Ionized gas in Active Galactic Nuclei

Hagai Netzer
School of Physics and Astronomy
Tel Aviv University

- Basic AGN Observations
- Physical processes in AGN
  - Photoionization
  - The spectrum of ionized gas
  - The motion of ionized gas
- Main AGN components
  - The broad line region (BLR)
  - The narrow line region (NLR)
  - Highly ionized gas (HIG)

Energy

Landscape

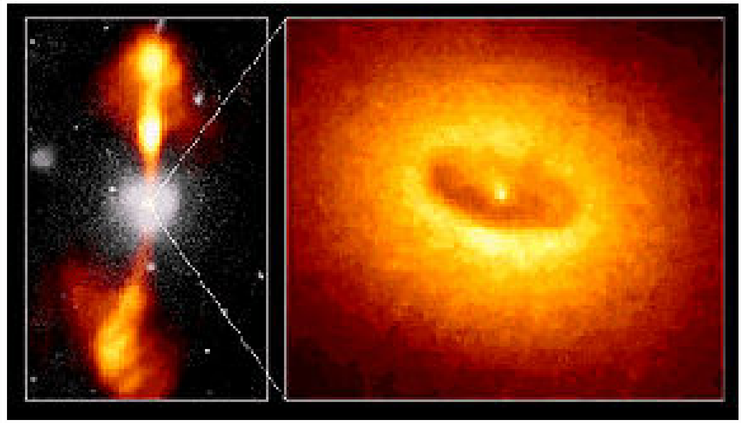
Time

Basic Observations of Active Galactic Nuclei (AGN)

Wow!

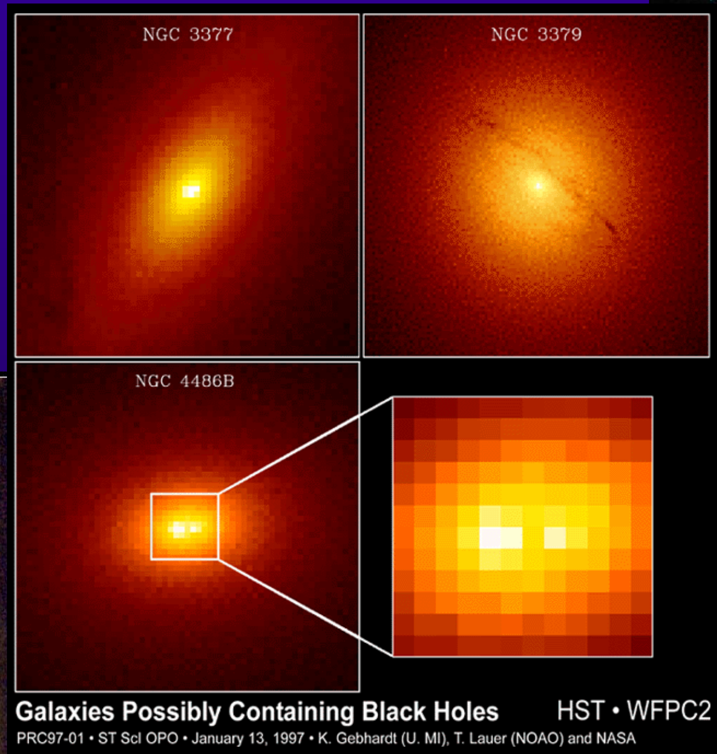
Quasars give off more energy than 100 normal galaxies combined.

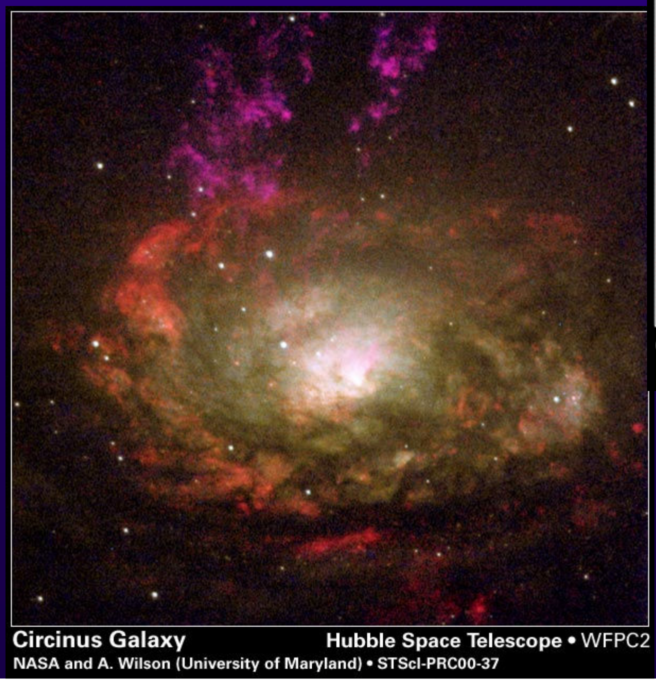
Many astronomers believe that quasars are the most distant objects yet detected in the Universe. Quasars give off enormous amounts of energy - they can be a trillion times brighter than the Sun! Quasars are believed to produce their energy from massive black holes in the center of the galaxies in which the quasars are located. Because quasars are so bright, they drown out the light from all the other stars in the same galaxy.



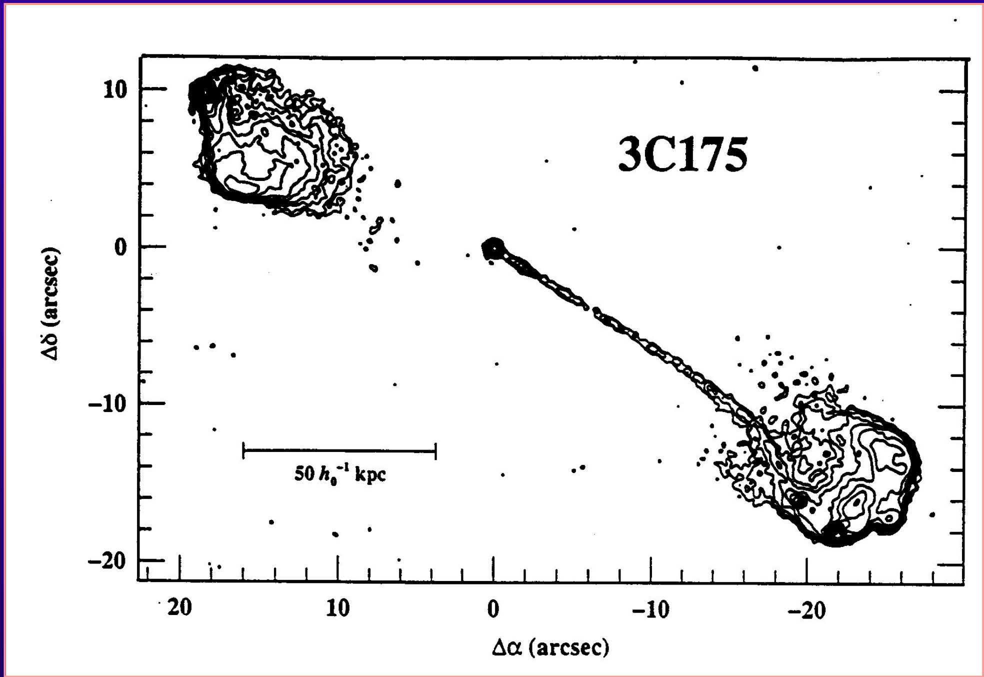
A Quasar

Stellar and non-stellar processes

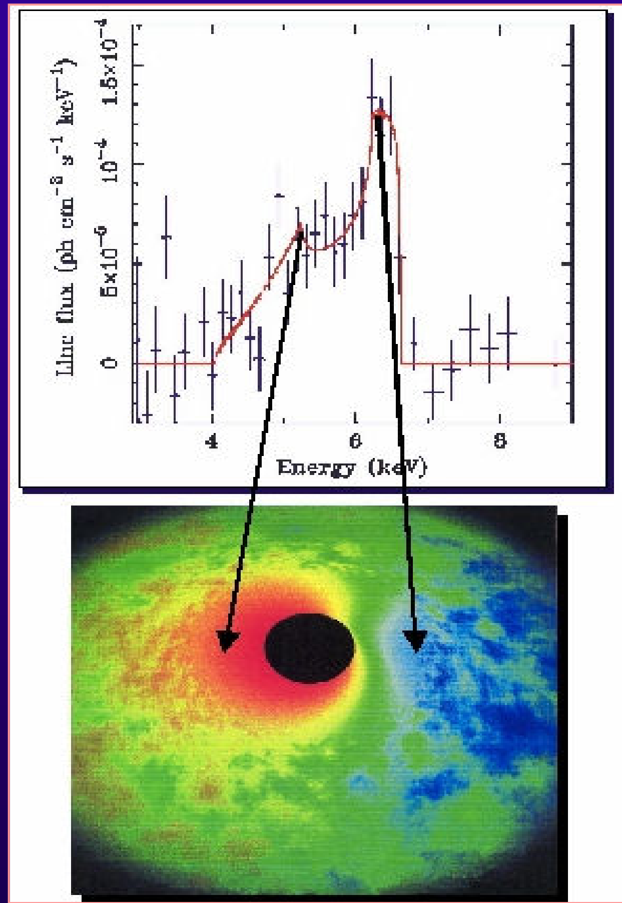




Examples of non-stellar emission

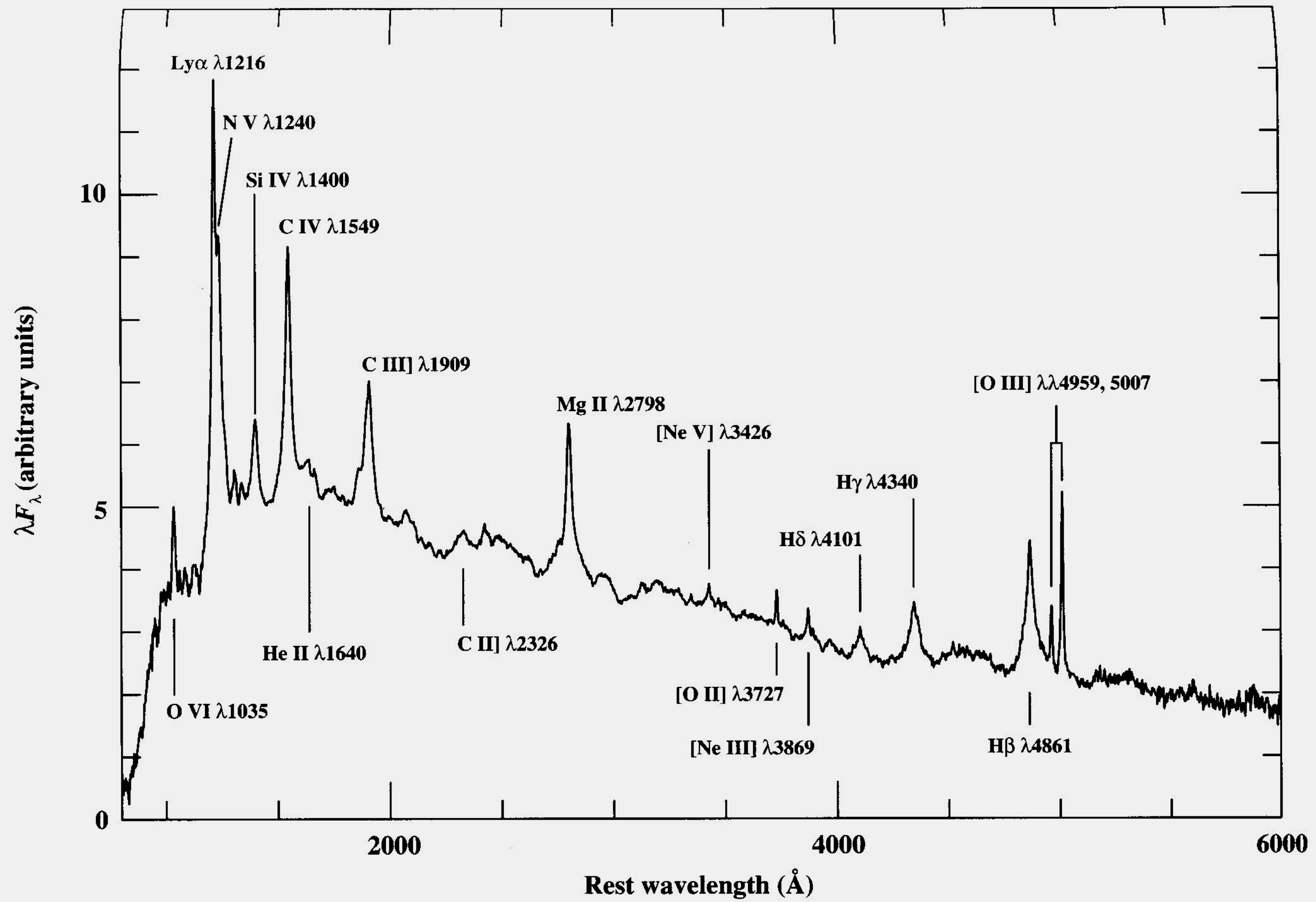


Radio emission

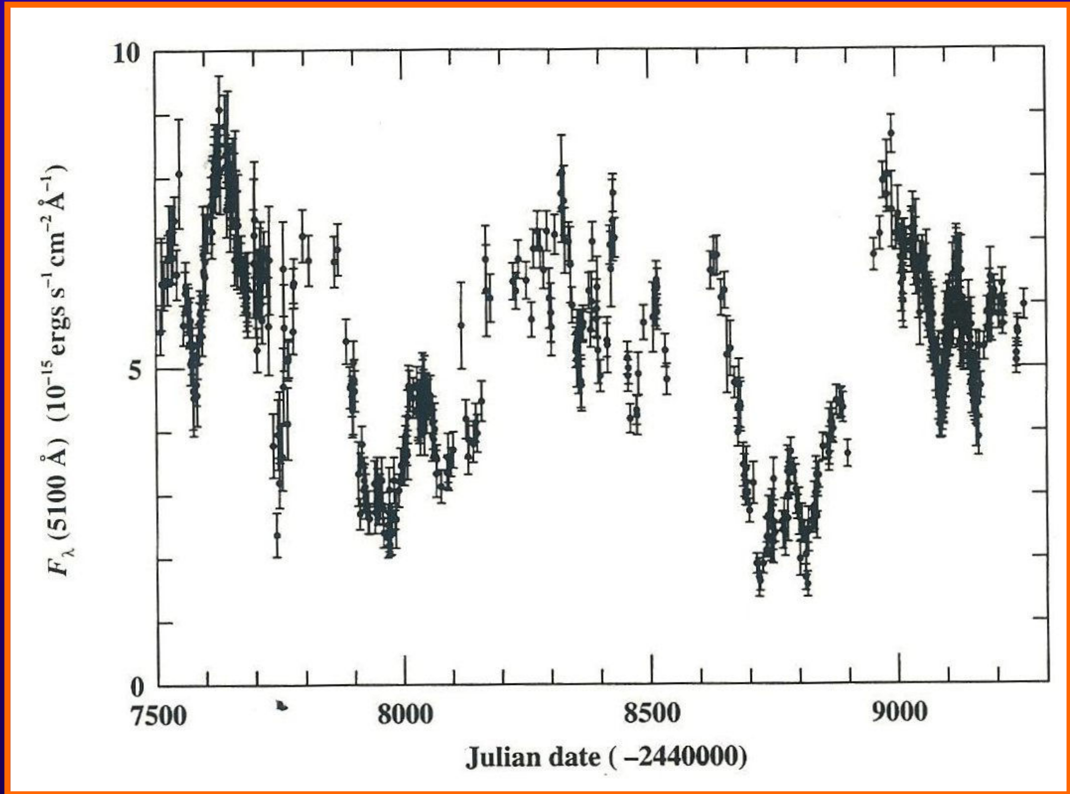


Relativistic effects

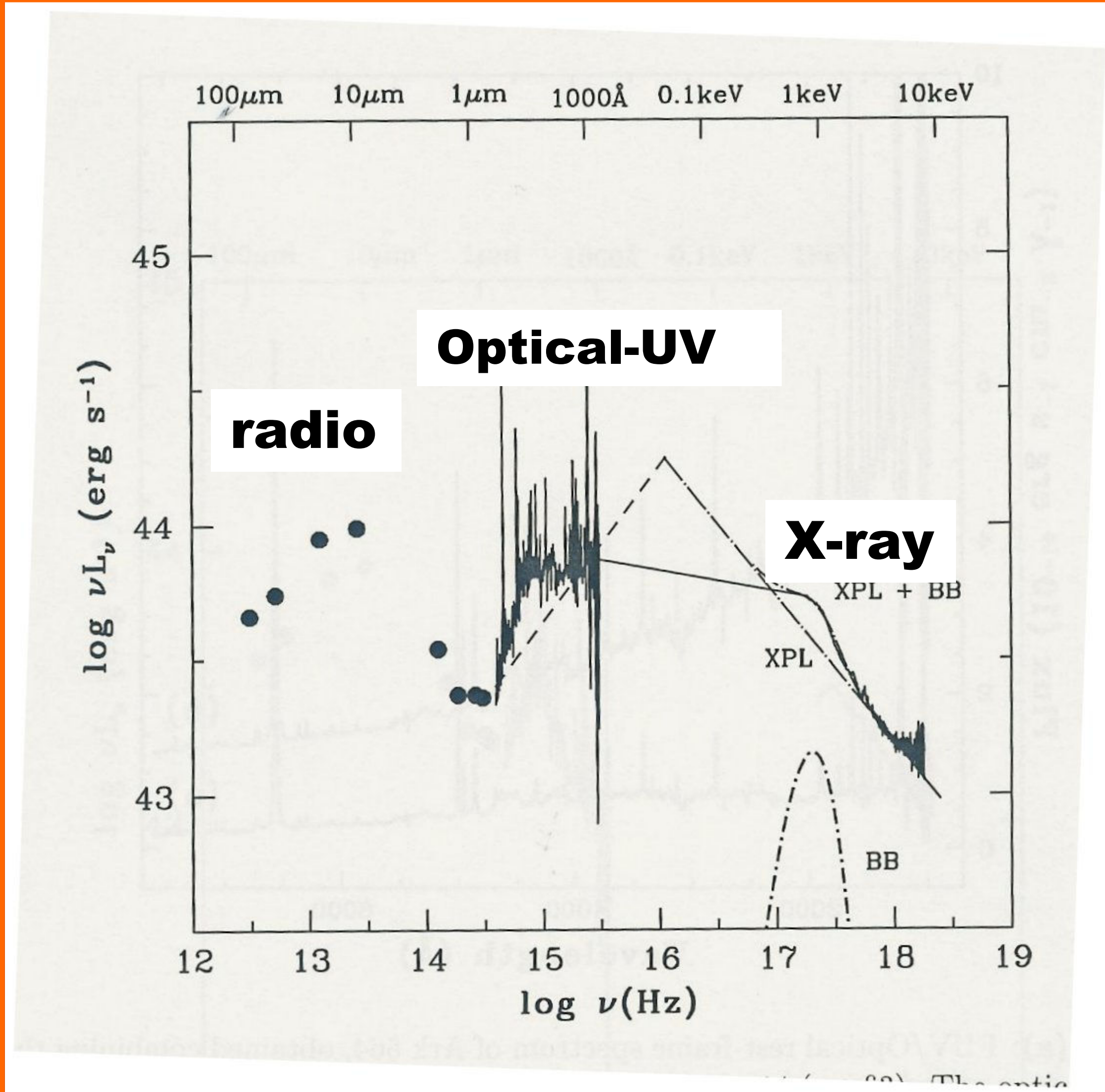
More nonsteller processes: AGN emission lines



