# Active Galactic Nuclei

## Sergio A. Cellone<sup>1,2</sup>

<sup>1</sup>Facultad de Ciencias Astronómicas y Geofísicas Universidad Nacional de La Plata, Argentina

> <sup>2</sup>Instituto de Astrofísica La Plata CONICET – UNLP

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FCAG, UNLP - AAA





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AGN phenomenology The SMBH model Testing the m

# Contents



#### Historical introduction









AGN phenomenology The SMBH model Testing the model concension of the second concension of the se

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# Active Galactic Nuclei



- 2 AGN phenomenology
- 3 The SMBH model
- 4 Testing the model



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Early discoveries

# Wild beasts in the astronomical zoo ...

(... long before GARRA)



- Seyfert galaxies,
- radio galaxies,
- and quasars.

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# Seyfert galaxies

## Fath 1909: strong emission lines in the optical spectrum of the "spiral nebula" NGC 1068

Slipher 1917: emissions in NGC 1068 were not monochromatic (i.e., broad)



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# Seyfert galaxies

#### Carl Seyfert (1943)

started the systematic study of spiral galaxies with stellar-like nuclei. They showed composite optical spectra:

G-type starlight ( $\equiv$  normal galaxy) + strong, high excitation emission lines.



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# Seyfert galaxies



NGC 5548 (Seyfert galaxy)

NGC 3277 (normal Sbc)

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#### Seyfert galaxies Spectra



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# **Radio galaxies**

- Up to 1609 (G. Galilei): milennia of naked-eye Astronomy
- 1609 1935 (K. Jansky): 3 centuries of optical telescopes

Optical identification of radio sources was (is) needed.

First (discrete) radio-sources identified (Bolton et al. 1949)

Tau A $\equiv$ Crab Nebula(SNR)Vir A $\equiv$ M87(radio galaCen A $\equiv$ NGC 5128(radio gala



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#### Note

Radio continuum:  $\nu = 60 - 80 - 100$  Mhz ( $\equiv \lambda = 5.0 - 3.7 - 2.0$  m, respec.) Non-thermal spectrum (synchrotron radiation)

The HI 21 cm ( $\equiv$  1.4 Ghz) line would not be detected until 1951

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### Jennison & Das Gupta (1953): radio source Cyg A $\rightarrow$ two-component radio morphology

### Baade & Minkowski (1954): optical object ~ "two colliding galaxies" $z = 0.056 \Rightarrow L_{rad} \approx 6 \times 10^{43} \text{ erg s}^{-1} (H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1}).$



#### Radio Image of Cygnus-A (FR-II)

z=0.056 (d=300 Mpc)

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Radio Image of Cygnus-A (FR-II)



z=0.056 (d=300 Mpc)

5 GHz Image ; Ø 200 kpc

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Quasars

# Edge et al. (1959): 3<sup>rd</sup> Cambridge survey of radio sources

A. Sandage (1960): radio-source  $3C48 \equiv 16 \text{ mag}$ , variable star-like object

Matthews & Sandage (1963): optical spectrum with broad unknown emission lines

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Early discoveries

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#### Maarten Schmidt (1963): optical spectrum

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## Quasars





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#### Maarten Schmidt (1963): optical spectrum



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## Quasars





## AGN phenomenology The SMBH model Testing the model

#### Maarten Schmidt (1963): optical spectrum



#### *z* = 0.158

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## AGN phenomenology The SMBH model Testing the n

### Quasars have high redshifts

#### Doppler redshifts: Nearby objects moving at high speeds

- no proper motions
- no blueshifts

#### Gravitational redshifts: supermassive object (GR)

 extremely high electron densities (no forbidden lines should be observed)

Cosmological redshifts:  $d \simeq c z H_0^{-1}$  (for  $z \ll 1$ )

L<sub>opt</sub> ≥ 10 − 30 times bright E galaxy
 size ≪ normal galaxy

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## Quasars

#### Sandage (1965): quasars have U excess



Large population of radio-quiet quasars

quasi-stellar objects  $\rightarrow$  QSO

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The AGN conception

# Origins of the SMBH model

#### Salpeter (1964); Zel'dovich & Novikov (1964): Energy source in quasars and radio galaxies is accretion onto a super-massive black hole (SMBH)

