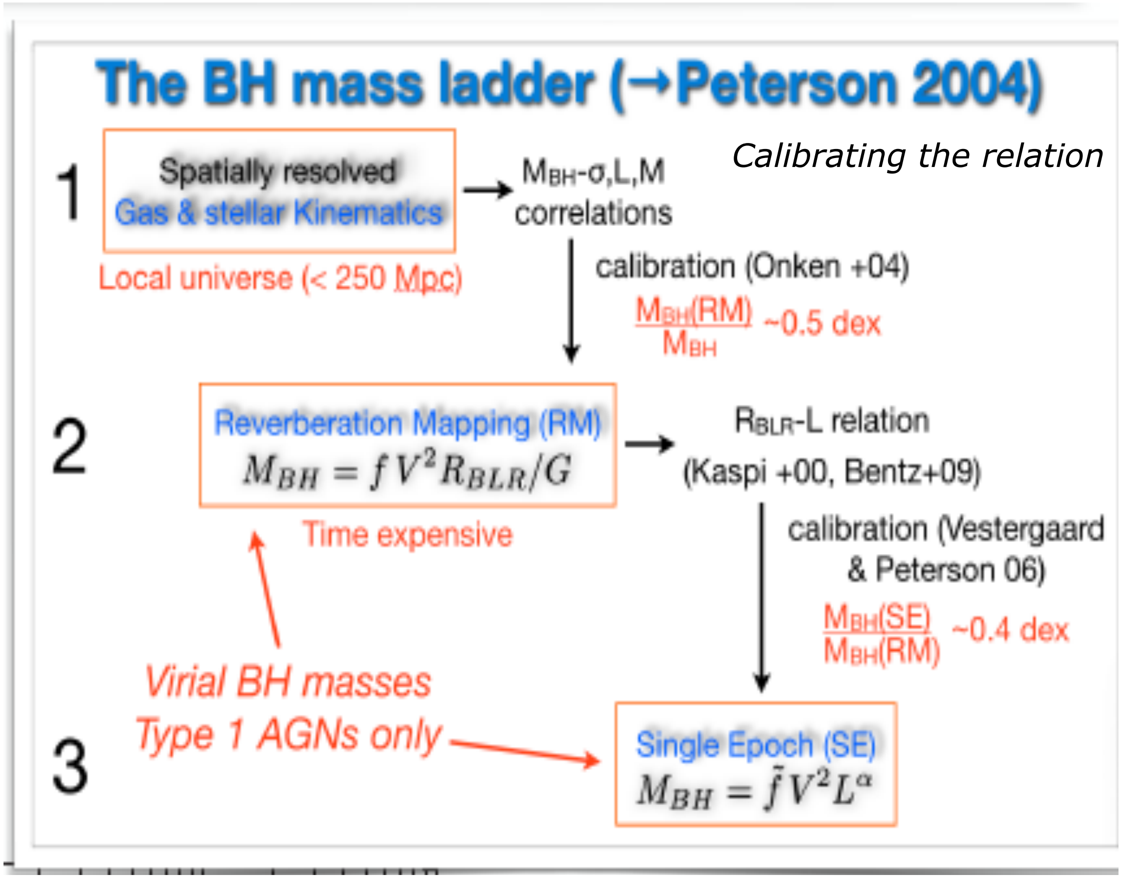
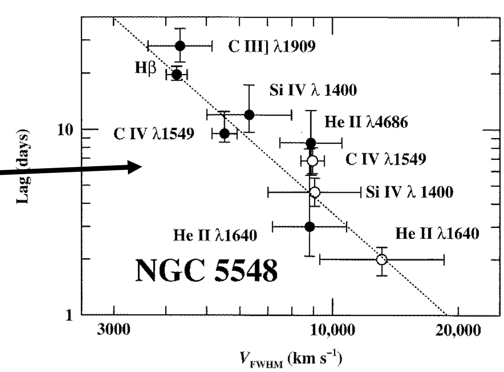


What is Observed??

- 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

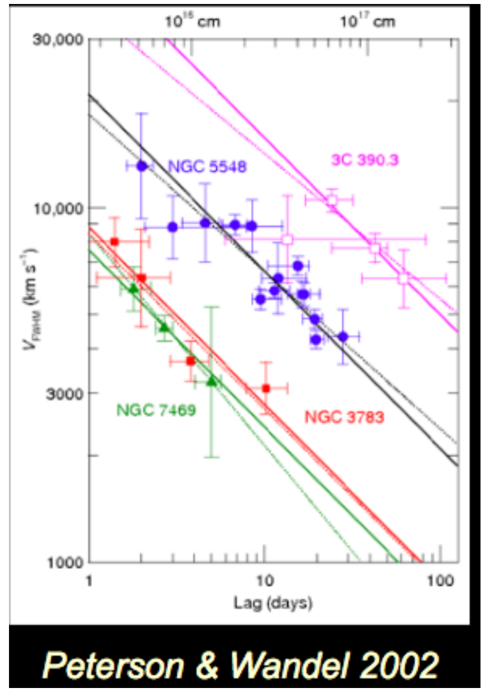
  ($v \sim r^{-1/2}$)



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

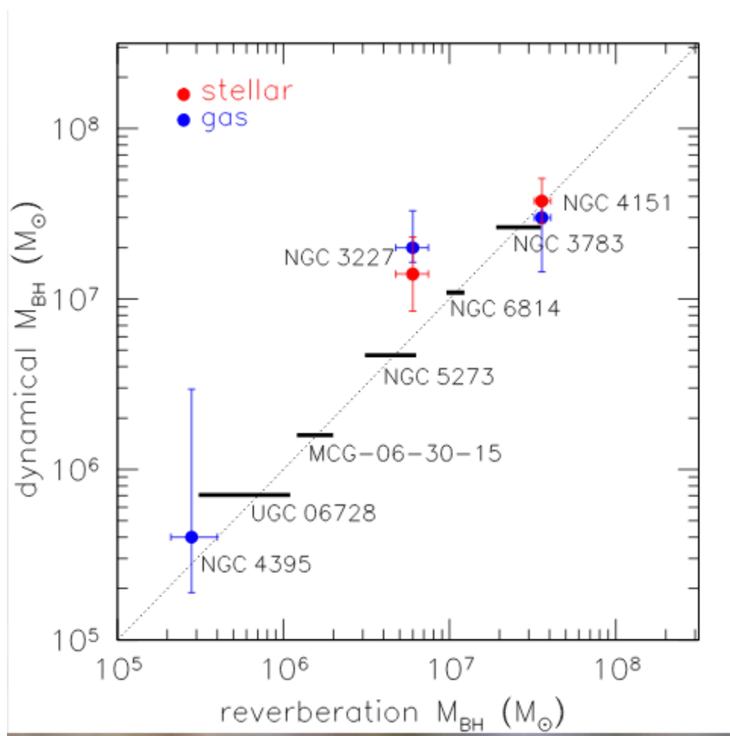
What is Observed??

