Cosmology and black holes: (towards) the first structures

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MPE

SKADS MCCT, 14/4/2008

TUM
LMU
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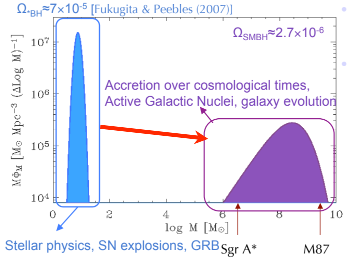
Black Holes in the local Universe



$\Omega_{baryon} \approx 4.5\times10^{-2}$; $\Omega_{stars} \approx 2.5\times10^{-3}$

- Density of stellar mass BHs increases w/galaxy mass
- How does the high-mass (Supermassive) peak grow?

This talk:

- What do we know about evolution of SMBH population (mass function, accretion rates, etc.)
  - A lot! (up to z~4-5)
  - Evolution of mass and accretion rate density
  - Constraints on radiative efficiency and avg. BH spin
  - Anti-hierarchical evolution (downsizing)
  - Radiative vs. kinetic energy output
- Frontiers: The first Black holes
  - Eddington or Super-Eddington?
  - The role of mergers
  - The first seeds

Accretion efficiency, Eddington limits

- In order to get close (R), a particle of mass m must get rid of energy $E_{lib} = GM_{BH}m/R$
- Efficiency of accretion in liberating rest mass energy:

  $\eta = E_{lib}/mc^2 = R_g/2R_{in}$, with $R_g = GM_{BH}/c^2$ GR $\rightarrow 0.06 < \eta(a) < 0.42$
- BHs grow by accreting mass: $\text{Power}_{\text{released}} = [\eta/(1-\eta)](dM_{BH}/dt)c^2$
- Self-regulating luminosity

$$L_{Edd} = 4\pi GMcm_p/\sigma$$

1. $L_{Edd,es} = 1.3 \times 10^{38} (M_{BH}/M_{sun})$[XRB, AGN]
2. $L_{Edd,\nu} = 8 \times 10^{53} (E_{\nu}/50\text{MeV})^{-2} (M_{BH}/M_{sun})$[GRB]

AGN and Cosmology: (very) early developments

No. 5052 August 27, 1966 NATURE 949

LETTERS TO THE EDITOR

ASTRONOMY

Evidence on the Evolutionary Character of the Universe derived from Recent Red-shift Measurements

Hoyle and Burbidge[1] have recently examined the red-shifts of a number of quasi-stellar radio sources[2,3] and have plotted their radio flux densities (S) against red-shift (z); they conclude that the results are inconsistent with a cosmological interpretation of these red-shifts.

This communication shows that this conclusion is not valid and that indeed the observed relationship between S and z provides valuable new information on the evolutionary nature of the Universe.

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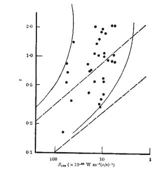
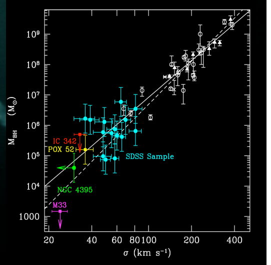


Fig. 1. The red-shift flux density plots expected in evolutionary cosmologies in which density evolution (dashed lines) and luminosity evolution (full lines) are included. The distribution of observational points is that presented by Hoyle and Burbidge restricted to $S_{178} \geq 8 \times 10^{-26}$ W m^{-2}(c/s)$^{-1}$.

Longair 1966

AGN and Cosmology: a shift of paradigm

- BH/Galaxy Scaling relations discovered in 2000 (HST)
- Nowadays QSOs/AGN can:
  - Regulate galaxy formation
  - Stop cooling flows
  - "produce" early type galaxies with the right colors
  - Keep the universe ionized
- QSOs/AGN tracks the history of star formation in the Universe



Gebhardt et al. 2000; Ferrarese et al. 2000; Greene et al. 2005

AGN and Cosmology: a shift of paradigm

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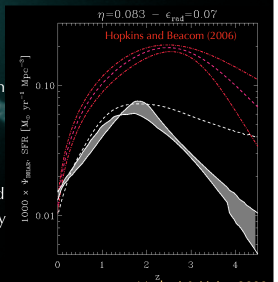
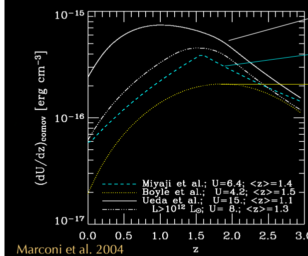


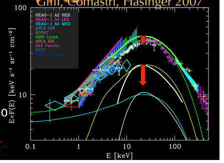
Merloni & Heinz 2008

Recent progresses in AGN activity census

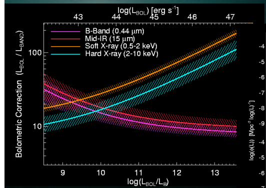


Marconi et al. 2004

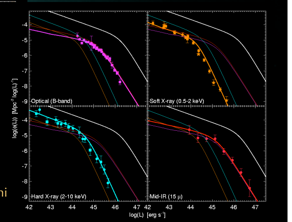
Gilli, Comastri, Hasinger 2007



Bolometric corrections robustness



Crucial: varying X-ray bolometric correction with luminosity (Marconi et al 2004)



Hopkins et al 2006

$$L_{\rm bol} = \epsilon \dot{M}_{\rm acc} c^2 = \epsilon \dot{M}_{\bullet} c^2 / (1-\epsilon)$$

