Open Questions About the First Galaxies

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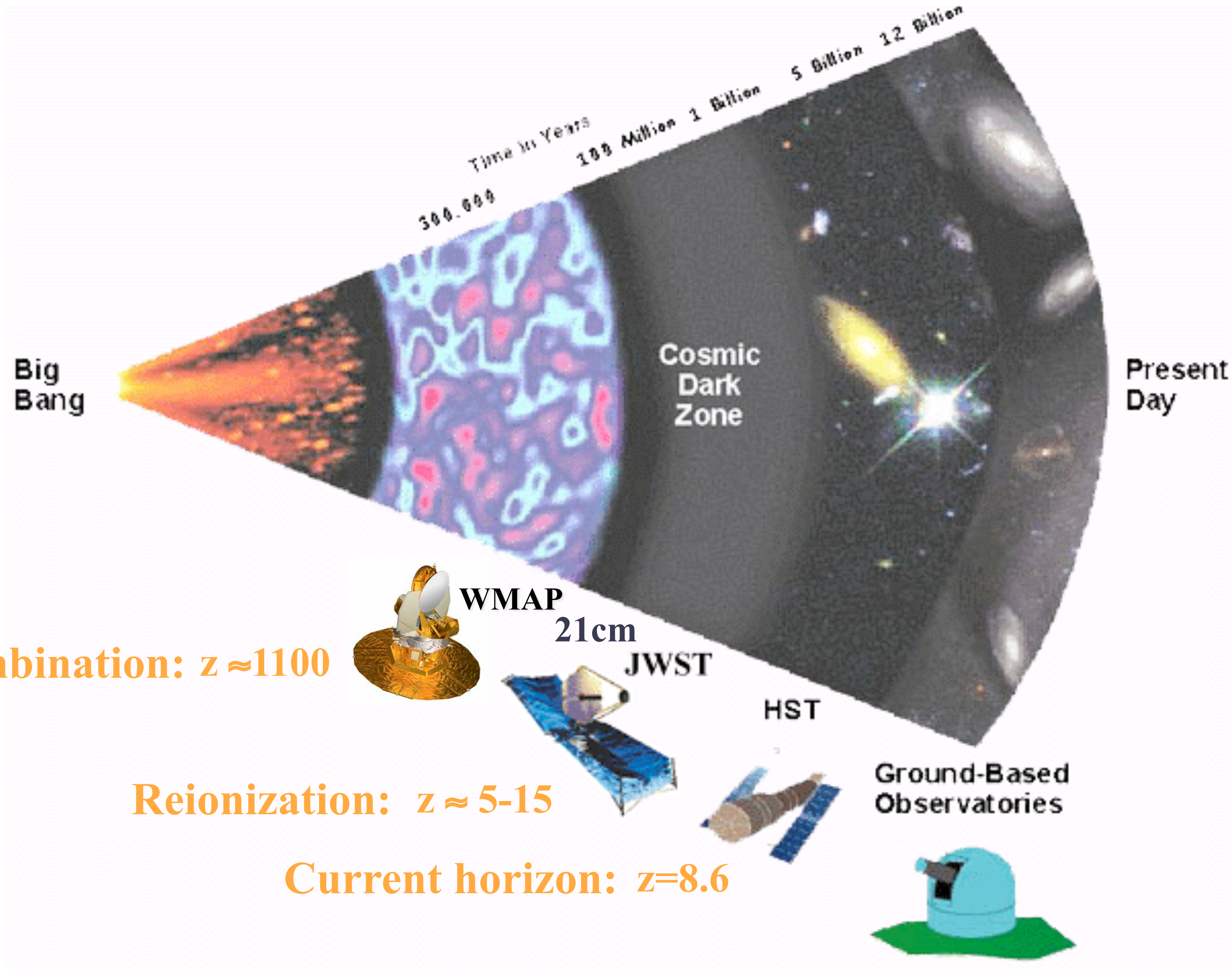
The Dark Age



(Re)combination: $z \approx 1100$

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

Current horizon: $z=8.6$

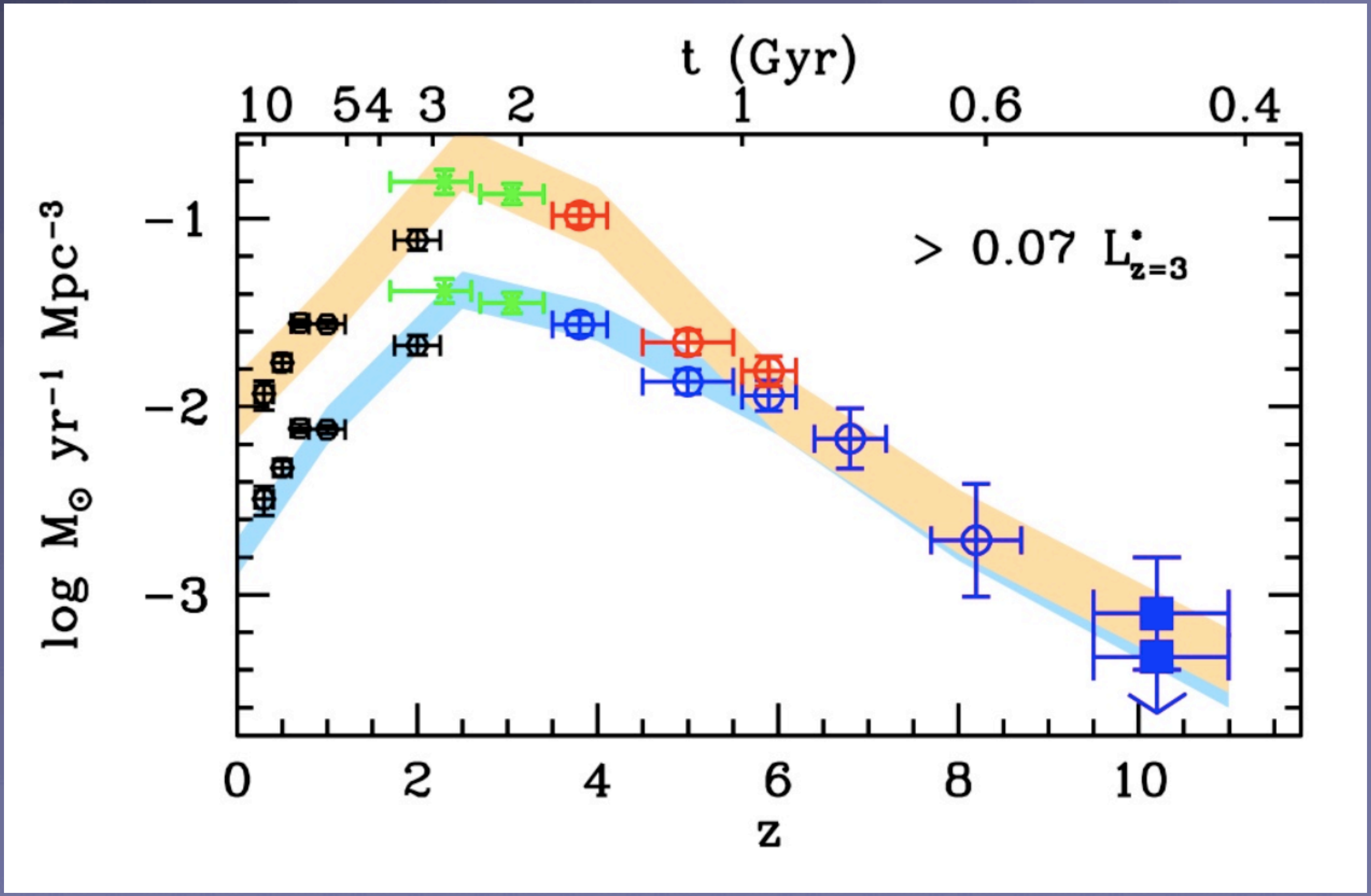
Even most basic questions are open!

- When did the first stars form, and what were their masses ? (rotation rates?)
- Were they isolated or multiple-star systems?
- When and how did they first assemble into something “stable” that we would call a galaxy?
- When did the first BHs appear, and how did they grow so rapidly into $10^9\,M_{\odot}$ BHs that are present at z=6?
- When and how was the universe re-ionized?

Challenge to audience: can you pose a question* about the first galaxies that has been settled uncontroversially?

* Question must be (i) intelligent and (ii) must have a non-trivial answer

Results from Hubble Ultra Deep Field



Bouwens et al. 2010; Illingworth et al. 2010, ….

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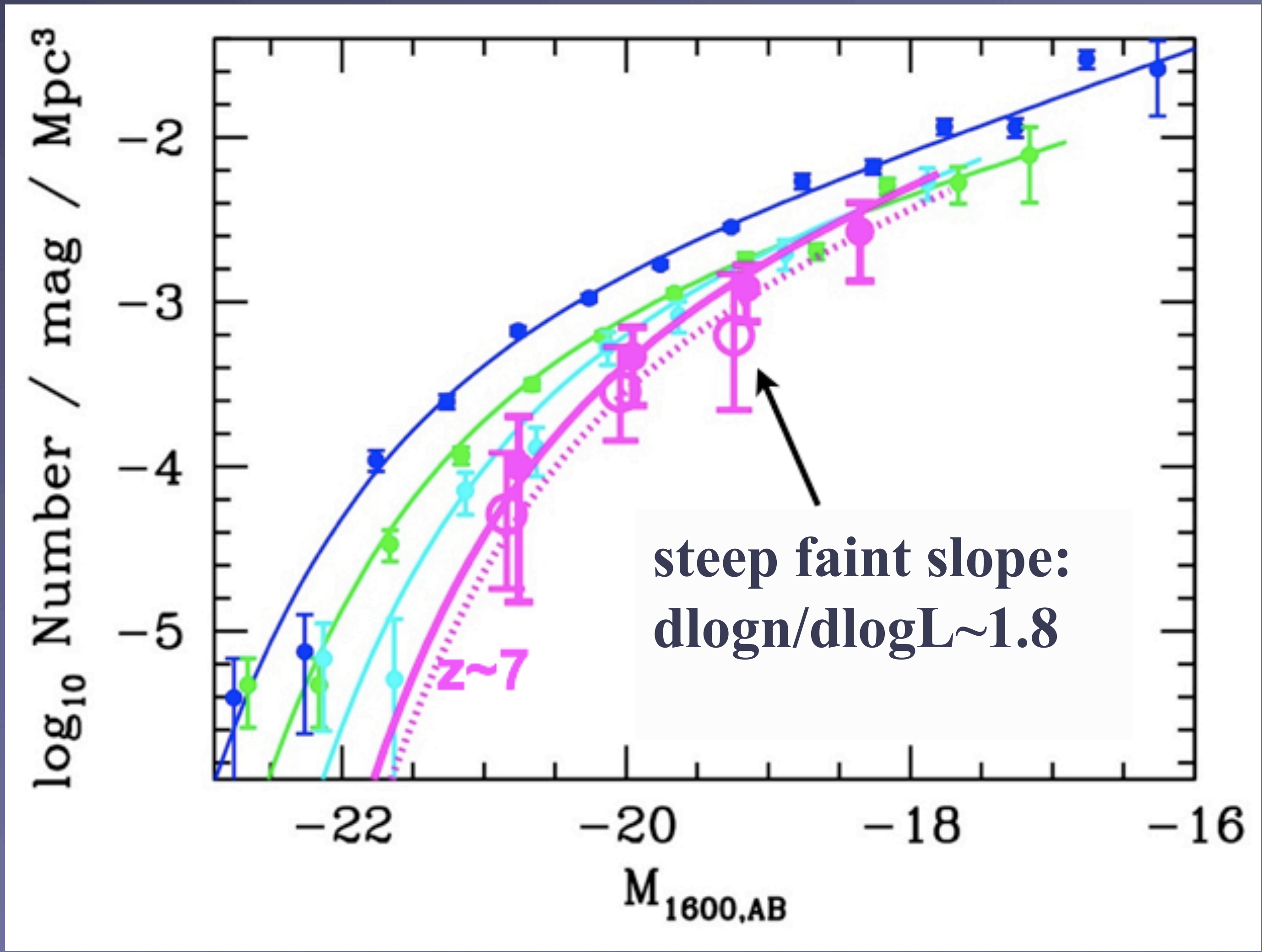
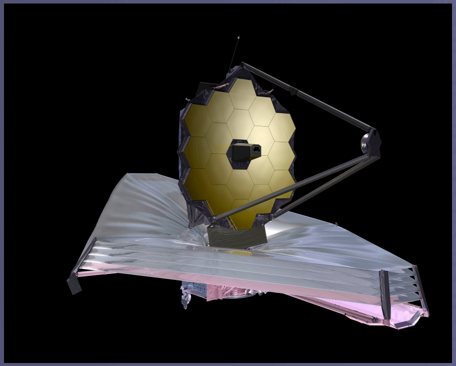


Bouwens et al. 2010; Illingworth et al. 2010, ….

James Webb Space Telescope (JWST)

a.k.a.
First Light
Machine

Launch: 2014 (?)

