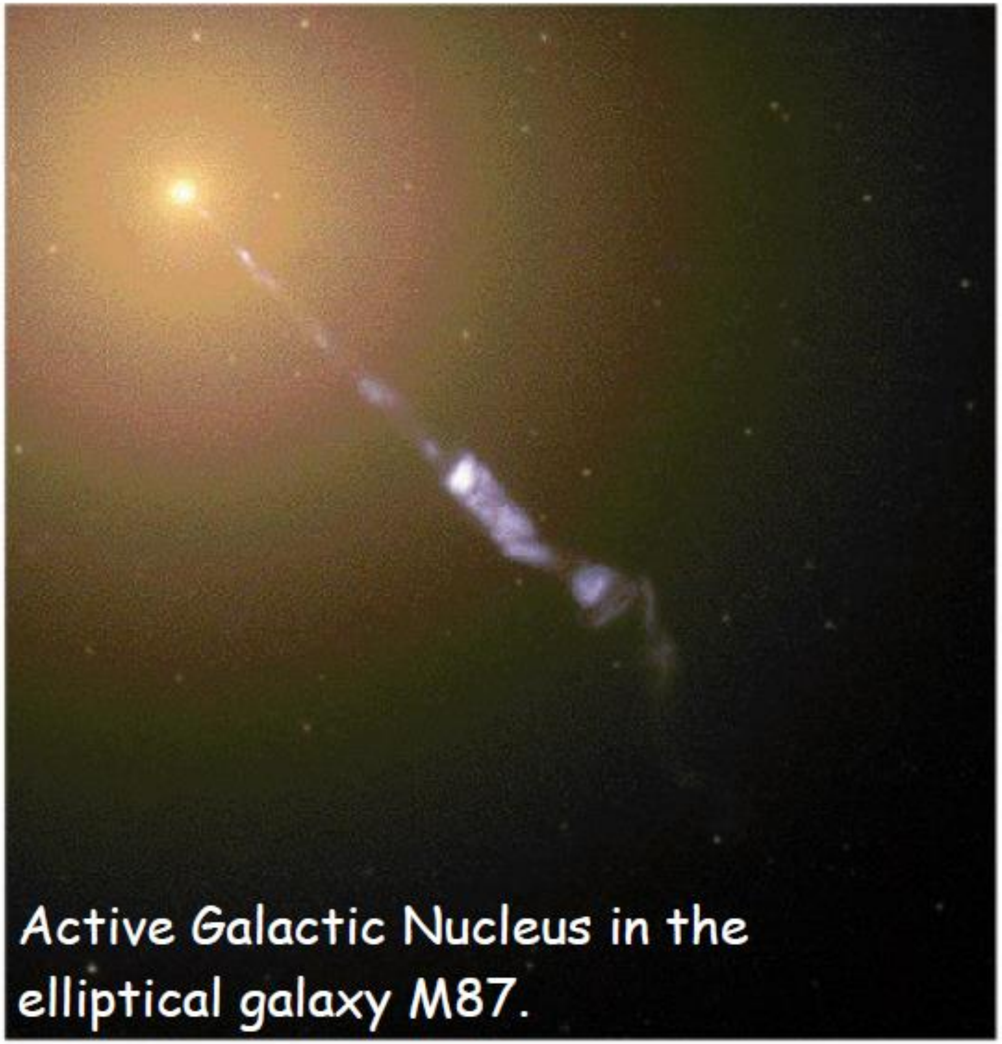
Active Galactic Nuclei

Black Hole Physics, 2018

What are Active Galactic Nuclei?



"AGN are the nuclei of galaxies which show energetic phenomena that can not clearly and directly be attributed to stars"

Some signs of AGN Activity

- Luminous UV emission from a compact region in the center of galaxy
- Strongly Doppler-broadened emission lines
- High Variability on time-scales of days to months
- Strong Non-Thermal Emission
- Compact Radio Core
- Extended linear radio structures (jets+hotspots)
- X-ray, γ-ray and TeV-emission
- Cosmic Ray Production

(Not all AGN show each of these, but often several of them)

Background & History

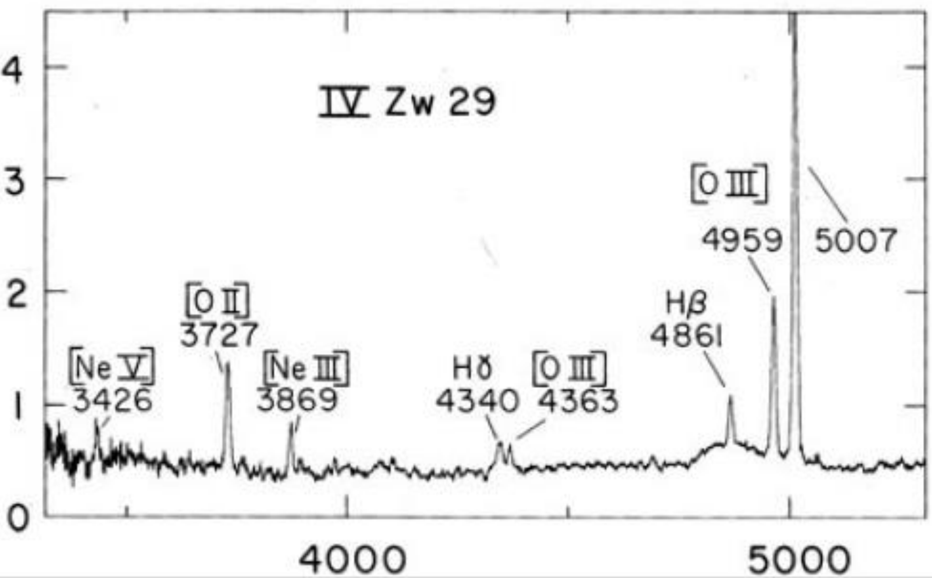
Two main classes of AGN hosts

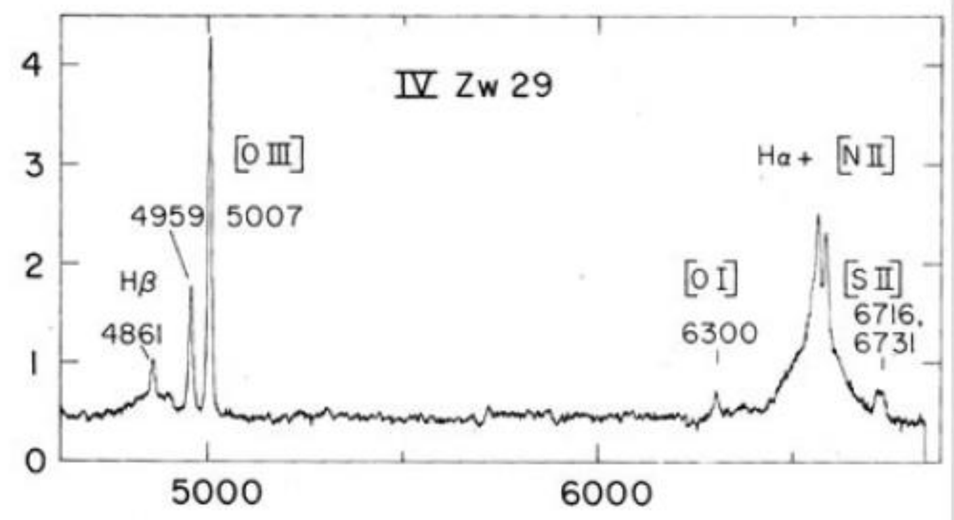
- "Seyfert" Galaxies → Often Spirals ($\sim L_{gal}$)
- "Quasars" → Often Ellipticals (upto $\sim 100\ L_{gal}$)

First Detections of Seyfert Galaxies

1908 – Fath & Slipher detect strong emission lines similar to PNae with line-width of several hunderd km/s in NGC 1068.

Galaxy centers show broad lines and/or high-excitation emission lines.

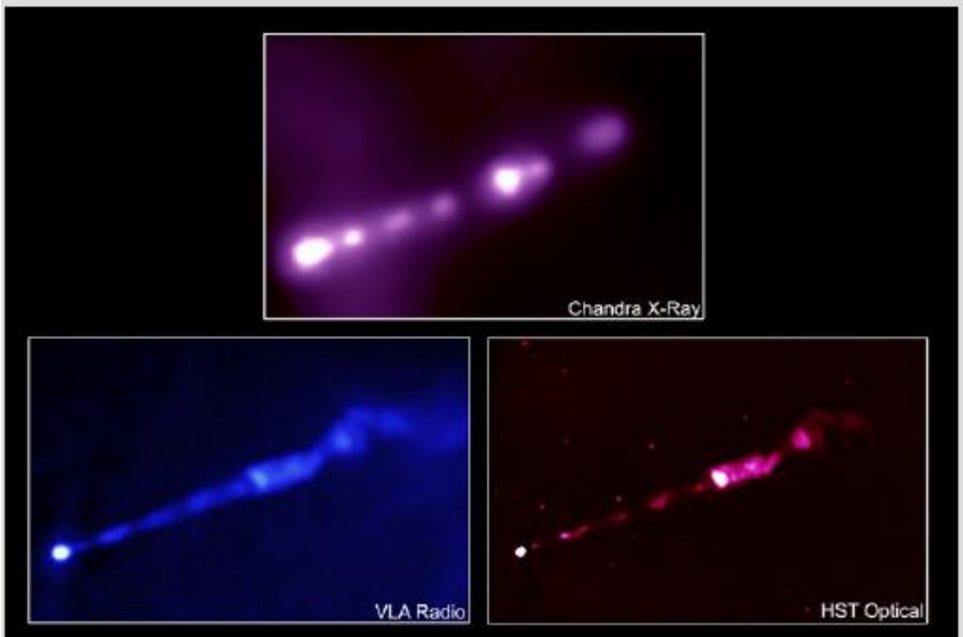


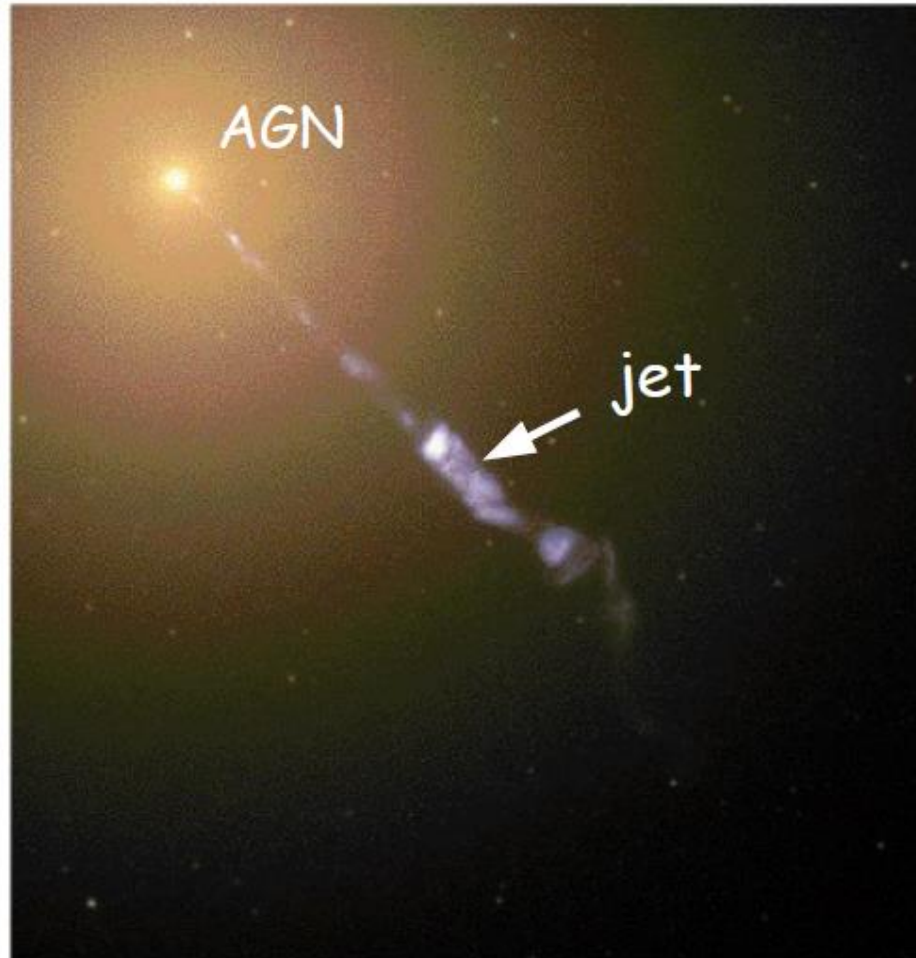


What causes these (broad) lines?

First Detections of Optical Jets

1913 - Detection of an optical jet in M87 by Curtis





"Re-discovery" of Seyfert Galaxies

1943 - Seyfert finds multiple galaxies similar to NGC1068
(Hence since then they are called by his name)

1955 - Detection of radio-emission from NGC1068 and NGC1275

1959 - Woltjer draws several important conclusions on "Seyfert" galaxies:

* Nuclei are unresolved (<100pc)
* Nuclear emission last for $>10^8$ years
  (1/100th spirals is a Seyfert and the Universe is 10^{10} yrs)
* Nuclear mass is very high if emission-line broadening is caused by bound material ($M \sim v^2 r/G \sim 10^{9\pm1} M_{sun}$)

First Radio Surveys

Early radio surveys played a crucial role in discovering quasars

- 3C and 3CR Third Cambridge Catalog (Edge et al. 1959) at 159 Mhz (>9Jy). Basis for extragalactic radio astronomy, cosmology and *discovery of Quasars*
- PKS Parkes (Australia, Ekers 1959) survey of southern sky at 408 Mhz (>4Jy) and 1410MHz (>1Jy).
- 4C 4^{th} Cambridge survey (today 8C). Deeper/smaller
- AO Aricibo Occultation Survey (Hazard et al. 1967). Occultation by moon (high positional accuracy)

First Radio Surveys

Sources found in radio surveys

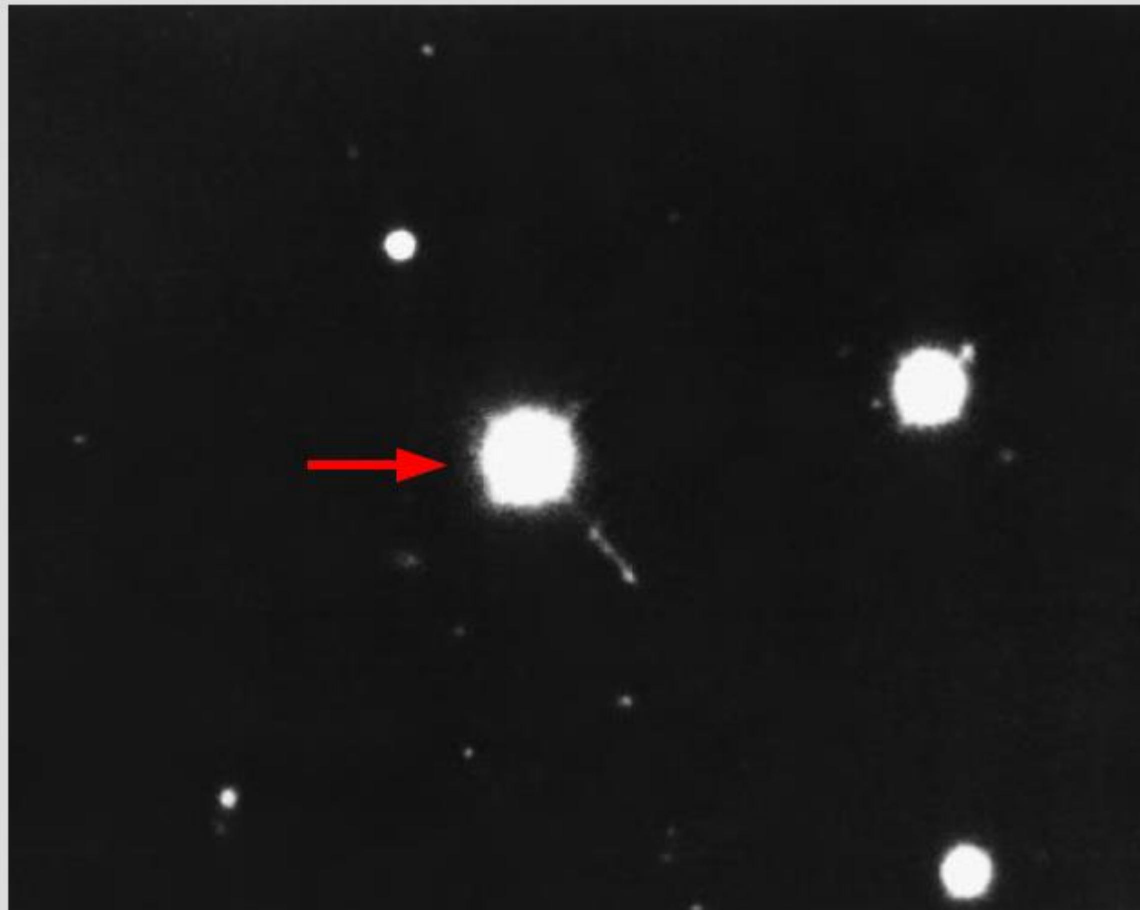
- Surveys excluded the Galactic Plane
- Mostly Normal Galaxies (e.g. Thermal emission of spiral galaxies like the MW)
- "Stars" with strange broad emission lines!

