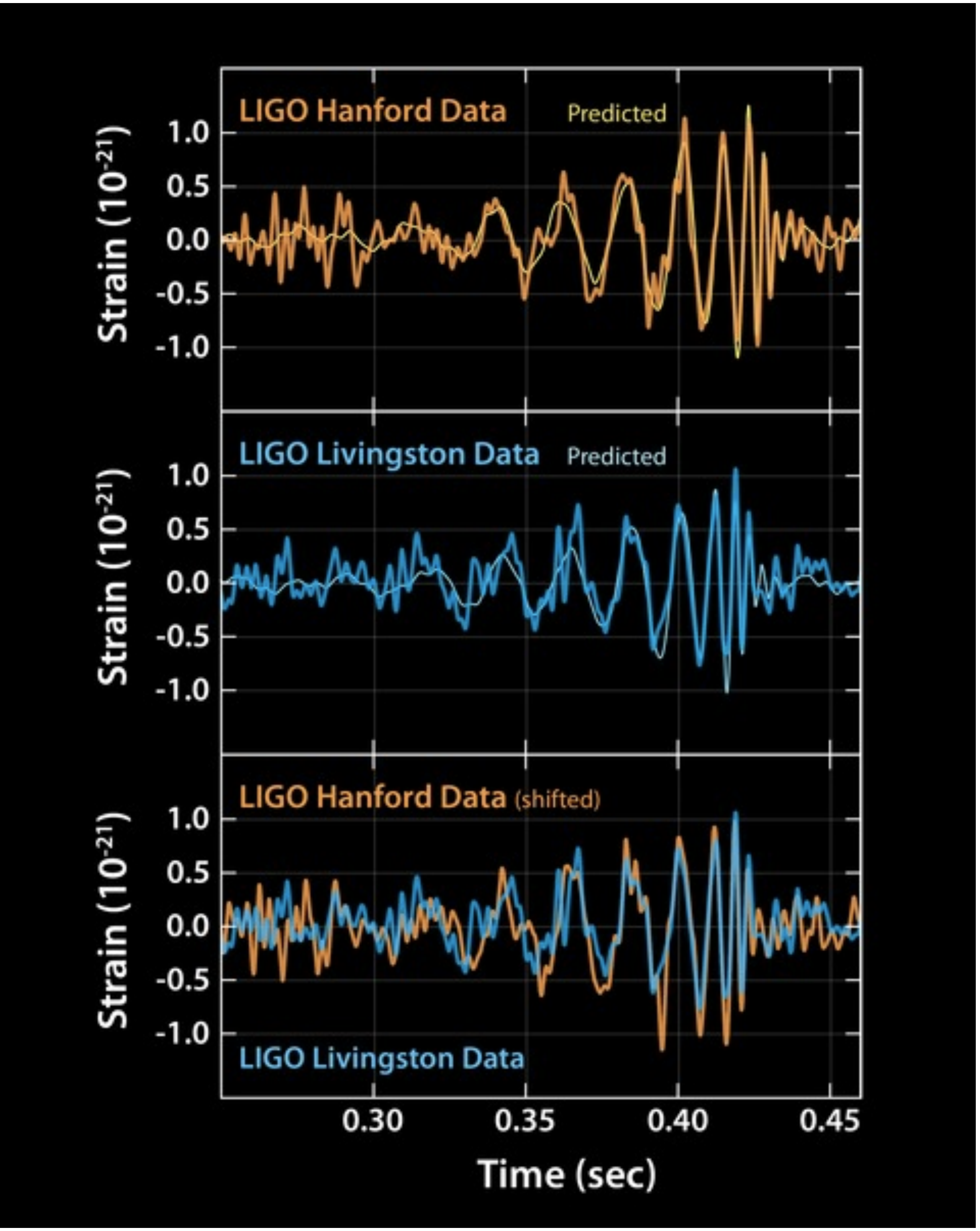
First Quasars and Supermassive Black Holes

Xiaohui Fan
University of Arizona

twitter: @xfan_astro

From seeds to supermassive black holes

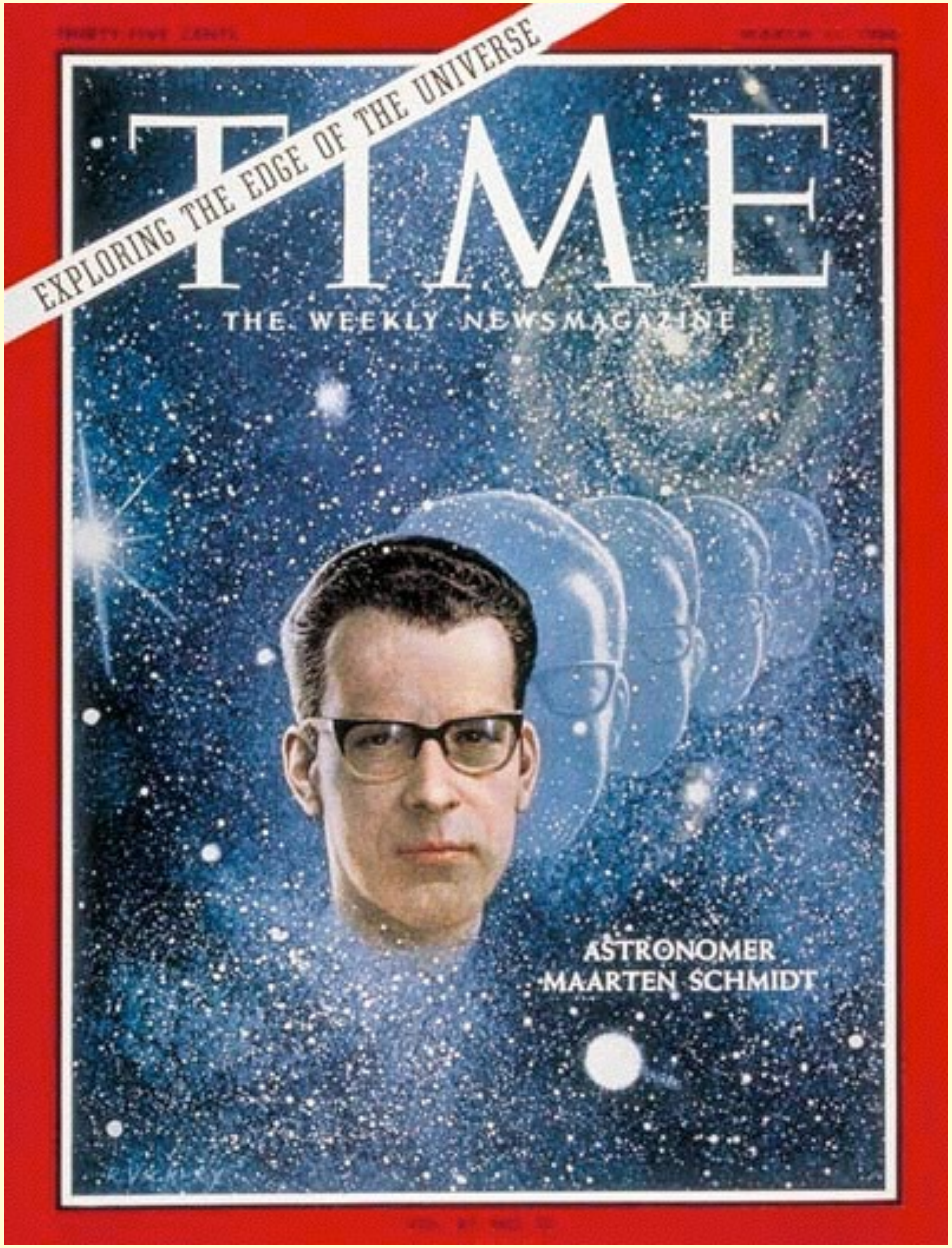


Outline

- Lecture 1: quasar and supermassive black hole basics

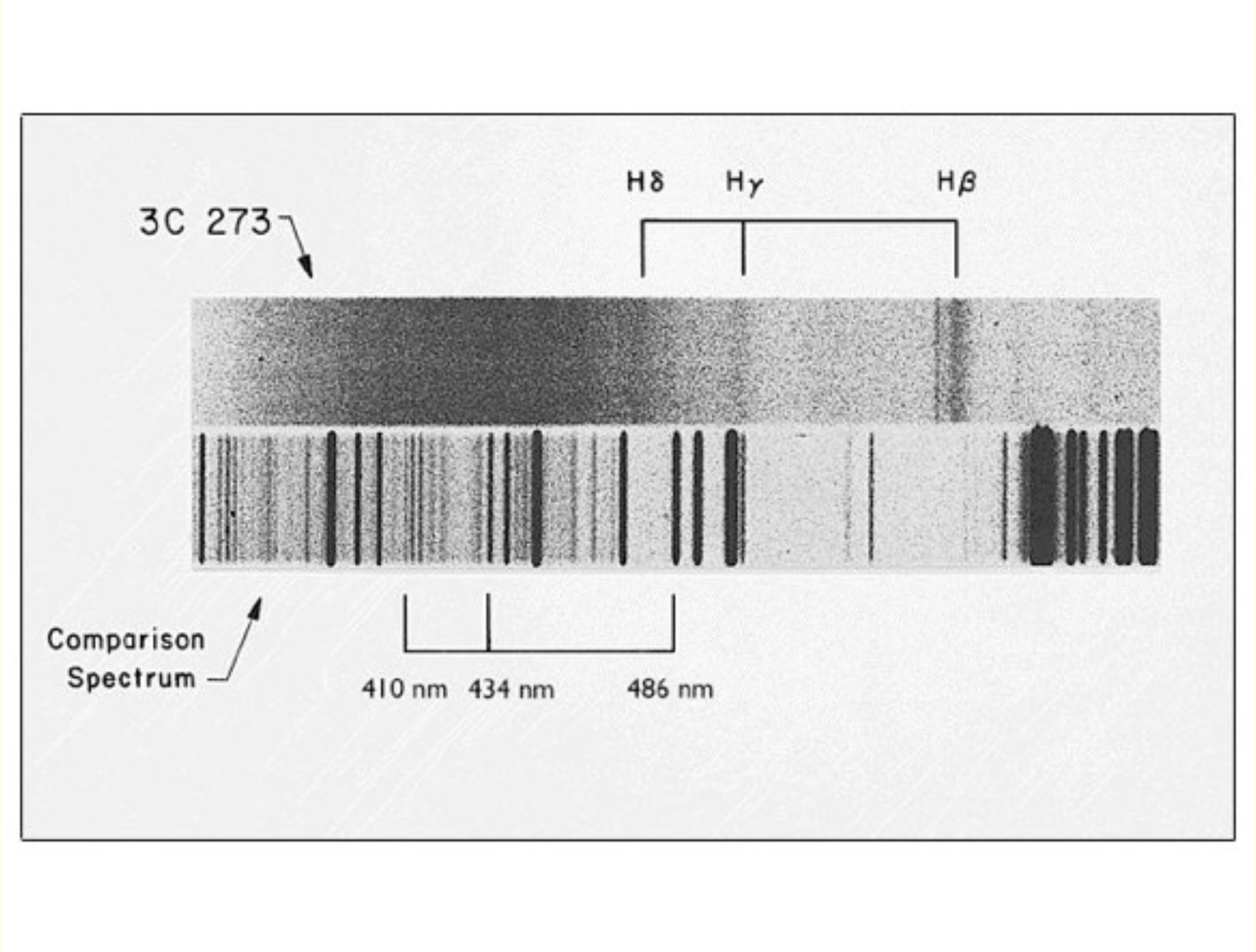
- Lecture 2: the highest redshift quasars and the first supermassive black holes