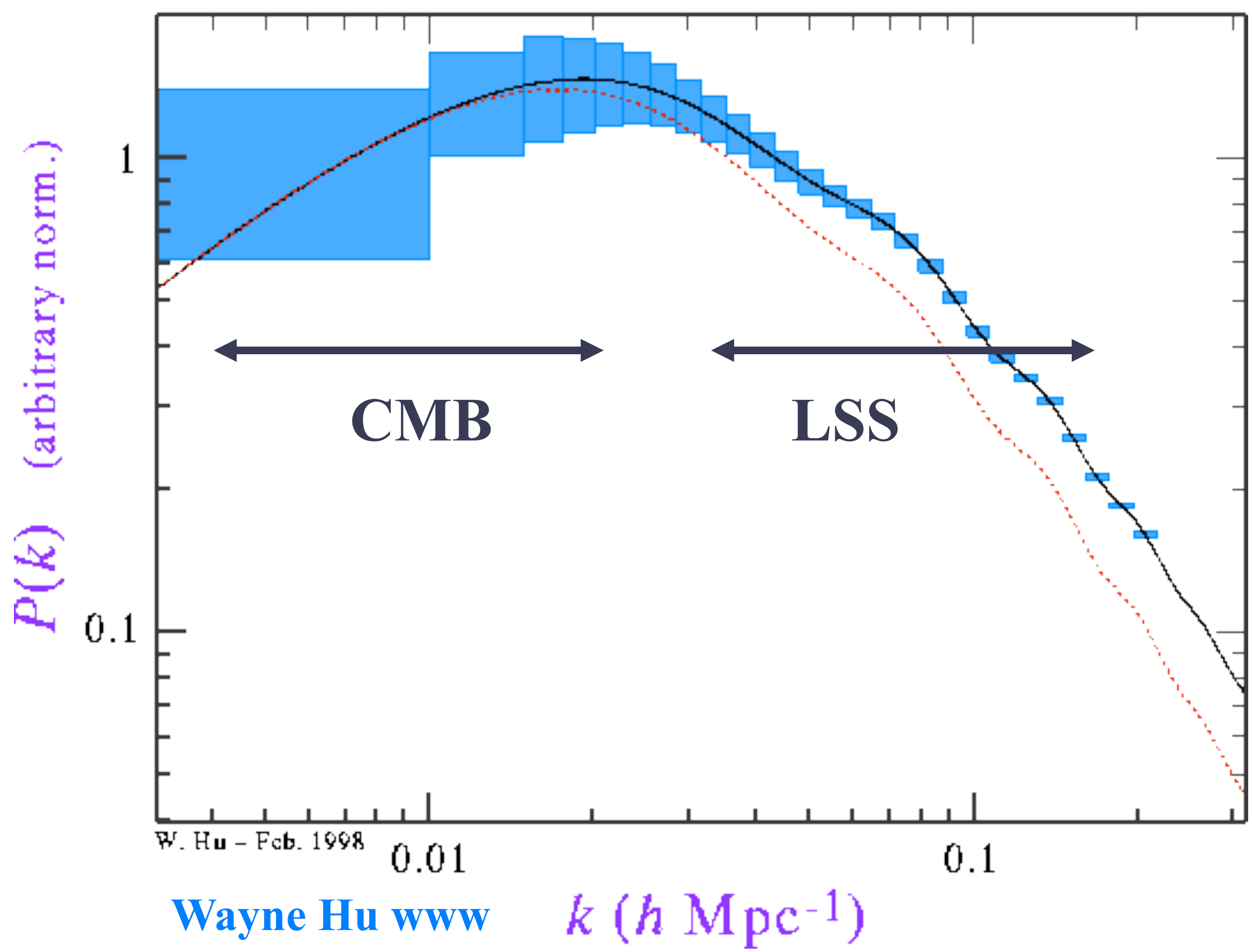


Detection Threshold: ~3 nJy (NIRCam) 1-5μm in 10^4 sec

- Corresponds to $M_{BH} = 10^5 M_\odot$ or $M_{stars} = 10^6 M_\odot$ at z=10
- DM halo mass of detectable quasars/galaxies: $\sim 10^9 M_\odot$
- Few mini-quasars, and few 10s of "dwarf-galaxies" $arcmin^{-2}$ at z>10
- z=10 galaxies with R(vir)~1kpc resolvable at 0.02"
- BUT: First galaxies may be more distant and below this threshold

How will we see these things? Only indirectly?
Through effects on IGM/CMB, or explosive remnants: SN,GRB

Seed Fluctuations on Small Scales



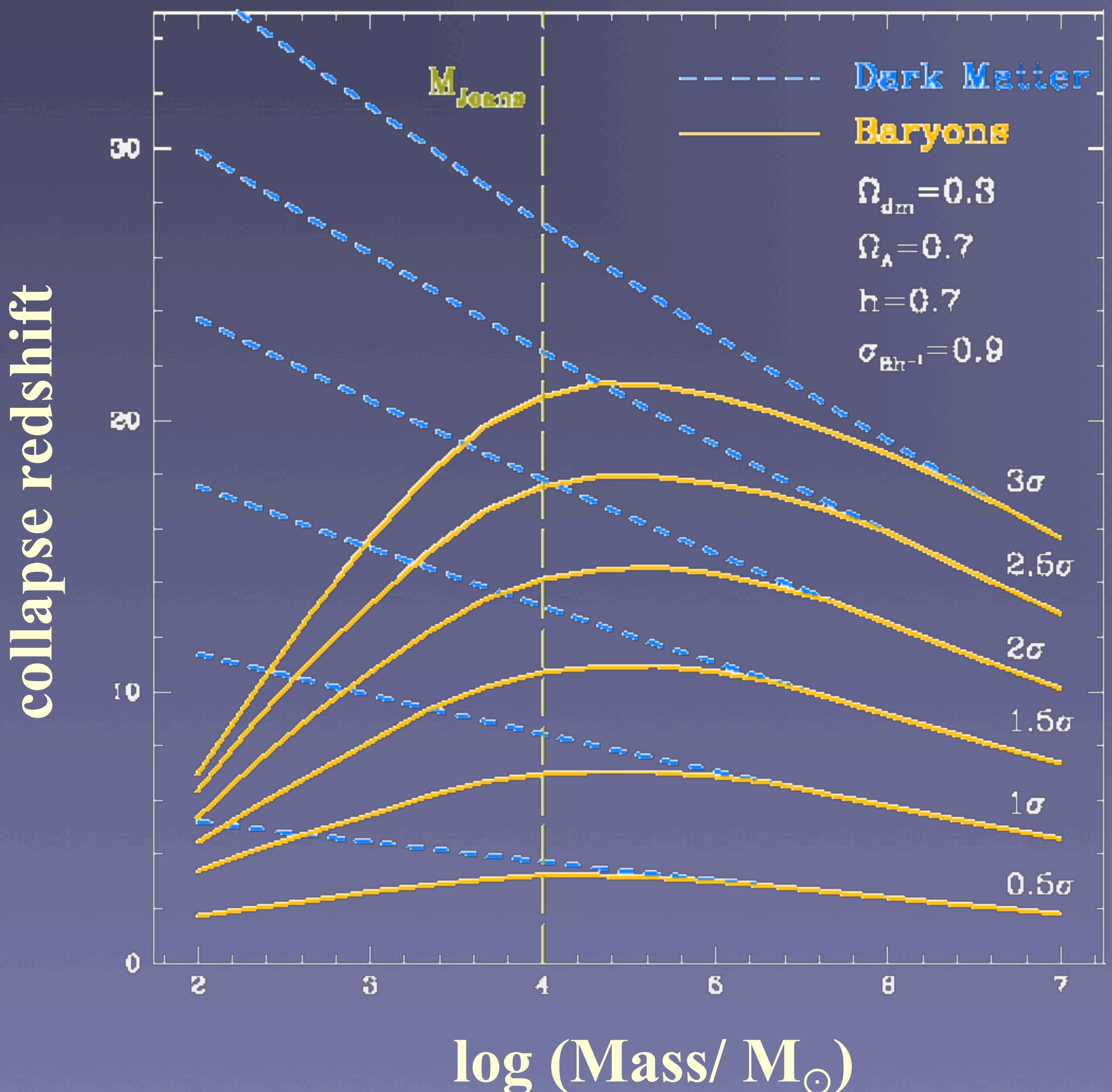
extrapolation by a factor of about 100 in linear scale

→ 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)

Halo Collapse in LCDM



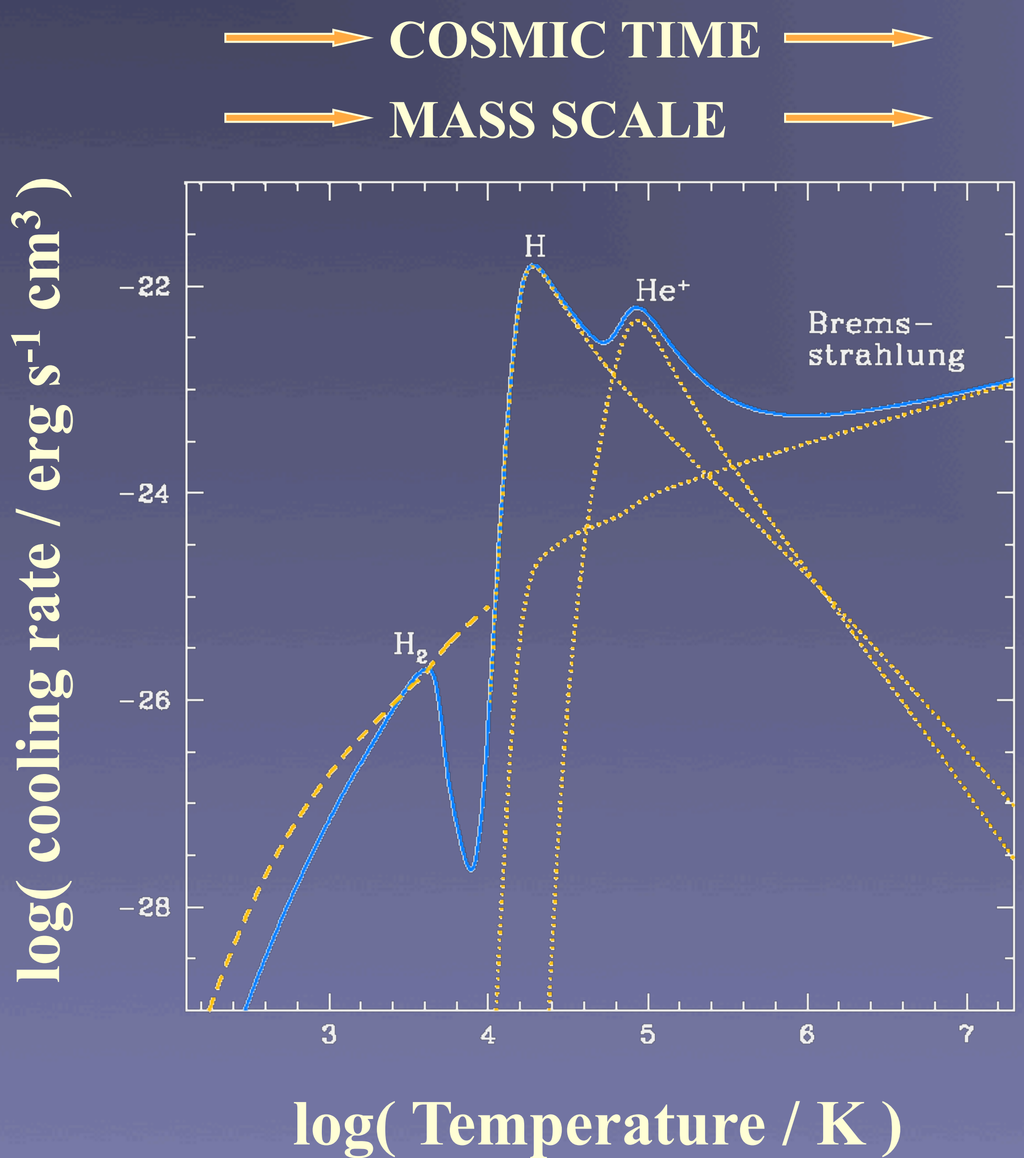
Smallest scales condense first

Jeans mass: ~10^4 M$_\odot$

possible further delay in gas by Δz~4:

Tseliakovich & Hirata (2010)
Greif et al. (2011)
Stacy et al (2010)
Maio et al. (2010)

Radiative Cooling Function (H+He gas)



cf. Halo virial temperature:

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

Gas Phase Chemistry:

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

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

Gas inside halos with $T_{vir} \gtrsim 200$ K can cool via H_2

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

3D Simulation of a Primordial Gas Cloud

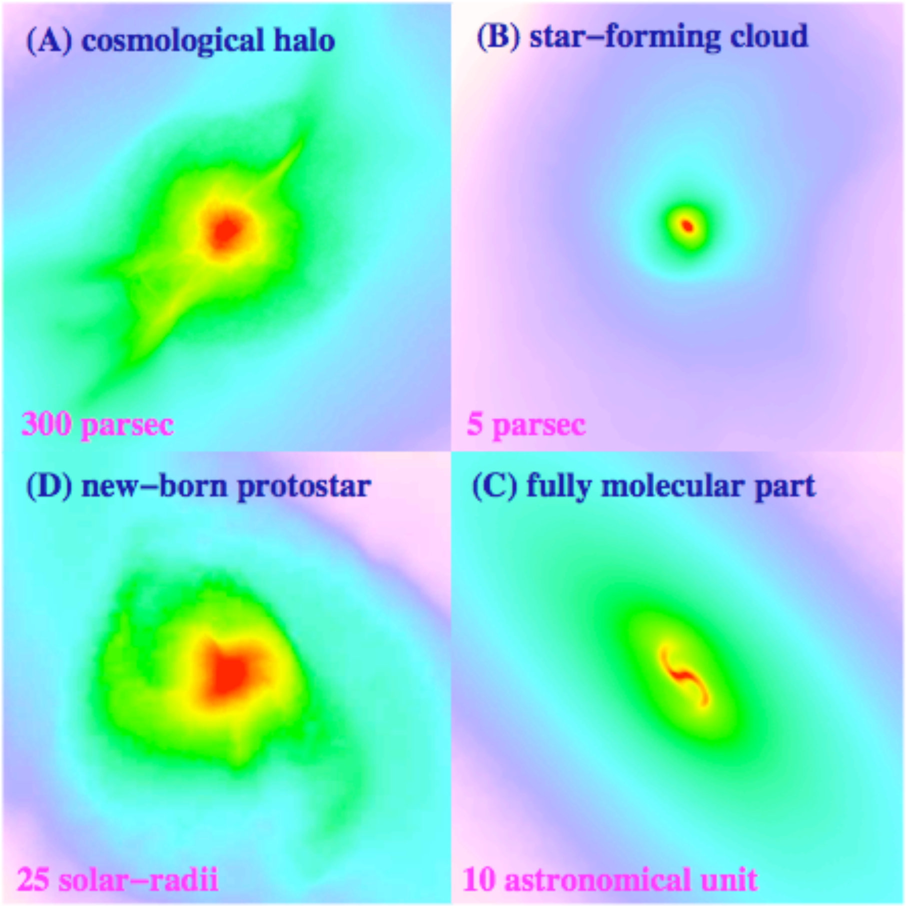


Fig. 1: Projected gas distribution around the protostar. Shown regions are, from top-left, clockwise, (A) the large-scale gas distribution around the cosmological halo (300 pc on a side), (B) a self-gravitating, star-forming cloud (5 pc on a side), (C) the central part of the fully molecular core (10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

Yoshida, Omukai & Hernquist (2008)

Cosmological halo:

$M_{tot} \approx 5 \times 10^5\, M_\odot$

$z \approx 14$

Protostar in core

$T \approx 10{,}000$ K

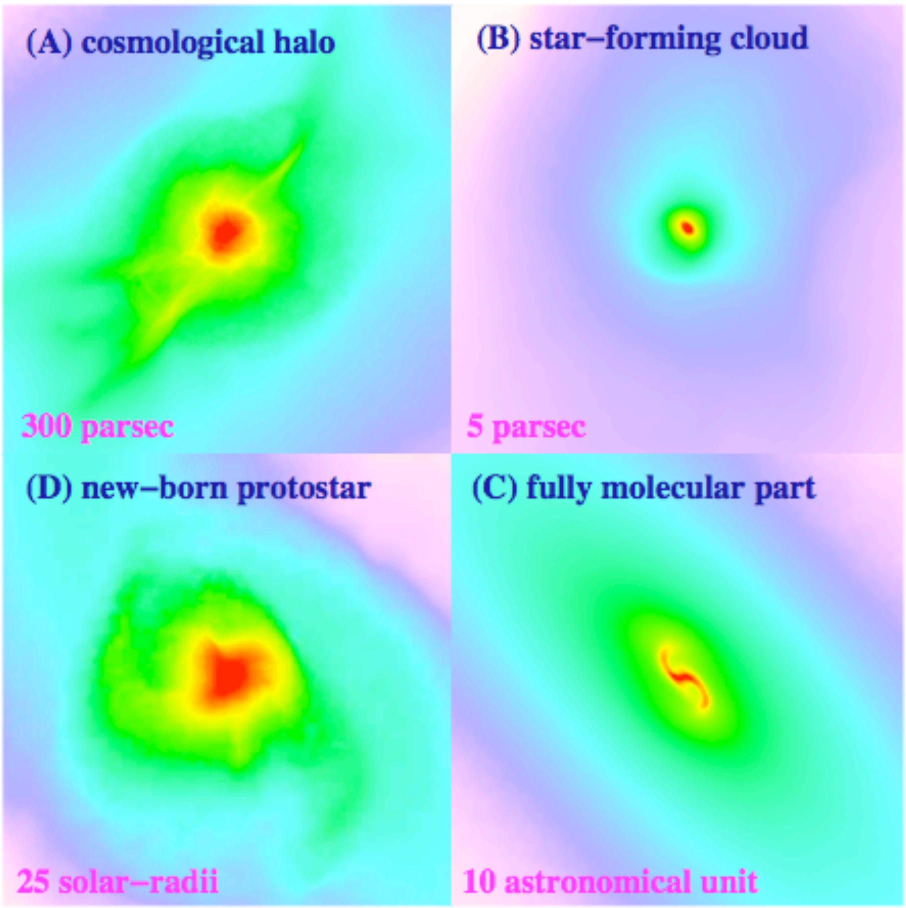
$n \approx 10^{21}$ cm^{-3}

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

Final stellar mass:

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

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



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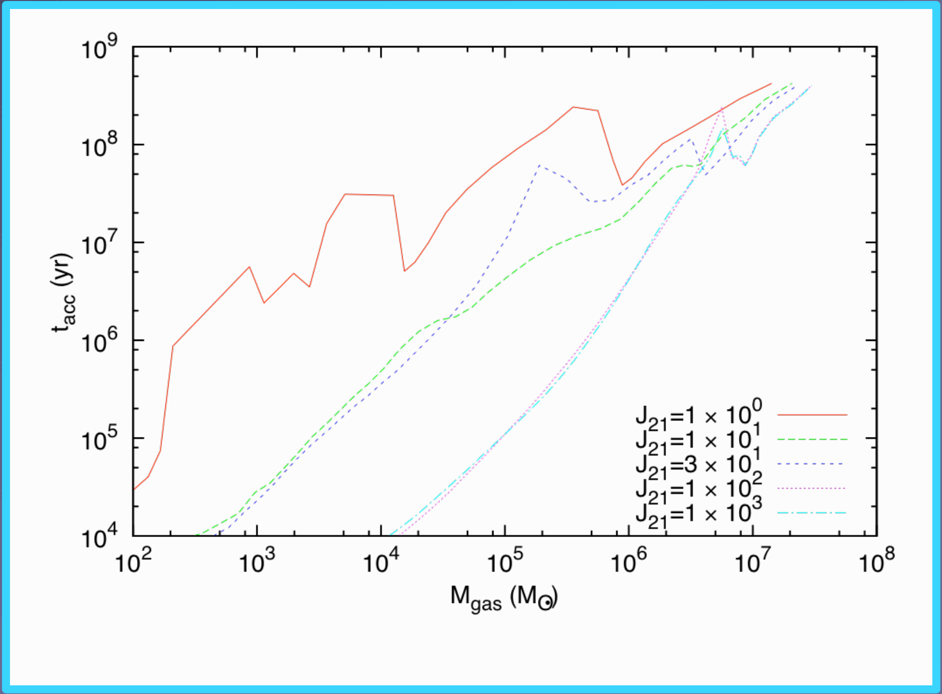
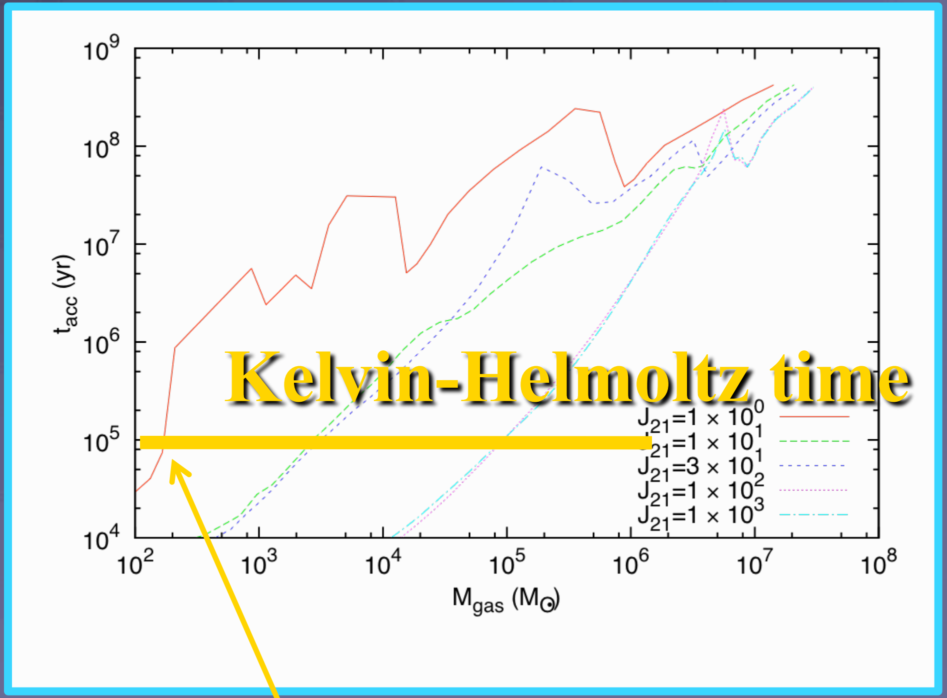
Final Stellar Mass?

Shang, Bryan & Haiman (2010)



Final Stellar Mass?

Shang, Bryan & Haiman (2010)

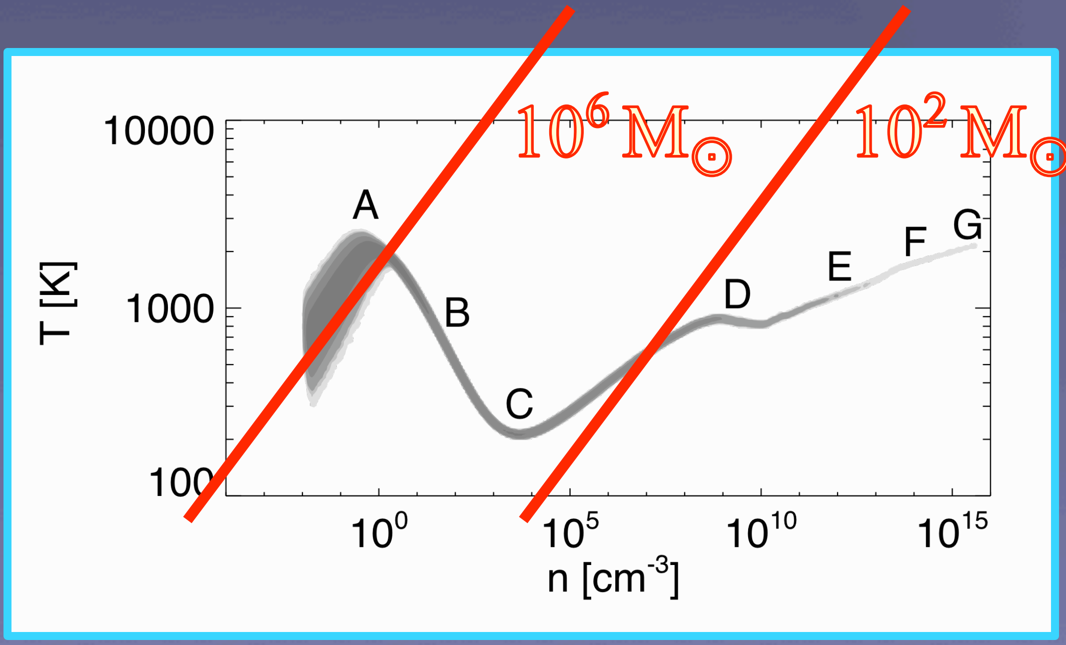


$10^{2\text{-}3}$ $M_\odot$ Pop III star Abel et al.; Bromm et al.; Yoshida et al.

No Fragmentation?