Variability



Combining all nonstellar emission: Spectral energy distribution (SED) of AGN



Discovering AGN

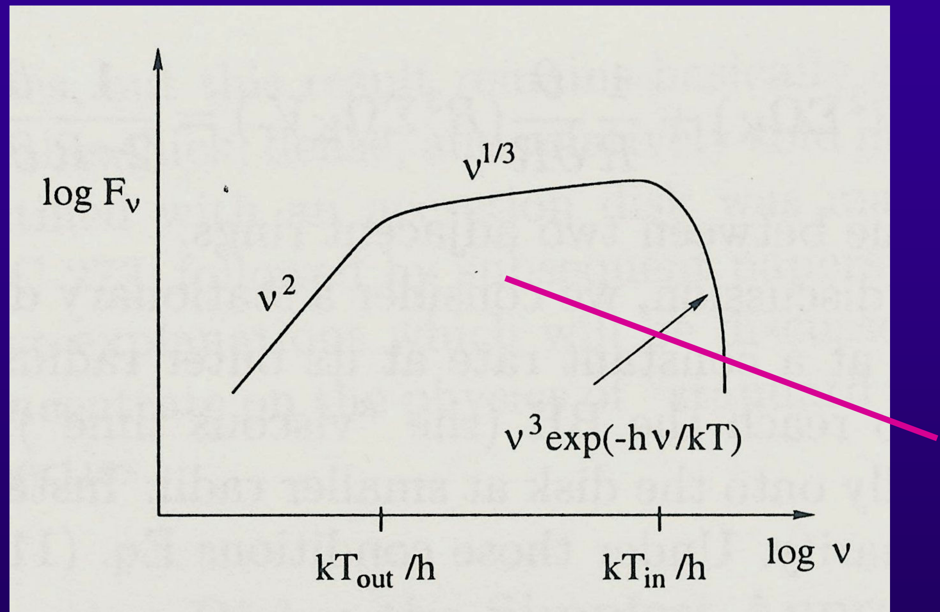
- By their (nonstellar) radio properties
- By their (nonstellar) color
- By their (nonstellar) emission line spectrum
- By their (nonstellar) X-ray properties
- By their (nonstellar) IR properties
- By their variability

Black holes and accretion disks

Gravitational and Schwarzschild radii

$$R_g = \frac{GM}{c^2} \;;\quad R_s = \frac{2GM}{c^2}$$

The (nonstellar) accretion disk spectrum



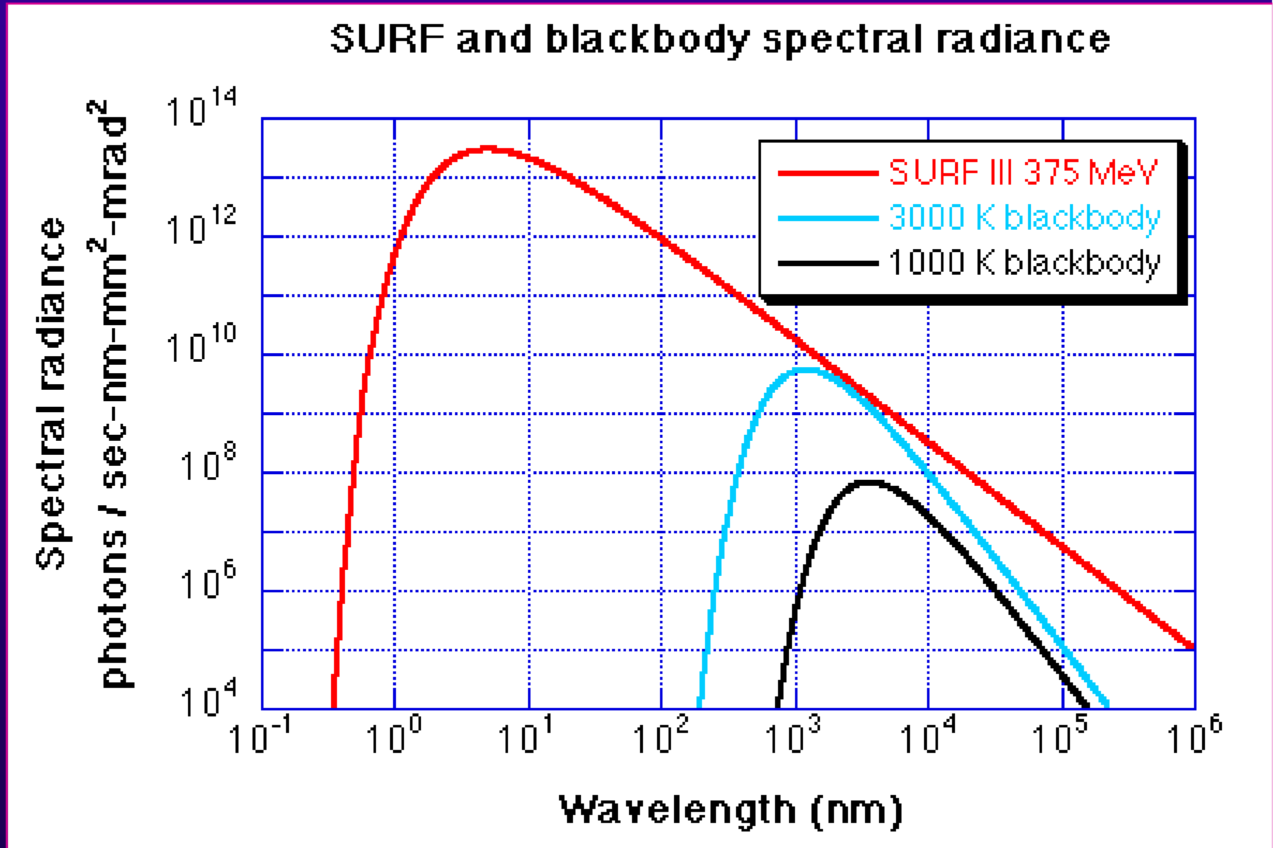
Stationary and rotating BHs

Accretion rate and accretion efficiency

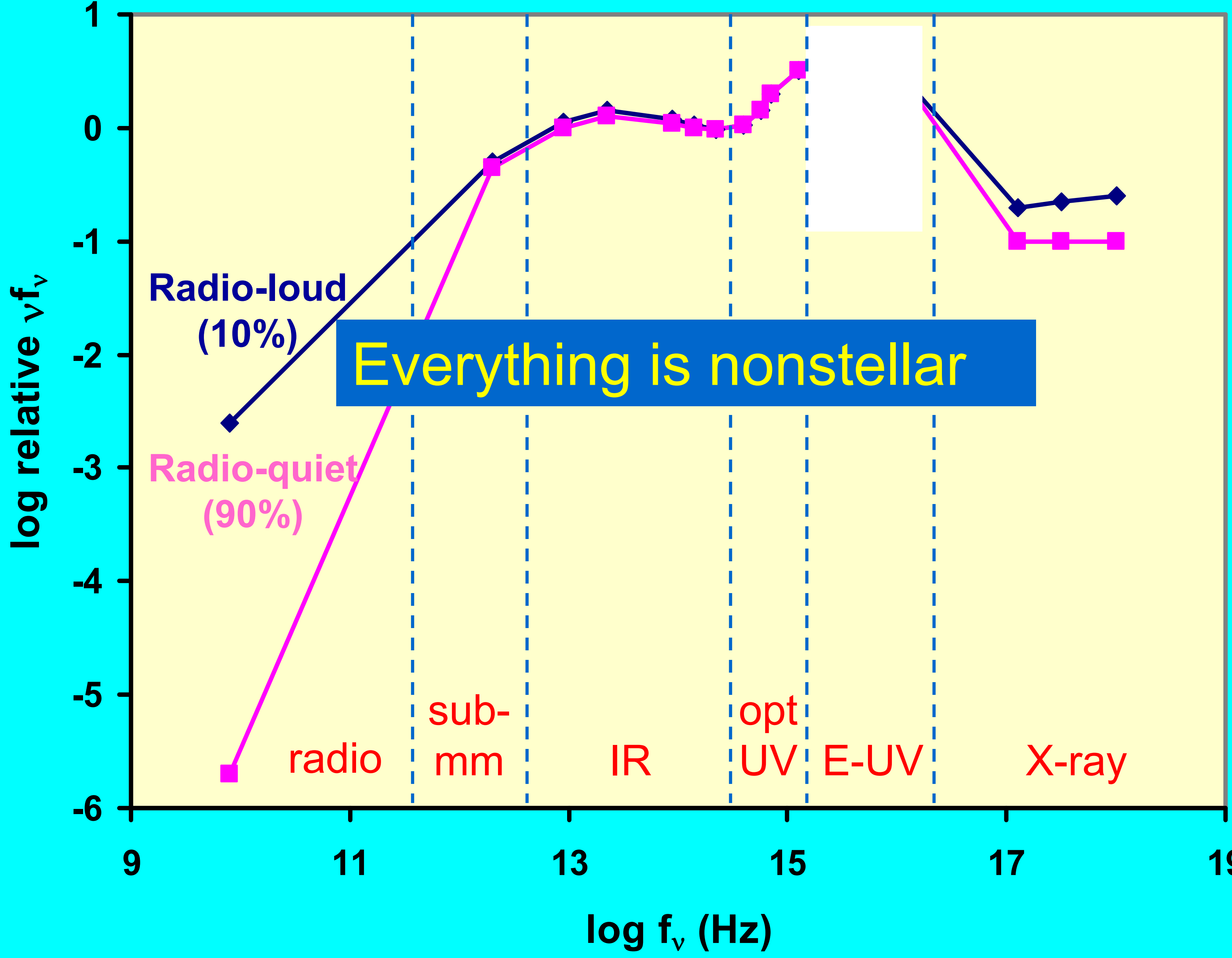
More nonstellar processes: Nonthermal radiation

Synchrotron radiation

Inverse Compton



QSO multifrequency spectrum



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Energy

Landscape

Time

Maps of the “universe”

Let There Be Light

- AGN is born
  - Ionization
  - Recombination
  - Collisional excitation
  - Radiation pressure
  - Shock waves
  - Magnetic fields

How does it look and
moves at various times?

The Physics of Ionized Gas

- Photoionization and recombination
  - Time dependent equations
  - Steady state equations
- Other atomic processes
  - Collisional processes
  - Dielectronic recombination
  - Auger and fluorescence
  - Charge exchange
- The spectrum of ionized gas
- The motion of ionized gas

Photoionization and recombination

Photoionization rate - I_X

$$I_x = \int_{\nu_x}^{\infty} \frac{(L_\nu / h\nu)\sigma_\nu e^{-\tau_\nu} d\nu}{4\pi r^2}$$

Radiative recombination rate - R_X

$$R_x = \alpha_x(T) N_e$$

Time dependent equation

$$\frac{dN_x}{dt} = -N_x\left[I_x + R_x\right] + \left[N_{x-1}I_{x-1} + N_{x+1}R_{x+1}\right]$$

The steady state solution:

$$\frac{dN_x}{dt} = 0 \Rightarrow \frac{N_{x+1}}{N_x} = \frac{I_x}{R_{x+1}}$$

Recombination time

$$\frac{1}{R_x}$$

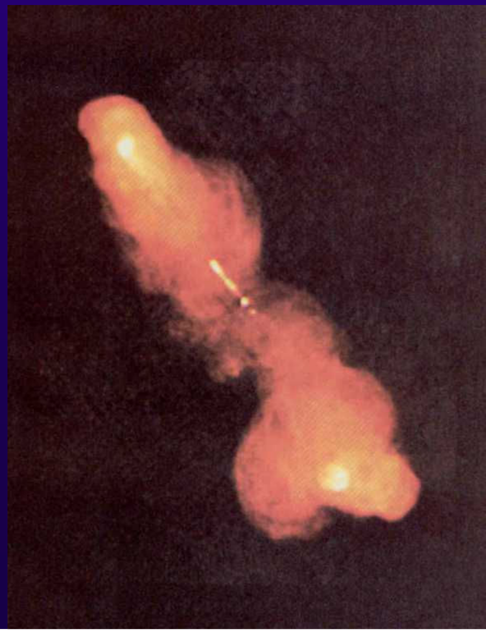
Ionization time

$$\frac{1}{I_x}$$

Other ionization/recombination processes

- Collisional processes
  - collisional ionization
  - three body recombination
- Dielectronic recombination
- Charge exchange
- Ionization by secondary electrons
- Auger ionization and fluorescence
- Ionization by shock waves

Something about shock heating efficiency



$$E_{sh} = \frac{1}{2} m_{sh} v^2 = \eta_{sh} m_{sh} c^2$$

$$\eta_{sh} \approx \frac{v^2}{2c^2}$$

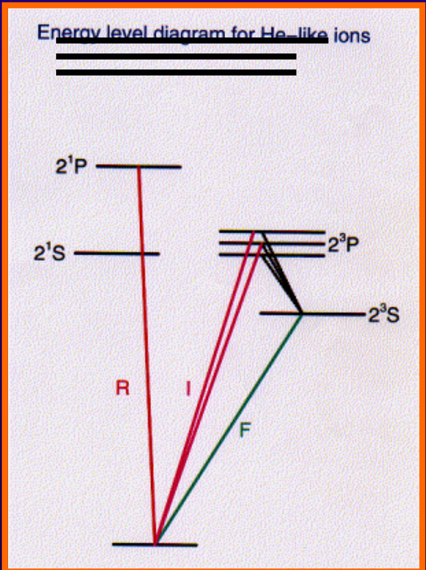
$$v_{NLR} \approx 500\ km/\sec$$

$$E_{acc} = m_{acc} \eta_{acc} c^2 \ (\eta_{acc} \approx 0.1)$$

$$\frac{E_{sh}}{E_{acc}} = \frac{m_{sh} \eta_{shock}}{m_{acc} \eta_{sh}} \approx 10^{-5} \frac{m_{sh}}{m_{acc}}$$

Thermal balance

- Heating - H
  - photoionization heating
  - other heating
- Cooling - C
  - collisional cooling
  - recombination cooling



$$h\nu_{21}$$
$$h\nu_{1,\infty}$$

Photoionization heating

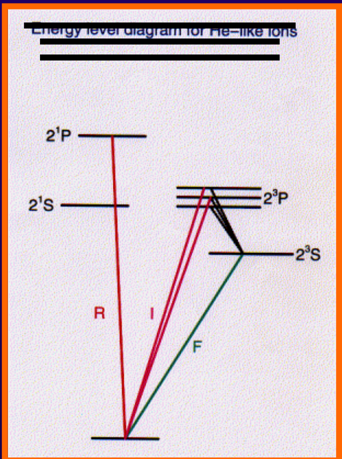
$$H_I = N_x \int_{\nu_x}^{\infty} \frac{(L_\nu / h\nu)\sigma_\nu e^{-\tau_\nu} [h\nu - h\nu_x]\; d\nu}{4\pi r^2}$$

recombination cooling

$$\varepsilon_{rec} = N_{x+1} N_e \alpha_{eff} h\nu_{1\infty}$$

Thermal balance

- Heating - H
  - photoionization heating
  - other heating
- Cooling - C
  - collisional cooling
  - recombination cooling



$$h\nu_{21}$$
$$h\nu_{1,\infty}$$

Statistical equilibrium

$$\frac{dn_2}{dt} = n_1 q_{12} - n_2(A_{21} + q_{21}) + N_{x+1} N_e \alpha_{eff}$$

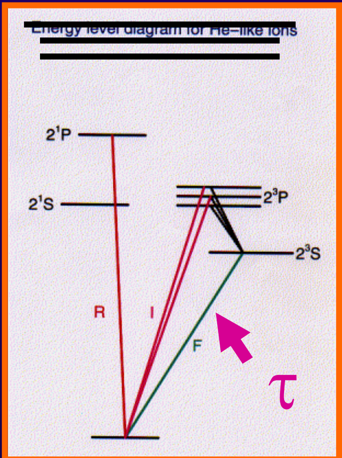
$$\frac{dn_2}{dt} = 0$$

Line cooling

$$\varepsilon_{coll} = n_2 A_{21} h\nu_{21} = n_1 A_{21} h\nu_{21} \left[\frac{N_e q_{12}}{A_{21} + N_e q_{12}} \right]$$

Thermal balance

- Heating - H
  - photoionization heating
  - other heating
- Cooling - C
  - collisional cooling
  - recombination cooling



$$h\nu_{21}$$
$$h\nu_{1,\infty}$$
$$\beta_{21} \propto \frac{1}{\tau_{21}}$$

Statistical equilibrium

$$\frac{dn_2}{dt} = n_1 q_{12} - n_2 (A_{21}\beta_{21} + q_{21}) + N_{x+1} N_e \alpha_{eff}$$
$$\frac{dn_2}{dt} = 0$$

Line cooling

$$\varepsilon_{coll} = n_2 \beta_{21} A_{21} h\nu_{21} = n_1 \beta_{21} A_{21} h\nu_{21} \left(\frac{N_e q_{12}}{A_{21}\beta_{21} + N_e q_{12}}\right)$$

H(T)=C(T)

Let There Be Light

How does it look and
moves at various times?

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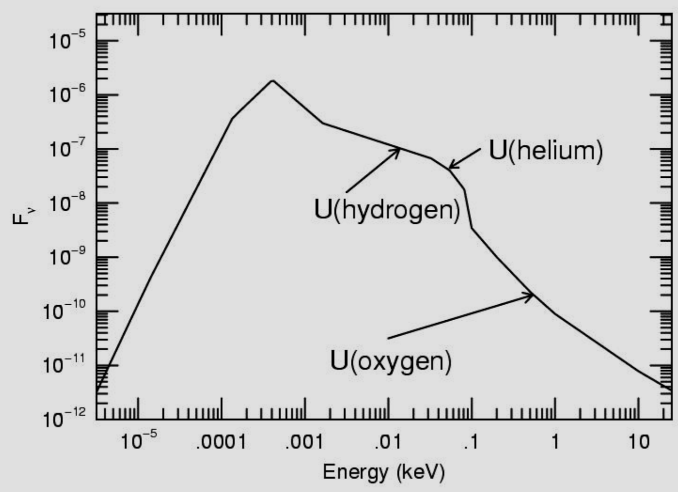
Energy

Landscape

Time

The spectrum of ionized gas - 1

SED



Ionization parameter

$$U = \int_{E_1}^{E_2} \frac{(L_E / E)\,dE}{4\pi r^2 c N_H} = \frac{\text{photon density}}{\text{gas density}}$$

Various ionization parameters

	E_1	E_2
U(hydrogen)	13.6 eV	∞
U(helium)	54.4 eV	∞
U(X-ray)	0.1keV	10 keV
U(oxygen)	0.54 keV	10 keV
$\xi = \frac{L}{N_e r^2}$	13.6eV	13.6 keV

The spectrum of ioniz

- Clouds
  - Confinement
    - Thermal confinement
    - Stability (heating=cooling) curve
    - Magnetic confinement

