The Formation of the First Supermassive Black Holes

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Outline of Talks

- Formation and Growth of SMBHs
  - did first SMBHs grow from stellar seeds or collapse directly?
  - did early BHs contribute to reionization?

    evidence for negative feedback
- Detection and Use of SMBHs
  - detecting coalescing SMBH binaries:

    finding the EM counterparts of LISA sources
  - unique signatures of quasar bubbles in 21cm

Supermassive Black Holes

- **Common locally:** “direct” detection in ~40 nearby galactic nuclei, total mass density consistent with being quasar remnants

- **At high redshift:** a handful of $>10^9 M_\odot$ holes known to exist already at z~6: seeds must form much earlier

- **Reionization:** the intergalactic medium (IGM) is highly ionized: helium ionization (z~3) requires hard photons

- **Grav. waves:** SMBHs mergers detectable by LISA to z~10, directly probing early BH assembly. Identifying electromagnetic counterparts could offer a new probe of BH physics and of large-scale gravity

Observation of SMBHs at z = 6

Very rare ("~5σ") objects - 9 found at z>6 (in ~10 Gpc^3)

Example: SDSS 1114-5251 (Fan et al. 2003)

$z=6.43$ $M_{bh} = L_{obs} / L_{Edd} \approx 4 \times 10^9 M_\odot$

How did this SMBH grow so massive? (Haiman & Loeb 2001)

e-folding (Edd) time:

$4 \times (\varepsilon/0.1)\ 10^7 \mathrm{yr}$

No. e-foldings needed

$\ln(M_{bh}/M_{seed}) \sim 20$ $M_{seed} \sim 100\ M_\odot$

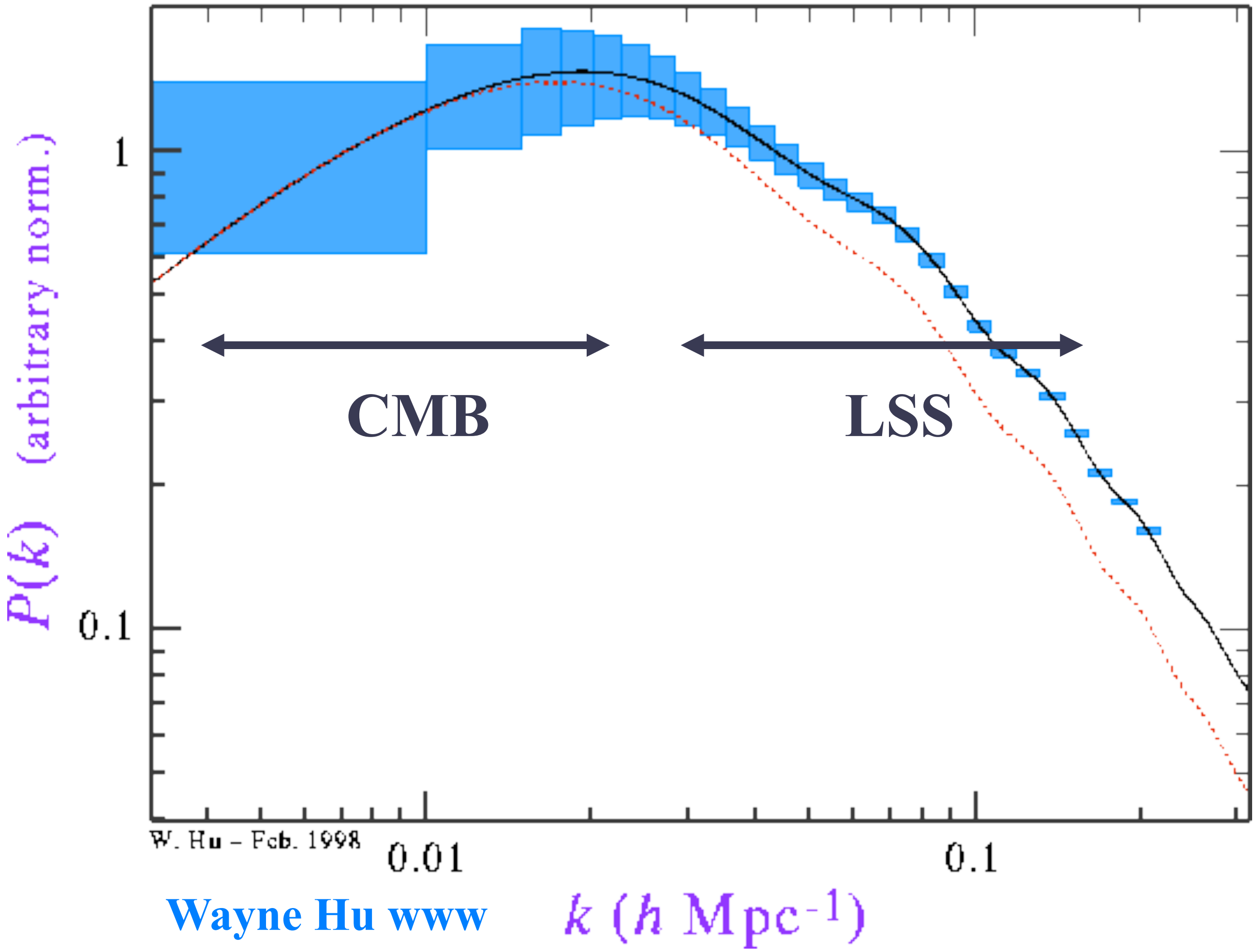
Age of universe (z=6.43)

8×10^8 yr ✓

Strong beaming? No. (Haiman & Cen 2002)

Gravitational lensing? No. (Keeton, Kuhlen & Haiman 2004)

Seed Fluctuations on Small Scales



Wayne Hu www

extrapolation by a factor of about 100 in linear scale

→

Dark Age

mass function of DM halos directly tested in simulations at z=20; $M=10^5\,M_\odot$

Yoshida et al. (2003)
Mesinger et al. (2006)

Jeans length for Baryons

- In general, Jeans mass:

$$M_J \equiv \frac{4\pi}{3}\left(\frac{\lambda_J}{2}\right)^3 \rho = const\,\frac{T^{3/2}}{\rho^{1/2}}$$

- Depends on evolution of background gas temperature T_b. At $z>z_{crit}\approx150$, Compton scattering with CMB photons keeps $T_b=T_{CMB}\sim(1+z)$, and

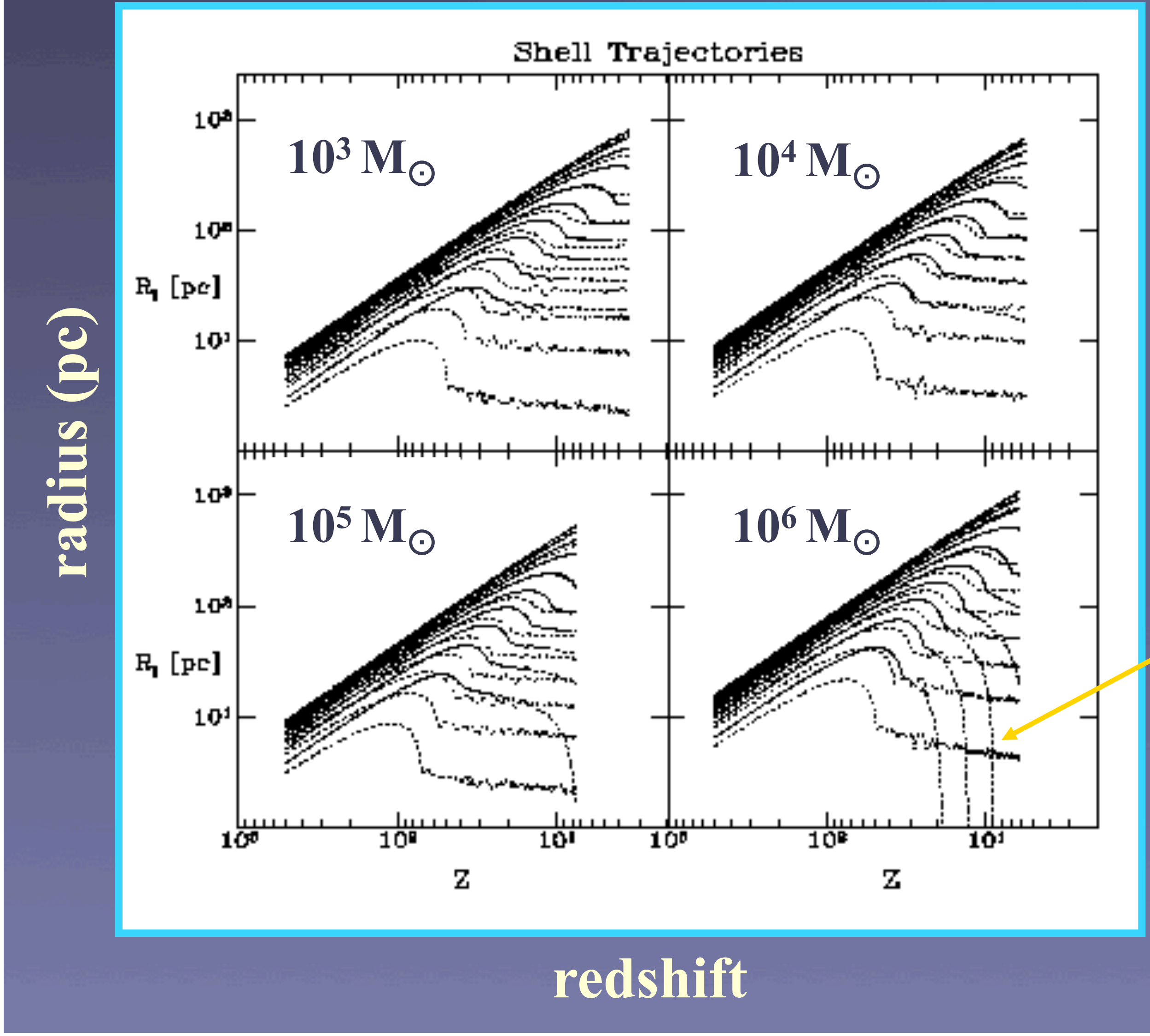
$$M_J = 1.35\times10^5\left(\frac{\Omega_{DM}h^2}{0.15}\right)^{-1/2} M_{sun} = const.$$

- At $z<z_{crit}\approx150$, gas decouples thermally from CMB, and temperature evolves adiabatically, $T_b\sim(1+z)^2$

$$M_J = 4.54\times10^3\left(\frac{\Omega_{DM}h^2}{0.15}\right)^{-1/2}\left(\frac{1+z}{10}\right)^{3/2}$$

Collapse of Spherical Cloud in Isolation

Haiman, Thoul & Loeb (1996)



