The Interplay Between Galaxies and Black Holes

A Theoretical Overview

Massimo Ricotti (U of Maryland)

..a tale of many sleepless nights

Maya and Noemi Ricotti

Outline

- **Cosmological Context**

- **Formation of “Seed Black Holes”**
    1. Primordial Black Holes
    2. Pop III Stars Remnants
    3. Direct Collapse
    4. Stellar Dynamics

- **Black Hole Growth**

1. Gas Accretion vs BH-BH Mergers
2. Feeding Black Holes
    - » M-sigma relation
    - » Feedback and duty cycles
3. Feedback on Environment
    - » Cosmic ionization and thermal history

Black Hole Jargon

Formation at z<30-50 in galaxies

- Stellar mass Black Hole (BH): roughly ~1-10 M_{sun}
- Intermediate mass BH (IMBH): ~100-1000 M_{sun}
- Massive BH (MBH): >1000 M_{sun}
- Supermassive BH (SMBH): > $10^6 M_{sun}$

Formation at z > 5000 from collapse of "radiation"

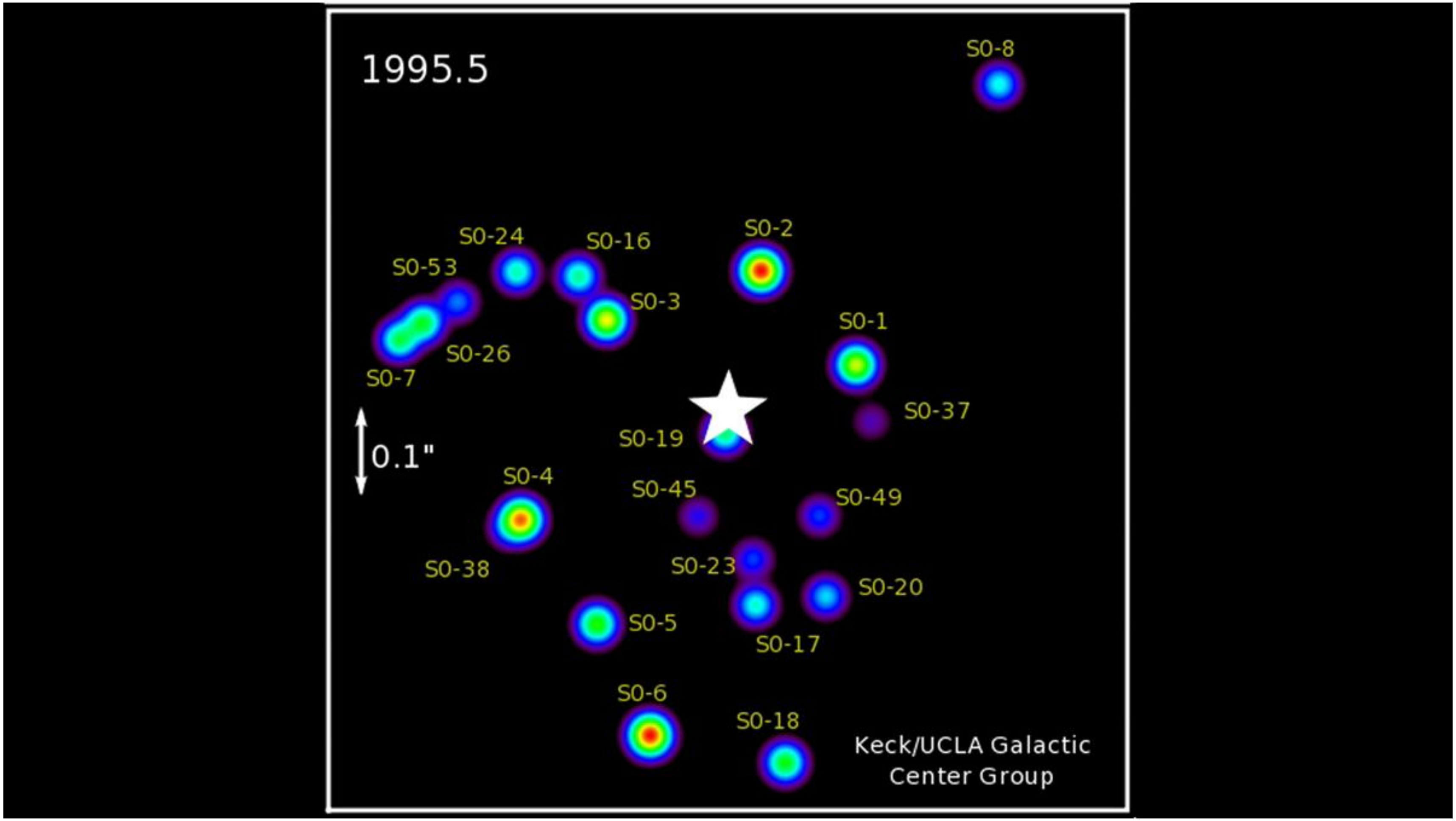
- Primordial BH (PBH): 10^{-5} g to 10^5 M_{sun}

How and when BH form?

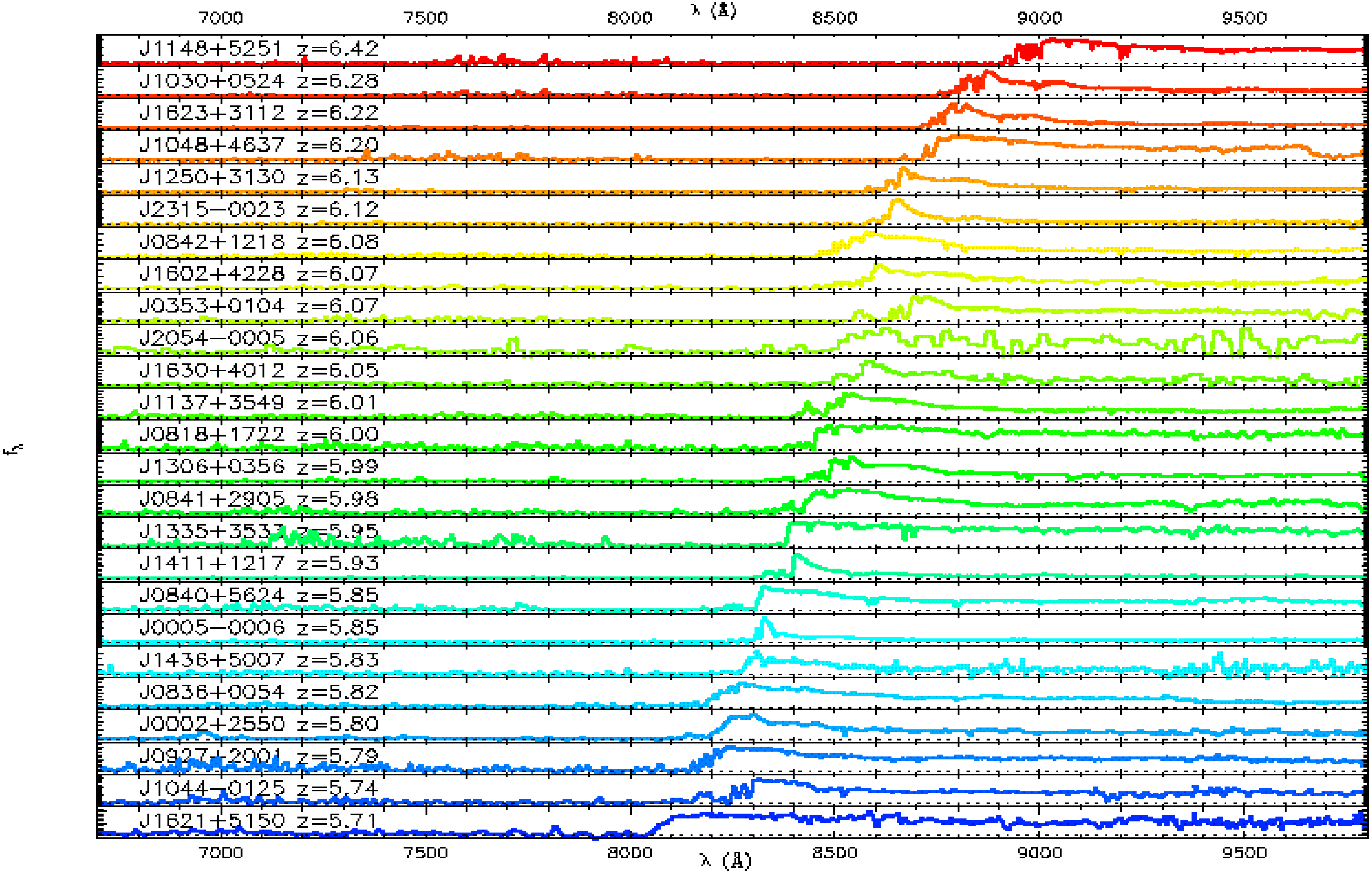
- Solid evidences of BH and SMBH existence
- Debatable evidences of IMBH existence
  - Ultraluminous X ray sources (ULX) in nearby galaxies (eg, Miller & Colbert 2004)
  - In GCs M15 and G1 (vanderMarel et al. 2002; Gerssen et al. 2002; Gebhardt et al. 2005, but see Baumgardt et al 2003)
- No direct evidence of PBH existence. Upper limits.

- Formation of stellar BHs is more or less understood. We do not know how all other BHs formed …

Evidence for SMBH at the center of our Galaxy



SMBHS form early! High-z Quasars



Fan 2006

How fast can a black hole grow? (by gas accretion)

1. Quasars shine by converting potential energy to radiative energy when accreting gas: radiative efficiency of ~10%
2. Quasar maximum accretion rate is limited by radiation pressure (Eddington limit). The growth is exponential with maximum accretion e-folding timescale 40 million years.
3. The age of the universe at z~6 is ~800 million years: maximum growth is 500 million times (about 20 e-folding timescale)
4. Earliest quasars have a mass of several billions solar masses: “seed” black holes must be massive (> 10-100 Msun)
5. <u>Feedback</u> effects likely to <u>prevent non-stop accretion</u> at maximum rate