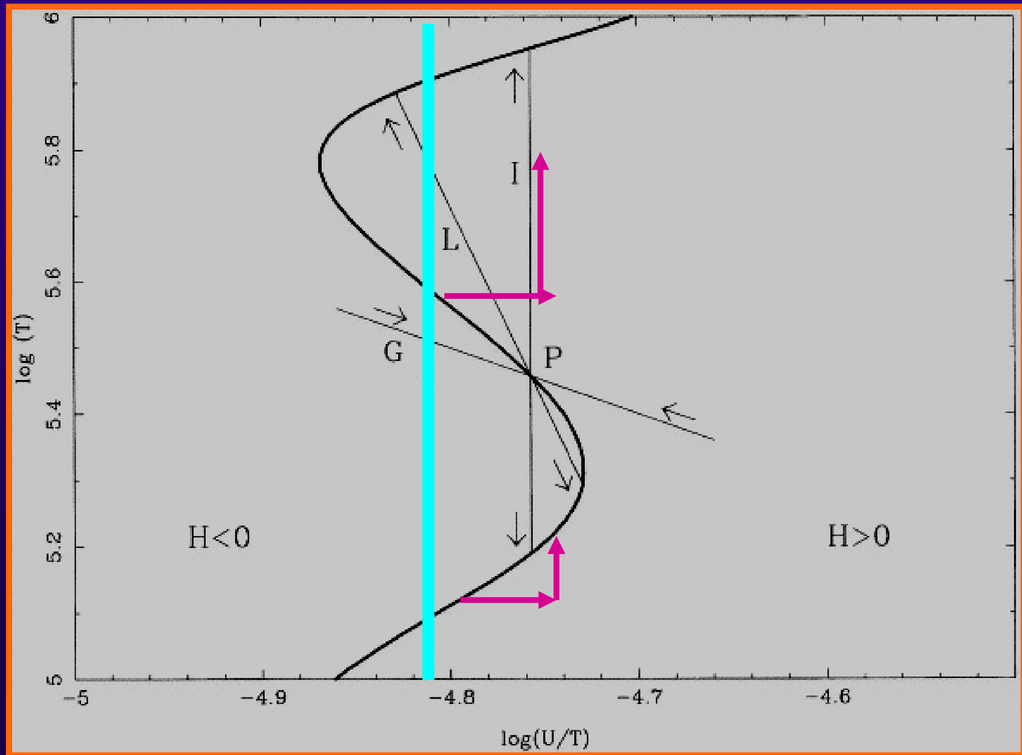
$$U_{hot} \propto \frac{L}{4\pi r^2 N_{hot}}$$

$$U_{cold} \propto \frac{L}{4\pi r^2 N_{cold}}$$

$$\frac{U}{T} \propto \frac{L/r^2 c}{TN} \propto \frac{P_{rad}}{P_{gas}}$$

$$P_{cold} = P_{hot} \Rightarrow \frac{U_{hot}}{T_{hot}} = \frac{U_{cold}}{T_{cold}}$$

$$\frac{B^2}{8\pi} \geq NkT$$



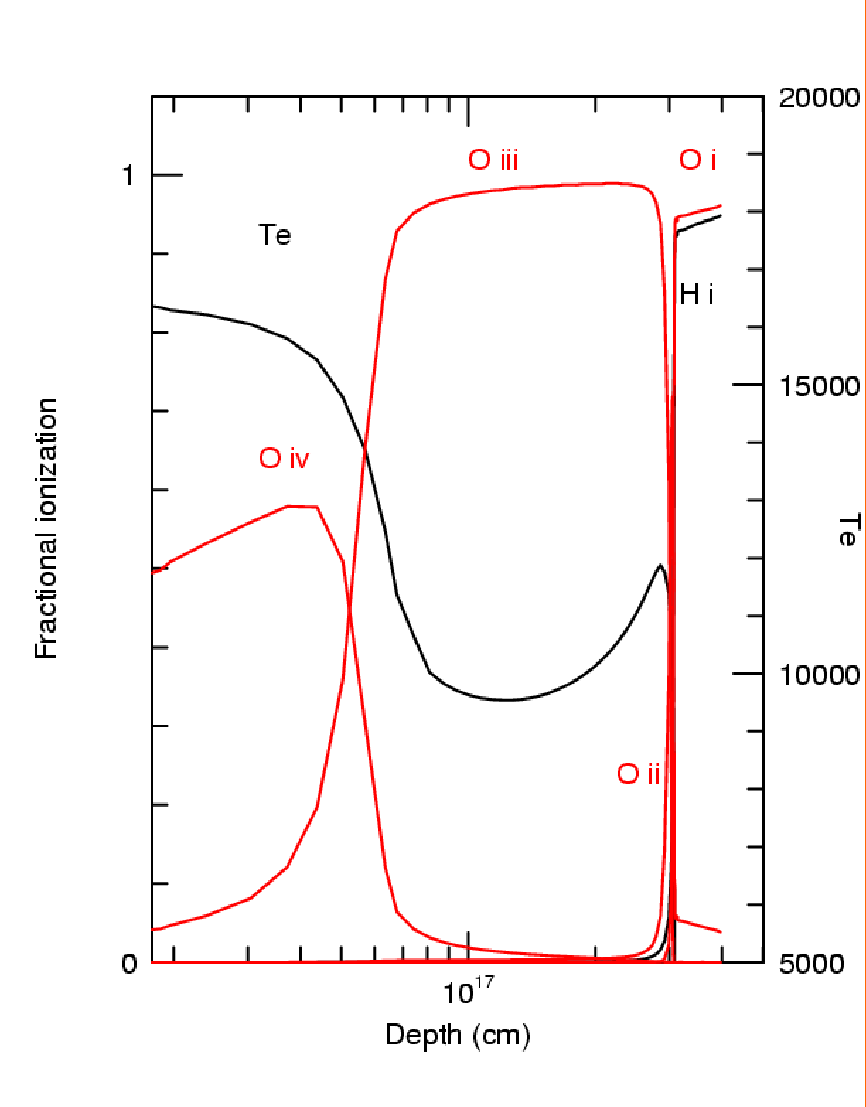
- Wind

The spectrum of ionized gas - 3

- Photoionization calculations
  - ionization structure
  - thermal structure

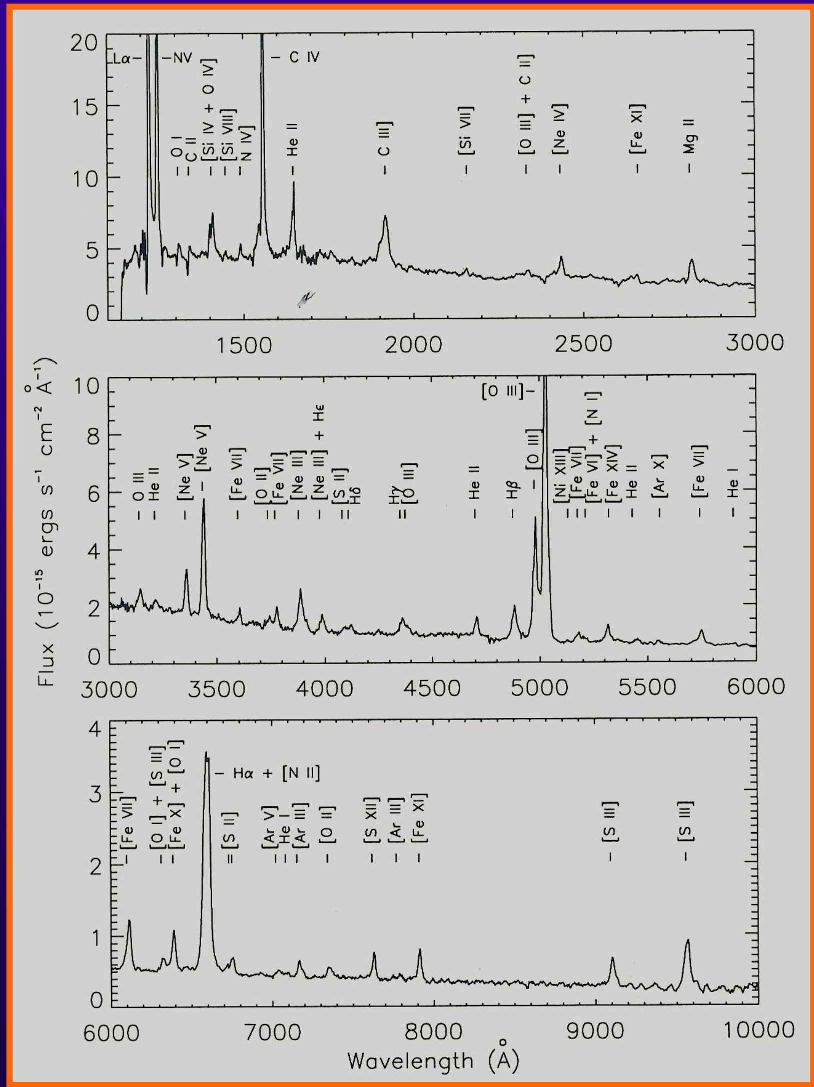
- Spectral calculations
  - line emission
  - continuum emission
  - line and continuum absorption

$$E_{line} \propto \int_{r_{in}}^{r_{out}} n_c(r) j_{line}(r) r^2 dr$$

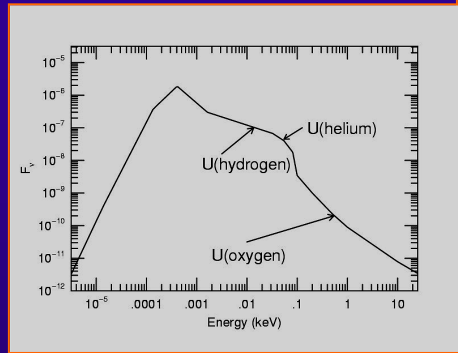


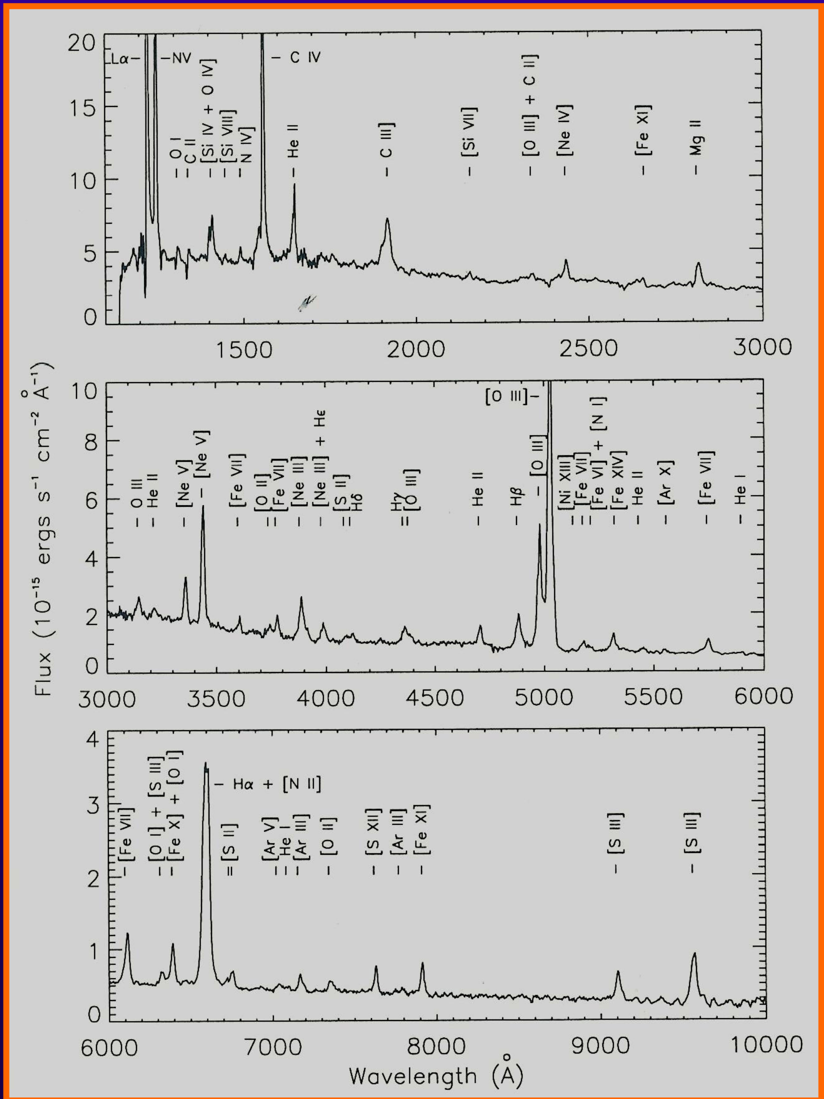
The spectrum of ionized gas - 4

- The emergent spectrum
  - The central continuum
  - Free-free emission
  - Bound-free emission
  - Bound-free absorption
  - Emission lines
  - Absorption lines



Physical processes - summary





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Maps of the “universe”

Main components -1: the BLR

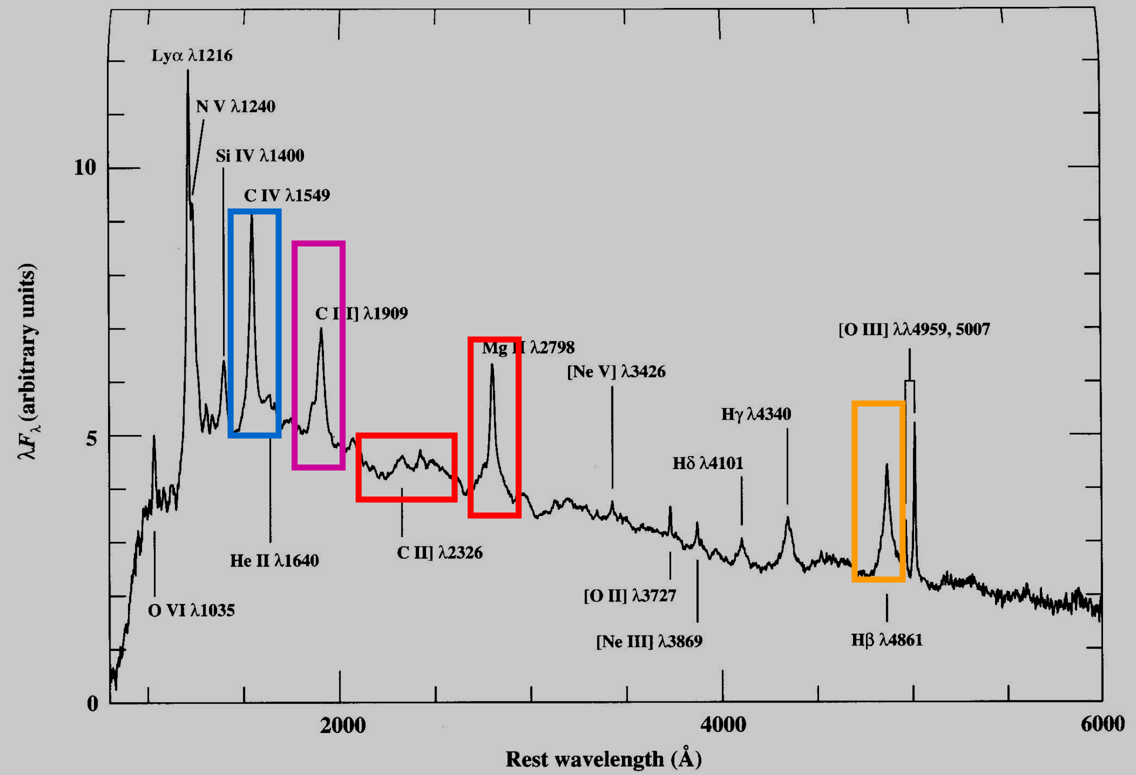
- Assumed clouds
  - Density 10^{9-11} cm^{-3}
  - Large column density
  - Location: ~ 0.1pc
  - Confinement
    - by hot gas
    - by magnetic fields
  - Covering fraction ~0.1

Bound system (gravity dominated)

FWHM ~ 3000 km/sec

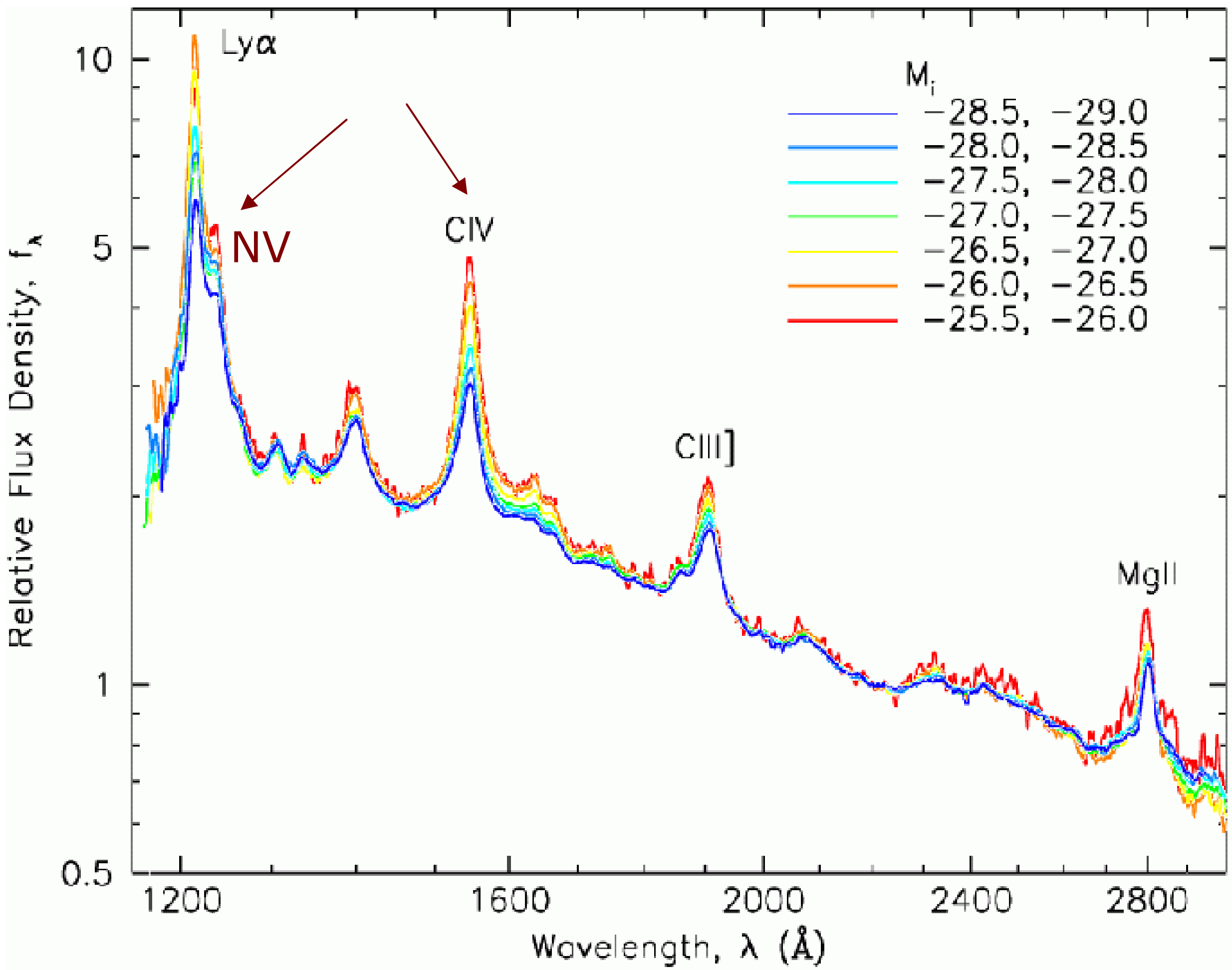
large EW emission lines

Weak absorption lines

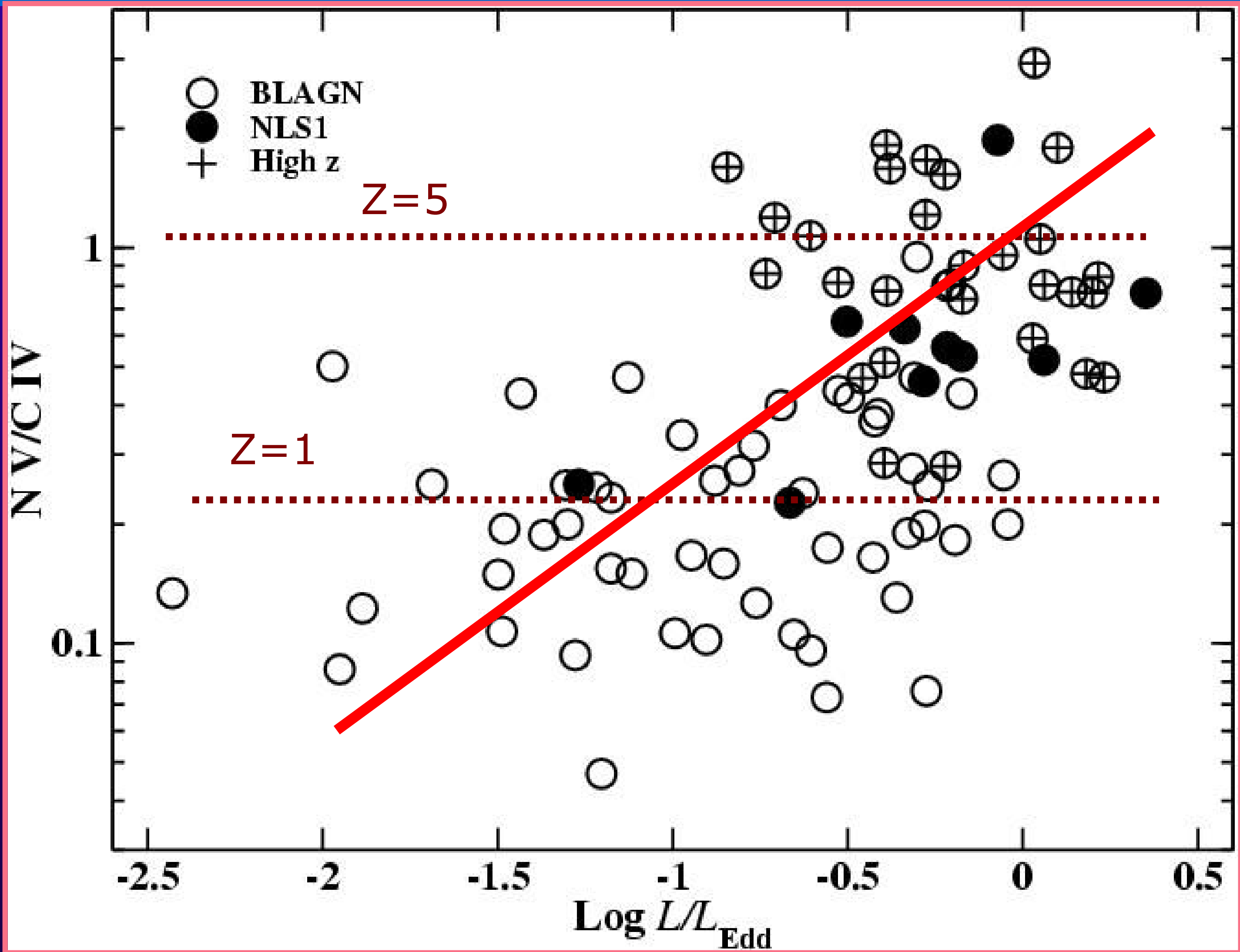


- The spectrum
  - Resonance lines
  - Semi-forbidden lines
  - Balmer lines
  - FeII and MgII lines
- The name of this region
- Gas composition?

