Test 2 Review

Covers everything since Exam 1 (Chs 6-9).
All constants needed will be given on test.

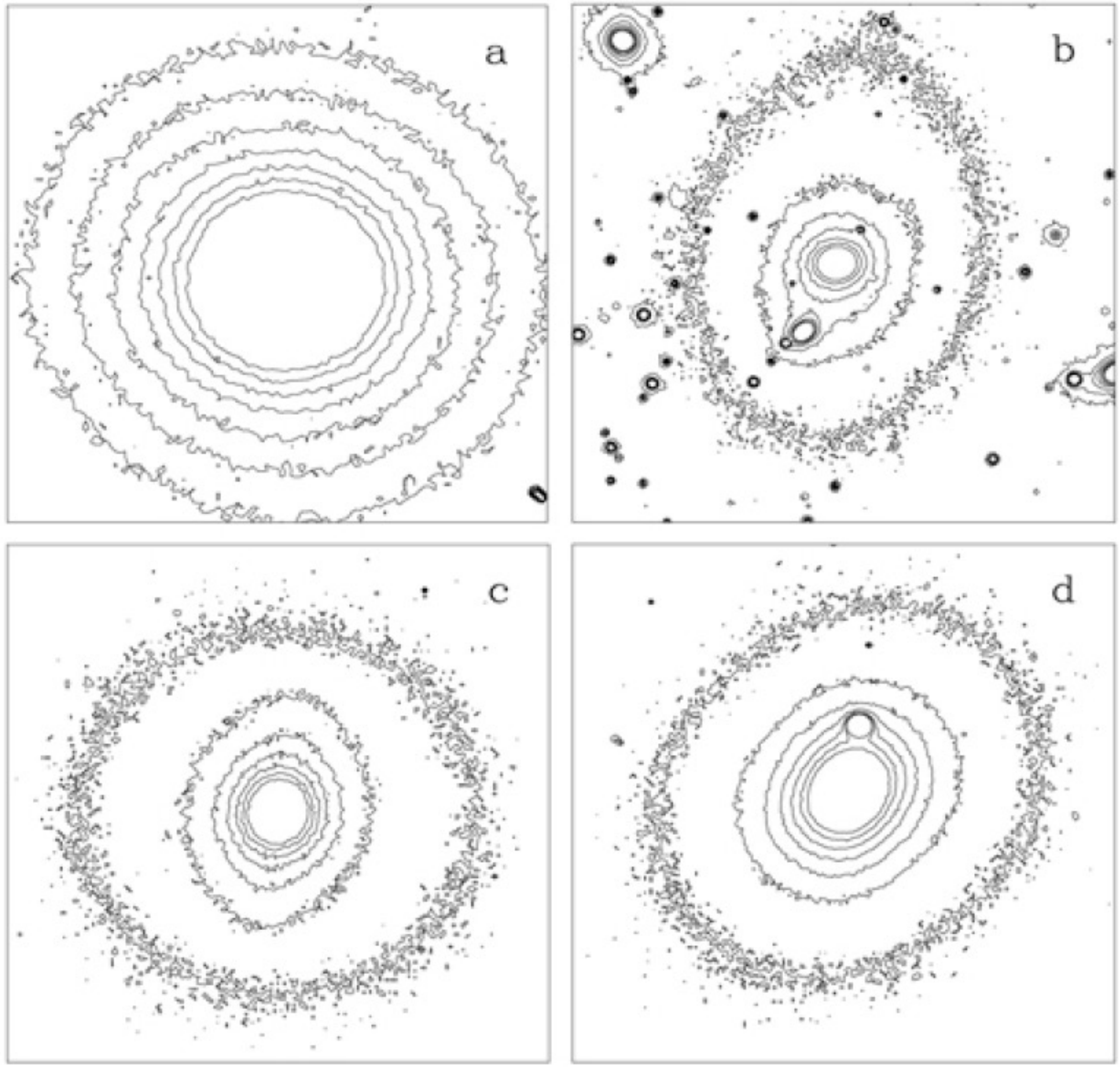
Test #2

- Covers material since first test
- Supporting reading chapters 6-9
- Some questions are “concept” questions, some involve working with equations, calculations
- Study your lecture notes, homeworks, worksheets, review supporting reading
- There will be at least one question from a paper we read
- Know equations/constants on the sheet just handed out.
- Bring calculator, something to write with. Closed book, closed notes
- Attempt every question – show what you know
- Don’t get bogged down on a question.

Astronomy 537

Lecture 12: Ellipticals

Isophotes



Twisted

Disklike

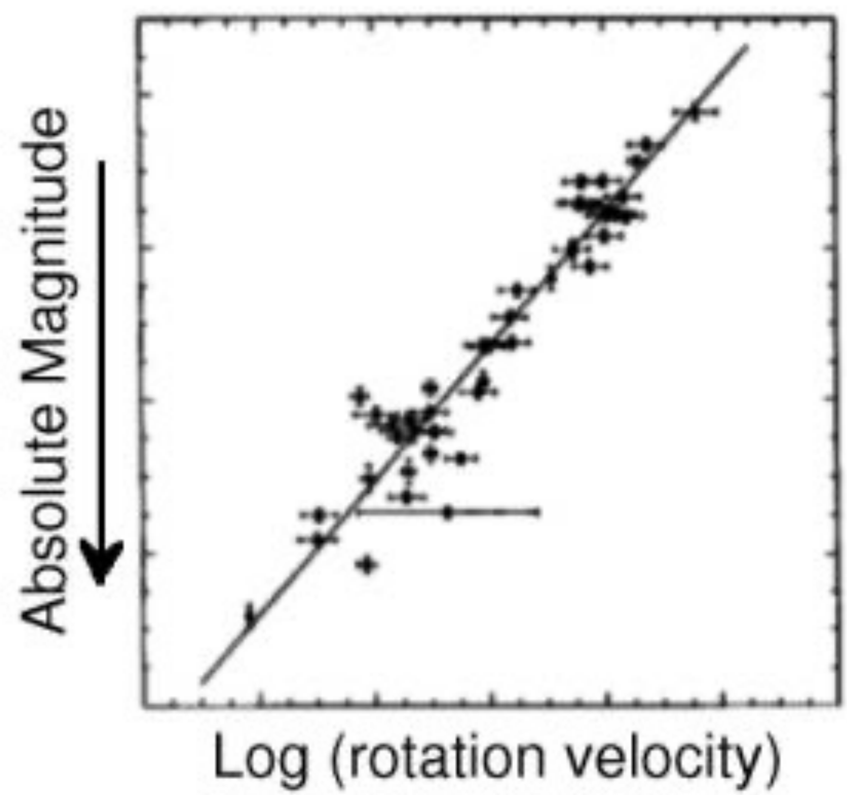
Boxy

Fig 6.1 (R. de Jong) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

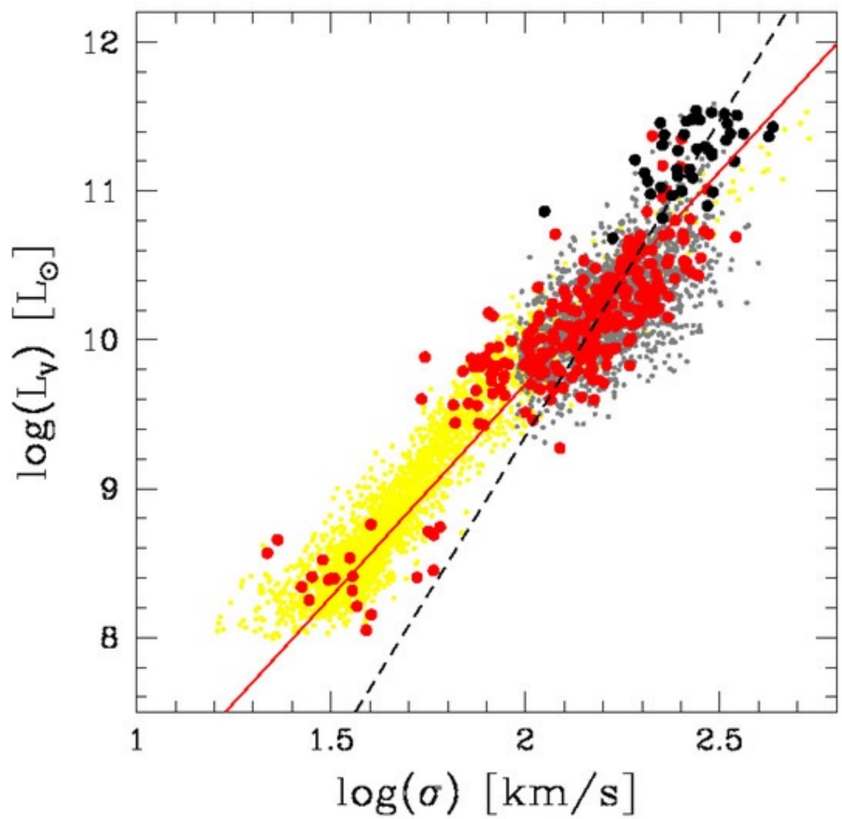
Faber-Jackson relation:

In 1976, Faber & Jackson found that $L \propto \sigma^4$

Tully Fisher (disk galaxies)



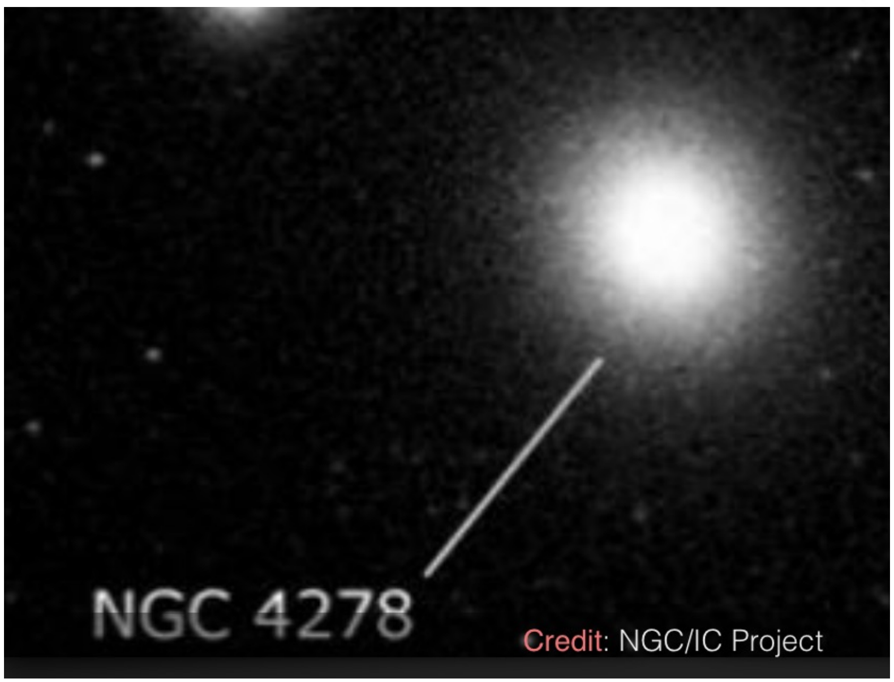
Faber Jackson (Es)



