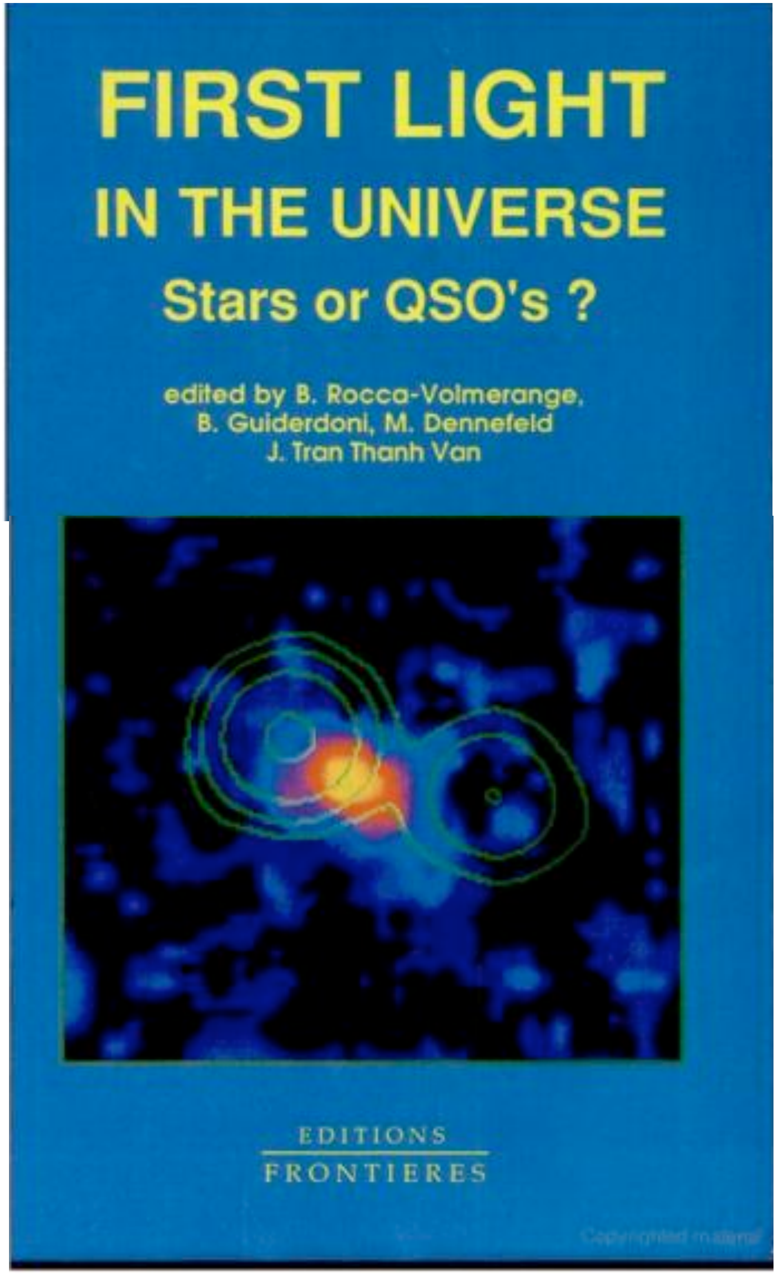
The early growth of (super-)massive black holes

Martin Haehnelt

8th IAP Colloquium
1992



FIRST LIGHT
IN THE UNIVERSE
Stars or QSO's ?

edited by B. Rocca-Volmerange,
B. Guiderdoni, M. Dennefeld
J. Tran Thanh Van

EDITIONS
FRONTIERES

Paris, 8th July 2008

IoA
UNIVERSITY OF
CAMBRIDGE

The Co-Evolution of galaxies and black holes

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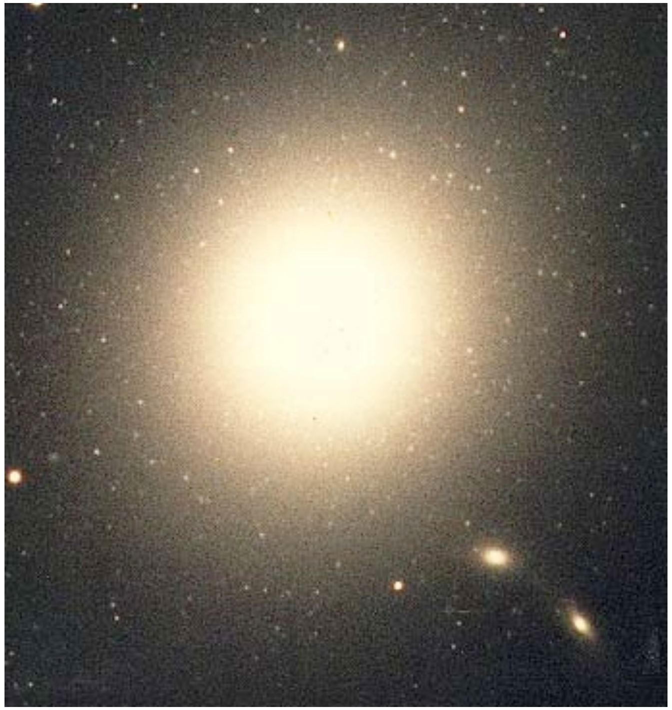
Massive black holes?

Giant Ellipticals/S0s



Yes

Spirals

Yes but black hole mass scales with bulge mass not total mass

Dwarfs

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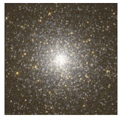
~~Possibly~~

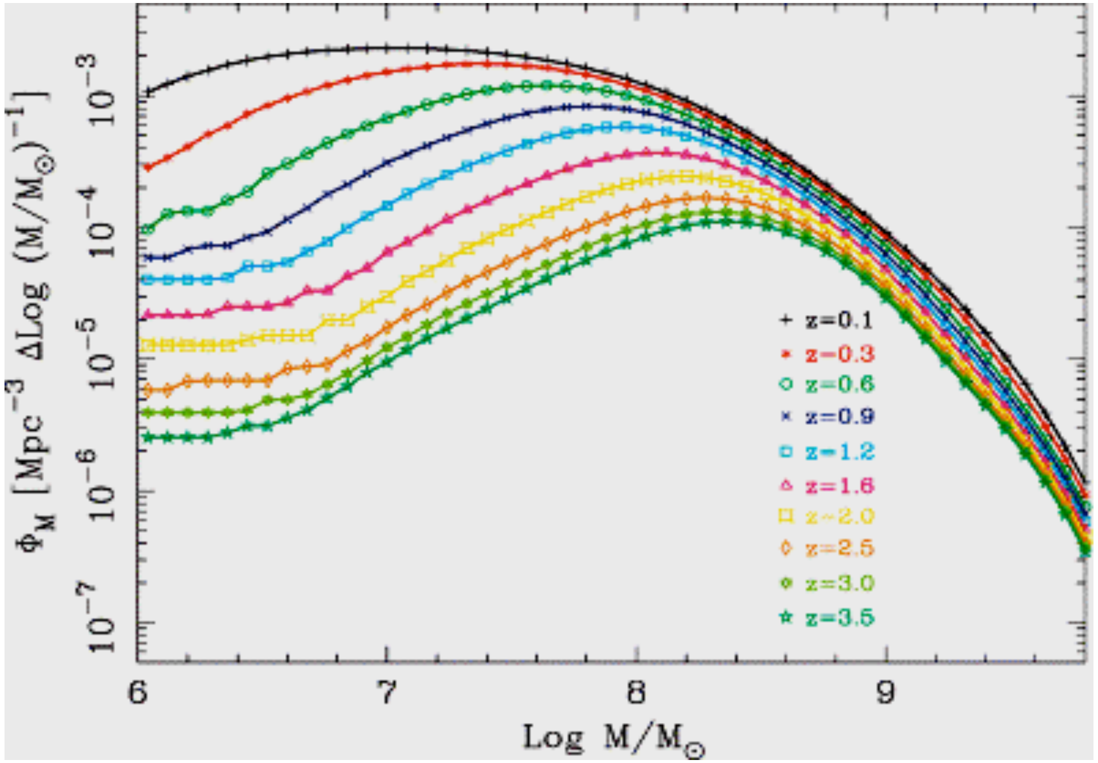
A few

Globular Clusters



Maybe

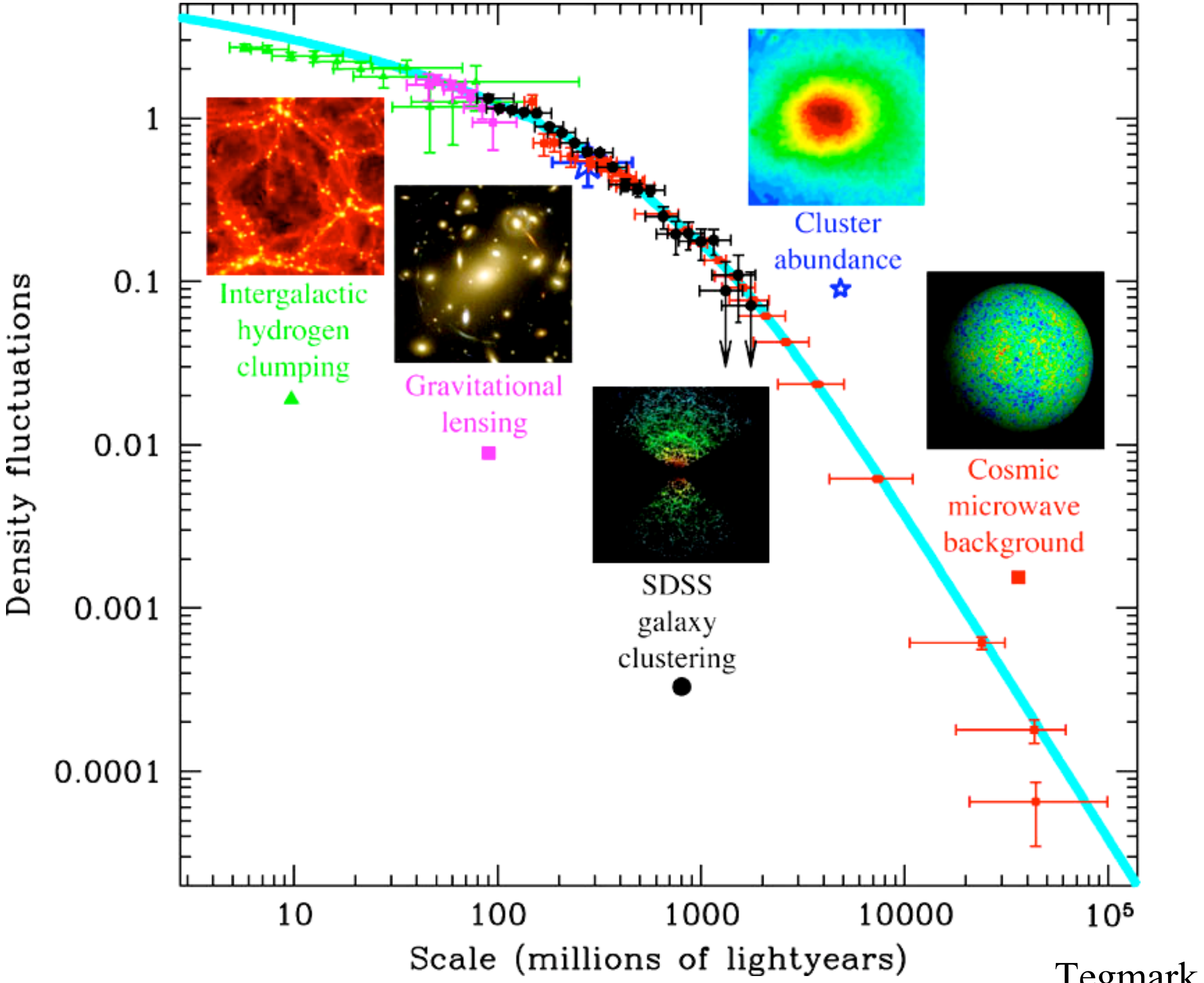
Evolution of the black hole mass function as reconstructed from accretion history



