The Origin and Detection of High Redshift Supermassive Black Holes

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Outline

- Formation and growth of SMBHs
  - did first SMBHs grow from stellar seeds or collapse directly?
  - did early BHs contribute to reionization and radiative feedback?
- Probing the SMBH assembly history
  - direct detections in optical, radio, X-ray
  - indirect detections through reionization topology
  - distinguishing assembly models in gravity waves with LISA

Observation of SMBHs near z = 6

Rare ("5σ") objects: 10 found in SDSS at z>6 (in ~10 Gpc^3)
20 in CFHQ (Willott et al. 2010) + few others

Example: SDSS 1114-5251 (Fan et al. 2003)
$z=6.43 \qquad M_{bh} = L_{obs} / L_{Edd} \approx 4 \times 10^9 M_\odot$

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

e-folding (Edd) time:
$4 \times (\varepsilon/0.1)\ 10^7$ yr

No. e-foldings needed
$\ln(M_{bh}/M_{seed}) \sim 20$ for $M_{seed} \sim 100\ M_\odot$

Age of universe (z=6.43)
8×10^8 yr ✓

Strong beaming? No. (Haiman & Cen 2002)

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

“Stellar seed” *vs* “direct collapse”

- **STELLAR SEEDS**

  uninterrupted near-Eddington accretion

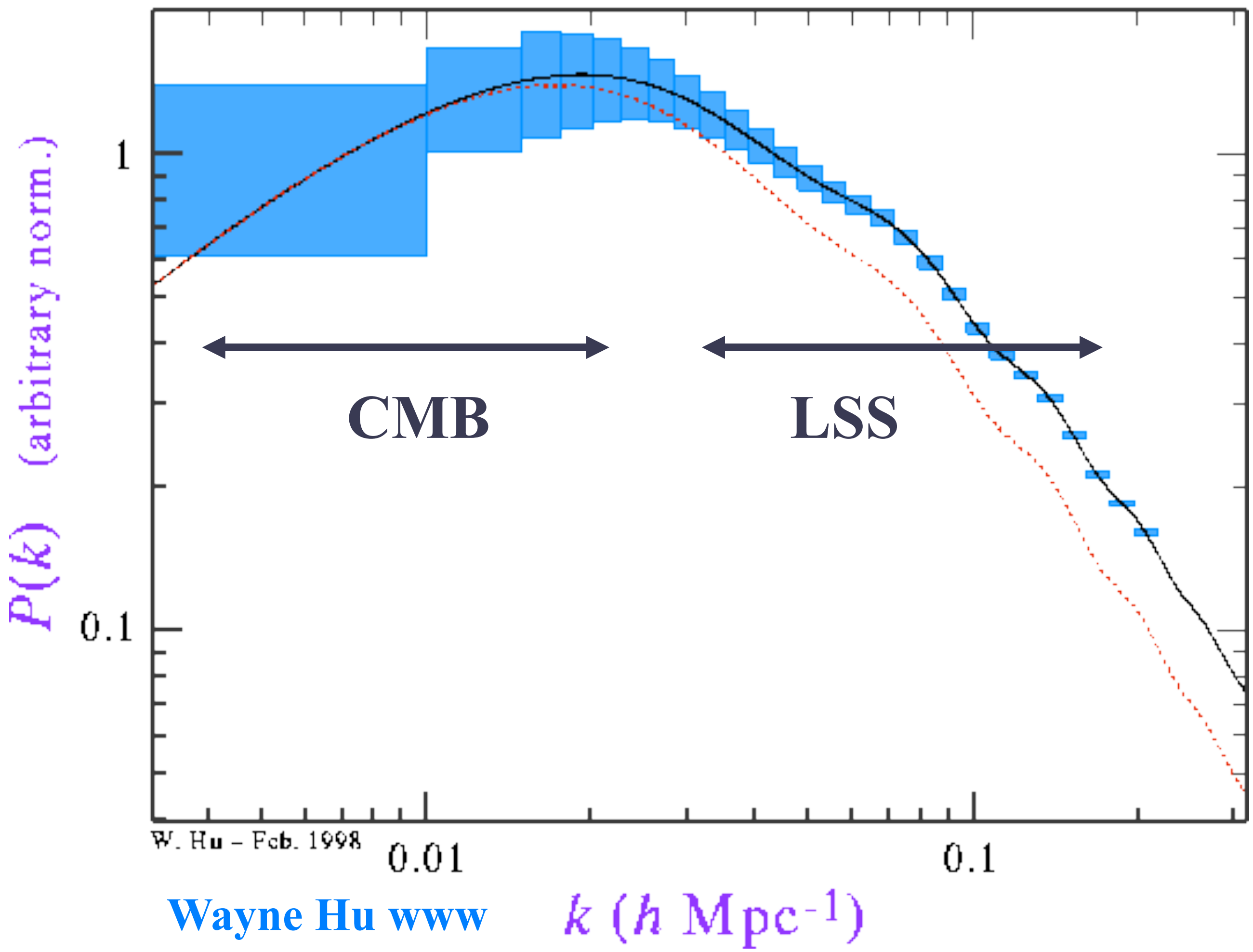
  - continuous gas supply
  - avoid radiative feedback depressing accretion rate
  - must avoid ejection from halos

- **DIRECT COLLAPSE**

  rapid formation of 10^5-10^6 $M_\odot$ black holes either by direct collapse of gas or super-Eddington accretion onto a lower-mass seed

  - gas must be driven in rapidly (deep potential)
  - must avoid fragmentation
  - transfer angular momentum

Seed Fluctuations on Small Scales



extrapolation by a factor of about 100 in linear scale

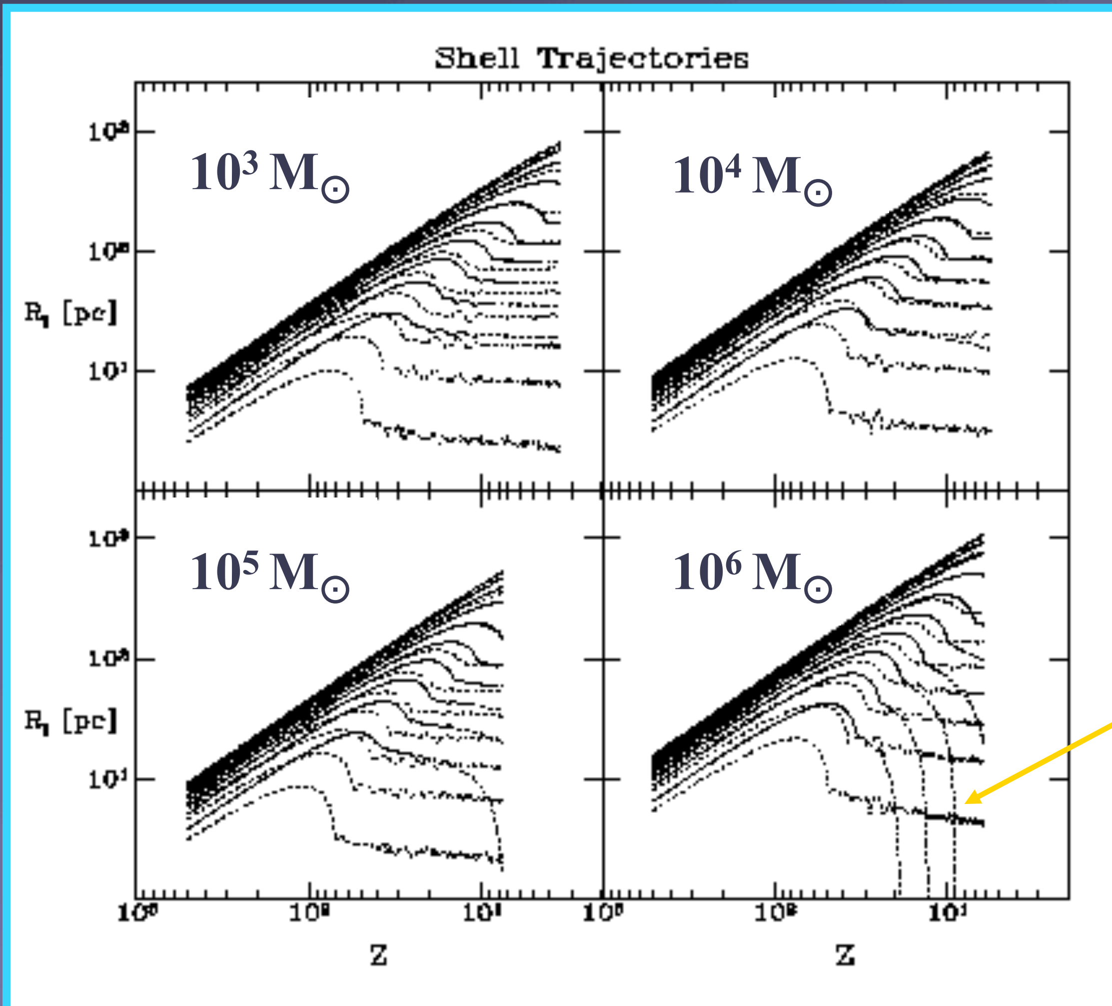
Dark Age

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

e.g. Yoshida et al. (2003)

Collapse of Spherical “Minihalo” in Isolation

radius (pc)



redshift

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

Haiman, Thoul & Loeb (1996)
Tegmark et al. (1997)

3D Simulation of a Primordial Gas Cloud

Yoshida, Omukai & Hernquist (2008)

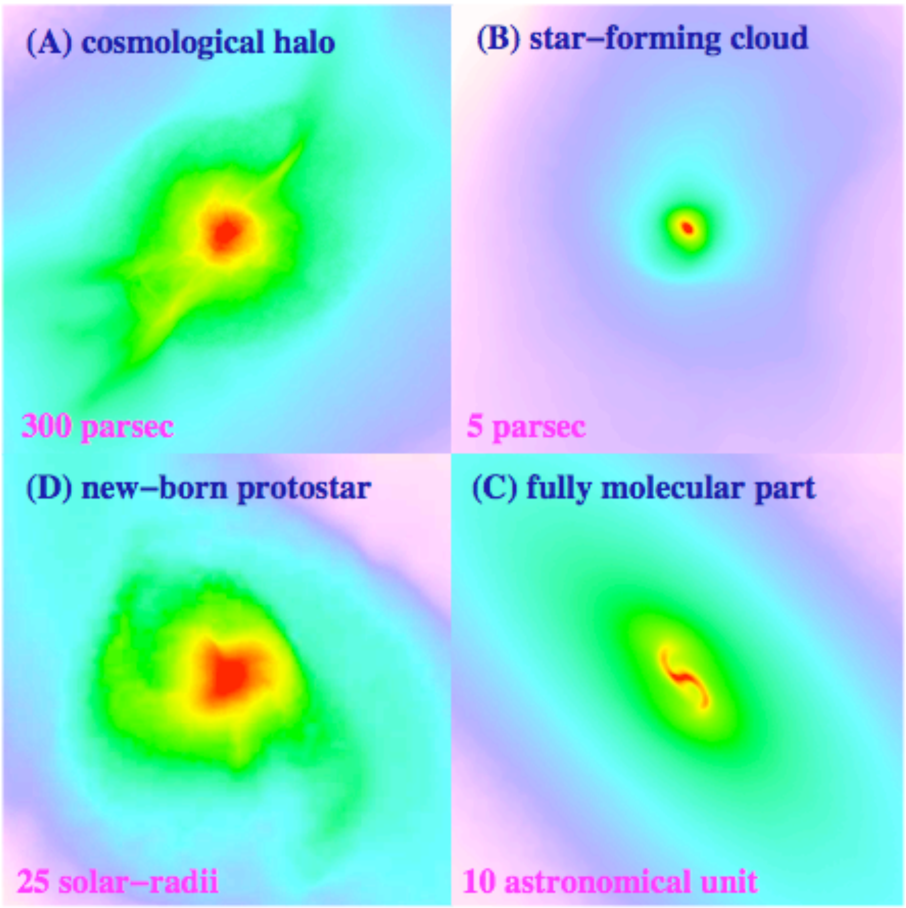


Fig. 1: Projected gas distribution around the protostar. Shown regions are, from top-left, clockwise, (A) the large-scale gas distribution around the cosmological halo (300 pc on a side), (B) a self-gravitating, star-forming cloud (5 pc on a side), (C) the central part of the fully molecular core (10 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.

