# AGN- Ch 14 of MBW, Ch9 of S&G

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;

(iii) strong emission lines;

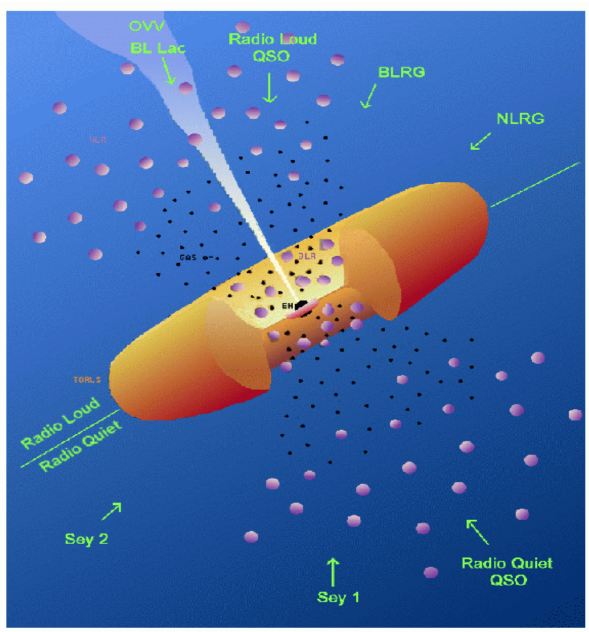
(iv) variability in continuum emission and/or in emission lines on relatively short time scale

(v) luminous non-thermal radio or x-ray emission

(vi) presence of luminous relativistic jets

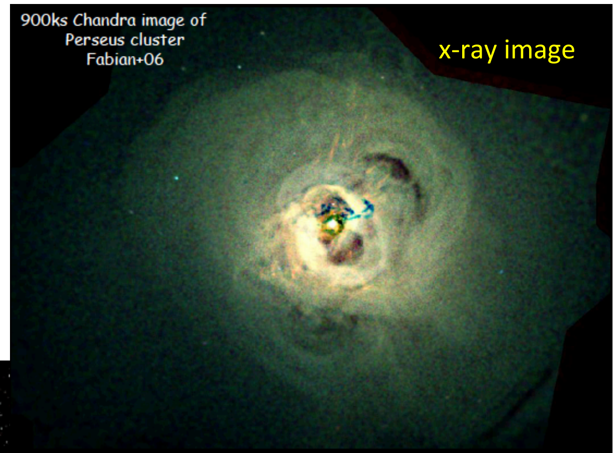
# AGN- Alias **Active** Galactic Nuclei

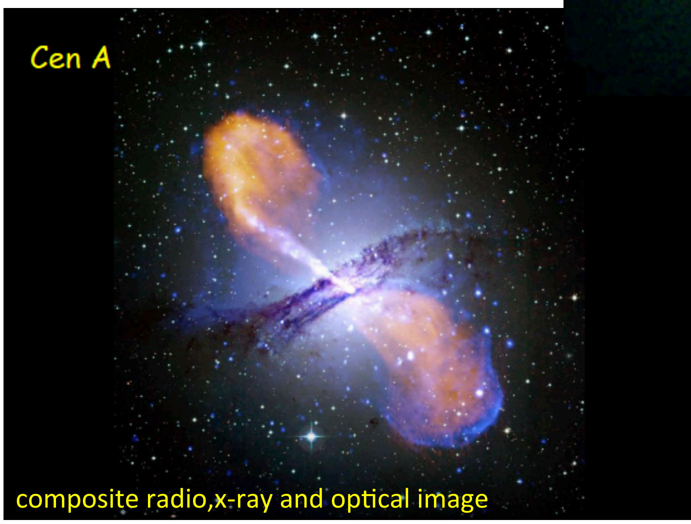
- AGN are **'radiating'** supermassive black holes-
  - They go by a large number of names (Seyert I, Seyfert II, radio galaxies, quasars, Blazars etc etc)
  - The names convey the observational aspects of the objects in the first wavelength band in which they were studied and thus do carry *some* information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

