Rapid Formation of ~10^6 $M_\odot$ Seed Black Holes in High Redshift Halos

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New Windows on the High Redshift Universe Ayers Rock 14-18 July, 2013

Goddard Institute for Space Studies (GISS)
Columbia University

(Broadway & West 112th Street)

John Archibald Wheeler (1911-2008)

(in 1999 at Princeton University)

"Geons, Black Holes, and Quantum Foam: A Life in Physics" (1998)

In the fall of 1967, Vittorio Canuto, administrative head of NASA's Goddard Institute for Space Studies at 2880 Broadway in New York City, invited me to a conference to consider possible interpretations of the exciting new evidence just arriving from England on pulsars. What were these pulsars? Vibrating white dwarfs? Rotating neutron stars? What?[1] In my talk, I argued that we should consider the possibility that at the center of a pulsar is a gravitationally completely collapsed object. I remarked that one couldn't keep saying "gravitationally completely collapsed object" over and over. One needed a shorter descriptive phrase. "How about black hole?" asked someone in the audience. I had been searching for just the right term for months, mulling it over in bed, in the bathtub, in my car, wherever I had quiet moments. Suddenly this name seemed exactly right. When I gave a more formal Sigma

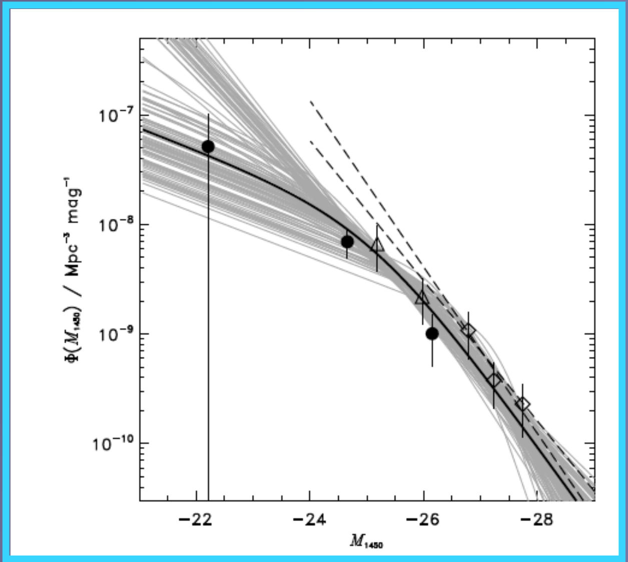
[1] Jocelyn Bell, the British student who found the first evidence for pulsars in 1967, began to refer jokingly to the source of the pulses as LGMs, or little green men.

High-redshift quasars

- **Rare (“4-5σ”) objects:**
  ~10 found in SDSS at z>6
  ~20 in CFHQS + few others

- **Record: z = 7.085 *(t=0.77 Gyr, UKIDDS)***
  Mortlock et al. (2011)

- **Tip of the iceberg (?):**
  Space density ~1 Gpc^{-3}



Willott et al. (2010)

- **Mass estimates**

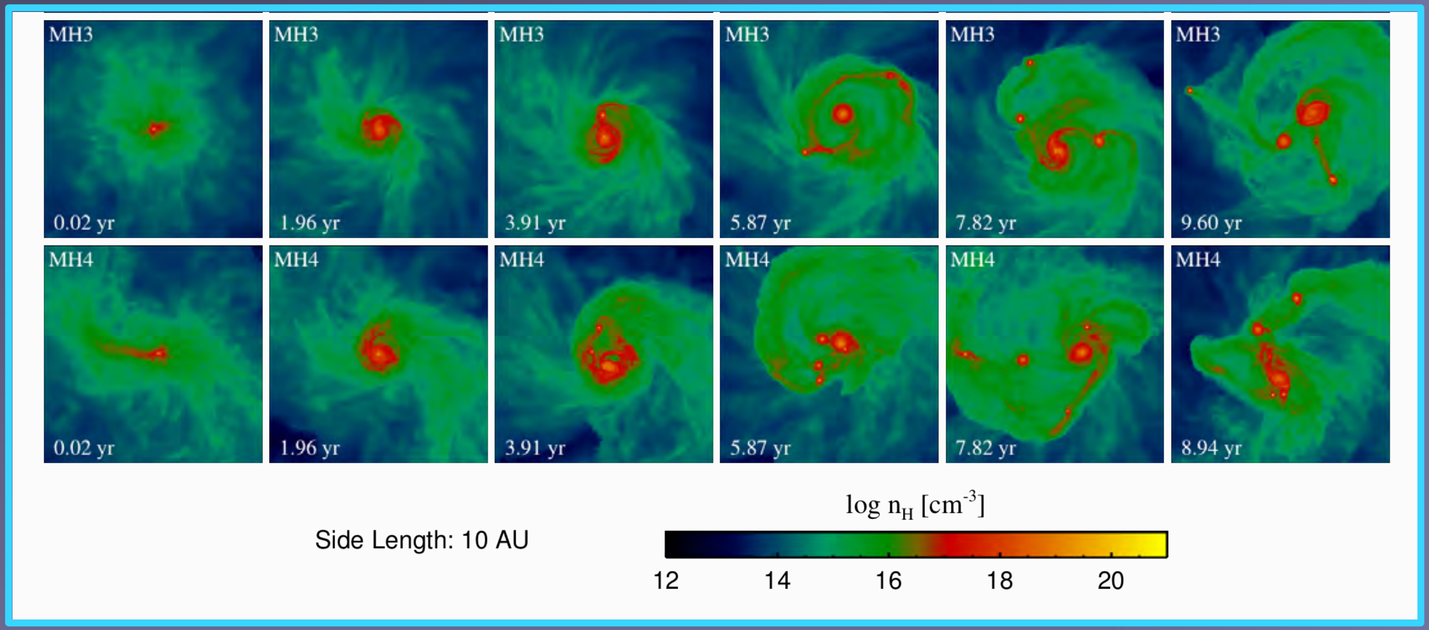
$$\mathbf{M_{bh} = L_{obs} / L_{Edd} \approx 10^{9\text{-}10}\, M_\odot}$$ **(Eddington luminosity)**

$$\mathbf{M_{halo} \approx 10^{12\text{-}13}\, M_\odot}$$ **(Matching space density)**

3D Simulation of a Primordial Gas Cloud

Greif et al. (2012)

Abel et al. (2002), Bromm et al. (2002), Yoshida, Omukai & Hernquist (2008), …



Cosmological mini-halo:

$M_{halo} \approx 3\times10^5\ M_\odot$

$z_{coll} \approx 20$

Protostar(s) in core:

$T \approx$ few$\times$100 K

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

$M_* \approx 0.1$ -1 $M_\odot$

Upper limit on stellar mass

Stellar-mass BH is left behind for $M_* > 25\ M_\odot$

(Heger et al. 2003)

