The Physics and Evolution of Active Galactic Nuclei

Beijing September 2011

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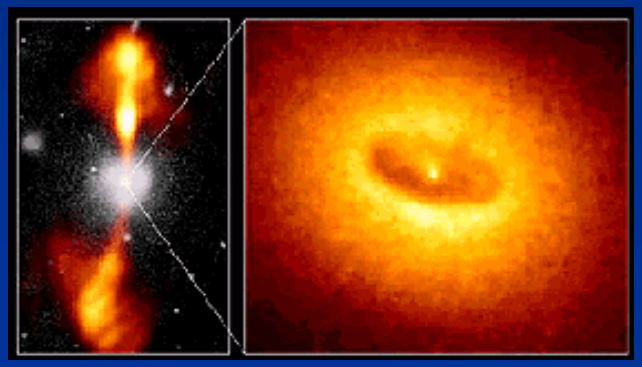
- Observations of AGNs
- Black holes and accretion physics
  - Black holes (BHs)
  - Accretion disks
- Physical processes
  - The physics ionized gas
  - The motion of ionized gas
  - Dust and extinction
- Main components of AGNs
  - The BLR and the NLR
  - BH mass
  - Highly ionized gas
  - Central obscuration
  - Accretion disk

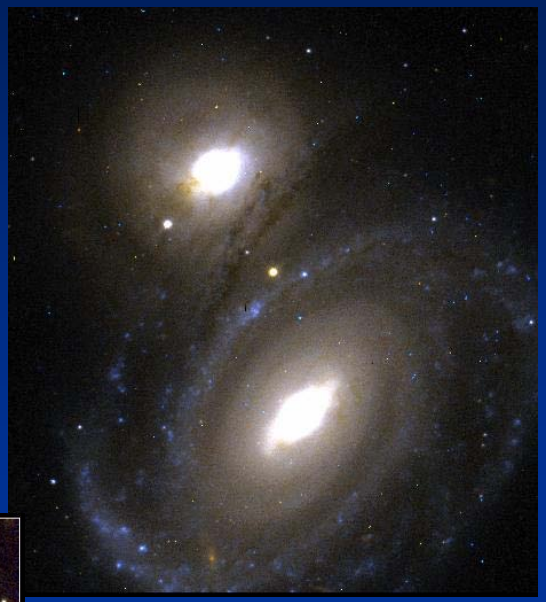
Observations of AGNs: 1

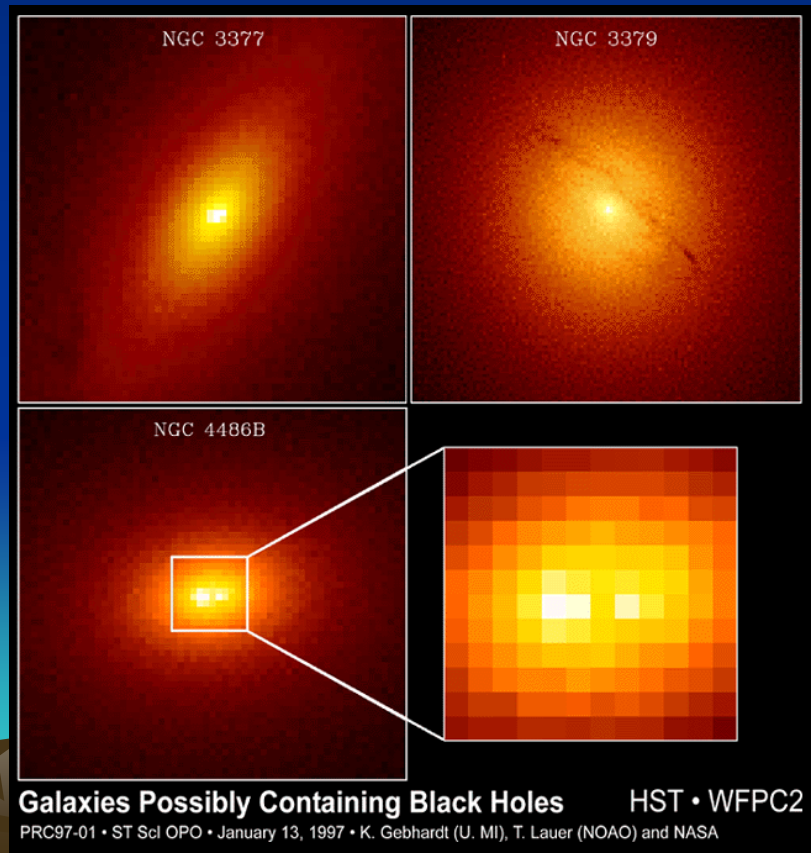
Basic observations and general definitions

- Optical observations
- IR observations
- X-ray observations
- Radio observations
- Gamma-ray observations
- Global SED
- Variability
- Definition of AGNs

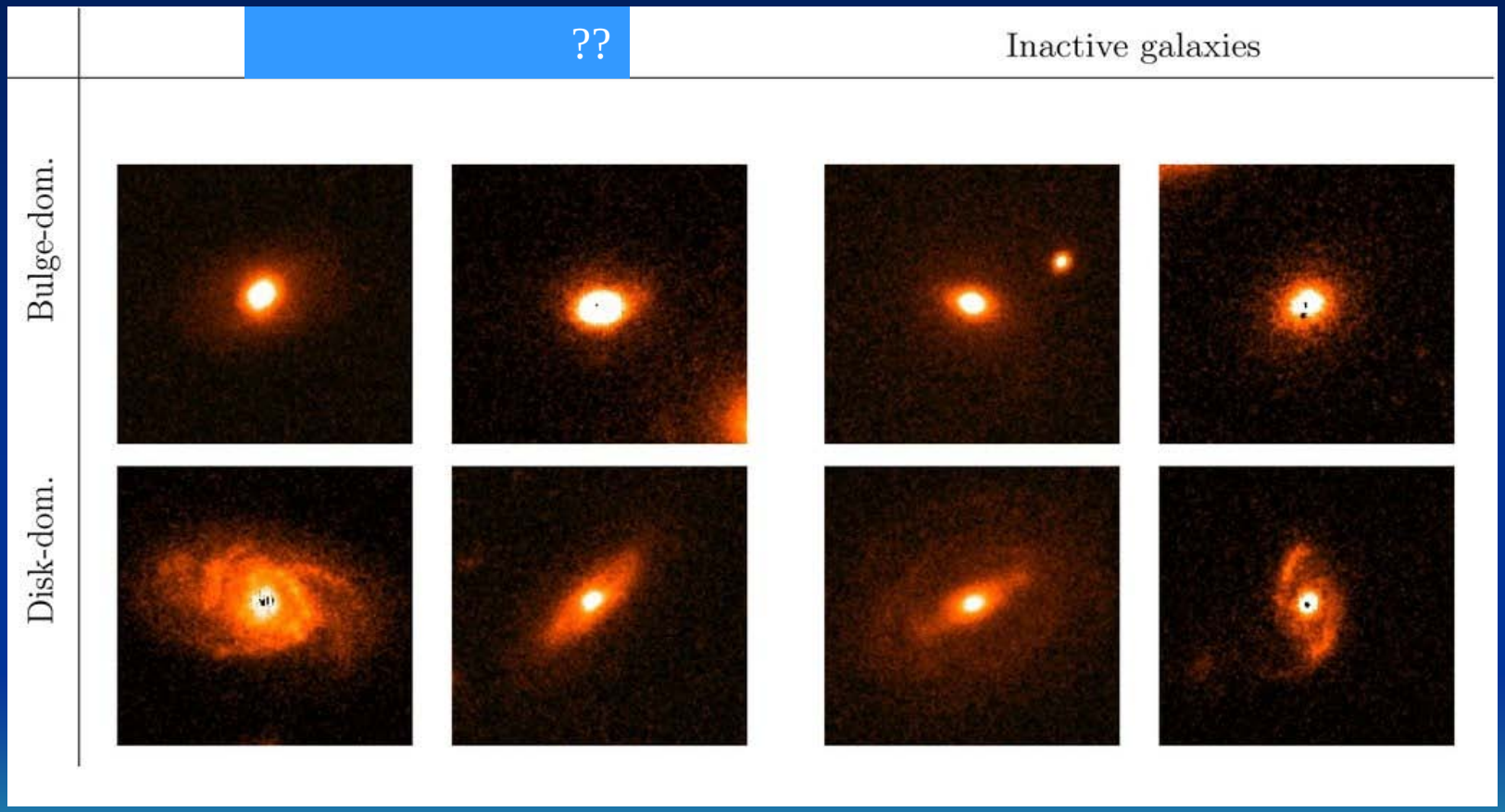


Normal and active galaxies





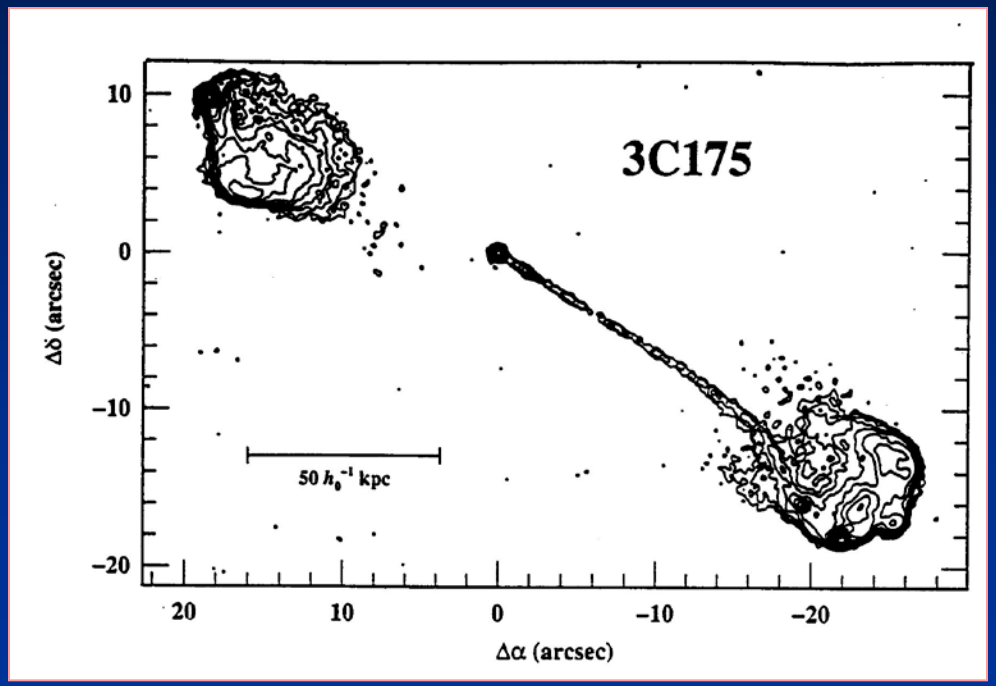
Luminous AGNs and their host galaxies



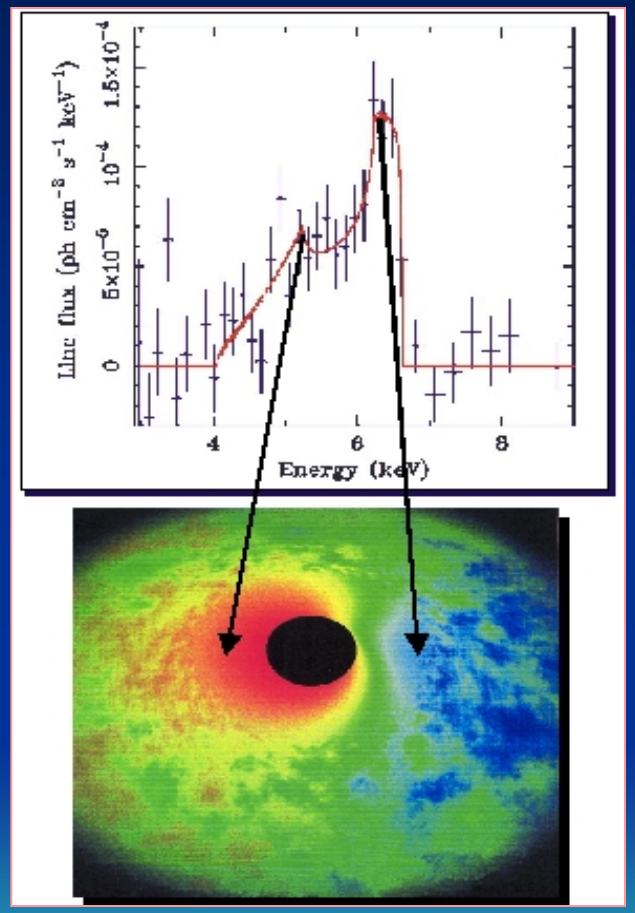
Cisternes et al. 2011

What about very high z AGNs?

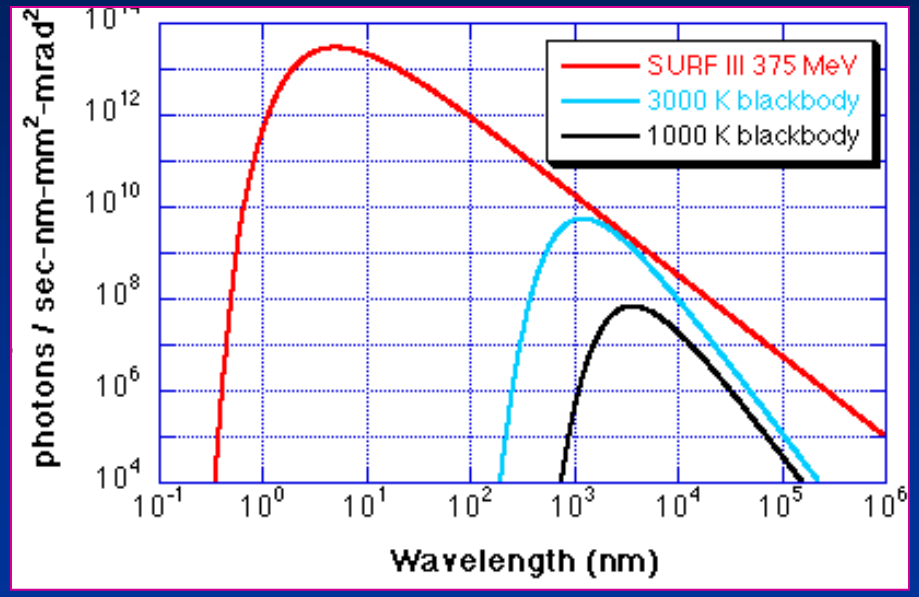
Non-stellar emission

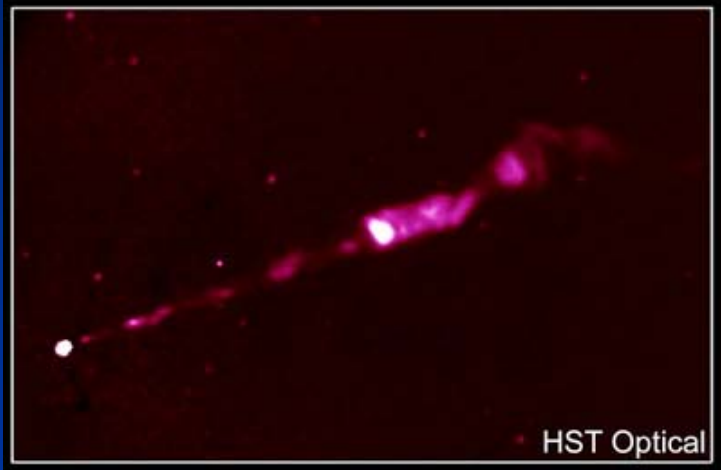


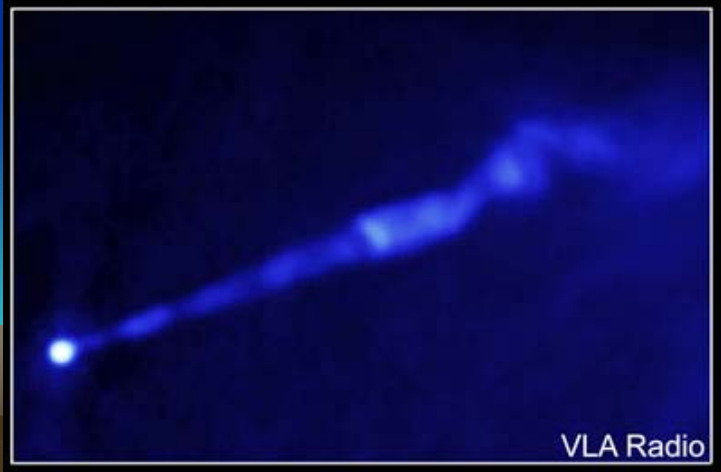
Radio emission



Relativistic effects

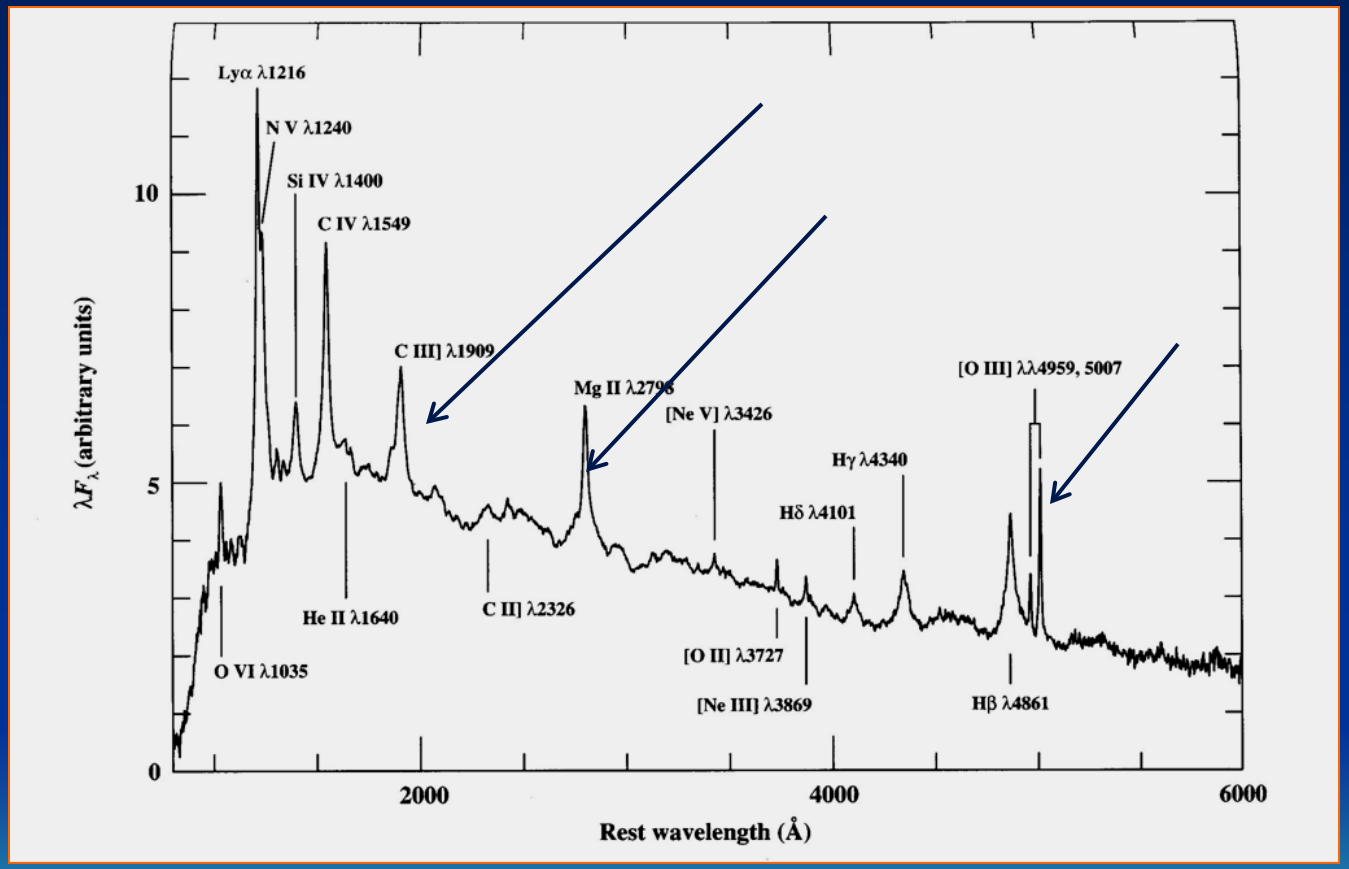






Nonthermal emission

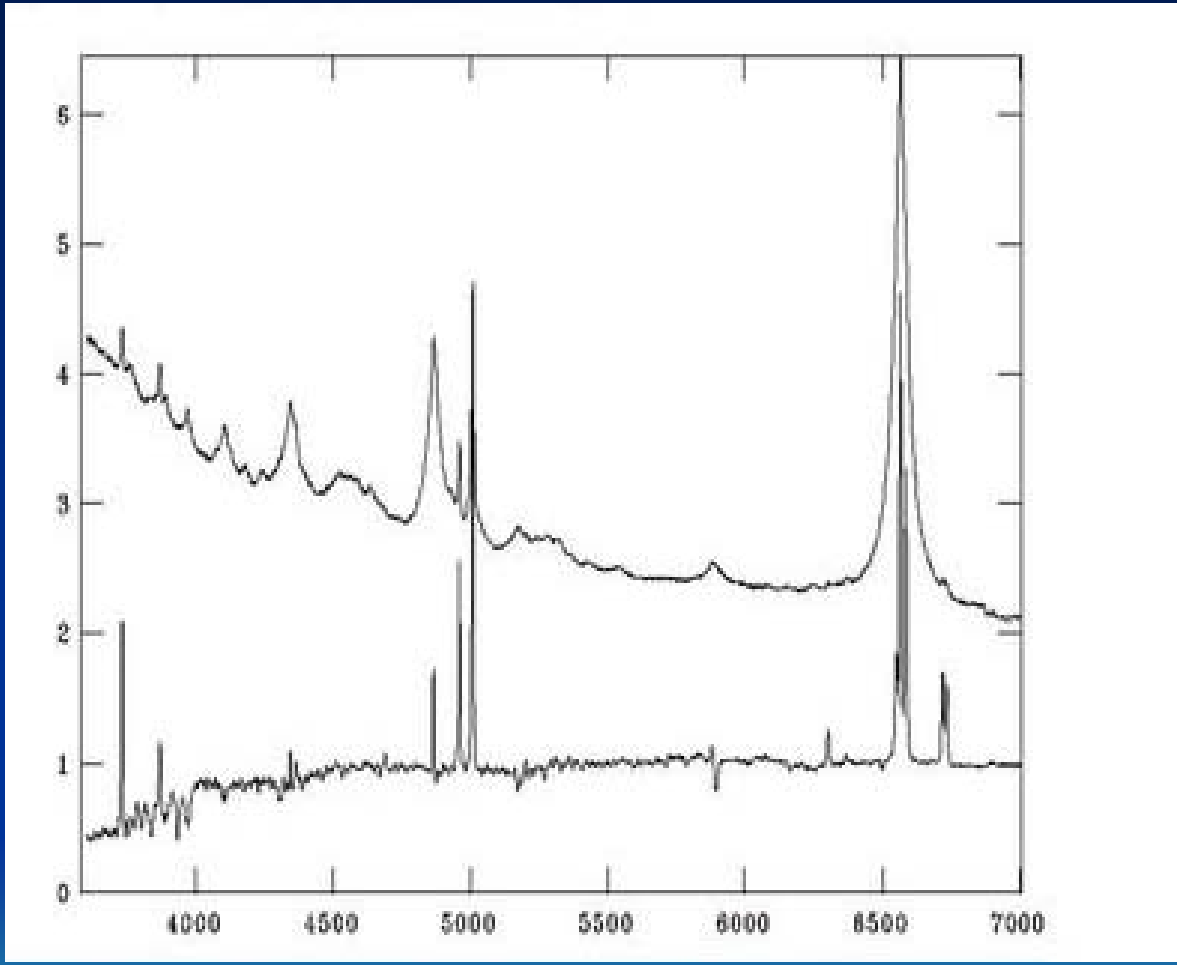
AGN emission lines



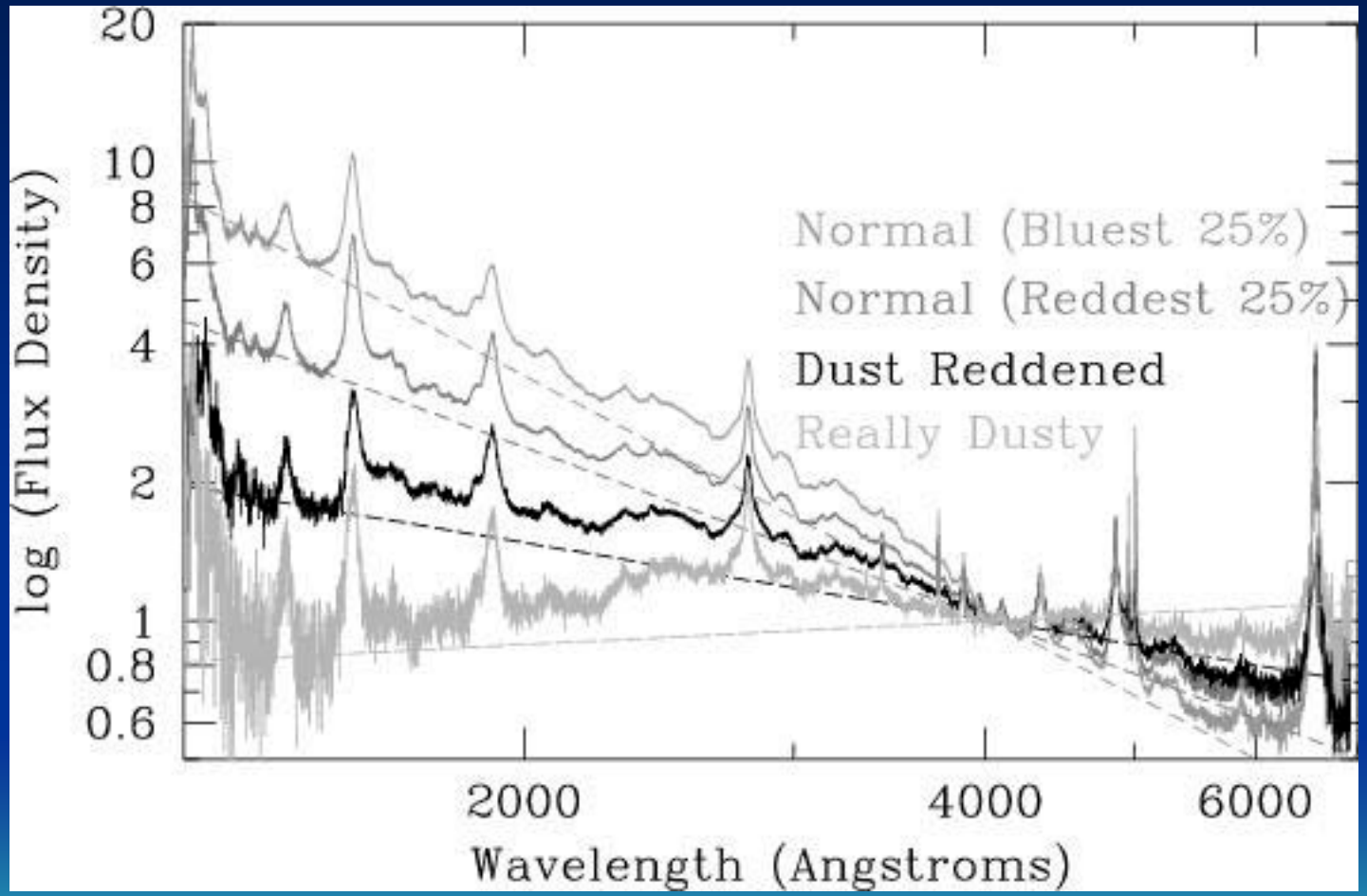
Permitted lines

Forbidden lines

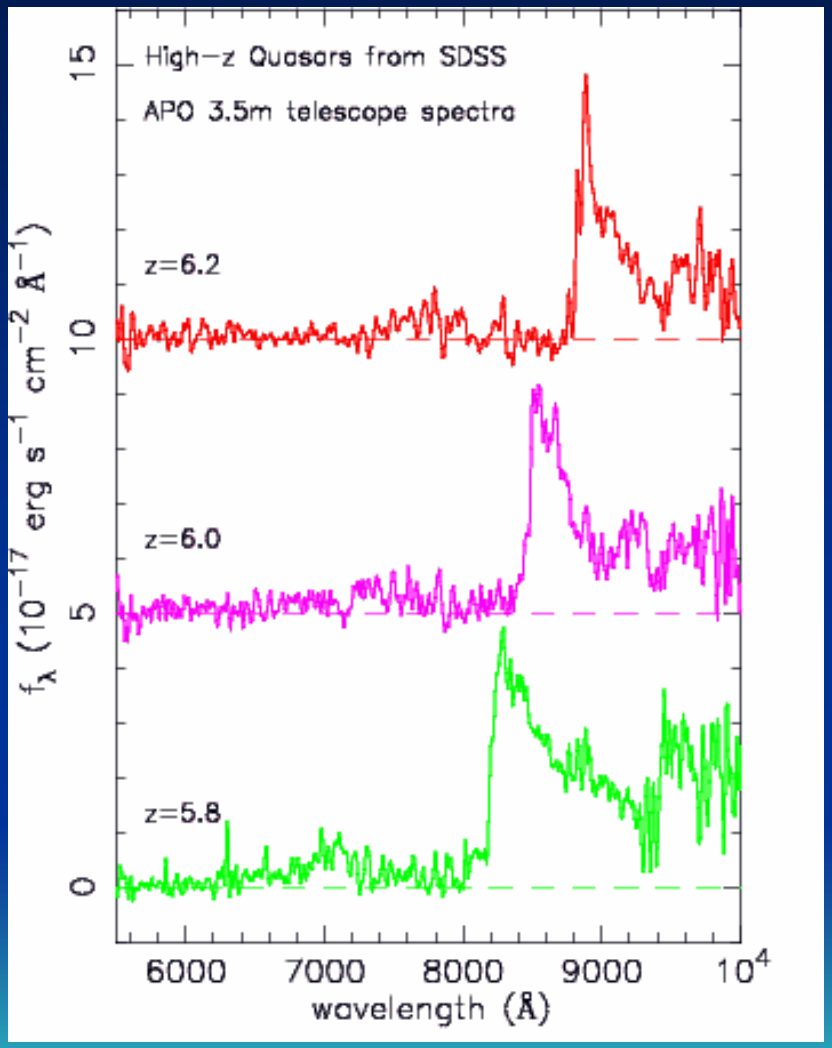
Semi-forbidden lines



Stellar or non-stellar?


20
10
8
6
4
2
1
0.8
0.6
log (Flux Density)
Normal (Bluest 25%)
Normal (Reddest 25%)
Dust Reddened
Really Dusty
2000
4000
6000
Wavelength (Angstroms)

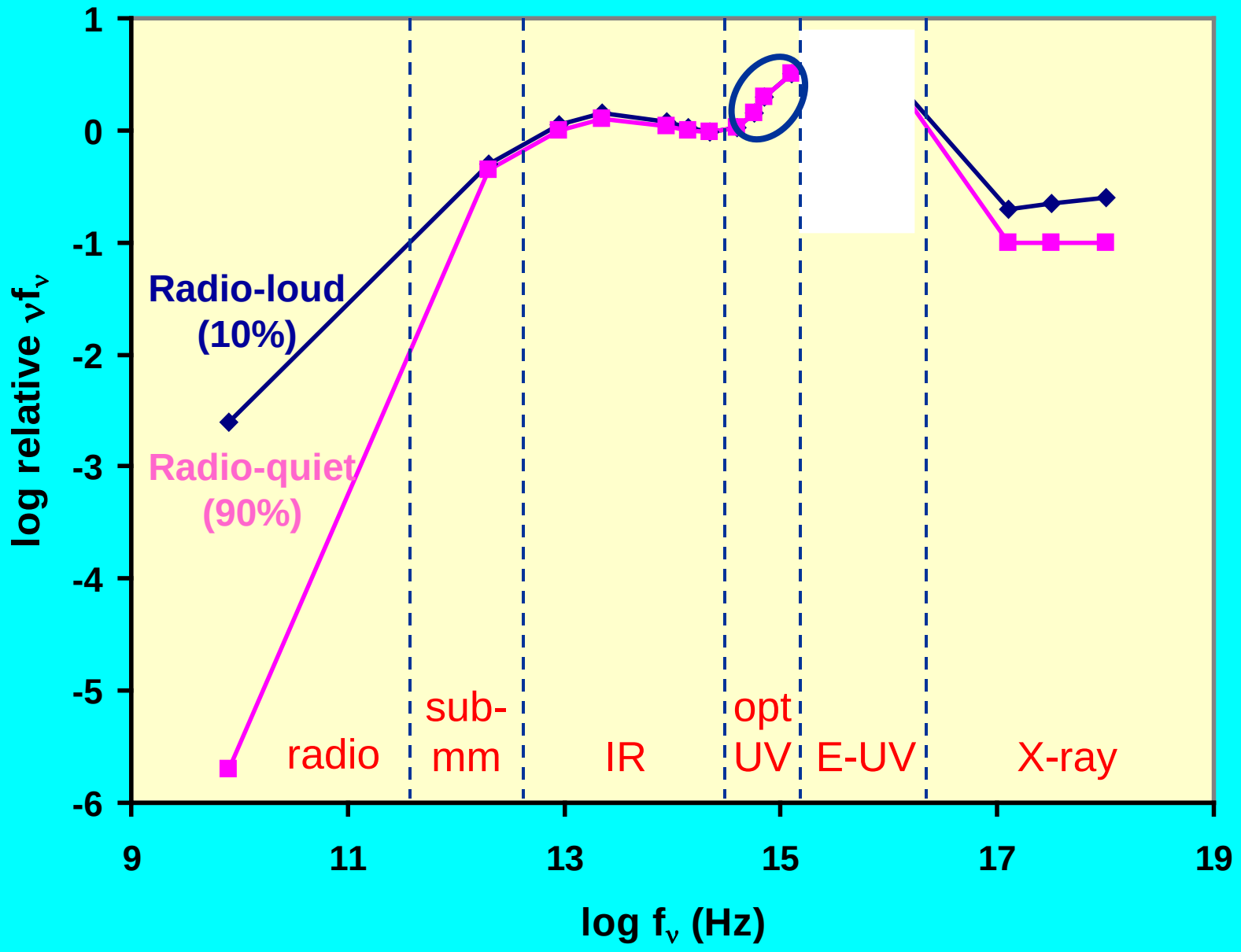
P. Hall et al



SDSS z>5.8 QSOs

Fan et al. 2001

QSO multifrequency spectrum



Basic definitions:
Luminosity and spectral energy distribution - SED

- Monochromatic luminosity
- Bolometric luminosity
- Spectral energy distribution

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

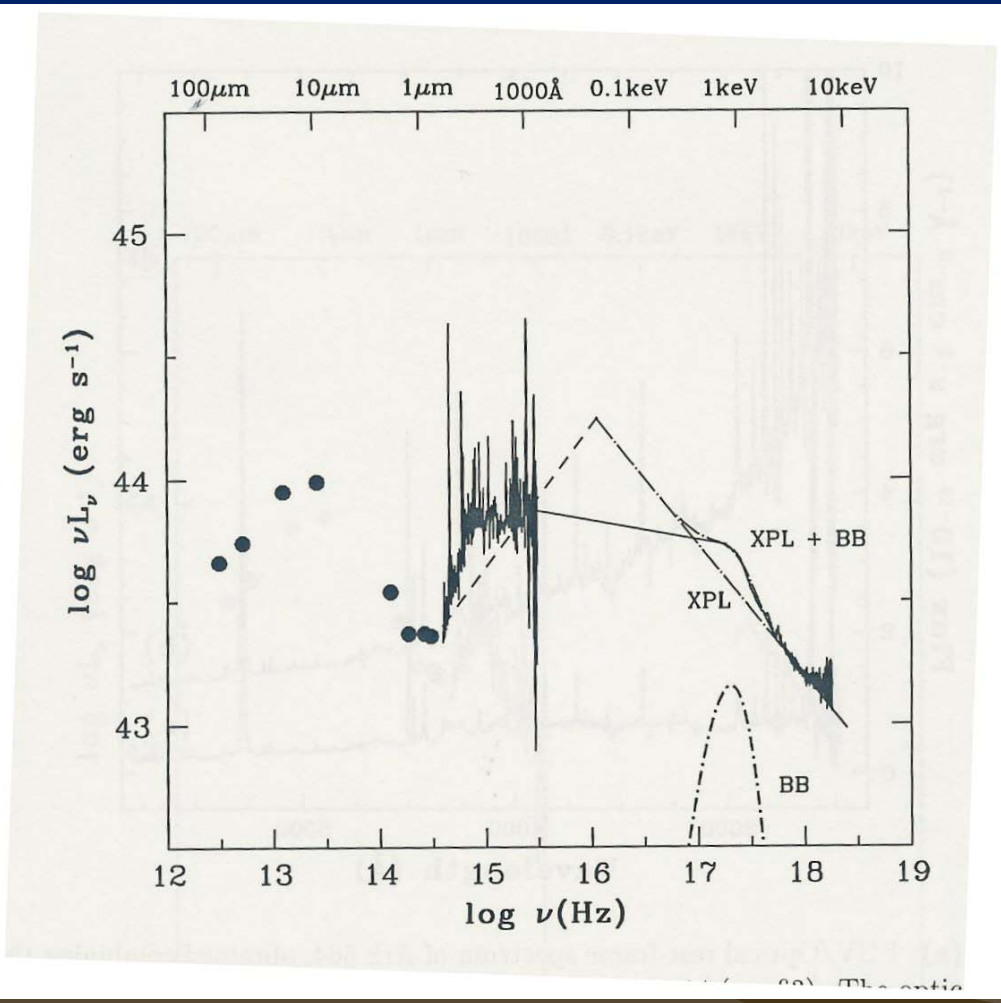
$$L_\lambda \propto \lambda^{-\beta}$$

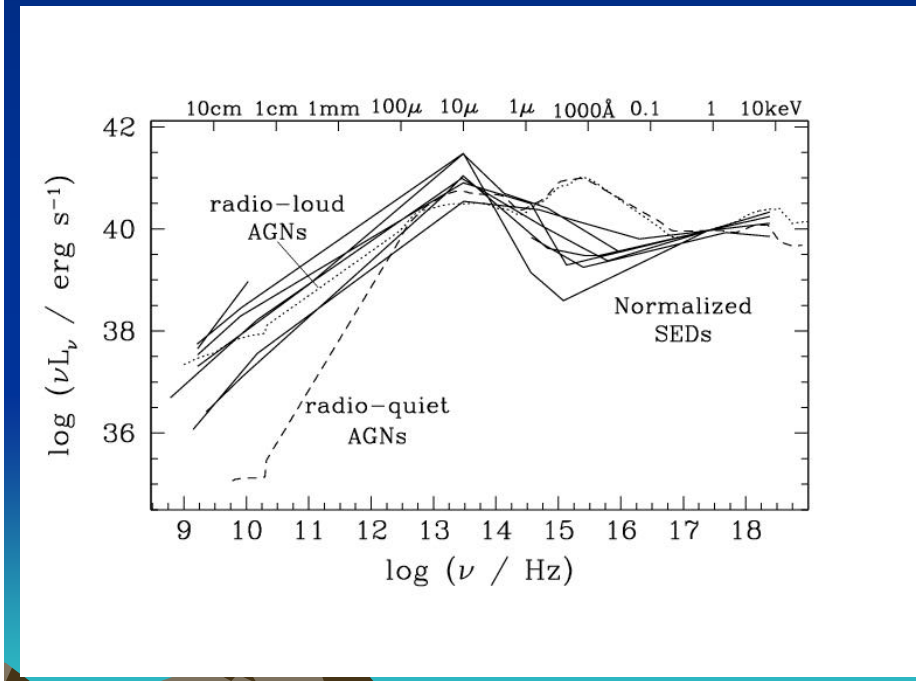
$$\beta = 2 - \alpha$$

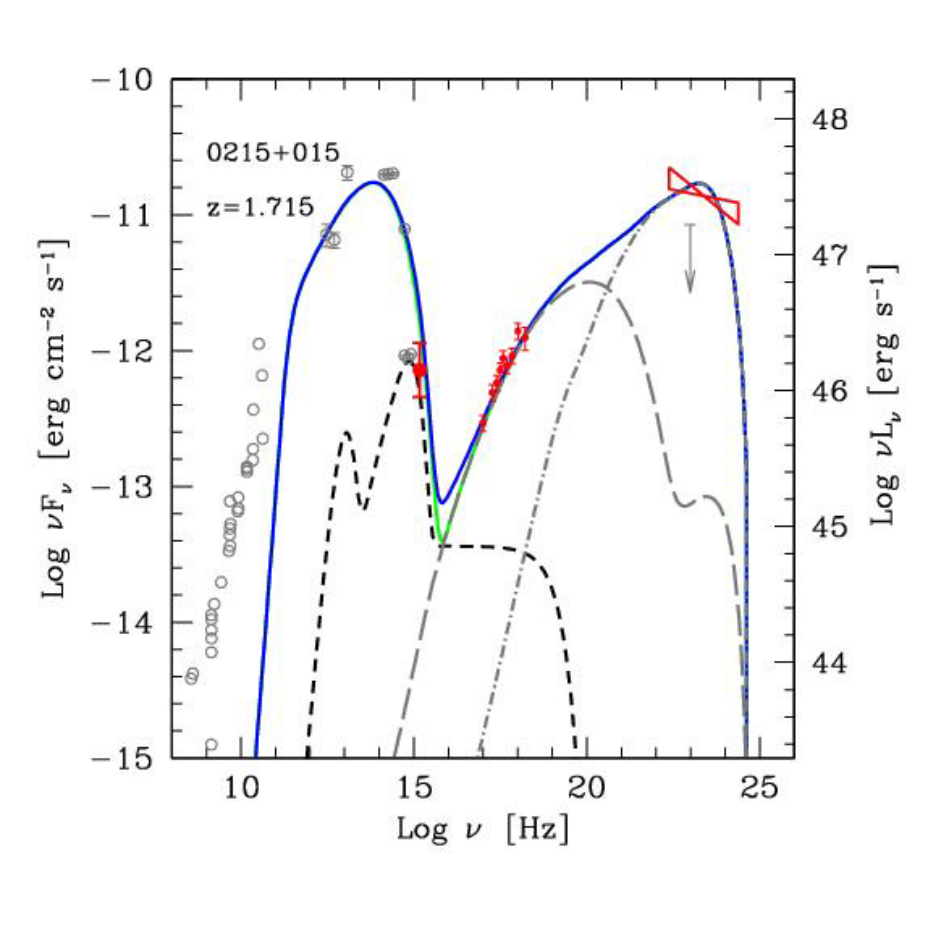
$$L_{bol} = \int_0^\infty L_\nu d\nu$$

$$L_\nu d\nu = L_\lambda d\lambda$$

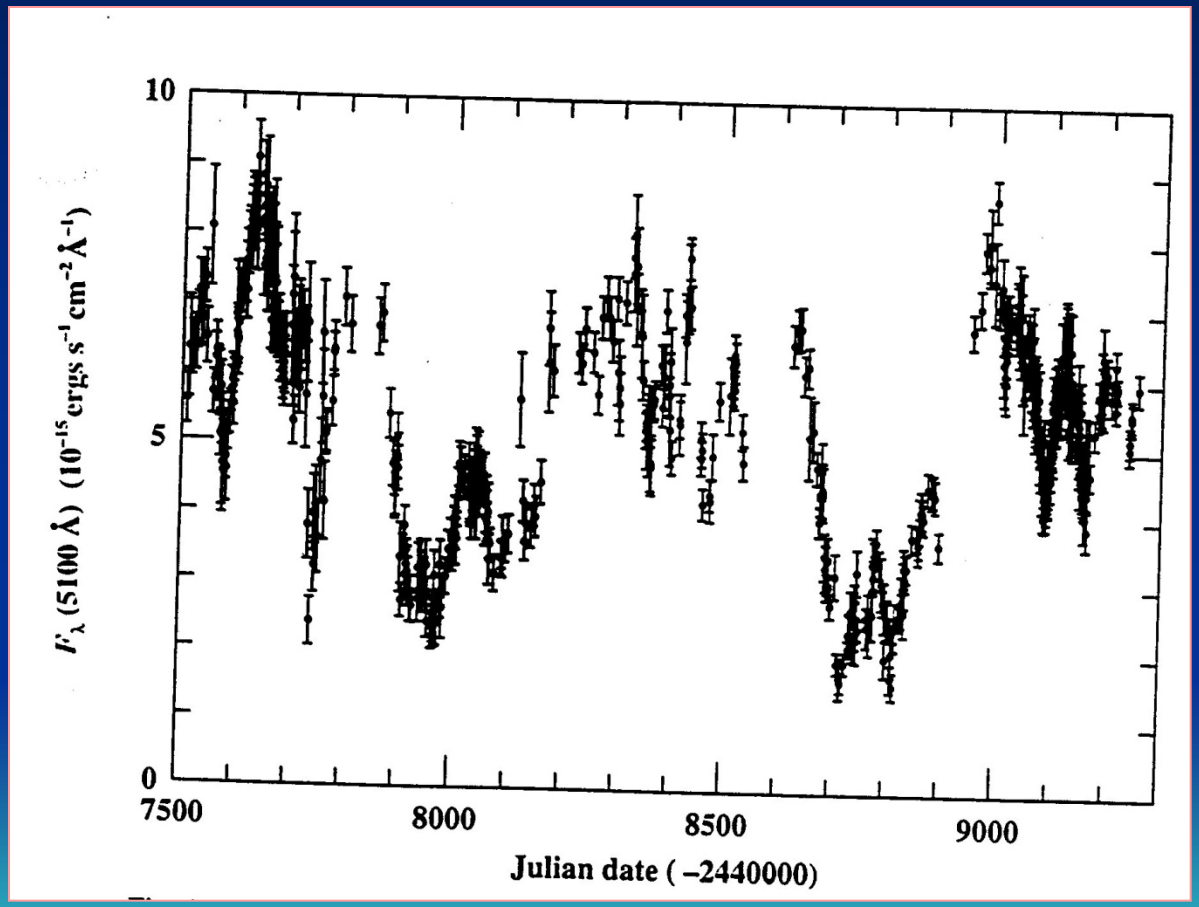
Spectral energy distribution (SED) of AGN



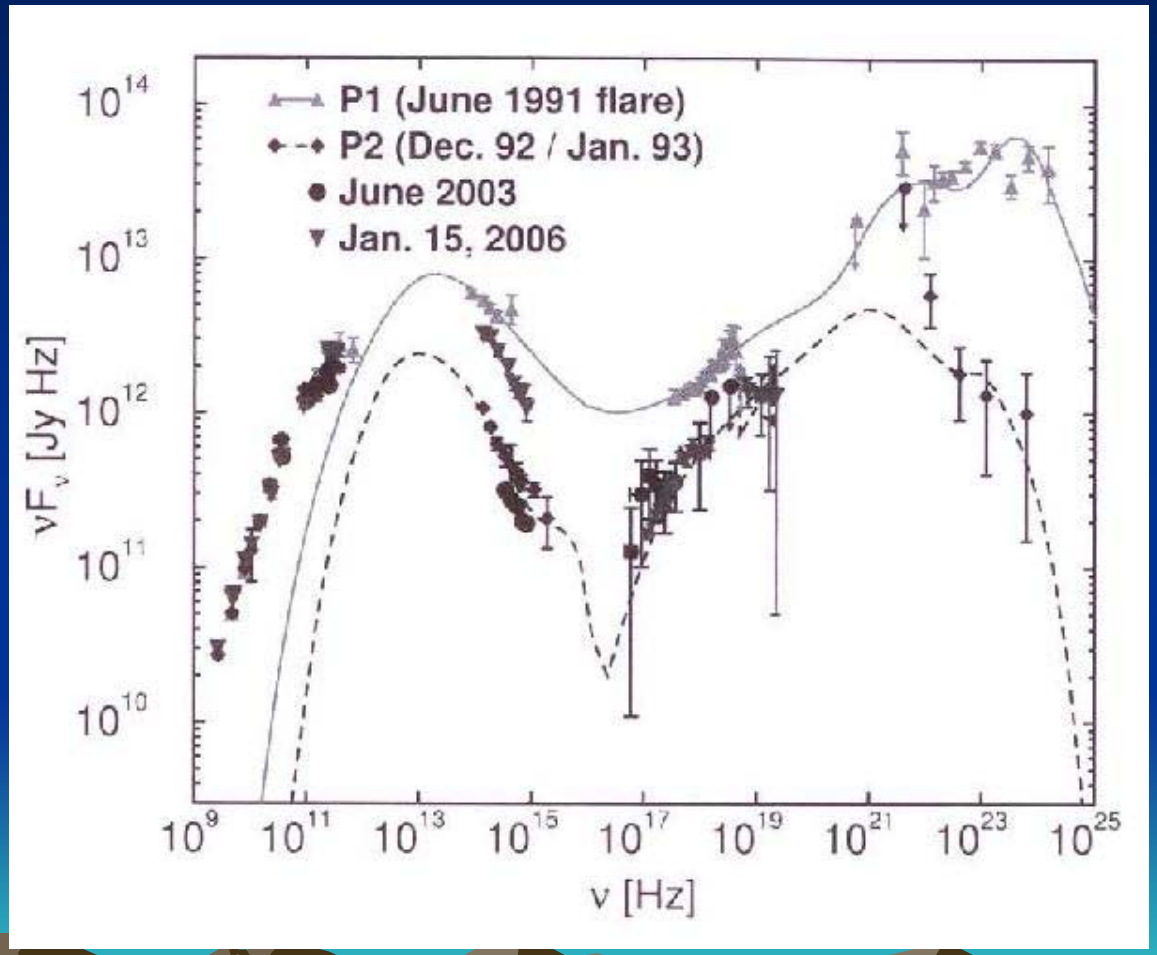



0215+015
z=1.715
Log νF_ν [erg cm^-2 s^-1]
Log νL_ν [erg s^-1]
Log ν [Hz]
−10
−11
−12
−13
−14
−15
48
47
46
45
44
10
15
20
25

Variability



3C279


P1 (June 1991 flare)
P2 (Dec. 92 / Jan. 93)
June 2003
Jan. 15, 2006
νF_ν [Jy Hz]
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9} 10^{11} 10^{13} 10^{15} 10^{17} 10^{19} 10^{21} 10^{23} 10^{25}
ν [Hz]

Definition of Active galactic nuclei

An extragalactic object is classified as an AGN if at least one of the following is fulfilled

- It contains a compact nuclear region emitting significantly beyond what is expected from stellar processes typical of this type of galaxies
- It shows the clear signature of a non-stellar continuum emitting process
- Its spectrum contains strong emission lines with line ratios that are typical of excitation by a non-stellar radiation field
- It shows line and/or continuum variations

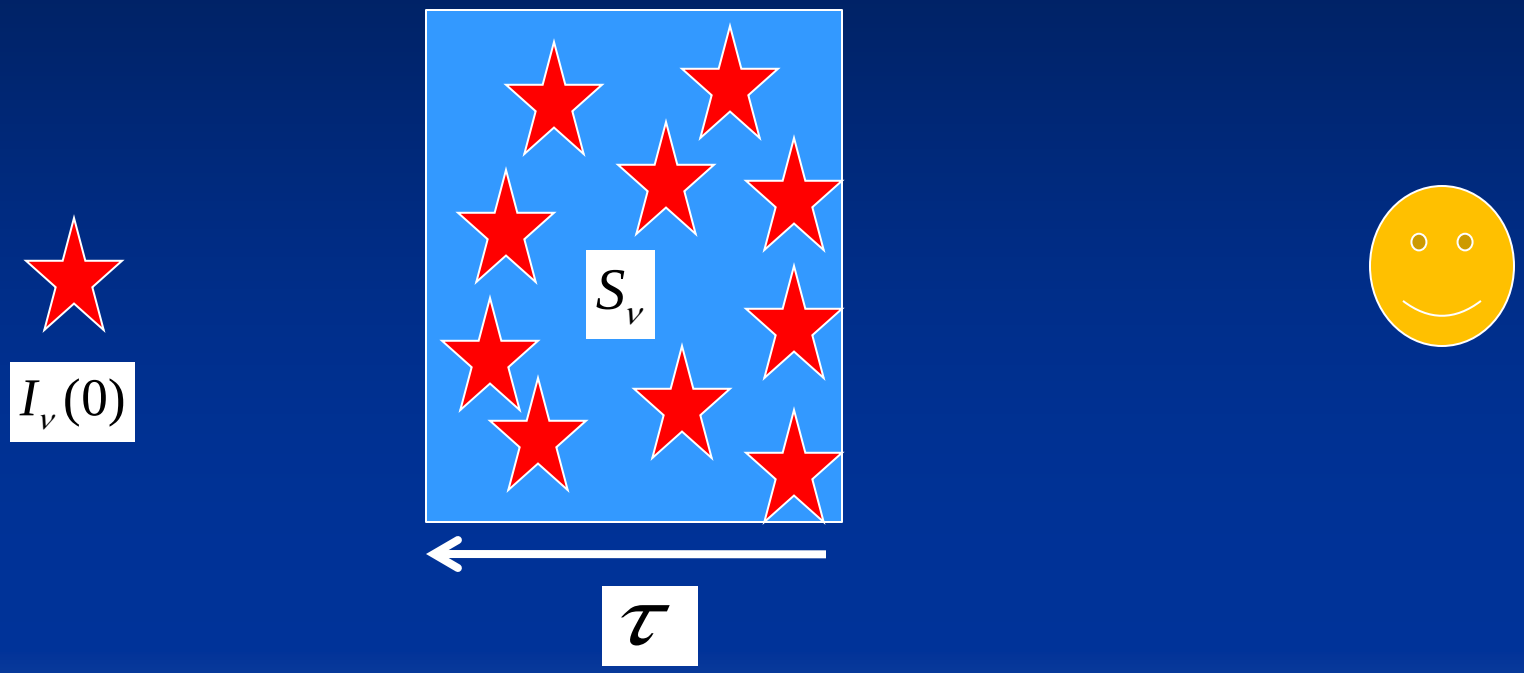
Basic definitions: Radiative transfer

- Specific intensity - I_ν
- Emission coefficient j_ν
- Absorption coefficient κ_ν
- Source function $S_\nu = \dfrac{j_\nu}{\kappa_\nu}$

