Active GALACTIC NUCLEI

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Lecture outline

- I. AGN BASICS
  - AGN definition
  - taxonomy
  - structure & unification models
  - radiation mechanisms
  - mass estimates
- II. AGN Physics & Observational COSMOLOGY
  - AGN surveys
  - AGN luminosity function & evolution
  - AGN/galaxy co-evolution (Magorrian relation)
  - Theoretical Models

AGN History

- Discovered 1943 C. Seyfert objects with prominent emision lines (the most prominent being NGC1068)

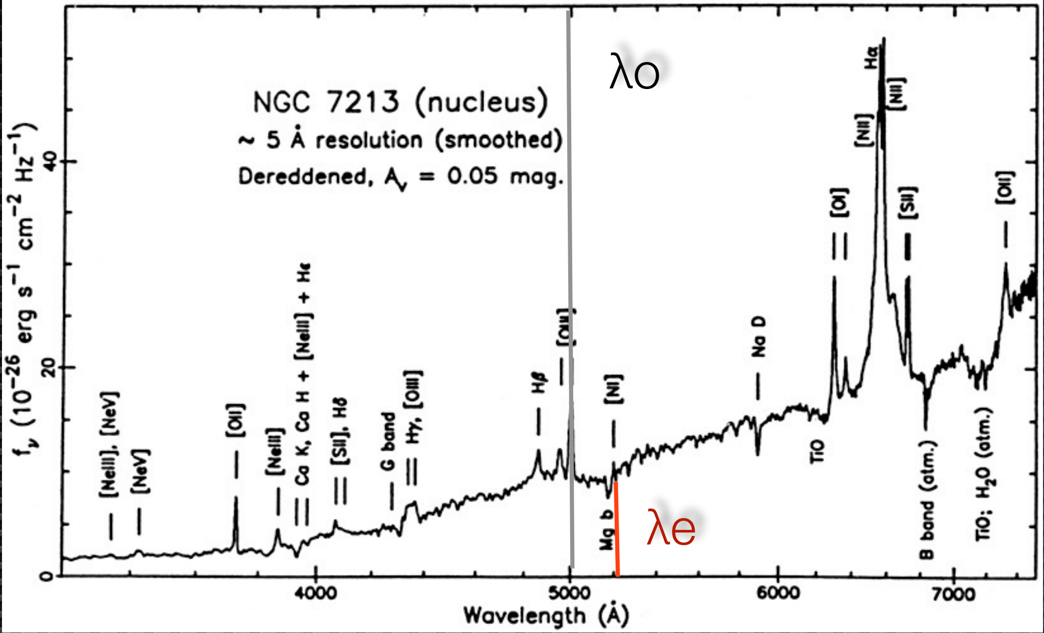
- 1963 M. Schmidt measures the redshift of the radio source ‘star’ 3C273 (z=0.158)

AGN characteristics

- very bright nucleus relative to the galaxy
- (sometimes only a point source QSOs - quasi -stellar -object)

The nearest AGN
NGC1068
(15 Mpc)

Redshift



Redshift z is defined as

$$1 + z = \lambda o / \lambda e$$

It is obtained from the spectrum where λo , λe are the observed and emitted wavelengths respectively

From the redshift we obtain the distance of the galaxy

Hubble law: $$r = c\ z / H_o$$

Emission Lines

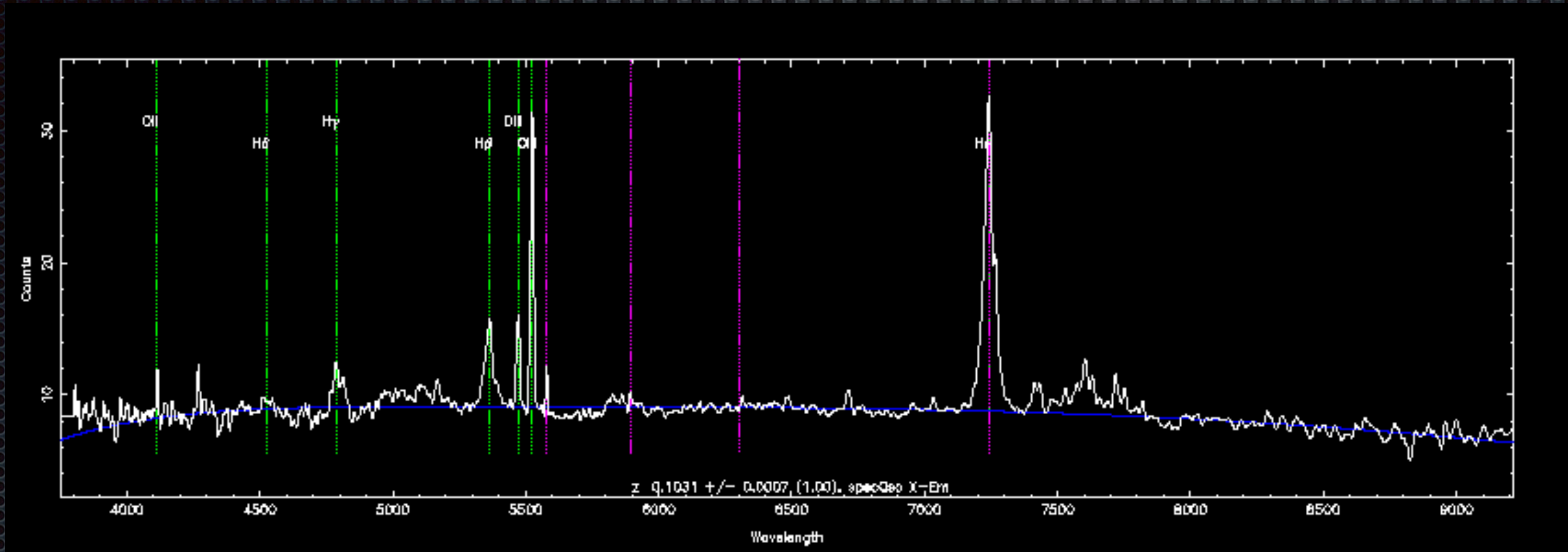
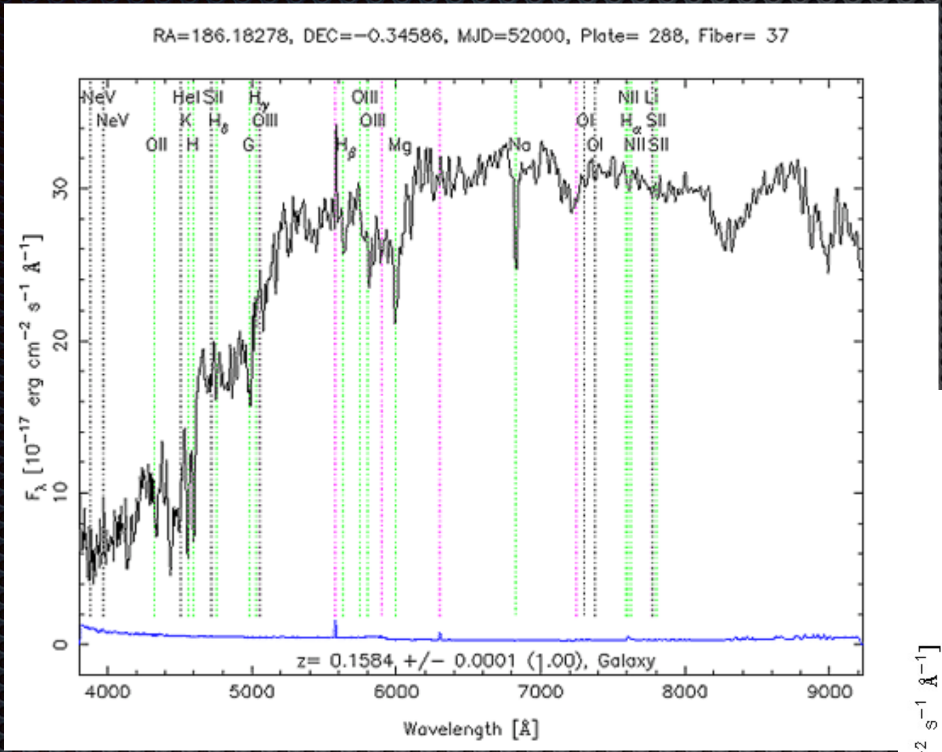
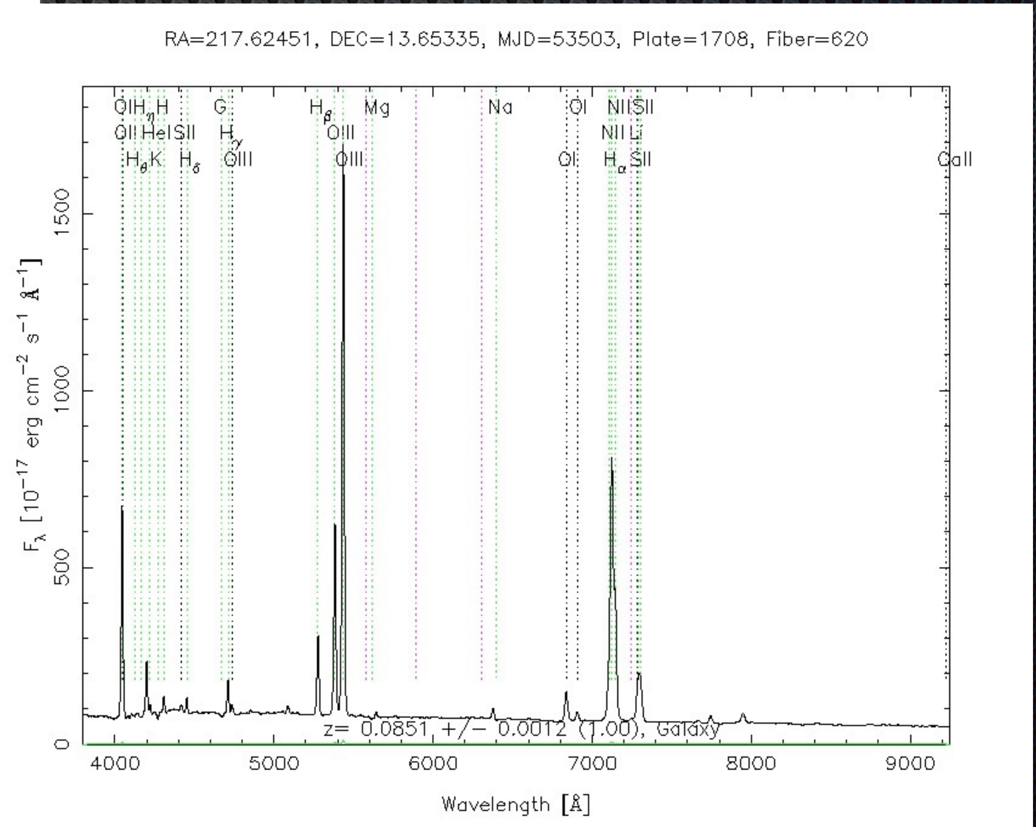


photo-ionization

Q. what other lines do we have ?

Comparison with Galaxy spectra





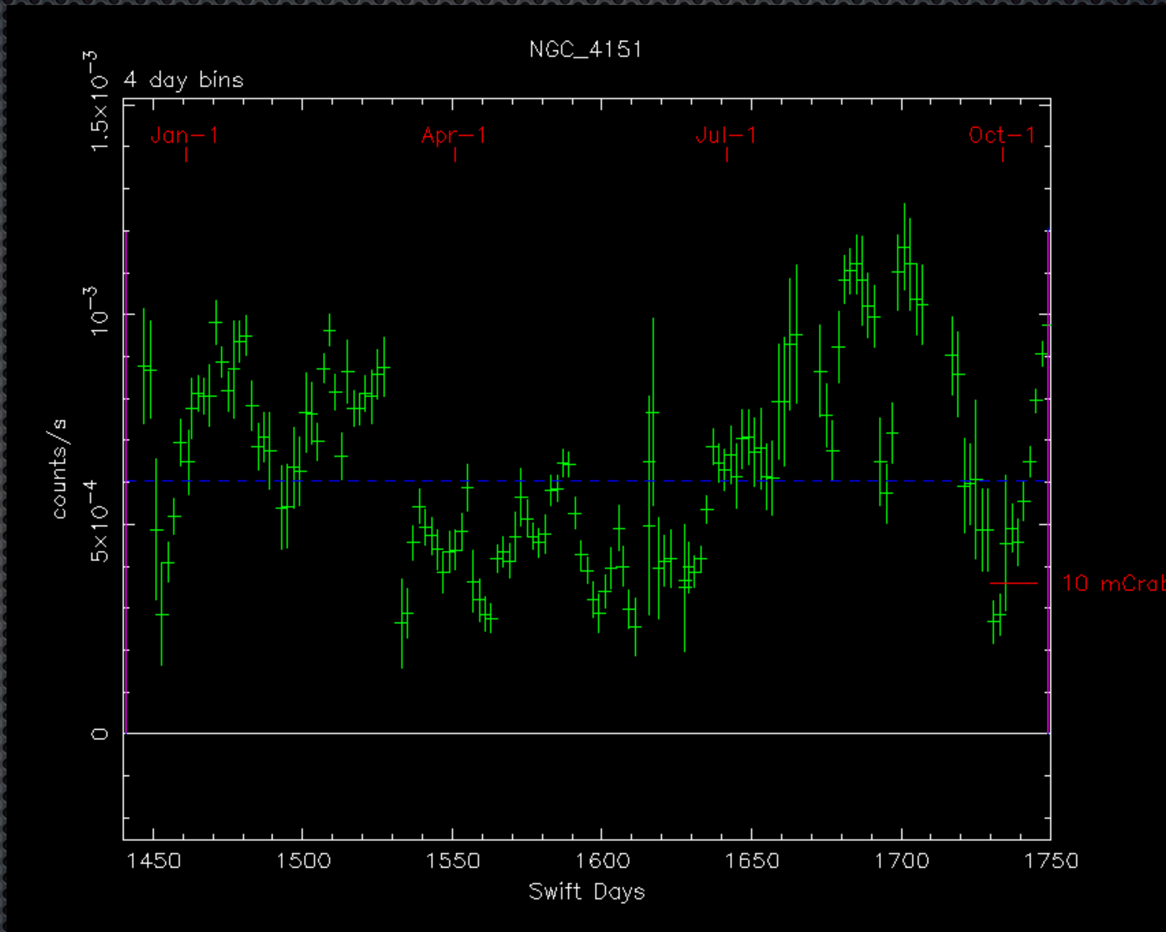
Most galaxies have absorption lines

Variability

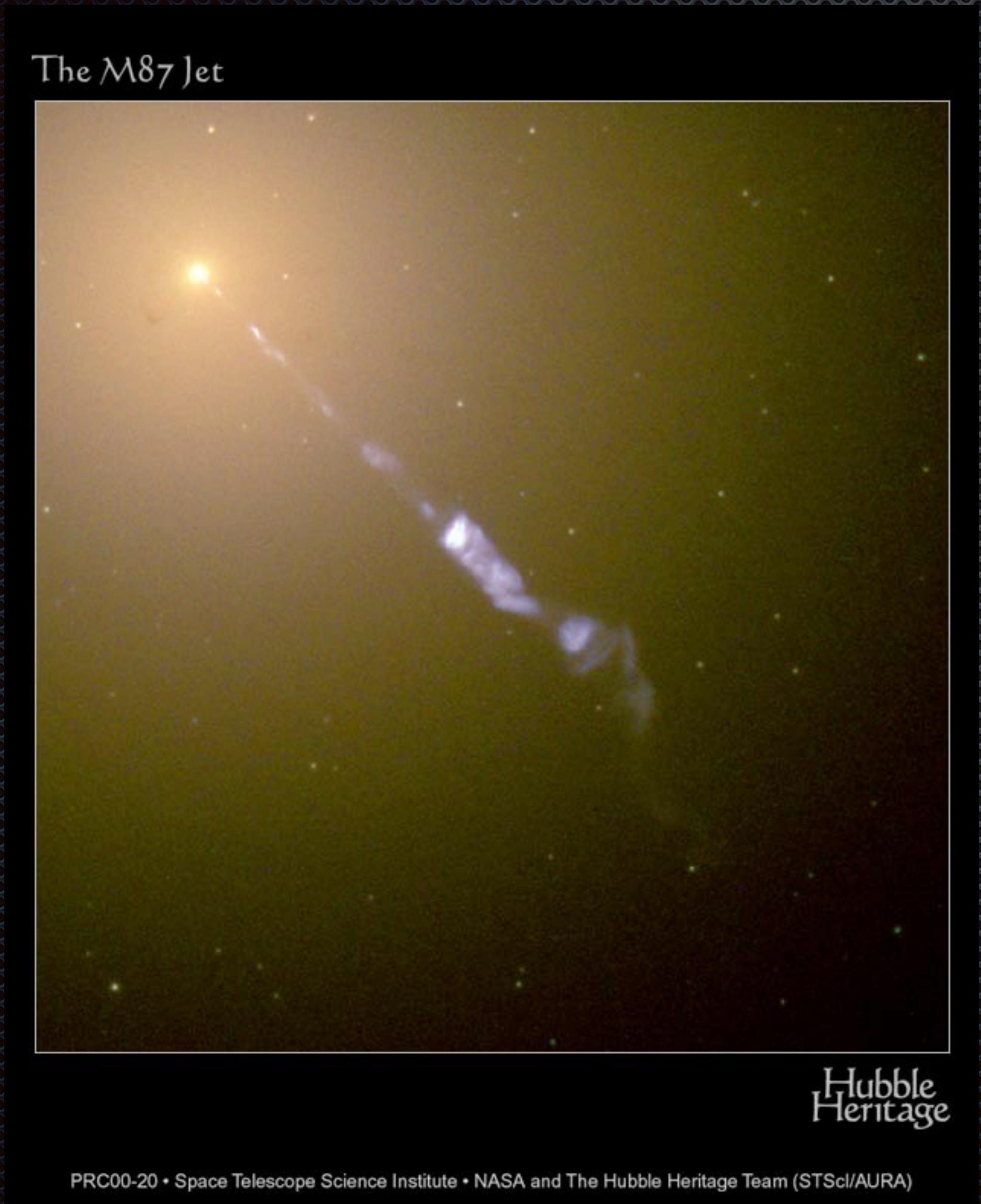
$r_S < c\,dt$

Schwarzild radius $r_S = 2GM/c^2$

$M/M_o = 10^{-3}\,dt$



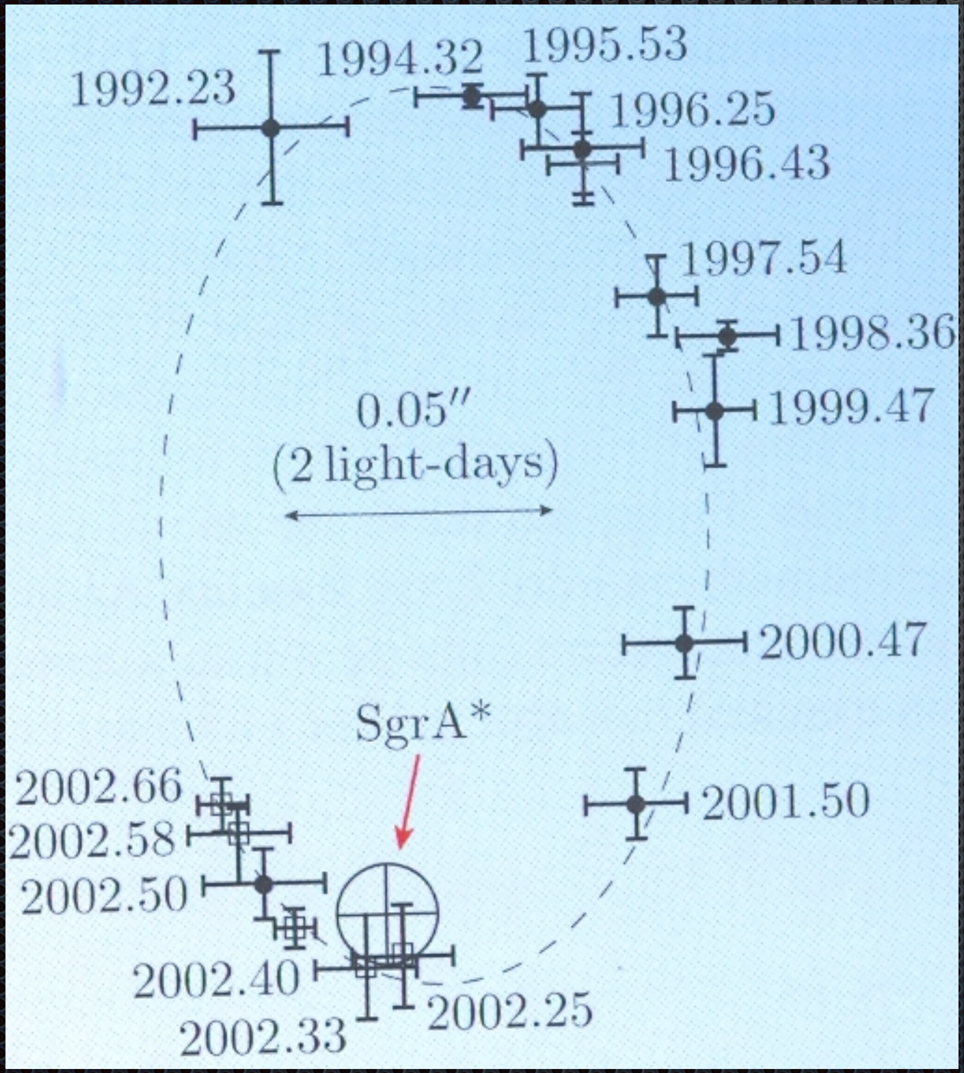
Radio emission



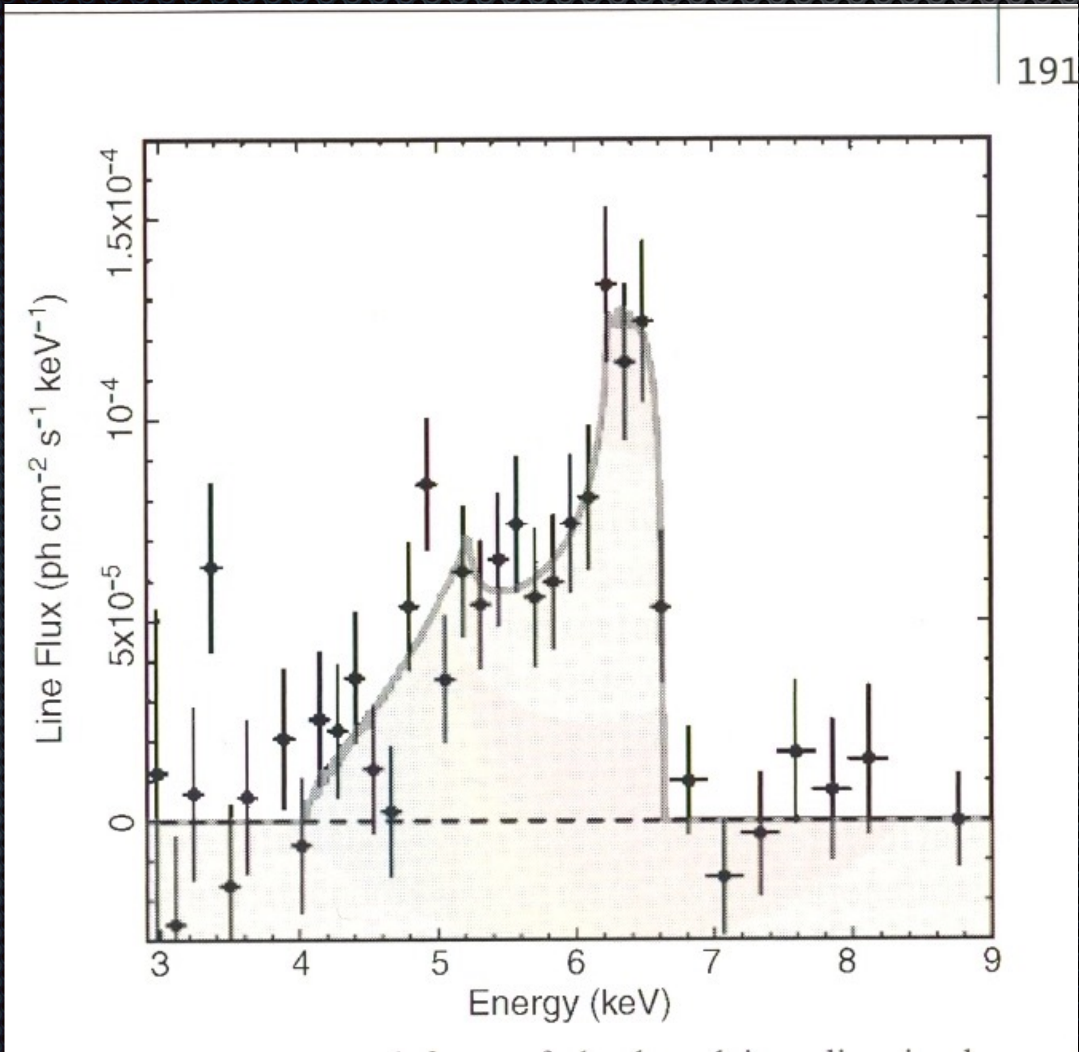
These jets extend up to Mpc scales, 100 times the size of the galaxy

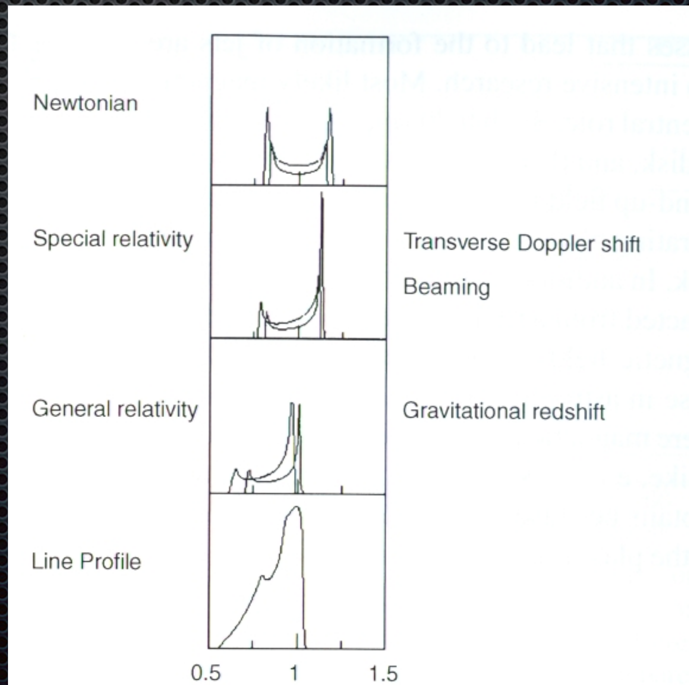
(energetic particles that emit through synchrotron emission)

why a black hole I ?

