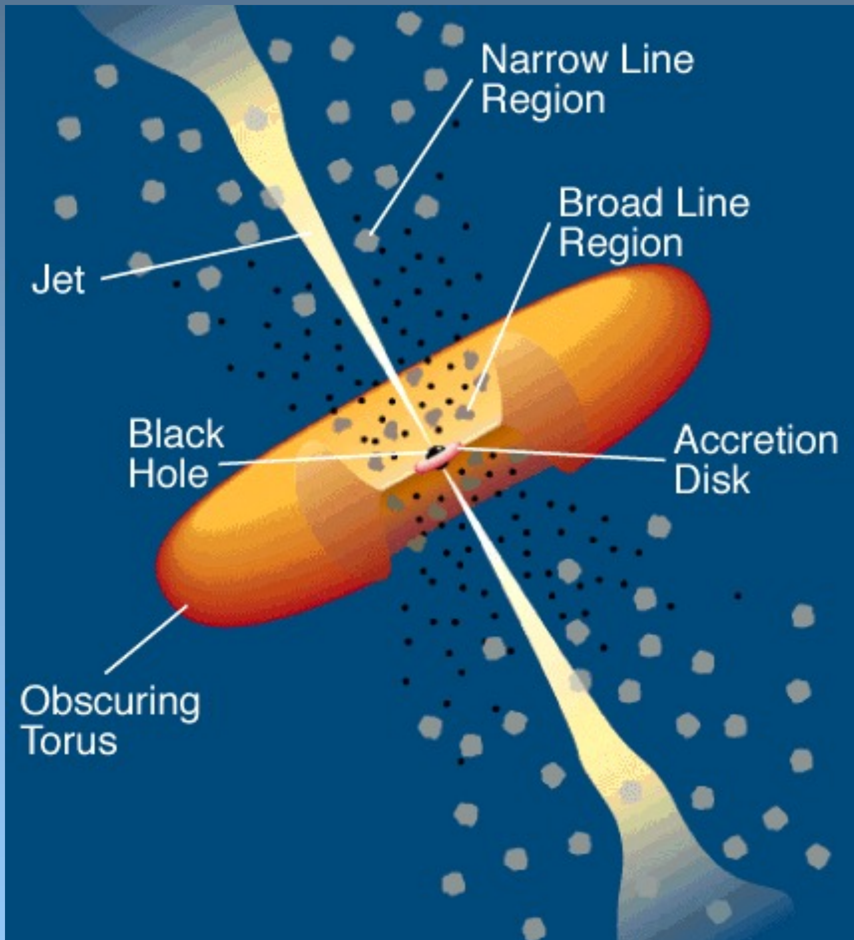
Courtesy of A. Merloni, ESO graphics, 2010