- Relationship between velocity and time lag
- Such data exist fora few sources



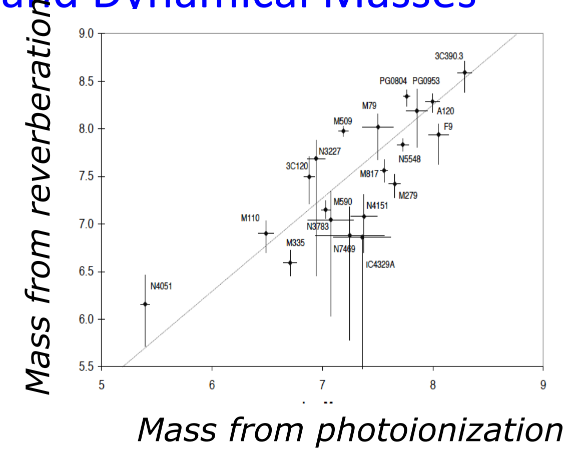
Comparison of Dynamical and Reverberation masses

- Comparison gives the 'fudge' factor in
- $M = f\sigma^2 L^{0.5}$



Reverberation Masses and Dynamical Masses

- **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 use the ionization parameter ξ 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 measure 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}

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

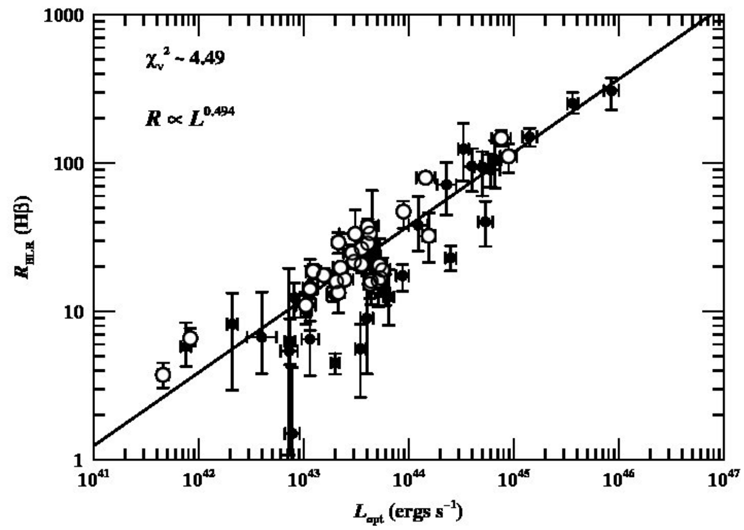
ξ is the ionization parameter (also sometimes called U)

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

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

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

R_{BLR}



Optical luminosity

Spatially Resolved BLR !!!

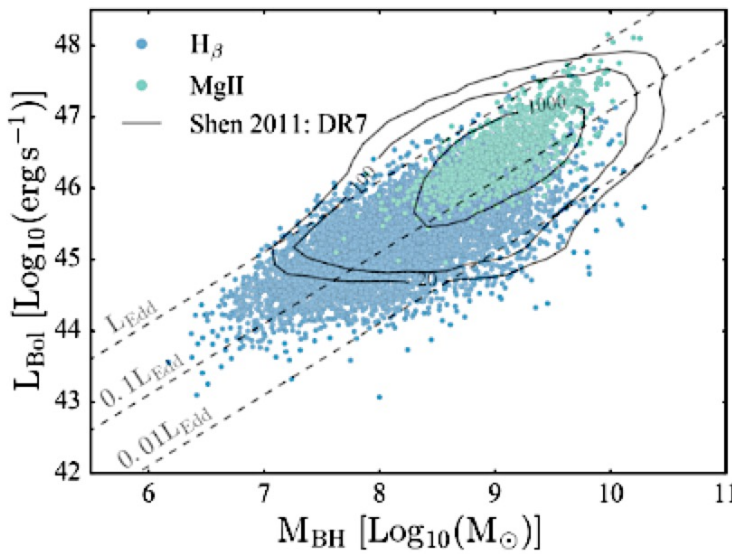
- Gravity data for 3C273

"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 $f = GM_{BH}/(v^2 R_{BLR})$, 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; $M_{BH}/M \approx 2.0 \times 10^{-3}$

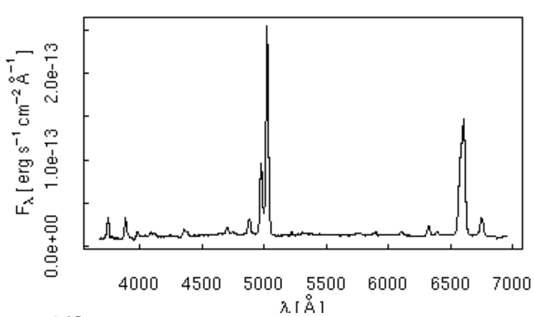
Black Hole Masses

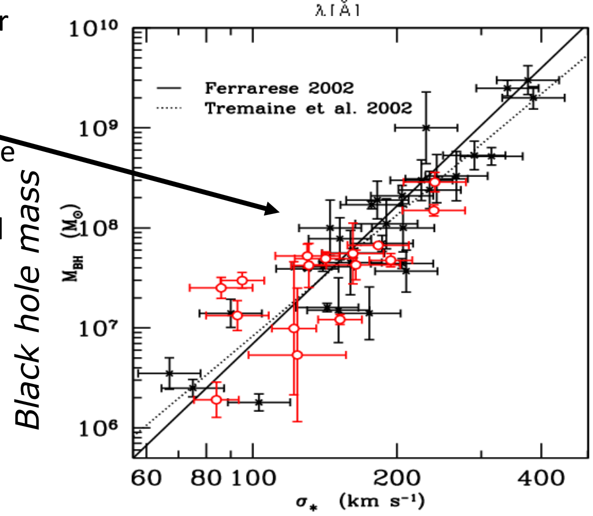
- Use of single epoch spectral masses gives a very large sample.
- Confirms the 'existence' of the Eddington limit (!) Coffey et al.2019



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 broad line velocity or continuum 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.