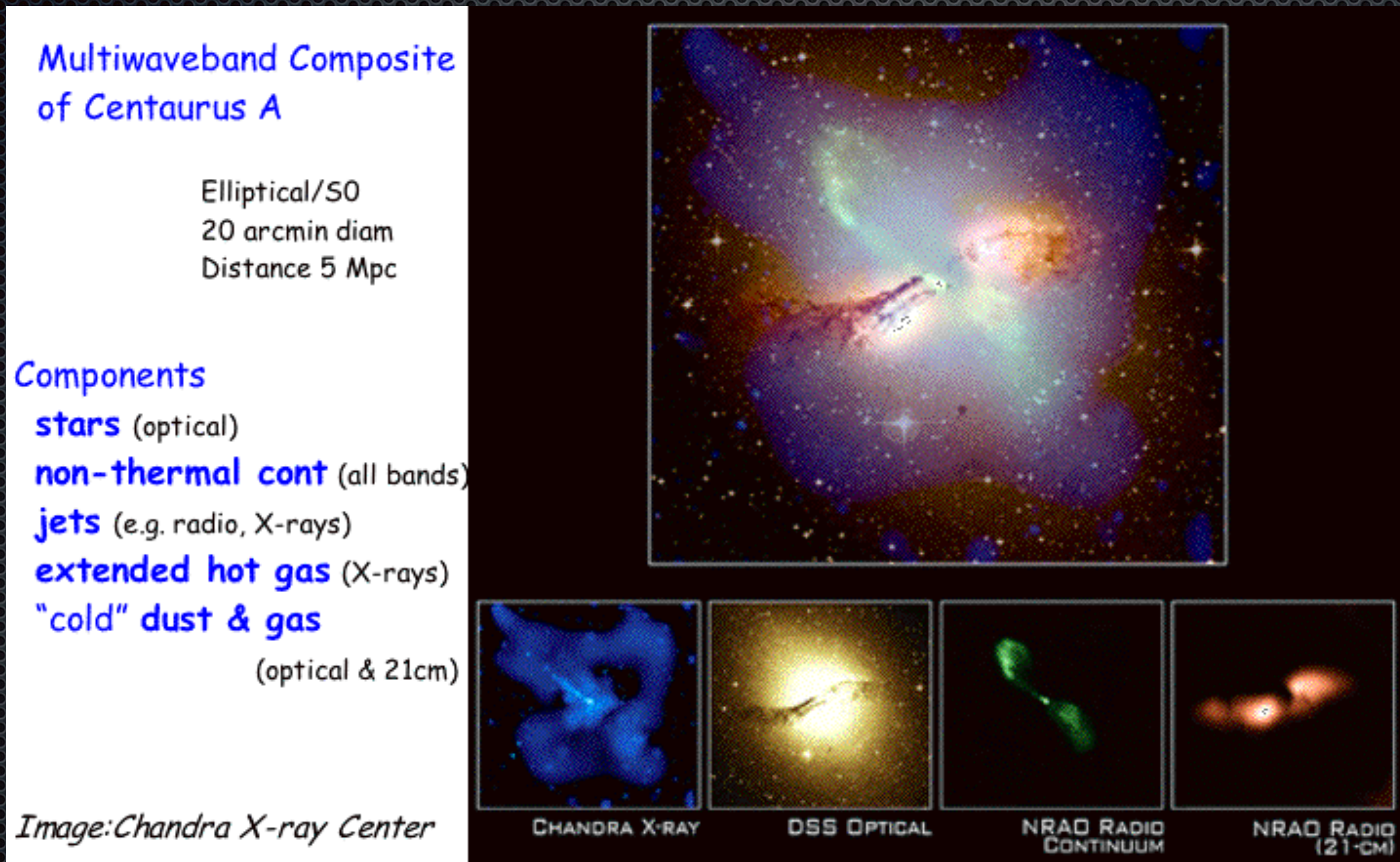


why a black hole II ?





A nearby AGN (Cen-A) in many wavelengths

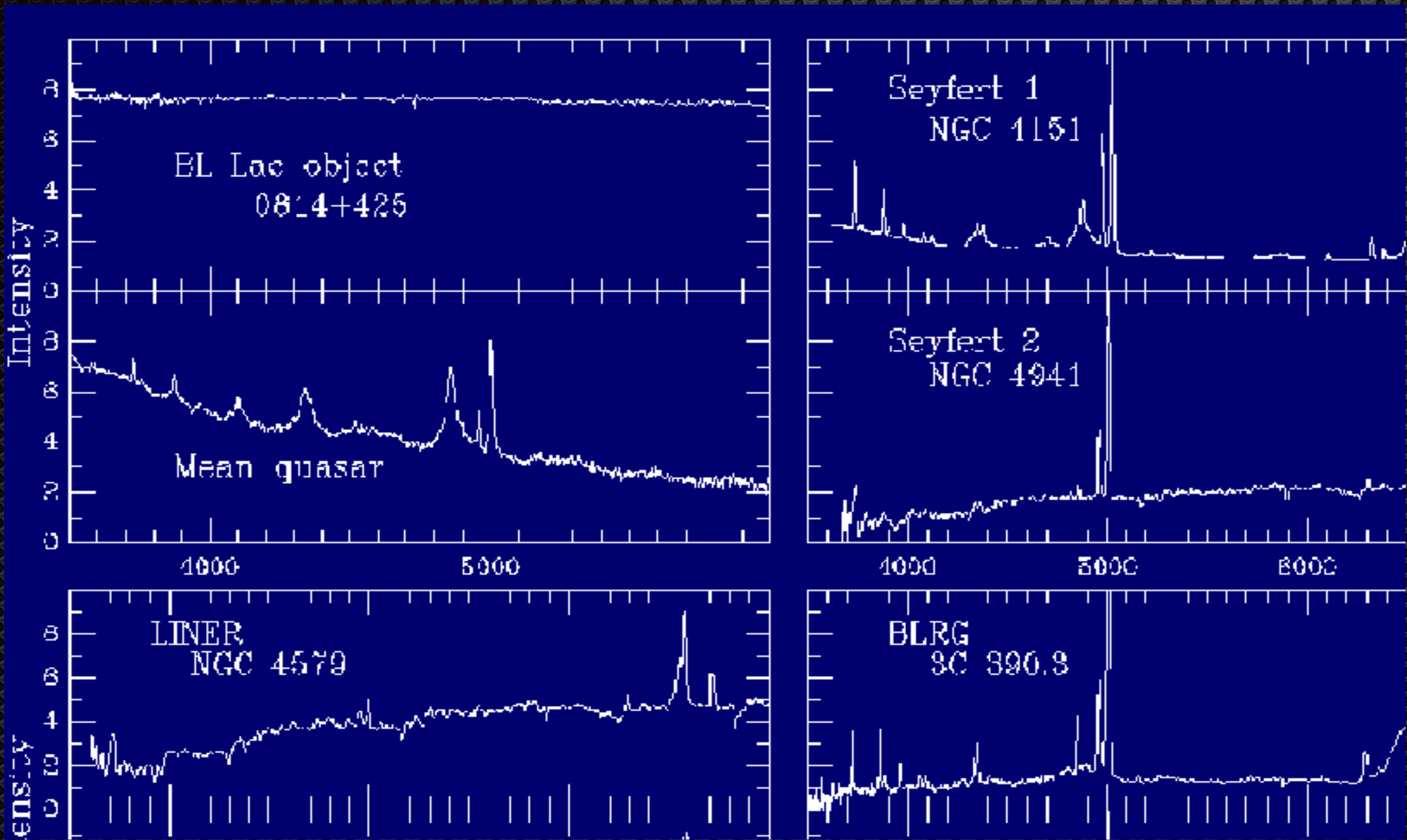


taxonomy

- QSOs (quasi-stellar object) $M_B<-23$
- Seyfert-galaxies (seyfert-1 broad-emission lines, seyfert-2 narrow emission lines)
- Blazars radio-loud AGN (>10^{25} W/Hz-1)

	strong jet	weak jet
rad. eff.	FRII	type-1, 2
rad. ineff.	FRI BLLac	LINERS

AGN classification



Type-1 AGN(eg Seyfert-1): Broad and narrow lines OPTICAL

Type-2 (eg Seyfert-2): Only narrow lines OPTICAL

The width of the lines reflects grav. potential

broad lines (BLR) ~5000 km s-1

narrow lines (NLR) ~500 km s-1

The width of the lines could be either from

a) velocity

b) thermal $kT \sim \upsilon^2 m_p$

if thermal 5000 km s-1 gives 10^9 K

broad lines are formed in distances 10^{16-17} cm

narrow lines 10^{18-20} cm

AGN structure

BLR

NLR

The Unified Model

Supermassive black hole (10^6-$10^{10} M_\odot$)

$M = 10^8 M_\odot \Rightarrow R_G \sim 3\times10^{13}$ cm.

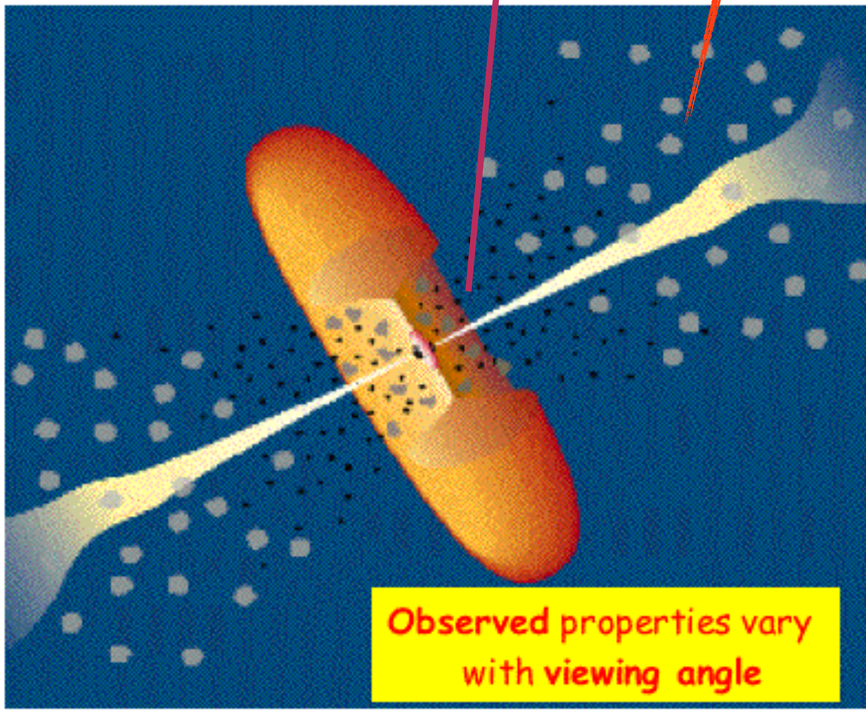
Accretion disk; thermal UV/X & lines from highly ionized atoms (3-100 R_G).

High velocity (>10^3 km/s) **broad-line** clouds ($R \sim 10^{3\text{-}4}\ R_G$).

Dusty torus, which orbits in/near plane of accretion disk ($R \sim 10^{4\text{-}5}\ R_G$).

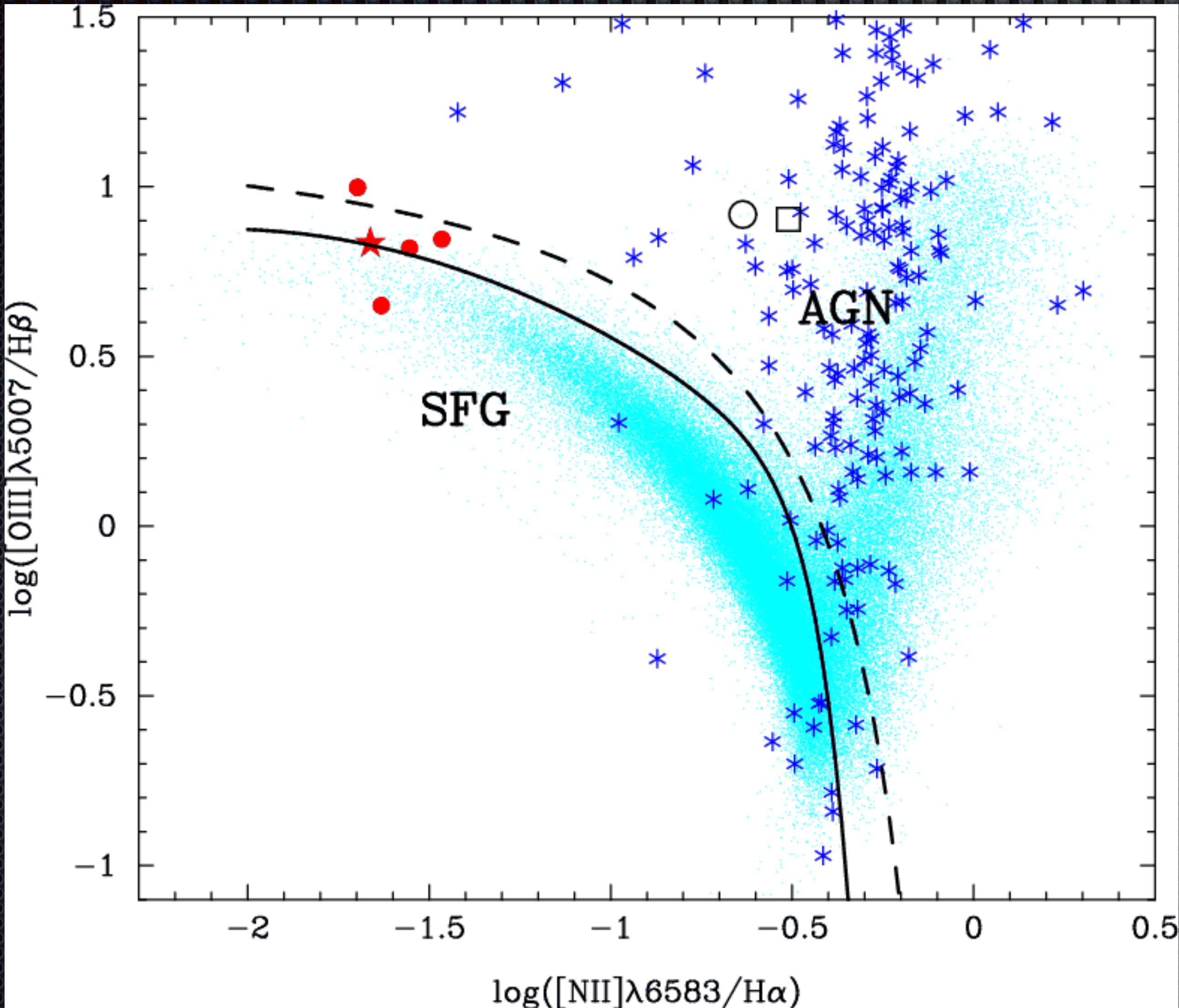
Lower velocity (few hundred km/s) **narrow-line** clouds ($R \sim 10^{5\text{-}7}\ R_G$).

Relativistic jet ($\Gamma \sim$ 5-30), which may be collimated on ~50 R_G scales.



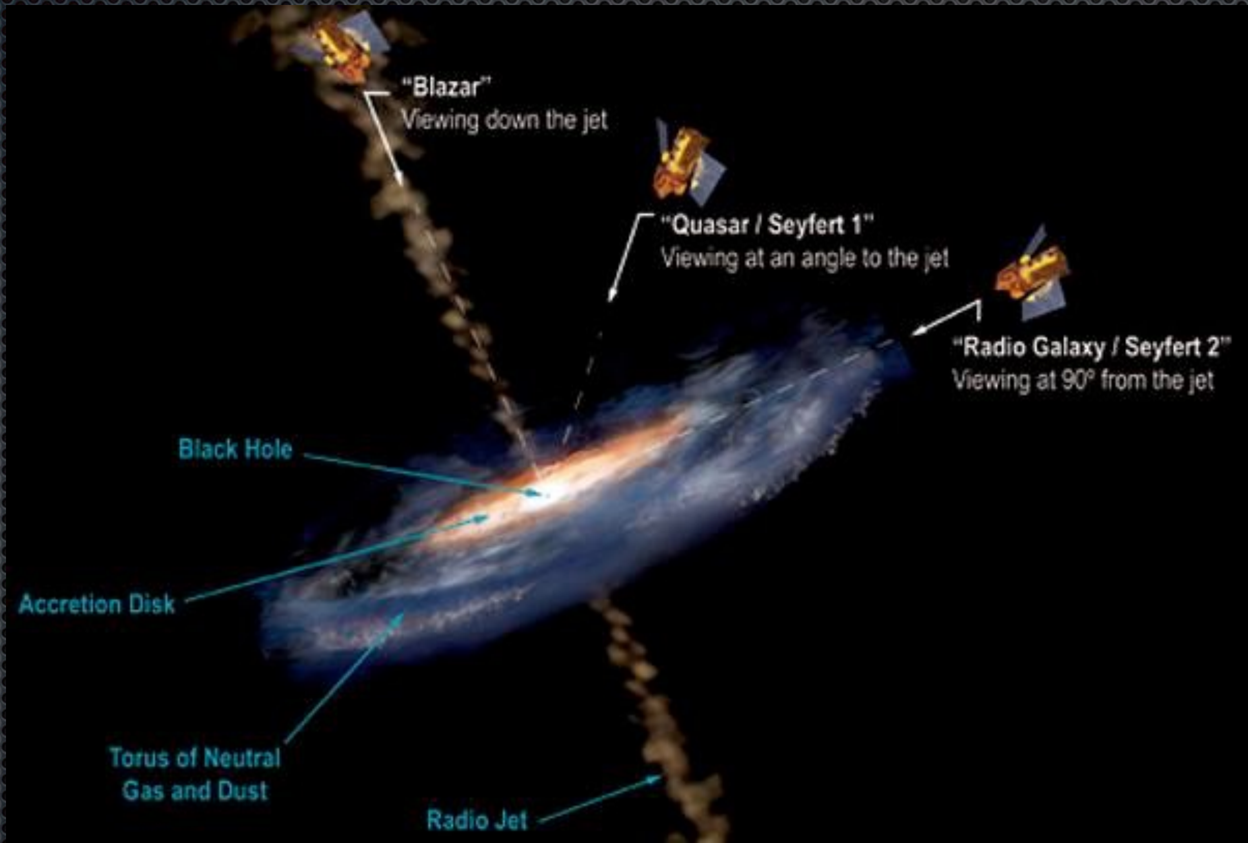
(Urry & Padovani 1995)

