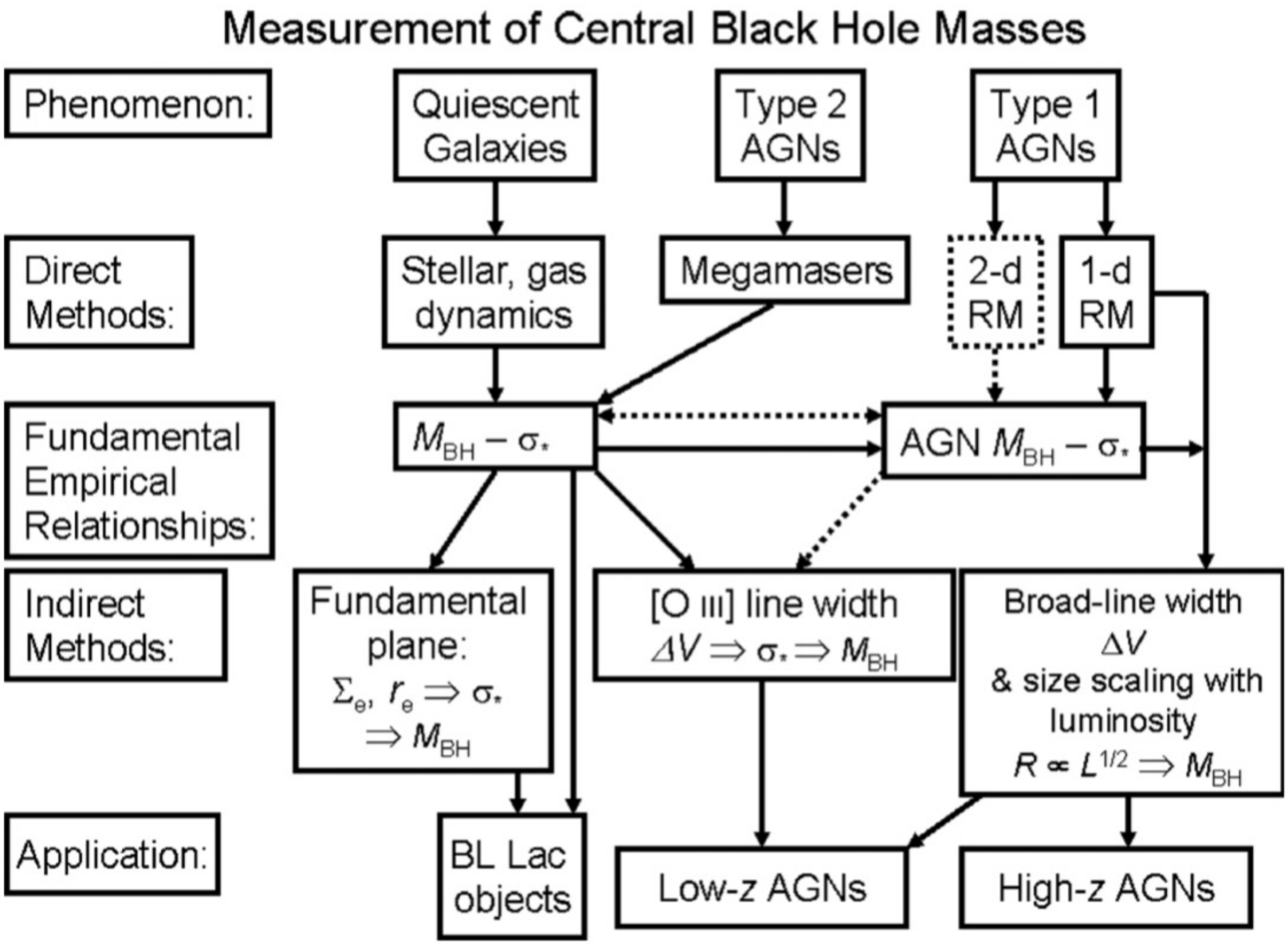
Black hole masses

Methods to estimate BH masses



Peterson (2010)

All have uncertainties and possible underlying selection biases

Direct vs. indirect methods

Mass measurements are based on how the central black hole (despite of being active/inactive) accelerates nearby matter (either stars or gas)

DIRECT METHODS

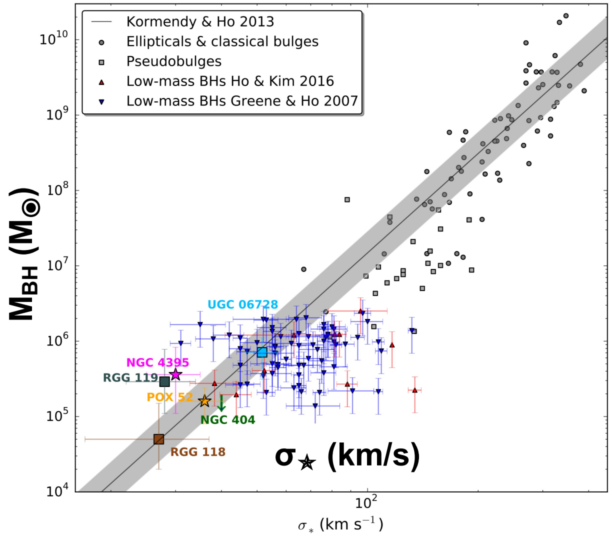
Direct sampling of observables in the region where the gravitational potential of the SMBH dominates over the surrounding material (stars, gas)

Stellar dynamics, gas dynamics, reverberation mapping

INDIRECT METHODS

These methods rely on observables somehow correlated with the mass of the central black hole

M_{BH}-$\sigma_\star$, M_{BH}-$L(M)_{bulge}$ relations, scaling relations (e.g., BLR radius-luminosity)



These M_{BH}-host relations may be biased (Bernardi+07, Shankar+16)
Need for an extension to lower masses (Mezcua+17)

see Shen Y. (2013) review for additional methods

Sphere of influence of the BH. I

The gravitational potential of the BH is equal to that of the surrounding stars

$$R_{BH} = \frac{GM_{BH}}{\sigma_\star^2} \sim 100 \left(\frac{M_{BH}}{10^9\ M_\odot}\right) \left(\frac{200\ km/s}{\sigma_\star}\right)^2\ pc$$

Radius of the sphere of influence of BH

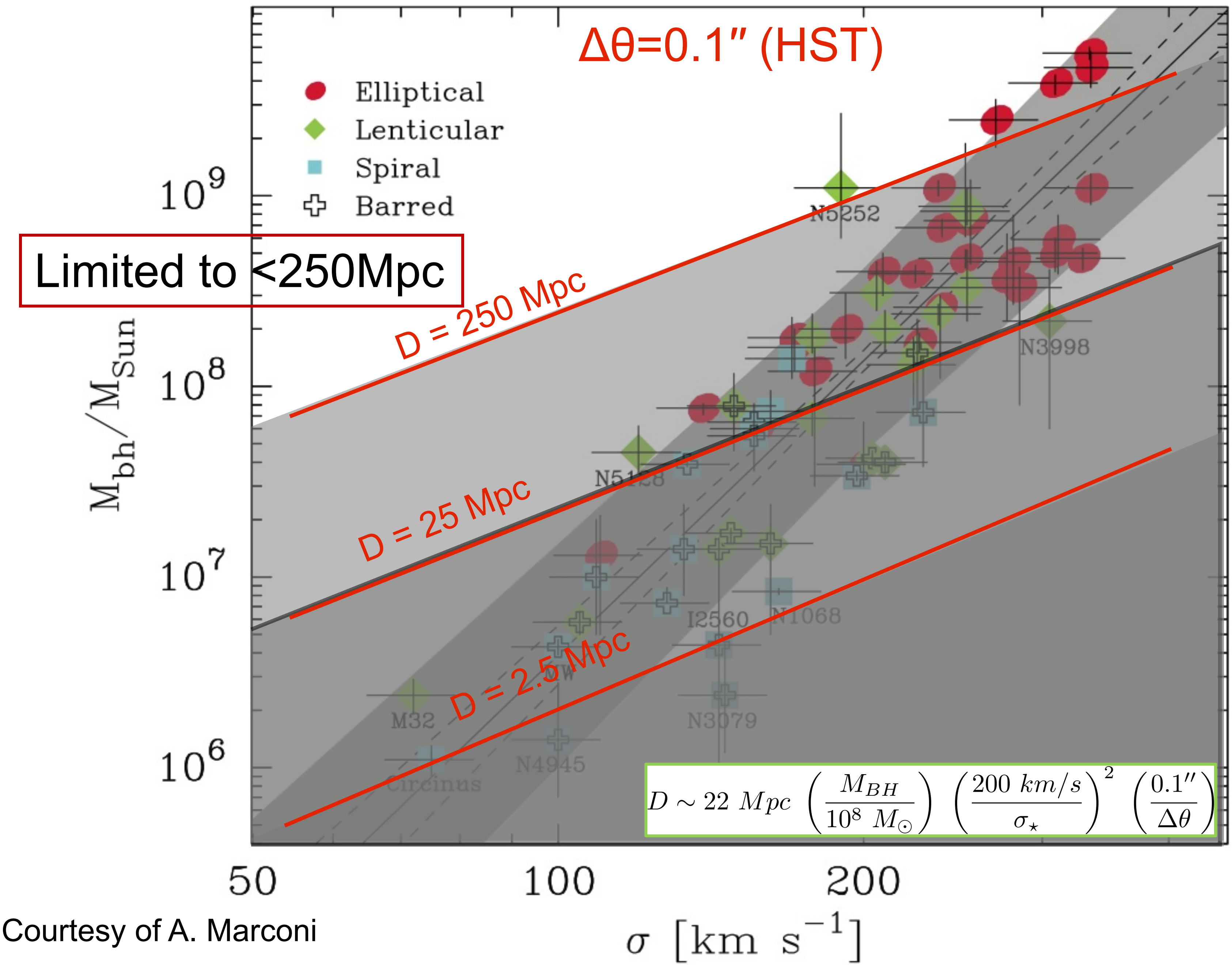
stellar velocity dispersion

At radii larger than the radius of the sphere of influence of the BH the gravitational potential of the BH rapidly vanishes