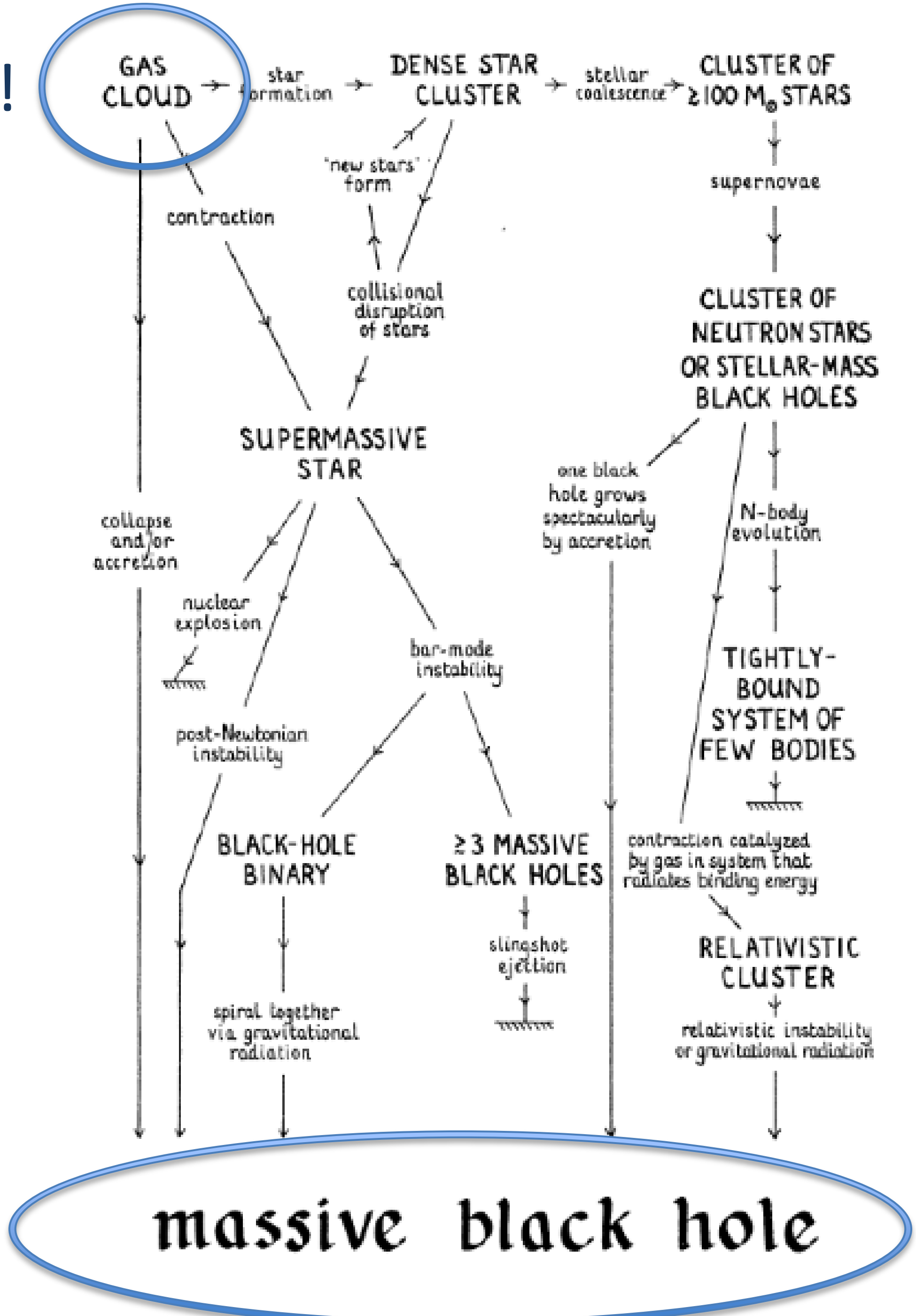
Outline

- **Cosmological Context**

- **Formation of "Seed Black Holes"**
    1. Primordial Black Holes
    2. Pop III stars remnants
    3. Direct collapse
    4. Stellar dynamics

- **Black Hole Growth**
    1. Gas Accretion vs BH-BH Mergers
    2. Feeding Black Holes
        - » M-sigma relation
        - » Feedback and duty cycles
    3. Feedback on Environment
        - » Cosmic ionization and thermal history

Start here!



Rees 1984

Arrival

General remarks to grow SMBHs

- Bondi accretion rate proportional to BH mass square: need massive seeds

- Golden rules for BH formation from gas cloud

1. Avoid gravitational fragmentation
2. Accrete gas with low angular momentum or dissipate angular momentum

High redshift Universe is ideal. Why?

1. Low metallicity and low cooling rate helps with fragmentation problem
2. Smaller amplitude of cosmological perturbations helps with angular momentum problem

However, there are no <u>direct</u> observations to guide us

Brief history of the Universe

PBHs?

IMBHs
from Pop III?

Direct collapse
of MBHs?

Quasars
(accreting
SMBHs)

S.G. Djorgovski et al. & Digital Media Center, Caltech

CMB **(observed)**

z ~ 1000: Last Scattering Surface

z ~ 7-30: first stars and quasars,
reionization begins

Not observed

H Reionizaton complete

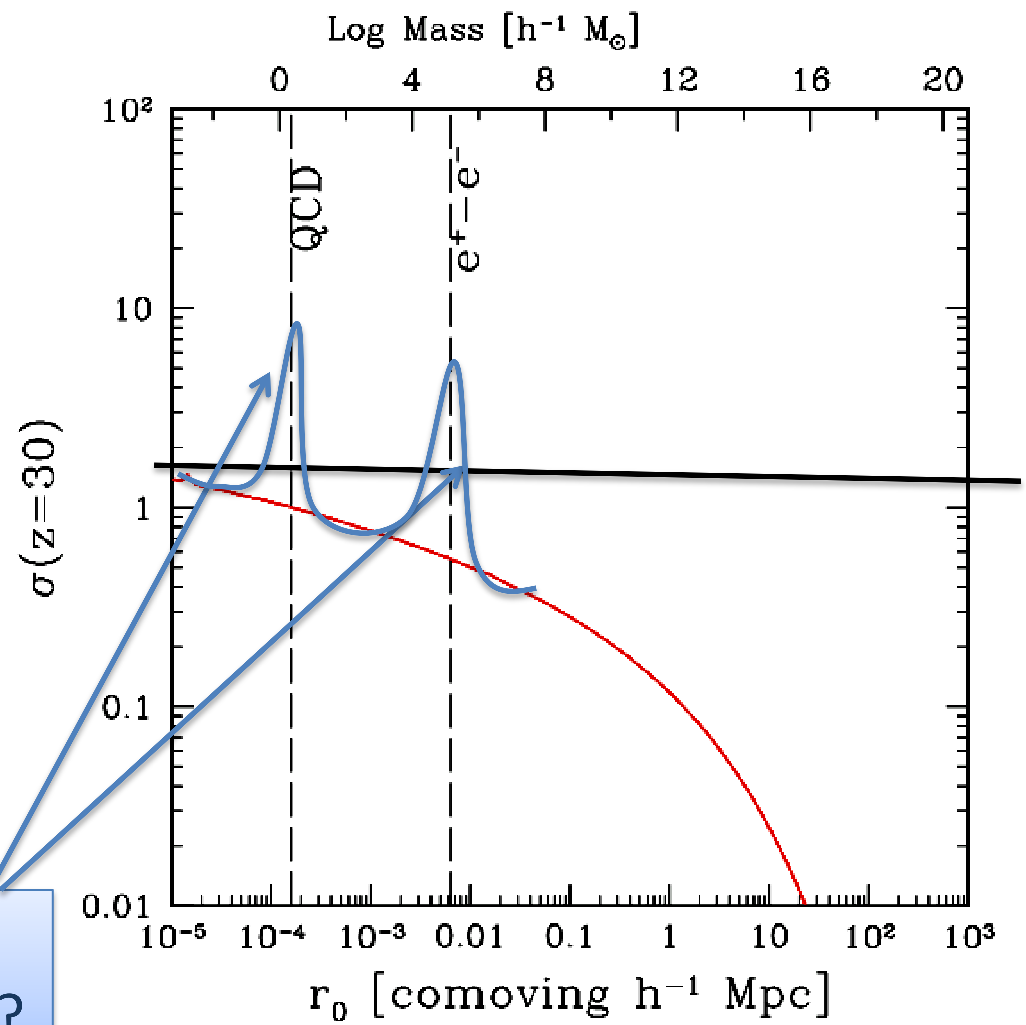
He Reionizaton complete

Observed Universe

Cosmological structure formation

- Gaussian perturbations from inflation + CDM

- Bottom-up galaxy formation



Phase transitions:
Non Gaussian perturbations?

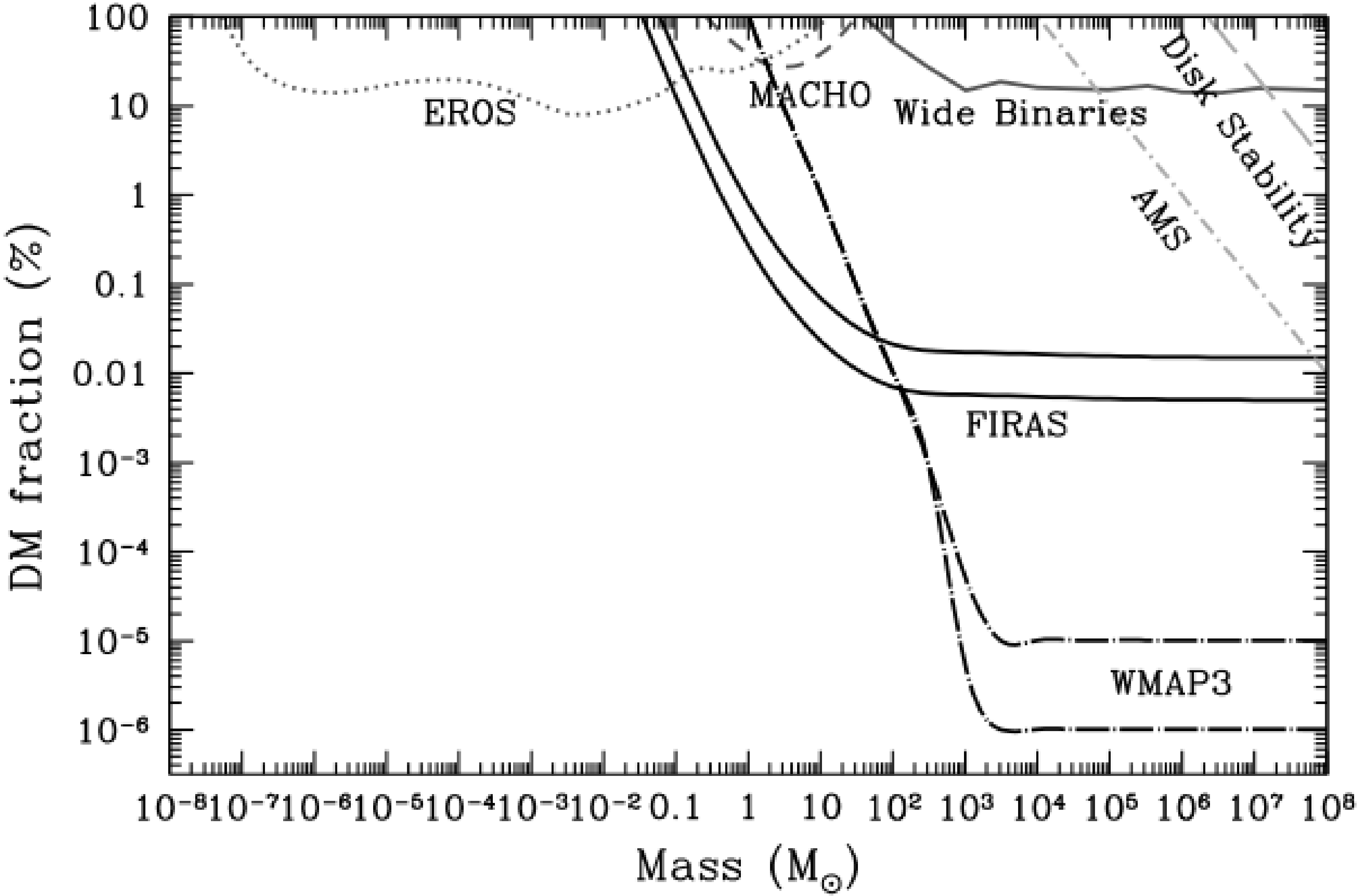
1 - Primordial black holes

1. PBHs modify recombination history and produce spectral distortions and anisotropies
2. New upper limits on f_{pbh} with WMAP3
3. PBHs promote formation of primordial H_2 and first stars

Refs: Ricotti 2007, Mack et al 2007, Ricotti et al 2008

Constraints on f_{pbh} from CMB

Ricotti, Ostriker & Mack 2008



Discussion

- Only upper limits on their existence. Do not know if they can form
- However, may provide plenty of IMBH to explain ULXs and the seeds to form SMBHs

- Note: Ultra-compact minihalos much more likely than PBHs. Can be probed as MACHOs and gamma-ray from DM self-annihilation (Ricotti & Gould 2009)
- First stars and BHs may form in ultra-compact minihalos at z>>30 (see also Loeb 1993)