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}

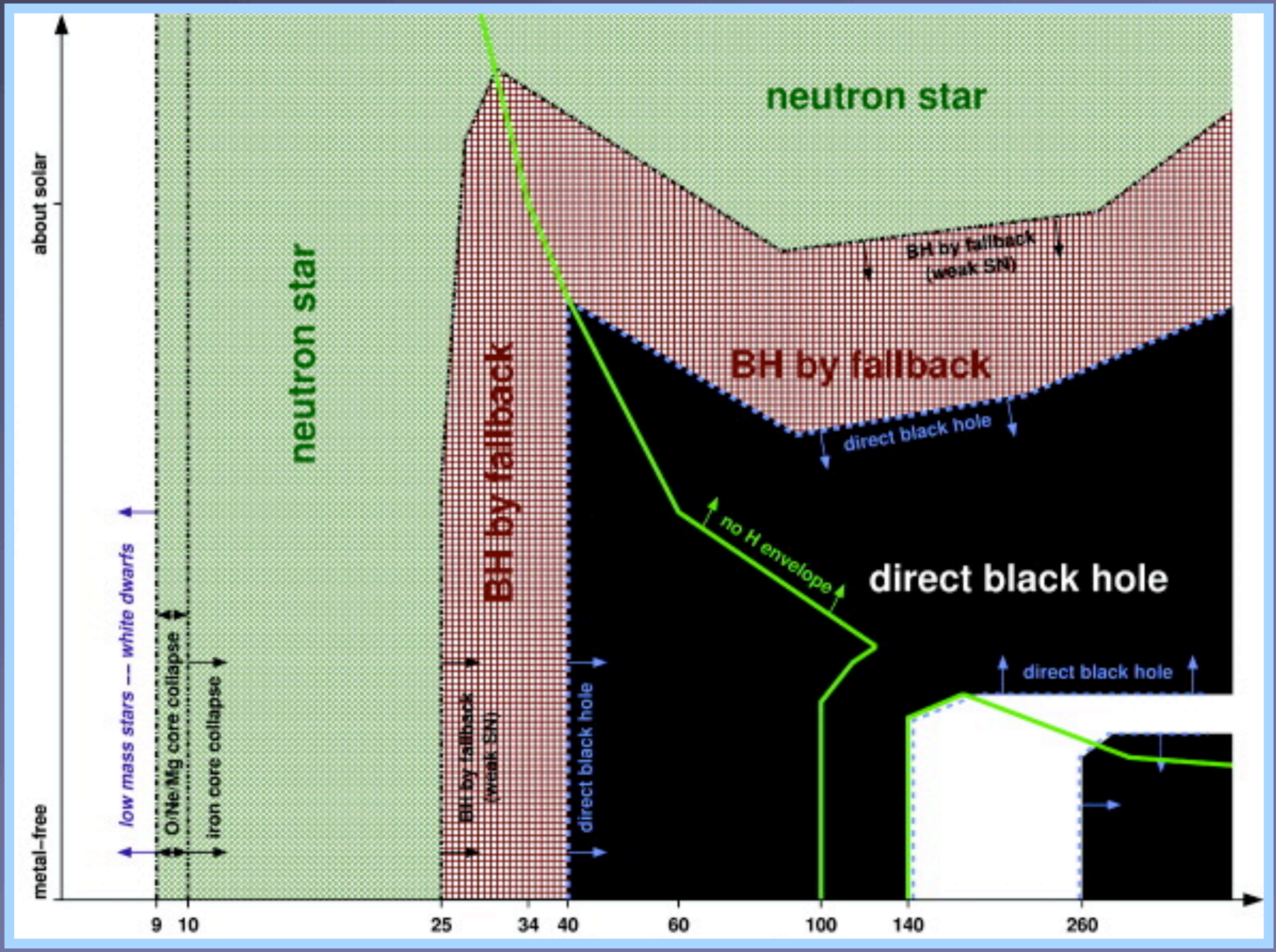
$M_* \approx 0.01\ M_\odot$

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

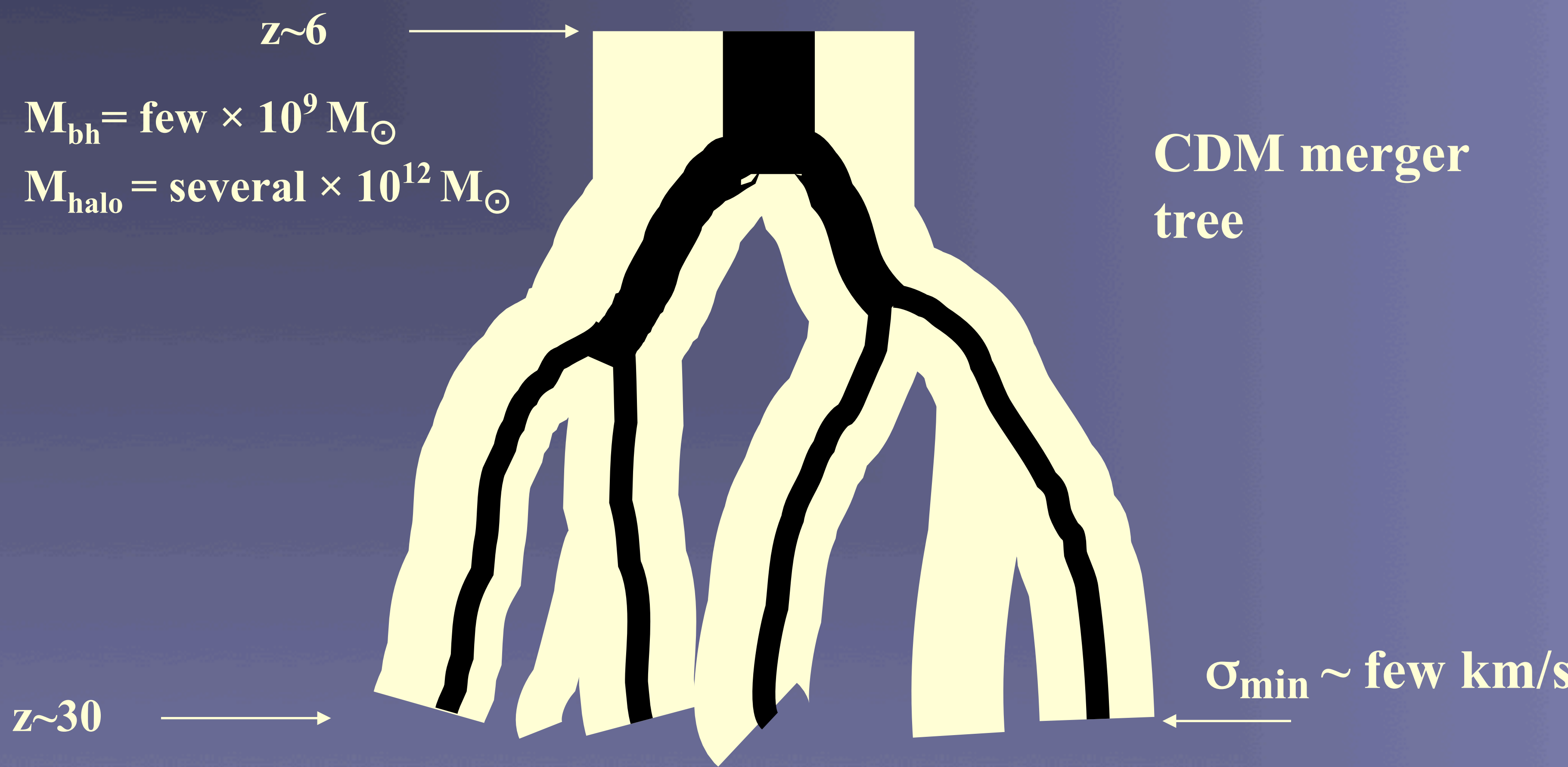
10M$_\odot$ 25M$_\odot$ 40M$_\odot$ 140M$_\odot$ 260M$_\odot$

Growth of High-z Supermassive BHs

M_{bh}= few × 10^9 $M_\odot$

M_{halo} = several × 10^{12} $M_\odot$

CDM merger tree



Haiman & Loeb (2001); Haiman (2004); Yoo & Miralda-Escude (2004);
Sesana et al. (2004); Bromley et al. (2004); Volonteri & Rees (2006), Shapiro (2005);
Tanaka & Haiman (2009)
Also hydro simulations: Li et al. (2007); Sijacki et al. (2009)

Merger-Tree Modeling Procedure

Tanaka & Haiman (2009)

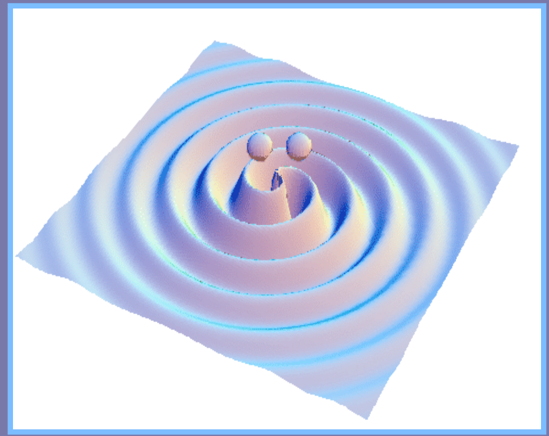
- **Construct Monte-Carlo DM halo merger tree from z=6 to z>40**
  - $10^8 M_\odot \leq M_{halo} \leq 10^{13} M_\odot$ (M_{res} =few $10^5 M_\odot$; N~10^5 trees)
  - seed fraction $\mathbf{f_{occ}}$ of new halos with BHs (M_{seed} =100 $M_\odot$)

