The Pop III IMF: A Progress Report

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Disclaimer

- Notion of Pop III IMF is not well-defined
  - We don’t observe Pop III stars
  - We believe Pop III stars formed in isolation in minihalos at high redshift……although some may be born binary stars
  - DM halos with enough mass to form a cluster of Pop III stars may be chemically enriched, and therefore form Pop II stars
- What is the sample we are averaging over?
  - Is there such a thing as a Pop III galaxy?
  - If not, we can define as a cosmic average <IMF(z)>
- Are we allowed to average over redshift too?
  - Duration of Pop III epoch is unknown
  - we can predict when it starts, but not when it ends

Nevertheless

- Significant progress has been made on better estimating the characteristic masses of Pop III stars from simulations and analytic theory

Outline

- Nomenclature: Pop III.1 and Pop III.2
- Formation of Pop III.1 protostars
- Formation of Pop III.2 protostars
- Final stellar masses (progress!)
  - accretion, stellar evolution, and radiative feedback
  - fragmentation and binarity
- A scenario for the rise and fall of Pop III
- How simulations need to evolve

Nomenclature

- Pop III.1
  - Gas of primordial composition
  - Initial conditions purely cosmological

- Pop III.2
  - Gas of primordial composition
  - Initial conditions modified by radiative or kinetic feedback of Pop III.1 stars, but not chemical feedback

Formation of Pop III.1 protostars

Bromm et al. 1999, 2002; Abel et al. 2000, 2002; Yoshida et al. 2003, 2006, 2008, 2009; O’Shea & Norman 2006, 2007, 2008; Turk et al. 2008, 2009

primordial matter power spectrum

→ hierarchical structure formation

→ DM minihalo (M$_{dyn}$ ~ 10^6 M$_s$, z~20)

→ primordial cloud (M$_{cl}$ ~ 10^4 M$_s$)

→ H_2 formation and cooling

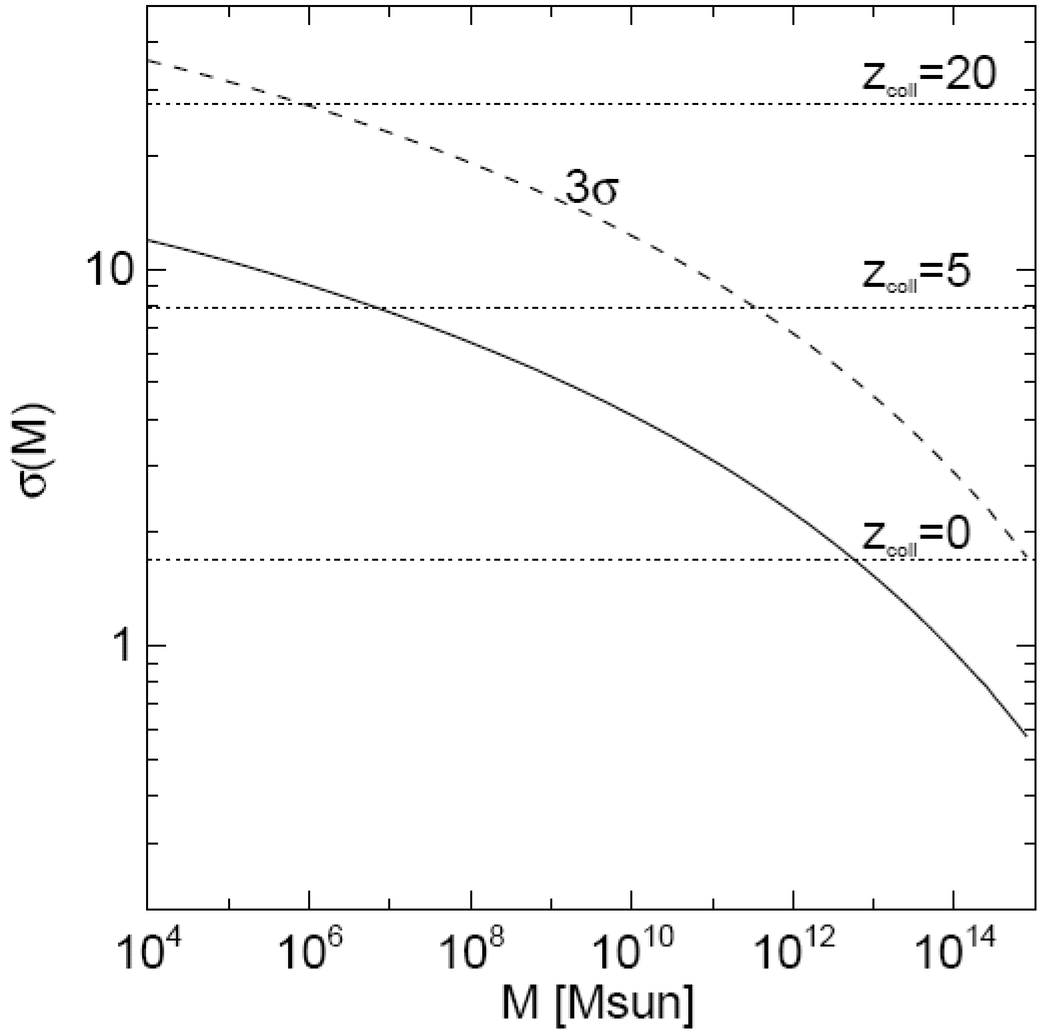
→ collapsing core (M$_{core}$ ~ 10^3 M$_s$)

→ accreting protostar (M$_{ps}$ ~ 10^{-2} M$_s$, m*~ 10^{-2} M$_s$/yr)

→ stellar evolution, accretion, and radiative feedback

→ endpoints (supernovae and black holes)

Mass variance in spheres enclosing mass M for concordance ΛCDM



rare peaks

typical fluctuations

Yoshida (2009)

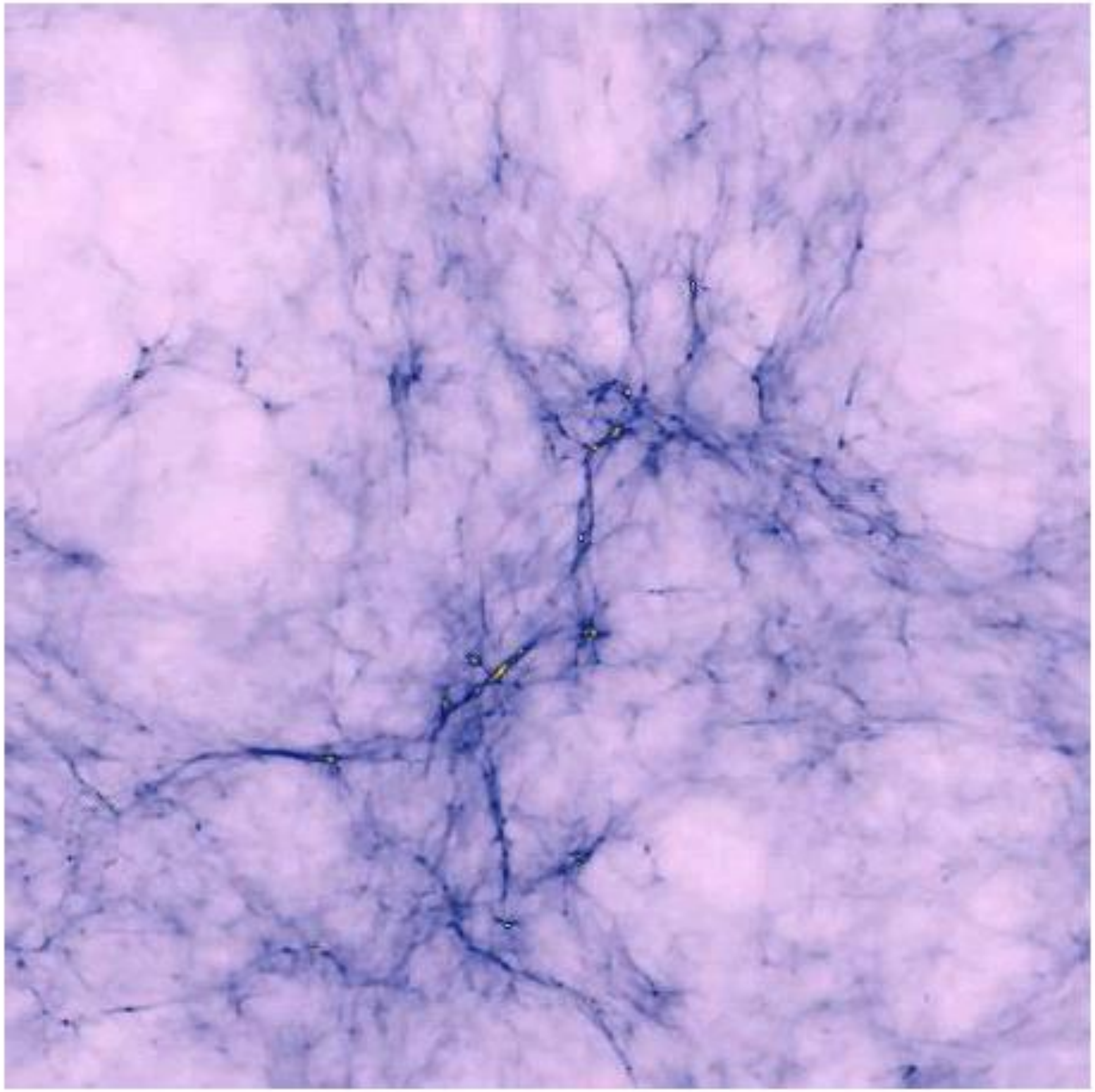


Figure 2: The projected gas distribution at $z = 17$ in a cubic volume of $600h^{-1}$kpc on a side. The cooled dense gas clouds appear as bright spots at the intersections of the filamentary structures. From Ref. (17).