Many arguments against fragmentation over past 10 yrs:

- growth time-scale + wavelength of linear perturbations
- growth of non-spherical deformation ($\gamma = d\ln P / d\ln\rho > 1$)
- rotation-induced fragmentation ($\alpha = E_{th}/E_{gr}$ $\beta = E_{th}/E_{gr}$)
- efficient turbulent mixing
- simulations with prescribed EOS (Clark et al. 2008)



Omukai, Schneider, ZH (2008)

Yoshida et al. (2007)

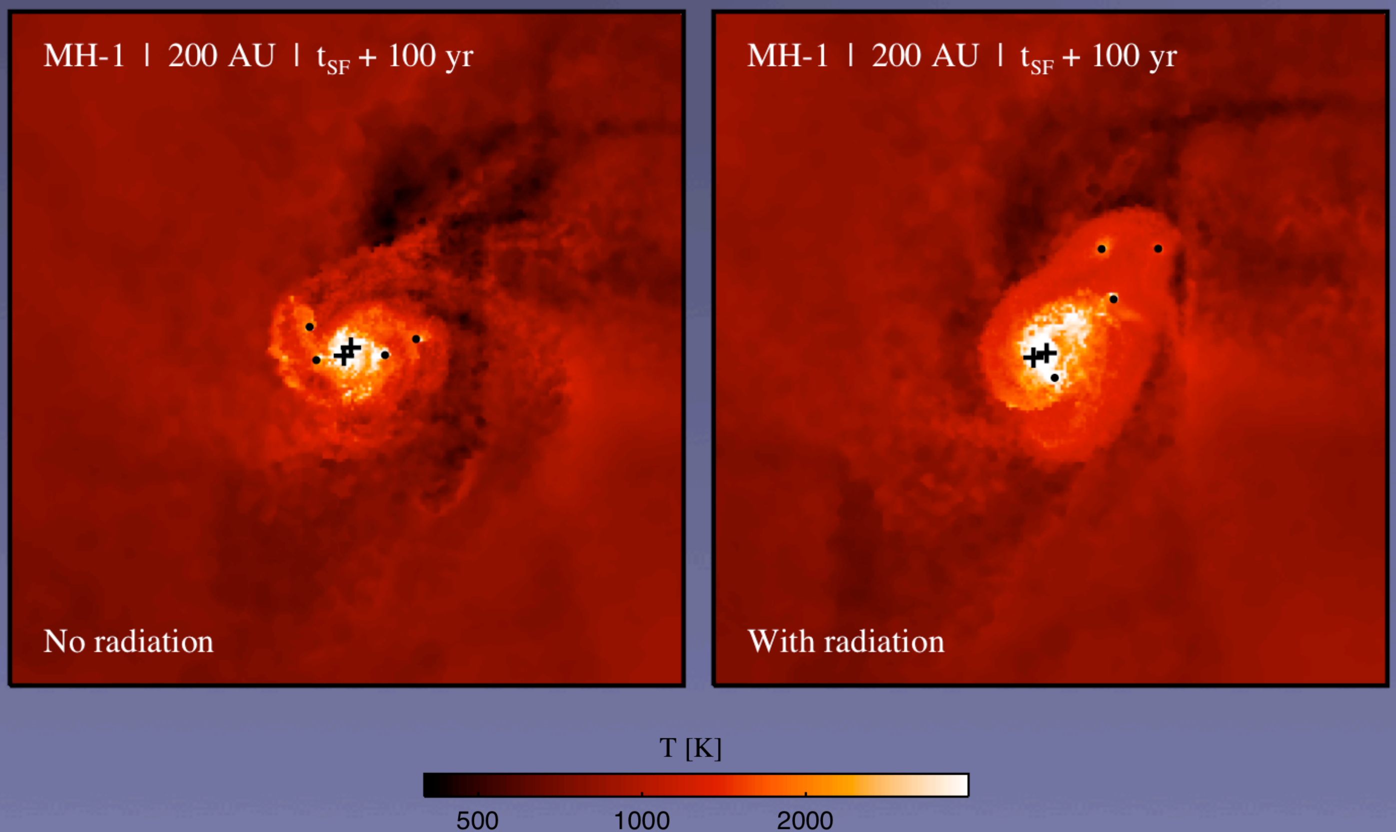
Or…Fragmentation?

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)



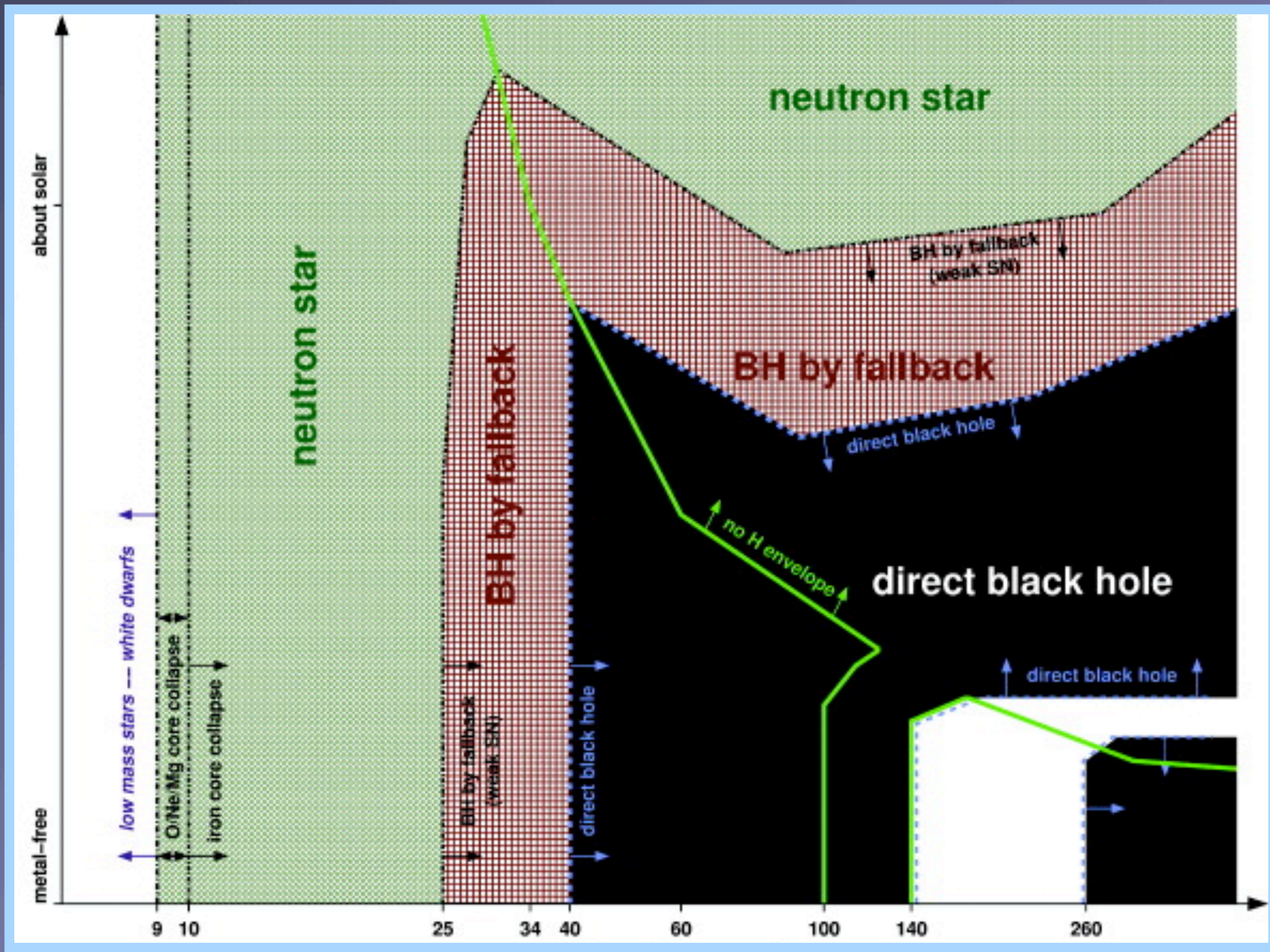
Remnants of Massive Stars

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

$Z=Z_\odot$

metalicity

$Z=0$



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

First Stars → First Galaxies…

- Formation of the 1st Star ✓
- Formation of the 2nd Star
- Formation of the 3rd Star
- Formation of the 4th Star
- Formation of the 5th Star

…..

- Formation of the 3743rd Star ← First Galaxy ?
- Formation of the 3744th Star

…..

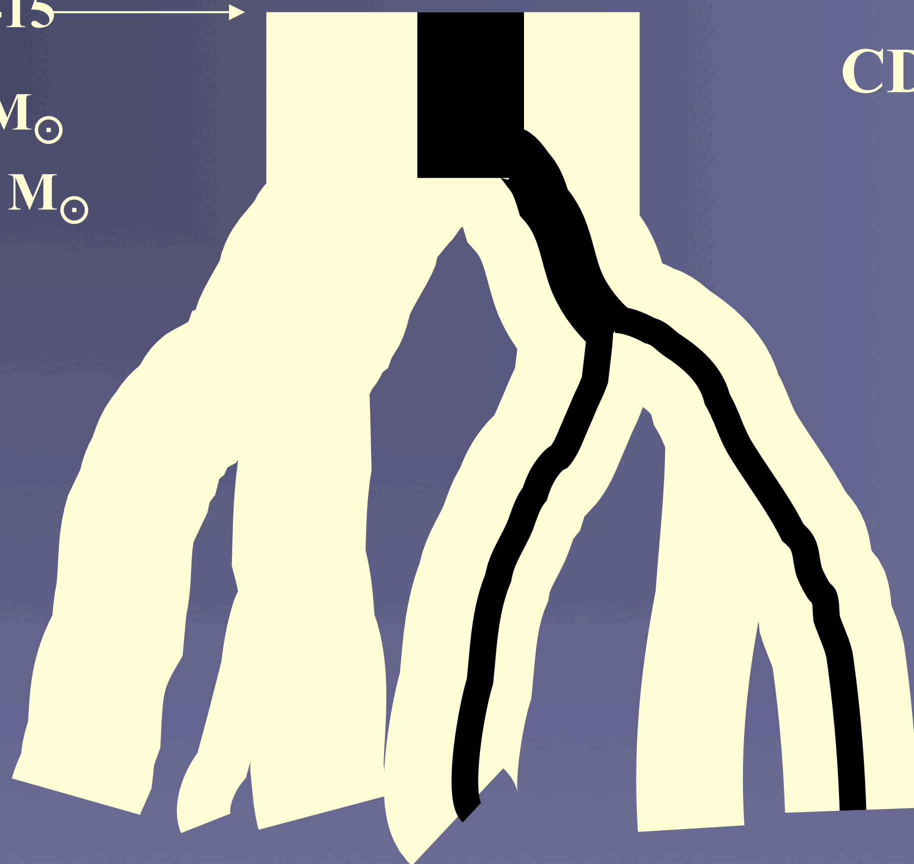
From First Stars to First Galaxies

z~10-15

M_{halo} = few × $10^8\,M_\odot$

M_{stars} = few × $10^3\,M_\odot$

CDM merger tree



z~30

$M_{halo} = 10^6\,M_\odot$

M_{stars} = few × $10^2\,M_\odot$

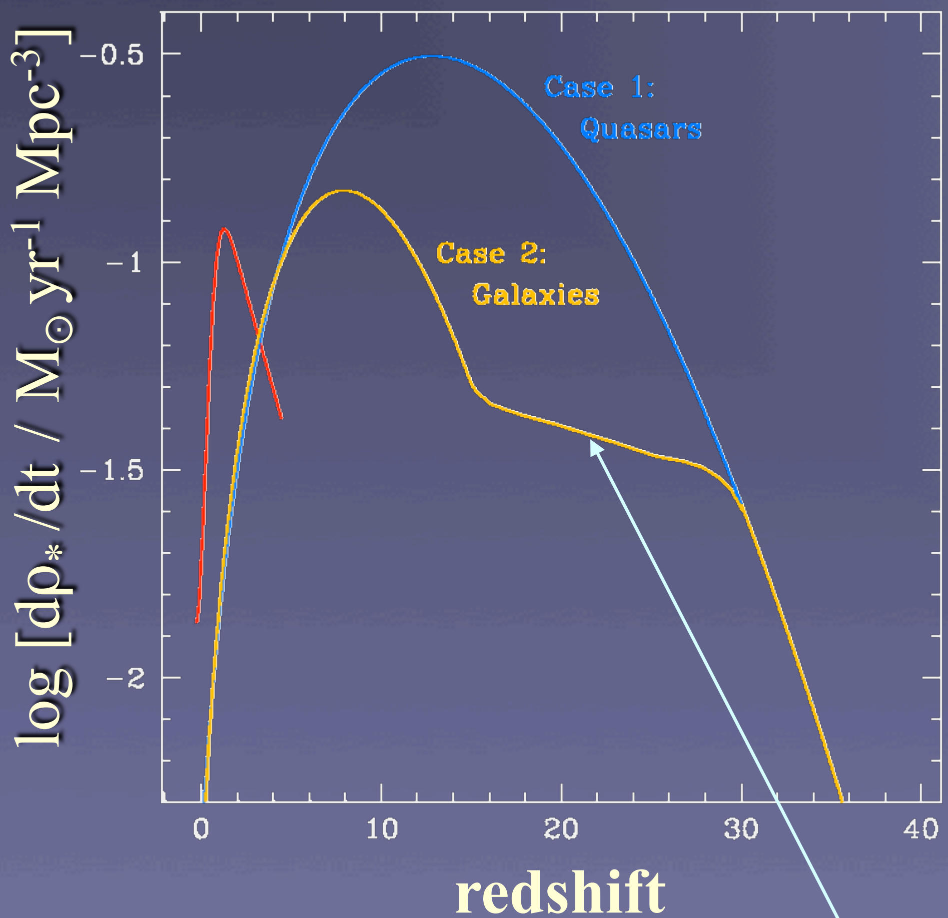
Feedback Processes

- **INSIDE MINIHALO**
  - UV flux unbinds gas
  - supernova expels gas, sweeps up shells
  - H_2 chemistry (positive and negative)
  - metal pollution: enable atomic C,O cooling

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

Does first galaxy have to wait for "atomic cooling" halo with deeper potential well ($T_{vir} > 10^4$K) ?