Discovery of Quasars

3C273

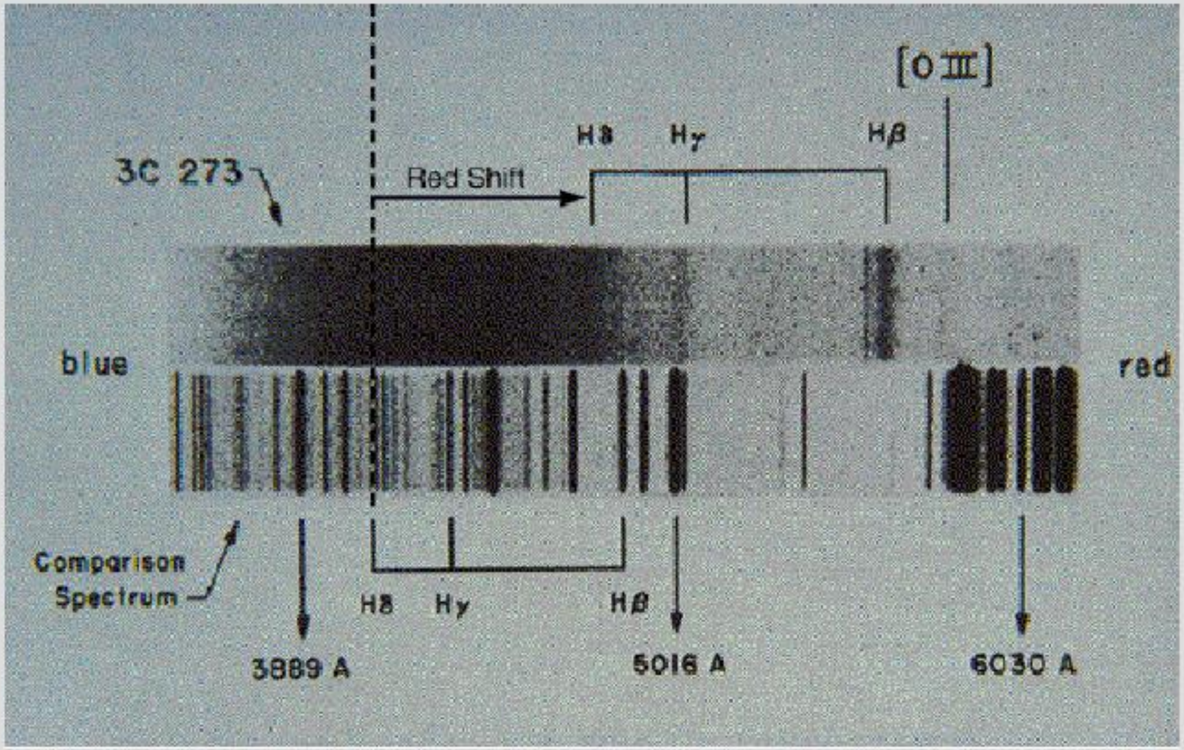
The 273rd radio source in the Cambridge Catalog

Compact radio source looks like a star except for that wisp of light!



Discovery of Quasars

Broad emission lines at "strange" positions



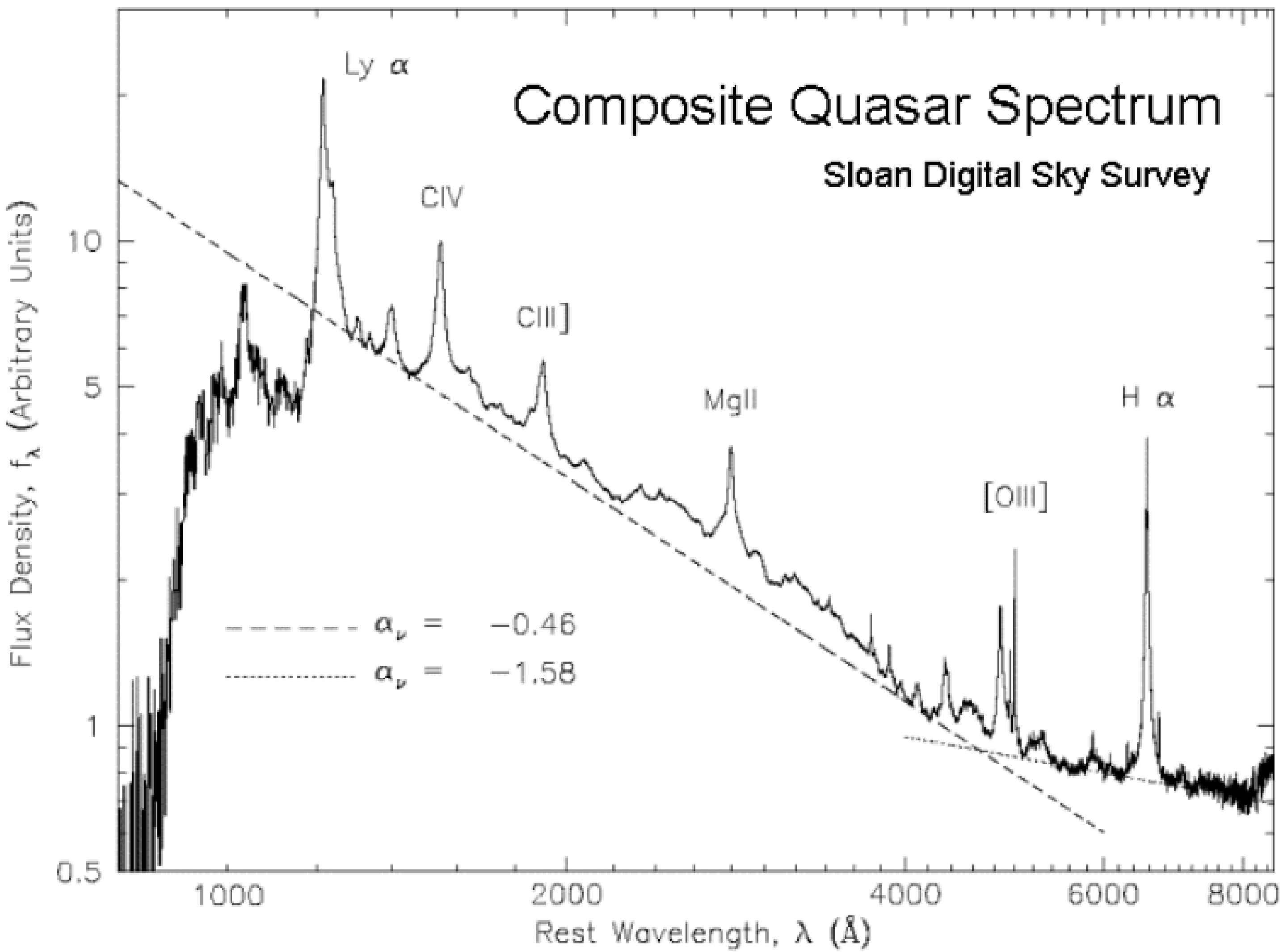
Discovery of Quasars

1964 – Schmidt studied sufficient quasars to find:

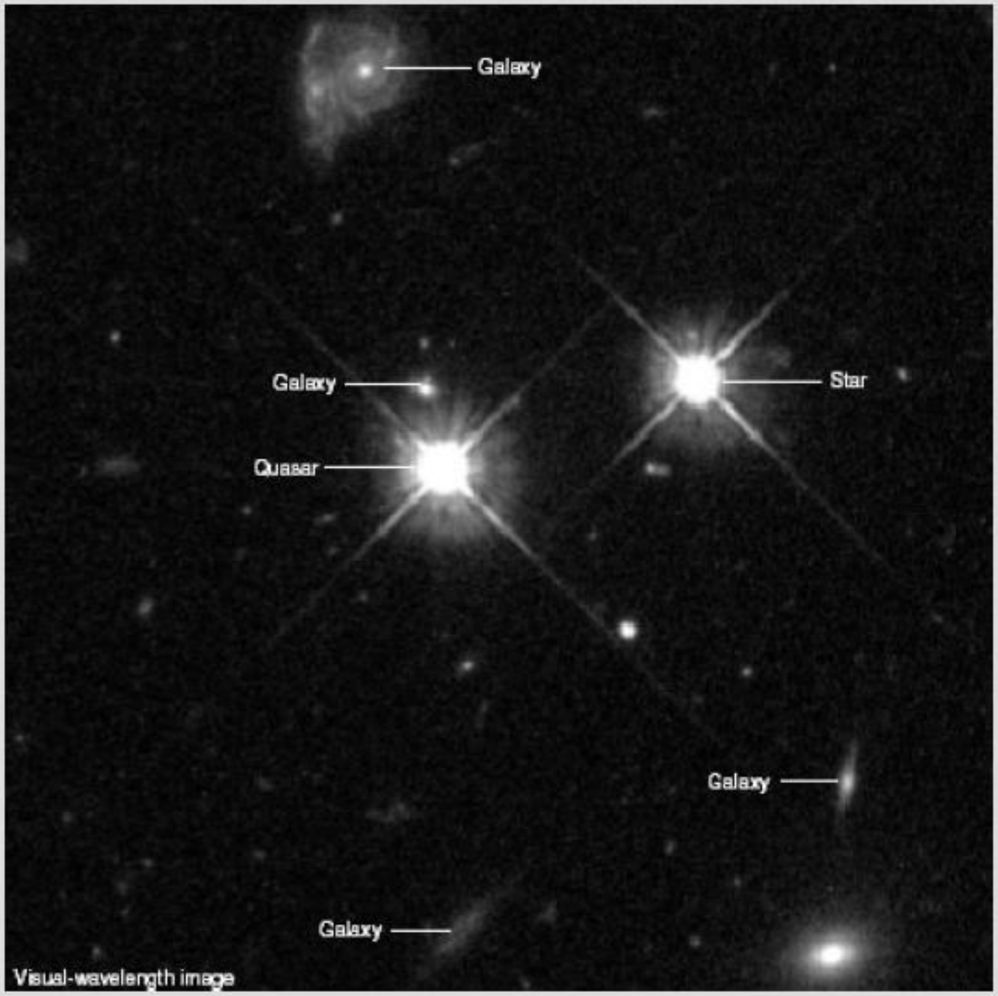
- Star-like, accociated with radio sources
- Time-variable in continuum flux
- Large UV fluxes
- Broad emission lines
- Large redshifts

Not all quasars have these properties, although most are X-ray luminous (Elvis et al. 1978)

Quasar Composite Spectra

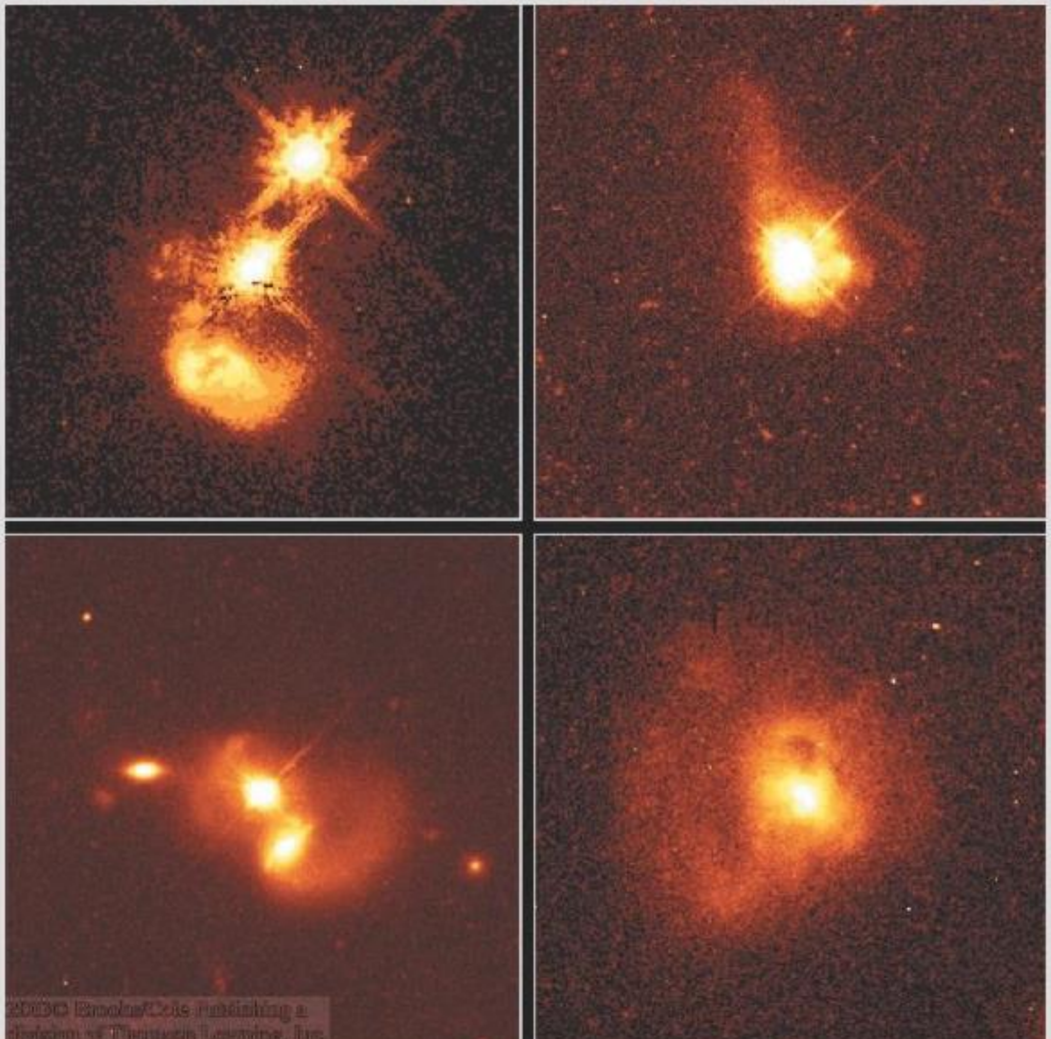


Some examples of QSOs - 1



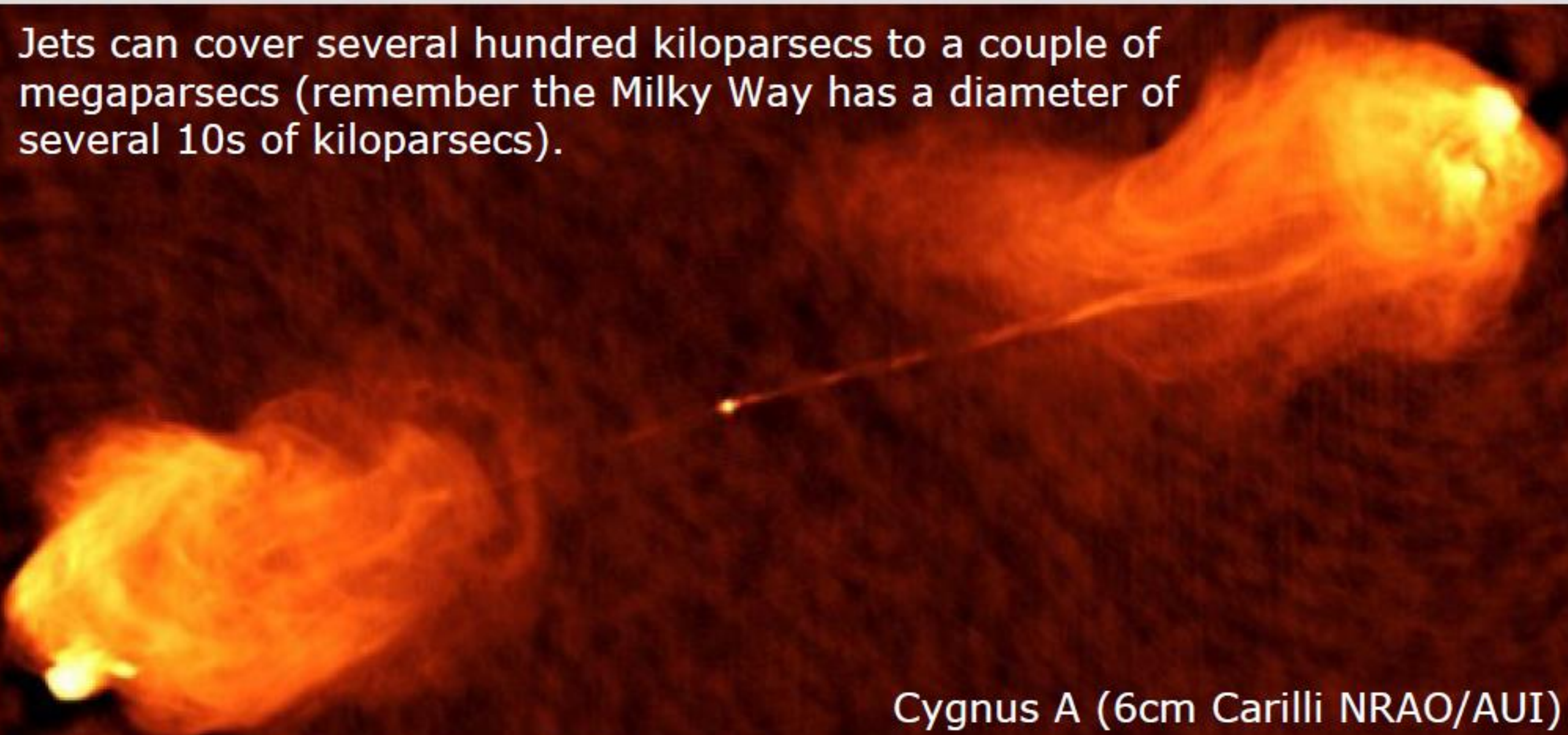
QSOs often outshine their host galaxies which can be difficult to detect!