Spectral diagnostics

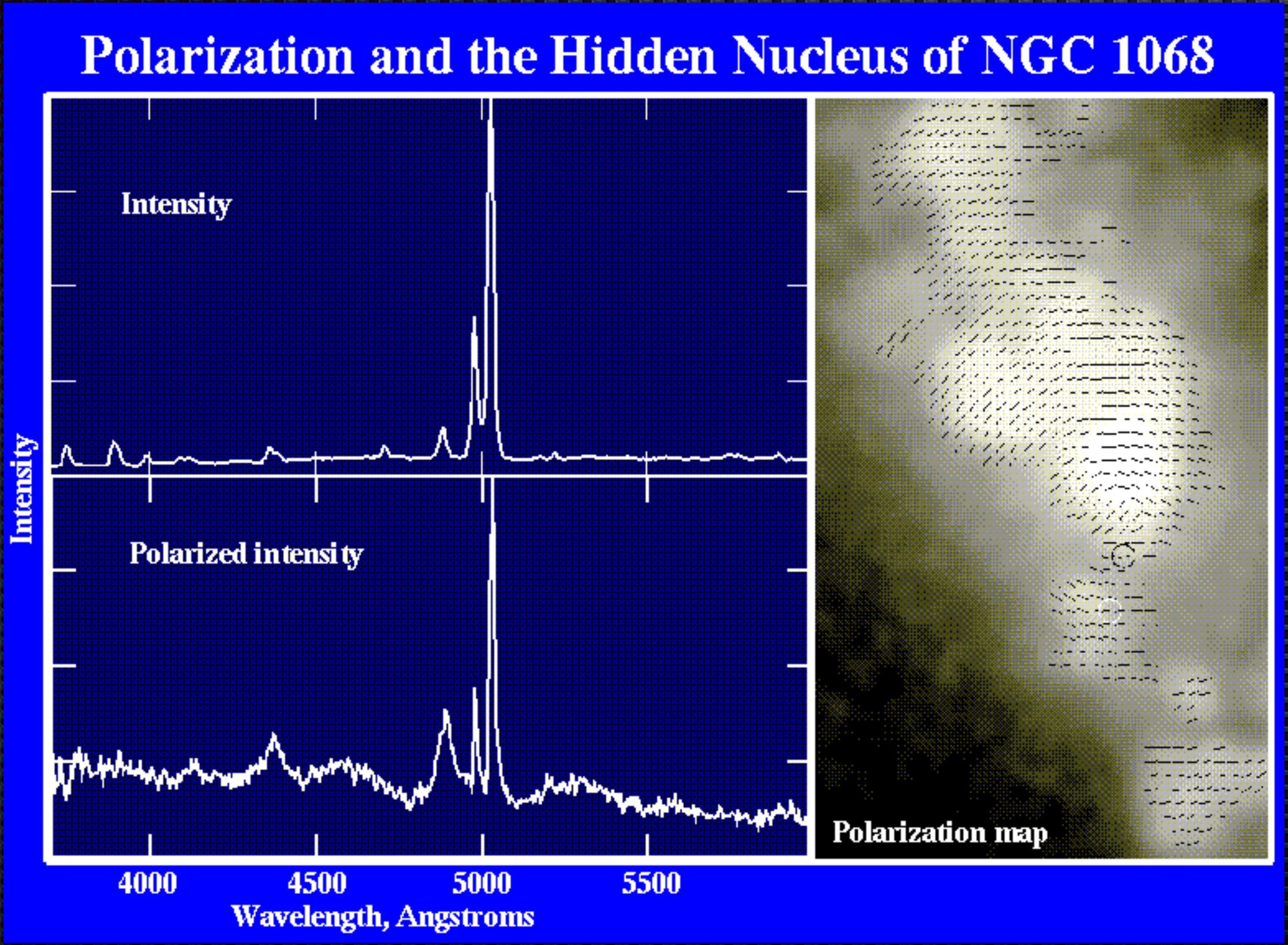


High excitation lines give away the AGN

The standard unification models

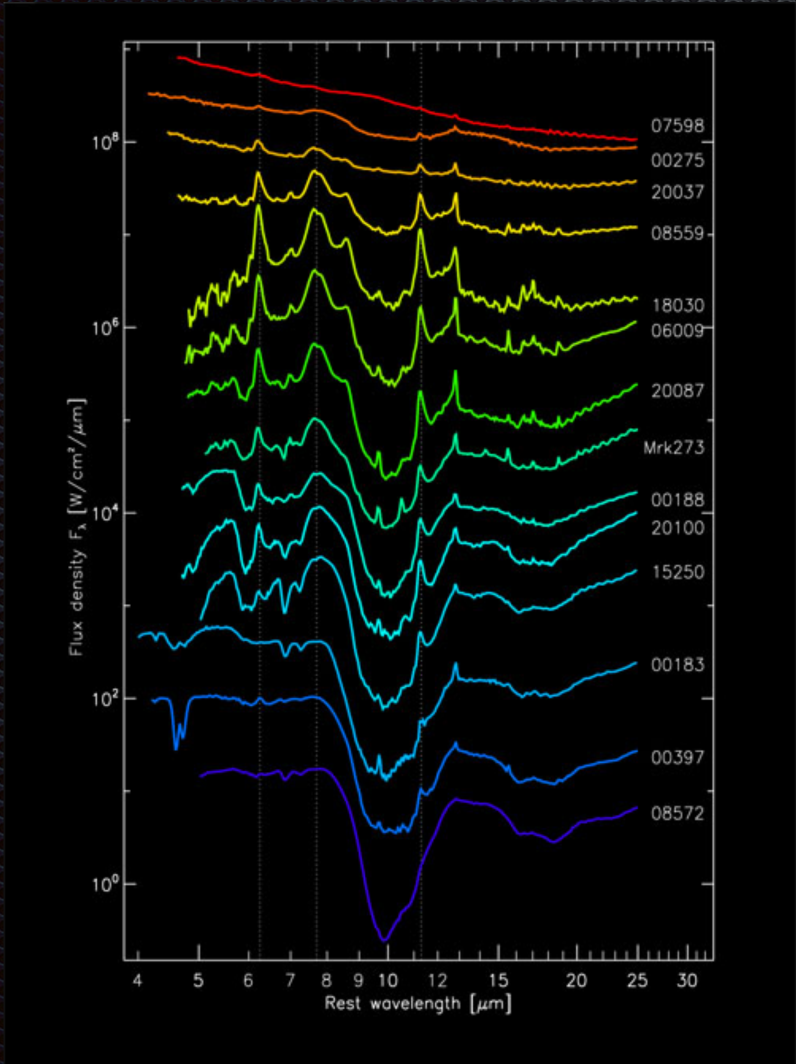


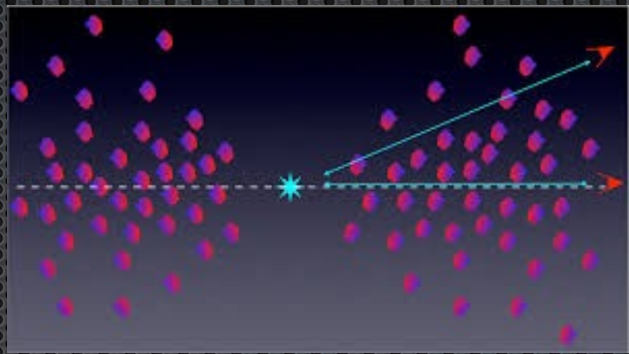
Proof of unification models: polarimetry

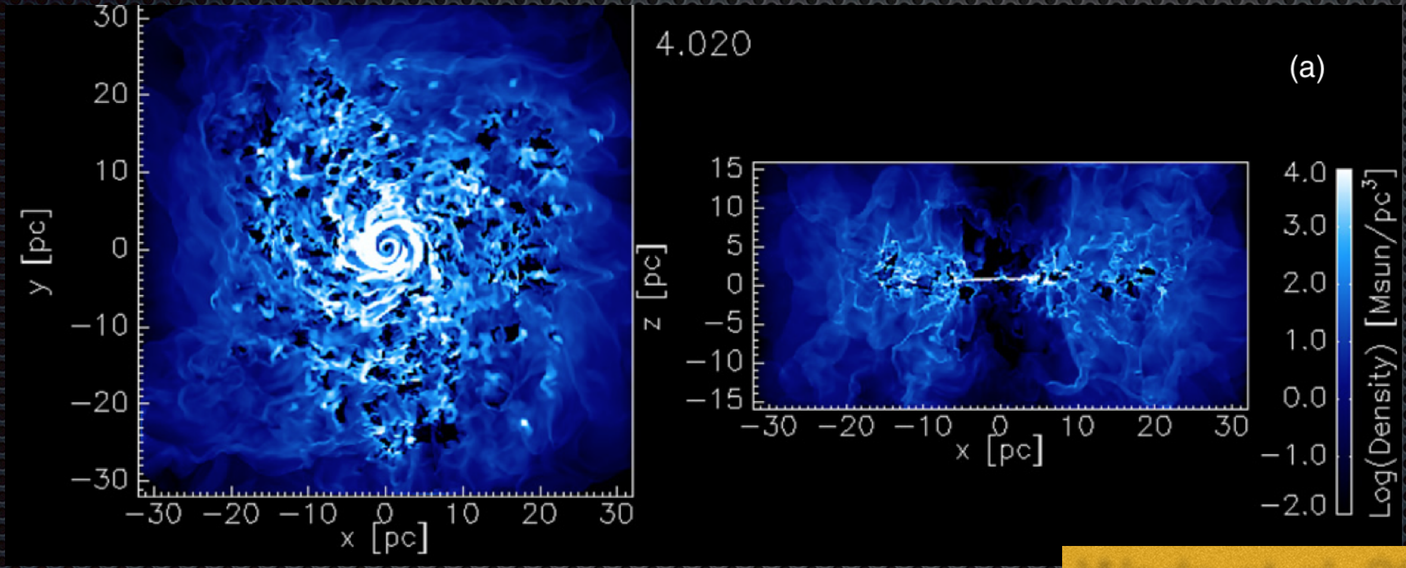


what is exactly the torus ?

- IR observations first suggested that the torus may be in form of clouds (a clumpy torus), see Nenkova et al. 2002





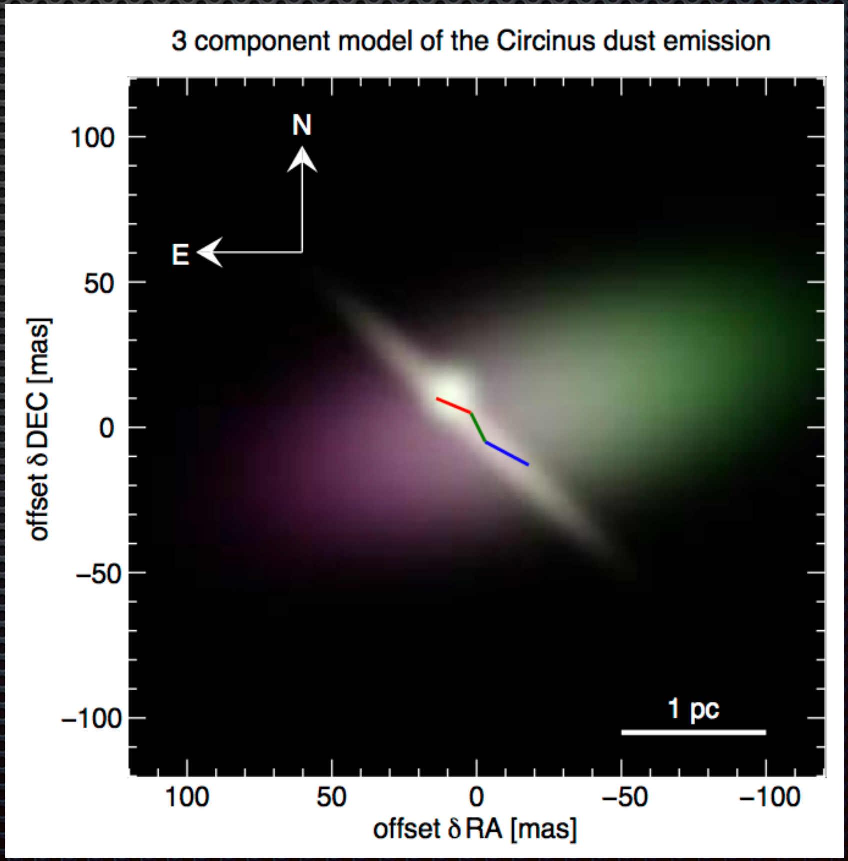


Wada et al. 2008

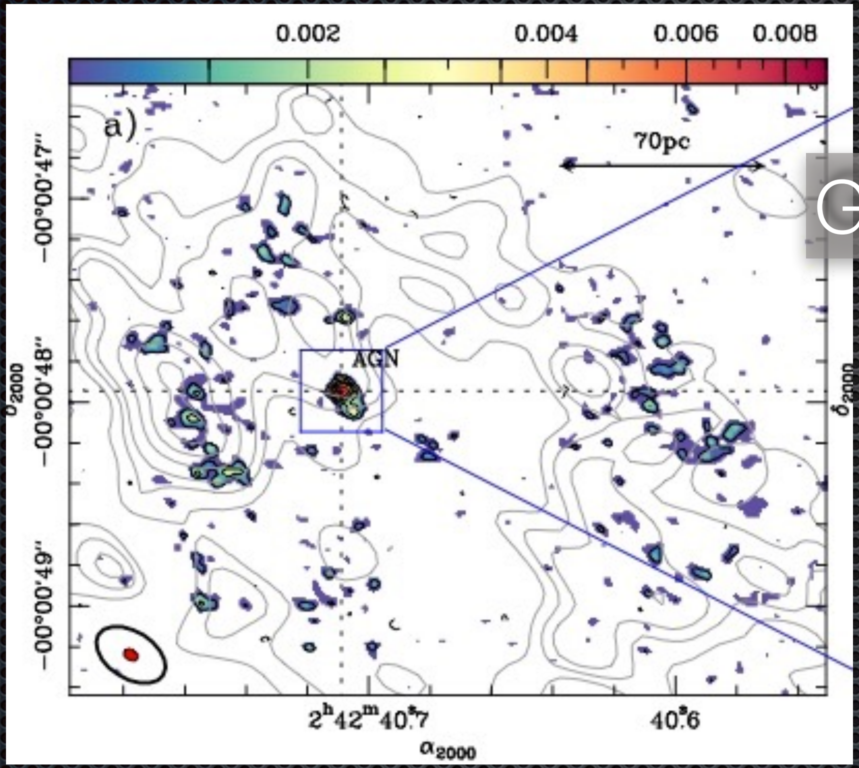
Hydrodynamic simulations of the torus

Interferometric observations VLT

- NGC1068 MIDI instrument, 8µm, 7marcsec resol.
- Jafe et al. 2003, Tristram et al. Raban et al.

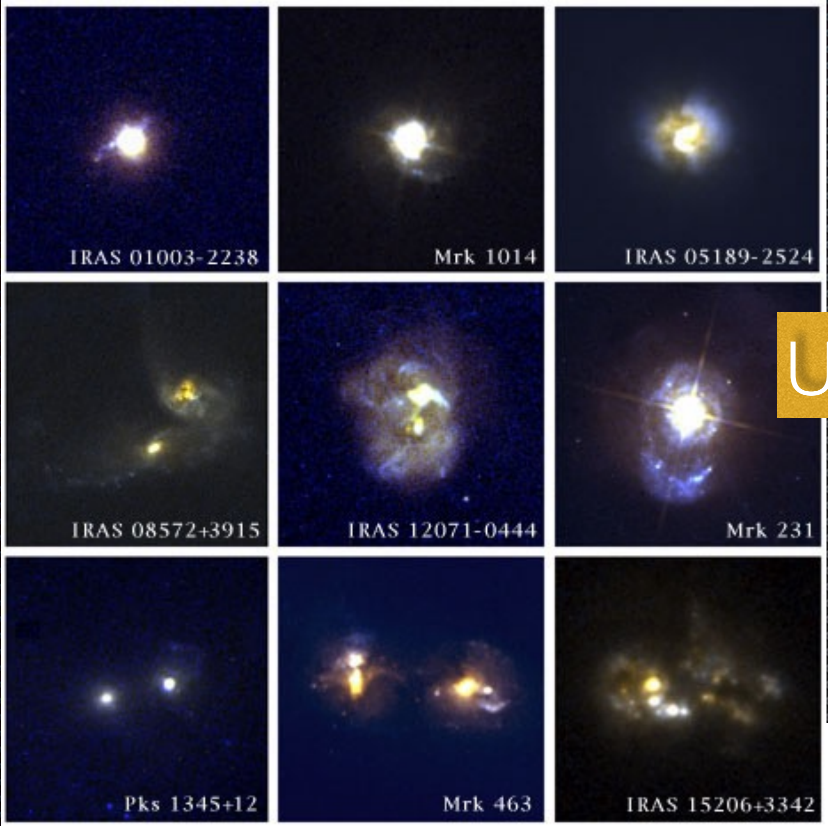


ALMA observations NGC1068

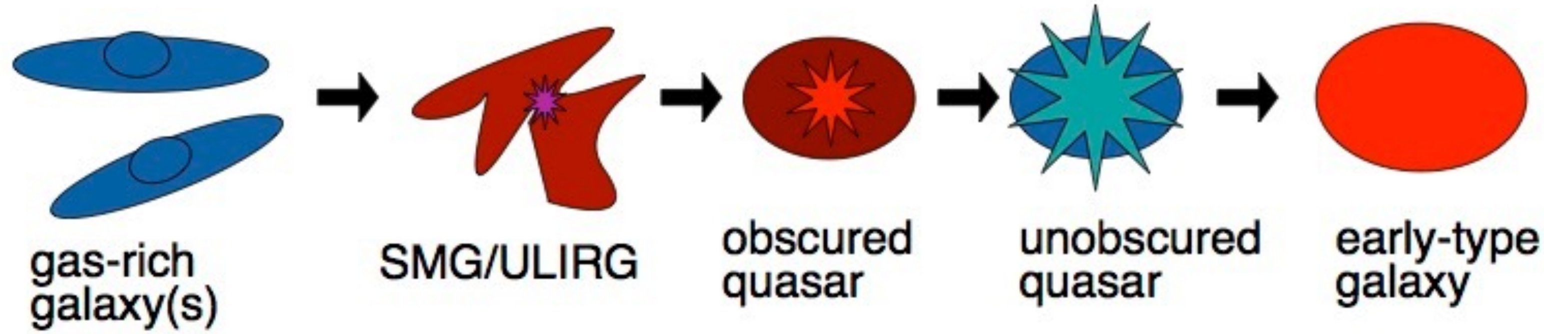


Garcia-Burilo+2016

Unification: may be not just orientation

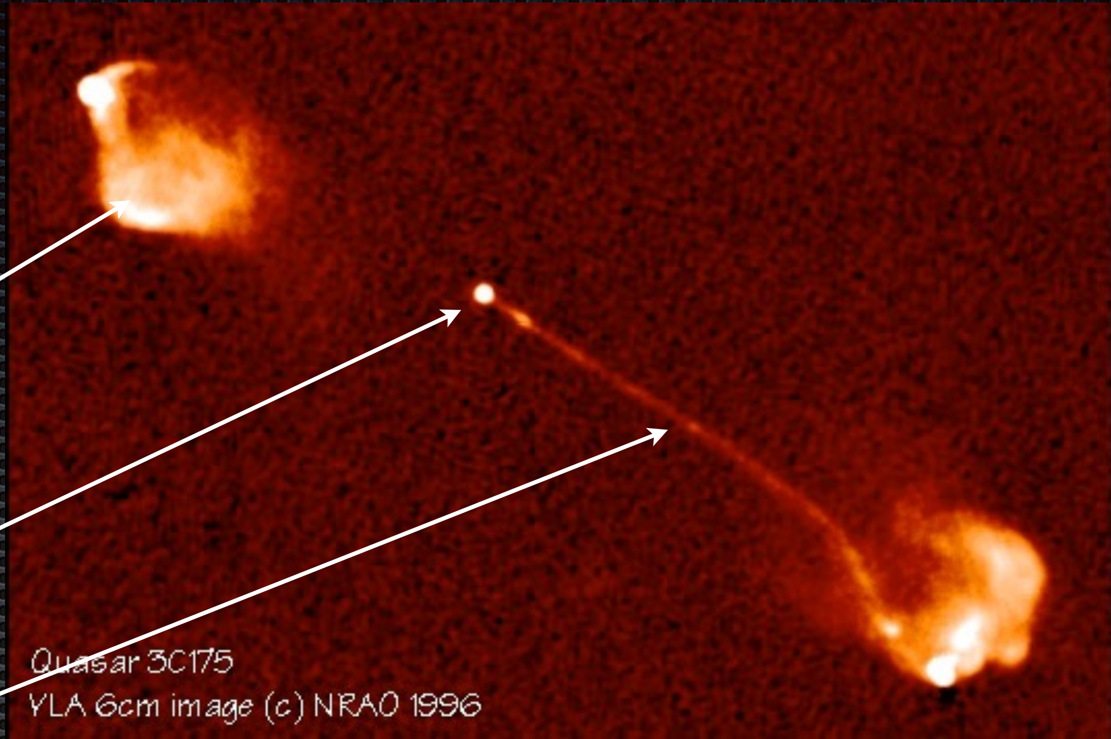


ULIRGS



A Model of AGN evolution: AGN
is born as heavily obscured and becomes adult as an unobscured AGN

Radio loud AGN

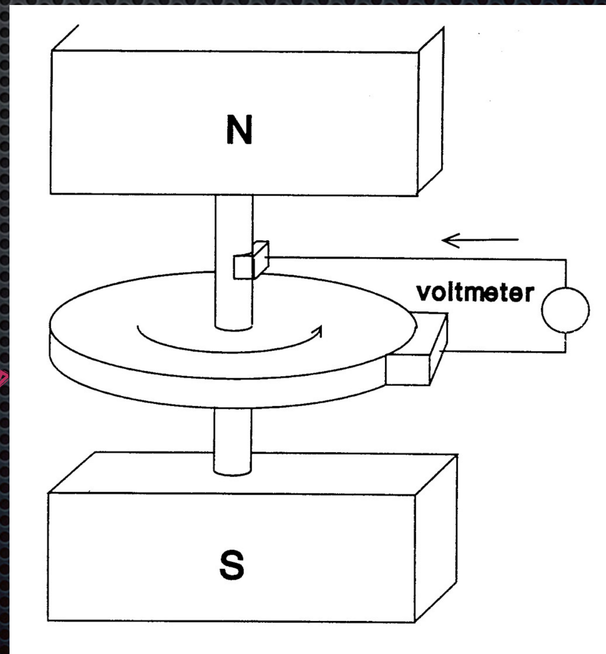


lobe

core

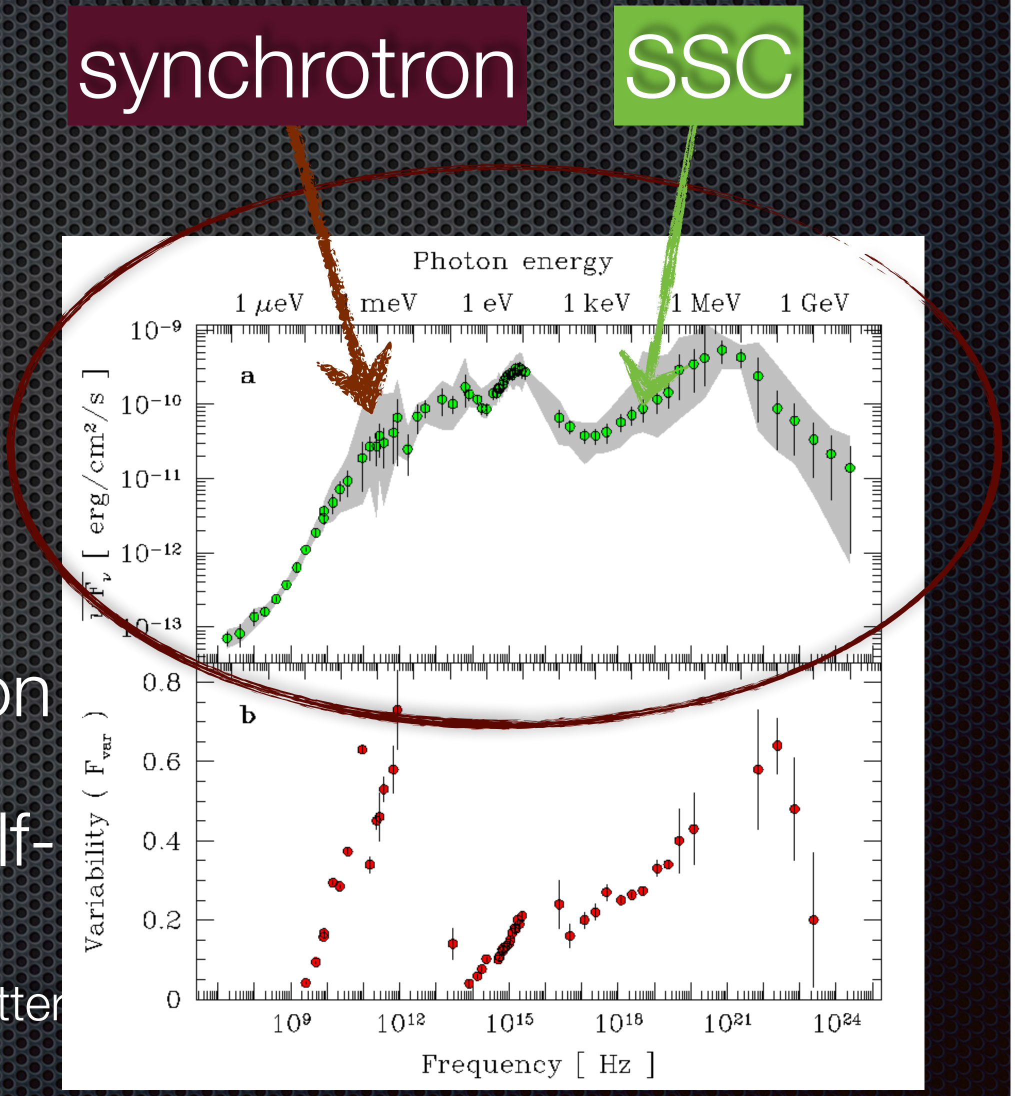
jet

- $L_{radio} > 10^{25}$ W/Hz   Only 10% of AGN are radio loud !!
- Their radio emission comes from jets or from a compact core
- How are jets formed ? Very roughly from a **dynamo** effect from a magnetic field embedded in the rotating accreion disc



Origin of radio emission

- in the jets emission extends from radio to X-rays.
- spectrum is a power-law ($F \propto N^{-\alpha}$) synchrotron emission
- In X-rays it is synchrotron self-compton SSC (the electrons that produce the radio/optical emission up-scatter the optical photons to higher energies)



Relativistic beaming

- Why do we see only one jet ?
- for a relativistic source moving at an angle ϕ to the line of sight with a Lorentz factor $\Gamma = 1 / \sqrt{(1-\beta^2)}$, ($\beta = \upsilon/c$) the observed flux is enhanced by the Doppler factor

$$\delta^{2+\alpha} \quad where \quad \delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$$

