Active Galactic Nuclei

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Physics of Galaxies 2019-2020 Q4
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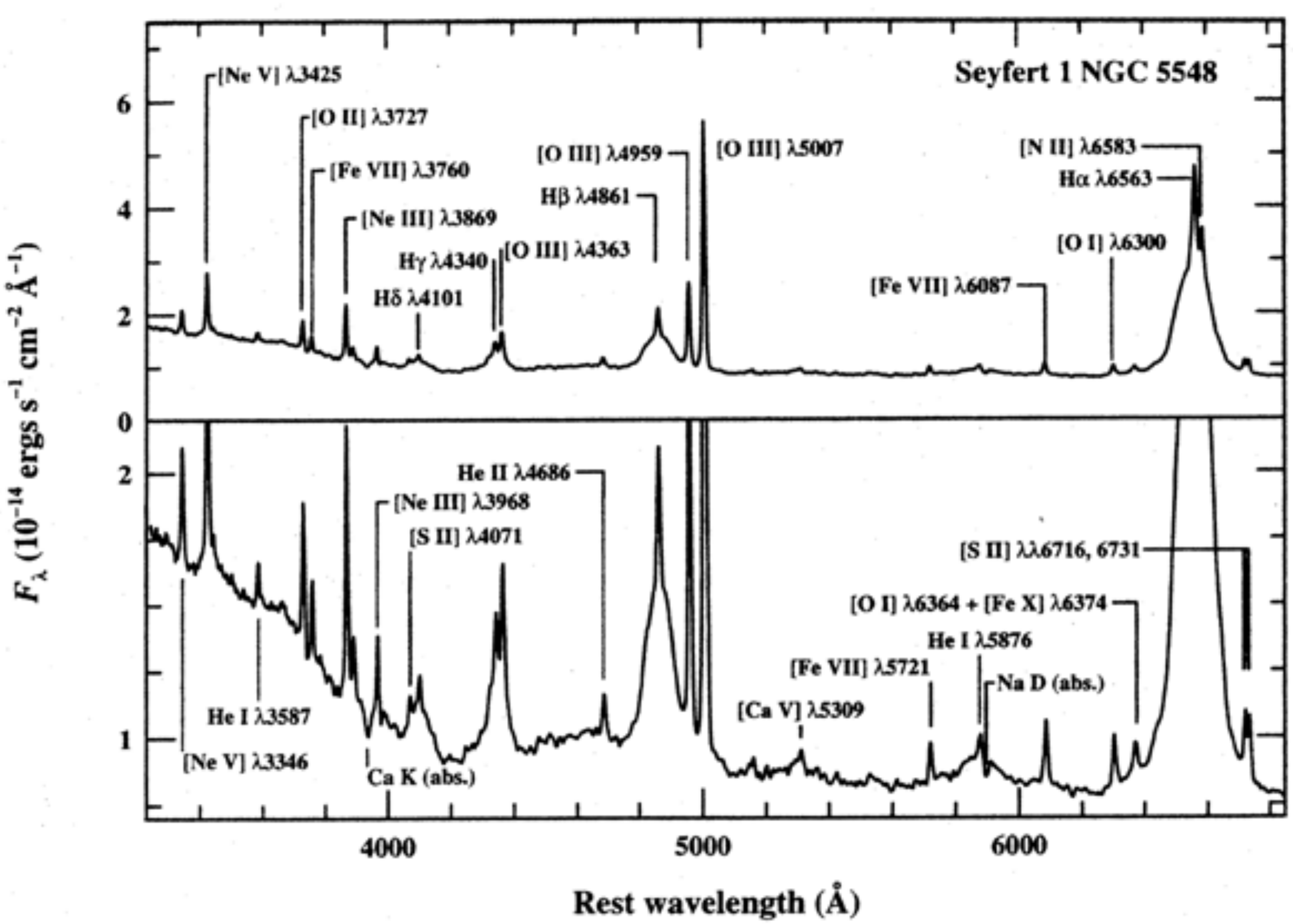
A bit of history…

Seyfert galaxies

Broad-line emission from galactic nuclei are know since early 1900's

The displayed broad lines could only be excited by photons more energetic than those from young stars



Carl Seyfert

QSO first discovery

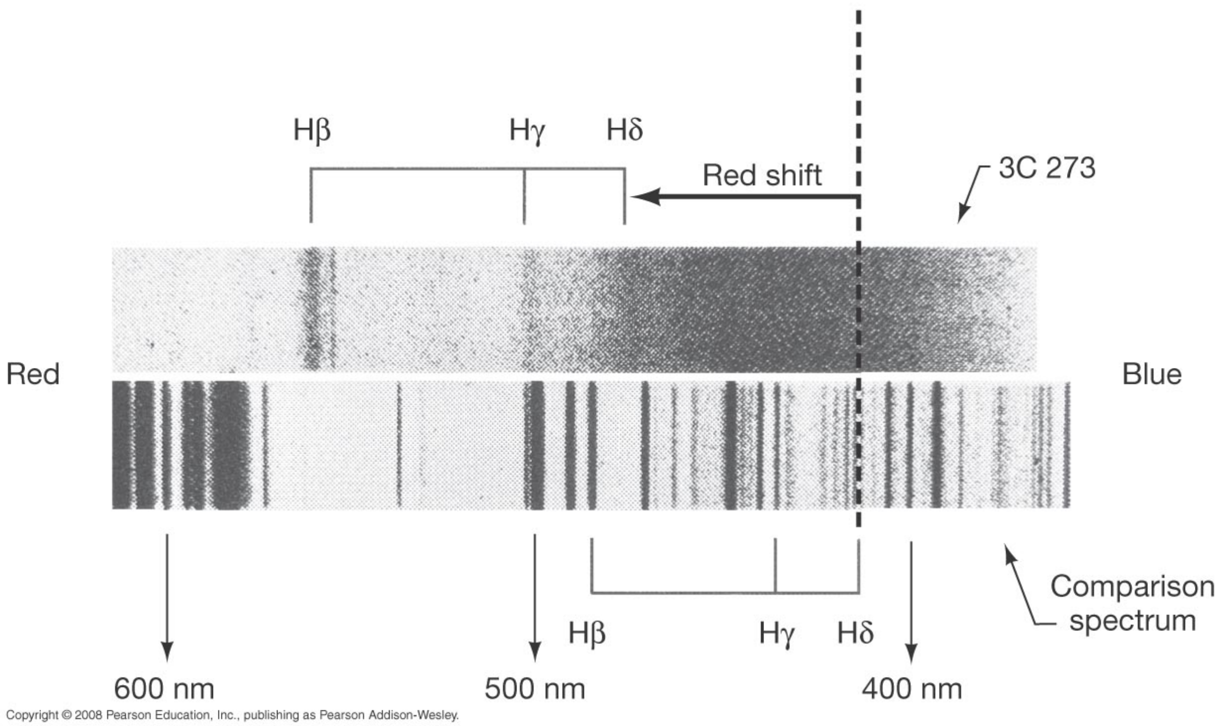
Boom of radioastronomy in 1950s: Third Cambridge (3C) Catalogue

Most 3C sources were identified with elliptical galaxies

…but a few looked point-like (like stars)

They indicated redshifts unusually high for such bright objects

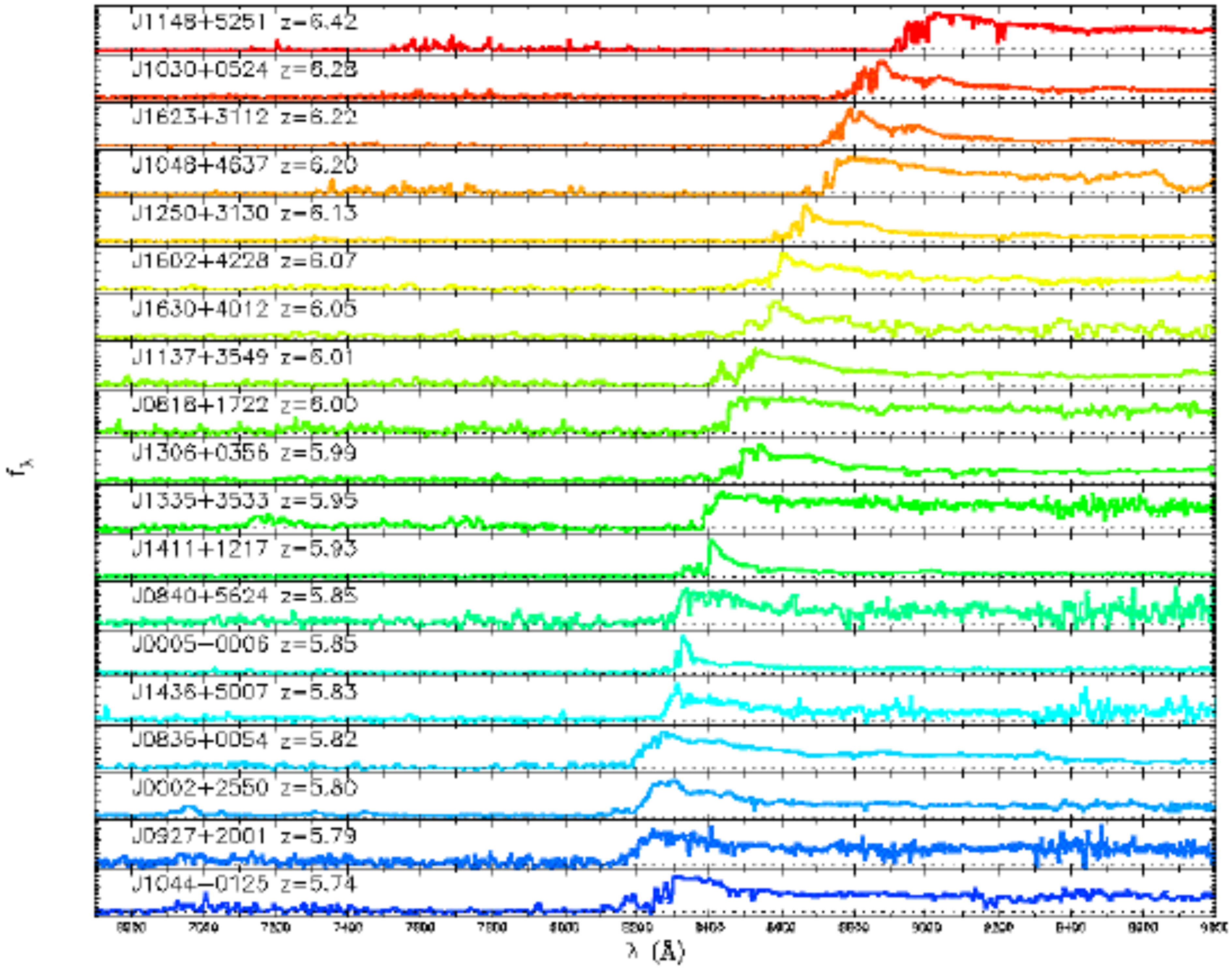
3C 273 has B,V < 13 mag and z=0.158



Maarten Schmidt

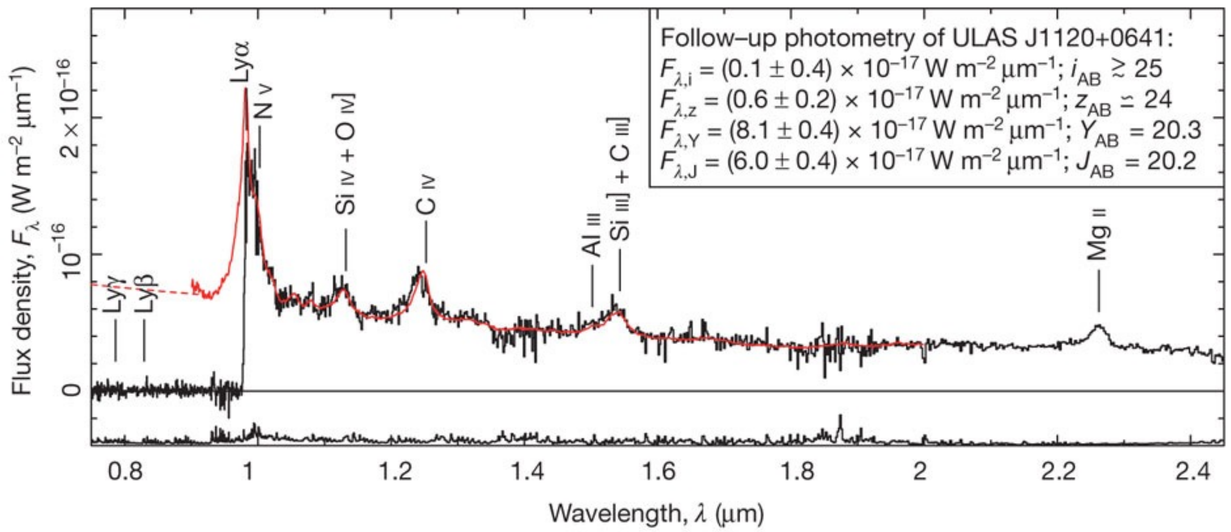
And contemporary works by Sandage, Matthews, etc.

Searching for far away QSOs



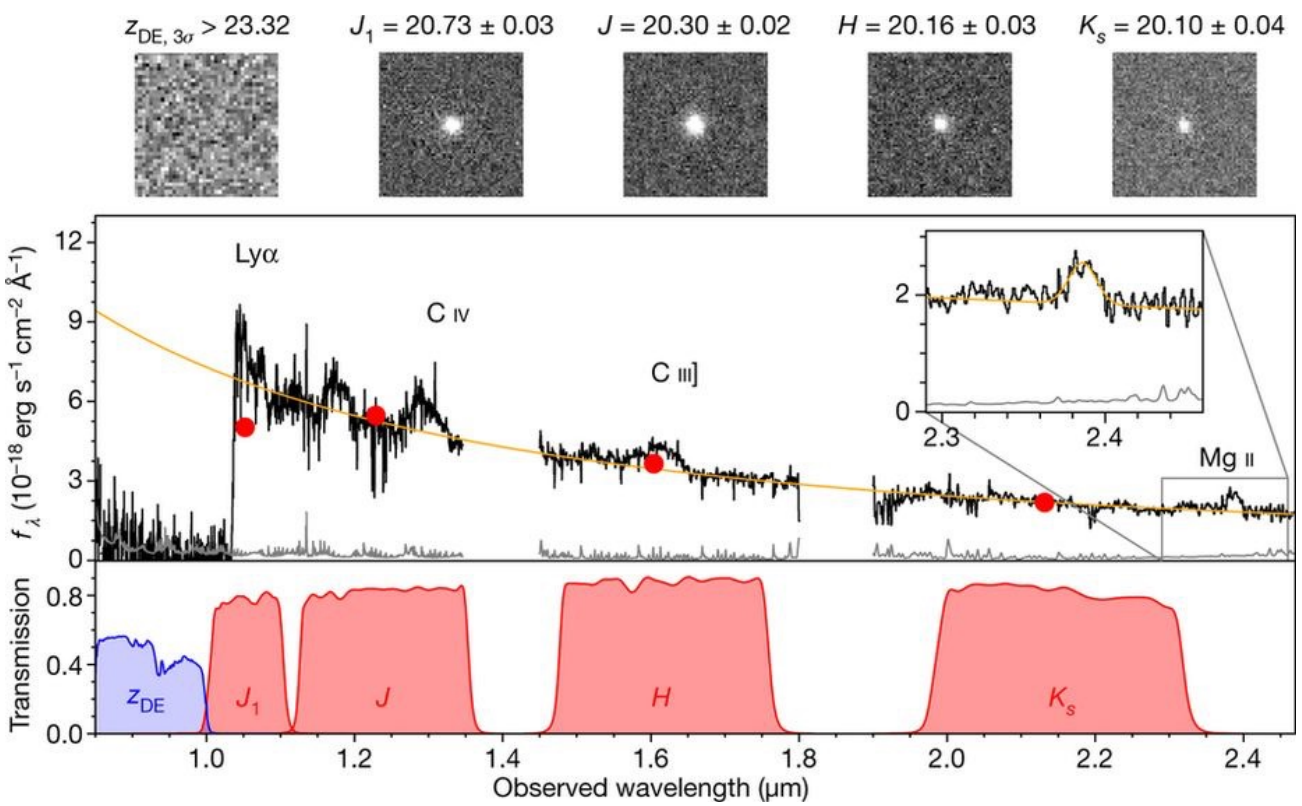
Fan et al. (2006)

Farthest QSOs known to date



z=7.085

Mortlock et al. (2011)



z=7.54

Bañados et al. (2017)

