INAF ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTROFISICO DI ARCETRI

UNIVERSITÀ DEGLI STUDI FIRENZE

# Lecture XII: Active Galactic Nuclei (AGN) Physical properties and relations with host galaxies

With slides taken and/or adapted from
Bradley Peterson's "Brera Lectures" 2011
http://ned.ipac.caltech.edu/level5/March11/Peterson/

# Astrophysics of Galaxies 2019-2020

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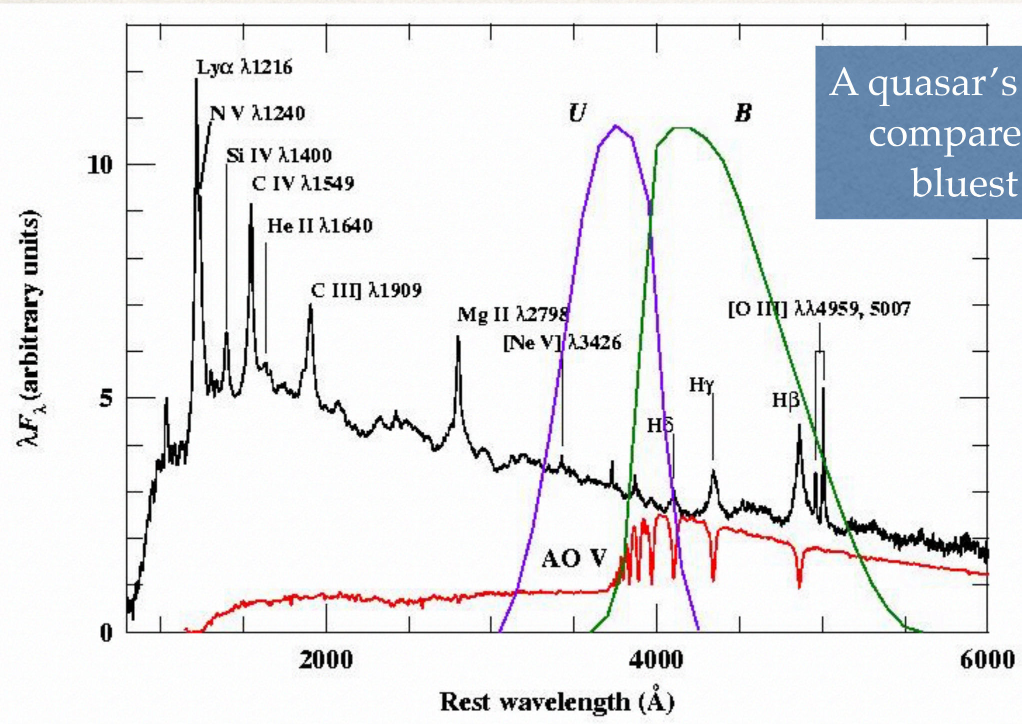
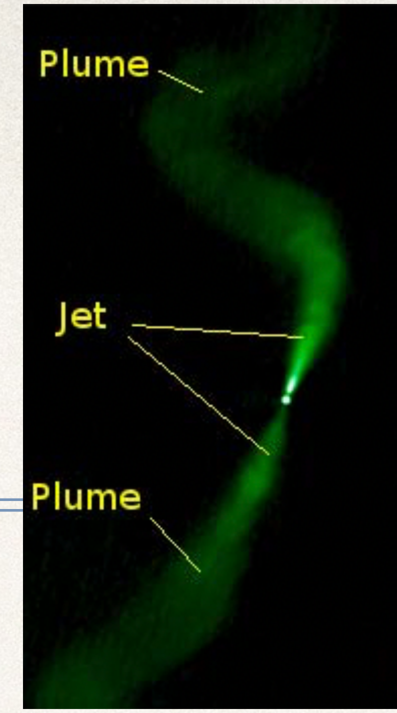
# Active Galactic Nuclei (AGN)

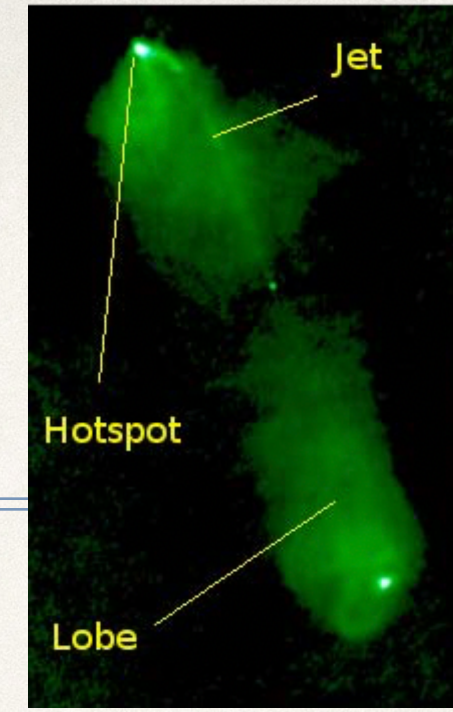
- "...energetic phenomena in the nuclei, or central regions, of galaxies which cannot be attributed clearly and directly to stars." Peterson 1997, An Introduction to Active Galactic Nuclei
- Modern definition: "Active nuclei are those that emit radiation that is fundamentally powered by accretion onto supermassive ($> 10^6\ M_\odot$) black holes."
- Properties (not all in all AGN):
  - Strong X-ray emission
  - Non-stellar UV-optical continuum
  - Relatively strong radio emission
  - UV-through-NIR spectrum dominated by strong (broad) emission lines

# AGN classification




A quasar's spectrum compared to the bluest stars

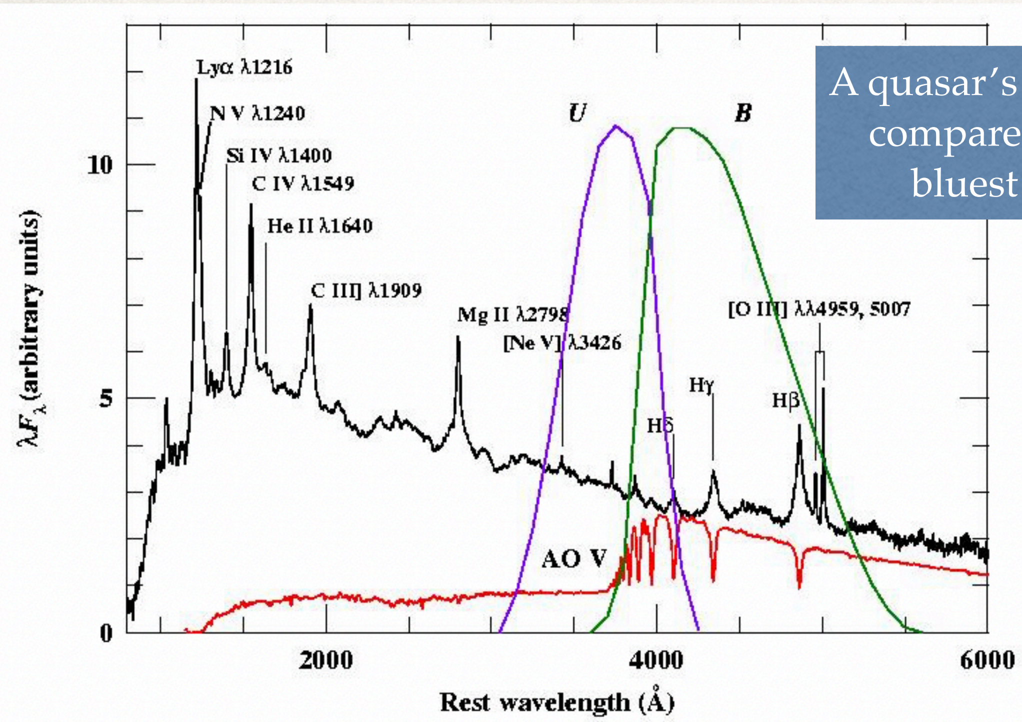



| | | | Radio Galaxies | |
|---|---|---|---|---|
| | Quasars (Quasi Stellar Radio Sources) | Seyferts | FR I | FR II |
| Luminosity | High | Low | Low | High |
| Accretion Rate | High | High | Low | Low |

- LINERs?
- QSOs (Quasi Stellar Objects): like Quasars but radio quiet

# AGN classification

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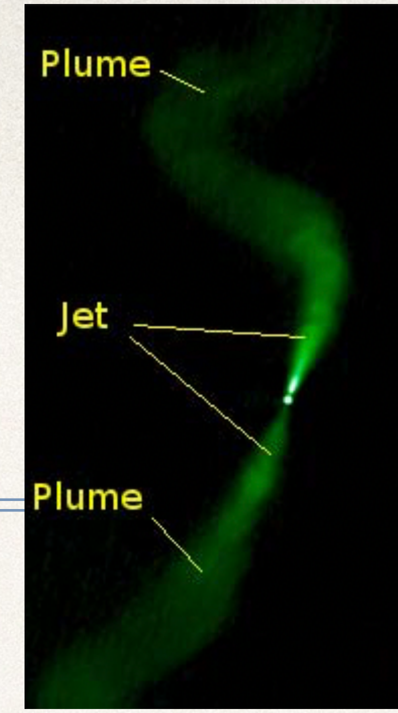


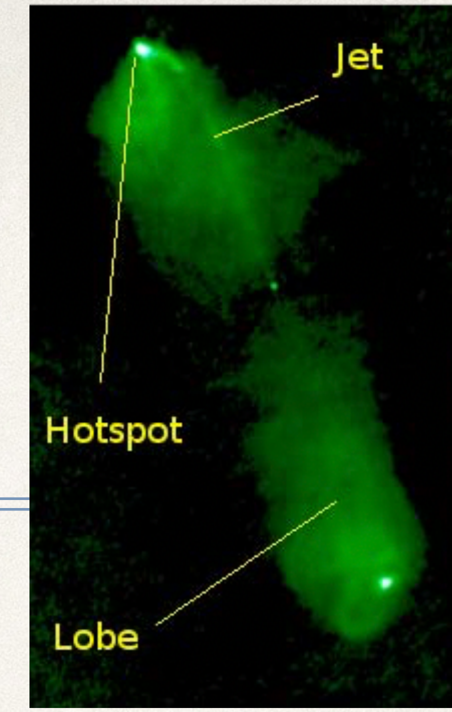


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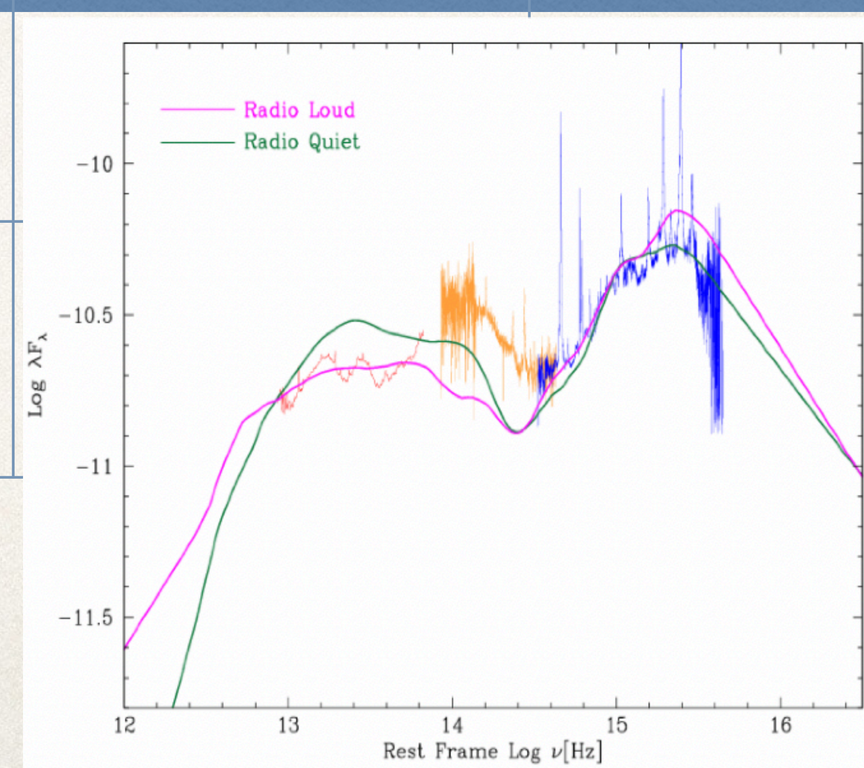


- LINERs?
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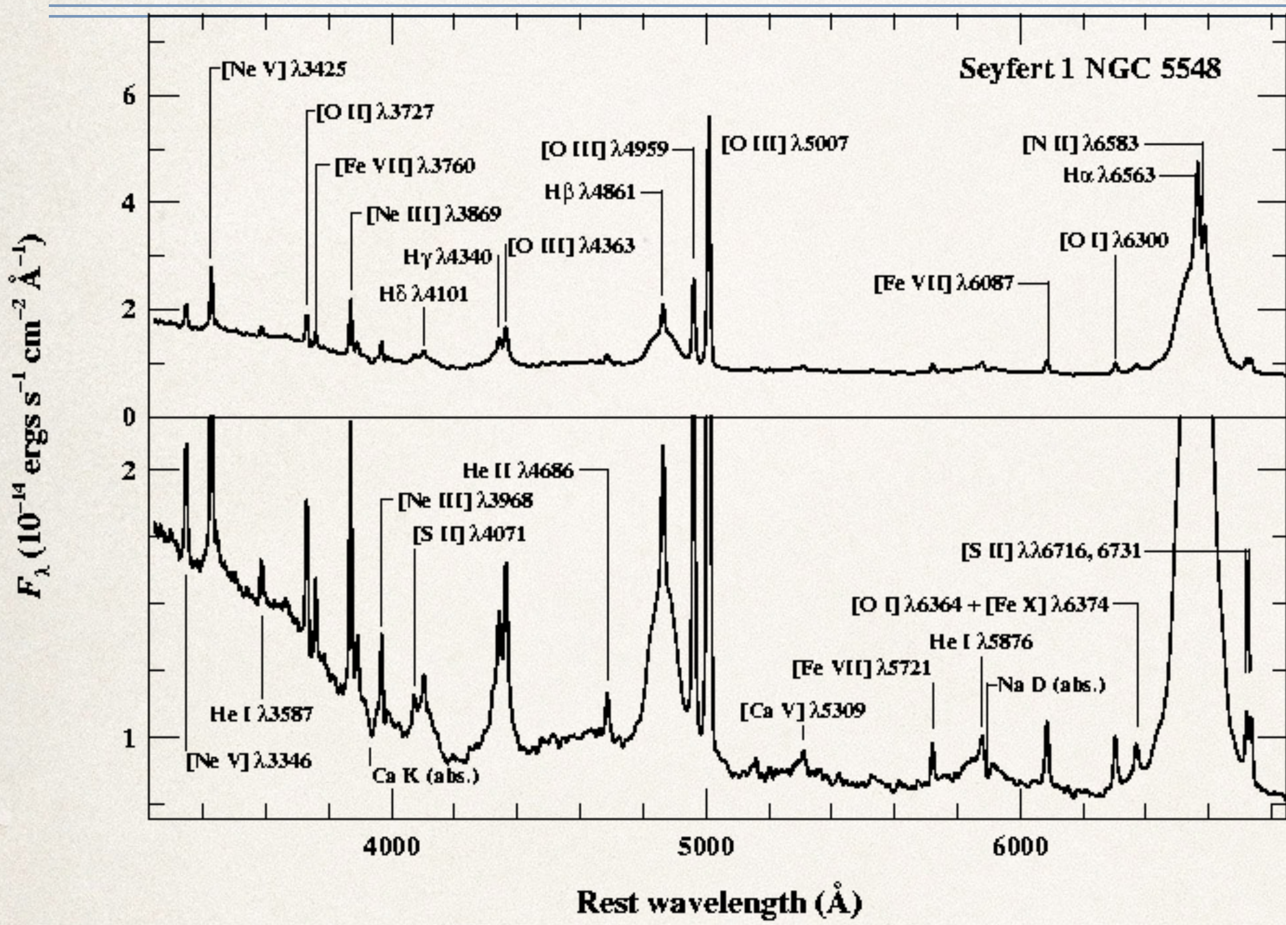
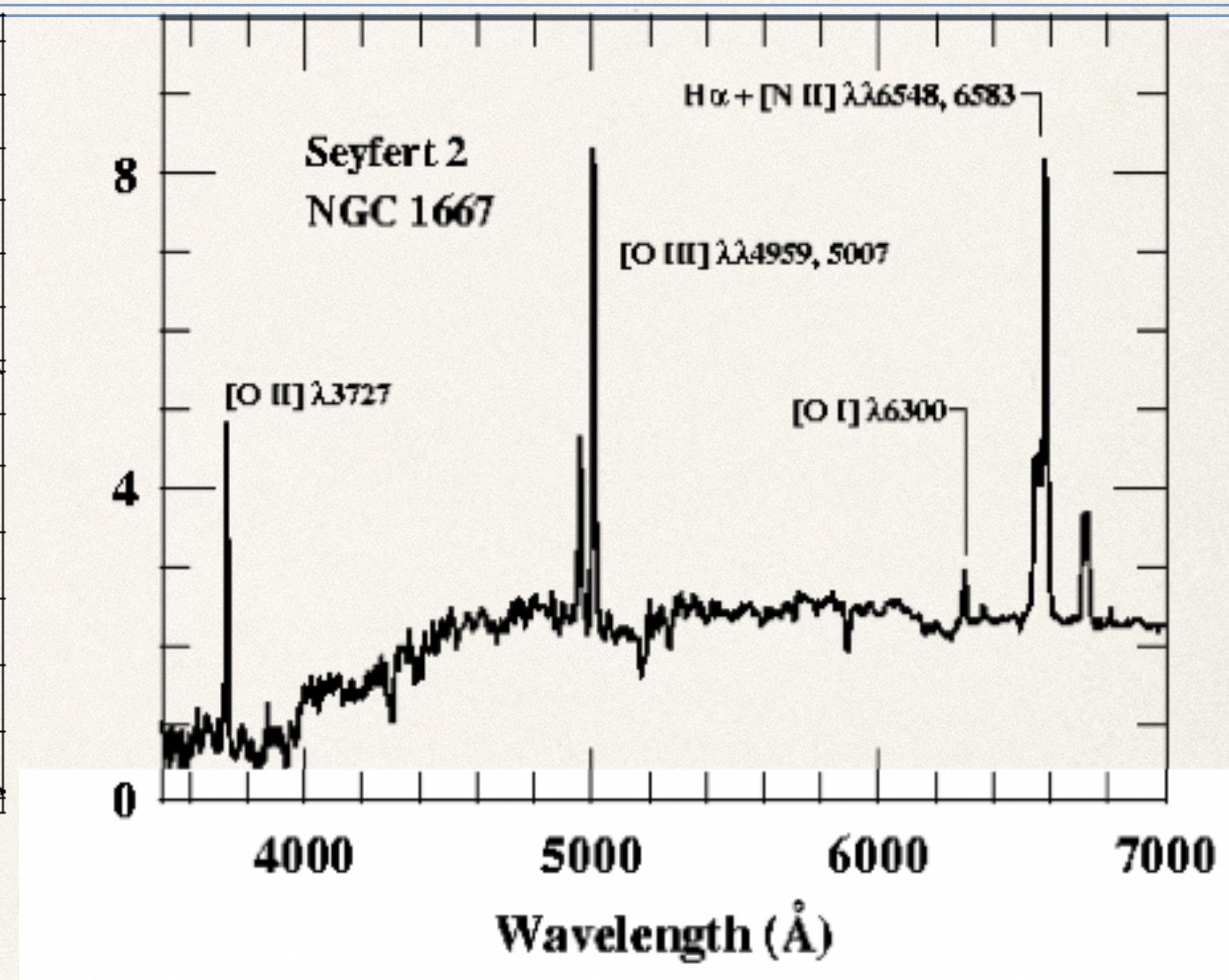
# UV-opt-NIR spectra of Seyferts (AGNs)