BLR metallicity

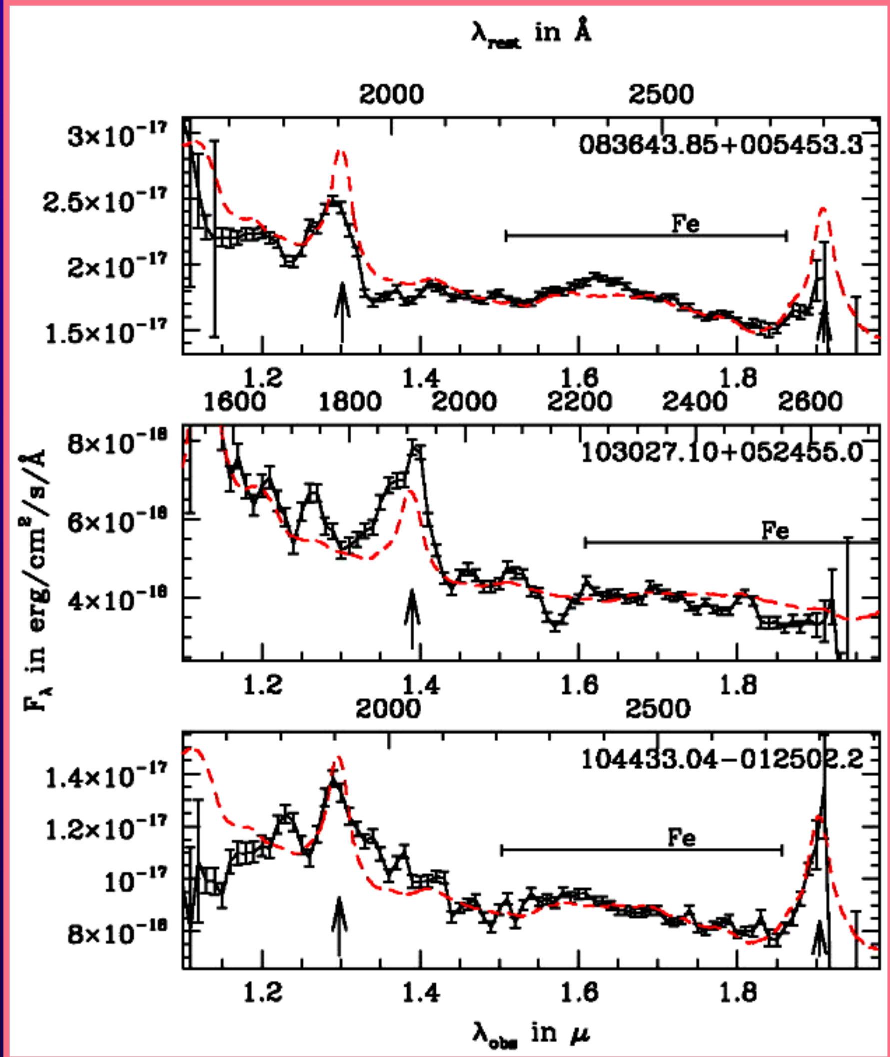


L/L_{Edd} – metallicity relationship



Shemmer, Netzer et al 2004

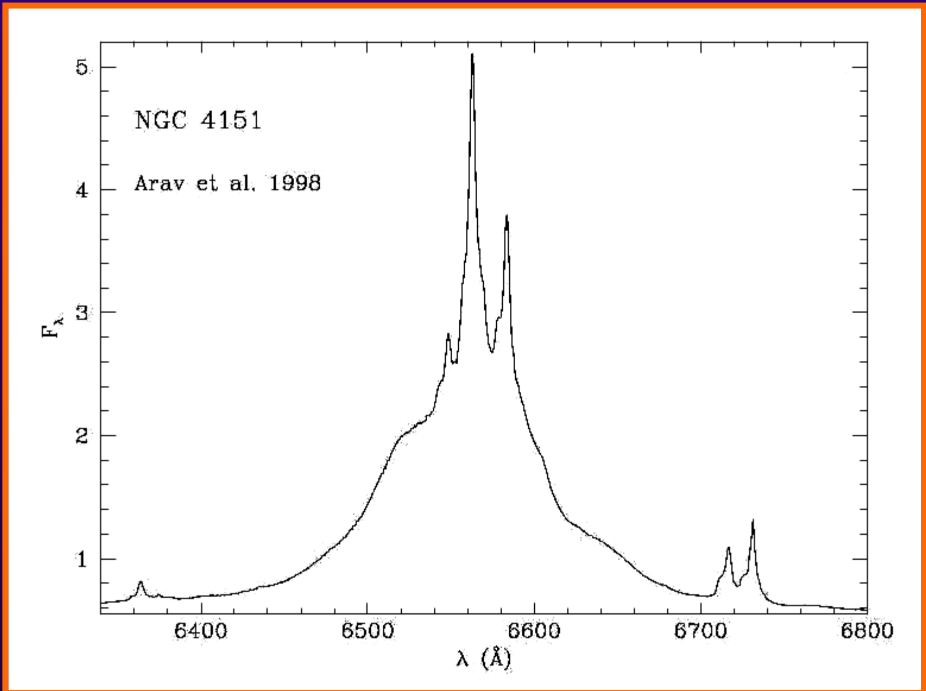
Iron abundance at high redshift

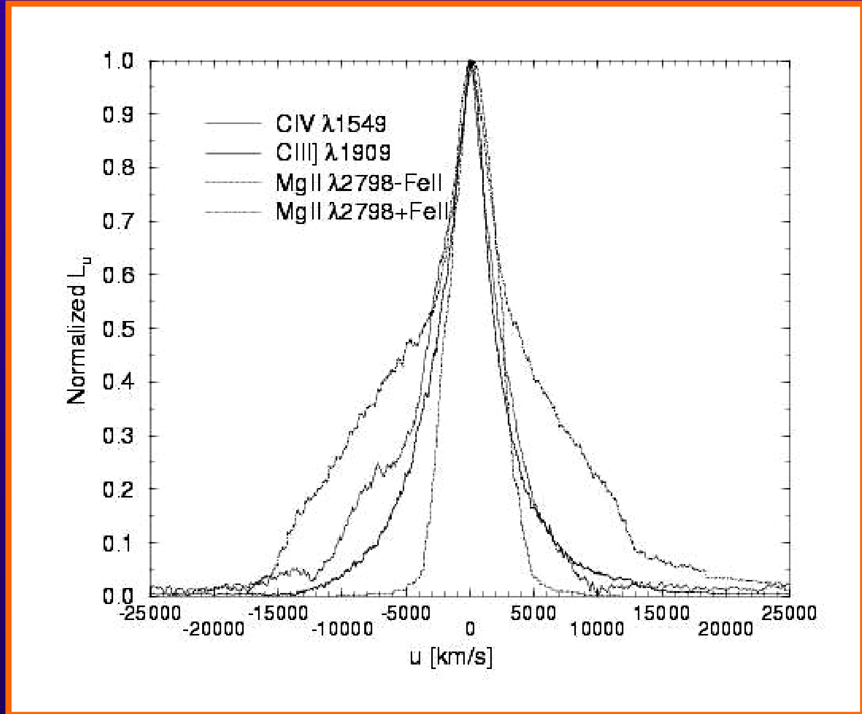


Freudling et al. 2003

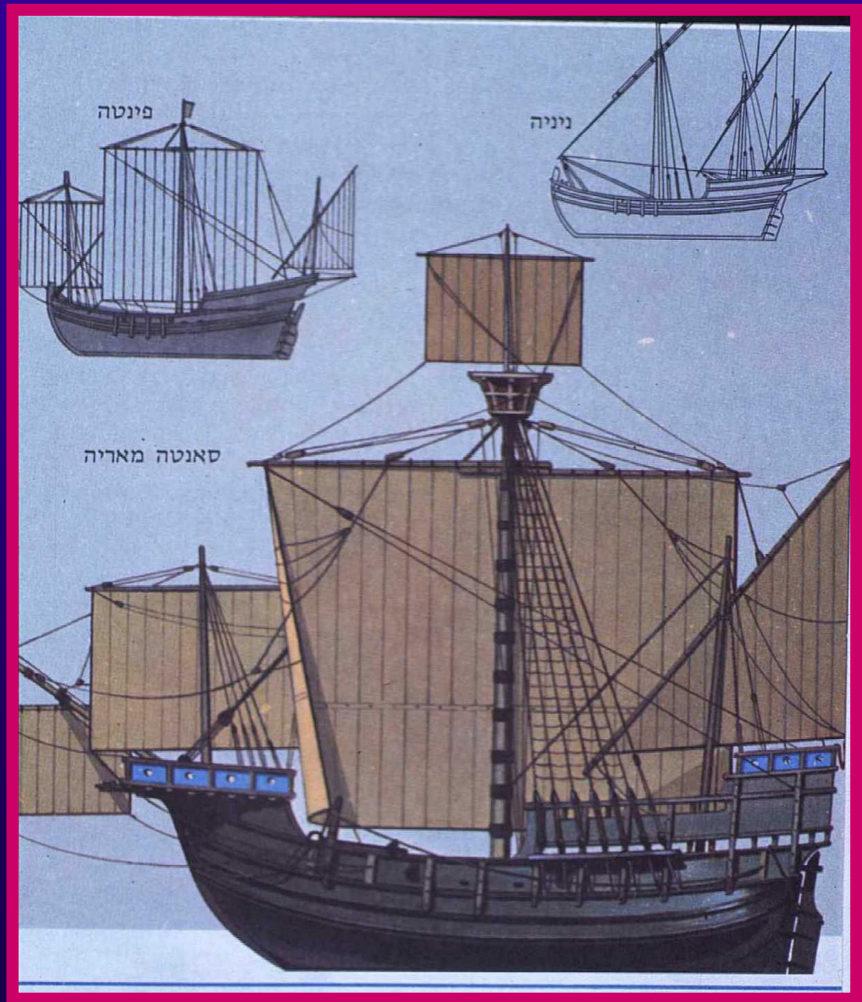
The BLR - 2

- Line profiles
  - cloud dynamics
  - the number of BLR clouds



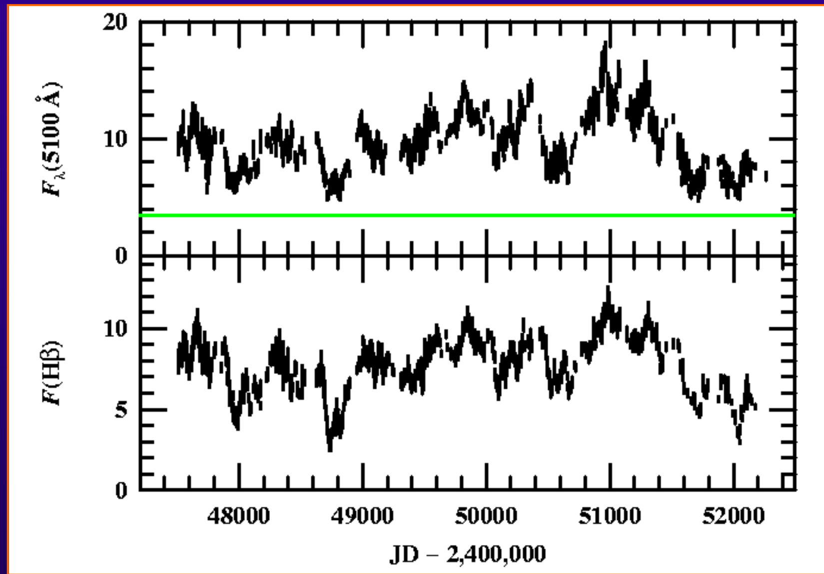


Navigation without time



Broad-Line Variability

- Emission line gas must respond to ionizing continuum radiation
- Let There be Brad Peterson



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The NLR - 1

- Assumed clouds
  - Density $10^{3\text{-}5}$ cm^{-3}
  - Large and small column density
  - Location ~300 pc
  - Radial distribution
  - Confinement
  - Covering factor ~0.02

Bound system?

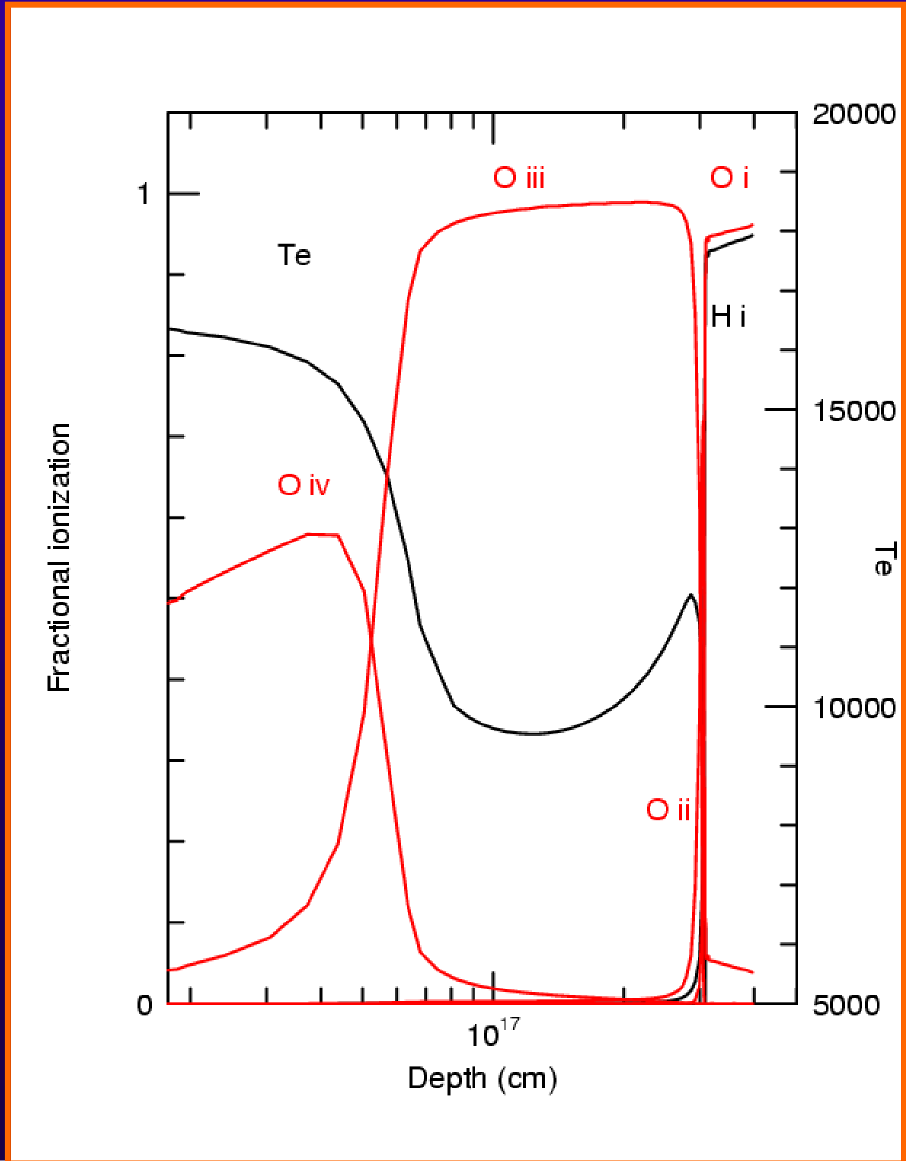
FWHM ~ 500 km/sec

small EW emission lines

Weak absorption lines

Time averaged spectral properties

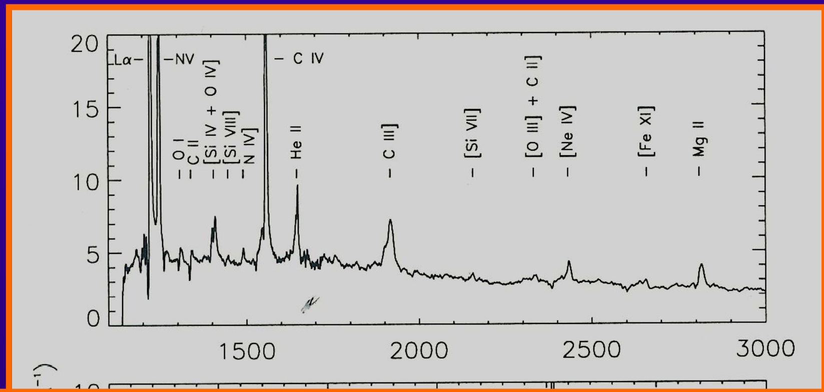
The NLR – 2: Photoionization calculations

