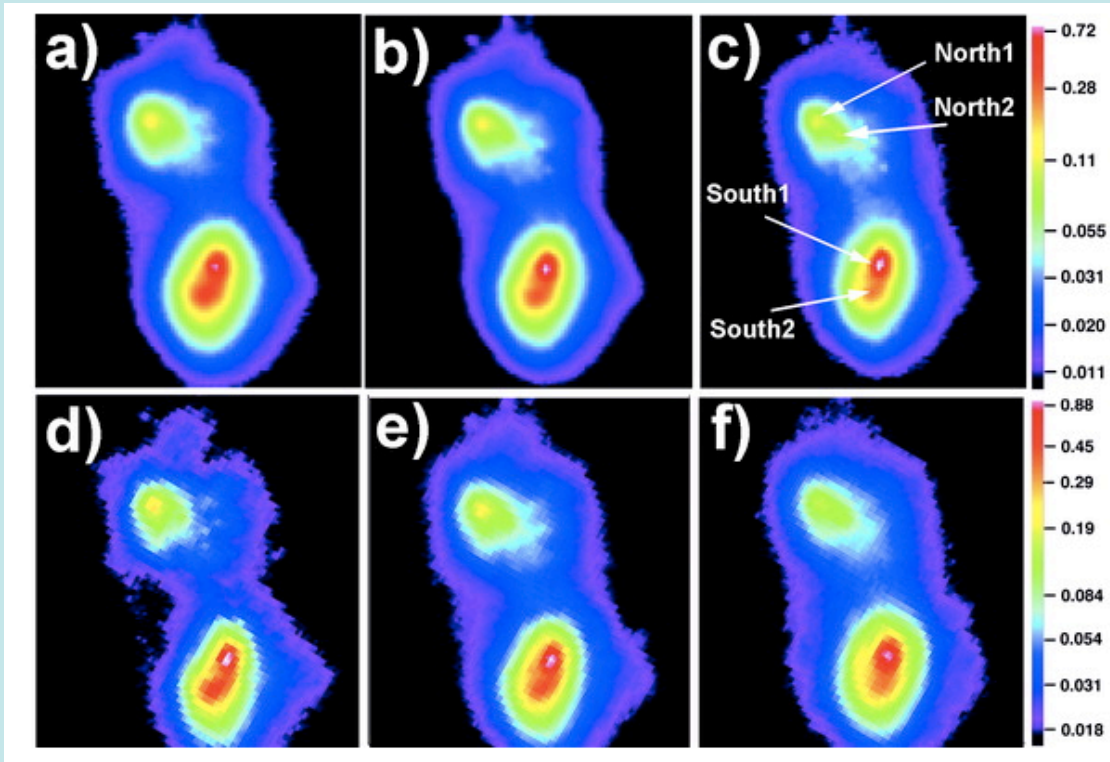
The formation of the first black holes



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ICGC, Goa, India   December 19, 2011

Talk outline

- The context - what do we know for certain about the accretion history of BHs?
- Observational evidence for BHs
- How did the first BHs form?
- How did they grow?
- Discriminating Pop III seeds from massive seeds
- Evidence for massive black hole seeds from high and low redshift
- Future prospects

Collaborators: Giuseppe Lodato, Ezequiel Treister, Marta Volonteri, Andrew Davis

BH accretion: what we do know

- The critical luminosity when radiation pressure balances gravity is the Eddington limit
- Depends on mass of accreting object and opacity of the surrounding gas

$$f_{rad} = f_{grav}; \frac{\kappa L}{4\pi c r^2} = \frac{GM}{r^2}; L_{Edd} = \frac{4\pi c G M}{\kappa_T} = 1.25 \times 10^{45} \left(\frac{M}{10^7 M_{sun}} \right) \text{erg s}^{-1}$$

Gas flowing toward black holes produces radiation as the gravitational potential energy is released

$$L_{accretion} = \varepsilon \dot{M} c^2$$

accretion luminosity

radiative efficiency of the accretion process = the *fraction* of the rest mass energy of the gas that is radiated

gas inflow rate (the accretion rate): units g s^{-1}

For a BH accreting gas through a disk, the radiative efficiency ~ 0.1

Characteristic growth timescale

- Bright quasars must have M > 10^8 Msun
- Eddington limit caps growth rate of mass

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

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

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

Salpeter timescale

Energy output from accreting BHs

- Accretion=> Gravitational Energy=> EM radiation

If all energy is thermalized, Black body with temperature

$$T_b = \{\frac{L_{acc}}{4\pi R^2 \sigma}\}^{\frac{1}{4}}$$

For SMBHs:

$$M \approx 10^8 M_{sun}; R = \frac{2GM}{c^2} \approx 3 \times 10^{13} cm$$

$$T_b \approx 10^7 (\frac{M_{sun}}{M})^{\frac{1}{4}} K \approx 10^5 K$$

Expect accreting BHs to be UV, X-ray and possibly gamma-ray emitters

Approach to building accretion histories

- Globally averaged constraint (Soltan 1982)

census of the total energy emitted by a population of accreting BHs

$$E = \iint E(L,t)\,dL\,dt = \frac{4\pi}{c}\int (1+z)\,dz \int n(S,z)\,S\,dS$$

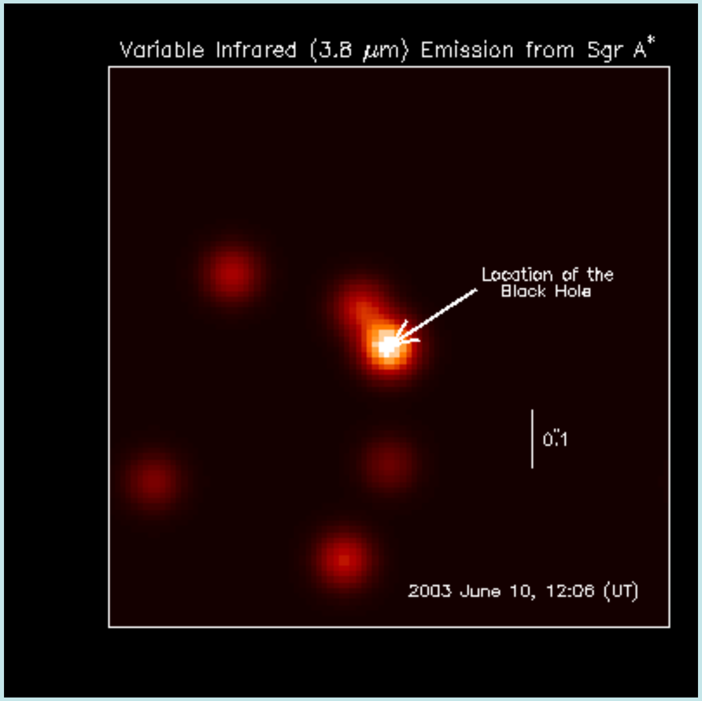
$$\rho_{BH} = \int_0^{t_{age}} dt \int_0^{\infty} d(\ln L)\,L\phi(L,t)$$

- Continuity argument for mass accumulation as a function of time (Small & Blandford 1992; Haehnelt, PN, Rees 1998, Haiman & Loeb 1999……Volonteri et al. 2005; Merloni & Heinz 2008)

attempt to relate the observed evolution of quasars to physical models of AGN

Astrophysical environment of BHs

Empirically, two modes of accretion in galactic nuclei, X-ray binaries



UCLA Galactic Center group

- radiatively inefficient accretion

e.g. Galactic Center

$$\dot{m} \equiv \dot{M} / \dot{M}_{Edd} \sim 10^{-7}$$

(Shcherbakov et al. 2010; Narayan & Yi)

Ubiquitous: fed by stellar winds,
"hot" $T_{ion} \sim T_{vir}$ quasi-spherical flow

- thin disk accretion: radiatively efficient (e ~ 0.1) AGN mode

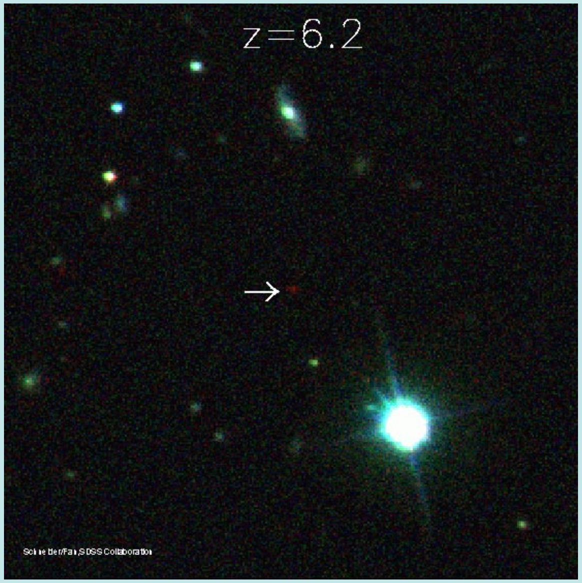
Feeding mechanism unclear, rare in the local Universe

Typical merger environment *only* if thin disks **cause** or are otherwise preferentially correlated with BH coalescences

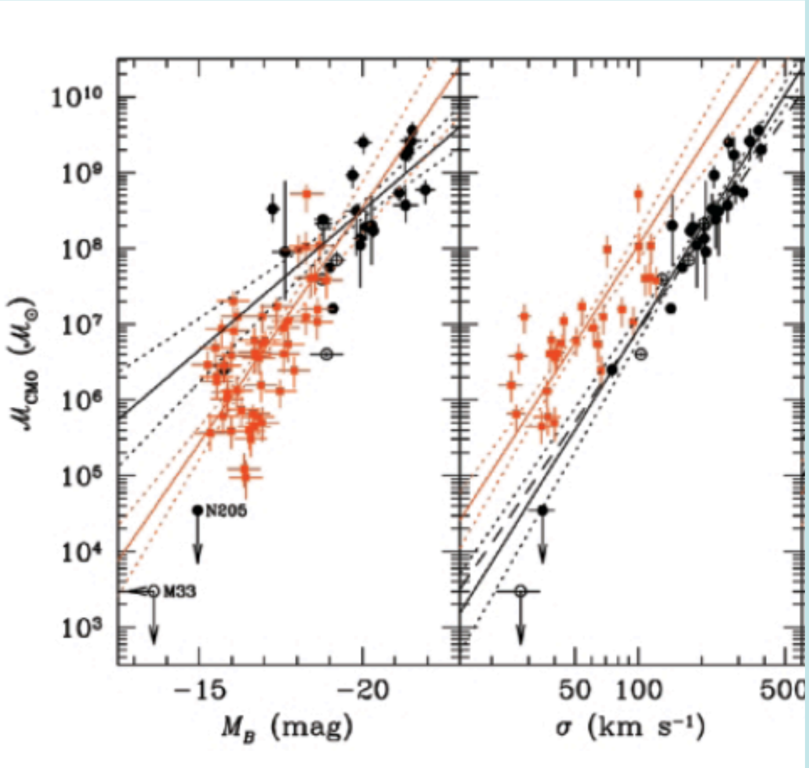
Observations from high and low redshift

Abundance & LF of
High redshift quasars

Age of the
Universe 2 Gyr!



Most recent census from
SDSS and 2dF Fan+ 2007;
Croom+ 2004



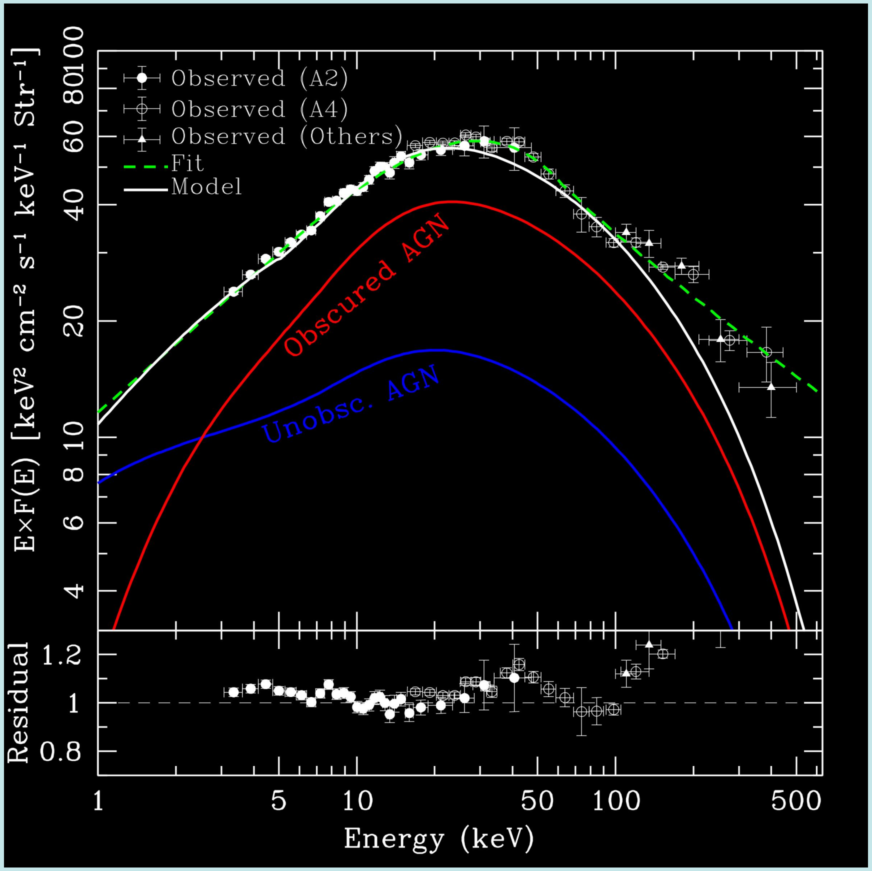
Observational estimates of masses of
central massive objects