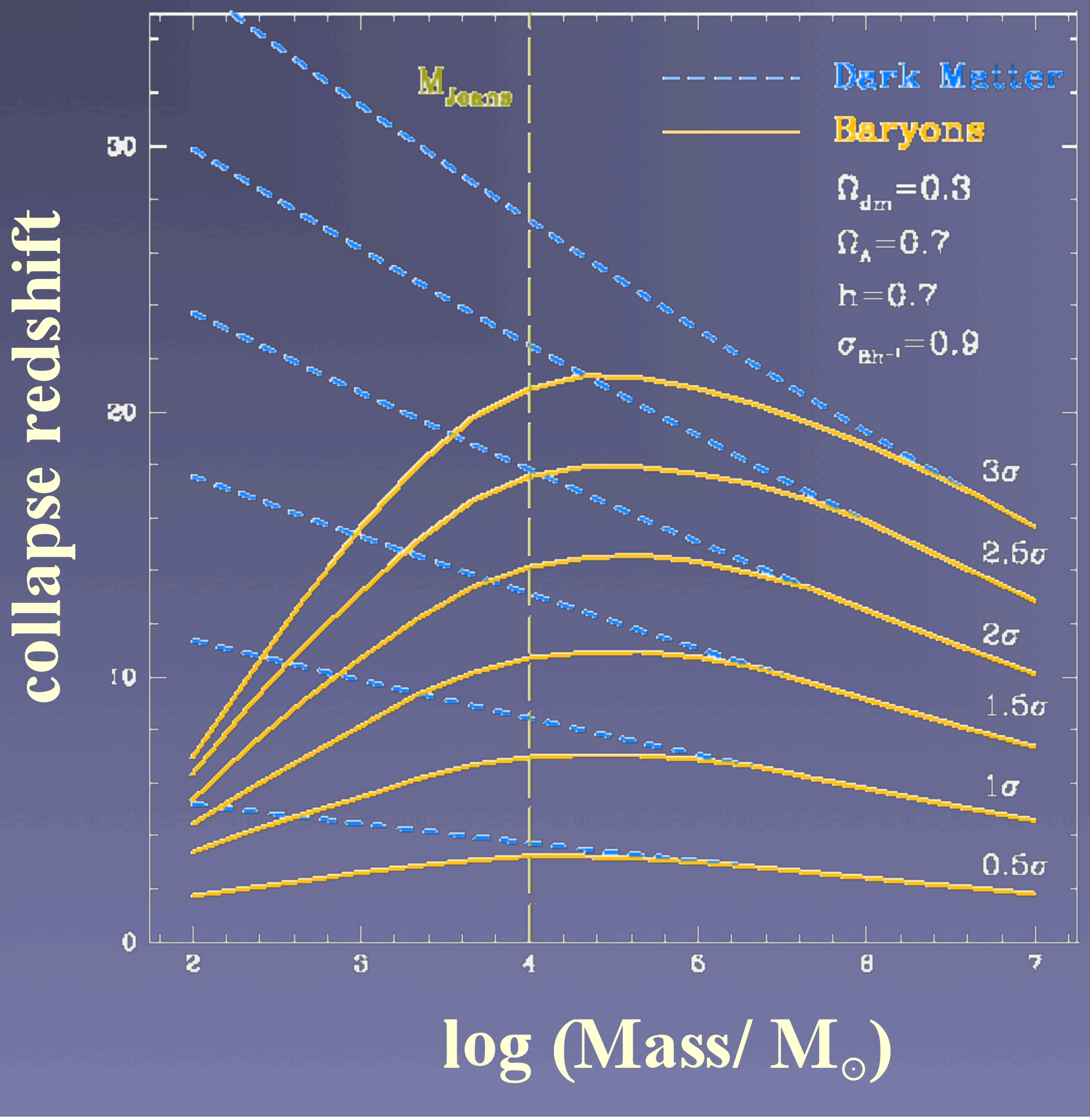
Gas Phase Chemistry:

$H + e^- \rightarrow H^- + \gamma$

$H^- + H \rightarrow H_2 + e^-$

Clouds with virial temperature $T_{vir} \gtrsim 200$ K can form H_2, cool and collapse

Collapse Redshifts



Z. Haiman
PhD thesis 1998

Condensations in Hierarchical Cosmology

- **Smallest scales condense first**
- **Jeans mass: ~$10^{4\text{-}5}$ $M_{\odot}$**
- **2-3 σ peaks appear at redshift z=15-20**

Cooling and Chemistry

Cooling is a **necessary condition** for continued contraction following virialization: i.e. for anything "interesting" to happen

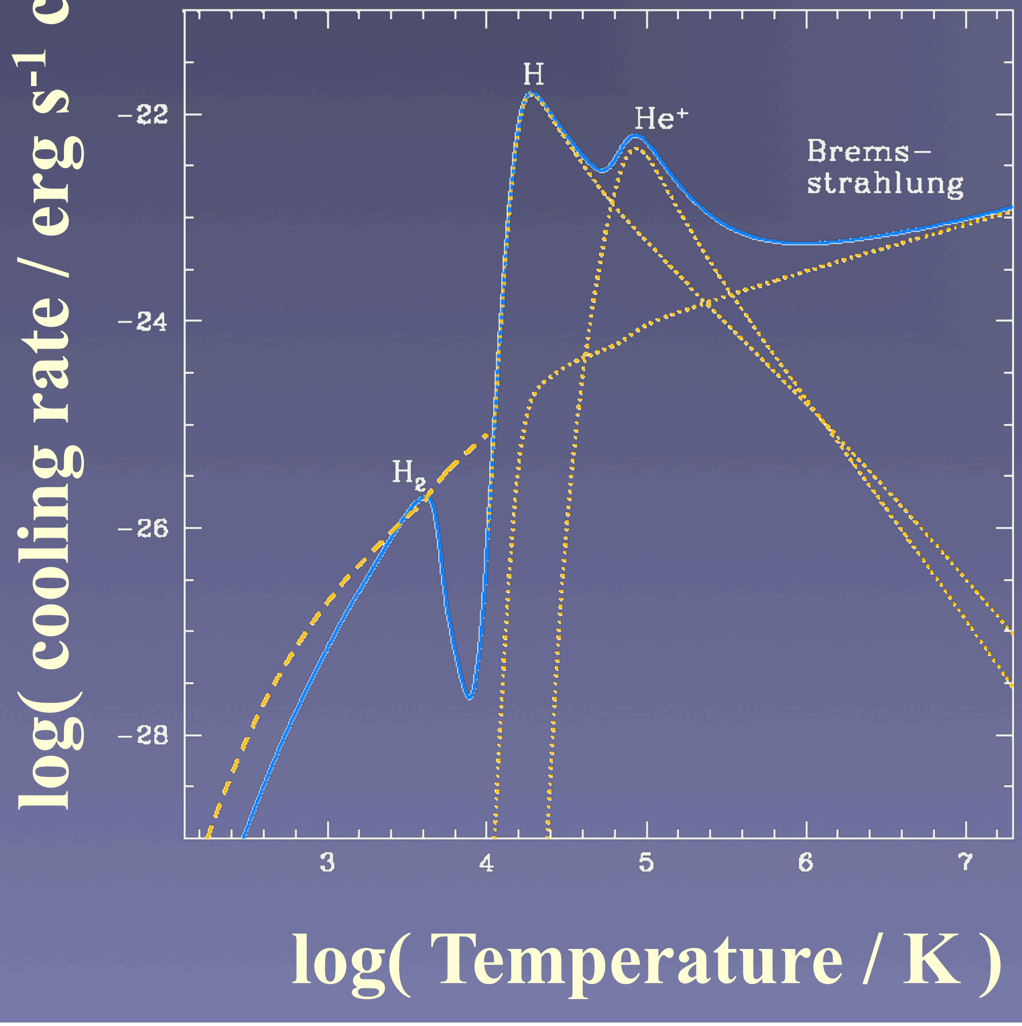
(Rees & Ostriker 1977; White & Rees 1978)

Primordial gas chemically simple: H, He, H_2

Radiative Cooling Function (H+He gas)

→ **COSMIC TIME** →

→ **MASS SCALE** →



cf. Halo virial temperature:

$$T_{vir}=10^4 K \times [(1+z)/11] \times$$

$$\times (M/10^8 M_\odot)^{2/3}$$

3D Simulation of a Primordial Gas Cloud

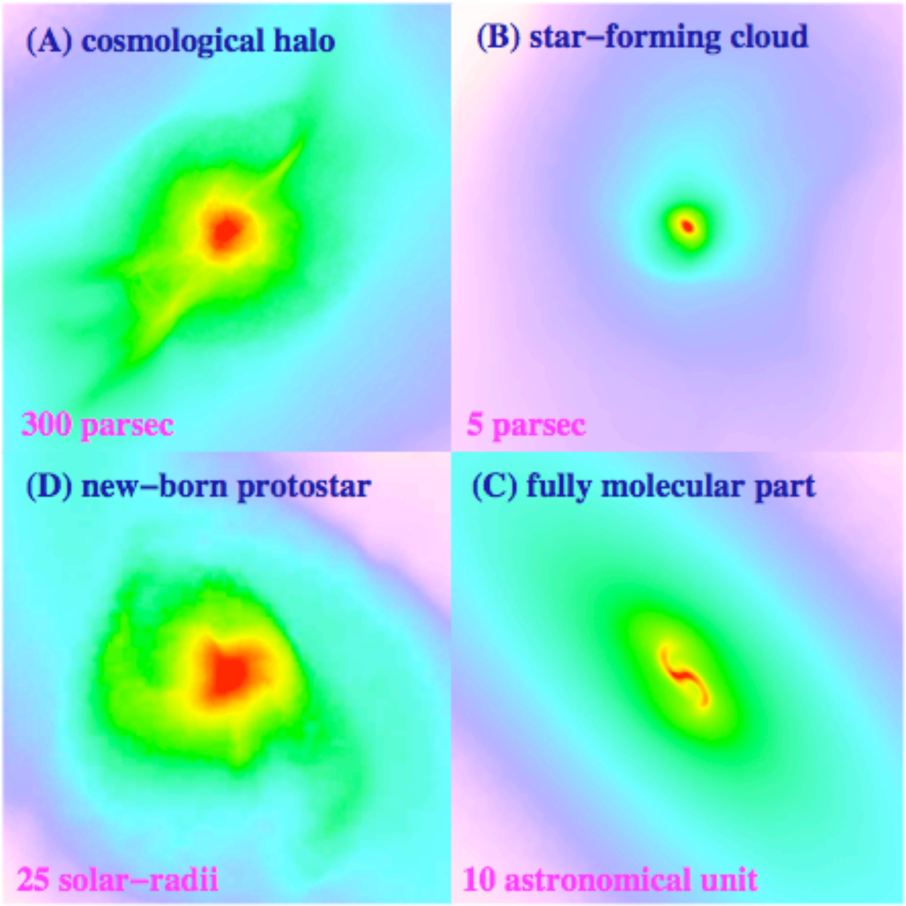


Fig. 1: Projected gas distribution around the protostar. Shown regions are, from top-left, clockwise, (A) the large-scale gas distribution around the cosmological halo (300 pc on a side), (B) a self-gravitating, star-forming cloud (5 pc on a side), (C) the central part of the fully molecular core (10 astronomical units on a side), and (D) the final protostar (25 solar-radii on a side). We use the density-weighted temperature to color (D), to show the complex structure of the protostar.