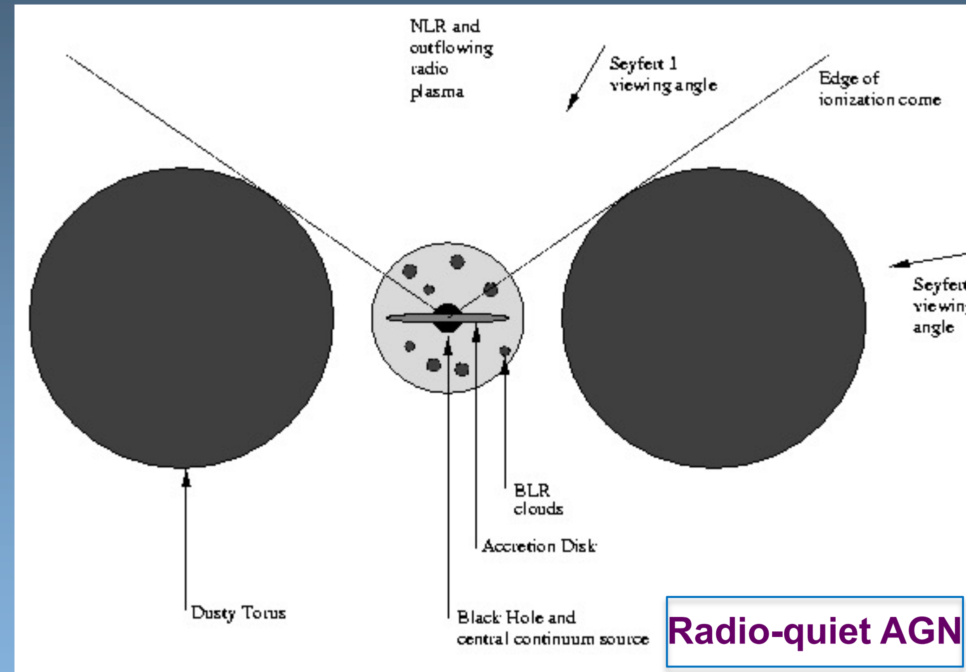
AGN Spectral Energy Distribution

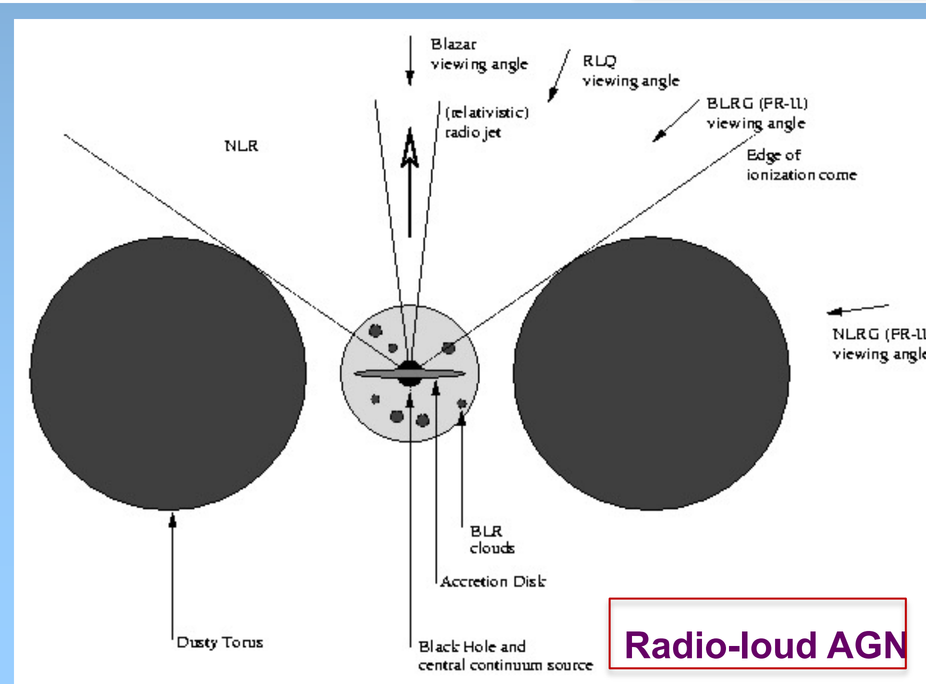


- ❑ What is the bolometric output of an AGN?
- ❑ What is the favourable band to pick up most of its emission?