Probing the sphere of influence of a BH requires high angular resolution, thus limiting this kind of studies to nearby objects

$$\Delta\theta \sim\ 0.1'' \left(\frac{M_{BH}}{10^9\ M_\odot}\right) \left(\frac{200\ km/s}{\sigma_\star}\right)^2 \left(\frac{200\ Mpc}{D}\right)$$

Angular resolution requirements imply a maximum distance at which R_{BH} can be 'recovered'



Courtesy of A. Marconi

Sphere of influence of the BH. II

How does the BH know about its host galaxy, and galaxy about its BH?

$$R_{BH} = \frac{GM_{BH}}{\sigma_\star^2}$$

Radius of the sphere of influence of BH

$$M_{BH} \sim 10^{-3} M_{sph}$$

Observed correlation ("Kormendy", "Magorrian" relation)

$$M_{sph} \sim 5 \, \frac{\sigma_\star^2 \, R_{sph}}{G}$$

Spheroid virial mass

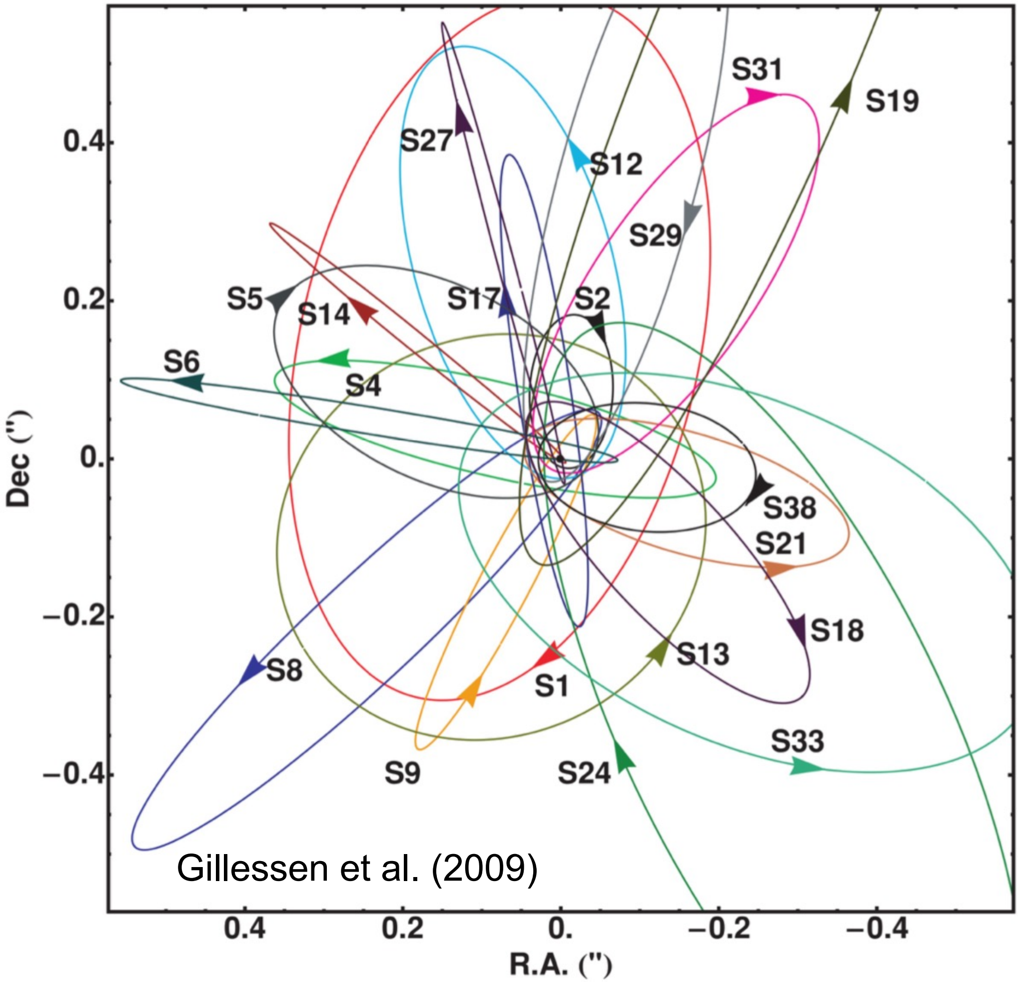
$$\Rightarrow \; R_{BH} = \frac{GM_{BH}}{\sigma_\star^2} \sim \; 5 \times 10^{-3} \; R_{sph}$$

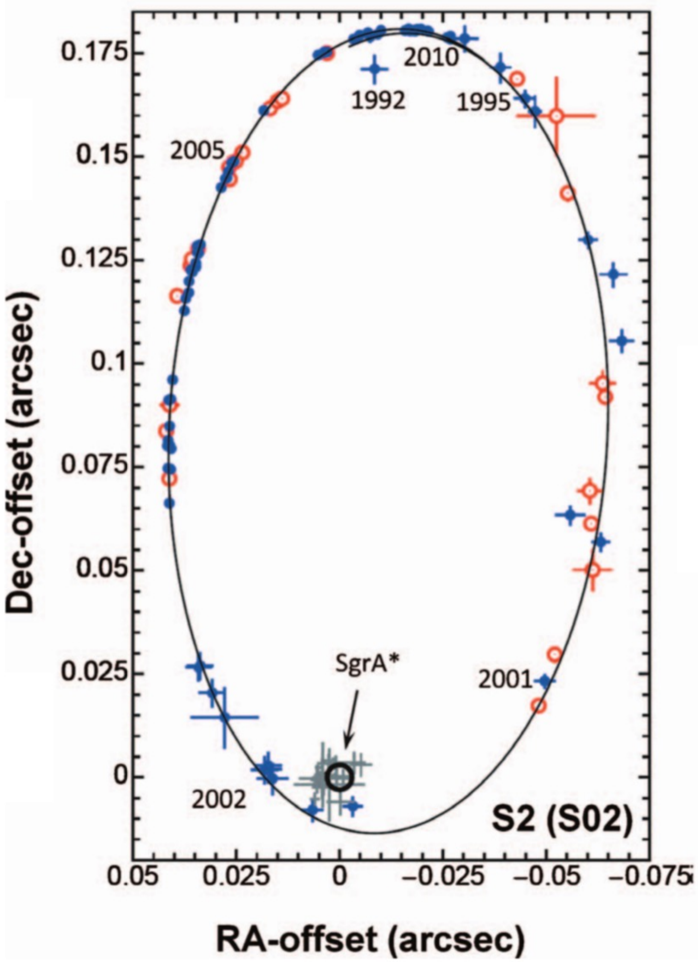
$$\Rightarrow \; V_{BH} \sim 1.3 \times 10^{-7} \; V_{sph}$$

→ The volume under the BH influence is a tiny fraction of the total volume → No gravitational 'exchange' of information

Direct methods. Dynamical measurement. I

SgrA* black hole mass

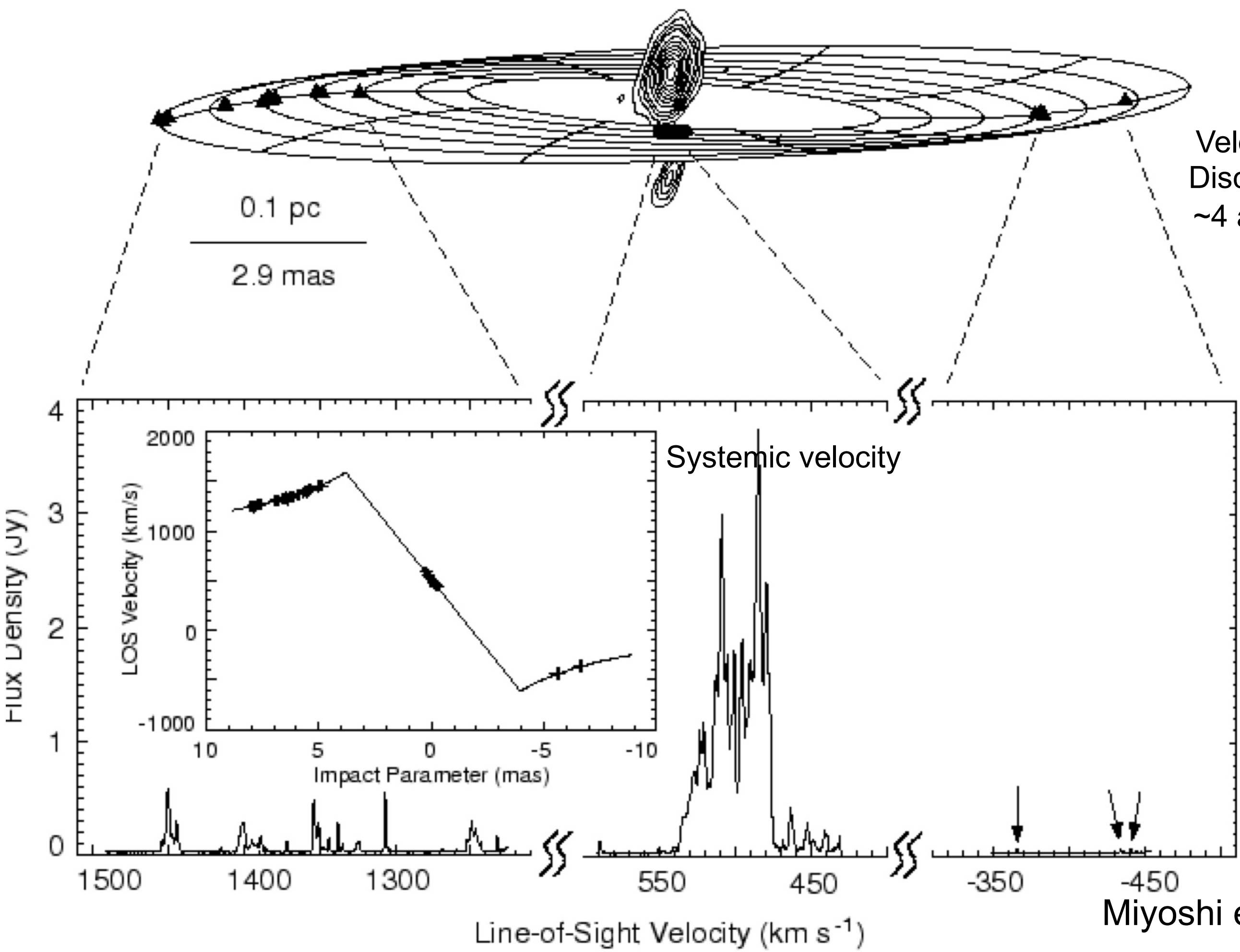




Position of 28 stars in the Galactic Center tracked for >16 yrs → $M_{BH}=(4.3\pm0.4)\times10^6\ M_\odot$ (complete orbit for S2, 125 AU) → advantage due to SgrA* vicinity to the Earth