Measuring E Galaxy Masses

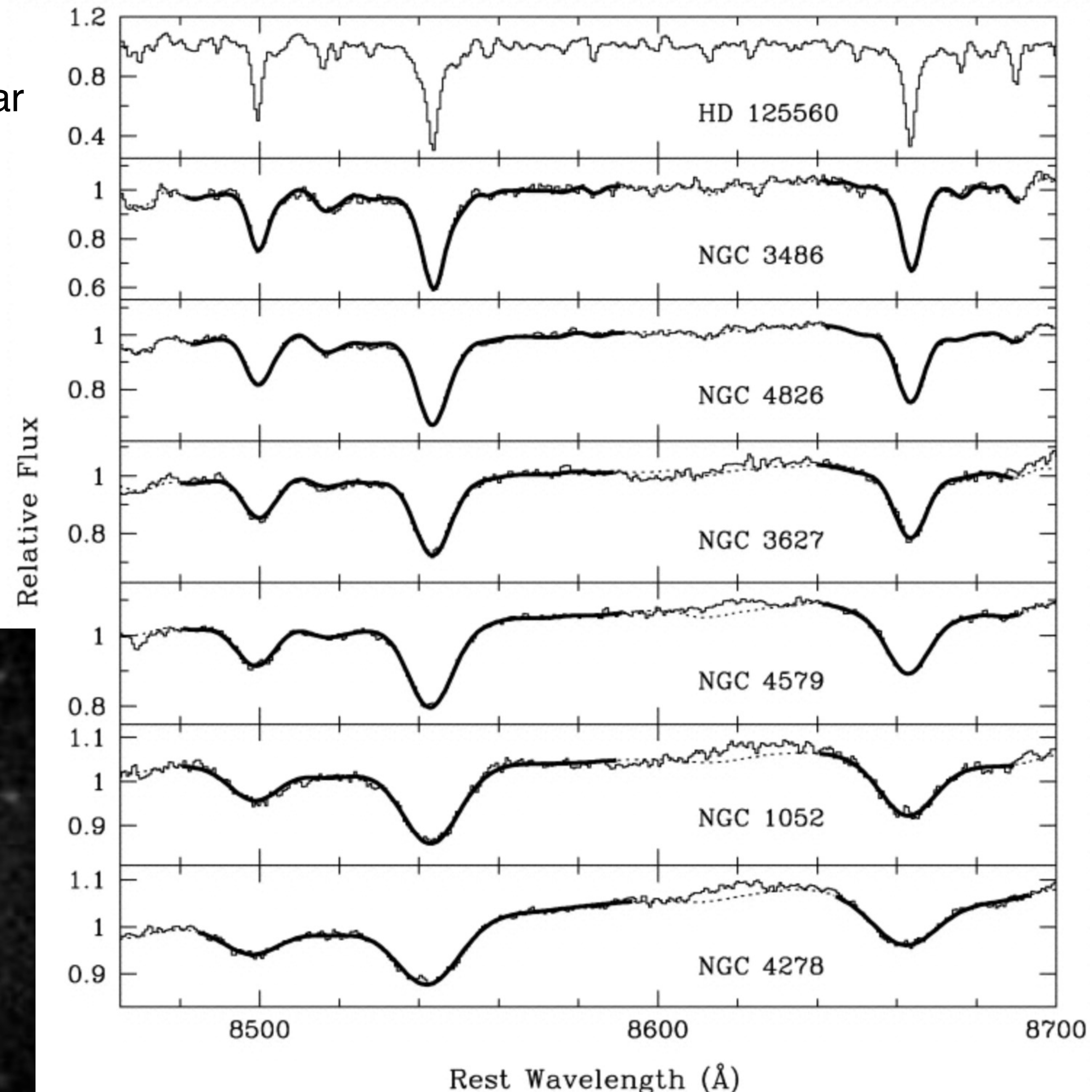
Virial Theorem

$M = \sigma^2 R/G$



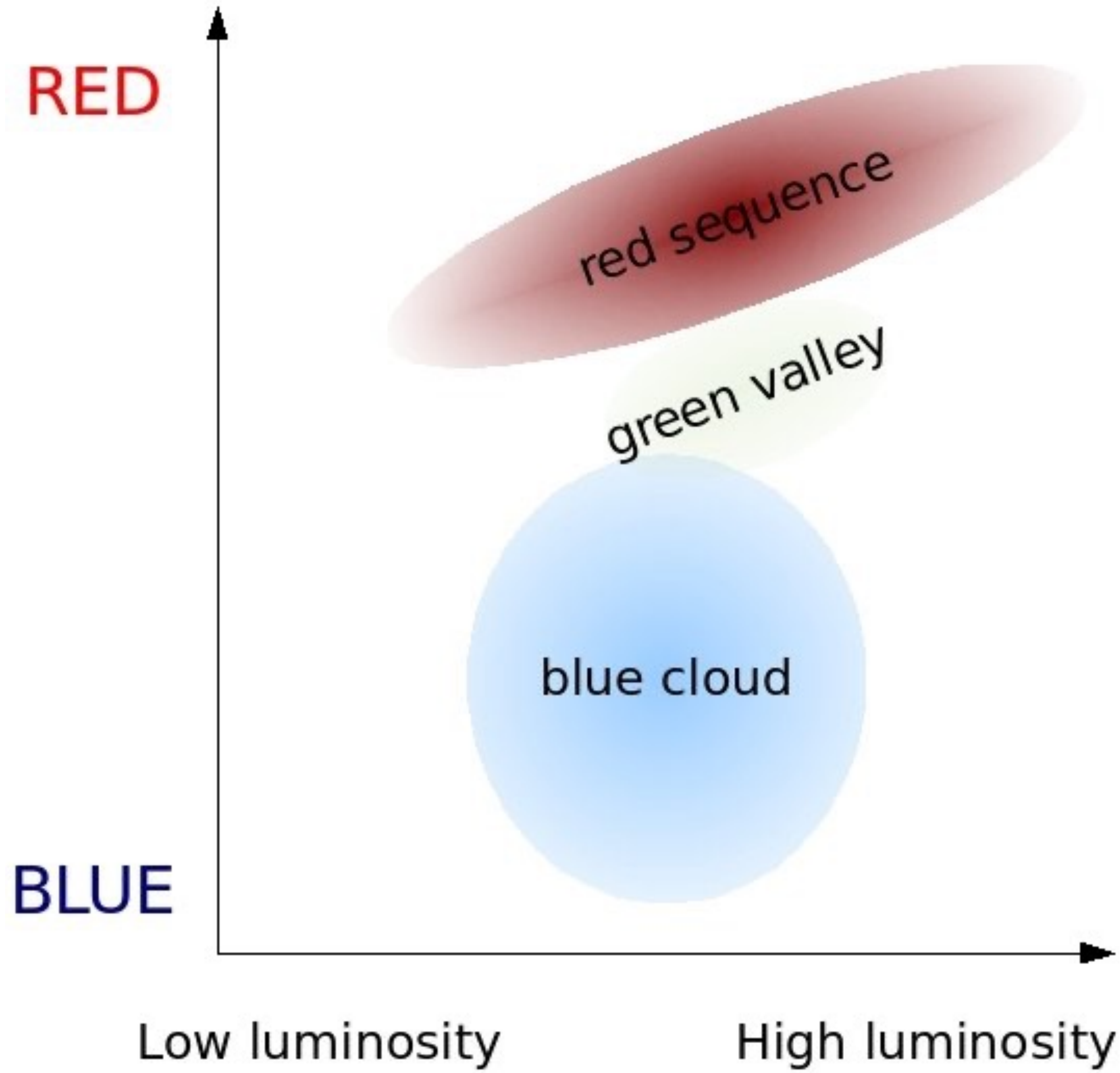
Ca II Triplet

star



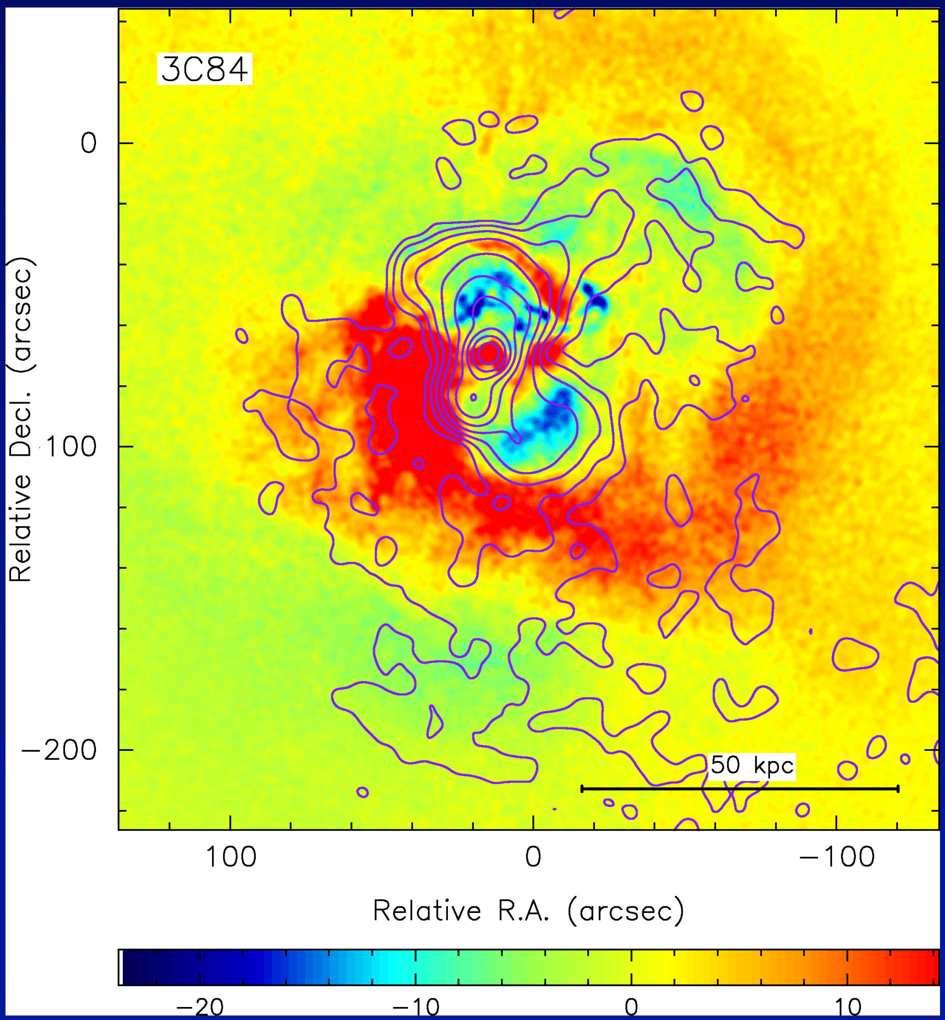
Barth et al. 2002

Galaxy Color-Magnitude Diagram

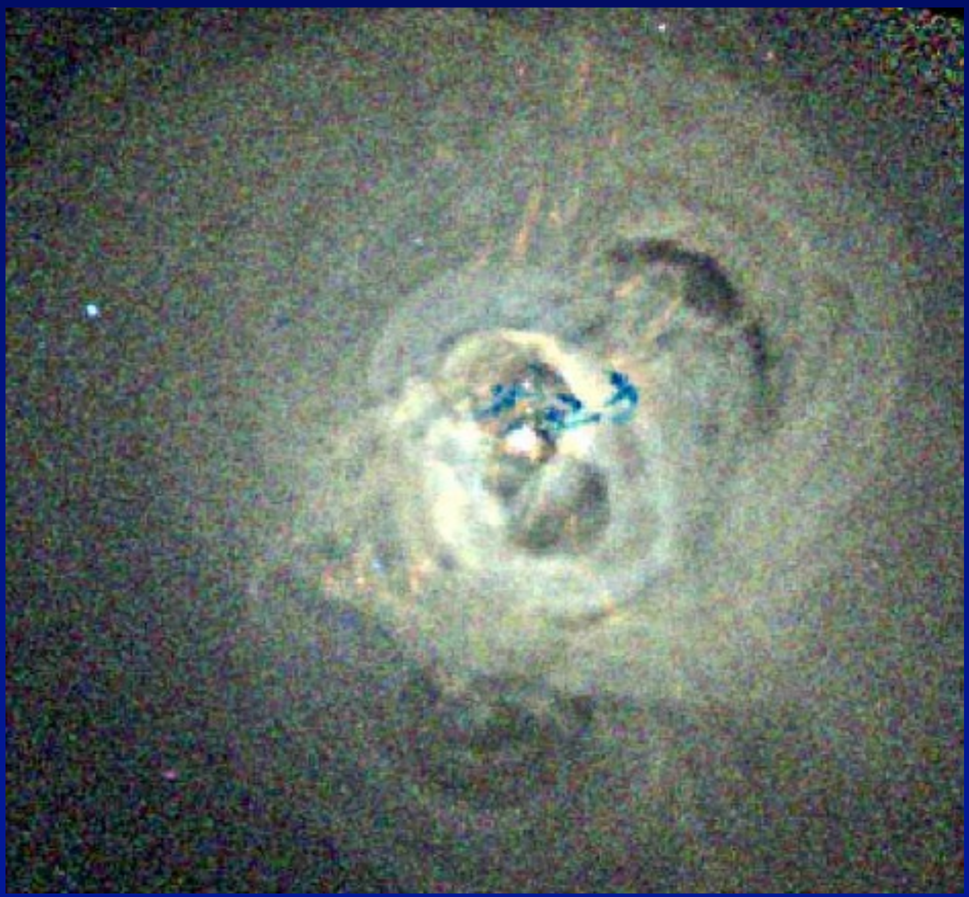


Fabian et al. 2003, 2005

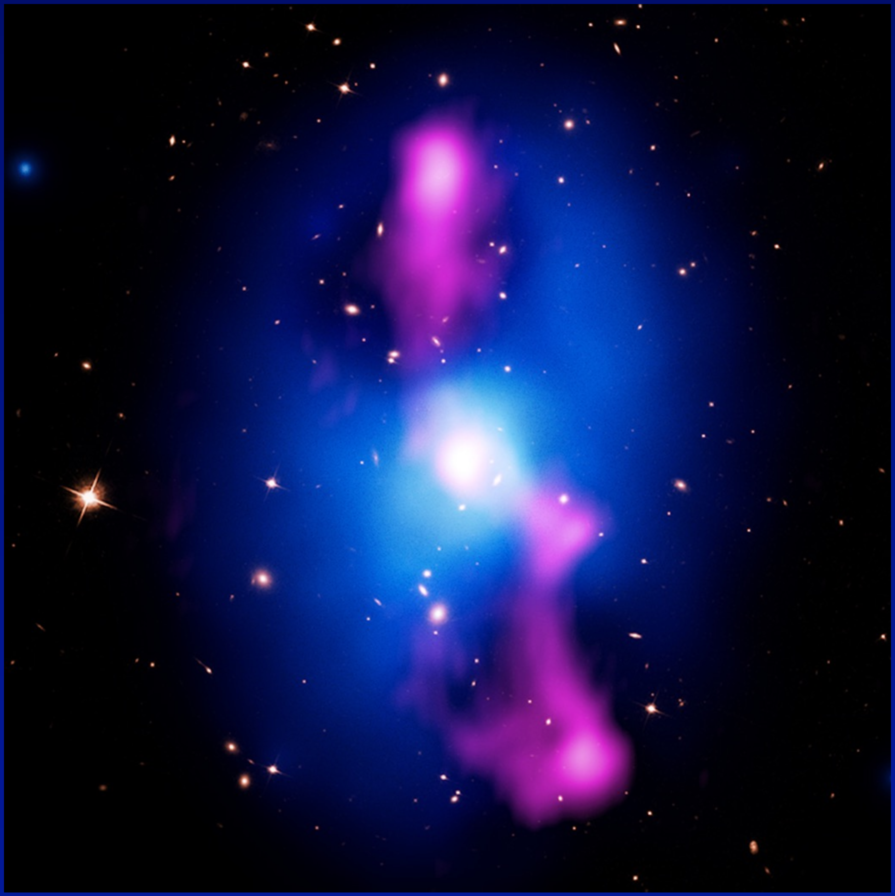
Chandra + VLA

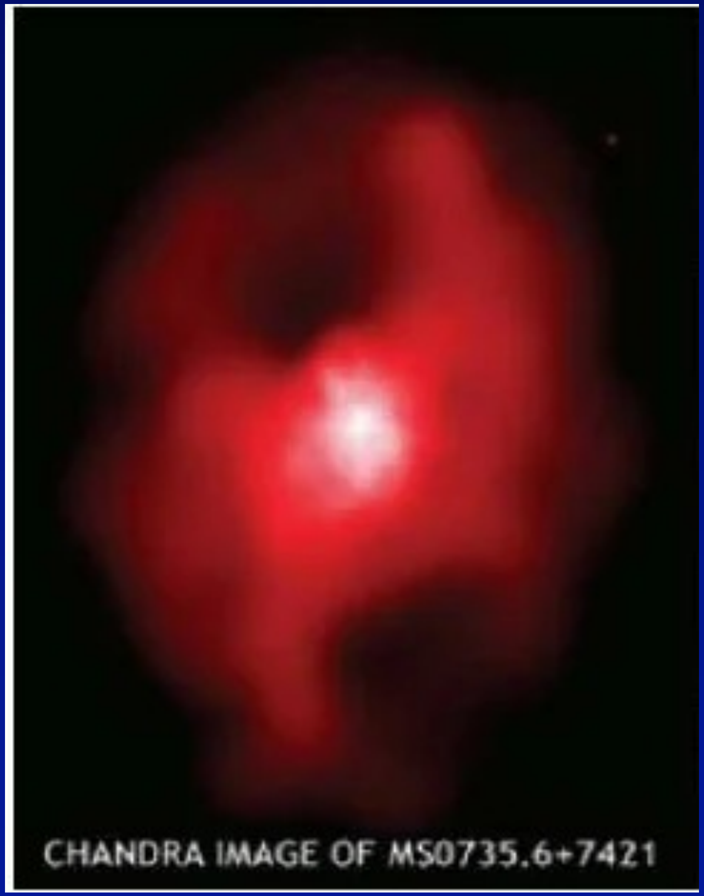


Chandra - unsharp mask



MS0735.6+7421 Galaxy Cluster



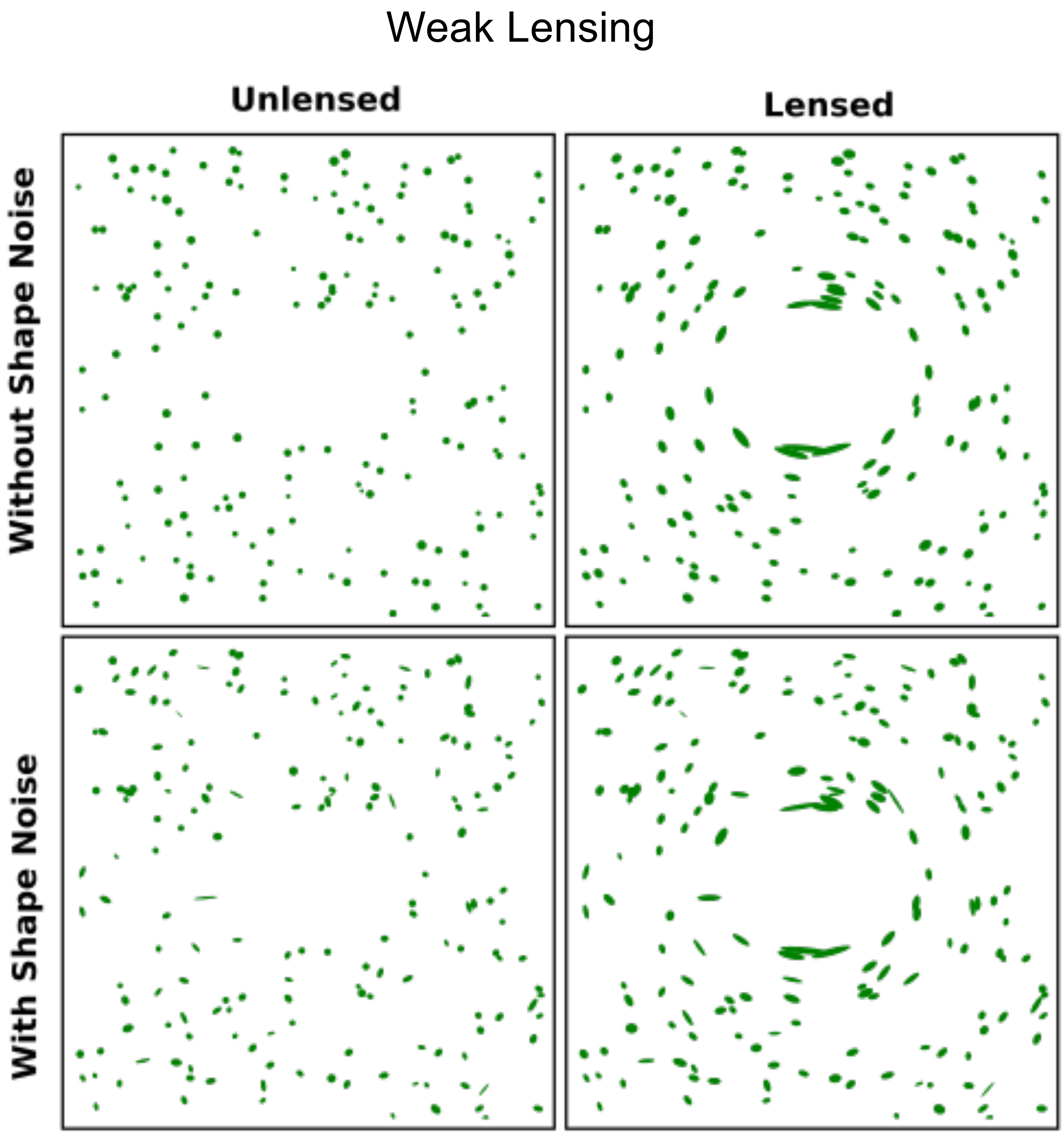


Ways to measure Cluster mass?

- X-ray luminosity of the hot gas [see previous slides]

- Gravitational lensing (strong and weak)
- S-Z effect
- Faraday rotation

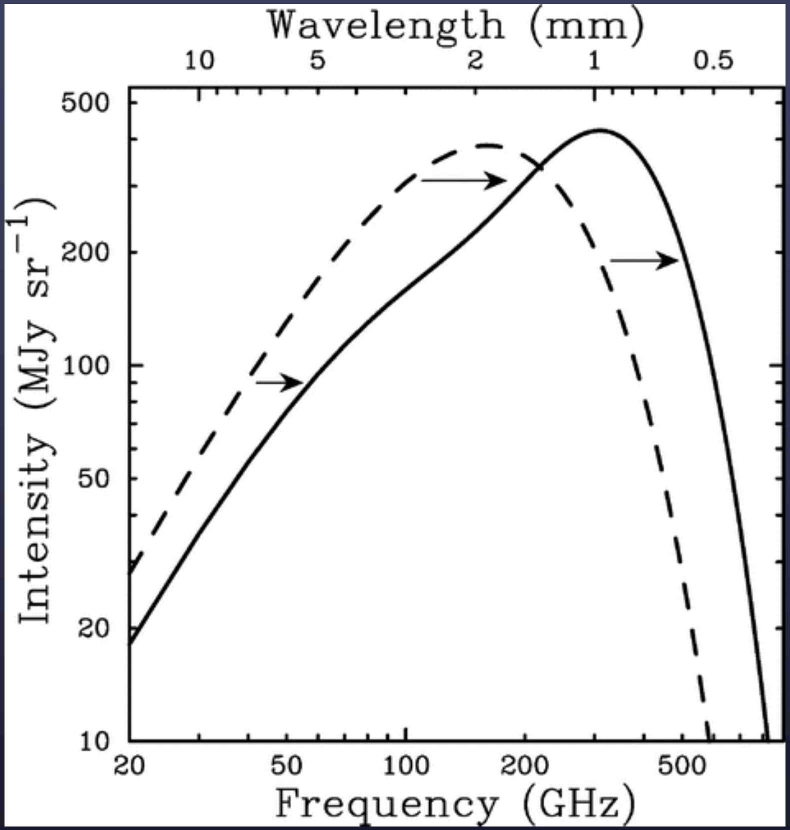
Strong lensing. The gravity of a foreground cluster of galaxies distorts the images of background galaxies into arcs

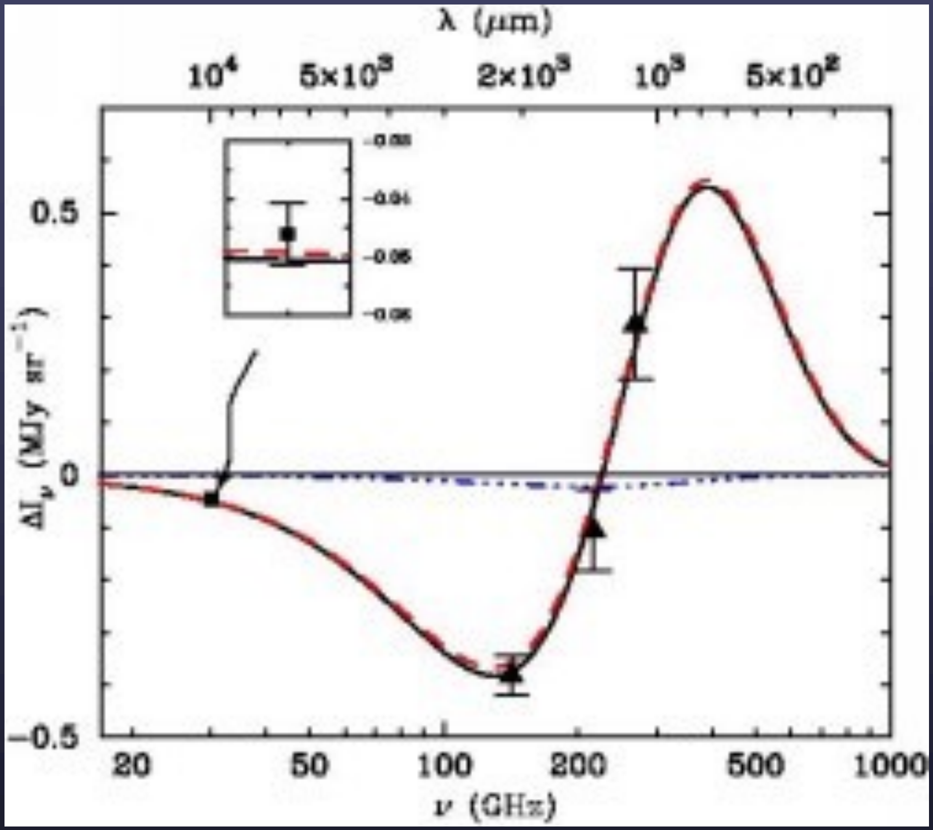

Weak Lensing
Unlensed
Lensed
Without Shape Noise
With Shape Noise

Strong and Weak Lensing of the bullet cluster

Blue = mass from lensing; Red = X-rays from hot gas

Sunyaev-Zeldovich effect



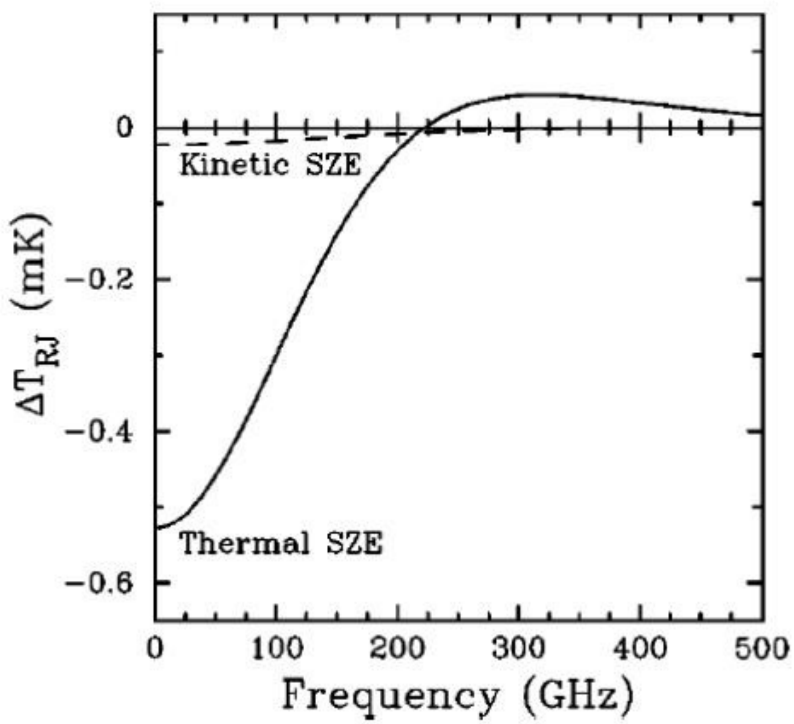


kSZ Effect

The Doppler effect of line of sight cluster velocity -> observed shift of the CMB spectrum.

In the nonrelativistic limit, the spectral signature of the kinetic SZE is a pure thermal distortion of magnitude of the CMB signal:

$$\frac{\Delta T_{SZE}}{T_{CMB}} = -\tau_e \left(\frac{v_{pec}}{c} \right)$$



Hot Gas in Clusters

- The gas is densest near the center of the cluster, and drops off
With radius as you might expect
Since X-ray emission goes as n^2 the gas at the center should cool,