AGN Masses

- Upper limit Eddington Luminosity
- **Width of Emission Lines**
- Bulge Luminosity - BH Mass relation

Problem 1: Eddington Luminosity

(a way to estimate an upper limit to the mass)

- Eddington Luminosity (upper limit only)

The force exerted by the radiation on a particle must be less than the gravitational force,

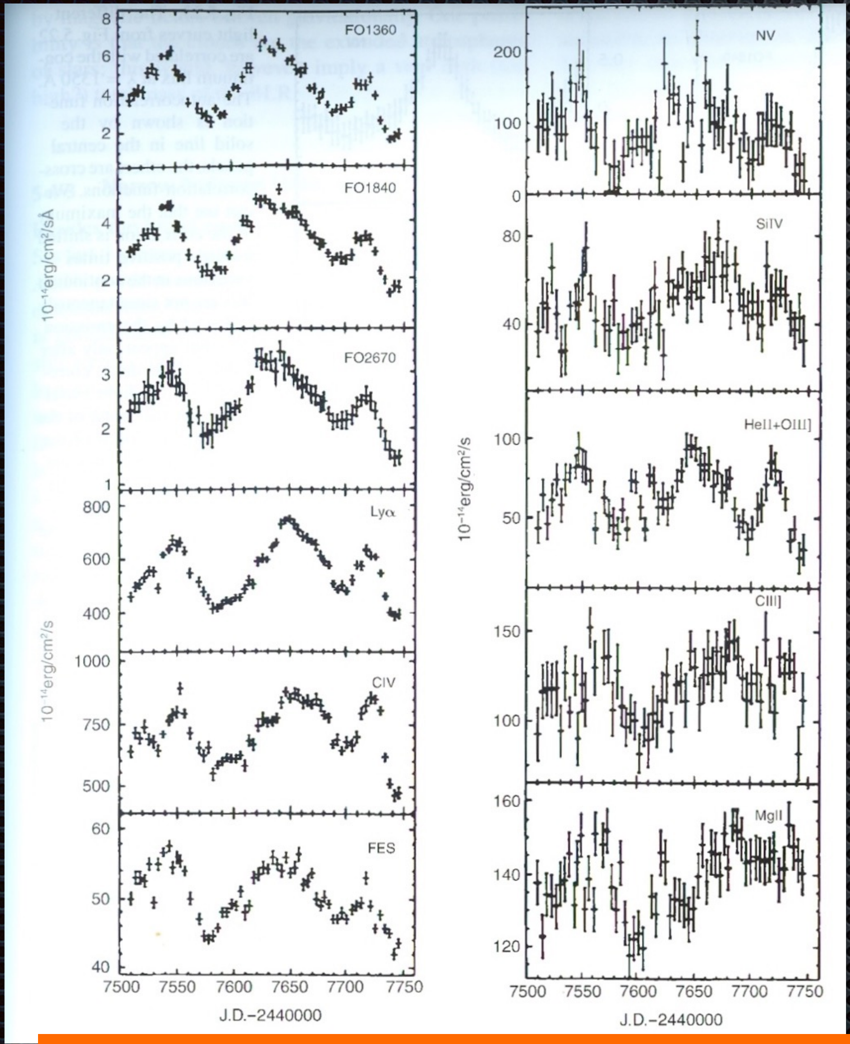
or the accretion disk will be destroyed

$F_{rad}=\sigma_e \ (L/4pr^2 c) < \ F_{grav}= GMm_p/r^2$

$$L_{EDD}< 1.3x10^{38} (M/M_\odot) \text{ erg s}^{-1}$$

for $L\sim10^{46}$ erg s^{-1} $M=10^8$ Mo

1.10 BH Mass from Hβ



$$\frac{m\ u^2}{r} = G\ \frac{M\ m}{r^2}$$

We can estimate M if we know:

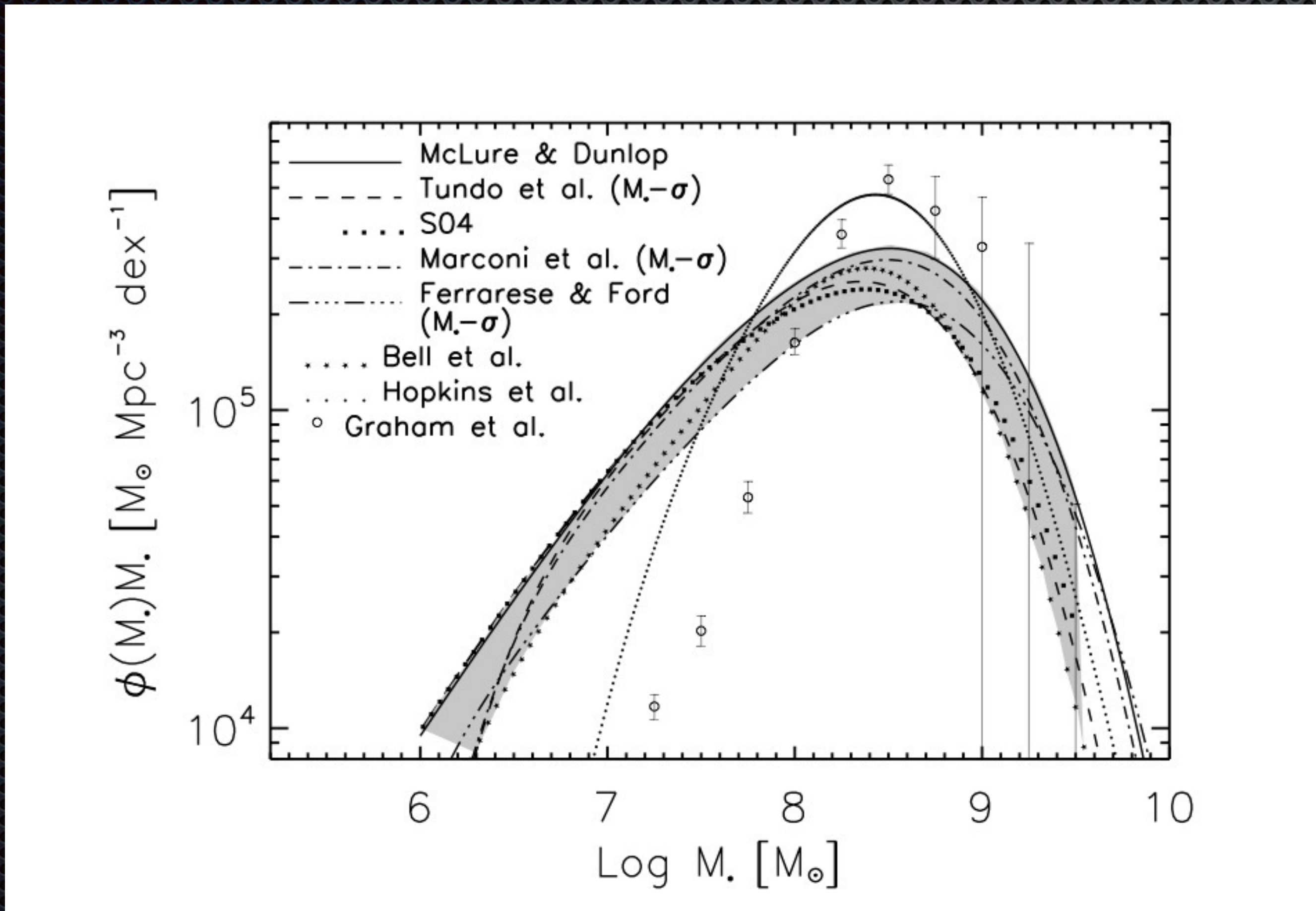
1. **rotational velocity** of BLR clouds u
2. **distance r** of clouds from BH

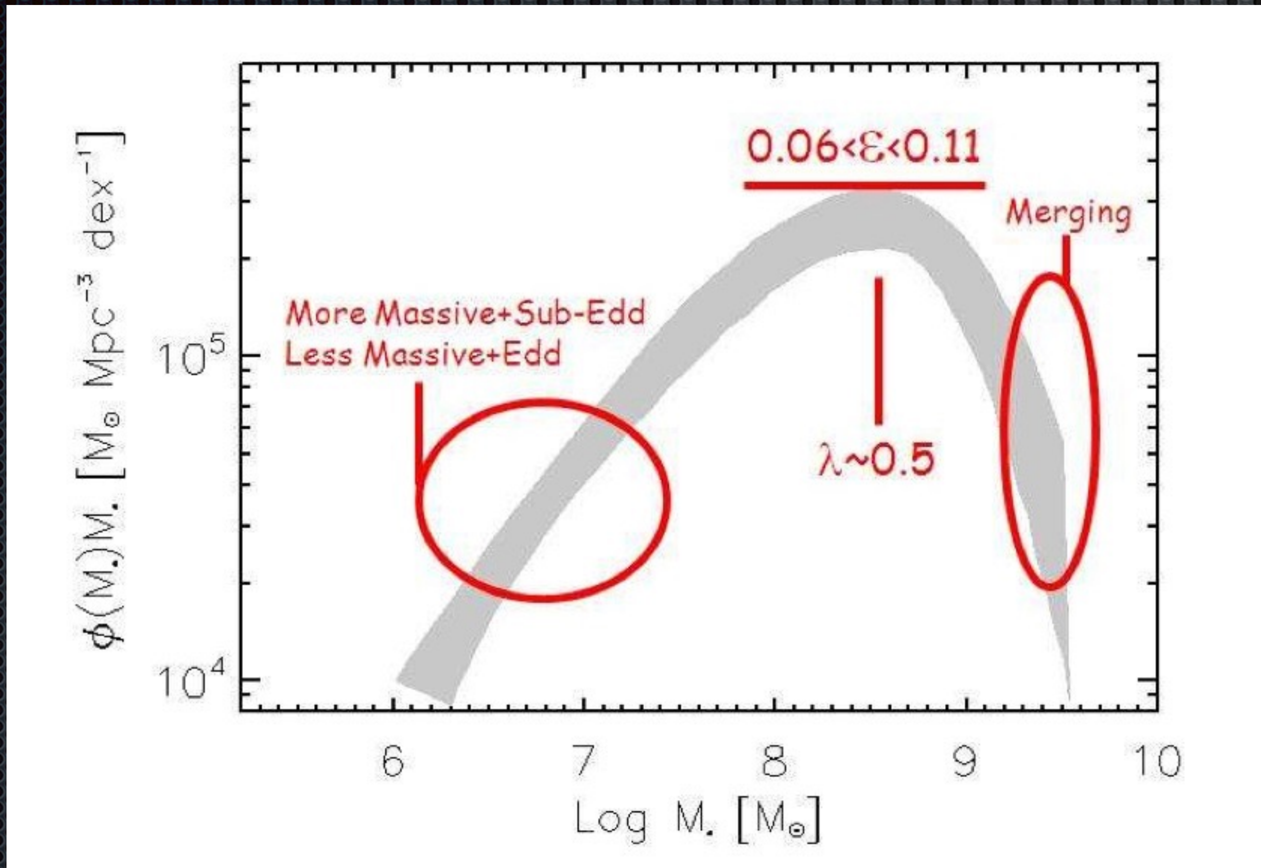
For a typical velocity of 5000 km s-1 and a BLR distance of $r=10^{17}$ cm

M_{BH} ~ 10^8 $M_\odot$

Distance comes from reverberation mapping

Distribution of BH masses



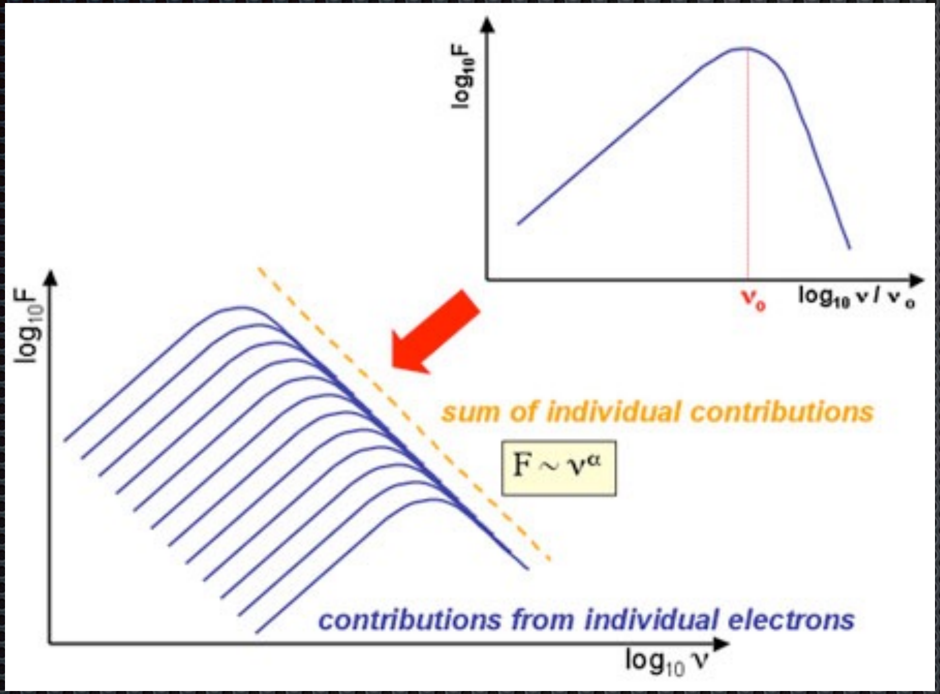


0.06<ε<0.11
Merging
More Massive+Sub-Edd
Less Massive+Edd
λ~0.5
10^5
10^4
$\phi(M_\bullet)M_\bullet$ [$M_\odot$ Mpc^{-3} dex^{-1}]
6
7
8
9
10
Log $M_\bullet$ [$M_\odot$]

1.11 radiation mechanisms

- free-free emission (bremsstrahlung)
- synchrotron
- compton radiation (power-law flux ~ $\nu^{-\alpha}$)
- blackbody (large optical depth)

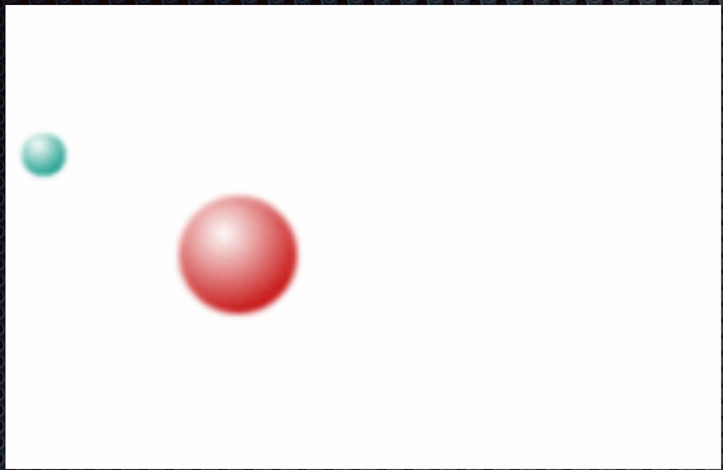
synchrotron

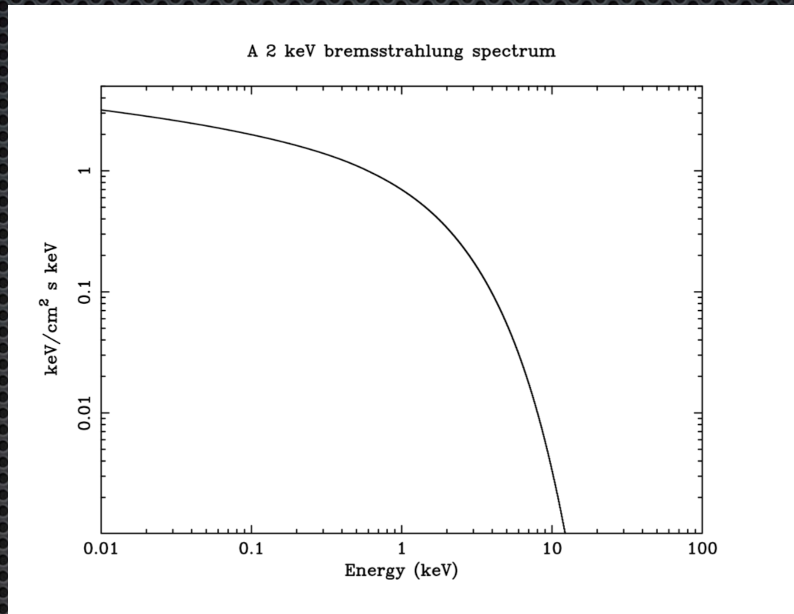


$$\nu_o \propto \gamma^2 \; B$$

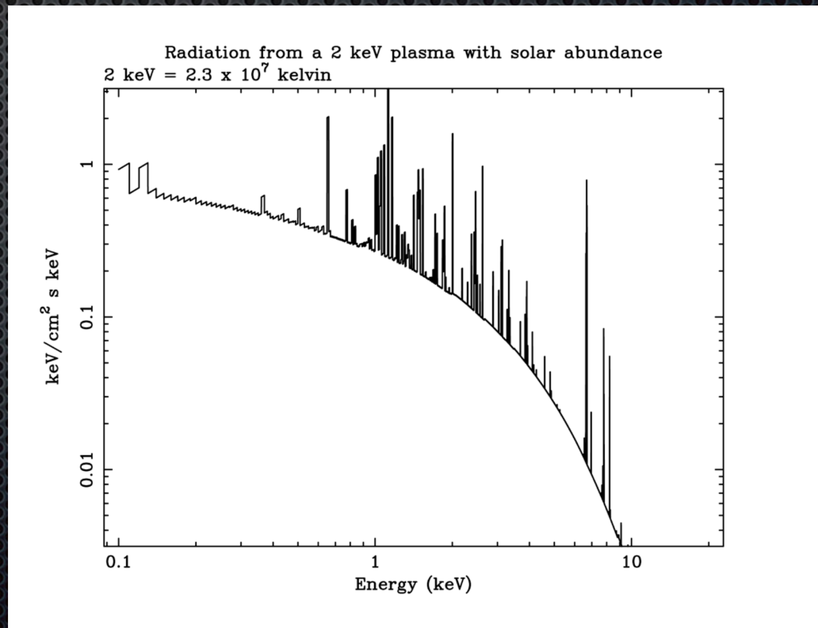
$$\frac{dE}{dt} = \frac{4}{3}\sigma_T \; c^{-1} \; U_{mag} \; \gamma^2 \; \upsilon^2$$

1.13 free-free emission



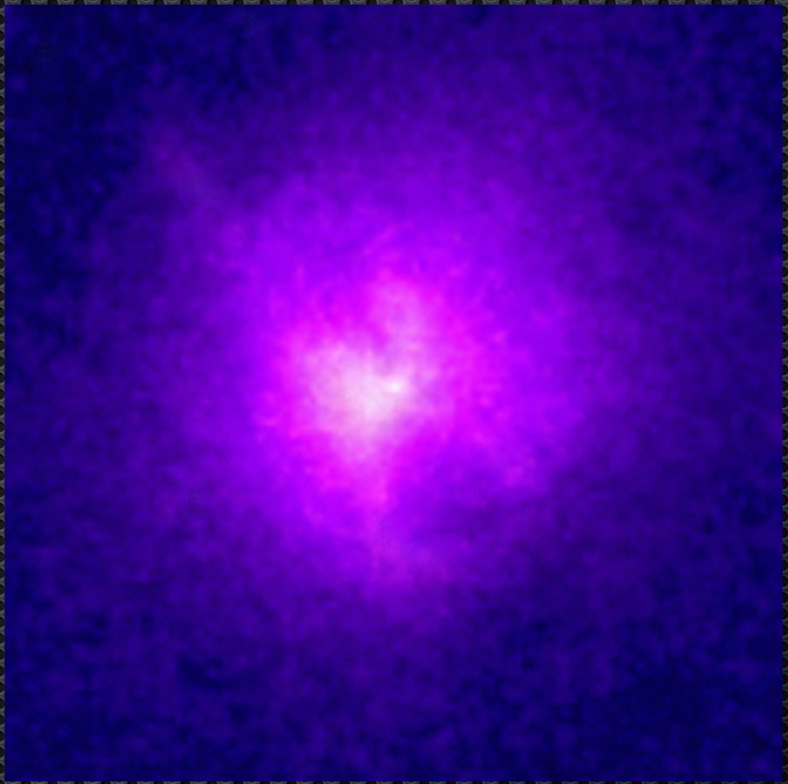


spectral index a~0.4
cut-off E characteristic
energy electrons



Free-Free emission from clusters

Perseus Cluster ROSAT (red) on optical (blue)

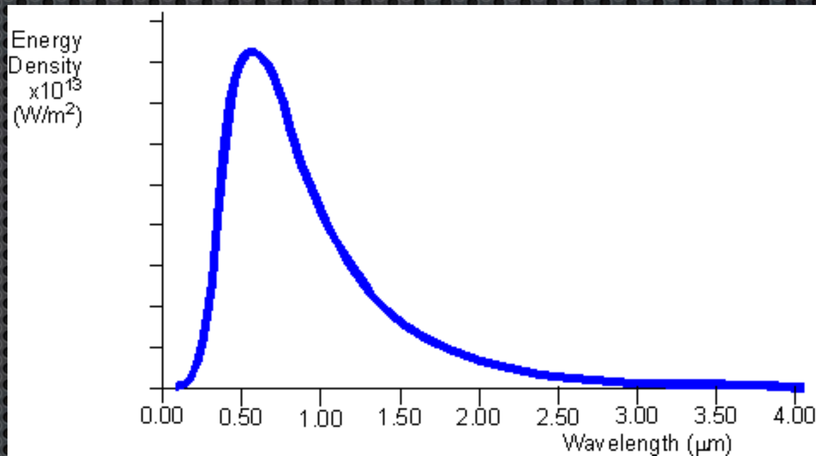


X-ray surveys are becoming the standard tool for detecting clusters (detection of diffuse emission much more efficient than galaxy overdensity used in optical surveys) WARPS (Jones et al.), EDCS (Rosati et al.)