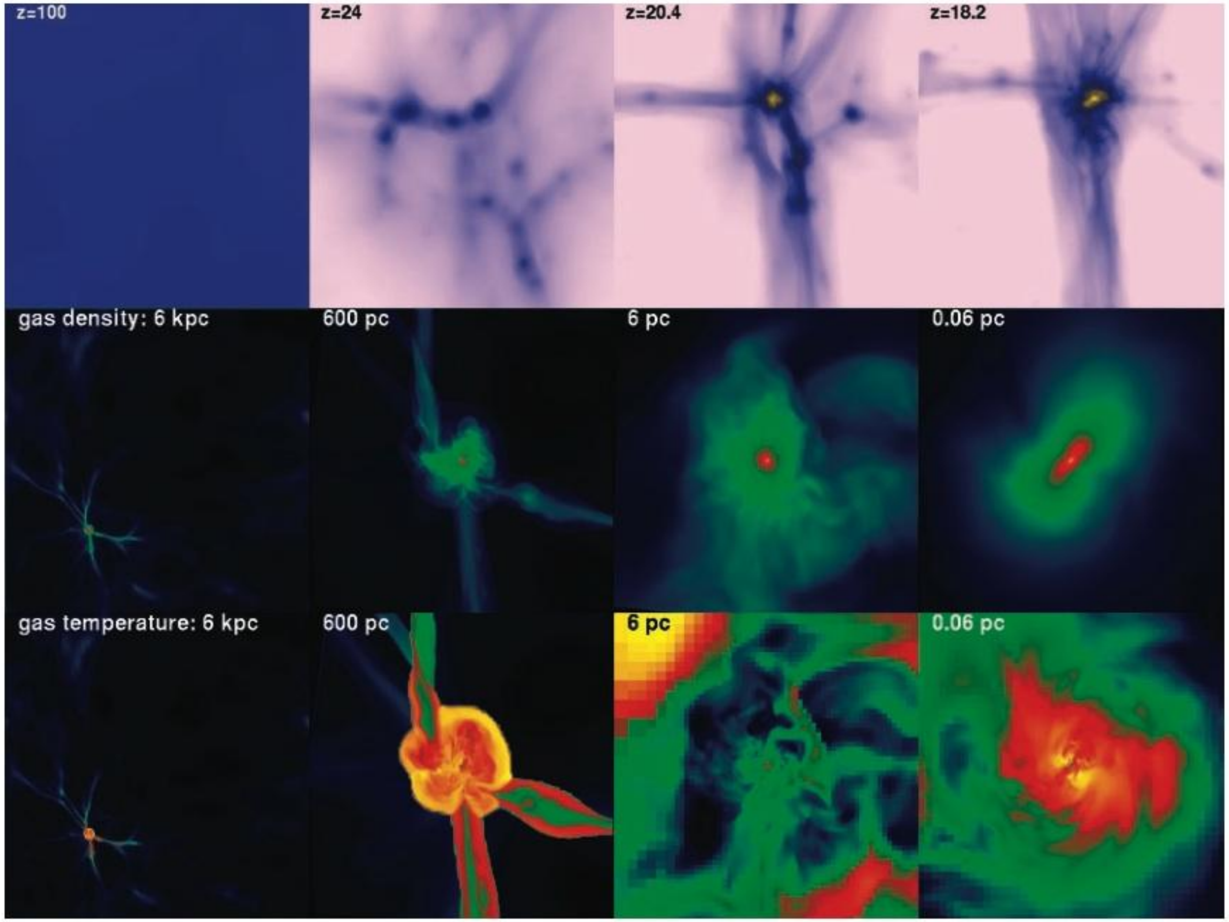
2 – First stars

Abel et al 2002

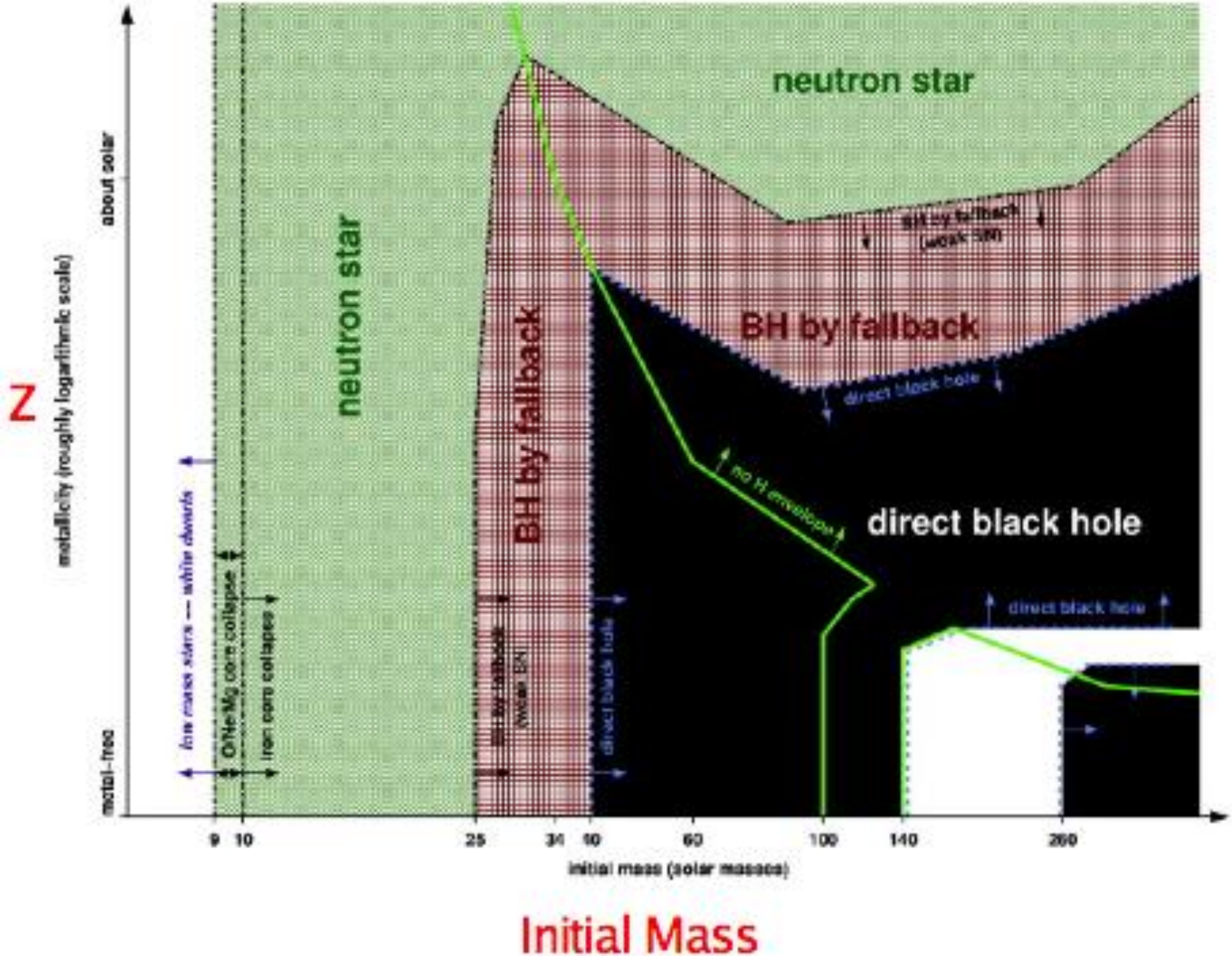
- Form in 10^5-10^6 M_{sun} minihalos
- Zero metallicity gas

- One star per halo
- Mass 20-300 M_{sun} ?

Refs: Bromm et al 1999, Abel et al 2002, Madau & Rees 2001, Gao et al 2005, O'Shea & Normal 2007, Yoshida et al 2008, Turk et al 2009



Heger et al. 03



Discussion

- Of course the first stars formed but we do not know their mass and number:
  - IMF depends on environment. In relic HII regions smaller mass due to HD cooling, metallicity contamination, etc..
  - Binary Pop III

- Remnants may be too small IMBHs

3 – Direct collapse of gas cloud

- Several models: Haehnelt & Rees 1993, Eisenstein & Loeb 1995, Bromm & Loeb 2003, Koushiappas et al. 2004, Begelman, Volonteri & Rees 2006, Lodato & Natarajan 2006
- General considerations:
  - Form later in more massive halos > 10^7-10^8 M_{sun}
  - Need to suppress star formation in cloud because SNe increase kinetic energy
  - Need to cool via atomic H and not molecular H, due to the temperature of these clouds
  - Perhaps possible if stars have already formed! (in other places, not the cloud). Then UV light dissociates H_2

Discussion

- Physical processes to prevent fragmentation:
  - Suppression of metal and H_2 cooling (Bromm & Loeb 2003)
  - Steepening of equation of state due to Lya trapping (Spaans & Silk 2006)
- Angular momentum dissipation:
  - Viscosity (Lodato & Natarajan 2006)
  - Bar-unstable self gravitating gas (Begelman, Volonteri & Rees 2006)
  - Compton Drag (Loeb 1993, Umemura et al 1993)

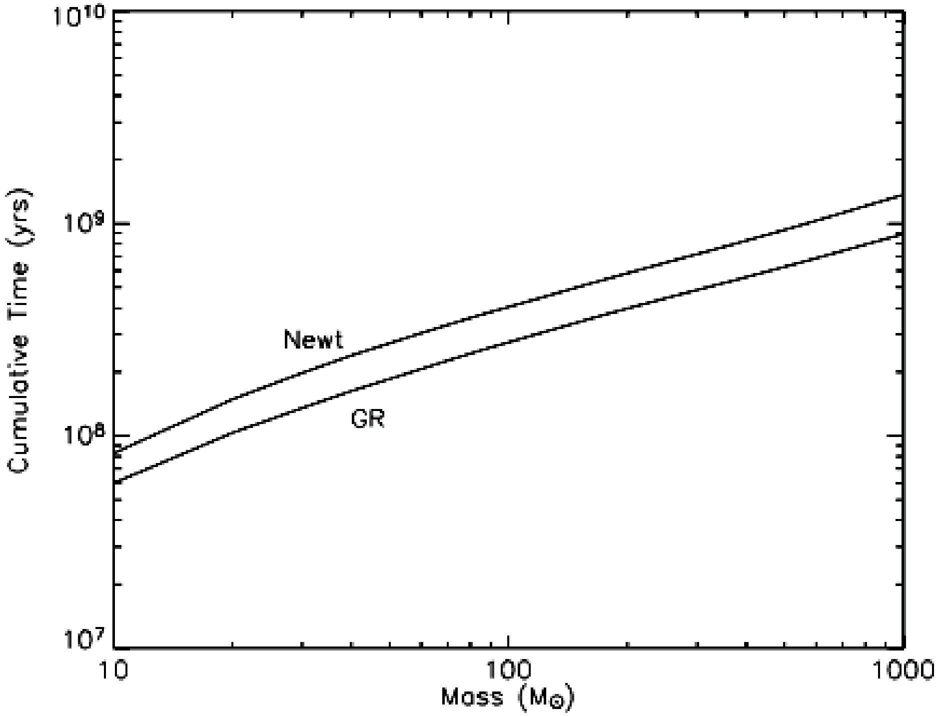
4 – MBHs from dense star clusters

1. Mergers of black holes in dense star clusters and protogalactic nuclei (Quinlan & Shapiro 1989, Kulkarni et al 1993, Sirgudsson & Hernquist 1993, Miller & Hamilton 2002, Gultekin et al 2004, O'Leary et al 2006)

