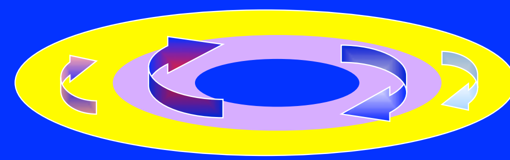
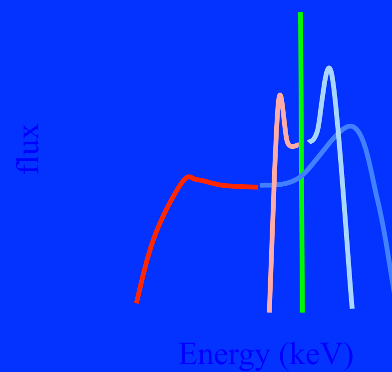
# Relativistic effects- C. Done

- Relativistic effects (special and general) affect all emission (Cunningham 1975)
- Hard to easily spot on continuum components
- Fe K$\alpha$ line from irradiated disc – broad and skewed! (Fabian et al 1989)
- Broadening gives an independent measure of Rin – so spin if ISO (Laor 1991)
- Models predict increasing width as go from low/hard to high/soft states

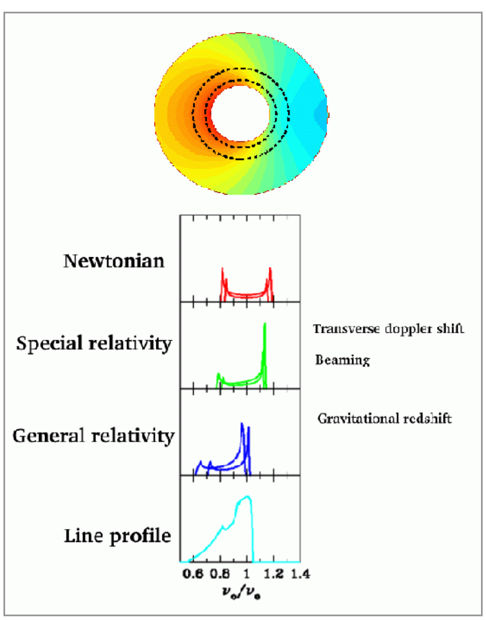




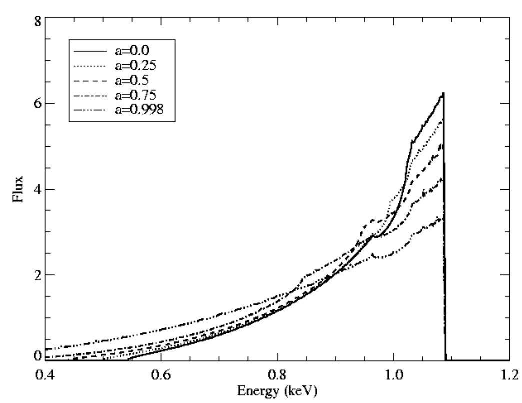

Fabian et al. 1989



Relativistic effects imprint characteristic profile on the emission line…



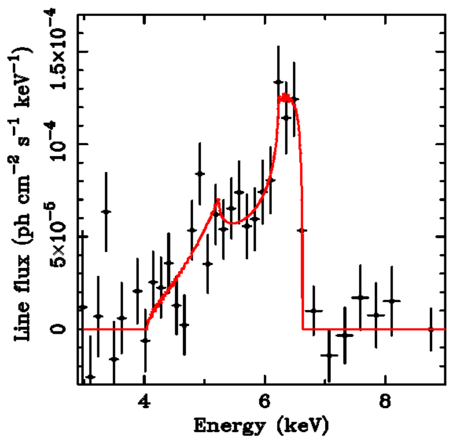

**Andy Young**




*Theoretical line profiles [Laura Brenneman]*

# Observations of relativistic emission lines

- First seen in 1994 with ASCA observatory
- 5 day observation of Seyfert-1 galaxy MCG-6-30-15
- Needed long observation to collect enough photons to form detailed spectrum

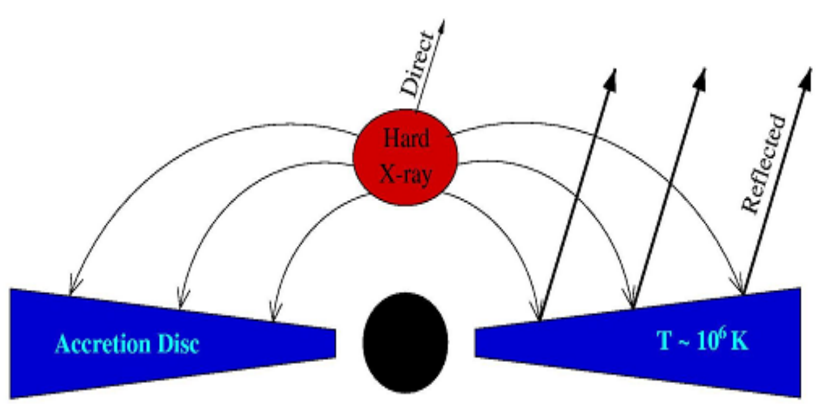



Power-law continuum subtracted
ASCA: Tanaka et al. (1995)

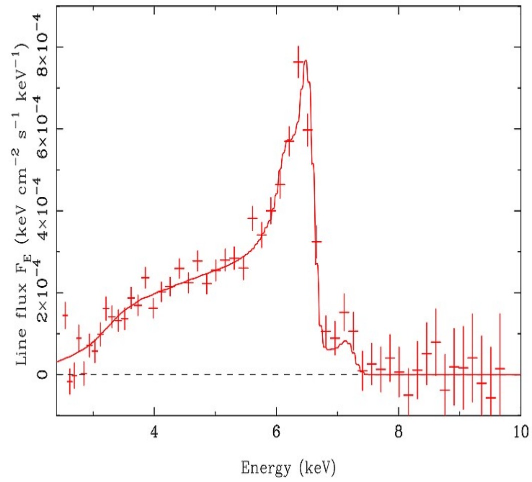


# Relativistic Effects

- Light rays are bent by strong gravity- making the geometry rather complicated
- Do not know 'where' x-ray source is - try to use data to figure it out – e.g. height above disk