# Type-1 vs Type-2



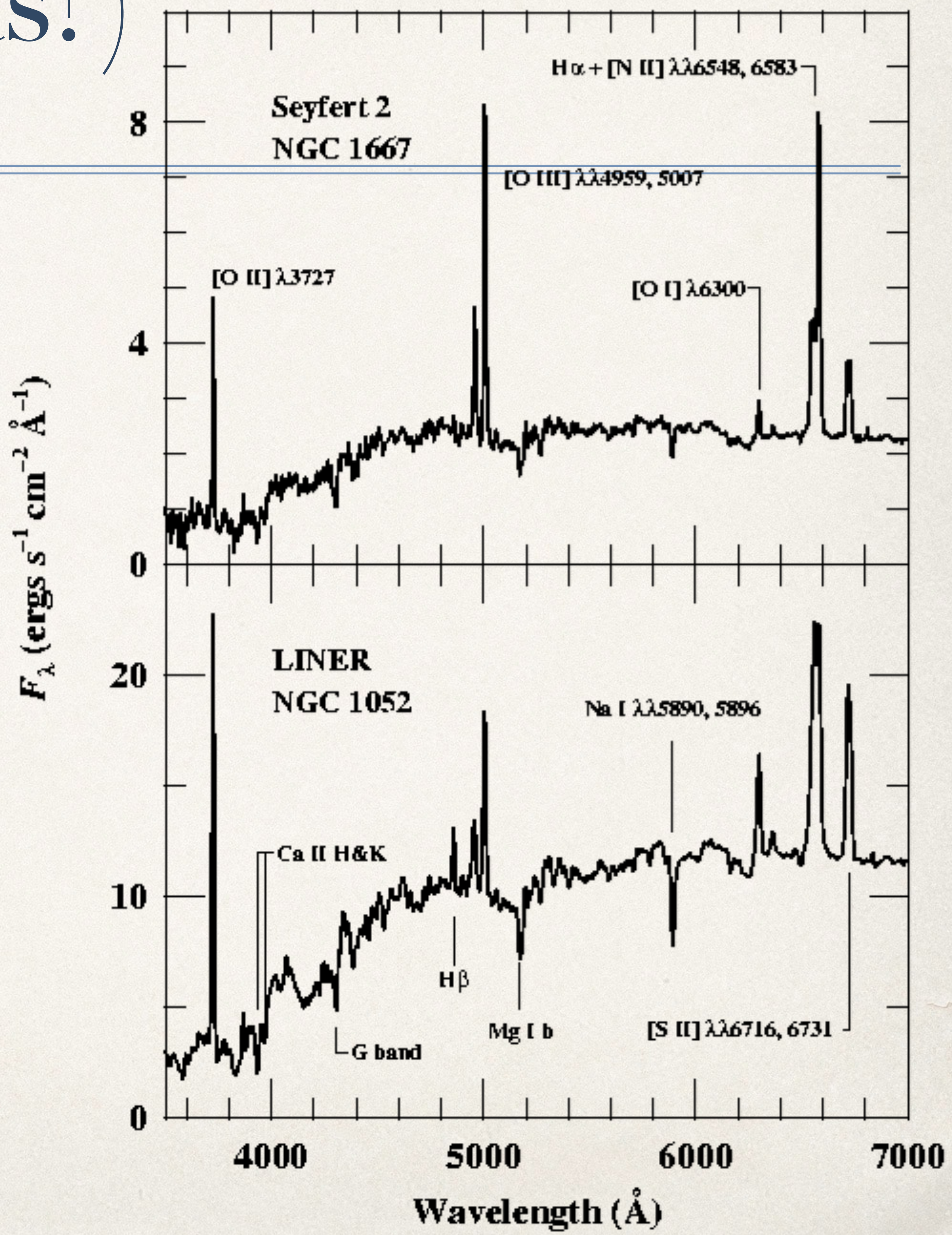




- Broad permitted lines (1000< FWHM/(km s$^{-1}$)< 25000)
- Narrow forbidden lines

- Only narrow forbidden lines

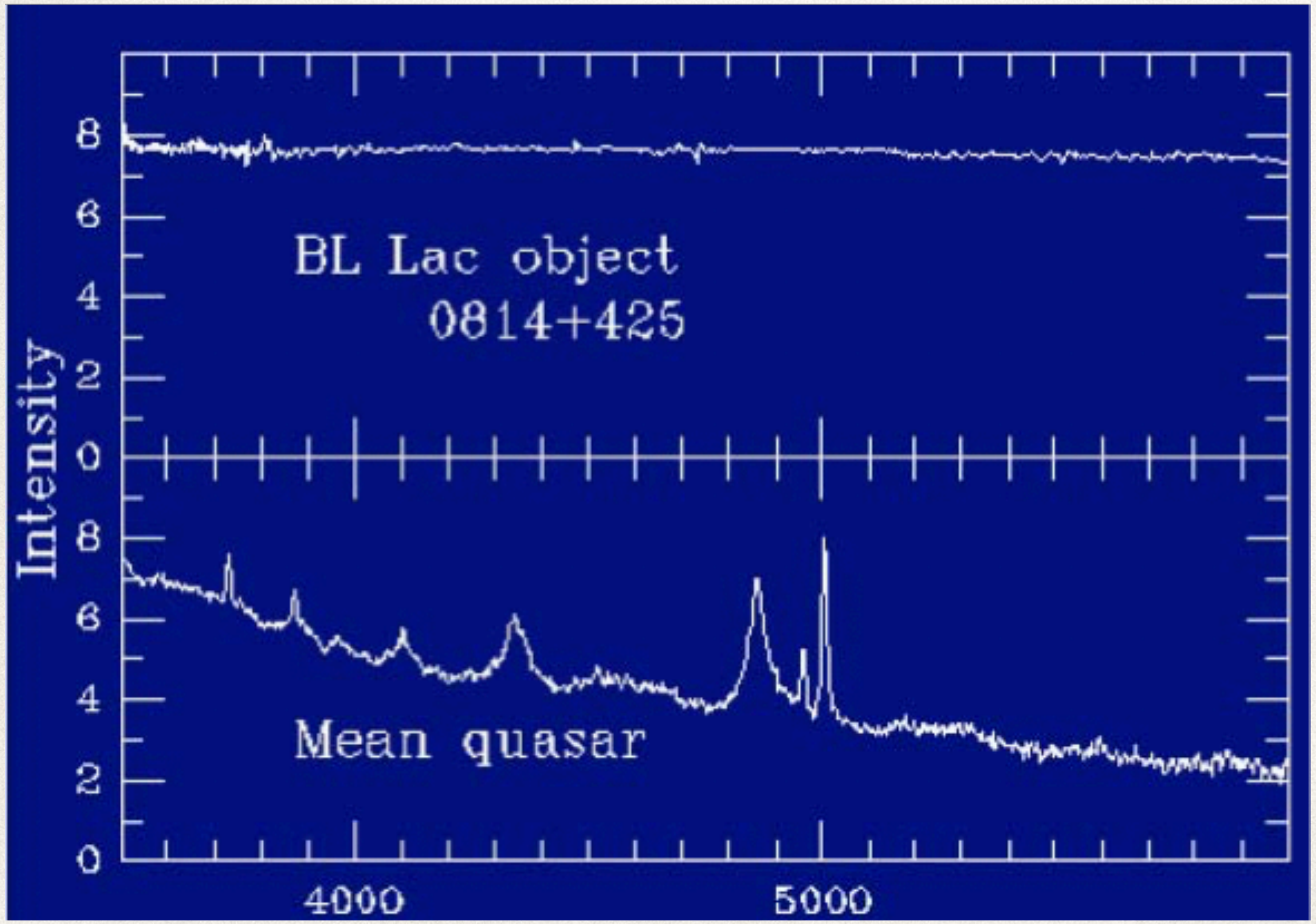
# LINERs (or LIERs?)

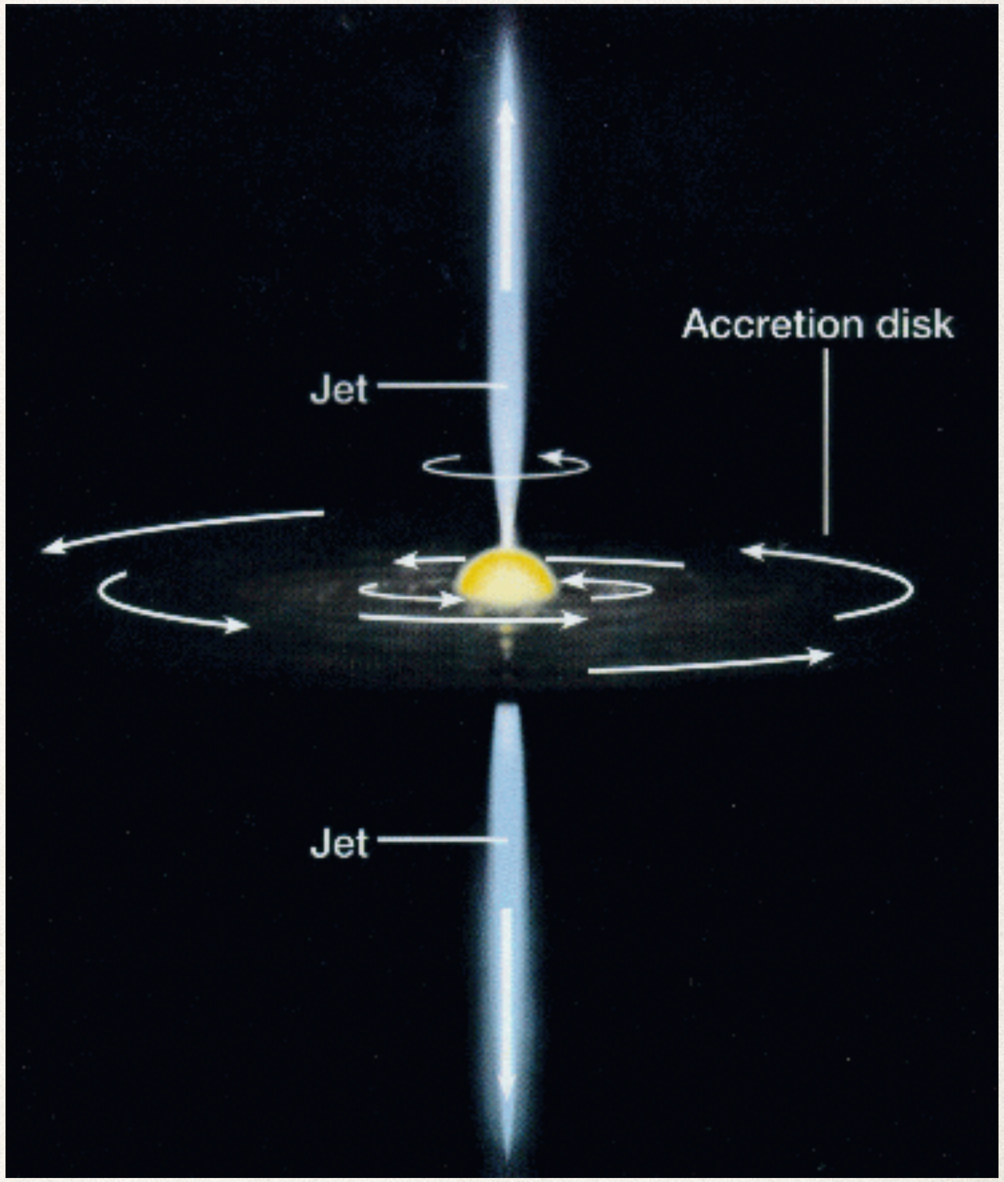
- Low-Ionization Nuclear Emission Region:
  - Lower ionization levels than in Sy2
- LINER emission is often found to be very diffuse rather than nuclear: LIERs? (Singh et al. 2013, CALIFA)
  - Possibly powered by evolved stars rather than SMBH



# BL Lac / Blazars

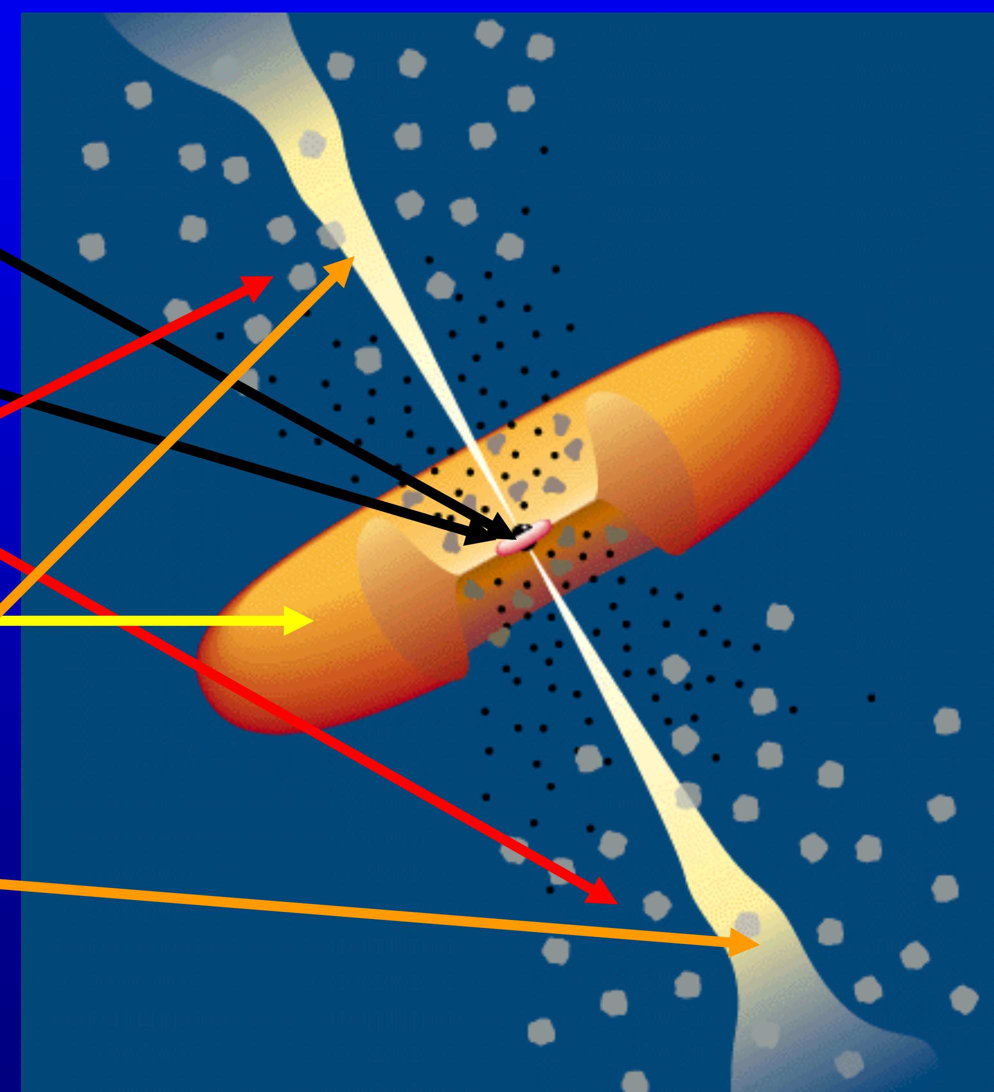
- Similar to quasars, but no emission lines
- Quasars seen along the jet axis??



# The AGN "unified model"

- Black hole plus accretion disk
- Broad-line region
- Narrow-line region
- Dusty "obscuring torus"
- Jets (optional?)



