# The Formation of Supermassive Black Holes at High Redshift

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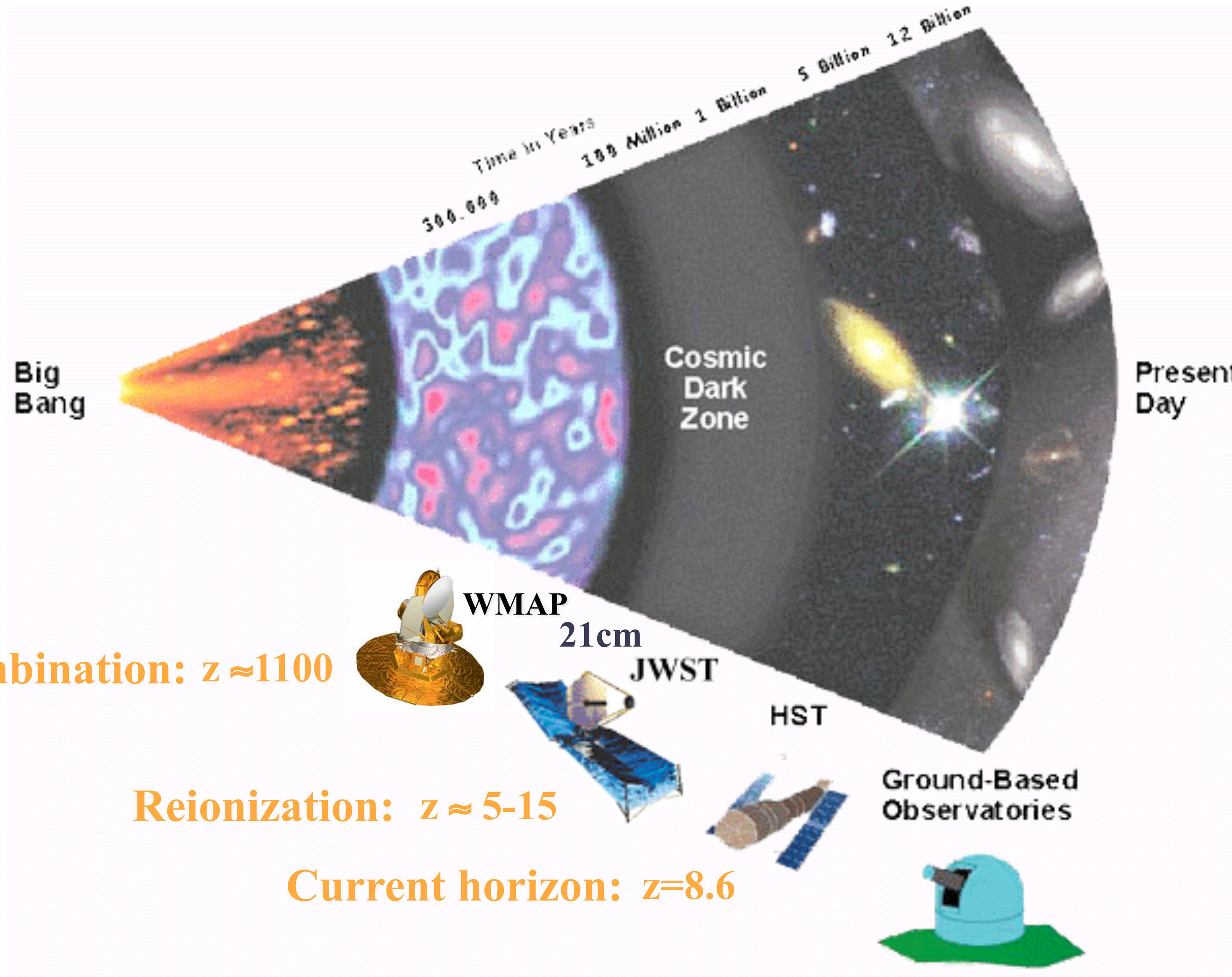
# Outline

- 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

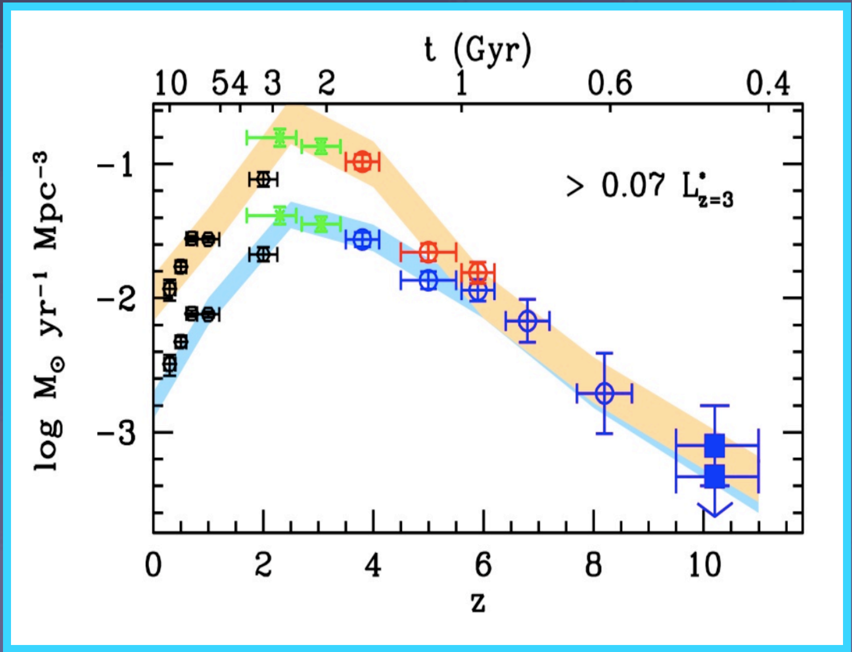



(Re)combination: $z \approx 1100$

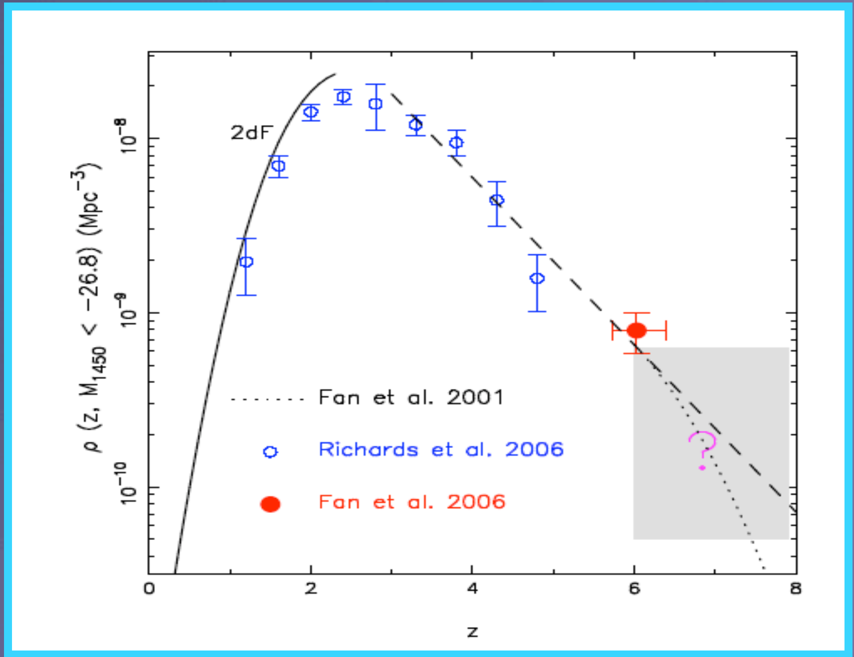
Reionization: $z \approx 5\text{-}15$

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

# Properties of z>6 Quasars

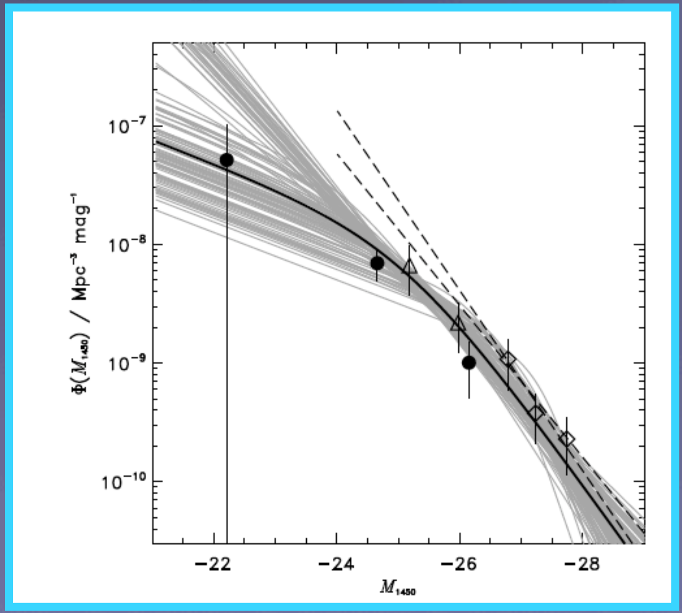
- Rare ("5σ") objects:

  *10 found in SDSS at z>6*

  *20 in CFHQ + few others*

- Tip of the iceberg:

  *Space density ~1 Gpc$^{-3}$*

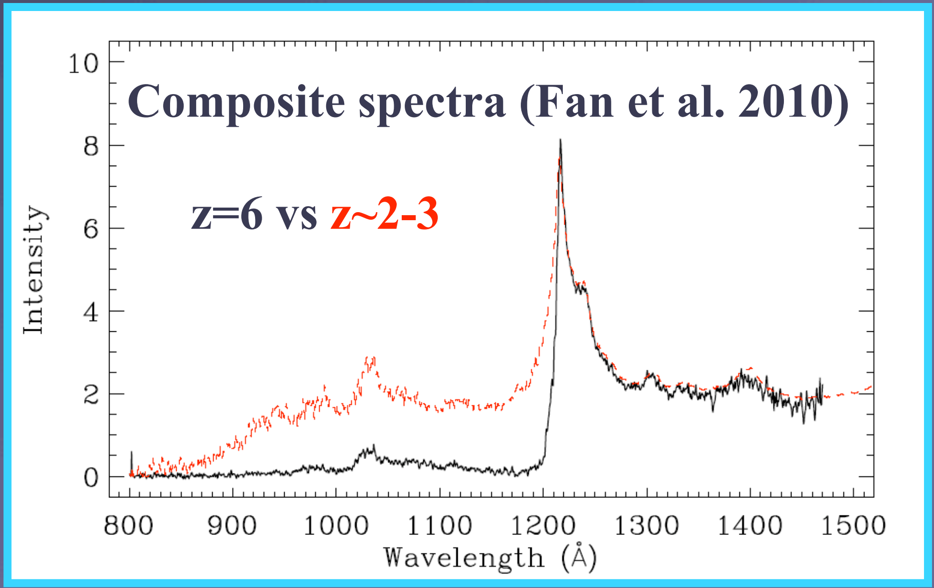



Willott et al. 2010

- 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**

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

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

# 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:**

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

**e-folding (Edd) time:**

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

**No. e-foldings needed**

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

**Age of universe (z=6.43)**

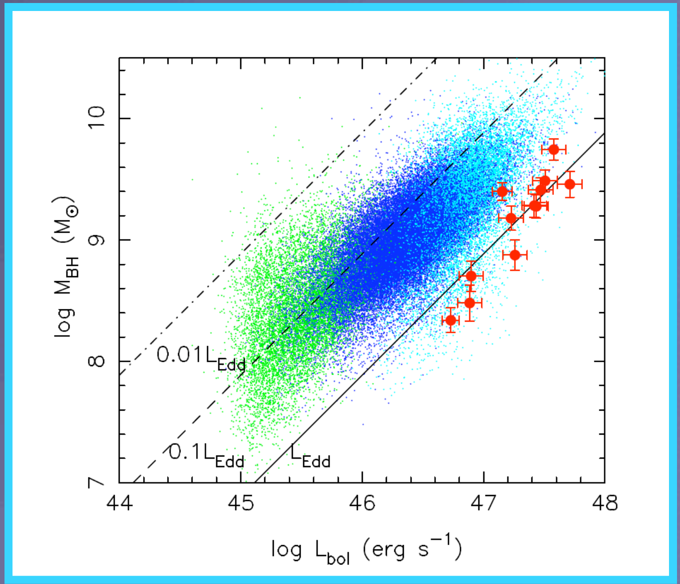
**$8 \times 10^8$ yr ✓**

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




- Empirical measurement of $L/L_{edd}$

  *from CIV and MgII line widths, calibrated from local reverberation mapping* $[GM/R = const\ \sigma^2]$

  (Vestergaard 2004; Kurk et al. 2007 Jiang et al. 2009; de Rosa et al. 2010)

*… and if* $L \gg L_{edd}$ *then* $dM/dt = L/\varepsilon c^2$ *is large*

$\rightarrow$ *BH anyway accretes* $4 \times 10^9\ M_\odot$ *in* $\ll 4 \times (\varepsilon/0.1)^{-1}\ 10^7$ *yr*

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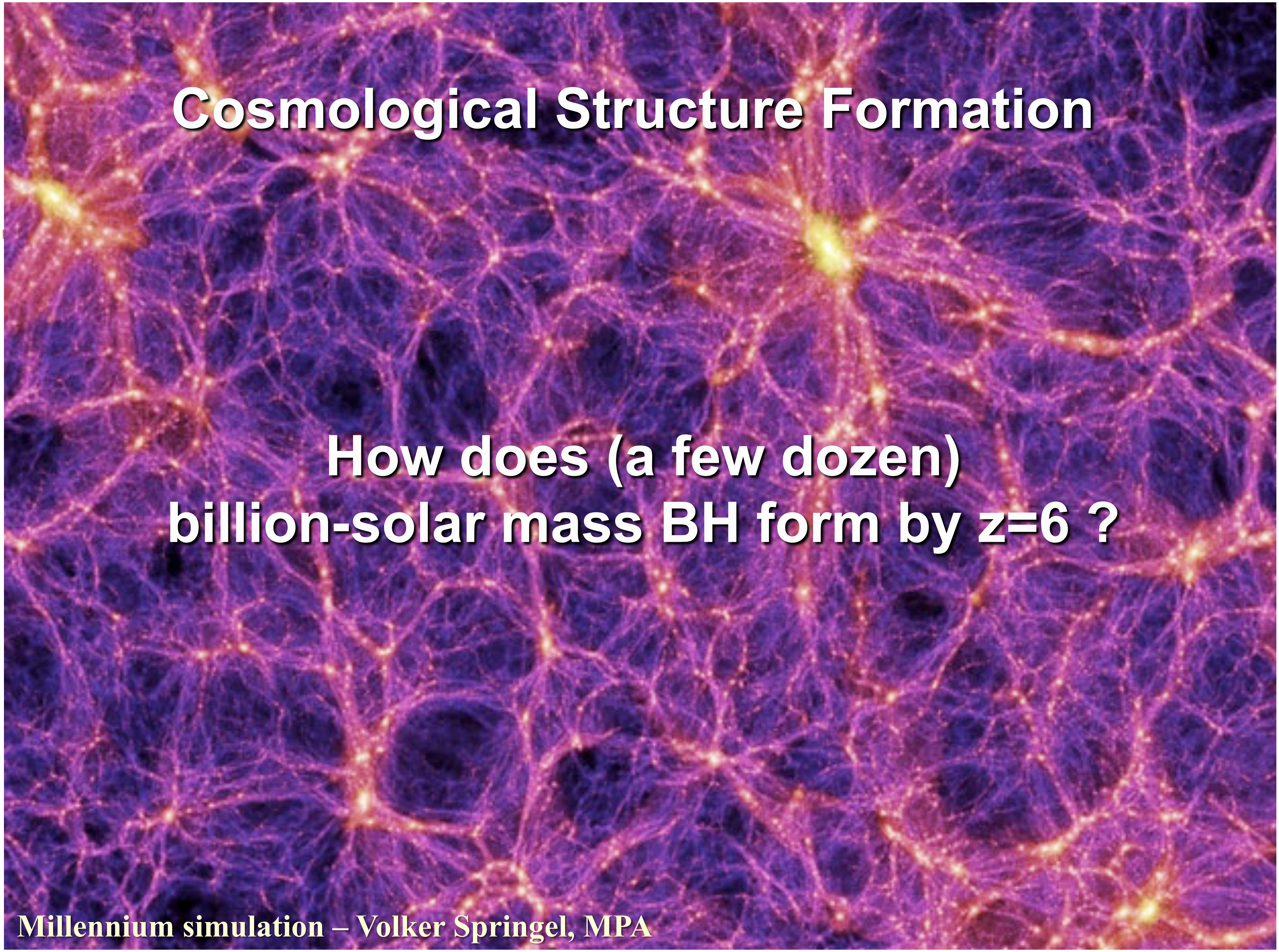
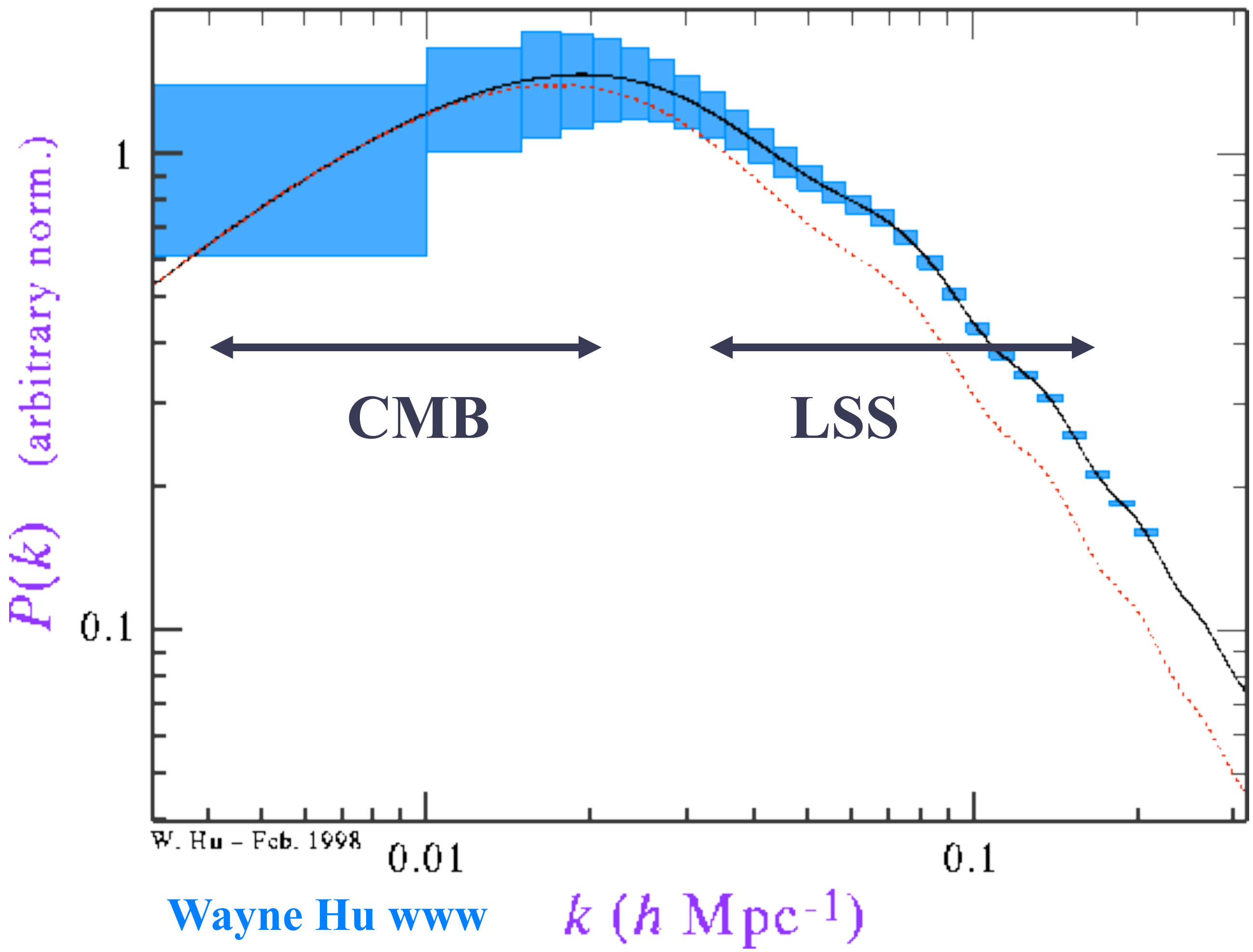
# Cosmological Structure Formation