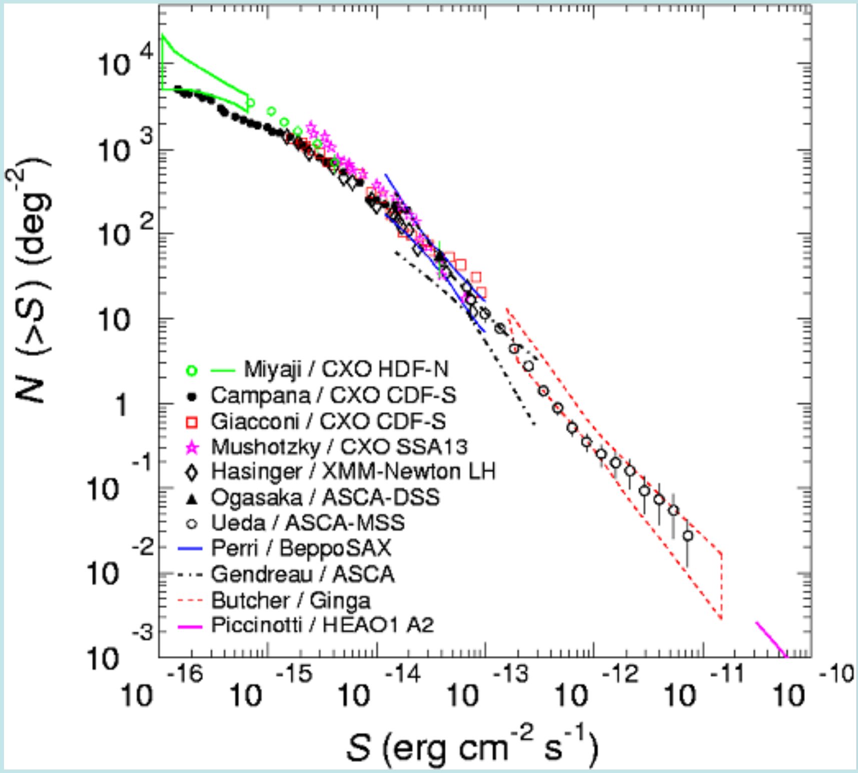
observed correlation between bulge
luminosity and BH mass => BH mass
and vel. Disp

Ferrarese+ 2006; Ferrarese & Merritt
2002; Tremaine+ 2002; Kaspi+ 2005

The X-Ray Background (XRB) spectrum and number counts

- The XRB is the integrated emission from all AGNs in the Universe, the energy density peaks at ~ 30 keV
- The shape of the XRB indicates that most of the AGNs are obscured, harder energies needed to detect the contribution of these obscured sources

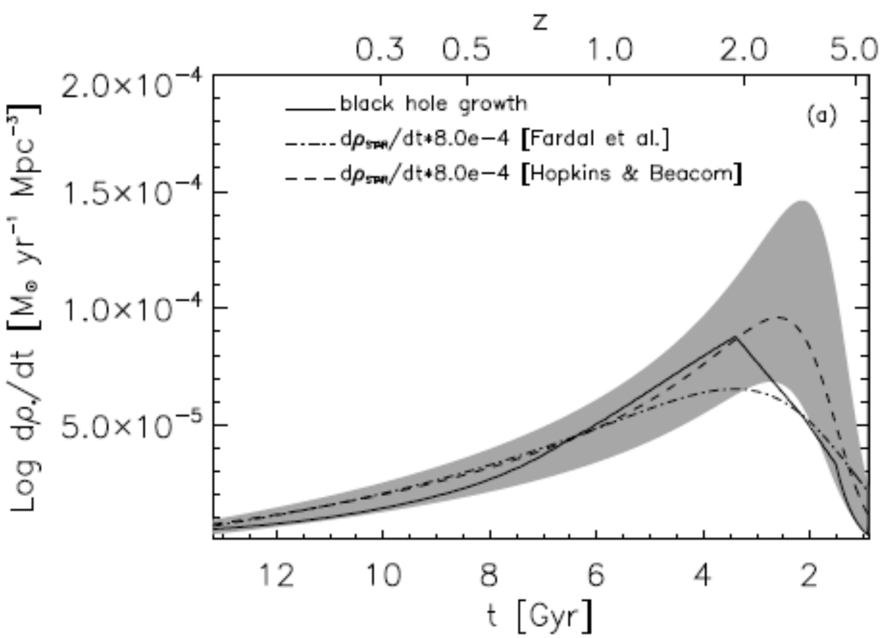




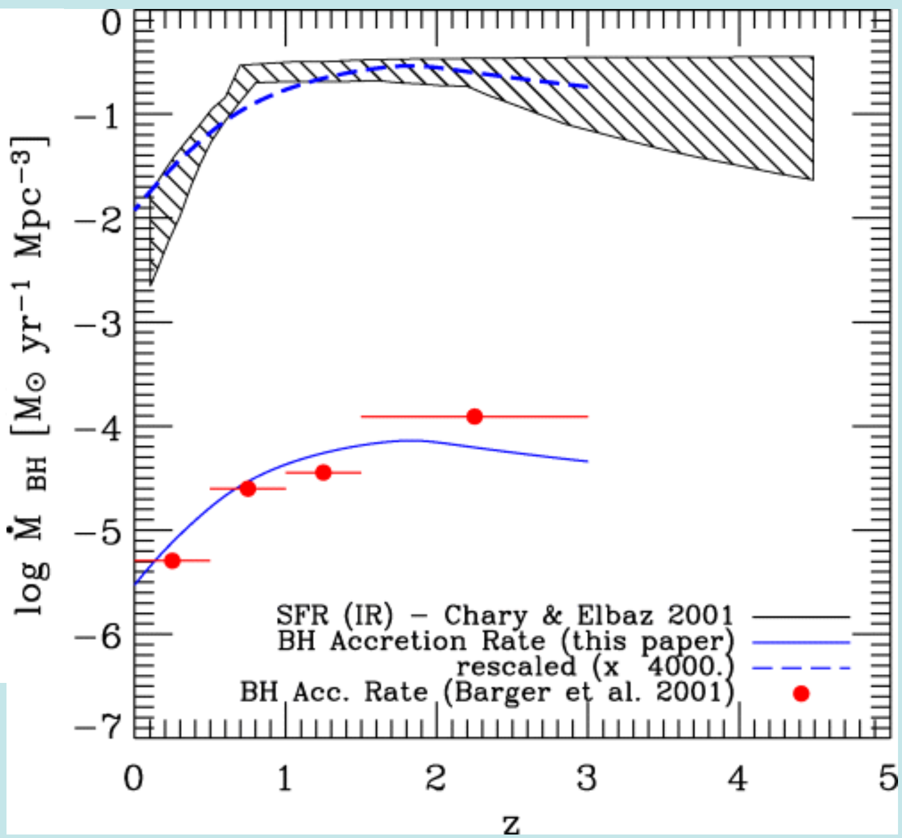
Comastri+ 1995; Ueda+ 2003; Treister & Urry 2005; Merloni+ 2004; PN & Treister 2008

Co-evolution of galaxy and super massive black holes in galactic centres

BH mass vs stellar mass



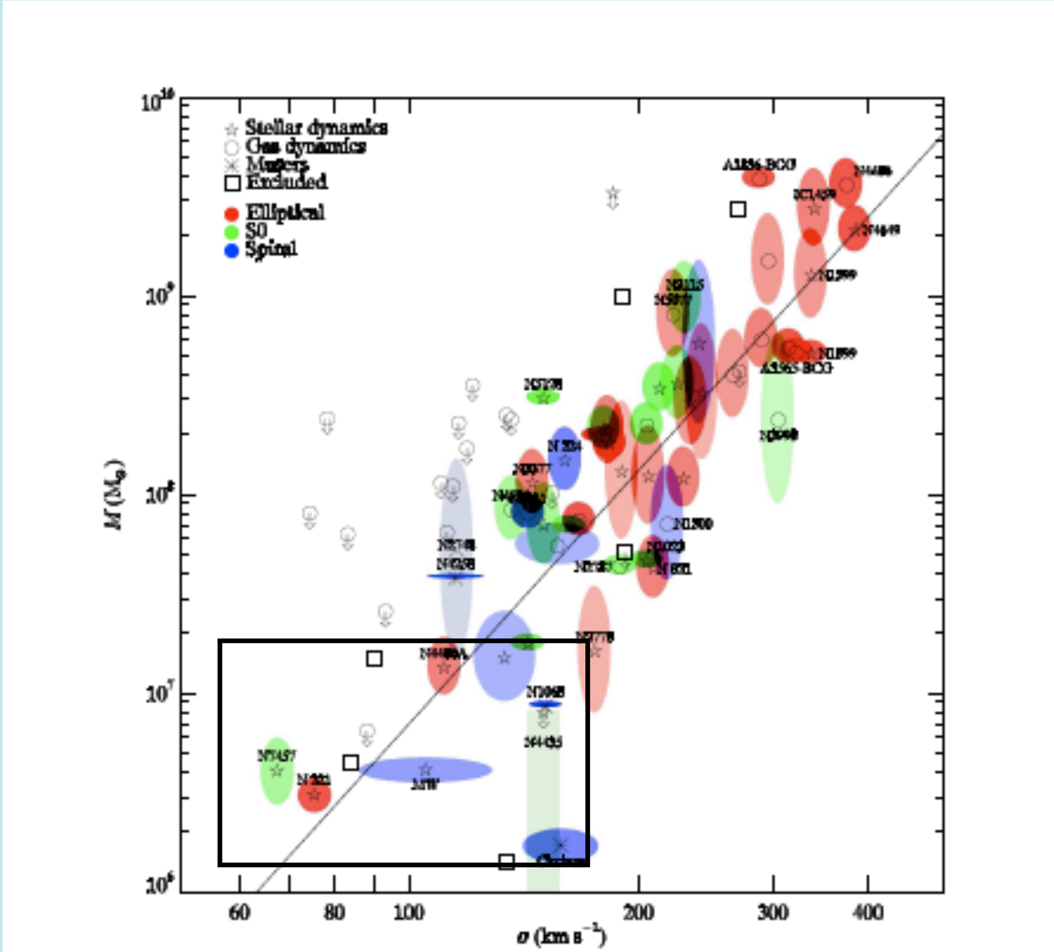
Star forming history vs accretion history



e.g., Marconi & Hunt 2003; Shankar, Weinberg & Miralda-Escude 2007

Marconi+ 2004

The M_{bh}-sigma relation



Most recent estimates: Gultekin+ 2010; Greene & Ho 2009, Greene+ 2011; Reines+ 2011

What is the origin of M-sigma?

- Merging history of DM halos naturally provides correlation
- Slope and scatter contain information on black hole seeds and feedback processes

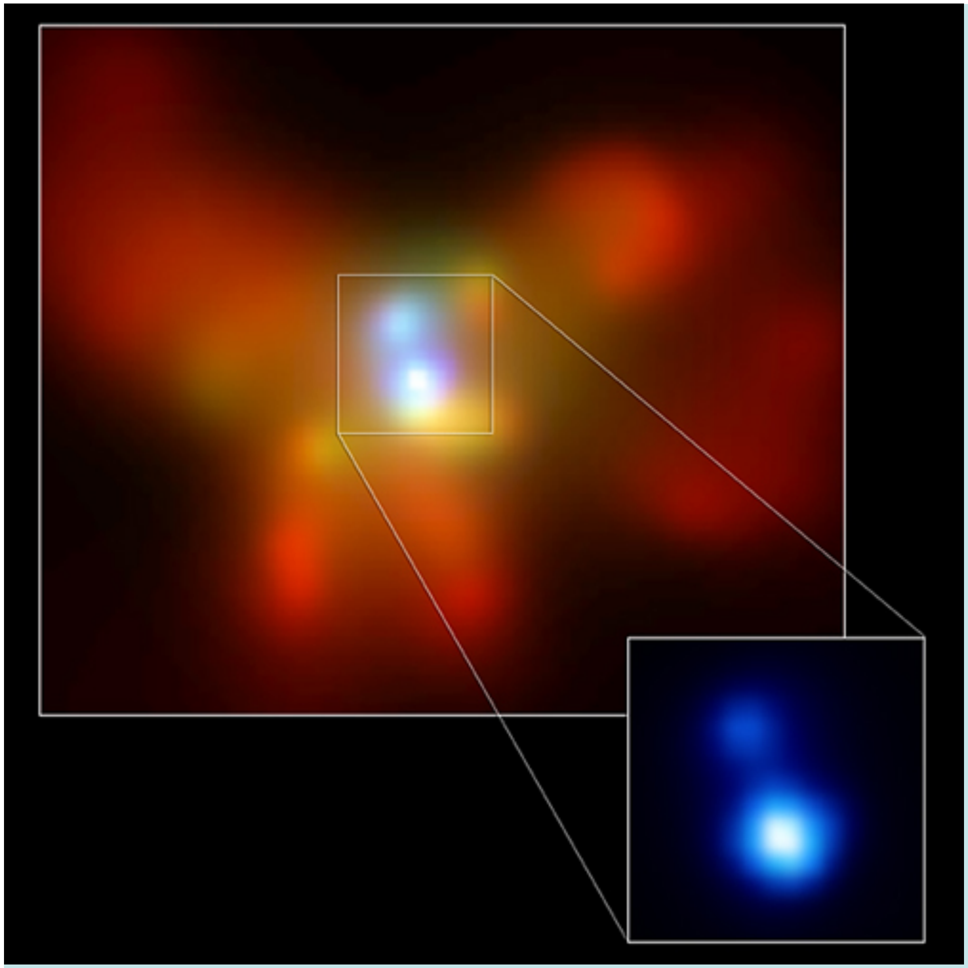
WHAT ARE THESE SIGNATURES?

Does an initial correlation between seed masses and halo masses survive the merging and accretion history of mass build up over cosmic time?

