Ahumada Mena,	Tomas	
Carvajal,	**Vivian**	**5/9**
Crnogorcevic,	Milena	
DeMartini,	Joseph	
Dittmann,	**Alexander**	**4/25**
Fu,	**Guangwei**	
Grell,	**Gabriel**	**5/2**
Hammerstein,	Erica	
Hinkle,	**Jason**	**4/25**
Hord,	**Benjamin**	**5/2**
Ih,	**Jegug**	
Karim,	Ramsey	
Koester,	**Kenneth**	
Marohnic,	Julian	
Mundo	**Sergio**	**4/30**
Park,	**Jongwon**	
Teal, '	**4/18**	
Thackeray,	**Yvette**	
Villanueva	Vicente	
Volpert,	Carrie	
Ward,	Charlotte	
Williams,	Jonathan	
Yin,	Zhiyu	

Oral Presentations

***2** students has 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 7 and May 9 and the 'last class'*

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.

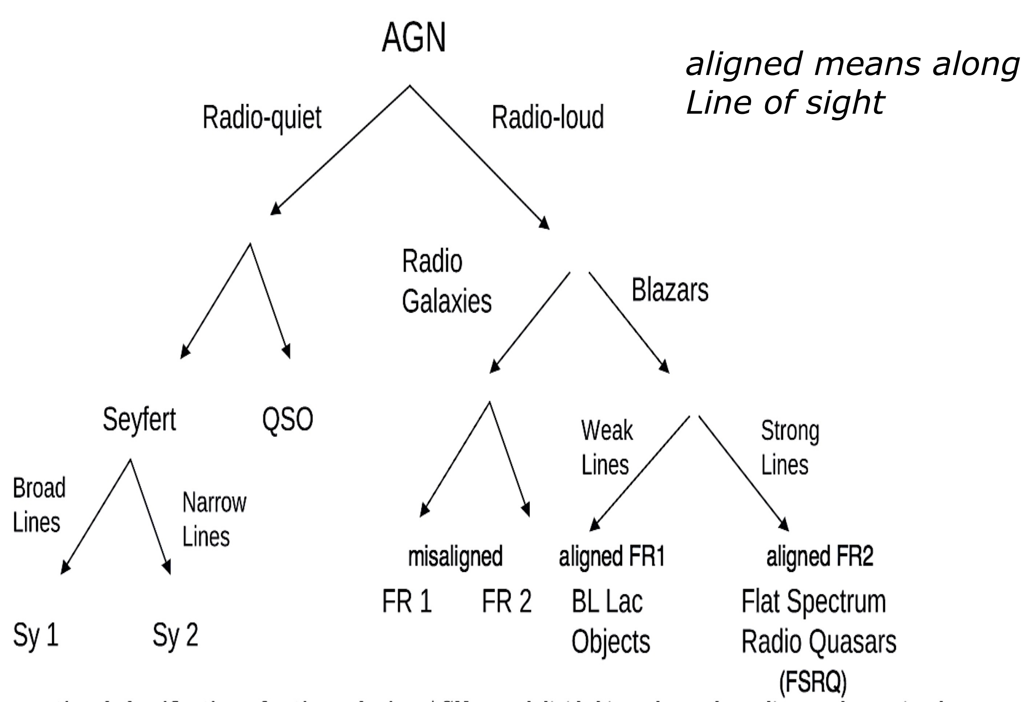
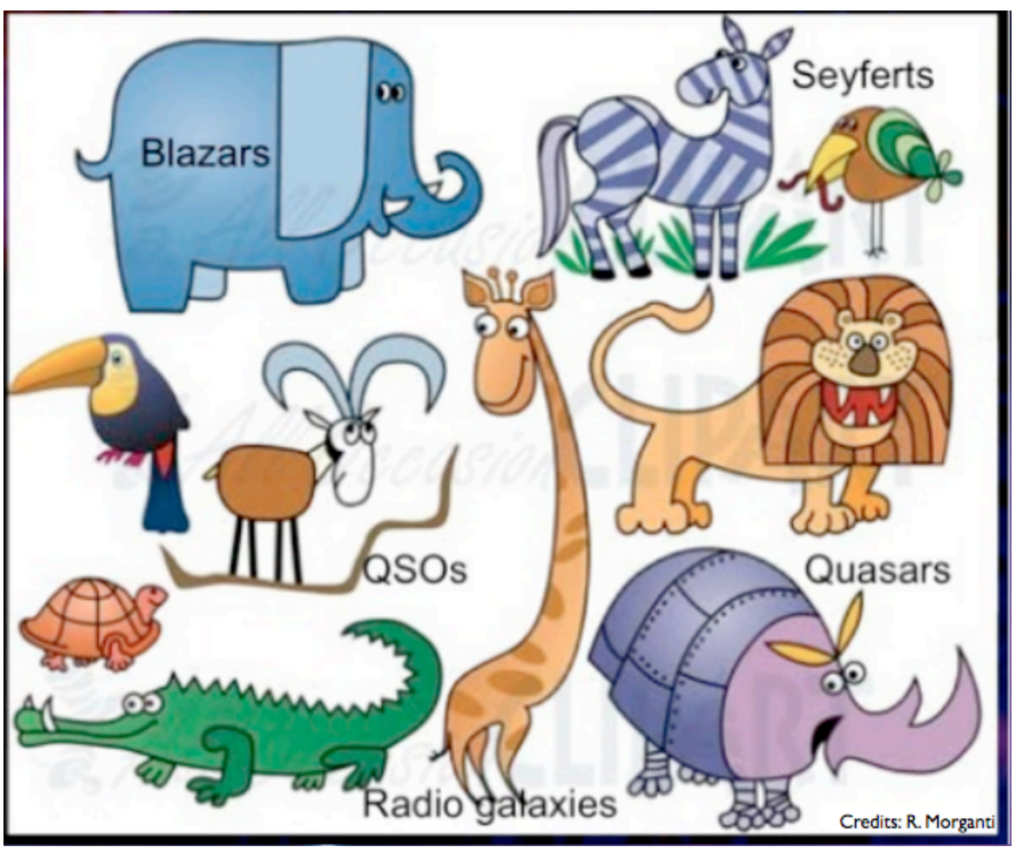


