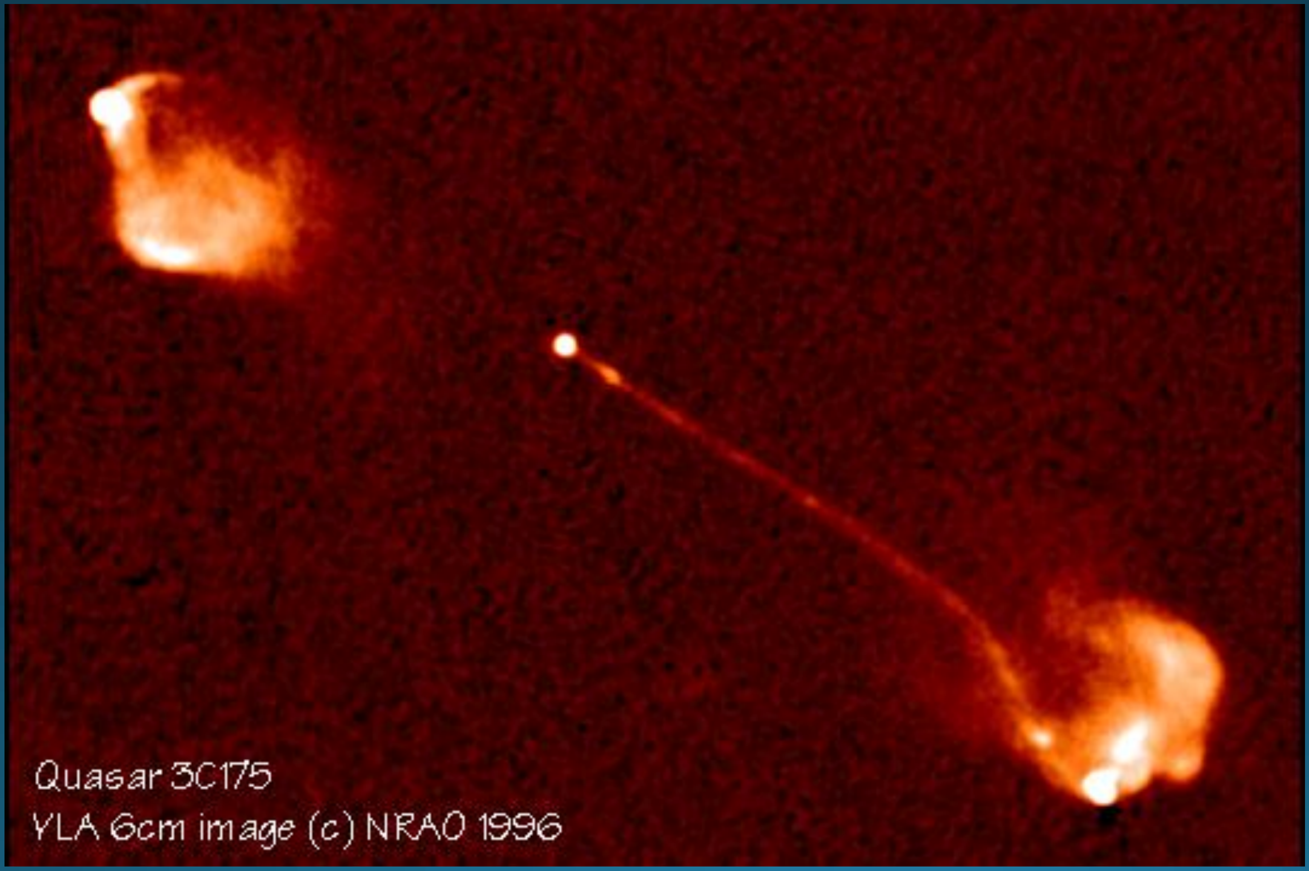
Physics of Galaxies 2020
10 credits
Lecture 6: Active galaxies and black holes



Outline

- Introduction to the database exercise
- Black holes in galaxies
  - How do we find them?
  - Relation between black hole mass and other galaxy properties
- Active galactic nuclei (AGN)
  - Basic AGN anatomy
  - Different types of AGN
  - Unification model
  - Quasar host galaxies
  - Quasar absorption systems

Database exercise

UPPSALA UNIVERSITET

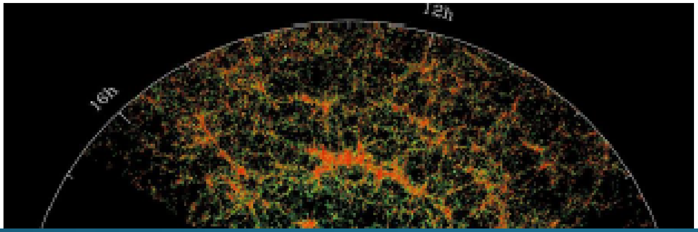
SDSS

Studying galaxies with the Sloan Digital Sky Survey

Database exercise, Physics of Galaxies, Spring 2020 (Uppsala Universitet)

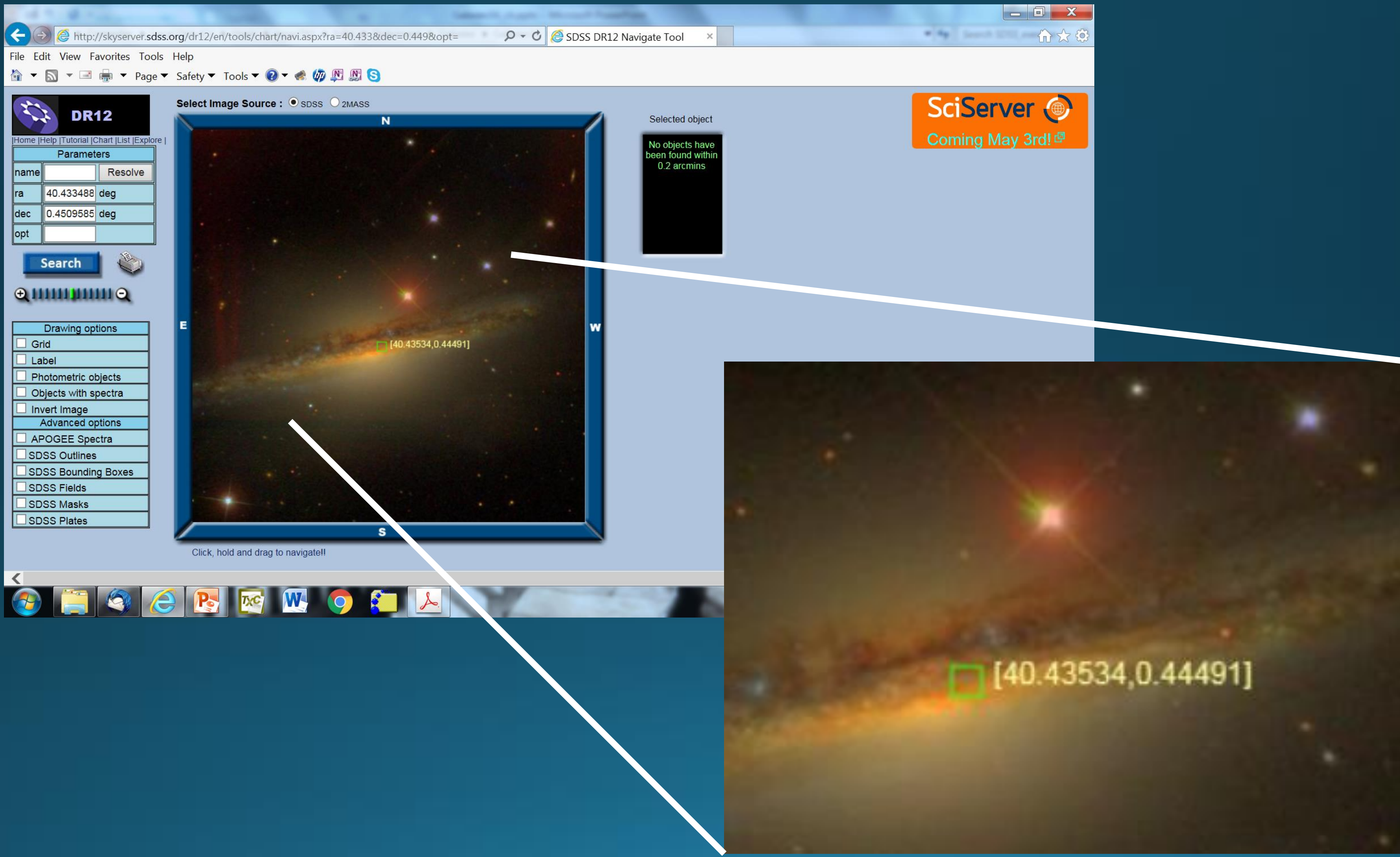
by

Beatriz Villarroel



Deadline June 5– preferably no more than 5 pages

Obstacles: Astronomical coordinates



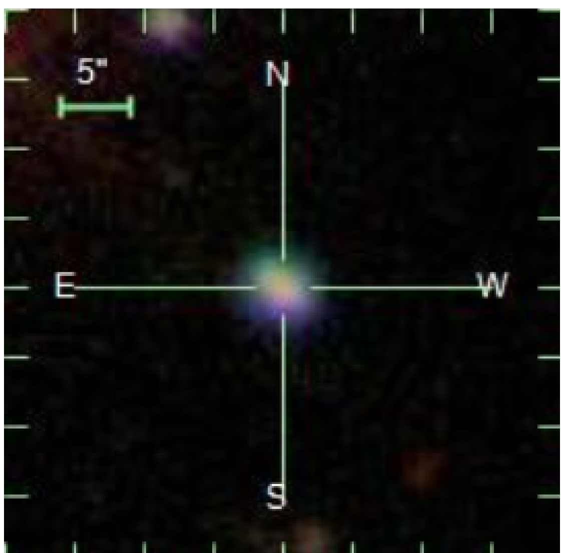
Obstacles: Bewildering photometric data

SDSS J113459.47+002509.1

GALAXY ra=173.74782136, dec=0.41921516, ObjId = 588848900446814264

Column names link to glossary entries. Move mouse over a column name to get its units.

mode	PRIMARY
status	TARGET PRIMARY OK_STRIPE OK_SCANLINE PSEGMENT RESOLVED OK_RUN GOOD SET
flags	STATIONARY MOVED BINNED1 CHILD
PrimTarget	TARGET_GALAXY
SecTarget	



u	g	r	i	z
19.55	18.04	17.55	17.35	17.21

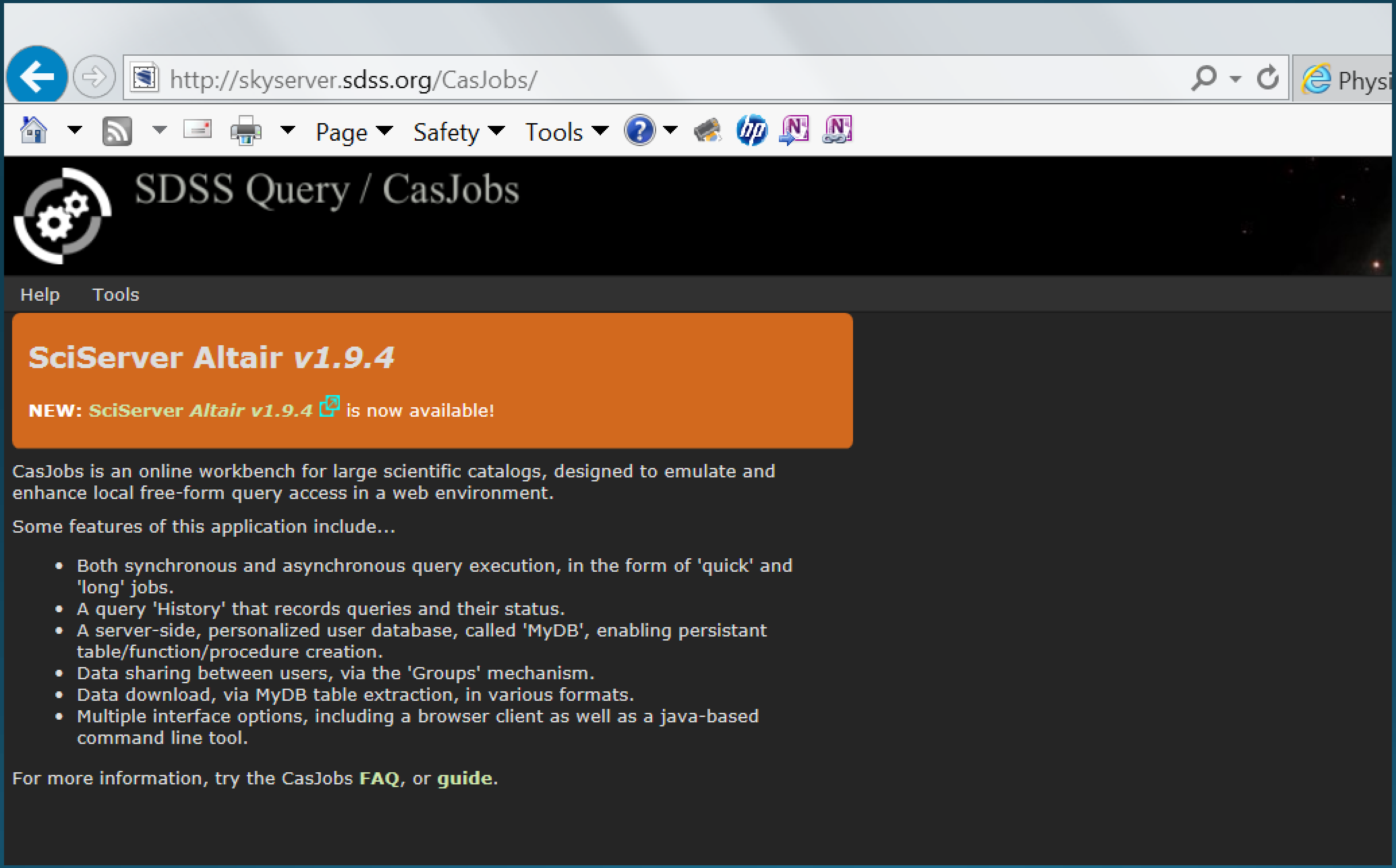
err_u	err_g	err_r	err_i	err_z
0.03	0.01	0.01	0.01	0.02

run	rerun	camcol	field	obj	rowc	colc
756	44	4	387	56	549.4	1974.6

fiberMag_r	petroMag_r	devMag_r	expMag_r	psfMag_r	modelMag_r
18.05	17.55	17.55	17.55	17.99	17.55

extinction_r	petroRad_r	parentId	nChild
0.06	1.796	588848900446814263	0

Register an account!