Yoshida et al. (2003)

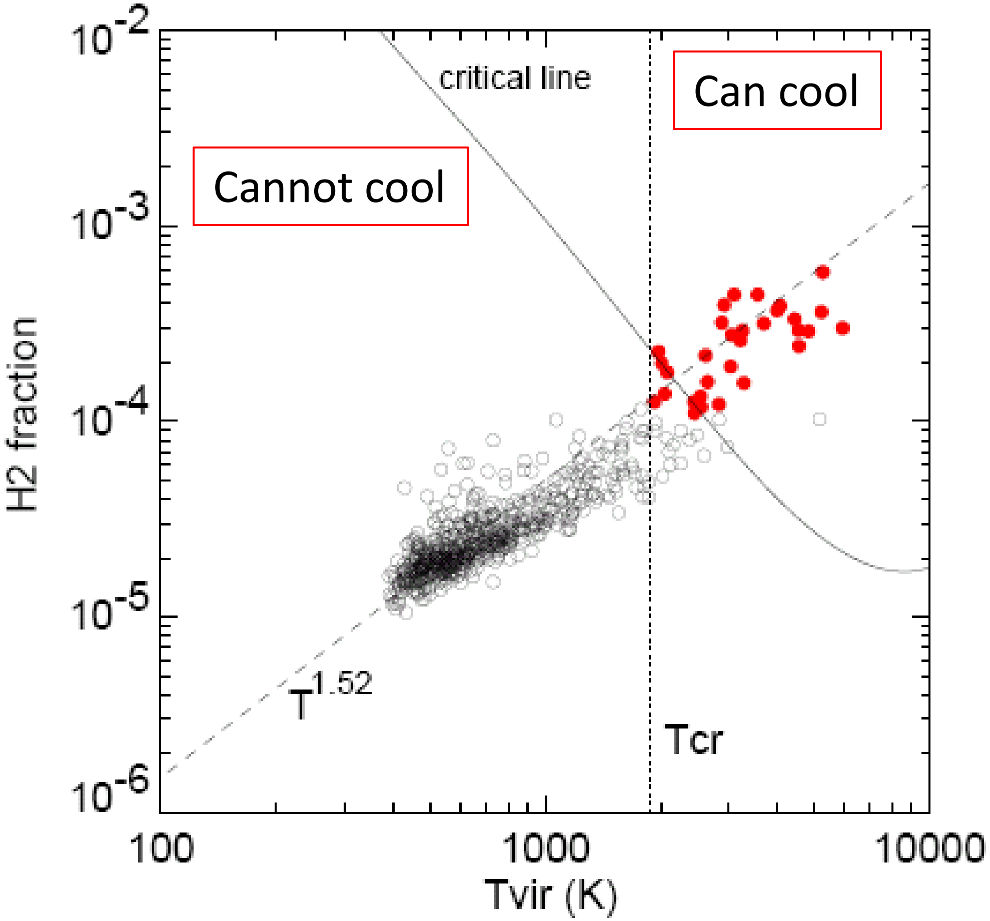
H_2 formation: the key to Pop III star formation

$$\mathrm{H} + e^- \rightarrow \mathrm{H}^- + \gamma,$$

$$\mathrm{H}^- + \mathrm{H} \rightarrow \mathrm{H}_2 + e^-.$$

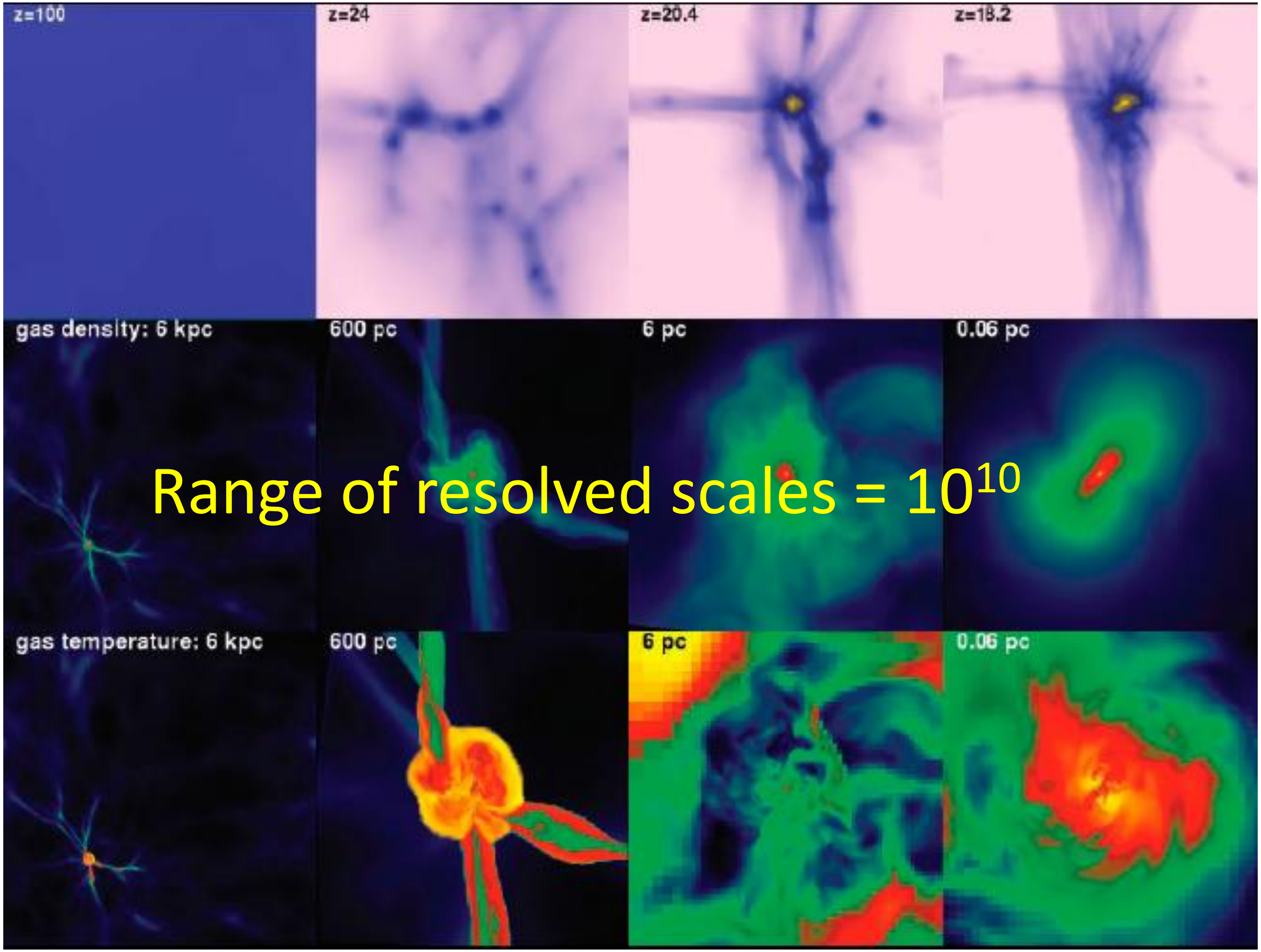
Catalytic reaction becomes efficient above 2000K

Cooling becomes efficient above f(H2)~10^{-4}



Yoshida et al. (2003)

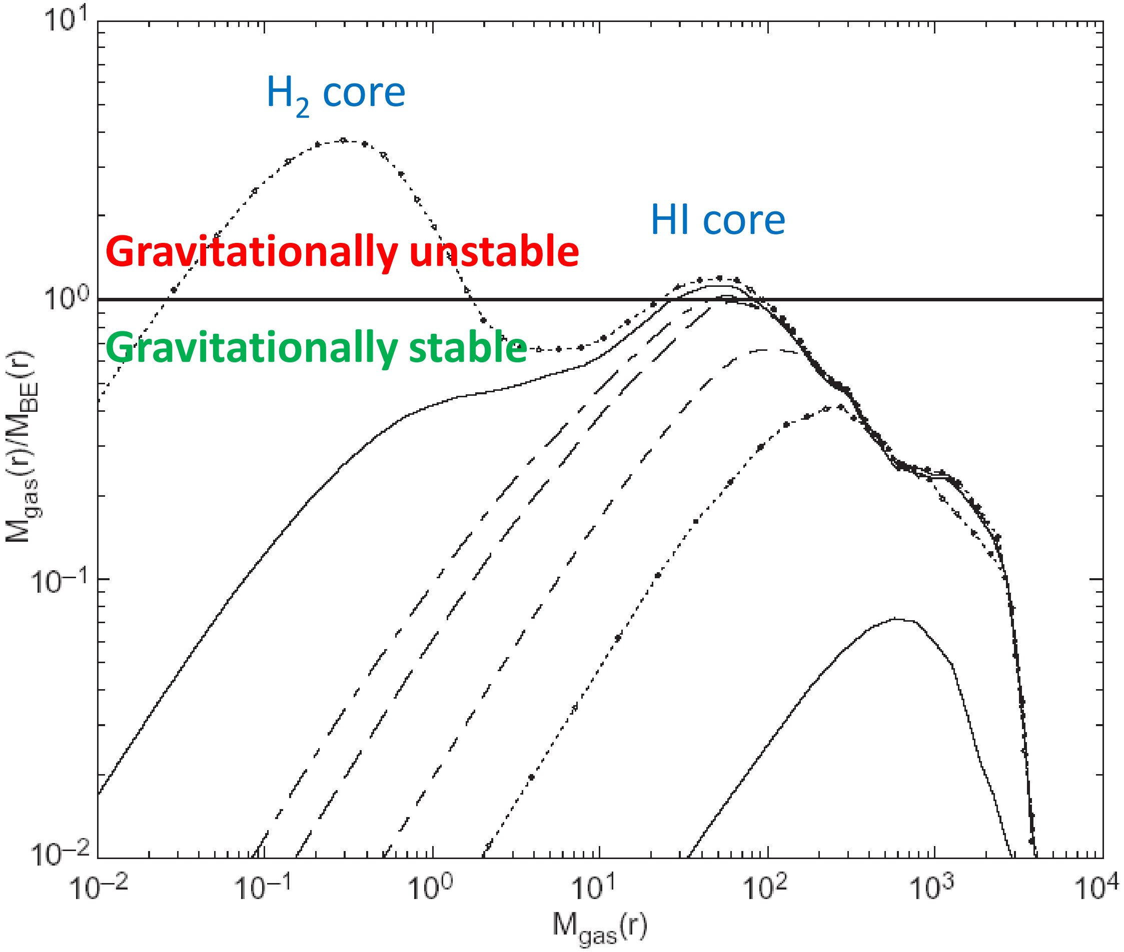
Pop III Star formation: the current paradigm