#### Lynden-Bell (1969):

energy in radio-galaxies (lobes)  $\rightarrow E_{\rm RG} \sim 10^{61}$  erg. Its associated mass is:

$$\mathcal{M}_E = E_{\rm RG} c^{-2} \simeq 6 \times 10^6 \, \mathcal{M}_{\odot},$$

if result of nuclear burning, requires an original mass

$$\mathcal{M} \geq rac{\mathcal{M}_E}{0.007} \simeq 10^9 \mathcal{M}_{\odot}.$$
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### Origins of the SMBH model

#### Lynden-Bell (1969):

Variability  $\Rightarrow R \le 10$  light-hs =  $10^{15}$  cm.

Binding energy

$$rac{G\,\mathcal{M}^2}{R}\simeq 2.7 imes 10^{62}\, ext{erg}.$$

Thus, with the aim to produce a model based on nuclear fuel, we have ended up with a model which has produced more than enough energy by gravitational contraction, while nuclear fuel has ended as an irrelevance. AGN phenomenology The SMBH model Testing the mo

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The AGN conception

#### Sy + RG + QSO = AGN

Seyfert nuclei & radio galaxies: scaled-down versions of QSO

Do quasars reside at the centres of galaxies?

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The AGN conception

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(Bahcall et al. 1997)

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The AGN conception

#### Sy + RG + QSO = AGN

#### Active Galactic Nuclei (AGN)

- Seyfert galaxies,
- radio galaxies,
- quasars (and blazars)

AGN phenomenology The SMBH model Testing to concern the second se

### Active Galactic Nuclei



- 2 AGN phenomenology
- 3 The SMBH model
- 4 Testing the model



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**Optical emission lines** 

#### What do we mean by high-excitation?



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**Optical emission lines** 

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**Optical emission lines** 

# What do we mean by *high-excitation*? Diagnostic diagrams



Diagnostic diagram (Baldwin, Phillips, & Terlevich 1981)

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**Optical emission lines** 

# What do we mean by *high-excitation*? Diagnostic diagrams



Sloan Digital Sky Survey (SDSS)

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Seyfert 2

**Optical emission lines** 

### Seyfert types 1 and 2

#### Seyfert 1



broad lines: only permitted broad lines: none narrow lines: permitted and prohibited

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**Optical emission lines** 

#### Quasars



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**Optical emission lines** 

### **BL Lac objects**



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**Optical emission lines** 

### **BL Lac objects**



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#### Continuum

#### Continuum spectral energy distribution



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#### Continuum

### Continuum spectral energy distribution



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**Radio features** 

## Radio emission



21 cm (1.4 GHz) VLA – 11 cm (2.7 GHz) MRAO

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**Radio features** 

#### Radio emission



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**Radio features** 





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Radio lobes: *steep* spectrum Jets: *flat* spectrum

Radio features

#### **Jets**



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Radio features





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**Radio features** 

#### Jets Apparent superluminal motions

$$\leftarrow 5 \text{ mas} \equiv 30 \text{ pc} \longrightarrow$$

(Image courtesy of NRAO/AUI)

Radio jet of the blazar 3C 279  $\sim$  25 light-years in  $\sim$  7 yr

$$\therefore$$
  $v_{app} \simeq 3.5 c$ 

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**Radio features** 

#### Jets Apparent superluminal motions



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Flux variability

#### Long-term variability



#### quasar 3C 273

historical light-curve (Angione & Smith 1985):  $\Delta m \simeq 1 \text{ mag}$ 

AGN phenomenology 

Flux variability

#### Long-term variability



#### quasar 3C 273

multi-v light-curve (Türler et al. 1999):

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Flux variability

### Long-term variability



#### blazar GC 0109+224

historical light-curve (Ciprini et al. 2003):  $\Delta m \simeq 4 \text{ mag}$ 

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Testing the model

#### Flux variability

### Long-term variability



blazar AO 0235+164

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optical – radio light-curve (Raiteri et al. 2006)  $\Delta m \gtrsim 7 \text{ mag}$ 