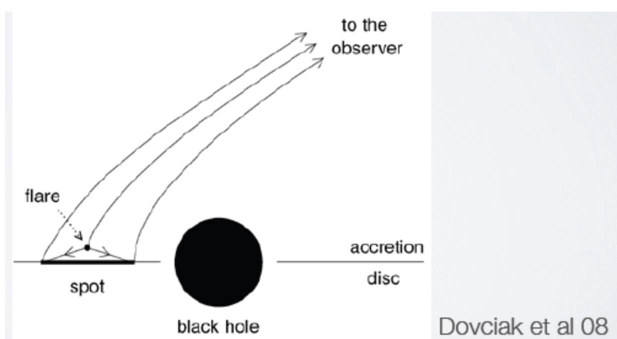
- Modern XMM-Newton observations
- Confirm relativistic line with extreme redshifts
- If no line emission from within ISCO, need to invoke spinning black hole to get strong enough redshifting

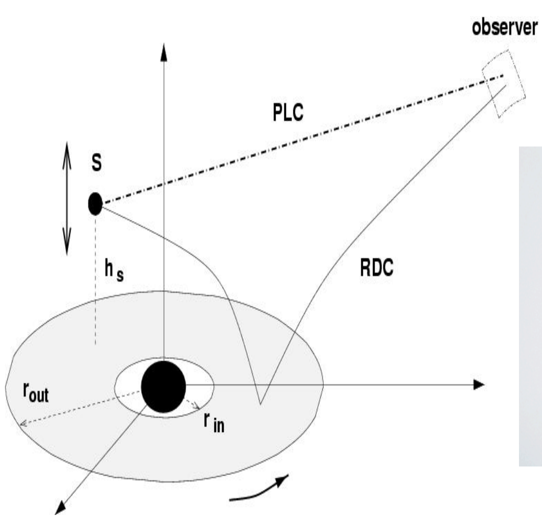


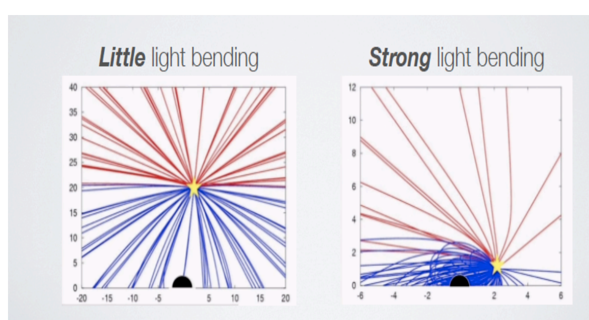

Power-law continuum subtracted
XMM: Fabian et al. (2002)



- if we only knew where the x-rays come from ($h_s \sim r_s$) from time variability arguments

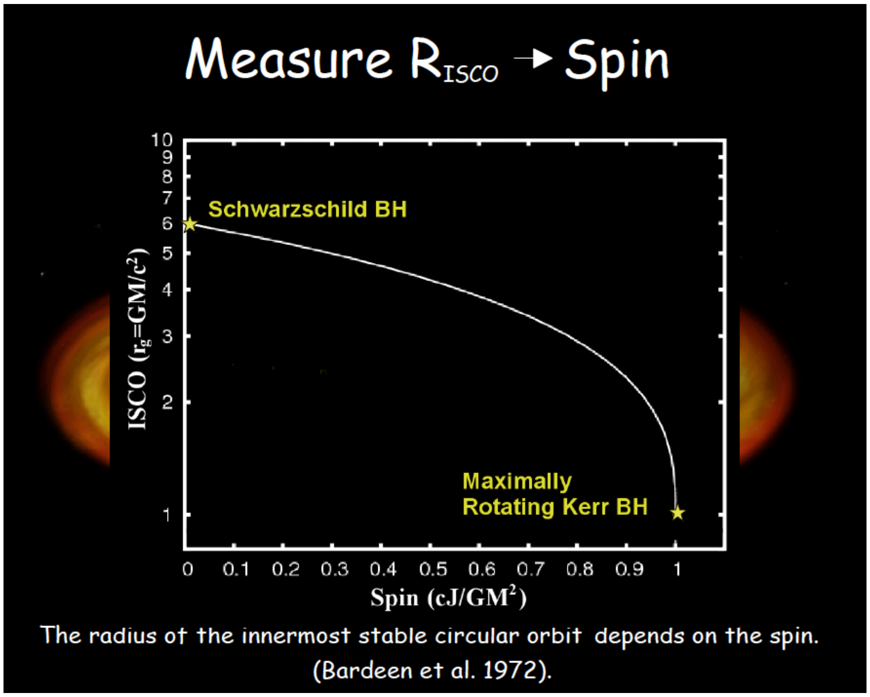


## Reminder- Radius of ISCO depends on Spin

- Spin- is measured in units of c/GM2



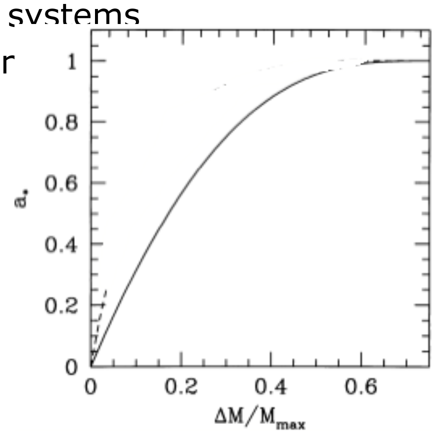



## Why Measure Spin

- BH has only 3 measurable properties Mass, spin, charge.
- Black hole spins affects
  - the efficiency of the accretion processes, hence the radiative output
  - how much energy is extractable from the hole itself
  - the retention of black holes in galaxies
  - gravitational wave signature
  - possible origin of jets.
- Origin of BH Spin
  - natal
  - history