Range of resolved scales = 10^{10}

From Abel, Bryan and Norman 2002, Science, 295, 93

Evolution of cloud core



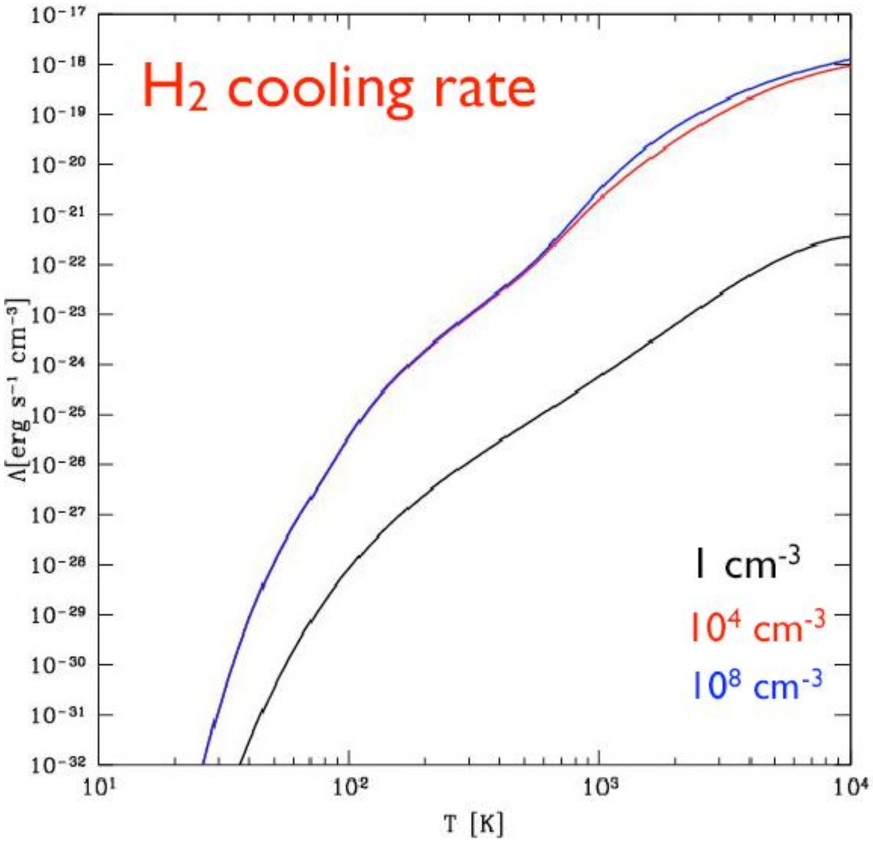
Z=19
+ 9 Myr
+ 300 Kyr
+ 30 Kyr
+ 3 Kyr
+ 1.5 Kyr
+ 200 yr (z=18.18)

Abel, Bryan & Norman (2002)

Origin of mass scale: H_2

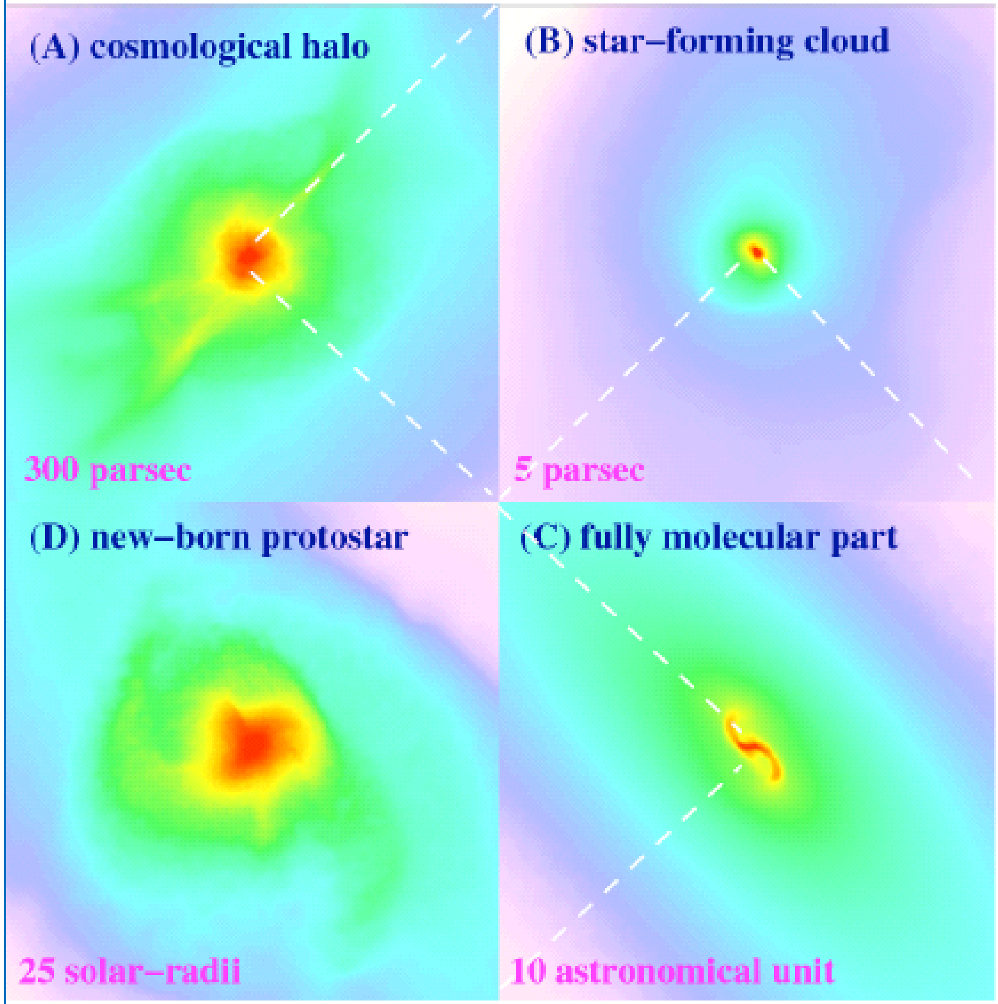
- H_2 cooling rate (per particle) becomes independent of density above $n=10^4\ \mathrm{cm}^{-3}$ (“critical density”)
- 0-1 ro-vib. excitation temperature =590K
  - T_{min}~200K
- Cloud core “loiters” at these conditions until a Jeans mass of gas accumulates, and then it collapses

$$M_J \approx 500 M_\odot \left(\frac{T}{200}\right)^{3/2} \left(\frac{n}{10^4}\right)^{-1/2}$$



Stellar Density Achieved!

Yoshida et al. (2008), Turk et al. (2008)