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Flux variability

### Microvariability



#### blazar AO 0235+164 optical microvariability: 1.2 mag in $\gtrsim$ 24 hs (Romero et al. 2000)

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Flux variability

### Polarization microvariability



blazar AO 0235+164 high and variable optical polarization:  $\Delta P \simeq 10\%$  in  $\gtrsim 48$  hs (Cellone et al. 2007)

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Flux variability

#### Polarization microvariability



blazar AO 0235+164 high and variable optical polarization:  $\Delta P \simeq 10\%$  in  $\gtrsim 48$  hs (Cellone et al. 2007)

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#### Flux variability

### Polarization microvariability



blazar AO 0235+164 high and variable optical polarization:  $\Delta P \simeq 5\%$  in  $\sim 5$  hs (Cellone et al. 2007)

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### Active Galactic Nuclei

- Historical introduction
- 2 AGN phenomenology
- 3 The SMBH model
- 4 Testing the model



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GN phenomenology The SMBH model Testin

Building the model

### **Basic properties of AGN**

#### AGN have:

# $\begin{array}{l} \mbox{High luminosity:} \sim 10^{42} \rightarrow 10^{48}\,\mbox{erg}\,\mbox{s}^{-1} \\ \mbox{i.e.}, \sim 10^{-2} \rightarrow 10^4\,\mbox{$L_{\star}$} \end{array}$

Small size: central engine  $\lesssim 10^{0}$  pc

- unresolved in nearby AGN
- variability time-scale  $\sim$  few years

Long life:  $\sim 10^9$  yr

- luminosity function with z
- density AGN vs. density bright galaxies

GN phenomenology The SMBH model Testing

Building the model

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Building the model

### **Energy production**

#### Most efficient way to release energy:

#### accretion into a relativistically deep gravitational potential

#### $\epsilon \sim 0.1$

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### **Eddington luminosity**

Acceleration due to radiation pressure:

$$a_{\rm rad} = rac{\sigma_{\rm T}}{\mu_{
m p}} rac{L}{4\pi c r^2}$$

$$\Rightarrow \quad \frac{a_{\rm rad}}{g} = \frac{\sigma_{\rm T} L}{4\pi c \,\mu_{\rm p} \,G \,\mathcal{M}_{\bullet}} = \frac{L}{L_{\rm E}}$$

where

$$L_{\rm E} = \frac{4\pi c \, G \, \mathcal{M}_{\bullet} \, \mu_{\rm p}}{\sigma_{\rm T}} = 1.51 \times 10^{38} \frac{\mathcal{M}_{\bullet}}{\mathcal{M}_{\odot}} \, \rm erg \, \rm s^{-1}$$

$$\therefore \quad L = 10^{47} \, \text{erg s}^{-1} \Rightarrow \mathcal{M}_{\bullet} = 10^9 \, \mathcal{M}_{\odot}$$

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Building the model

### **Eddington luminosity**

Acceleration due to radiation pressure:

$$a_{\rm rad} = rac{\sigma_{\rm T}}{\mu_{\rm p}} rac{L}{4\pi c r^2}$$

$$\Rightarrow \quad \frac{a_{\rm rad}}{g} = \frac{\sigma_{\rm T} L}{4\pi c \,\mu_{\rm p} \,G \,\mathcal{M}_{\bullet}} = \frac{L}{L_{\rm E}}$$

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Building the model

### Nature of the engine

#### Need for a large mass

- energy output
- Eddington luminosity
- broad emission lines
- relativistic outflows (jets)

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Building the model

### Nature of the massive object(s)

### single super-massive black hole (SMBH)

- stability
- oherent variability
- well collimated jets

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Building the model

### Phenomenology

- nature of continuum emission
- nature of line emission
- broad lines vs. narrow lines
- radio loud vs. radio quiet
- jets & radio lobes
- blazar phenomenology

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Building the model

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Building the model

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Building the model

### The SMBH model



The SMBH model AGN phenomenology 

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### The SMBH model



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### The SMBH model



(Brooks/Cole Thomson Learning)

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Confrontation to observations

