Active Galactic Nuclei

I. Classification and unification scheme
II. AGN X-ray emission and internal structure
III. X-ray surveys and AGN evolution
IV. AGN mid-IR emission and the quest for heavily obscured AGN
V. Formation and evolution of AGN at high redshift

Active Galactic Nuclei – I
Classification and Unification Model

Two main themes in modern high-energy astrophysics

- Physics of accretion and ejection in massive black holes

  Needs characterization of the X-ray and γ-ray emission from AGN, hence high counting statistics (large effective area) and, possibly, high-resolution X-ray spectra.

- Census of SMBHs to "map" the growth of massive structures up to high redshifts: AGN/galaxy co-evolution, feedback processes, etc.

  Needs large, well-defined samples of AGN, including the most elusive, heavily obscured ones, and the first SMBHs to form in the Universe. Large source numbers are more important than individual source photon statistics, typically very limited (e.g., in deep X-ray surveys).

NUCLEAR EMISSION IN SPIRAL NEBULAE*

1943

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.

Apparent relative intensities of the emission lines in the six spirals were reduced to true relative intensities. 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.

Class of spiral galaxies with optical emission lines

EMISSION NUCLEI IN GALAXIES

1959

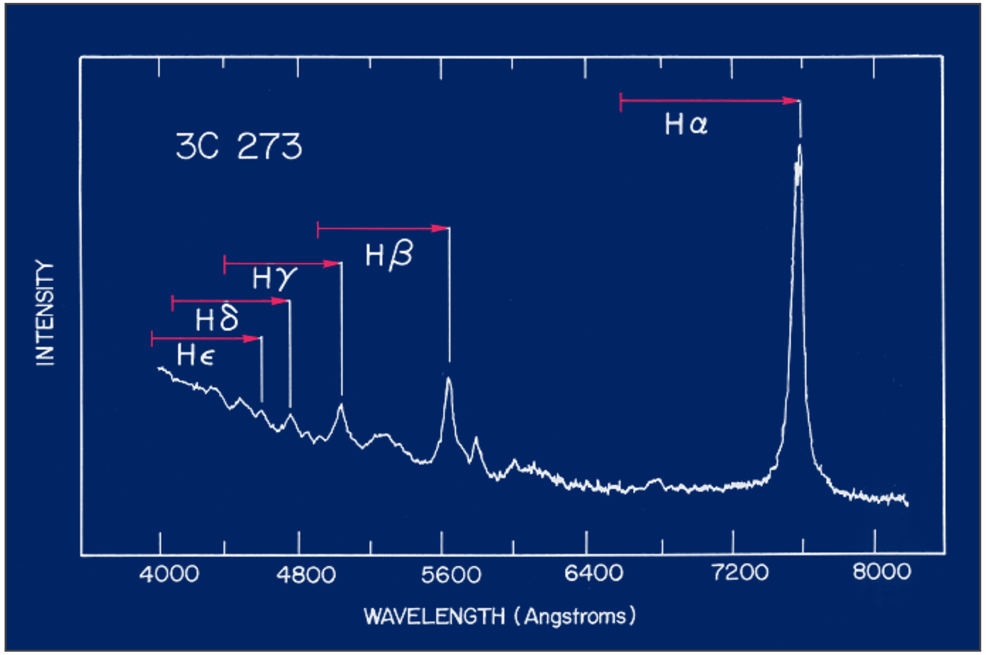
L. Woltjer*
Yerkes Observatory, University of Chicago
Received February 16, 1959

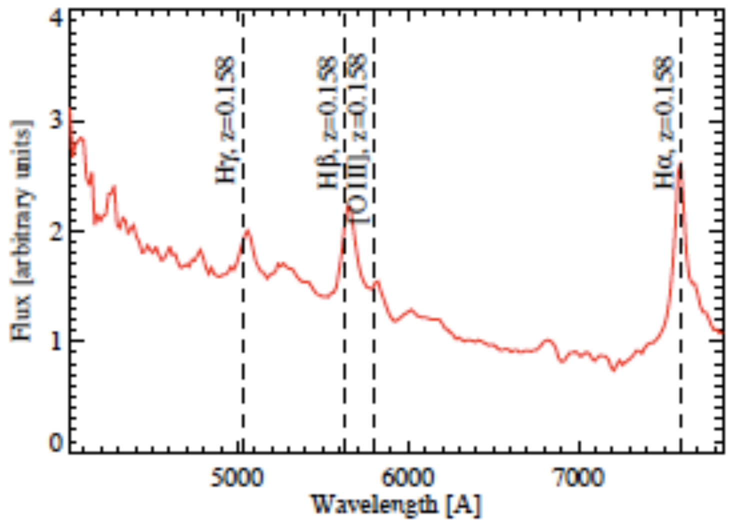
ABSTRACT

Some galaxies which show wide emission lines in the spectra of their nuclei are discussed. It is shown that, on statistical grounds, the nuclear emission must last for several times 10^8 years at least. The nuclei are extremely narrow, of the order of 100 parsecs, and, if a normal mass-to-light ratio applies, extremely massive. The width of the emission lines, which indicates velocities of a few thousand kilometers per second, is probably due to fast motions, circular or random, in the gravitational fields of the nuclei. The high star density in the nuclei may provide a source of excitation. In the nucleus of our own Galaxy the radio source Sagittarius gives evidence of strong magnetic fields and large amounts of relativistic particles. A mass of a few times 10^8 solar masses is needed to prevent disintegration of the source. The Andromeda Nebula has a nucleus with a somewhat smaller mass. The occurrence of dense nuclei may be a common characteristic of many galaxies.

Objects must have very large masses

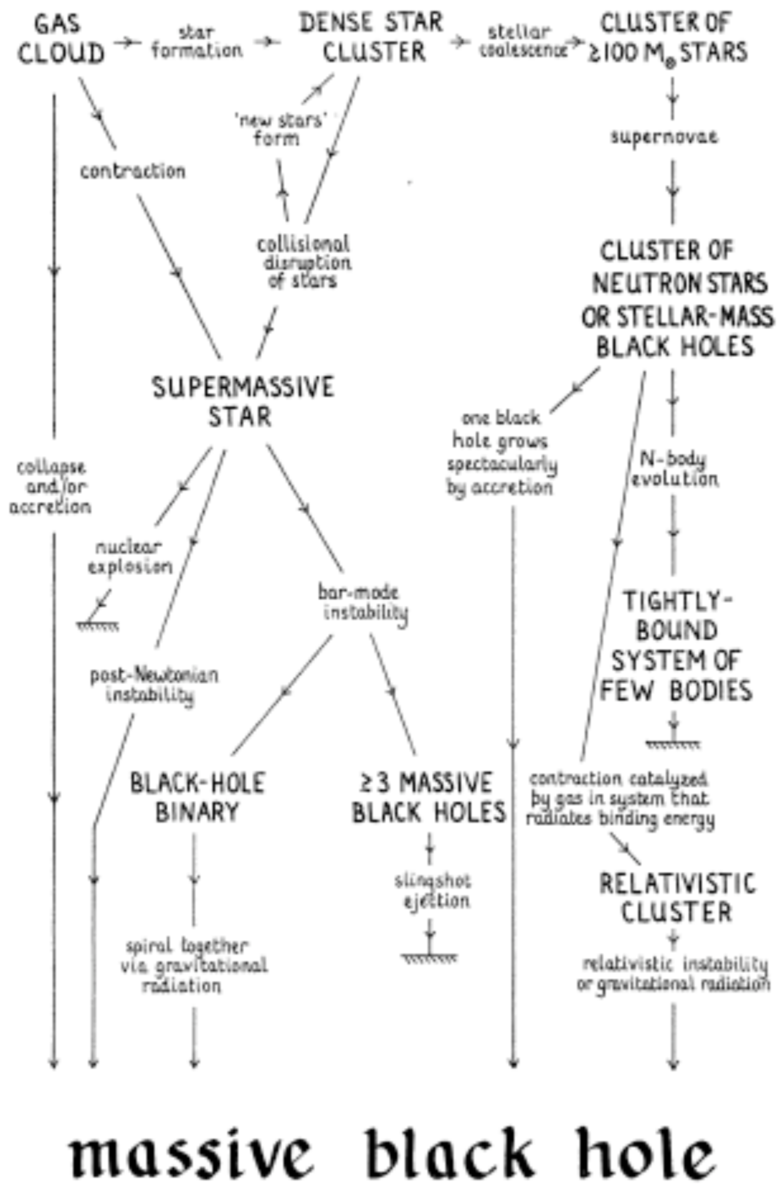
1963





Schmidt et al. (1963; paper on *Nature*): 3C 273: z=0.158 (v_r = 47500 km/s)
➔ This object is far away

How do massive black hole form?



Rees 1978, 1984

Lynden-Bell 1969

Energy output not explained by stellar processes ➔ accretion onto compact sources is the solution

Gravitational radiation

The super-massive black hole paradigm

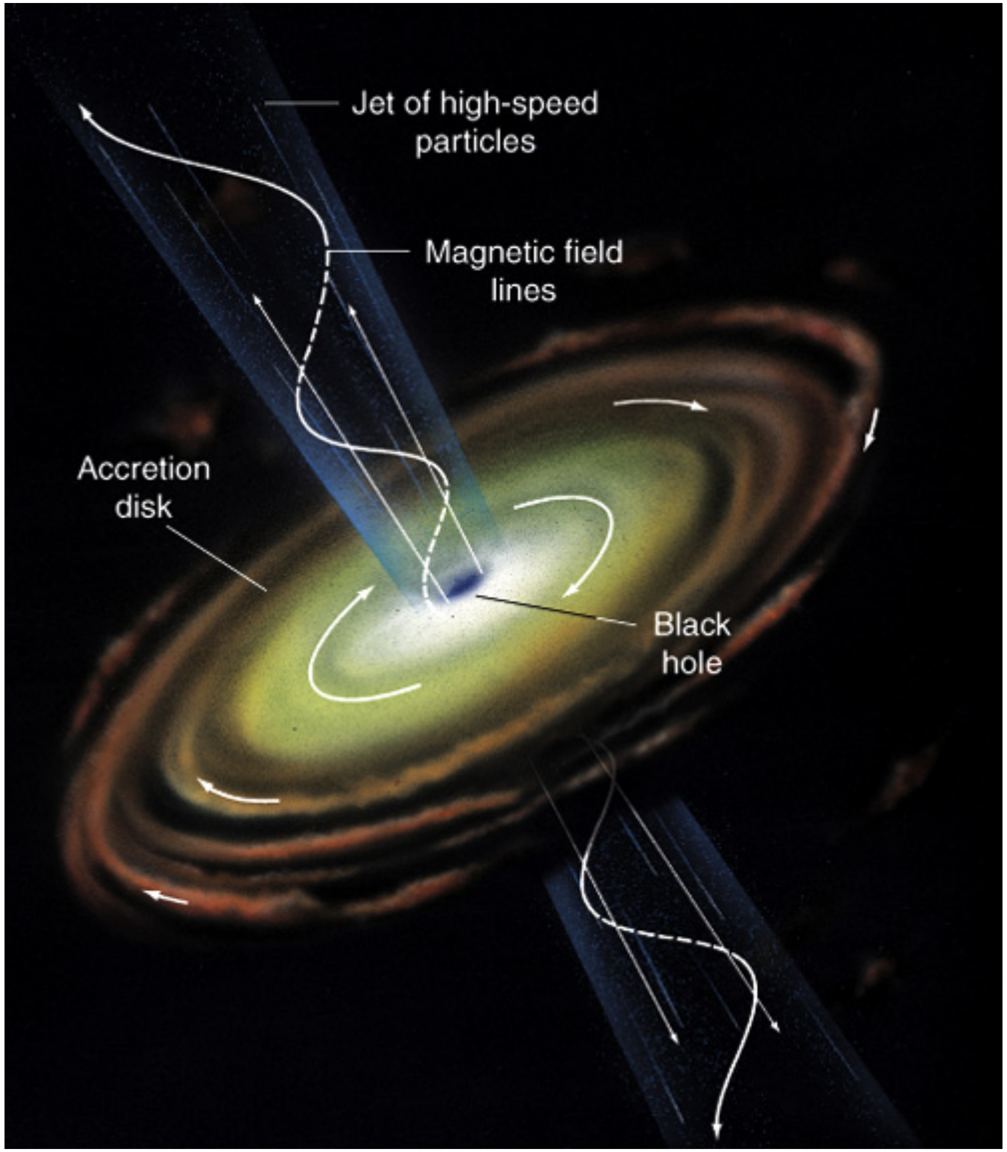
A super-massive black hole (SMBH) is present in most galaxies

• BH mass vs. galaxy bulge luminosity/velocity dispersion have confirmed this paradigm over the last 20 years (Magorrian relation; e.g., Gebhardt et al. 2000)

• The width of the broad emission lines reflects the presence of a deep potential

• Galaxy mergers/encounters may drive matter to the inner regions, thus providing the fuel for the SMBH, but "secular" (smooth) evolution is likely fundamental for most active galaxies

Powering Active Galactic Nuclei



(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.