Some examples of QSOs - 2

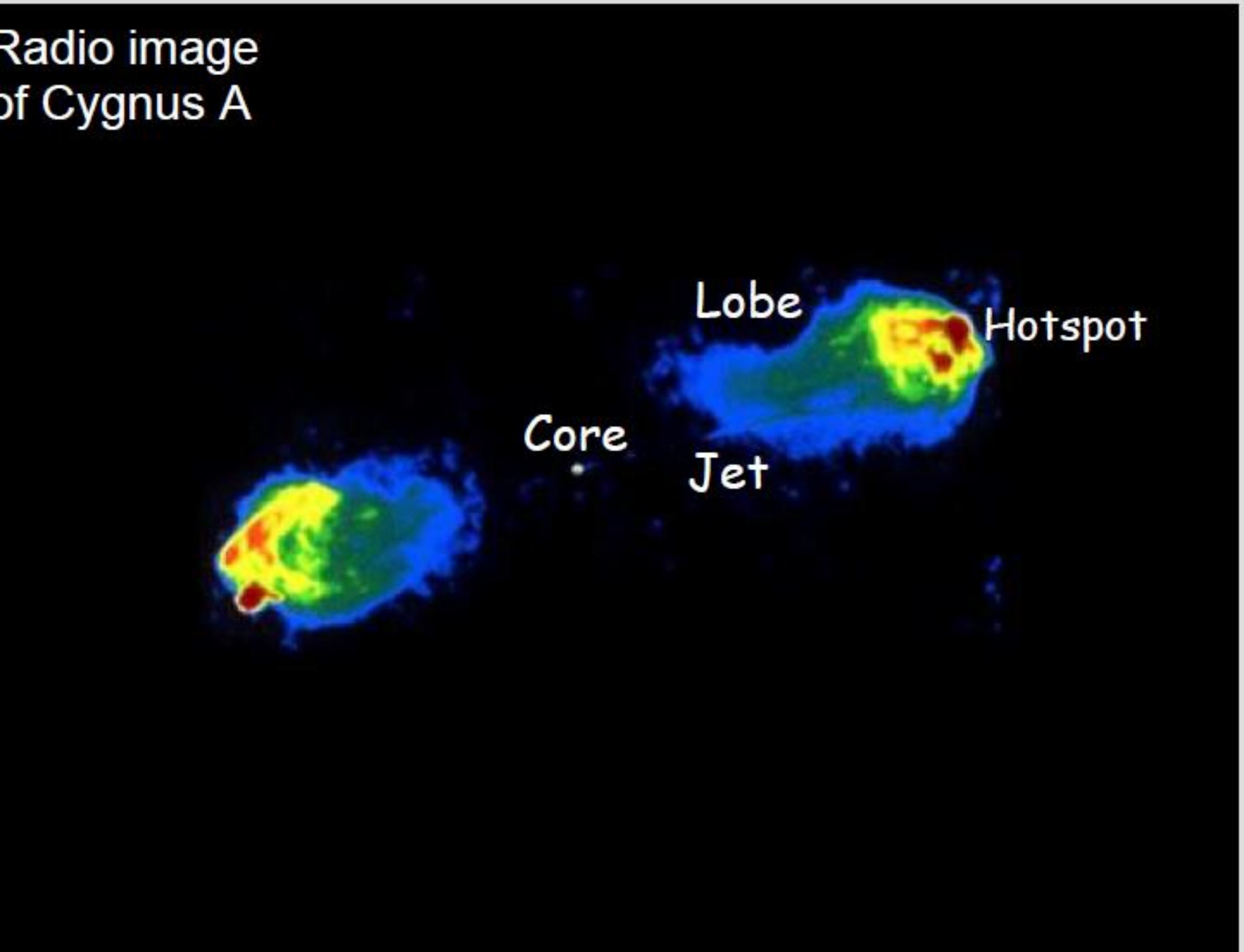


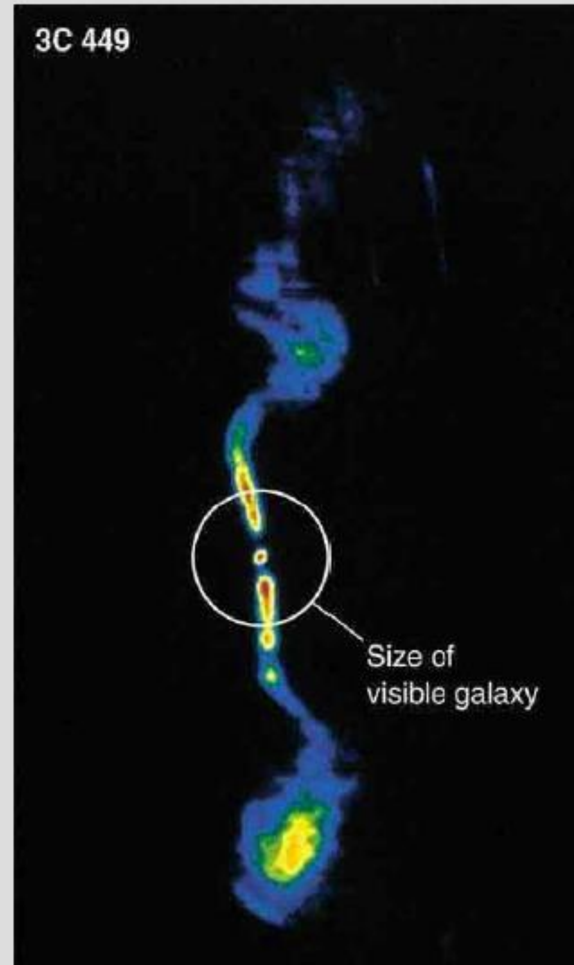
Quasars host-galaxies often show interactions

Some examples of radio-galaxies - 1

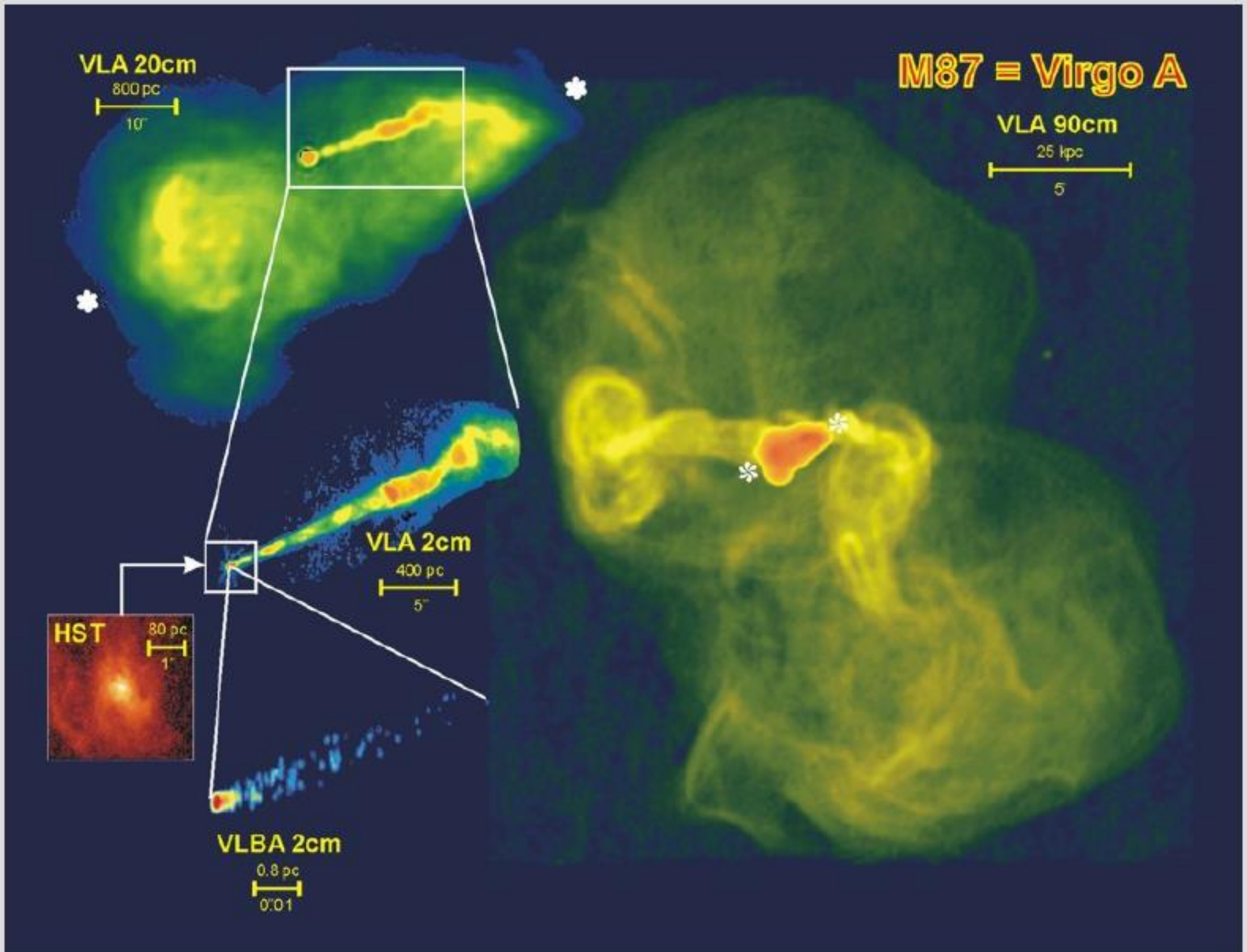


Some examples of radio-galaxies -2





Some examples of radio-galaxies -3



Classes of Radio-Galaxies

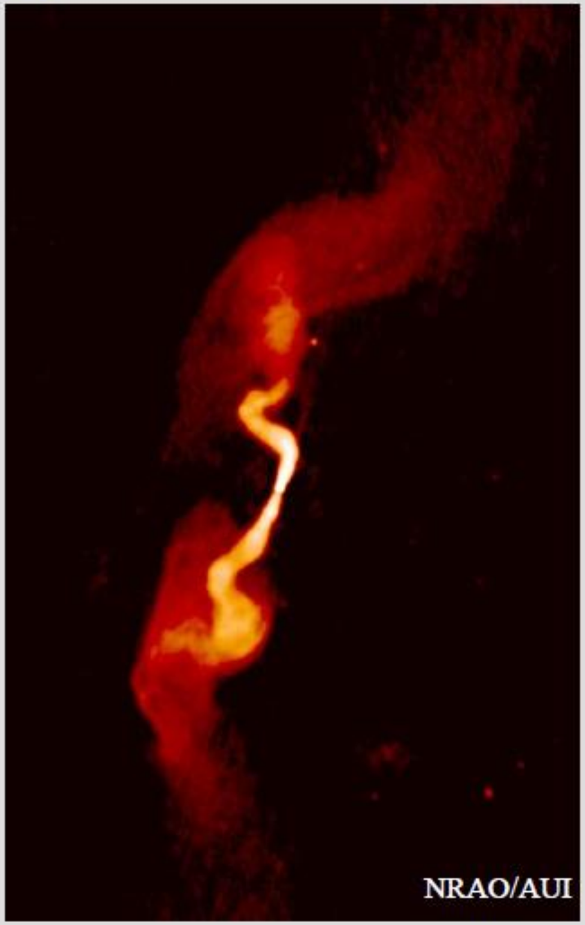
Large radio-galaxies with lobes can be divided in two types Fanaroff-Riley (1974):

- FR-I : Weaker radio sources that are bright in the center and fainter toward the edges
- FR-II : Limb-brightened (see images)

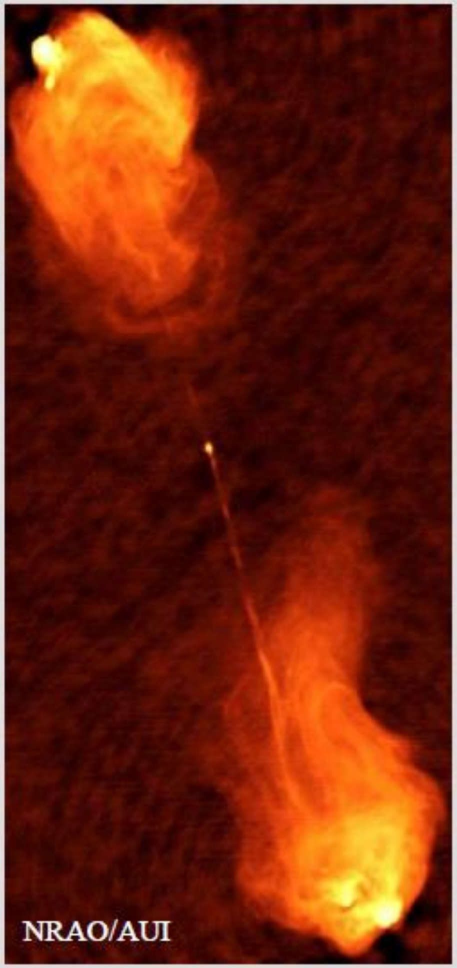
Transition around $L_{1.4GHz} = 10^{32}$ ergs/s/Hz