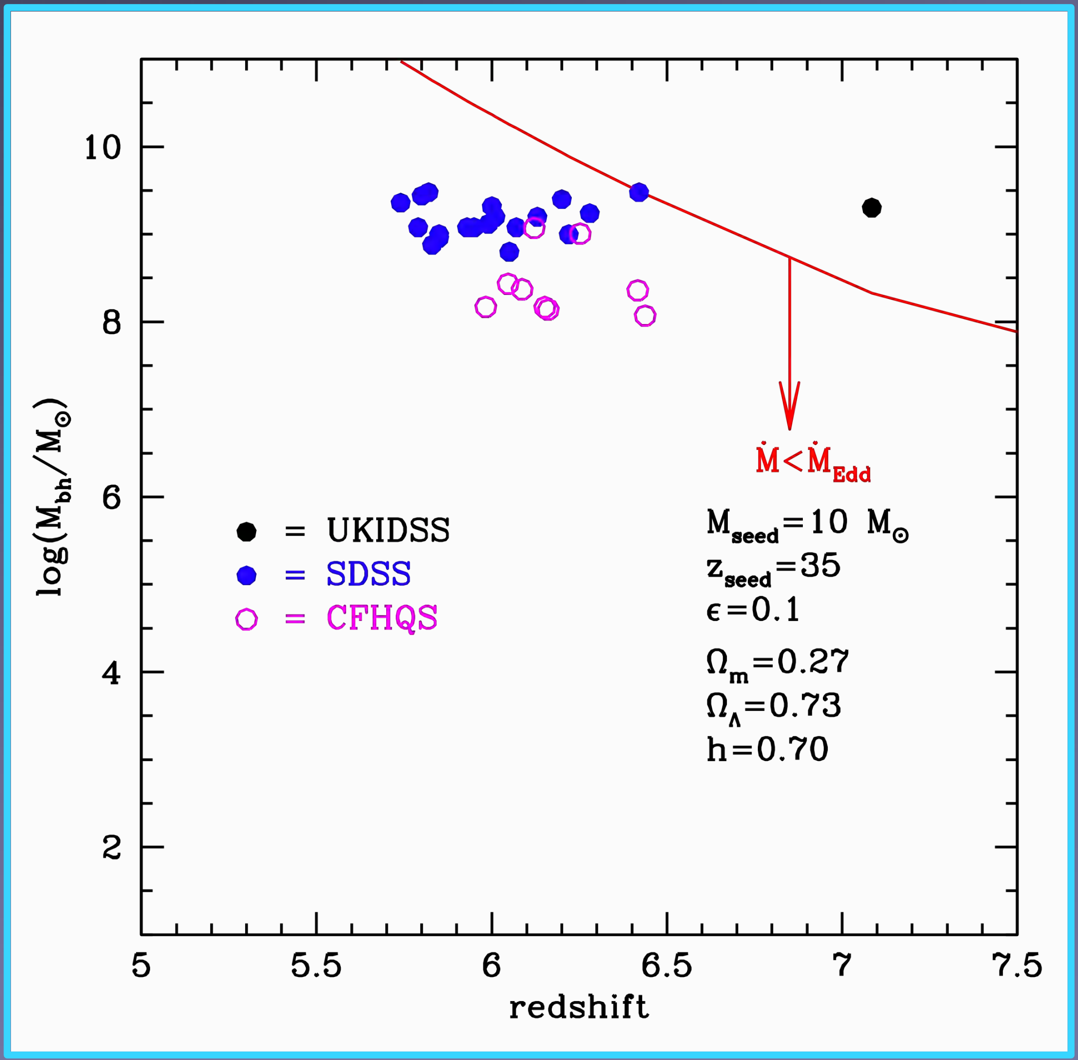
- **Gas infall at sound speed:** $c_s \approx$ 1-2 km/s **dictated by H_2**
- **Mass accretion rate:** $M_{acc} \approx c_s^3/G$ = few × $10^{-3}\ M_\odot\ yr^{-1}$
- **Star's mass:** $M \approx M_{acc} \times t_{KH} \approx M_{acc} \times 10^5$ yr = few × $10^2 M_\odot$
- ***Result: massive stars and stellar-mass BH remnants***

- **Final stellar masses can be reduced by:**

  - fragmentation (Greif et al. 2012)

  - radiation of protostar (43 $M_\odot$ - Hosokawa et al. 2012)

Can stellar seeds grow into z=6 quasar BHs?



e-folding (Edd) time:
$M/(dM/dt) = 4\ (\varepsilon/0.1)\ 10^7 yr$

Age of universe (z=6-7)
$(0.8 - 1) \times 10^9$ yr

Must start early!

Accretion rate must keep up w/ Eddington most of the time

Obvious alternatives:
(1) merge many BHs
(2) grow faster

Masses estimated from: Fan et al. (2006); Willott et al. (2010); Mortlock et al. (2011)

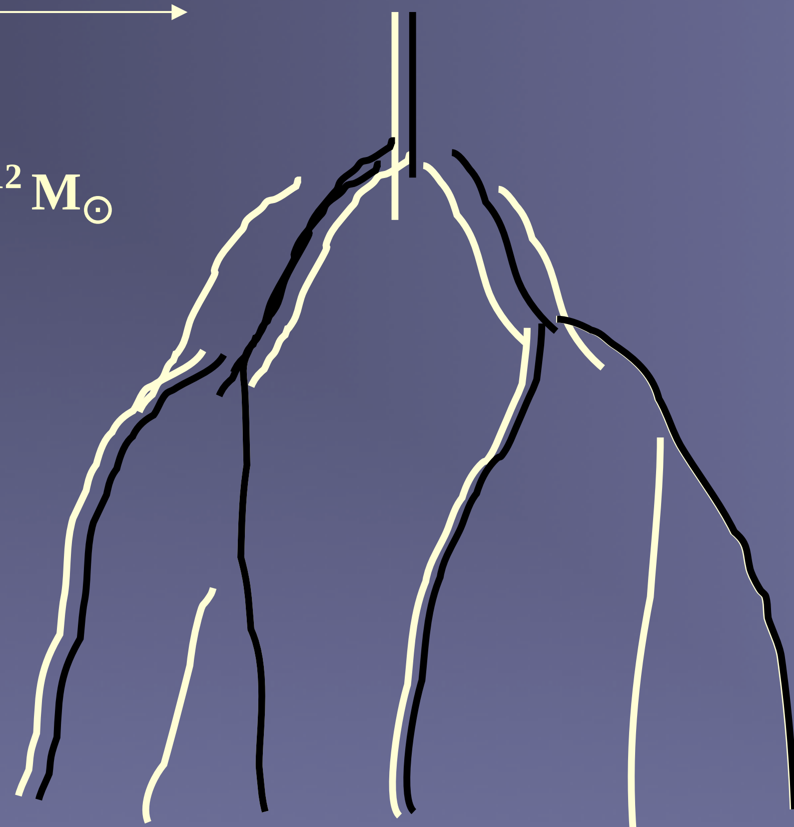
Growing SMBHs by Accretion + Mergers

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

Merger trees: 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), Volonteri & Natarajan (2010), …

Hydro simulations: Li et al. (2007); Pelupessy et al. (2007); Sijacki et al. (2009) Bellovary et al. (2011), di Matteo et al. (2012), …

Growing SMBHs by Accretion + Mergers

Tanaka, Perna & Haiman (2012)

Construct Monte-Carlo DM halo merger trees from z=6 to z>45

$$10^8 M_\odot \leq M_{halo} \leq 10^{13} M_\odot$$

($\mathbf{M_{res} = 3\times10^4\, M_\odot}$; N~$10^5$ trees; $\mathbf{V_{eff} \sim 5\ Gpc^3}$)

Q1: Fraction of minihalos forming stellar BH seeds ?

- $M_{seed} \approx 20\, M_\odot$
- $\mathbf{f_{seed}} \sim 0.01$-1 (requires only 1 star with $M_* > 25\, M_\odot$ - most can be low-mass)

Q2: Time-averaged mass accretion rate ?