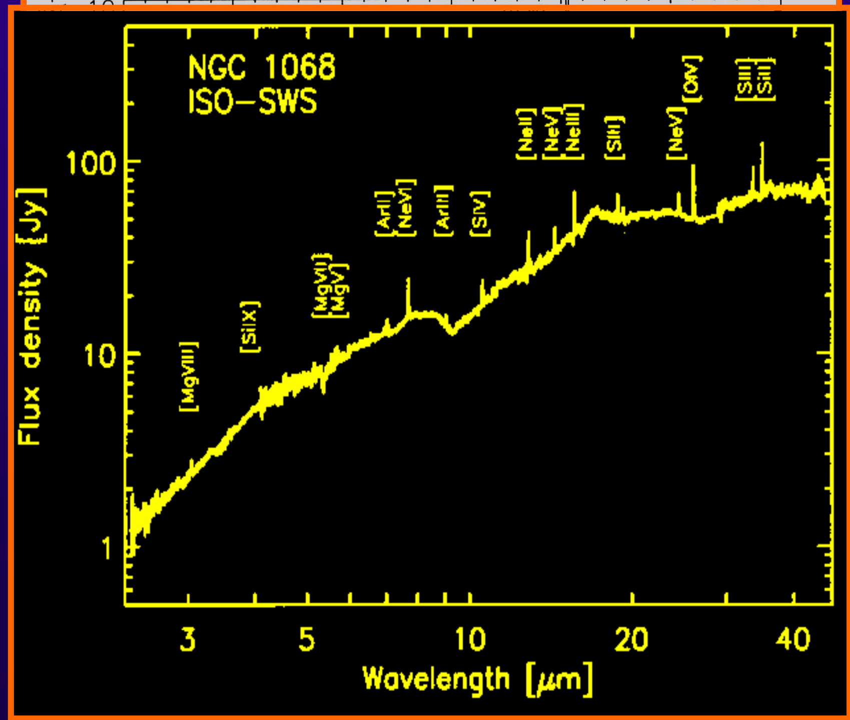


The NLR – 3: The observed spectrum

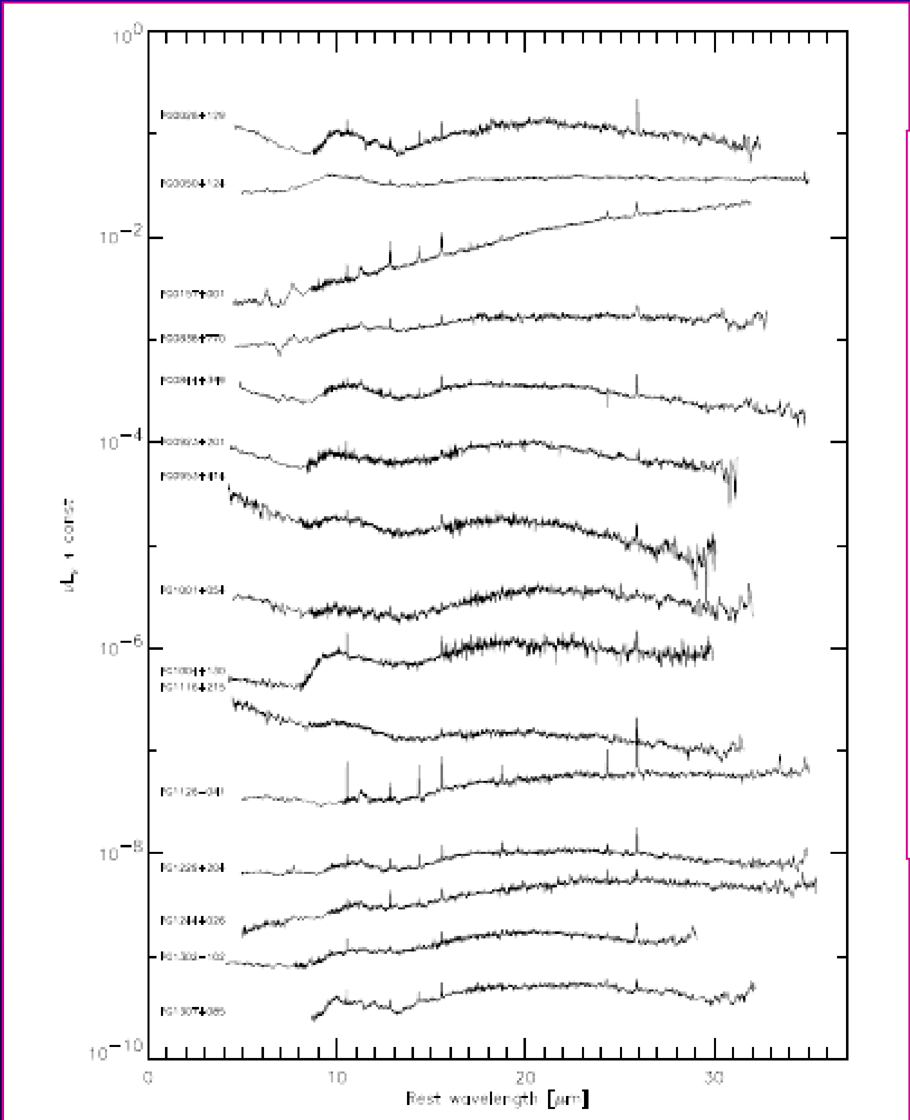
- The NLR spectrum
  - optical and UV lines
    - permited, semi-forbidden and forbidden lines
  - IR lines
    - coronal lines

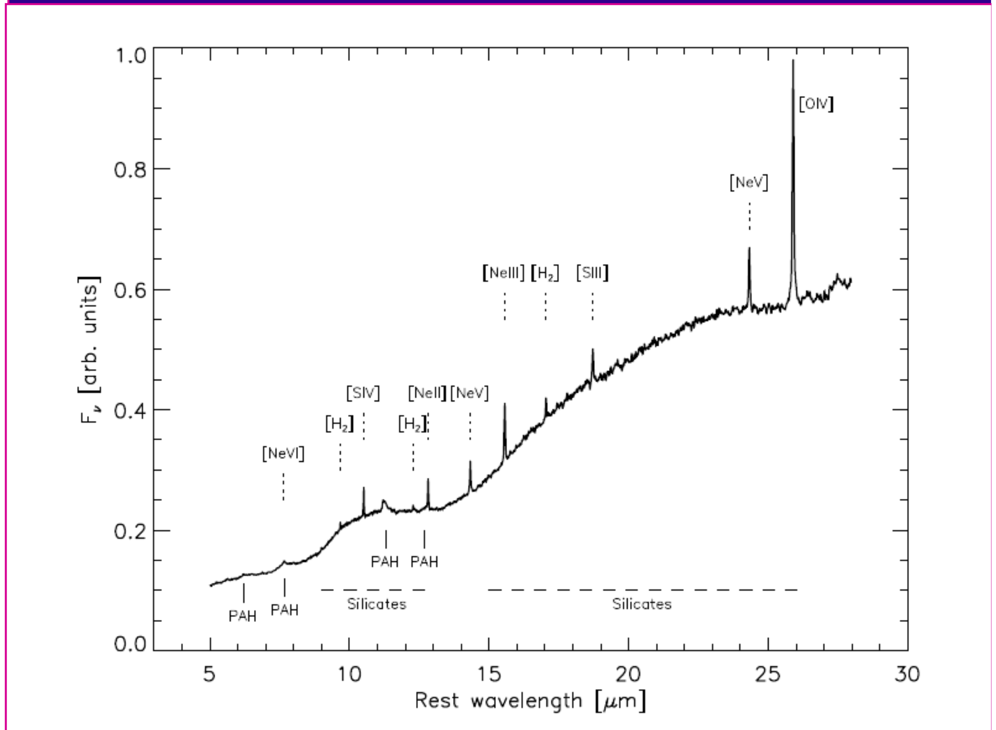
Time averaged spectral properties





The NLR – 4: Infrared observations

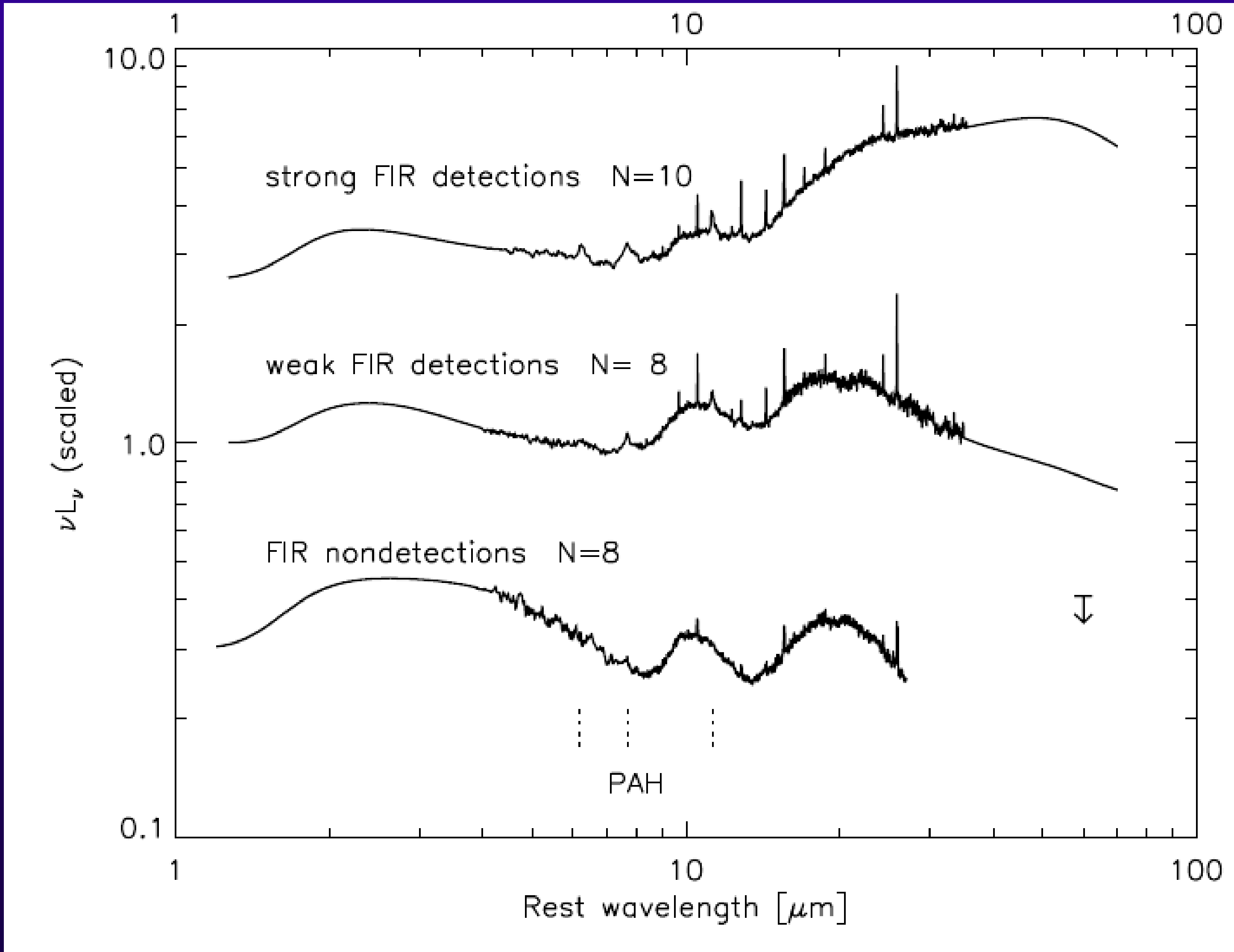




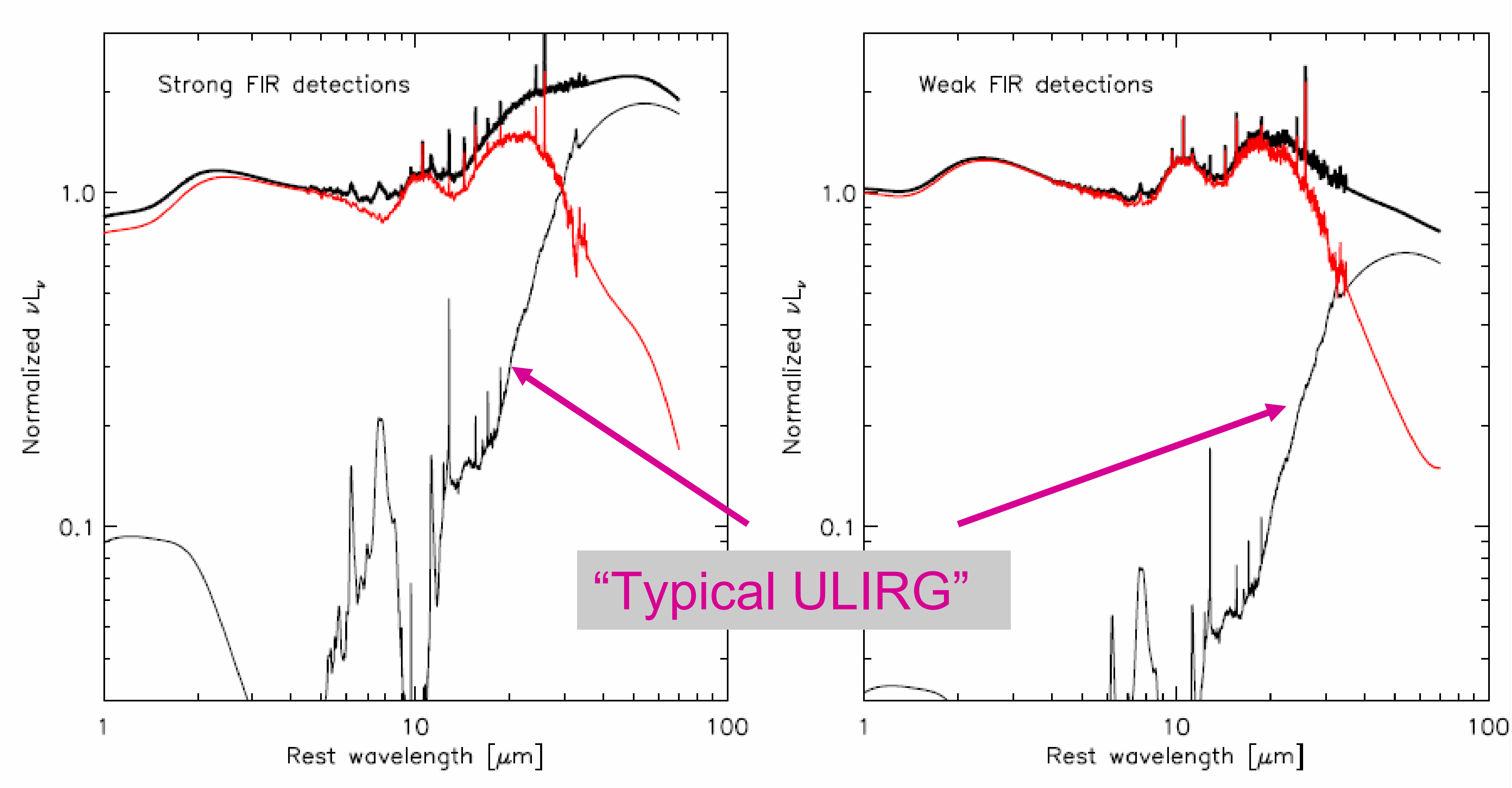
Netzer et al. 2007

29 PG QSOs

Weak and strong FIR emitters



The "intrinsic" torus spectrum



The NLR - 5

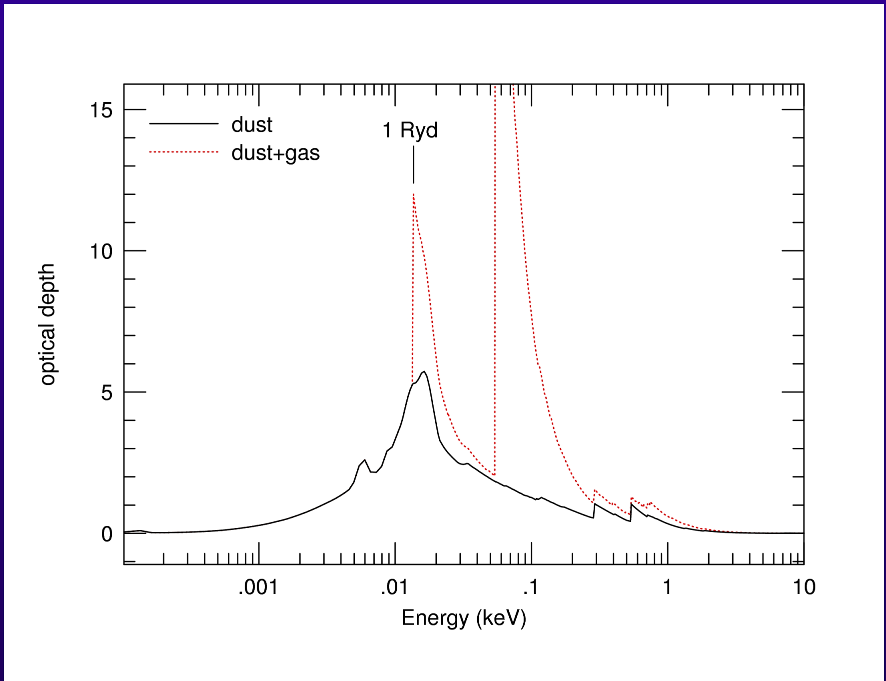
- Dust
  - Sublimation distance
  - The BLR radius
  - The physics of dusty ionized clouds

Let There Be Dust !

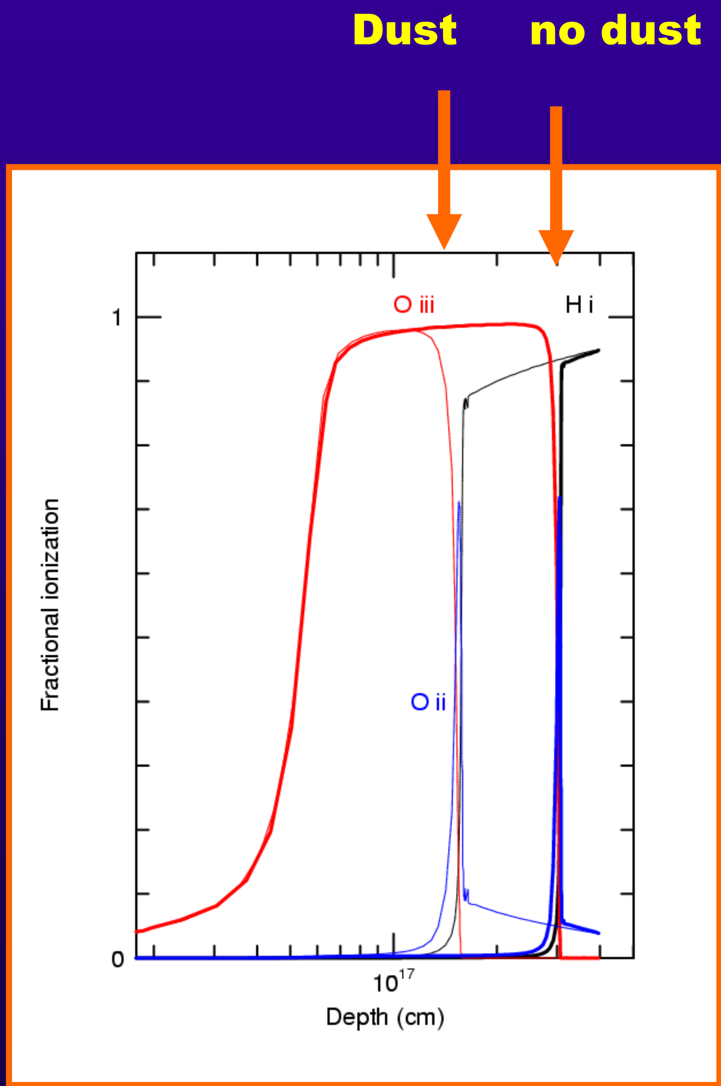
$$r_{sub\,\lim} \cong 0.5 L_{46}^{1/2} \;\; pc$$

$$r_{BLR} \approx 0.3 L_{46}^{0.65} \;\; pc$$

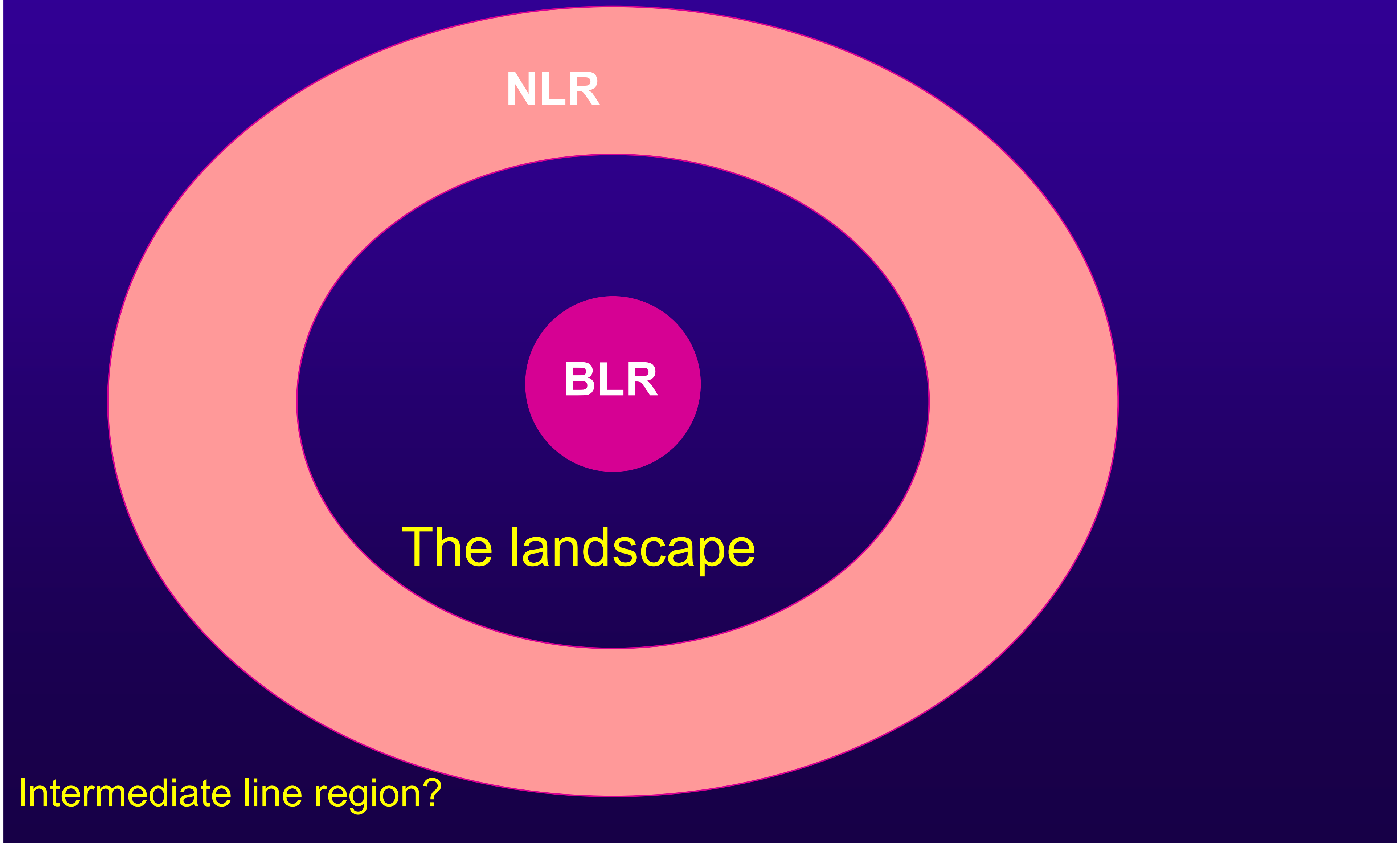
Absorption cross section and modified level of ionization