**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

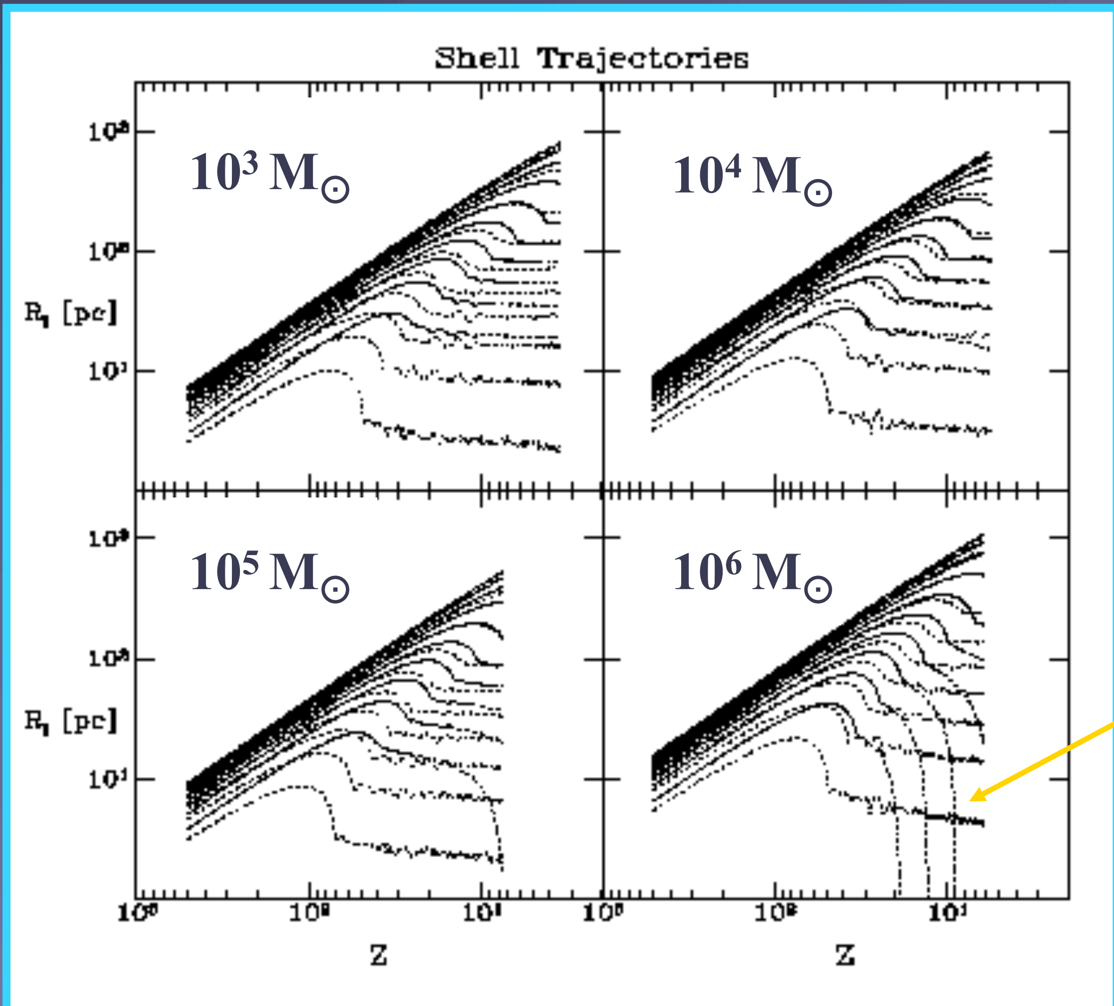
Dark Age

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

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

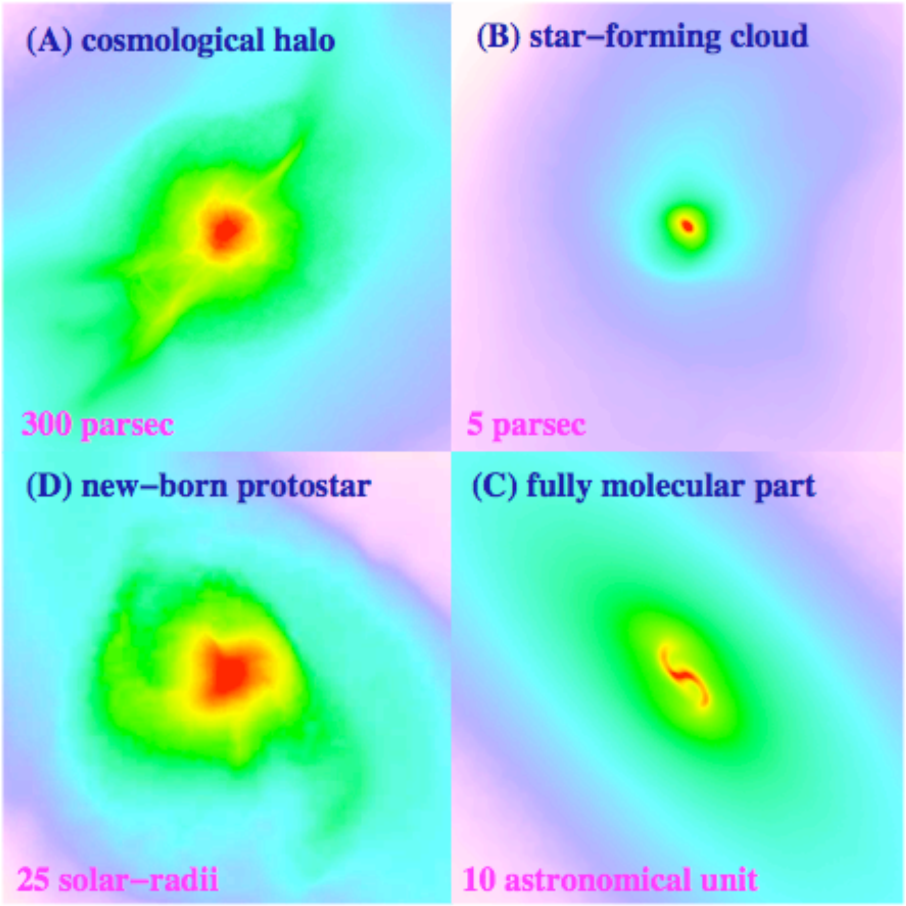



Fig. 1: Projected gas distribution around the protostar. Shown regions are, from top-left, clockwise, (A) the large-scale gas distribution around the cosmological halo (300 pc on a side), (B) a self-gravitating, star-forming cloud (5 pc on a side), (C) the central part of the fully molecular core (10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

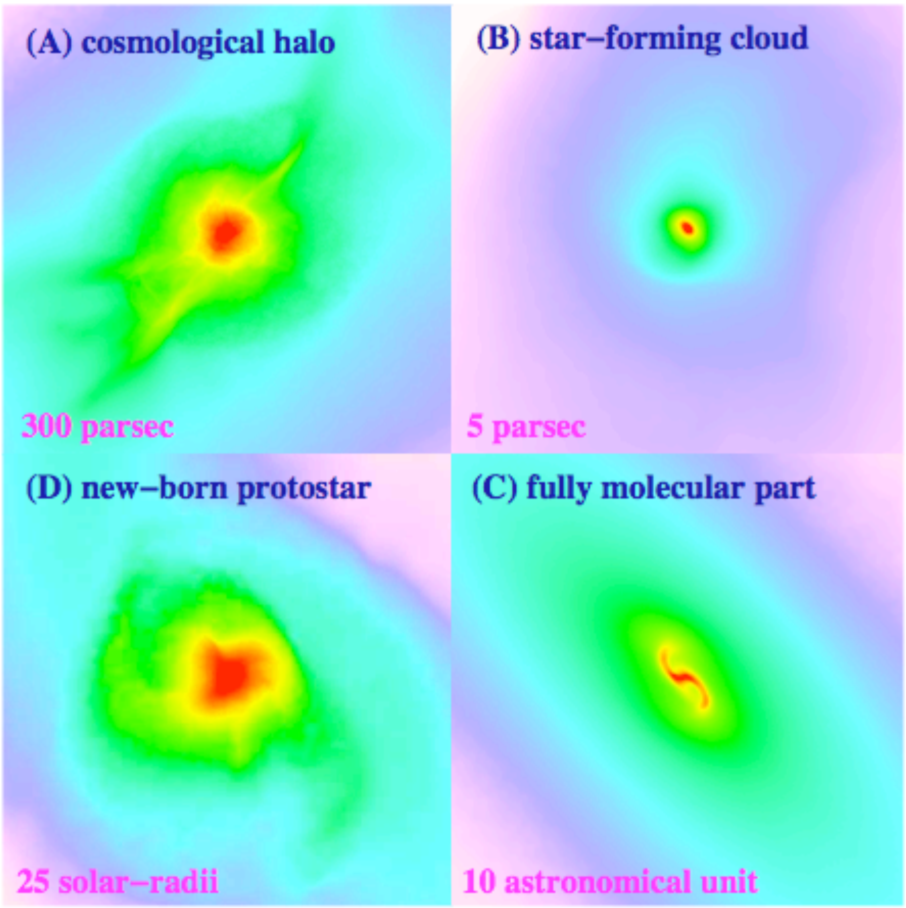
$n \approx 10^{21}$ cm$^{-3}$

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

**Final stellar mass:**

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

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

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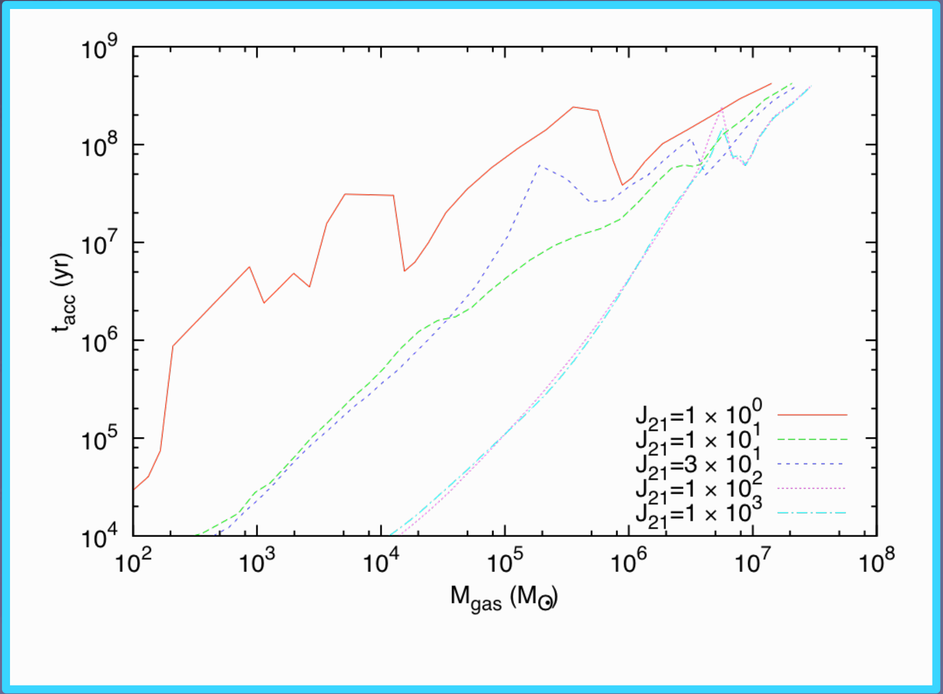
# Final Stellar Mass?