Powering AGN: accretion disc vs. Bondi-Hoyle accretion

$$\dot{M} = \pi\, r_{acc}^2 v \rho$$

v, ρ: wind velocity and density if accretion is spherical and from a uniform ambient wind

$$r_{acc} = \frac{2GM}{v^2}$$

The effective accretion (capture) radius is linked to the escape velocity at a distance r from the BH

$$\Rightarrow \dot{M} \approx \frac{4\pi\rho G^2 M_{BH}^2}{v^3}$$

actually

$$\Rightarrow \dot{m}_{accr} = \alpha \frac{4\pi G^2 m_{BH}^2 \rho}{\left(c_s^2 + v^2\right)^{3/2}},$$

c_s: sound speed of the local medium; v: BH velocity relative to the local medium; α: adimensional parameter from simulations (≈100−300)

$$\dot{M} \approx 5\times10^{-9}\left(\frac{M_{BH}}{10^8\ M_{sun}}\right)^2 M_{sun}/yr$$

vs.

$$\dot{M}_{Edd} \approx 2.2\left(\frac{M_{BH}}{10^8\ M_{sun}}\right)/\eta_{0.1}\ M_{sun}/yr$$

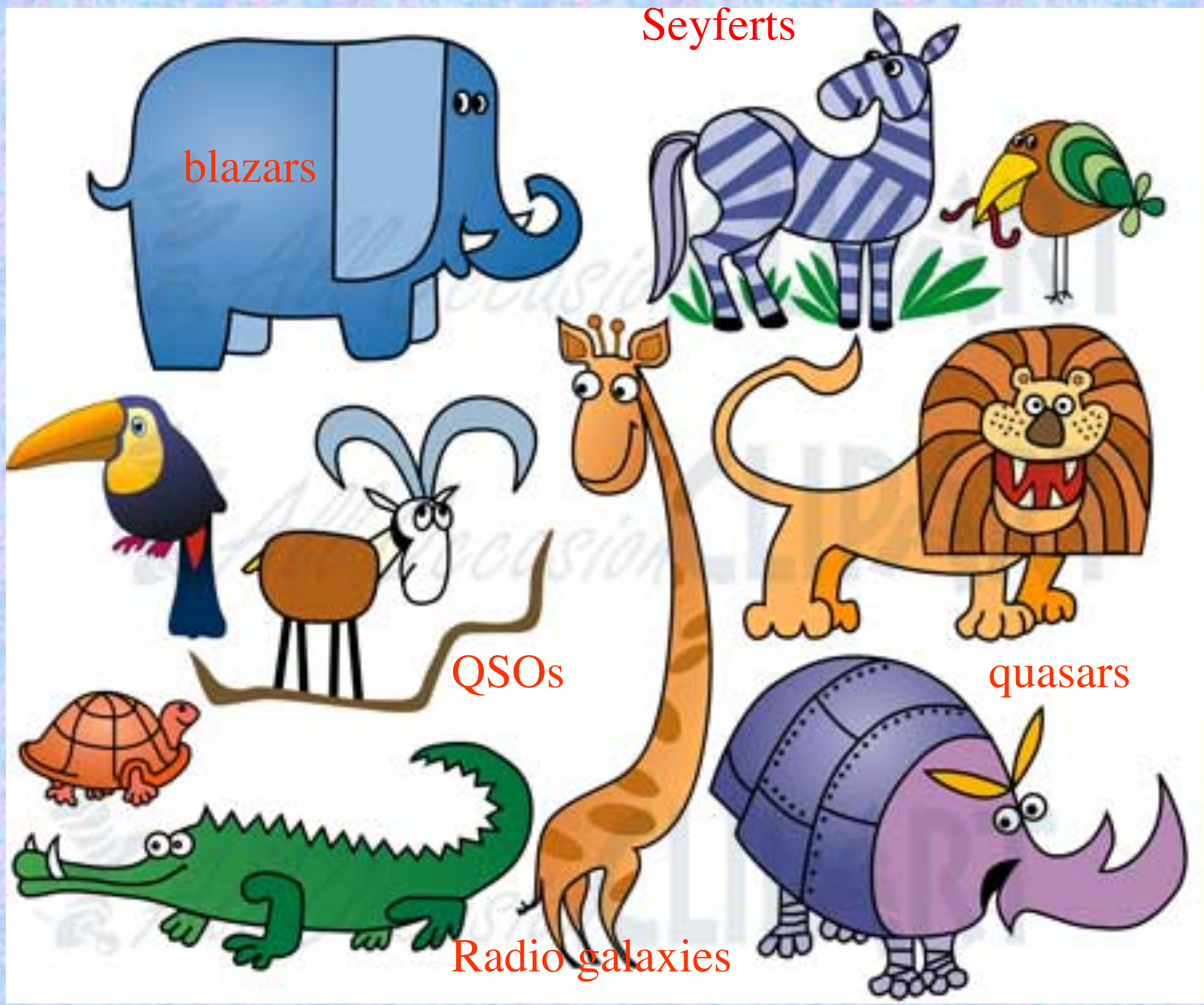
accretion via a disc is more efficient

Some 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 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

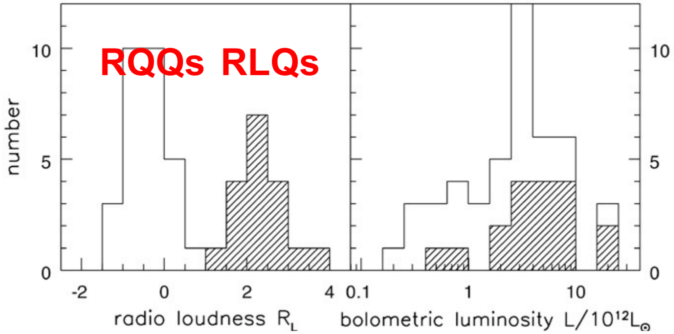
AGN Taxonomy

THE AGN ZOO



AGN classification

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

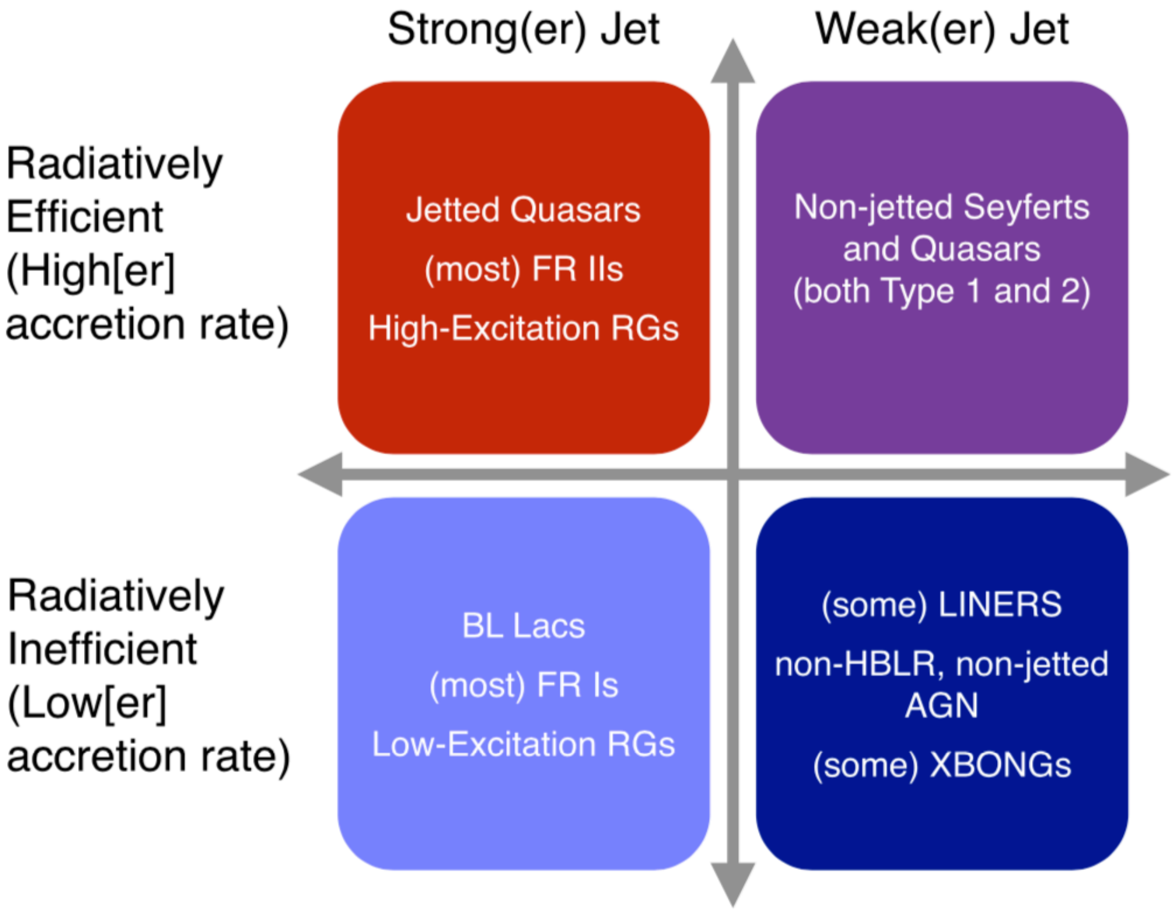
main

additional 'sub-classes'

Padovani et al. (2017)

A more recent definition: jetted/non-jetted AGN

[see Padovani+2017 review on AGN]



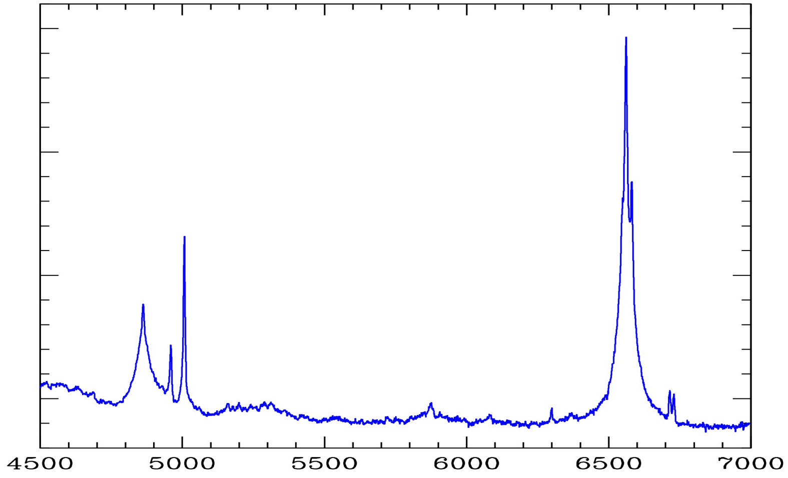
➢ Type 1 AGN:

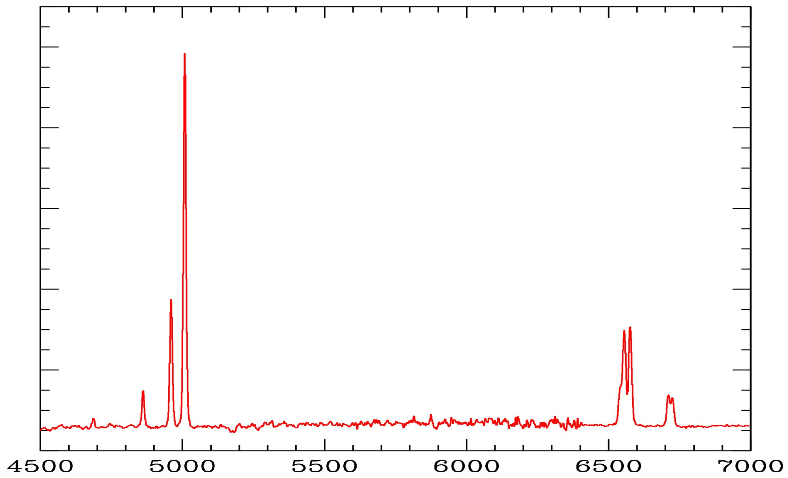
- broad optical/UV permitted emission lines (FWHM~1500-15000 km/s)
- narrow (FWHM~500-1000 km/s) forbidden lines
- Width due to rotational motion around the BH ➔ BH mass
- $n \approx 10^{9-10}$ cm^{-3} (photo-ionized clouds with small volume filling factor)
- Collisional de-excitation dominates over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