SQL (Structured Query Language)

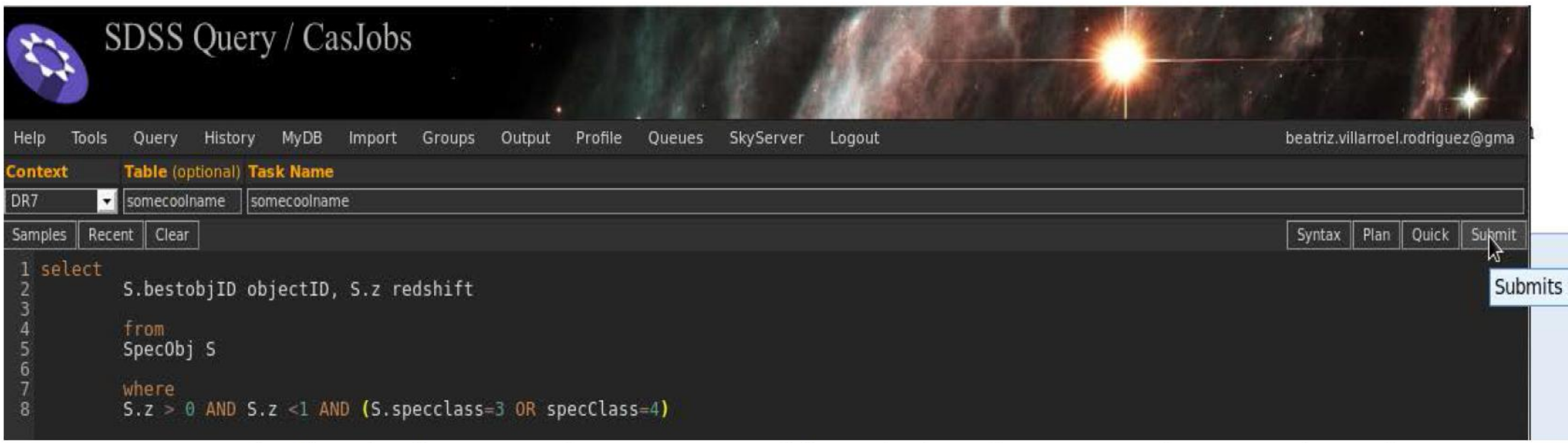


Fig.6. The Casjobs Query interface. Write your SQL code for selecting your favourite objects here.

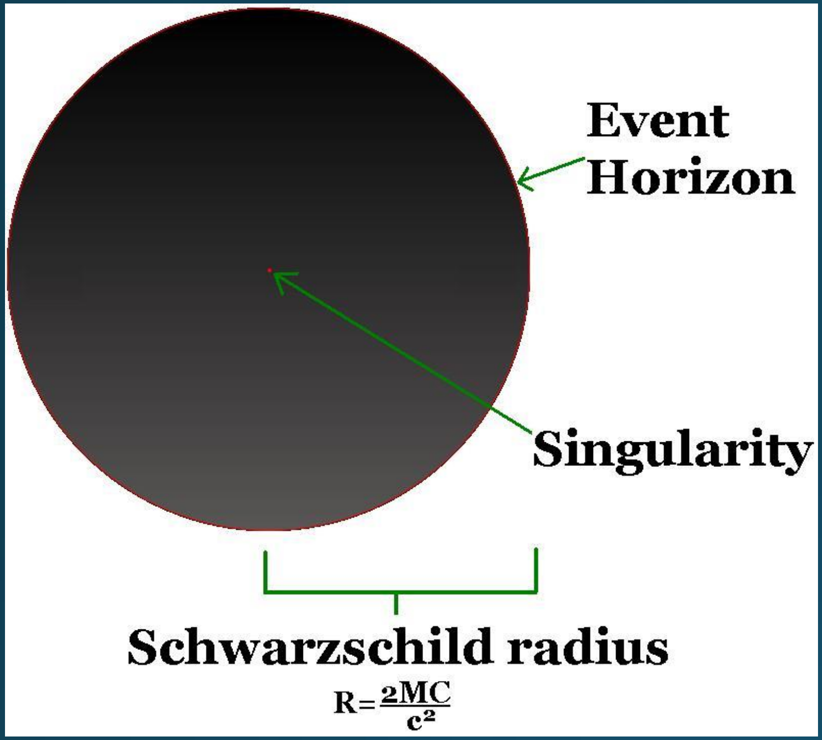
Connection to your literature report

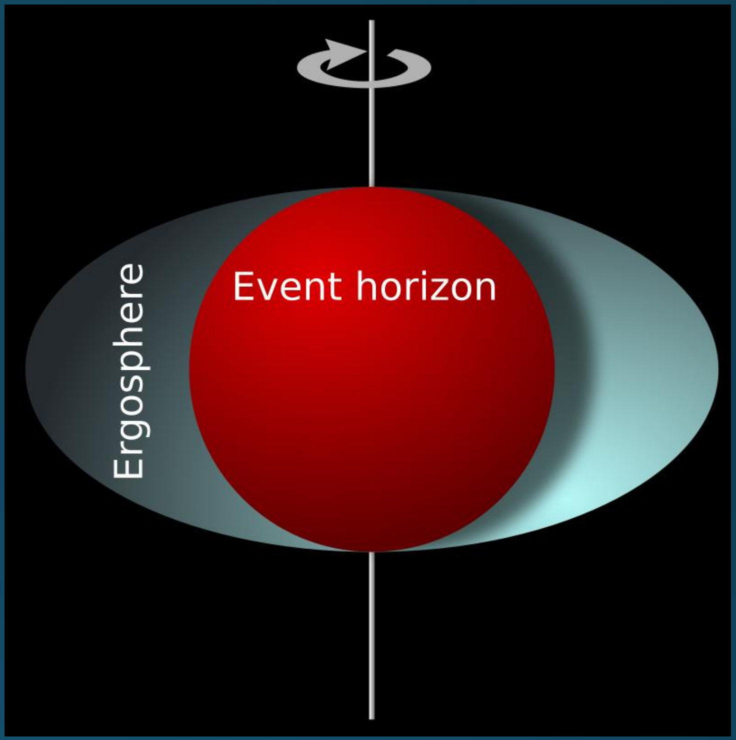
Finally, I'd like you to reconnect this exercise to the **topic of your written essay or a specific research problem described in it**. Many research problems can be solved using the SDSS and sometimes one only has to figure out a clever way to approach them. Other times, even if one cannot solve the problem using the SDSS directly, the survey is helpful for e.g. selecting interesting candidate objects.

Exercise 4: *(a) Describe the most interesting research problem from the essay very briefly.*

(b) How could you approach this fascinating research problem using the SDSS? If it is not possible to use the SDSS, explain what the solution requires that cannot be met by the SDSS data.

Black holes





Non-rotating black hole

Rotating black hole

Current observational evidence supports the existence of stellar-mass black holes (~10 $M_\odot$) and supermassive black holes (~10^6-10^{10} $M_\odot$).

The evidence for intermediate-mass black holes (~ 10^2-10^5 $M_\odot$) remains scant

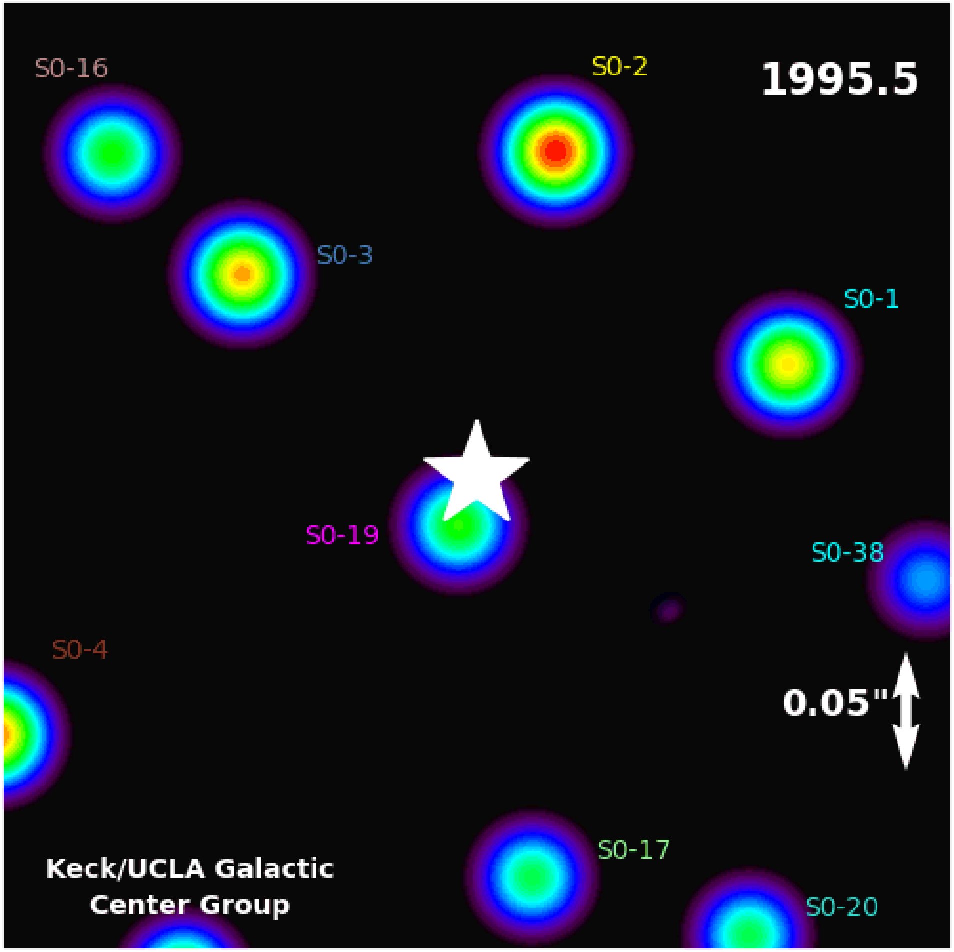
Hunting down black holes

- Motion of stars
  - Milky Way: Proper motion of indivdual stars
  - Other galaxies – velocity distribution from integrated stellar population spectrum
- The ”black hole shadow”
- Active galactic nuclei
- Gravitational waves
- X-ray binaries
- Ultraluminous X-ray sources
- Gravitational lensing

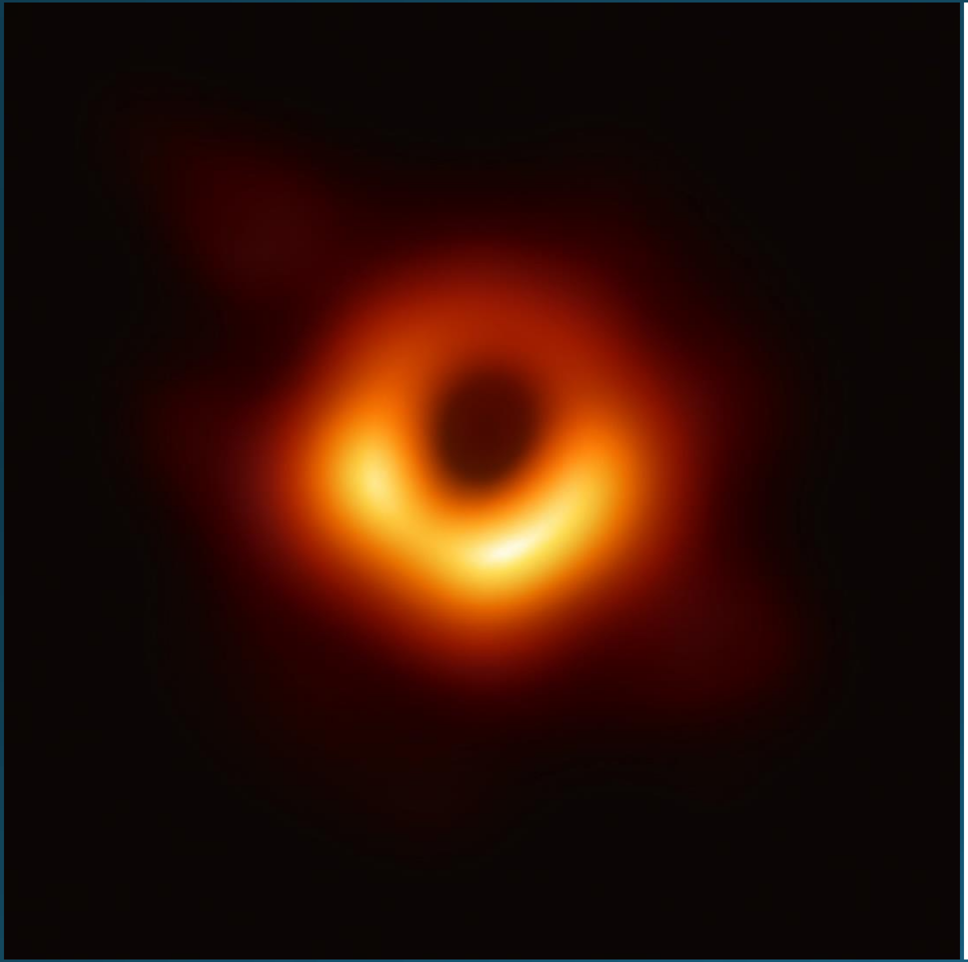
The black hole at the centre of the Milky Way