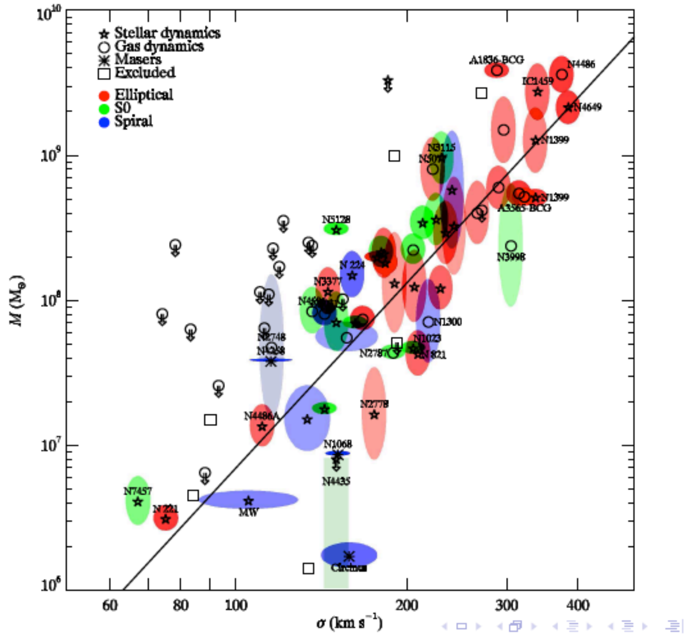
*But at* *z=0* *only ~10% are 'active'*

# 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 11th!

# Mass of Black Hole Compared to Velocity Dispersion of Spheroid

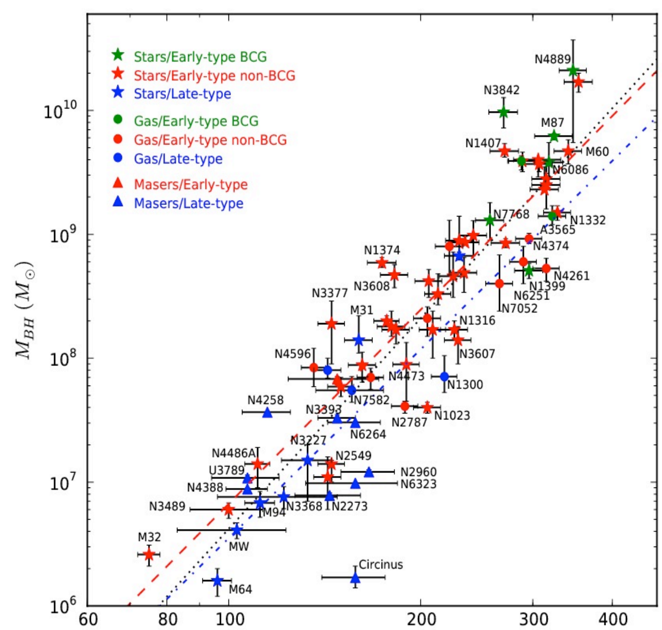
- Sample of non-active galaxies compare mass of black hole (derived later) with velocity dispersion of stars
- Very high detection rate of BHs in 'normal' galaxies- both spheroids and disks.

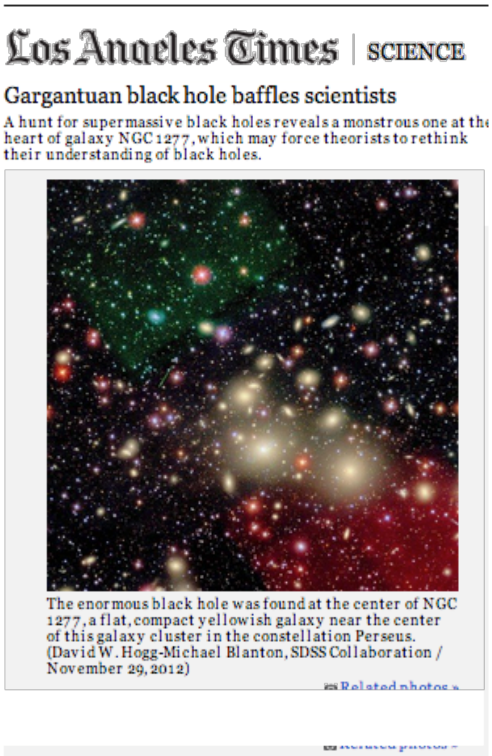



Gultekin 2009

# 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

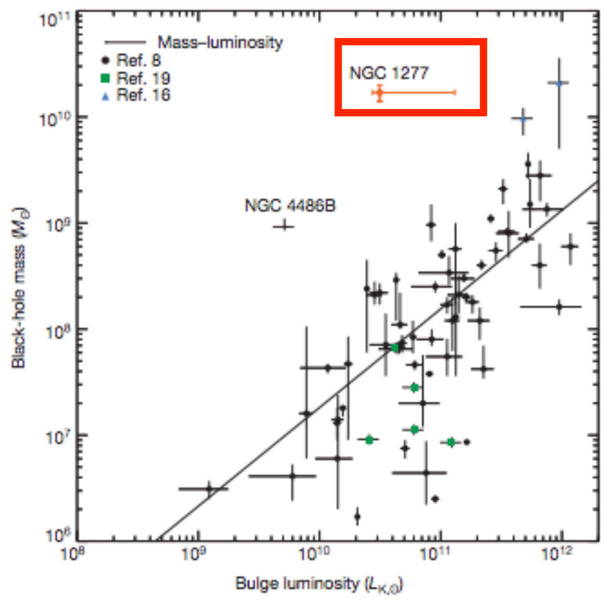
Gargantuan black hole baffles scientists

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 !!!

## 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

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

see Kormendy and Ho 2013 ARA&A , vol. 51. 511- for a recent review

Black holes play an important role in galaxy formation theories

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

- $M_B$-$\sigma$ 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:**

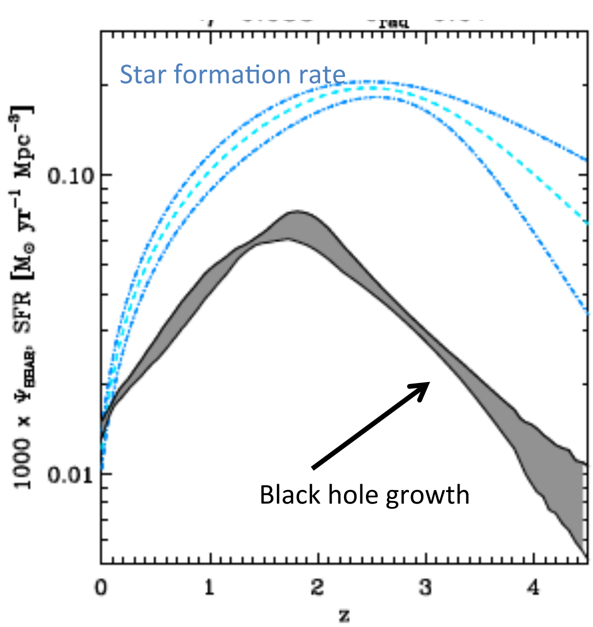
- Solve the cooling flow riddle in clusters of galaxies
- Explain the cluster-scaling relations, e.g. the tilt of the $L_x$-T relation
- Explain why ellipticals are so gas-poor
- Drive metals into the IGM by quasar-driven winds
- Help to reionize the universe and surpress star formation in small g