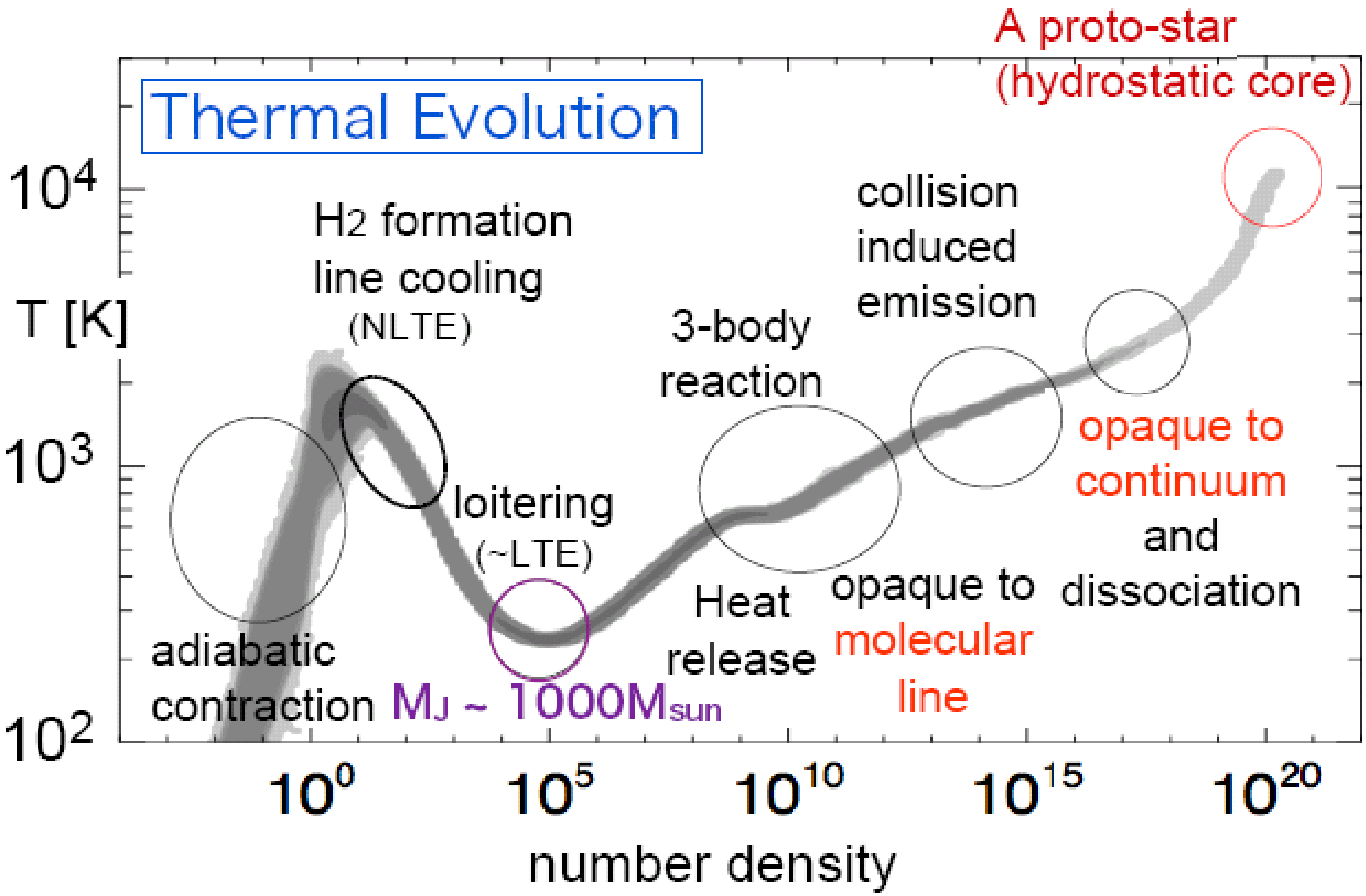


A complete picture of the formation process of a primordial protostar.

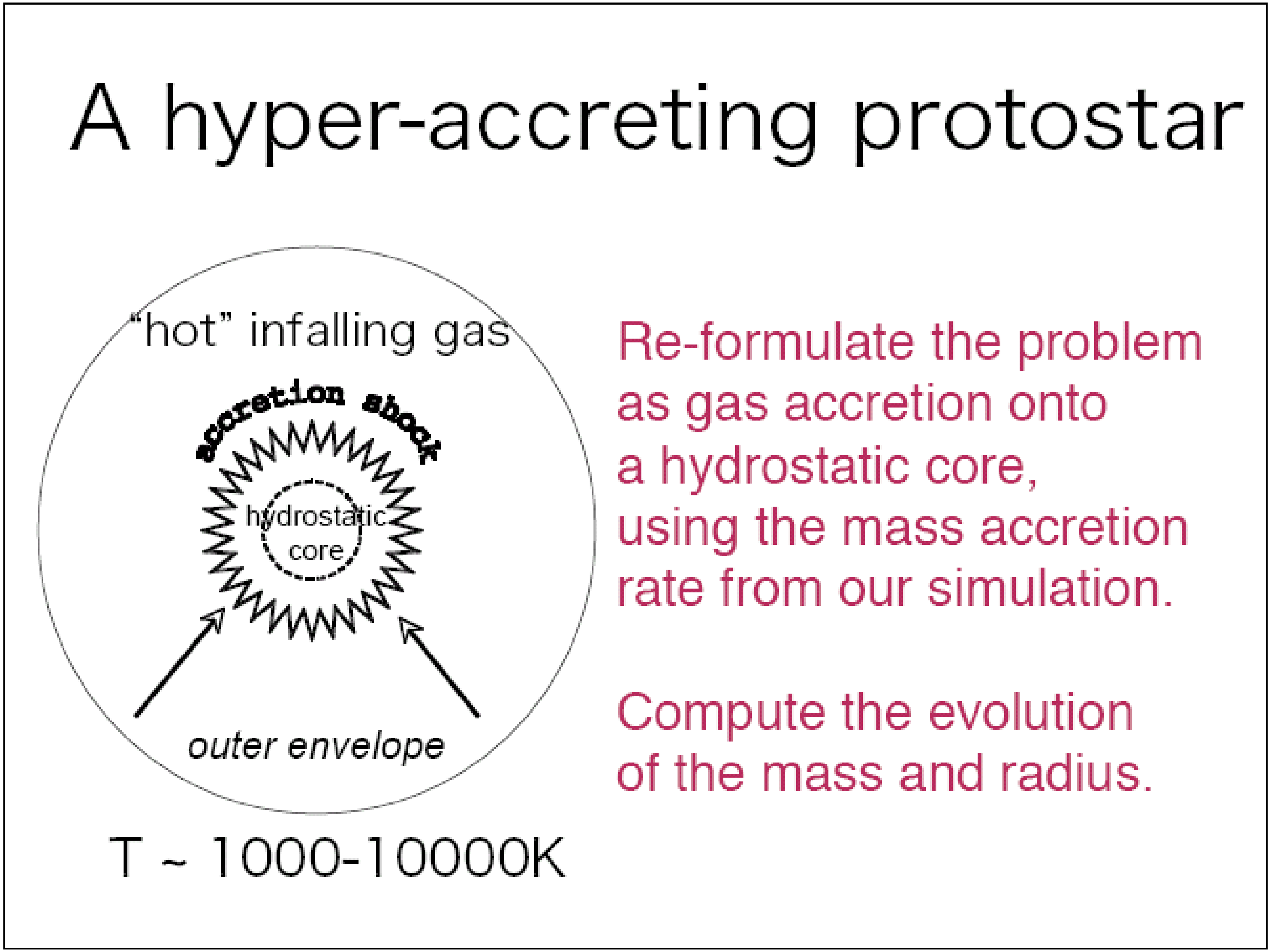
Dynamic range 10^{13}
Resolving planetary scale structures in a cosmological volume!

NY, Omukai, Hernquist
Science 2008

An early universe "experiment"



slide courtesy N. Yoshida



A hyper-accreting protostar

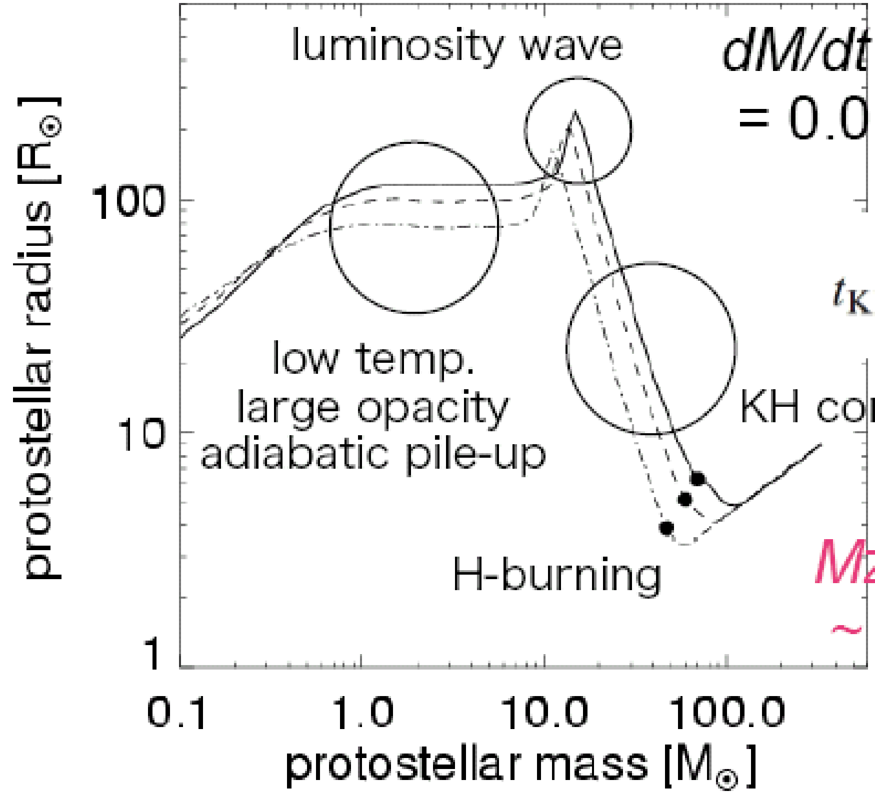
T ~ 1000-10000K

Re-formulate the problem
as gas accretion onto
a hydrostatic core,
using the mass accretion
rate from our simulation.