Yoshida, Omukai & Hernquist (2008)

Cosmological halo:

$M_{tot} \approx 5\times10^5\ M_\odot$

$z \approx 14$

Protostar in core

$T \approx 10{,}000$ K

$n \approx 10^{21}$ cm^{-3}

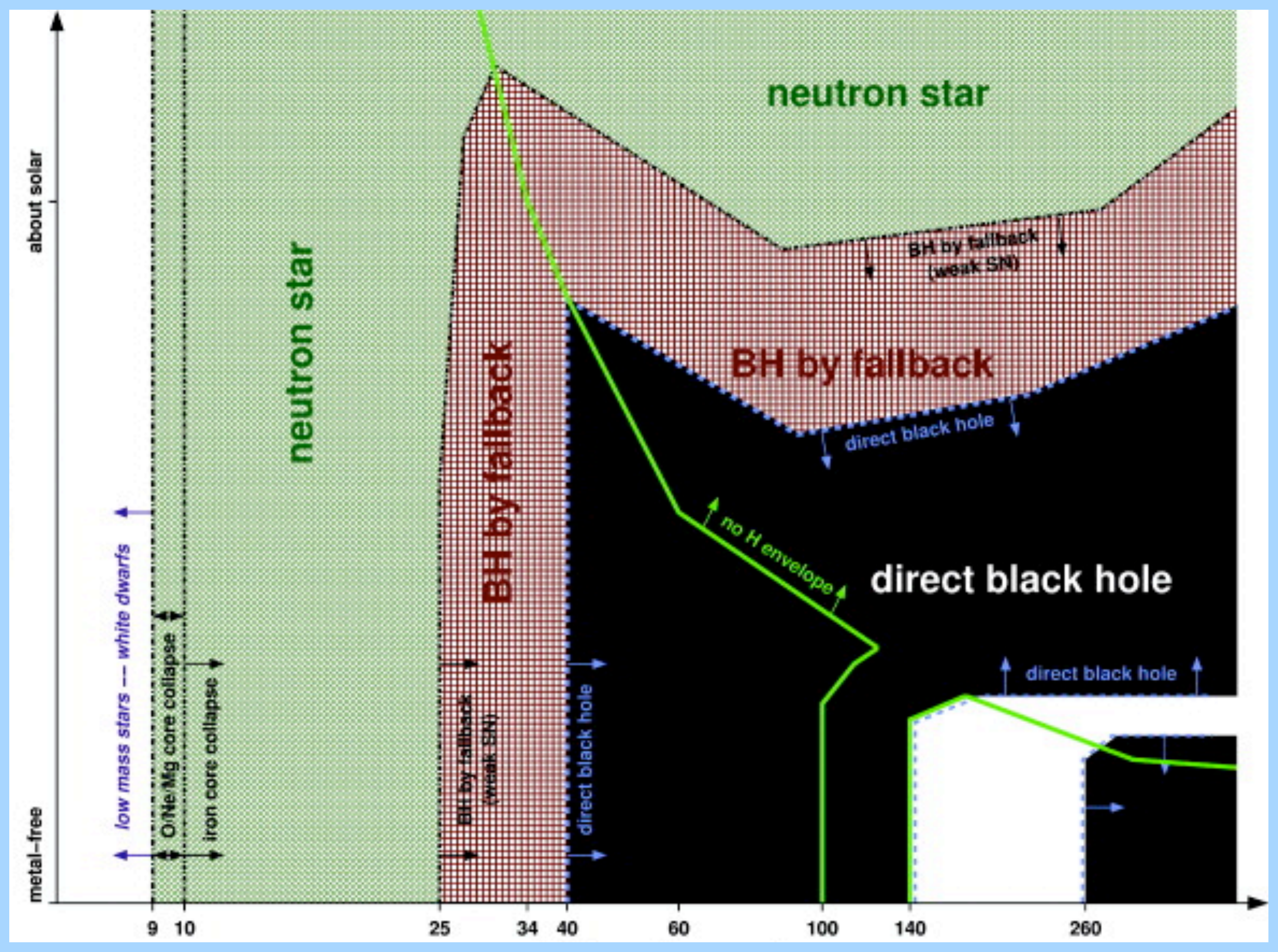
$M_* \approx 0.01\ M_\odot$

Final stellar mass:

$M_* \sim 100\ M_\odot$

Remnants of Massive Stars

Heger et al. 2003 (for single, non-rotating stars)



$Z = Z_\odot$

metalicity

$Z = 0$

$10M_\odot$ $25M_\odot$ $40M_\odot$ $140M_\odot$ $260M_\odot$

Growth of High-z Supermassive BHs: Mergers and Acquisitons

z~6

M_{bh}= few × 10^9 $M_\odot$

CDM merger tree

σ_{min} ~ few km/s

z~30

Do Most Minihalos Form Stars?

many possible feedback effects:

- **INTERNAL TO SOURCES**
  - UV flux unbinds gas
  - supernova expels gas, sweeps up shells
  - H_2 chemistry (positive and negative)
  - metals enhance cooling

- **GLOBAL (*FAR REACHING* OR *LONG LASTING*)**
  - H_2 chemistry (LW: negative   X-rays: positive)
  - entropy floor (inactive fossil HII regions or X-rays)
  - photo-evaporation (minihalos with $\sigma < 10$ km/s)
  - photo-heating (halos with $10 \text{ km/s} < \sigma < 50$ km/s)
  - global dispersion of metals (pop III → pop II)
  - mechanical (SN blast waves)

First Global Feedback on H_2

Soft UV background:

this background inevitable and it destroys molecules

⊖

H_2 dissociated by 11.2-13.6 eV Lyman-Werner photons:

$$H_2+\gamma \rightarrow H_2^{(*)} \rightarrow H+H+\gamma'$$

(Haiman, Rees & Loeb 1997)

Soft X-ray background:

this background from quasars promotes molecule formation

⊕

~ 1 keV photons promote free electrons → more H_2

$$H+\gamma \rightarrow H^{+}+\underline{e}^{-}+\gamma'$$

$$\downarrow$$

$$H + \underline{e}^{-} \rightarrow H^{-} + \gamma$$

$$H^{-} + H \rightarrow H_2 + e^{-}$$

(Haiman, Rees & Loeb 1996)

Effects cancel when $L_X \sim 0.01\ L_{LW}$ (Haiman, Abel & Rees 2000)

Global Feedback: Entropy Floor

Fossil HII Regions:

(Oh & Haiman 2002)

- First star creates ~ 100 kpc ionized bubble
- Star dies after ~10^6 yrs and HII region recombines
- "Fossil" Compton cools off CMB
- T~300 K implies excess entropy
- Inhibits contraction, H_2 formation
- BUT positive feedback at high density from extra non-equilibrium free e-

(e.g. Ricotti, Gnedin & Shull 2003, 2004)

Soft X-ray background:

(Oh 2001; Venkatesan & Shull 2001 Madau et al. 2005; Ricotti & Ostriker 2005)

- X-rays partially ionize IGM, with secondary e^-'s, up to x_{HII}~20%
- Roughly uniform heating of the IGM to T~10,000 K

Combined Effects of UV + LW flux

(Mesinger, Bryan & Haiman 2006)

- **AMR Simulations with Enzo**
  - $(1\ h^{-1}\ \mathrm{Mpc})^3$, 128^3 root grid, run from z=99 to z=15
  - re-simulate inner $(0.25\ h^{-1}\ \mathrm{Mpc})^3$
  - 10 levels of refinement - 0.36 h^{-1} pc resolution at z=20
  - biased (2.4σ) region, yields several hundred DM halos in mass range of $10^5 M_\odot < M < 10^7 M_\odot$

- **Examine Effects of Transient Photoheating**
  - J(UV) = 0 (test run)
  - Flash ionization **(c.f. O'Shea et al. 2006)**
  - J(UV) = 0.08 or 0.8 for Δt = 3×10^6 years (uniform, opt.thin)

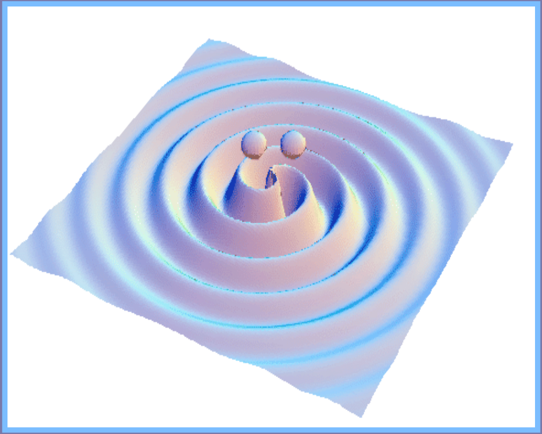
- **Examine Effect of Constant LW background**
  - $10^{-3} < J(LW) < 10^{-1}$ added to J(UV)=0 and 0.8 runs

UV Feedback Simulation: Summary

- H_2 cooling in minihalos is strongly suppressed for a soft UV background of
  $J(LW) \gtrsim 0.01 \times 10^{-21}$ erg s cm^{-2} Hz^{-1} sr^{-1}
- Transient UV photo-heating strengthens negative feedback near sources, where flux is
  $J(UV) \gtrsim 0.1 \times 10^{-21}$ erg s cm^{-2} Hz^{-1} sr^{-1}
- Smallest halos with $M_{halo} \sim 10^6\ M_\odot$ most vulnerable
- Feedback switches from UV to LW at ~100 Myr
- For comparison, flux needed to ionize universe is
  $J(ion) \approx 10 \times 10^{-21}$ erg s cm^{-2} Hz^{-1} sr^{-1}

Strong feedback well before reionization ($f_{ion} \gtrsim 0.1\text{-}1\%$)

Another obstacle: gravitational recoil



- **Gravitational radiation produces sudden recoil**
  — kick velocity depends on mass ratio and on spin vectors
  — typical v(kick) ~ few × 100 km/s **(Baker et al. 2006, 2007**
  — maximum v(kick) ~ 4,000 km/s **Gonzalez et al. 2007)**

- **Most important at high redshift when halos are small**
  — escape velocities from z>6 halos is <u>few</u> km/s

- **Is there a ‘sweet spot’ for fraction of halos with BH seeds?**

Merger-Tree Modeling Procedure

Tanaka & Haiman (2008)

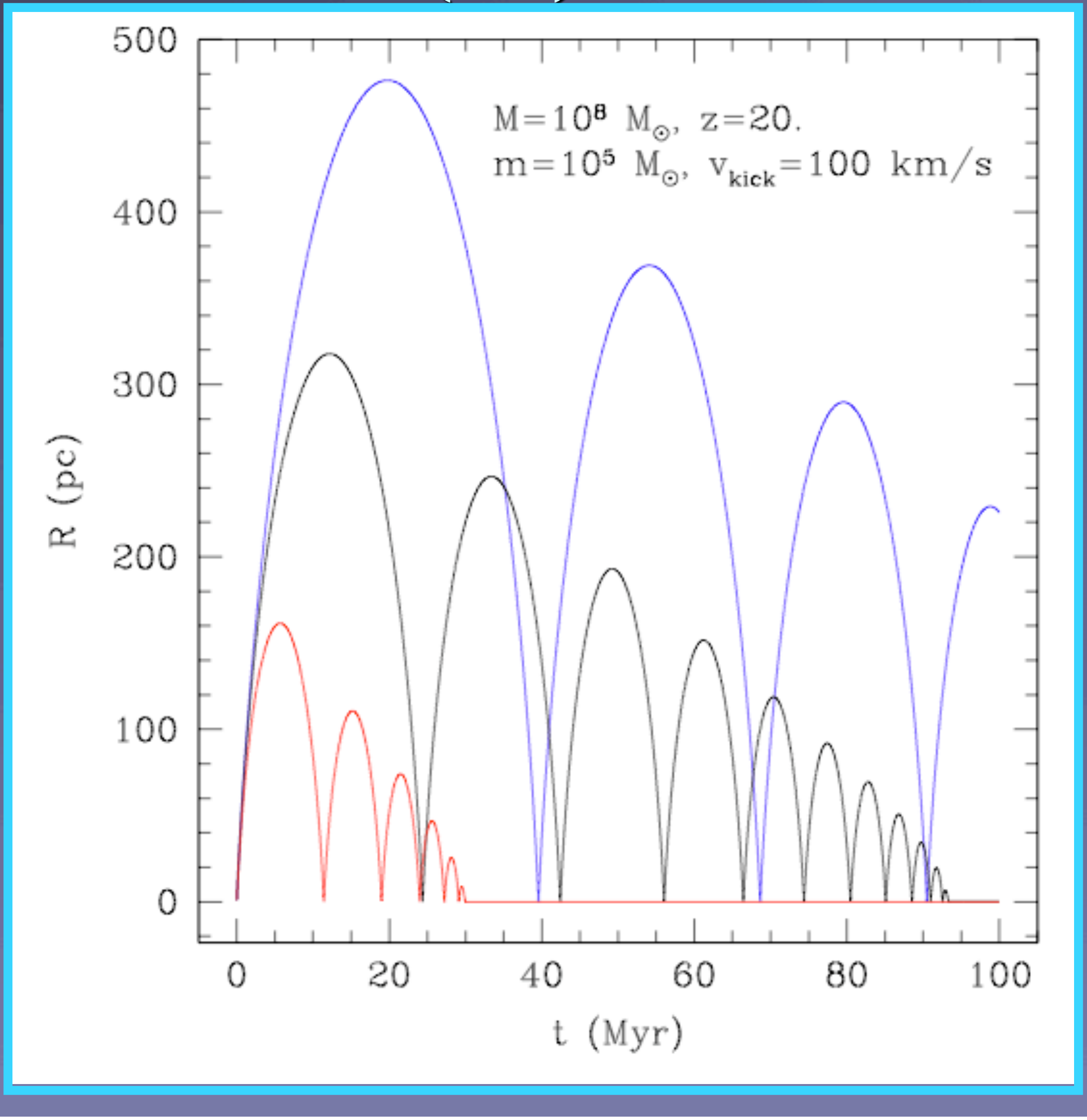
- **Construct Monte-Carlo DM halo merger tree from z=6 to z>40**
  - $10^8 M_\odot \leq M_{halo} \leq 10^{13} M_\odot$ (M_{res} =few $10^5 M_\odot$; N~10^5 trees)
  - seed fraction f_{occ} of new halos with BHs (M_{seed} =100 $M_\odot$)

