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1) Active galactic nuclei (AGN) and radio AGN: introduction of their properties

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and
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Me in a “nutshell”

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

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RadioLife

ExGal-Twin
Excellence in Galaxies · Twinning the IAC
Funded by the European Union

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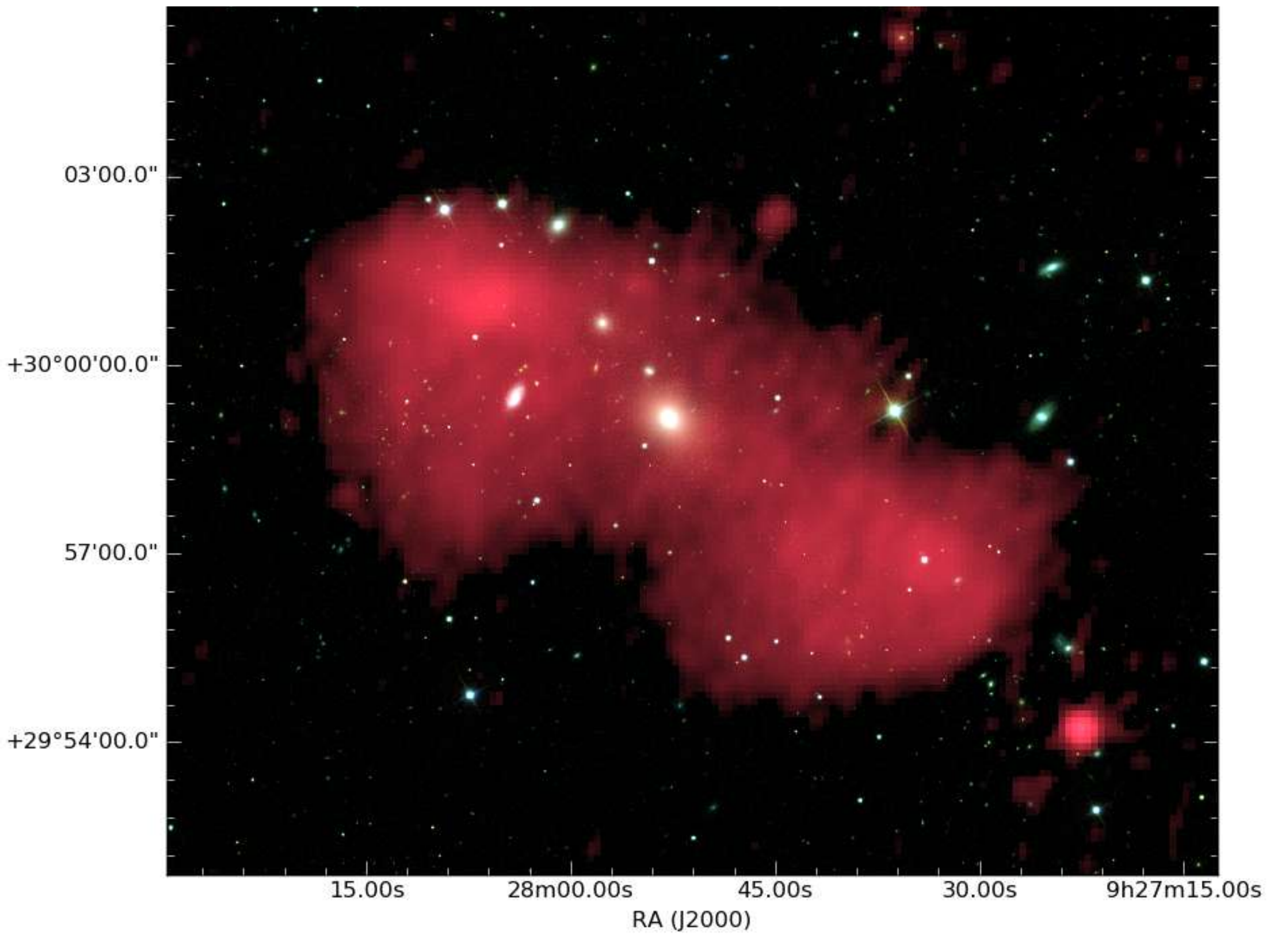
Me in a “nutshell”

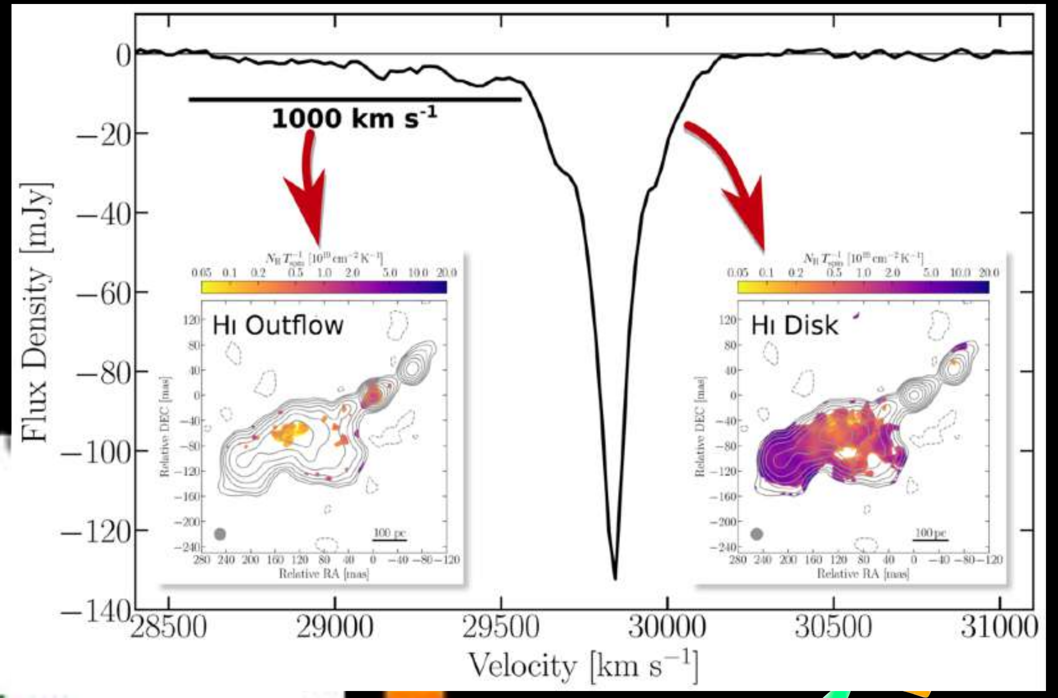
http://www.astron.nl/~morganti

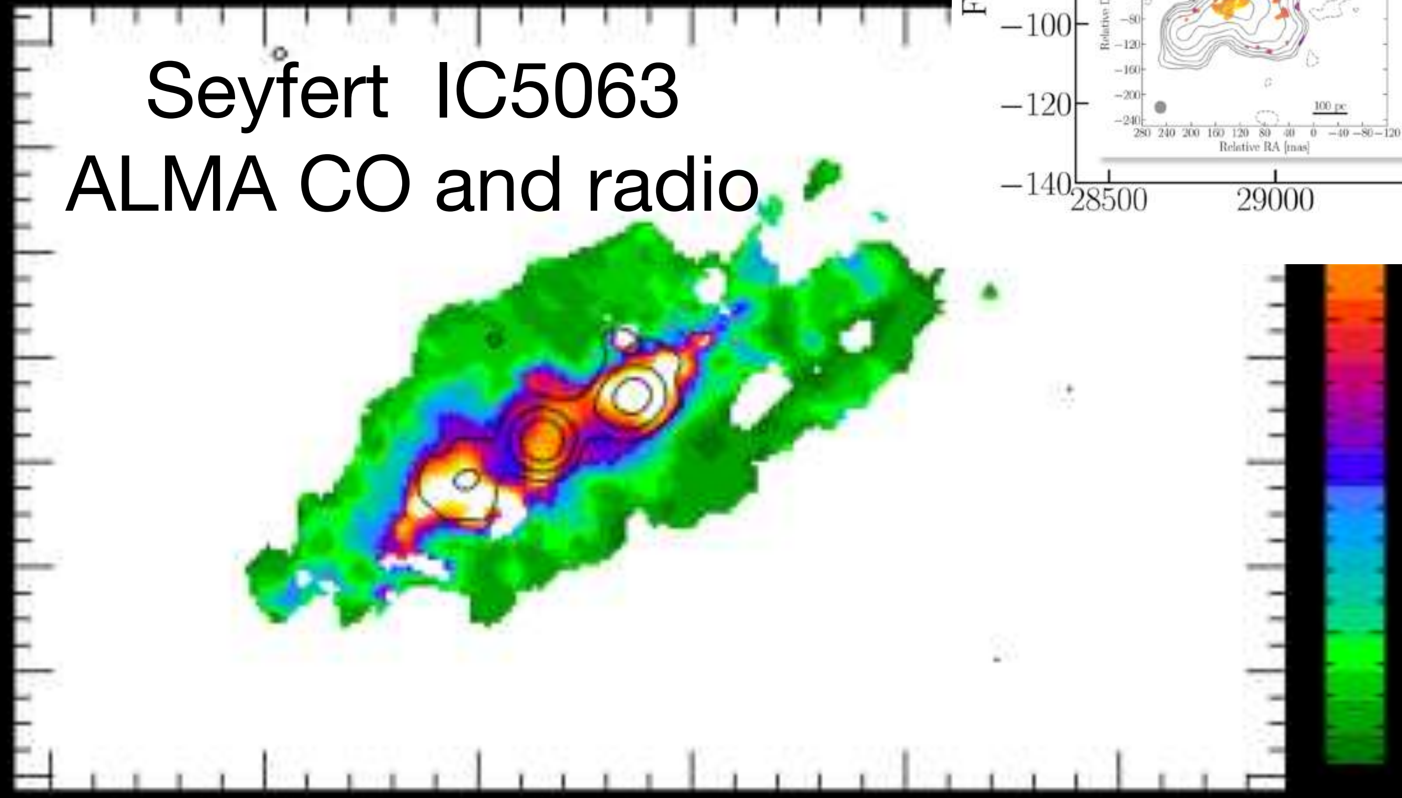
My expertise: technical and science - observer
Radio astronomer ➙ LOFAR, Apertif-WSRT,
SKA-pathfinders/precursors

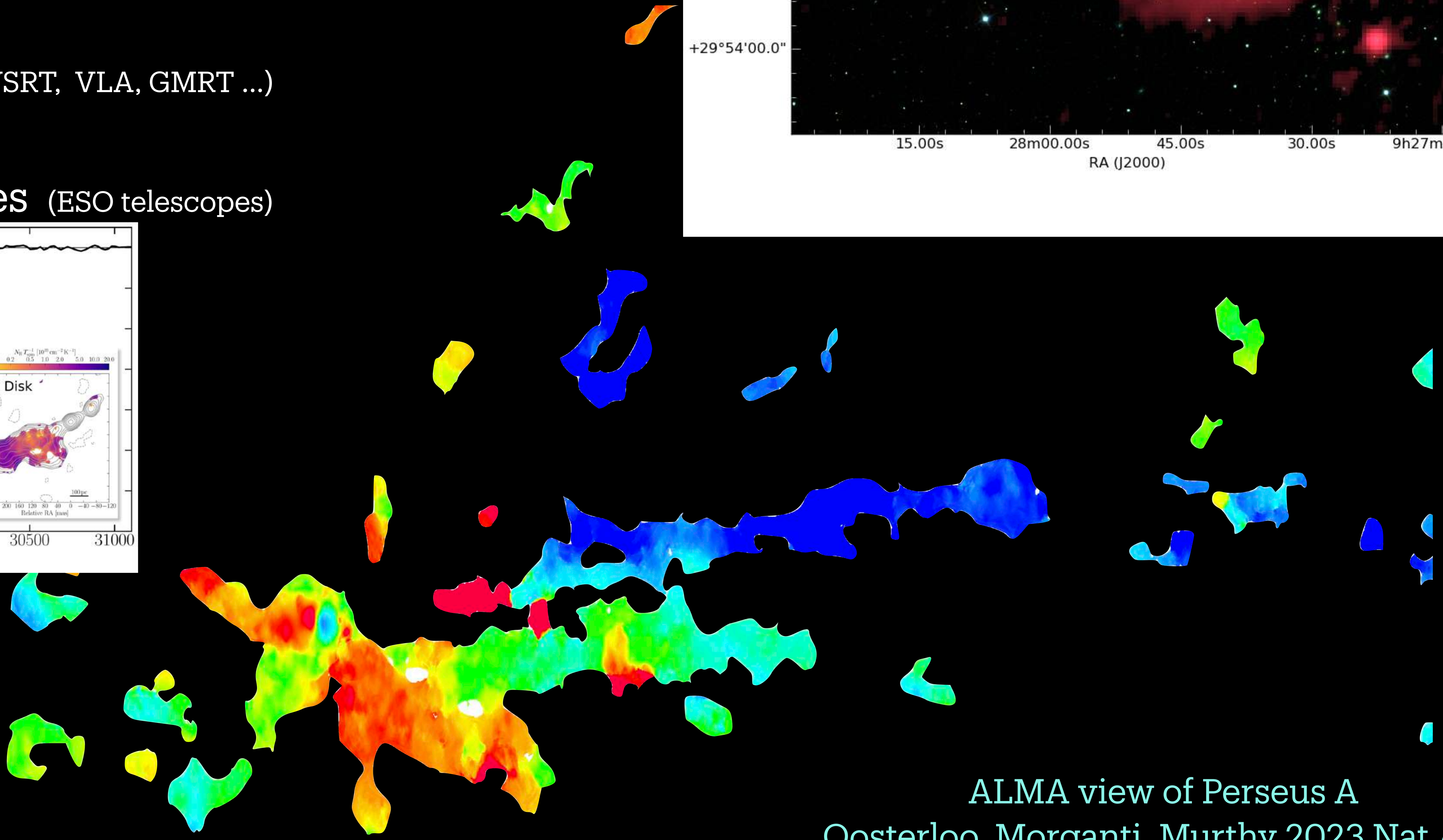
Radio AGN (jets/lobes), their evolution and their role in galaxy evolution
Interaction of jets with cold gas - 21cm HI (WSRT, VLA, GMRT …)
and cold molecular gas (ALMA, NOEMA)
and warm ionised gas, optical emission lines (ESO telescopes)

LOFAR image of the remnant B2 0924+30
Shulevski et al. 2017









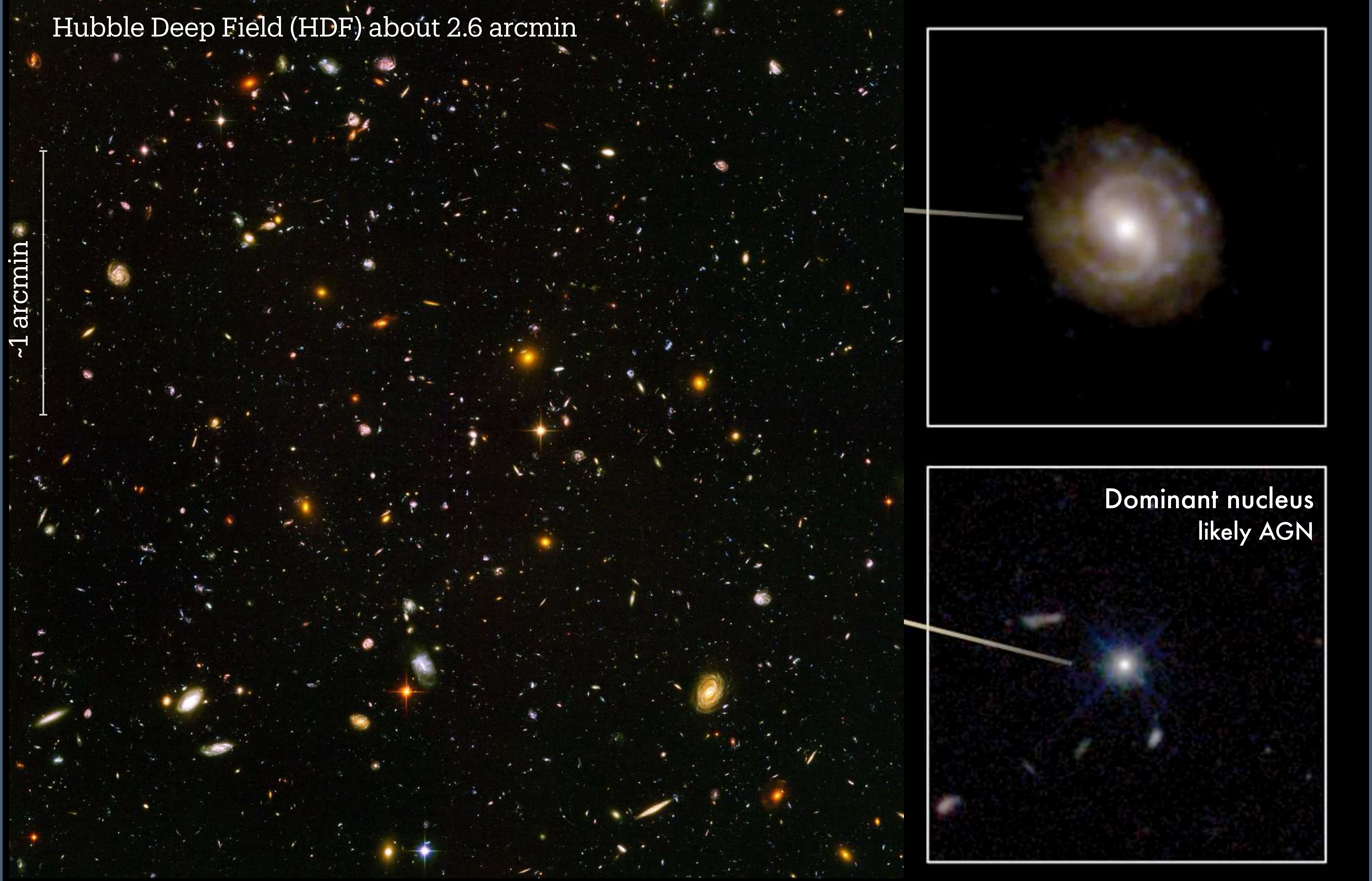
ALMA view of Perseus A
Oosterloo, Morganti, Murthy 2023 Nat Astr

Active galactic nuclei at radio wavelengths: properties, life and impact

Themes of the lectures

- ➡ Active galactic nuclei (AGN): introduction of their properties (only a small part on radio today!)
- ➡ Structure of radio AGN and their life cycle
- ➡ Radio jets and their impact in galaxy evolution

➡ a lot of material taken from F. Combes's book


Hubble Deep Field (HDF) about 2.6 arcmin
~1 arcmin
Dominant nucleus
likely AGN

1) Active galactic nuclei (AGN) and radio AGN: introduction of their properties

Plan of this lesson

a) What is an AGN - more than a super massive black hole
b) Why to study AGN
c) Short detour on the history
d) A step back: properties of the BH and central regions, i.e. (sub)pc scales
e) What kind of emission can be observed in an active SMBH and where it comes from?
The multi-wavelengths properties
f) How about the radio emission in galaxies: origin and how to recognise a radio AGN

I assume I have a mixed audience: experts and non-experts on AGN

a) What is an AGN - more than a super massive black hole

The phenomenon called active galactic nucleus (AGN)

➡ a phenomenon more than a type of objects!

Wikipedia

Active galactic nucleus

46 languages

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From Wikipedia, the free encyclopedia

An **active galactic nucleus** (**AGN**) is a compact region at the center of a galaxy that emits a significant amount of energy across the electromagnetic spectrum, with characteristics indicating that this luminosity is not produced by the stars. Such excess, non-stellar emissions have been observed in the radio, microwave, infrared, optical, ultra-violet, X-ray and gamma ray wavebands. A galaxy hosting an AGN is called an **active galaxy**. The non-stellar radiation from an AGN is theorized to result from the accretion of matter by a supermassive black hole at the center of its host galaxy.

Active galactic nuclei are the most luminous persistent sources of electromagnetic radiation in the universe and, as such, can be used as a means of discovering distant objects; their evolution as a function of cosmic time also puts constraints on models of the cosmos.

➡ working definition: a nucleus is active when the super-massive BH accretes at an Eddington ratio $L_{bol}/L_{Edd} > 10^{-5}$ (our MW is not active according to this definition)

Eddington luminosity: max luminosity for a given BH mass (we get back to this in a few slides...)