## Spin

- For **galactic black holes**- not enough accretion to account for spin being due to accretion of angular momentum- need to accrete ~3/4 of the mass to spin it up to the maximal spin (see graph- spin vs accreted mass)
- If accreting at the Eddington limit takes a very long time (~$10^8$ yrs)
  - too long for wind fed or Roche Lobe systems
  - too much mass for low mass compar
- **Spin is natal**

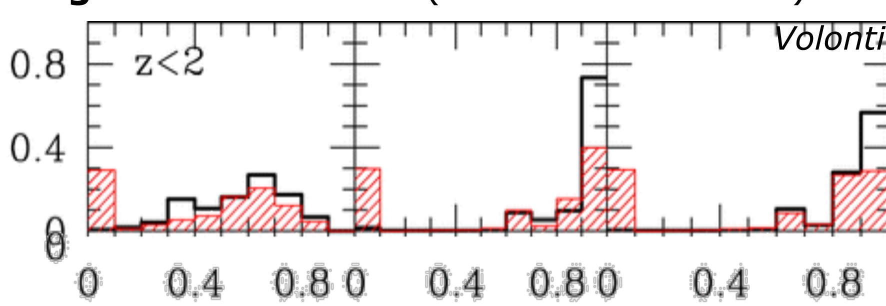



## Spin

- For **supermassive black holes**- If accreting at the Eddington limit (~$10^8$ $M_\odot$ accretes 0.25 $M_\odot$/yr) so takes 4x$10^8$ yrs to double its mass and spin up
- Spin can be due to accretion
- Requires 'organized' accretion of angular momemtum

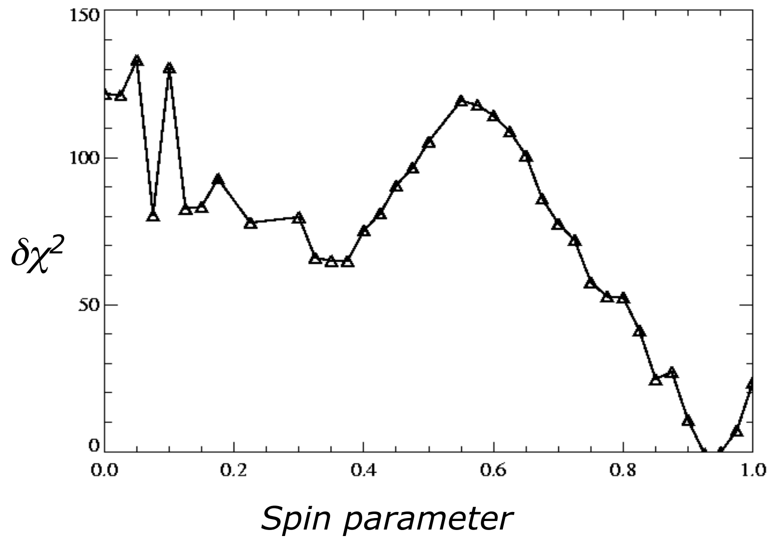
Alternatively spin could be due to **mergers** of black holes (Gravitational waves)

*Volontieri et al 201*




mergers only (left), mergers and prolonged accretion (center), and mergers and chaotic accretion

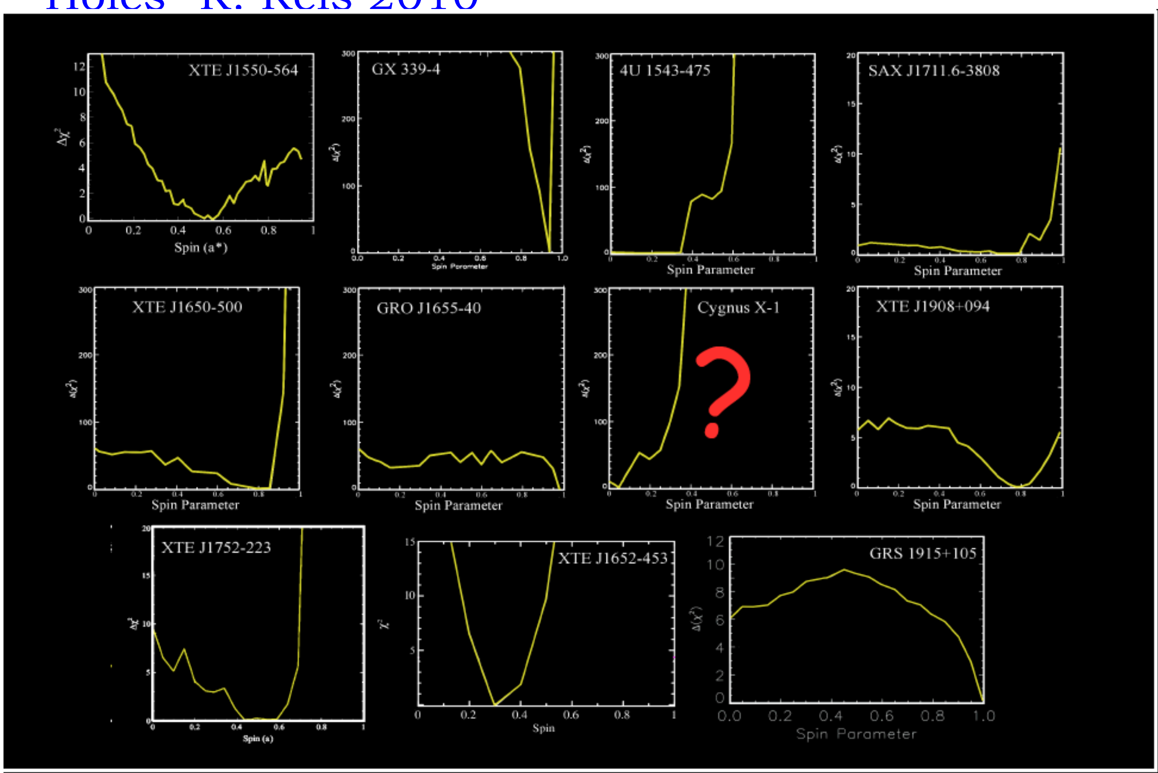
- Applied models to long (350ks) XMM dataset for MCG-6-30-15
  - Data strongly prefers rapidly spinning BH solution
  - a ~ 0.93