- $\varepsilon = 0.07$ (radiative efficiency)
- $0.5 \leq \mathbf{f_{duty}} \leq 1.0$ (time-averaged Eddington rate)

Q3: What happens to the BHs when halos merge?

- **gas drag** leads to coalescence of BHs
- **gravitational recoil**: v_{kick} - spins aligned or random **(Lousto et al. 2010)**
  follow kicked BH trajectory - damped oscillation (gas drag)

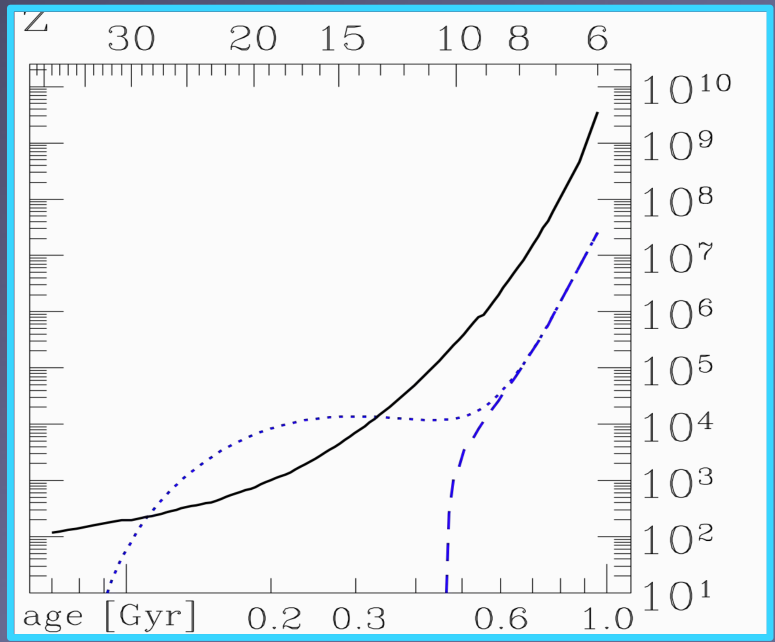
Making the ~10^9 $M_\odot$ SMBHs

Tanaka, Perna & Haiman (2012)

redshift

M_{BH} [$M_\odot$]

ρ_{BH} [$M_\odot Mpc^{-3}$]



age of universe (Gyr)

$10^9 M_\odot$ BHs from unusually massive ($10^2 M_\odot$) runaway early seeds (z>20) that avoided ejection at merger: asymmetric mass ratio q<0.01

Making the ~10^9 $M_\odot$ SMBHs

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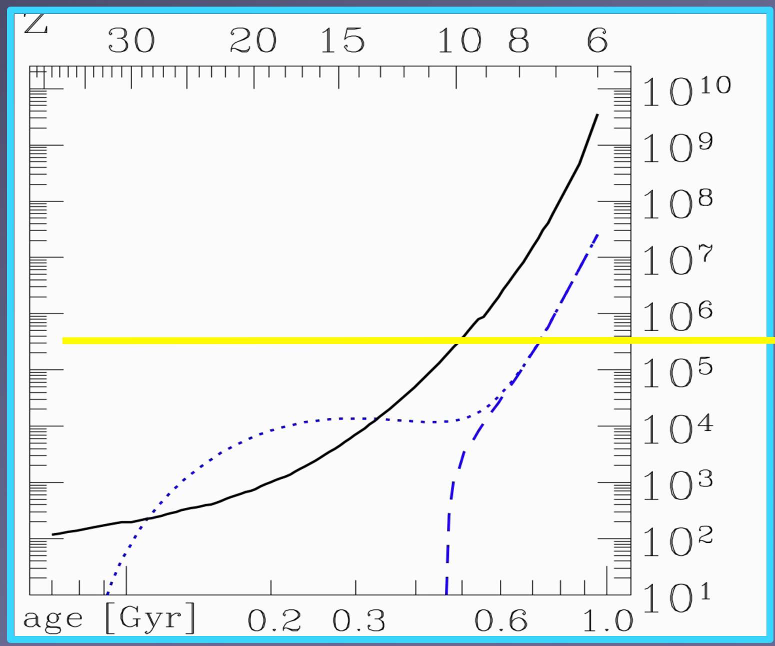

age of universe (Gyr)

Local SMBH Mass density:

$\rho_{tot} \approx 4\times10^5$ $M_\odot Mpc^{-3}$

$10^9 M_\odot$ BHs from unusually massive ($10^2 M_\odot$) runaway early seeds (z>20) that avoided ejection at merger: asymmetric mass ratio q<0.01

Self-regulation by X-ray "Global Warming"

Tanaka, Perna & Haiman (2012)

redshift

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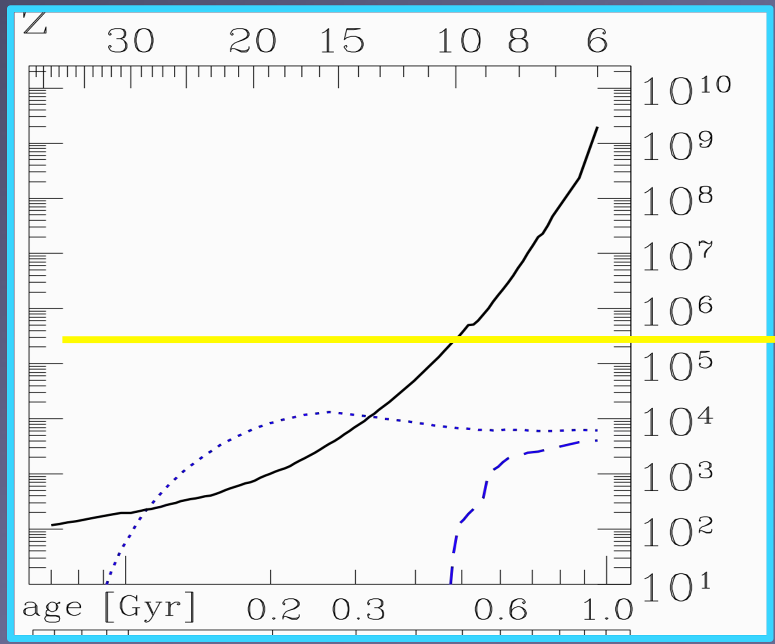

age of universe (Gyr)

Local SMBH Mass density: $\rho_{tot} \approx 4 \times 10^5$ $M_\odot Mpc^{-3}$

Total BH mass density remains below 10% of its present-day value

Self-regulation by X-ray "Global Warming"

Tanaka, Perna & Haiman (2012)

redshift

M_{BH} [$M_\odot$]

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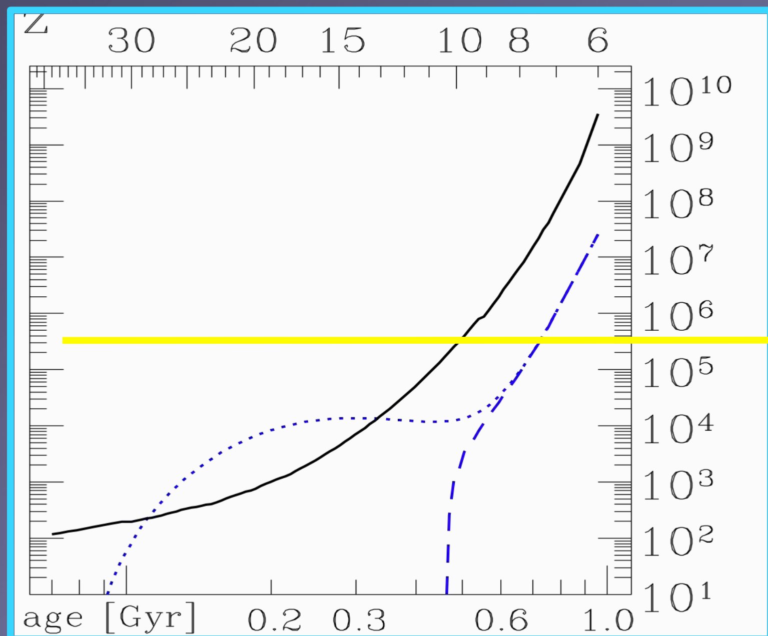

age of universe (Gyr)

Local SMBH Mass density:

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(not everyone like this)

Watts Up With That?