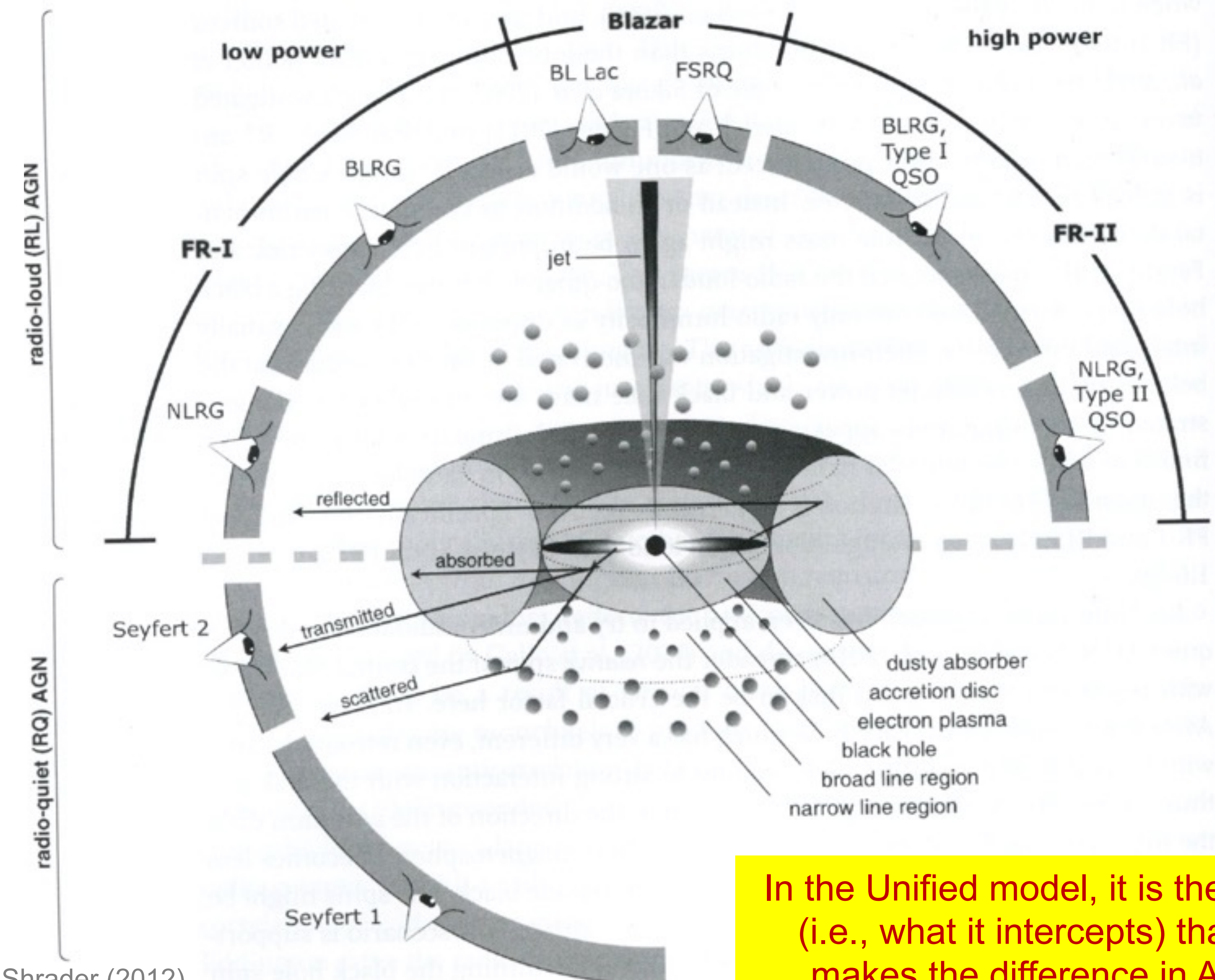
Harrison (2014)


Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus


NLR and outflowing radio plasma
Seyfert 1 viewing angle
Edge of ionization come
Seyfert 2 viewing angle
BLR clouds
Accretion Disk
Dusty Torus
Black Hole and central continuum source
Radio-quiet AGN


Blazar viewing angle
RLQ viewing angle
(relativistic) radio jet
BLRG (FR-II) viewing angle
NLR
Edge of ionization come
NLRG (FR-II) viewing angle
BLR clouds
Accretion Disk
Dusty Torus
Black Hole and central continuum source
Radio-loud AGN

