The Formation of Supermassive Black Holes at High Redshift

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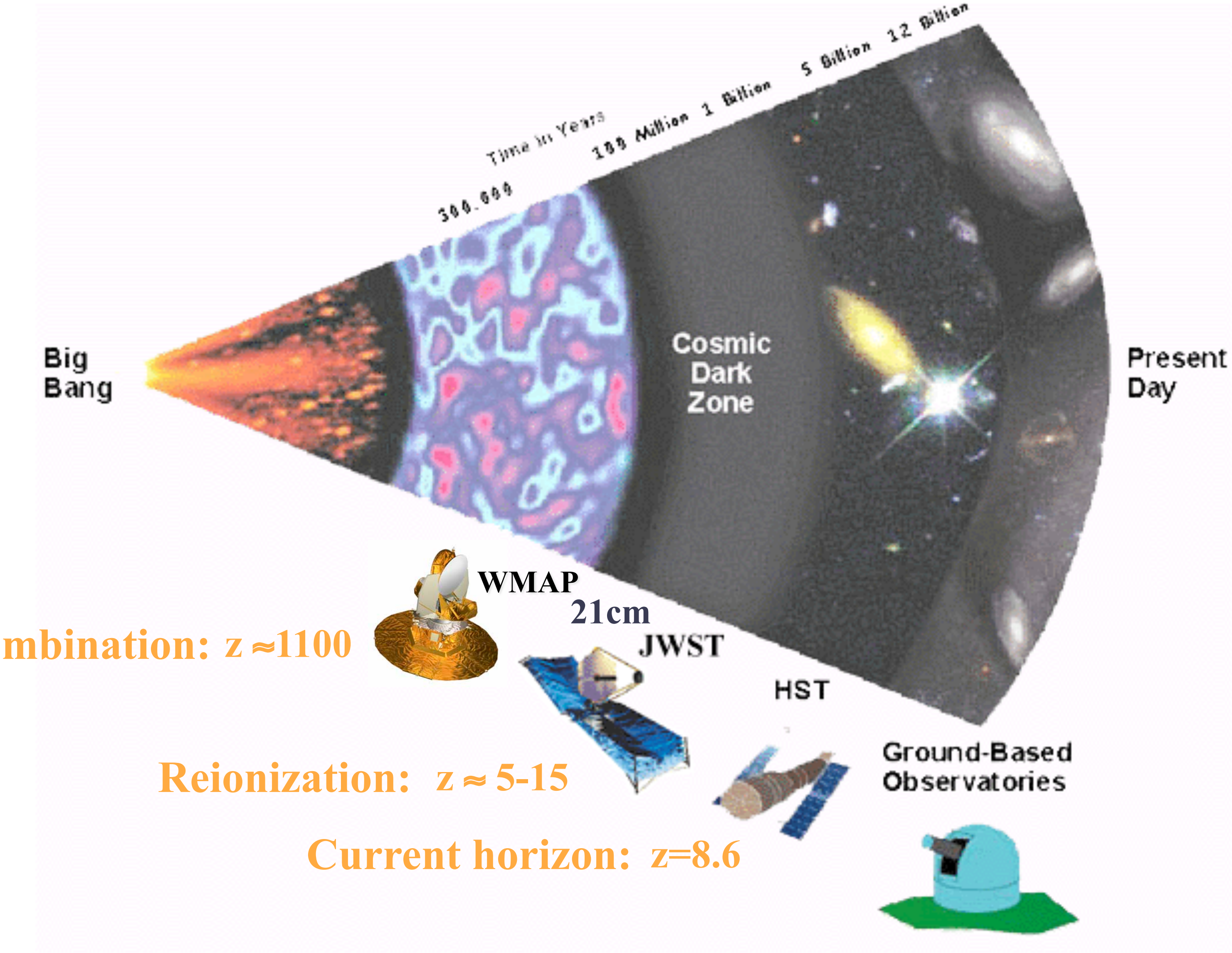
Outline

- High-redshift quasars – observations [6]
- High-redshift structure formation:

  BH remnants of the first stars – theory [6]
- Using stellar-mass seed BHs to build SMBHs [7]
- Rapid direct collapse in more massive halos [9]
- Probing SMBH assembly with future observations [3]

The Cosmic Dark Age

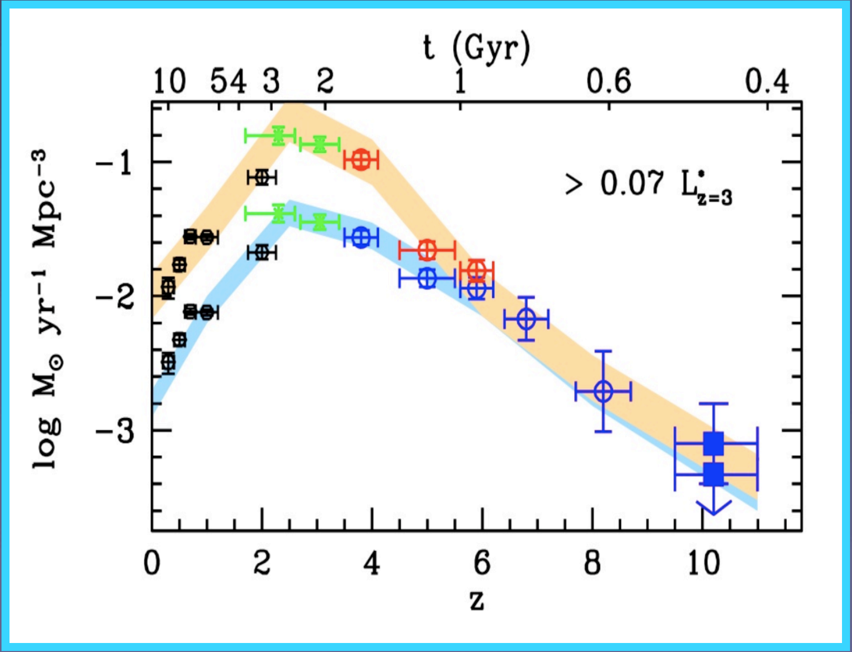


(Re)combination: z ≈1100

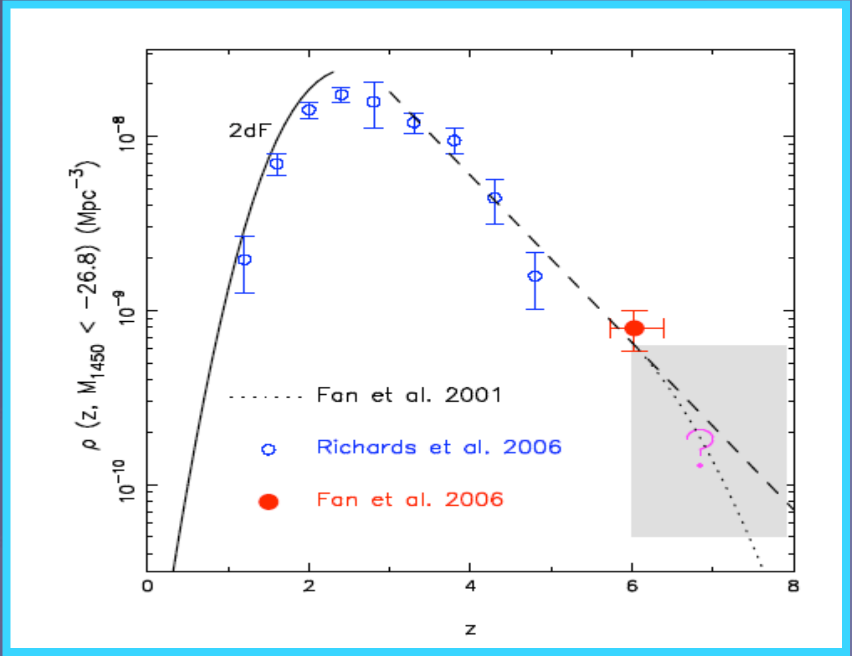
Reionization: z ≈ 5-15

Current horizon: z=8.6

Cosmic Evolution of Galaxies and Quasars



Hubble Ultra Deep Fields
Bouwens et al. 2010
Illingworth et al. 2010



SDSS + CFHQS
Fan et al. 2006
Willott et al. 2010

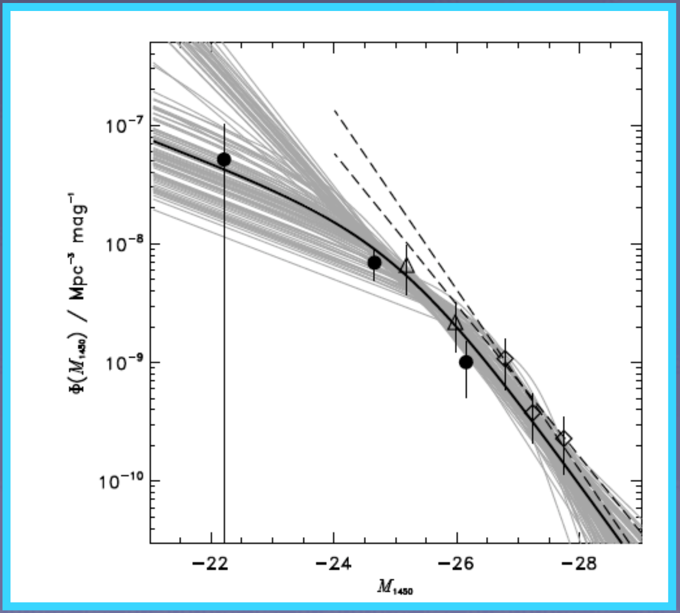
Abundance of z>6 Quasars

- Rare (“5σ”) objects:

  10 found in SDSS at z>6
  20 in CFHQ + few others

- Tip of the iceberg (?):

  Space density ~1 Gpc^{-3}

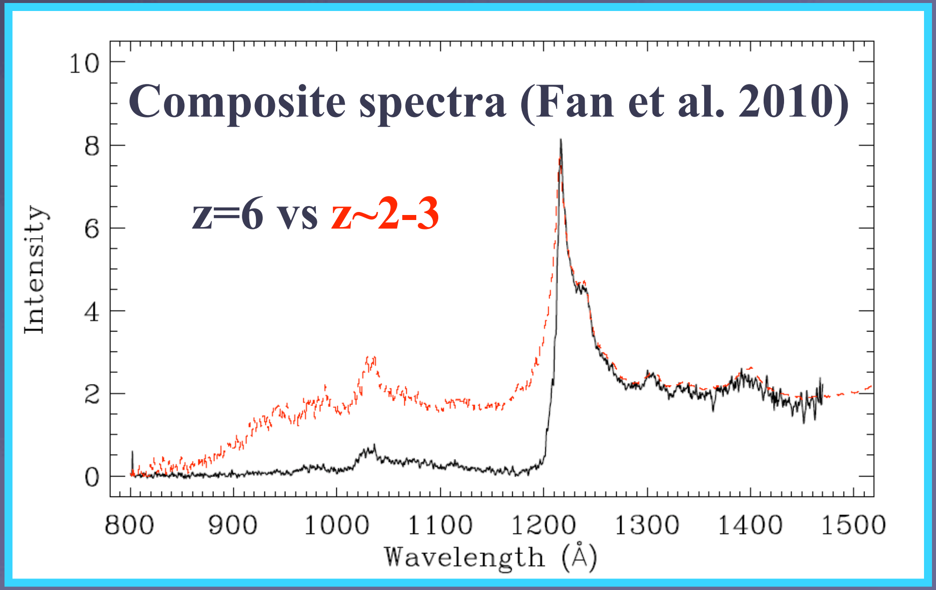


Willott et al. 2010

- Record: z=7.08 (t=0.77 Gyr – 5% of current age; UKIDSS)

Properties of z>6 Quasars

- As fully developed as their z=2.5 counterparts:
  host galaxies already polluted with heavy elements