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

Milosavljević et al. (2009): f_{duty}<0.32

- **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)

A possible obstacle: gravitational recoil



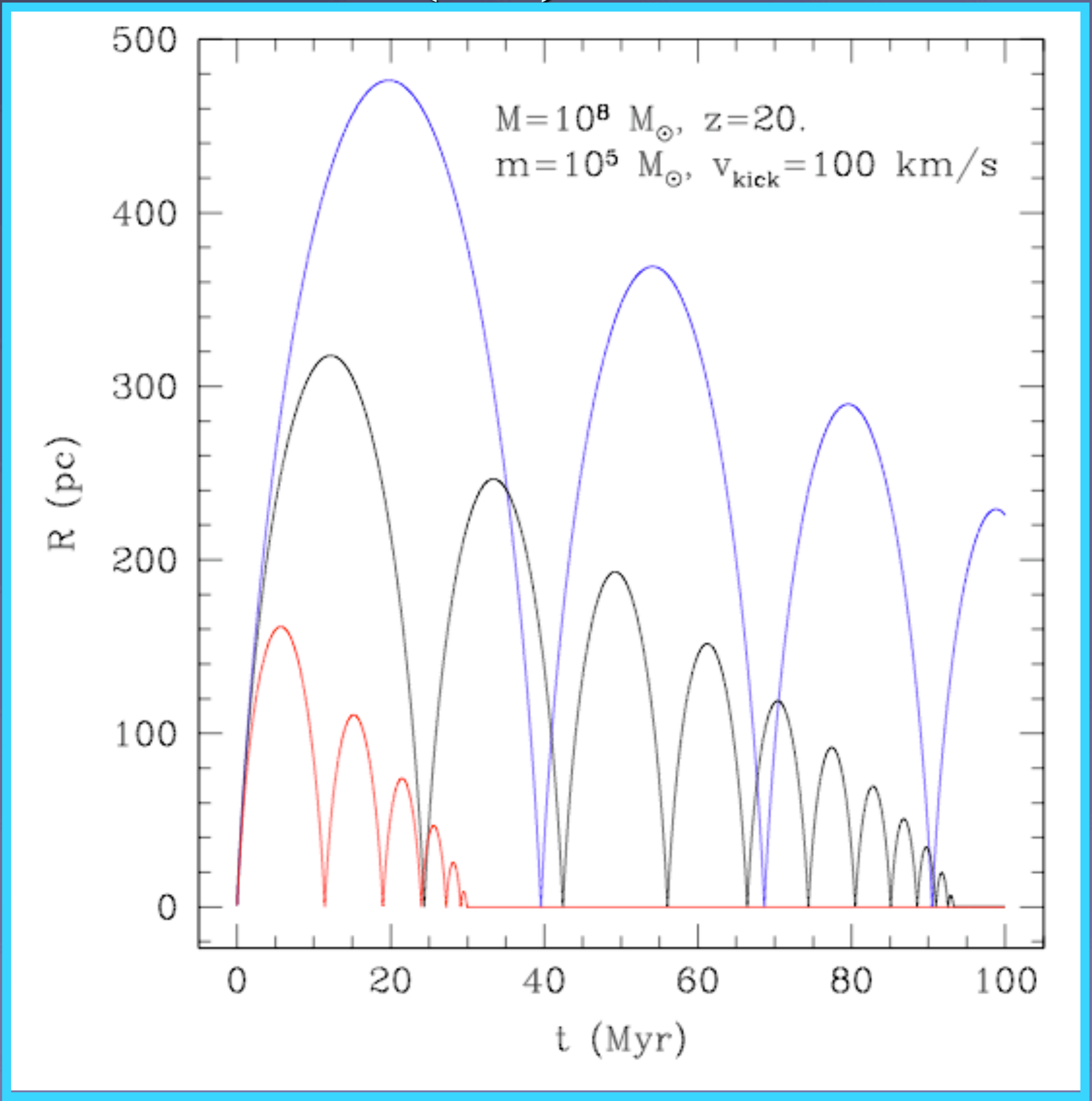
- **Gravitational radiation produces sudden recoil**
  — kick velocity depends on mass ratio and on spin vectors
  — typical v(kick) ~ few × 100 km/s **(Baker et al. 2006, 2007**
  — maximum v(kick) ~ 4,000 km/s **Gonzalez et al. 2007)**

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

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

BH trajectory : dynamical friction vs. gas

Tanaka & Haiman (2009)

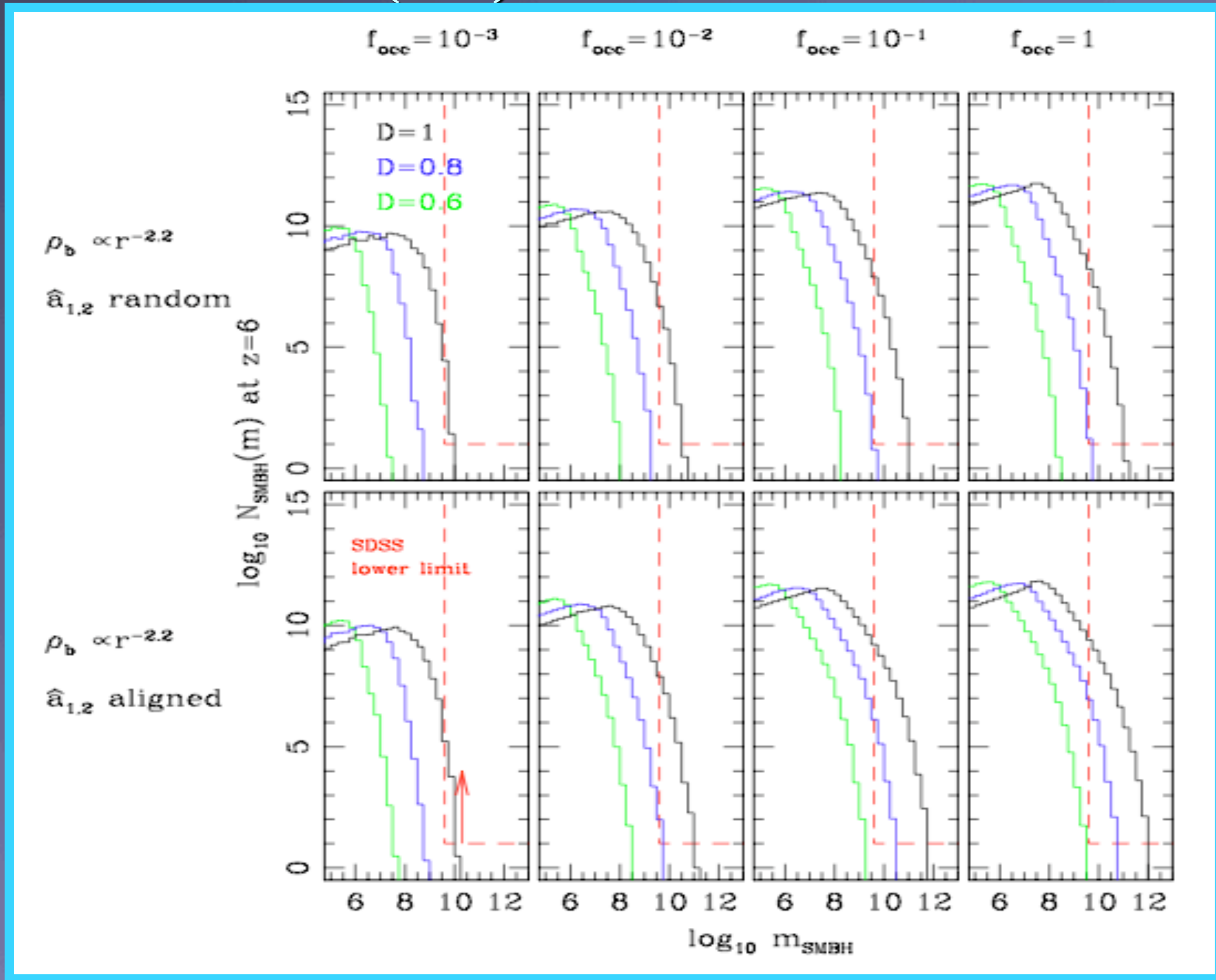


- DM halo NFW
- gas with flat core (Shapiro et al. 1999)
- gas with steep cusp (Abel et al. 2000 Bromm et al. 2002 Yoshida et al. 2003)

Asymmetry in 3D makes return harder (Guedes et al. 2009)