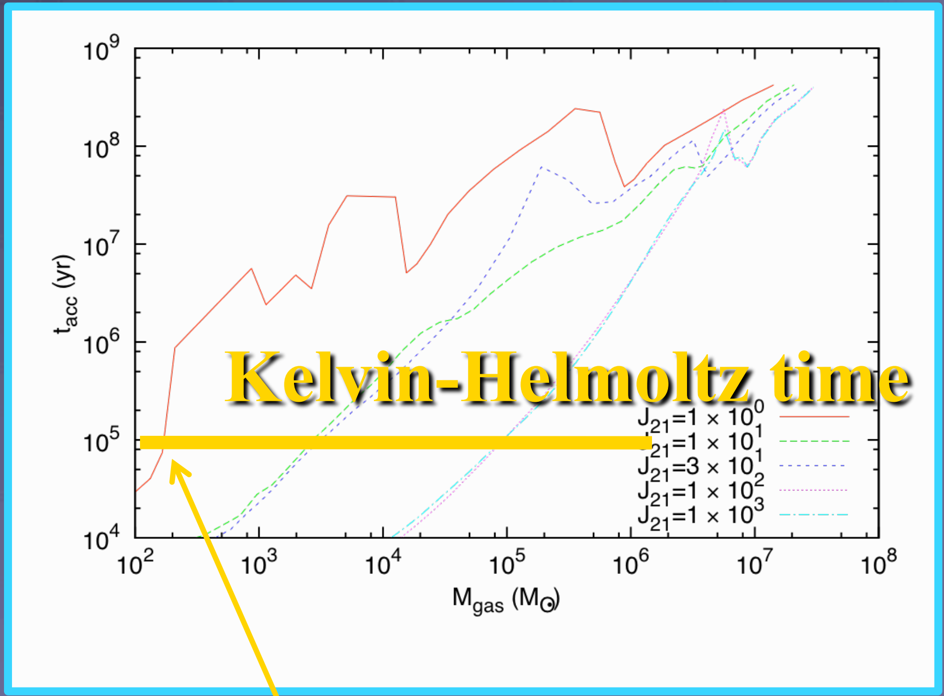
Shang, Bryan & Haiman (2010)




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

# Final Stellar Mass?

Shang, Bryan & Haiman (2010)




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

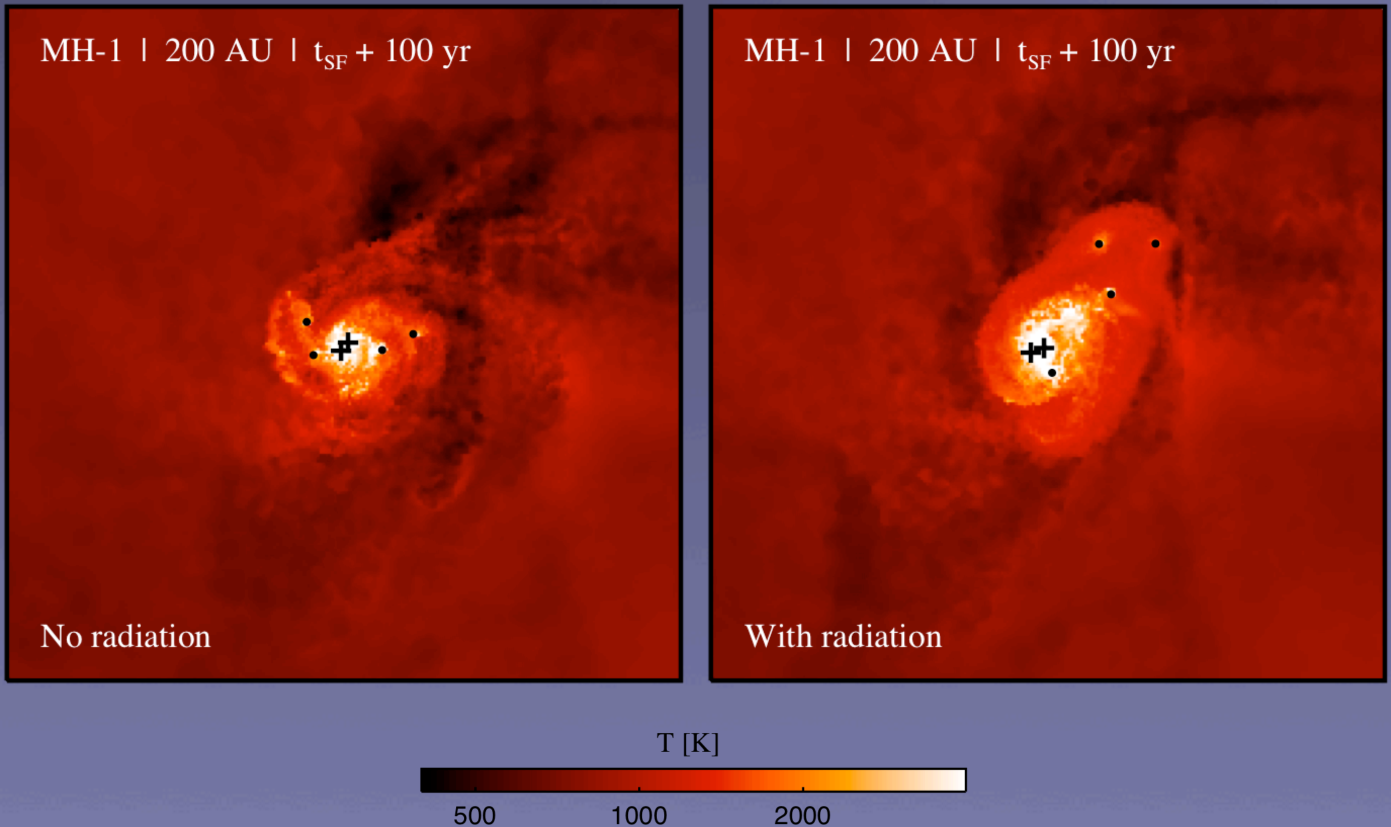
# Or…Fragmentation?

**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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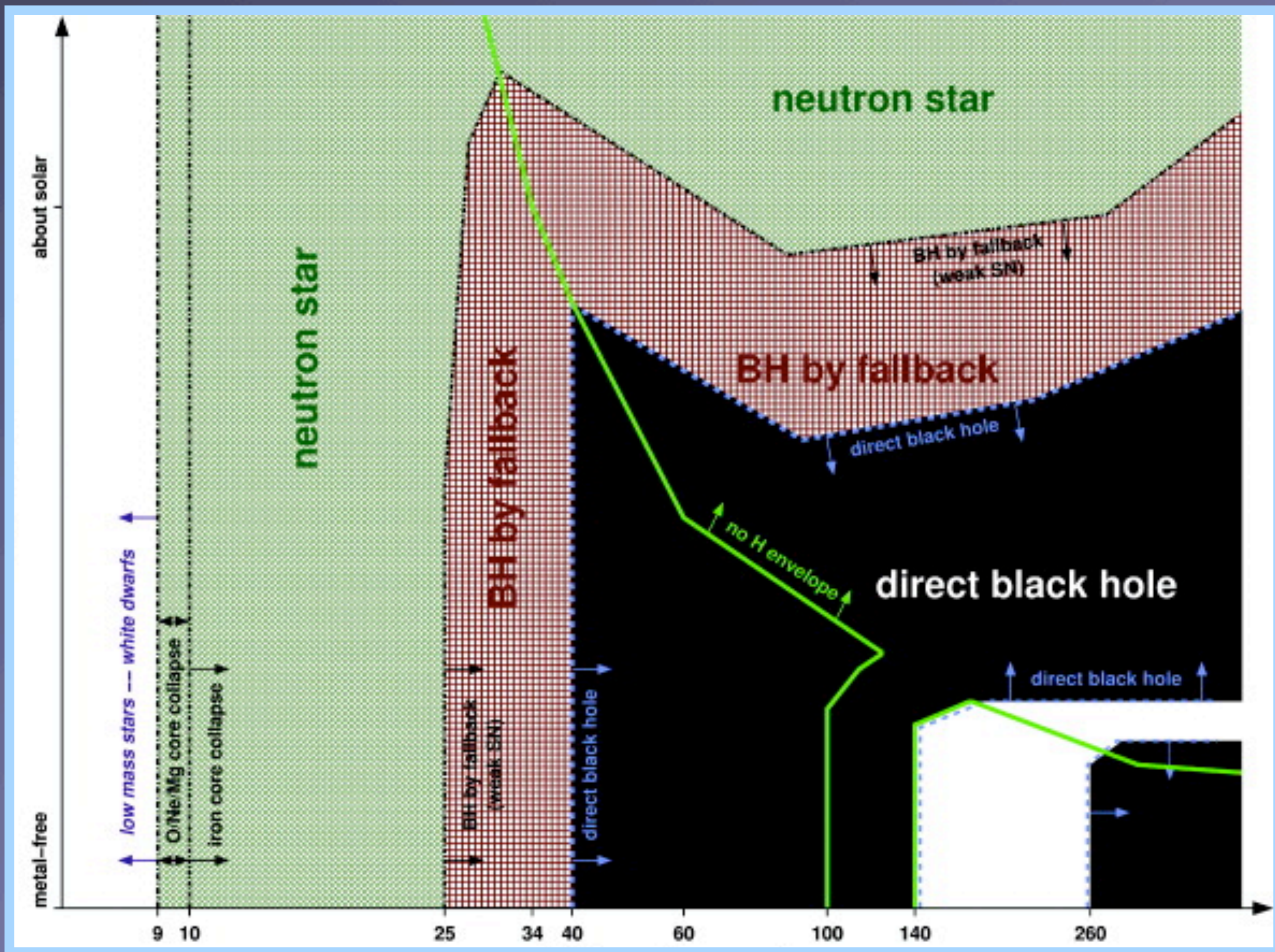
# Remnants of Massive Stars