Direct methods. Dynamical measurement. II

NGC4258 (water maser, 1.35cm) black hole mass

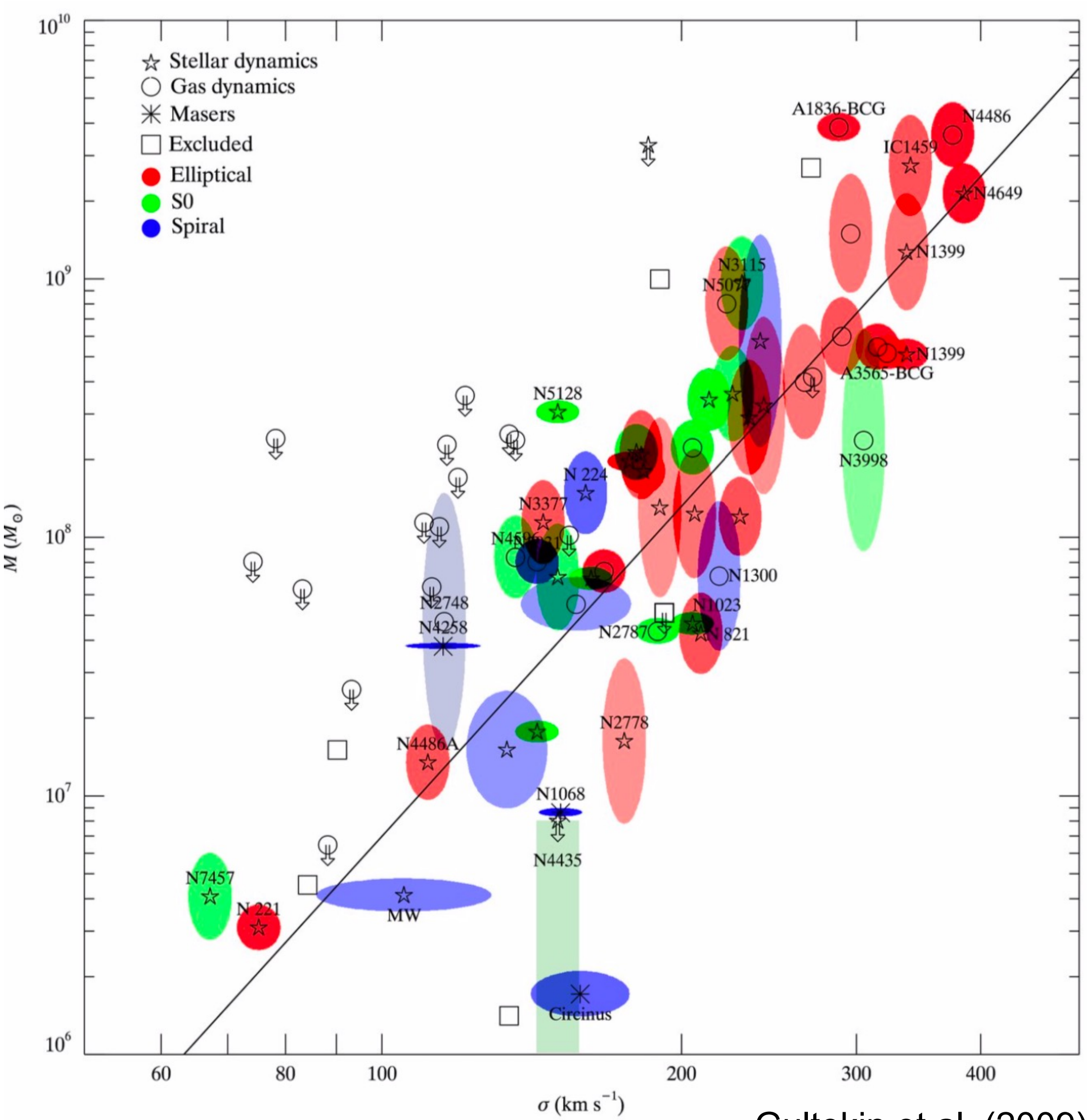


Velocity decreases as $\mathbf{r^{-1/2}}$
Disc with inner/outer size of ~4 and 8 mas, respectively

Miyoshi et al. (1995, Nature)

Probing scales of ~0.1 pc, within R_{BH}. Most accurate way to determine the differential rotation in the maser disc because of the edge-on (83±4 deg) orientation → M_{BH}=(3.6±0.1) × 10^7 $M_\odot$ → limited to few sources thus far (see also Hagiwara et al. 2021)

Direct methods. Dynamical measurement. III



Gultekin et al. (2009)

Dynamical methods are based on either stellar or gas kinematics

Tracers are the stellar absorption features in one case and the gas emission lines in the other

In both cases, the observables are the average velocity and velocity dispersion of the matter within the sphere of influence of the BH

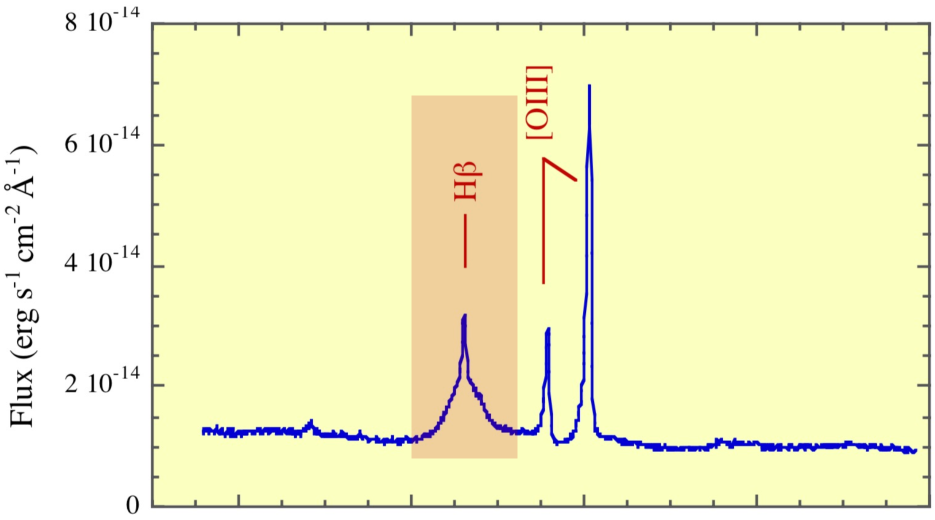
Applied to **quiescent galaxies** (otherwise the light from the AGN would most likely overwhelm the stellar light within the sphere of influence of the BH)/**weekly emitting AGN**

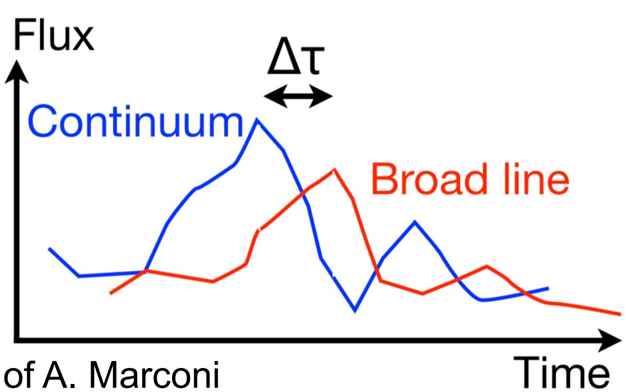
Direct methods:
The reverberation-mapping (RM) technique. I

BLR in Type 1 AGN: Doppler-broadened lines (FWHM>1000 km/s)

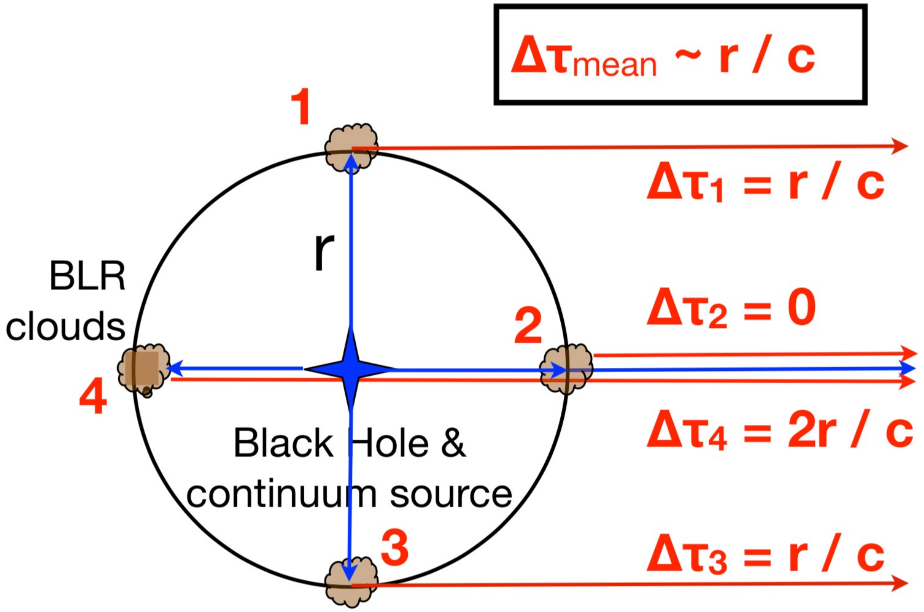
The line reberberates (responds to) changes in the continuum flux ←→ time delay of the broad line wrt the continuum light curves is light travel time

→ *Spatial resolution is 'subsituted' by time resolution*





Courtesy of A. Marconi



A step backward: the BLR. I

The broad line region has an electron density so high (up to ~10^{11} cm^{-3}) that the metastable levels of ions are collisionally de-excited → no forbidden lines
The typical temperature is ~10^4 K. A thermal broadening of ~5000 km/s would require temperatures of ~10^9 K → *broadening due to bulk motion of the emitting clouds*