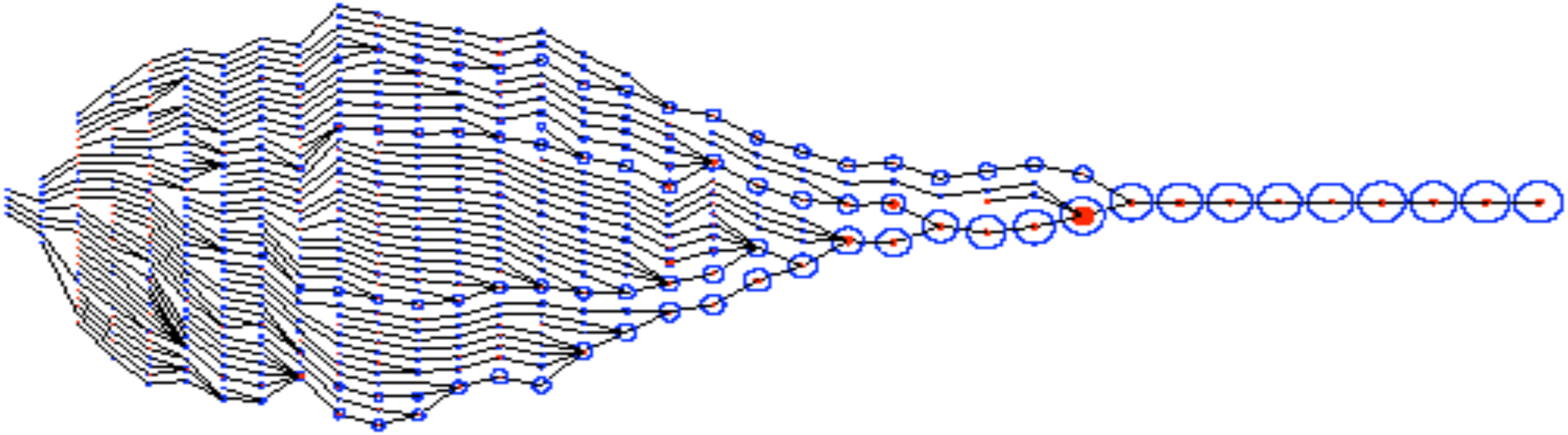
Merloni 2004

Cosmic Downsizing

Most of the big black holes form at high redshift. Most of the black holes still growing at the present day are small. These small black holes have gained most of their mass recently.



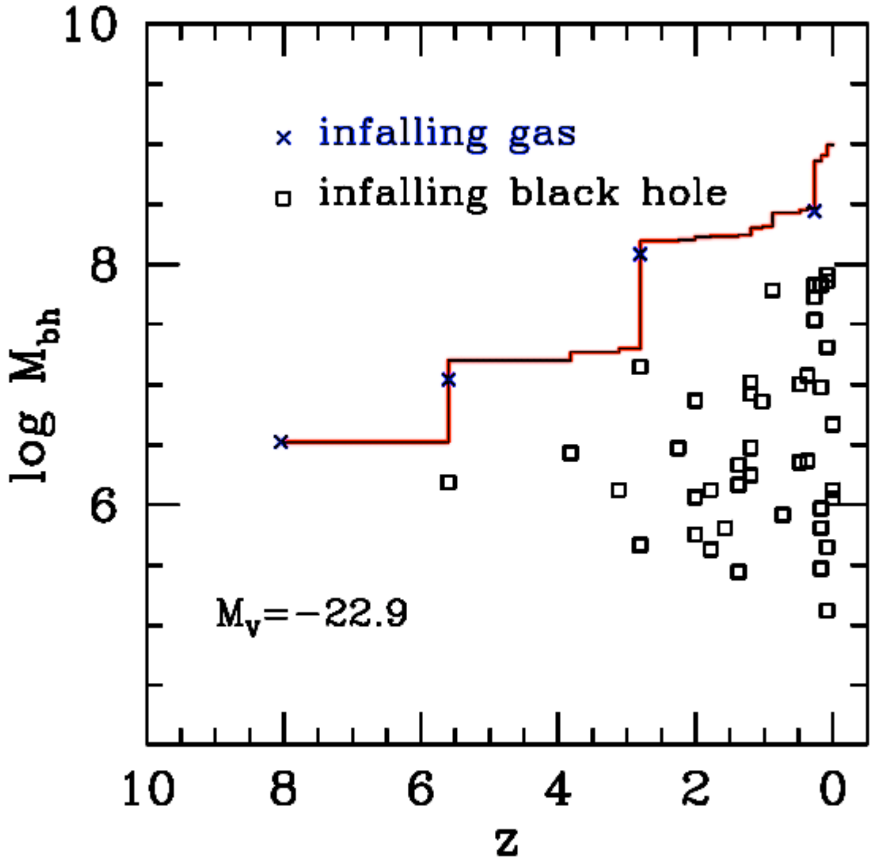
We know the DM power spectrum very well!



Bullock et al.

DM haloes grow by merging

Typical merging history in a bright elliptical

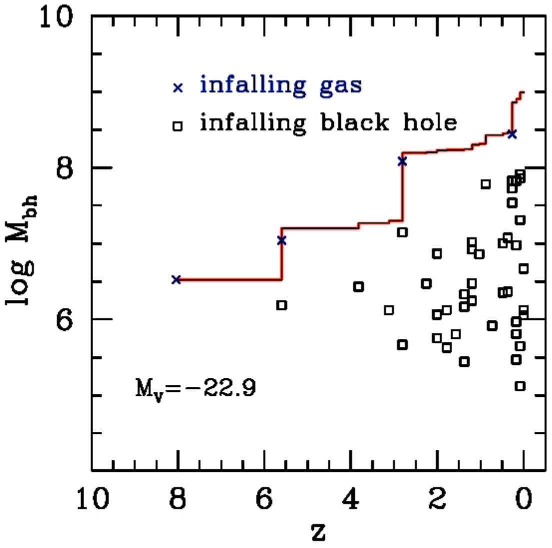


Kauffmann & Haehnelt 2008

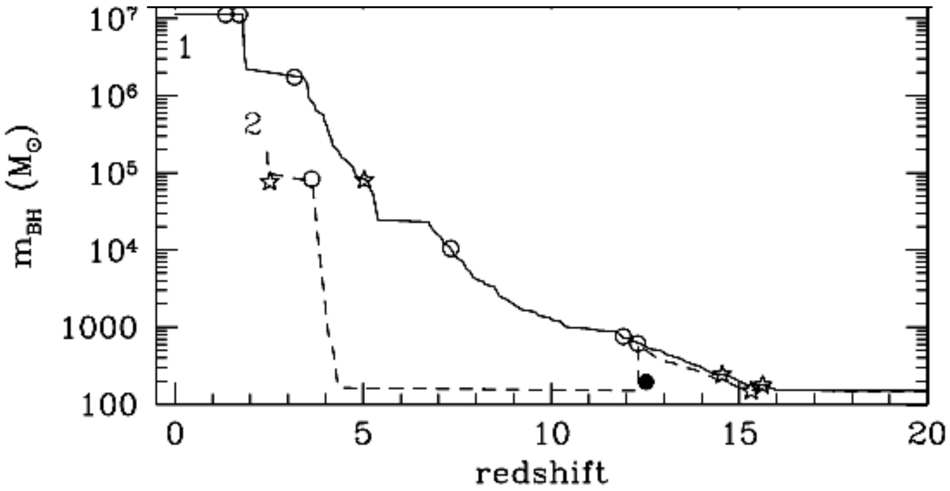
Growth of black holes dominated by accretion of gas and feedback regulated

At late time also growth by infall and merging of black holes

How do 10^6 Msol black holes form?



Kauffmann & Haehnelt



Volonteri et al.

Does the hierarchical growth start with a minimum seed mass?

or

Does the hierarchical assembly extend all the way to stellar mass black holes?