The AGN phenomenon along different lines of sights

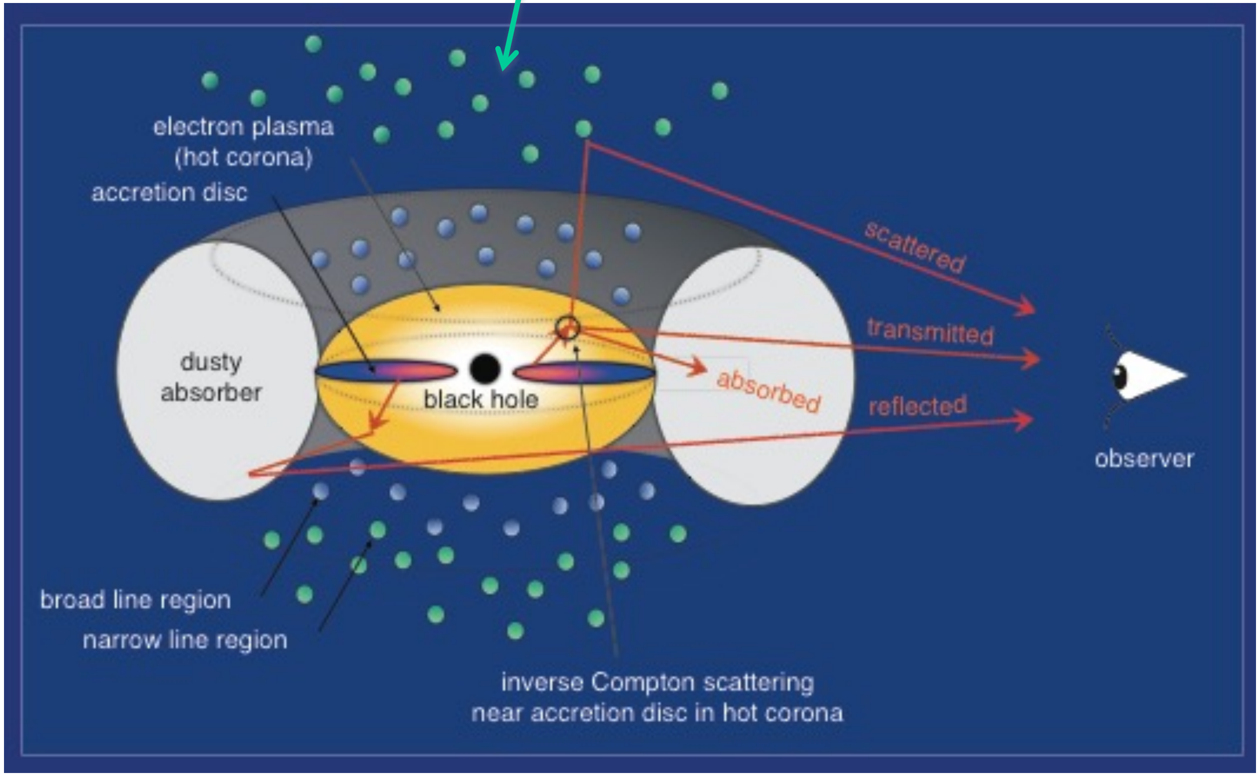


Beckmann & Shrader (2012)
Graphic by Marie-Luise Menzel

In the Unified model, it is the line of sight (i.e., what it intercepts) that primarily makes the difference in AGN types (broadly, Type 1 vs. Type 2 AGN)

The AGN phenomenon along different lines of sights

scattering material in the polar regions allowing
the view of the central regions even in obscured AGN
(e.g., Antonucci original work)



Main AGN Classifications

Radio quiet		Radio loud
Radio quiet quasar (RQQ) *Broad absorption line (BAL)* **Seyfert 1** *Sy 1.0.....1.9* *Narrow line Sy 1 (NLS1)*	Type 1	**Radio loud quasar** (RLQ) *Steep radio spectrum (SSRLQ)* *Flat radio spectrum (FSRLQ)* **Broad line radio galaxy** (BLRG)
Seyfert 2 *NL X-ray galaxy (NLXG)*	Type 2	**Narrow line radio galaxy** (NLRG)
LINER	Type 3	**Weak line radio galaxy** (WLRG)
	Type 0	**Blazar: BL Lac/OVV**
		Fanaroff Riley class I (FRI) **Fanaroff Riley class II** (FRII)

Tadhunter (2008 review)