Galaxies and SMBH

➡ key ingredient: a (super-)massive BH

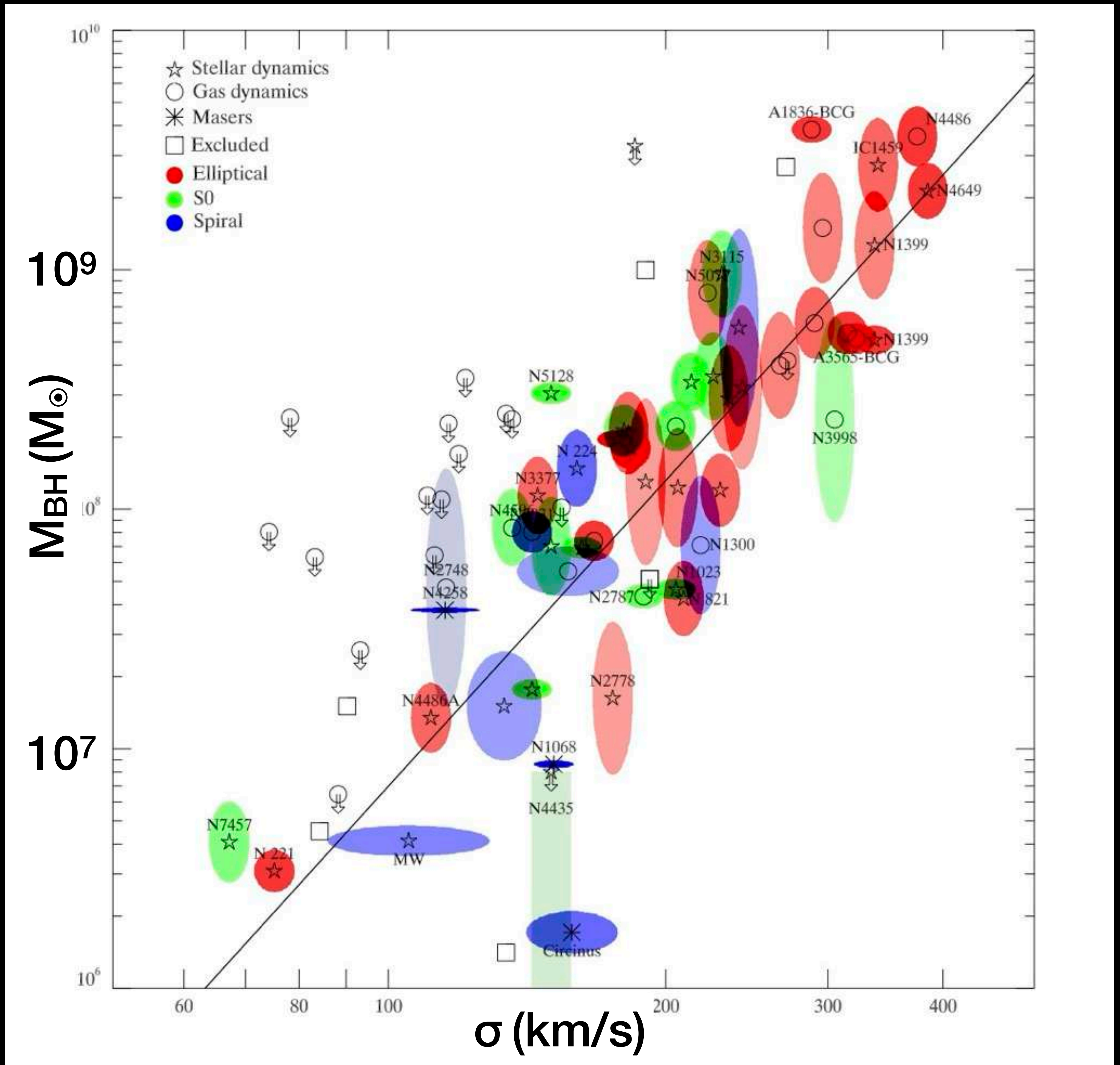
All massive galaxies host a supermassive black hole (SMBH)

➙ relation M_{BH}-σ velocity dispersion of the stars in the bulge of the galaxy

⬇

but not all SMBH are active (right now...)

Gültekin et al.



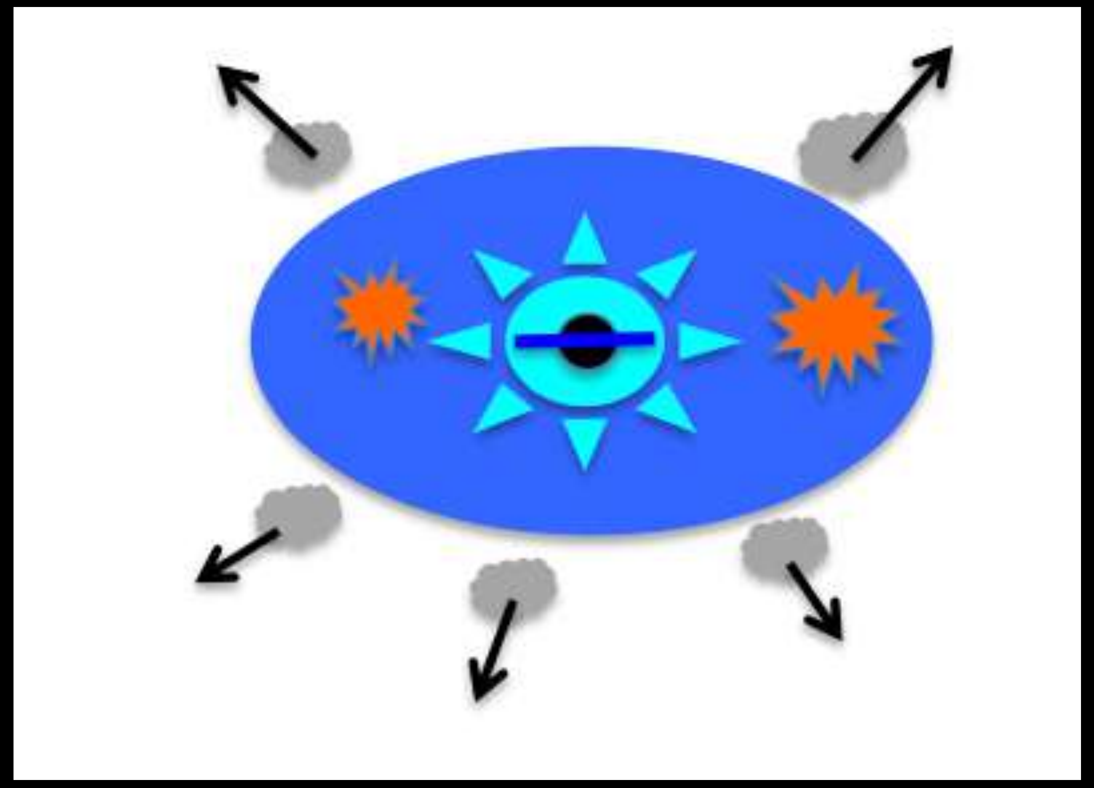
only a subset of these SMBH are “active”

b) Why to study AGN?

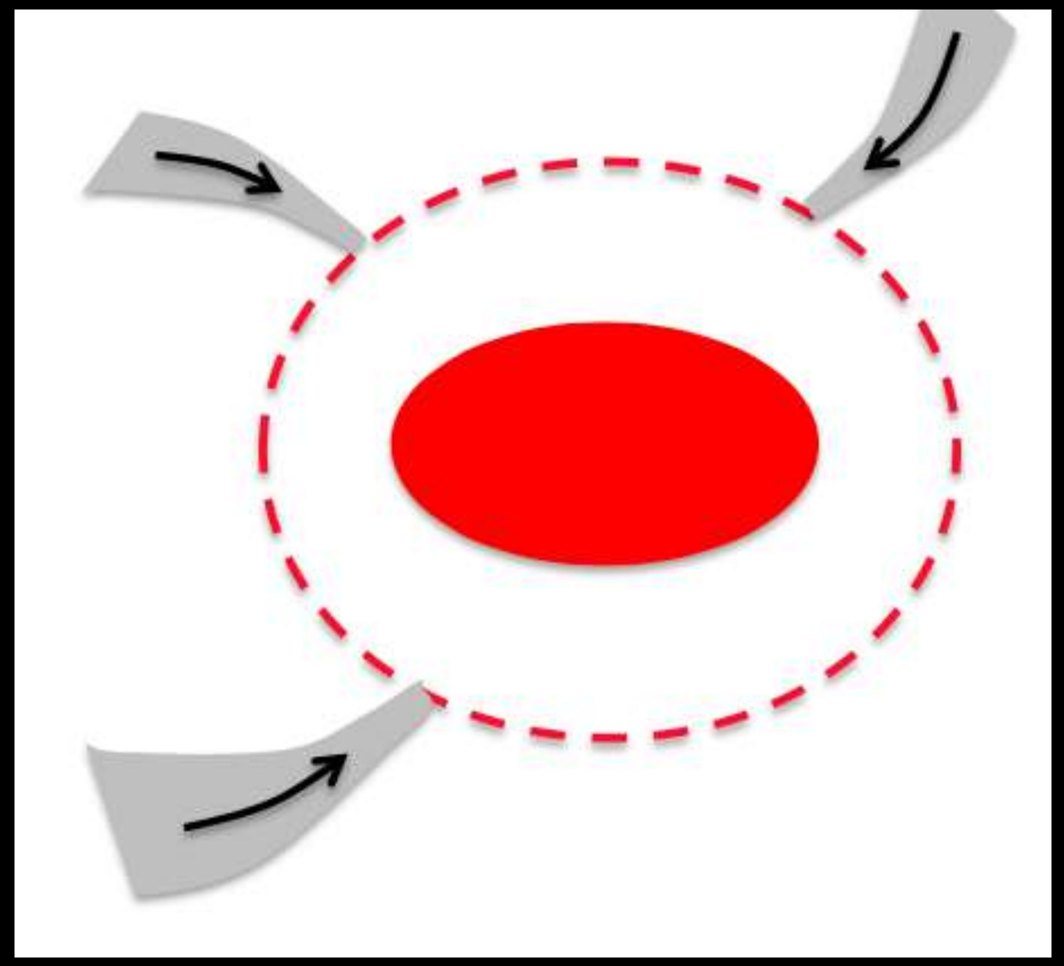
Since the 60th a lot of studies on AGN and the emphasis has also changed

- Variety of physical phenomena to understand - covering all wavebands
- Impact on the host galaxy ➙ lift/heats the gas preventing star formation in the host galaxy ➙ connection to galaxy evolution
- Variety of types of AGN which could have different impact

Role of AGN in galaxy evolution: cosmological simulations



ejecting mode (gas outflows)



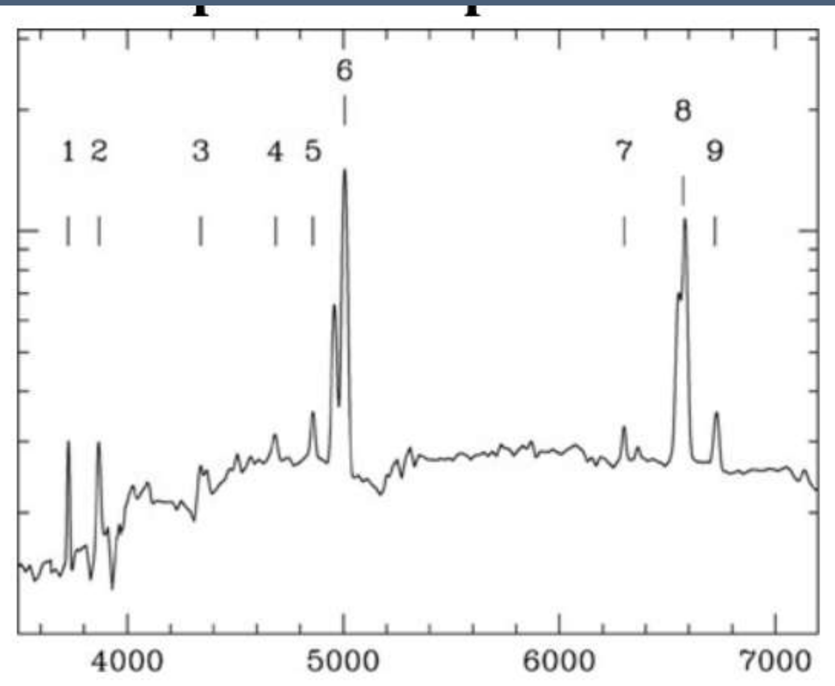
“maintenance” mode
preventing gas from cooling/halt gas supply

from R. Maiolino lectures

The AGN has to be recurrent to have the required impact on the host galaxy

c) Short detour on the history of AGN

- the first spectroscopic detection of emission lines from the nuclei of NGC 1068 and Messier 81: Fath & Slipher (1909) detect strong emission lines similar to PNe BUT with line-width of several hundred km/s in NGC 1068.
- 1926 – Hubble finds that "nebulae" are extragalactic (galaxies)
- 1943 – Carl Seyfert finds multiple galaxies similar to NGC1068 (hence since then they are called by his name)



At that time, the phenomena was not yet associated to an active nucleus and a massive black hole!!!
Most of the progresses were done after the second World War
(also re-using technology equipment left over from the war)

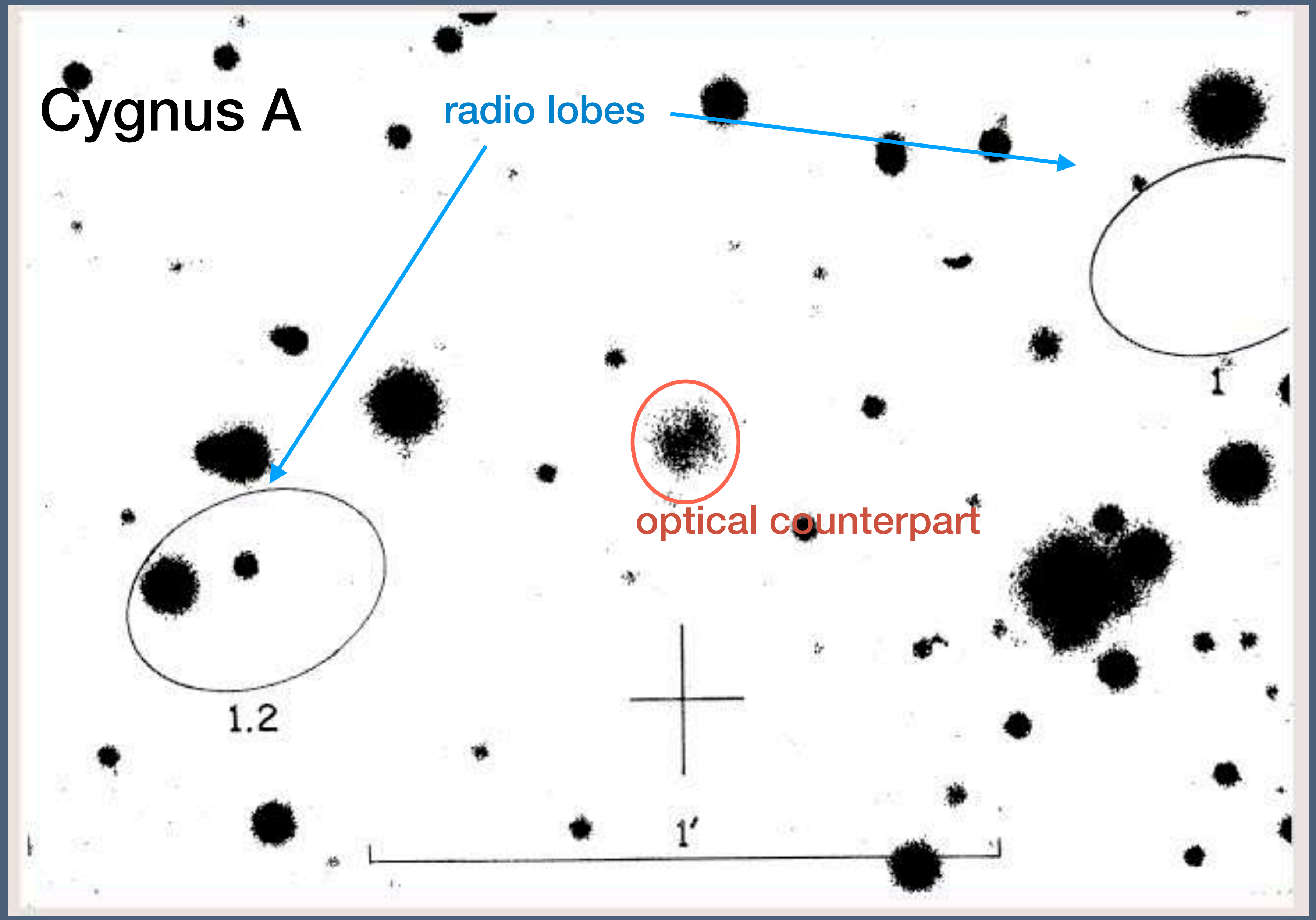
Optical and radio coming together....

- Discovery of extragalactic radio sources (1948) - Centaurus A etc. - limitations in the spatial resolution and the accuracy of the positions

- Discovery of two components in the radio emission of what will be identified as Cygnus A - Jennison & Das Gupta, 1953

Identification of the radio source Cygnus A with an optical object with distorted morphology. Using the emission lines Baade & Minkowski (1954) derived a large distance and estimated an enormous (for that time) luminosity

- 1963 discovery of quasar (quasi stellar radio source) In 1963, Maarten Schmidt and Bev Oke published a pair of papers in Nature reporting 3C 273 with redshift of 0.158



Matthews, Morgan, and Schmidt 1964

- For an overview: Shields G. "A brief history of AGN" 1999PASP..111..661

Detour on the history of AGN

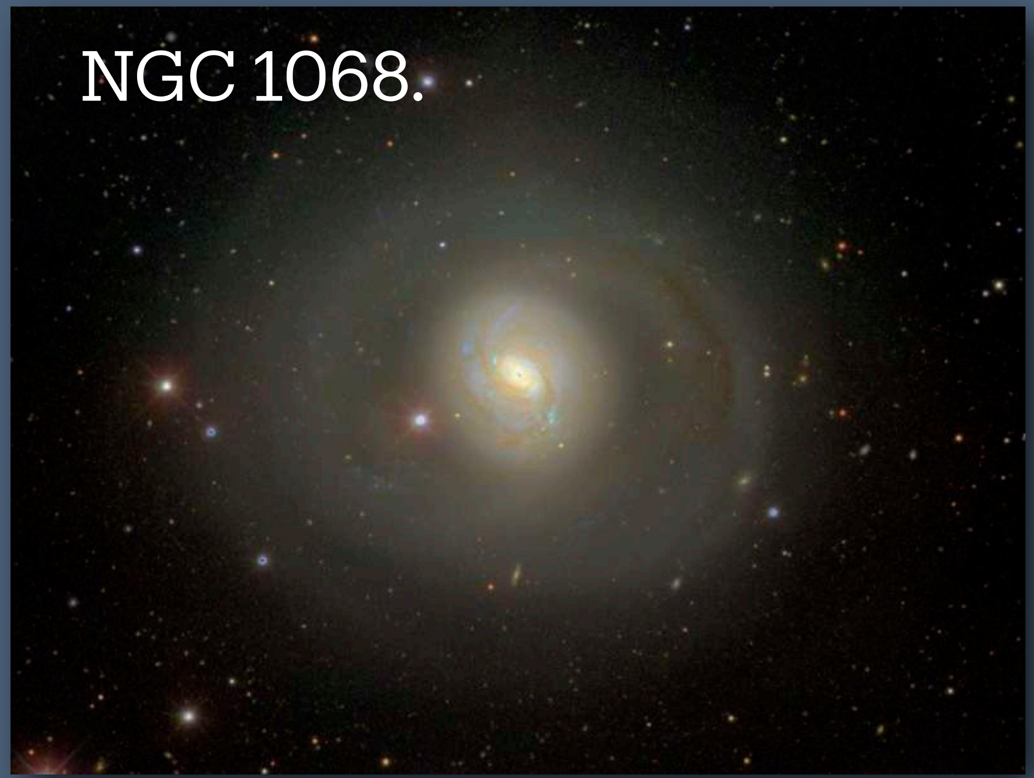
1955 – Detection of radio-emission from NGC1068 and NGC1275 (Perseus A), Cen A, Cygnus A etc.
1959 – Woltjer draws several important conclusions on “Seyfert” galaxies:

EMISSION NUCLEI IN GALAXIES

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.