Quote of the Week: 'global warming stunts black holes'

Posted on June 10, 2012 by Anthony Watts

It appears "global warming" is now the most potent force in the universe, according to a scientist from the Max Planck Institute for Astrophysics. An actual scientific paper preprint published in the Cornell University science archive makes the connection to black holes in the title, and includes "climate change" in the abstract.

Sigh. It isn't even past coffee on Sunday morning and already we have our winner. This one... is weapons grade stupidity. I would not believe that a scientist from a prominent research institute could utter such a statement had I not read it in a prominent science magazine. It's another "Vinerism" in the making: *Children just aren't going to know what black holes are.*

It immediately reminded me of the famous line uttered by Tom Cruise in the movie a *A Few Good Men*:

> ***"Should we or should we not follow the advice of the galactically stupid!***

But then again, this is *The New Scientist*. Read on, emphasis mine.

> ...
>
> *Something must have limited the growth of these black holes. Now Takamitsu Tanaka at the Max Planck Institute for Astrophysics in Garching, Germany, and colleagues* ***have a climate-based explanation.***
>
> ...
>
> *Black holes need cool gas to grow so this would have slowed down the growth of other black holes in smaller protogalaxies, even as the growth of black holes in the most massive protogalaxies continued apace (arxiv.org/abs/1205.6467v1).*

Alternative: direct collapse ($\dot{M} >> \dot{M}_{Edd}$)

rapid formation of 10^5-10^6 $M_\odot$ black holes at $z>10$

- by direct collapse of gas

- or via intermediary: supermassive star, quasi-star, or ultra-dense cluster of low-mass stars

  - gas must be driven in rapidly (requires deeper potential)
  - transfer angular momentum
  - must avoid fragmentation
  - *avoid cooling via H_2 to $T \sim$ few 100 K*

a promising site: $T_{vir}>10^4$ K ($M>10^8$ $M_\odot$) halos
abundance: $n \sim 1$ Mpc^{-3} at $z=10$

A promising site: $T_{vir} \gtrsim 10^4$K halos?

- **Rapid infall if gas remains hot $T_{gas} \approx 10^4$ K (due to lack of H_2) but cools efficiently via atomic HI:** $\dot{M}_{acc} \approx c_s^3/G \approx 1\ M_\odot\ yr^{-1}$

  cf: Eddington rate **$10^{-2}\ (\varepsilon/0.1)^{-1}(M_{BH}/2\times10^5 M_\odot)\ M_\odot\ yr^{-1}$**

  need closer to **$\sim 1 M_\odot\ yr^{-1}$** to accrete **$\sim 10^5 M_\odot$** in KH time of **10^5 yr**

- **"Mo-Mao-White" disk with isothermal gas at $T_{vir} > T_{gas} \approx 10^4$ K is *fat* and *Toomre-stable*, gas could avoid local fragmentation**
  (Oh & Haiman 2002)

- **No fragmentation seen in simulations in absence of H_2**
  (Bromm & Loeb 2003; Wise & Abel 2007; Regan & Haehnelt 2009; Shang et al. 2010)

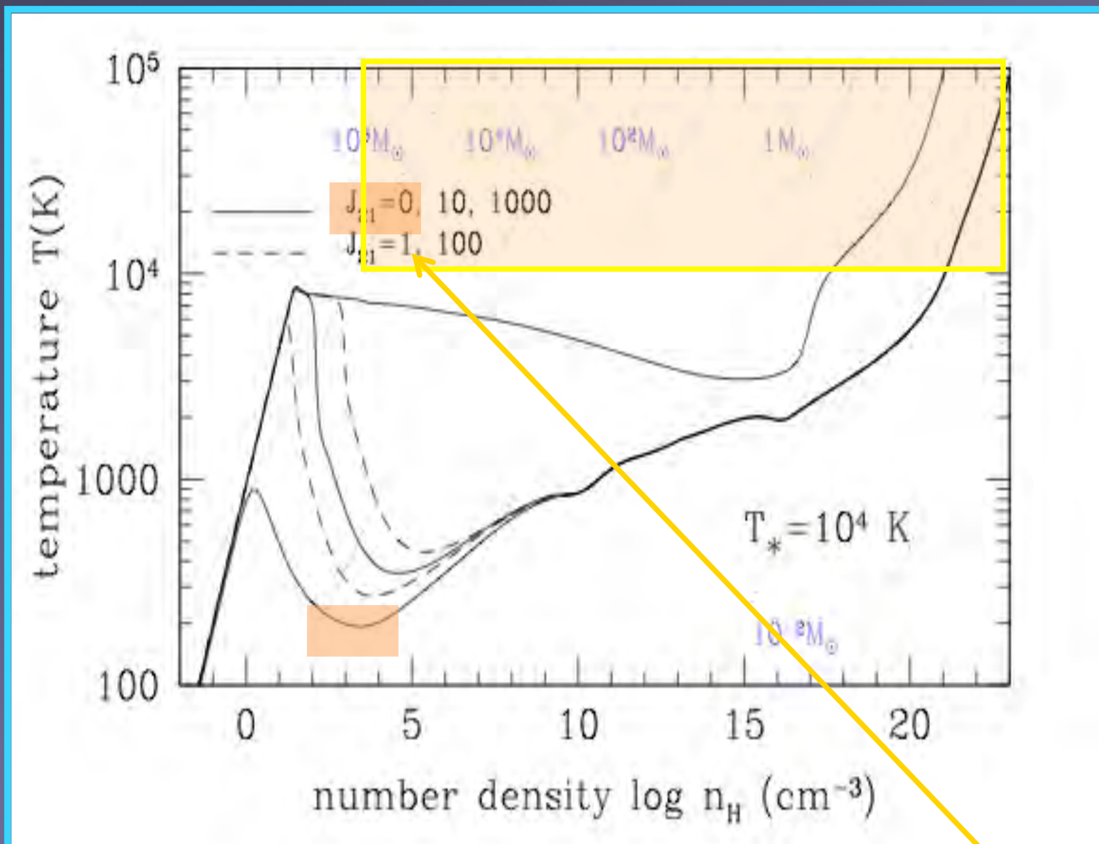
- **Gas can then:**

  - collapse rapidly onto a stellar-mass seed BH
  (Volonteri & Rees 2005)

  - 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)

  - fragment into ultra-dense $10^4 M_\odot$ **star cluster via metals/dust ➔** IMBH
  (Omukai, Schneider & ZH 2008; Devecchi & Volonteri 2009)

How to avoid H_2 cooling & fragmentation?



