UNIVERSITÀ DEGLI STUDI FIRENZE

High angular resolution observations of Active Galactic Nuclei

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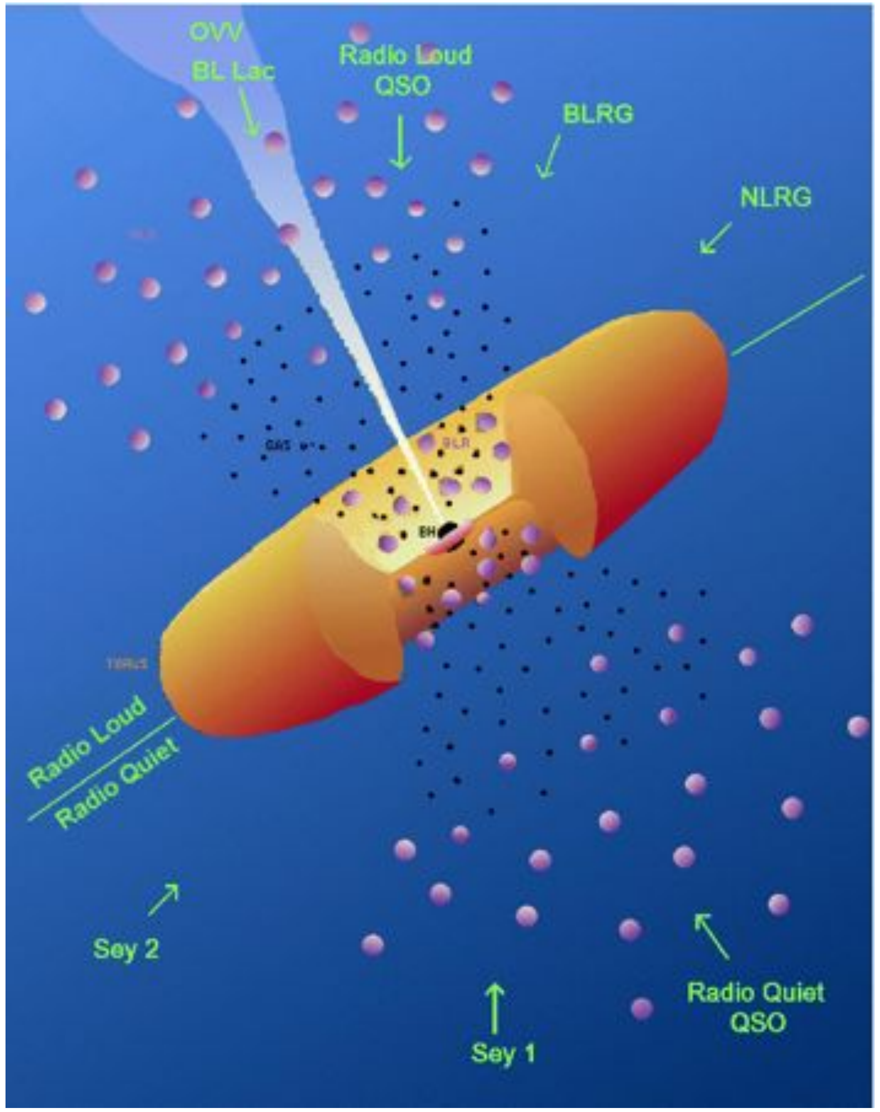
The Unified model

Our pre-2000 view of AGN

- AGN are powered by accretion onto supermassive Black Holes (e.g. Salpeter 1964, Zel'dovich 1964)
- Broad Line Region: clouds close to AGN with large velocities (> 1000 km/s) …
- Narrow Line Region: clouds at larger (galactic) scales, smaller velocities (a few 100 km/s)
- Different classes of AGN are the effect of different inclination of line of sights w.r.t. to dusty torus (Antonucci & Miller 1985; Antonucci 1993): torus can hide BLR and accretion disk from view, reprocesses accretion disk emission and re-emits IR radiation



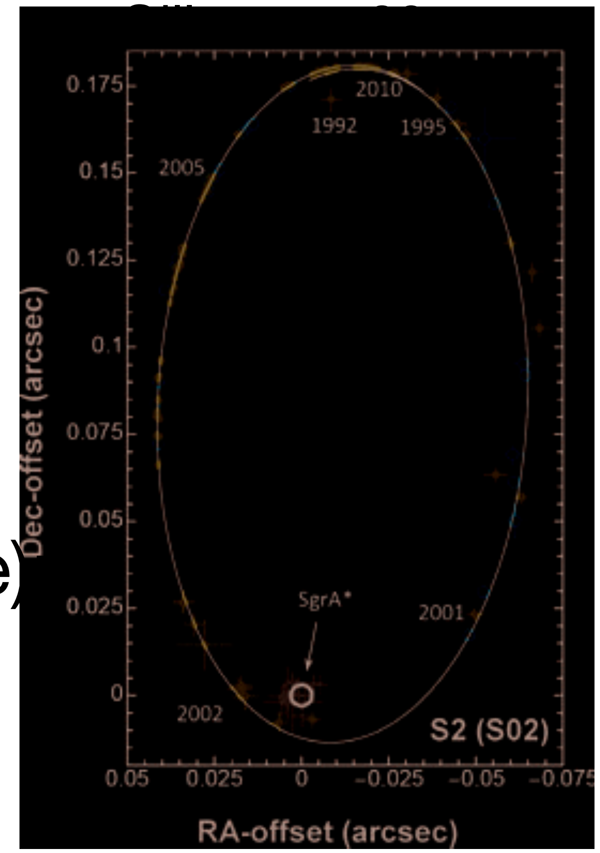
Urry & Padovani 1995

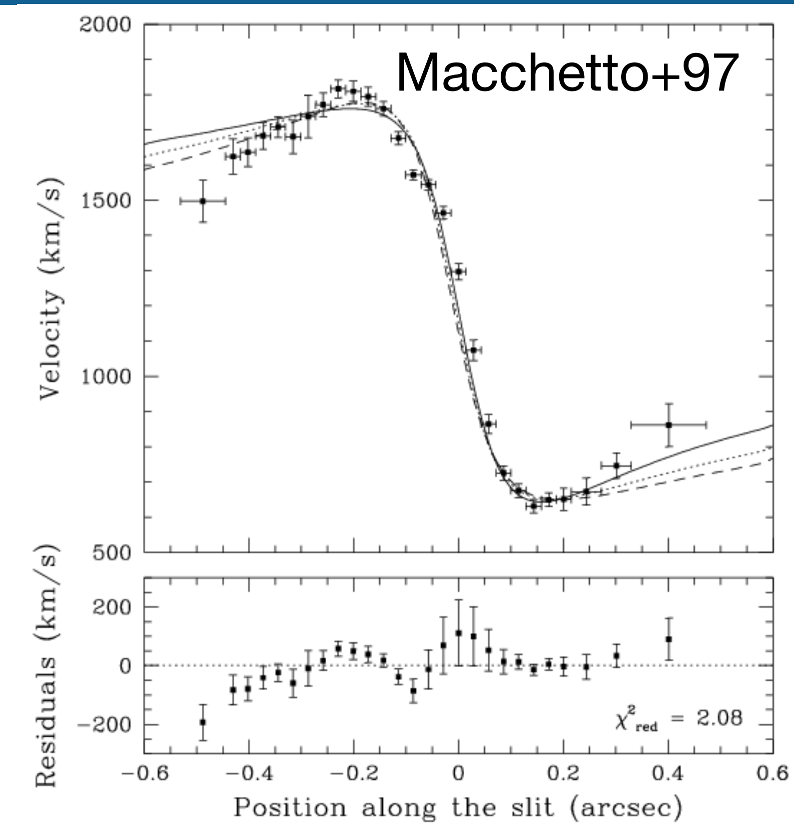
- AGN as "exotic" objects, laboratories for strong gravity physics and other interesting phenomena

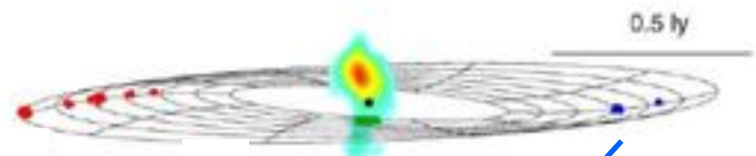
Supermassive Black Holes

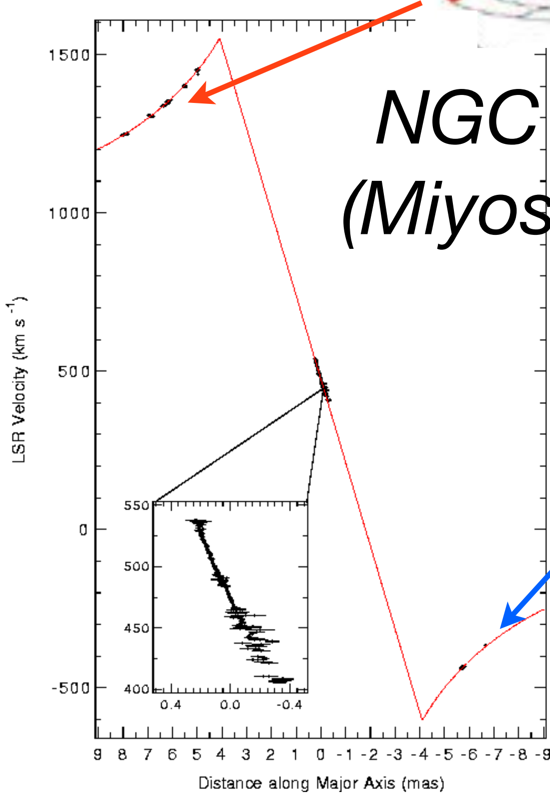
Our view changes in early 2000

- End of 1990s: HST discovery of many supermassive BHs in galactic nuclei
- Correlations between M_{BH} and properties of host spheroid (bulge) M_{BH}-σ relation
- Local BHs are relics of past AGN activity



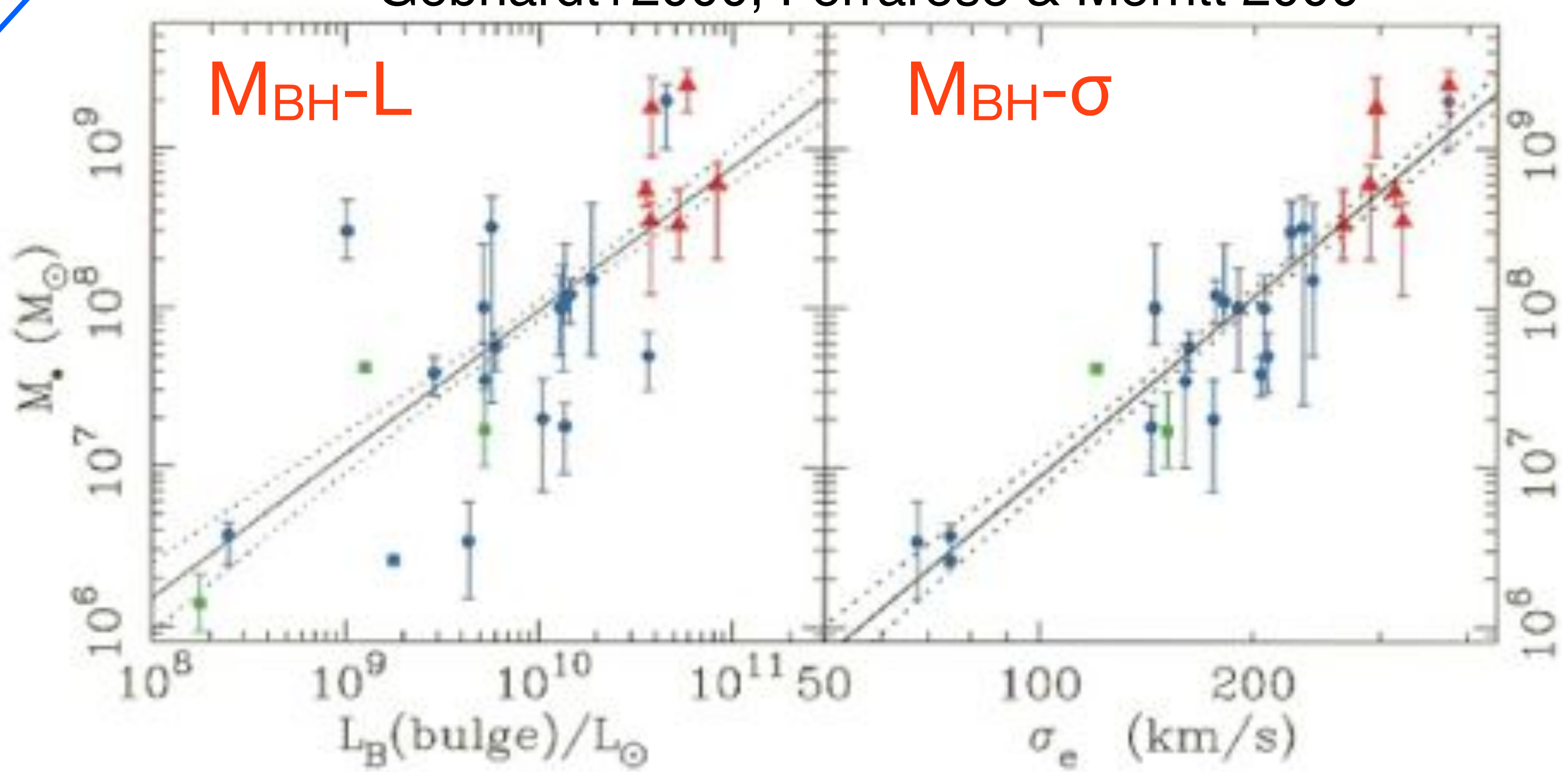






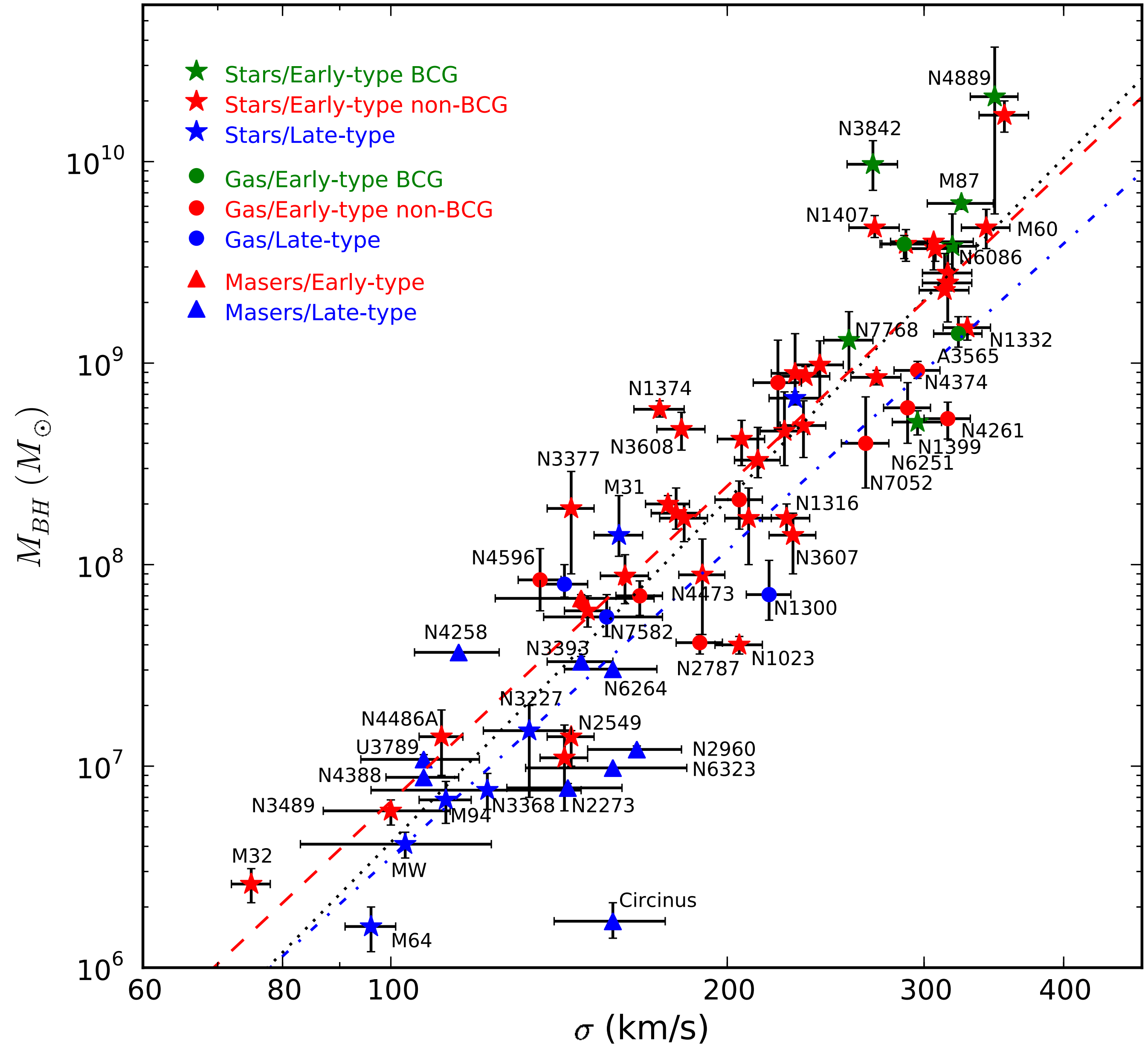
NGC 4258 (Miyoshi+95)

Gebhardt+2000, Ferrarese & Merritt 2000



Importance of BH-galaxy relations

- BH gravitational influence over a volume ~10^{-7} that of host galaxy
- How can BH know about galaxy and vice-versa?
- AGN feedback: with massive BH ($M_{BH} > 10^7\ M_\odot$), AGN luminous enough ($L \sim L_{Edd}$) to affect host galaxy
- Gas is expelled quenching both BH accretion and star formation: situation in frozen when $M_{BH}/M_{gal} \sim 10^{-3}$ (but it is not so simple ...)



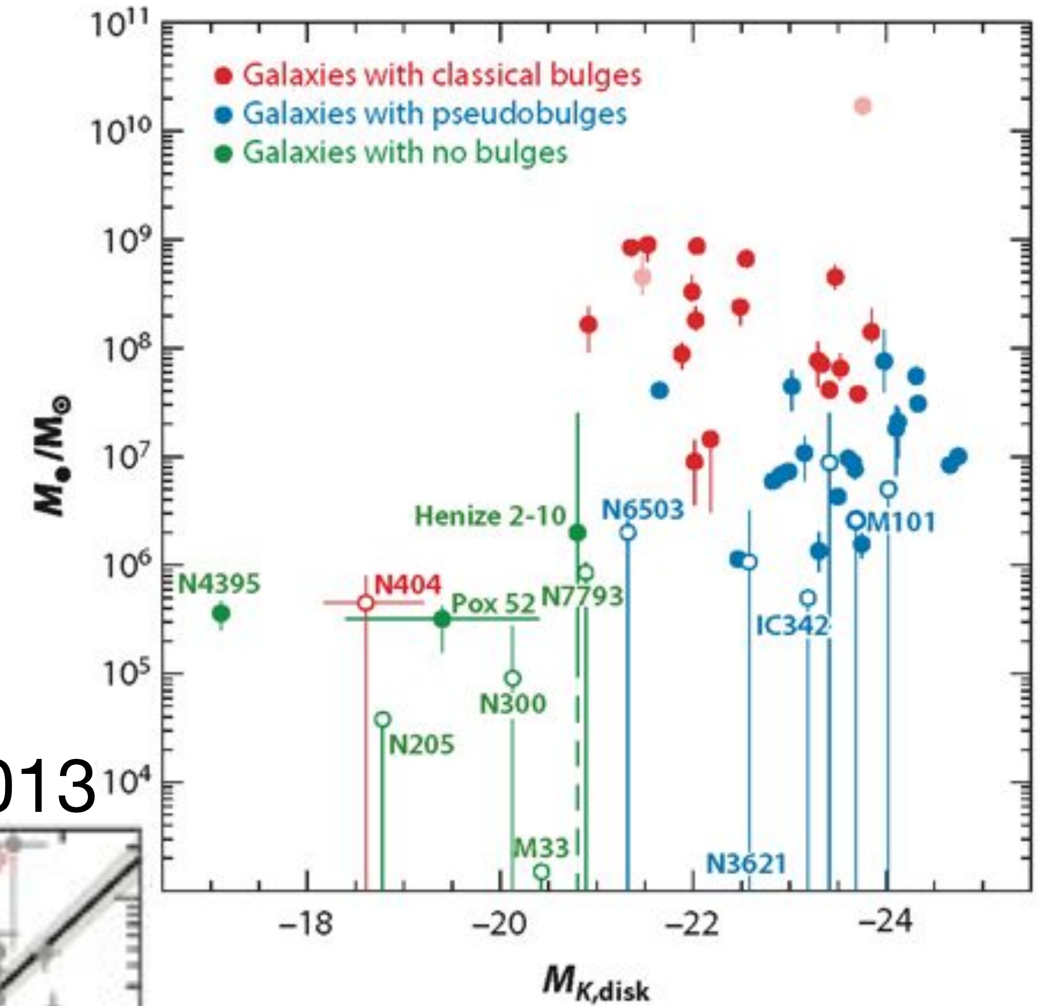
McConnell+2011

- *Co-evolution of BHs and host galaxies (see, eg, Kormendy & Ho 2013)*
- *AGN are protagonists of galaxy evolution!*

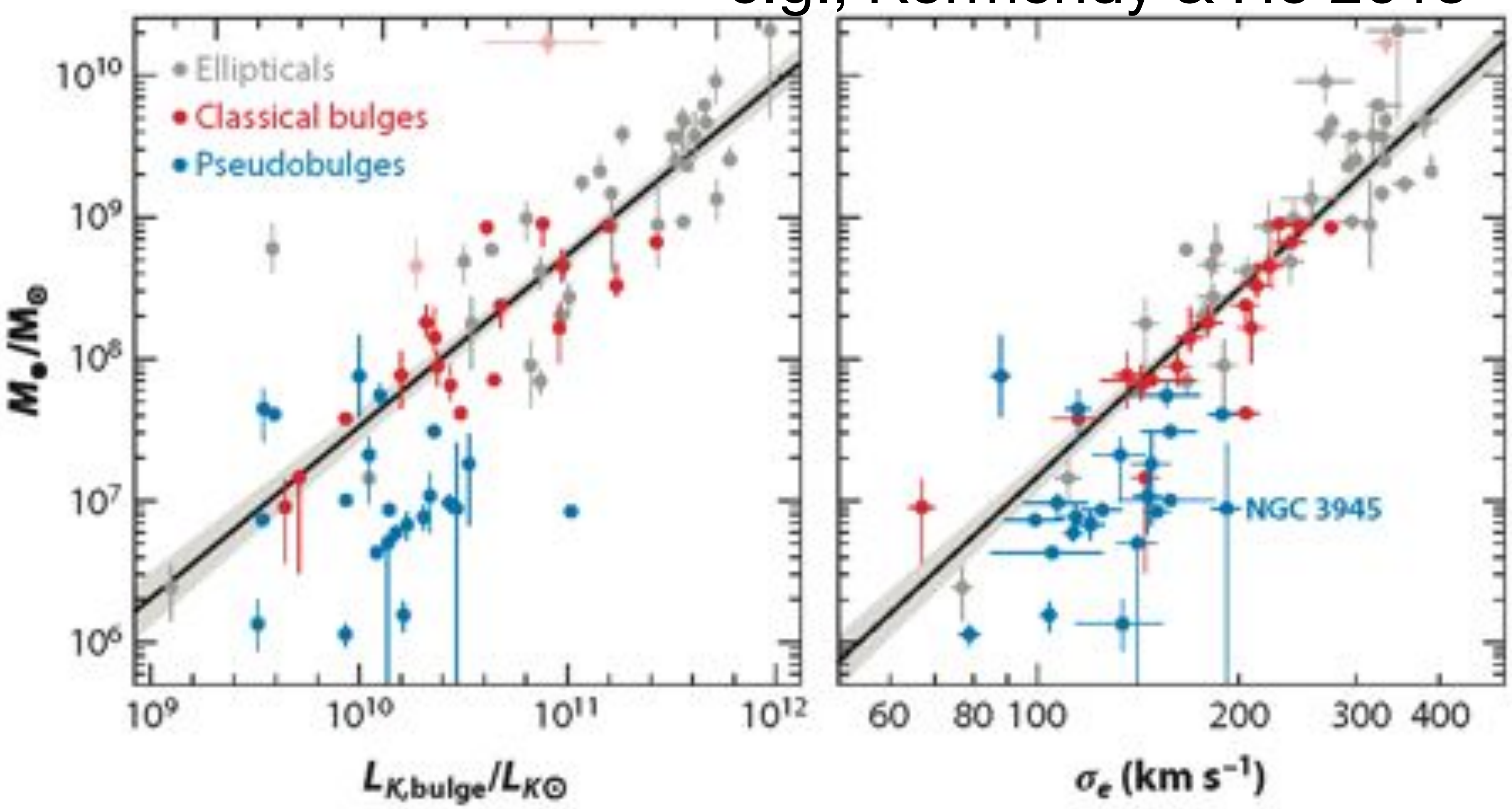
Complex BH-galaxy relations

Our view has further changed in recent years

- different BH-galaxy relations for different “bulges”, disks do not correlate
- classical bulges: form after merger events, feedback is important
- pseudo bulges: form by secular processes, no feedback required



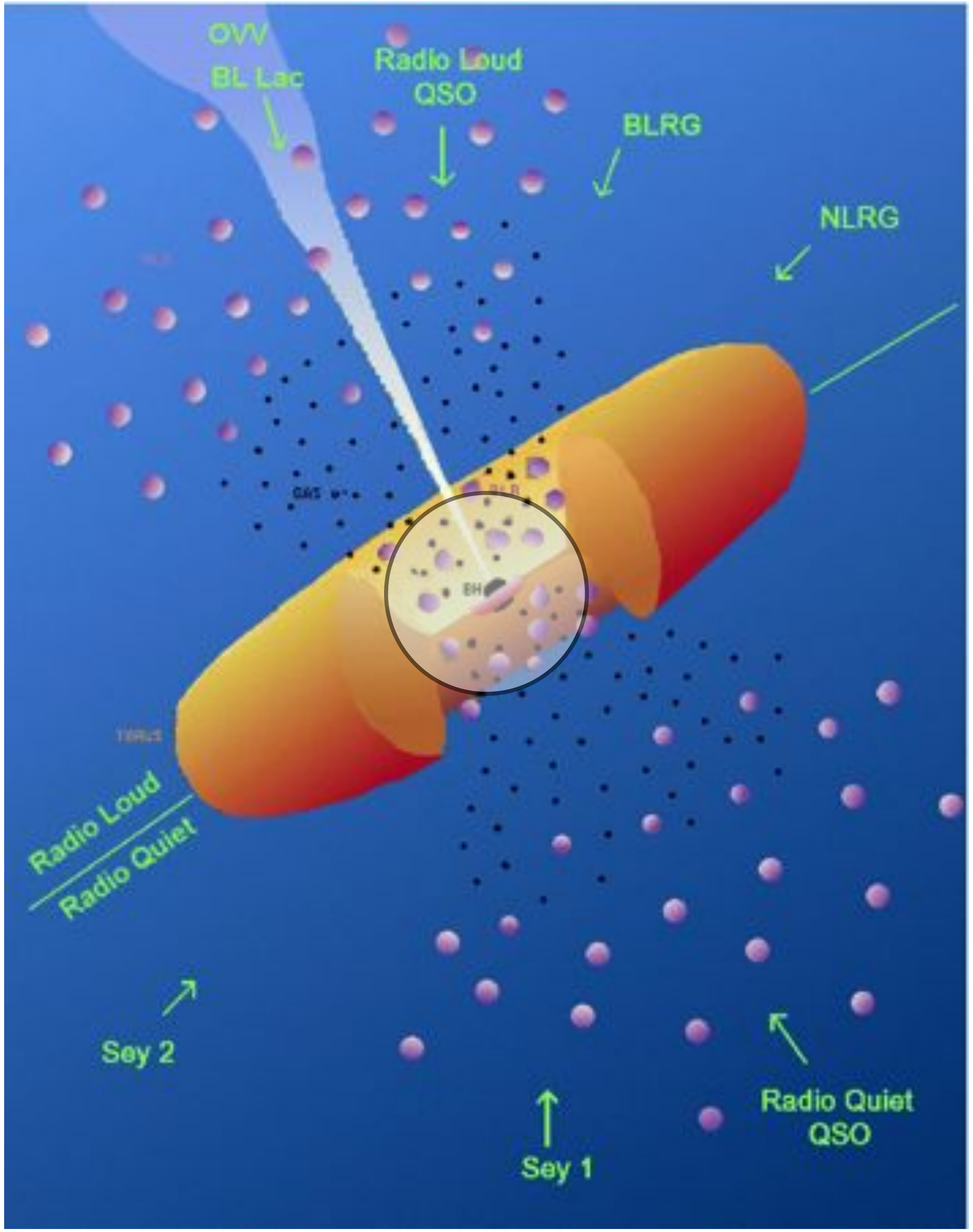
e.g., Kormendy & Ho 2013



- but there are BHs in bulgeless galaxies …

More complex than we previously thought …

BLR, Torus & Beyond



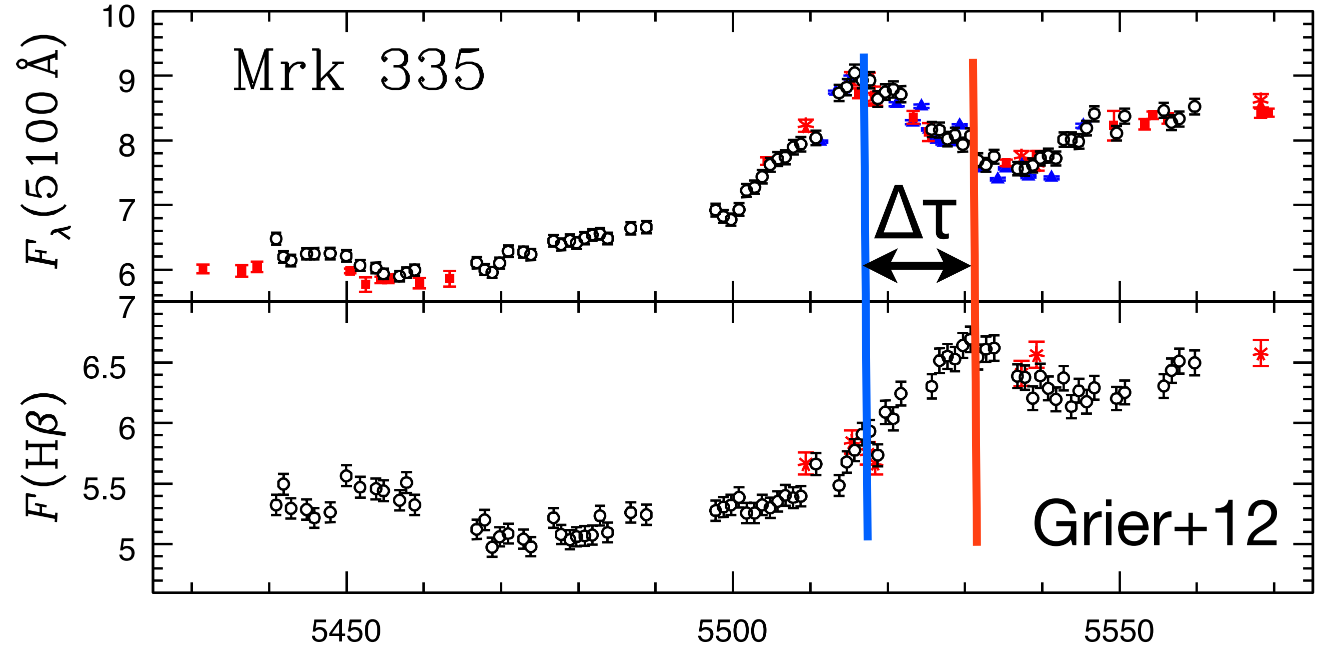
Reverberation mapping of BLR

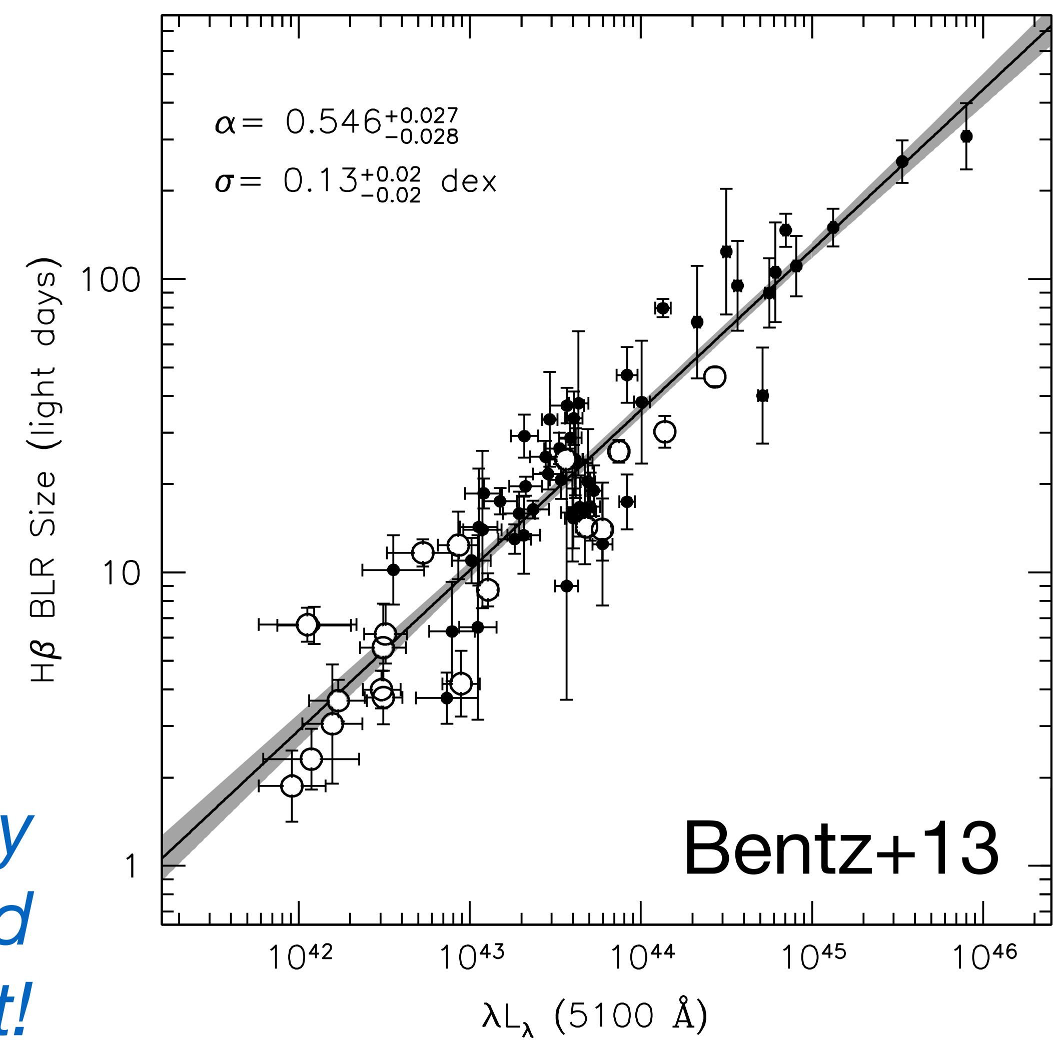
- Light curves of continuum and broad emission lines are similar
- time lag (= light crossing time) implies small dimensions of BLR ($R_{BLR} = c\,\Delta\tau$)
- Combine line widths with time lags to estimate BH mass (e.g. Peterson et al.)