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




$Z = Z_\odot$

metalicity

$Z = 0$

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

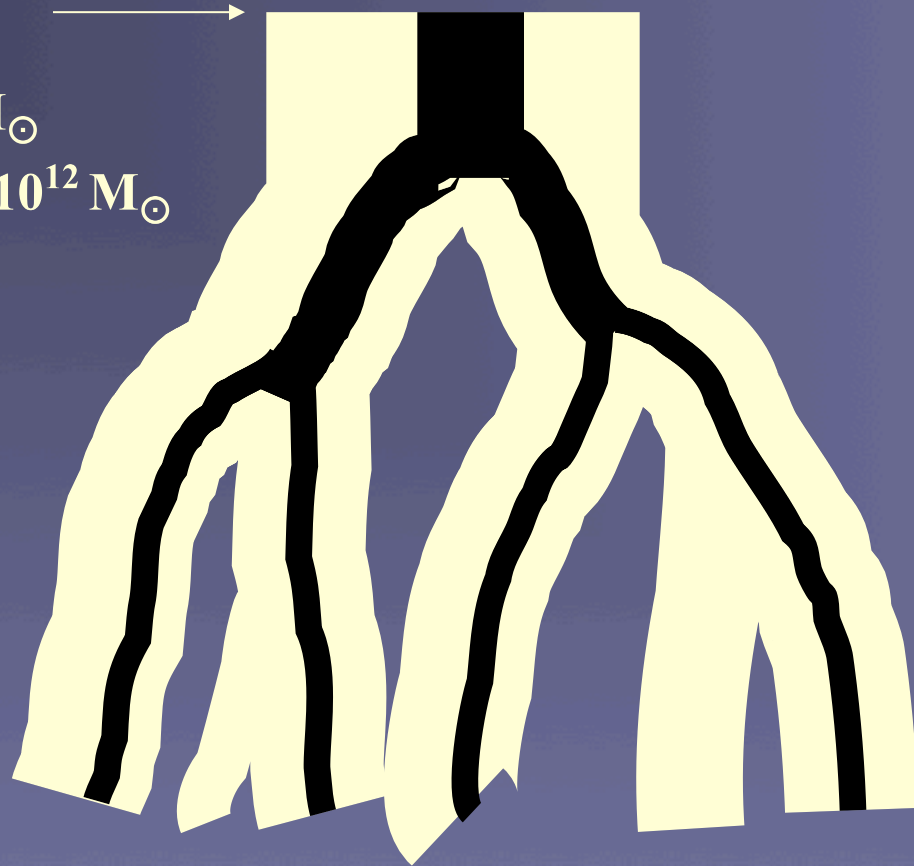
# Growing SMBHs by Accretion + Mergers

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 (2010)

Also hydro simulations: Li et al. (2007); Sijacki et al. (2009)

# Growing SMBHs by Accretion + Mergers

**Tanaka & Haiman (2010)**

**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~$10^5$ trees)

- **Fraction of minihalos forming stellar BH seeds ?**
  - $\mathbf{f_{seed}}$ depends on IMF and global feedback ($M_{seed}$ ~10-100 $M_\odot$)

- **Time-average mass accretion rate ?**
  - duty cycle **"$\mathbf{f_{duty}}$"** for accretion ($\mathbf{f_{duty}}$~1.0)
  - maximum of Bondi and Eddington rate

- **What happens to BHs when halos merge? 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)

# Do Most Minihalos Form Stars?

**Minihalos are fragile - many possible feedback effects**

- **LOCAL FEEDBACK IN & NEAR MINIHALO**
  - 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 km/s $< \sigma <$ 50 km/s)
  - global dispersion of metals (pop III $\rightarrow$ pop II)
  - mechanical (SN blast waves)

# Time-averaged Mass Accretion Rate ?

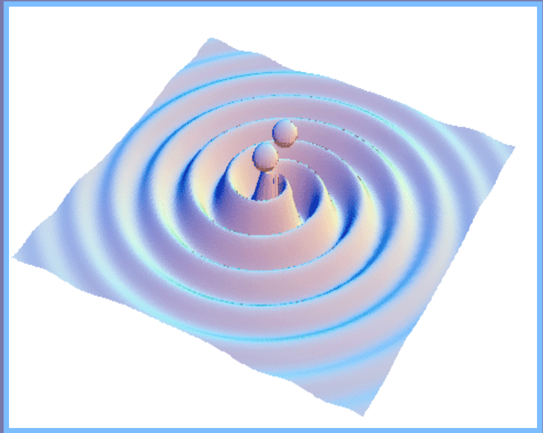
- **LIMIT FROM AMBIENT CONDITIONS**
  - Bondi rate ($\propto \rho M_{BH}^2/c_s^3$) initially sub-Eddington
  - Quickly catches up with Eddington rate, <u>if ρ high</u>

- **LIMIT BY RADIATIVE FEEDBACK**
  - Radiation from star + hole ionizes and heats gas
  - No steady-state solution in *spherical symmetry*
  - Episodic accretion with time-averaged $\mathbf{f_{duty}} \sim 0.3$

**Milosavljević et al. (2009)**

- **SUPER-EDDINGTON MASS ACCRETION?**
  - Radiation trapped and advected with flow (RIAF's)
  - Problem: winds – only few % of mass reaches BH
  - Radiation leaks out – photon bubble MHD instability
  - $\mathbf{f_{duty}} \sim 2\text{-}3$ possible (?)

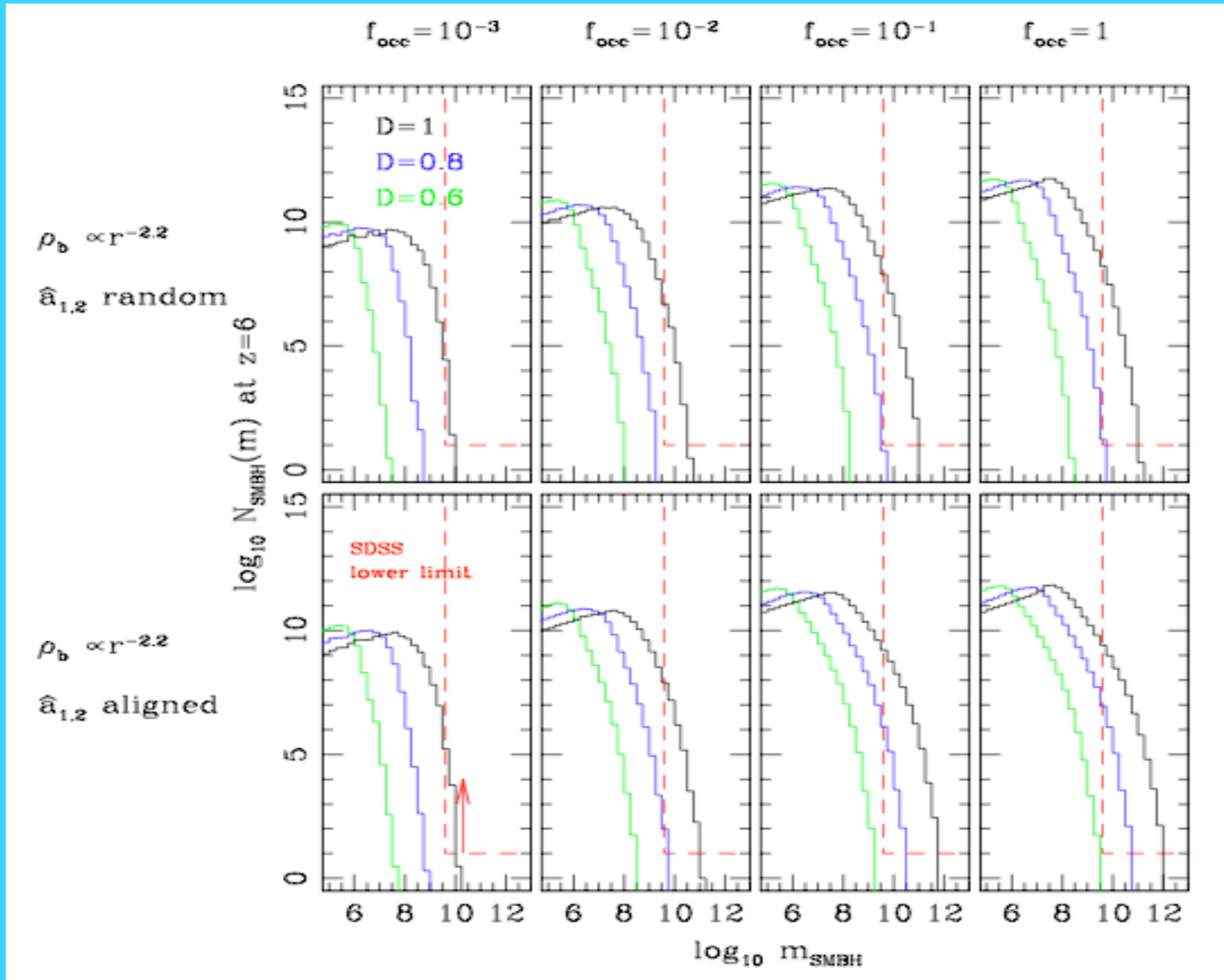
# A possible obstacle: gravitational recoil



- **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 (2010)



# SMBHs from stellar seeds: Results

- (i) density cusp
  (ii) $f_{seed} \gtrsim 10^{-3}$
  (iii) $f_{duty} \gtrsim 0.8$
  } very optimistic assumptions required!

- Making few $\times$ $10^9$ $M_\odot$ BHs by z=6 without overproducing the number of few $\times$ $10^5$ $M_\odot$ BHs ($\rho_{BH} \lesssim 4 \times 10^4$ $M_\odot Mpc^{-3}$) suggests $f_{seed} \approx 10^{-2}$ and negative feedback at z~25