Urry & Padovani 1995

# Central engine: 1. not stars!

- Must be small: limits on size from variability

$$\Delta t \sim 10^4 s \;\Rightarrow\; R \leq c\Delta t \sim 3\times 10^{12} m \sim 10^{-4} pc \sim 20 AU$$

- Must be efficient in converting mass to energy

    - Cannot be stars: $$L = \frac{\varepsilon\, f\, M_\star\, c^2}{\Delta t}$$

*f* fraction of mass burnt~10%

ε nuclear fusion efficiency~0.7%

stars lifetime: $\Delta t$~$10^7$ yr

To get $10^{45}$ erg $s^{-1}$ it would imply at least $10^8$ $M_\odot$ of stars in $10^{-4}$ pc, i.e.

$$\rho \sim 10^{20}\ M_\odot\ pc^{-3}$$

# Central engine: 2. SuperMassive Black Hole

- The Eddington Luminosity argument
  - Self-gravity must exceed radiation pressure, thus posing a lower limit to the mass of the central engine
  - For a moderately luminous Seyfert galaxy with $L \sim 10^{44}$ erg $s^{-1}$, $M > 10^6 M_\odot$
- Energy from infall of matter onto a BH in a stable accreting disk if produced with ~10% efficiency
- This makes much more energy available than nuclear fusion (0.7%)

# Eddington Luminosity Limit

- Energy flux $$F = \frac{L}{4\pi r^2}$$
- Momentum flux $$P_{\rm rad} = \frac{F}{c} = \frac{L}{4\pi r^2 c}$$
- Force due to radiation $$F_{\rm rad} = P_{\rm rad}\sigma_e = \frac{L\sigma_e}{4\pi r^2 c}$$
- This must be less than gravity $$\frac{L\sigma_e}{4\pi r^2 c} < \frac{GMm}{r^2}$$

$$L < \frac{4\pi Gcm}{\sigma_e} M \approx 1.26\times 10^{38}\left(\frac{M}{M_\odot}\right)\text{ergs s}^{-1}$$

**"The Eddington Limit"**

# Available energy

- Potential energy of infalling mass *m* is converted to radiant energy with some efficiency $\eta$ so $E = \eta m c^2$
- Potential energy is $U = GM_{BH}m/r$
- Energy dissipated at ~10 $R_g$ where $R_g = GM_{BH}/c^2$ (to be shown)
- Available energy:

$$U = \frac{GM_{\rm BH}m}{10R_g} = 0.1\frac{GM_{\rm BH}m}{GM_{\rm BH}/c^2} = 0.1mc^2$$

- Thus the efficiency of accretion $\eta \approx 0.1$

Compare to hydrogen fusion 4H $\rightarrow$ He with $\eta = 0.007$

# Eddington Rate

- Accretion rate necessary to attain Eddington luminosity is the maximum possible

$$\dot{M}_{\rm Edd} = \frac{L_{\rm Edd}}{\eta c^2} = \frac{1.47 \times 10^{17}}{\eta} \left( \frac{M_{\rm BH}}{M_\odot} \right) \text{gm s}^{-1}$$

- Eddington rate is ratio of actual accretion rate to maximum possible

$$\dot{m} \equiv \lambda = \dot{M} \big/ \dot{M}_{\rm Edd}$$

# Temperature of the engine

- Dissipation of energy as matter "decays" to lower and lower orbits in the accretion disk
- Dimensional analysis:
  - Approximate Luminosity with black-body radiance

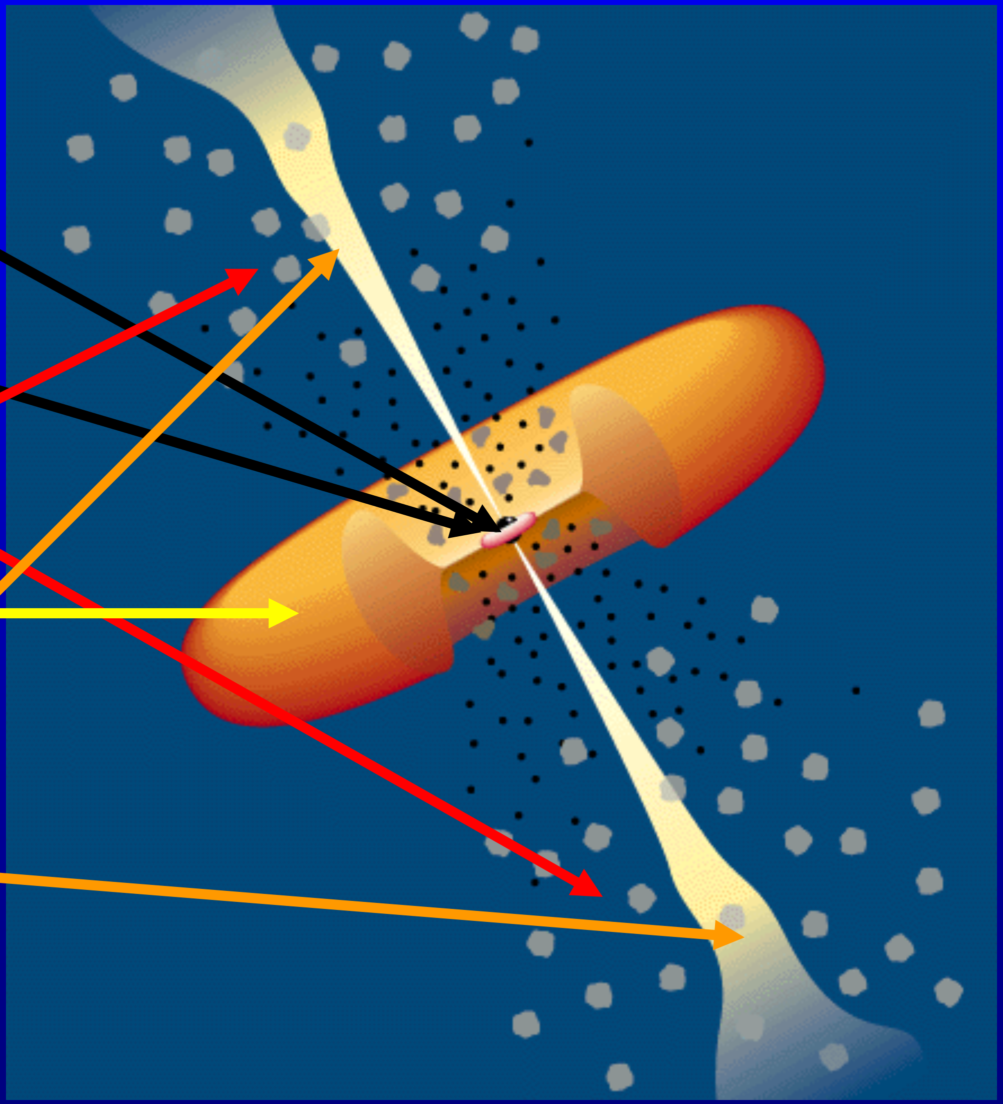
$$L = \frac{G M_{BH} \dot{M}}{2r} = 2\pi r^2 \sigma T^4$$

$$T(r) \approx 3.7 \times 10^5 \dot{m}^{1/4} \left( \frac{M_{BH}}{10^8 M_\odot} \right)^{-1/4} \left( \frac{r}{R_g} \right)^{-3/4} \mathrm{K}$$

HOT!!!

# The AGN "unified model"

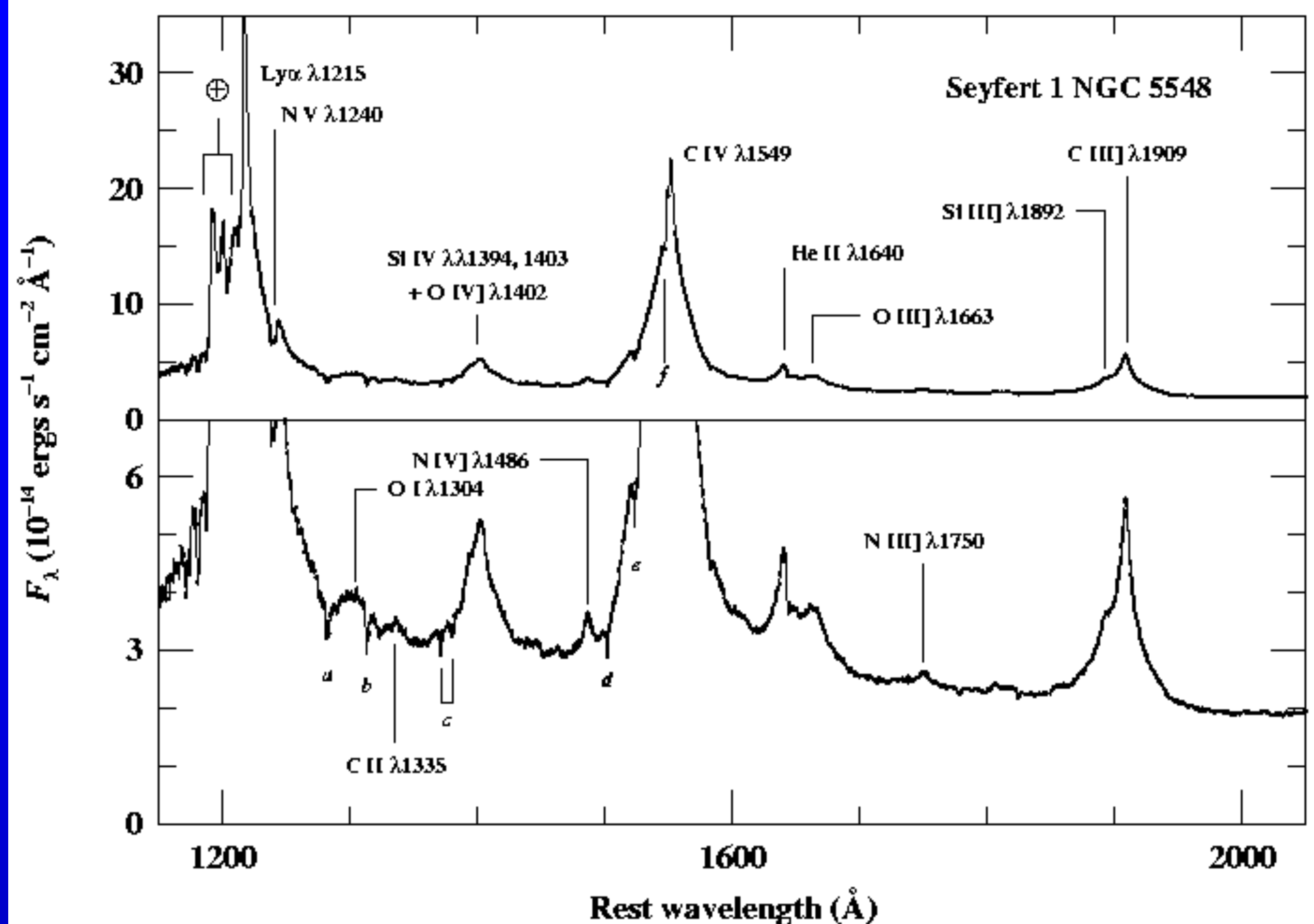
- Black hole plus accretion disk
- Broad-line region
- Narrow-line region
- Dusty "obscuring torus"
- Jets (optional?)

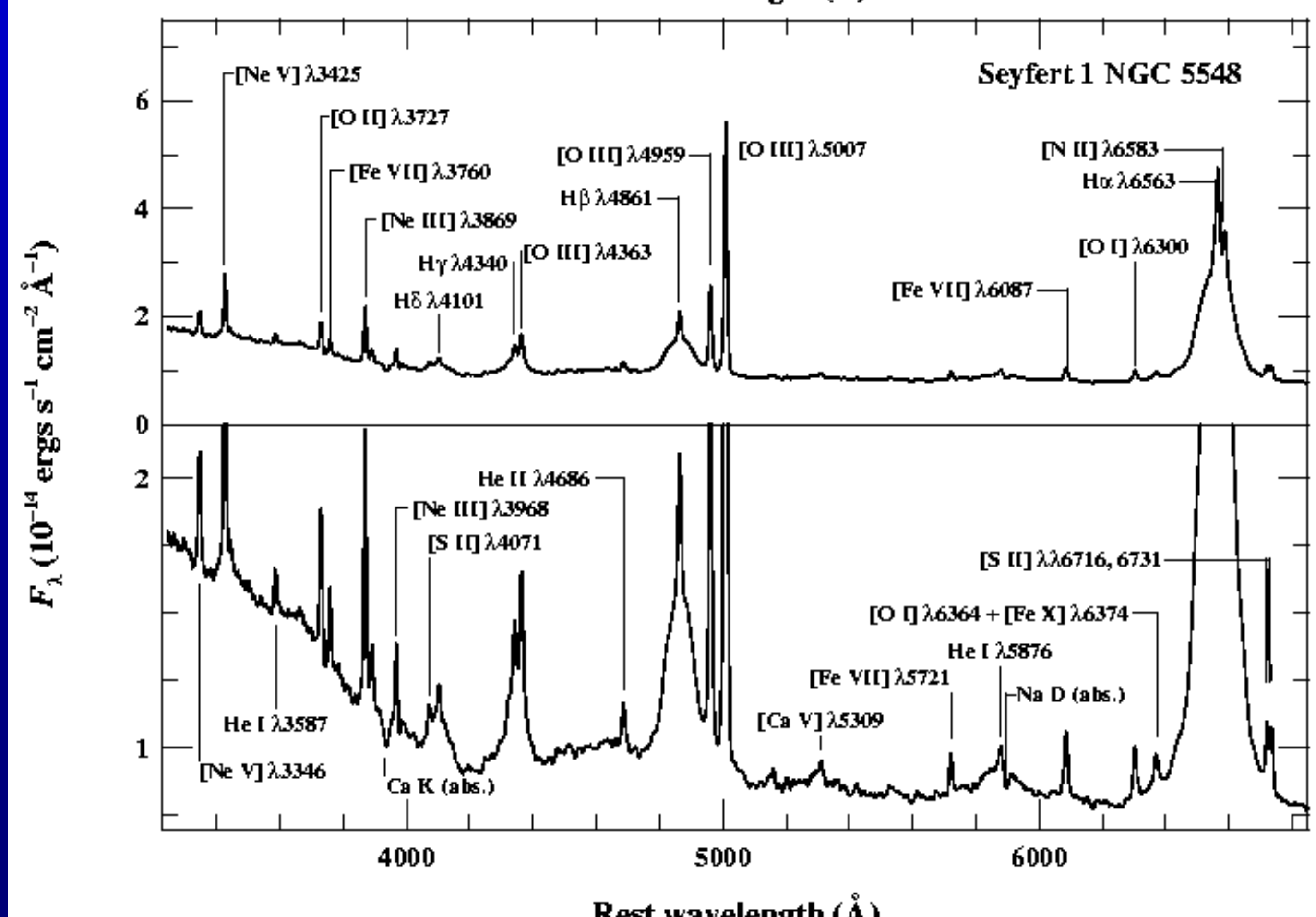


Urry & Padovani 1995

# The Broad-Line Region

- UV, optical, and IR permitted lines have broad components
  - $1000 \leq \text{FWHM} \leq 25{,}000\ \text{km s}^{-1}$
  - Spectra are typical of photoionized gases at $T \approx 10^4$ K
  - Absence of forbidden lines implies high density
    - C III] $\lambda$1909 $\Rightarrow$ $n_e < 10^{10}\ \text{cm}^{-3}$



# Self-similarity of BLRs

## BLR Scaling with Luminosity

- To first order, AGN spectra look the same:

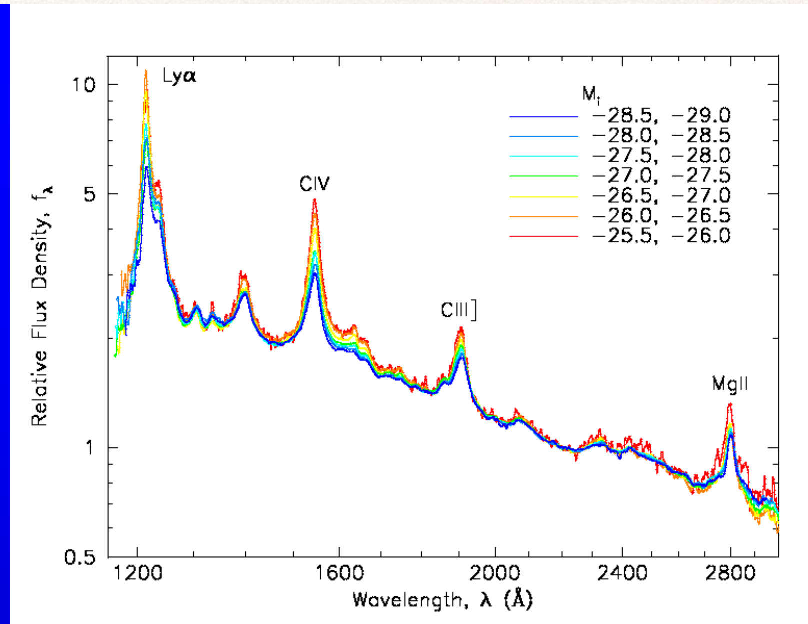
$$U = \frac{Q(\mathrm{H})}{4\pi r^2 n_{\mathrm{H}} c} \propto \frac{L}{n_{\mathrm{H}} r^2}$$

$\Rightarrow$ Same ionization parameter

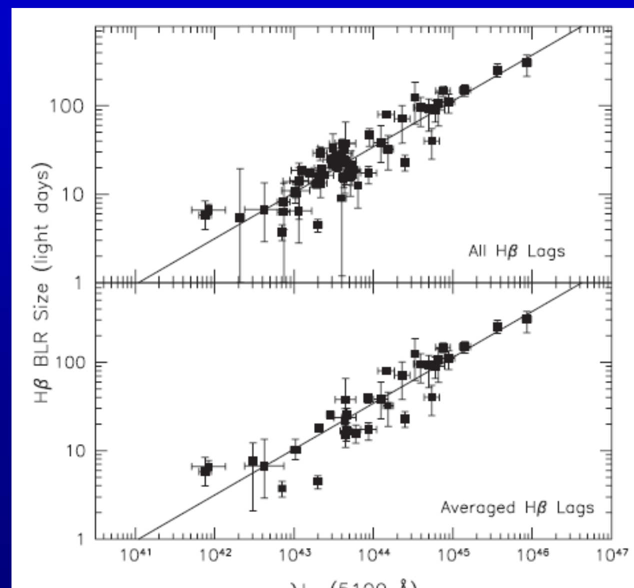
$\Rightarrow$ Same density

$$r \propto L^{1/2}$$

$$Q_{\mathrm{ion}}(H) = \int_{\nu_{\mathrm{ion}}}^{\infty} \frac{L_\nu}{h\nu}\, d\nu$$




