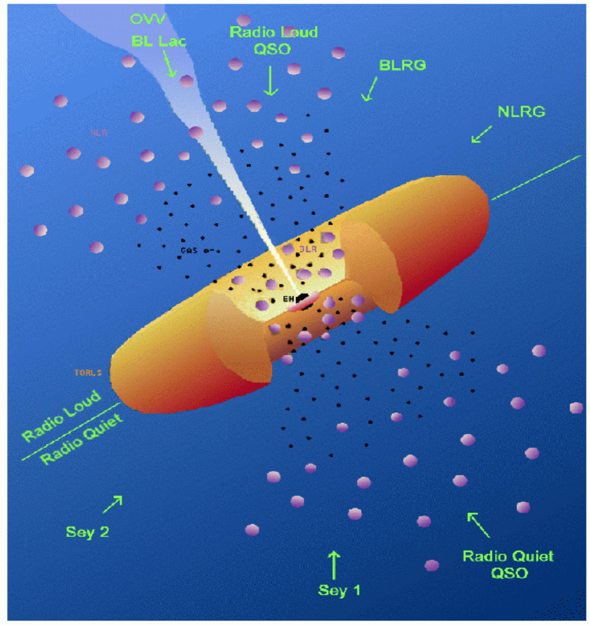
AGN- Alias **Active** Galactic Nuclei

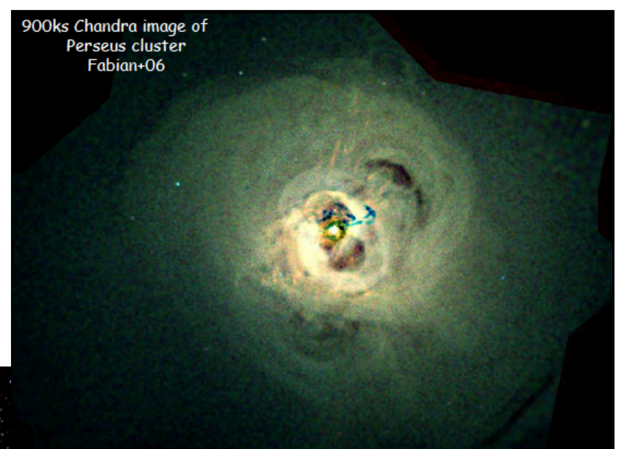
- AGN are **'radiating'** supermassive black holes-
  - They go by a large number of names (Seyert I, Seyfert II, radio galaxies, quasars, Blazars etc etc)
  - The names convey the observational aspects of the objects in the first wavelength band in which they were studied and thus do carry *some* information

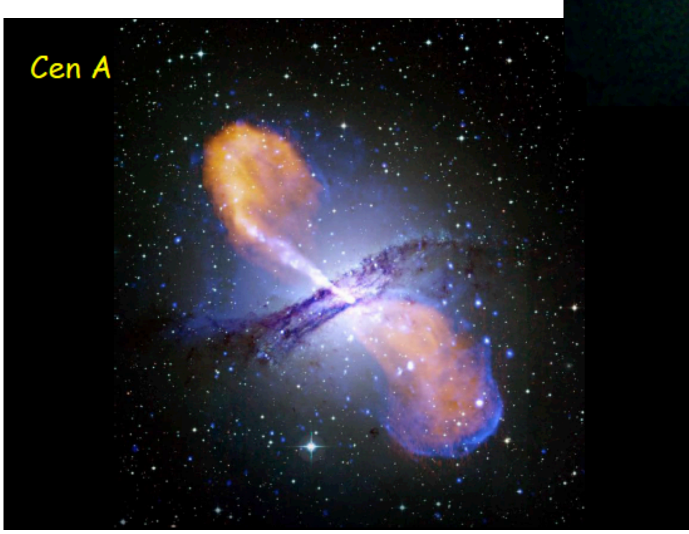
- See http://nedwww.ipac.caltech.edu/level5/Cambridge/Cambridge_contents.html for an overview



Schemtaic diagram of regions near the SMBH
Urry and Padovani 1995

AGN- Black Holes





It is now believed that almost all massive galaxies have supermassive ($M>10^6 M_{\odot}$) black holes

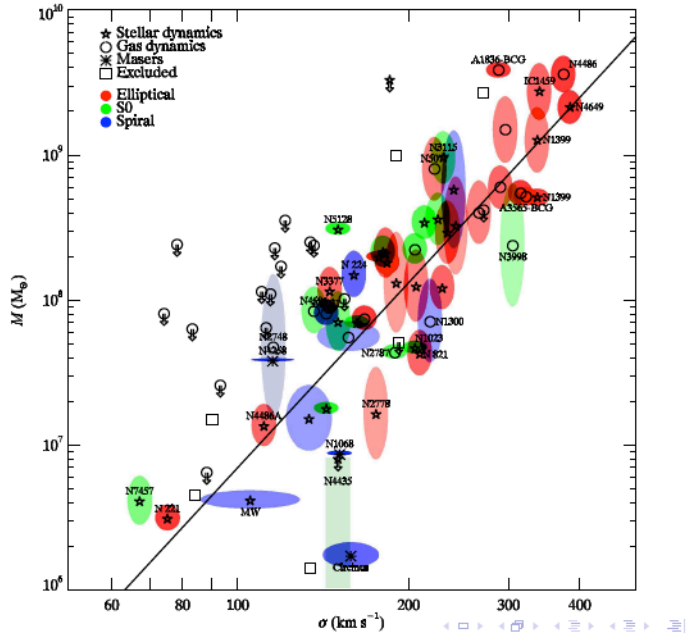
But at z=0 only ~10% are 'active'

Course evaluations are open- Please Respond!

- www.courseevalum.umd.edu
- Why?
  - For the benefit of your peers
  - Because your comments count and we use it to improve our teaching and/or redesign the course
  - Because your opinion is used to evaluate our performance
- Don't put it off till Dec 12th!

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.



Gultekin 2009

Galaxy formation and accretion on supermassive black holes appear to be closely related

Black holes play an important role in galaxy formation theories

Observational evidence suggests a link between BH growth and galaxy formation:

- M_B-σ relation
- Similarity between cosmic SFR history and quasar evolution

Theoretical models often assume that BH growth is self-regulated by **strong** feedback:

- Blow out of gas in the halo once a crtitical M_B is reached
  Silk & Rees (1998), Wyithe & Loeb (2003)

Feedback by AGN may:

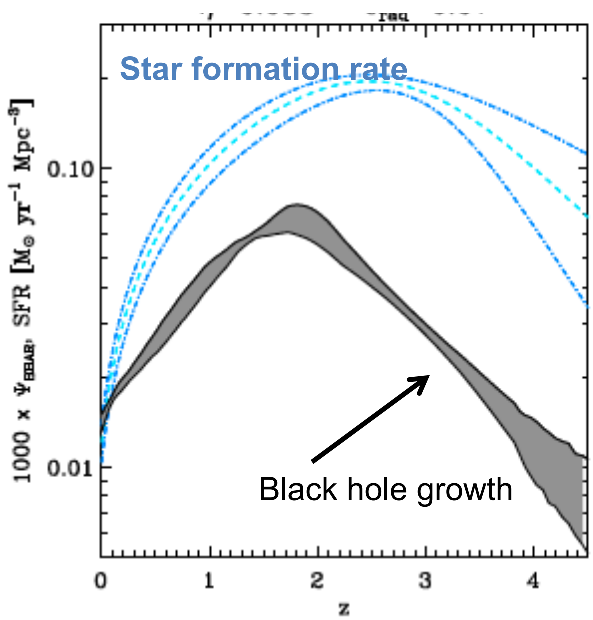
- Solve the cooling flow riddle in clusters of galaxies
- Explain the cluster-scaling relations, e.g. the tilt of the L_x-T relation
- Explain why ellipticals are so gas-poor
- Drive metals into the IGM by quasar-driven winds
- Help to reionize the universe and surpress star formation in small g

Springel 2004

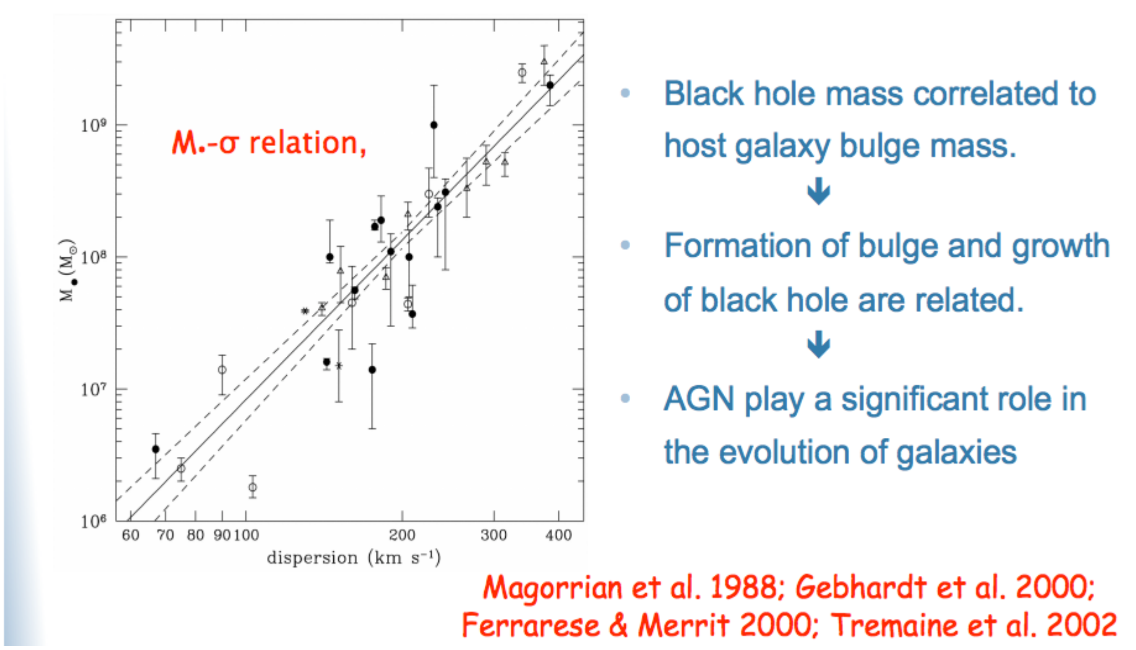
Galaxy formation models need to include the growth and feedback of black holes !

SFR Rate and AGN Growth

- To first order the growth of supermassive black holes (as traced by their luminosity converted to accretion rate) and the star formation rate are very similar
  - showing similar rises and falls
  - It this cause and effect?



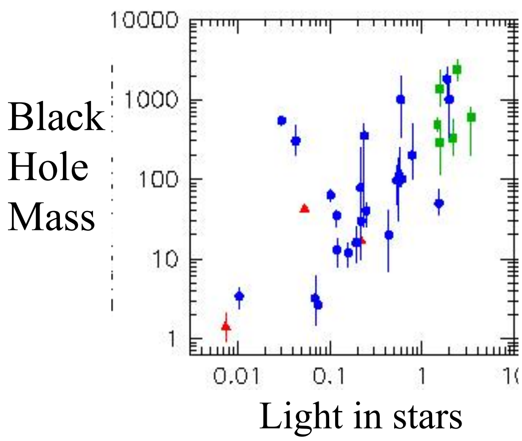
Merloni 2010

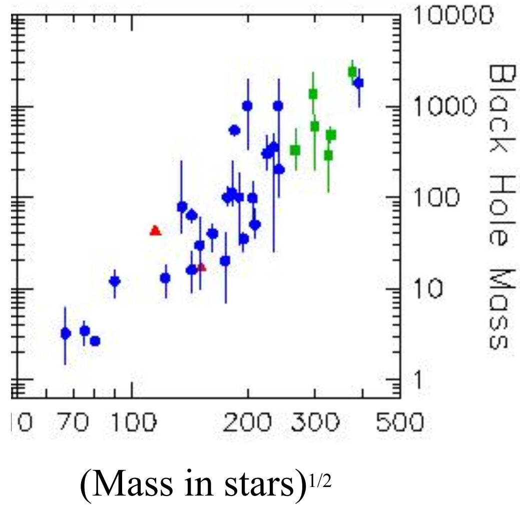


- Relation of mass of central black (M_{BH}) hole to the velocity dispersion of the stars in the bulge (σ)