Generate optical line emission, and form molecular gas and stars
There is some evidence for cooler gas, but not enough

$$t_{\mathrm{cool}} = \frac{3nk_{\mathrm{B}}T}{3 \times 10^{-27} n^2 \sqrt{T}}\,\mathrm{s} \approx 14 \left(\frac{10^{-3}\,\mathrm{cm}^{-3}}{n} \right) \left(\frac{10^7\,\mathrm{K}}{T} \right)^{1/2} \mathrm{Gyr}.$$

Astronomy 422

Lecture 15: Galaxy Mergers

Galaxy interactions

Not all galaxies fall on the Hubble sequence, many are *peculiar.*

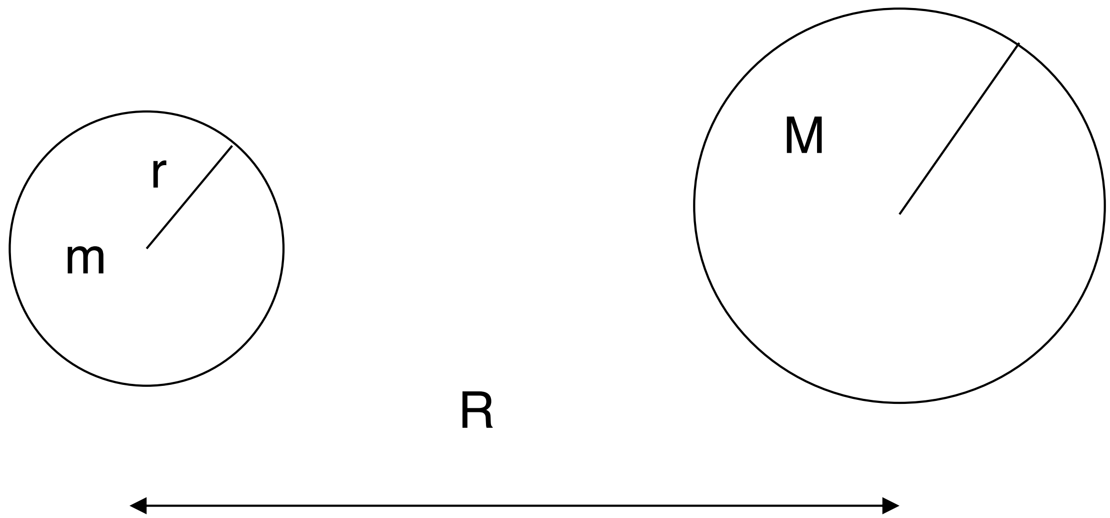
Arp made an Atlas of Peculiar Galaxies in 1966 (based on the Palomar Sky Survey), later extended to the Southern hemisphere (1982).

Arp found

- Very distorted morphologies
- Tidal tails
- Polar rings around ellipticals
- Ring shaped galaxies
- Rings of dust and gas
- Warps in spiral disks
- Shells and ripples around ellipticals
- Accretion of dwarf galaxies

Tidal stripping

Consider two galaxies:



Galaxy m, radius r is self-gravitating as is galaxy M.

$$\Delta a = \frac{2GMr}{R^3}$$

Stars at edge of m feel gravitational acceleration to m of

$$a_m = \frac{Gm}{r^2}$$

That means that stars will be *stripped* off m if :

$$\frac{2GMr}{R^3} > \frac{Gm}{r^2}$$

$$\text{or} \quad R < \left(\frac{2M}{m}\right)^{1/3} r$$

Roche limit

Interactions and mergers also lead to "<u>starbursts</u>": unusually high rates of star formation. Cause is the disruption of orbits of star forming clouds in the galaxies. They often sink to the center of each galaxy or the merged pair. Resulting high density of clouds => squeezed together, many start to collapse and form stars.