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

- $M_{BH} \sim 10^6$-$10^9\ M_\odot$ found
- Radius luminosity relation: $R_{BLR} \sim L_{AGN}^{0.5}$ (Kaspi+00,Bentz+13)
- BLR is photoionized from central continuum source

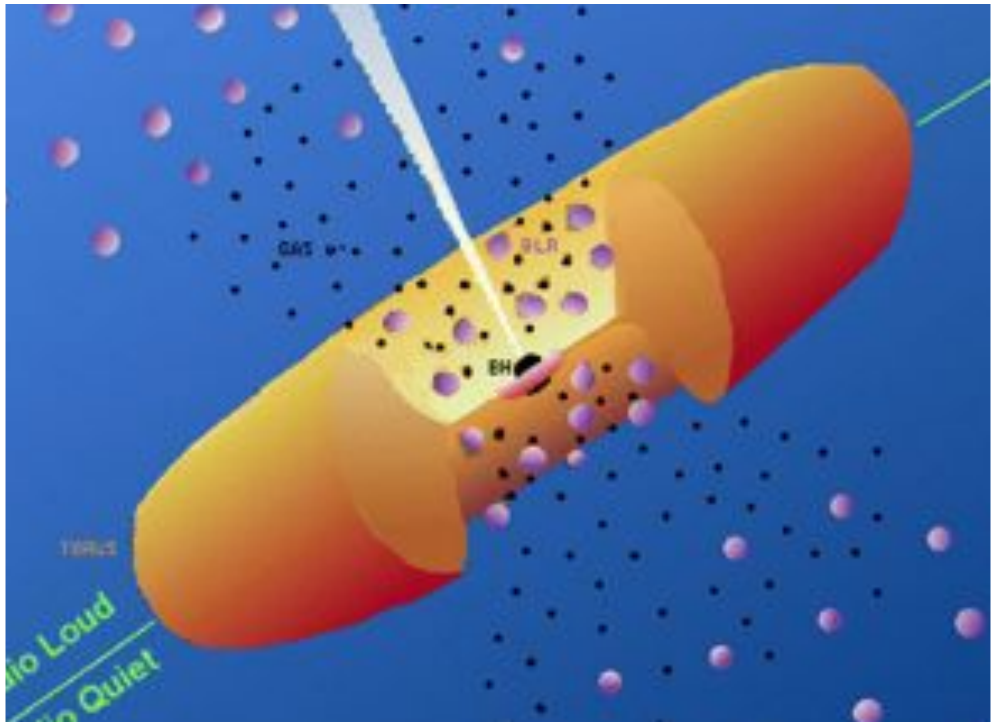
Possible to measure BH masses from any type 1 spectrum (combine line width and L_{AGN}); no distance limit!

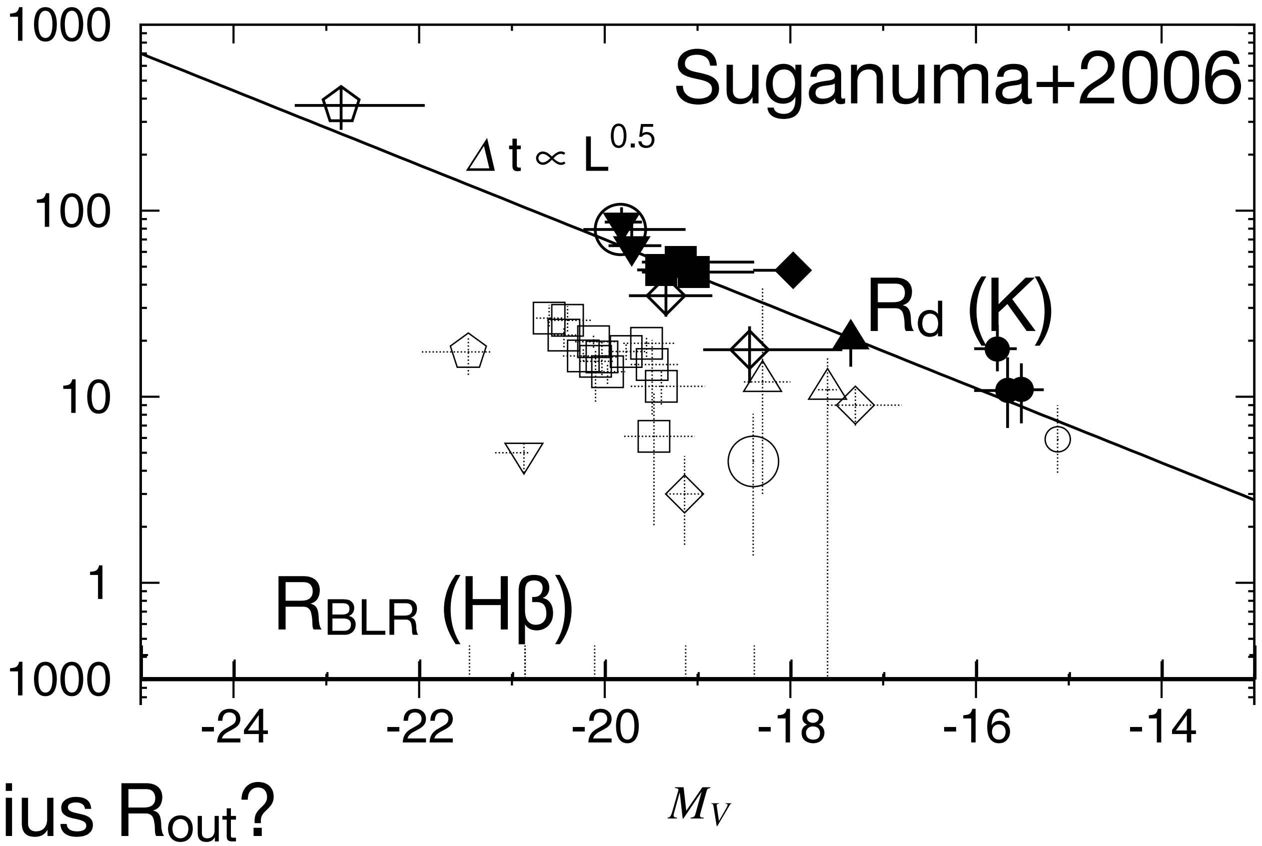




The Obscuring Torus

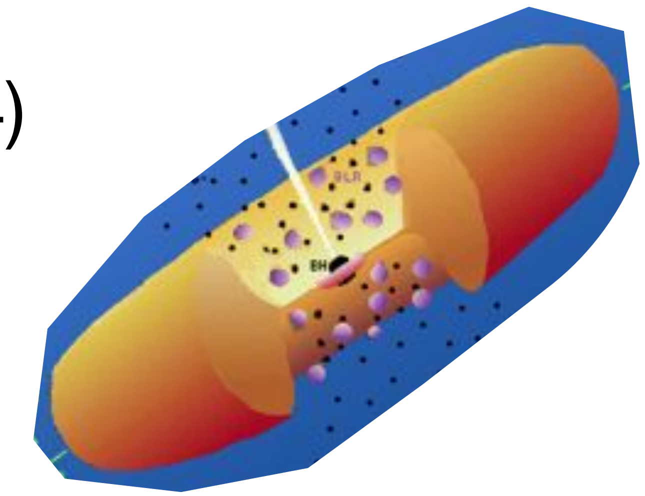
- provides selective nuclear obscuration required by unified model (Antonucci 1993)
- contributes significantly to IR emission of AGN (reprocessed UV radiation)
- possible contribution to IR cosmic background (Gruppioni+10, Pozzi+12)
- might provide X-ray absorption to explain X ray background (Setti & Woltjer 1989, Gilli+2007)
- Inner radius set by dust sublimation $R_d \sim 0.4\ L_{45}^{1/2}$ pc
- Dust sublimation radius confirmed by K band reverberation mapping
- R_d outer boundary of BLR, Outer radius R_{out}?

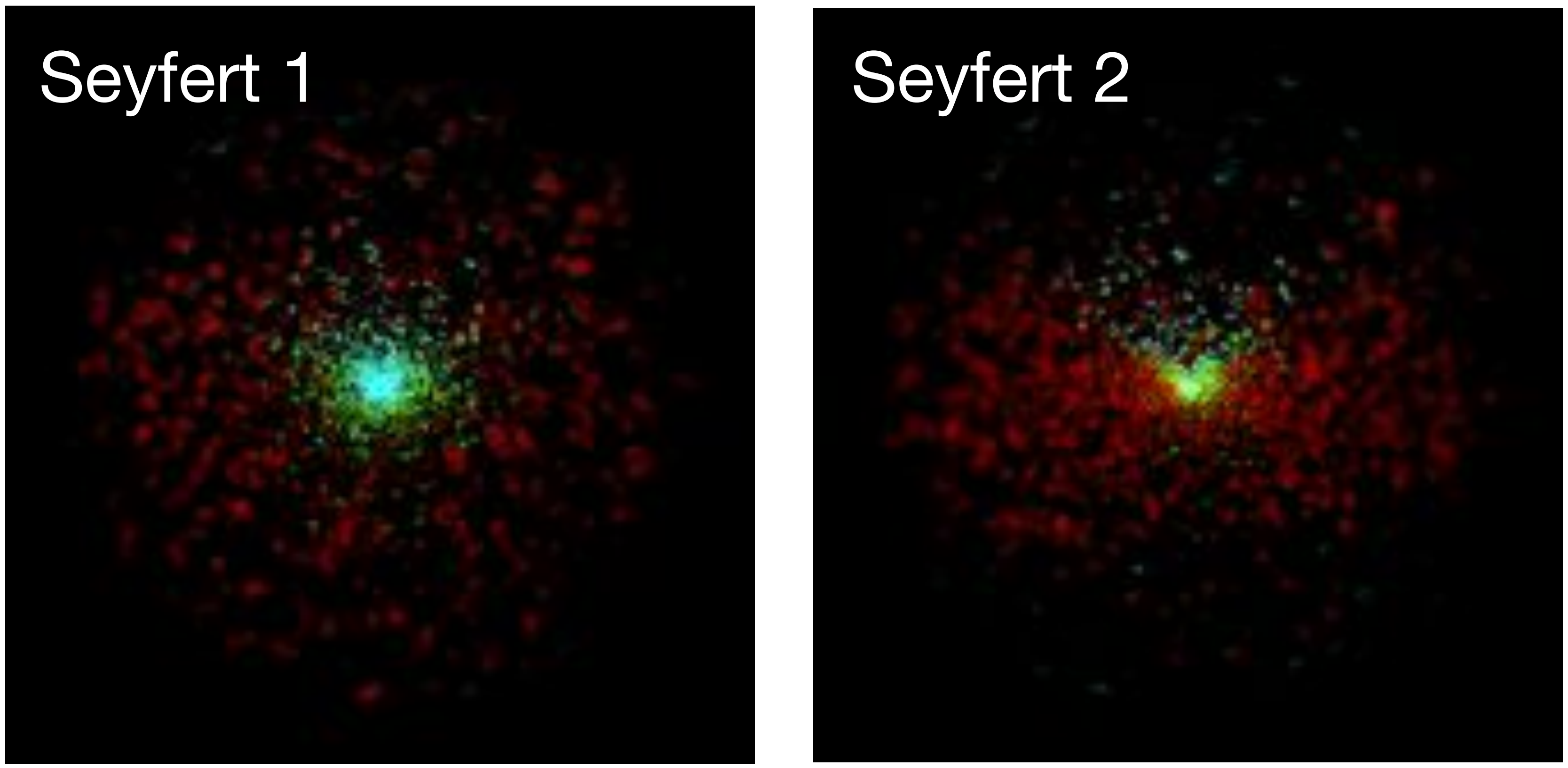




The Obscuring Torus

- Two flavours of torii:
  smooth (e.g. Pier & Krolik 1992, Granato & Danese 1994)
  clumpy (e.g. Nenkova+2004, Hoenig+2006)



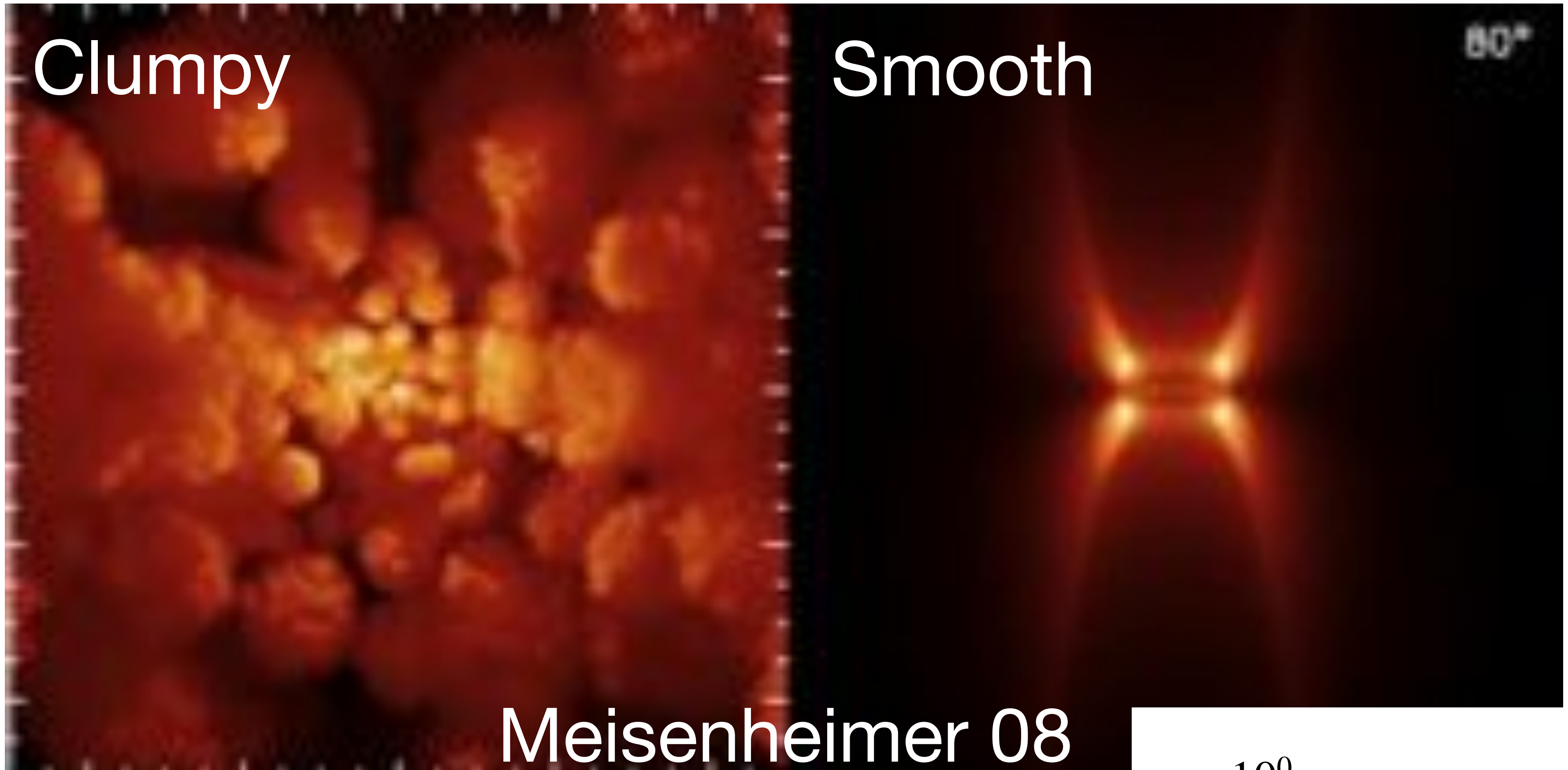


Hoenig & Kishimoto 2010

- Smooth and clumpy models provide different SEDs in terms of silicate features, width & peak of IR bump (Feltre+2012), but need very high spatial resolution, high quality data to disentangle the two cases.

- Smooth density distributions require large sizes to fit observed SED
  $R_{out}/R_d \sim$ 300-1000 ~ 120-400 $L_{45}^{1/2}$ pc (eg Granato & Danese 2004)

The Obscuring Torus



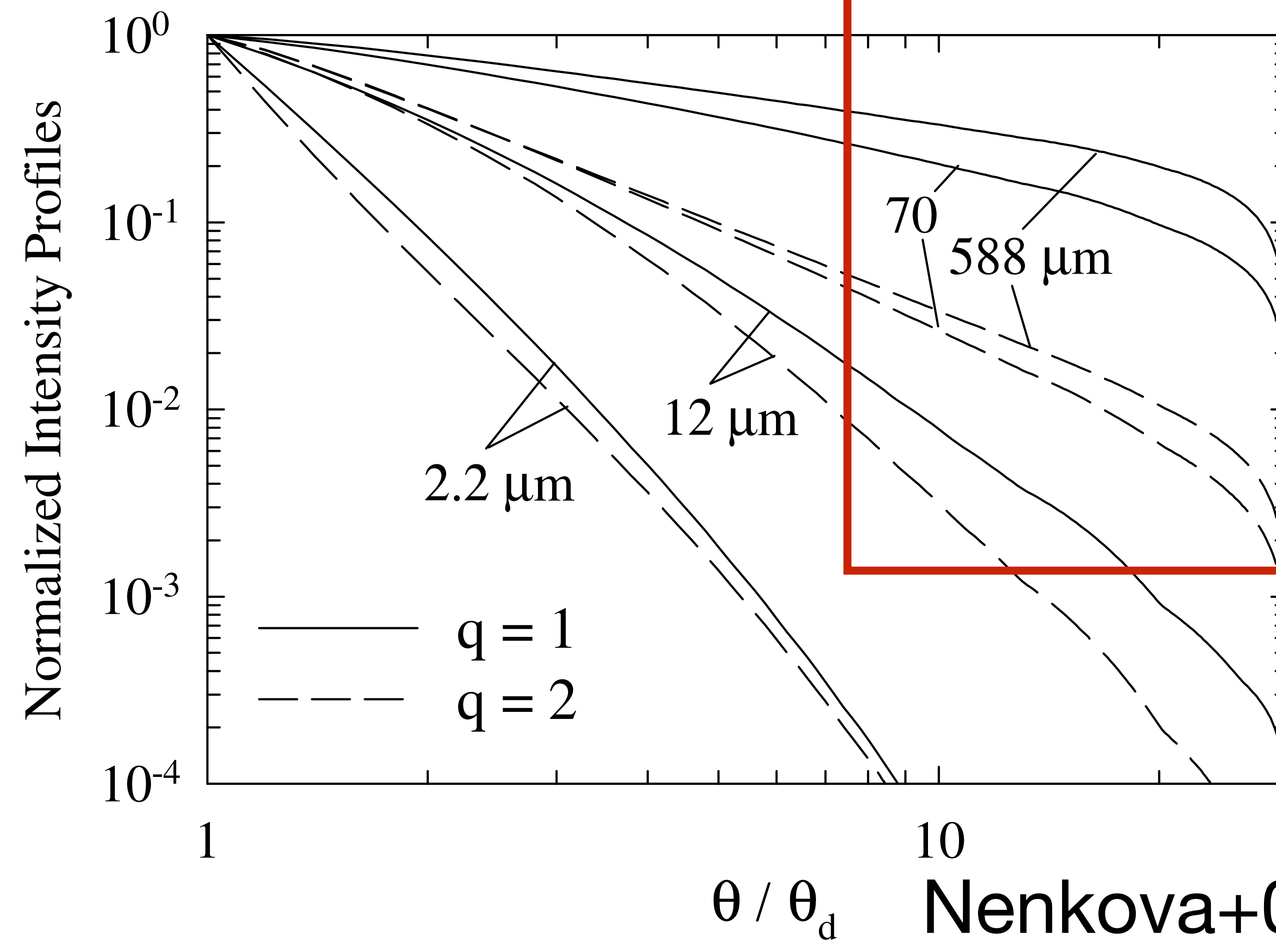
Meisenheimer 08

Clumpy models allow more compact MID-FIR emission (Nenkova+08, Hoenig+06, Hoenig & Kishimoto 10) …

… but even the SED of clumpy tori is insensitive to R_{out}/R_d

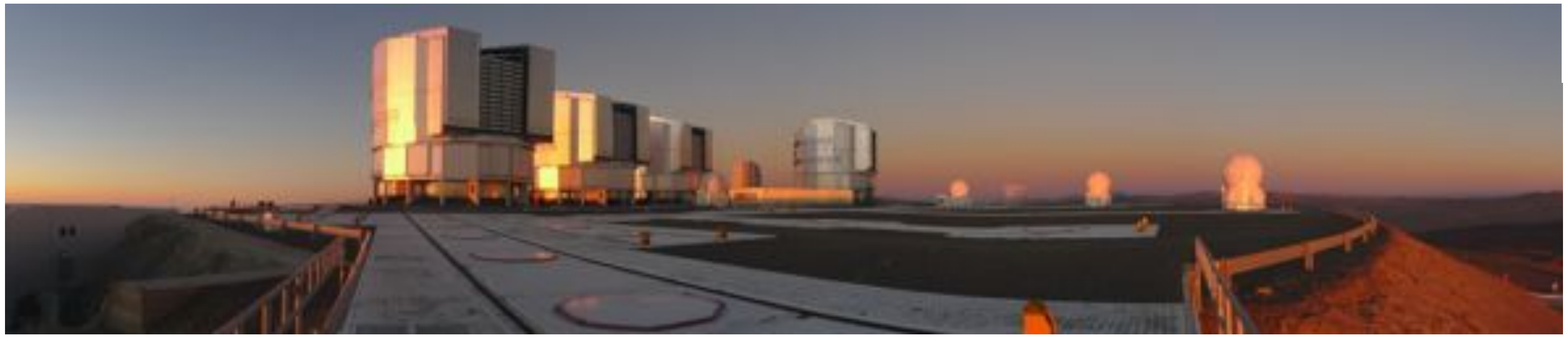
So, what is the size of the torus?

Solution is resolving torus emission at longer wavelengths!

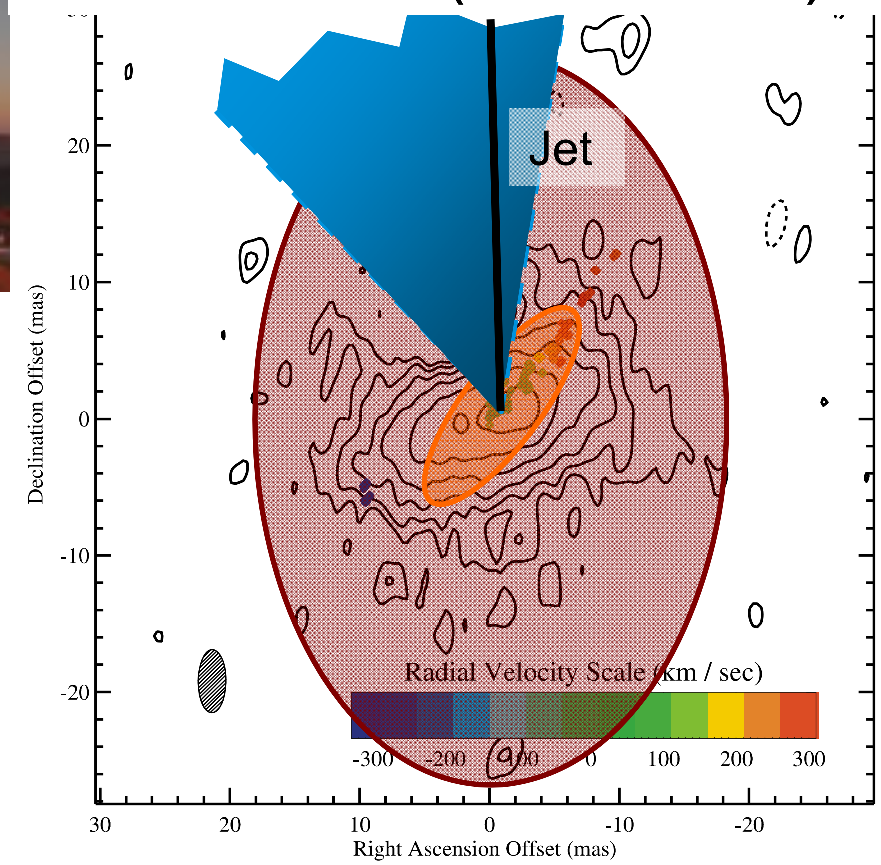


Nenkova+08

IR Interferometric Observations



NGC 1068 (Raban+08)



- ⭐ Observations from Keck-I, VLTI/MIDI (8-13 μm), VLTI/AMBER(J,H,K)

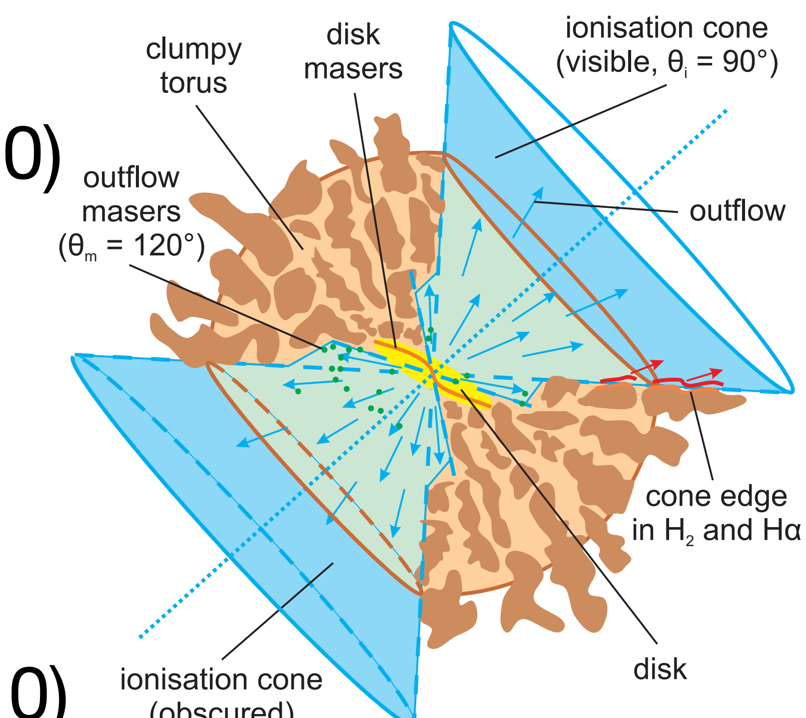
- ⭐ VLTI/MIDI:

  emission in NGC 1068 out to Rout ~ 2 pc with only R_{out}/R_d~3 (Jaffe+04, Raban+08)

  In Circinus R_d~0.1 pc, R_{out}/R_d~10 (Tristram+10)

- ⭐ Emission more compact than expected from smooth torus models!

- ⭐ Fit with Clumpy models!