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



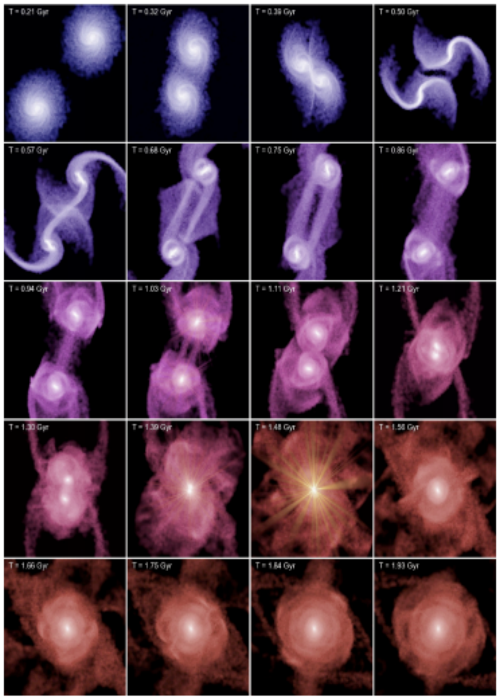


Scaling relations that allows estimate of BH mass in distant galaxies

Problems with the Formation of the Universe

- How did the universe come to look like it does?
- Detailed numerical simulations show that gravity + hydrodynamics does not produce the universe we see -many things are wrong e.g. galaxies are too big, too bright too blue, form at wrong time, wrong place (previous lecture)
- What else is required?
  - FEEDBACK-The influence of objects on the universe (stars and AGN)
  - Stars don't have enough energy
  - So it has to be AGN
    - How ?
    - Where ?
    - When ?
- reasons to believe in feedback
  - baryon fraction in galaxies,
  - IGM absorption in metal lines at moderate z
  - Entropy in groups
  - Detection of effects of radio sources on gas in galaxies and clusters

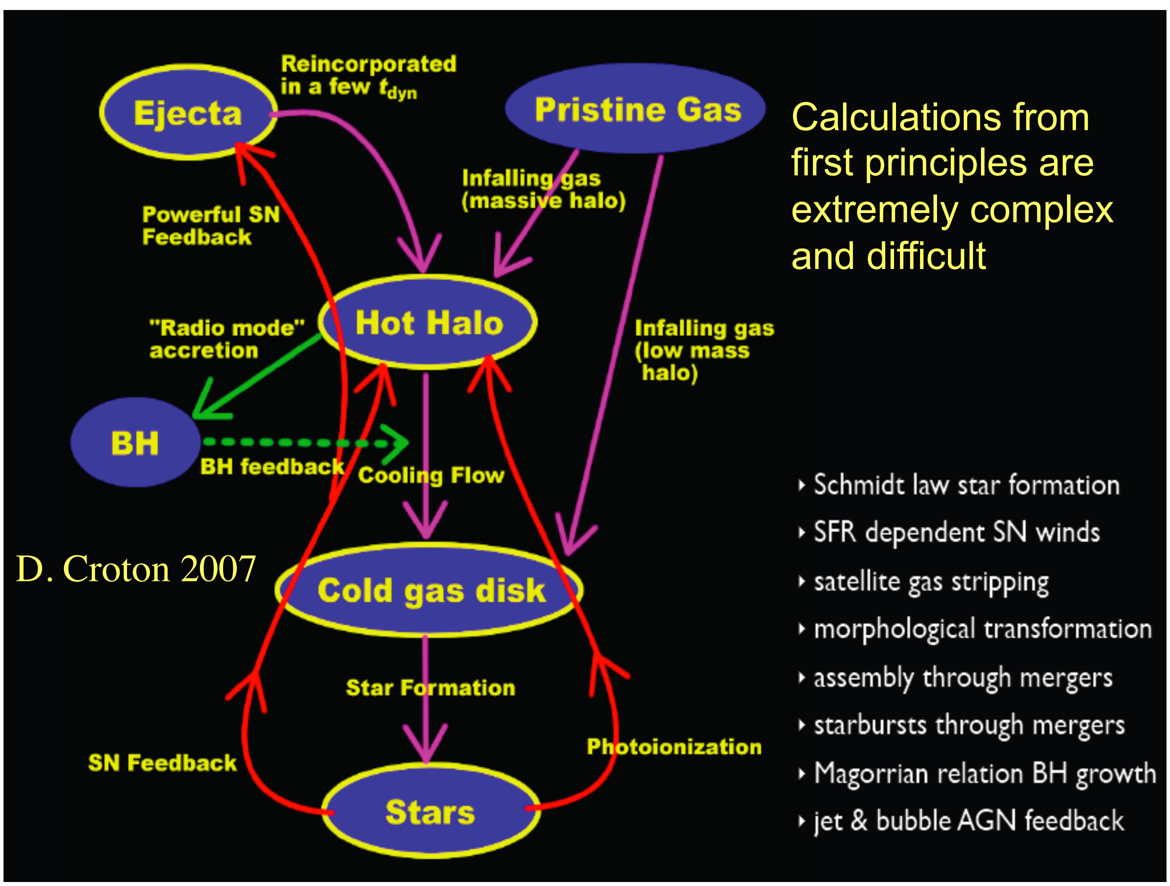
Paradiso Canto 31

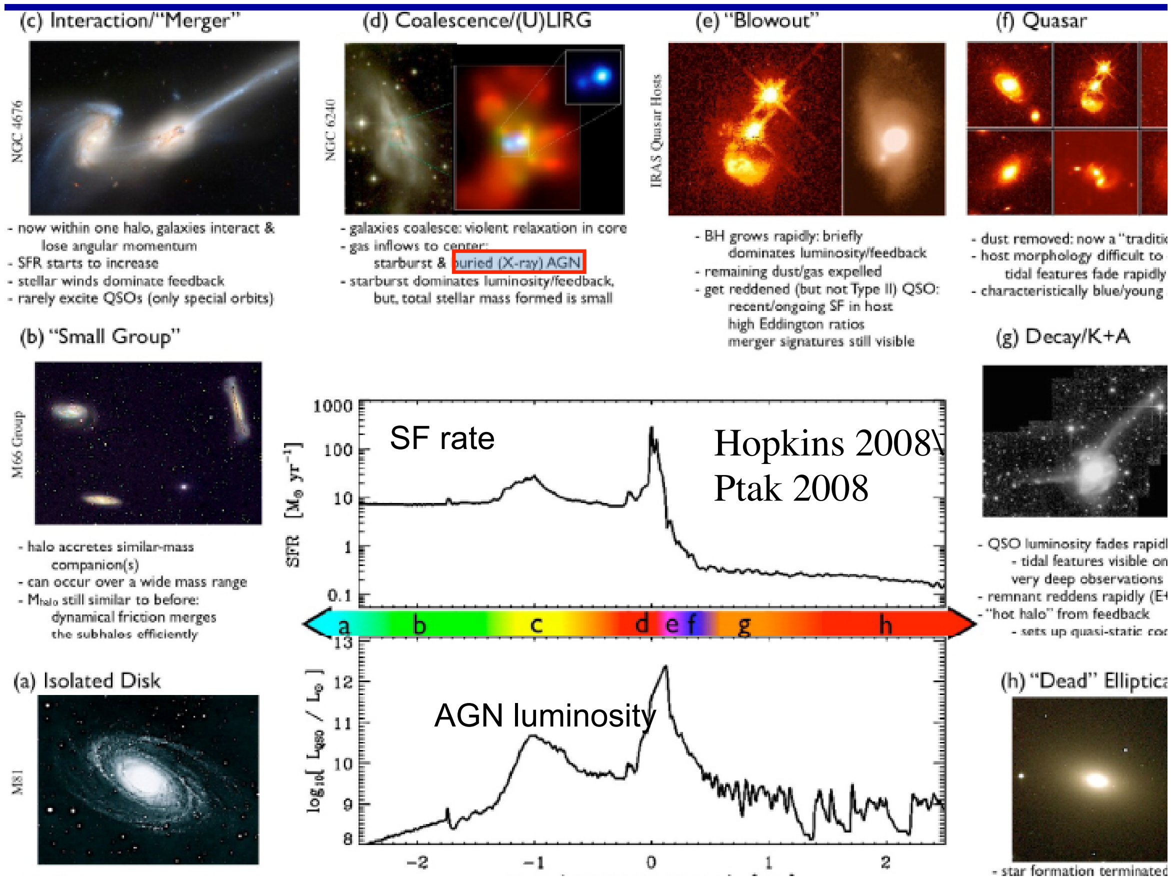


- Gas rich major merger
- Inflows trigger BH accretion & starbursts
- Dust/gas clouds obscure AGN
- AGN wind sweeps away gas, quenching SF and BH accretion.

Hernquist (1989)
Springel et al. (2005)
Hopkins et al. (2006)

One scenario for how AGN are triggered





The Bottom Line..

- Since mass of black holes scales linearly with mass of bulge

$$E_{BlackHole} > 30 \times E_{Galaxy}$$

Energy released by growth of Black Hole

Gravitational Binding Energy of Host Galaxy

If the energy is in the right form and available at the right time AGN can have a strong influence on the baryons in the galaxy

Some Details

- **AGN have more energy than supernova**
  - for a given galaxy (take M87) M_{BH}~$6x10^9$; $E=10^{-1}M_{BH}c^2$~10^{63} ergs; binding energy of galaxy E_{bind}~$GM_{baryon}M_{DM}/R_{galaxy}$ ~10^{62} ergs
  - Characteristic time to radiate at the maximum allowed (Eddington limit) ~40Myr

Average over universe

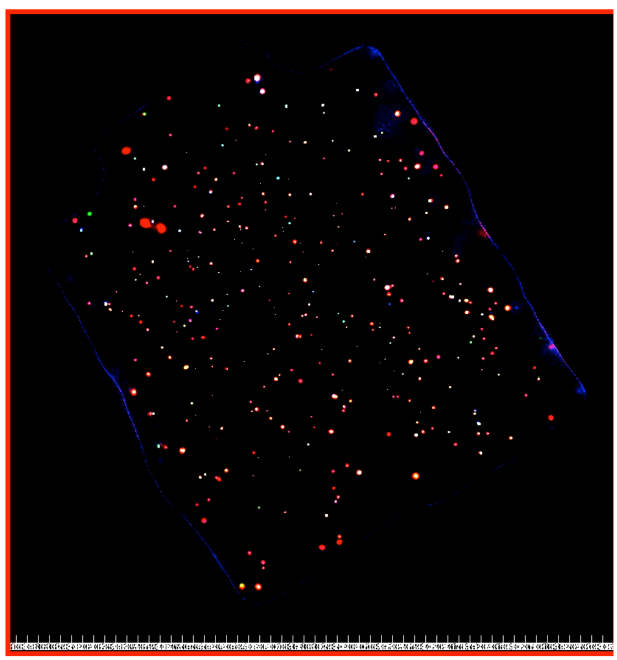
E_{SN}~$10^{-4}M_{star}c^2$ E_{AGN}~$10^{-1}M_{BH}c^2$

  - mass density of SN ρ_{SN}~$4x10^7 M_\odot$ Mpc^{-3} over life of galaxy* (1/MW/100yrs)
  - mass density of AGN ρ_{AGN}~$4x10^5 M_\odot$ Mpc^{-3} at z=0
  - total energy E_{SN}~$10^3M_{\odot r}c^2$
  - E_{AGN}~$4x10^4M_\odot c^2$
  - AGN have 10x more total energy than SN !

- Do they have enough energy to do the trick ?
  - convert energy to motion : take total mass of baryons in galaxy and dump the SN or AGN luminosity into it
  - $\varepsilon_{bh}/\rho_{baryons}$~$(750km/s)^2$ $\varepsilon_{SN}/\rho_{baryons}$~$(100\text{-}250km/s)^2$
  - since potential depth of galaxies like MW ~500km/sec AGN can expel the gas

The History of Active Galaxies

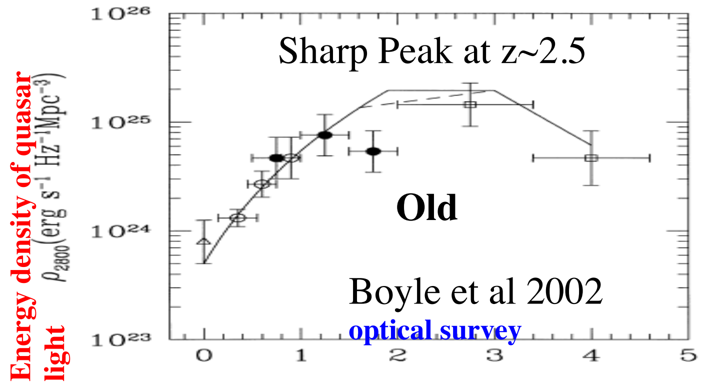
- Active Galaxies (AKA quasars, Seyfert galaxies etc) are radiating massive black holes with L~10^8-$10^{14}L_{sun}$
- The change in the luminosity and number of AGN with time are fundamental to understanding the origin and nature of massive black holes and the creation and evolution of galaxies
- ~20% of all energy radiated over the life of the universe comes from AGN- a strong influence on the formation of all structure.