**L.Brenneman**



## Present knowledge of spin in Galactic Black Holes- R. Reis 2010



# Constraints on Mass Growth of Black Holes

- As Just discussed 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

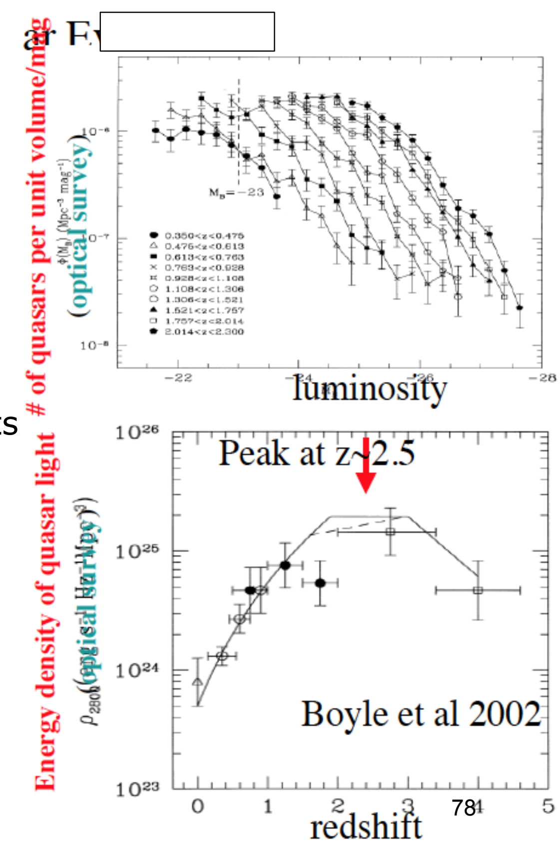
- Alternatively (or in parallel) we know that BHs are growing via accretion.

**See Longair ch 23**



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



## 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

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

where

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

is the *Salpeter timescale*



# The AGN BH Mass Function

## Alessandro Marconi

- Assume accretion onto BH is the powering mechanism of AGN to link $L_{AGN}$ with $M_{BH}$
- $L= \lambda M_{BH}c^2/t_E= \varepsilon(dM/dt)c^2$; alternatively the accreted mass is
  - $M_{BH}=Lt_E/c^2\varepsilon$
- $\lambda$= Eddington ratio; $\varepsilon$= accretion efficiency;

Saltpeter time (e-fold time increase mass)

$t_{saltpeter}=\varepsilon\, t_E/(1-\varepsilon)\, \lambda=4\times10^7$yr for $\varepsilon=0.1$, $\lambda=1$

Or more generally $t_{saltpeter}=4\times10^7\text{yr}\, [(1-\varepsilon)/9\, \varepsilon)]\, \lambda^{-1}$

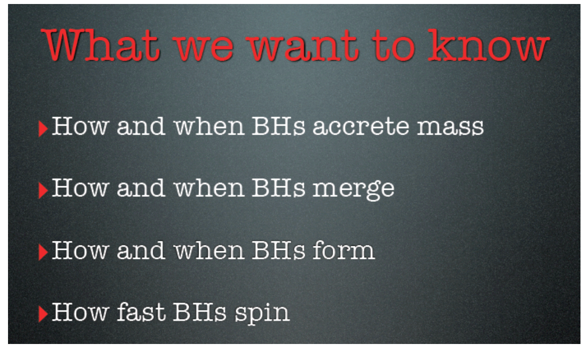
Independent of $M_{BH}$

So to grow from, $10^3 M_\odot$-$10^6$ $M_\odot$ requires 7 $t_{saltpeter}$

So to grow from, $10^3 M_\odot$-$10^9$ $M_\odot$ requires 14 $t_{saltpeter}$

## 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.






## '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 ~$4\times10^{-5}$ $M_\odot/Mpc^3$

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

# Continuity equation for SMBH growth

Need to know simultaneously mass function $\Psi(M,t_0)$
and accretion rate distribution F(dM/dt,M,t) ["Fueling function"]

$$\frac{\partial\psi(M,t)}{\partial t} + \frac{\partial}{\partial M}\left(\psi(M,t)\int \dot{M} F(\dot{\mu},\mu,t)\,\mathrm{d}\dot{\mu}\right) = 0$$