Omukai, Schneider & Haiman (2008)

- In "minihalos" gas cools by H_2 and forms PopIII stars
- In "T_{vir}>10^4K" halos (with no prior star-formation) gas cools via Lyα
  - ➔high density
  - ➔H_2 cooling activated
  - ➔ $M_{acc} \propto c_s^3 \sim 10^{-2}\ M_\odot\ yr^{-1}$
  - ➔ similar to popIII !

To avoid this, gas must stay 10^4K until 'safe zone' at $n>n_{crit} \sim 10^4\ cm^{-3}$

➔ Destroy H_2 with huge LW flux: $J_{21}(crit) \approx 10^4$ Shang et al. (2010)

Self-Shielding of H_2 Lyman Werner lines

Wolcott-Green, Haiman & Bryan (2011)

- **Critical for SMBH formation:**

  $f_{shield} = J(N_{H2})/J(N_{H2}=0) \approx$ several $\times$ 0.01

- **Two-step process: $H_2 + \gamma \rightarrow H_2^{(*)} \rightarrow H + H + \gamma'$**

- **Radiative transfer must be followed for O(10) lines in ground state; O(100) lines at T=few × 1000 K**

- **Also: anisotropic density, velocity, temperature gradients**

→ Previous works assume optically thin gas, or (mis)use local N_{H2} with $f_{shield}(N_{H2})$ from Draine & Bertoldi 1996

$$\boxed{\text{J(crit) reduced by a factor of >10 to } J_{crit} \approx 10^3}$$

Achieved in close (~10kpc) pairs of 10^8 $M_\odot$ halos Dijkstra et al. (2009)

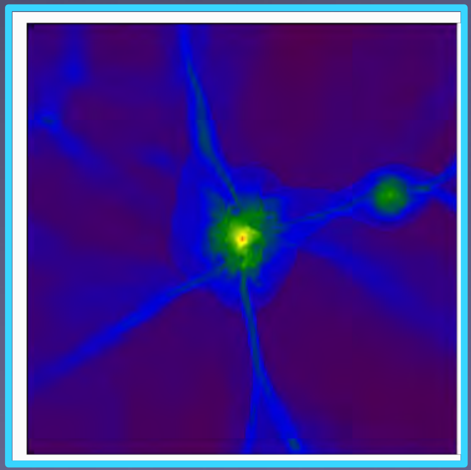
3D proto-galaxy simulation with $J_{21}=10^3$

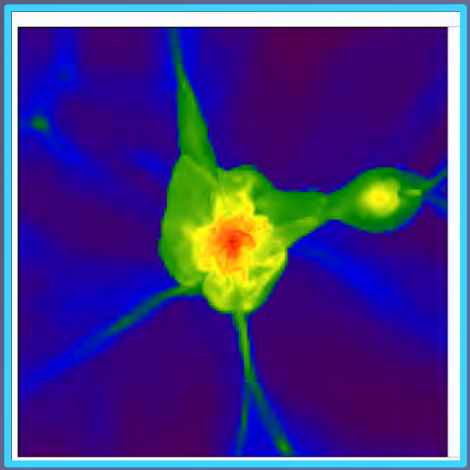
Enzo - atomic cooling halos with $M_{halo} \approx 10^8 M_\odot$ $z_{coll} \approx 14$

Fernandez, Bryan, Haiman & Li (2013)

Gas stays near 10^4K – never forms enough H_2 to cool further

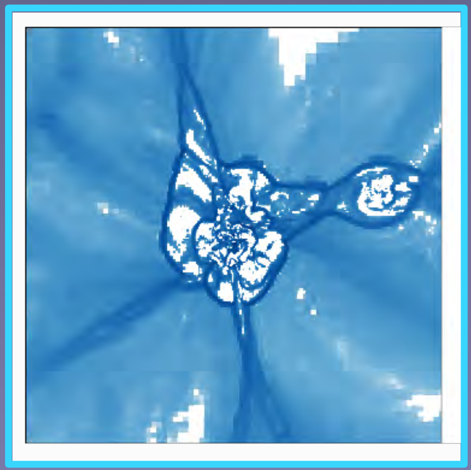
density





Temperature

$-\nabla \cdot v$

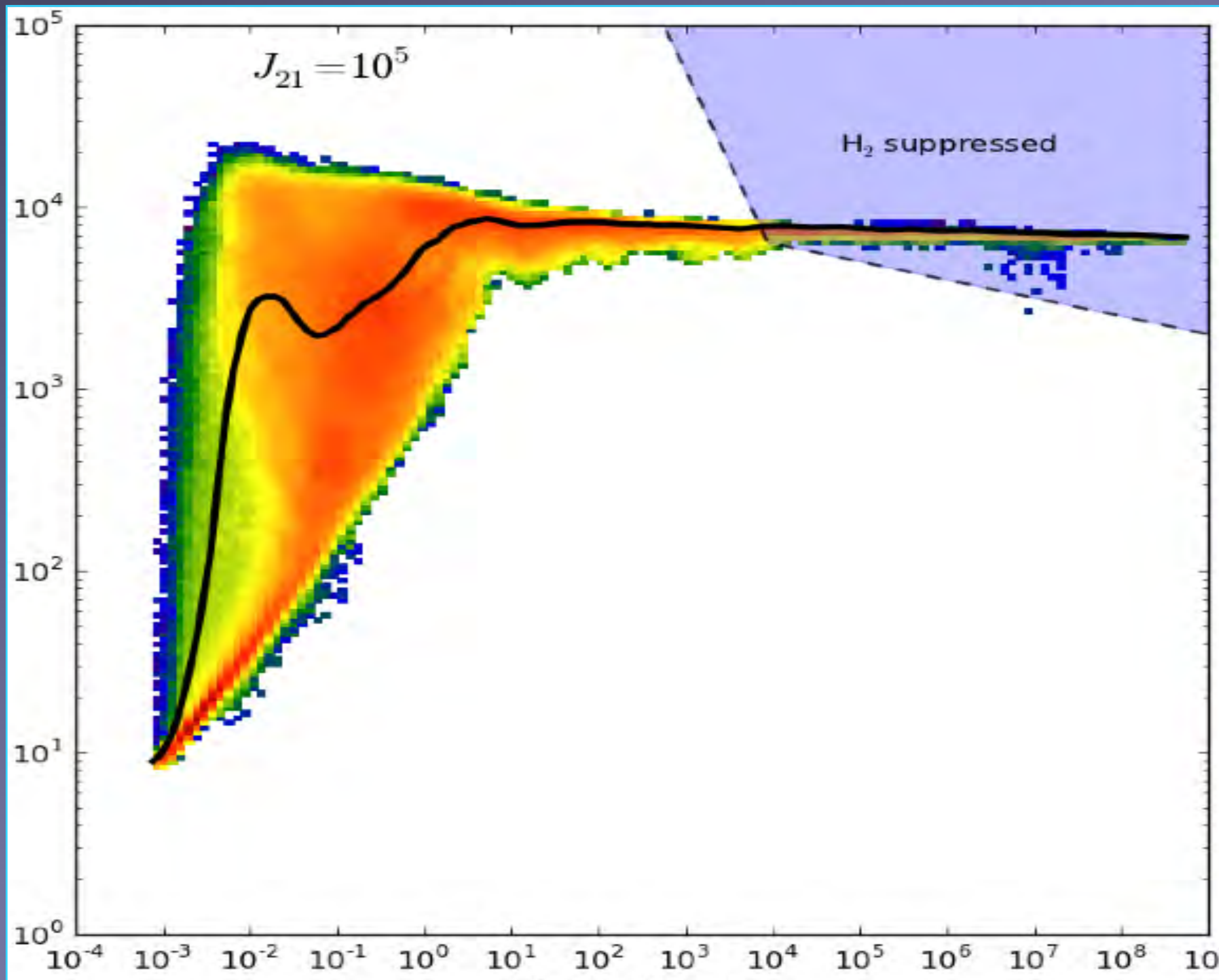


Mach number

3D proto-galaxy simulation with $J_{21}=10^3$

Fernandez, Bryan , Haiman & Li (2013)