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

# Reasons to believe in feedback

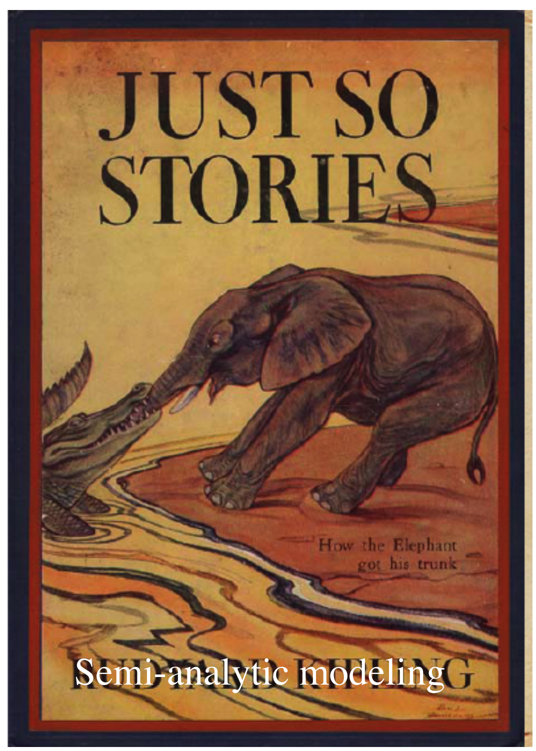
- Ability to match galaxy mass function with a CDM halo function
- AND
  - baryon fraction in galaxies,
  - IGM absorption in metal lines at moderate z
  - Entropy in groups
  - Detection of effects of radio sources on gas in galaxies and clusters

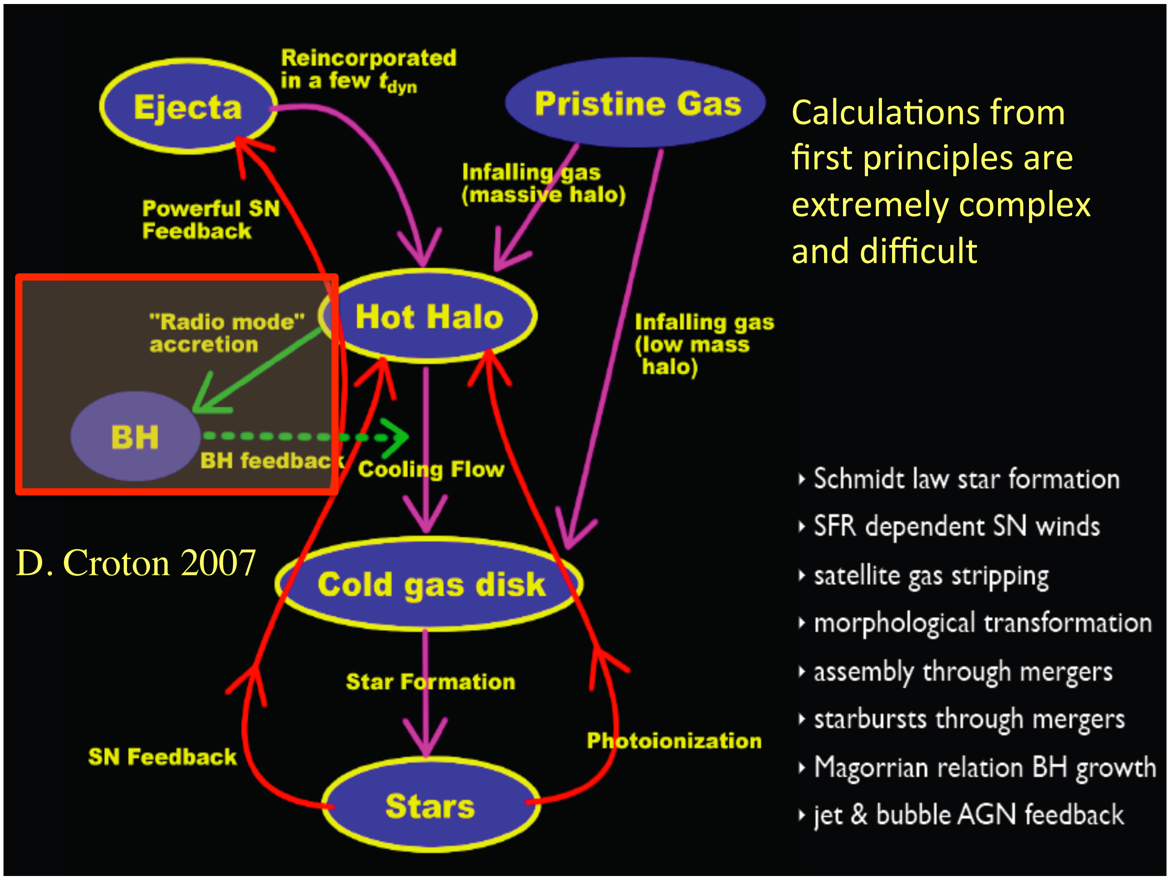
Problems feedback is invoked to solve

- Maintain the close correspondence between the growth of SMBH and galaxies across cosmic time
- Ensure a tight relationship between BH mass and galaxy velocity dispersion/spheroid mass
- Prevent galaxies from getting too massive in a LCDM universe
- Solve the cooling flow problem in clusters