M82

Mergers: two main types

Minor mergers

- large galaxy eats dwarf.
- May relate to
  - Growth of bulges (multiple nuclei in M31, metallicity range in MW bulge)
  - thick disks

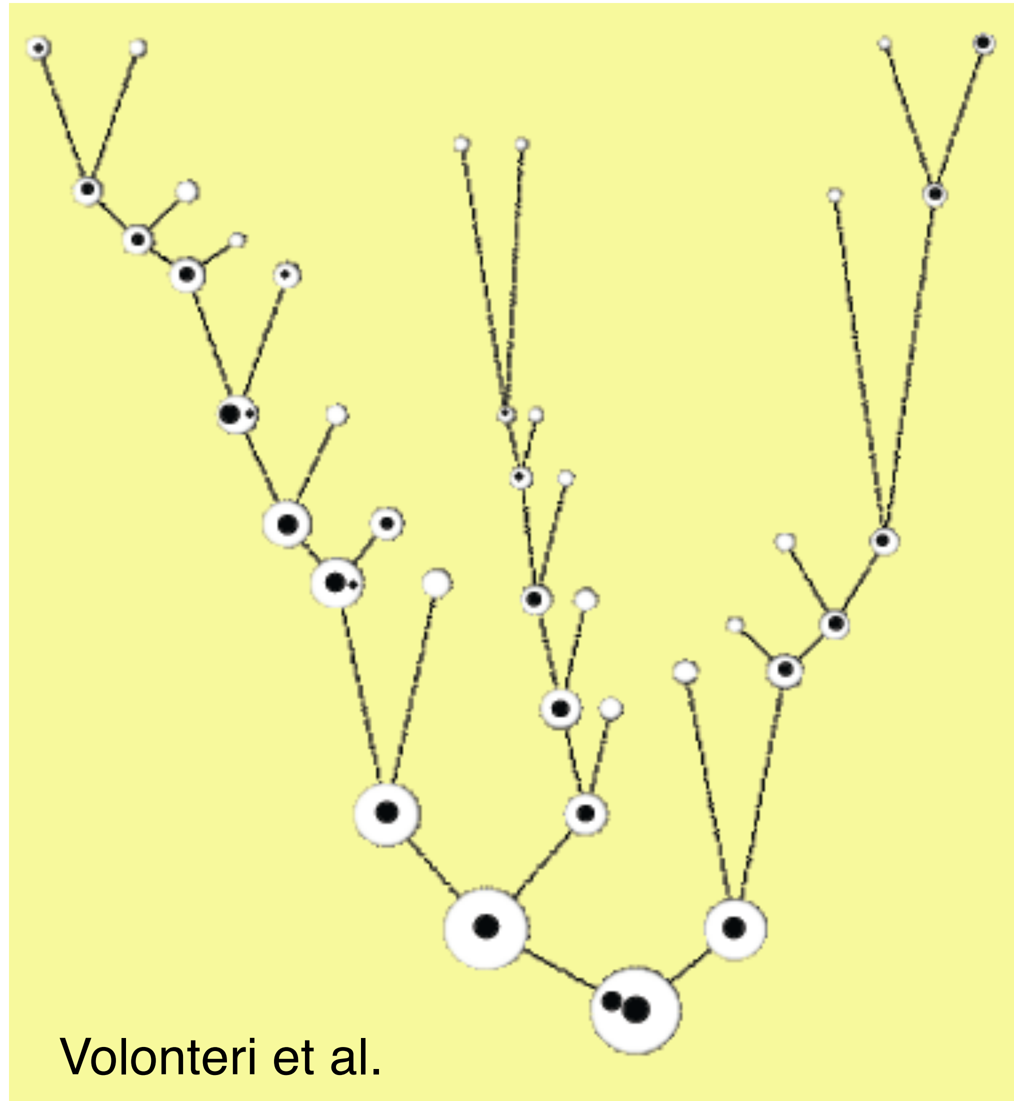
Major mergers:

- two large galaxies
- Growth of cDs
- 2 spirals => E?

What fraction of E's formed this way?

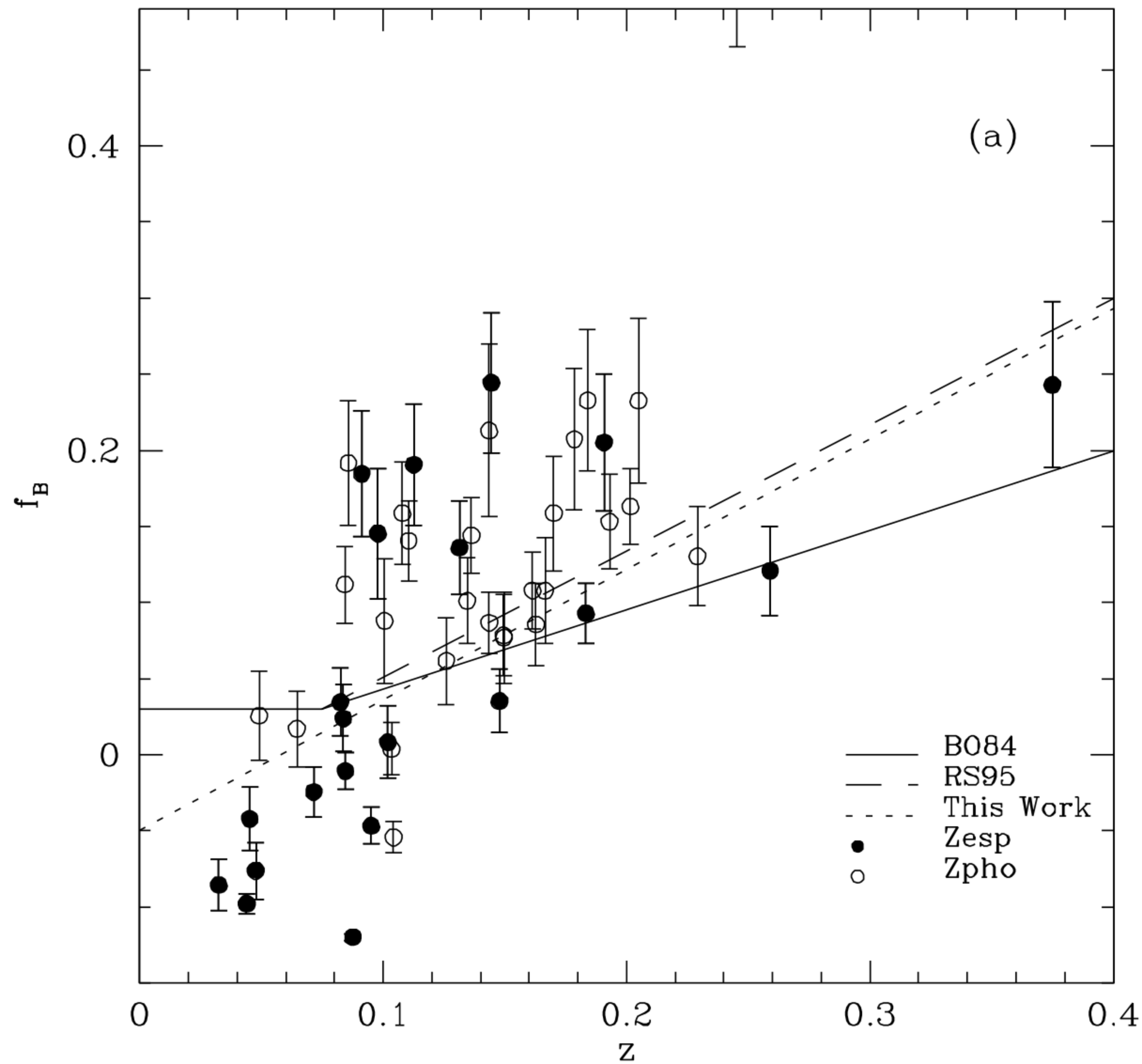
Black Hole Formation

- Assembly+accretion
- Gravitational Rocket problem (Fitchett 1983)
- Slingshot Problem (Volenteri 06)



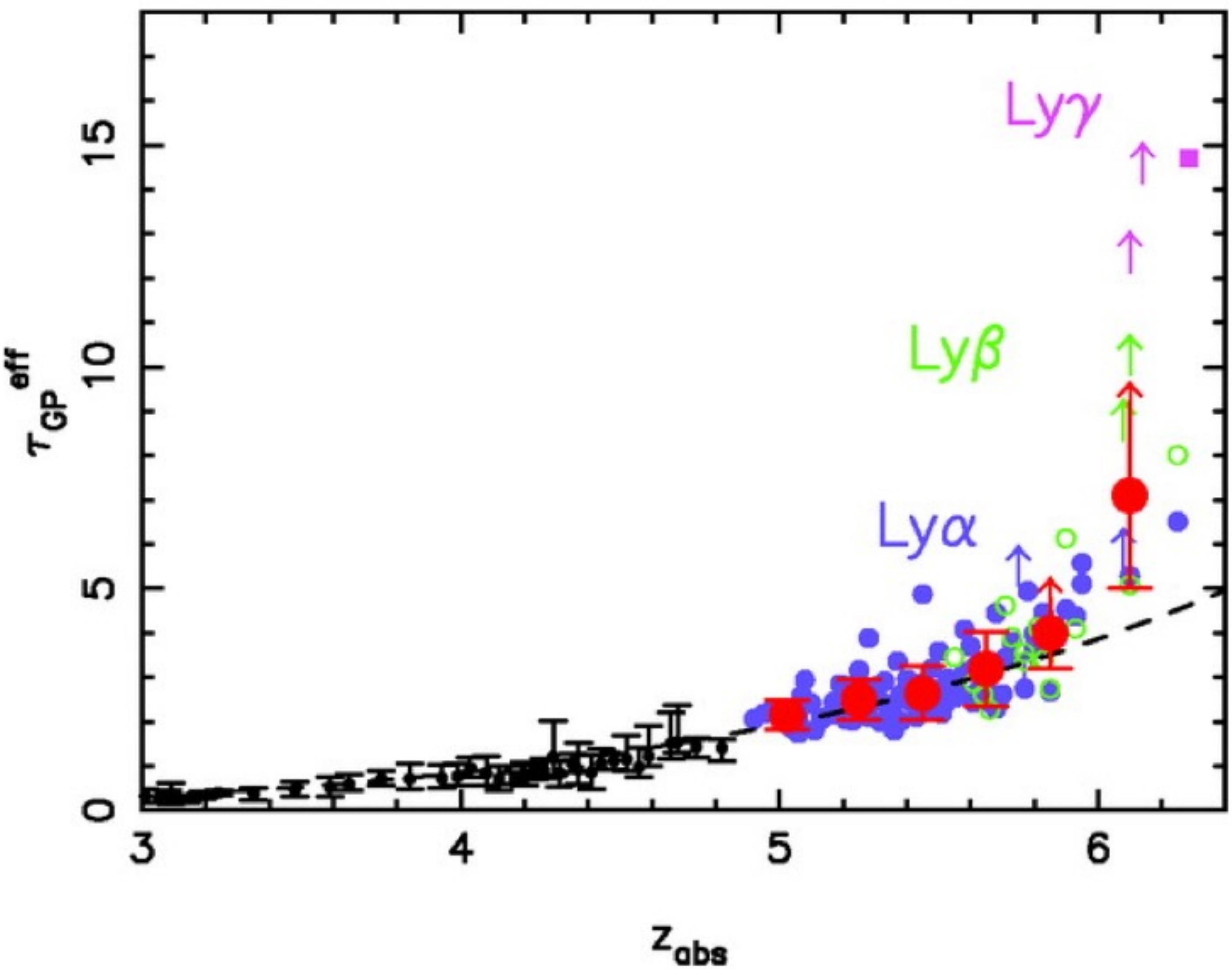
Butcher – Oemler effect

Blue fraction in central 0.7 Mpc of cluster



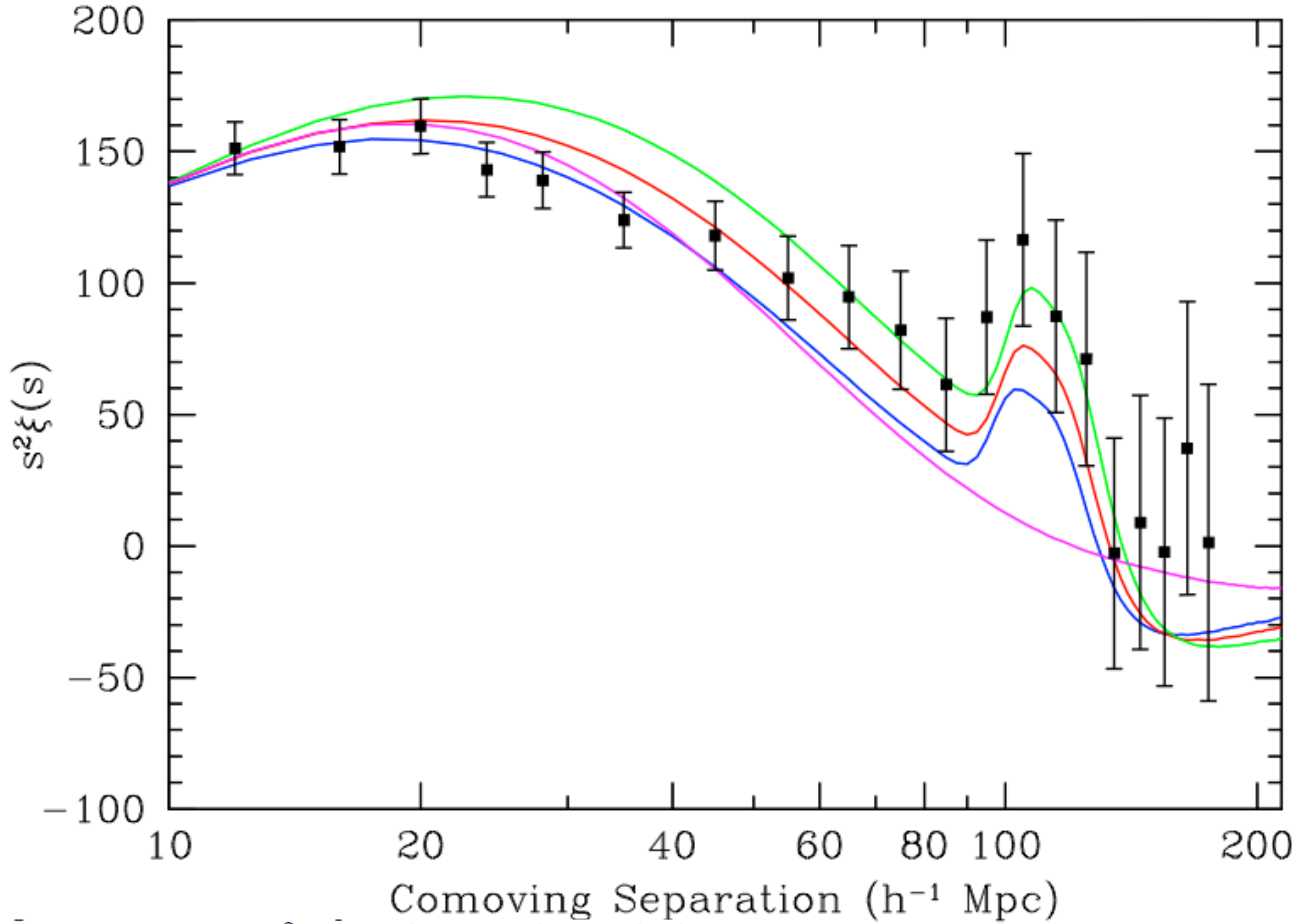
Margoniner & De Carvalho 2000

Rapid increase in H I Opacity at z ~ 6



Fan et al (2006)

Baryon Acoustic Oscillations



axis. The models are $\Omega_m h^2 = 0.12$ (top, green), 0.13 (red), and 0.14 (bottom with peak, blue), all with $\Omega_b h^2 = 0.024$ and $n = 0.98$ and with a mild non-linear prescription folded in. The magenta line shows a pure CDM model ($\Omega_m h^2 = 0.105$), which lacks the acoustic peak. It is interesting to note that although the data ap-

Eisenstein et al. 2004

Sound Horizon

- Electrons in the early universe scatter the photons which provide most of the pressure
- If there is a pressure gradient then the electrons will move down it, pulling protons with them. This drives a spherical sound wave.