SDSS composites. Vanden Berk et al. (2004)

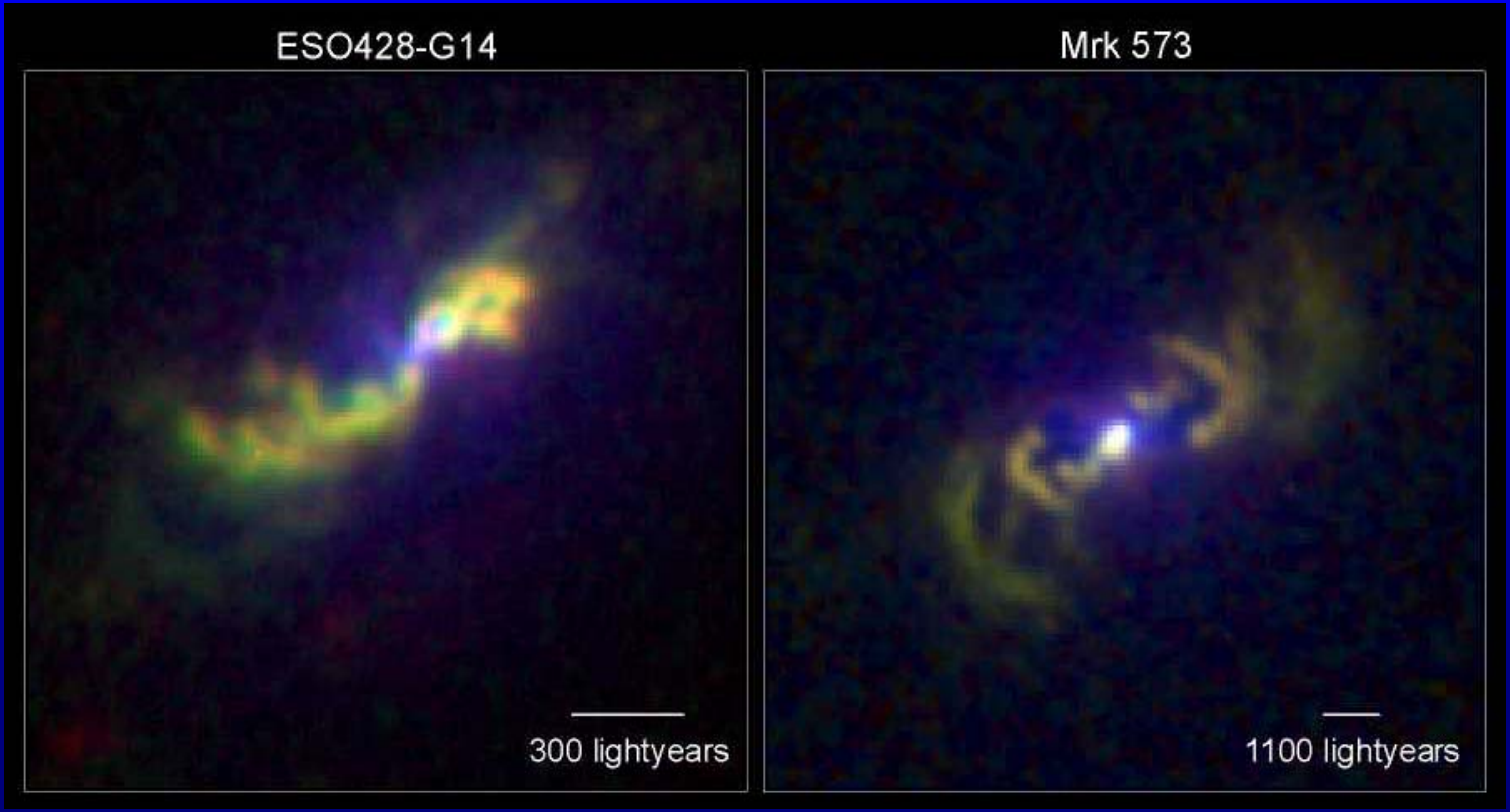



Bentz et al. (2009)

- Exception: Baldwin effect — CIV $\lambda$1549 is weaker in more luminous objects — unknown origin

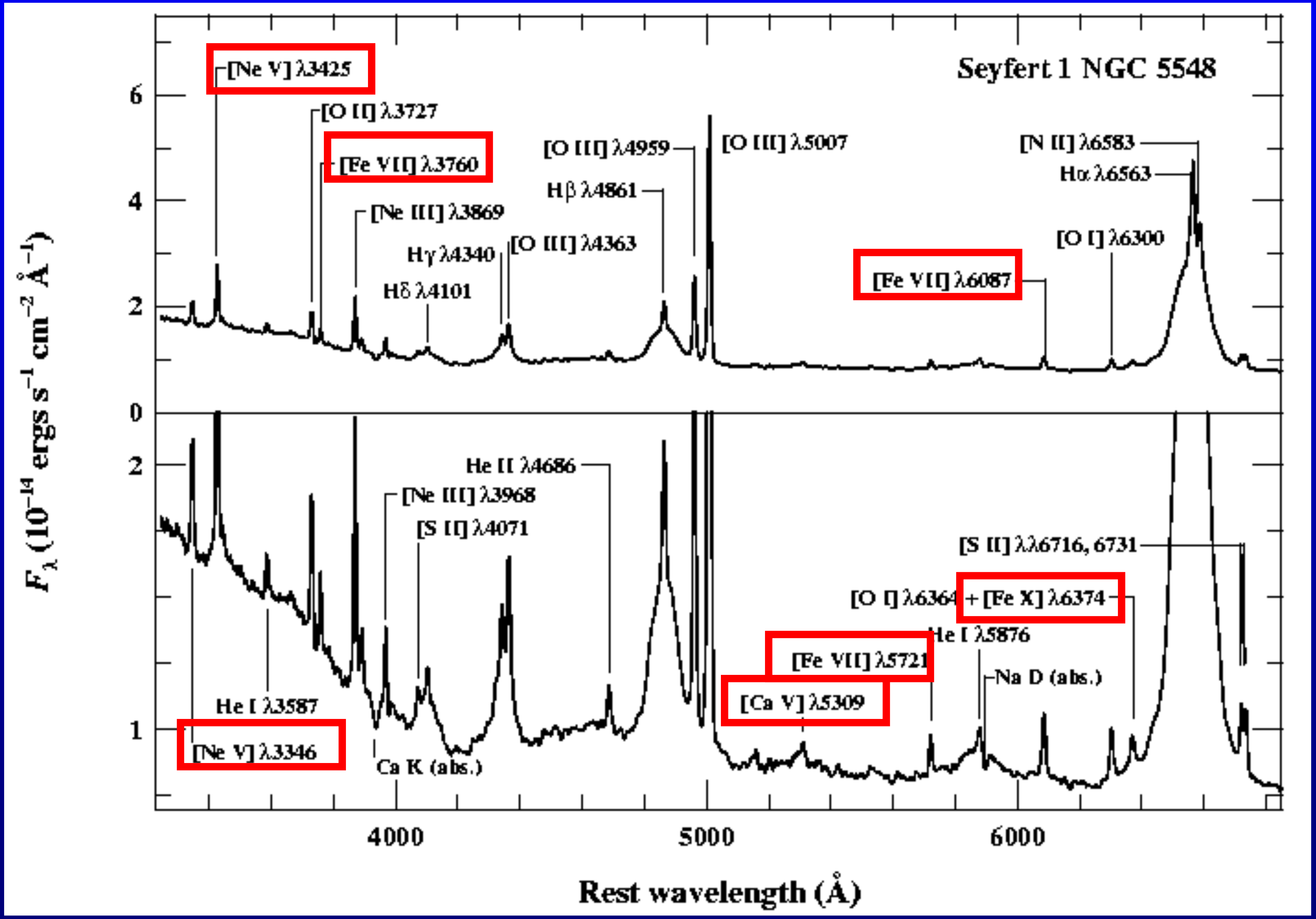
# The Narrow-Line Region

- 200 < FWHM < 1000 km s$^{-1}$
- Partially resolvable in nearby AGNs
- In form of “ionization cones”



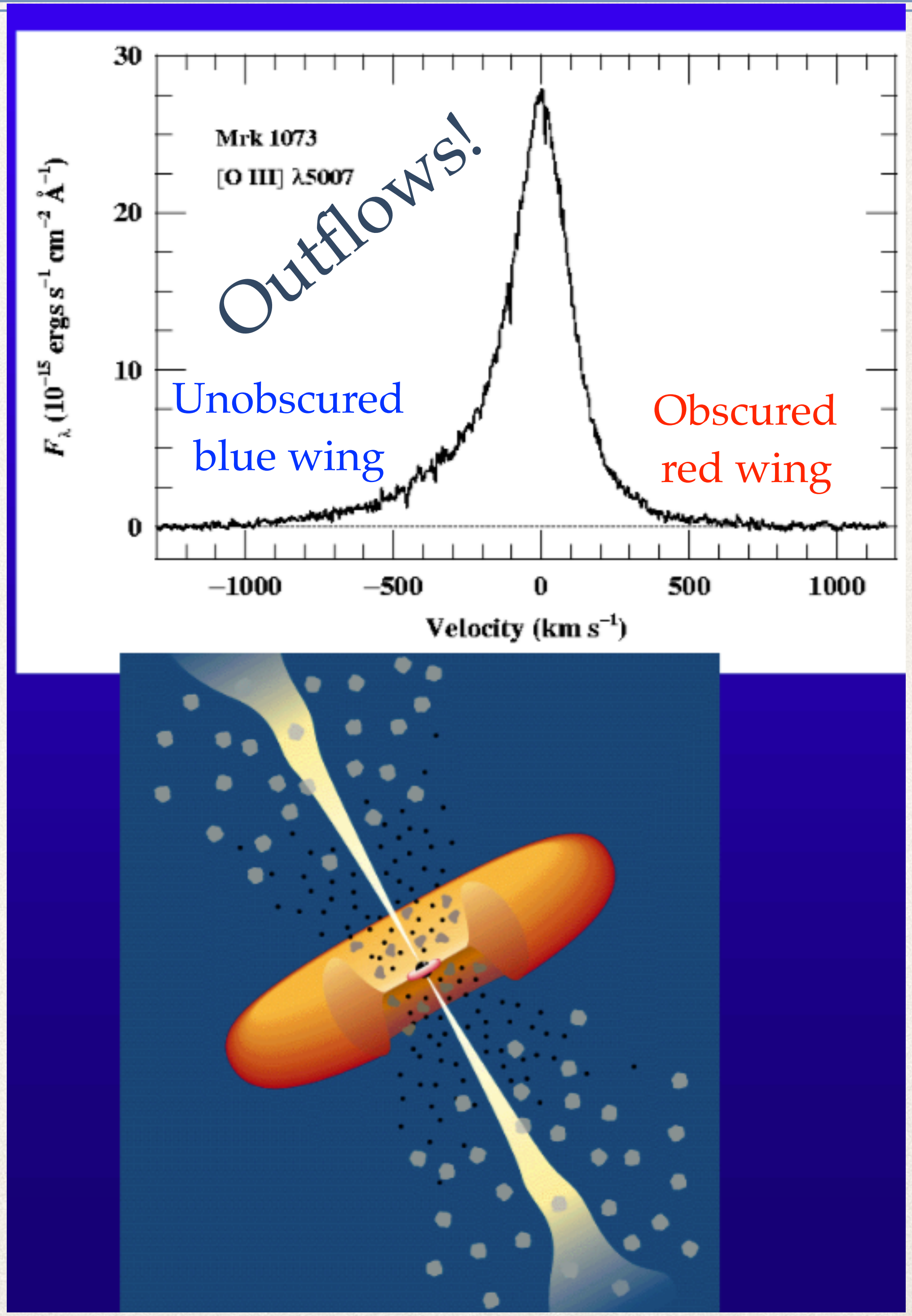

Falcke, Wilson, & Simpson 1998

# NLR Spectra characterized by very high ionization lines



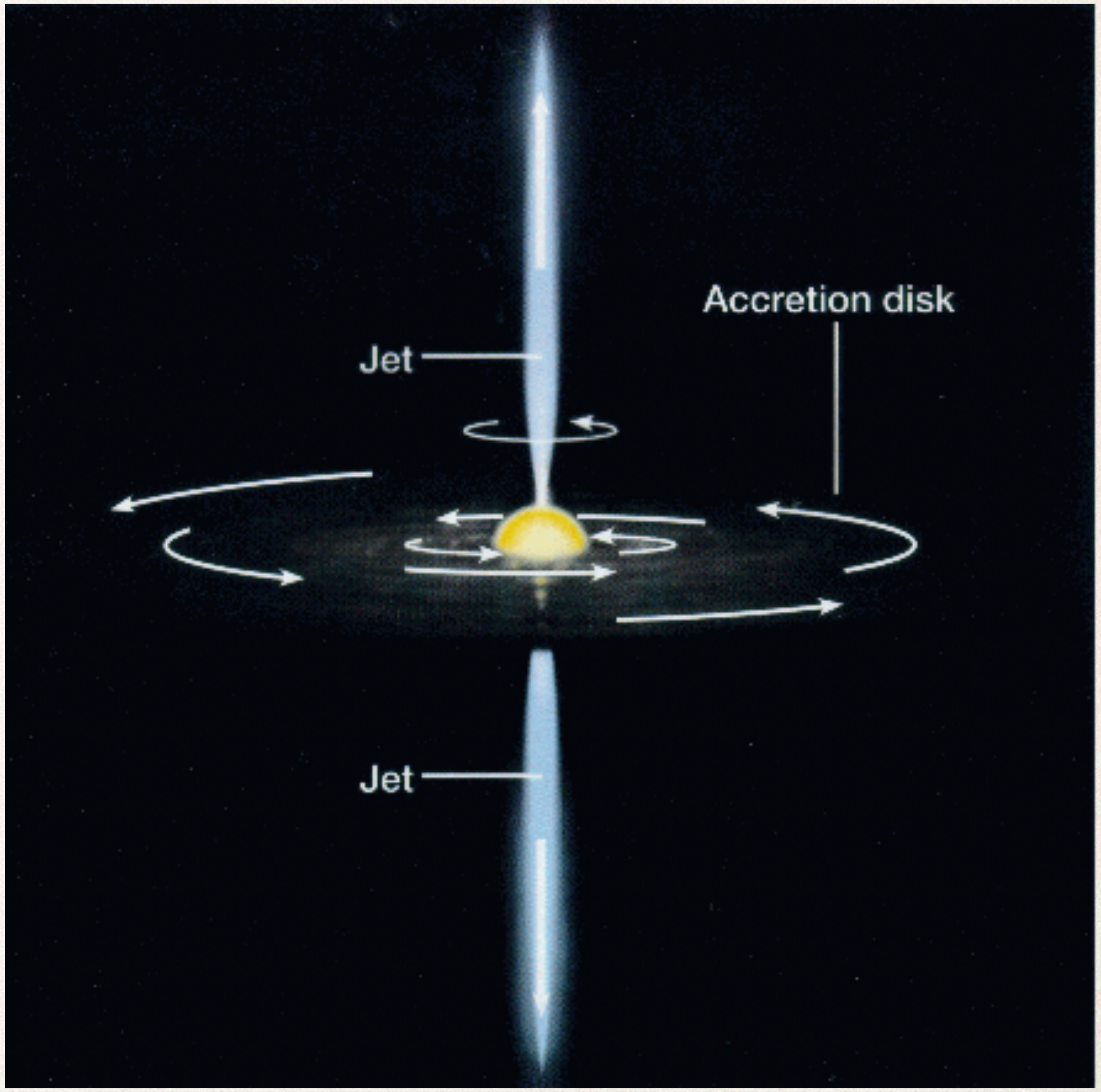
# NLR diagnostics

- Forbidden lines: properly apply photoionisation models and line diagnostics ($T_e$, $n_e$), no self-absorption
- Kinematics
- Possible interpretation problems with dust



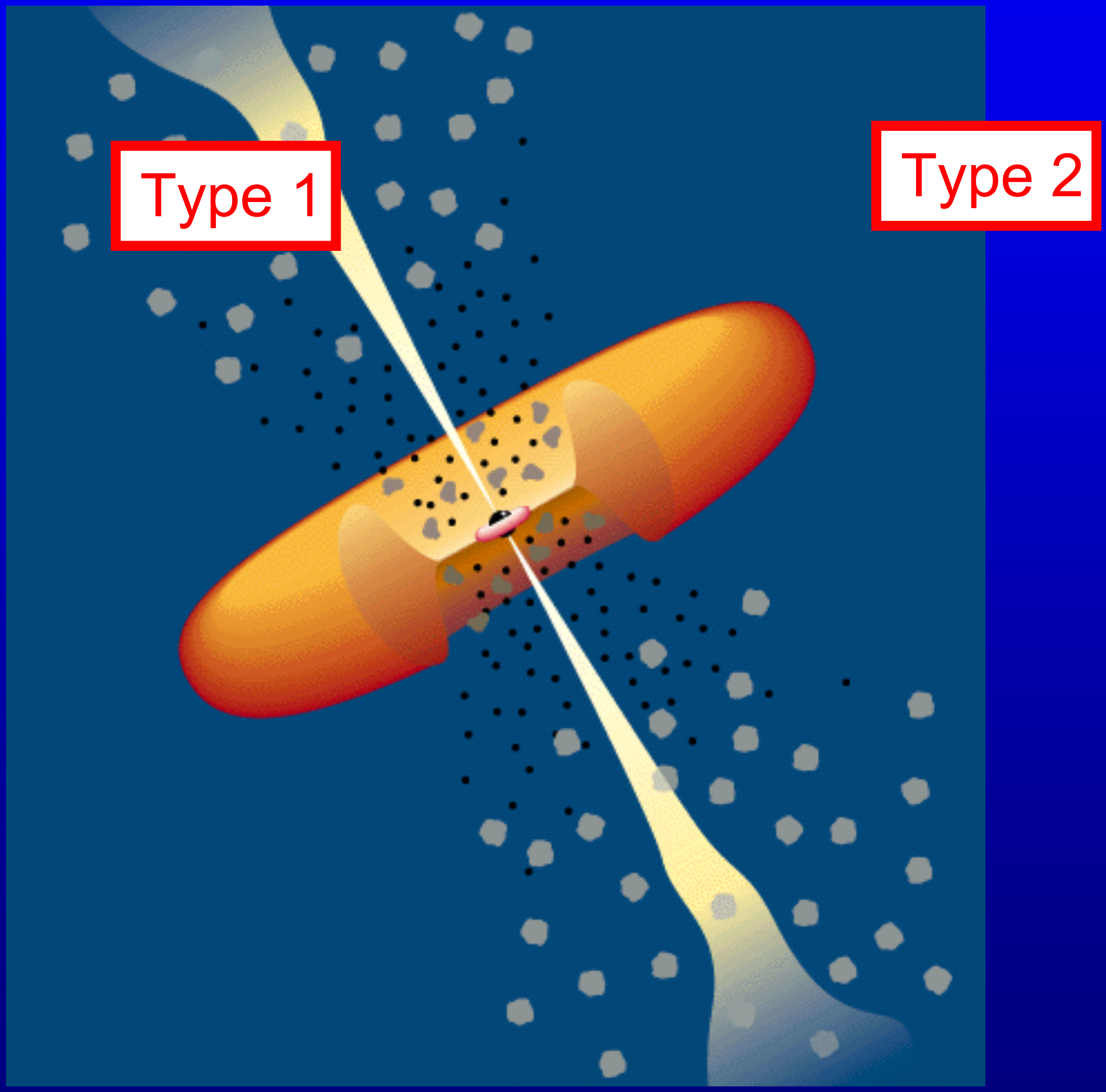
# Why jets?