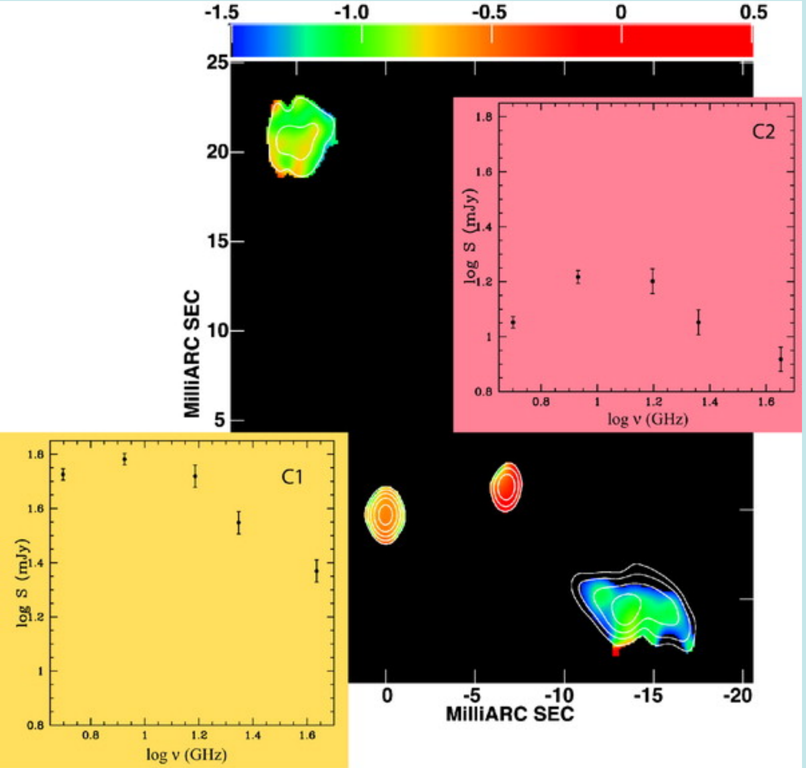
Volonteri & PN 08; Peng 07

Observationally

Handful of identified pre-merger binary black holes



NGC 6240: d ~ kpc
Komossa+ 2003



0402+379: d = 7pc (Rodriguez+ 2006)

Challenges posed by high-z quasars

- Properties of high redshift quasars (10 found at $z > 6$ in SDSS, 20 in CFHQS; record $z = 7.08$ Mortlock et al. 2011)
- Luminosities suggest $M_{bh} = L_{obs}/L_{Edd} \sim 10^{9-10}$ Msun assembled and in place when $t = 0.77$ Gyr
- And these are just the tip of the iceberg!
- Number of e-foldings required for a Pop III seed ~ 25 in the time available
- Need to be accreting steadily at Eddington or super-Eddington the entire time

Conditions for BH seeds

STELLAR SEEDS

* uninterrupted near-Eddington accretion onto ~100 M_{sun} seed
* continuous gas supply
* need to avoid radiative feedback depressing accretion rate
* must avoid ejection from halos and loosing BHs

DIRECT COLLAPSE

* rapid formation from direct collapse of gas or via supermassive star, quasi-star, or ultra-dense star cluster
* gas must be driven in rapidly (deep potential)
* transfer angular momentum and must avoid fragmentation

Pathways to making BH seeds

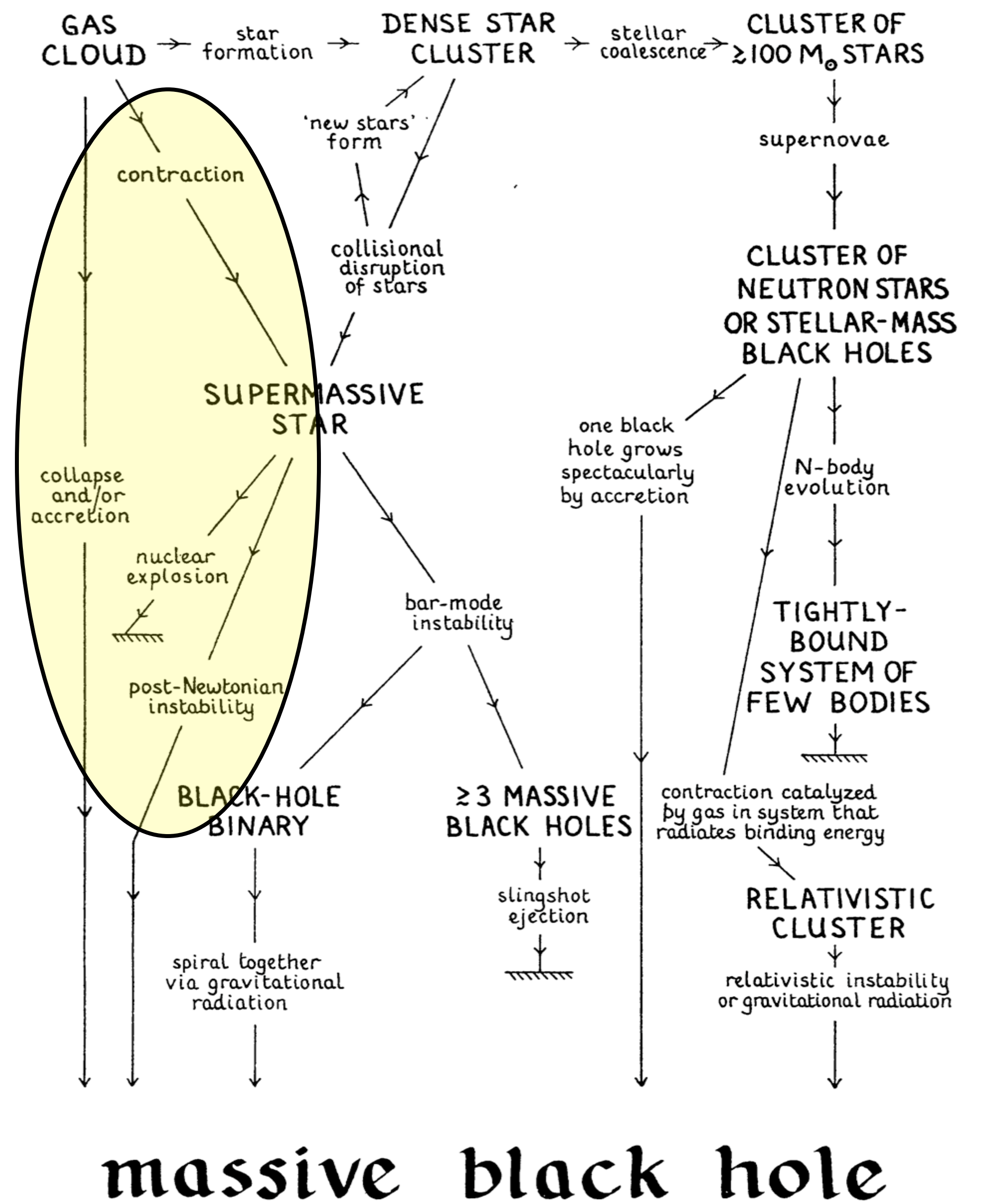


Figure 1 Schematic diagram [reproduced from Rees (106)] showing possible routes for runaway evolution in active galactic nuclei.

Rees 1978

First black holes in pre-galactic halos z ~20-30

$M_{BH} \sim 100 - 500\ M_{sun}$

Pop III remnants

Simulations suggest that the first stars were massive 100 - 500 M_{sun} (Bromm+ 2002 ; Abel+ 2002; Abel+ 2000; Alvarez+ 2008)

Metal free Pop III stars with $M > 260\ M_{sun}$ leave remnant BHs with $M_{seed} > 100\ M_{sun}$ (Fryer, Woosley & Heger)

$M_{BH} \sim 10^3 - 10^6\ M_{sun}$

Viscous transport - efficient angular momentum transfer,

formation of central concentration (Eisenstein & Loeb 1995; Koushiappas+ 2004)

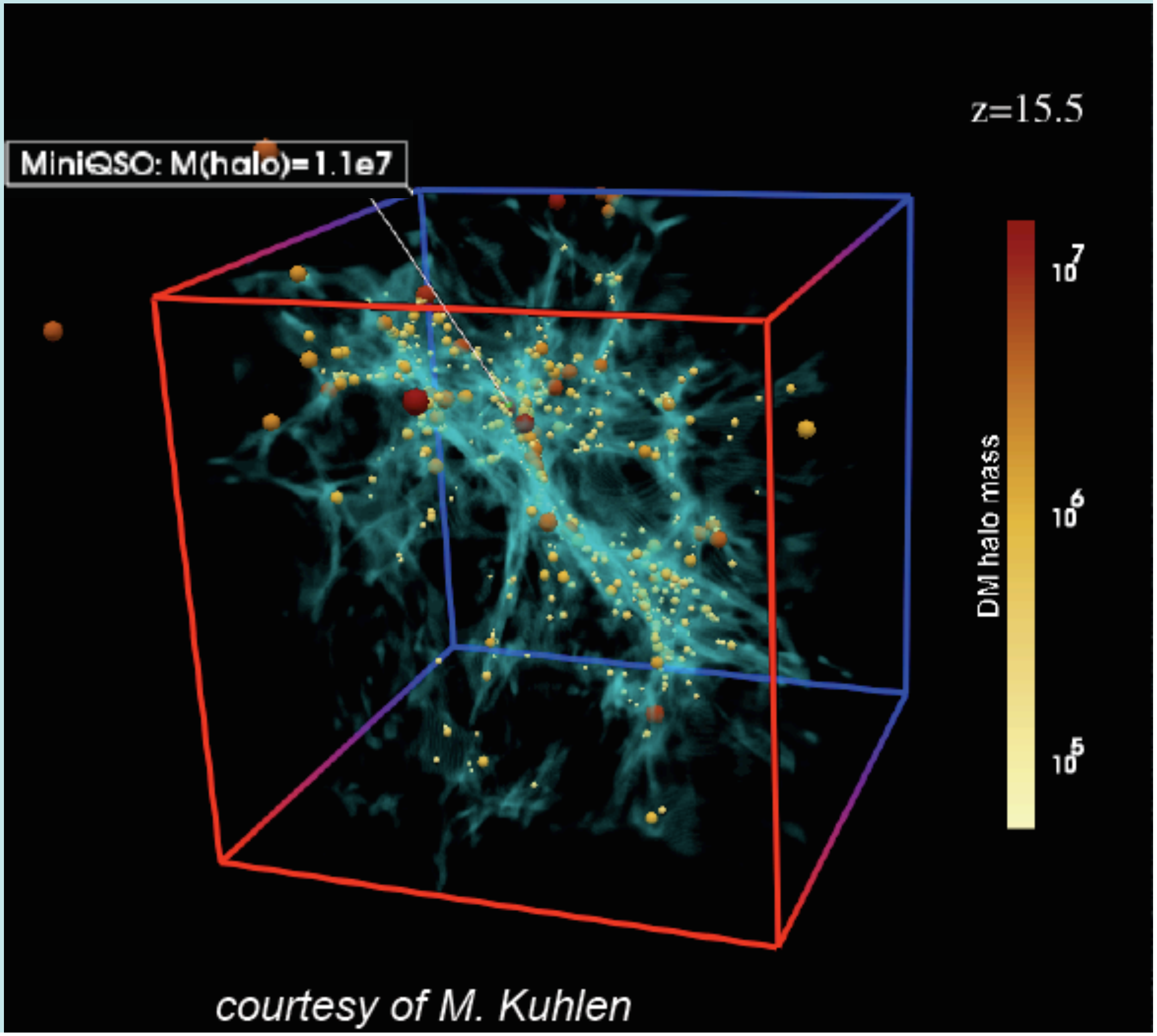
+ proper dynamical treatment of disk stability (Lodato & PN 2006, 2007)

Supermassive star (Haehnelt & Rees 1993)

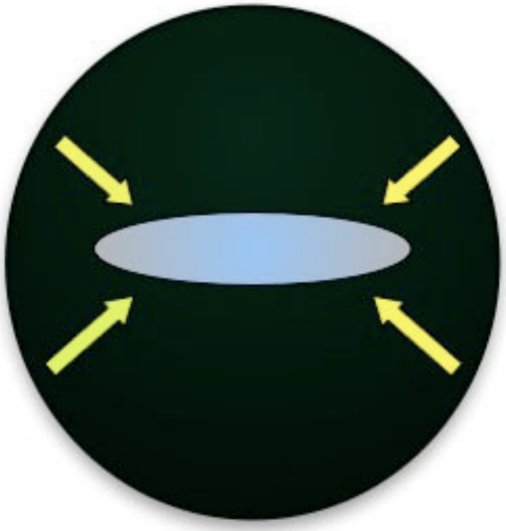
Bar unstable self-gravitating gas + large quasi-star (Begelman, Volonteri & Rees 2006)

First black holes

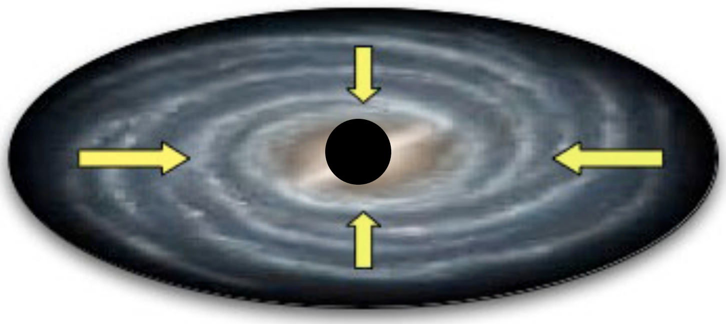
- Unclear if PopIII remnants will do as seeds (Alvarez+ 2008!)
- Other ways of making more massive BH seeds need to be considered



BH seed formation at high z



Baryons inside DM halo collapse and form a rotating pre-galactic disc



Disc becomes gravitationally unstable and accretes to the center

Lodato & PN 2006, 2007

Sequence of events

DM halo mass M, T_{vir}, no metals, gas mass $f_b M$
hot disc ~4000 K, cold disc ~ 400 K

↓

$T_{vir} > T_{gas}$ gas collapses and forms rotationally supported disc, disc subject to grav. instabilities, onset when Toomre Q_{crit} ~ 1 - 3

Disc evolution tussle between accretion and fragmentation

↓

Bars lead to redistribution of J, feed matter to center continues till central mass stabilizes the disc

Accumulated central mass depends on spin, halo mass, T_{gas}/T_{vir}, max. spin for which the disc is grav. Unstable, provides upper bound on M_{BH}

Evolution of self-gravitating discs

- Controlled mainly by two parameters:

$$Q = \frac{c_s \kappa}{\pi G \Sigma}$$

$$t_{cool}\Omega = \frac{t_{cool}}{t_{dyn}}$$

- $Q>1$ non-self-gravitating
- $Q \sim 1$ subject to grav. instabilities
- $t_{cool}/t_{dyn} < 1$ fragmentation
- $t_{cool}/t_{dyn} > 1$ self-regulation

- Zero-metallicity: long cooling times --> fragmentation can be avoided

- When disc self-regulated, steady ang. mom. transport

- Max. mass accretion rate

$$\dot{M}_{max} = 2\alpha_{crit}\frac{c_s^3}{G}$$

$$\dot{M}_{max} \approx 10^{-2} M_\odot/\mathrm{yr}$$ No H_2

$$\dot{M}_{max} \approx 3\ 10^{-4} M_\odot/\mathrm{yr}$$ H_2 present

$\alpha_{crit} \sim 0.06$ (Rice, Lodato & Armitage 2005)

(Gammie 2001, Lodato & Rice 2004, 2006, Mayer et al., Durisen et al., etc....)