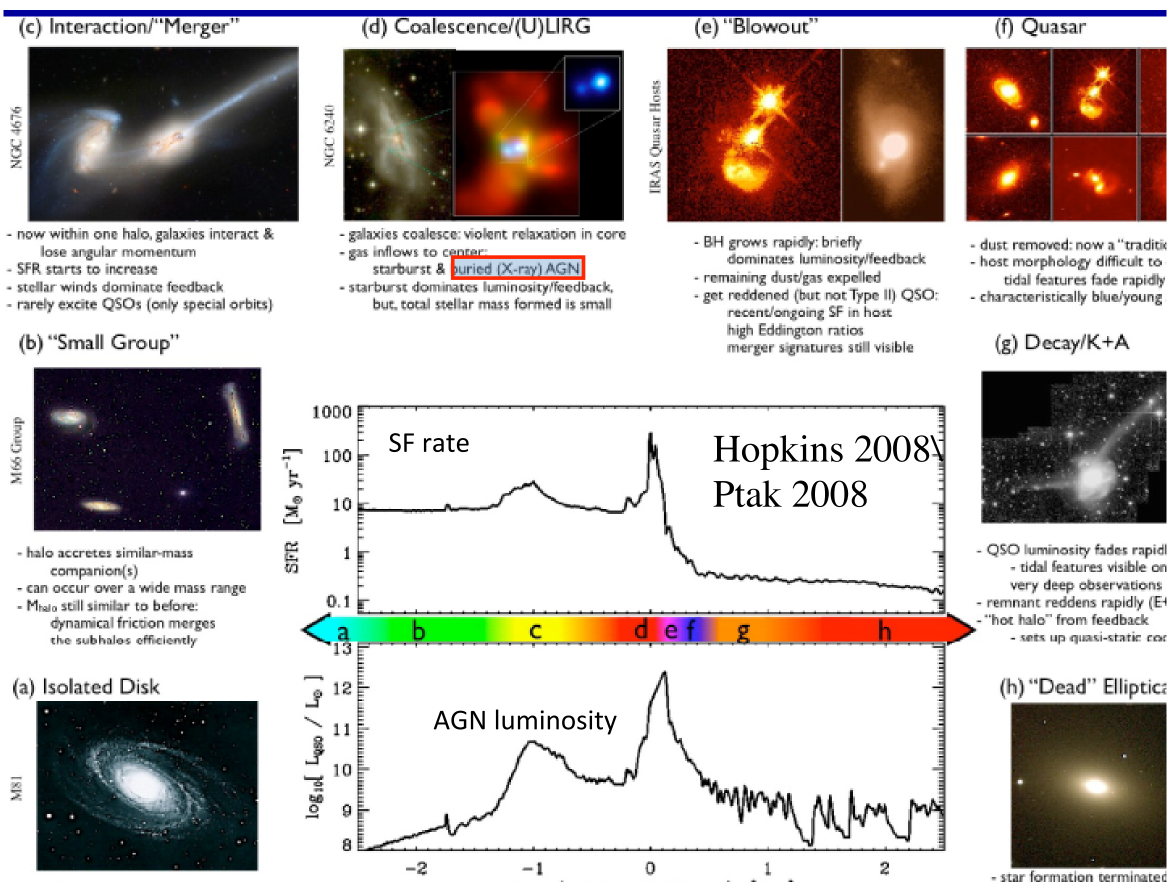
# *How the Observable Universe Came to Be*

- Dark matter evolution in the universe now understood
  - **it is not at all understood how 'baryonic structures' (galaxies, groups, clusters) form.**
- For models to fit the data additional physics (beyond gravity and hydrodynamics) is required (heating, cooling, mass and metal injection, gas motions etc)
- Up until now this has been parameterized in 'semi-analytic' models -
- ***The critical problem is to put physics into these stories***





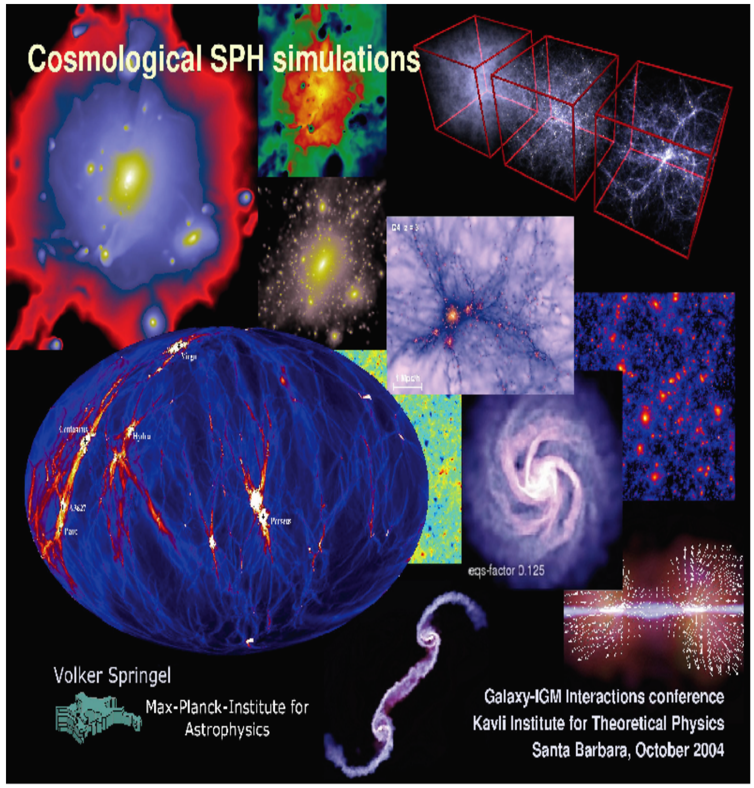
Reincorporated in a few $t_{dyn}$
Ejecta
Pristine Gas
Calculations from first principles are extremely complex and difficult
Powerful SN Feedback
Infalling gas (massive halo)
"Radio mode" accretion
Hot Halo
Infalling gas (low mass halo)
BH
BH feedback
Cooling Flow
Schmidt law star formation
SFR dependent SN winds
satellite gas stripping
morphological transformation
assembly through mergers
starbursts through mergers
Magorrian relation BH growth
jet & bubble AGN feedback
D. Croton 2007
Cold gas disk
Star Formation
SN Feedback
Photoionization
Stars