- **BH growth by accretion**
  - duty cycle for accretion between 0.6-1.0
  - maximum of Bondi and Eddington rate
    - [- merger delayed by dynamical friction time]
    - [- seed initially in empty halo]

- **Gravitational Recoil**
  - at merger, draw random v_{kick} (Baker et al. 2008)
  - spin orientation: random or aligned
  - follow kicked BH trajectory - damped oscillation (gas drag)
  - profile either $\rho \propto r^{-2.2}$ (cool gas) or flat core (adiabatic)

Trajectory of kicked BH

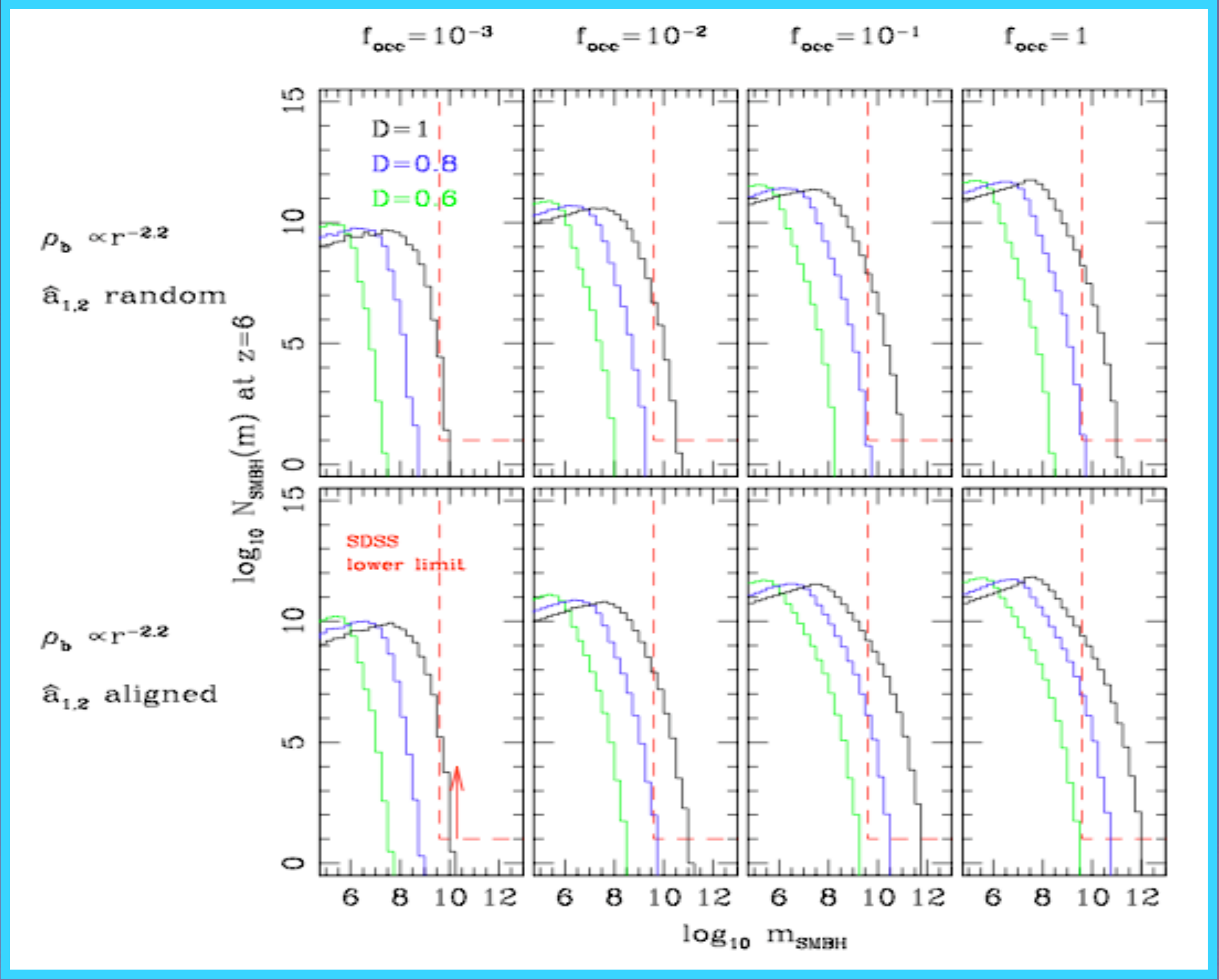
Tanaka & Haiman (2008)



- DM halo NFW
- gas with flat core (Shapiro et al)
- gas with steep cusp (Abel & Bryan)

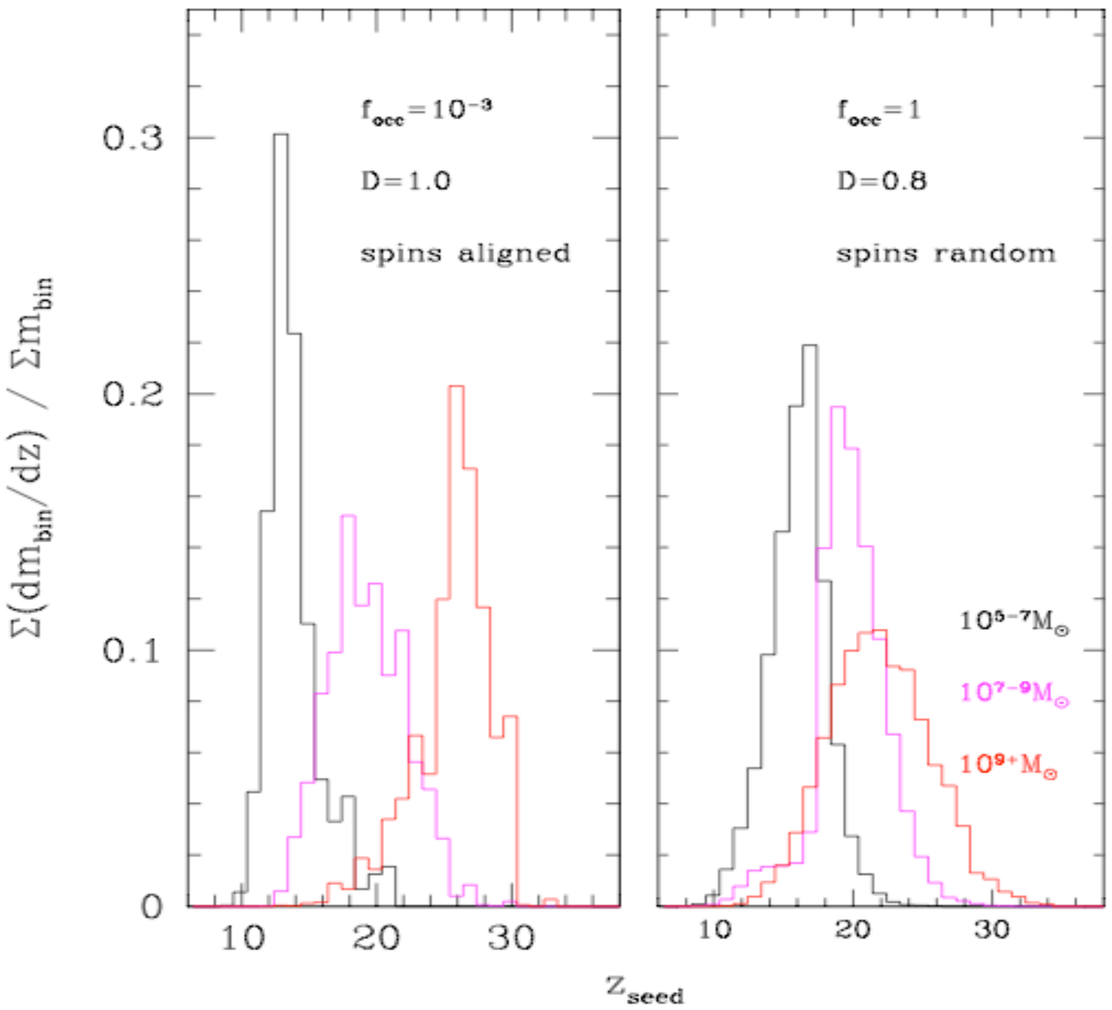
SMBH mass function at z=6

Tanaka & Haiman (2008)



Total mass in $>10^5\,M_\odot$ SMBHs: overproduced by a factor of 100-1000

Tanaka & Haiman (2008)



Local SMBH mass density:
$\rho_{tot} \approx 4\times10^5\,M_\odot\,Mpc^{-3}$

At most ~10% can come from $z > 6$

Over-prediction is generic in all models

→ Introduce redshift cutoff: no new seeds below z_{cut} (for low f_{seed})

Avoiding steep BH mass function:

- Require low $f_{seed} \lesssim 10^{-2}$ to spread seeds in redshift
- Also require high cutoff redshift $z_{cut} \gtrsim 30$