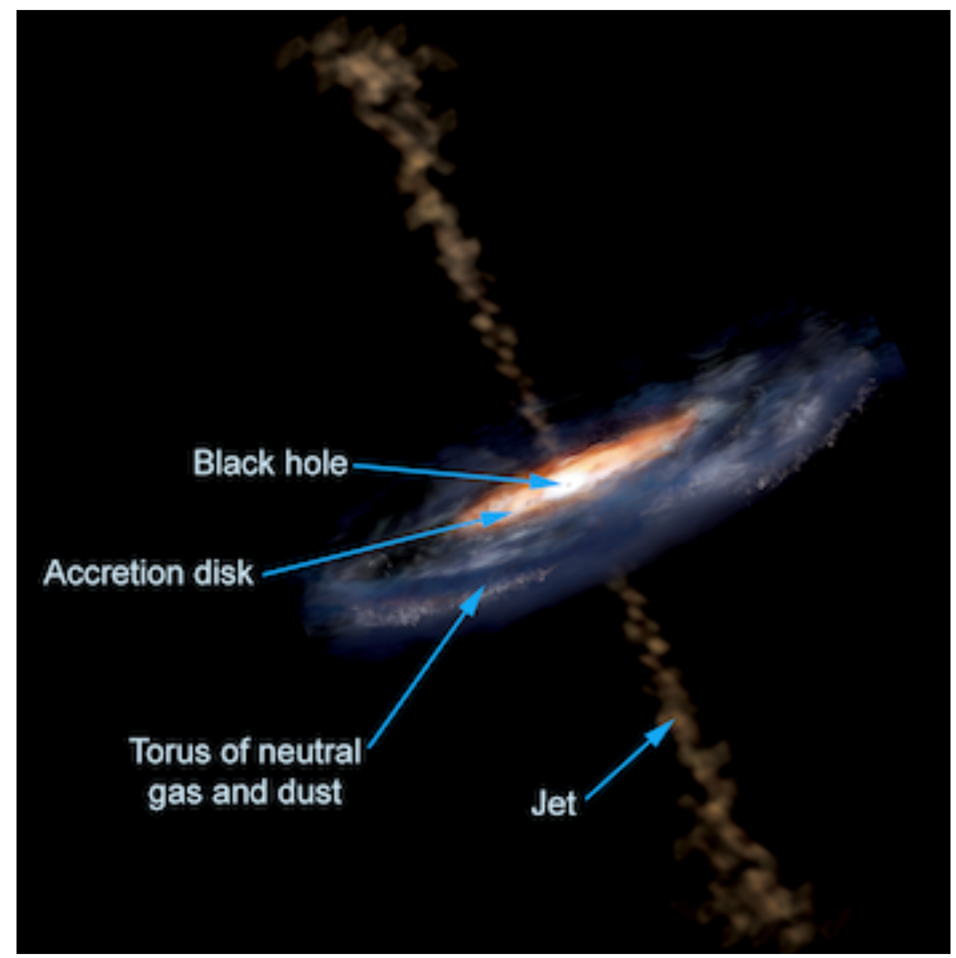
Very rare objects: < 1 quasar per Gpc^3 at z=6, or <1 per 100 sq. deg.

The AGN components

QSO and AGN

AGN/QSO classification is complex - QSO are the the most luminous AGN
(outshine host galaxy, so they look point-like)

- ✦ X-ray emission due to accretion
- ✦ some have broad (> 1000 km/s) line emission (permitted lines) - AGN type 1
- ✦ Others only narrow lines - AGN type 2
- ✦ radio quiet or loud (some with jets)
- ✦ blue light excess
- ✦ light variability in some cases
- ✦ optical light polarisation



Credit: A. Simonnet

The central engine

The central engine is a supermassive black hole accreting gas

Black hole mass ~ 10^6 - 10^8 Msun - event horizon size of solar system

Gas supplied at a rate of ~ 1 Msun/yr

Gas being accreted forms a disk which is heated by friction

UV, optical and X-ray

The energy released by accretion is approximately

$$\Delta E_{\rm acc} = G\frac{Mm}{R},$$

where M is the mass of the object, R is its radius, and m is the mass accreted.

Let us assume for the moment, unrealistically, that all kinetic energy generated by conversion of gravitational energy in accretion is radiated from the system (we address the issue of efficiency for realistic accretion shortly). Then the accretion luminosity is

$$L_{\rm acc} = \frac{GM\dot{M}}{R} \simeq 1.3\times10^{21}\left(\frac{M/M_\odot}{R/\rm km}\right)\left(\frac{\dot{M}}{\rm g\,s^{-1}}\right)\ \rm erg\,s^{-1},$$

if we assume a steady accretion rate $\dot{M}$.

Energy released by accretion onto various objects

Accretion onto	Max energy released (erg g^{-1})	Ratio to fusion
Black hole	4.5×10^{20}	75
Neutron star	1.3×10^{20}	20
White dwarf	1.3×10^{17}	0.02
Normal star	1.9×10^{15}	10^{-4}

Credit: M. Guidry

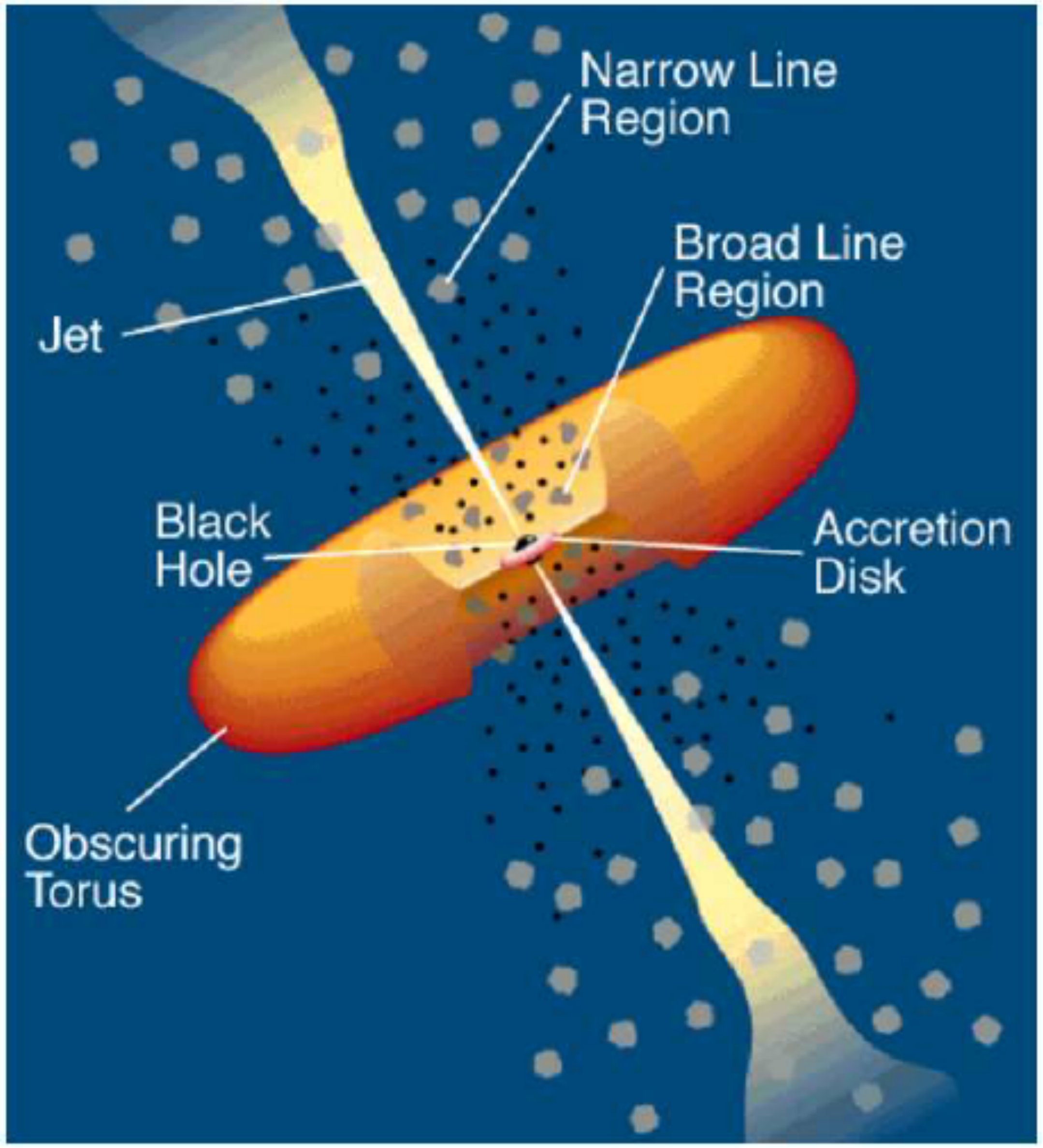
The broad-line region

Broad-line region extends 0.01-0.1 pc around central engine

Direct visibility is extremely difficult

Very hot gas clouds w/ *v ~1000-10,000 km/s*

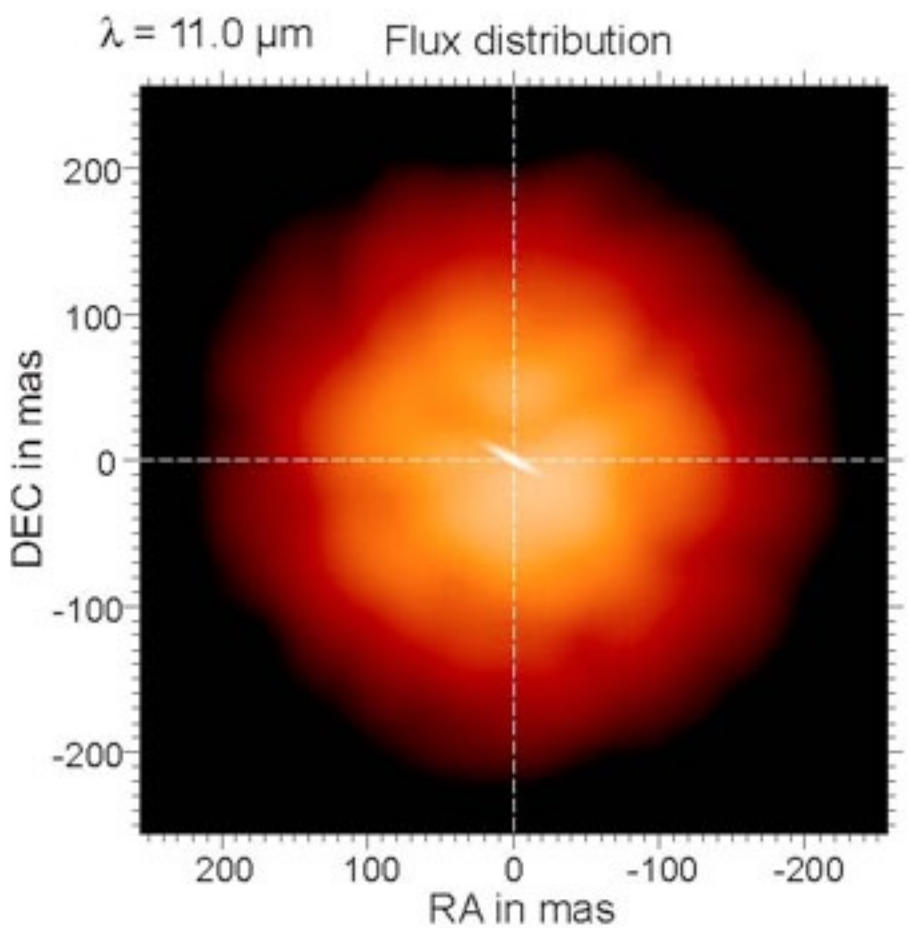
Although different components are present (scaled) in both stellar and supermassive black holes, *broad-line regions are exclusive to supermassive black holes*



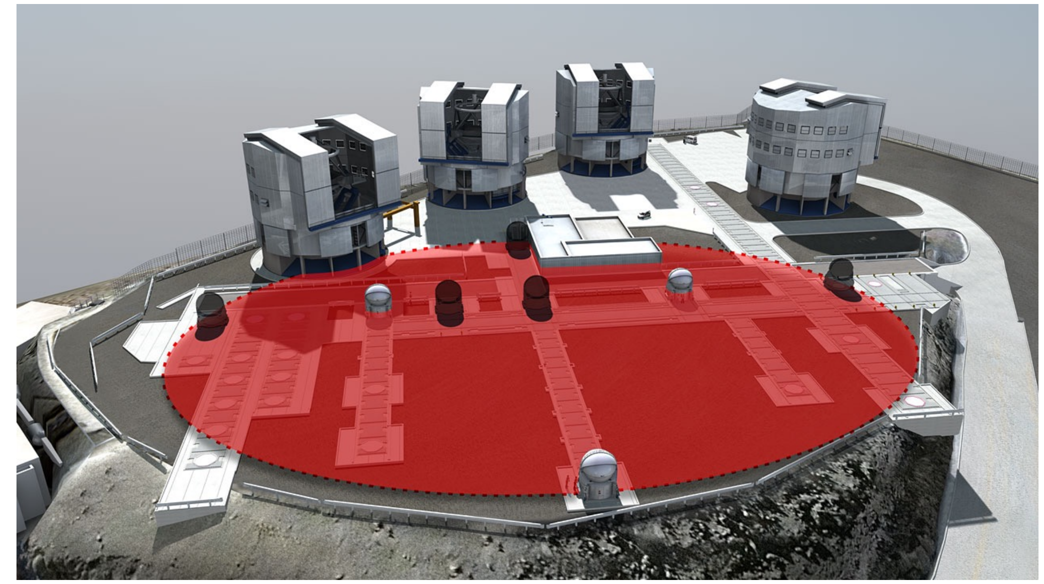
Urry & Padovani (1995)

The dusty torus

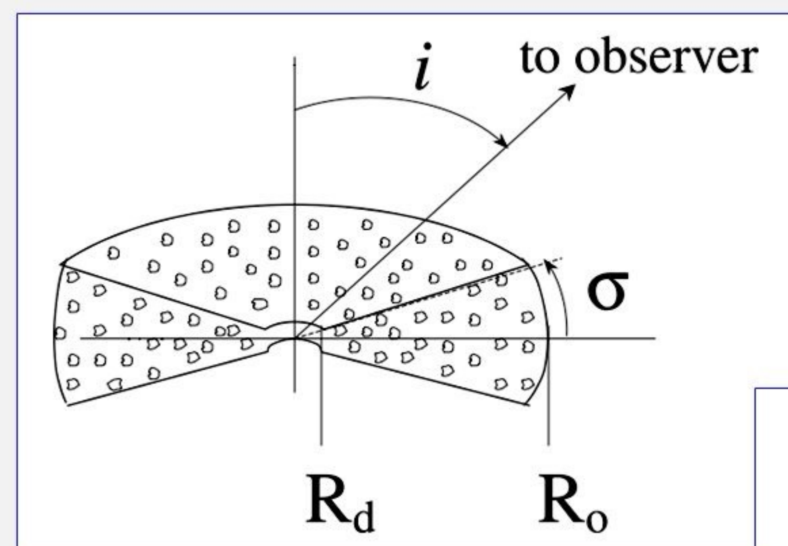
Circinus



Tristram et al.