- Mass estimates

$$M_{bh} = L_{obs} / L_{Edd} \approx 10^{9\text{-}10}\, M_{\odot} \quad \text{(Eddington luminosity)}$$

$$M_{halo} \approx 10^{12\text{-}13}\, M_{\odot} \quad \text{(match space density)}$$

Timescale for BH growth

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

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

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

Eddington accretion:

$L_{edd} = \varepsilon\,(dM/dt)\,c^2$ $\quad\varepsilon$ ~ few percent from ISCO

e-folding (Edd) time:

$M/(dM/dt) = 4 \times (\varepsilon/0.1)\,10^7 \mathrm{yr}$

No. e-foldings needed

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

Age of universe (z=6.43)

8×10^8 yr ✓

Must start early – accretion rate must keep up w/ Eddington

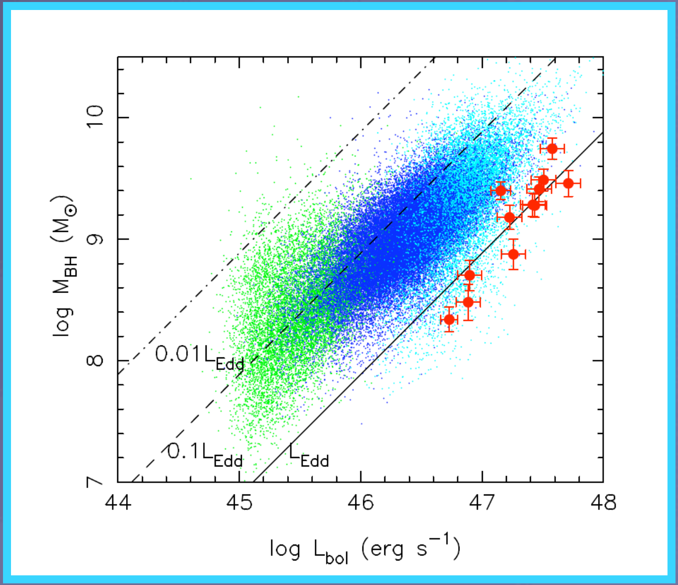
[obvious alternatives: (1) grow faster or (2) merge many BHs]

Can we be fooled?

- **Short answer: NO. Several $10^9\,M_\odot$ masses are here to stay.**

- **Gravitational lensing? No.** **(Keeton, Kuhlen & Haiman 2004)**
- **Strong beaming? No.** **(Haiman & Cen 2002; Willott et al. 2003)**

- **Empirical measurement of L/L_{edd}**
  from CIV and MgII line widths, calibrated from local reverberation mapping [$GM/R = \text{const}\ \sigma^2$]
  (Vestergaard 2004; Kurk et al. 2007 Jiang et al. 2009)



… and if $L >> L_{edd}$ then $dM/dt = L/\varepsilon c^2$ is large
→ BH anyway accretes $4 \times 10^9\,M_\odot$ in << $4 \times (\varepsilon/0.1)^{-1}\ 10^7$yr

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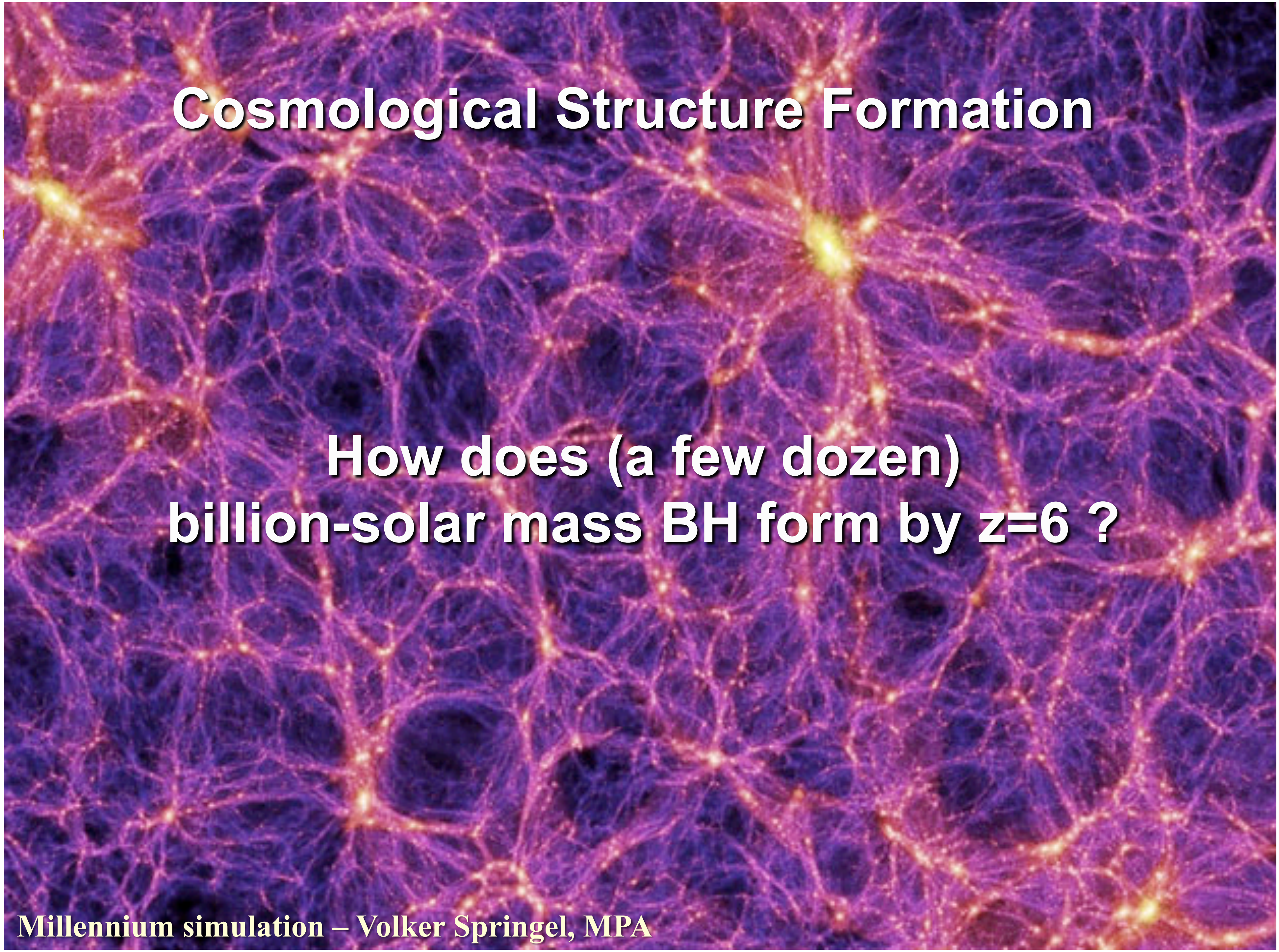
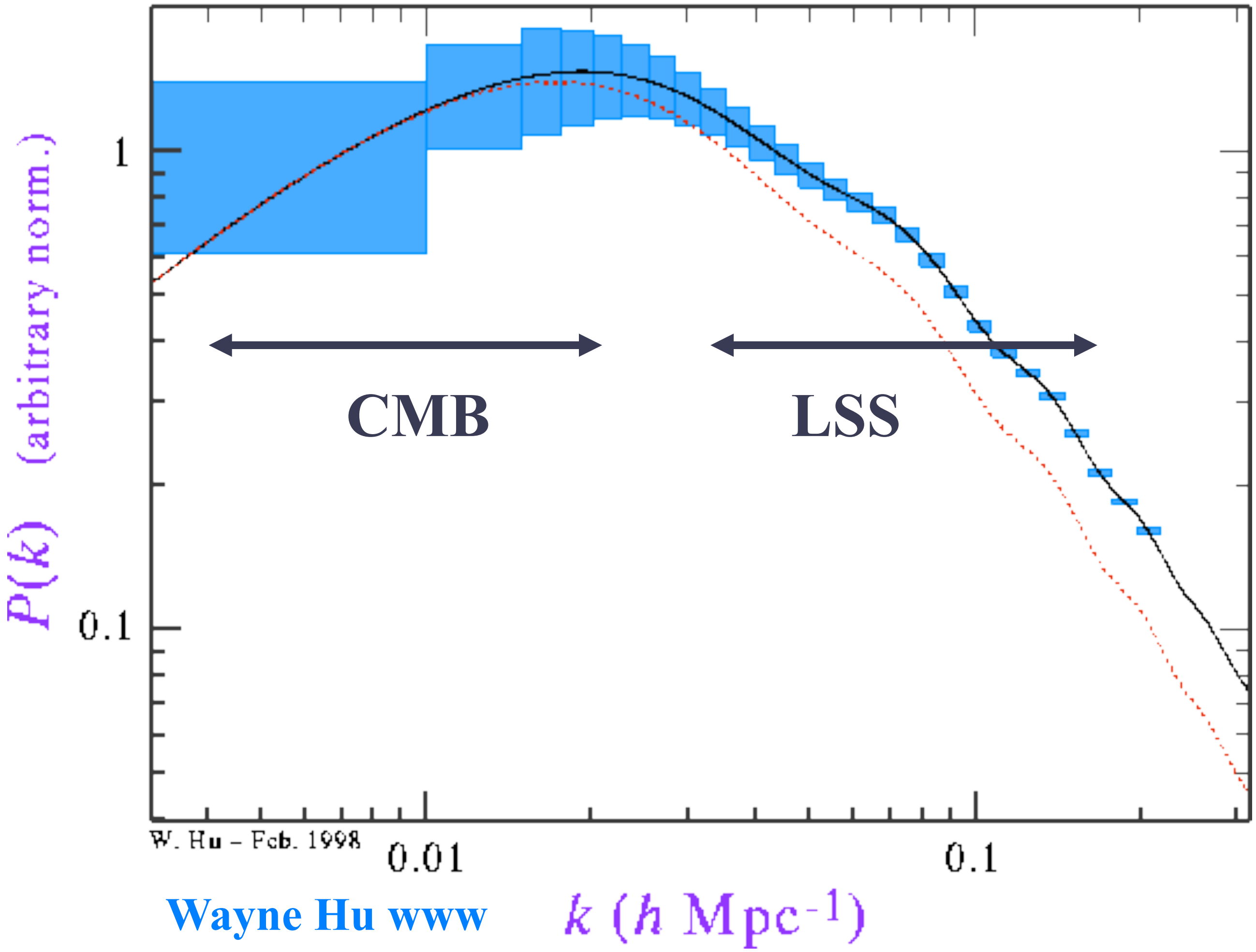
Cosmological Structure Formation



How does (a few dozen)
billion-solar mass BH form by z=6 ?