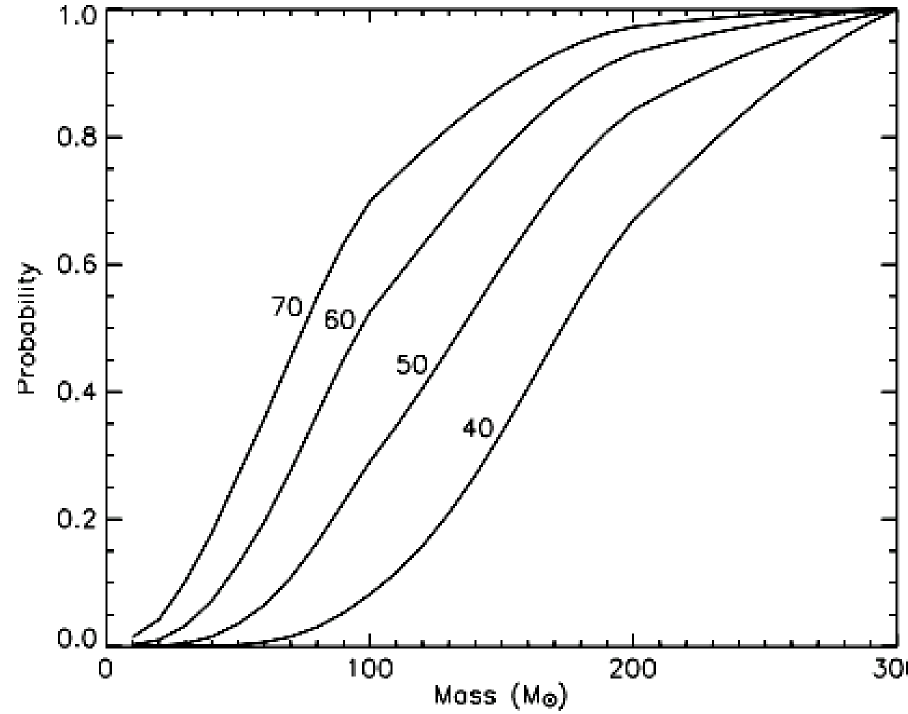
2. Runaway collisions of stars and formation of VMS (Portegeis Zwart & McMilliam 2002, Rasio et al 2003, Gurkan et al 2004, Gurkan et al 2006)

Stellar BH mergers

Gultekin, Miller & Hamilton 2004



Time to grow to mass M from seeds of 10 M_{sun}



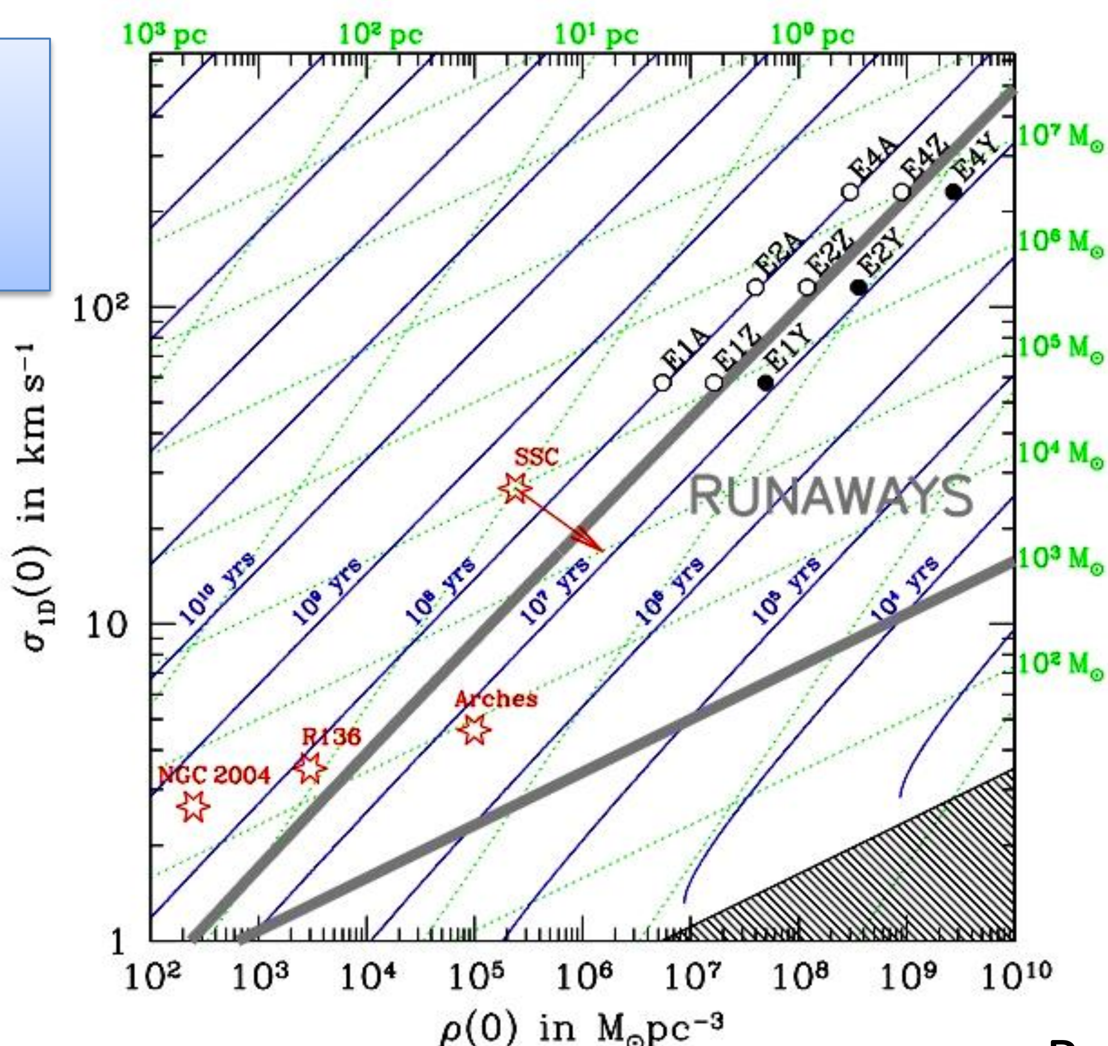
Probability of remaining in the cluster and build up to 300 M_{sun} vs starting mass

1. Run out of BH before growth to 300 $M_{sun.}$
2. Starting from small 10 M_{sun} seed lead to high probability of ejection

MBH from collapse of star clusters by runaway collisions

Cluster must collapse before its massive stars do

velocity dispersion



total mass

initial central density

Rasio et al 2003

Discussion

- BH mergers:
  - Relatively slow growth per BH ejected from cluster
  - Favors clusters with larger escape velocity
- Runaway stellar collisions:
  - Star cluster must have quite small initial mass and size
  - Need to understand when and where such clusters may form (in cosmological volume)

Outline

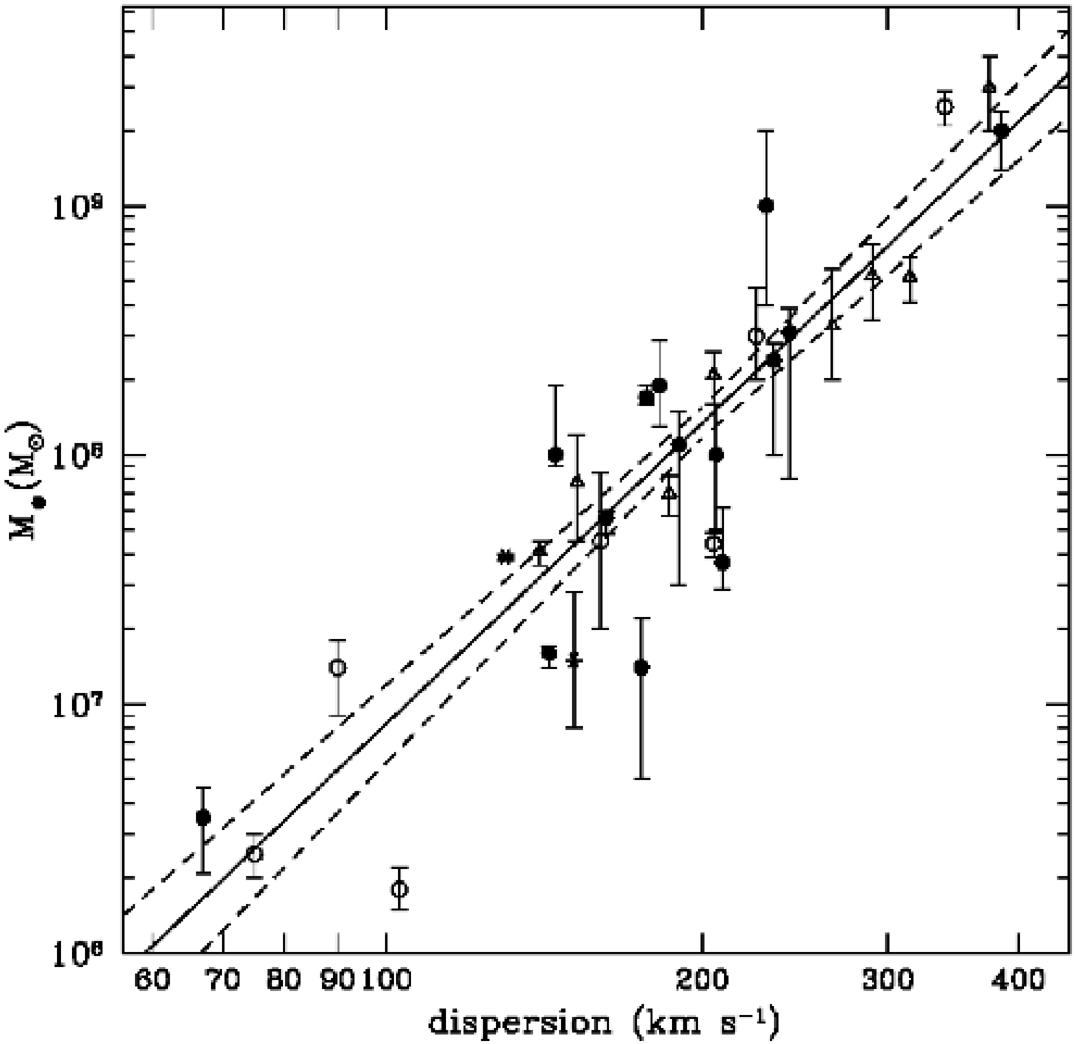
- **Cosmological Context**

- **Formation of “Seed Black Holes”**
    1. Primordial Black Holes
    2. Pop III stars remnants
    3. Direct collapse
    4. Stellar dynamics

- **Black Hole Growth**
    1. Gas Accretion vs BH-BH Mergers
    2. Feeding Black Holes
        - » M-sigma relation
        - » Feedback and duty cycles
    3. Feedback on Environment
        - » Cosmic ionization and thermal history