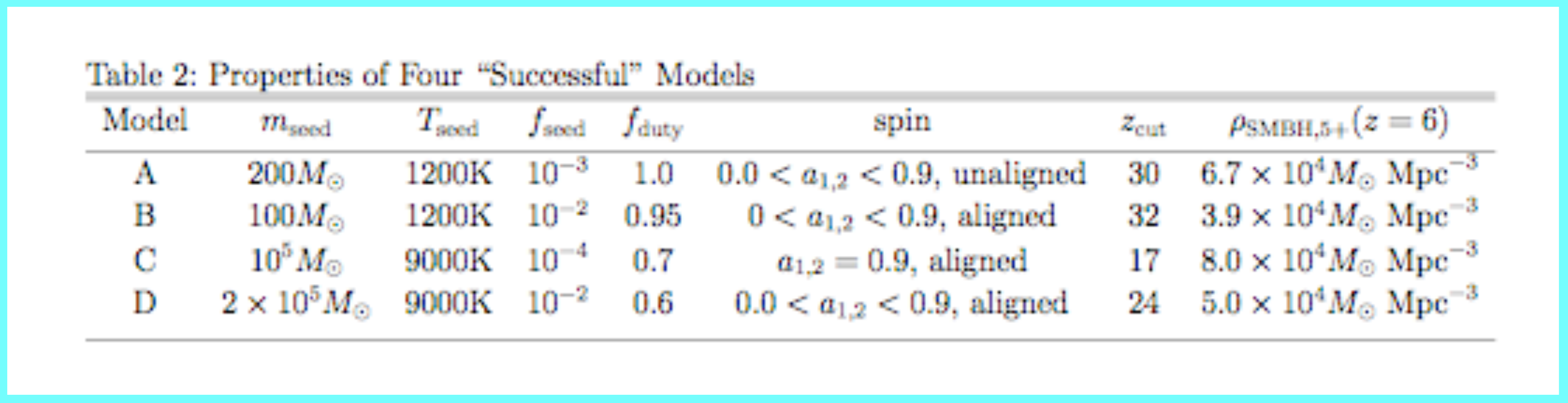


Table 2: Properties of Four "Successful" Models

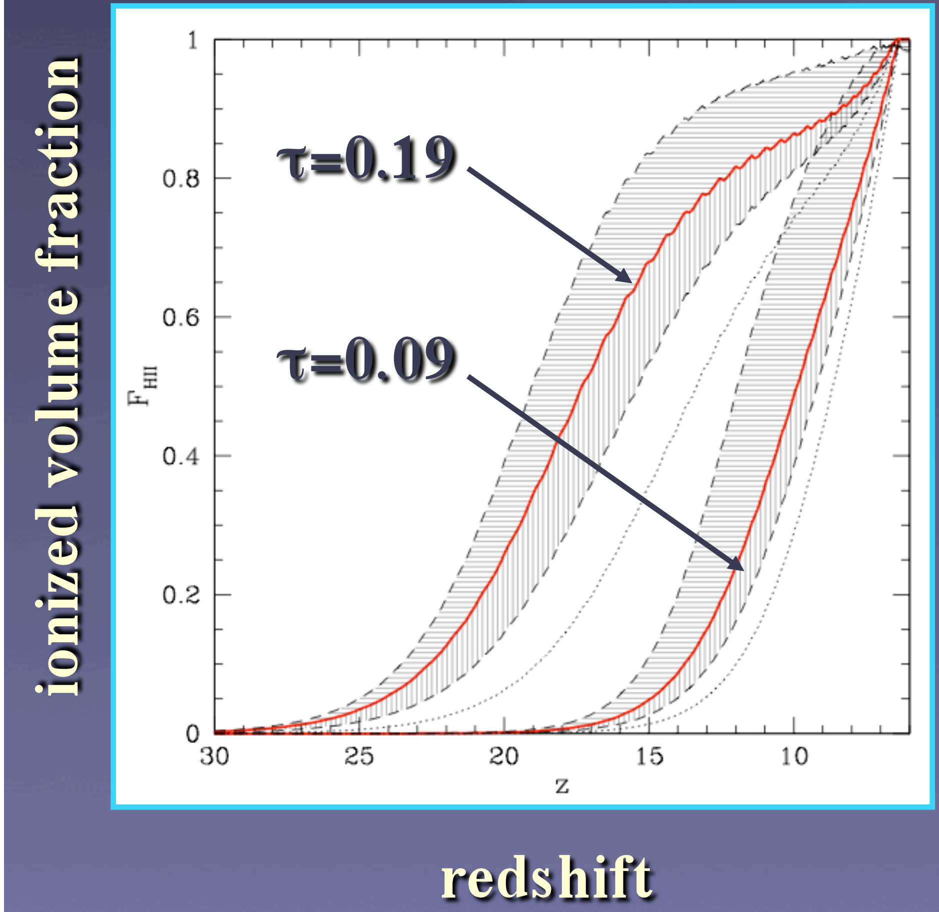
Model	m_{seed}	T_{seed}	f_{seed}	f_{duty}	spin	z_{cut}	$\rho_{SMBH,5+}(z=6)$
A	$200 M_\odot$	1200K	10^{-3}	1.0	$0.0 < a_{1,2} < 0.9$, unaligned	30	$6.7 \times 10^4 M_\odot$ Mpc^{-3}
B	$100 M_\odot$	1200K	10^{-2}	0.95	$0 < a_{1,2} < 0.9$, aligned	32	$3.9 \times 10^4 M_\odot$ Mpc^{-3}
C	$10^5 M_\odot$	9000K	10^{-4}	0.7	$a_{1,2} = 0.9$, aligned	17	$8.0 \times 10^4 M_\odot$ Mpc^{-3}
D	$2 \times 10^5 M_\odot$	9000K	10^{-2}	0.6	$0.0 < a_{1,2} < 0.9$, aligned	24	$5.0 \times 10^4 M_\odot$ Mpc^{-3}

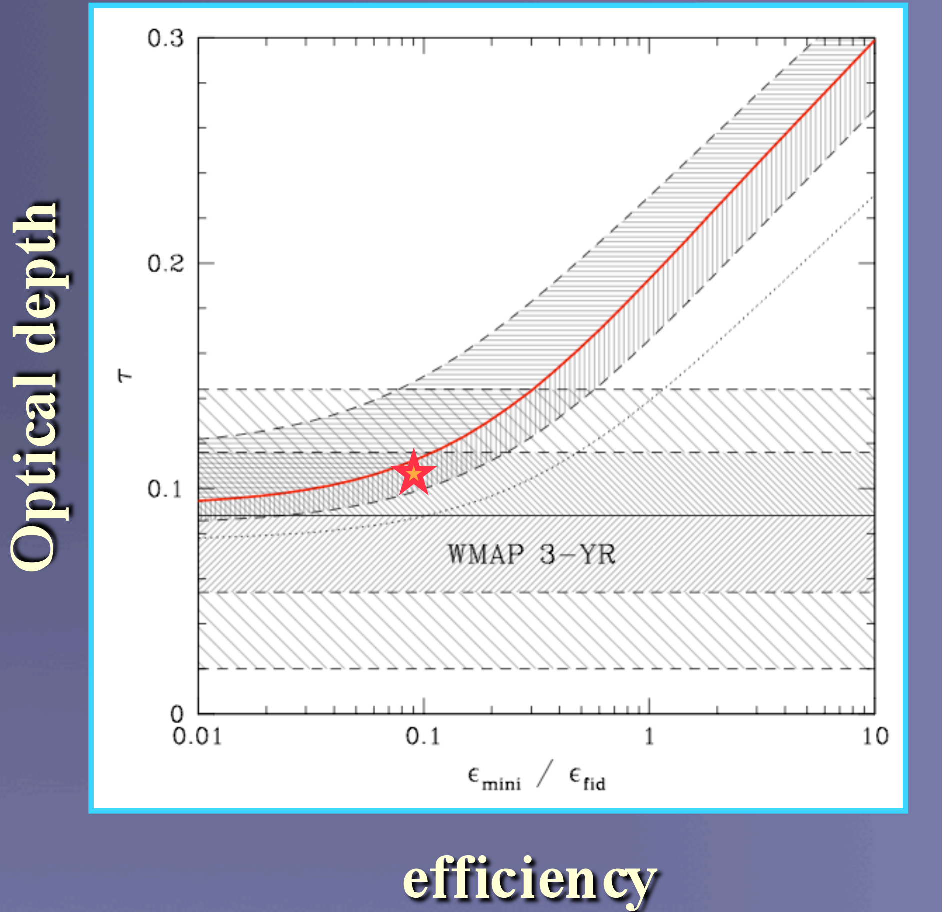
Results: High-z SMBH Assembly

- (i) density cusp
  (ii) $f_{seed} \gtrsim 10^{-3}$
  (iii) $f_{duty} \gtrsim 0.8$
  $\}$ optimistic assumptions required
- Making few × 10^9 $M_\odot$ BHs by z=6 without overproducing the number of few × 10^5 $M_\odot$ BHs
  ($\rho_{BH} \lesssim 4 \times 10^4\ M_\odot \mathrm{Mpc}^{-3}$)
  suggests $f_{seed} \approx 10^{-2}$ and negative feedback at z~30
- The 10^9 $M_\odot$ BHs result from runaway early seeds (z>25) that avoided ejection at merger: asymmetric mass ratio
- Kick and spin alignment makes little difference for low f_{seed}
- Growing BHs: X-ray pre-ionization (10-20%) and heating ?
- Alternative : a rapid (super-Eddington) growth phase

Negative Feedback in Reionization History

Haiman & Bryan (2006)





Minihalo contribution suppressed by a factor of ~10 (2σ)

Direct SMBH formation in $T_{vir} > 10^4$K halos?

- **Highly super-Eddington growth may be possible if gas remains $T=10^4$K (due to lack of H_2) and cools via atomic H**
- **Jeans mass** $M_J \propto T^{3/2}/\rho^{1/2} \approx 10^{5-6} M_\odot$
- **A Mo-Mao-White disk model with isothermal gas at $T=10^4$K is Toomre-stable, gas could avoid fragmentation**
  (Oh & Haiman 2002)
- **No fragmentation seen in simulations**
  (Bromm & Loeb 2003; Wise & Abel 2007; Regan & Haehnelt 2008)
- **Gas can collapse rapidly onto a seed BH (Volonteri & Rees 2005) or collapse directly into a** $10^{5-6} M_\odot$ **SMBH**
  (Koushiappas et al. 2004; Begelman et al 2006; Spaans & Silk 2006; Lodato & Natarajan 2006; Wise & Abel 2007; Regan & Haehnelt 2008)

Two Criteria for Direct Gas Collapse

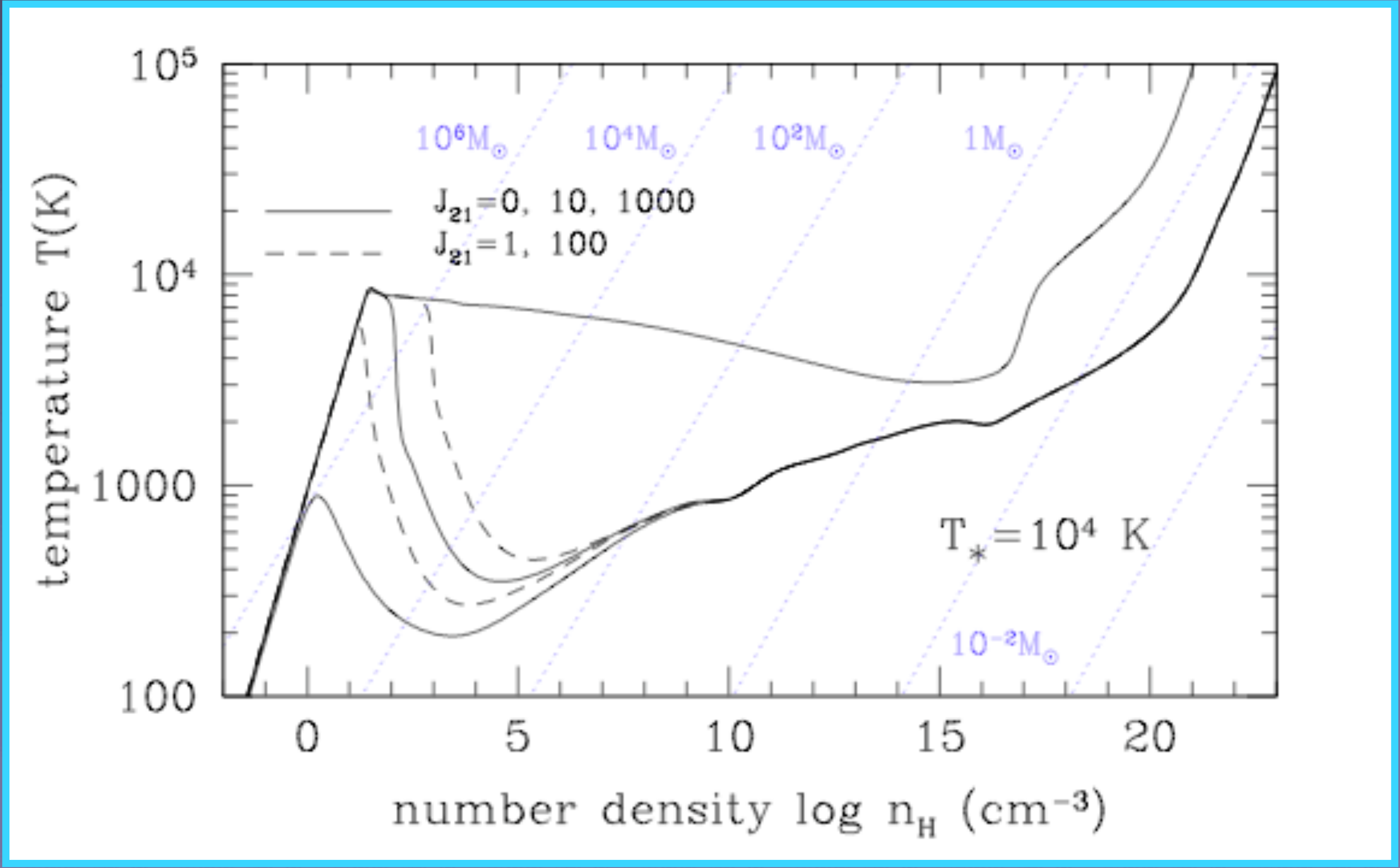
- **ANGULAR MOMENTUM**
  - large viscosity (global dynamical instabilities?)
  - use low-J tail (either rare halos or fraction of gas in given halo).