- The equation of radiative transfer

$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + j_\nu$$

The simplest solution of the equation of radiative transfer



$$I_\nu = I_\nu(0)e^{-\tau_\nu} + S_\nu(1-e^{-\tau_\nu})$$

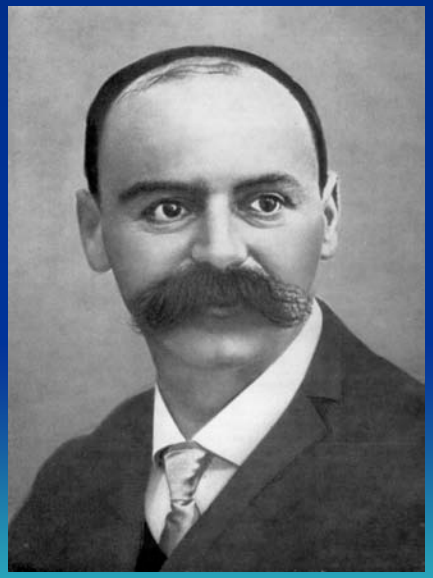
Black holes and accretion physics 1

- General properties of Black Holes (BHs)
  - BH mass
  - BH spin
  - Energy production efficiency

- The Eddington luminosity
  - Electron scattering and radiation pressure (1)
  - Spherical accretion

The first black hole

$$\boxed{d\underline{s}^2 = \underbrace{\left(1-\frac{r_s}{r}\right)\cdot(c\,dt)^2}_{\text{Rotverschiebung}} - \underbrace{\left(1-\frac{r_s}{r}\right)^{-1}\cdot d\vec{r}^{\,2}}_{\text{Raumkrümmung}}}$$



Karl Schwarzschild (1917†)

General properties of Black Holes (BHs)

- The no-hair theorem
  - Mass - M
  - Spin - s
  - Charge – Q
- Definitions
  - Gravitational radius:
    - $r_g = GM/c^2$
  - Spin parameter:
    - a
- Energy production efficiency
  - $0.038 \leq \eta \leq 0.421$

$$\underbrace{ds^2 = \left(1 - \frac{r_s}{r}\right) \cdot (c\,dt)^2}_{\text{Rotverschiebung}} - \underbrace{\left(1 - \frac{r_s}{r}\right)^{-1} \cdot d\vec{r}^{\,2}}_{\text{Raumkrümmung}}$$

$$ds^2 = \left[1 - \frac{2 r_g r}{\Sigma}\right] c^2 dt^2 + \ldots - \frac{\Sigma}{\Delta} dr^2$$

$$\Sigma = r^2 + \alpha^2 \cos^2\theta$$

$$\Delta = r^2 - 2 r_g r + \alpha^2$$

$$\alpha = a r_g$$

$$-1 \leq a \leq 1$$

$$r_g = \frac{GM}{c^2}$$

Accretion onto black holes- summary

- Spherical accretion
  - Eddington luminosity
  - Eddington accretion rate
  - Eddington time
  - Bondi accretion and efficiency

$$f_{rad} = \frac{N_e L}{4\pi R^2}\frac{\sigma_T}{c}$$

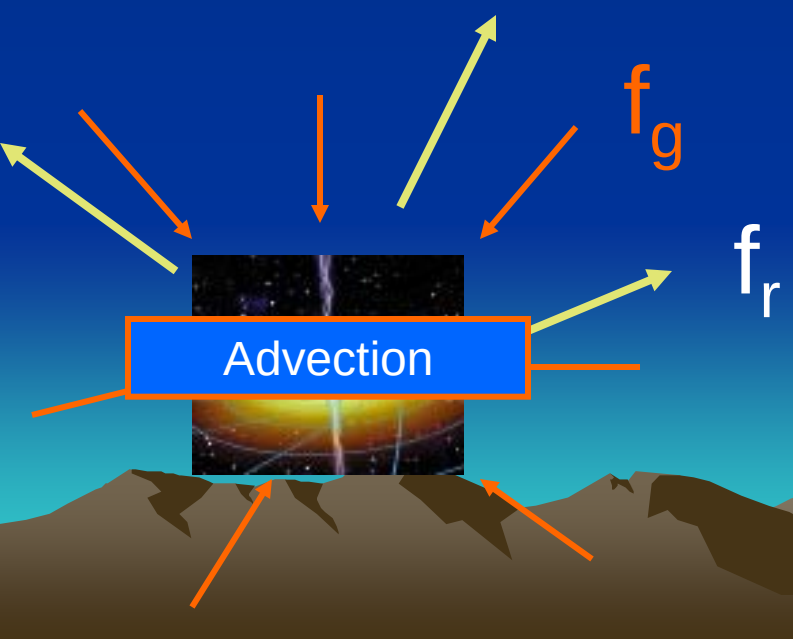
$$f_g = \frac{GM}{R^2}\mu m_p N_e$$

$$f_{rad} = f_g$$

$$L_{Edd} = \frac{4\pi GM\,\mu m_p c}{\sigma_T} \cong 1.5x10^{46} M_8$$

$$t_{Edd} = \frac{M}{\dot{M}_{Edd}} \approx 4x10^8 \eta \ yr$$

$$\dot{M}(Bondi) = 4\pi\lambda v_s \rho r_A^2$$



Black holes and accretion physics 2

- Thin accretion disks 1:
  - Optically thick geometrically thin accretion disks
  - Angular momentum
  - Torque
  - Luminosity
  - Emissivity and temperature

Accretion disks
Definition of disk parameters

$$S = m v_k R$$

$$\frac{S}{m} = (GMR)^{1/2}$$

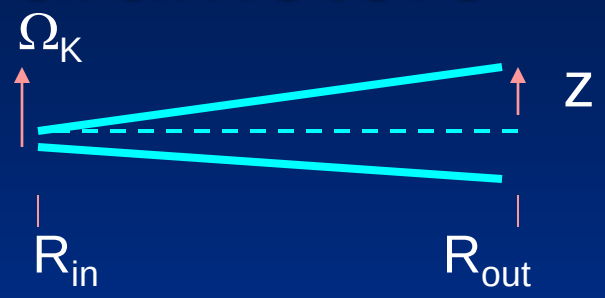
$$\mathrm{N} = \frac{dS}{dt} = \frac{dm}{dt} v_k R =$$

$$= \dot{M}\left(\frac{S}{m}\right) = \dot{M}(GMR)^{1/2}$$

$$\Sigma = 2\langle \rho \rangle H$$

$$\dot{M} = -2\pi R \Sigma v_r$$

$$\Omega_K = \frac{v_k}{R} = \left(\frac{GM}{R^3}\right)^{1/2}$$



S - angular momentum

N - torque

Σ - surface density

V_r - radial velocity

V_K- Keplerian velocity

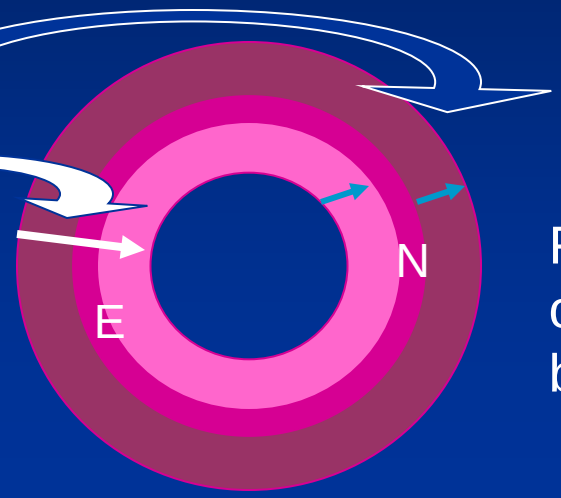
Ω_K - Keplerian angular velocity

Accretion disks
Total radiated energy

$$dL_N = -d(N\Omega_K) = -d\left(\dot{M}\frac{GM}{R}\right)$$

$$dL_g = -d\left(\dot{M}\frac{GM}{2R}\right)$$

$$\frac{dL}{dR} = \frac{3GM\,\dot{M}}{2R^2}\left[1-\left(\frac{R_{\min}}{R}\right)^{1/2}\right]$$



For a stationary BH, 50% of the energy is emitted between 6 and 32 R_g

Total radiated energy

$$L(R) = \int_R^\infty \frac{dL}{dR}dR \propto \frac{\dot{M}\,GM}{2R}$$

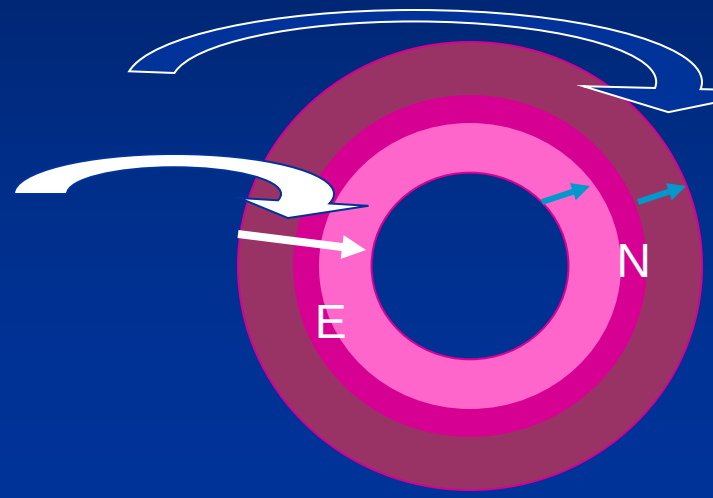
Accretion disks

Energy and temperature

Emissivity per unit area

$$D = \frac{3GM\dot{M}}{8\pi R^3}\left[1-\left(\frac{R_{\min}}{R}\right)^{1/2}\right]$$

$$D = \sigma T^4$$



Surface temperature

$$T = \left\{\frac{3GM\dot{M}}{8\sigma\pi R^3}\left[1-\left(\frac{R_{\min}}{R}\right)^{1/2}\right]\right\}^{1/4}$$

$$T \propto M_8^{-1/4}\left(\frac{\dot{M}}{M_8}\right)^{1/4}\left(\frac{R}{R_g}\right)^{-3/4}$$

Disks around larger BHs are cooler

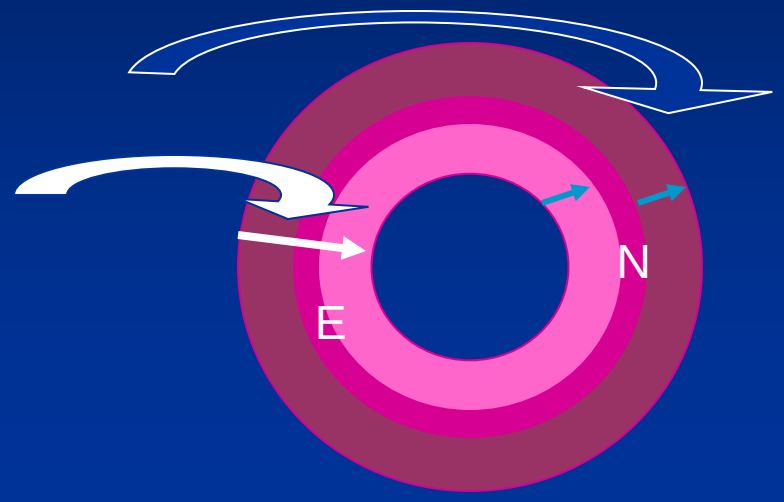
$$T(r) \approx 10^6\left[\frac{\dot{M}}{M_\odot}\right]^{1/4} M_8^{-1/2}\left[\frac{r}{r_g}\right]^{-3/4} K$$

Black holes and accretion physics 3

- Thin accretion disks 2
  - Viscosity
  - Geometry
  - The emitted SED
    - Generic disk spectrum
    - Dependence on BH mass and accretion rate
    - Disk inclination

Accretion disks
Radial velocity and viscosity

What is the accretion rate (or V_r)?



Viscosity - ν

$$v_r = \frac{3\nu}{2R}$$

$$\nu\rho A = \alpha P$$

$$\left(\frac{3\nu\rho\Omega_k}{2} = \alpha P\right)$$

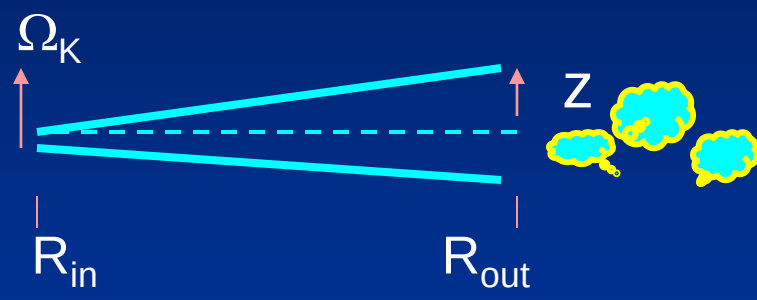
Alpha disk

Accretion disks
Disk boundaries

$$\text{self gravity} = 2\pi G\Sigma = 2\pi G(2\rho z)$$

$$\text{central gravity} = \Omega_k^2 z$$

$$\textit{Diks fragments when } 2\pi G\Sigma > \Omega_k^2 z$$



Inner boundary = last stable orbit

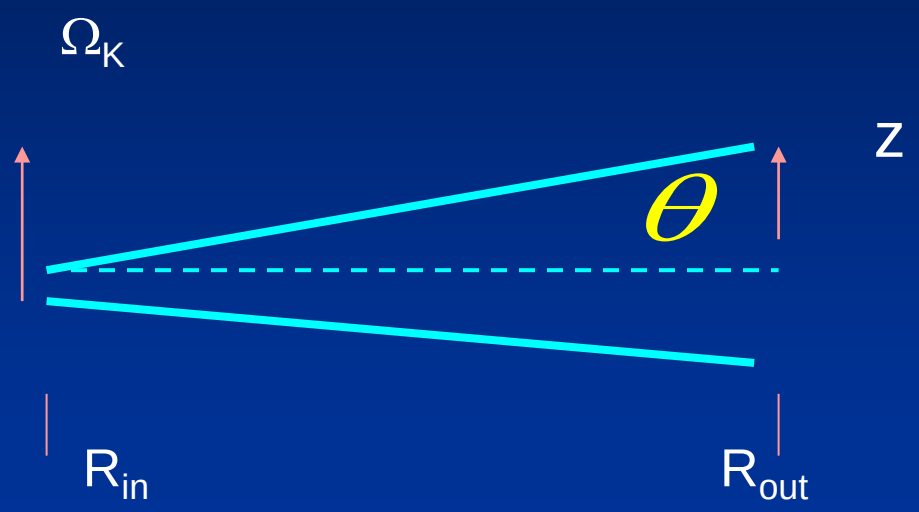
Outer boundary = self-gravity radius

stationary BH - $6R_g$

max. rotating (a=0.998) - BH - 1.24 R_g

Accretion disks

Disk scale height - H



Local gravity (no self gravity)

$$g_z = \frac{GM}{R^2}\sin\theta \cong \frac{GM}{R^3} z = \Omega_k^2 z$$

Hydrostatic equation

$$\frac{dP}{dz} = -\rho g_z = -\rho\Omega_k^2 z$$

$$P = P_r + P_g = \tfrac{1}{3}aT^4 + \frac{\rho kT}{\mu m_p}$$

assume P=Pg

$$P = \rho c_s^2$$

$$\frac{dP}{dz} = c_s^2 \frac{d\rho}{dz} = -\rho\Omega_k^2 z$$

Vertical density structure

$$\rho = \rho_0 \exp(-\frac{z^2}{H^2})\ ;\ H \approx \frac{c_s}{\Omega_k}\ ;\ \frac{H}{R} \approx \frac{c_s}{v_k}$$

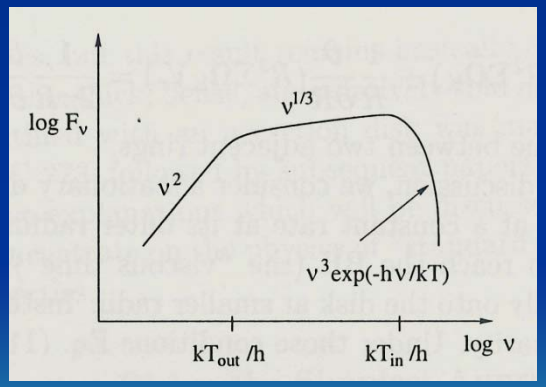
Accretion disks

- The spectrum of accretion disks
  - Steady state spectrum
- Spectral energy distribution
- Orientation

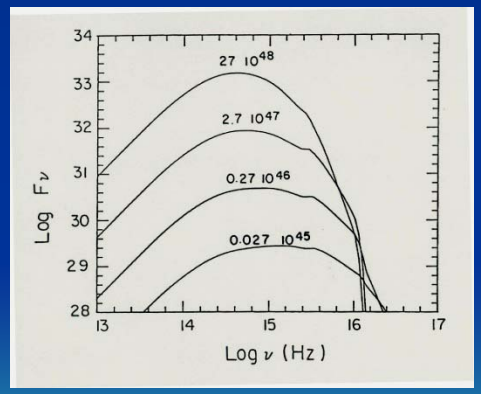
$$dL_\nu = 2\pi R(\pi B\nu)dR$$

$$L_\nu = \int_{R_{in}}^{R_{out}} dL_\nu = \frac{4\pi^2 h\nu^3}{c^2}\int_{R_{in}}^{R_{out}} \frac{RdR}{\exp(h\nu/kT)-1} \propto \nu^{1/3}$$

Schematic spectrum



Calculated spectrum



Black holes and accretion physics 4

- Real AGN disks
  - Comptonization
  - Relativistic effects
  - Disk corona and X-ray illuminated disks
- Slim and thick accretion disks
- Radiation inefficient accretion flows (RIAFs)
  - Advection dominated accretion flows (ADAF)
  - Two temperature disks
  - Radiative efficiency revisited

Accretion disks

Slim and thick disks

$$g_z = \frac{GM}{R^2}\sin\theta \cong \frac{GM}{R^3} z = \Omega_k^2 z$$

$$\frac{dP}{dz} = -\rho g_z = -\rho\Omega_k^2 z$$

$$P = P_r + P_g = \tfrac{1}{3}aT^4 + \frac{\rho kT}{\mu m_p}$$

Larger L/L_{Edd} =>

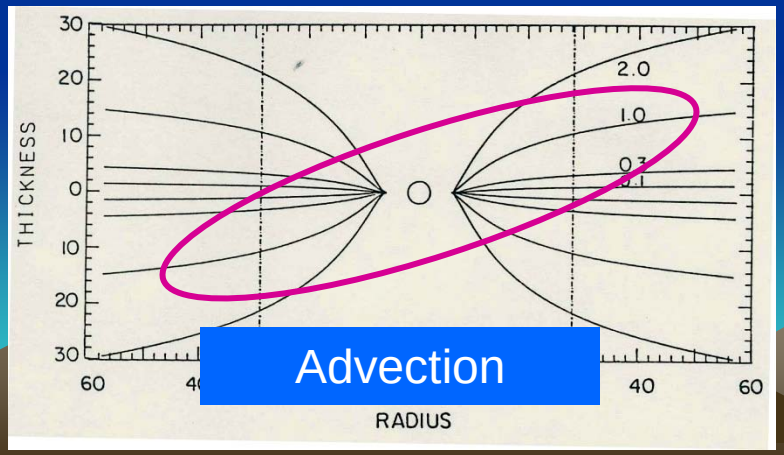
larger P_r =>

thicker disk

assume P=Pg

$$P = \rho c_s^2$$

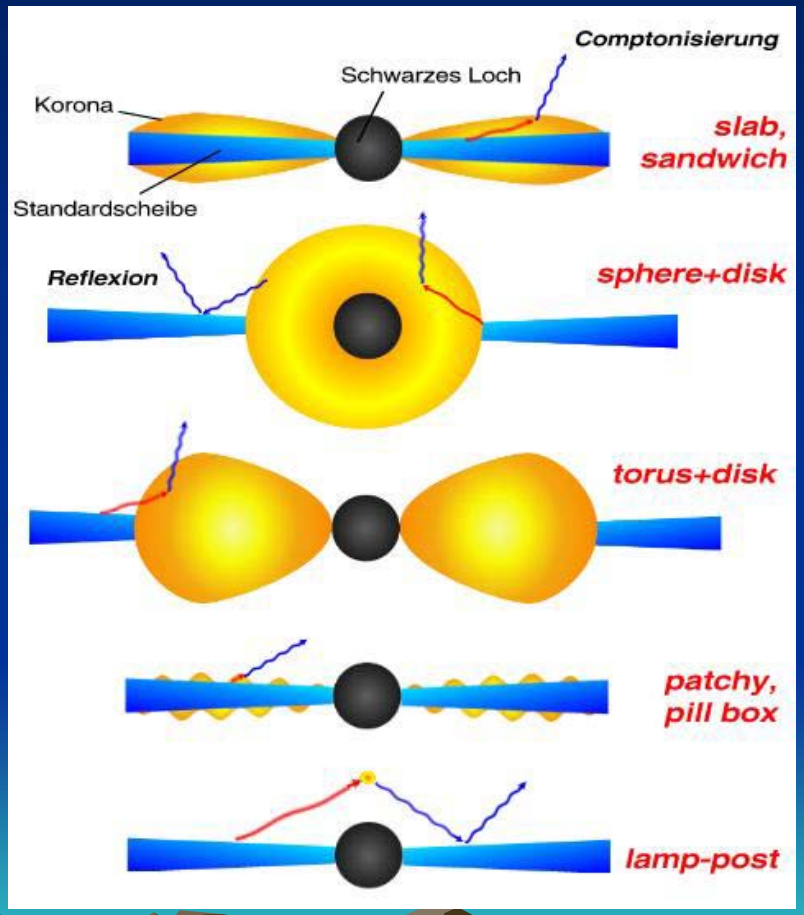
$$\frac{dP}{dz} = c_s^2 \frac{d\rho}{dz} = -\rho\Omega_k^2 z$$



$$\rho = \rho_0 \exp(-\frac{z^2}{H^2})\ ;\ H \approx \frac{c_s}{\Omega_k}\ ;\ \frac{H}{R} \approx \frac{c_s}{v_k}$$

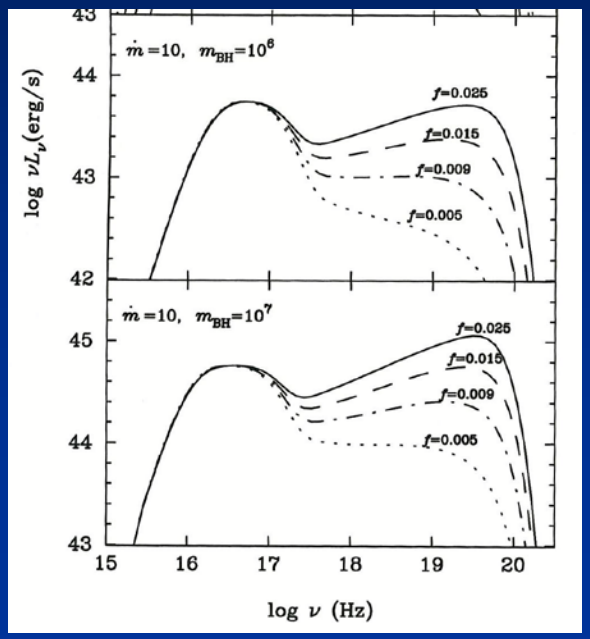
Accretion disks

Slim disks and disk corona



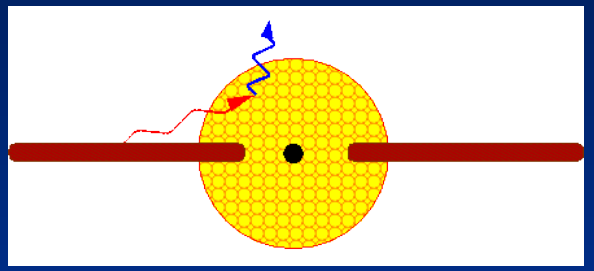
Comptonization

Accretion disks
Slim disks with coronae



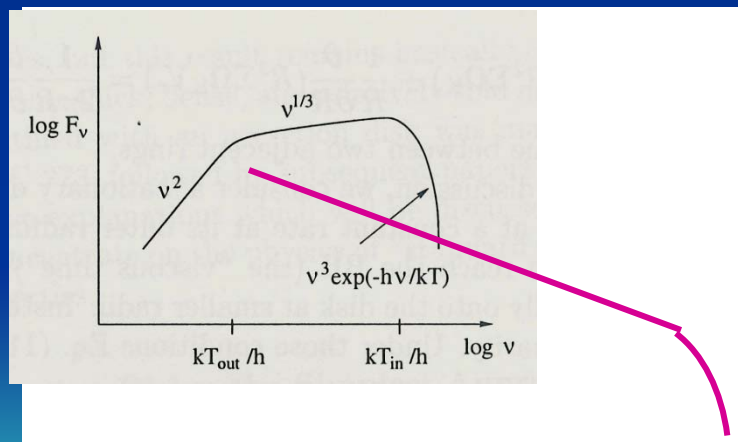
The spectrum of slim accretion disks

Wang and Netzer 2005



Schematic spectrum

Calculated spectrum

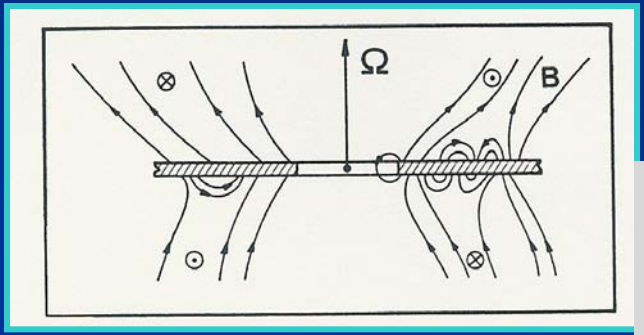


Thermal or non-thermal

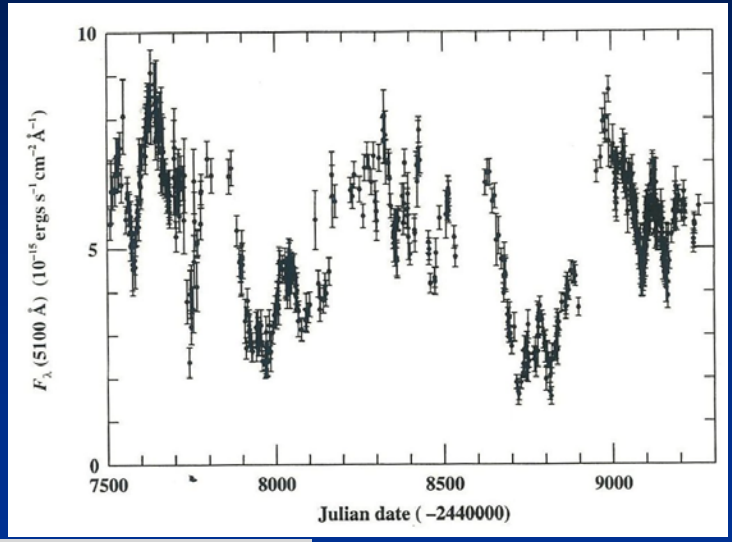
This is the question!

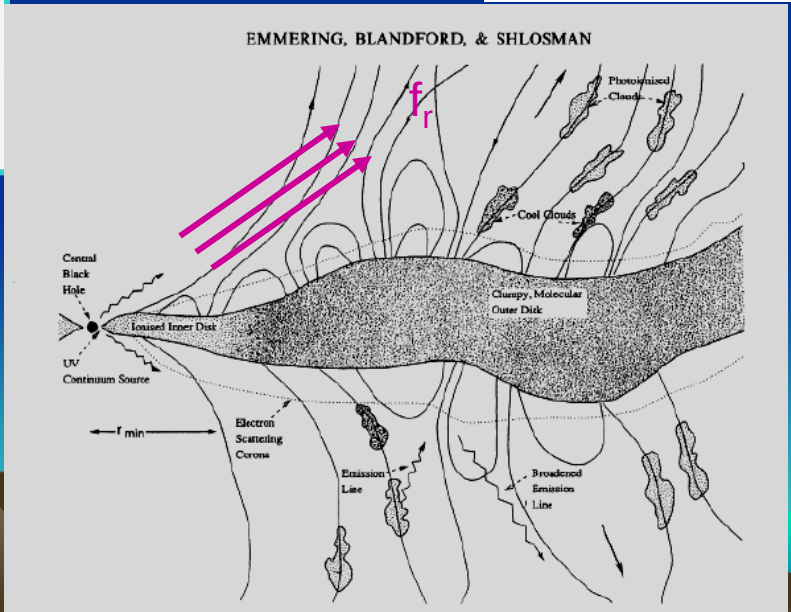
Accretion disks

- Magnetic disks
- Evaporation and winds
- Instabilities



Blandford 1990

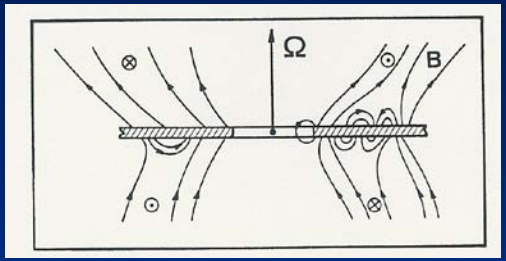


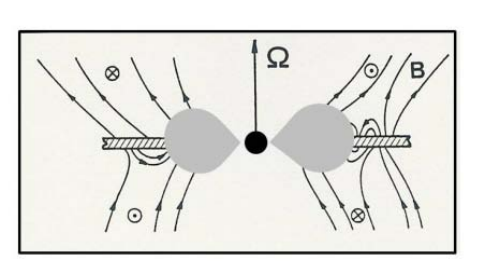


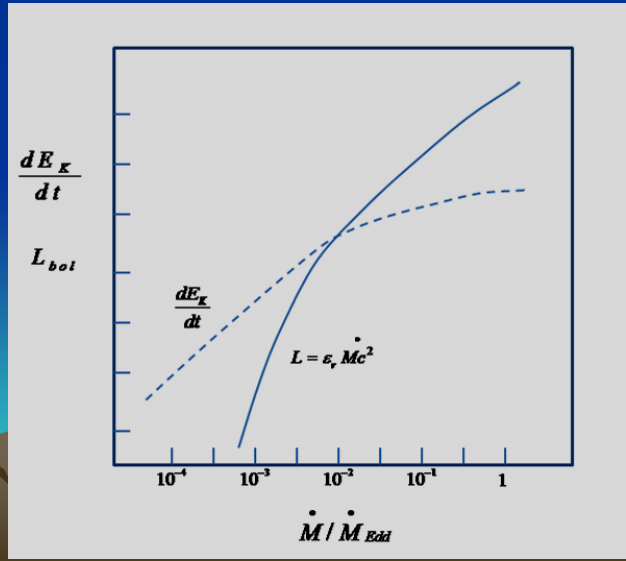
Accretion disks

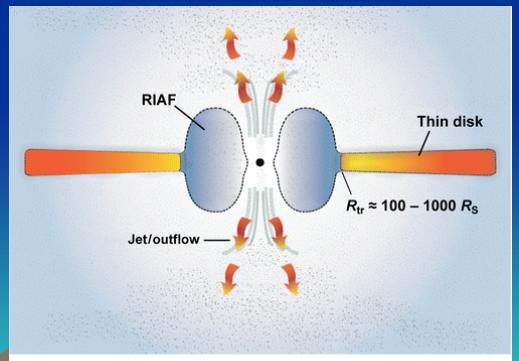
Real AGN disks - RIAFs

- Radiation inefficient accretion flows (RIAFs)
  - Advection dominated accretion flows (ADAF)
  - Two temperature disks
  - Radiative efficiency revisited



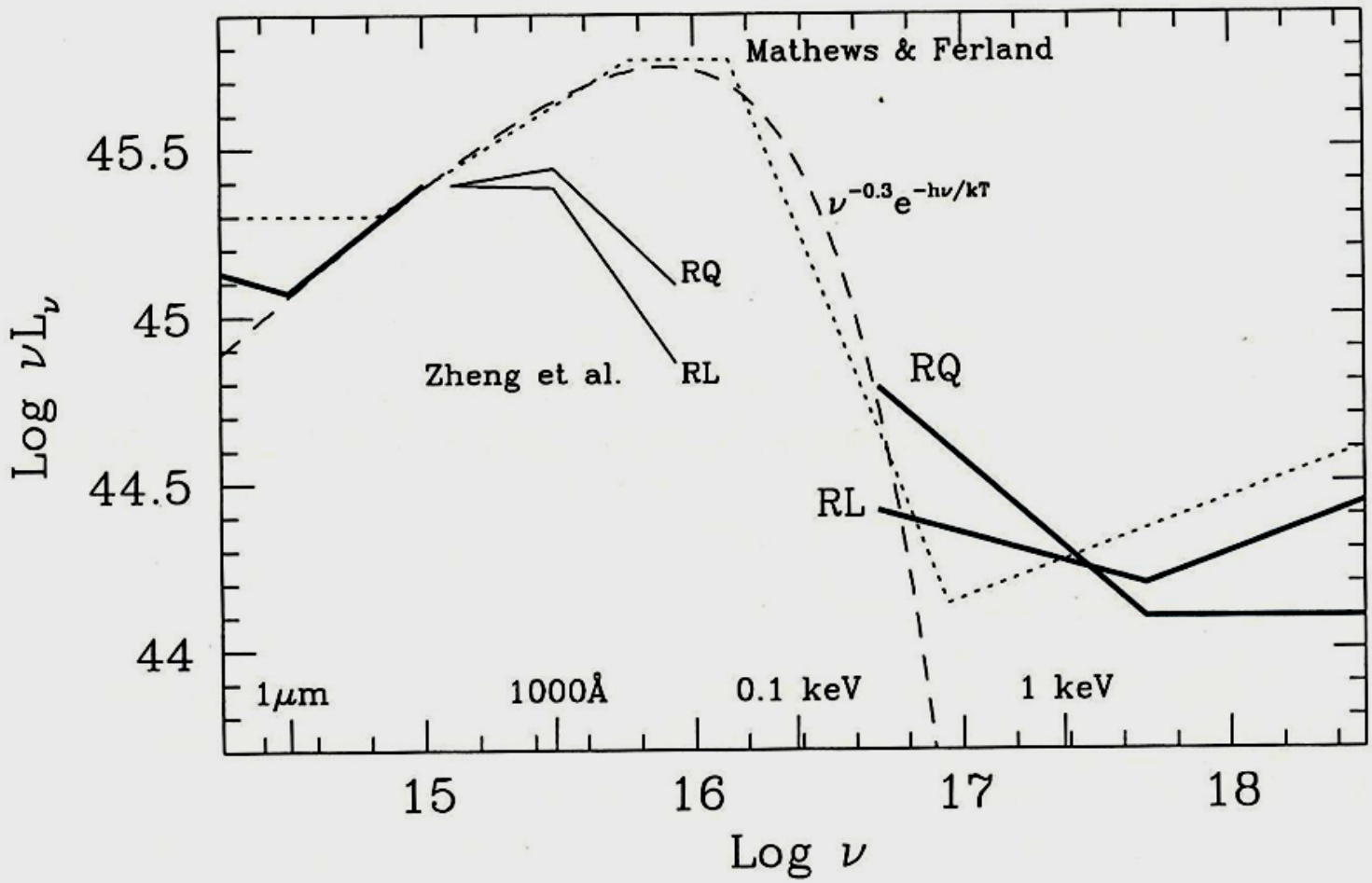




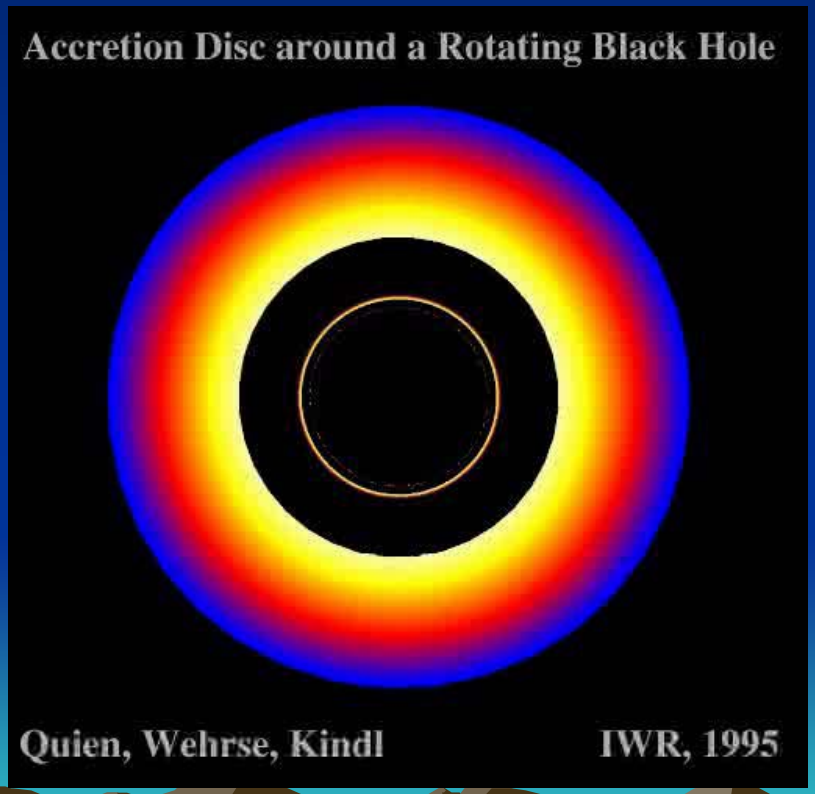


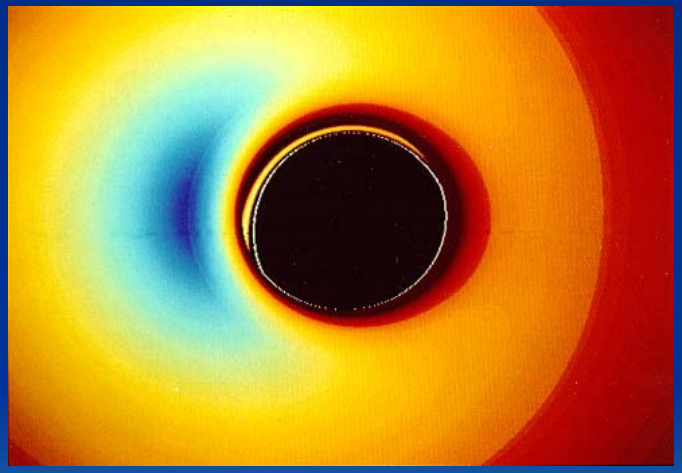
Ho LC. 2008.

Observed SEDs



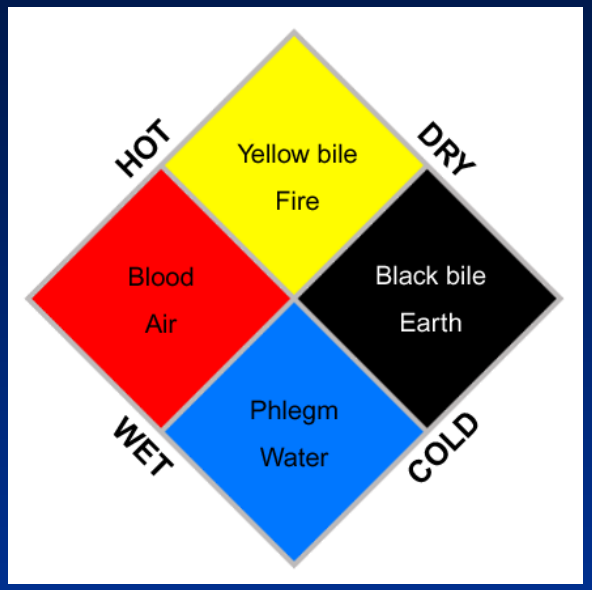
Accretion disks
relativistic effects





Γαληνός

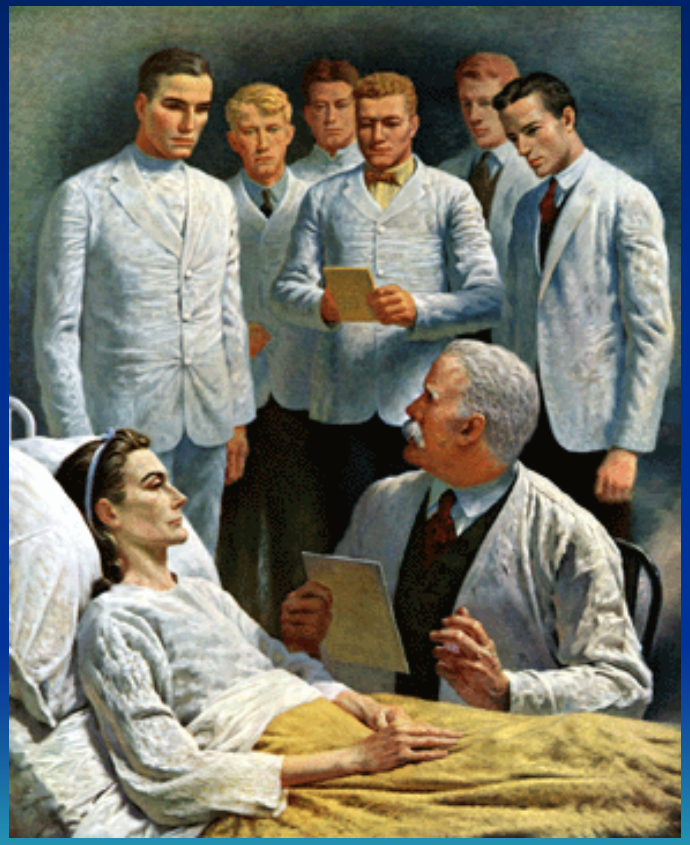
Ptolemy

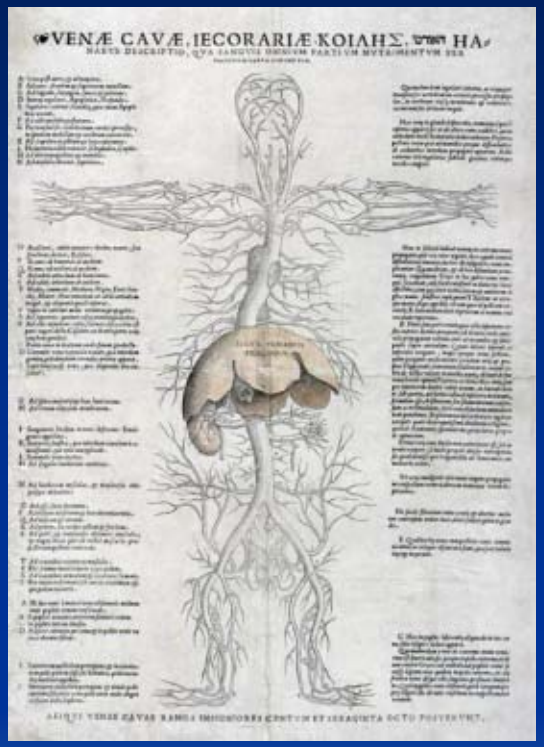


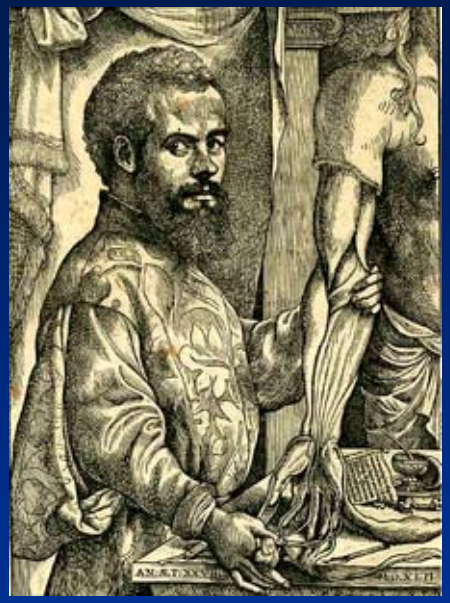
The four body humors

Galen of Pergamon
The **four humors** of Hippocratic medicine remained uncontested until 1543 Vaselius showed
The circulatory system endured until 1628, when William Harvey published his treatise entitled *De motu cordis*,

The proper way of lecturing

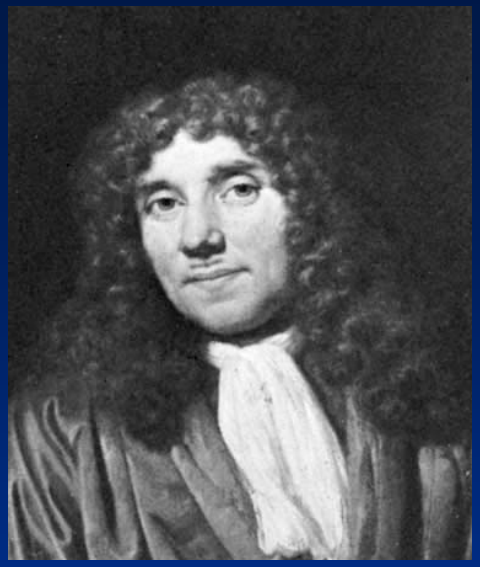




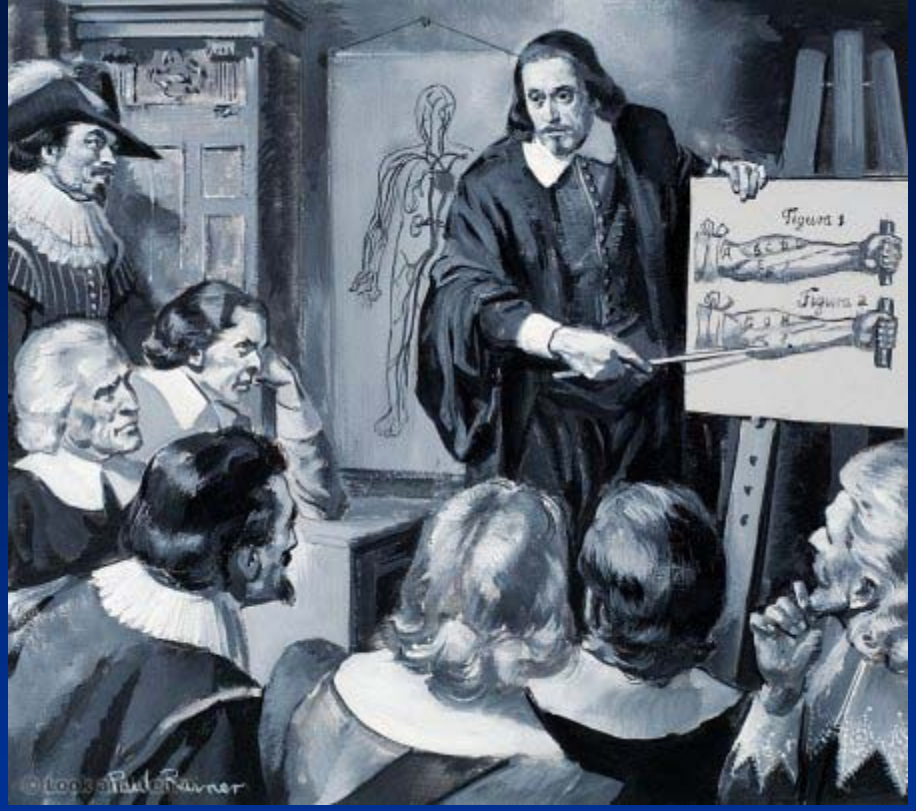


Andreas Vesalius 1514 1564
the founder of modern human anatomy

1543: wonder year



Leeuwenhoek
Dutch microscopist who was the first to observe bacteria and protozoa. His researches on lower animals refuted the doctrine of spontaneous generation,



Harvey

Physical processes - 1

- The physics of ionized gas – 1
  - Photoionization and recombination
  - Additional processes
    - Dielectronic recombination
    - Auger ionization
    - Secondary electrons
    - Charge exchange
    - Collisional ionization and three body recombination
  - Thermal balance

Physical Processes - 1
(Let There Be Light)

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

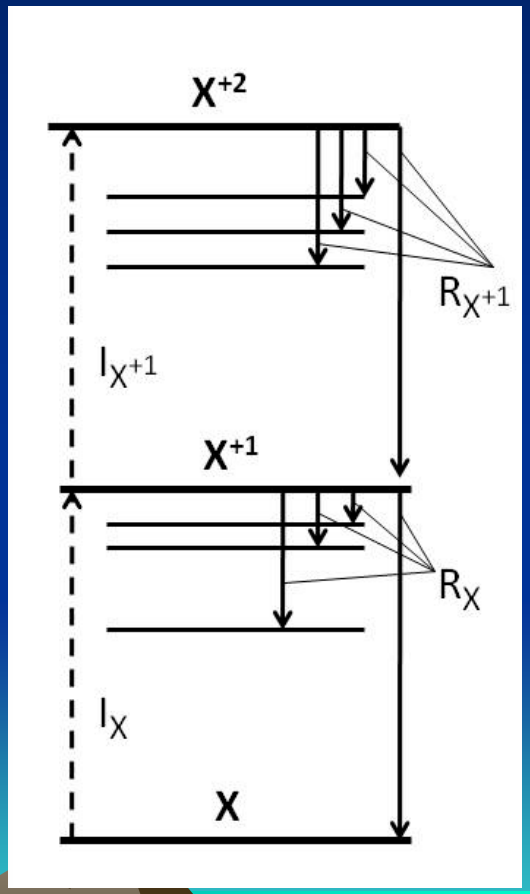
How does it look and move at various times in different places?

