Ahumada Mena,	Tomas
Carvajal,	**Vivian**
Crnogorcevic,	Milena
DeMartini,	Joseph
Dittmann,	**Alexander 4/25**
Fu,	**Guangwei**
Grell,	**Gabriel**
Hammerstein,	Erica
Hinkle,	**Jason 4/25**
Hord,	**Benjamin**
Ih,	**Jegug 4/23**
Karim,	Ramsey
Koester,	**Kenneth**
Marohnic,	Julian
Mundo	**Sergio 4/30**
Park,	**Jongwon 4/23**
Teal, '	**4/18**
Thackeray,	**Yvette**
Villanueva	Vicente
Volpert,	Carrie
Ward,	Charlotte
Williams,	Jonathan
Yin,	Zhiyu

Oral Presentations

5 *students have not presented or signed up yet...after today we have only 4 lectures; the math is obvious*

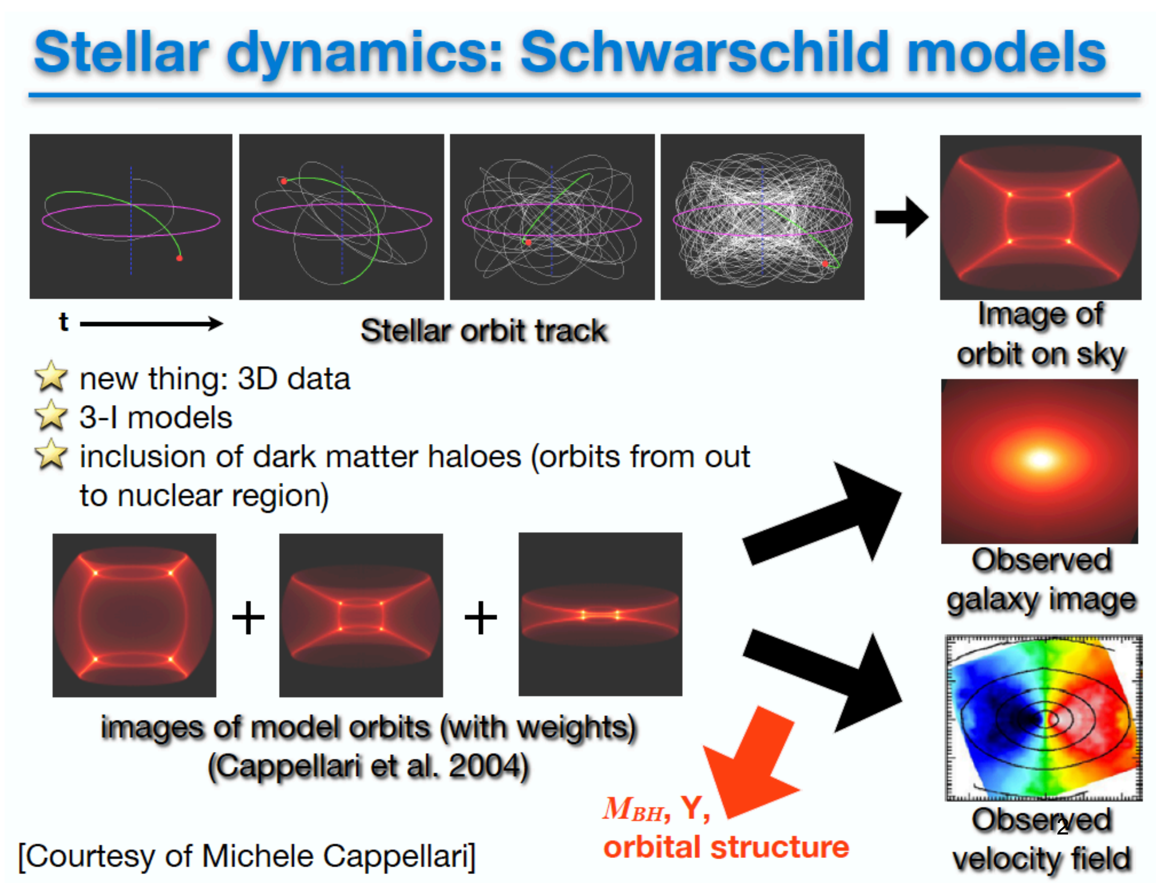
If no one volunteers I will assign talks in reverse alphabetical order; e.g ***Teal*** *would be next, then* ***Jongwon, Sergio*** *etc. Aiming for 2 per lecture. This will start: dates left April 30 (1 slot), May 2, May 7 and May 9 and the 'last class'*

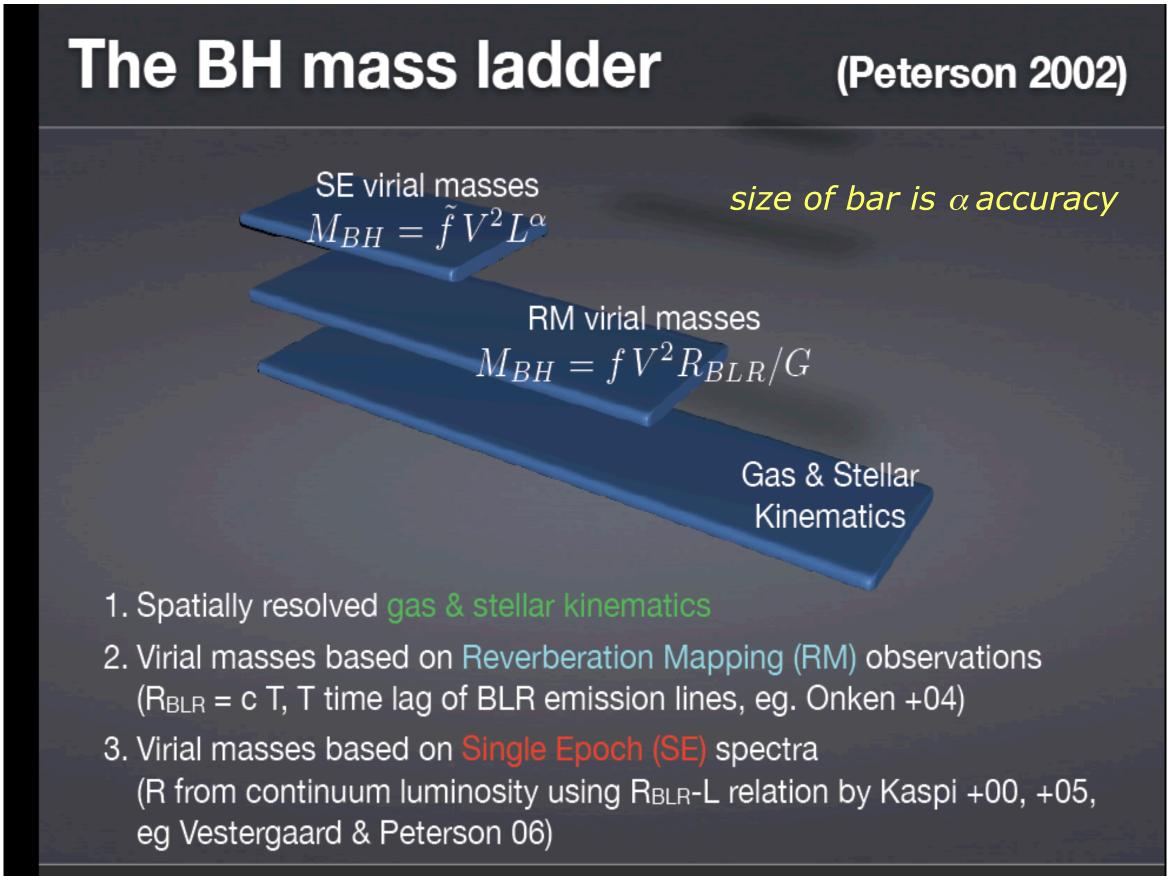
I will consider changing this if the next person in line agrees.