- Lecture 3: quasars as first light probe: reionization and galaxy/SMBH co-evolution


EXPLORING THE EDGE OF THE UNIVERSE
TIME
THE WEEKLY NEWSMAGAZINE
ASTRONOMER
MAARTEN SCHMIDT

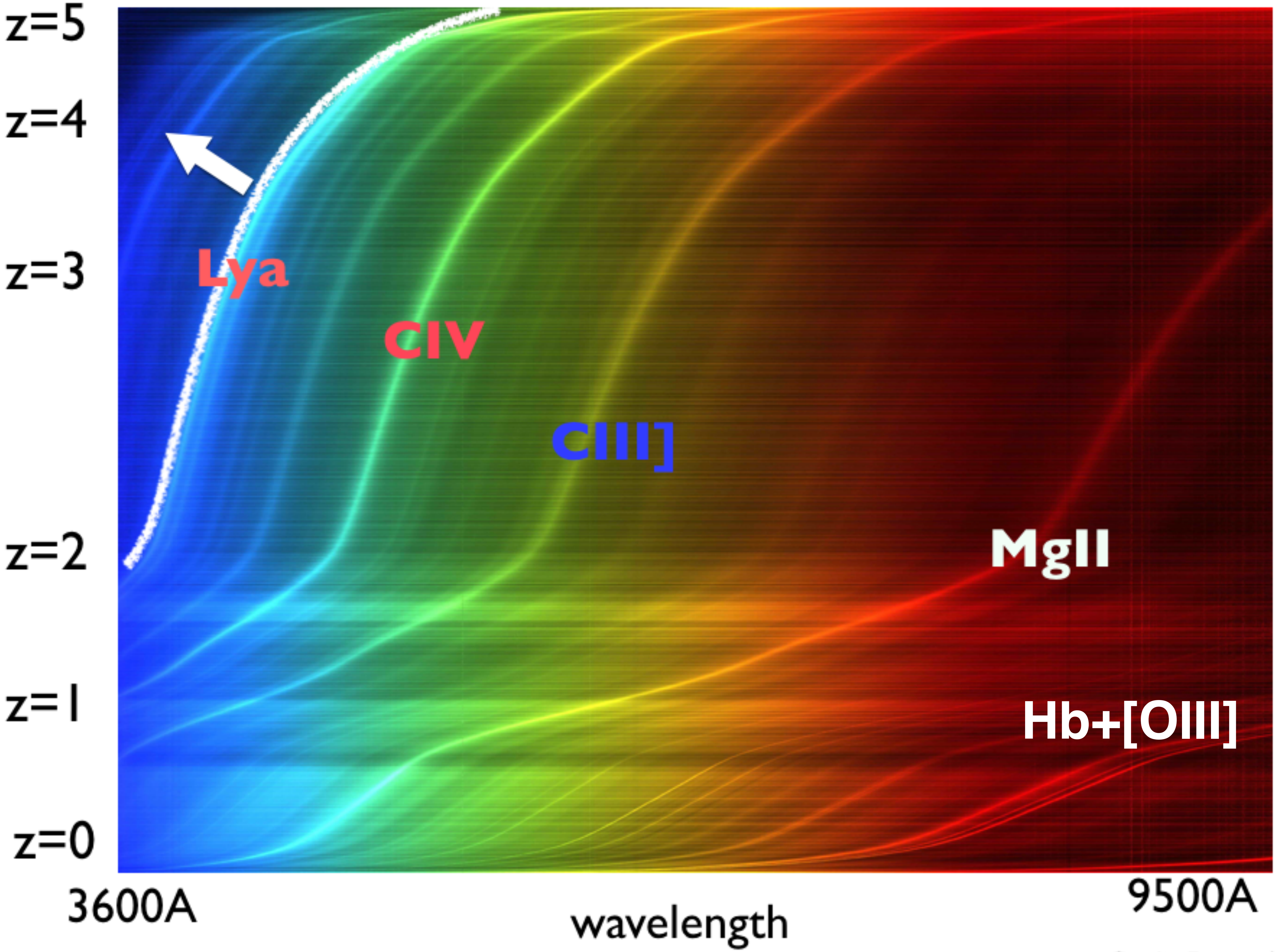
1963

The First Quasar Discovered z=0.158



- Quasar: quasi-stellar radio source
- QSO: quasi-stellar object
- Most QSOs are radio-quiet
- 1970s: quasar redshift debate

SDSS DR12 (2016) : 300,000 quasars



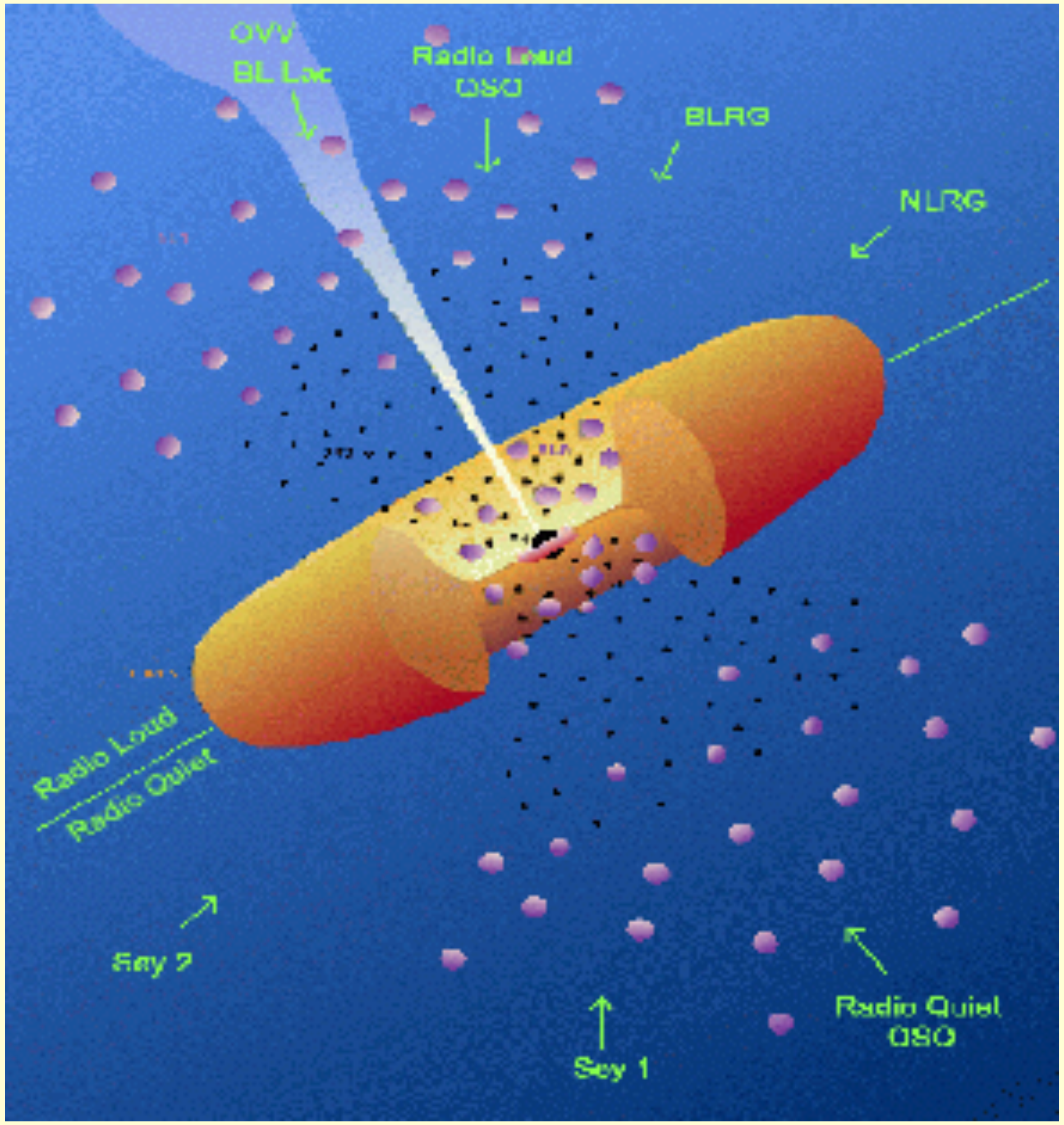
Credit: Franco Alberti

Observational Properties of quasars/AGNs

- Textbook definition
  - Small angular sizes (compact)
  - Cosmological distance
  - High luminosity?
  - Broad-band continuum emission
  - Emission Lines indicative of hard ionizing source
  - Variability
  - Polarization (subset)
- Combination of these properties support the black hole paradigm
- AGN surveys utilize one or more of these properties