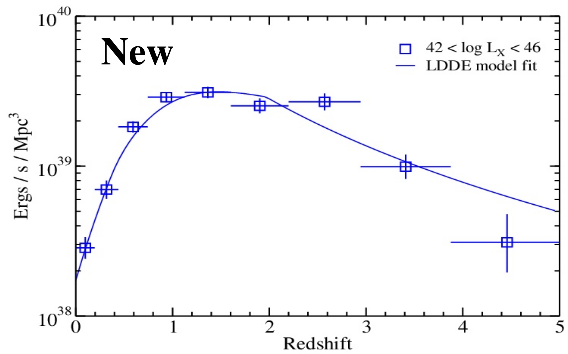


X-ray Color Image (1deg) of the Chandra Large Area X-ray Survey-all of the 'dots' are x-ray detected AGN- except 2 red blobs which are clusters

AGN Evolution

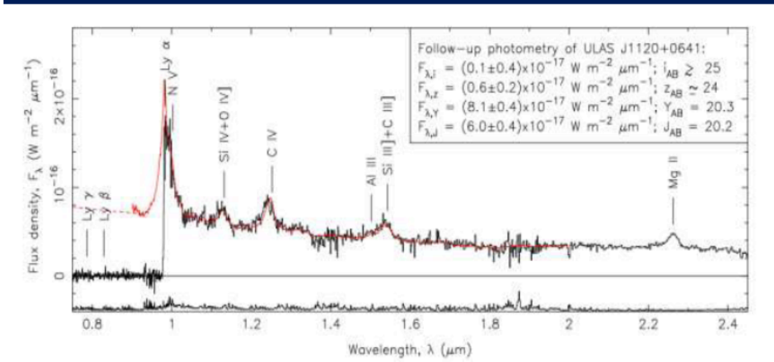
- AGN evolve rapidly in low z universe- reach peak at z~1 and decline rapidly at z>2.5
- Highest z QSO ~7 (universe 780Myrs old)
- most of the AGN in the universe are obscured- strong effect on optical/UV surveys





Yencho et al 2009- xray survey

Gemini Quasar at z=7.1



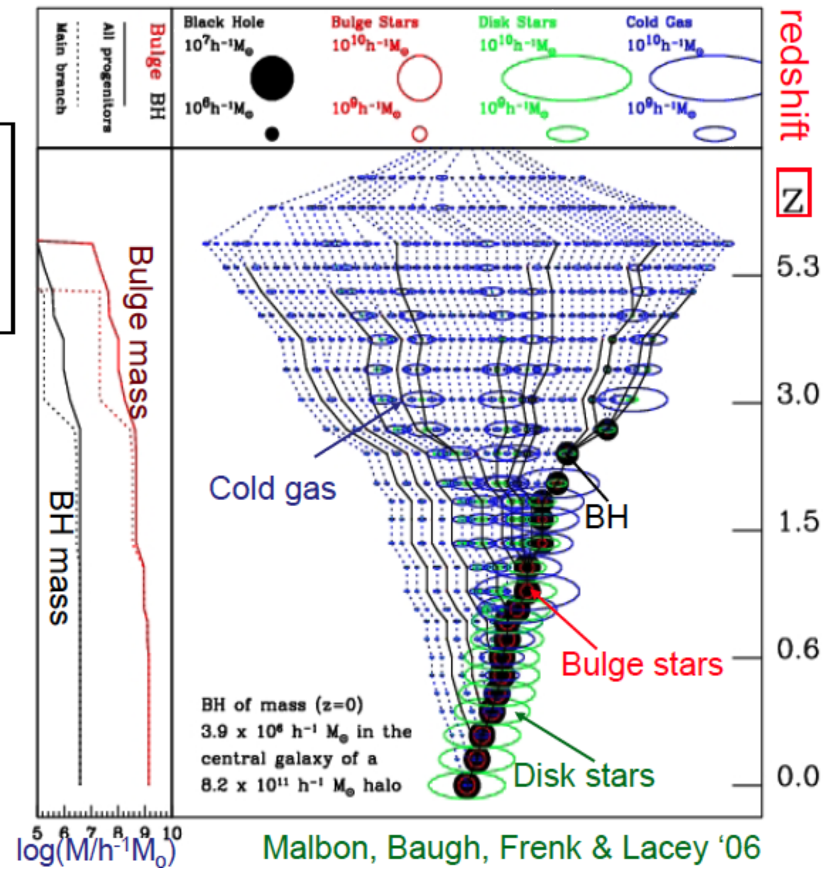
- GNIRS + VLT spectrum of most distant QSO yet discovered. Massive black holes existed when universe was 750 MY old. IR-optimized Gemini was key to this discovery.

Mortlock et al. 2011, Nature, 474, 616

$M \sim 10^9 M_\odot$

QSO is the red object in the center of the frame.

Joint growth of BH and galaxy (bulge stars, disk stars, cold gas)



Malbon, Baugh, Frenk & Lacey '06

Total Lifetime of active BHs

ε= efficiency of converting mass to energy

λ= Eddington ratio

$$t_{Salp} = \frac{\varepsilon t_E}{(1-\varepsilon)\lambda} = 4.2\times 10^7 yr \left[\frac{(1-\varepsilon)}{9\varepsilon}\right]^{-1} \lambda^{-1}$$

M_{BH} e-fold time (t_{Sap}, Salpeter's e-foldimg timescale):

Idea is that matter falls into the black hole at a some rate (which we normalize to the maximum rate) and the some of the matter is converted into energy before disappearing beyond the event horizon

- To grow a mass BH from a small seed SEVERAL t_{Salp} needed:

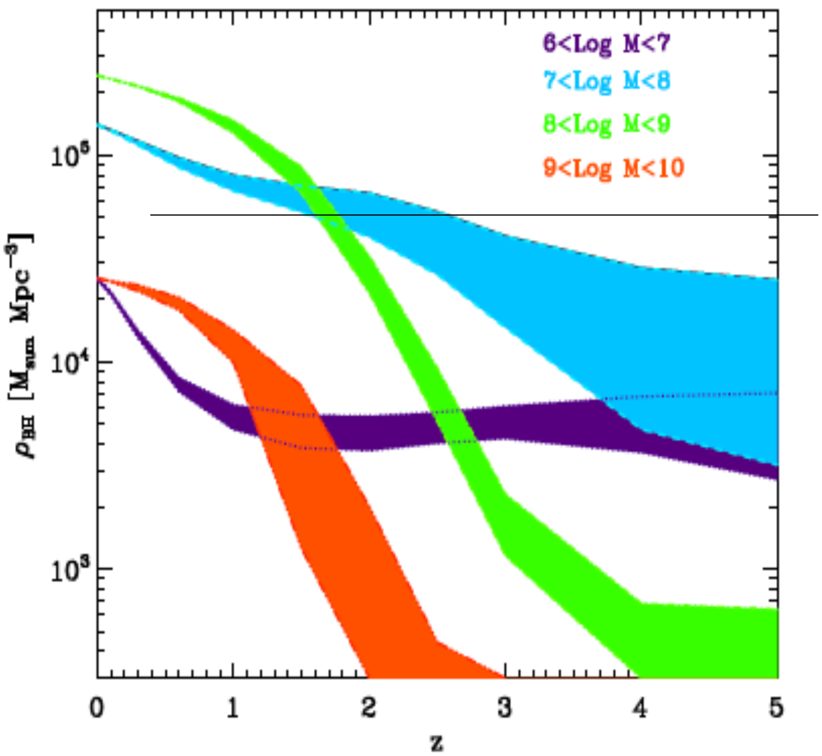
  7 t_{Salp} 10^3 ⇨ 10^6 $M_⊙$

  14 t_{Salp} 10^3 ⇨ 10^9 $M_⊙$
- t_{Salp} independent of M_{BH}.

- Eddington ratio is the ratio of the observed luminosity to the maximum possible if radiation balances gravity L_{Edd}=1.3x10^{38}Msun ergs/sec

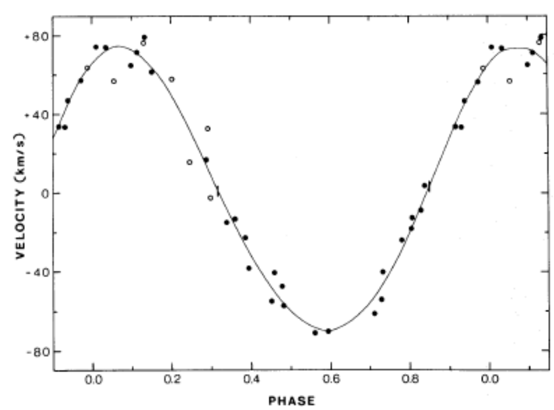
How Black holes grow
Merloni 2009

- Most of the mass in BHs today is in the 10^8-10^9 $M_\odot$ range
- BH in mass range 10^6-10^7 $M_\odot$ are growing rapidly today like spiral galxies
- Massive $>10^9$M BHs grew fast in early universe, slowly today (like elliptical galaxies)



Discovery of black holes

- First evidence for an object which 'must' be a black hole came from discovery of the X-ray source Cygnus X-1
  - Binary star system… black hole in orbit around a massive O-star; period =5.6 days - not eclipsing
  - Mass of x-ray emitting object 7-13 $M_\odot$- too high for a NS. Object emits lots of x-rays little optical light.
  - X-rays produced due to accretion of stellar wind from O-star
  - 2kpc away



Velocity curve of the stellar companion
It is a massive O star

Keplers laws give (where K is the velocity of the companion)

$f(M) = P_{orb}K^3 /2\pi G = M_1 \sin^3 i/(1 + q)^2$.
$q=M_2/M_1$
the value of the mass function is the absolute minimum mass of the compact star

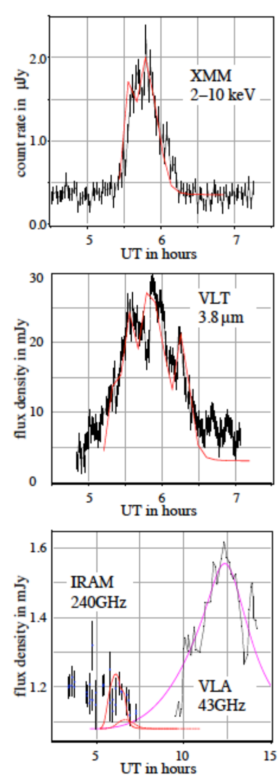
4 J. Casares

Table 1. Confirmed black holes and mass determinations

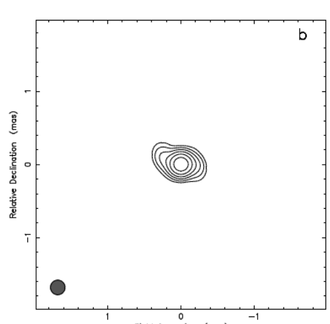
System	P_{orb} [days]	$f(M)$ [$M_\odot$]	Donor Spect. Type	Classification	M_x † [$M_\odot$]
GRS 1915+105[a]	33.5	9.5 ± 3.0	K/M III	LMXB/Transient	14 ± 4
V404 Cyg	6.471	6.09 ± 0.04	K0 IV	,,	12 ± 2
Cyg X-1	5.600	0.244 ± 0.005	09.7 Iab	HMXB/Persistent	10 ± 3
LMC X-1	4.229	0.14 ± 0.05	07 III	,,	> 4
XTE J1819-254	2.816	3.13 ± 0.13	B9 III	IMXB/Transient	7.1 ± 0.3
GRO J1655-40	2.620	2.73 ± 0.09	F3/5 IV	,,	6.3 ± 0.3
BW Cir[b]	2.545	5.74 ± 0.29	G5 IV	LMXB/Transient	> 7.8
GX 339-4	1.754	5.8 ± 0.5	–	,,	
LMC X-3	1.704	2.3 ± 0.3	B3 V	HMXB/Persistent	7.6 ± 1.3
XTE J1550-564	1.542	6.86 ± 0.71	G8/K8 IV	LMXB/Transient	9.6 ± 1.2
4U 1543-475	1.125	0.25 ± 0.01	A2 V	IMXB/Transient	9.4 ± 1.0
H1705-250	0.520	4.86 ± 0.13	K3/7 V	LMXB/Transient	6 ± 2
GS 1124-684	0.433	3.01 ± 0.15	K3/5 V	,,	7.0 ± 0.6
XTE J1859+226[c]	0.382	7.4 ± 1.1	–	,,	
GS2000+250	0.345	5.01 ± 0.12	K3/7 V	,,	7.5 ± 0.3
A0620-003	0.325	2.72 ± 0.06	K4 V	,,	11 ± 2
XTE J1650-500	0.321	2.73 ± 0.56	K4 V	,,	
GRS 1009-45	0.283	3.17 ± 0.12	K7/M0 V	,,	5.2 ± 0.6
GRO J0422+32	0.212	1.19 ± 0.02	M2 V	,,	4 ± 1
XTE J1118+480	0.171	6.3 ± 0.2	K5/M0 V	,,	6.8 ± 0.4