Red has given talk, green signed up

Time of the last class !!! 5:00 pm

Homework to be returned on Tuesday and last homework handed out.





New paper (s)
Central Masses and Broad-Line Region Sizes of Active Galactic Nuclei.II. A Homogeneous Analysis of a Large Reverberation-Mapping Database

Peterson, B. M. et al 2004ApJ...613..682P
(1062 citations) seems long, but lots of tables and graphs

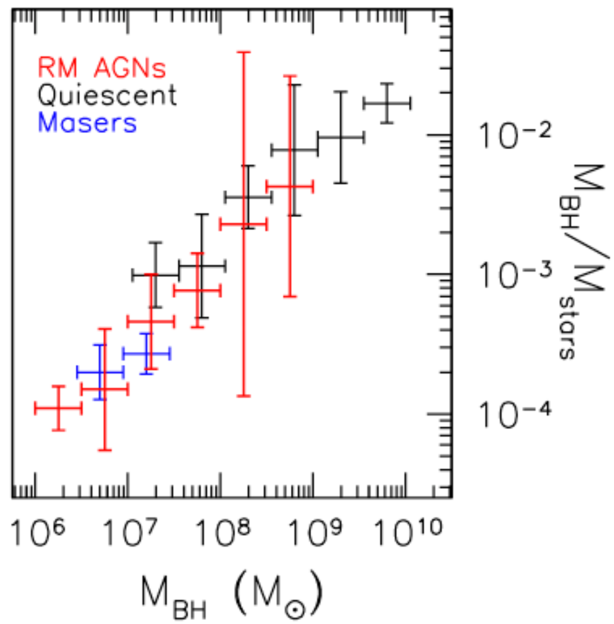
OR
Masses of quasars ***A. Soltan*** *1982 MNRAS.200..115,* (770 citations)

OR
Spatially resolved rotation of the broad-line region of a quasar at sub-parsec scale
GRAVITY Collaboration Nature**volume 563**, *pages657–660 (2018)*

Masses 2019

- Lots of work summarized in Shankar et al 2019- see Kormendy and Ho 2013   for a review

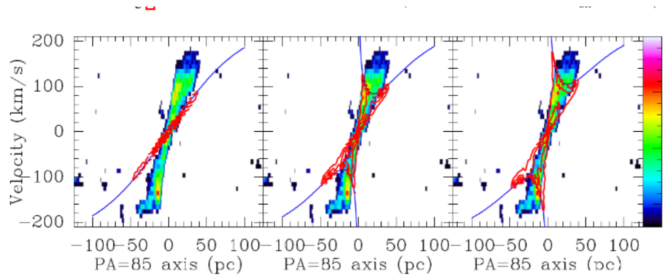
Method	Reference
Active	
Reverberation	Ho & Kim (2014)
Single Epoch	Martín-Navarro & Mezcua (2018)
Single Epoch	van den Bosch (2016)
Masers	van den Bosch (2016)
Masers	Greene et al. (2016)
Single Epoch	Busch et al. (2014)
Single Epoch	Reines & Volonteri (2015)
Single Epoch	Bentz & Manne-Nicholas (2018)
Quiescent	
Dynamical	Savorgnan & Graham (2016)
Dynamical	Kormendy & Ho (2013)



All 3 techniques agree within errors error bars represent range not errors in each bin for each sample

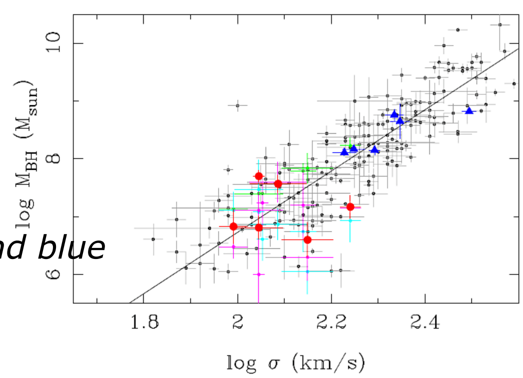
Masses 2019

- ALMA now has the sensitivity and angular resolution to measure dynamics 'close enough' to the black hole (Combes et al 2019, 1811.00984,Davis et al 2018) and can reach low masses



left panel- no BH middle wrong inclination

Fig. 10. Position-velocity diagram of the CO(3-2) line in NGC 1672, with a linear color scale (TM1 only). S the model without any black hole and torus inclination of 66° (left panel), with a black hole as derived from 10^7 $M_\odot$ with i= 66° (middle panel), and the best fit: a black hole of 5.0 x 10^7 $M_\odot$, with i= 66° (right panel). galfit decomposition, and the predicted circular velocity is reproduced in blue lines (Fig 9).



CO points in red and blue

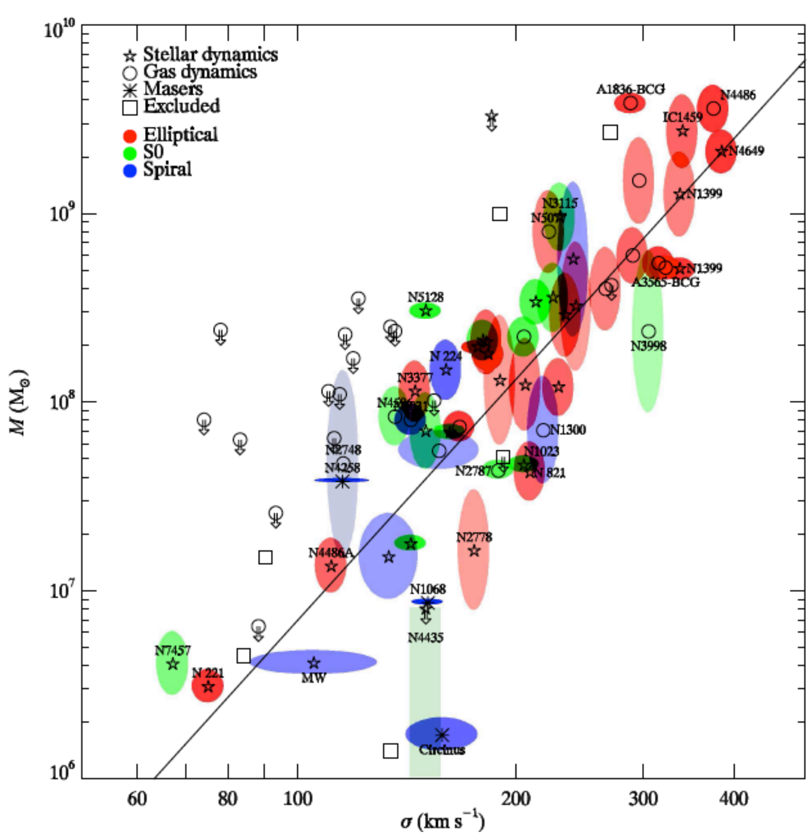
Status of Dynamics

- ~80 'normal' galaxies with secure BH masses
- ~40 with reasonable estimates (see De Nicola et al 2018)
- But limited to local universe (~250 Mpc) until ELTs and JWST

- Nearby Galaxies with **Dynamical Masses for their Central Black Holes** (Gultekin 2009)
- scaling of the mass of the black hole with the velocity dispersion of the stars in the bulge of the galaxy