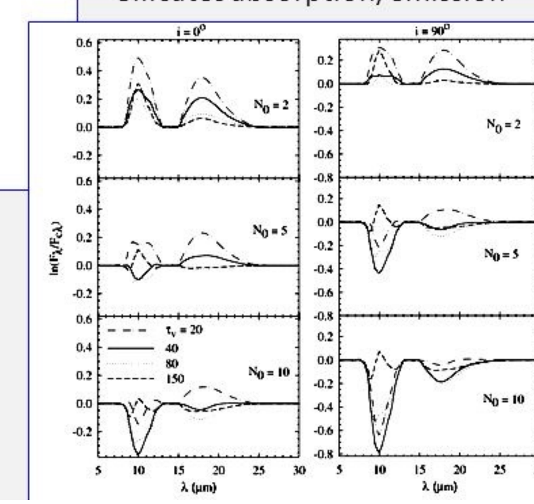


(dusty) TORUS: clumpy structure



Nenkova et al. 2008a,b

Silicates absorption/emission



Current evidence suggests that dusty torus is clumpy rather than homogenous

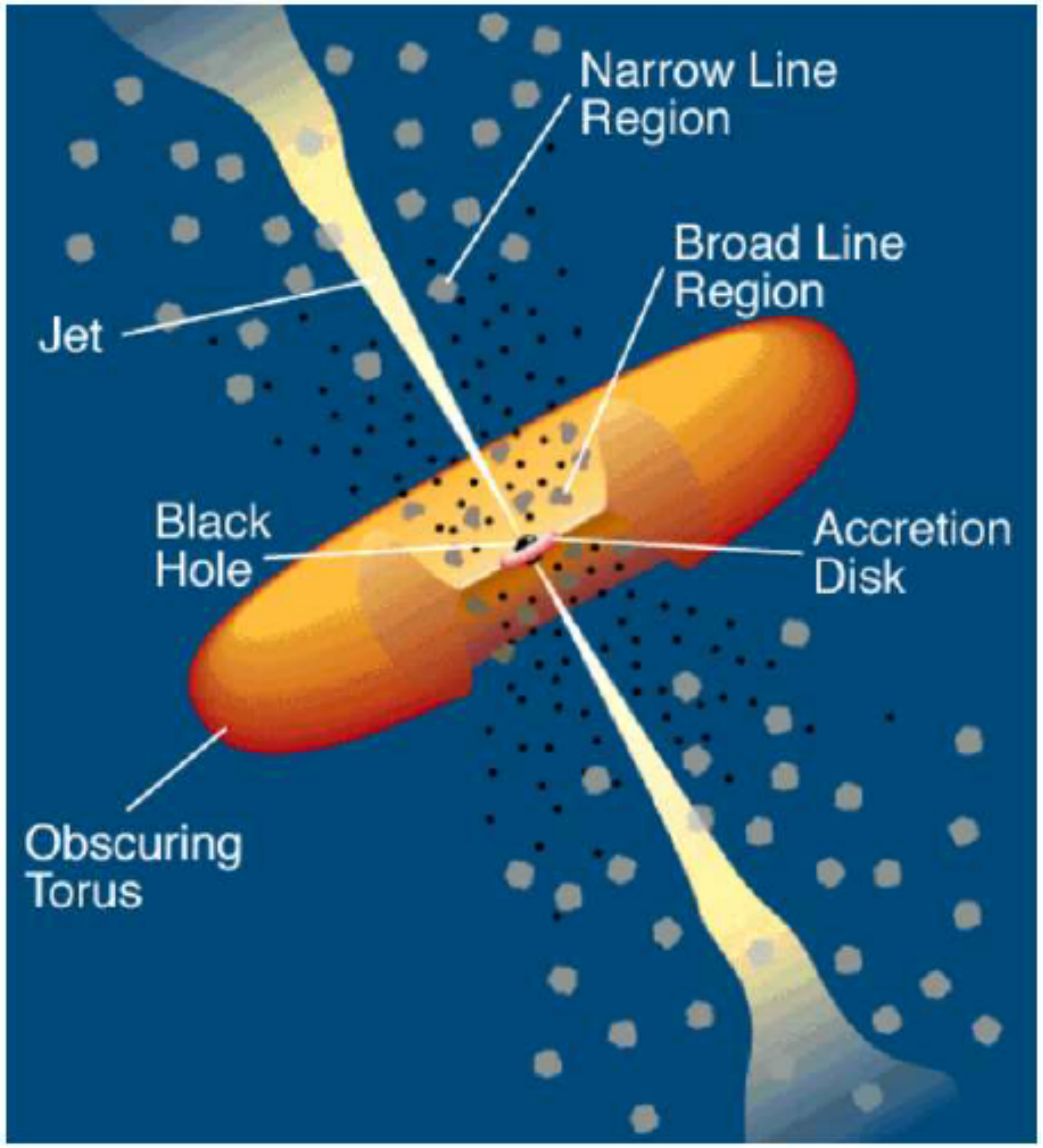
The narrow-line region

Narrow-line region extends 100-1000 pc out of central engine

Overlaps host galaxy (distinction unclear)

Well resolved for nearby AGN with HST

Gas clouds w/ *v ~100-500 km/s*



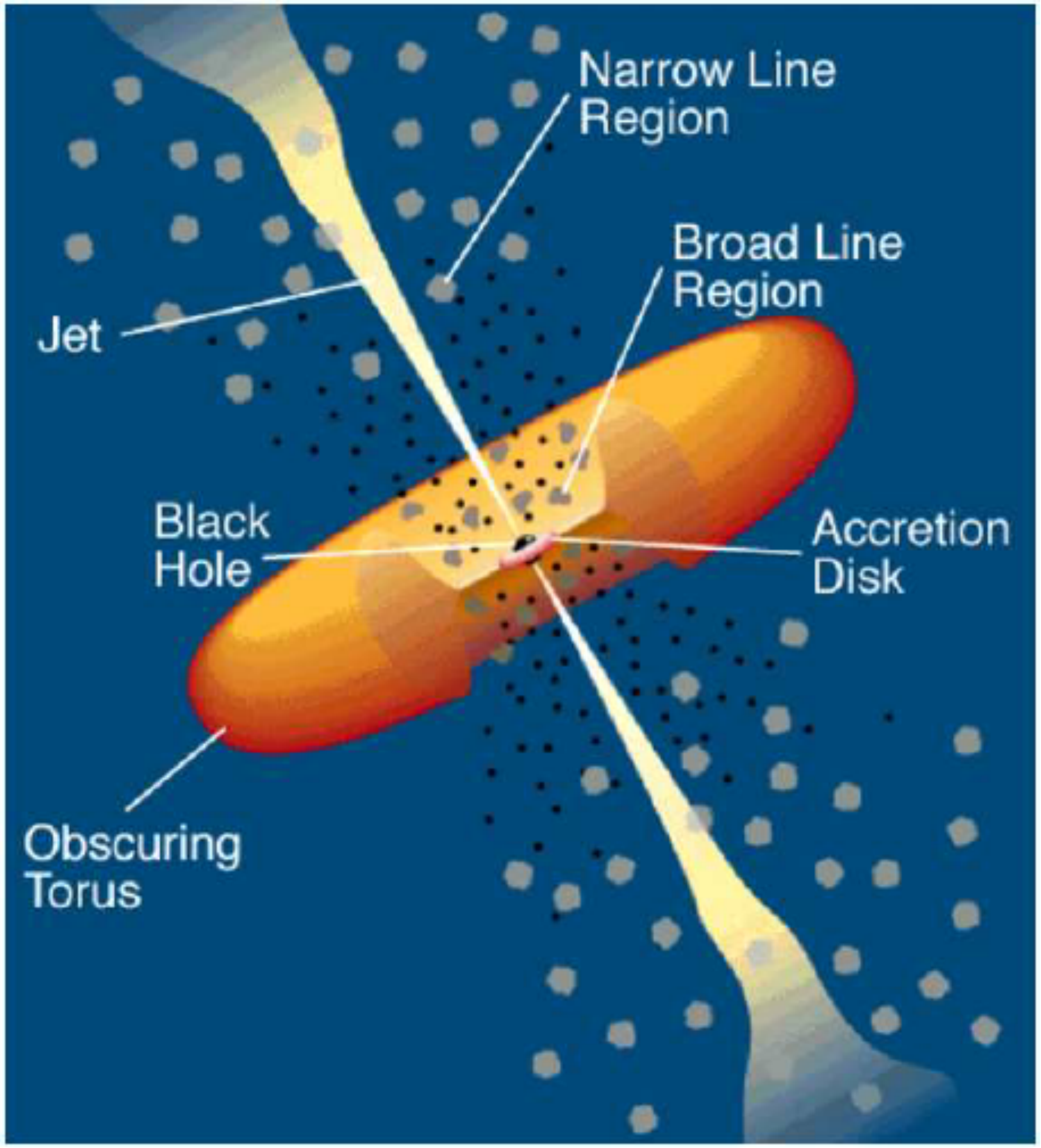
Urry & Padovani (1995)

AGN Classification

The Unification Scheme

AGN type 1-2 classification depends only on the viewing angle

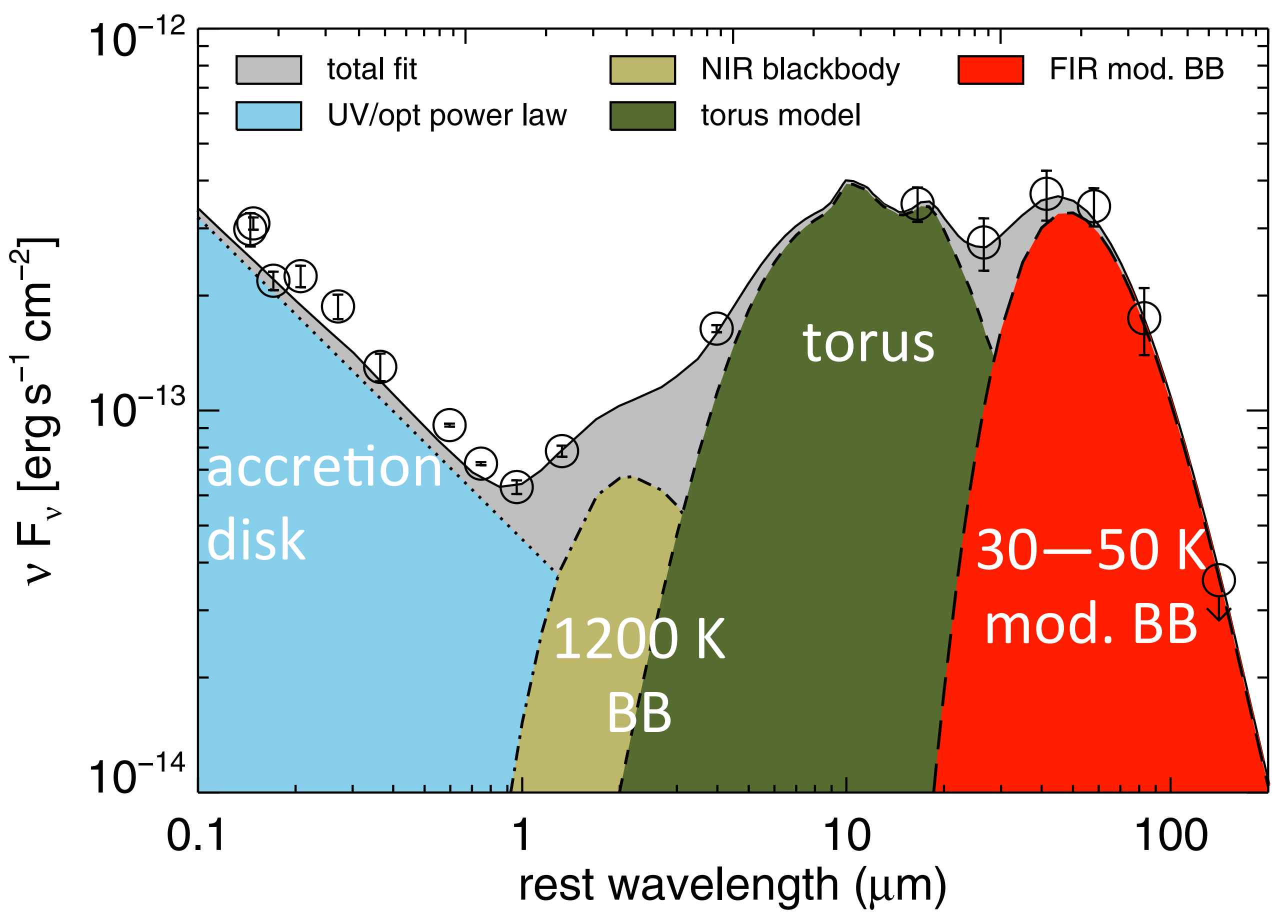
<u>Key:</u> polarised light



Urry & Padovani (1995)

Spectral Properties

The SED contribution of different regions

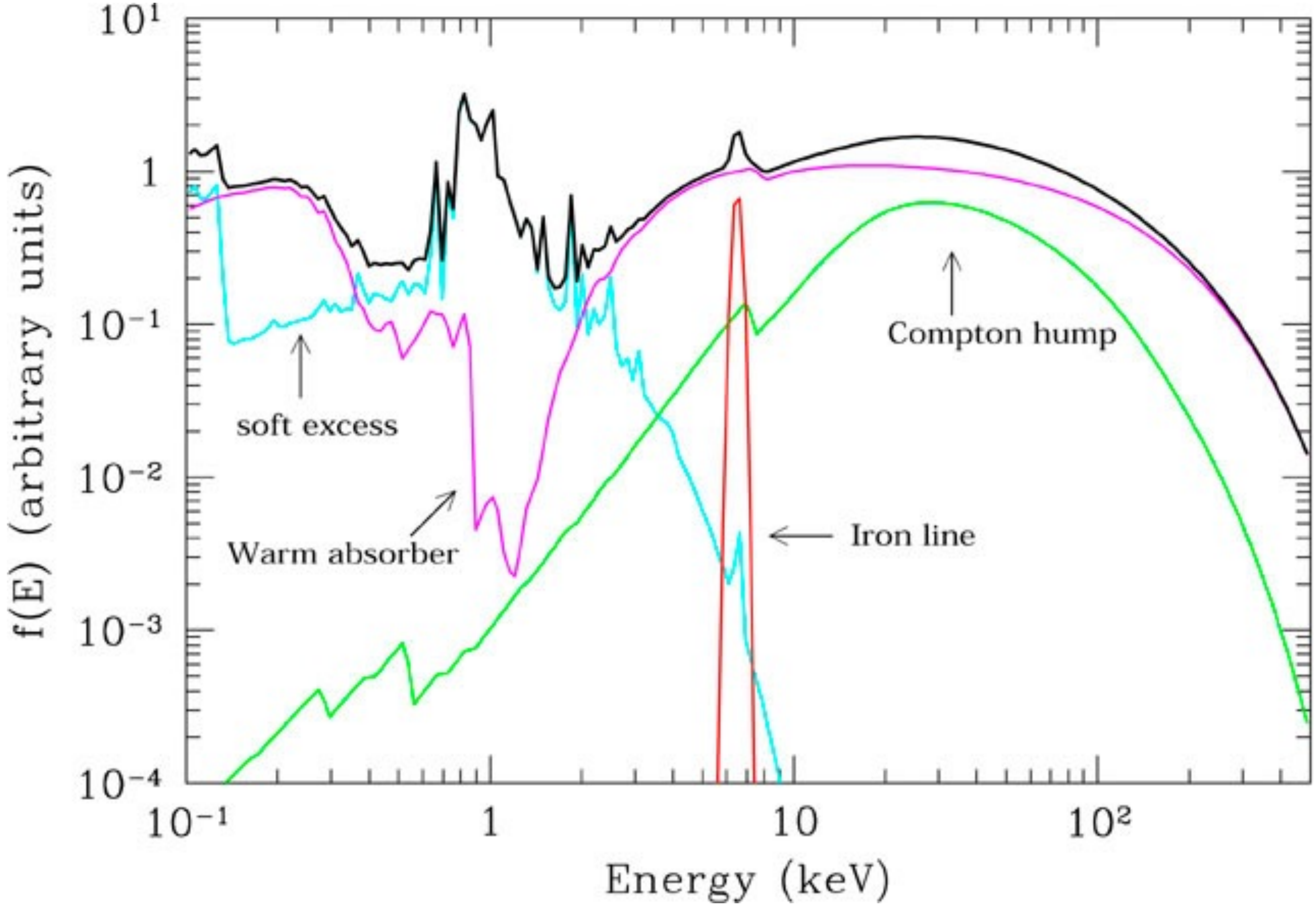


Spectral energy distribution

- UV/optical: accretion disk
- mid-infrared: hot dust and torus
- far-infrared: cold dust → host galaxy