Radiative efficiency

Accretion rate

BH growth rate

Note: radiative efficiency vs. accretion efficiency

radiative efficiency

accretion efficiency (BH spin)

$$\epsilon \equiv \epsilon(a, \dot{m}, \dot{m}_{\rm cr}) = \eta(a) f(\dot{m}, \dot{m}_{\rm cr})$$

Non Spinning BH $0.06 \leq \eta(a) \leq 0.42$ Maximally Spinning BH

$$f(\dot{m}, \dot{m}_{\rm cr}) = \begin{cases} 1, & \dot{m} \geq \dot{m}_{\rm cr} \\ \dot{m}/\dot{m}_{\rm cr}, & \dot{m} < \dot{m}_{\rm cr} \end{cases}$$

Determined by the complex physics of gas accretion

Integral constraints

- Soltan (1982) first proposed that the mass in black holes today is simply related to the AGN population integrated over luminosity and redshift

$$\mathrm{BHAR}(z) = \Psi_{\mathrm{BH}}(z) = \int_0^{\infty} \frac{(1-\epsilon)L_{\mathrm{bol}}(L_{\mathrm{X}})}{\epsilon c^2} \phi(L_{\mathrm{X}}, z') dL_{\mathrm{X}}$$

$$\frac{\rho_{\mathrm{BH}}(z)}{\rho_{\mathrm{BH},0}} = 1 - \int_0^{z} \frac{\Psi_{\mathrm{BH}}(z)}{\rho_{\mathrm{BH},0}} \frac{dt}{dz'} dz'$$ (Normalized SMBH mass density)

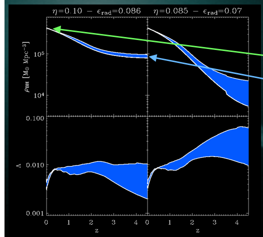
Convergence in local mass density estimates

Table 3. Modification of Table 1. Here, the local SMBH mass density estimates have been fully corrected for their dependence on h, and transformed to $H_0 = 70$ km s^{-1} Mpc^{-1}. While some estimates of $\rho_{bh,0}$ appear not to have changed from Table 1, one should note that the quoted dependence on h may have changed. The term $f(h)$ is used to denote that a more complicated dependence on h exists and needs to be taken into account if one is to transform these values to a different Hubble constant (see, e.g. equation 2).

Study	Method	$\rho_{bh,0}$ (E/S0) $10^5 M_\odot$ Mpc^{-3}	$\rho_{bh,0}$ (Sp) $10^5 M_\odot$ Mpc^{-3}	$\rho_{bh,0}$ (total) $10^5 M_\odot$ Mpc^{-3}	
Graham et al. (2007)	M_{bh} n	$(3.46 \pm 1.16)h_{70}^3$	$(0.95 \pm 0.49)h_{70}^3$	$(4.41 \pm 1.67)h_{70}^3$	✔
Wyithe (2006)	M_{bh} σ	...	...	$(1.98 \pm 0.38)h_{70}^3$	
Fukugita & Peebles (2004)	$\rho_{spheroid}$	$(3.4^{+2.4}_{-1.7})h_{70}$	$(1.7^{+1.7}_{-0.8})h_{70}$	$(5.1^{+2.8}_{-1.9})h_{70}$	✔
Marconi et al. (2004)	M_{bh} (L, σ)	$3.3h_{70}^{0.74} f(h)$	$1.3h_{70}^{0.74} f(h)$	$(4.6^{+1.9}_{-1.4})h_{70}^{0.74} f(h)$	✔
Shankar et al. (2004)	M_{bh} L	$(4.3^{+1.3}_{-1.1})h_{70}^{0.8} f(h)$	$(1.5^{+0.7}_{-0.7})h_{70}^{0.8} f(h)$	$(5.9^{+1.8}_{-1.8})h_{70}^{0.8} f(h)$	✔
Shankar et al. (2004)	M_{bh} σ	$(3.4^{+1.1}_{-0.7})h_{70}^3$	$(1.4^{+0.8}_{-0.3})h_{70}^3$	$(4.8^{+1.2}_{-0.8})h_{70}^3$	✔
McLure & Dunlop (2004)	M_{bh} L	$(4.8 \pm 0.7)h_{70}^{0.8} f(h)$	...	...	
Wyithe & Loeb (2003)	M_{bh} σ	...	...	$(2.1^{+2.4}_{-1.3})h_{70}^3$	
Aller & Richstone (2002)	M_{bh} σ	$(4.5 \pm 1.5)h_{70}^{0.39} f(h)$	$(1.4 \pm 1.3)h_{70}^{0.39} f(h)$	$(5.9 \pm 2.0)h_{70}^{0.39} f(h)$	✔
Yu & Tremaine (2002)	M_{bh} σ	$(2.0 \pm 0.2)h_{70}^3$	$(0.9 \pm 0.2)h_{70}^3$	$(2.9 \pm 0.4)h_{70}^3$	
Merritt & Ferrarese (2001)	$\rho_{spheroid}$	...	...	$4.6h_{70}$	
Salucci et al. (1999)	$\rho_{spheroid}$	$6.2h_{70}^2$	$2.0h_{70}^2$	$8.2h_{70}^2$	

Graham and Driver (2007)

Constraints on avg. radiative efficiency $\langle \varepsilon_{rad} \rangle$



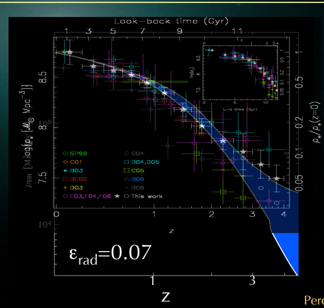
$\xi_0 = \rho_{BH,0} / (4.2 \times 10^5)$

$\xi_i = \rho_{BH}(z = z_i) / \rho_{BH,0}$

(Input from seed BH formation models needed!)