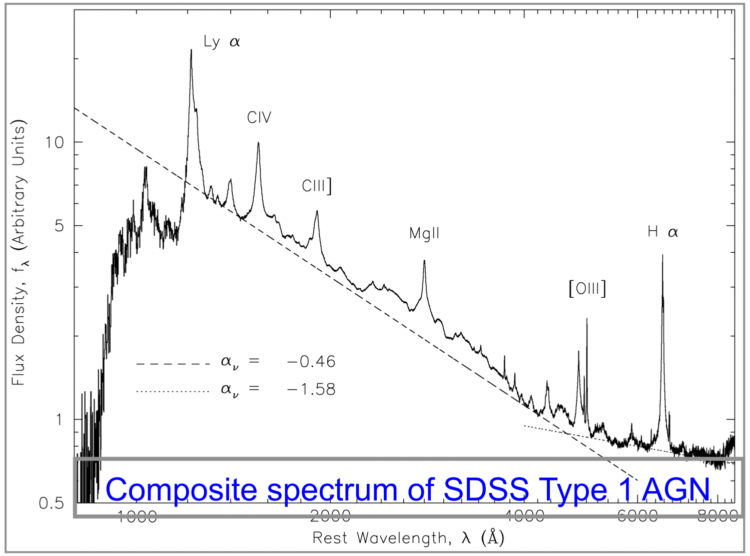
Seyfert Galaxies

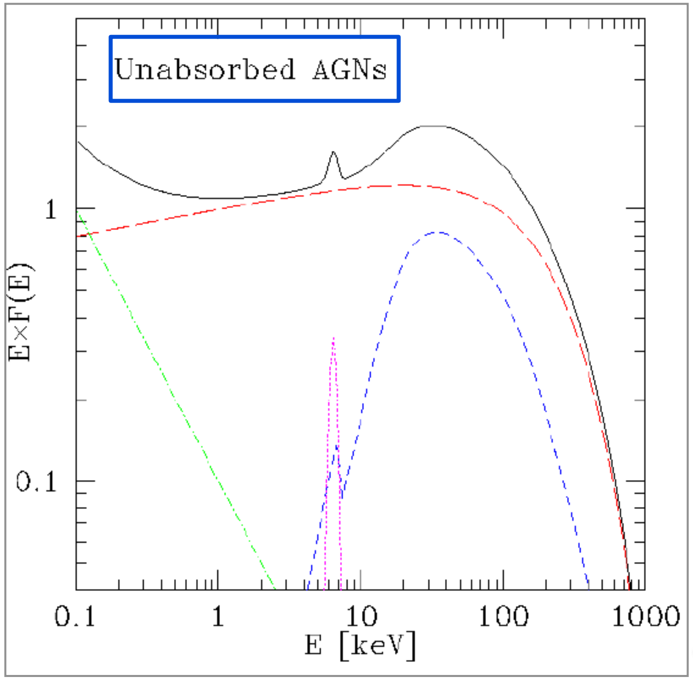




Classification (Type 1, Type 2) valid for most AGN and vastly related to Unification Scheme

Type 1 AGN



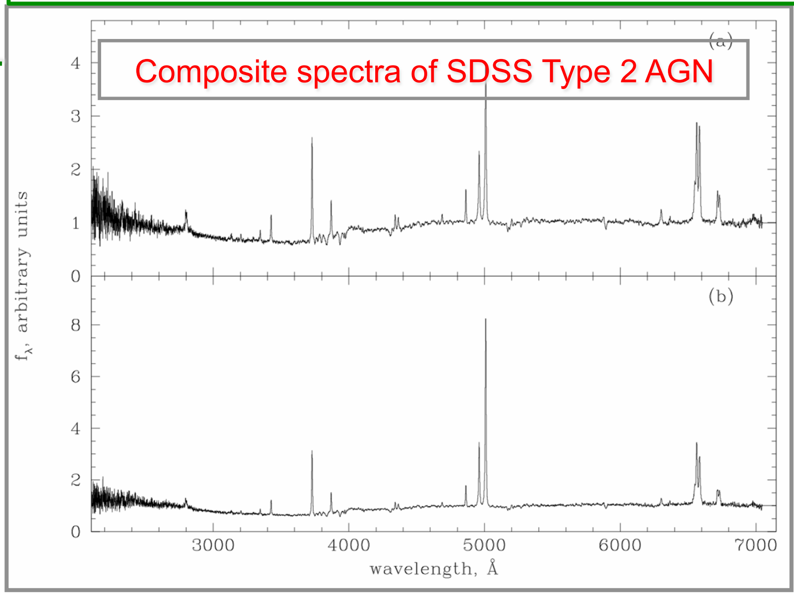


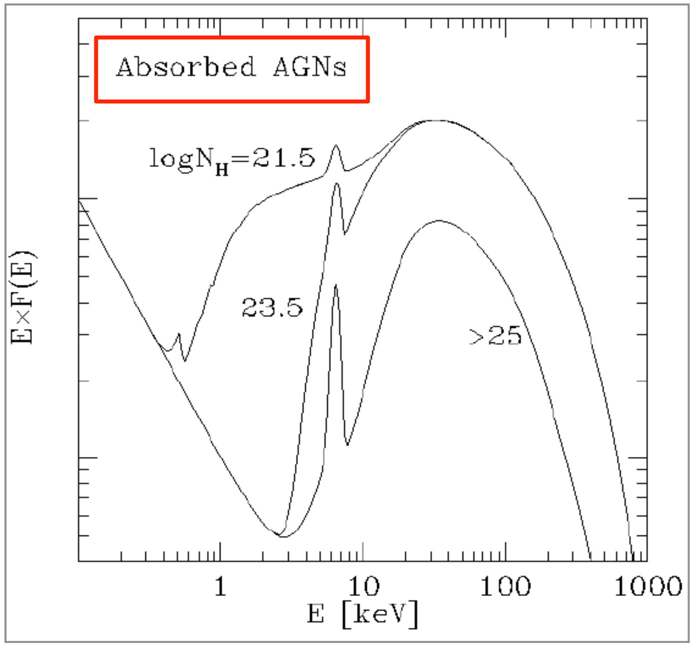
Optical band

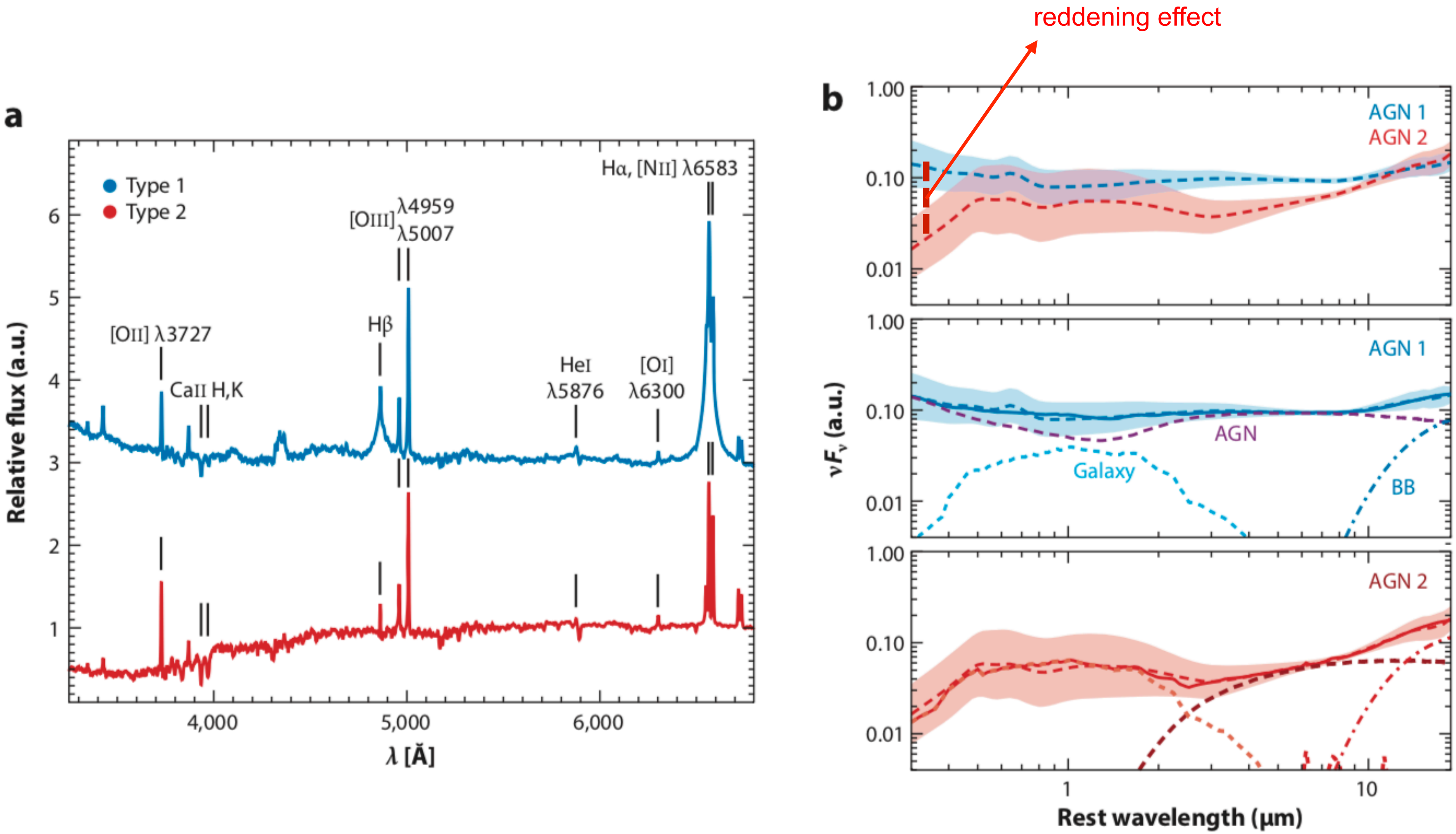
Type 2 AGN easily missed in optical and partly in X-ray surveys

X-ray band

Type 2 AGN





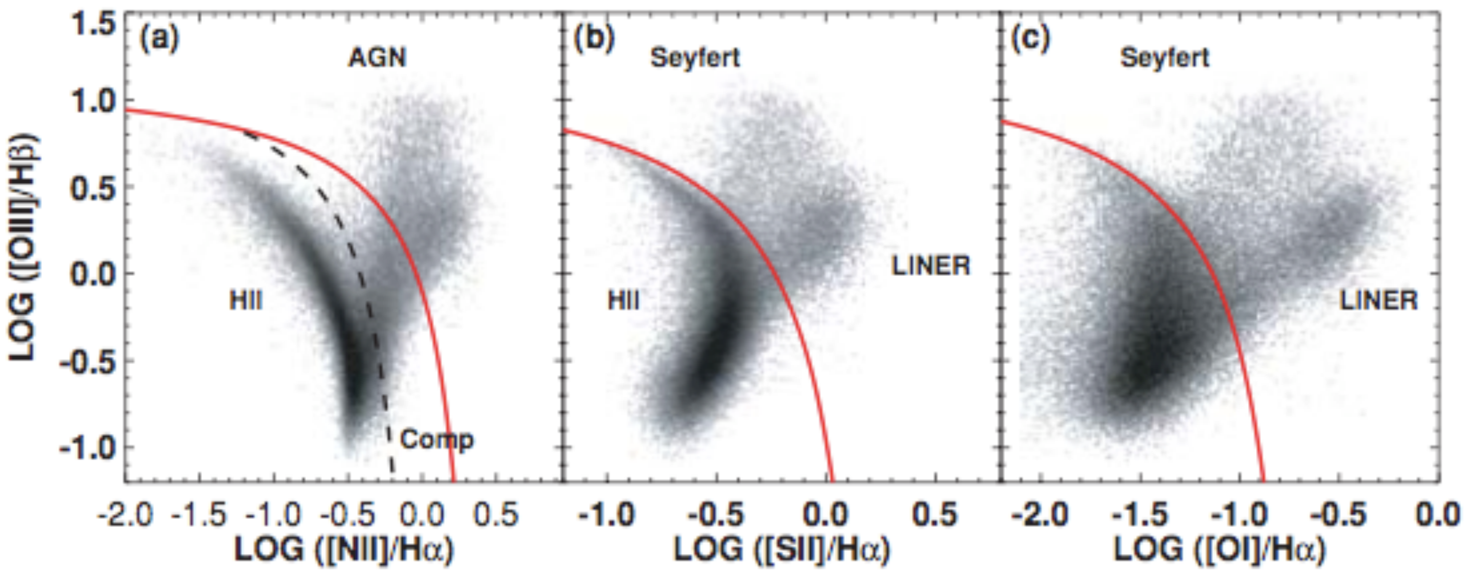


adapted from Di Pompeo+18 and Hickox+17

reddening of the nuclear component in Type 2 AGN allows the study of the host galaxy at optical rest-frame wavelengths