Photoionization

Photoionization rate - I_X

Radiative recombination rate - R_X

Time dependent ionization



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

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

The steady state solution:

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

Photoionization and recombination

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

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

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

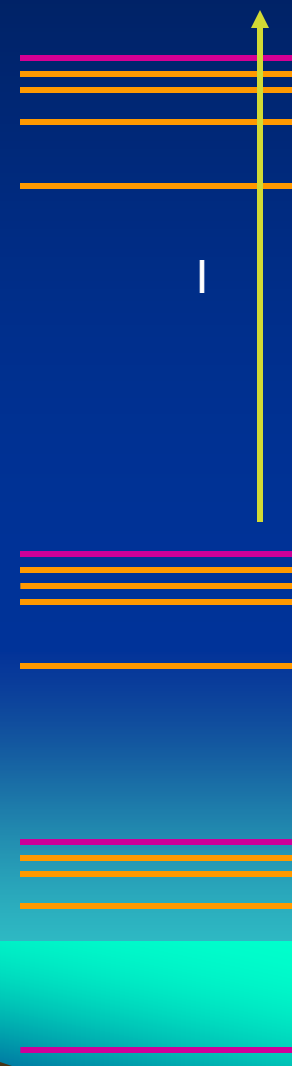
$$\frac{dN_x}{dt} = 0 \Rightarrow \frac{N_{x+1}}{N_x} = \frac{I_x}{R_x}$$

Recombination time

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

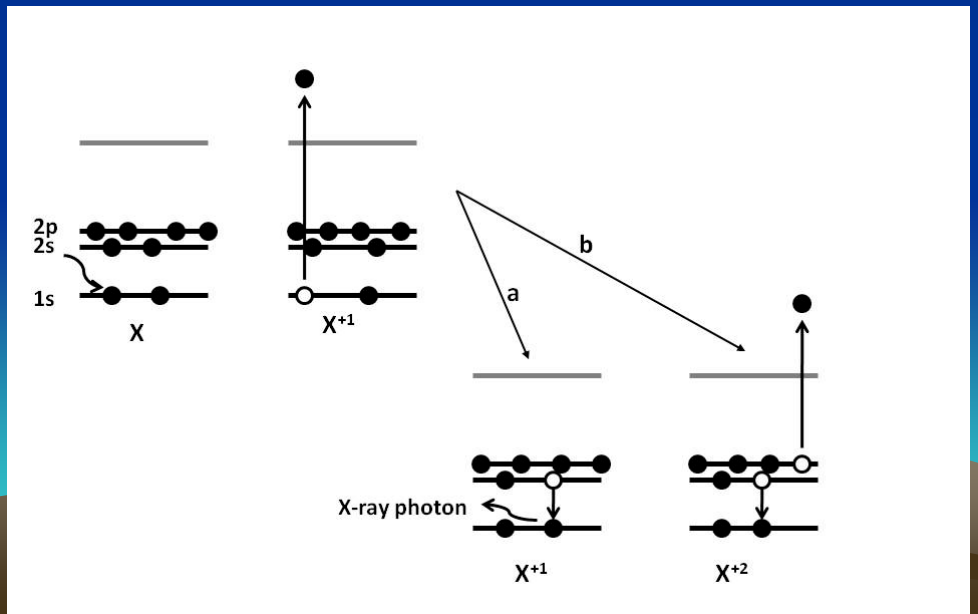
Ionization time

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

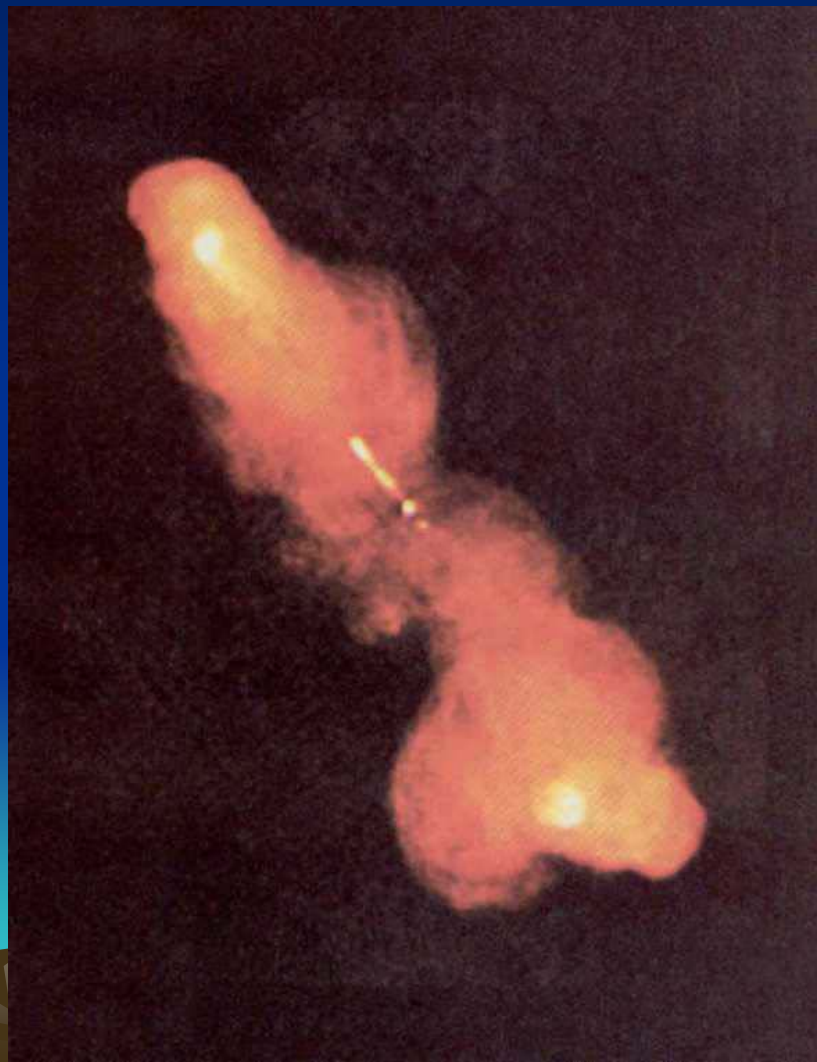


Other ionization and recombination processes

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



Ionization by shocks



Shock (mechanical energy) efficiency

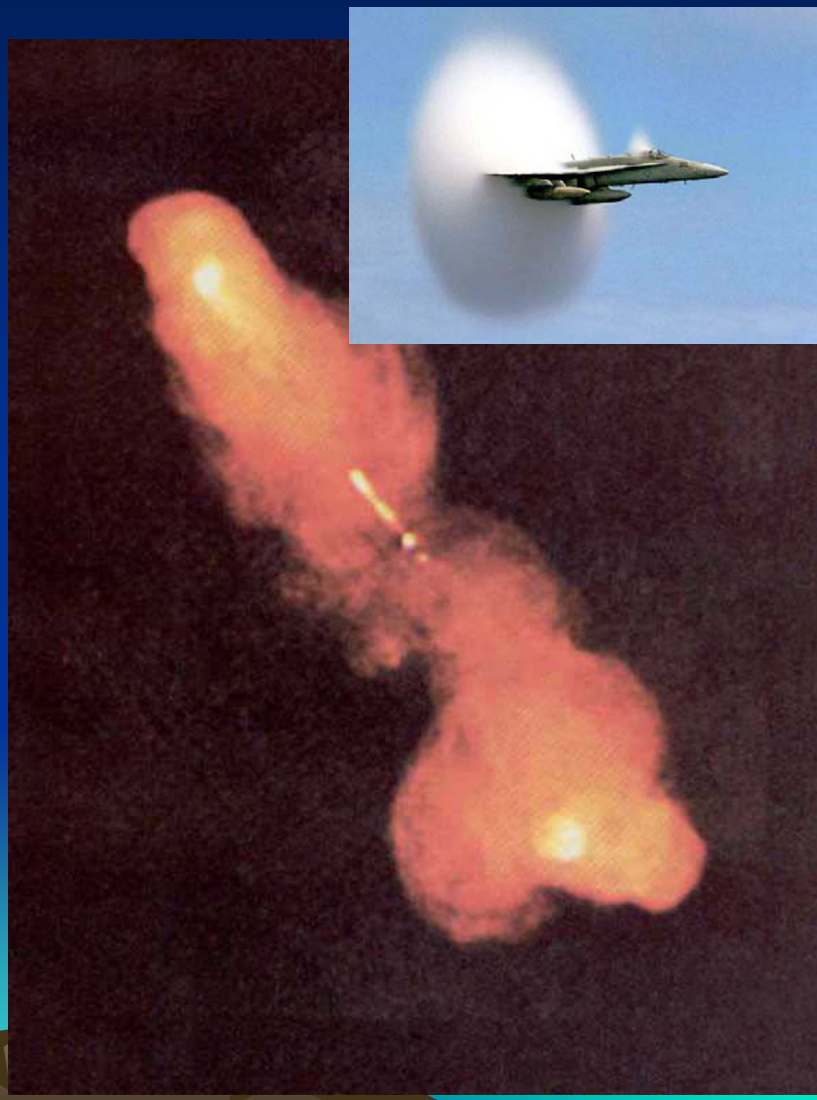
$$E_{sh} = \frac{1}{2} m_{sh} \mathrm{v}^2 = \eta_{sh} m_{sh} c^2$$

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

$$\mathrm{v}_{NLR} \approx 500\ km/\sec$$

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

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



Thermal balance

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

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

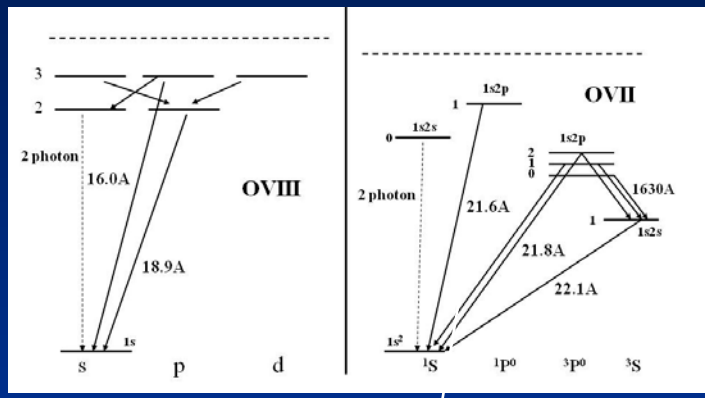
$$\varepsilon_{rec} = N_{x+1} N_e \alpha_{eff} h\nu_{1\infty}$$

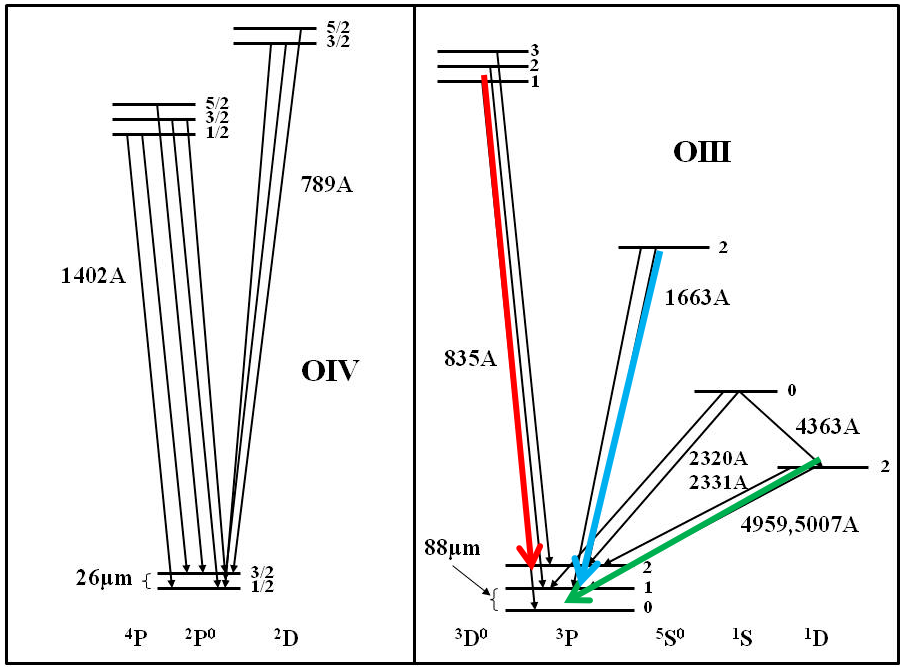
Physical processes - 2

- The physics of ionized gas – 2
  - Basic spectroscopy
  - Line emission
    - Recombination
    - Collisional excitation and de-excitation
    - Radiative excitation
  - Continuum emission
  - Photoionization models
  - Collisionally ionized plasma

Basic spectroscopy

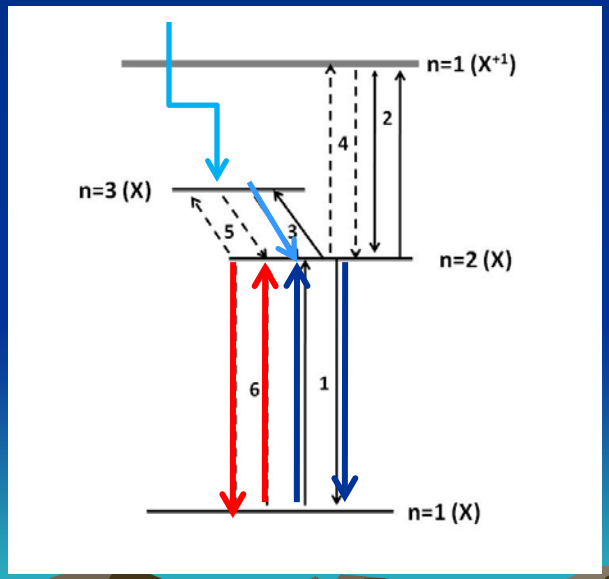
- Energy levels and atomic transitions
  - Levels terms and selection rules
    - Permitted transitions
    - Forbidden transitions
    - Semi-forbidden transitions
  - Examples
  - OIII, OIV, OVII, OVIII





Basic spectroscopy

- Recombination lines
- Collisional excitation and de-excitation
- Radiative excitation (line absorption)



$$R_2 = \alpha_{eff} N_{X+1} N_e$$

$$c_{12} = n_1 q_{12} \quad c_{21} = n_2 q_{21}$$

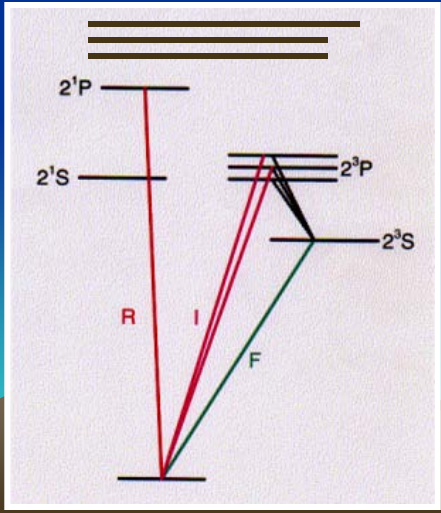
$$q_{12} = \frac{8.63x10^{-6} N_e}{\sqrt{T_e}} \left(\frac{\Upsilon_{12}}{g_1} \right) e^{-E_{12}/kT_e}$$

$$r_{21} = n_2 A_{21}$$

$$r_{12} = n_1 B_{12} I_{12}$$

Back to thermal balance

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



Statistical equilibrium

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

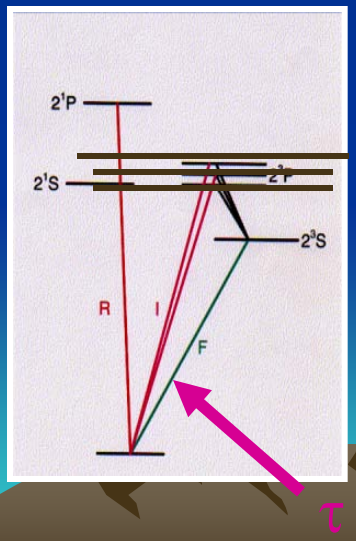
$$\frac{dn_2}{dt} = 0$$

Line cooling

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

Back to thermal balance

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



$$A_{21}h\nu_{21} \Rightarrow A_{21}h\nu_{21}\beta_{21}$$

$$\beta_{21} \propto \frac{1-e^{-\tau}}{\tau_{21}} \approx \frac{1}{\tau_{21}}$$

Statistical equilibrium

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

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

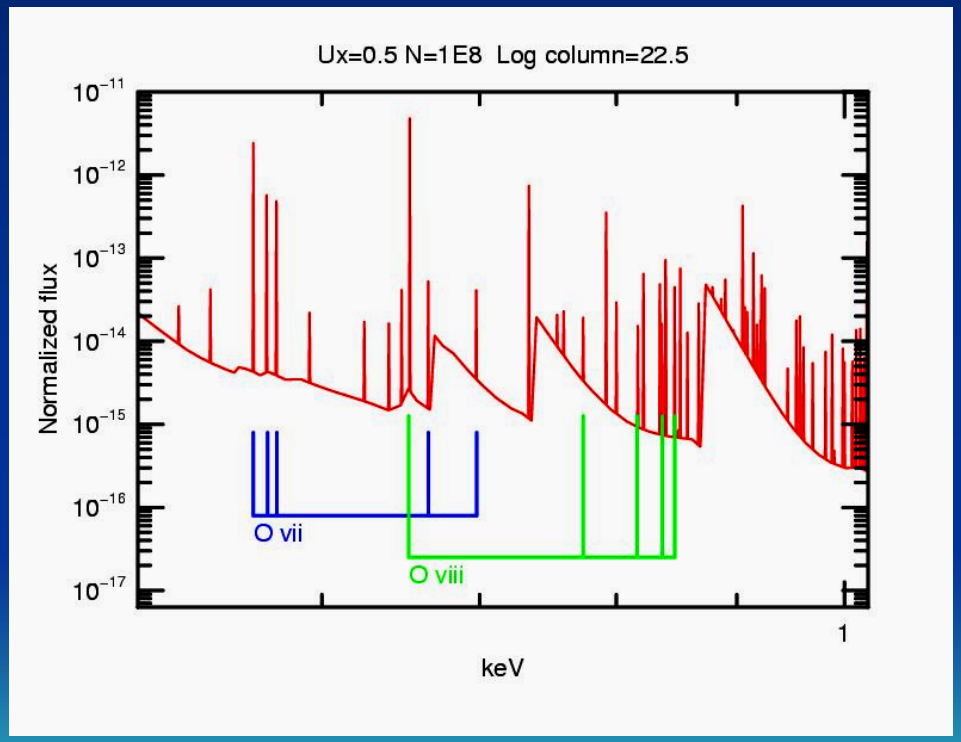
Line cooling

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

H(T)=C(T)

Continuum emission and absorption

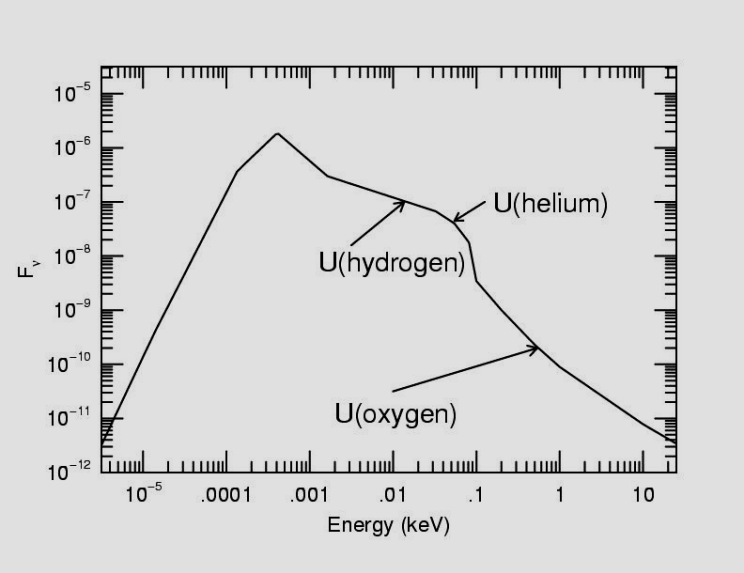
- Bound free (b-f) transitions
- Free-free (f-f) transitions



$$j_\nu \propto T_e^{-0.5} N_e N_i Z^2 g_{ff}(\nu, T) e^{-h\nu/kT}$$

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)	0.1 keV	10 keV
U(oxygen)	0.54 keV	10 keV
$\xi = \frac{L}{N_e r^2}$	13.6 eV	13.6 keV

The spectrum of photoionized gas

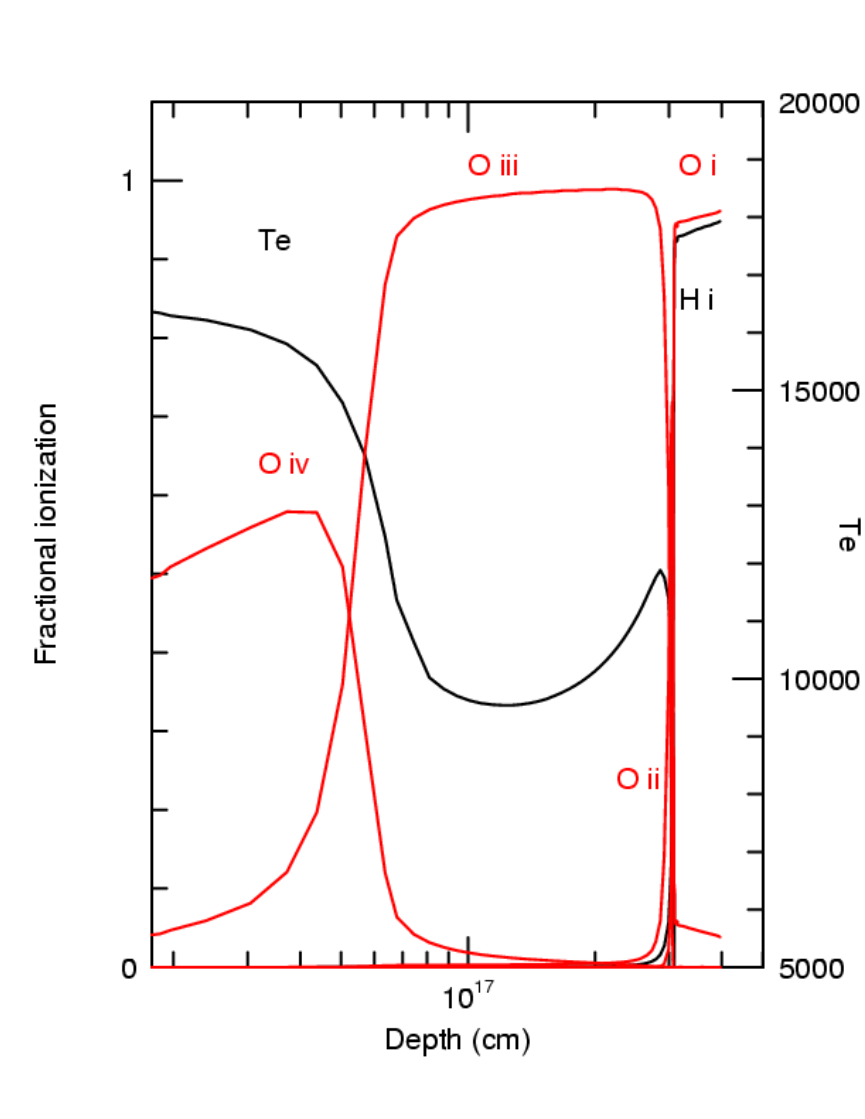
Photoionization calculations

- ionization structure
- thermal structure

Spectral calculations

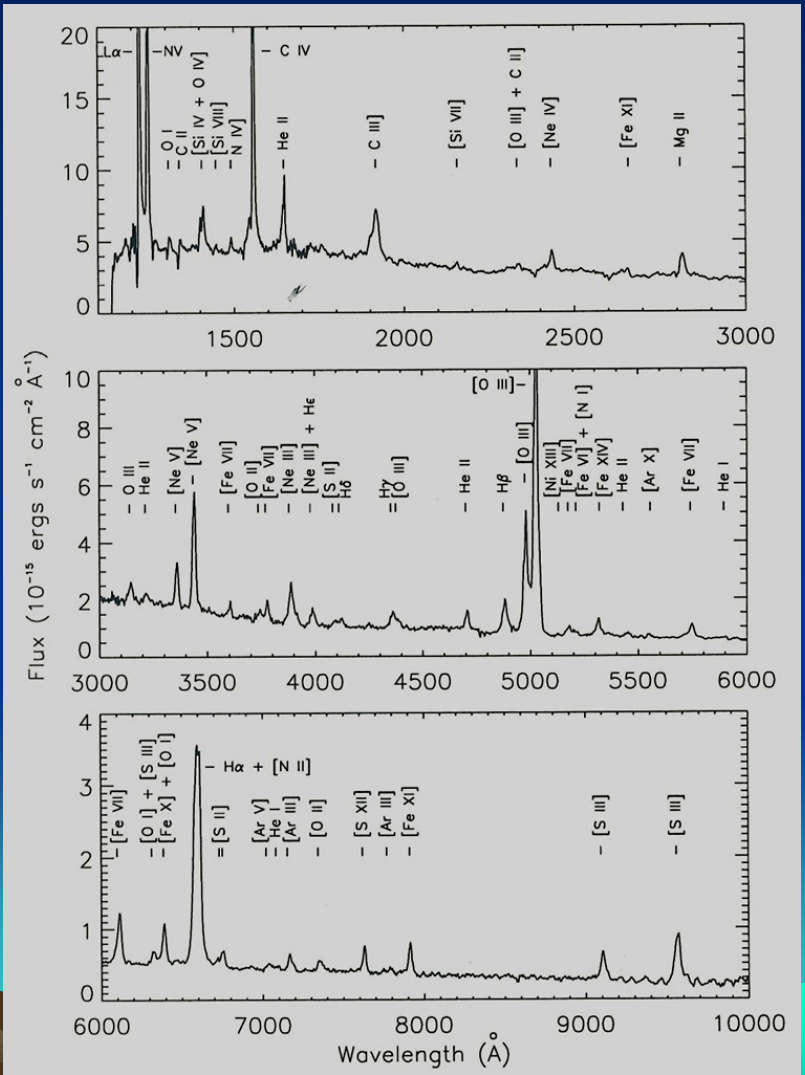
- line emission
- continuum emission
- line and continuum absorption

Ionization by hot stars compared with ionization by an AGN SED



The spectrum of ionized gas

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



Physical processes - 3

- The motion of ionized gas
  - The equation of motion
  - Radiation pressure
- Non-thermal processes
  - Synchrotron emission
  - Inverse Compton
  - Relations to radio and gamma-ray emission

The motion of ionized gas

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

$$a(r) = a_{rad}(r) - g(r) + \Psi$$

cloud $\Psi = \frac{f_d}{M_c}$

wind $\Psi = -\frac{1}{\rho}\frac{dP}{dr}$

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

Simple wind solution

$$\dot{M} = 4\pi r^2 \rho(r) v(r) = const.$$

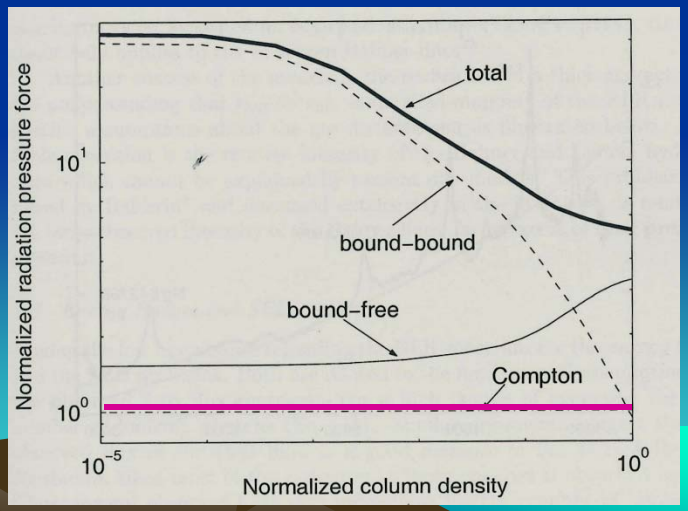
$$v(r) \propto \frac{1}{r^2 \rho(r)} \quad for\ \rho(r) \propto r^{-2} \quad v(r) = cons.$$

The force multiplier

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

$$a_{rad}(r) = a_{rad}(Compton) \cdot M(r)$$

M(r)=force multiplier



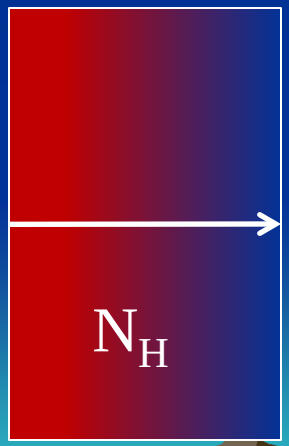
The motion of ionized gas

$$a(r) = a_{rad}(r) - g(r) + \Psi$$

cloud $\Psi = \frac{f_d}{M_c}$

wind $\Psi = -\frac{1}{\rho}\frac{dP}{dr}$

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

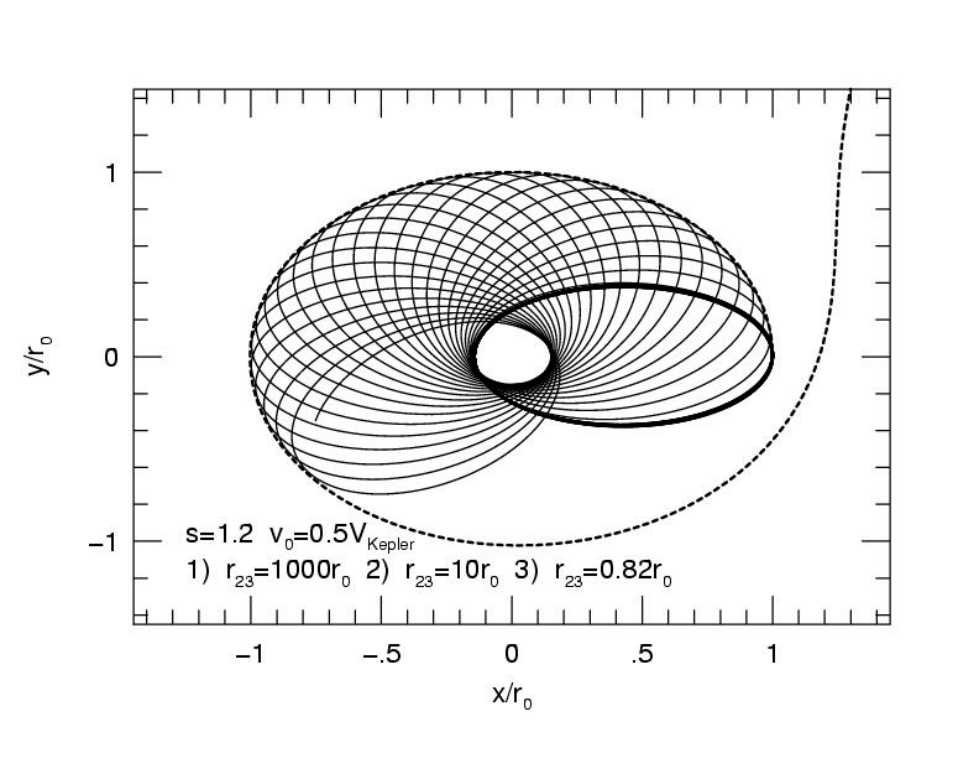


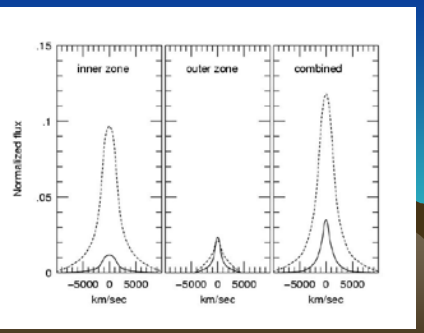
Accelerating a block

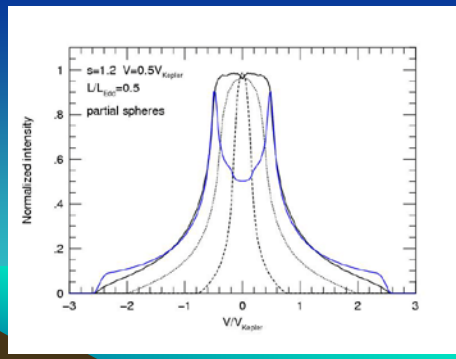
$$a_{rad} - a_g = \frac{a(r)L}{4\pi r^2 c M_c} - \frac{GM_{BH}}{r^2} =$$

$$= \frac{L}{r^2}\left[\frac{a(r)}{4\pi r^2 c m_p N_H(r)} - \frac{G}{7.5x10^4 (L/L_{Edd})} \right]$$

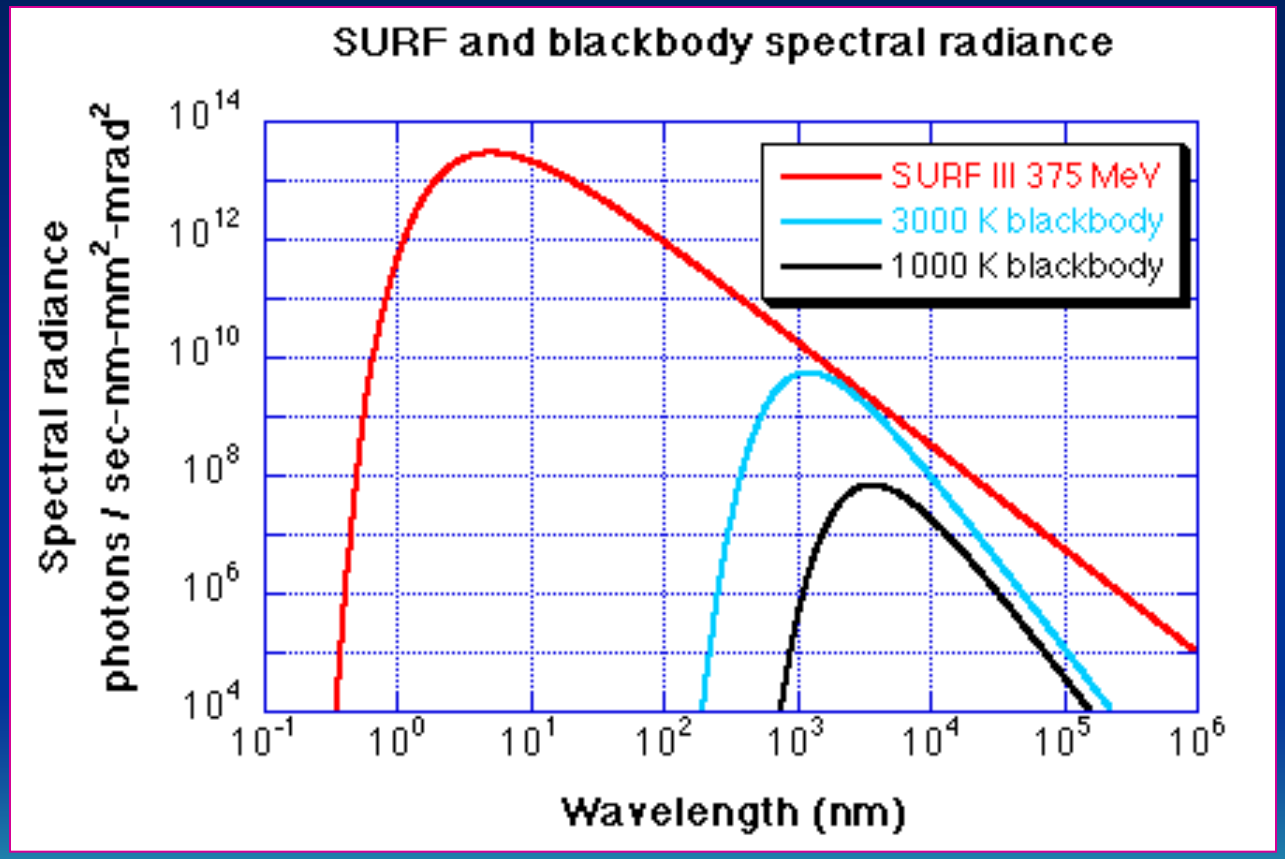
Real calculations

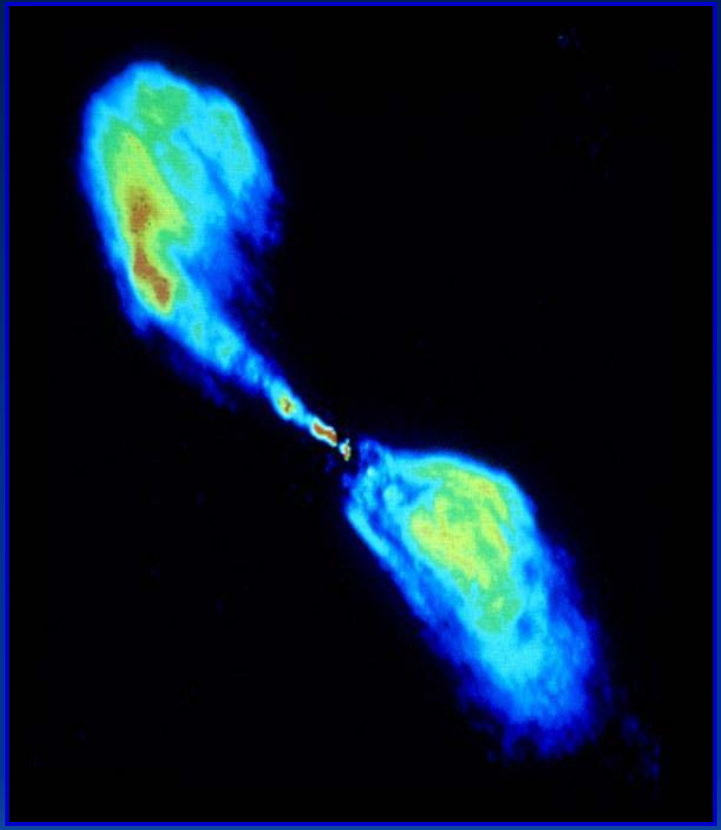






Thermal and nonthermal spectral energy distributions (SEDs)





Nonthermal radiation processes

$$n(\gamma)d\gamma = n_0\gamma^{-p}d\gamma$$

$$\langle P \rangle = \frac{4}{3}\beta^2\gamma^2 c\sigma_T u_B$$

$$j_\nu \propto u_B \nu^{-0.5(p-1)}$$

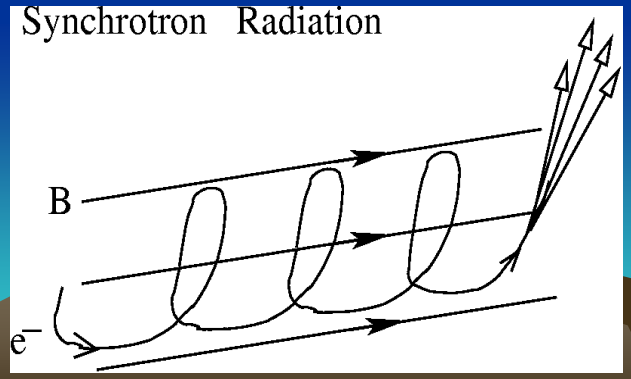
Synchrotron radiation

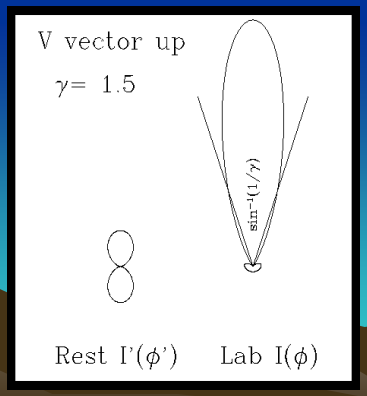
$$n(\gamma)d\gamma = n_0\gamma^{-p}d\gamma$$

$$\langle P \rangle = \frac{4}{3}\beta^2\gamma^2 c\sigma_T u_{rad}$$

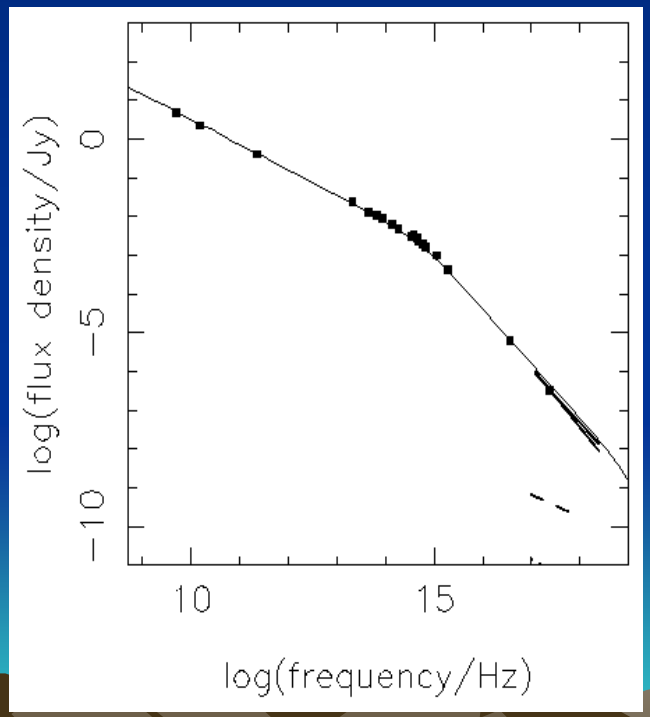
$$j_\nu \propto u_{rad} \nu^{-0.5(p-1)}$$

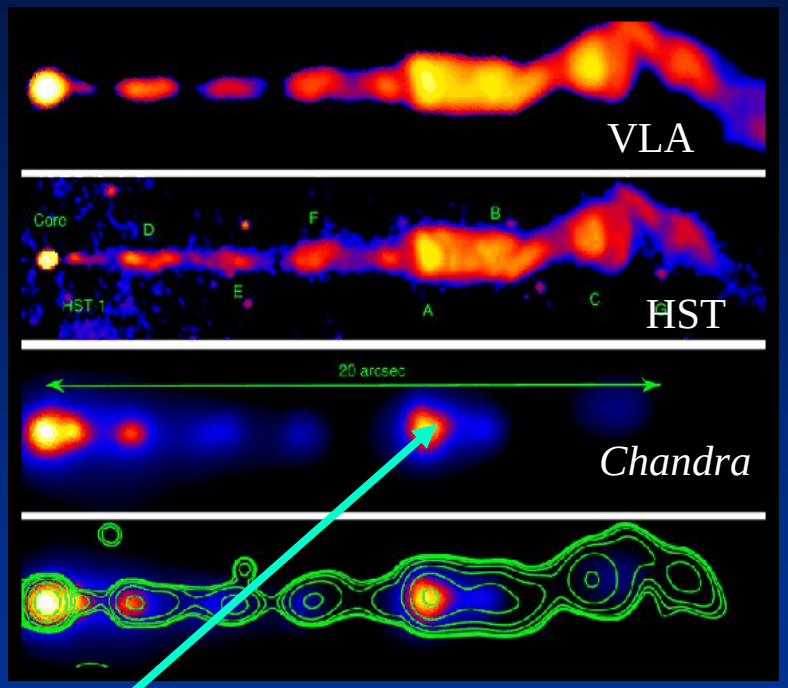
Inverse Compton





Synchrotron with broken power law fits X-ray spectrum

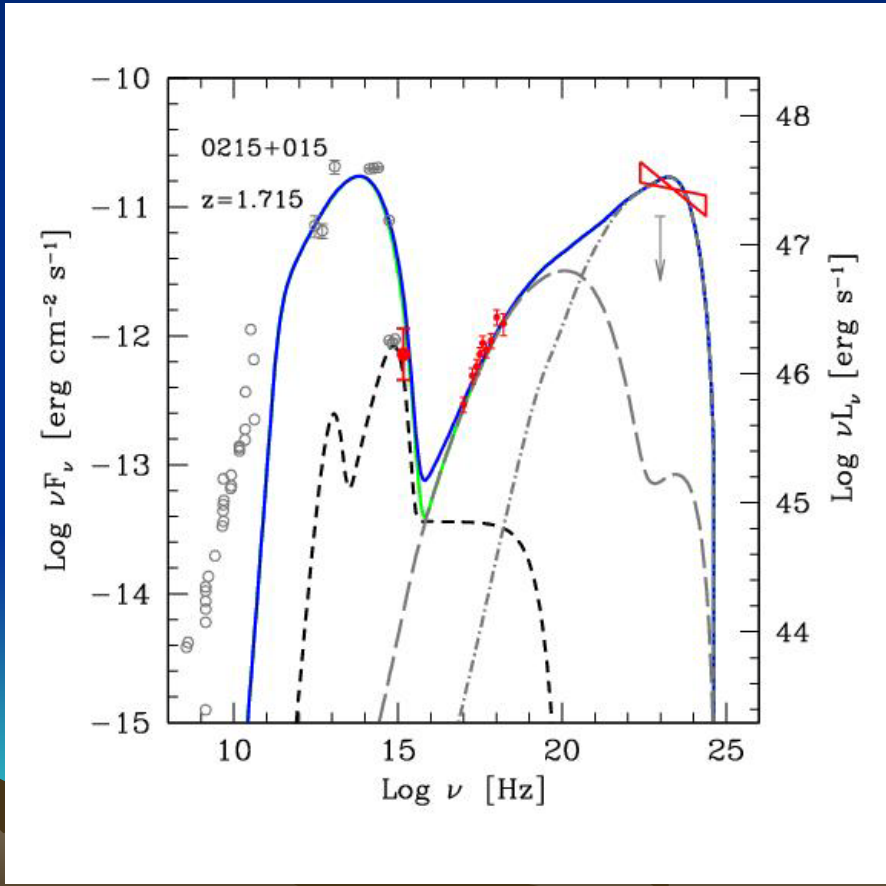




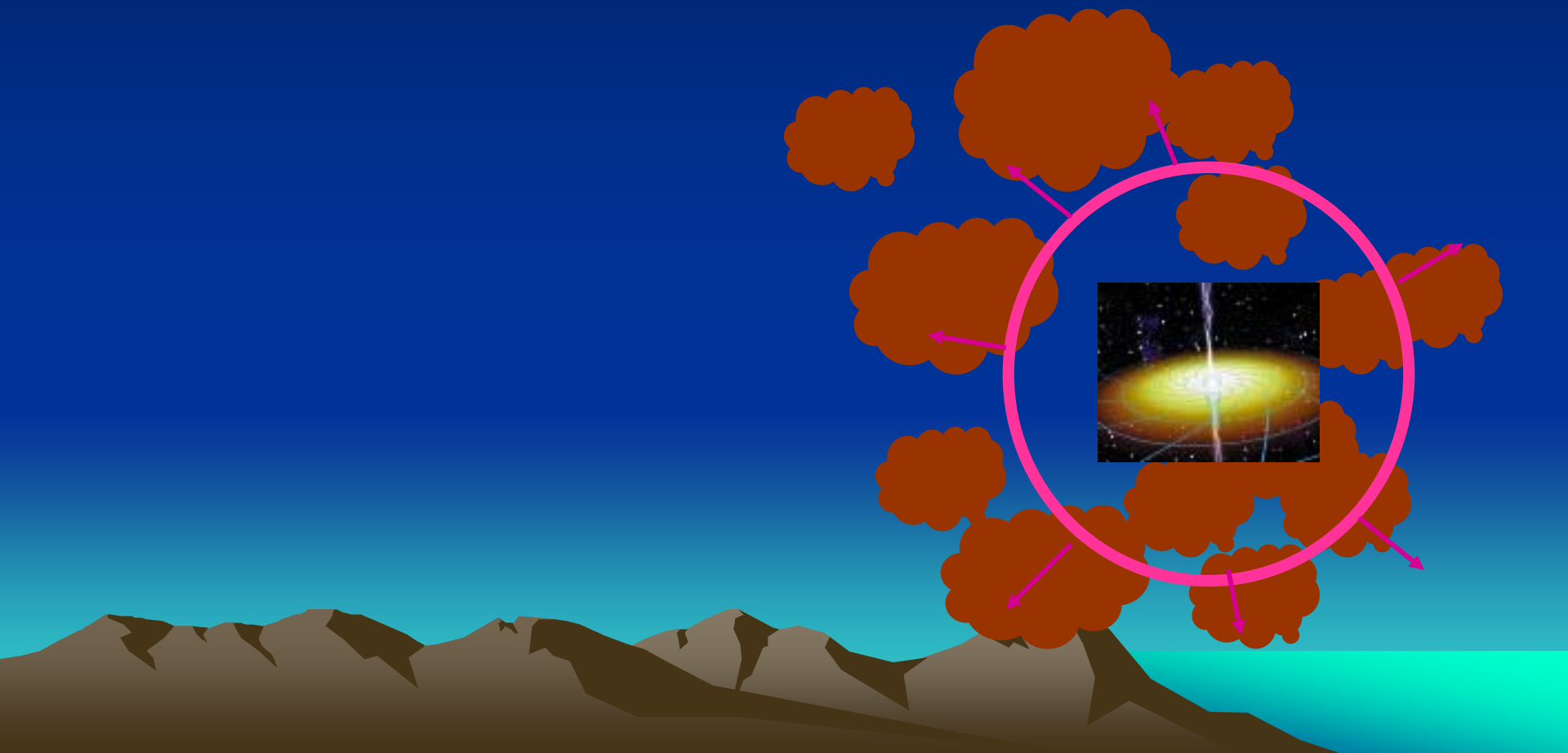
Marshall et al. 2002

M 87 Knot A

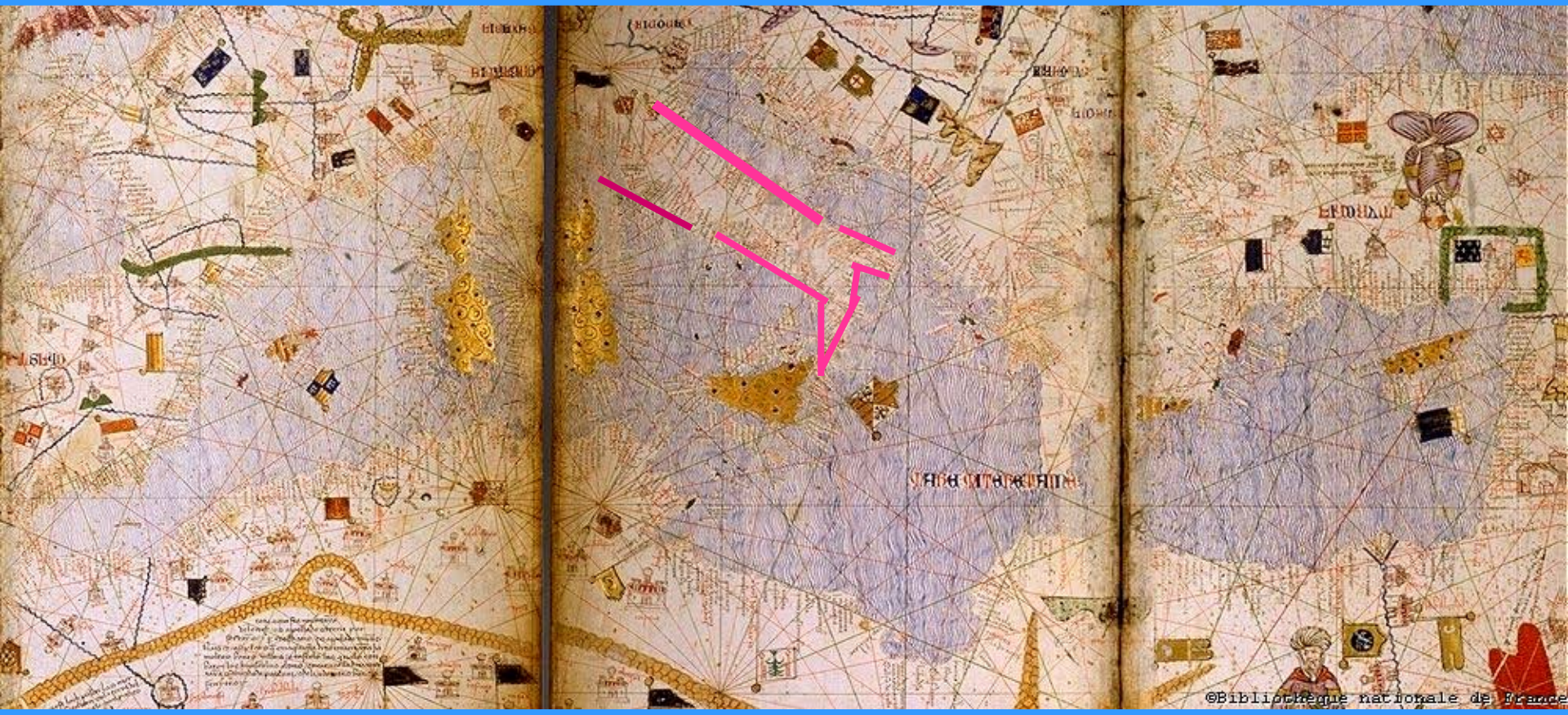
Synchrotron
Inverse Compton
Synchrotron self Compton



Exploring the landscape



Ptolemy’s map



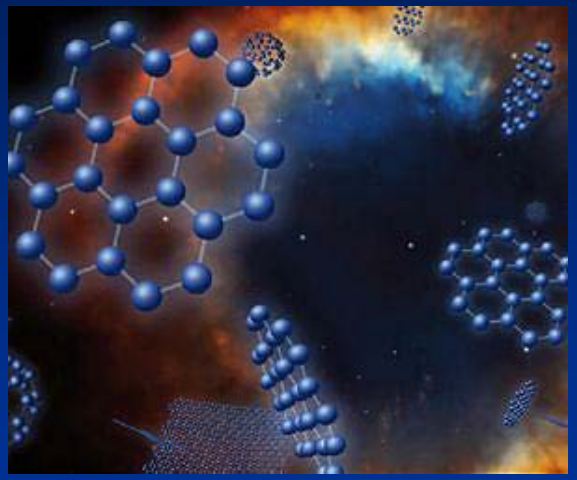
Catalan Atlas

Physical processes - 4

- AGN dust
  - General dust properties
    - Dust grains
      - Formation and sublimation
      - Metallicity and depletion
    - Dust temperature and dust emission
  - Dust in ionized gas
  - Extinction by dust

General dust properties

- Dust grains
  - Silicate dust
  - Carbon (graphite) dust
  - Grain size
  - PAHs
- Galactic (ISM) dust
  - Metallicity and depletion



Graphene bucky balls
(2011 discovered in space)

Dust grains

- ISM dust
- Grain composition
  - Graphite grains
  - Silicate grains
- Grain size distribution
- Depletion

$$\frac{dn(a)}{da} = k_d a^{-\alpha}$$

$$0.01 \le a \le 0.3\,\mu m$$

$$\alpha \approx 3.5$$

Element	Abundance	Relative depletion
H	1	0
C	2.5×10^{-4}	0.5
O	4.5×10^{-4}	0.35
Ne	9×10^{-5}	0
Mg	3.2×10^{-5}	0.9
Fe	2.5×10^{-4}	0.97

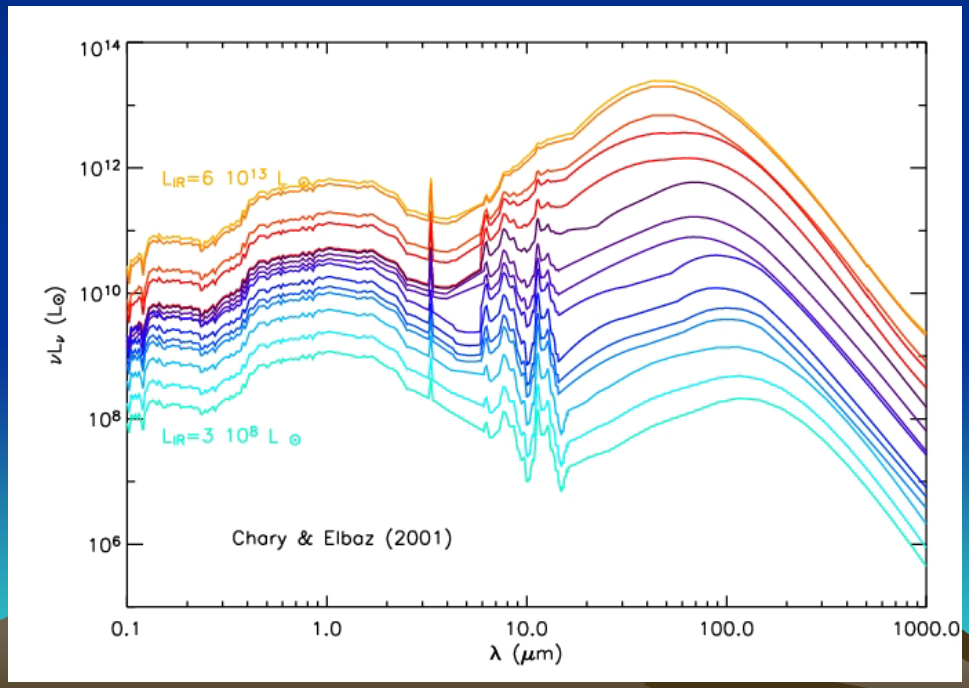
Emission and absorption by dust

- Blackbody emission
- Modified (grey) blackbody emission
- Observations of dust emission

$$I(abs) = \frac{\pi a^2}{4\pi r^2} \int_0^\infty Q_\nu L_\nu d\nu$$

$$I(emit) = 4\pi a^2 \int_0^\infty \pi Q_\nu B_\nu (T_{dust}) d\nu$$

$$I(abs) = I(emit)$$



$$I_\nu = B_\nu (1 - e^{-\tau_\nu}) \approx B_\nu \tau_\nu$$

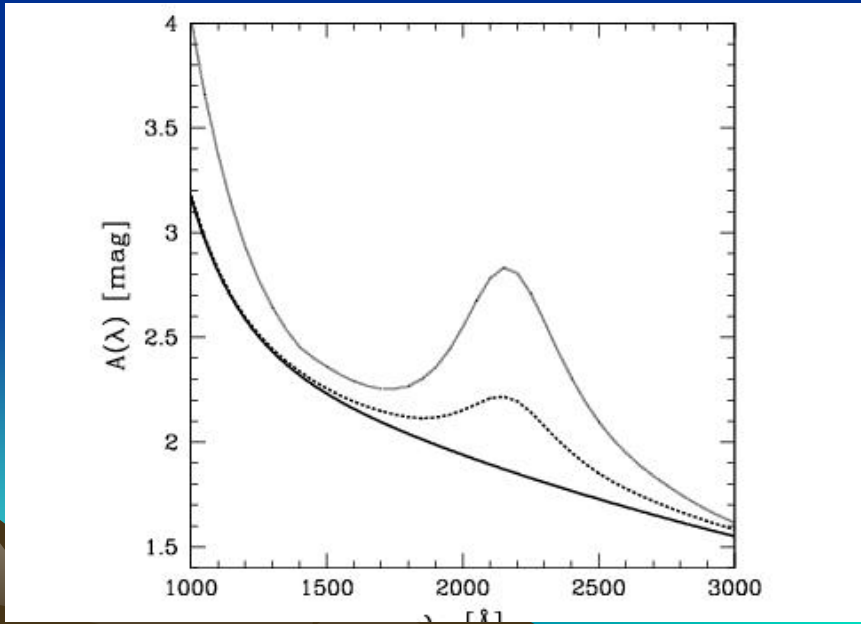
$$\tau_\nu \propto \nu^\beta \propto \lambda^{-\beta}$$

$$I_\nu \propto B_\nu \nu^\beta = \frac{(2h/c^2)\nu^{3+\beta}}{\exp(h\nu/kT) - 1}$$