blackbody emission

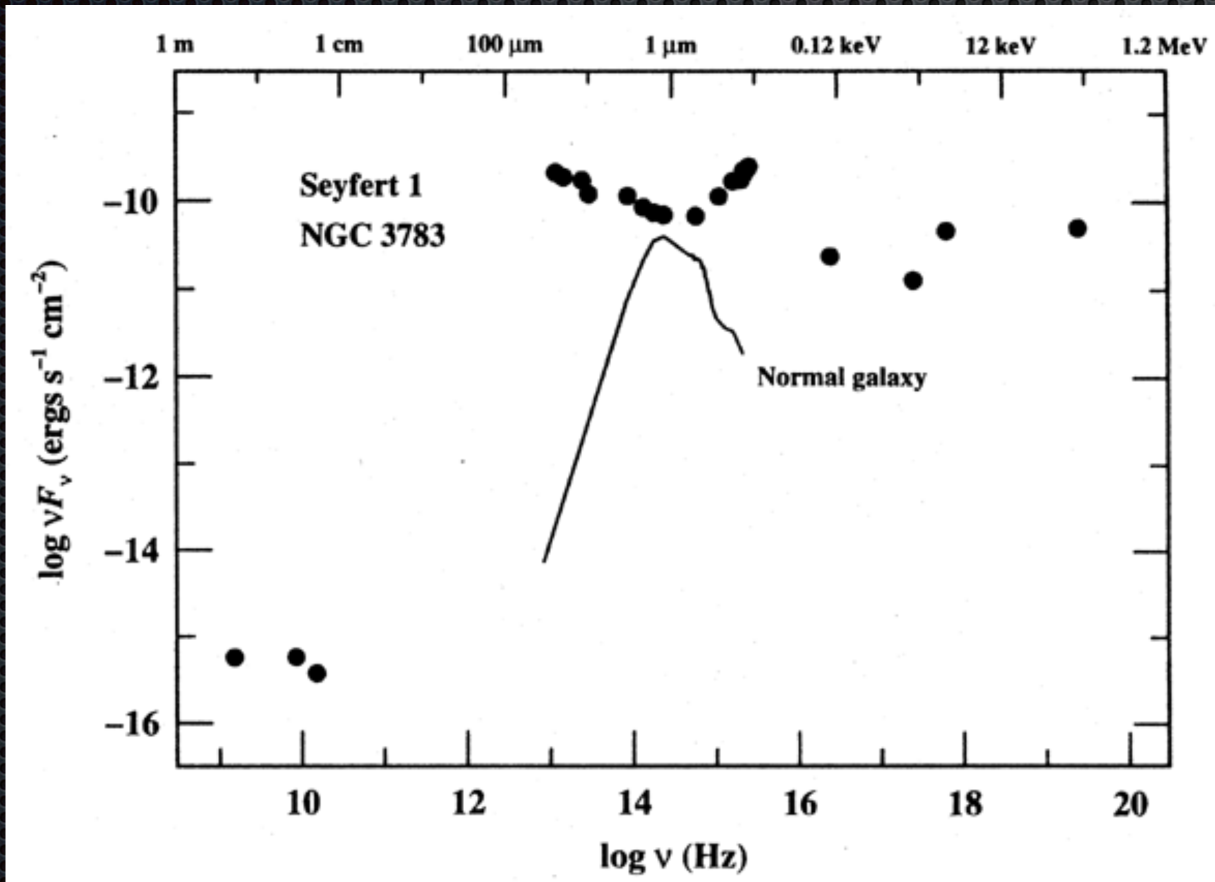
optically thick material, $\tau >> 1$

$$u(\nu, T) = \frac{2h\nu^3}{c^2} \cdot \frac{1}{e^{h\nu/k_B T} - 1}$$

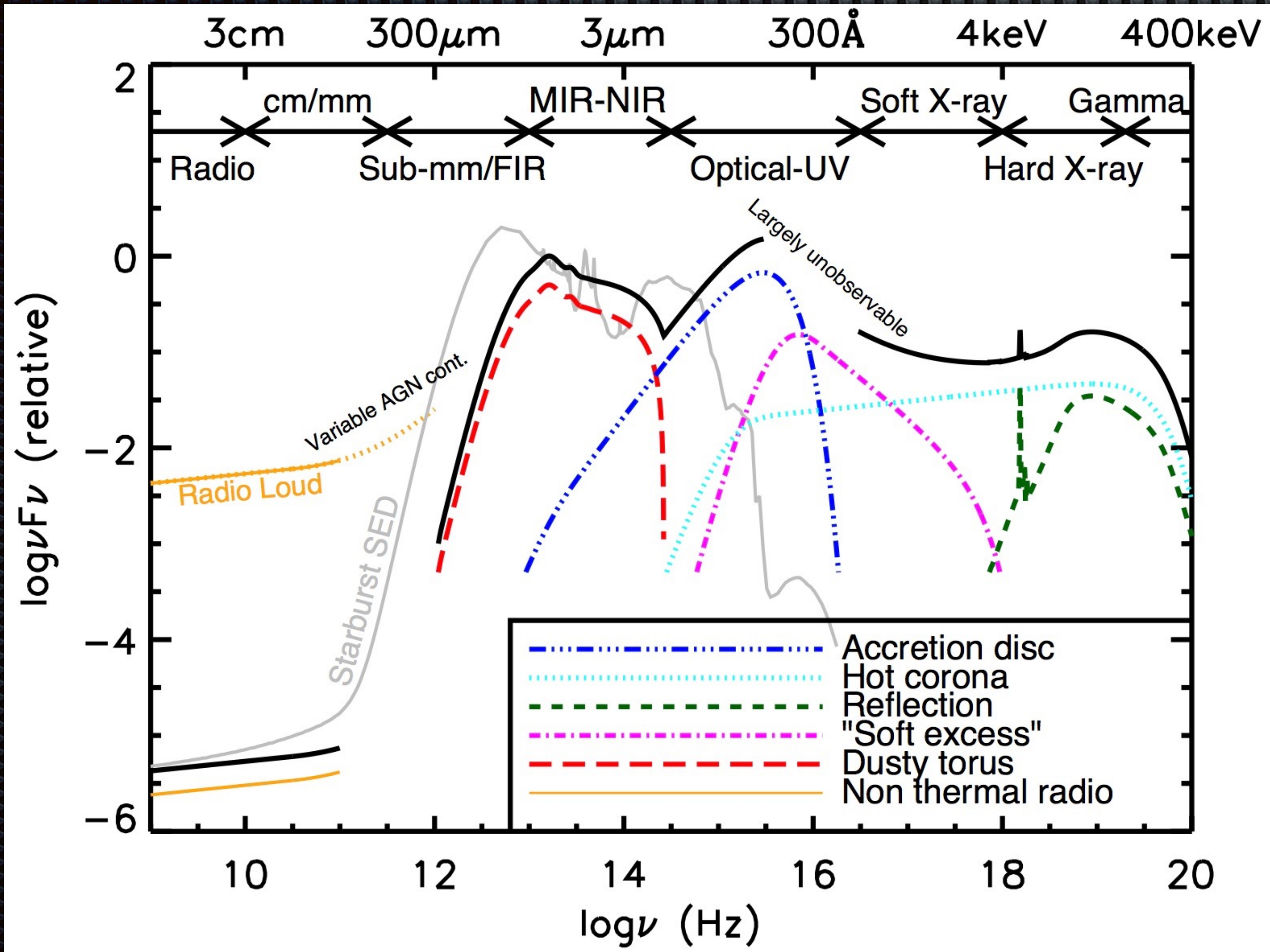


- Q1 some examples of astrophysical BB emission ?

Spectral energy distribution



Spectral energy distribution



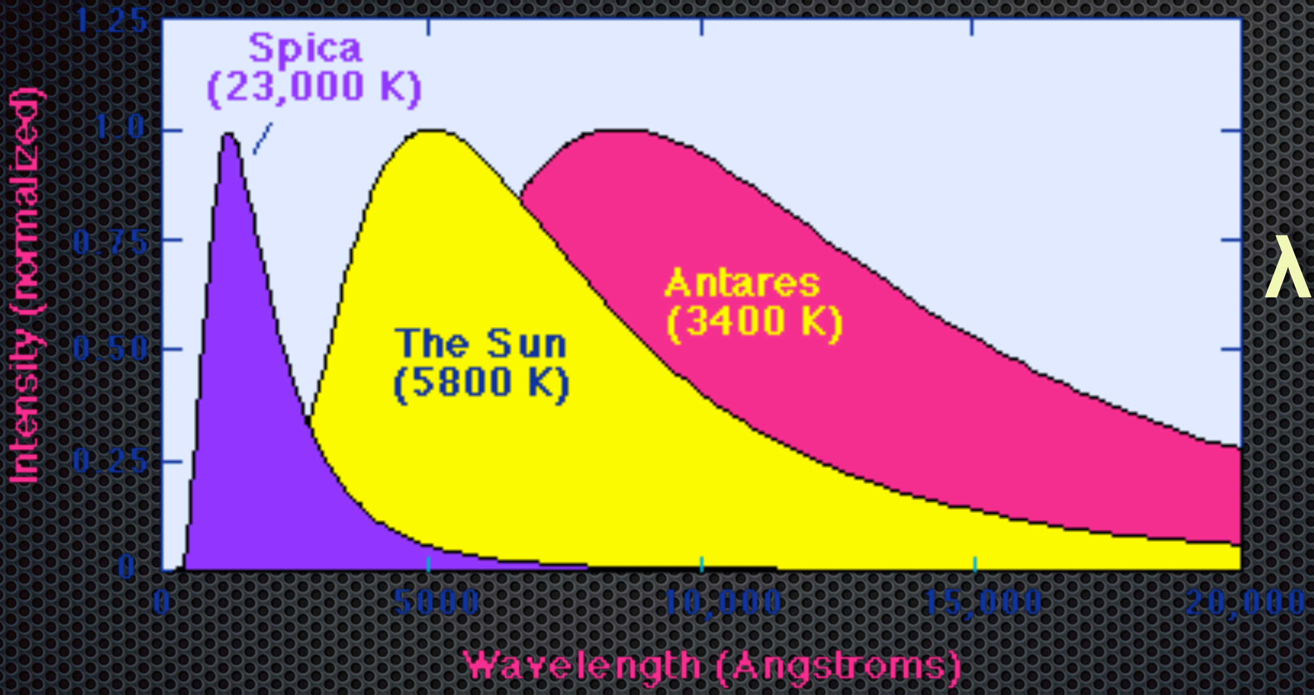
1.14 AGN emission mechanisms

- Optical: UV bump from accretion disc
- Mid-IR hot dust (heated by the AGN)
- X-rays (power-law from Inverse Compton)
- Radio: Radio-loud AGN: radio emission from jets (synchrotron emission)/ Radio quiet: ?

X-rays from AGN

Wien's law

Temperature $\propto$ radiation frequency

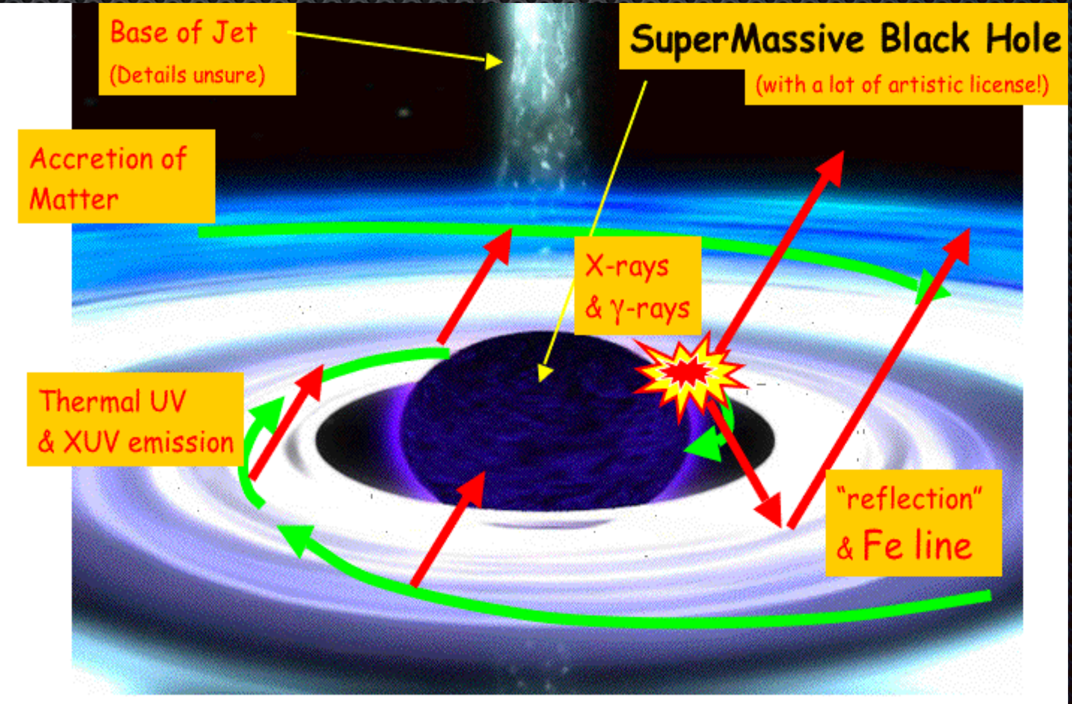


$\lambda max = 3x10^7 / T$

- Q1 what temperatures are needed to produce x-rays ?

The production of energy in AGN

Very strong X-ray emitters $\sim 10^{46}$ erg s
(up to 10^8 more luminous than the galaxy)



Potential enegy = Kinetic Energy =

Radiation

$L = \varepsilon \; dM/dt \, c^2$

[energy emitted does not depend on the mass of the black hole]

mass needed to power AGN

Schwarzild radius (last point where the photon cannot escape)

$$R_s = 2\,G\,M / c^2 = 3 \times 10^{13}\, M_8 \text{ cm}$$

Potential energy at this radius

$U = G\, M_{BH}\, m_{acc} / R_s$

where m_{acc} is the mass falling into the black hole

Assuming $U \sim L = 10^{43}$ erg s^{-1}

for $M_{BH} = 10^8$ Mo we need $m_{acc} = 10^{20}$ g only (or 10^{-13} Mo)

Can we get X-rays from the accretion disc ?

Problem: $T = k\, M^{-1/4}$

i.e for a typical BH mass $M=10^8\, M_\odot$ $T=10^6$ K (UV)

X-rays can be produced in an

X-ray binary where

M=10 Mo but not in AGN

We need another mechanism

(Inverse Compton scattering)

Problem 2. Temperature of accretion disk

Gravitational energy is

$U = GM\dot{m}/r$

and the energy radiated away

$L = 2\pi\ r^2\ \ \sigma T^4 \sim U$

$$T = \left(\frac{GM\dot{m}}{4\pi\sigma\ r^3}\right)1/4$$

using $R_s = 2GM/c^2$ *and* $\dot{m}_{EDD} = \dfrac{L_{EDD}}{\varepsilon\ c^2}$

$T(r) \sim \dot{m}^{1/4}\ M^{-1/4}\ r^{-3/4}$

Inverse Compton scattering

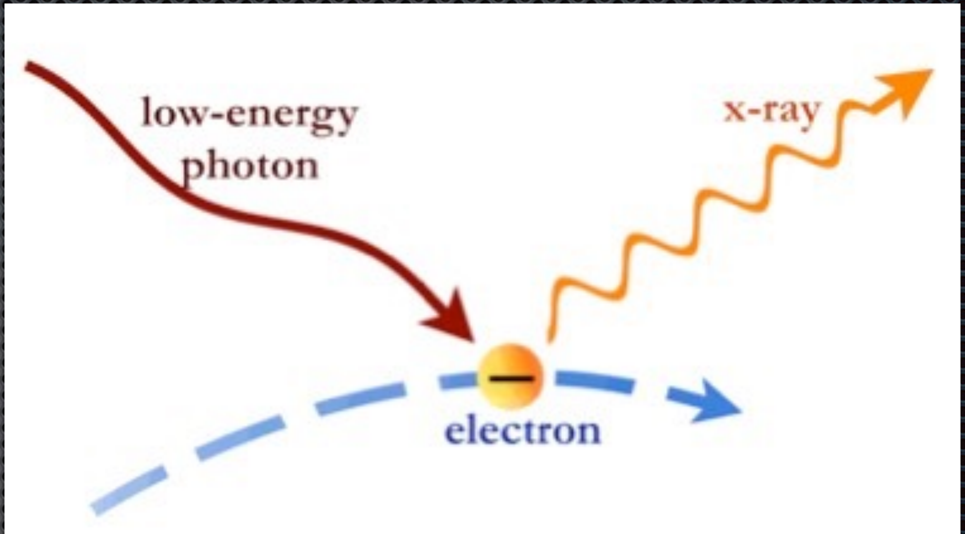
upscatter UV photons to X-rays

$kT >> h\nu$

Energy gained

$\delta E/E \sim 4\kappa T / mc^2$

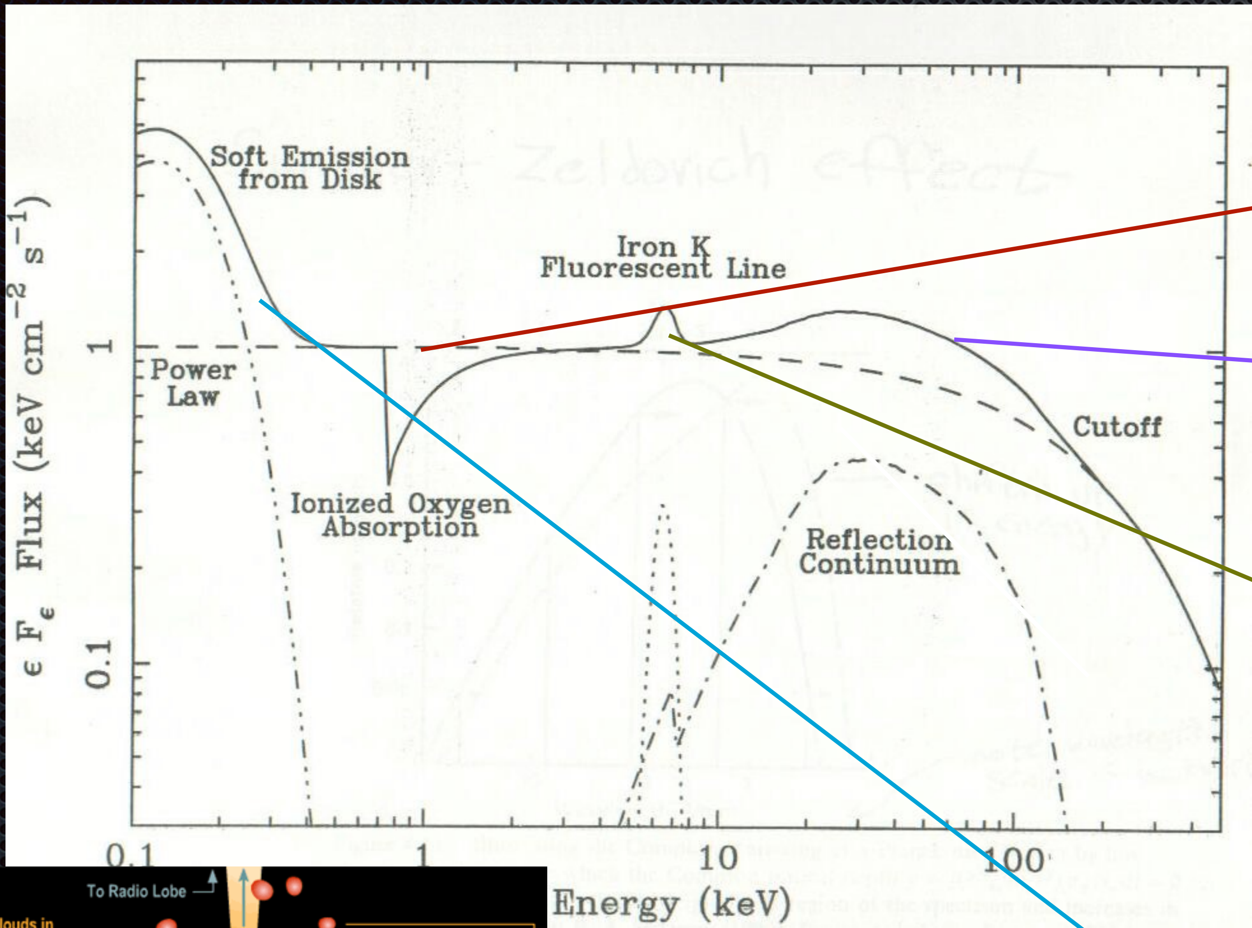
Temperature of the ‘corona’ about 40 keV. The physical conditions (temperature, Optical depth) define the spectrum