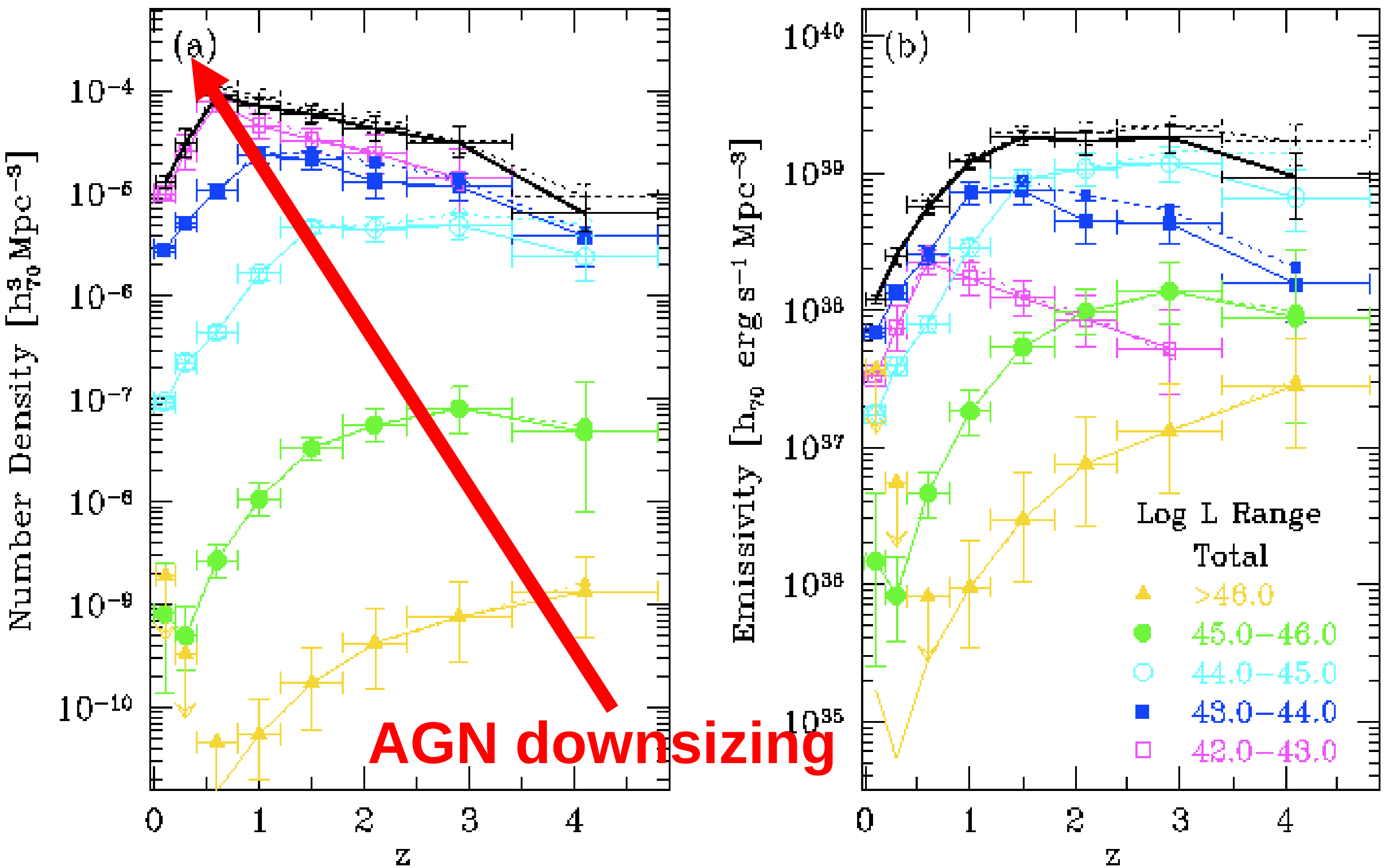
The black hole-galaxy connection

Tremaine et al 2002



- Black hole mass is related to host galaxy properties
- Many models to explain this. In general feedback require feedback regulation

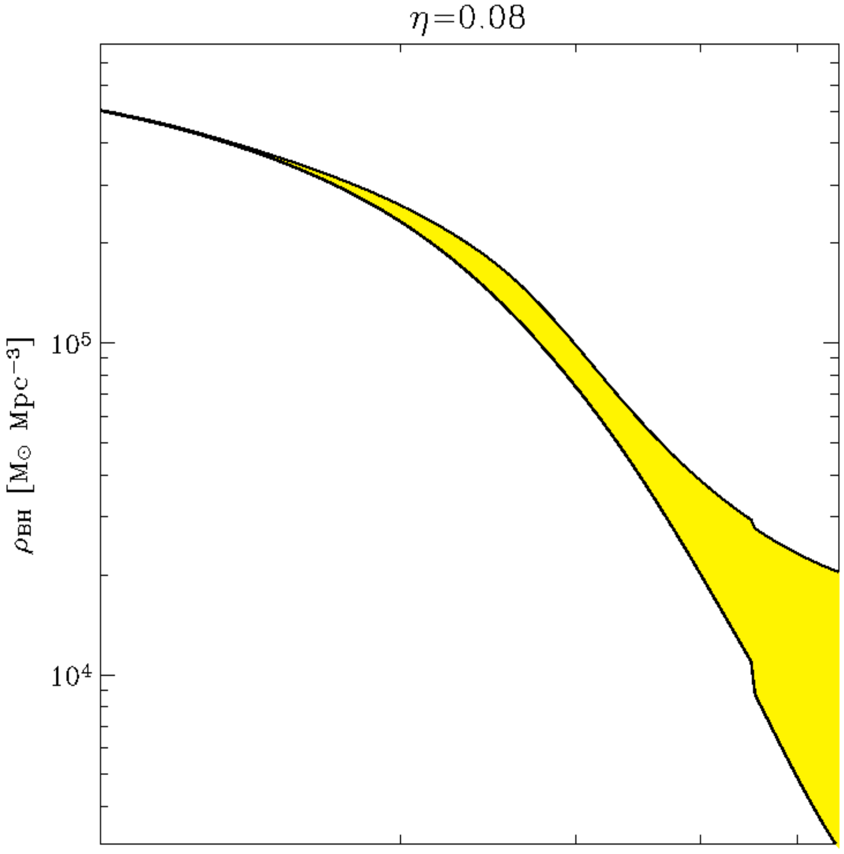
Evidence for gas accretion and AGN downsizing



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

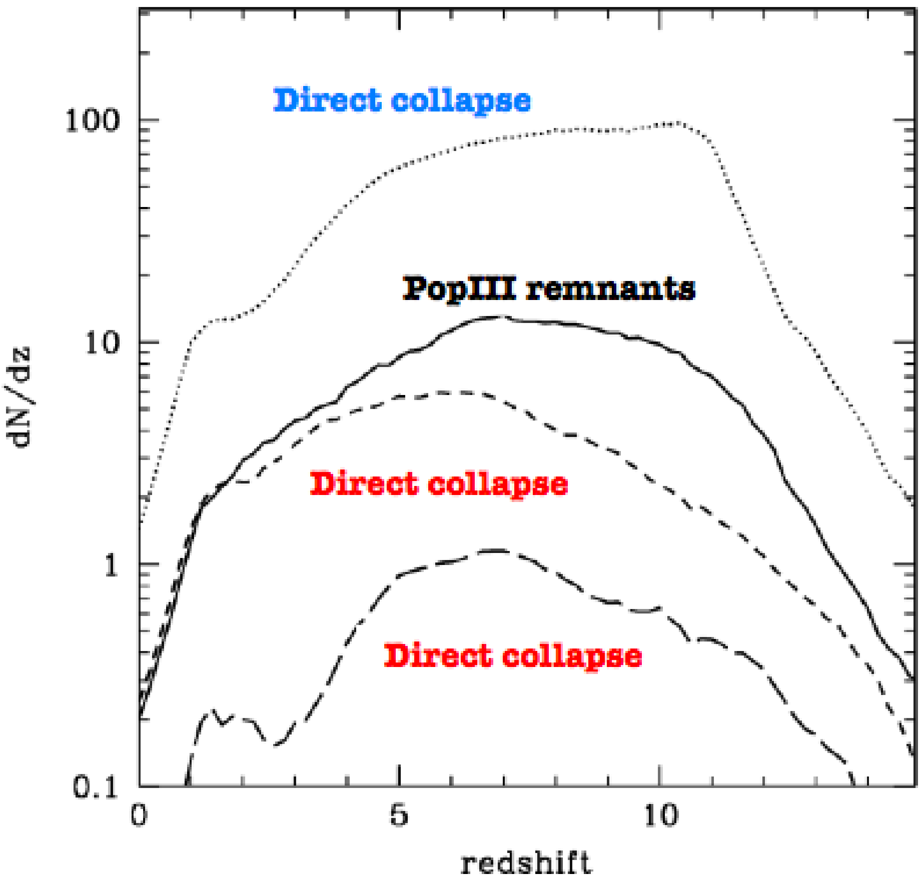
Gas Accretion vs BH-BH Mergers

Soltan's argument: Yu & Tremain 2002, Merloni et al 2004, etc



Redshift

Merger rate: Volonteri et al



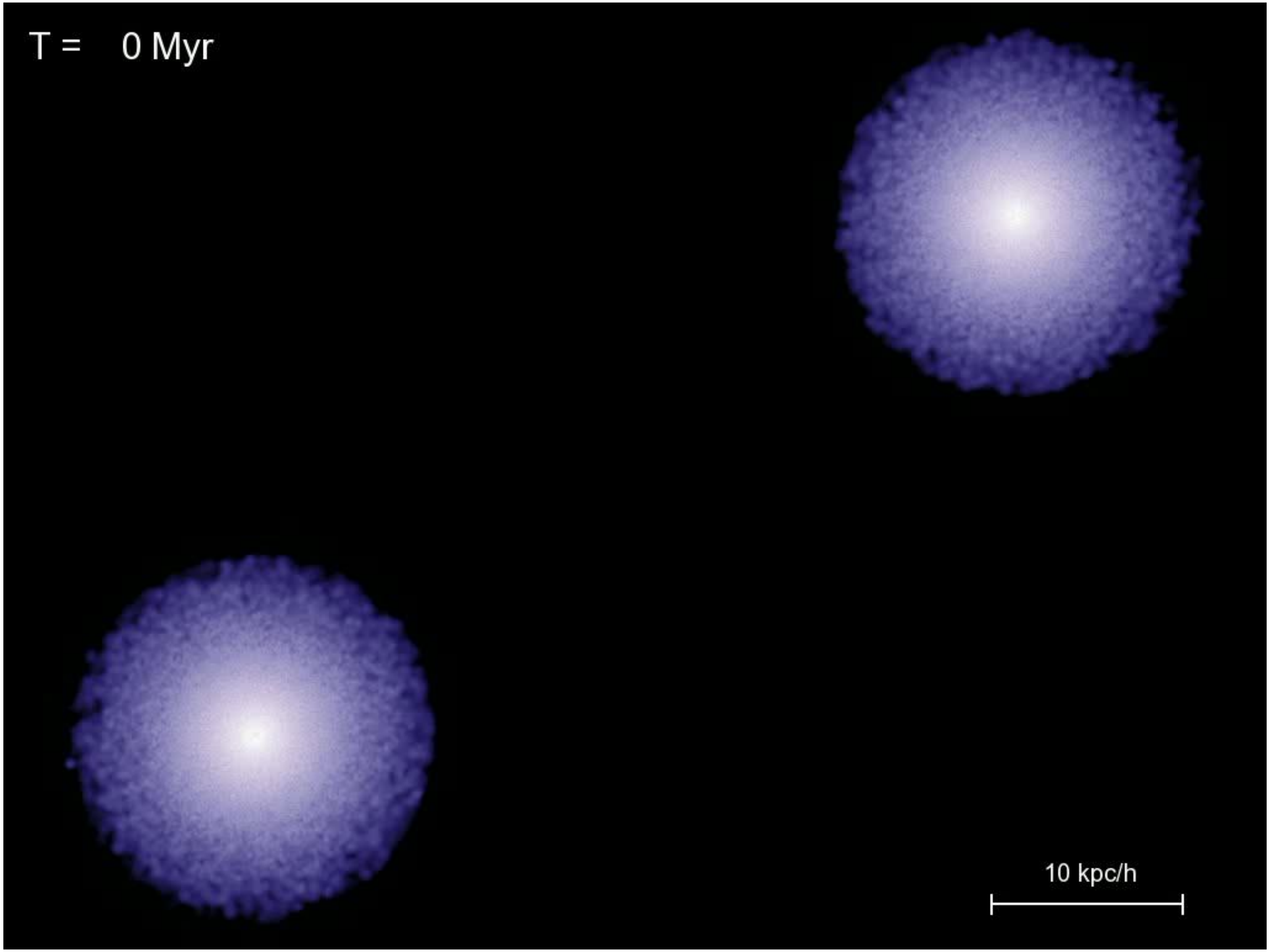
Outline

- **Cosmological Context**

- **Formation of “Seed Black Holes”**
    1. Primordial Black Holes
    2. Pop III stars remnants
    3. Direct collapse
    4. Stellar dynamics

- **Black Hole Growth**
    1. Gas Accretion vs BH-BH Mergers
    2. Feeding Black Holes
        » M-sigma relation
        » Feedback and duty cycles
    3. Feedback on Environment
        » Cosmic ionization and thermal history