- High spin + conservation of the magnetic flux results in strong B fields, which "guide" accelerated particles
- Note that jets are common but apparently not mandatory



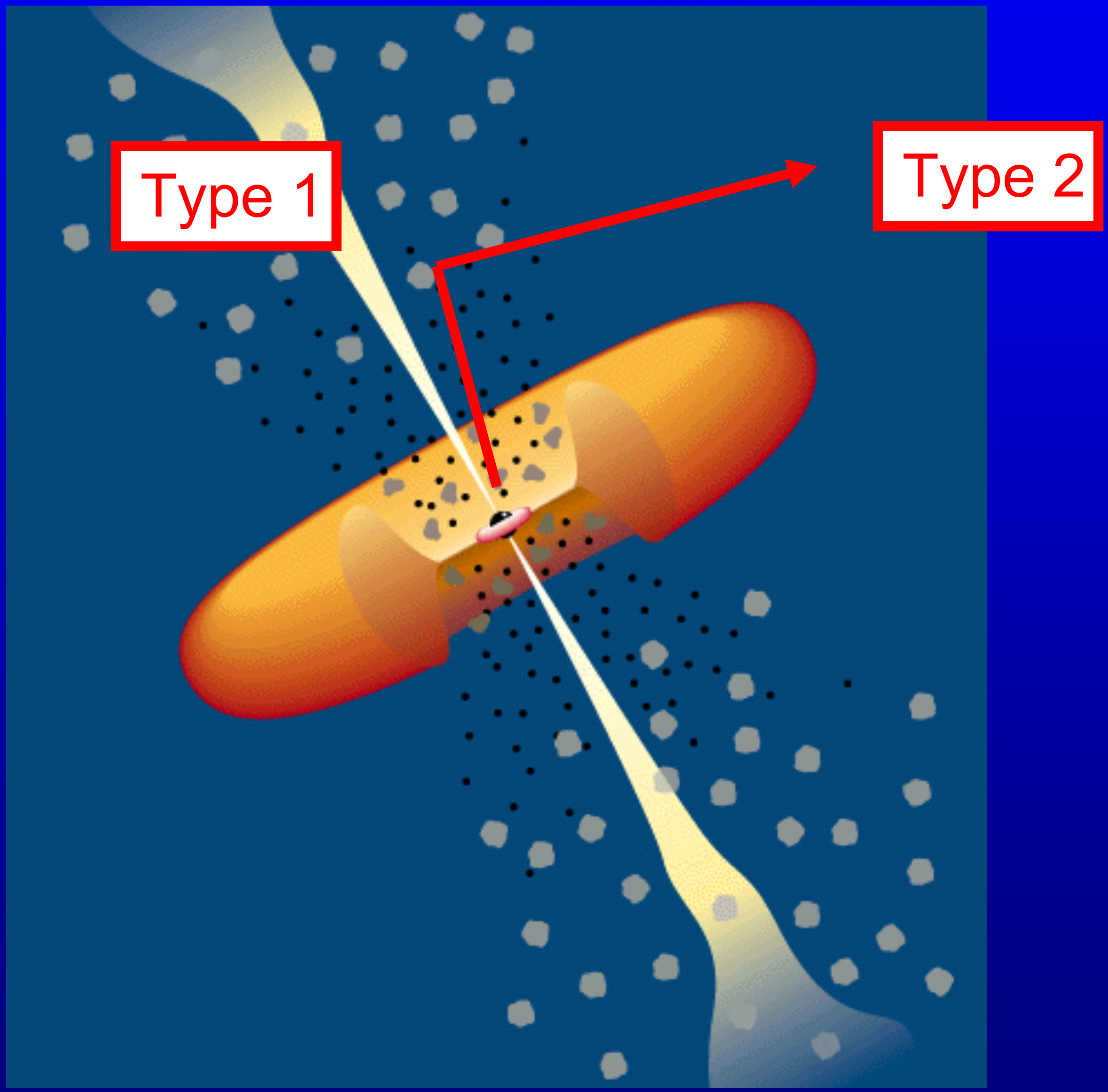
# The "Obscuring Torus"

- The answer to the question: "why don't Seyfert 2s have broad lines?"
- Osterbrock (1978) suggested this since a simple absorbing medium would:
  - Redden the continuum
  - Completely obscure the continuum as well as the BLR



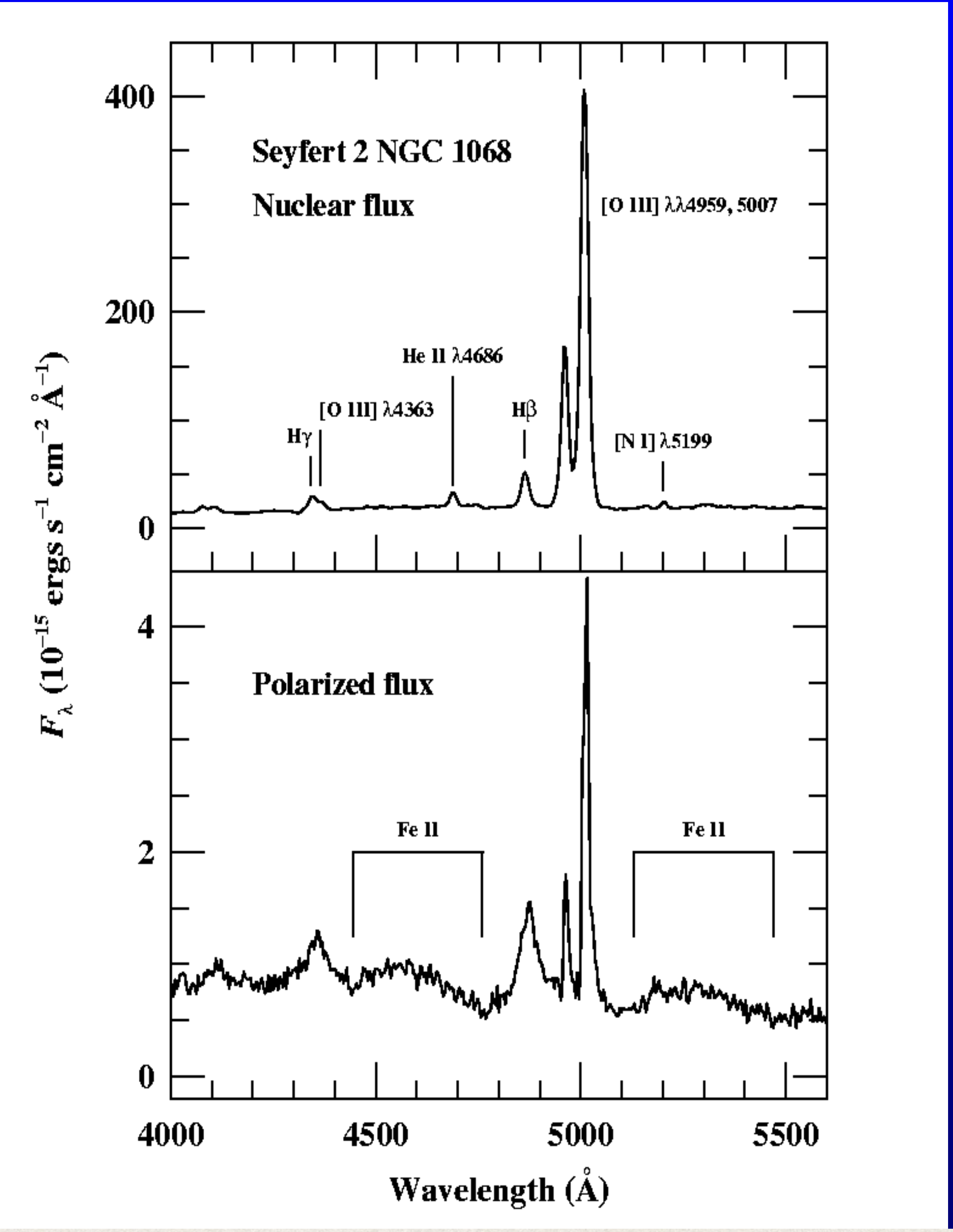
# The "Obscuring Torus"

- The key to making this work is scattering by material in the throat of the torus.
  - Prediction: scattering introduces polarization, with E vector perpendicular to axis



# Spectropolarimetry of Seyfert 2 Galaxies

- Spectropolarimetry of the nuclei of Type 2 Seyferts shows Type 1 spectra in polarized light, as predicted.



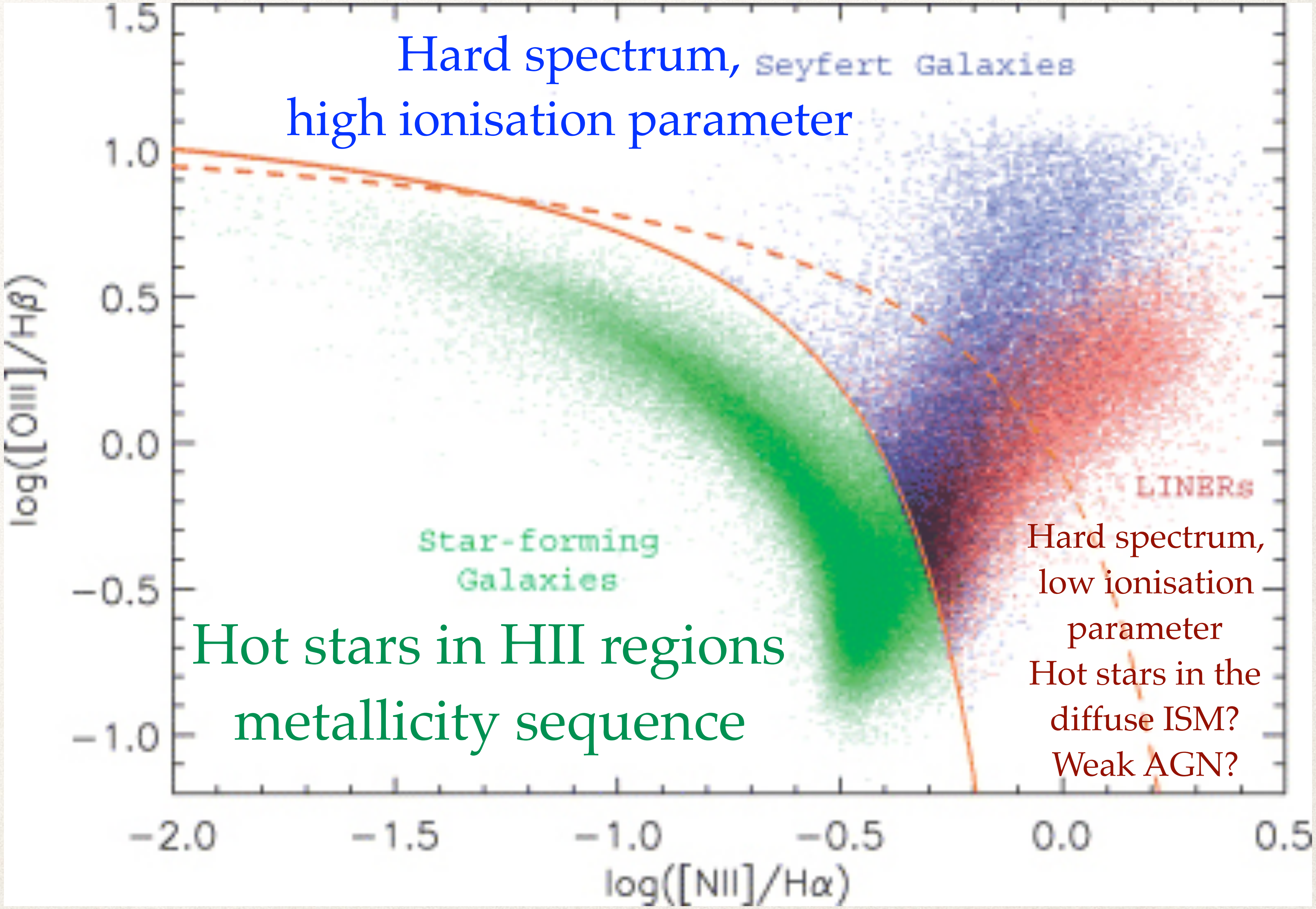
# Summary of the AGN unified model

- Black Hole in the center: $M_{BH} \sim 10^6 \ldots 10^{10} M_\odot$.
- Accretion disk extending to $\sim 100 - 1000 R_S$, that is emitting radiation in the X-ray, EUV, UV, ... optical and TeV.
- Broad line region: Clouds of thick gas ($n_e \simeq 10^9 - 10^{10} cm^{-3}$) that are moving with $v_{BLR} \lesssim 10^4 \frac{km}{s}$ around the black hole and extend to $\sim 0.1 \ldots 1pc$. Emission of broad allowed lines.
- Narrow line region: Clouds of thin gas ($n_e \lesssim 10^5 cm^{-3}$) that are moving with $v_{NLR} \simeq 10^2 - 10^3 \frac{km}{s}$ around the black hole and extend to some $pc$. Emission of narrow allowed and forbidden lines.
- Dust/molecular torus with inner radius: $\sim 1pc$ and outer radius: $\sim 50 - 100pc$ produces IR - mm emission.
- Jets: Synchrotron radiation over the whole spectrum on scales from $0.1 - 10^6 pc$.