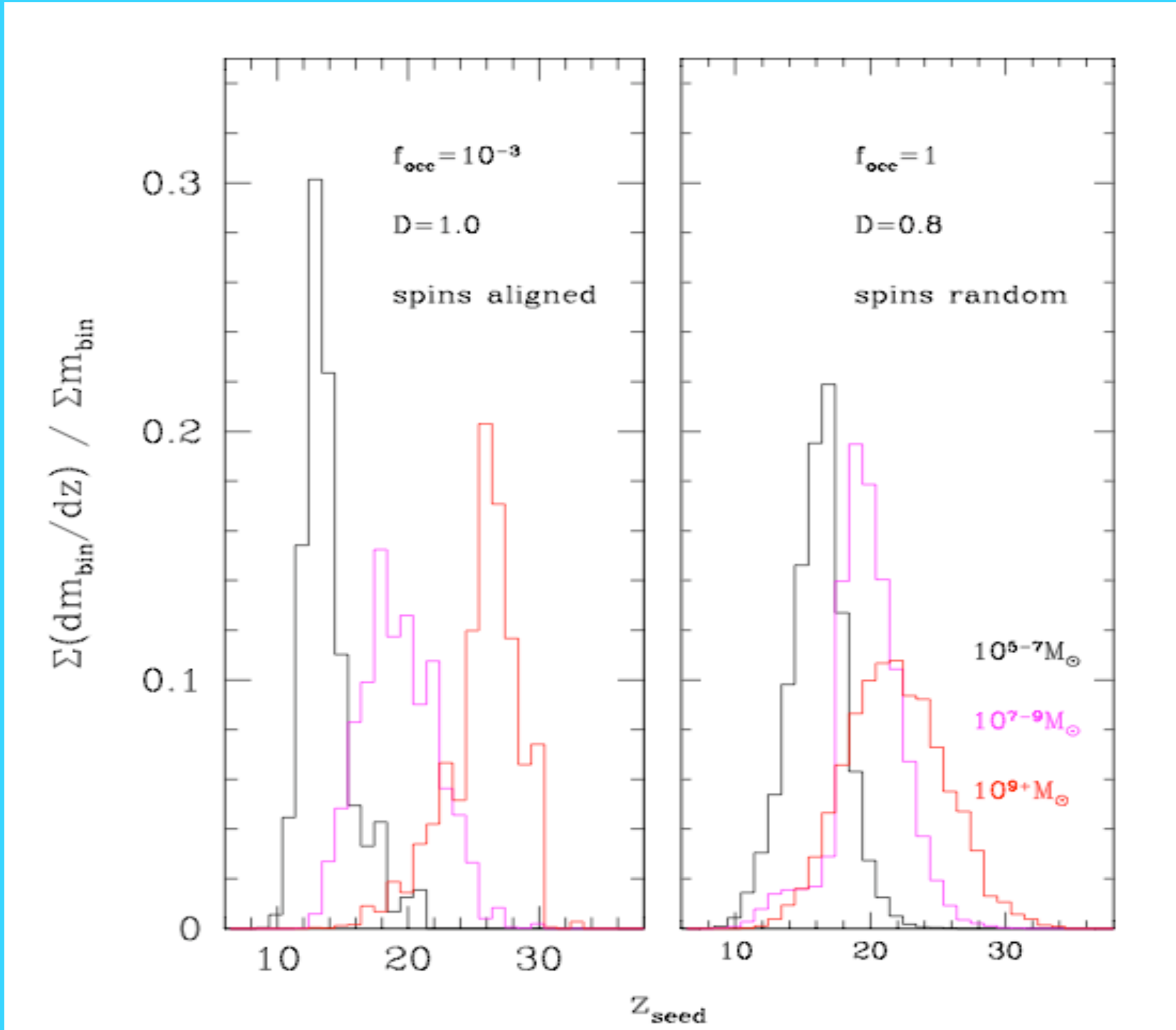
SMBH mass function at z=6

Tanaka & Haiman (2009)



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

Tanaka & Haiman (2009)



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	$200M_\odot$	1200K	10^{-3}	1.0	$0.0 < a_{1,2} < 0.9$, unaligned	30	$6.7 \times 10^4 M_\odot$ Mpc^{-3}
B	$100M_\odot$	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}

Other ideas to "flatten" the BH mass function :

- start with much more massive seeds (lowers z_{cut})
- internal feedback always maintains M_{BH}-σ relation
  - many more mergers in this model (good news for LISA)
  - also solves puzzle of connecting z>6 and z<6 universe

SMBHs from stellar seeds: Summary

- (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 ($\rho_{BH} \lesssim 4 \times 10^4\ M_\odot Mpc^{-3}$) suggests $f_{seed} \approx 10^{-2}$ and negative feedback at z~25

- 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}

Ultra-Early Pause in Structure Formation?

Soft UV background:

this background inevitable destroys molecules

⊖

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

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

→ H_2 cooling in minihalos suppressed already when $J_{21} \sim 0.01$

Haiman, Rees & Loeb 1997
Mesinger, Bryan & Haiman 2008

Soft X-ray background:

this background from BHs themselves (or X ray binaries?)

⊕

~ 1 keV photons produce fast photoelectrons

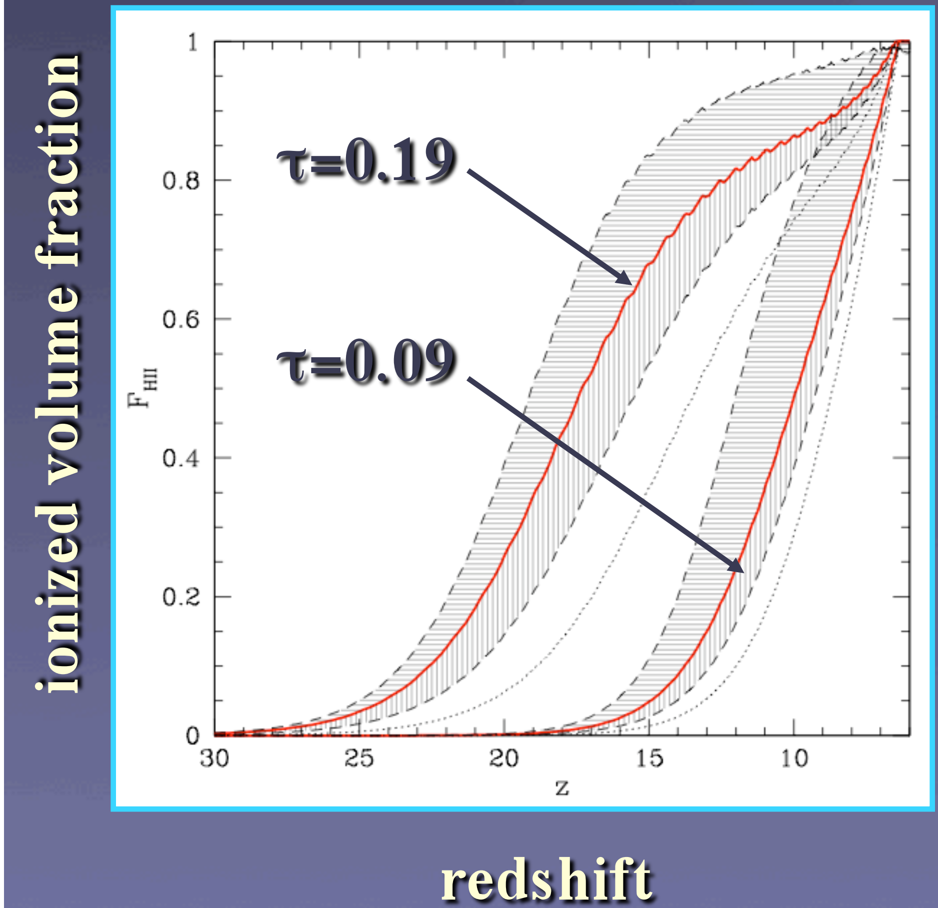
$H+\gamma \rightarrow H^{+}+\underline{e^{-}}$

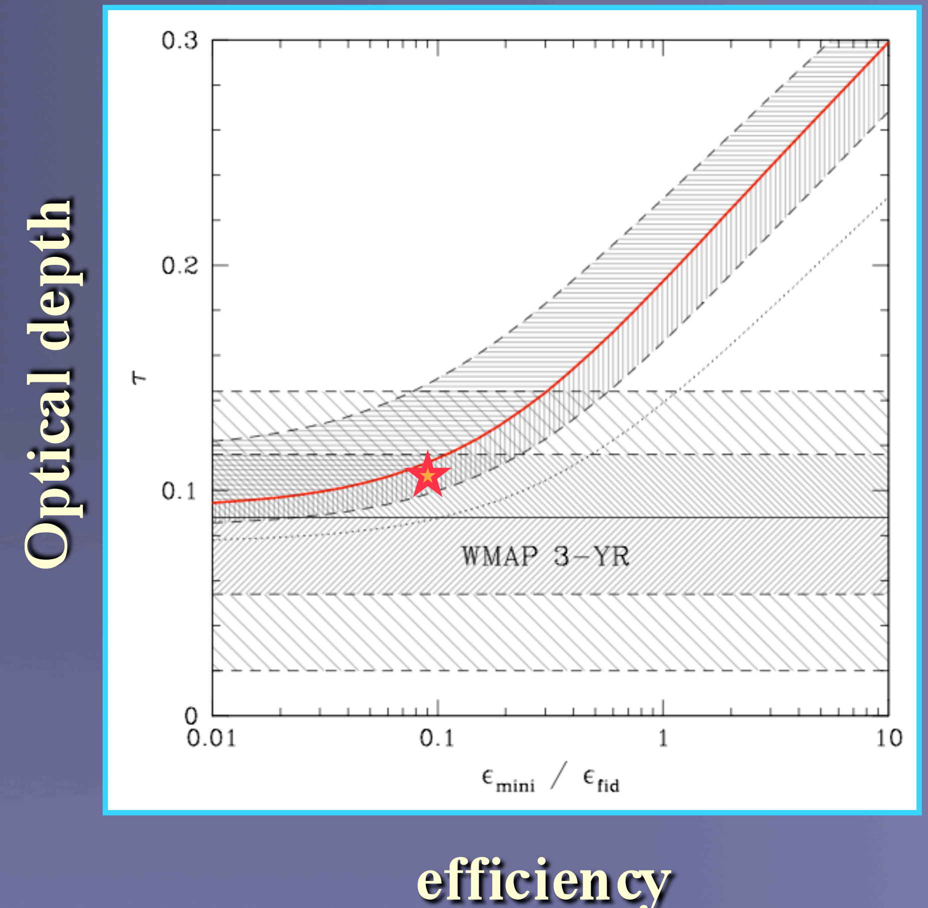
→ early partial (pre)ionization and IGM heating

Madau et al. 2004
Ricotti & Ostriker 2004

Negative Feedback in Reionization History

Haiman & Bryan (2006)





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

Alternative: 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 cooling by metals and dust
  - avoid H_2 formation (otherwise: fragmentation, star-formation will be similar to mini-halos)
  - supersonic turbulence may prohibit fragmentation

- **THESE TWO CRITERIA MAY BE RELATED**
  - age-old "BH fueling problem" for quasars
  - key: stable locally *(gravity vs pressure/turbulence)*
    unstable globally *(rotational vs potential energy*
  - recent simulations to 0.1pc **(Mayer et al. 2009, Levine et al. 2008 Hopkins & Quataert 2010)**

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** $M_J \propto T^{3/2}/\rho^{1/2} \approx 10^{5\text{-}6} M_\odot$
- **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 2009; Shang et al. 2010)
- **Gas can collapse rapidly onto a seed BH (Volonteri & Rees 2005) or collapse directly into** $10^{5\text{-}6} M_\odot$ **SMBH by *global instability***
  (Koushiappas et al. 2004; Begelman et al 2006; Spaans & Silk 2006; Lodato & Natarajan 2006; Wise & Abel 2007; Regan & Haehnelt 2008)

If gas in T_{vir} >10^4K halos cools to ~100K:

(Oh & Haiman 2002; Shang et al. 2010)

Similar to mini-halos:

Rely on H_2 cooling and fragment on similar (~ 100 $M_\odot$) scales;

no rapid in-fall (c_s *vs* v_{ff})

Main differences:

1. contract to high densities less susceptible to feedback

2. HD possibly lowers mass (bad for SMBH formation)

cf: SMBHs

Volonteri &Rees 2005
Bromm & Loeb 2005
Begelman et al. 2006
Lodato et al. 2006
Spaans & Silk 2006

cf: HD reduces temperature and fragmentation scale?