Figure credit: B. Venemans

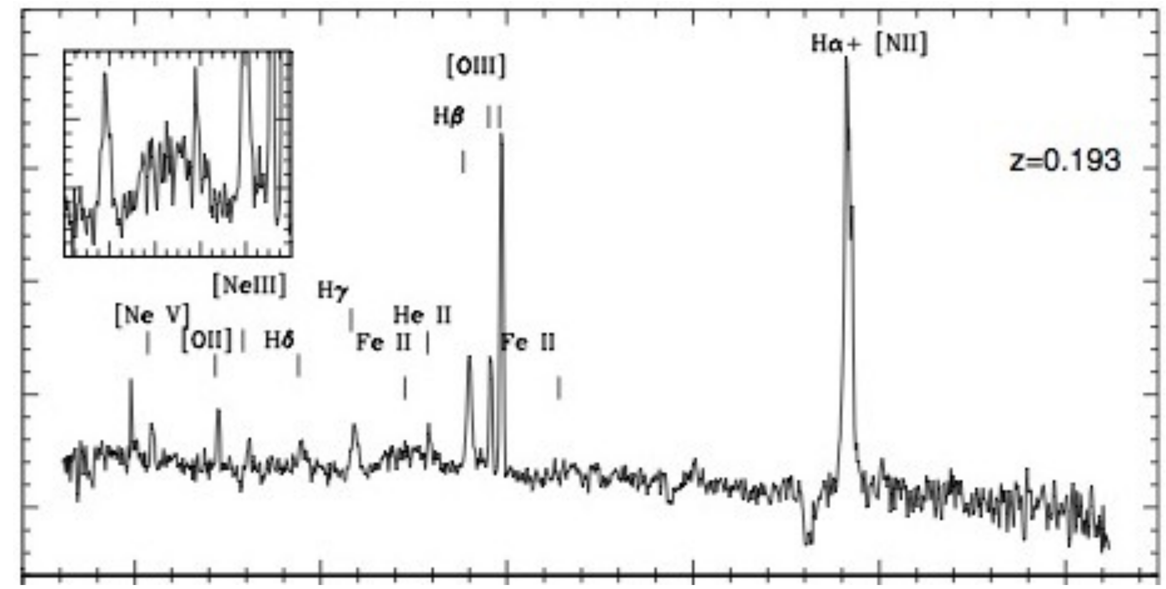
The X-ray spectrum



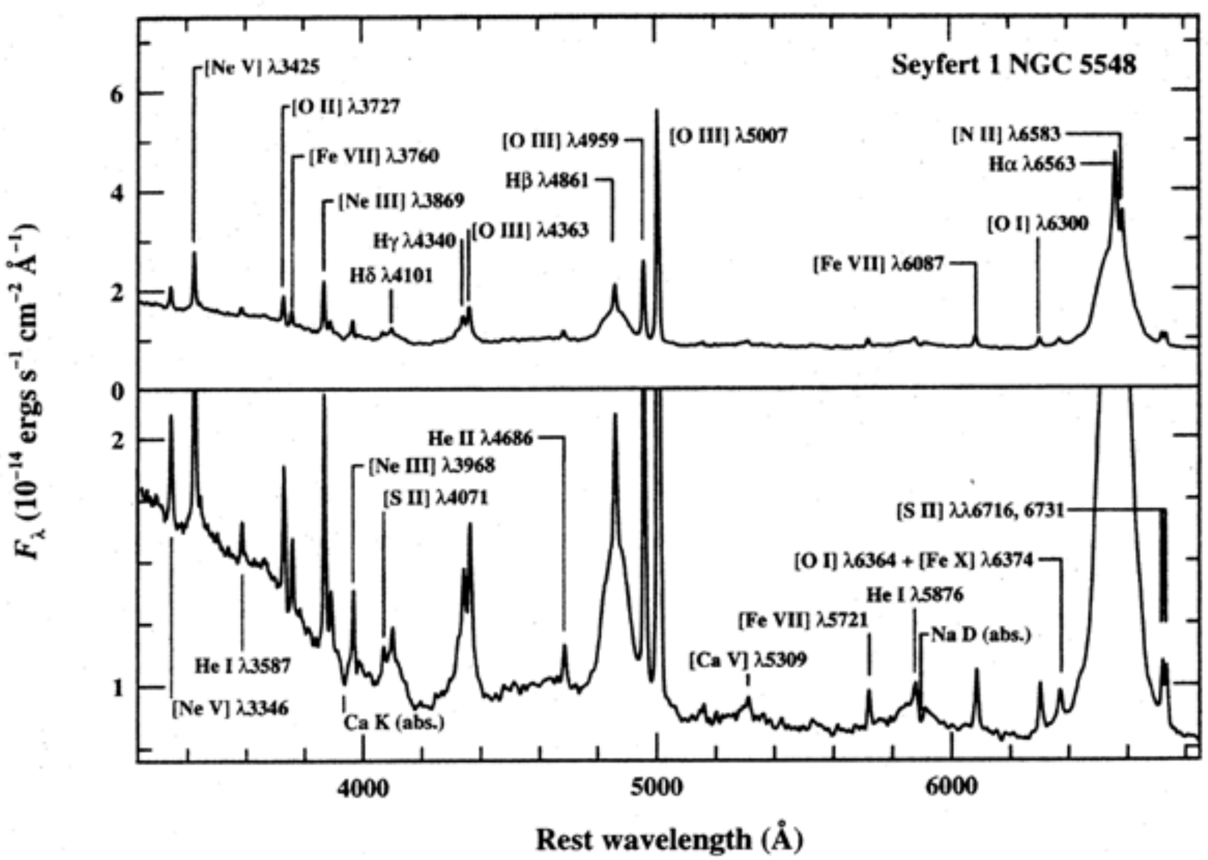
Credit: G. Risaliti

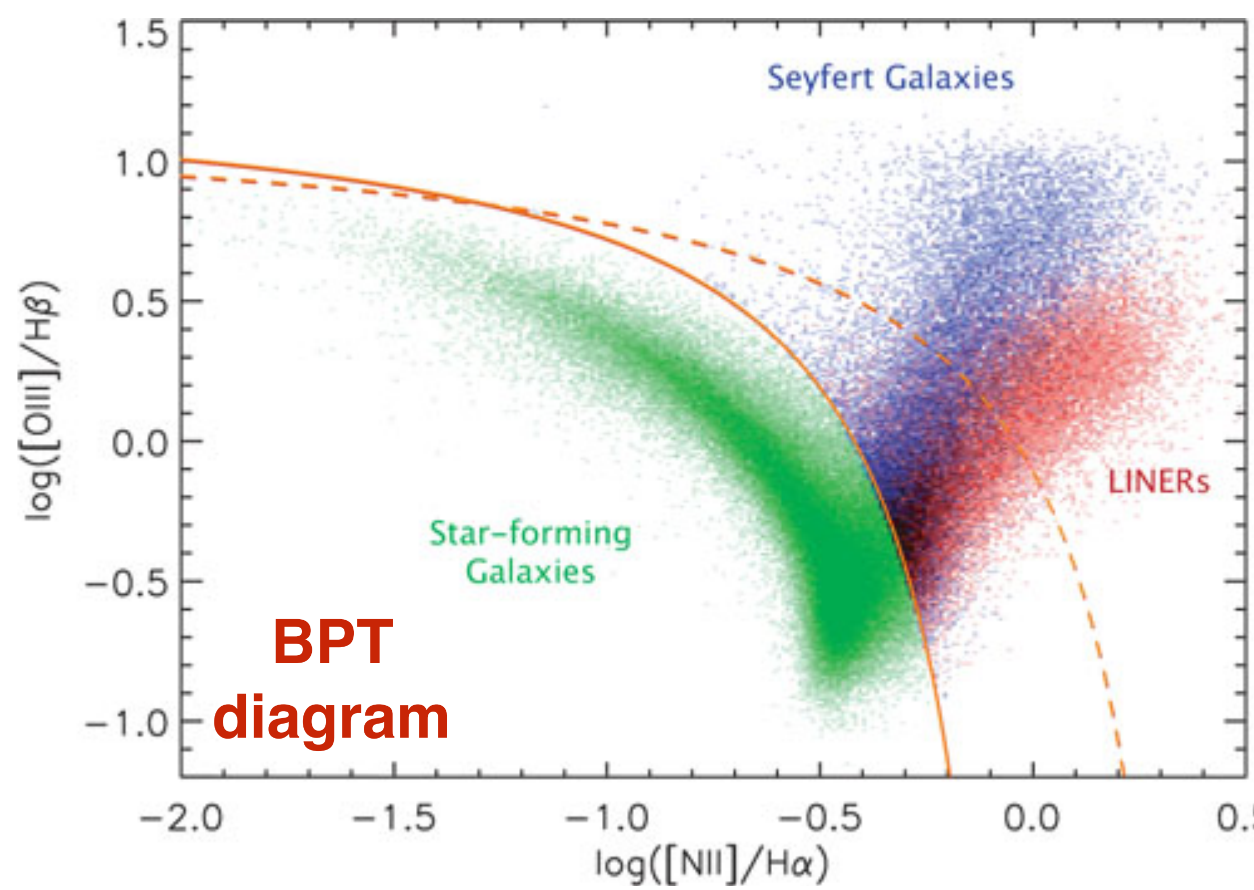
The optical spectrum

Narrow lines



Broad lines





BPT diagram

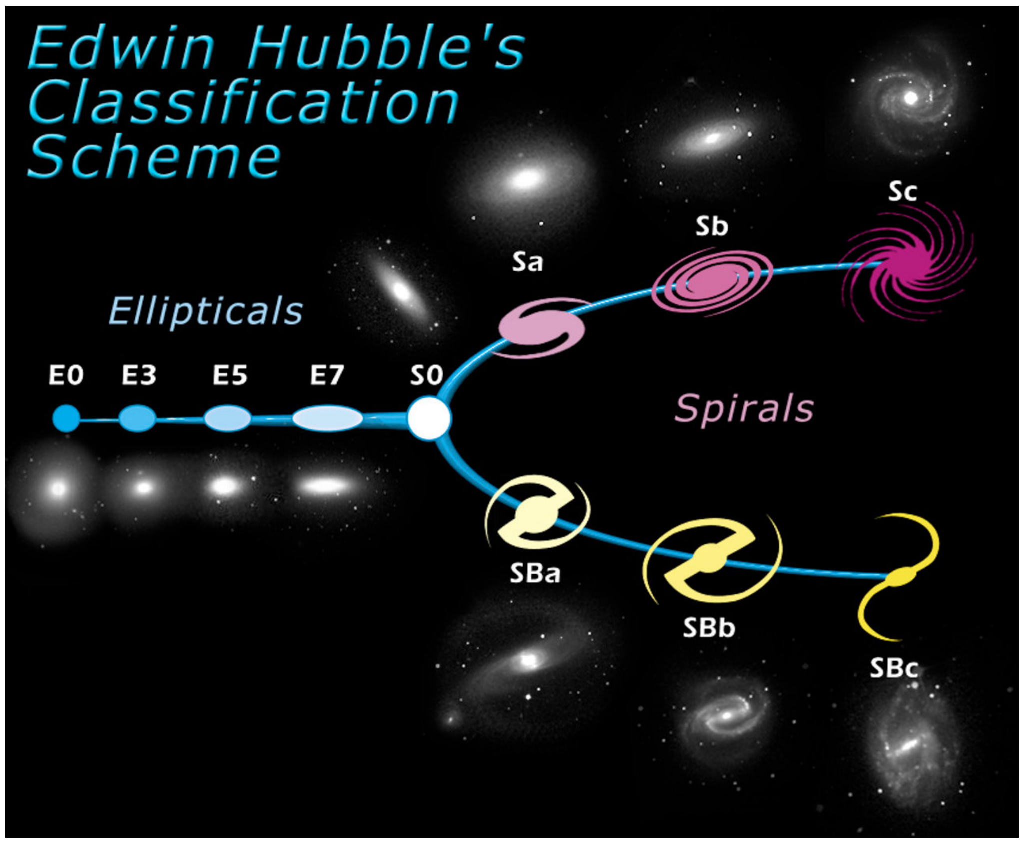
General Review

Summary of what you have learned in this course

- Classify galaxies according to morphology
- Measure galaxy light profiles
- Quantitatively describe the statistical properties of stellar populations within galaxies
- Measure distances to different astronomical objects
- Quantitatively describe stellar motions in a galaxy as consequence of gravitational potential
- Basics of gravitational lensing / reionisation
- Basics of the dynamics and other main properties of the Milky Way
- Main photometric and spectral differences between elliptical and spiral galaxies
- Differences in the study methodology between nearby and distant galaxies (resolved vs. integrated galaxy view)
- Calculate, under simple assumptions, the level of a galaxy chemical enrichment
- Fundamental properties and classification of AGN
- Techniques to search for high-redshift galaxies

Galaxy Morphology

Galaxy morphology is a consequence of galaxy formation, evolution and environment



$$I(r) = I_e\, exp\left\{-b_n\left[(r/r_e)^{1/n} - 1\right]\right\}$$

$$L = \int_0^{2\pi}\int_0^{\infty} I(r) r dr = 2\pi I_0 \int_0^{\infty} r \exp(-(r/\alpha)^{1/n}) dr$$

Substitute: $x = (r/\alpha)^{1/n},\ \ r = x^n\alpha,\ dr = nx^{n-1}\alpha$

$$L = 2\pi I_0 \int_0^{\infty} x^n \alpha n x^{n-1}\alpha \exp(-x) dx$$

$$L = 2\pi I_0 \alpha^2 n \int_0^{\infty} x^{2n-1} \exp(-x) dx$$

Recognise this as the Gamma fn (Euler's integral or factorial fn):

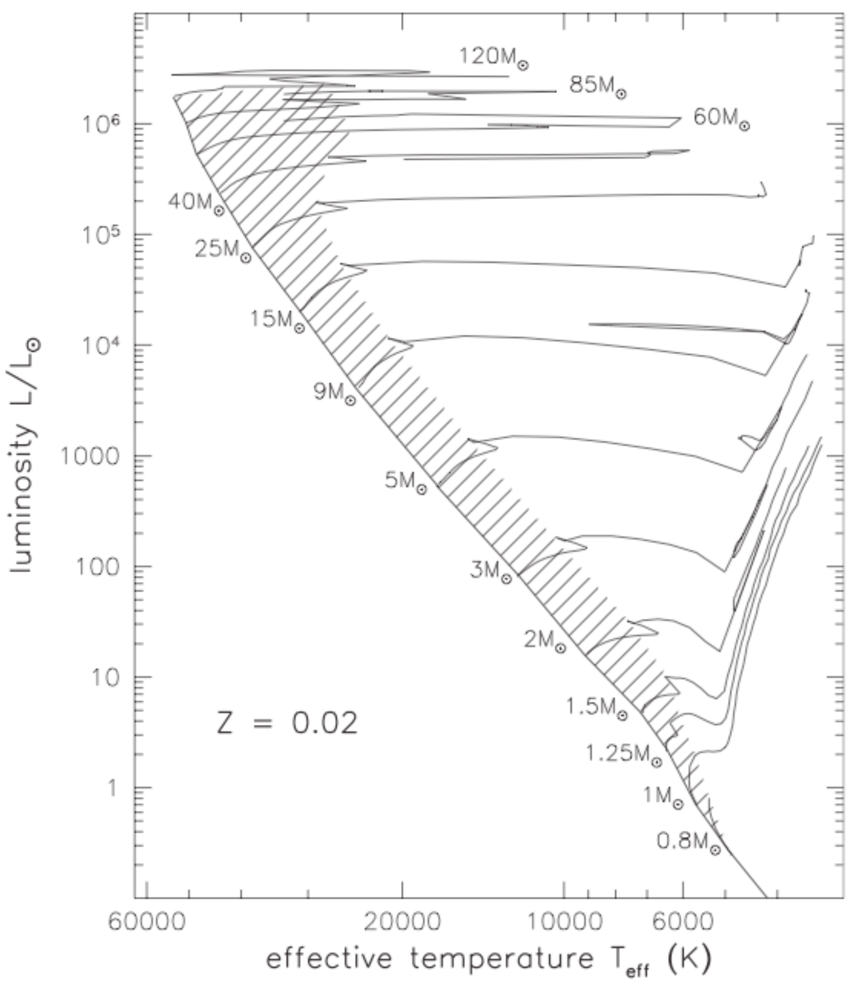
$$\Gamma(z) = \int_0^{\infty} t^{z-1} e^{-t} dt = (z-1)!$$

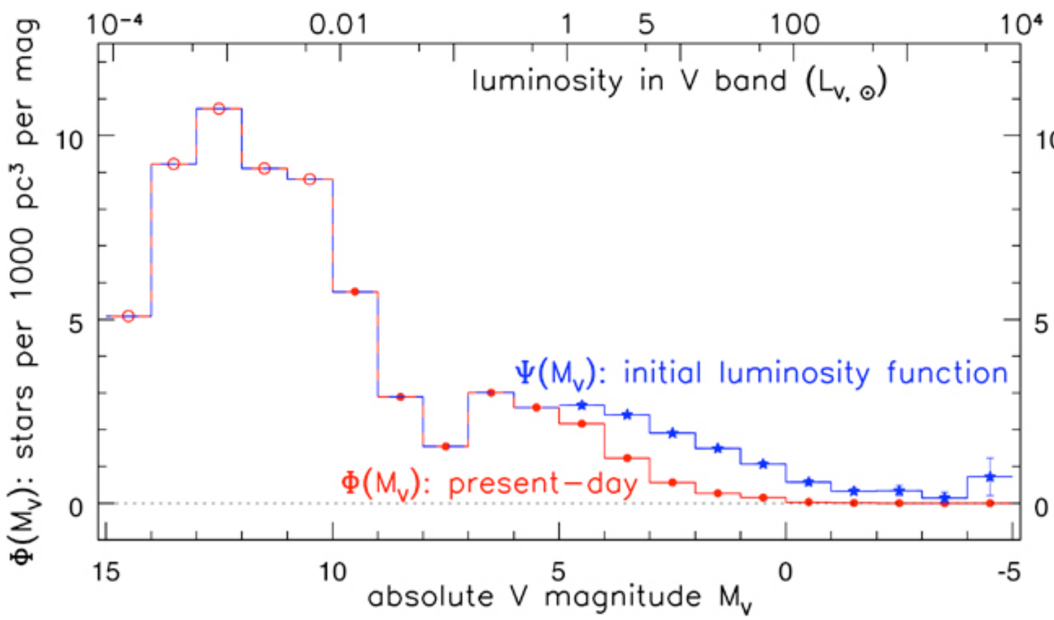
So: $L = 2\pi I_0 \alpha^2 n \Gamma(2n)$