Compute the evolution
of the mass and radius.

slide courtesy N. Yoshida

Protostellar evolution



NY+ 2006, ApJ

dM/dt = 0.01-0.1 *M*sun/yr

$$t_{\rm KH} = \frac{GM_*^2}{R_* L_*} \propto \frac{1}{M_* R_*}$$

$M_{\rm ZAMS}$ ~ 100 *M*sun

slide courtesy N. Yoshida

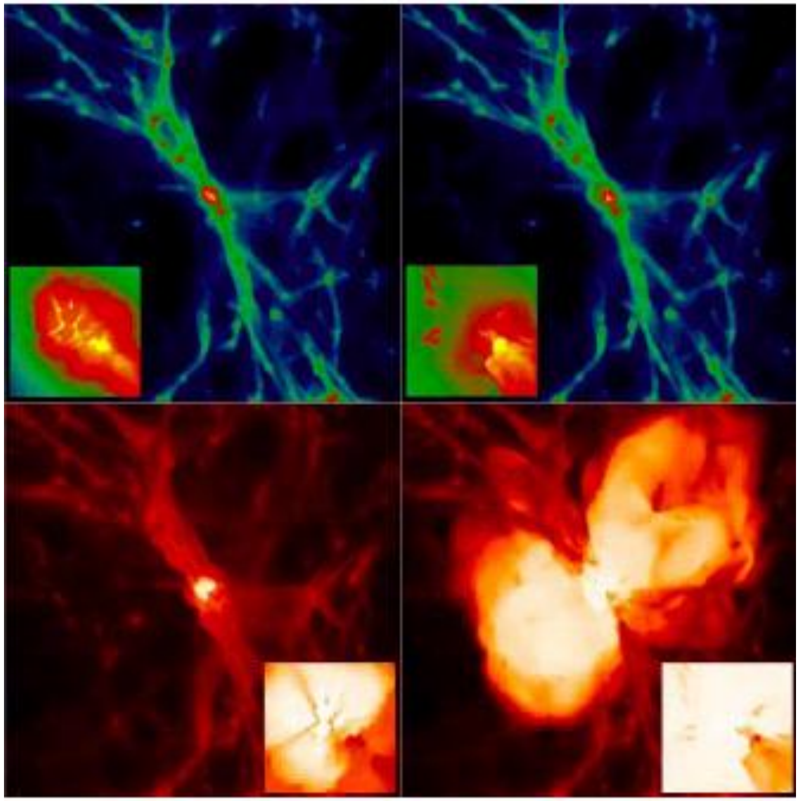
Formation of Pop III.2 protostars

Machacek et al. 2001, 2003; O'Shea et al. 2005; Ahn & Shapiro 2006; Yoshida et al. 2007; Wise & Abel 2008; Whalen et al. 2008

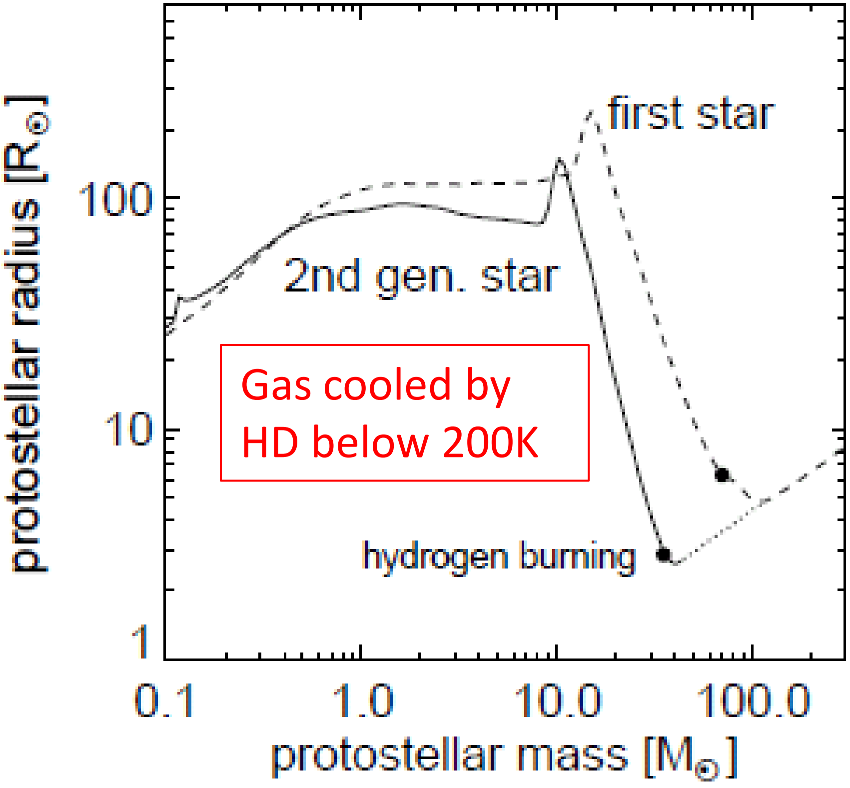
- Initial conditions disturbed by radiative feedback from a Pop III.1 star
  - EUV radiation pre-ionizes gas, which recombines and cools via H_2 and HD
    - local
  - FUV radiation photodissociates H_2, delays cooling and collapse
    - local or global (Lyman-Werner background)

Pop III star formation in a relic HII region

(O’Shea et al. 2005, Yoshida et al. 2007)



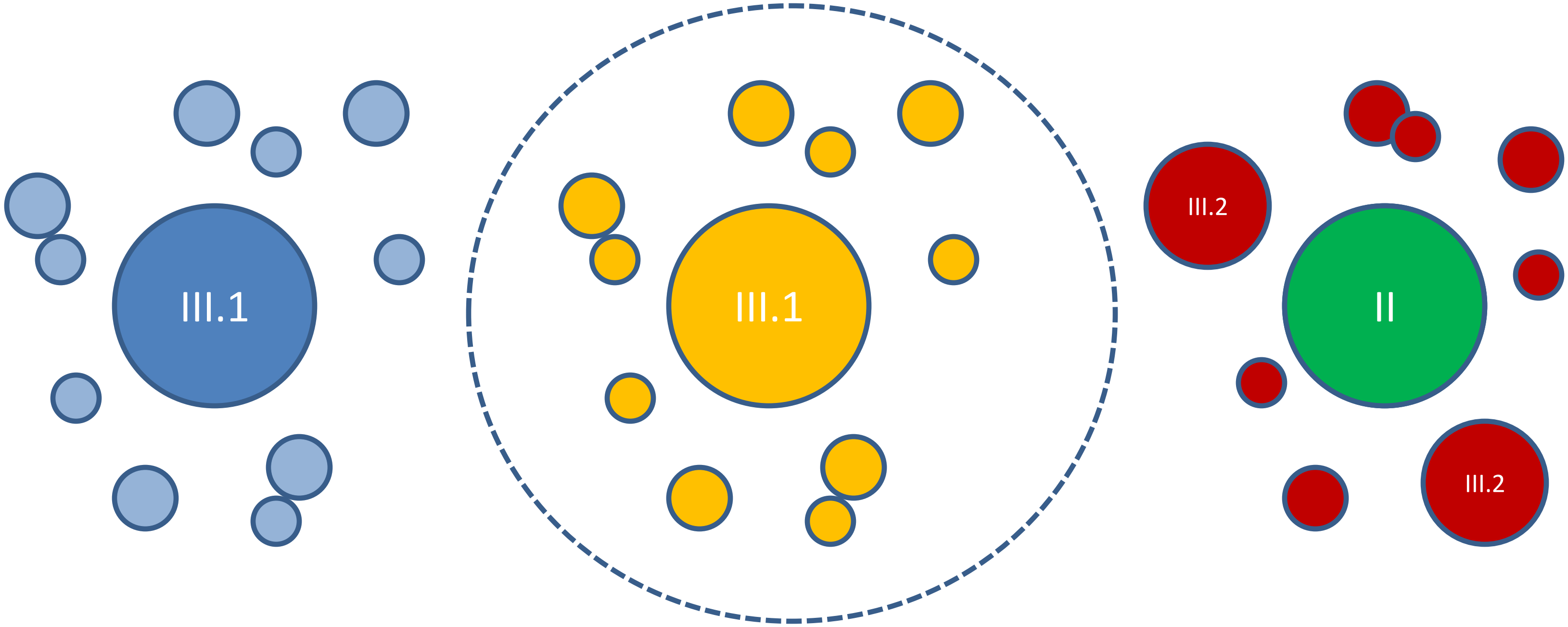
Abel, Wise & Bryan (2007)



Gas cooled by HD below 200K

Yoshida et al. (2007)