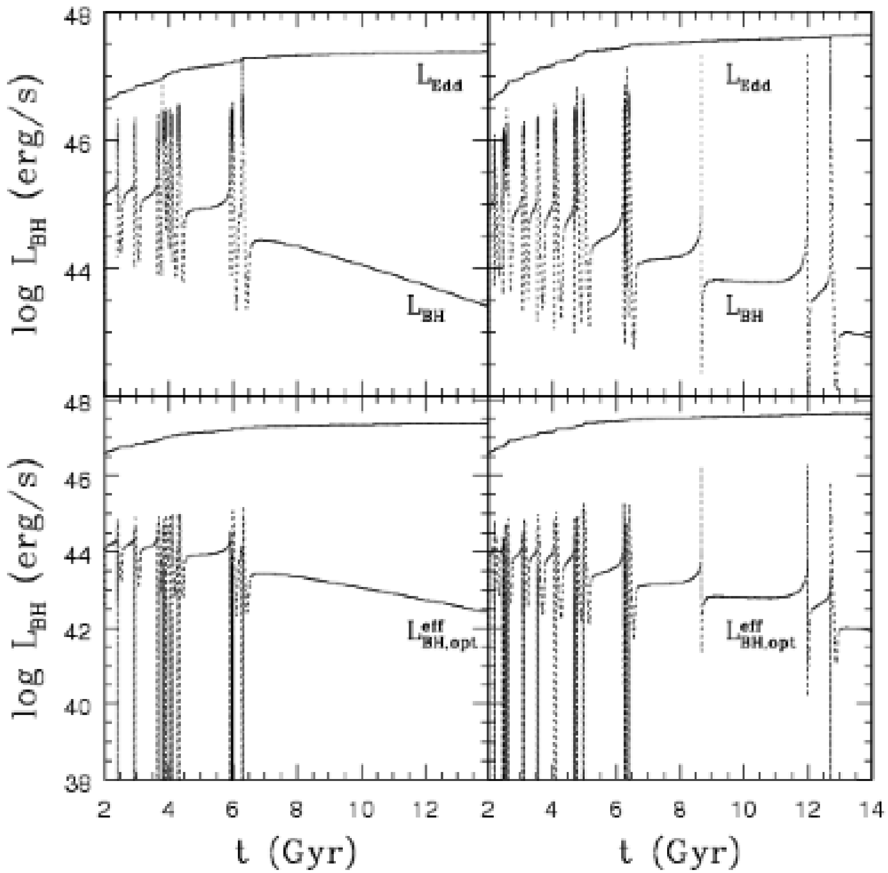
Feeding BHs through galaxy mergers

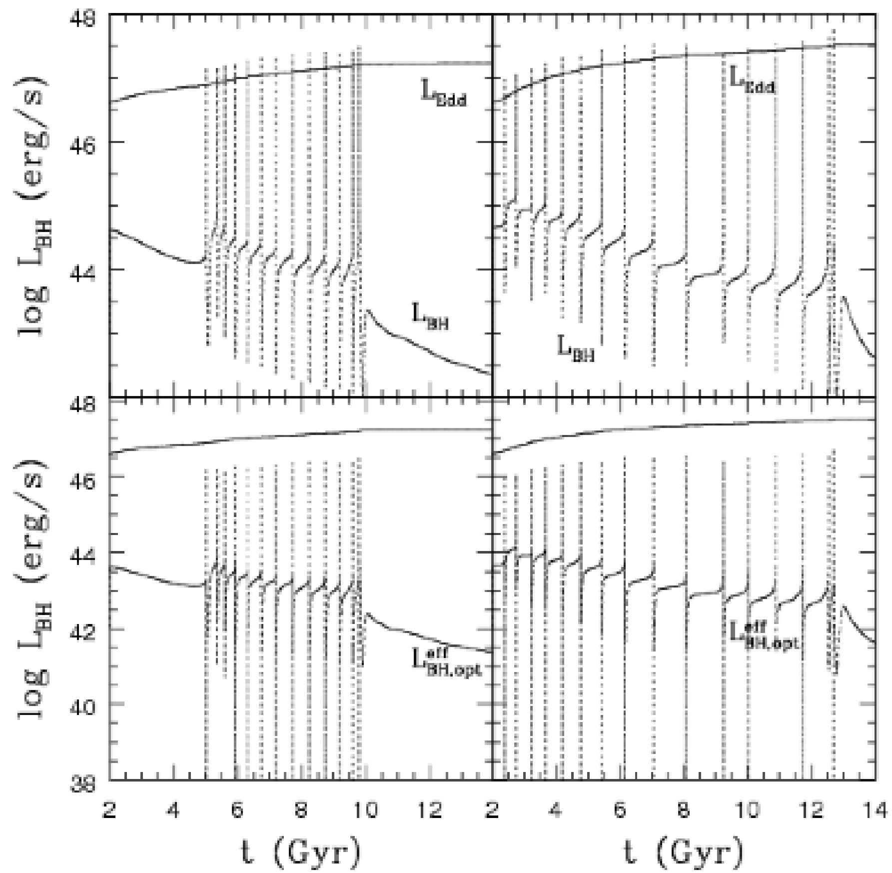


DiMatteo et al

Duty cycles: 1D simulations

Ciotti, Ostriker & Proga 2009





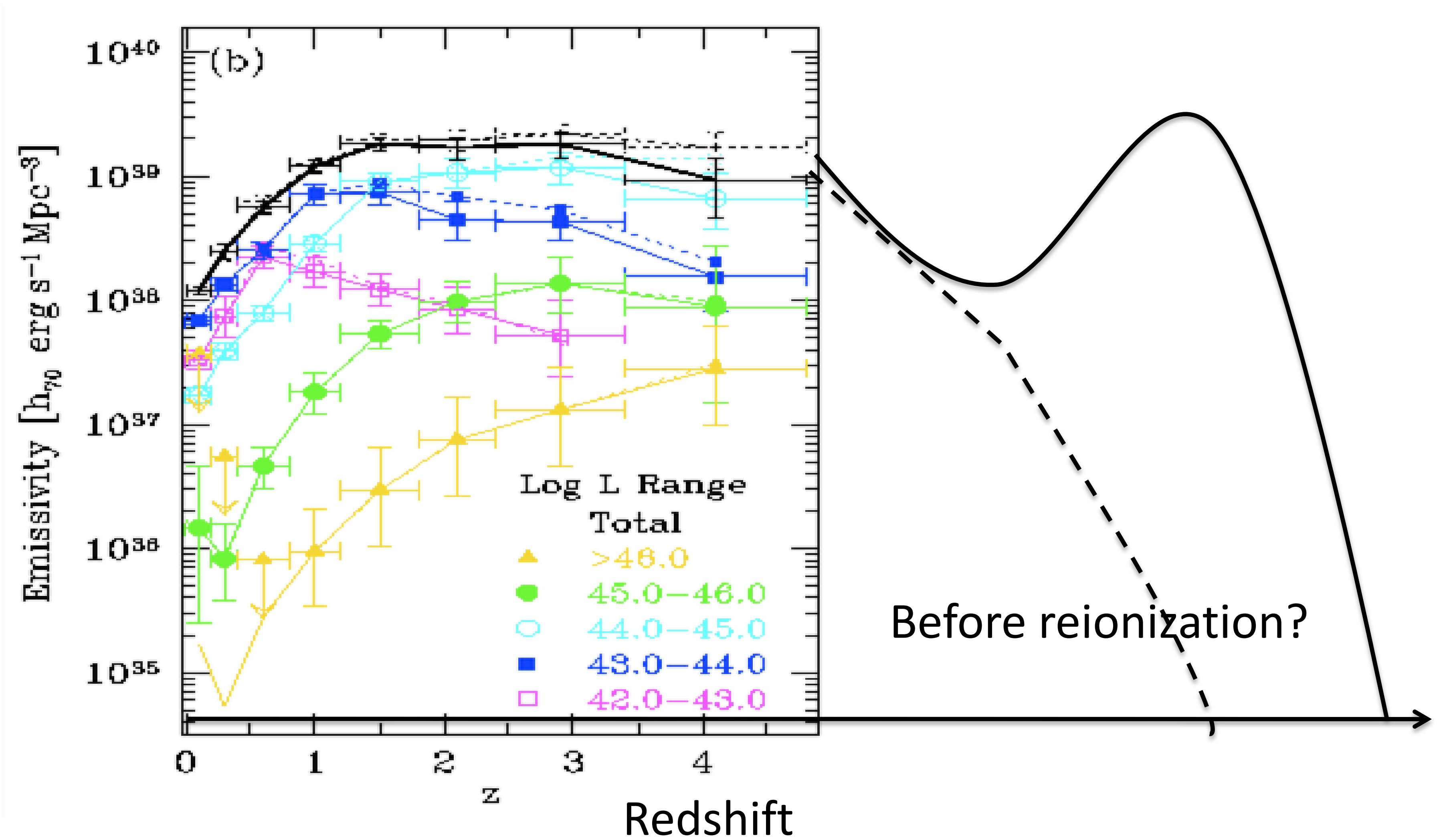
Radiative feedback:
0.2 efficiency (left), 0.1 (right)

Mechanical feedback:
0.5% efficiency (left), 0.03% (right)

Discussion

- Types of feedback: Compton heating, photoionization, winds (radiation driven), relativistic jets (do not work well: see Vernaleo & Reynolds 2006)
- Gas feeding: galaxy mergers or recycled gas from stellar evolution
- Reproduce M-sigma relation or properties of giant elliptical. Do not reproduce both.

Early accretion onto IMBHs?