Sublimation radius and Extinction curve

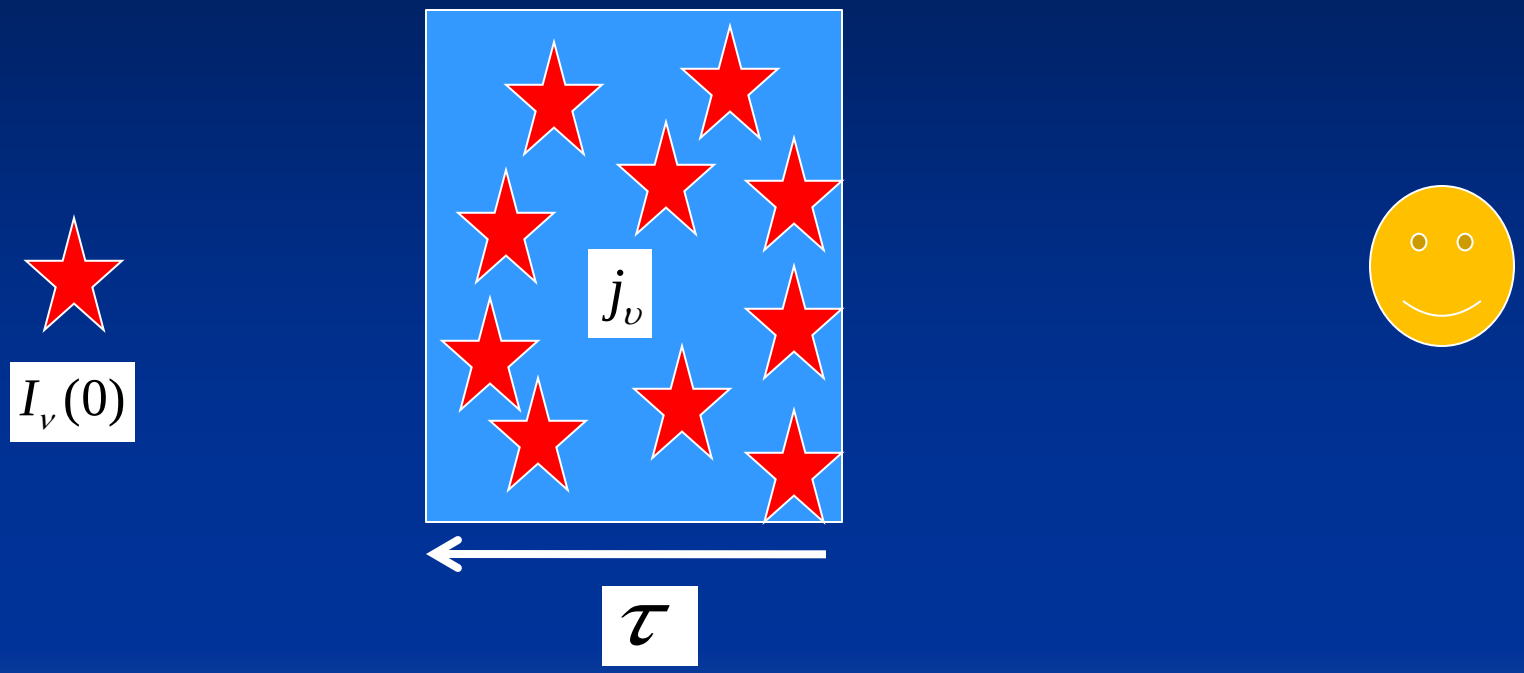
- Sublimation distance
  - Graphite dust T~1800K
  - Silicate dust T~1500K
- Extinction laws
  - External dust
  - Internal dust

$$R_{sublimation} \approx \left[\frac{L}{10^{46}}\right]^{1/2} \left[\frac{1600}{T_{sub}}\right]^{2.6} pc$$



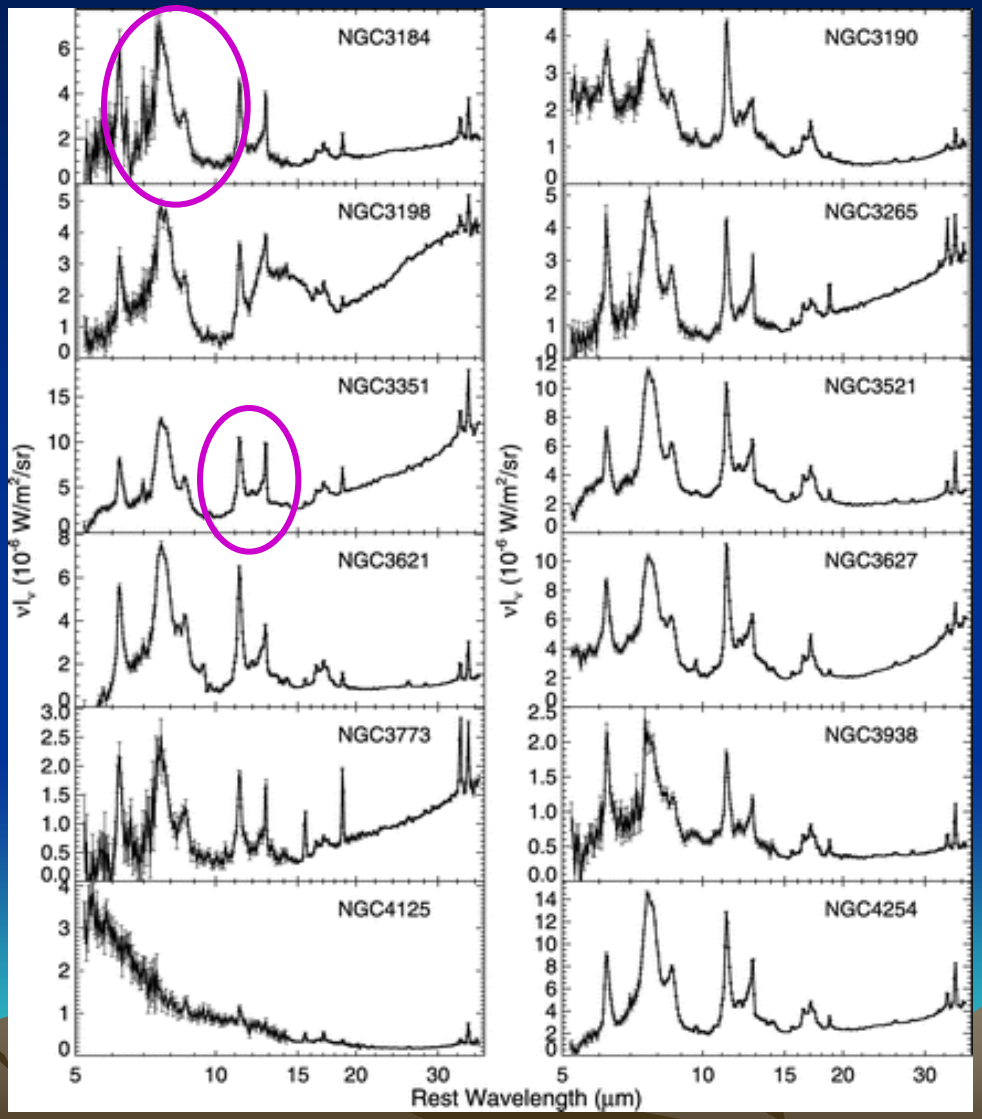
Differential dust absorption (for E(B-V) = 0.2) according to Calzetti's law (solid line), a superposition of Calzetti's law with a 2175 A bump of amplitude α = 0.25 (dashed line), and the Seaton (1979) extinction curve for the Milky Way (dotted line).

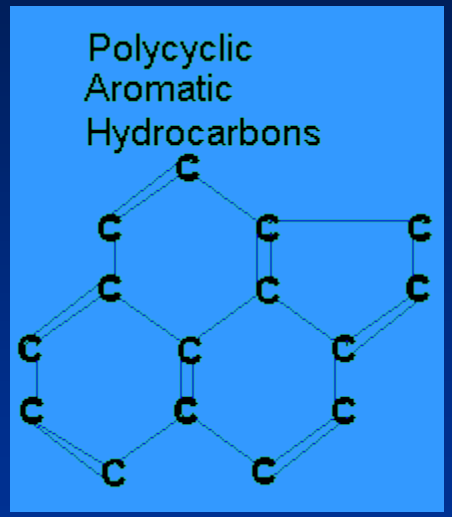
The simplest solution of the equation of radiative transfer



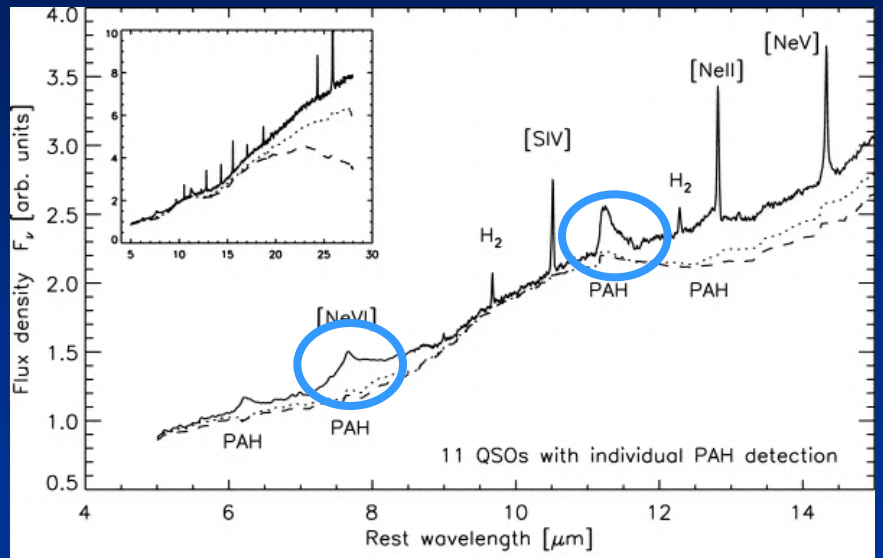
$$I_\nu = I_\nu(0)e^{-\tau_\nu} + S_\nu(1-e^{-\tau_\nu})$$

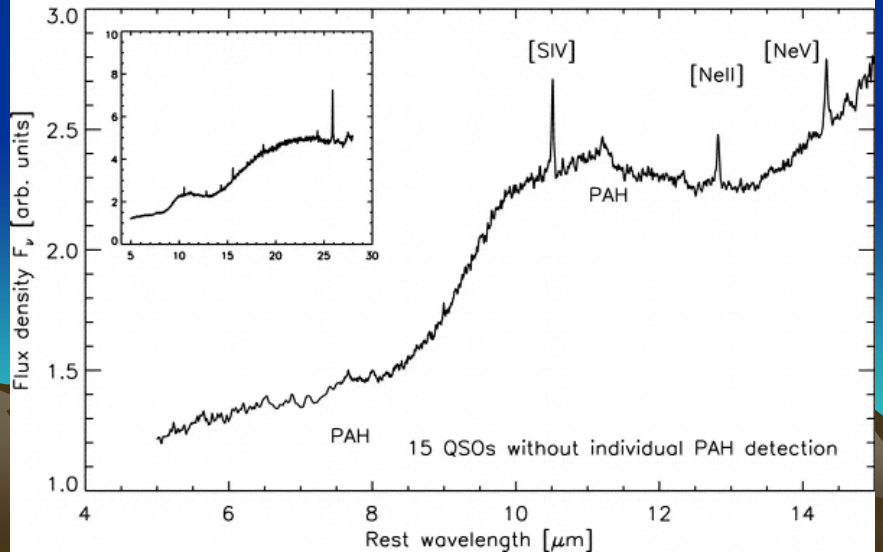
PAH emission

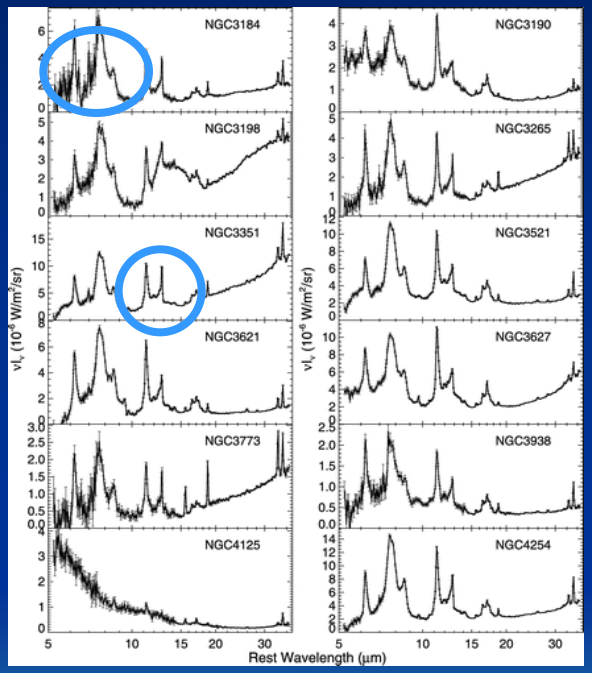




Starburst spectral features in AGN (PAHs)

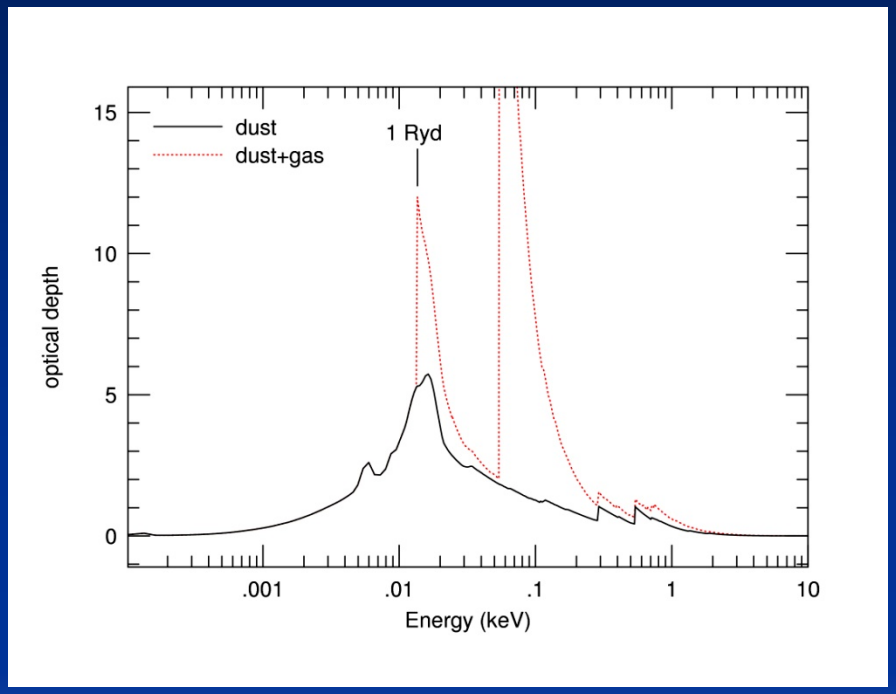


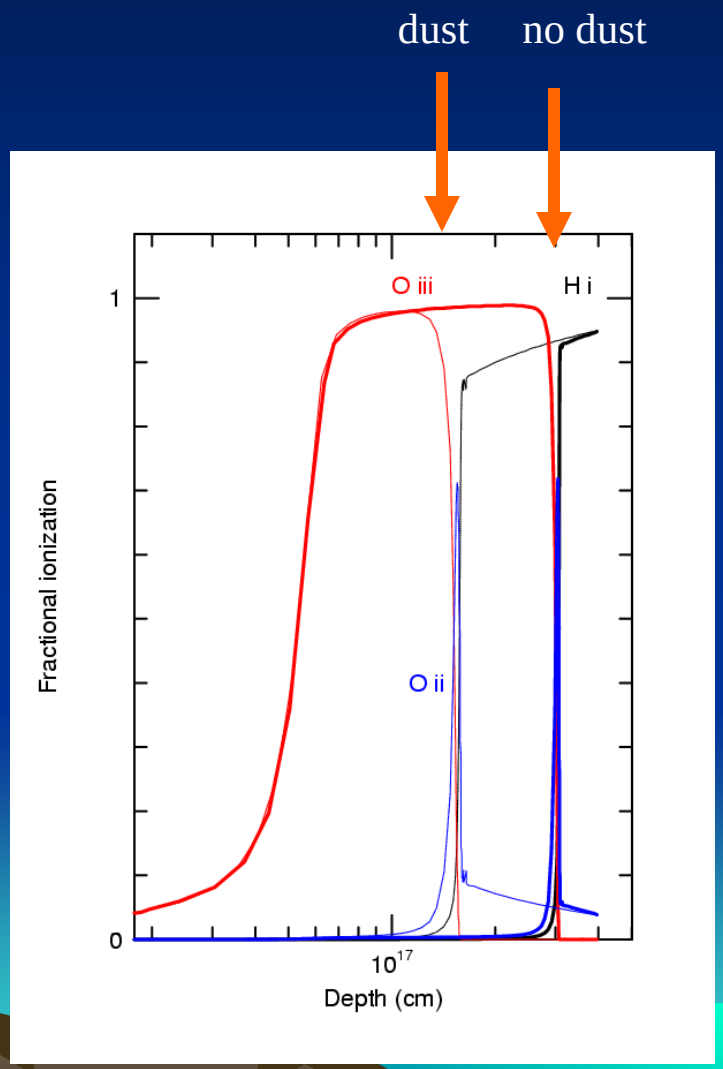




Starburst galaxies

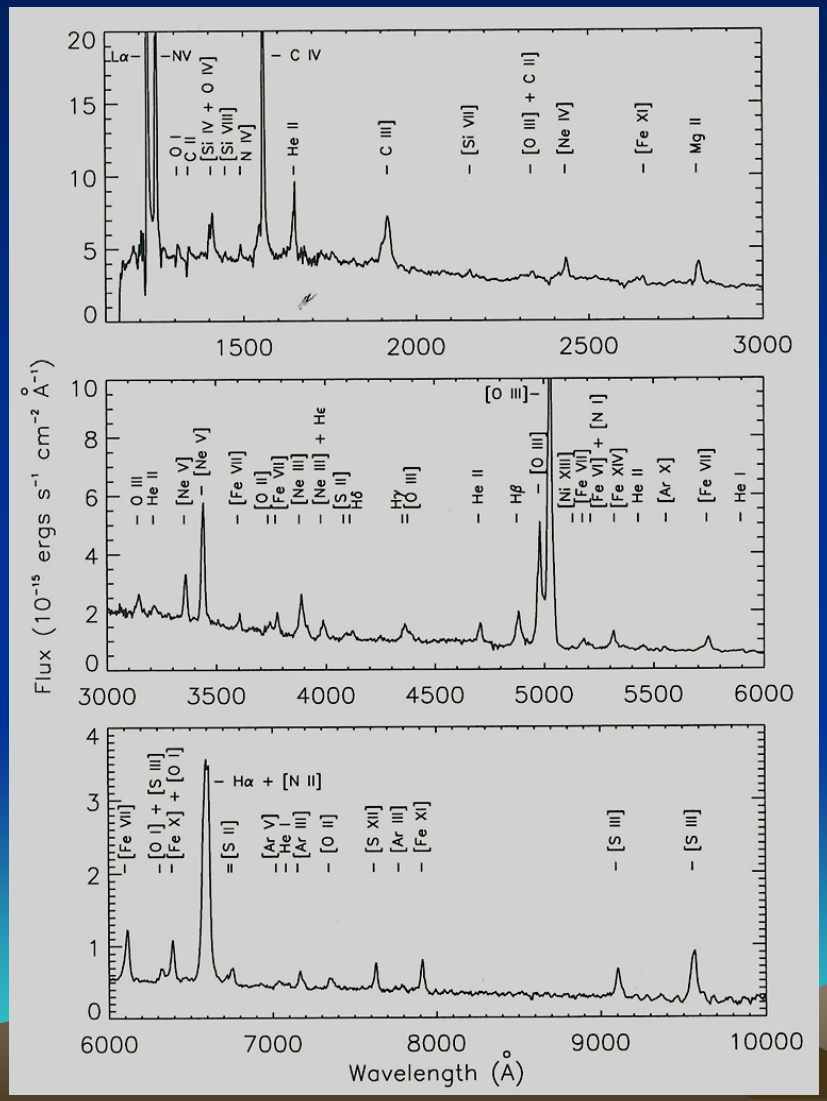
Absorption cross section and modified level of ionization

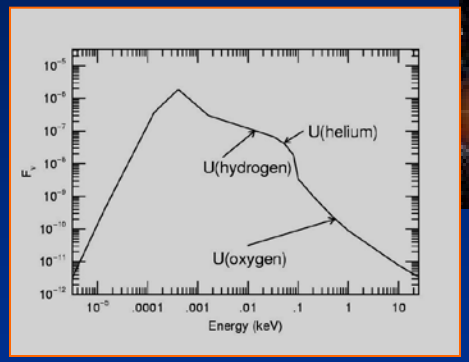




$$\frac{\tau(dust)}{\tau(gas)} \propto \frac{N_{dust}}{N_{H^0}} \propto \frac{N(H^+)}{N(H^0)} \propto U(hydrogen)$$

Physical processes - summary





Main components of AGNs 1

- The broad line region (BLR)
  - Clouds and confinement
  - The BLR spectrum
  - Gas motion in the BLR
- The narrow line region (NLR)
  - Dust in the NLR
  - Diagnostic diagrams

Main components : The BLR

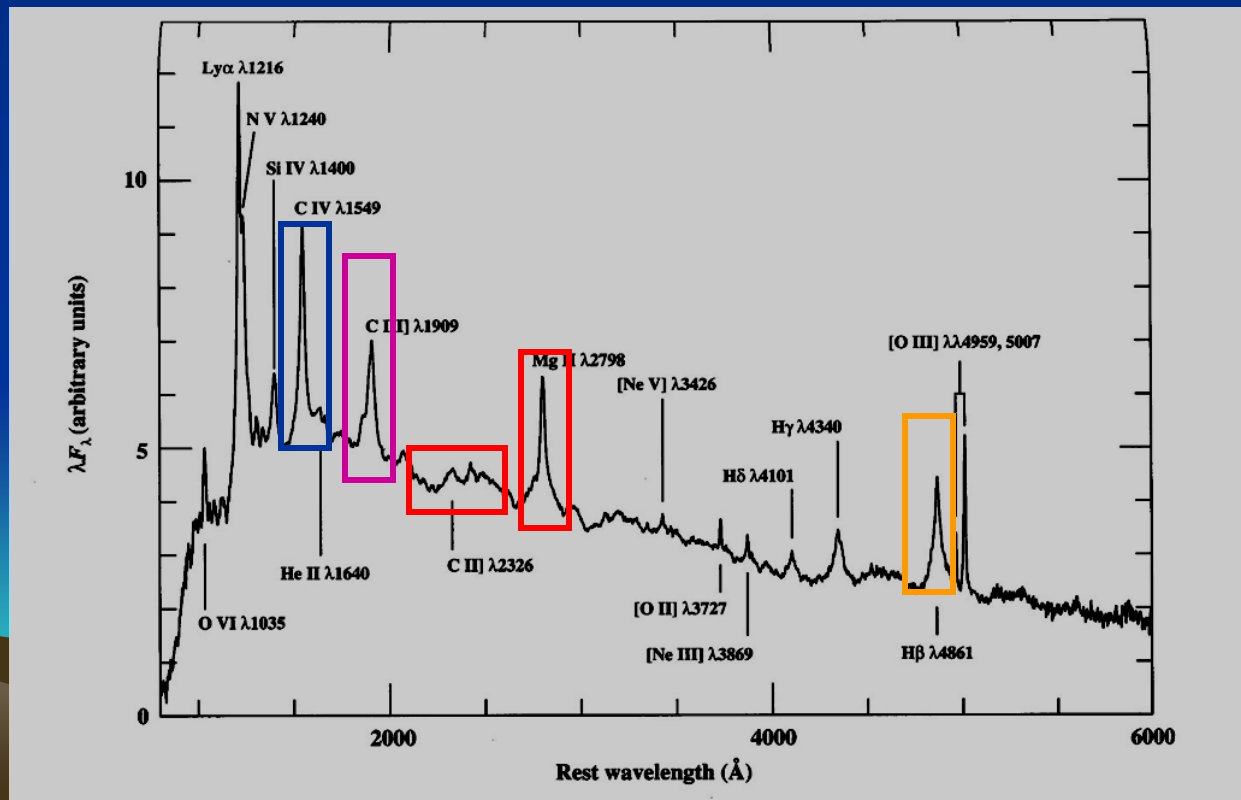
- Assume BH mass 10^8 $M_\odot$
- Assumed clouds
  - Density $10^{9\text{-}11}$ cm^{-3}
  - Large column density
  - Location: ~ 0.1pc
  - Confinement
    - by hot gas
    - by magnetic fields
  - Covering fraction ~0.1
- The spectrum
  - Resonance lines
  - Semi-forbidden lines
  - Balmer lines
  - FeII and MgII lines

Bound system (gravity dominated)

Gas velocity ~ 3000 km/sec

large EW emission lines

Weak absorption lines

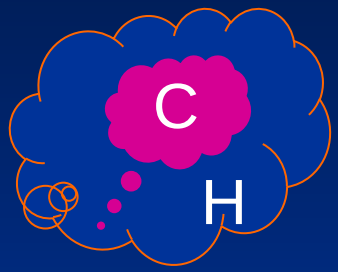


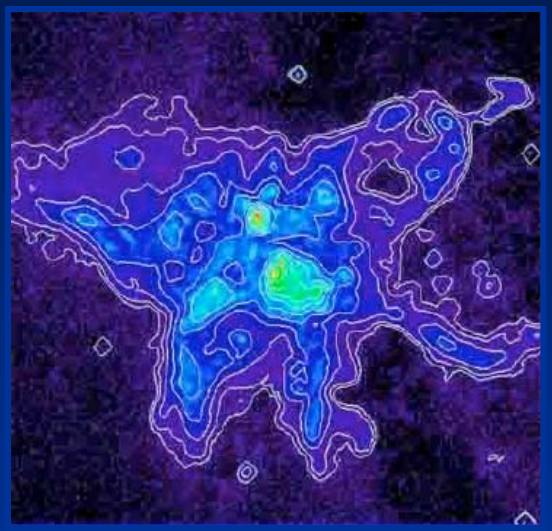
Main components of AGNs
The BLR

- BLR properties
  - High density clouds
  - LOC
  - Disk outflow
- BLR Boundary
  - Dust in the BLR
- BLR dynamics
- BLR metallicity

Clouds LOC and winds

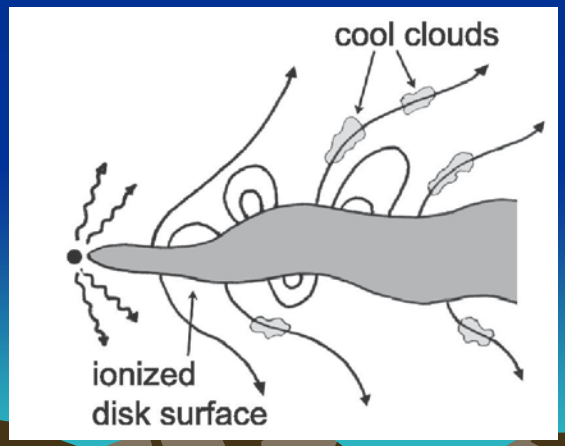
Clouds



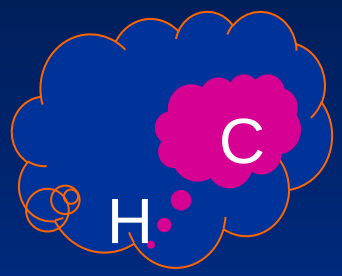


Locally Optimally emitting Clouds (LOC)

Winds



Confinement



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

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

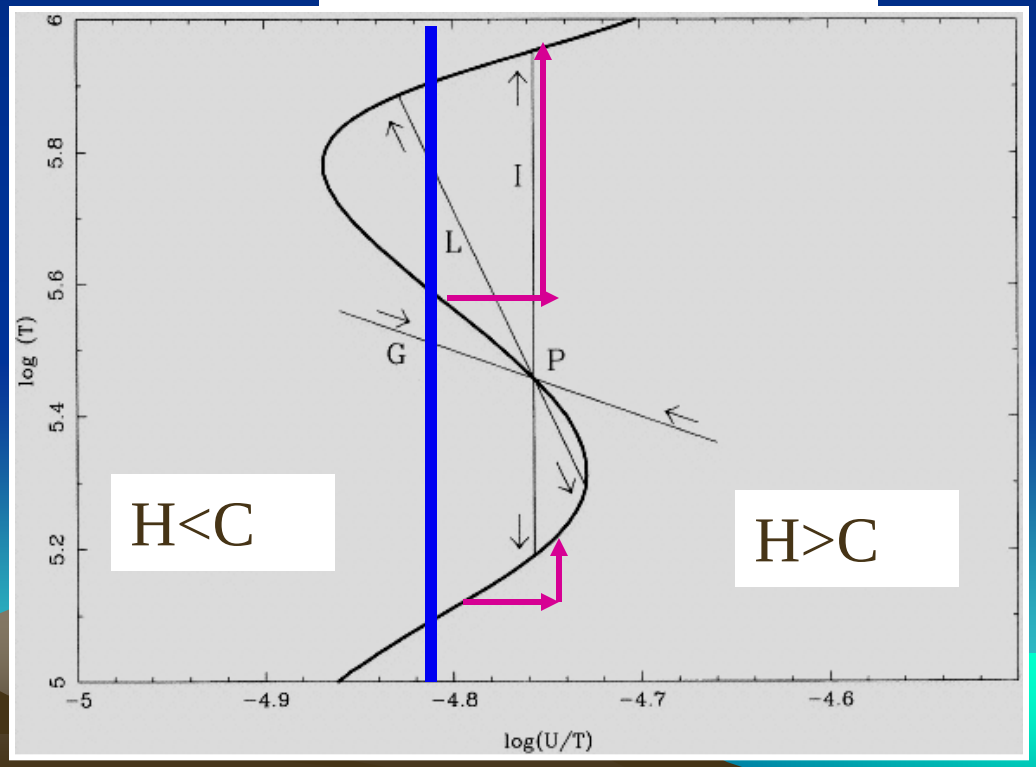
$$\frac{U}{T} \propto \frac{L / r^2 c}{TN} \propto \frac{P_{rad}}{P_{gas}}$$

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

Magnetic confinement

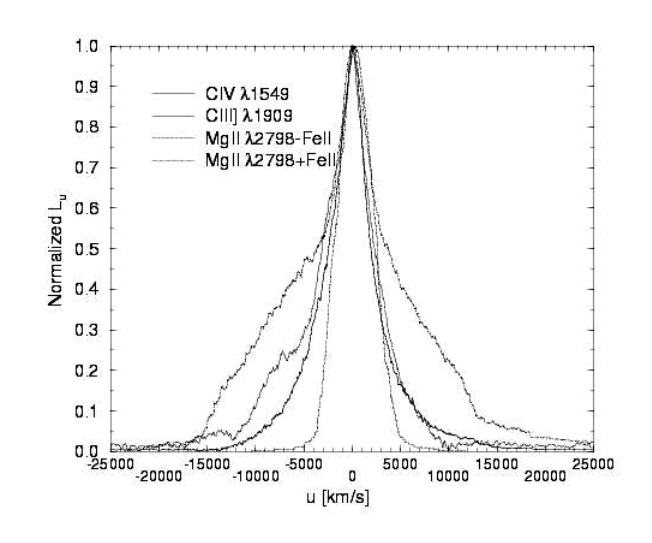
$$\frac{B^2}{8\pi} \geq NkT$$

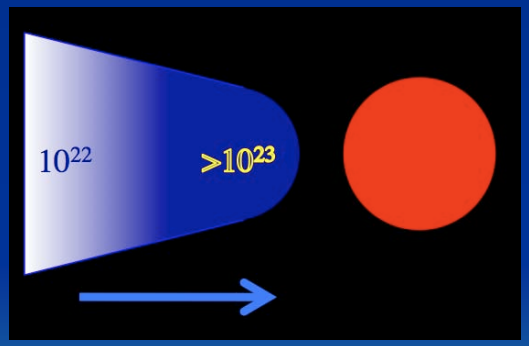
Stability curve H=C

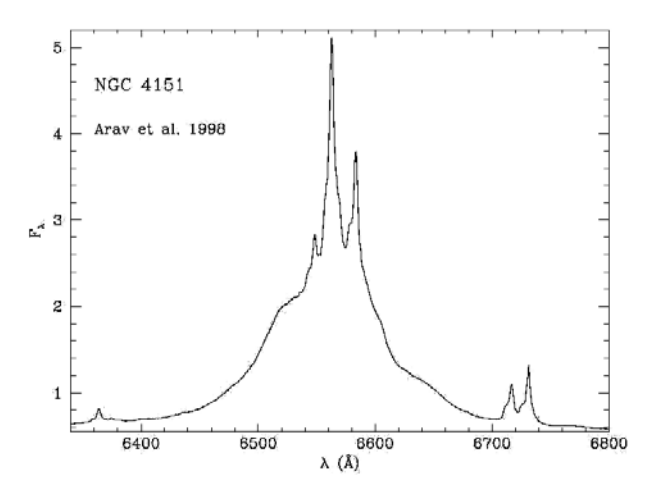


The BLR

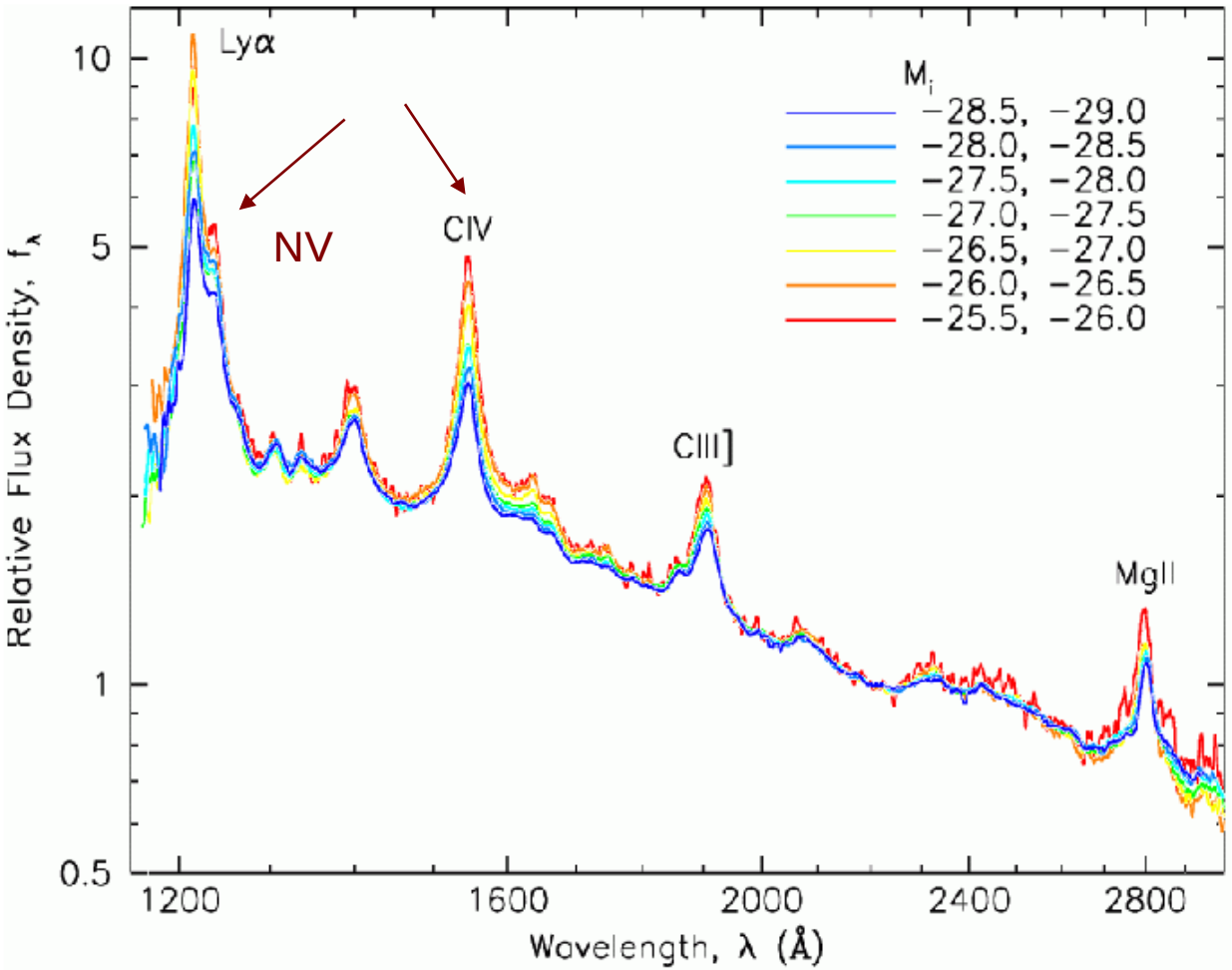
- Line profiles
  - cloud dynamics
  - the number of BLR clouds
  - Direct observations of BLR clouds?







BLR metallicity



The NLR

- Assume BH mass 10^8 $M_\odot$
- Assumed clouds
  - Density $10^{3\text{-}5}$ cm^{-3}
  - Large and small column density
  - Location ~ 1 kpc
  - Radial distribution
  - Confinement
  - Covering factor ~0.03

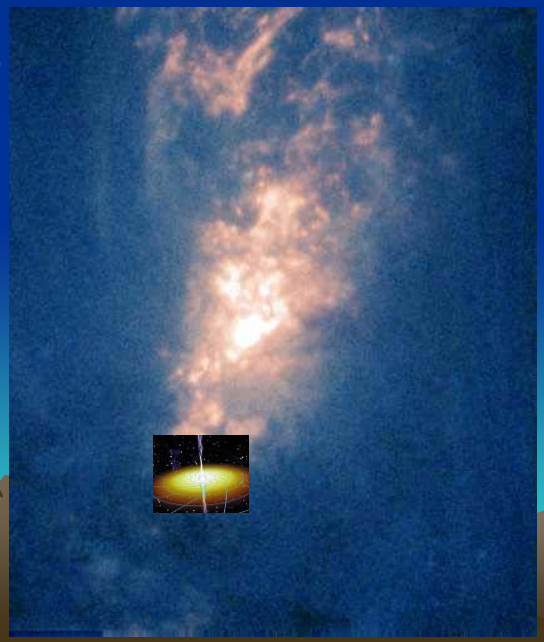
Bound system?

Gas velocity ~ 500 km/sec

small EW emission lines

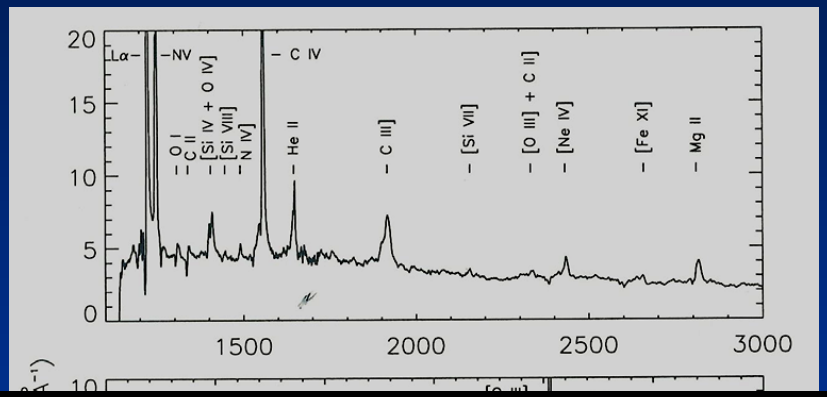
Weak absorption lines

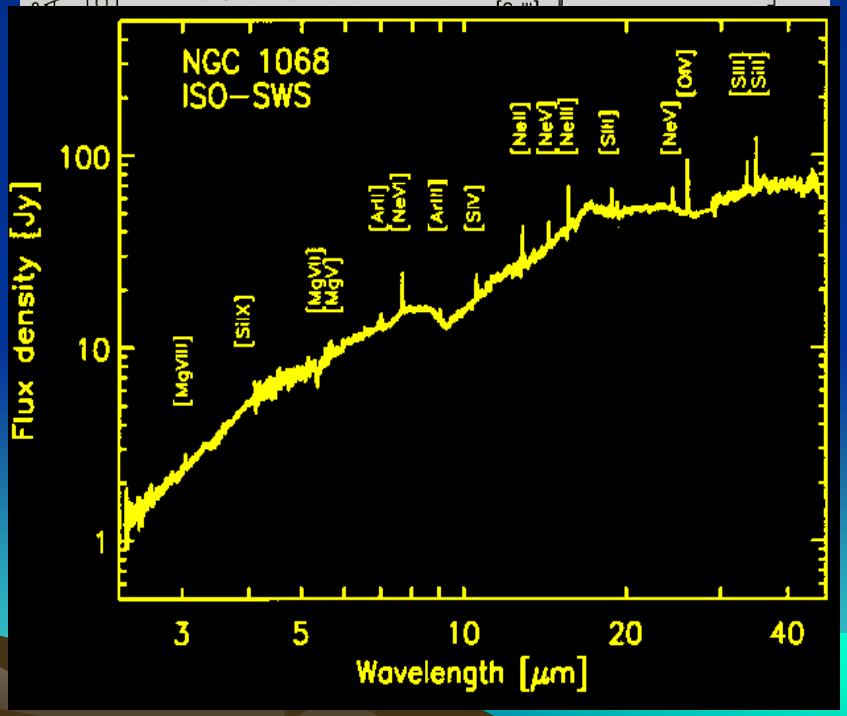
Time averaged spectral properties



The NLR: The observed spectrum

- The NLR spectrum
  - optical and UV lines
    - permitted, semi-forbidden and forbidden lines
  - IR lines
    - coronal lines
    - Low ionizaion lines
    - PAHs





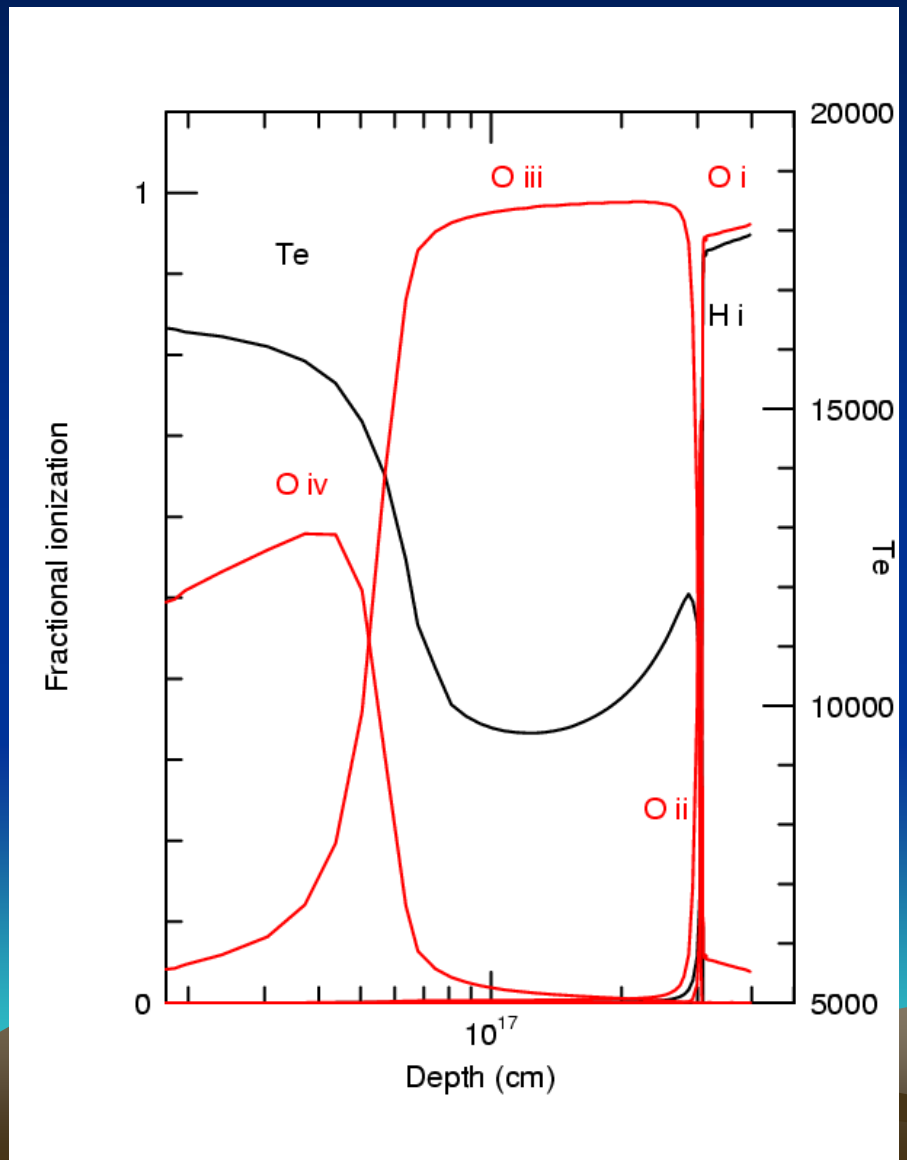
In the NLR we can only see

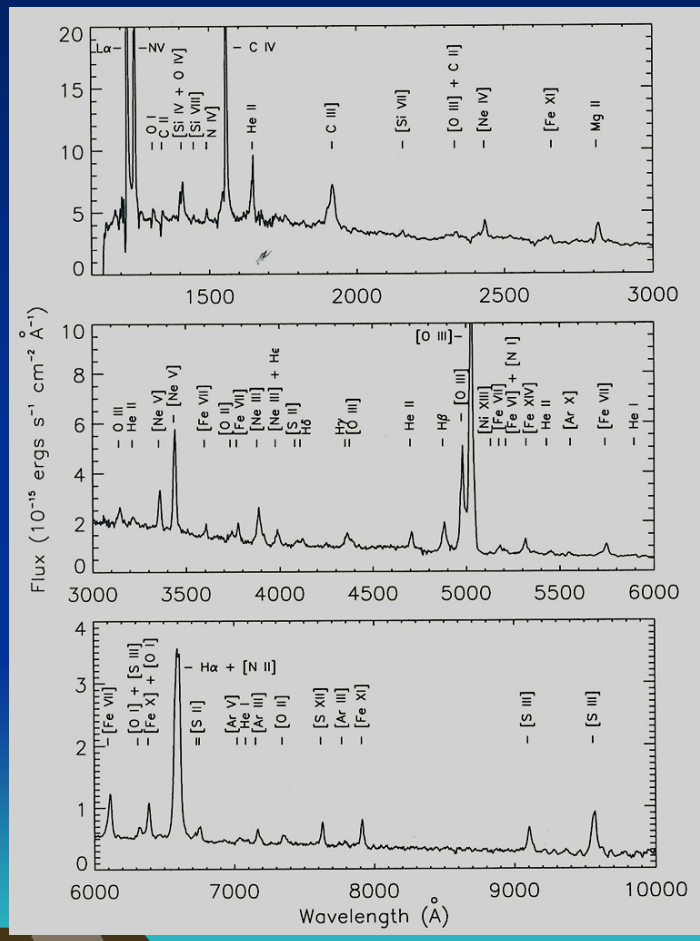
Time averaged spectral properties

because of the

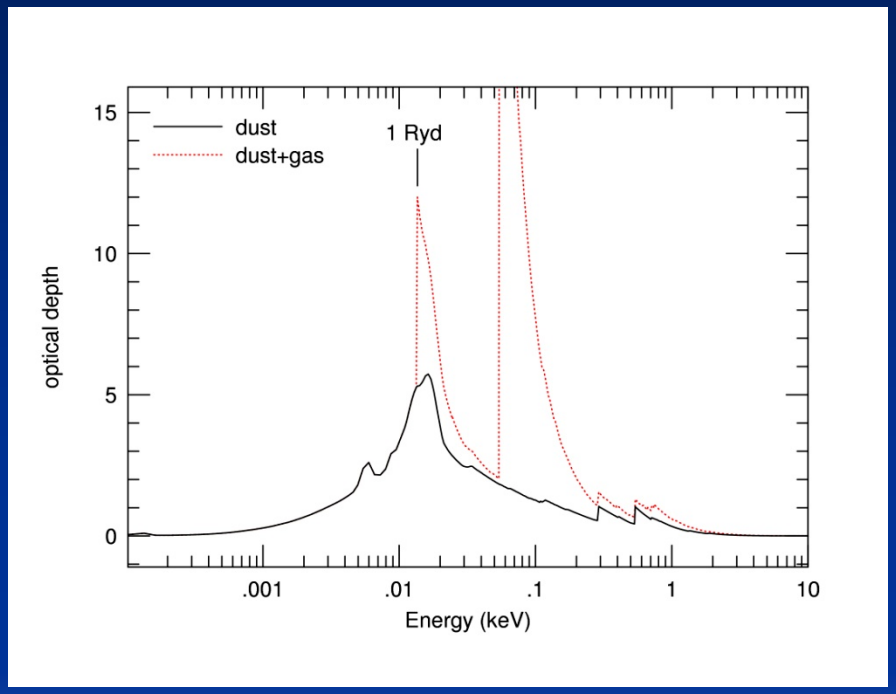
- **Large dimensions**
- **Long recombination times**

The NLR: Photoionization calculations

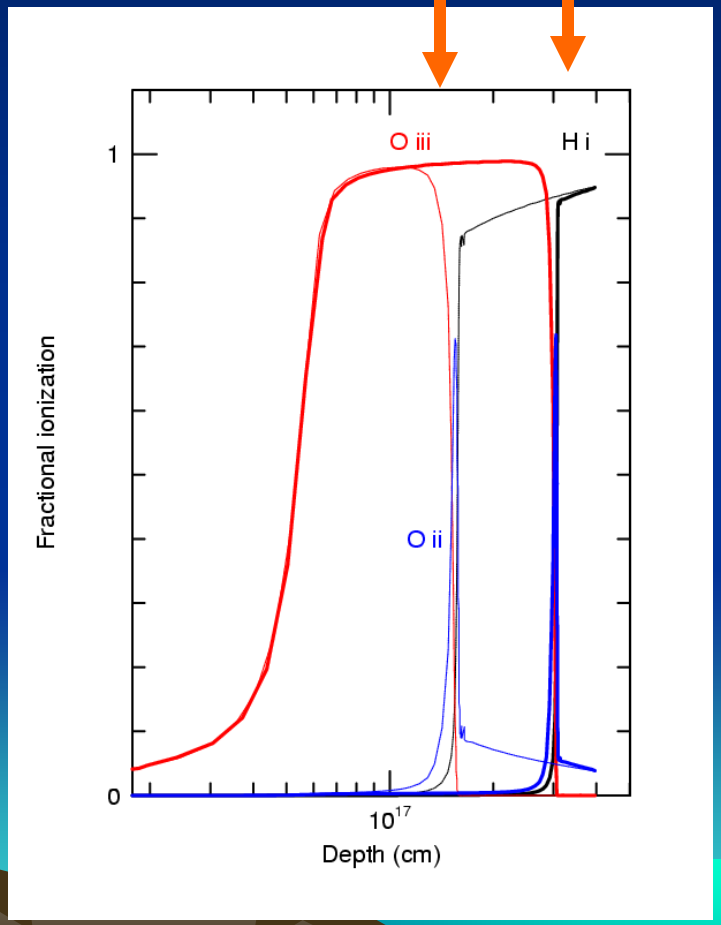




Photoionized dusty NLR gas



Dust no dust



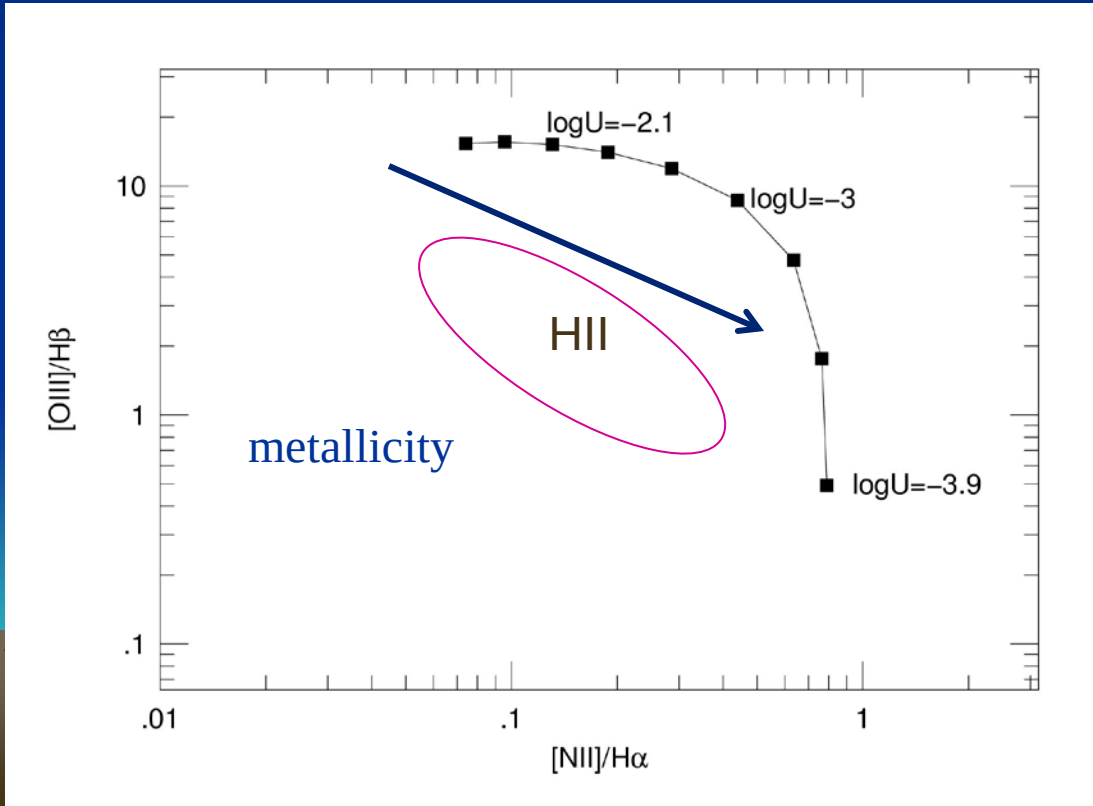
$$\frac{\tau(dust)}{\tau(gas)} \propto \frac{N_{dust}}{N_{H^0}} \propto \frac{N(H^+)}{N(H^0)} \propto U(hydrogen)$$