The Center of the Milky Way

- The center of the MW is called Sagitarius A*(SgrA*) from the name of the radio source at the dynamical center of the MW.
- This is also the location of a weak, time variable x-ray (log L_x~34- 100x less than a typical x-ray binary) and IR source
- The radio source is very small (VLBI) (<0.0005"<$50R_s$ for M=$4 \times 10^6 M_\odot$ BH at d=8kpc)
- At SgrA* 1"=0.04pc=1.2×10^{17} cm ,0.5mas=6AU



Radio, near IR and x-ray light curves



Radio image of SgrA*

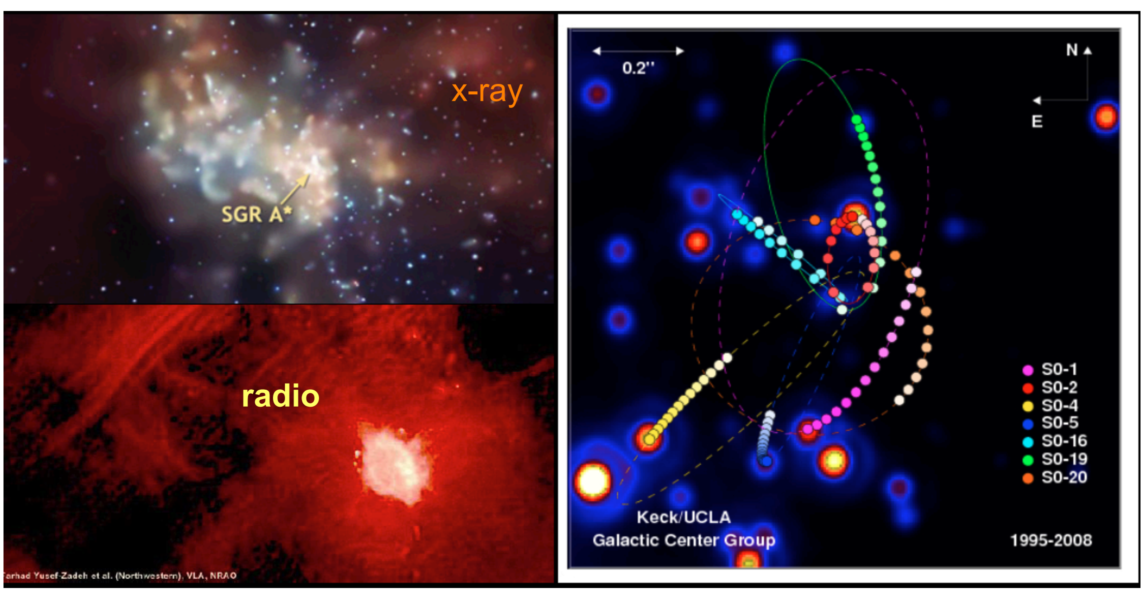
Some Problems with Sgr A*

- There is lots of gas for accretion in the galactic center from the ISM and stellar winds
- Yet the observed luminosity is very low ($L/L_{Edd} \sim 10^{-10}$)
- What happens to the accretion energy- where does the mass and energy go

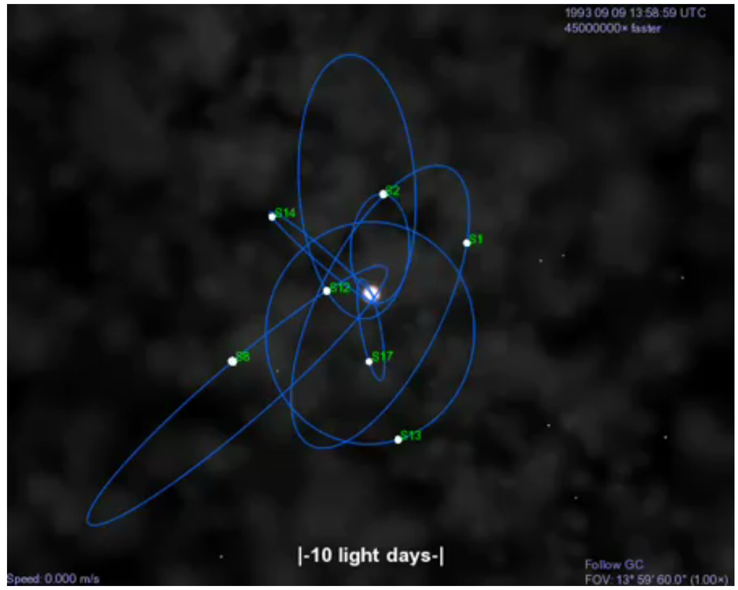
- Sgr A* is similar to >95% of all massive galaxies- they have big black holes, but low luminosities **TODAY**! (AGN evolution)

MW Galactic Center

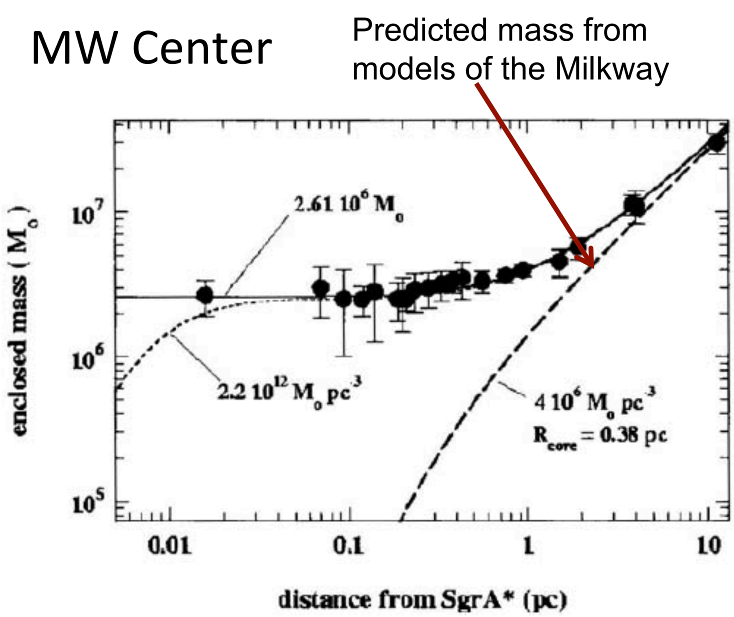
- galactic centers are 'special' places
- MW galactic center



Motion of Stars Around the Center of the Milkyway- see http://www.youtube.com/watch?v=ZDxFjq-scvU
http://www.mpe.mpg.de/ir/GC/



MW Center



- Two teams led by R. Genzel and A. Ghez have measured the 3-D velocities of individual stars in the galactic center
- This allows a determination of the mass within given radii
- The inferred density of the central region is >$10^{12} M_\odot/pc^3$

•As shown by Genzel et al the stability of alternatives to a black hole (dark clusters composed of white dwarfs, neutron stars, stellar black holes or sub-stellar entities) shows that a dark cluster of mass 2.6 x 10^6 M_{sun}, and density $20 M_{sun} pc^{-3}$ or greater can not be stable for more than about 10 million years

Velocity Distribution of Stars Near the Center of the MW

A Supermassive Black Hole in the Milky Way 29

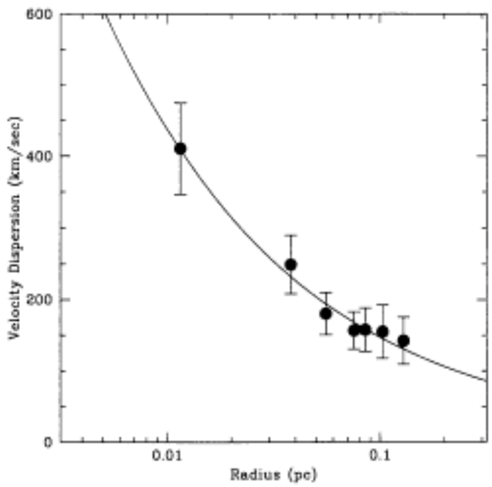
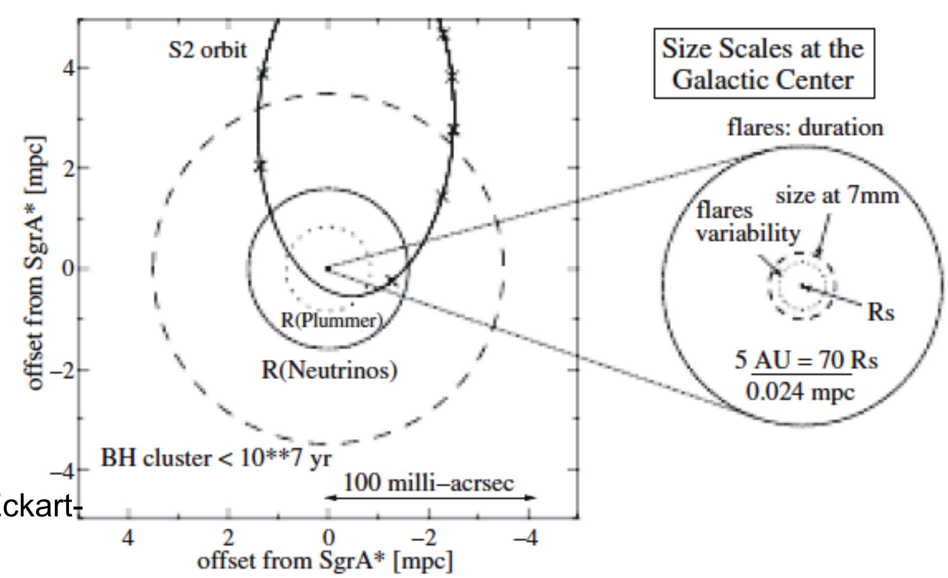


Figure 7. The projected stellar velocity dispersion as a function of projected distance from Sgr A* is consistent with Keplerian motion, which implies that the gravitational field is dominated by mass within 0.1 pc.

Ghez et al 1998

The Milky Way's Black Hole and the Central Stellar Cluster



Eckart-

Schwarzschild and Kerr Metric

- for a Schwarzschild BH the innermost stable radius is $3r_G=6GM/c^2$ - there are no stable circular orbits at smaller radii
  - the binding energy from this orbit is 0.0572 of the rest mass energy
- For a Kerr the innermost stable radius is at $r_+=GM/c^2$ The spinning black hole drags the the inertial frame-
- The smaller critical radius allows more energy to be released by infalling matter
  - **For a Kerr BH, 0.423 of the rest mass energy can be released.**

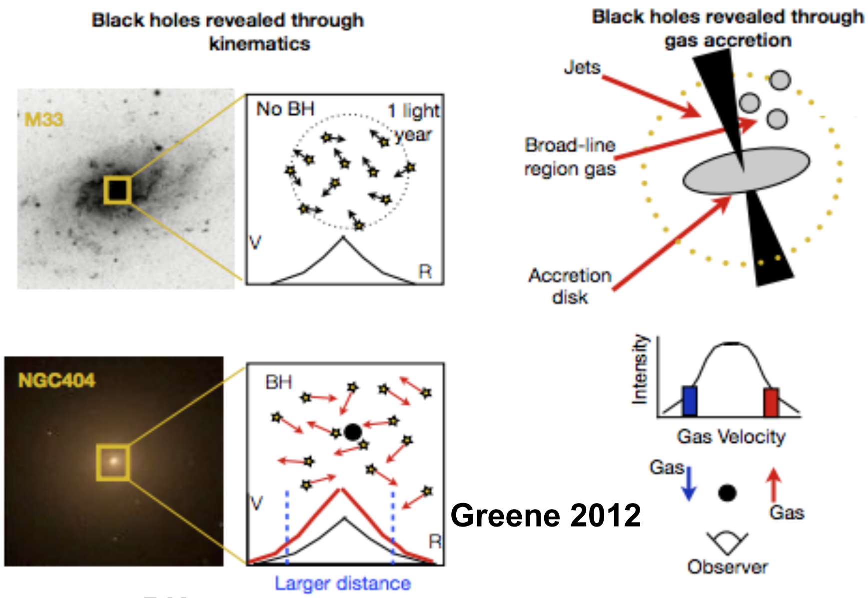
Please fill in your course evaluation!-

only 3 people have done so as of this morning

- www.CourseEvalUM.umd.edu
- Have you been challenged and learned new things? Have I been effective, responsive, respectful, engaging, etc?-or dull,boring, stodgy, unprepared?
- Your responses are strictly anonymous. I only see the statistics.
- Helps me and future students!