## **Emission properties**



component	emission mechanism	spectral range
accretion disk dusty torus	thermal ( $T \lesssim 10^5$ K) reprocessed AD emission	optical $\rightarrow$ soft X-rays sub-mm $\rightarrow$ IR
BLR – NLR jet	recombination in photo-ionized gas synchrotron non-thermal (inverse Compton)	optical (emission line spectrum) radio up to $\gamma$ -rays

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### **Continuum emission**



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Confrontation to observations

### **Continuum emission**



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### **Continuum emission**



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Confrontation to observations

### **Continuum emission**



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### **Continuum emission**



Cen A: non-thermal contribution in the mid - far IR

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Confrontation to observations

#### Unification Broad lines vs. narrow lines

NGC 1068 (Antonucci & Miller 1985):

- "normal" light  $\rightarrow$  Sy 2
- polarized light →
   Sy 1 features



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#### BLR light scattered by electrons into the line of sight

Confrontation to observations

#### Unification Broad lines vs. narrow lines

NGC 1068 (Antonucci & Miller 1985):

- "normal" light  $\rightarrow$  Sy 2
- polarized light →
   Sy 1 features



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BLR light scattered by electrons into the line of sight

Confrontation to observations

#### Unification Broad lines vs. narrow lines

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#### BLR light scattered by electrons into the line of sight

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Confrontation to observations

### Unification

- obscuration
- beaming



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### Unification

- obscuration
- beaming





Sy 2 or NLRG (or "obscured" QSO)

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Confrontation to observations

# Unification

- obscuration
- beaming





(or "normal" QSO)

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# Unification

- obscuration
- beaming





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Confrontation to observations

#### Blazars The wildest of all beasts



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#### BL Lacs + FSRQs = blazars

- Strong emission from radio to  $\gamma\text{-rays}$
- Fast, high-amplitude flux variability
- High and variable polarization
- Superluminal motions (radio jet)

Historical introduction	AGN phenomenology	The SMBH model	Testing the model
Confrontation to observations			
Blazars Relativistic beaming			

Plasma with bulk motion  $\beta = \frac{v}{c} \lesssim 1$  and angle  $\theta \gtrsim 0^{\circ}$  $\rightarrow$  emission is beamed in the observer's direction

Lorentz factor:  $\gamma = (1 - \beta^2)^{-\frac{1}{2}}$ Doppler factor:  $\delta = [\gamma(1 - \beta \cos \theta)]^{-1}$ 

	rest frame	observer's frame
time interval	t	$\delta^{-1}t$
frequency	$\nu$	$\delta \nu$
intensity	$I_{\nu}(\nu)$	$\delta^3 I_{\nu}(\nu)$
flux density	$F_{\nu}(\nu)$	$\delta^{(3+\alpha)}F_{\nu}(\nu)$
broad-band flux	F	$\delta^4 F$

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Historical introduction	AGN phenomenology	The SMBH model	Testing the model
Confrontation to observations			
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Doppler factor: 
$$\delta = [\gamma(1 - \beta \cos \theta)]^{-1}$$

	rest frame	observer's frame
time interval	t	$\delta^{-1}t$
frequency	u	$\delta   u$
intensity	$I_{ u}( u)$	$\delta^{3}I_{\nu}(\nu)$
flux density	$F_{\nu}(\nu)$	$\delta^{(3+lpha)}F_{ u}( u)$
broad-band flux	F	$\delta^4 F$

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Plasma with bulk motion  $\beta = \frac{v}{c} = 0.99$  and angle  $\theta = 5^{\circ}$ 

Lorentz factor:  $\gamma = (1 - \beta^2)^{-\frac{1}{2}} = 7$ . Doppler factor:  $\delta = [\gamma(1 - \beta \cos \theta)]^{-1} = 10$ .

	rest frame	observer's frame	example
time interval	t	$\delta^{-1}t$	0.1 <i>t</i>
frequency	u	$\delta   u$	10 $ u$
intensity	$I_{ u}( u)$	$\delta^3 I_{\nu}(\nu)$	$10^{3}I_{\nu}( u)$
flux density	$F_{\nu}(\nu)$	$\delta^{(3+\alpha)}F_{\nu}(\nu)$	$10^{(3+\alpha)}F_{\nu}(\nu)$
broad-band flux	F	$\delta^4 F$	10 <sup>4</sup> <i>F</i>