Classes of Radio-Galaxies

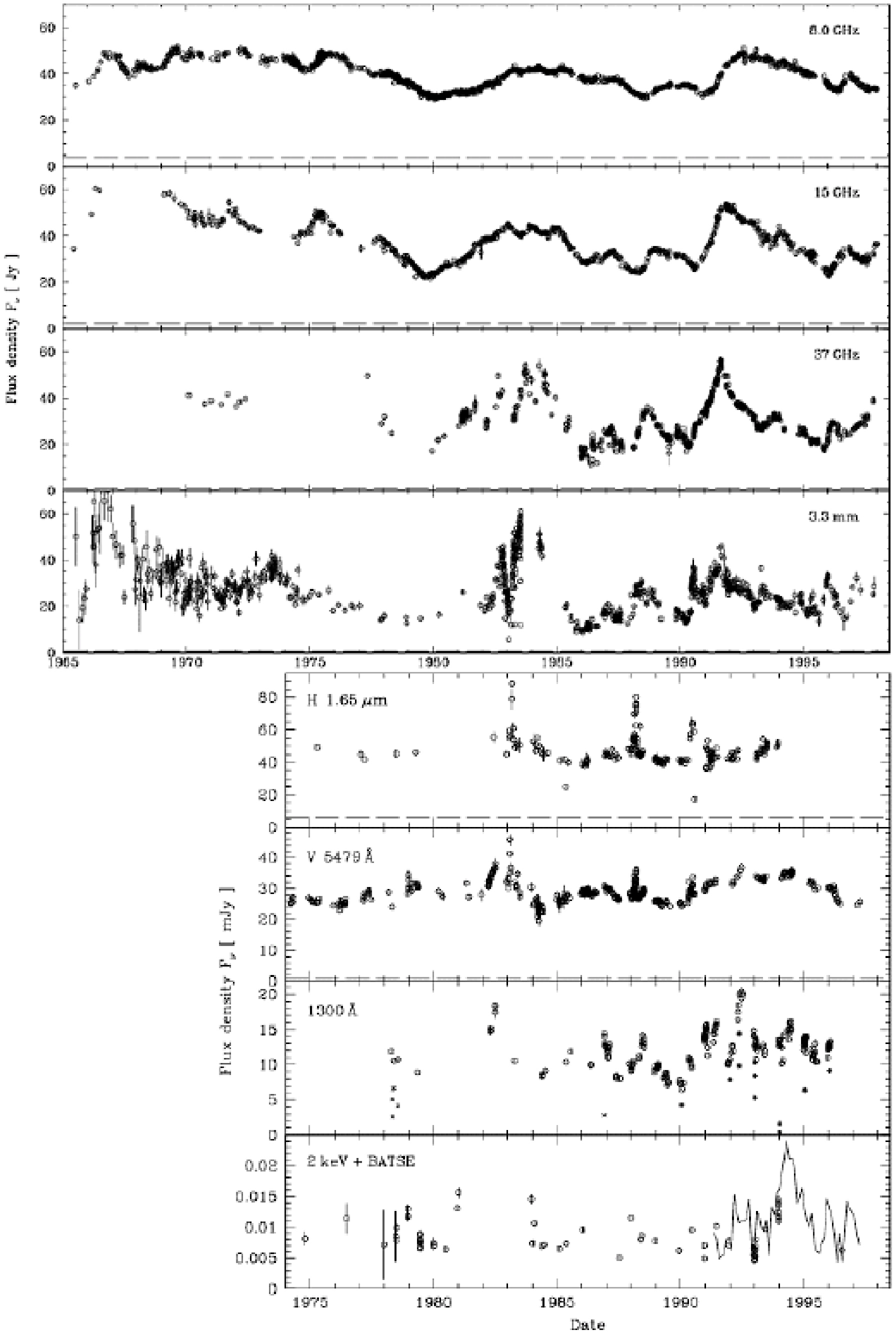
- FRI



- FRII



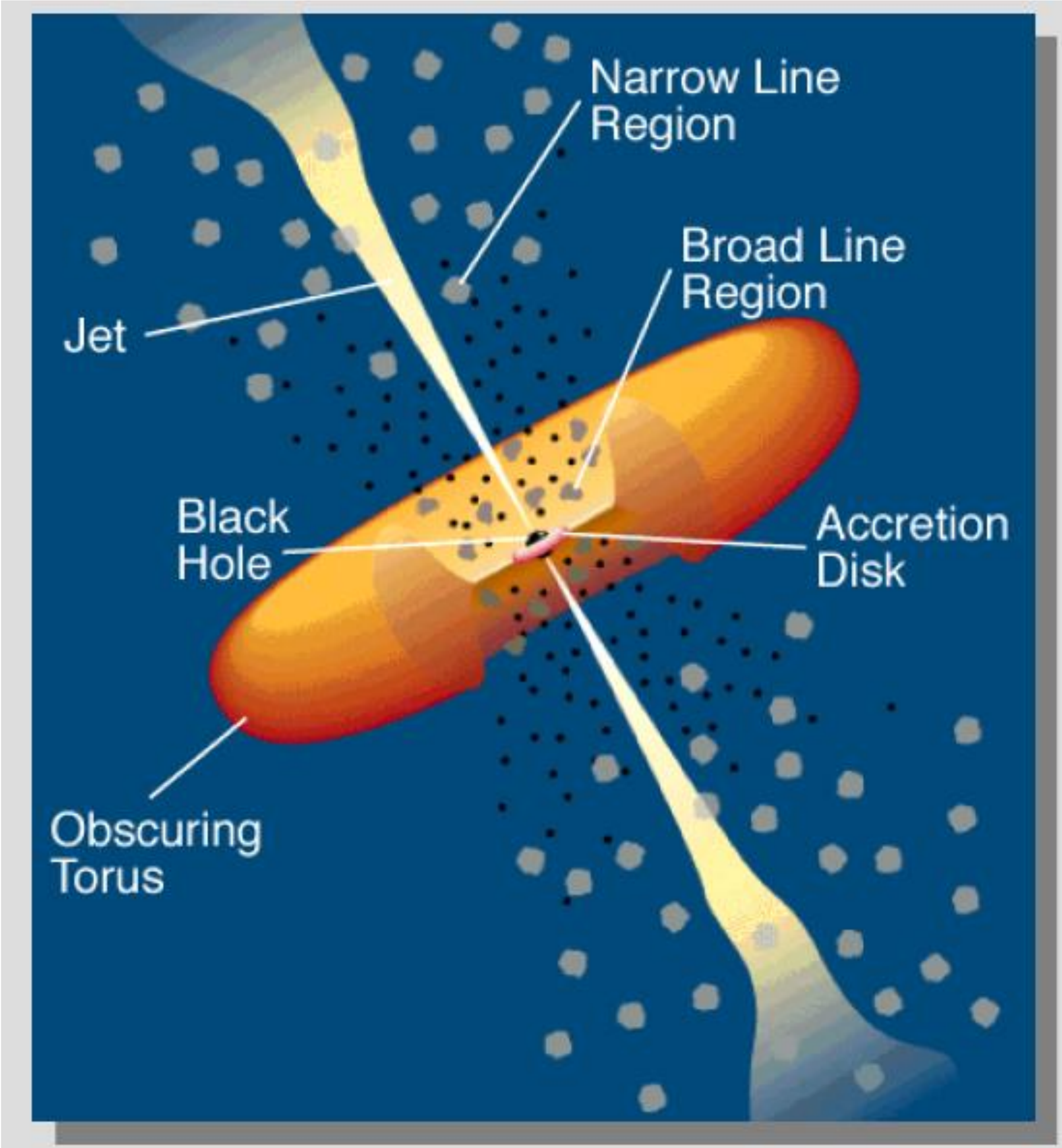
Quasar Variability



30 years of multi-wavelength observations of 3C273
Astron. Astrophys. Suppl. Ser. 134, 89-101
M. Türler et al. 1998 July 28 http://obswww.unige.ch/3c273/

- Quasars are variable in every waveband and emission lines
- Variability time-scale can be days to months
- Hence size of emission regions is light-days to light-months

- Seyfert Galaxies
- Quasars & QSOs
- BAL QSO
- BL Lacs/OVV -> Blazar
- LINERS
- Radio Galaxies
  - FRI
  - FRII


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

Measuring Central Black-Hole Masses

- Virial mass measurements based on motions of stars and gas in nucleus.
  - Stars
    - Advantage: gravitational forces only
    - Disadvantage: requires high spatial resolution
      - larger distance from nucleus $\Rightarrow$ less critical test
  - Gas
    - Advantage: can be observed very close to nucleus, high spatial resolution not necessarily required
    - Disadvantage: possible role of non-gravitational forces (radiation pressure)

Direct vs. Indirect Methods

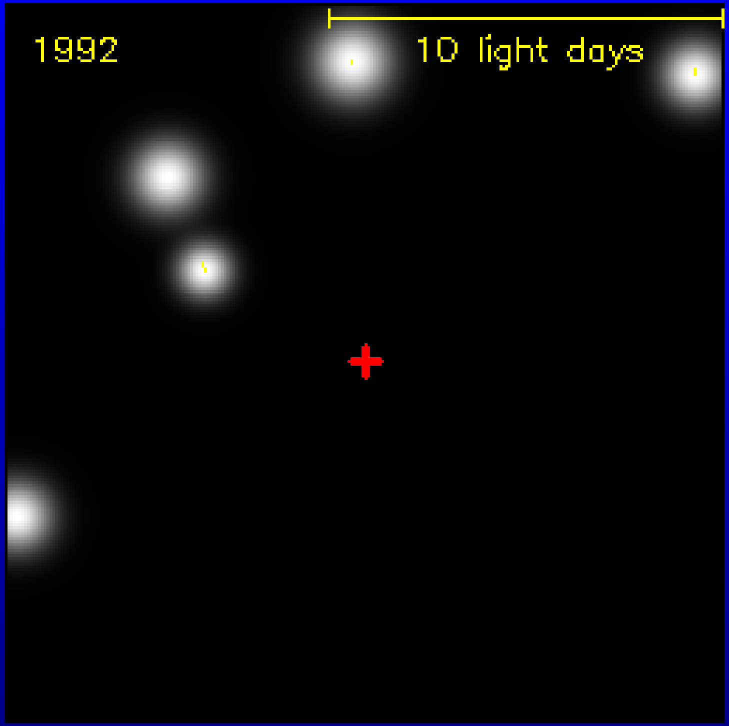
- *<u>Direct methods</u>* are based on dynamics of gas or stars accelerated by the central black hole.
  - Stellar dynamics, gas dynamics, reverberation mapping
- *<u>Indirect methods</u>* are based on observables correlated with the mass of the central black hole.
  - M_{BH}–σ_* and M_{BH}–L_{bulge} relationships, fundamental plane, AGN scaling relationships (R_{BLR}–L)

"Primary", "Secondary", and "Tertiary" Methods

- Depends on model-dependent assumptions required.
- Fewer assumptions, little model dependence:
  - Proper motions/radial velocities of stars and megamasers (Sgr A*, NGC 4258)
- More assumptions, more model dependence:
  - Stellar dynamics, gas dynamics, reverberation mapping
    - Since the reverberation mass scale currently depends on other "primary direct" methods for a zero point, it is technically a "secondary method" though it is a "direct method."

The Center of the Milky Way

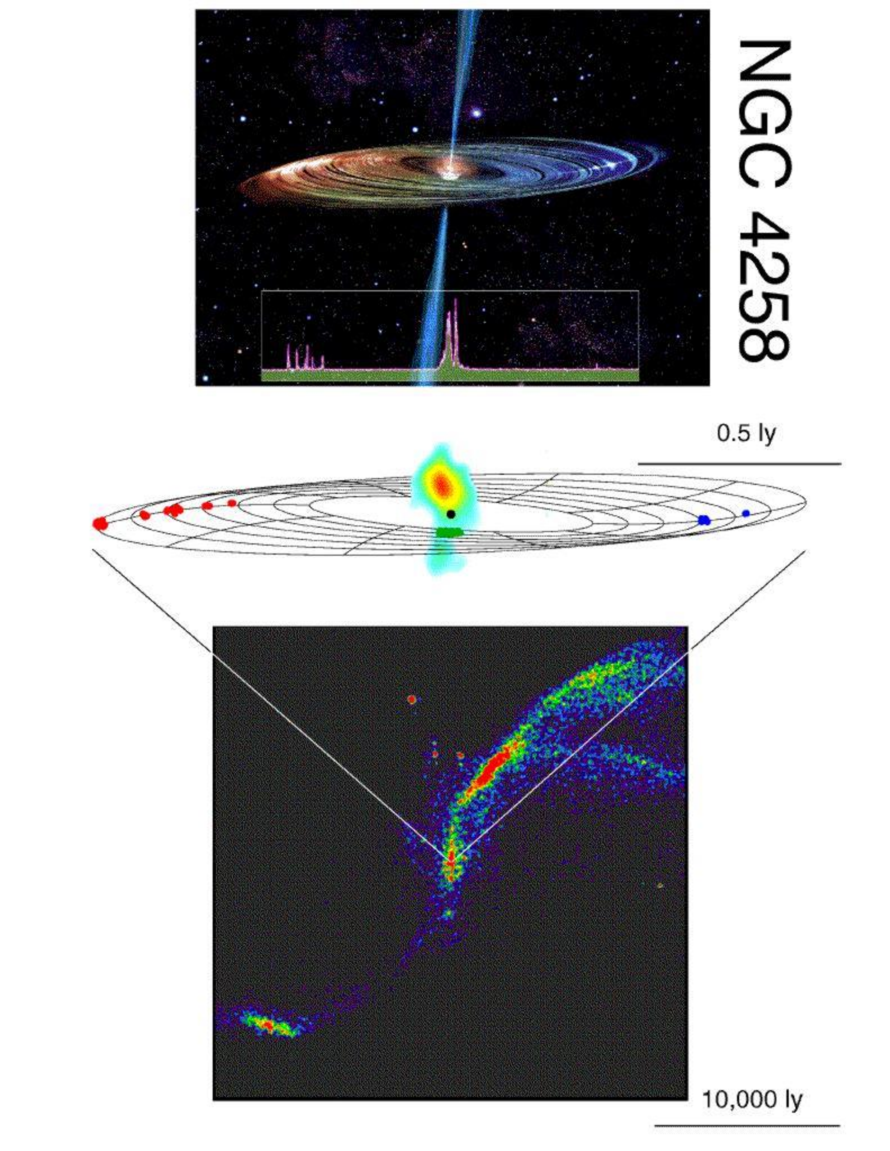
- Infrared observations of stars suggested a dark massive object.
  - Mid-80s: radial velocities
  - 90s: add proper motions
  - Sgr A* BH mass of $3.6 \times 10^6\ M_\odot$.



Genzel group at MPE Garching
Ghez group at UCLA

Observing Supermassive Black Holes

- The first reliable measurement of a supermassive black hole mass in an AGN **Miyoshi et al. (1995)**
- Detection of H_20 maser sources orbiting a BH of mass 3.78 $\times 10^7 M_\odot$.
  - Requires special geometry, so only a handful of BH masses measured this way.



MCG-6-30-15: Kα Fe line

- X-ray spectroscopy in Seyferts has revealed highly broadened iron Kα lines on the order of 10^4 km/s
- Future X-ray observations will give better estimate on mass of central object
- Greene et al. derived a mass of about $5 \times 10^6 M_{sun}$

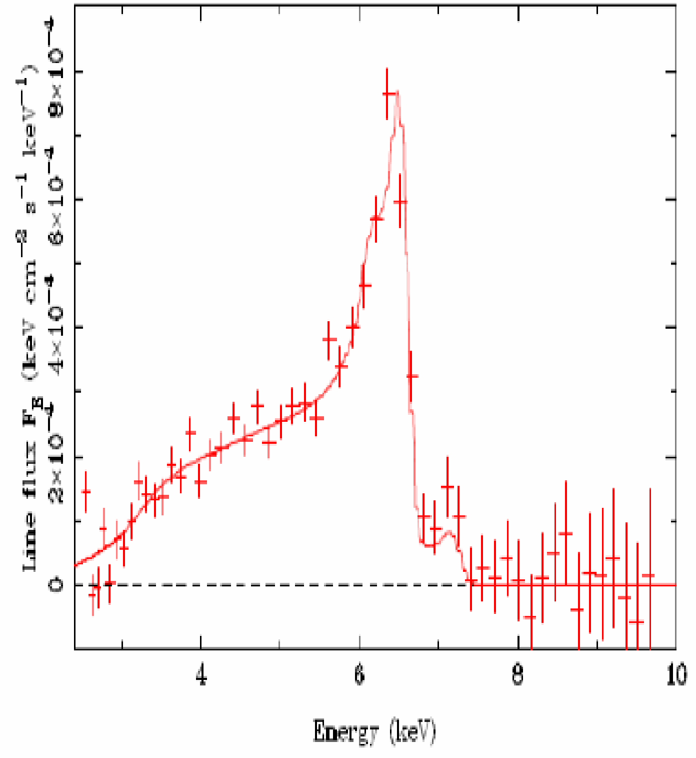


Figure 5. Continuum subtracted relativistic iron line profile from an XMM-Newton observation of MCG-6-30-15 (Taken from Fabian *et al.* 2002).

Virial Estimators for AGNs

Source	Distance from central source
X-Ray Fe Kα	3-10 R_S
Broad-Line Region	200–10^4 R_S
Megamasers	4×10^4 R_S
Gas Dynamics	8×10^5 R_S
Stellar Dynamics	10^6 R_S

In units of the Schwarzschild radius $R_S = 2GM/c^2 = 3 \times 10^{13}\, M_8$ cm .

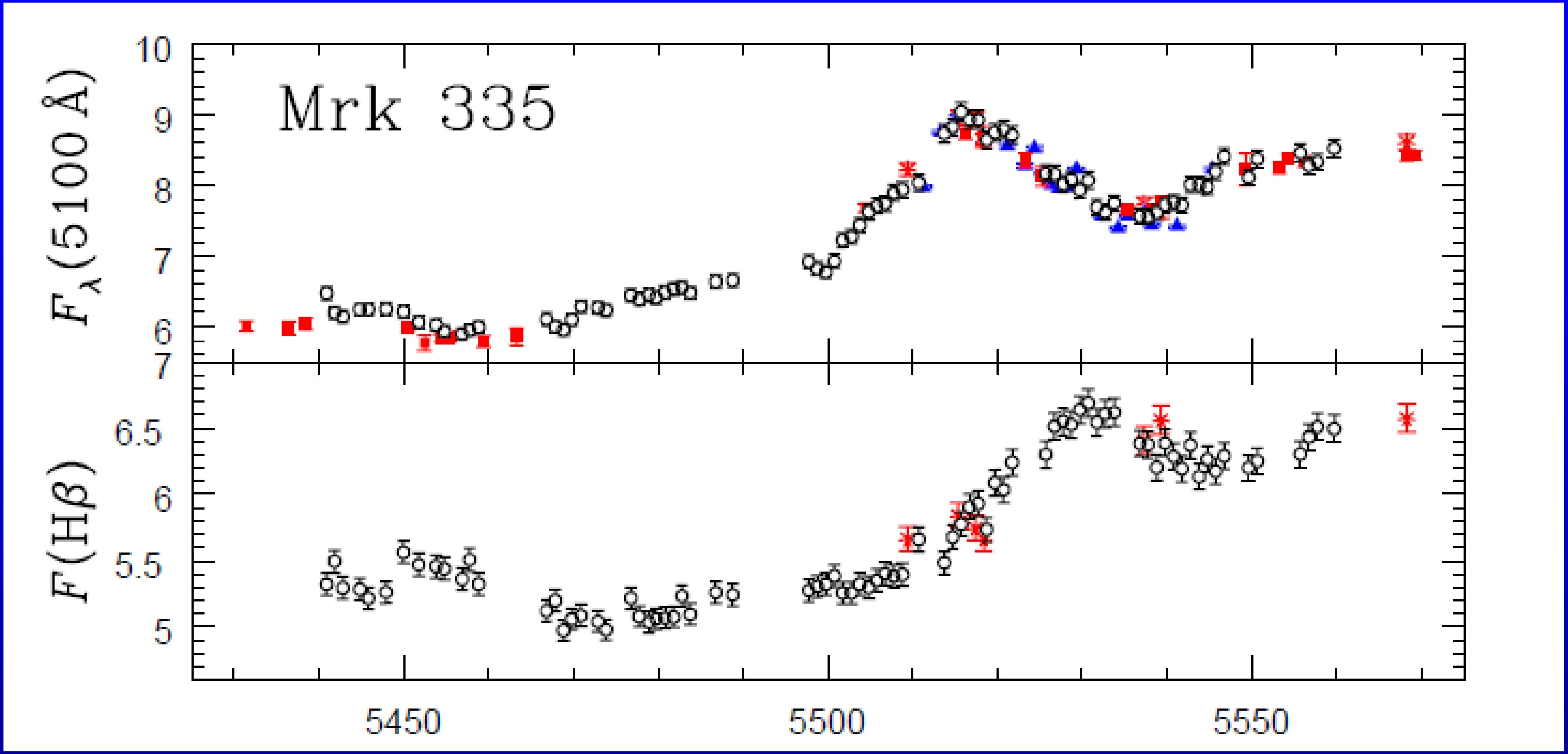
Mass estimates from the virial theorem:

$$M = f\,(r\,\Delta V^{2}/G)$$

where

- r = scale length of region
- ΔV = velocity dispersion
- f = a factor of order unity, depends on details of geometry and kinematics