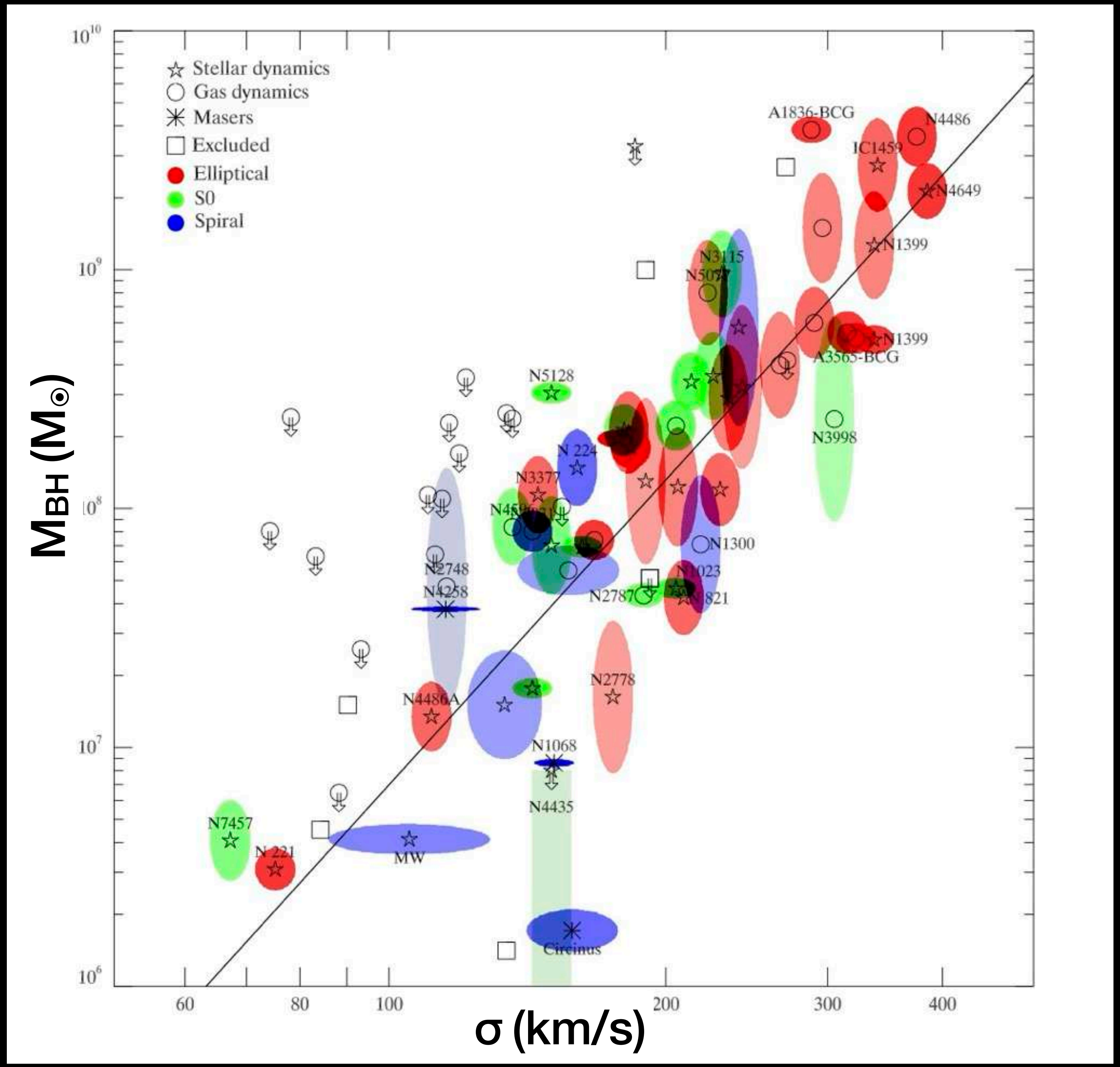
* Nuclei are unresolved (<100pc)
* Nuclear mass is very high if emission-line broadening is caused by bound material ($M \sim v^2 r/G \sim 10^{9\pm1} M_\odot$)
* Nuclear emission last for $>10^8$ years (1/100th spirals is a Seyfert and the Universe is 10^{10} yrs) ➜ assuming all spiral galaxies pass a Seyfert phase!

AGN short (but recurrent) phenomenon in the life of a galaxy?

- For an overview: Shields G. “A brief history of AGN” 1999PASP.111..661

Gültekin et al. 2009

not all SMBH are active…



What is special with the central regions of an active galaxy and what is the origin of the emission

d) A step back: properties of the BH and central regions, i.e. (sub)pc scales

…e central regions of an active galaxy: …ain components of an AGN

In an active nucleus …rgy is resulting from accretion onto a …act and massive object (supermassive …hole) and from the associated release of the binding gravitational energy.

…e energy can be emitted via thermal and/or …non-thermal radiation (e.g. synchrotron emission, relativistic electrons and magnetic field)

Super massive black hole (SMBH)

BH is characterised by: mass, spin (angular momentum) & charge
Full characterisation would require considering the rotation (Kerr BH) and General Relativity

Typical masses of a SMBH in AGN ➙ between 10^7 and 10^9 $M_\odot$

Event horizon: radius at which the escape speed from the surface of the sphere would equal the speed of light ➙ no share of information possible

Approximation for non-rotating BH: Schwarzschild radius

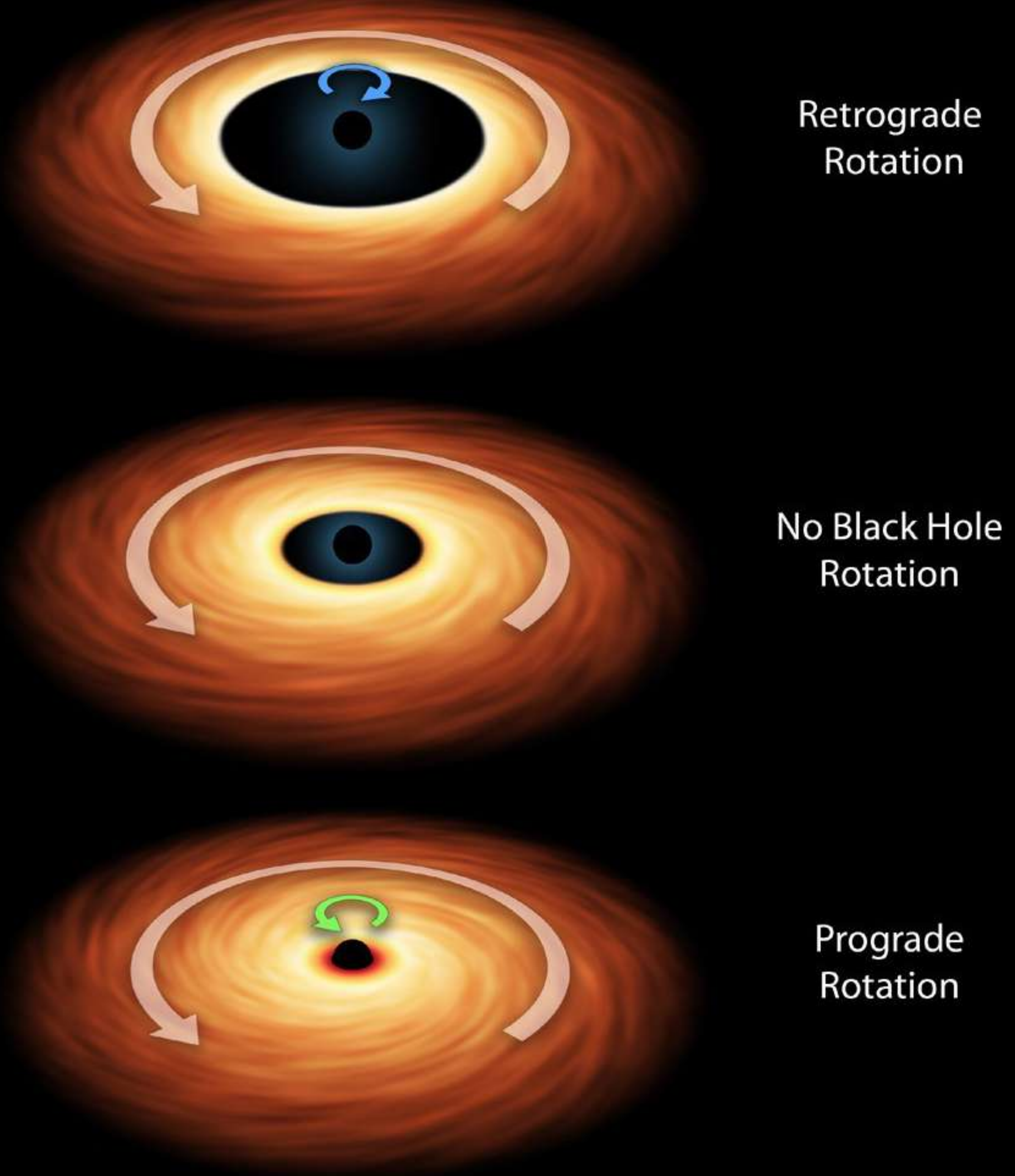
$R_S = 2GM/c^2$ *G=gravitational constant ➙ also used* r_g $R_S=2r_g$

Mass of the earth (10^{-6} $M_\odot$) ➙ R_S=1cm ➙ inside the radius of the object

Quasar 10^8 $M_\odot$ ➙ $R_S = 3x\ 10^{13}$ cm (2AU)

Innermost stable circular orbit (ISCO): orbit beyond which the particle loses its orbital motion and falls directly into the event horizon ➙ inner edge of the accretion disk. For non rotating BH: 3 x R_S but for realistic rotating (Kerr) BH it depends on the rotation

ISCO smaller for prograde rotation (BH - thin accretion disk) ➙ why interesting?



$9\ r_g$

ISCO $6\ r_g$

$< 6\ r_g$

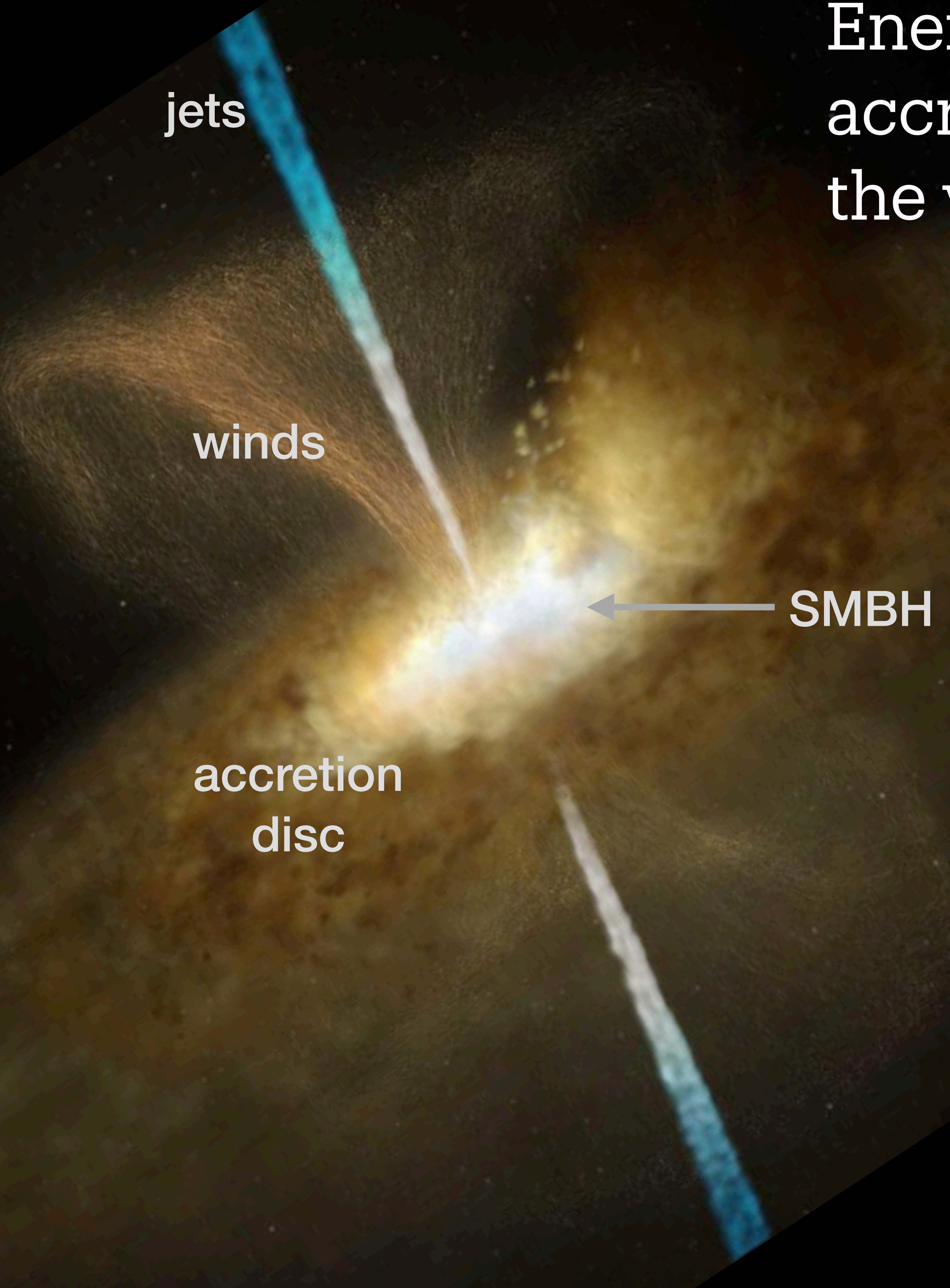
The smaller ISCO is, the larger the fraction of gravitational potential energy that is converted in electromagnetic radiation during the accretion

→ higher efficiency

Accretion disc

(thin disc approximation: two dimensional, axisymmetric accretion flow)

When mass falls towards the black hole potential energy is converted into kinetic energy and creation of a rotating disc. Due to the differential rotation, internal "friction" (viscous disc) this is converted in thermal energy ➙ release of energy.



Energy can be estimated assuming an element of mass (*dm*) in the accretion disc moving from orbit radius r+dr to r ➙ virial theorem half of the variation of gravitational potential energy must be radiated away:

$$dL = \frac{dE_{rad}}{dt}$$

$$L = \int_{R_{out}}^{R_{in}} dL = \frac{1}{2} G M \dot{M} \left(\frac{1}{R_{in}} - \frac{1}{R_{out}} \right) \simeq \frac{1}{2} \frac{G M \dot{M}}{R_{in}}$$

accretion rate

$L = \eta \dot{M} c^2 \simeq$ $\eta = GM/(2c^2 R_{in}) \simeq 0.1$

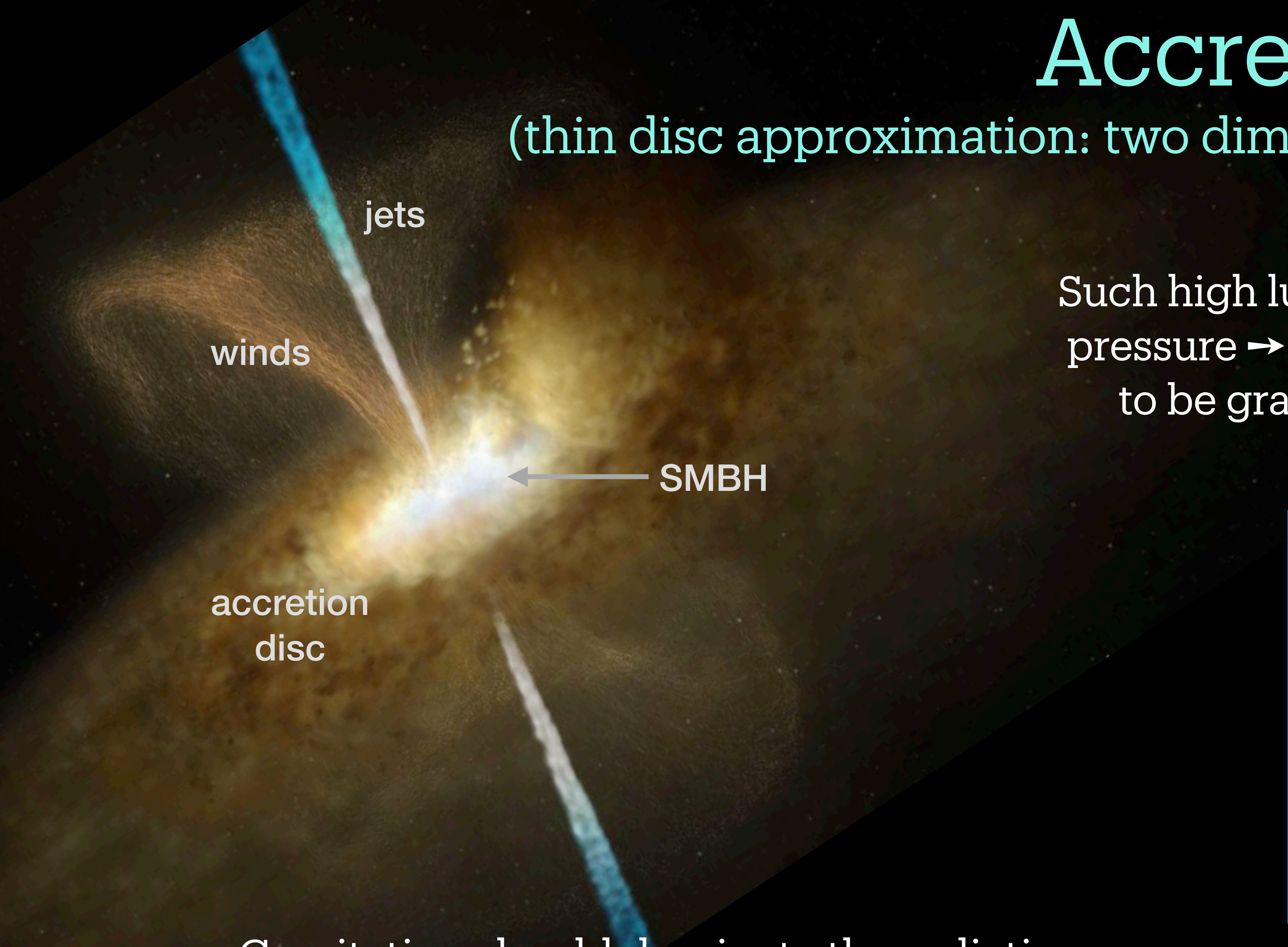
10% ➙ **high efficiency AGN** (but can be as low as 10^{-4})

- For η=0.1 an AGN of L~10^{45} erg/s requires $\dot{M}$~0.1 $M_\odot$ yr^{-1} accretion rate

A number of parameters can influence the high/low efficiency rate, for example the spin of the BH and the size of the ISCO (R_{in}).

Accretion disc

(thin disc approximation: two dimensional, axisymmetric accretion flow)



Such high luminosity will produce an enormous radiation pressure ➝ requires a minimum central mass for material to be gravitational bound to the centre of the galaxy

$$\frac{GM_{BH}m_p}{r^2} > \frac{\sigma_T S}{c} = \frac{\sigma_T}{c} \cdot \frac{L}{4\pi r^2}$$

$$L \leq L_{Edd} = \frac{4\pi G c m_p}{\sigma_T} M_{BH}$$

$$L \leq 1.26 \times 10^{38} \frac{M_{BH}}{M_\odot} erg\ s^{-1}$$

σ_T cross section for Thomson scattering of the electron.

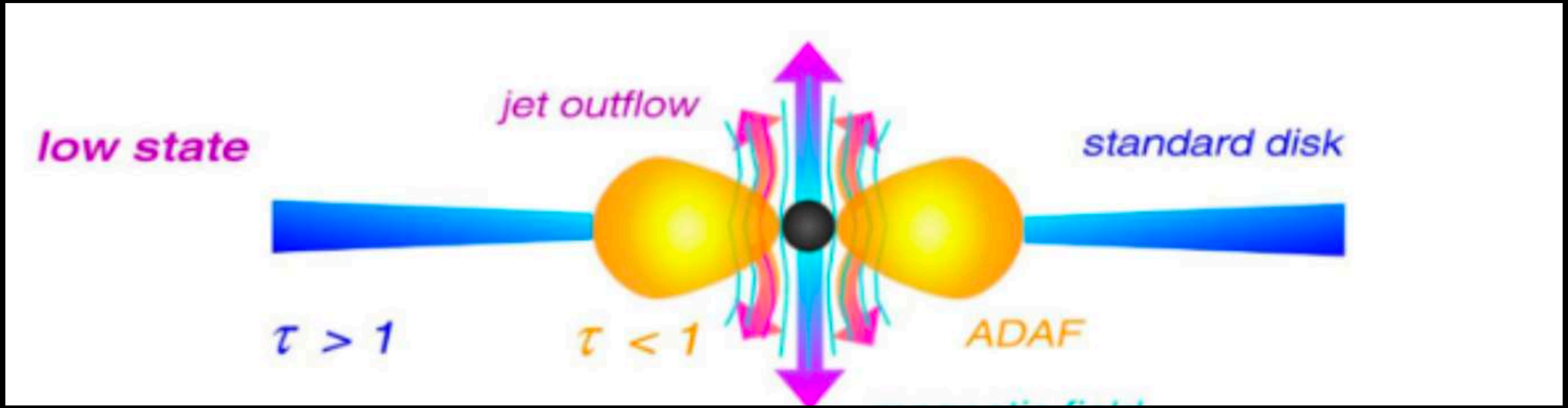
Gravitation should dominate the radiation: for a given central mass the luminosity cannot exceed the Eddington luminosity

Ratio between Eddington and AGN luminosities ➝ efficiency of the AGN

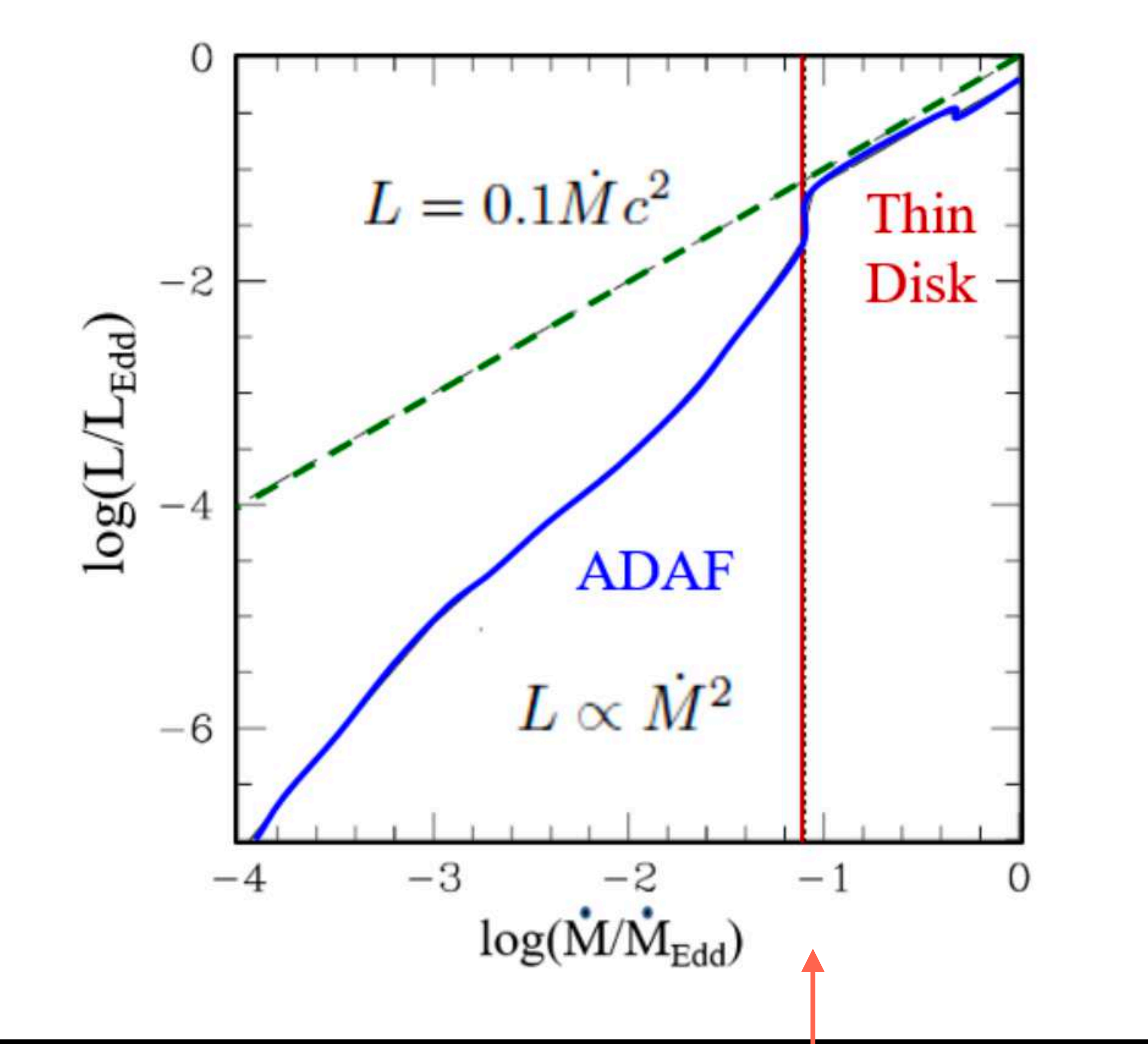
Not all AGN are highly efficient!