Millennium simulation – Volker Springel, MPA

Seed Fluctuations on Small Scales



Wayne Hu www

extrapolation
by a factor of
about 100 in
linear scale

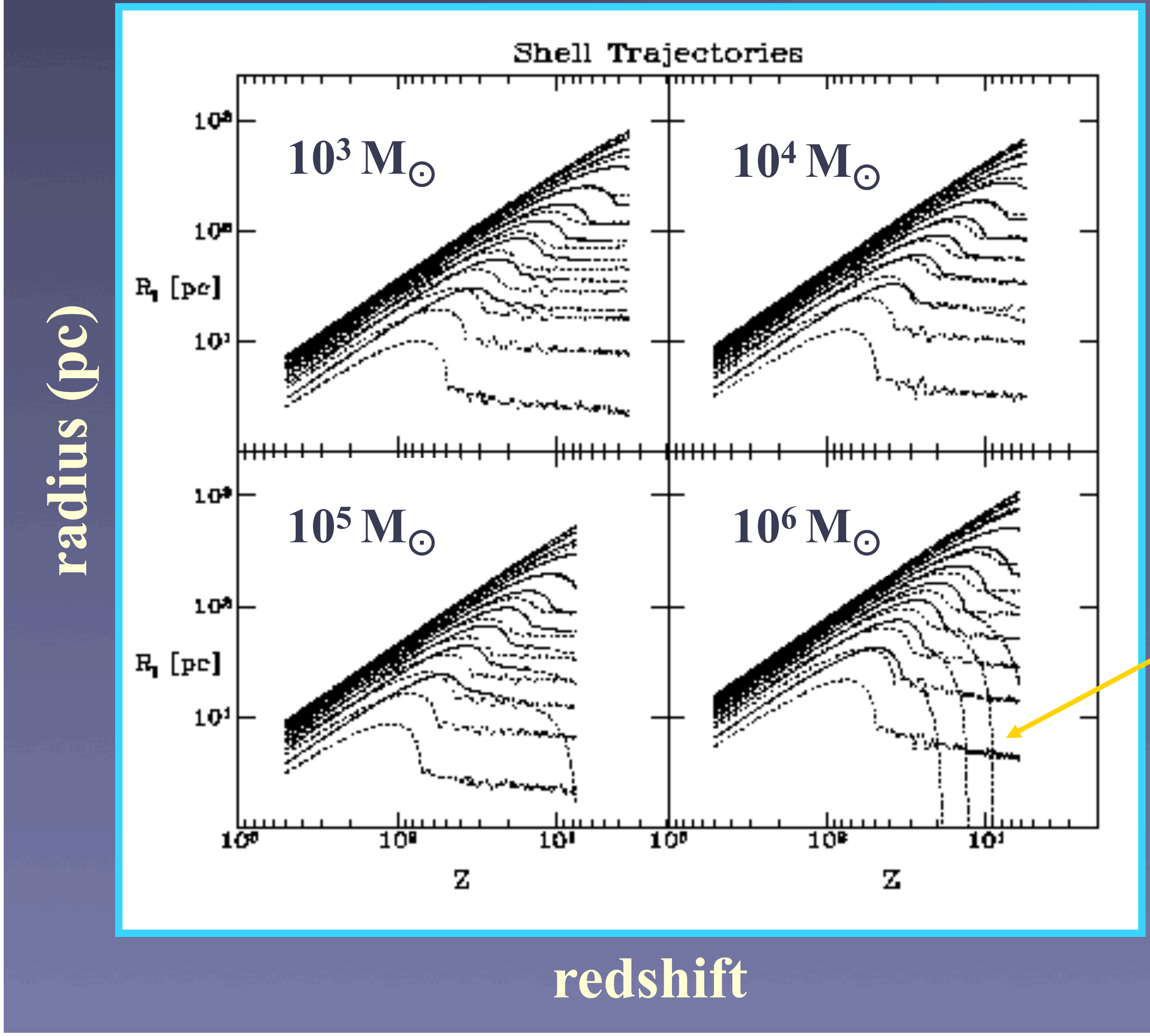
→

Dark Age

mass function
of DM halos
directly tested
in simulations at
$z=30$; $M=10^6\ M_\odot$

e.g. Lukic et al. (2007)
Reed et al. (2007)

Collapse of Spherical "Minihalo" in Isolation



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

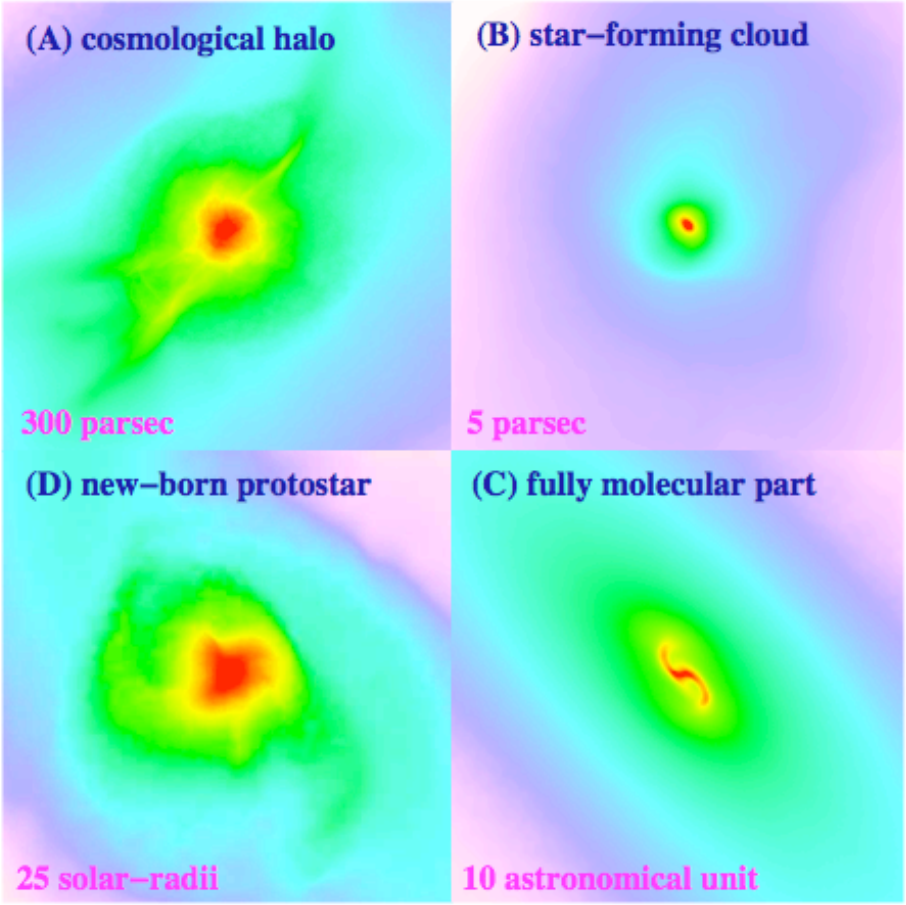


Fig. 1: Projected gas distribution around the protostar. Shown regions are, from top-left, clockwise, (A) the large-scale gas distribution around the cosmological halo (300 pc on a side), (B) a self-gravitating, star-forming cloud (5 pc on a side), (C) the central part of the fully molecular core (10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

Abel et al. (2002), Bromm et al. (2002)
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

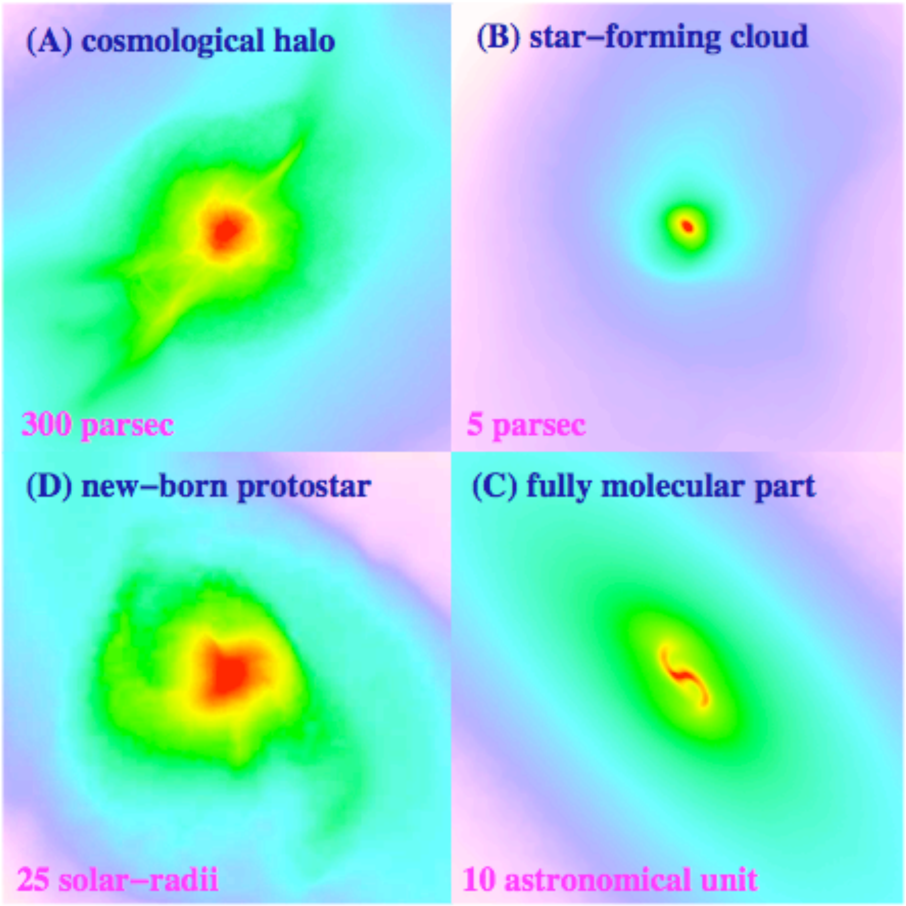
$n \approx 10^{21}\ \mathrm{cm}^{-3}$

$M_* \approx 0.01\, M_\odot$

Final stellar mass:

$M_* \sim 100\, M_\odot$

Computation?
3D ~~Simulation~~ of a Primordial Gas Cloud



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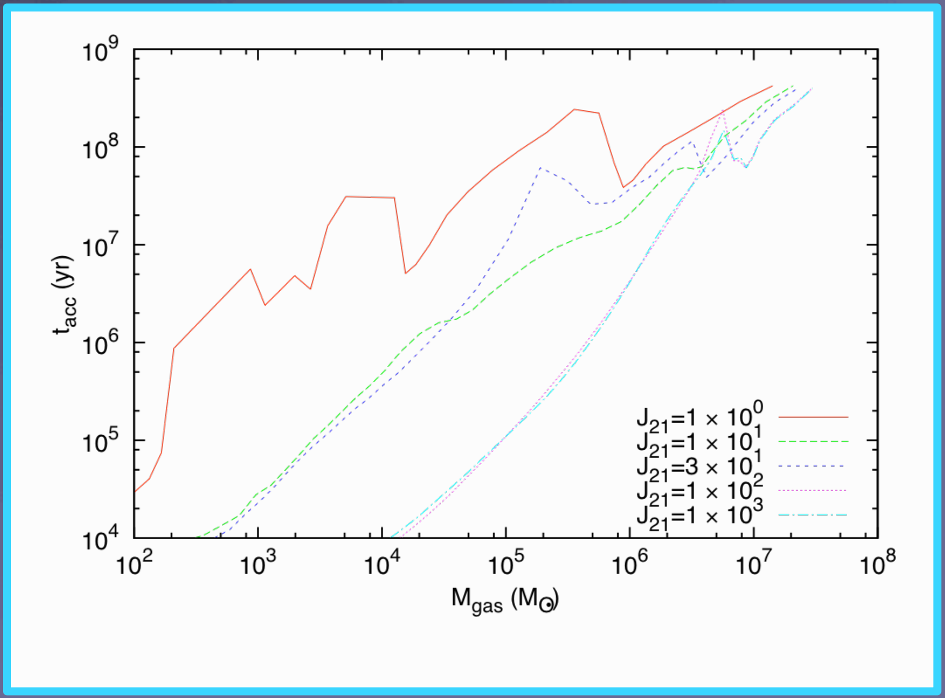
Final Stellar Mass?