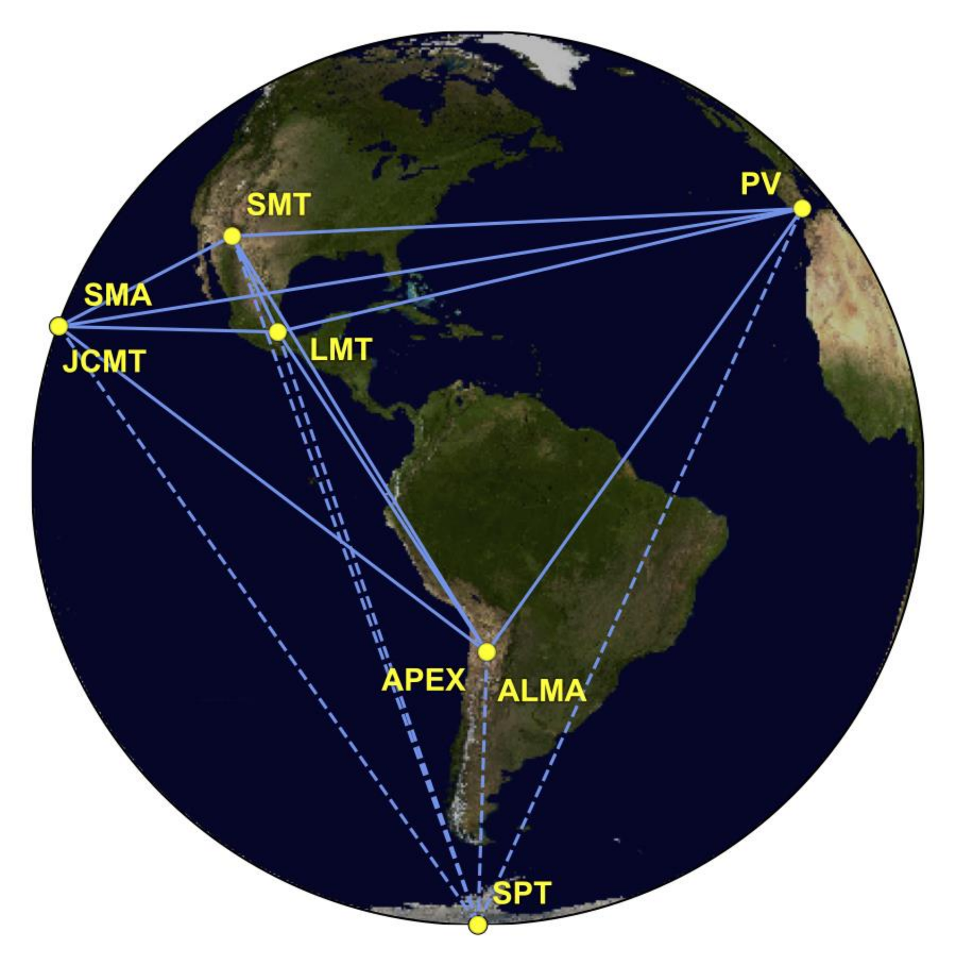
Milky Way:

$M_{BH} \approx 4\times10^{6}\ M_{\odot}$



The "black hole shadow"



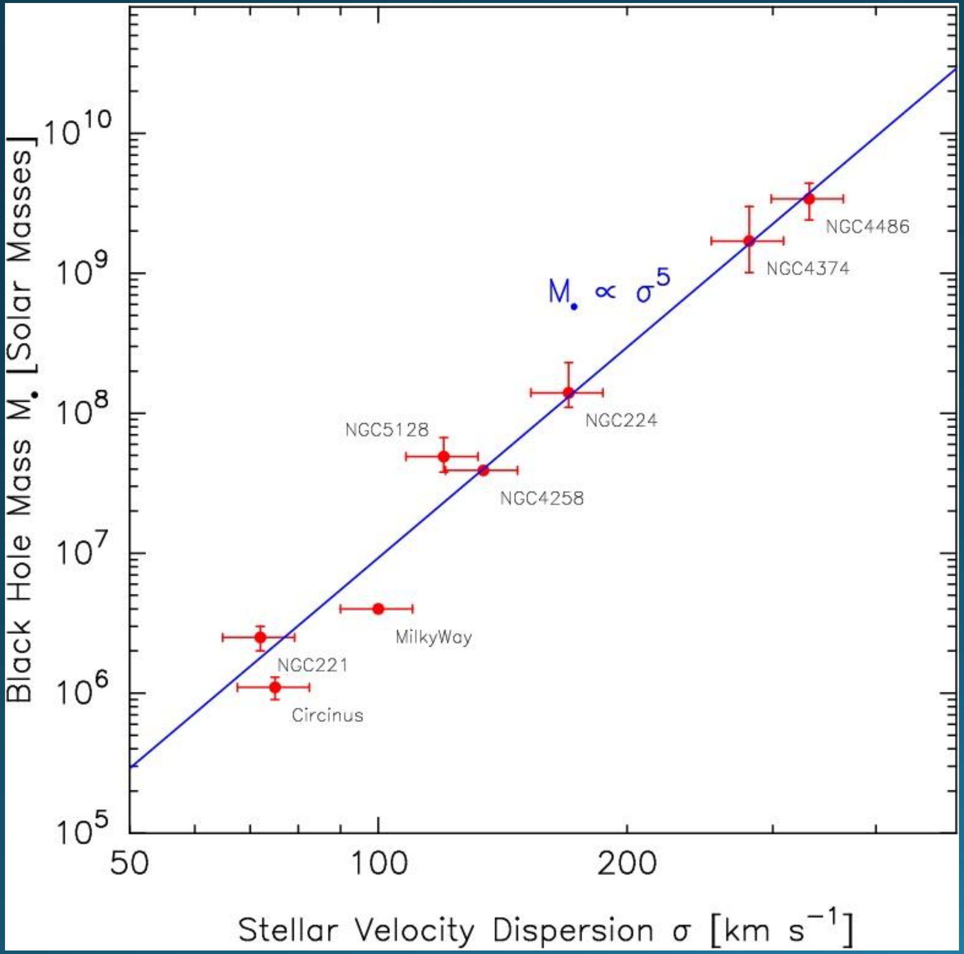


M≈7×10⁹ Msolar black hole in M87 (Elliptical/Seyfert galaxy)

Event Horizon Telescope

https://www.youtube.com/watch?v=zUyH3XhpLTo

Relation between black hole mass and stellar velocity dispersion (or mass) of bulge



$$\frac{M_{\mathrm{SMBH}}}{M_{\mathrm{Bulge}}} \sim 0.003$$

Supermassive black holes in AGN

- Doppler broadened emission lines in AGN indicate gas velocities ~ 10 000 km/s
- Line variability time scale (weeks) → size of line-emitting region
- Velocity & size → Mass(<size) & Density, indicating that the gas orbits a SMBH
- Schwarzschild radius:

$$R_S = \frac{2GM_{\mathrm{BH}}}{c^2} \approx 3 \times \frac{M_{\mathrm{BH}}}{M_{\mathrm{solar}}}\,\mathrm{km}$$

Characteristics of Active Galactic Nuclei

- High luminosity produced in small region
- Fast variability
- High fraction of polarized light
- Non-thermal spectrum: Not stars!
  - Synchrotron radiation
  - Emission-line ratios$\rightarrow$ Ionization source more energetic than hottest known stars

Intermission: Music from AGN

Dr Fiorella Terenzi

Music from the Galaxies (1991): Radio waves from the active galaxy UGC 6697 converted into music

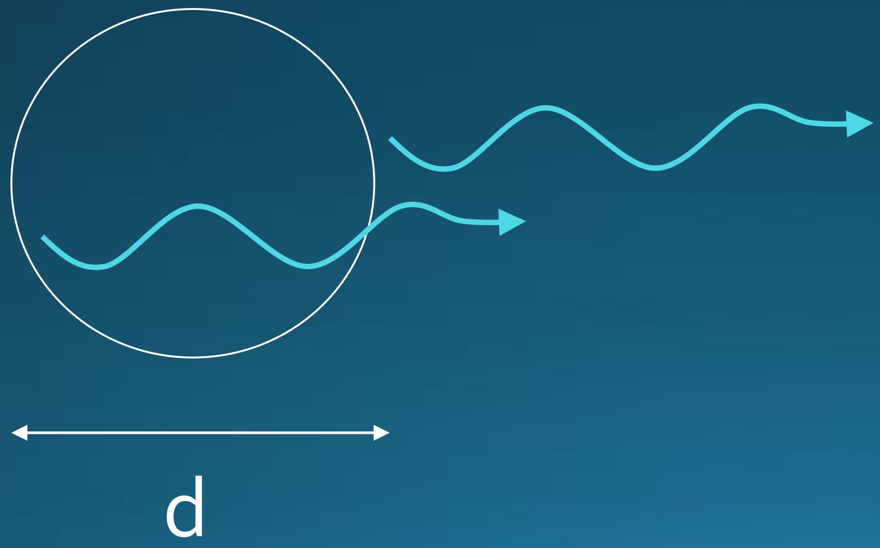
Intermission: Music from AGN

NGC 4151 (1993):
Rest-frame UV emission-line and continuum variability from the Seyfert galaxy NGC 4151 converted into music

Professor Emeritus Nils Bergvall

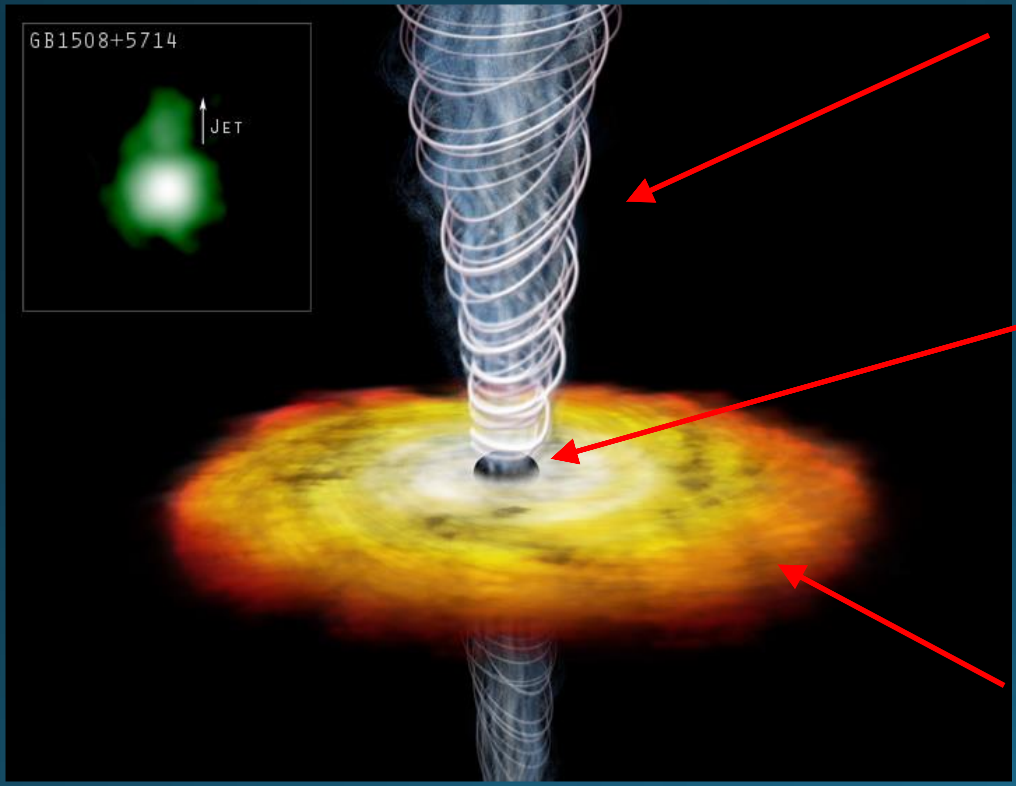
Variability-Size Relation

- Fast variability indicates that the luminosity is produced inside a small region
- Light variations on scales down to 1 hour $\rightarrow$ size smaller than the Solar system



$$\frac{d}{c} < \Delta t_{\mathrm{var}}$$

Accretion Disks



Magnetic field channel matter into relativistic jets

SMBH

Angular momentum of infalling material→ matter spirals inward in an accretion disk

Eddington Luminosity

Too high radiation pressure of AGN may overcome inward gravitational force → upper limit on AGN luminosity which still allows material to fall inwards

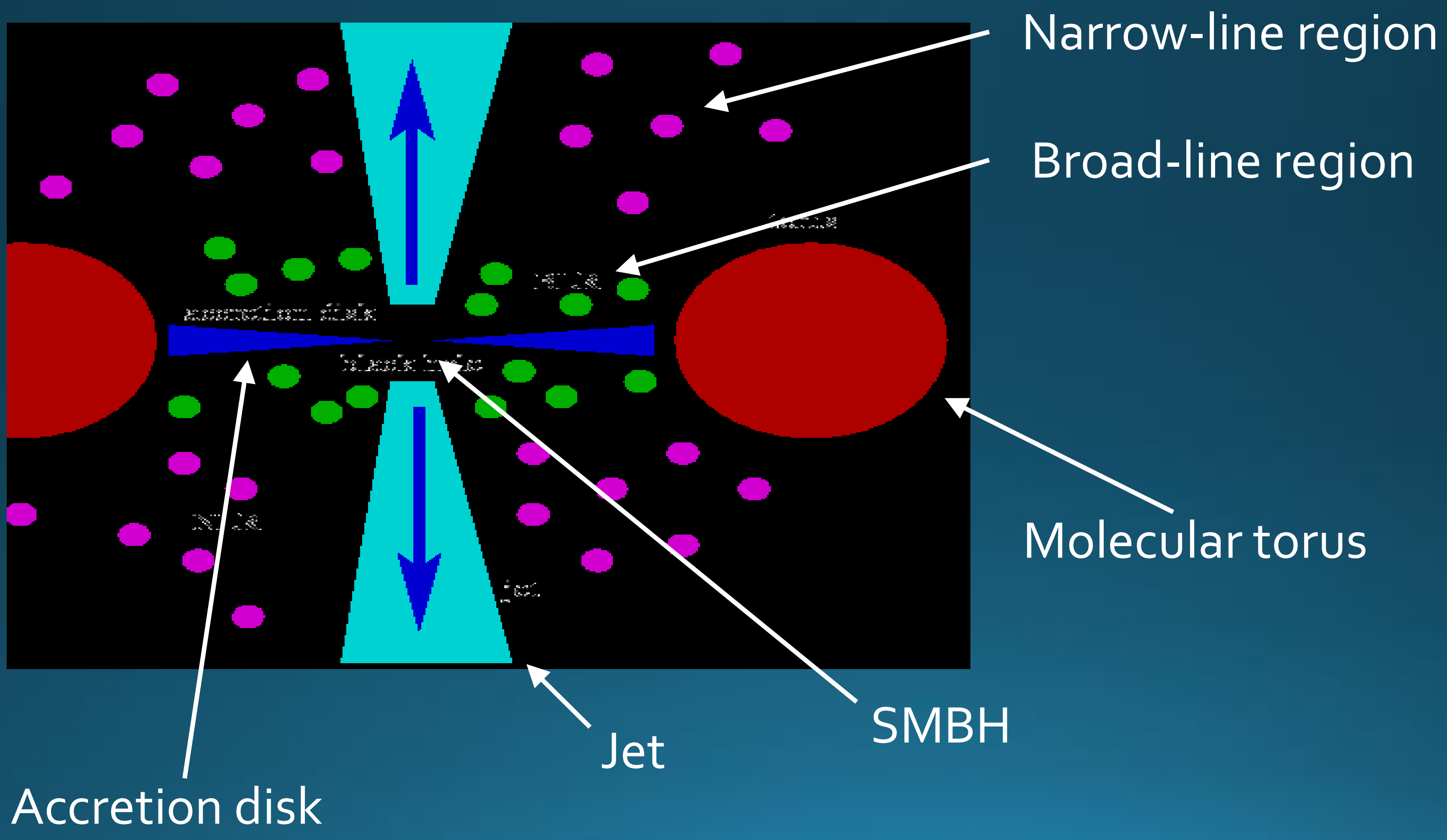
$$L_{\mathrm{E}} \approx 30000 \frac{M}{M_{\mathrm{solar}}} L_{\mathrm{solar}}$$