Seyfert 2 galaxies (Narrow-Line AGN)

• can be differentiated from normal emission line galaxies through the flux ratios of certain emission lines
• shape of the underlying ionizing source determines how many photons are available to produce particular emission lines



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

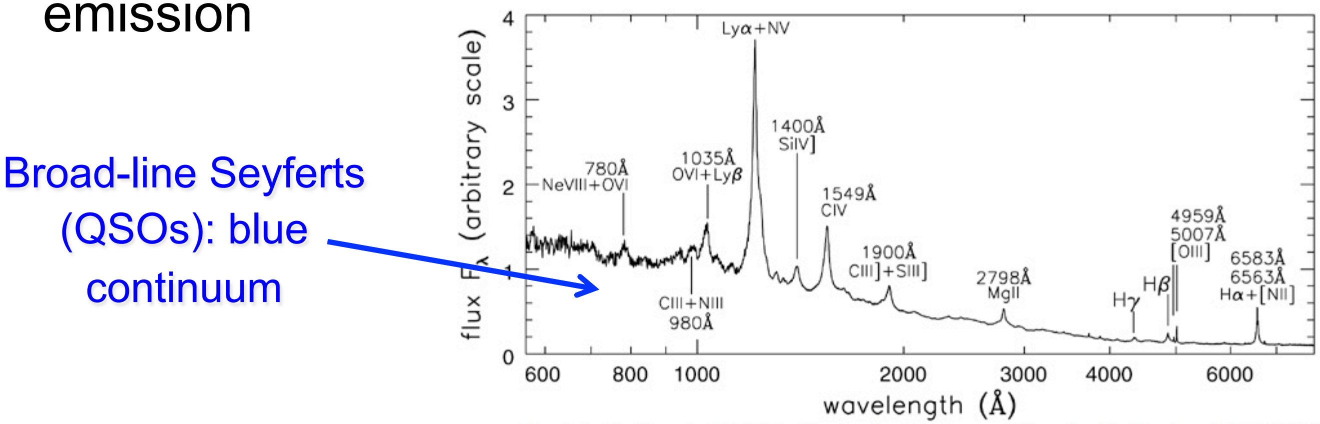


Fig 9.1 (Telfer et al.) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

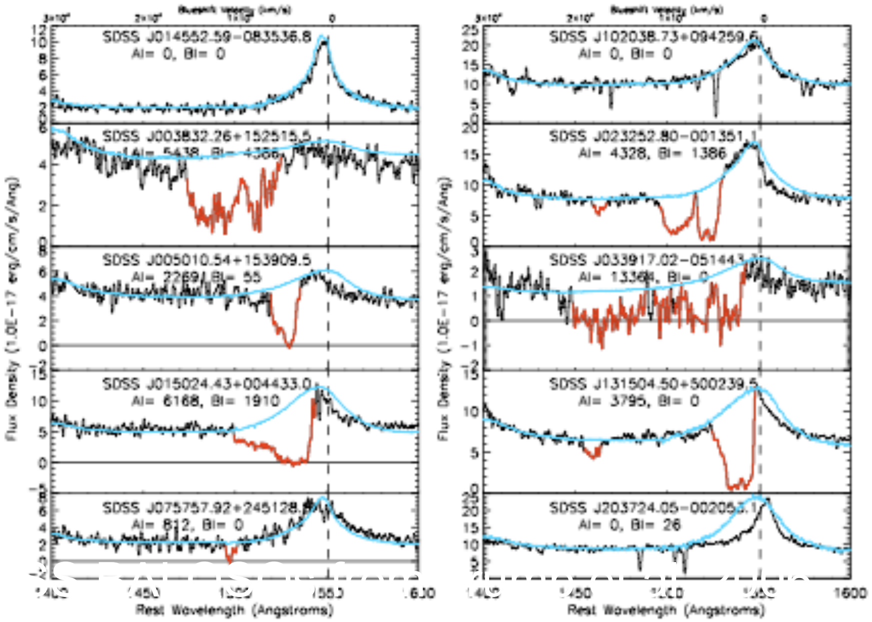
Broad absorption-line quasars (BALQSOs)

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

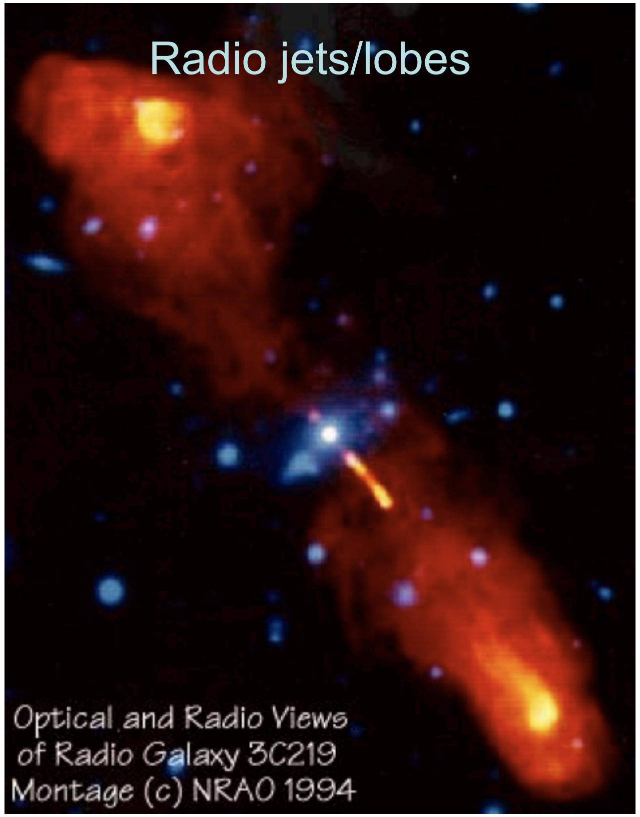


Trump+06

Radio Galaxies:
optical spectroscopic classification

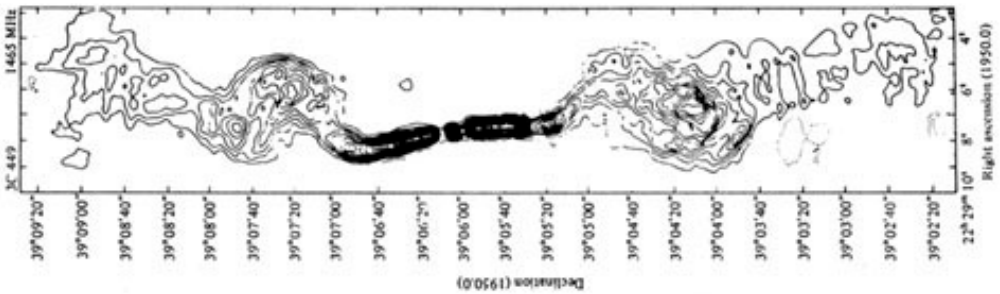
- Broad Line Radio Galaxies:
  - Emission line widths similar to those in a Seyfert Type 1

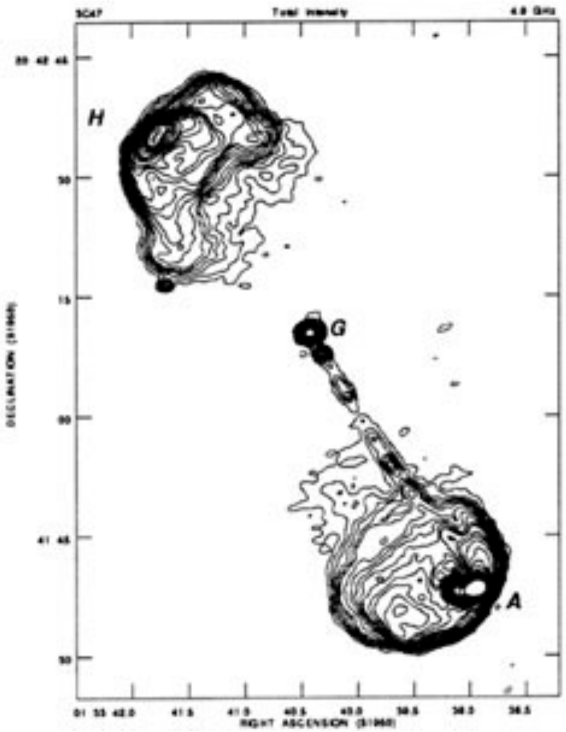
- Narrow Line Radio Galaxies:
  - Emission line widths similar to those in a Seyfert Type 2



Radio Galaxies:
classification based on radio power and morphology

- 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 deboosting of receding jet)
  - Efficient to transport energy up to the hot spots, where shocks are produced by the relativistic jet

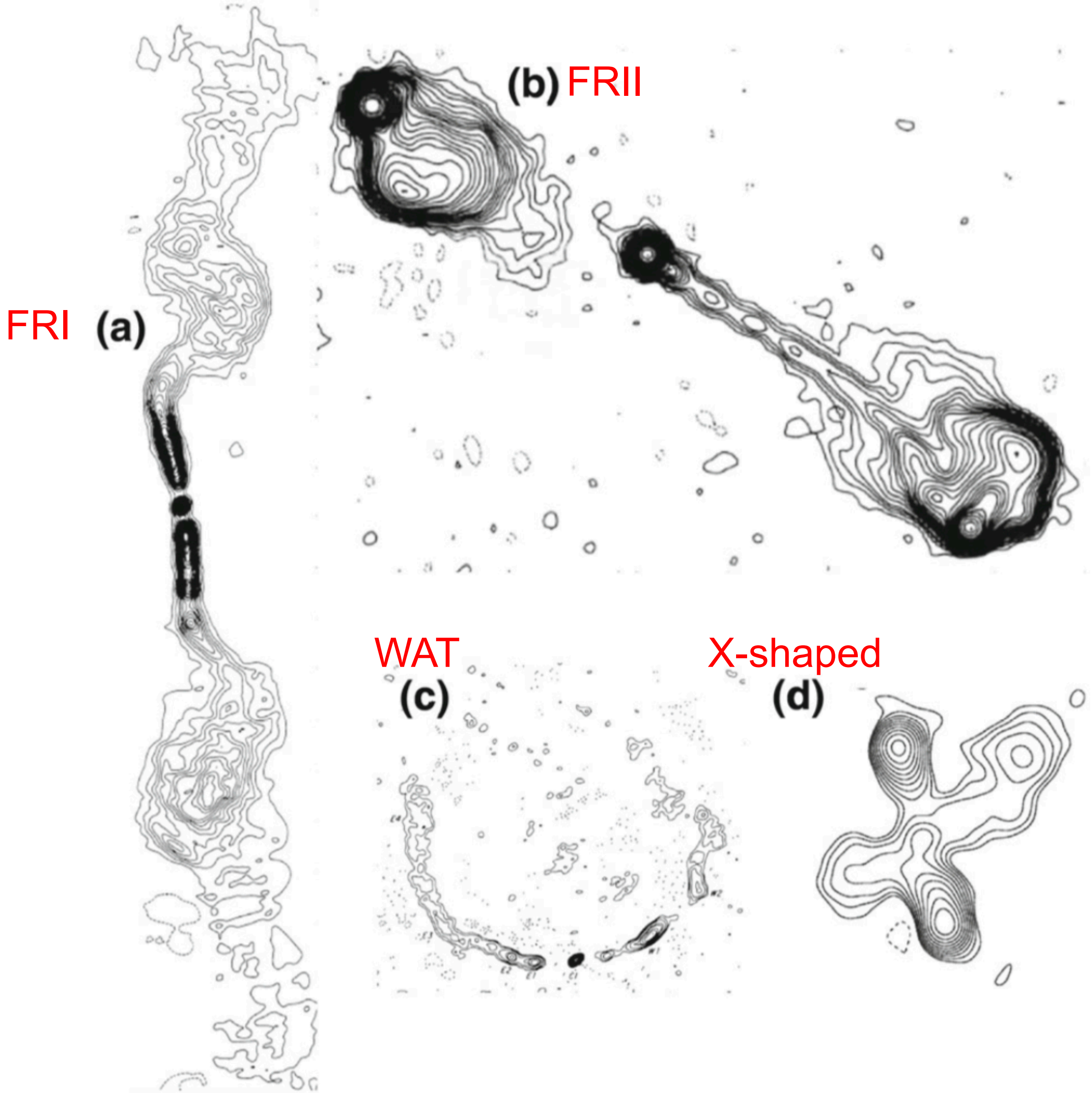




FR I – 3C47

FR II – 3C449

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



Environment and mergers have a role in shaping radio galaxies

Blazars

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

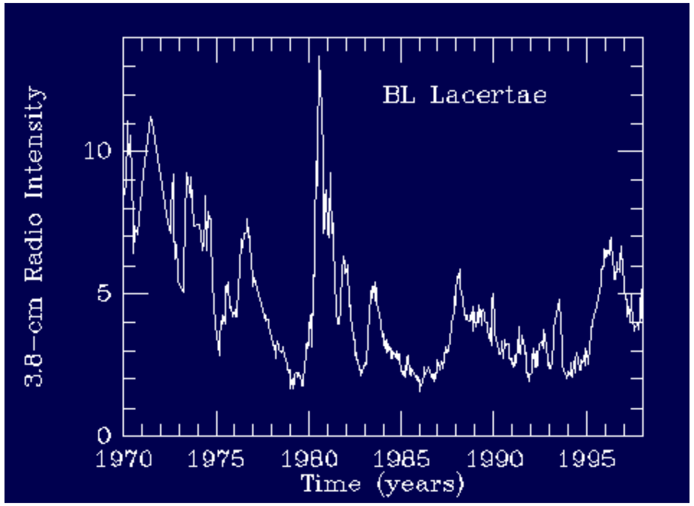
• Hosts are typically giant elliptical galaxies