Figure 1. **Observational classification of active galaxies.** AGN are subdivided into classes depending on observational aspects, such as their radio loudness or the presence of optical lines in their spectra. QSO = quasi-stellar objects; Sy1 and Sy2 = Seyfert 1 and 2; FR1 and FR2 = Fanaroff-Riley 1 and 2.

table 27-2 Properties of Active Galactic Nuclei (AGNs)

Object	Found in which type of galaxy	Strength of radio emission	Type of emission lines in spectrum	Luminosity (watts)	Luminosity (Milky Way Galaxy = 1)
Blazar	Elliptical	Strong	Weak (compared to synchrotron emission)	10^{38} to 10^{42}	10 to 10^5
Radio-loud quasar	Elliptical	Strong	Broad	10^{38} to 10^{42}	10 to 10^5
Radio galaxy	Elliptical	Strong	Narrow	10^{36} to 10^{38}	0.1 to 10
Radio-quiet quasar	Spiral or elliptical	Weak	Broad	10^{38} to 10^{42}	10 to 10^5
Seyfert 1	Spiral	Weak	Broad	10^{36} to 10^{38}	0.1 to 10
Seyfert 2	Spiral	Weak	Narrow	10^{36} to 10^{38}	0.1 to 10

- Some of different classes of AGN are truly different 'beasts' - (e.g. radio loud vs radio quiet) but
- Much of the apparent differences are due to geometry/inclination effects- this is called the Unified Model for AGN (e.g. type I vs Type I radio quiet objects, blazars - radio loud objects observed down the jet)
- The ingredients are: the black hole, accretion disk, the jet, some orbiting dense clouds of gas close in (the broad line region), plus a dusty torus that surrounds the inner disk, some less dense clouds of gas further out (the narrow line region) (adapted from T. Treu)