Note: L_E assumes spherical accretion.
Super-Eddington luminosities (a few times L_E) can be produced in accretion disks

Radiation Efficiency

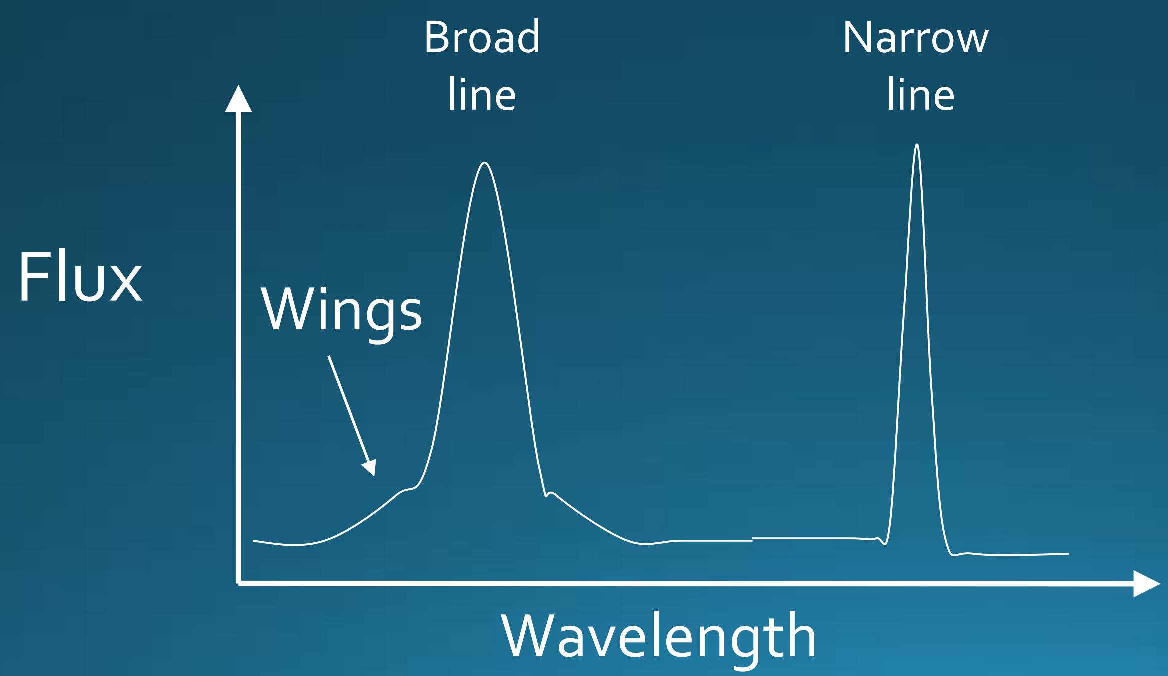
- Mass M falling into a SMBH$\rightarrow$
  energy Mc^2 added
- Theoretical maximum:
  42% of Mc^2 is converted into luminosity
  The rest increases the SMBH mass
- But typically, $\leq$10% of Mc^2 is converted into luminosity
- SMBHs in a typical quasar grows with $\geq 1\ M_{solar}$/yr
- Activity is expected to last for $\sim$ 100 Myr $\rightarrow$
  $M_{SMBH} \geq 10^8\ M_{solar}$ in faded quasars

The Central Power Source

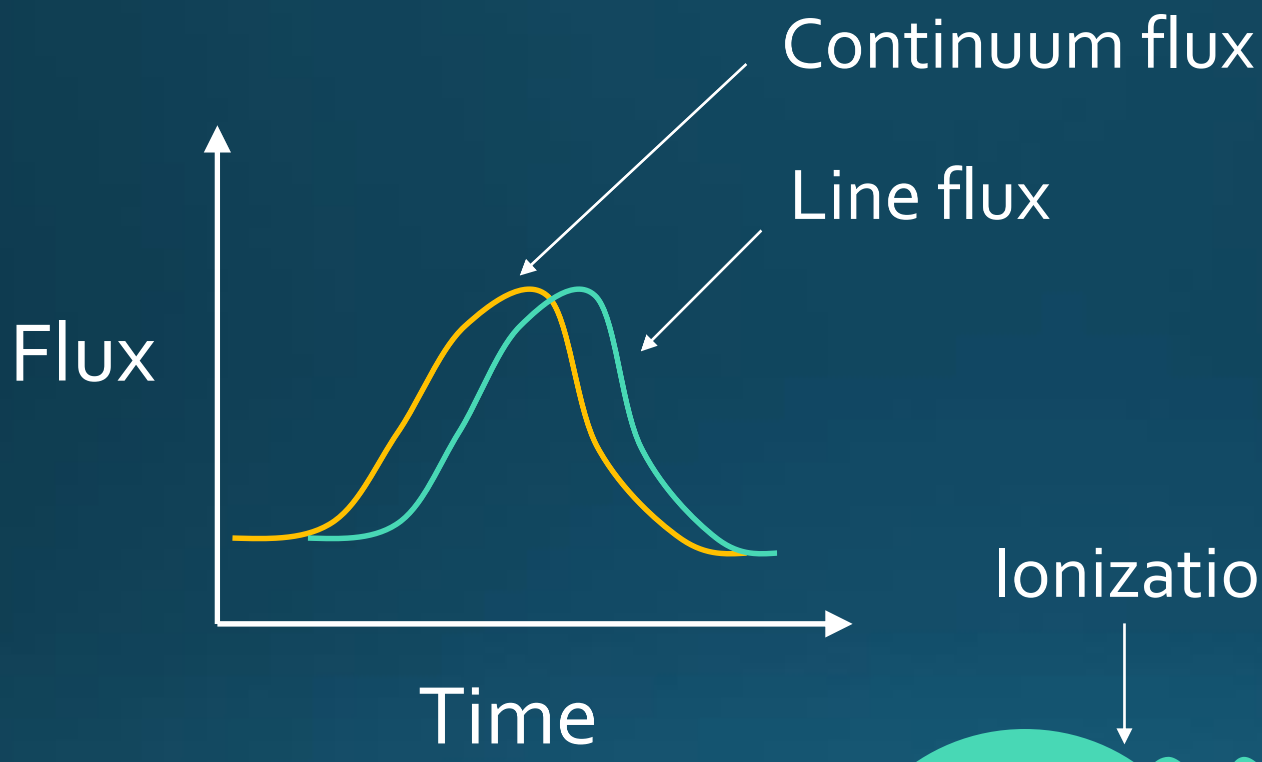


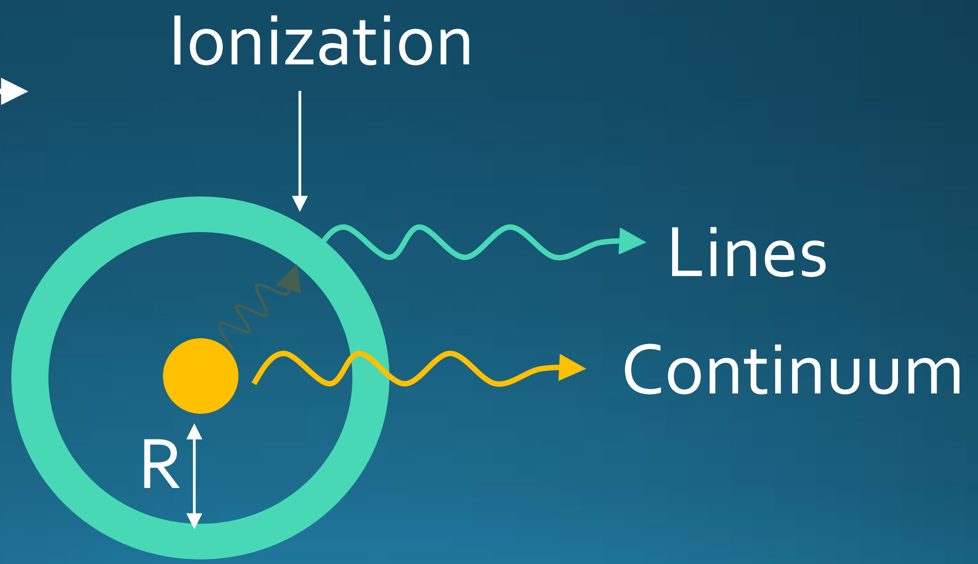
Transitions and Line Profiles

- Forbidden lines (e.g. [OII]3727Å, [OIII]5007) originate in low-density gas ($n_H \leq 10^8$ atoms/cm³)
- Allowed lines (e.g. Hα, Hβ) can originate in denser gas as well
- Broad lines, Δv~10000 km/s – Allowed (originate close to the nucleus, in dense medium)
- Narrow lines, Δv<1000 km/s – Forbidden (originate further out, in less dense medium)