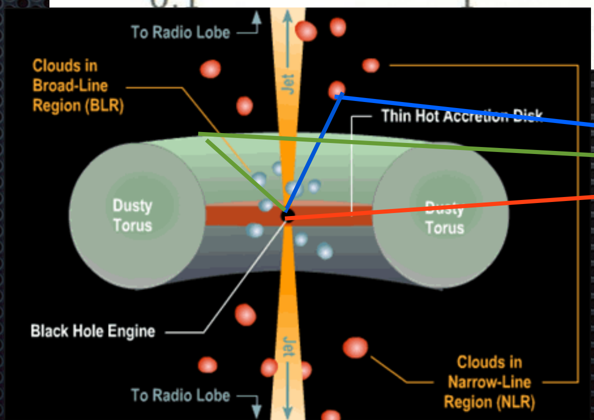


Comptonization parameter

$$y = 4kT_e\tau^2/m_ec^2$$

AGN X-ray spectrum





Power-law

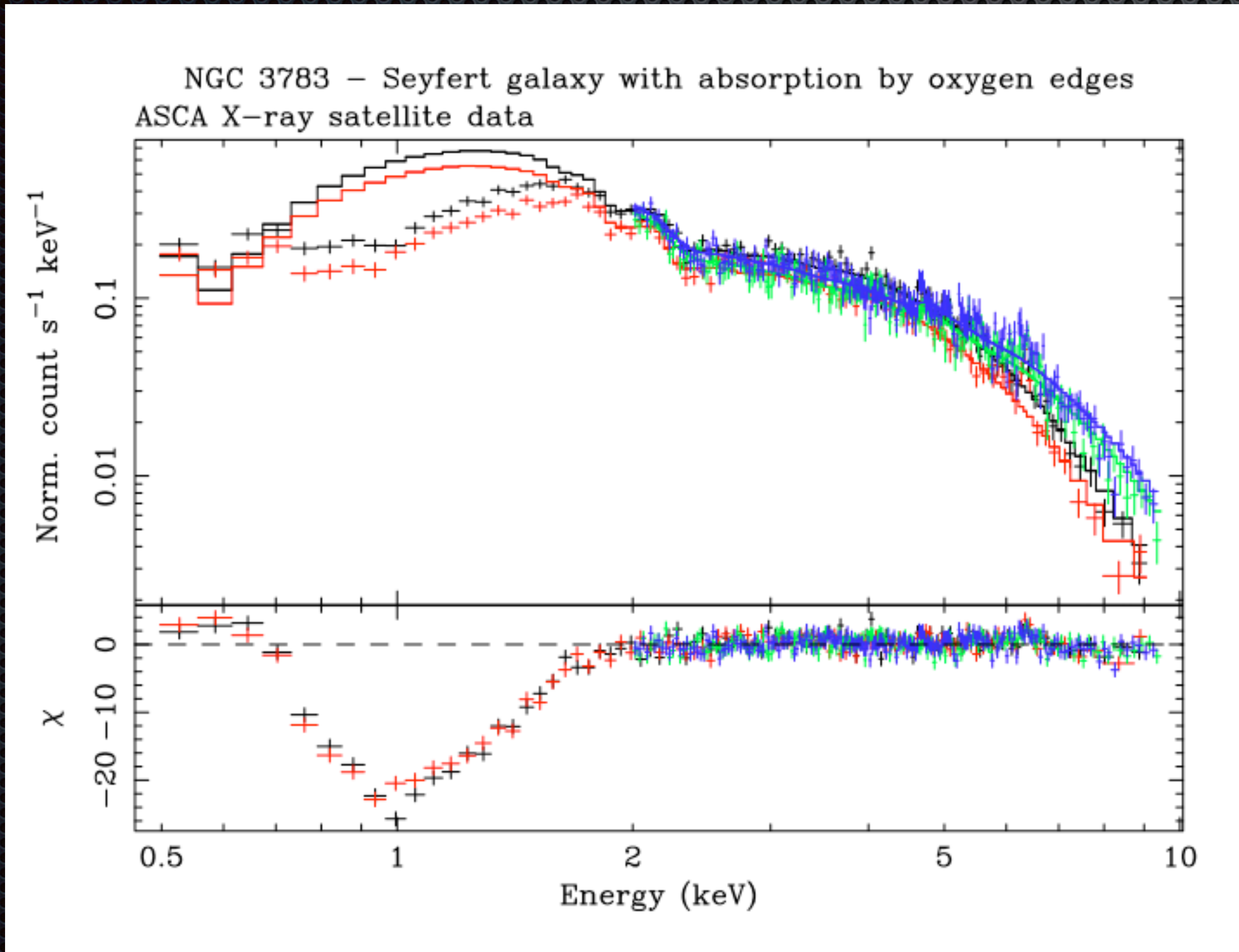
Refletion cold-matter

Fe line

Absorption cold material

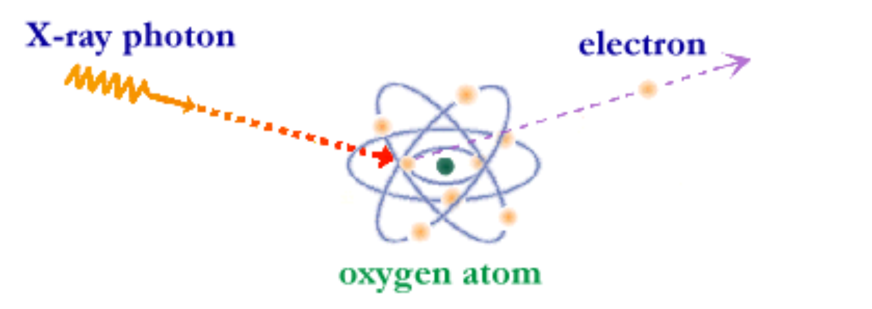
soft component accretion disk

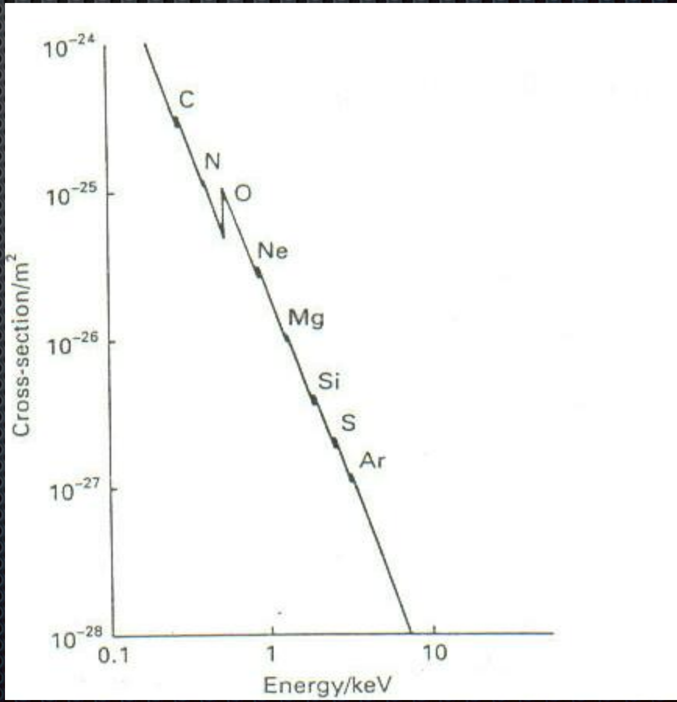
An example X-ray spectrum



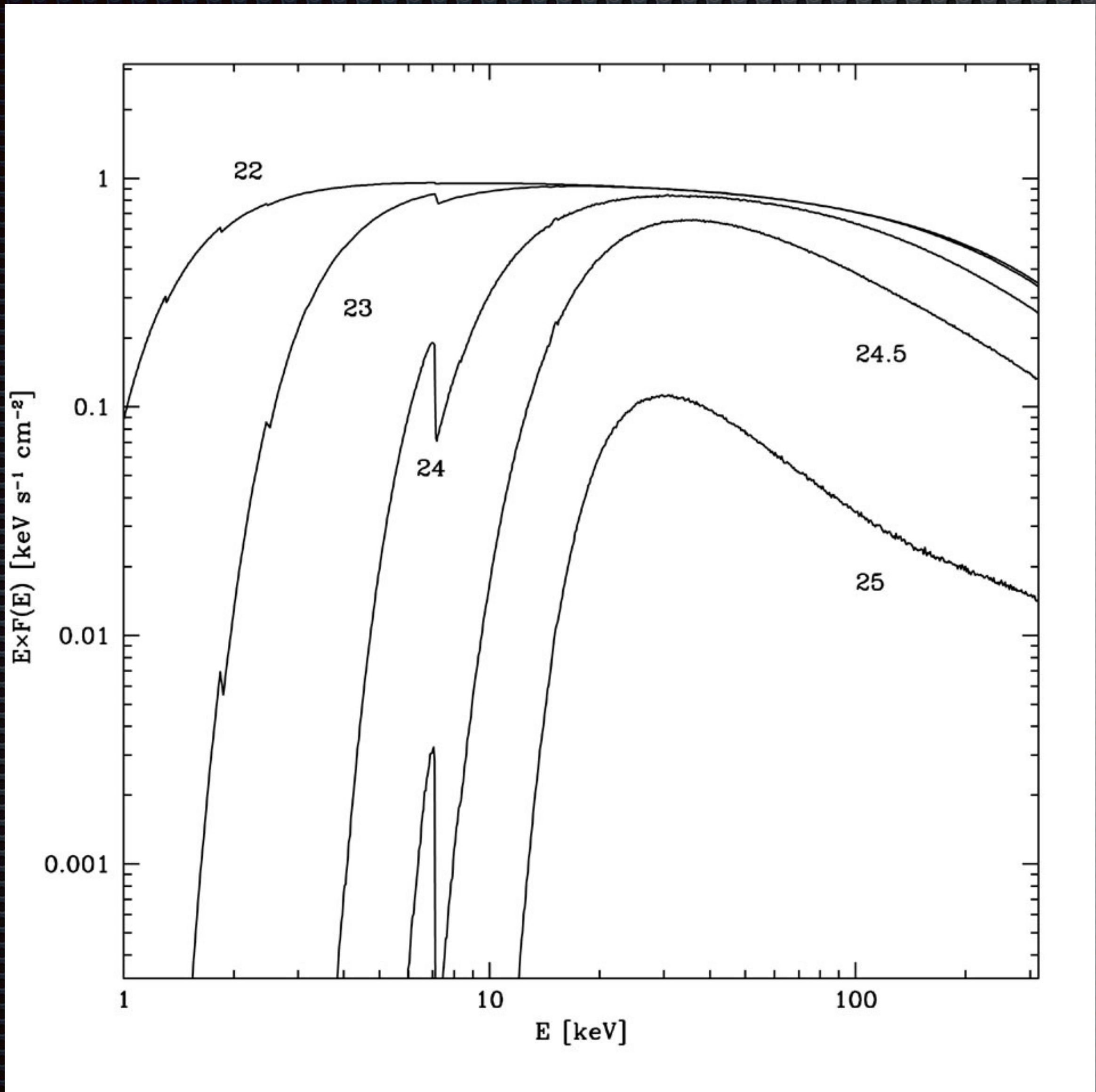
X-ray absorption

- While the optical is extinct by dust the X-rays (0.1 > keV) are absorbed by gas (photoelectric Absorption)





effects of absorption



as hydrogen column density increases soft energies get attenuated because of photoelectric absorption

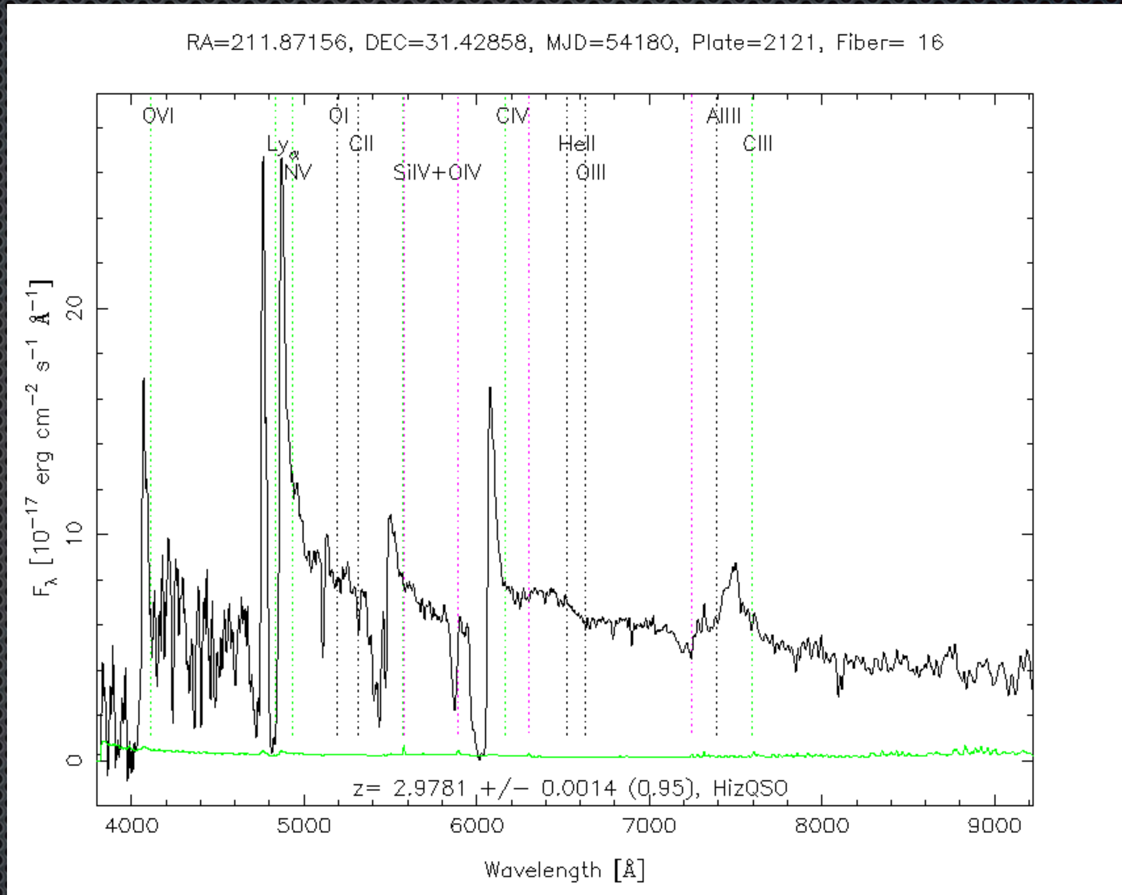
for example looking at the center of our own galaxy NH~10^{22} cm-2 or A_V~4mag

Does hydrogen absorb X-rays ?

AGN surveys

optical qso surveys

- UV excess U-B < -0.5 works z<2.2 (e.g. Boyle et al. 2005, Richards et al. 2005)
- This technique exploits the accretion disc UV bump
- The largest QSO surveys are the SDSS, 2QZ
- However, largely incomplete. Missing the low-luminosity AGN as well as the obscured AGN.



IR surveys

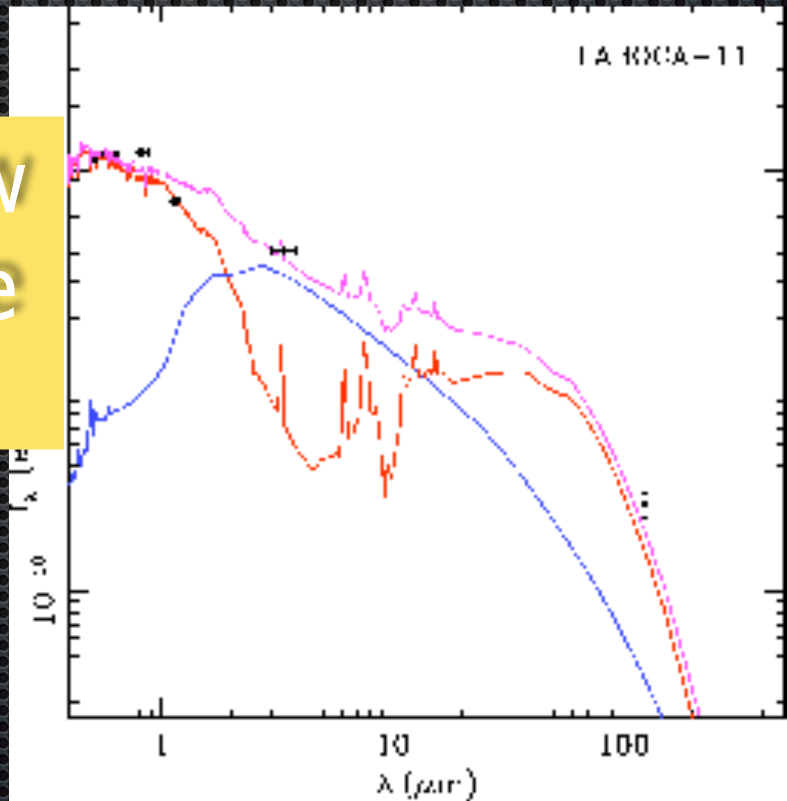
- IR can provide insight on obscured objects as the absorbed radiation is re-emitted at IR wavelengths.

In the IR you get both SFR and accretion and the task Is to separate one from the other

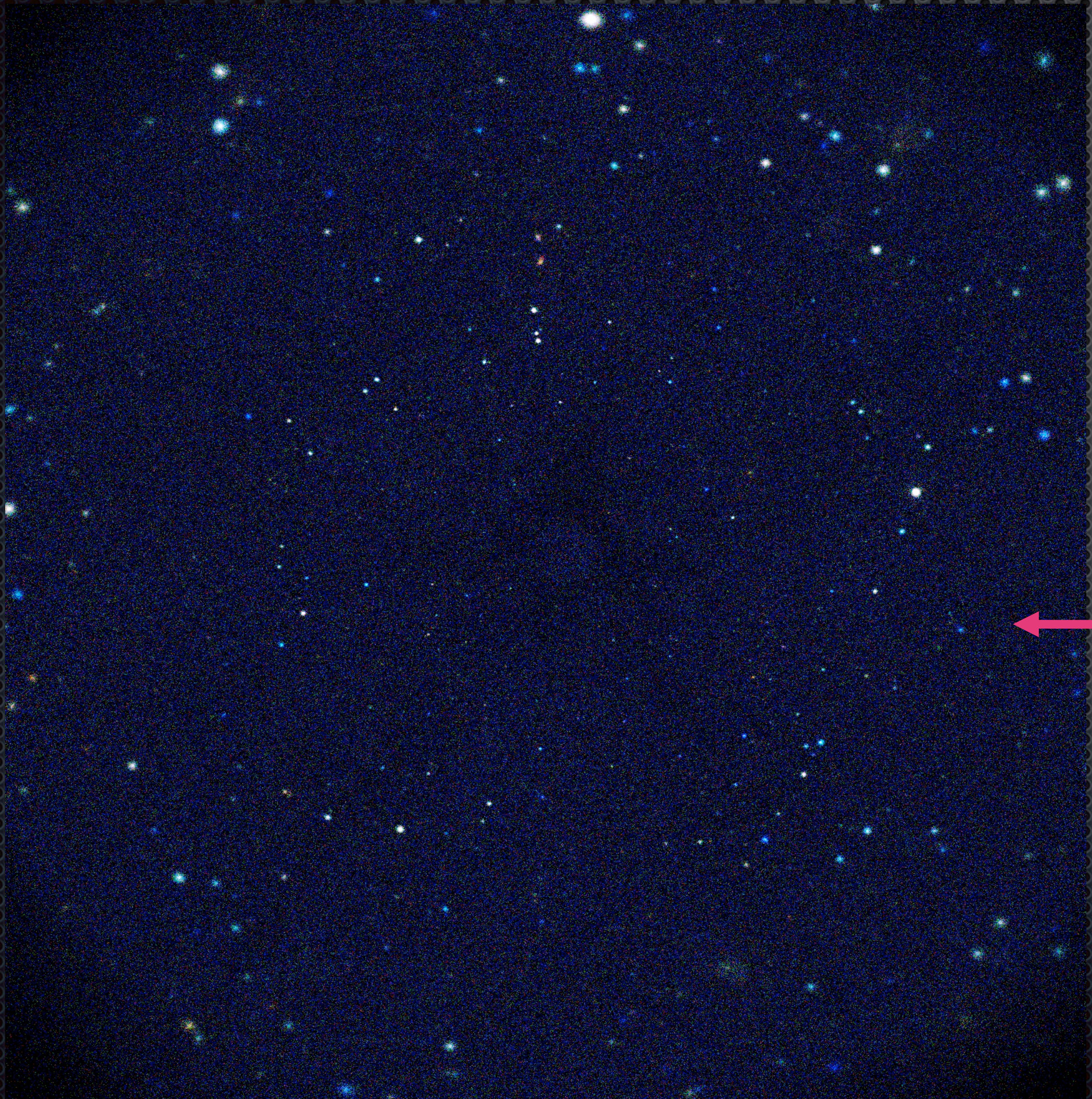
Spitzer/MIPS 24µm CDFS

Spitzer: photometry

Photometric example of how an agn is found through the hot dust



The deepest X-ray observation



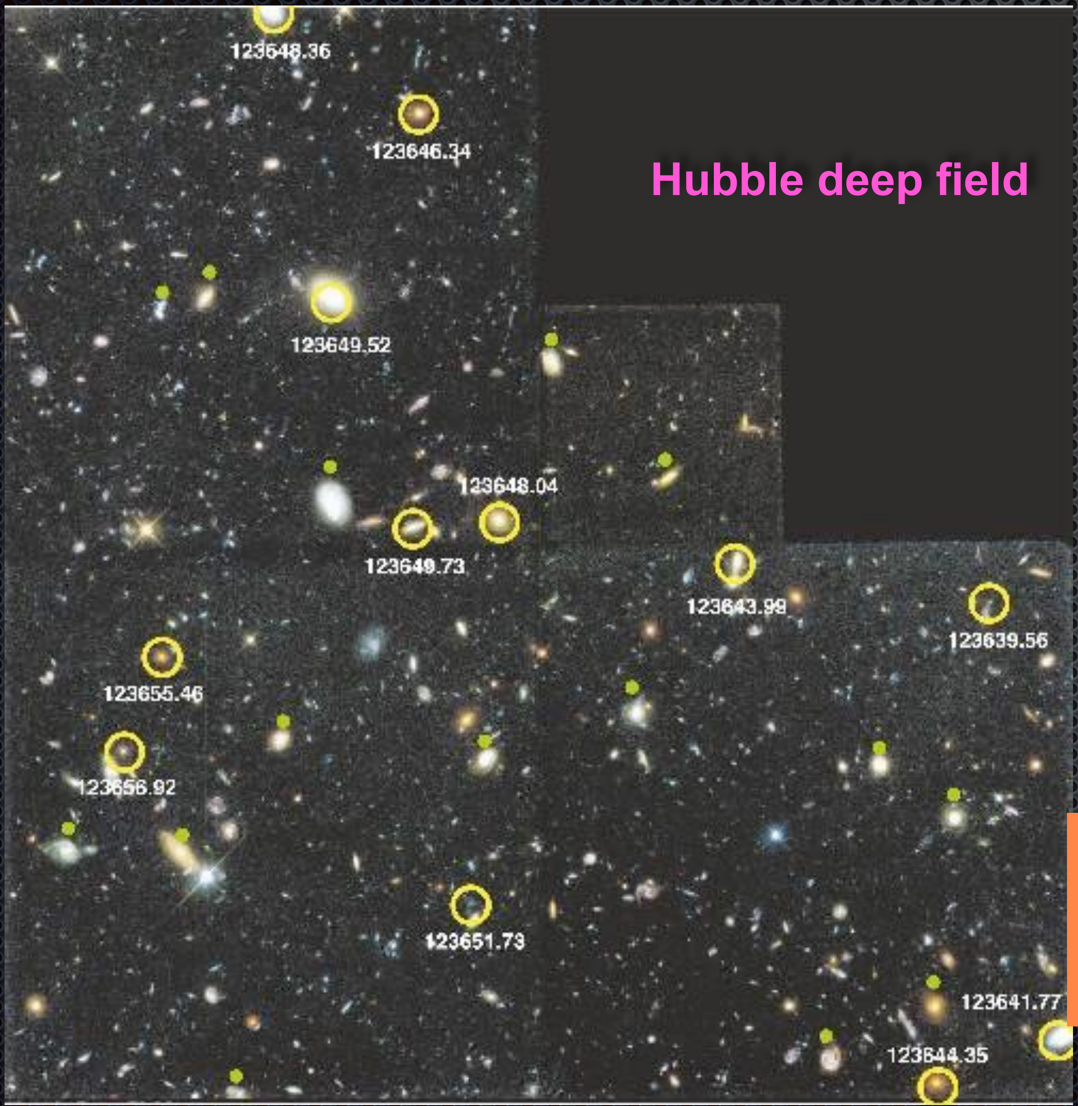
- X-ray surveys have proved to be the most efficient way for finding AGN

The Proof
CDFS 4Ms

20,000 deg-2

In contrast optical QSO surveys
reach sky densities of few hundred per square degree

Difference between X-ray and optical



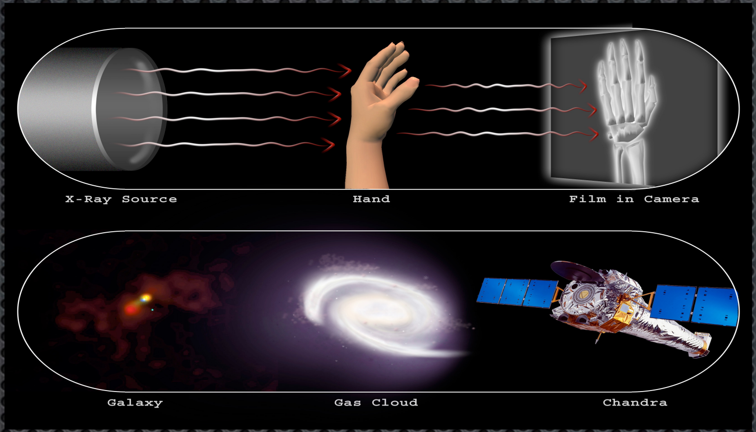
3000 galaxies in a few sq. arcmin

Yellow circles: Chandra x-ray sources

X-rays detect matter around black holes while optical detects star-formation

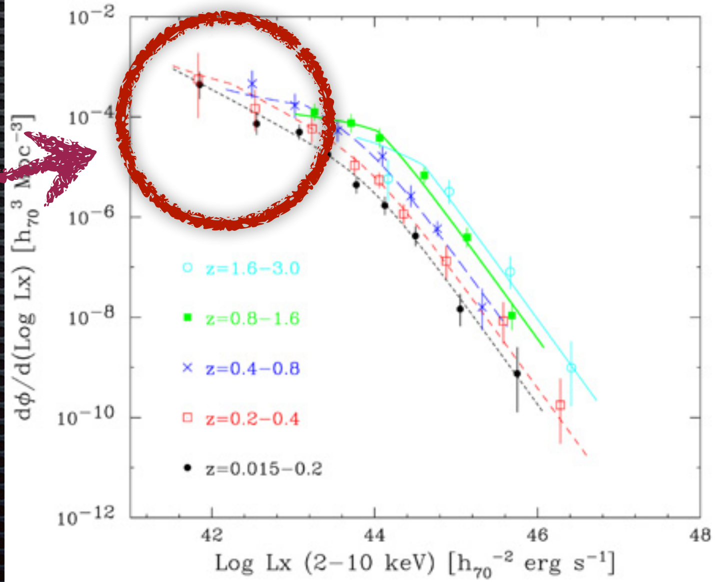
X-rays are the best way to find AGN

X-rays can penetrate large amounts of gas and dust (eg 10^{23} cm^{-2} or A_V~40 mag !)