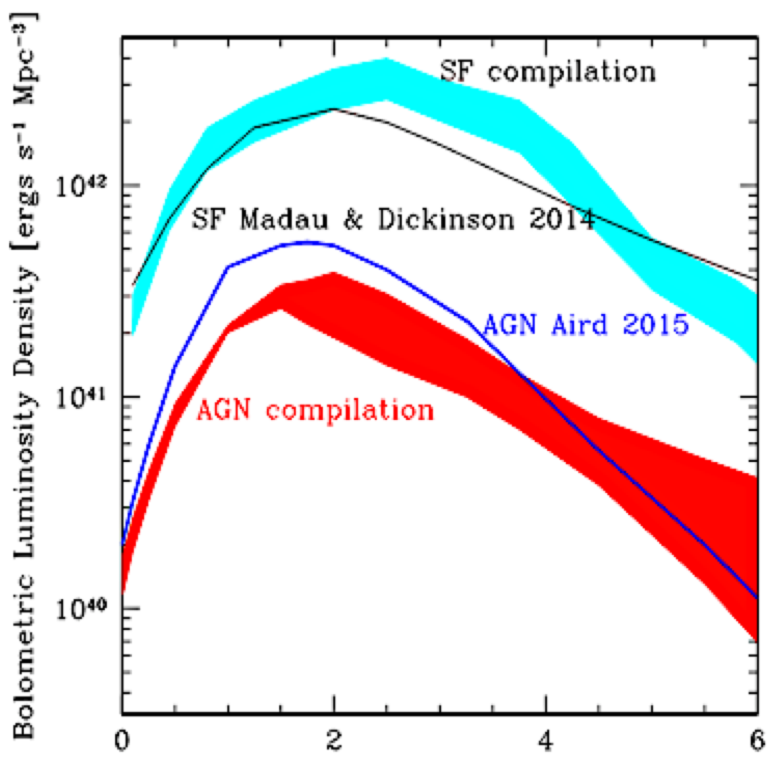
Problems with the Formation of the Universe

- 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

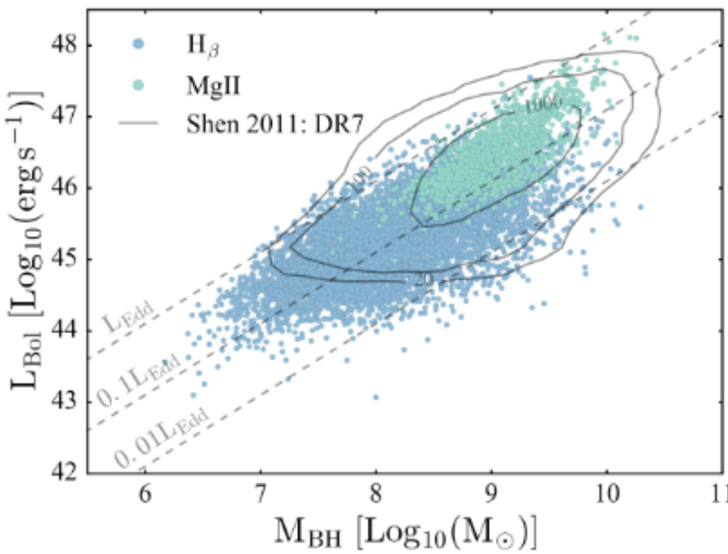
Co-evolution of Galaxies and Black Holes