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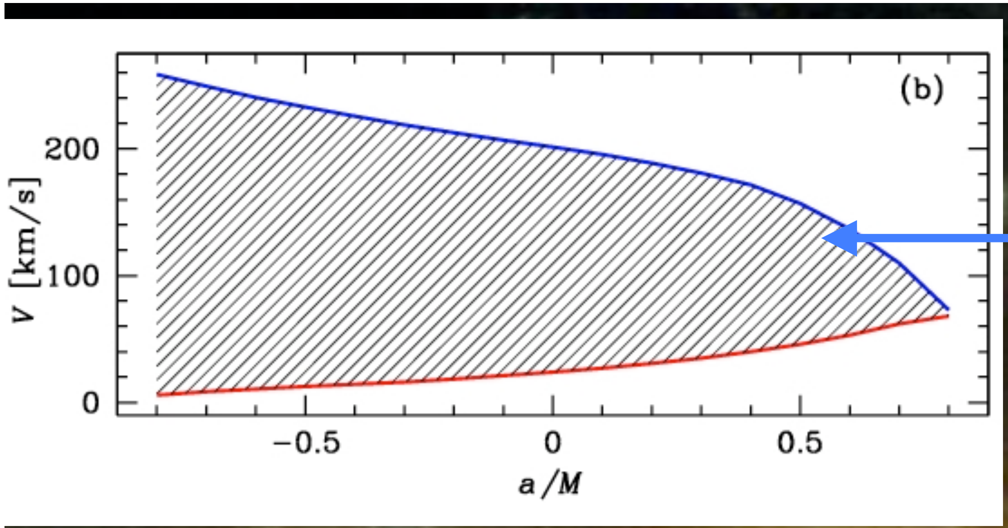
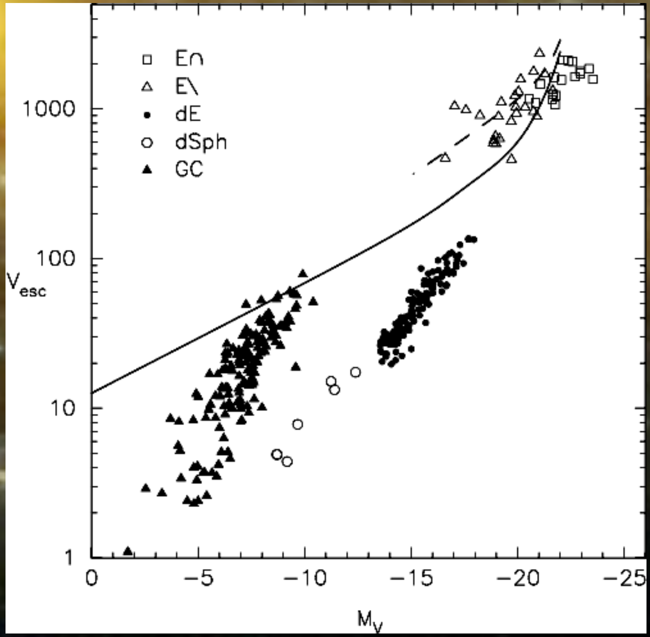


Favata et al. 2004

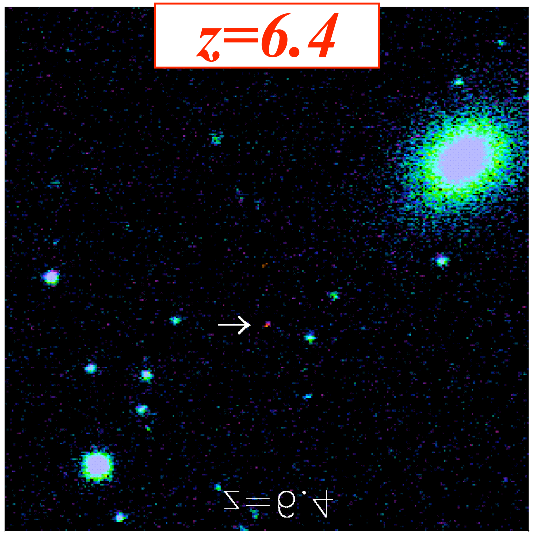
estimated kick velocity after binary merger

can be > 2000 kms^{-1} for anti-aligned spins!

escape velocity from galaxies



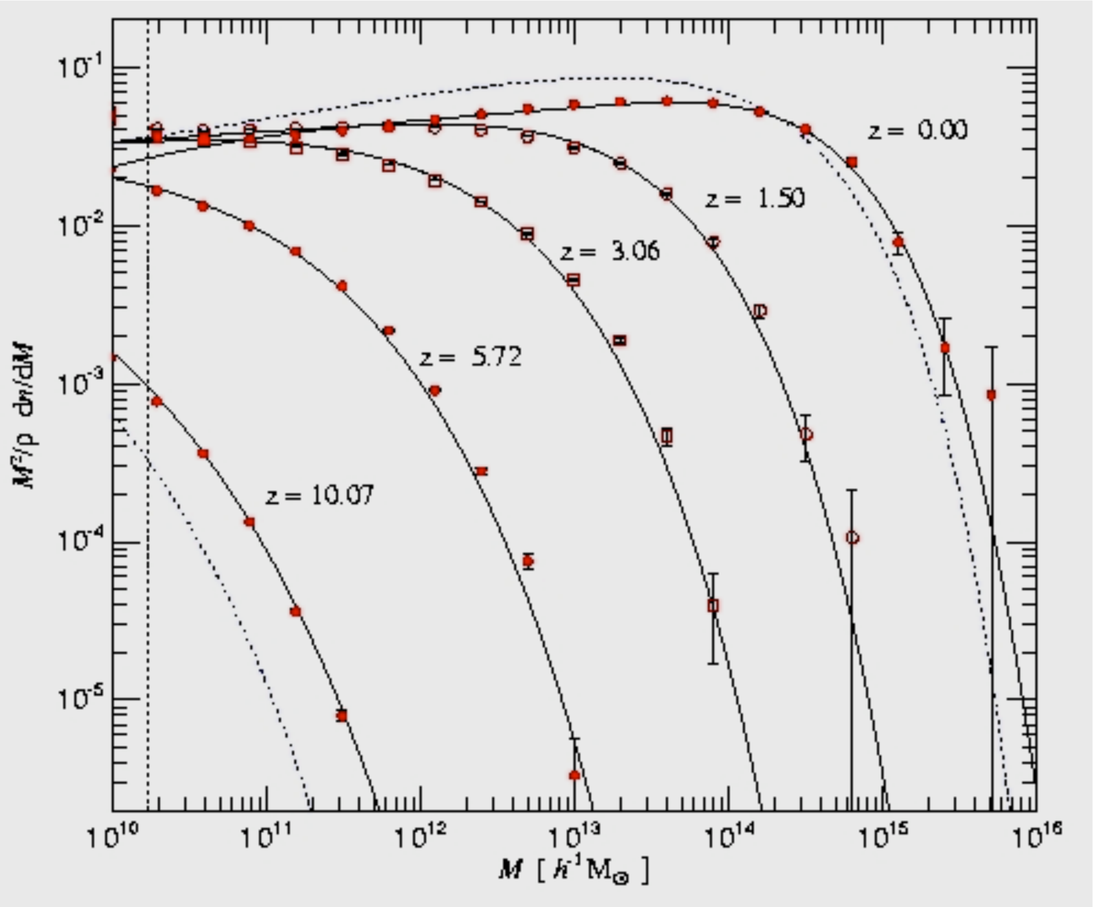
Merritt et al. 2004



Fan et al.

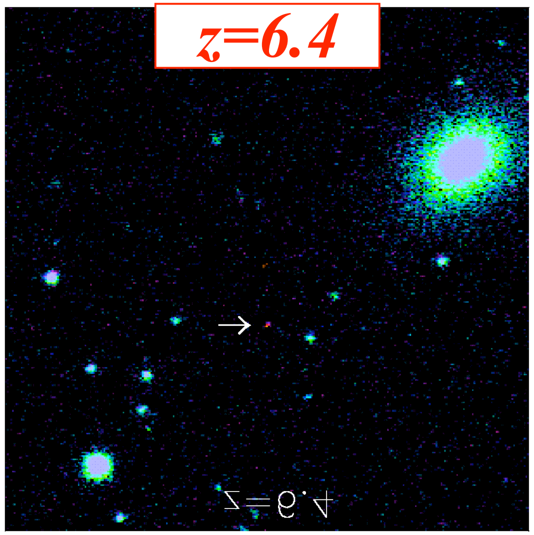
Black holes as massive as the most massive black holes today have already formed at $z=6.4$.

Estimated mass: 3 x 10^9 Msol



Springel et al 2005

Sufficiently massive haloes do exist at z=6.



Black holes as massive as the most massive black holes today have already formed at z=6.4.

Estimated mass: 3 x 10^9 Msol

Fan et al.

Age of Universe at z=6.4: 0.8-0.9 Gyr

→ For Eddington limited accretion only 20 $\varepsilon_{0.1}^{-1}$ e-foldings possible!

Growth from stellar mass seeds requires

Eddington-limited accretion with duty cycle close to one

and

efficient growth in shallow potential wells

and

("fine tuning" of space density of stellar mass black hole seeds to avoid excessive ejection by black hole recoils in hierarchically merging proto-galaxies)

or

super-Eddington accretion

We most probably need massive seed black holes.
How do massive seed black holes form?