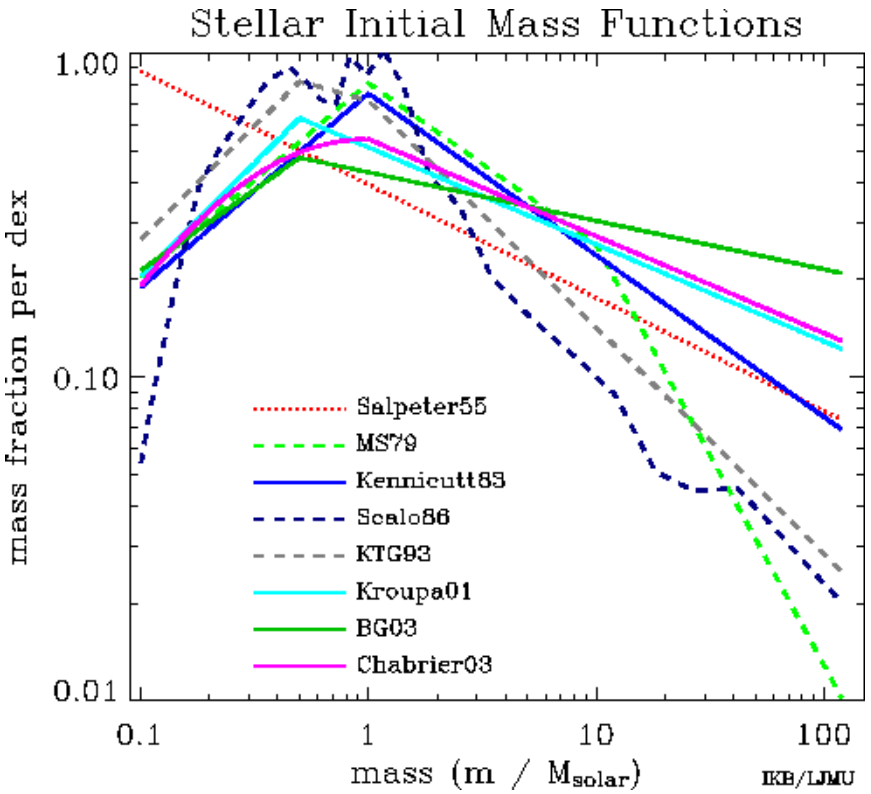
Or for integer n: $L = \pi I_0 \alpha^2 2n(2n-1)! = \pi I_0 \alpha^2 (2n)!$

Stellar Populations

Integrated galaxy properties are the consequence of the dominant stellar populations

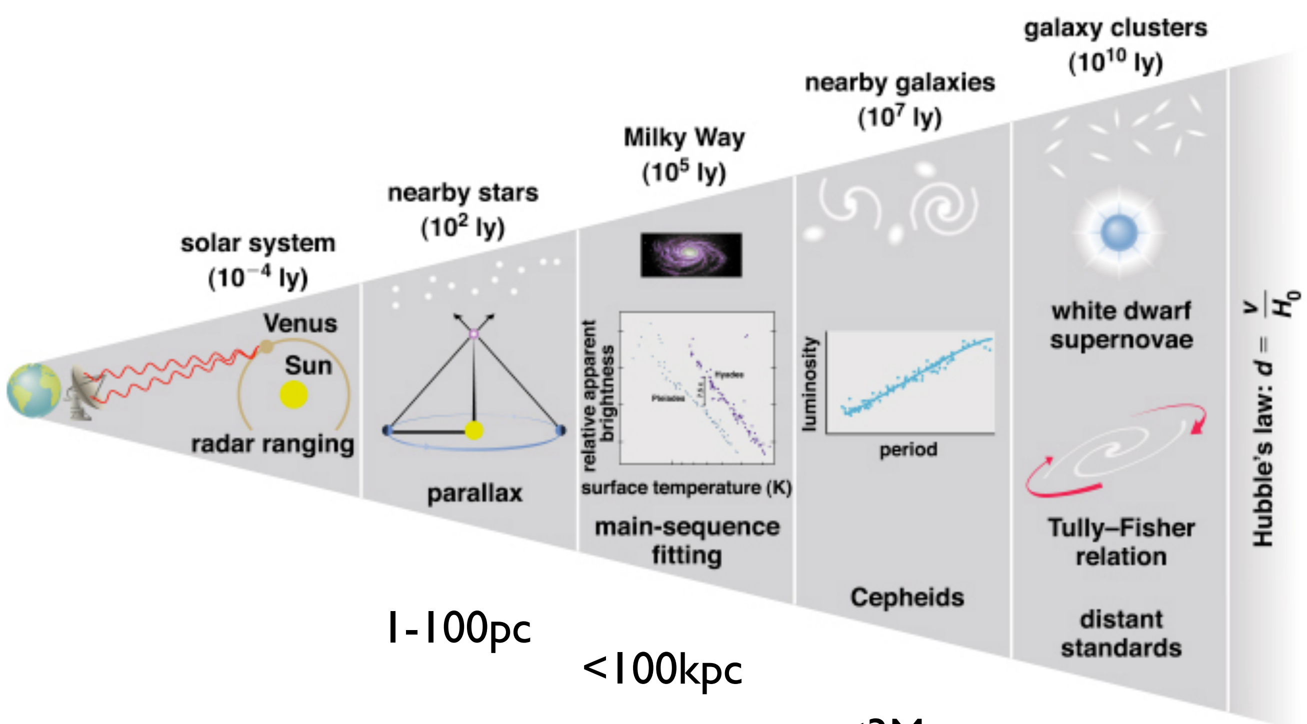






The Cosmic Distance Scale

Independent distance measurements allow for calibration of Hubble's law



1-100pc

<100kpc

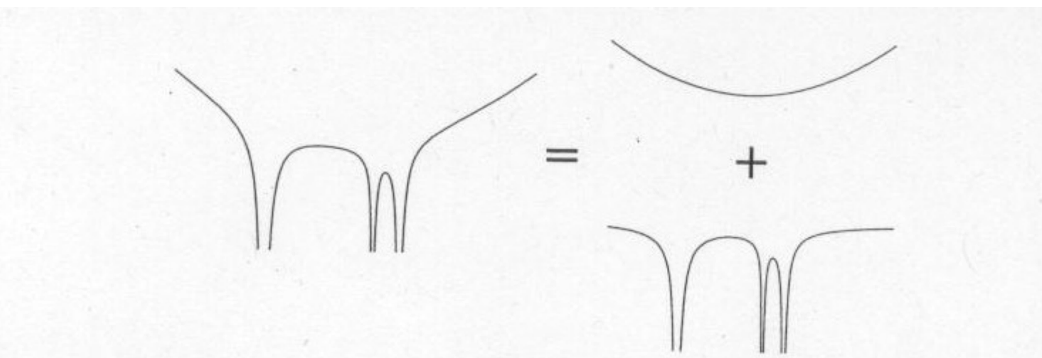
<3Mpc

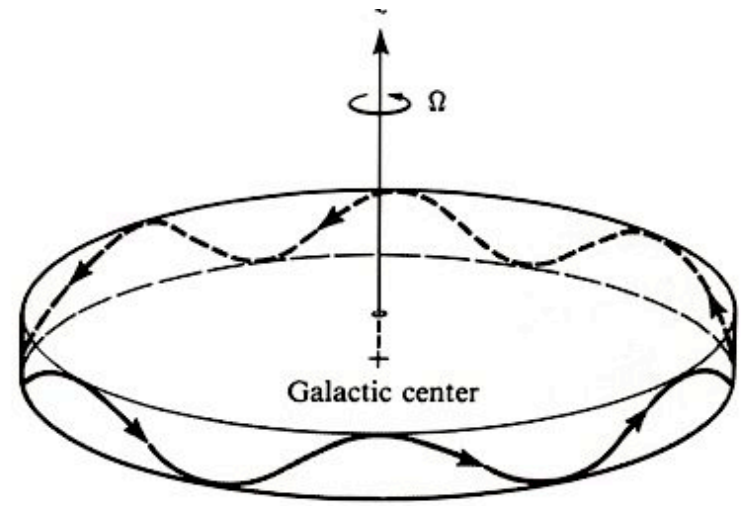
<3000Mpc

PRIMARY	SECONDARY	TERTIARY
PARALLAX	CEPHEIDS	TULLY_FISHER
SUNYAEV-ZELDOVICH *	MS-FITTING	FABER-JACKSON
LENSING TIME DELAY*	RR-LYRAE	SBF
	SNIa*	GC LF
		PN LF
* cosmological	↑ Stellar based	↑ Galaxy based

Galaxy Dynamics

The motion of stars and gas clouds within galaxies reveals matter distribution





$$\Phi(\mathbf{x}) \equiv -G \int d^3\mathbf{x}' \frac{\rho(\mathbf{x}')}{|\mathbf{x}' - \mathbf{x}|}$$

$$\nabla^2 \Phi = 4\pi G \rho.$$

$$\langle \Delta V_\perp^2 \rangle = \int_{b_{\min}}^{b_{\max}} n V t \left(\frac{2Gm}{bV} \right)^2 2\pi b \, db = \frac{8\pi G^2 m^2 n t}{V} \ln\left(\frac{b_{\max}}{b_{\min}} \right)$$

- After a time t_{relax}, such that $\langle \Delta V_\perp^2 \rangle = V^2$ the memory of the initial path is lost.
- This is called the relaxation timescale:

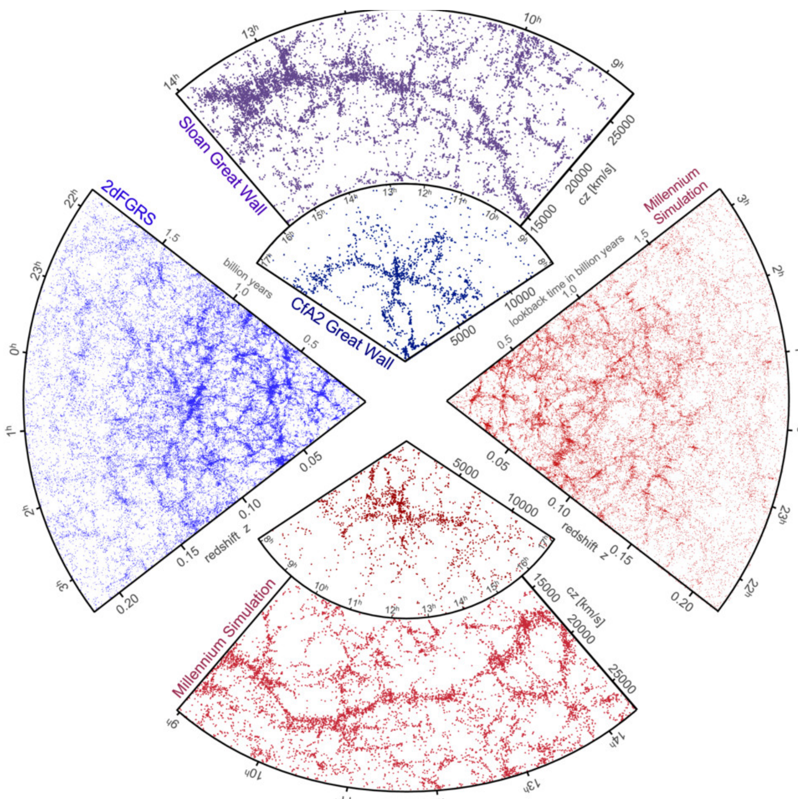
$$t_{\rm relax} = \frac{V^3}{8\pi G^2 m^2 n \ln \Lambda} = \frac{t_s}{2 \ln \Lambda} \qquad \Lambda = (b_{max}/b_{min})$$

$$\approx \frac{2 \times 10^9 \text{ yr}}{\ln \Lambda} \left(\frac{V}{10 \, \text{km s}^{-1}} \right)^3 \left(\frac{m}{\mathcal{M}_\odot} \right)^{-2} \left(\frac{n}{10^3 \, \text{pc}^{-3}} \right)^{-1}$$

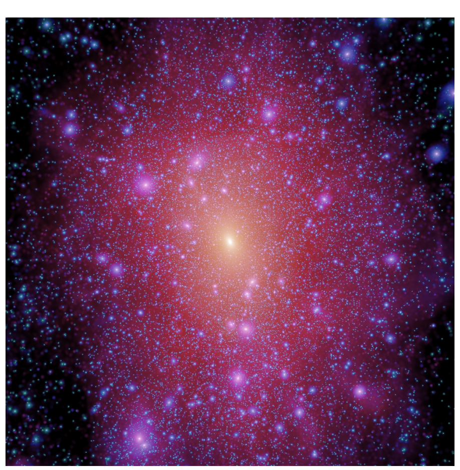
- It is the timescale required for a star to change its velocity by the same order, due to weak encounters with a "sea" of stars. Compared to the strong collisions timescale, $t_{relax} < t_s$

Large Scale Structure

Different galaxy populations have different clustering properties

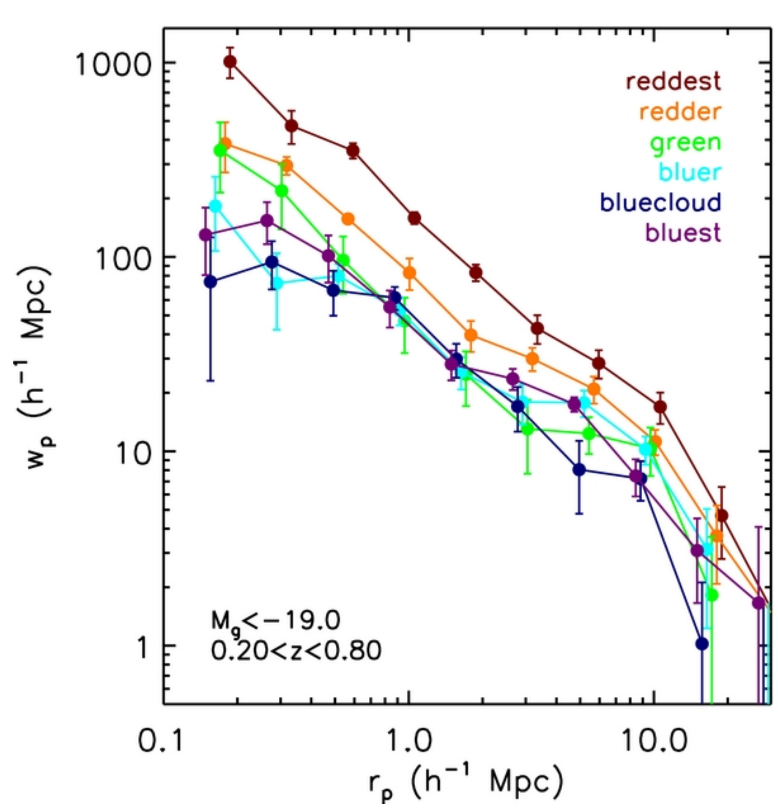


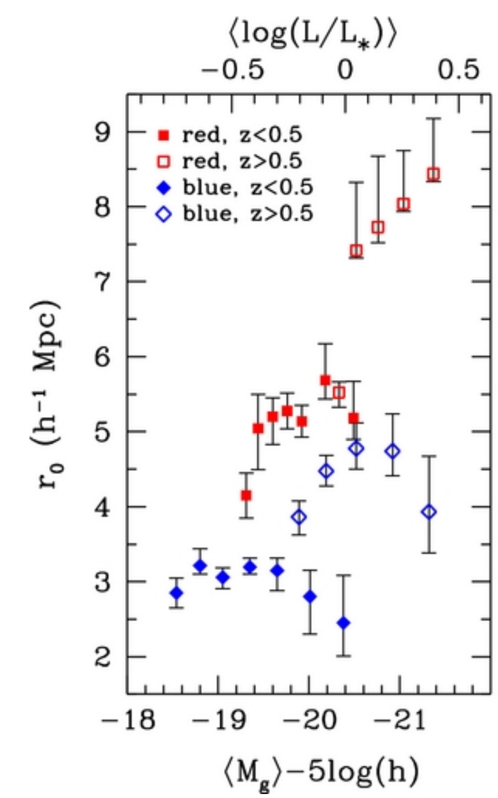
2dFGRS/Virgo Consortium



$$\delta^2 P_{12} = \bar{n}^2 \, [1 + \xi(r_{12})] \, \delta V_1 \, \delta V_2$$

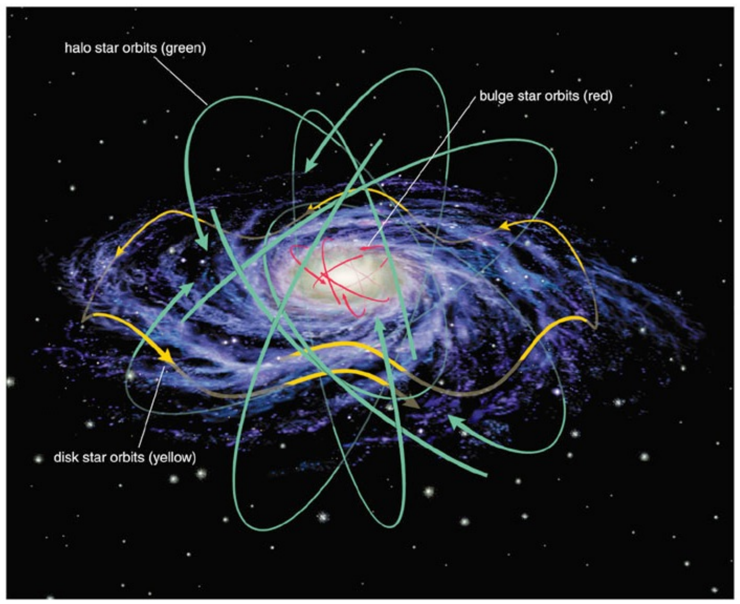
$$\delta^2 P_{12} = \bar{\eta}^2 \, [1 + w(\theta_{12})] \, \delta\Omega_1 \, \delta\Omega_2$$