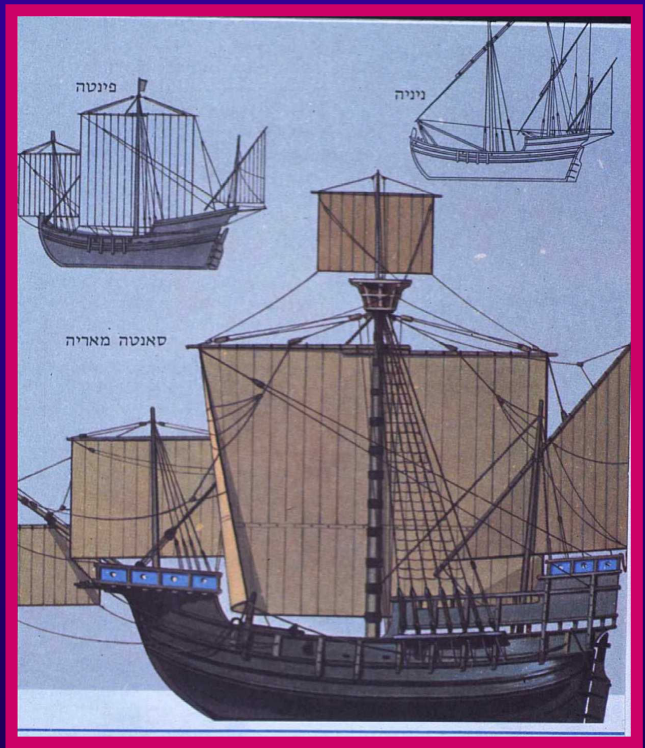
$$\frac{\tau(dust)}{\tau(gas)} \propto \frac{N_{dust}}{N_{H^0}} \propto \frac{N(H^+)}{N(H^0)} \propto U(hydrogen)$$



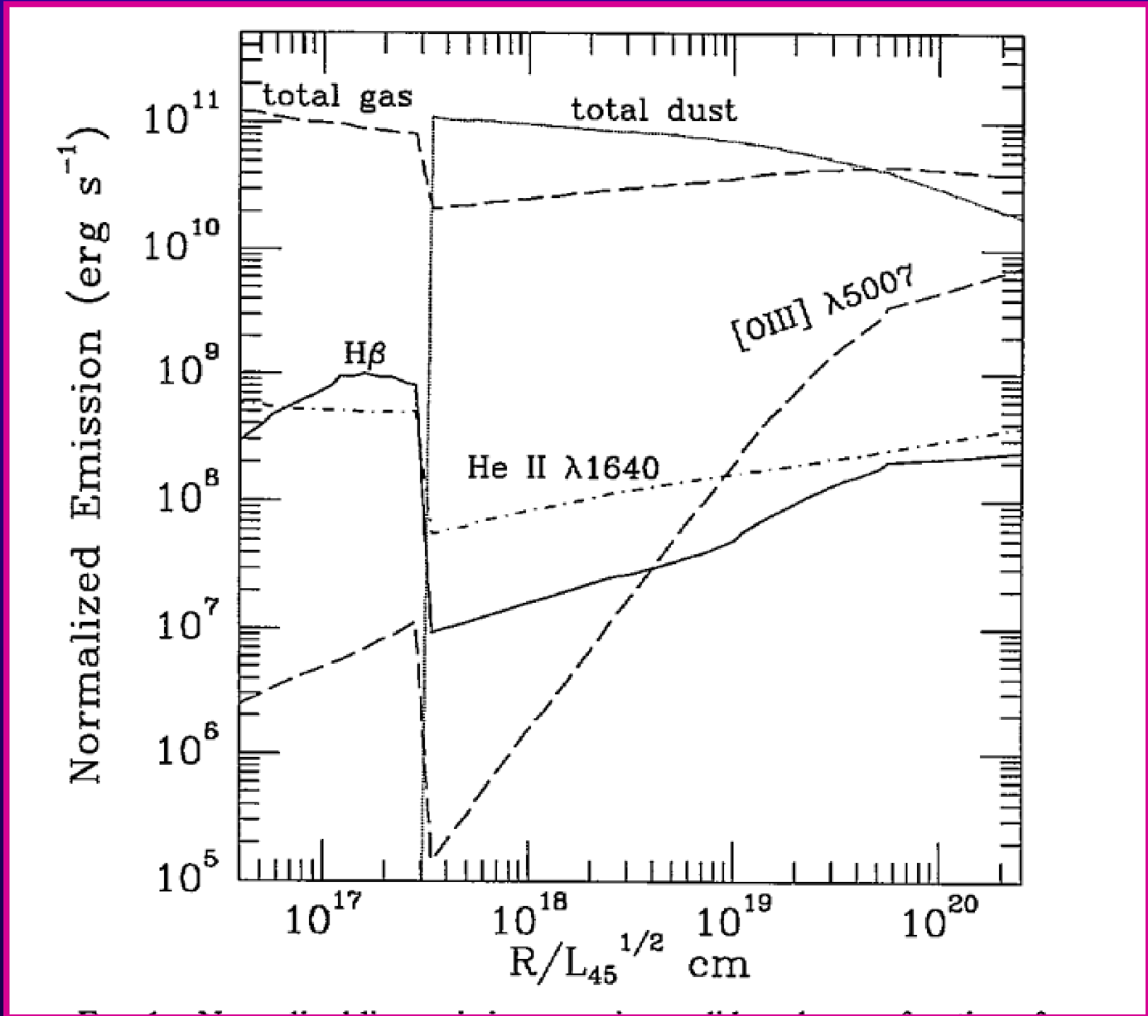
Dust outside the BLR



Let There Be Light



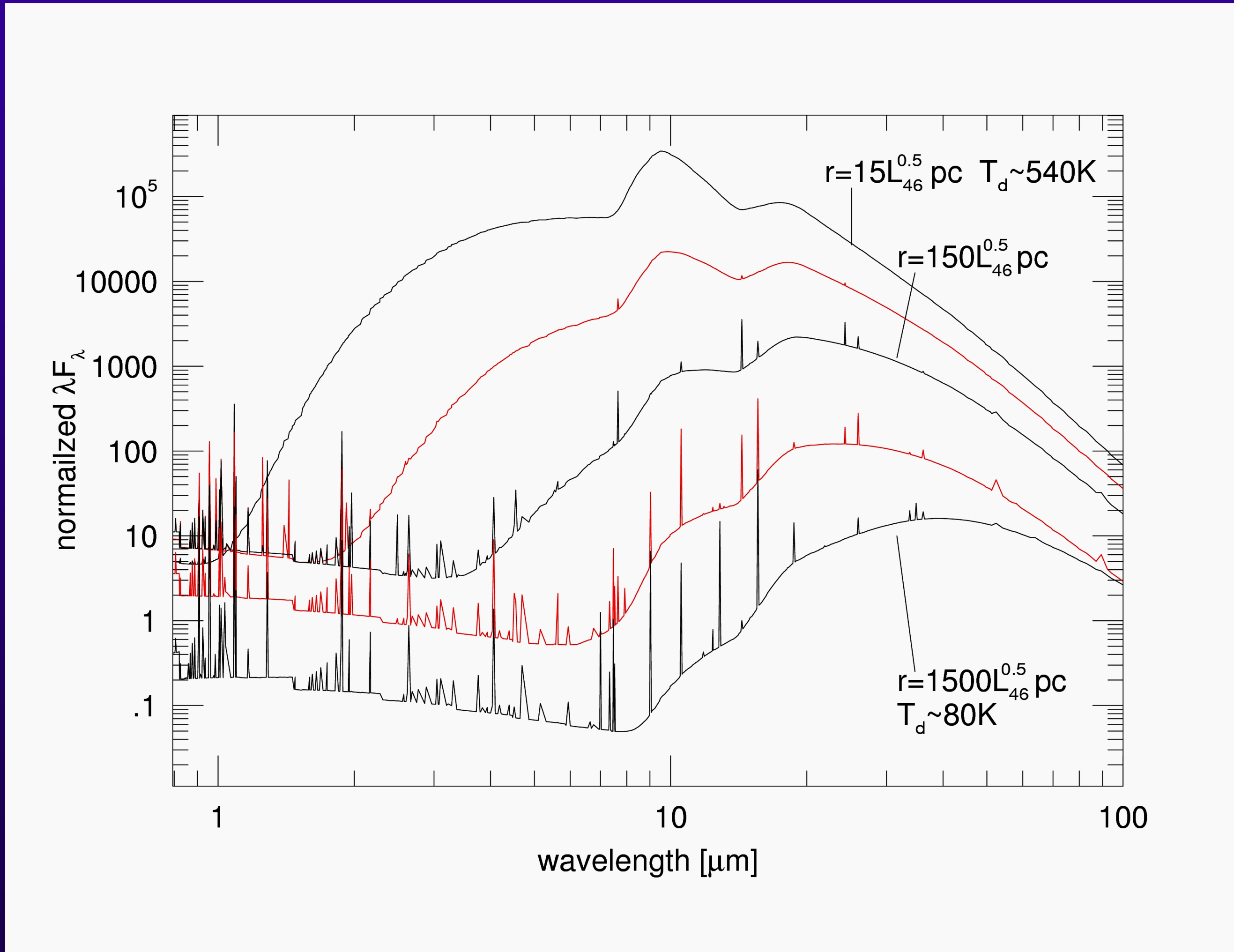
Dust outside the BLR



Intermediate line region?

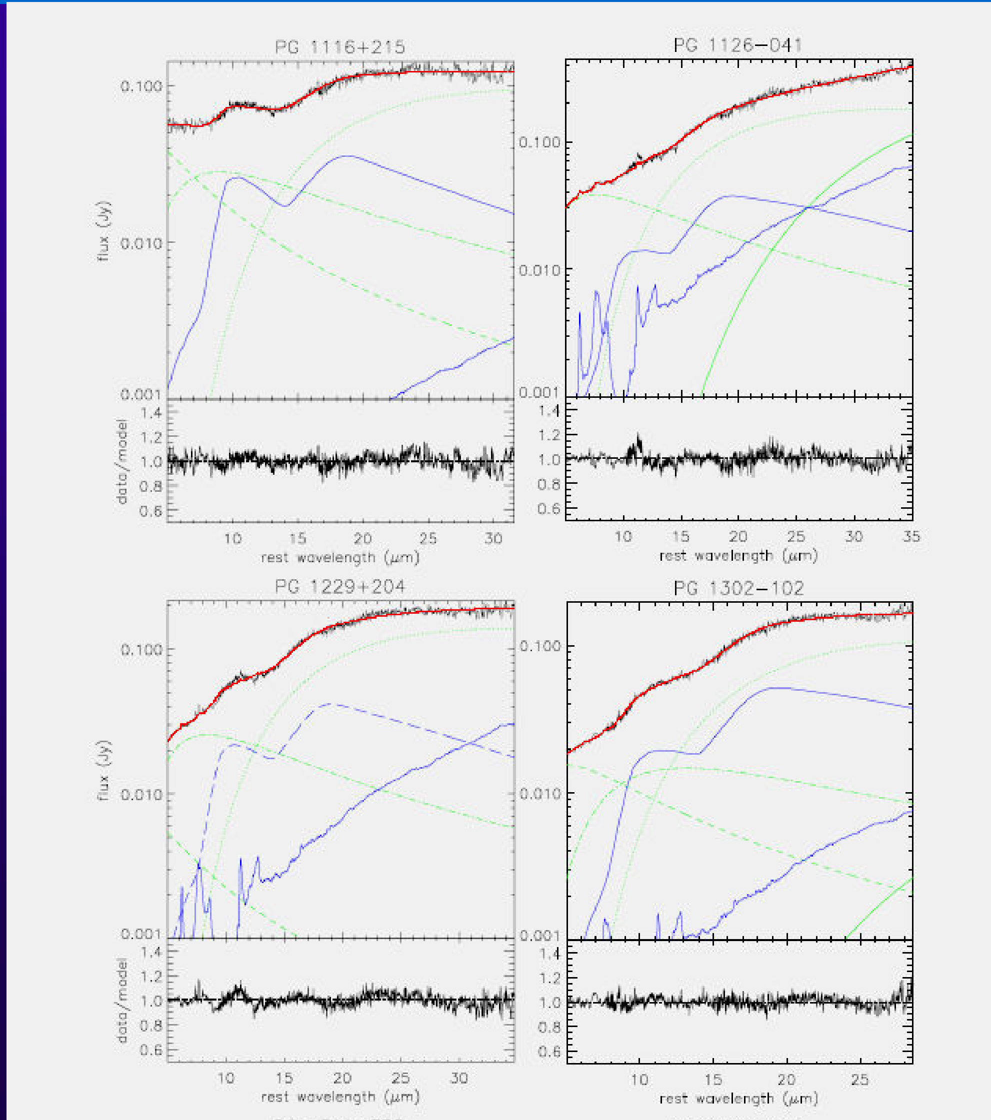
Netzer and Laor 1993

Dust outside the BLR



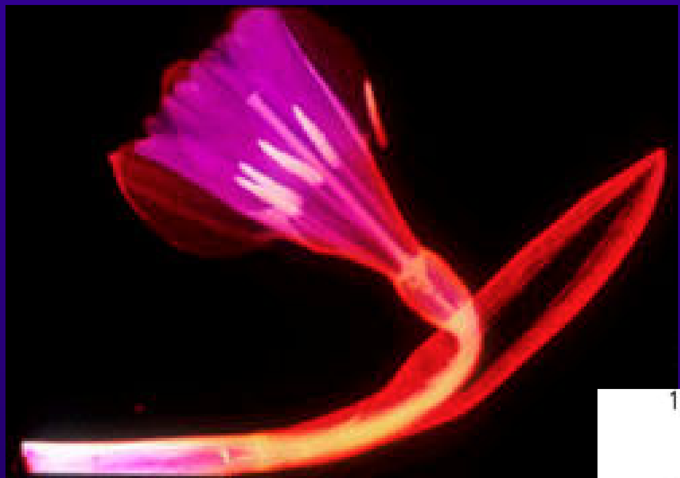
Intermediate dust (silicate) emission region?

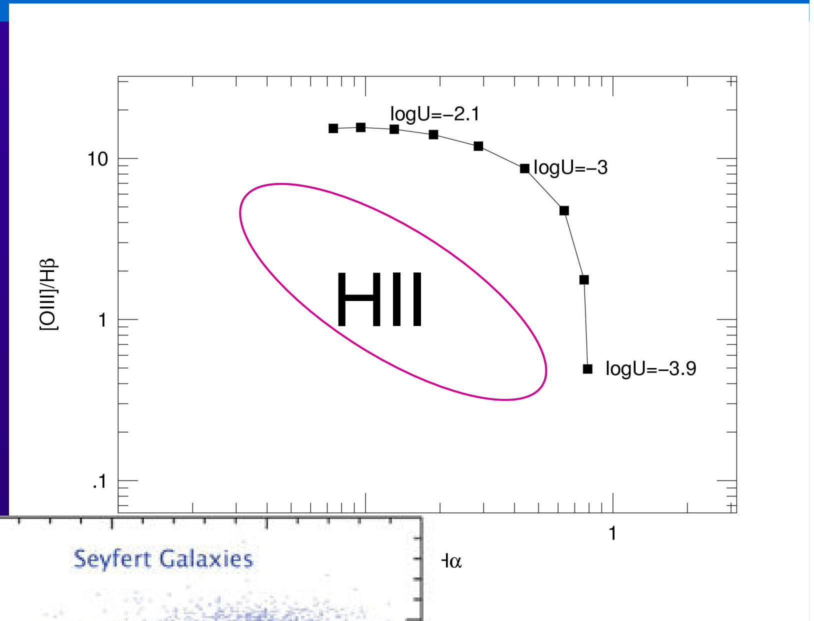
Silicate emission from the NLR

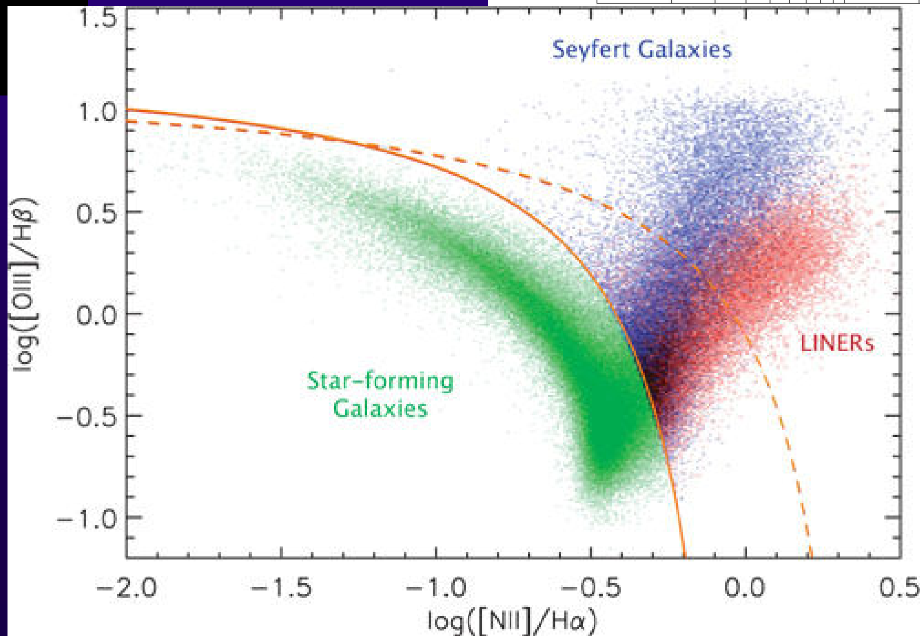


Schweitzer et al. 2007

Diagnostic diagrams







Ionized gas in Active Galactic Nuclei

Hagai Netzer
School of Physics and Astronomy
Tel Aviv University

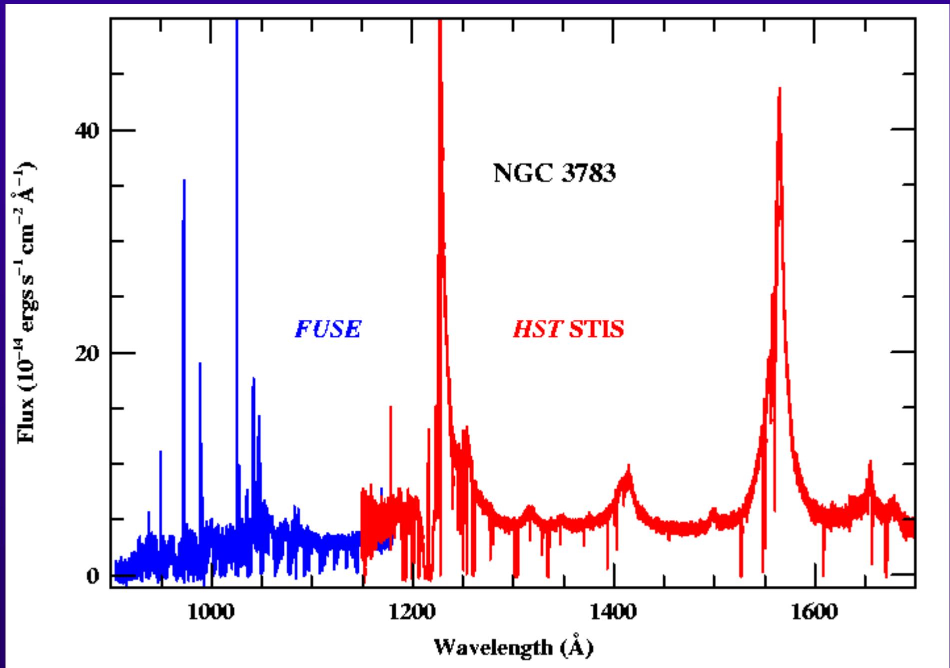
- Basic AGN Observations
- Physical processes in AGN
  - Photoionization
  - The spectrum of ionized gas
  - The motion of ionized gas
- Main AGN components
  - The broad line region (BLR)
  - The narrow line region (NLR)
  - Highly ionized gas (HIG)