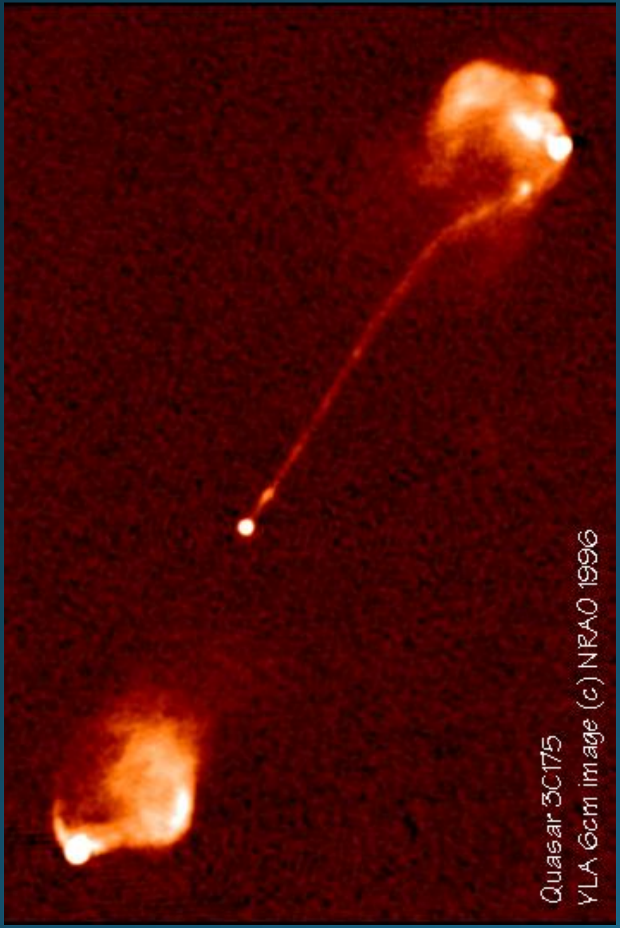
Reverberation Mapping

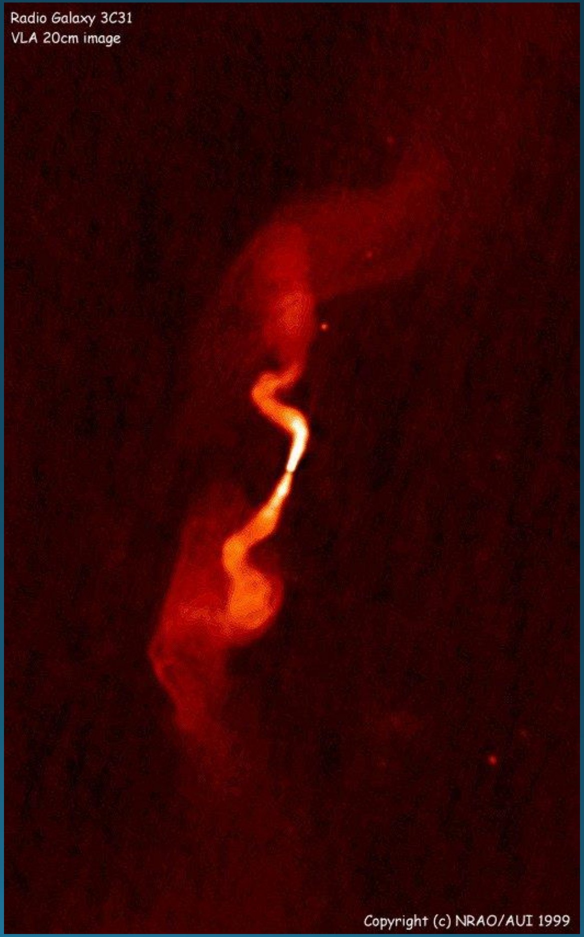




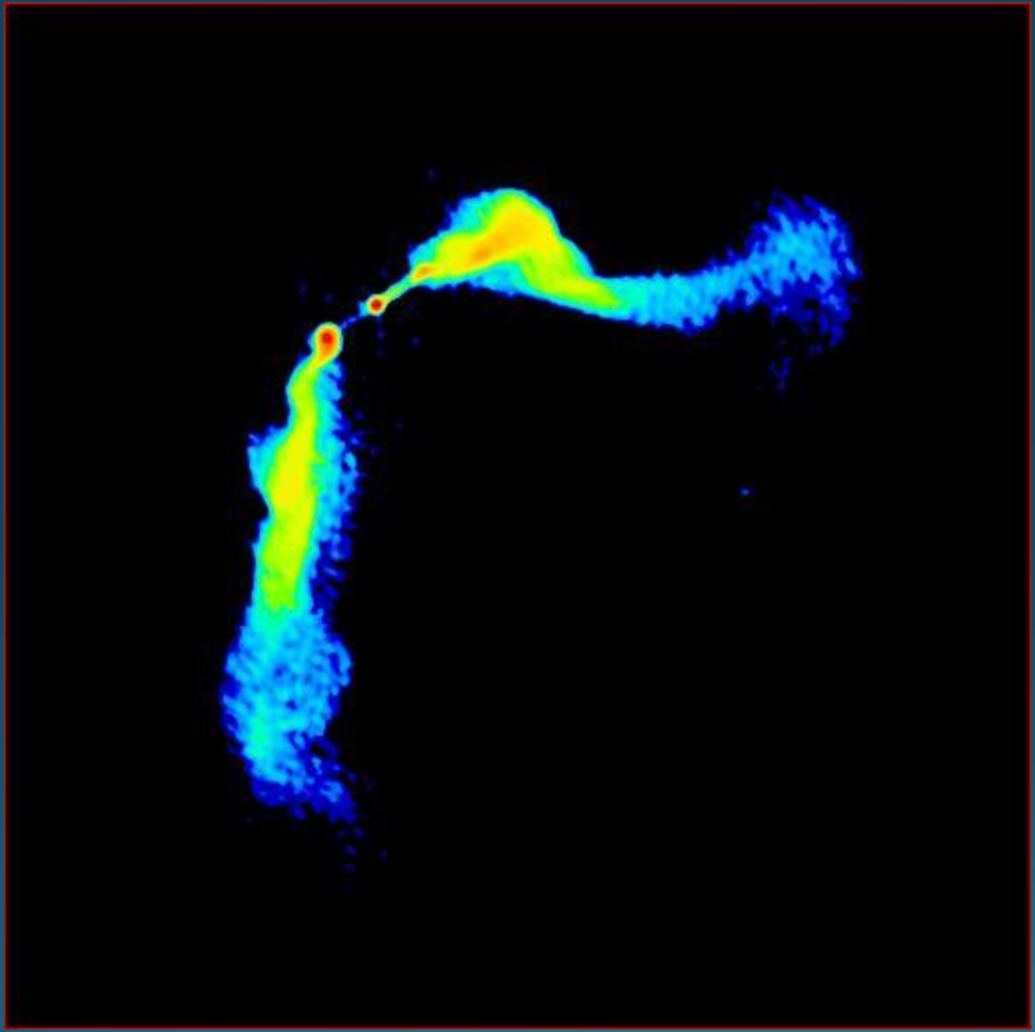
Time lag $\rightarrow$ R

Jets and Lobes



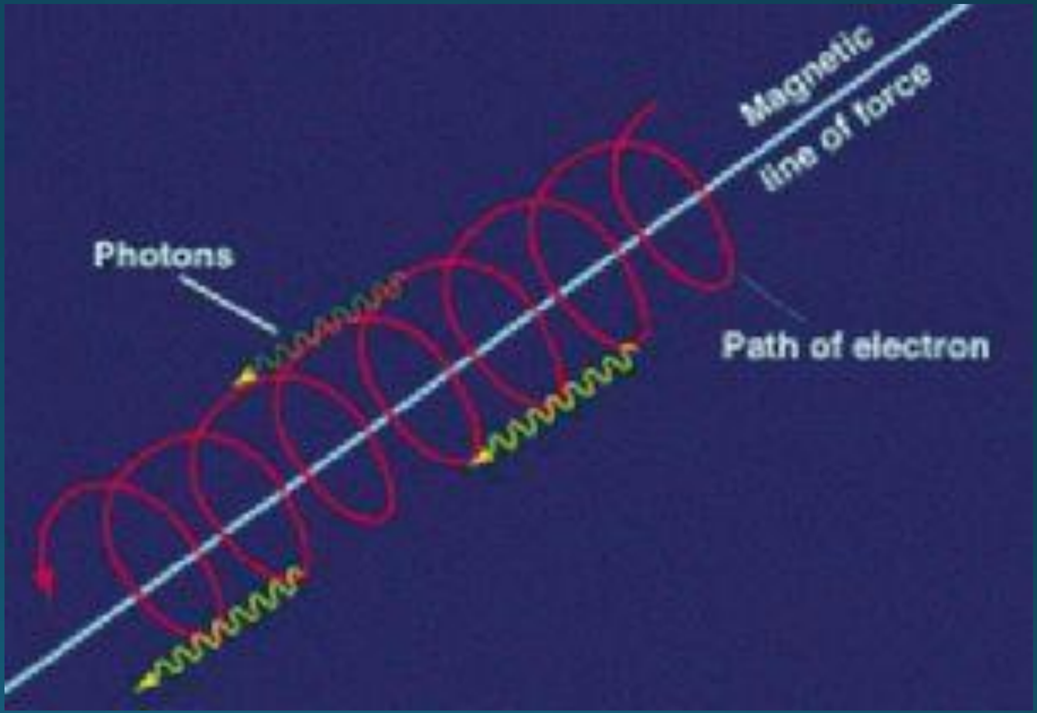


Intermission: What is happening here?



Synchrotron Radiation

- Relativistic electrons spiralling around magnetic field lines
- B=1-10 μG in lobes (same as B close to the Sun)
- B=0.1 G in active cores



Power-Law Spectrum

$$f_\nu \propto \nu^{-\alpha}$$

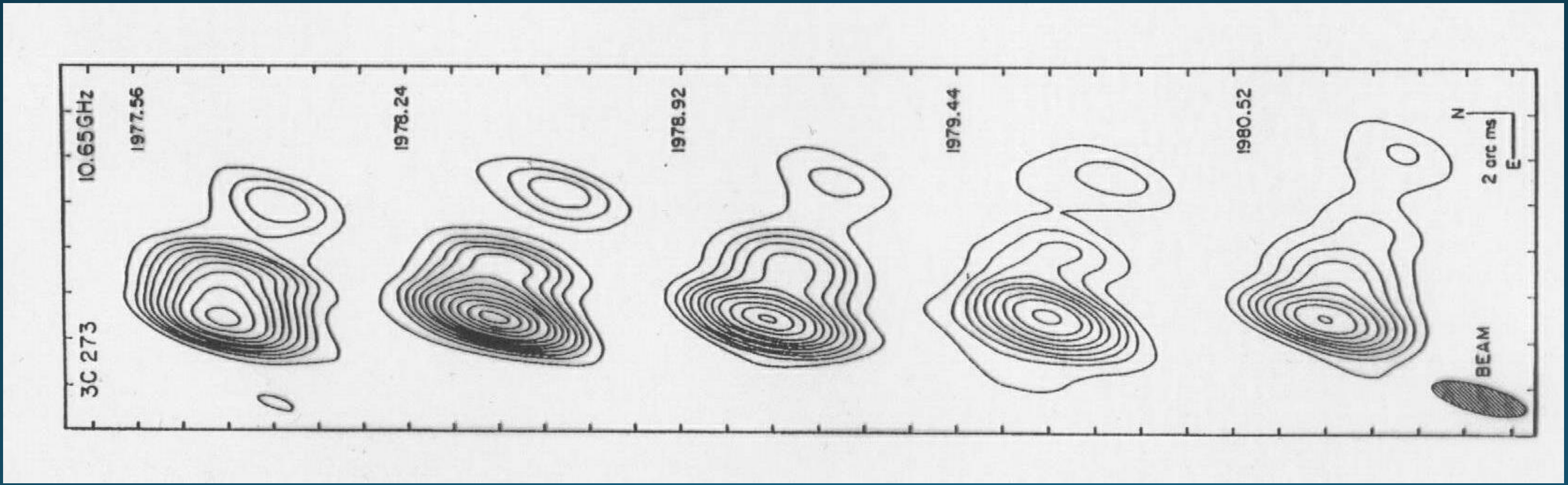
- In radio, due to synchrotron radiation:

  α=0.7—1.2
- In optical, probably caused by thermal radiation from the accretion disk:

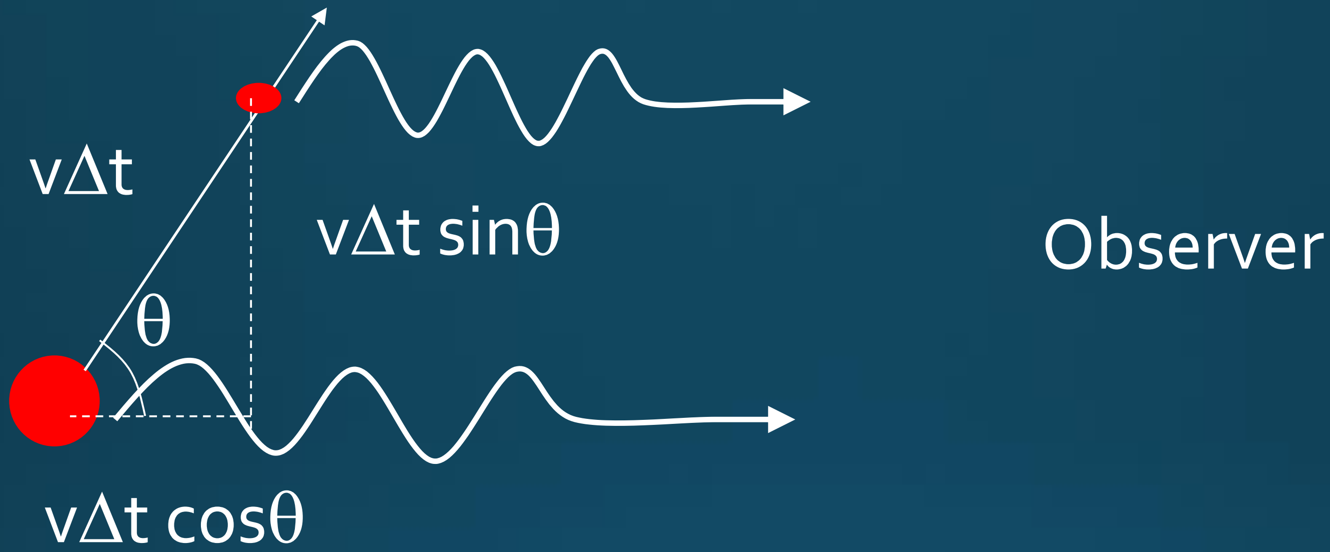
  α=0—2

Superluminal motion

Blobs appear to move outwards at 5-50c
What's going on?



Superluminal motion



$$\Delta t_{\text{obs}} = \Delta t(1-(v/c)\cos\theta)$$

In Δt_{obs}, the blob travels v Δt sinθ across the sky,
With apparent velocity v_{obs}:

$$v_{\text{obs}} = \frac{v\sin\theta}{1-(v/c)\cos\theta}$$

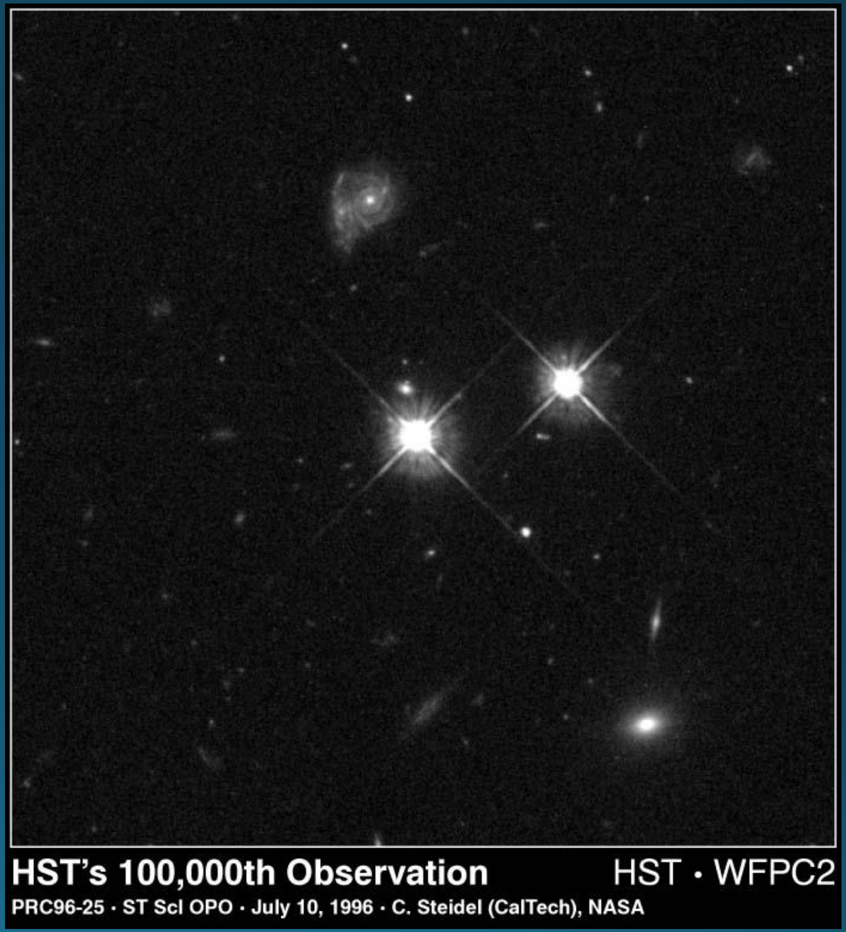
$v \approx c \rightarrow v_{obs} > c$

The number densities of AGN at z=0

Type	Number/Gpc^3
Spiral galaxies	$\sim 5\times10^6$
E/S0 galaxies	$\sim 1\times10^6$
Seyfert galaxies	$\sim 1\times10^5$
Radio galaxies	$\sim 3\times10^3$
Quasars	~ 100
Blazars	~ 80

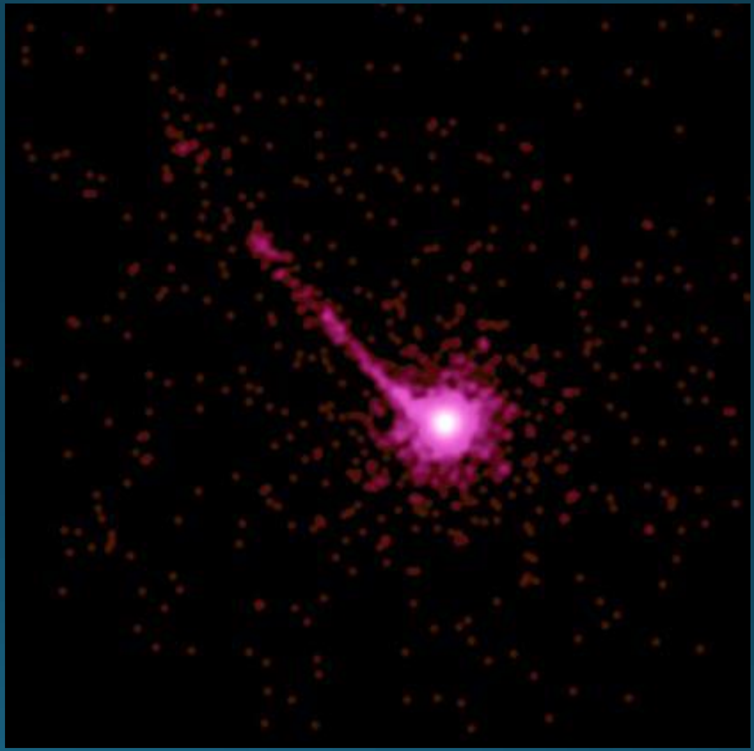
Quasars

- Originally:
  - Quasar = “Quasi-stellar radio source” (radio-loud)
  - QSO = “Quasi-stellar object” (radio-quiet)
- Today: Quasar = Both types