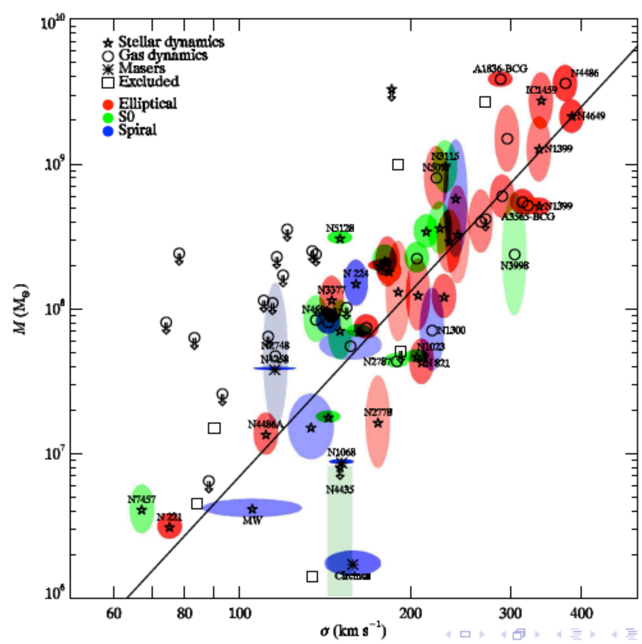
Velocity dispersion of stars in the bulge

And Finally

- Correlations between M_{BH} and galaxy properties

Mass of Black Hole Compared to Velocity Dispersion of Spheroid

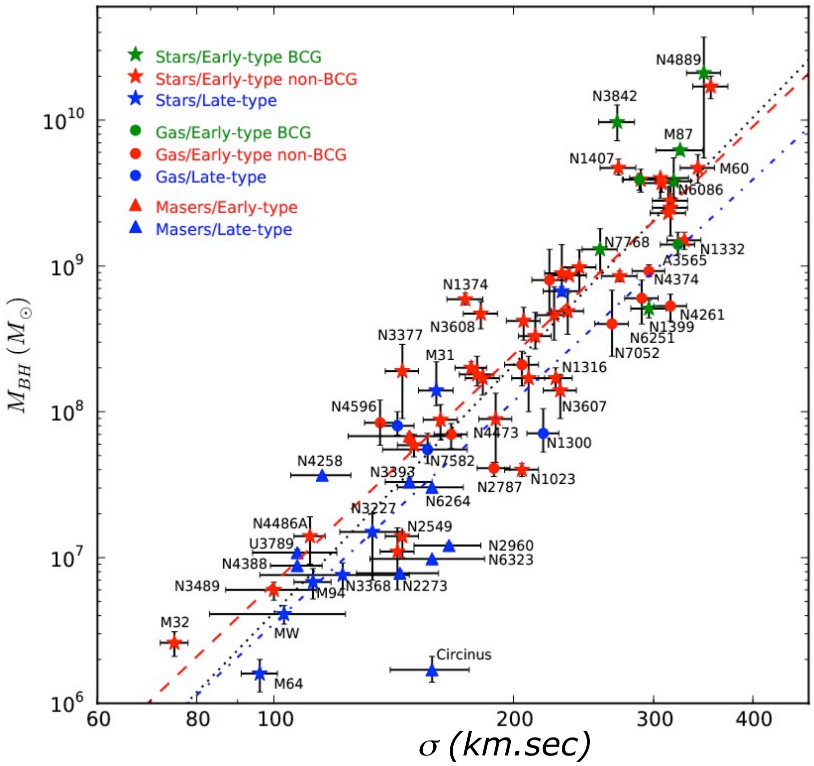
- Sample of non-active galaxies compare mass of black hole (derived later) with velocity dispersion of stars
- Very high detection rate of BHs in 'normal' galaxies- both spheroids and disks (notice the upper limits)

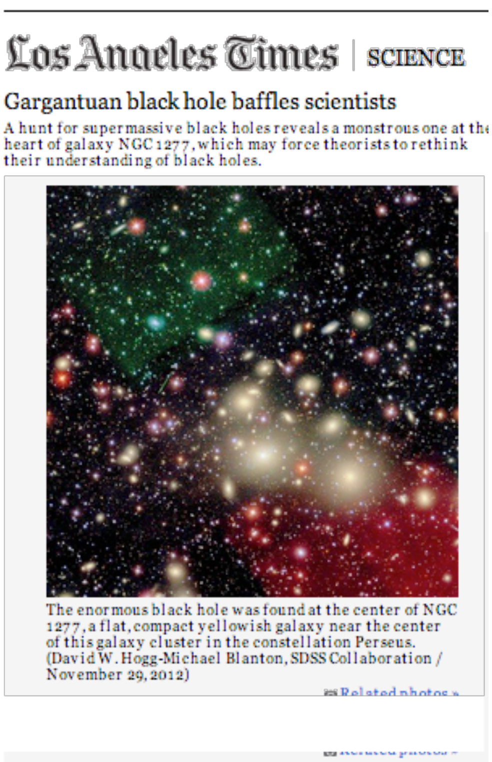


Gultekin 2009

M-Sigma relation

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




Los Angeles Times | SCIENCE

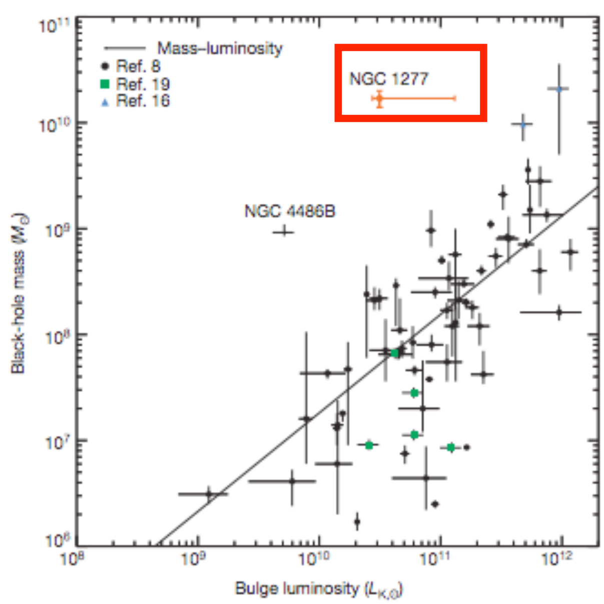
Gargantuan black hole baffles scientists

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 »

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)