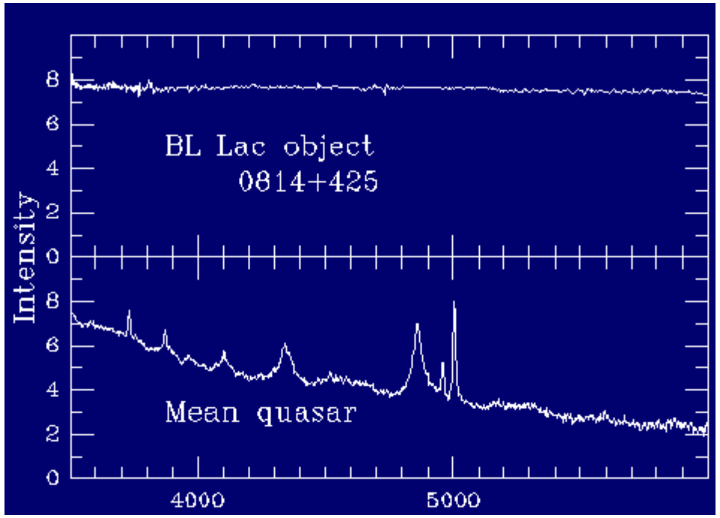
BL LACs: flat and usually featureless (EW<5Å) optical spectrum

Highly polarized, strong and fast variability

OVVs: optical spectrum with features

Even stronger variability than BL Lacs, but lower polarization





LINERs

• Sources characterized by narrow, low-ionization emission lines

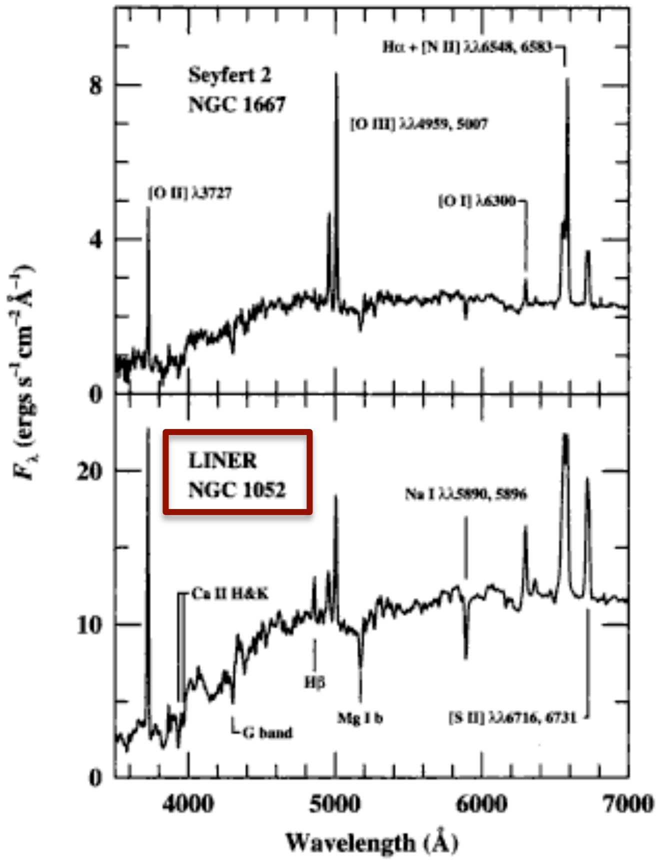
• Weak non-thermal continuum

• 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



AGN Unification

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

R. R. J. ANTONUCCI
National Radio Astronomy Observatory,[1] Charlottesville

AND

J. S. MILLER
Lick Observatory

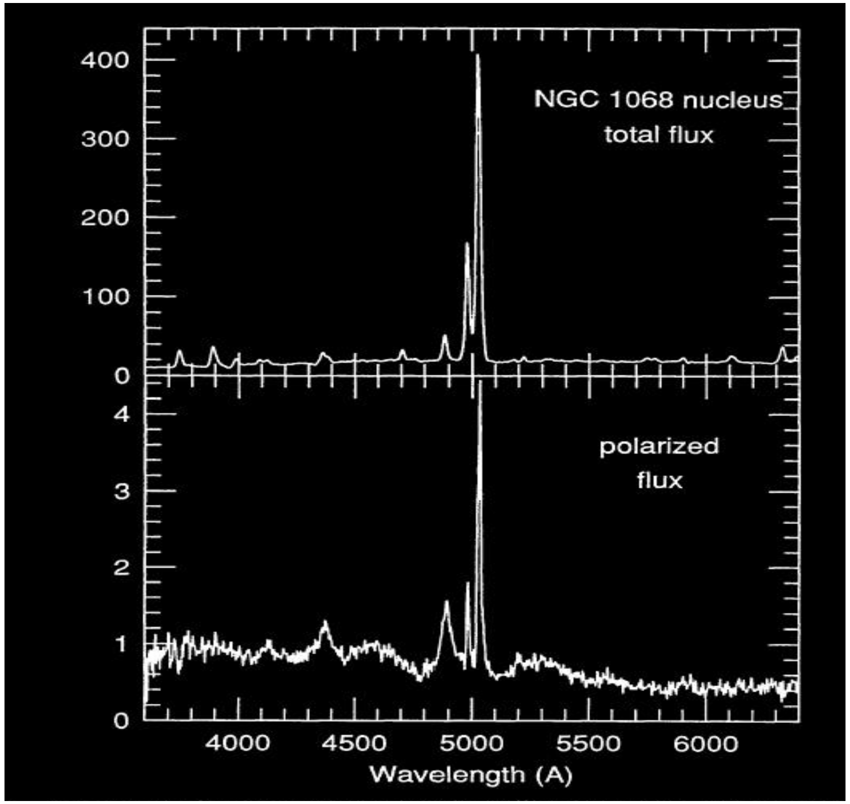
Received 1985 February 1; accepted 1985 April 17