Credits: Ralf Bender's IMPRS course

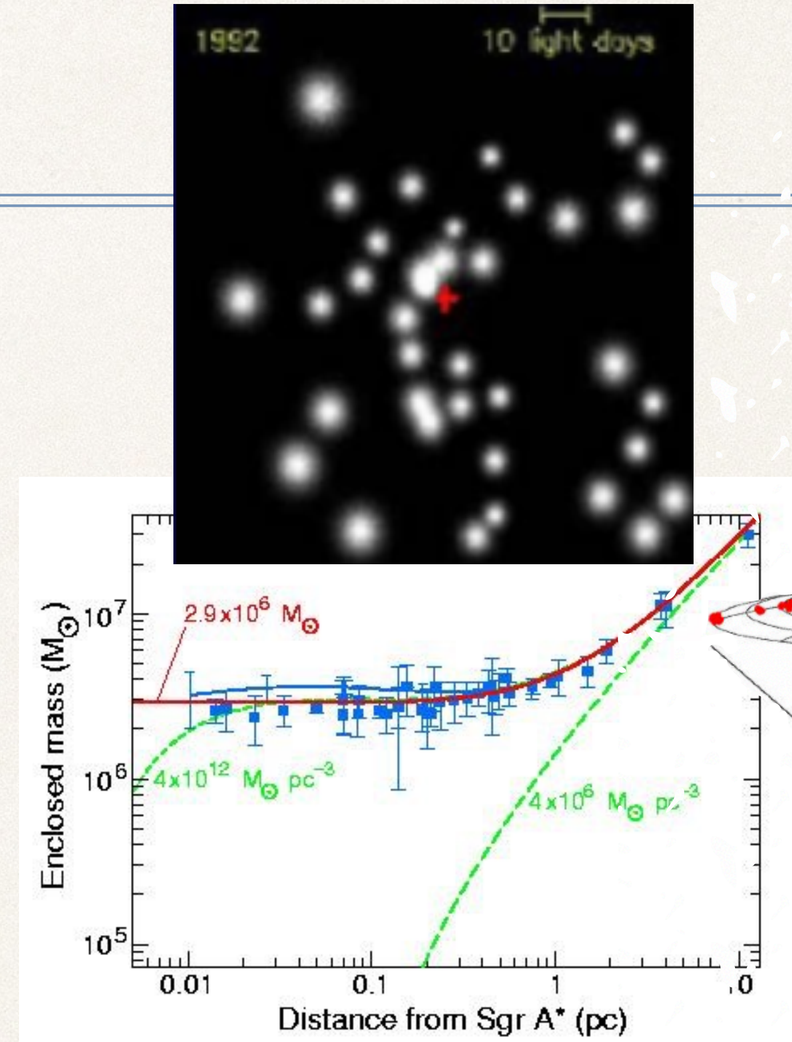
# Seyfert-2 nuclei vs "normal" galaxies

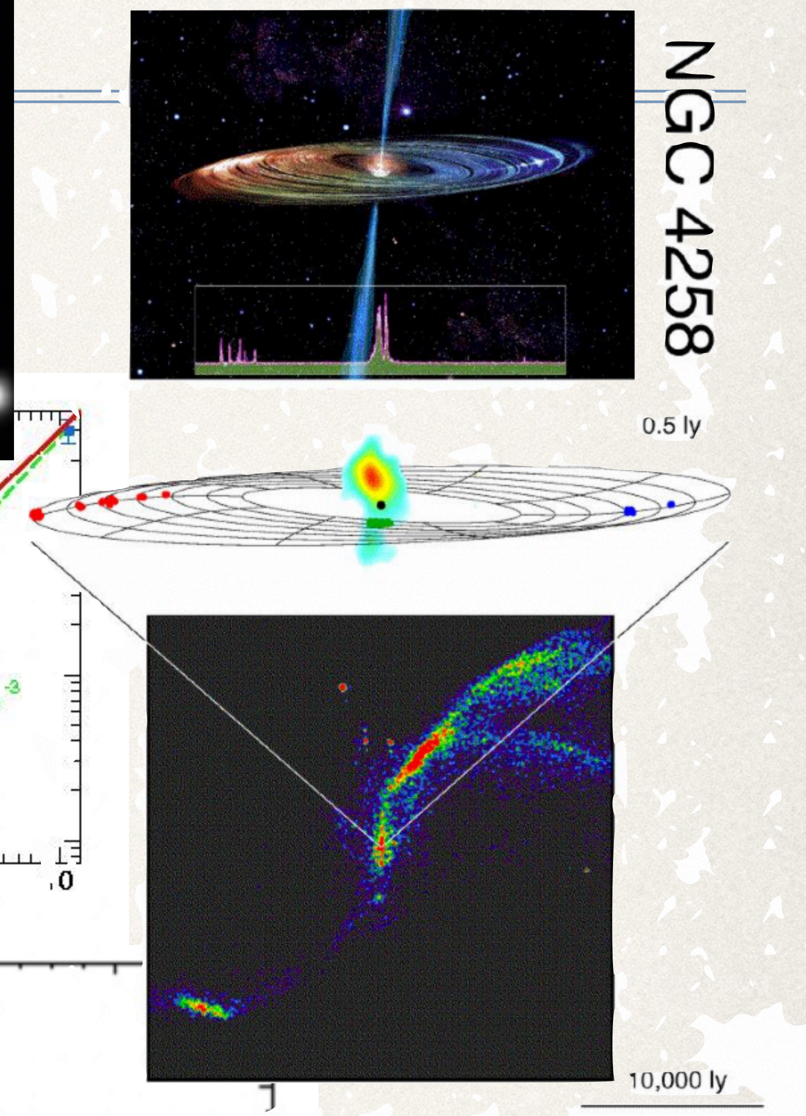
- Use line-ratio diagrams to distinguish different ionization sources

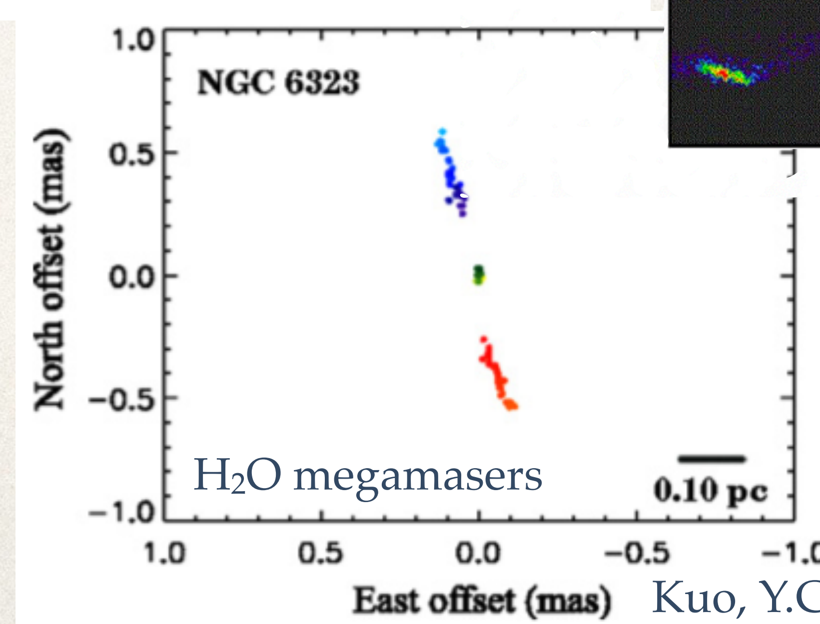


# SuperMassive Black Holes: mass

- Discrete dynamical tracers:
  - Stars (MW): optical/NIR high-resolution observations over long time
  - $H_2O$ megamasers in the keplerian disk surrounding the BH: precise radial velocities and position with radio interferometry — handful of SMBH
- Virial methods: $M_{BH} \propto \frac{\Delta V^2 R}{G}$
  - Reverberation maps ("direct" method)
  - Indirect methods based on calibrated scaling relations



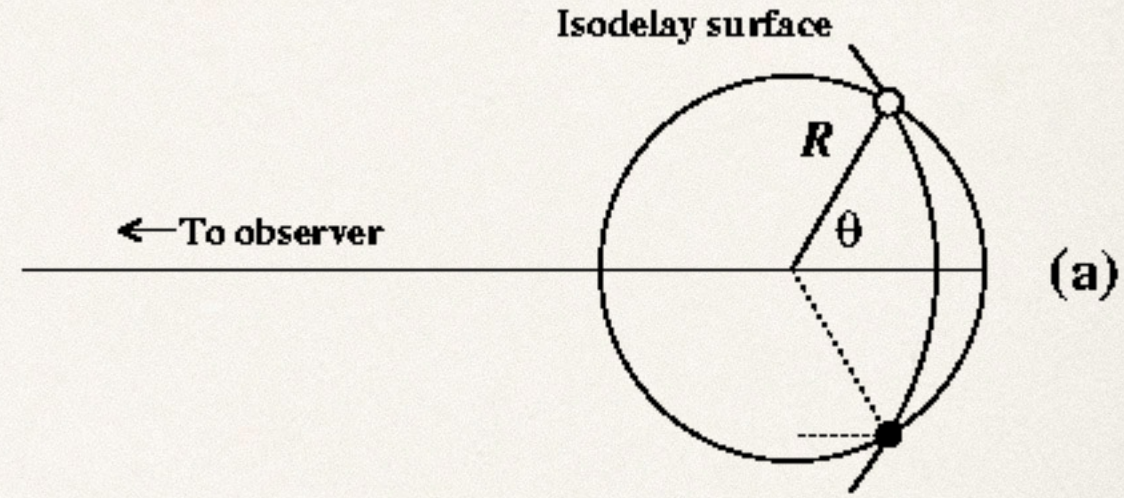



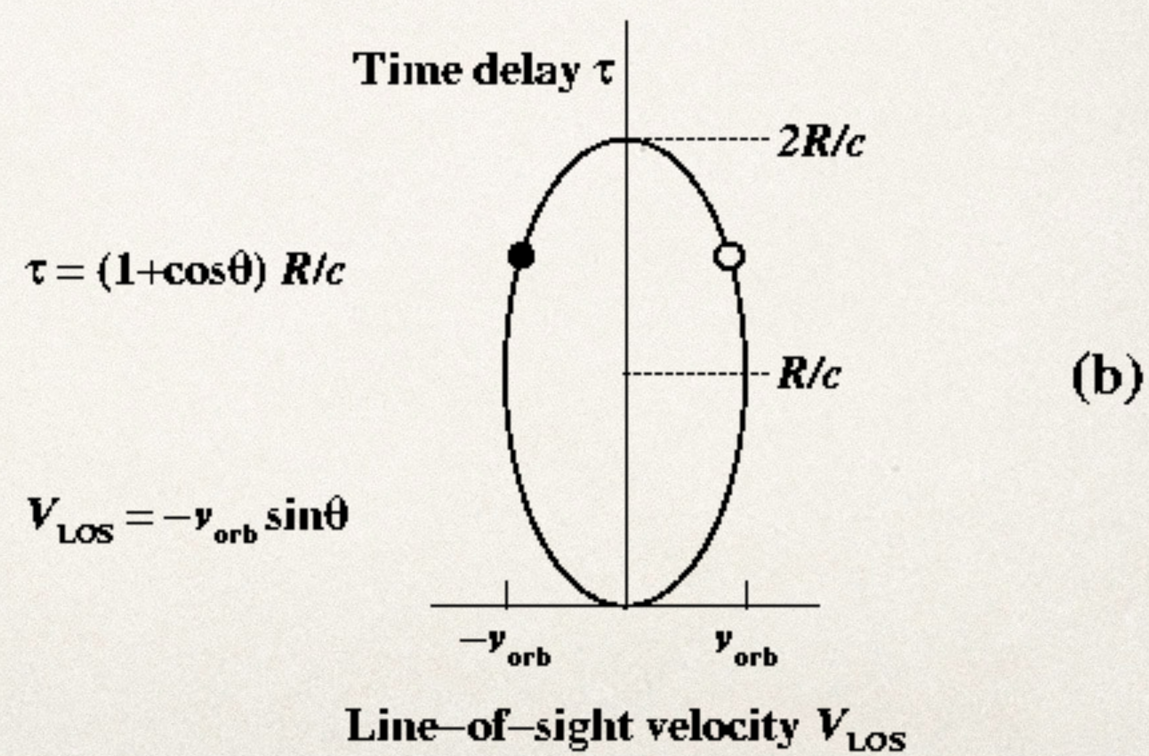




Kuo, Y.C. et al. (2011)

# Reverberation Maps (RM)

- Time variability of the luminosity of the central ionising source
- BLR are illuminated by the ionising flux with the time delay corresponding to the light travel time $R/c$
- Broad lines are emitted and reach the observer with a time lag corresponding to the time delay $R/c$ plus the recombination time scale (<< 1 sec, typically) and a **Δ**t depending on the different path to the observer (also of the order of $R/c$)



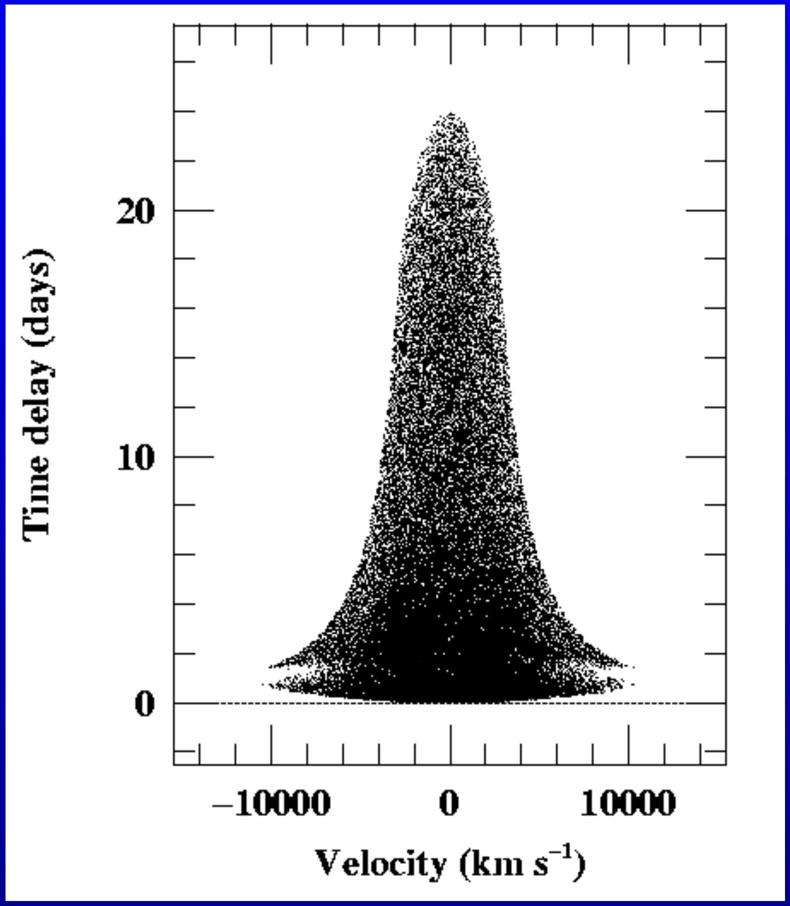
# Observed Response of an Emission Line

The relationship between the continuum and emission can be taken to be:

$$L(V,t) = \int_{-\infty}^{\infty} \Psi(V,\tau)\,C(t-\tau)\,d\tau$$

Emission-line light curve — "Velocity-Delay Map" — Continuum Light Curve

Velocity-delay map is observed line response to a δ-function outburst

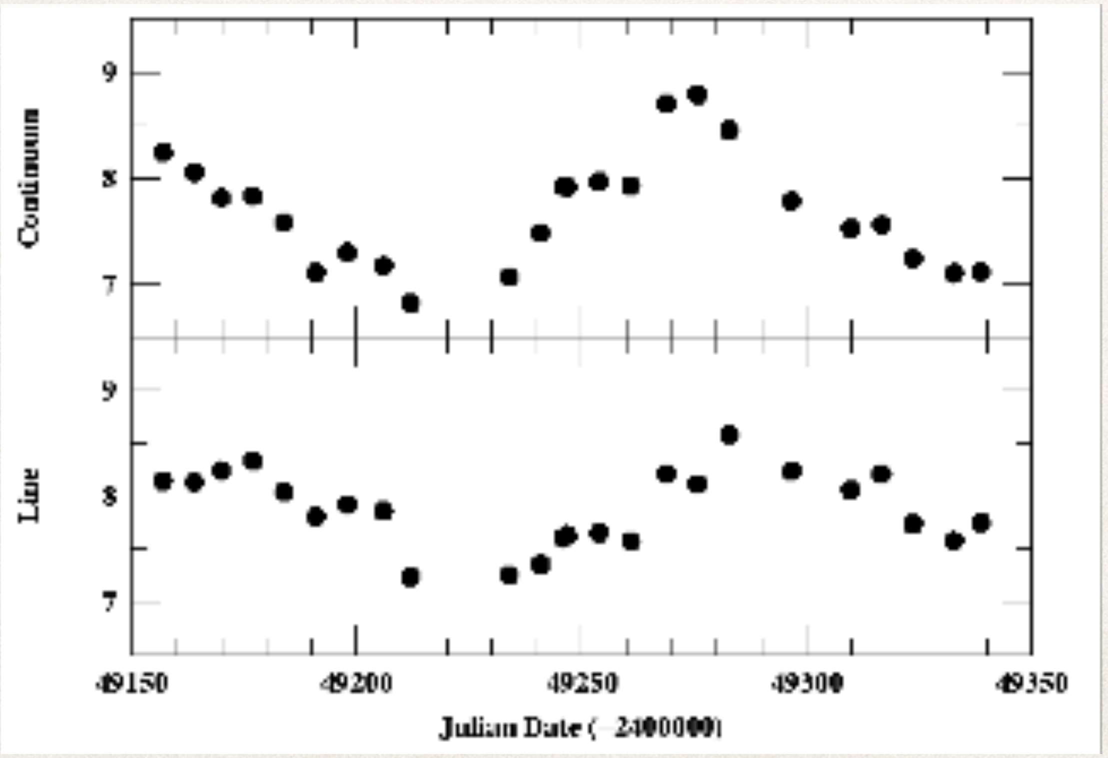


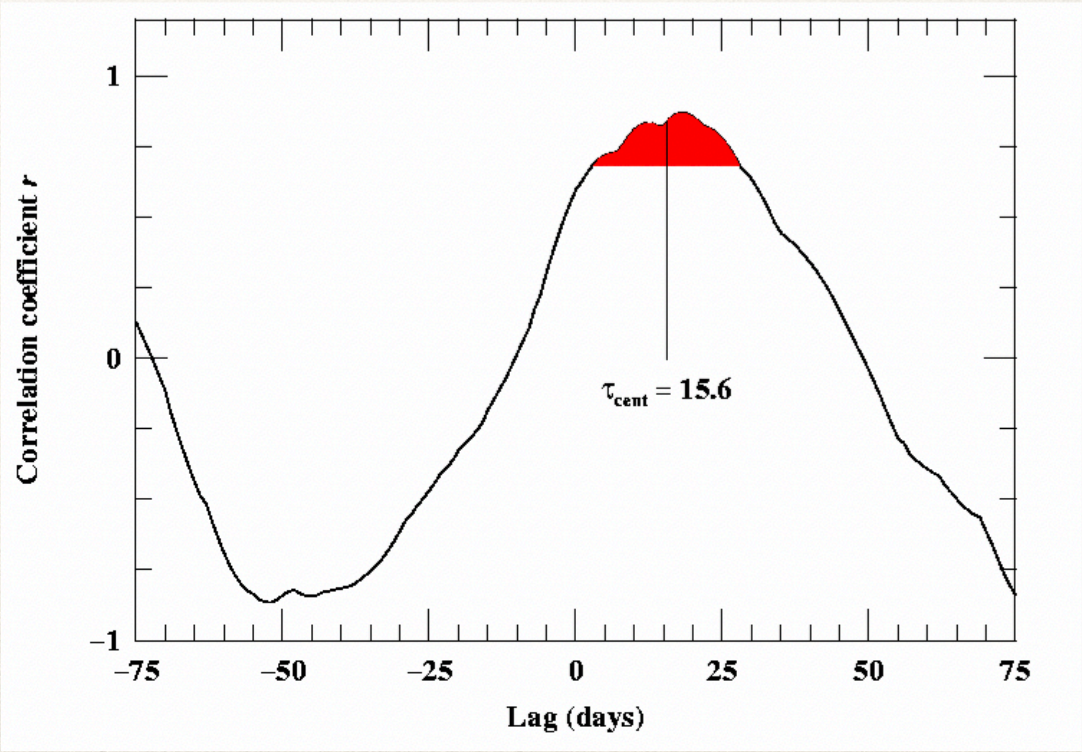

**Simple velocity-delay map**

# Reverberation Mapping

- First order approximation: the light curve of emission lines lags behind the light curve of the continuum by ~$R/c$, where $R$ is the "characteristic" distance of the line-emitting regions to the central source of ionising continuum