$M_{BH} \sim 10^{-3}/M_{bulge}$

- Galaxies know about their BH and vice versa



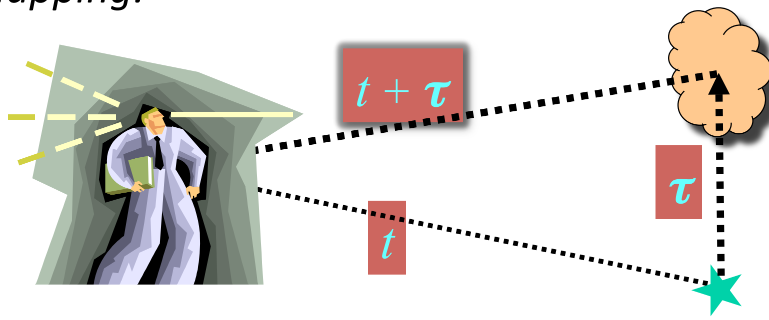
Virial Mass Estimates/Reverberation Mapping- Longair 20.5

$$\underline{M_{BH} = f\ v^2\ R_{BLR}/G}$$

Reverberation Mapping:

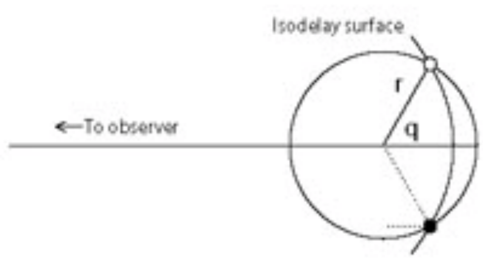
- $R_{BLR} = c\,\tau$
- v_{BLR}

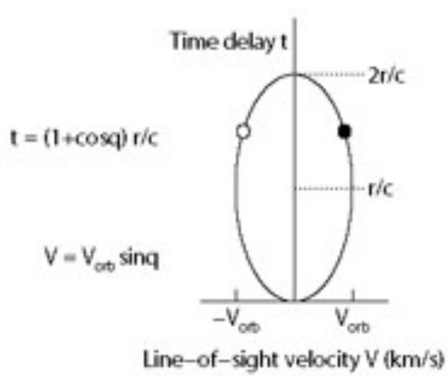
Line width in variable spectrum



What About AGN in General??

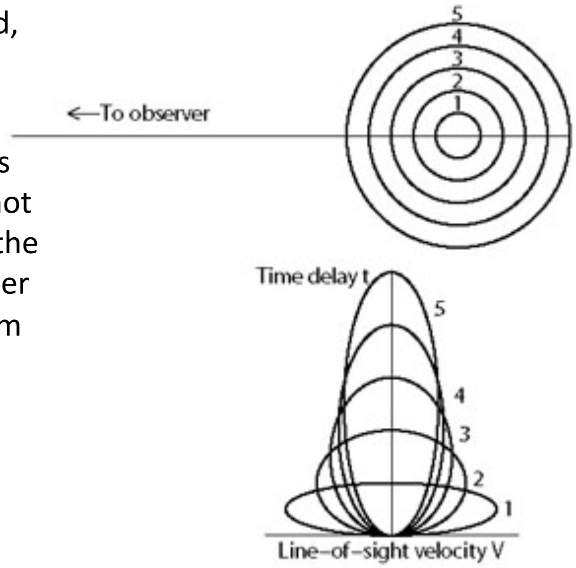
- The 'glare' of the black hole makes measuring the dynamics of stars and gas near the black hole very difficult
- Technique: reverberation mapping (Peterson 2003)
  - The basic idea is that there exists gas which is moderately close to to the Black Hole (the so-called broad line region- more later) <u>whose ionization is controlled by the radiation from the black hole</u>
  - Thus when the central source varies the gas will respond, with a timescale related to how far away it is





The Geometry

- Points (r, θ) in the source map into line-of-sight velocity/time-delay(τ) space (V, τ) according to $V = -V_{orb} \sin(\theta)$, where V_{orb} is the orbital speed, and $\tau = (1 + \cos(\theta))r / c$.



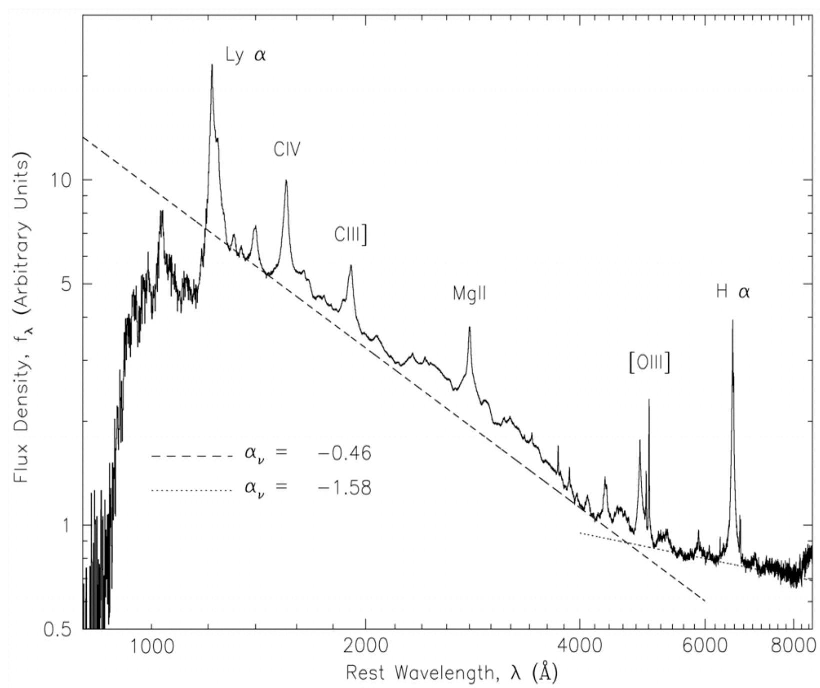
- The idea is that the broad line clouds exist in 'quasi-Keplerian' orbits (do not have to be circular) and respond to the variations in the central source. Lower ionization lines are further away from the central source.
- So

$$M_{BH}=frV^2/G$$

f is a parameter related to geometry- and

the orbits of the gas clouds

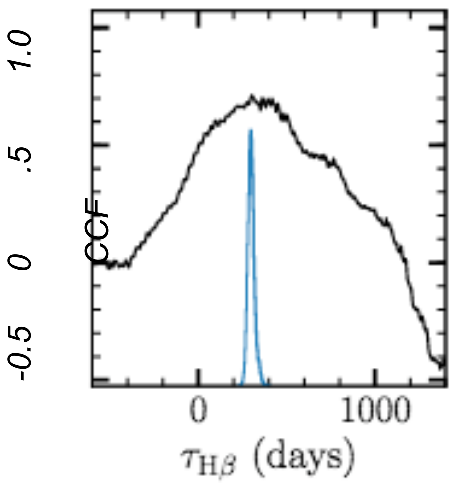
- AGN (type I) optical and UV spectra consist of a 'feature less continuum' with strong 'broad' lines superimposed
- Typical velocity widths (s, the Gaussian dispersion) are ~2000-5000km/sec
- The broad range of ionization is due to the 'photoionzation' of the gas- the gas is not in collisional equilibrium
- At short wavelengths the continuum is thought to be due to the accretion disk