- X-ray heating from BHs themselves, or 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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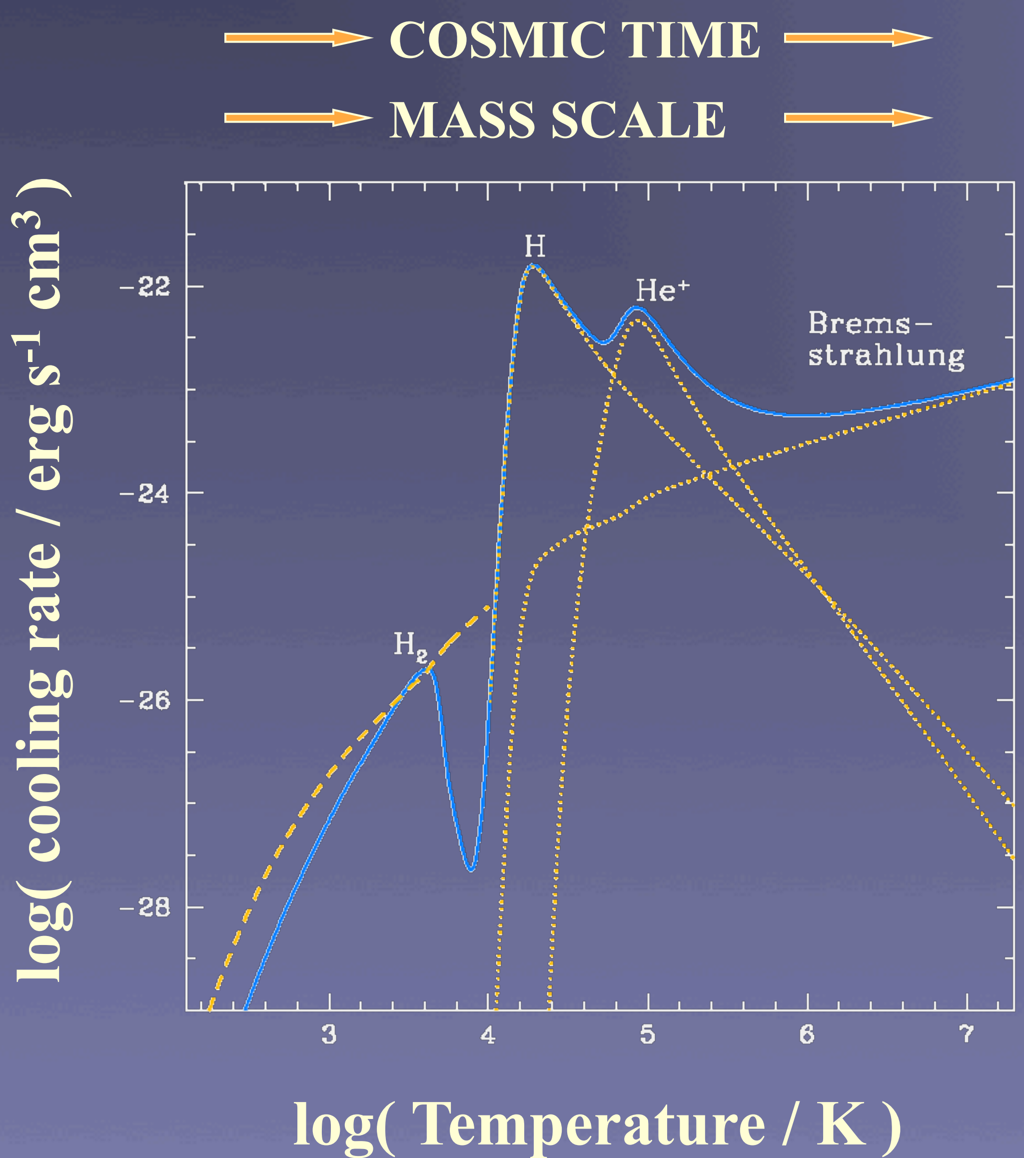
# Direct SMBH formation in $T_{vir} > 10^4$K halos?




**cf. Halo virial temperature:**

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

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)

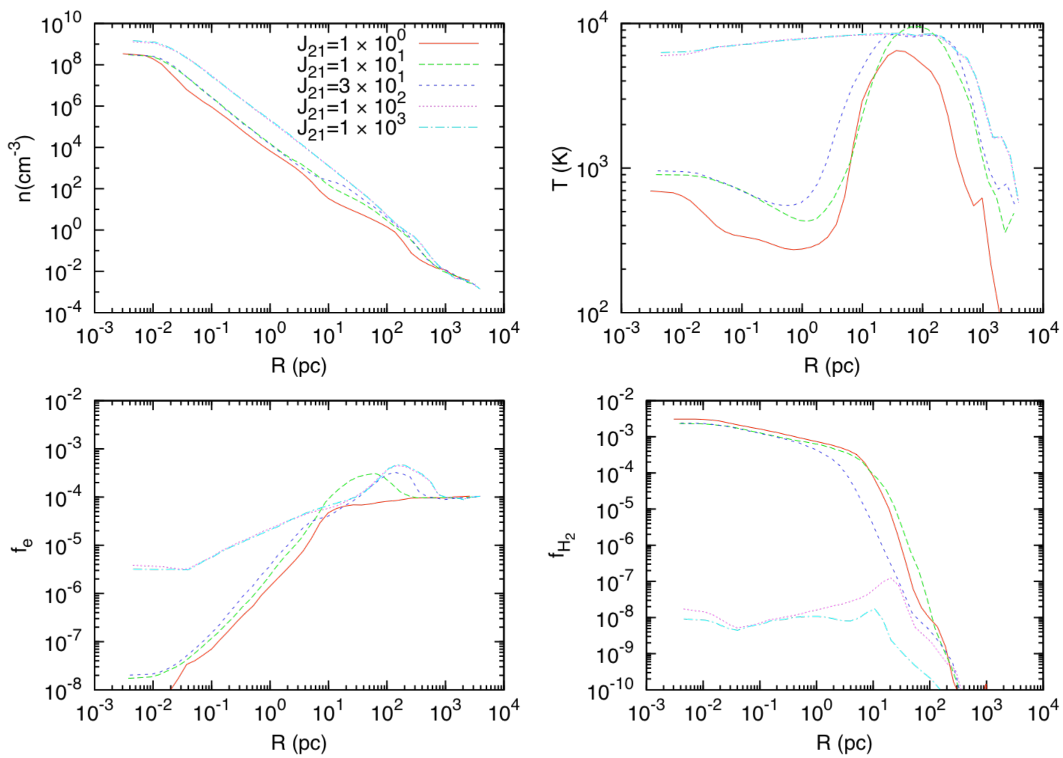
# Avoiding $H_2$ – cooling with UV flux

- $H_2$-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)

# Critical UV flux: 3D simulations

**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

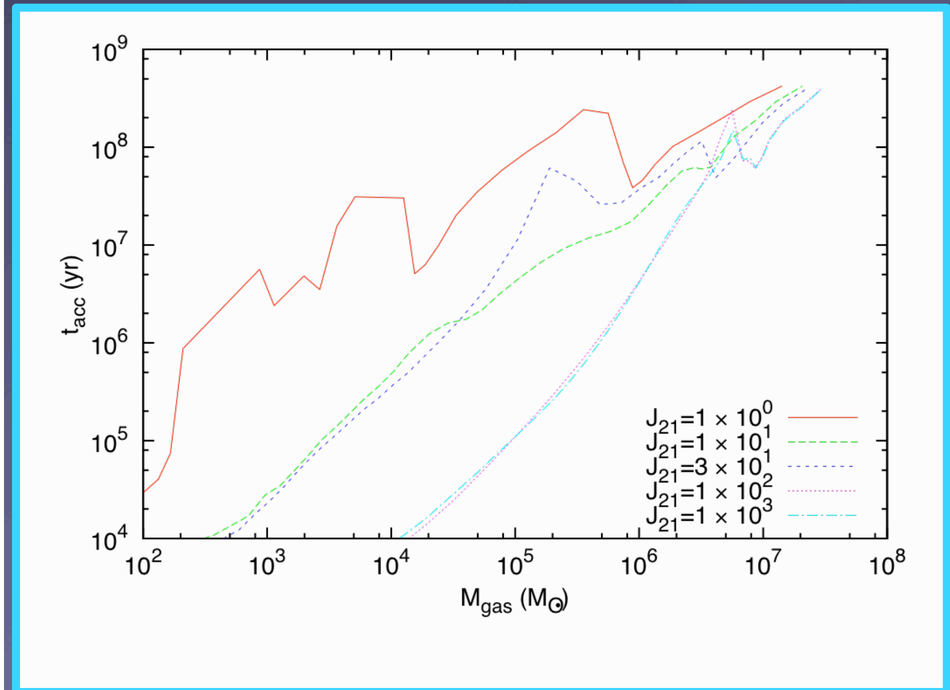
$30 < J_{crit} < 100$

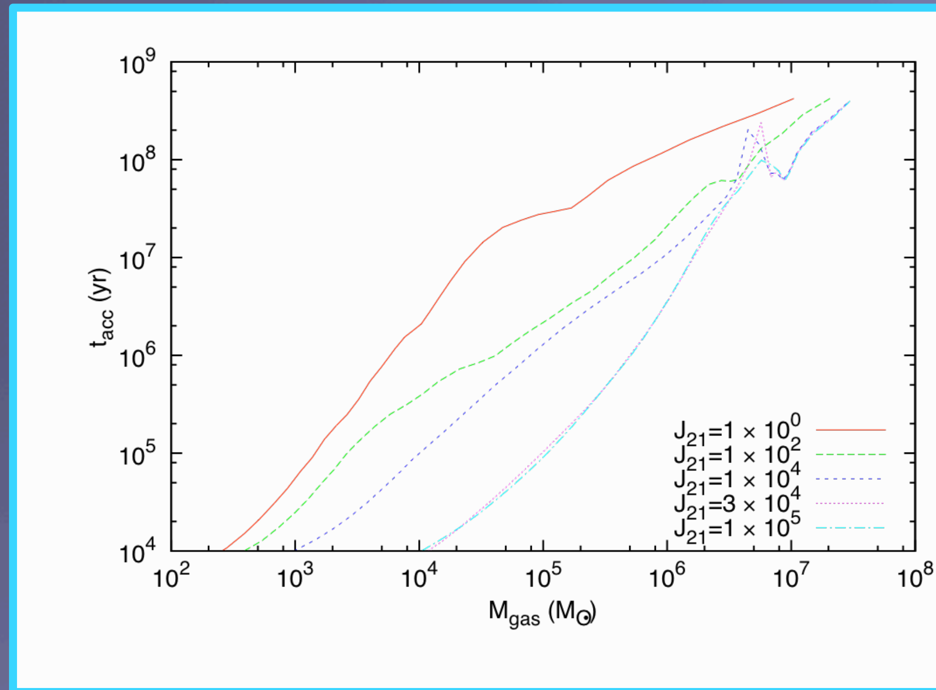
# SMBH by direct collapse possible (?)