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



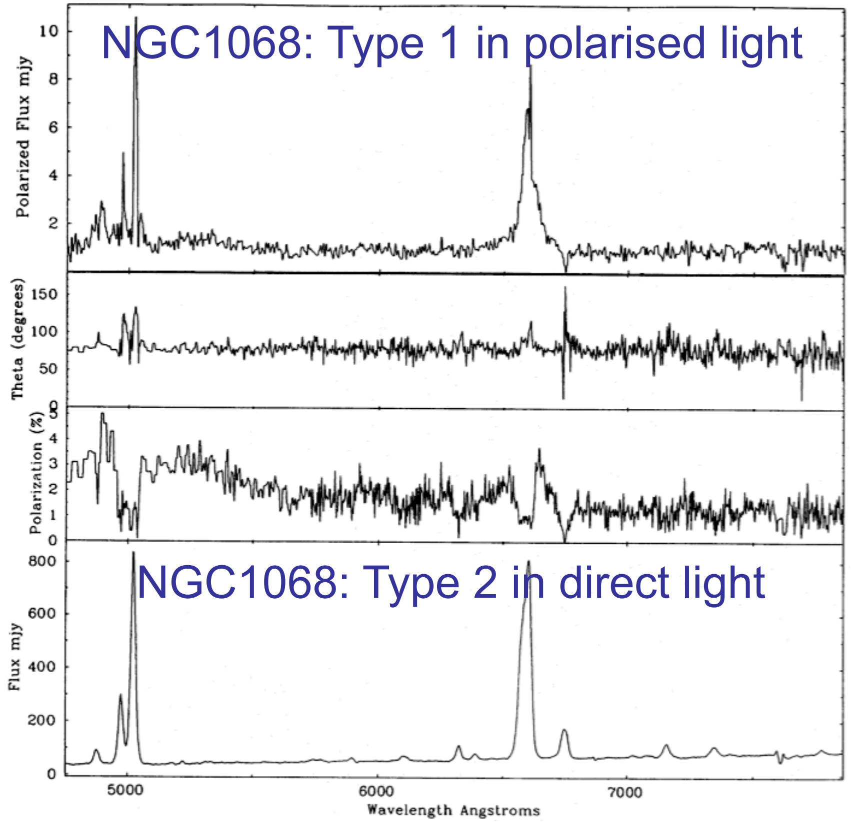
Antonucci & Miller 1985

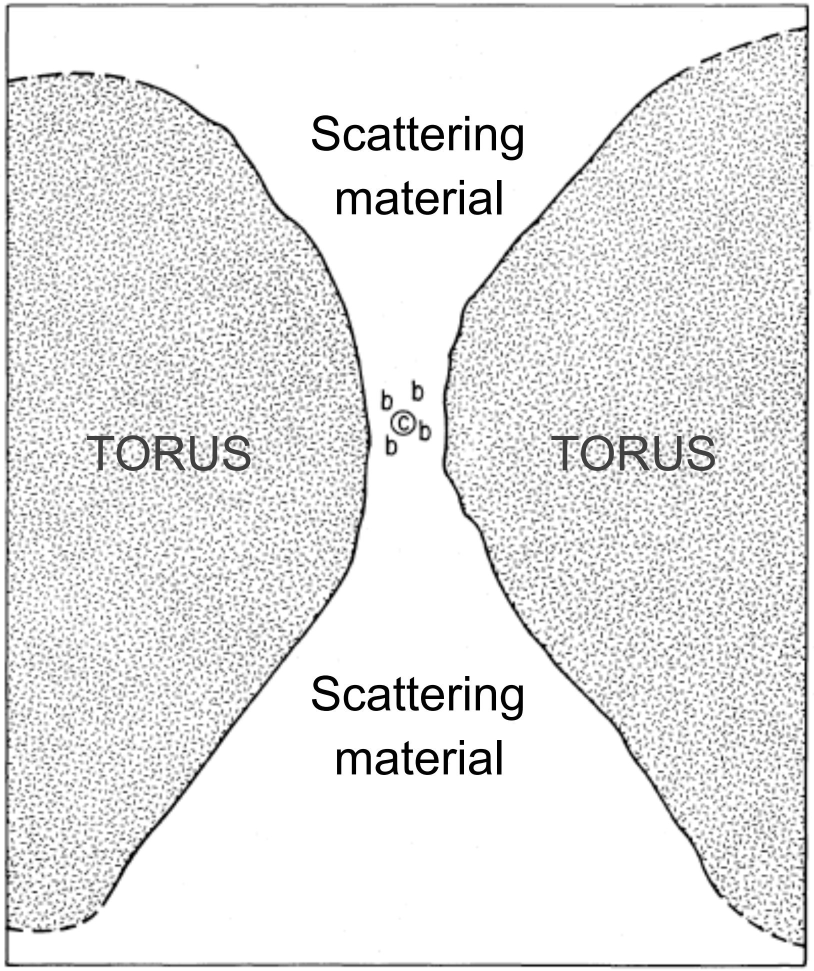
A milestone in AGN unification. II

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

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

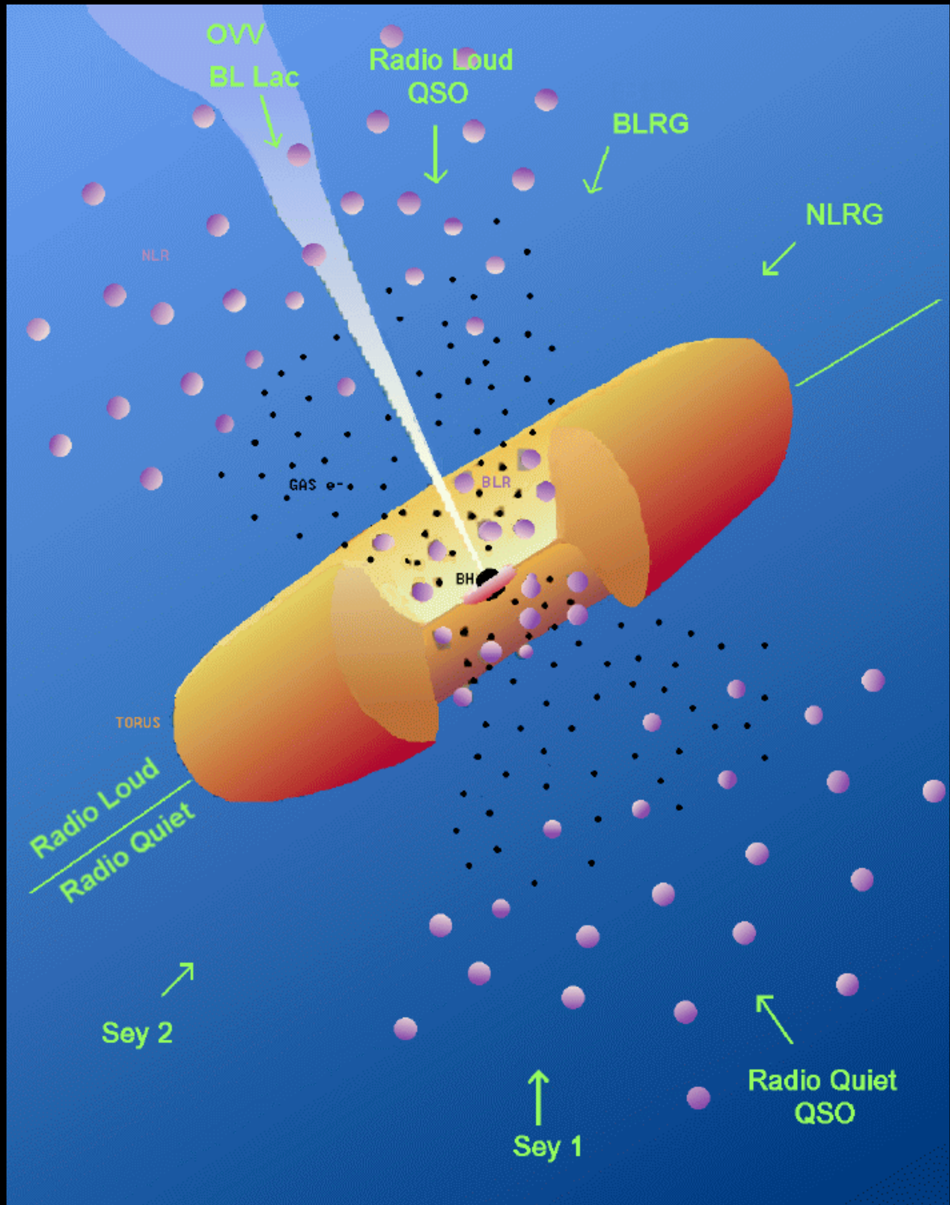
→ Polarised emission is scattered light that is hidden from direct view





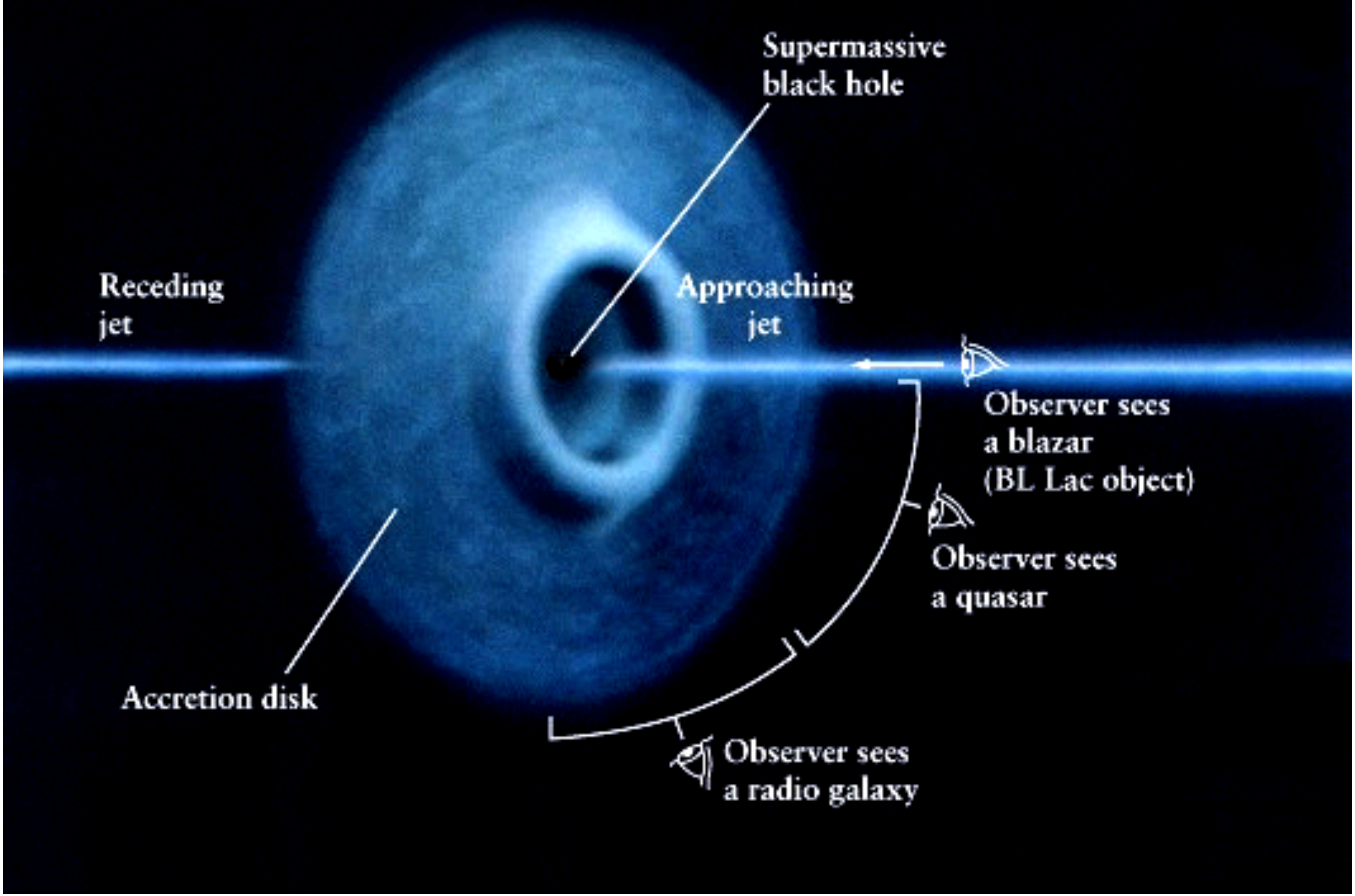
Antonucci & Miller 1985; Antonucci 1993, ARA&A