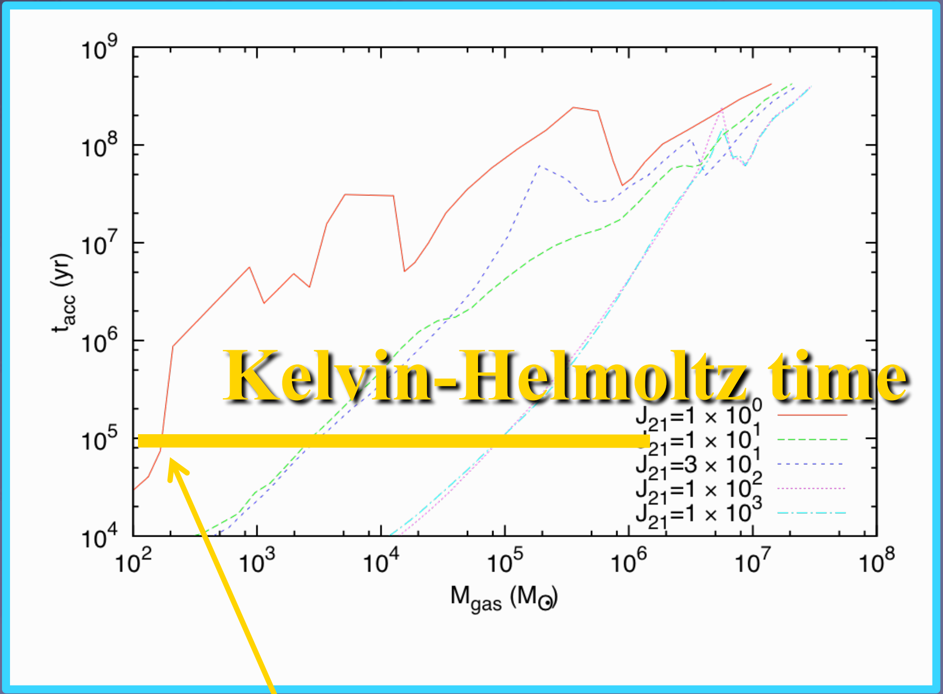
Shang, Bryan & Haiman (2010)



$$dM/dt = \text{few} \times 10^{-3}\ M_\odot\ \text{yr}^{-1}$$

Final Stellar Mass?

Shang, Bryan & Haiman (2010)



Kelvin-Helmoltz time

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

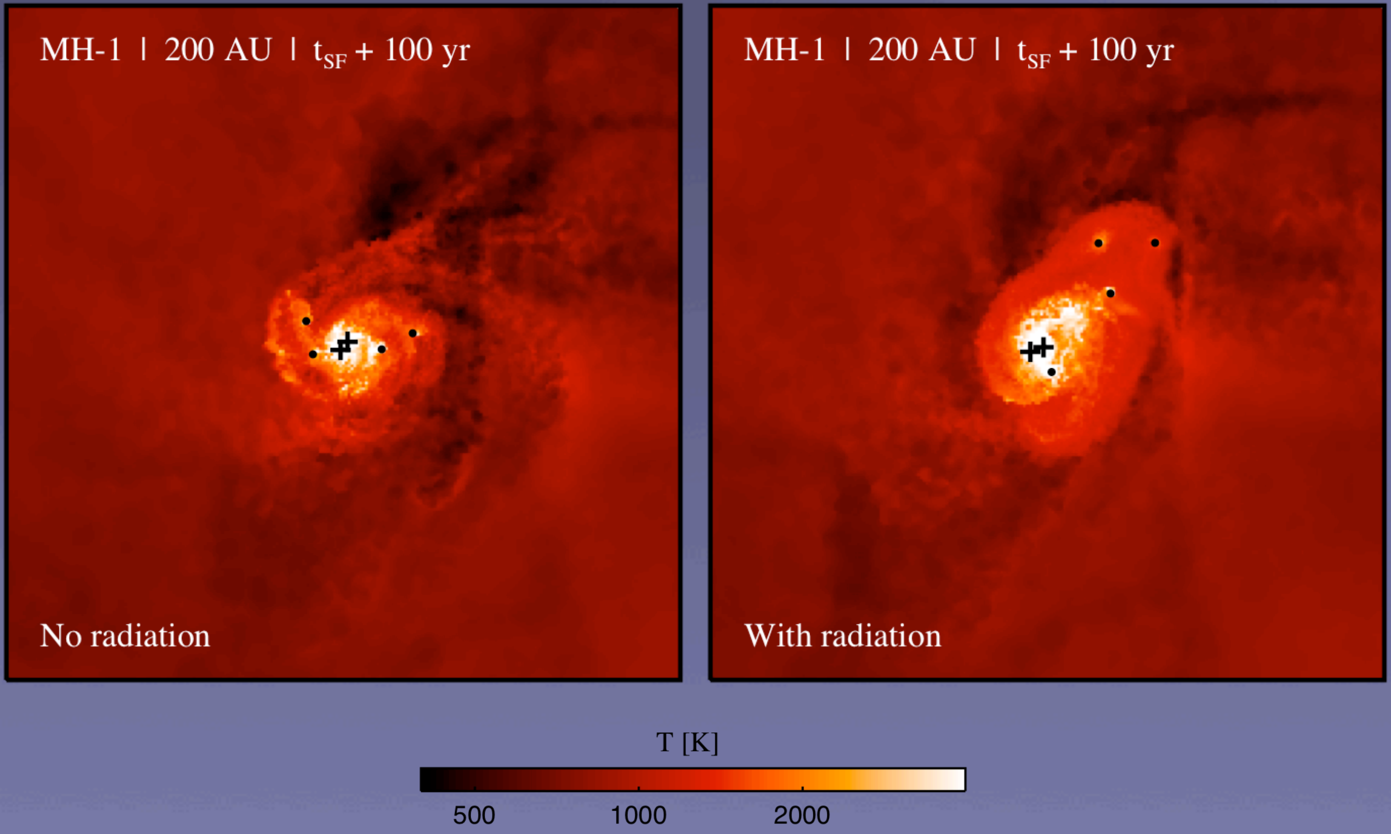
Or…Fragmentation?

Using sink particles to follow post-1st-clump evolution

~10 fragments with masses of 0.1-10 $M_\odot$

Driven by turbulence and disk self-gravity?

Greif et al. (2011); also Prieto et al. (2011), Clark et al. (2010); Stacy et al. (2010)



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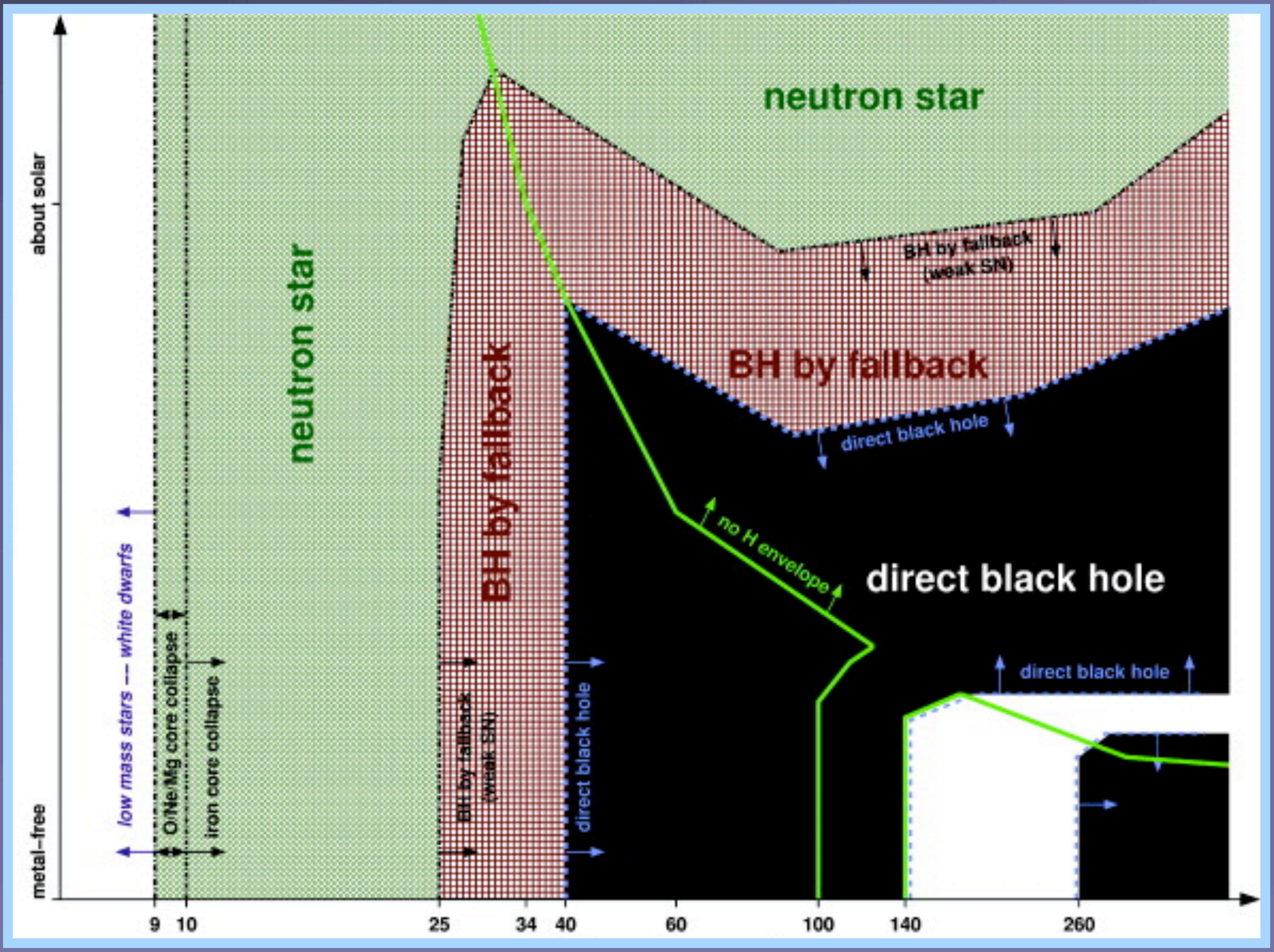
Remnants of Massive Stars

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



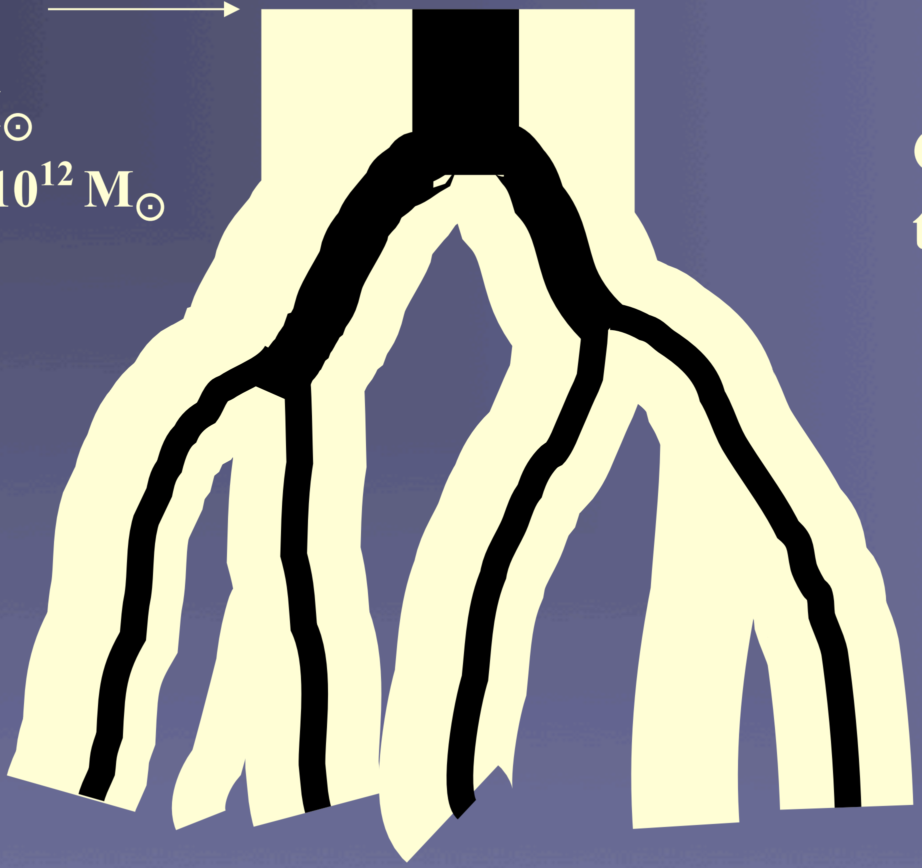
$Z=Z_\odot$

metalicity

$Z=0$

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

Growing SMBHs by Accretion + Mergers



z~6

M_{bh}= few × $10^9\ M_\odot$

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

CDM merger tree

M_{halo} ~$10^6\ M_\odot$

v_{esc} ~ few km/s

z~30

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); Pelupessy et al. 2007; Sijacki et al. (2009)