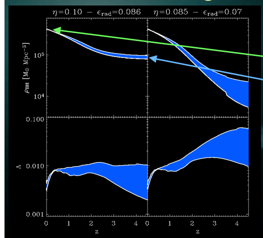
Merloni and Heinz 2008

SMBH vs TOTAL stellar mass densities



Perez-Gonzalez et al.(2007)

Constraints on avg. radiative efficiency $\langle \varepsilon_{rad} \rangle$



$\xi_0=\rho_{BH,0}/(4.2\times10^5)$

$\xi_i=\rho_{BH}(z=z_i)/\rho_{BH,0}$

(Input from seed BH formation models needed!)

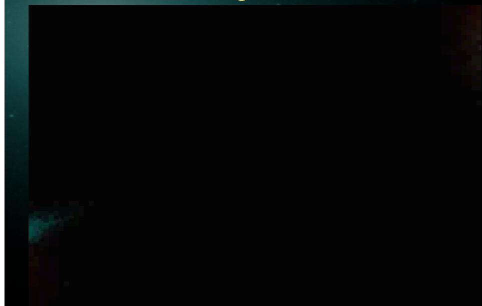
$\xi_{lost}=\rho_{BH,lost}/\rho_{BH,0}$

(Mass density of SMBH ejected from galactic nuclei due to GW recoil after mergers)

$$0.065/[\xi_0\,(1+\xi_{lost})] \leq \langle \varepsilon_{rad} \rangle \leq 0.069/[\xi_0\,(1-\xi_i+\xi_{lost})]$$

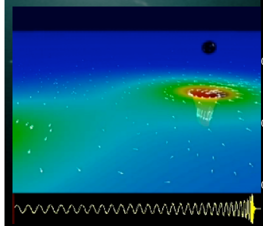
Merloni and Heinz 2008

Excursus: SMBH mergers

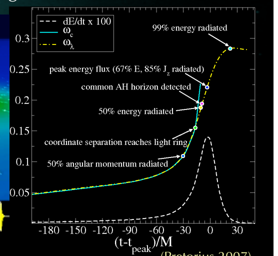


Excursus: SMBH mergers

- Recently, great progress in the general relativistic simulations of coalescing Black Holes (Pretorius 2007)

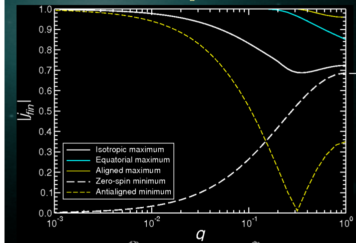


Boyle et al. 2007

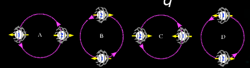


(Pretorius 2007)

Excursus: final spin and GW recoil



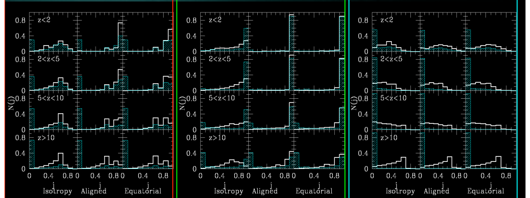
Zero spin, equal mass merger case
Final spin = 0.69
Berti and Volonteri (2008)



Spin in the equatorial plane: maximum kick (>2000km/s)
(Pretorius et al., Buonanno et al)

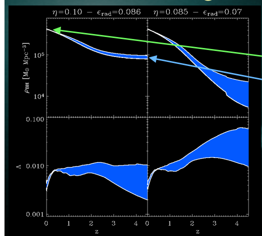
SMBH spin evolution: accretion vs. mergers

Mergers Only | **Mergers+disc accretion** | **Mergers+chaotic accretion**



Berti and Volonteri (2008)

Constraints on avg. radiative efficiency $\langle \varepsilon_{rad} \rangle$



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(Input from seed BH formation models needed!)

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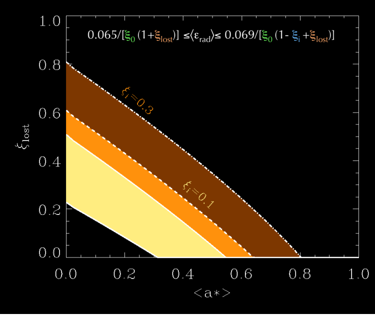
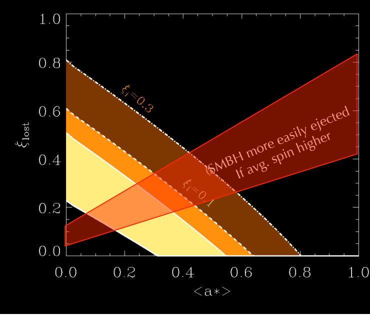
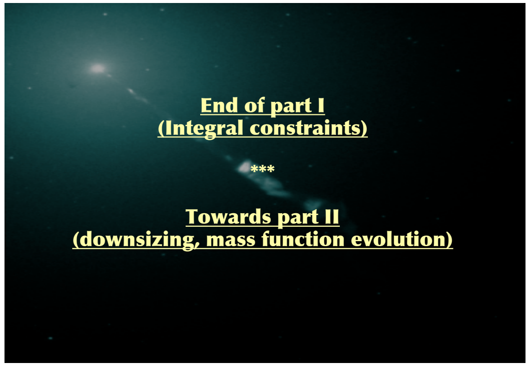
Merloni and Heinz 2008