SF/Reionization History Self-Regulates?



Case 1 : No net feedback

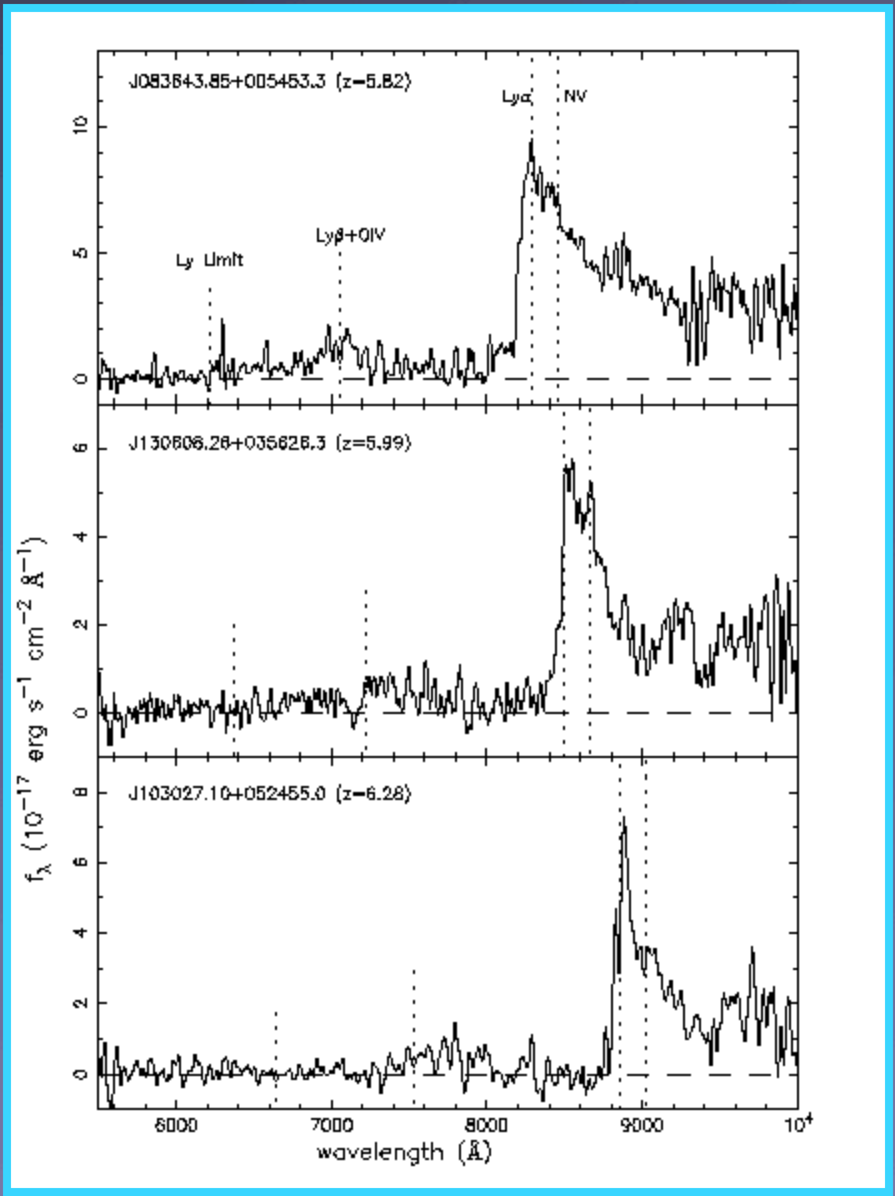
- reionization completes early
- small halos
- high source density
- smooth
- He/H close in time

Case 2 : Negative feedback

- reionization completed later
- larger halos,
- more sparce sources
- patchy “swiss cheese”
- He/H farther in time

IF H_2-feedback regulates reionization history, then there will be a period with a robust ‘steady state’ solution for the star formation history - need to know $J_{crit}(M_{halo},z)$

Distant Quasars: Reionization at z~6?



Observational Breakthrough in 2002: SDSS quasars at z~6

$\langle x_H \rangle \approx 10^{-4}$ z=5.82

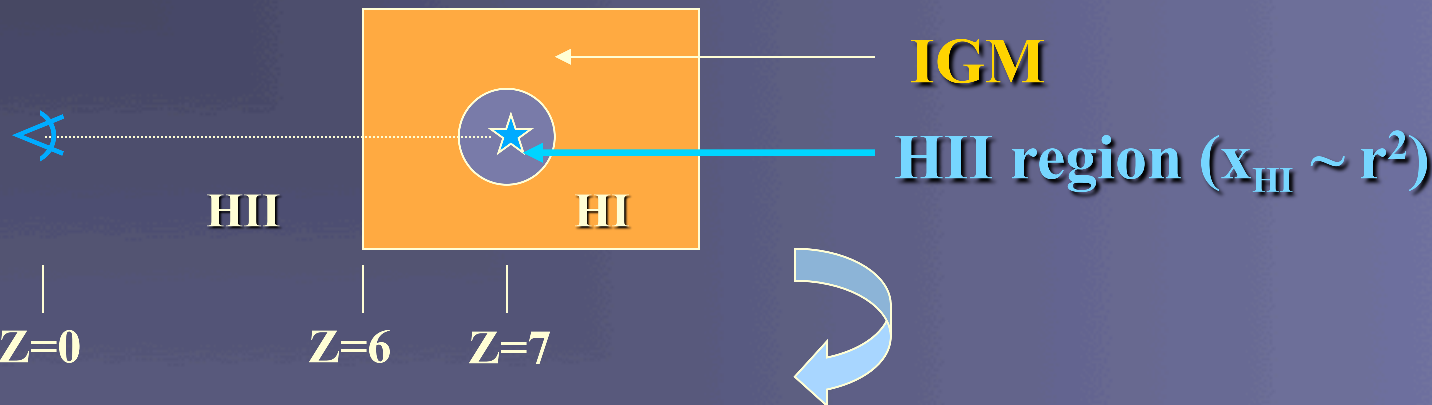
$\langle x_H \rangle \approx 2\times10^{-4}$ z=5.99

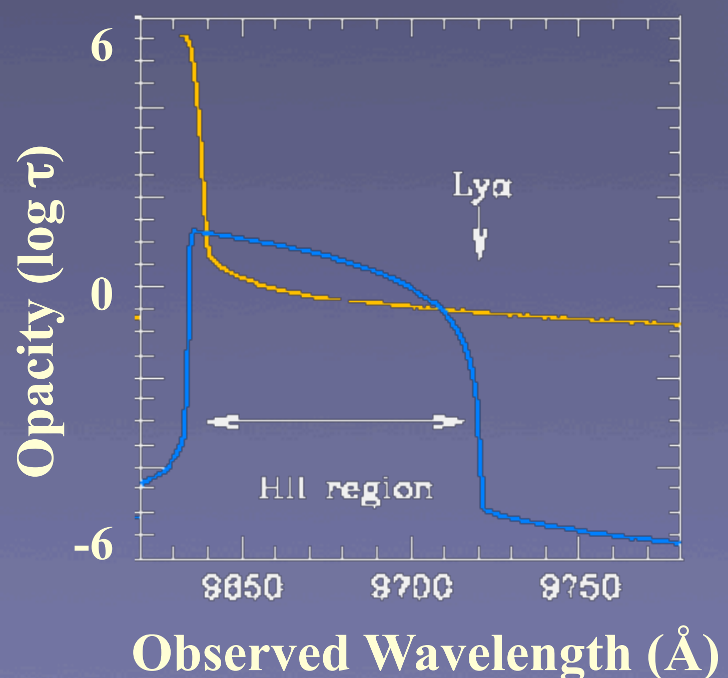
Gunn-Peterson trough:

$\langle x_H \rangle \gtrsim 10^{-3}$ z=6.28

Fan et al. 2002

Reionization Constraint from QSO Spectra





Two contributions to Lyα absorption:

HII region ($x_{HI} \sim r^2$)
Gunn-Peterson wing

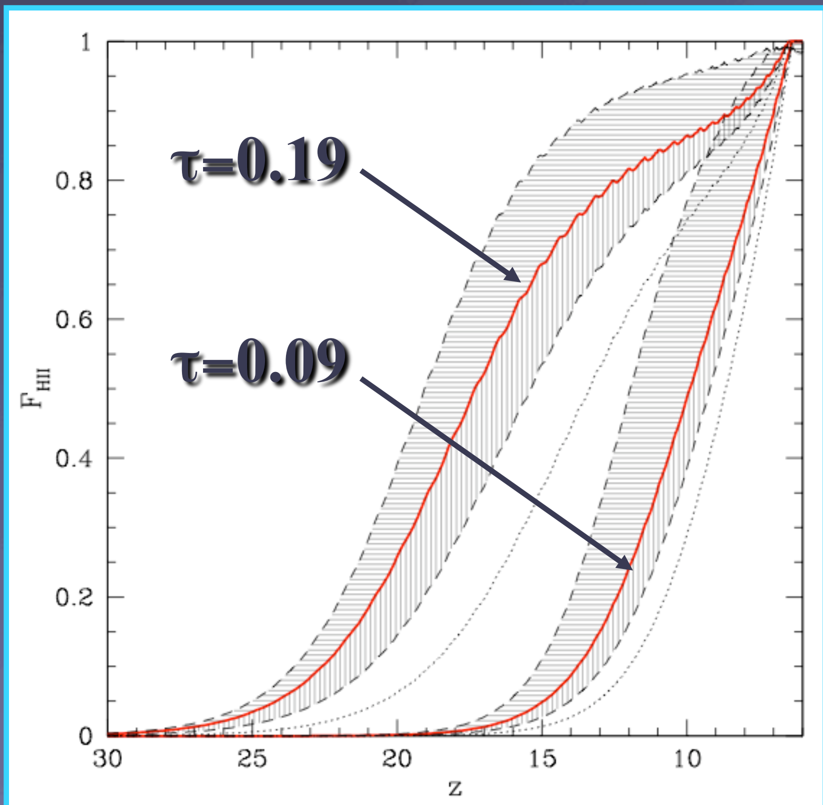
3 quasars yield:
$X_{HI} \gtrsim 0.04 - 0.1$

(Mesinger & Haiman 2007)

WMAP: Evidence for Negative Feedback

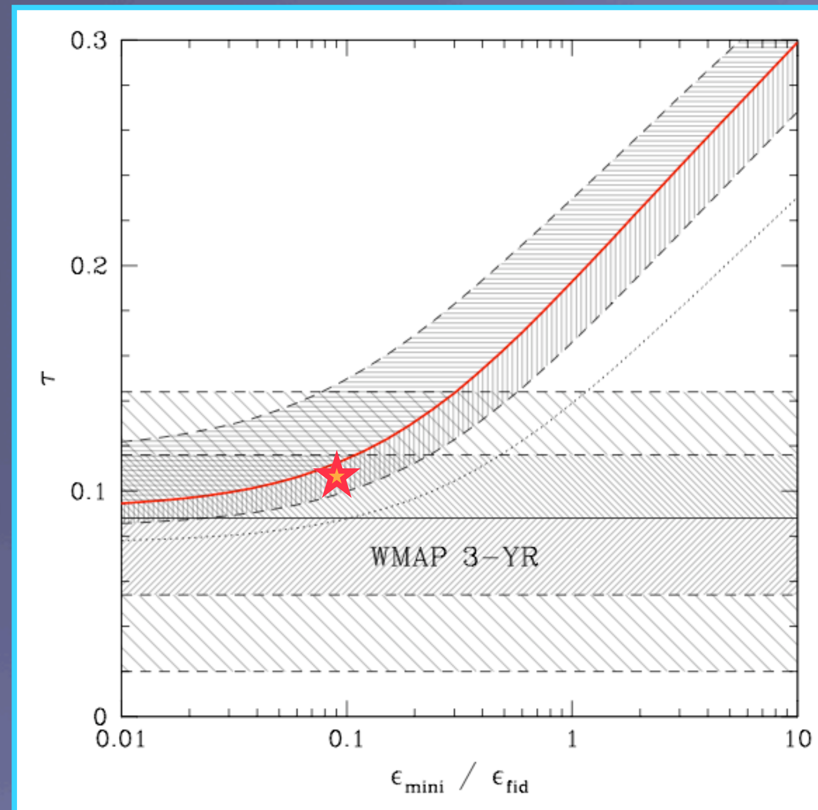
Haiman & Bryan (2006)

ionized volume fraction



redshift

Optical depth

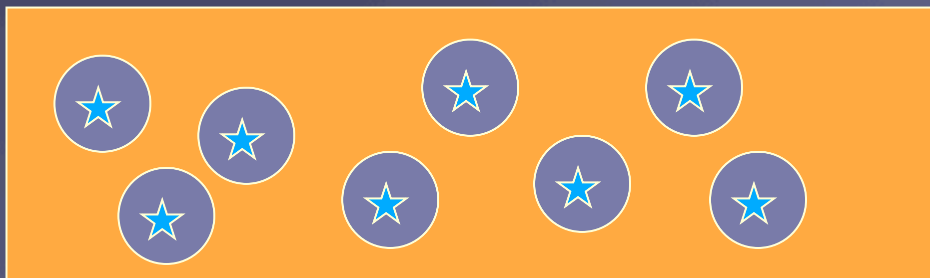


efficiency

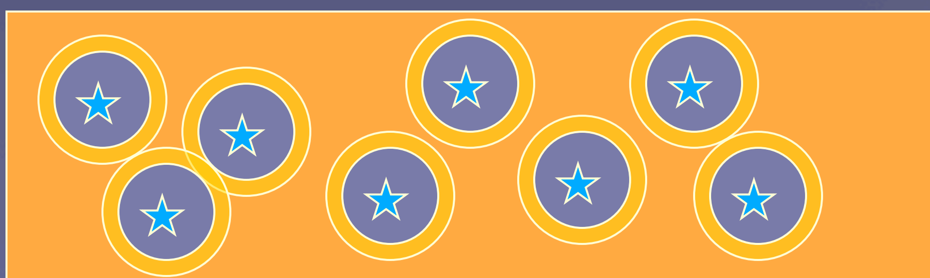
Minihalo contribution suppressed by a factor of ~10 (2σ)