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Testing the model

Confrontation to observations

#### Blazars Spectral energy distribution



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Confrontation to observations

#### Blazars Spectral energy distribution



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Confrontation to observations

#### Alternative models

#### Terlevich et al. (1992):

#### AGN phenomenology explained by starburts

#### Previous dichotomy "monster" vs. starburst now replaced by realization that each phenomenon has its own significance

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#### The radio-loud radio-quiet dichotomy



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Confrontation to observations

# The radio-loud radio-quiet dichotomy

# The SEDs of RL and RQ quasars do not differ at higher frequencies

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The existence or not of a radio jet is basically independent from accretion

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Testing the model

Confrontation to observations

# The radio-loud radio-quiet dichotomy

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The existence or not of a radio jet is basically independent from accretion

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# The radio-loud radio-quiet dichotomy

# RL AGN: never in S galaxies RQ AGN: rarely in E galaxies (e.g., Wilson & Colbert 1995)

Galaxy mergers  $\rightarrow$  E galaxies with spinning SMBH

Radio jet powered by SMBH spin

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Confrontation to observations

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AGN phenomenology The SMBH model

Testing the model

Confrontation to observations

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Historical introduction	
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#### Spatial scale

Approximate sizes for components of an AGN  $\mathcal{M}_{BH} = 10^8 \mathcal{M}_{\odot}$ ,  $d = 1 \, \text{Gpc}$ 

Region	Size			
-	[LTT]	[AU] – [pc]	[arcsec]	
R <sub>S</sub>	15 min	2 AU	$2 imes 10^{-9}$	
AD	$1h\sim 1d$	$7\sim 200\text{AU}$	$7 imes 10^{-9}\sim 2 imes 10^{-7}$	
BLR	$8\sim 80~d$	$10^3 \sim 10^4 \; \text{AU}$	$10^{-6} \sim 10^{-5}$	
R <sub>DT</sub> (inn.)	$\sim$ 40 d	$\sim 5 imes 10^3 AU$	$5 imes 10^{-6}$	
NLR	$1\sim 100{ m yr}$	$0.3\sim 30{ m pc}$	$5 imes 10^{-5} \sim 5 imes 10^{-3}$	
radio jets	$\lesssim 10^{6}{ m yr}$	$\lesssim$ 300 kpc	$\lesssim$ 60	

Historical introduction	
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Confrontation to observations

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Historical introduction	
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Confrontation to observations

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#### Testing the model

# Active Galactic Nuclei

- Historical introduction
- 2 AGN phenomenology
- 3 The SMBH model
- 4 Testing the model





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High spatial resolution observations

#### Radio interferometry Evidence for a gas disc



d = 15.1 Mpc ↓ 1″ ≡ 75 pc 0′′01 ≡ 0.75 pc

Gallimore et al. (1997)

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High spatial resolution observations

Radio interferometry Gas disc rotation

Syfert galaxy NGC 4258: 22 GHz (µ-wave) maser emission

annulus:

 $egin{aligned} D_{\text{inn}} &= 0.13\,\text{pc} - D_{\text{out}} = 0.26\,\text{pc} \ &\Rightarrow & 3.6 imes 10^7\,\mathcal{M}_{\odot} \ &\text{within}\ R \lesssim 0.012\,\text{pc}\ (\equiv 2500\,\text{AU}) \end{aligned}$ 

(Miyoshi et al. 1995)



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High spatial resolution observations

Optical (HST) Gas disc rotation



M 84 (d = 17 Mpc): central 3" ( $\equiv 240$  pc) H $\alpha$  spectrum disc:  $D \simeq 80$  pc;  $\Delta v = 1445$  km s<sup>-1</sup>  $\Rightarrow M_{BH} \simeq 2 \times 10^9 M_{\odot}$ 

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Historical introduction	AGN phenomenology	The SMBH model	Testing the model
High spatial resolution observations			
Optical (HST) Binary BH signatures			