In the photoionization equilibrium, the amount of ionizing photons is in balance with the rate of recombination (as already described in the lessons of *Emission Processes*) → this relates the density field of ionizing photons to the particle density

$$U = \frac{Q_{ion}}{4\pi R^2 n_e c}$$

Ionization parameter

$$Q_{ion} = \int_{h\nu > E_{ion}} \frac{L(\nu)}{h\nu} d\nu$$

Number of ionizing photons emitted by the central engine

High-ionization emission lines (higher E_{ion}, lower Q_{ion}) are expected to be generated closer to the central engine wrt. those of low ionization
→ **BLR stratification**

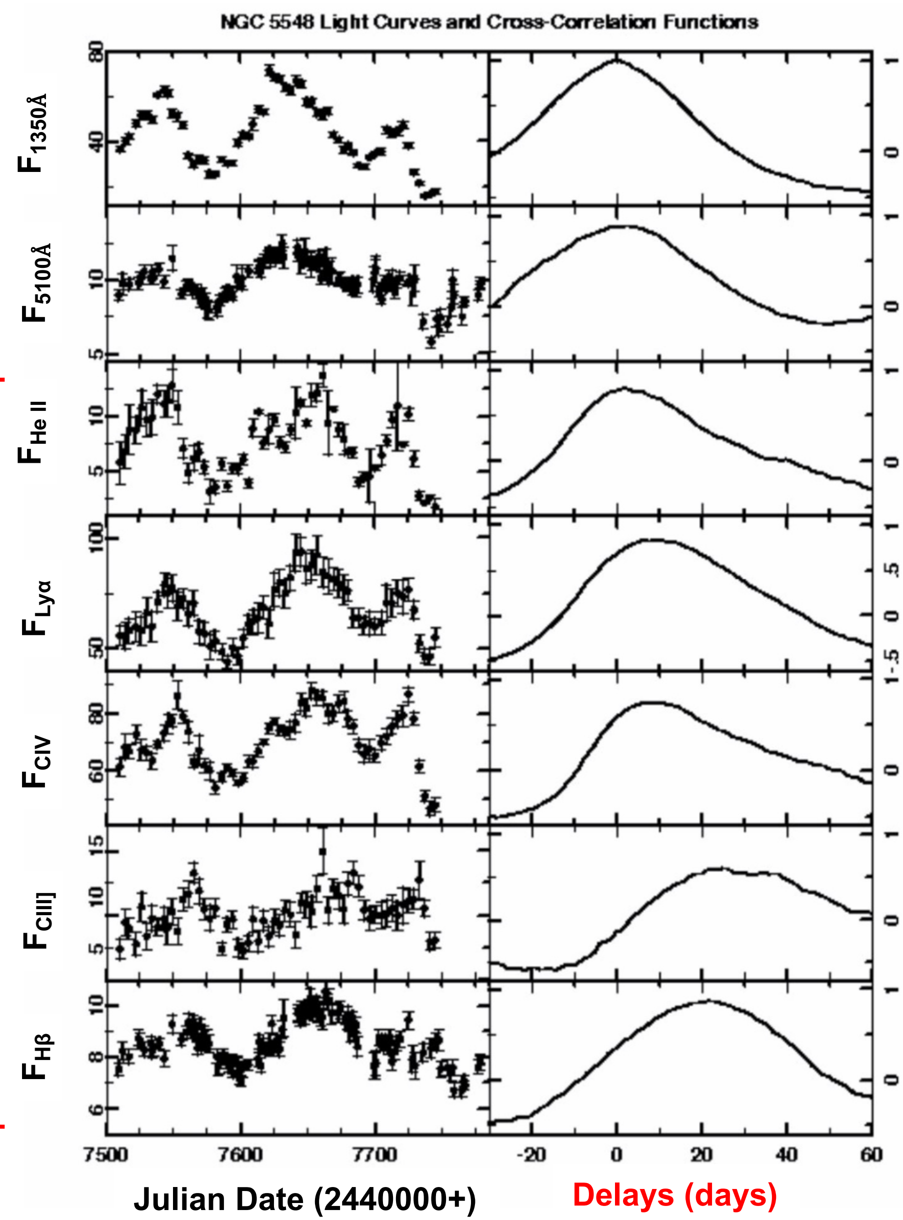
A step backward: the BLR. II

Continuum and emission line light curves (*left panels*) and cross-correlation functions (*right panels*) for time delay estimate

Emission lines 'follow' changes of the continuum emission (shorter delays for emission lines produced in the BLR closer to the BH) → **broad lines reverberate 'following' the continuum emission**

continuum

broad lines



Peterson (1997)

A step backward: the BLR. III

At a 'characteristic' distance of ~10^{17} cm (~700 R_g for a 10^9 $M_\odot$ BH), the kinematics of the BLR is mostly influenced by the gravitational field of the BH.
An example below:

$$V_K \sim \; 1.6 \times 10^4 \; \left(\frac{M_{BH}}{10^9 \; M_\odot} \; \frac{20 \; ld}{R} \right)^{1/2} \quad km/s$$

Velocity in a circular Keplerian orbit

Velocity in a circular Keplerian orbit. The observed Doppler broadening is related to the velocity component along the line of sight, i.e., multiplied by sin(Θ), with Θ being the angle between the normal to the plane of the orbit and the line of sight

Possibility that the line profile/width reflect other effects unrelated to the BH mass (inflows, outflows, etc.)

The reverberation-mapping technique. II

Apply virial theorem to estimate M_{BH}

$$M_{BH} = f\frac{V^2 R}{G}$$

V=FWHM (BLR)
R=R_{BLR}=c$\Delta\tau$=characteristic size of the line-emitting region
f=depends on the geometry and distribution of gas clouds (dynamics, orientation; several different estimates in literature)

The reverberation method applied on the same source at different times using different broad emission lines is supposed to provide always the same M_{BH} within the uncertainties (~0.5 dex, CIV-based likely more uncertain)
→ the **virial product $V^2\tau$** should be constant (broader lines are produced closer to the BH, thus responding quicker – lower τ – to changes of the continuum)
Every line has its own lag wrt. continuum variations

Often, instead of the FWHM of the emission line, the σ of the RMS spectrum (where the variable part of the emission line, arising in the very gas for which the time delay is measured, is 'isolated' from the constant part) is used (noisier but more reliable method)

$$\tau_{rec} \sim 40\ n_{11}^{-1}\ sec$$

The hydrogen recombination time in the BLR is short: the incident radiation (from the AGN accretion disc) is absorbed and reprocessed into emission-line photons quickly

The reverberation-mapping technique. III RMS spectrum

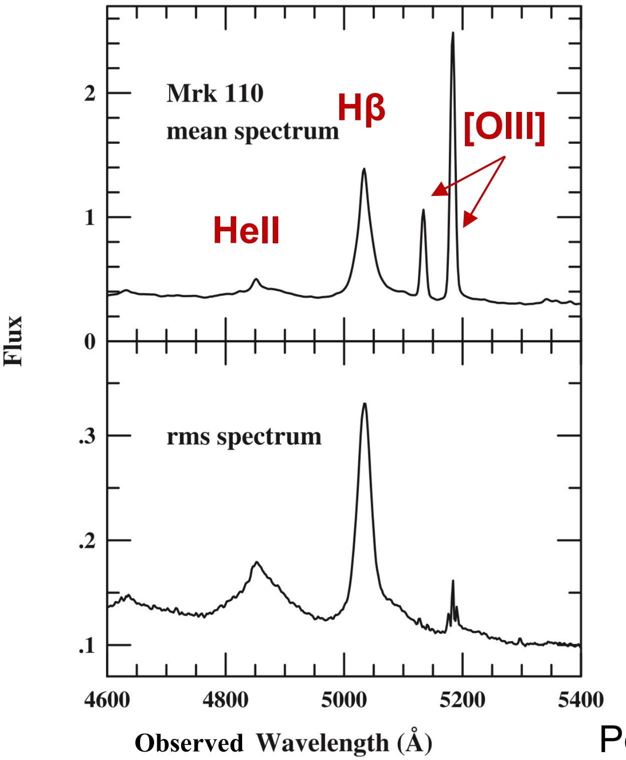
$$\overline{F(\lambda)} = \frac{1}{N} \sum_{i=1}^{N} F_i(\lambda)$$

Average spectrum of a source with N observations

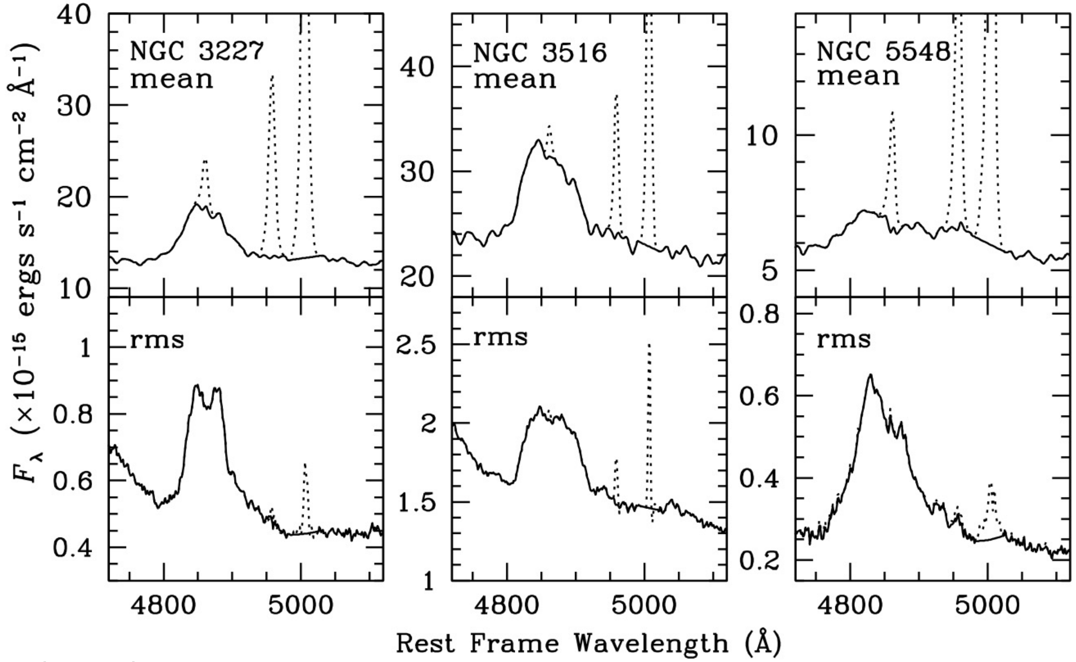
$$S(\lambda) = \left(\frac{1}{N-1} \sum_{i=1}^{N} [F_i(\lambda) - \overline{F(\lambda)}]^2 \right)^{1/2}$$