The Begelman & Rees roadmap

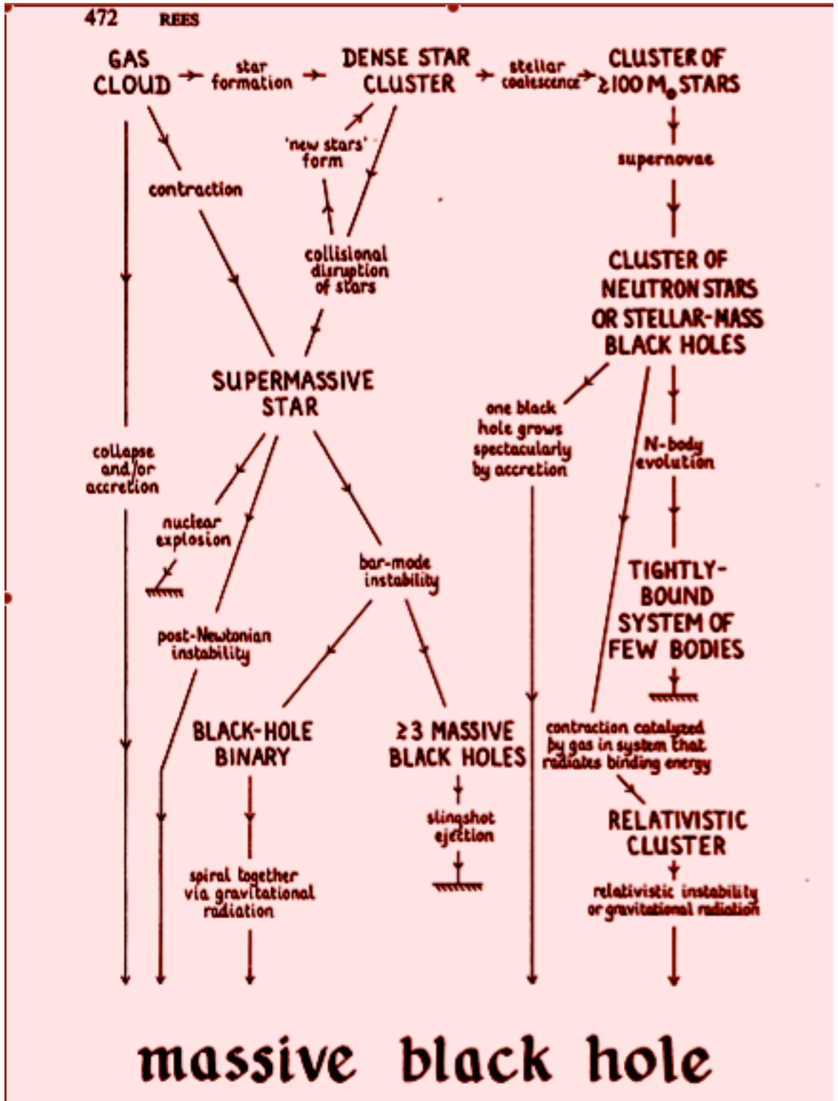
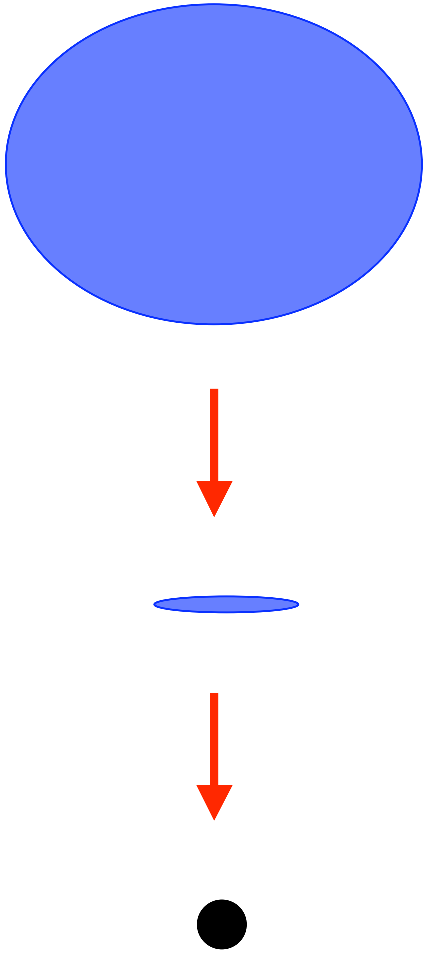


Figure 1 Schematic diagram [reproduced from Rees (106)] showing possible routes for runaway evolution in active galactic nuclei.

Direct collapse into a compact massive self-gravitating disc

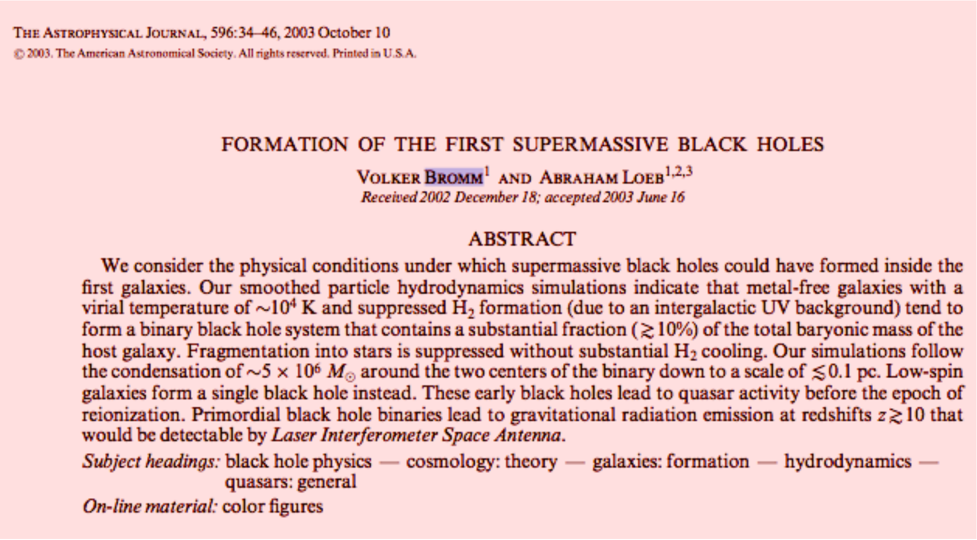


H_2 cooling
metal cooling

↔

fragmentation

haloes with $T_{vir} \geq$ 10000K
with no metals (and H_2 supression)
are least prone to fragmentation



THE ASTROPHYSICAL JOURNAL, 596:34–46, 2003 October 10

FORMATION OF THE FIRST SUPERMASSIVE BLACK HOLES

VOLKER BROMM[1] AND ABRAHAM LOEB[1,2,3]

Received 2002 December 18; accepted 2003 June 16

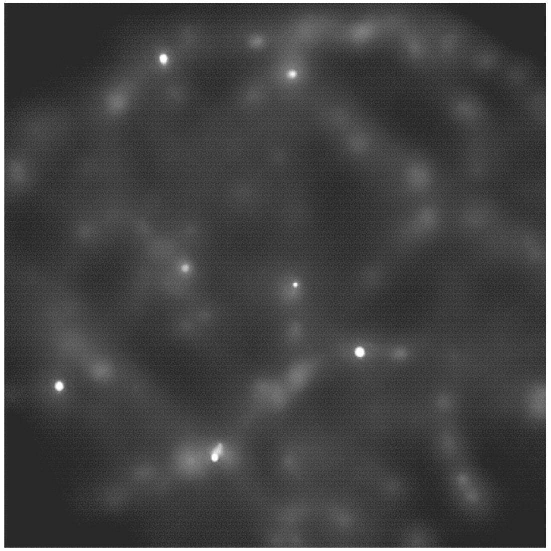
ABSTRACT

We consider the physical conditions under which supermassive black holes could have formed inside the first galaxies. Our smoothed particle hydrodynamics simulations indicate that metal-free galaxies with a virial temperature of $\sim 10^4$ K and suppressed H_2 formation (due to an intergalactic UV background) tend to form a binary black hole system that contains a substantial fraction ($\gtrsim 10\%$) of the total baryonic mass of the host galaxy. Fragmentation into stars is suppressed without substantial H_2 cooling. Our simulations follow the condensation of $\sim 5 \times 10^6 M_\odot$ around the two centers of the binary down to a scale of $\lesssim 0.1$ pc. Low-spin galaxies form a single black hole instead. These early black holes lead to quasar activity before the epoch of reionization. Primordial black hole binaries lead to gravitational radiation emission at redshifts $z \gtrsim 10$ that would be detectable by *Laser Interferometer Space Antenna*.

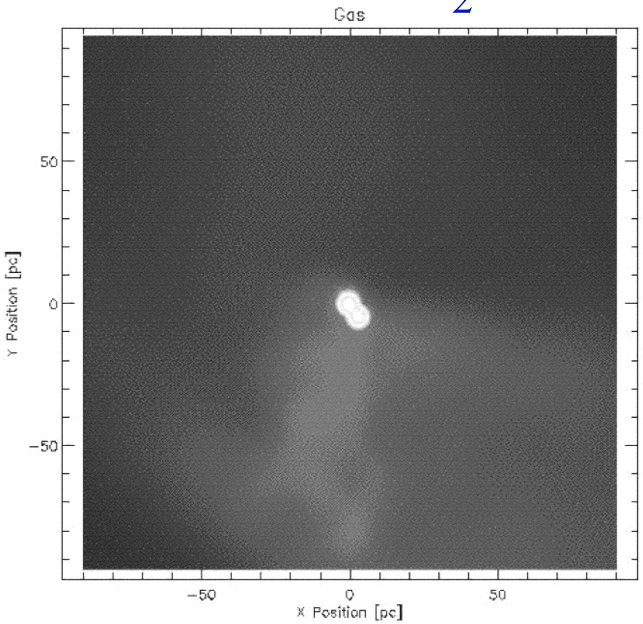
Subject headings: black hole physics — cosmology: theory — galaxies: formation — hydrodynamics — quasars: general

On-line material: color figures

with H_2



without H_2



collapsing 10^4K halo:

strongly suppressed fragmentation without H_2 cooling

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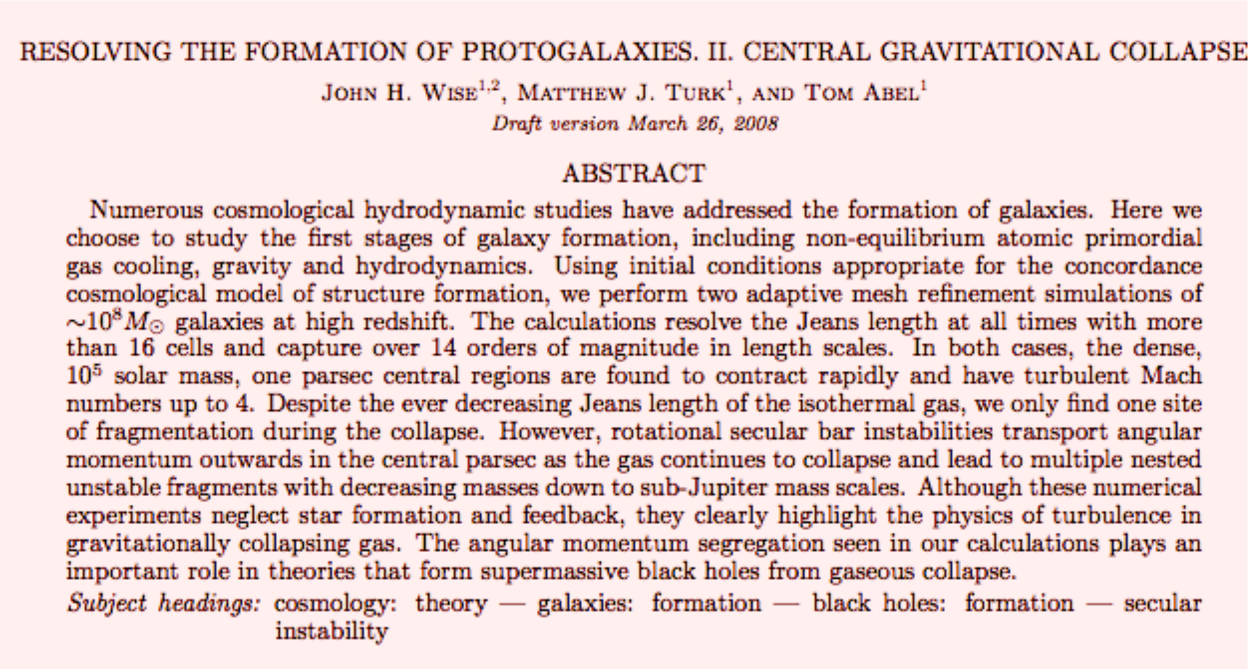
15000K halo