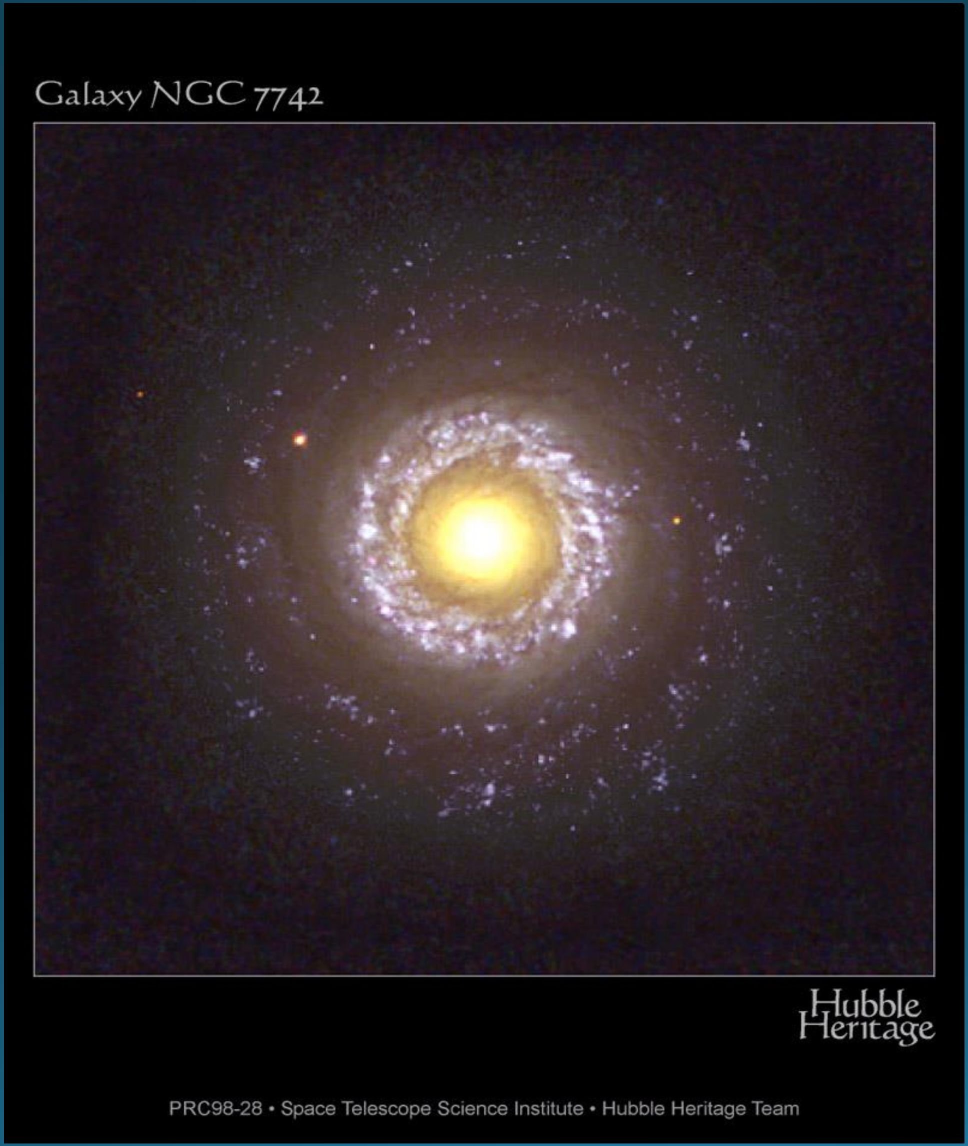
Quasars

- Most luminous of the non-transient objects in the Universe: M_B<-23
- Radio-quiet quasars >10 times more common than radio loud ones
- Both broad and narrow lines



X-ray quasar with jet

Seyfert Galaxies



Seyfert Galaxies

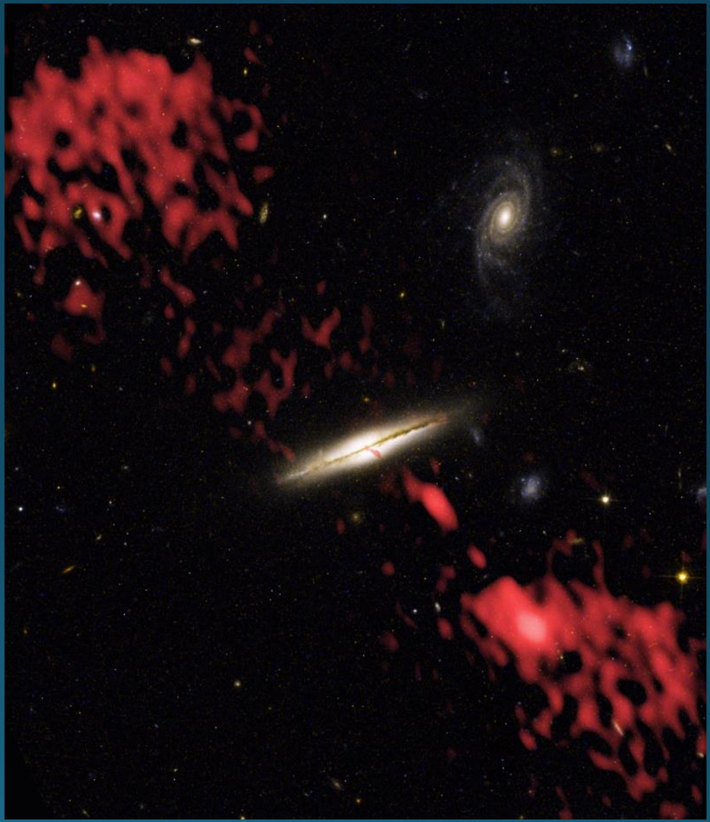
- "Low-luminosity quasars"
- Almost always in S- or So-galaxies
- Seyfert 1 nuclei
  - Broad lines (allowed) & Narrow lines (forbidden)
  - High optical luminosity
- Seyfert 2 nuclei
  - Narrow lines only, but with wings
  - Low optical luminosity

LINERs

- LINER = Low Ionization Nuclear Emission Line Region
- Low luminosities (lower than Seyfert 2)
- Exhibit lines which do not require very energetic power sources – hot stars sufficient
- Many LINERs are probably starbursts, not genuine AGN

Radio Galaxies

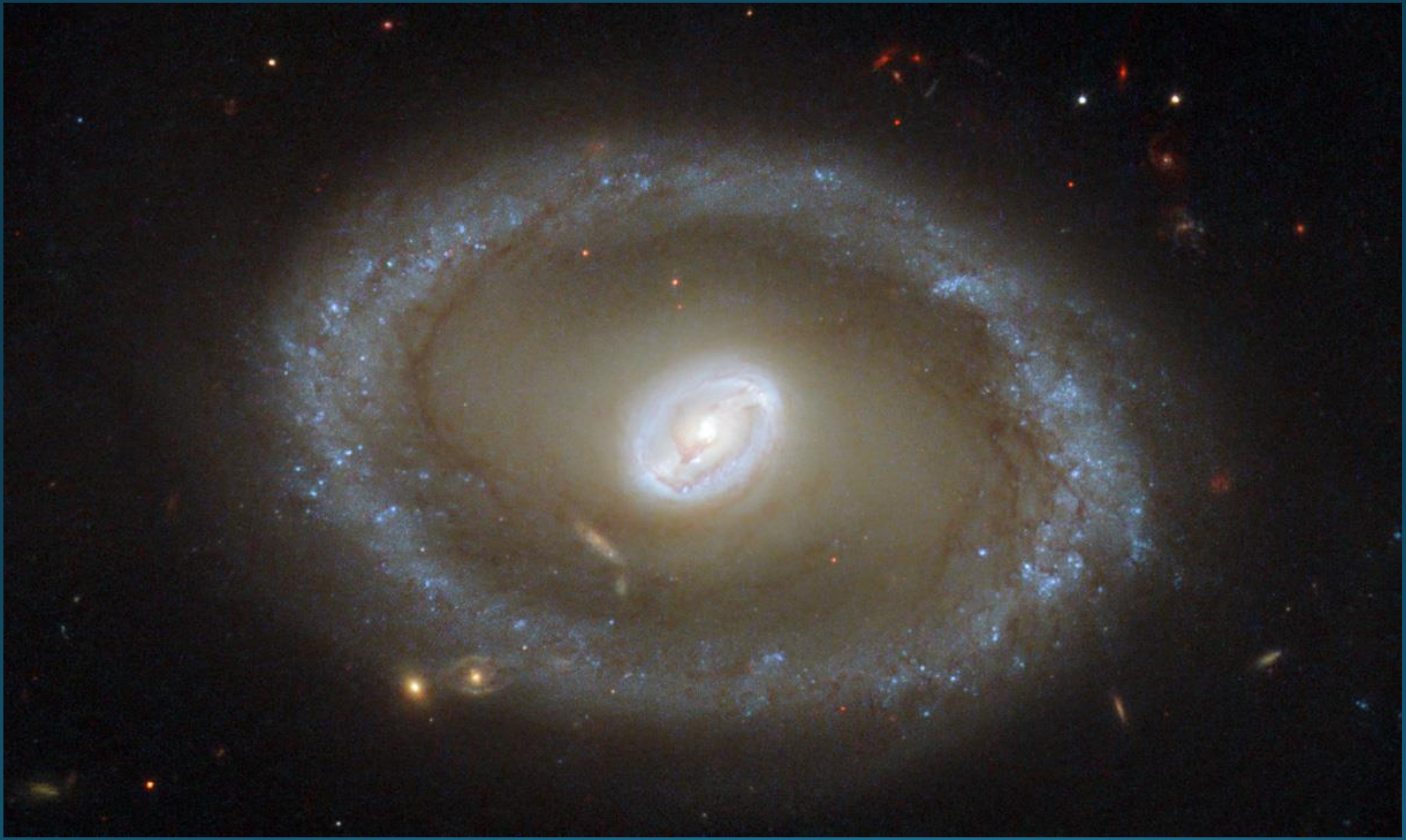
- Milky Way: 10^{30} W in radio
- Radio galaxies $\geq 10^{34}$ W in radio
- Lobes and hot spots
- Always elliptical galaxies



Blazars

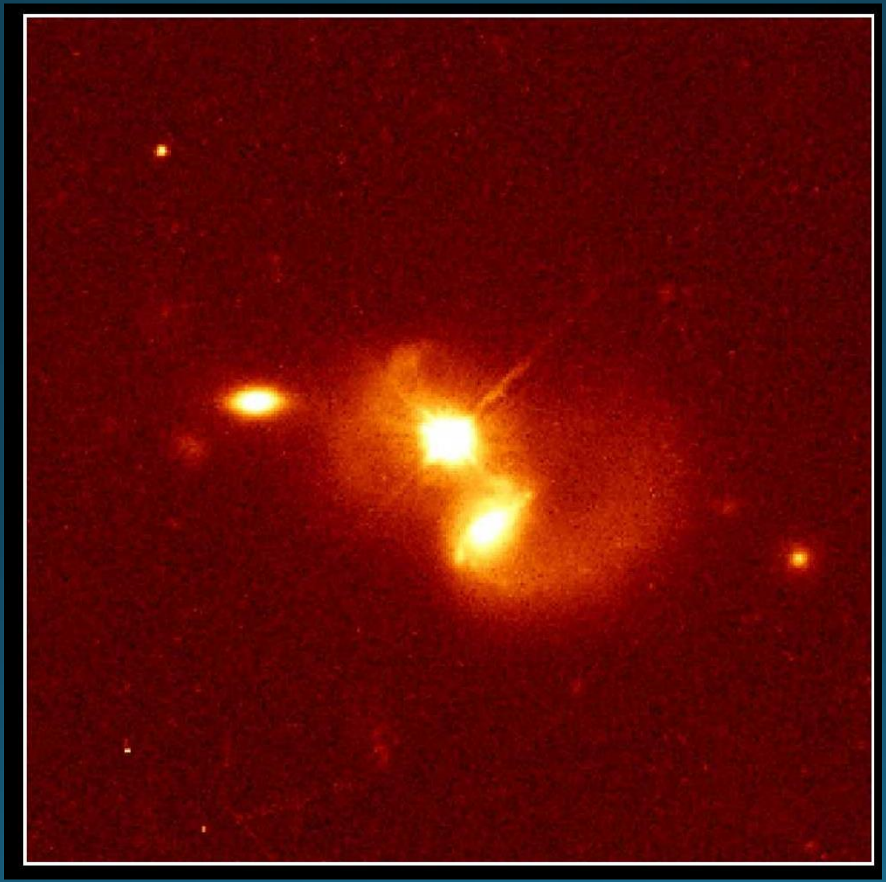
- The most rapid and large variations among AGN
- Originally:
  - BL Lac (very weak emission lines)
  - OVV = Optically violent variable (strong emission lines)
- Today: Blazar = BL Lac & OVVs
- *Appear* to be the most luminous objects in the Universe, but this is due to beaming
- Often completely featureless spectrum
  - Emission-lines weak or absent

Intermission: What sort of AGN is this?



Optical spectrum reveals lots of narrow emission lines

Intermission:
What sort of AGN is this?