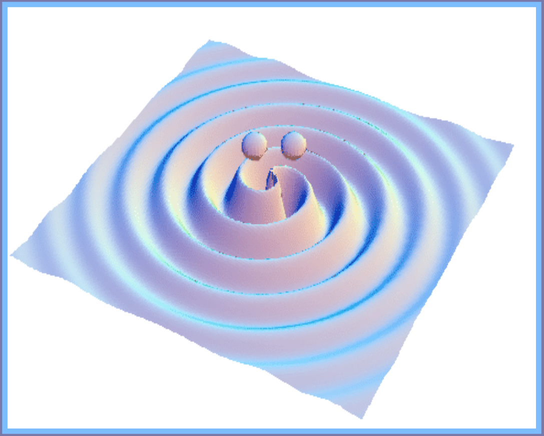
Growing SMBHs by Accretion + Mergers

Tanaka & Haiman (2009)

Construct Monte-Carlo DM halo merger trees from $z=6$ to $z>40$
$10^8 M_\odot \leq M_{halo} \leq 10^{13} M_\odot$ (M_{res} =few $10^5 M_\odot$; $N \sim 10^5$ trees)

- **Fraction of minihalos forming stellar BH seeds ?**
  - **f_{seed}** depends on *IMF* and *feedback* **(e.g: $H_2+\gamma \rightarrow H_2^{(*)} \rightarrow H+H+\gamma$)**
  - $M_{seed} \sim 10\text{-}100\ M_\odot$
- **Time-averaged mass accretion rate ?**
  - duty cycle **"f_{duty}"** for accretion (**f_{duty}**~ 1.0)
  - maximum of Bondi ($\propto \rho M_{BH}^2/c_s^3$) and Eddington rate
- **What happens to BHs when halos merge? Gravitational Recoil ?**
  - **profile** either $\rho \propto r^{-2.2}$ (cool gas) or flat core (adiabatic)
  - at merger, draw random v_{kick} (Baker et al. 2008)
  - **spin orientation**: random or aligned
  - follow kicked BH trajectory - damped oscillation (gas drag)

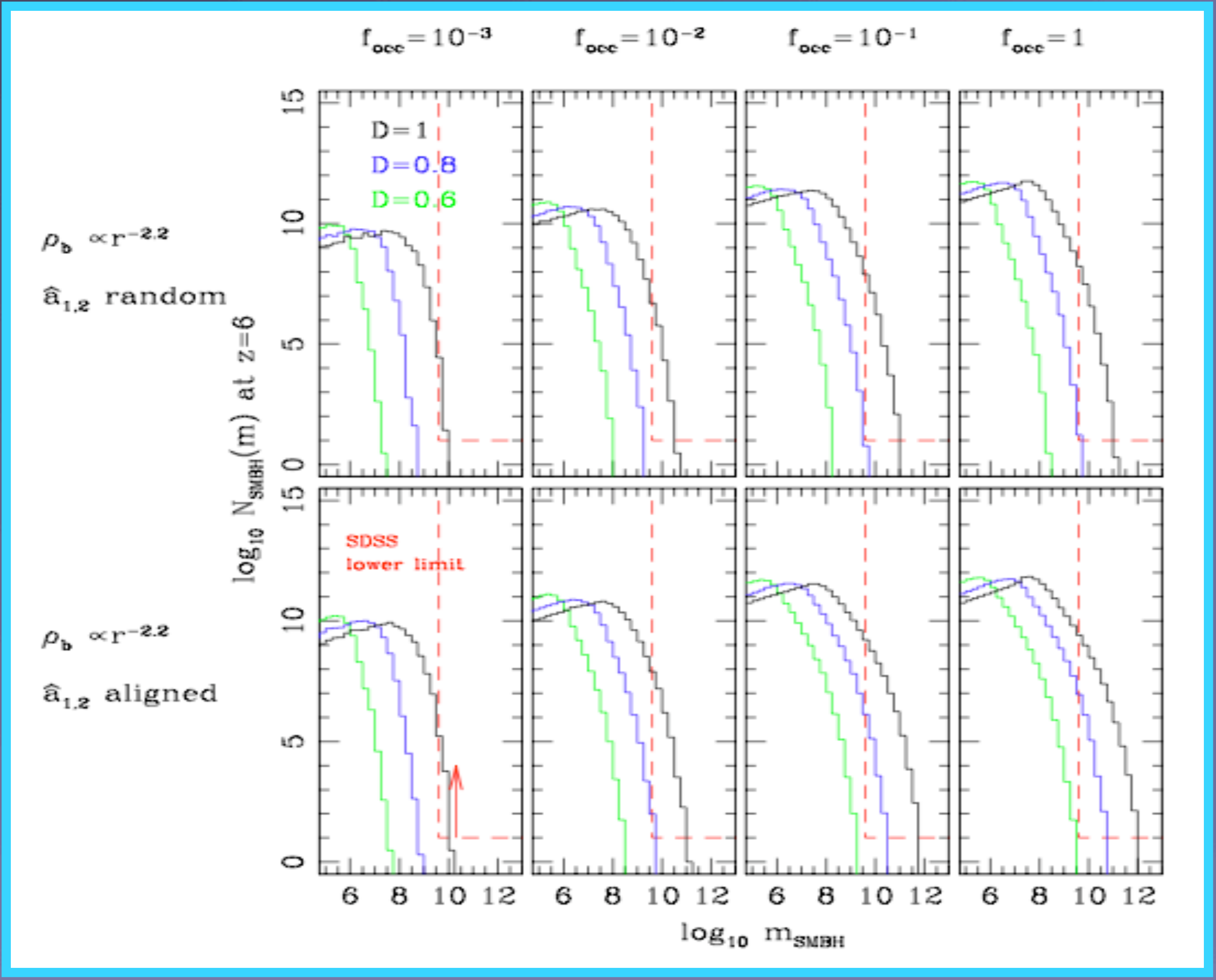
A possible obstacle: gravitational recoil



- **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)**
  — v(kick) ≤ 1 km/s for unequal BH masses ($q < 0.01$)
- **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?**

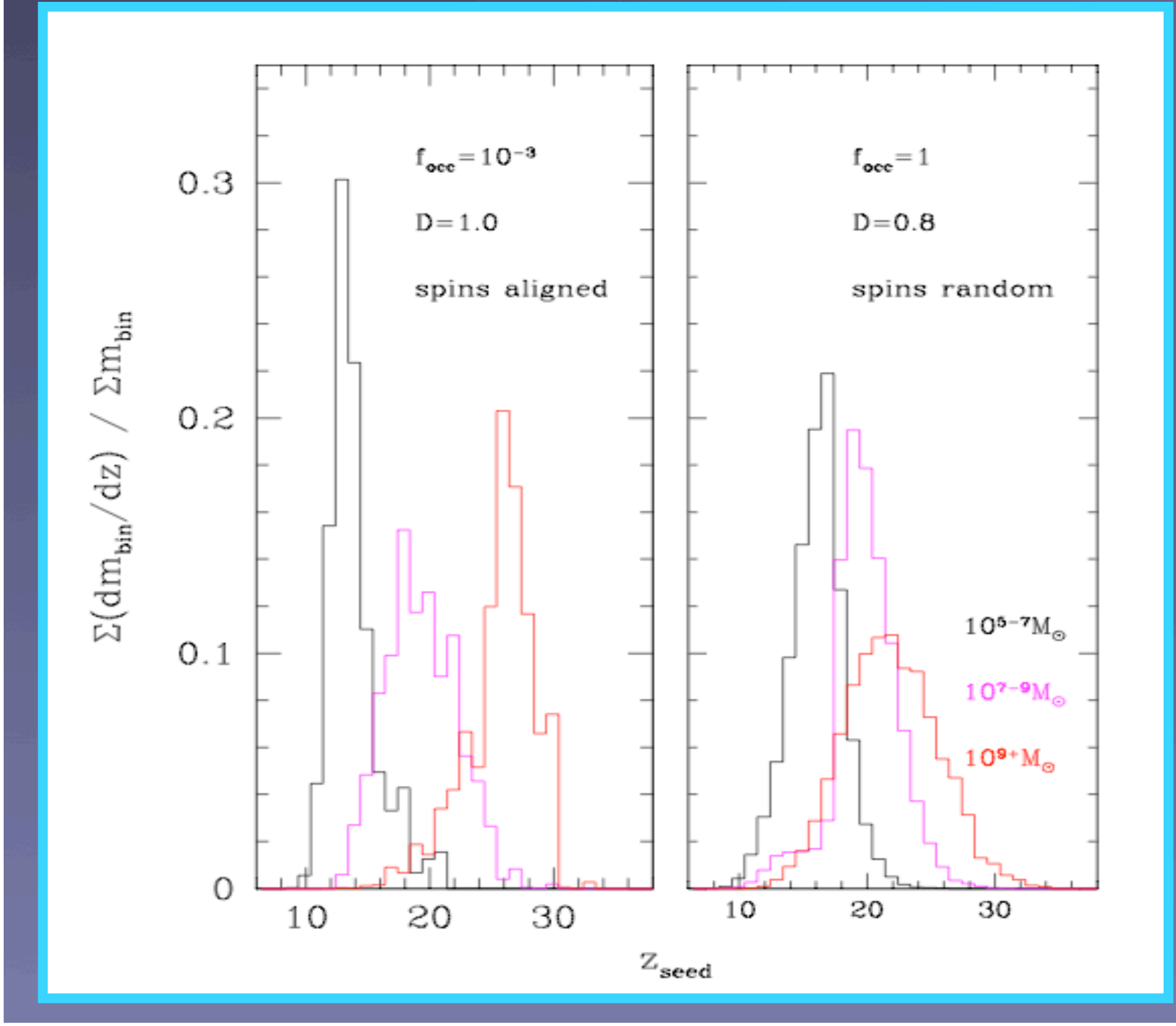
SMBH mass function at z=6

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:
$\rho_{tot} \approx 4 \times 10^5\ M_\odot \mathrm{Mpc}^{-3}$

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})

SMBHs from stellar seeds: Results

- (i) density cusp
  (ii) $f_{seed} \gtrsim 10^{-3}$
  (iii) $f_{duty} \gtrsim 0.8$ $\Big\}$ very 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~20

- H2-dissociation by soft UV? X-ray heating from BHs? Growth self-regulates?