Reionization by Stars vs BHs

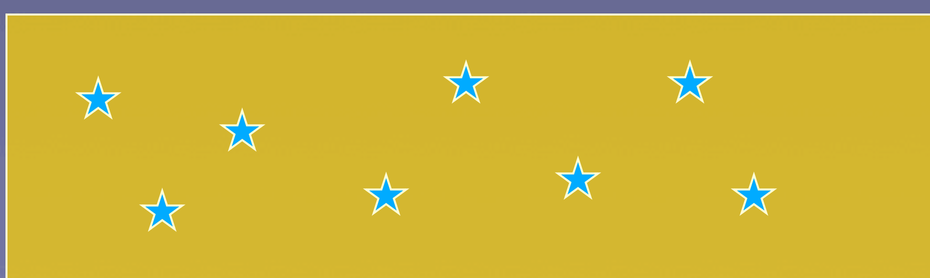
note: photon mean free path ~ Gpc $(E/1\ \mathrm{keV})^3\ [(1+z)/10]^{-3}\ f_{HI}^{-1}$



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

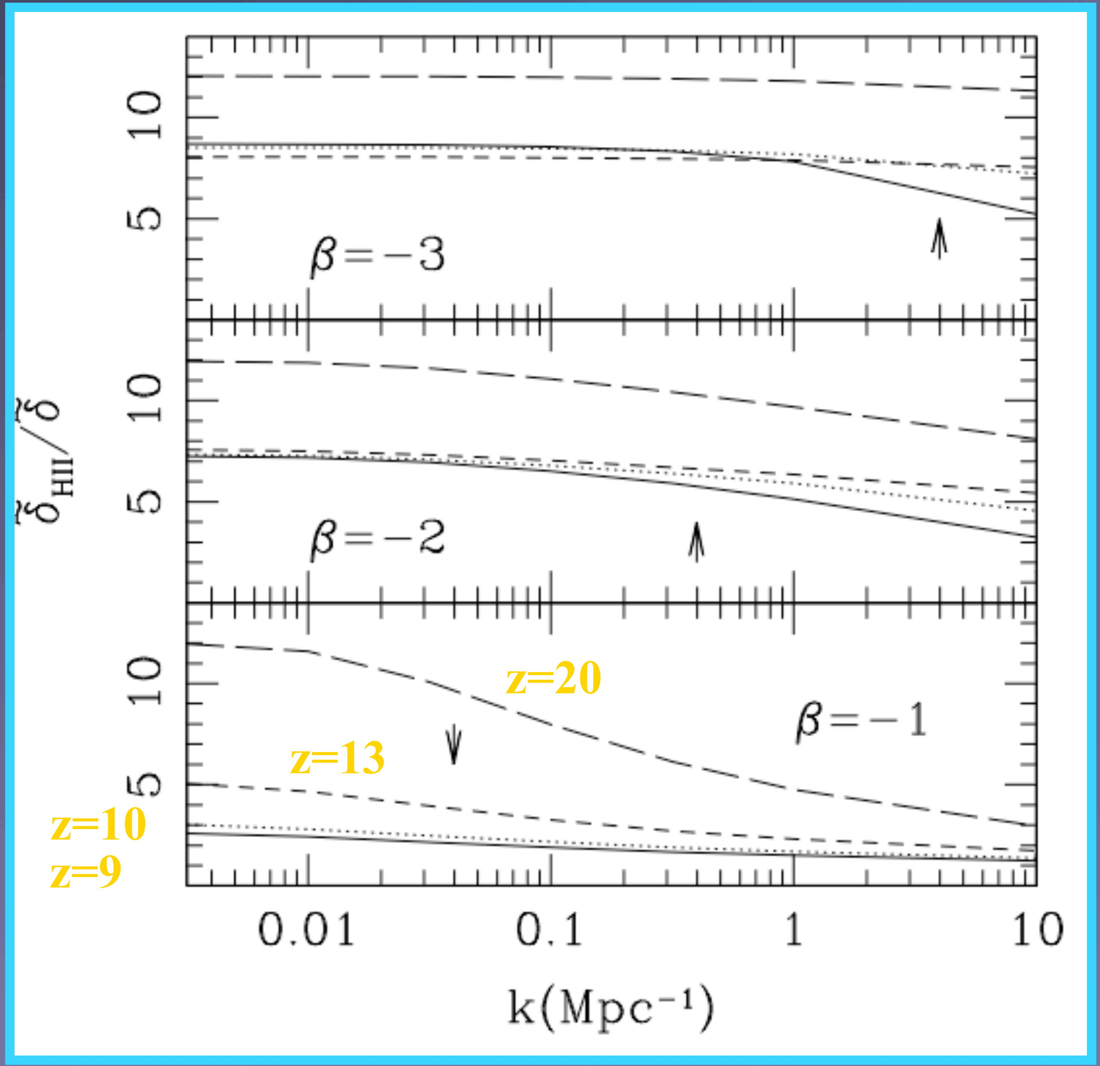
A Perturbation Theory of Reionization

Zhang, Hui & Haiman (2007)

- *Power spectrum of fluctuations (HI, HII) will be smoothed on scales below the mean free path of ionizing photons leaking into the IGM*
- **We will need parameterized model to fit to future data (such as 21cm) probing ionization topology**
- **Semi-numerical simulations** (Mesinger & Furlanetto 2008)
- **On large scales ($k \lesssim 0.1$ Mpc^{-1}), linear perturbation theory should be adequate:**
  define small δ_H, δ_{HII}, δ_γ, δ_{gal}, and solve ionization balance and radiative transfer → power spectra as a function of parameters
- **Example: typical spectral slope $\beta = - d \ln F_\nu / d \ln \nu$**

Power Spectra: Stellar vs BH Reionization

Zhang, Hui & Haiman (2007)



Soft spectrum

Hard spectrum

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)

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

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
  - successful model can be made, but overproduces 10^5-10^6 $M_\odot$ BHs – needs ‘feedback’ (Tanaka & Haiman 2010)

- **DIRECT COLLAPSE**

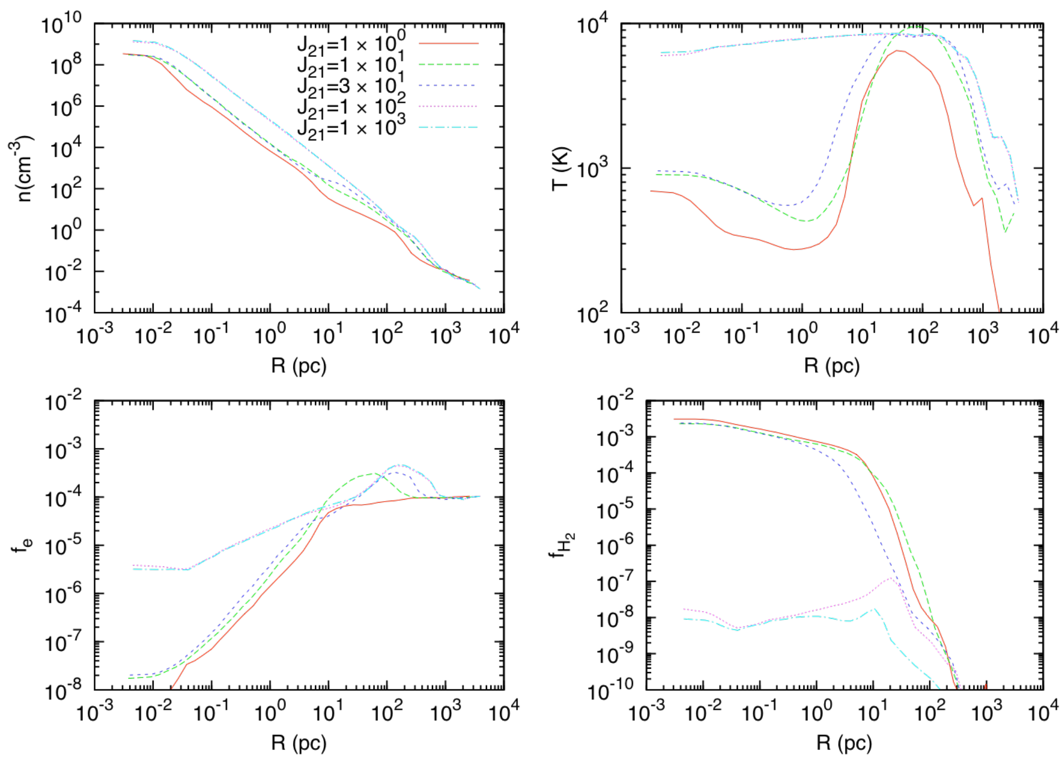
  rapid formation of 10^5-10^6 $M_\odot$ black holes either by direct collapse of gas or super-Eddington accretion onto a lower-mass seed

  - gas must be driven in rapidly (deep potential)
  - must avoid fragmentation
  - transfer angular momentum
  - successful model can be made, but requires very high UV flux to suppress H_2 formation (Shang, Bryan & Haiman 2010)

Critical UV flux for SMBH formation

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

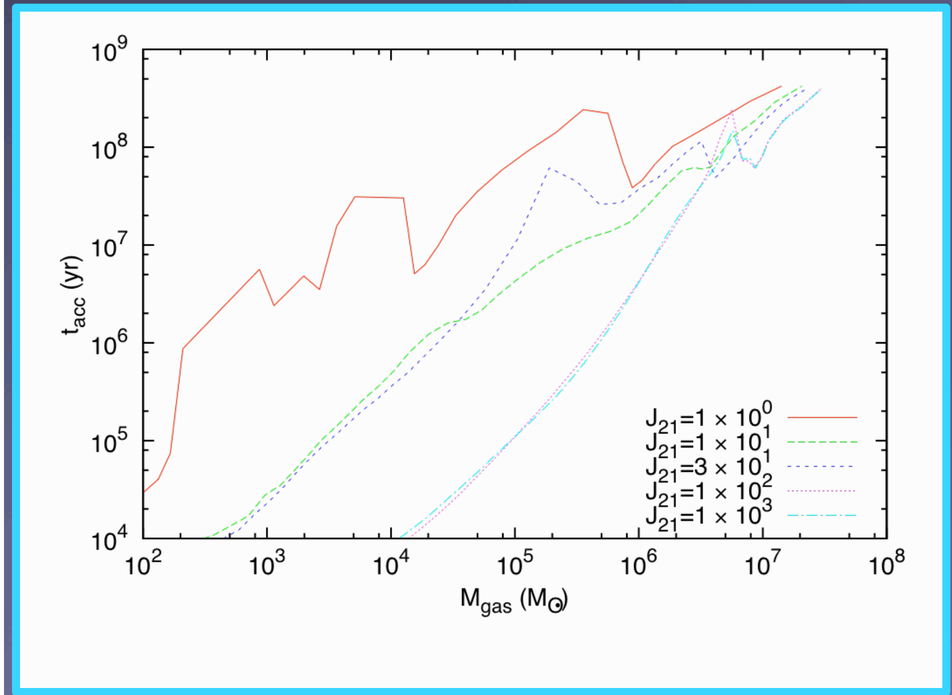
$30 < J_{crit} < 100$

SMBH by direct collapse possible (?)