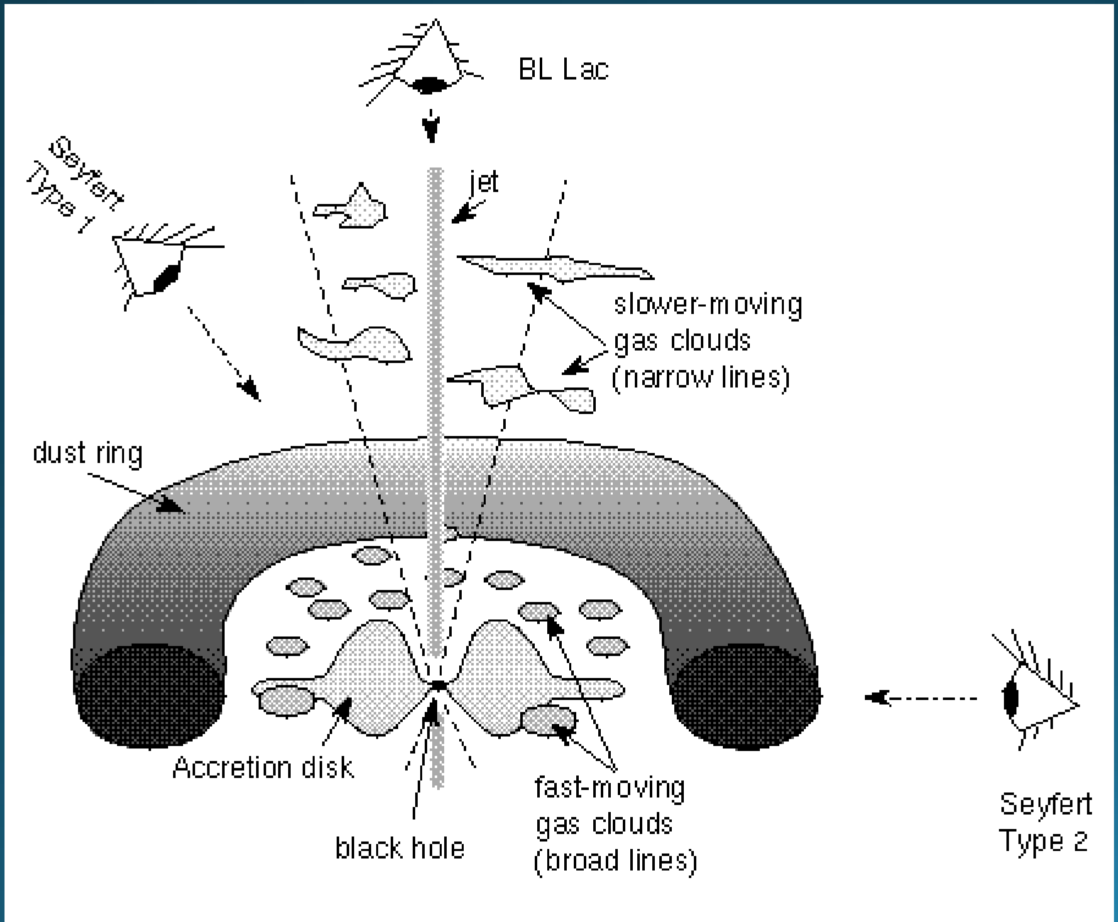


The Unification Model

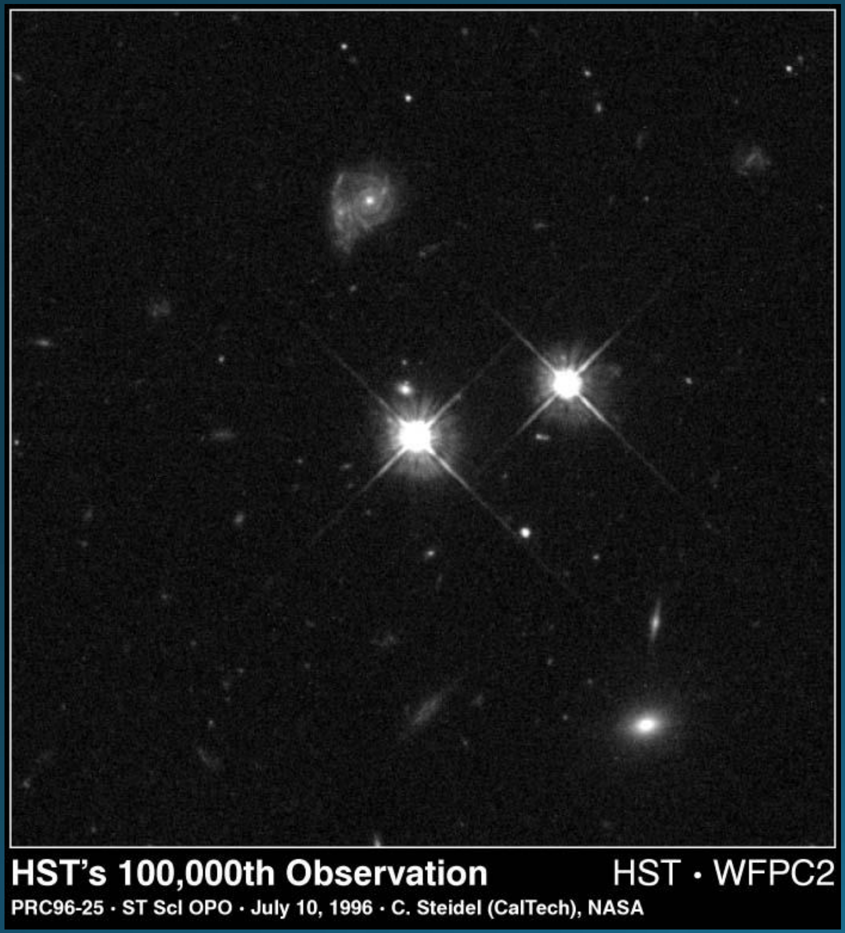
Quasar

Radio galaxy

Radio galaxy



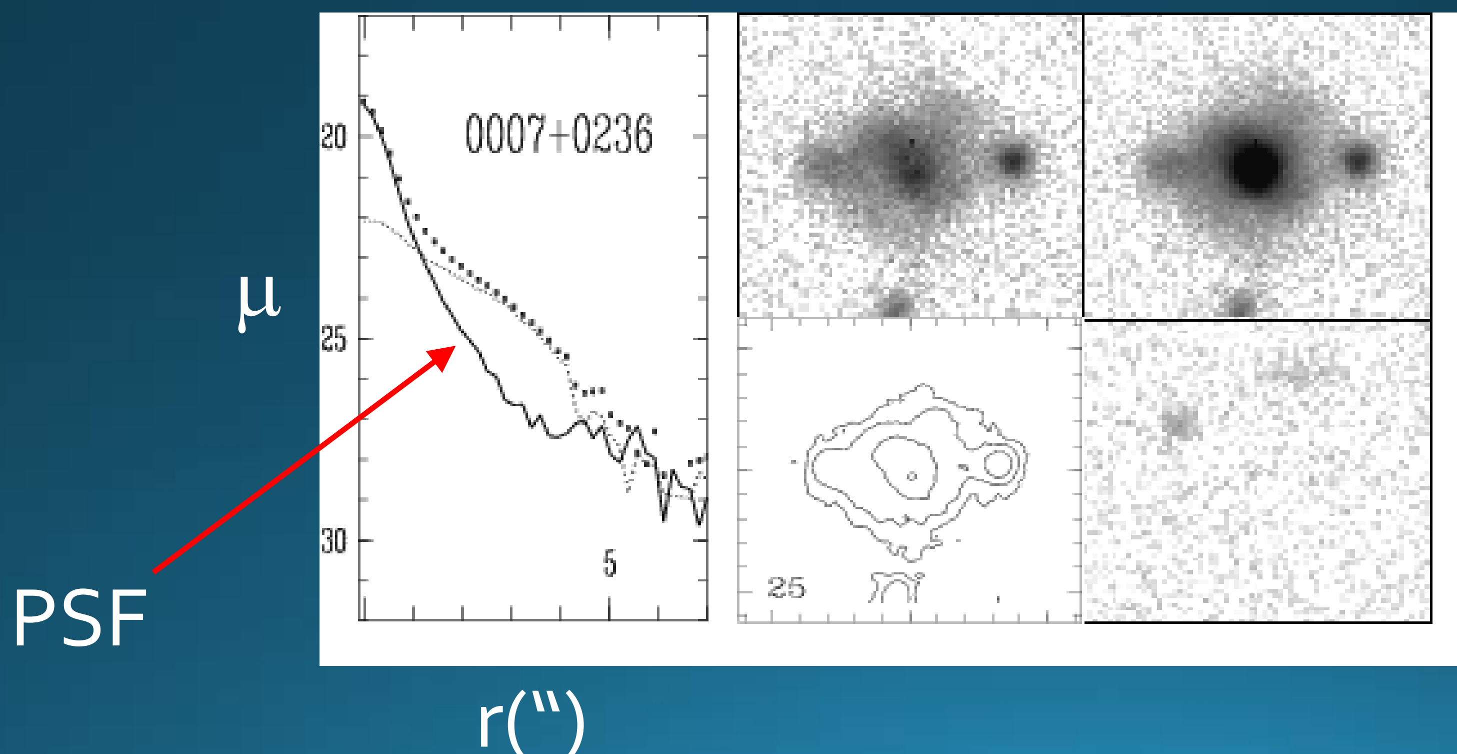
Quasar Host Galaxies



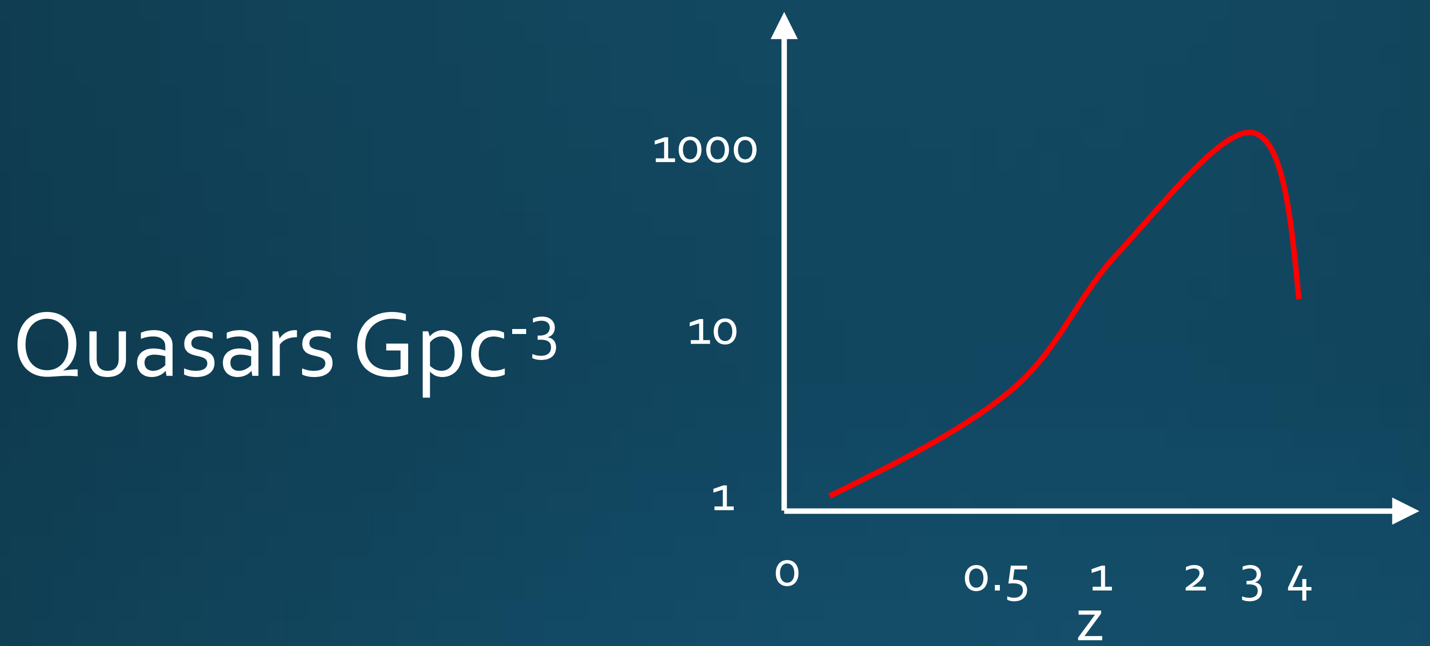
- The AGN of a quasars typically outshines its host galaxy
- To study the host galaxy, one utilizes the fact that the AGN is a point source wheras the host is an extended object

Quasar Host Galaxies

- Point spread function (PSF): Describes how the light of a perfect point source is distributed on the detector (CCD) because of telescope imperfections, diffraction etc.