$$\phi(\ell,t) = \int F(\dot{\mu},\mu,t)\psi(\mu,t)\,\mathrm{d}\mu$$

luminosity function mass function

$\mu = Log\, M$

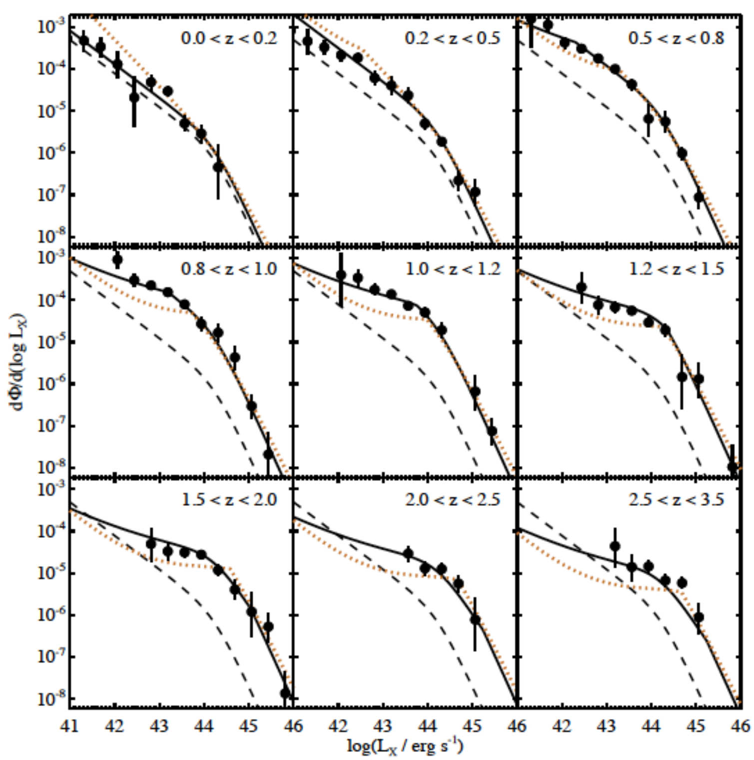
$\ell = Log\, L_{\rm bol}$

$\dot{\mu} = Log\, \dot{M}$

Cavaliere et al. (1973); Small & Blandford (1992); Marconi et al. (2004); Merloni (2004)

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

Aird et al 2009 (ignore red line)

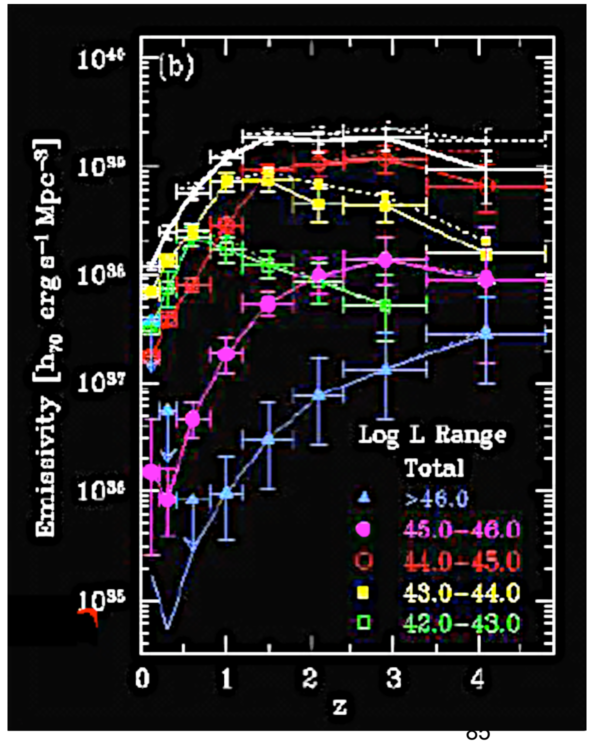



# Luminosity function vs z

## 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 x$10^{61}$ erg <u>per galaxy</u> 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)



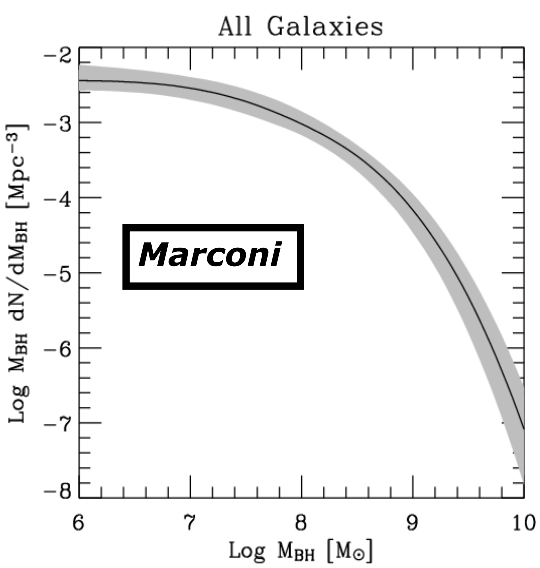

*Brandt and Hasinger 2005 ARAA*

## The local Black Hole Mass Function

- Convolve Galaxy Luminosity functions with $M_{BH}$-$L_{bulge}$ and $M_{BH}$-$\sigma$ to obtain the local BH mass function.
  - $M_{BH}$-$L_{bulge}$ and $M_{BH}$-$\sigma$ provide consistent BH mass functions

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

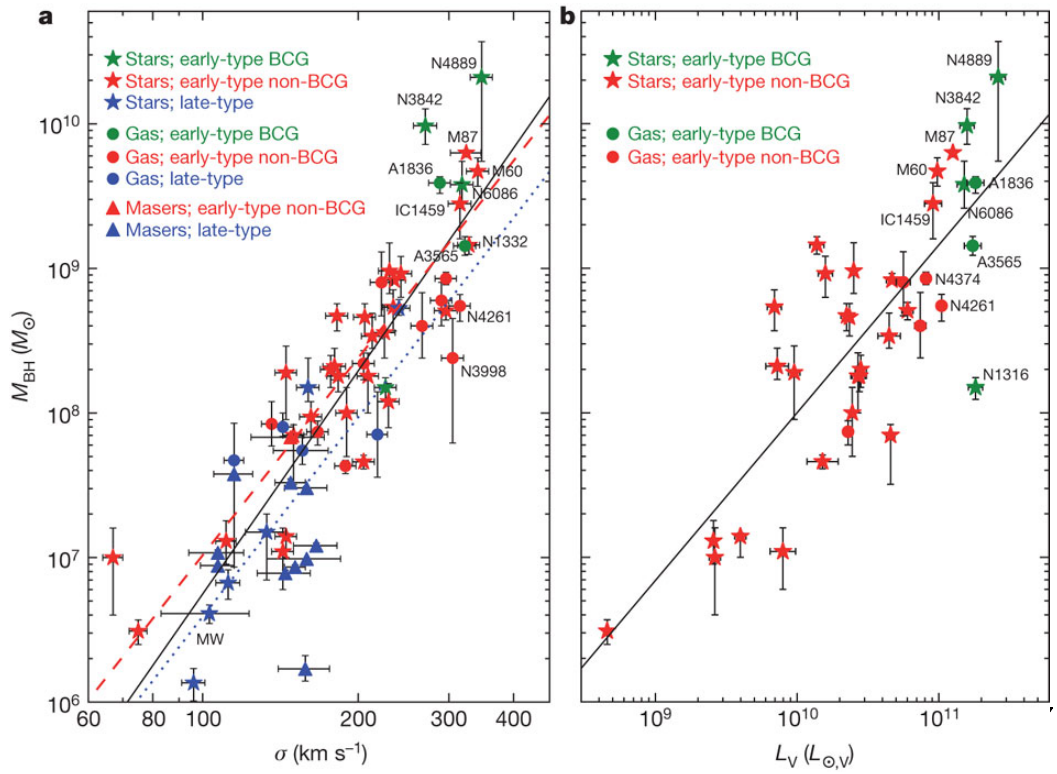
(cf. Merritt & Ferrarese 2001, Ferrarese 2002, Shankar et al. 2004)