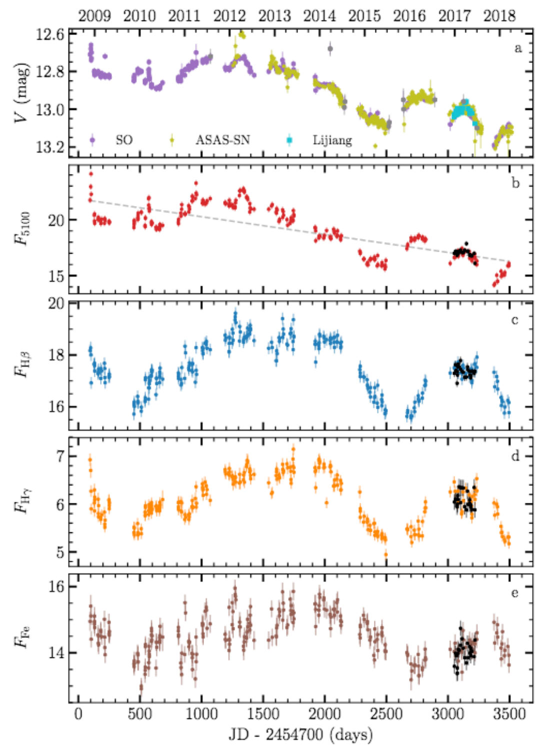


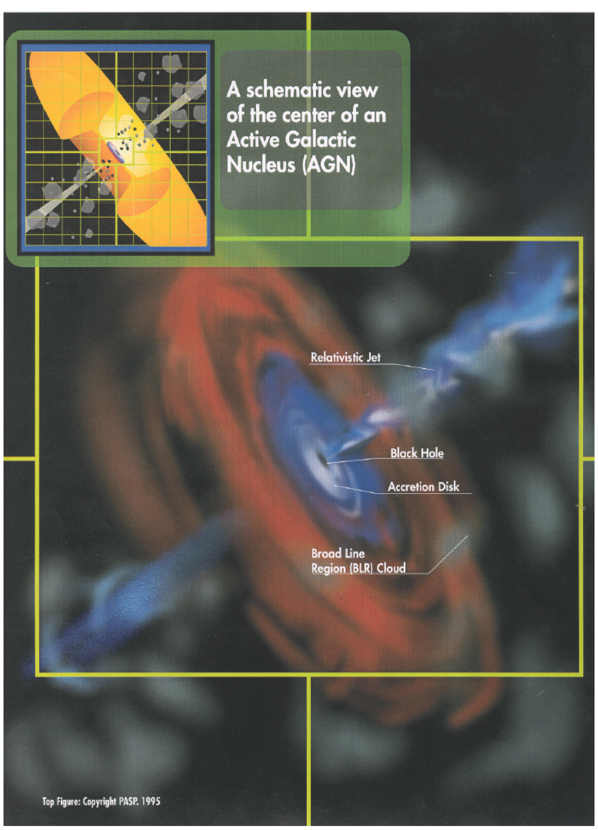
Van den Berk et al 2001

Data for Reverberation Analysis

Zhang et al 2018 data for 3c273 and cross correlation of Hβ and continuum- clear lag of 146d







Source	Distance from central source
X-Ray Fe K$^{\alpha}$	3-10 R_S
Broad-Line Region	600 R_S
Megamasers	4 $\times 10^4$ R_S
Gas Dynamics	8 $\times 10^5$ R_S
Stellar Dynamics	10^6 R_S

A Quick Guide to Photoionized Plasmas- Reminder

- Fundamental idea photon interacts with ion and electron is ejected and ion charge increased by 1
- $X^{+q} + h\nu \rightarrow X^{+(q+1)} + e^-$
- Ionization of the plasma is determined by the balance between photionization and recombination
- Photoionization rate is proportional to the number of ionizing photons x number of ionsxthe cross section for interaction and the recombination rate to the number of ions x number of electrons x atomic physics rates

- Steady state ionization determined not by temperature, but by balance between photo-ionization ($\sim F_E$ spectrum) and recombination (n_e):

$$n_q \int F_E \sigma^{PI}(E) dE = n_{q+1} n_e \alpha(T_e)$$

- Ionization $n_{q+1}/n_q \propto F/n_e \propto L/n_e r^2 \equiv \xi$

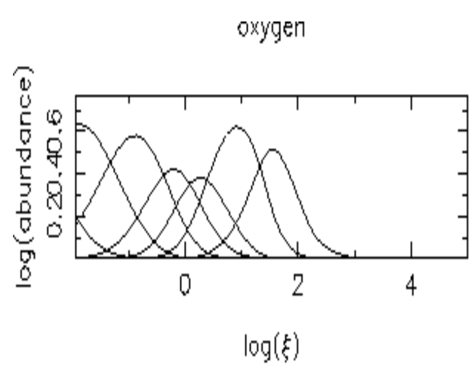
ξ is the ionization parameter (also sometimes called U)

$$\xi = L/n_e r^2$$

if know ξ from spectrum, measure L and derive r from timing analysis have a solution

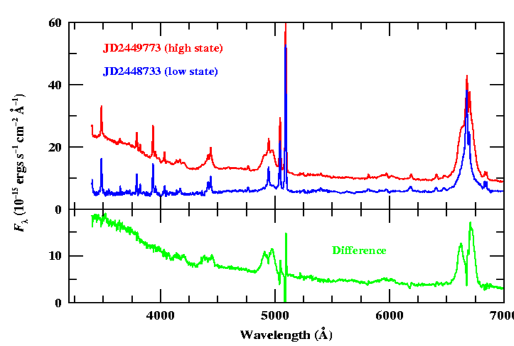
In Other Words

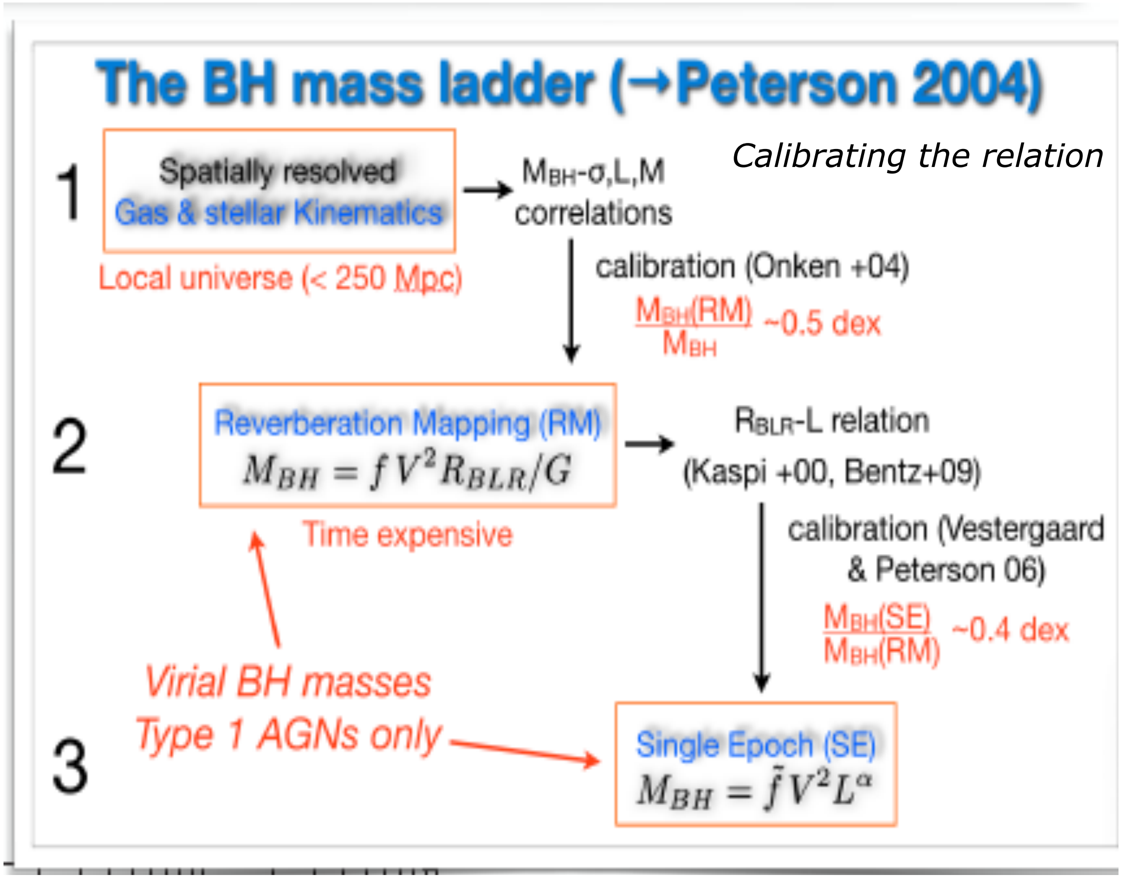
- For each ion:
  - Ionization = recombination
  - ~photon flux ~electron density
- For the gas as a whole
  - Heating = cooling
  - ~photon flux ~electron density
- => All results depend on the ratio photon flux/gas density or "ionization parameter"
- Higher ionization parameters produce more highly ionized lines (higher flux or lower density)