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

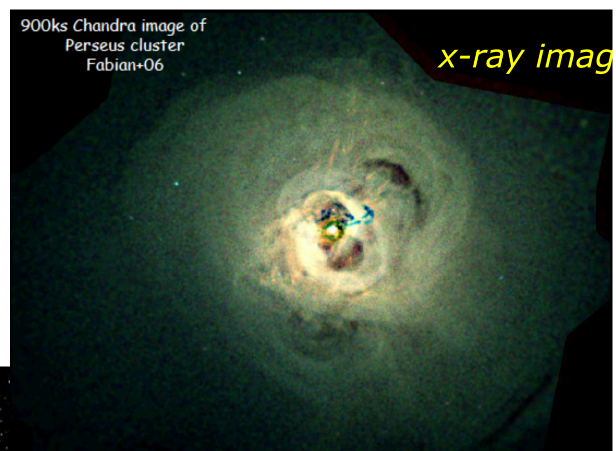


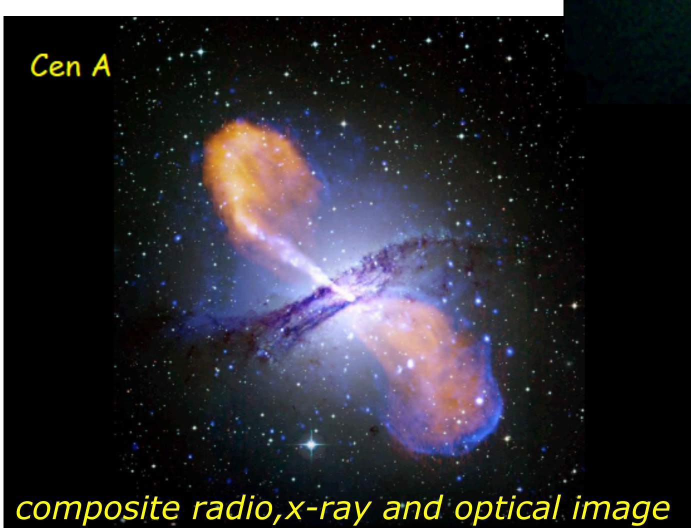
Black Hole Masses

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



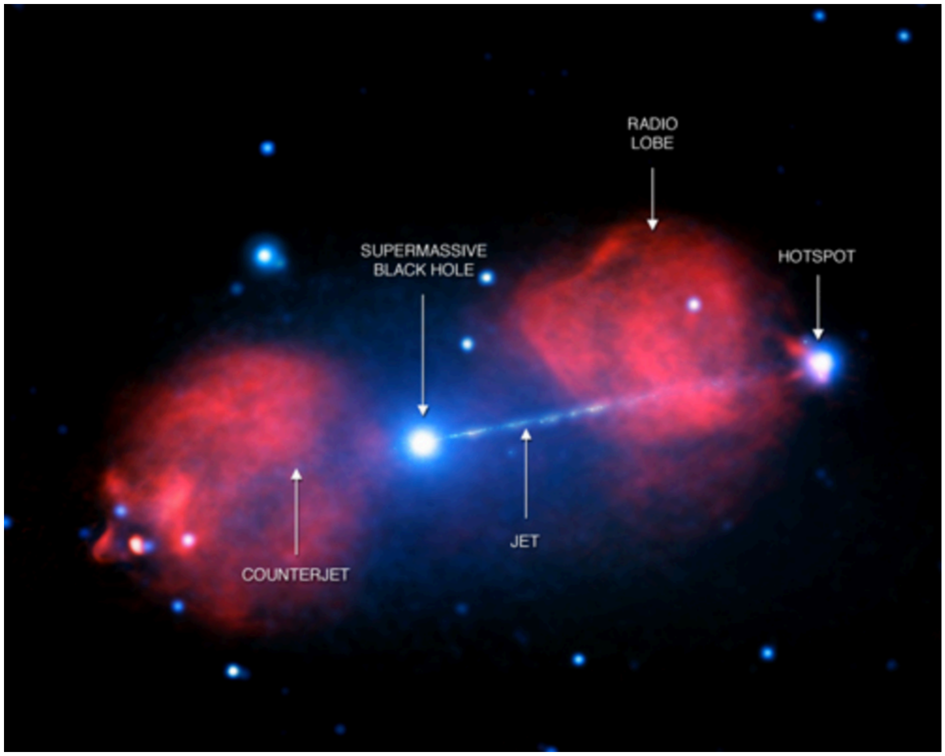
Effect of AGN on their environment





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

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



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

Evolution of BHs - Cosmological evolution of AGN Obscured AGN

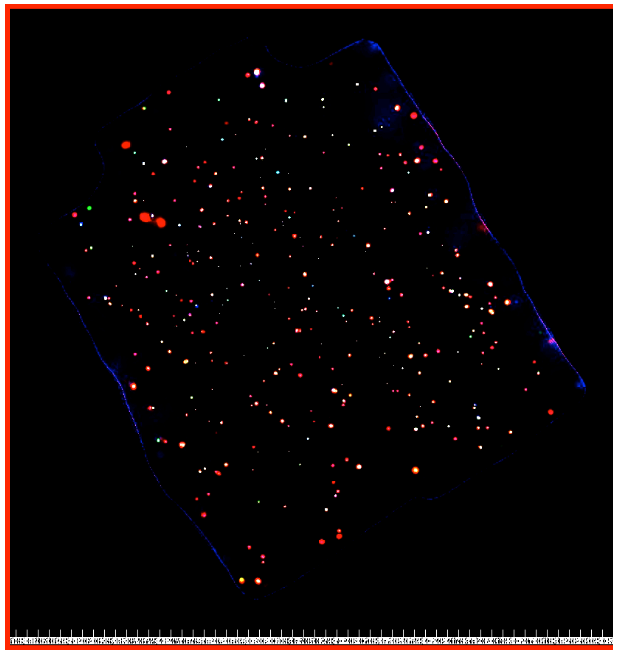
2005 ARA&A..43,827 Brandt, W. N.; Hasinger, G. Deep Extragalactic X-Ray Surveys

2004ASSL..308, 53Mushotzky, R. How are AGN Found?