For large M, the internal torques needed to redistribute J too large to be sustained, causes disc to fragment when $T_{vir} > T_{max}$

Happens for critical value of $\alpha \sim 0.06$ in Keplerian discs

Fragmentation is rapid, timescale local dynamical time stops when enough mass is converted into stars to make disc stable, no J losses, no mass funnelled to center

Key property is T_{gas}, atomic or molecular H cooling
2 extreme cases: fragmentation quenches accretion and fragmentation not taken into account in all previous treatments

$$\frac{dn}{dM_{bh}}(M_{bh};z) = \int_{M(T_{min})}^{M(T_{max})} \frac{dn}{dM}(M;z)\, p[\lambda(M_{bh},M)] \left| \frac{d\lambda}{dM_{BH}} \right| dM$$

n(M) of DM halos Sheth & Tormen 1999; Gammie+ 2001; Rice & Lodato 2005

Conditions to assemble a central mass rapidly

- Small baryon angular momentum (spin parameter $\lambda<0.05$) ---> disc becomes grav. unstable
- Avoid fragmentation:
  - Need long cooling times: zero-metallicity, atomic hydrogen dominated cooling (high redshift)
  - Small infall rates from the halo (relatively low DM halo mass)
- Final state known: the disc will be exactly marginally stable ($Q=Q_c$) and excess mass will have been accreted at the center

$$M_{\mathbf{BH}} = m_{\mathrm{d}} M \left[1 - \sqrt{\frac{8\lambda}{m_{\mathrm{d}} Q_{\mathrm{c}}} \left(\frac{j_{\mathrm{d}}}{m_{\mathrm{d}}} \right) \left(\frac{T_{\mathrm{gas}}}{T_{\mathrm{vir}}} \right)^{1/2}} \right]$$

Fragmentation criteria

3 interesting regimes:

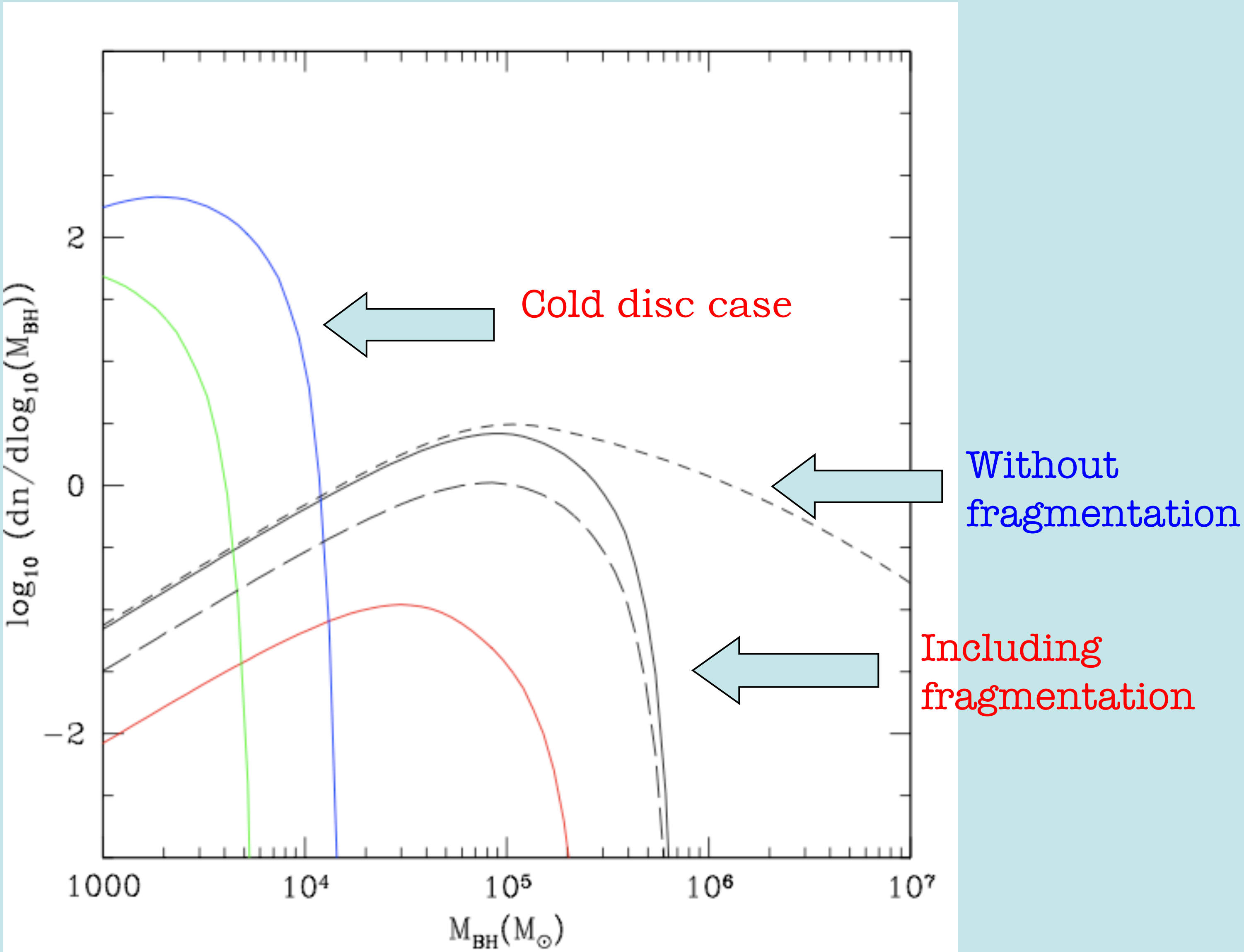
$T_{vir}/T_{gas} > 3$ will fragment and form stars and no central mass concentrations

$2 < T_{vir}/T_{gas} < 3$ will fragment and form stars and central mass concentrations

$T_{vir}/T_{gas} < 2$ will not fragment to form stars, will accrete gas into central mass concentrations that will form BHs

Oh+ 2003; Lodato & PN 2006

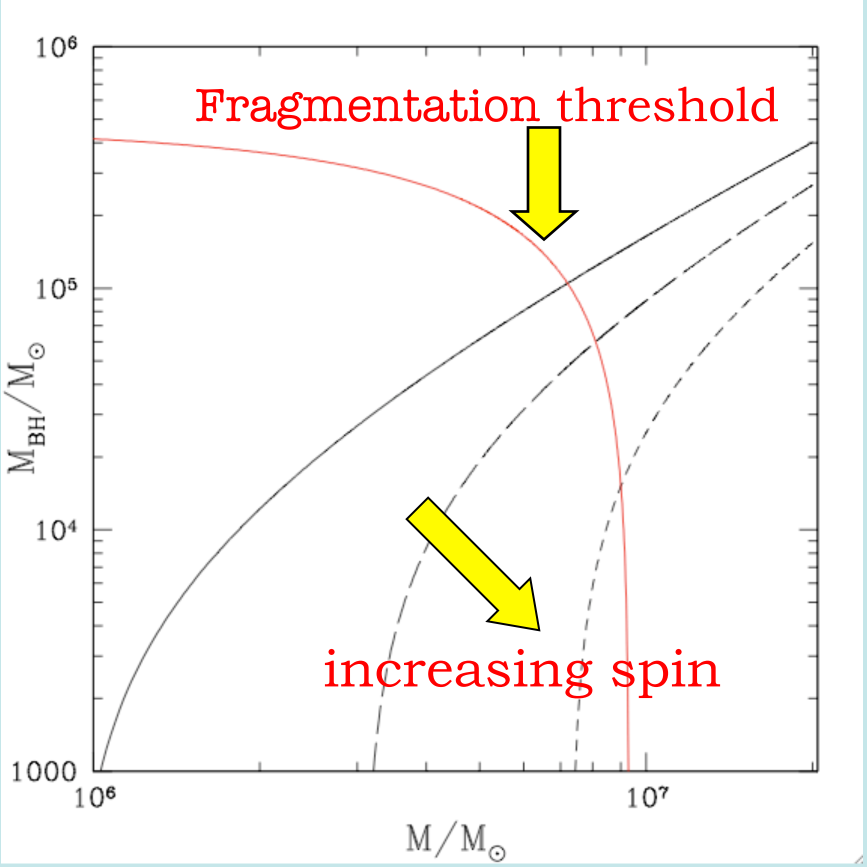
Mass function of seed BHs at z = 15



Koushiappas+ 2004; Lodato & PN 2006a, 2006b

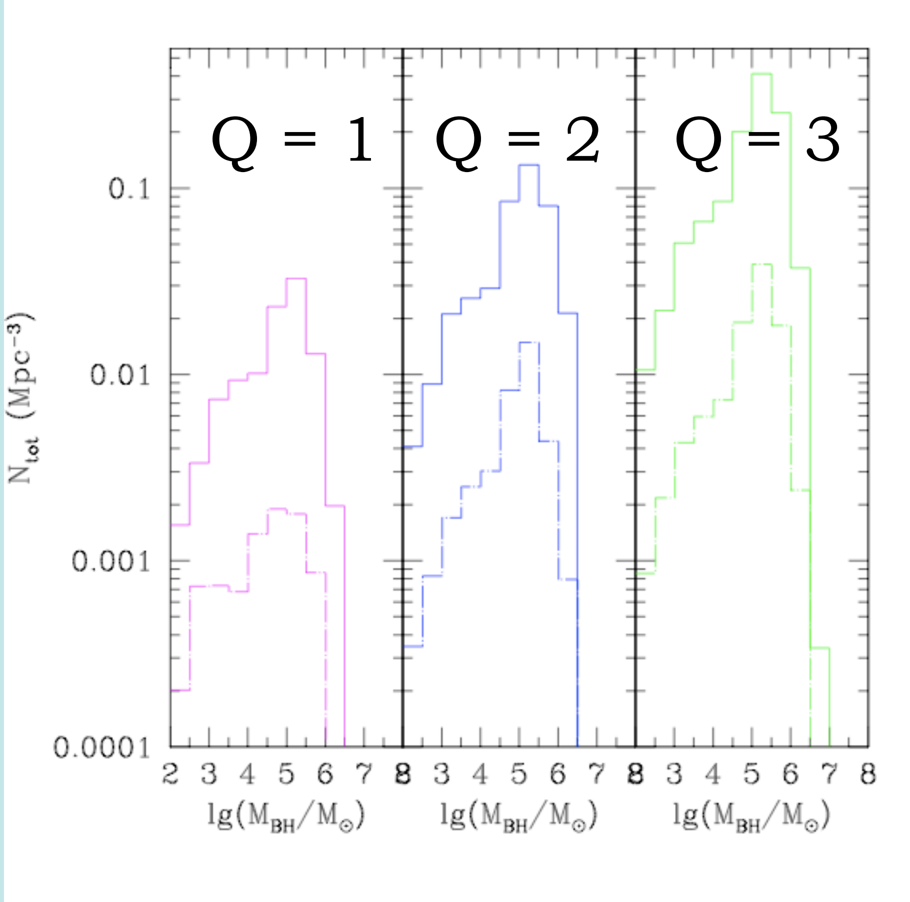
Key features of the model

- Different relationship between M_{BH} and spin parameter
- High spin halos do not host BHs at early times as disc is not massive enough, stable to grav. instabilities
- Massive, low spin halos host the most massive seeds