- **AVOIDING FRAGMENTATION**
  - must avoid cooling to $T \ll 10^4$K
  - avoid H_2 formation (otherwise: fragmentation, star-formation will be similar to minihalos)
  - avoid cooling by metals and dust

Direct SMBH formation?

Evolution of irradiated, metal-free gas: $J_{21}(\mathrm{crit}) \approx 10^3$

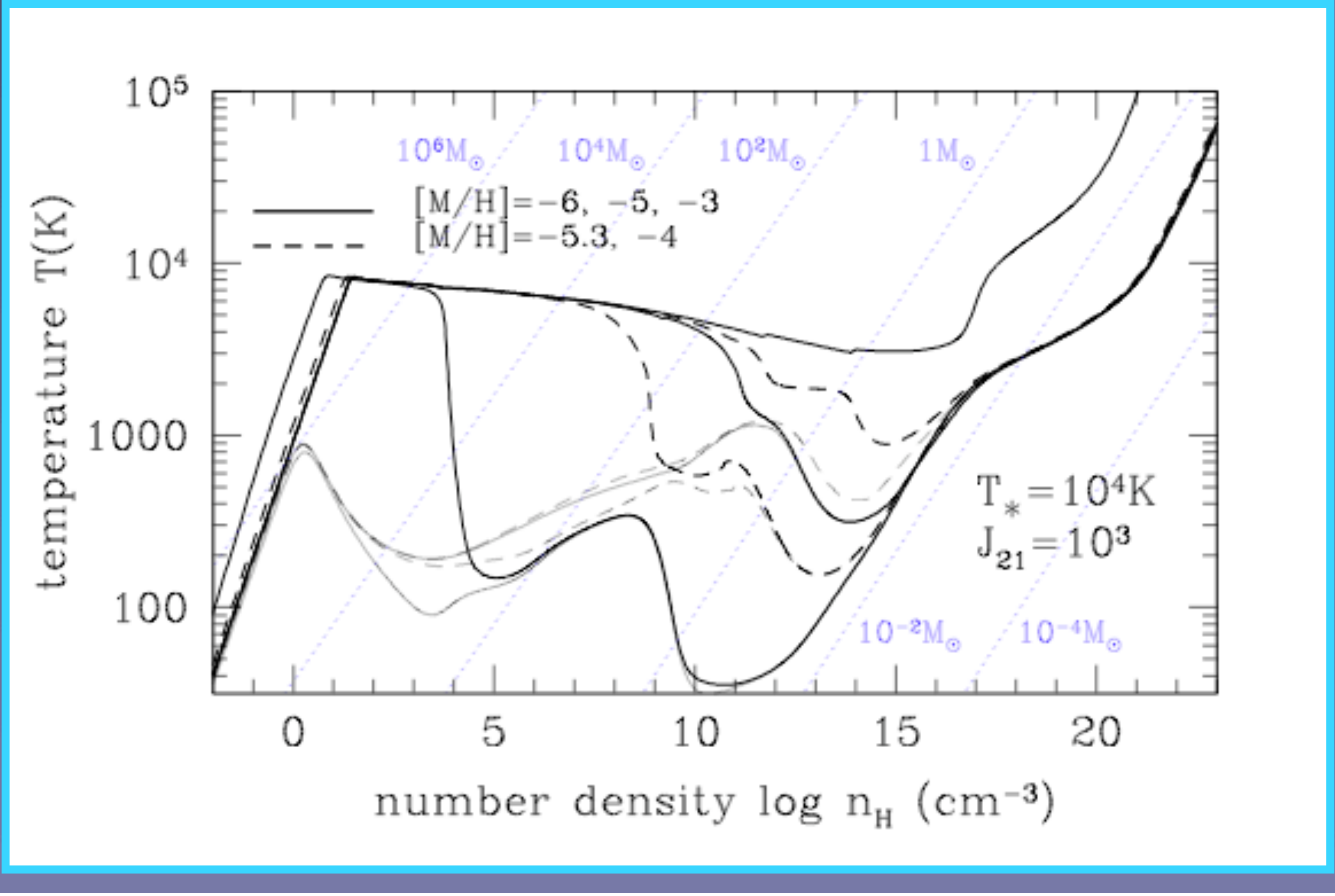
Omukai, Schneider & Haiman (2008)



Direct SMBH formation: impact of metals

Including the effect of (1) irradiation and (2) metals

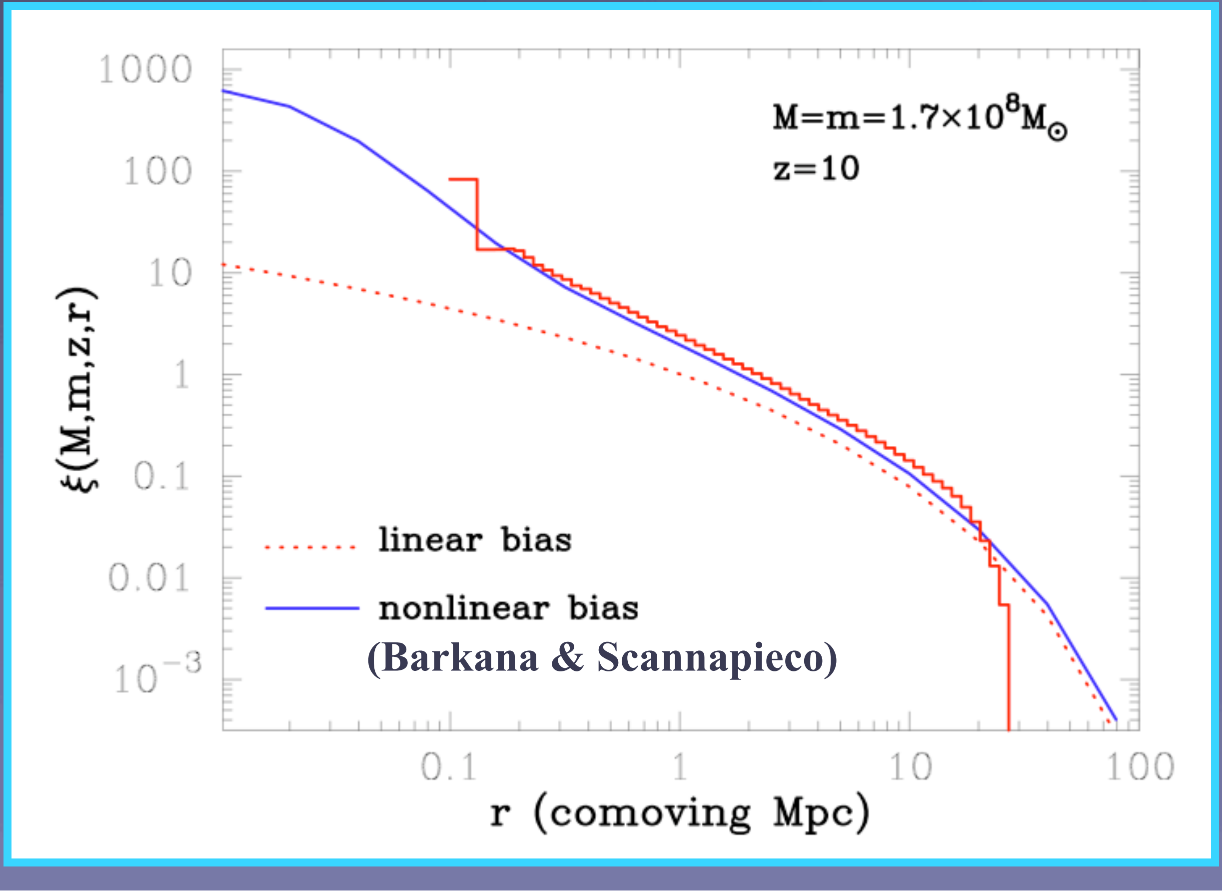
Omukai, Schneider & Haiman (2008)



Probability for sufficiently large UV flux?

Dijkstra, Haiman, Mesinger & Wyithe (2008)

Need: $J(LW) \gtrsim$ few $10^3 \times 10^{-21}$ erg s cm^{-2} Hz^{-1} sr^{-1}
Factor of ~100 above mean. Must come from
nearby sources. High-redshift halos are strongly clustered

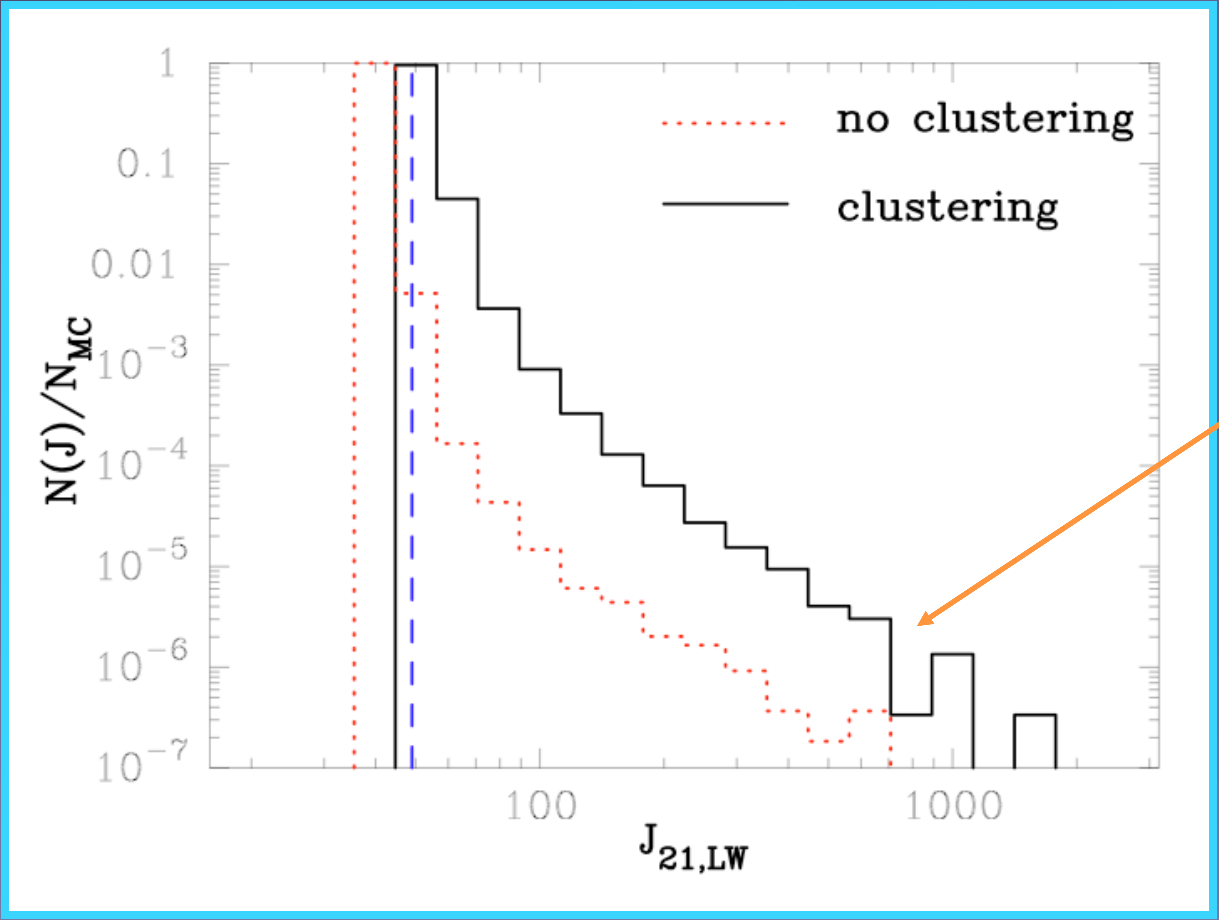


(Barkana & Scannapieco)