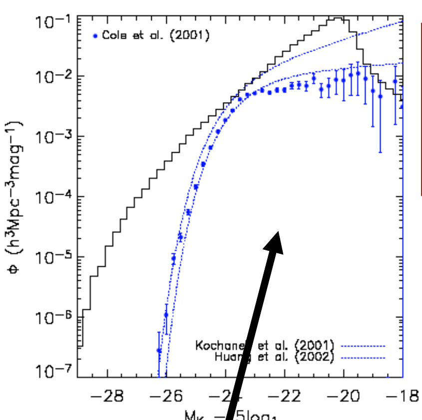



(c) Interaction/"Merger"
NGC 4676
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)
(d) Coalescence/(U)LIRG
NGC 6240
- galaxies coalesce: violent relaxation in core
- gas inflows to center:
starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but, total stellar mass formed is small
(e) "Blowout"
IRAS Quasar Hosts
- BH grows rapidly: briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO: recent/ongoing SF in host
high Eddington ratios
merger signatures still visible
(f) Quasar
- dust removed: now a "traditi
- host morphology difficult to
tidal features fade rapidly
- characteristically blue/young
(b) "Small Group"
M66 Group
- halo accretes similar-mass companion(s)
- can occur over a wide mass range
- $M_{halo}$ still similar to before:
dynamical friction merges the subhalos efficiently
SF rate
Hopkins 2008
Ptak 2008
SFR $[M_\odot\ yr^{-1}]$
1000
100
10
1
0.1
a b c d e f g h
AGN luminosity
$\log_{10}[L_{QSO} / L_\odot]$
13
12
11
10
9
8
−2
−1
0
1
2
(g) Decay/K+A
- QSO luminosity fades rapidl
- tidal features visible on very deep observations
- remnant reddens rapidly (E+
- "hot halo" from feedback
- sets up quasi-static coo
(a) Isolated Disk
M81
(h) "Dead" Elliptica
- star formation terminated

# Formation of structure in the Universe

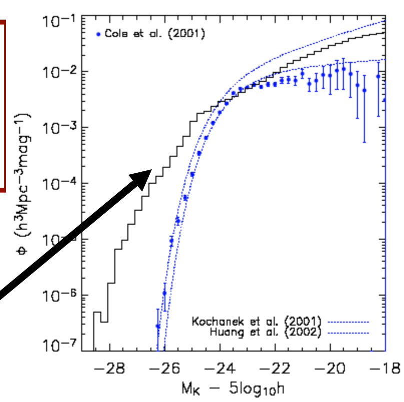
- Detailed numerical calculations of the formation of structure via the collapse of gravitational perturbations in a $\Lambda$CDM universe (Springel et al 2003, White et al 2004) cannot 'produce' the present day universe without invoking 'feedback' (the injection of energy, heat momentum)
- Similar results are obtained in analytic work (Ostriker and colleagues)
- The nature of the feedback is not clear, but must be related to star formation and AGN - the only possible sources with sufficient energy



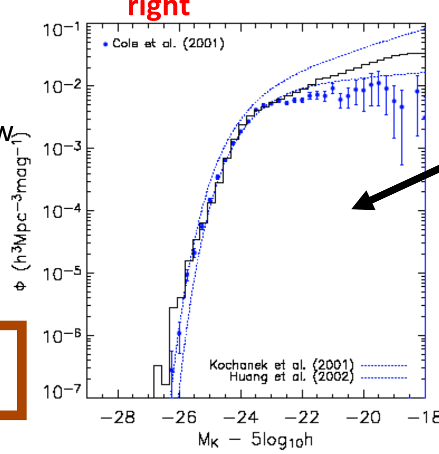




Calculation of K band galaxy luminosity function in N body simulation

Gravity+ hydrodynamics no AGN+ starburst+ reionization - **get low luminosity range 'right'**




Gravity+ hydrodynamics only- **get it all wrong**- low luminosity, slope, high luminosity slope and number and mass in galaxies




Gravity+ hydrodynamics +**AGN**+ starburst+ reionization - **get it all 'right'**

Blue lines are data-black models

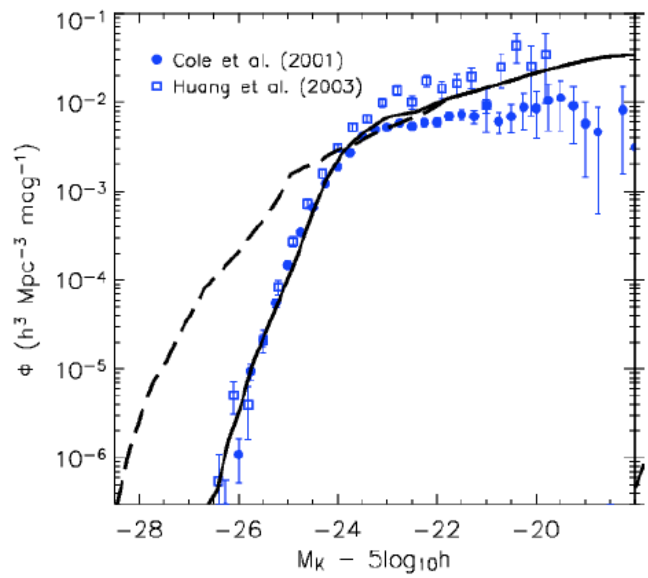
**Thanks to V. Springel and S. White**

# AGN to the Rescue !

In classical LCDM massive galaxies grow too fast and get too massive

With AGN feedback this is prevented

In addition feedback apparently 'ejects' metals into the IGM since massive galaxies retain only 20% of the oxygen generated by stellar evolution (Tolstoy et al.2009)




# Why AGN ?

- **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

  For SN $E_{SN}$~$10^{-4}M_{star}c^2$ $E_{AGN}$~$10^{-1}M_{BH}c^2$
  - mass density of SN $\rho_{SN}$~$4x10^7 M_\odot$ $Mpc^{-3}$ over life of galaxy (1/MW/100yrs)
  - mass density of AGN $\rho_{AGN}$~$4x10^5 M_\odot$ $Mpc^{-3}$ at z=0

  - total energy $E_{SN}$~$4x10^3M_\odot c^2$
  - $E_{AGN}$~$4x10^4M_\odot c^2$

  - **AGN have 10x more total energy than SN**

  - 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)$^2$; $\varepsilon_{SN}/\rho_{baryons}$~(100-250km/s)$^2$

  - since potential depth of galaxies like MW ~500km/sec AGN can expel the gas Sn can't
  - BUT for a dwarf galaxy with vexcape ~100km/sec SN can do the job