The comoving sound horizon r_s is the integral of the sound speed over conformal time from the Big Bang ($z = \infty$) to the redshift of recombination ($z_* \approx 1090$).

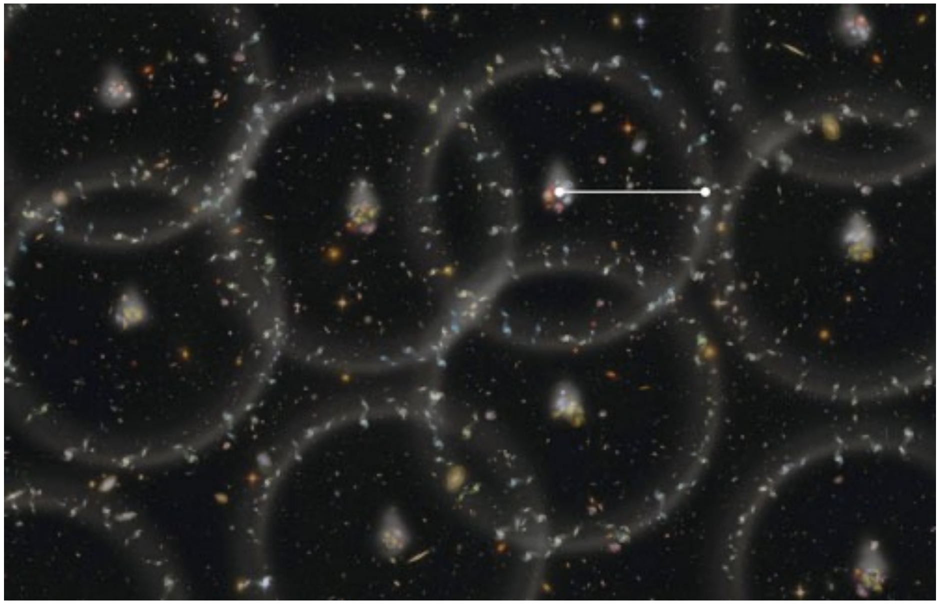
$$r_s = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)}\, dz$$

Assuming matter dominates:

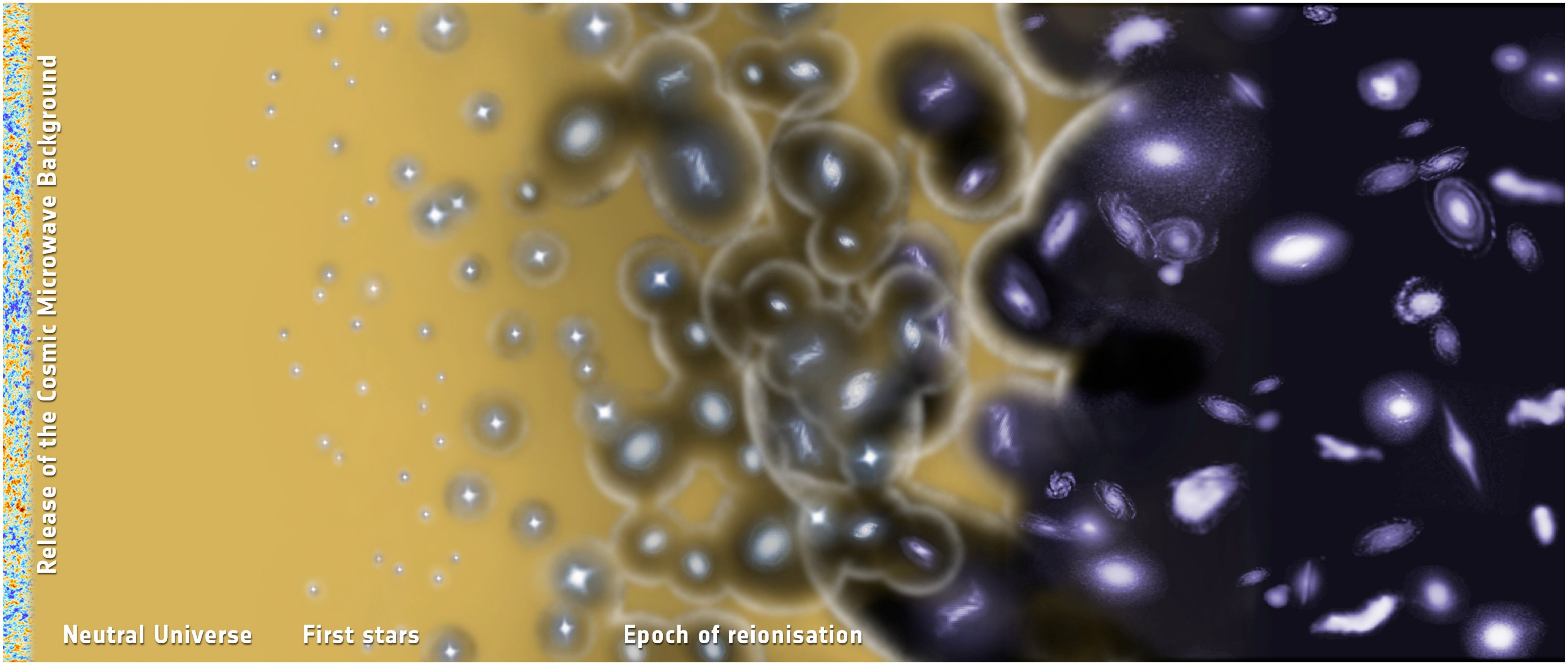
$$H(z) \approx H_0 \Omega_m^{1/2} (1 + z)^{3/2}),$$

And c_s is approximately c/sqrt(3)

After recombination, universe is transparent and photons fly off, leaving baryons behind



Epoch of Reionization



z =30-14

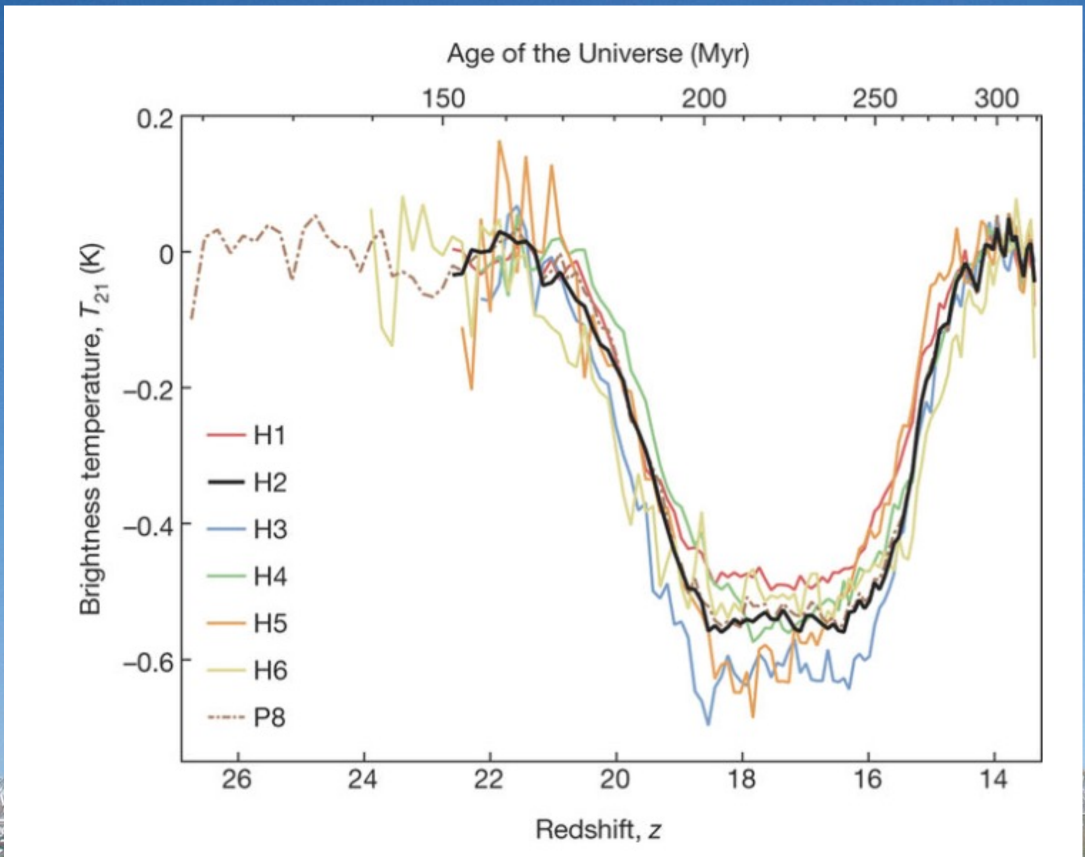
45-100 MHz

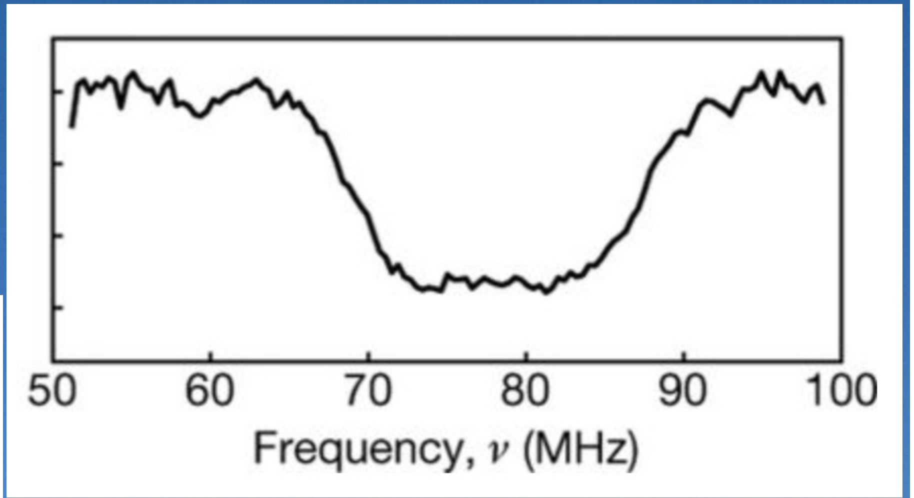
z = 14-6

100-200 MHz

Detection of HI at z=17

Bowman et al. 2018



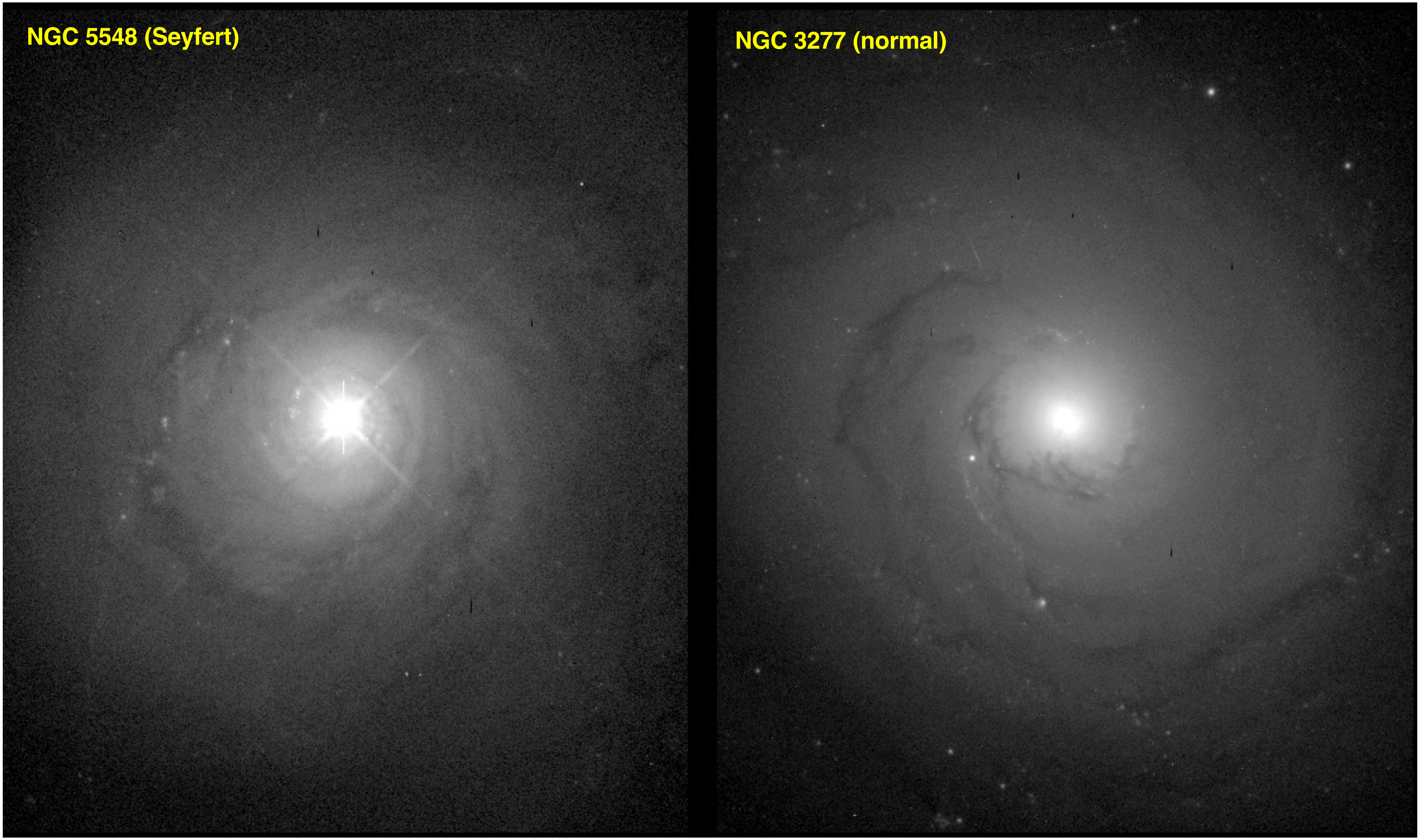


Active galaxies

AGN are the nuclei of galaxies which show energetic phenomena that can not clearly and directly be attributed to stars.