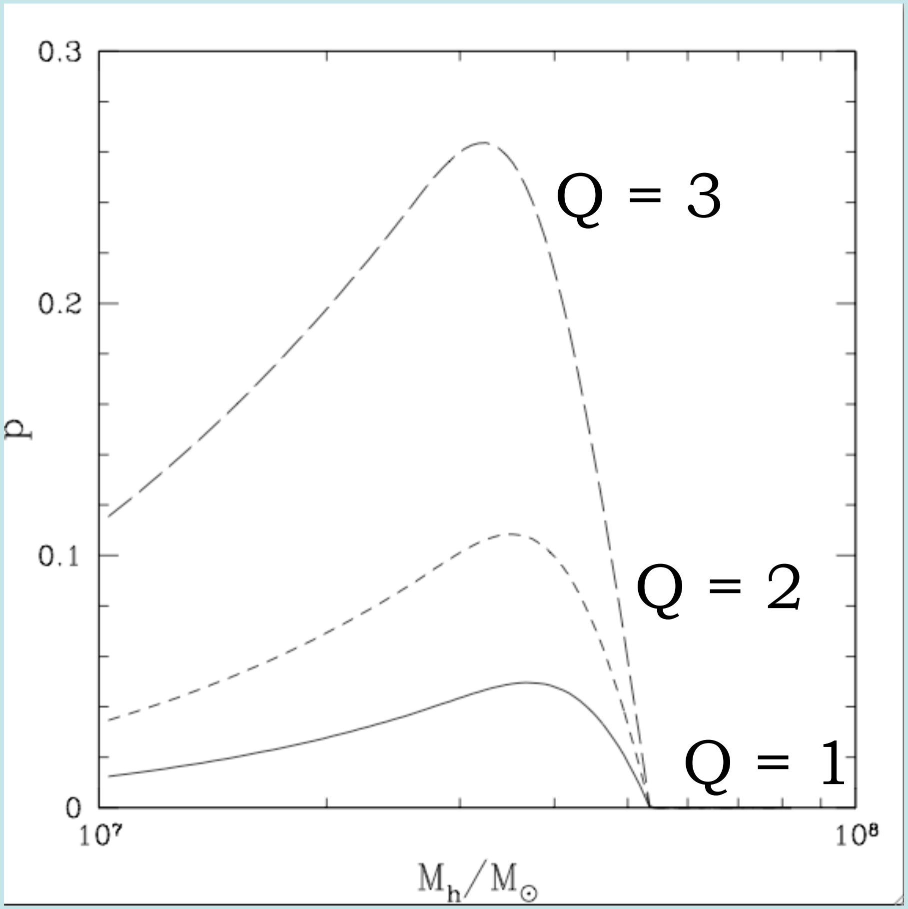


$T_{gas} \sim 4000$ K, $m_d = j_d = 0.05$, $Q = 2$

Model features

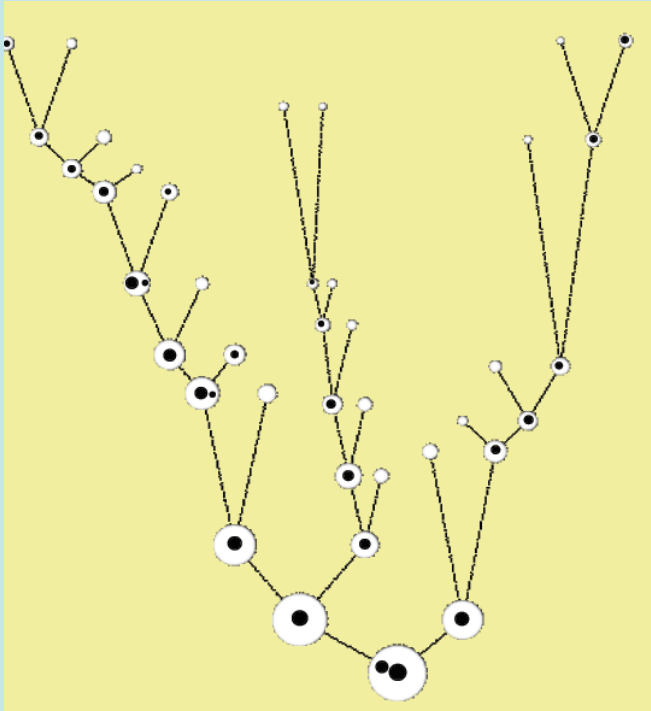


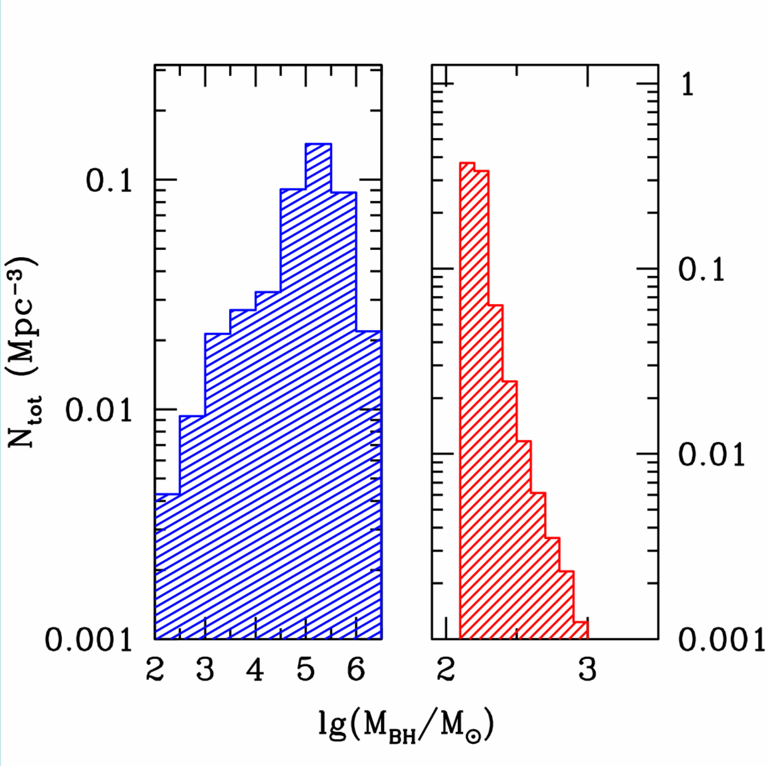
The mass function of seeds for
3 different BH formation efficiency
models



Probability of hosting a BH
seed of any mass

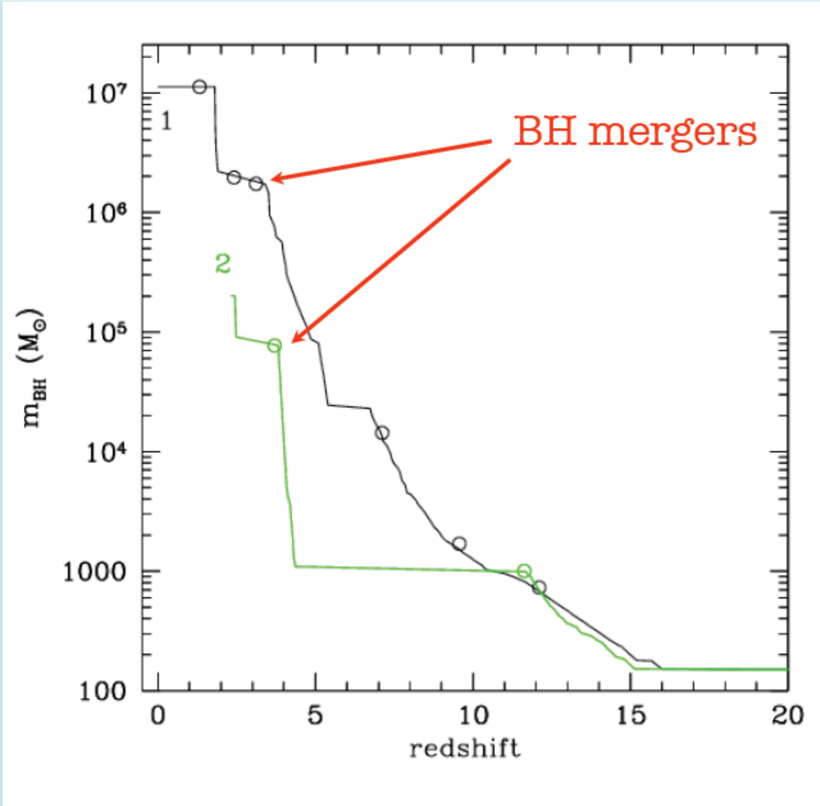
Merger induced accretion + CDM merger tree + seeds





- Plant with initial mass function of seeds
- Generate Monte Carlo merger tree in LCDM
- MBH seed formation ceases at z ~ 12
- Propogate different BH seed models
- Every major merger (mass ratii 1:10 or greater) induces accretion of gas
- 2 models: (I) gas mass accreted scales with v_c^5 and (II) BH mass simply doubles

Hernquist+ 2007; Kauffmann & Haehnelt 2000; Croton+ 2006; Bower+ 2006; Kimm+ 2008; Volonteri, Haardt & Madau 2003; Miloslavjevic & Merritt 2001; Armitage & PN 2004; Hopkins+ 2007; 2008; 2009



- MBH mergers are rare events, as they require the merger of two galaxies each with a central BH
- Not only all MBHs experience a major merger during their lifetime, only ~ 40 - 50 %
- Dynamical and gravitational interactions can displace MBHs
- Mergers detectable with signatures EM and GW signatures, predict event rates for LISA

Sesana+ 2004; Dotti+ 2006; PN& Volonteri 2008

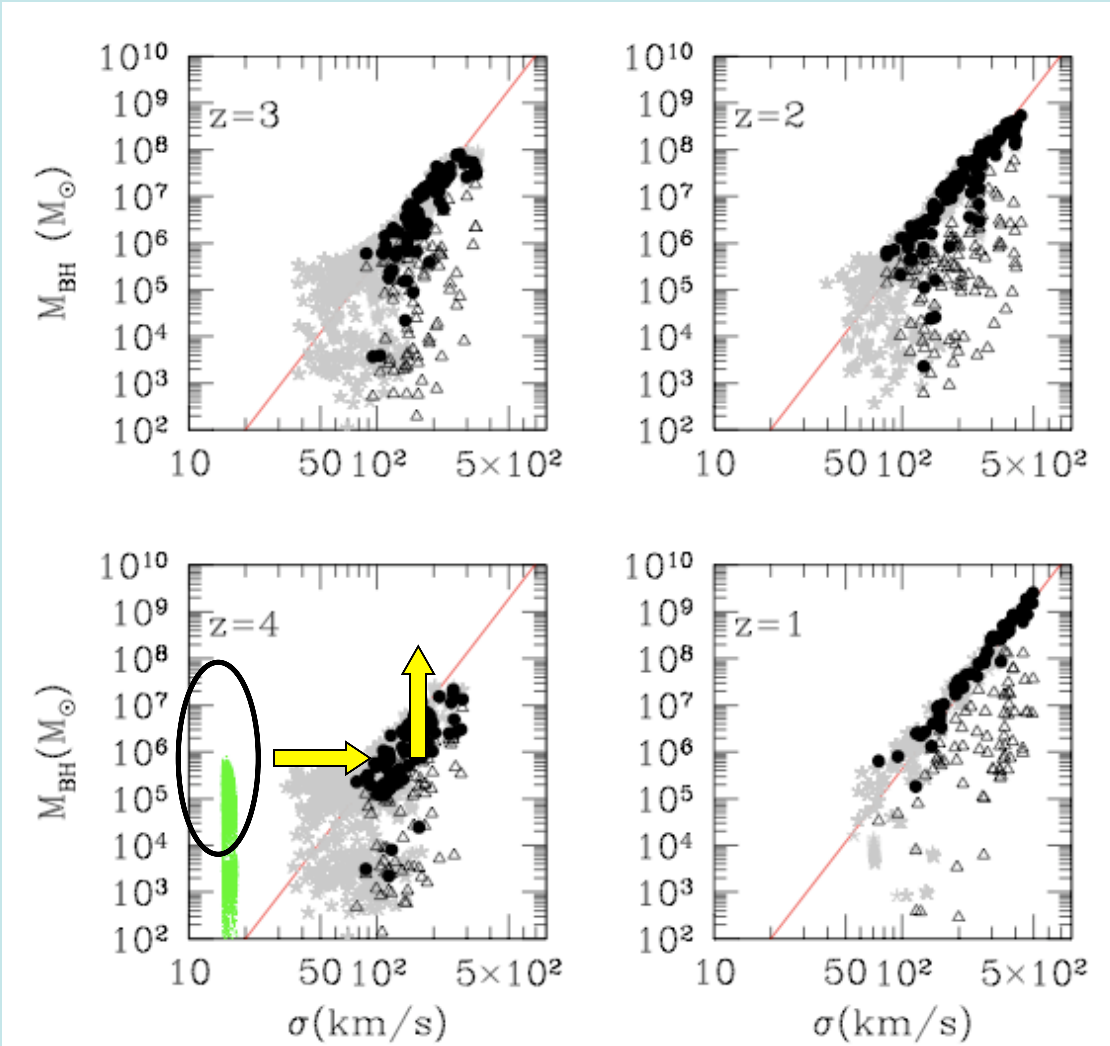
Including a model for mergers

- Black holes grow during major mergers
- A fixed fraction of the available cold gas driven to the center and accreted at arbitrarily high rates
- Amount of cold gas is set by cooling and stellar feedback
- Growth during the optically bright quasar and the obscured phase
- Simple light curve with luminosity independent/dependent lifetime

Growth dominated by accretion + at late times by merging of BHs

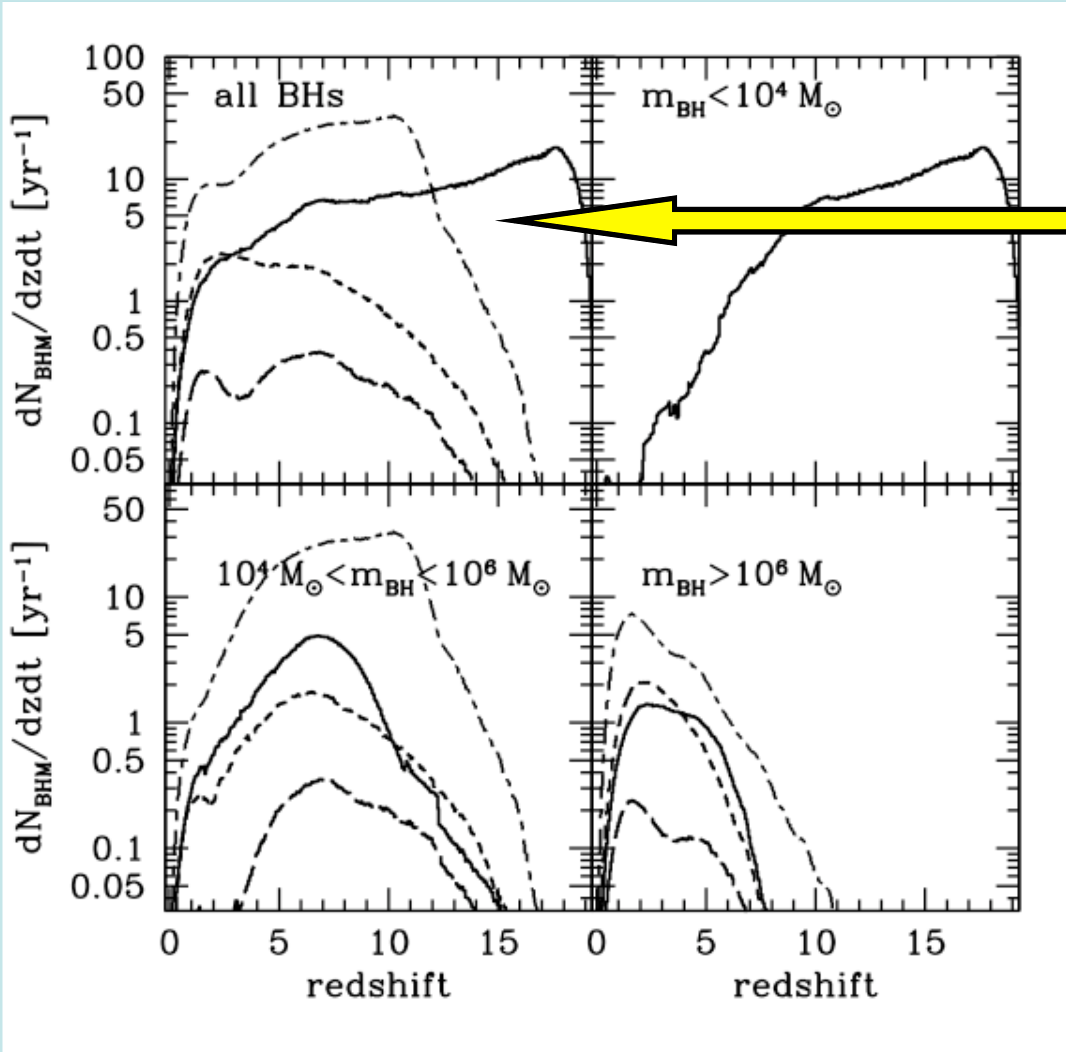
Haehnelt, PN & Rees 1998; Haiman & Loeb 1999; PN 2003; Yu & Tremaine 2002; Kauffmann & Haehnelt 2000,2003; Wyithe & Loeb 2004; Granato+ 2004; Shanker+ 2005; PN 2006; Kauffmann & Haehnelt 2000, 2003