Uehara & Inutsuka 2000
Machida et al. 2005
Johnson & Bromm 2005
but:
Mc Greer & Bryan 2008

Avoiding H_2 – cooling with UV flux

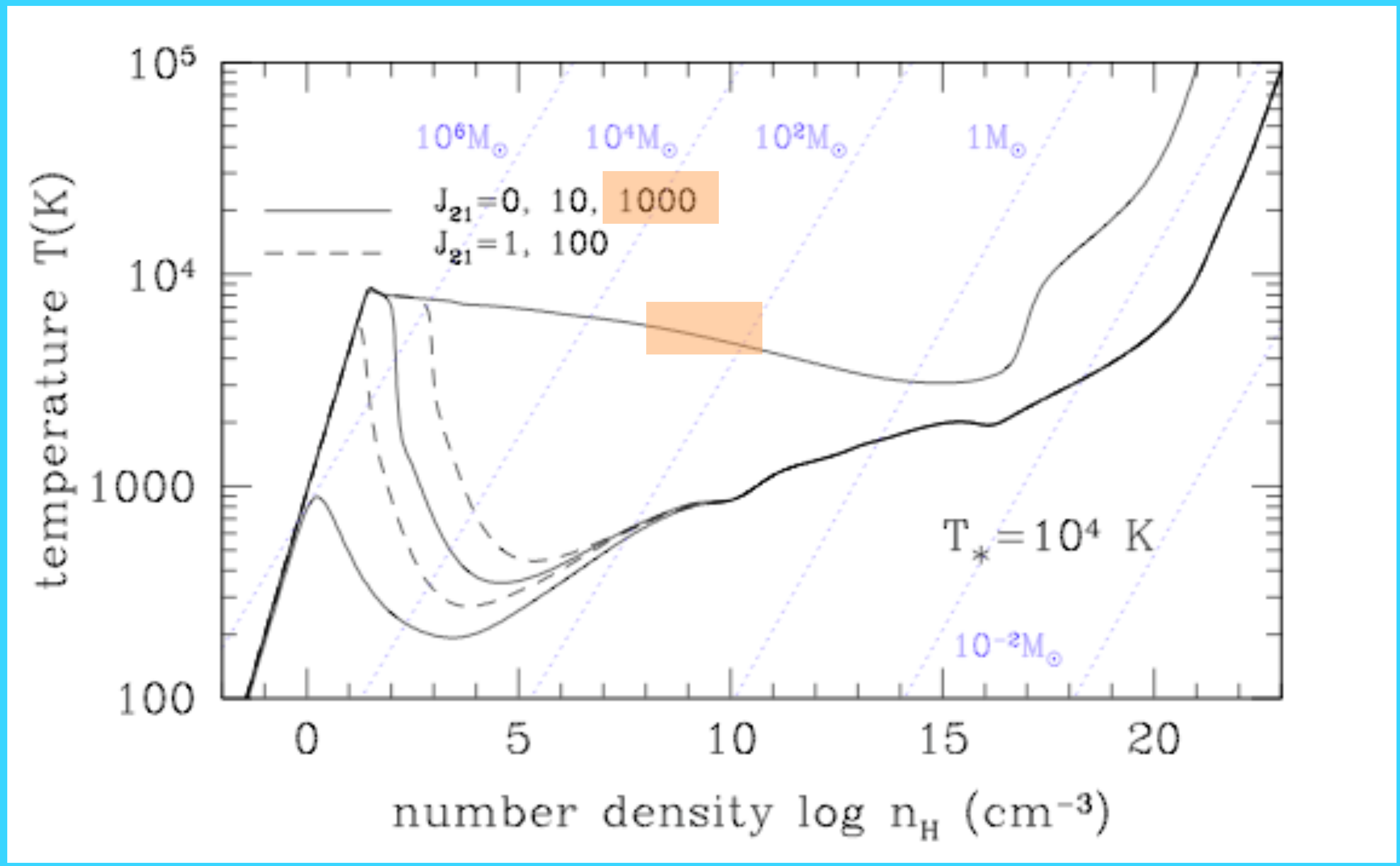
(Omukai 2001; Oh & Haiman 2002)

- H_2-formation rate $\propto \rho^2$ but photo-dissoc. rate $\propto J\rho$
- Critical flux $J \propto \rho$
- $J_{21,crit}$ low ~ 0.01-0.1 in low-mass mini-halos ($n \sim 0.1\text{-}1\ cm^{-3}$)
- Key: avoid H_2-cooling up to critical density of H_2: $n \sim 10^4\ cm^{-3}$
- $J_{21,crit}$ increased to $10^3\text{-}10^5$
- Normal stars more effective than Pop III:
  softer spectrum produces high H^- -dissociation rate
- Compare to $J \sim 1$ (at z~3) or $J \sim 10$ (at reionization)

Direct SMBH formation in Irradiated Gas?

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

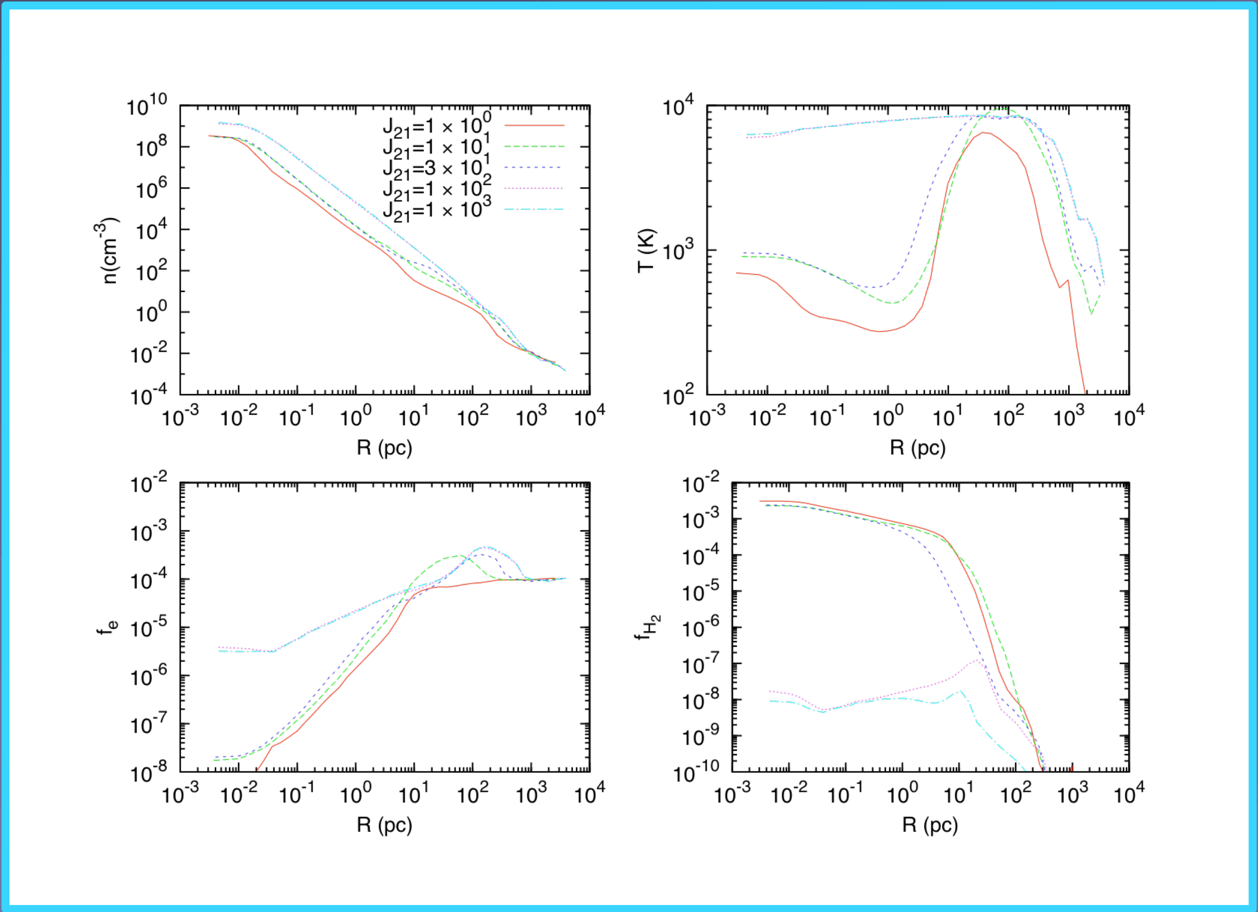
Omukai, Schneider & Haiman (2008)



Critical UV flux: 3D simulations

Shang, Bryan & Haiman (2010)

- Simulations with enzo: 3 halos with $M \sim 10^8\, M_\odot$ identified in 1 Mpc box
- re-simulate each halo, 13-18 refinement levels, with J=0, 10, 100, 10^4, 10^5



Collapse with UV flux from normal stars (T^*=10,000 K)

Expected background flux at z~10:

J(UV) ~ 10

$30 < J_{crit} < 100$

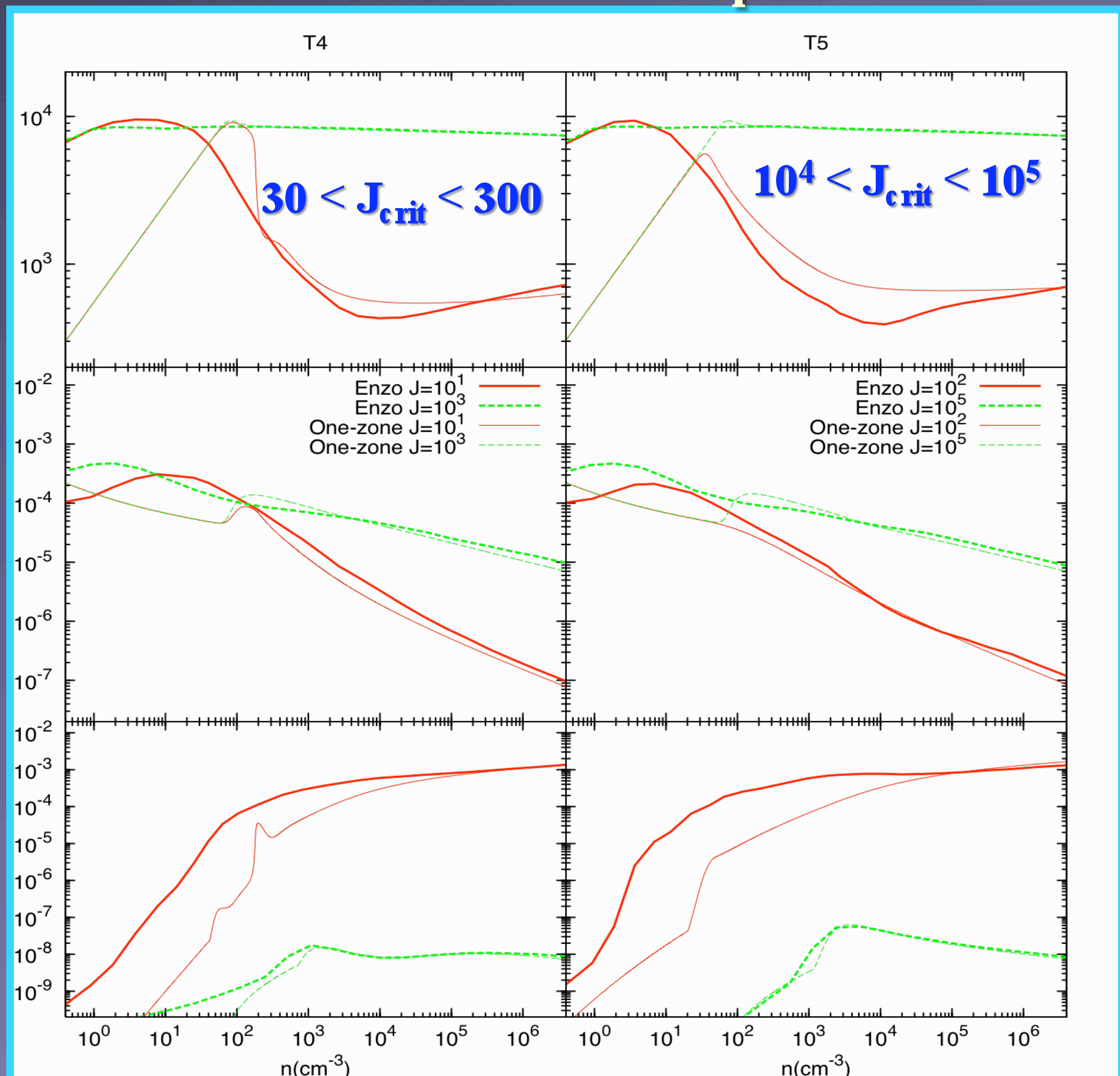
Critical UV flux: 3D simulations

Normal stars PopIII stars

T(K)

f(e)