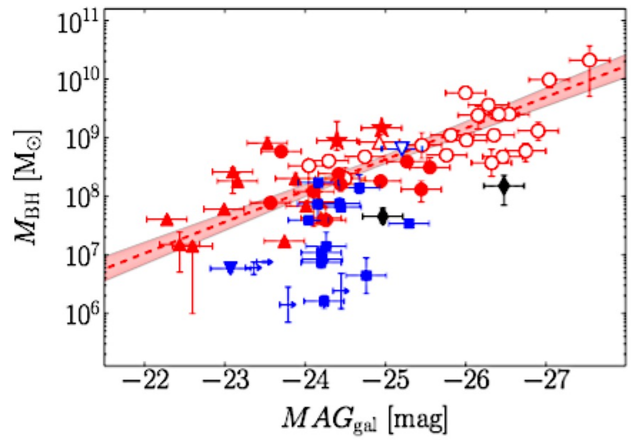


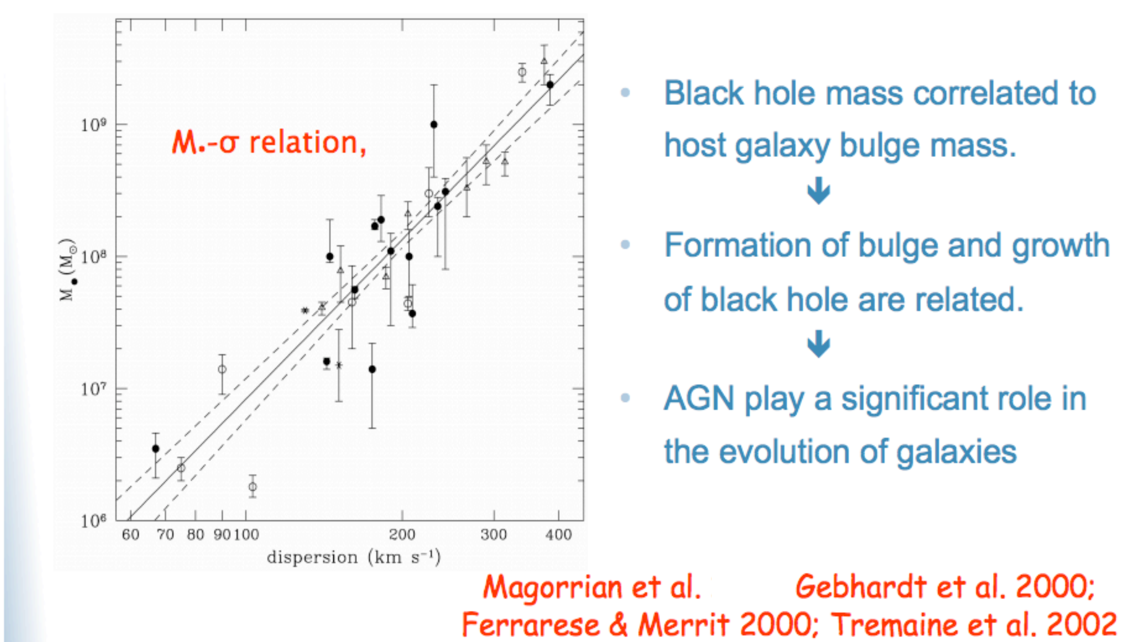
FIG. 1.— Black hole mass plotted against 3.6 μm galaxy absolute magnitude. Symbols are coded according to the galaxy morphological type: red circle = E, red star = E/S0, red upward triangle = S0, blue downward triangle = S0/Sp, blue square = Sp, black di-

- Acronym translation

ETG= ellipticals

LTGs= spirals

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



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

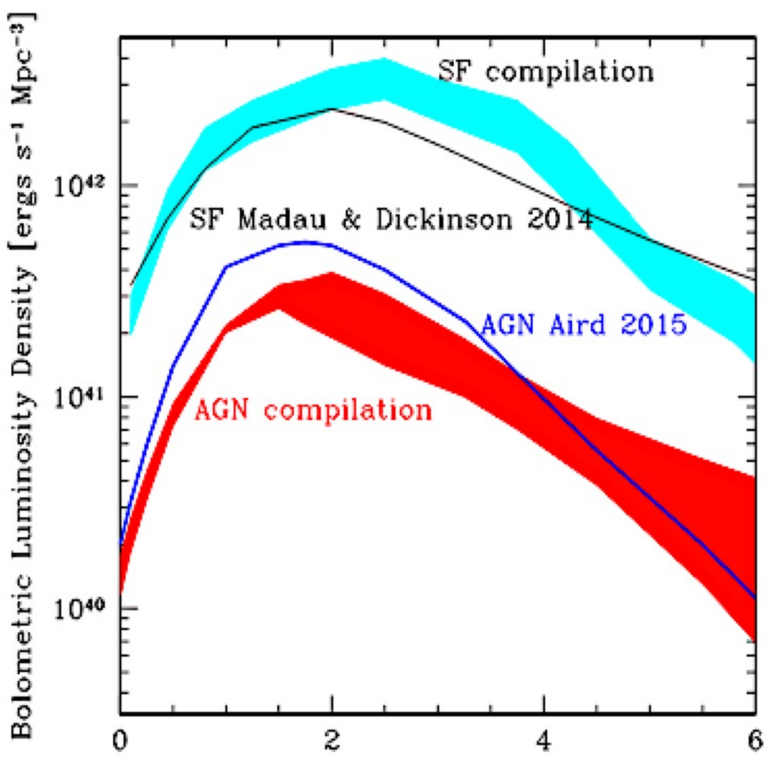
Problems with the Formation of the Universe

- 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
- What else is required?
  - FEEDBACK-The influence of objects on the universe (stars and AGN)
  - Stars don't have enough energy for massive galaxies
  - So it has to be AGN
    - How ?
    - Where ?
    - When ?

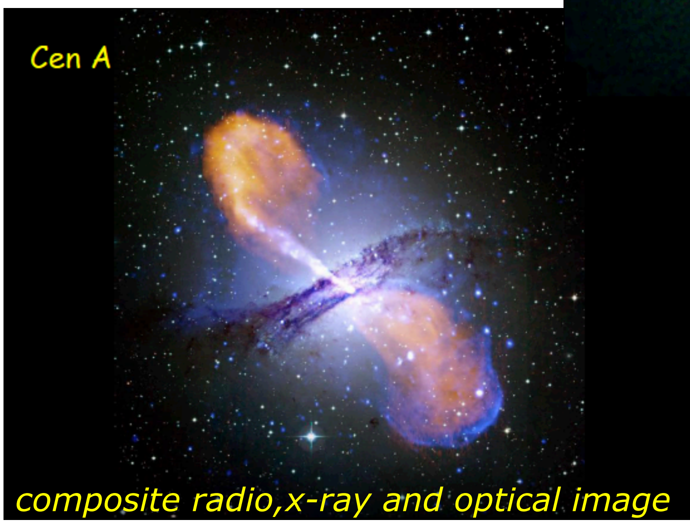
Paradiso Canto 31

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)