2005AJ....129..578 Barger, A. et al The Cosmic Evolution of Hard X-Ray-selected Active Galactic Nuclei

The History of Active Galaxies

- Active Galaxies (AKA quasars, Seyfert galaxies etc) are radiating massive black holes with $L \sim 10^{8}\text{-}10^{14} L_{sun}$
- 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^*

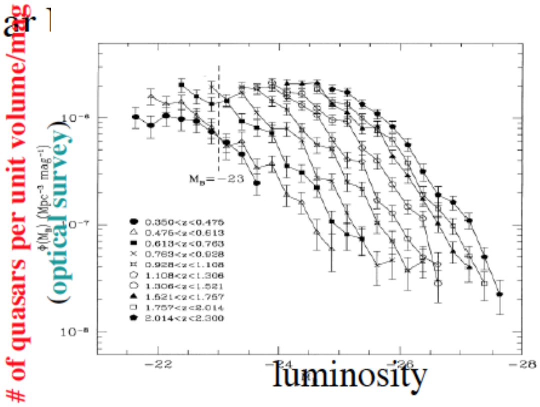
The luminosity function is the number of AGN per unit comoving volume, per unit luminosity:

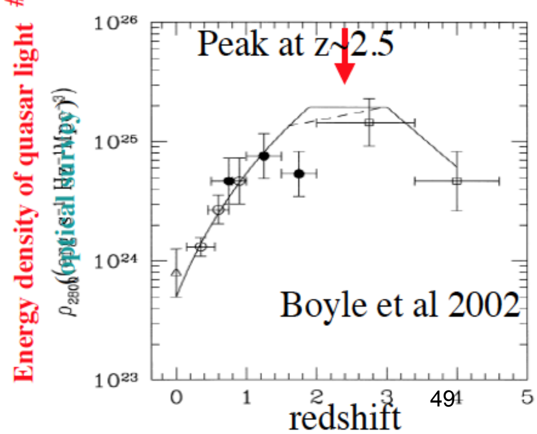
$$\frac{d\Phi(L_X,z)}{dLogL_X}=\frac{dN(L_X,z)}{dV_c\,dLogL_X}$$

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 were more numerous and luminous in the past** with the numbers rising as $(1+z)^N, N\sim4$