$f(H_2)$



Hydro (enzo) simulation of collapse with UV flux

Shang Bryan & Haiman (2010)

Expected background flux at z~10:

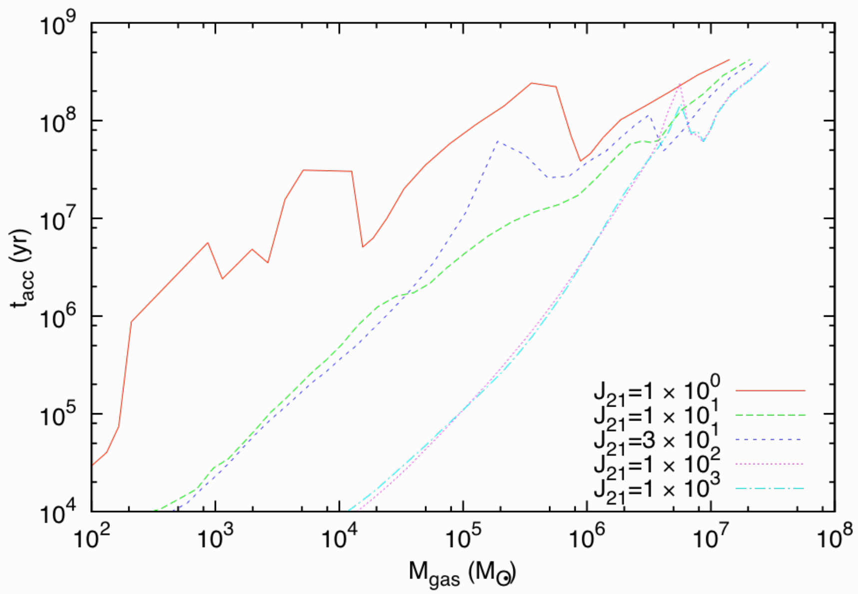
J(UV) ~ 10

SMBH by direct collapse possible (?)

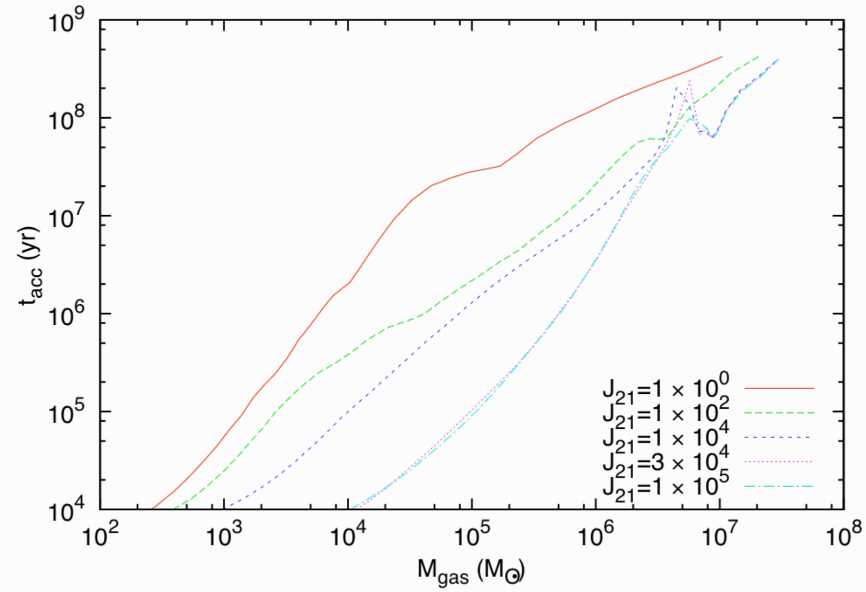
- **In-fall proceeds at sound speed** $c_s \approx 10$ km/s
- **Mass accretion rate** $M_{acc} \propto c_s^3$
- **Fragmentation is not seen in simulations**
- **Central object has mass** $M \approx 10^5 M_\odot$
  (cf. $M \approx 10^2\ M_\odot$ **with** H_2**, when** $c_s \approx 1\text{-}2$ km/s**)**

SMBH by direct collapse possible (?)

Shang, Bryan & Haiman (2010)



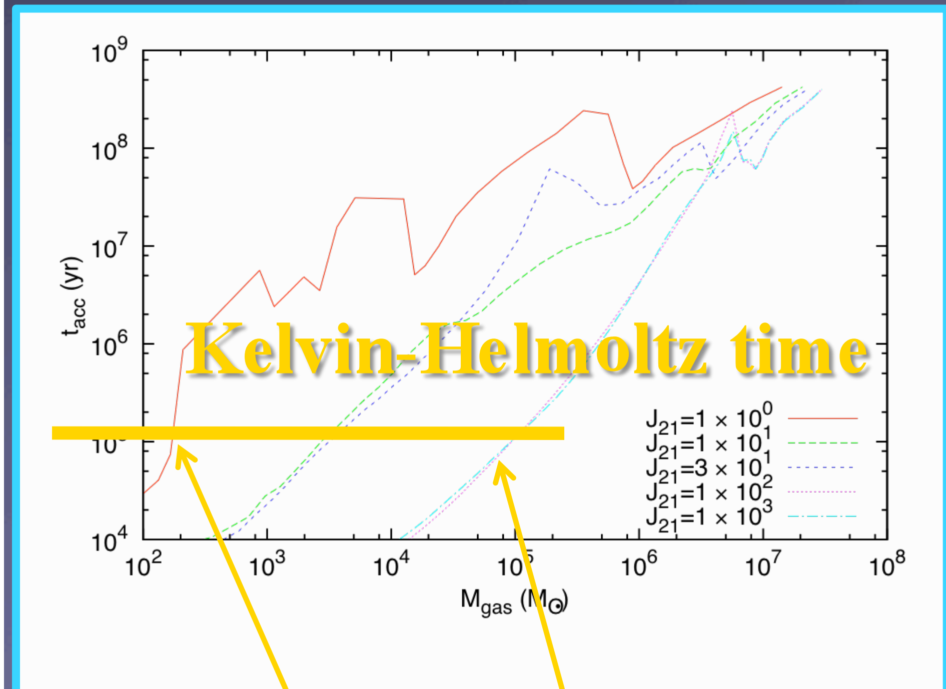
Normal stars (soft UVB)

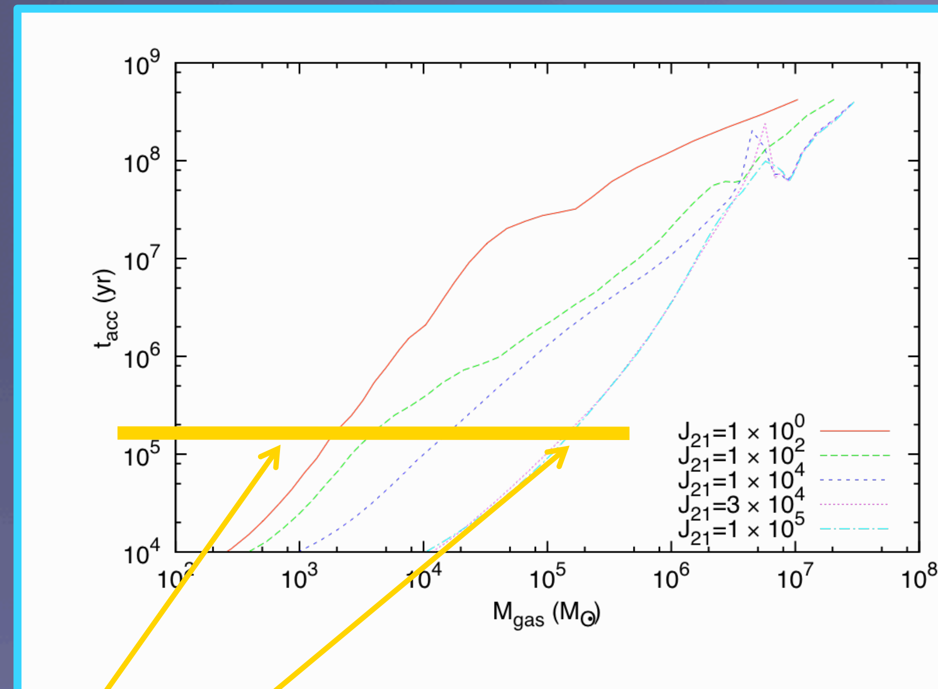


Pop III stars (hard UVB)

SMBH by direct collapse possible (?)

Shang, Bryan & Haiman (2010)





$10^{2\text{-}3}$ $M_\odot$ Pop III star Abel et al.; Bromm et al.; Yoshida et al.