Low accretion rates - low efficiency

...most of the AGN accrete at much lower rate. For example, weak-line radio galaxies accrete at rate ~10^{-4} Eddington (low!).



ISCO = Outer radii (selfgravity dominates)

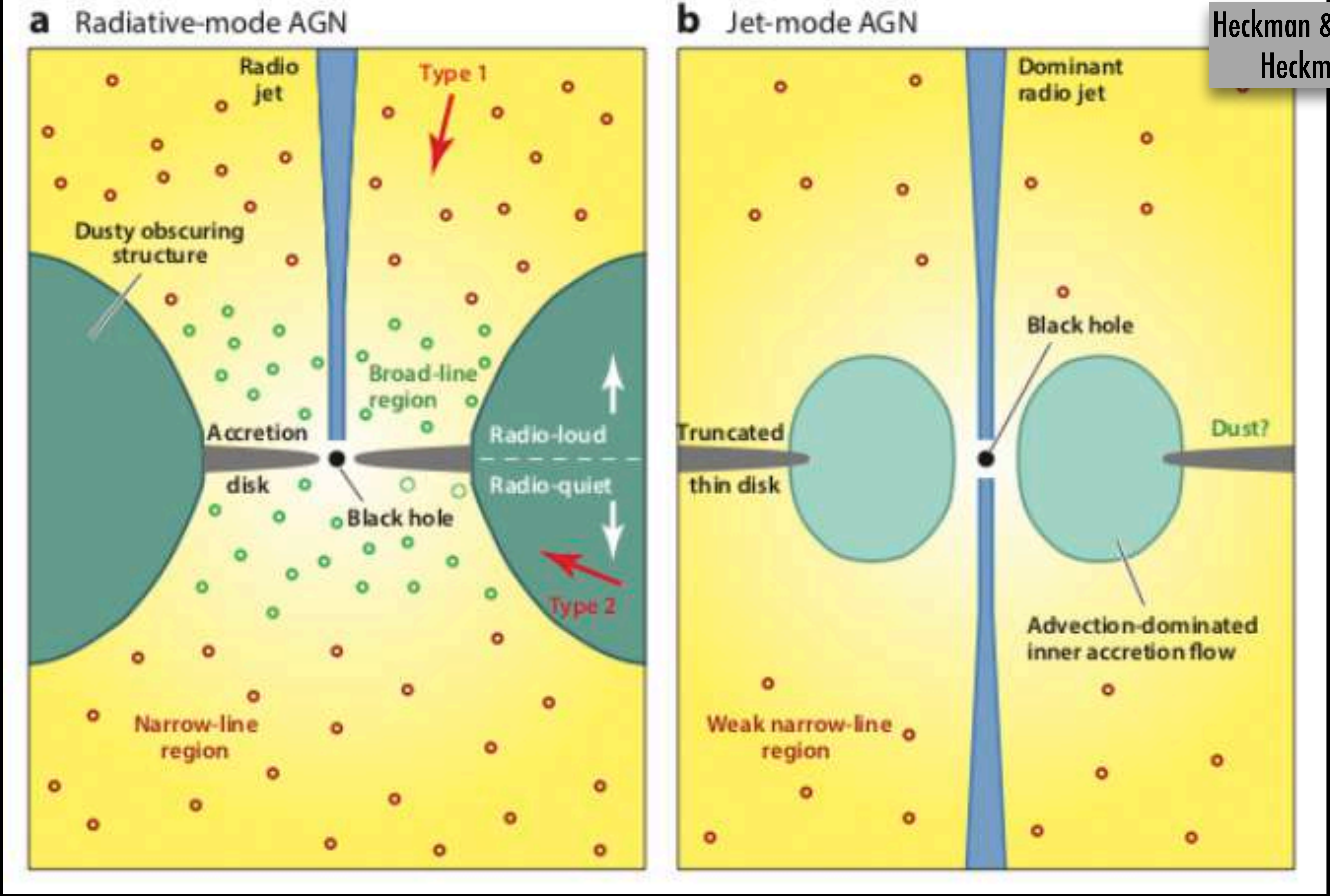


critical accretion rate

Esin et al. 1997, Muller 2014, Combes 2024

Accretion discs with very low accretion rate different from the thin disc approximation.
They have low density and hence the gas has very long cooling times. They can equal or exceed the inflow time: the particle can advect into the BH without releasing their energy
→ Advection-Dominated Accretion Flow (ADAF) or Radiatively Inefficient Accretion Flow (RIAF).
They are less luminous (optical, UV, X-ray) but they can release the energy via radio jets.

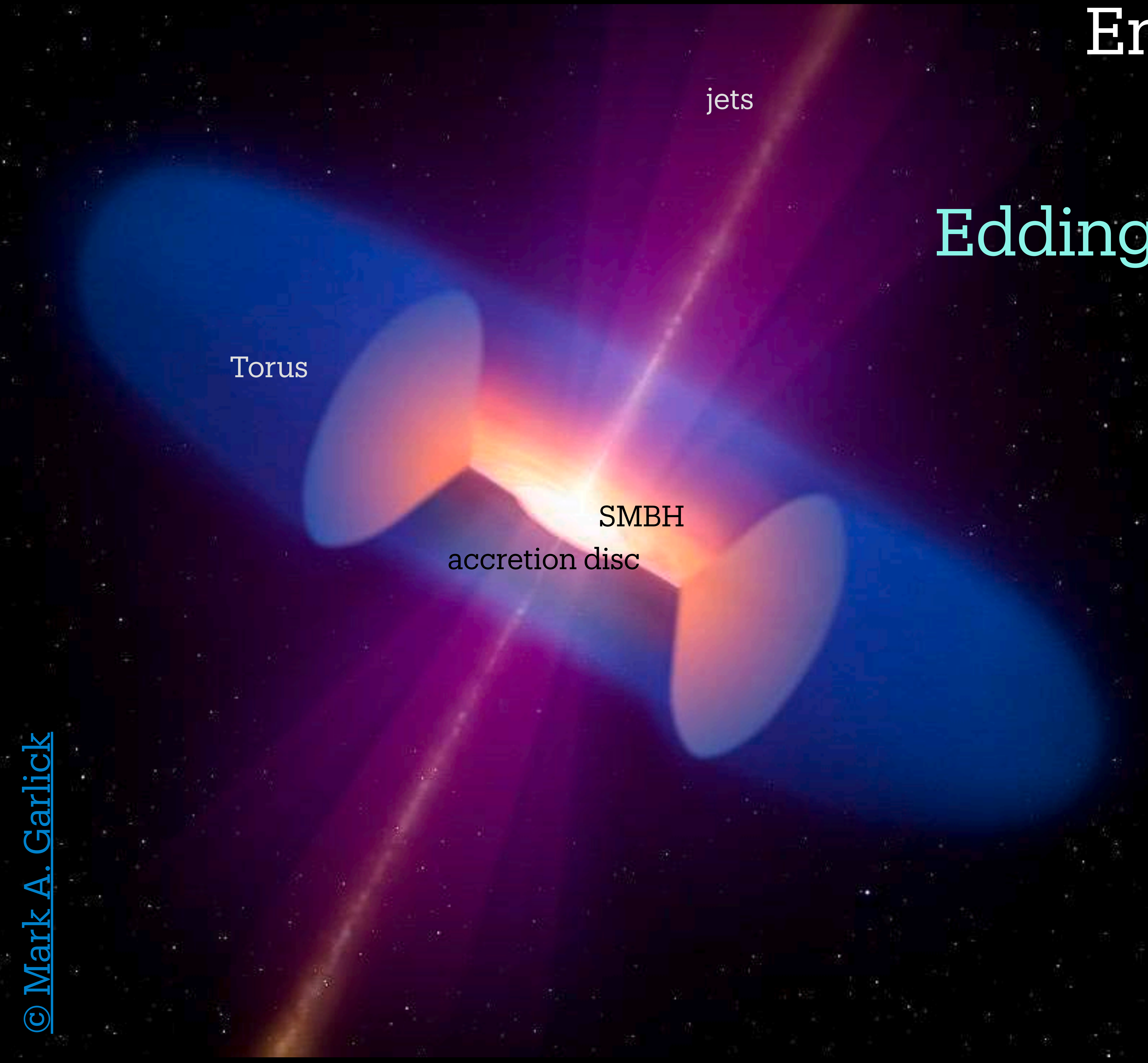
Heckman & Best 2014 - ARAA
Heckman et al. 2024



Radiatively efficient AGN (less commonly have radio jets)

Radiatively inefficient AGN

Are you still with me?



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Energy resulting from accretion onto a compact and massive object

Eddington luminosity: max luminosity for a given BH mass

Event horizon and ISCO ➙ the closer the material gets to the SMBH, the largest the energy tapped

(thin) Accretion disc ➙ high accretion rate
➙ high luminosity AGN

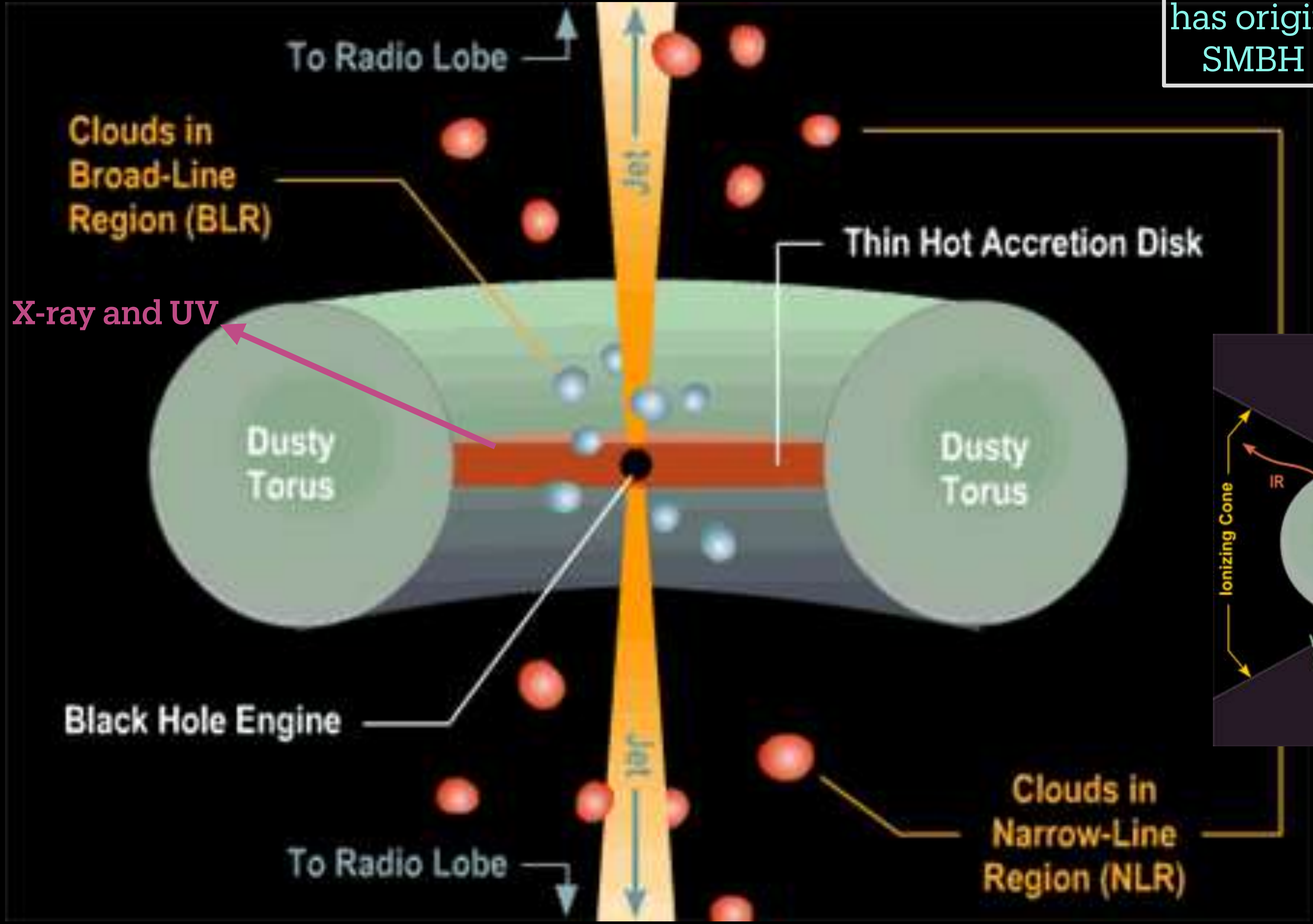
not all AGN have an thin accretion disc:
➙ advection dominated flow:
low efficiency, low luminosity AGN

most of the energy is released via radio jets.

e) What kind of emission can be observed in an active SMBH and where it comes from?

the multi-wavelengths properties of AGN (optical, X-ray and radio)

Every manifestation of an active nucleus has origin from phenomena related to the SMBH and its immediate surrounding



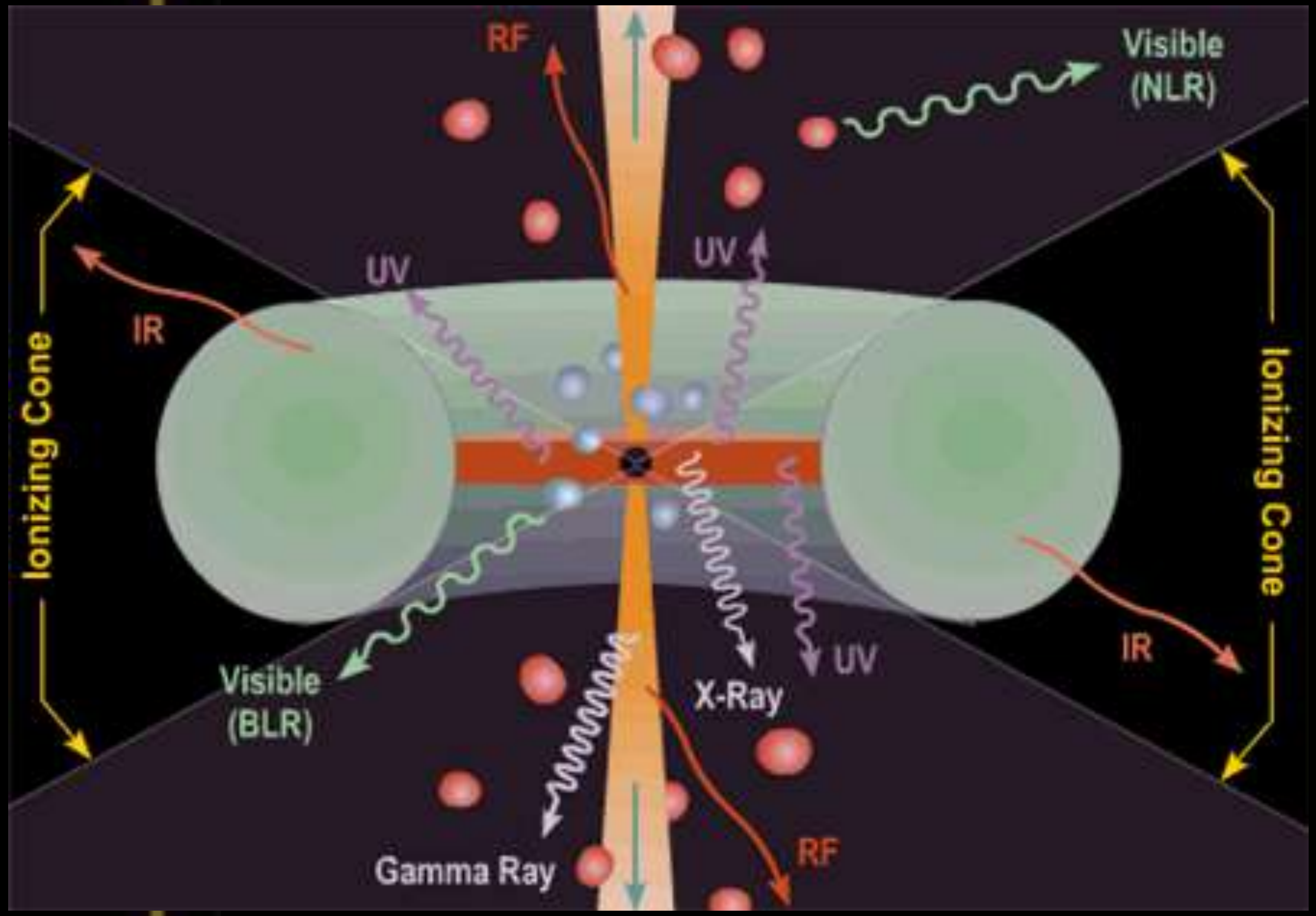
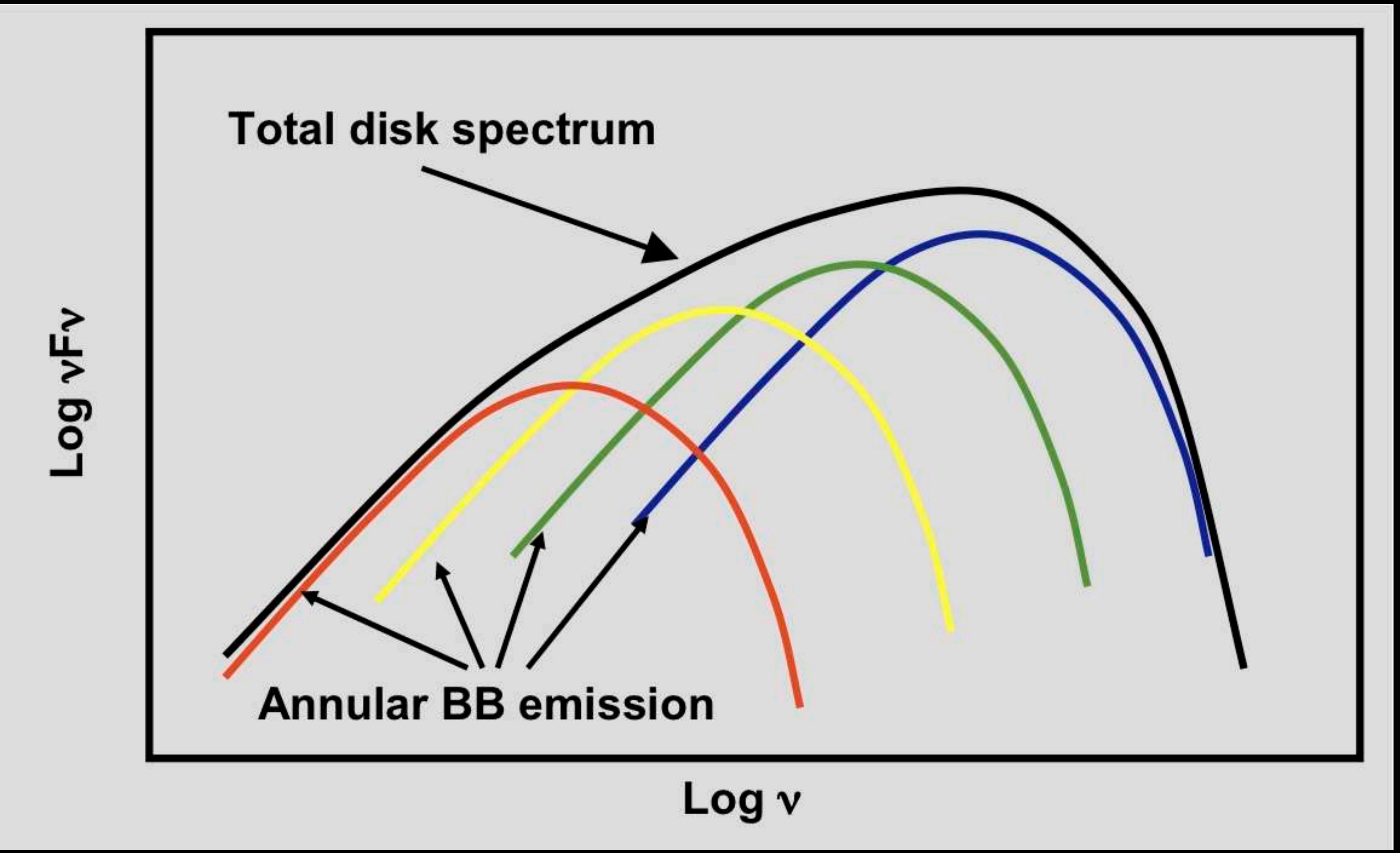