- 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}

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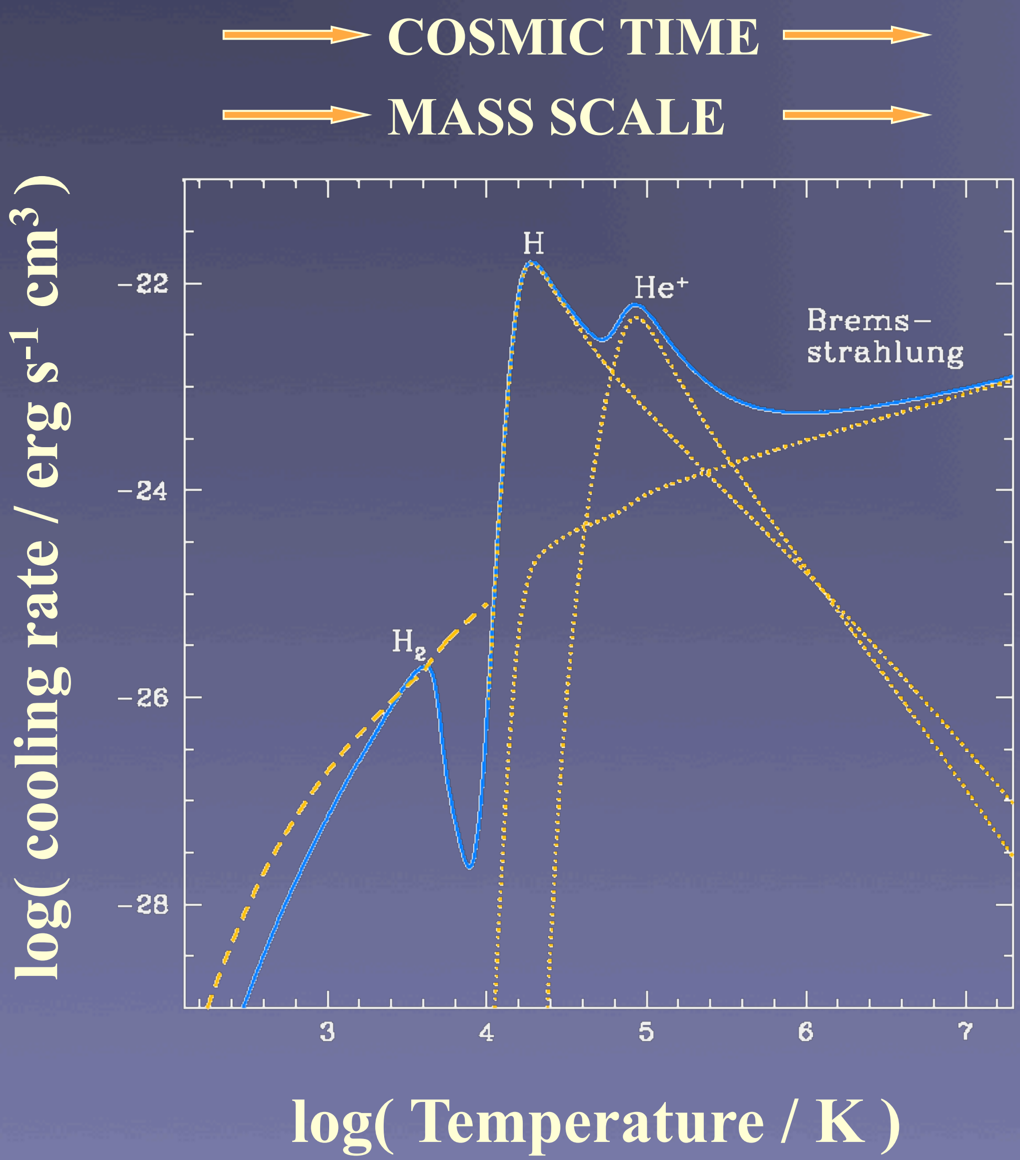
Alternative: Direct Gas Collapse

- **RAPID GAS INFALL**
  - must exceed Eddington rate **2×10^{-2} $(\varepsilon/0.1)^{-1}(M_{BH}/10^6 M_\odot)$ $M_\odot$ yr^{-1}**
- **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: popIII stars as in mini-halos)
- **LAST 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)*
  - sims to ~0.1pc **(Mayer et al. 2009, Levine et al. 2008; Hopkins & Quataert 2010)**

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



cf. Halo virial temperature:

$$T_{\rm vir} = 10^4 \left(\frac{M}{10^8 M_\Theta}\right)^{\frac{2}{3}} \left(\frac{1+z}{11}\right) {\rm K}$$

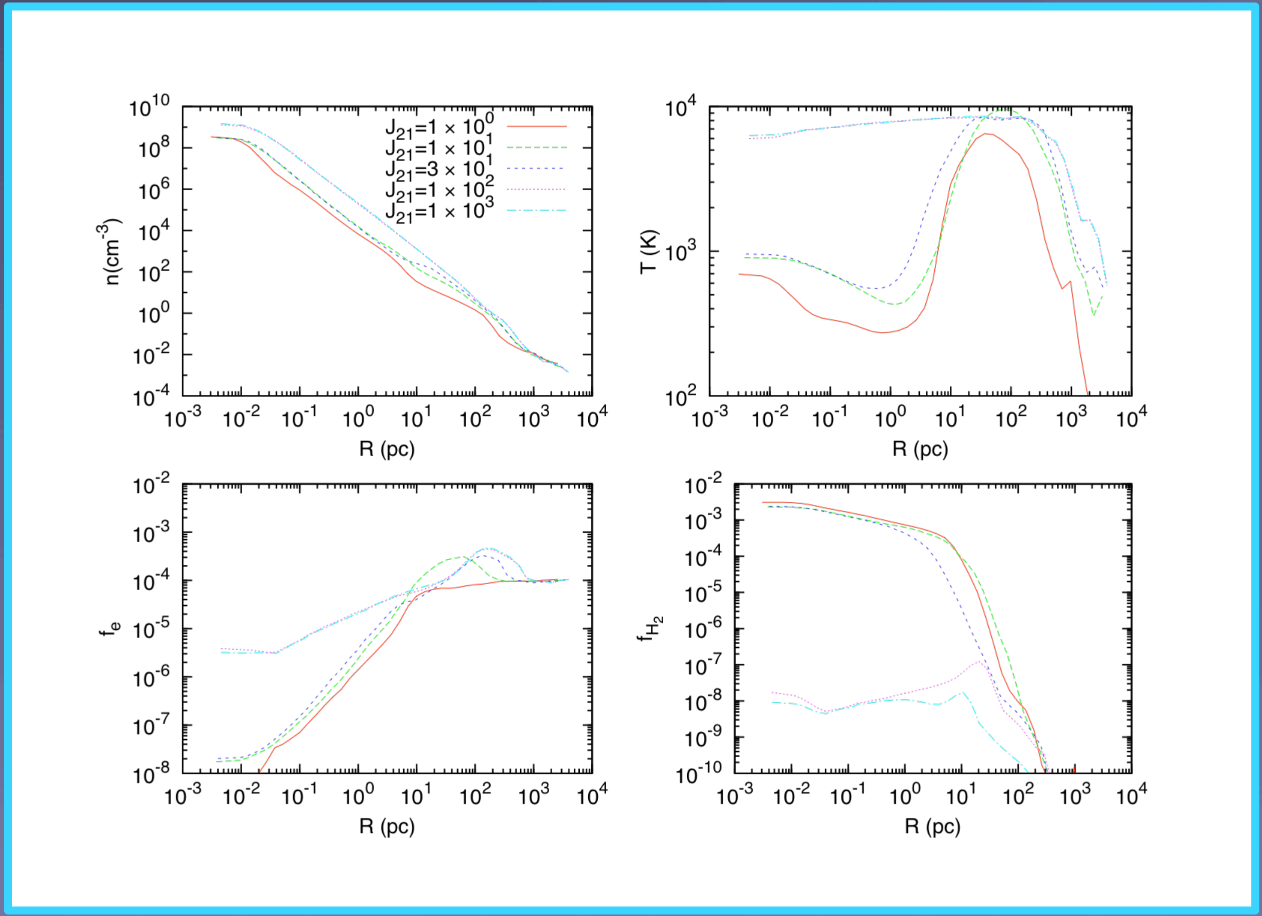
Gas collapses to 10^5-10^6 $M_\odot$ SMBH directly, or via a supermassive star or a dense stellar cluster

- gas driven in rapidly
  (deep potential)
- no fragmentation
  (avoid cooling)
- shed angular momentum
  (global instability)

Avoiding H_2 – cooling with UV flux

Shang, Bryan & Haiman (2010)

- Simulations with enzo: 3 halos with M ~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

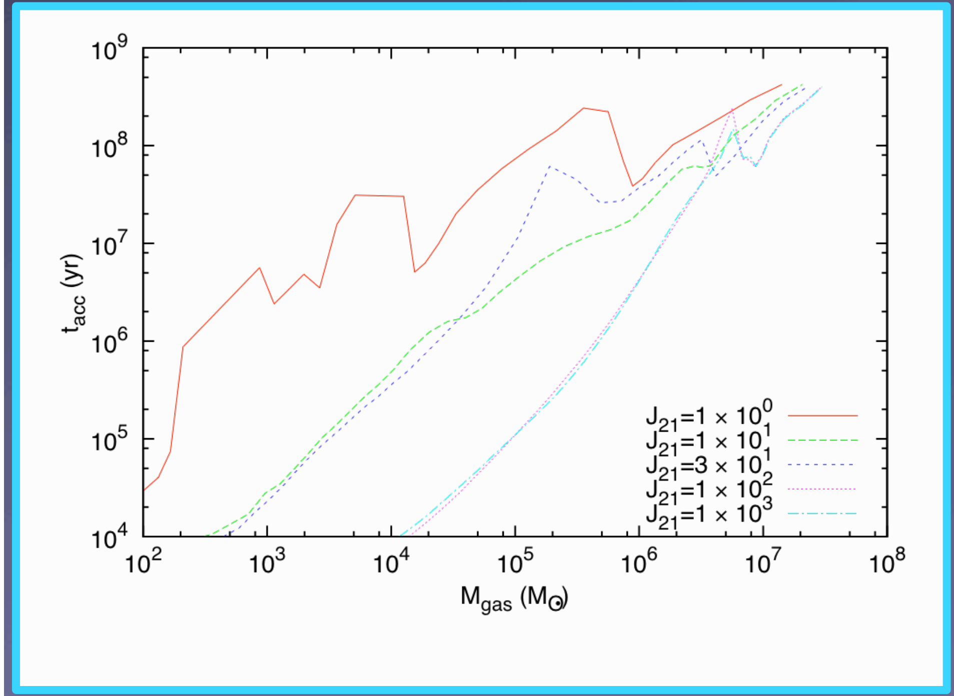
$30 < J_{crit} < 100$

Critical UV flux

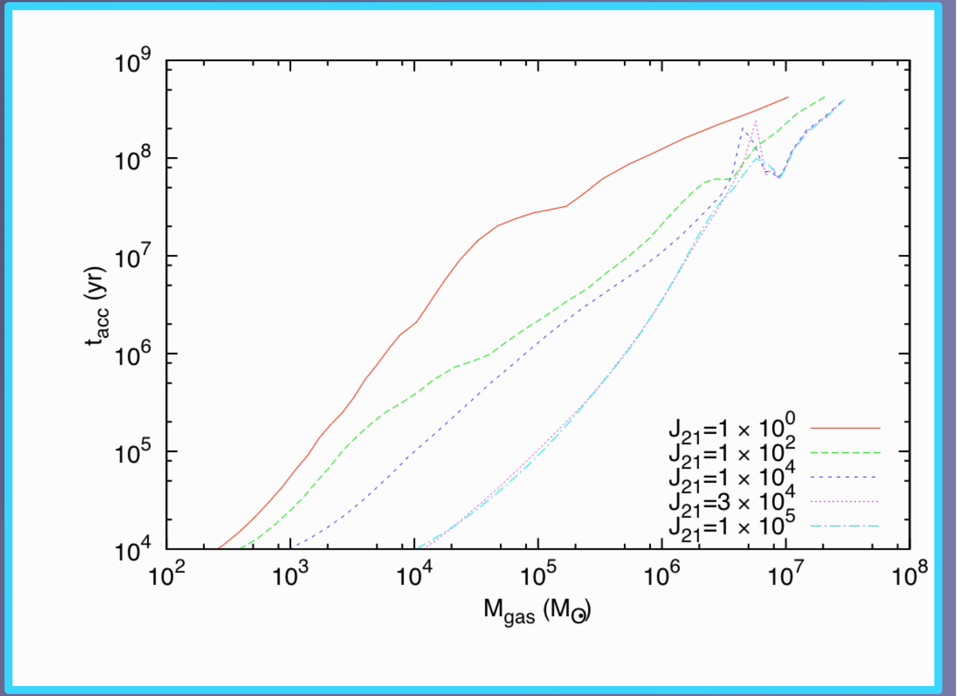
- H_2-formation rate $\propto \rho^2$ *vs* photo-dissoc. rate $\propto J\rho$
- Critical flux: $J \propto \rho$
- $J_{21,crit}$ low ~ 0.01-0.1 in low-mass mini-halos (n ~ 0.1-1 cm^{-3})
- Key: avoid H_2-cooling up to critical density of H_2: n ~ 10^4 cm^{-3}
- $J_{21,crit}$ increased to 10^3-10^4 NB: H_2 self-shielding crucial **(Wolcott-Green, ZH, Bryan 2011)**
- Normal stars more effective than Pop III:
  softer spectrum produces high H^- -dissociation rate
- Compare to J ~ 1 (at z~3) or J~ 10 (at reionization)

SMBH by direct collapse possible (?)