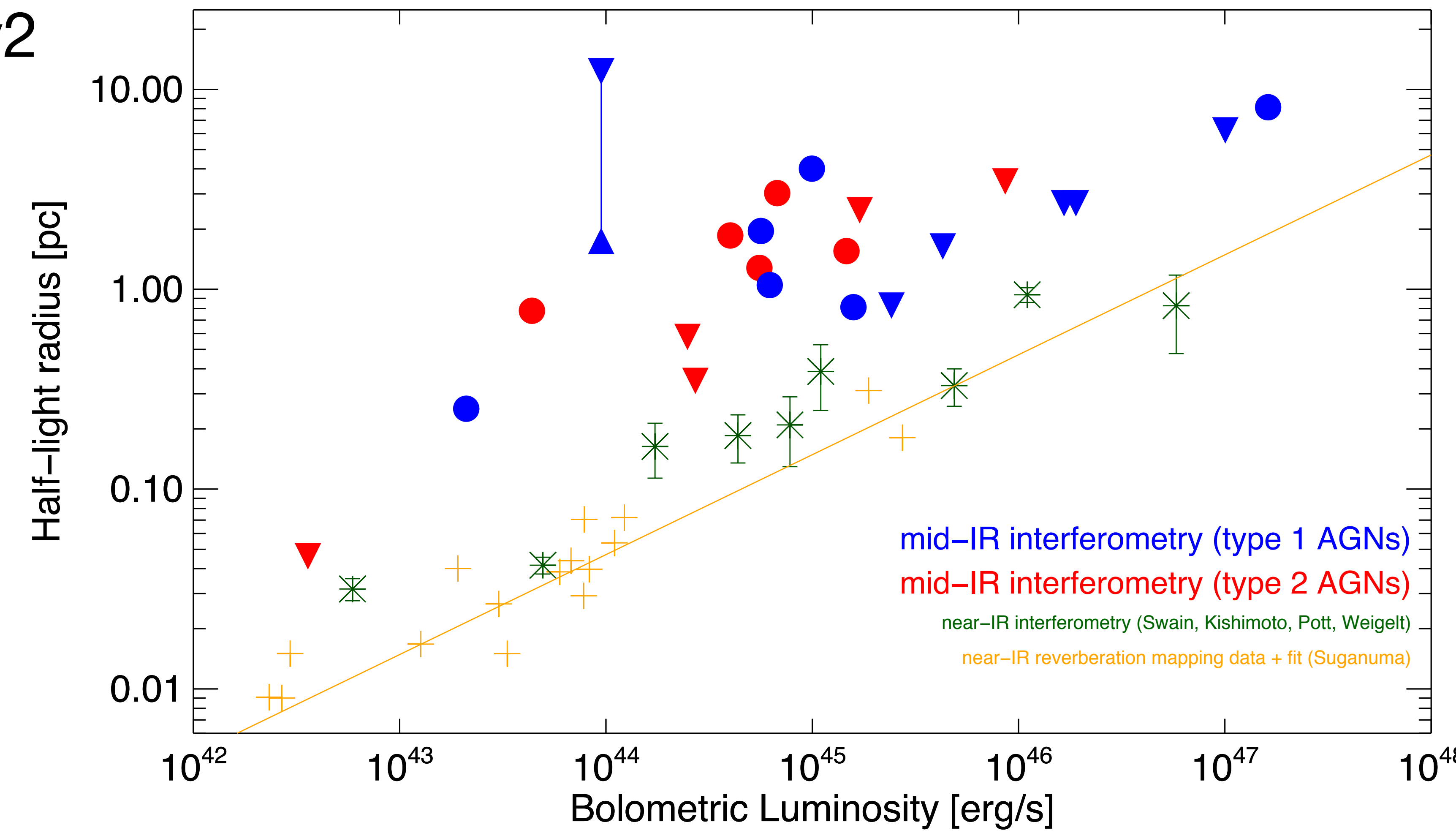
Circinus (Tristram+10)

IR Interferometric Observations

VLTI/MIDI observations of >30 nearby AGN observed at ~10 mas resolution

- compact MID IR sizes, more than expected from simple smooth models
- different MID IR morphologies consistent with evidence for polar elongation in several sources: dust "above" torus in ionisation cone?
- no differences Sy1/Sey2

much larger scatter of R_{MIR} vs L than R_{NIR} vs L: $R_{MIR} \sim 4\text{-}20 \times R_{NIR}$ ($\sim R_d$), different structure and components in different sources?

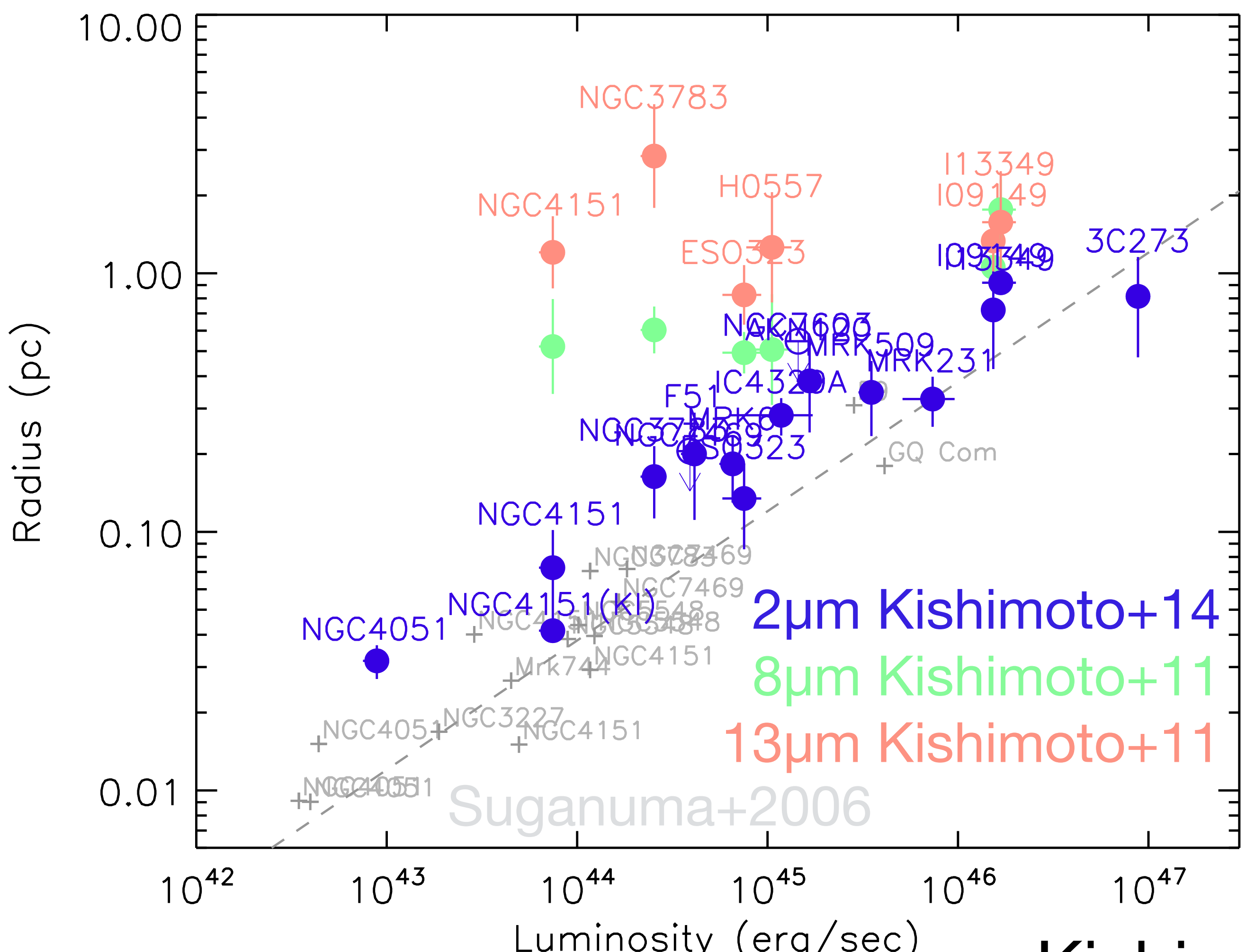


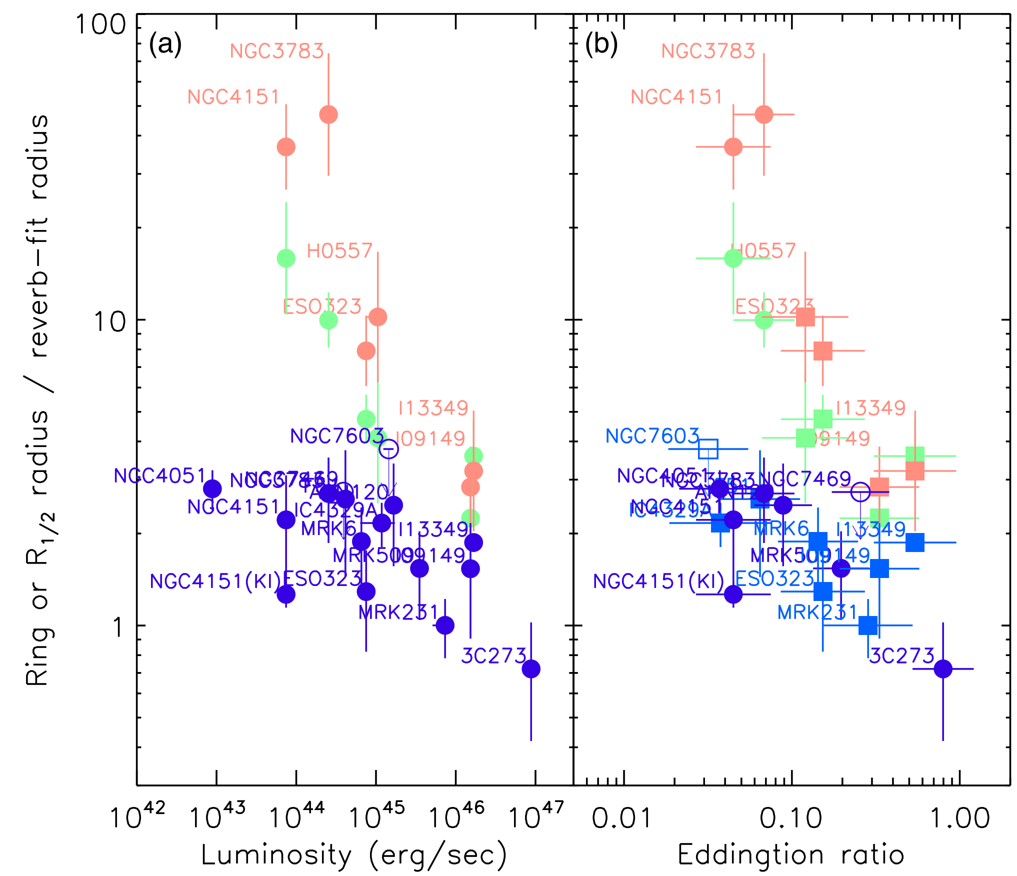
Burtscher+2013

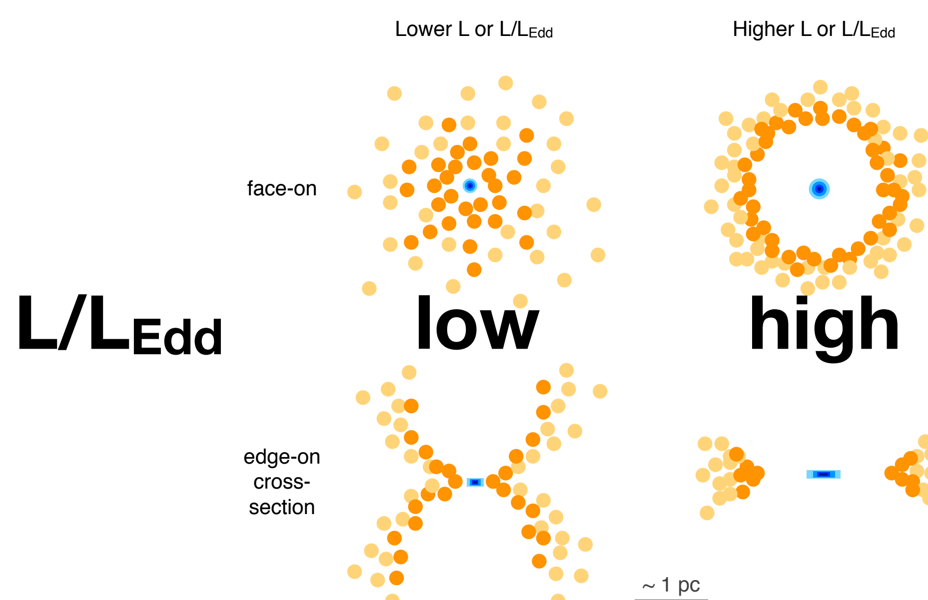
IR Interferometric Observations

NIR interferometric observations with Keck-I and VLT-I/AMBER probe size of torus at ~2 μm with ~few mas spatial resolution (e.g. Kishimoto+11,+14)

- small sizes, consistent with K band reverberation mapping
- fit with clumpy tori, ring like structures, R_{em}/R_d depends on L/L_{Edd}



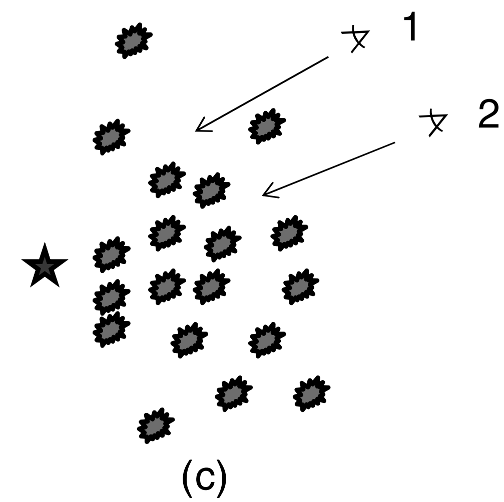




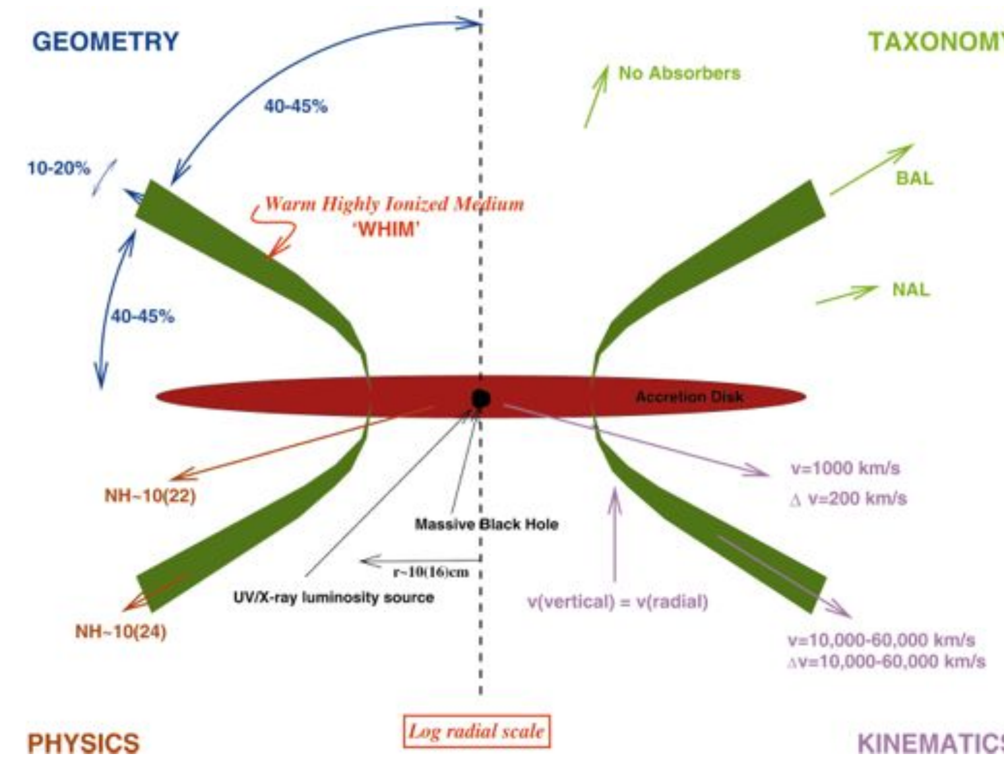
Kishimoto+14, in prep.

New view of the torus

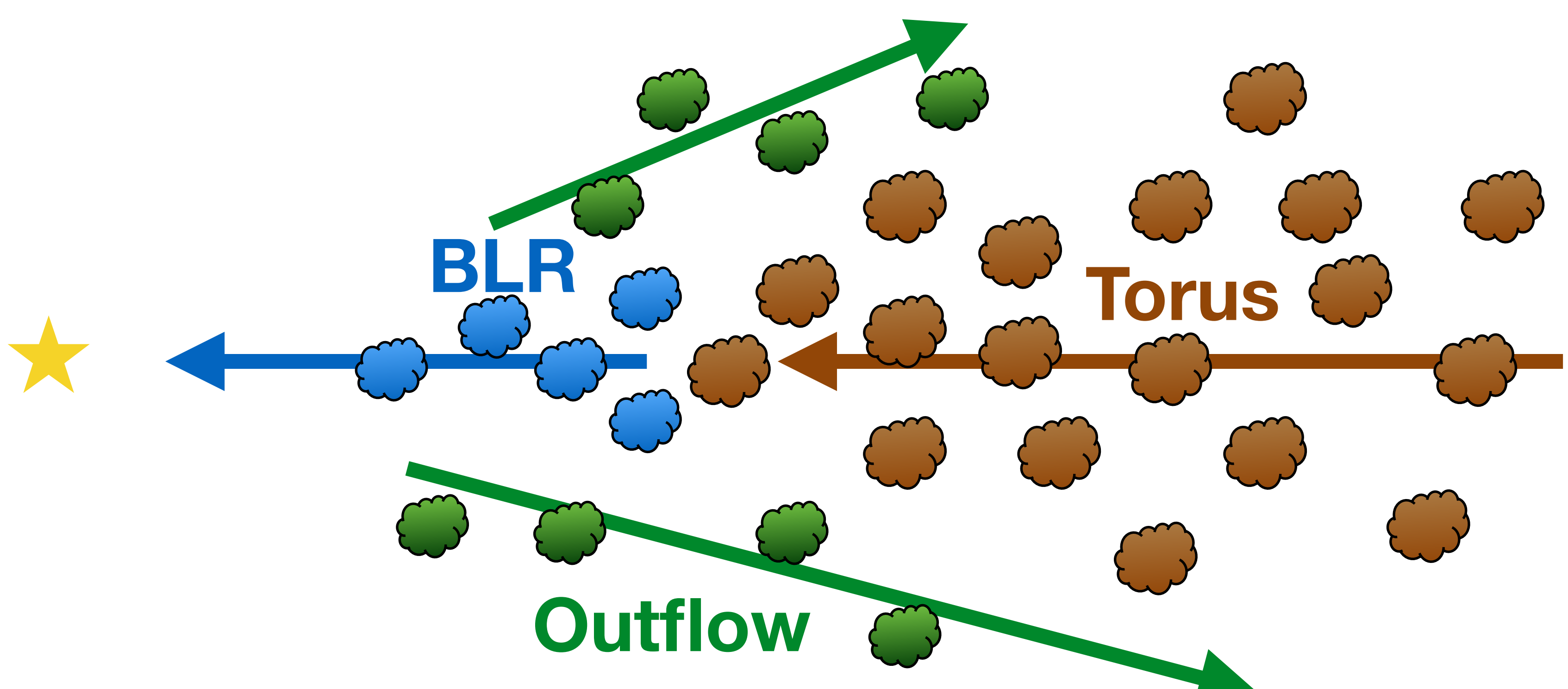
- Disk - wind structure (Elvis 2000)
- Toroidal obscuration made by dusty clouds (e.g. Elitzur 2012)
- Clumpy obscuring medium part of the accretion flow/outflow?



Elitzur 2012



Elvis 2000

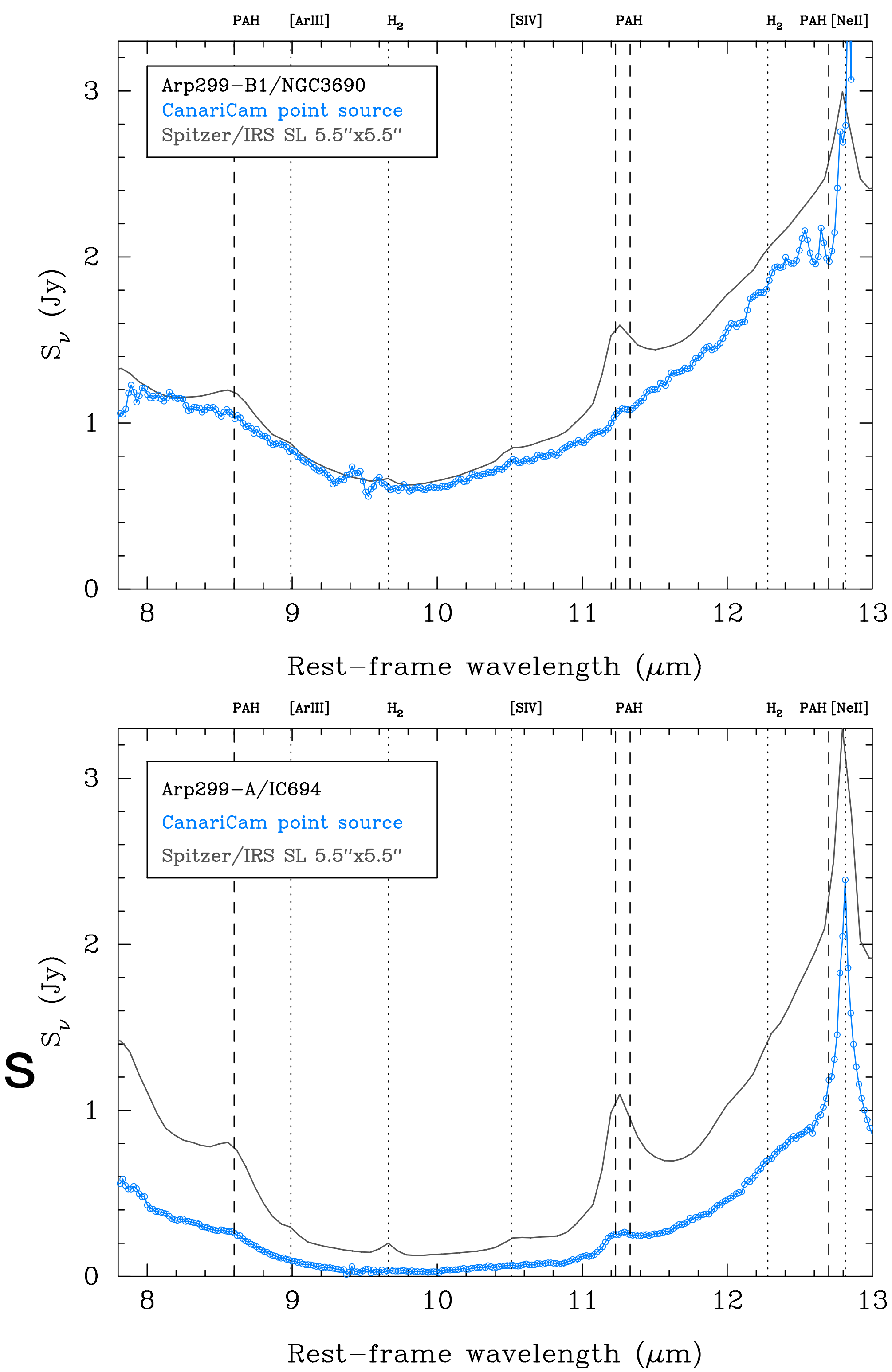


Beyond the torus?

- What makes the torus thick?
- Is the dusty (molecular) gas in the (outer parts of) torus forming stars?
- What is the relation between the torus and accretion/outflow?
- The importance of spatial resolution …

MIR observations at 0.5” resolution from GTC/CanariCam of Arp299 compared with Spitzer spectra from ~5”x5” apertures

point source spectra show much lower PaHs than larger scales revealing
two deeply embedded AGN
but also compact star formation

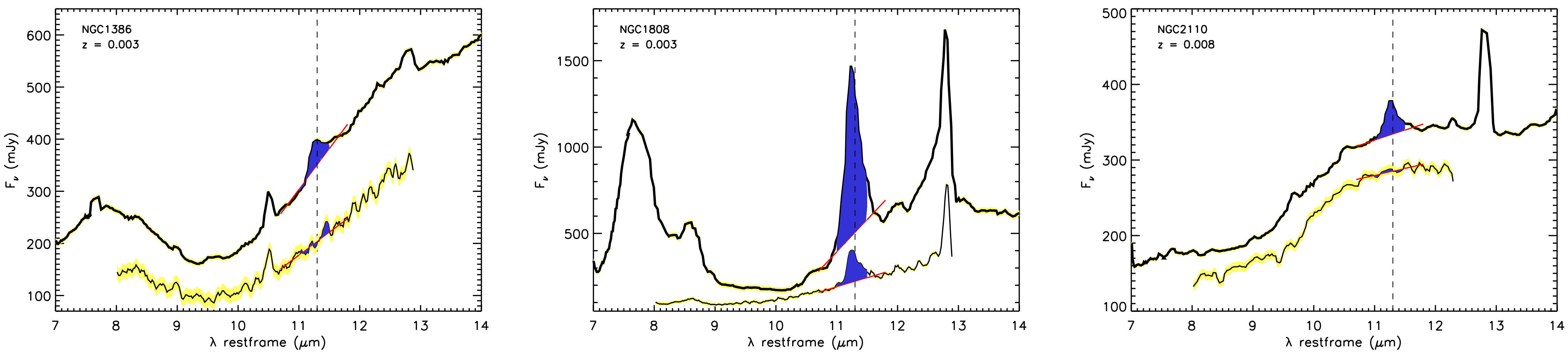


Alonso-Herrero+13

Beyond the torus?

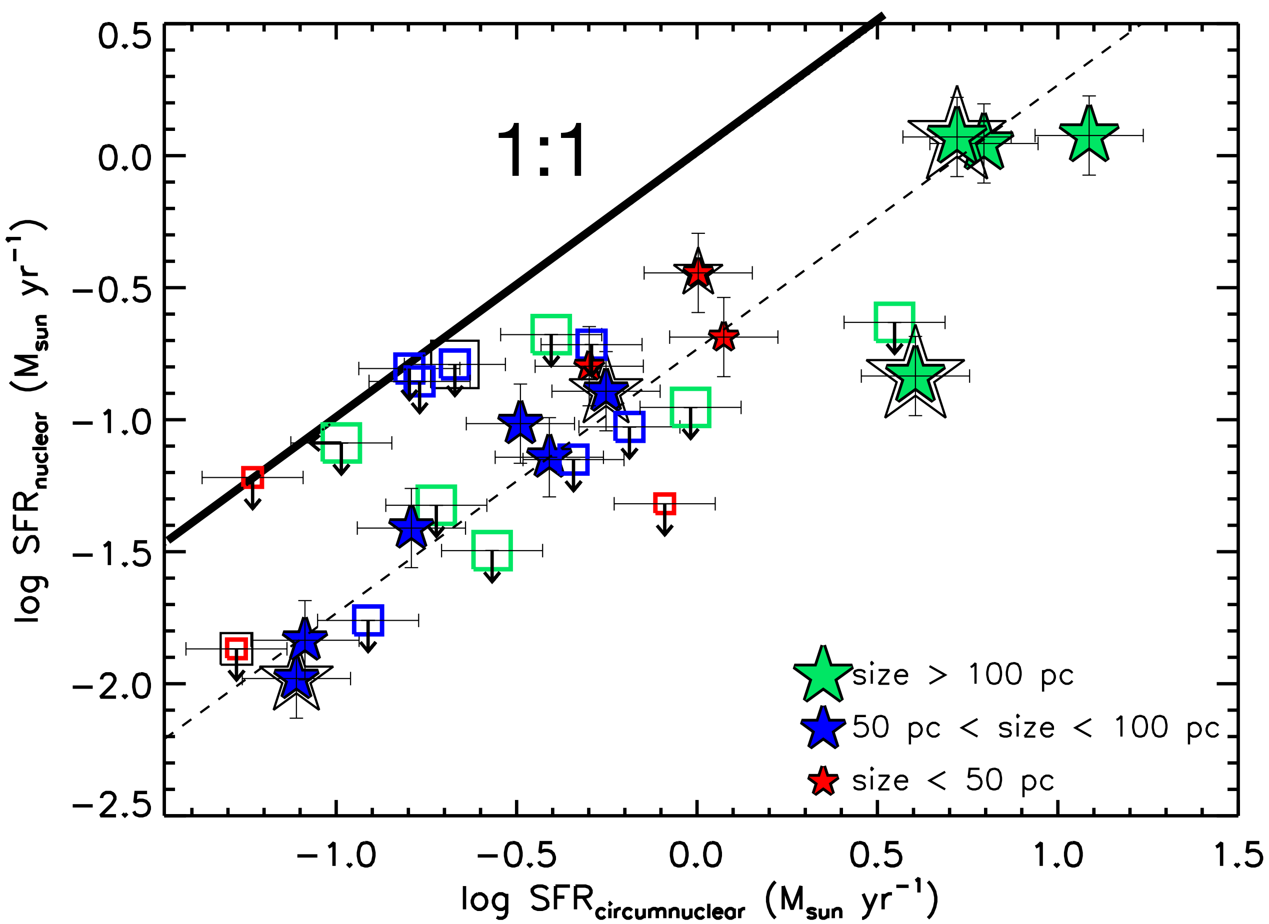
High spatial resolution to disentangle large scale from small scale SF:

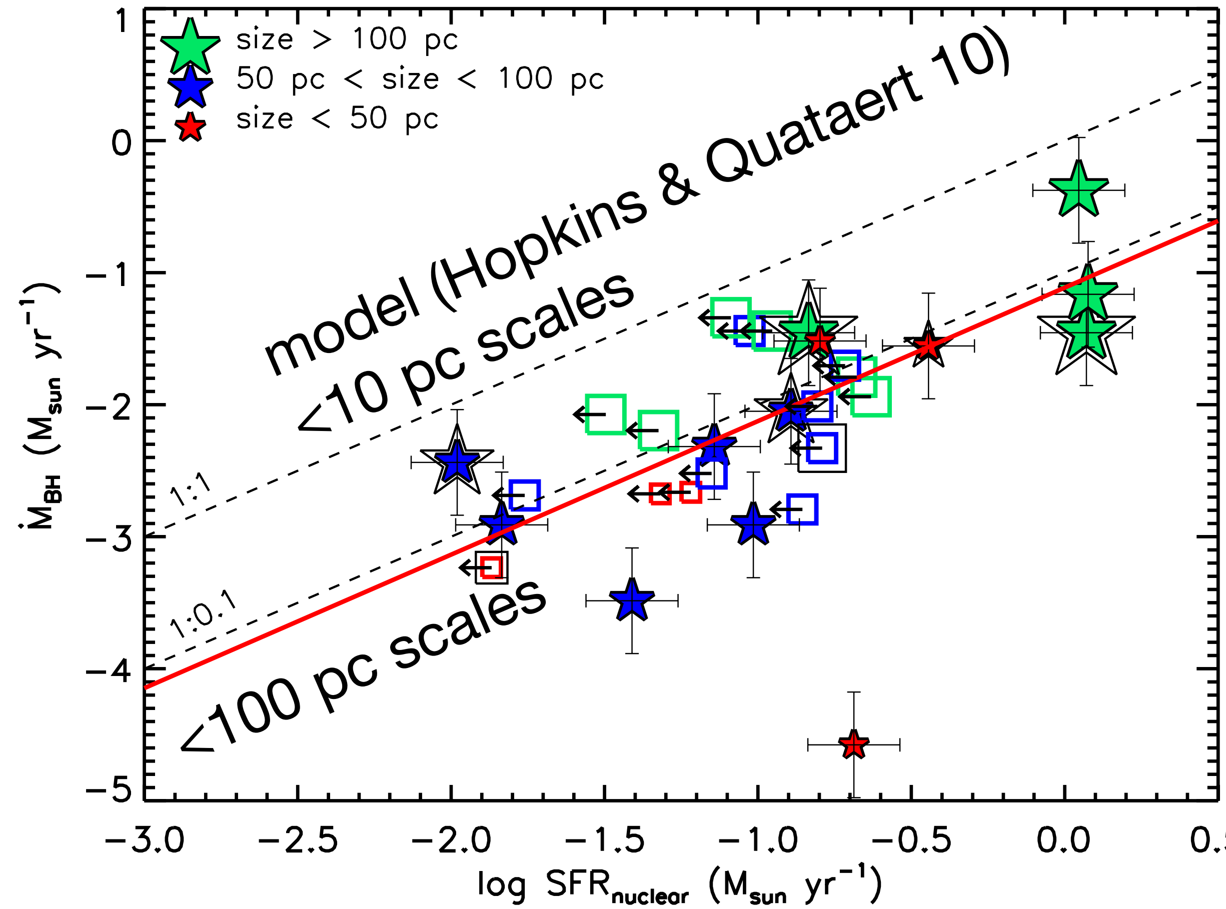
nuclear SF ~5× lower than large scales but SFR densities ~20× (Esquej+14)



dM$_{BH}$/dt vs nuclear SFR

scales ~65 pc —>

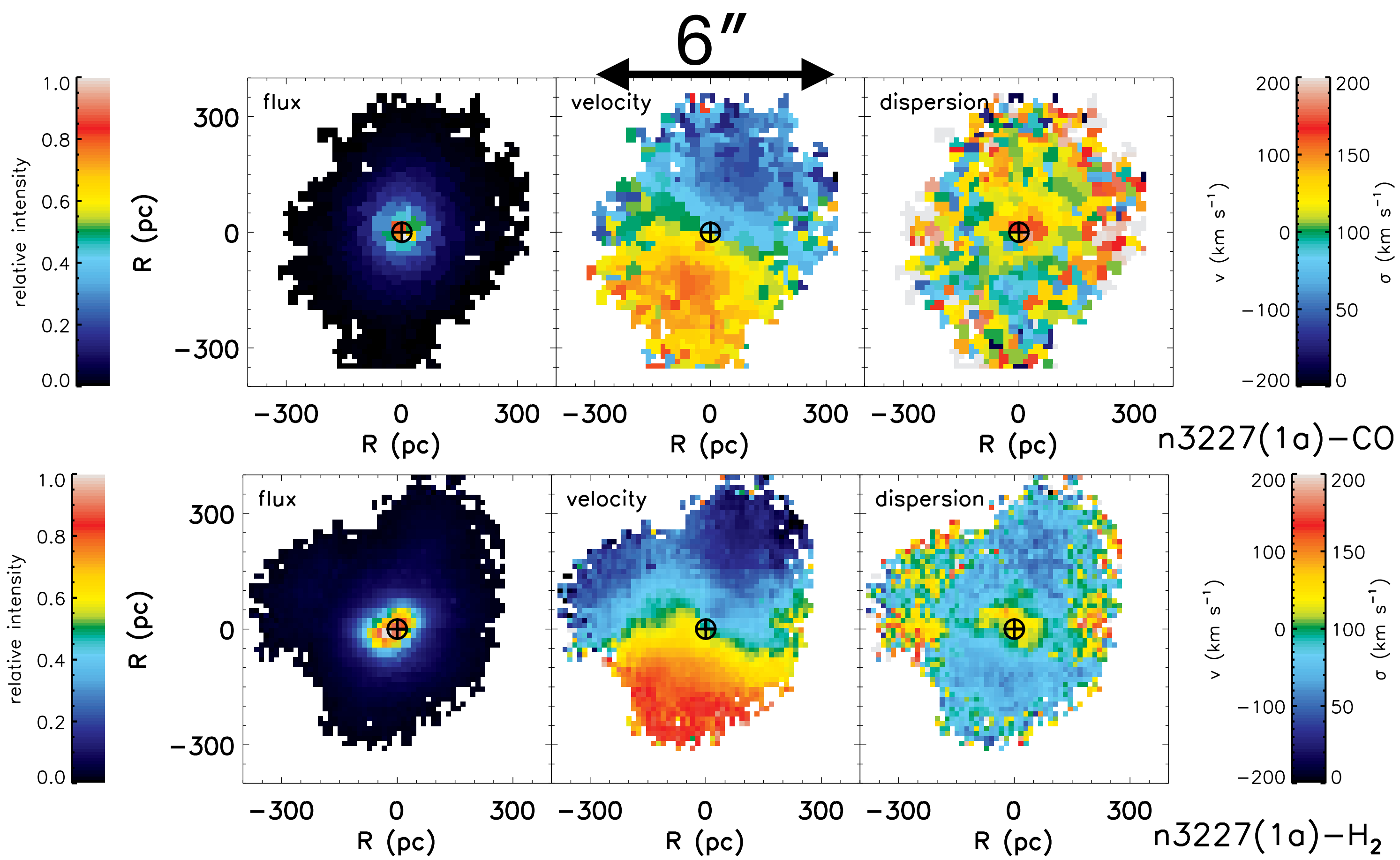




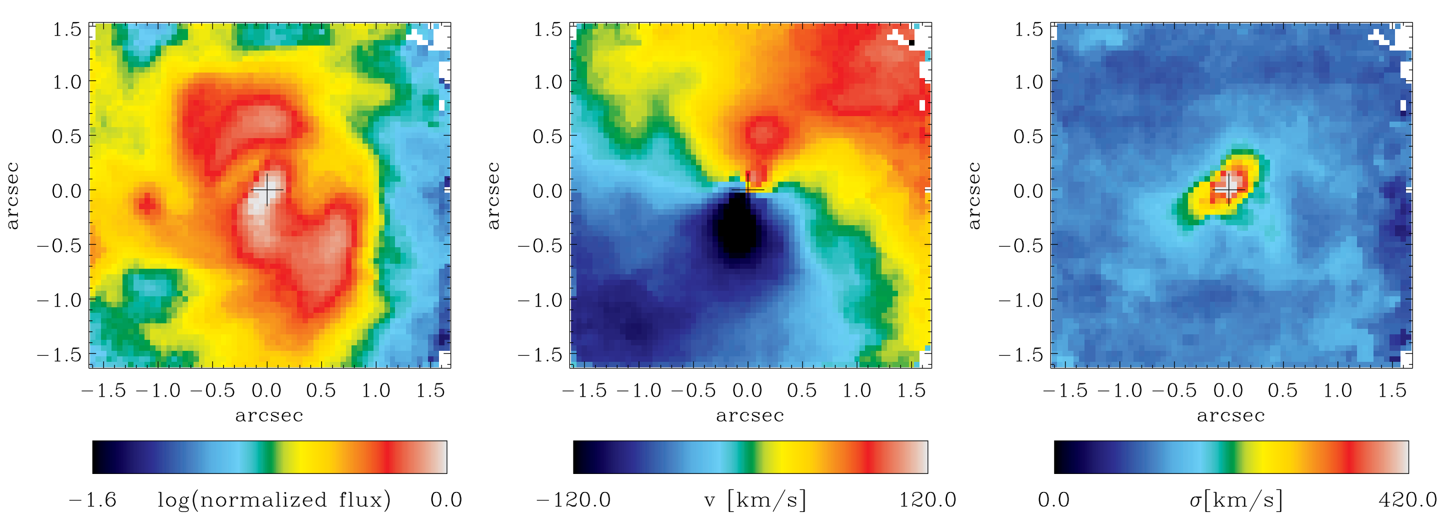
scales ~0.6 kpc —>

Esquej+2014

Subsarsec IFU obs. of local AGN



e.g. NGC 3227, Hicks+13



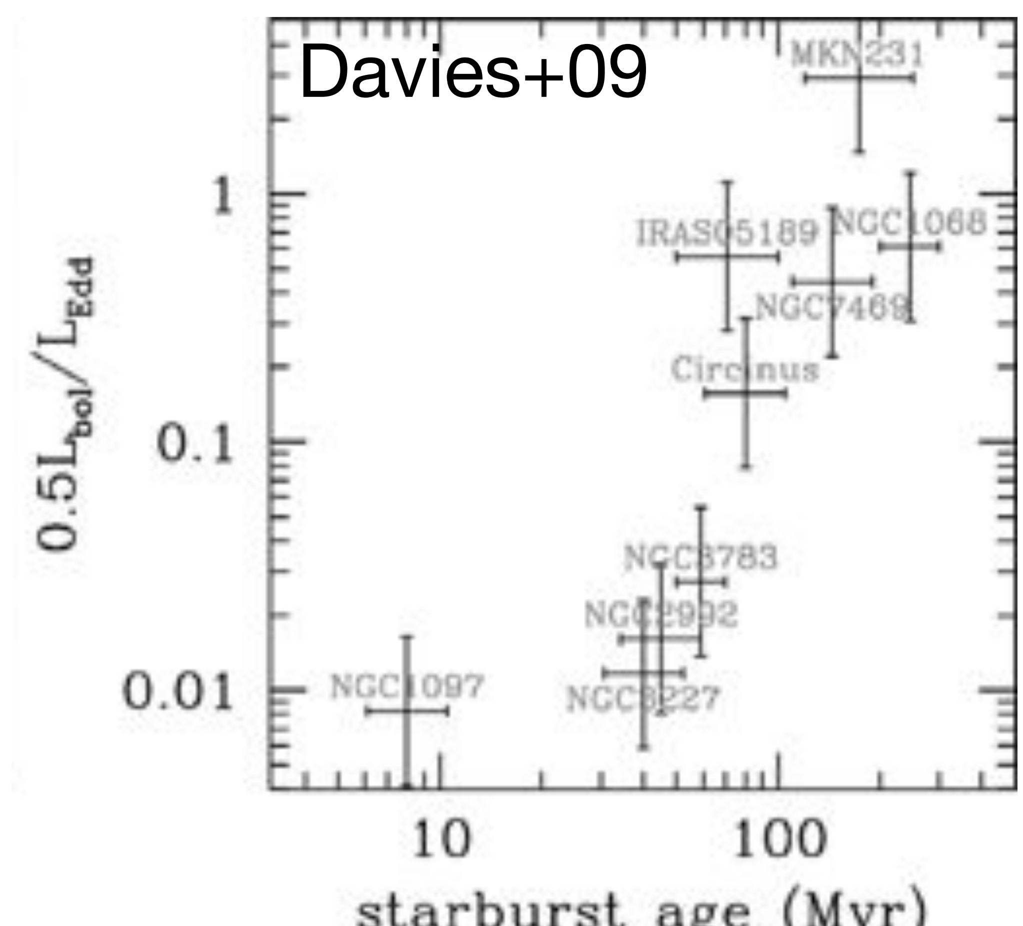
e.g. Centaurus A

H_2: Neumayer+07 Stars: Cappellari+09

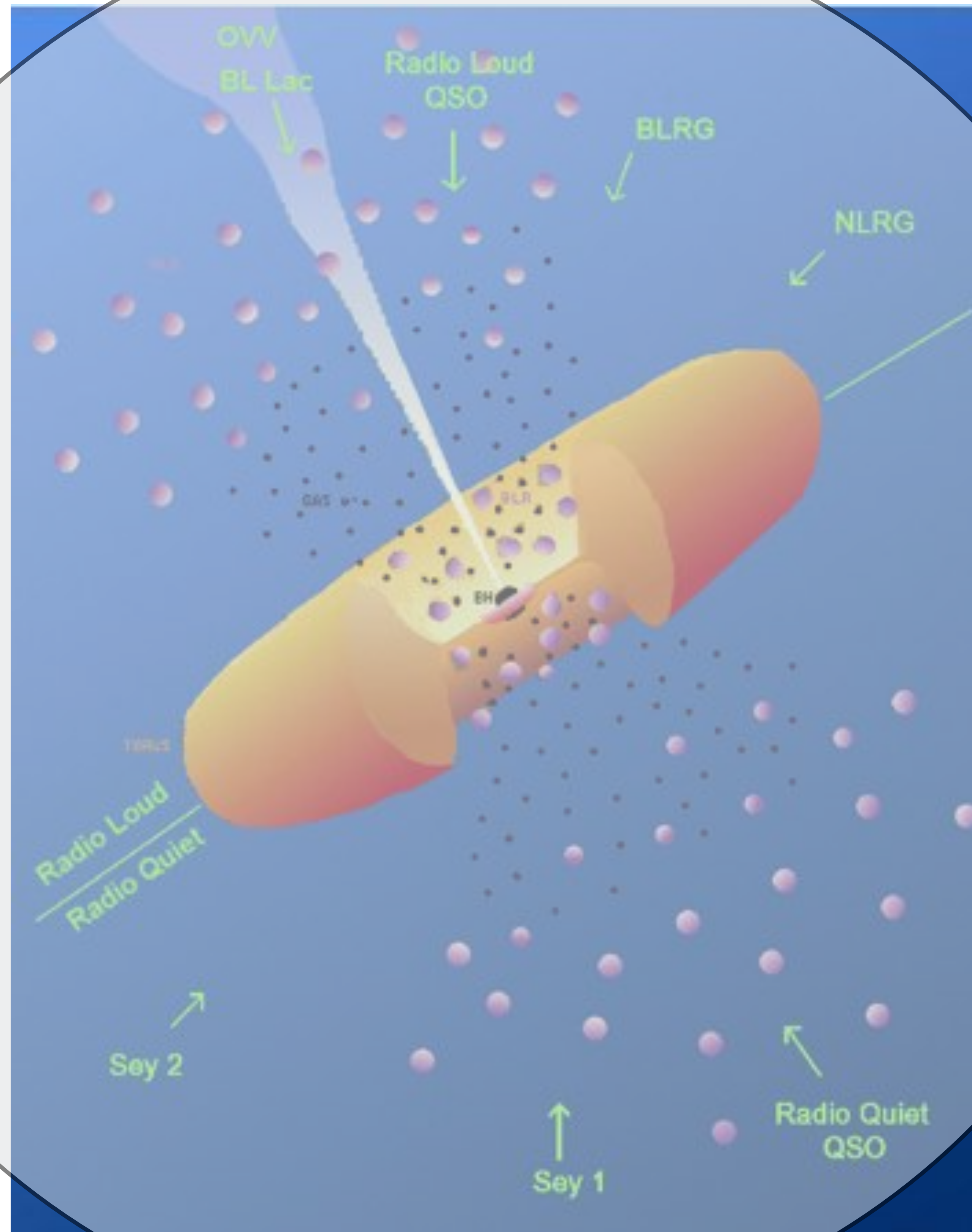
VLT SINFONI ~0.1″ spatial resolution can probe distribution of gas and stars at <100 pc scales in nearby galaxies

to study inflow/outflow, triggering of star formation and AGN

… or to measure BH mass from kinematics of age and/or stars



AGN Galaxies & M_{BH}-σ evolution

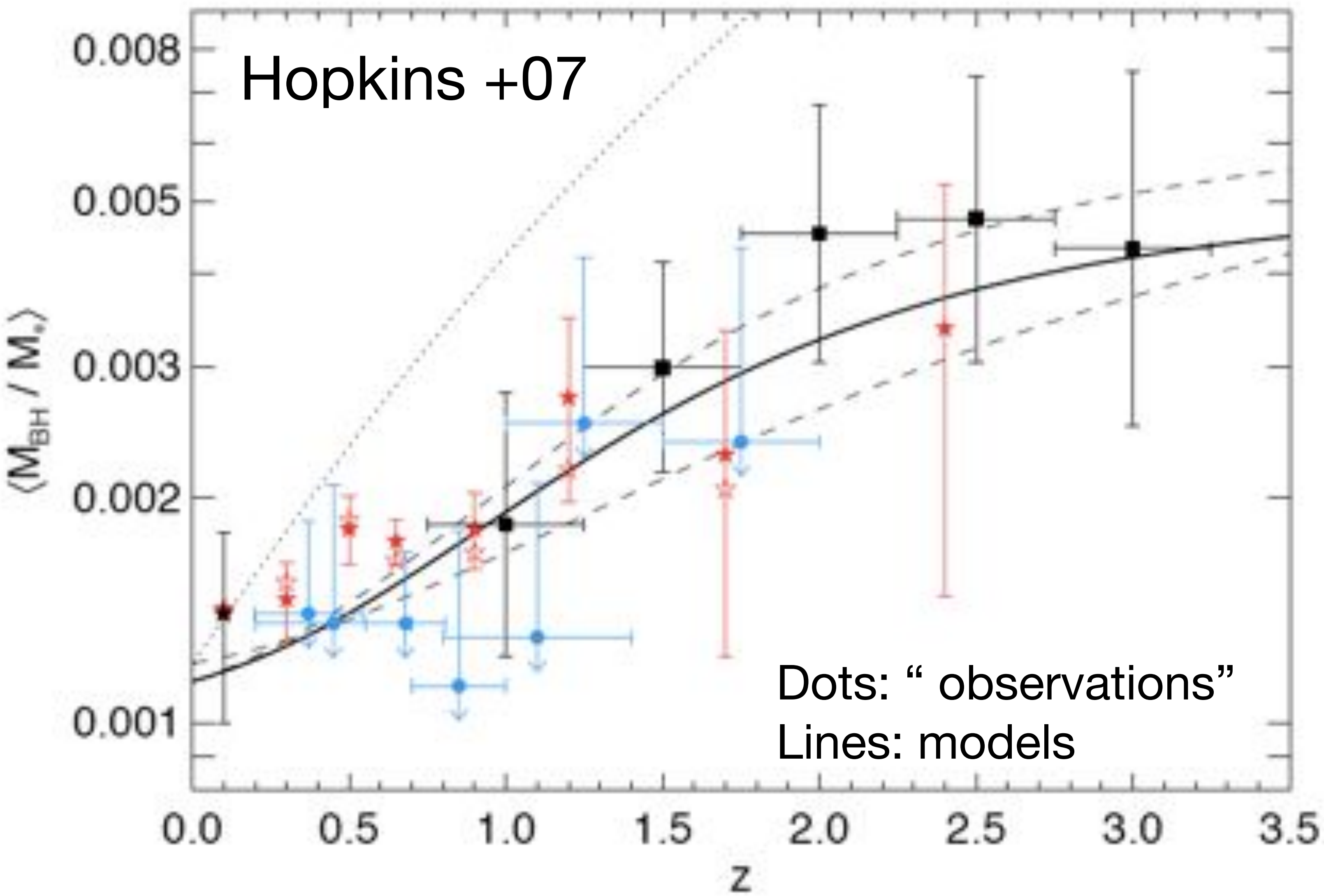


The ultimate goal...

Several models can explain M_{BH}-galaxy relations with various “flavours” of AGN feedback on the host galaxy.

Silk & Rees 98, Kauffman & Haehnelt 00, Cavaliere & Vittorini 00, Granato+ 04, 06, Murray +04, Di Matteo+05, Cattaneo+ 05, Miralda-Escudè & Kollmeier 05, Monaco & Fontanot 05, Croton +06, Hopkins +06, Malbon +06, Marulli +08 ...

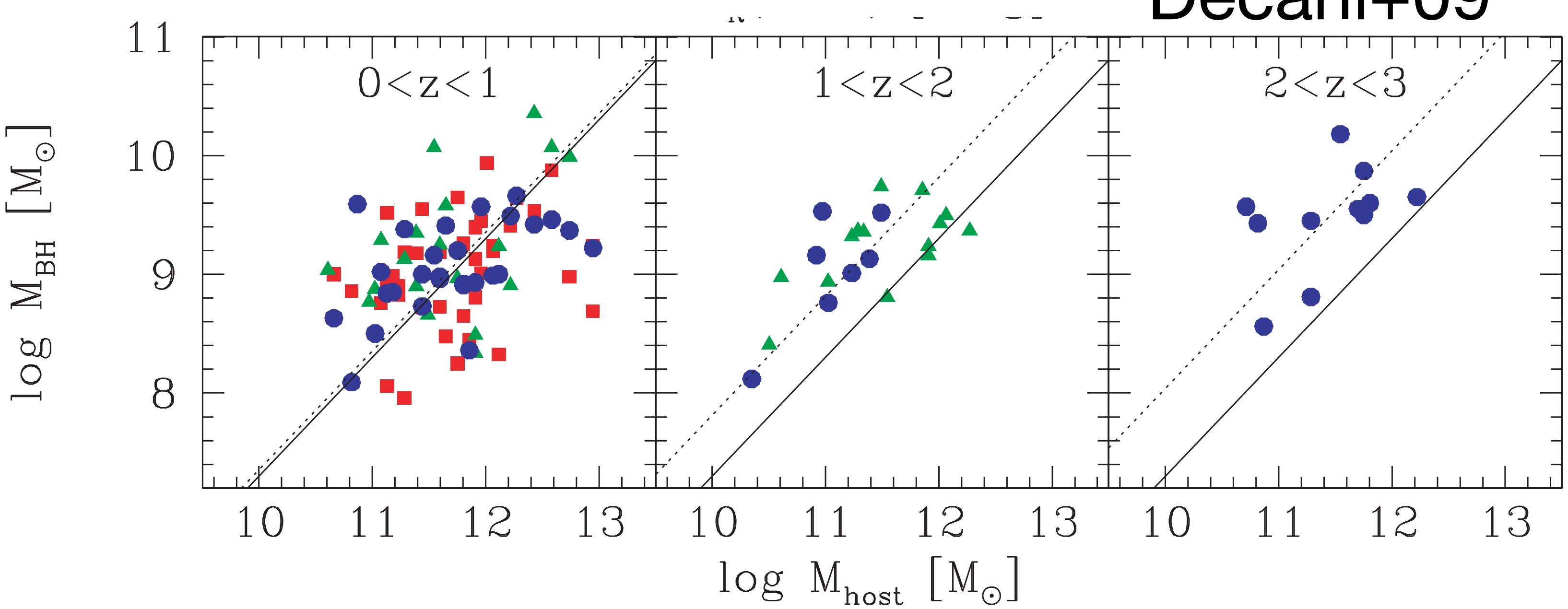
Redshift evolution of M_{BH}-galaxy relations can constraint BH growth and galaxy evolutionary models.



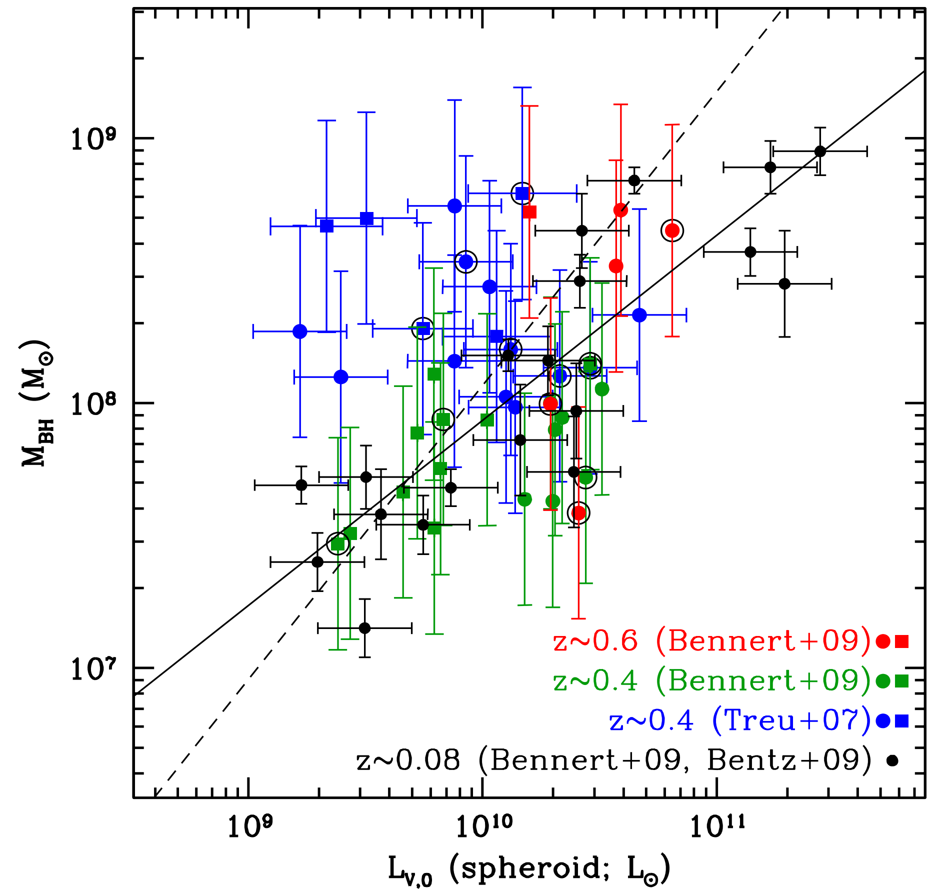
Fundamental to measure M_{BH} at ALL redshifts!

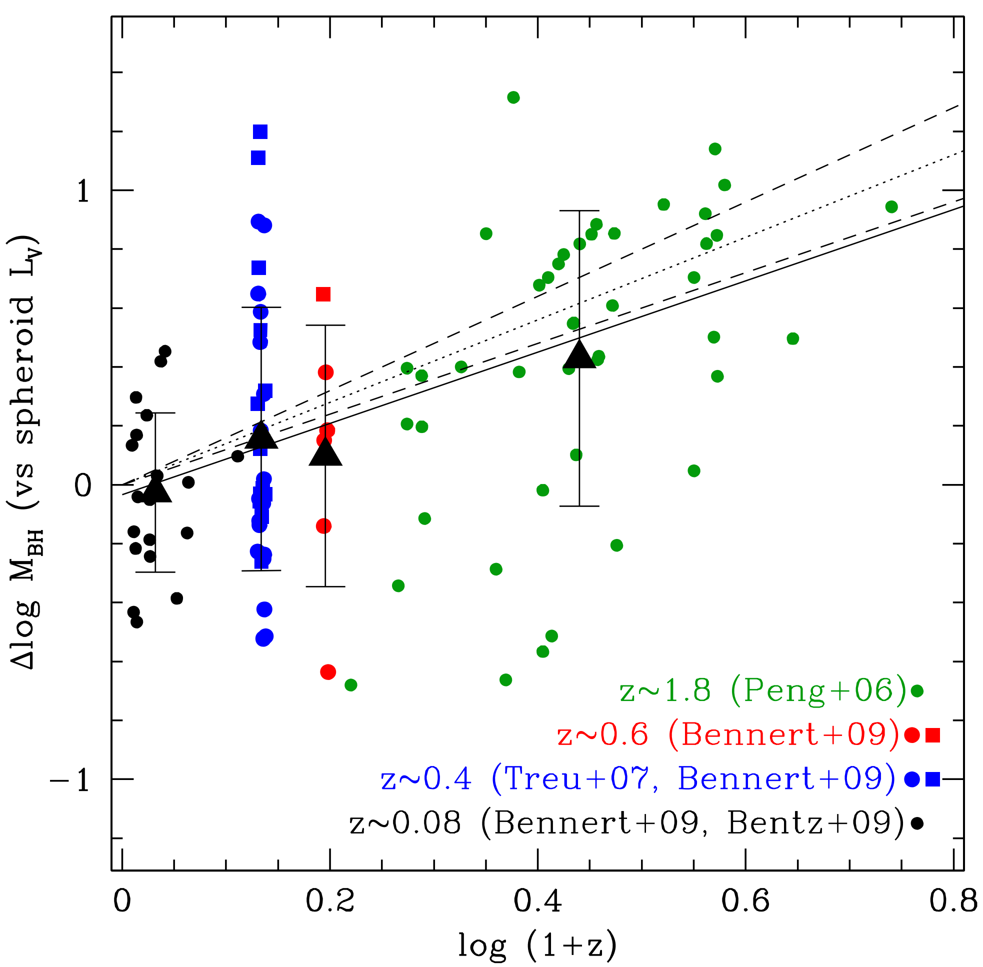
M_{BH}-galaxy relations at high z

Decarli+09



Bennert+11

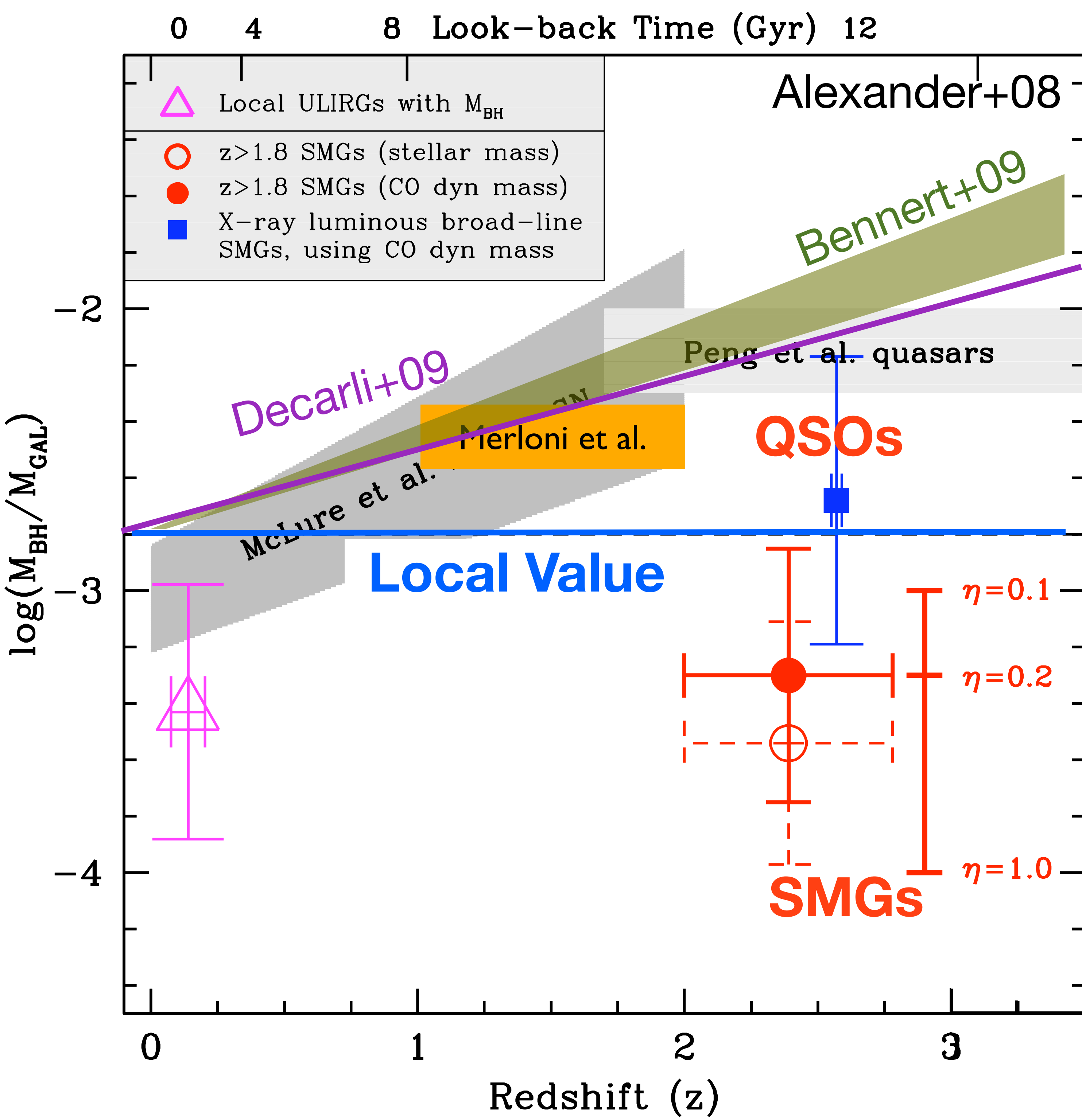




At high z BH appears to be over sized compared to host galaxy (stellar) mass (see also, McLure+03, Peng+06, Schramm+08, Salviander+07, Maiolino 09, Walter+10, Wang+10, Merloni+10, Targett+12,

M_{BH}-galaxy relations vs z

Quasar at z~6.4
(Willot+03, Walter+09)



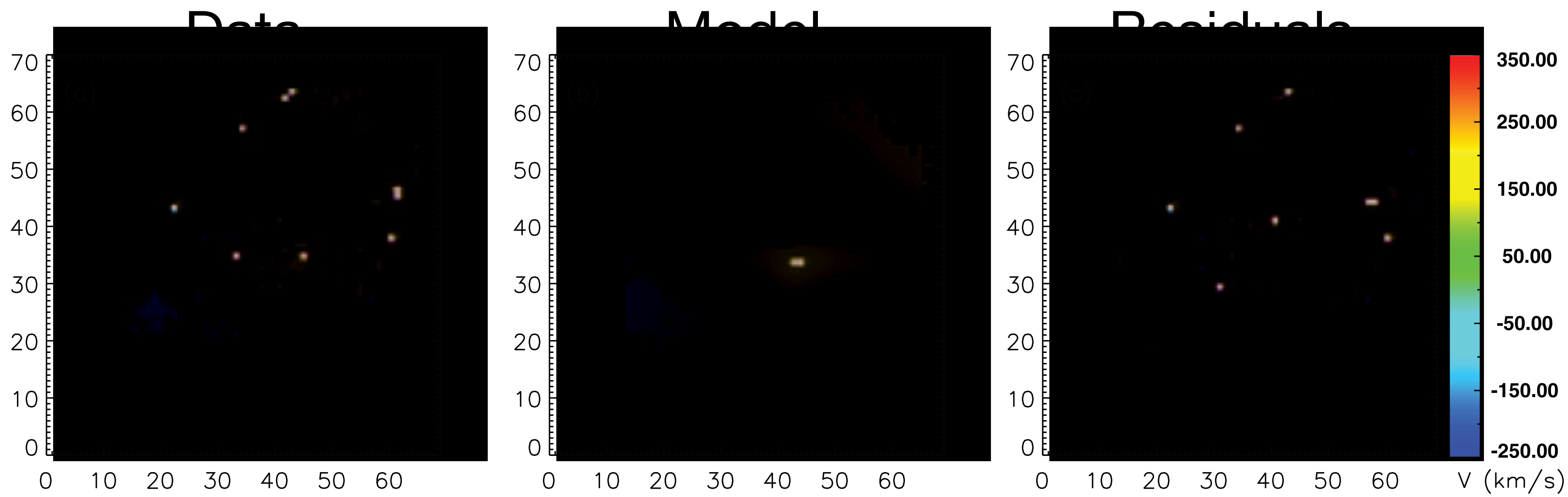
Maiolino 2009,
Lamastra+2010
Targett+2012

Overall, with few exceptions (SMG, obscured AGN), BH growth seems to precede bulge growth …

… but position on M_{BH}-galaxy relations depends on the evolutionary stage probed (Lamastra+10)

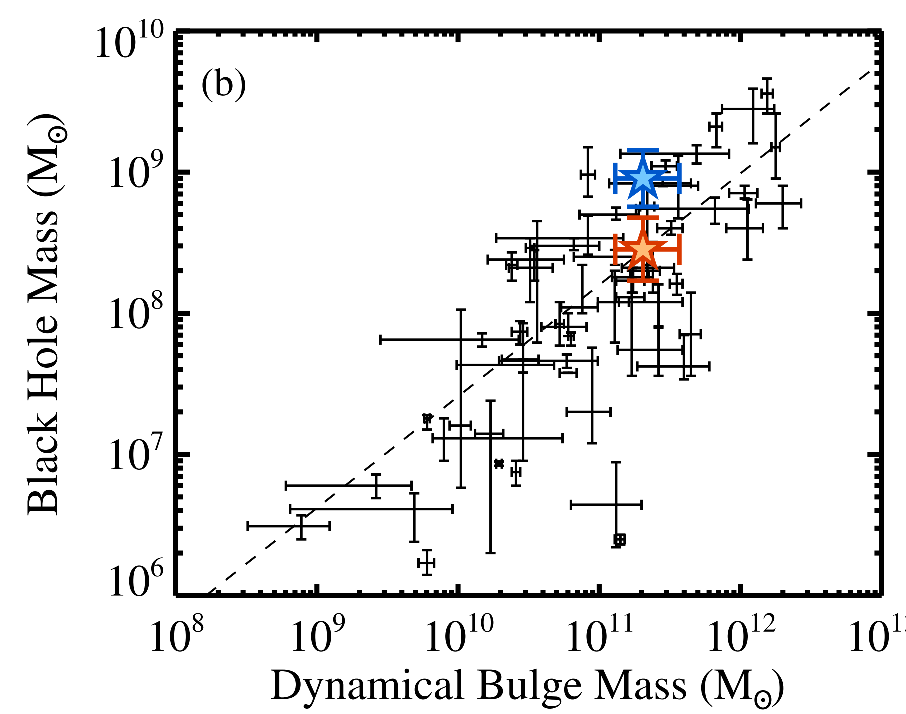
Dynamical host galaxy masses

- Stellar mass depends on galaxy evolutionary stage
- Ideally one should measure the dynamical mass



Inskip+11 measure dynamical mass of quasar host galaxy at z~1.3

Quasar is on M_{BH}-M_{bul} relation!