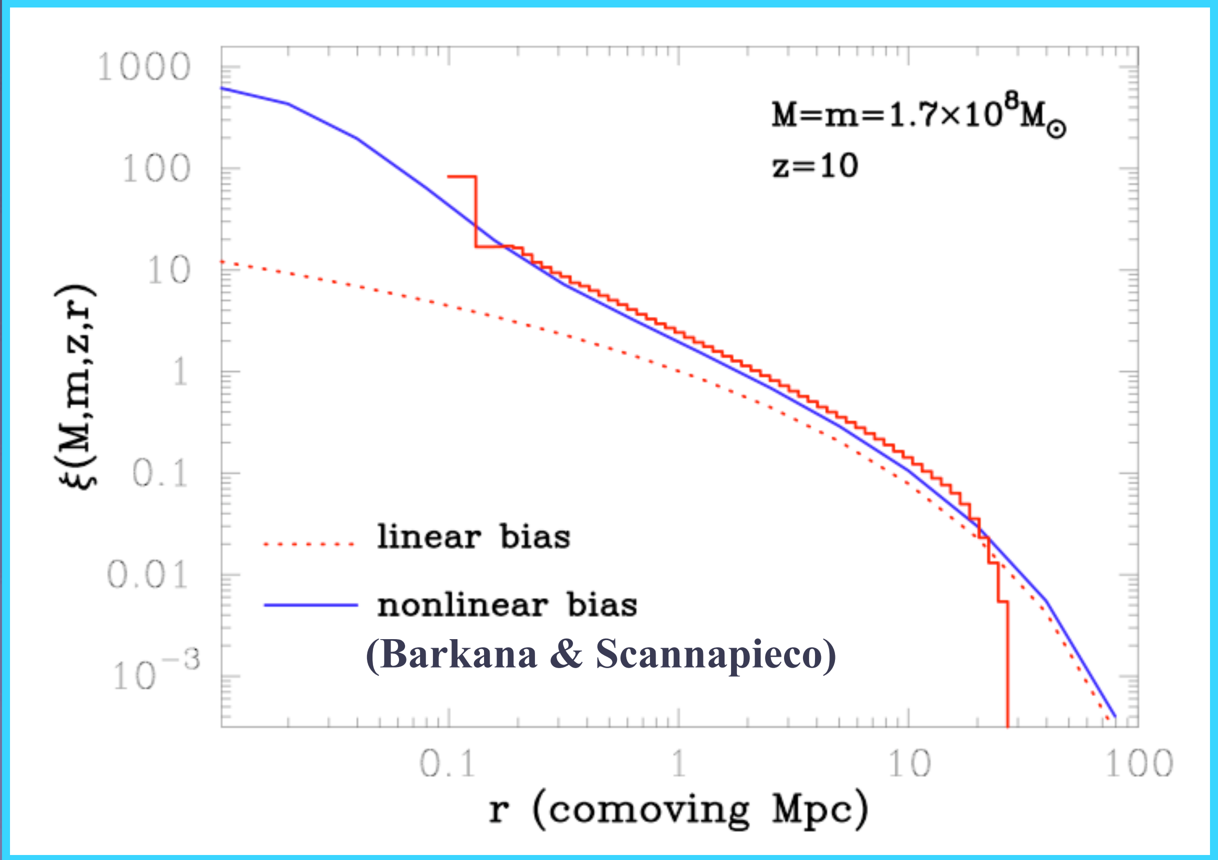
10^5 $M_\odot$ supermassive star/BH Fuller, Woosley & Weaver (1986)

Can we have sufficiently large UV flux?

Dijkstra, Haiman, Mesinger & Wyithe (2008)
Ahn et al. (2009)

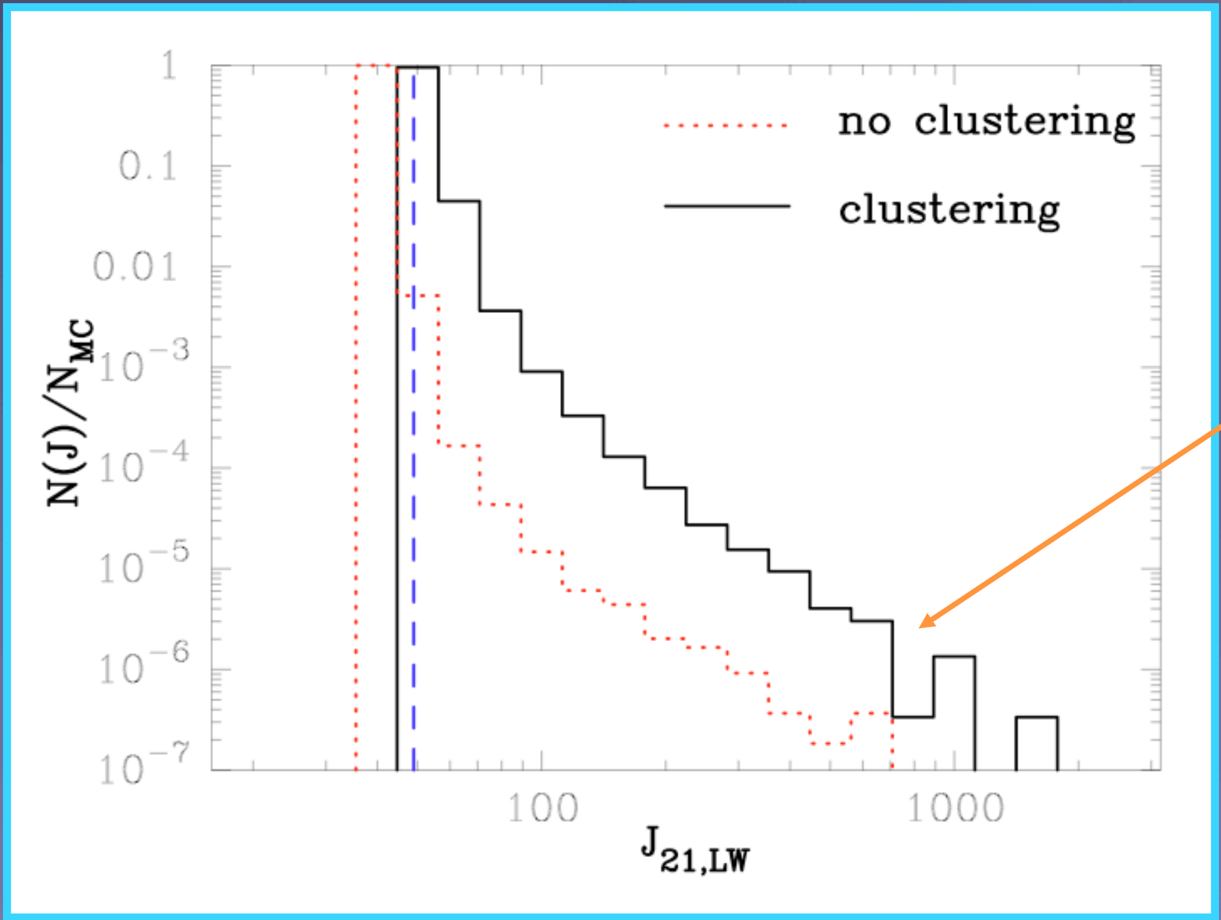
Need: $J(LW) \gtrsim 10^3 \times 10^{-21}$ erg s cm^{-2} Hz^{-1} sr^{-1}

Factor of ~100 above mean. Must come from nearby sources. High-redshift halos are strongly clustered



Compute UV Flux PDF Sampled by Halos

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



Dijkstra, Haiman
Mesinger & Wyithe (2008)
Ahn et al. (2009)

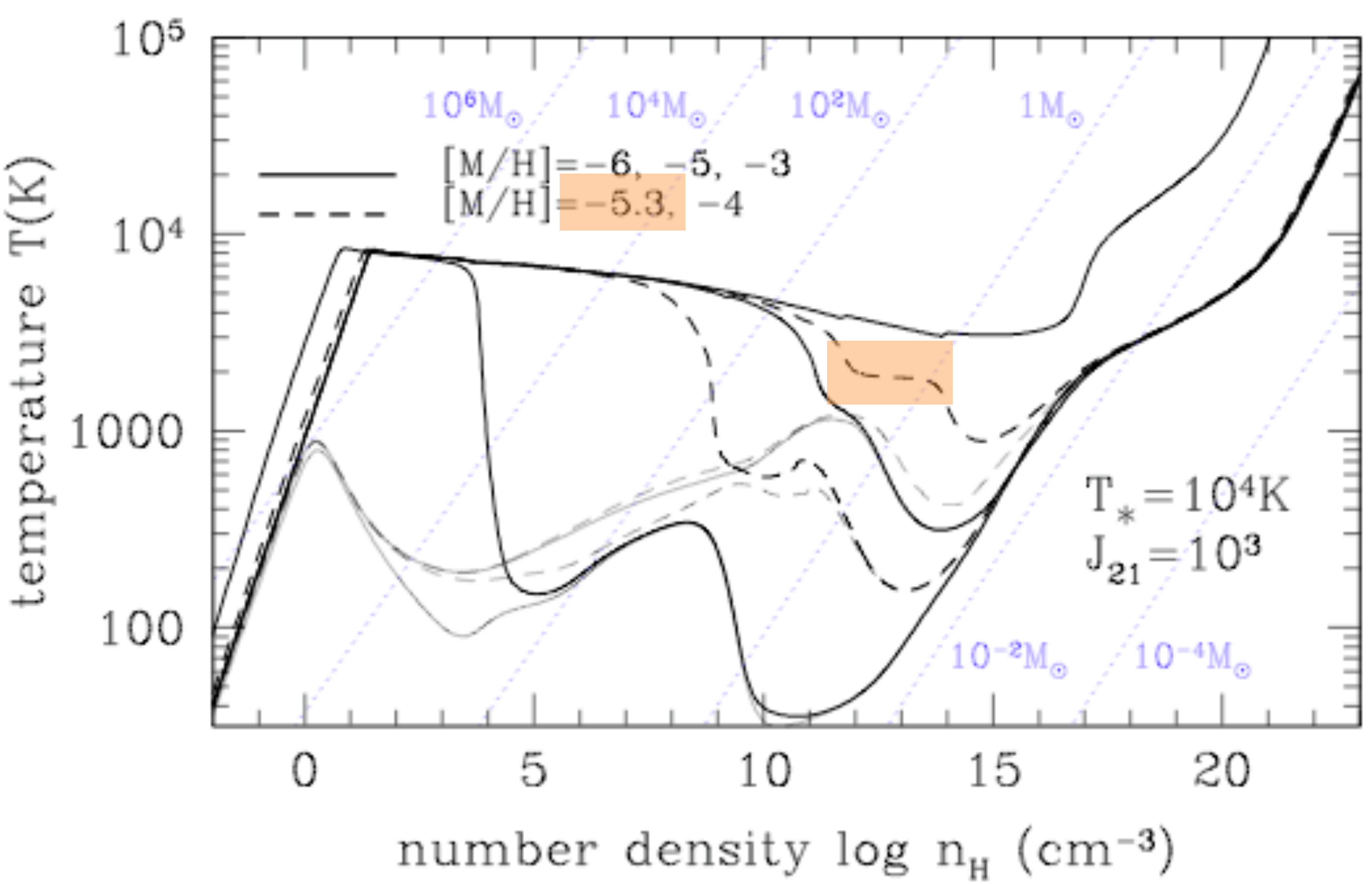
1 in ~10^7 halos has a close (≲10 kpc) bright and synchronized neighbor, so flux is ~ 30 × mean

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

Direct SMBH formation: impact of metals

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

Omukai, Schneider & Haiman (2008)



Direct SMBH formation in close halo pairs?