Neutral <----------->fully stripped

Peterson (1999)

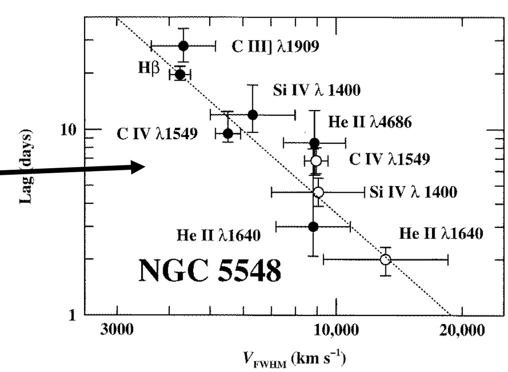




What is Observed??

- The higher ionization lines have a larger width (rotational speed) and respond faster (closer to BH)
- Line is consistent with idea of photoionization, density ~r^{-2}

  and Keplerian motions dominate the line shapes (v ~ $r^{-1/2}$)



- Such data exist for ~70 sources
- At present M_{BH} estimated to

within a factor of a few: M ∝ FWHM^2 L$^{0.5}$

Dotted line corresponds to a mass of 6.8x10^7 M$_{\odot}$
Peterson and Wandel 1999
For the latest see Pancoast et al 2019ApJ.871.108
and Williams et al 2018ApJ... 866...75W

More detailed analysis shows a variety of orbits from near-circular elliptical orbits to inflowing or outflowing trajectories.

The structure of the gas is consistent with a thick disk more or less face-on (see Gravity result on 3C273 Nature 563, 657)

Spatially Resolved BLR !!!

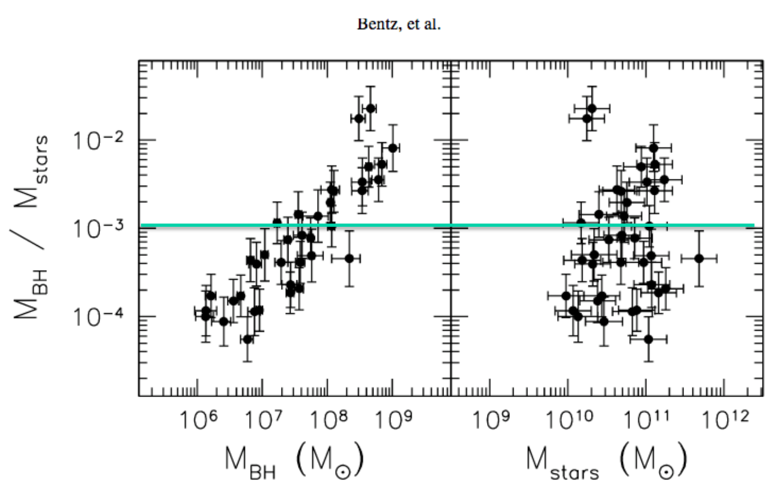
- Gravity data for 3C273

"a spatial offset (with a spatial resolution of 10^{-5} arcsec (~0.03 pc) ..between the red and blue photo-centres of the broad Paschen-α line ..perpendicular to the direction of its radio jet. This spatial offset corresponds to a gradient in the velocity of the gas and thus implies that the gas is orbiting the central supermassive black hole. .. well fitted by a broad-line-region model of a thick disk of gravitationally bound material orbiting a black hole of 3×10^8 solar masses...

- In reverberation mapping experiments, M_{BH} is obtained by combining Balmer-line time-delay measurements with the gas velocity obtained from the line profile. This requires the use of a velocity-inclination factor $f = GM_{BH}/(v^2_{RBLR})$, GRAVITY data favor f=4.7+/-1.4 .. reverb typical finds (Williams et al) f~4.3 and the broad line width is dominated by bound motion in the gravitational potential of the black hole.
- Zhang et al 18.11.03812 "The time lag of variations in Hβ relative to those of the 5100 A continuum is 146.8+8.3−12.1 days , which agrees very well with the Paschen-α region measured by the GRAVITY at The Very Large Telescope Interferometer; $M_{BH}/$ $M \approx 2.0\times10^{-3}$

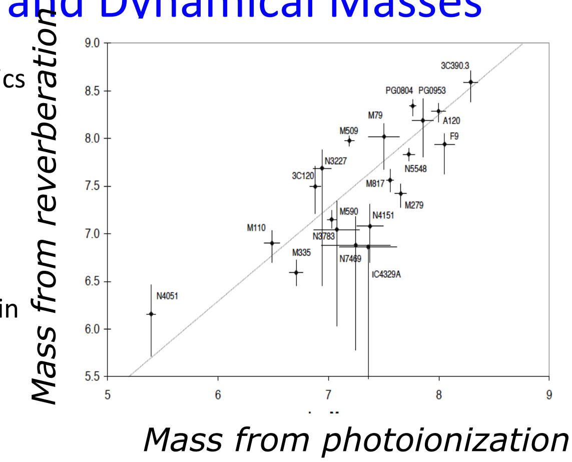
Latest on Reverberation Masses

- Black Hole - Galaxy Scaling Relationships for Active Galactic Nuclei with Reverberation Masses
- . Bentz, Emily Manne-Nicholas (1808.01329)~70 sources with reasonable estimates
- see http://www.astro.gsu.edu/AGNmass/



Reverberation Masses and Dynamical Masses

- In general for the same objects mass determined from reverberation and dynamics agree within a factor of 3.
- This is 'great' but
  - dyanmical masses very difficult to determine at large distances (need angular resolution)
  - Reverberation masses 'very expensive' in observing time (timescales are weeks-months for the response times)
  - If AGN have more or less similar BLR physics (e.g. form of the density distribution and Keplerian dynamics for the strongest lines) them we can just use the ionization parameter and velocity width (σ) of a line to measure the mass $\xi = L/n_e r^2$- find that $r \sim L^{1/2}$
  - Or to make it even simpler just L and σ and normalize the relation (scaling relation)- amazingly this works !