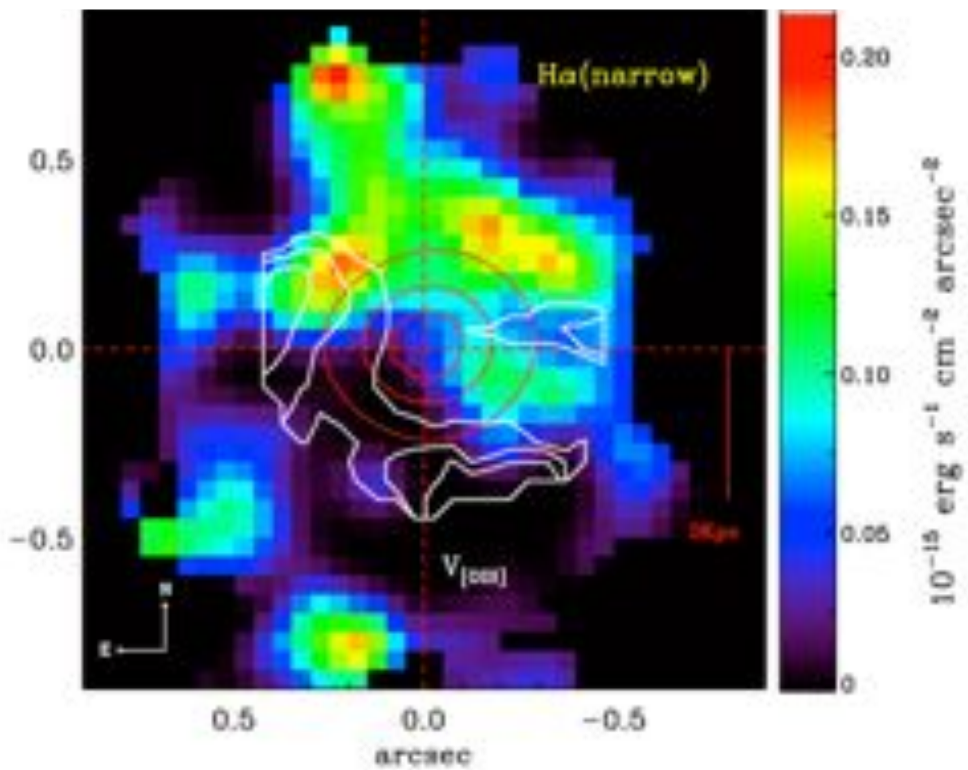


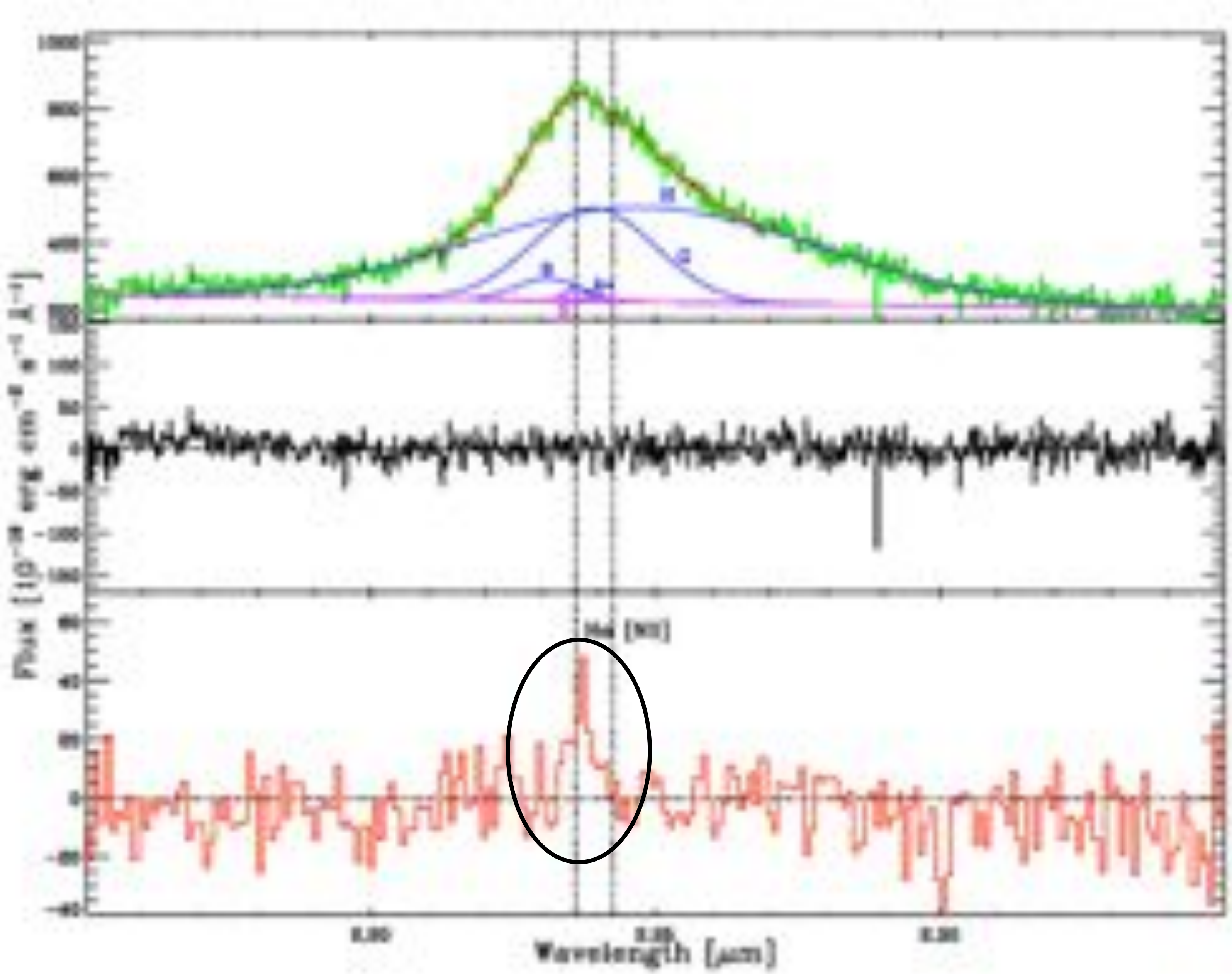
Dynamical host galaxy masses

- Stellar mass depends on galaxy evolutionary stage
- Ideally one should measure the dynamical mass
- BH masses can be measured only in type 1 AGN: the bright AGN continuum hinders measurements on host galaxy!

Strong AGN emission

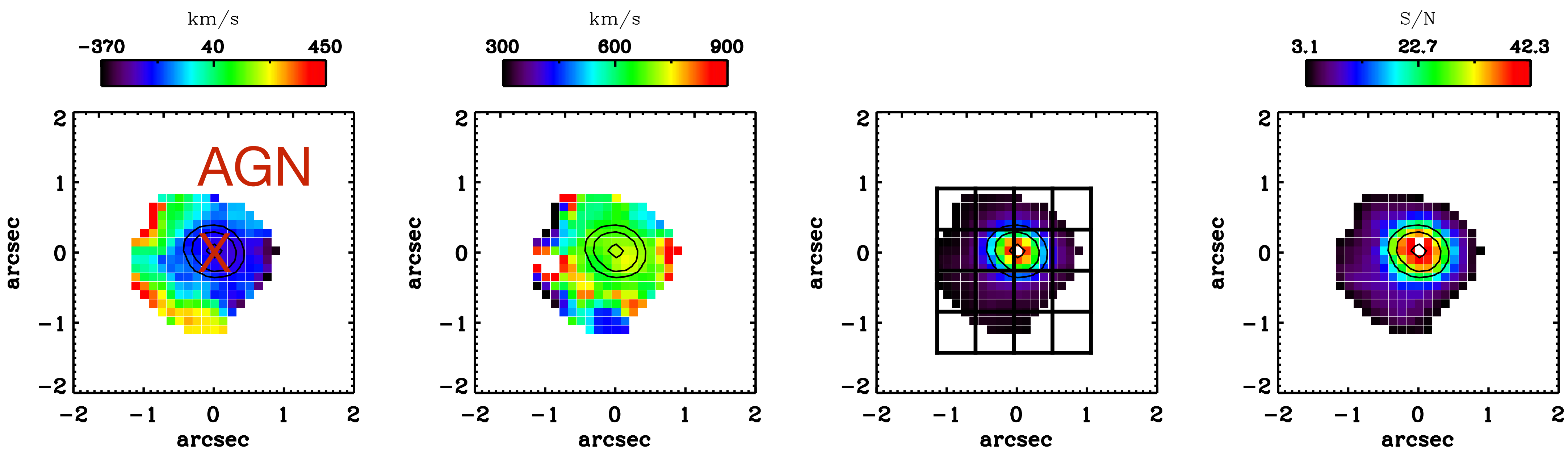
z~2 Quasar showing evidence for fast outflows quenching star formation (Cano-Diaz+12)

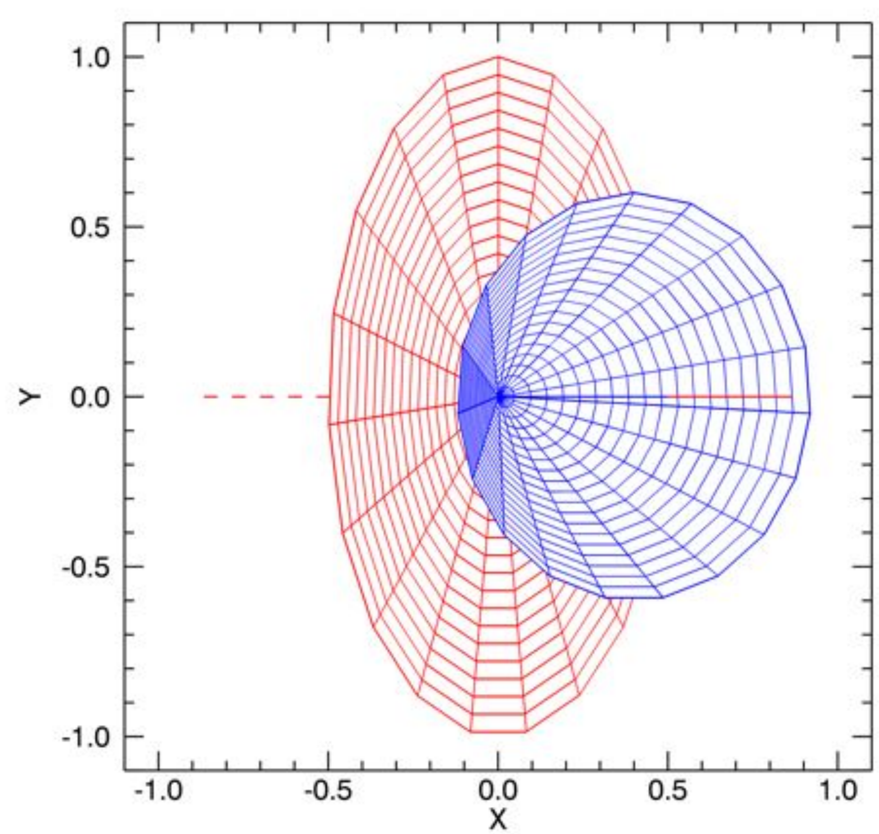


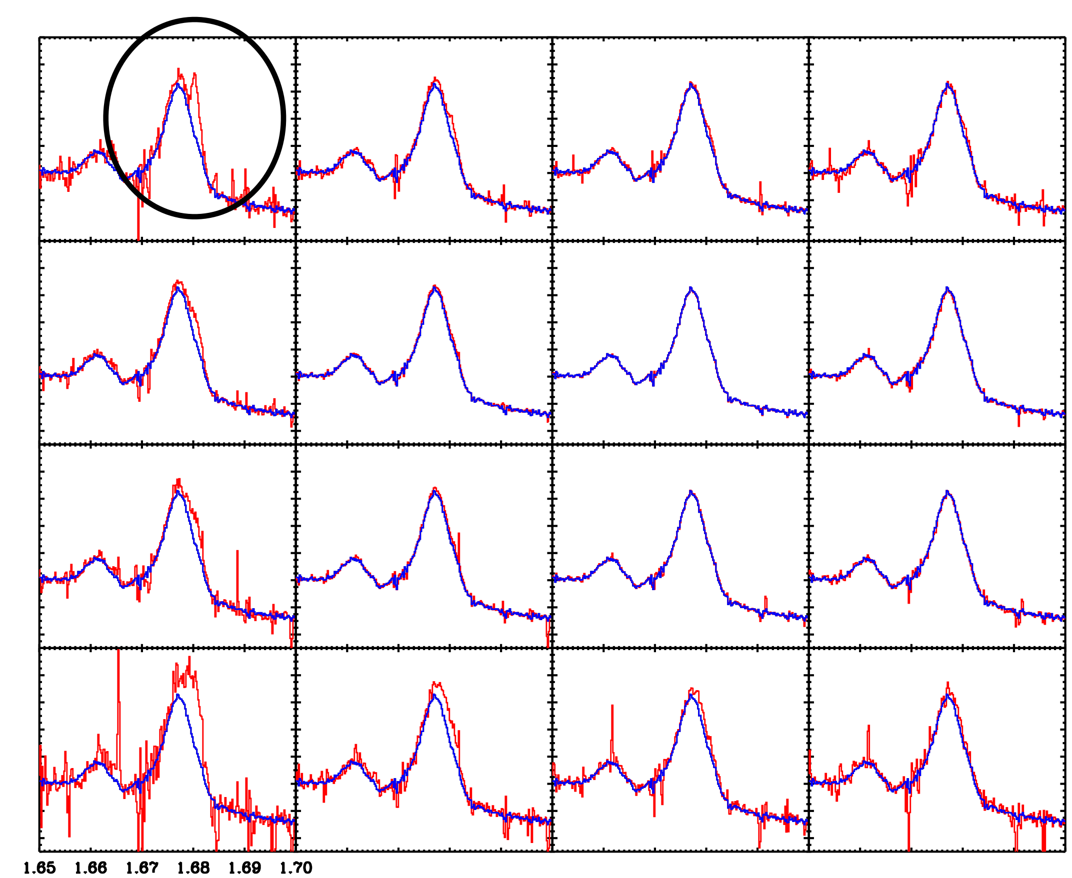


Strong AGN emission

z~2.5 quasar showing evidence for fast outflows (Carniani+14, in prep.)

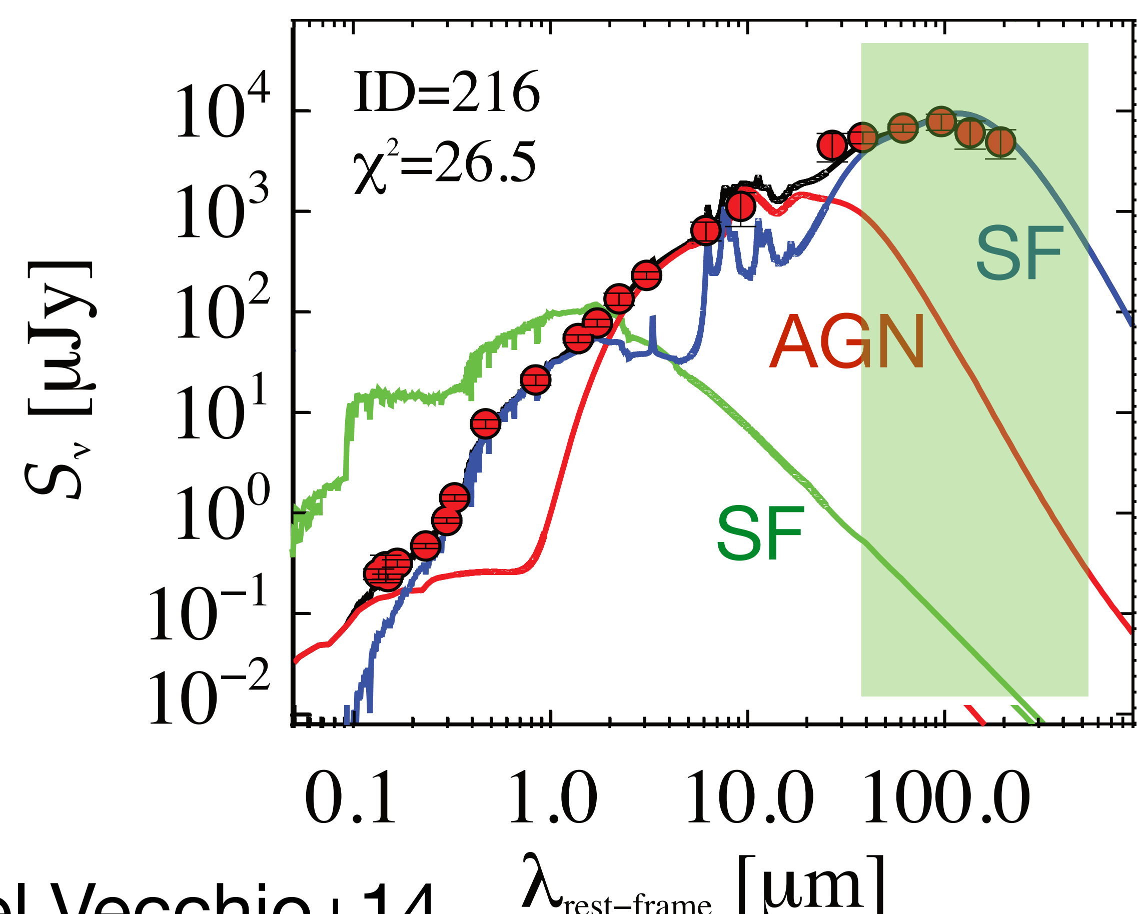




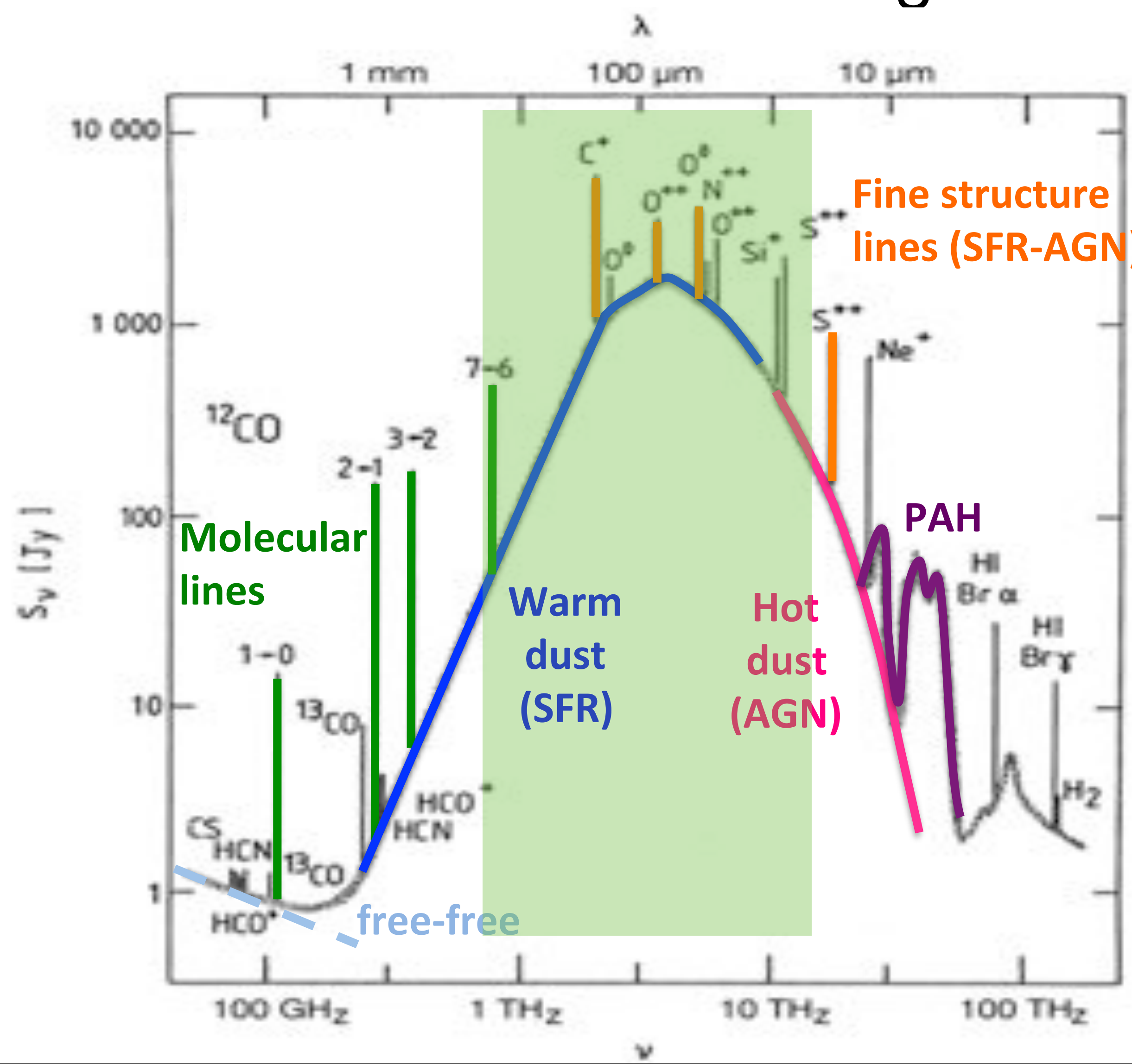


Dynamical host galaxy masses

- ⭐ Stellar mass depends on galaxy evolutionary stage
- ⭐ Ideally one should measure the dynamical mass
- ⭐ BH masses can be measured only in type 1 AGN: the bright AGN continuum hinders measurements on host galaxy!
- ⭐ Solution is to use fine structure or molecular lines in FIR-submm regime where AGN is much less strong.



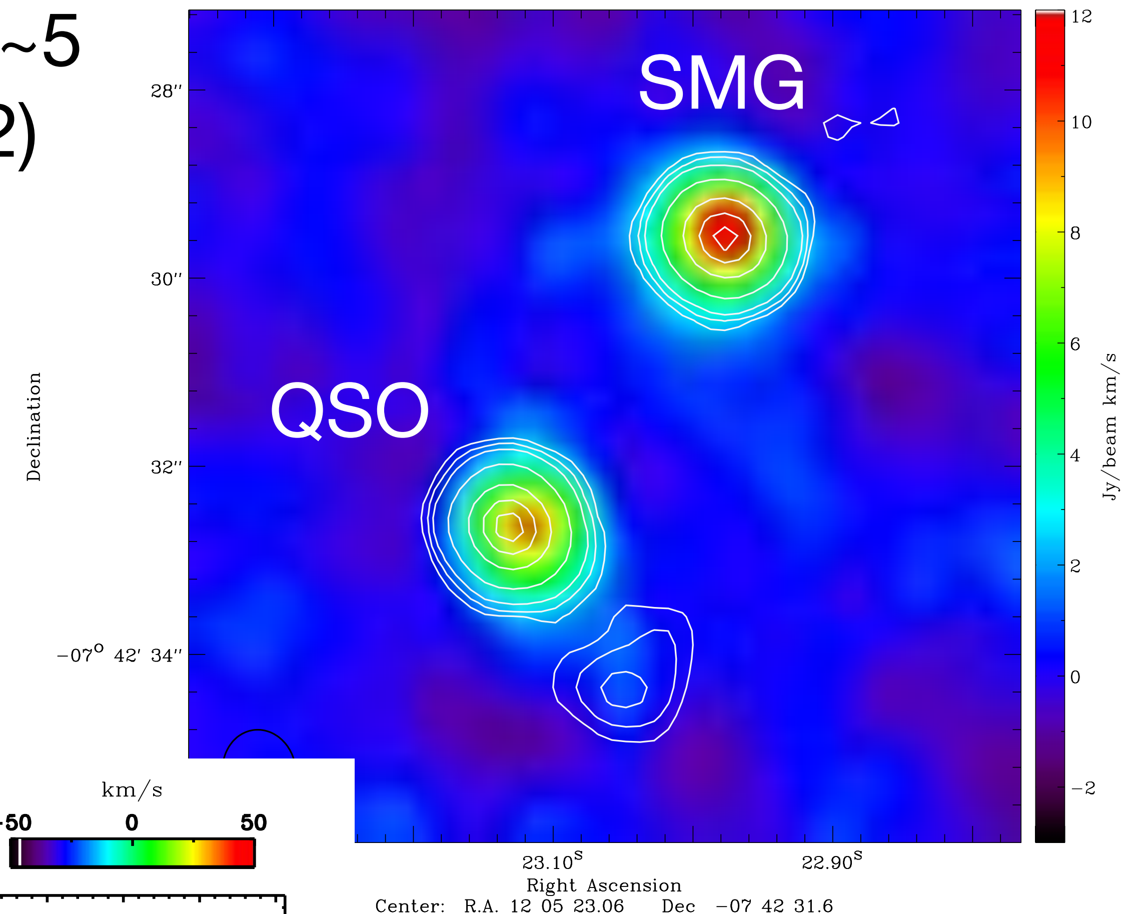
Del Vecchio+14

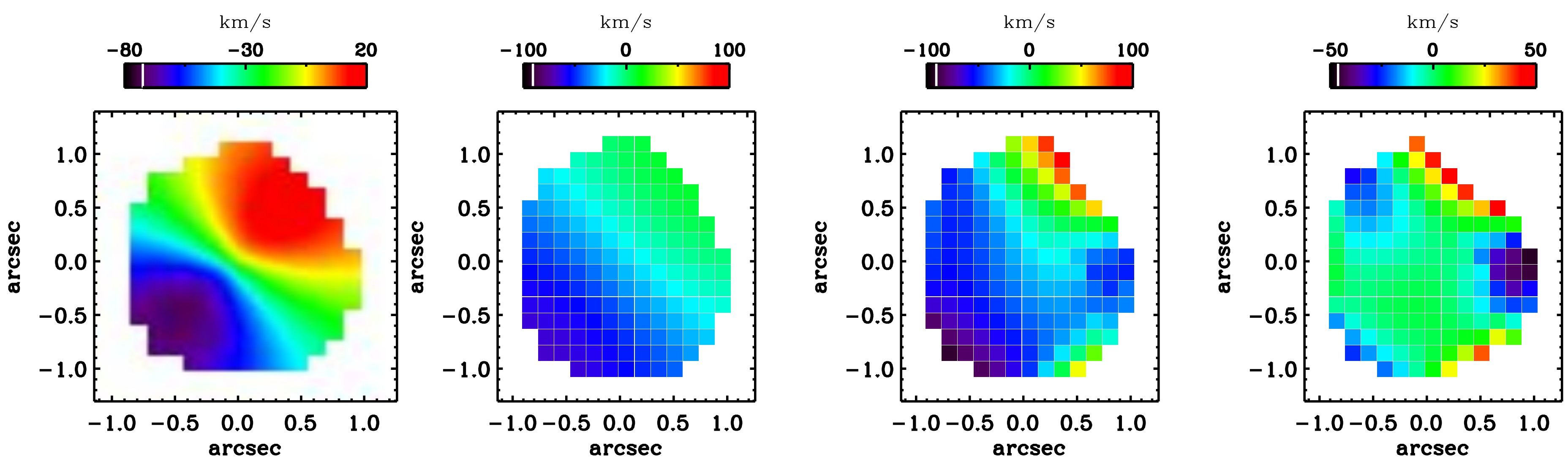


Dynamical mass from [CI] at z~5

BR1202-075 interacting/merging system at z~5 with ALMA (Wagg+12) and IRAM (Salome+12) submm observations:

- QSO and SMG at ~24 kpc
- strong Star Formation (~5000 M⊙/yr both)
- large molecular masses (~10^{11} M⊙)

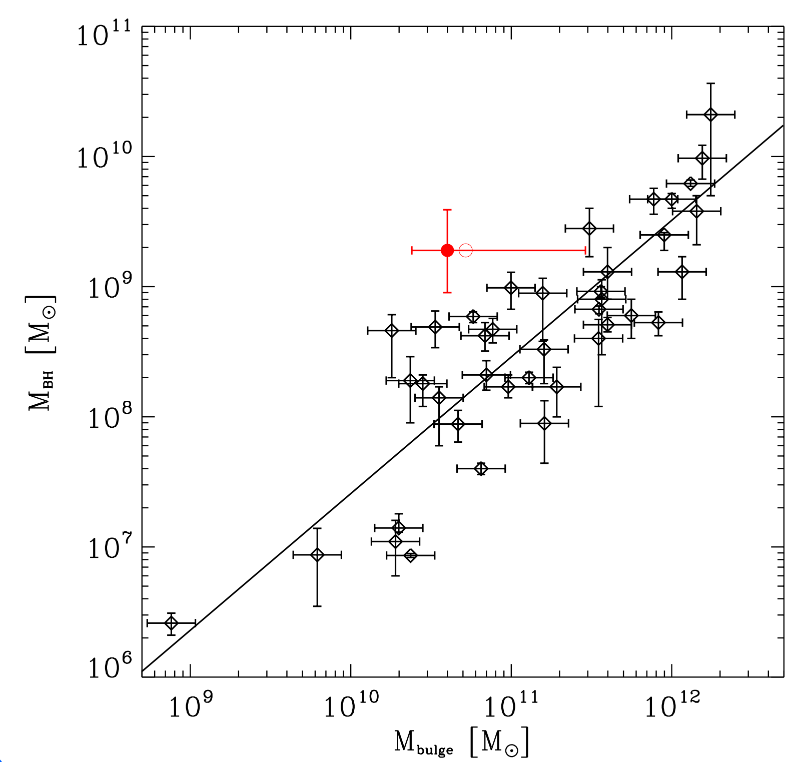




Model Data Residuals

Dynamical mass of QSO host galaxy from spatially resolved kinematics: ~ 3 10^{11} M⊙

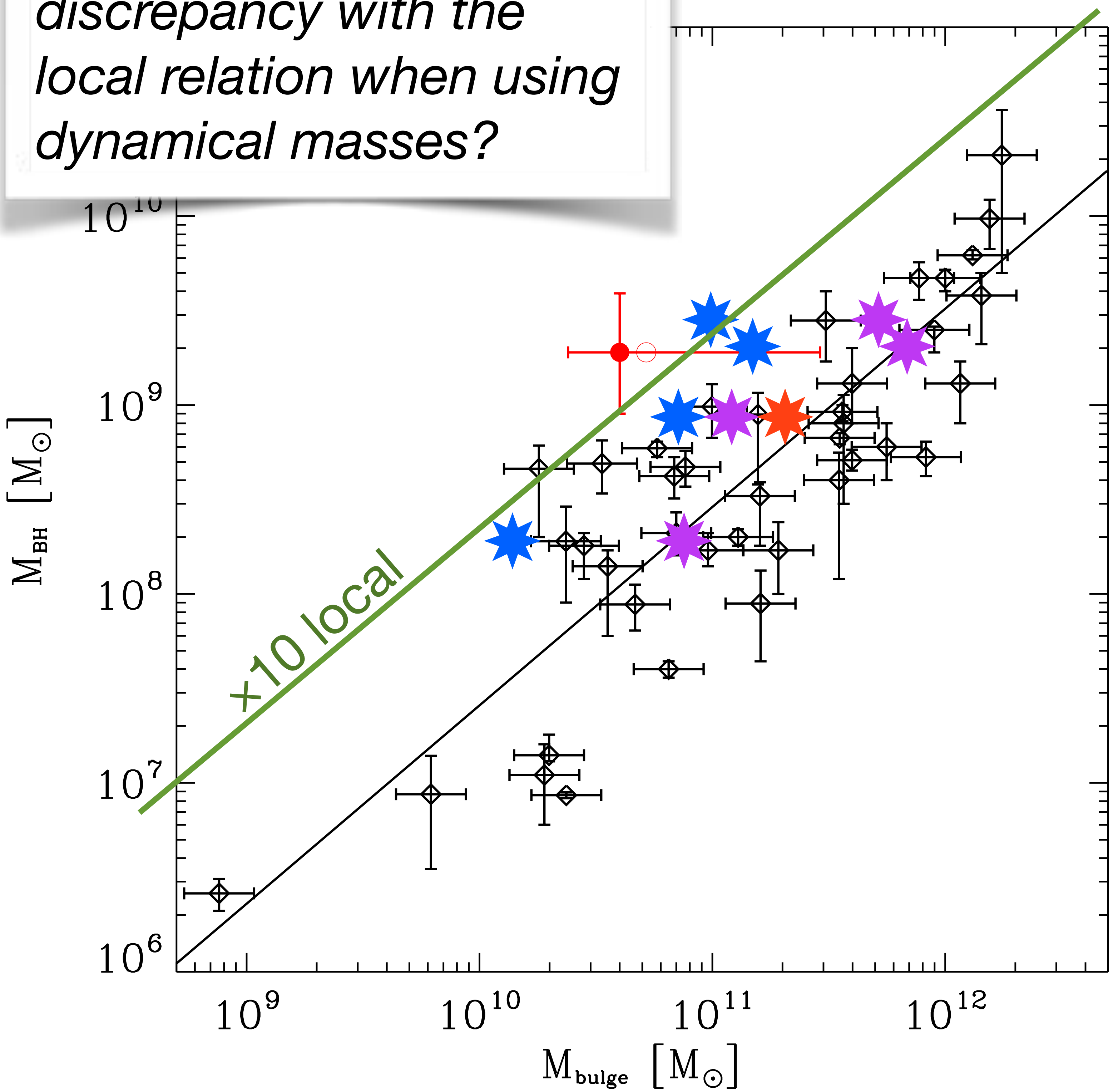
BH Mass of Quasar from MgII (X-Shooter): ~1.5 10^{9} M⊙



Carniani+13

ALMA SDT: BR1202-075

Is there really a discrepancy with the local relation when using dynamical masses?

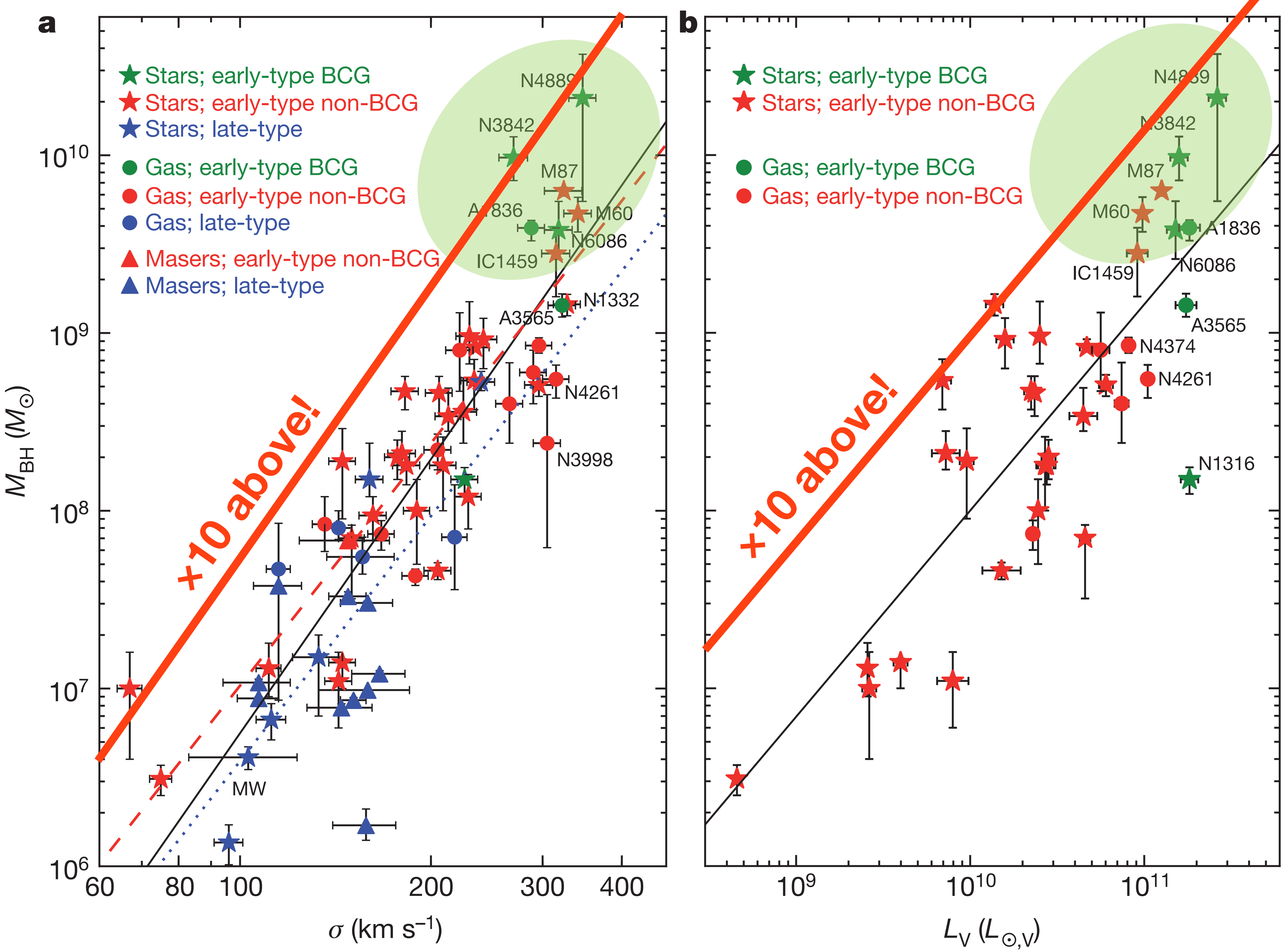


Wang+13
Galaxy masses from virial estimates of ALMA data V^2R
assume inclination from shape of line SB isophotes (i~25-60 deg); no kinematical modeling

Wang+13
assume inclination is 20 deg

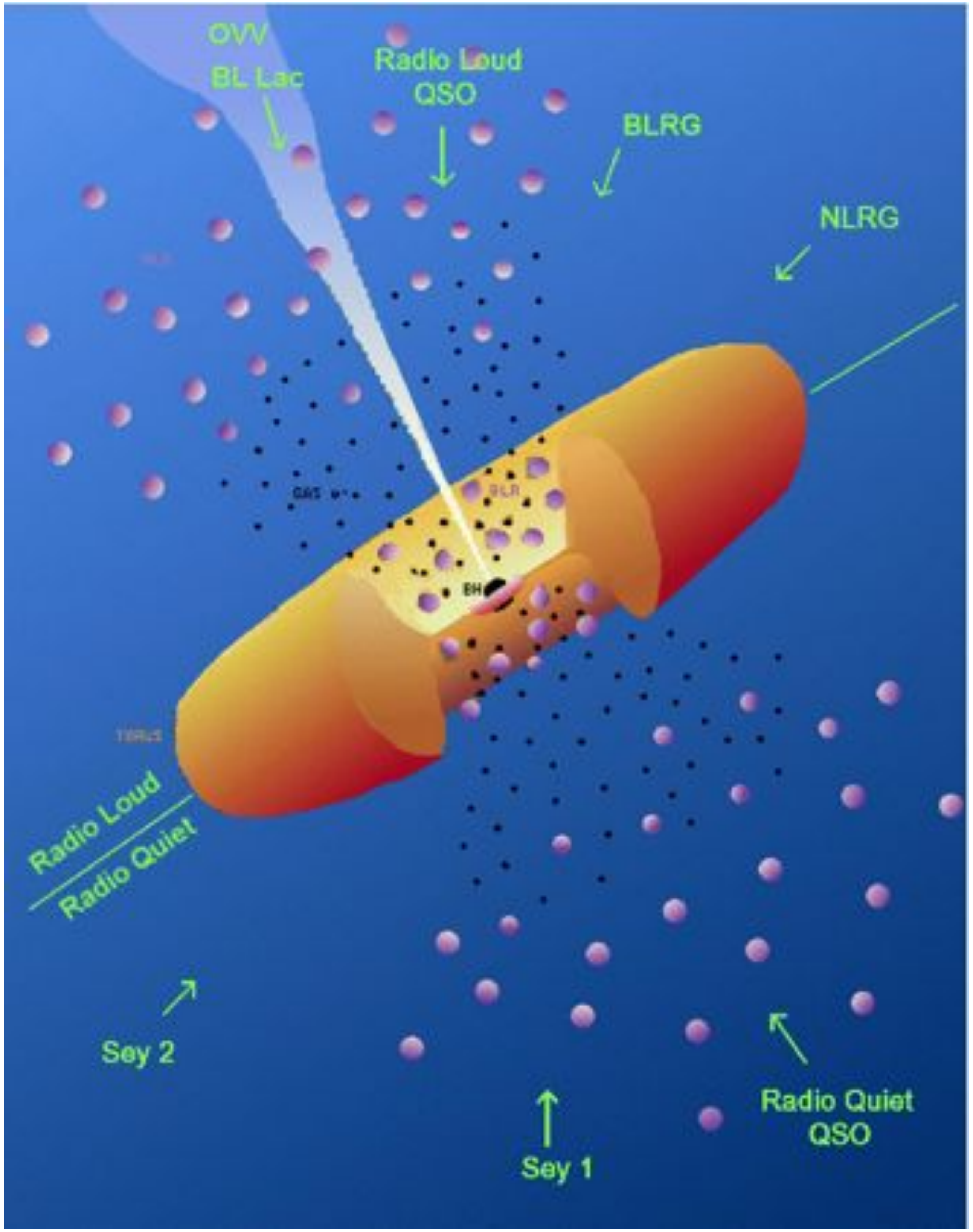
Inskip+11
galaxy mass from modeling SINFONI kinematics

MBH-σ & MBH-L: high mass end?



McConnell+11,13

Beyond the spatial resolution

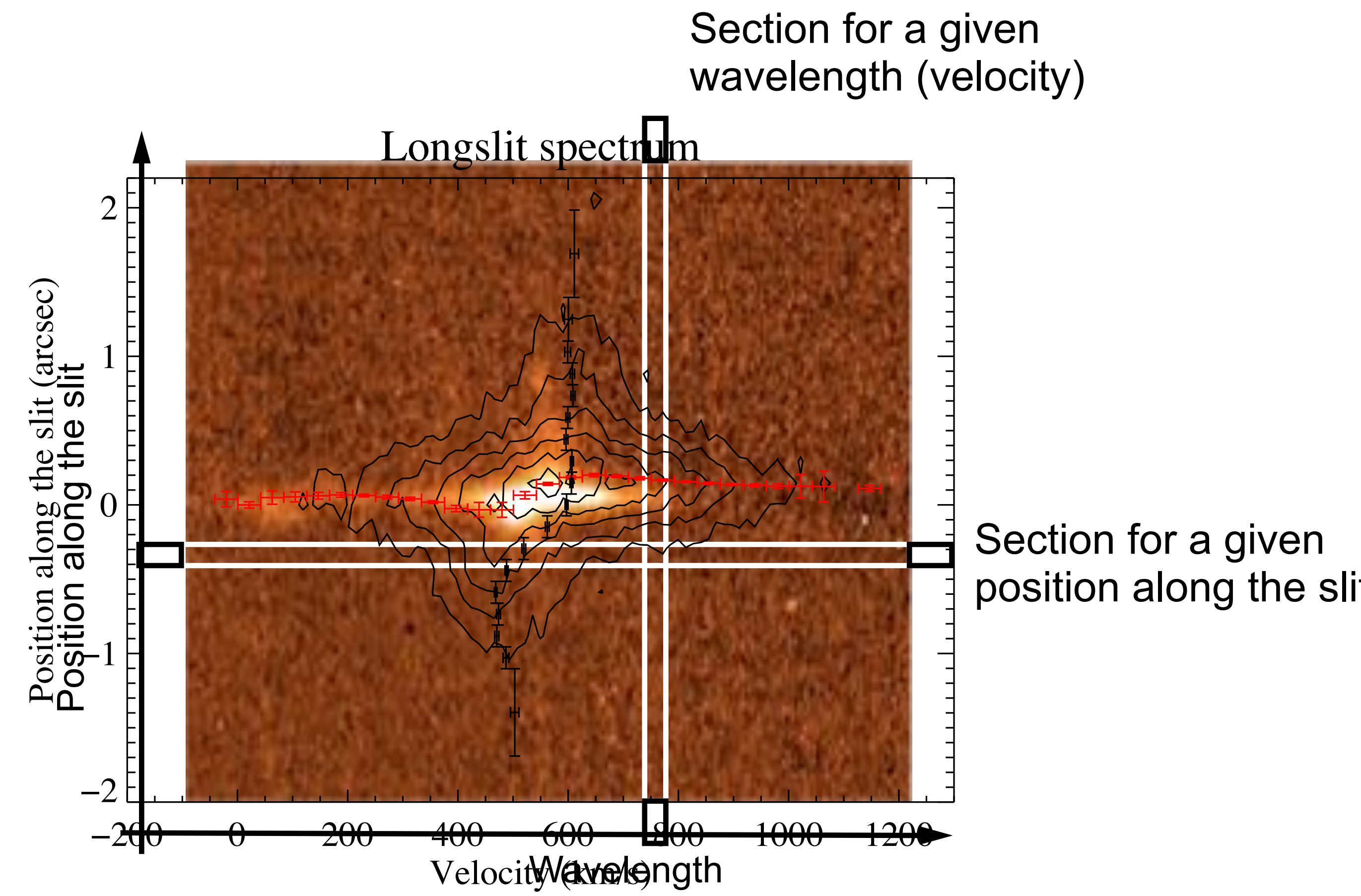


The spectroastrometric approach

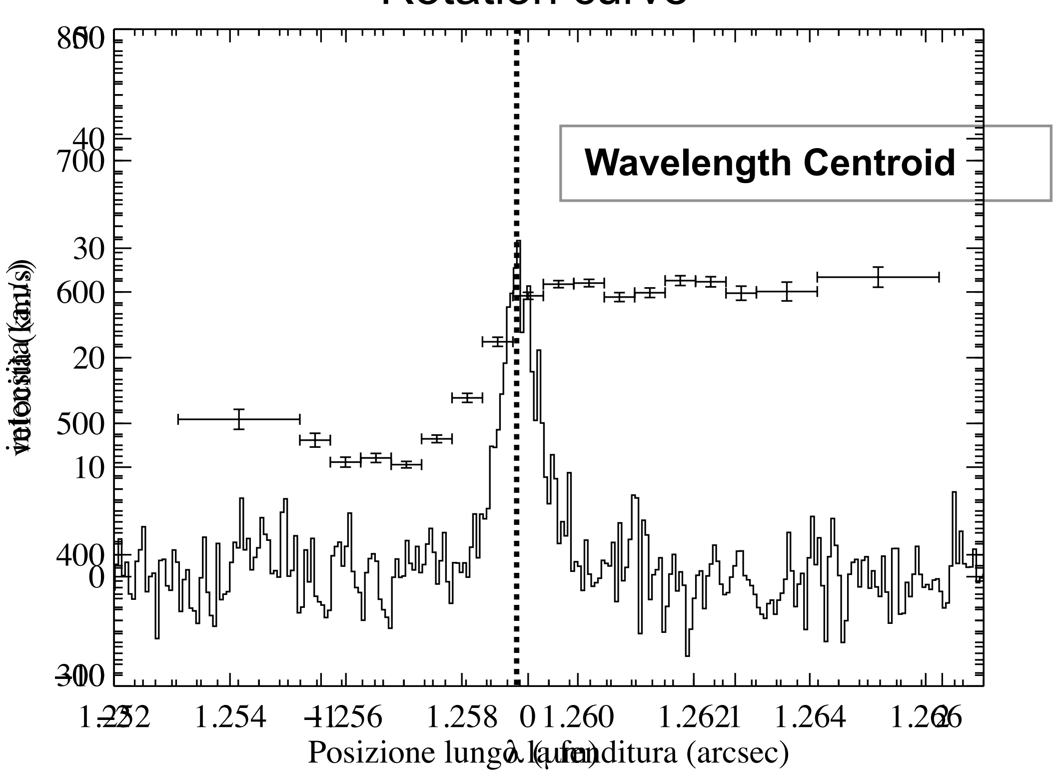
Spectroastrometry is well known from radio astronomers and, more recently, in the field of star formation …

much less in extragalactic astronomy.

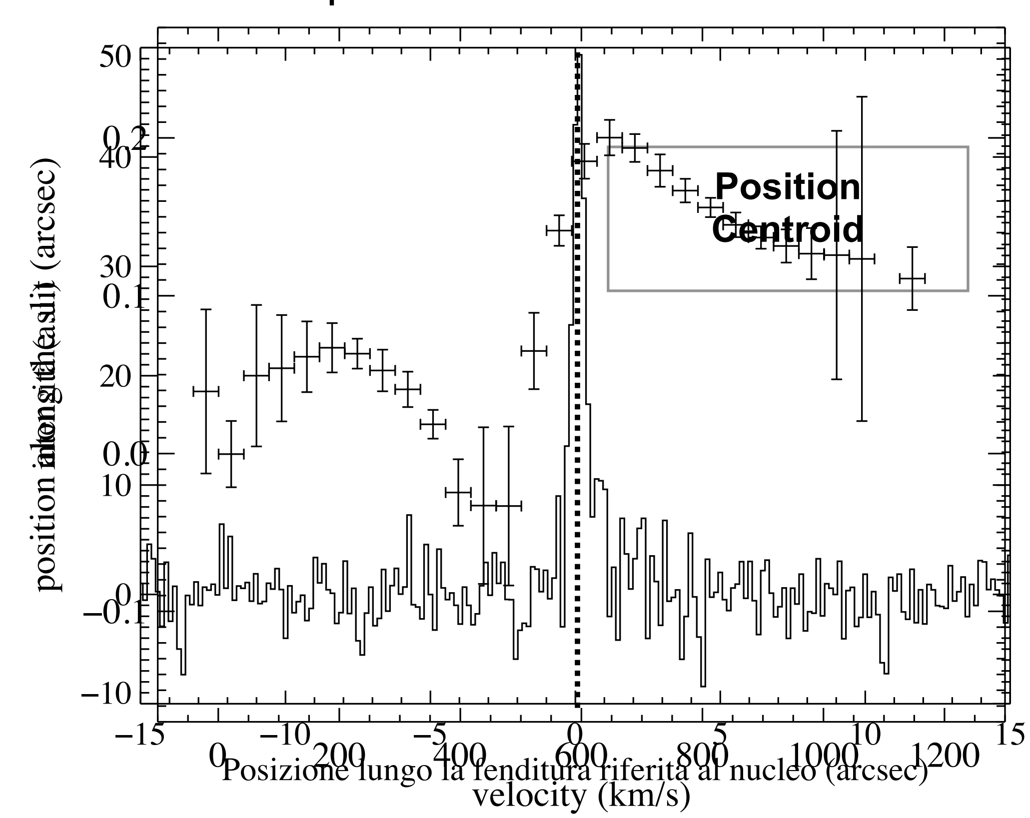
Sometimes is just a matter of different names!



Rotation curve

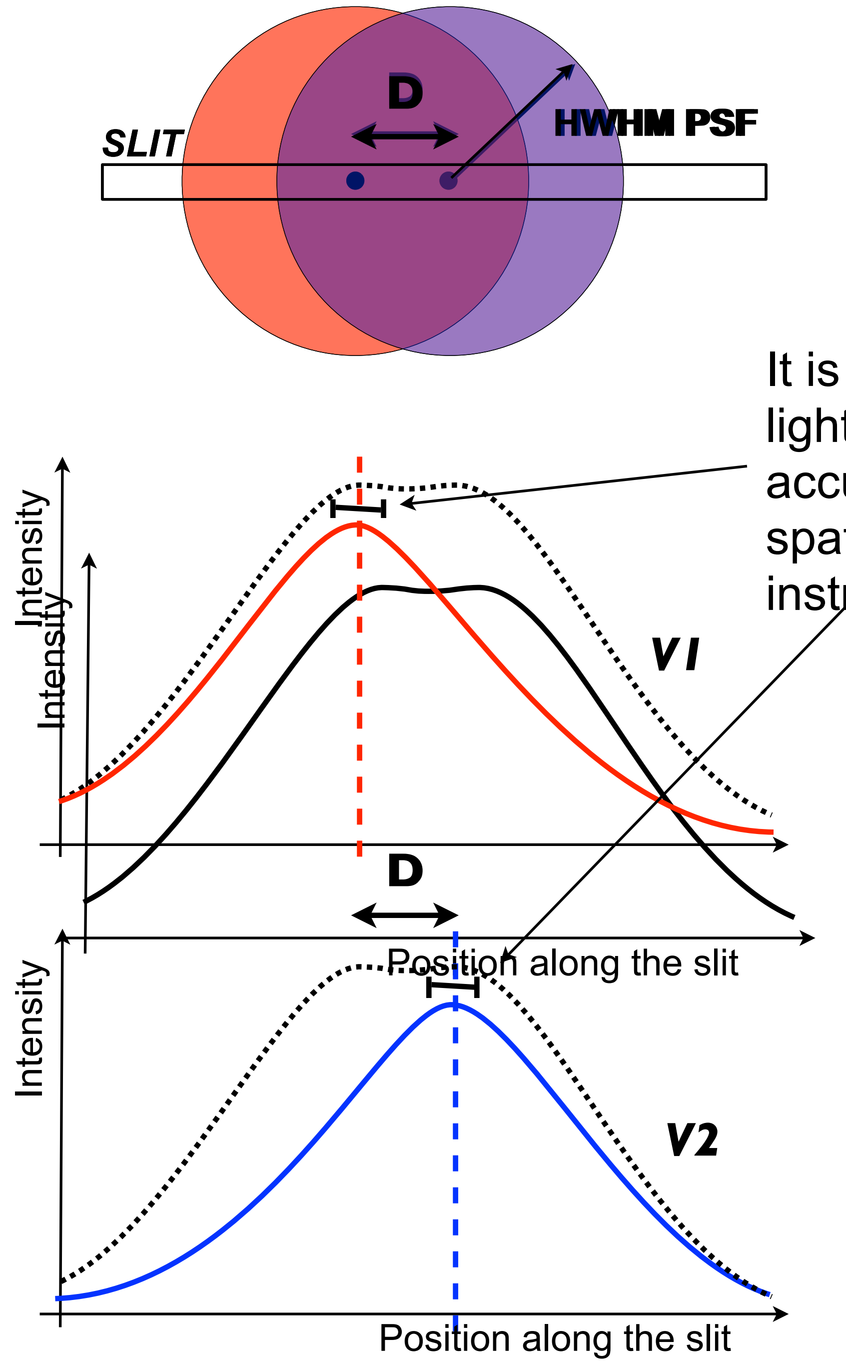


Spectroastrometric curve



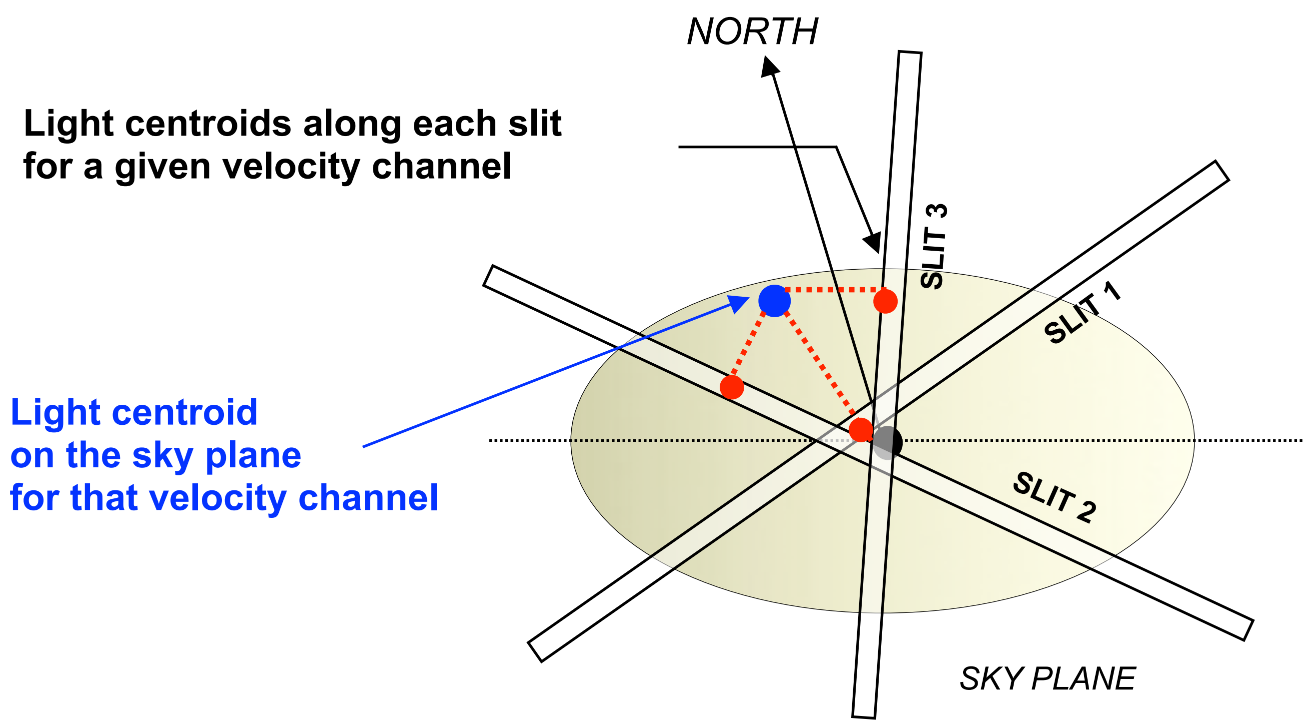
“Overcoming” the spatial resolution

Two pointlike sources imaged trough a slit

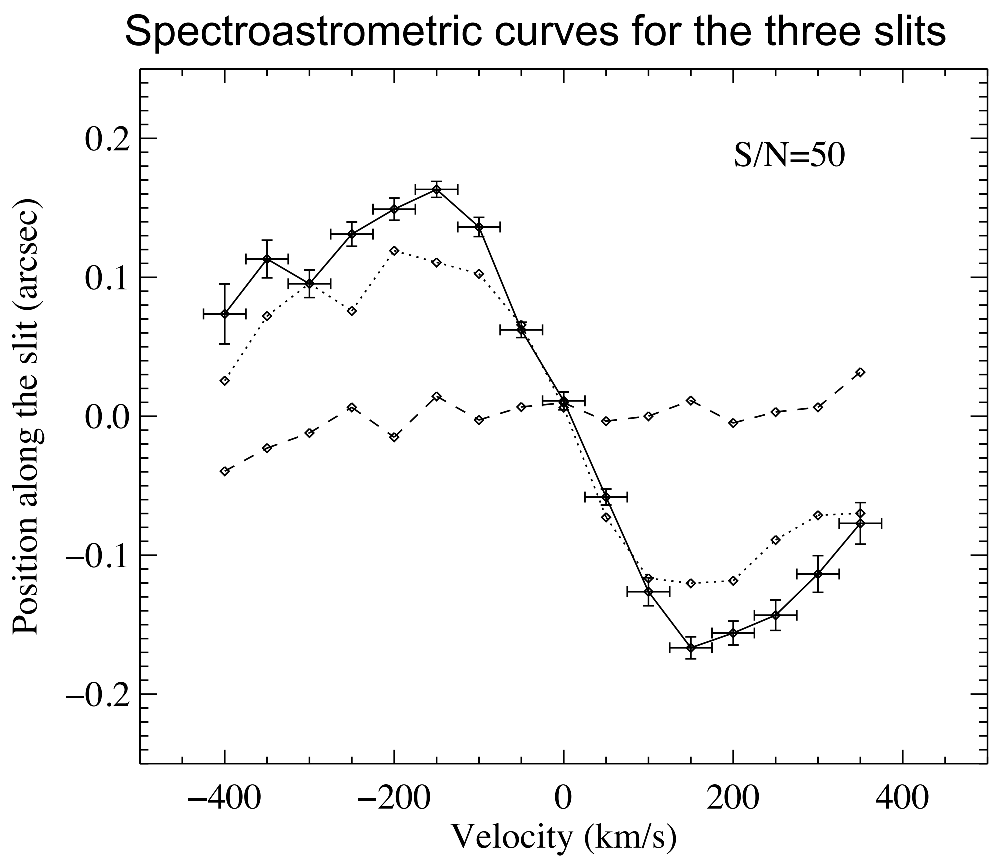


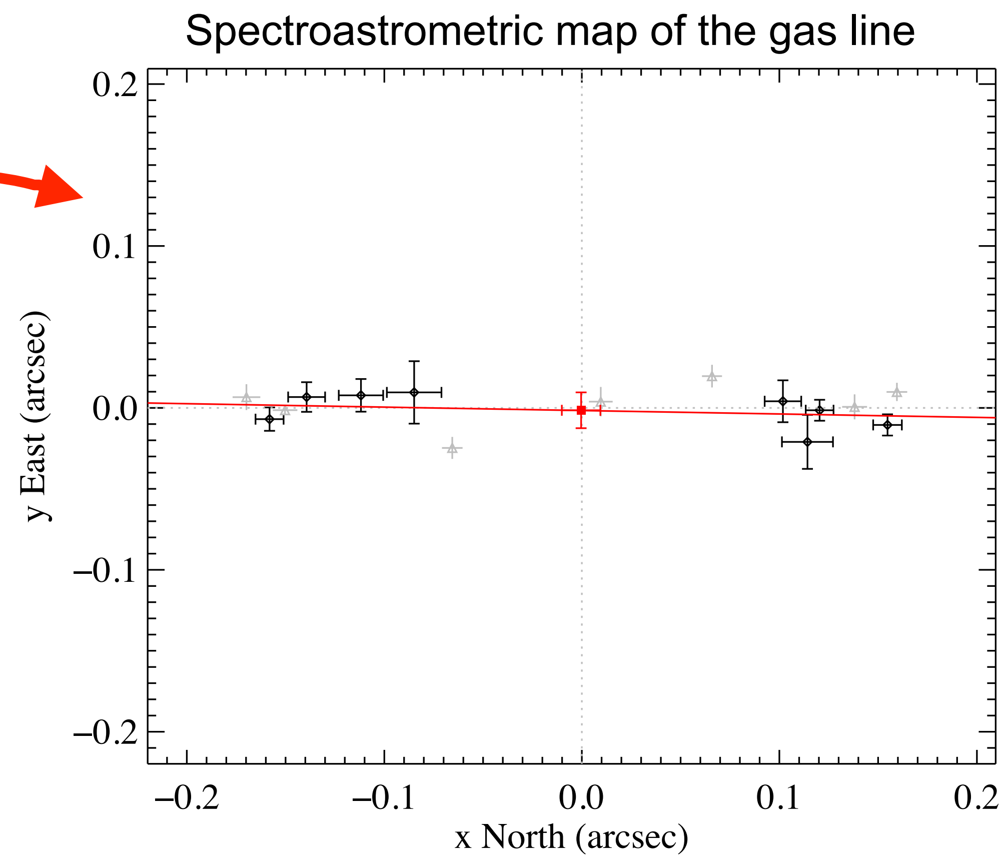
It is possible to measure the light centroid position with an accuracy smaller than the spatial resolution (FWHM of the instrumental PSF)