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

- First condition may be satisfied in rare case of a very close, bright & synchronized neighbors (Dijkstra, Haiman, Wyithe & Mesinger 2008)

- First condition eased for normal IMF (H^--dissociation) (Shang, Bryan & Haiman 2010)

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

- Gas with trace metals forms dense cluster of low-mass stars → *collapse to IMBH of $10^{2\text{-}3}$ $M_\odot$* (Omukai et al. 2008)

Future Detections

1. SMBHs with $<10^6 M_\odot$ should be directly detectable at z~10

    (i) optical/IR with JWST (~10 nJy at few μm)

    (ii) radio with EVLA, SKA (~1-10μJy at 1-10 GHz)

    (iii) X-rays: CXO deep fields correspond to $\sim 10^8 M_\odot$ (IXO 2021)

2. SMBHs cannot dominate re-ionization at z~6 (would overproduce unresolved soft XRB). **(Dijkstra et al. 2004; Salvaterra et al. 2005)**

    However, accreting BHs can cause “pre-ionizaton” at z>10

    → *topology: swiss-cheese vs. nearly uniform due to X-rays.*

    power spectrum (21cm, kSZ) depressed on scales < m.f.p.

3. LISA event rates (z>6): 0 to ~30 event/yr/dz

Quasar BH Signatures in 21cm

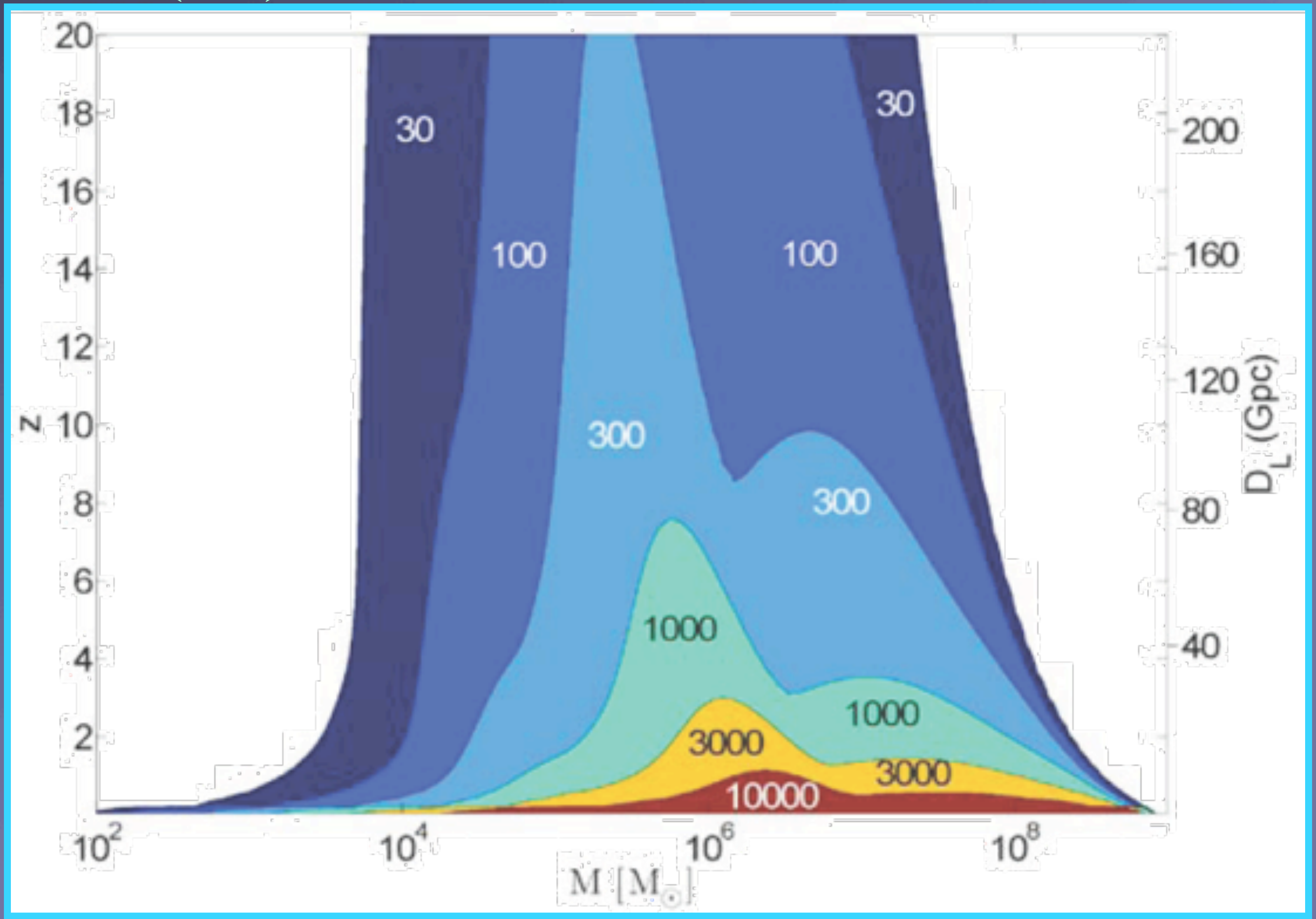
- Blurred HII bubble boundary for hard sources
  - suppression of 21cm power spectrum
    Iliev, Shapiro, Furlanetto et al.
  - parameter-fitting through linear perturbation approach
    Zhang, Hui & Haiman (2007)
  - imaging individual bubbles: diagnose quasars, constrain spectrum **Kramer & Haiman (2008); Zaroubi & Silk (2005)**

- Fossil quasar bubbles
  - 'grey bubbles', modify power spectra
  - constrain quasar duty cycle and clumping
    Furlanetto, Haiman & Oh (2008)

- Finite-speed-of light distorts the shapes of quasar bubbles
  - observable as an anisotropy in the power spectrum (MWA) ?
  - diagnose quasar contribution, constrain abundance/lifetime
    Sethi & Haiman (2008)

LISA sensitivity

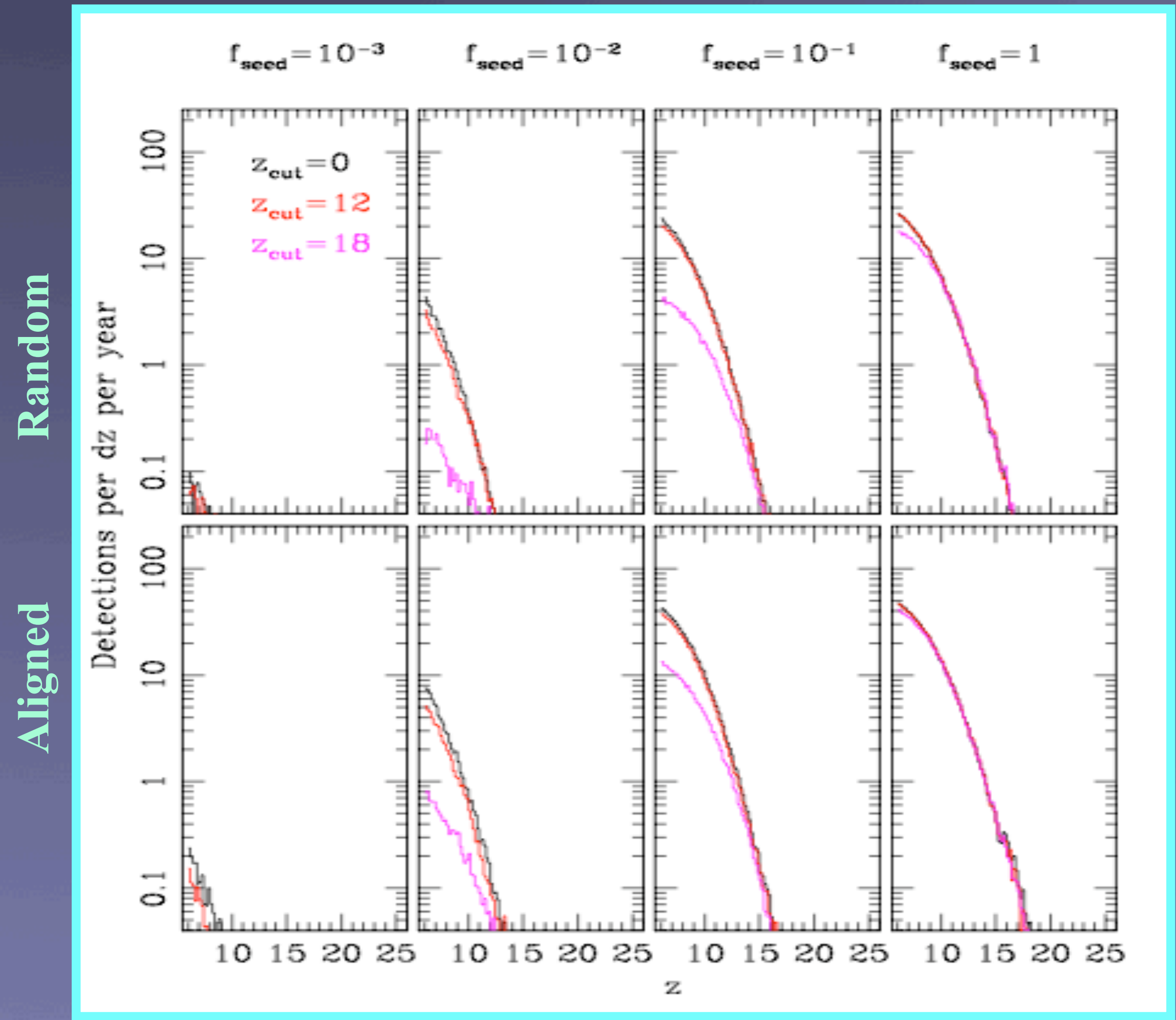
Jennrich (2010)



LISA event rate: M-σ model

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

Tanaka & Haiman (2009)



- Internal feedback regulates BH mass
  set to maintain extrapolated M-σ relation

- Growth driven by mergers:
  slow accretion, tracks halo growth on Hubble time

- Many ejections
  can exceed half ρ_{BH}

Conclusions

1. Explaining z=6 quasar SMBHs with $\sim 10^9 M_\odot$ is a challenge, requiring optimistic assumptions, unique to these objects

   (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, or

   (iii) global instabilities and supersonic turbulence (?)

2. Extra challenge: not to overproduce number of $\sim 10^{5\text{-}6} M_\odot$ SMBHs. (i) seed formation stops at ultra-high z~25 ?

   (ii) internal feedback always maintains M_{BH} - σ relation?

3. Direct detections (optical/radio/X-ray) down to $\sim 10^{5\text{-}6} M_\odot$ at $z=10$

   0-30 LISA merger events/yr + Indirect reionization signatures (21cm)

Le Fin