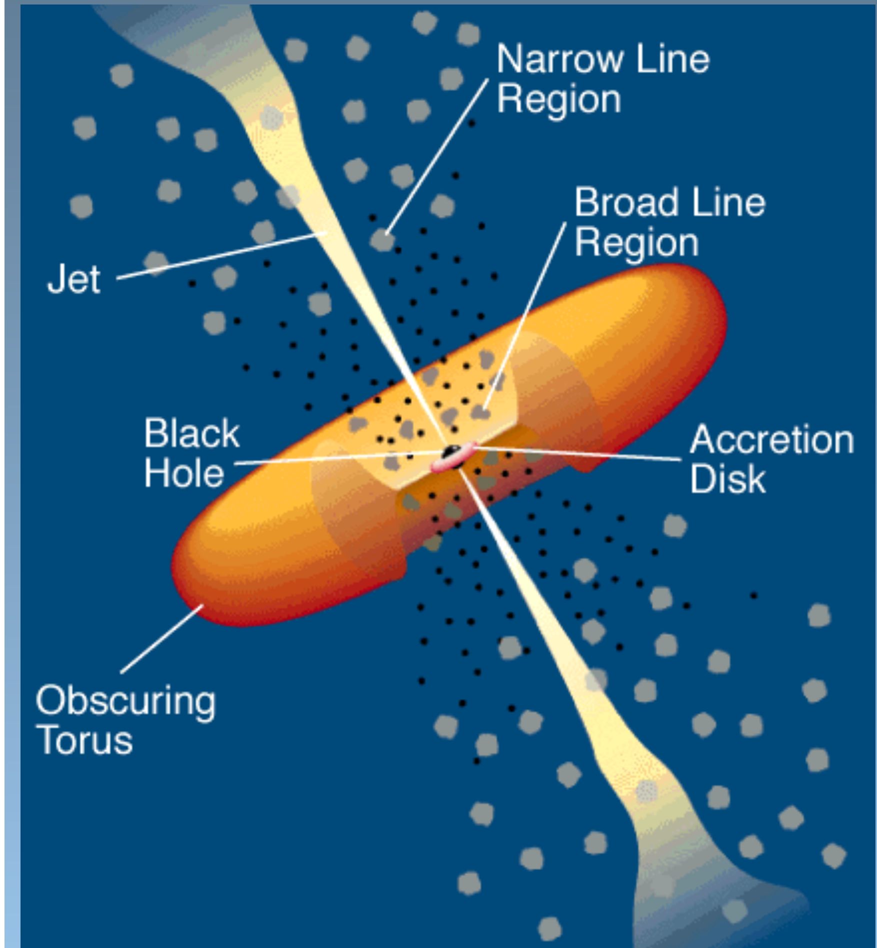
AGN TAXONOMY/CLASSIFICATION

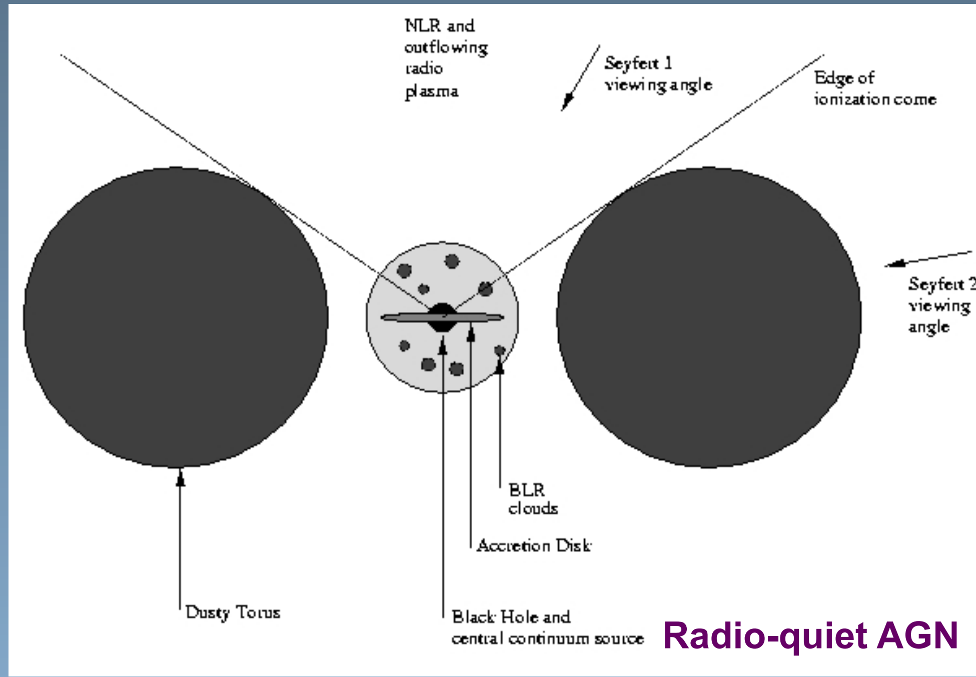


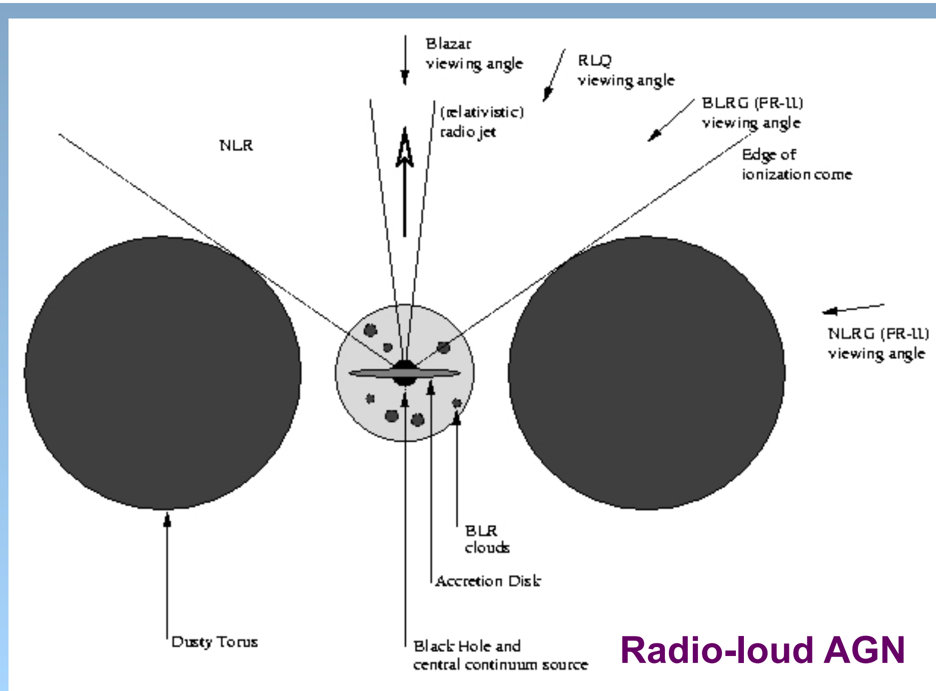
adapted from Urry
& Padovani 1995

From where you observe it might make all the difference ...

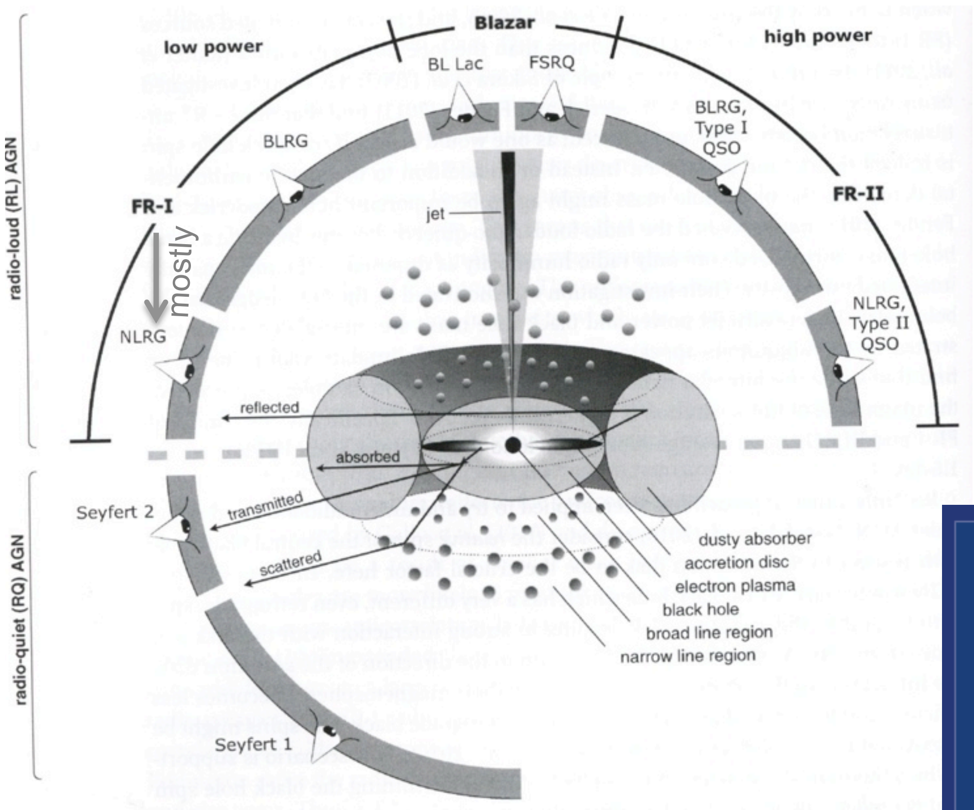



Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus


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

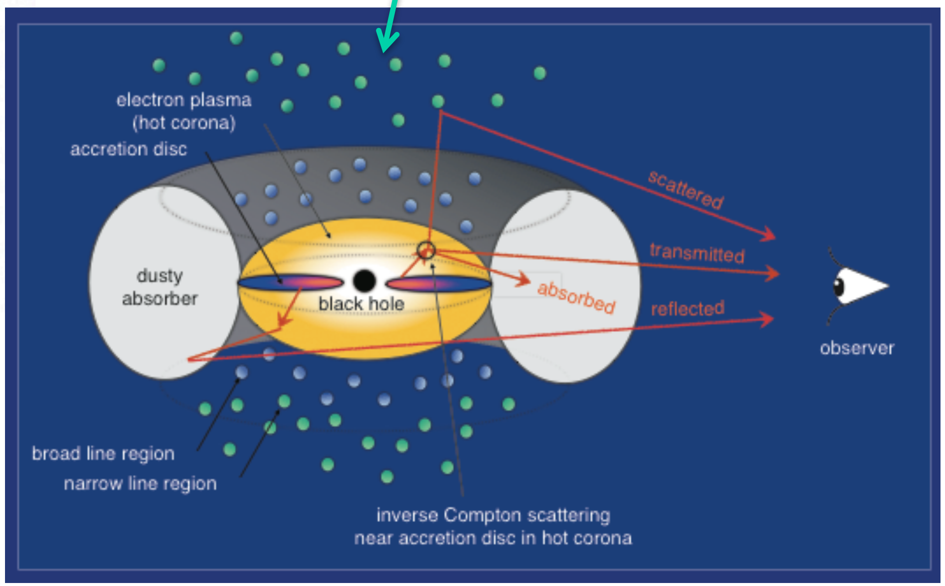

Blazar viewing angle
RLQ viewing angle
(relativistic) radio jet
BLRG (FR-II) viewing angle
NLR
Edge of ionization cone
NLRG (FR-II) viewing angle
BLR clouds
Accretion Disk
Dusty Torus
Black Hole and central continuum source
Radio-loud AGN

The AGN phenomenon along different line of sights

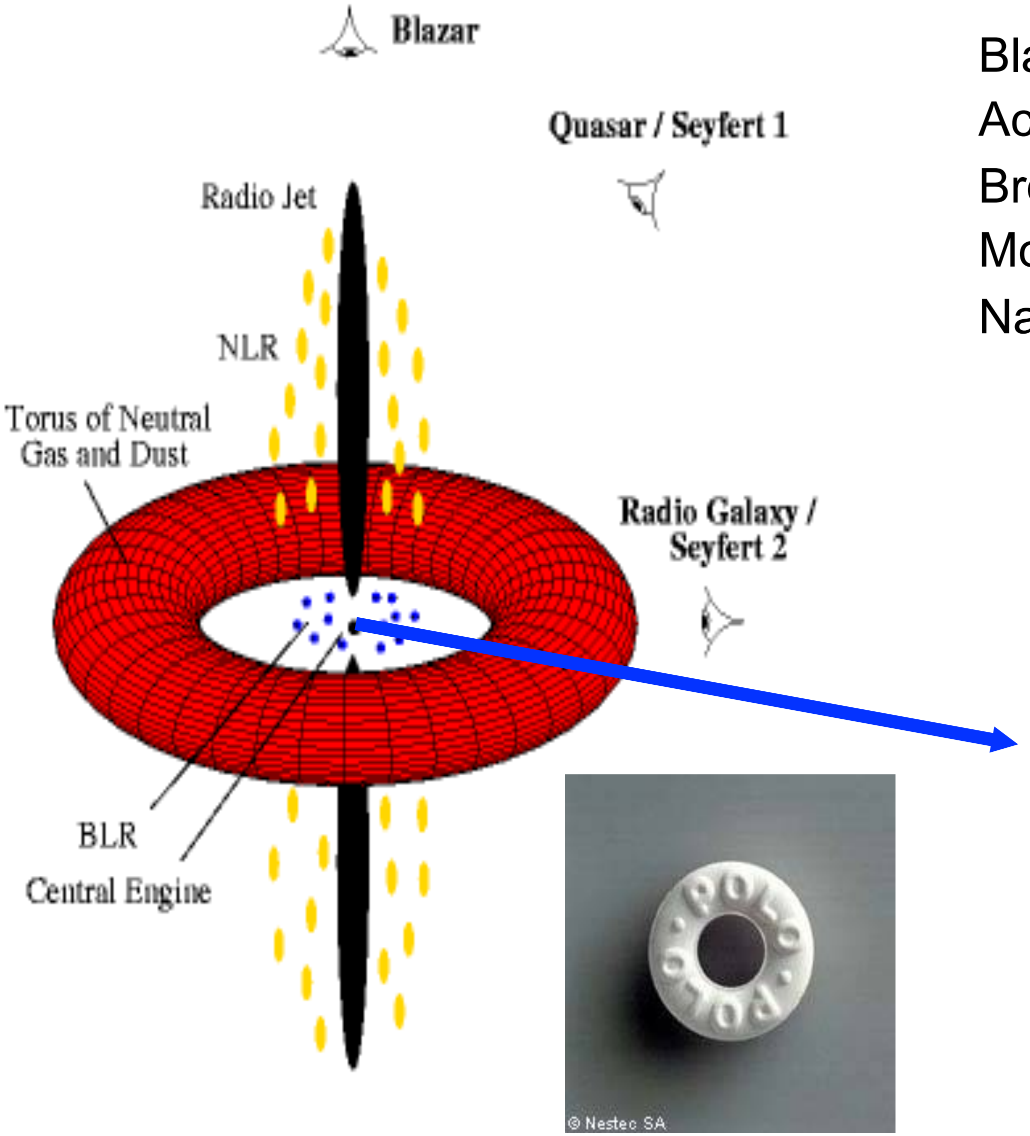


Beckmann & Shrader (2012)
Graphic by Marie-Luise Menzel

scattering material in the polar regions allowing
the view of the central regions even in obscured AGN



AGN Type 1 and 2 Unification



Size-scales

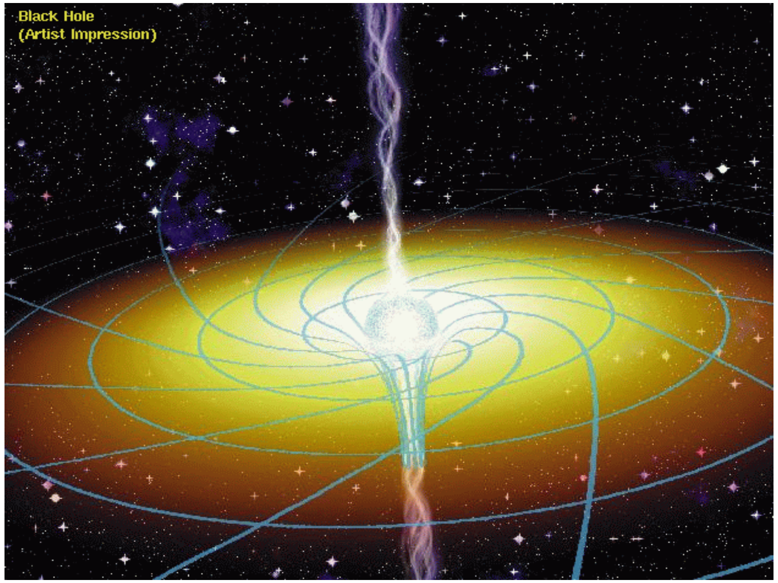
Black-hole: Rs $=3\times10^{11}\ M_6$ cm