- Use cross-correlation to precisely determine the lag

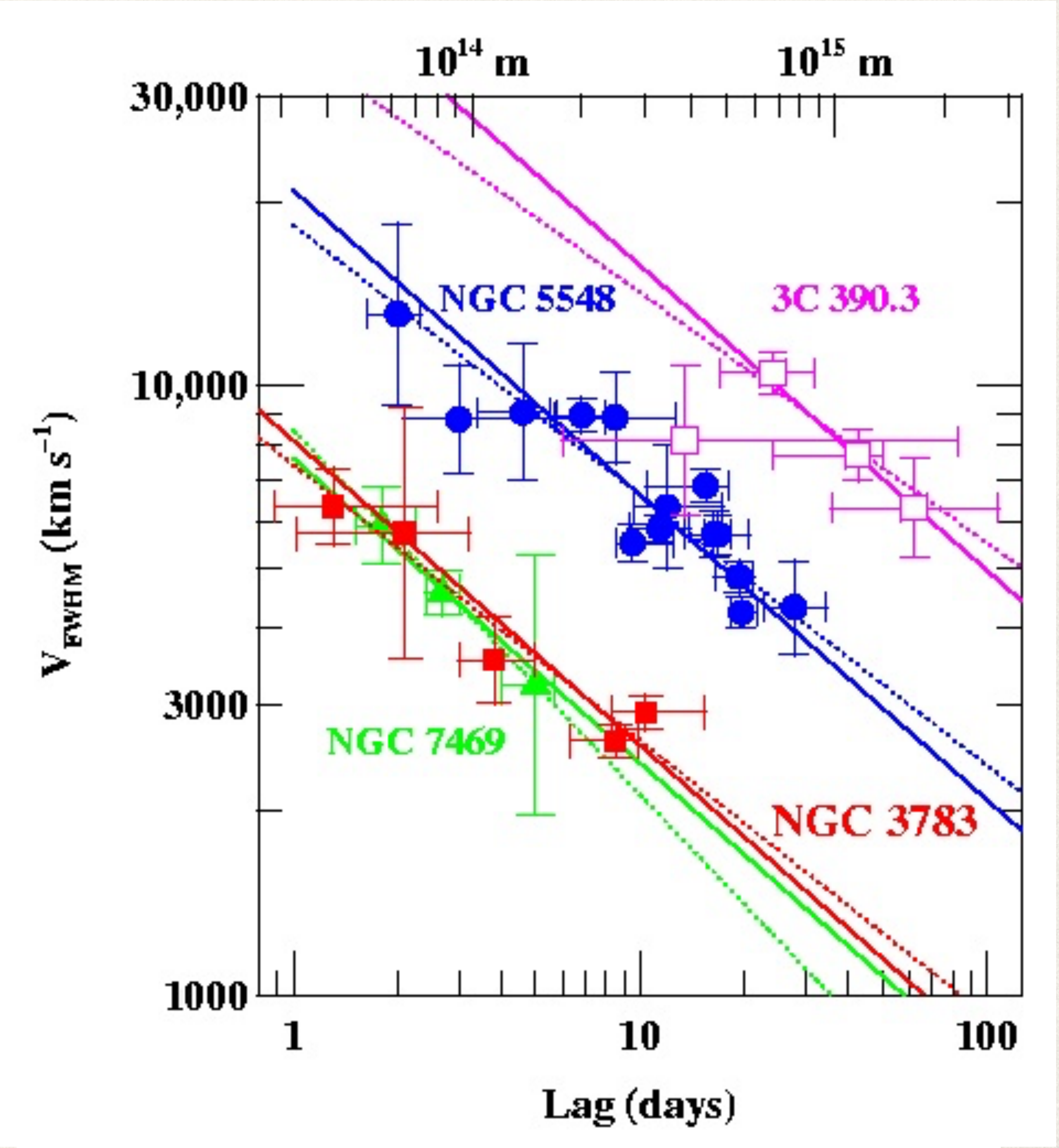


# RM: the stratified structure of BLRs

- Different lines correspond to different ionisation states (hence T and n)
- Time lag (∝R) is anti-correlated with $\Delta v^2$ as expected for keplerian orbits

$$M_{\rm BH} \propto \frac{\Delta V^2 R}{G} \Rightarrow \Delta V \propto R^{-1/2}$$




The relationship between emission-line Doppler width and reverberation lag for multiple emission lines in four AGNs. The $\Delta V \propto R^{-1/2}$ dependence is expected for a system dominated by the gravity of the central black hole. The dashed lines are the best fits to the data, and the solid lines have a forced slope of -1/2. Based on data from Peterson & Wandel (2000) and Onken & Peterson (2002).
https://blogs.stsci.edu/universe/2016/12/13/the-agn-space-telescope-and-optical-reverberation-mapping-project-agn-storm/

# Radius-Luminosity relation for BLRs

- RM is observationally expensive: long campaigns and deep observations
- Rely on empirical relations that allow to use just 1 single-epoch spectrum
- Calibrate on RM sample

## BLR Scaling with Luminosity

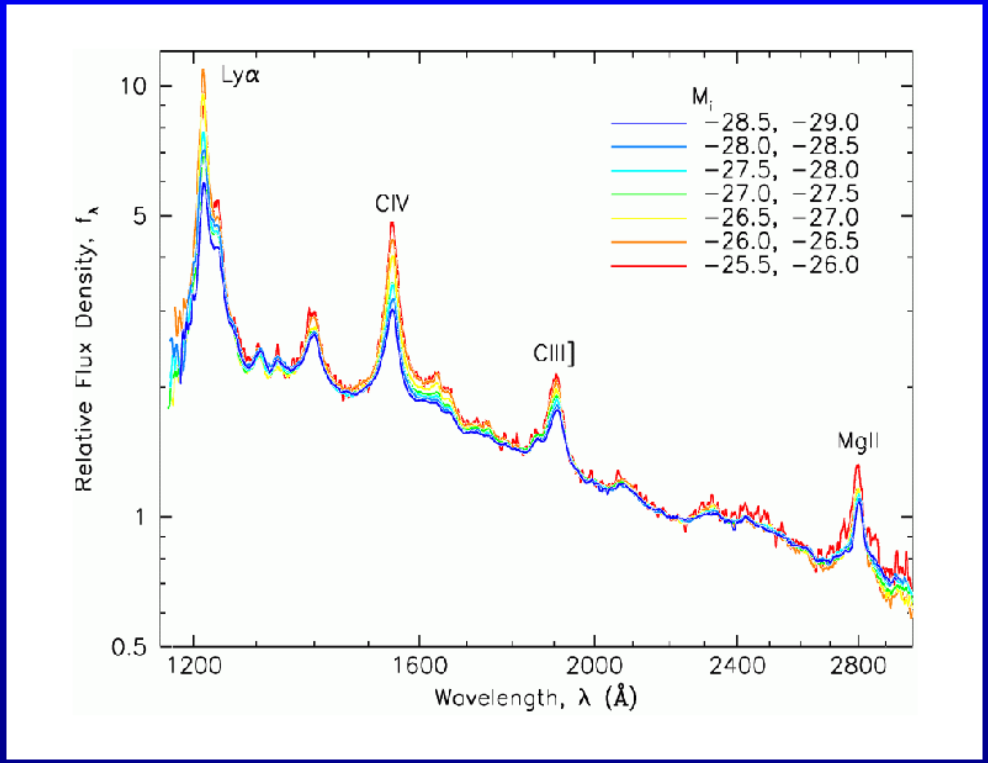
- To first order, AGN spectra look the same

$$U = \frac{Q(\mathrm{H})}{4\pi r^2 n_\mathrm{H} c} \propto \frac{L}{n_\mathrm{H} r^2}$$

$\Rightarrow$ Same ionization parameter $U$

$\Rightarrow$ Same density $n_\mathrm{H}$

$$r \propto L^{1/2}$$



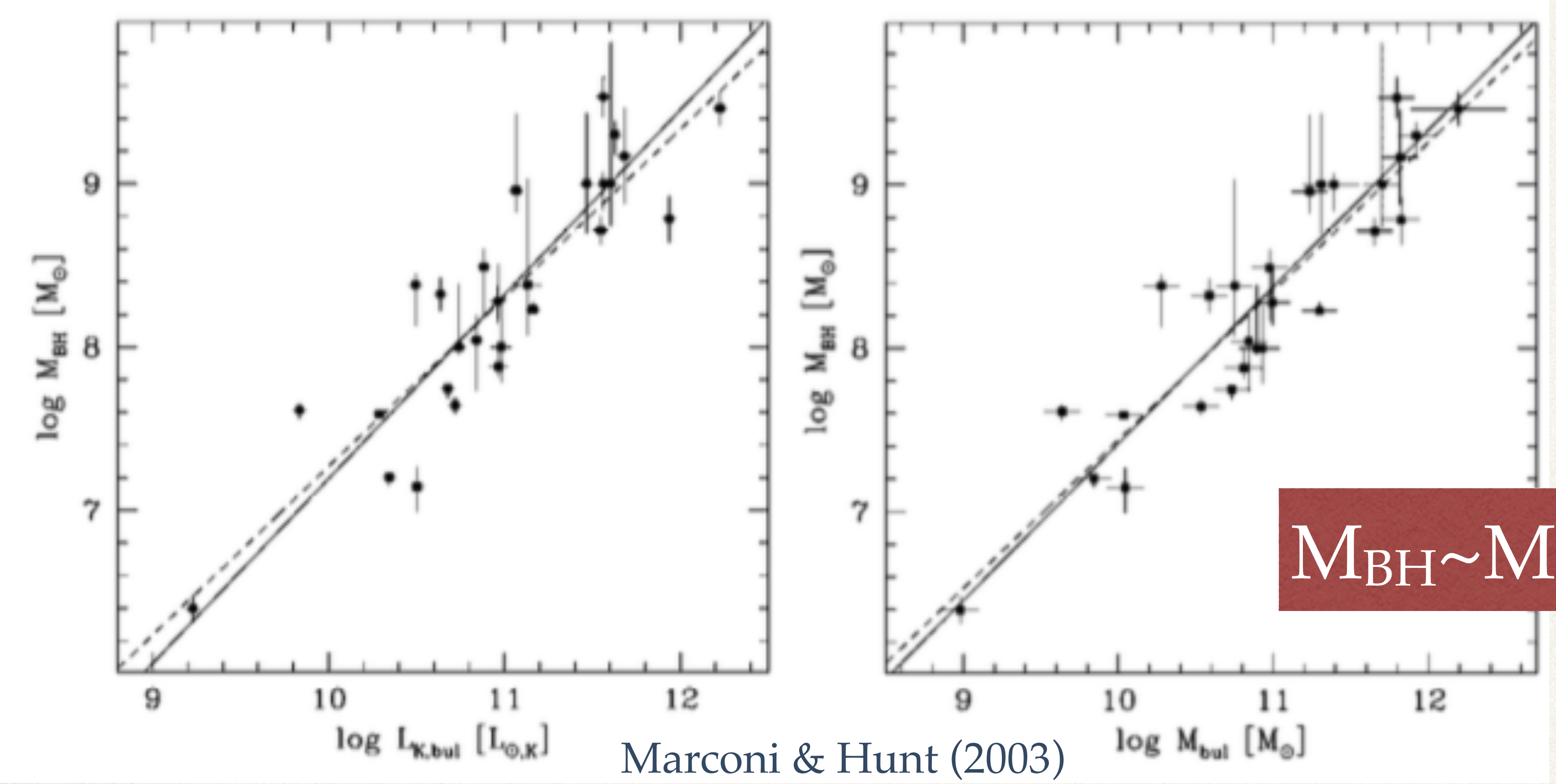

SDSS composites, by luminosity
Vanden Berk et al. (2004)

# BH mass from single-epoch spectra

- Take a broad line, eg Hβ
- Measure L(Hβ) and get R from the Radius-Luminosity relation
- Measure **Δ**v
- Derive $M_{\mathrm{BH}} \propto \frac{\Delta V^2 R}{G}$,

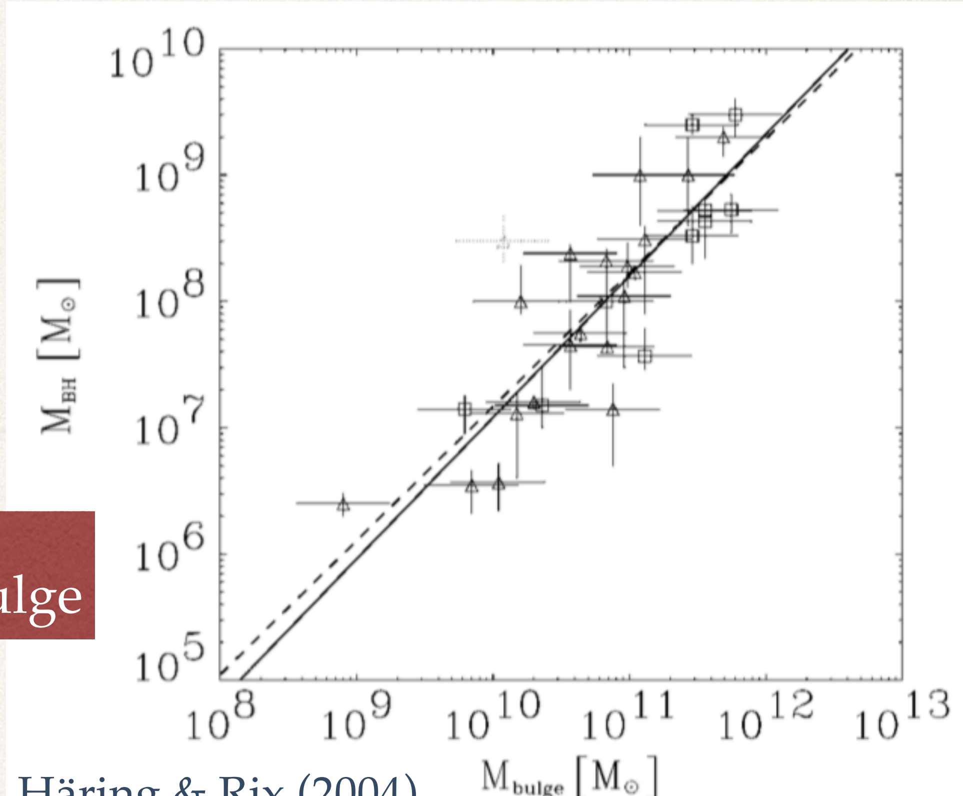
  where the proportionality constant is calibrated on detailed RM

# SMBH-galaxy scaling relations




Marconi & Hunt (2003)

$M_{BH}$~$M_{Bulge}$

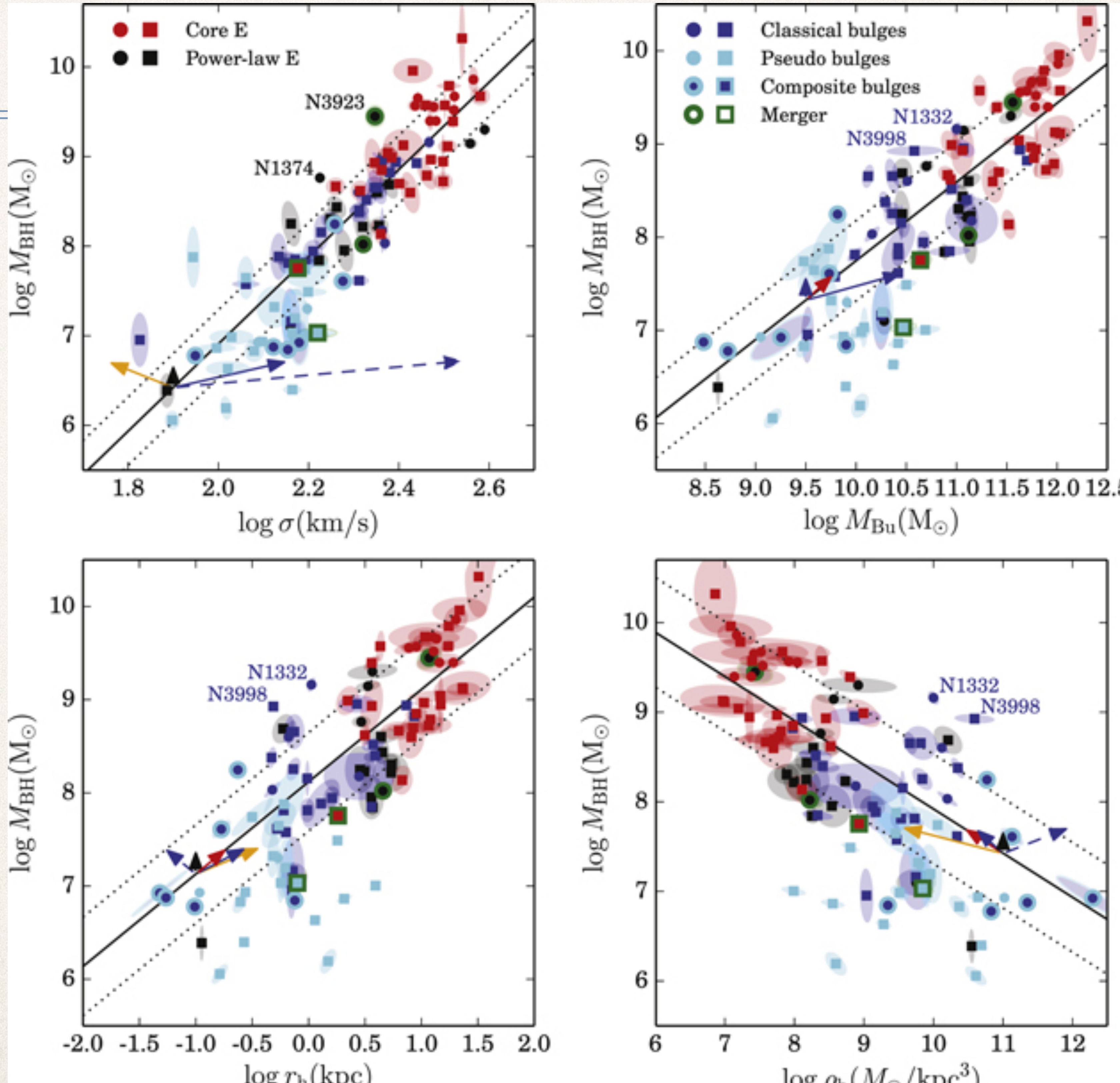



Häring & Rix (2004)