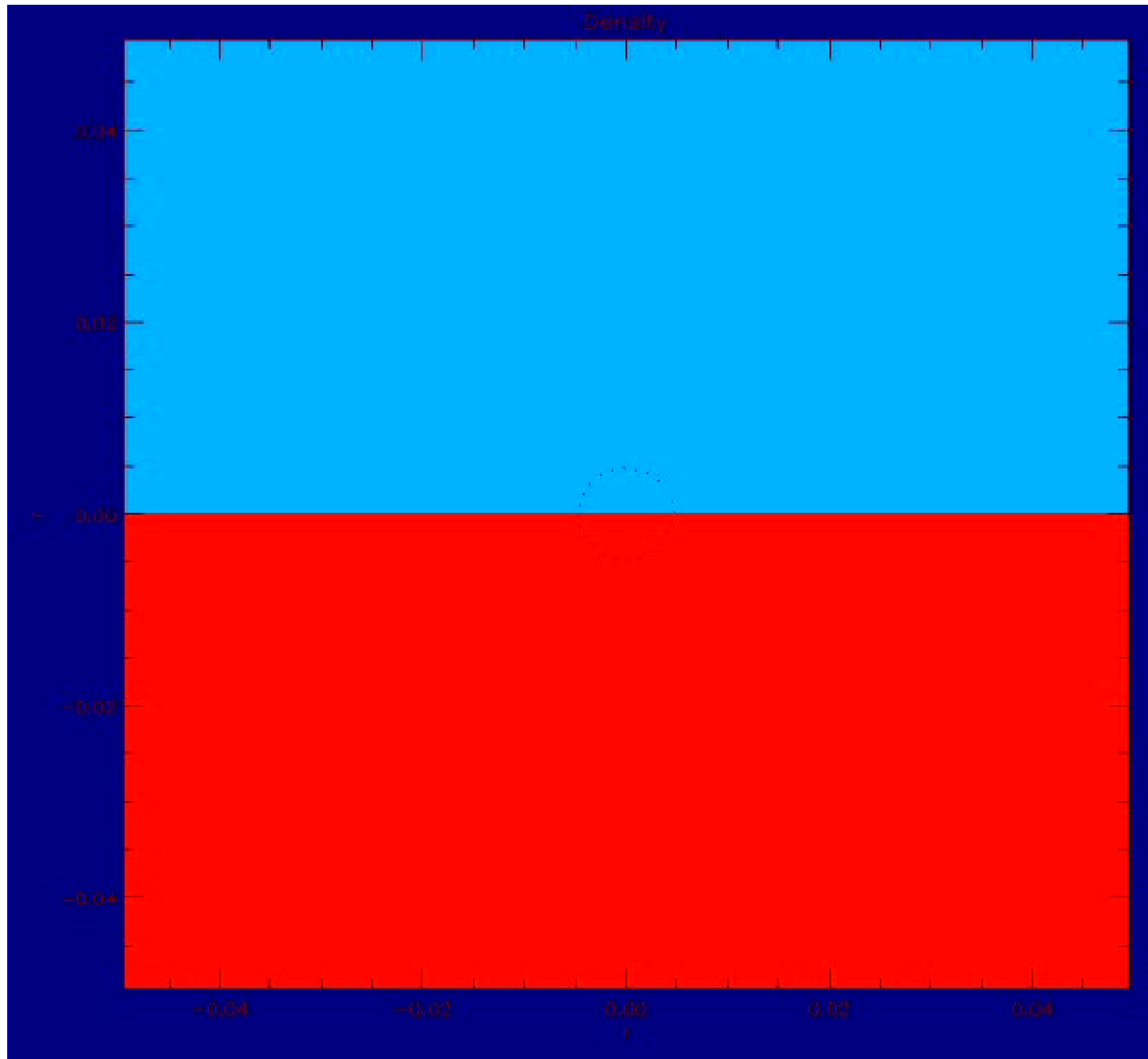
Bondi accretion with radiation feedback

Park & Ricotti, in preparation

100 M_{solar} IMBH

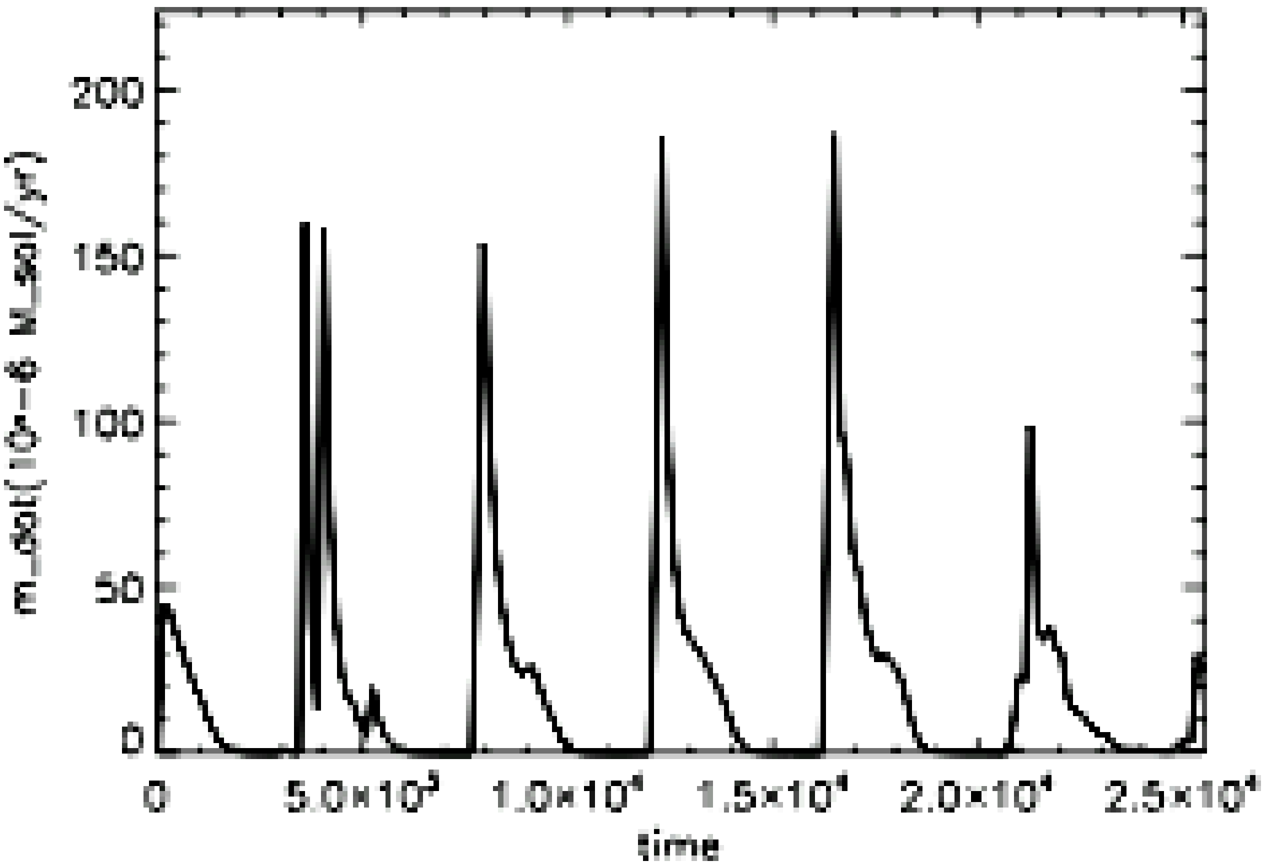
Gas density

Ionization fraction



Accretion rate

Park & Ricotti, in preparation



See also Milosavljevic et al 2008

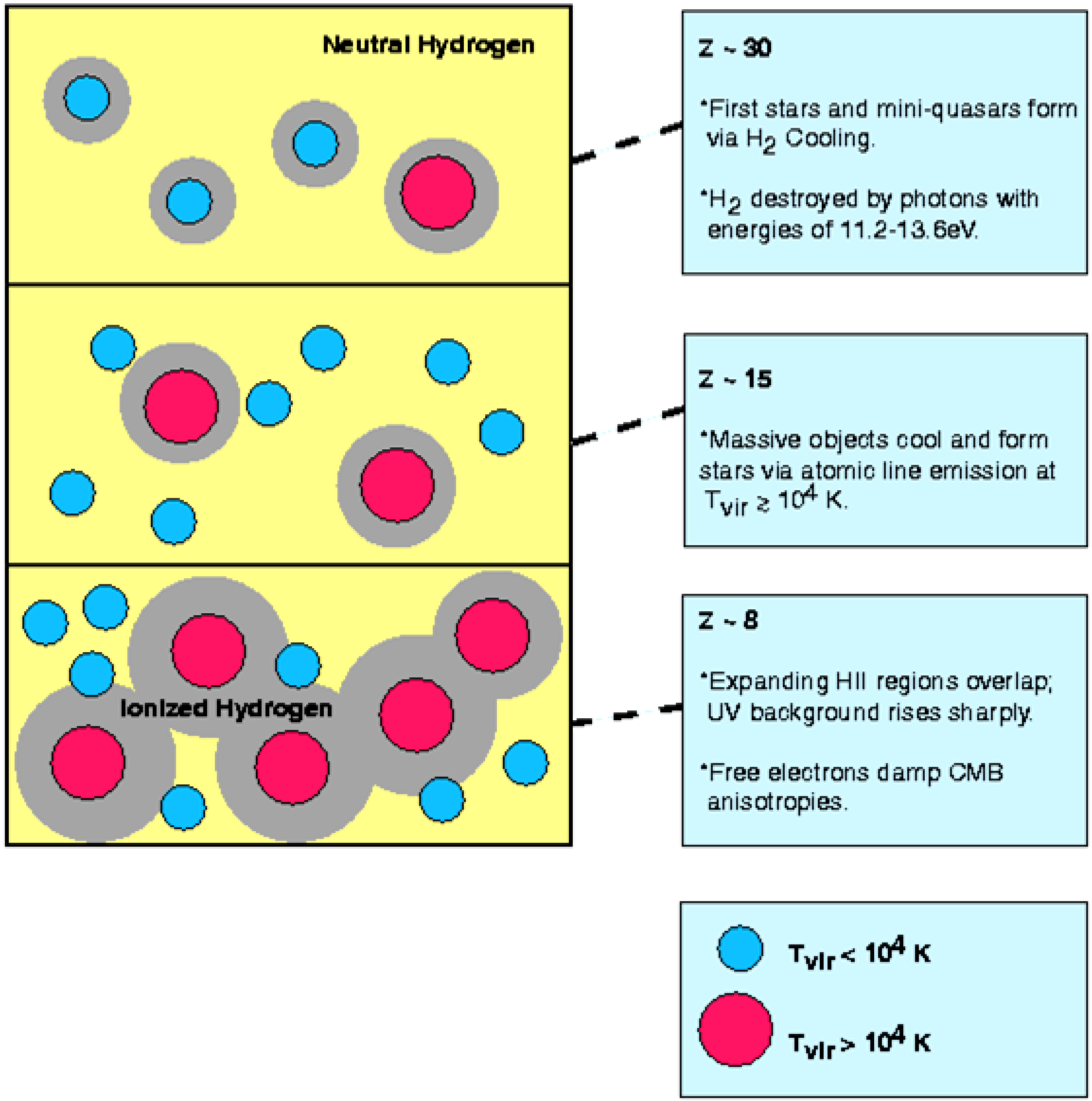
Outline

- **Cosmological Context**

- **Formation of “Seed Black Holes”**
  1. Primordial Black Holes
  2. Pop III stars remnants
  3. Direct collapse
  4. Stellar dynamics

- **Black Hole Growth**
  1. Gas Accretion vs BH-BH Mergers
  2. Feeding Black Holes
     - » M-sigma relation
     - » Feedback and duty cycles
  3. Feedback on Environment
     - » Cosmic ionization and thermal history