Merger history of a present day $10^{13} M_{sun}$ halo (merging BHs)



initially over-massive, massive seeds in 3.5-4 sigma peaks

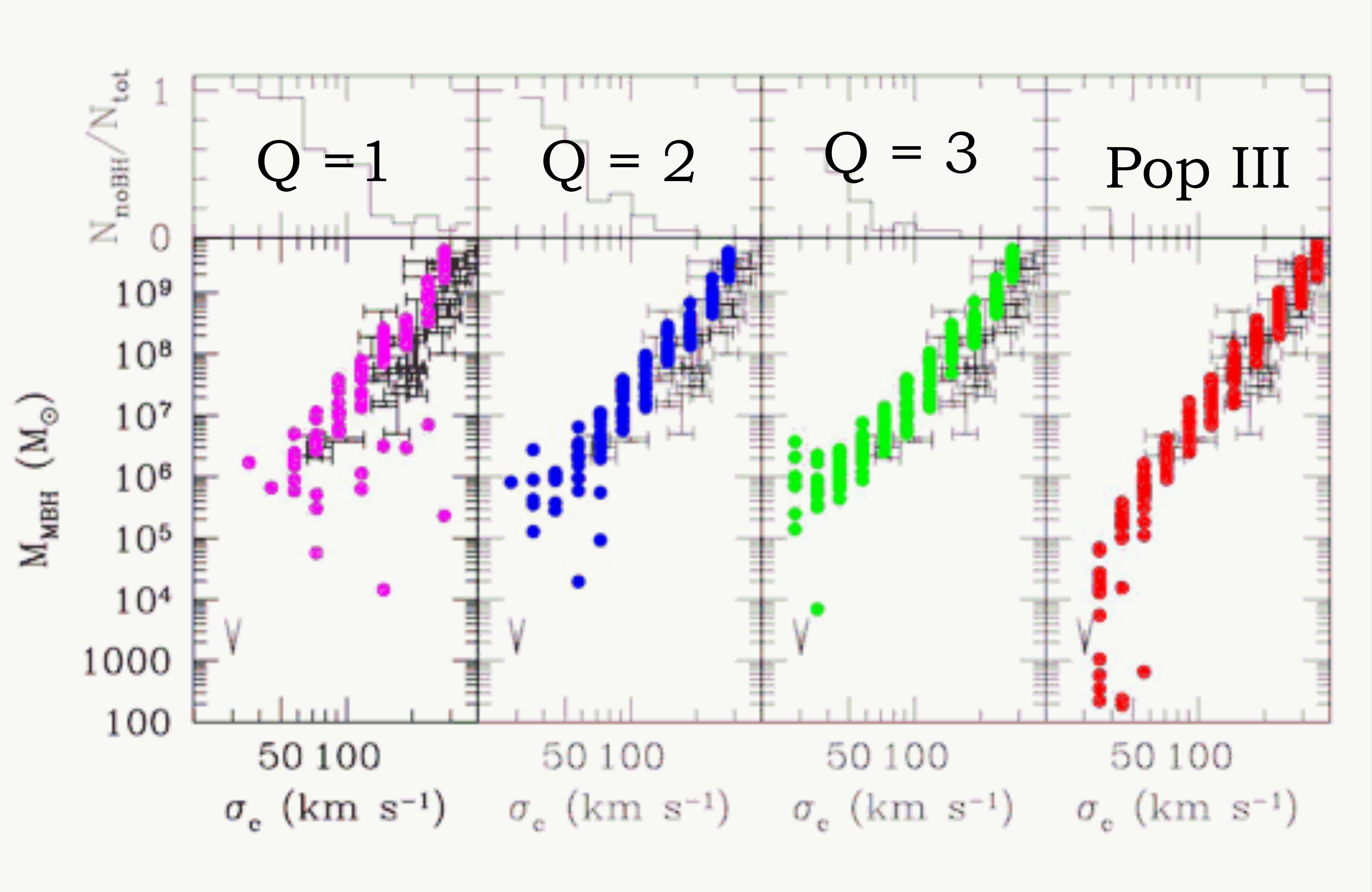
Number of MBHB mergers/yr



Massive seed
Models
(dot dash, solid)

Sesana+ 2007;Volonteri & PN 2010

Key prediction at the low mass end



Volonteri, Lodato & PN 2007

Observations at the low mass end

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BLACK HOLE MASS AND BULGE LUMINOSITY FOR LOW-MASS BLACK HOLES

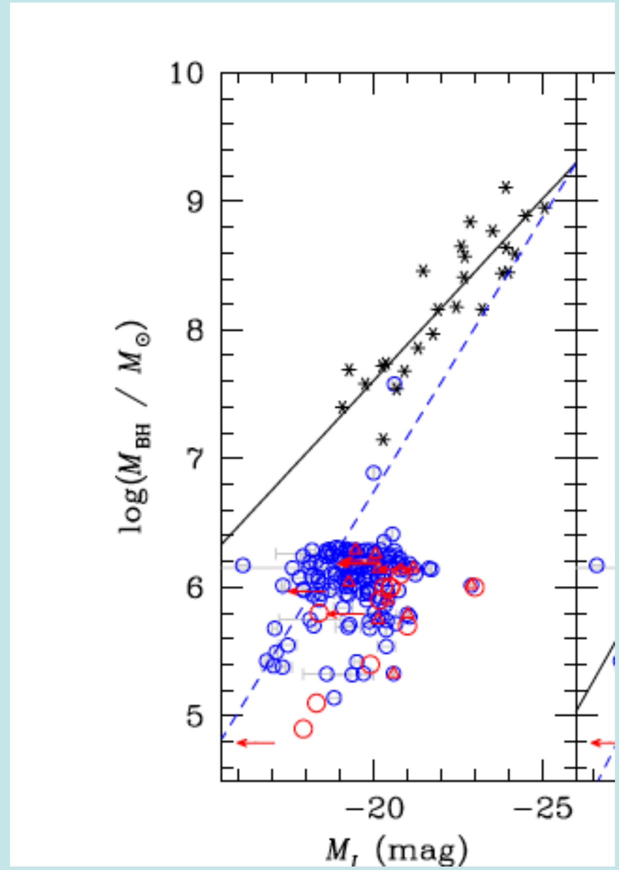
YAN-FEI JIANG [1], JENNY E. GREENE [1] AND LUIS C. HO [2]

Draft version July 25, 2011

ABSTRACT

We study the scaling between bulge magnitude and central black hole (BH) mass in galaxies with virial BH masses $\lesssim 10^6 M_\odot$. Based on careful image decomposition of a snapshot *Hubble Space Telescope* I-band survey, we found that these BHs are found predominantly in galaxies with pseudobulges. Here we show that the $M_{\rm BH} - L_{\rm bulge}$ relation for the pseudobulges at low mass is significantly different from classical bulges with BH masses $\geq 10^7 M_\odot$. Specfically, bulges span a much wider range of bulge luminosity, and on average the luminosity is larger, at fixed $M_{\rm BH}$. The trend holds both for the active galaxies from Bentz et al. and the inactive sample of Gültekin et al. and cannot be explained by differences in stellar populations, as it persists when we use dynamical bulge masses. Put another way, the ratio between bulge and BH mass is much larger than ~ 1000 for our sample. This is consistent with recent suggestions that $M_{\rm BH}$ does not scale with the pseudobulge luminosity. The low-mass scaling relations appear to flatten, consistent with predictions from Volonteri & Natarajan for massive seed BHs.

Subject headings: galaxies: active — galaxies: nuclei — methods: observational



Jiang, Greene & Ho 2011

Self regulation of SF and BH growth

Quasar driven wind sweeps up gas shell and expels it, inhibiting SF and limiting BH mass that depends on spin

$$M_{bh} > \alpha \frac{\sigma^5 \kappa}{G^2 c} = 8 \times 10^8 \gamma (\frac{\sigma}{500 km/s})^5 M_\Theta$$

$$M_{bh} \approx 10^8 (\frac{f_{kin}}{0.001})^{-1} j_d^{-5} (\frac{\lambda}{0.05})^{-5} (\frac{m_d}{0.1})^5 (\frac{v_{halo}}{400 km/s})^5 M_\Theta$$

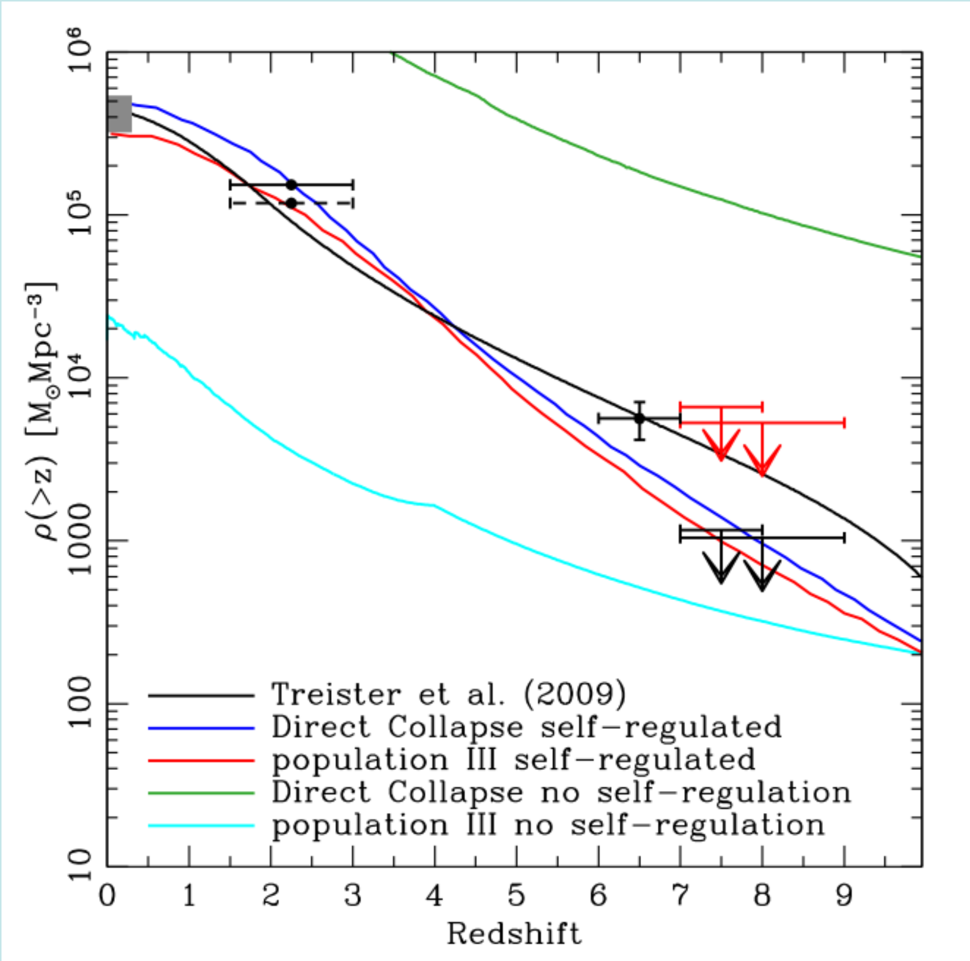
Momentum-driven winds

$$L_{crit} = \frac{4 f_g c}{G} \sigma^4$$

$$M_{\bullet,crit} / M_{sun} = 0.12 \eta_{Edd}^{-1} \left(\frac{f_g}{0.1}\right) \left(\frac{\sigma}{km/s}\right)^4$$