RMS spectrum

Constant components of the spectrum, or those that vary on timescales much longer than the duration of the experiment, vanish → only the parts of the emission lines which are varying are measured



Peterson et al. (2004)



Denney et al. (2009)

The reverberation-mapping technique. IV

BASIC ASSUMPTIONS (Peterson 1993, 1997)

- The continuum originates in a single source that is much smaller than the BLR

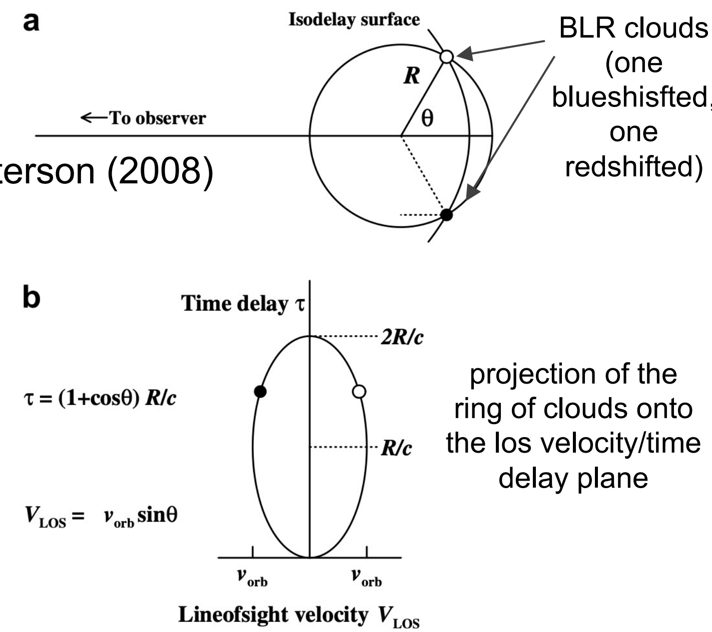
- BLR clouds occupy a small fraction of the total BLR volume (i.e., their filling factor is small), and photons propagate freely at the speed of light within such volume

- There is a simple (maybe linear) relationship between the observable UV/continuum (disc) flux and the ionizing flux which is driving the line variability

- The light-travel time across the BLR (τ_{LT} =R/c) is the dominant time scale. The recombination time (τ_{rec}) is short given the density of the medium, and τ_{LT} is short compared to the timescales on which significant geometrical changes in the BLR may occur (i.e., its dynamical timescale: $\tau_{dyn} \sim R/\Delta V_{FWHM} \rightarrow \tau_{dyn}/\tau_{LT} \sim c/\Delta V_{FWHM} \sim 100$)

The reverberation-mapping technique. V

In the real case, the observer sees at some fixed time *t* the line radiation from all isodelay surfaces, with the response of each surface being a function of the continuum level at a different time in the past
The *emission line flux at time t* is then given by integrating over all of the isodelay surfaces



Peterson (2008)

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

L(t): emission-line light curve	Transfer equation (velocity-delay map) Transfer function to a δ-function continuum pulse	C(t): continuum light curve

What it is typically done (especially in case of few/lesser quality data) consists of cross-correlating the continuum and emission-line light curves to find the temporal shift (lag) between them which maximizes the correlation

Time consuming method

The radius-luminosity relation in BLR. I

'Unknown' terms: R and f

$$M_{BH} = f\frac{V^2 R}{G}$$

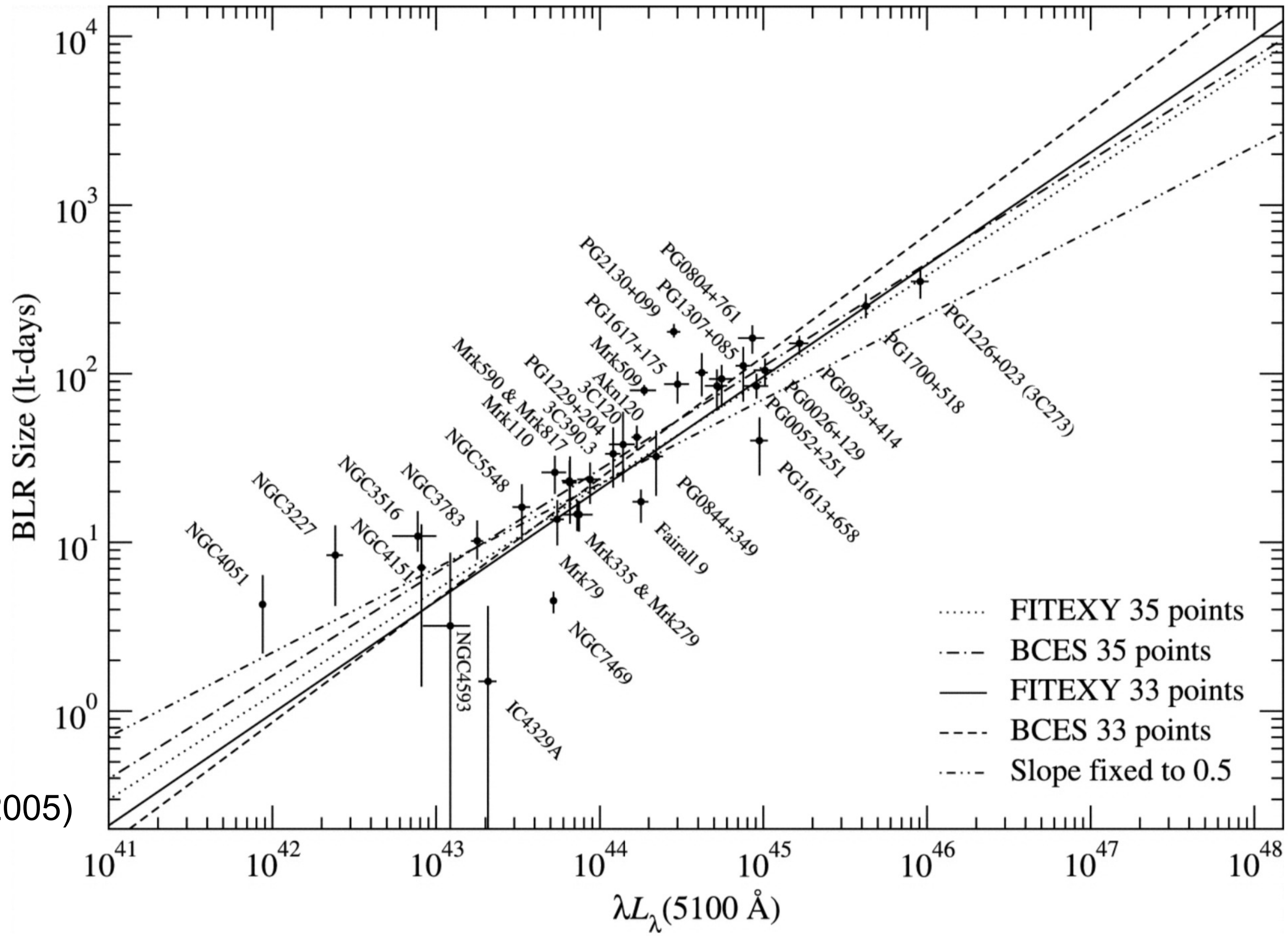
V=FWHM (BLR)
R=R_{BLR}=$c\Delta\tau$=characteristic size of the line-emitting region
f=depends on the geometry and distribution of gas clouds
(term where we place all our ignorance on BLR, see later slides)

Observationally, to some lower order of approximation (ignoring, e.g., the Baldwin effect), all AGN spectra have similar U (ionization parameter) and n_e (electron density) and $Q_{ion}/\lambda L\lambda$ ratio

$$L/R^2 \sim cons \rightarrow \; R \propto L^{0.5}$$

A given line is efficiently generated wherever the flux density of ionizing photons is in balance with the density of electrons

The radius-luminosity relation in BLR. II



Kaspi et al. (2005)

$$R \sim L^{\alpha}$$

The index is ~0.5−0.7 depending on the sample, optical/UV continuum choice, and adopted emission lines

Later results (Bentz et al. 2009) point toward **α~0.5** as theory predicts

Intrinsic scatter ~0.11 dex (Peterson 2010)

The *f* factor. I

$$M_{BH} = f\frac{V^2 R}{G}$$

V=FWHM (BLR)
R=R_{BLR}=c$\Delta\tau$=characteristic size of the line-emitting region
f=depends on the geometry and distribution of gas clouds
(term where we place all our ignorance on BLR, see later slides)

$$f = 3$$

Isotropic case

$$f = \left[\left(\frac{H}{R}\right)^2 + sin^2(\theta)\right]^{-0.5}$$

Disc-shaped BLR
H/R=height-to-radius ratio of the BLR
Θ=angle between the normal to the equatorial plane of the BLR and the observer direction