- **In-fall proceeds at sound speed** $c_s \approx 10$ km/s
- **Mass accretion rate** $M_{acc} \propto c_s^{\ 3} \sim 1\ M_\odot\ yr^{-1}$
- **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** $c_s \approx 1\text{-}2$ km/s**)**

# SMBH by direct collapse possible (?)

Shang, Bryan & Haiman (2010)



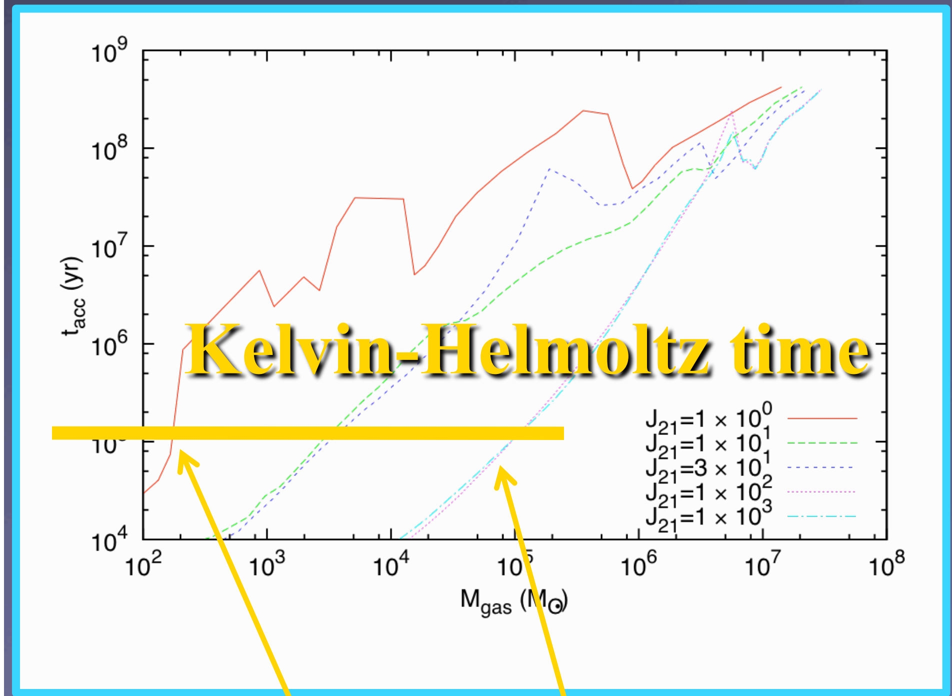



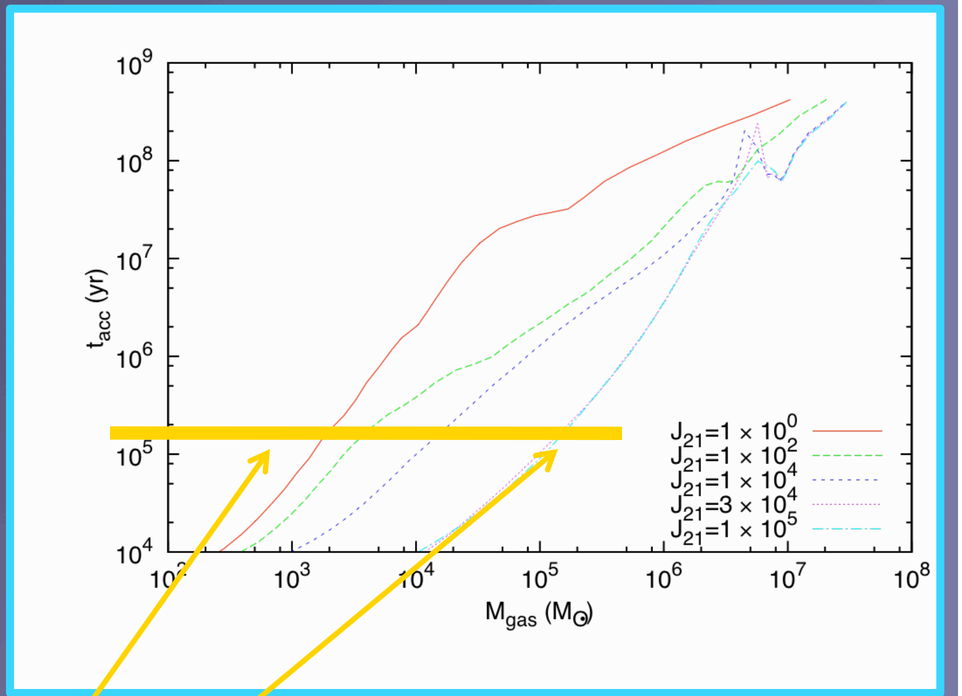

**Normal stars (soft UVB)**

**Pop III stars (hard UVB)**

# SMBH by direct collapse possible (?)

Shang, Bryan & Haiman (2010)



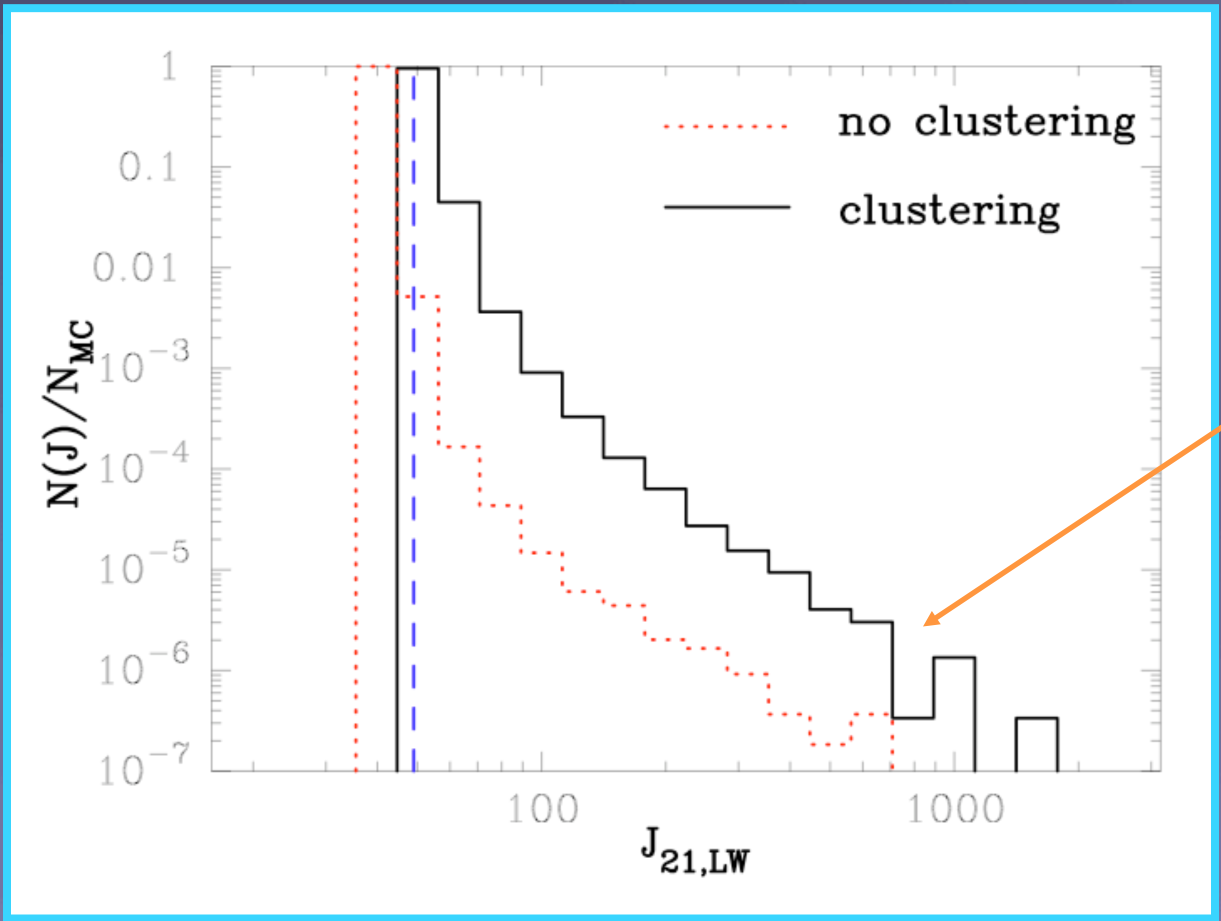




$10^{2-3}\ M_\odot$ Pop III star Abel et al.; Bromm et al.; Yoshida et al.

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

# 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)

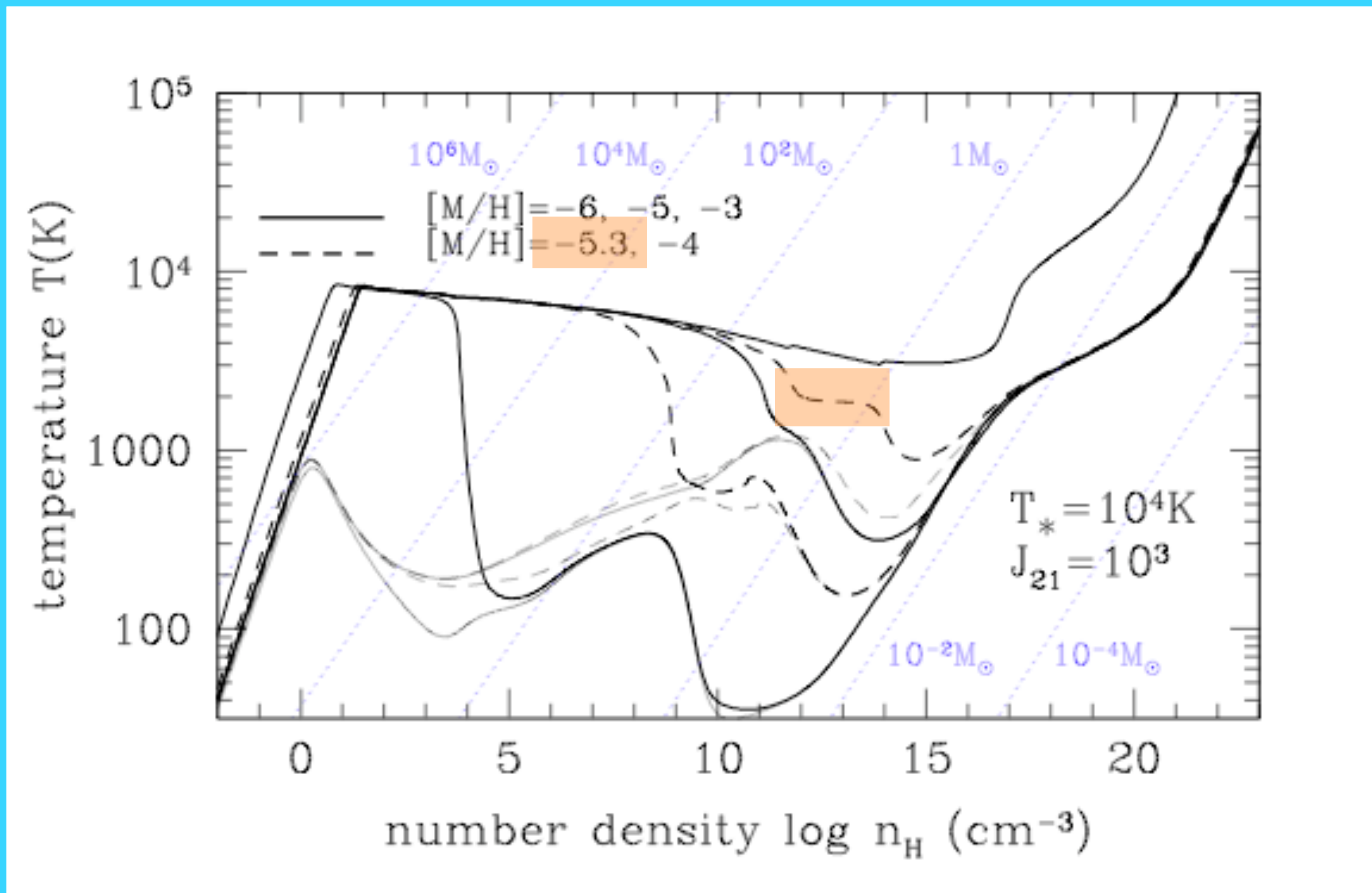
1 in ~$10^7$ halos has a close (≲10 kpc) bright and synchronized neighbor, so flux is ~ 30 × mean