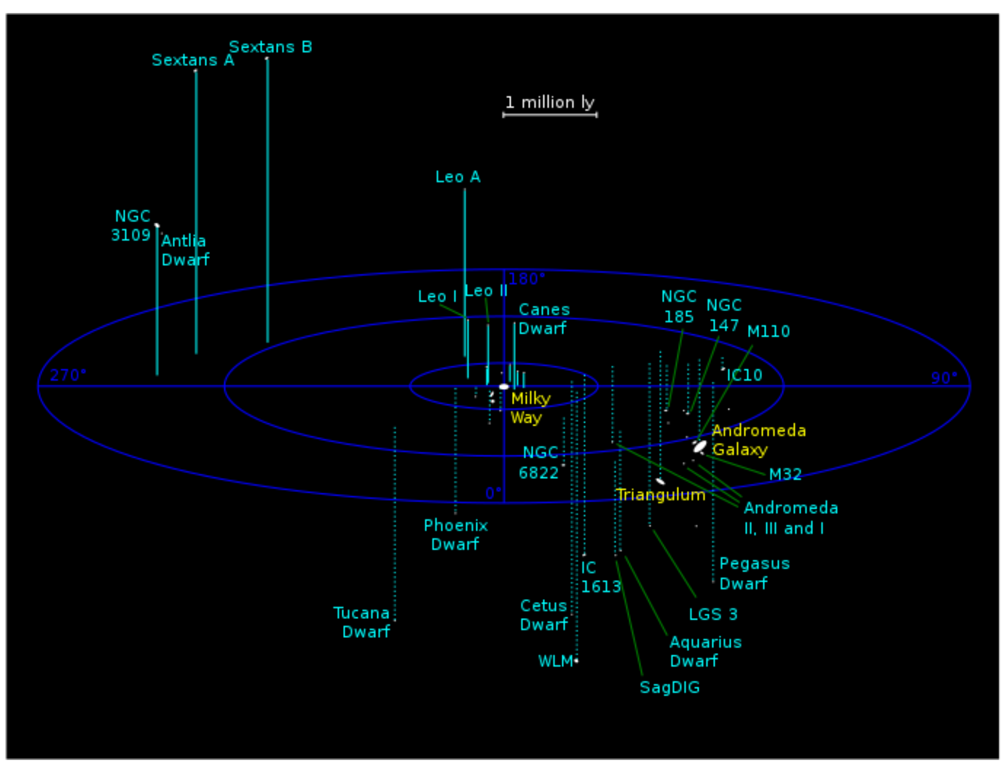


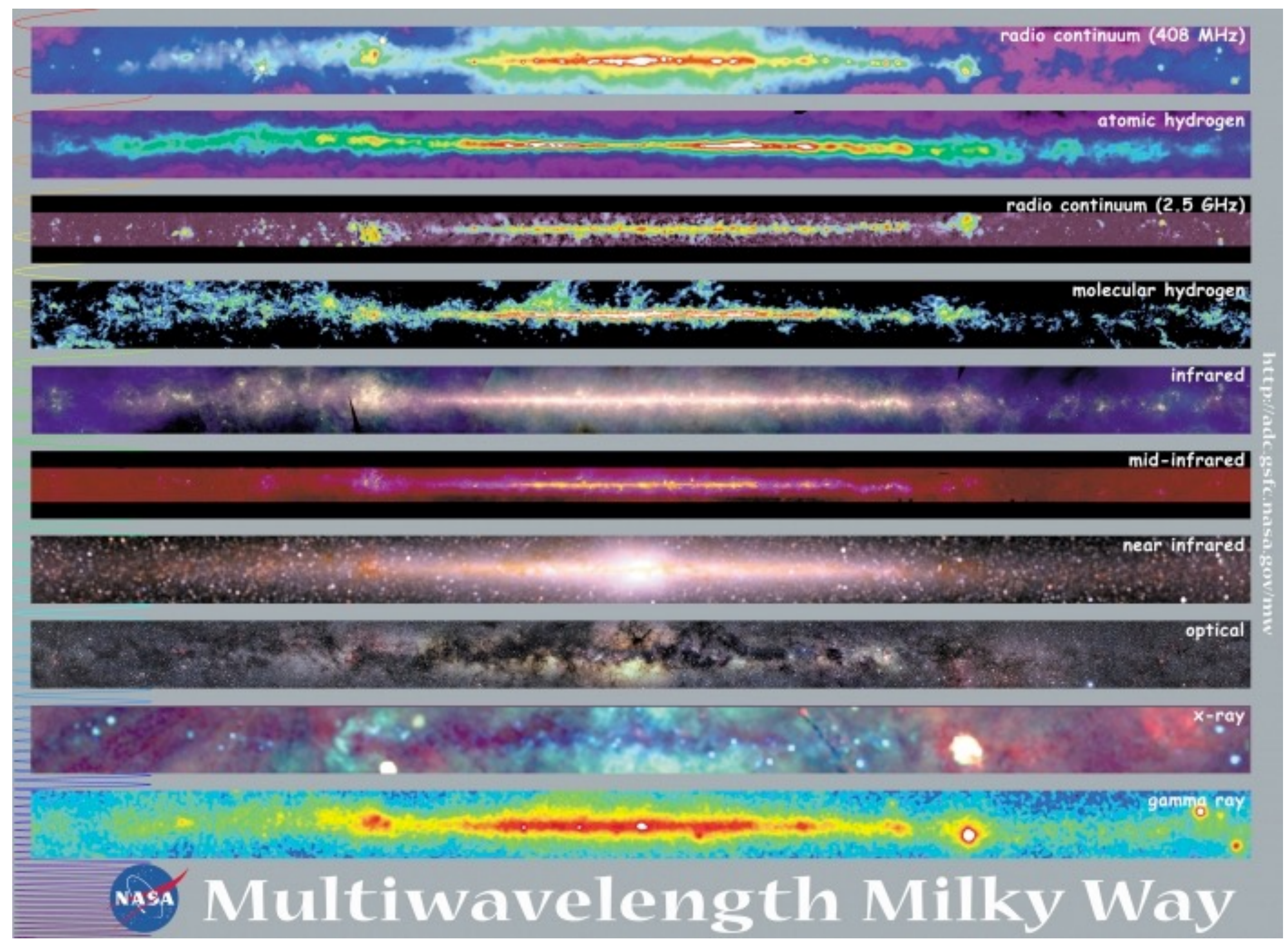


Milky Way

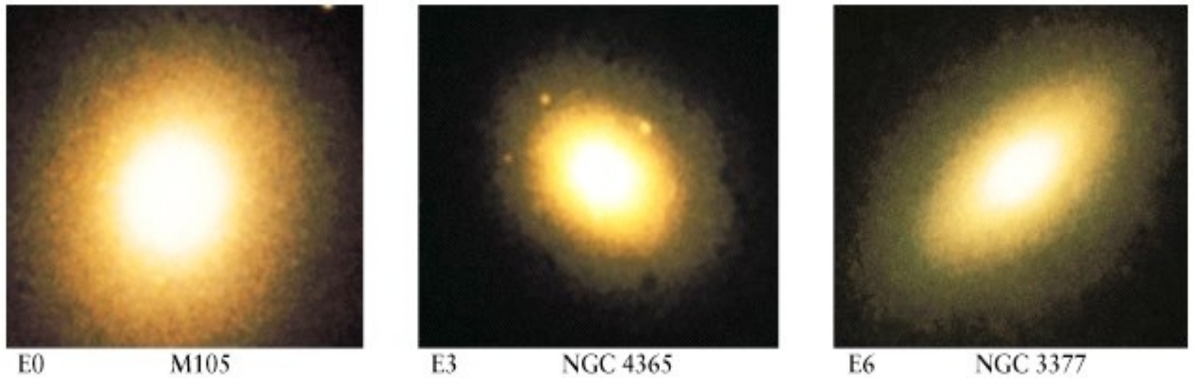
A unique test case for understanding in detail how a galaxy internally works

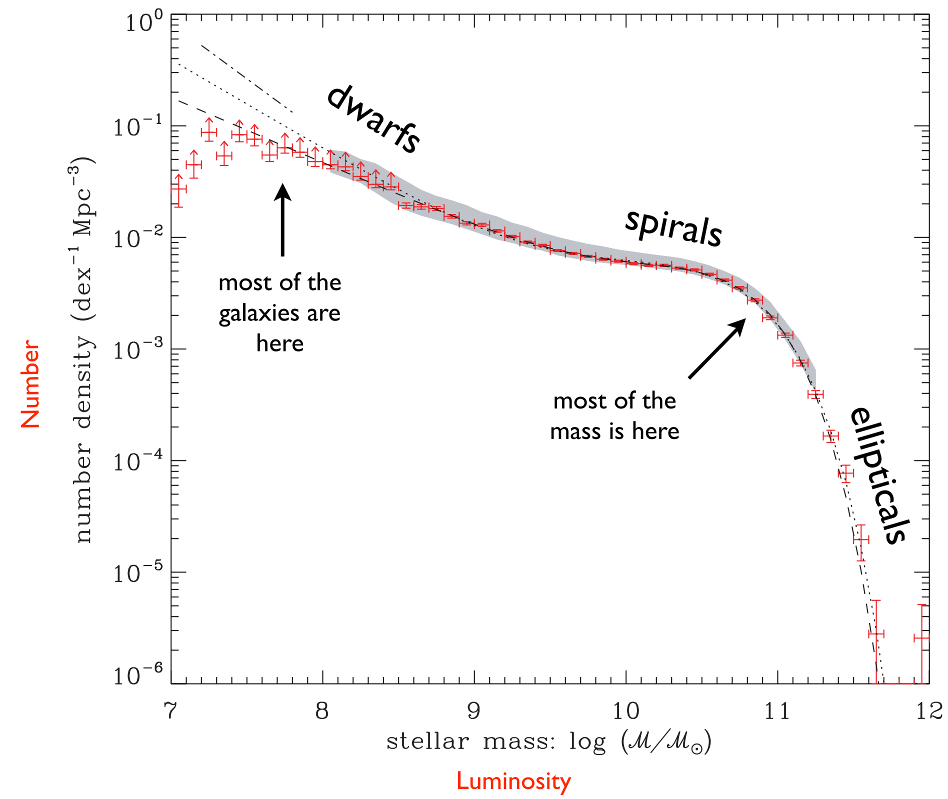






Elliptical and Spiral Galaxies





z=0

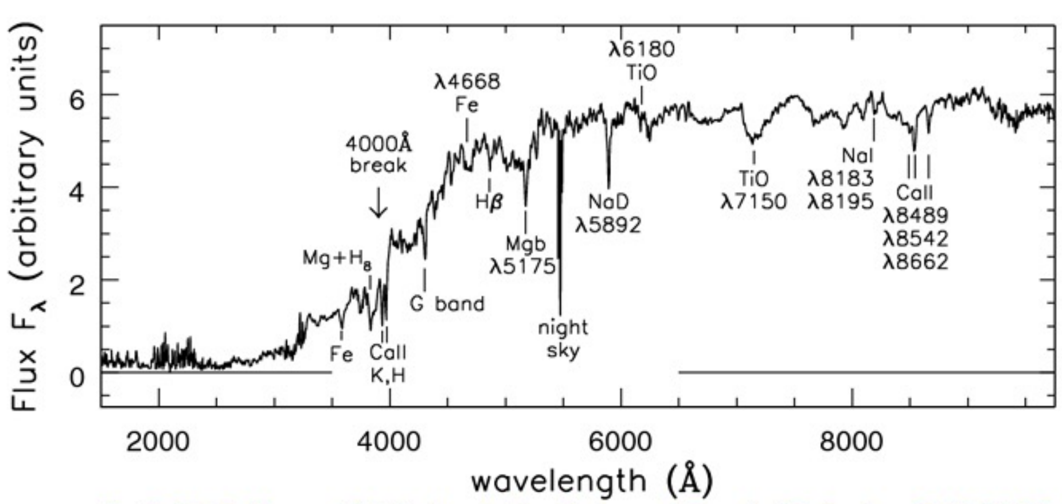
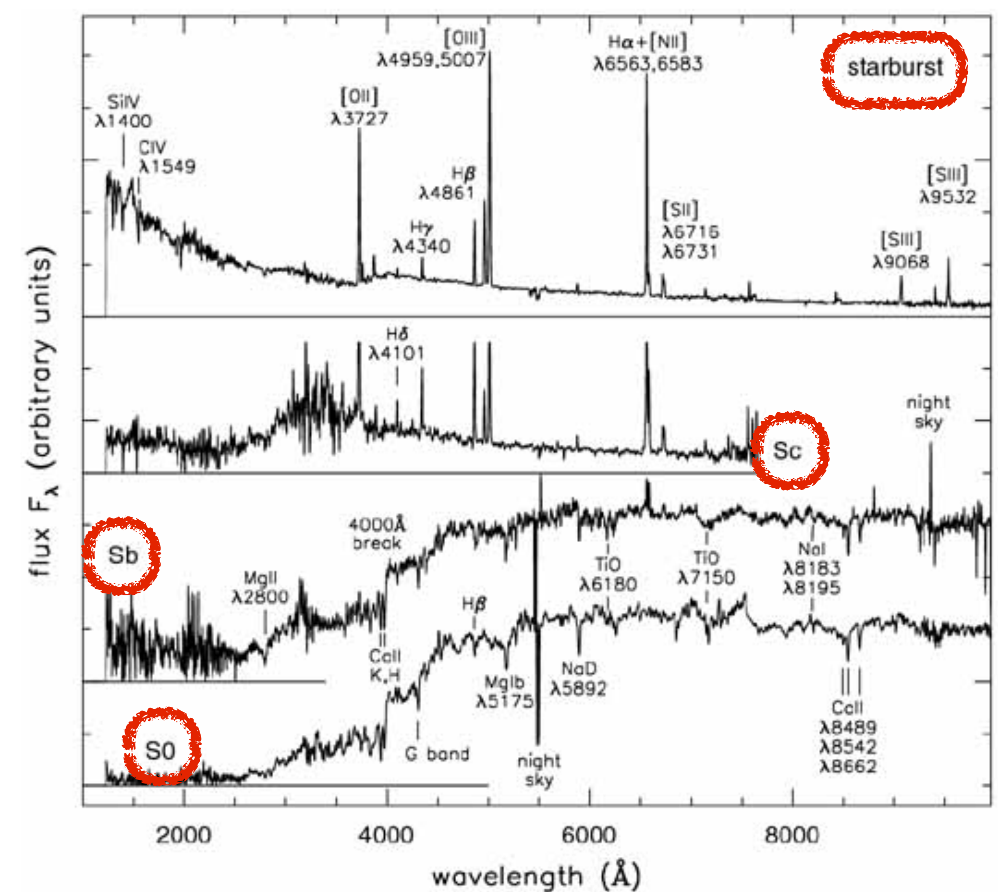
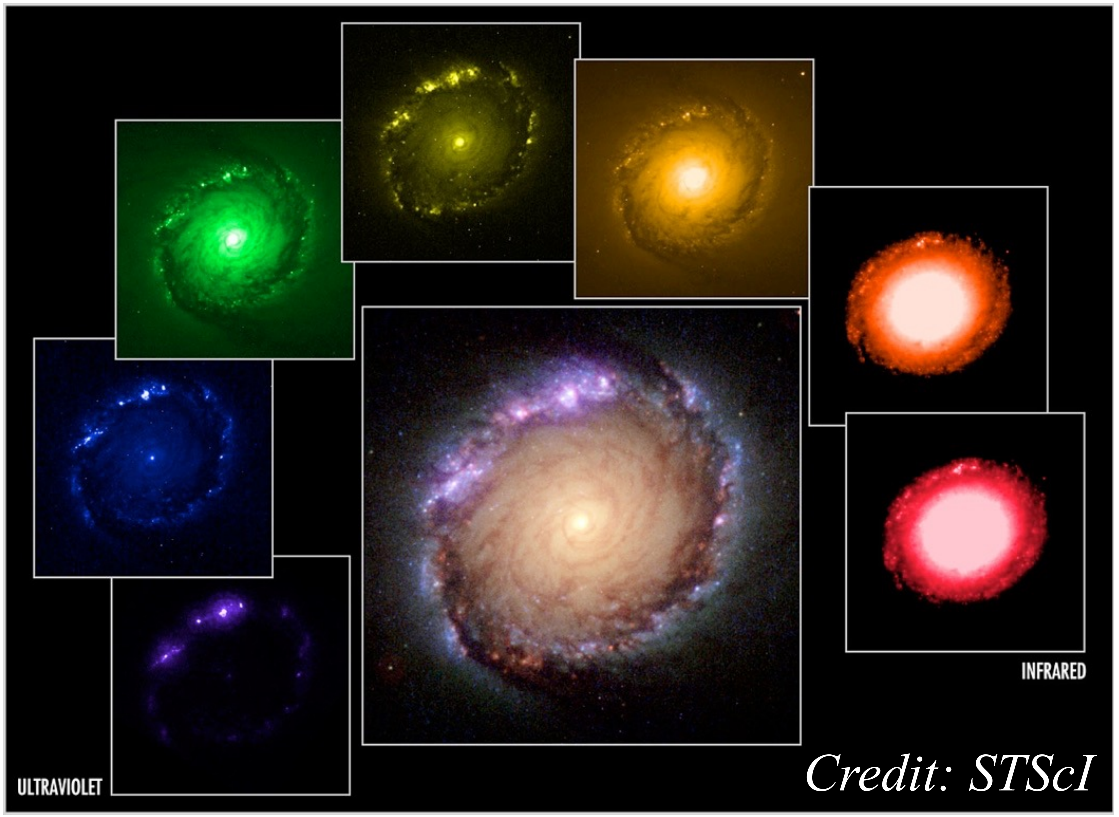