Challenge I: quasars are multi-wavelength, multi-scale phenomena

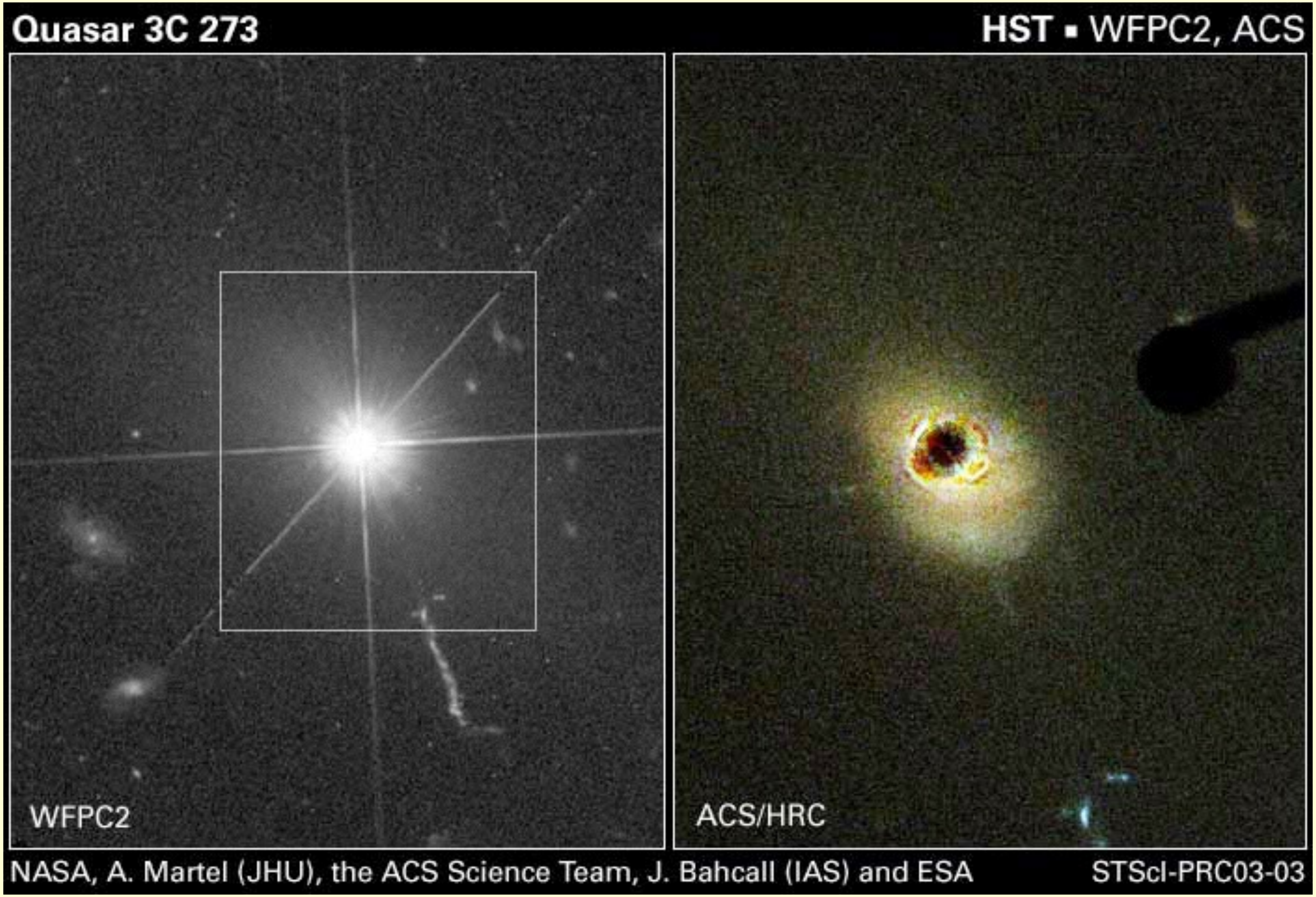
Challenge II: We do not observe the central engine



"Sometimes you can't stick your head in the engine, so you have to examine the exhaust"

-- D. E. Osterbrock

Challenge III: Quasars outshine their host galaxies by large factor



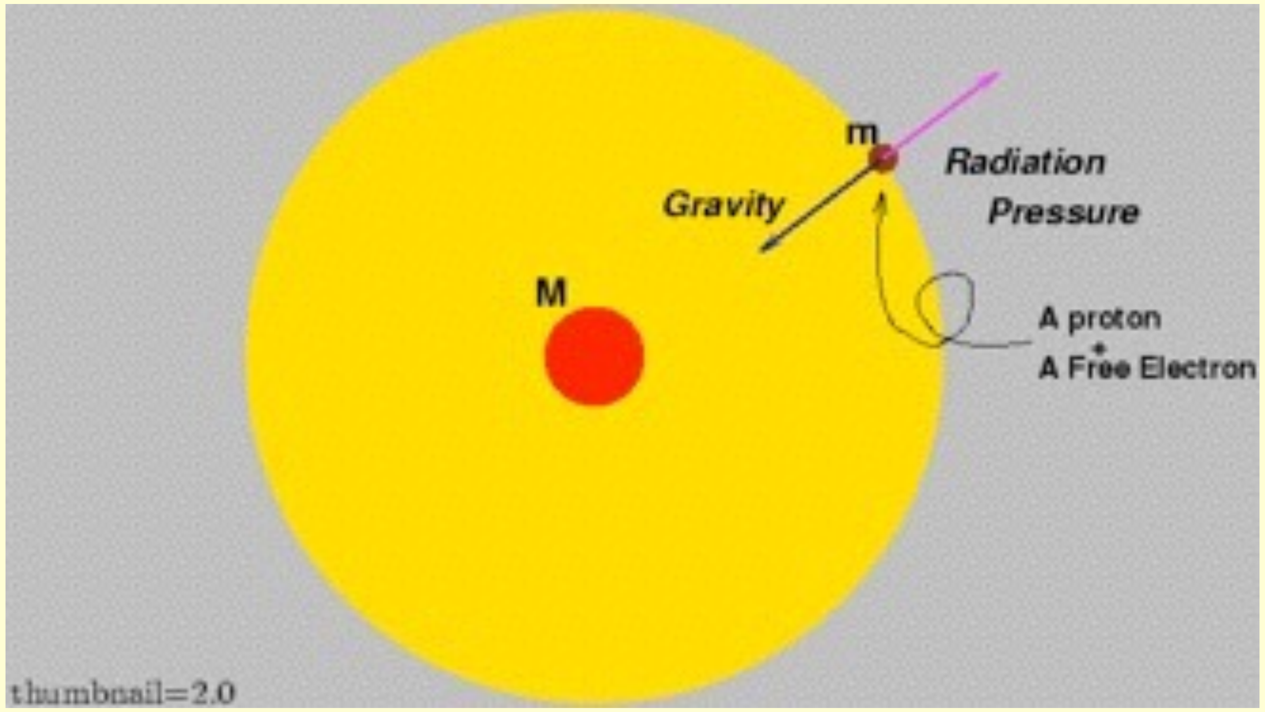
Quasar energy source

- Quasar variability: size of solar system
- High luminosity: >10^11 L_sun
- Resulted in “great debate” on the nature of quasar redshift in 1970s – which lingered until this day
- Radiative efficiency: $L = \eta\, dM/dt\, c^2$
    - H-burning: $\eta = 0.007$
    - How about accretion to compact object?

Radiative Efficiency

- Luminosity $$L = dE/dt = \eta \dot{M} c^2.$$
- Energy Conversion $$L = |d(PE)/dt| = GM/R\dot{M}.$$
- Schwarzschild radius $$R_s = 2GM/c^2$$
- Last stable orbit: a few R_s $$\eta \sim 0.1.$$
- Kerr BH: radiative efficiency could be ~ 0.2 – 0.3

Eddington Limit



$$F_{rad} \leq F_{grav},$$

$$\frac{\sigma_T L}{4\pi c r^2} \leq \frac{G M m_p}{r^2}.$$

$$L_E = \frac{4\pi G M M_p c}{\sigma_T} \sim 3 \times 10^4 \frac{M}{M_\odot} L_\odot \sim 1.26 \times 10^{38} \frac{M}{M_\odot}.$$

- quasar: L~10^44
- BH mass: 10^8 M_sun

Eddington Timescale

$$L_E = \eta \dot{M} c^2,$$

$$L_E = \frac{4\pi G c m_p}{\sigma_T} M = \eta \dot{M} c^2.$$

$$\dot{M} \sim 2.2 \times 10^{-8} M \mathrm{yr}^{-1} = (\mathrm{M}/\mathrm{t_E}),$$

$$M = M_0 \exp(t/t_E).$$

Eddington timescale $= 4.4 \times 10^7$ years if η is 0.1

Typical Quasar

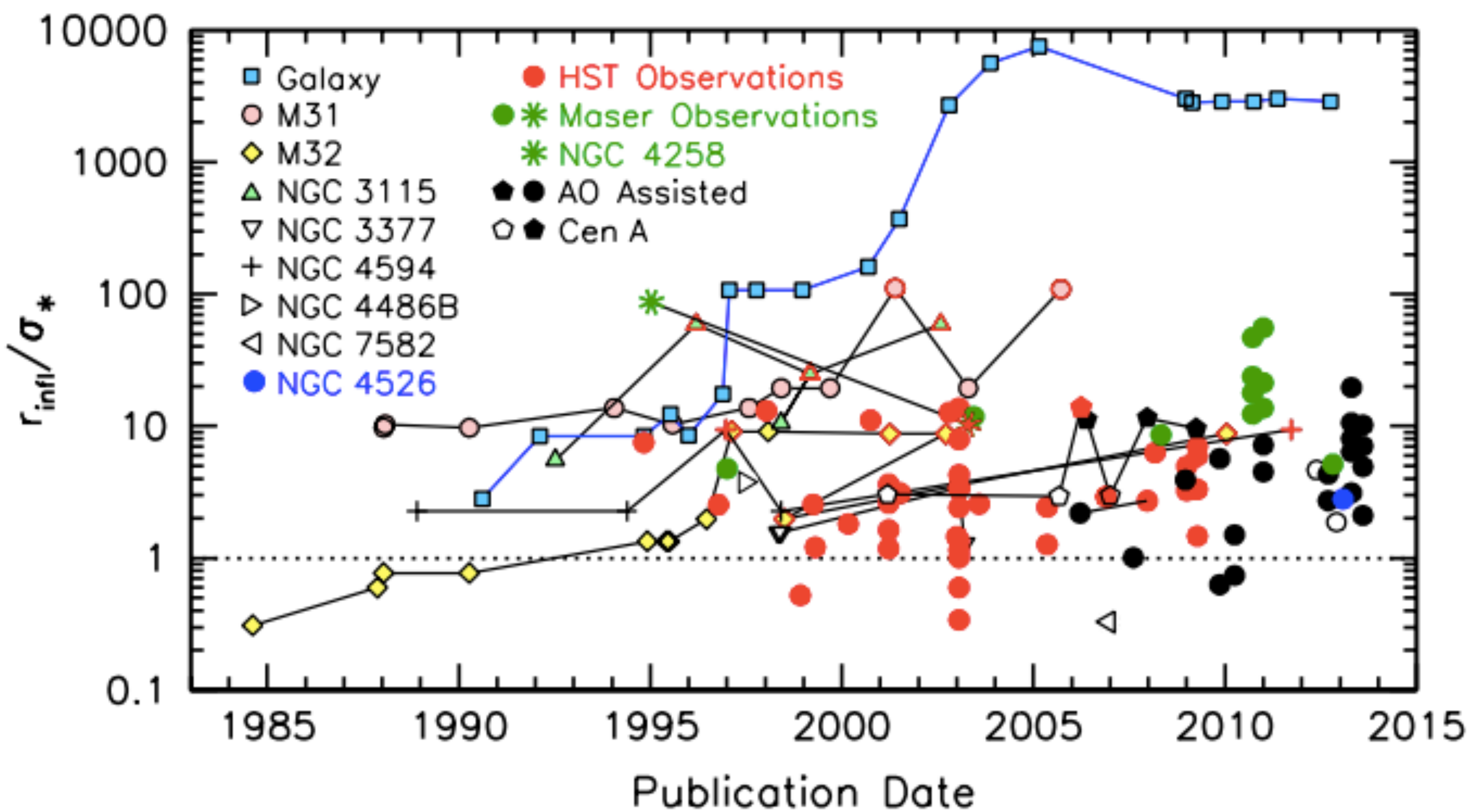
- Luminosity 10^44 erg/s
- BH mass 10^8 M_sun
- Accreting : few M_sun per year
- Mass doubling time: few tens of million years

- High-redshift? Limit on the pace of BH growth

"It's black, and it looks like a hole.
I'd say it's a black hole."