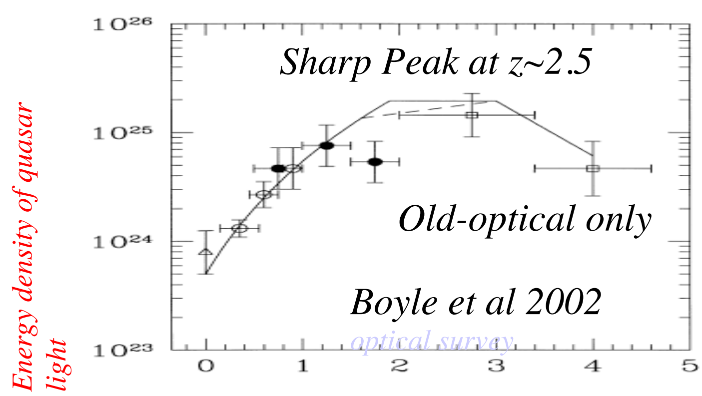


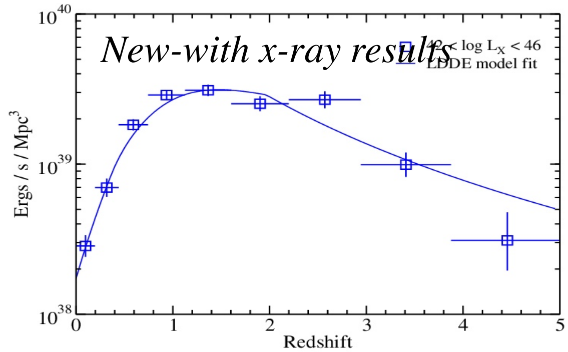
AGN Evolution

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



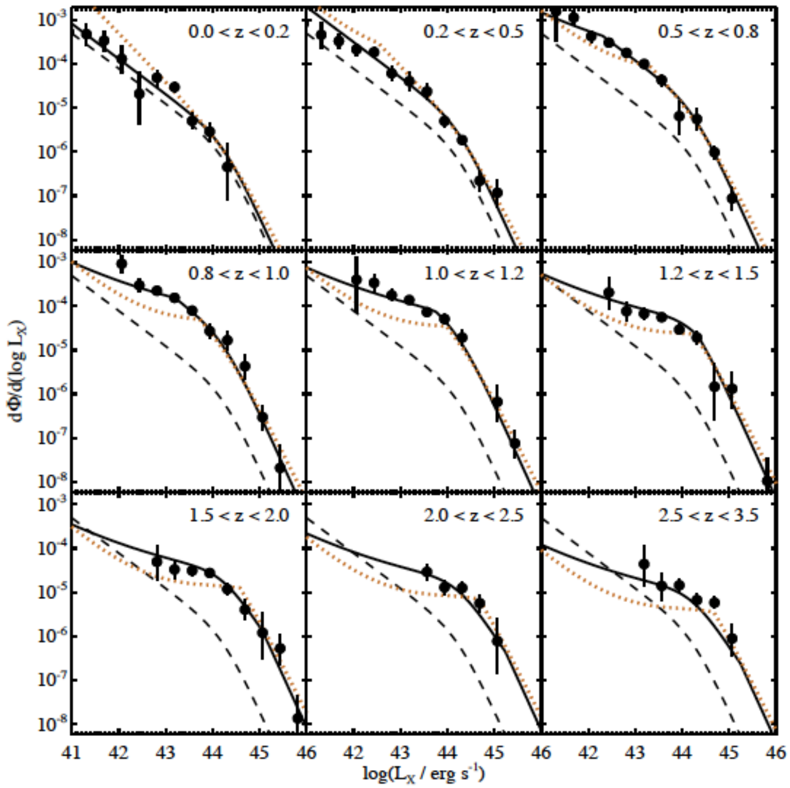


Yencho et al 2009- xray survey

- 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*

Luminosity function vs z

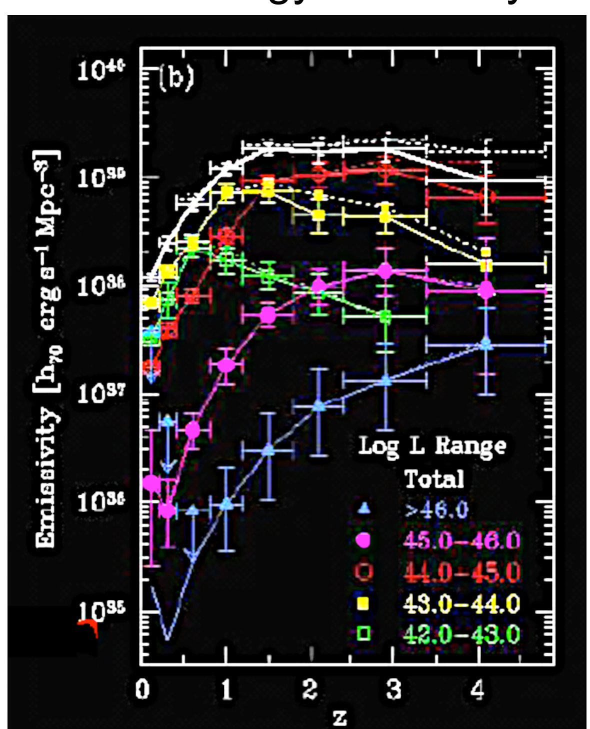
Aird et al 2009 (ignore red line)



Transform Luminosity Function to Energy Emissivity