Marconi et al. 2004

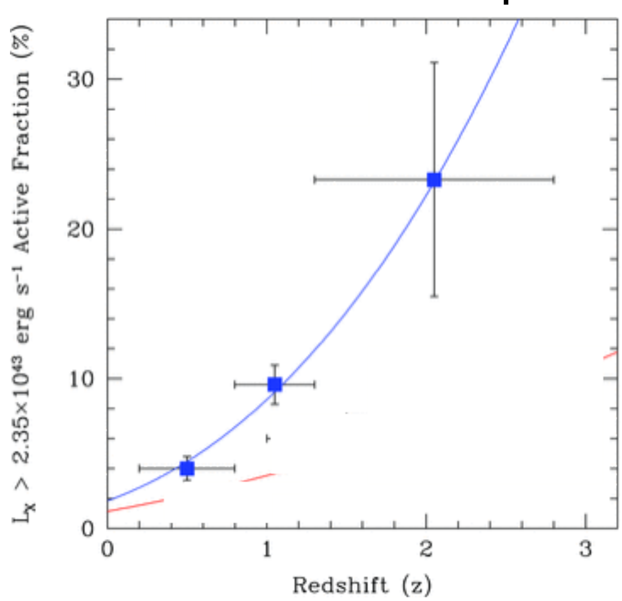
# Scaling of BH Mass with Galaxy properties-

McConnell et al 2011




# Larger Fraction of Galaxies Active in the past

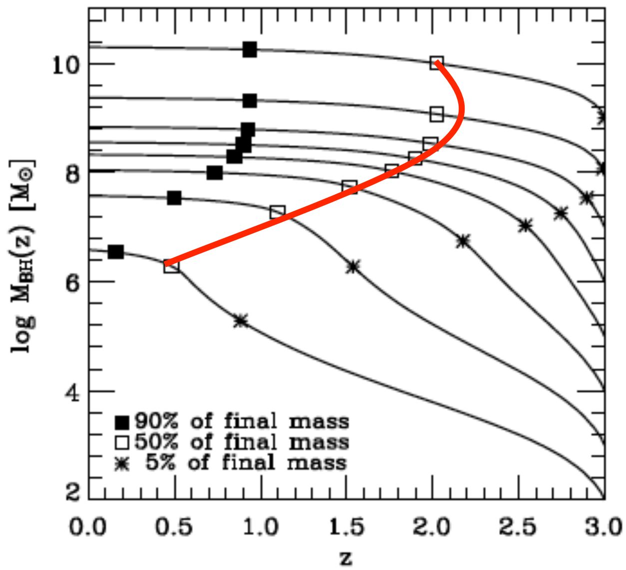
- The evolution seen in luminosity and number is reflected in the fact that a greater fraction of 'normal' galaxies host AGN at higher redshifts




(Bluck et al 2011)

# One realization of BH growth

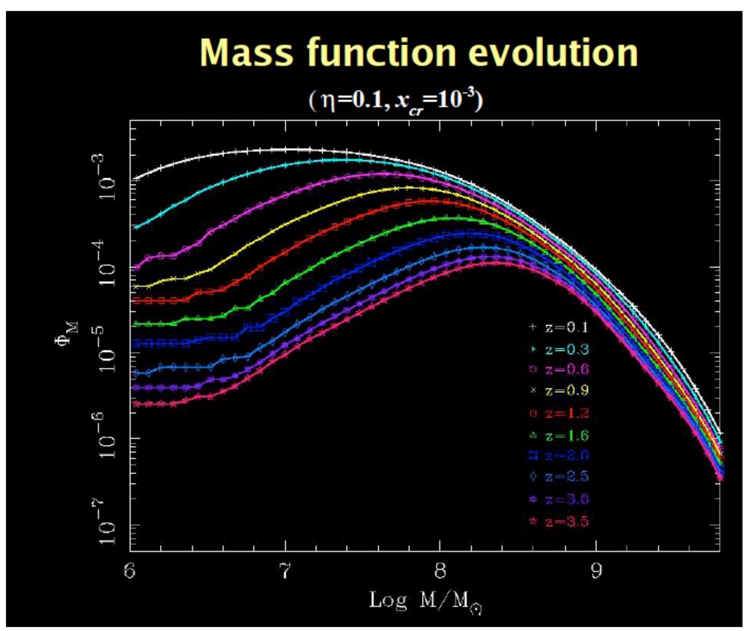
- Big BHs form in deeper potential wells ⇨ they form first.
- Smaller BHs form in shallower potential wells ⇨ they form later and take more time to grow.
  - Marconi 2003, Merloni 2004