Resolve BH sphere of influence

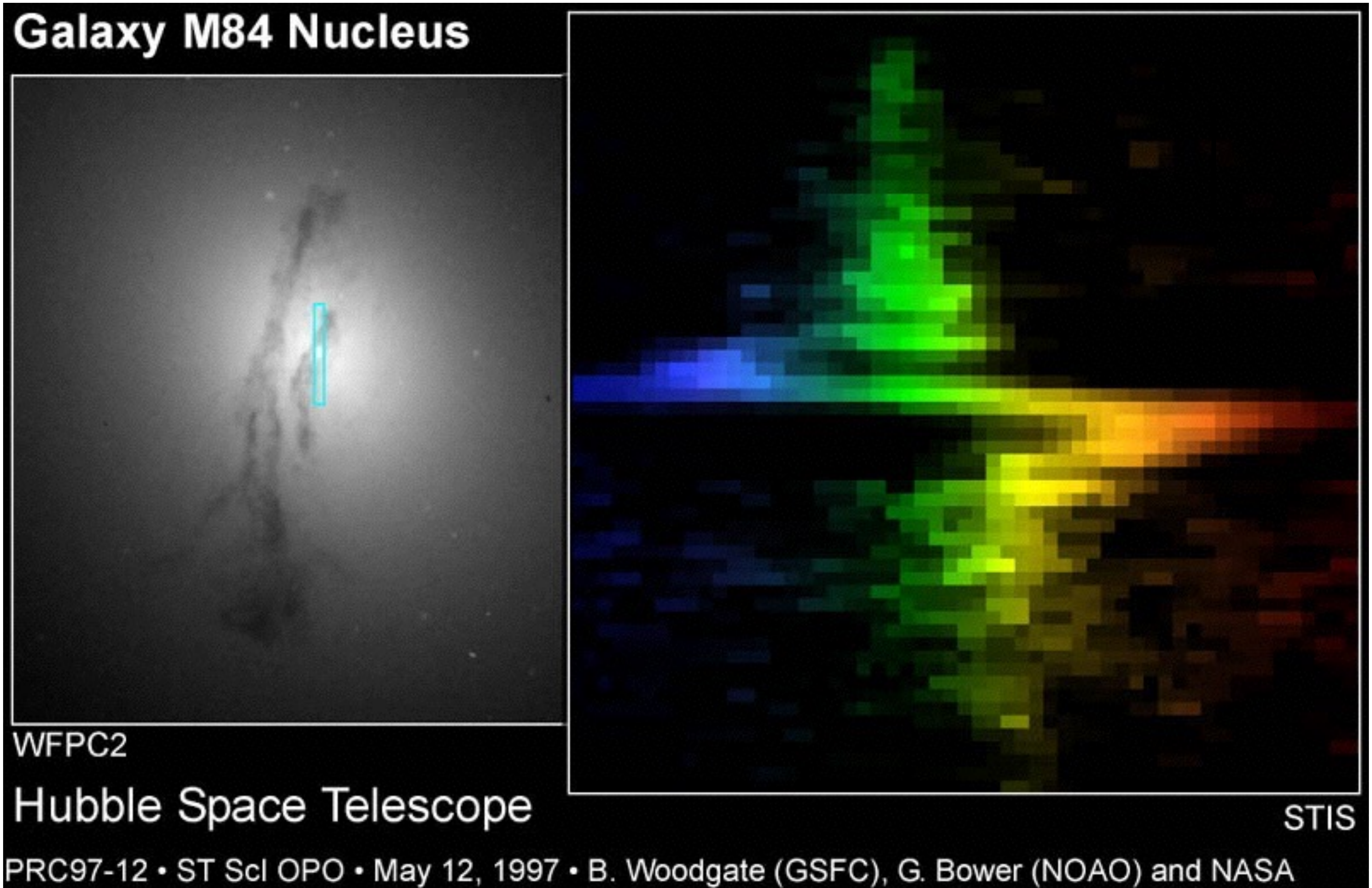
$$r_h = \frac{GM_{\mathrm{BH}}}{\sigma^2}$$



Kormendy and Ho 2013

Black Hole Mass

$$M_{BH} \sim v^2 R / G$$



BH at the Galactic Center

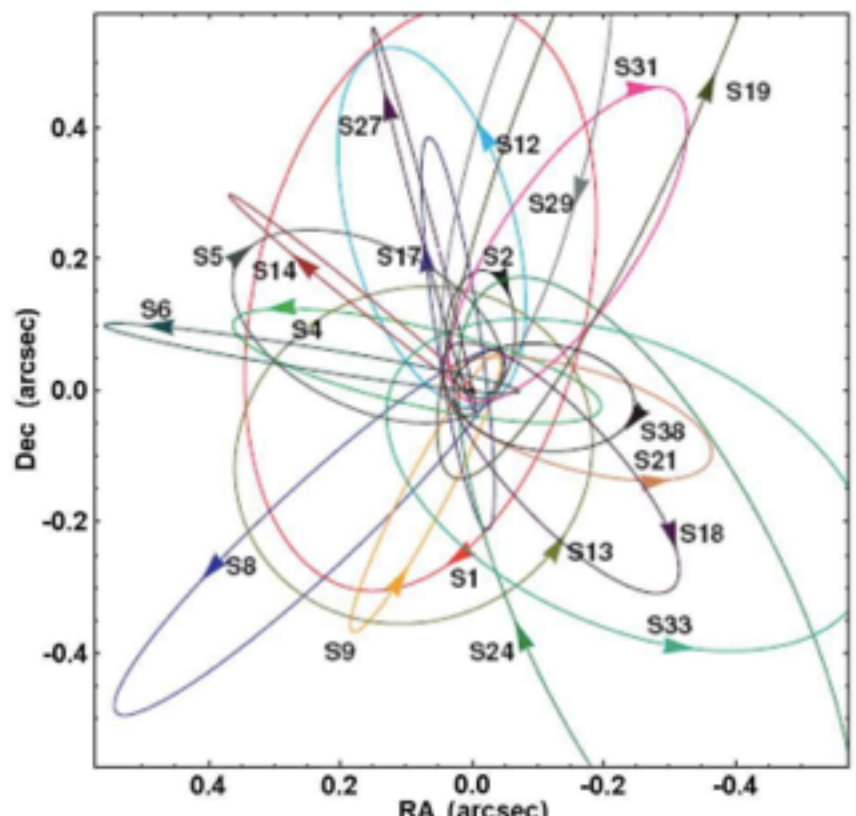
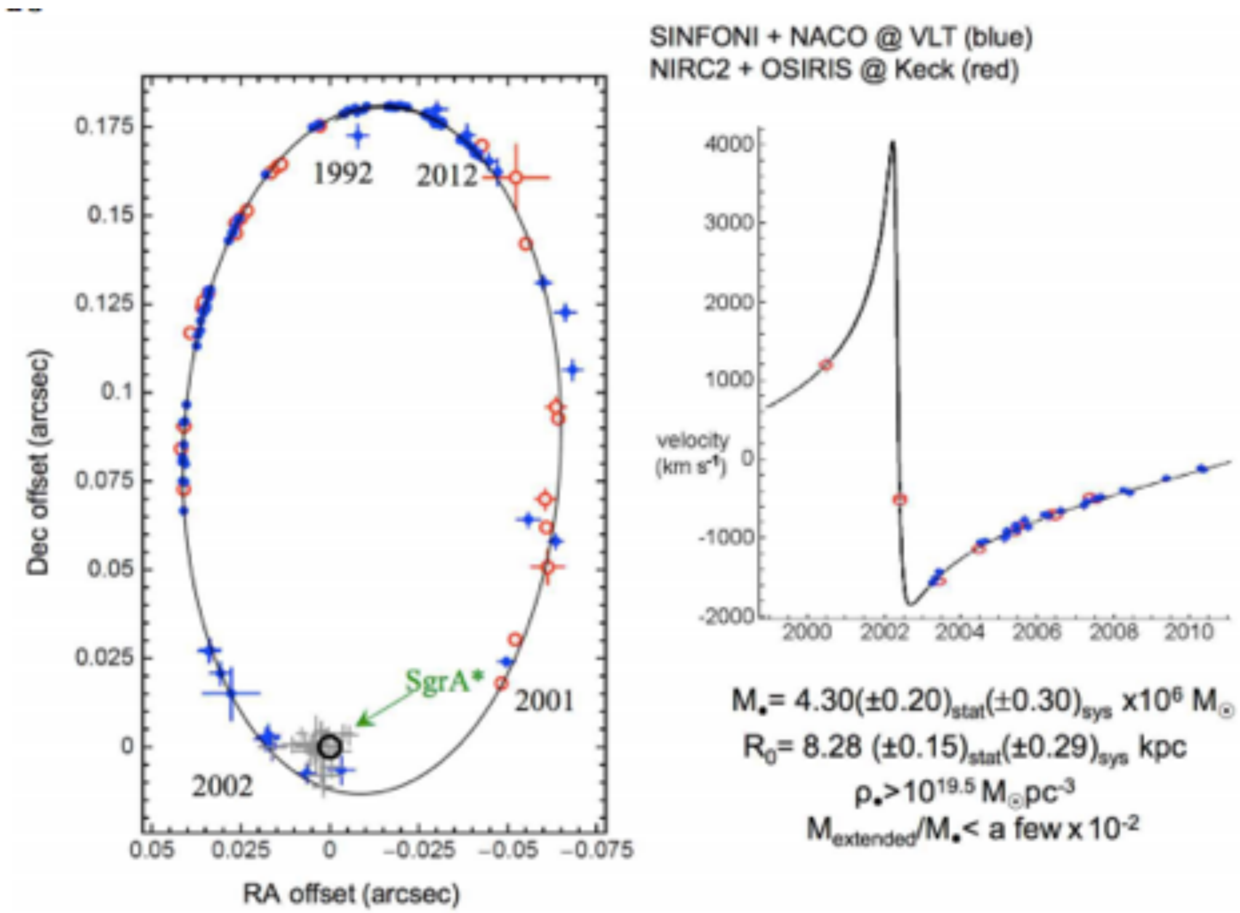


Figure 5



Kormendy and Ho 2013

Measure BH mass in normal galaxies

- Individual stars: only Milky Way

- Stellar dynamics: solve Boltzmann equation

$$M(r) = \frac{V^2 r}{G} + \frac{\sigma_r^2 r}{G}\left[-\frac{d\ln\nu}{d\ln r} - \frac{d\ln\sigma_r^2}{d\ln r} - \left(1 - \frac{\sigma_\theta^2}{\sigma_r^2}\right) - \left(1 - \frac{\sigma_\phi^2}{\sigma_r^2}\right)\right],$$