Finding SMBHs

- Detect SMBHs via presence of an AGN (~10% today) OR
- Via dynamics (motion of stars or gas)... imply ~100% at $M_{galaxy}>10^{10}M$.



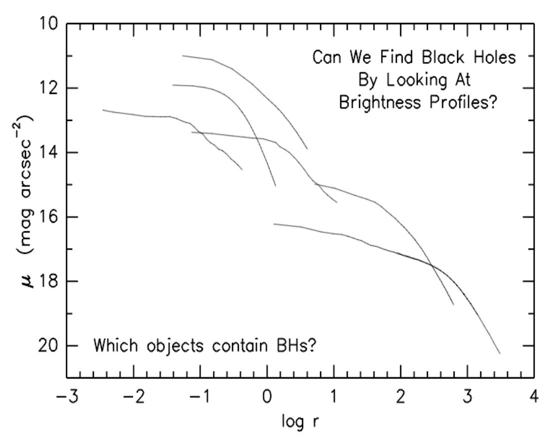
Greene 2012

stars near BH move more rapidly because of BH

broad emission lines-gas moving rapidly near BH

What About Other Supermassive Black Holes

- At the centers of galaxies- much more distant than SgrA*
- First idea: look for a 'cusp' of stars caused by the presence of the black hole- doesn't work, nature produces a large variety of stellar density profiles… need dynamical data
- Dynamical data: use the collisionless Boltzman eq (seen this before)
- V=rotational term; velocity dispersion has 3 components σ_r, σ_ϕ, σ_θ

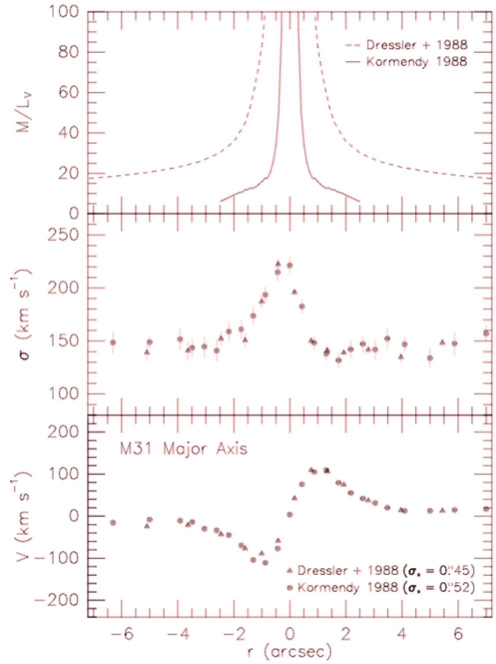


Kormendy and Richstone (2003)

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

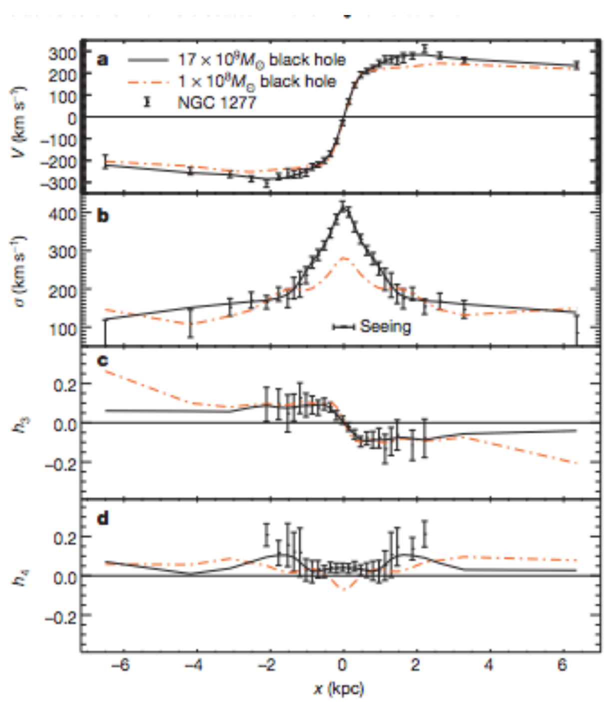
Example of data for the nearest galaxy M31

- Notice the nasty terms
- V_r is the rotation velocity σ_r $\sigma_{\theta,}$ σ_ϕ are the 3-D components of the velocity dispersion ν is the density of stars
- All of these variables are 3-D; we observe projected quantities !
- The analysis is done by generating a set of stellar orbits and then minimizing
- Rotation and random motions (dispersion) are both important.
- Effects of seeing (from the ground) are importan:t smear the image, reduce BH dynamical signal-



NGC1277- Velocity Data and BH Mass

- Top is rotation curve vs distance from center
- Middle is velocity dispersion vs distance from center
- Bottom 2 curves are measures of the non-gaussianity of the velocity field (sensitive to distribution of orbits)

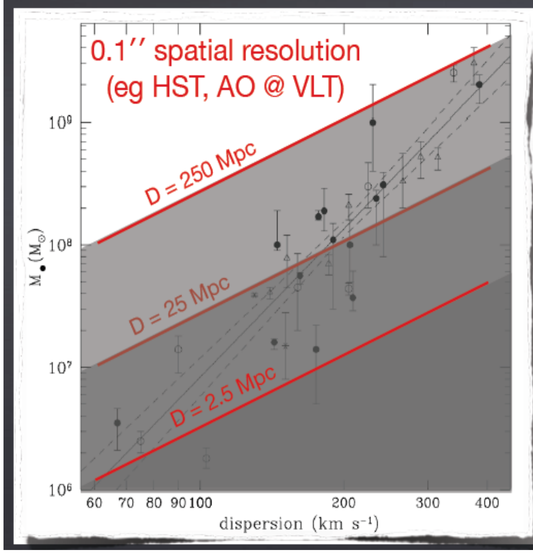


Direct BH mass measurements

BH sphere of influence

$$r_{BH} = \frac{G\,M_{BH}}{\sigma_\star^2} = 10.7\,\mathrm{pc}\left(\frac{M_{BH}}{10^8\,M_\odot}\right)\left(\frac{\sigma_\star}{200\,\mathrm{km/s}}\right)^{-2}$$

$$\theta_{BH} = 0.11''\left(\frac{M_{BH}}{10^8\,M_\odot}\right)\left(\frac{\sigma_\star}{200\,\mathrm{km/s}}\right)^{-2}\left(\frac{D}{20\,\mathrm{Mpc}}\right)^{-1}$$

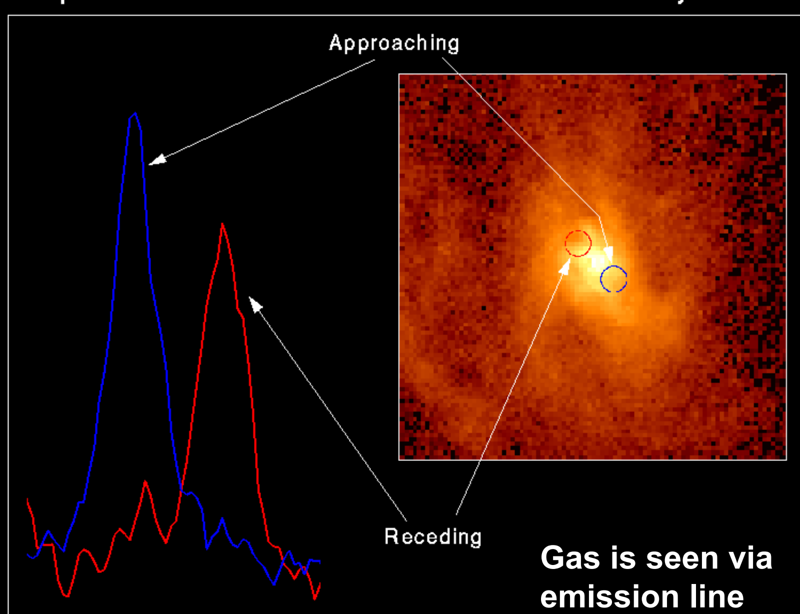


BHs are directly detectable with spatially resolved kinematics ONLY in the local universe

Need to calibrate indirect BH mass estimators like for the cosmological distance ladder

Marconi

Spectrum of Gas Disk in Active Galaxy M87



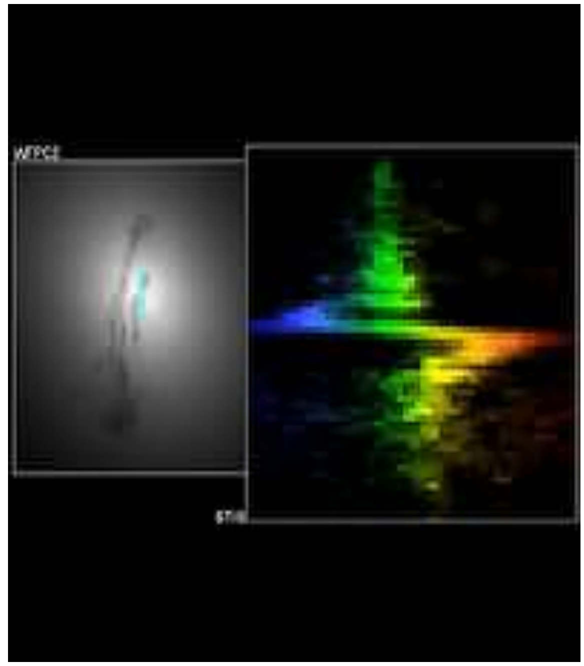
Hubble Space Telescope • Faint Object Spectrograph

SPACE TELESCOPE SCIENCE INSTITUTE

Harms et al 1999

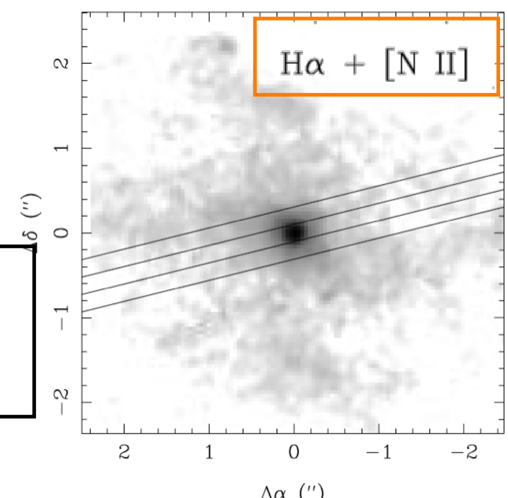
Measuring the Mass of a SuperMassive Black hole

- Image of central regions and Velocity of gas near the center of M84 a nearby galaxy (Bower et al 1998) -
- The color scale maps the range of velocity along the slit, with blue and red color representing velocities (with respect to systemic) that are blueshifted and redshifted, respectively.
- The dispersion axis (horizontal) covers a velocity interval of 1445 km s-1, while the spatial axis (vertical) covers the central 3 arcsec;.

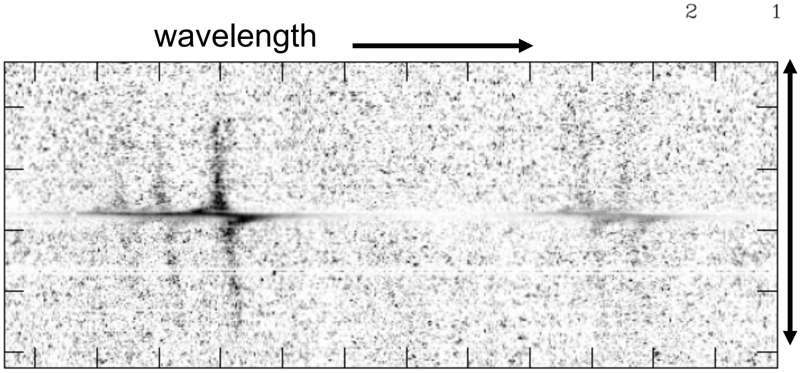


Measurement of Kinematics o Gas

- Image of optical emission line emitting gas around the central region of the nearby giant galaxy M84



HST STIS Observations of the Nuclear Ionized Gas in the Elliptical Galaxy M84
G. A. Bower, R. F. Green, D.