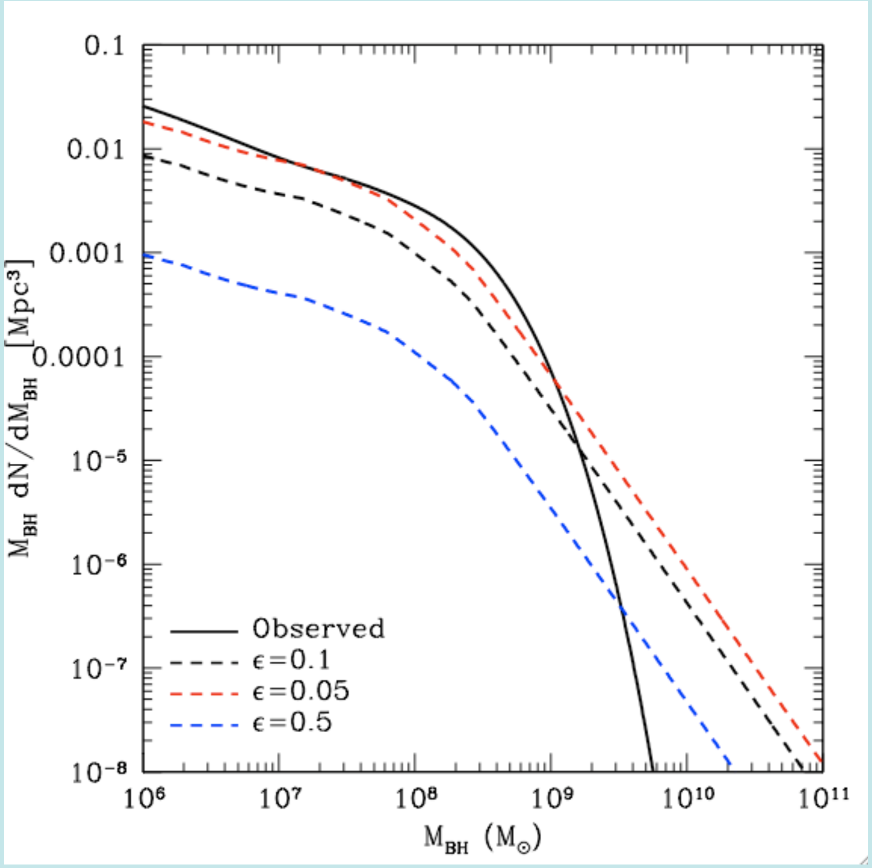
Haehnelt, PN & Rees 1998; Silk & Rees 1998; Wyithe & Loeb 2003; King 2004; Thompson, Murray & Quataert 2004; PN 2008

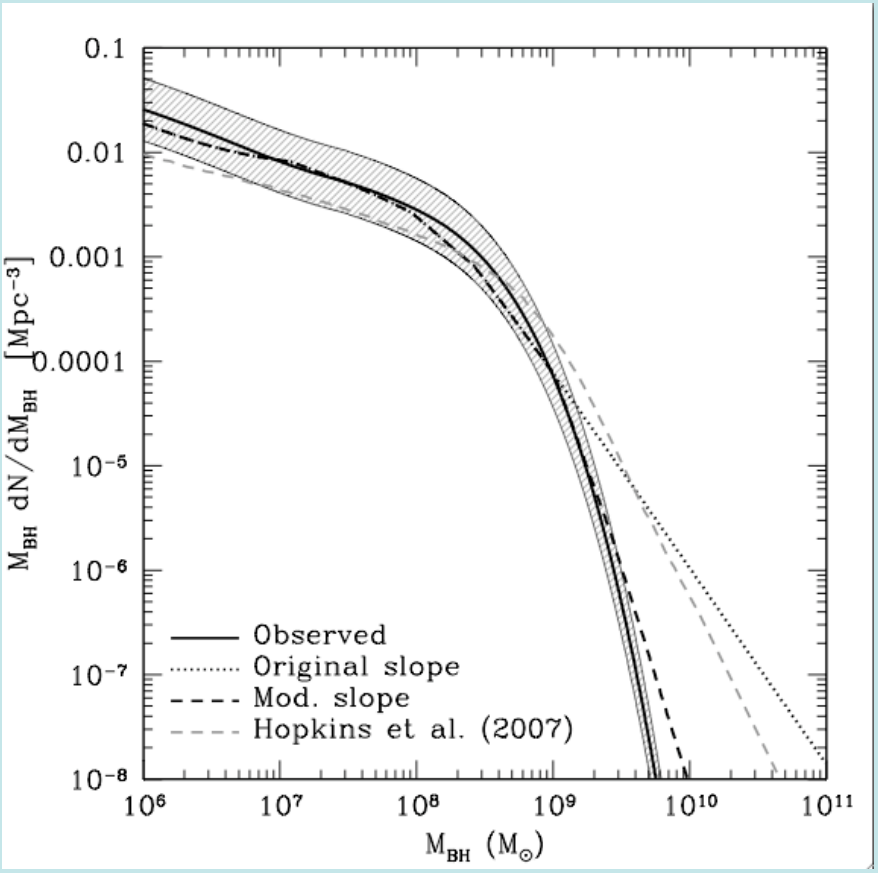
Evidence for self-regulation?



Treister+ *Nature*, 2011

An upper limit to BH masses?

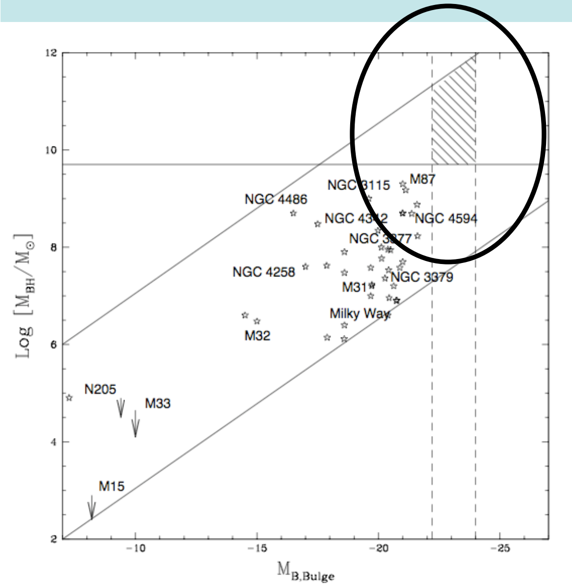


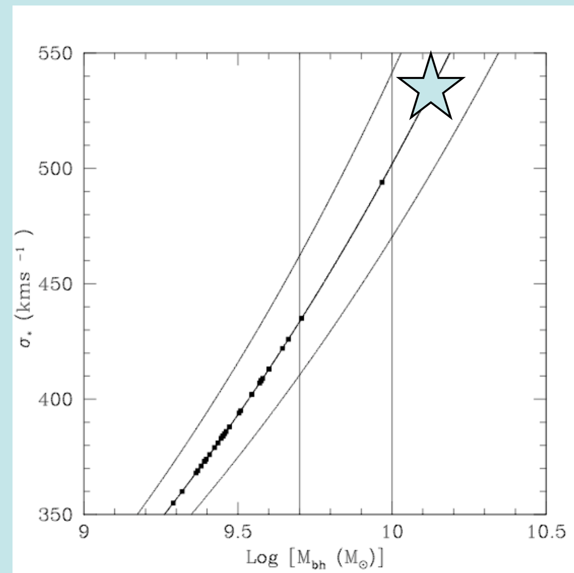


$M_{upper\text{-}limit}$ (BH) ~ few times X 10^{10} Msun for cD galaxies

PN & Treister 2008

Predict existence of UMBHs



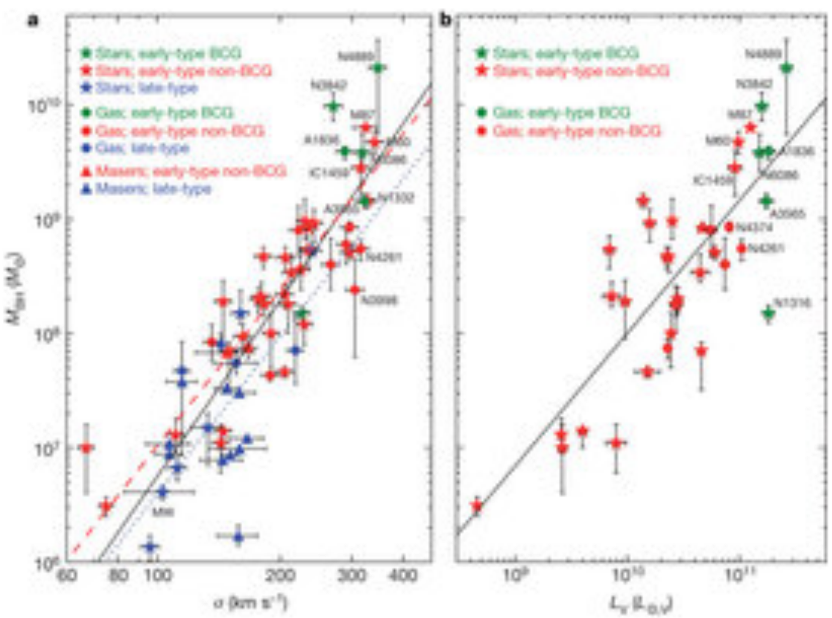


Expected in the centers of cDs

SDSS results of nearby cDs and bright ellipticals

Lauer+ 2005; 2006; Bernardi+ 2006

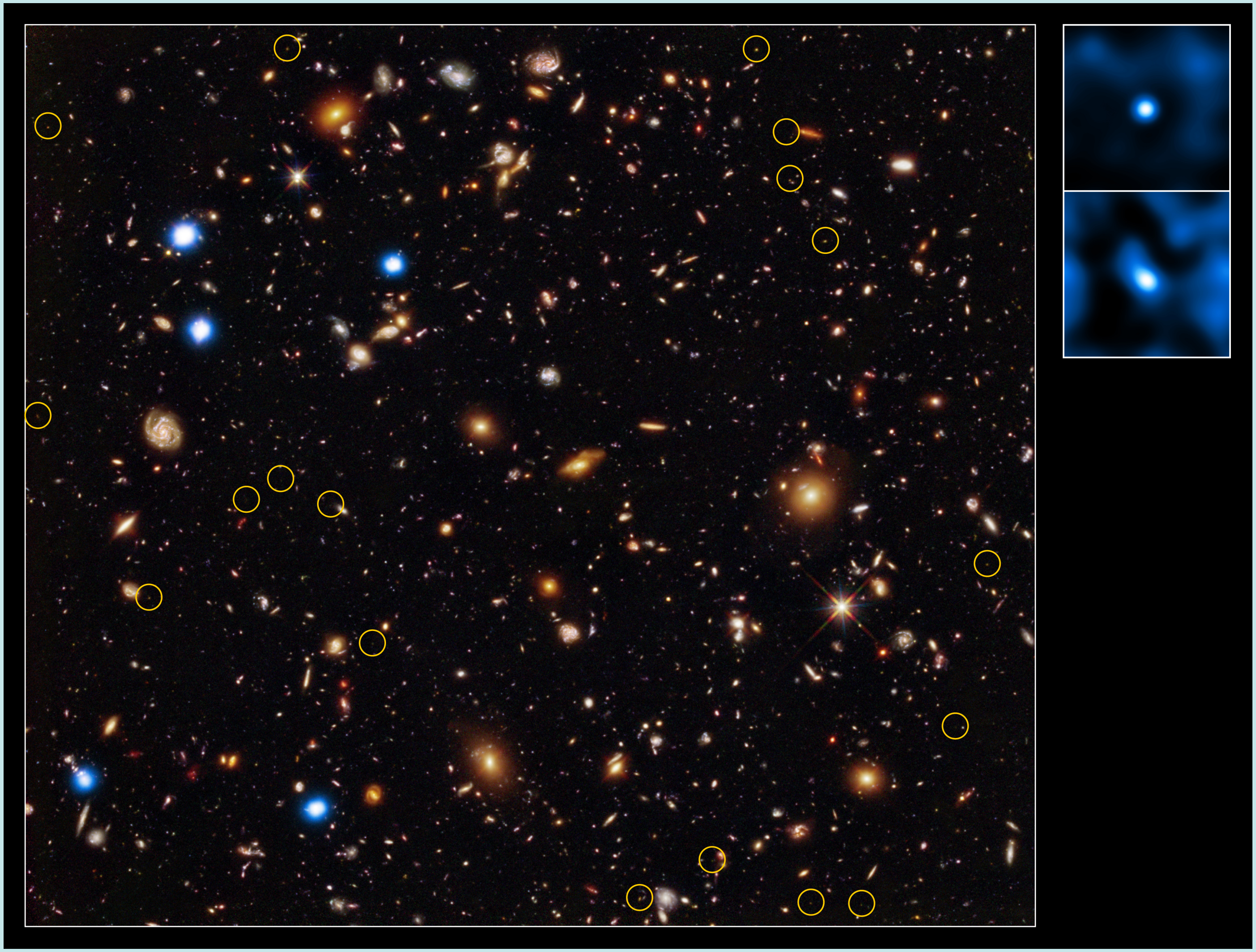
Ultra-massive BHs?



a, Black-hole mass (M_{BH}) versus stellar velocity dispersion (σ) for 65 galaxies with direct dynamical measurements of M_{BH}. For galaxies with spatially resolved stellar