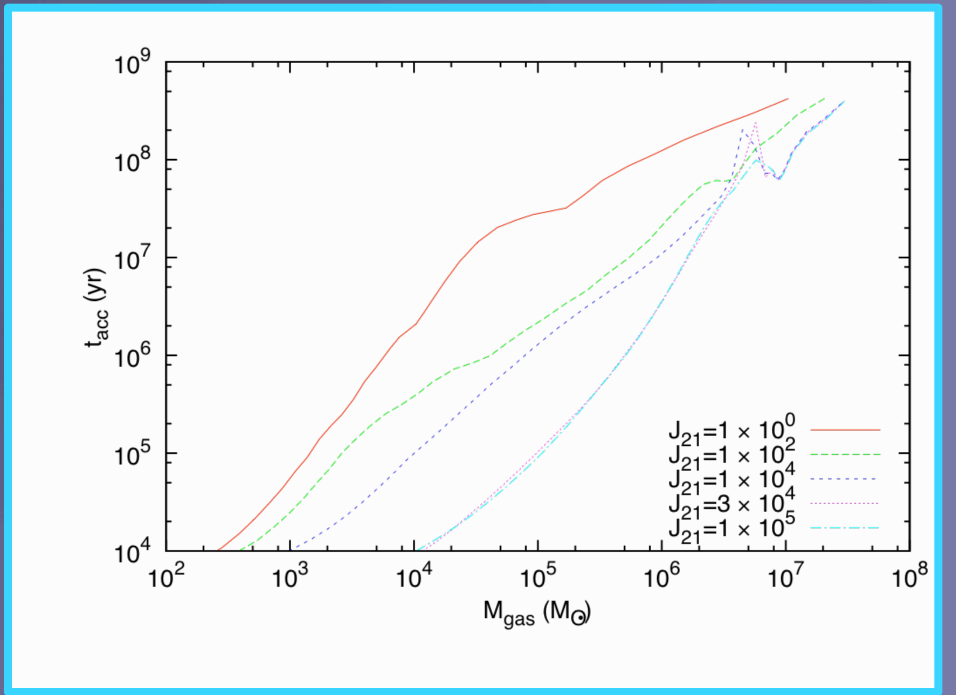
- **In-fall proceeds at sound speed** $c_s \approx 10$ km/s
- **Mass accretion rate** $M_{acc} \propto c_s^3$
- **Fragmentation is not seen**
- **Central object has mass** $M \approx 10^5 M_\odot$
  (**cf.** $M \approx 10^2 M_\odot$ **with** H_2, **when** $c_s \approx 1\text{-}2$ km/s)

SMBH by direct collapse possible (?)

Shang, Bryan & Haiman (2010)



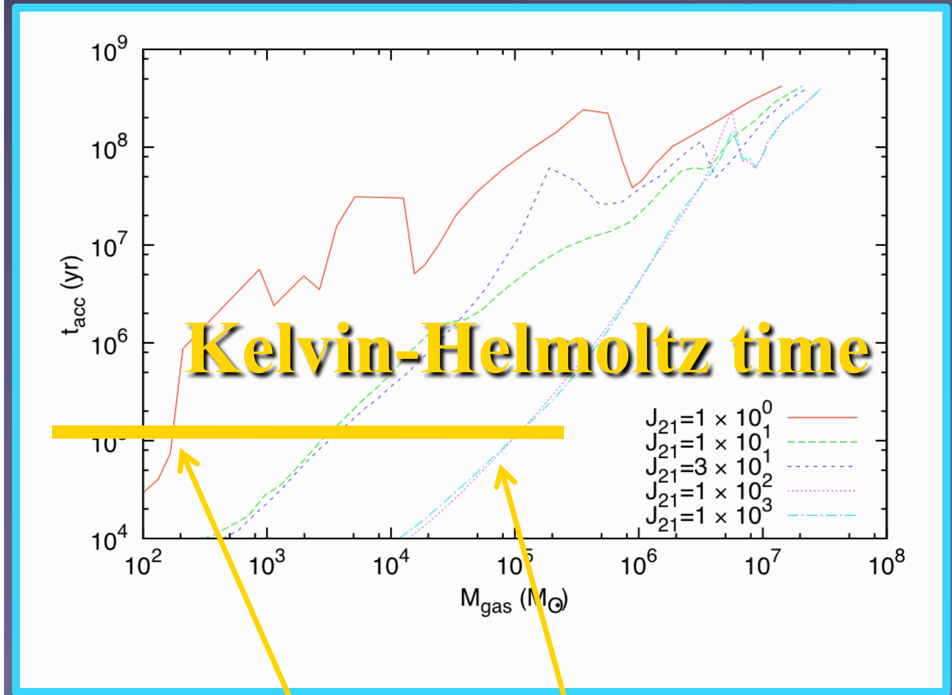
Normal stars
(soft UVB)

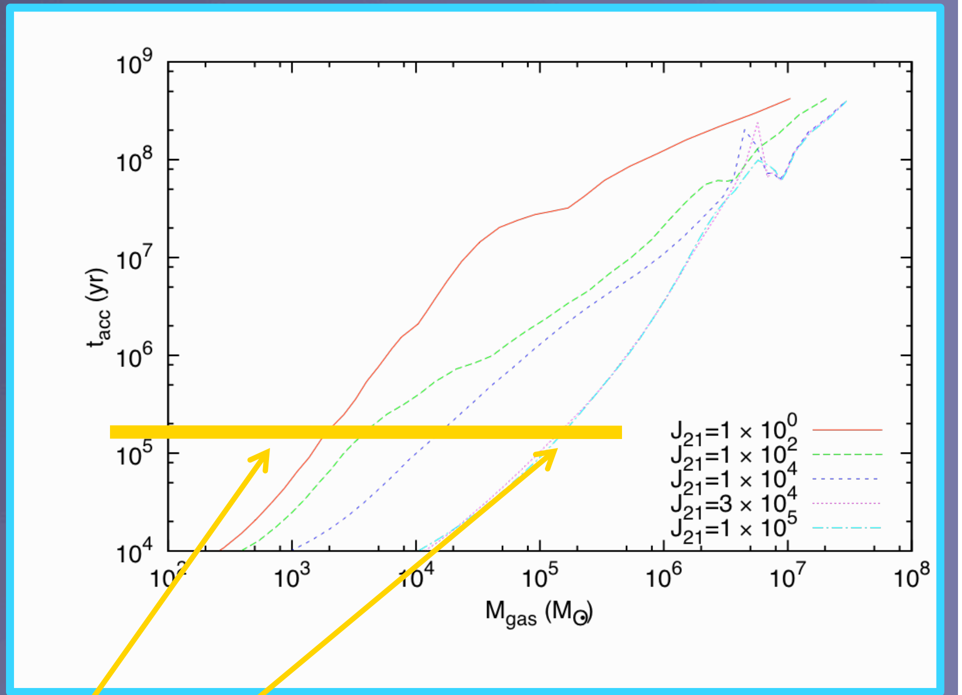


Pop III stars
(hard UVB)

SMBH by direct collapse possible (?)

Shang, Bryan & Haiman (2010)



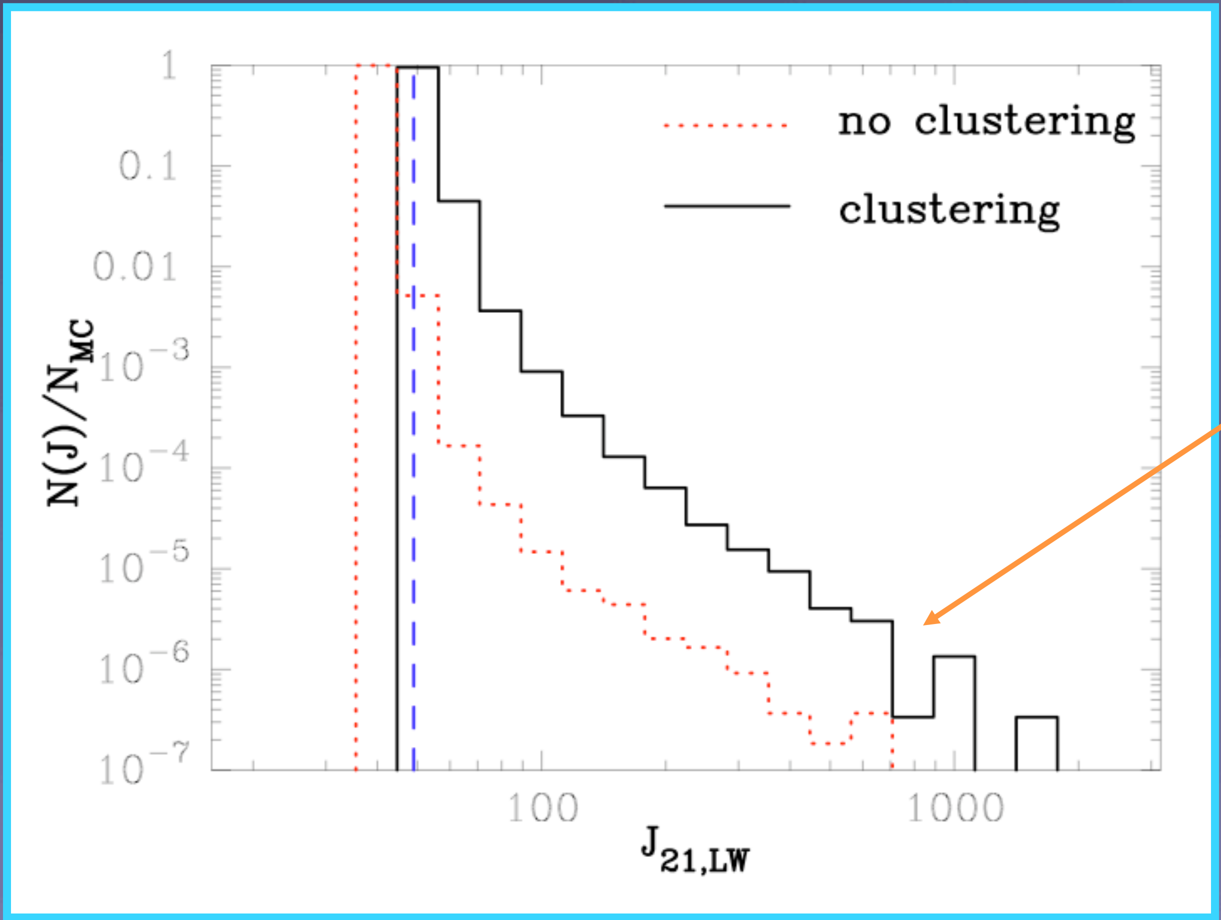


$10^{2\text{-}3}$ $M_\odot$ Pop III star Abel et al.; Bromm et al.; Yoshida et al.

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

Can we have sufficiently large UV flux?

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



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

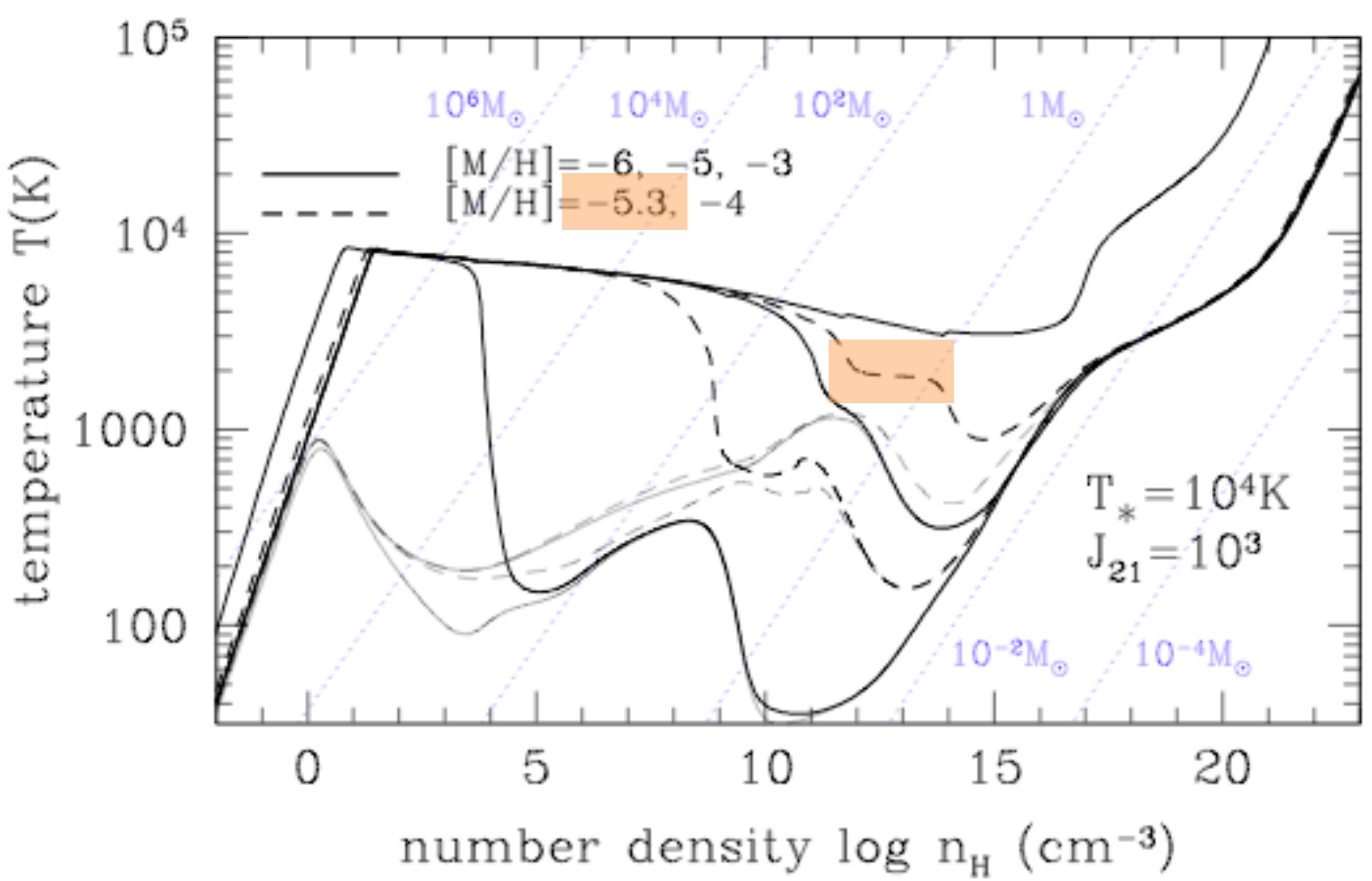
1 in ~10^7 halos has a close (≲10 kpc) bright and synchronized neighbor, so flux is ~ 30 × mean