Diagnostic (BPT) diagrams

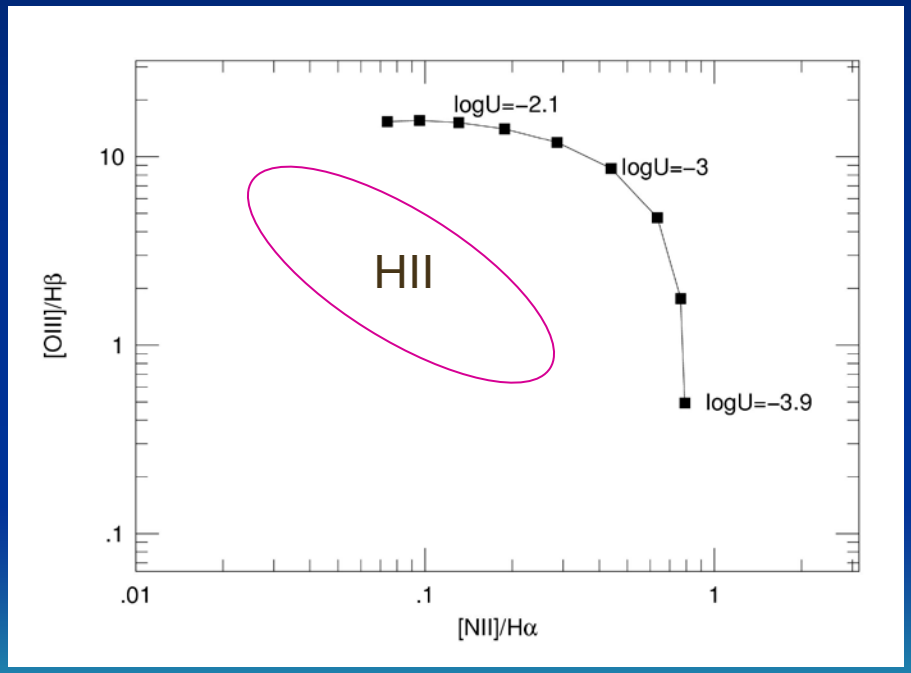
Photoionization calculations for a low density gas with a range of U and:

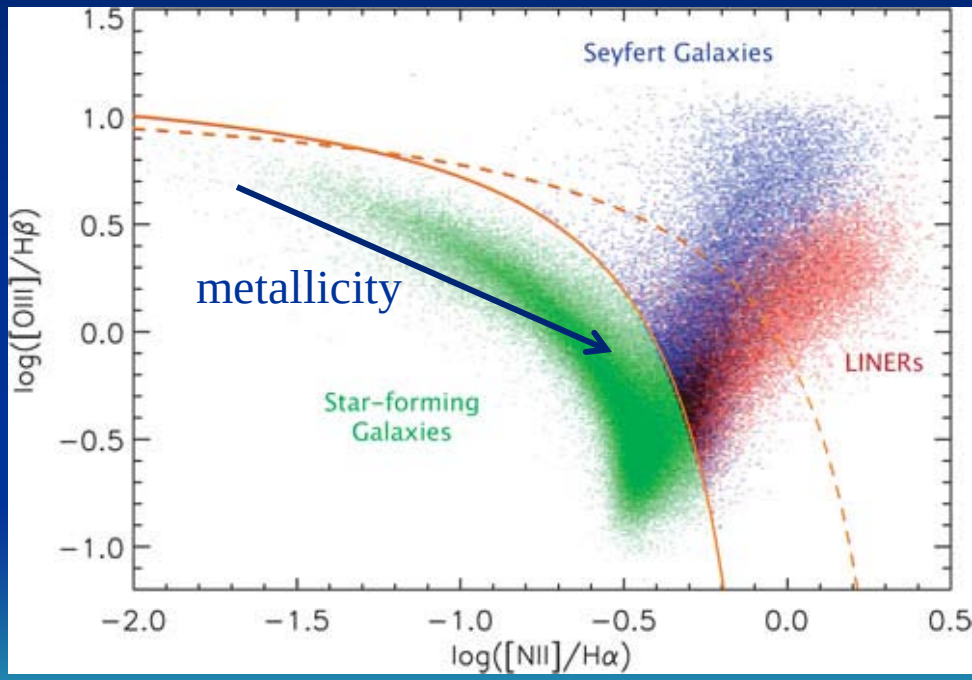
A: Young stars SED

B. AGN SED

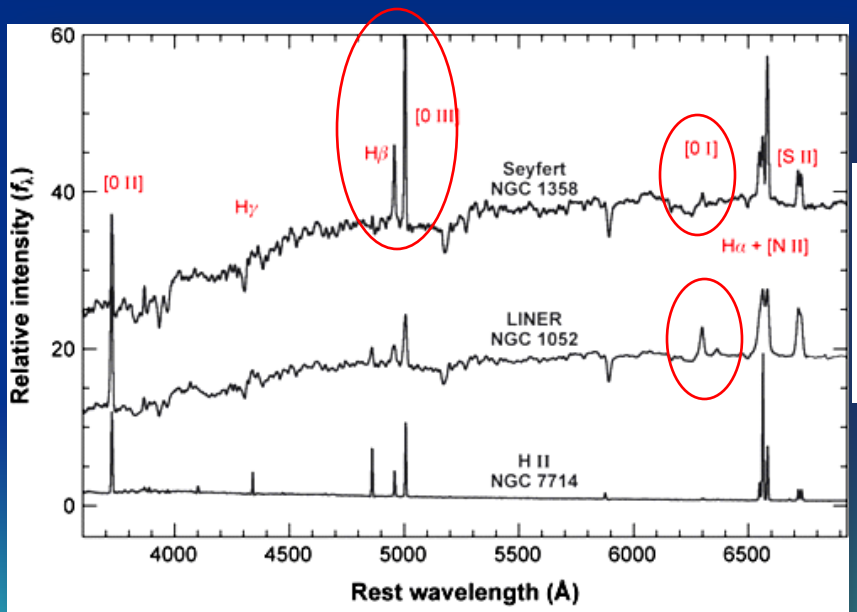


Diagnostic (BPT) diagrams





Using NLR properties to infer L_{AGN}

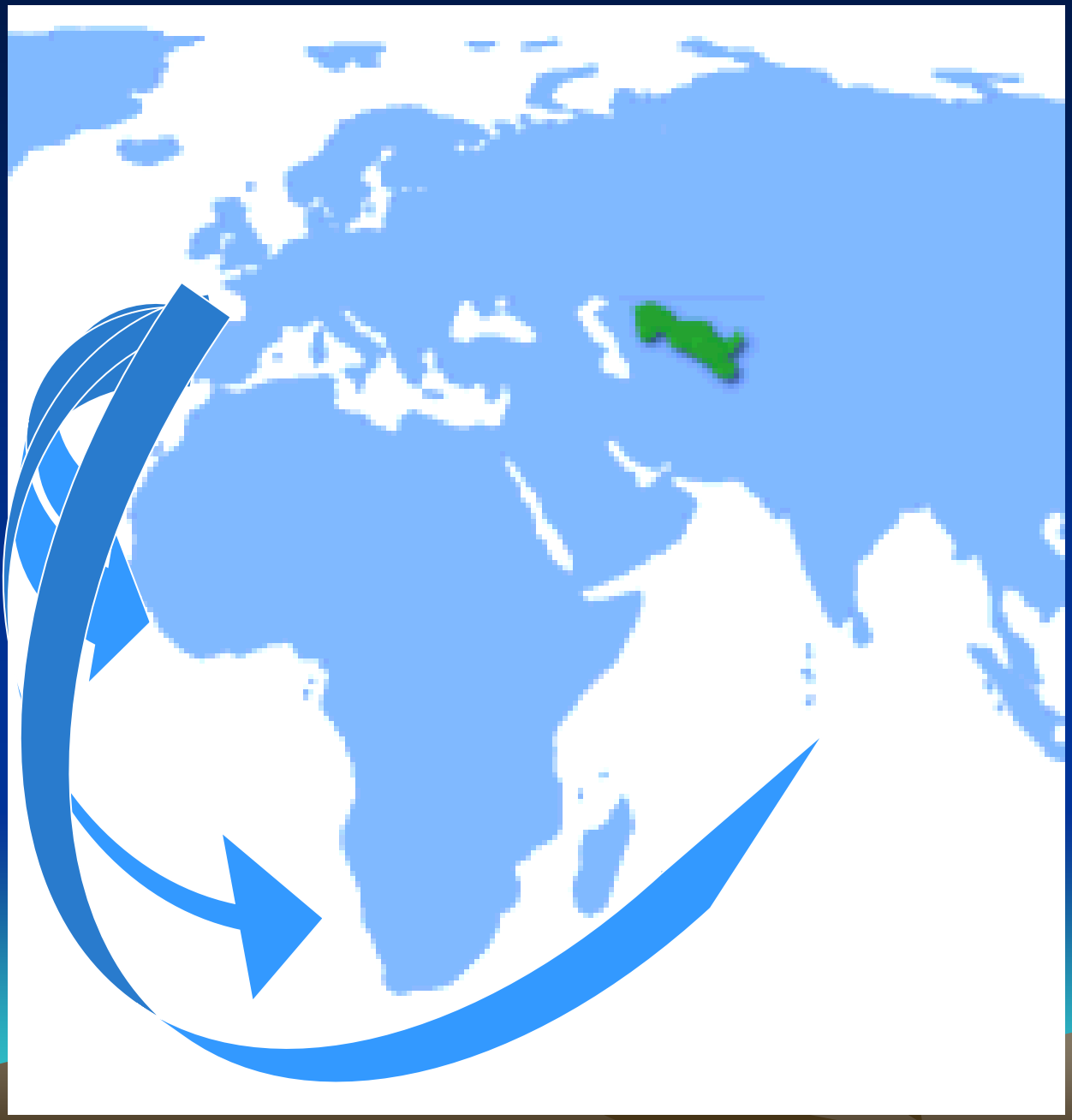


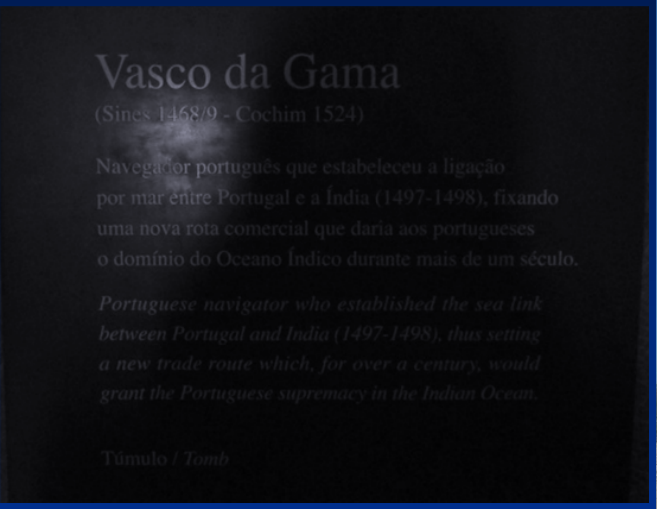
Ho LC. 2008.

$$L_{bol} = aL([OIII]) + bL([OI])$$

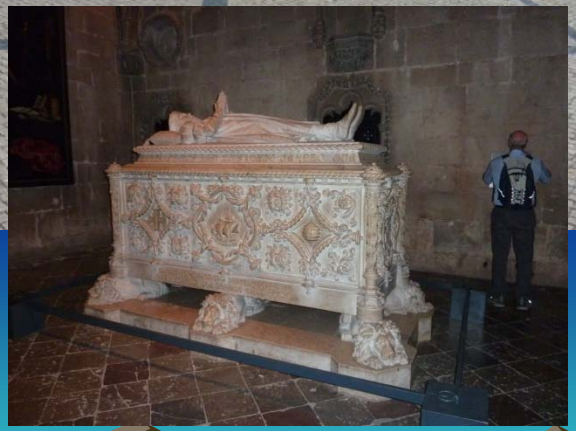
$$e.g.\ \ L_{bol} \approx 1000L([OIII])$$

$$e.g.\ \ L_{bol} \approx 2000L(H\alpha)$$




Vasco da Gama
(Sines 1468/9 - Cochim 1524)
Navegador português que estabeleceu a ligação por mar entre Portugal e a Índia (1497-1498), fixando uma nova rota comercial que daria aos portugueses o domínio do Oceano Índico durante mais de um século.
Portuguese navigator who established the sea link between Portugal and India (1497-1498), thus setting a new trade route which, for over a century, would grant the Portuguese supremacy in the Indian Ocean.
Túmulo / *Tomb*


CABO DA BOA
ESPERANÇA

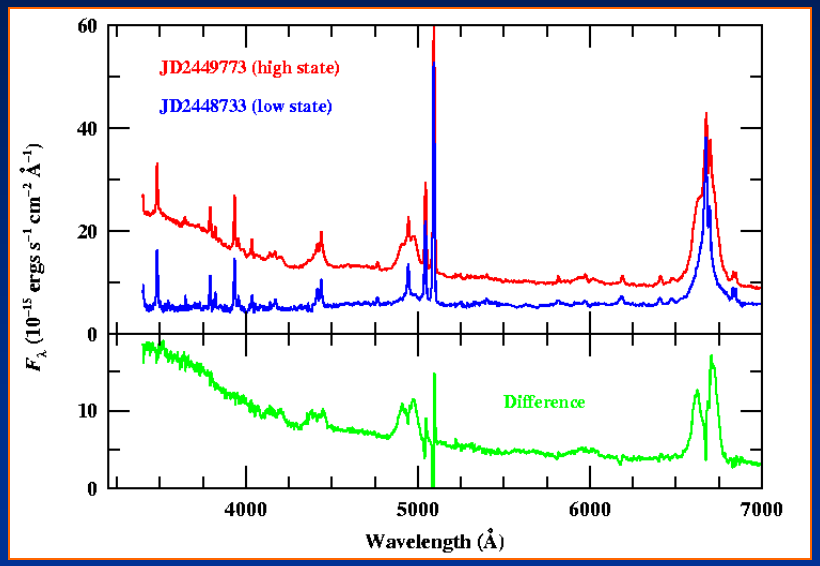


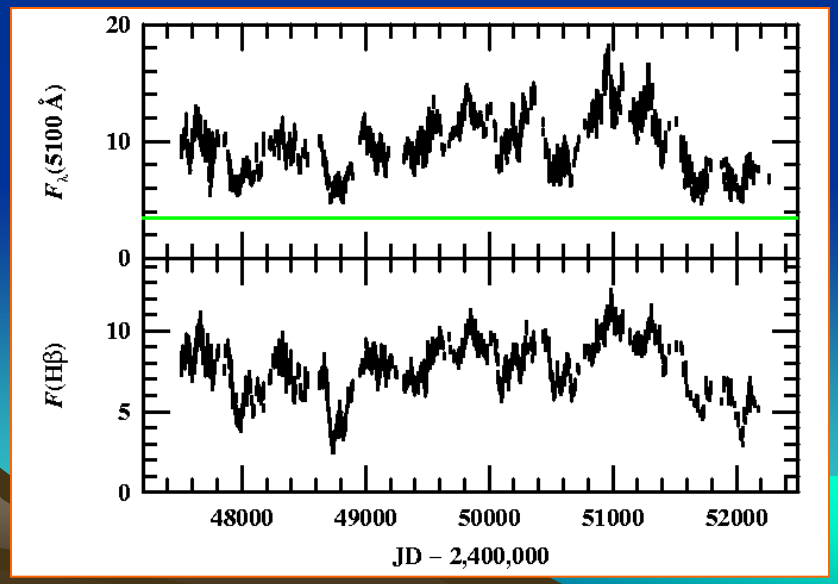
Main components of AGNs - 2

- Measuring BH mass – 1
  - Emission line variability
  - Reverberation mapping (RM)
  - The outer boundary of the BLR
    - Dust sublimation
  - Cloud motion and BH mass

Broad-Line Variability

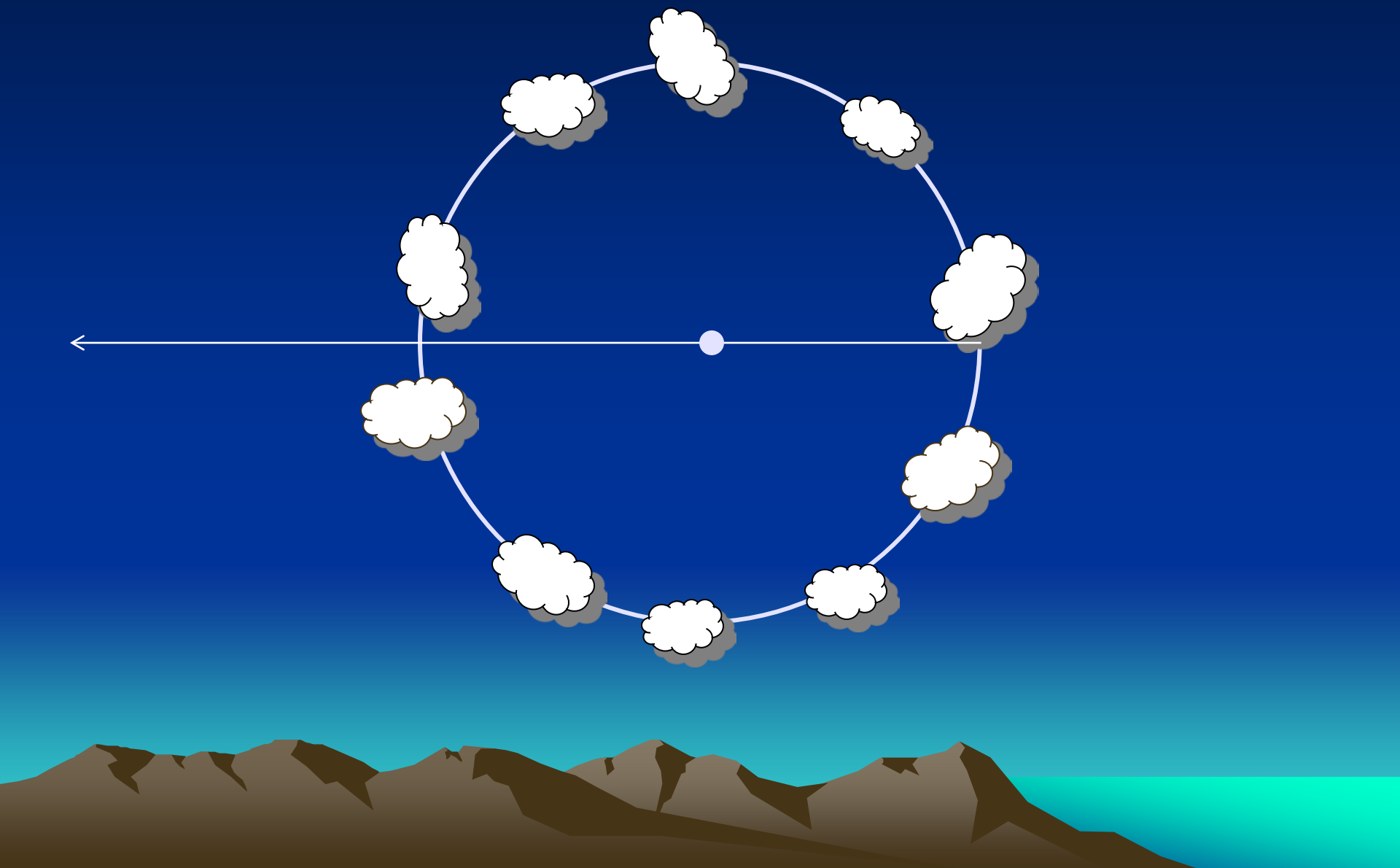
- Emission-line fluxes vary with the continuum, but with a time delay.
- Inferences:
  - Gas is photoionized and optically thick
  - Line-emitting region is not large compared with typical $c\Delta t$



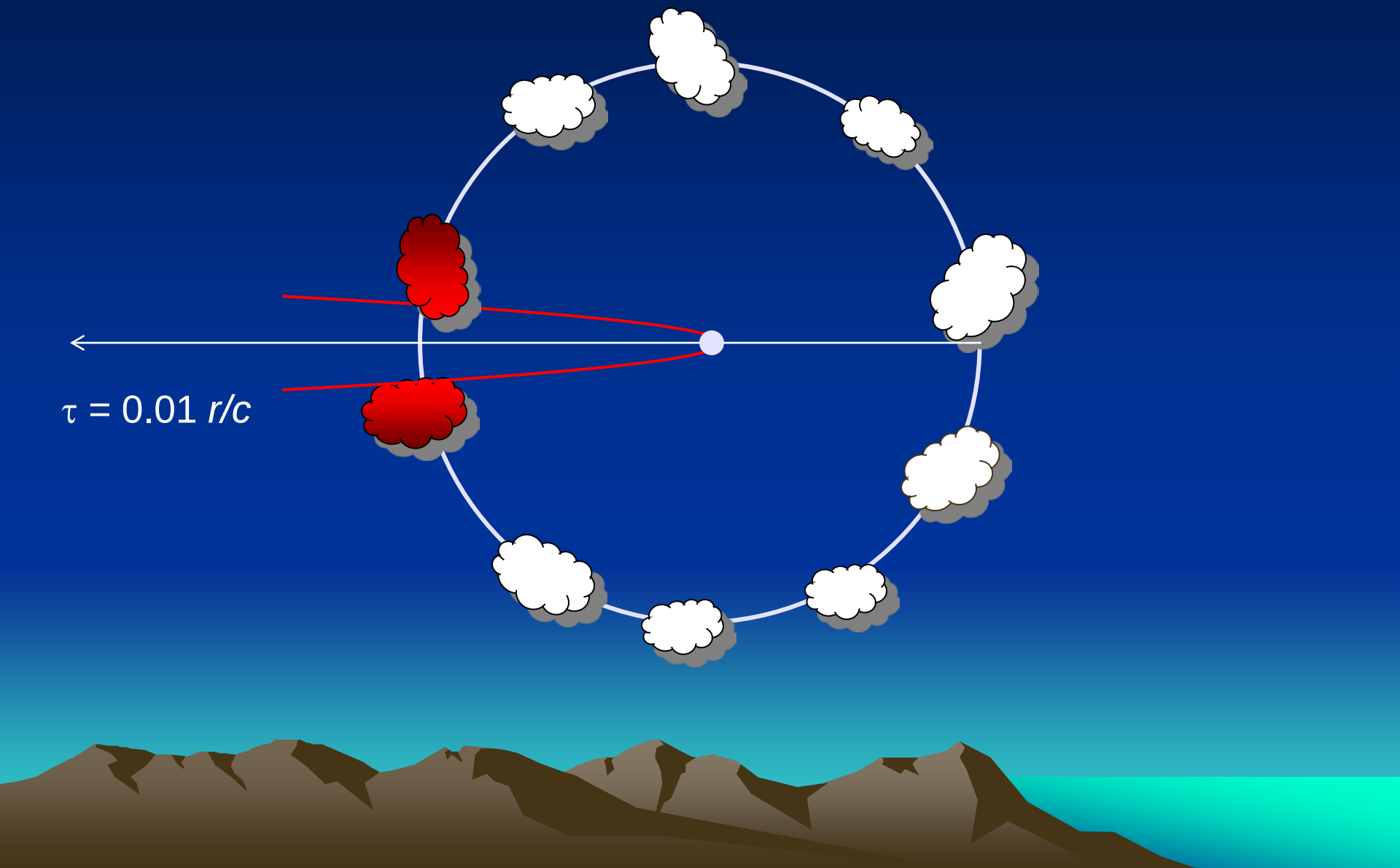


“Isodelay surfaces”

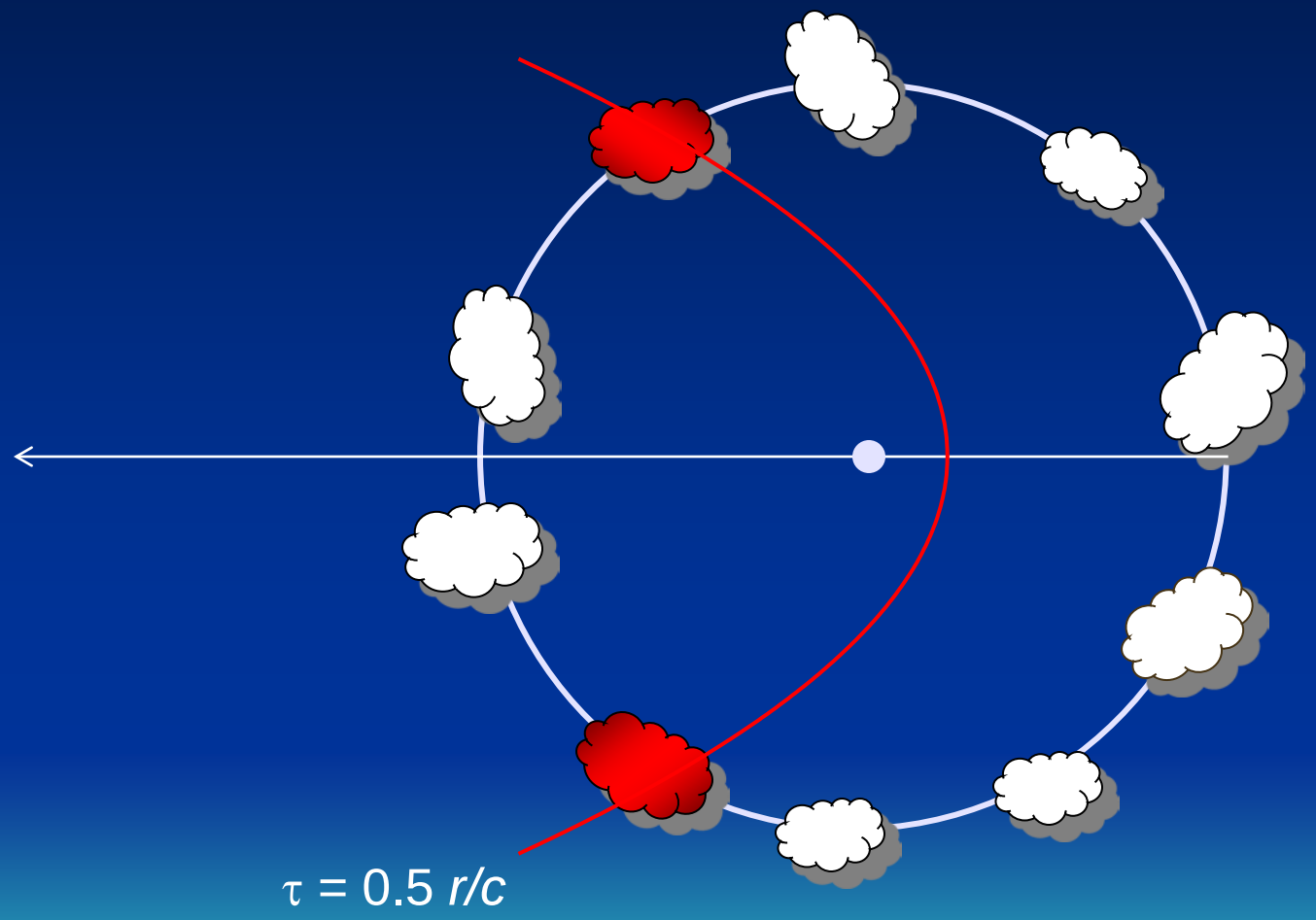
Response of a cloud system to a delta-function pulse



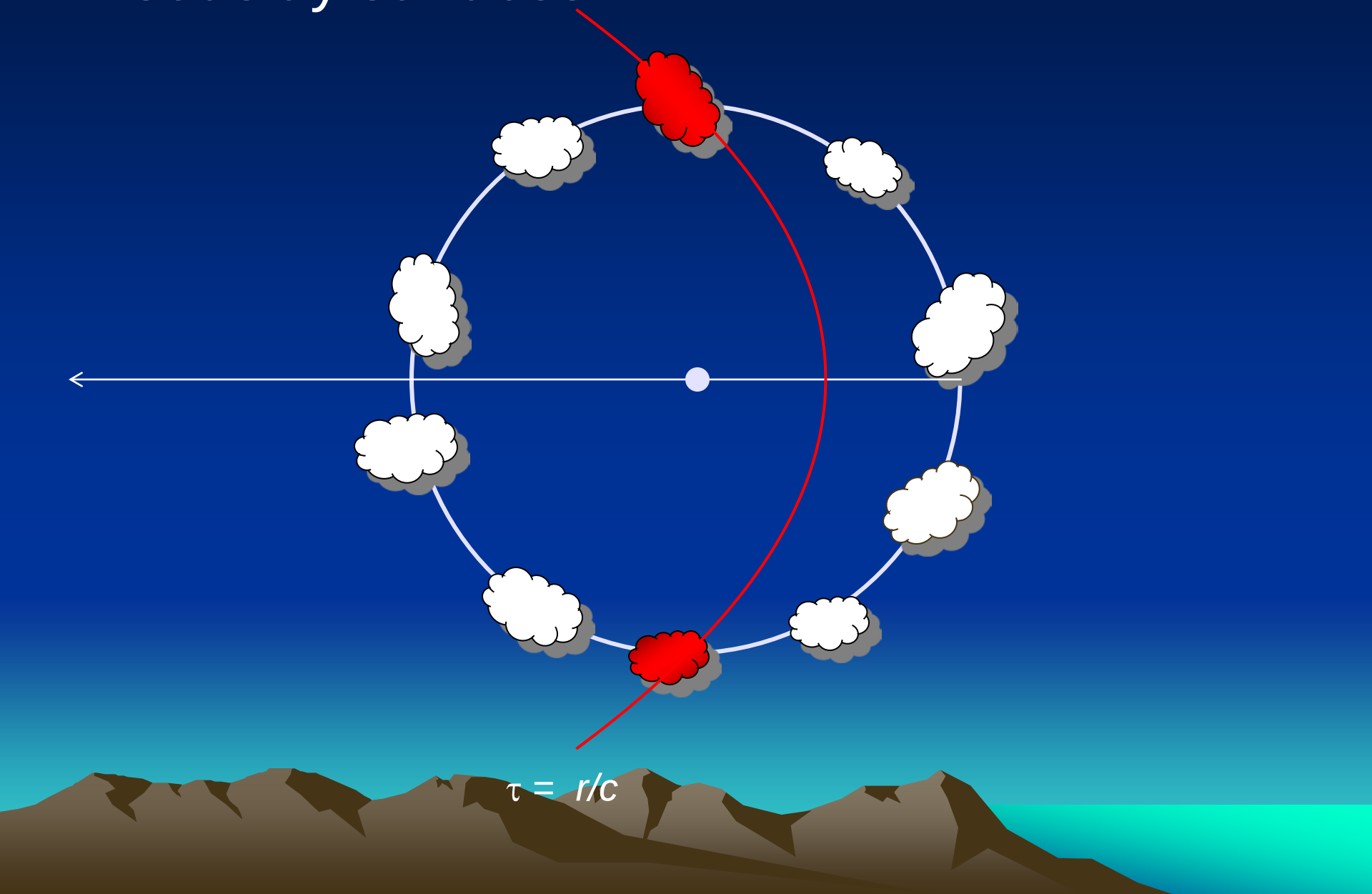
“Isodelay surfaces”



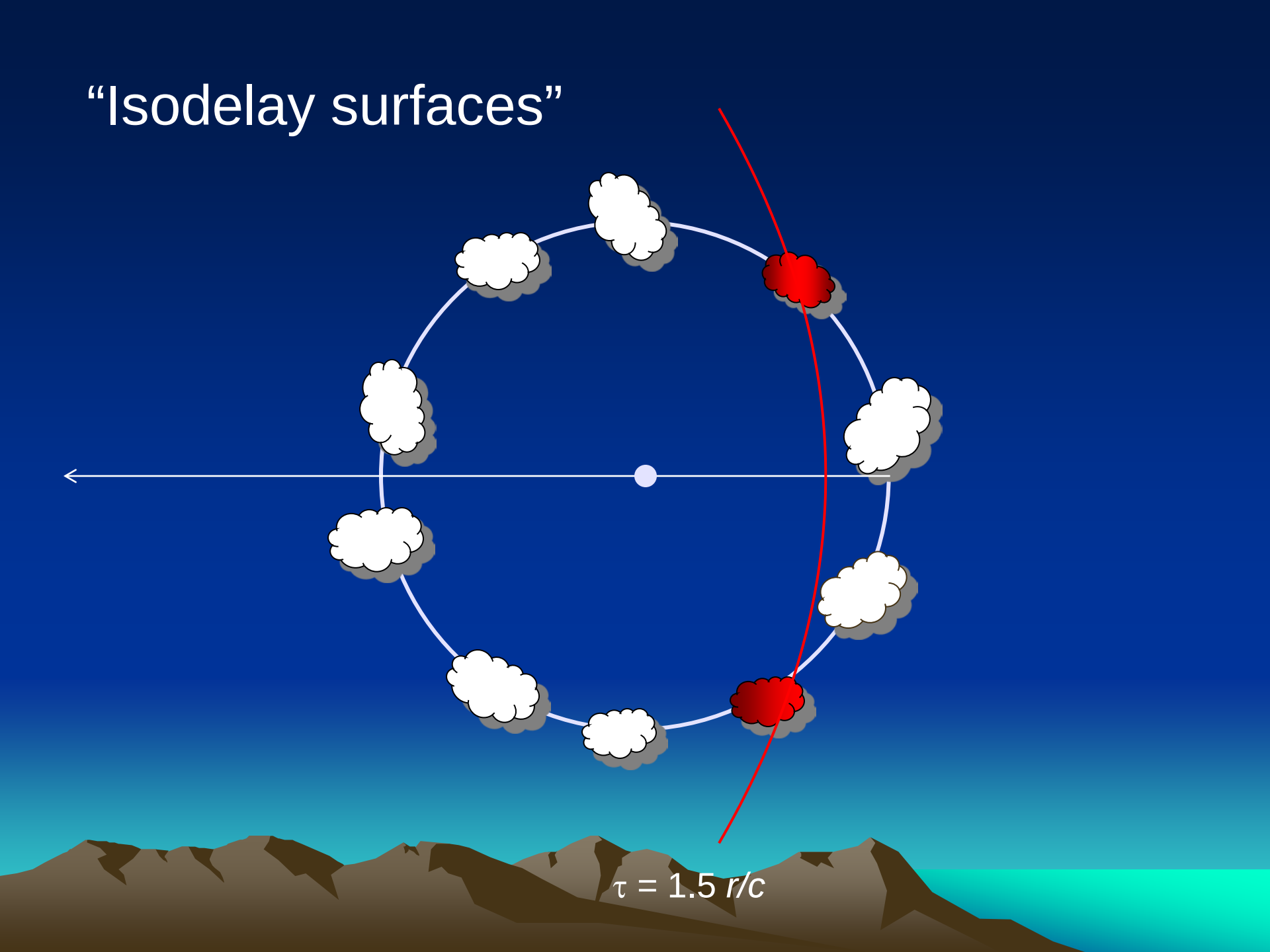
“Isodelay surfaces”



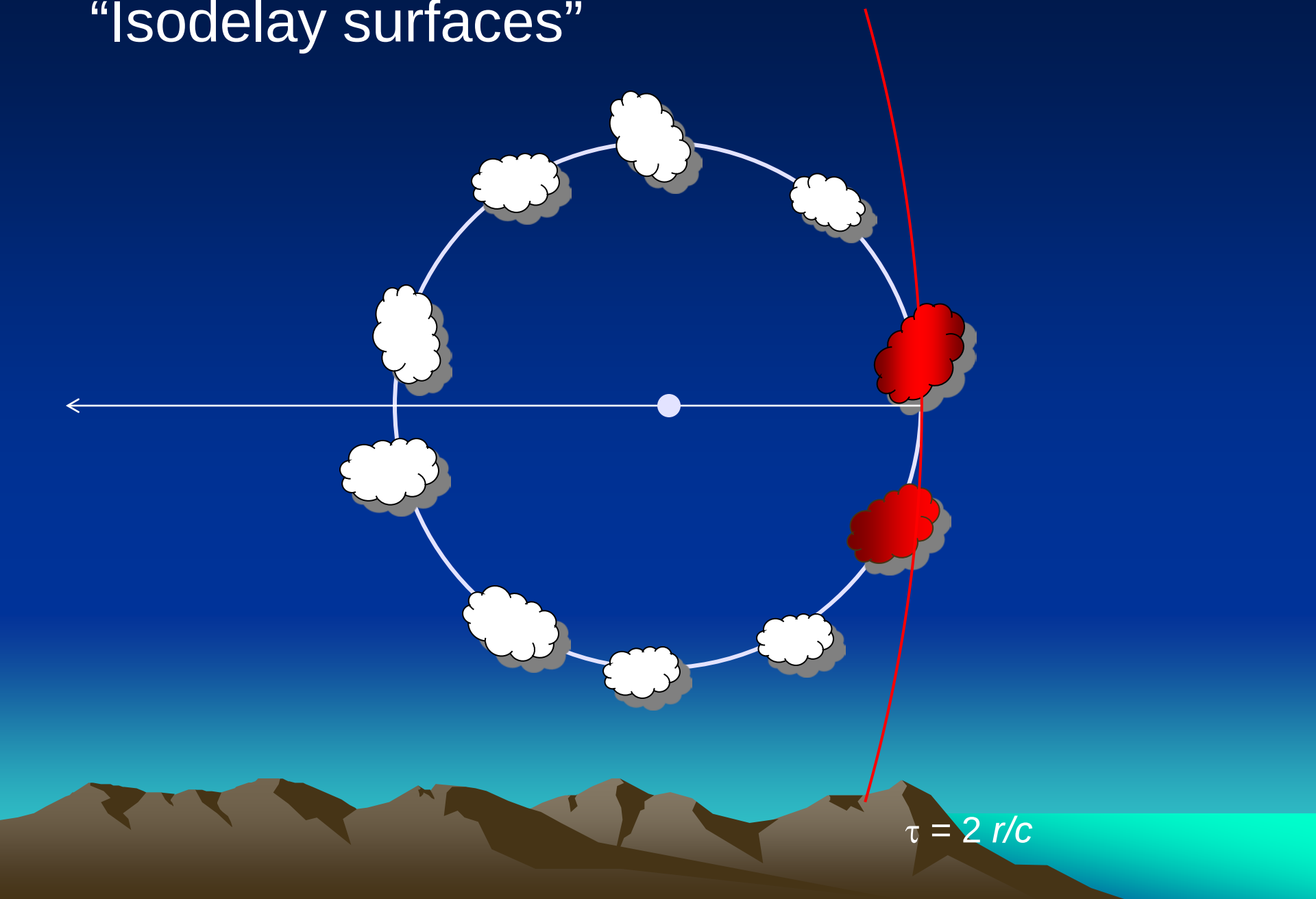
“Isodelay surfaces”



“Isodelay surfaces”

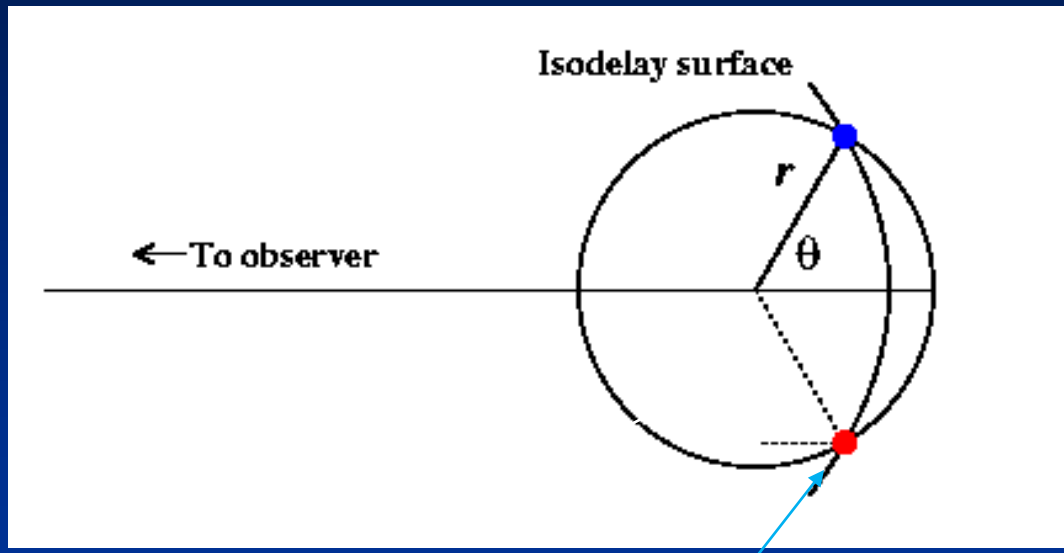


“Isodelay surfaces”



Response of an Edge-On Ring

- Suppose line-emitting clouds are on a circular orbit around the central source.
- Compared to the signal from the central source, the signal from anywhere on the ring is delayed by light-travel time.
- Time delay at position (r,θ) is $\tau = (1 + \cos\theta)r/c$



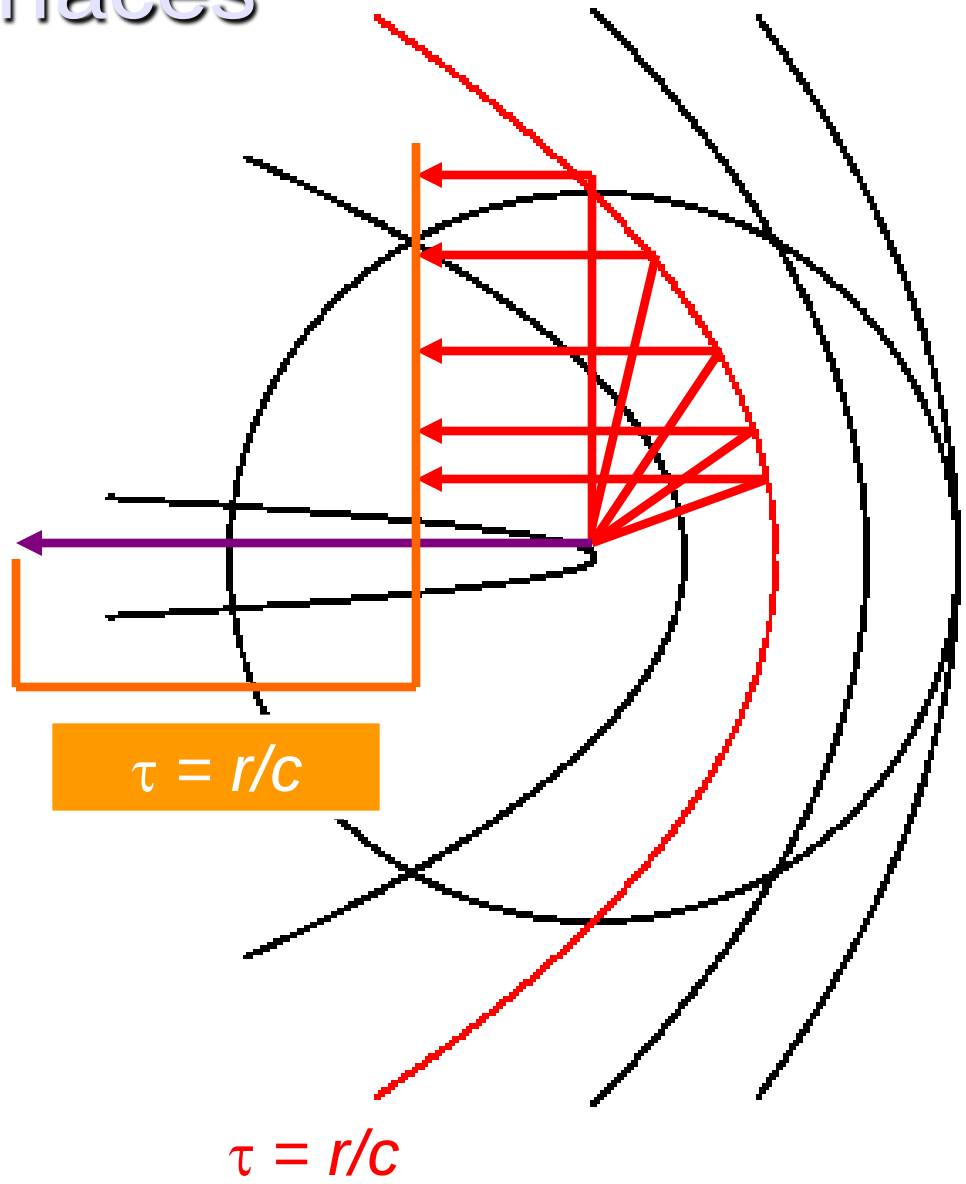
$$\tau = r\,(1+\cos\theta)\,/c$$

The isodelay surface is a parabola:

$$r = \frac{c\tau}{1+\cos\theta}$$

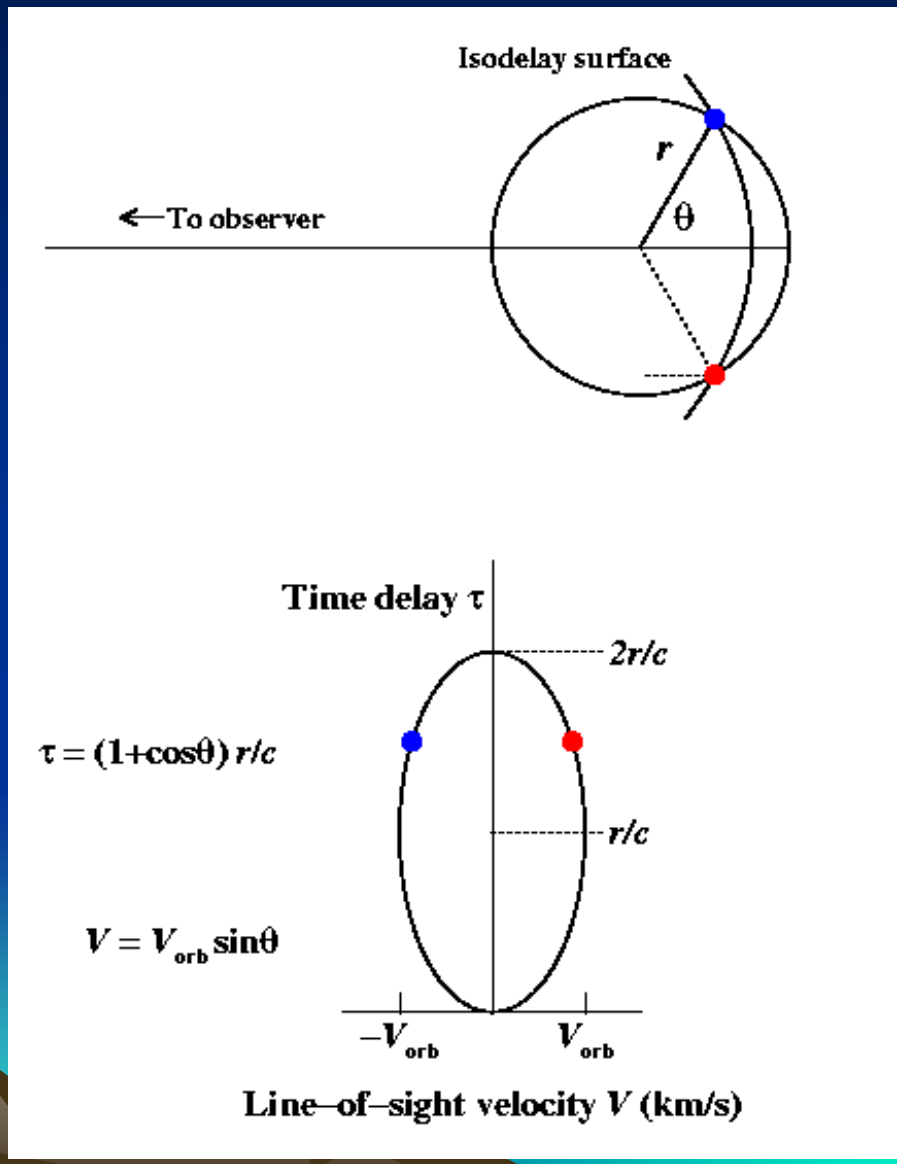
“Isodelay Surfaces”

All points on an “isodelay surface” have the same extra light-travel time to the observer, relative to photons from the continuum source.



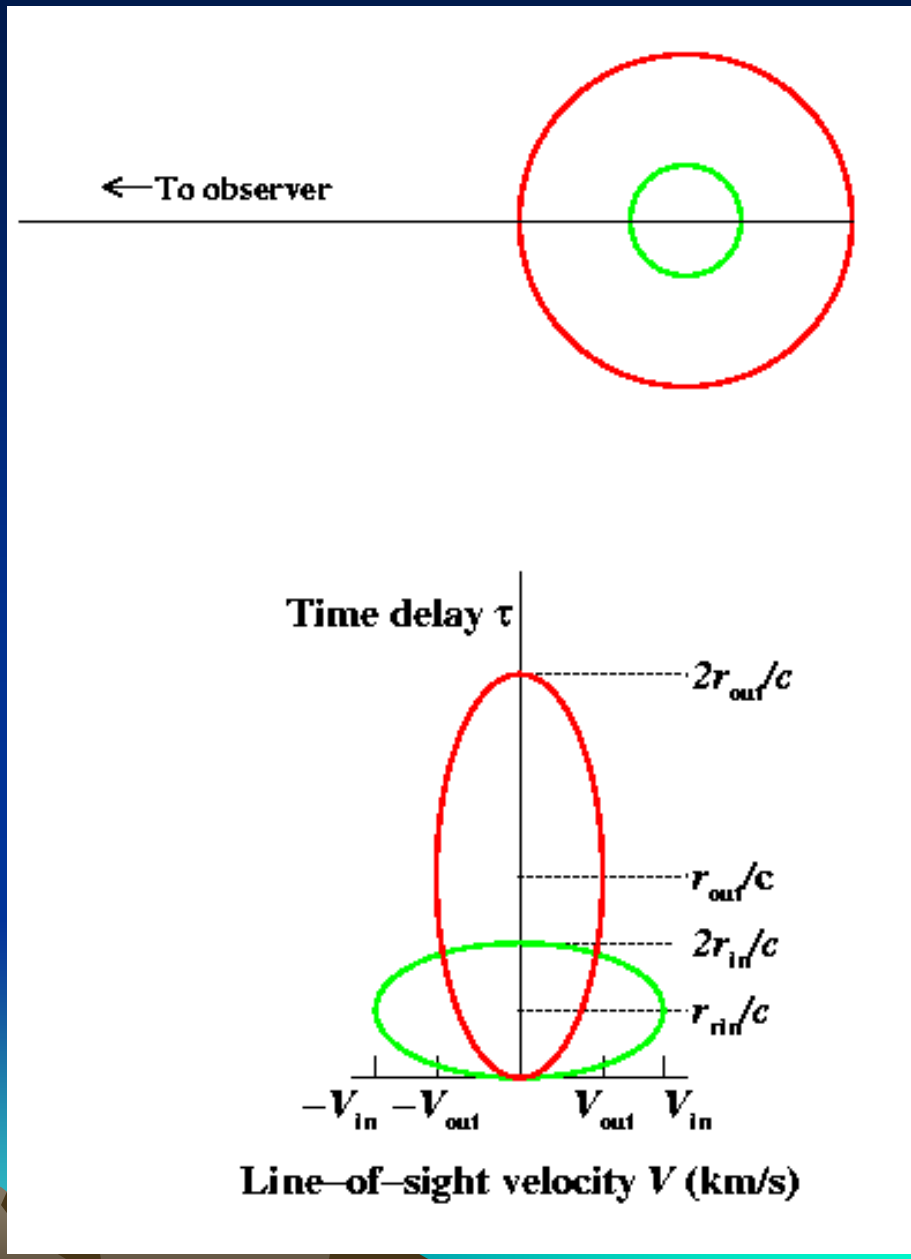
Velocity-Delay Map for an Edge-On Ring

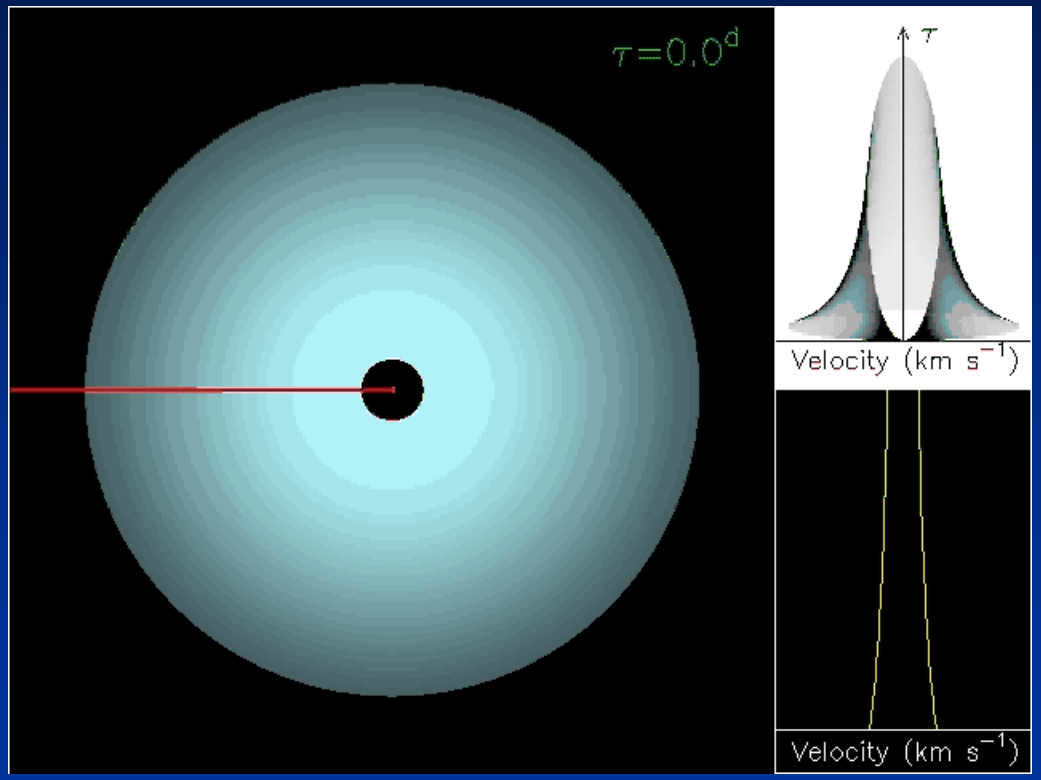
- Consider simple case of clouds in circular orbits at inclination $i = 90°$, orbital speed V_{orb}.
- Clouds at intersection of isodelay surface and orbit have line-of-sight velocities $V = \pm V_{orb} \sin\theta$.
- Circular orbit projects to an ellipse in the (V, τ) plane.