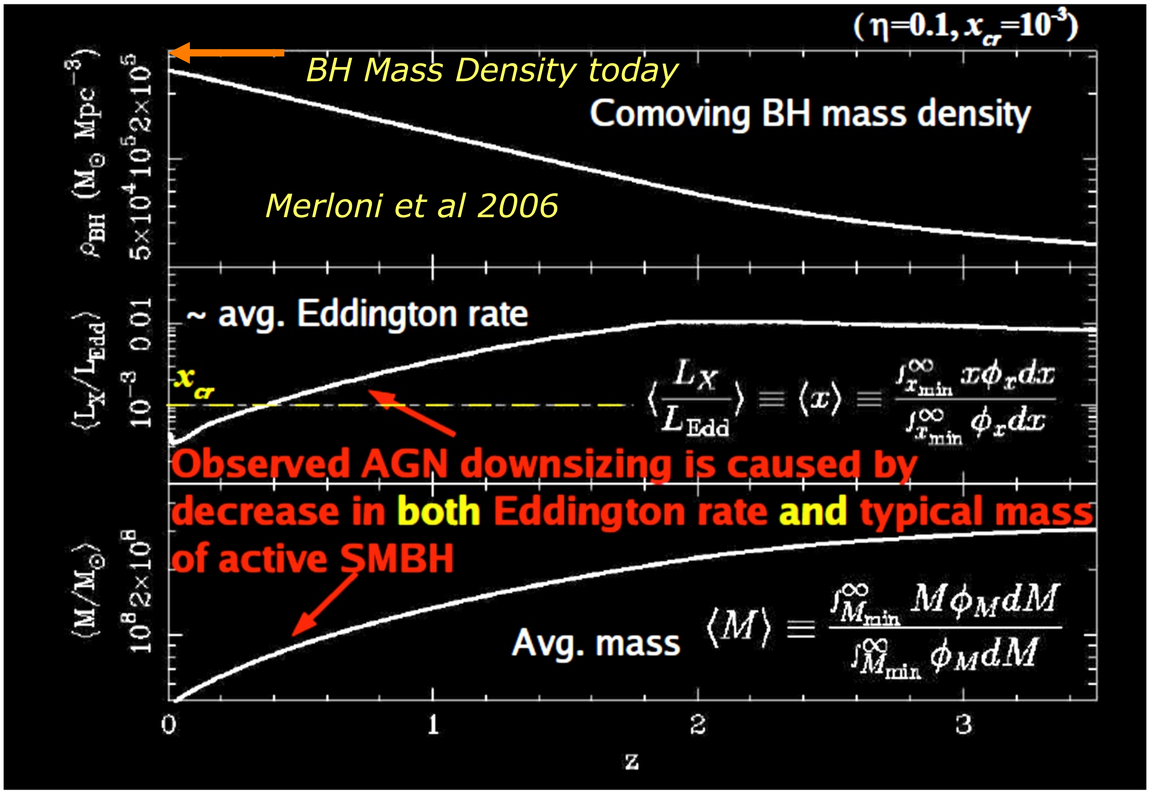



# Transform to Mass Growth

- 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

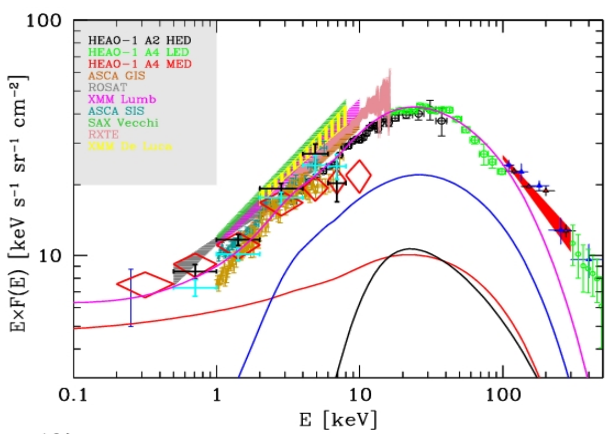


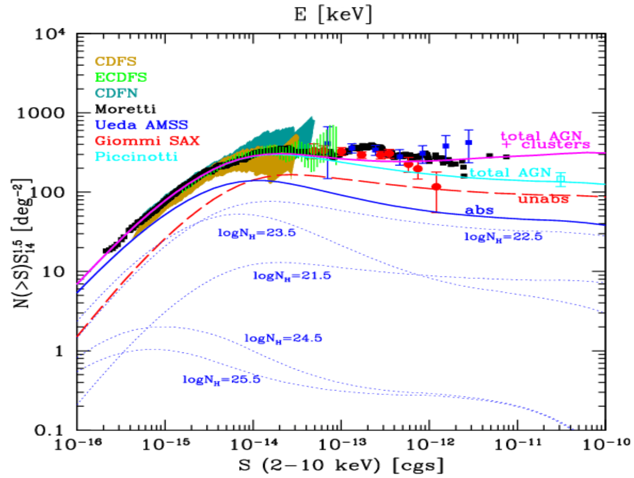
# And See Where You Get to




# X-ray Background constraints

- Integral of x-ray emission over cosmic time produces the XRB
- XRB models provide the total x-ray energy emitted by AGN summed over cosmic time.
  - Synthesis models of the XRB (Gilli et al 2007) involve how the sources evolve and the properties of the sources
    - 3 types of sources
      - unabsorbed (Seyert Is)
      - absorbed (log N(H)>22
      - Highly absorbed ($\tau_{C}$ … >1)



# Constraints on Spin and Efficiency

The present estimate of the BH mass density is ~ $3x10^5 M\odot/Mpc^3$ based on the correlation of BH mass and bulge velocity dispersion

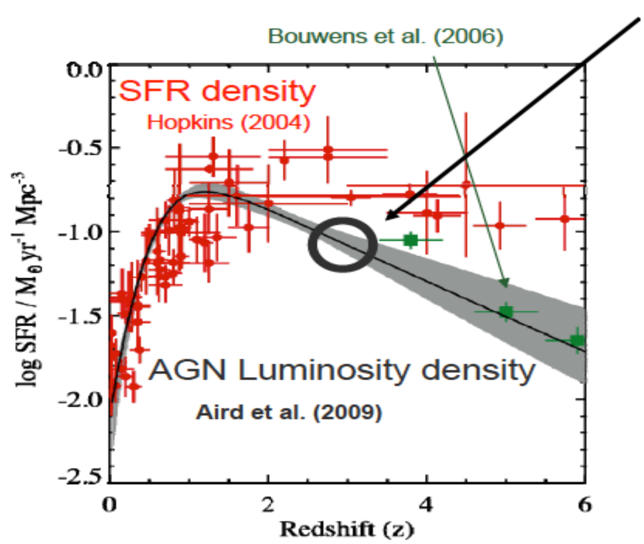
- This is consistent with the integrated comoving energy density AGNs, if efficiency is ~10% and thus the average spin does not need to be large