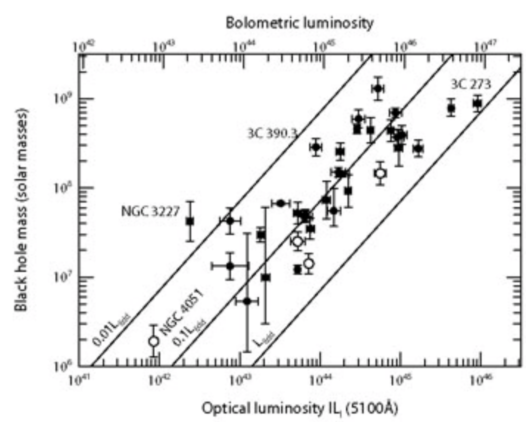
$M_{BH} \sim K\sigma^2 L^{1/2}$

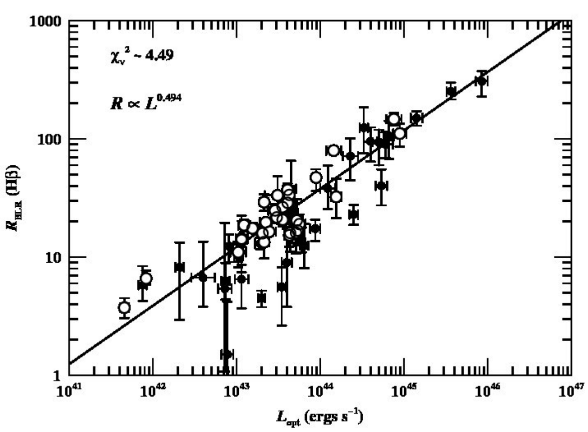
Where K is a constant (different for differnet lines which is determined by observations

This is just

$M_{BH} = v^2 R_{BLR}/G$ with an observable (L) replacing R_{BLR}

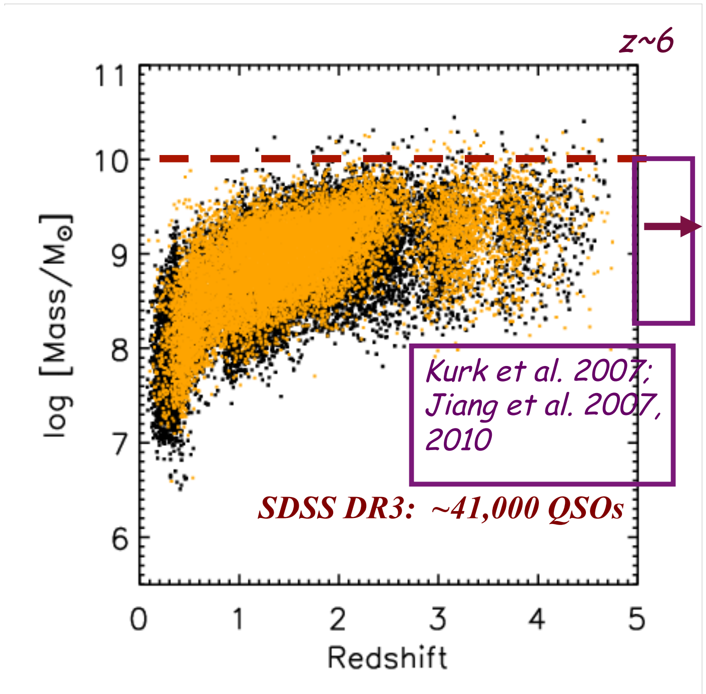
- Nature has chosen to make the size of the broad line region proportional to $L^{1/2}$





Masses of Distant Quasars- M. Vestergaard

- *Using this technique very large sample of objects from the Sloc Digital Survey (SI*
- *Ceilings at $M_{BH} \approx 10^1$*
- *$L_{BOL} < 10^{48}$ e*
- *$M_{BH} \approx 10^9 M_\odot$ -*

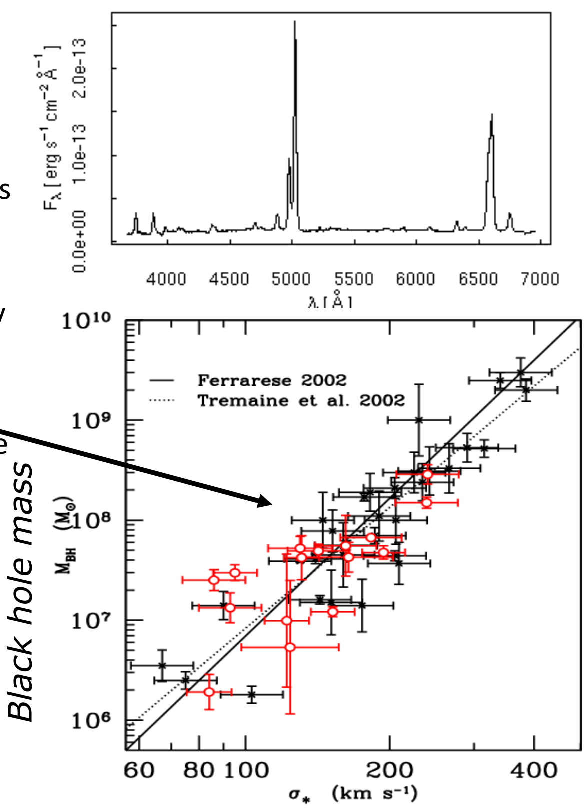


(DR3 Qcat: Schneider et al. 2005)

(MV et al. in prep)

But What About Objects without a Strong Continuum

- There exists a class of active galaxies (type II) which do not have broad lines and have a weak or absent 'non-stellar' continuum
- Thus there is no velocity or luminosity to measure -
- We thus rely on 'tertiary' indicators.
- It turns out (very surprisingly) that the velocity dispersion of the stars in the bulge of the galaxy is strongly related to the BH mass
  - This is believe to be due to 'feedback' (more later) the influence of the AGN on the formation of the galaxy and VV.



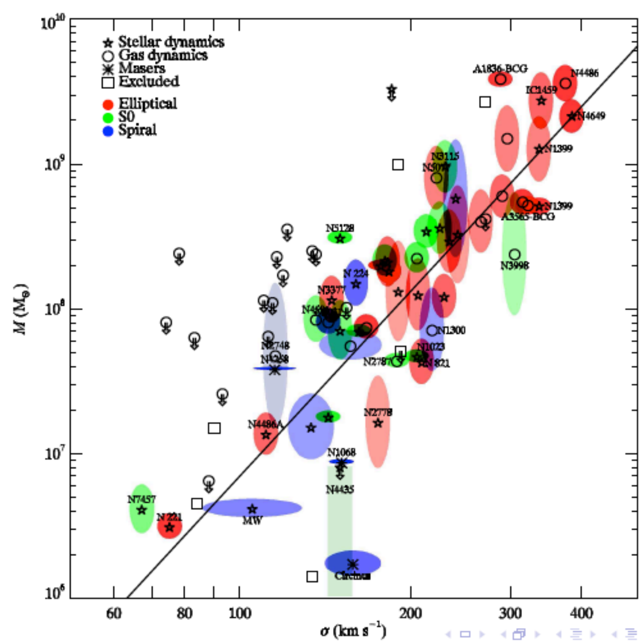
Velocity dispersion of stars in the bulge