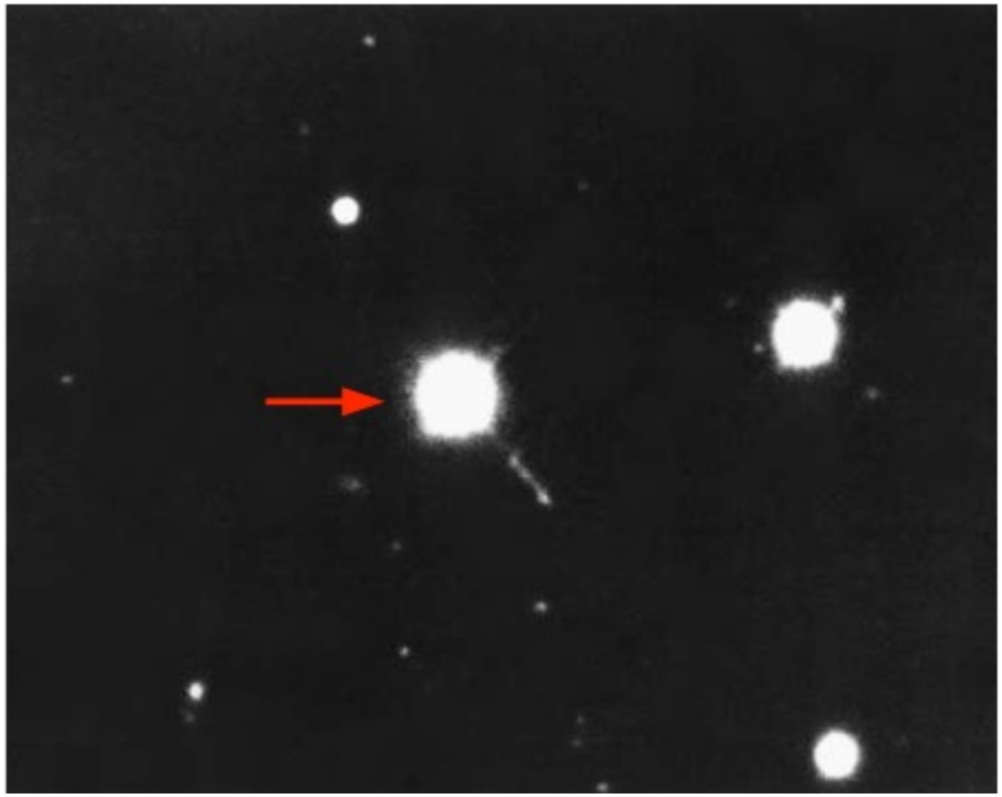
- Signs of AGN activity
  - Luminous optical and UV emission from a compact region
  - Very broad emission lines
  - Variability on time scales of days to months
  - Strong non-thermal emission
  - Highly polarized emission
  - Compact radio core
  - Extended linear radio structures (jets, hotspots)
  - X-ray, gamma-ray and TeV emission
  - Cosmic ray production
- Not all AGN show all of these signs, but all AGN exhibit some

Seyfert vs Normal Galaxy



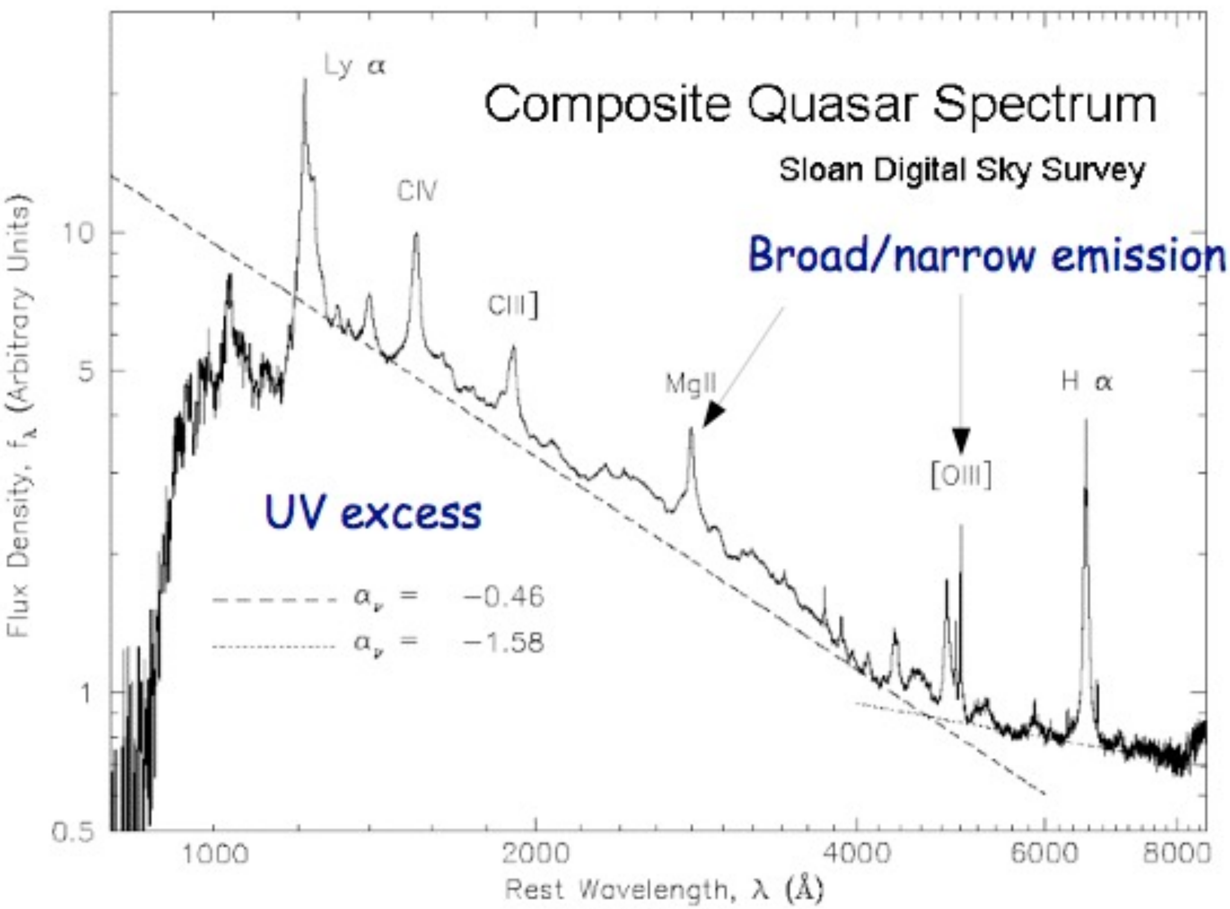
3C273

The 273rd radio source in the Cambridge catalog: a compact radio source that looks like a star except for a 'wisp' of light.

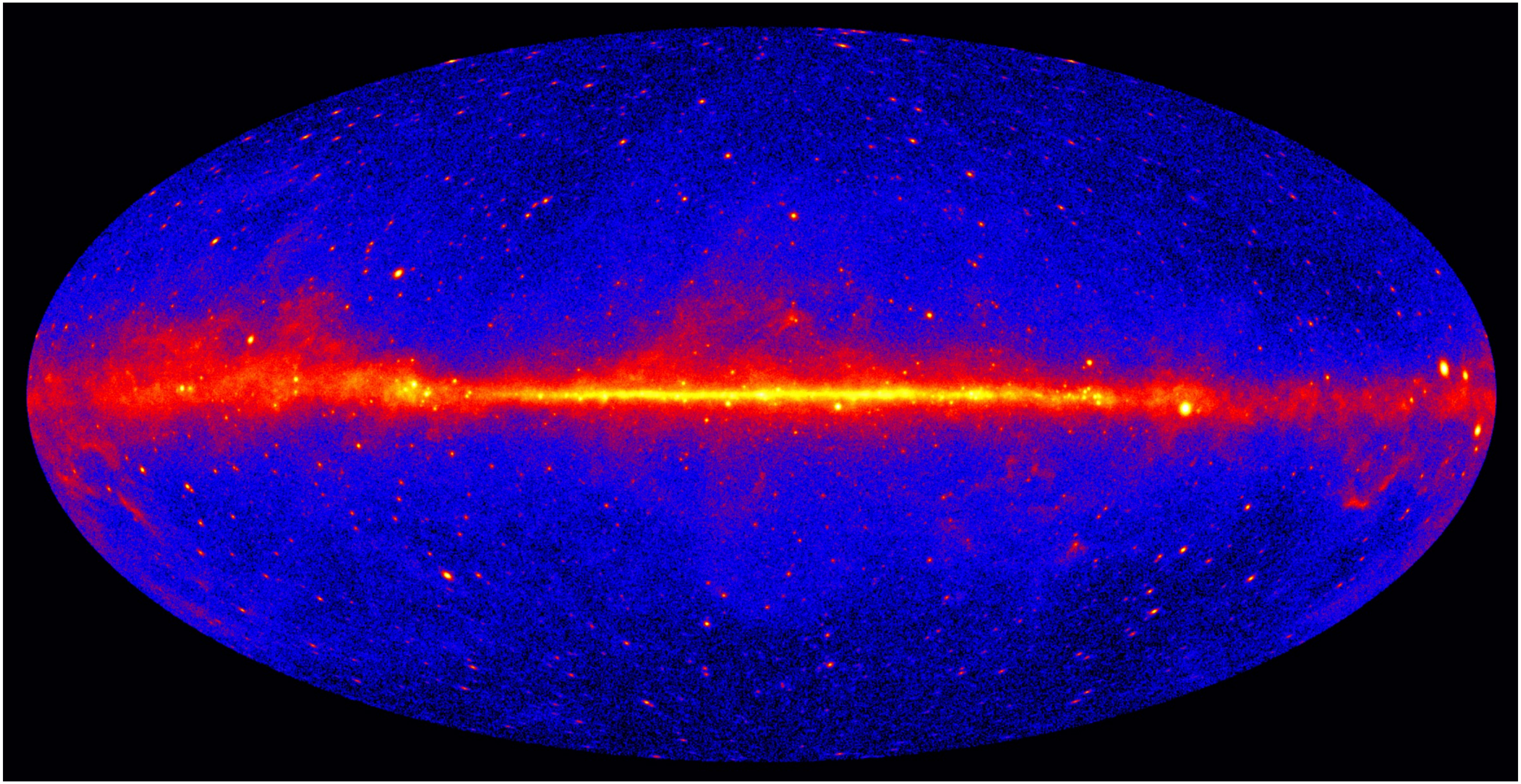


Their optical counterparts are "starlike", thereby the name "quasi-stellar radio sources", or quasars.