Thick Geometries

- Disk or thick shell (result is illustrated with simple two ring system).




τ=0.0d
τ
Velocity (km s−1)
Velocity (km s−1)

The transfer function

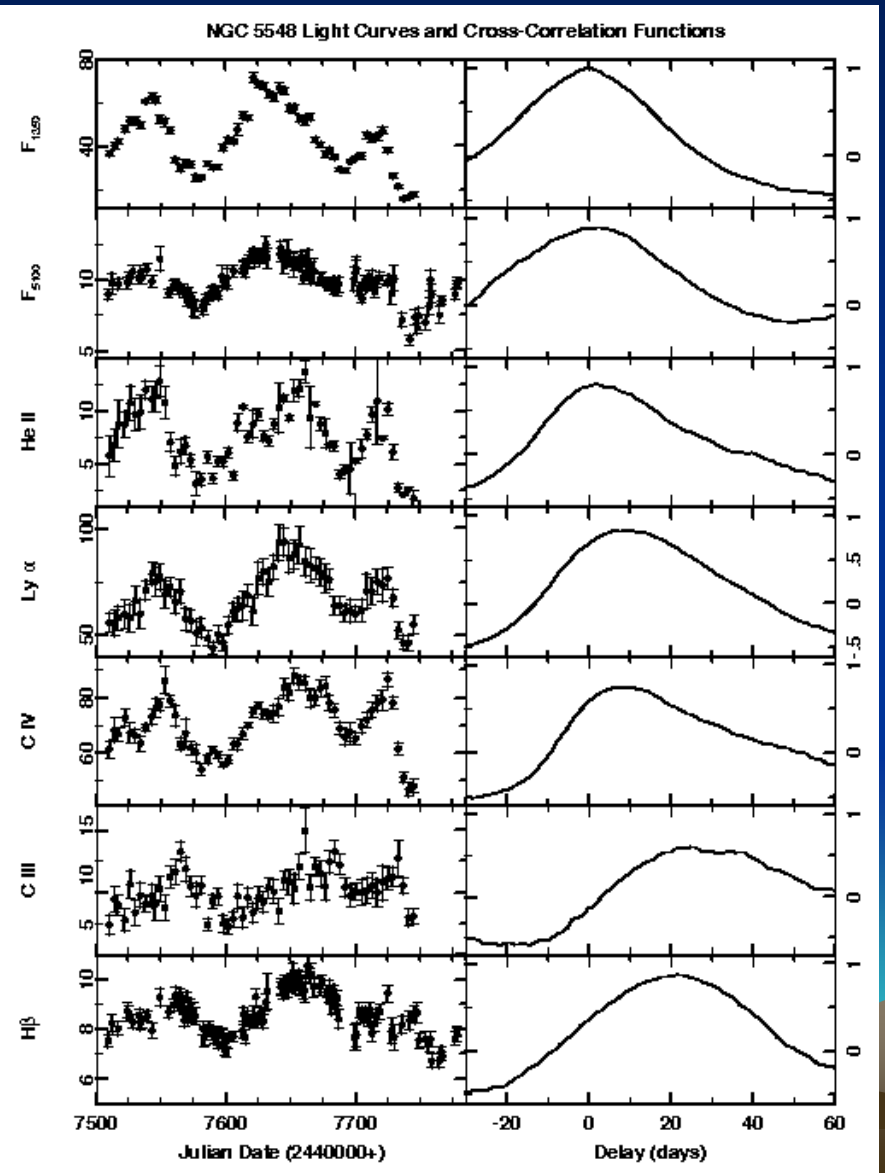
- The cross correlation function (CCF)
- The transfer function
  - Thin shell
  - Thick shell
  - Inclined ring

$$L_l(v,t) = \int_{-\infty}^{\infty} \Psi(v,t) L_c(t-\tau) d\tau$$

$$L_l(t) = \int_{-\infty}^{\infty} \Psi(t) L_c(t-\tau) d\tau$$

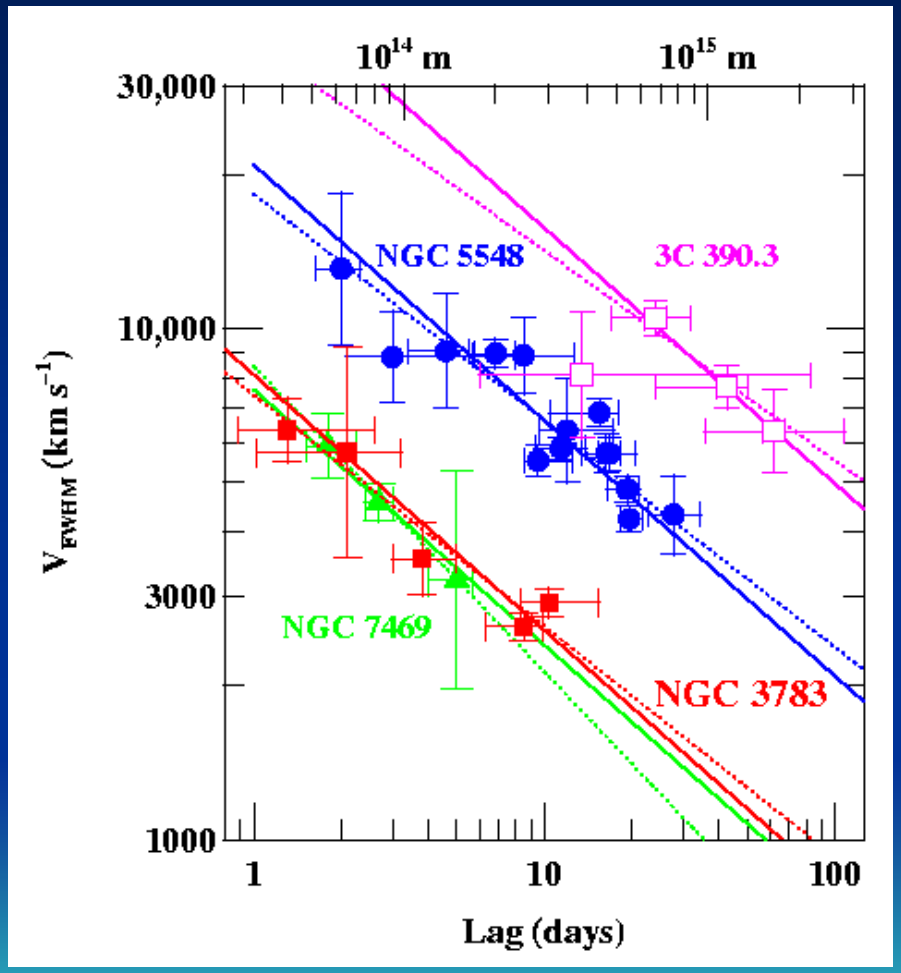
$$\tilde{\Psi}(\omega) = \frac{\tilde{L}_l(\omega)}{\tilde{L}_c(\omega)} \quad [\omega = 1/t]$$

Reverberation Mapping Results



- AGNs with lags for multiple lines show that higher ionization emission lines respond more rapidly to continuum variations
- This implies ionization stratification

Reverberation and AGN Black Hole Masses

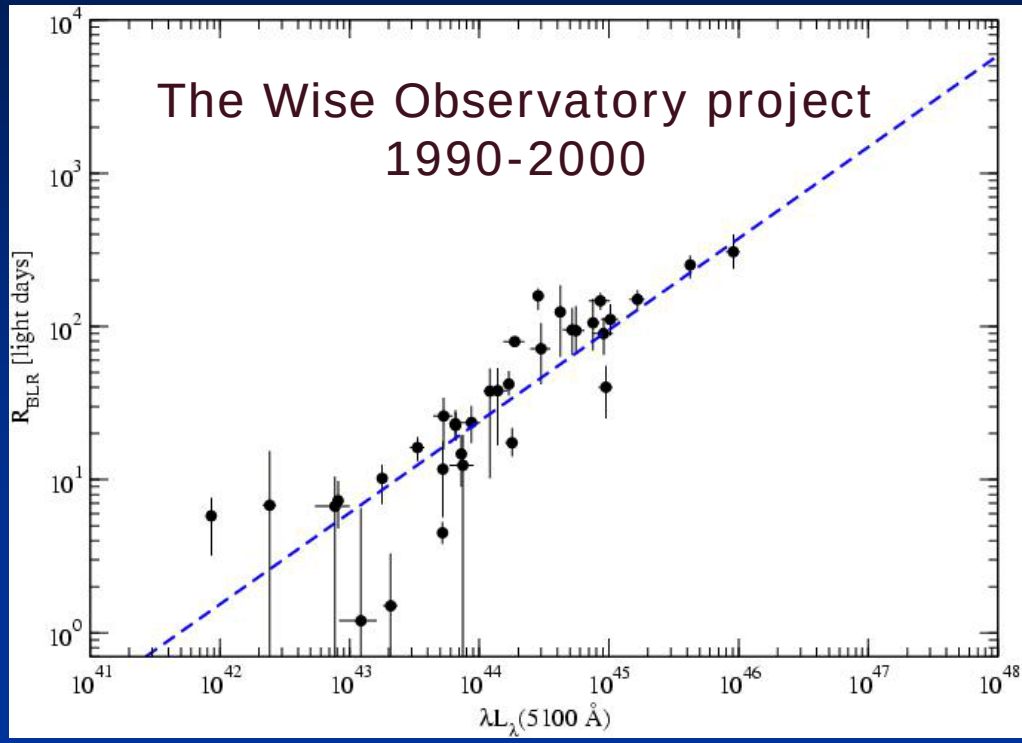


- For AGNs with multiple reverberation measurements, there is virial relationship between line width and lag:

Onken & Peterson (2002)
Peterson & Wandel (1999, 2000)

BLR size and BH mass - results

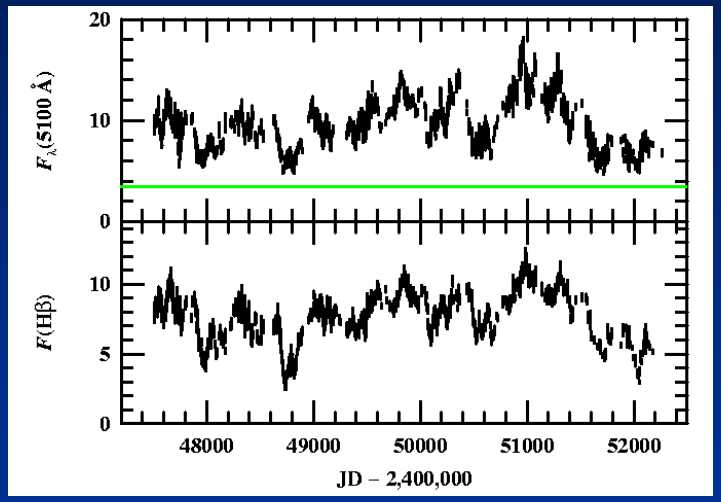
$$R_{BLR}(H\beta) = 0.37\left[\frac{\lambda L_{\lambda}(5100A)}{10^{46} erg\ s^{-1}}\right]^{0.65} pc$$



Kepler law => Single epoch mass determination

$$M_{BH} = 8.6x10^{7}\left[\frac{\lambda L_{\lambda}(5100A)}{10^{46}\ erg/\sec}\right]^{0.65}\left[\frac{FWHM(H\beta)}{1000\ km/\sec}\right]^{2} M_{\Theta}$$

Using BLR properties to infer BH mass and accretion rate



What is the factor f ?

$$r_{BLR}(H\beta) \simeq 0.15 L_{bol,46}^{0.6\pm0.1}\ pc$$

$$r_{BLR}(CIV1549) \simeq 0.05 L_{bol,46}^{0.6\pm0.1}\ pc$$

$$M_{BH} = f V_{line}^2 r_{BLR}$$

Looking into f

$$M = f\frac{Rv_l^2}{G}$$

$$v_l = v_K \Rightarrow f = 1$$

$$v_l = \frac{FWHM}{2} \Rightarrow f = 3/4$$

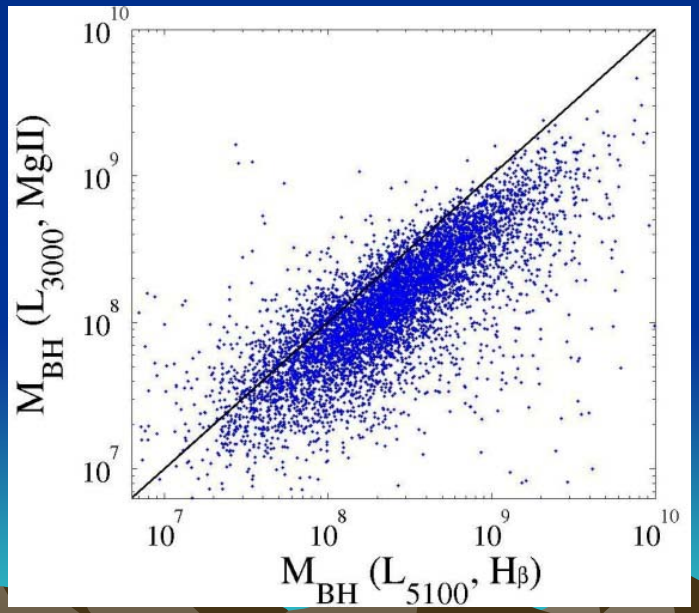
Best method to determine f is by comparing with the M(BH)-sigma relationship in local AGNs

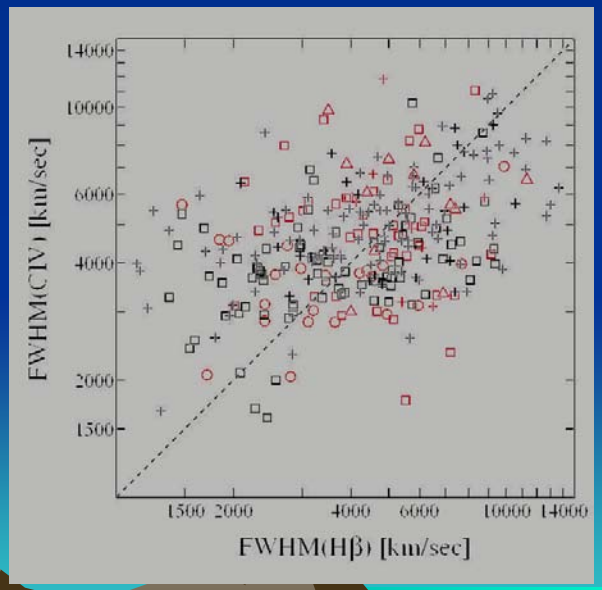
Using BLR properties to infer mass
What line to use?

$$r_{BLR}(H\beta) \simeq 0.15 L_{bol,46}^{0.6\pm0.1}\ pc$$

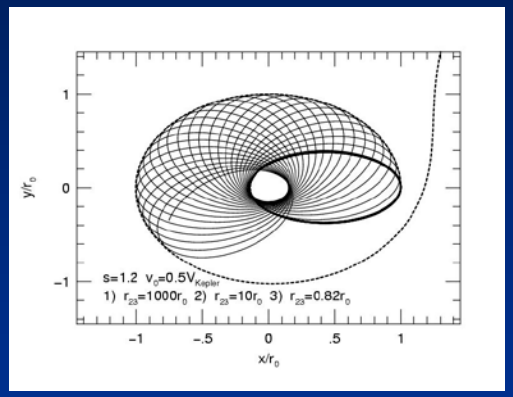
$$r_{BLR}(CIV1549) \simeq 0.05 L_{bol,46}^{0.6\pm0.1}\ pc$$

$$M_{BH} = f V_{line}^2 r_{BLR}$$

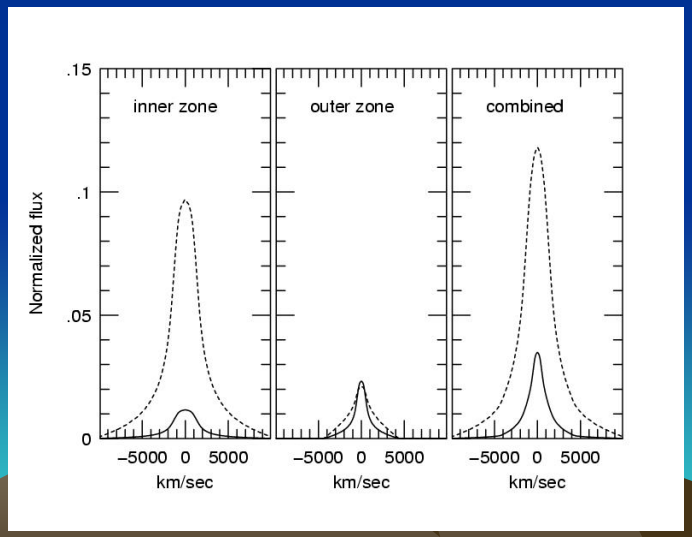




Using BLR properties to infer BH mass
Radiation pressure revisited

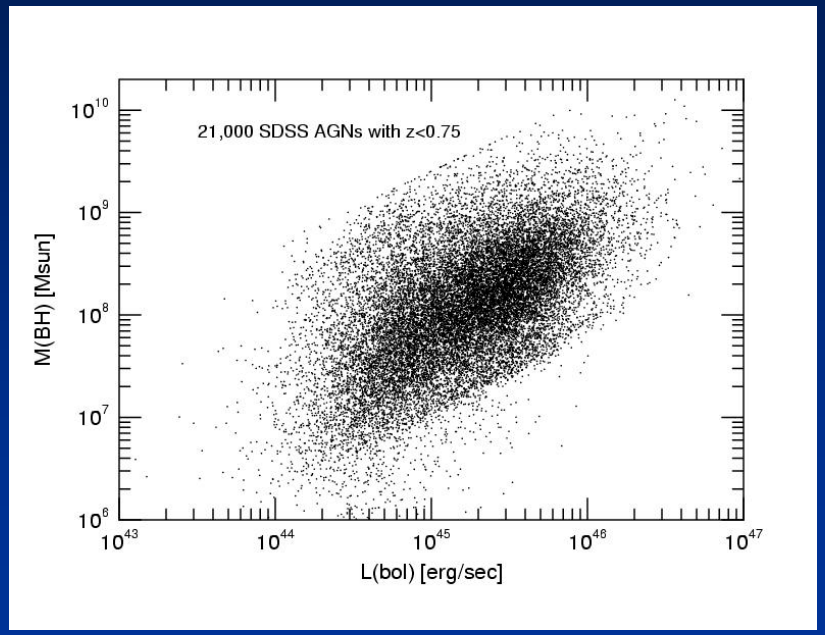


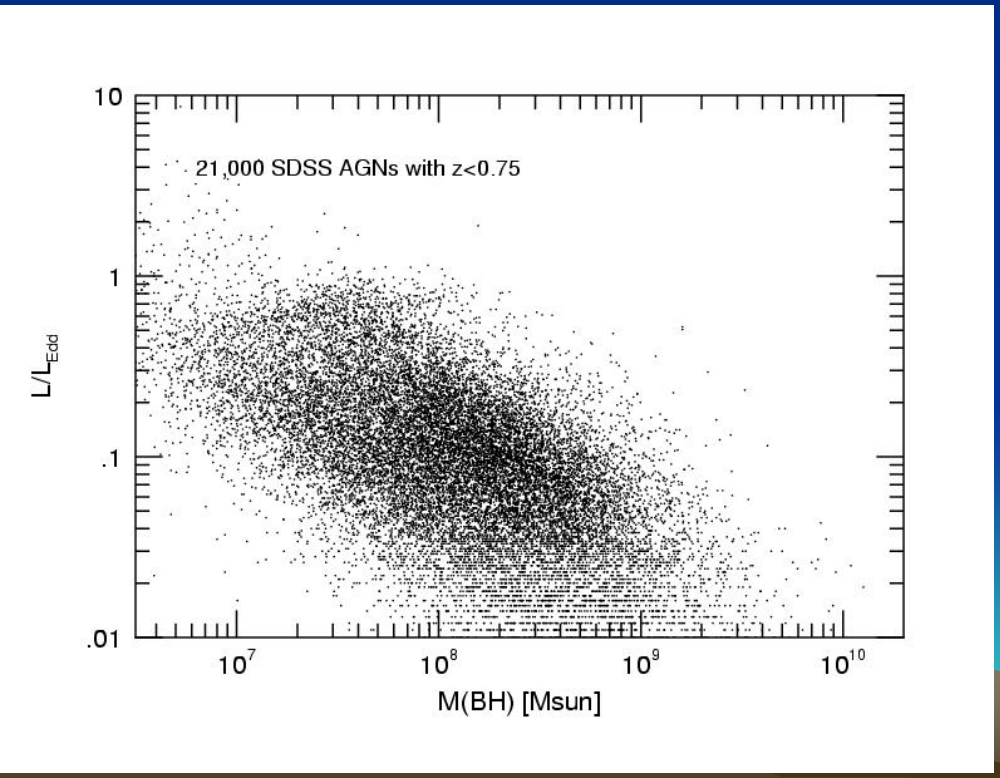
Hβ and CIV1549 calculations



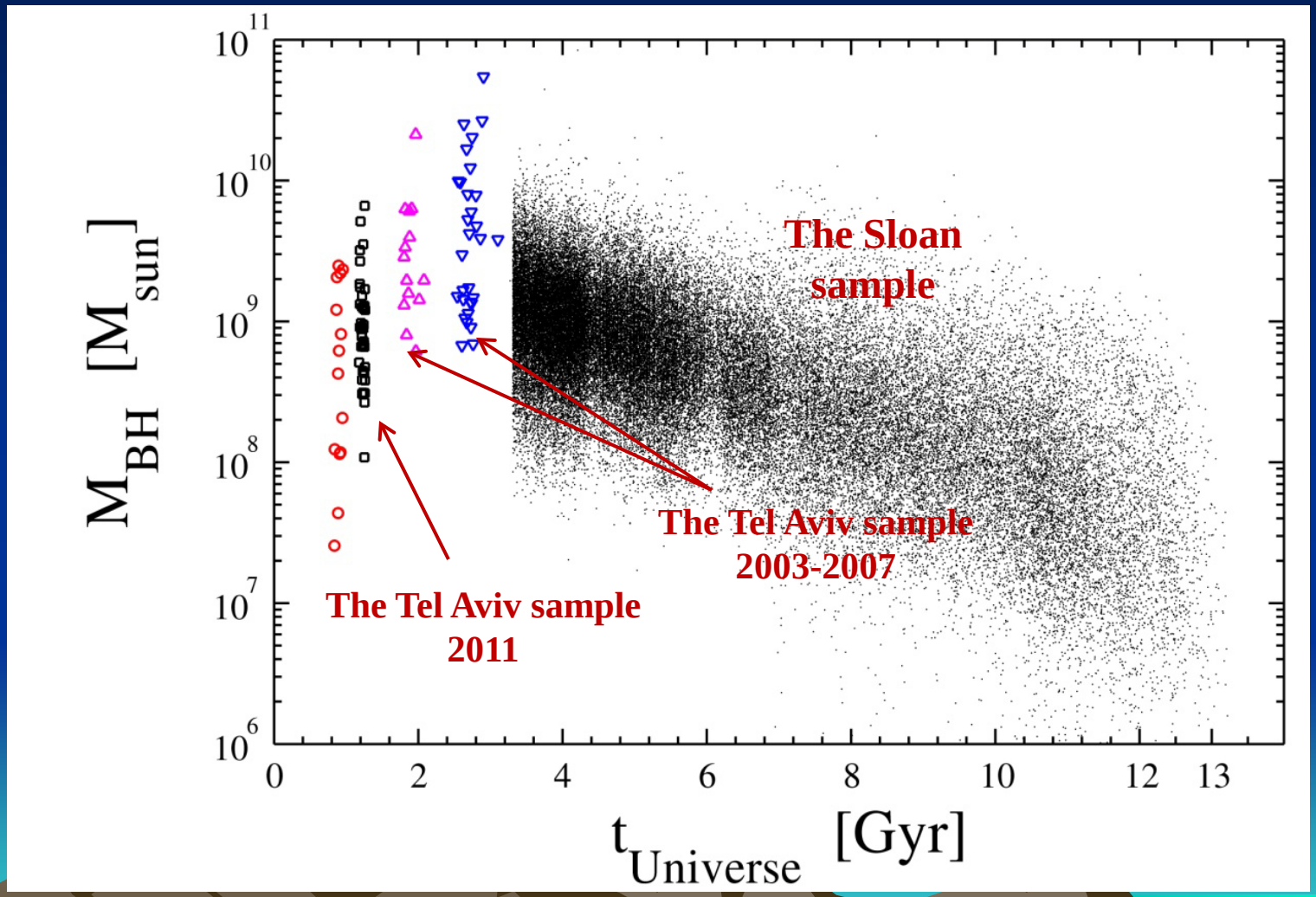
$$a_{rad} - a_g = \frac{aL}{4\pi r^2 c m_c} - \frac{GM_{BH}}{r^2} =$$

$$= \frac{L}{r^2}\left[\frac{a}{4\pi r^2 c m_p N_H} - \frac{G}{7.5x10^4 (L/L_{Edd})}\right]$$


21,000 SDSS AGNs with z<0.75
M(BH) [Msun]
L(bol) [erg/sec]


21,000 SDSS AGNs with z<0.75
L/L_Edd
M(BH) [Msun]

Black hole evolution



Trakhtenbrot et al. 2011

Main components of AGN 3

- The Central obscuration and other dust-related issues
  - The sublimation distance – 2
  - The outer boundary of the BLR
  - Dust in the NLR
  - The central torus
    - Uniform and clumpy tori
    - The torus spectrum
  - Hot warm and cold AGN dust
  - Dust emission from AGN and SF heated dust

Main components of AGNs
Let There Be Dust

Sublimation distance

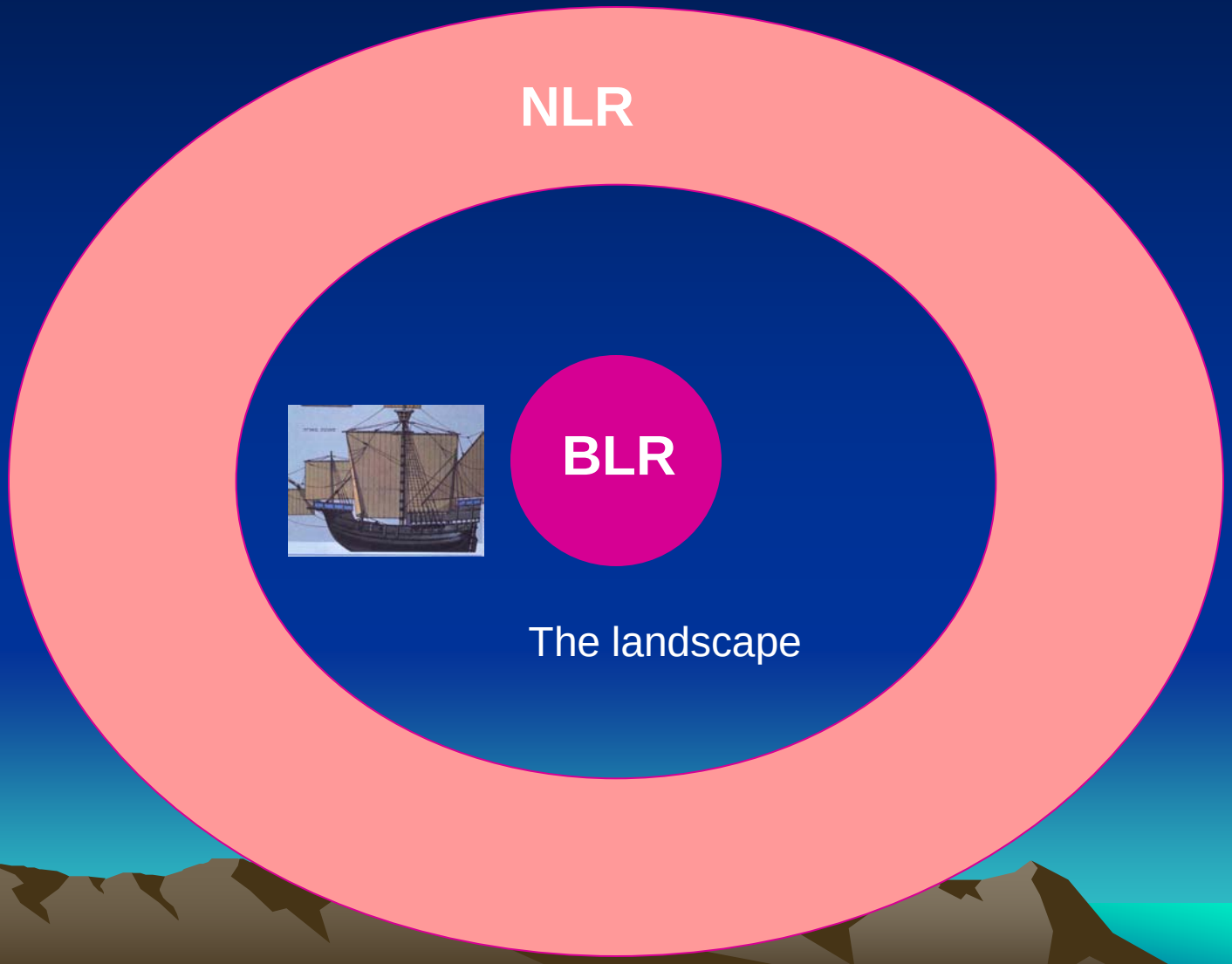
$$r_{sub,Si} \cong 1.3 L_{46,bol}^{1/2} \left(\frac{1500K}{T_{sub}} \right)^{2.6} pc$$

$$r_{sub,C} \cong 0.5 L_{46,bol}^{1/2} \left(\frac{1800K}{T_{sub}} \right)^{2.6} pc$$

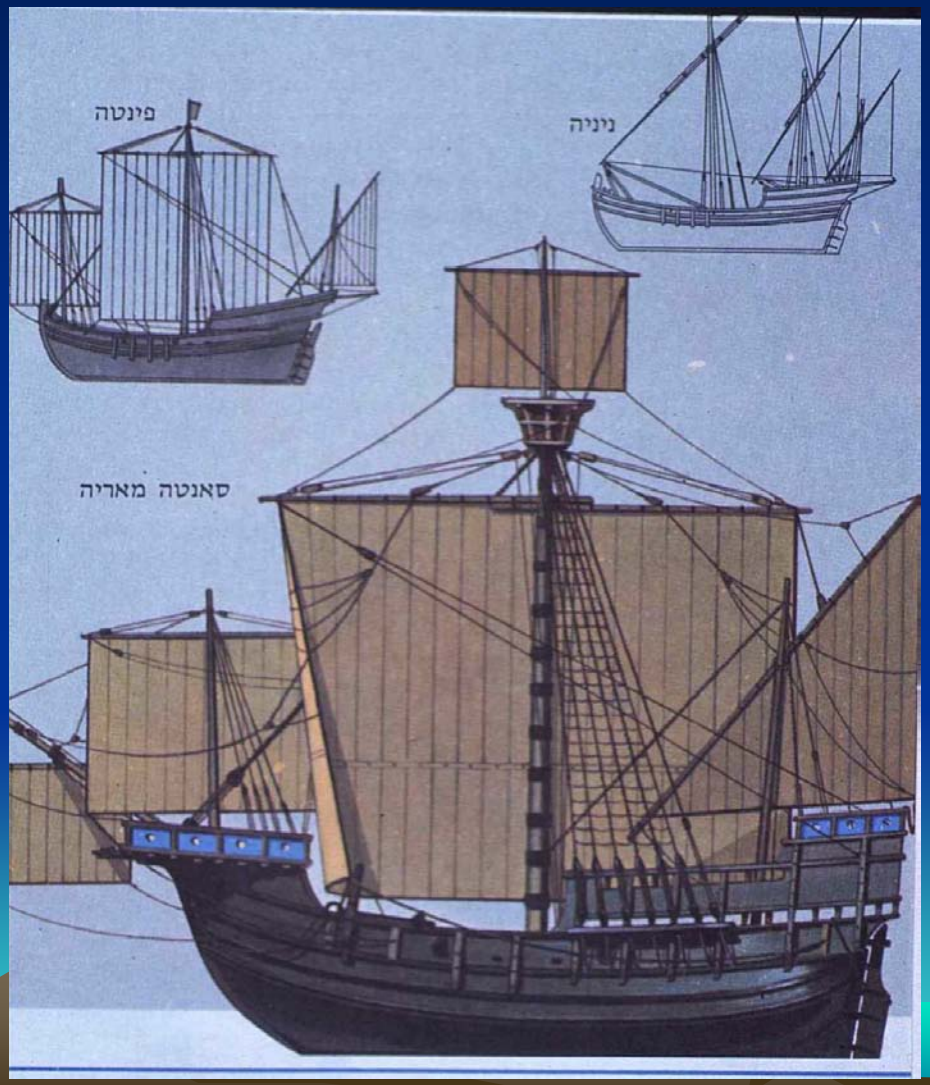
The BLR radius

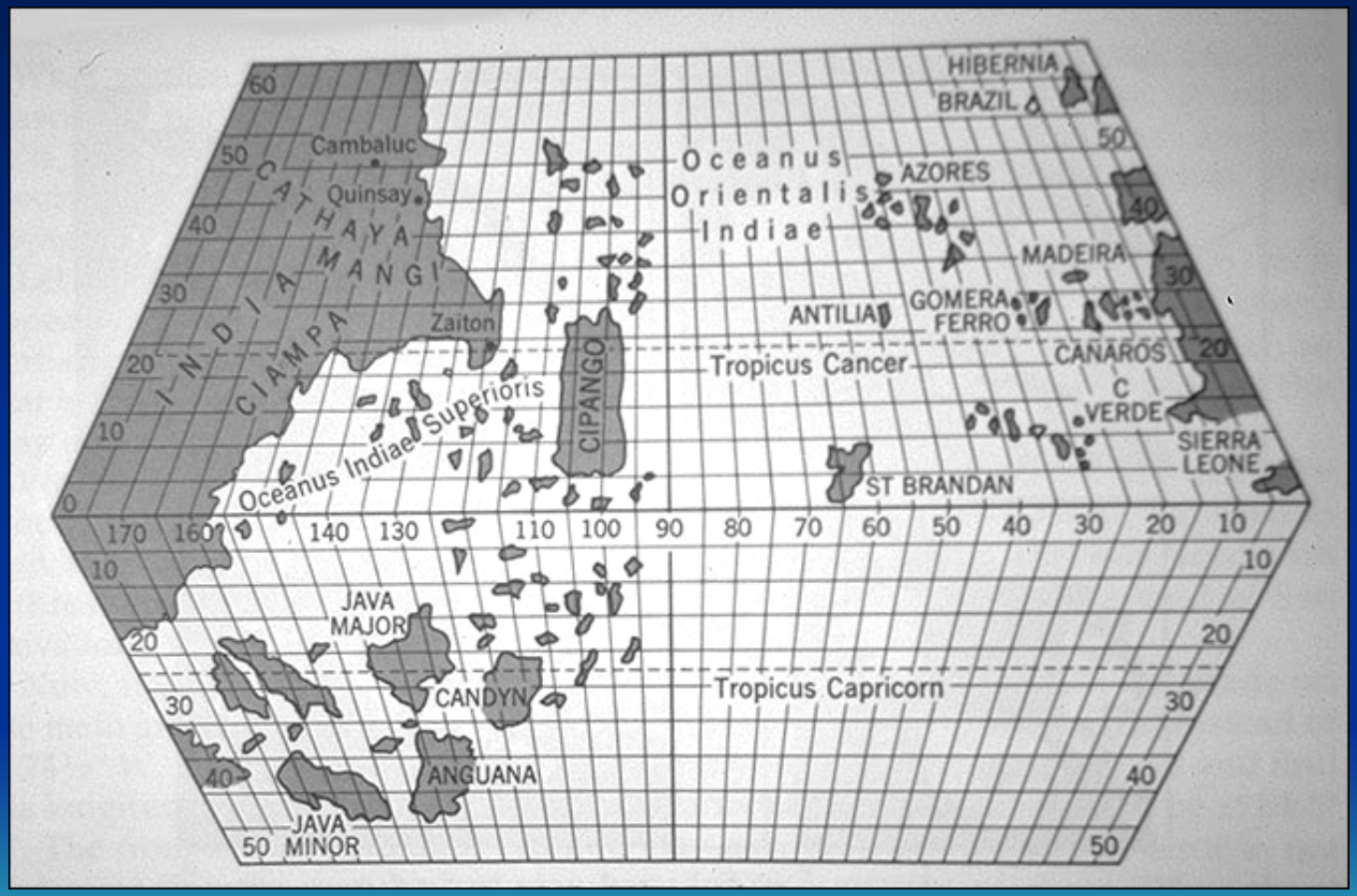
$$r_{BLR}(H\beta) \simeq 0.15 L_{46,bol}^{0.6\pm0.1} \; pc$$

The outer boundary of the BLR



Navigation without time

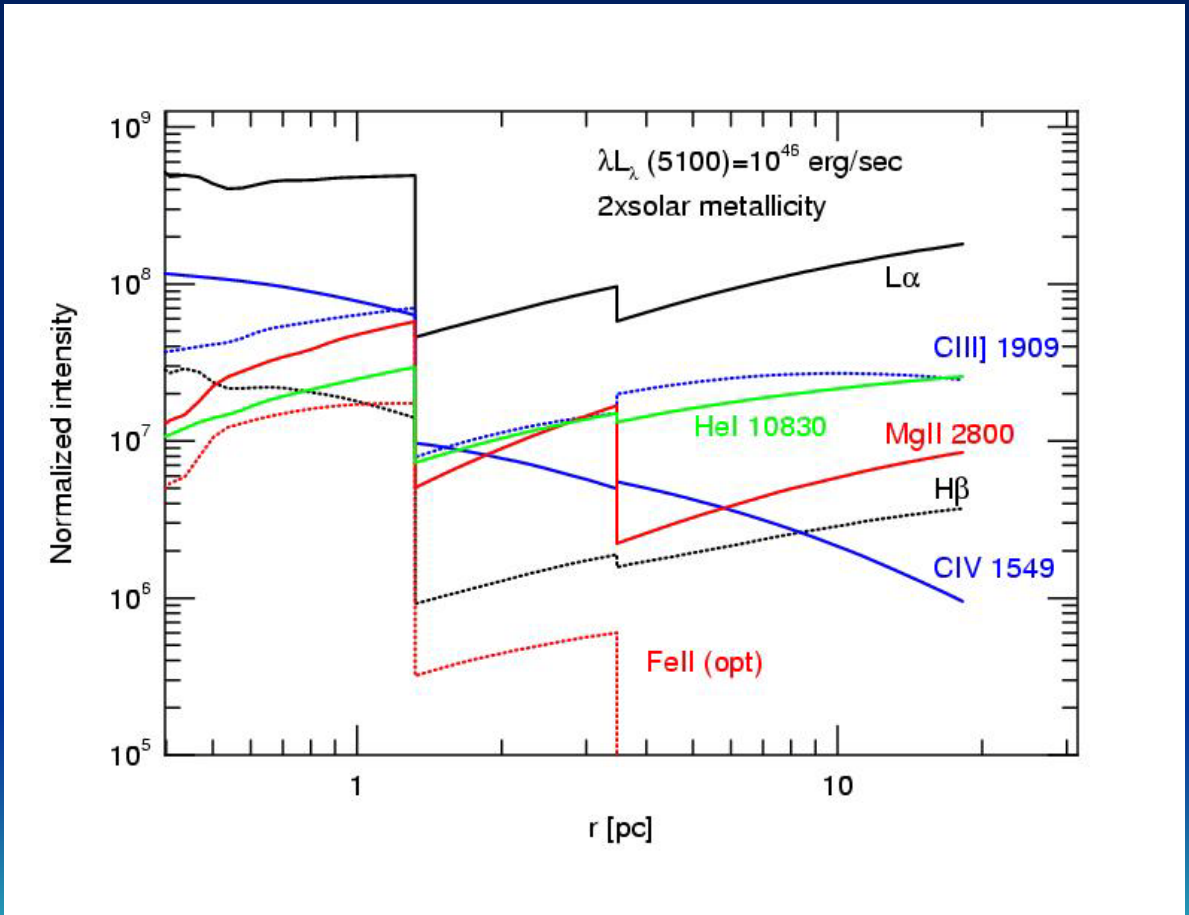


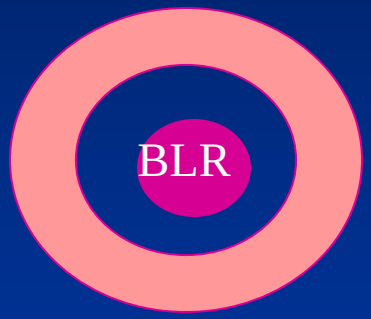


Toscanelli map 1474 –

Distance to India is about 7000 km

Three dusty components
1. Hot dust just outside the BLR

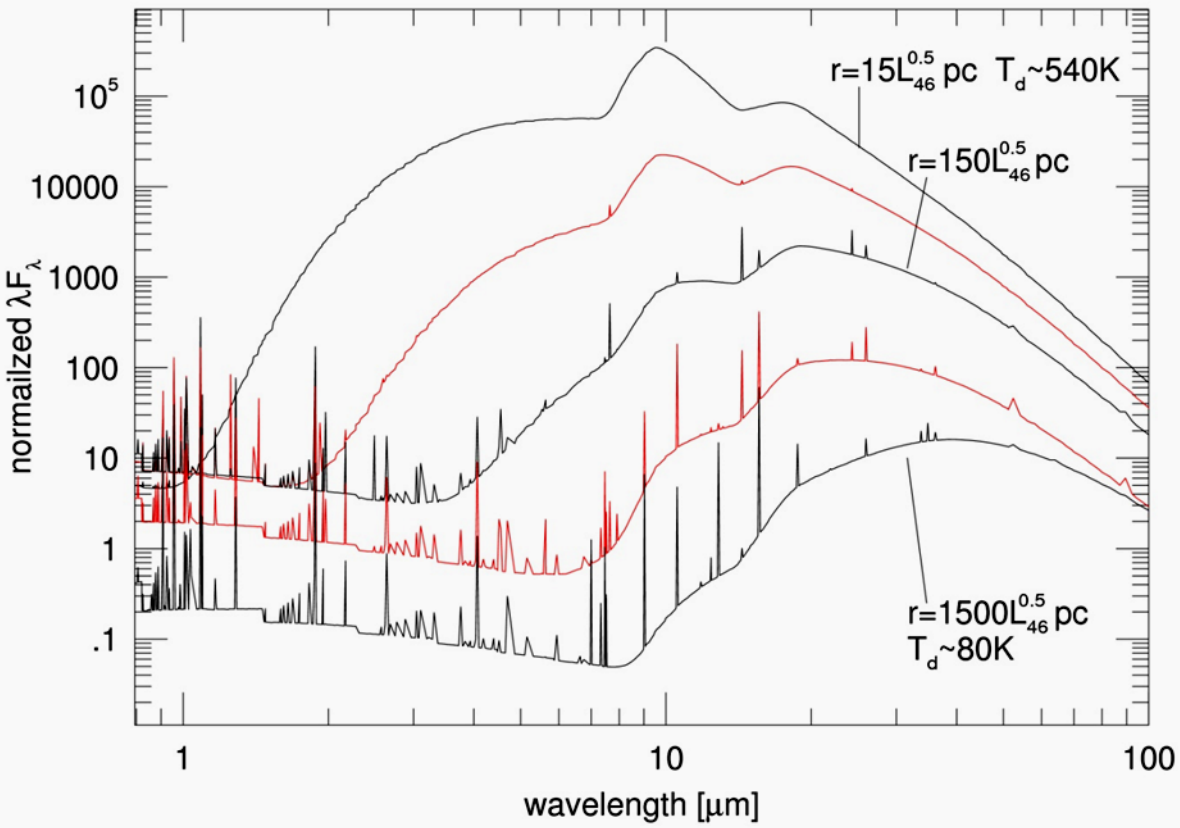




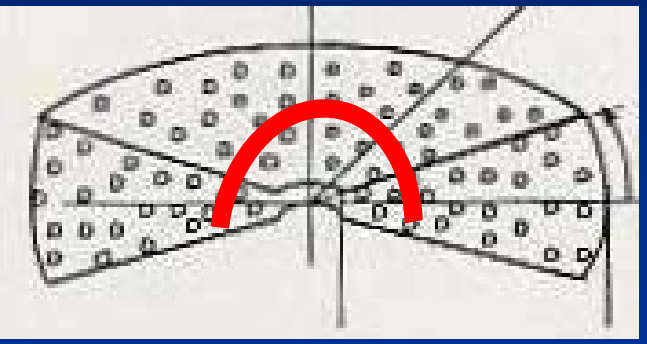
Mor and Netzer 2011

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

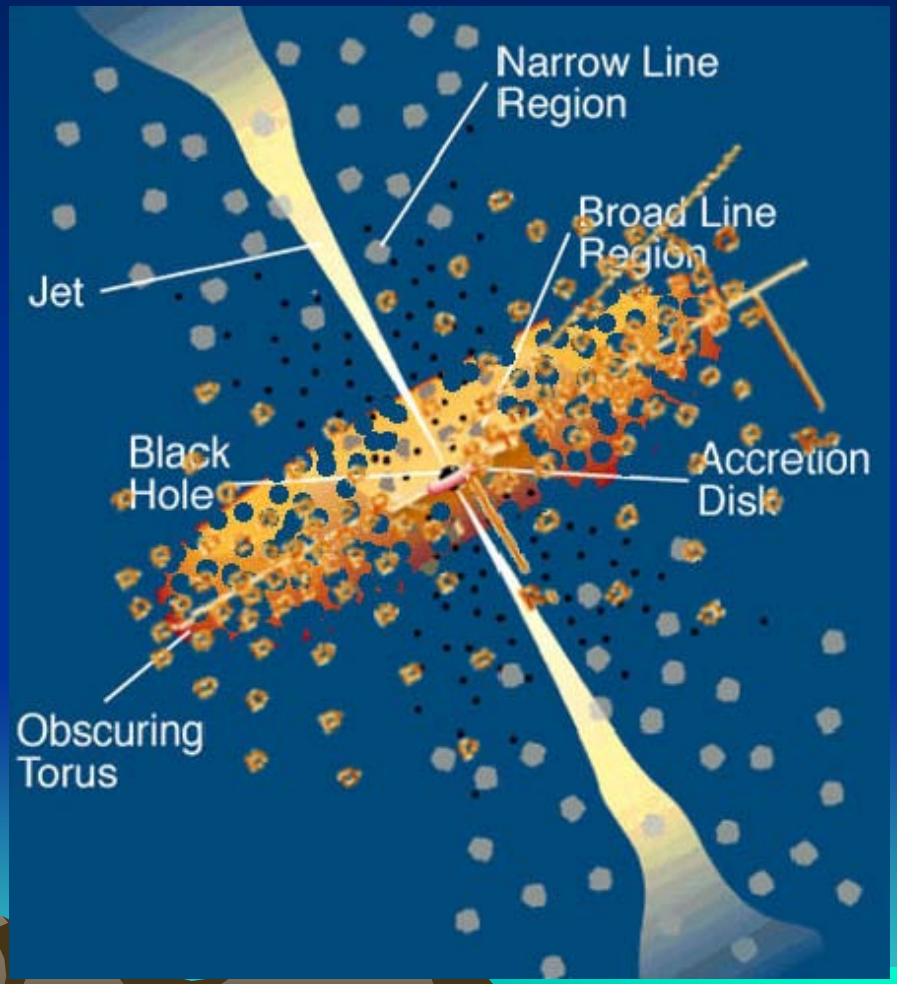
Three dusty components
2. Dust in the NLR