# 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

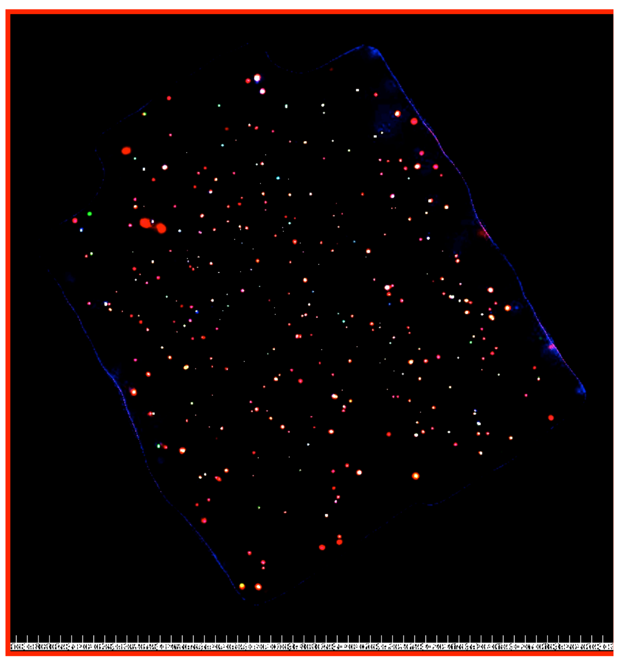
If the energy is in the right form and available at the right time AGN can have a strong influence on the baryons in a massive galaxy

# 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.



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

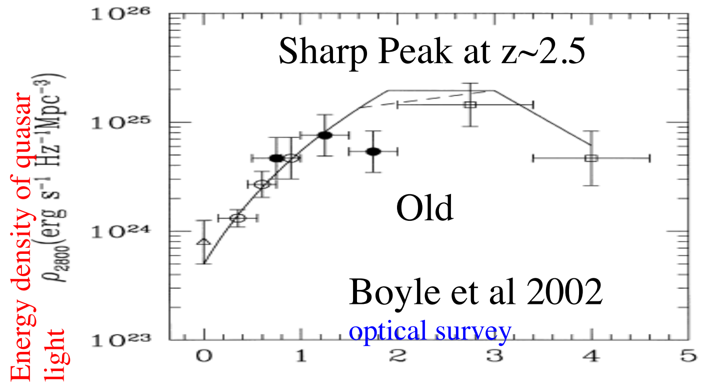
**see** Evolution of active galactic nuclei A. Merloni S. Heinz

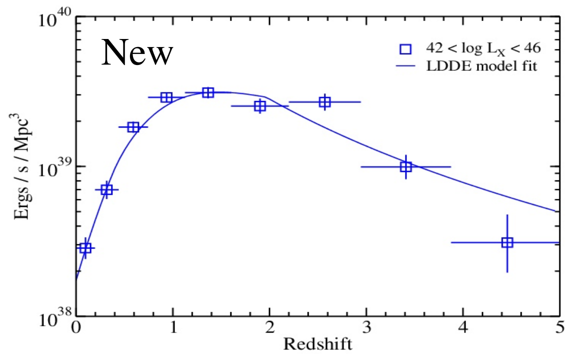
1204.4265v1.pdf

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



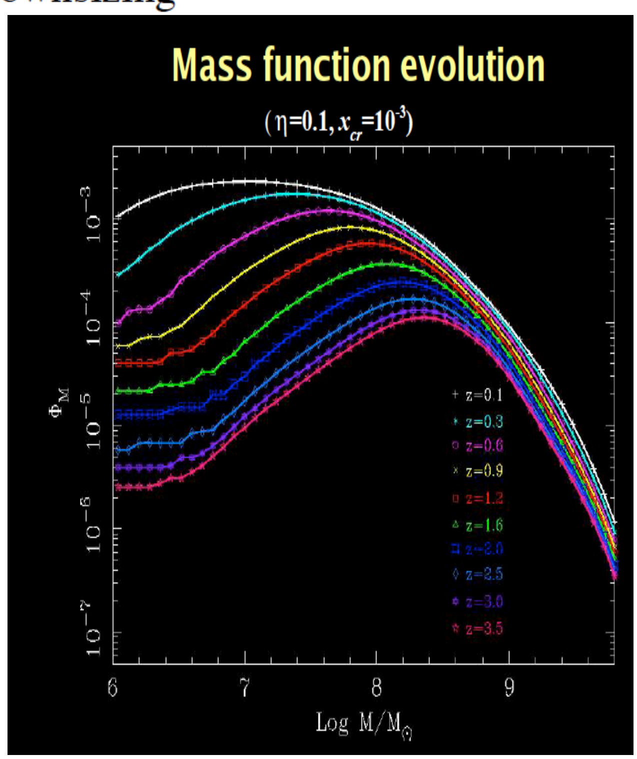

Yencho et al 2009- xray survey

## Downsizing

- The evolution of AGN depends on their luminosity
  - High L AGN were more prominent in the early universe
  - Low L AGN in the low redshift universe