Compute UV Flux PDF Sampled by Halos

- (non-linear) source clustering.
- Poisson fluctuations in # of neighbors.
- UV luminosity scatter

Dijkstra, Haiman
Mesinger & Wyithe (2008)



1 in ~10^7 halos has a close (≲10 kpc) bright and synchronized neighbor, so flux is ~ 20 × mean

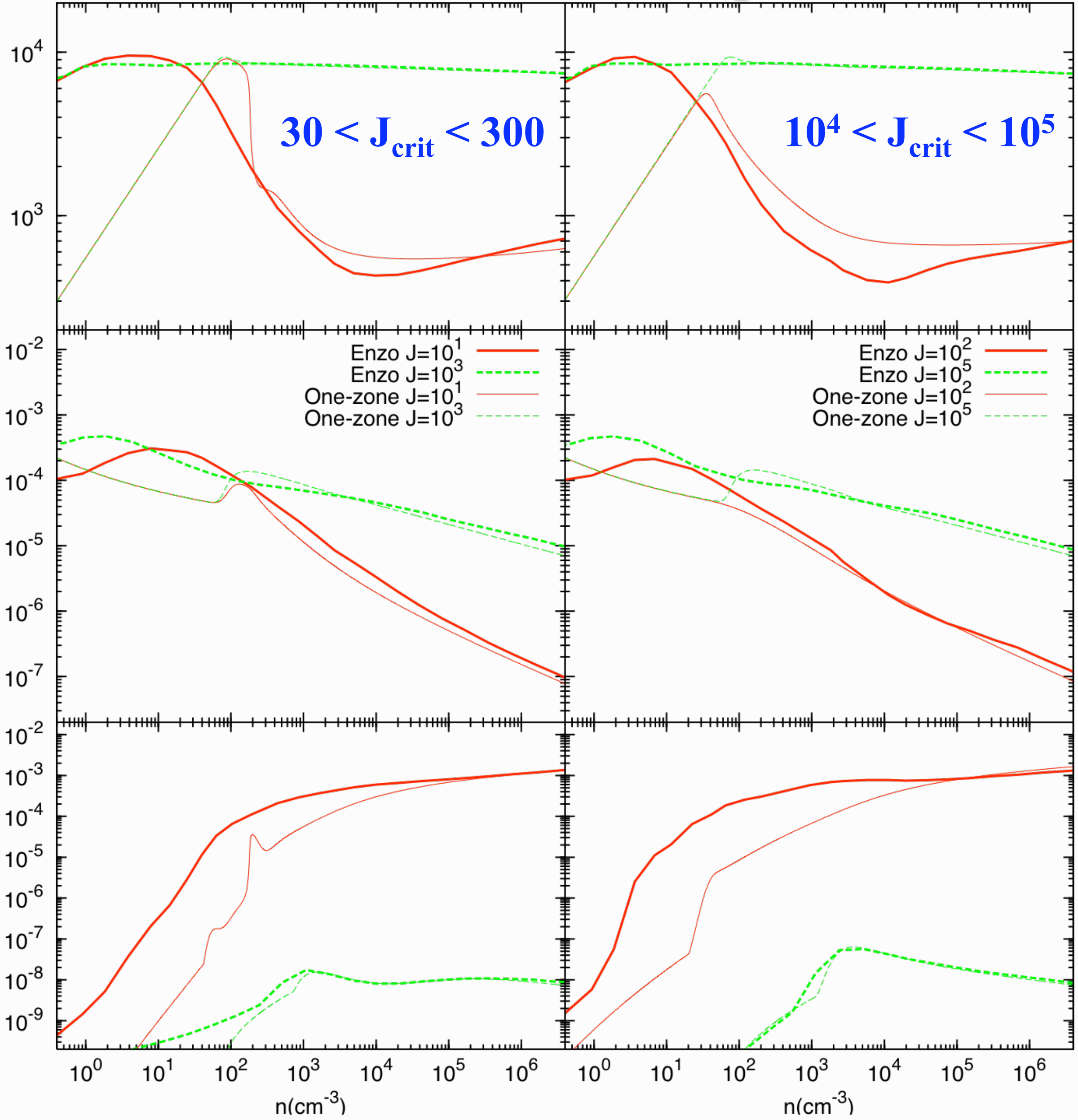
N~10^3 Gpc^{-3} halos, could all end up in z=6 QSO hosts

Normal stars PopIII stars

T(K)

f(e)

$f(H_2)$



hydro simulation of collapse with UV flux

Shang Bryan & Haiman (2009)

Expected background flux at z~10:

J(UV) ~ 10

Direct SMBH formation in close halo pairs?

- Two conditions needed to avoid fragmentation:
  (i) $J(LW) \gtrsim$ few $10^{2-3} \times 10^{-21}$ erg s cm^{-2} Hz^{-1} sr^{-1}
  (ii) $Z \lesssim 5 \times 10^{-6} Z_{\odot}$

- First condition may be satisfied in rare ($\sim 10^{-7}$) case of 1-2 very close, bright & synchronized neighbors
  (Dijkstra, Haiman, Wyithe & Mesinger 2008)

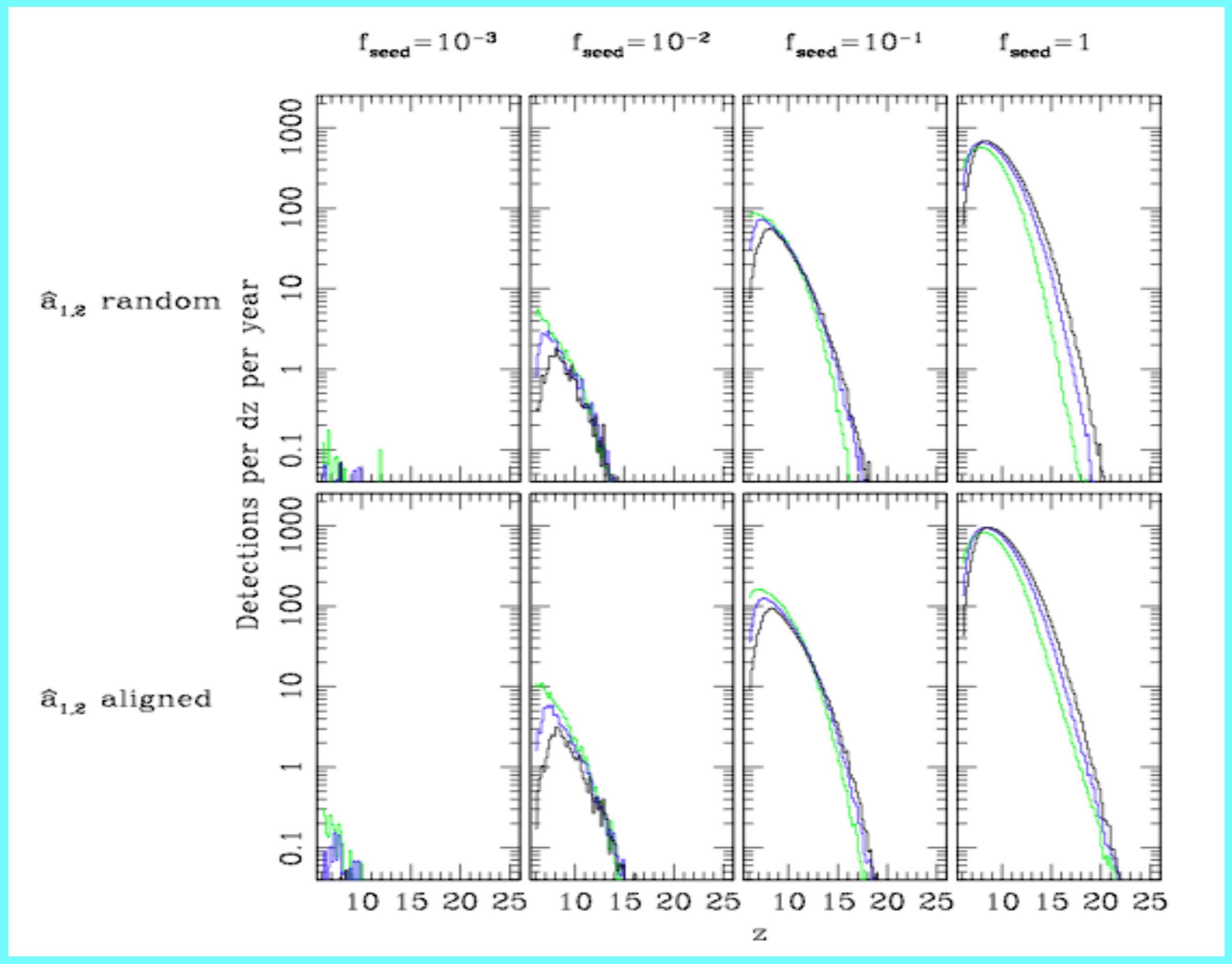
- Second condition eased by factor of 100 if no dust (CII and OI cooling).