no H_2 cooling

isothermal collapse gas does not reach rotational support in the simulation



RESOLVING THE FORMATION OF PROTOGALAXIES. II. CENTRAL GRAVITATIONAL COLLAPSE

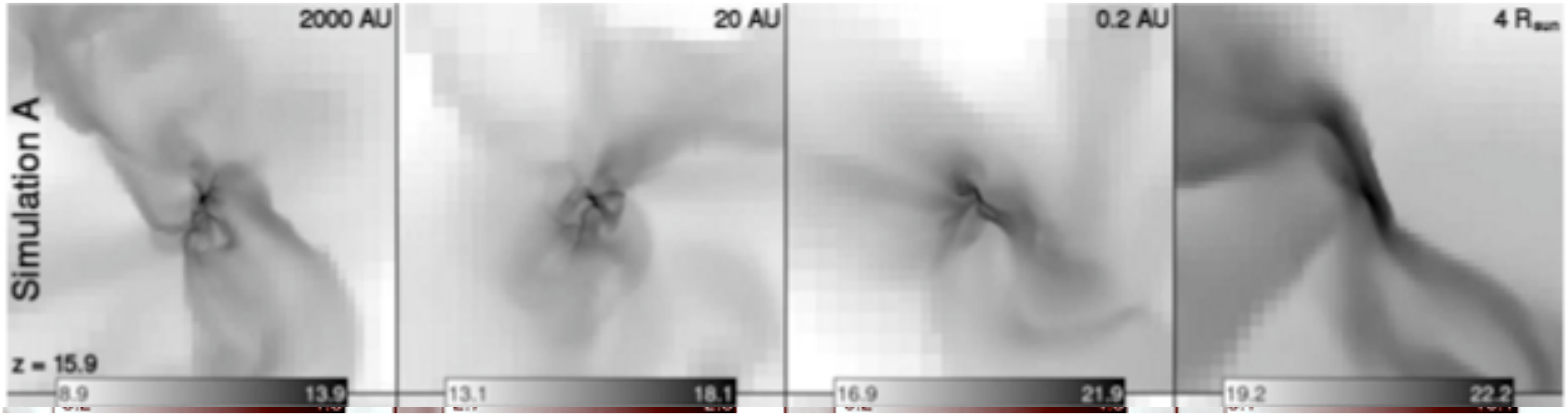
JOHN H. WISE[1,2], MATTHEW J. TURK[1], AND TOM ABEL[1]

Draft version March 26, 2008

ABSTRACT

Numerous cosmological hydrodynamic studies have addressed the formation of galaxies. Here we choose to study the first stages of galaxy formation, including non-equilibrium atomic primordial gas cooling, gravity and hydrodynamics. Using initial conditions appropriate for the concordance cosmological model of structure formation, we perform two adaptive mesh refinement simulations of $\sim 10^8 M_\odot$ galaxies at high redshift. The calculations resolve the Jeans length at all times with more than 16 cells and capture over 14 orders of magnitude in length scales. In both cases, the dense, 10^5 solar mass, one parsec central regions are found to contract rapidly and have turbulent Mach numbers up to 4. Despite the ever decreasing Jeans length of the isothermal gas, we only find one site of fragmentation during the collapse. However, rotational secular bar instabilities transport angular momentum outwards in the central parsec as the gas continues to collapse and lead to multiple nested unstable fragments with decreasing masses down to sub-Jupiter mass scales. Although these numerical experiments neglect star formation and feedback, they clearly highlight the physics of turbulence in gravitationally collapsing gas. The angular momentum segregation seen in our calculations plays an important role in theories that form supermassive black holes from gaseous collapse.

Subject headings: cosmology: theory — galaxies: formation — black holes: formation — secular instability

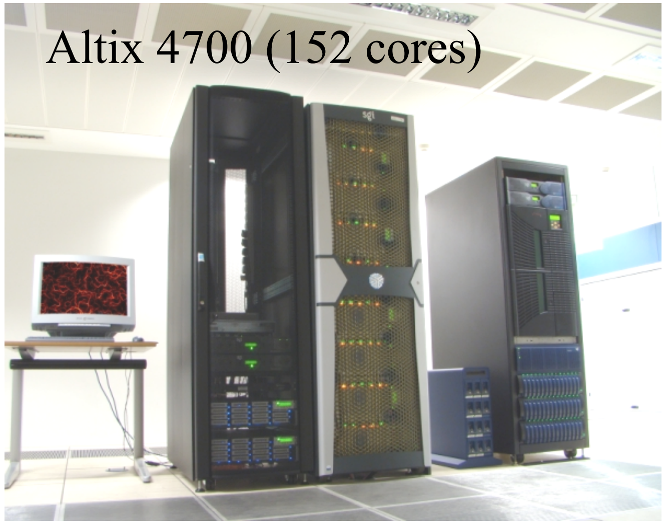


The formation of compact massive self-gravitating disks in haloes with virial temperatures of 30000K

Paris, 8th July 2008

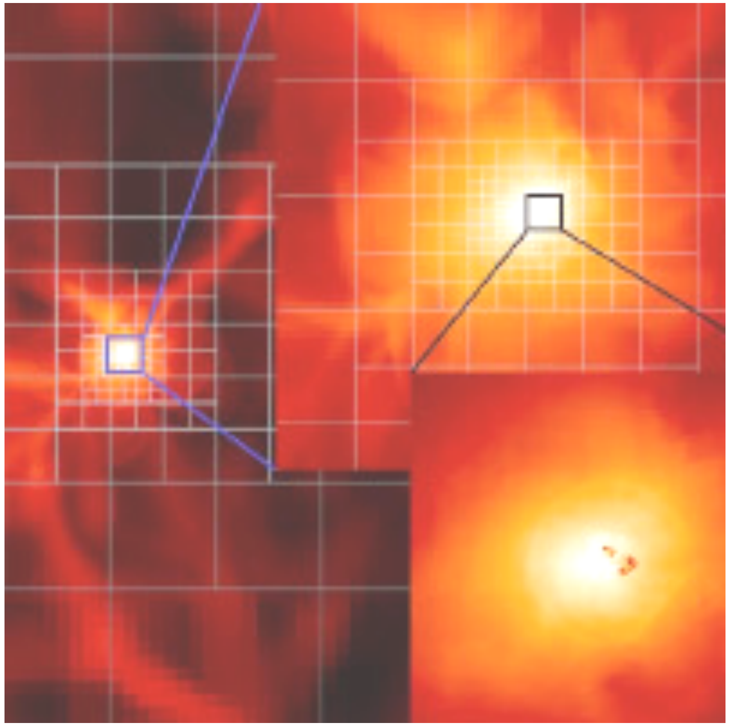
John Regan

Cosmos



Darwin

ENZO AMR



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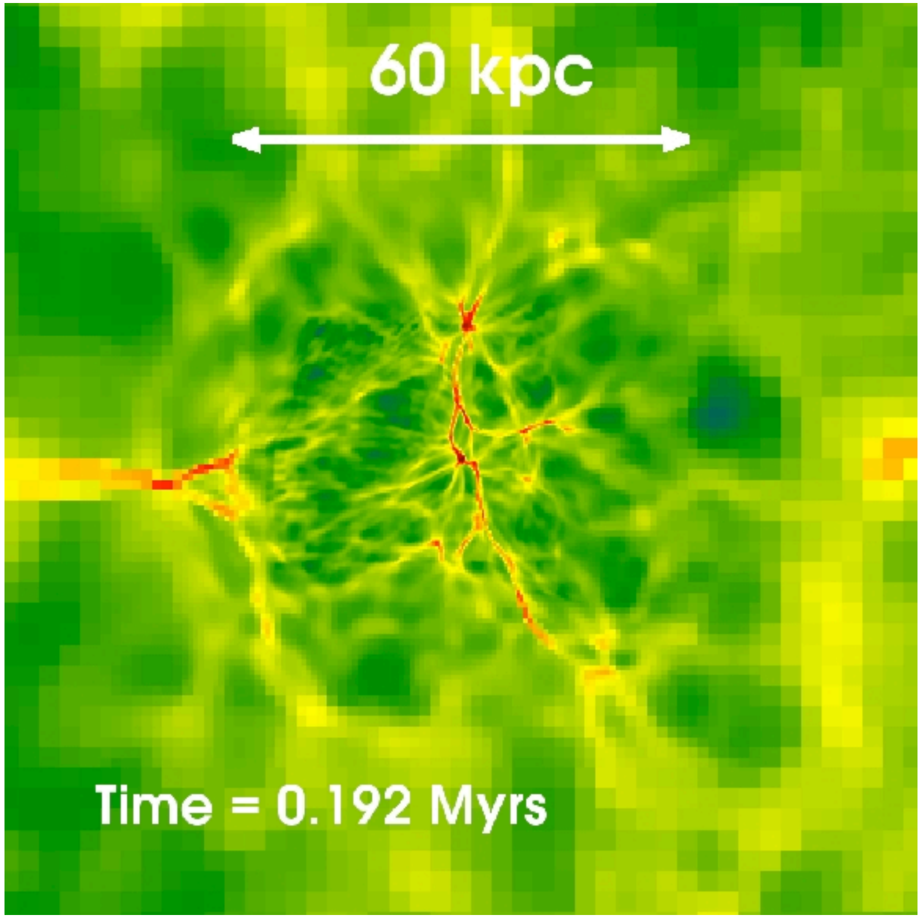
$T_{vir} \sim 35000K$