- Gas dynamics: thin rotating disk

M-sigma relation

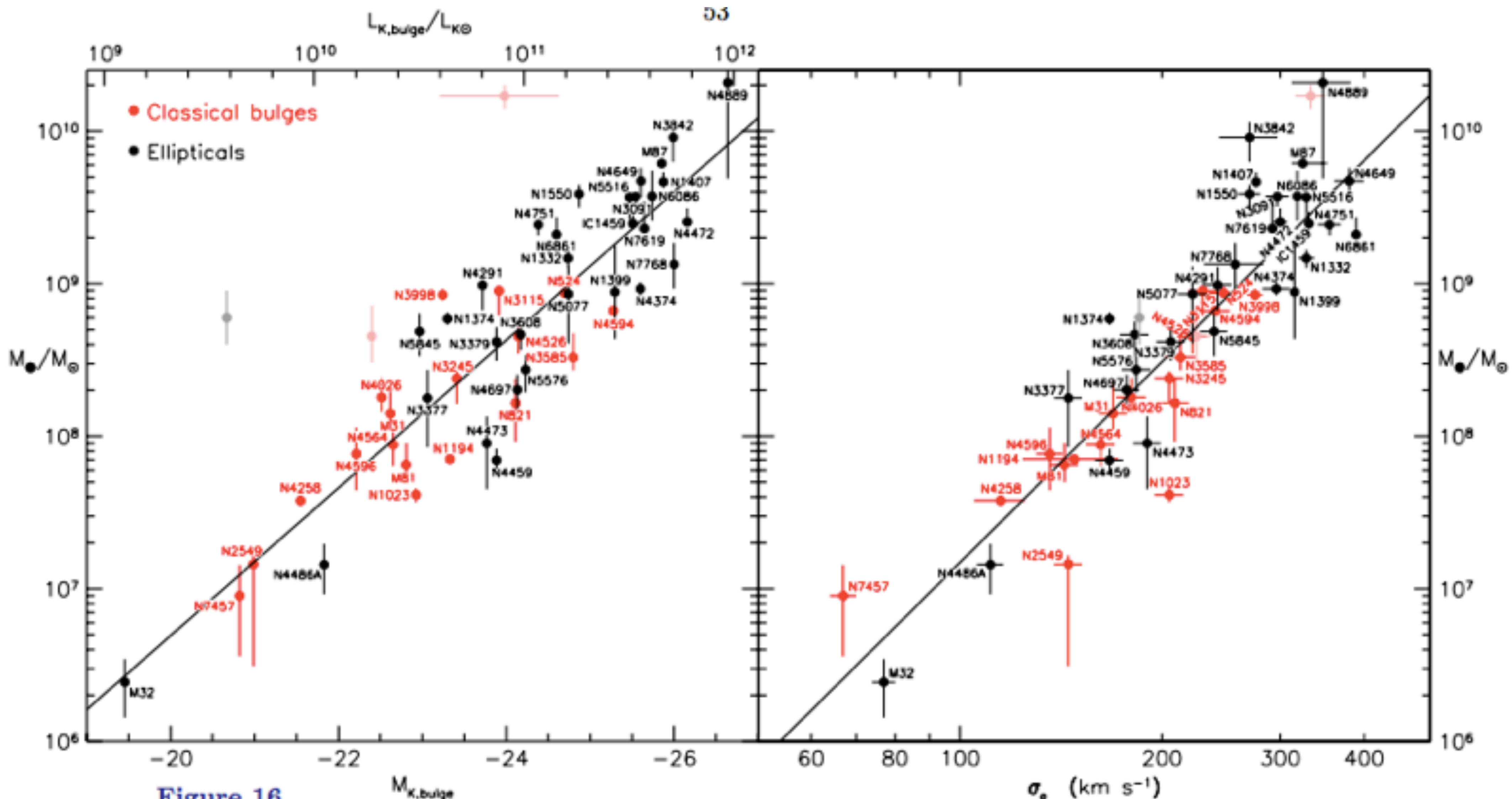


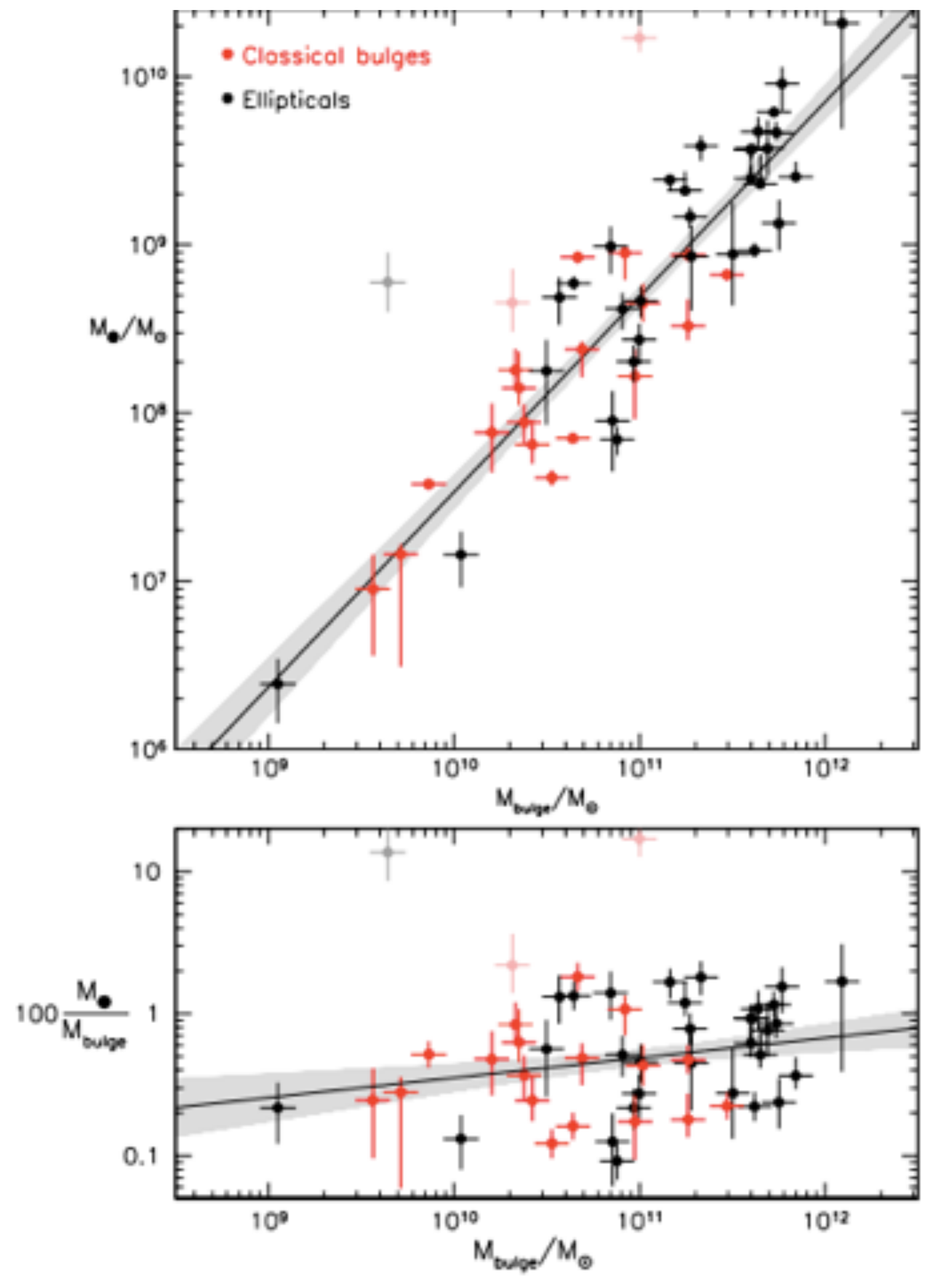
Figure 16

$$\log\left(\frac{M_\bullet}{10^9\,M_\odot}\right) = -(0.266\pm0.052)-(0.484\pm0.034)(M_{K,\mathrm{bulge}}+24.21);\ \text{intrinsic scatter} = 0.31;\ (2)$$

$$\log\left(\frac{M_\bullet}{10^9\,M_\odot}\right) = -(0.510\pm0.049)+(4.377\pm0.290)\log\left(\frac{\sigma}{200\ \mathrm{km\ s^{-1}}}\right);\ \text{intrinsic scatter} = 0.29.\ (3)$$

Kormendy and Ho 2013

M_bh vs. M_bulge



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$$100\left(\frac{M_\bullet}{M_{\rm bulge}}\right) = \left(0.49^{+0.06}_{-0.05}\right)\left(\frac{M_{\rm bulge}}{10^{11}\,M_\odot}\right)^{0.14\pm0.08}, \quad \text{intrinsic scatter} = 0.29 \text{ dex.}$$

Kormendy and Ho 2013

What BH mass doesn’t correlate with?

- Be very careful about which M and which sigma!
- It only works for bulge of the galaxy
- BH mass doesn’t correlate with galaxy total mass (if there is such a thing)
- BH mass doesn’t correlate with galaxy disk mass
- M-sigma probably breaks down at the highest and lowest mass end (more on that in Lecture 2)
- Redshift evolution (later)

Measure BH masses in quasars and AGN

- Problem 1: can not resolve sphere of influence (too far)