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

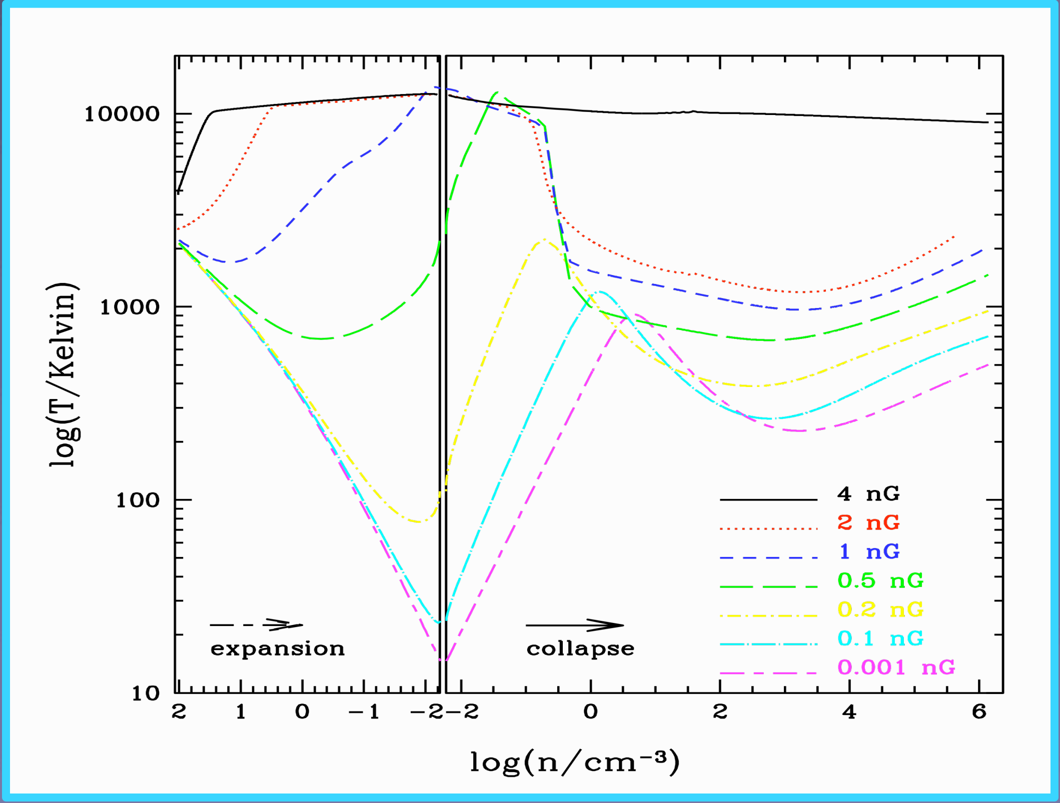
Omukai, Schneider & Haiman (2008)



Alternative heating: magnetic field

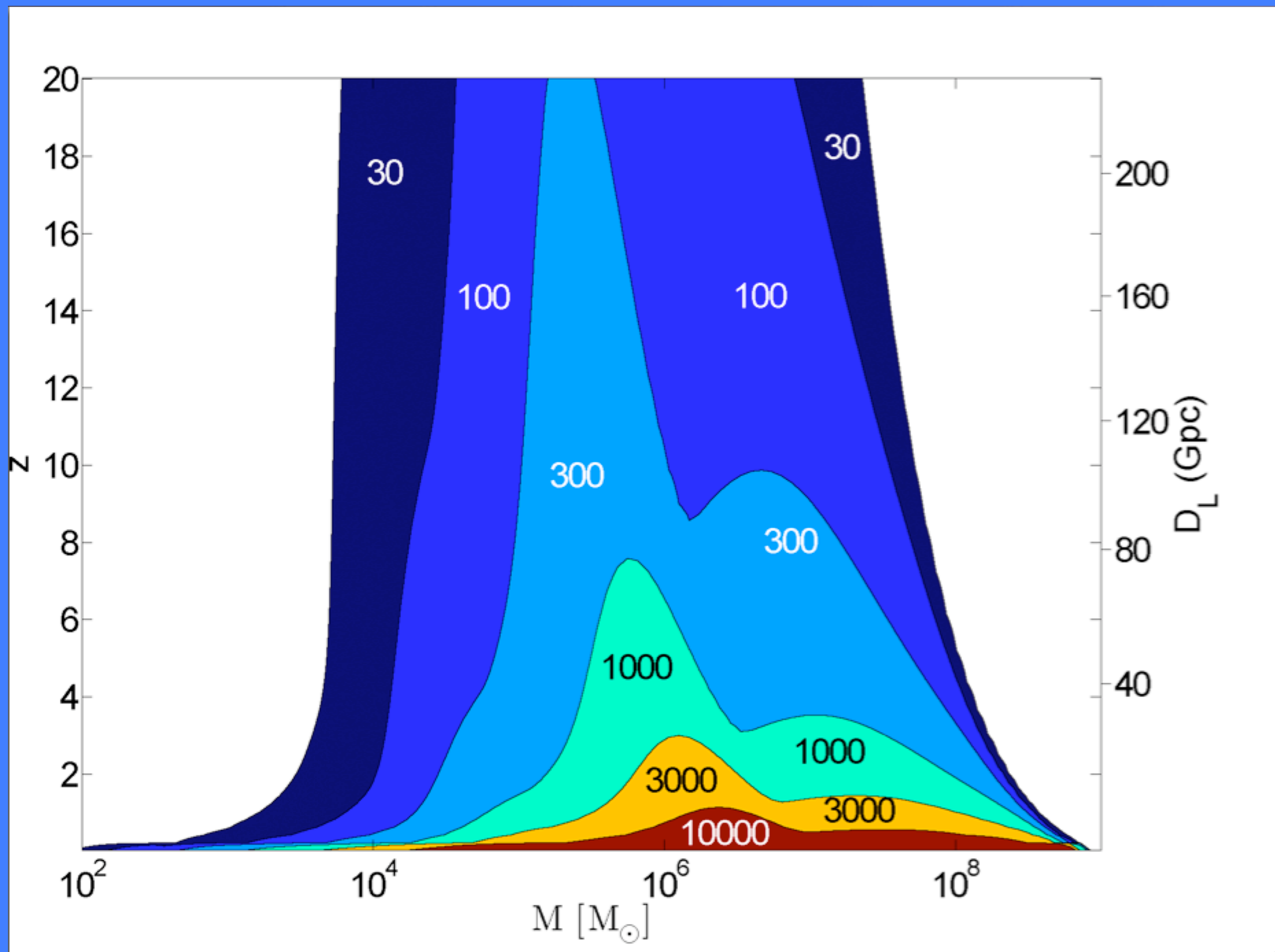
Sethi, Haiman & Pandey (2010)

- 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 in collapsing halo balance HI cooling?



How do we figure this out? LISA ?

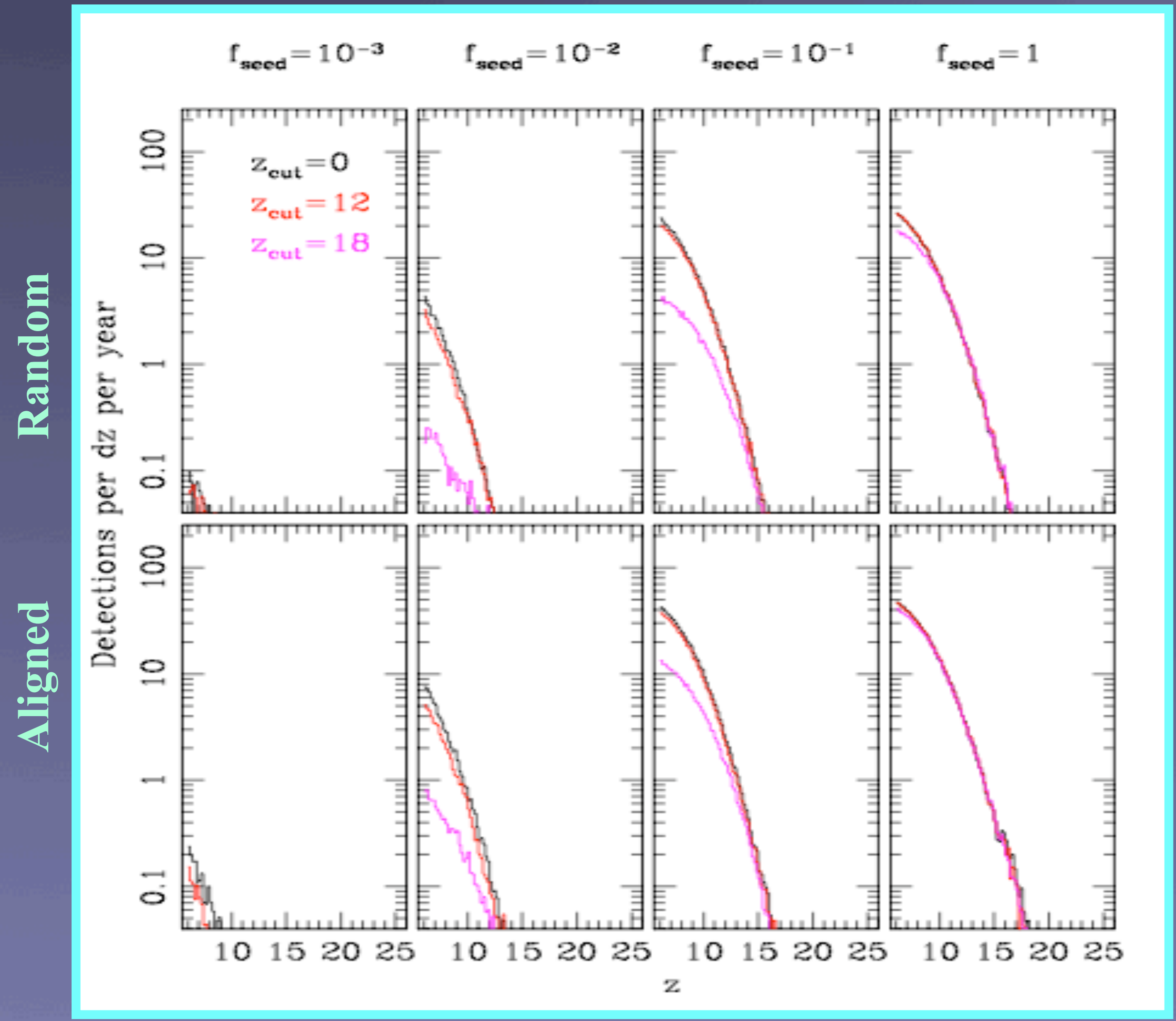
Baker et al. (2007)



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}

Probing Star-formation: High-z Supernovae

Mesinger, Johnson & Haiman (2006)
Miralda-Escude & Rees (1998)

- Even normal core-collapse SNe visible for months at z>10
- 4 - 24 SNe per ~10 $arcmin^2$ field at $z \geq 5$ at the detection threshold of 3 nJy (obtainable with a 10^5 s exposure in the 4.5 μm band)
- 2-yr survey: several hundred SNe/unit-z at z ~ 6
- SNe rates can be used to measure SFR out to z ~ 13
- 1% - 50% of SNe at z=10 are pair-instability
- Challenge: SN long lasting, need repeat observations separated by ~yr.
- **Worthy investment: only (almost) direct trace of total SFR**

- When did the first stars form, and what were their masses ? (rotation ?)

  z=20-30 all the way to z=3-4? M_*=0.1-100 $M_\odot$

- Were they isolated or multiple-star systems?

  N_*=1-10, depending on fragmentation and ejection

- When and how did they first assemble into something "stable" that we would call a galaxy?

  z=10-15 $M_{halo}=10^8\ M_\odot$ $N_{stars} < 10^3$ Below JWST limit!

- When did the first BHs appear, and how did they grow so rapidly into 10^9 $M_\odot$ BHs that are present at z=6?

  stellar seeds, direct collapse,… or something more exotic

  (large-scale magnetic field? DM annihilation-powered stars?)

- When and how was the universe re-ionized?

  between z=6-15 - by stars (swiss-cheese) or accreting BHs (smooth)