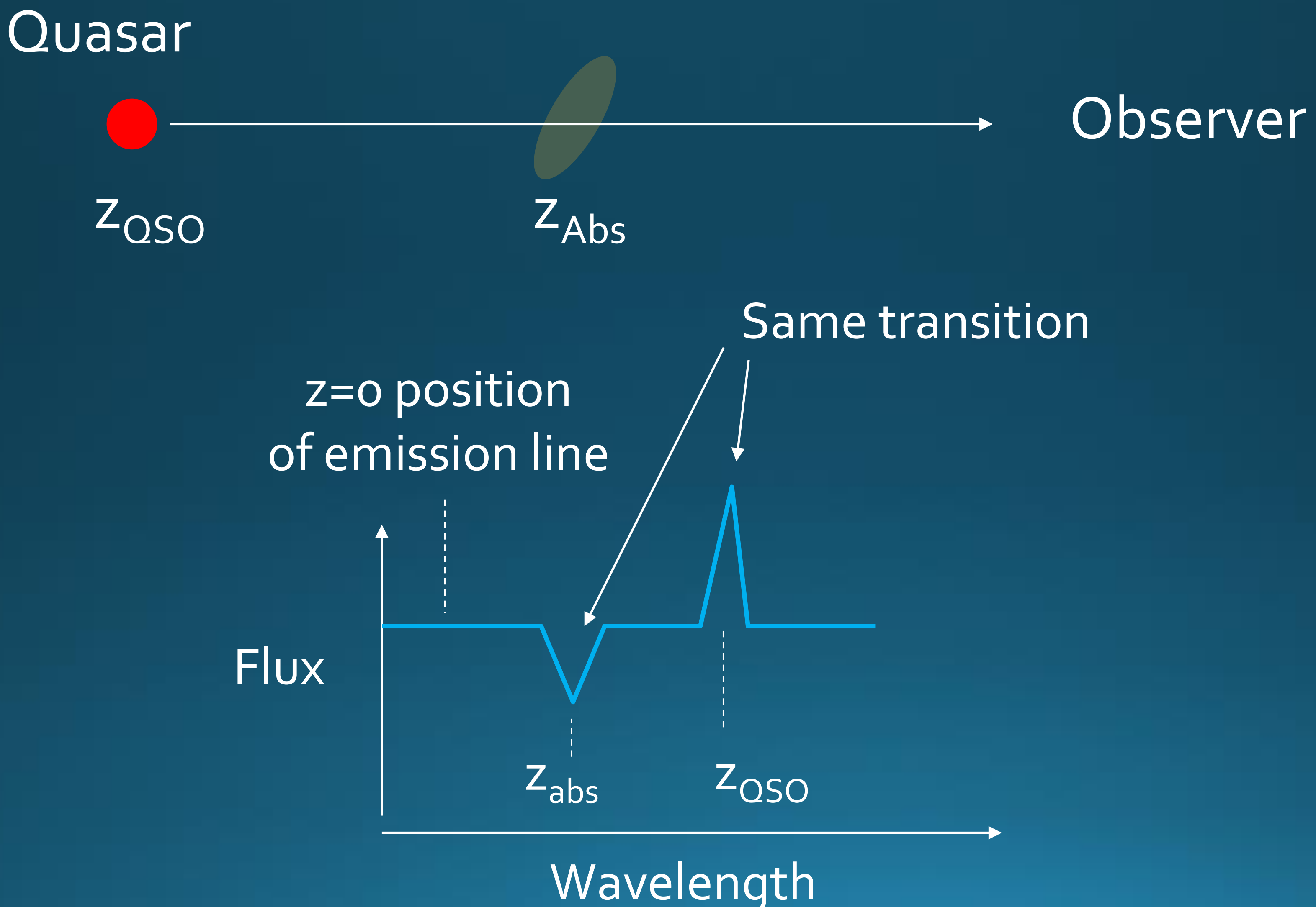


Cosmological Evolution



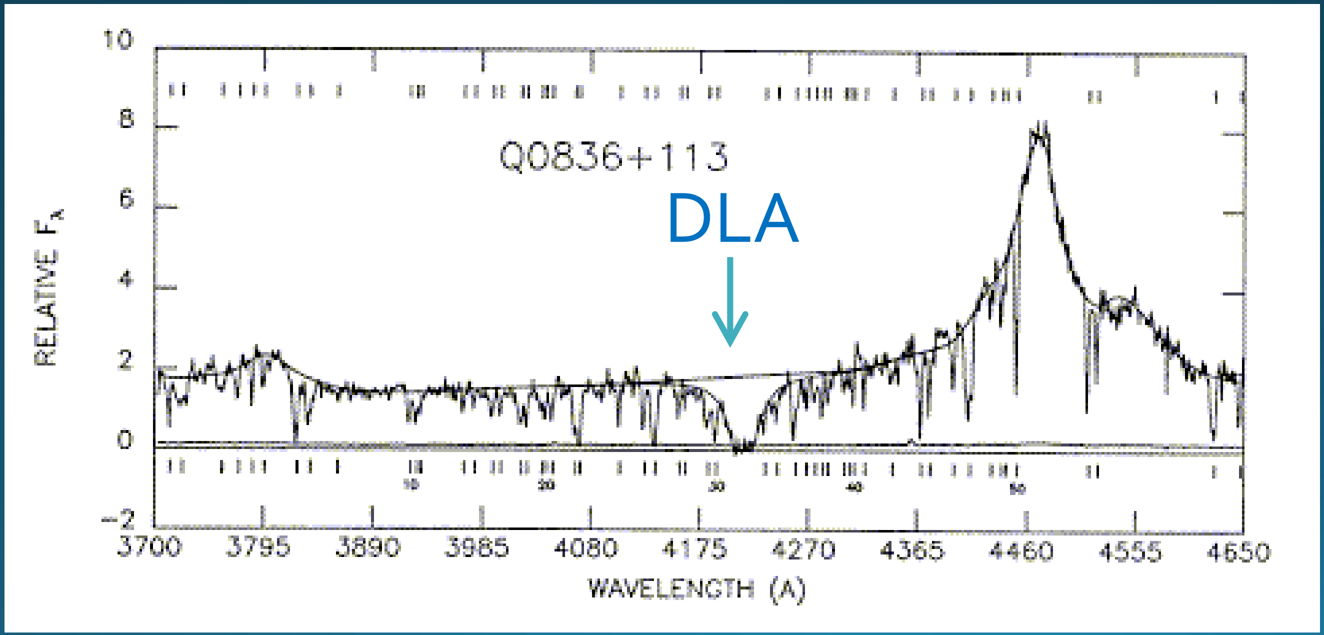
- At z≈3, bright quasars appear ~1000 times more common than today
- Quasar activity drops at even higher redshifts
- The highest-redshift quasar detected so far has z≈7
- Very challenging to build a SMBH by z=7 (less than 1 Gyr after the Big Bang) – exotic formation channel required?

Quasar Absorption Systems



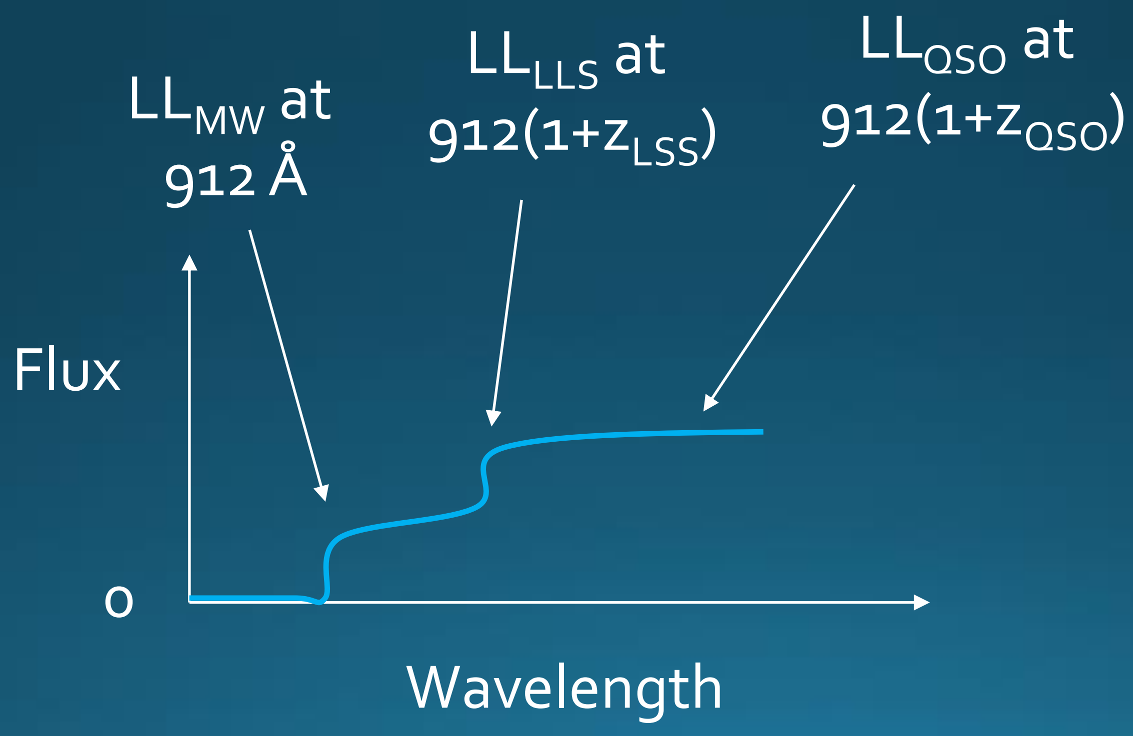
Damped Lyman-Alpha Clouds

- Very dense, neutral gas N(HI) $\geq 2\times10^{20}$ cm^{-2}
- Often interpreted as gas associated with intervening galaxies
- Many DLAs are also Lyman-limit systems

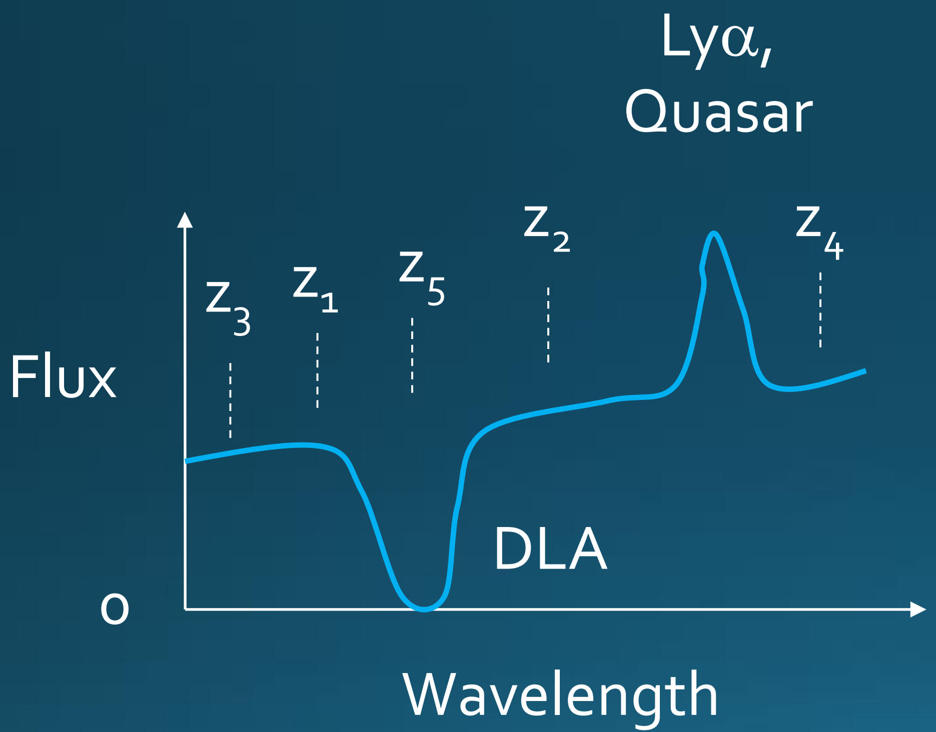


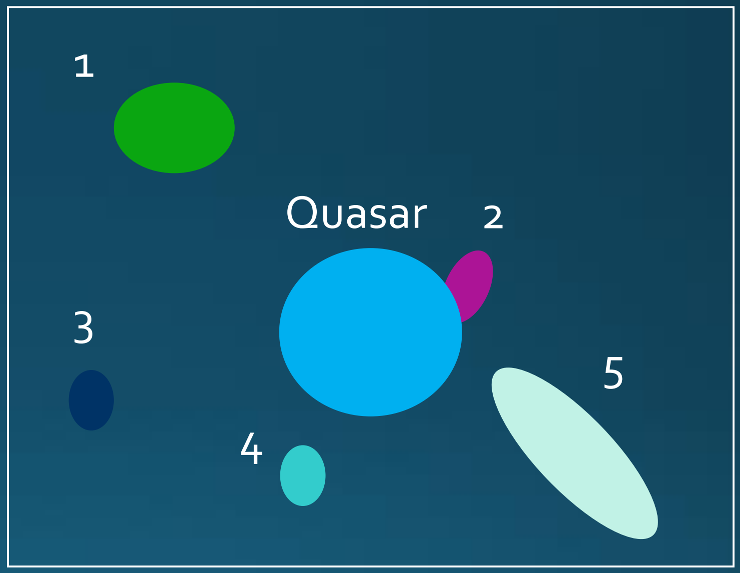
Lyman-Limit Systems

- Dense, neutral gas $N(HI) \geq 10^{17}$ cm^{-2}
- Absorbs hydrogen-ionizing radiation at $\lambda < 912(1+z_{LLS})$ Å



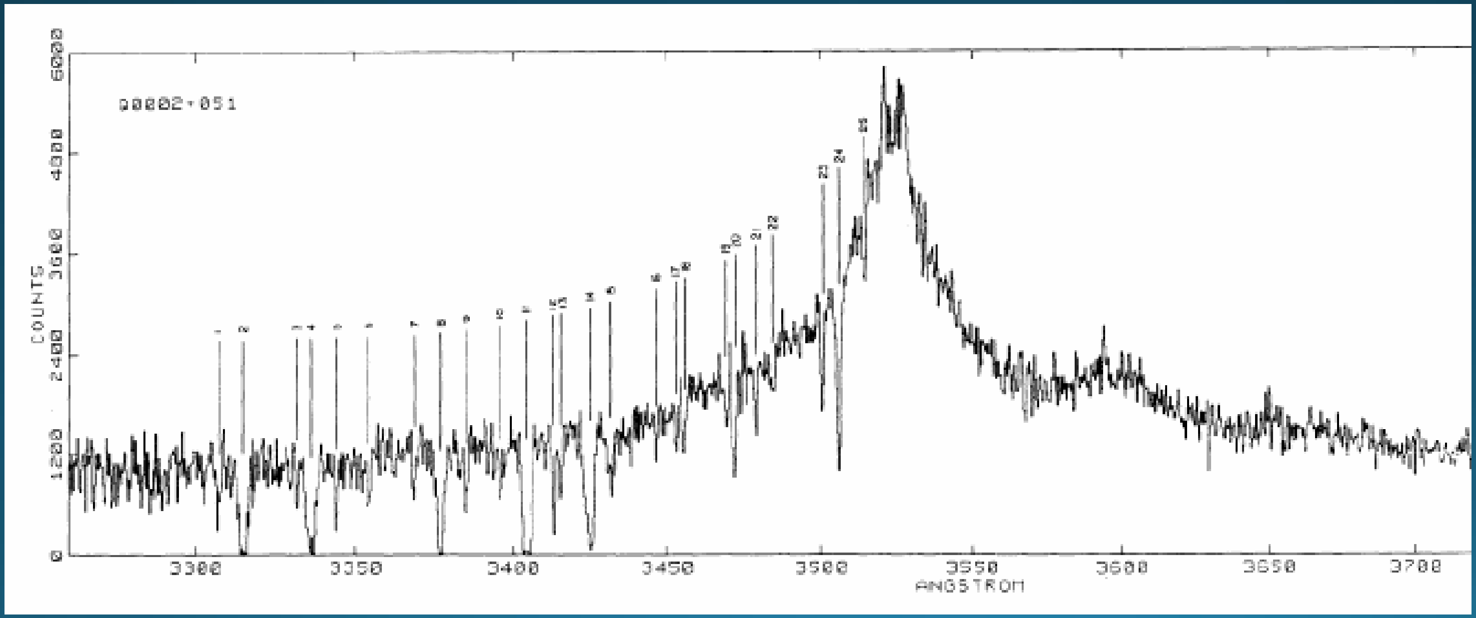
Identifying the Absorber





The Lyman-Alpha Forest

- Low-density, very extended clouds in the intergalactic medium
- Proximity effect:
  - Lyα-forest thinner at $z_{abs} \approx z_{QSO}$
  - Indicates that clouds close to the quasar are photoionized by it



The Gunn-Peterson Test

- If the Universe (the intergalactic medium, IGM) is neutral at z_{QSO}, then a strong absorption feature blueward of Lyα in quasars should appear – *the Gunn-Peterson trough.*
- This does indeed appear – at $z_{QSO}\approx 6$, indicating that the transition from an neutral to ionized IGM takes place at around this redshift