Origin of Pop III.2



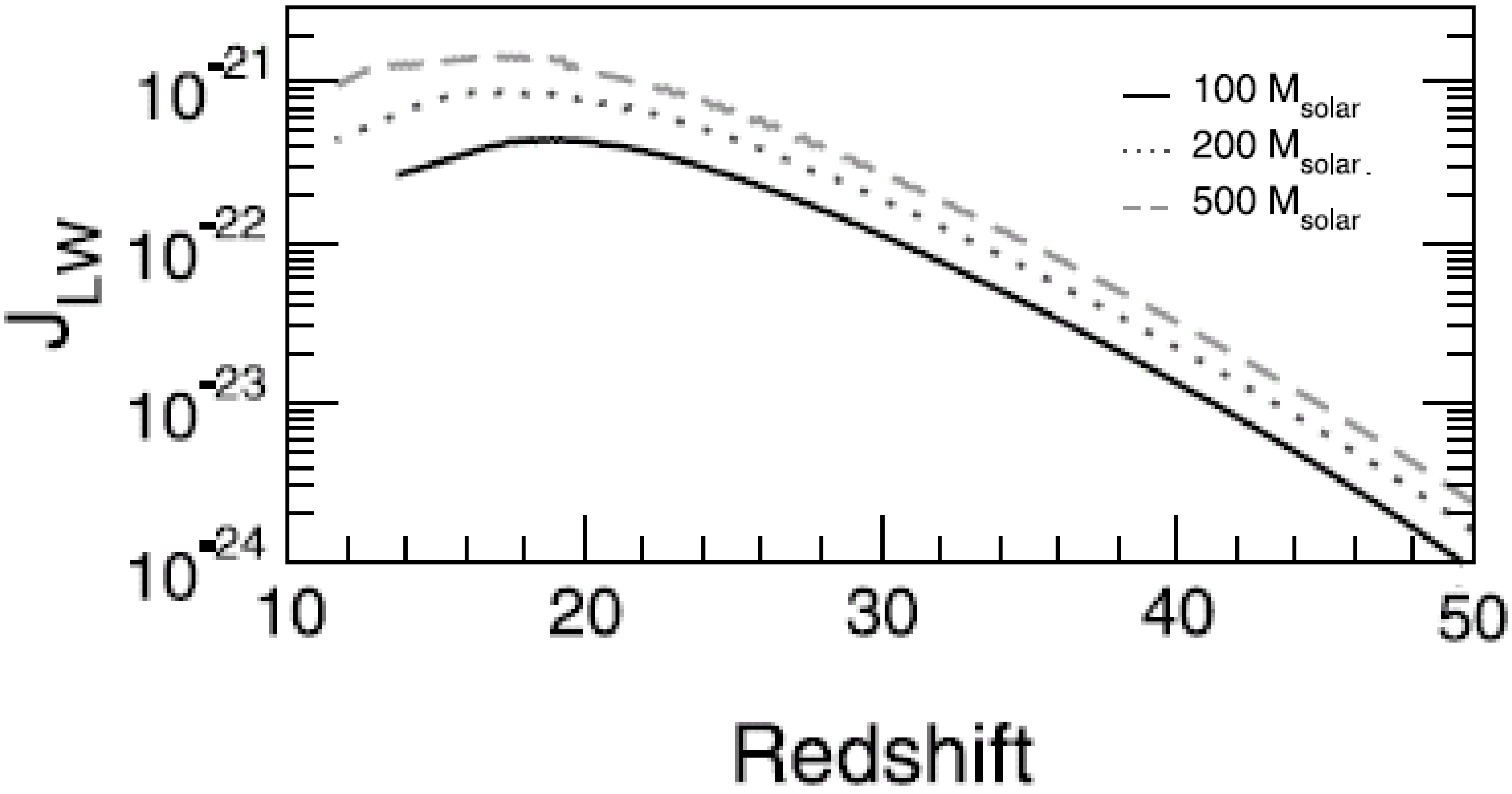
Neutral
H_2 formation

ionized
H_2 destruction

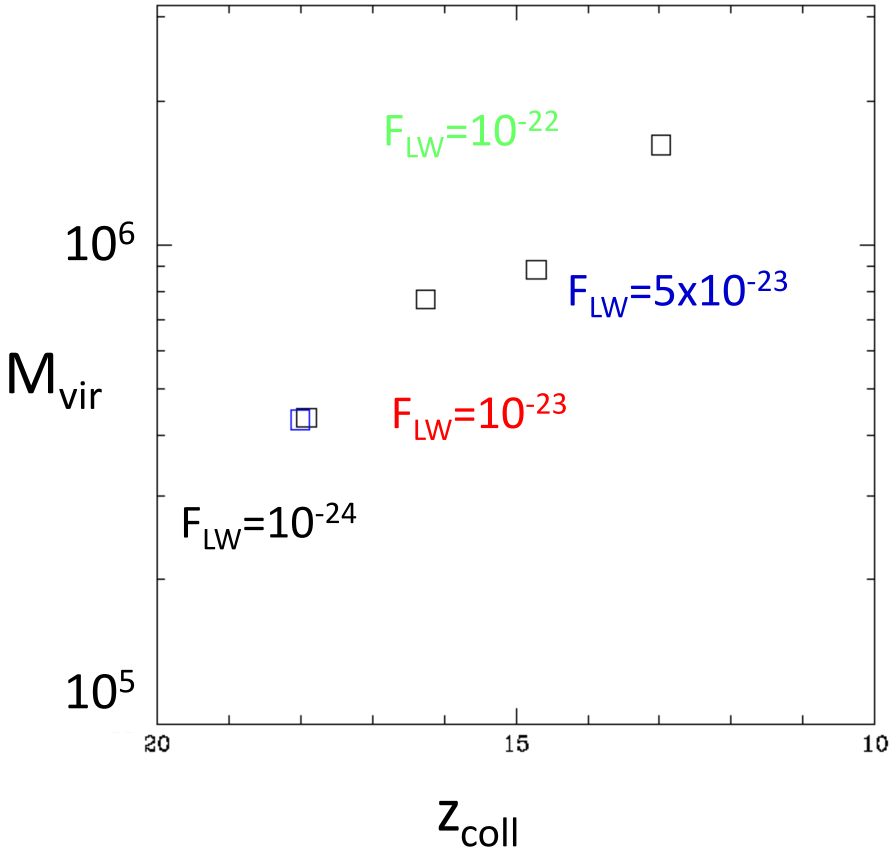
recombining
H_2 & HD formation

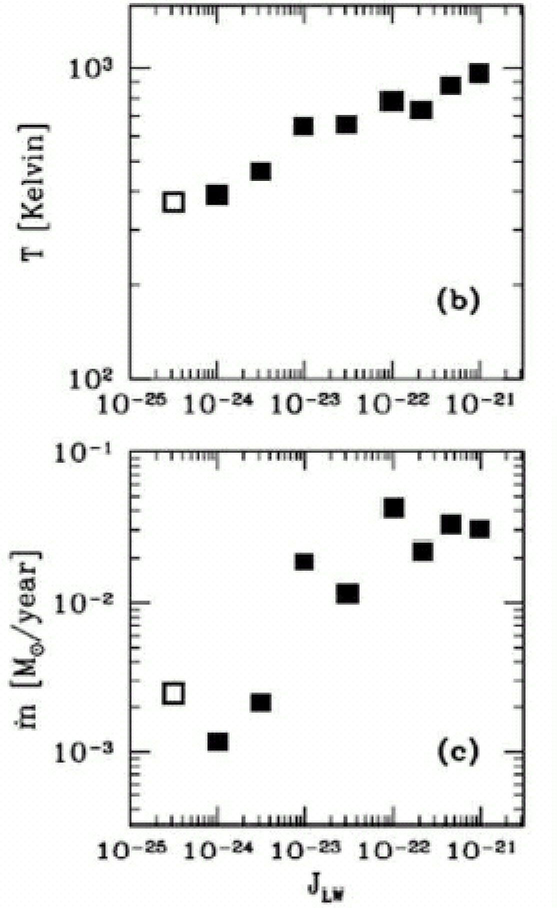
Evolution of the FUV background

Wise and Abel (2005)



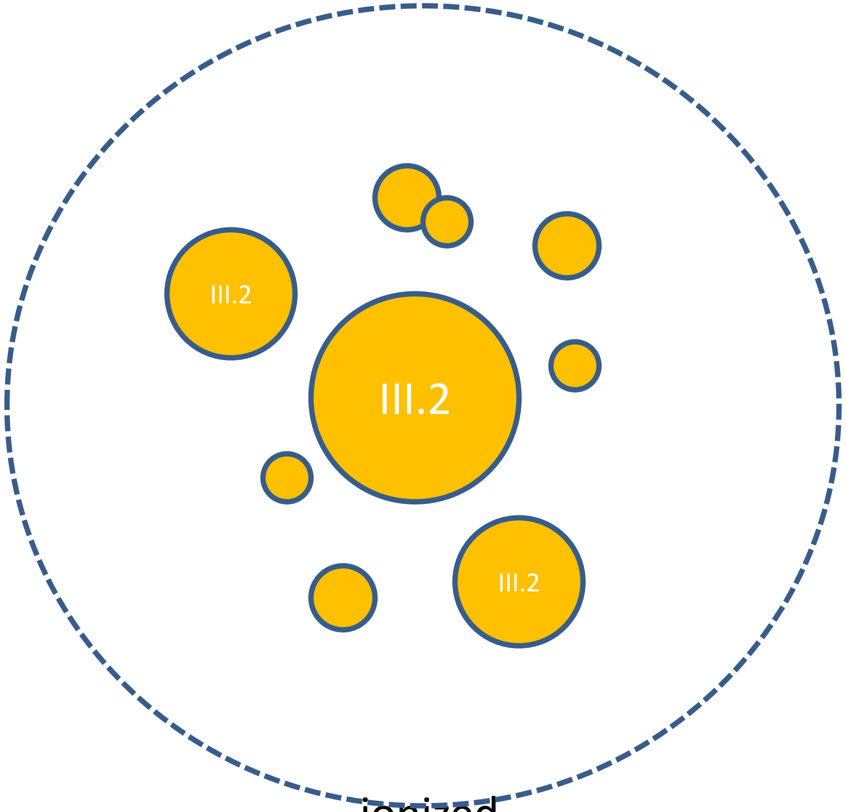
FUVB delays collapse, and raises core temperature and accretion rate (O’Shea & Norman 2008)