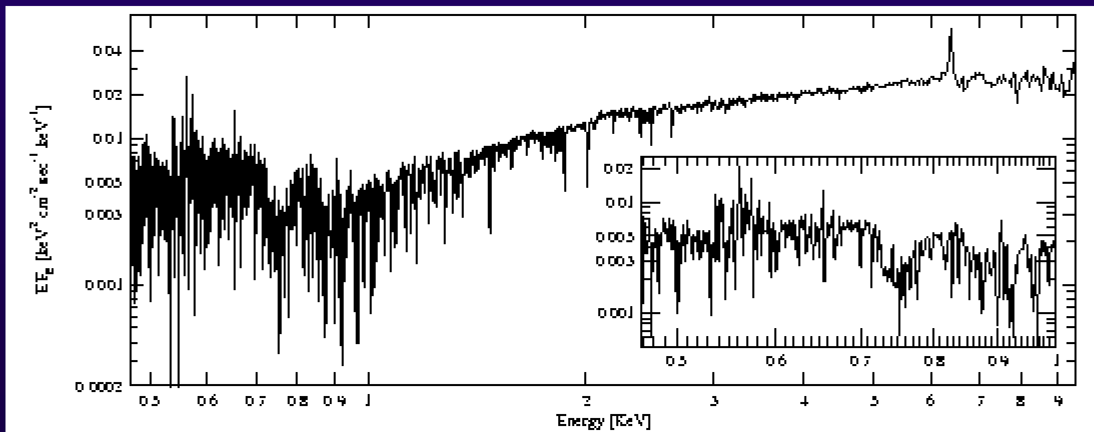
Energy

Landscape

Time

Evidence for outflows in AGNs





Chandra: Kaspi et al. (2002)
HST: Crenshaw et al. (2002)
FUSE: Gabel et al. (2002)

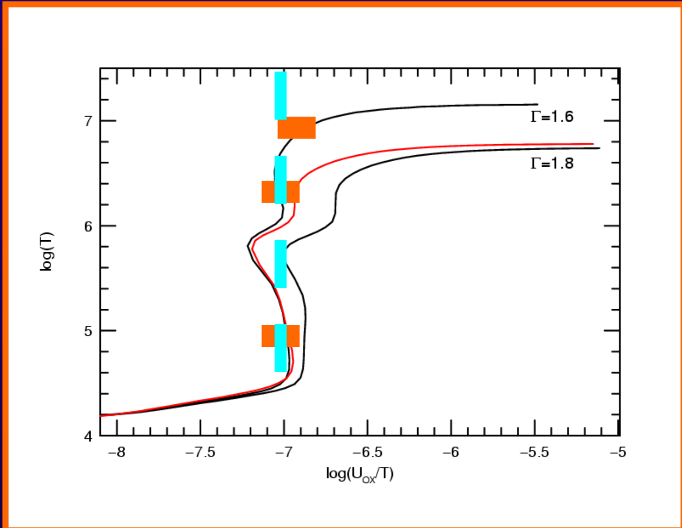
The highly ionized gas (HIG) - 1

- Assumed clouds
  - Density 10^{3-5} cm^{-3}
  - Large and small column density
  - Location ~1 pc
  - Radial distribution
  - Confinement?
  - Covering factor (absorption?, emission?)

$$U = \int_{E_1}^{E_2} \frac{(L_E / E)\, dE}{4\pi r^2 c N_H}$$

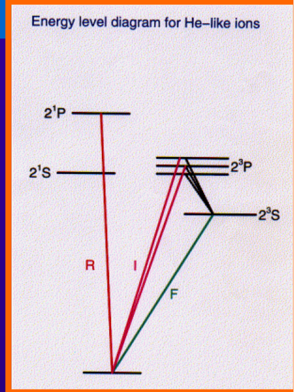
U_{OX} (E_1=0.54 keV, E_2=10 keV)

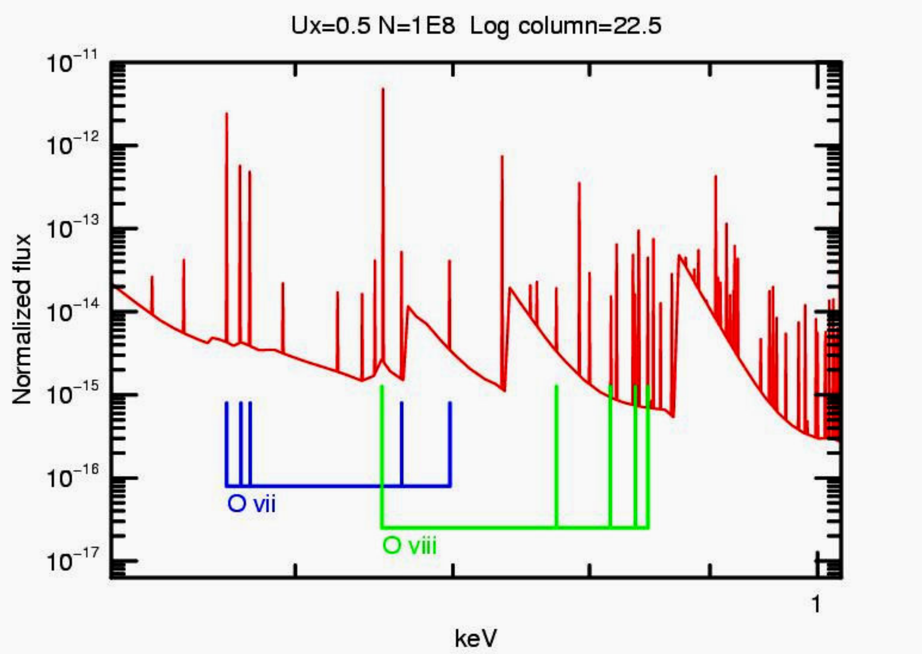
U_{OX} = 0.1 - 1

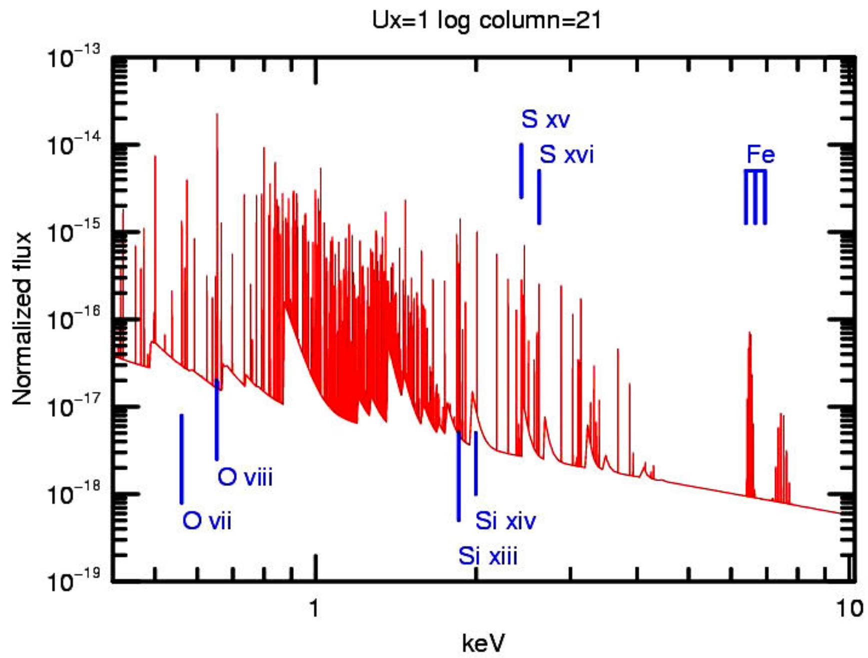


The HIG – 2: X-ray spectra

- Absorption
- Emission
- Reflection







The HIG – 2: X-ray spectra

- Absorption
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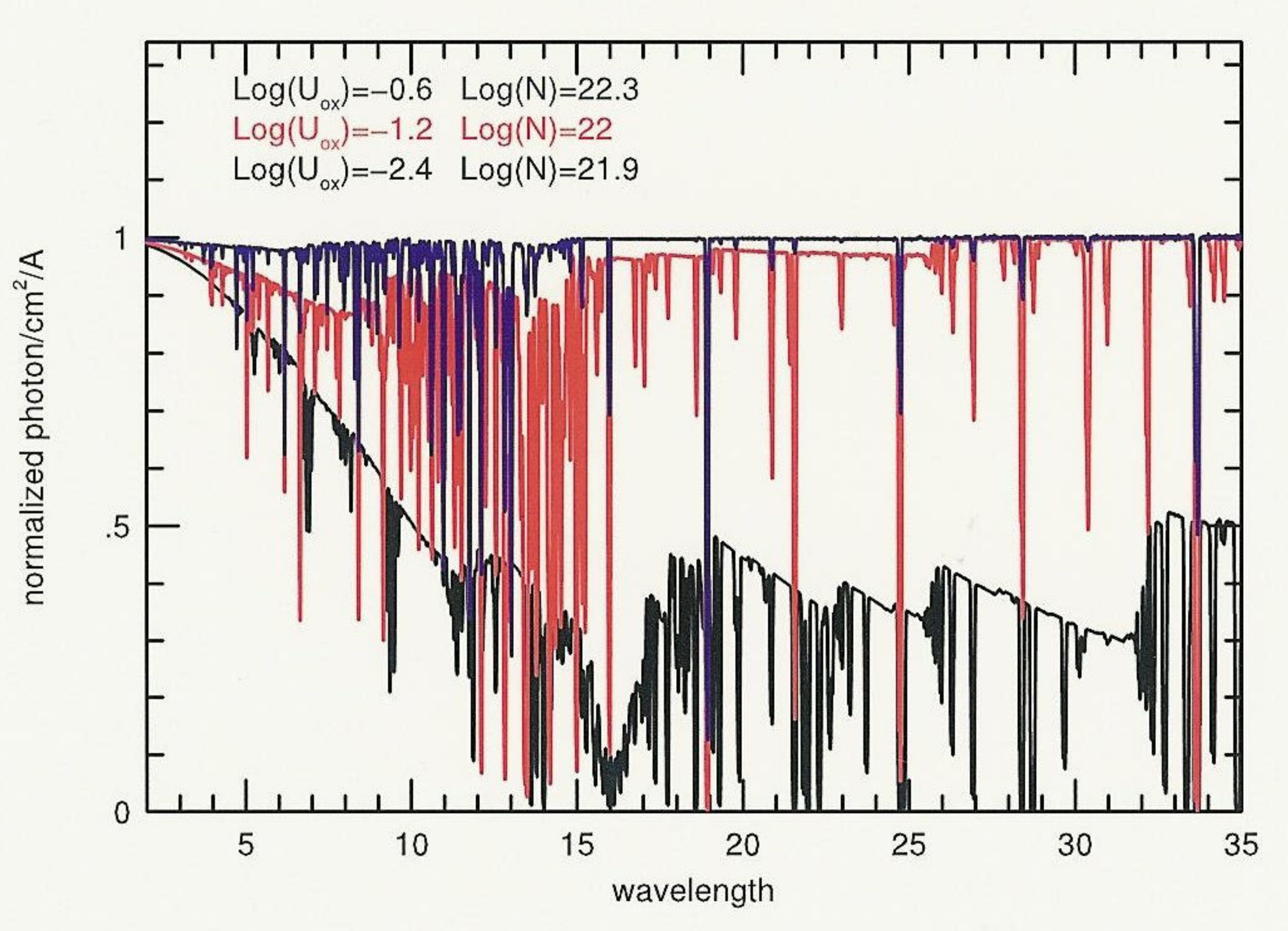
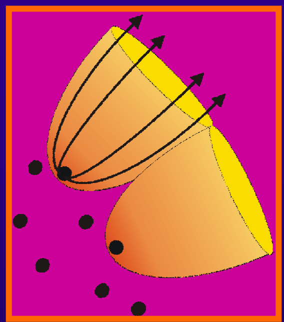
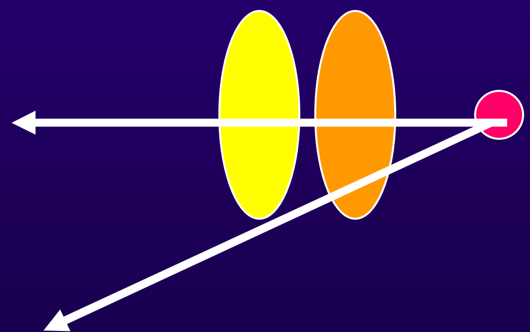


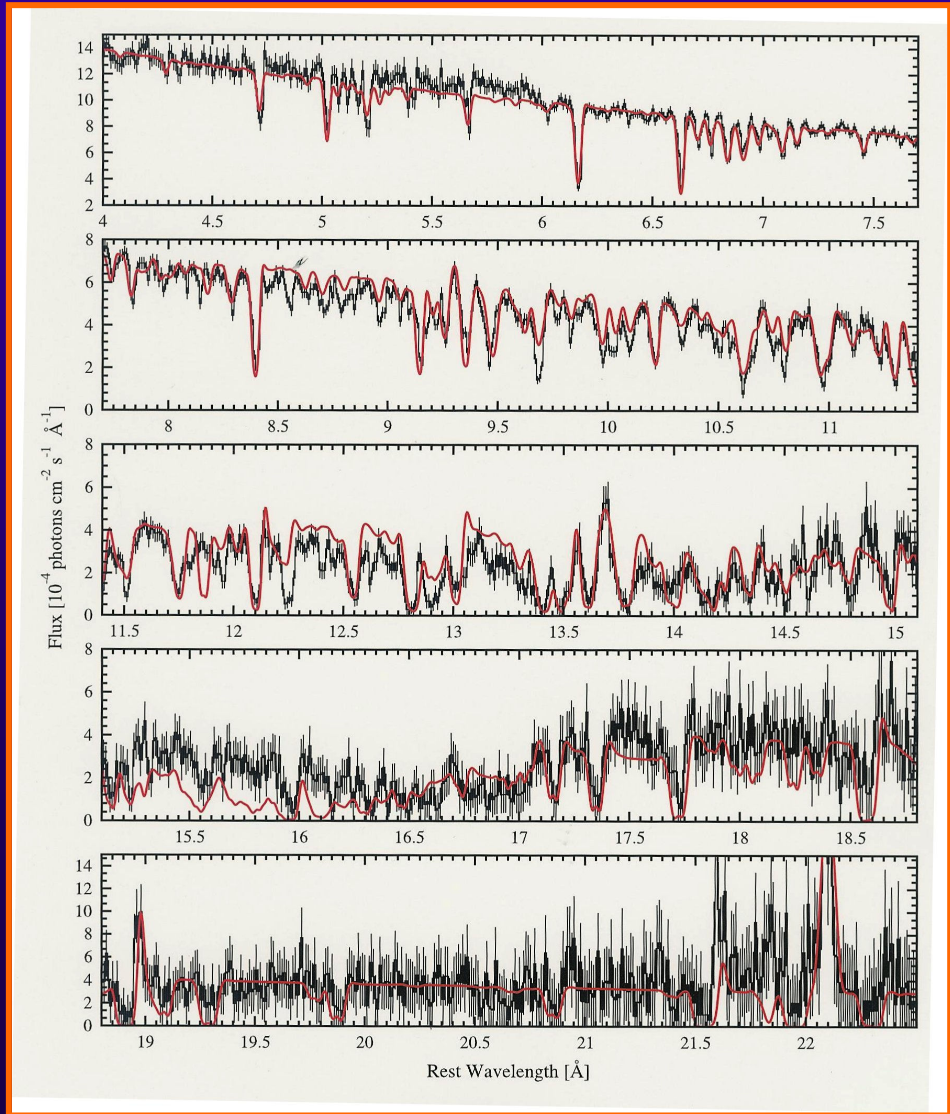
The Torun connection

The HIG - 3

- The HIG spectrum
- The HIG mass





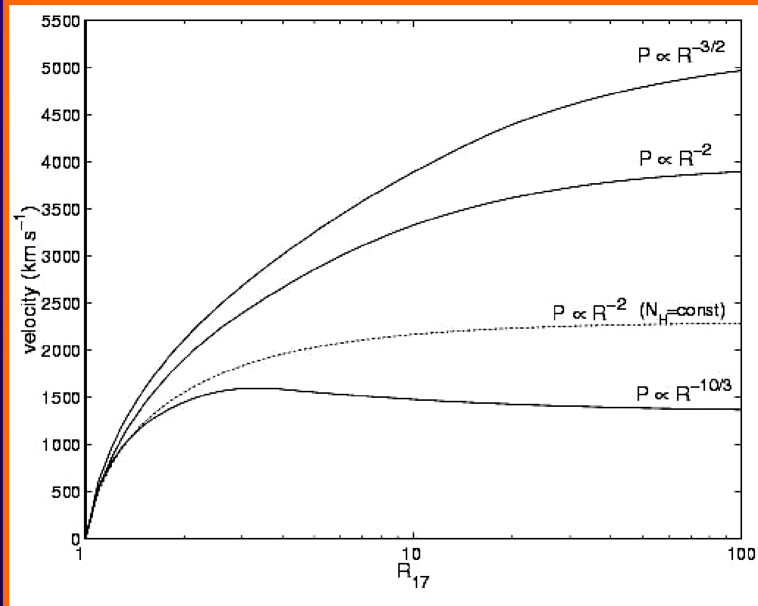


The motion of ionized gas

- The equation of motion
  - Gravity - g(r)
  - Radiation pressure - $a_{rad}(r)$
  - Drag force (cloud) - f_d
  - Pressure gradient