Accretion disc: ~3 – 10^4 Rs

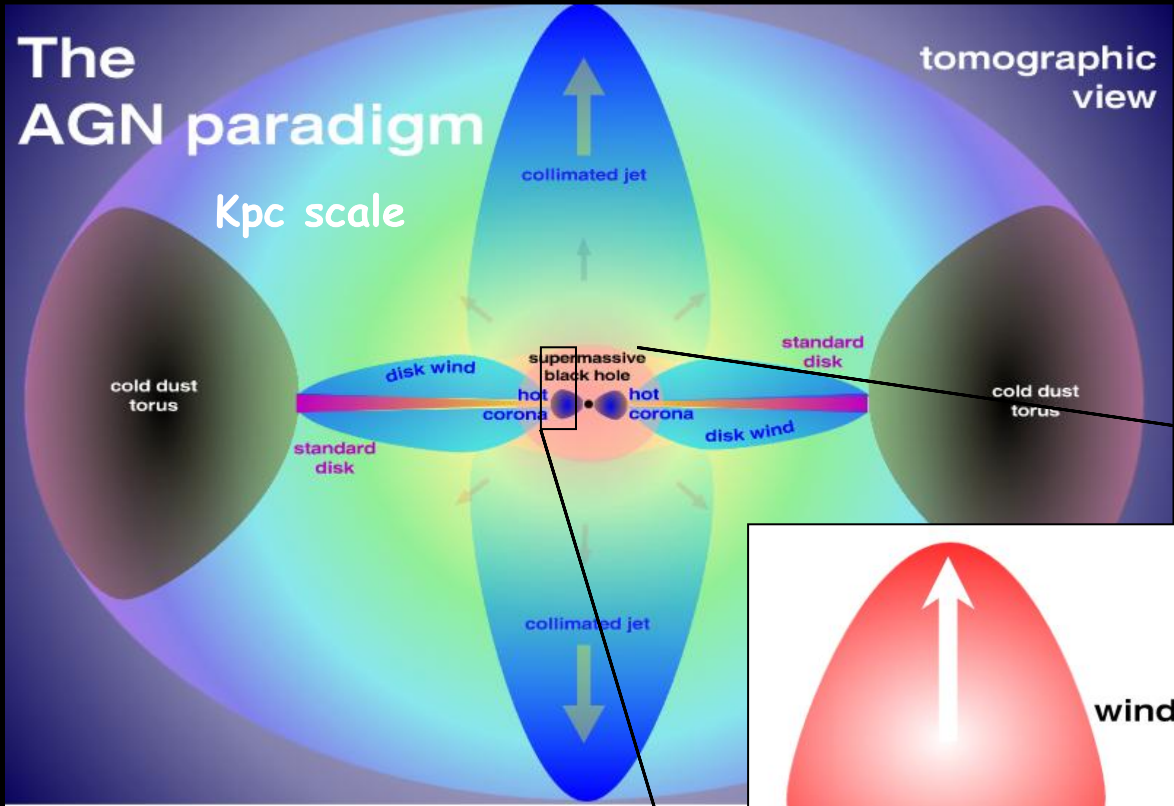
Broad Line Region: ~1-100 light days

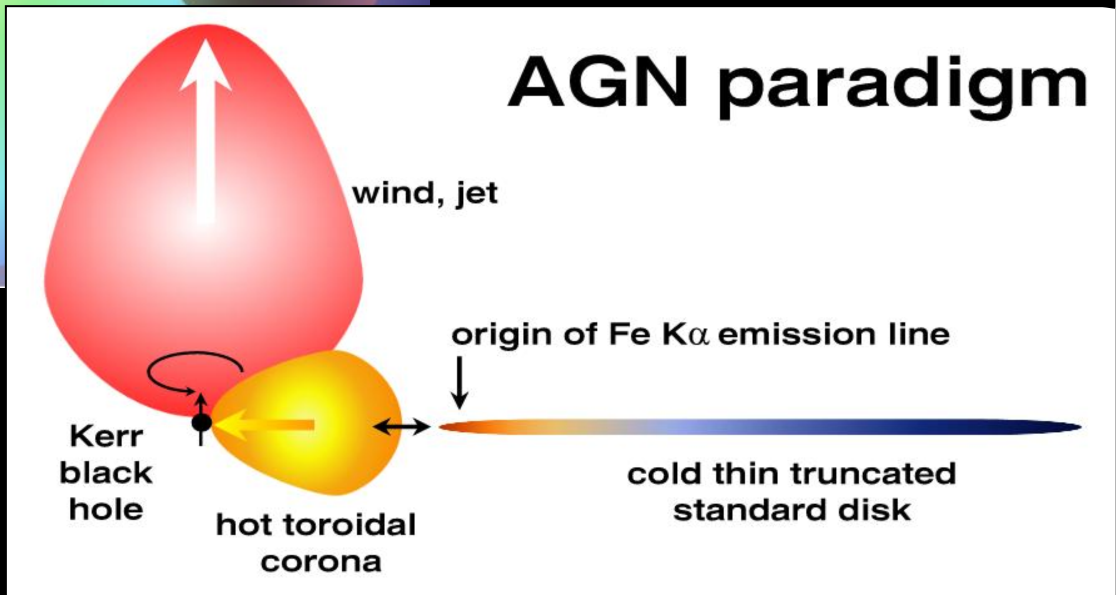
Molecular Torus: ~1-10 light years

Narrow Line Region: ~300-3000 ly



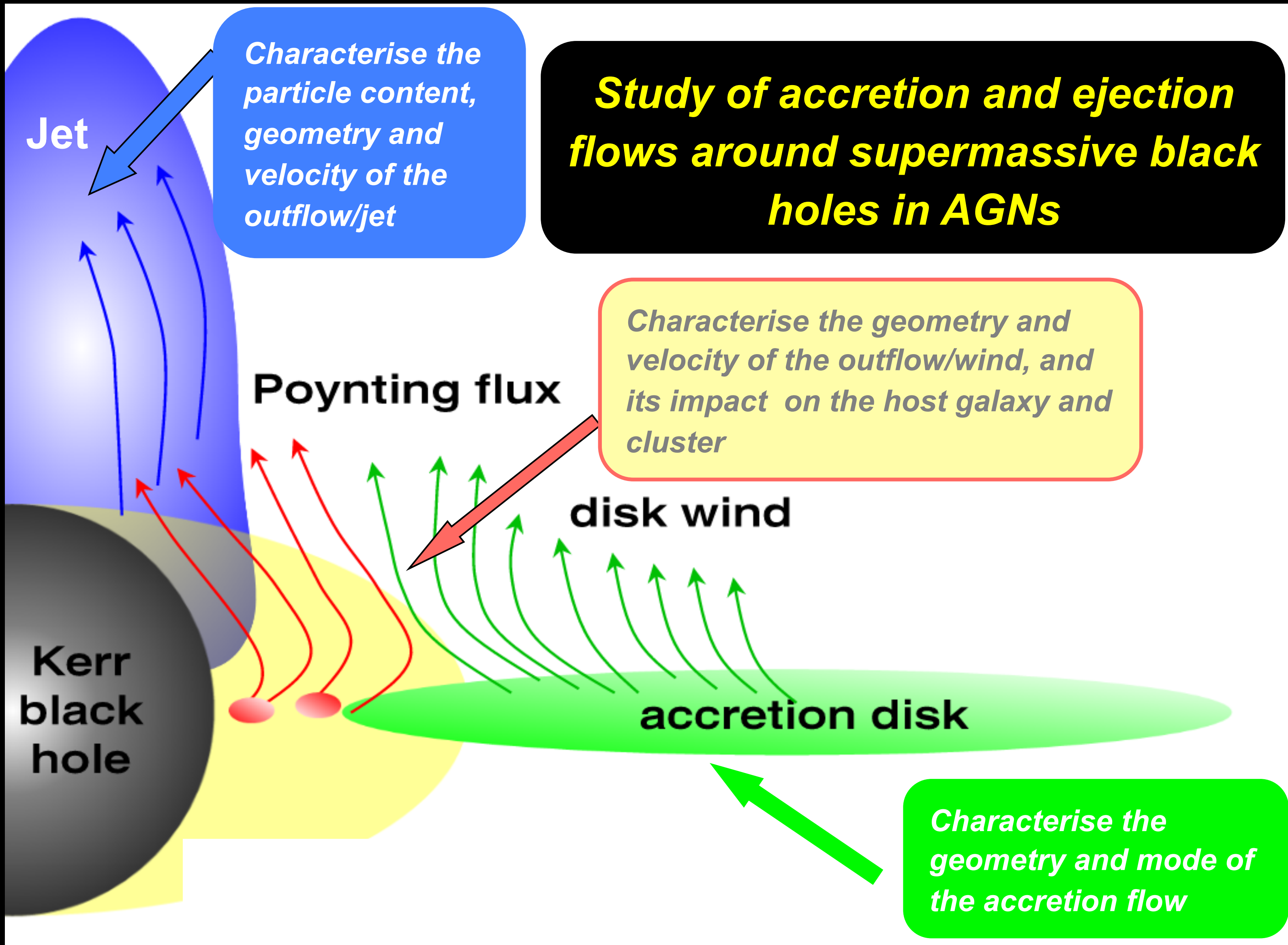
A deeper look at the inner regions around the SMBH





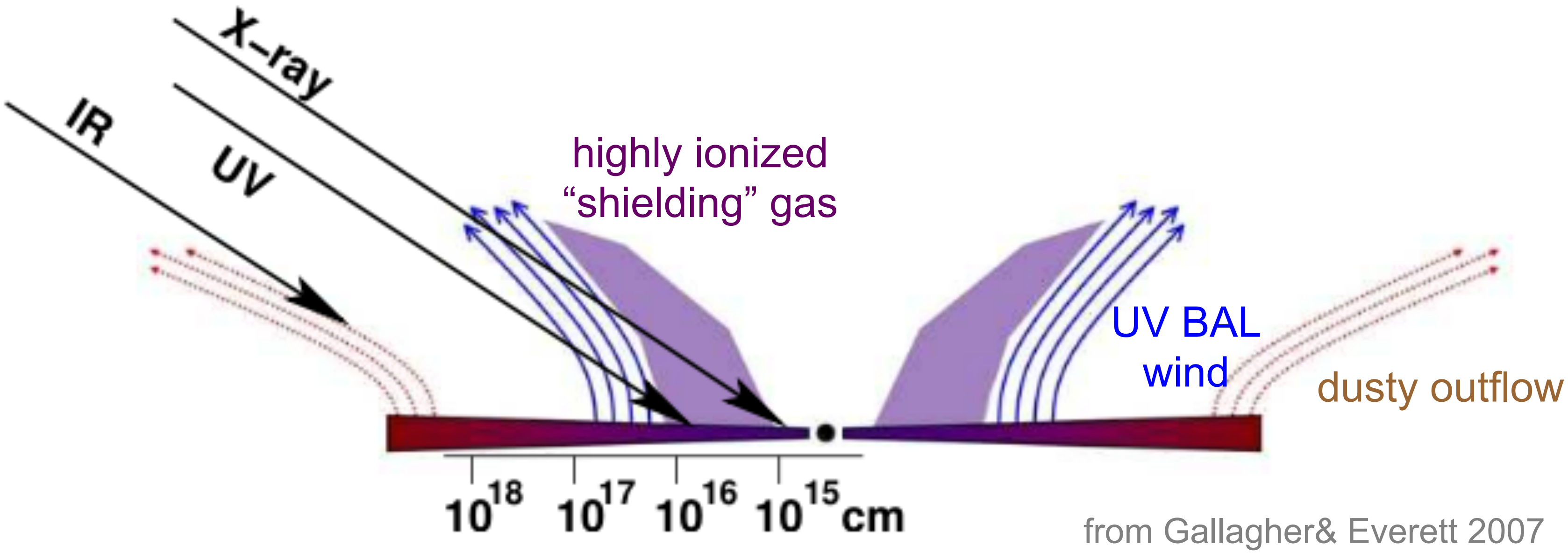
Credit: A. Muller

A few open issues



Credit: A. Mueller

A stratified wind region?



from Gallagher& Everett 2007

At work: magnetic forces, radiative acceleration on resonance lines, radiation pressure

Properties of the Stratified Quasar Wind

Wind Component	$R_{\rm launch}$ (cm)	$f_{\rm cov}$	$N_{\rm H}$[a] ($\rm cm^{-2}$)	ion. state[b]	v ($\rm km\ s^{-1}$)
Shielding Gas	10^{15-16}	$> f_{\rm cov,UV}$	10^{22-24}	O VII, O VIII	≥0.1c
UV BAL Wind	10^{17}	$0.2(1-f_{\rm type2})$	10^{21-22}	C IV, O VI	10^{3-4}
Dusty Outflow	$10^{18.5}$	$f_{\rm type2}$	...	neutral	10^{2-3}

[a]Line-of-sight column density. [b]Common ions representing the ionization state.