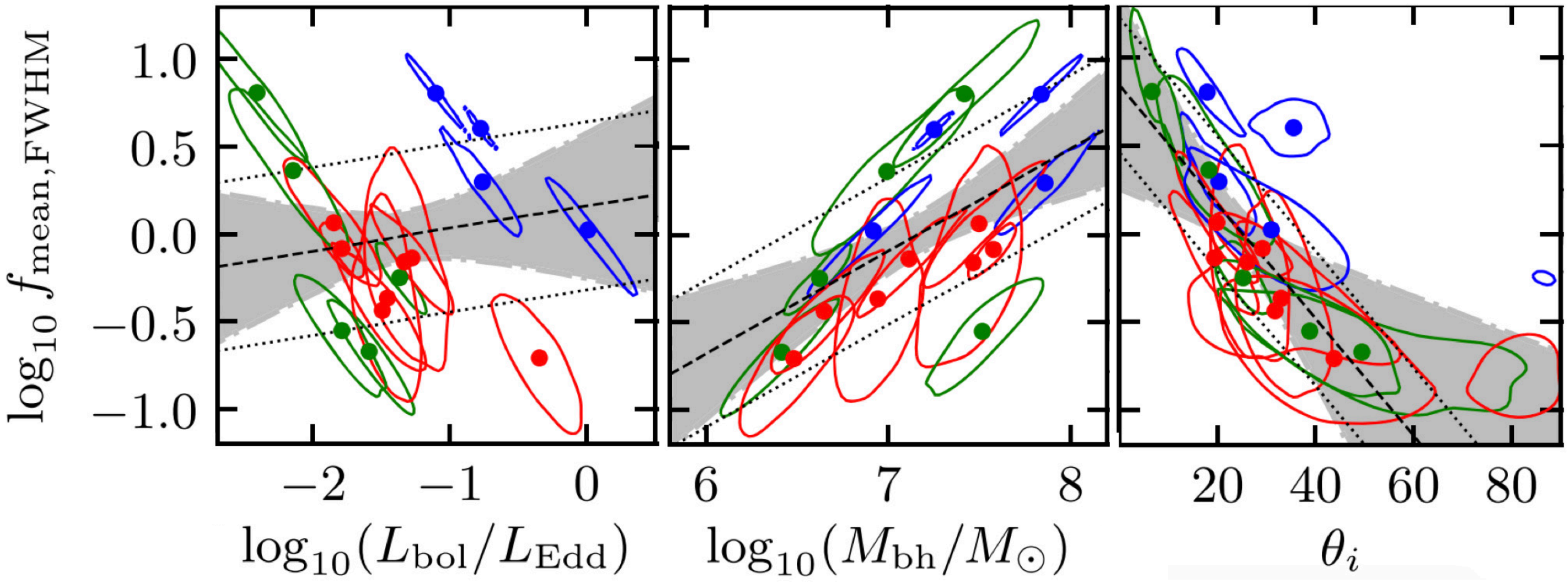
From literature:

- ⟨f⟩=5.5±1.4 (Onken+04 – normalizing the AGN (14) to the M_{BH}-$\sigma_\star$ relation)
- ⟨f⟩=5.2±1.2 (Woo+10, 24 AGN)
- ⟨f⟩=2.8±0.7 (Graham+11, 64 AGN)

Different sample size and selection, different regression analysis
Maybe finding an average *f* is an ill-posed question

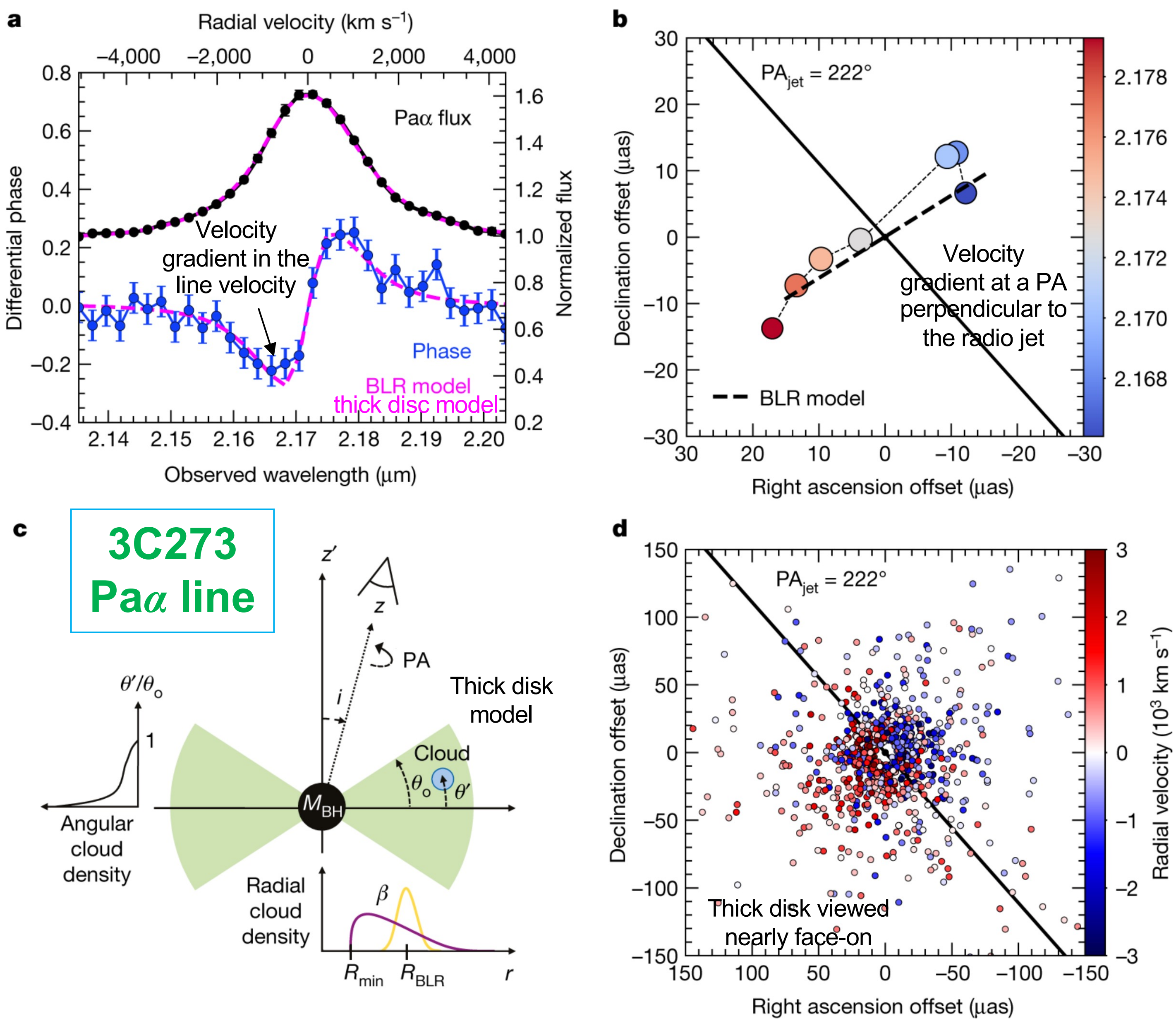
The *f* factor. II

Stronger correlation of f vs. the inclination angle of the BLR disc



Courtesy of F. Ricci

Spatially resolved BLRs: VLTI/GRAVITY



Gradient in BLR velocity perp. to jet emission

R_{BLR}=150±40 ld

see also IRAS09149-6206 GRAVITY results (2020, Brγ)

GRAVITY Coll. (2018, Nature)

Single-epoch Virial method. I

The RM method is time-consuming and can be applied mostly to low-redshift luminous AGN [luminous AGN vary with smaller amplitudes and on longer timescales than lower-luminosity, nearby AGN; also longer timescales due to time dilation: $t_{obs}=t_{rest} \times (1+z)$]

How can we possibly derive BH mass estimates in quasars at high redshift?

Single-Epoch Virial (SEV) method → scaling relations requiring FWHM and L_{cont}
Single epoch means that one spectrum is sufficient to derive the BH mass (~0.5 dex unc.)
– care must be taken line blending/narrow components, etc.

$$\log\left(\frac{M_{BH}}{M_\odot}\right) = A + 2\log\left(\frac{FWHM}{1000\ km/s}\right) + B\log\left(\frac{\lambda\ L_\lambda}{10^{44}\ erg/s}\right)$$

A, B depending on the chosen broad line and the wavelength for continuum (disc emission) evaluation. Different authors may report different values depending on the adopted sample and analyses applied. They are calibrated from RM AGN.
Typically used: Hβ (4863Å), MgII (2798Å), CIV (1549Å → often blueshifted due to outflows) and 5100Å, 3000Å and 1350Å for the continuum (each line with a continuum 'close-by' measurement)

Single-epoch Virial method. II

BASIC ASSUMPTIONS/ISSUES THAT MUST BE CONSIDERED – Part I

- The method relies on the assumption that the BLR clouds are in Keplerian orbital motion around the SMBH (i.e., the dynamics is dominated by the BH gravitational field)

- The calibration of the SEV method relies on the M_{BH}-σ and R-L relation derived from RM studies, which are 'calibrated' locally. In other words, we are assuming that the same relations hold at all redshifts, with no significant dependence on the host-galaxy type

- The virial factor *f* depends on the unknown BLR geometry and inclination wrt. the line of sight. Average *f* factors are typically assumed ($\tilde{f}$)