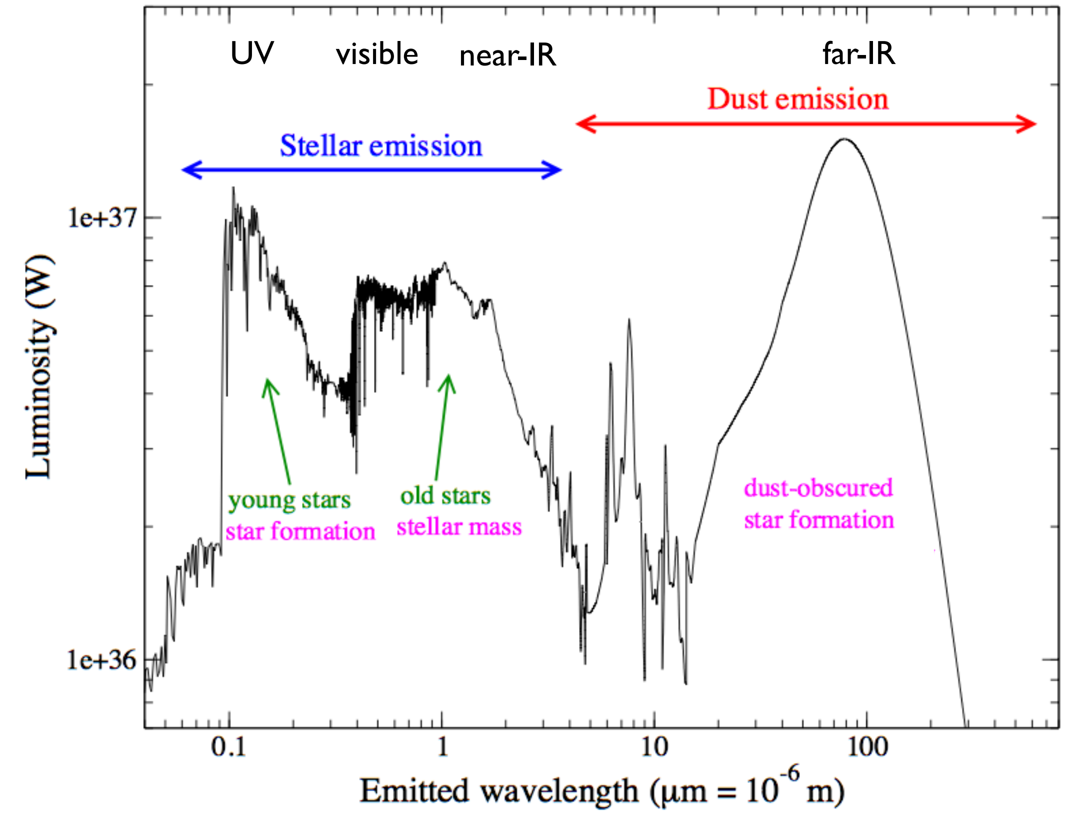
Fig 6.17 (A. Kinney) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



The integrated galaxy view



Credit: STScI



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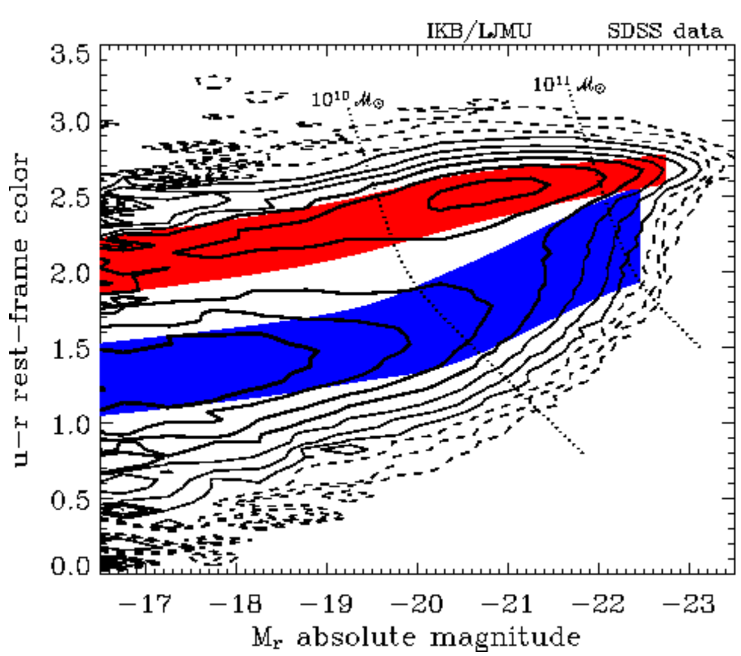
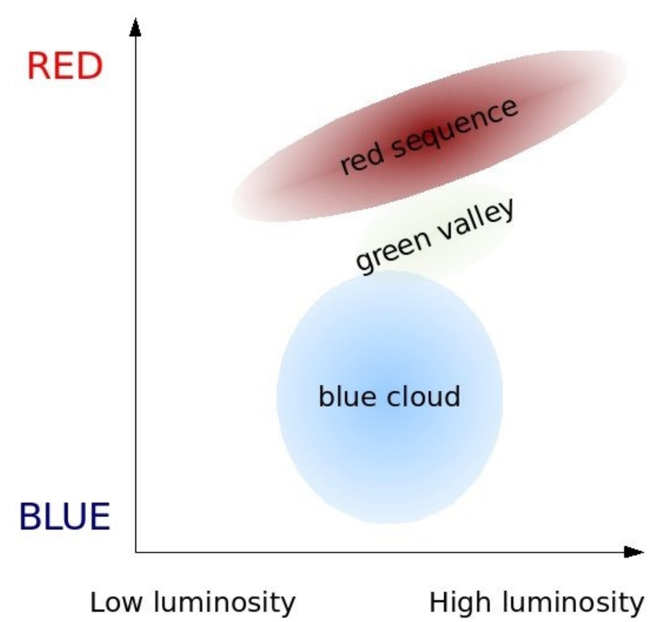
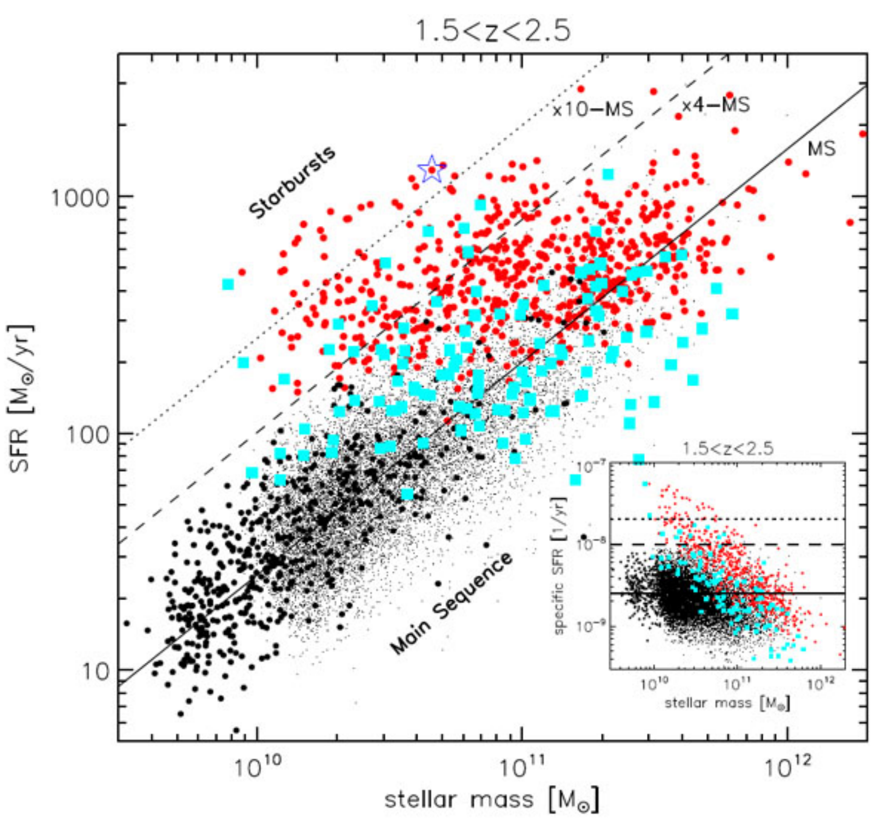


Credit: Baldry et al.

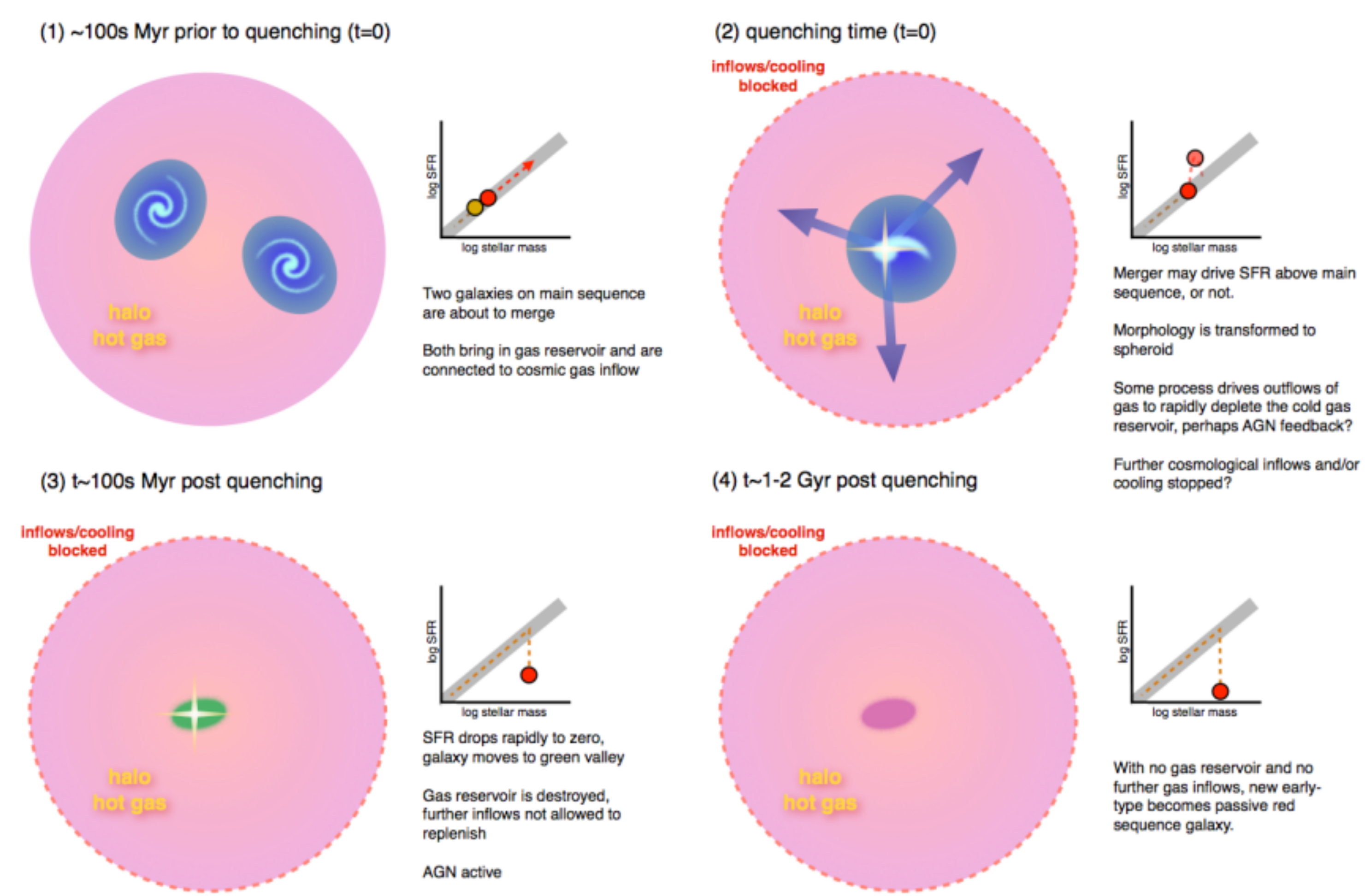


Chemical Enrichment and Galaxy Growth

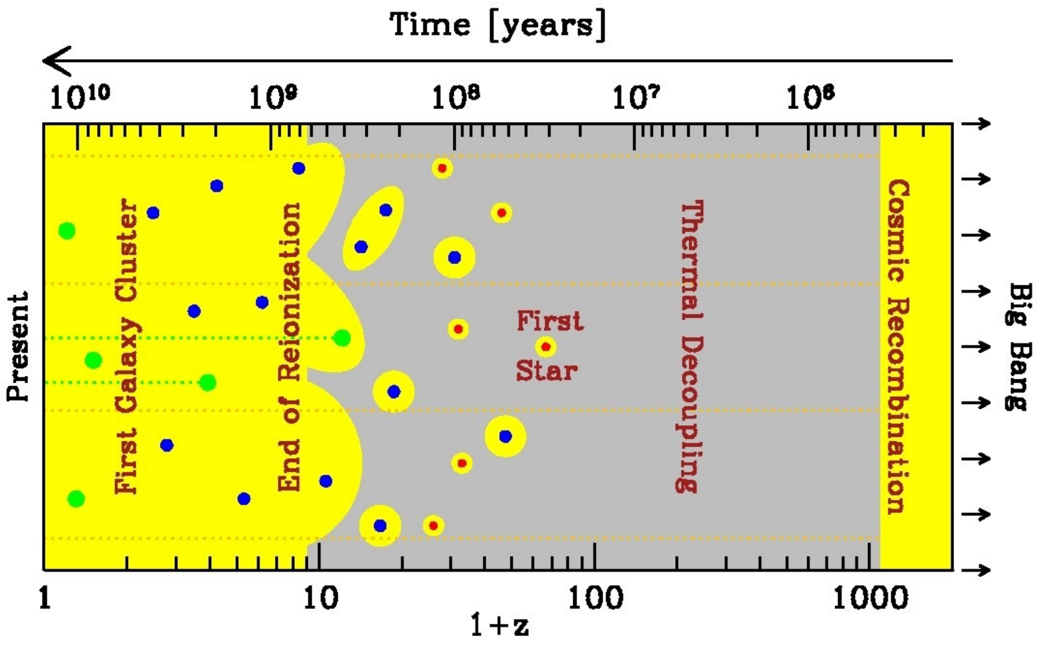
$$Z(t) = -p \ln\left[\frac{M_g(t)}{M_g(0)}\right]$$