Constraints on avg. SMBH spin ⟨a*⟩



Constraints on avg. SMBH spin ⟨a*⟩




End of part I
(Integral constraints)
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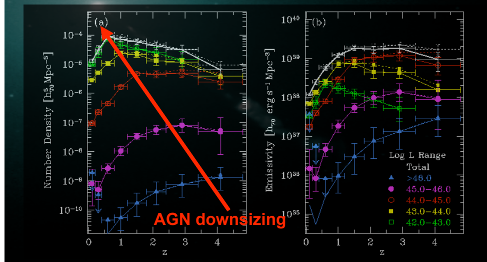
Towards part II
(downsizing, mass function evolution)

AGN/SMBH downsizing: clues from X-rays



Ueda et al. 2003; Fiore et al. 2003; Barger et al. 2005; Hasinger et al. 2005

Unveiling the growth of SMBH

1. BH mass can only increase*
2. BHs do not transform into something else as they grow**
3. BHs are like teenagers: they clearly let us know when they grow up (AGN as signposts of BH growth)

*Kicked BH after mergers can introduce a loss term in the continuity equation
**Merging BH alter the Mass function

Continuity equation for SMBH growth

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

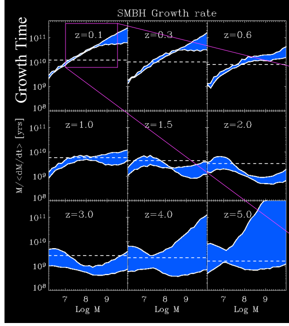
$$\frac{\partial \Phi_{\rm M}(M,t)}{\partial t} + \frac{\partial [\Phi_{\rm M}(M,t) \cdot \langle \dot{M}(M,t) \rangle]}{\partial M} = 0.$$

1- Need to know simultaneously mass function $\Phi_M(M,t_0)$ and accretion rate distribution

2- At any *z* (or t), it is possible to combine mass function and bolometric luminosity function to calculate accretion rate distribution

Picture from Di Matteo et al. (2007)

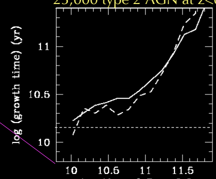
SMBH downsizing



The anti-hierarchical evolution at low z seems reversed at high z

Merloni and Heinz 2008

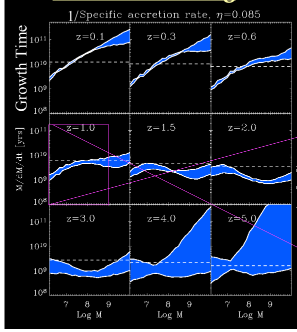
23,000 type 2 AGN at $z<0.1$



$\log M_* \sim 3 \operatorname{Log} M_{BH}$

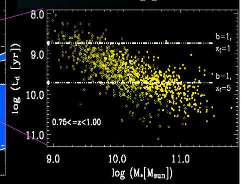
Heckman et al. 2004

SMBH downsizing

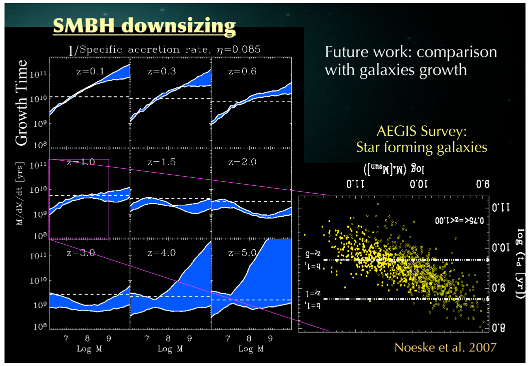


Future work: comparison with galaxies growth

AEGIS Survey:
Star forming galaxies

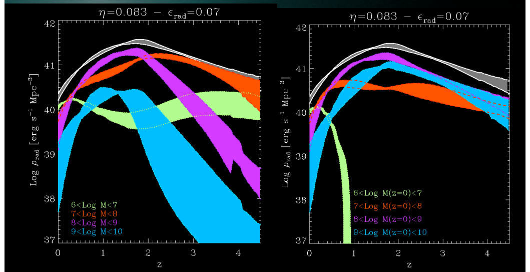


Noeske et al. 2007



SMBH downsizing
1/Specific accretion rate, η=0.085
Growth Time
M/dM/dt [yrs]
z=0.1
z=0.3
z=0.6
z=1.0
z=1.5
z=2.0
z=3.0
z=4.0
z=5.0
Log M
Future work: comparison with galaxies growth
AEGIS Survey:
Star forming galaxies
Noeske et al. 2007

Radiated energy density by BH mass



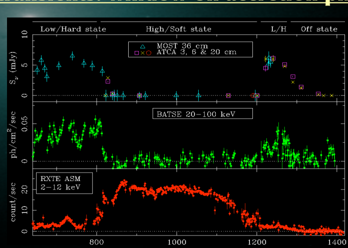
Merloni and Heinz (2008)

We can follow the history of progenitors of local black holes

AGN downsizing: changing accretion modes

- SMBH must accrete at lower (average) rates at later times
- Accretion theory (and observations of X-ray Binaries) indicate that
  - The energy output of an accreting BH depends crucially on its accretion rate
  - Low-accretion rate systems tend to be "jet dominated"
- In the recent Cosmology jargon: Quasar mode vs. Radio mode (explosive vs. gentle)