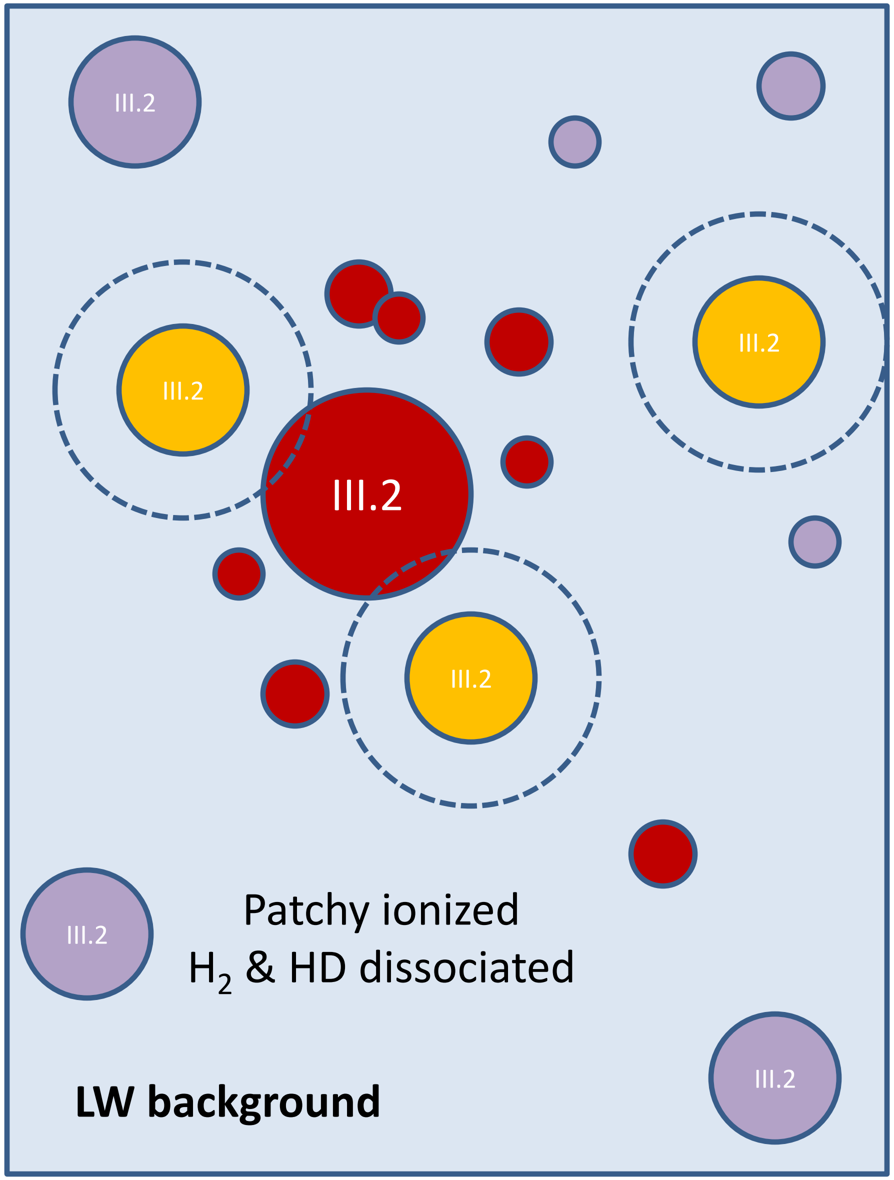


Implies Pop III stars formed at lower redshift are more massive

Origin of Pop III.2



ionized
H_2 & HD destruction



Patchy ionized
H_2 & HD dissociated

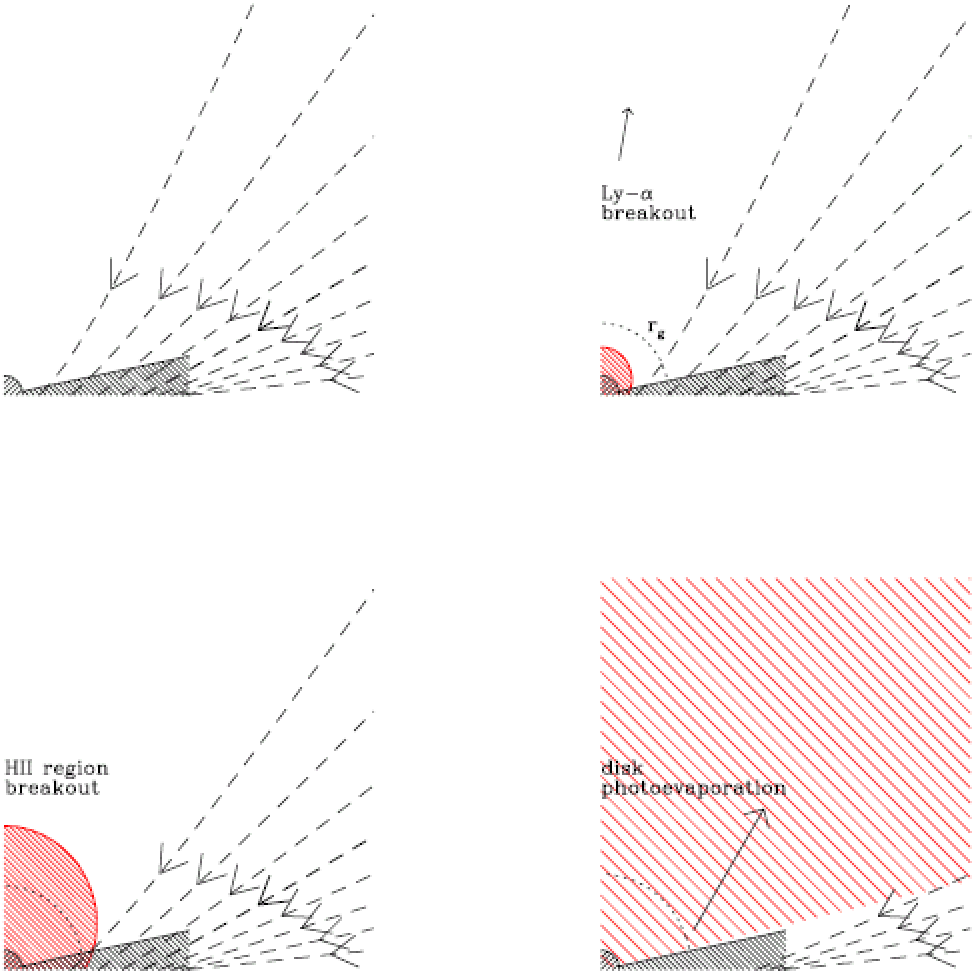
LW background

Final Stellar Masses

- Pop III.1 (III.2) stars enter main sequence at M~100 (40) Ms while they are still accreting mass from their birth cloud (~1000 Ms)
- How massive can they become?
  - Mass loss due to stellar winds presumed negligible (Baraffe et al. 2001, Kudritzki 2002)
  - Radiation pressure on grains not a factor
  - Consider other radiative feedback effects

Final Pop III Masses: Radiative Feedback

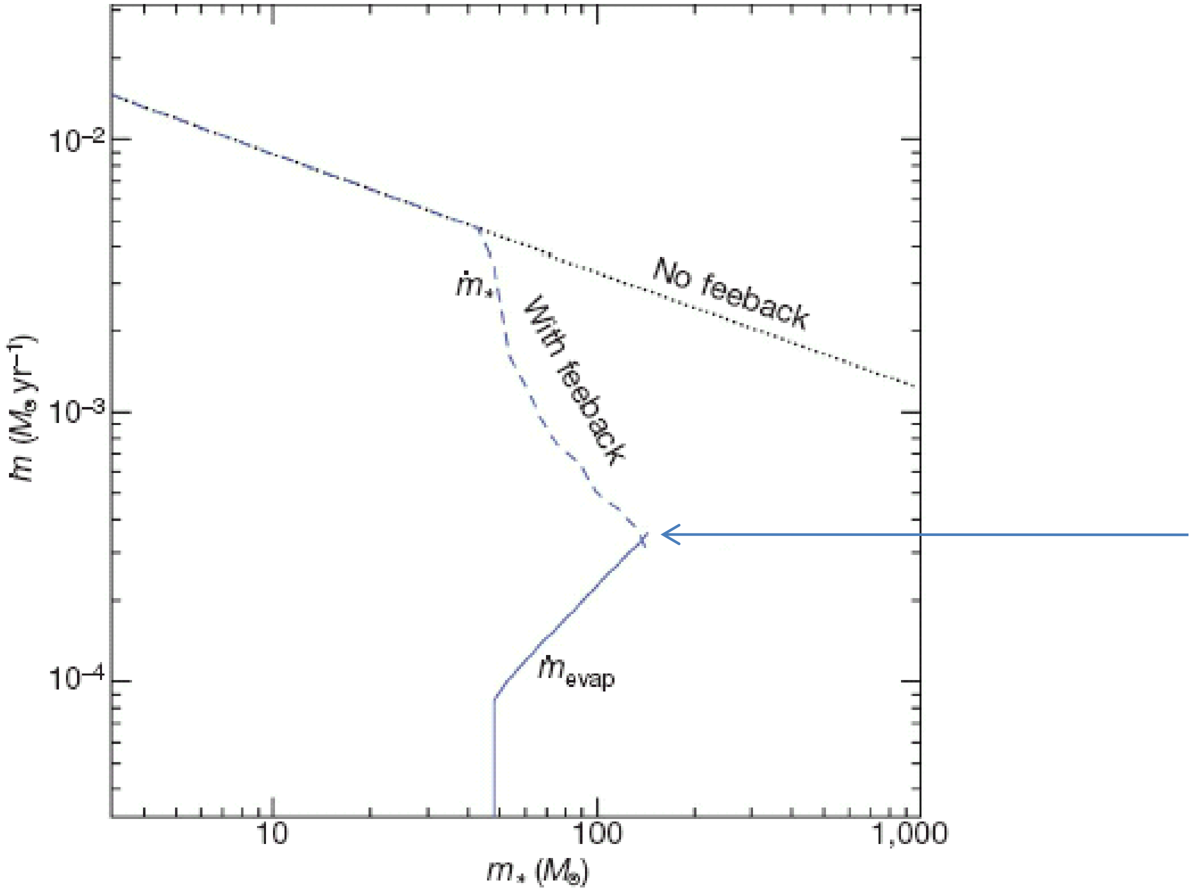
- Analytic models of McKee & Tan (2008)
- Radiative feedback effects from accreting Pop III.1 stars
  - Photodissociation
  - Ly α pressure
  - Ly C pressure
  - HII region breakout
  - accretion disk photoevaporation
- Conclude stars as massive as 100 M_s can form by disk accretion