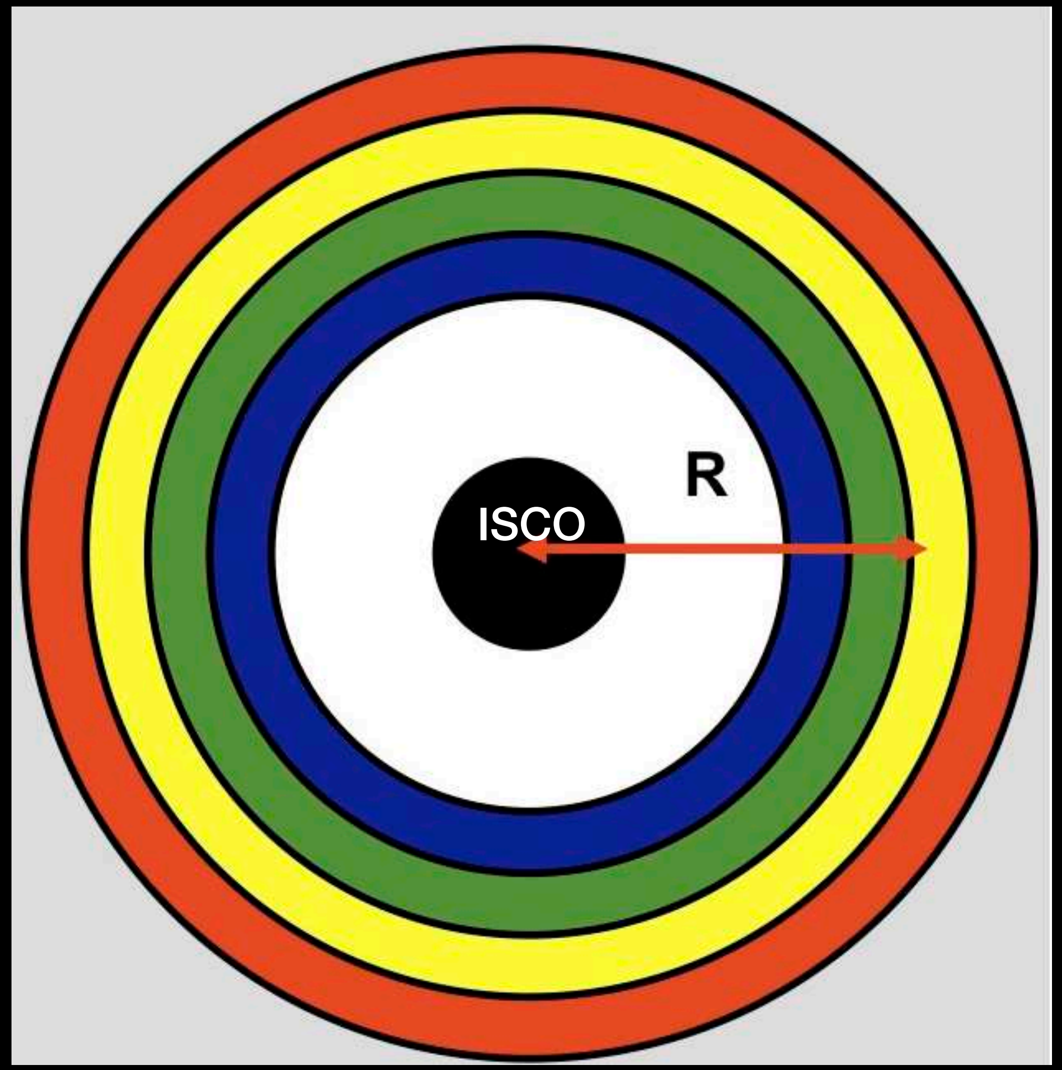
Image credit: Brooks/Cole Thomson Learning)

Emission from the accretion disc

Depending on the accretion and the BH mass the disc emits most of its energy in the UV part of the spectrum (range of temperatures across the accretion disc).

The superposition of these BB spectra will thus look like:



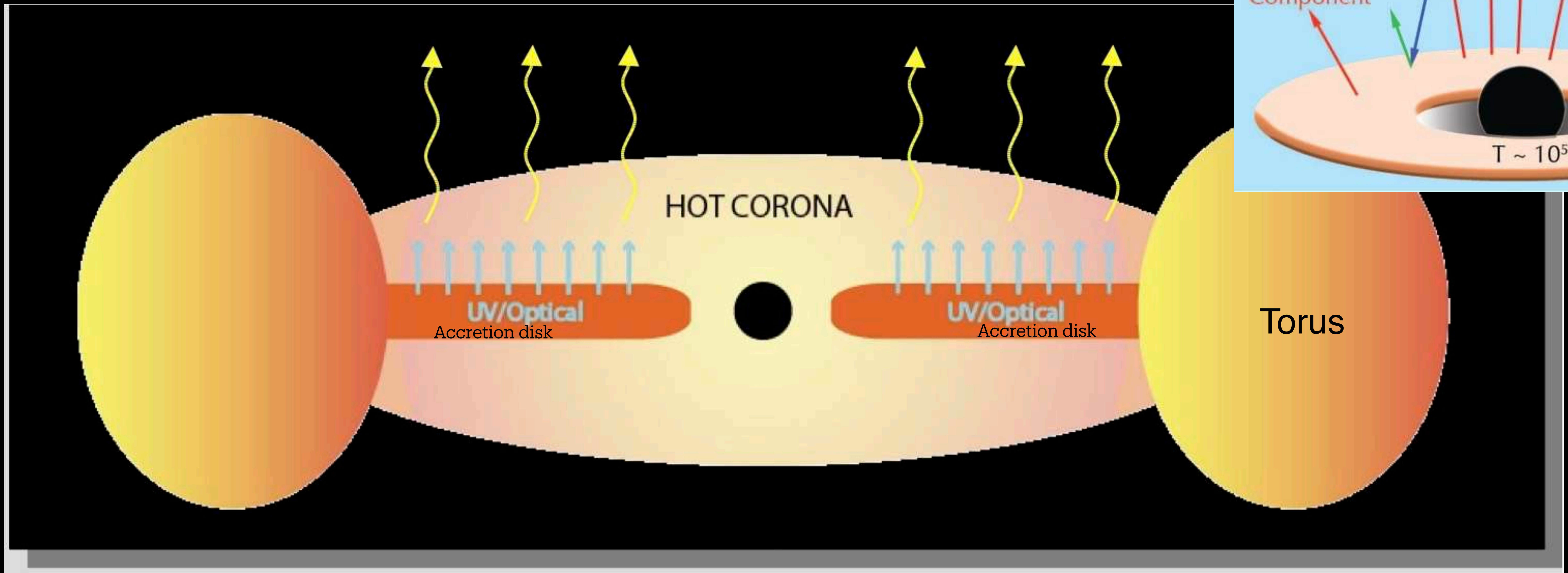


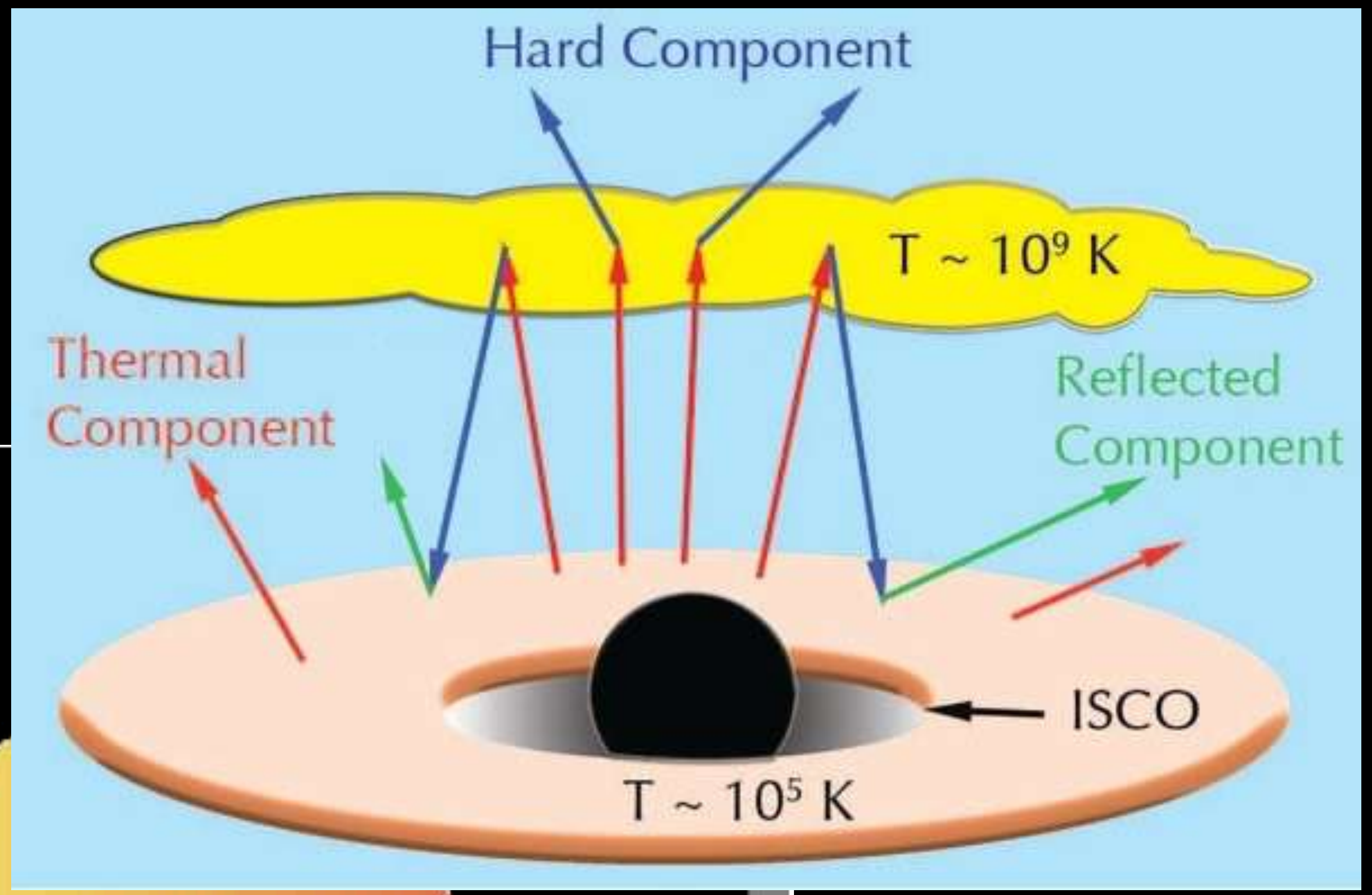
Temperature increases inward ($r^{-3/4}$): accretion disk continuum spectrum superposition of many BB's with different temperatures

UV and optical should come from different part of the disk

Temperature increases with decreasing radius and increasing accretion rate
➙ radiatively efficient (high accretion) AGN have more UV
➙ radiation which can ionised the surrounding gas: good tracer of AGN

X-ray emission: Origin





- **Strong magnetic fields** likely present in the accretion disc providing an important source of viscosity.
- Above the accretion disc, the corona made of hot plasma, heated by reconnection of magnetic fields, generated by buoyancy instability in the cold accretion disc.
- From this region arise X-ray emission ➙ either synchrotron emission, or inverse Compton, where softer radiation from the disk is reflected on the corona, gaining energy (up-scattered) from relativistic electrons

➙ X-ray emission good tracer of AGN

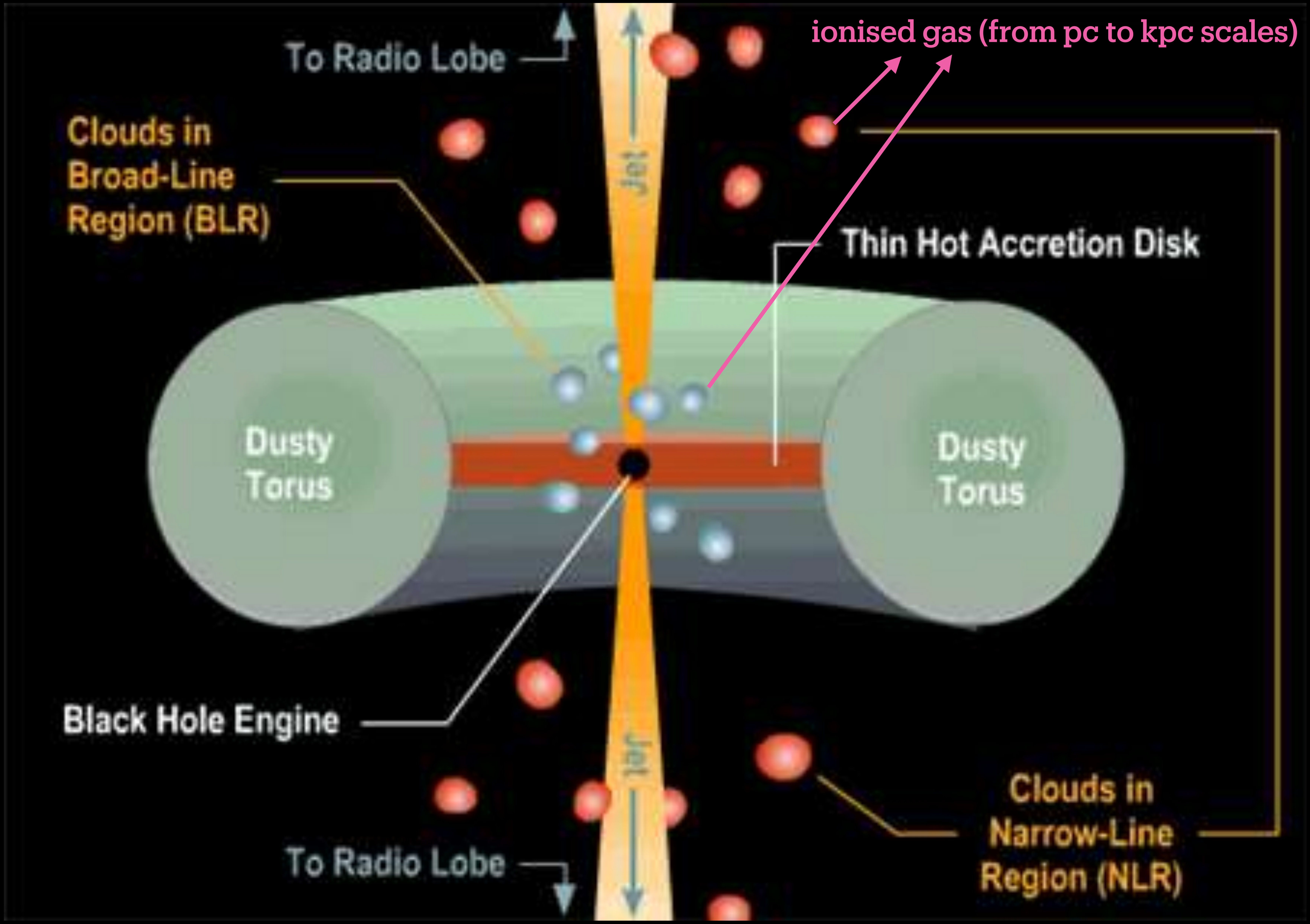
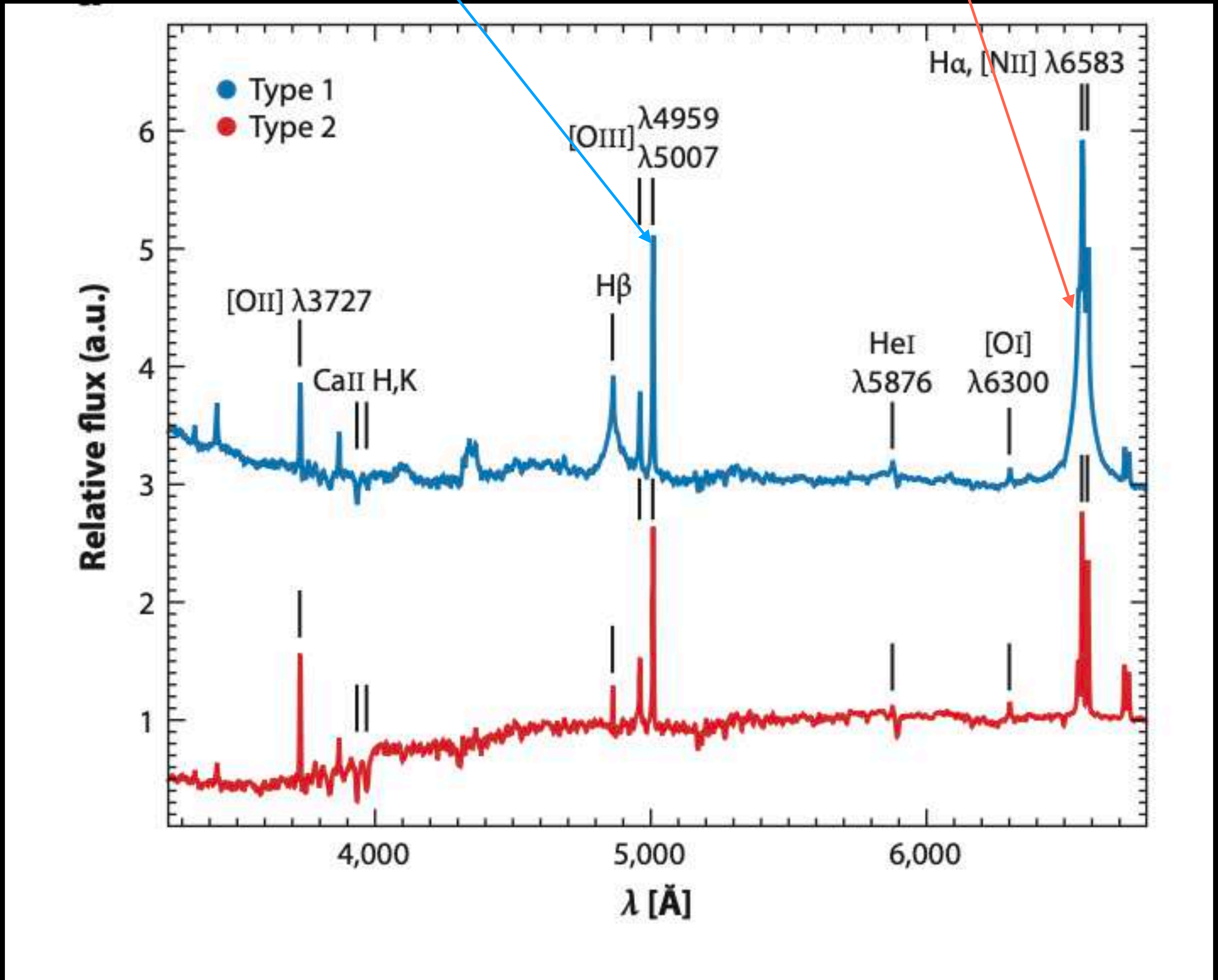


Image credit: Brooks/Cole Thomson Learning)