Single-epoch Virial method. III

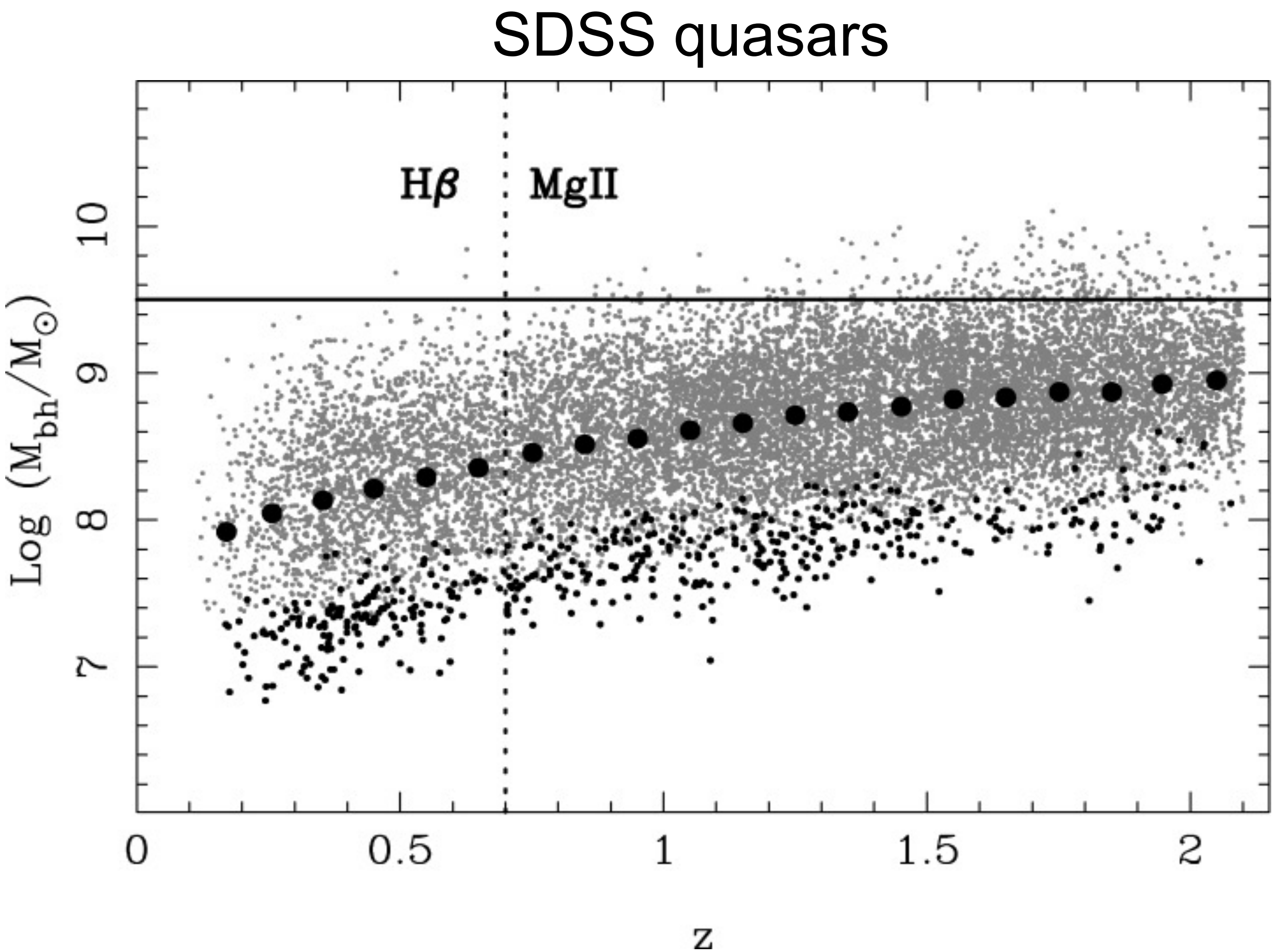
BASIC ASSUMPTIONS/ISSUES THAT MUST BE CONSIDERED – Part II

- The radiation pressure experienced by the electrons in the BLR may play a role in determining the kinematic properties of the BLR clouds (Marconi et al. 2008; Chiaberge & Marconi 2011), which would provide an under-estimation of the BH mass derived using SEV.
  $M_{BH}=f\Delta v^2 R/G + gL$, where **gL** is the term of $\mathbf{P_{rad}}$; $g \propto 1/4\pi G c m_p N_H$ → probably MgII line, being characterized by larger N_H than Hβ and CIV, is less affected by radiation-pressure effects – Marconi+12)

- Broad lines can show asymmetries which may affect the black hole mass estimate. Broad/narrow line decomposition is not unique, and a line profile should be assumed

- Host-galaxy starlight may contaminate the continuum emission. Similarly, jet emission in radio-jetted AGN may provide a further source of contamination

Single-epoch Virial method. IV

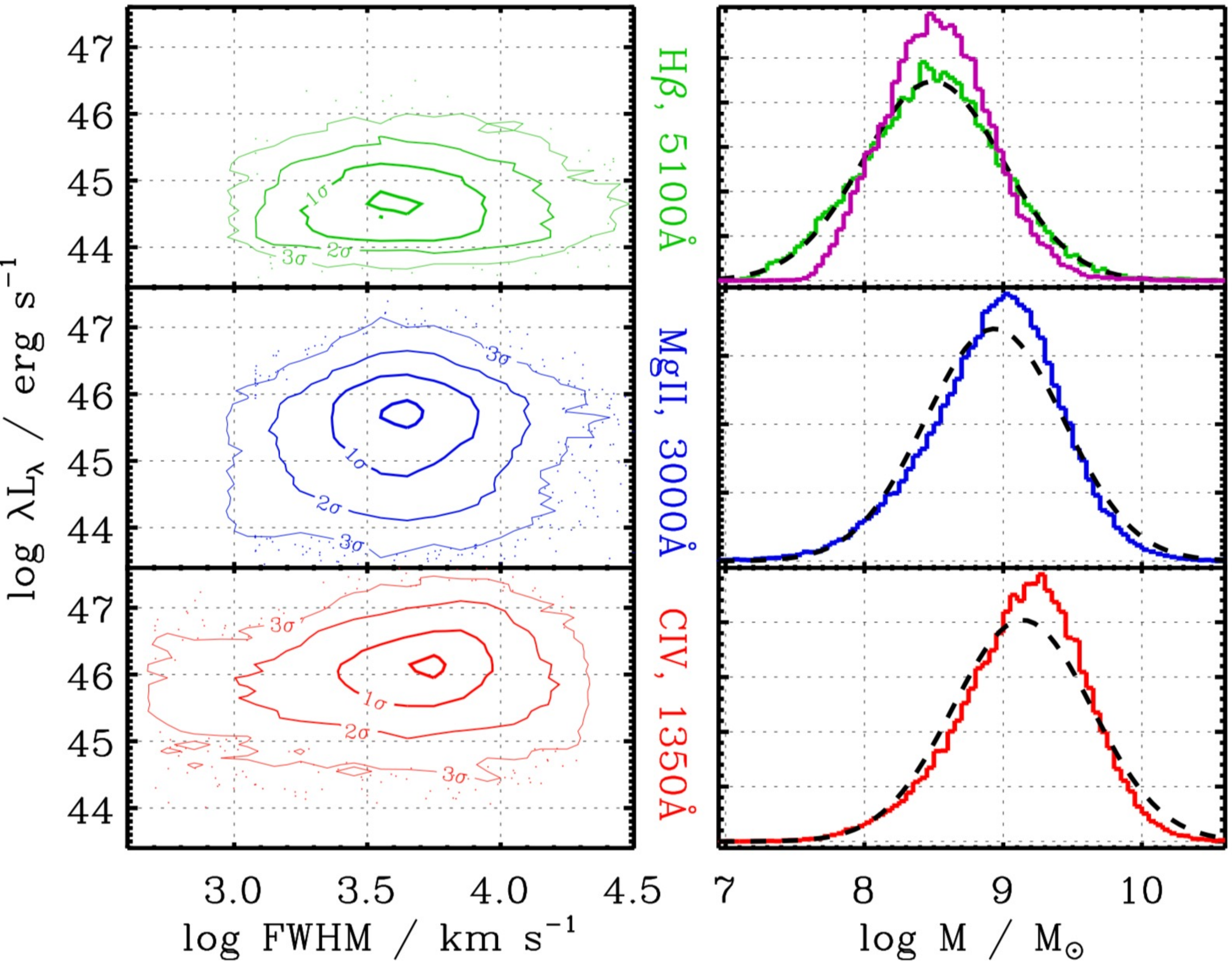


BL: grey points
(larger points:
average values)

McLure & Dunlop (2004)

Single-epoch Virial method. V

Shen+11 SDSS catalog | **BH mass distributions**



Vestergaard & Peterson (2006): **Hβ**+**CIV**

Shen+11: (**MgII**)

Chiaberge & Marconi (2011): **CIV** + **Prad** correction

What about BH masses in obscured AGN? I

One approach relies on scaling relations using the bulge of the host galaxy/stellar mass (e.g., Sani et al. 2011)

Otherwise, in order to have a direct view of the BLR also in obscured systems, near-IR observations are required → near-IR Paschen lines

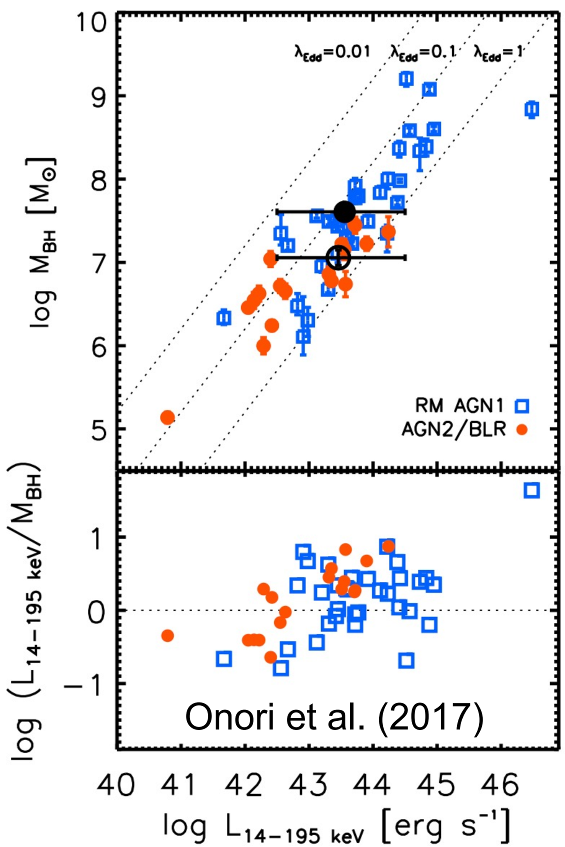

Courtesy of F. Ricci

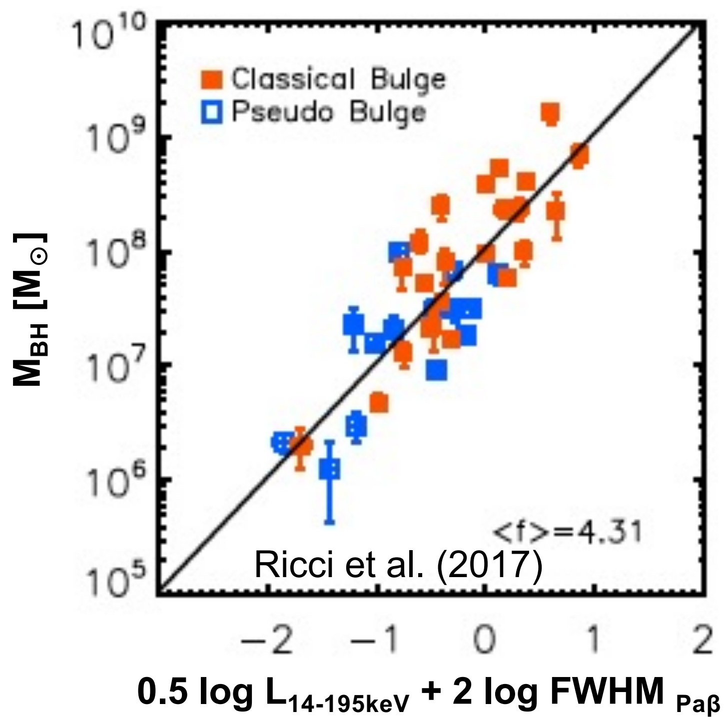
- Near-IR observations at high SNR have revealed broad Paschen emission lines in Type 2 AGN in the past (e.g., Veilleux+97, Riffel+06, Cai+10)
- In the near-IR, dust extinction is less severe than in the optical band (by ~a factor of 10; e.g., Veilleux+02)
- Paschen α (1.87μm) and β (1.28μm) lines are the strongest hydrogen emission lines observed in the near-IR and are almost unblended (e.g., Riffel+06, Landt+08)
- Other near-IR lines are also viable (e.g., HeI)