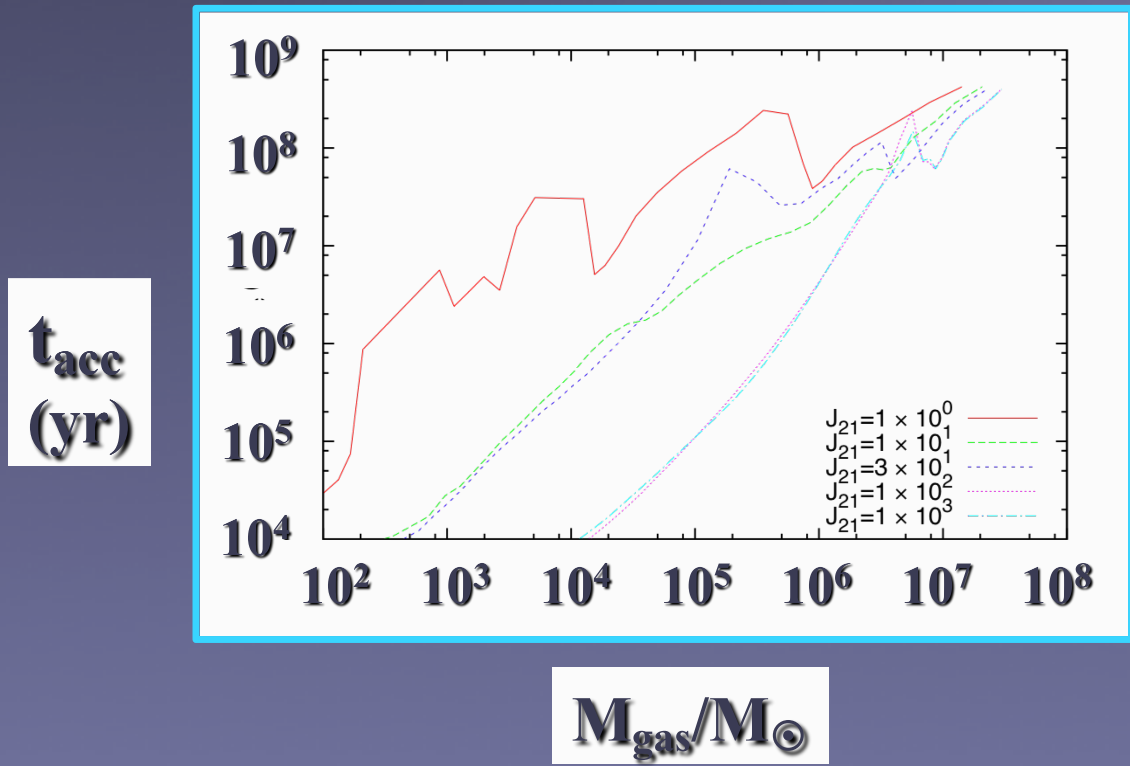
Temperature



number density

Mass of Central Object

Shang, Bryan & Haiman (2010); Fernandez et al. (2013)



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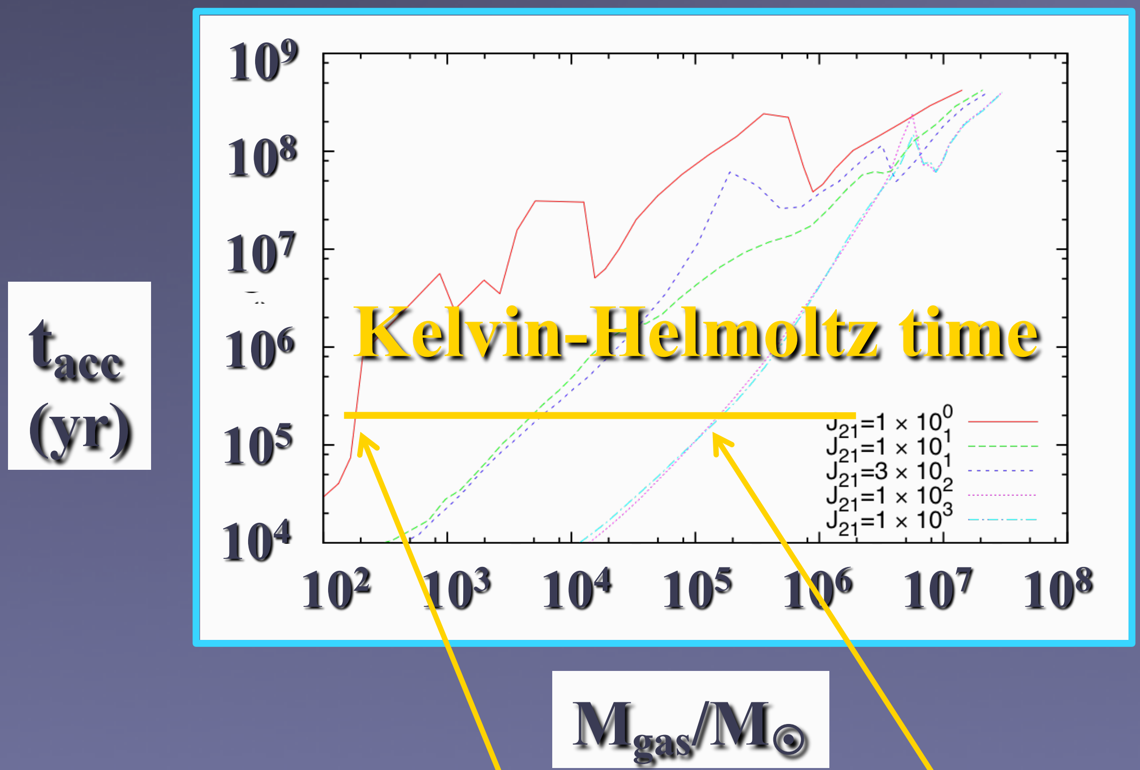


10^2 $M_{\odot}$ Pop III star

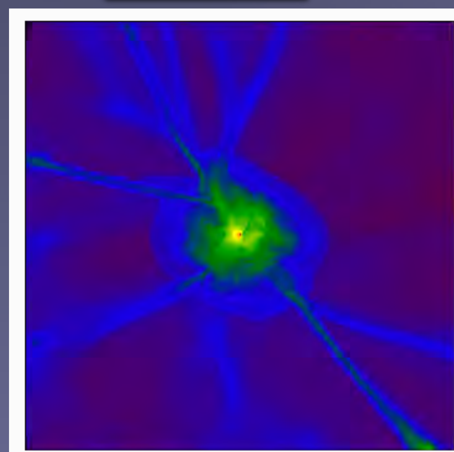
10^5 $M_{\odot}$ supermassive star/BH ($M_{acc} \sim 1$ $M_{\odot}$ yr^{-1})

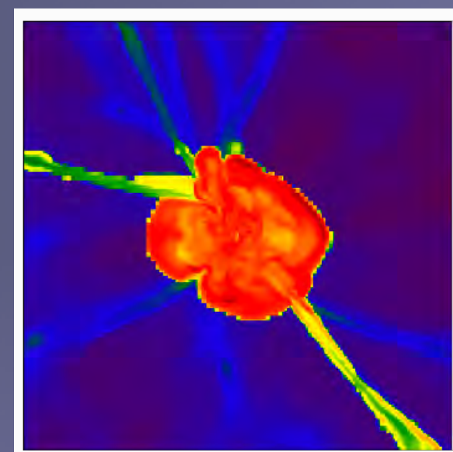
H_2 cooling avoided without huge J_{LW}?