# SMBH-galaxy scaling relations

$M_{BH} \sim \sigma_{Bulge}$

$M_{BH} \sim M_{Bulge}$

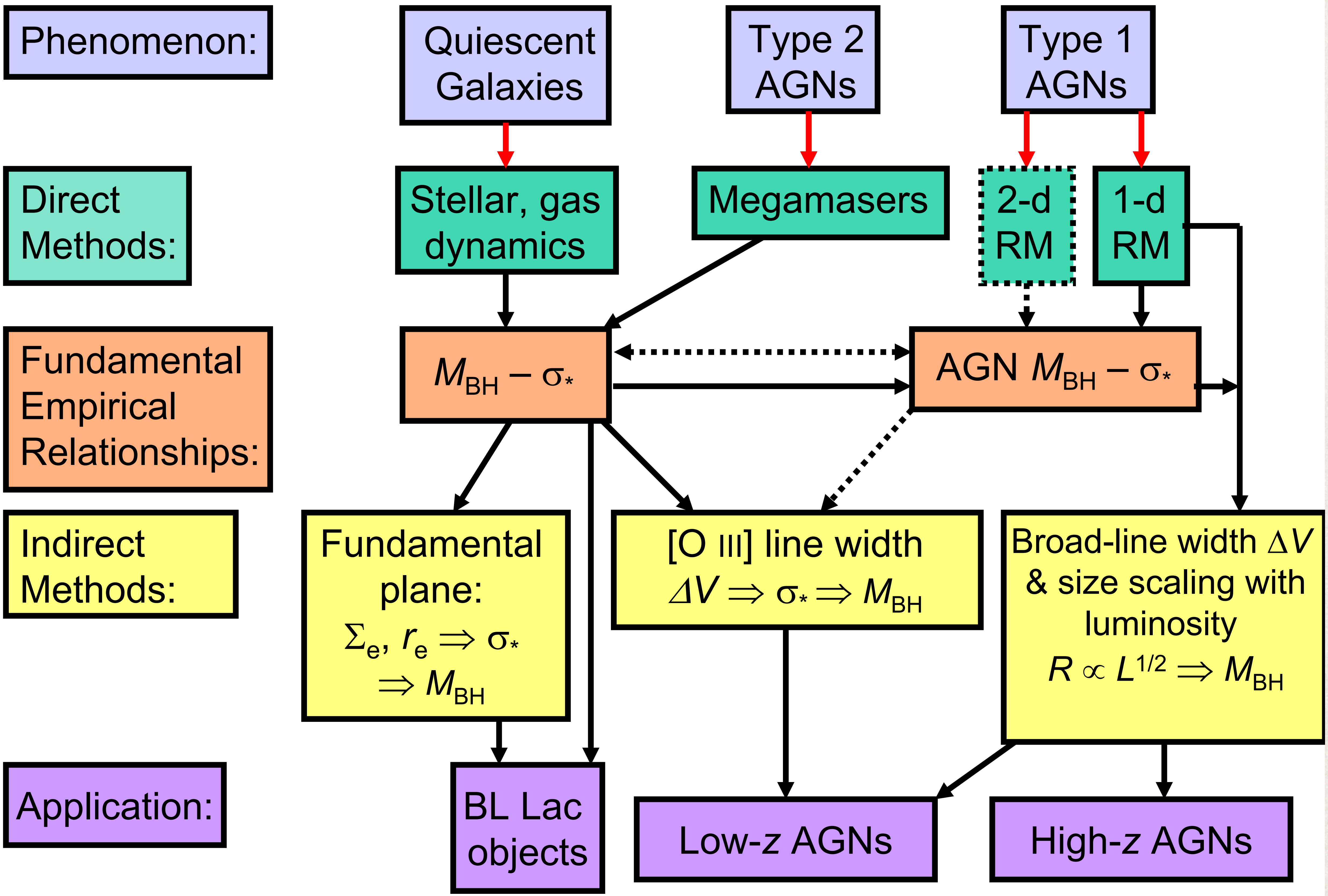



$M_{BH} \sim r_{Bulge}$

$M_{BH} \sim \varrho_{Bulge}$

Saglia et al. (2016)

# Measurement of Central Black Hole Masses: The Mass Ladder



# Scaling Relationships: Use with Caution

- When you think you're measuring mass, you're really measuring

$$M_{BH} \propto R(\Delta V^2) \propto L^{1/2}(\Delta V^2)$$

- When you think you're measuring Eddington ratio, you're really measuring

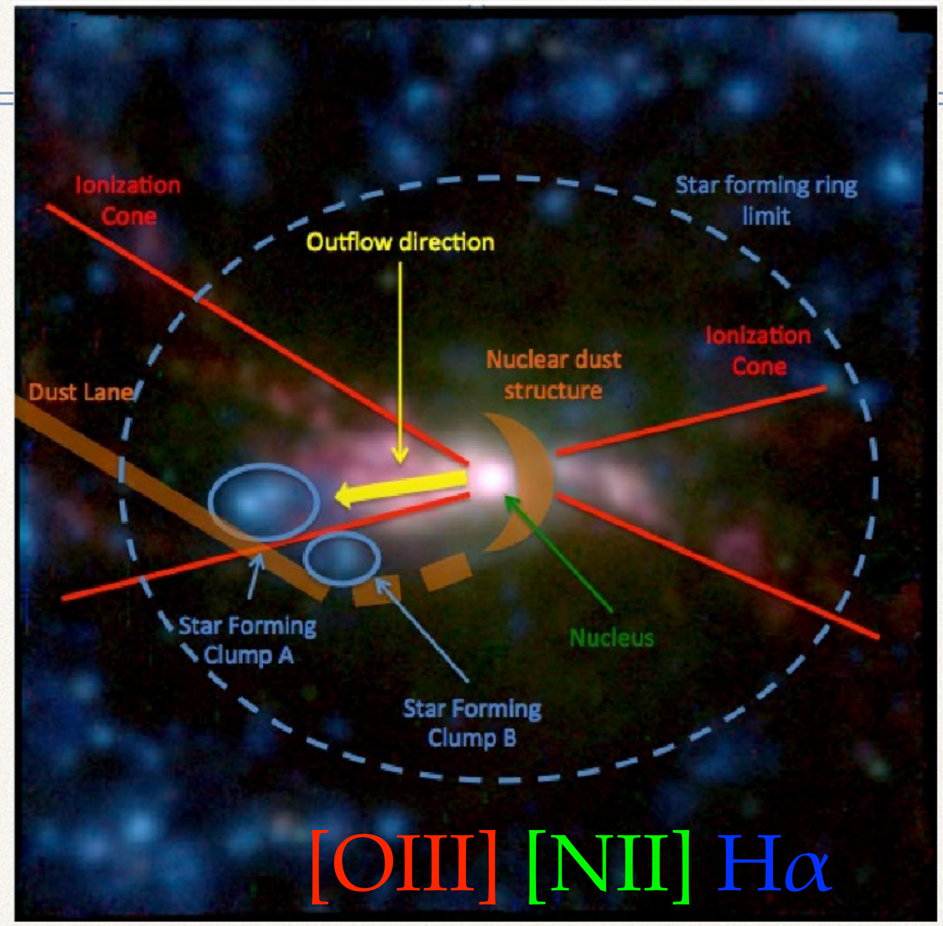
$$L/L_{Edd} \propto L/M_{BH} \propto L/L^{1/2}(\Delta V^2) \propto L^{1/2}/\Delta V^2$$

# BH-galaxy coevolution?

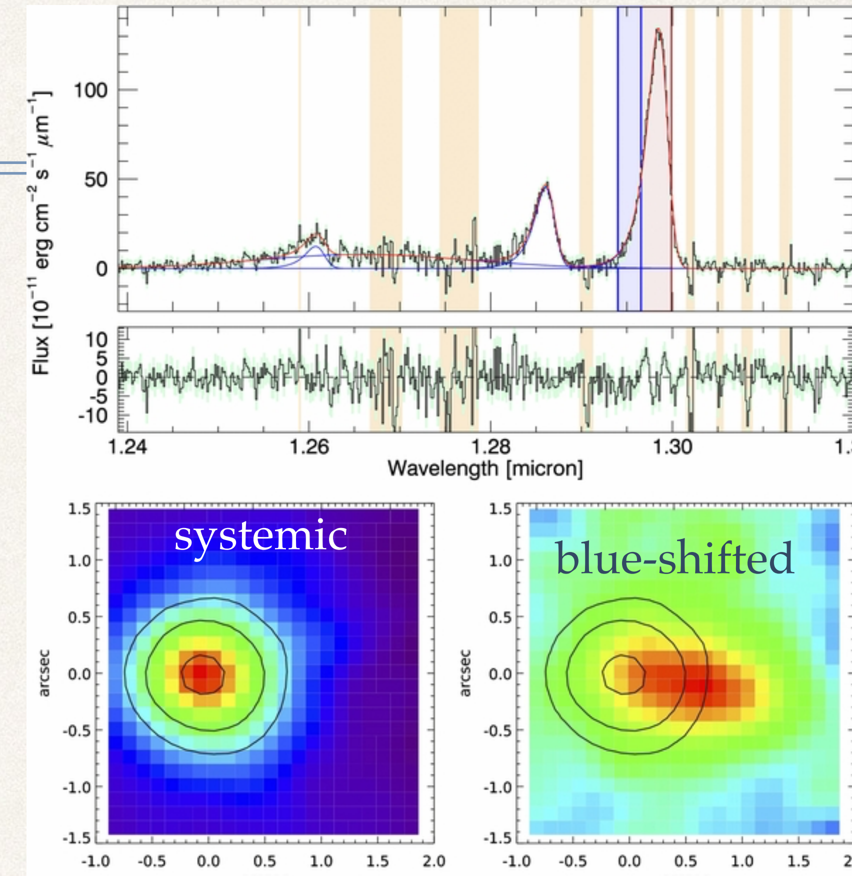
- Scaling relations indicate that the SMBH and the host galaxy (actually, its bulge) know about each other
- Common growth in parallel through mergers?
- Growth of SMBH and consequent AGN activity drive bulge growth via “feedback” and gas removal? on >3 orders of magnitude in mass?
- Growth of bulge simultaneously lead to SMBH growth by funnelling matter to the central SMBH?

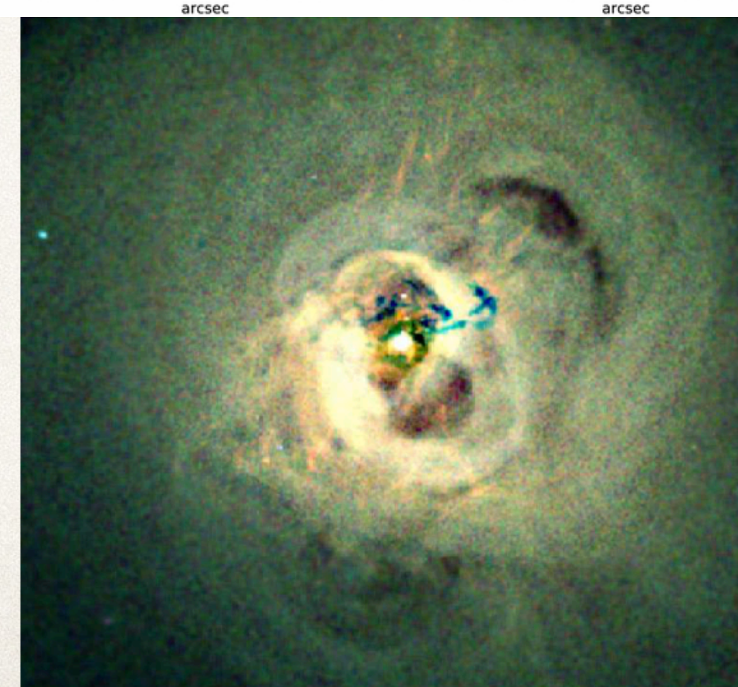
# Evidence for AGN feedback

- Ionization cones
- Outflows in different phases (ionized and molecular in partic.)
- Injection of energy/momentum into the IGM
- How much "damage" is actually made?




Cresci et al. (2015) - NGC5643

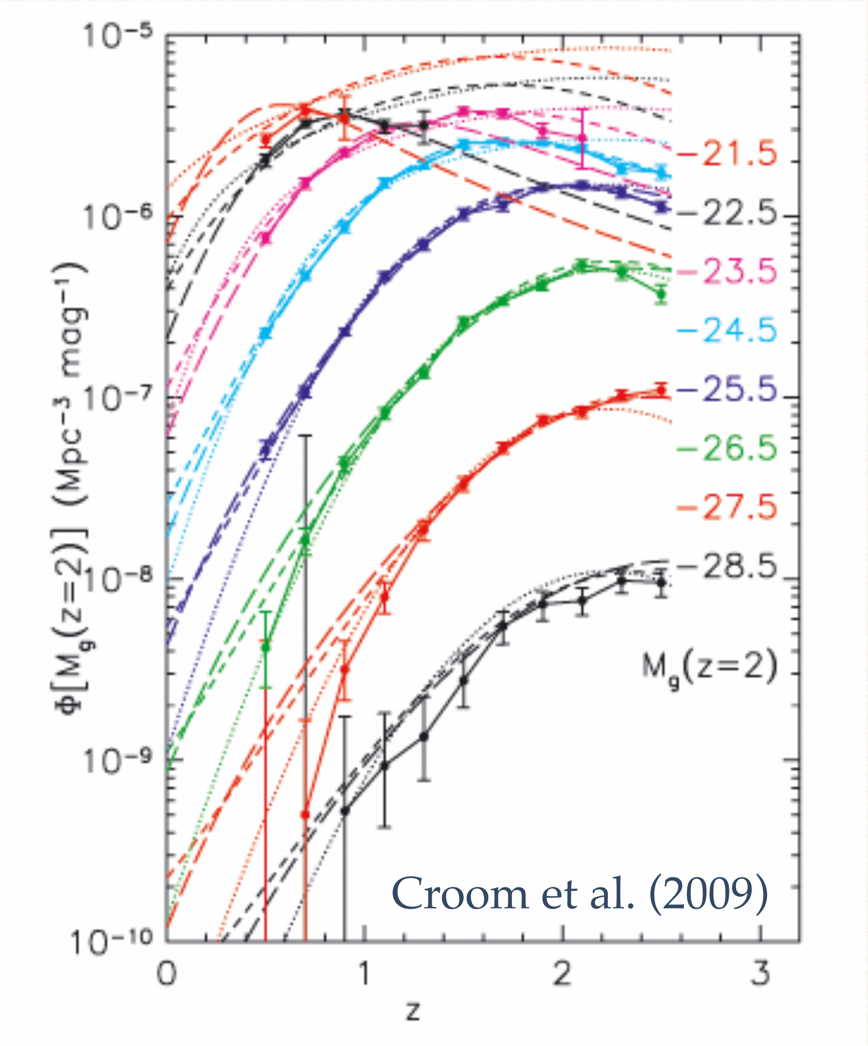


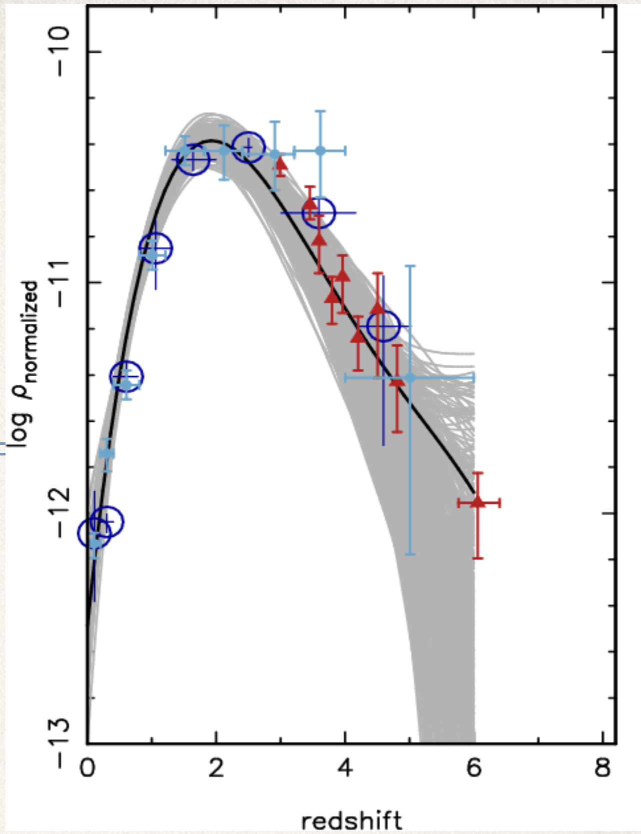



Fabian et al. (2012) - Perseus cluster in X-rays with Chandra

# SMBH through cosmic times

- SMBH activity reached a peak at z~2, then gradual switch-off
- "Downsizing": the peak of space density moves to higher redshift for more luminous QSOs
- Much higher space density of QSOs in the past
  +
  (Integrated Flux Density) ~ (Integral of Accreted Mass) [Soltan 1982]
  ⇓
  large number of quiescent SMBH in the local Universe




Space density of QSOs as a function of redshift (see Wall et al., 2005, Fig. 11)