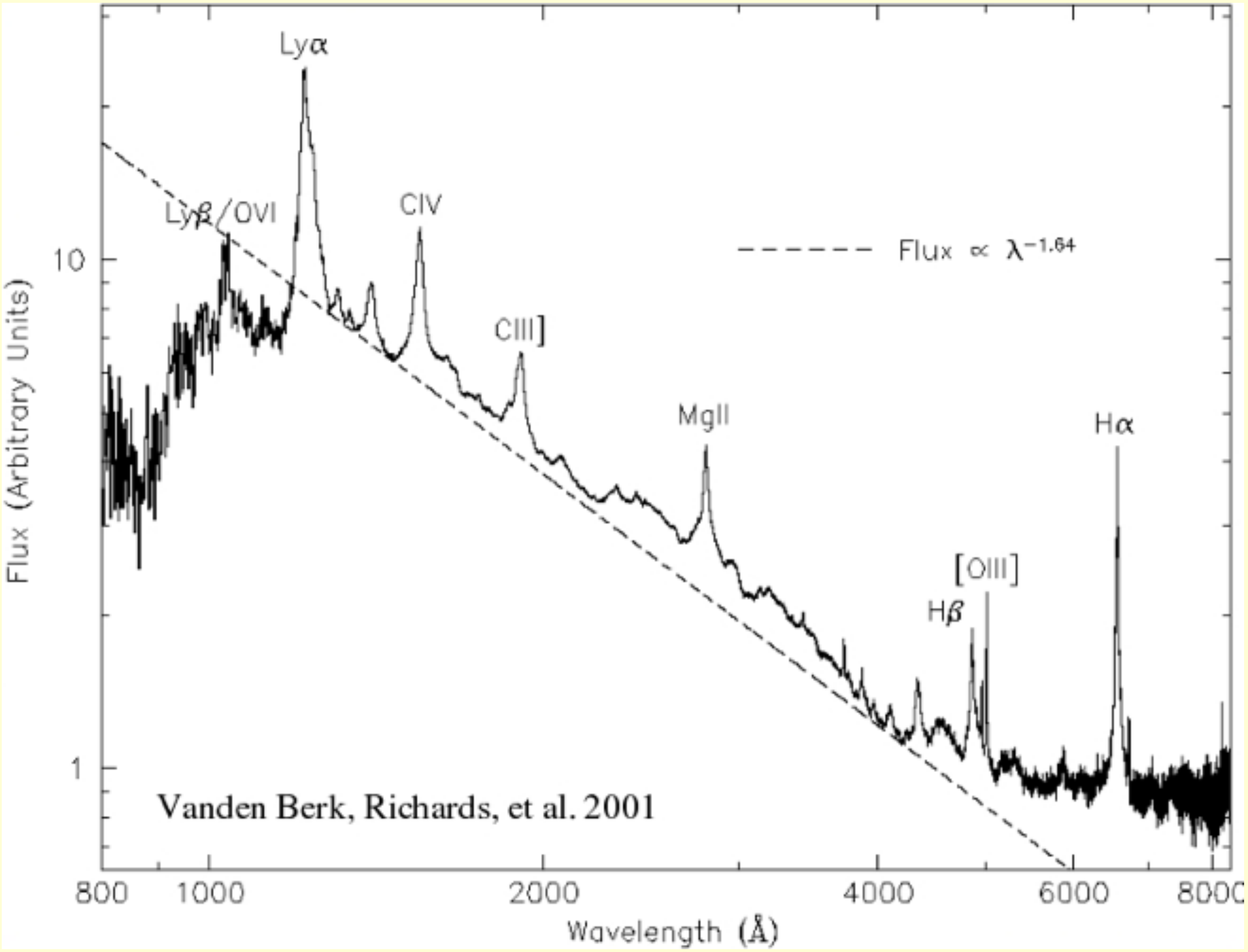
- Problem 2: can not detect host galaxy light; stellar light or emission line (too bright)

- For luminous quasars: only observables are broad emission lines and continuum; both comes within the BH sphere of influence

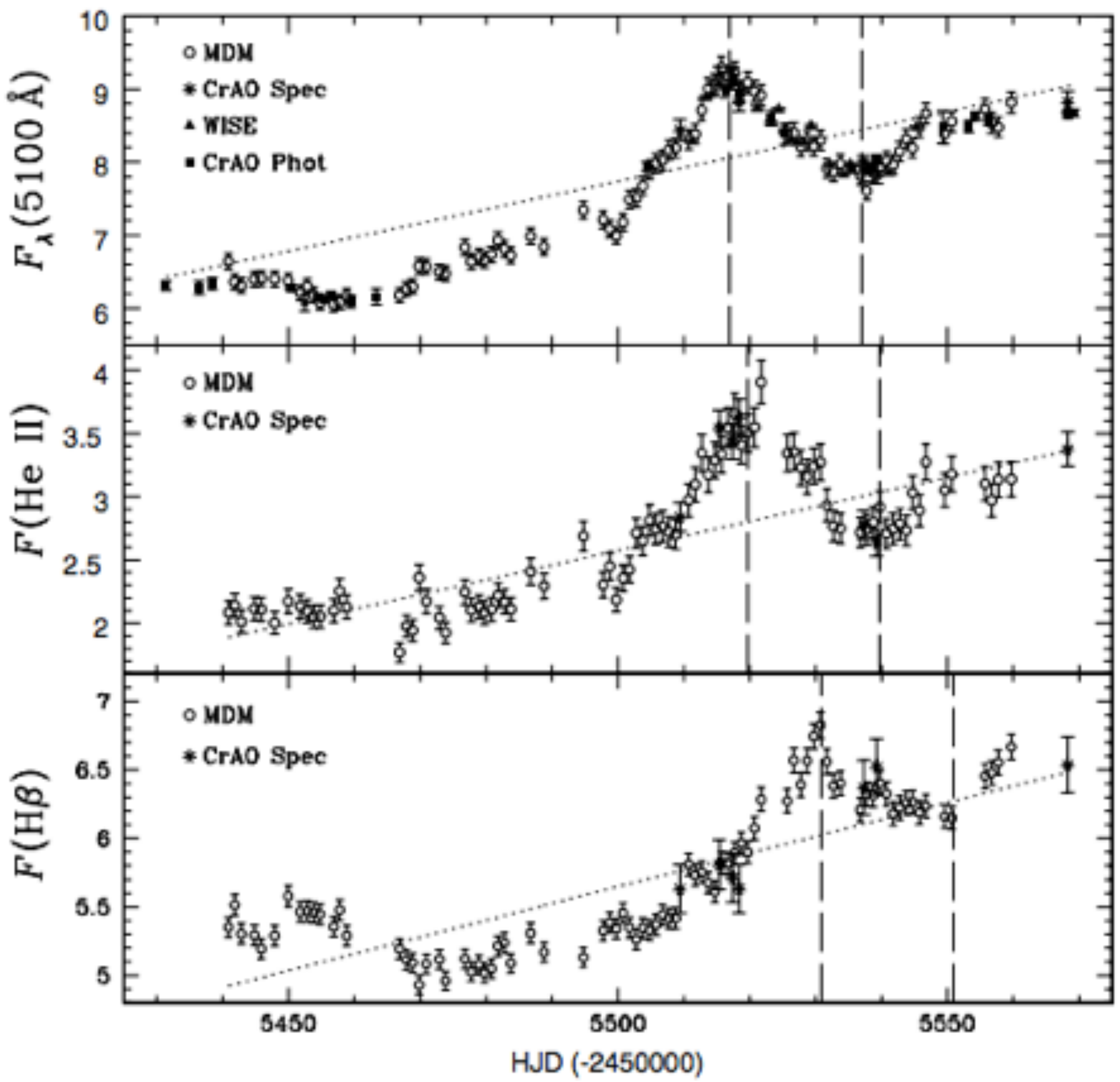
- Answer: reverberation mapping

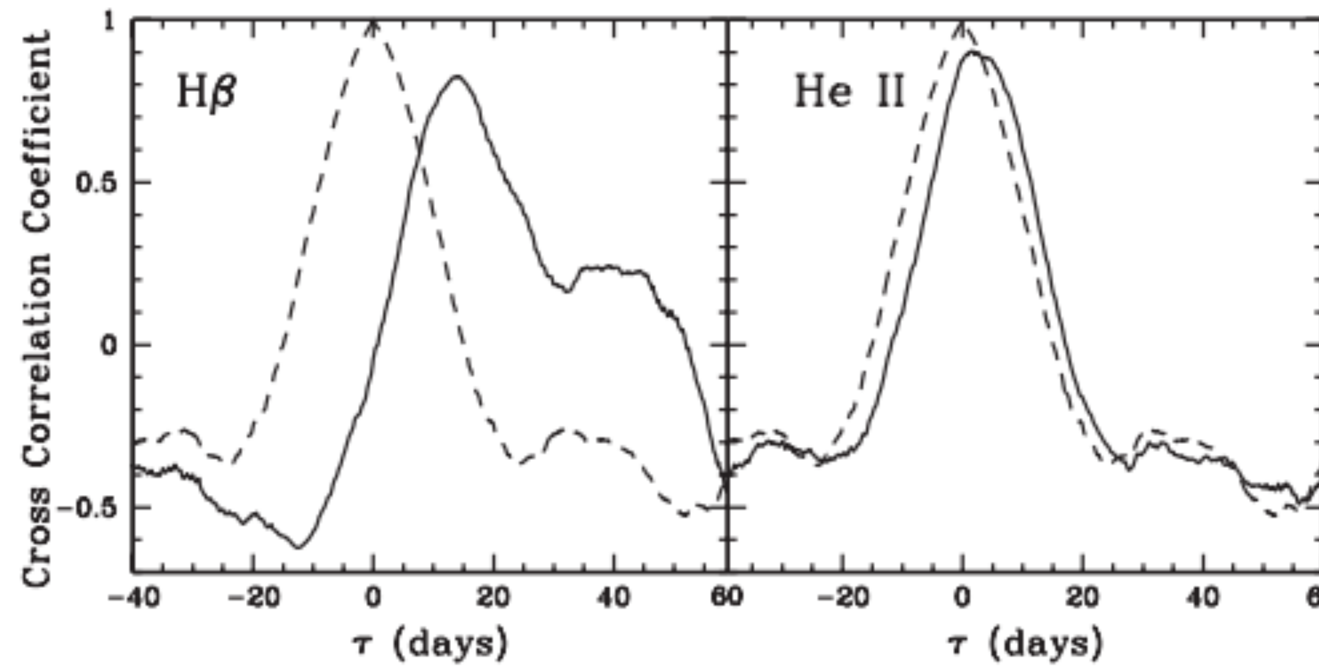
The average spectrum of quasars

1. Hot (blue) continuum
2. Broad emission lines (~5000 km/s) – type-1
3. Narrow emission lines (~500 km/s) – type-2 (narrow-line only)



Reverberation Mapping





Grier et al. 2012

- Emission line variation follows that of continuum, with a time delay of 14 days for H-beta, and 3 days for HeII, due to travel time across the emission line regions.

Reverberation-Based Masses

"virial product" (units of mass)