And Finally

- Correlations between M_{BH} and galaxy properties

Mass of Black Hole Compared to Velocity Dispersion of Spheroid

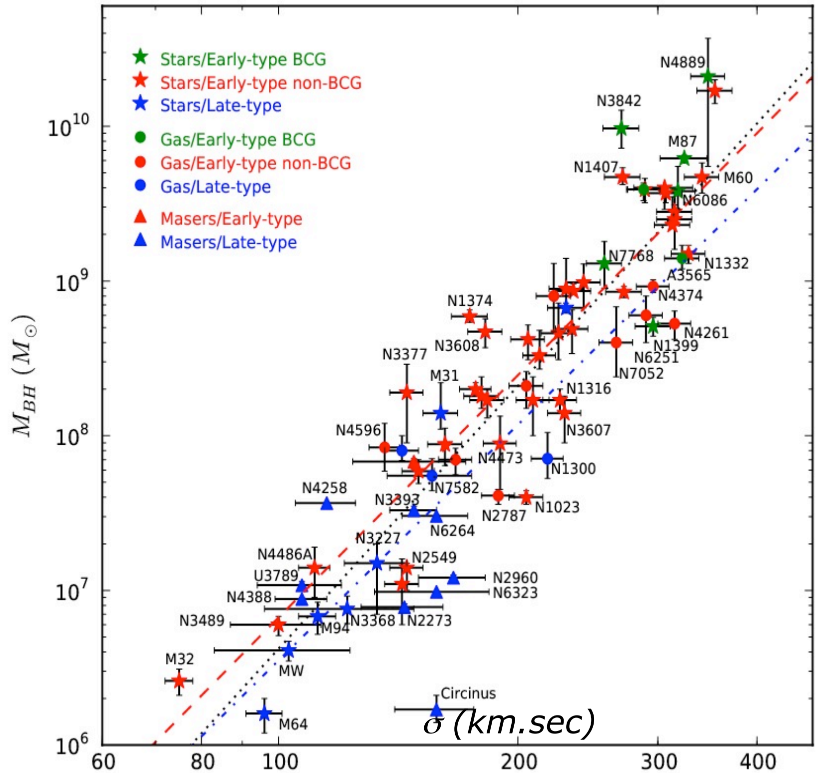
- Sample of non-active galaxies compare mass of black hole (derived later) with velocity dispersion of stars
- Very high detection rate of BHs in 'normal' galaxies- both spheroids and disks (notice the upper limits)



Gultekin 2009

M-Sigma relation

- **Hunting for Supermassiv Black Holes i Nearby Galaxies witł the Hobby-Eberly Telescope arXiv: 1502.00632**
- R van den Bosch K.Gebhardt , K. Gültekin , A. Yıldırım , J. Walsh



Los Angeles Times | SCIENCE

Gargantuan black hole baffles scientists

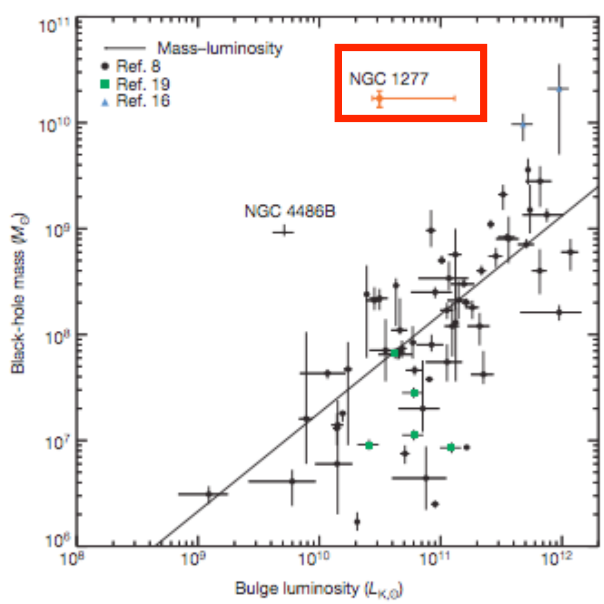
A hunt for supermassive black holes reveals a monstrous one at the heart of galaxy NGC 1277, which may force theorists to rethink their understanding of black holes.

The enormous black hole was found at the center of NGC 1277, a flat, compact yellowish galaxy near the center of this galaxy cluster in the constellation Perseus. (David W. Hogg-Michael Blanton, SDSS Collaboration / November 29, 2012)

Related photos »

Related photos »

Not everything fits



- Galaxy with the highest ratio of BH mass to total galaxy mass 2:3 !!!

BH Mass vs Galaxy Luminosity

- The BH mass correlates with **the bulge** but not **the disk luminosity** (Savorgnan 1511.07437v1.pdf)

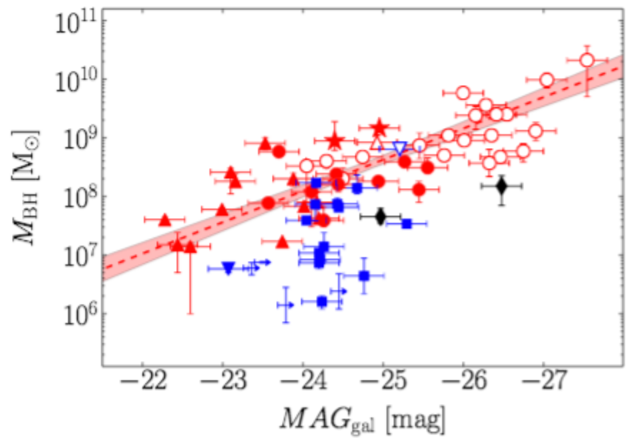
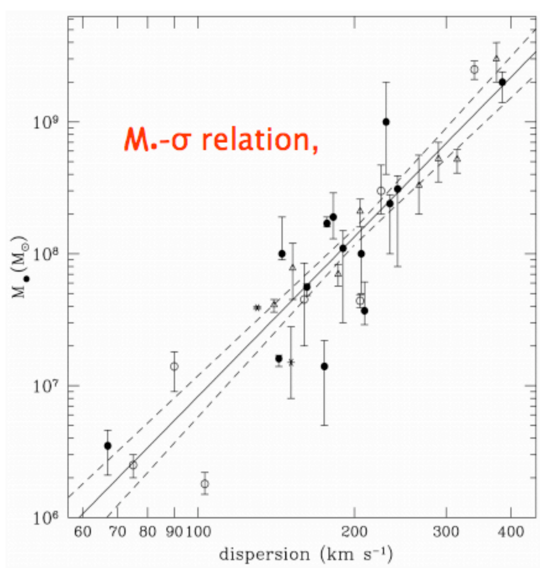


FIG. 1.— Black hole mass plotted against 3.6 μm galaxy absolute magnitude. Symbols are coded according to the galaxy morphological type: red circle = E, red star = E/S0, red upward triangle = S0, blue downward triangle = S0/Sp, blue square = Sp, black di-

BH mass vs bulge luminosity luminosity- red= ETGs blue =LTGs



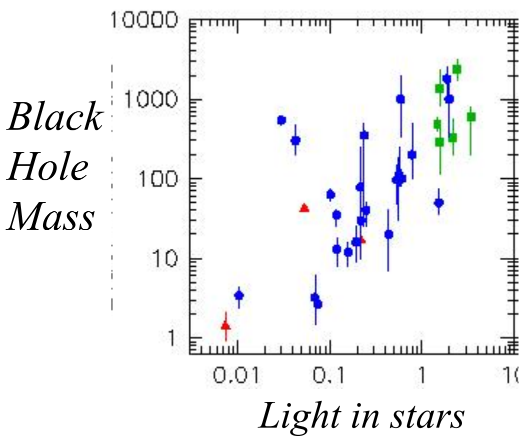
- Black hole mass correlated to host galaxy bulge mass.
- Formation of bulge and growth of black hole are related.
- AGN play a significant role in the evolution of galaxies