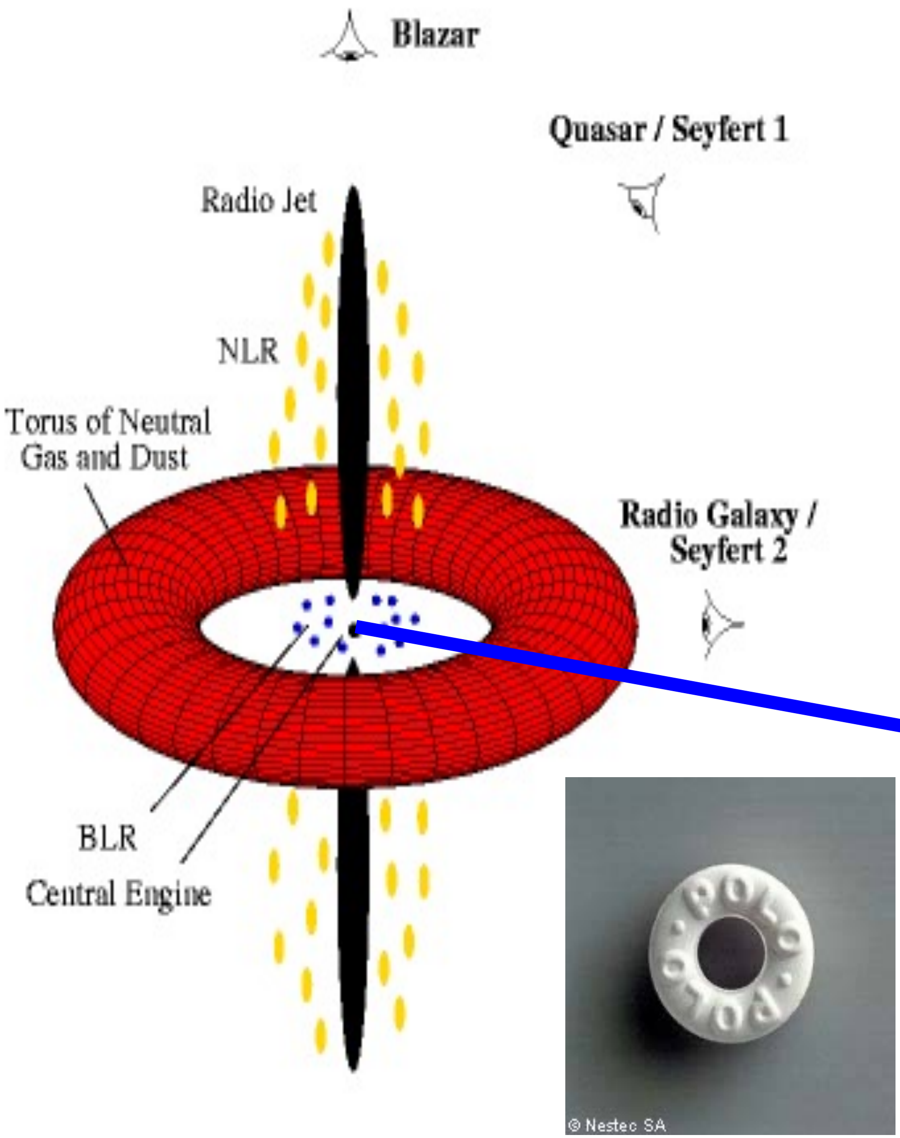
Type	Optical lines	Radio-quiet	Radio-loud
Type 1	Broad and narrow lines	Seyfert 1 Seyfert 1.5 NLS1	FSRQ, SSRQ, BLRG
Type 2	Narrow lines only Weak narrow lines	Seyfert 1.8, 1.9, 2 LINER /LLAGN	NLRG, type 2 QSO WLRG
Type 0	No lines	Sgr A*? Dormant AGN[a]	BL Lac, OVV

Beckmann and Shrader book

Radio loud?	AGN type	Subtype	X-ray absorbed? $N_H > 10^{22}$ cm^{-2}	Broad Balmer lines?	Narrow Balmer lines?	FeKα?	γ-rays?
RL							
	Radio galaxy						
		WLRG	Yes	Yes	Yes	No	No
		BLRG	No	Yes	Yes	Yes	Few
		FR I/II	No	Some	Yes	No	No
	Quasar	Type 1	No	Yes	Yes	Yes	Some
	Quasar	Type 2	Yes	No	Yes	Yes	No
	Blazar						
		FSRQ	No	Yes	Yes	Some	Yes
		BL Lacs	No	No	No	No	Yes
RQ							
	Seyfert 1		< 10%	Yes	Yes	Yes	No
	Seyfert 1.5		~ 30%	Yes	Yes	Yes	No
	Seyfert 2		> 90%	No	Yes	Yes	No
	NLS1		< 10%	Yes	Yes	Yes	Few
	ULIRGs		Yes	Yes	Yes	No	No
	LINER		Yes	No	Yes	Yes	No

Many attempts to provide AGN unification (here some examples)

AGN Type 1 and 2 unification



Size-scales

Black-hole: < size ISCO acc. disc
Accretion disc: ~3 – 10^4 Rs
Broad Line Region: ~1-100 light days
Molecular Torus: ~1-10 light years
Narrow Line Region: ~300-3000 ly