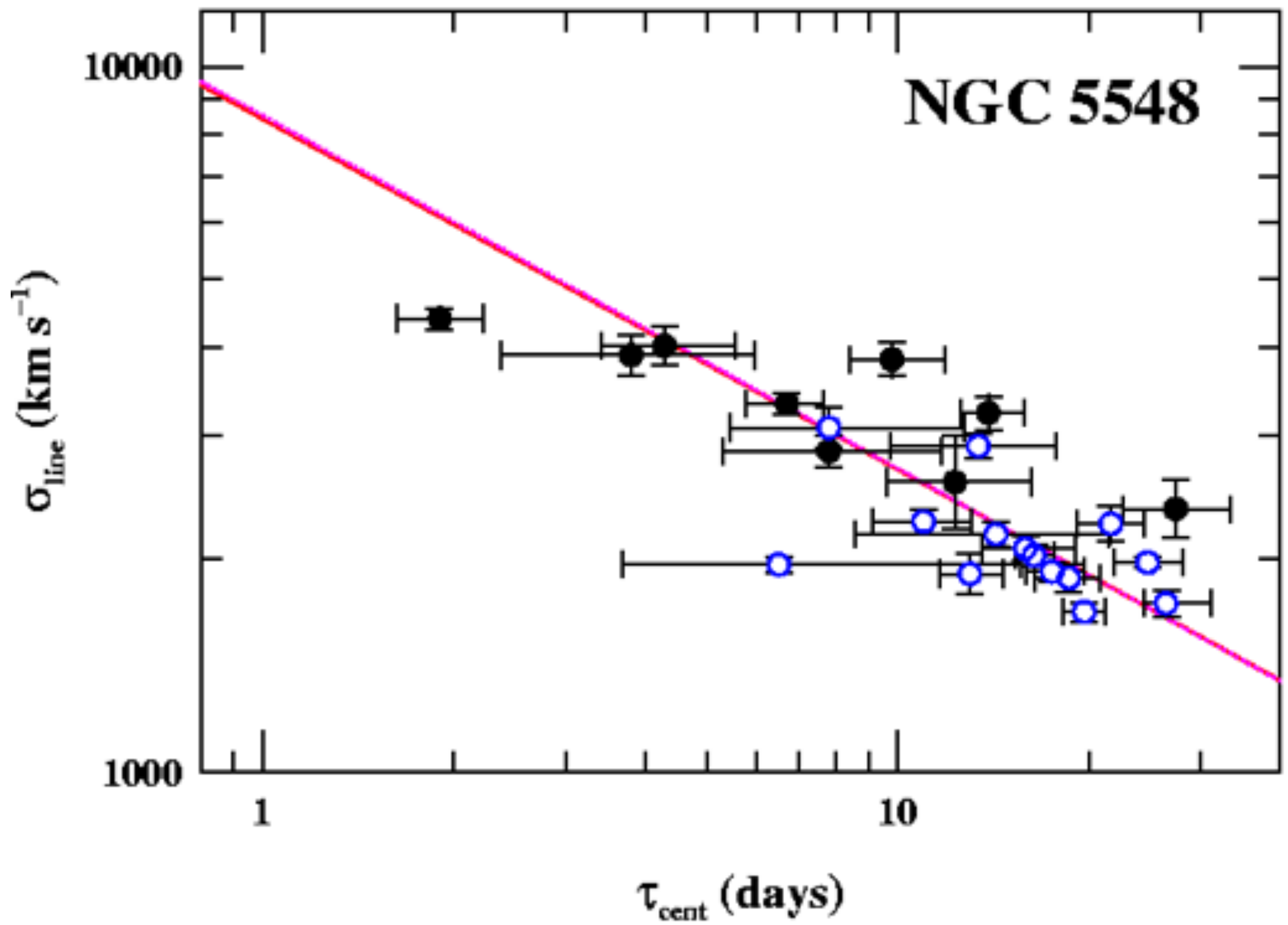
$$M_{BH} = f \boxed{R\,\Delta V^2 / G}$$

set by geometry and inclination
(everything that we don't know)

Observables:
R = BLR radius (from reverberation mapping(
Δv = emission line width

Evidence for a Virialized BLR

- Gravity is important
  - Broad-lines show virial relationship between size of line-emitting region and line width, $r \propto \sigma^{-2}$