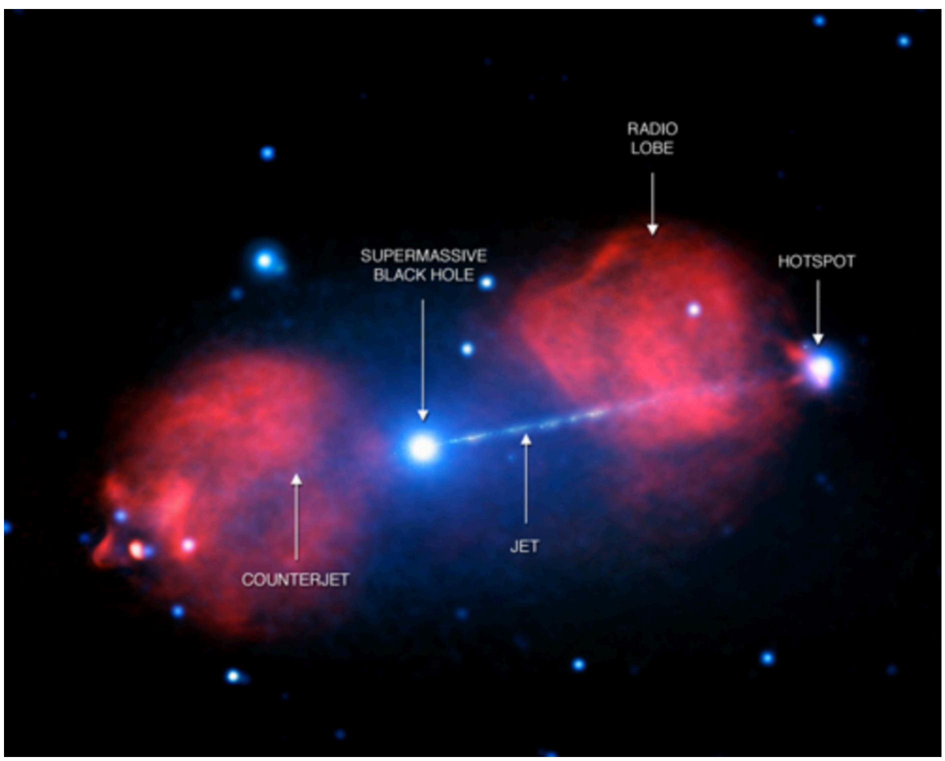


Effect of AGN on their environment



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

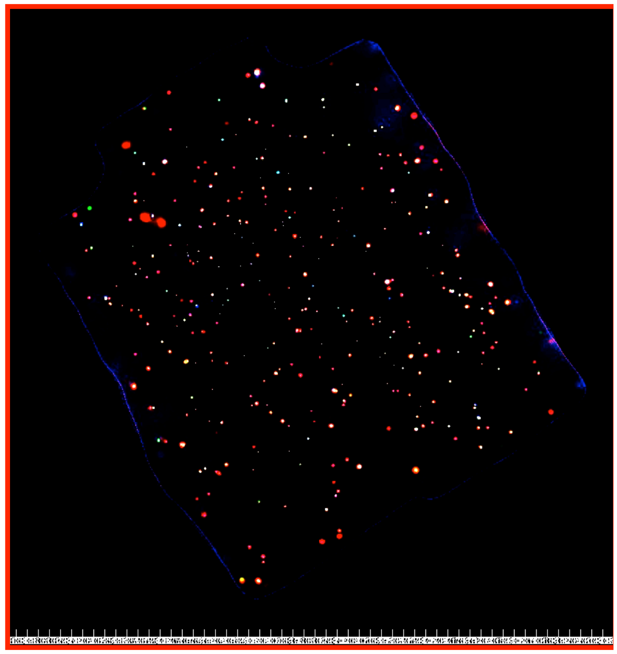
But at ***z=0*** *only ~10% are 'active'*



Pictor A: X-ray in blue, radio in red

The History of Active Galaxies

- Active Galaxies (AKA quasars, Seyfert galaxies etc) are radiating massive black holes with $L \sim 10^{8}$-$10^{14} L_{sun}$
- 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.
- See The Co-Evolution of Galaxies and Supermassive Black Holes: Heckman and Best ARA&A Vol 52 2015



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

Luminosity Function

- Large optical surveys (Boyle et al 2000) found that $\phi(L)$ can be described by 'luminosity' evolution)
- e.g. $L(z)=L(0)\exp(k\tau)$
  - where τ is lookback time and k is a constant

$\phi(L)$ has the form

$\phi(L,z)=\phi(L)/\{(L/L^*)^a+(L/L^*)^b\}$

where a and b are constants and L* is a fiducial luminosity

e.g. a broken power law such that the slope is flat at low L and steep at high L with a 'break' at L*

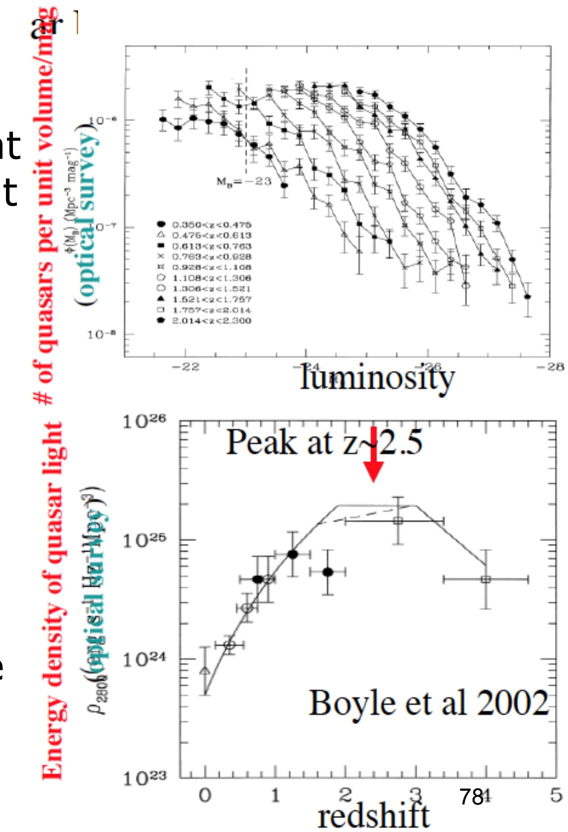
The luminosity function is the number of AGN per unit comoving volume, per unit luminosity:

$$\frac{d\Phi(L_X,z)}{dLogL_X}=\frac{dN(L_X,z)}{dV_c\,dLogL_X}$$

However a large fraction of AGN are missed in optical surveys

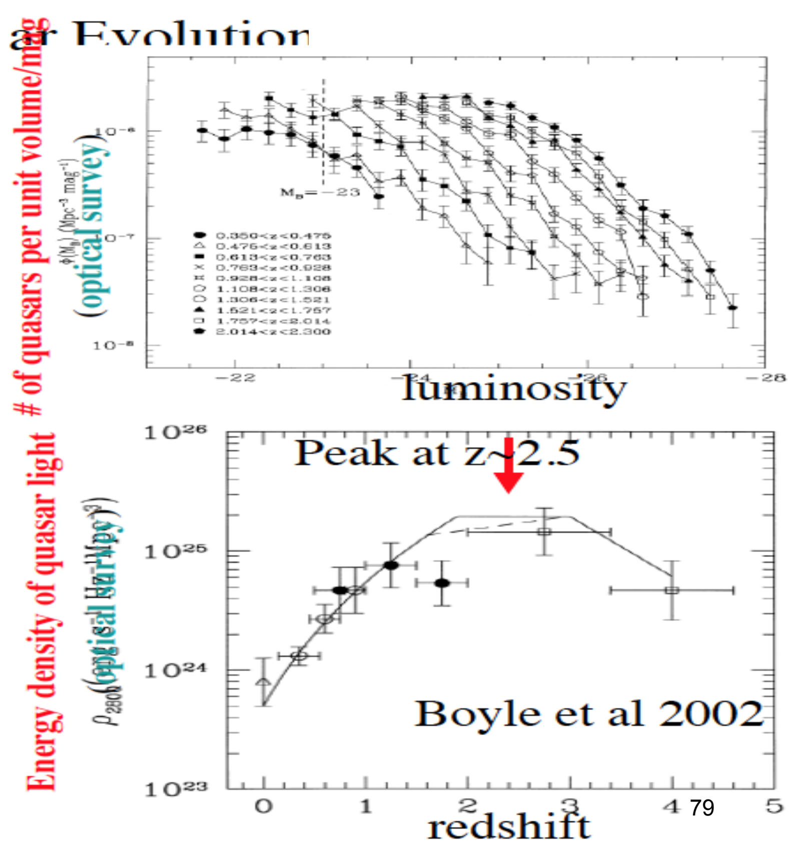
A Little History

- In the1960-70s (Schmidt 1968-1978) discovered that the number of AGN per unit volume per unit luminosity (f(L), the luminosity function) **changed strongly with redshift**
  - Schmidt used 'complete' samples (e.g. a flux limited sample in which all the objects were identified and had redshift)-original sample had 33 sources (!))



AGN evolution

- **AGN are more numerous and luminous in the past** with the numbers rising as $(1+z)^N$,N~4

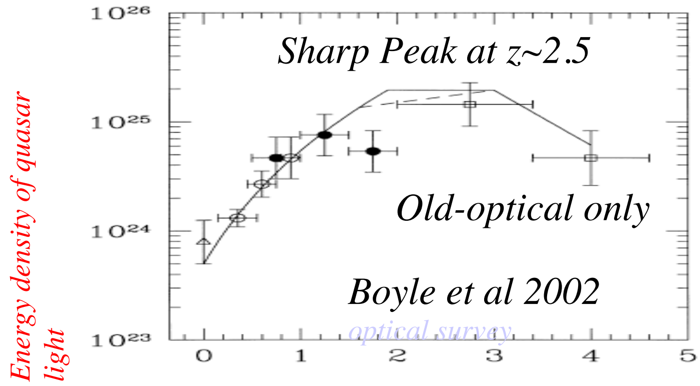


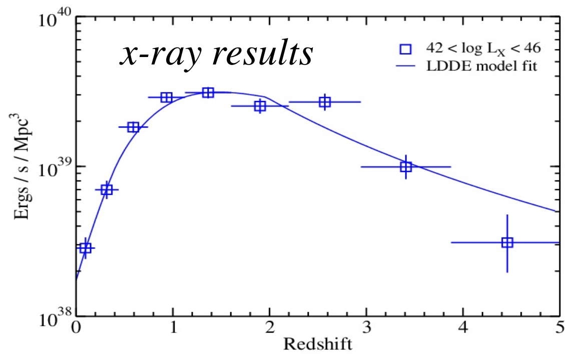
AGN Evolution

see Evolution of active galactic nuclei A. Merloni S. Heinz 1204.4265v1.pdf

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

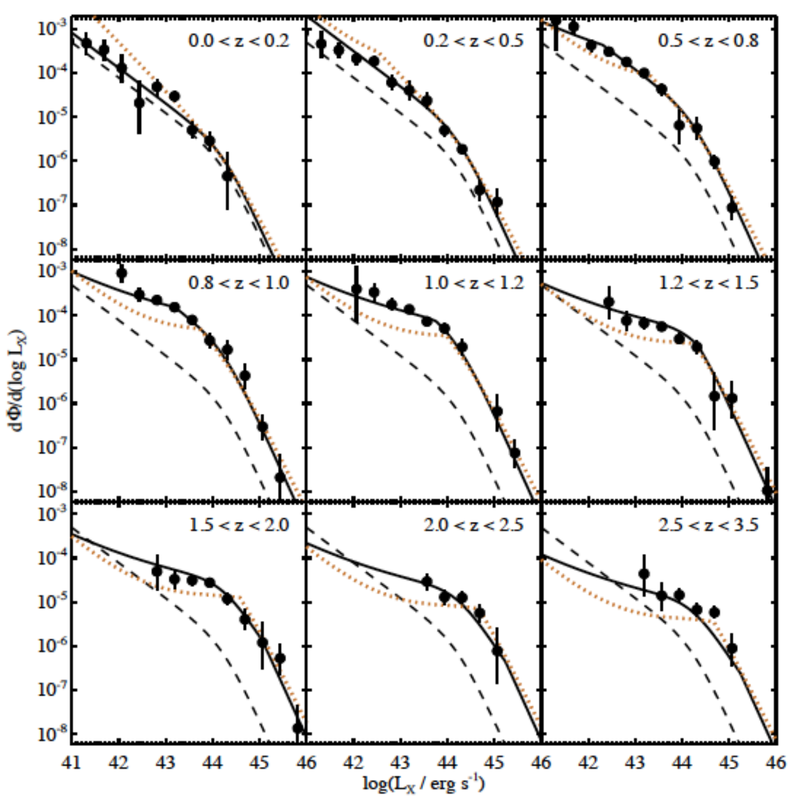




Yencho et al 2009- xray survey

- Evolution in X-ray Luminosity Function of AGN vs cosmic time
  - #/Volume/ luminosity
  - *In each plot the dotted grey line is the z=0 function*

Aird et al 2009 (ignore red line)