Gas clouds ionised by the AGN

only narrow forbidden lines
(with critical density 10^6 cm^{-3})

broad permitted lines



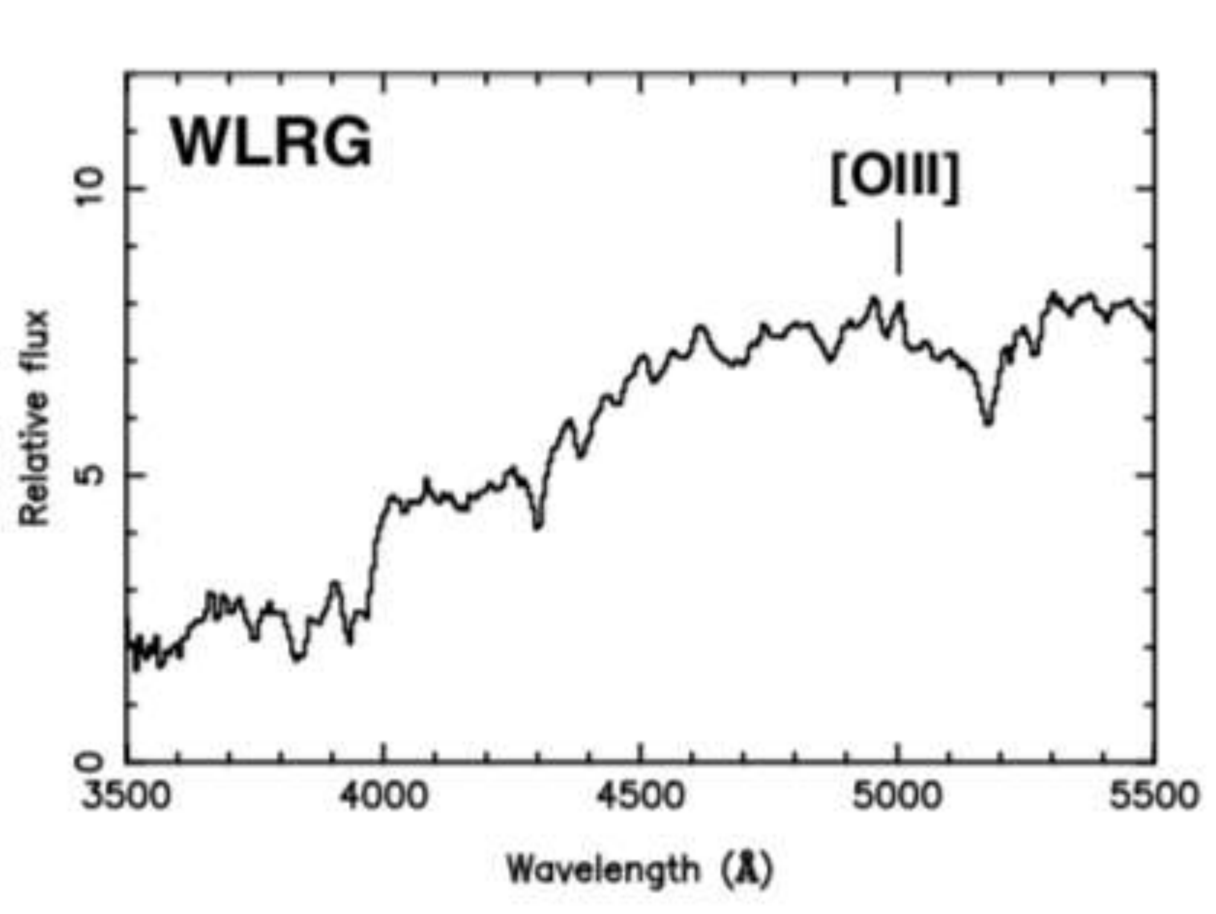
Hickox & Alexander 2018 review ARAA
adapted from Di Pompeo et al. 2018

Broad line Region (BLR)
- size of the region <0.1 pc
- density >10^8 cm^{-3}
- high velocity dispersion (>1000 km/s)

Narrow line Region (NLR)
- size ~100 pc (but can also be extended to several kpc)
- density ~10^{2-4} cm^{-3}
- galactic velocity dispersion (<100 km/s), but they can be disturbed by the interaction with the radio plasma

but their width can be increased if disturbed kinematics of the gas, e.g. shocks

Low efficiency AGN have weaker lines
(different line ratios)



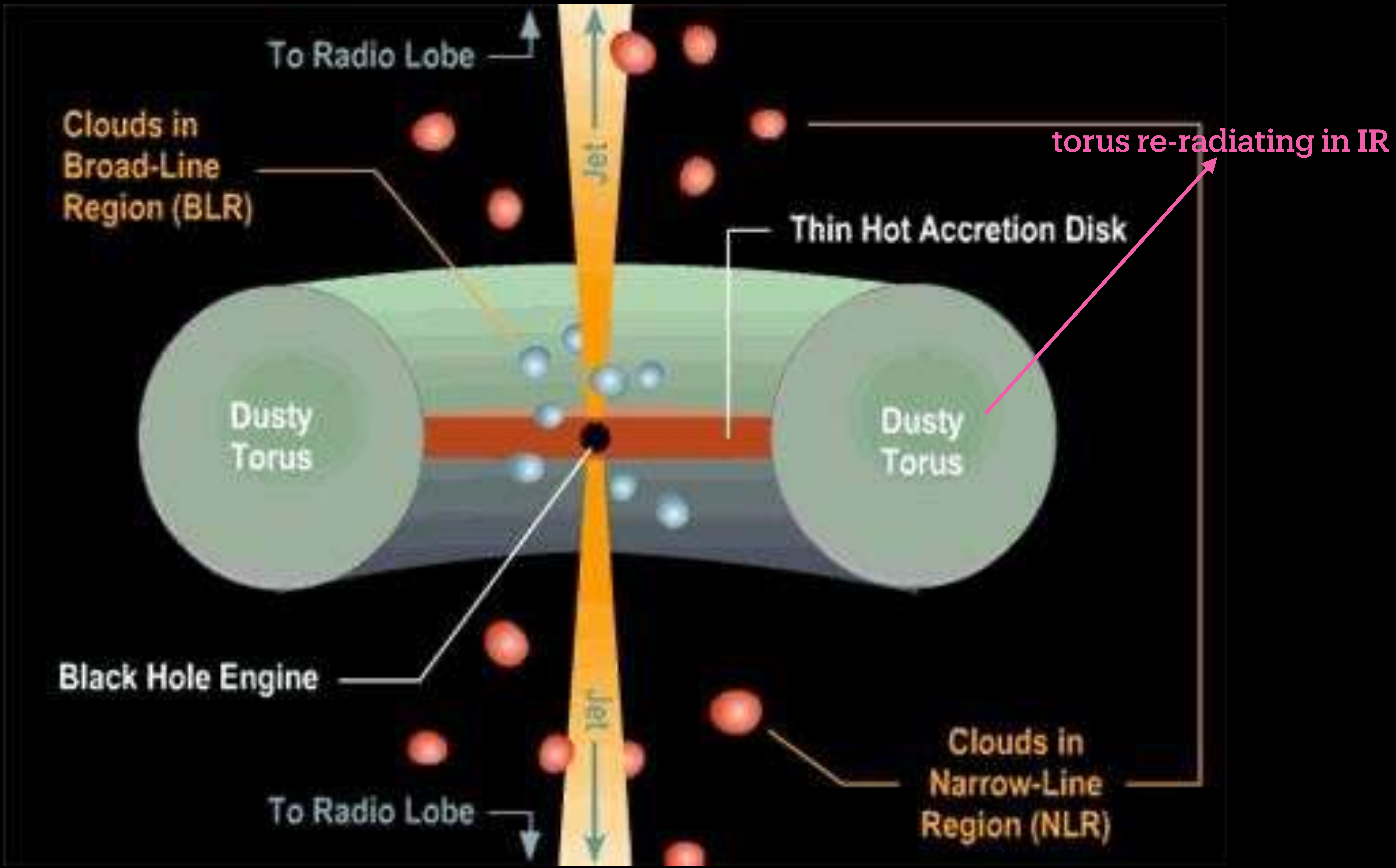
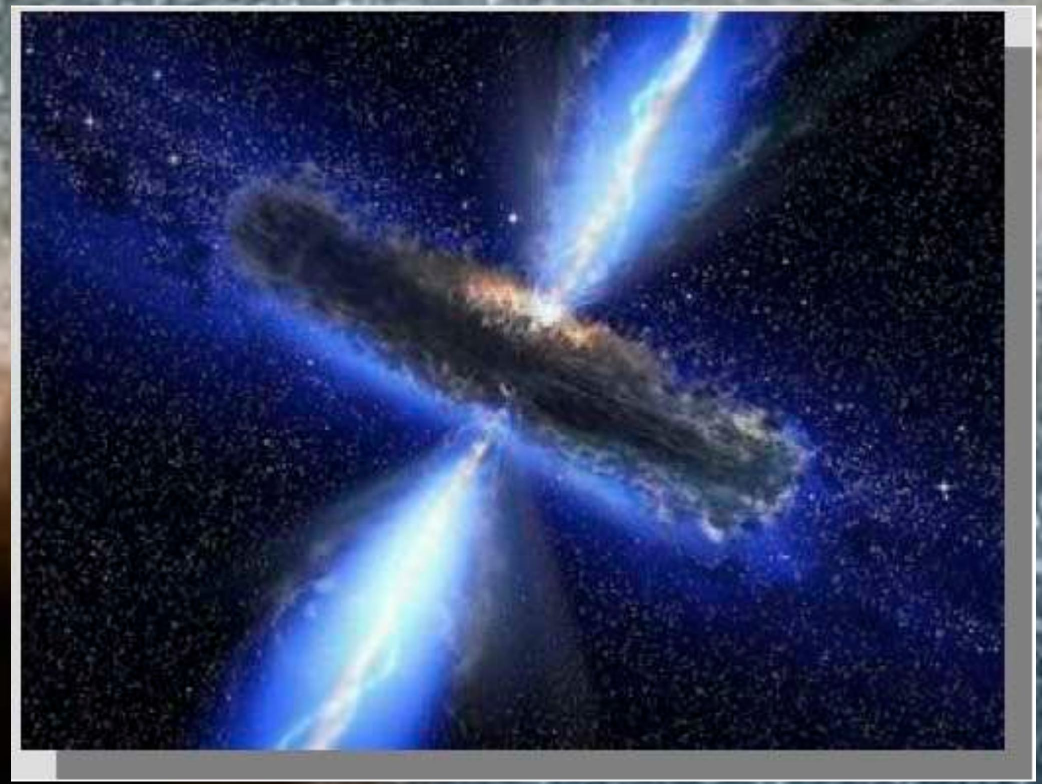


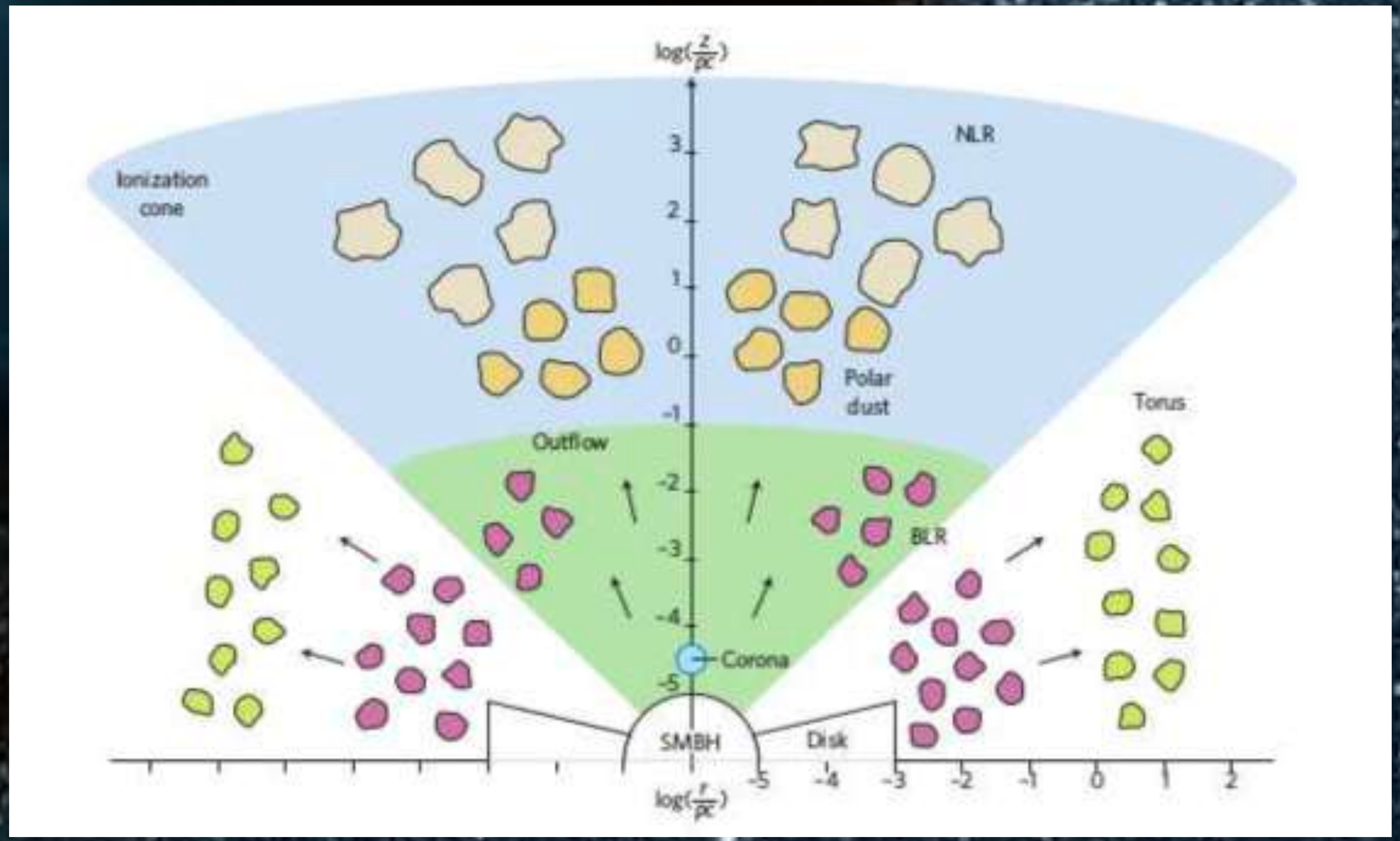
Image credit: Brooks/Cole Thomson Learning)

Obscuring torus

(but also re-radiating)



"unified model" of AGN, Antonucci & Miller 1985
From donuts structure (mainly to obscure the BLR - column density needed at least 10^{23} cm^{-2})...



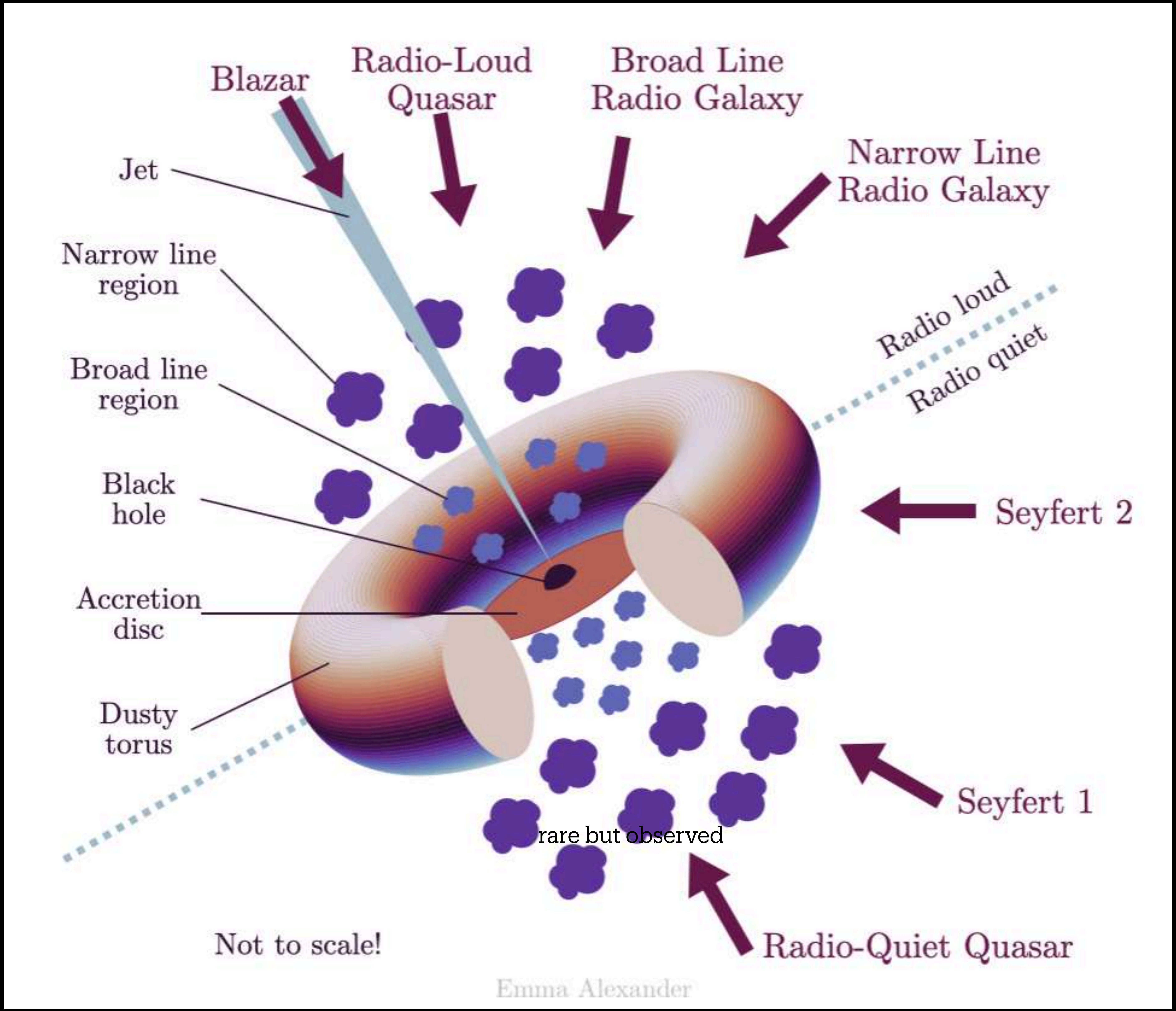
...to clumpy structure (Nenkova et al. 2002)
overview in Ramos Almeida & Ricci (2017) to ....

Relatively high velocity dispersion (50-100 km/s) to maintain the thickness, has to be clumpy otherwise at these velocities the temperature is too high (~10^6K) for the dust to survive.

NASA/JPL-Caltech

The “zoo” of AGN

see Padovani 2017 for an overview



Large variety of AGN due to:

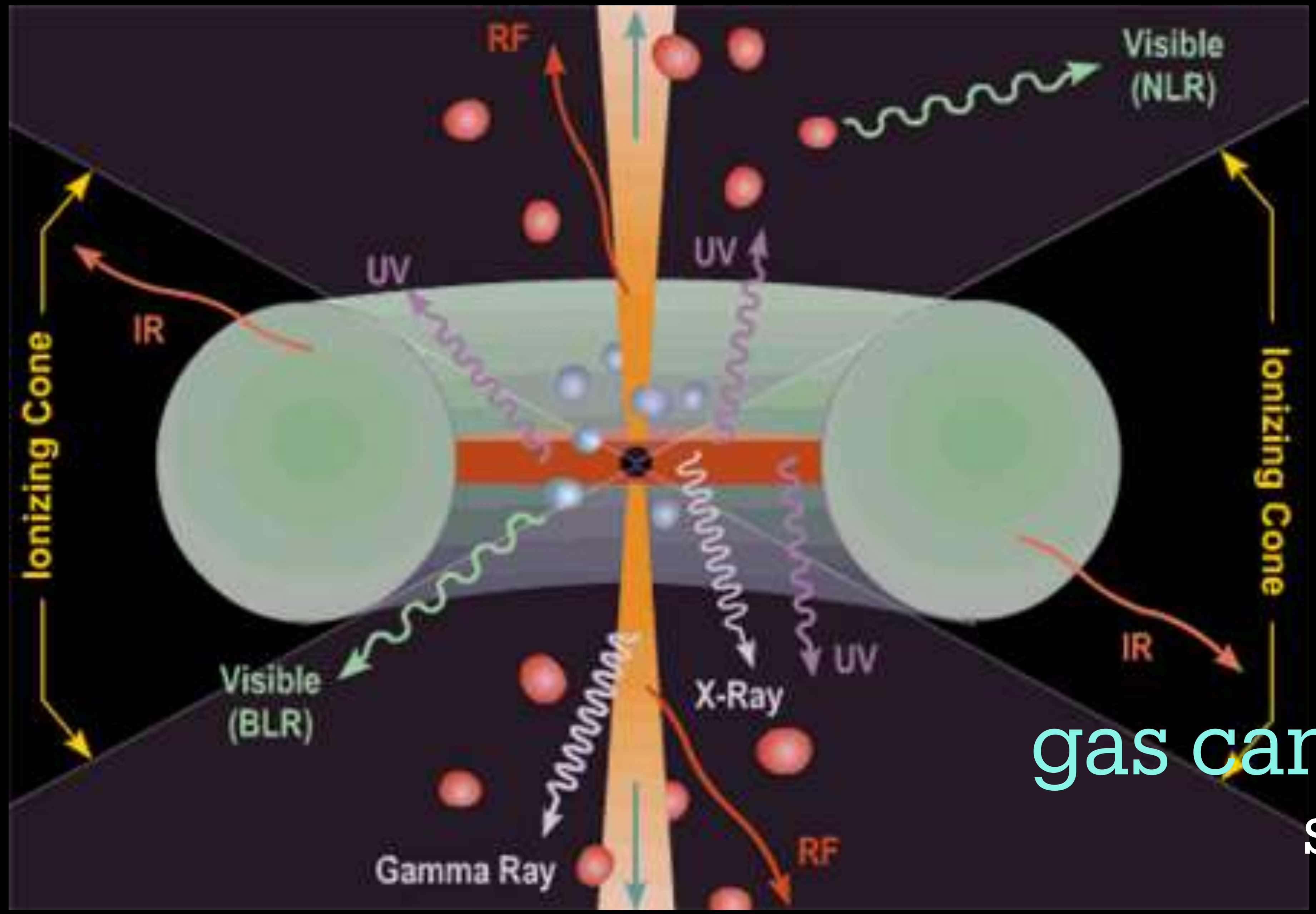
➡ efficient vs inefficient (optical/radio)