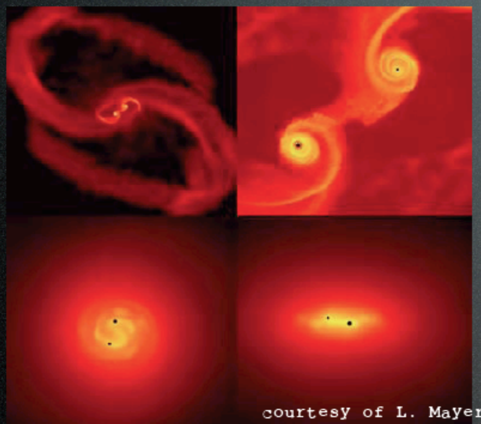
# AGN Luminosity Density and Star Formation 'track'

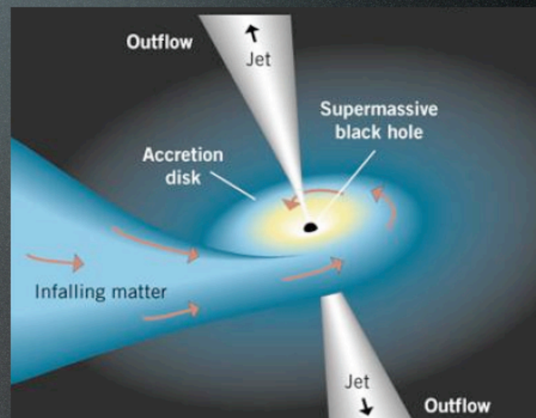
- 'good' correlation of SF and AGN luminosity density based on x-ray surveys. Aird et al 2009, Nandra 2009,Heinz and Merloni 2008
  - plot of AGN luminosity density vs star formation rate scaled by a factor of 100

Heinz and Merloni 2008



## How do MBH seeds grow to become supermassive?
## BH-BH mergers vs gas accretion




**Total mass density in MBHs is almost constant in time: just reshuffle the mass function**

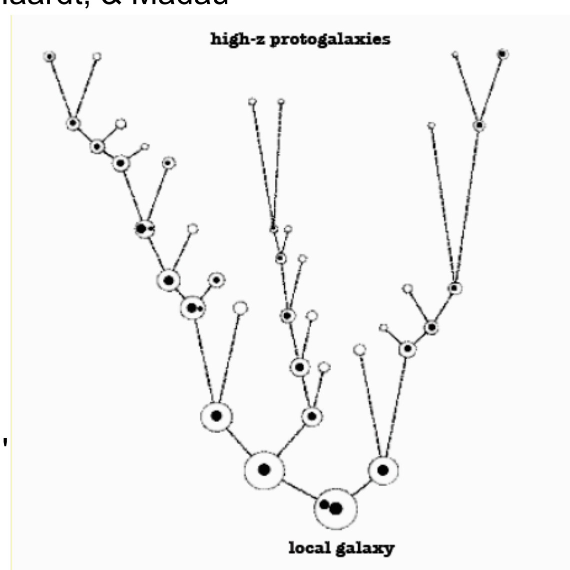
**Total mass density in MBHs grows with time**

- Volonteri 2008

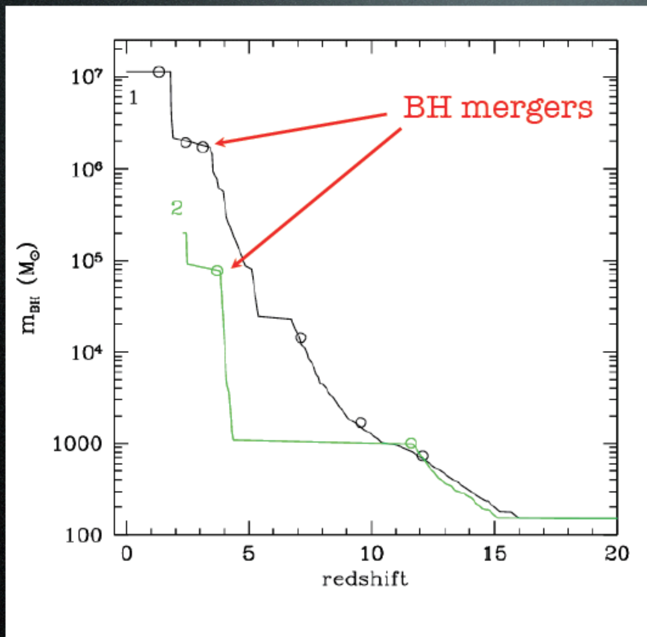


ASSEMBLY AND MERGING HISTORY OF SUPERMASSIVE BLACK HOLES IN HIERARCHICAL MODELS OF GALAXY FORMATION
Volonteri, Haardt, & Madau

- Gravitational instability due to the non-uniform matter distribution caused matter to condense until small regions become gravitationally bound
- The first collapsing objects (halos) are small and merge later to form
- more massive systems: BOTTOM-UP/HIERARCHICAL
- Make Assumption that these 'small' objects host BHs and that as the galaxies merge the BHs also do
- When they merge they emit gravitational waves



## Folding in mergers and accretion in a hierarchical model... *Volonteri 2008*




- ✔ MBH mergers are rare events, as they require a merger between two galaxies BOTH with a central MBH
- ✔ not ALL MBHs experience a merger in their lifetime, only ~40-50%
- ✔ mass growth dominated by accretion (cfr. Soltan's argument)