Application to rotating disks

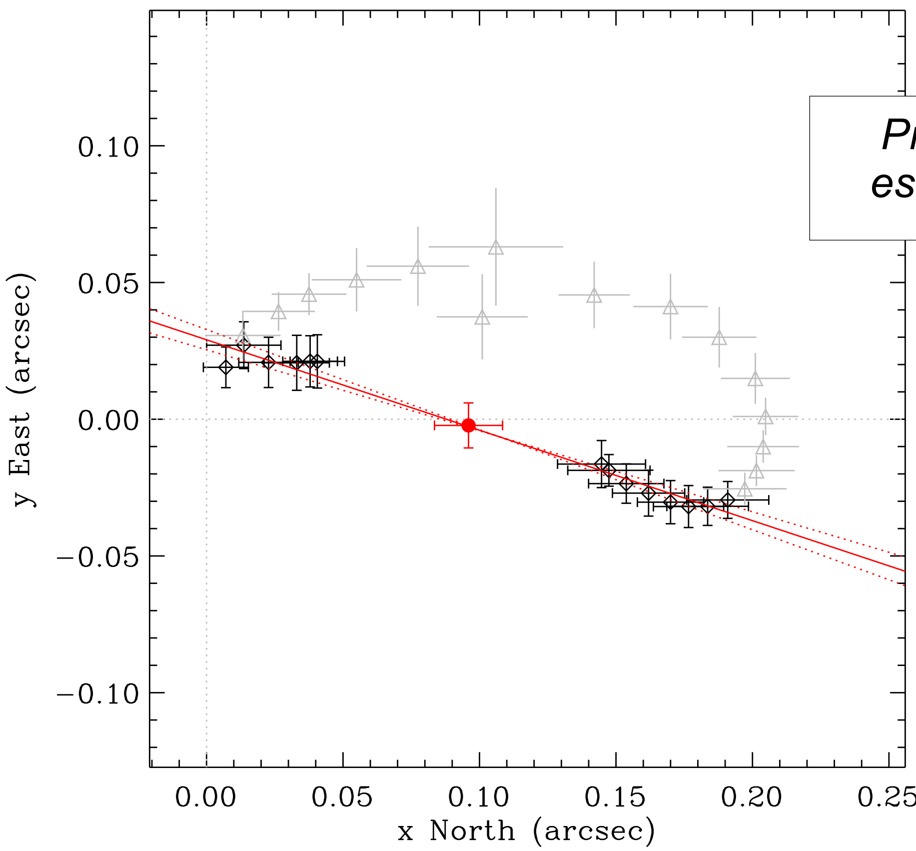


The application to Integral-field spectra is straightforward!

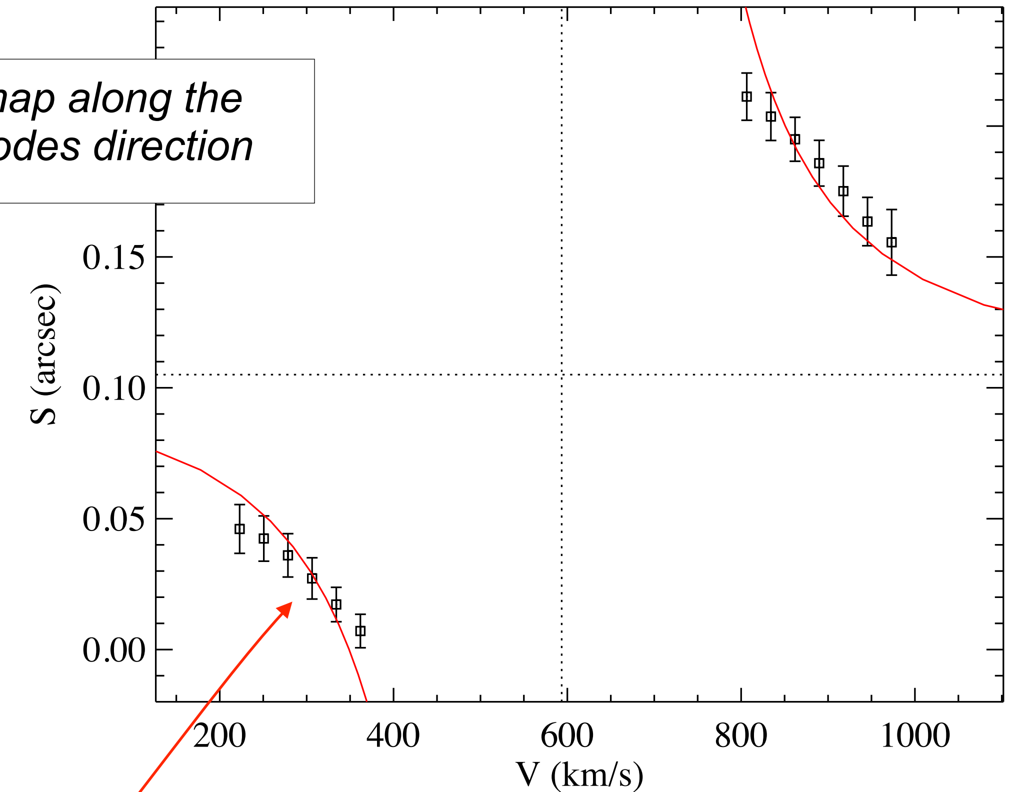




BH mass from spectroastrometric map

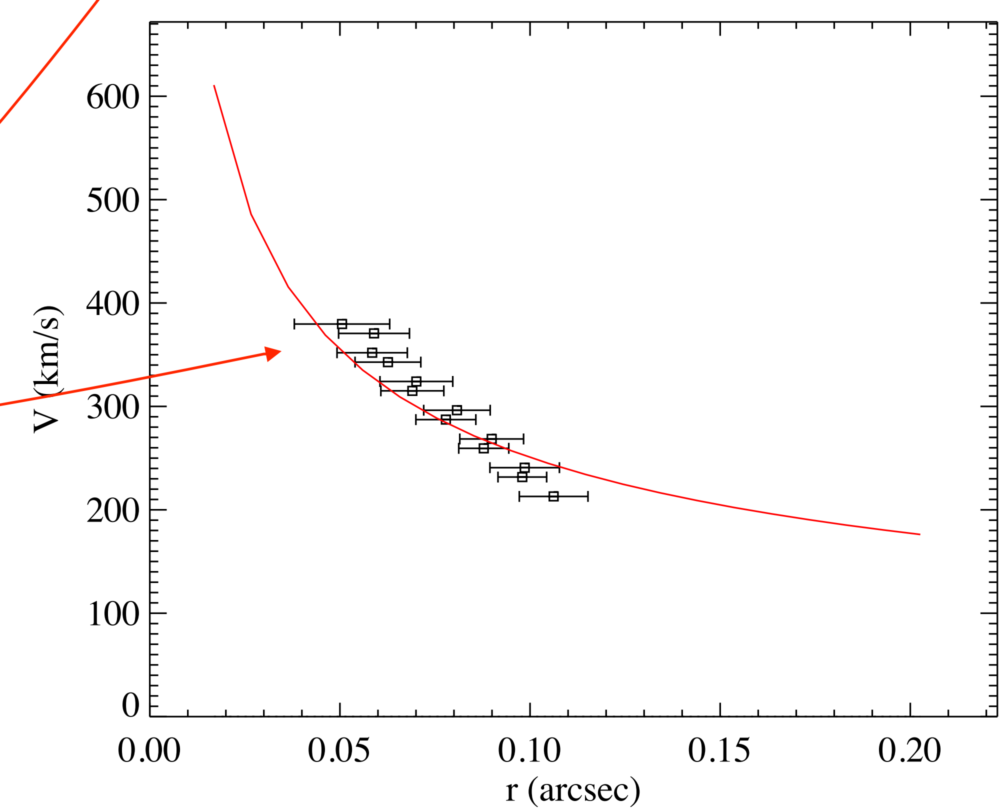


Projection of the map along the estimated line of nodes direction



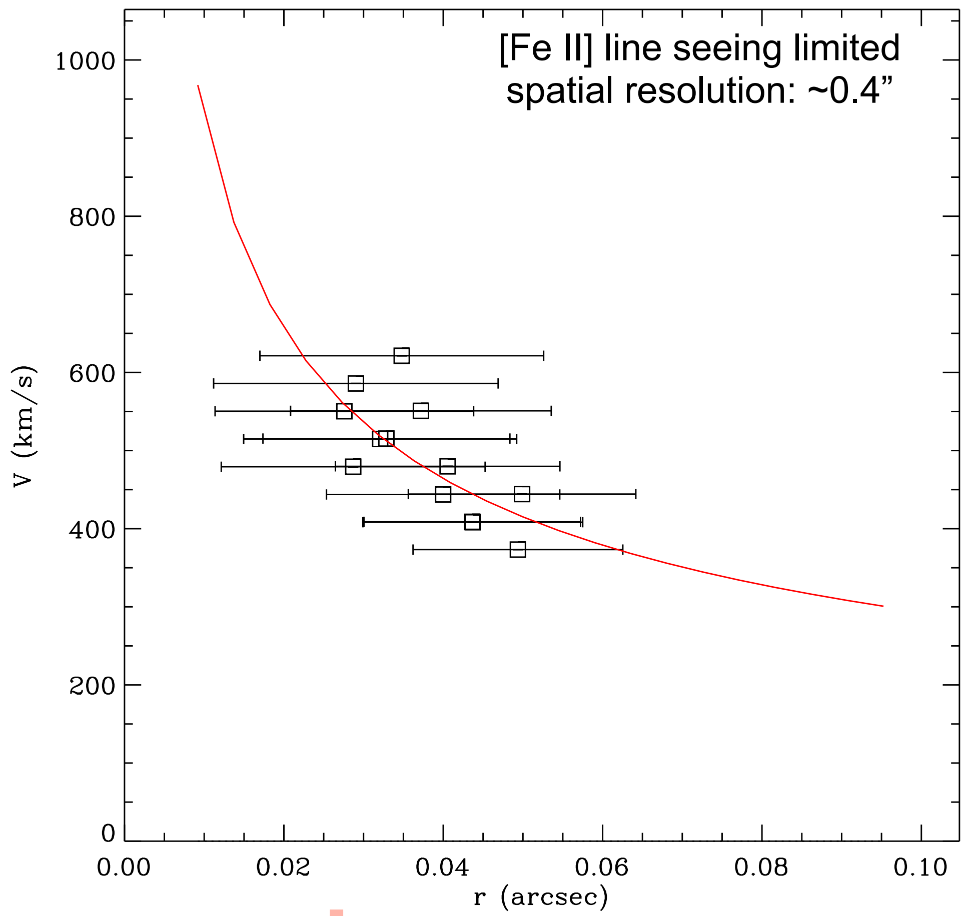
"*Spectroastrometric*" Rotation curve
based on ***"mean position"*** measurements
(instead of ***"mean velocity"*** measurements)

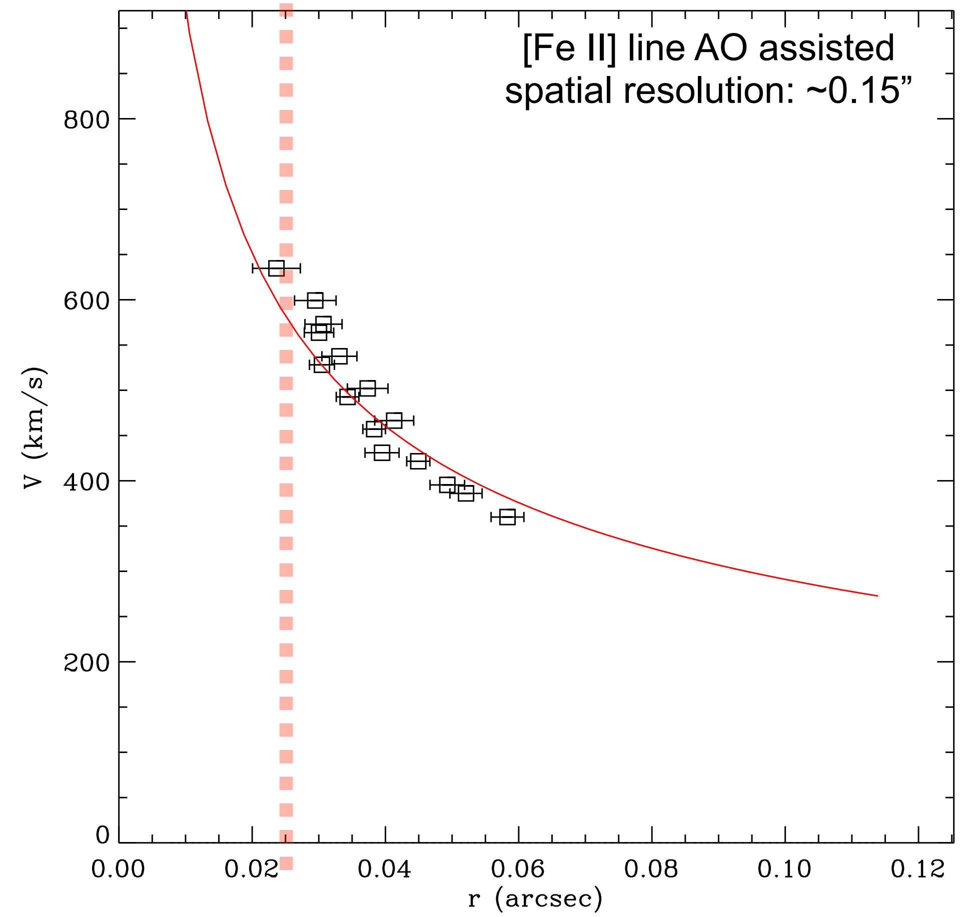
$$V_{rot} = \sqrt{\frac{GM_{BH}}{r}}$$

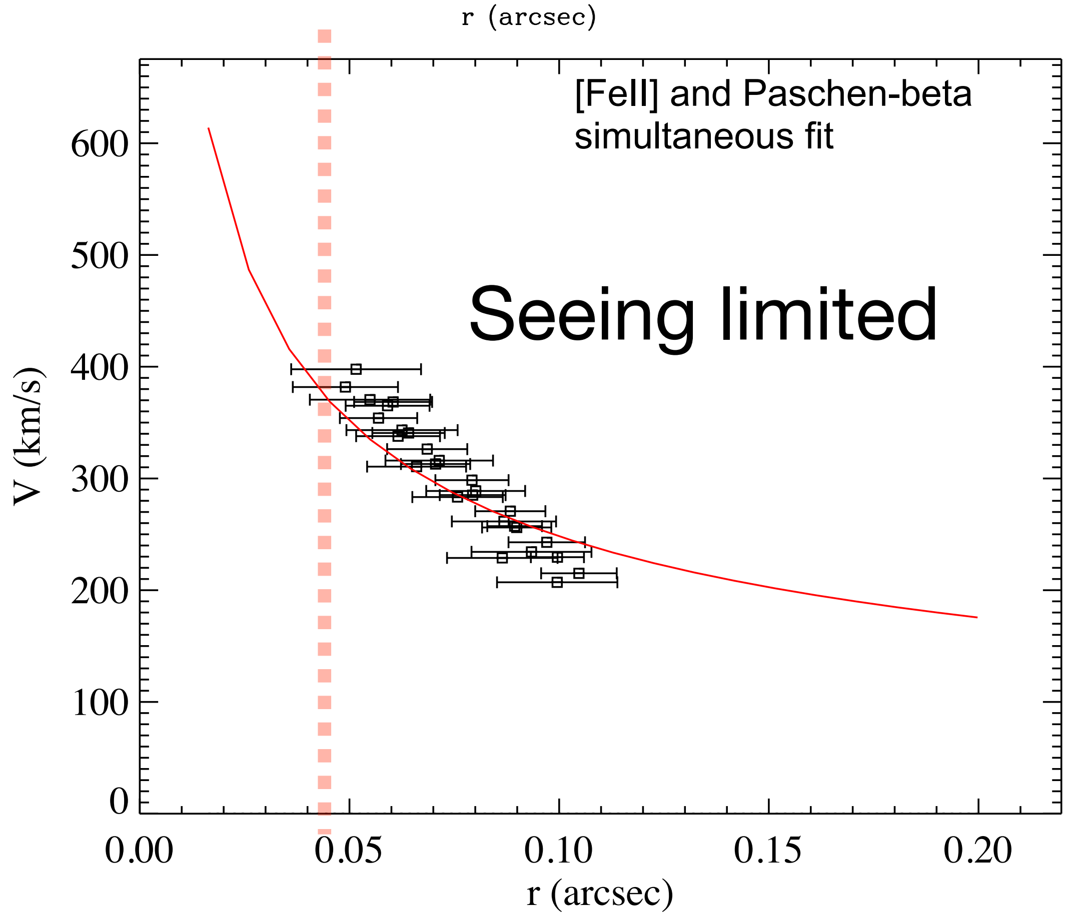


Gnerucci, AM+10

Example: Centaurus A





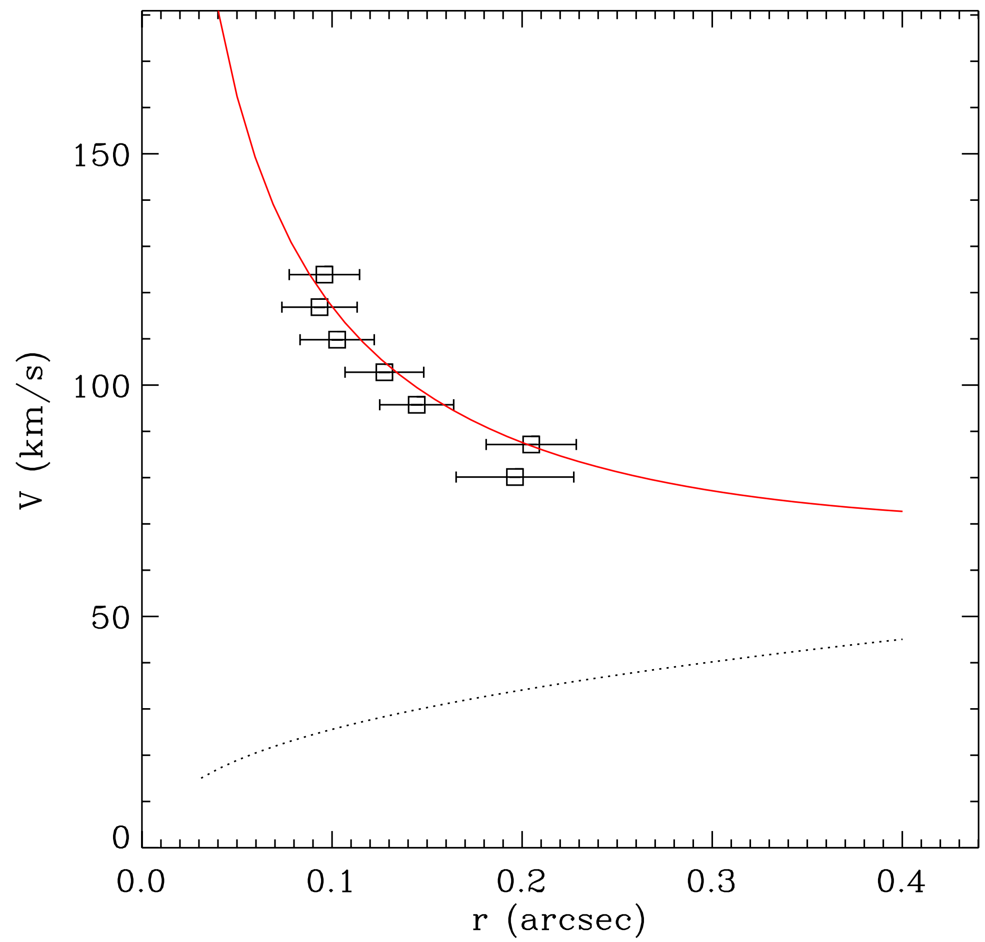


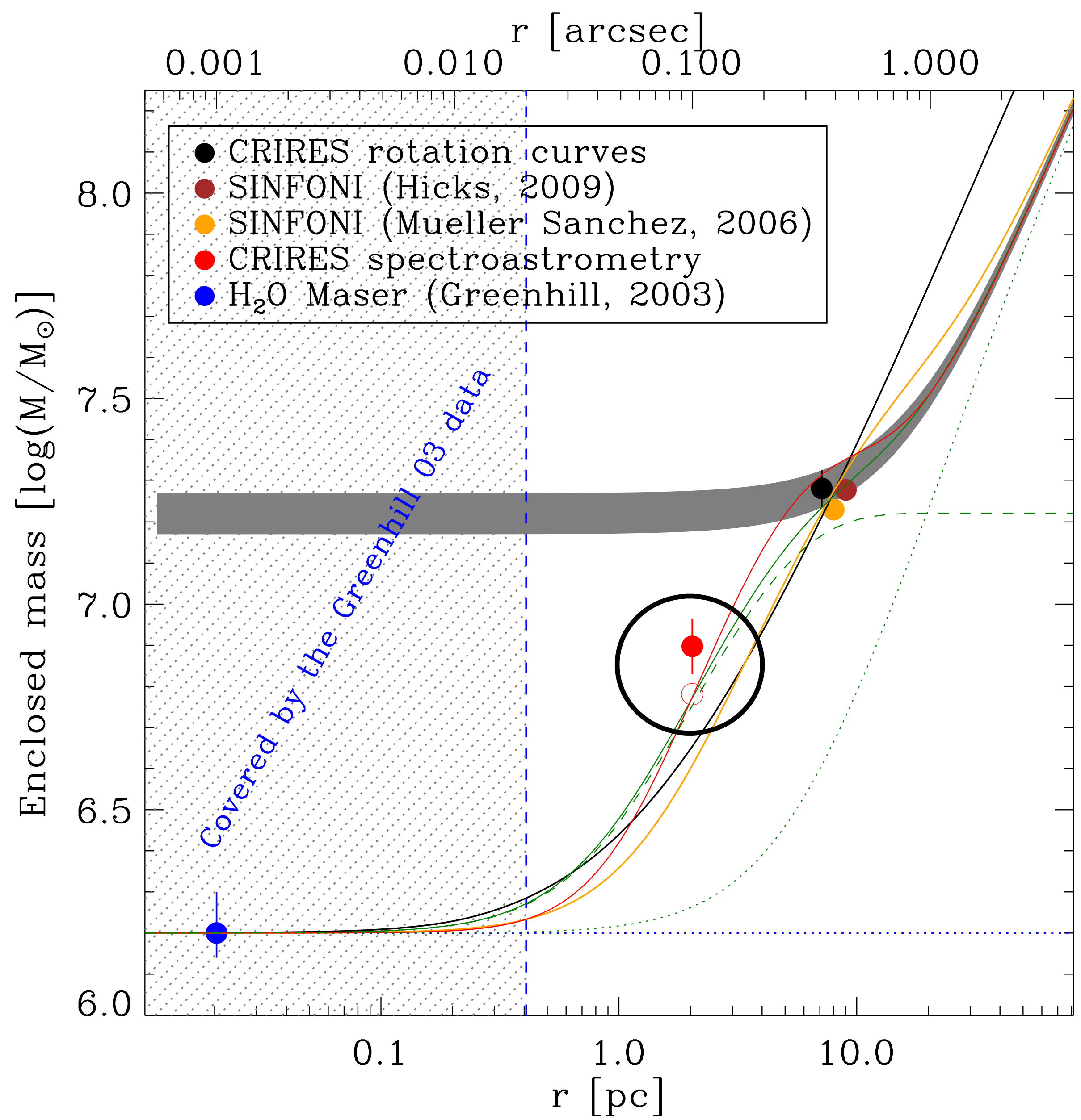
- ***Estimated BH mass:*** $\sim 1.9 \times 10^8 M_\odot$
- ***We can probe the rotation curve down to radii of*** $\sim 0.025''$ ***:*** $\sim 1/16$ ***of the spatial resolution (*** $0.4''$***) for seeing limited observations and*** $\sim 1/7$ ***of the spatial resolution (*** $0.15''$***) for AO assisted observations.***

Gnerucci, AM+11

Example: Circinus galaxy

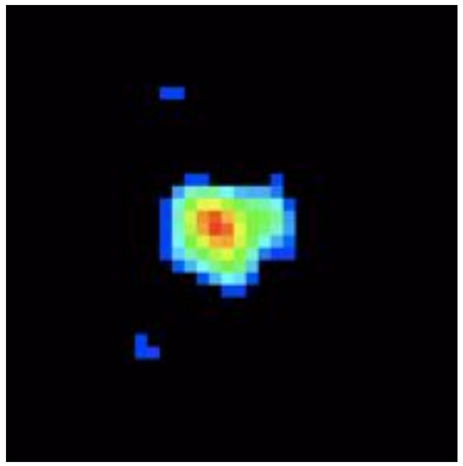
CRIRES Paβ observations of Circinus galaxy: well known BH mass from H_2O made observations (Greenhill+03)

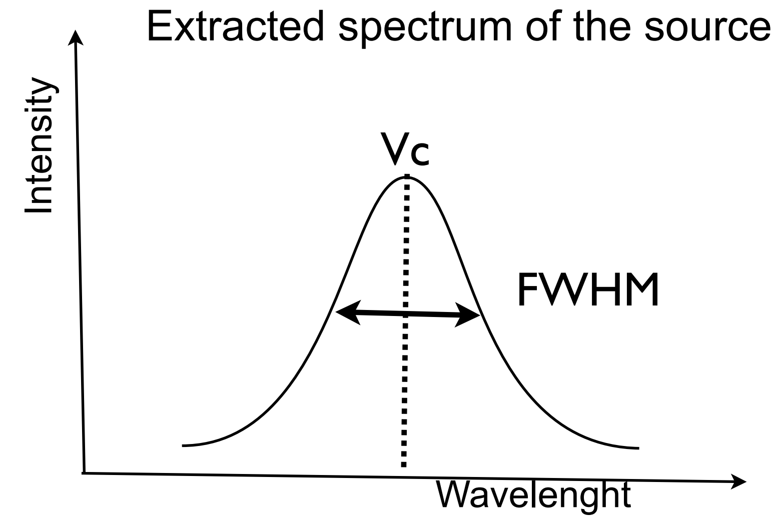




Gnerucci, AM+13

High redshift galaxies





Virial theorem

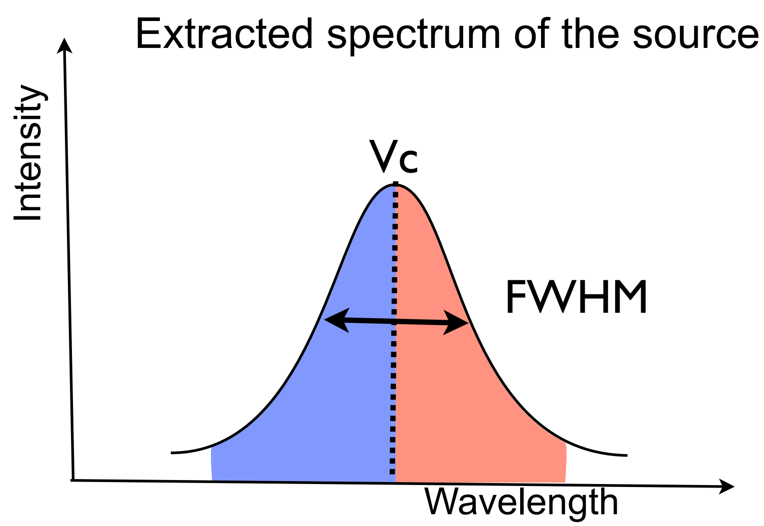
$$V_{circ}(r) = \sqrt{\frac{GM(r)}{r}}$$

$$M(r_e) = f\,\frac{r_e V_{circ}^2}{G}$$

$V_{circ}(r) \equiv FWHM$ *(corrected for the instrumental response)*

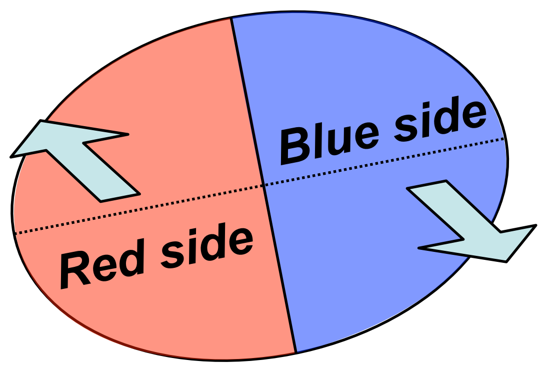
the characteristic radius is usually estimated as the half-light radius of the continuum or line emission (corrected for the instrumental response)