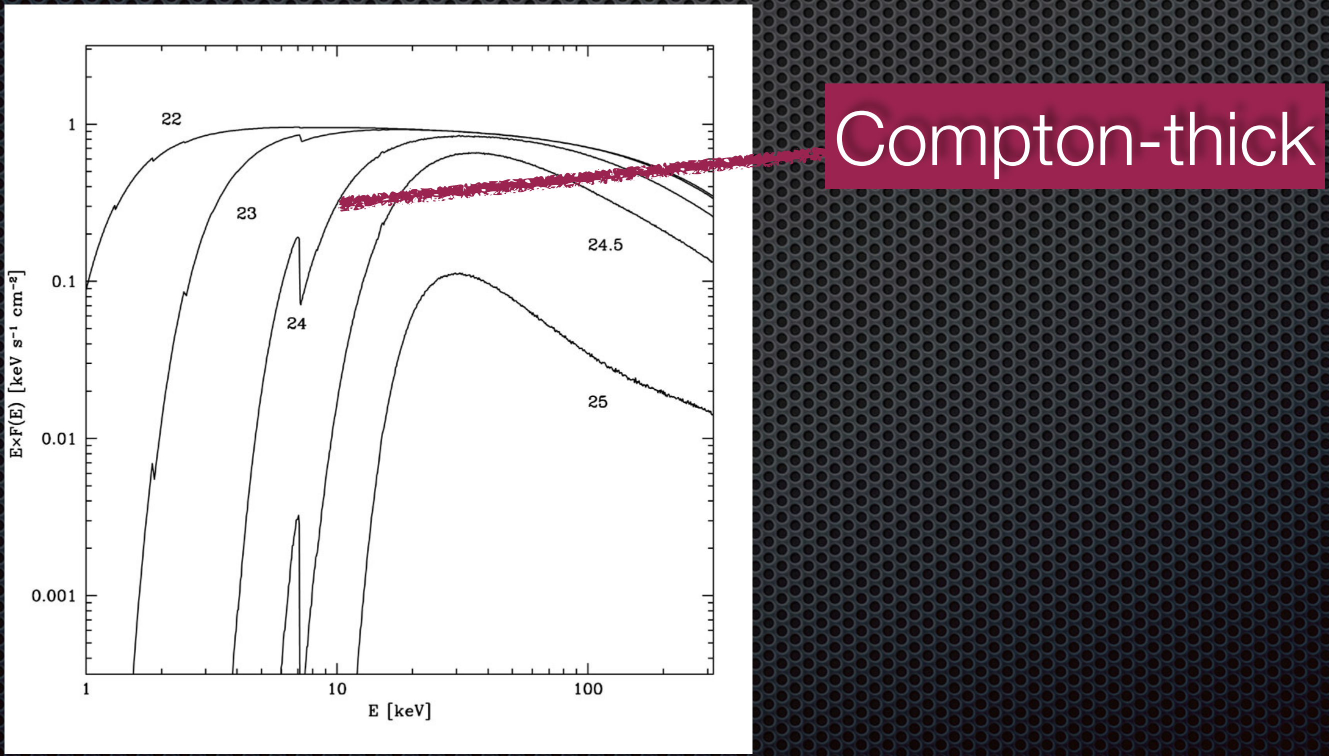
X-rays probe the low luminosity AGN (these are hidden by star-formation in other wavelengths)

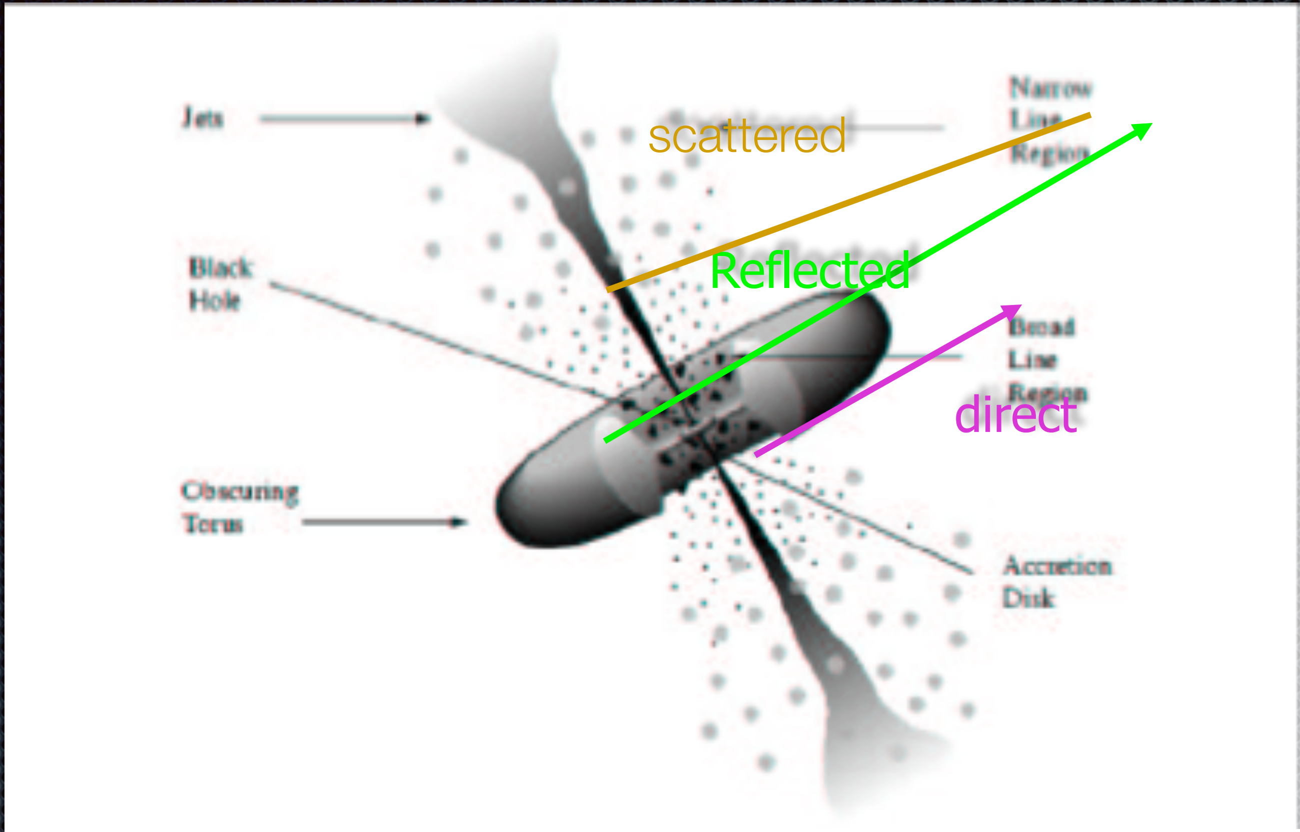
Low Luminosities



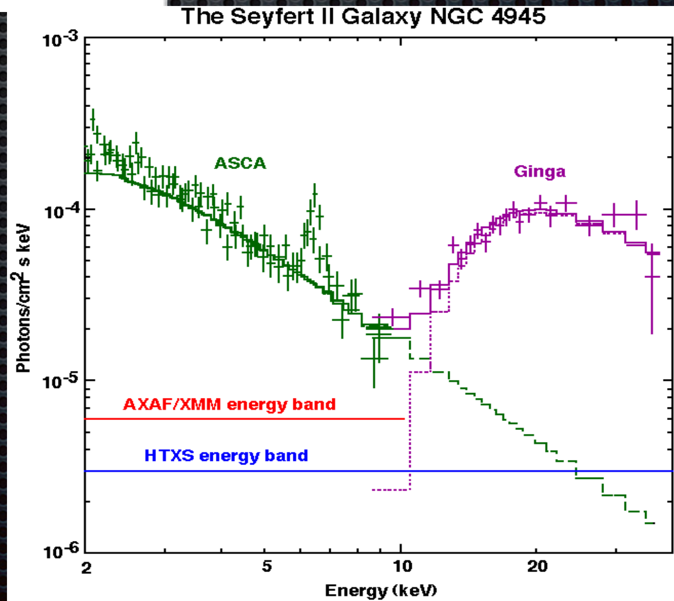
Even X-rays have limitations: compton-thick AGN

When the gas around the black hole is very dense (NH~10^{24} cm^{-2}) the major mechanism is Compon scattering of X-rays on electrons





We still see either **scattered** or **reflected** or even **direct** emission



SOLTAN argument

We will attempt to estimate the mass of the Black holes in the Universe

X-ray energy density at redshift z

$$\int L_X \Phi(L_X, z) \mathrm{dLog} L_X.$$

erg s^{-1} Mpc^{-3}

$L_x = \varepsilon mc^2$ where $\varepsilon=0.1$, m=accreted mass

Mass deposited in Black hole

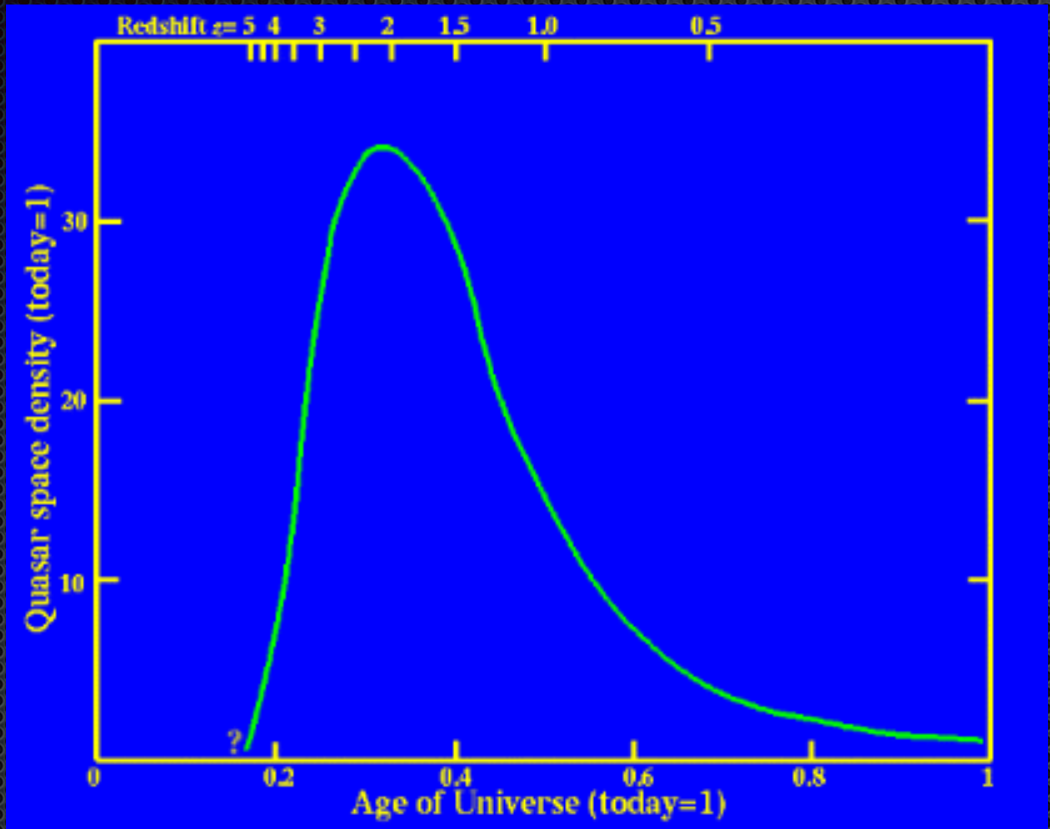
$$M_\bullet = L_{bol}(1-\epsilon)/\epsilon c^2$$

$$\dot{\rho}_\bullet(z) = \frac{1-\epsilon}{\epsilon c^2} \int K L_X \Phi(L_X, z) \mathrm{dLog} L_X$$

Integrating over redshift we obtain $3.2\times10^5\ M_\bullet\ Mpc^{-3}$

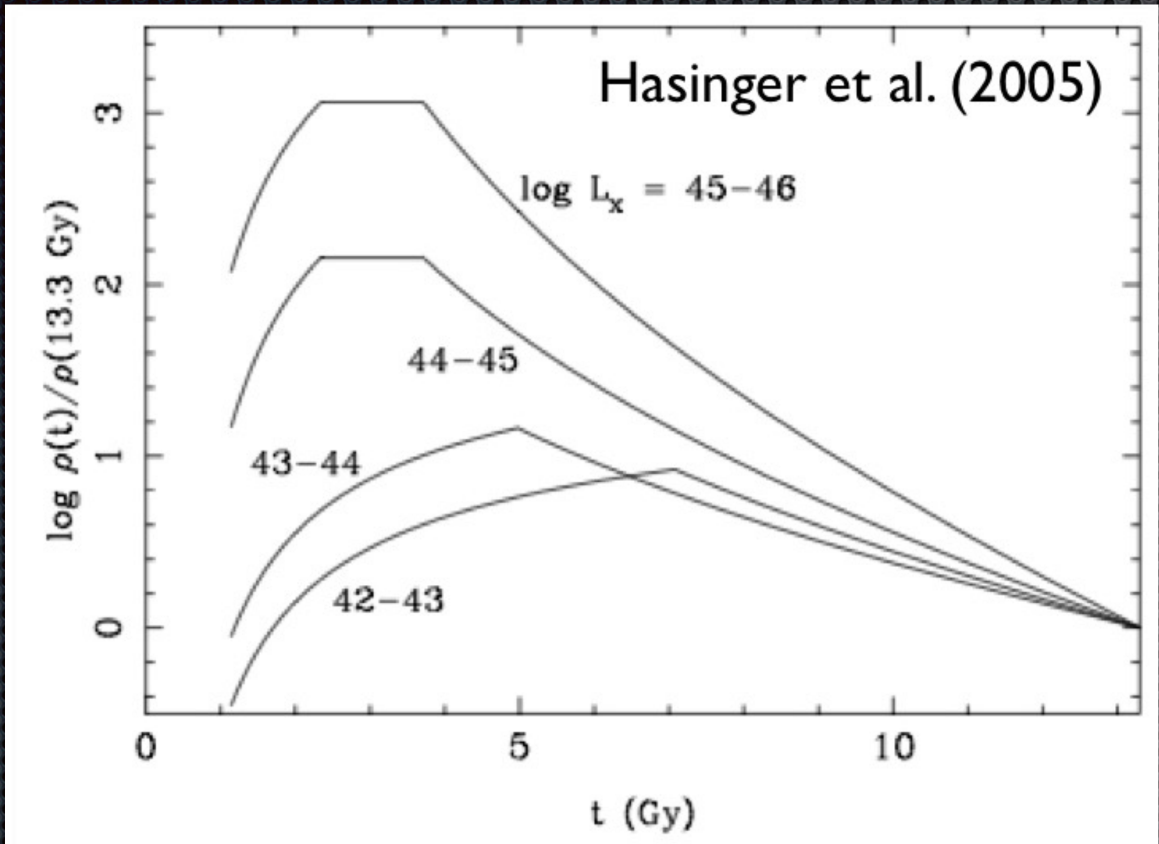
AGN evolution

AGN evolution vs redshift



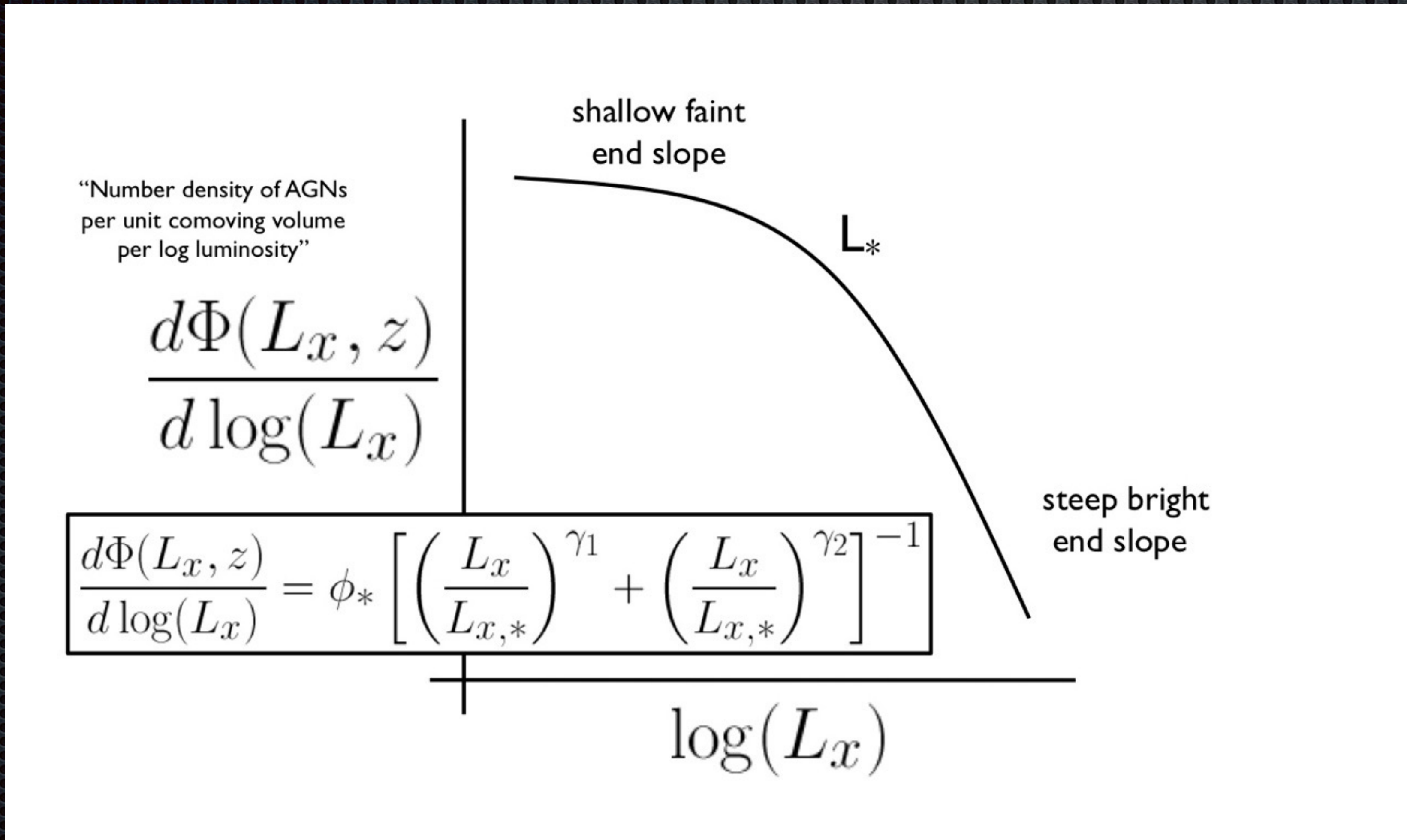
The peak of the BH formation is at z=2
But do all AGN form at z=2 ?

Examining the evolution at different luminosities

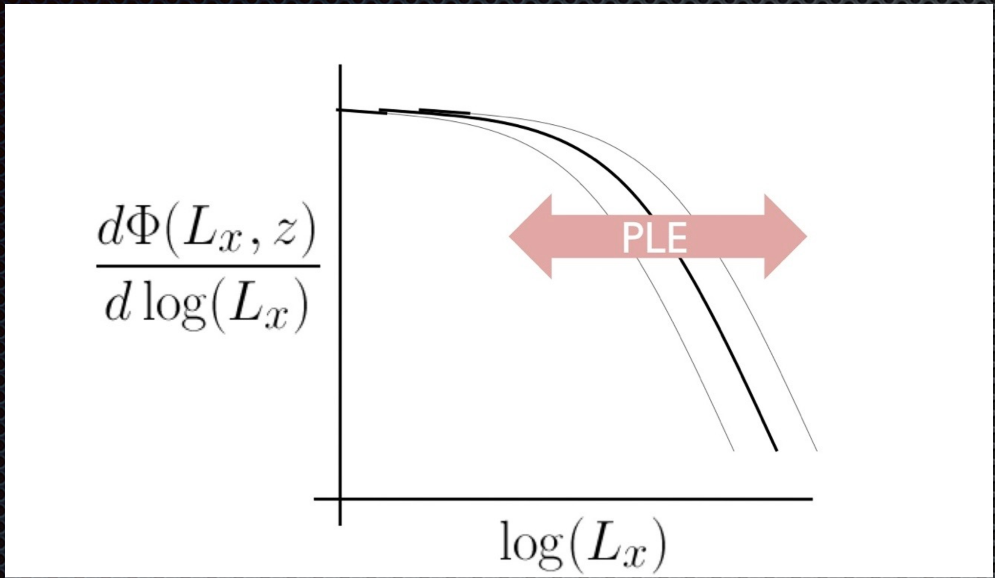


The most massive BH get their mass at high redshift while at low redshifts low mass BH are formed and grow