➡ obscuration and orientation effects: unified schemes

➡ this is why in different wavebands different types of AGN are selected

Are you still with me?

signatures of an active nucleus



from corona (above accretion disc): X-ray emission
(and from beginning of the jet high energy in general e.g. gamma)

from accretion disc: UV emission which can ionised gas clouds (up to kpc scales)

gas can be ionised: broad (permitted) emission lines from the pc region
strong forbidden emission lines (extended up to kpc scales)

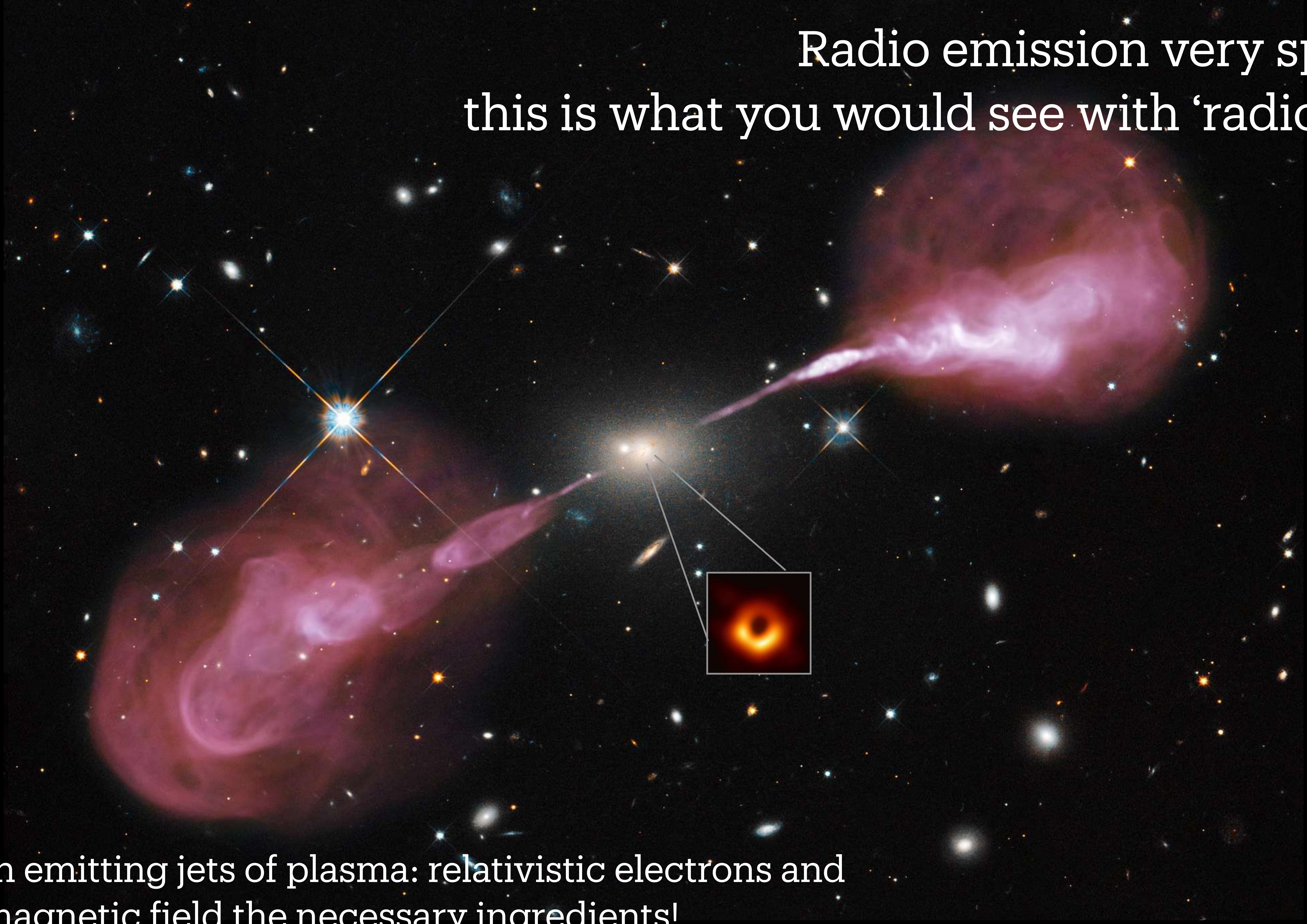
dusty torus absorbing and re-radiating (in IR) and making some of the radiation anisotropic

how about the radio?

The radio is a class apart!

f) Radio emission in galaxies: origin and how to recognise a radio AGN

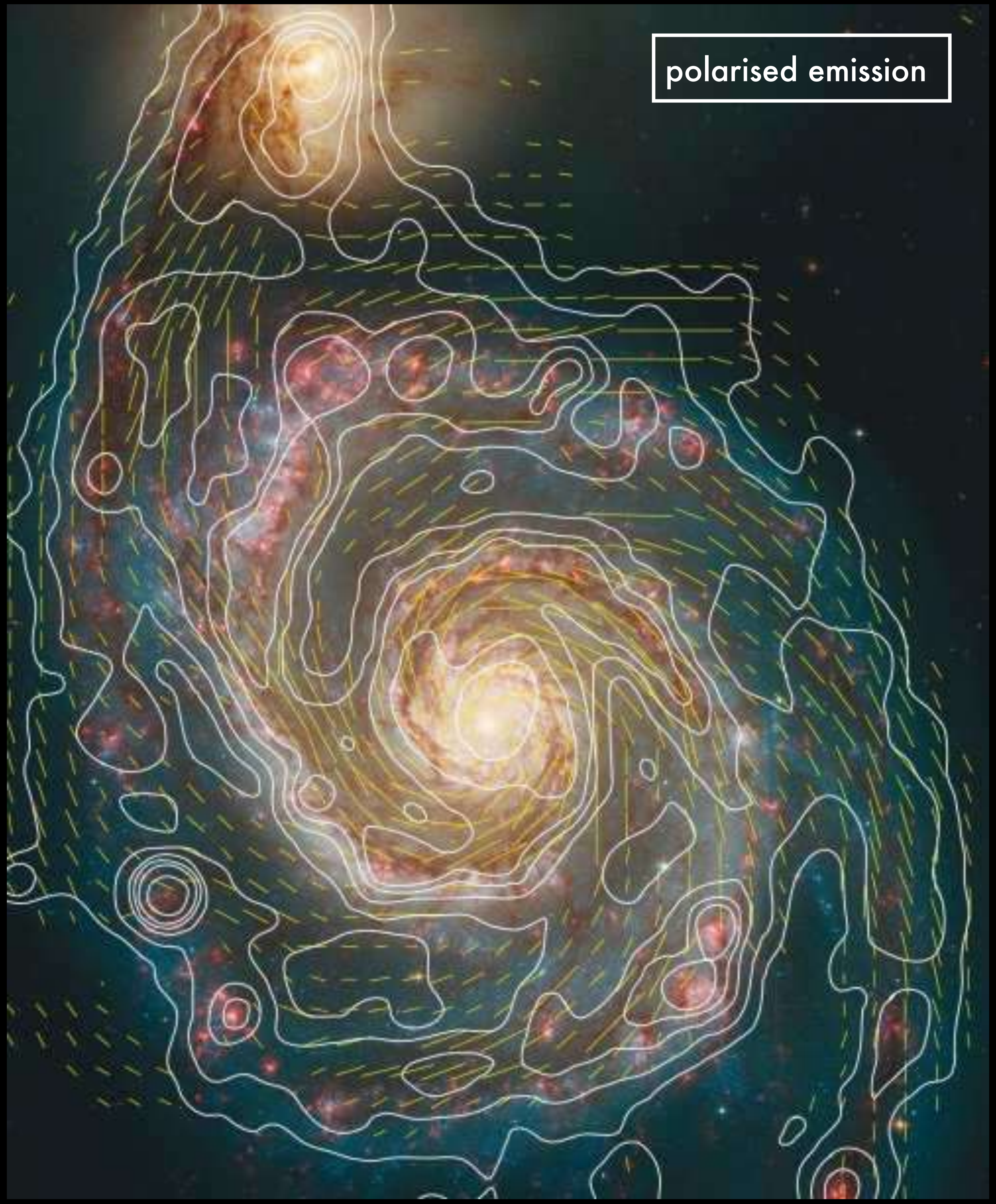
Radio emission very special: this is what you would see with ‘radio”eyes!



R. Perley and W. Cotton (NRAO/AUI/NSF),S. Baum and C. O'Dea (RIT),, and the Hubble Heritage Team (STScI/AURA)

an AGN can emitting jets of plasma: relativistic electrons and magnetic field the necessary ingredients!

Radio emission mechanisms: “normal” galaxies

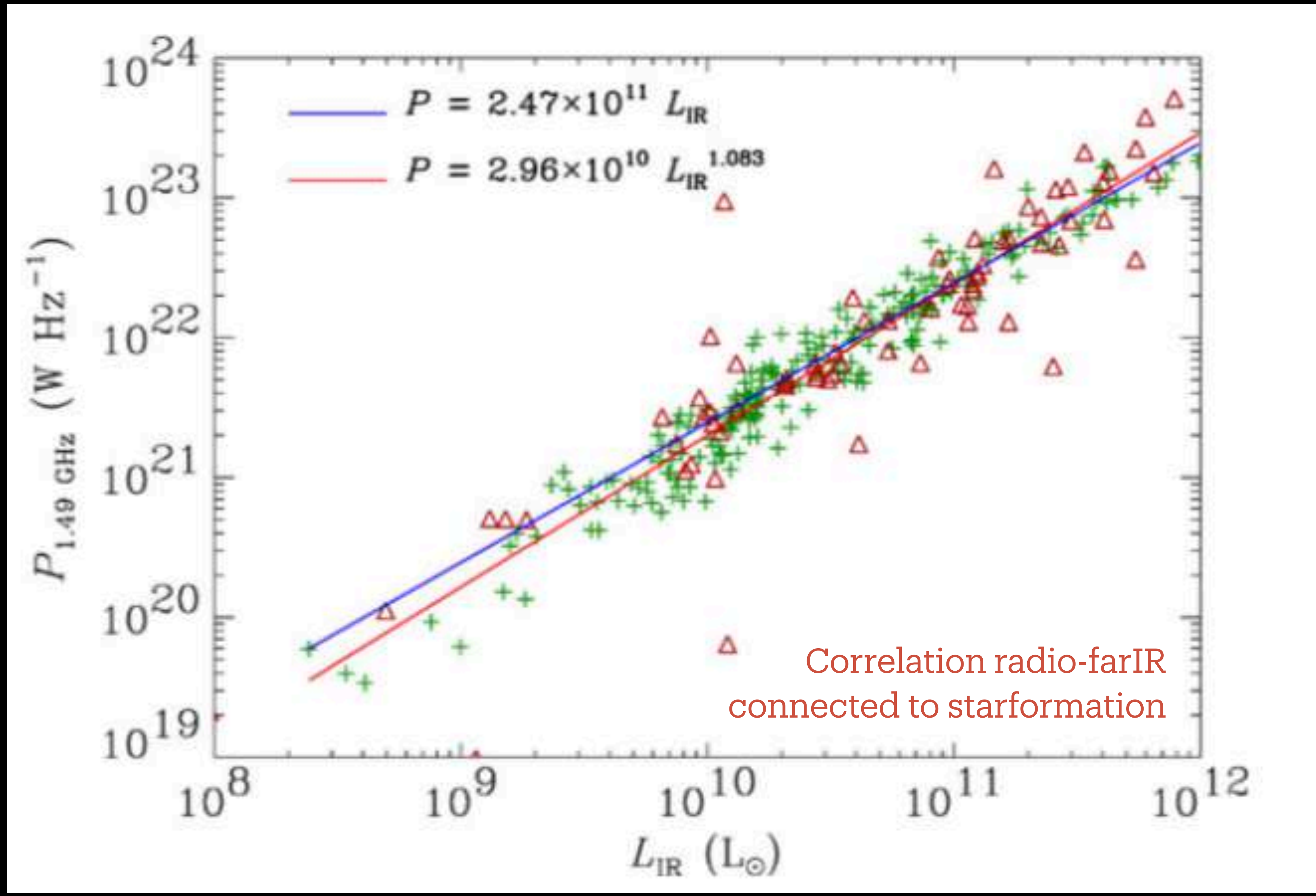


M51 at 48-GHz from VLA and Effelsberg 100-m

Massive stars can be responsible for the radio emission in two ways:
- the **ionising photons that they emit produce the thermal (free-free) radio emission** in HII regions
- supernovae (SN) whose remnants accelerate Cosmic Rays Electrons (CREs) **emitting radio synchrotron emission** on their way through the interstellar magnetic field.

Condon J. ARA&A 1992

From the radio emission the SFR can be derived IF no contribution of the AGN is present

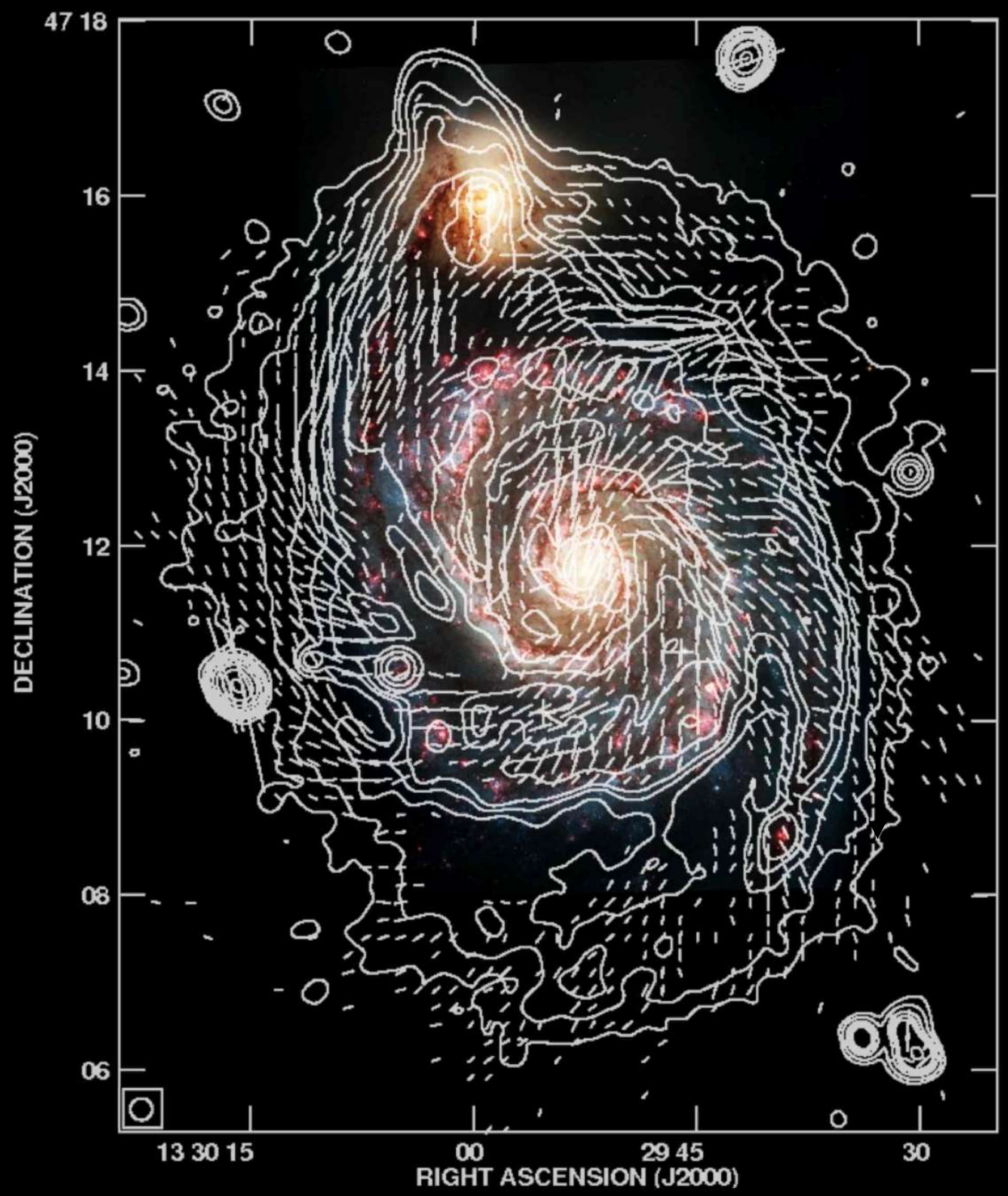


Morphology ➙ following the stellar distribution

Also line emission - in particular 21 cm HI and molecular gas (ALMA)