Composite Quasar optical/UV spectrum



Fermi Gamma-Ray Sky



Fermi 5 year sky map

Spectral energy distribution (SED) of AGN

Broad-band SED of AGN can often be approximated by

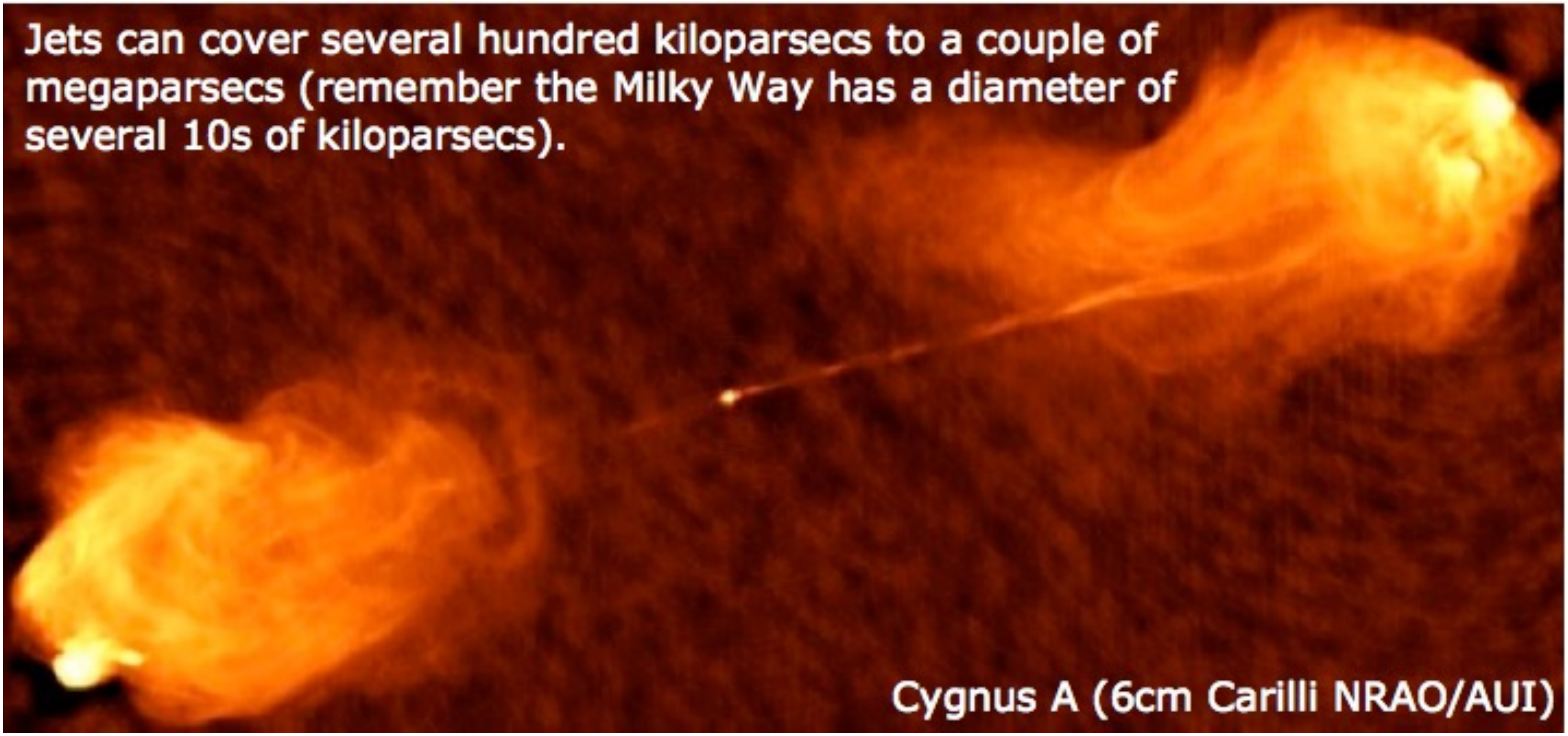
$$F_\nu = C\nu^{-\alpha}$$

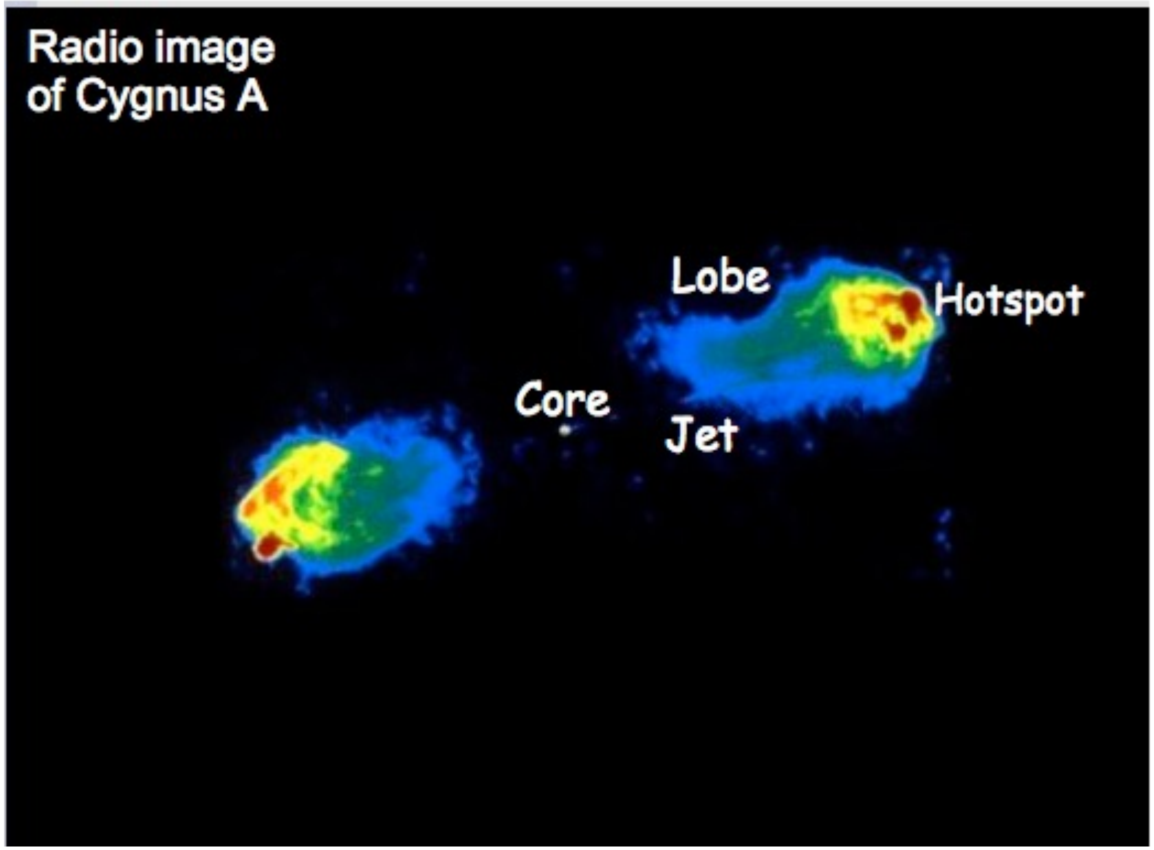
The power in a given frequency range is

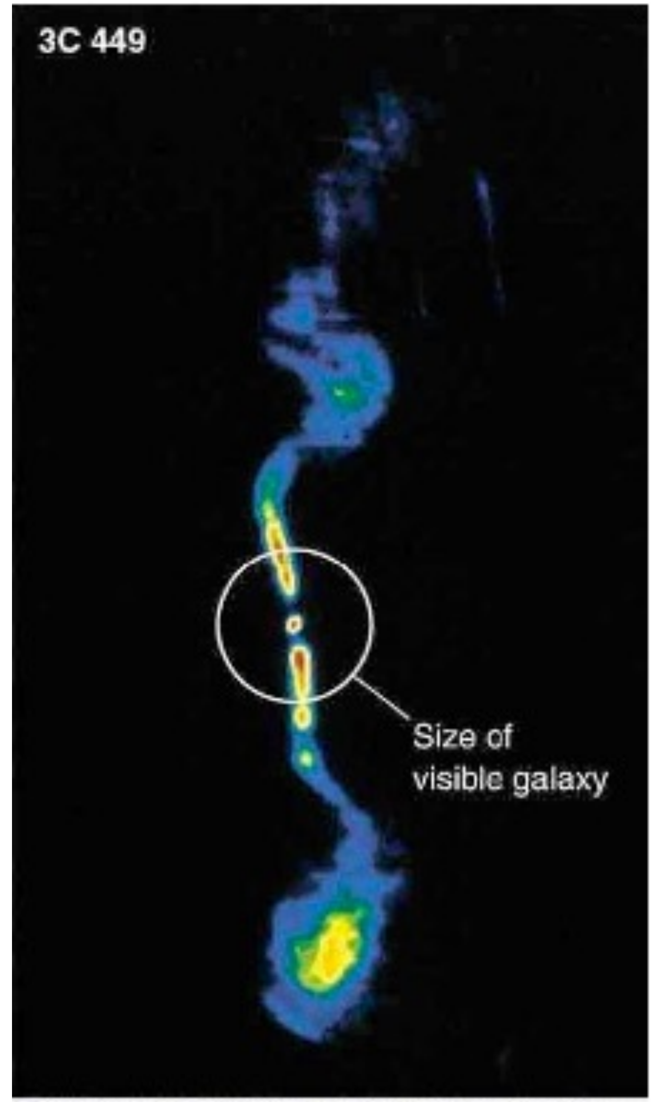
$$P = \frac{C}{1-\alpha}\left(\nu_2^{1-\alpha} - \nu_1^{1-\alpha}\right) \quad (\alpha \neq 1)$$

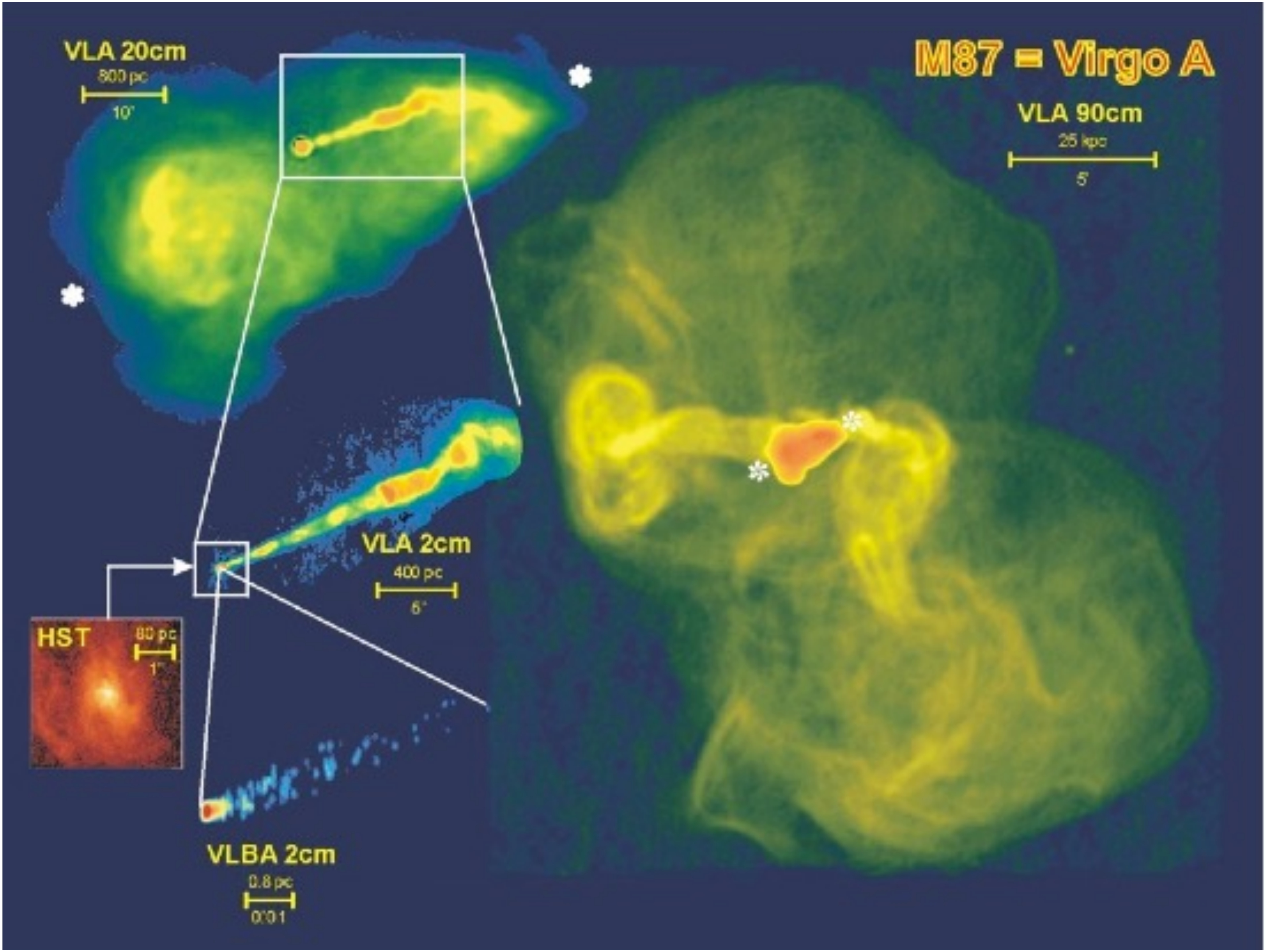
$$P = C\ln\left(\frac{\nu_2}{\nu_1}\right) \quad (\alpha = 1)$$

Examples of radio galaxies: Cygnus A




Radio image
of Cygnus A
Lobe
Hotspot
Core
Jet

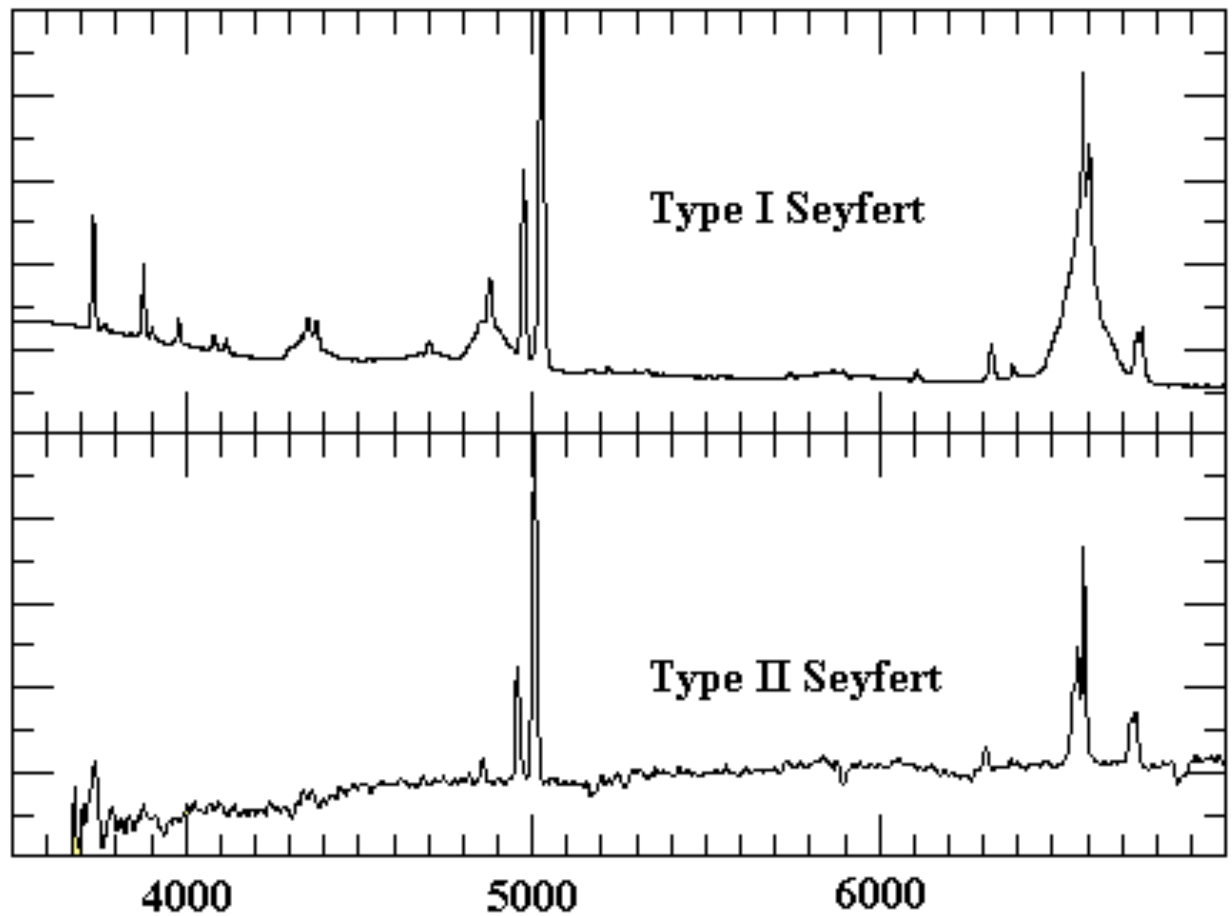

3C 449
Size of
visible galaxy



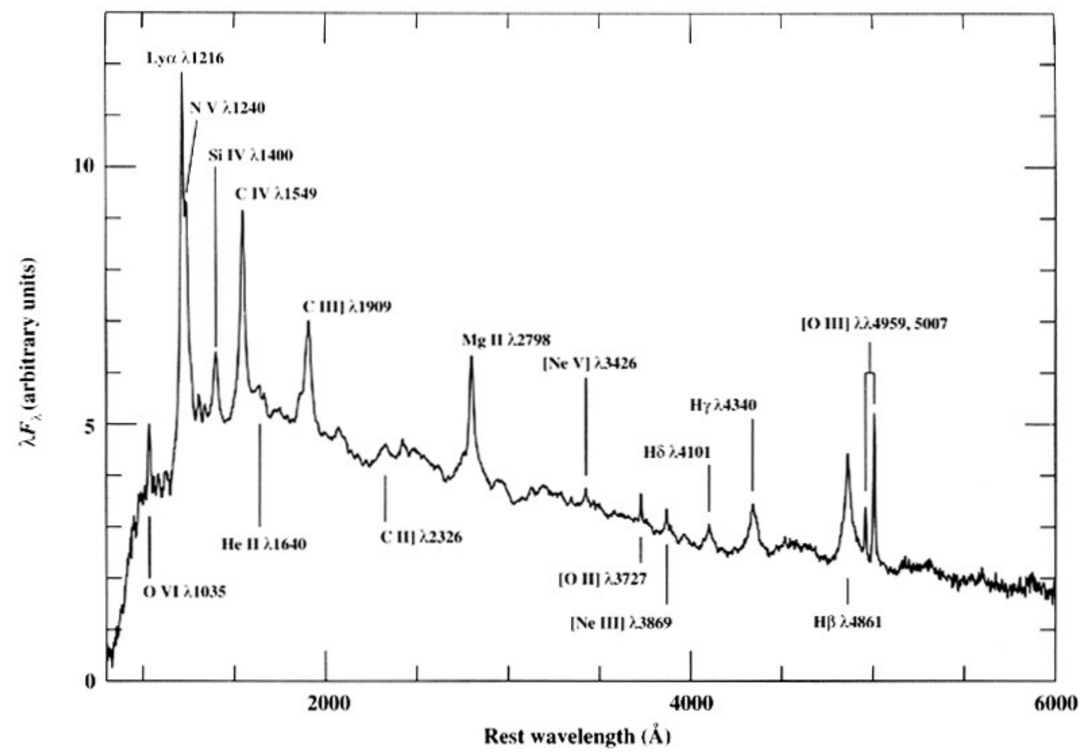
M87 = Virgo A
VLA 20cm
800 pc
VLA 90cm
25 kpc
VLA 2cm
400 pc
HST
80 pc
VLBA 2cm
0.8 pc