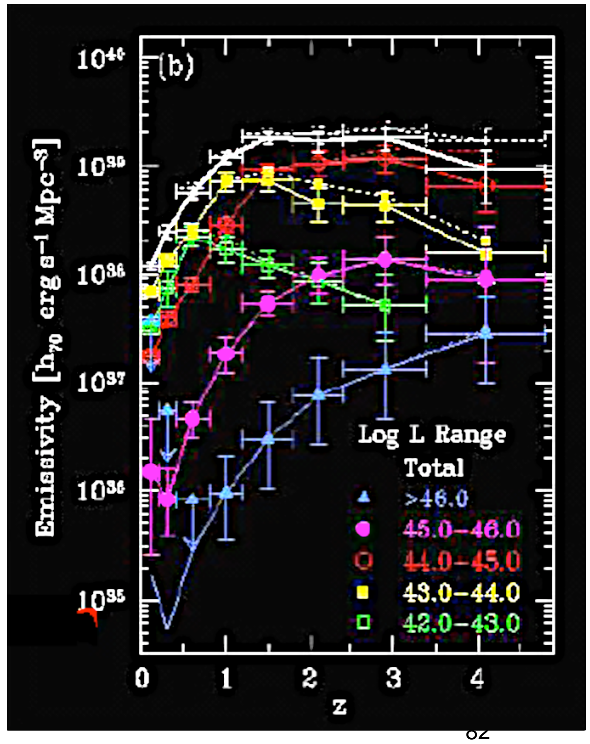


Luminosity function vs z

Transform Luminosity Function to Energy Emissivity

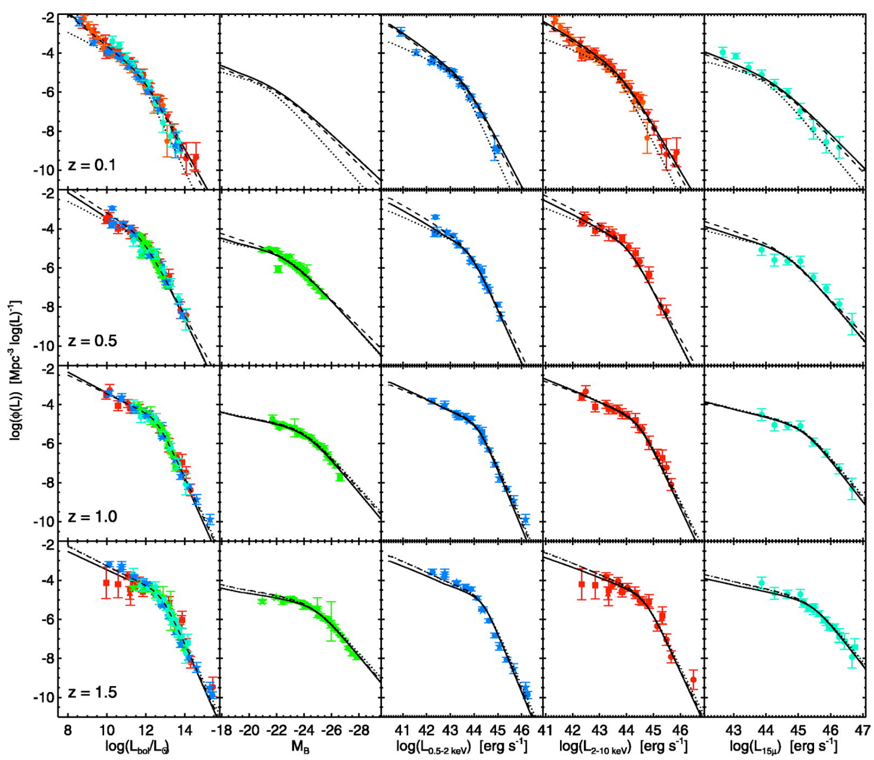
- Integrate the luminosity function in redshift shells
- Notice downsizing: more luminous objects are more dominant at high redshift and evolution is a function of luminosity
- E_{AGN}~1.4 +/- 0.25 x10^{61} erg per galaxy since z = 3. (e.g. ~10% of all the energy emitted by all stars over the Hubble time)
- Average AGN luminosity density of L_{AGN} ~10^{57} erg Mpc^3 /Gyr (Bluck et al 2011)

(see Longair fig 23.8 and accompanying text)



Brandt and Hasinger 2005 ARAA

- Hopkins et al 2007 compilation of the AGN luminosity function in different redshift shells and for different wave bands.



L_{Bol} L_{opt} $L_{0.5-2}$ L_{2-10} L_{IR}

Why Backward??

- Cold Dark Matter (CDM) theory of structure formation says that
  - small things form first
  - merge together over time to form big things
- Expect massive (luminous)BHs to appear later in the universe than smaller mass BHs

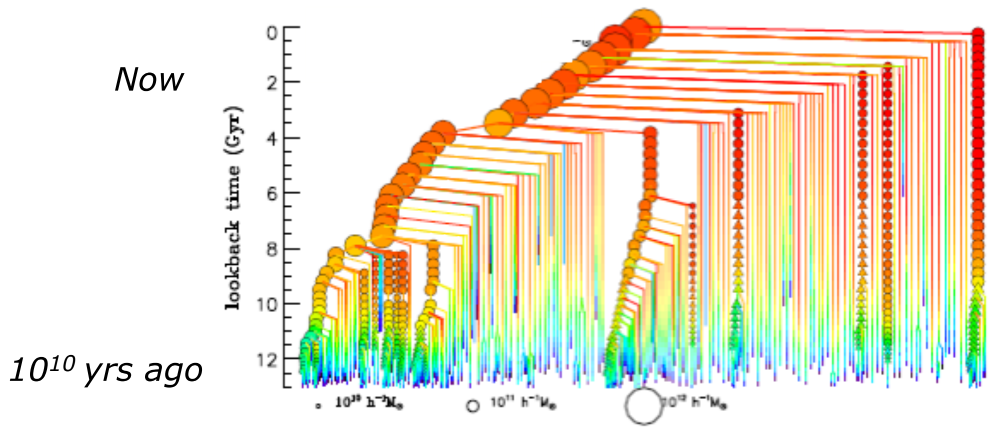
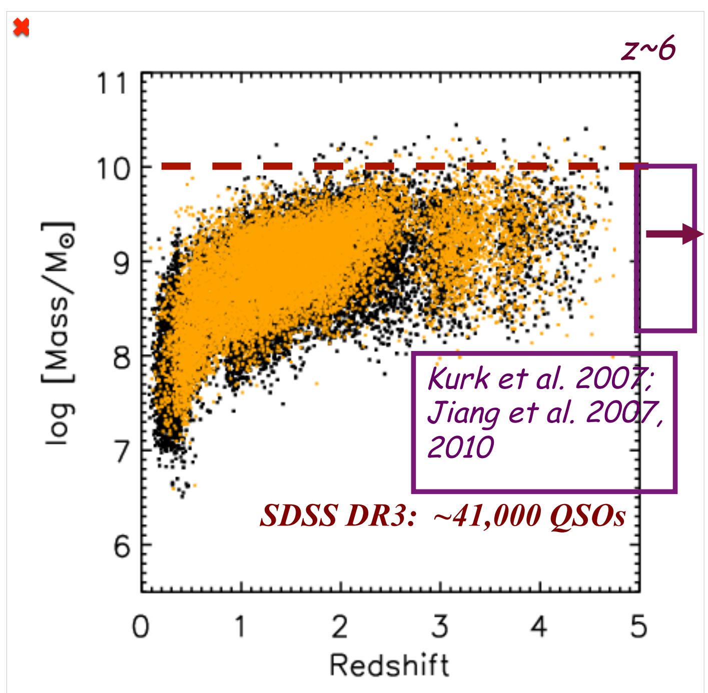


Figure 1. BCG merger tree. Symbols are colour–coded as a function of B - V colour and their area scales with the stellar mass. Only progenitors more massive than $10^{10}\ M_\odot\ h^{-1}$ are shown with symbols. Circles are used for galaxies that reside in the FOF group inhabited by the main branch. Triangles show galaxies that have not yet joined this FOF group.