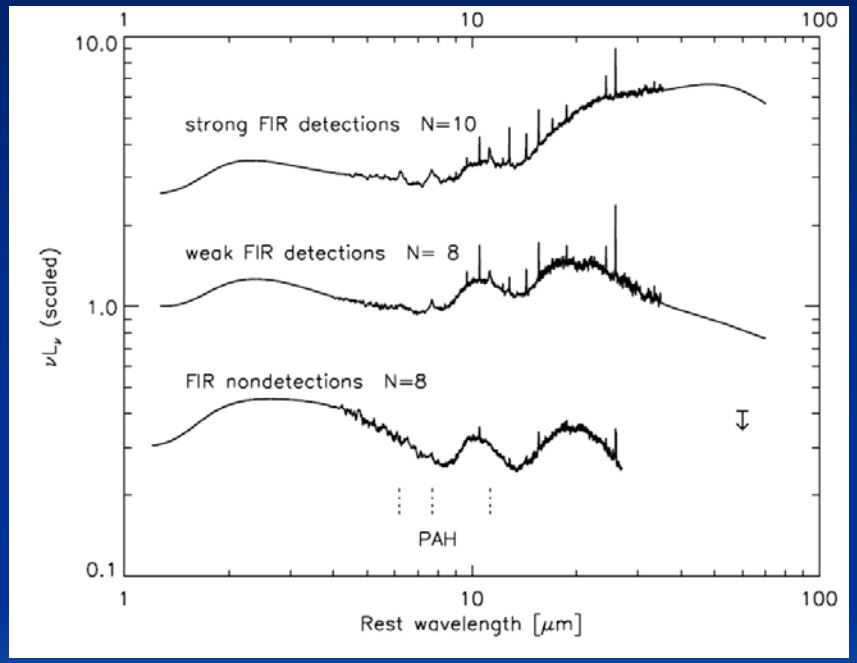
Three dusty components
3. Dusty torus

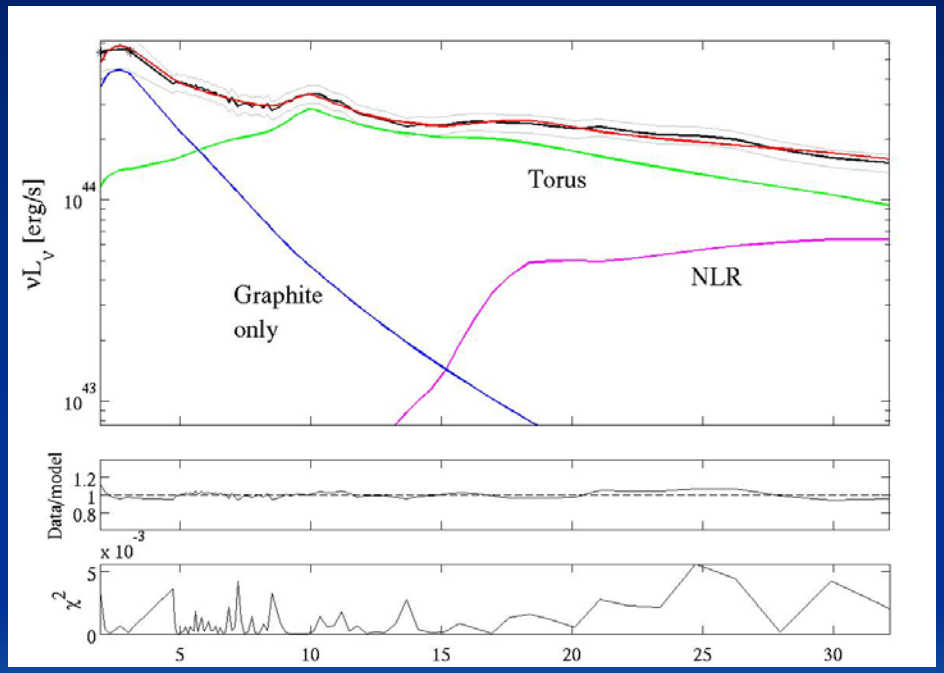


Continuous or clumpy torus



Dusty torus and dusty NLRs





MIR spectra of luminous AGNs

Mor, Netzer, Elitzur 2009

The torus – looking from the side

N_H

21.25

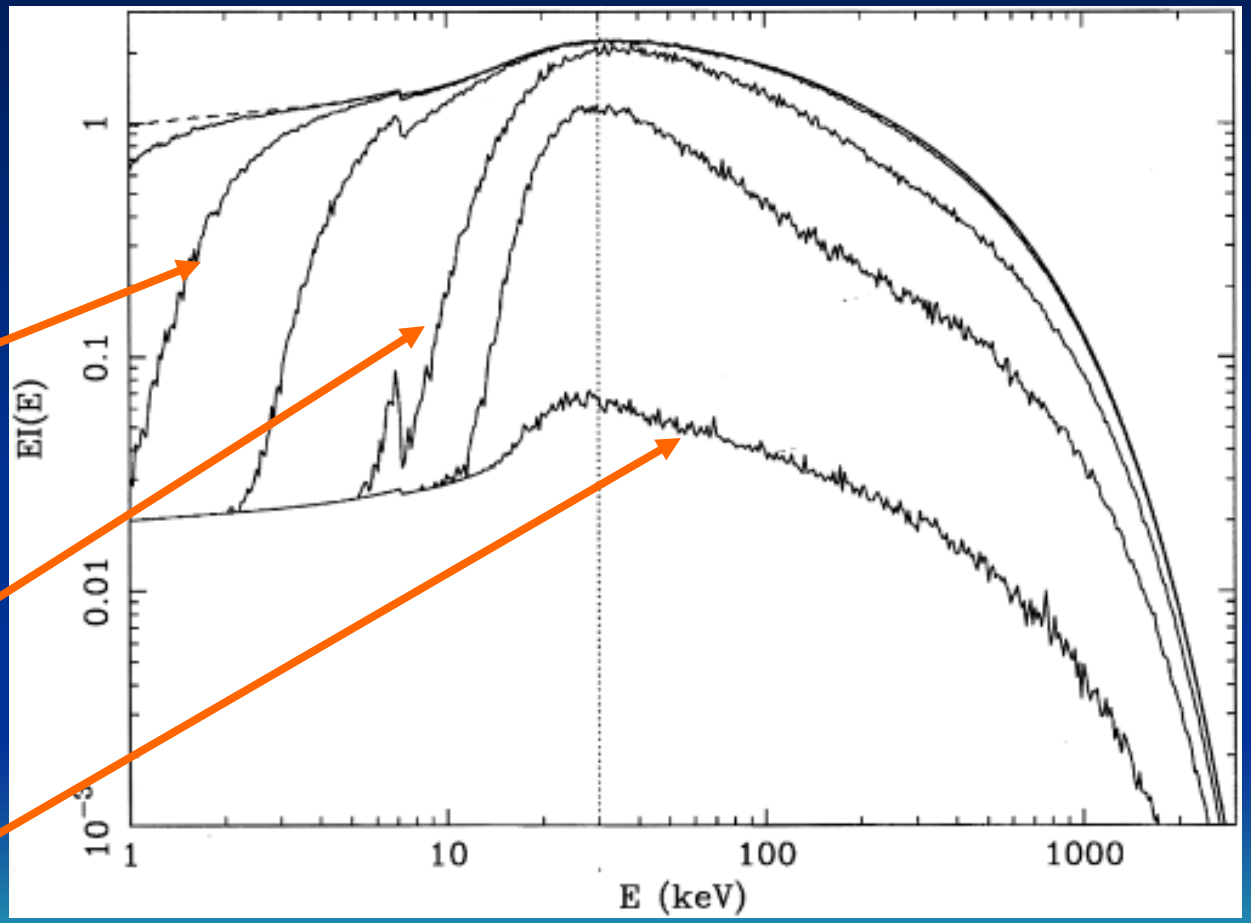
22.25

23.25

24.25

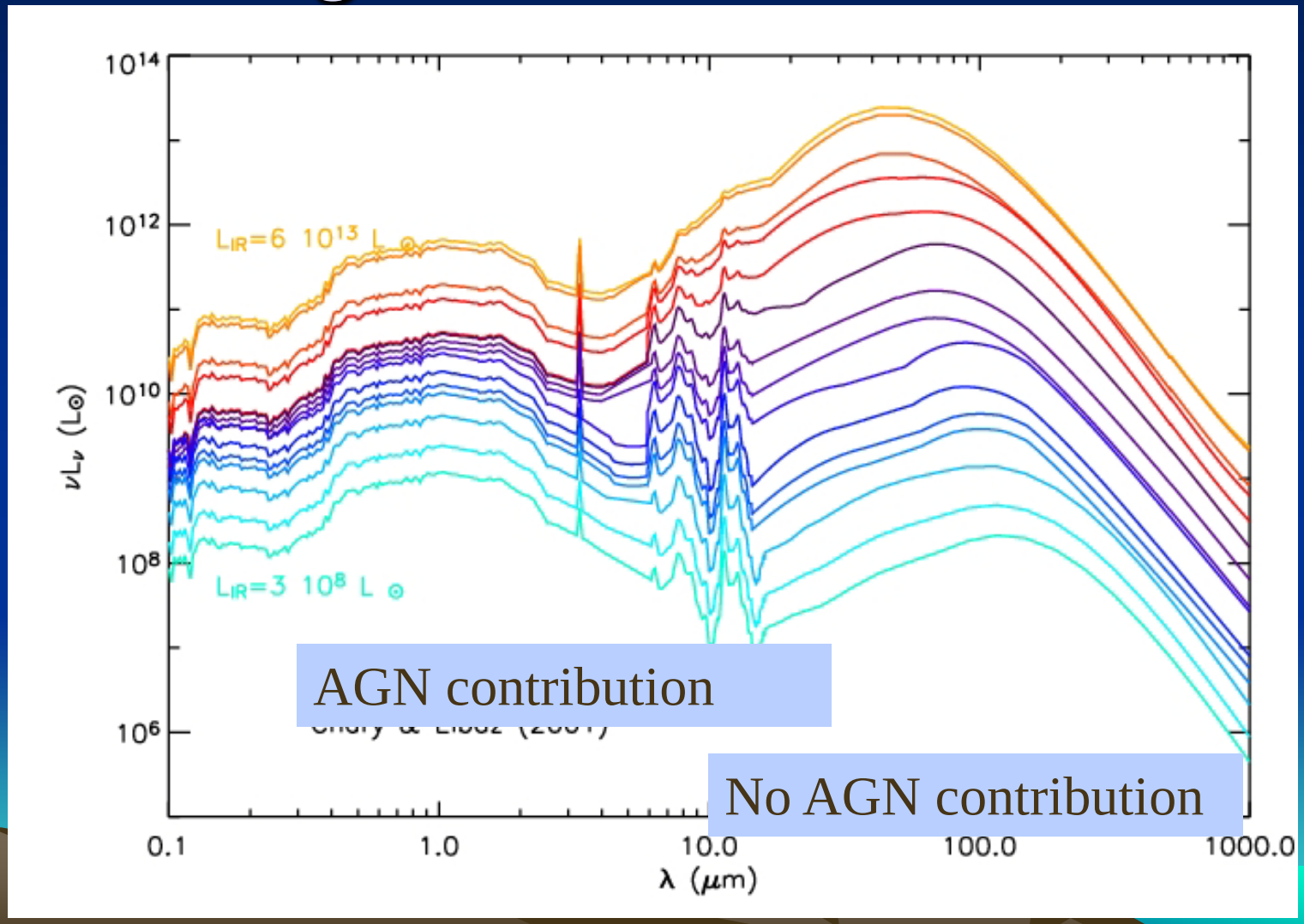
24.75

25.25



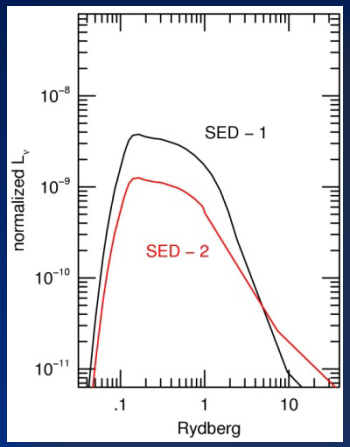
Wilman and Fabian 1999

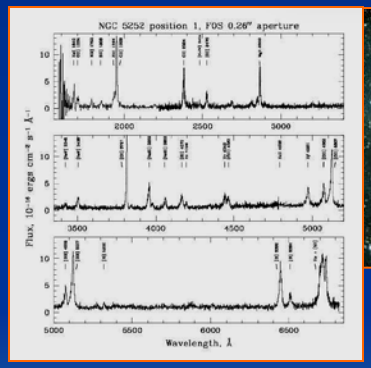
Cold warm and hot dust in host galaxies of AGNs

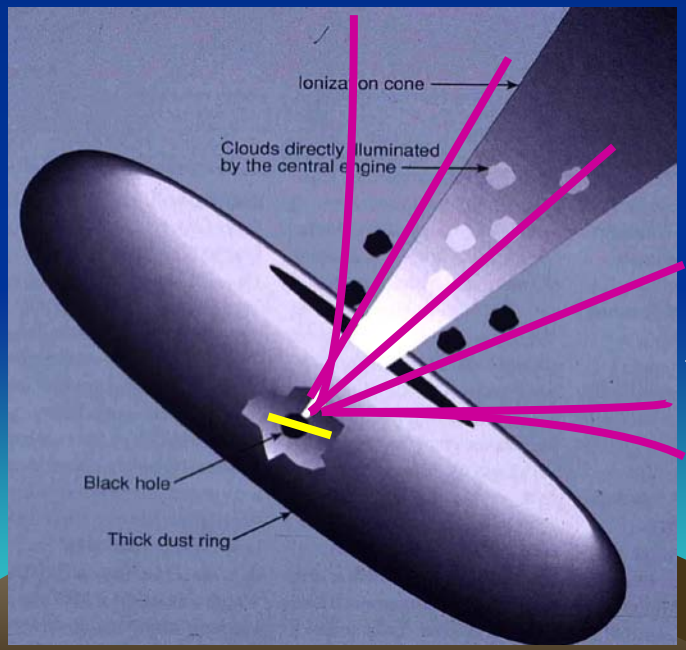


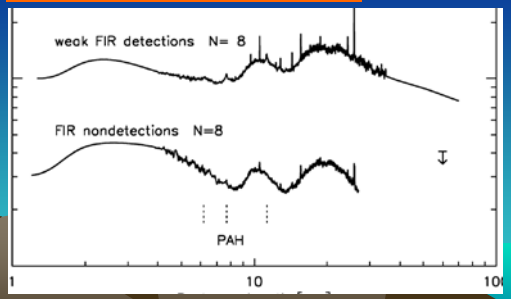
Main components of AGNs “Miracles”

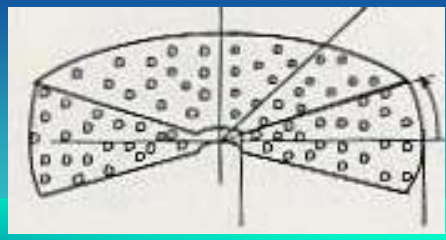
We need an additional miracle - wind







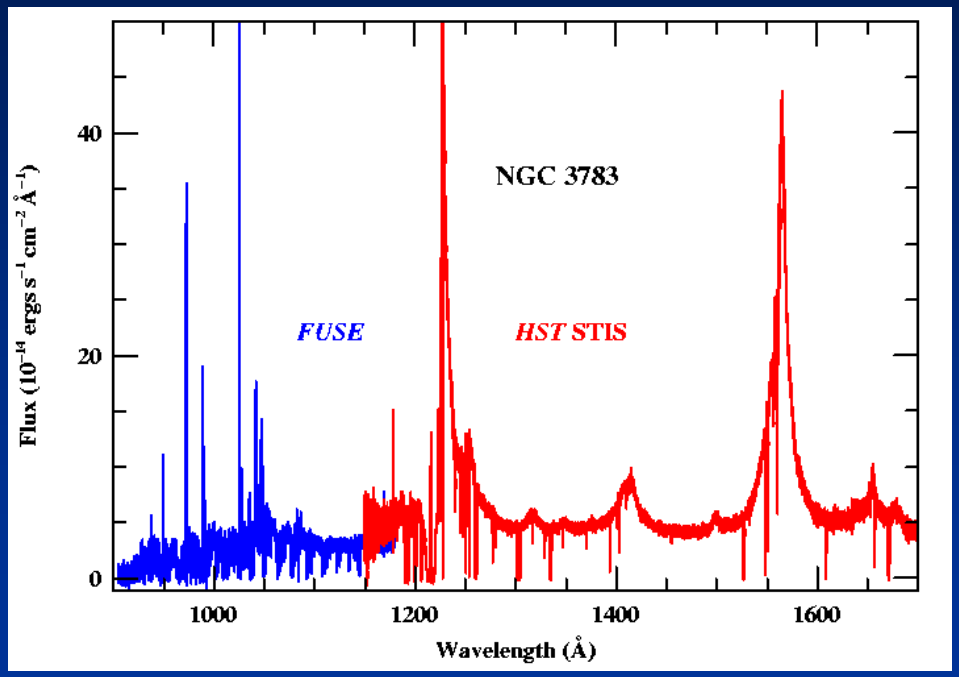




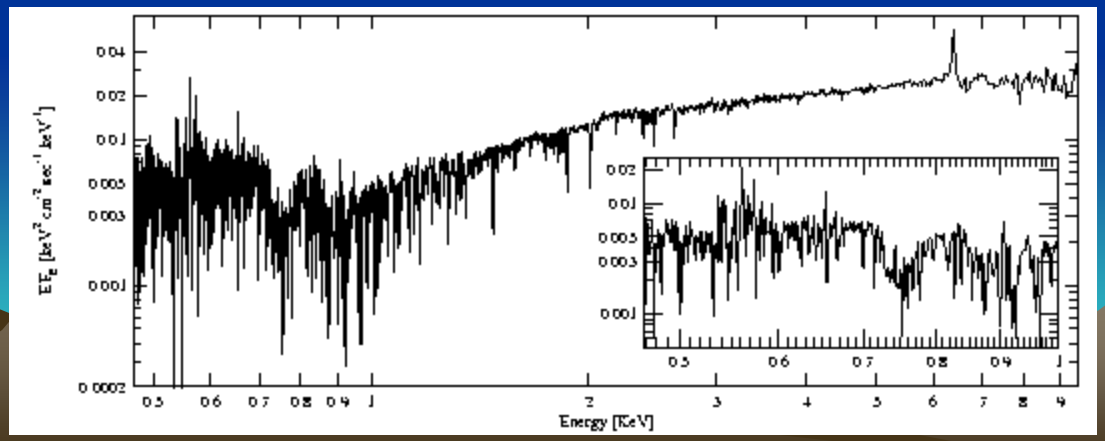
Main components of AGNs 4

- Highly ionized gas in AGN (HIG)
  - X-ray emission and absorption lines
  - The coronal line region
  - Optical and IR coronal lines
- Emission and reflection from accretion disks
  - Disk emission
  - Disk reflection
  - Relativistic disk lines
- Gas outflow from AGN disks

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)

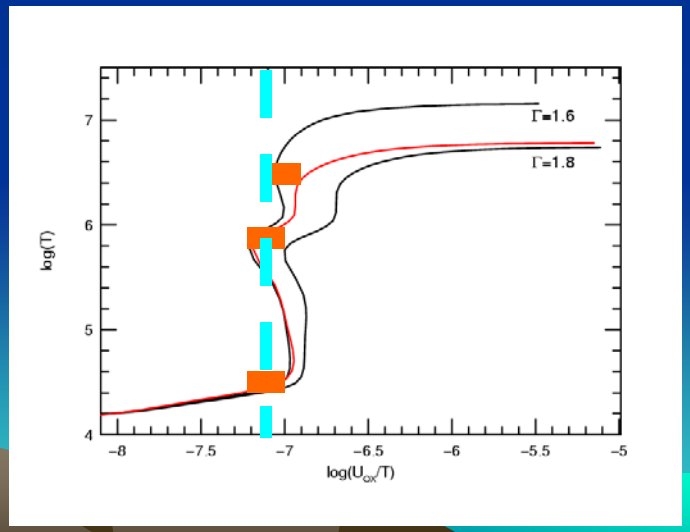
$$U = \int_{E_1}^{E_2} \frac{(L_E / E)dE}{4\pi r^2 c N_H}$$

$$E_1 = 0.54\,keV \quad E_2 = 10\,keV$$

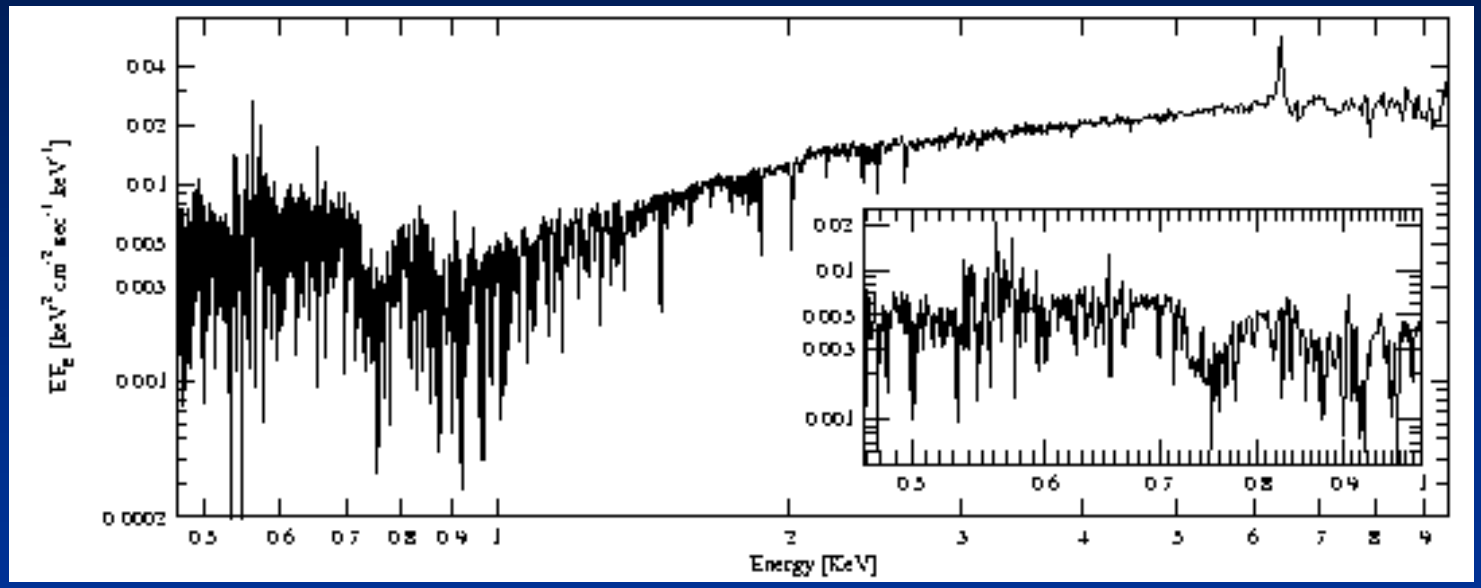
$$U(oxygen) = 0.1 - 1$$

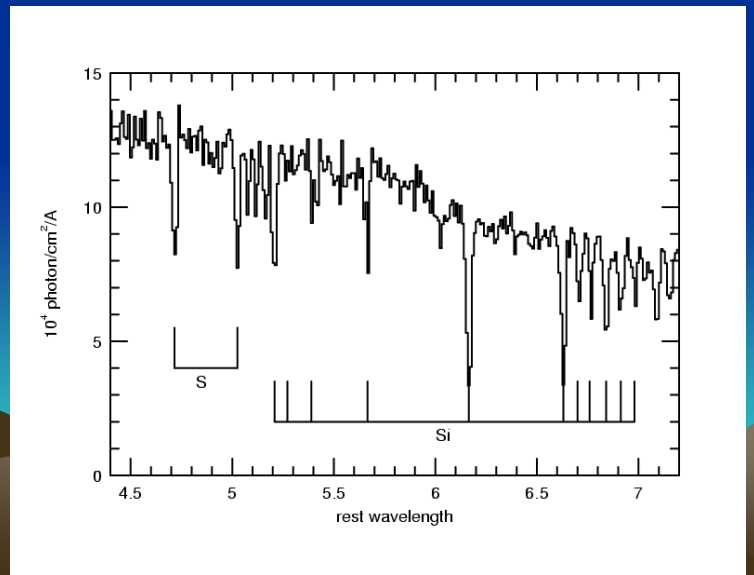
- Assumed clouds
  - Density $10^{3\text{-}5}$ cm^{-3}
  - Large and small column density
  - Location ~1 pc
  - Radial distribution
  - Confinement?
  - Covering factor (absorption?, emission?)

Stability analysis



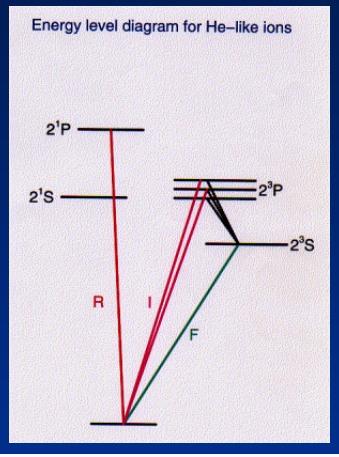
The X-ray spectrum of NGC 3783

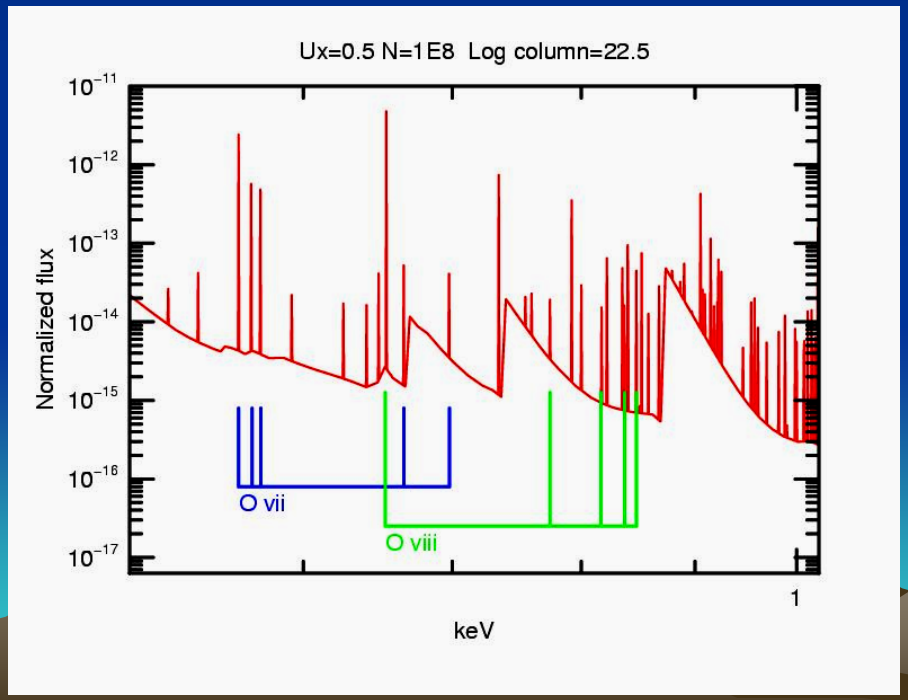


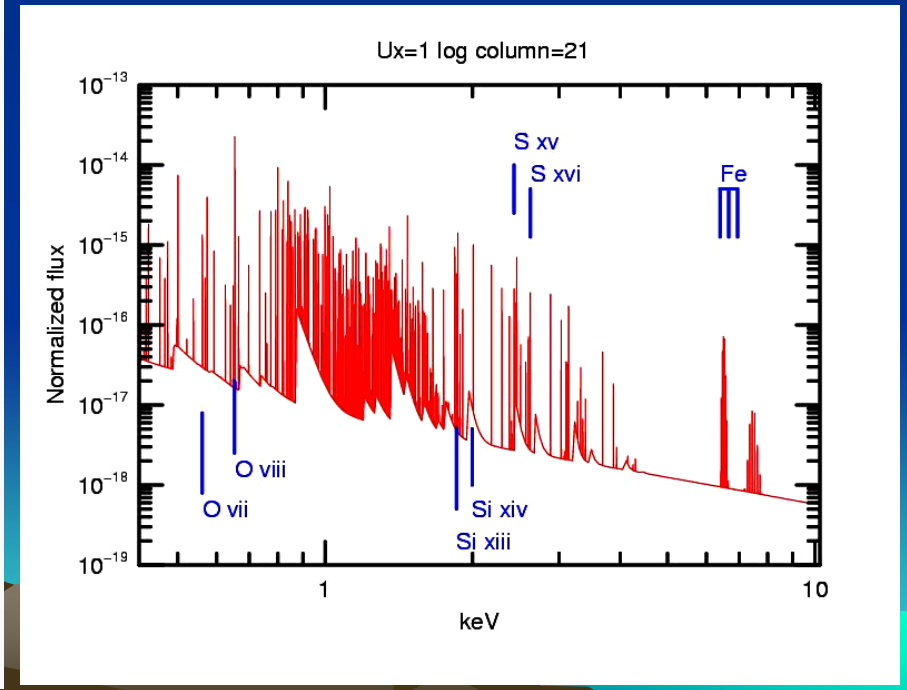


X-ray spectral components

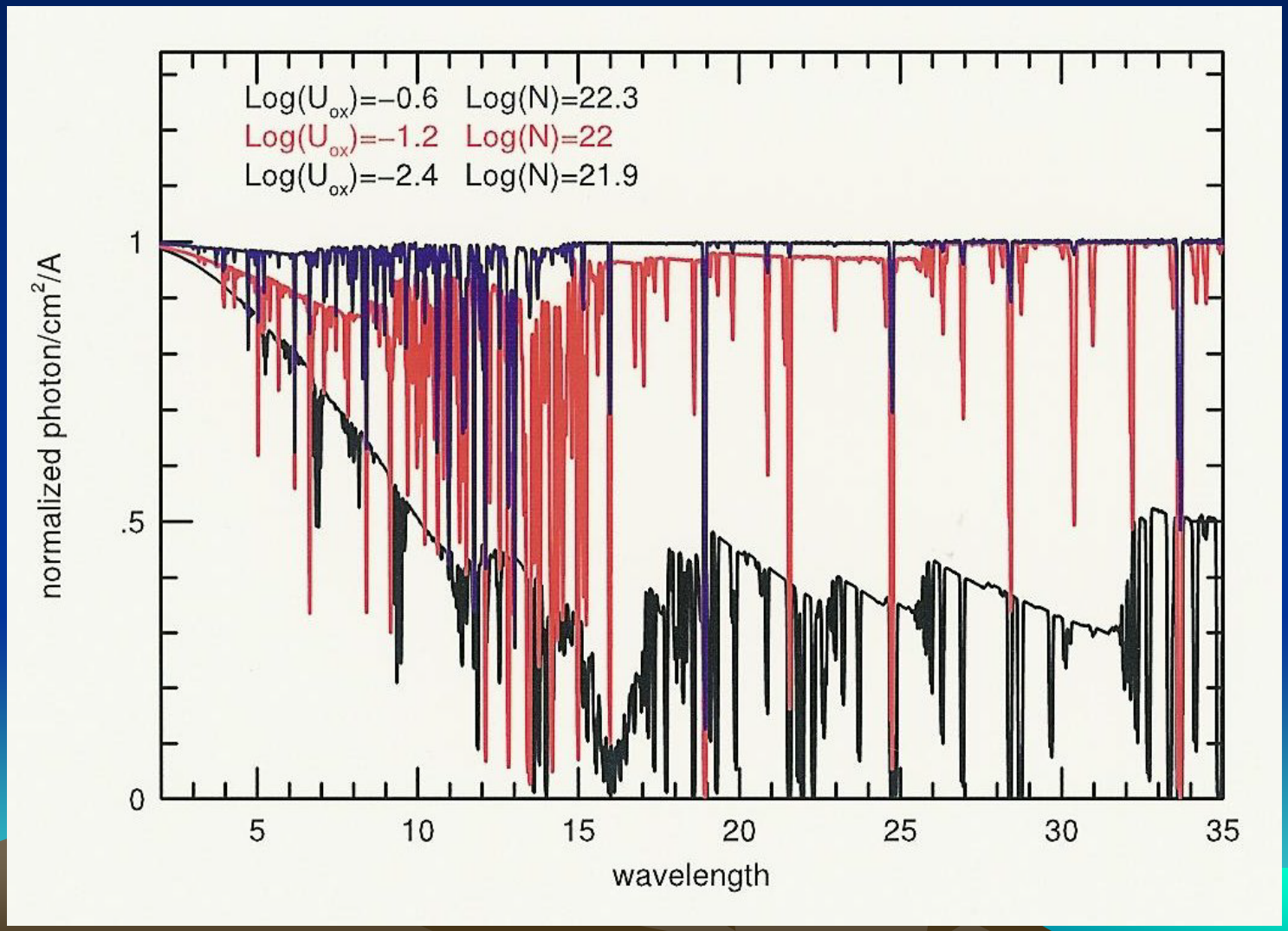
- Emission
- Absorption
- Reflection





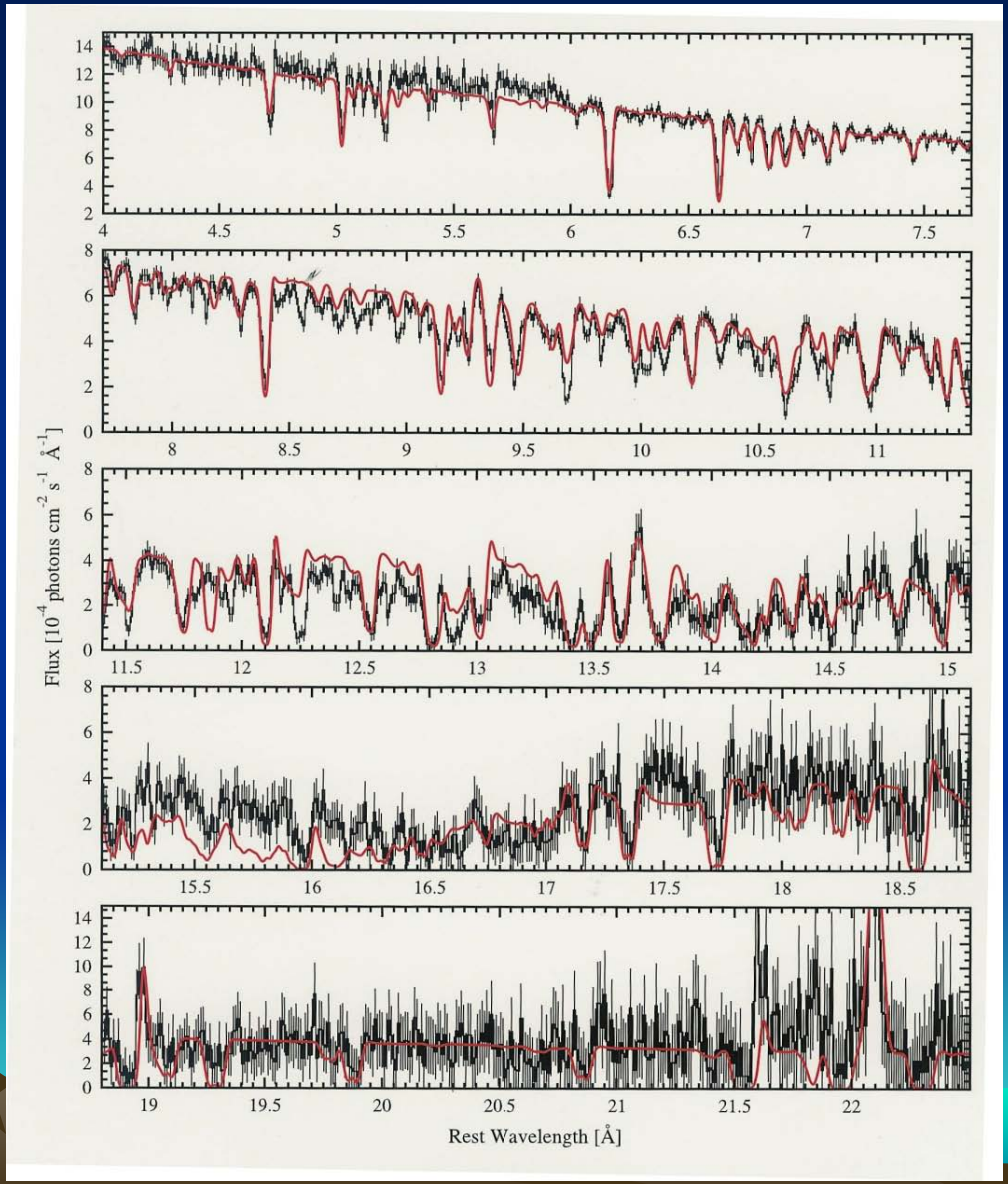


X-ray absorption

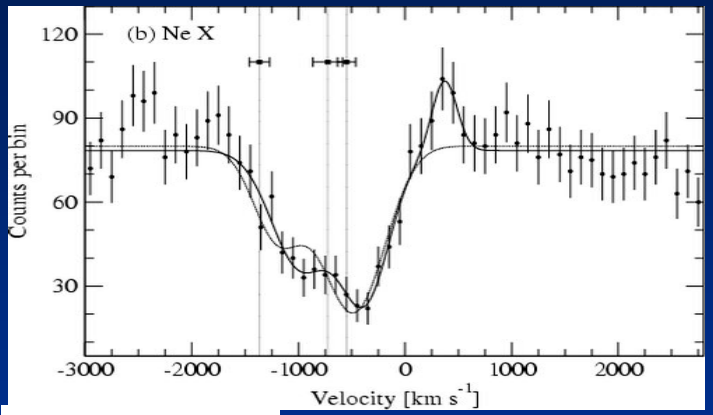


NGC 3783: model vs. observations

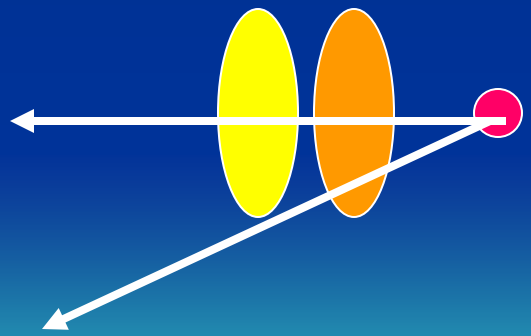
Netzer et al. 2003

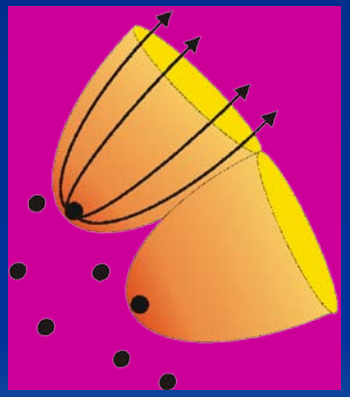


The HIG



Kaspi et al. 2002

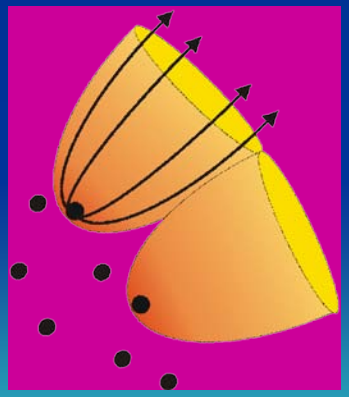


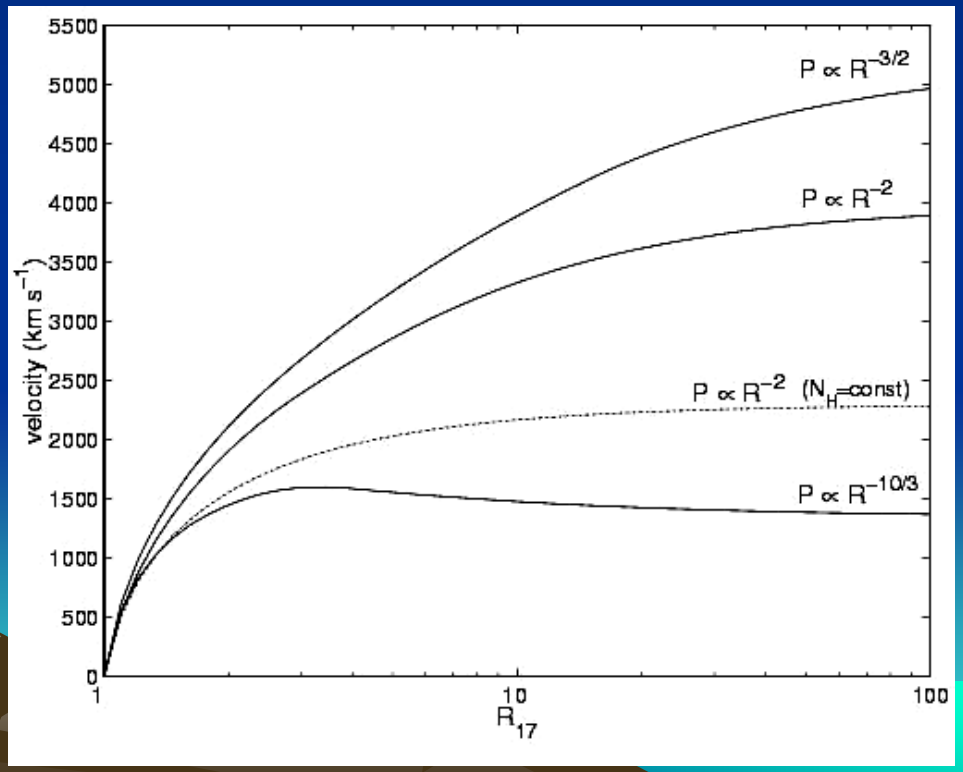


The motion of the HIG

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

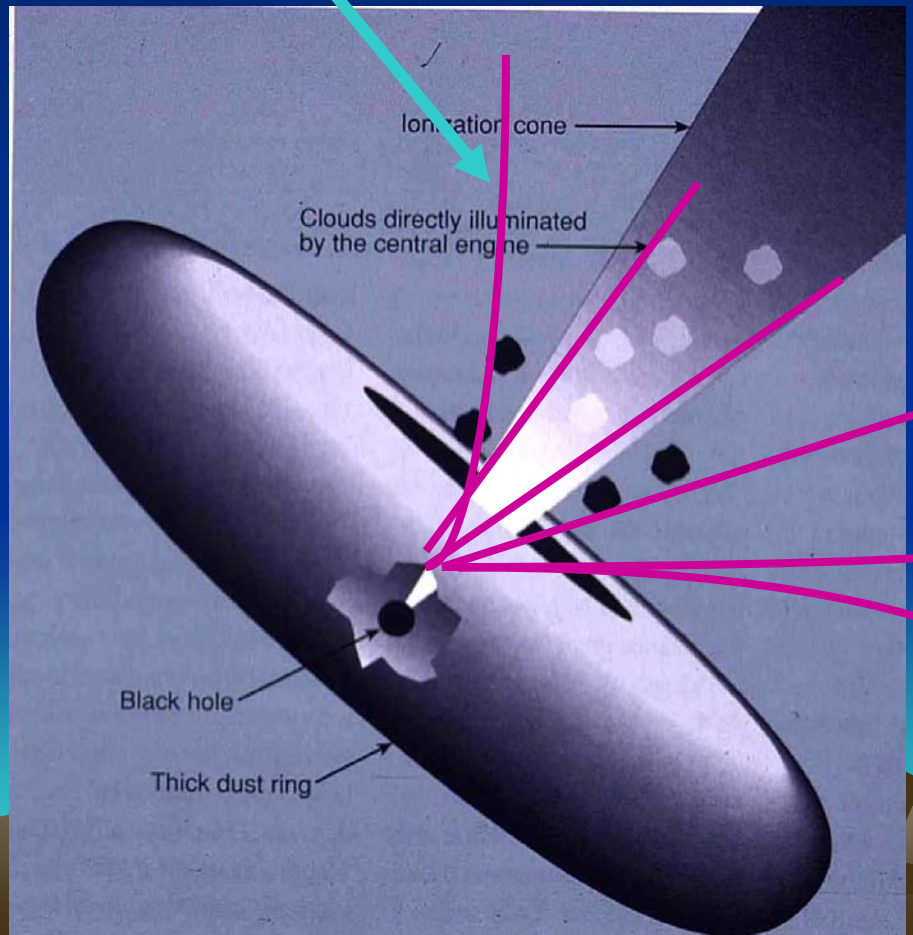
$$a(r) = a_{rad}(r) - g(r) - \frac{1}{\rho}\frac{dP}{dr} + \frac{f_d}{M_c}$$



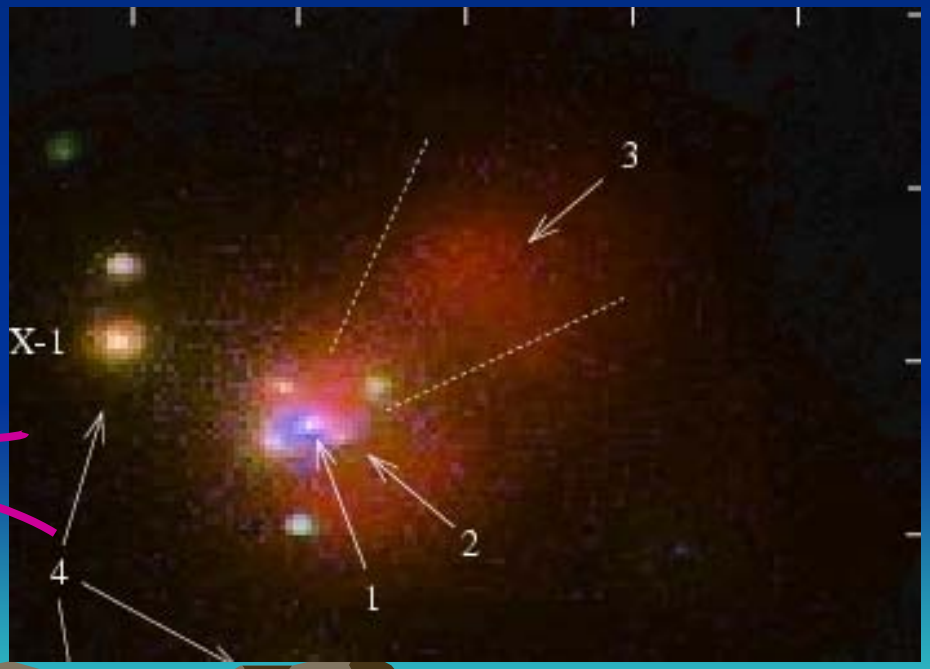


HIG in Seyfert 2s

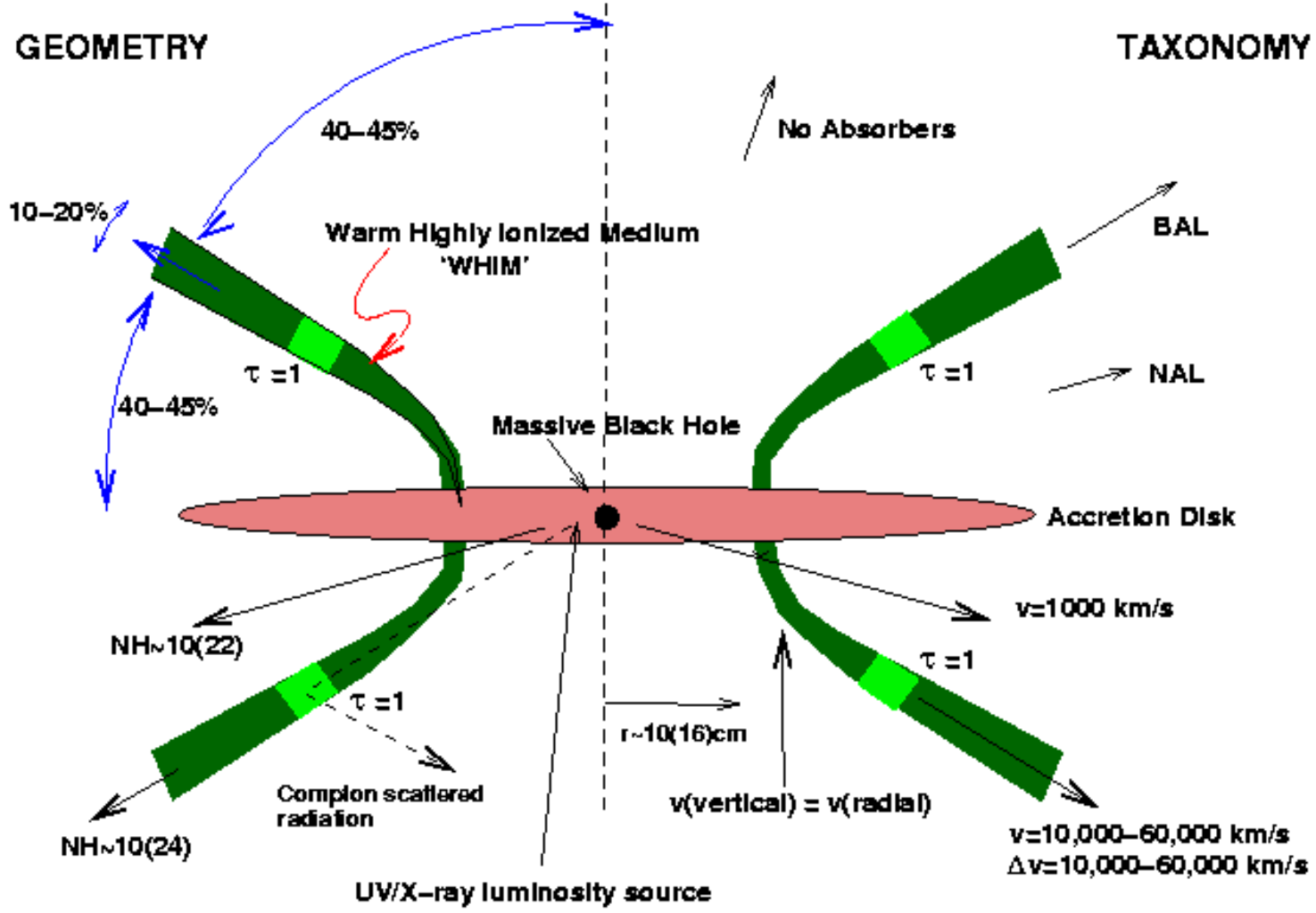
ouflow?