Fernandez, Bryan, Haiman & Li (2013)

- Analogous to 'cold accretion': central shock heats gas to 'safe zone'
- Can live with ~100 times lower flux of J~10? Inayoshi & Omukai (2012)
- Look for shocks <u>in core</u> with Mach number > 4-5

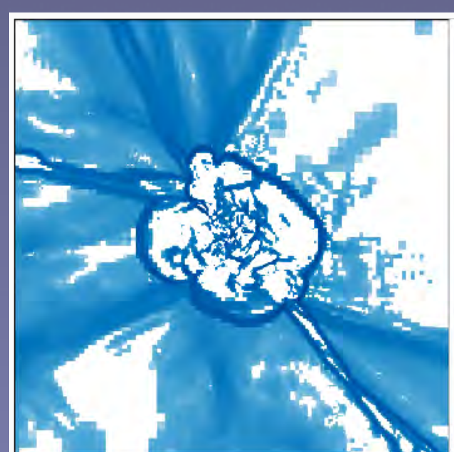
density

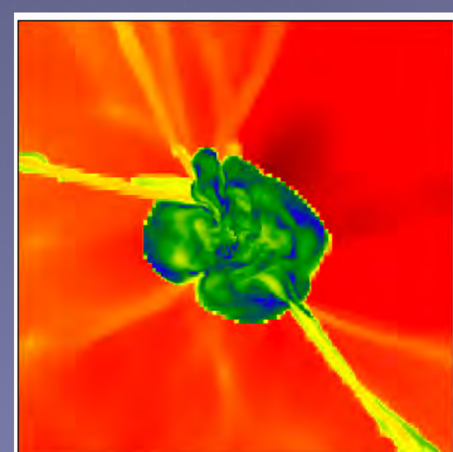




Temperature

$-\nabla\cdot v$





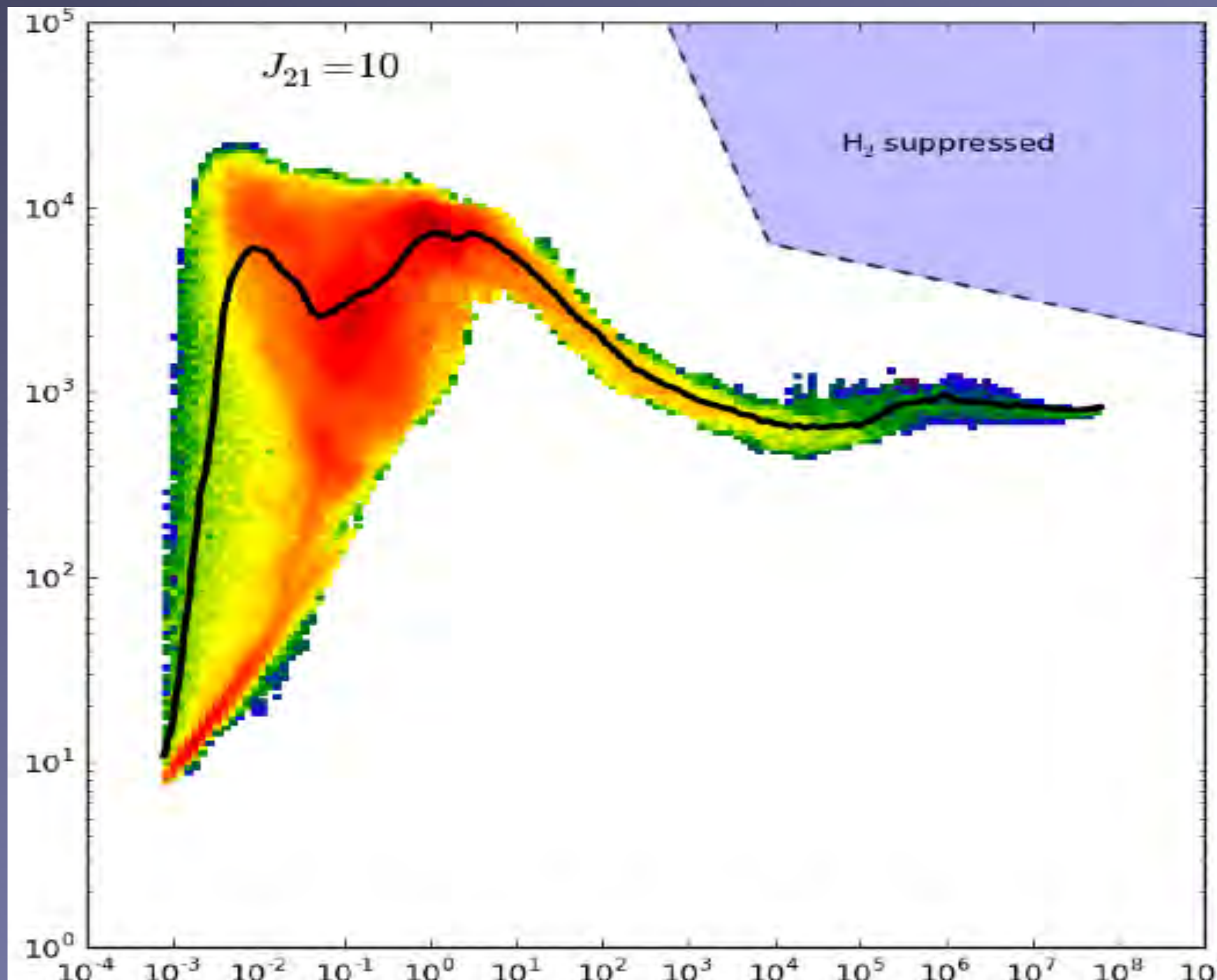
Mach number

(3×3 kpc)

No strong shocks in dense core (J_{21}=10)

Fernandez, Bryan, Haiman & Li (2012)

Temperature



number density

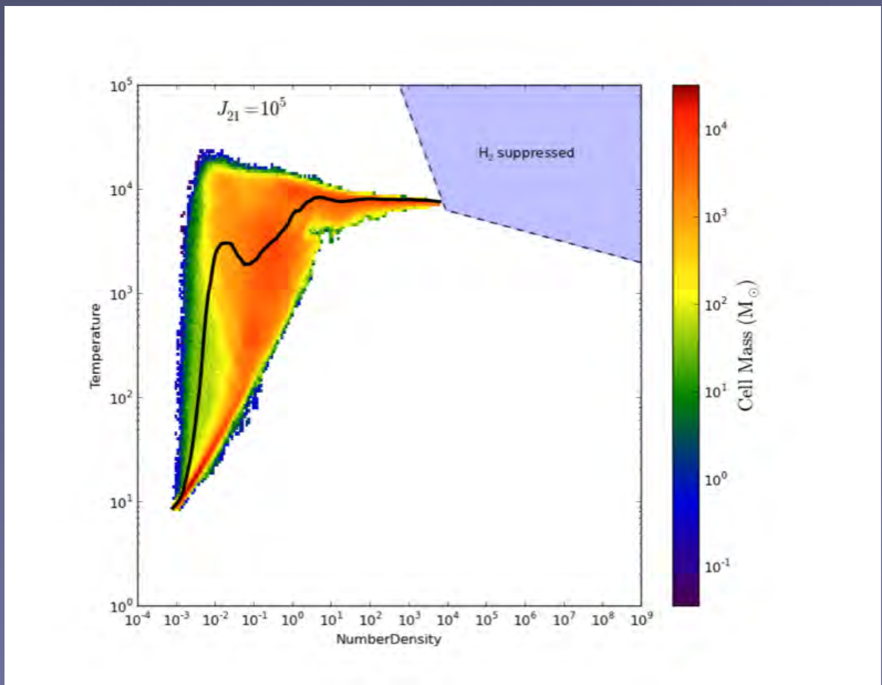
But: physics of "safe zone" still works (question is how to get there)