- more massive objects have evolved more rapidly than lower mass BHs

backward from what one naively expects in $\Lambda$CDM



# 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

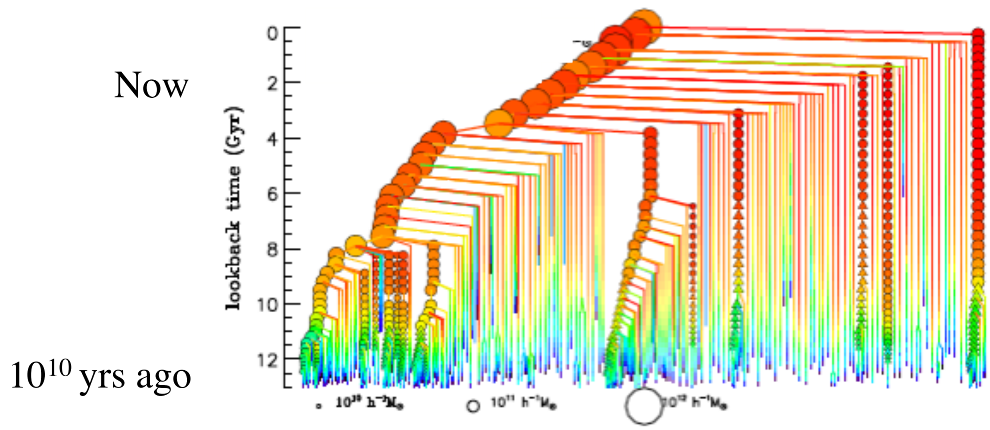
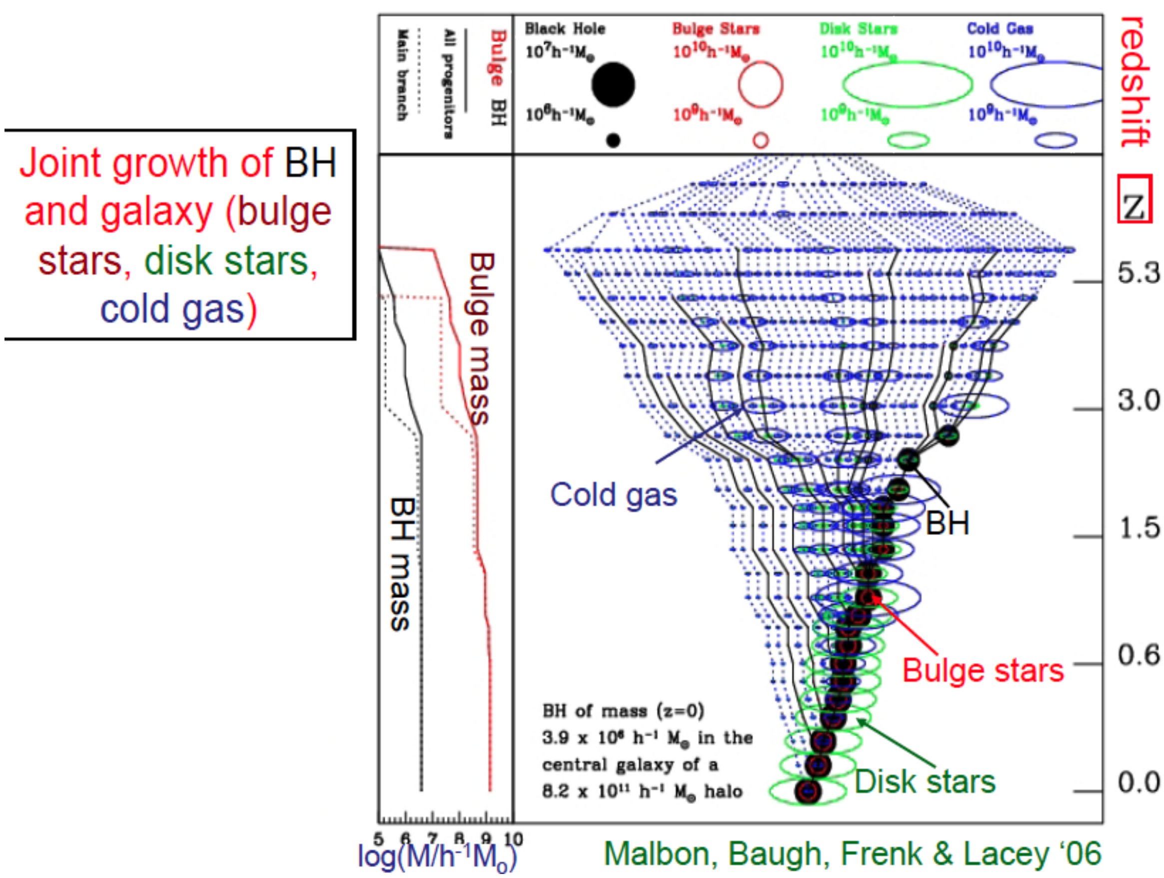
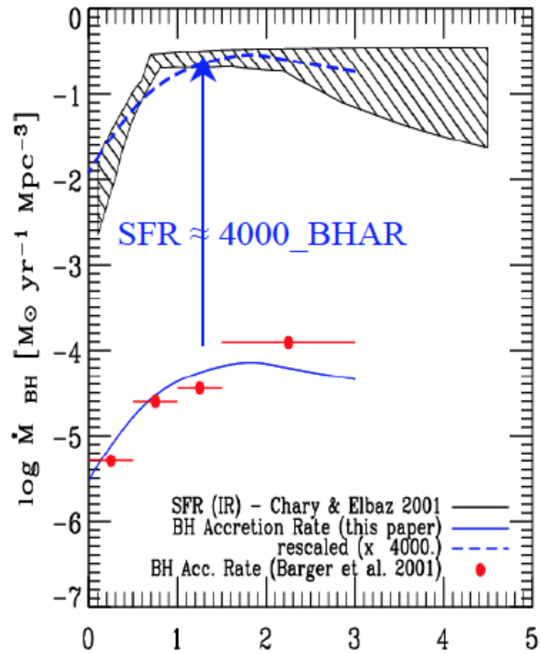



**Figure 1.** BCG merger tree. Symbols are colour-coded as a function of B - V colour and their area scales with the stellar mass. Only progenitors more massive than $10^{10}$ $M_{\odot}$ $h^{-1}$ are shown with symbols. Circles are used for galaxies that reside in the FOF group inhabited by the main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



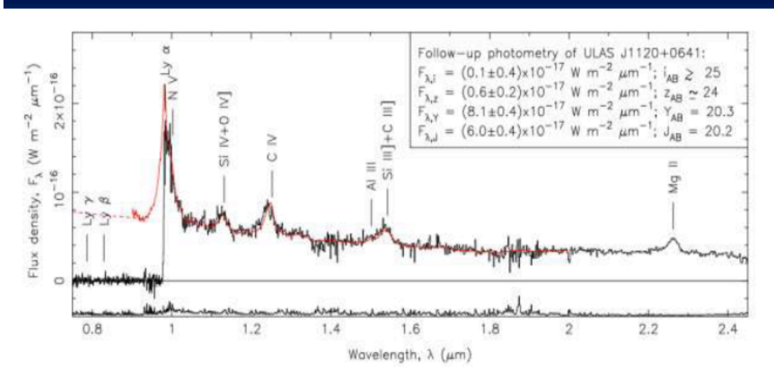
# Evolution of AGN and Galaxies

- Star formation rate (red circles)
- AGN evolution rate (grey band) scaled up by 5000 (Aird et al 2010)
- half of the accreted supermassive black hole mass density has formed by z~ 1




z (redshift)

# Gemini Quasar at z=7.1




when did it all begin?