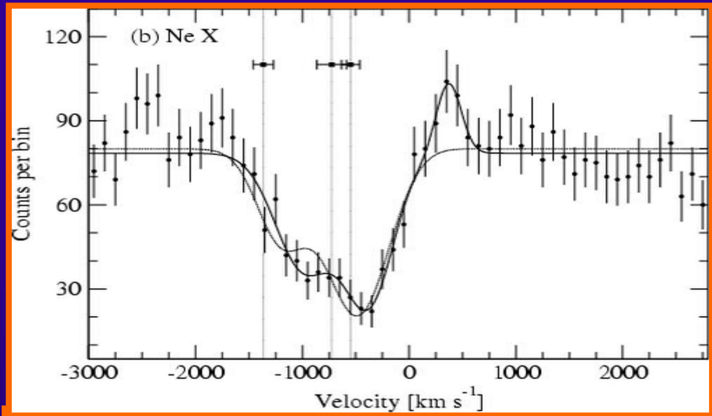
$$a(r) = a_{rad}(r) - g(r) - \frac{1}{\rho}\frac{dP}{dr} + \frac{f_d}{M_c}$$

$$a_{rad} = \frac{N_x}{c\rho(r)} \int_{\nu_x}^{\infty} \frac{(L_\nu / h\nu)\sigma_\nu e^{-\tau_\nu} d\nu}{4\pi r^2} = \left[\frac{N_x}{c\rho(r)}\right] I_x$$

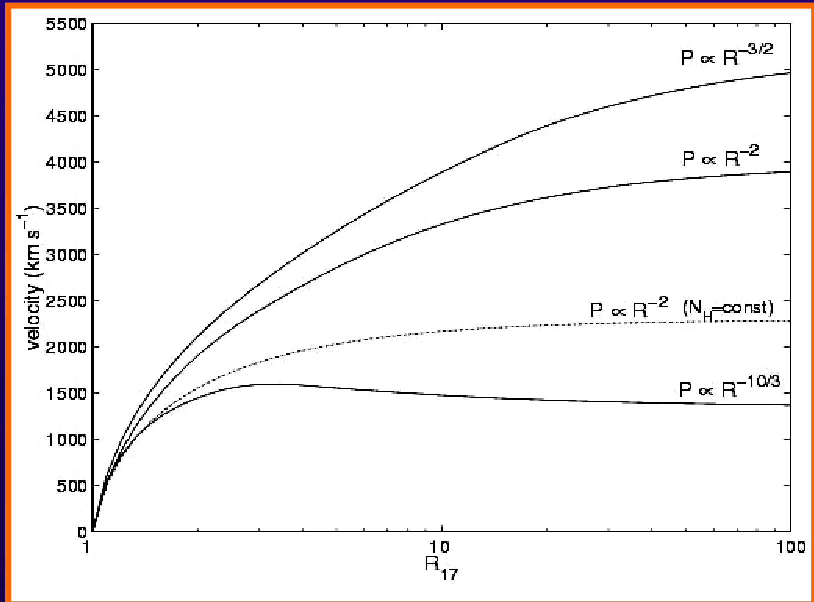


The HIG - 4

- The motion of the HIG
  - radiation pressure acceleration
  - outflow
    - clouds
    - winds
  - Mass outflow rate



Kaspi et al. 2002

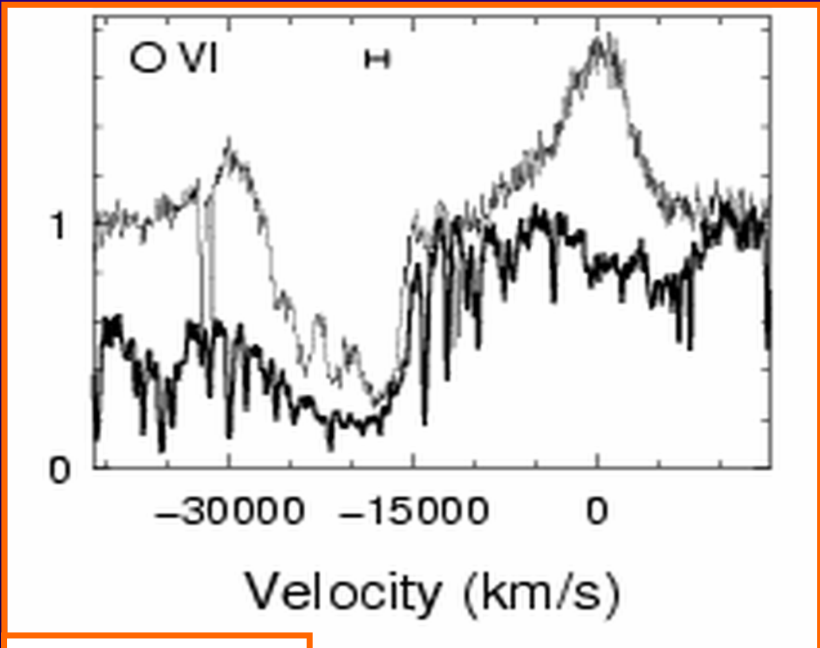


For more information

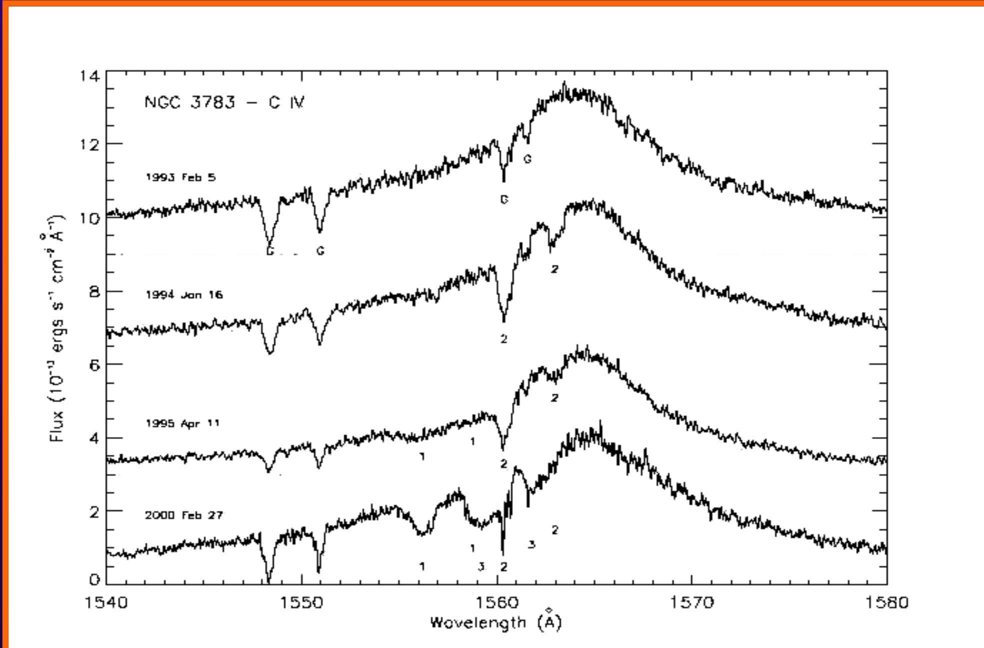
see A. King lectures

UV absorbers

- Associated absorbers
  - Column density
  - Mass outflow rate
  - Association with X-ray absorber
- BAL



Korista et al. 1993



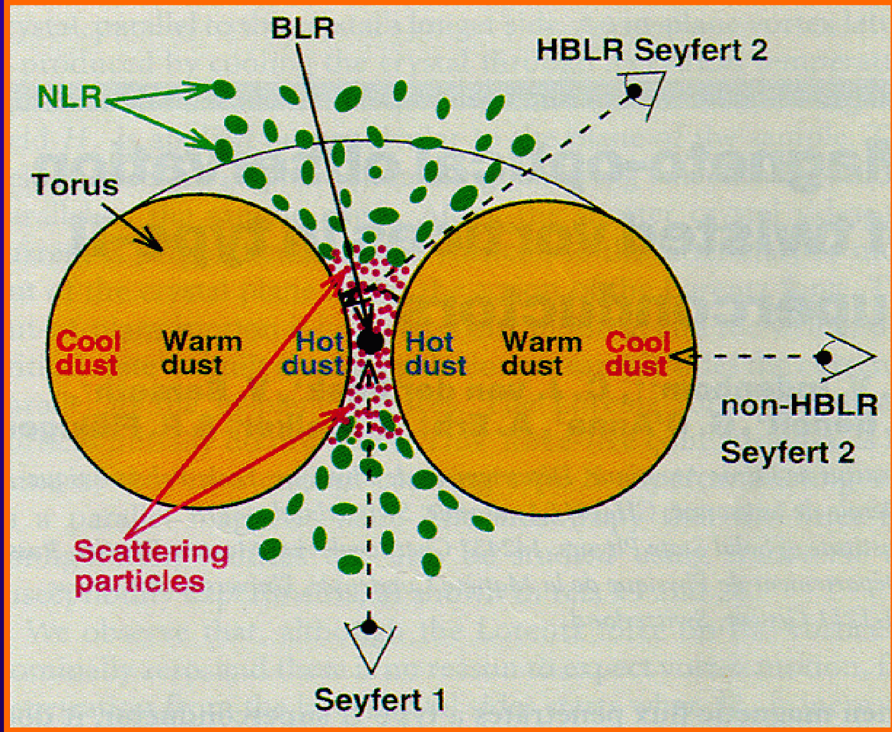
Photoionized gas – where else

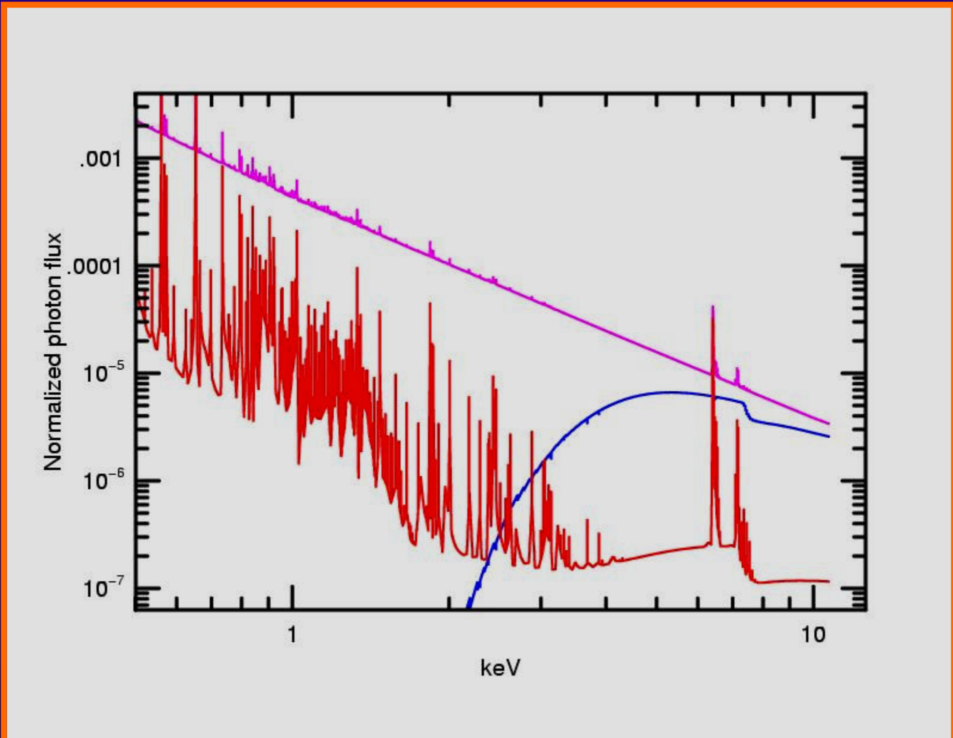
Component	Location	Density
Disk	10^{-3} pc	10^{15}
BLR	0.1 pc	10^{10}
HIG	1-10 pc	$10-10^{5}$
Torus	**~1 pc**	**10^{3-6}**
NLR	300 pc	10^{3-4}
The starburst	~1 kpc	1-10

The HIM and the torus

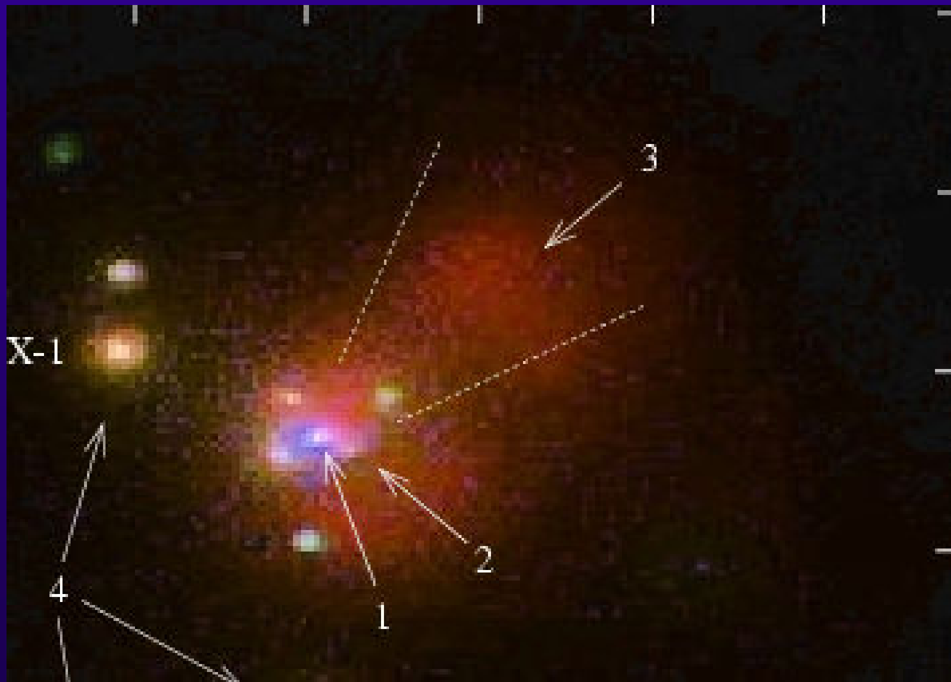
The X-ray emitting region

Compton-thick gas



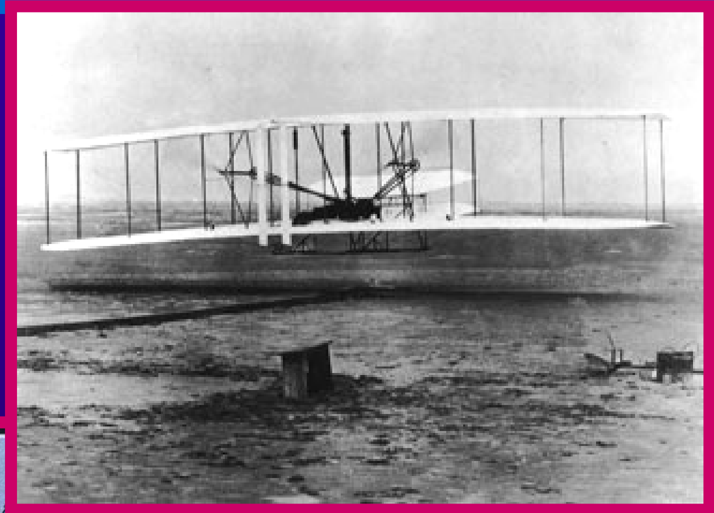


HIG in Seyfert 2s



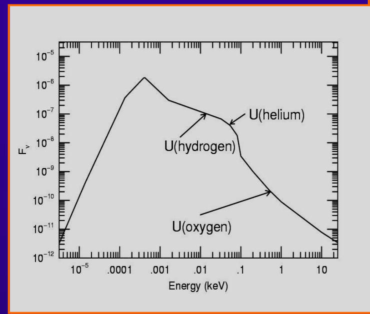
Circinus

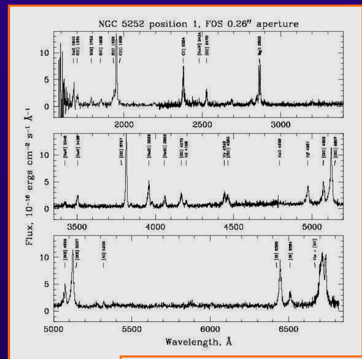
Scientific (astronomical) explorations

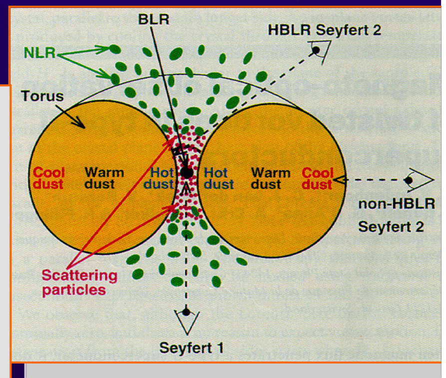


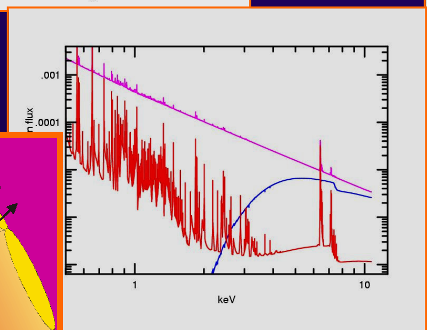
Landscape exploration

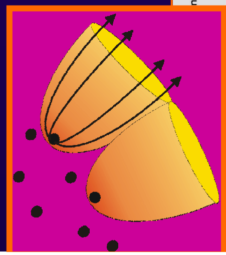
AGN exploration

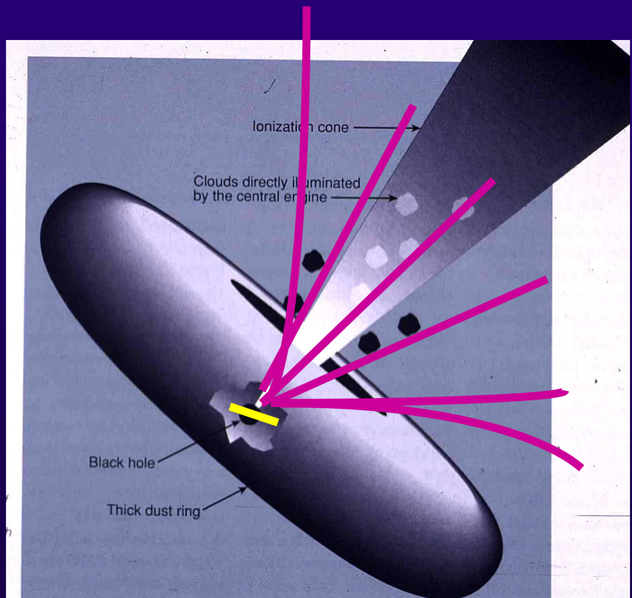






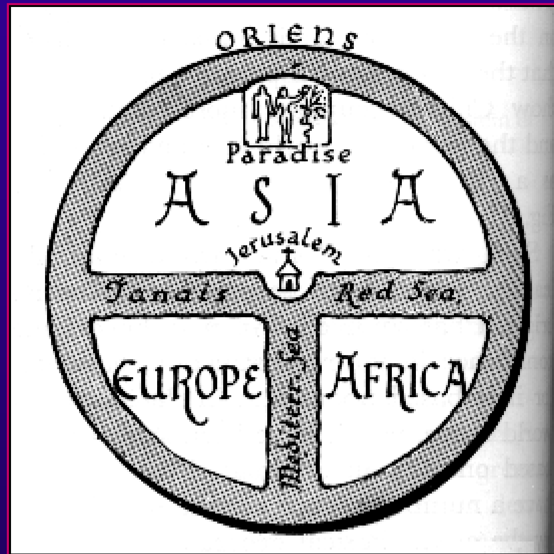






Ionized gas in Active Galactic Nuclei

- It is about energy
- It is about landscape exploration
- It is about time



Torun, August 2007