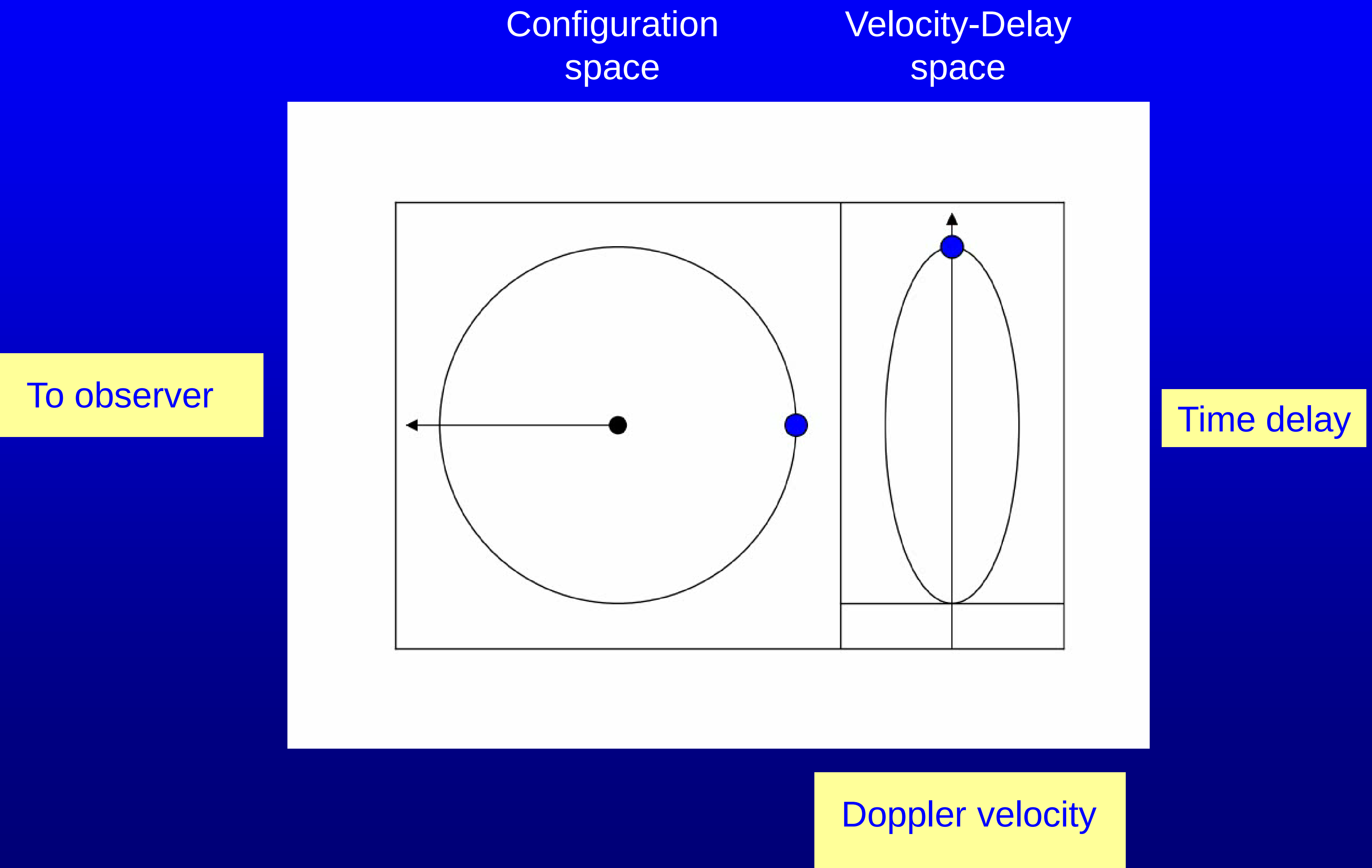
Reverberation Mapping



Emission line variations follow those in continuum with a small time delay (14 days here) due to light-travel time across the line emitting region.

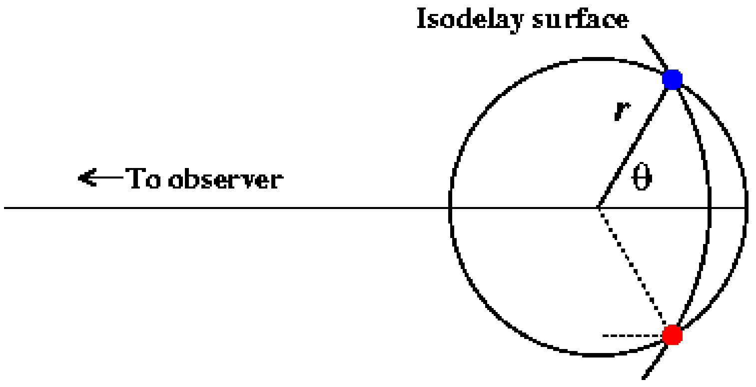
Grier et al. 2012a, ApJ, 744, L4

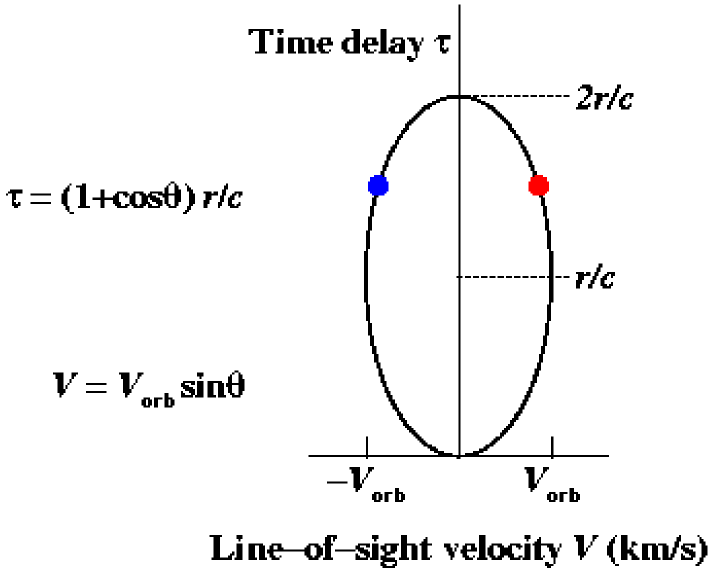
Velocity-Delay Map



Velocity-Delay Map for an Edge-On Ring

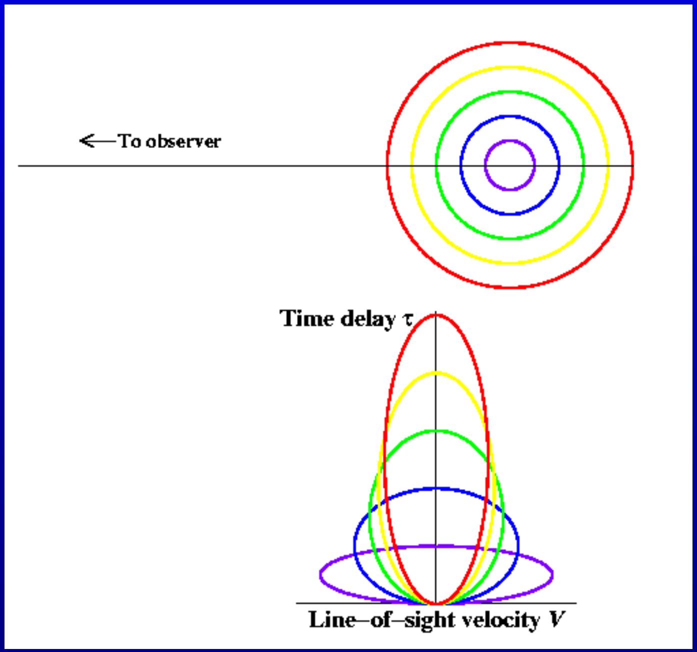
- Clouds at intersection of isodelay surface and orbit have line-of-sight velocities $V = \pm V_{orb} \sin\theta$.
- Response time is $\tau = (1 + \cos\theta) r/c$
- Circular orbit projects to an ellipse in the (V, τ) plane.



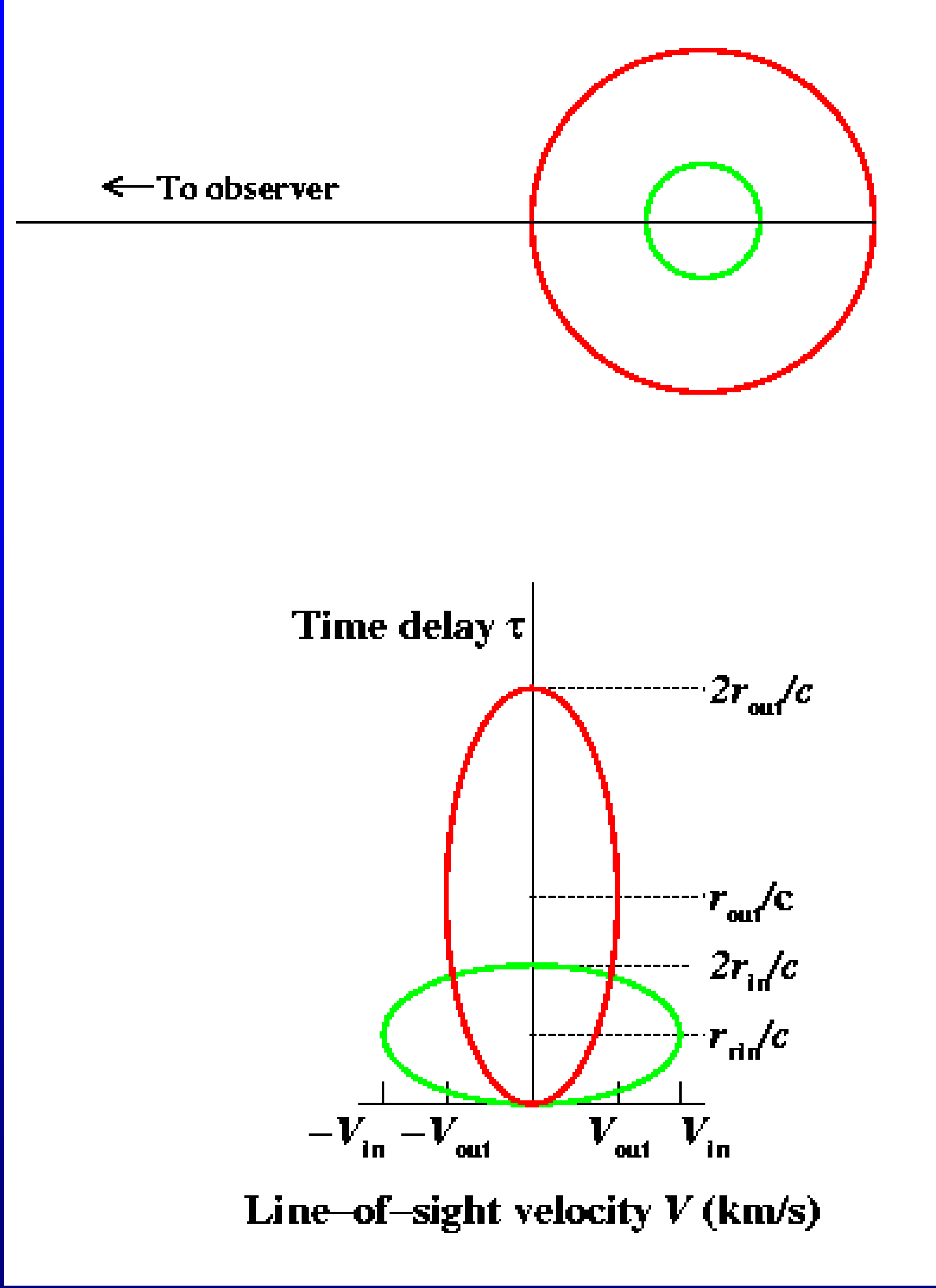


Thick Geometries

- Generalization to a disk or thick shell is trivial.
- General result is illustrated with simple two ring system.

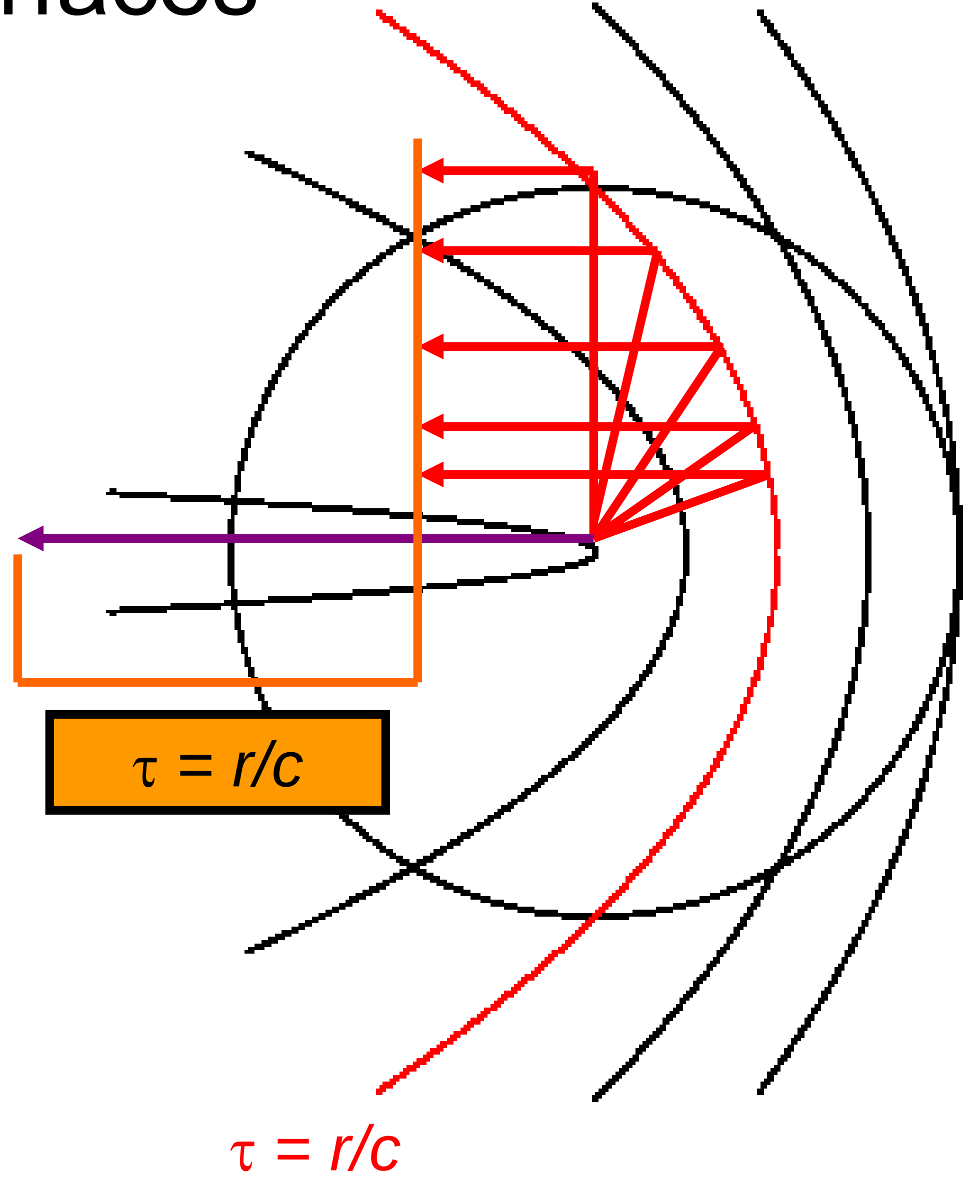


A multiple-ring system

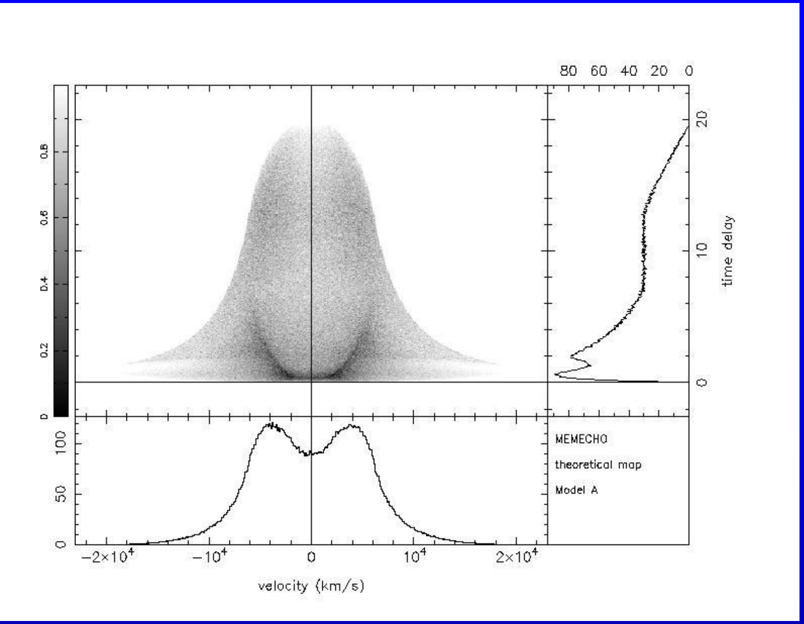


“Isodelay Surfaces”

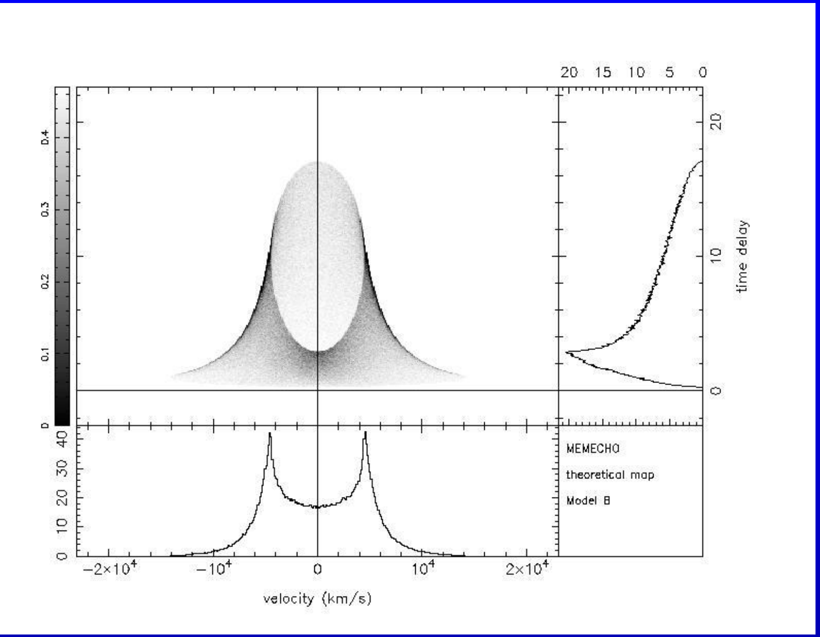
All points on an “isodelay surface” have the same extra light-travel time to the observer, relative to photons from the continuum source.