Summary of AGN classes

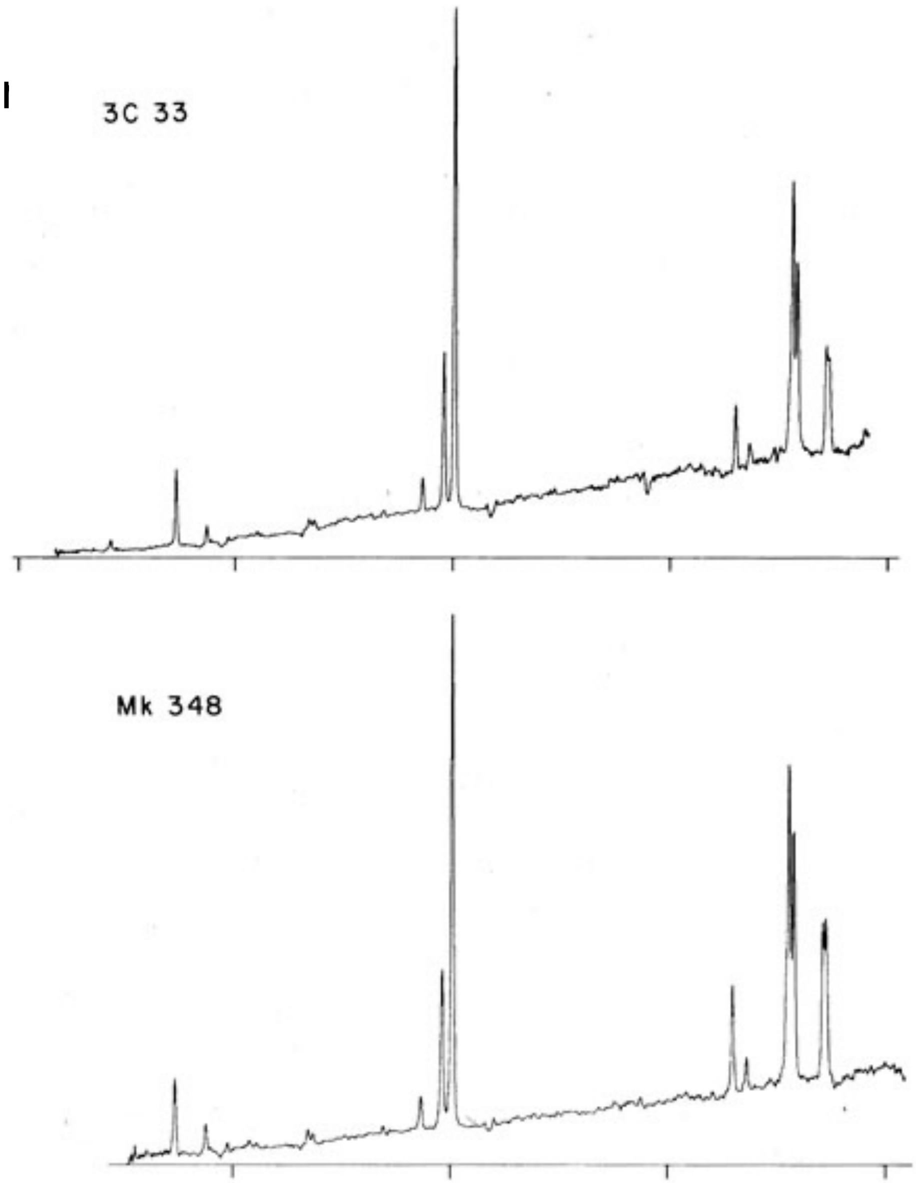
- Seyferts
  - Type I and II: broad and narrow emission lines
  - weak radio emision
  - X-ray emission
  - Spiral host galaxie
  - Variability



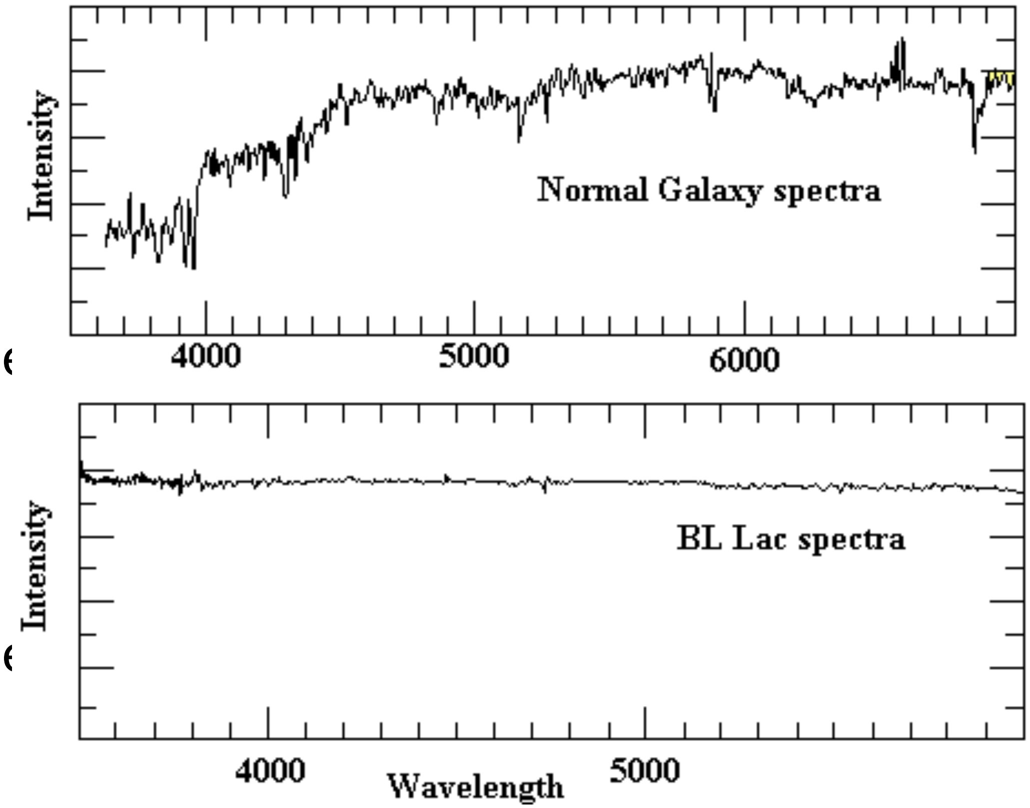
- Quasars
  - Radio loud
    - broad and narrow emissior
    - Strong radio emission
    - Some polarization
    - FRII morphology
    - Variability
  - Radio quiet
    - broad and narrow emissior
    - weak radio emission
    - weak polarization
    - Variability



- Radio galaxies
  - BLRG
    - broad and narrow emission li
    - strong radio emission
    - FRII morphology
    - weak polarization
    - Elliptical host galaxies
    - Variable
  - NLRG
    - narrow emission line only
    - strong radio emission
    - FRI and FRII morphologies
    - no polarization
    - Elliptical host galaxies
    - No variability



- Blazars
  - BL Lacs
    - almost no emission lines
    - strong radio emission
    - strong polarization
    - 90% have elliptical host galaxie
    - Strong variability
  - OVV quasars/ FSRQs
    - broad and narrow emission line
    - strong radio emission
    - strong polarization
    - Strong variability
    - Much more luminous than BL Lacs

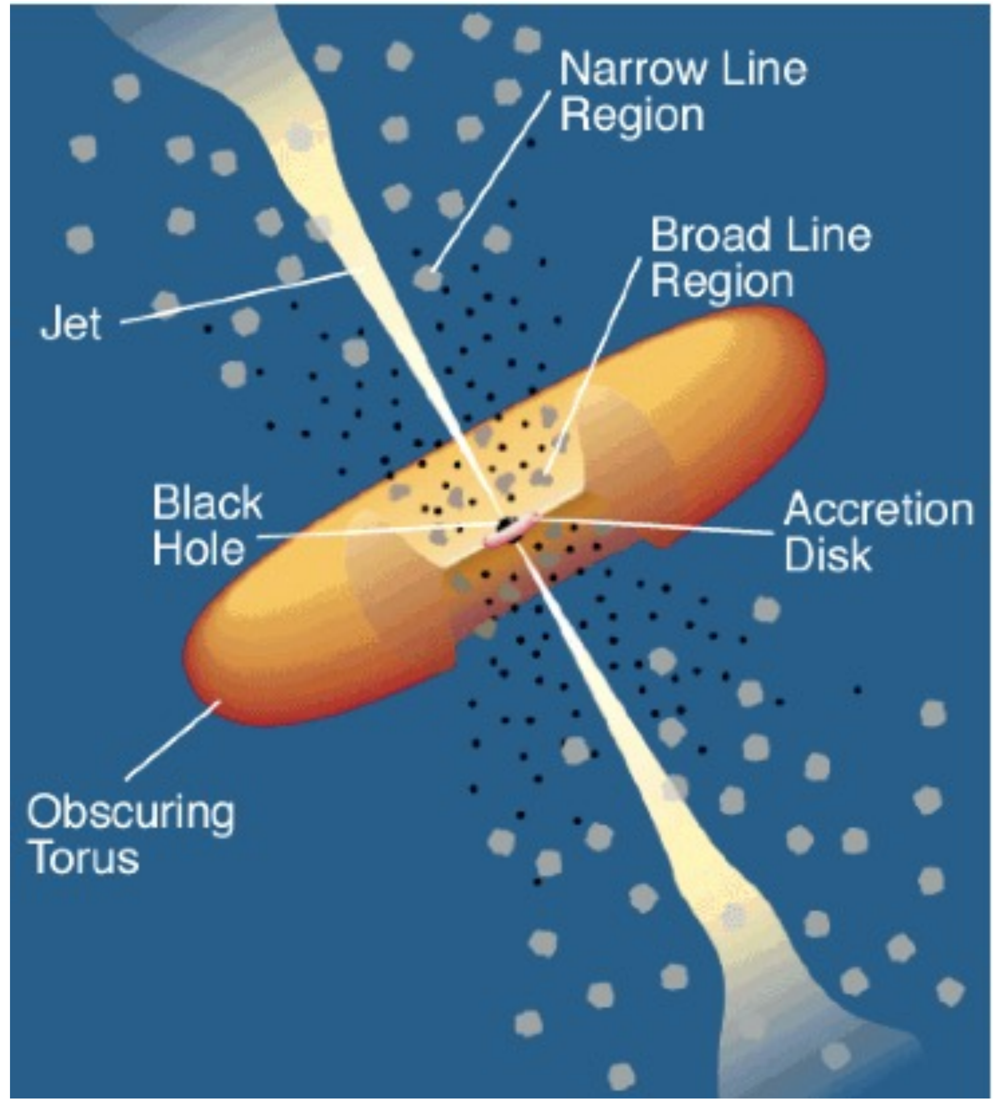


The Unified Model for AGN

- Radio galaxies, quasars, QSOs, Seyferts, Blazars etc are *the same type* of objects viewed from different angles

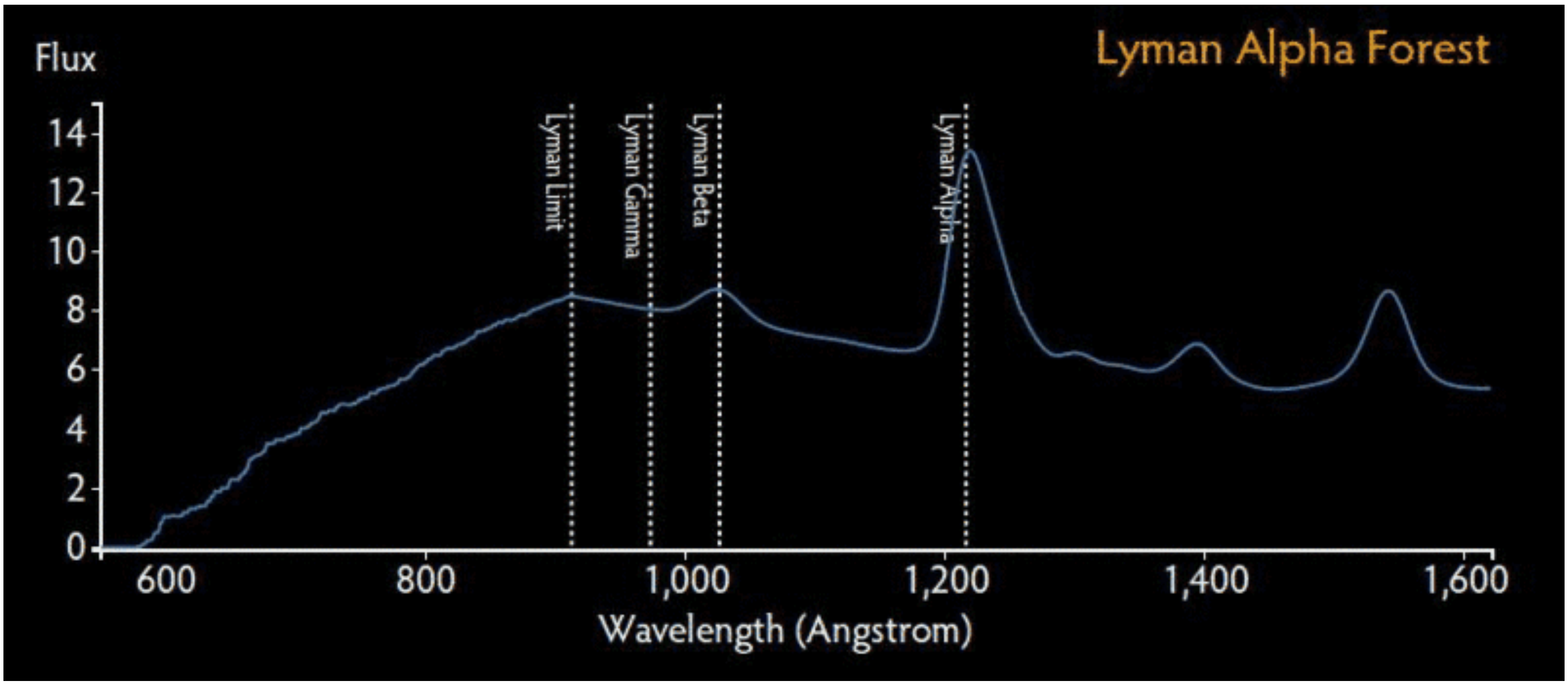
- The center of the galaxy is a supermassive black hole surrounded by an accretion disk, clouds of gas and a dusty torus.

- The energy output is ascribed to accretion of material onto the black hole



The Lyman α Forest

Quasars form a convenient background source for studies of intervening systems. Discovered by Roger Lynds in 1970



Extragalactic Background Light

Summary: The Unsolved Mystery

- **Gamma-Rays:** Resolved (Blazars).
- **X-Rays:** Resolved (AGNs).
- **Optical:** Resolved (Stars/Galaxies).
- **Microwave:** Resolved (CMB).
- **Radio: UNSOLVED** (Excess of ~500 mK).

1. The Ledger We have precisely mapped the Universe's energy history across almost the entire spectrum.

2. The Anomaly The Radio window contains a bright, unexplained background that exceeds known source counts by a factor of ~5.

3. The Stakes This excess is this excess is potentially linked to the 'Cosmic Dawn.' It suggests either a hidden population of sources or fundamental changes to our understanding of physics.

The radio sky is not quiet. It is humming with a signal we have yet to decode.