- The (more likely?) case with floor metals will form a dense cluster of low-mass stars → collapse to IMBH of 10^{2-3} $M_{\odot}$ (Omukai, Schneider & Haiman 2008)

LISA event rate: stellar seed model

$10^4\ M_\odot < (1+z)M_{bh} < 10^7\ M_\odot$

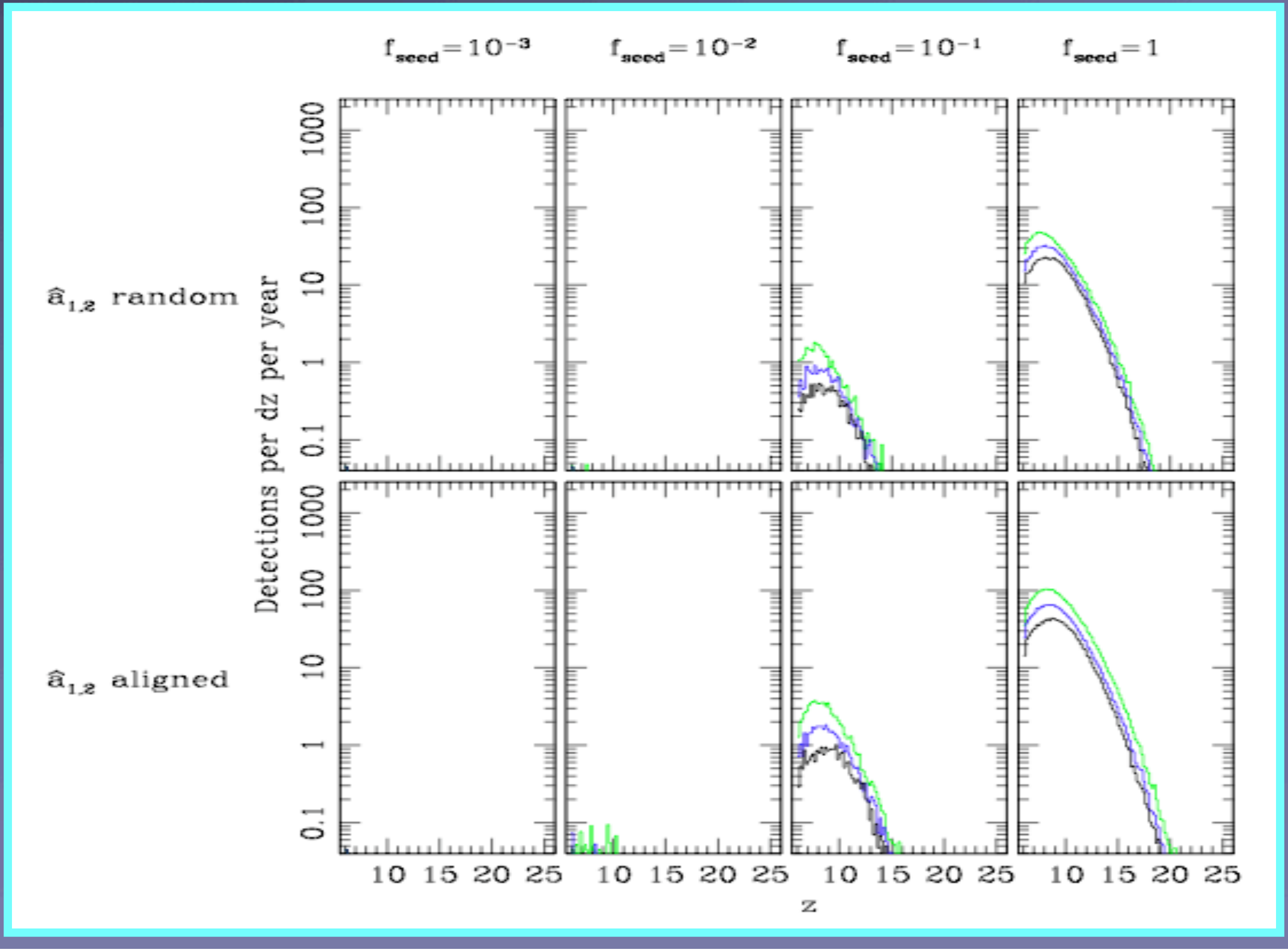
Tanaka & Haiman (2008)



LISA even rate: direct collapse

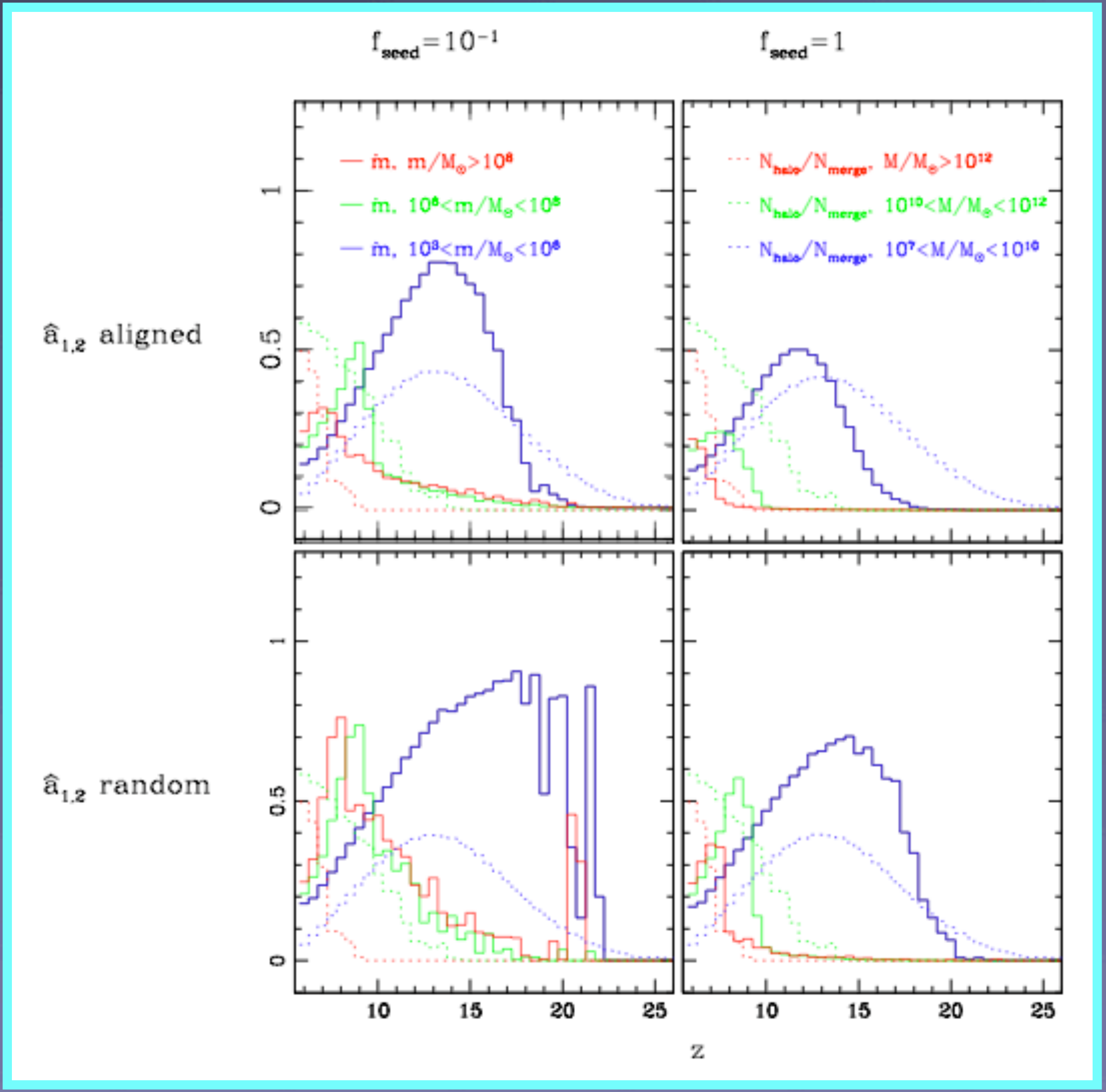
$10^5\ M_\odot$ seeds in $T_{vir} > 1.5 \times 10^4$K halos

Tanaka & Haiman (2008)



Mass accretion rate: “M-σ” model

Tanaka & Haiman (2008)

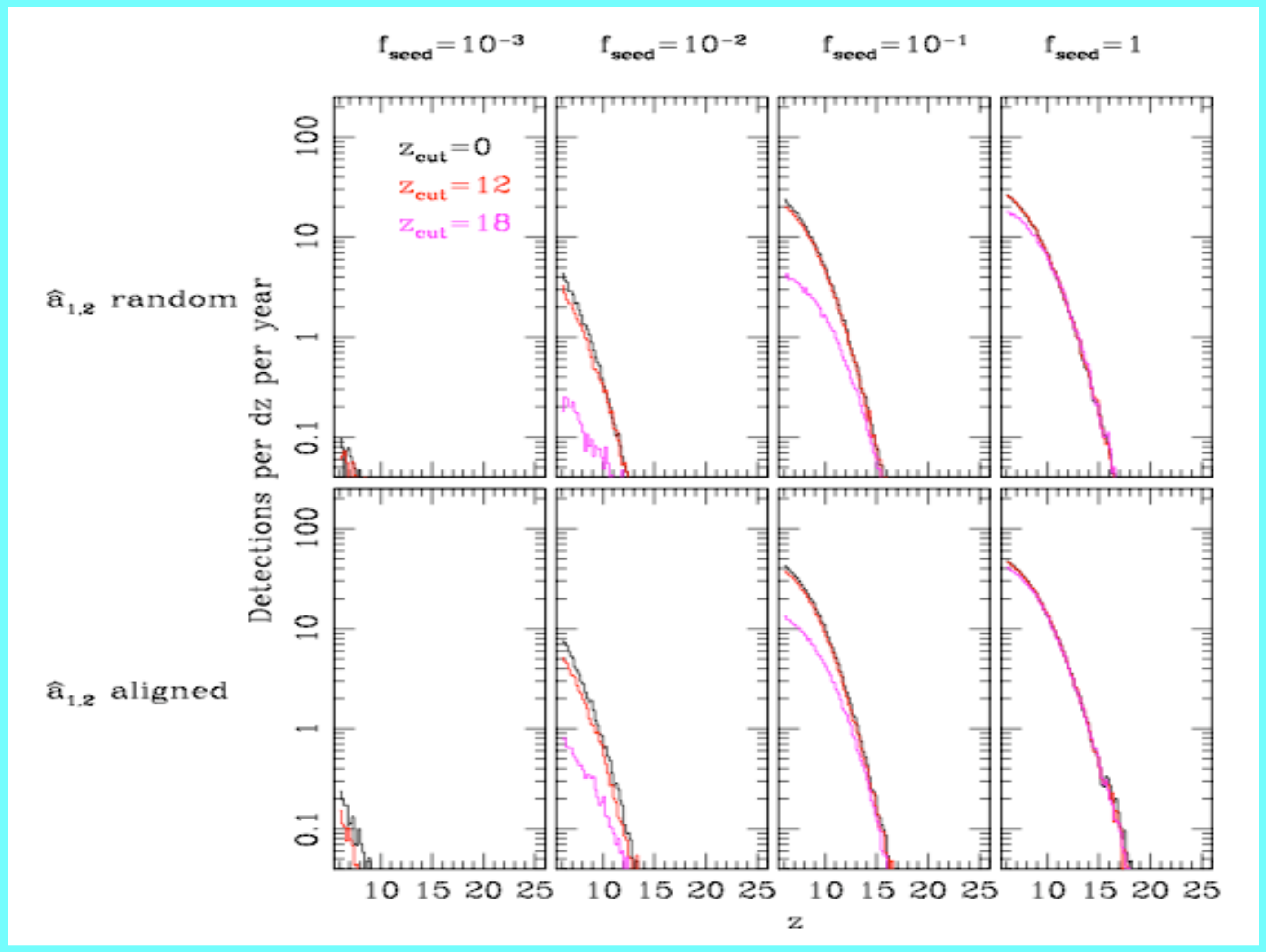


Similar to models where BH feeding tracks major mergers:
(Bromley et al. 2004;
Volonteri, Lodato & Natarajan 2008
Wyithe & Loeb 2003)

LISA even rate: M-σ model

$10^4\ M_\odot < (1+z)M_{bh} < 10^7\ M_\odot$

Tanaka & Haiman (2008)



Conclusions (Part I)

1. Explaining z=6 quasar SMBHs with $\sim 10^9 M_\odot$ is a challenge, requiring some optimistic assumptions:
   (i) stellar seeds common, embedded in dense gas, can grow at Eddington rate without interruption, or
   (ii) rapid "direct collapse" in rare special environment in "second generation" halo with no metals or H_2
2. Challenge is even worse, if models are not to overproduce number of $\sim 10^{5\text{-}8} M_\odot$ SMBHs. Seed formation stops at z~30 ?
3. Negative feedback consistent with reionization history.
4. LISA rates from 0 to ~30 events/yr are a discriminator.