Radio emission in galaxies

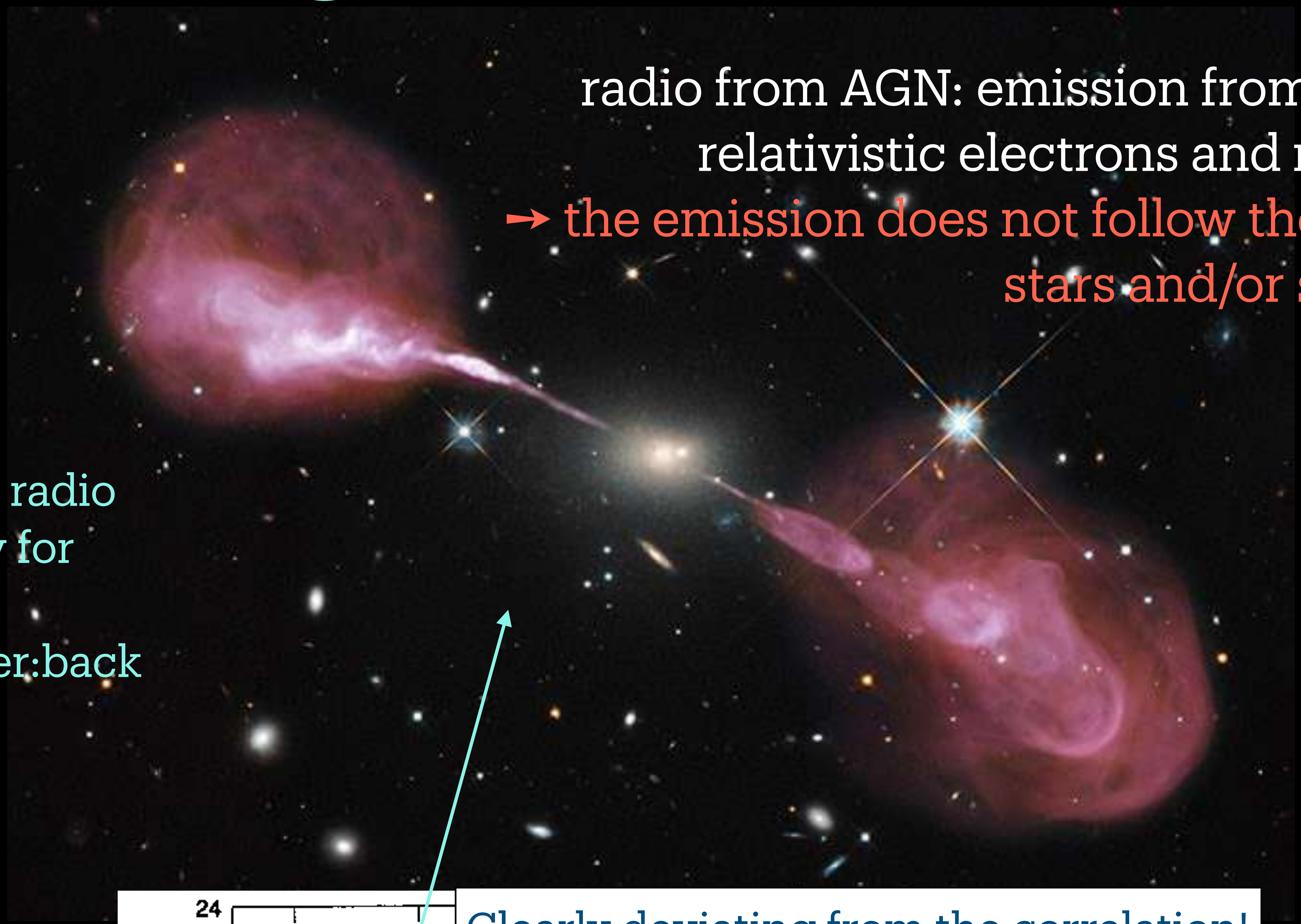
radio from starformation

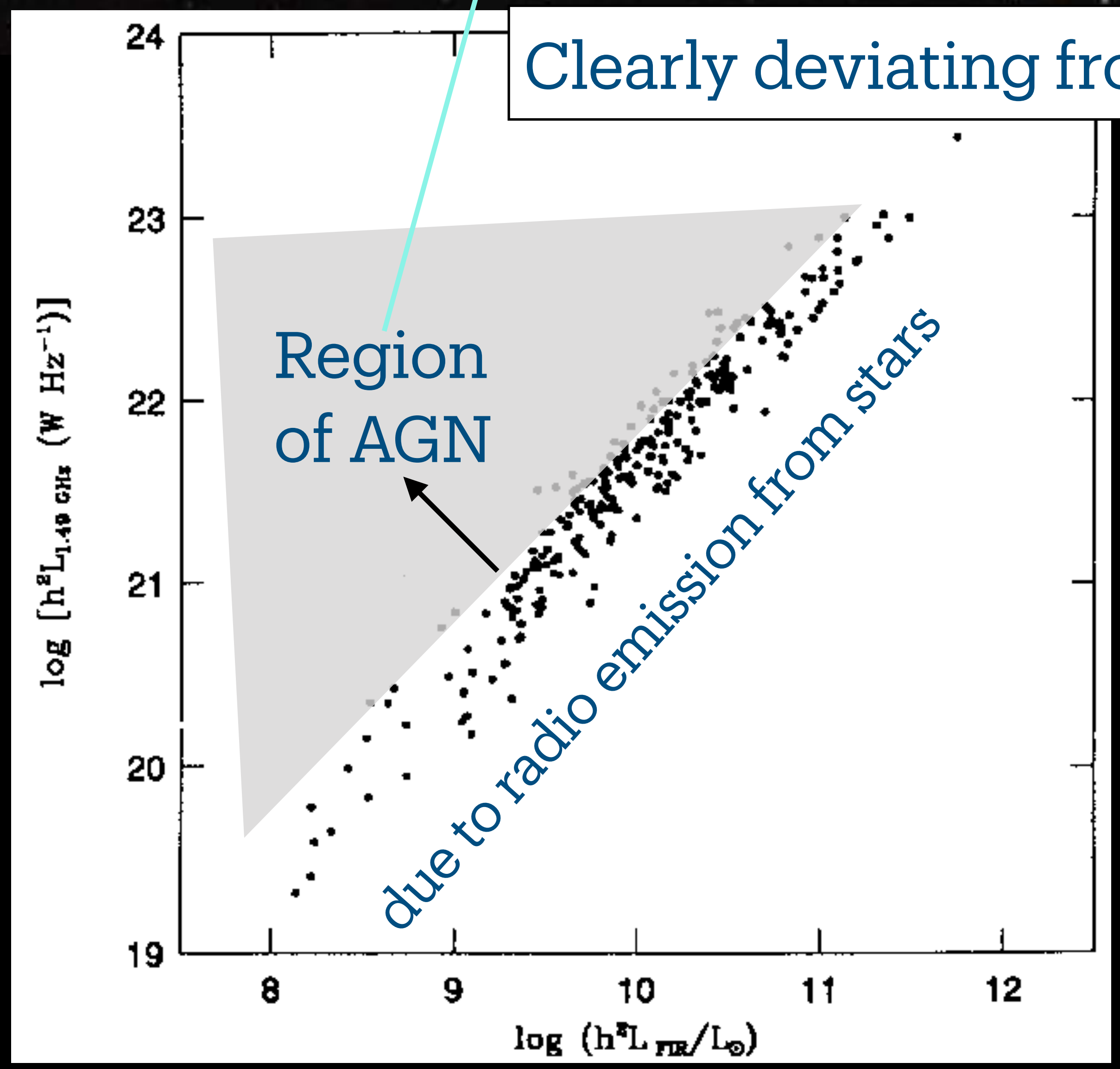


How to establish the radio is from an AGN: easy for the radio loud, more difficult for the fainter:back to this at the end!

radio from AGN: emission from synchrotron, relativistic electrons and magnetic field

➙ the emission does not follow the regions with stars and/or star formation





FIR-radio correlation (Condon 1992)

➙ the emission follows the regions with stars and/or star formation

AGN they are often separated in radio loud and radio quiet

$$R = F_{\nu_r}/F_\nu(4400\AA)$$

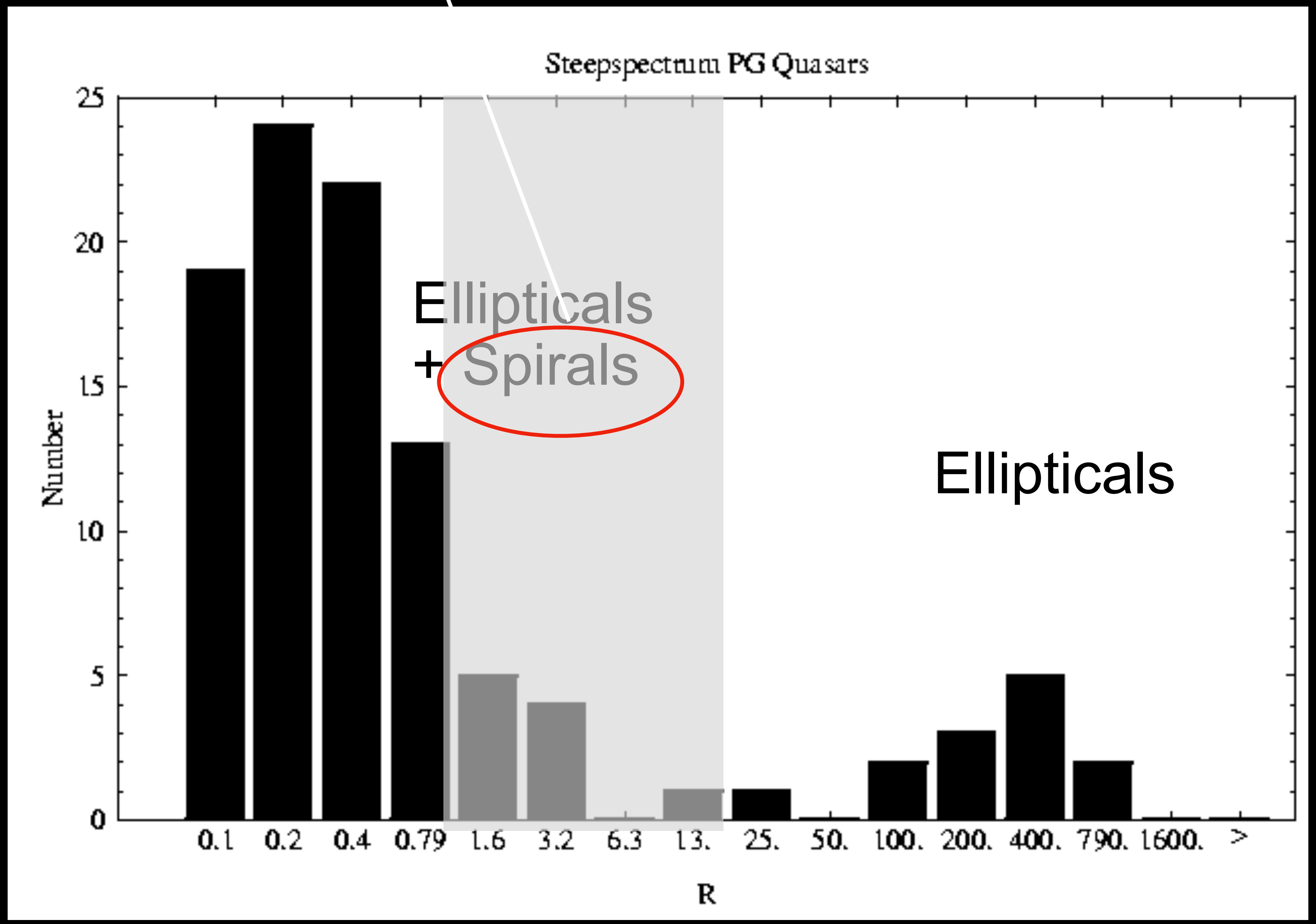
or in term of luminosity

$$R = L_{5GHz}/L_B$$

Radio-quiet objects show values of R concentrated between 0.1-1, while in radio-loud sources the R values range from 10 to 100 (Kellerman et al. 1989)

can be a way to distinguish if the radio emission comes (mainly) from stars or from AGN
BUT can also be misleading: radio quiet doesn't mean radio silent!

spiral galaxies host only low radio luminosity (radio-quiet) AGN



radio-quiet radio-loud

R=radio/optical flux

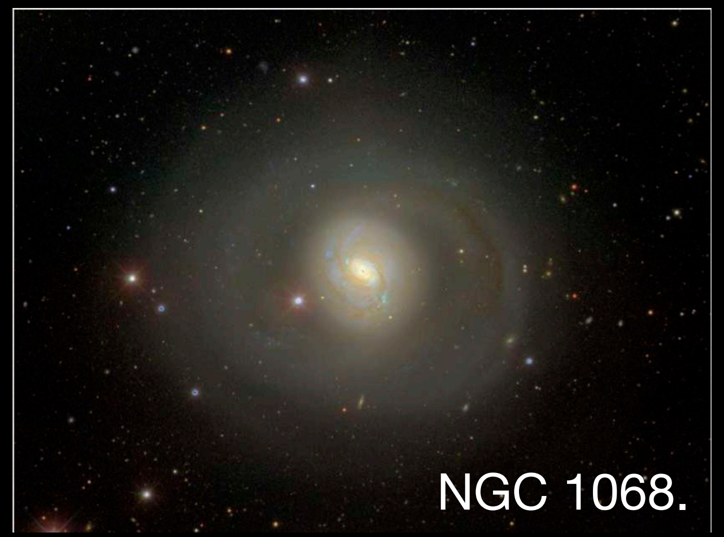
Kellermann et al. (1989)
Falcke, Sherwood, Patnaik (1996)

radio quiet AGN can have radio jets! ➝ see Les 2 & 3

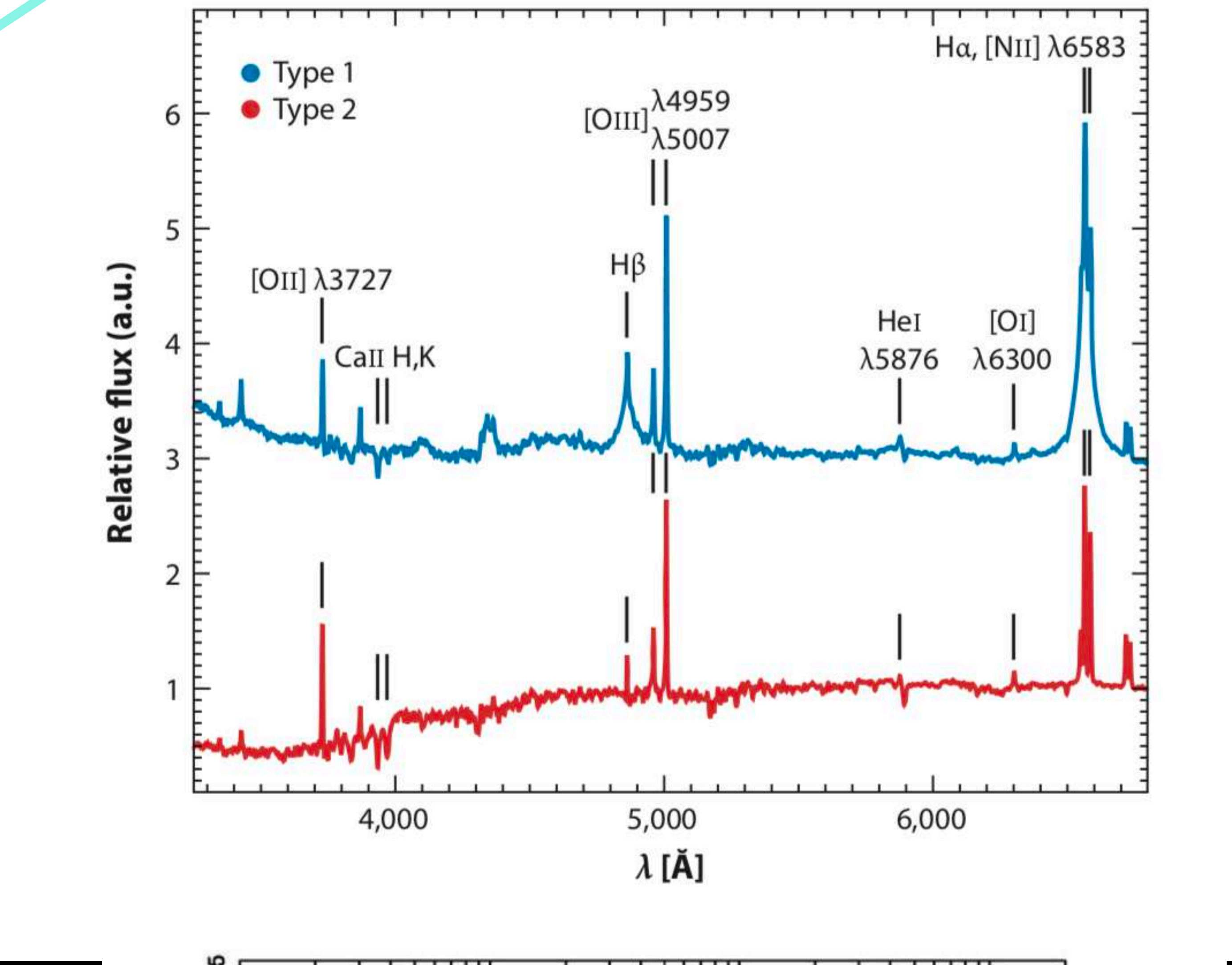
Les 2: main focus on radio-loud,
with a part on radio-quiet

(both relevant for AGN feedback - Les 3)

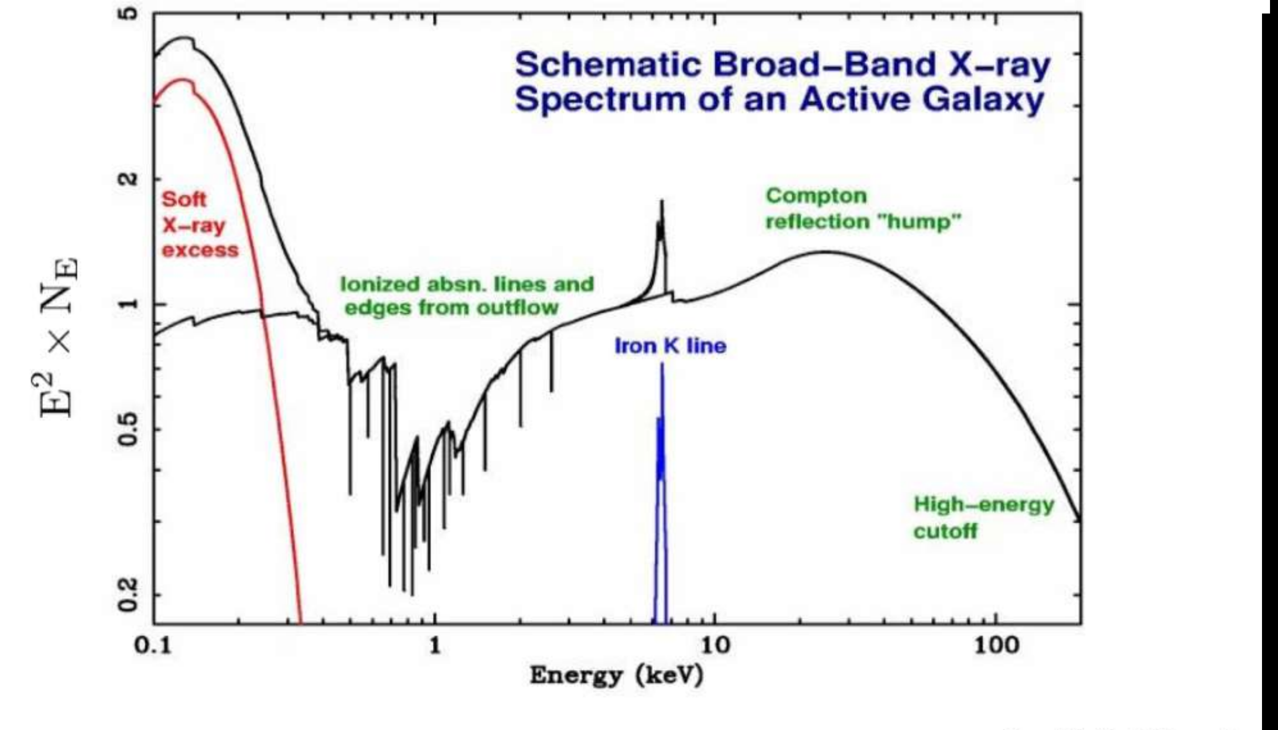
In summary: some of the signatures of an AGN



not all simultaneously present!



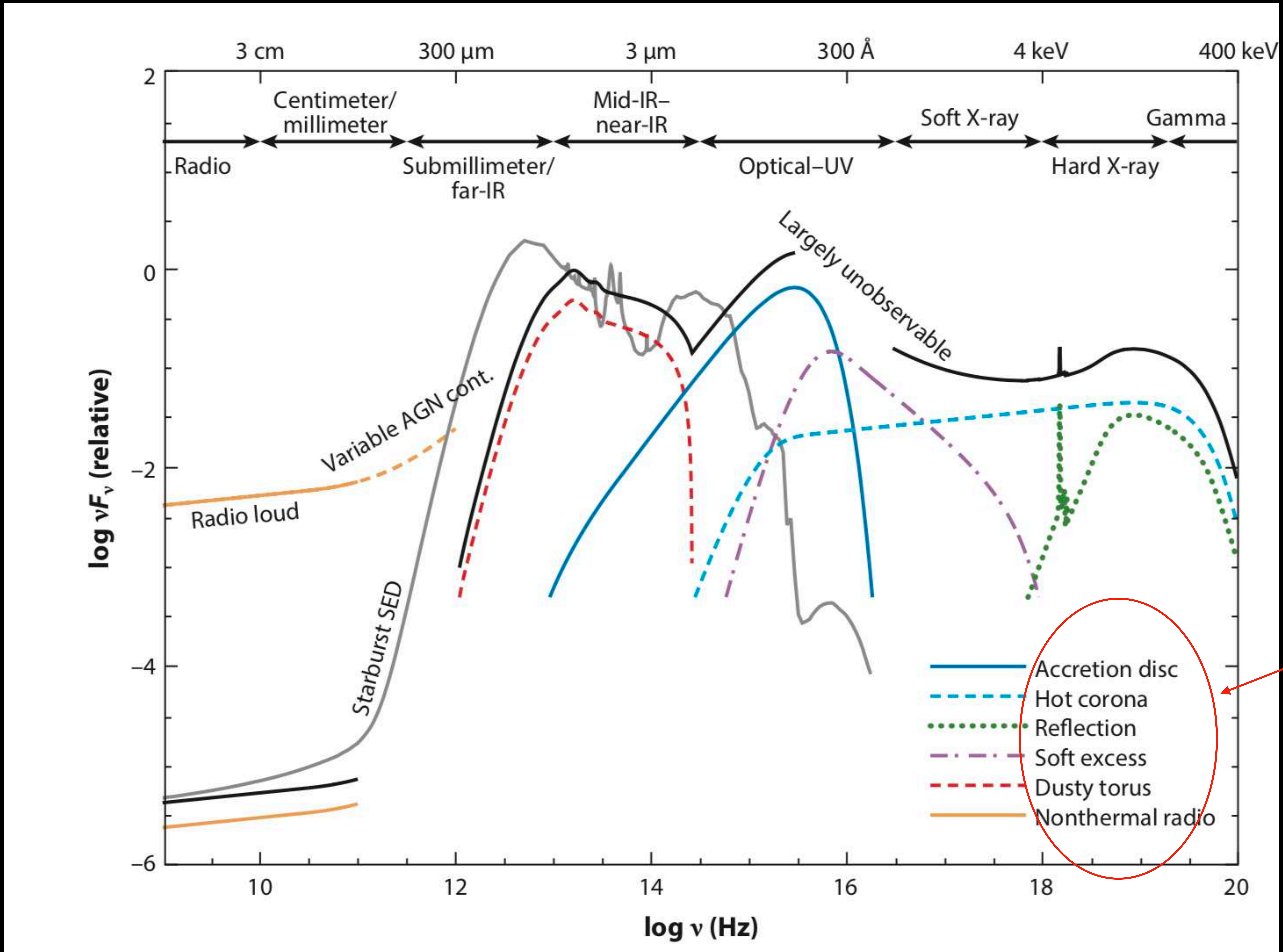
- Luminous UV emission from a compact region in the centre of galaxy
- Strong emission lines, sometimes highly Doppler-broadened
- High Variability on time-scales of days to months
- Strong Non-Thermal Emission
- X-ray, γ-ray and TeV-emission
- Cosmic Ray Production
- Compact Radio Core
- Extended linear radio structures (jets+hotspots)



Credit: Neil Brandt

because of this variety, AGN means different objects to different people...

Multiwavelengths phenomenon!



Structures/emission characteristics of (some)AGN

The properties of the continuum can be used to identify whether the galaxy hosts an AGN

Spectral energy distribution (SED)

Hickox & Alexander 2018

In summary...

- not much mass accretion required to make a SMBH active but not all SMBH are active. AGN phase short compared to life host galaxy: results of the interplay accretion - outflow? instabilities of the accretion disc? secular process? discrete accretion events?

- complex structure of the central regions of an active galaxy: every component (not only the SMBH) has a role in the resulting spectrum.

- emission can cover all wavebands ➙ different emission from different regions/structures

- some physical properties (e.g. spin of BH, accretion rate etc.) define the type of AGN observed (e.g. radiatively efficient vs inefficient AGN)

- radio from AGN very different in morphology compared to other manifestation of AGN non-thermal emission ➙ more in the next two lessons

- AGN means different objects to different people!!!