Circinus



A Structure for Quasars



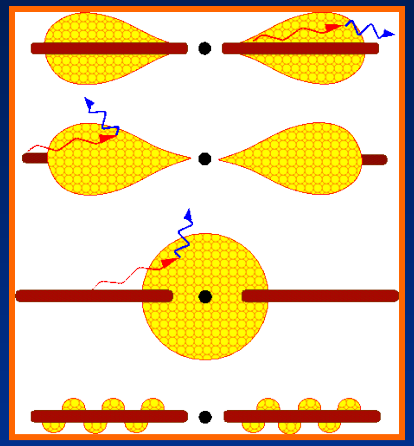
Elvis M. 2000 Ap.J. 545,63. (astro-ph/0008064)

Summary of locations so far

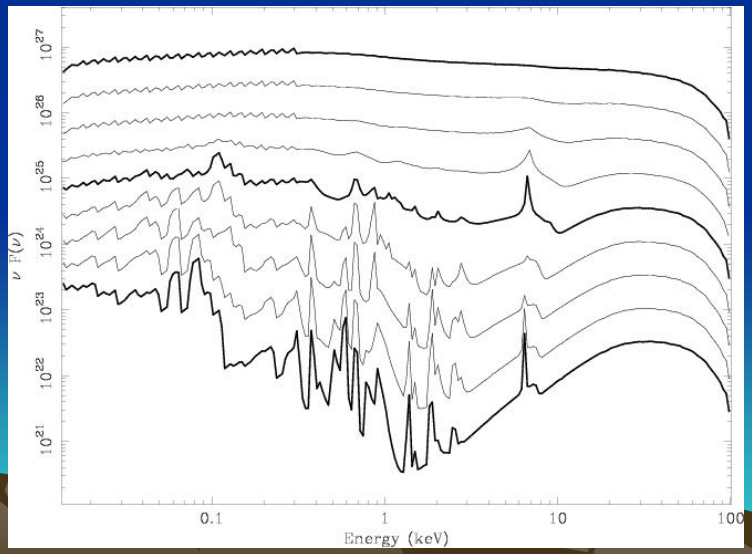
Component	Location	Density
Disk	10^{-3} pc	10^{15}
BLR	0.01-1 pc	10^{10}
HIG	1-10 pc	$10\text{-}10^{5}$
Torus	1-10 pc	$10^{3\text{-}6}$
NLR	300-2000 pc	$10^{3\text{-}4}$

The accretion disk - 2

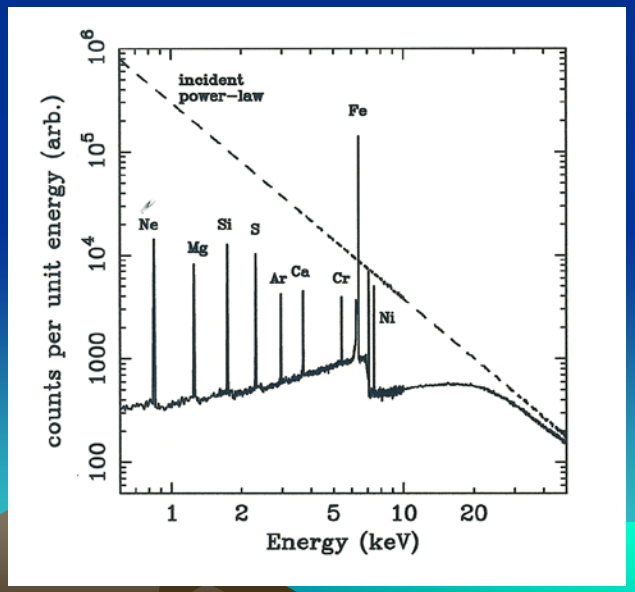
- X-ray continuum
- X-ray lines
- X-ray reflection



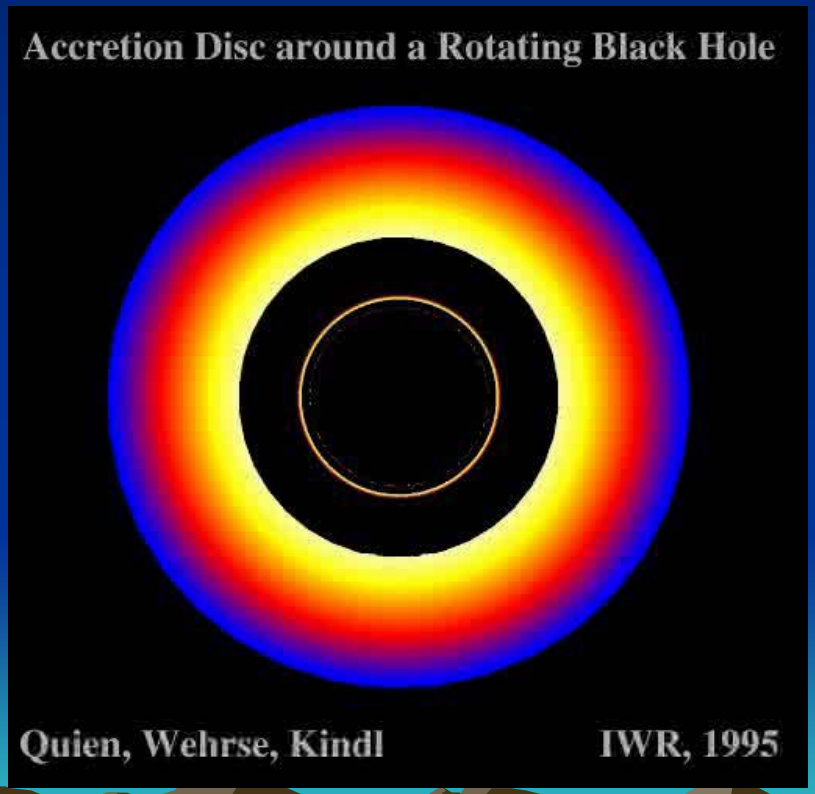
Ionized “reflection”

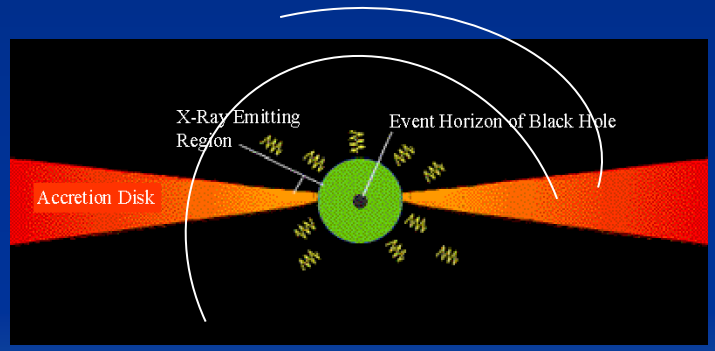


Neutral “reflection”

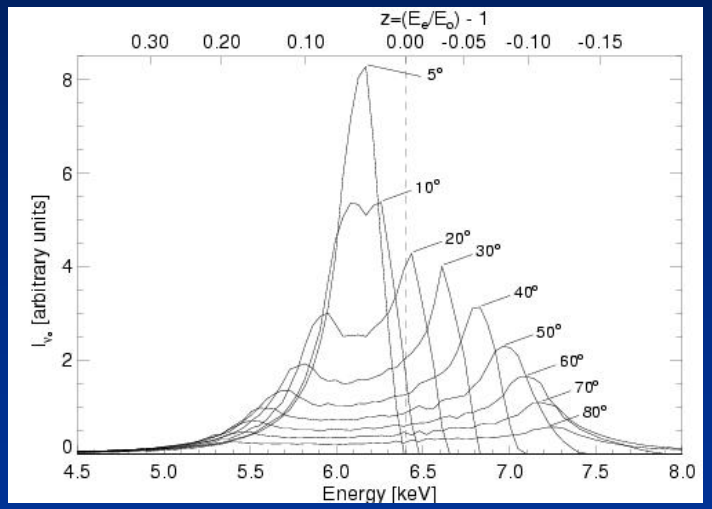


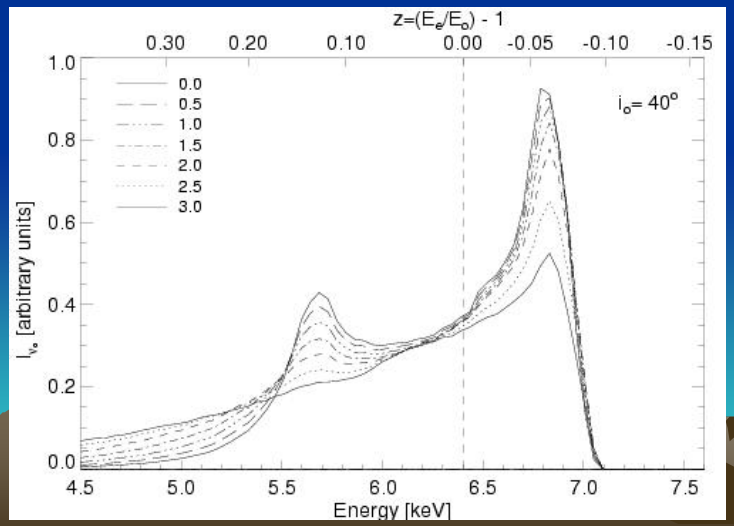
Accretion disks
relativistic effects

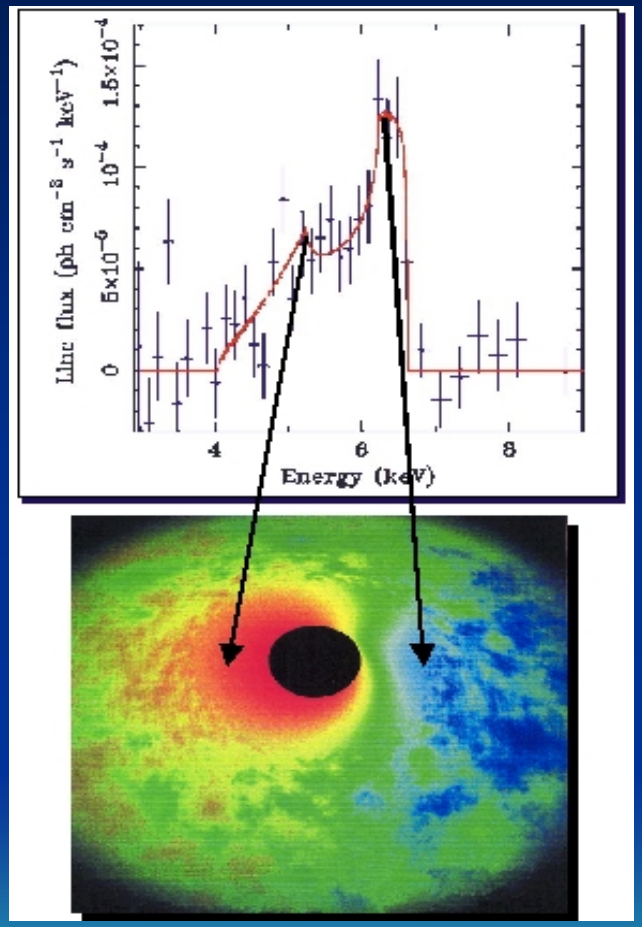




Relativistic disk lines

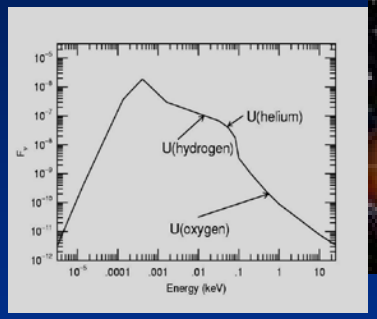


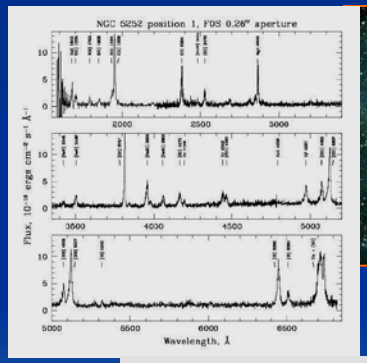


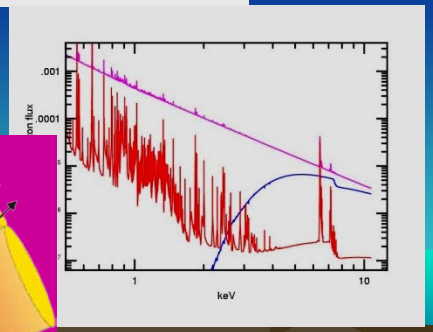


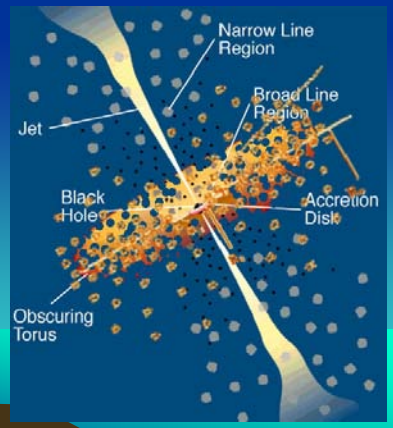
$$I(i,r) = f(i)r^{-\beta}$$

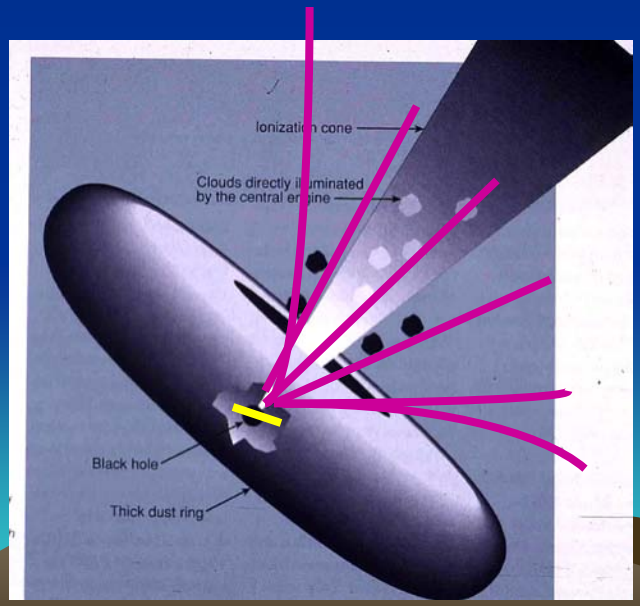
Summary


U(helium)
U(hydrogen)
U(oxygen)
Energy (keV)

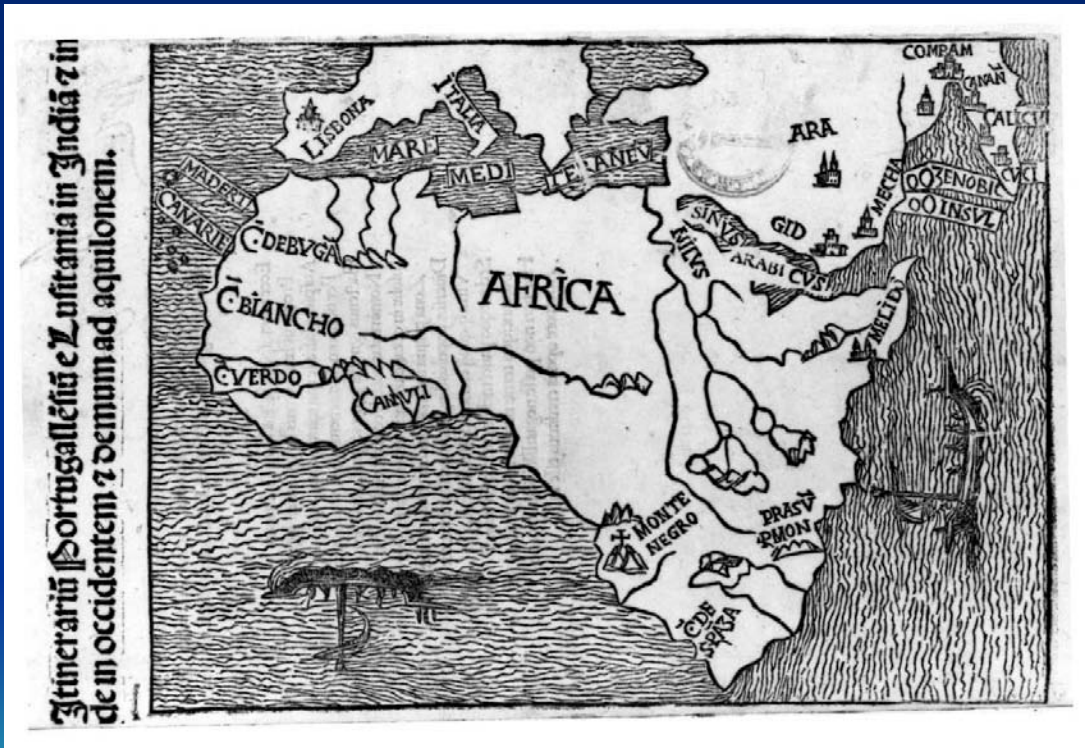

NGC 5252 position 1, FOS 0.26" aperture
Wavelength, Å


keV

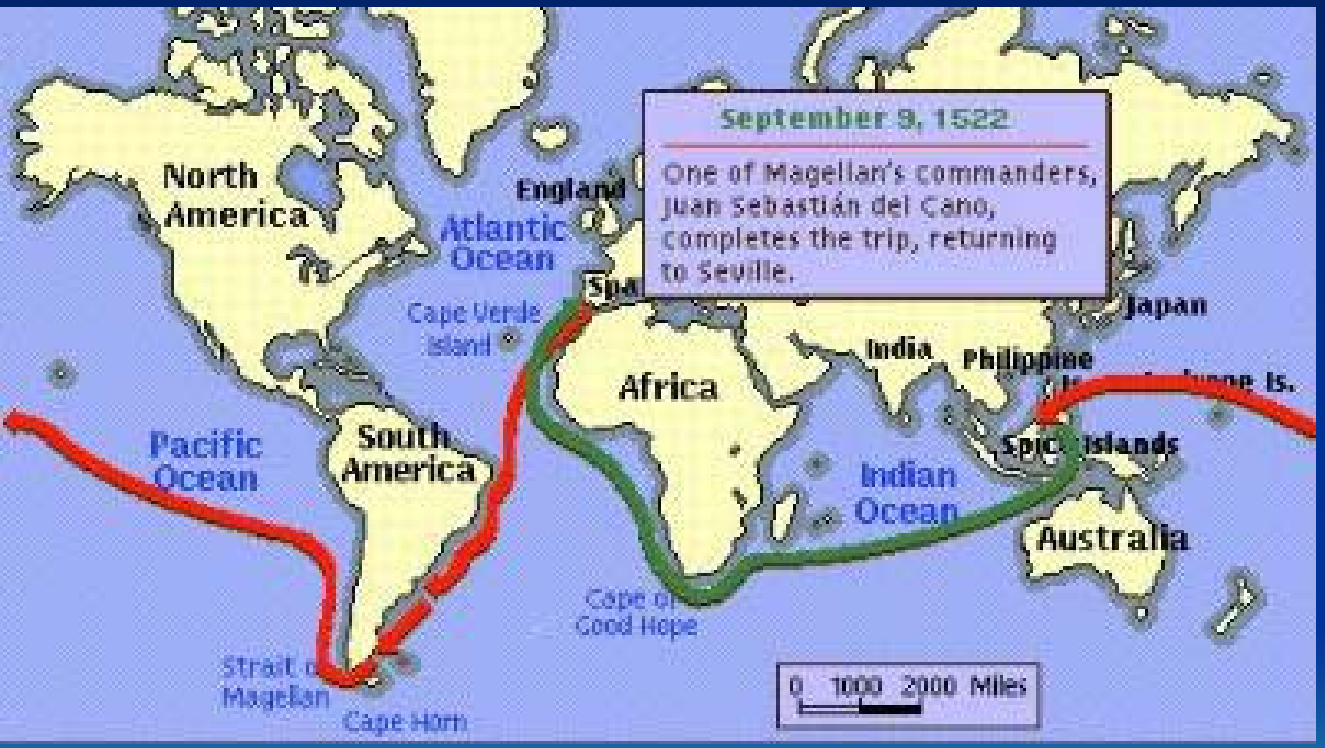

Narrow Line Region
Broad Line Region
Jet
Black Holes
Accretion Disk
Obscuring Torus


Ionization cone
Clouds directly illuminated by the central engine
Black hole
Thick dust ring

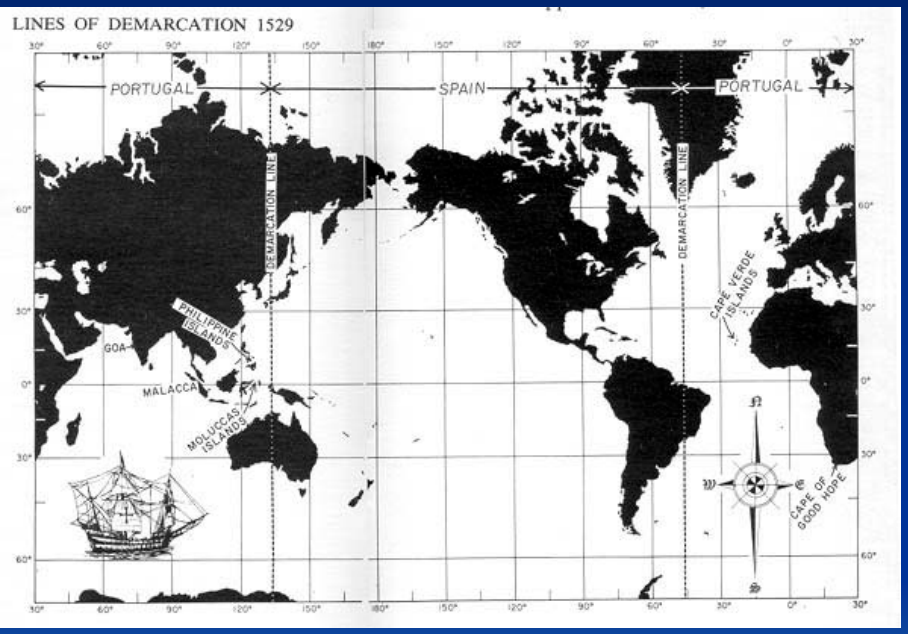
Vasco da Gama

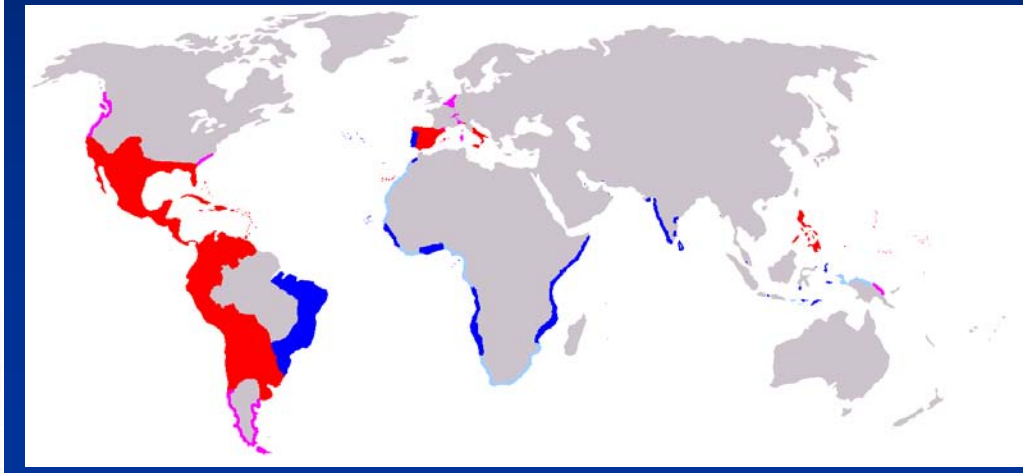


Magellan 1519-1521



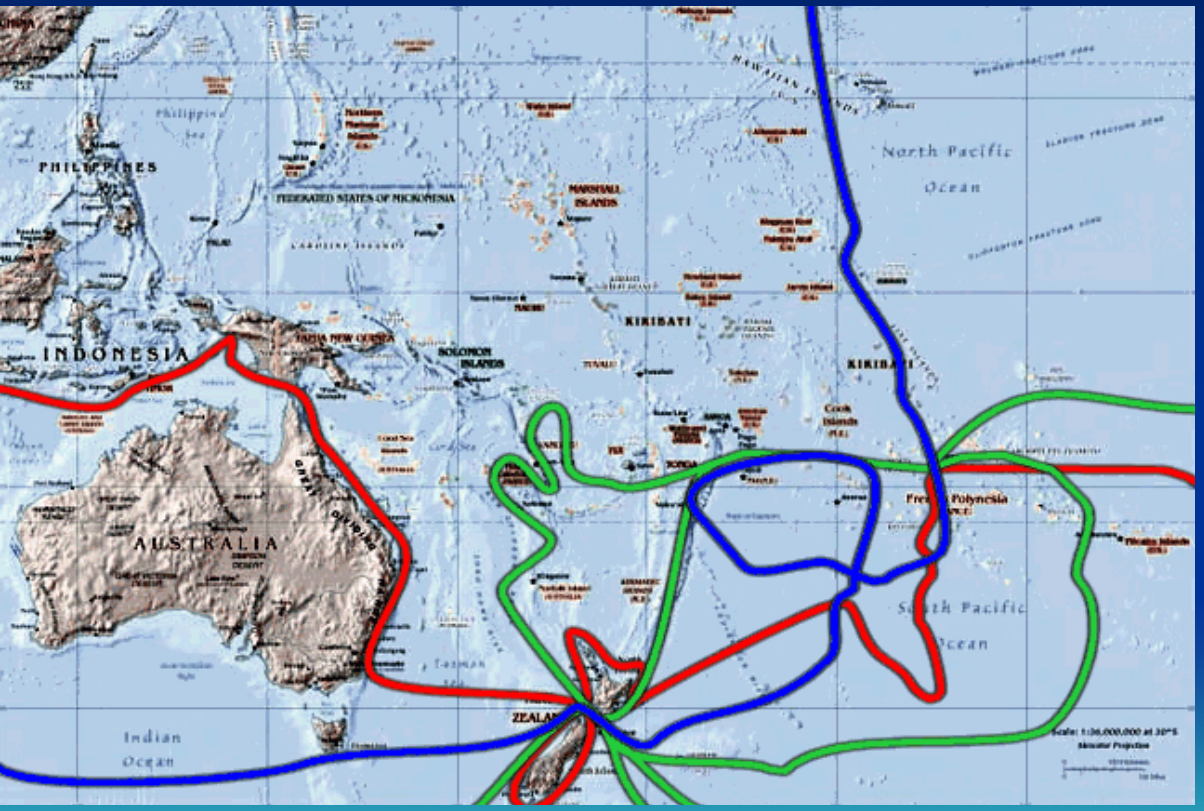
The division of the world



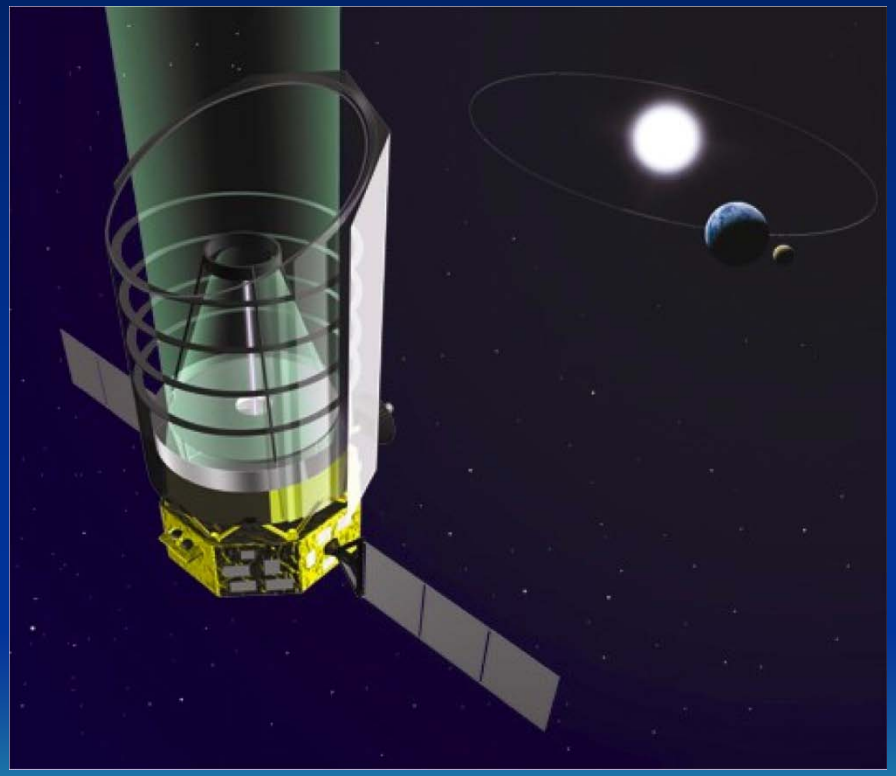


The big empires1581-1640

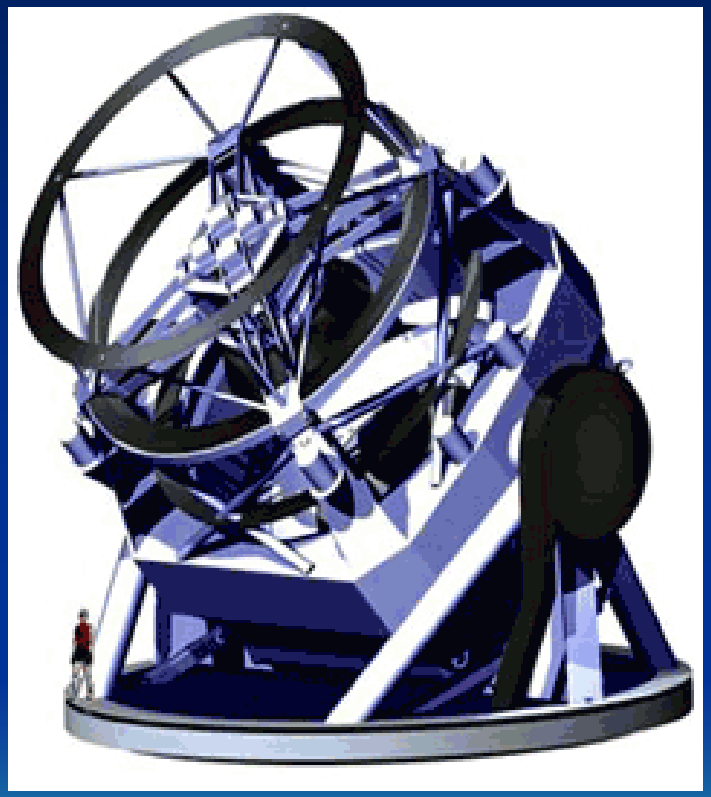
James Cook 1768-1772



Future observations: LSST and SPICA

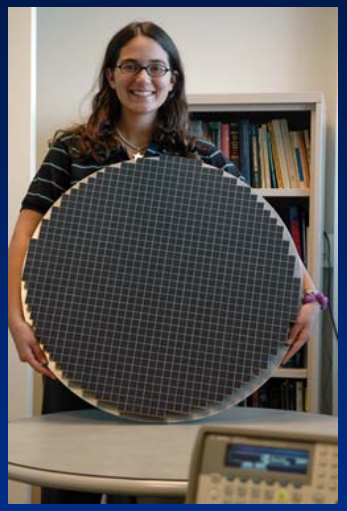


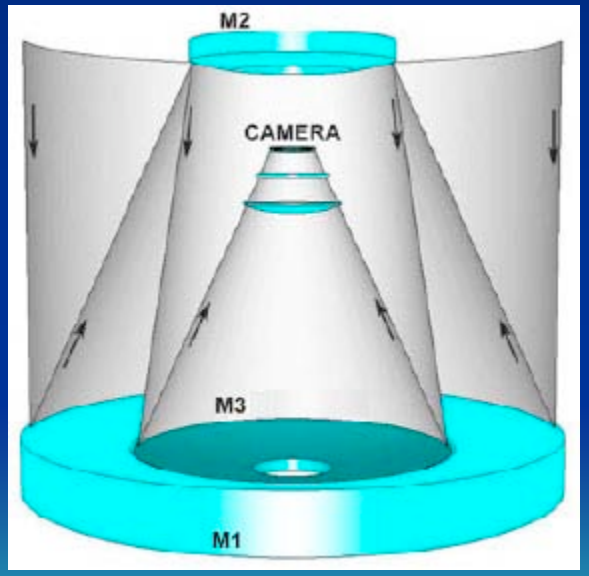
2020(???)

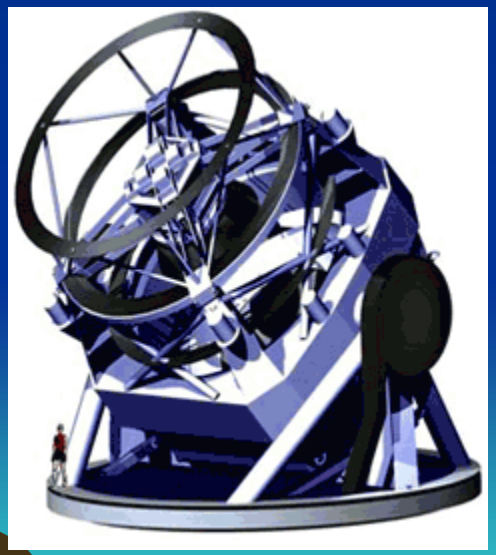


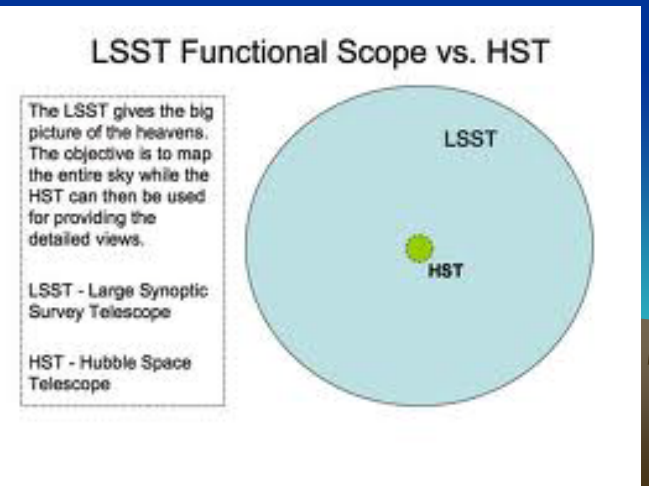
2018(?)

LSST




M2
CAMERA
M3
M1




LSST Functional Scope vs. HST
The LSST gives the big picture of the heavens. The objective is to map the entire sky while the HST can then be used for providing the detailed views.
LSST - Large Synoptic Survey Telescope
HST - Hubble Space Telescope
LSST
HST

Science Opportunities with the Large Synoptic Survey Telescope

Steven M. Kahn
Stanford/SLAC

Deputy Project Director
LSST

LSST Survey

Large Synoptic Survey Telescope

- 6-band Survey: *ugrizy* 320–1080 nm
- Frequent revisits: 2 x 15 s, 25 AB mag/visit
- Sky area covered: > 20,000 deg^2, 0.2 arcsec / pixel
- Each 9.6 sq.deg FOV revisited ~ 1000 times
- 10-Year Duration: Yields 27.7 AB magnitude @ 5σ
- Photometric precision: 0.01 mag absolute; 0.0005 mag reptability

The Science Book

Large Synoptic Survey Telescope

- Contents:
  - Introduction
  - LSST System Design
  - System Performance
  - Education and Public Outreach
  - The Solar System
  - Stellar Populations
  - Milky Way and Local Volume Structure
  - The Transient and Variable Universe
  - Galaxies
  - Active Galactic Nuclei
  - Supernovae
  - Strong Lenses
  - Large-Scale Structure
  - Weak Lensing
  - Cosmological Physics

Galaxies

Large Synoptic Survey Telescope

- LSST will be a unique tool for studies of galaxy formation and galaxy properties.
- The database will include photometry for 10^{10} galaxies from the Local Group to $z > 6$.
- We will have 6-band photometry for 4×10^9 galaxies.
- Key diagnostic tools will include:
  - Luminosity functions
  - Color-luminosity relations
  - Size-luminosity relations
  - Quantitative morphological classifications
  - Dependence on environment

Active Galactic Nuclei

Large Synoptic Survey Telescope

- Active Galactic Nuclei involve massive black holes at the centers of galaxies that release prodigious amounts of energy through gravitational in-fall.

- In recent years, we have learned that the formation and growth of central black holes plays a crucial role in galaxy evolution through "AGN feedback".

- The enormous dynamic range offered by LSST in luminosity and redshift will revolutionize our understanding of AGN demography and the correlation between AGN properties and their host dark matter haloes.

- LSST will produce a high purity sample of > 10^7 optically-selected AGNs. This is at least an order of magnitude larger than current AGN samples using all wavelengths.

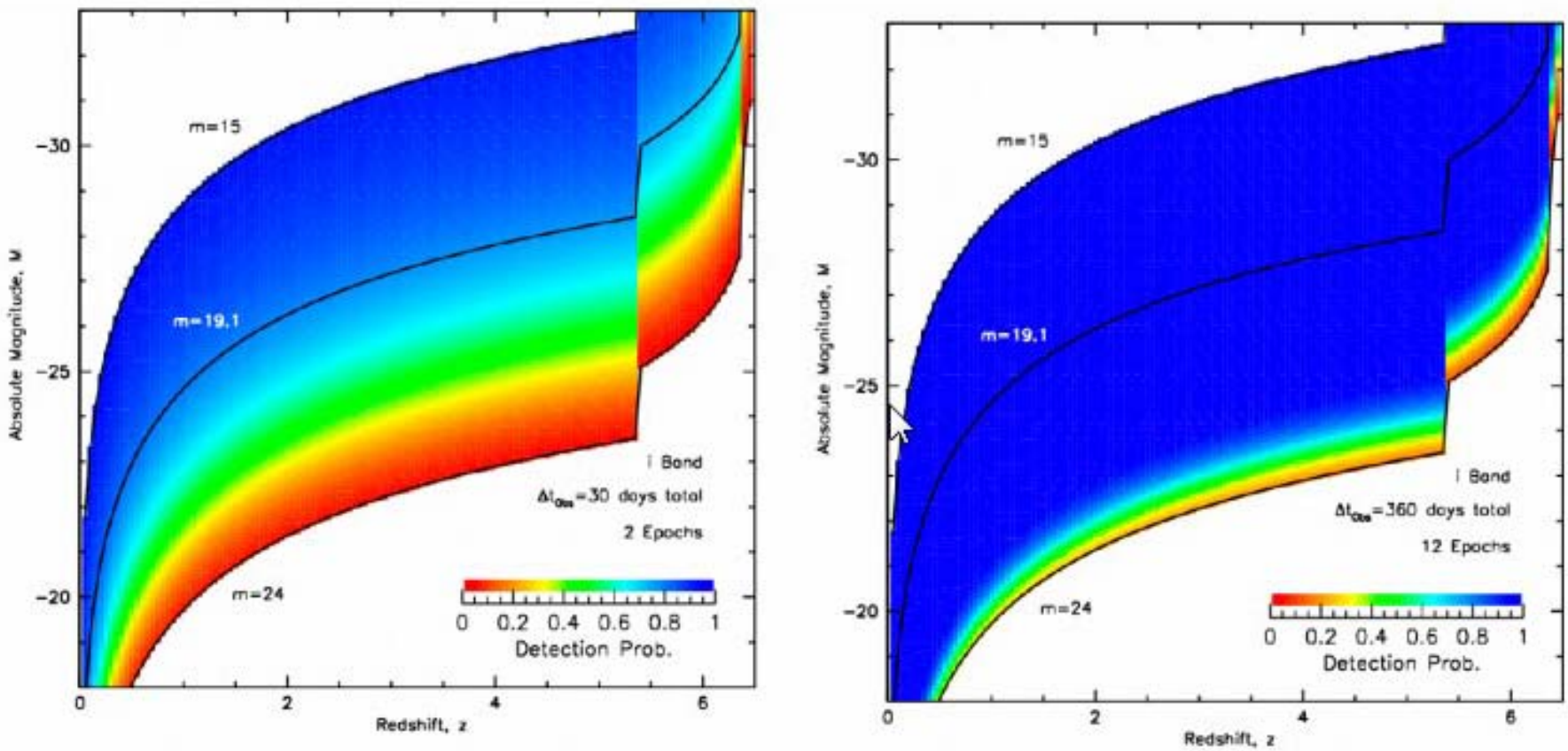


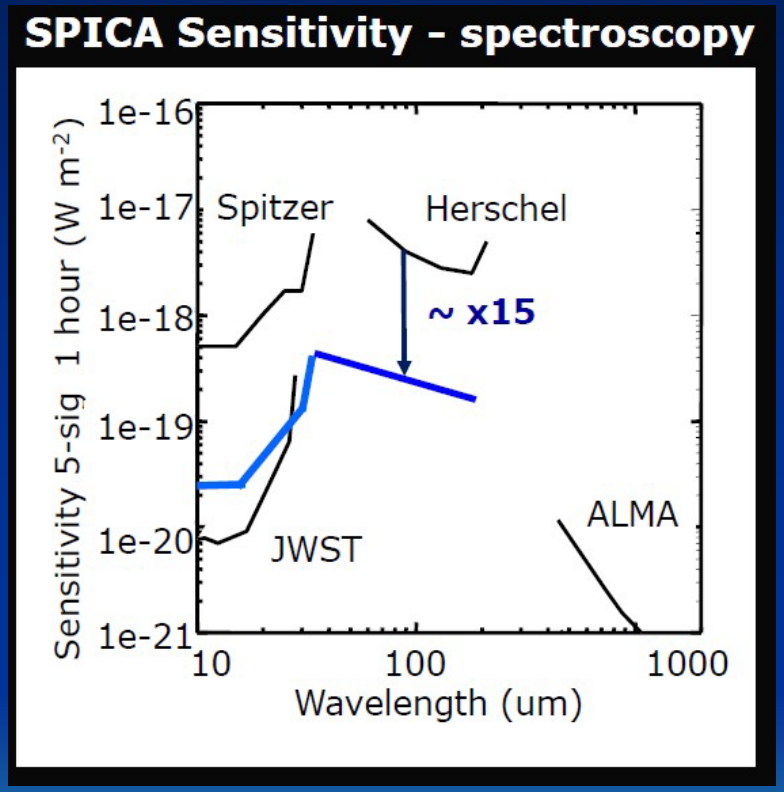
Figure 10.2: The probability of detecting an AGN as variable as a function of redshift and absolute magnitude. *Left:* two epochs separated by 30 days. *Right:* 12 epochs spanning a total of 360 days. Nearly all of the AGN between the limiting apparent magnitudes would be detected as variable after one year.

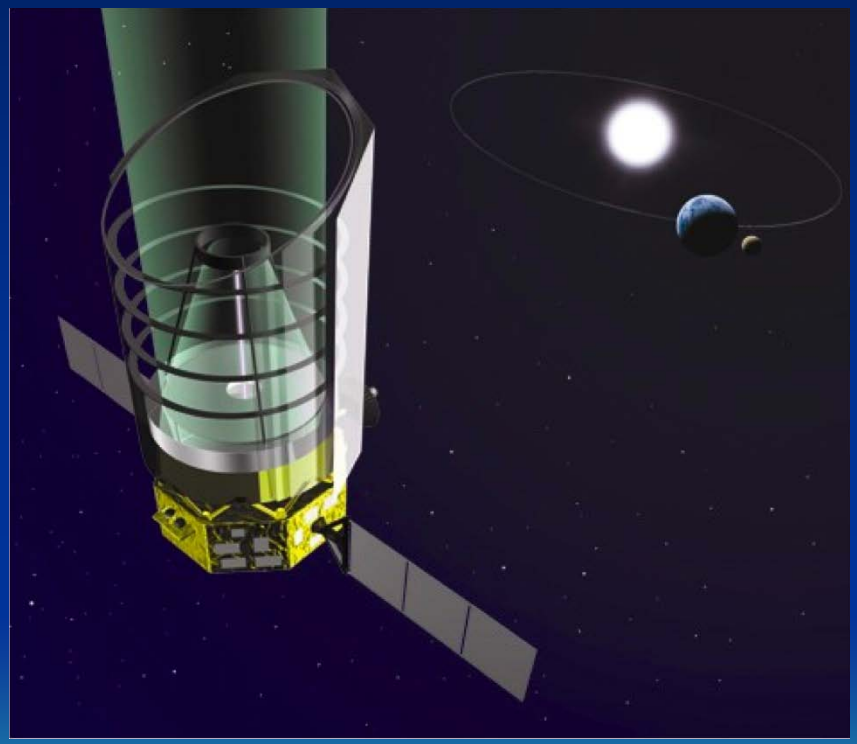
SPICA


JAXA
次世代赤外線天文衛星
esa
SPICA
Space Infrared Telescope for Cosmology and Astrophysics
REVEALING THE ORIGINS OF PLANETS AND GALAXIES


SAMSUNG
SAMSUNG

SPICA


SPICA Sensitivity - spectroscopy
Sensitivity 5-sig 1 hour (W m-2)
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
Spitzer
Herschel
~ x15
JWST
ALMA
10
100
1000
Wavelength (um)



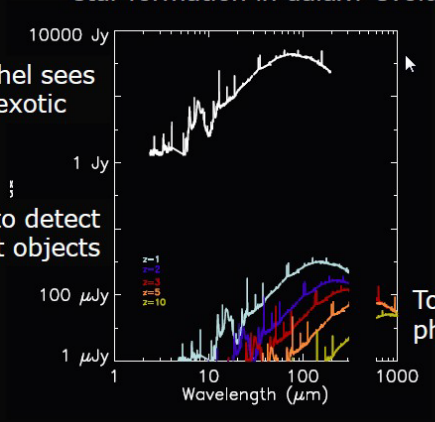
Spectroscopy of high redshift FIR galaxies

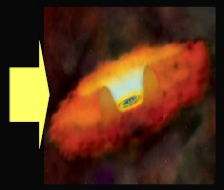
Herschel and SCUBA-2 → thousands of objects in photometric surveys

Only spectroscopy can reveal nature and role of AGN and star formation in galaxy evolution

Herschel sees local/exotic

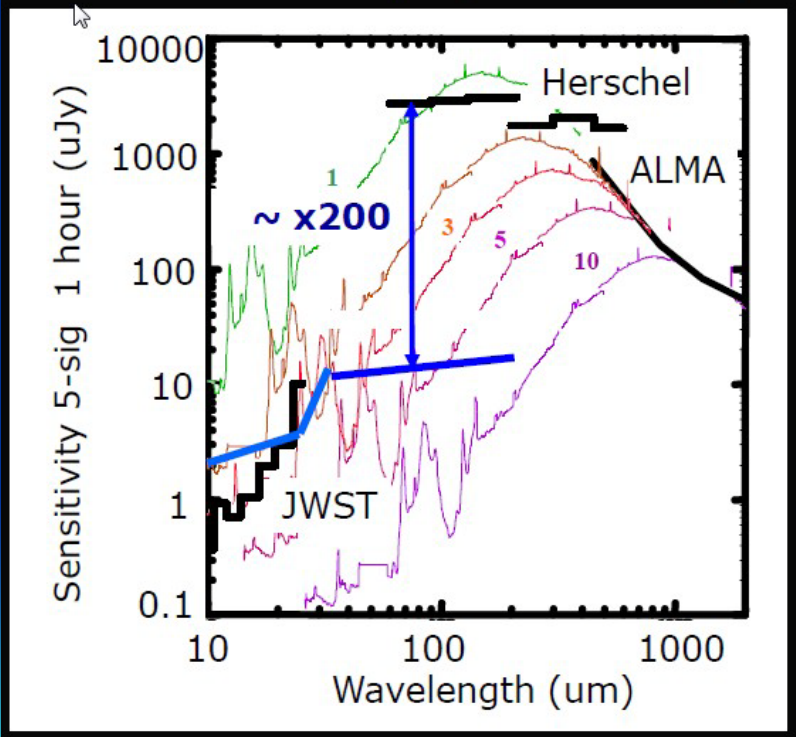
Need to detect distant objects



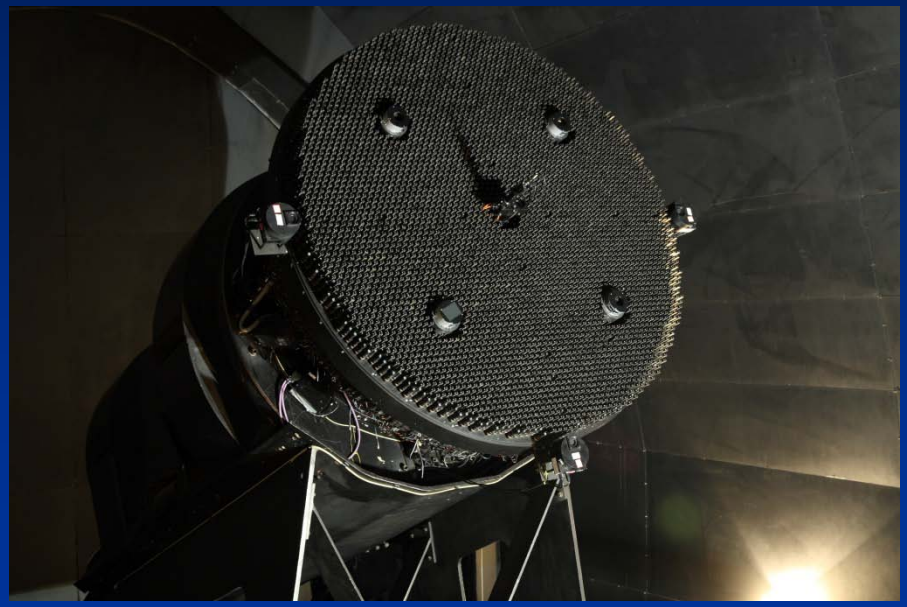


To reveal their nature and physics and chemistry

SPICA Sensitivity - photometry

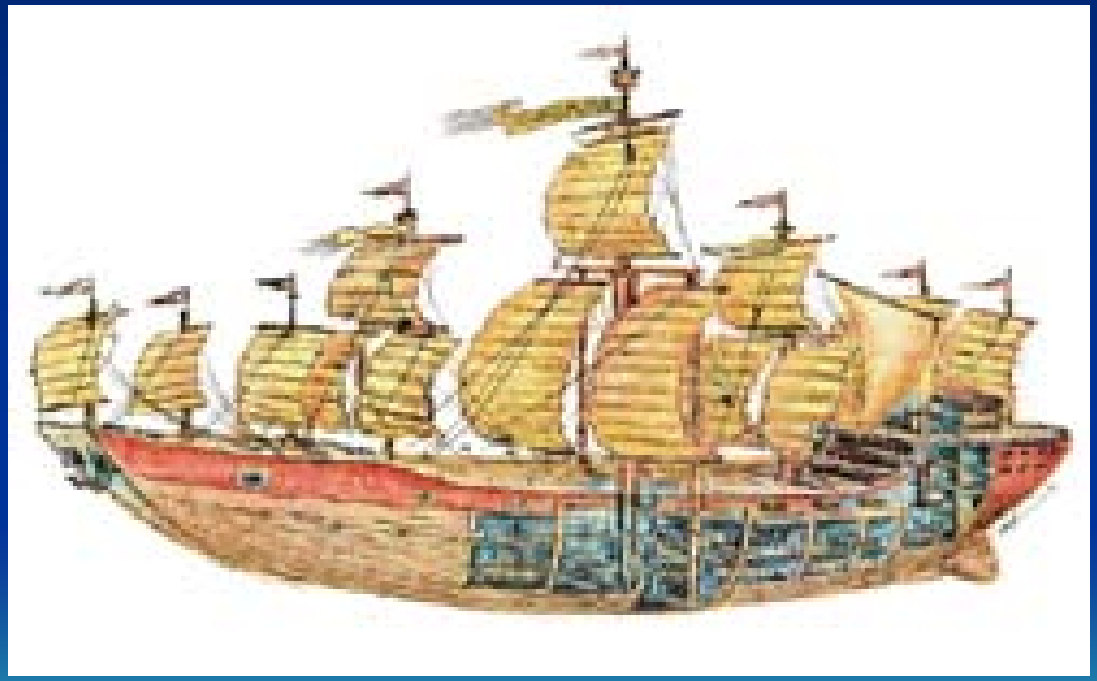


The LAMOST project



5 degree field
4000 fibers in the focal plane

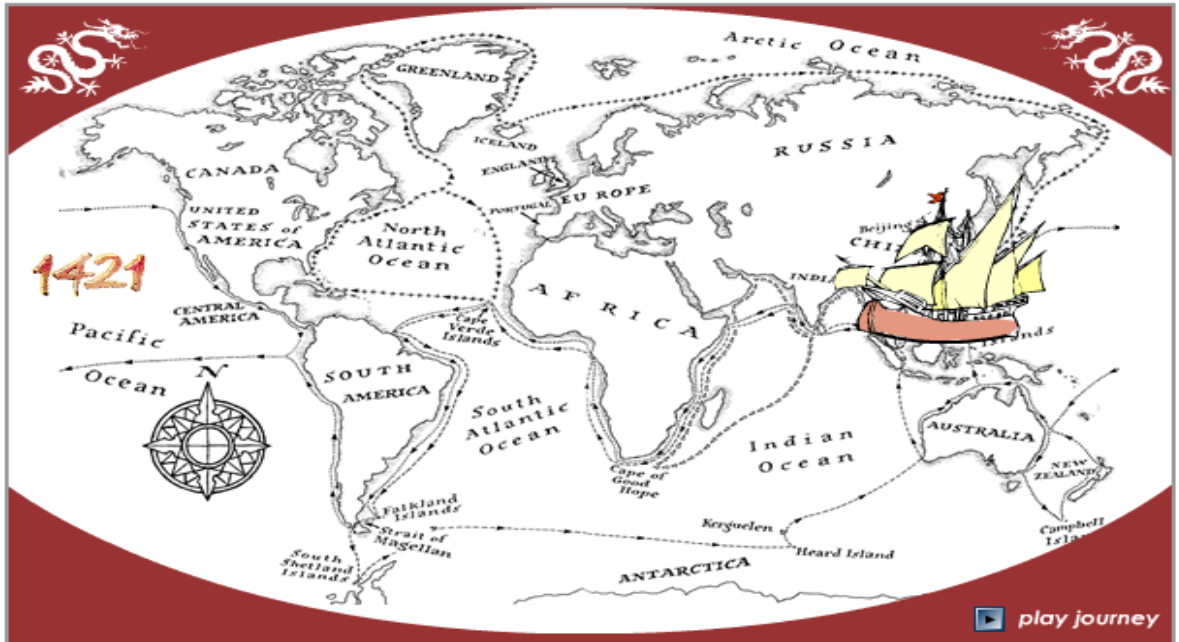
1421



1421 The year China discovered the World

Evidence | Maps | Gallery | The Book | News | About | Contact

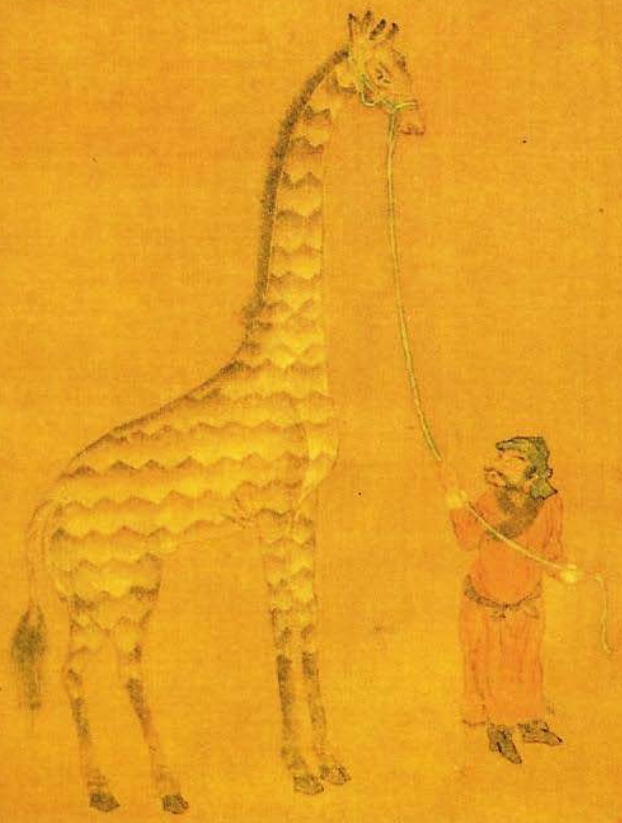
Maps : **Voyages** Back>>



The Emperor Zhu Di's four great fleets left China for Malacca on the 3rd of March 1421, numbering over 100 ships in total. They provisioned there and then sailed on to Calicut.

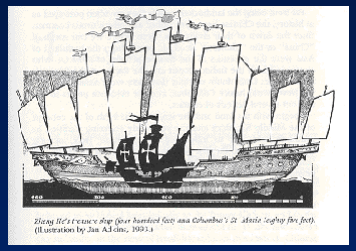
A giraffe, with its attendant, sent from Africa
to the Ming imperial court as tribute.

הג׳ירף שנשלח לקיסר סין ממזרח אפריקה

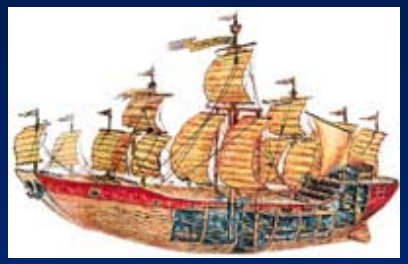


Zheng He 1371-1435

The fleet



A Comparision of Zheng He's Flagship



Baochuan (Treasure Ship)

Machuan (Horse Ship)

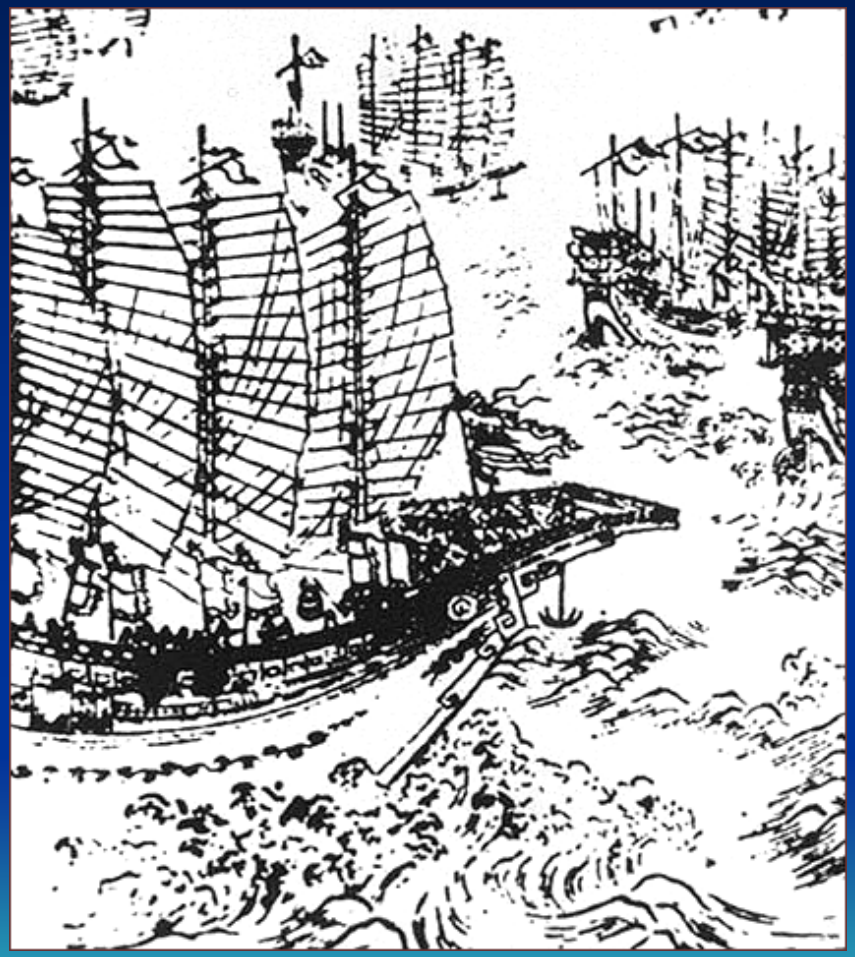
Liangchuan (Supply Ship)

Shuichuan (Water Tanker)

Zuochuan (Troop Transport)

Luchuan (Patrol Boat)

Treasure ships



Length 150 m

Width 60 m

16 isolated parts

Hundreds of people in each

A simple comparison

Navigator	Number of ships	Crew members
Zheng He 1405 1433	48 - 317	28,000
1492 Columbus	3	90
1498 Gama Da	4	160
1521 Magellan	5	265

play journey

The Emperor Zhu Di's four great fleets left China for Malacca on the 3rd of March 1421, numbering over 100 ships in total. They provisioned there and then sailed on to Calicut.