Two Simple Velocity-Delay Maps



Inclined Keplerian disk

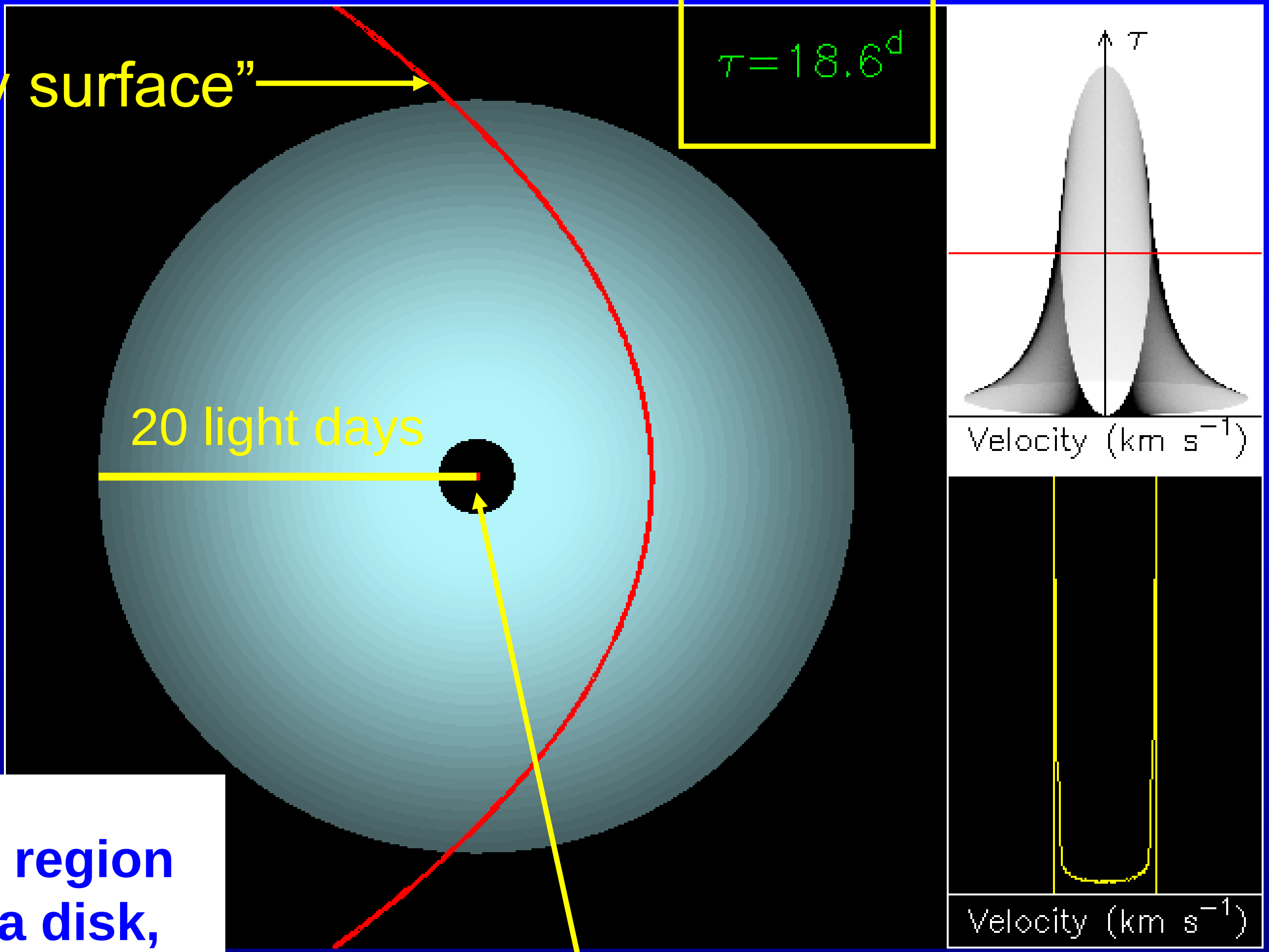


Randomly inclined circular Keplerian orbits

The profiles and velocity-delay maps are superficially similar, but can be distinguished from one other and from other forms.

Time after continuum outburst

“Isodelay surface”



Time delay

Broad-line region as a disk, 2–20 light days

Black hole/accretion disk

Line profile at current time delay

Reverberation Response of an Emission Line to a Variable Continuum

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

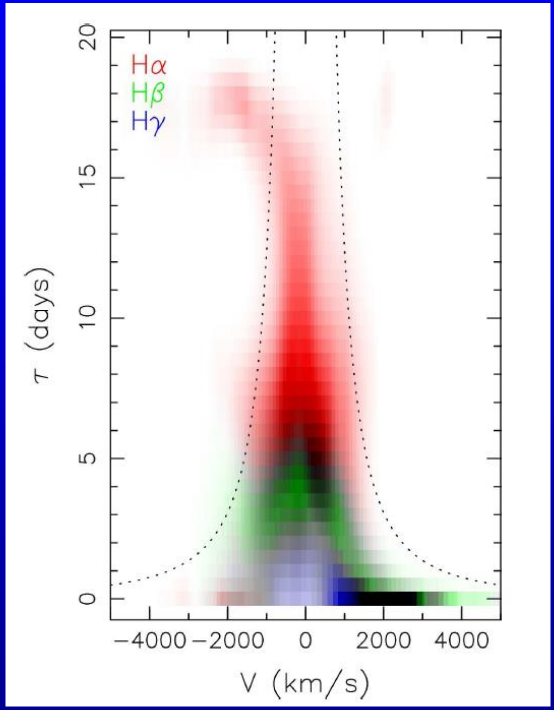
$$L(V,t) = \int \Psi(V,\tau)\, C(t-\tau)\, d\tau$$

Velocity-resolved emission-line light curve

"Velocity-delay map"

Continuum light curve

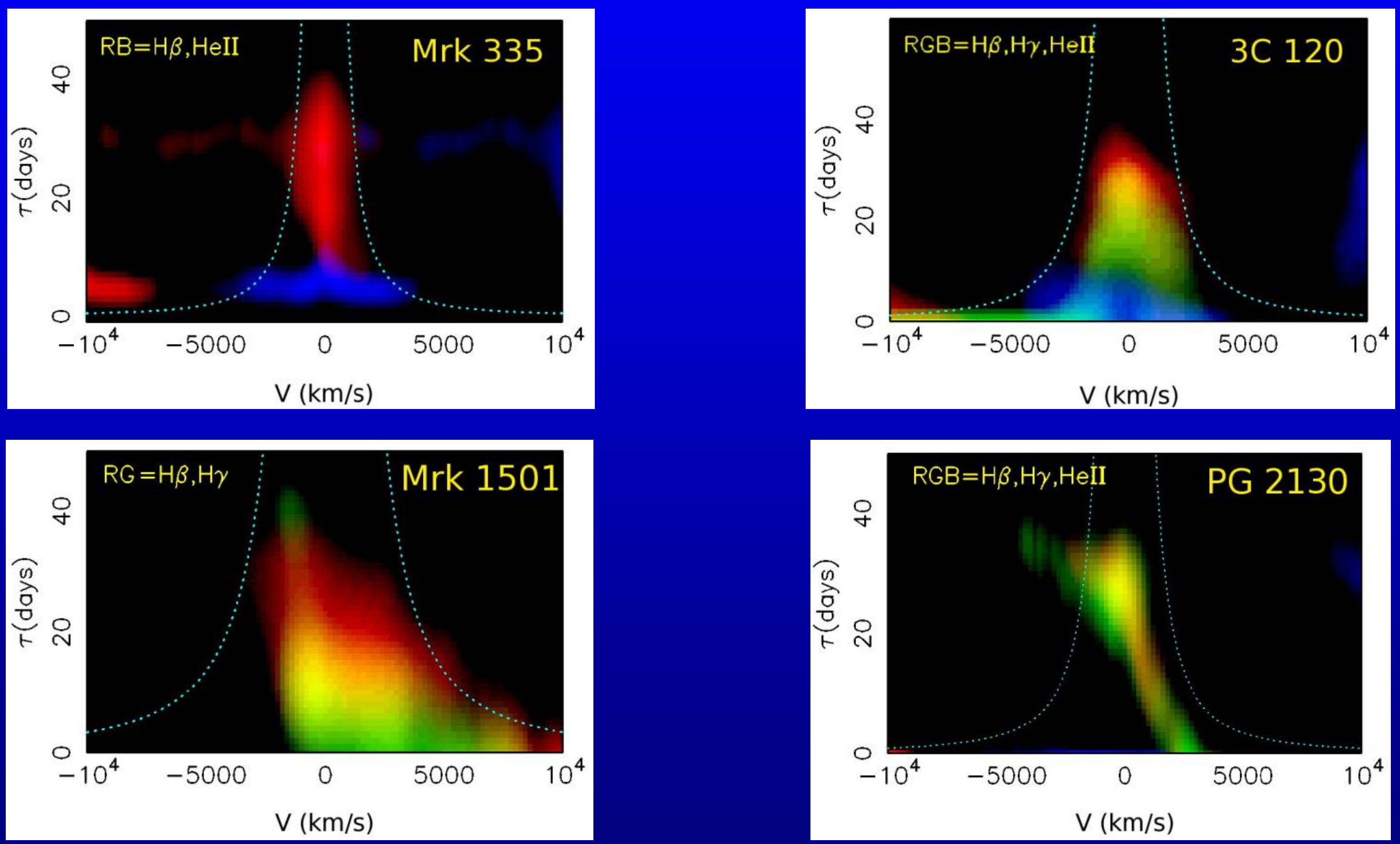
Velocity-delay map is observed line response to a δ-function outburst



Arp 151

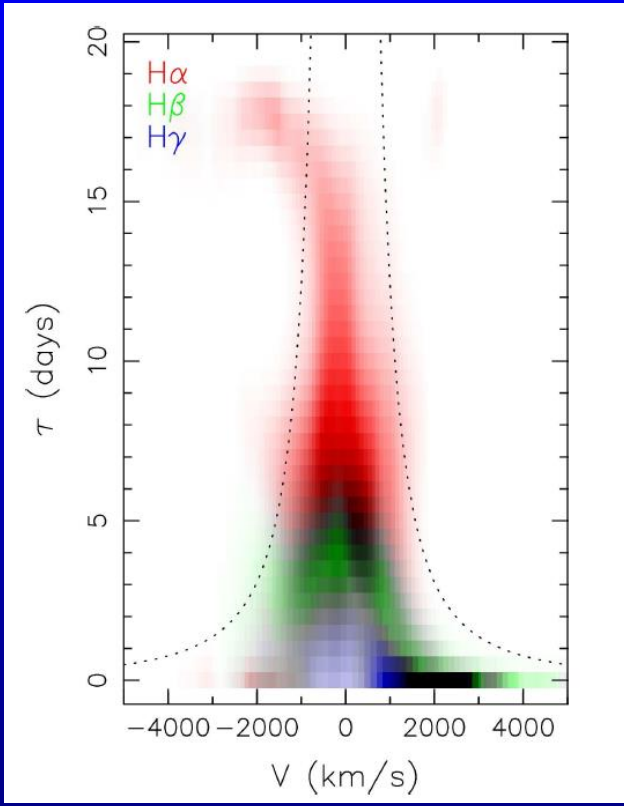
LAMP: Bentz et al. 2010

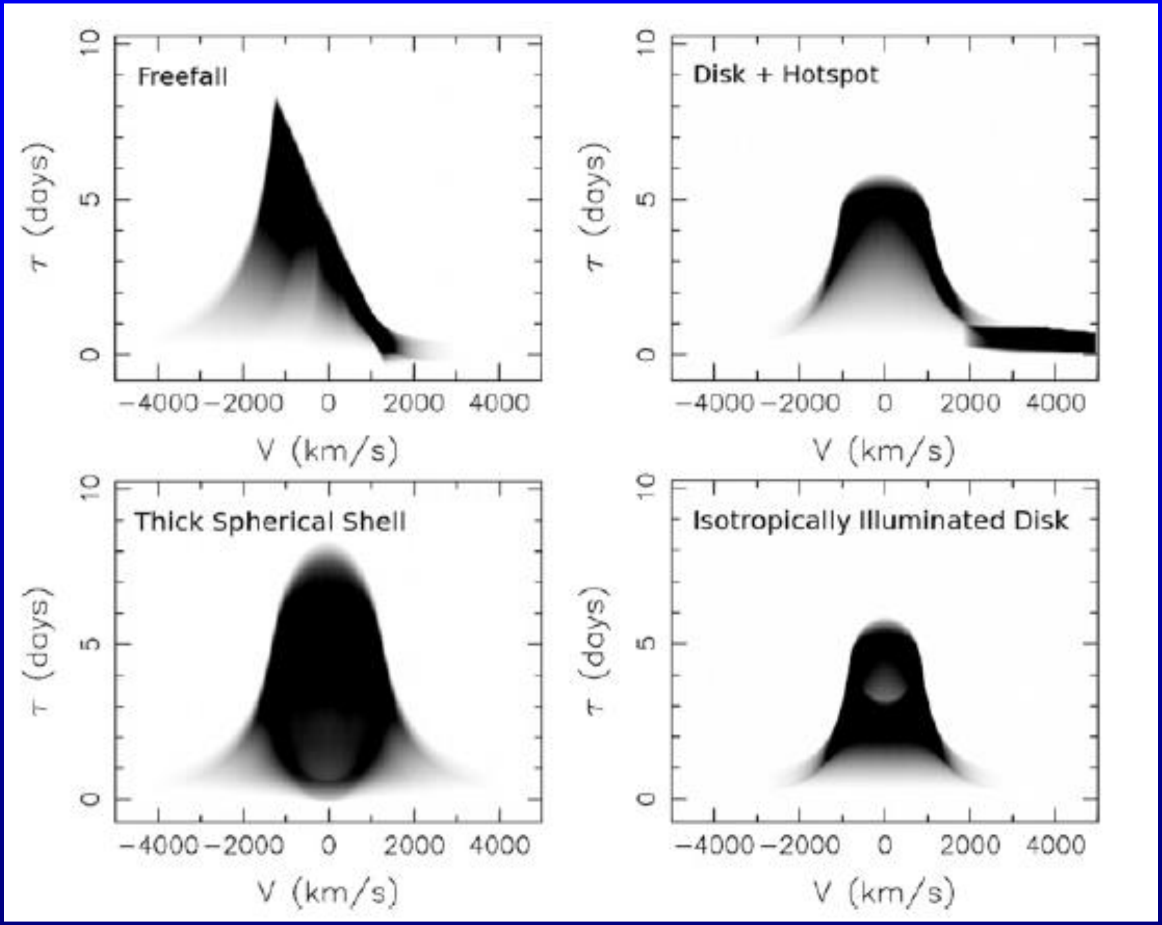
Optical Velocity Delay Maps Show Infall in Balmer Lines