BH transients: window on accretion physics

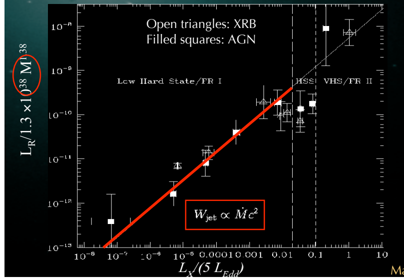


GX 339-4

Fender et al. 1999

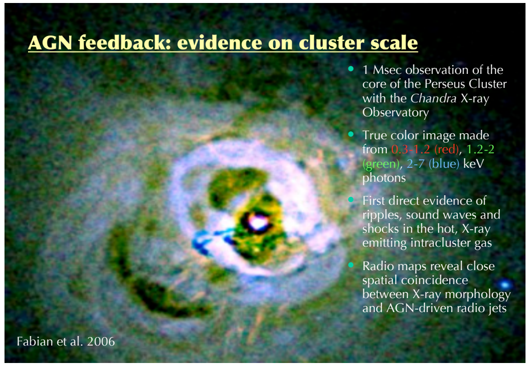
Radio cores scaling with M and mdot

A "fundamental plane" of active BHs [Merloni et al. 2003; Falcke et al. 2004]

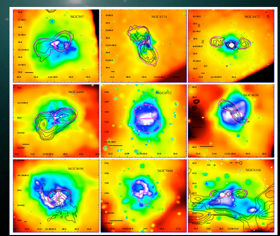


Very little scatter if only flat-spectrum low-hard state sources are considered (Körding et al. 2006)

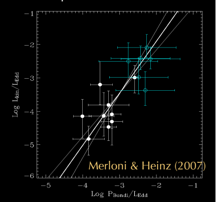
Maccarone et al. 2003


AGN feedback: evidence on cluster scale
1 Msec observation of the core of the Perseus Cluster with the Chandra X-ray Observatory
True color image made from 0.3-1.2 (red), 1.2-2 (green), 2-7 (blue) keV photons
First direct evidence of ripples, sound waves and shocks in the hot, X-ray emitting intracluster gas
Radio maps reveal close spatial coincidence between X-ray morphology and AGN-driven radio jets
Fabian et al. 2006

Estimating Jet power in nearby ellipticals

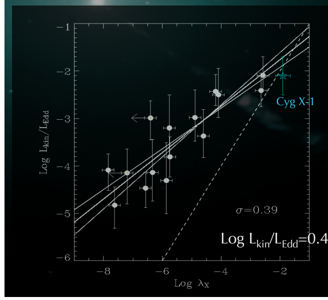


- Allen et al. (2006): correlation between Jet kinetic power and Bondi power



Chandra 0.5-8keV (colour), 1.5GHz VLA radio (contours), bubbles (magenta ellipses).
Allen et al. (2006), Birzan et al. (2004), Rafferty et al. (2006)

Low Power AGN are jet dominated

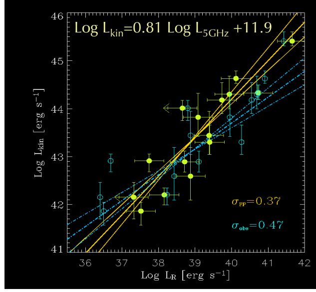


- By studying the nuclear properties of the AGN we can establish a link between jet power and accretion power
- The observed slope (0.50±0.045) is perfectly consistent with radiatively inefficient "jet dominated" models (see E. Churazov's talk)

$$\text{Log } L_{kin}/L_{Edd} = 0.49 \text{ Log } L_{bol}/L_{edd} - 0.78$$

Merloni and Heinz (2007)

Core Radio/L_{Kin} relation: effects of beaming



Slope=0.81

Slope=0.54

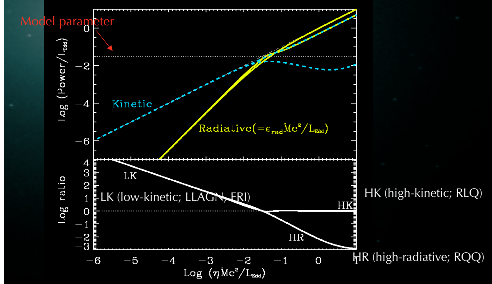
Observed L_R (beaming)
Derived from FP relation

Monte Carlo simulation: Statistical estimates of mean Lorentz Factor Γ~8

Not a distance effect: partial correlation analysis $P_{nul}=2 \times 10^{-4}$

Merloni and Heinz (2007)

Accretion diagram for LMXB & AGN



(Blandford & Begelman 1999, Merloni 2004, Körding et al. 2007)

What is the “radio mode” of AGN?

- The energy source that counterbalance cooling in the cores of groups and clusters. Prevents overproduction of massive galaxies at late times (a FEEDBACK mode; Croton et al. 2006; Bower et al. 2006)
  - CANNOT be associated to QSOs: their number density declines too fast
- A FEEDING mode (hot gas vs. cold gas, Hardcastle et al. 2007)
- HERE: The physical state of ALL black holes at low accretion rate ~less than a few % of the Eddington rate (an ACCRETION mode)

Continuity equation for SMBH growth

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

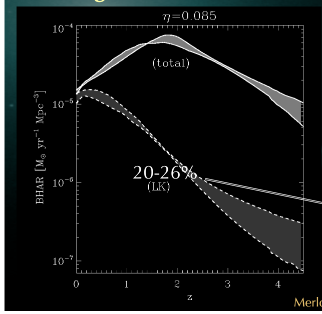
$$\frac{\partial \Phi_{\rm M}(M,t)}{\partial t} + \frac{\partial [\Phi_{\rm M}(M,t) \cdot \langle \dot{M}(M,t) \rangle]}{\partial M} = 0.$$