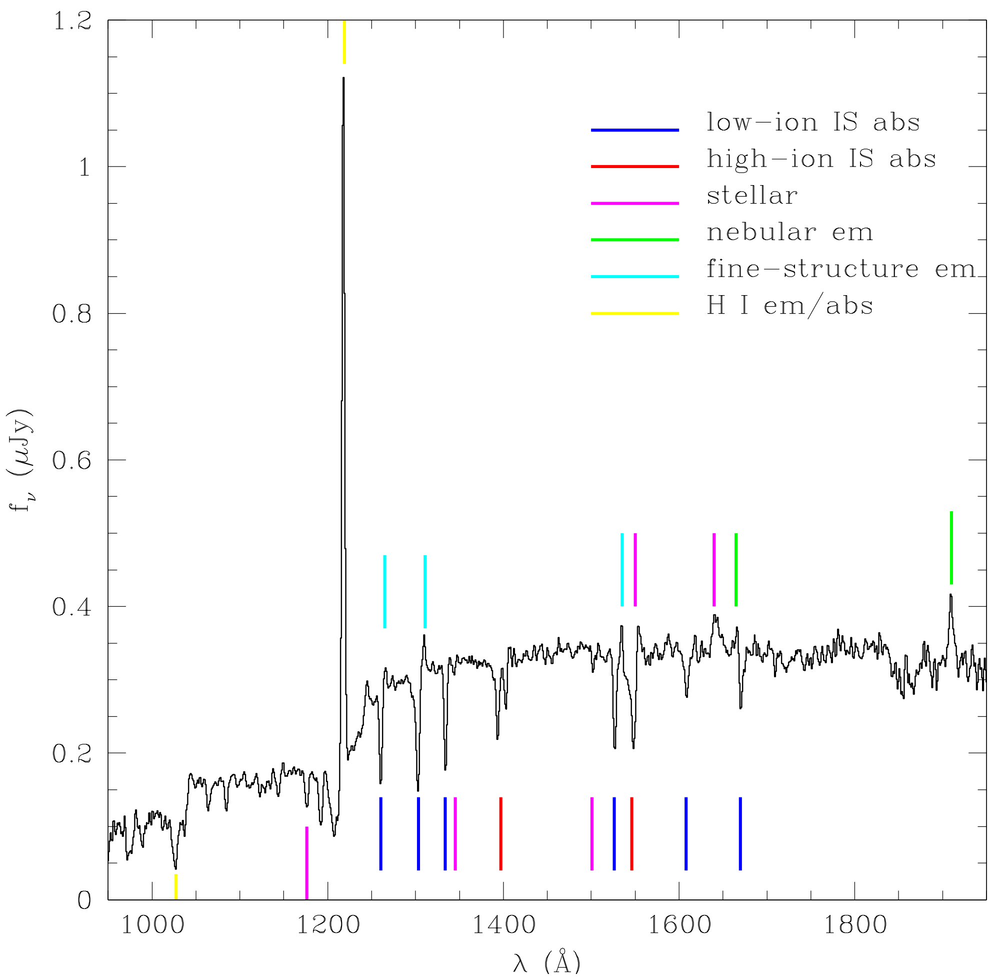


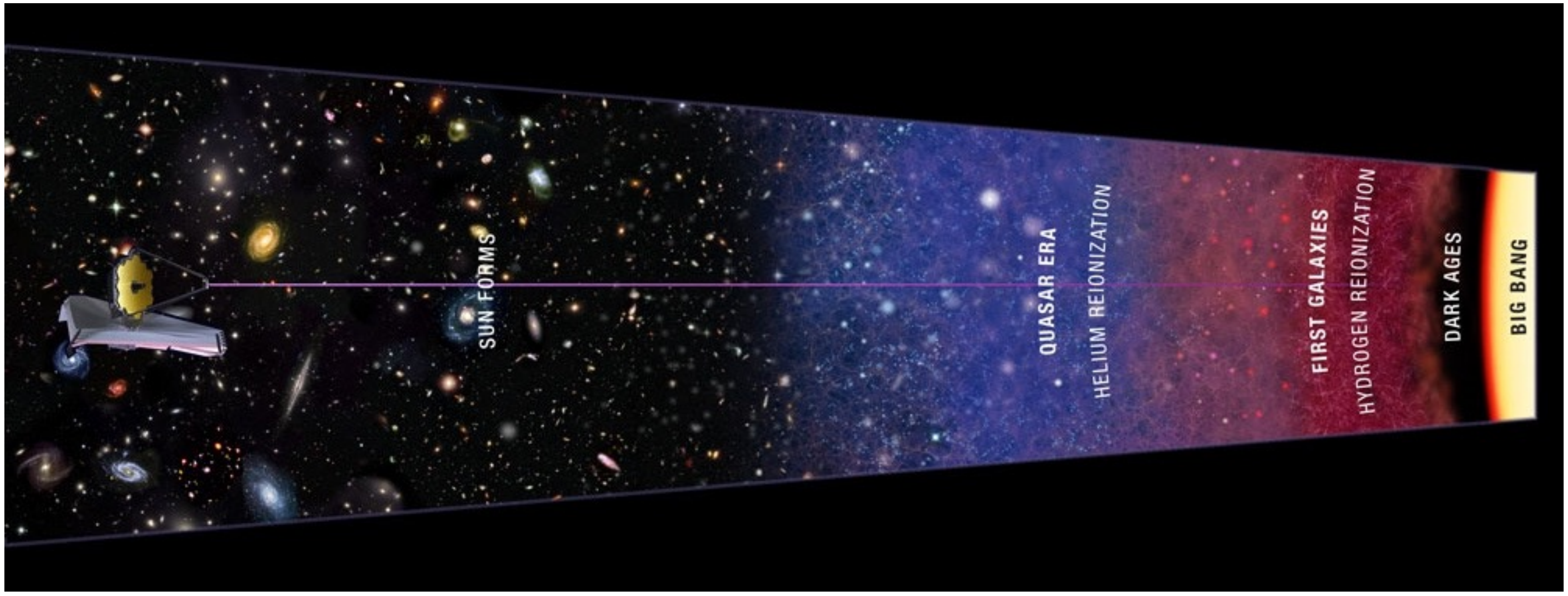
Early-type galaxy star formation quenching schematic



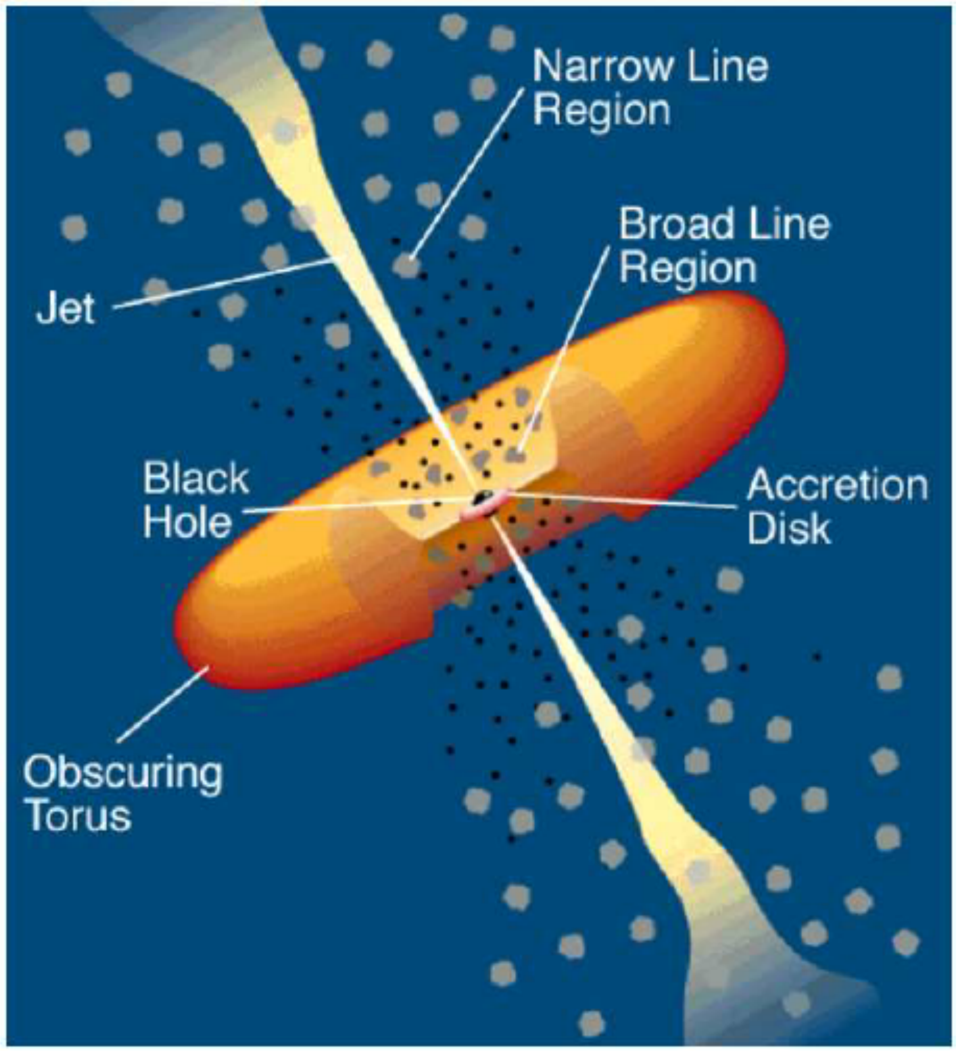
High-Redshift Galaxies

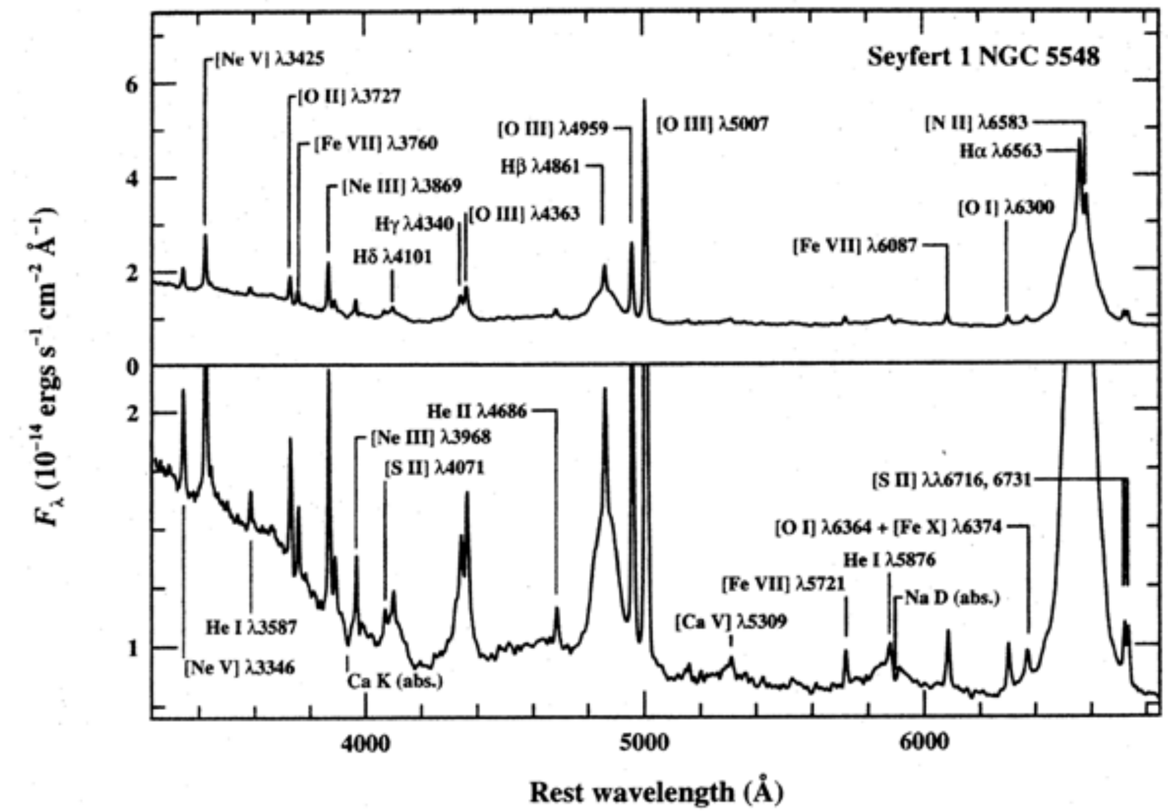


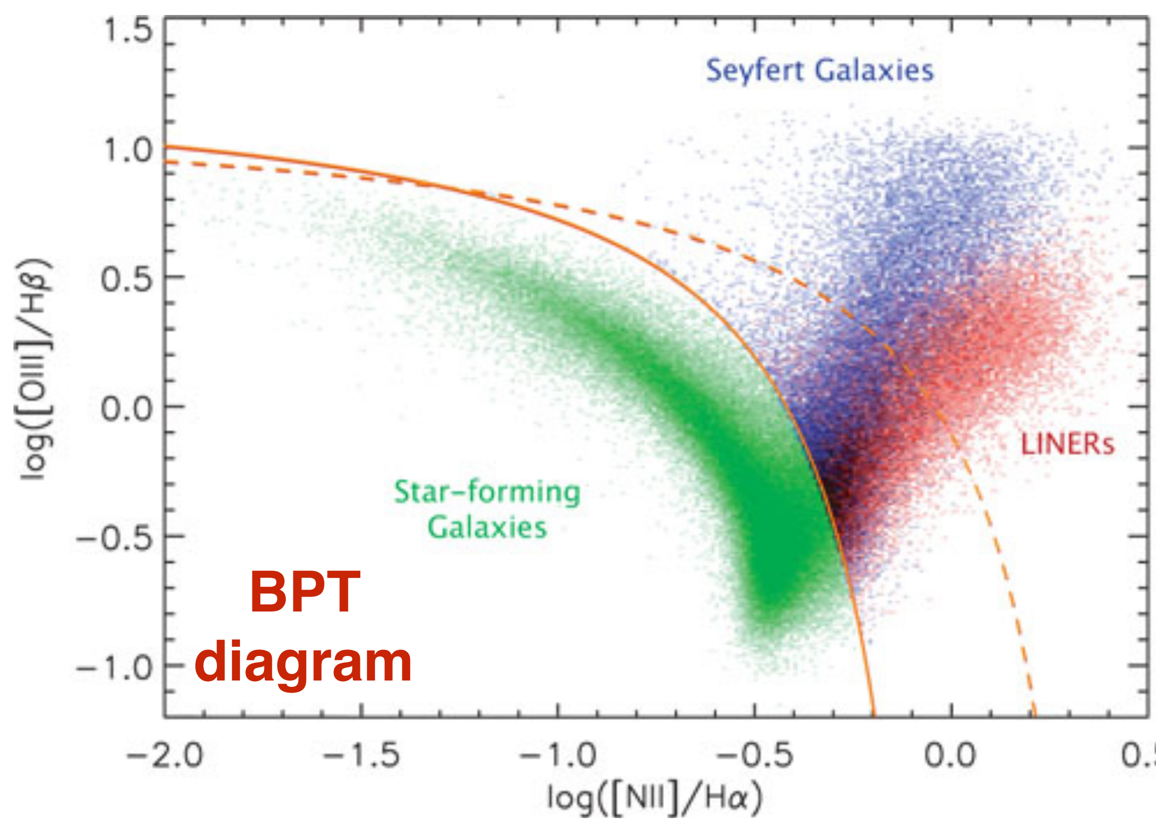




AGN


Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus


Seyfert 1 NGC 5548
[Ne V] λ3425
[O II] λ3727
[Fe VII] λ3760
[Ne III] λ3869
Hγ λ4340
Hδ λ4101
[O III] λ4363
[O III] λ4959
Hβ λ4861
[O III] λ5007
[N II] λ6583
Hα λ6563
[O I] λ6300
[Fe VII] λ6087
He II λ4686
[Ne III] λ3968
[S II] λ4071
[S II] λλ6716, 6731
[O I] λ6364 + [Fe X] λ6374
He I λ5876
[Fe VII] λ5721
Na D (abs.)
[Ca V] λ5309
He I λ3587
[Ne V] λ3346
Ca K (abs.)
F_λ (10^{-14} ergs s^{-1} cm^{-2} Å^{-1})
Rest wavelength (Å)
0
1
2
4
6
4000
5000
6000


Seyfert Galaxies
LINERs
Star-forming Galaxies
BPT diagram
log([OIII]/Hβ)
log([NII]/Hα)
1.5
1.0
0.5
0.0
−0.5
−1.0
−2.0
−1.5
−1.0
−0.5
0.0
0.5

Were you expecting to learn something in this course that you haven't learned?