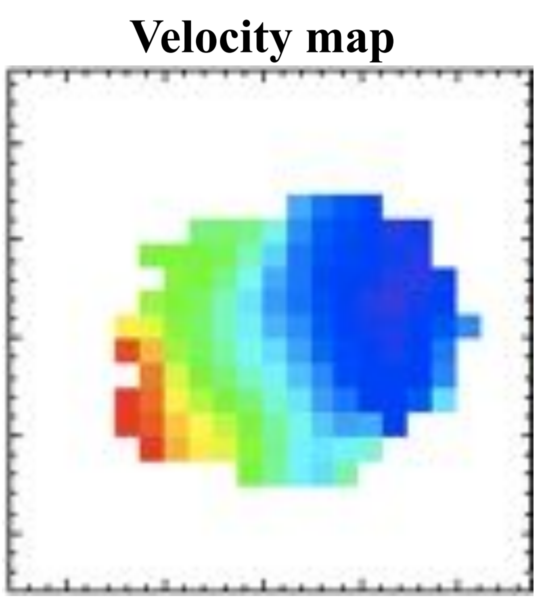
Specast based virial masses

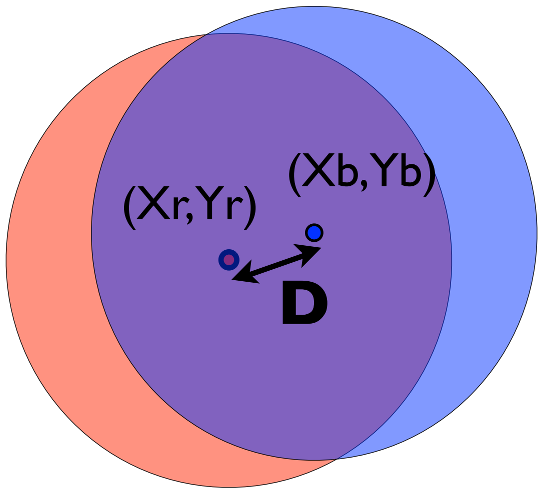


"Classical" virial mass estimator

$$M(r_e) = f\frac{r_e V_{circ}^2}{G}$$





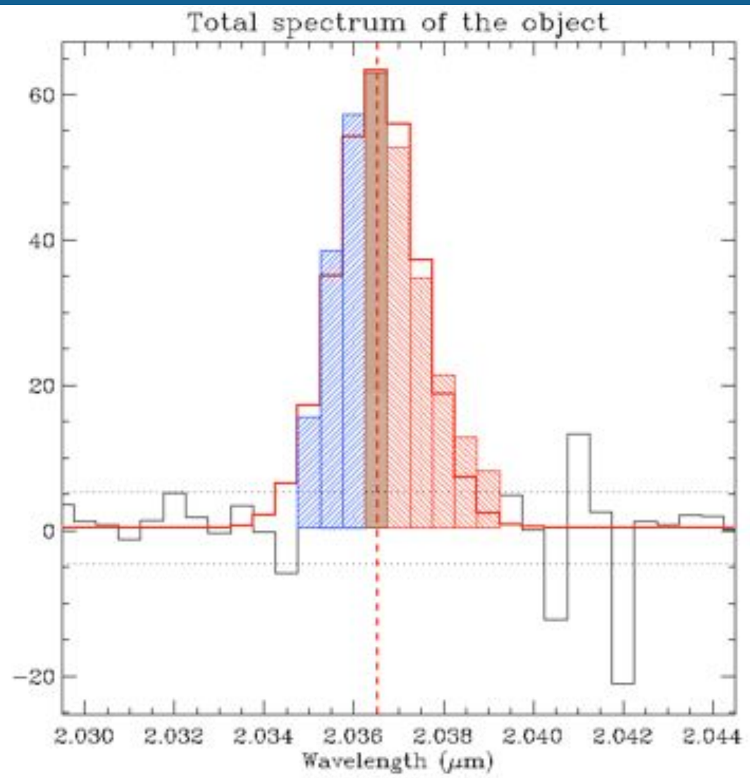


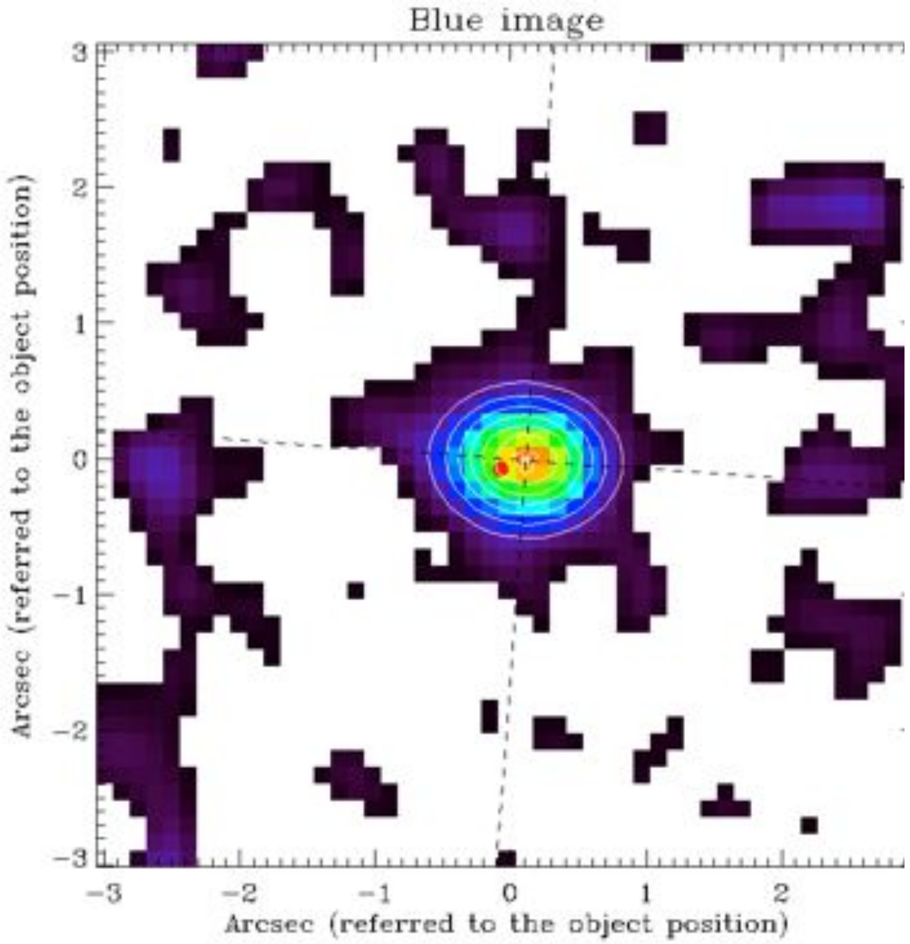
$$r_{spec} = D/2$$

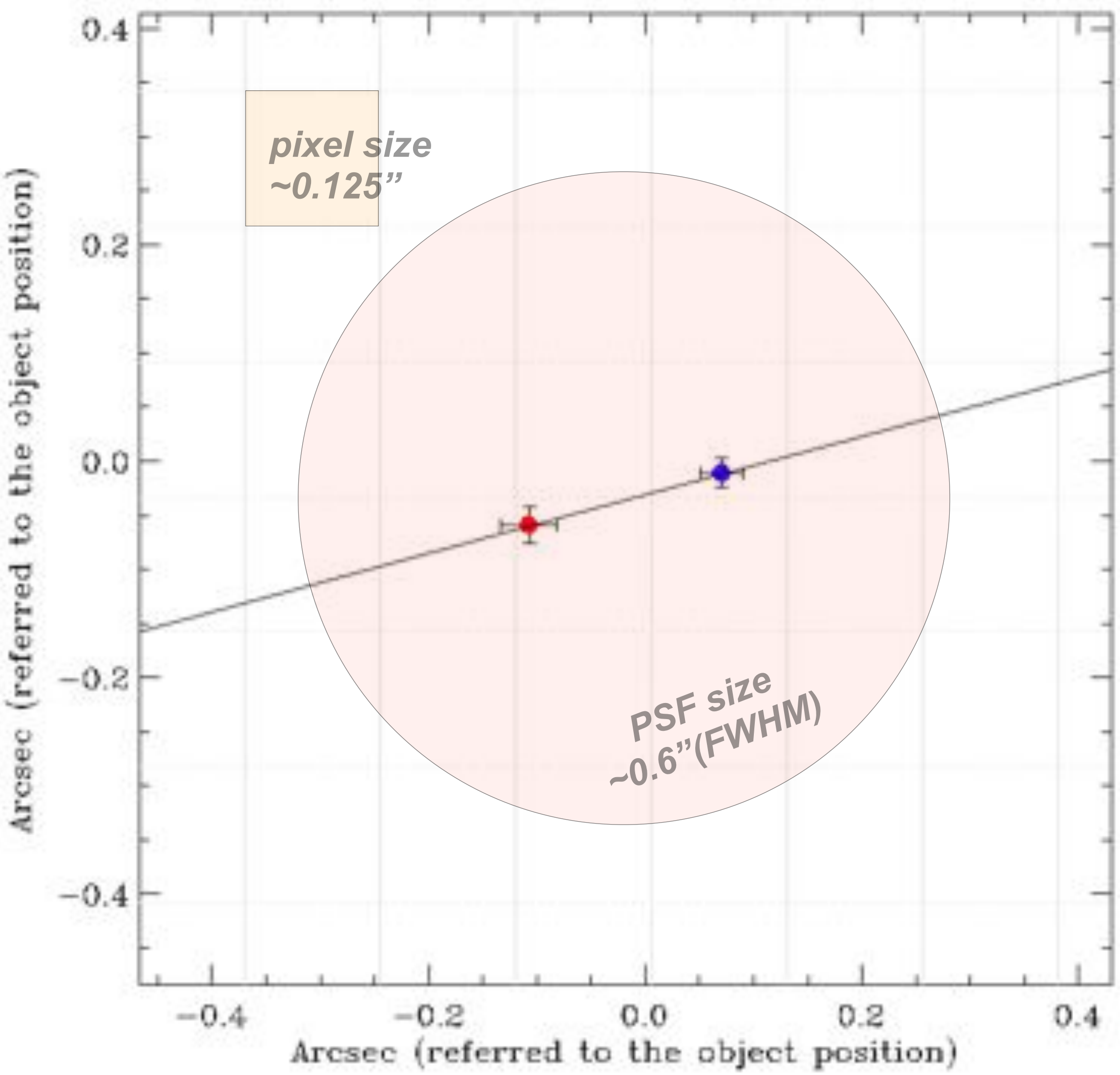
"Spectroastrometric" *virial mass estimator*

$$M(r_e) = f\frac{r_{spec} FWHM^2}{G}$$

Specast based virial masses







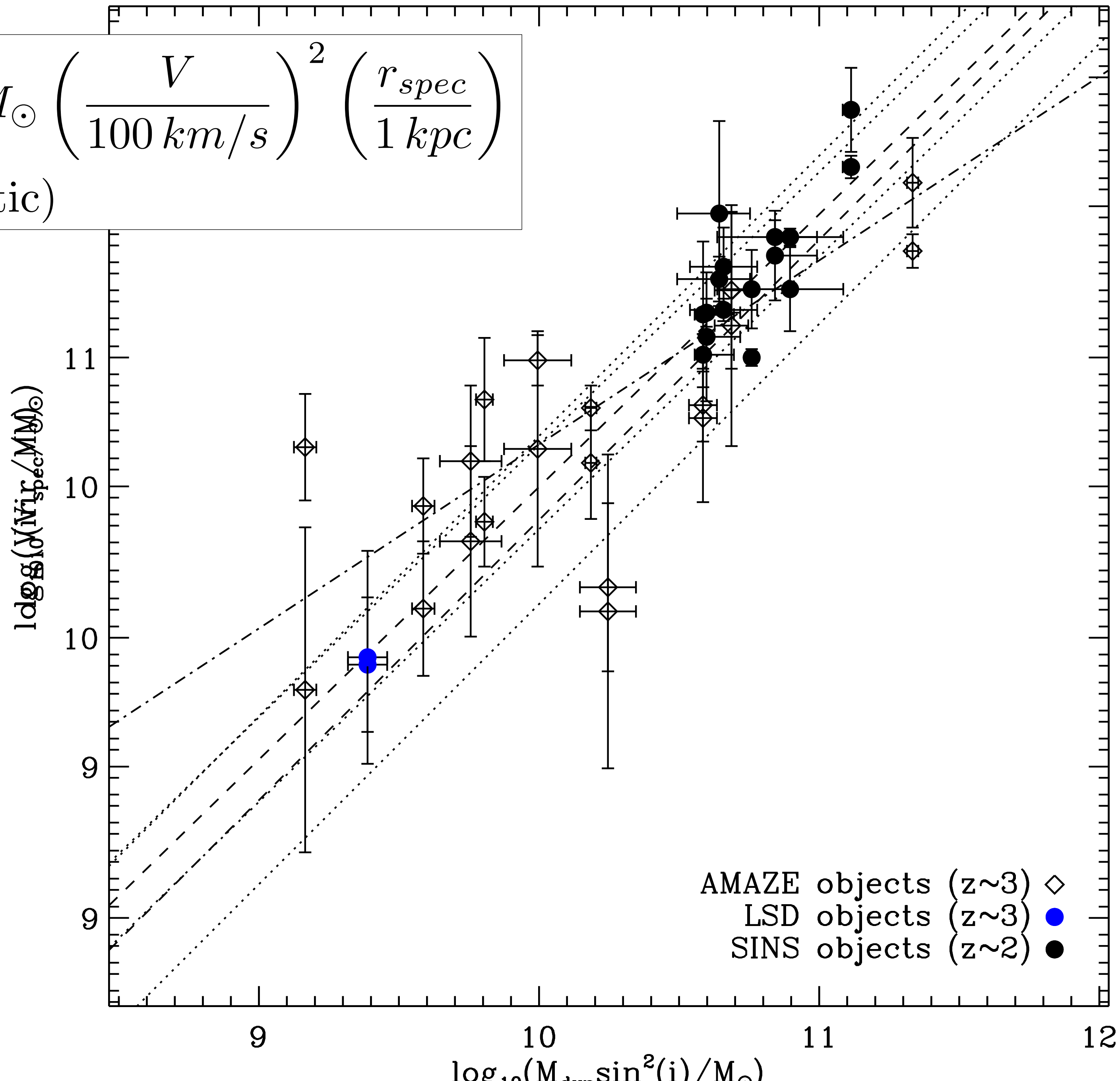
Calibration of mass estimator

19 objects from the AMAZE, LSD (z~3) e SINS (z~2) samples

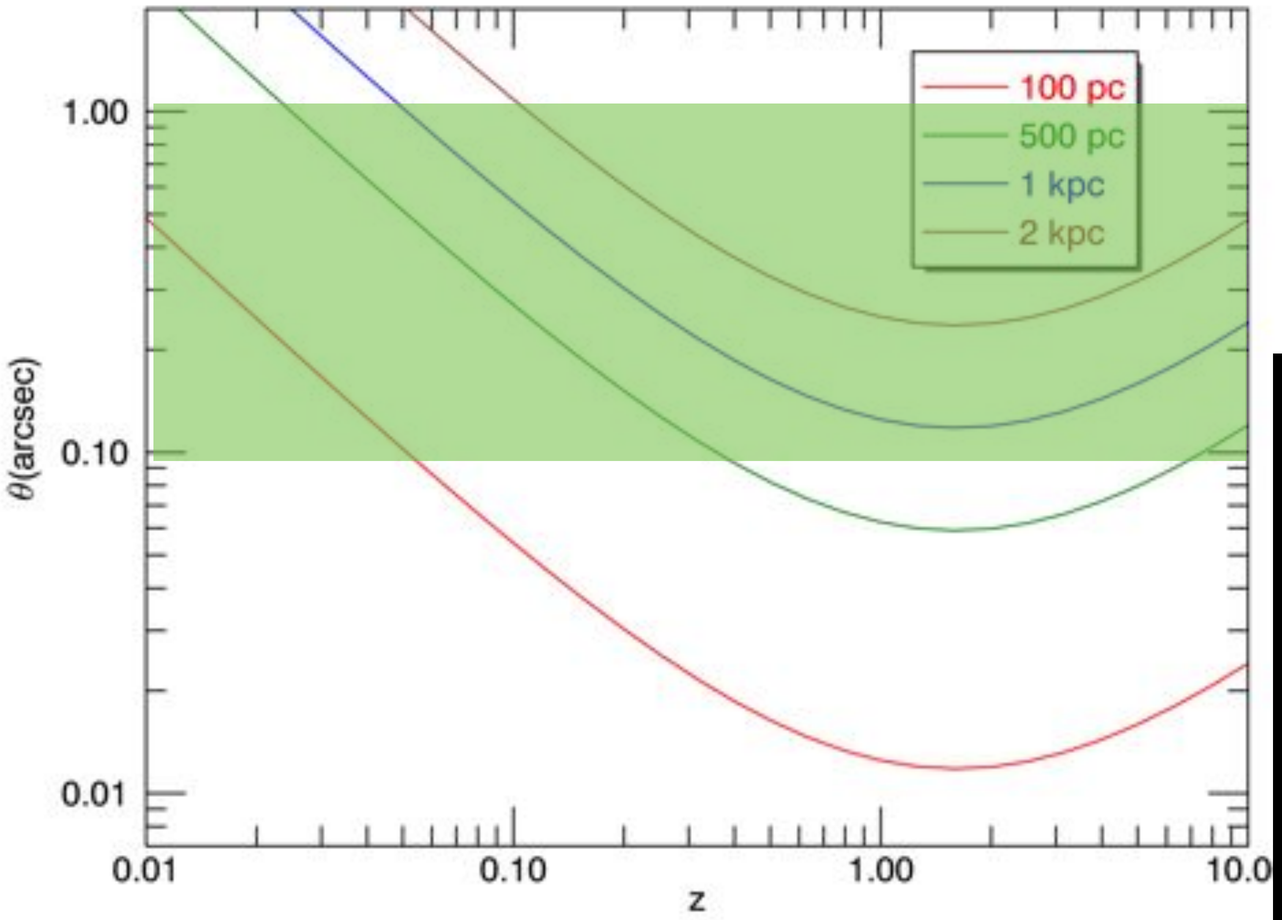
$$M_{dyn} sin^2 i = f_{spec} \frac{FWHM^2\, r_{spec}}{G} = f_{spec}\, Vir_{spec}$$

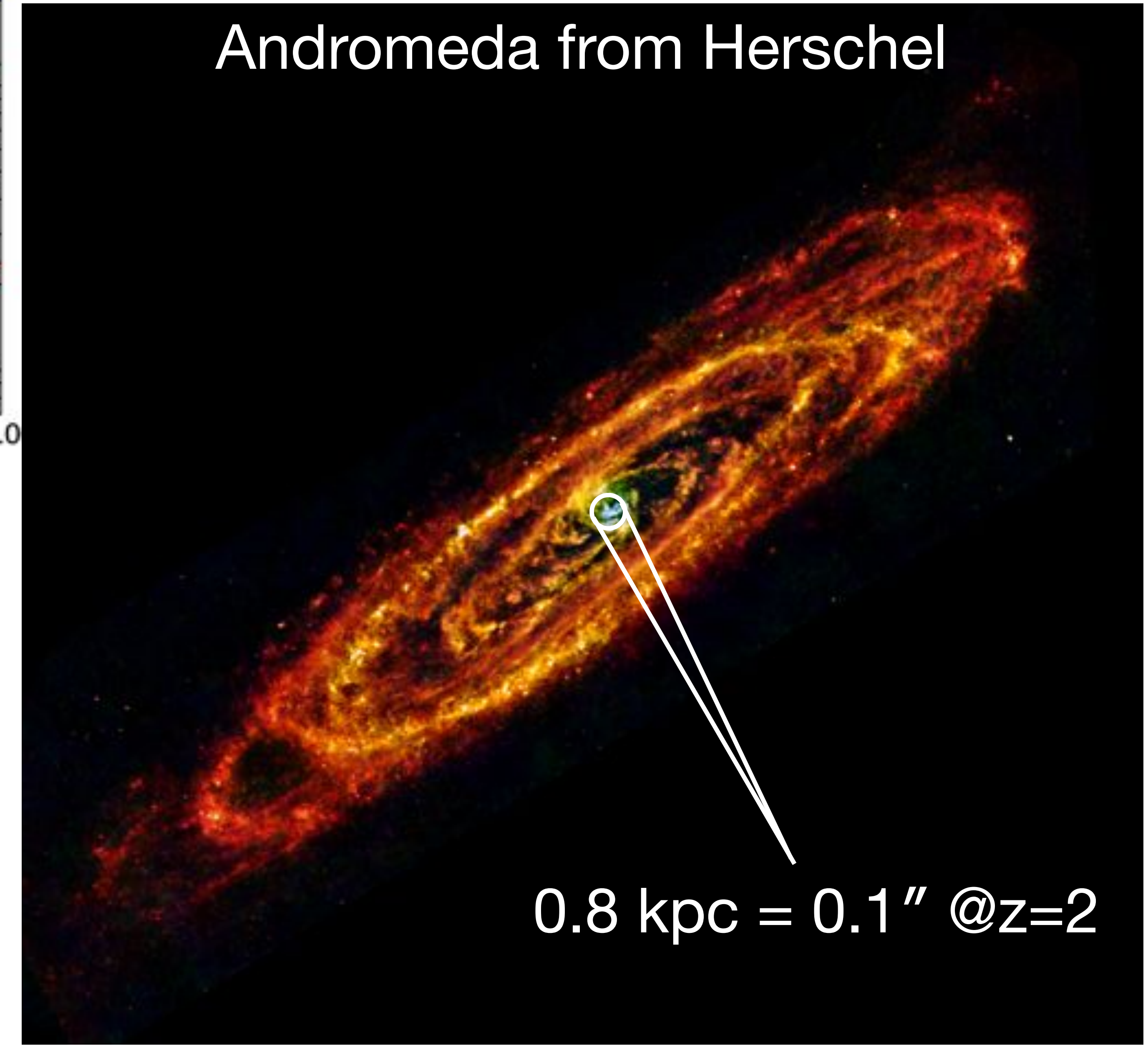
$$M_{dyn} sin^2 i \quad = \quad (1.0 \pm 0.1)\, 2.3 \times 10^9\, M_\odot \left(\frac{V}{100\, km/s}\right)^2 \left(\frac{r_{spec}}{1\, kpc}\right)$$

$$(\pm 0.15\, dex - \text{systematic})$$

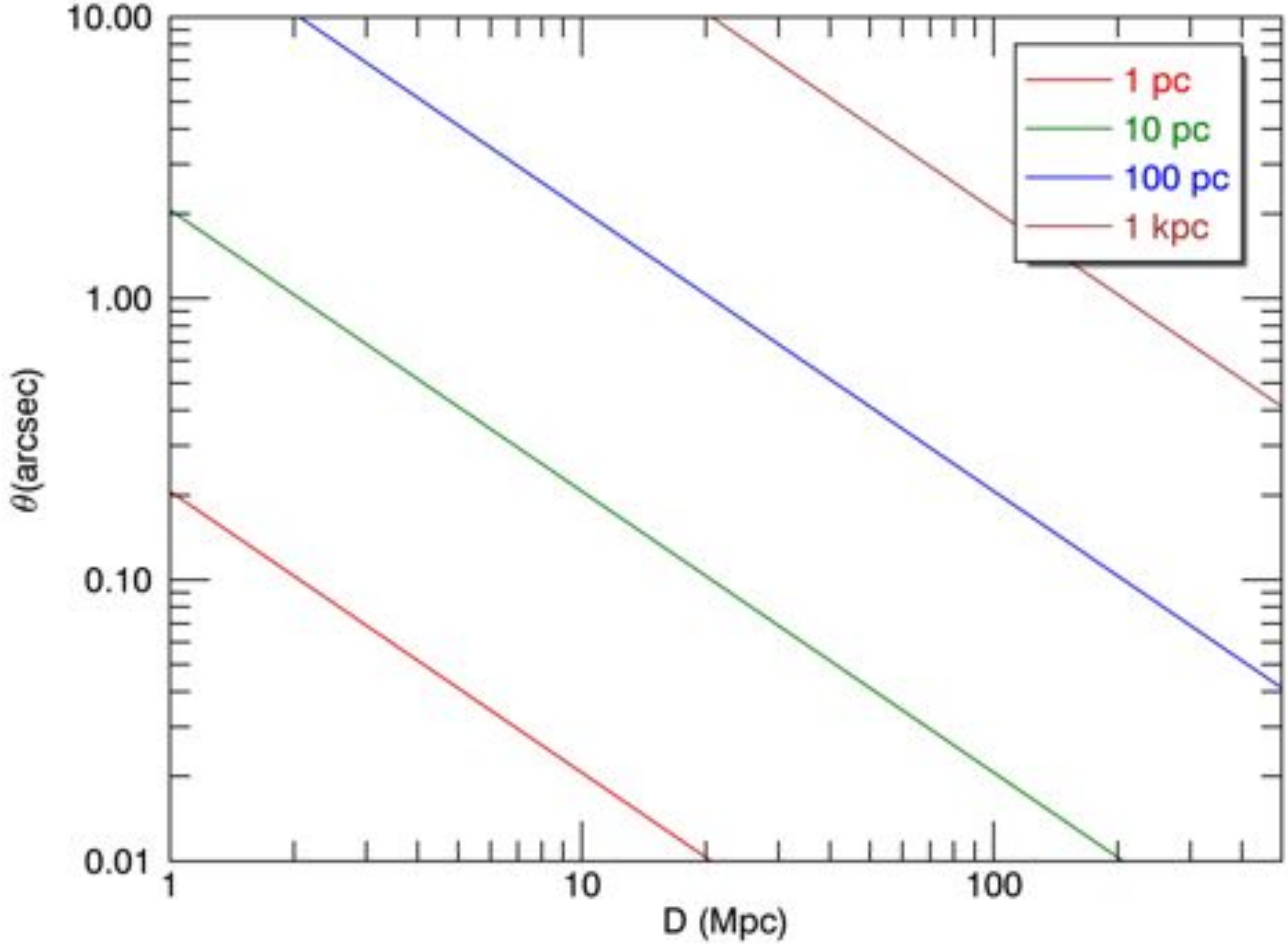


Spatial scales at high redshift



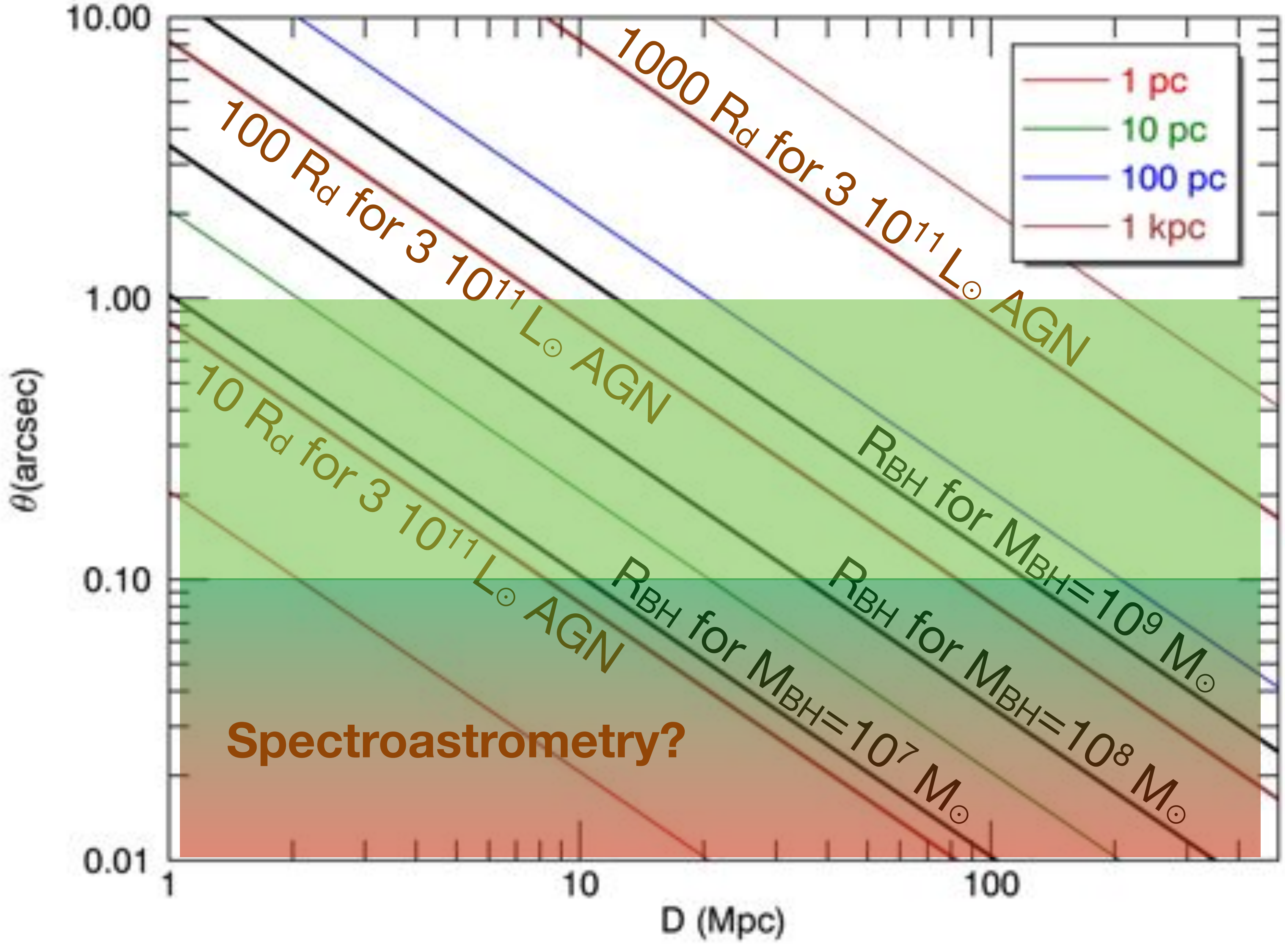


Spatial scales in local universe



Spatial scales in local universe

- R_{BH} radius of BH sphere of gravitational influence (BH grav. pot. dominates)
- R_d inner torus radius



Conclusions

Selected open questions that can be addressed by ~~a longslit spectrograph~~ an Integral Field Unit with high angular resolution ~0.1″ (see other talks for more!)

- What is the outer boundary of the obscuring torus?
  Is the torus forming stars?
  What is the relation between BH accretion and star formation?

- What are the masses of BHs in nearby galaxies?
  What is the cosmological evolution of the BH-galaxy relations?
  What are the dynamical masses of AGN host galaxies at high redshift?

- Can obtain observations at similar spatial resolution as current AO-assisted NIR observations with 8m class telescopes

- Spectroastrometry can allow to go beyond the spatial resolution limit …