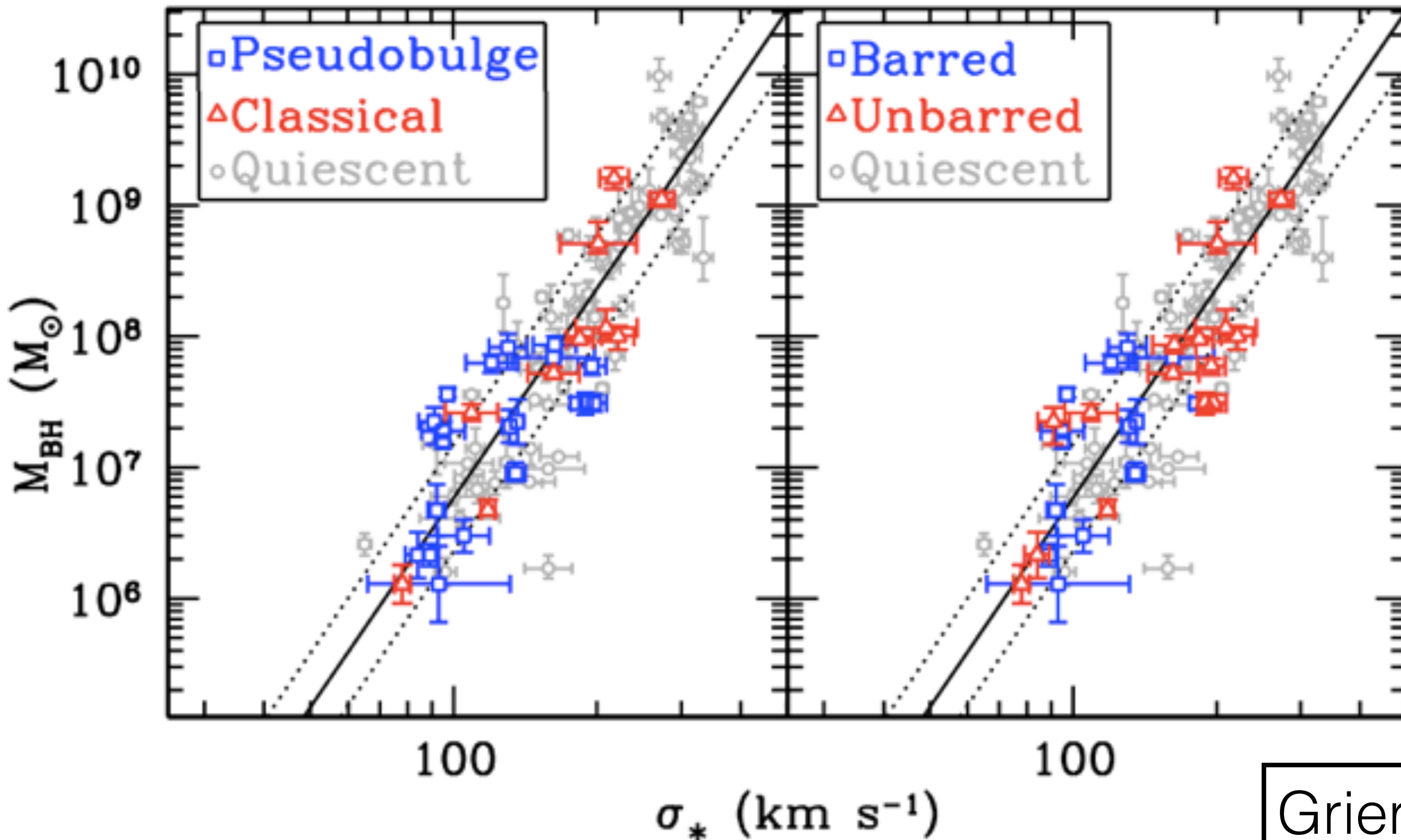


o Hβ

● Other Lines

B. Peterson

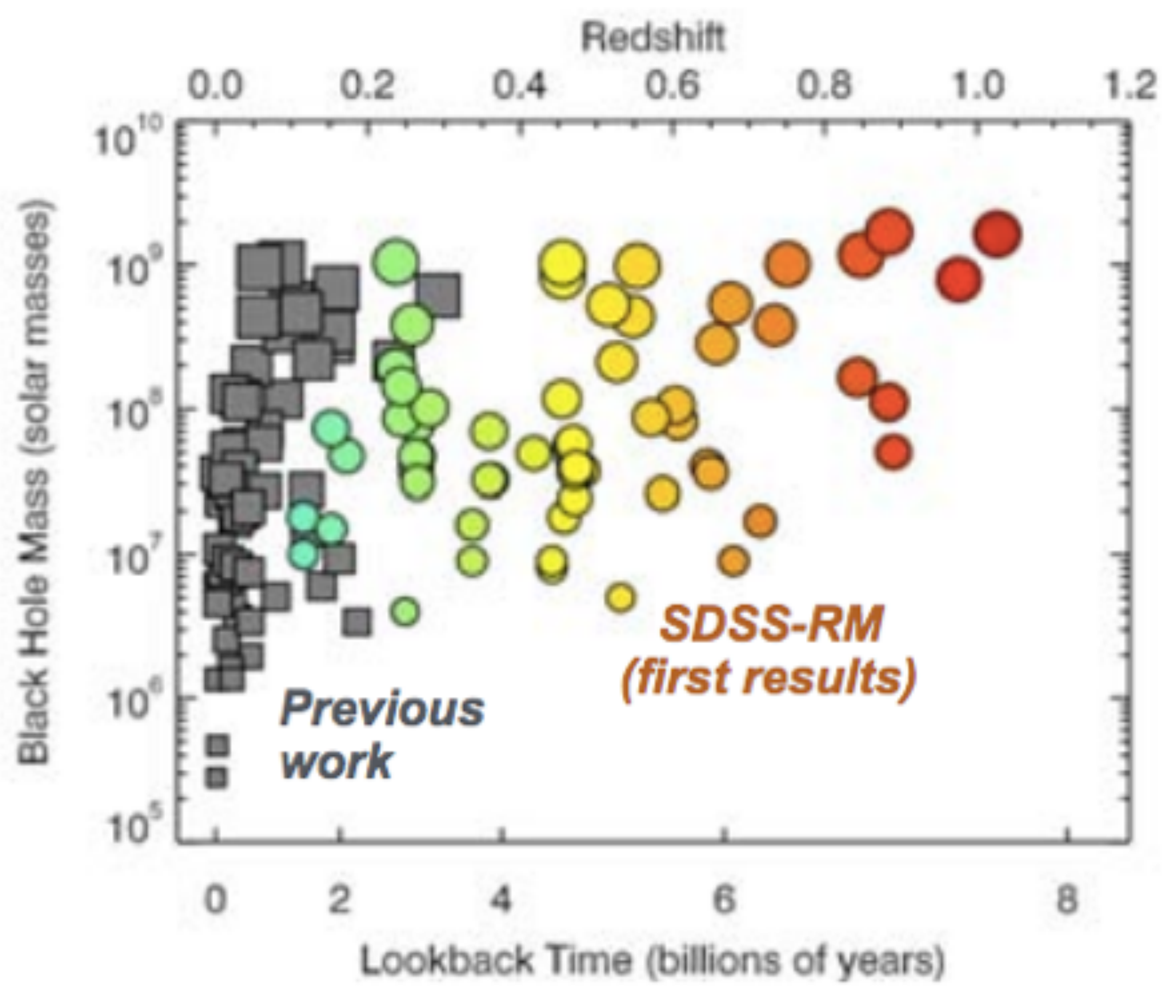
The AGN M-sigma relation

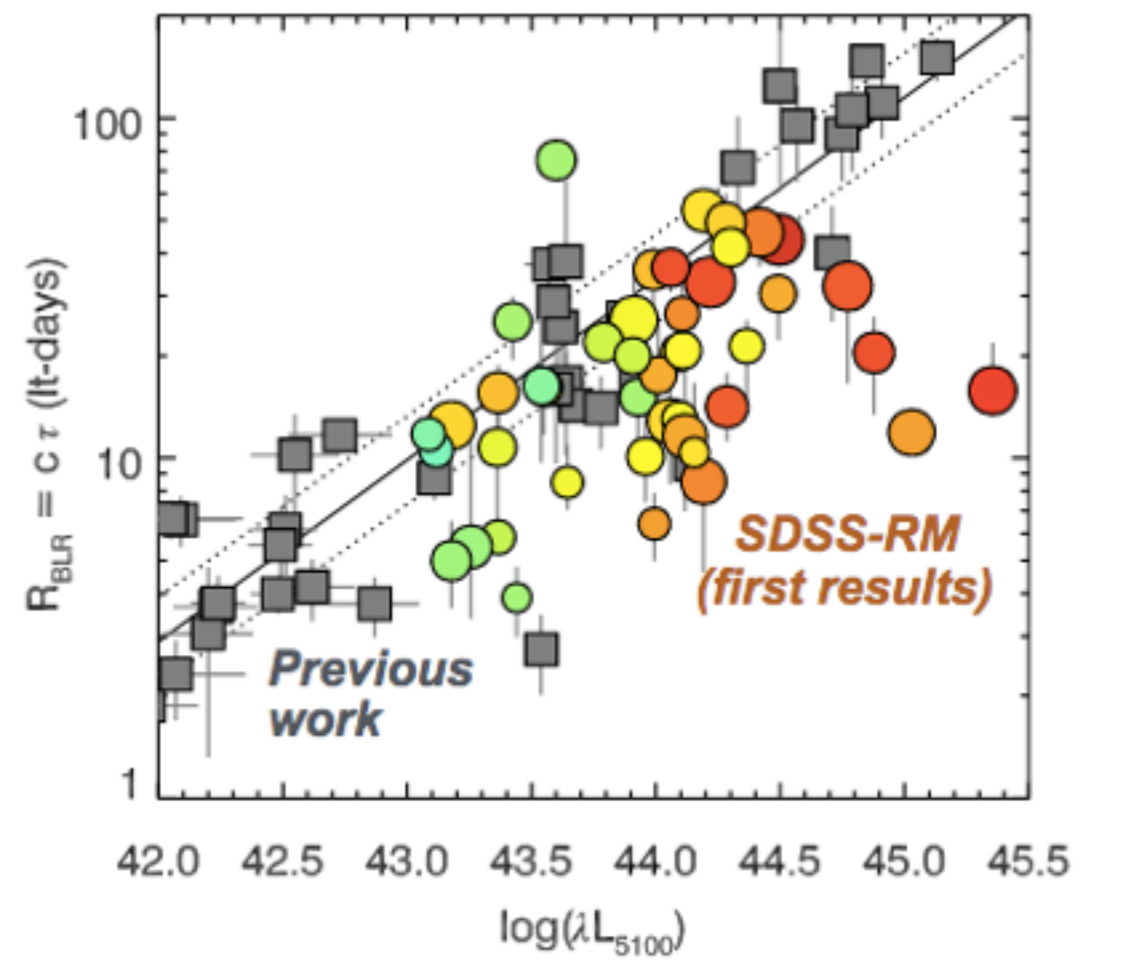


Grier et al. 2013

- no independent absolute calibration
- Assume zeropoint of quiescent galaxy calibration: f=4.19±0.10
- intrinsic scatter of the relation is ~0.4 dex

Current status of reverberation BH masses: the SDSS RM project





- Reaching cosmological distance and high luminosity
- requiring year/decade long campaigns for high-z, high-luminosity sources
- more economical way for quasar BH-mass measurements?

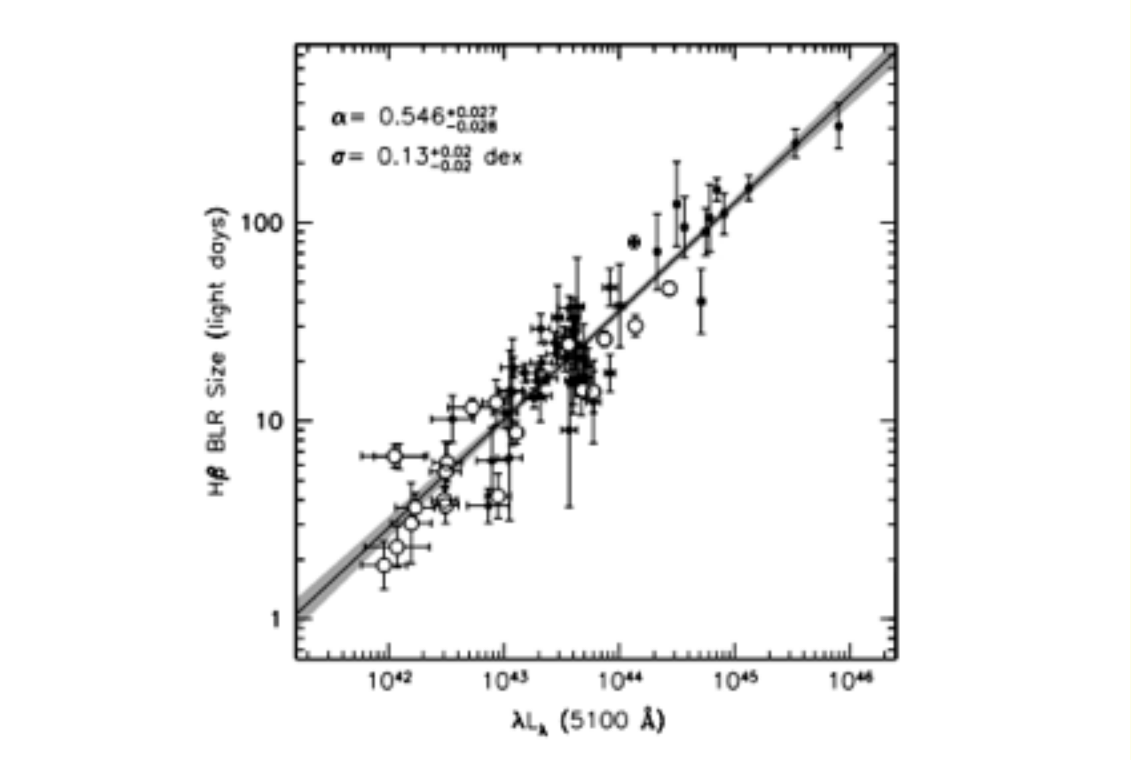
Virial Mass Estimates

$$M_{BH} \sim v^2 R_{BLR}/G$$

- Reverberation Mapping: $R_{BLR} = c\tau$
- **Radius – Luminosity Relation:** $R \sim L^{\beta}$
- Scaling Relationships:

$$M_{BH} \propto FWHM^2 L^{\beta}$$

  - **Single epoch spectroscopy sufficient**
  - **works for high-z, high-L sources**
  - **But what is β?**
    - **Photoionization predicts:** $R \sim L^{1/2}$



Bentz+2013

Virial BH mass: Which line to use

- H-beta (4861A): well calibrated. But doesn’t work at high-z
- MgII (2800A): calibration OK. Accessible at high-z, but in near-IR
- CIV (1549): strongest line. Affected by AGN winds, accessible at high-z. Controversial.

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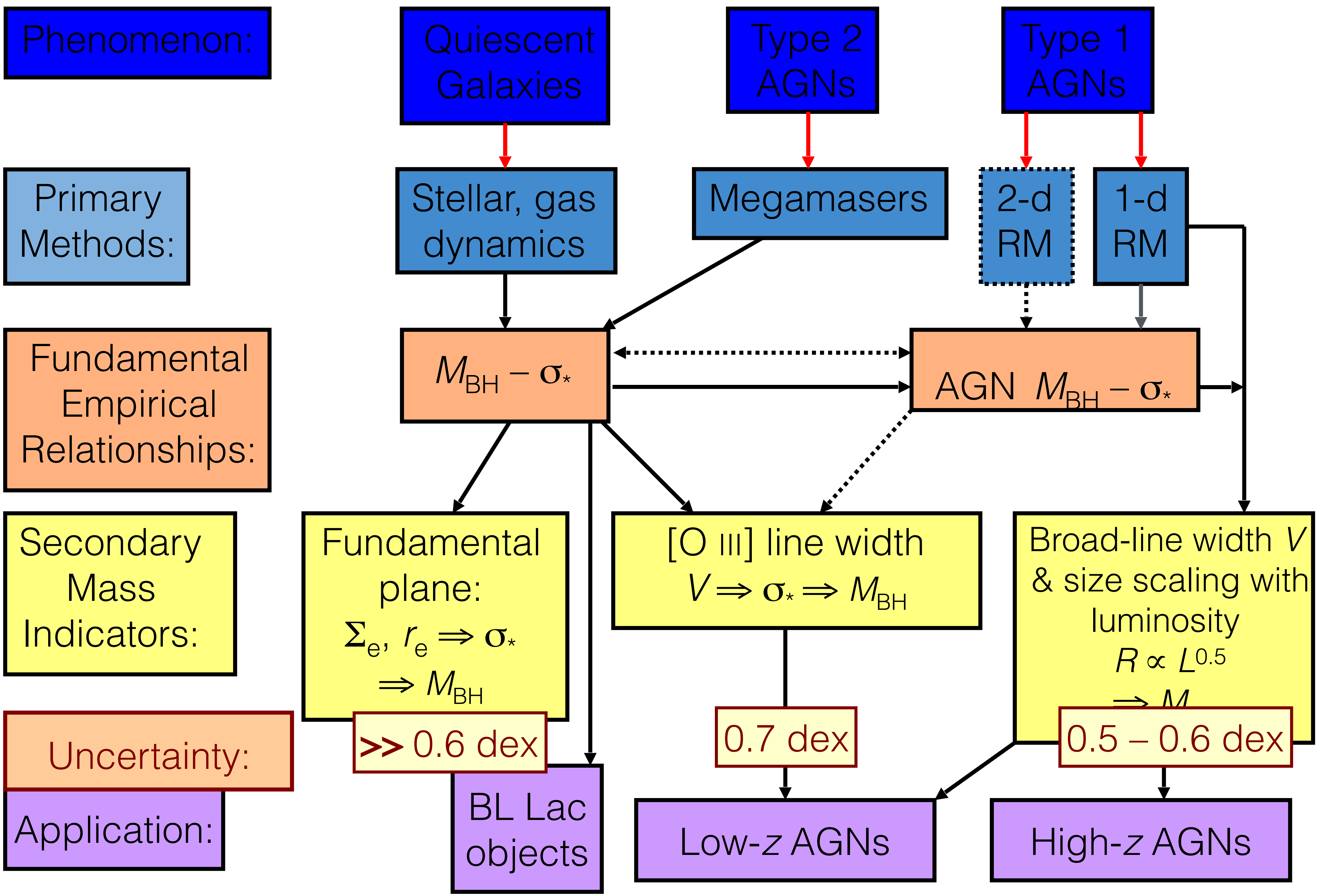
Estimating AGN Black Hole Masses



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Reverberation Masses: Separating Fact from Fiction

- Reverberation-based masses are *real* mass measurements

- Reverberation masses are *not high-precision masses* (yet?)
  $M_{\mathrm{BH}} = f\, c\tau\, \sigma^2/G$

  - ~30% uncertainty in precision

  - ~35% uncertainty in zero-point calibration

  - ~0.5 dex (factor of 3) uncertainty in accuracy for any given AGN