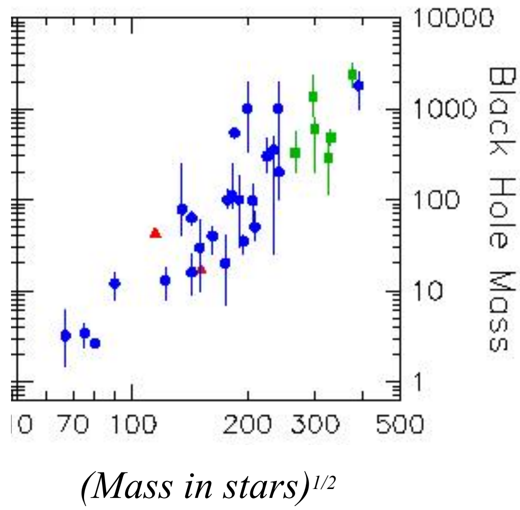
Magorrian et al. Gebhardt et al. 2000; Ferrarese & Merrit 2000; Tremaine et al. 2002

- Relation of mass of central black (M_{BH}) hole to the velocity dispersion of the stars in the bulge (σ)

Strong relationship between galaxy and its central massive black hole

- The mass of stars in the galaxy is strongly correlated with the mass of the central black hole
- Black holes have had a strong influence on galaxy formation and vv

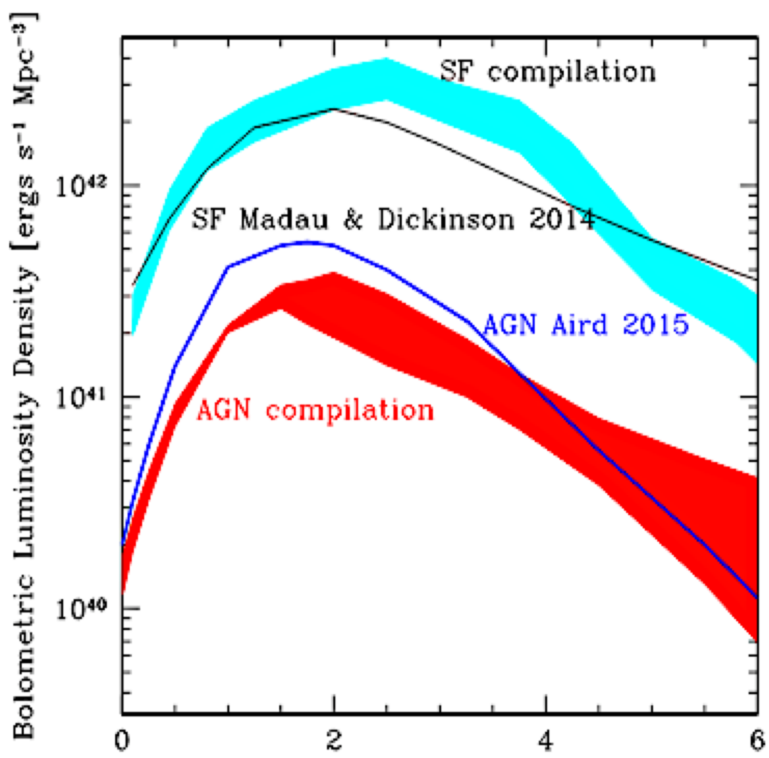




Scaling relations that allows estimate of BH mass in distant galaxies

Co-evolution of Galaxies and Black Holes

Comparison of growth of galaxies (Star formation luminosity density) vs growth of AGN (luminosity density) of AGN (Fiore et al 2018)



Radiating black holes

- The AGN Zoo
- Black Hole systems
  - The spectrum of accreting black holes
  - X-ray “reflection” from accretion disks
  - Strong gravity effects in the X-ray reflection spectrum

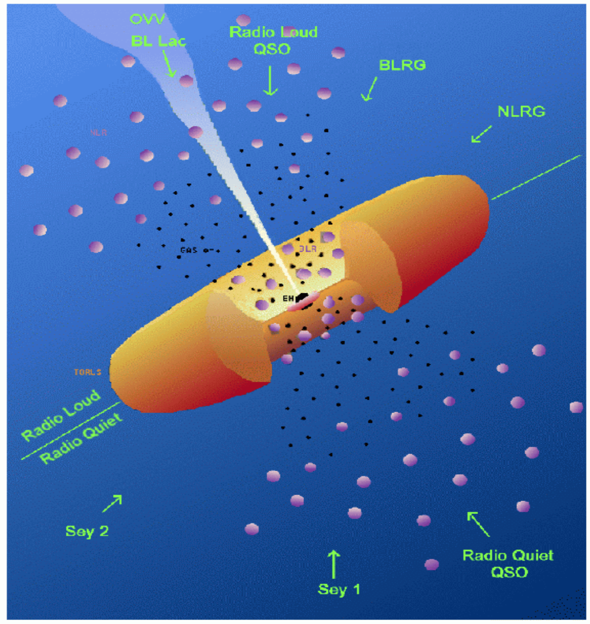
AGN in Longair- chapters 18,19,20,21

- **18 Active galaxies** 585
- 18.1 Introduction
- 18.2 Radio galaxies and high energy astrophysics
- 18.3 The quasars
- 18.4 Seyfert galaxies
- 18.5 Blazars, superluminal sources and γ -ray sources
- 18.8 X-ray surveys of active galaxies
- 18.9 Unification schemes for active galaxies
- **19 Black holes in the nuclei of galaxies**
- 19.1 The properties of black holes
- 19.2 Elementary considerations
- 19.3 Dynamical evidence for supermassive black holes in galactic nuclei
- 19.5 Black holes and spheroid masses
- 19.6 X-ray observations of fluorescence lines in active galactic nuclei
- 19.7 The growth of black holes in the nuclei of galaxies
- **20 The vicinity of the black hole**
- 20.1 The prime ingredients of active galactic nuclei
- 20.2 The continuum spectrum
- 20.3 The emission line regions – the overall picture
- 20.5 The broad-line regions and reverberation mapping
- 20.7 Accretion discs about supermassive black holes
- **21 Extragalactic radio sources**
- 21.5 Jet physics

I am covering only a fraction of this material ! (Notice that I have left some sections out entirely)

AGN- Alias Active Galactic Nuclei

- AGN are 'radiating' supermassive black holes-
  - They go by a large number of names (Seyert I, Seyfert II, radio galaxies, quasars, Blazars etc etc)
  - The names convey the observational aspects of the objects in the first wavelength band in which they were studied and thus do carry some information
- See http://nedwww.ipac.caltech.edu/level5/Cambridge/Cambridge_contents.html for an overview



Urry and Padovani 1995

AGN- Ch 18,19 of Longair

Roughly speaking, a galaxy is said to host an AGN if one or more of the following properties are observed:

(i) a compact nuclear region much brighter than a region of the same size in a normal galaxy;

(ii) non-stellar (non-thermal) continuum emission in optical/IR;

(iii) strong 'broad' ($\sigma_{lines} >> \sigma_{stars}$) optical/UV emission lines;

(iv) variability in continuum emission and/or in emission lines on 'relatively' short time scale

(v) luminous non-thermal radio or x-ray emission (>>expected from star formation)

(vi) presence of luminous relativistic jets

Strong gravity and accreting black holes- Longair Ch 18

- The AGN Zoo
- Black Hole systems
  - The spectrum of accreting black holes
  - X-ray "reflection" from accretion disks
  - Strong gravity effects in the X-ray reflection spectrum

Radio Loudness	**Optical Emission Line Properties**		
	Type 2 (Narrow Line)	**Type 1** (Broad Line)	' *XBONGS*
Radio-quiet:	Seyfert 2	Seyfert 1 QSO	*'no' AGN lines*
Radio-loud:	NLRG { FR I / FR II	BLRG SSRQ FSRQ	Blazars { BL Lacs / (FSRQ) *'no' AGN lines*
	decreasing angle to line of sight ->		

Table 1: AGN Taxonomy: A Simplified Scheme.