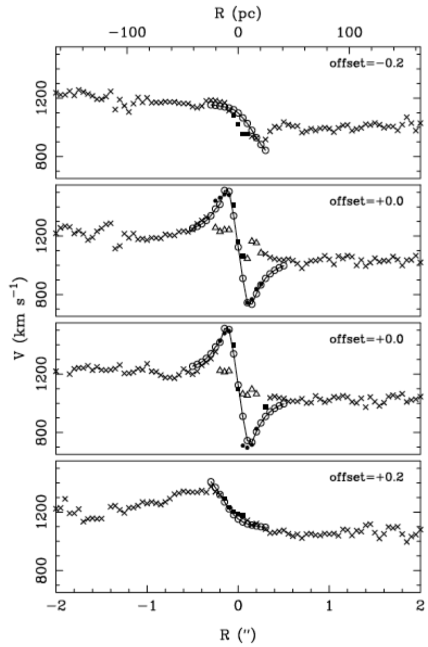
Analysis of Spectral Data for M84

- Mass of central object 1.5×10^9 M_{sun}

TABLE 1
KEPLERIAN DISK MODEL PARAMETERS

Parameter	Best Fit	Uncertainty Range
Black hole mass ($M_\odot$)	1.5×10^9	$(0.9–2.6) \times 10^9$
Disk inclination (deg)	80	75–85[a]
Disk P.A. (deg)	83	80–85
Gas systemic velocity (km s^{-1})	1125	1100–1150
Intensity law	$I(r) \propto r^{-1}$	...
$I(r)$ inner radius (pc)	1	0.3–3
$V(r)$ inner radius (pc)	0.03	0.01–0.1
PSF σ (arcsec)	0.05	0.04–0.06

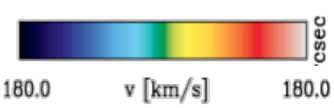
[a] Lower mass requires lower inclination.

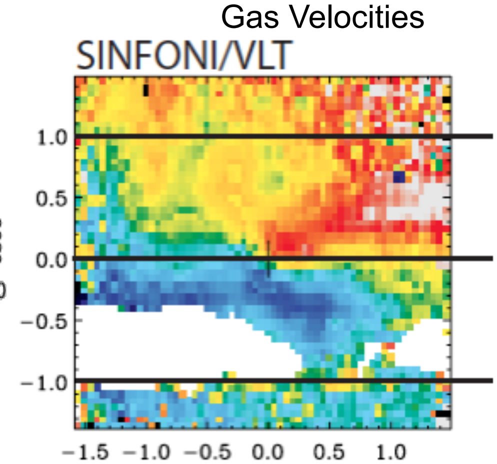


Velocity of gas vs distance from center of emission along 3 parallel lines

Centaurus -A

- 2 dimensional velocity maps for gas and stars allow assumptions to be checked (Neumayer et al,Cappelari et al)





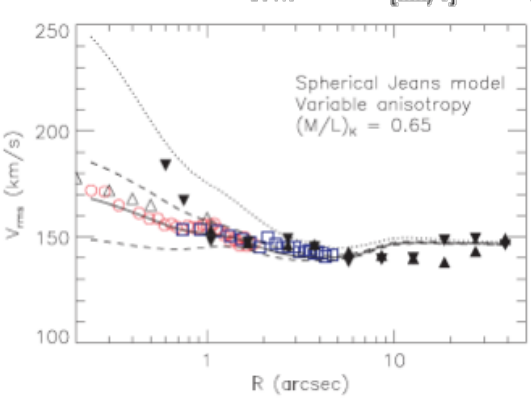
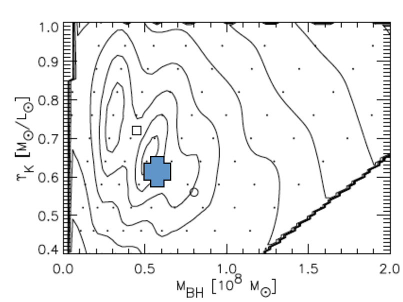
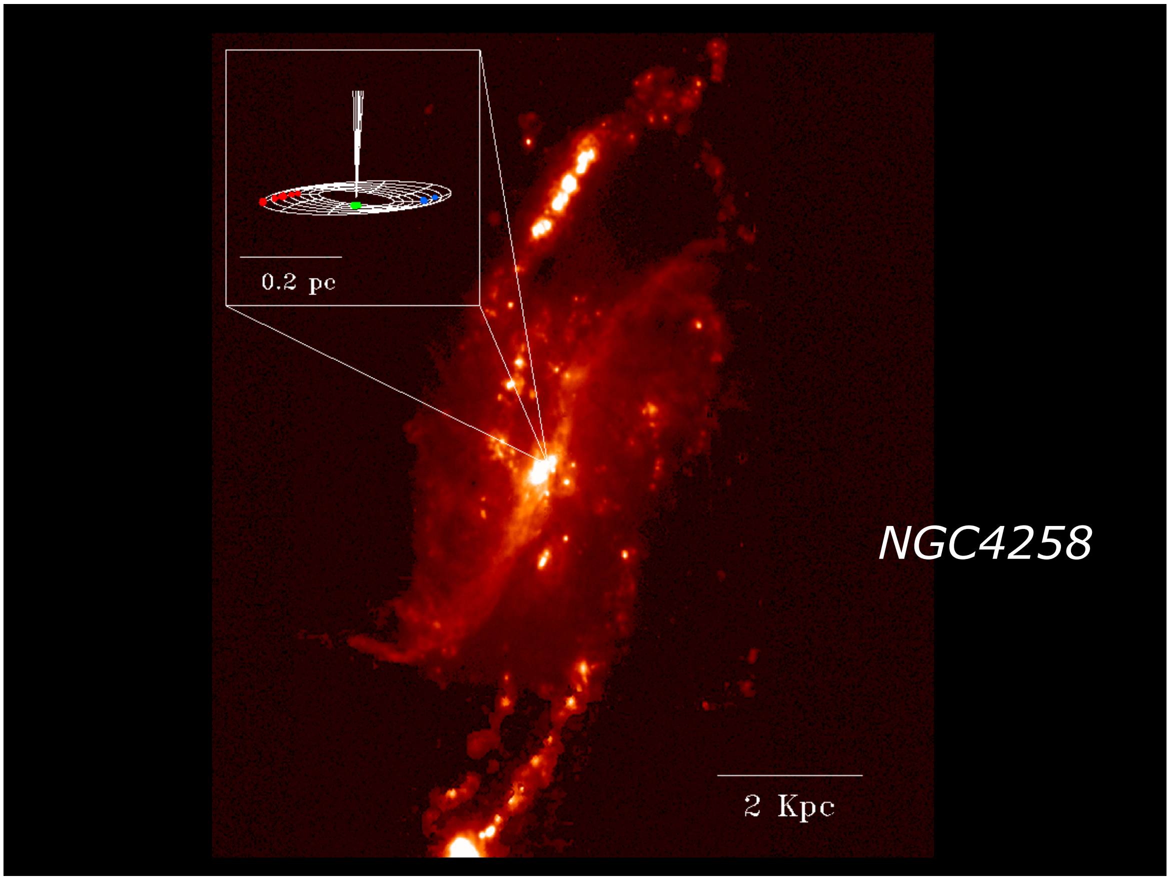


Figure 4: Spherical anisotropic Jeans model

$$M_{\rm BH} = (5.5 \pm 3.0) \times 10^7 M_\odot.$$

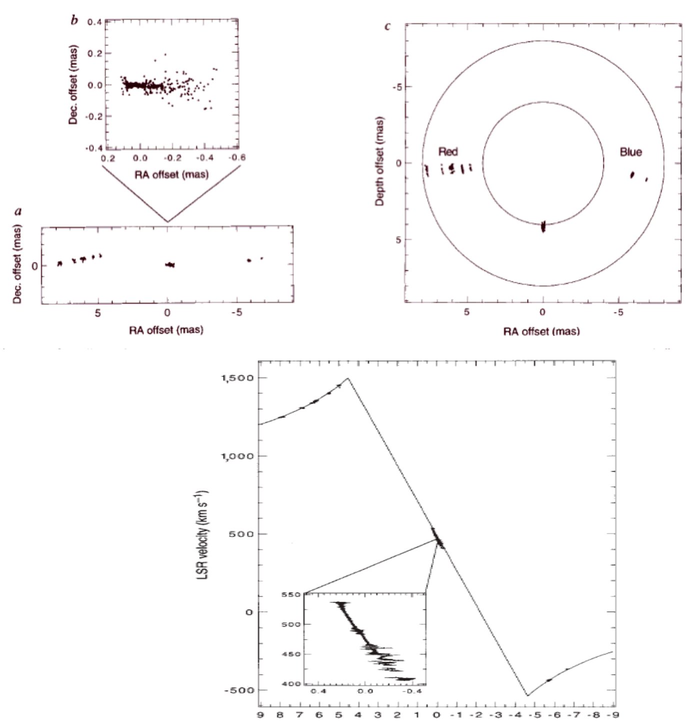


Constraints from stars compared to those from Gas Velocities

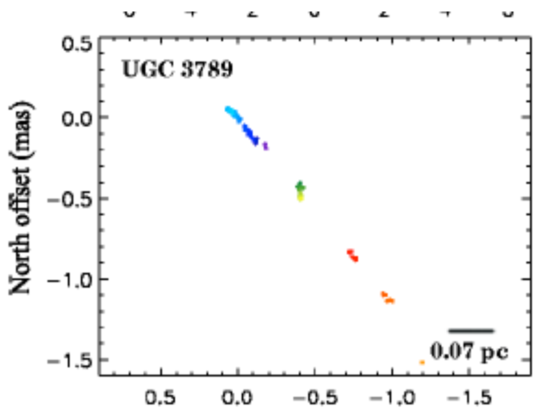


Use of Masers for an AGN

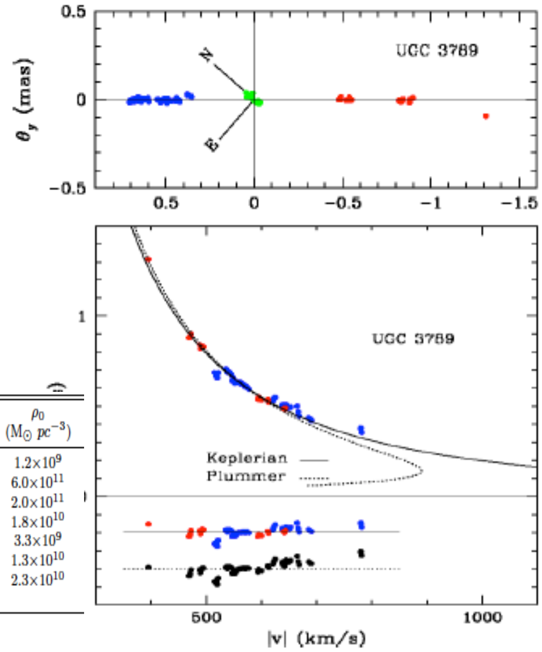
- The nearby galaxy NGC4258 has a think disk which is traced by water maser emission
- Given the very high angular and velocity resolution possible with radio observations of masers the dynamics of the system are very well measured.



Other Masers



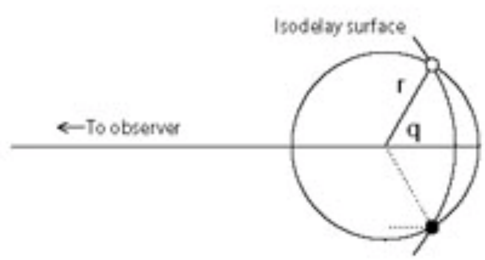
Name	Dist. (Mpc)	BH mass (10^7 $M_\odot$)	Disk Size (pc)	P.A. (°)	Incl. (°)	r_c (pc)	ρ_0 ($M_\odot$ pc^{-3})
NGC 1194	52	6.4±0.3	0.53-1.30	157	85	0.250	1.2×10^9
NGC 2273	26	0.76±0.04	0.028-0.085	153	84	0.015	6.0×10^{11}
UGC 3789	50	1.12±0.05	0.09-0.32	41	> 88	0.024	2.0×10^{11}
NGC 2960	71	1.14±0.05	0.13-0.36	−131	89	0.055	1.8×10^{10}
NGC 4388	19	0.84±0.02	0.24-0.29	107	–	0.090	3.3×10^9
NGC 6264	136	2.84±0.04	0.23-0.78	−85	90	0.083	1.3×10^{10}
NGC 6323	105	0.93±0.01	0.13-0.30	10	89	0.046	2.3×10^{10}



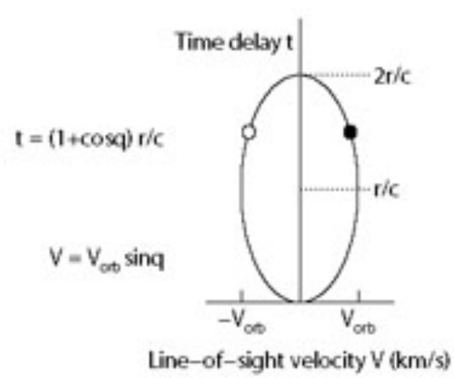
Kuo et al 2010

What About AGN in General??