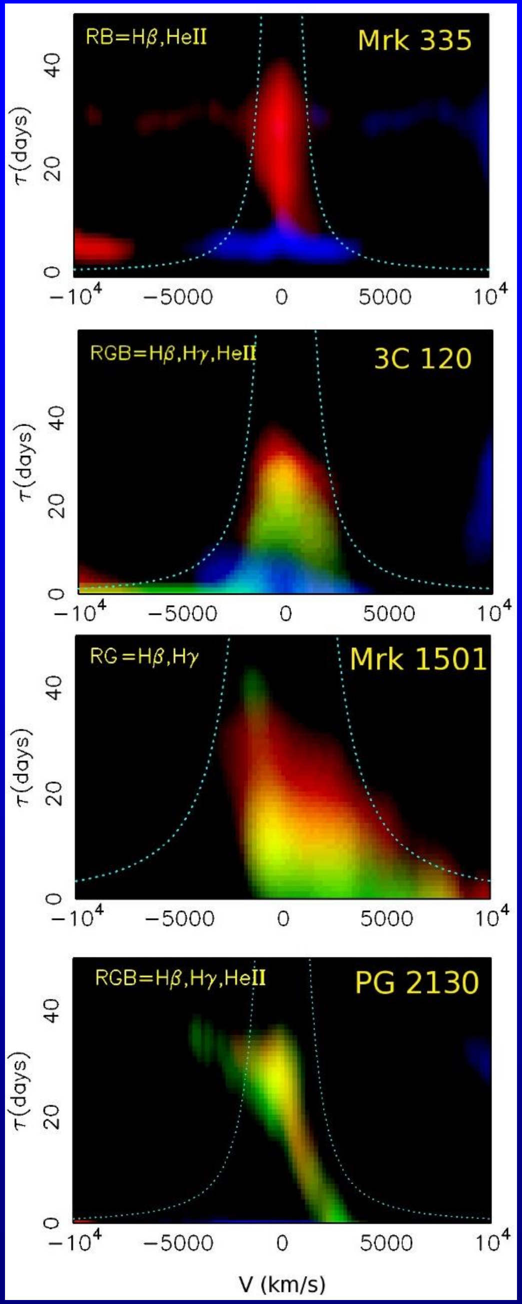


Grier et al. 2012c, submitted to ApJ

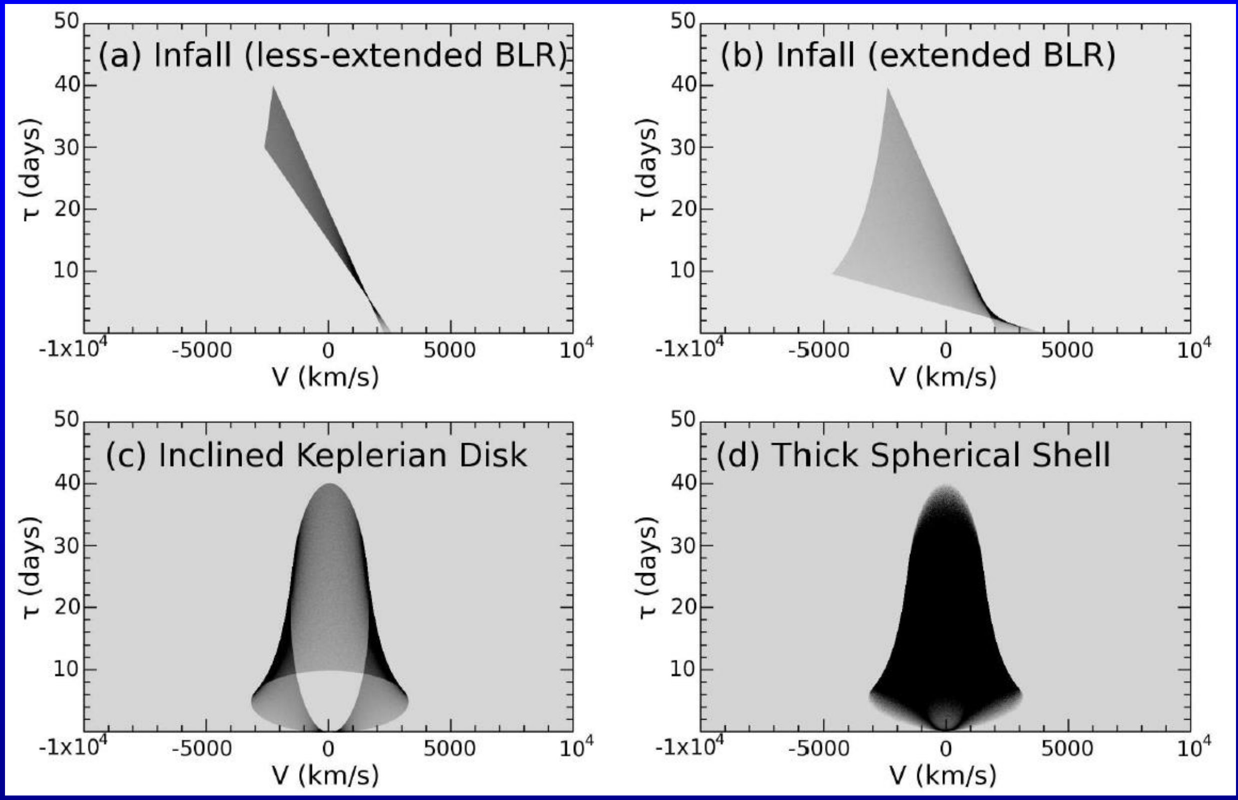
A Complex Multicomponent Broad-Line Region?







Toy Models

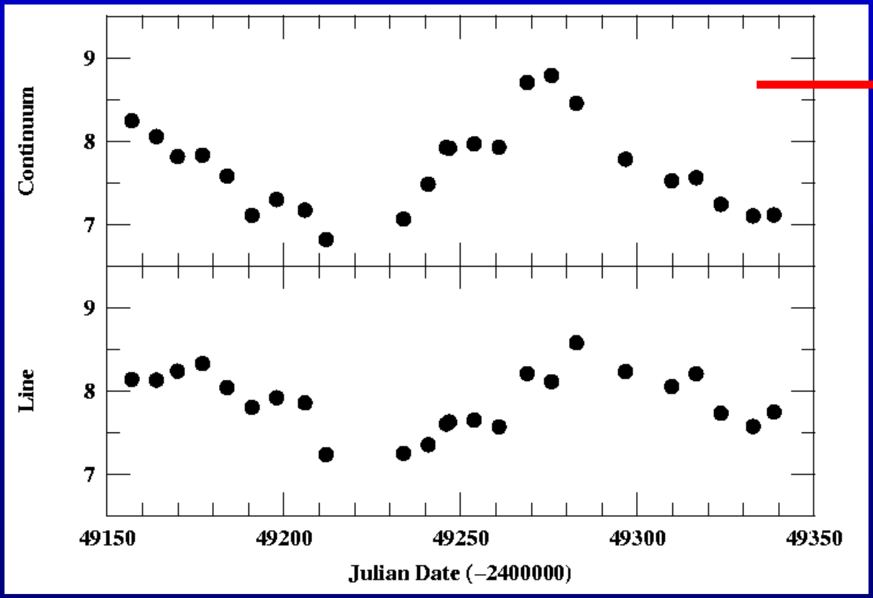


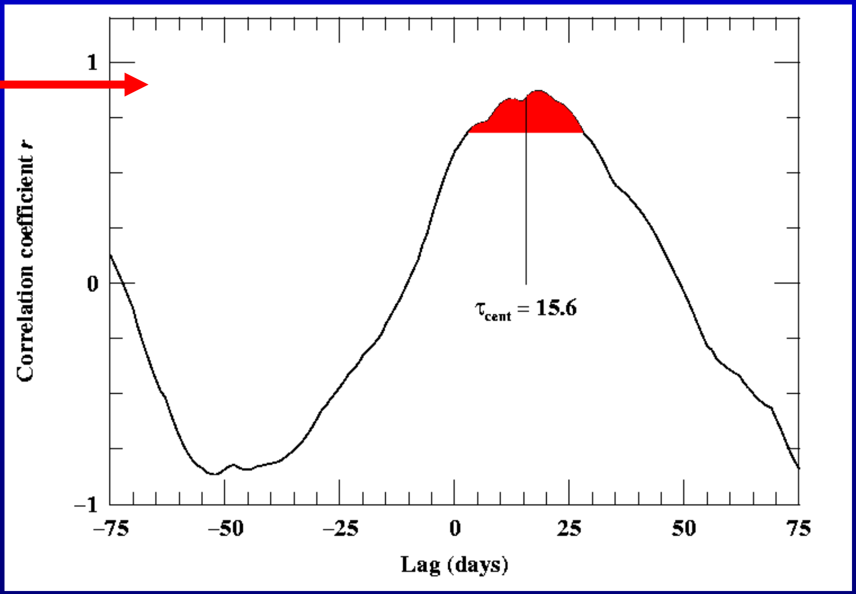
Grier et al. 2012c, submitted

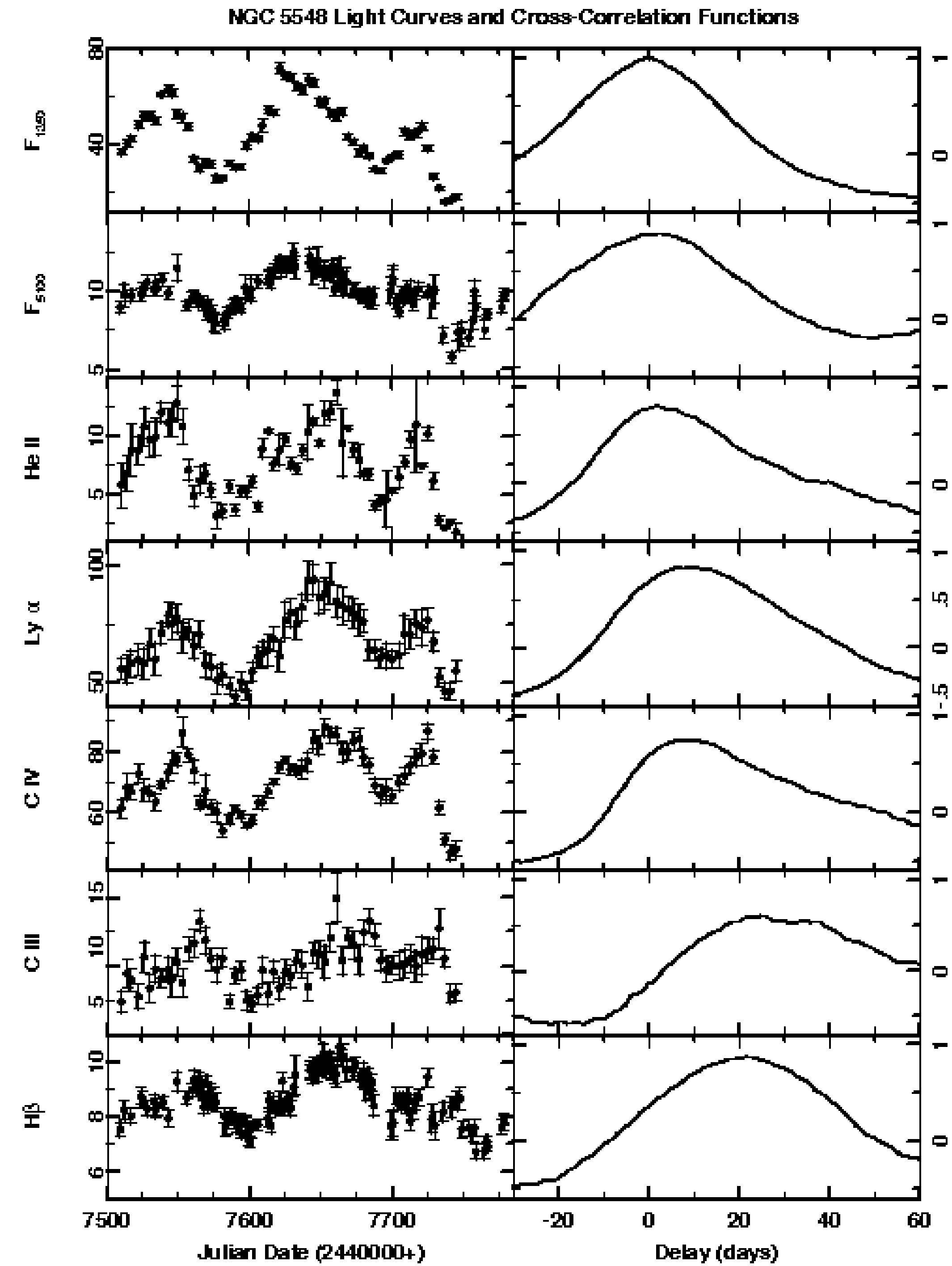
Emission-Line Lags

- Because the data requirements are *relatively* modest, it is most common to determine the cross-correlation function and obtain the "lag" (mean response time):

$$\mathrm{CCF}(\tau) = \int \Psi(\tau')\ \mathrm{ACF}(\tau - \tau')\, d\tau'$$



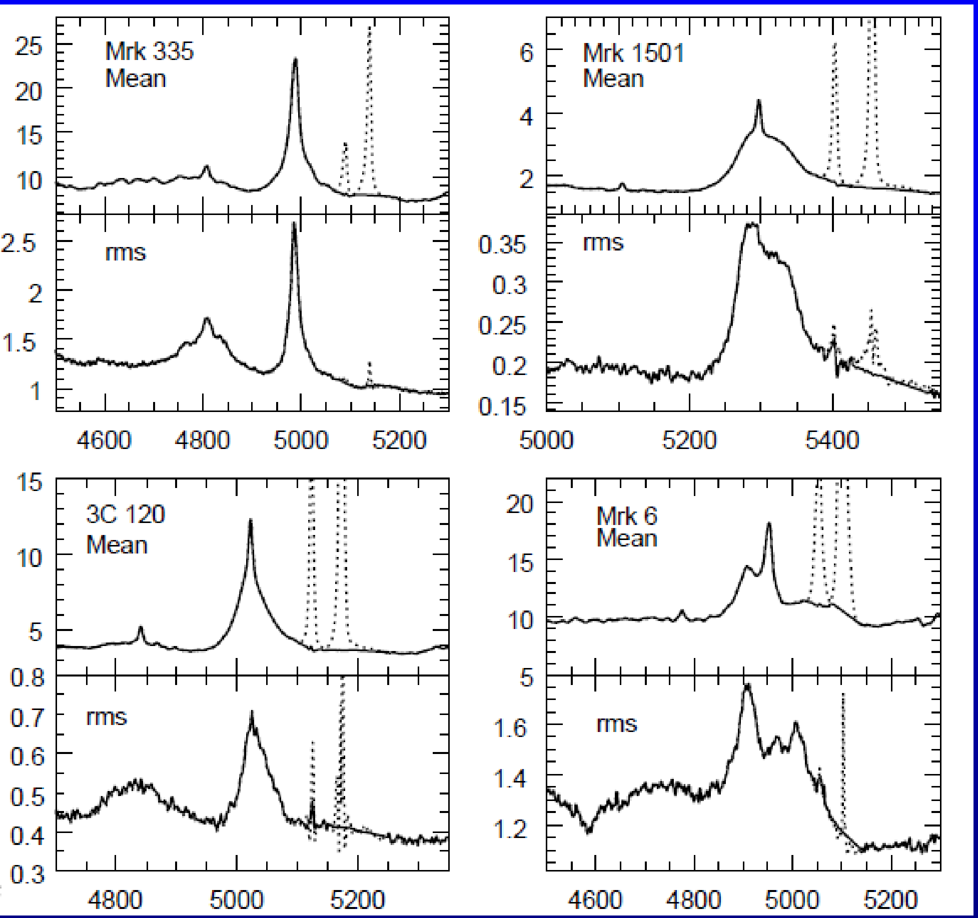




Reverberation Mapping Results

- Reverberation lags have been measured for nearly 50 AGNs, mostly for Hβ, but in some cases for multiple lines.
- AGNs with lags for multiple lines show that highest ionization emission lines respond most rapidly ⇒ ionization stratification

Measuring the Emission-Line Widths

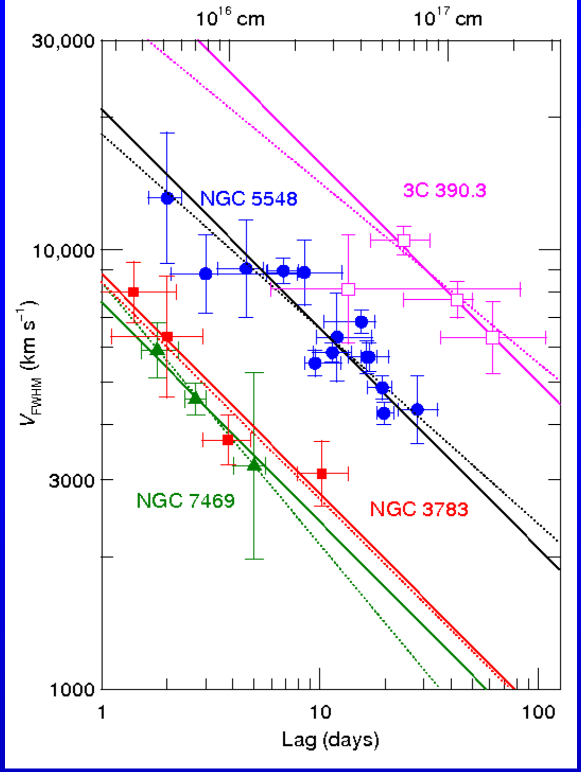


- We preferentially measure line widths in the rms residual spectrum.
  - Constant features disappear, less blending.
  - Captures the velocity dispersion of the gas that is responding to continuum variations.

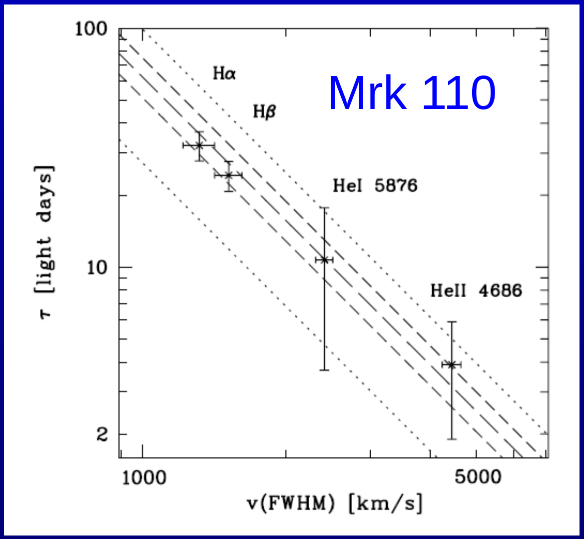
Grier et al. 2012b, ApJ, 755:60

A Virialized BLR

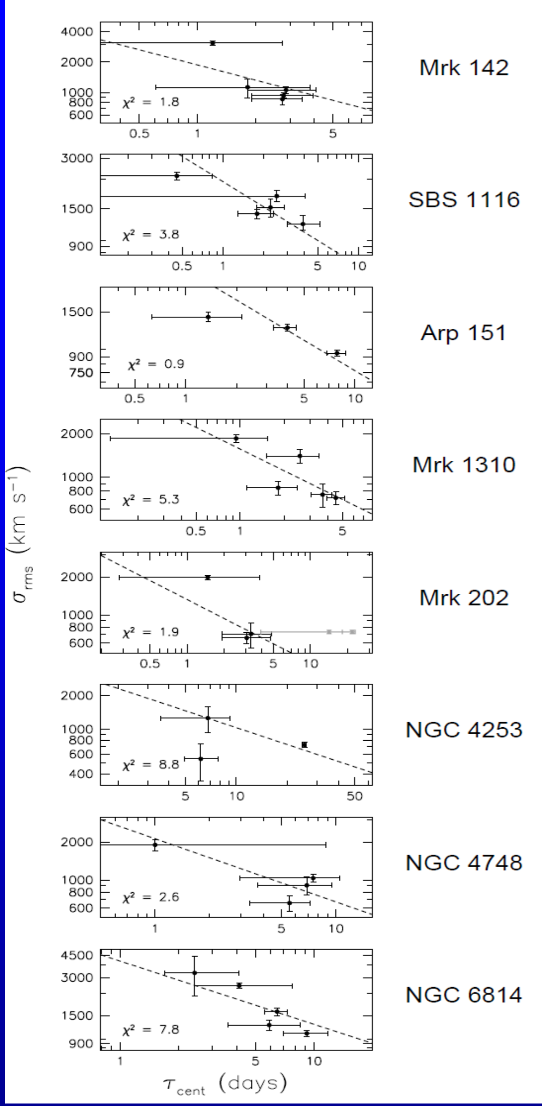
- $\Delta V \propto R^{-1/2}$ for every AGN in which it is testable.
- Suggests that gravity is the principal dynamical force in the BLR.
  - Caveat: radiation pressure!