Shang, Bryan & Haiman (2010)



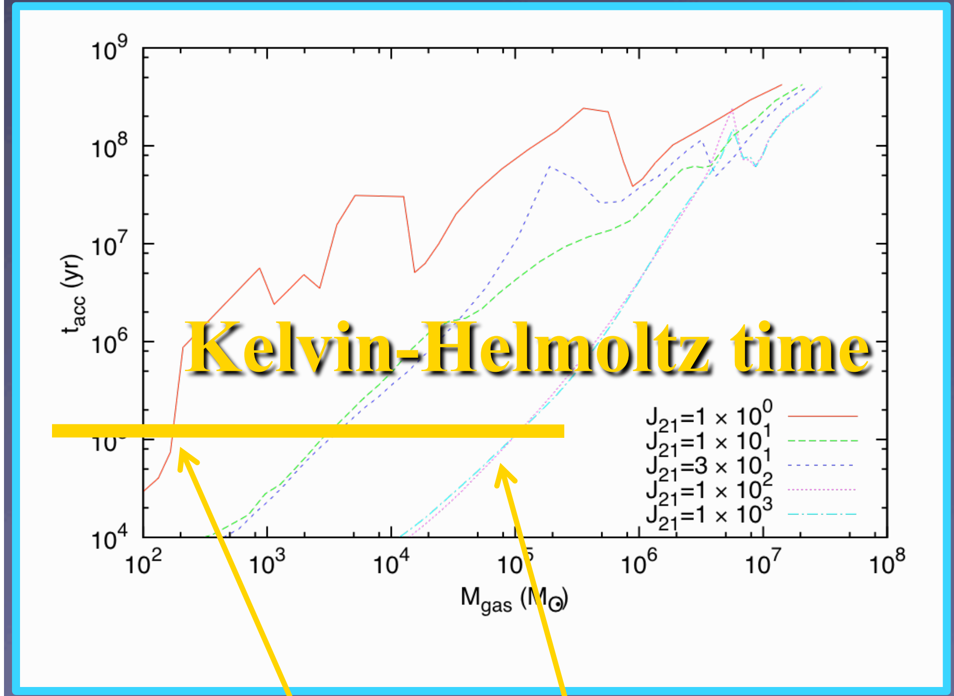
Normal stars
(soft UVB)



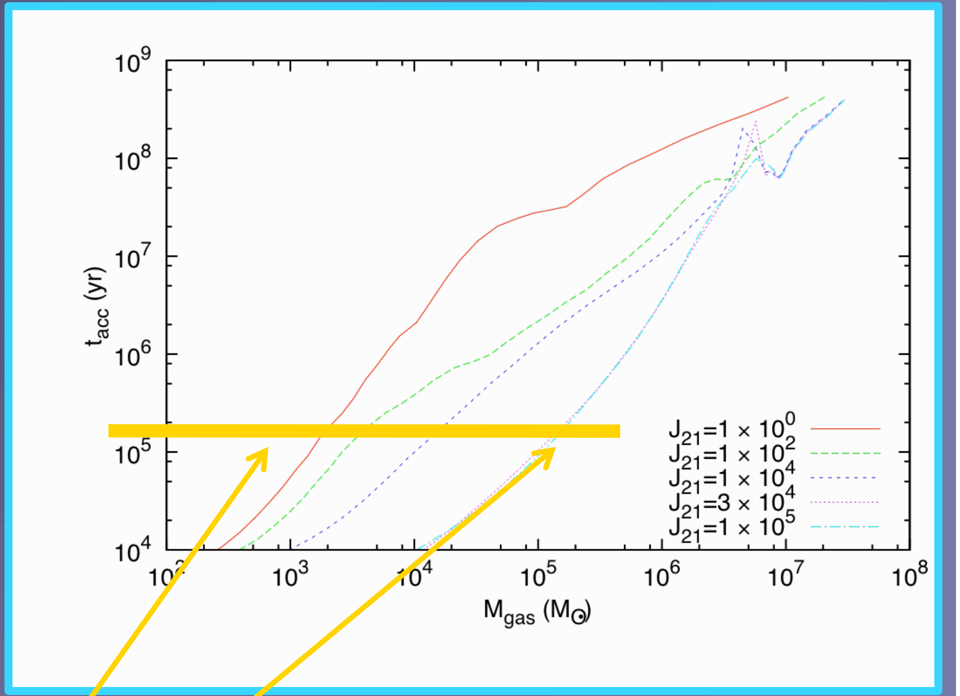
Pop III stars
(hard UVB)

SMBH by direct collapse possible (?)

Shang, Bryan & Haiman (2010)



Kelvin-Helmoltz time



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

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

SMBH by direct collapse: summary

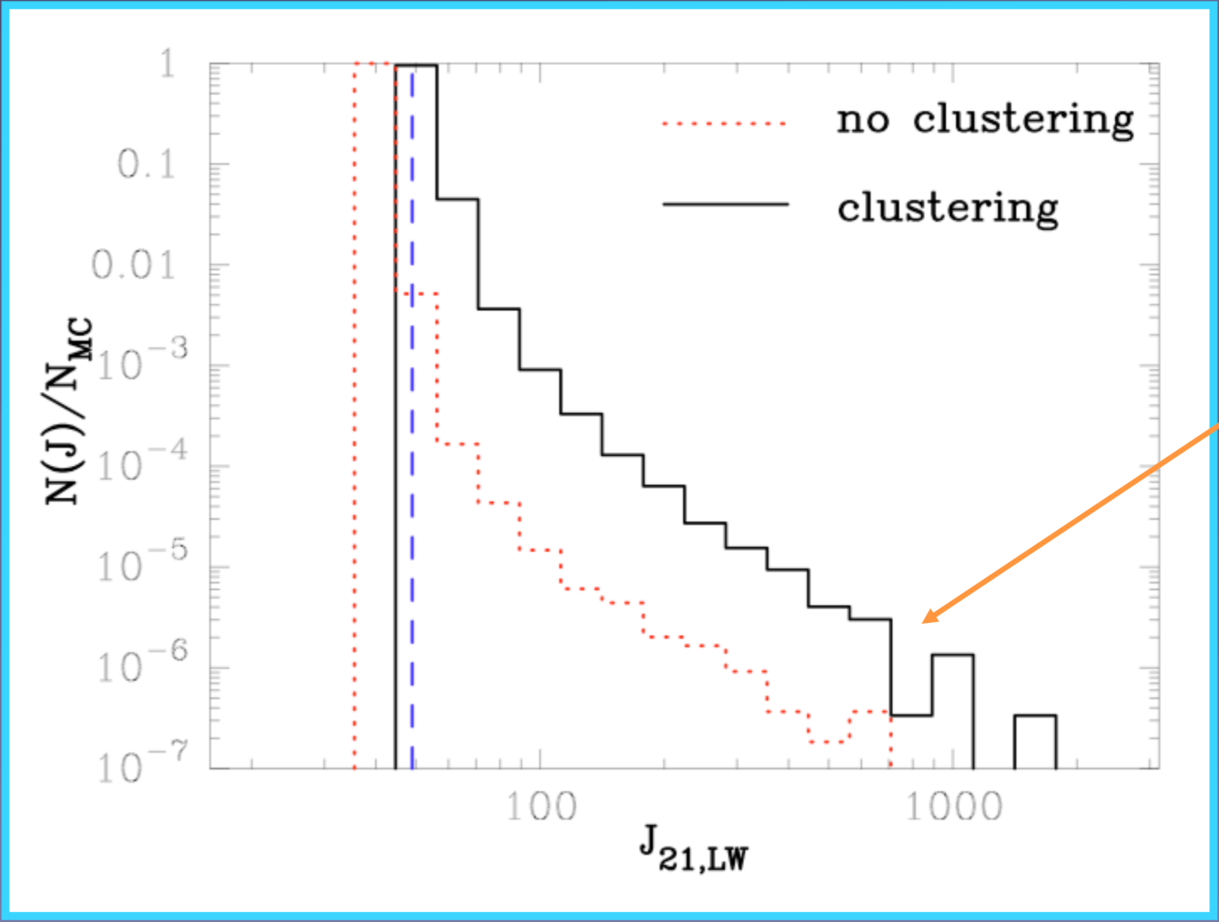
- In-fall proceeds at sound speed $c_s \approx 10$ km/s
- Mass accretion rate $M_{acc} \propto c_s^{\ 3} \sim 1\ M_\odot\ yr^{-1}$
- Fragmentation is not seen in simulations
- Central object has mass $M \approx 10^5 M_\odot$
  (cf. $M \approx 10^2\ M_\odot$ with H_2, when $c_s \approx 1$-2 km/s)

- BUT –

- Worry 1: fragments ultimately ?
- Worry 2: such large UV flux possible ?
- Worry 3: metals present ?

UV Flux PDF Sampled by Halos

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



Dijkstra, Haiman
Mesinger & Wyithe (2008)

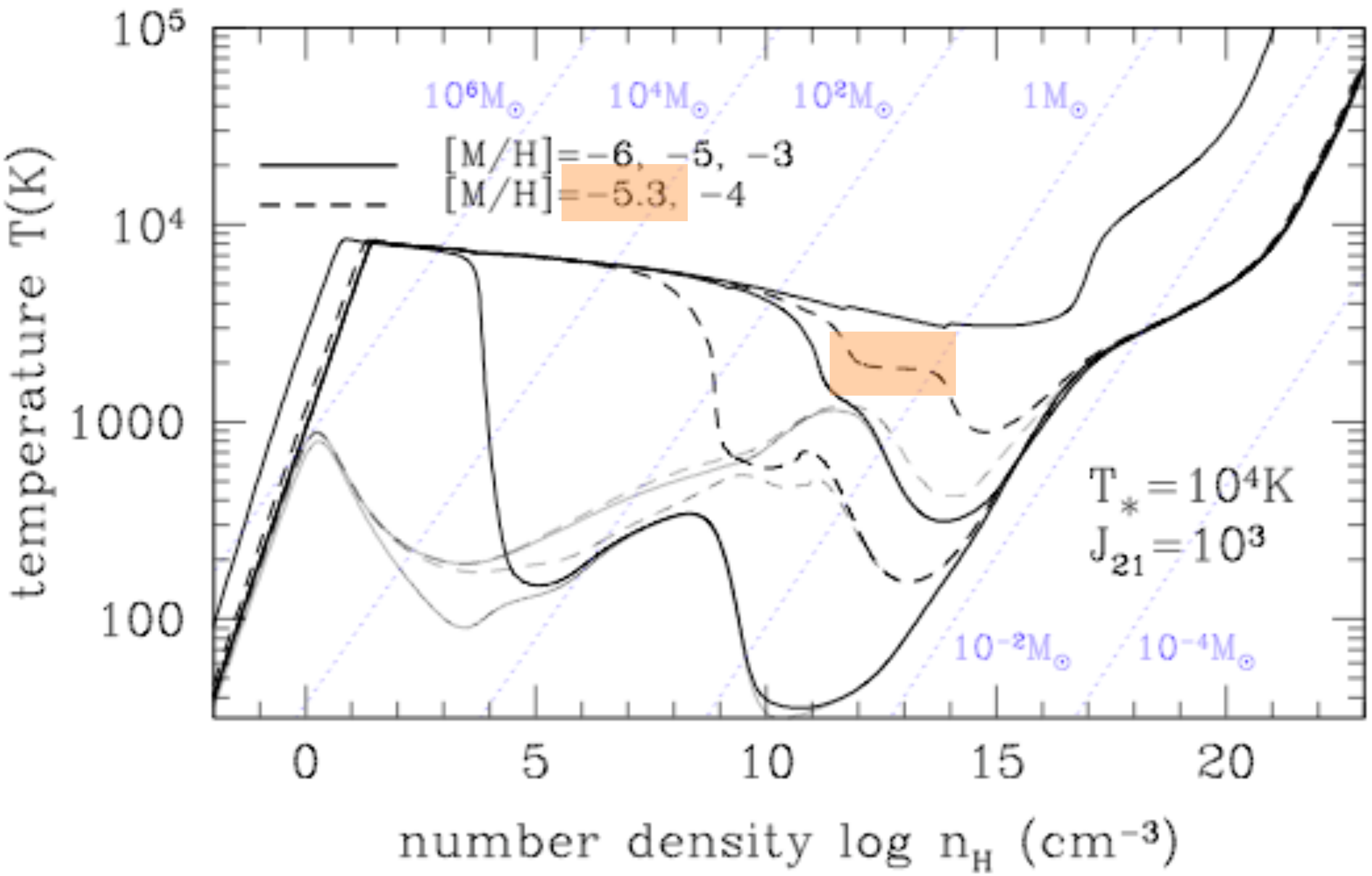
1 in ~10^7 halos has a close (≲10 kpc) bright and synchronized neighbor, so flux is ~ 30 × mean