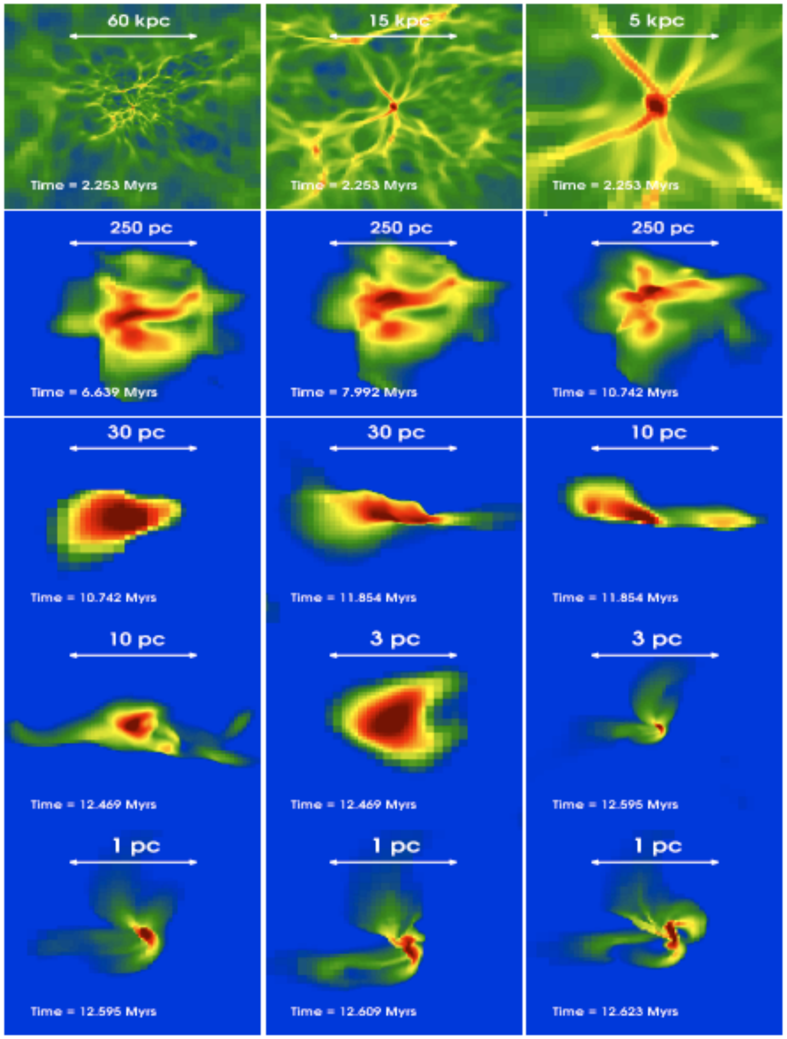
McConnell+ 2011

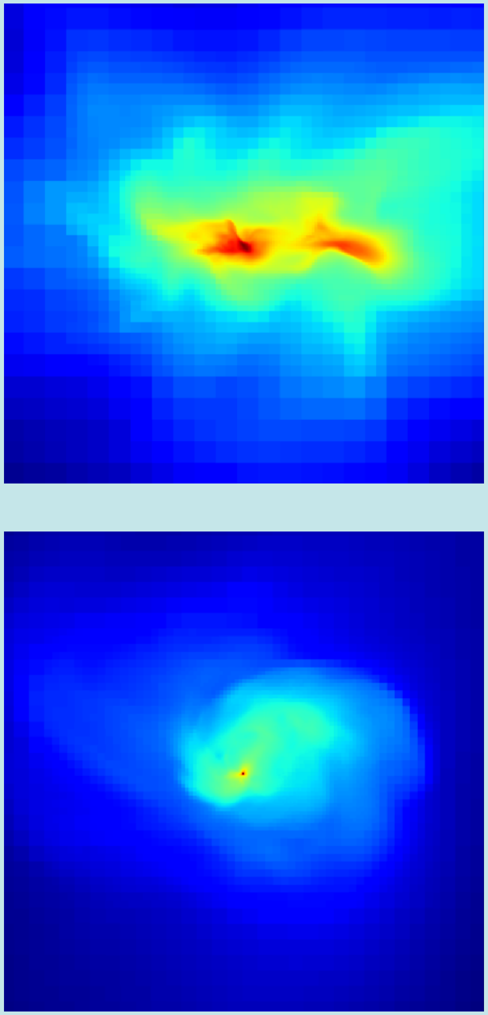
Discovery of a new population of baby BHs at z = 6 – 8?



Treister, PN + *Nature*, June 2011; see also Cowie, Barger & Hasinger preprint; Fiore et al and Willott

Massive BH seed formation

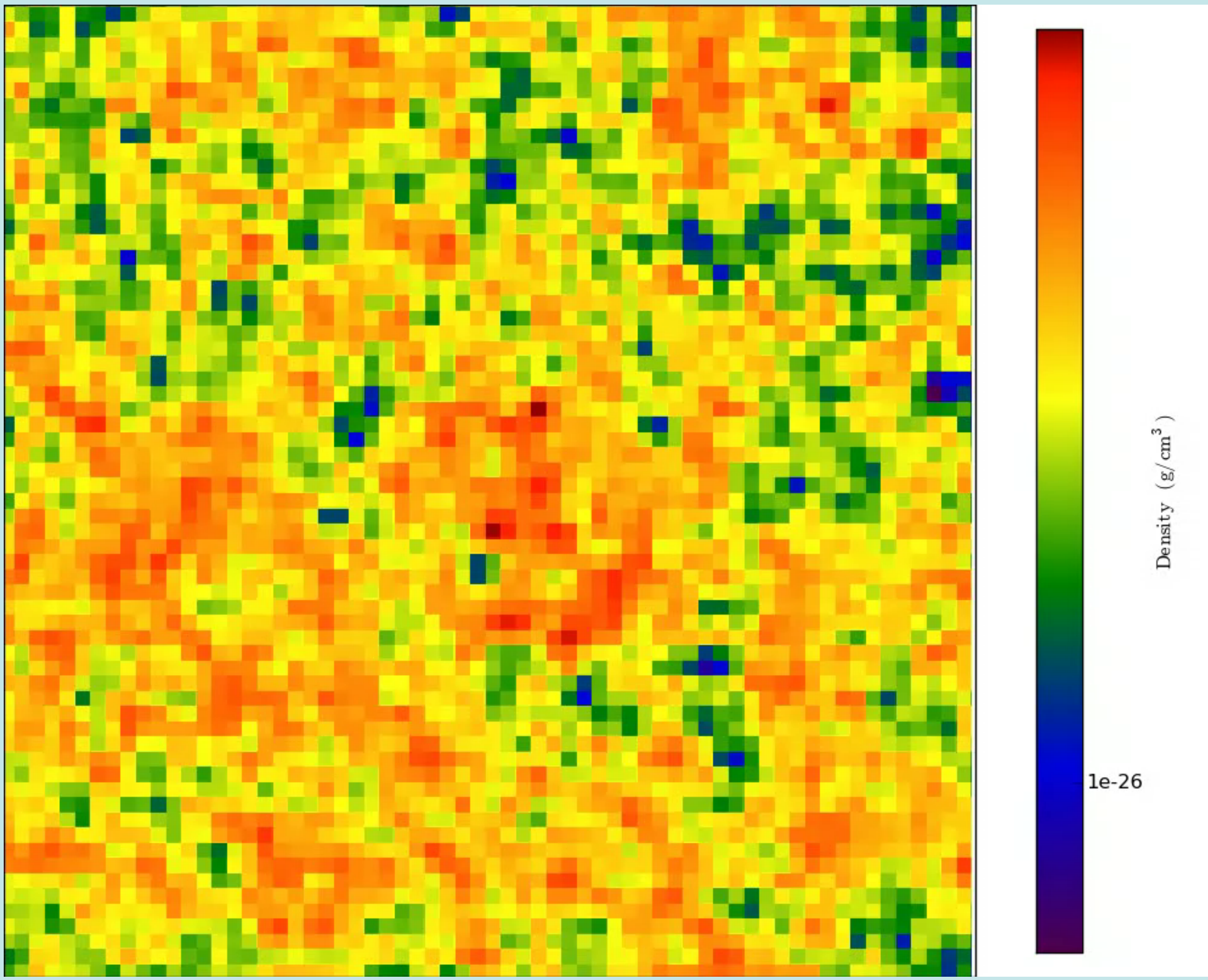




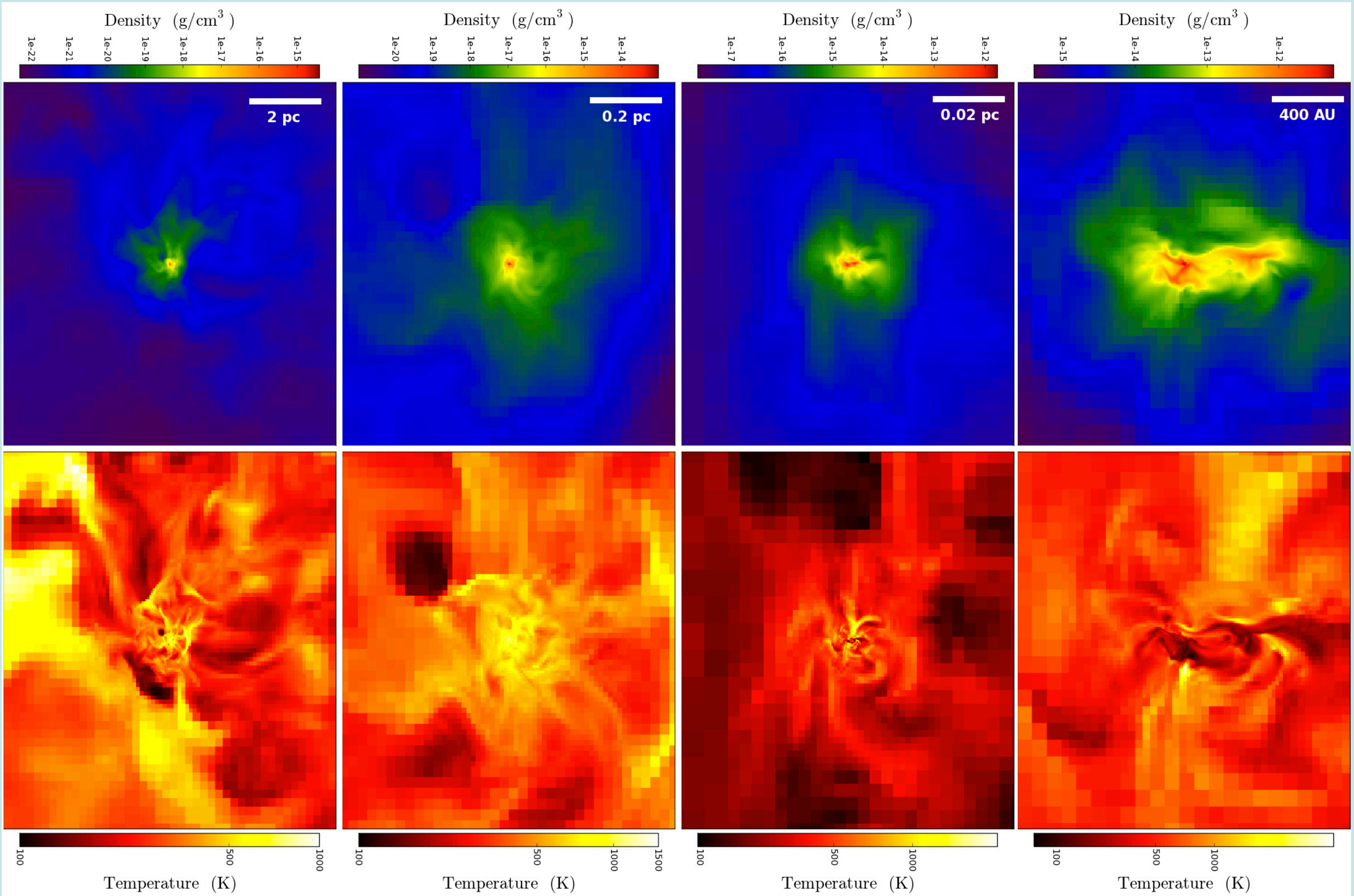
Regan & Haehnelt 2008

Smith, Davis & PN 2011

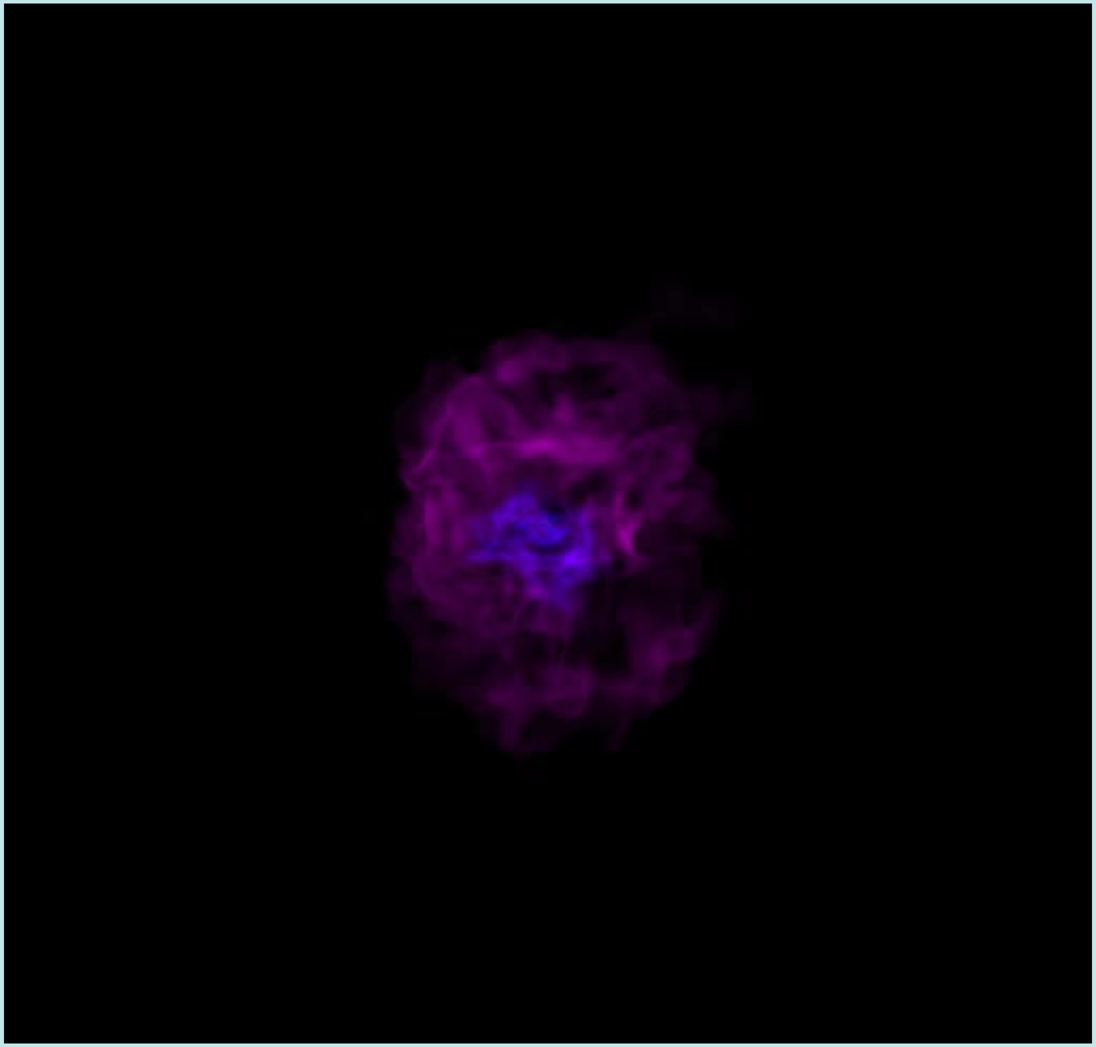
Baryonic collapse in a high spin halo



The fate of rotating fat disks



Davis, Smith, Turk, PN, in prep



Work in progress....