1- Need to know simultaneously mass function $\Phi_M(M,t_0)$ and accretion rate distribution

2- At any z (or t), it is possible to combine mass function and bolometric luminosity function to calculate accretion rate distribution

3-For each accretion mode, use observed scaling relations between (core) radio and X-ray (bolometric) luminosity to "couple in" the evolution of radio LF

SMBH growth

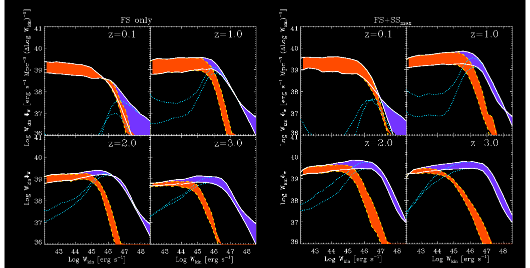


Most of SMBH growth in radiatively efficient mode

ε ≈ 0.065-0.07
Marconi et al. (2004)

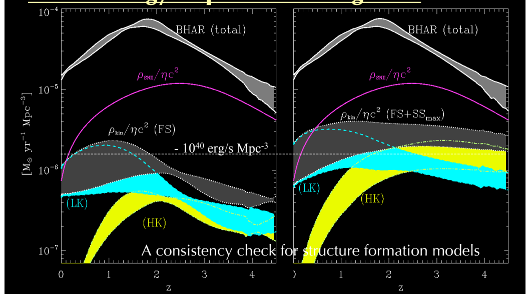
Merloni 2004; Merloni & Heinz 2008

AGN Kinetic Luminosity function



Körding, Jester and Fender (2007); Merloni and Heinz. (2008)

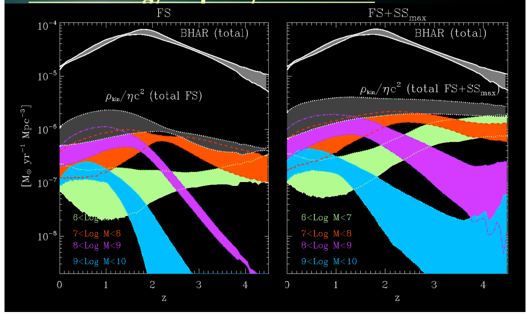
Kinetic Energy output and SMBH growth



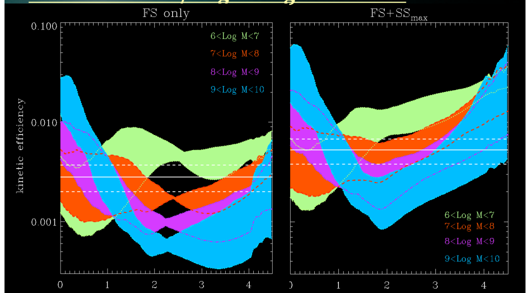
A consistency check for structure formation models

Körding, Jester and Fender (2007); Merloni and Heinz. (2008)

Kinetic Energy output by SMBH mass

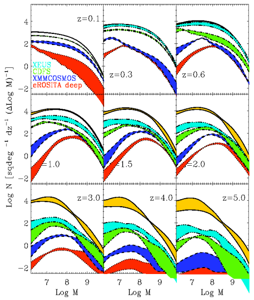


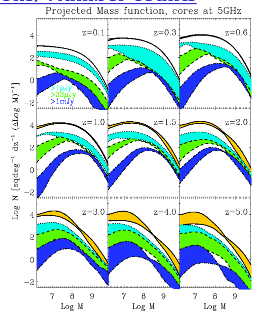
Kinetic efficiency of growing black holes

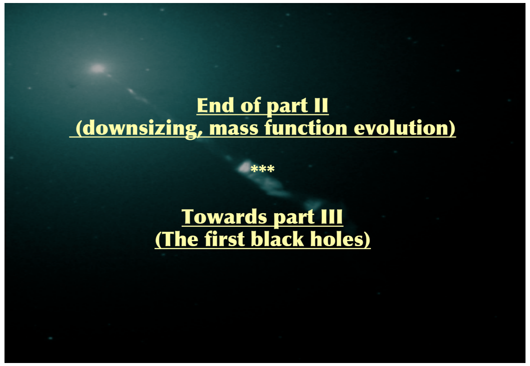


Merloni and Heinz. (2008)

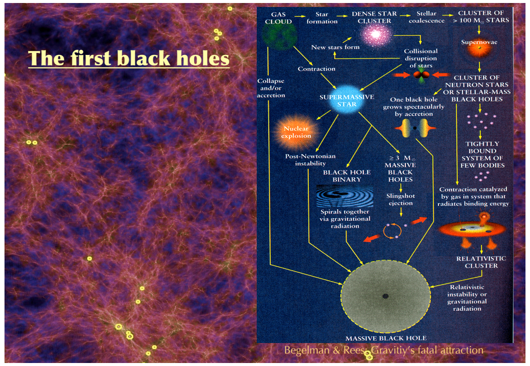
“Active” BH Mass Functions/ Number counts





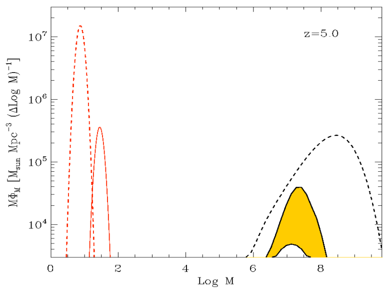

End of part II
(downsizing, mass function evolution)
***
Towards part III
(The first black holes)