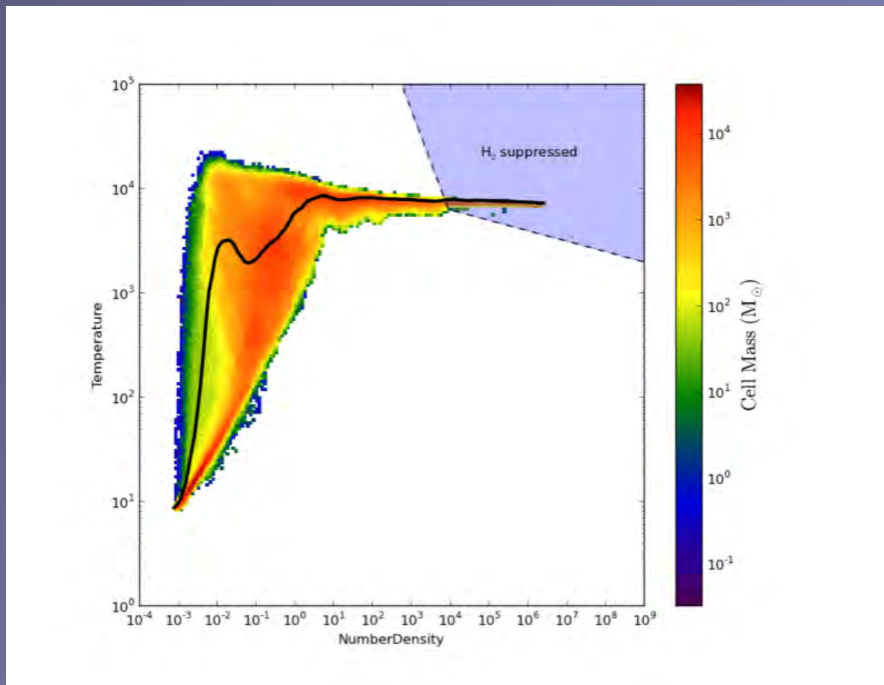
Fernandez, Bryan, Haiman & Li (2013)

J off *just before*

J off *just after*

Temperature



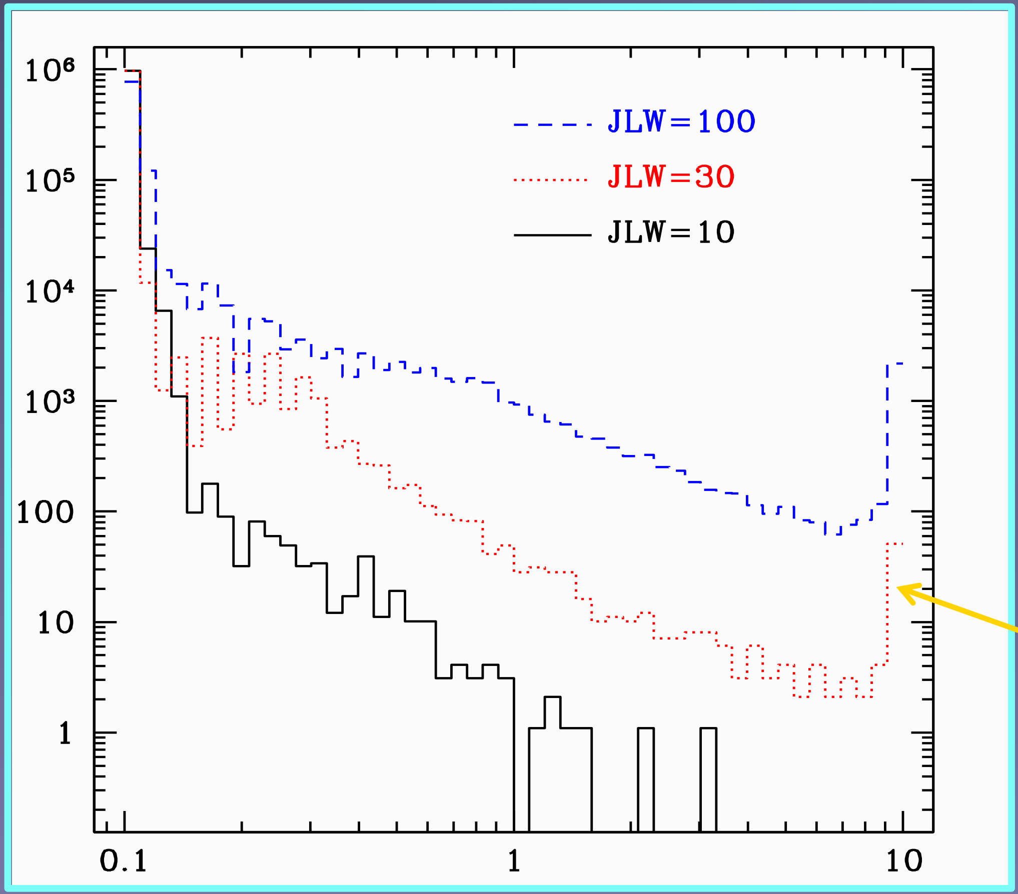


number density

number density

Solution: unusually rapid merger history !

Requirement: *<u>all</u> progenitor halos always experience a merger before they are could cool by H_2 & collapse*



Number of halos

Look-back redshift

10^6 merger trees

Example: J=20

fraction 10^{-5} of z=10 parent halos have no progenitors that could cool:

10^4 such halos per Gpc^3

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

   mass ratio is a diagnostic

3. 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.

4. Fossil evidence: occupation fraction of BHs in local dwarfs

Conclusions

1. Growing z>6 SMBHs with $\sim 10^9 M_\odot$ requires extreme assumptions:

   (i) stellar seeds grow at Eddington rate without interruption, or

   (ii) rapid "direct collapse" in rare special environments

2. Challenge (i): not to overproduce number of $\sim 10^{5\text{-}6} M_\odot$ SMBHs.

   → seed formation AND growth are suppressed by X-ray "global warming"

3. Challenge (ii): not to cool by H_2 and fragment into PopIII stars.

   → large Lyman-Werner flux ($J_{21} \sim 10^3$) in close halo pairs, or rapid halo assembly

4. Future Observations:

   faint-end quasar LF (optical/radio/X-ray) to $\sim 10^{5\text{-}6} M_\odot$ (e.g. JWST)

   BH demography in dwarfs; GWs from eLISA up to 10's of mergers/yr

   smooth reionization topology (e.g. 21cm, kSZ) to diagnose X-rays

Le Fin