Masses of Distant Quasars- *M. Vestergaard*

- *Using this technique for a very large sample of objects from the Sloan Digital Sky Survey (SDSS)*
- *Ceilings at* $M_{BH} \approx 10^{10} M_\odot$
- $L_{BOL} < 10^{48}$ *ergs/s*
- $M_{BH} \approx 10^9 M_\odot$ -



(DR3 Qcat: Schneider et al. 2005)

(MV et al. in prep)

Eddington Limit and Growth Rate

- Balance the accretion rate onto the BH against the Eddington limit (λ)
- $dM_{BH}/dt=L_{acc}/\varepsilon c^2 \leq 4\pi G m_p M/\varepsilon c\sigma_t$
- solution is $\mathbf{M=M_o e^{t/\tau}}$
- where $\tau=\varepsilon c\sigma_t/4\pi G m_p \sim 45\varepsilon_{0.1}10^6$years, where the efficiency of converting mass to energy $\varepsilon \sim 0.1$ (McLure & Dunlop (2004)) and $\lambda=1$ (remember a Schwarschild BH $\varepsilon \sim 0.057$, Kerr $\varepsilon=0.423$)
- see http://www.astro.yale.edu/coppi/pubs/bhgrowth4.pdf for a discussion of the issues.

Limits to Growth

Eddington implies limit on *growth rate of mass*: since

$$\dot{M} = \frac{L_{acc}}{\eta c^2} < \frac{4\pi G M m_p}{\eta c \sigma_T}$$

we must have

η= efficiency of converting mass to energy

$$M \leq M_0 e^{t/\tau}$$

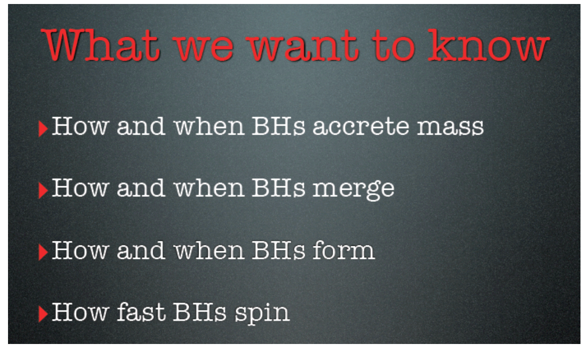
where

$$\tau = \frac{\eta c \sigma_T}{4\pi G m_p} \approx 5 \times 10^7 \, yr$$

is the *Salpeter timescale*

Constraints on Growth of Black Holes- Longair 19.4

- 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 and the energy they emit
  - Adding up the total quasar light and assuming an efficiency of ~0.1 implies that virtually all galaxies should have massive black holes with <M>~10^7 M



The average density of mass in the Universe in the form of massive black holes is determined by integrals over the observed number– flux density relation for quasars and the observed redshift distribution in each flux density interval.

Eddington Limit and Growth Rate

- If SMBH grow primarily by accretion then the integral of the accretion rate across cosmic time should be equal to their present mass. (**Soltan** 1982 MNRAS.200..115, 770 citations)-
- Integrating the bolometric luminosity function -compare this to the present day mass of black holes integrated over all objects.
- $L_{bol}=\varepsilon(dM_{acc}/dt)c^2= \varepsilon(dM_{BH}/dt)c^2$
- dM_{acc}/dt=accretion rate
- dM_{BH}/dt= BH growth rate
- ε=efficiency of converting mass to energy
- black hole accretion rate (BHAR) density is (Merloni and Heinz 2011)

$$\Psi_{BH}(z) = \int_0^\infty \frac{(1-\epsilon_{rad})L_{bol}}{\epsilon_{rad}c^2}\phi(L_{bol}, z)dL_{bol}$$

- requires no assumptions beyond the identification of the ultimate quasar power source as black hole accretion
- the directly measured quasar radiation density in the Universe today requires that a corresponding amount of mass per unit volume must have been accreted (assuming that 'light' represents all the energy
- Neither the absolute luminosities of individual quasars(hence cosmological models,H_0 values,beaming factors,and even the attribution of redshifts to the cosmic expansion)affect the result

Choksi and Turner 1992

Total Lifetime of active BHs

- M_{BH} e-fold time (t_{Salp}Salpeter):

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

- To grow a BH SEVERAL t_{Salp} needed: 7 t_{Salp} 10^3 ⇨ 10^6 $M_\odot$

  14 t_{Salp} 10^3 ⇨ 10^9 $M_\odot$
- t_{Salp} independent of M_{BH}, longer t_{BH} at lower M_{BH} indicates a more difficult growth of smaller BHs (feedback?).
- Estimated AGN lifetimes range from 10^6 to 10^8 yr (AGNs from SDSS imply lifetimes > 10^8 yr; Miller et al. 2003).

ε= efficiency

λ= Eddington ratio

$$\langle M_{bh}\rangle = 1.6 \times 10^7 \left(\frac{F_{bol}}{10F_B}\right)\left(\frac{\langle 1+z\rangle}{3}\right) \times \left(\frac{h}{0.75}\right)^{-3}\left(\frac{\xi}{0.1}\right)^{-1} \quad M_\odot \text{ per } L^* \text{ galaxy}.$$

'Soltan' Argument

- If supermassive black holes grow primarily by accretion then the integral of the accretion rate across cosmic time should be equal to their present mass.
- Integrating the bolometric luminosity function and assuming a conversion factor, ε, from mass to energy one can compare this to the present day mass of black holes integrated over all objects

$L_{bol}=\varepsilon(dm_{acc}/dt)c^2=\varepsilon(dm_{BH}/dt)c^2(1-\varepsilon)$

- dm_{acc}/dt=accretion rate
- dm_{BH}/dt= BH growth rate

The higher the conversion factor for converting energy to mass the smaller the predicted BH mass at a given redshift is for a fixed observed luminosity

ε derived this way is independent of the cosmological model

At z=0 the observed BH mass density is ~4x10[5] $M_\odot/Mpc^3$

Utilizing the best estimate of evolution of luminosity vs redshift this gives ε=0.06, marginally consistent with a non-spinning BH

Highest Redshift Quasars

- 2 curves
  - Mass of a BH growing at the Eddington limit from z=35 with initial mass 10 and 100 M
  - (1911.05791.pdf Inayoshi, Visbal,Haiman)