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)

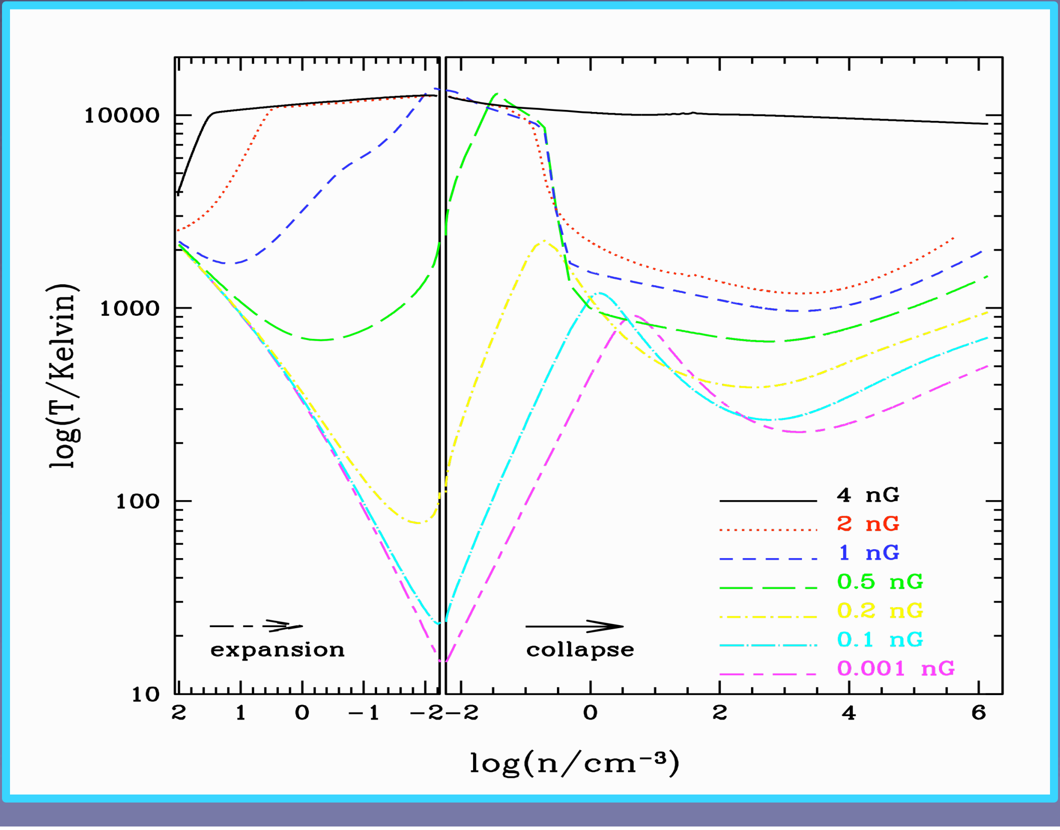
- Second condition eased by factor of 100 if no dust (CII and OI cooling).

- Gas with trace metals forms dense cluster of low-mass stars → *collapse to IMBH of $10^{4}\, M_{\odot}$* (Omukai et al. 2008)

Alternative heating: magnetic field

Sethi, Haiman & Pandey (2010)

- Primordial magnetic field can be generated during phase transitions in the early universe
- Current best upper limit from CMB anisotropy: B~1nG
- Can ambipolar diffusion heating in collapsing halo balance HI cooling?



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Future Observational Probes

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. Accreting BHs can cause "pre-ionizaton" at z>10

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

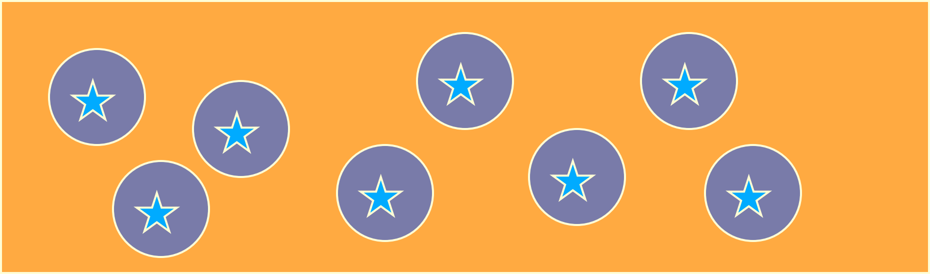
   power spectrum (21cm, kSZ) depressed on scales < m.f.p.

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

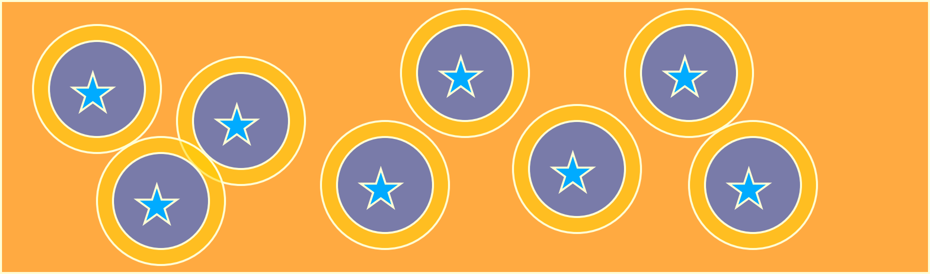
   mass ratio is a diagnostic

Reionization by Stars vs BHs

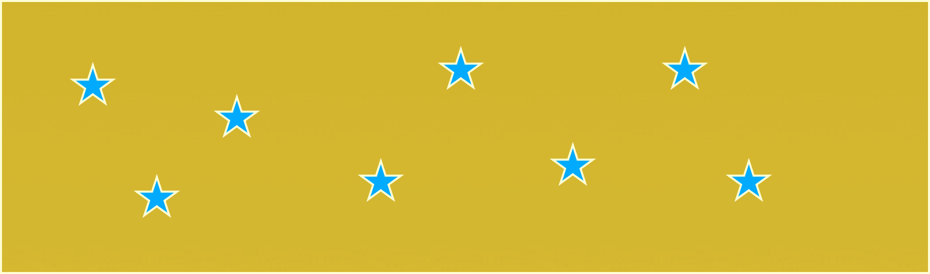
note: photon mean free path $\sim$ Gpc $(E/1\ \mathrm{keV})^{3}\ [(1+z)/10]^{-3}\ f_{HI}^{-1}$



Stars only:
Photon m.f.p. << source sep.
swiss cheese



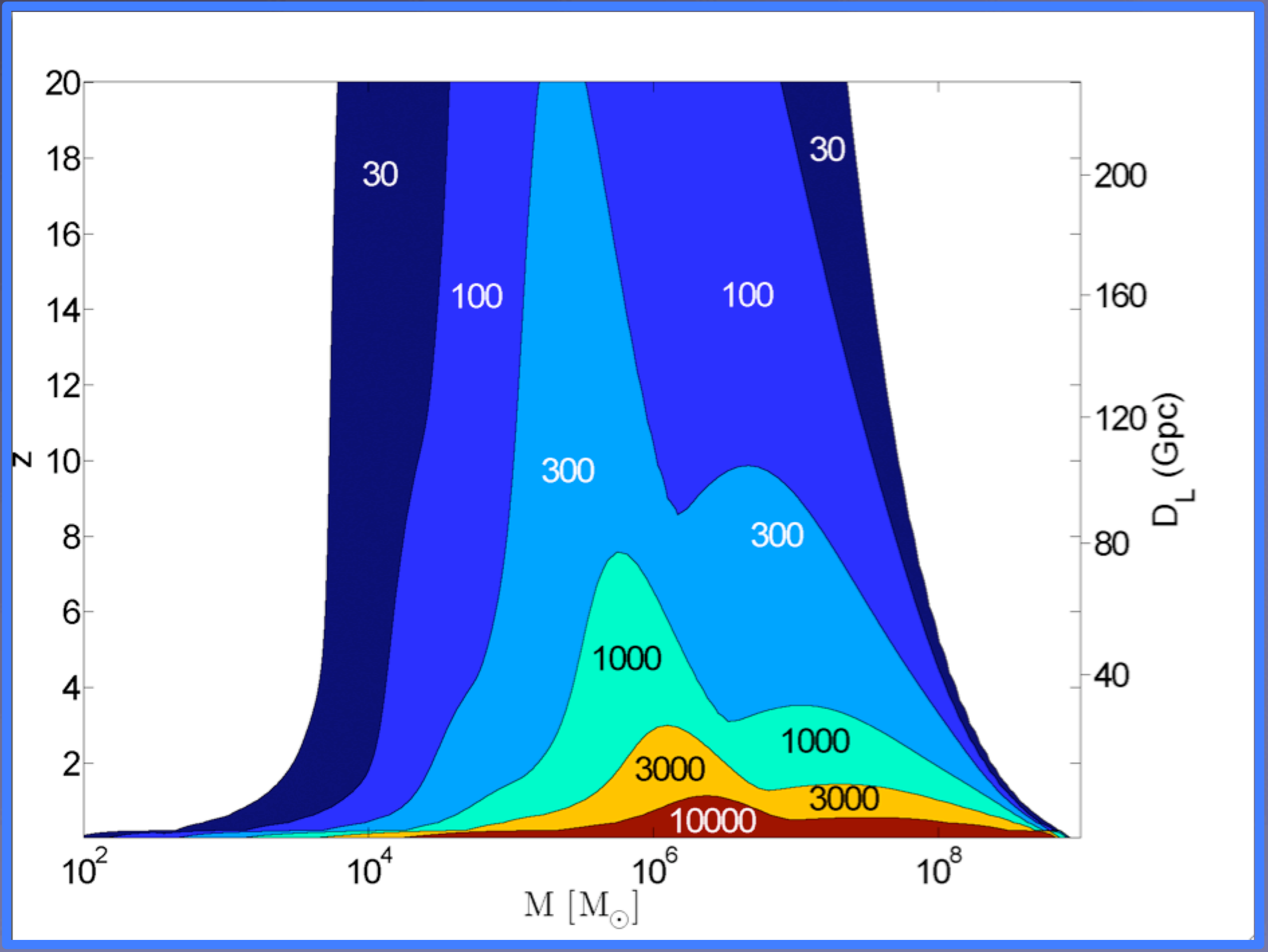
Stars + BH mix:
Photon m.f.p. ~< source sep.
Blurred swiss cheese



Accreting BHs dominate:
Photon m.f.p. >~ source sep.
Nearly uniform ionization

LISA sensitivity

Baker et al. (2007)



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

2. Extra challenge: not to overproduce number of $\sim 10^{5\text{-}6} M_\odot$ SMBHs.

   (i) seed are not too common, and their formation stops at z~25 ?

   (ii) internal feedback always limits growth and 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