- We believe that the incredible luminosity of AGN comes from accretion onto a black hole
- However 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) whose ionization is controlled by the radiation from the black hole
  - Thus when the central source varies the gas will respond, with a timescale related to how far away it is

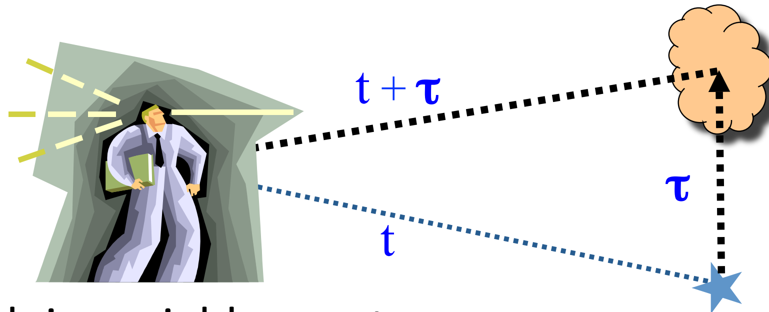


Virial Mass Estimates

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

Reverberation Mapping:

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



- v_{BLR}

Line width in variable spectrum

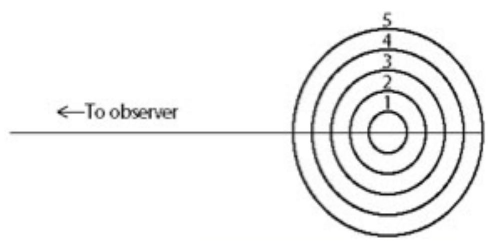
The Geometry

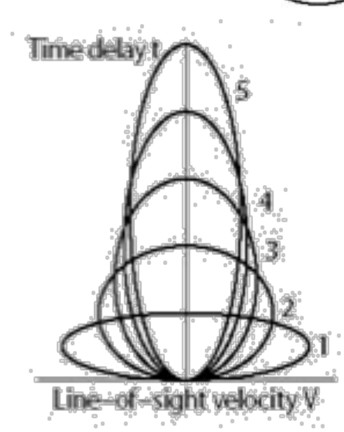
- Points (r, θ) in the source map into line-of-sight velocity/time-delay(τ) space (V, τ) according to $V = -V_{orb}\sin(\theta)$, where V_{orb} is the orbital speed, and $\tau = (1 + \cos(\theta))r / c$.

- The idea is that the broad line clouds exist in 'quasi-Keplerian' orbits 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- assumption is that gas is in a bound orbit around the BH





r=ct, where t is the time delay

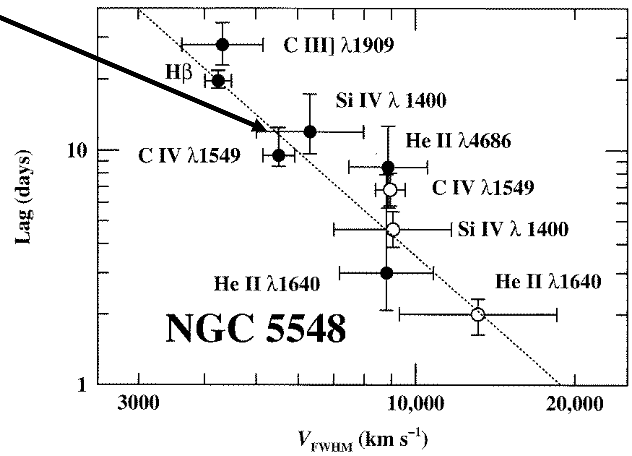
What is Observed??

- 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 dominating the line shapes

  ($v \sim r^{-1/2}$)

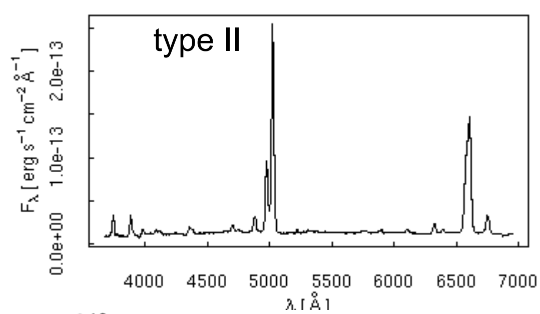
- Such data exist for ~40 sources
- At present M_{BH} can be estimated to within a factor of a few: $M \propto FWHM^2 L^{0.5}$

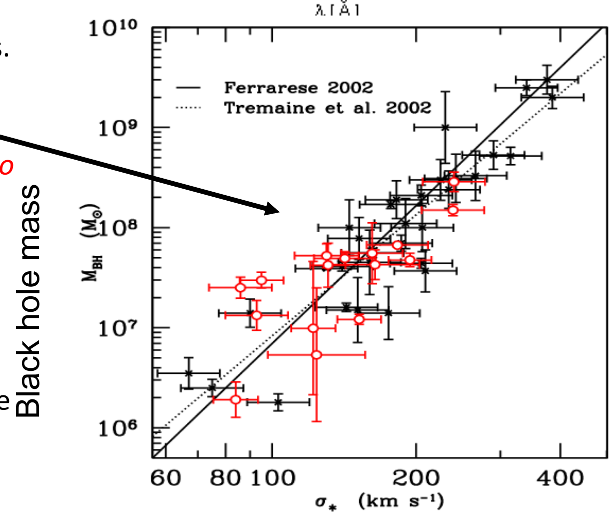


Dotted line corresponds to a mass of 6.8×10^7 $M_\odot$
Peterson and Wandel 1999

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 -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
  - The strong connection between the BH and the galaxy means that each know about each other

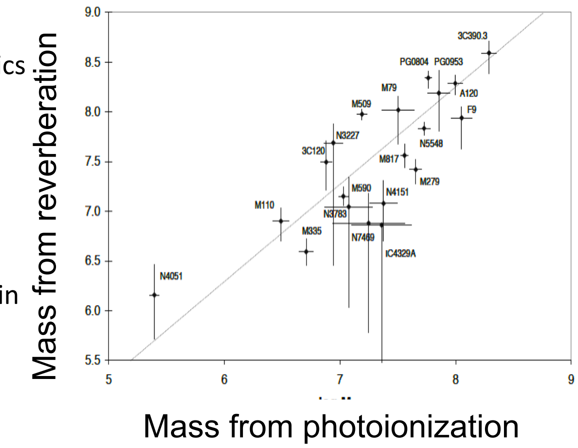




Velocity dispersion of stars in the bulge

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
  - dynamical 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 !



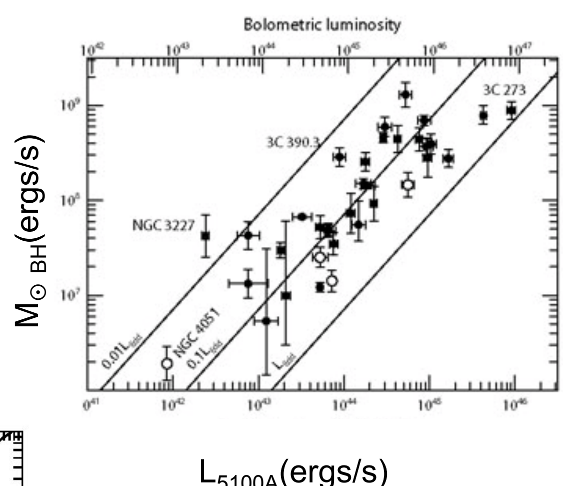
$M_{BH} \sim K\sigma^2 L^{1/2}$

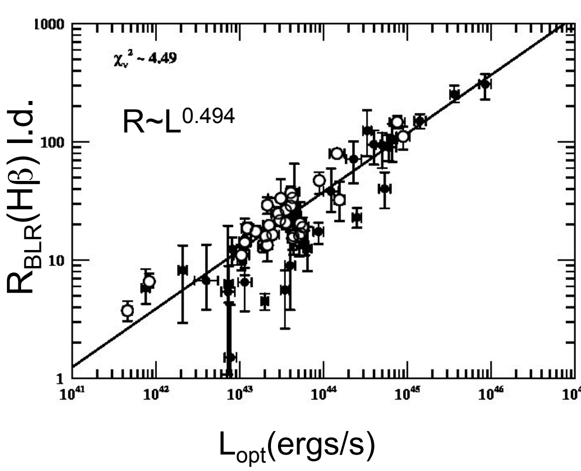
Where K is a constant (different for different lines which is determined by observations

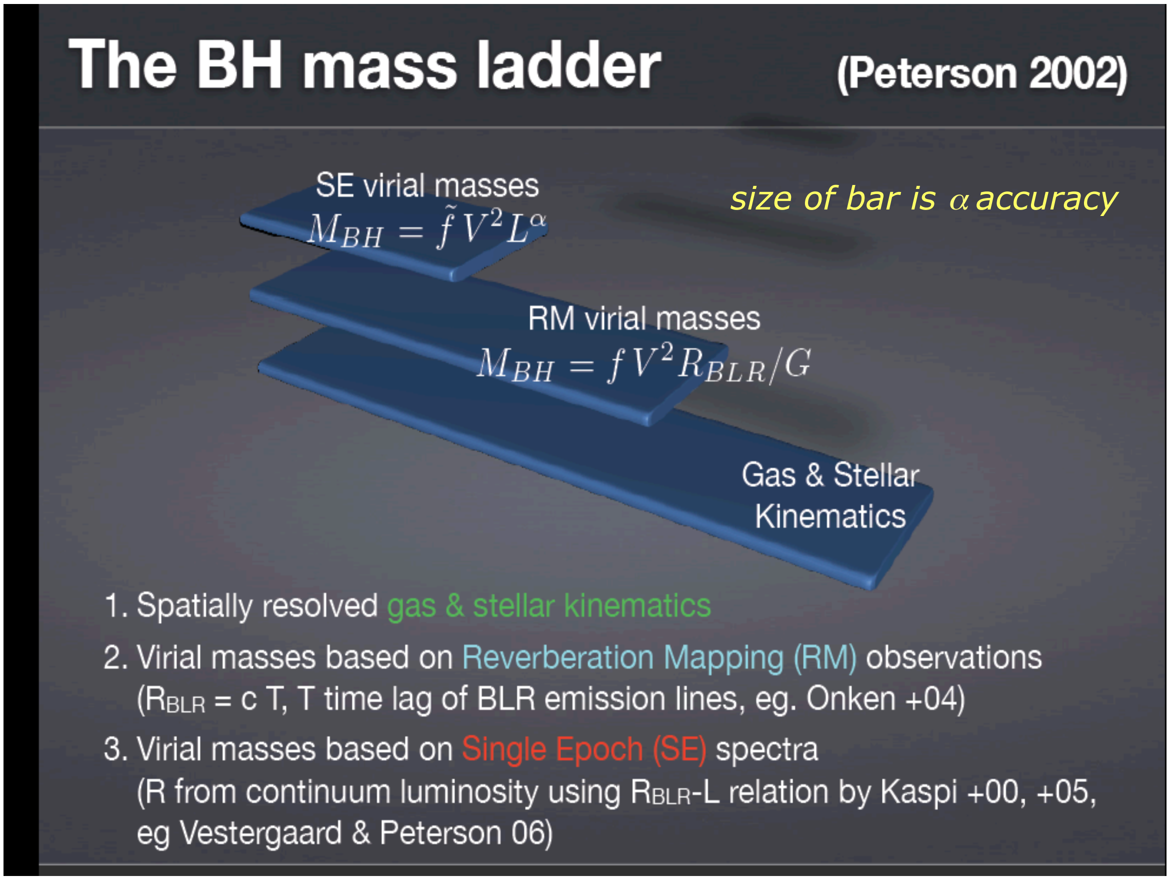
This is just

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

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



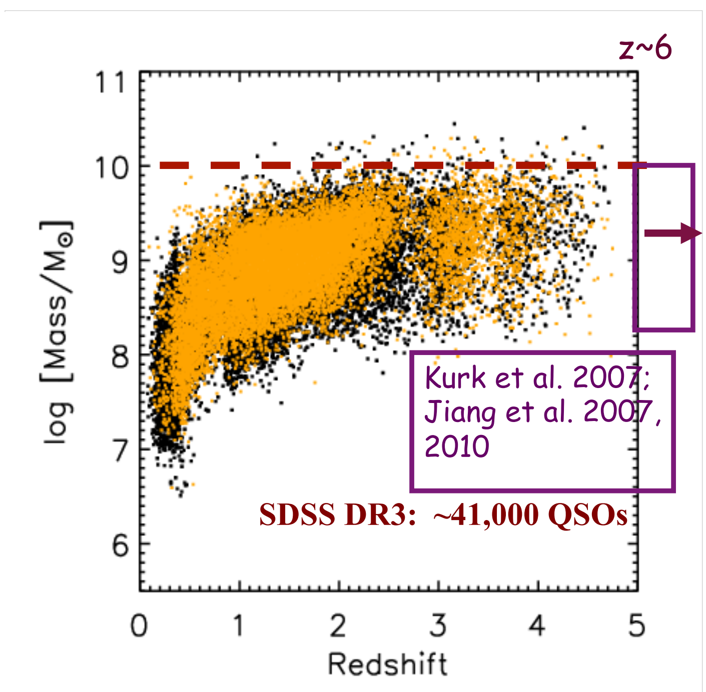




Masses of Distant Quasars- M. Vestergaard

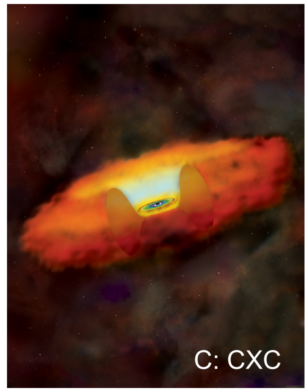
- Using this technique for a very large sample of objects from the Sloan Digital Sky Survey (SDSS)