- 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.

$M \sim 10^9 M_\odot$

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

Mortlock et al. 2011, Nature, 474, 616

# 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)x$\sigma$ ($\sigma$ 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 $\mathbf{L\sigma_T/4\pi r^2 c}$ ; ($\sigma_T$ is the Thompson cross section ($6.6\times10^{-25}$ cm$^2$)

The gravitational force on the proton is $\mathbf{Gm_p M_{BH}/R^2}$
$m_p$ is the mass of the proton) and $\mathbf{M_{BH}}$ is the mass of the accretor
equating the two
$[L\sigma_T/4\pi r^2 c]=[Gm_p M_{BH}/r^2]$

Gives the Eddington limit

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

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

# Eddington Limit and Growth Rate

- Balance the accretion rate onto the BH against the Eddington limit ( $\lambda$)
- $dM_{BH}/dt=L_{acc}/\eta c^2<4\pi G m_p M/\eta c\sigma_t$
- solution is $M=M_o e^{t/\tau}$
- where $\tau=\eta c\sigma_t/4\pi G m_p$~$5\times10^7$yrs where the efficiency of converting mass to energy $\eta$~0.1 and $\lambda=1$
- 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. (Soltan 1982 MNRAS.200..115)-

- Integrating the bolometric luminosity function -compare this to the present day mass of black holes integrated over all objects.
- $L_{bol}=\eta(dM_{acc}/dt)c^2=\eta(M_{BH}/dt)c^2/(1-\eta)$
- $dM_{acc}/dt$=accretion rate
- $dM_{BH}/dt$= BH growth rate

$$\rho_{\rm BH,acc}(z) = \int_z^\infty \frac{dt}{dz'}dz' \int_0^\infty \frac{(1-\epsilon)L_i\kappa_i}{\epsilon c^2}\phi(L_i,z)dL_i$$

## Total Lifetime of active BHs

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

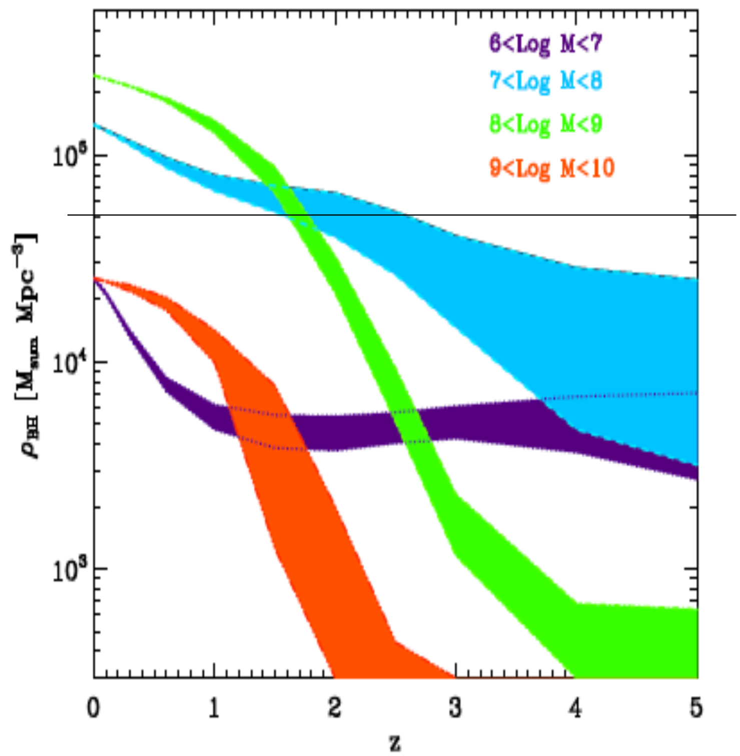
$$t_{Salp} \quad = 4.2\times10^7\,yr\left[\frac{(1-\varepsilon)}{9\varepsilon}\right]^{-1}\lambda^{-1}$$

- 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).

$\varepsilon$= efficiency
$\lambda$= Eddington ratio

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 >$10^9 M_\odot$ BHs grew fast in early universe, slow today (like massive elliptical galaxies)




# What Are Active Galactic Nuclei

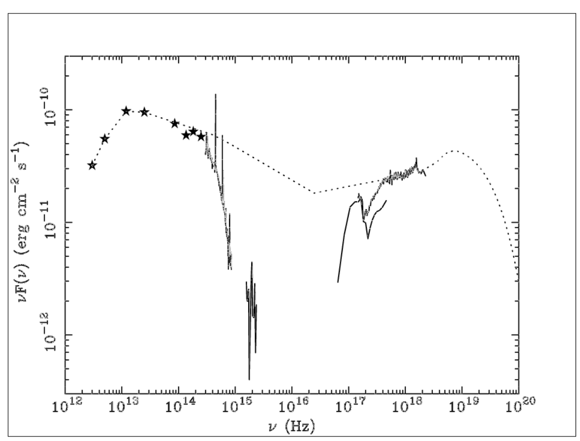
Radiating supermassive black holes in the centers of galaxies

Properties

- 'Point-like'
- luminous non-stellar broad band spectra- very broad range in luminosity log L~ 40-48 ergs/sec
- located in center of *some* galaxies

- More details
  - Optical spectra 3 classes
    - strong broad emission lines
    - strong narrow emission lines
    - strong non-thermal continuum
  - radio ~10% of AGN show strong radio emission (jets/extended emission) due to synchrotron radiation
  - IR- emission reprocessed from optical-UV-soft x-ray
  - X-ray

    non-thermal power law spectra highly variable



# Next Lecture

- Properties of AGN