What about BH masses in obscured AGN? II

$$\log\left(\frac{M_{BH}}{M_\odot}\right) = 7.75 + \log\left[\left(\frac{FWHM_{NIR}}{10^4\ km/s}\right)^2 \left(\frac{L_{14-195keV}}{10^{42}\ erg/s}\right)^{0.5}\right]$$

La Franca et al. (2015), Ricci et al. (2017), Onori et al. (2017);
see also Kim et al. (2010, 2018) and Landt et al. (2013)





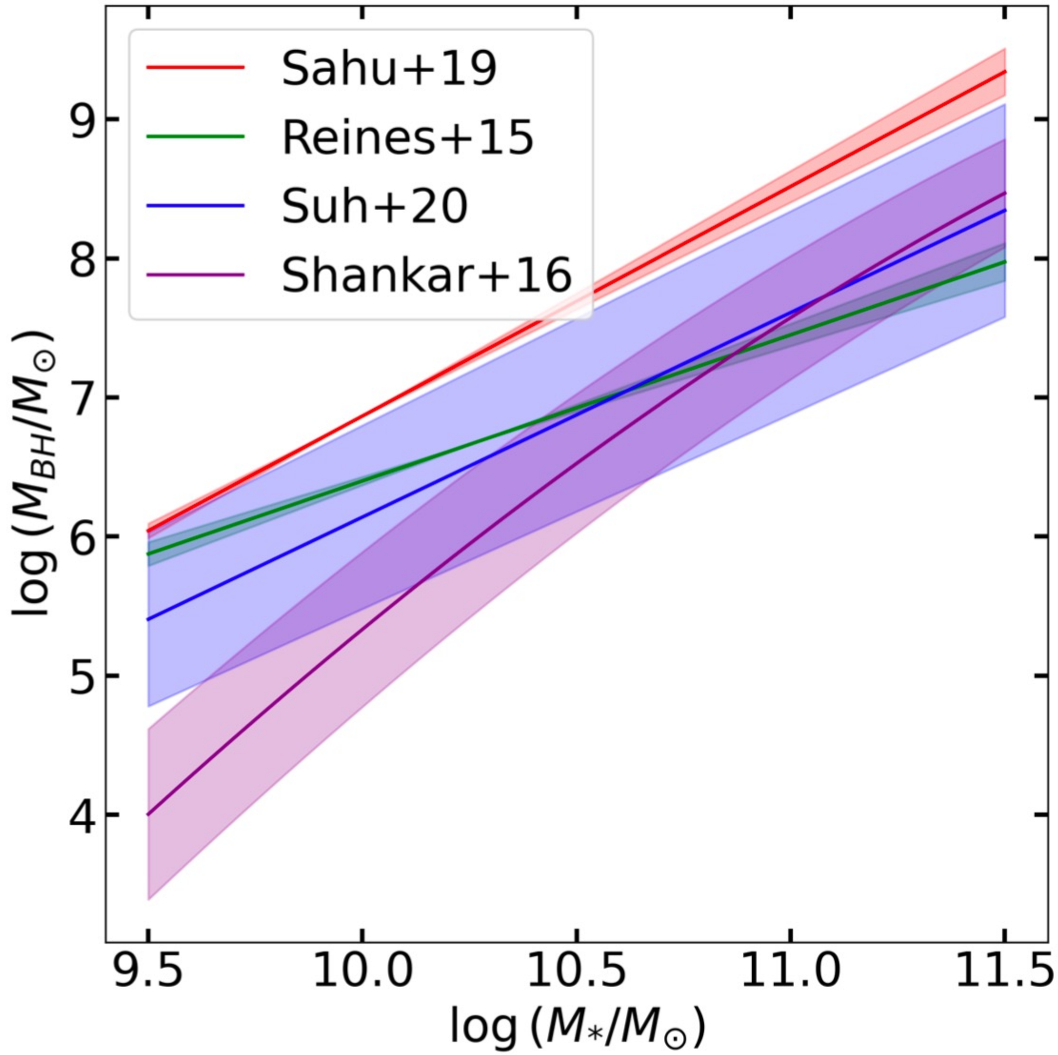
Near-IR lines instead of optical/UV lines

Hard X-ray luminosity instead of optical/UV continuum lum.

L_X virial-based BH mass

Possible applications:
Type 2 AGN, low-lum BL AGN

What about BH masses in obscured AGN? III



Courtesy of L. Barchiesi

Sahu+19: 84 early-type galaxies with a direct SMBH mass measurement (modelling of stellar/gas dynamics, H_2O megamasers)

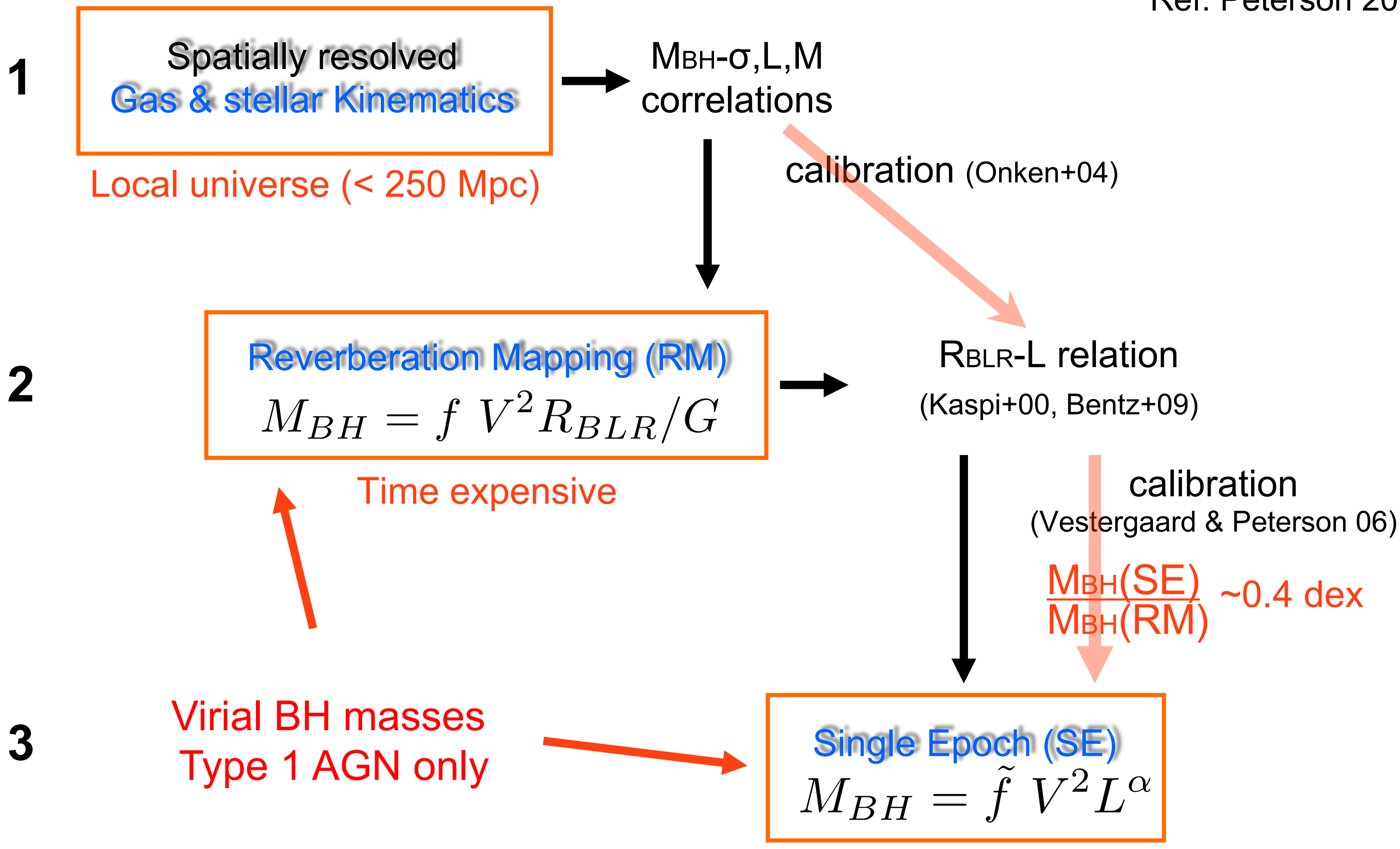
Reines & Volonteri 15: Type 1 AGN + galaxies (masses from single-epoch measurements + RM for AGN; stellar/gas dynamics + masers for galaxies)

Suh+20: X-ray selected AGN with single-epoch BH measurements (only Type 1 AGN)

Shankar+16: sources from five different literature samples of galaxies with BH dynamical mass measurements

The BH mass ladder

Ref: Peterson 2004



Courtesy of A. Marconi

All the pieces of the puzzle …

Courtesy of A. Marconi