$V_{vir} \sim 30 kms^{-1}$

$M_{tot} \sim 3.3 \times 10^8 M_\odot$

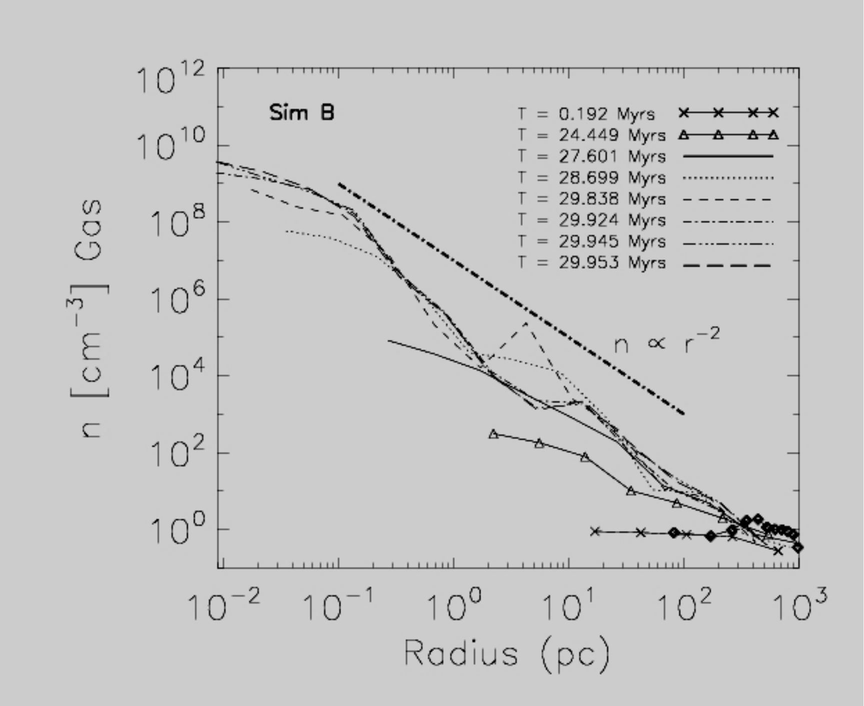
$z \sim 15$

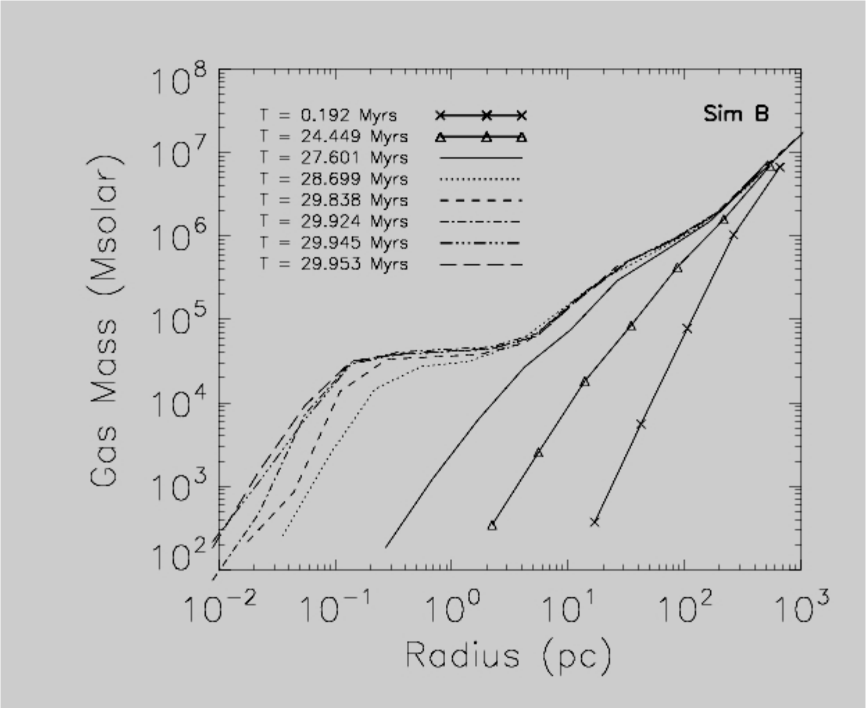
no H_2 cooling



Regan & Haehnelt 2008

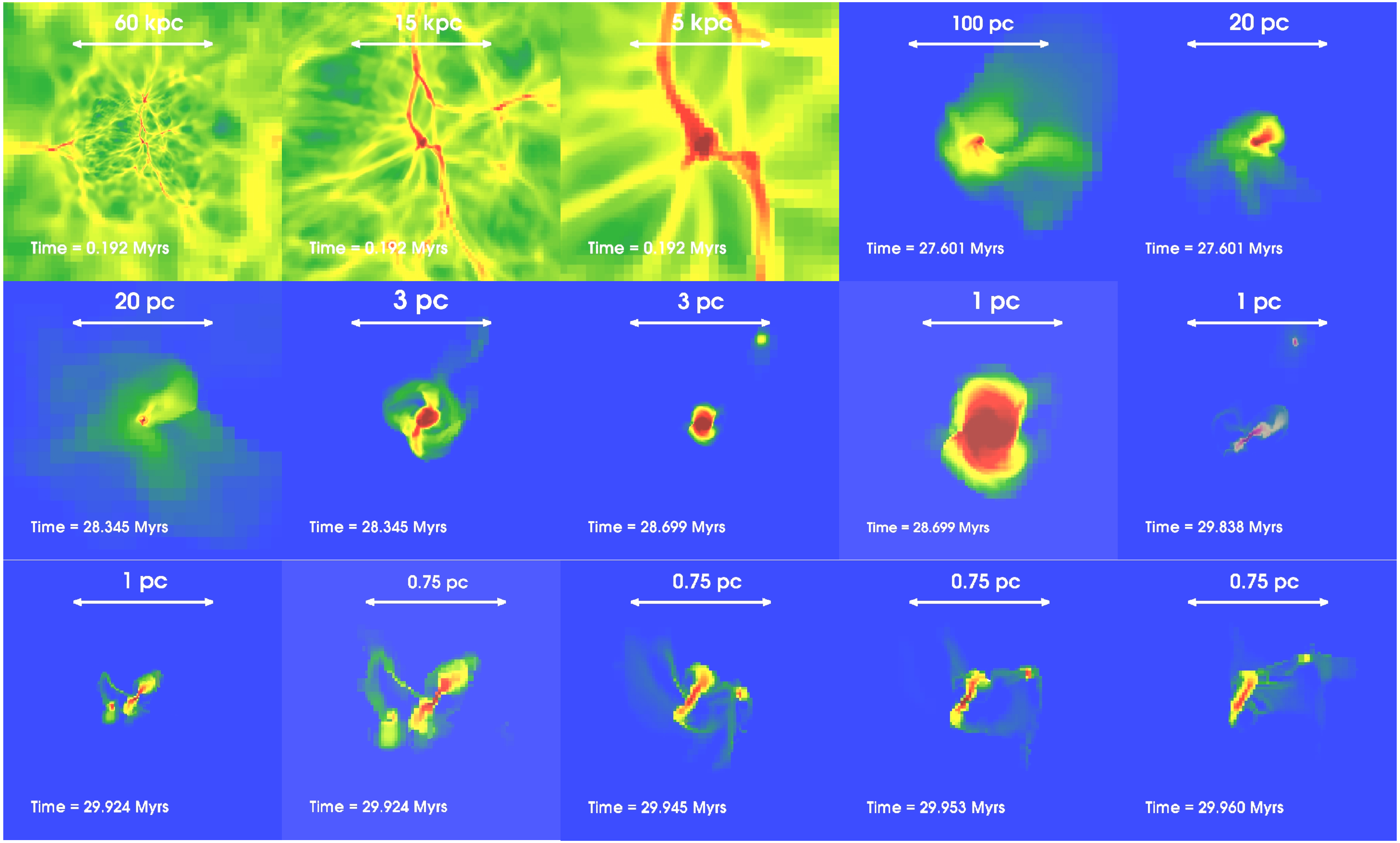
Isothermal collapse at T~7000-8000K





Regan & Haehnelt 2008

The inner $2x10^4$ $M_{\odot}$ collapse by a factor 1000 in radius before they settle into rotational support!