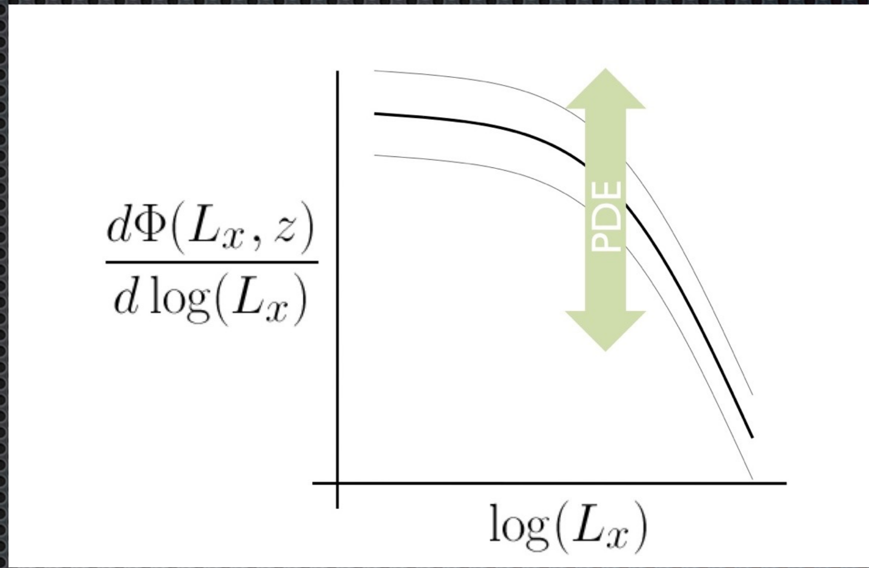
What is a luminosity function



LF plots courtesy of UCLA's AGN course 278

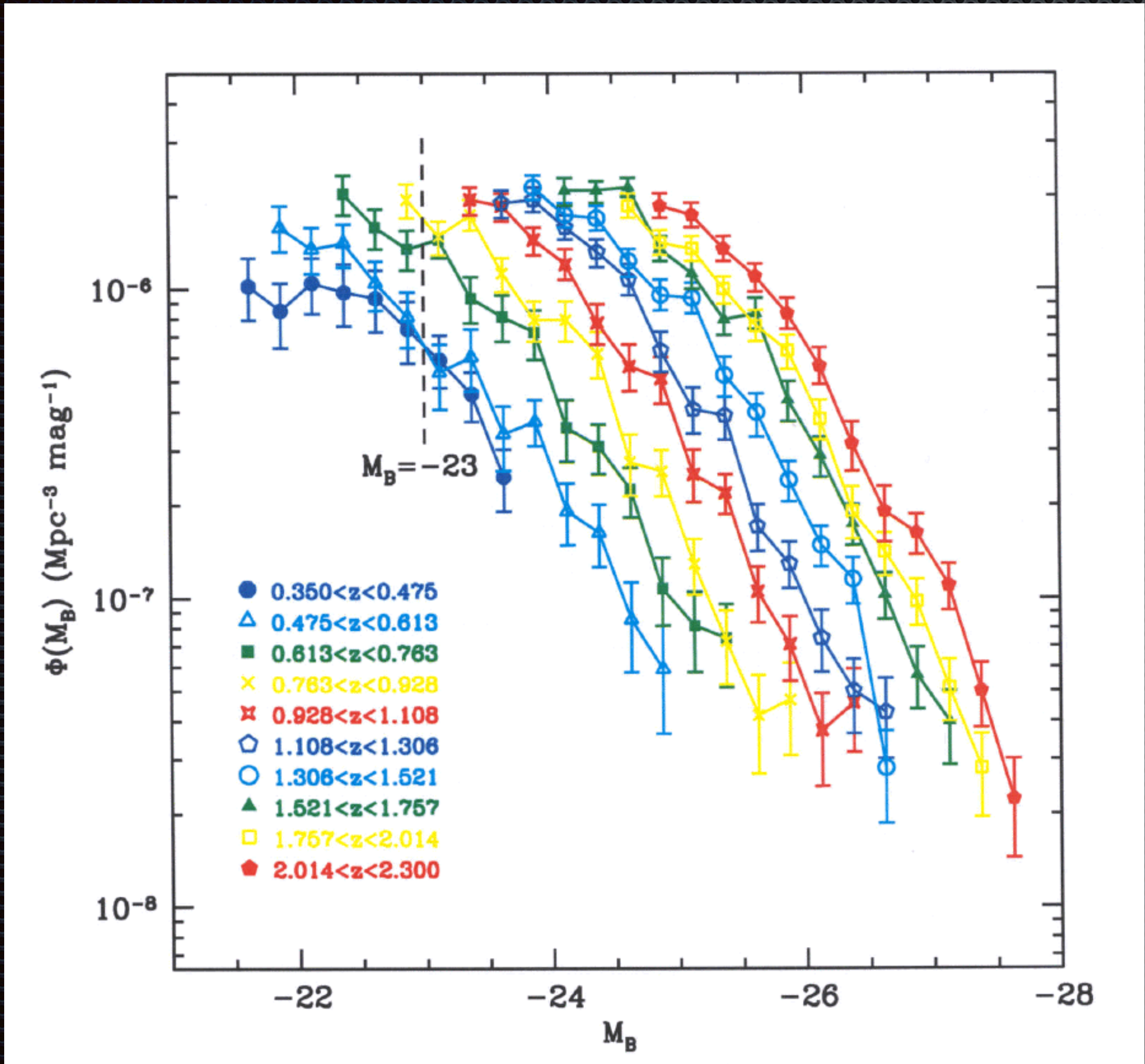


pure luminosity evolution



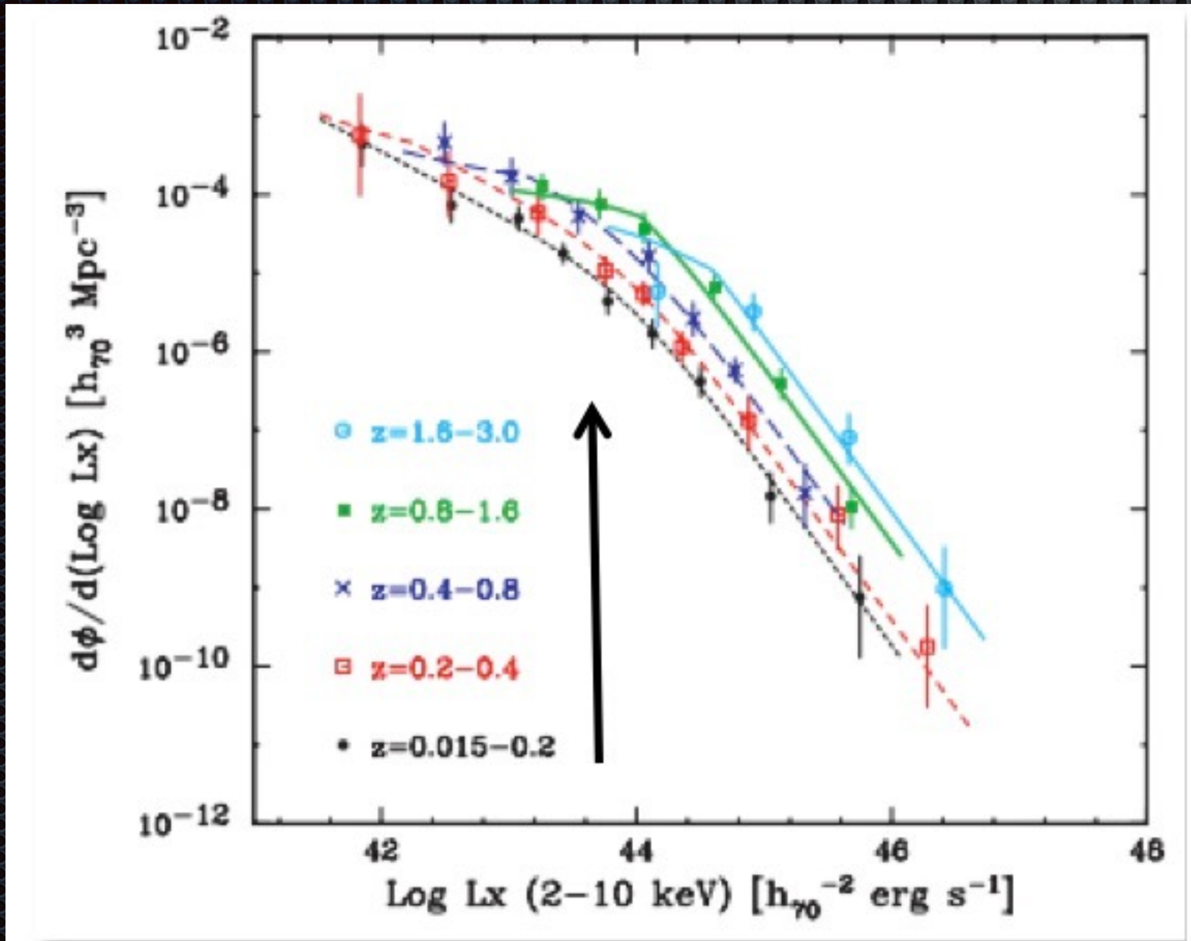
pure density evolution

optical LF



PLE

X-ray luminosity function



More complicated: Lumin. dependent density evolution

AGN Lifetime Δ

The AGN lifetime Δ is given by

$$\int_{x_{\min}}^{\infty} \Phi(x,z)\,dx = \int_{0}^{\infty} dy\,\Delta_h(y,z)\Phi_h(y,z)$$

$\Phi(x,z)$ is the AGN luminosity function (x = luminosity)

$\Phi_h(y,z)$ is the distribution of halo masses (y = halo mass)

The first black holes

Highest redshift QSO (optical) at z=7.1 (Mortlock et al. 2011, Nature)

Black hole mass ~**$2x10^9$ $M_\odot$**! How can be formed that early in the life of the Universe ? 0.75 Gyr old

Two scenaria for BH formation:

1. population-III stars M=100 solar masses

2. collapse of a primordial cloud   M>1000 solar masses

Problem: growth of the black hole

$$L = \varepsilon\ c^2 dM/dt \qquad (1)$$

assuming it radiates at the Eddington luminosity

$$L = \frac{4\pi G m_p}{\sigma_T} M \qquad (2)$$

combining (1) and (2)

$$\frac{dM}{dt} = \frac{4\pi G m_p}{c\ \varepsilon\ \sigma_T} M$$

$$\frac{dM}{M} = \frac{4\pi m_p G}{c\varepsilon\sigma_T} dt = \frac{dt}{\tau\varepsilon}$$

$$M = M_o\ e^{t/\tau\varepsilon}$$

where M_o *is the initial mass of the black hole and* $\tau = 4.6 \times 10^8$ *years*

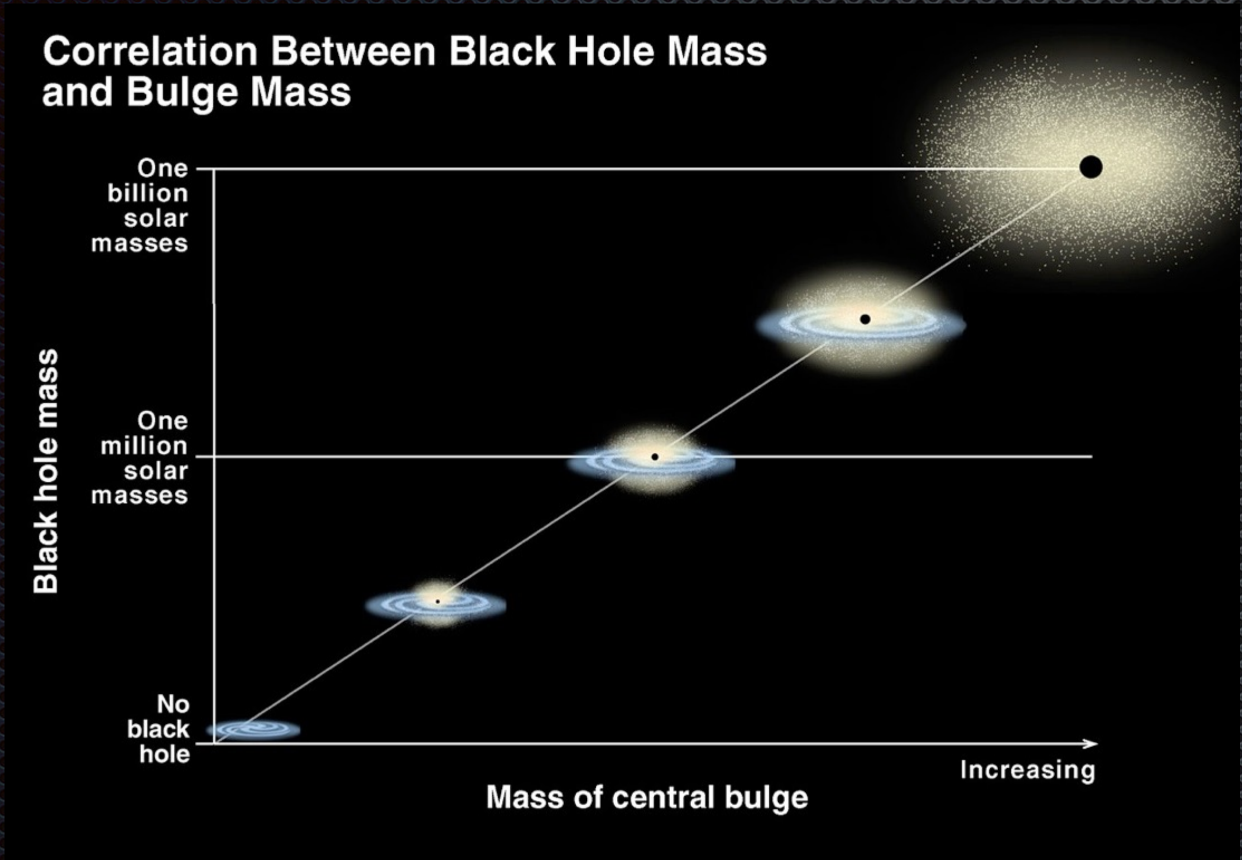
The initial BH mass is above the upper limit of the theoretical models

- In 0.5 Gyr the BH grows by 2×10^4
- Hence, for the BH to become $M = 2 \times 10^9\ M_{\odot}$ at z=7, we need an initial mass of $10^5\ M_{\odot}$

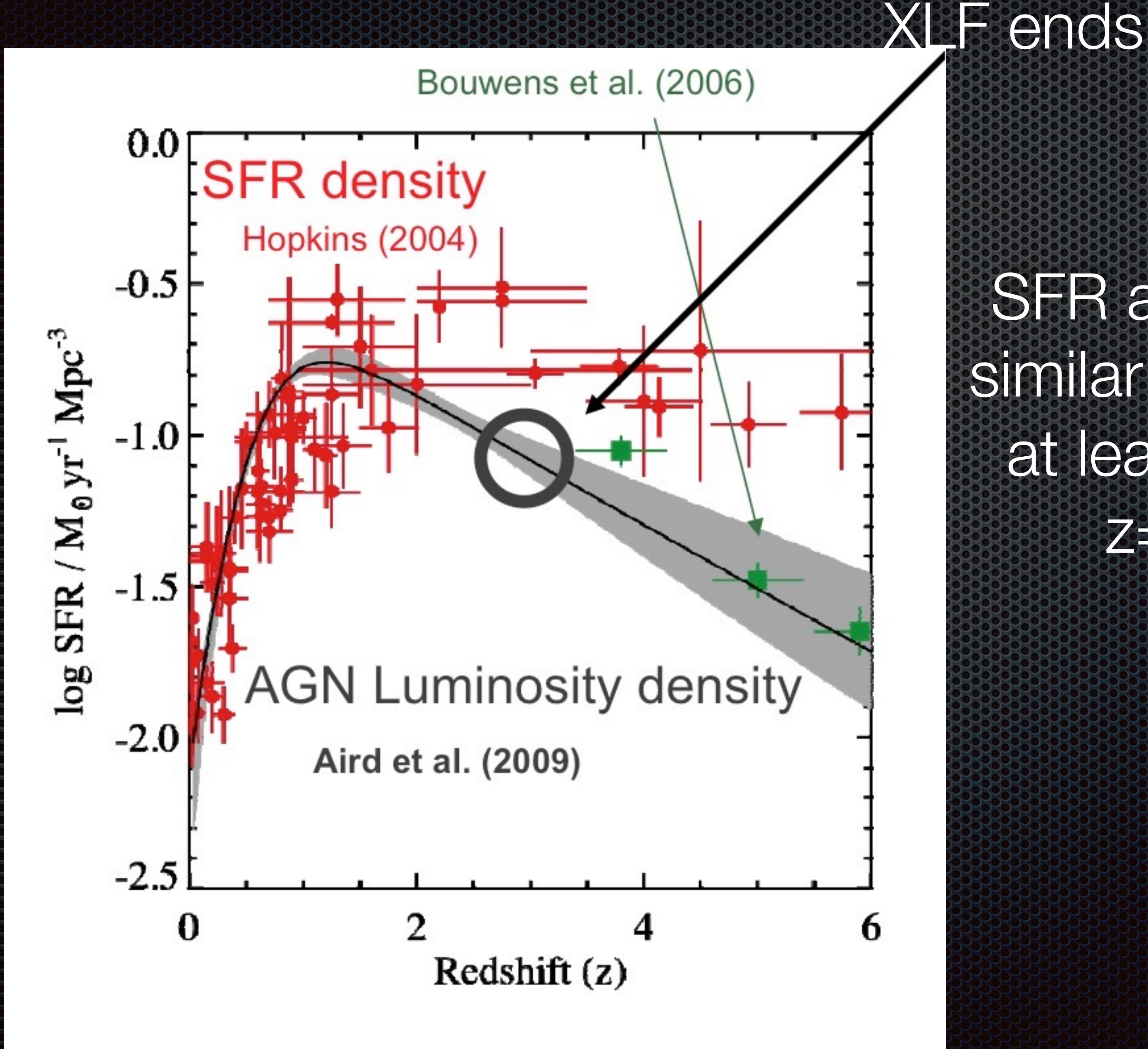
AGN galaxy co-evolution

- two facts:
- 1) relation between bulge and BH mass
- 2) AGN and Star-formation rate evolve in the same way

BH-Bulge relation



Practically all galaxies have (apart from the very late-type ones (Sc onwards)
(Gebhardt et al. 2000, Magorian 1998)



SFR and AGN similar evolution at least up to z=2-3

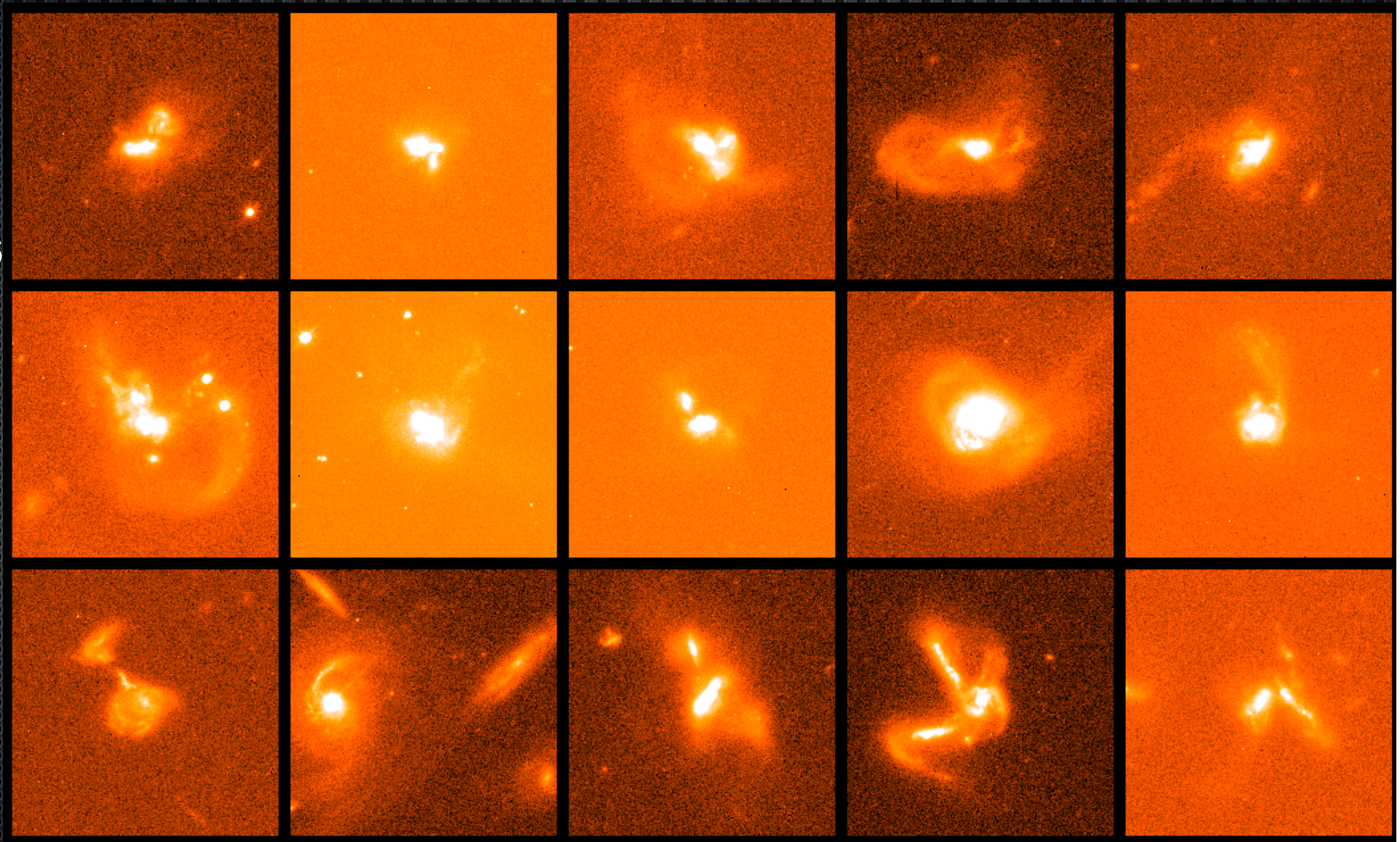
why are agn active ?

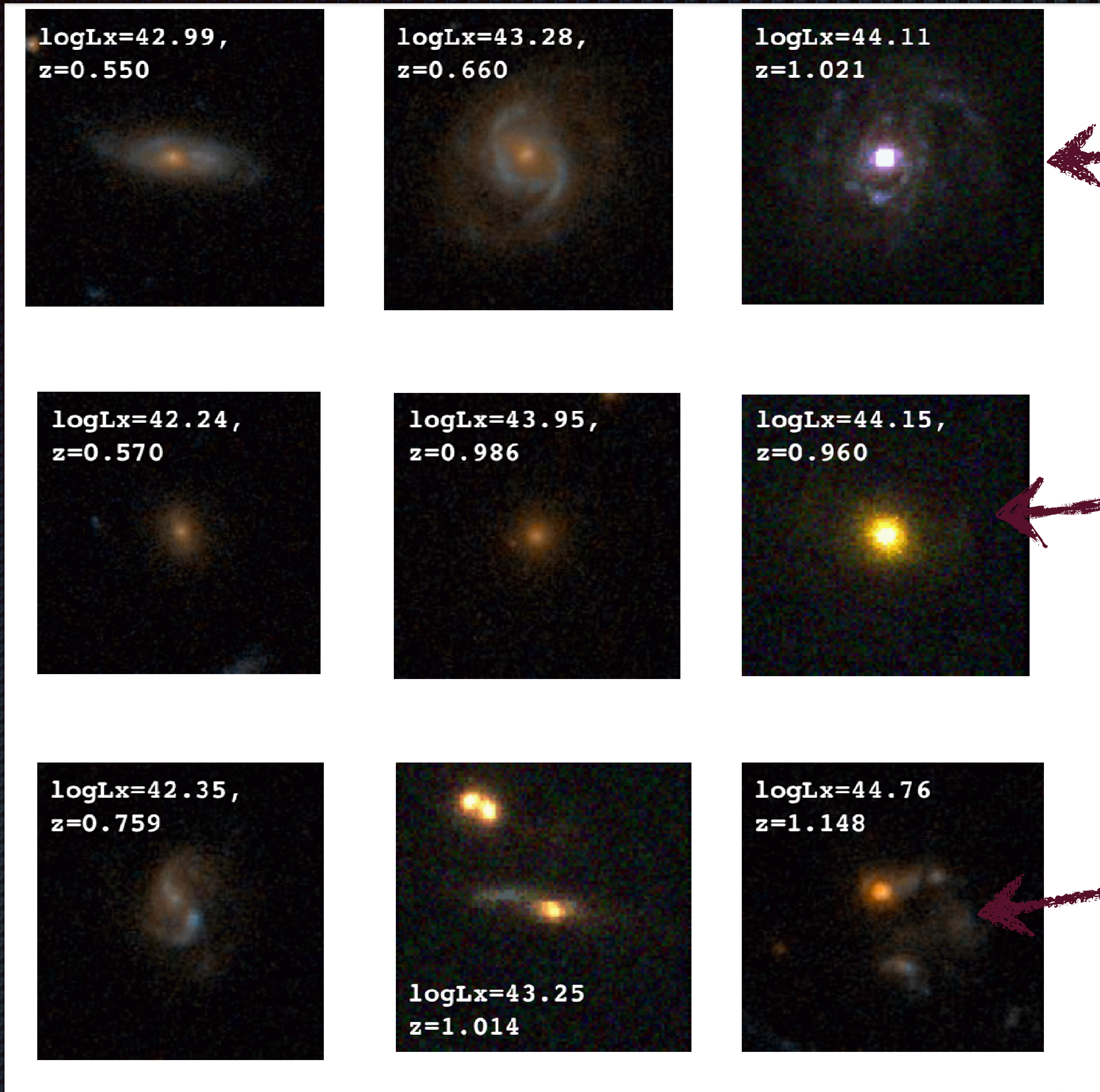
- Practically all galaxies have a black-hole (including our own galaxy)
- But not all are AGN   (20% present Seyfert or QSO activity)

What brings matter the BH ?

major mergers ?
Hopkins et al. 2006
(objects like
Ultraluminous IR
galaxies are the
QSO precursors)

alternatively minor
interactions





spiral

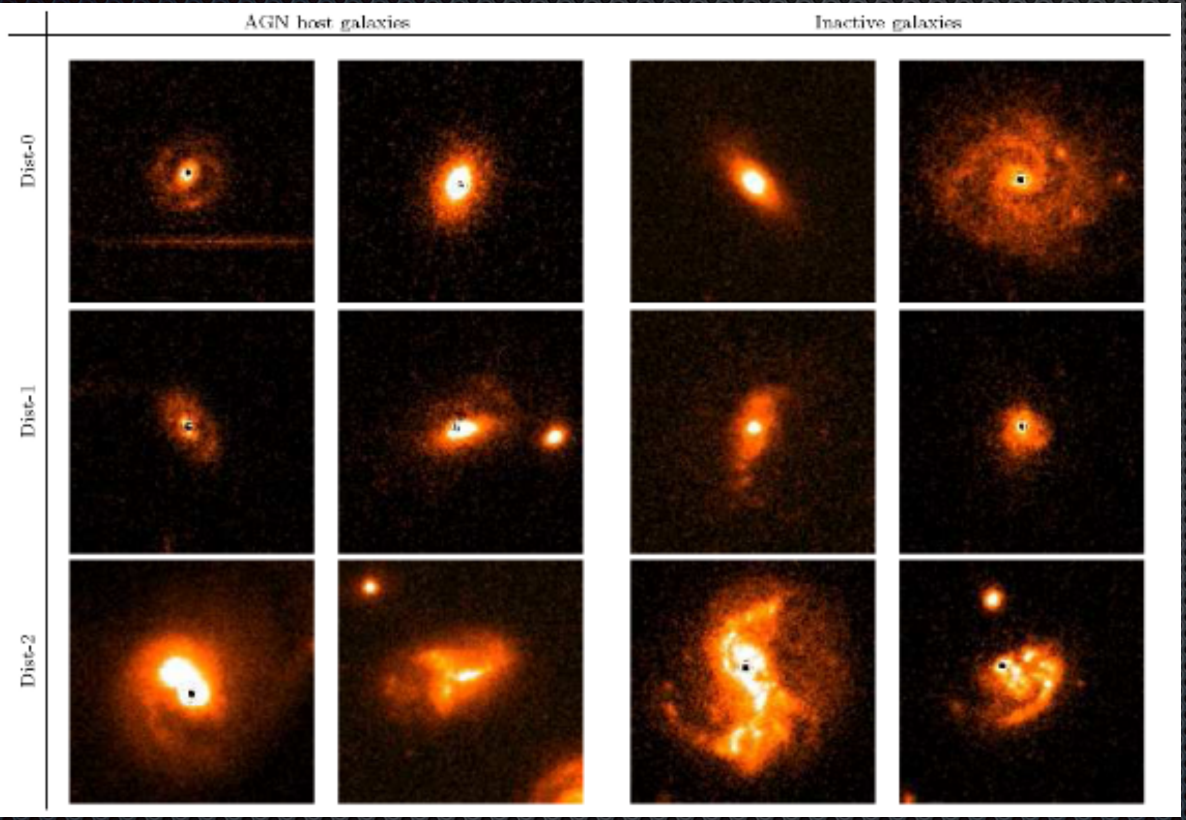
elliptical

disturbed morphology

Morphologies of X-ray selected AGN at high redshifts

the more massive galaxies have higher probabilty for hosting an AGN

AGN morphology



comparison between the morphologies of AGN and normal galaxies shows no difference

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