The first black holes

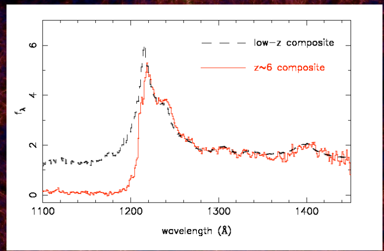


Begelman & Rees: Gravitiy's fatal attraction

Black Holes mass function evolution

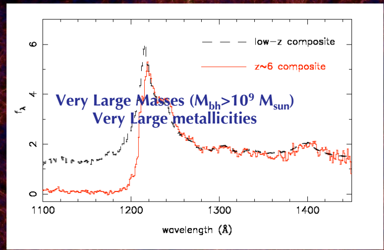


The highest redshift QSOs



Fan et al. (2004)

The highest redshift QSOs



Fan et al. (2004)

The highest redshift QSOs: the time problem

Available time from $z=30$ till $z=6$ is about 0.8 Gyr.
Assume SMBH growth at the **Eddington limit**:

$$dM/dt=(1-\eta)\, L_{edd}/(\varepsilon_{rad}\, c^2)$$

Assuming, for simplicity, $\eta=\varepsilon_{rad}$

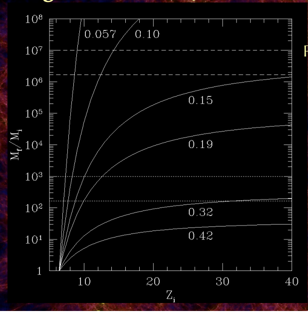
$$M(t)=M(0)\exp\left[(1-\eta)/\eta * t/t_{edd}\right]$$

With $t_{edd}=0.45$ Gyr

↓

Upper limit on η !

The highest redshift QSOs: the time problem



PopIII remnants seeds
($100<M/M_{sun}<600$)

Massive seeds
($10^4<M/M_{sun}<6x10^4$)

Shapiro (2005)

The highest redshift QSOs: efficiency problem

BH growth by accretion via standard thin disc from an initial state with $M=M_i$ and spin $a=a_i$

Spin evolves according to:

$$a_f=(r_{ISCO,i}^{1/2}/3) * \chi * [4-(3 r_{ISCO,I} * \chi^2 -2)^{1/2}]$$

Where $\chi=M_i/M_f$

➔ An initially non-rotating BH is spun up to $a_f=1$ if $\chi=M_i/M_f=6^{1/2} \approx 2.45$

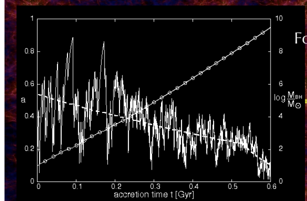
↓

Prolonged coherent accretion episodes imply high efficiency!

Keeping the spin low: chaotic accretion

Accretion proceeds via a succession of small episodes in which the disc angular momentum is always smaller than the hole's one

$$a \approx (M_{disc}/M) r_d^{-1/2}$$



For r_d ~ self-gravitating radius, M_{disc} ~ 0.1% M

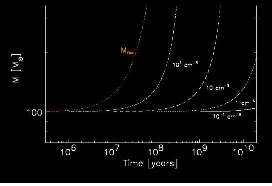
King and Pringle (2006)
King et al. (2008)

More problems: fueling rates

$$\frac{dM_{\rm BH}}{dt}|_{\rm Bondi} = \frac{2\pi(1-\eta)(GM_{\rm BH})^2 m_{\rm H} n}{c_{\rm s}^3}$$

$$\frac{M_{\rm BH}}{M_i} = \frac{1}{1 - t/t_{\rm Bondi}}$$

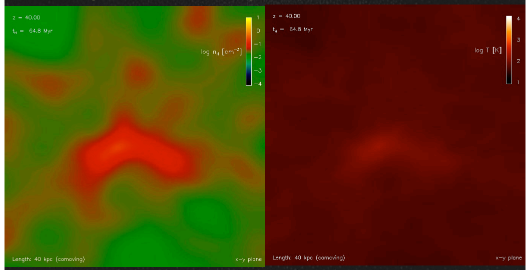
$$t_{\rm Bondi} \simeq 3.5\times10^8 \left(\frac{M_i}{100M_\odot}\right)^{-1} \left(\frac{0.9}{1-\eta}\right) \left(\frac{T}{200K}\right) \left(\frac{n}{cm^{-3}}\right)^{-1} \ {\rm yrs}$$



Johnson and Bromm (2007)

Simulations **without feedback** found very low gas densities ($<1cm^{-3}$ for $\sim10^8$ yrs) around first PopIII stars

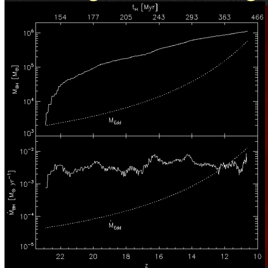
Fueling rates: the first galaxy

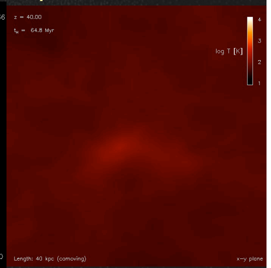


Simulations without feedback of atomic hydrogen cooling halo ($T>10^4K$)

Grief et al. (2008)