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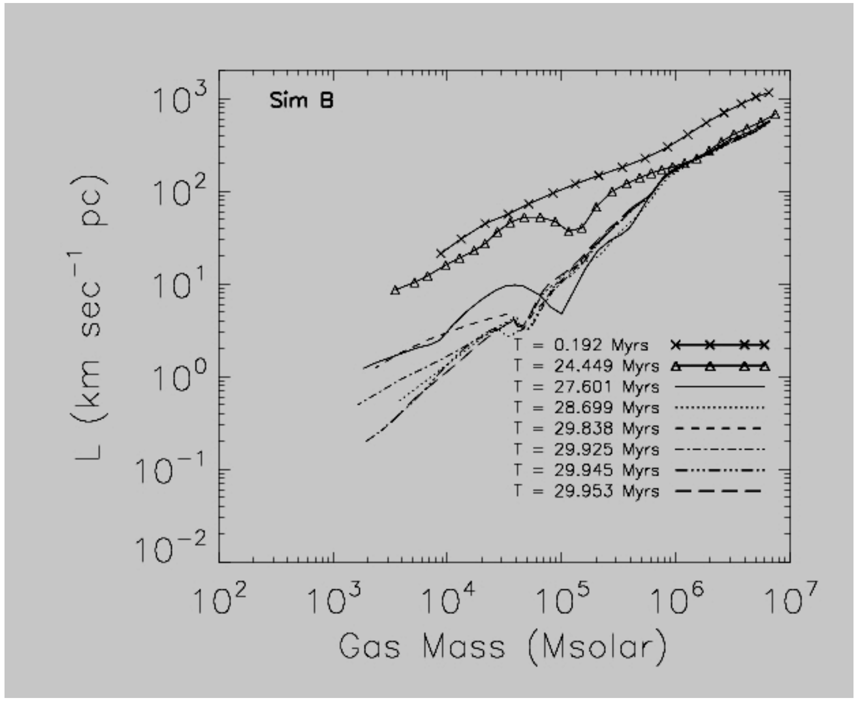
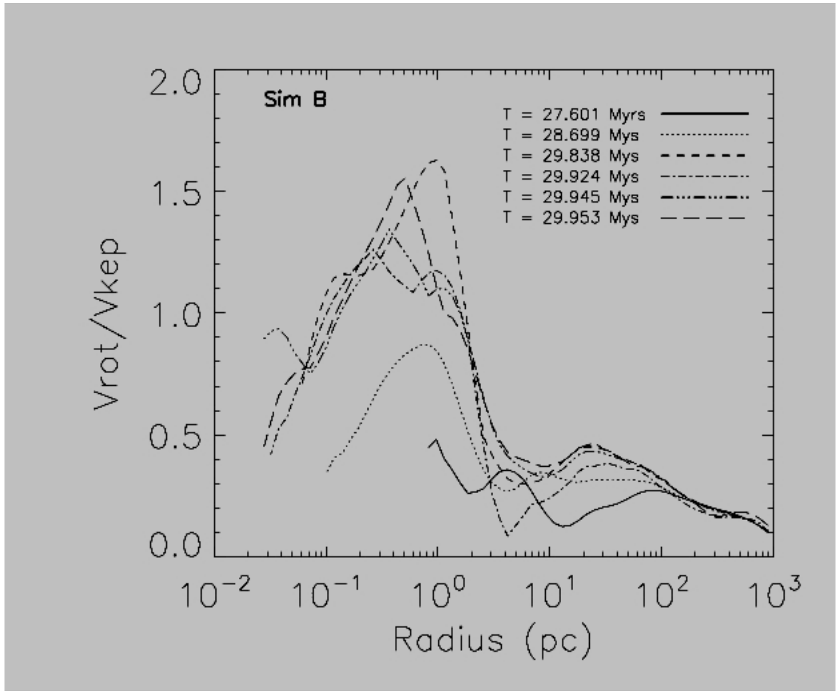
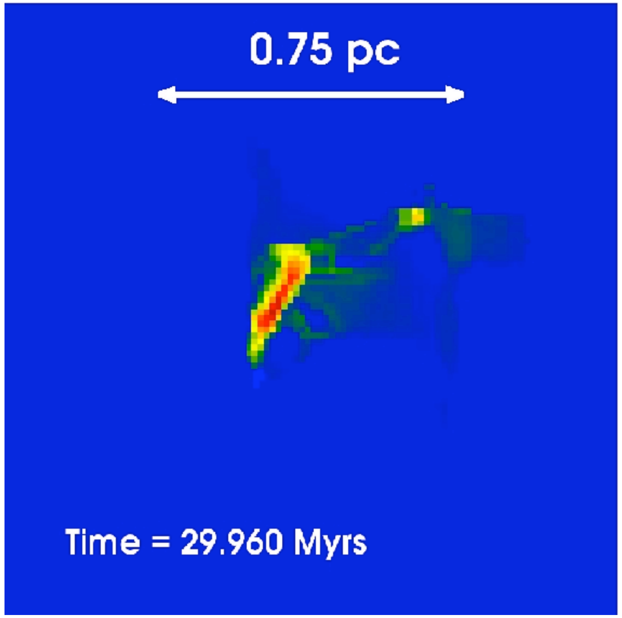
Angular momentum loss and rotational support

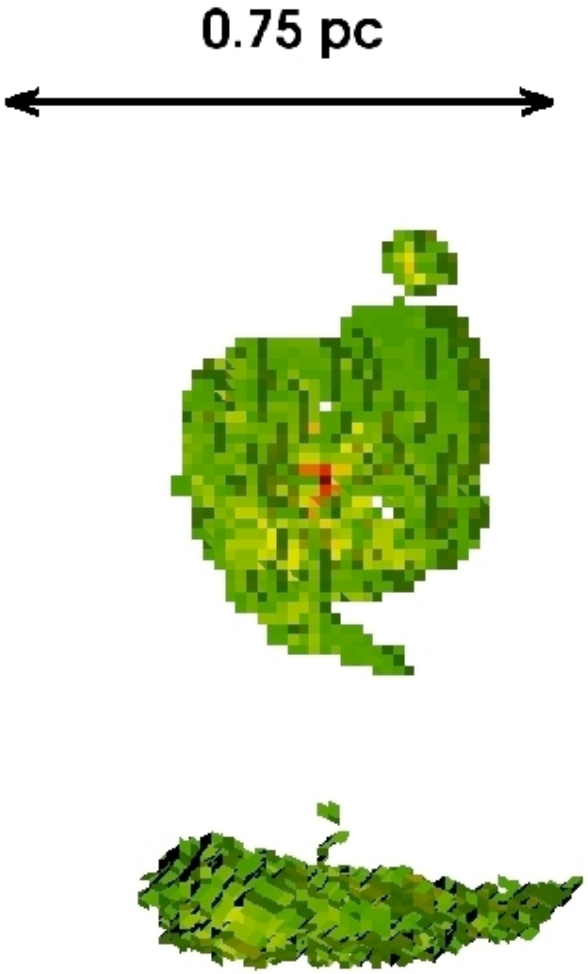




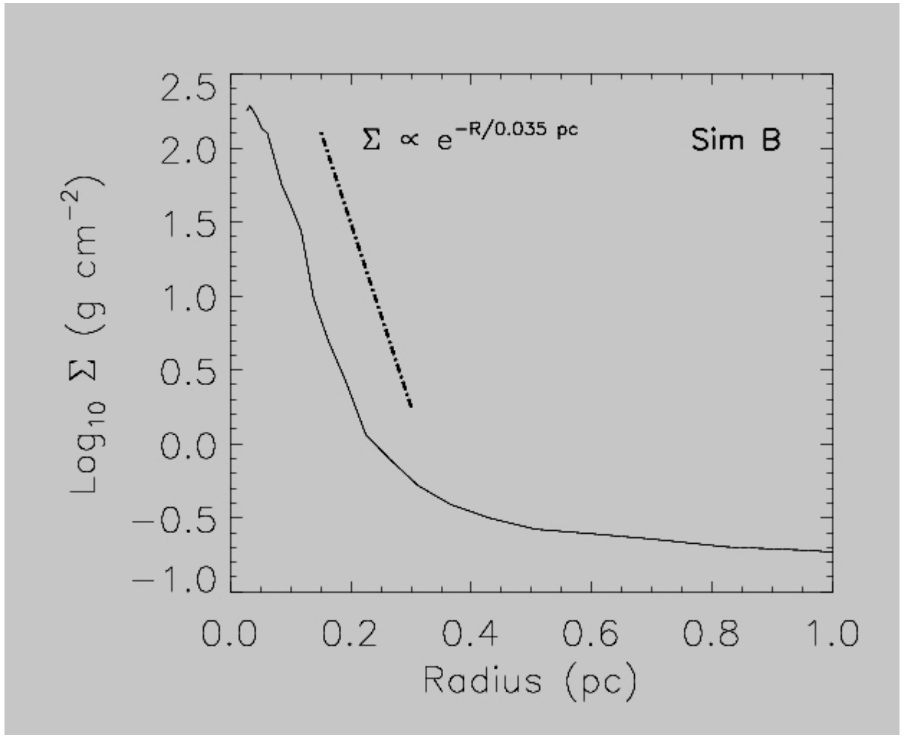
Regan & Haehnelt 2008

The inner $2x10^4 M_{\odot}$ loose more than 95% of their initial angular momentum.



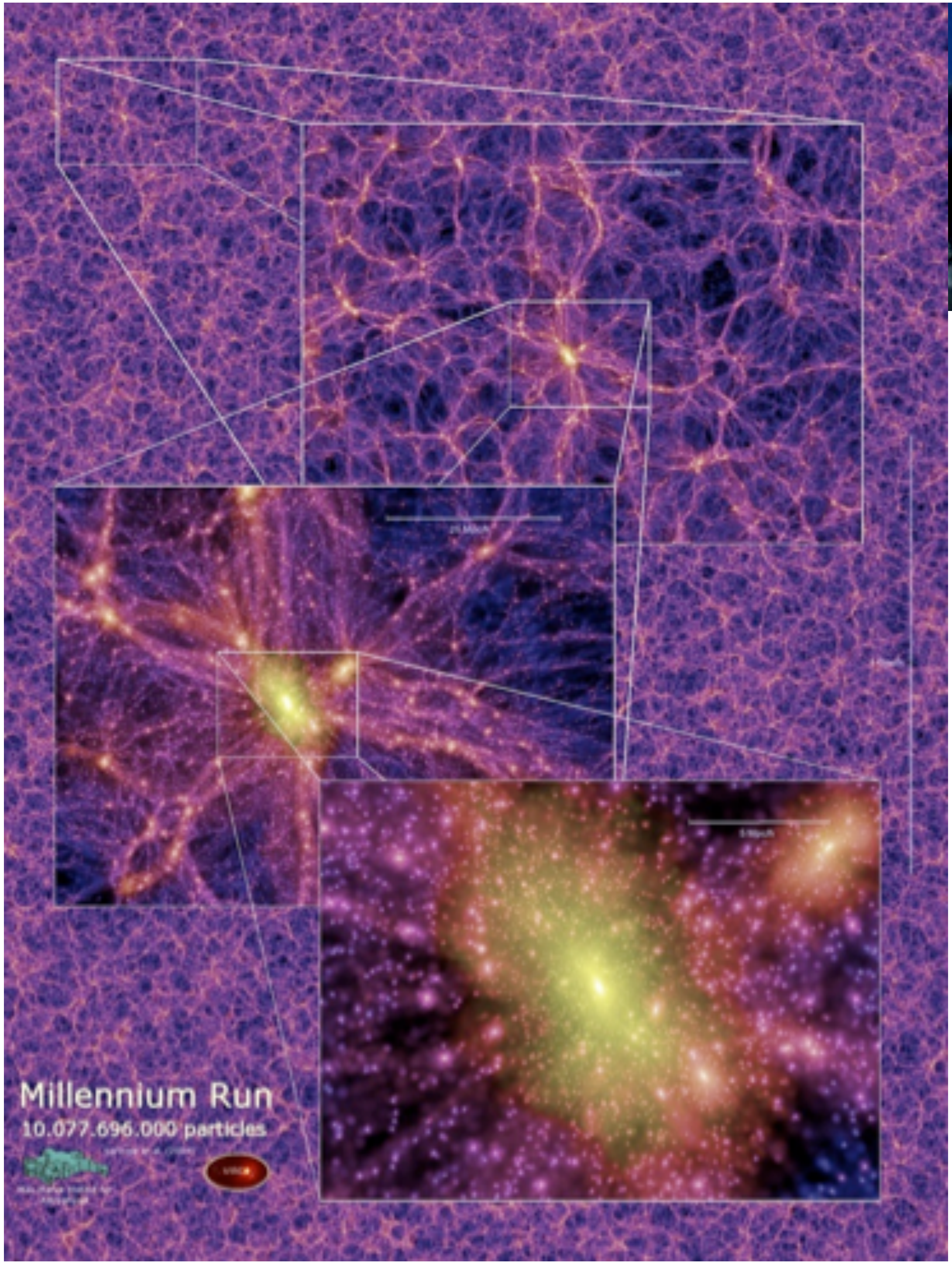


The inner $2x10^4\ M_{\odot}$ settle into rotational support and form a compact fat self-gravitating disc with “radius” ~ 0.3pc.