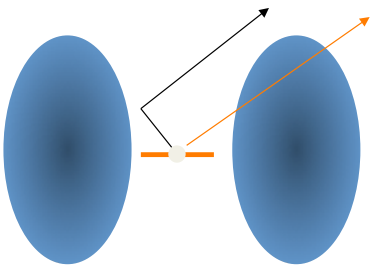
- Maximum mass M_{BH} ~$10^{10} M_\odot$
- $L_{BOL} < 10^{48}$ ergs/s

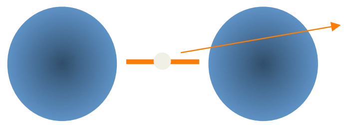


(DR3 Qcat: Schneider et al. 2005)

Some Variation in Geometry







- Effects of geometry can be seen in the spectra

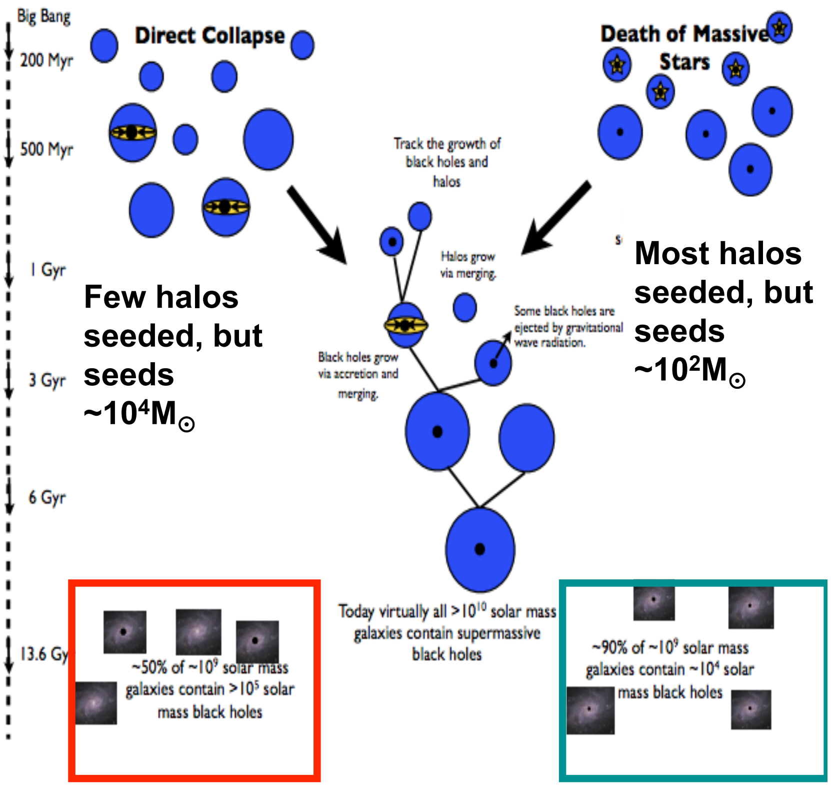
Co-evolution of Galaxies and Black Holes-Summary

- Theoretical models for the coevolution of galaxies and supermassive black holes are based on combining analytic models and numerical simulation of structure formation in the dark matter with ideas about how star formation
  and black hole accretion operate in practice
- Over cosmic time, galaxies grow through two main mechanisms: accretion of gas and mergers
- In a merger, the disk component of each galaxy is scrambled and tidal forces between the two galaxies drain away angular momentum from the cold gas in the disk of the galaxy, allowing it to flow into the inner region, delivering gas to the supermassive black hole.
- The scrambled disk material settles into a newly created spheroid.
- If the each of the merging galaxies contained their own supermassive black
  holes, these too might merge to form a single larger one.
- The release of energy from the merger-induced AGN and starburst is so intense that it may blow away most or all of the remaining gas in a powerful outflow.
- The end result is a single galaxy with a larger bulge and a substantially more massive black hole (Heckman and Kauffmann 2012)

2 Scenarios for Birth of SMBHs

How do SMBHs get started?? Detect M~10^9M BH at z~7- need to grow fast!

Distinguish the 2 paths based on the fraction of *small* galaxies that today contain SMBHs
Greene 2012



Constraints on Rest Mass of Black Holes

- Black holes can grow via two paths
  - accretion
  - merger

- It is thought that, at z>1 that many galaxies (esp elliptical galaxies) grow through mergers.

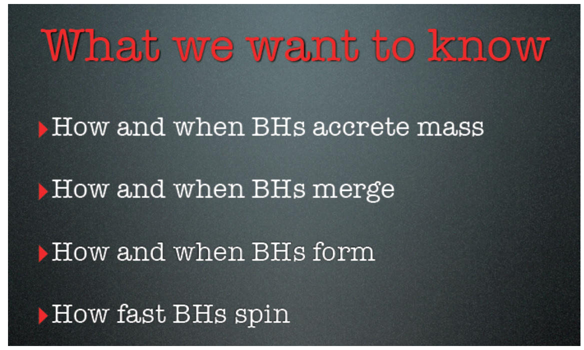
If these galaxies had modest black holes, and if the black holes also merged, one could grow the supermassive black holes that lie in most large galaxies observed today.

This process would produce strong gravitational radiation which is the goal of the LISA mission

- Alternatively (or in parallel) we know that BHs are growing via accretion- e.g. **see AGN.**

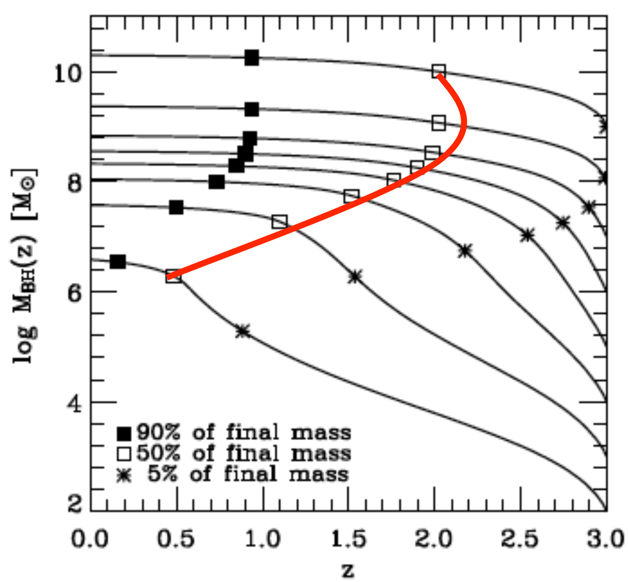
Constraints on Growth of Black Holes

- To calculate how much mass has been accreted by black holes over cosmic time we need to know how they have grown (Soltan 1982)
  - that is measure the number per unit volume per unit time per unit mass.



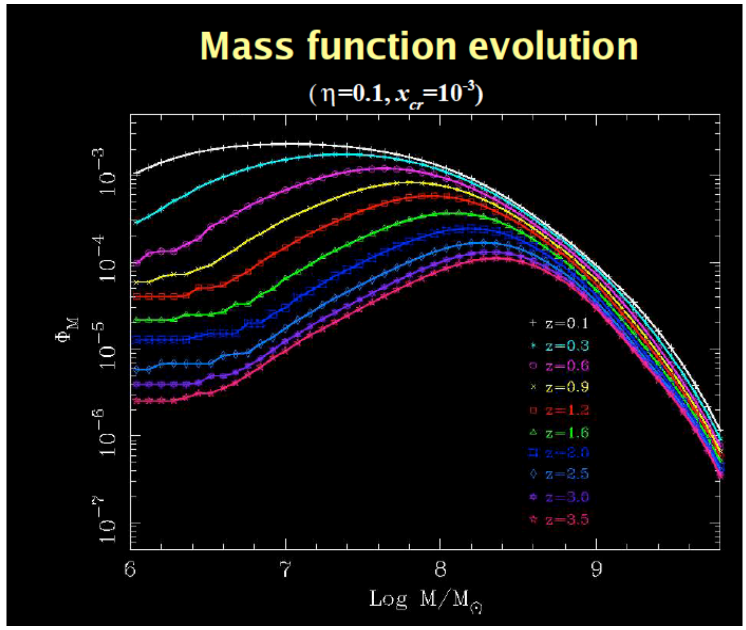
One realization of BH growth

- Big BHs form in deeper potential wells ⇨ they form first.
- Smaller BHs form in shallower potential wells ⇨ they form later and take more time to grow.
  - Marconi 2003, Merloni 2004

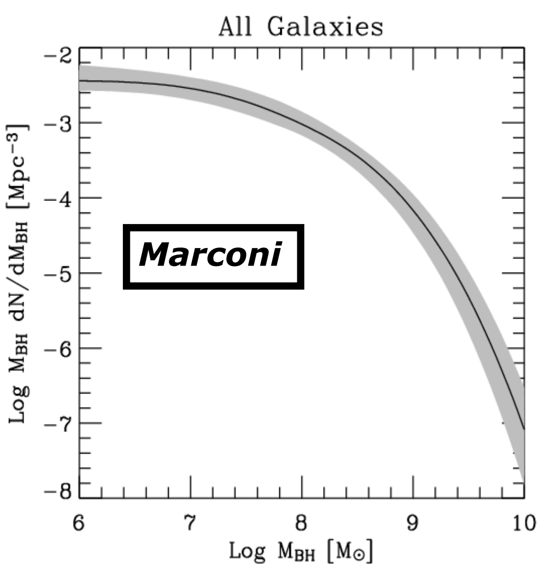


Transform to Mass Growth

- Take accretion rate and some model of initial BH mass distribution and watch them grow (Merloni et al 2006)
- Notice 'down sizing' big black holes grow first and small black holes later



The local Black Hole Mass Function



Marconi et al. 2004

- Convolve Galaxy Luminosity functions with M_{BH}-L_{bul} and M_{BH}-σ to obtain the local BH mass function.
  - M_{BH}-L_{bul} and M_{BH}-σ provide consistent BH mass functions provided that dispersions are taken in to account (shaded area indicates uncertainties)

$\rho_{BH} \sim 4.1^{+1.9}_{-1.4} \times 10^5\ M_\odot\ Mpc^{-3}$

(cf. Merritt & Ferrarese 2001, Ferrarese 2002, Shankar et al. 2004)

- In summary: $3\text{-}5 \times 10^5\ M_\odot\ Mpc^{-3}$ (see Ferrarese & Ford 2005 for a review)

Sizes and Time Variability (see Begelman, Fabian and Rees 2008, Fabian and Rees 1979)

- Assume each emitting region has a size ℓ' in its co-moving frame and is causally connected over a time $\Delta t'$ -- implying $\ell' < c\,\Delta t'$
- In the laboratory frame the time scale is dilated to $\Gamma\Delta t'$ ($\Gamma=1/\mathrm{sqrt}(1-\beta^2)$; $\beta=v/c$
- From an observers point of view the duration is reduced by $1/(1-\beta\cos\theta)$- in the limit $\beta\sim1$ and $\theta<1/\Gamma$ this is $\sim2\Gamma^2$
- **Thus a observed time scale, t_{var} gives a length scale $\ell' < c\, t_{var}\Gamma$**

- Generalized Efficiency argument (similar to the Eddington limit)
- the mass required to produce a total amount of energy $E=\Delta L\Delta t=\varepsilon Mc^2$ (ε is the efficiency of converting matter to energy)
- This is related to the optical depth τ by $M=4R^2\tau m_p/\sigma$ and the emitted photons emerge on a time scale $\Delta t=R/c(1+\tau)$ − then minimize Δt for a given mass M

  giving $\Delta L<\varepsilon c^2\,\Delta t m_p/\sigma$
- which for the Thompson cross section and 10% efficiency gives

  $\Delta L<2\mathrm{x}10^{41}\varepsilon_{0.1}\Delta t$ ergs/sec