Reionization of the Universe



Pre-overlap

↓

Overlap

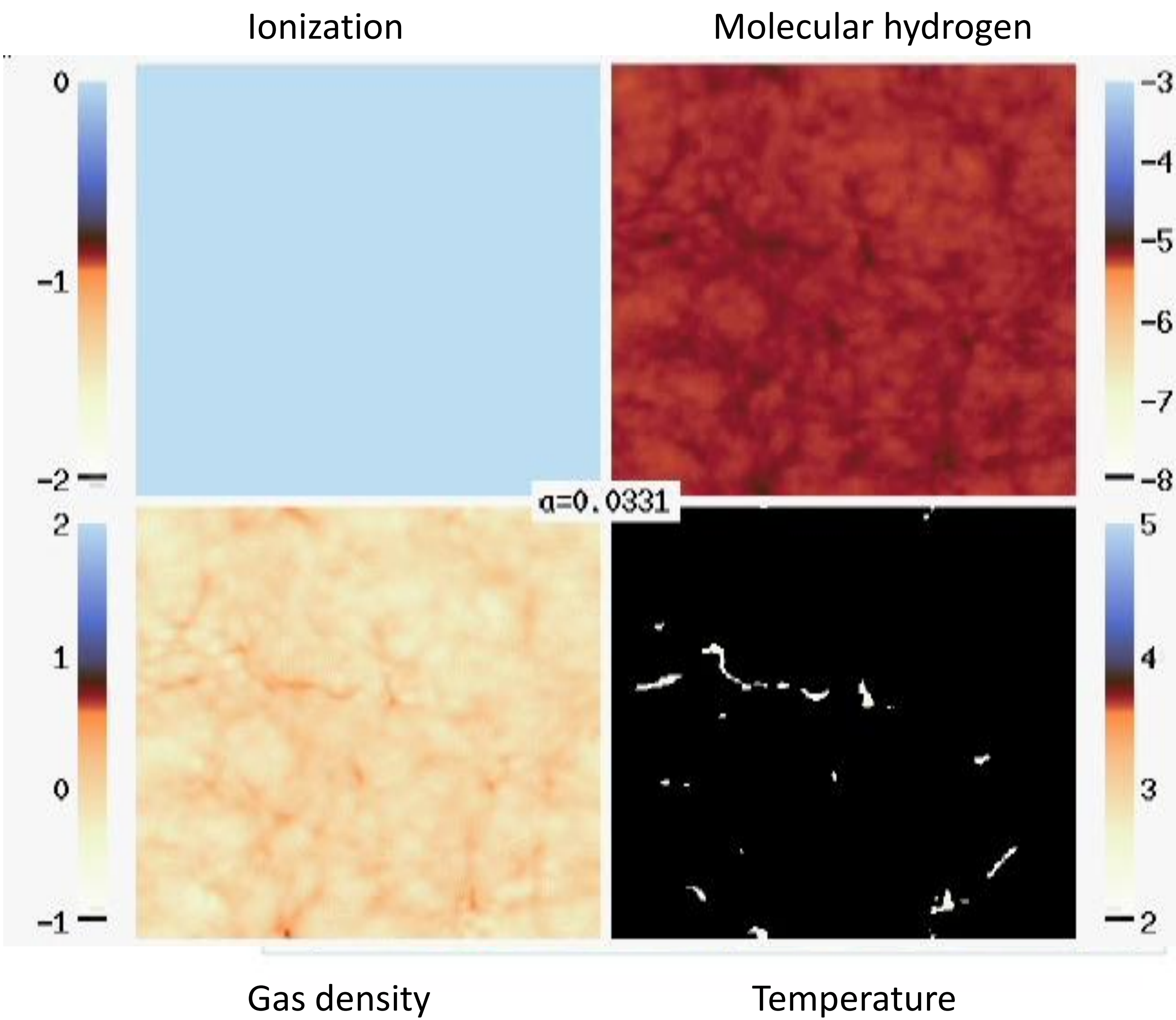
↓

Post-overlap

From Haiman & Loeb

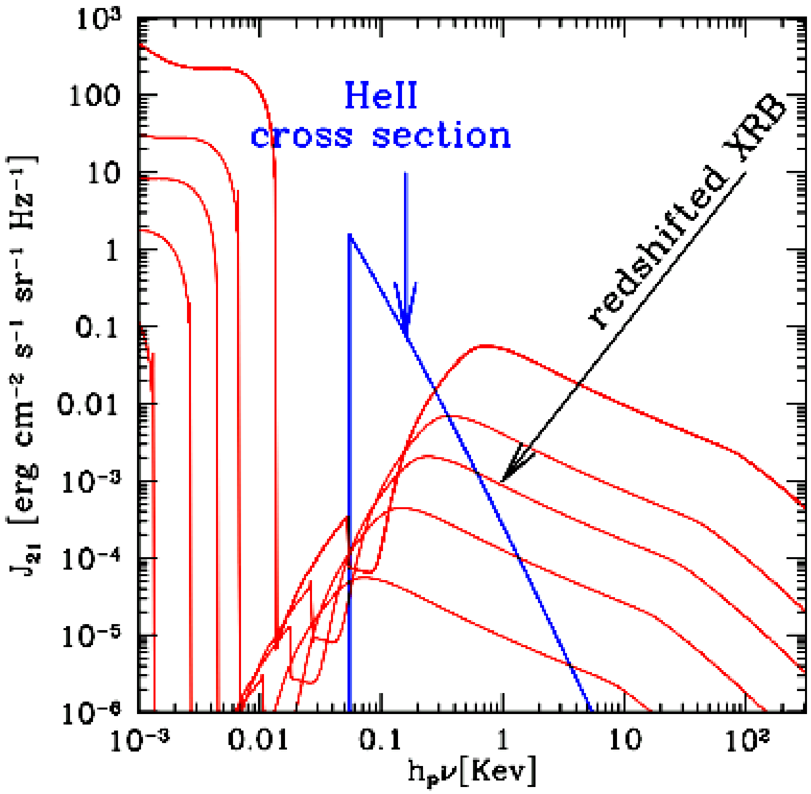
Effects of early X-ray sources

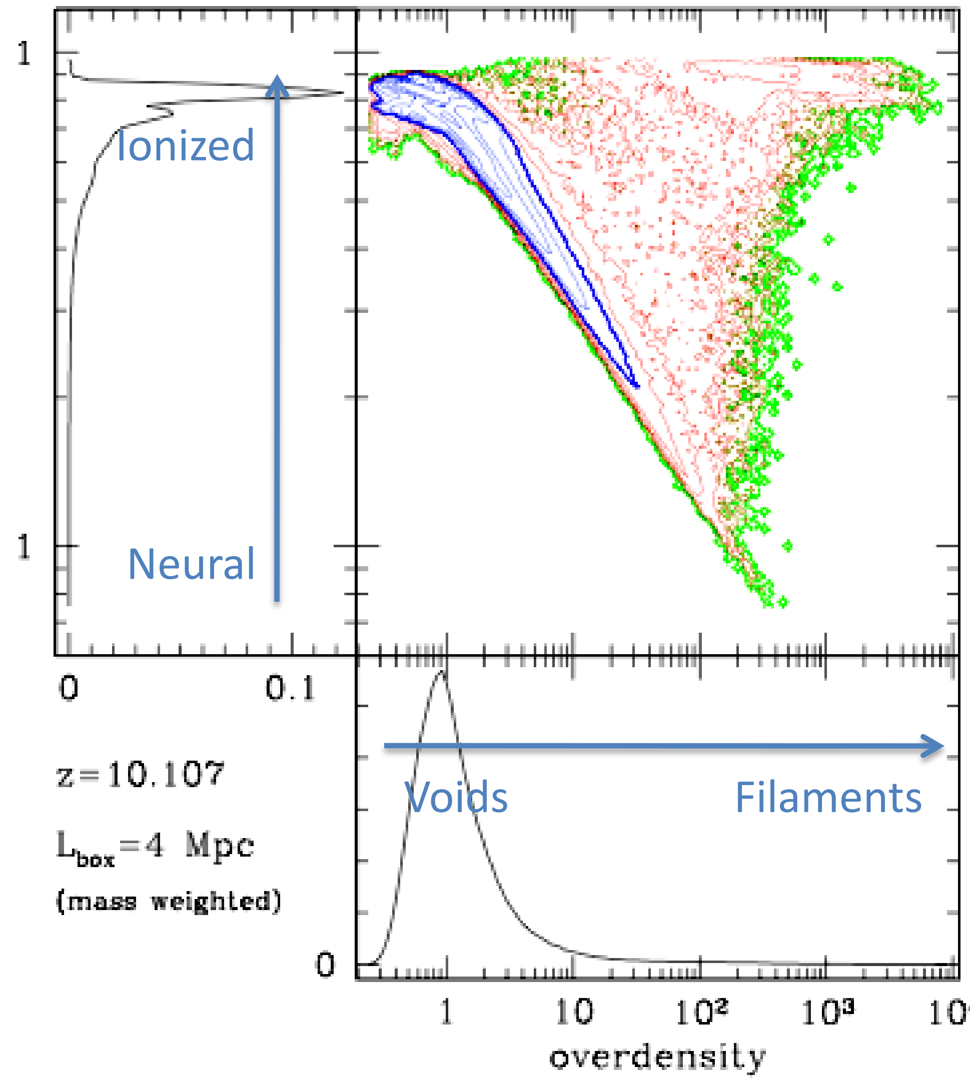
Refs: Oh 2001 , Venkatesan & Shull 2001, Ricotti & Ostriker 2004,2005 …

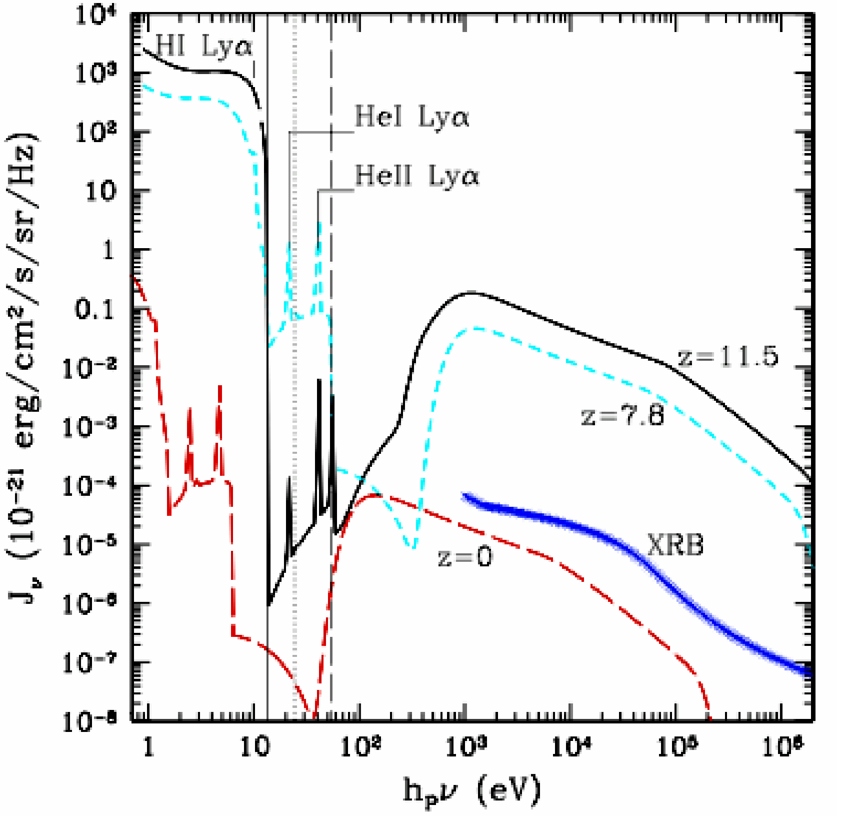


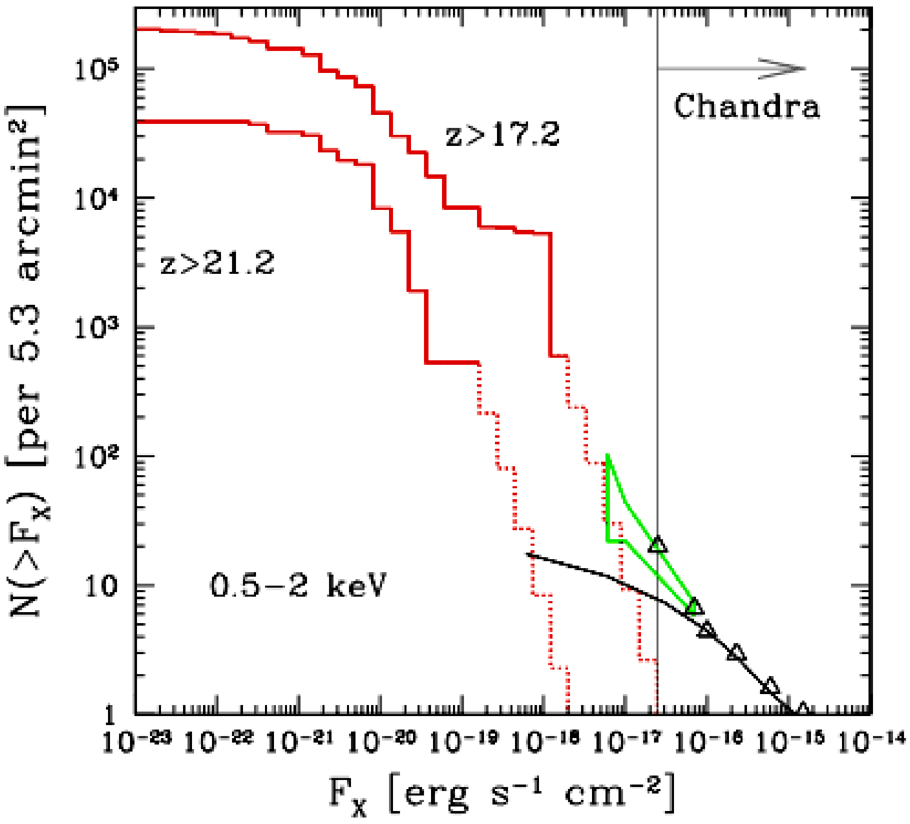
Outside -> in reionization

Red-shifted X-rays









Ricotti, Ostriker & Gnedin 2005

Outline

- **Cosmological Context**

- **Formation of "Seed Black Holes"**
    1. Primordial Black Holes
    2. Pop III Stars Remnants
    3. Direct Collapse
    4. Stellar Dynamics

- **Black Hole Growth**

1. Gas Accretion vs BH-BH Mergers
2. Feeding Black Holes
    - » M-sigma relation
    - » Feedback and duty cycles
3. Feedback on Environment
    - » Cosmic ionization and thermal history