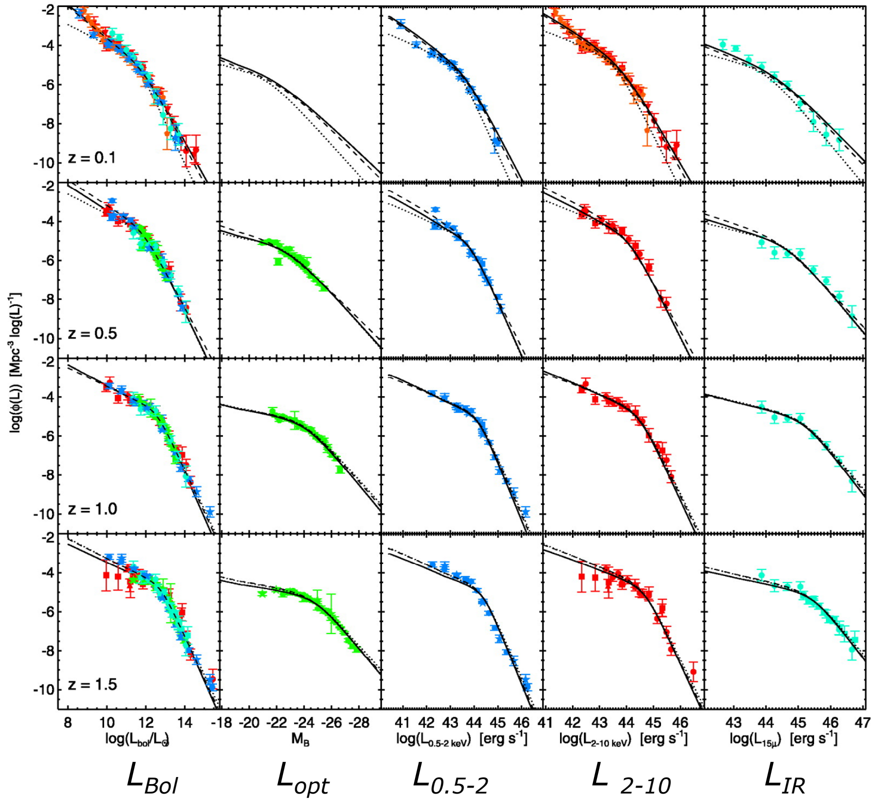
- Integrate the luminosity function in redshift shells
- Notice downsizing: more luminous objects are more dominant at high redshift and evolution is a function of luminosity
- E_{AGN}~1.4 +/- 0.25 x10^{61} erg per galaxy since z = 3. (e.g. ~10% of all the energy emitted by all stars over the Hubble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