Regan & Haehnelt 2008

An exponential disc with scale length 0.035pc.

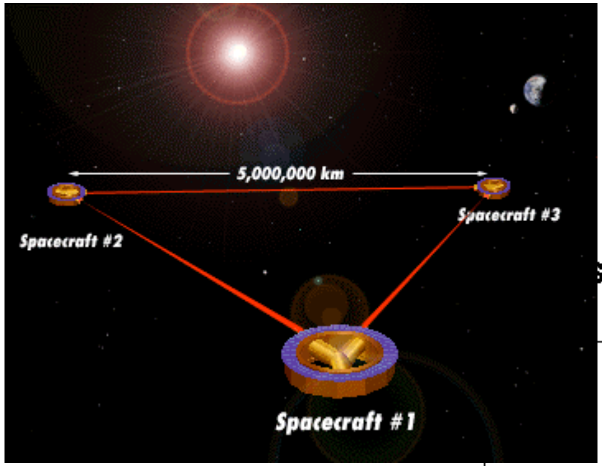


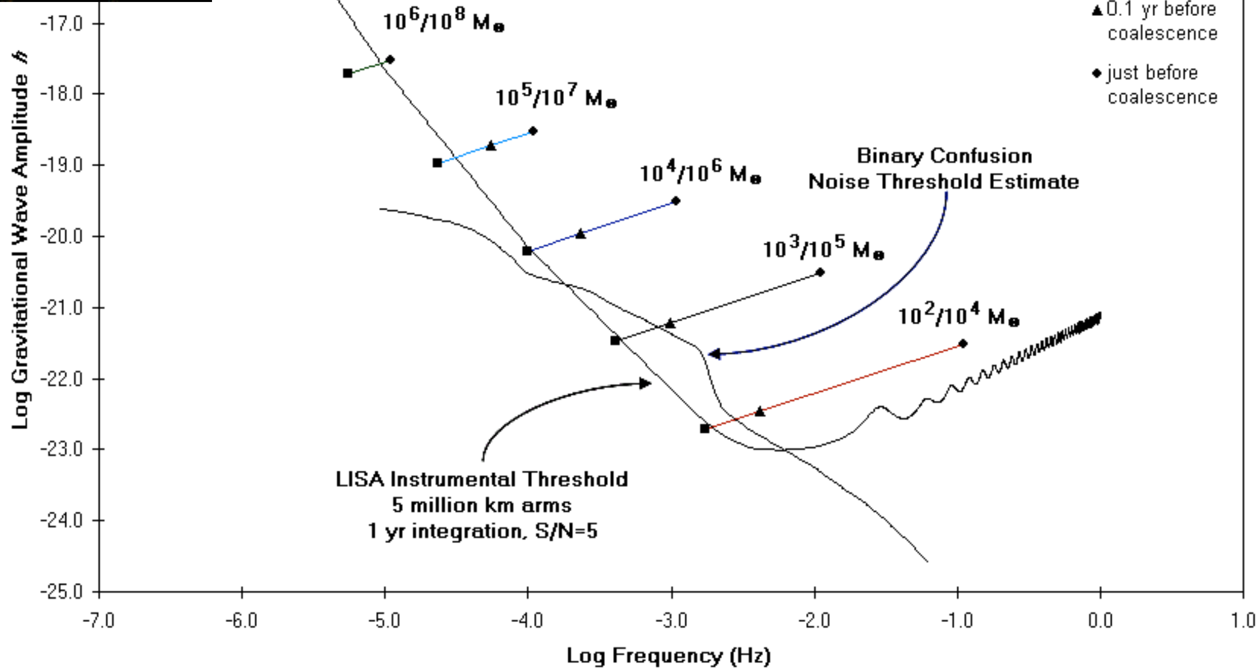

Volker Springel


Deborah Sijacki

Resimulating the build-up of galaxies and black holes (including spin history and kicks due to gravitational wave re-coil) in the most massive halo at z=6 with higher resolution.

How will we ever know?

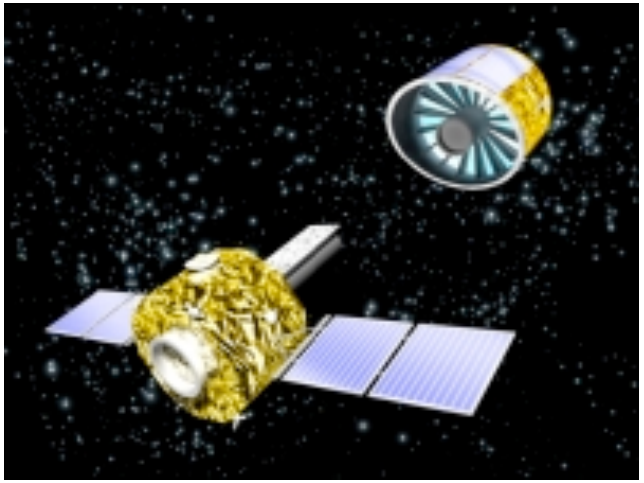


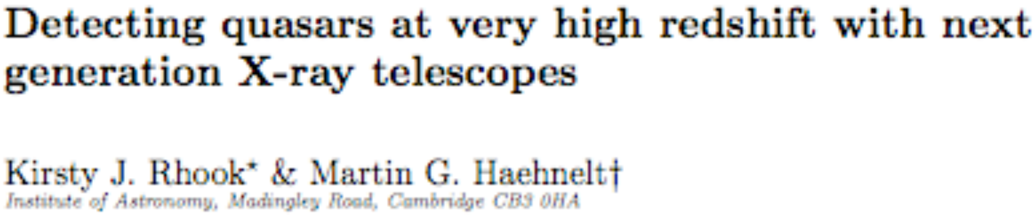


~~2011?~~

2017?

LISA will see mergers of 10^5 – 10^7 $M_\odot$ binary black holes with high S/N





Detecting quasars at very high redshift with next generation X-ray telescopes

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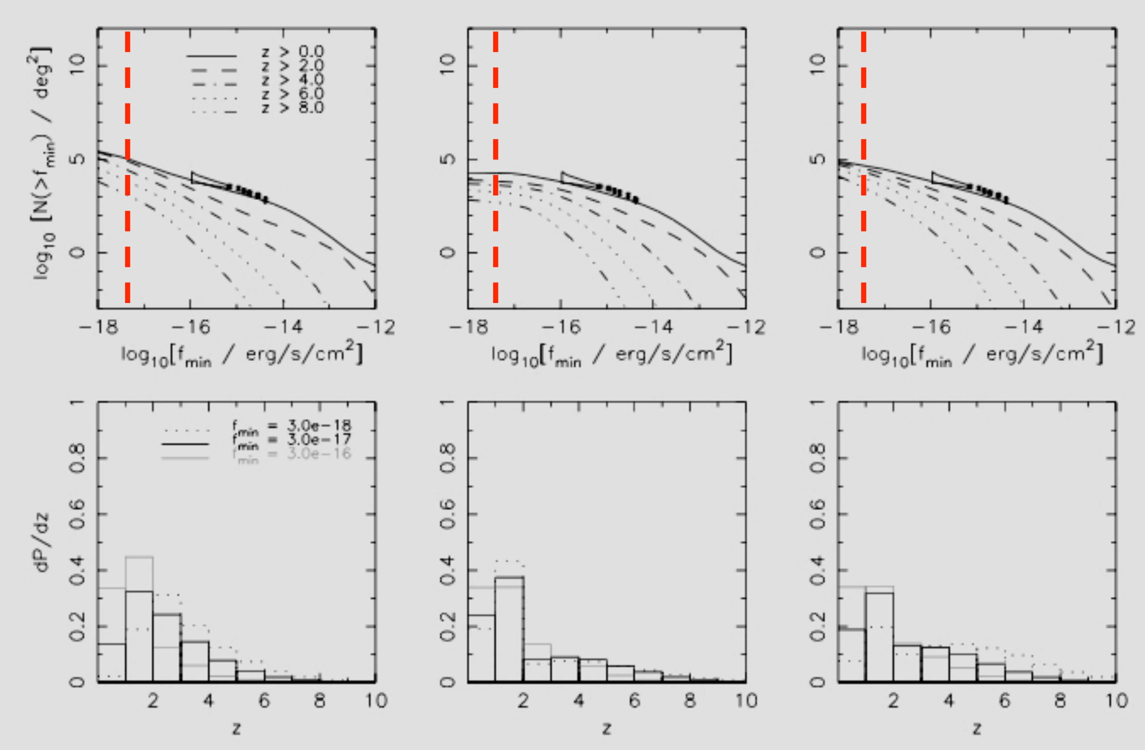
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

A significant fraction of the X-ray sources detected by XEUS should be at z>6. Should be able to see black holes with masses as small as $10^5 M_{\odot}$.



Paris, 8th July 2008

Summary

- Feedback regulated co-evolution of galaxies and their central black holes.
- We still don't know how (and when) massive black holes form in the first place!
- Most probably require massive seed black holes. Direct collapse of gas in haloes with $T_{vir} \geq 10000K$ with no metals (and H_2 supression) is least prone to fragmentation
- The inner $2\times10^4 M_\odot$ in $T_{vir} \geq 10000K$ collapse by a factor 1000 in radius, settle into rotational support and form a compact fat self-gravitating exponential disc with scale length 0.035pc.
- LISA and future X-ray missions offer excellent prospects for unravelling the early build-up and determining detailed properties of supermassive black holes.