Balmaverde & Capetti (2006): core galaxies invariably host a radio-loud nucleus



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High spatial resolution observations

#### X-rays (Chandra) Binary AGN

#### Bianchi et al. (2008): Binary AGN in Mrk 463

MRK 463

Optical galaxy

X-ray/NIR Nuclei

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Variability observations

#### **Reverberation mapping**



Testing the model

(Netzer & Peterson 1997)

Variability observations

#### **Reverberation mapping**





NGC 7469 Light Curves Cross-Correlation Functions

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Variability observations

# **Reverberation mapping**

Line variability delayed  $\tau = \frac{r}{c} (1 + \cos \theta)$ with respect to UV flux variability



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Variability observations

# **Reverberation mapping**

Line variability delayed  $\tau = \frac{r}{c} (1 + \cos \theta)$ with respect to UV flux variability



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Variability observations

# **Disk-jet interaction**



3C 120 (BLRG)



RXTE + VLBI (Marscher et al. 2002)

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Variability observations

# Polarimetric microvariability





 $\Delta heta \sim 2^{\circ} \Rightarrow \Delta P \simeq 10 \%$ 

(Andruchow et al. 2003)

Testing the model 

Variability observations

#### Polarimetric microvariability



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Variability observations

# Polarimetric microvariability



(Andruchow et al. 2003)

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Variability observations

#### Extremely violent microvariability?



PKS 1510-089  $\Delta R \simeq 2 \text{ mag in} \sim 40 \text{ min}$ (Dai et al. 2001)  $\Delta R \simeq 1.3 \text{ mag in} \sim 90 \text{ min}$ (Xie et al. 2004)

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Variability observations

# Extremely violent microvariability?



#### PKS 1510-089

(Cellone, Romero, & Araudo 2007)  $\Delta V \simeq 0.6 \text{ mag in} \sim 4 \text{ days}$  $\Delta V \lesssim 0.1 \text{ mag in} \sim 1 \text{ hr}$ 

Variability observations

## Extremely violent microvariability?



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Variability observations

# Extremely violent microvariability?

#### Significance of the variability: $\frac{\sigma_{\rm T}}{\sigma_2}$

Howell et al. (1988): *Statistical error analysis in CCD time-resolved photometry with applications to variable stars and quasars* 

$$\Gamma^{2} = \left(\frac{N_{2}}{N_{T}}\right)^{2} \left[\frac{N_{1}^{2}(N_{T}+P) + N_{T}^{2}(N_{1}+P)}{N_{2}^{2}(N_{T}+P) + N_{T}^{2}(N_{2}+P)}\right]$$
$$\frac{\sigma_{T}}{\Gamma_{T}\sigma_{2}}$$

Variability observations

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$$\frac{\sigma_{T}}{\Gamma \sigma_{2}}$$

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Variability observations

## Extremely violent microvariability?



test using an incorrect photometric technique

#### Field star

 $\Delta \textit{V} \simeq 1.2^{mag}$  in  $\sim 35$  min

$$\frac{\sigma_{\rm T}}{\sigma_2} = 24.0$$

$$\frac{\sigma_{\rm T}}{\Gamma \sigma_2} = 1.0$$

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 $\rightarrow$  spurious variability!

Variability observations

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 $\rightarrow$  spurious variability!

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BHs and their host galaxies

### **BH** mass

#### The BH mass can be measured by:

- optical emission line widths (BLR)
- gas dynamics (radio optical)
- reverberation mapping
- accretion disk spectrum
- X-ray variability

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BHs and their host galaxies





### A 2.6 $\times$ 10<sup>6</sup> $\mathcal{M}_{\odot}$ BH at the centre of the Milky Way (Schödel et al. 2002)

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BHs and their host galaxies

### The BH mass vs. bulge mass relation



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BHs and their host galaxies

### The BH mass vs. bulge mass relation



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BHs and their host galaxies

### The AGN stage

BH lie at the centres of massive spheroids (E galaxies and bulges)

Nuclear activity needs gas supply

- interactions / mergers
- bars
- inner disks

Histor	ical i	ntrodu	lction	
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BHs and their host galaxies

...etc.