Peterson & Wandel 2002



Kollatschny 2003



Bentz et al. 2009

Reverberation-Based Masses

"Virial Product" (units of mass)

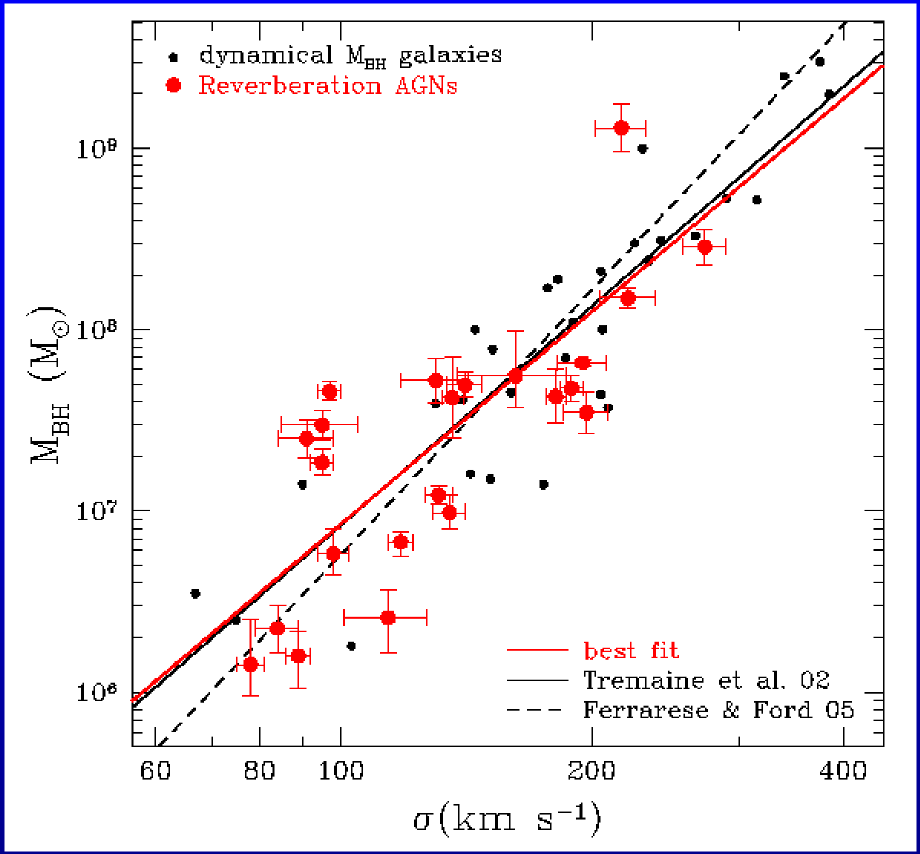
$$M_{BH} = f \; \boxed{\underline{r \, \Delta V}^2 / G}$$

Observables:
r = BLR radius (reverberation)
ΔV = Emission-line width

Set by geometry and inclination
(subsumes everything we don't know)

If we have independent measures of M_{BH}, we can compute an ensemble average $\langle f \rangle$

The AGN M_{BH}–σ_* Relationship



Woo et al. 2010

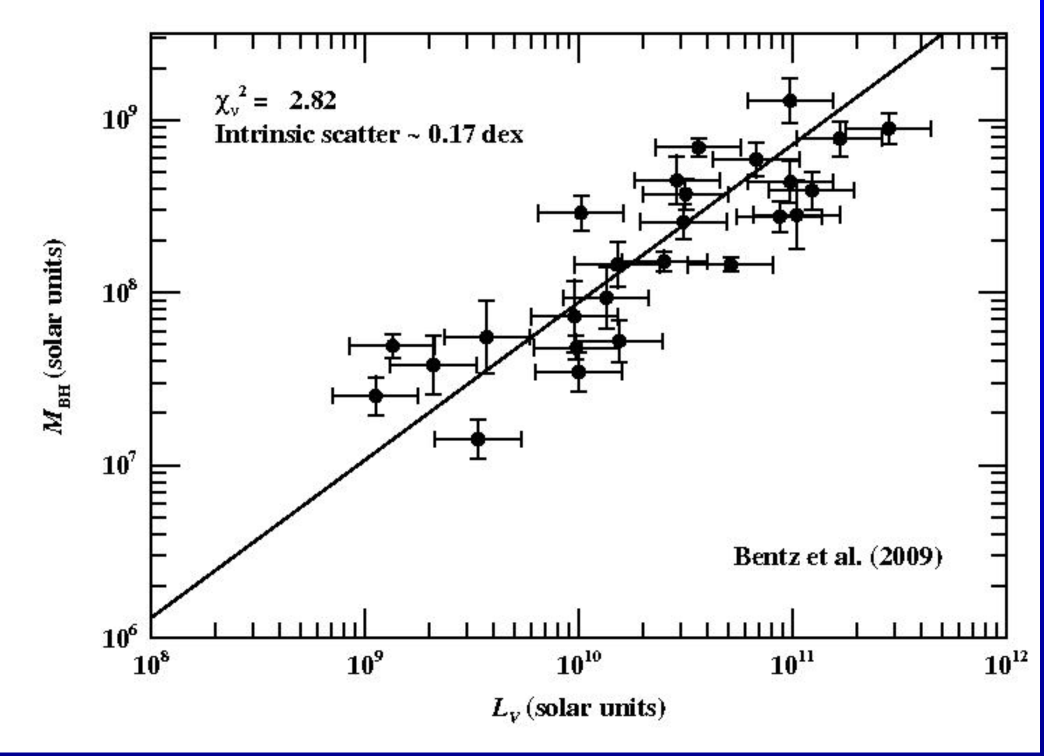
- Assume slope and zero point of most recent quiescent galaxy calibration.

  $\langle f \rangle = 5.25 \pm 1.21$

  Woo et al. 2010

- Maximum likelihood places an upper limit on intrinsic scatter $\Delta \log M_{BH} \sim 0.40$ dex.
  - Consistent with quiescent galaxies.

The AGN M_{BH}–L_{bulge} Relationship



- Line shows best-fit to quiescent galaxies
- Maximum likelihood gives upper limit to intrinsic scatter $\Delta\log M_{BH}$ ~ 0.17 dex.
  - Smaller than quiescent galaxies ($\Delta\log M_{BH}$ ~ 0.38 dex).

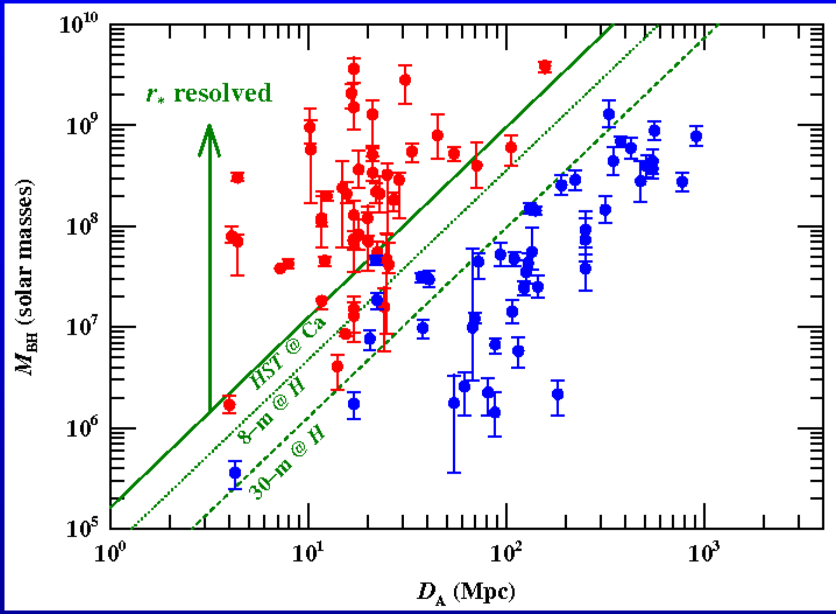
Black Hole Mass Measurements (units of $10^6 M_\odot$)

Galaxy	NGC 4258	NGC 3227	NGC 4151
Direct methods:			
Megamasers	38.2 ± 0.1	N/A	N/A
Stellar dynamics	33 ± 2	7–20	< 70
Gas dynamics	25 – 260	20^{+10}_{-4}	$30^{+7.5}_{-22}$
Reverberation	N/A	7.63 ± 1.7	46 ± 5
Quoted uncertainties are statistical only, not systematic.			

References: see Peterson (2010) [arXiv:1001.3675]

Masses of Black Holes in AGNs

- Stellar and gas dynamics requires higher angular resolution to proceed further.
  - Even a 30-m telescope will not vastly expand the number of AGNs with a resolvable r_*.
- Reverberation is the future path for direct AGN black hole masses.
  - Trade time resolution for angular resolution.
  - Downside: resource intensive.
- To significantly increase number of measured masses, we need to go to secondary methods.



BLR Scaling with Luminosity

- To first order, AGN spectra look the same

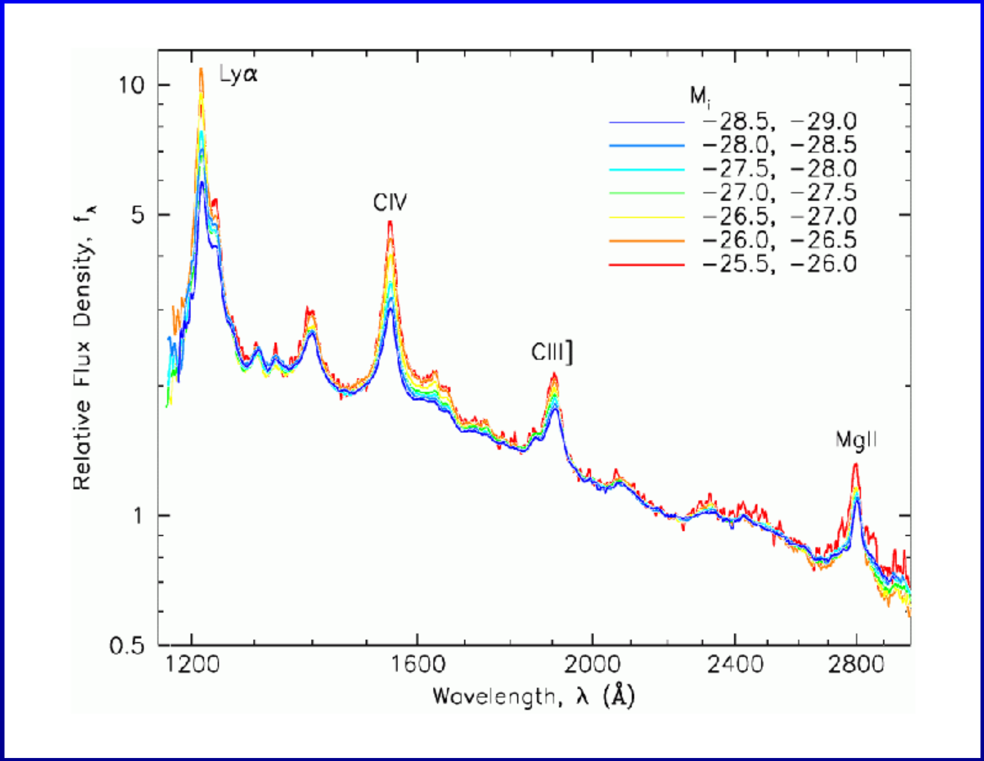
$$U = \frac{Q(\mathrm{H})}{4\pi r^2 n_{\mathrm{H}} c} \propto \frac{L}{n_{\mathrm{H}} r^2}$$

? Same ionization parameter U

? Same density n_{H}

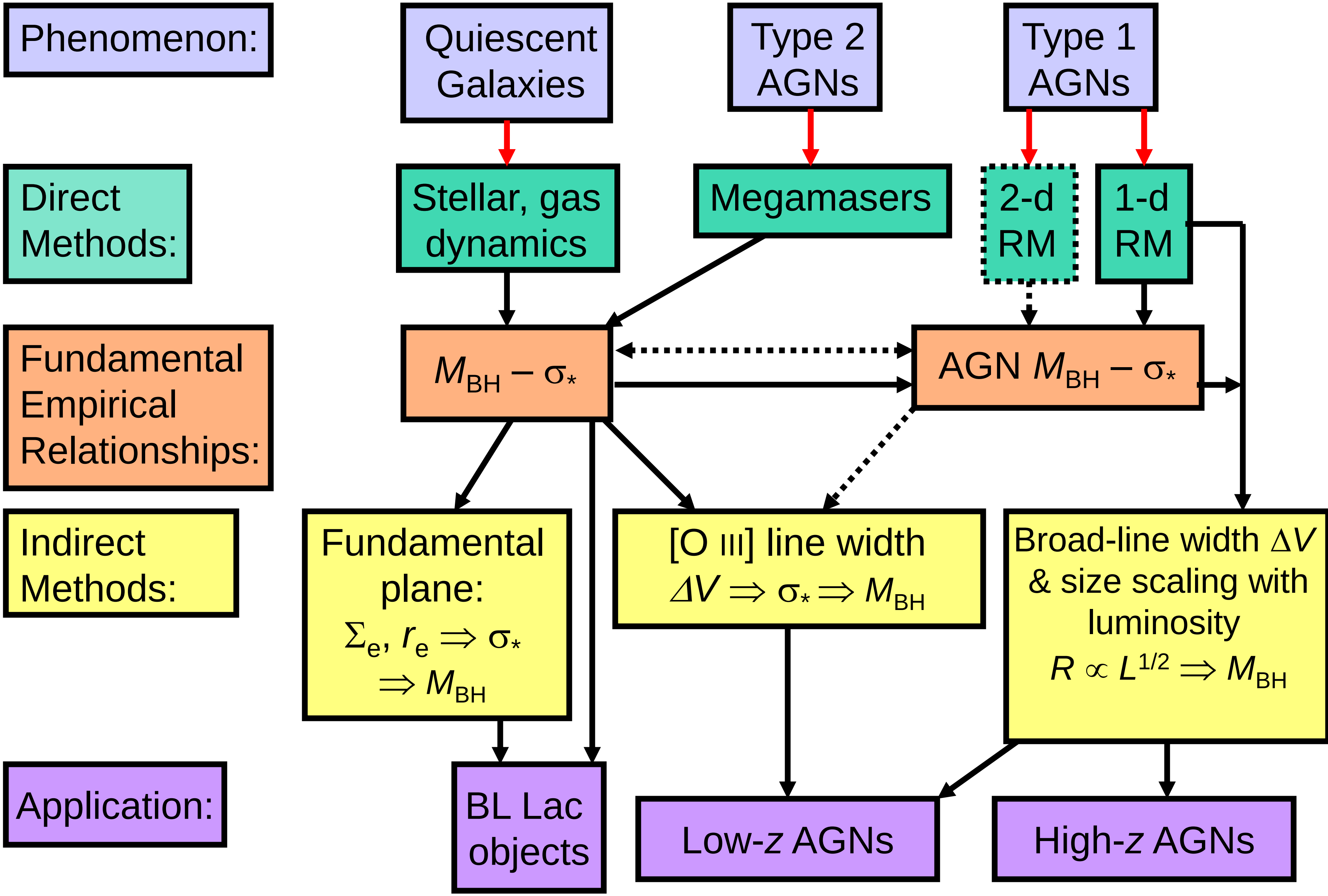
r ? $L^{1/2}$

Kris Davidson 1972



SDSS composites, by luminosity
Vanden Berk et al. 2004

Measurement of Central Black Hole Masses



Black Hole Mass Measurements (units of $10^6\ M_\odot$)

Galaxy	NGC 4258	NGC 3227	NGC 4151
Direct methods:			
Megamasers	38.2 ± 0.1	N/A	N/A
Stellar dynamics	33 ± 2	7–20	< 70
Gas dynamics	25 – 260	20^{+10}_{-4}	$30^{+7.5}_{-22}$
Reverberation	N/A	7.63 ± 1.7	46 ± 5
Indirect Methods:			
M_{BH}–σ_*	13	25	6.1
R–L scaling	N/A	15	65

References: see Peterson (2010) [arXiv:1001.3675]

Black Hole Masses

- All direct methods have systematic uncertainties at the factor of 2 level (at least!).
  - NGC 4258 (megamasers) and Galactic Center are exceptions
- Ignoring zero-point uncertainties, the prescriptions for AGN masses are probably believable at the 0.5 dex level.
- If we desire higher accuracy, many difficulties appear.
  - e.g., should we characterize line widths by FWHM or line dispersion?