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

Now

10^{10} yrs ago

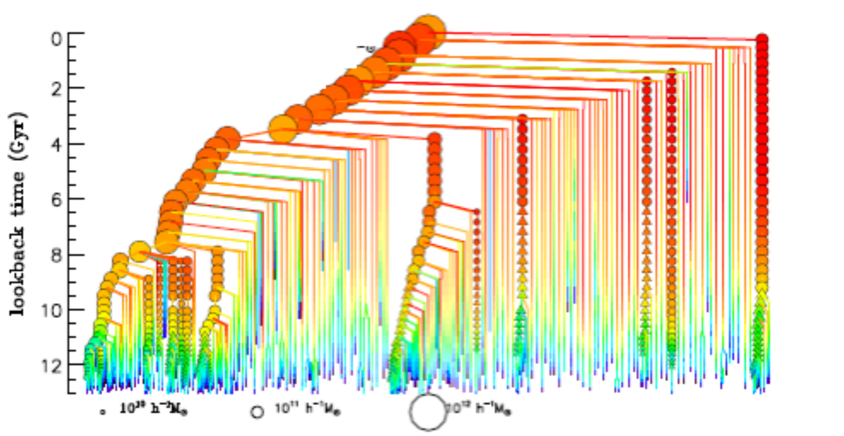


Figure 1. BCG merger tree. Symbols are colour–coded as a function of B - V colour and their area scales with the stellar mass. Only progenitors more massive than 10^{10} $M_{\odot}$ h^{-1} are shown with symbols. Circles are used for galaxies that reside in the FOF group inhabited by the main branch.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

Eddington Limit and Growth Rate

- Is there a limit on accretion?- Eddington limit- maximum rate a black hole can grow
- Derived by balancing radiation pressure against gravity
- Assumption is that the relevant cross section for radiation pressure is the Compton cross section
- If the accreting material is exposed to the radiation it is producing it receives a force due to radiation pressure

Eddington Limit

Radiation pressure is (Flux/c)xσ (σ is the relevant cross section)

The Thompson cross section is the minimum cross section and thus since the flux is $L/(4\pi r^2)$; L is the luminosity the radiation pressure is $\boldsymbol{L\sigma_T/4\pi r^2 c}$; (σ_T is the Thompson cross section (6.6×10^{-25} cm^2)

The gravitational force on the proton is $\boldsymbol{Gm_pM_{BH}/R^2}$ m_p *is the mass of the proton) and* $\boldsymbol{M_{BH}}$ *is the mass of the accretor equating the two*

$[L\sigma_T/4\pi r^2 c]=[Gm_pM_{BH}/r^2]$

Gives the Eddington limit

$$L_{Edd}=4\pi M_{BH}Gm_pc/\sigma_T=1.3\times10^{38}M_{sun}\,erg/sec=\lambda$$

Frank, King & Raine, "Accretion Power in Astrophysics",

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

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

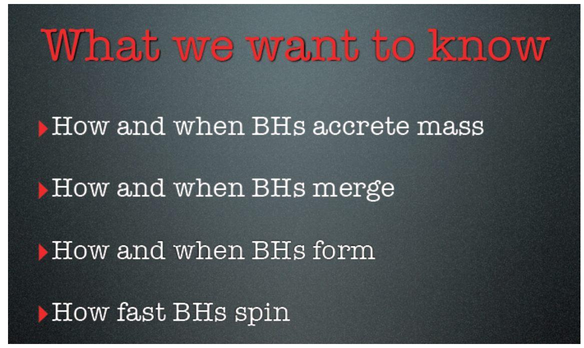
is the *Salpeter timescale* η= *efficiency*

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 $M=M_o e^{t/\tau}$
- 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.

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.
  - Adding up the total quasar light and assuming an efficiency of ~0.1 implies that virtually all galaxies should have massive black holes with $\langle M \rangle \sim 10^7$ 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.
- $L_{bol}=\varepsilon(dM_{acc}/dt)c^2= \varepsilon(M_{BH}/dt)c^2$
- 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)

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