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)

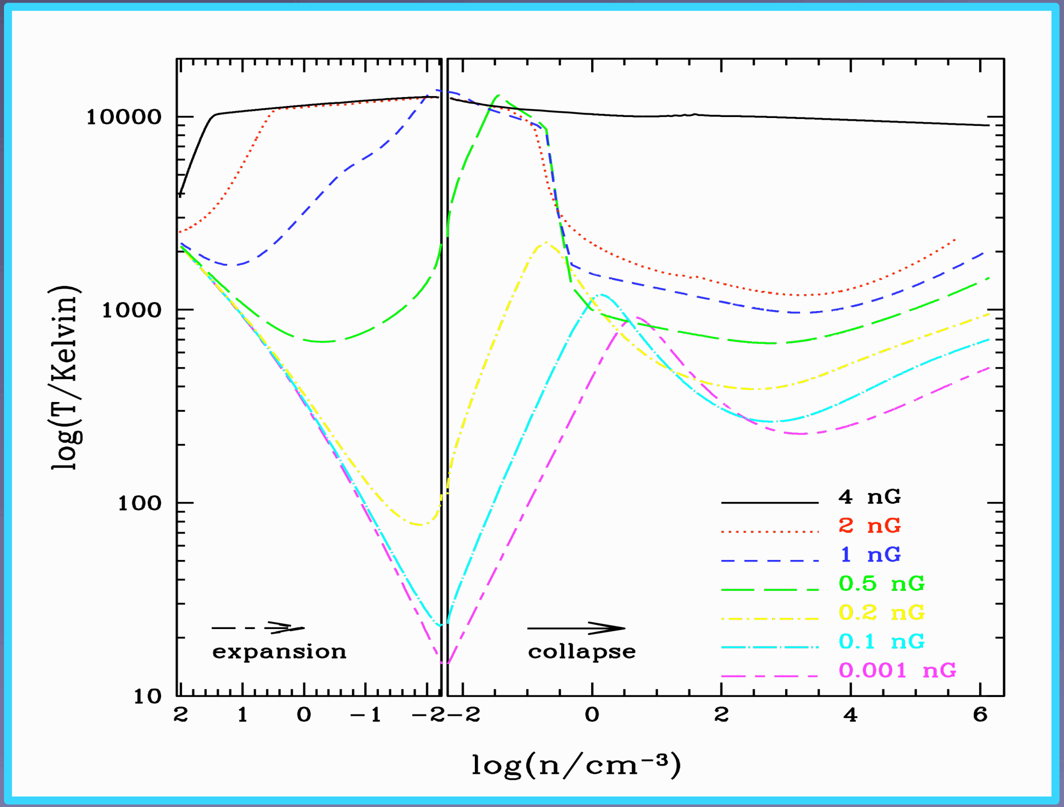
- Second condition eased by factor of 100 if no dust (CII and OI cooling).

- Gas with trace metals forms dense cluster of low-mass stars → *collapse to IMBH of $10^3\, M_\odot$* (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.*

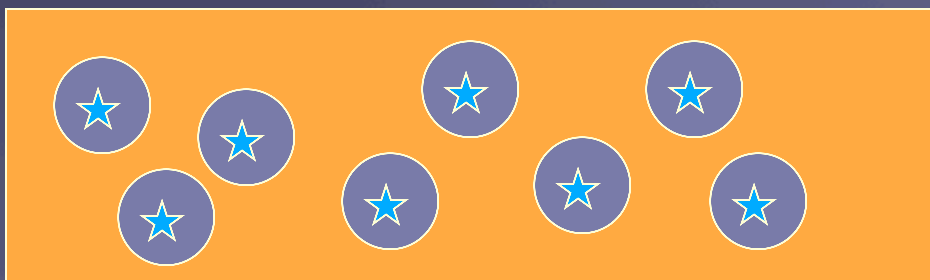
   power spectrum (21cm, kSZ) depressed on scales < m.f.p.

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

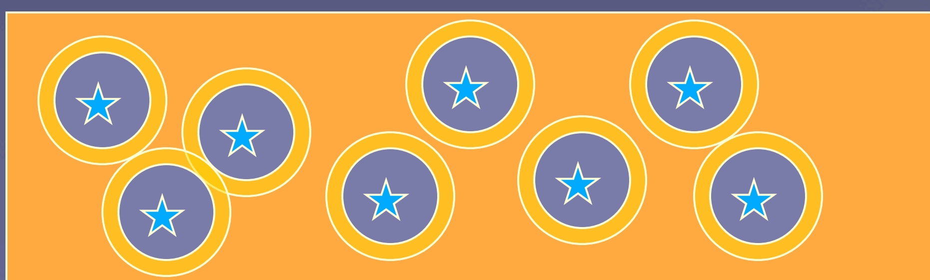
   mass ratio is a diagnostic

# Reionization by Stars vs BHs

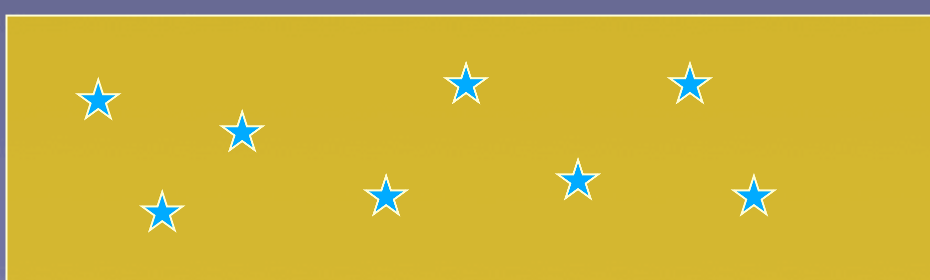
note: photon mean free path $\sim$ Gpc $(E/1\ \mathrm{keV})^{3}\ [(1+z)/10]^{-3}\ f_{HI}^{-1}$



**Stars only:**
Photon m.f.p. $\ll$ source sep.
swiss cheese



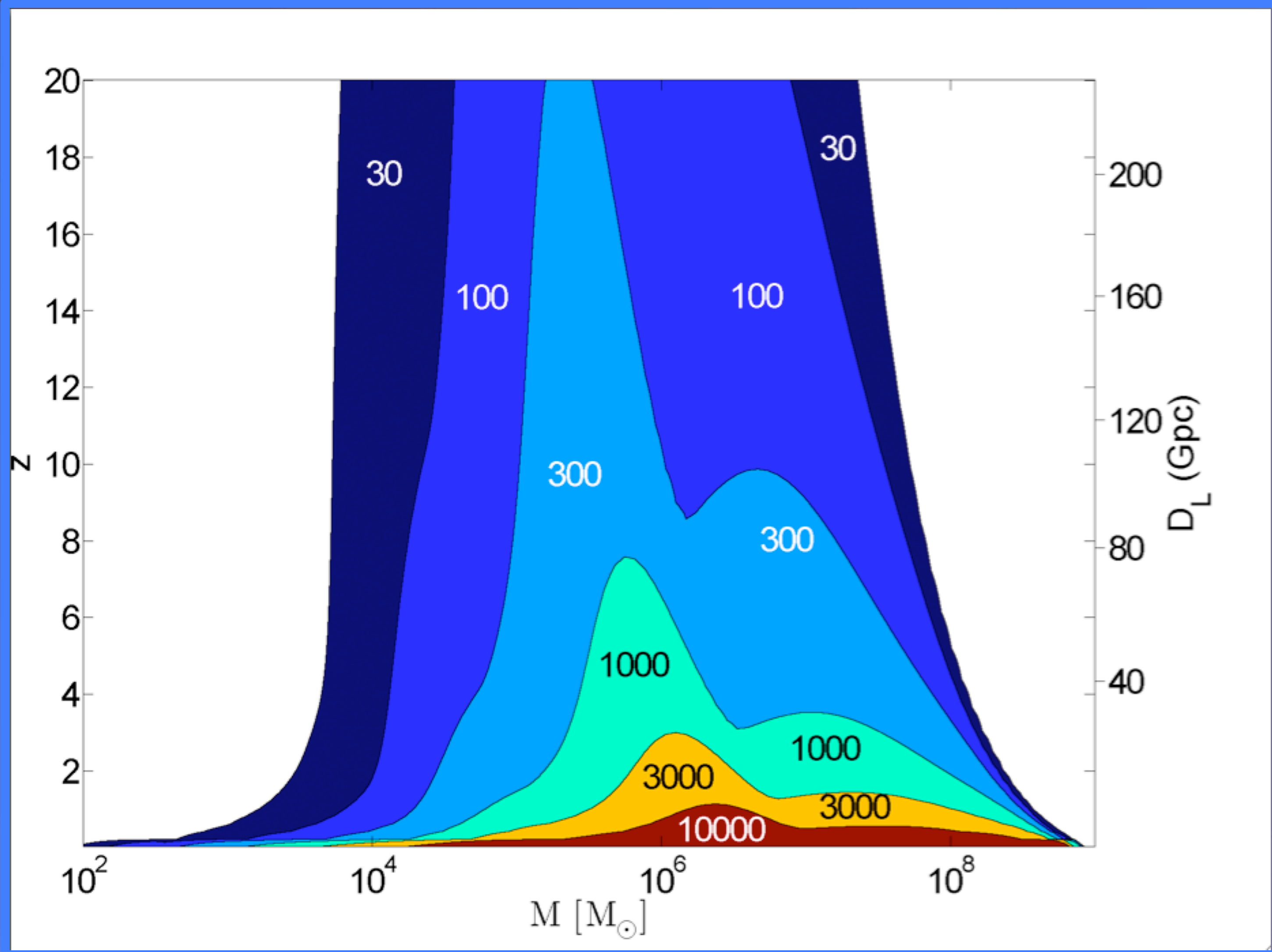
**Stars + BH mix:**
Photon m.f.p. $\lesssim$ source sep.
Blurred swiss cheese



**Accreting BHs dominate:**
Photon m.f.p. $\gtrsim$ 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 $M_{BH}$ - $\sigma$ 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