Fueling rates: the first galaxy

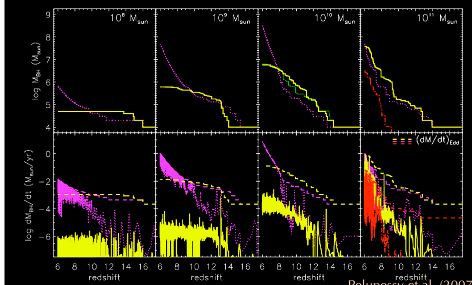




Simulations without feedback of atomic hydrogen cooling halo ($T>10^4$K)

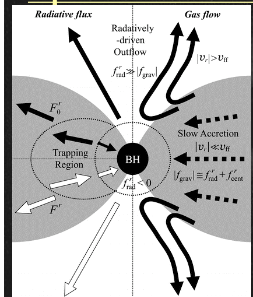
Grief et al. (2008)

Fueling rates: effect of feedback

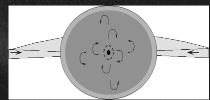


Pelupessy et al. (2007)

Supercritical Accretion and Quasistars



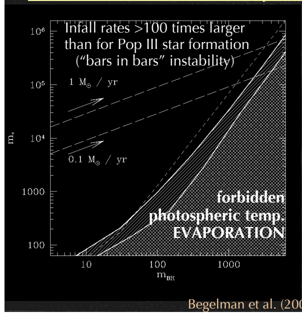
Begelman et al. '82; Ohsuga et al. (2007)

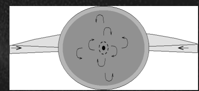


Begelman et al. (2006;2008)

- In a **supercritical accretion** disc (left) BH growth rate can be super-Eddington, as the photons are trapped in the flow
- In a **Quasistar**, a BH sits in the center of a convective envelope and grows at the Eddington rate of a supermassive star

Growth and death of a Quasistar

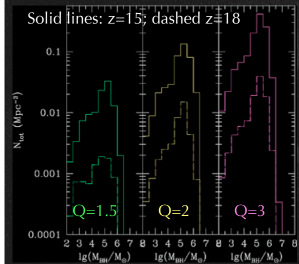




- A PopIII **Quasistar** may form by direct collapse in the core a pristine pre-galactic halos where atomic hydrogen cooling is efficient
- In less than a million years a 10^4 BH may be born

Begelman et al. (2008)

Predictions: early (seed) BH mass functions

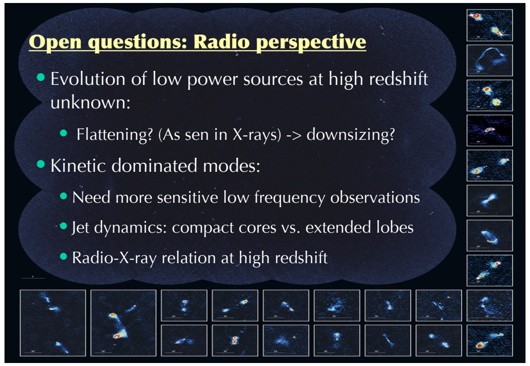


- Using a model for gas collapse in pre-galactic halos that ccounts for **gravitational stability and fragmentation**
- Q is a **stability** parameter: lower Q implies more stable discs

Volonteri et al. (2008)

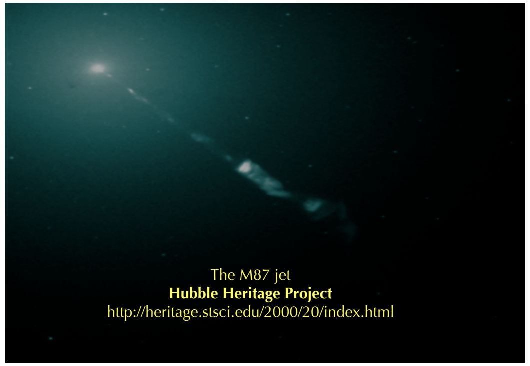
Conclusions: SMBH evolution at z<4

- SMBH grow with a broad accretion rate distribution
- Most of SMBH growth occurred in radiatively efficient episodes of accretion.
- The anti-hierarchical trend is clearly seen in the low-z evolution of SMBH mass function. Reversal at higher z?
- Feedback from "Low-luminosity AGN" are most likely dominated by kinetic energy
- The efficiency with which growing black holes convert mass into mechanical energy is 0.3-0.5% (but strongly dependent on BH mass and redshift).


Open questions: Radio perspective
Evolution of low power sources at high redshift unknown:
Flattening? (As sen in X-rays) -> downsizing?
Kinetic dominated modes:
Need more sensitive low frequency observations
Jet dynamics: compact cores vs. extended lobes
Radio-X-ray relation at high redshift

Open questions: the first Black holes

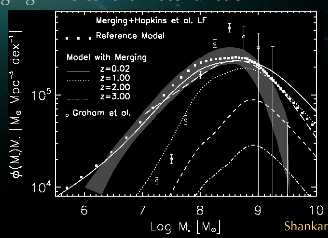
- What typical mass (where the peak of Mass Function)
  - PopIII star remnants vs. direct collapse
- What growth mode:
  - Standard accretion vs. chaotic accretion vs. super-critical accretion
- What is the mass of typical host halo
  - Correlation function
  - Early M-sigma?


The M87 jet
Hubble Heritage Project
http://heritage.stsci.edu/2000/20/index.html

Footnotes:

*Kicked BH after mergers can introduce a loss term in the continuity equation

**Merging BH alter the Mass function



Shankar et al. 2007