McKee & Tan (2008)

Feedback-limited accretion

McKee & Tan (2008)

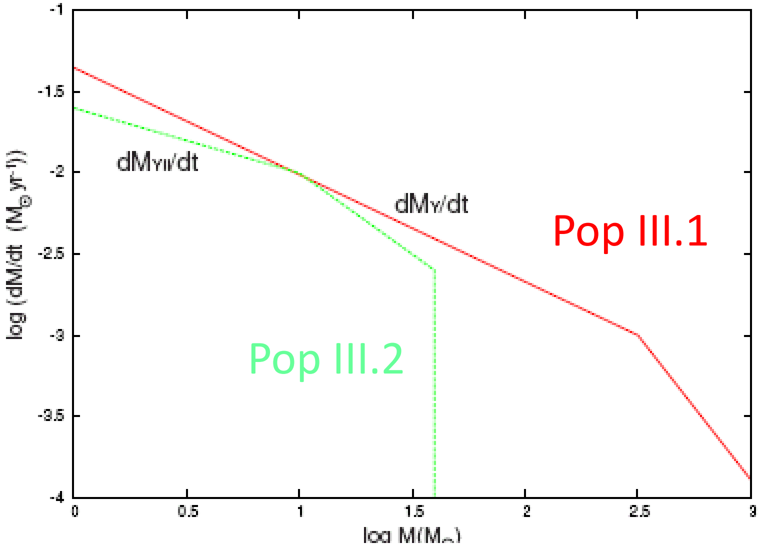


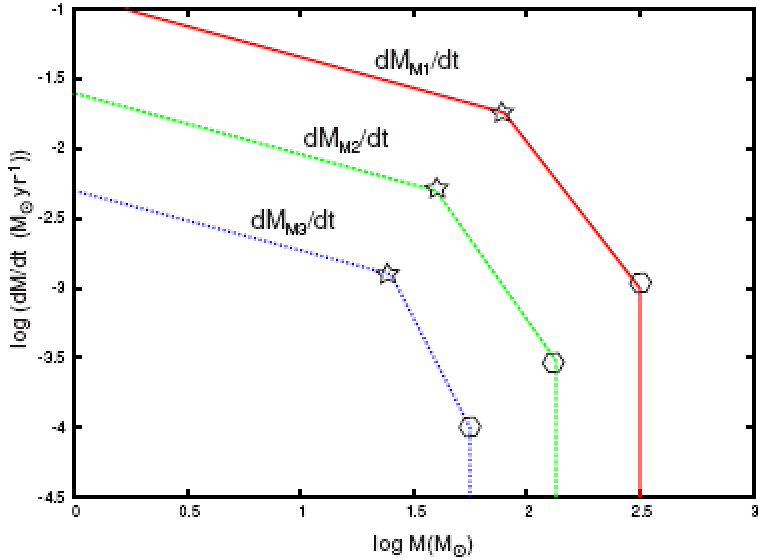
Zero net accretion:

Accretion gain = evaporative loss

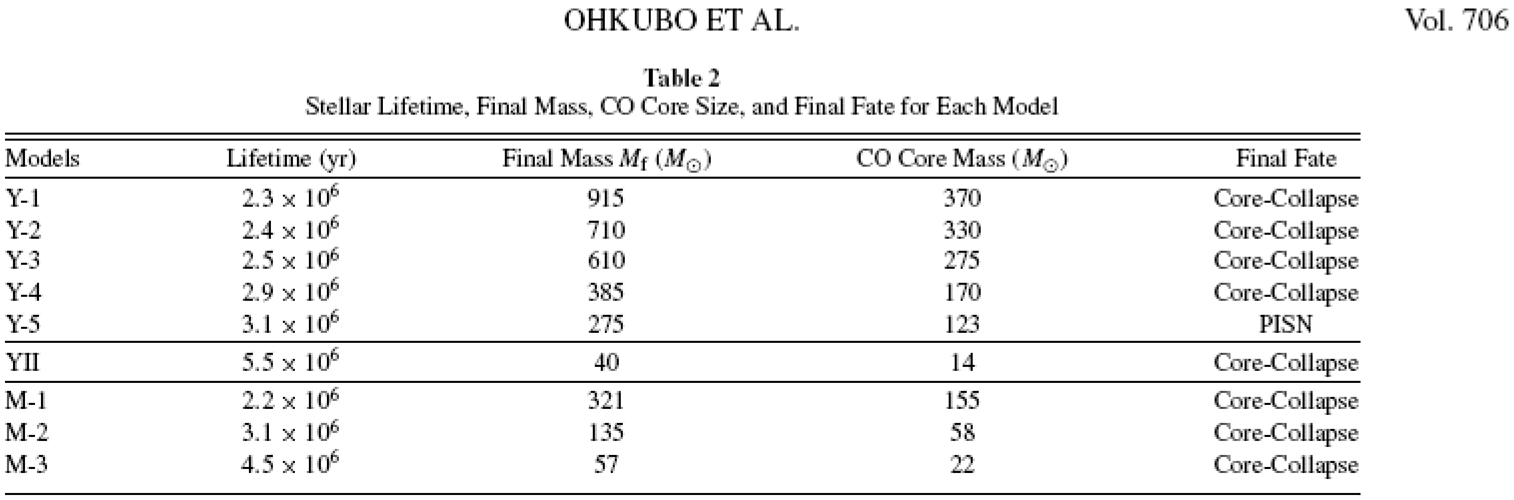
Final Pop III Masses: Stellar Evolution

- Ohkuba et al. (2009) have used accretion histories from Yoshida et al. (2006, 2007) to carry out Pop III stellar evolution calculations through to end points
- Parameterize angular momentum, radiative feedback effects of McKee & Tan (2008)





Final Masses and Fates

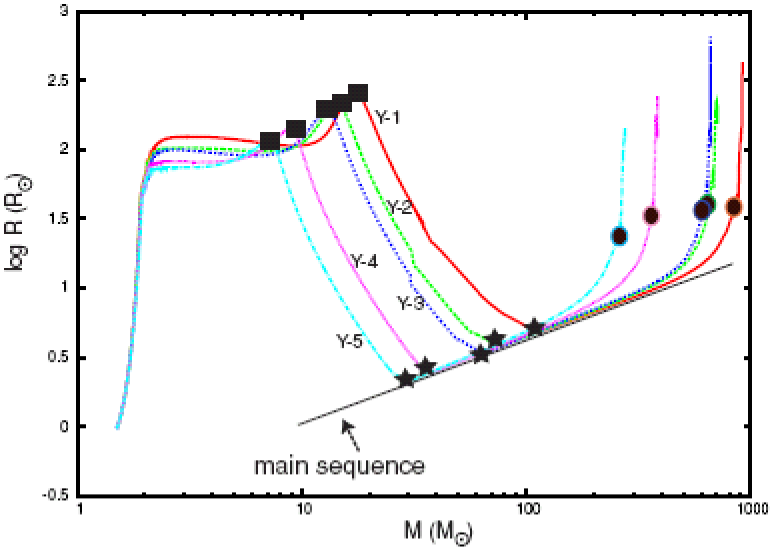


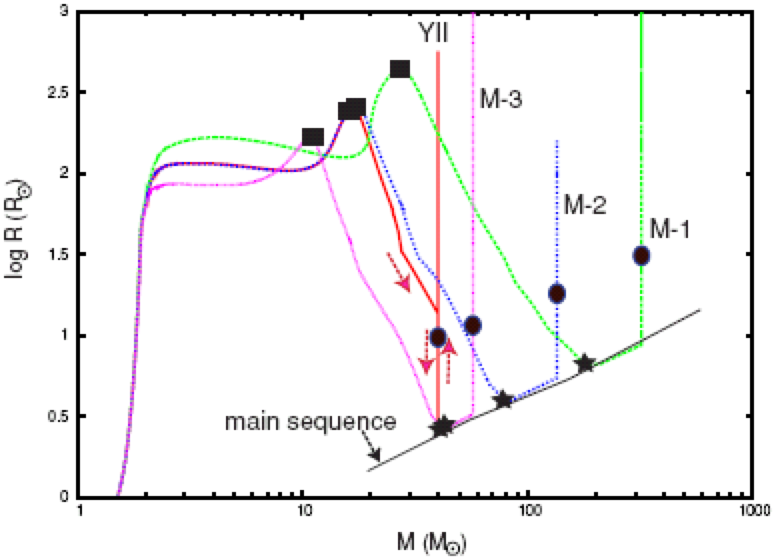
OHKUBO ET AL. Vol. 706

Table 2

Stellar Lifetime, Final Mass, CO Core Size, and Final Fate for Each Model

Models	Lifetime (yr)	Final Mass M_{f} ($M_\odot$)	CO Core Mass ($M_\odot$)	Final Fate
Y-1	2.3×10^6	915	370	Core-Collapse
Y-2	2.4×10^6	710	330	Core-Collapse
Y-3	2.5×10^6	610	275	Core-Collapse
Y-4	2.9×10^6	385	170	Core-Collapse
Y-5	3.1×10^6	275	123	PISN
YII	5.5×10^6	40	14	Core-Collapse
M-1	2.2×10^6	321	155	Core-Collapse
M-2	3.1×10^6	135	58	Core-Collapse
M-3	4.5×10^6	57	22	Core-Collapse





Ohkuba et al. (2009) summary

- Ignoring radiative feedback, Pop III.1 stars die as core-collapse very massive stars (CVMS) in the range 300 – 1000 Ms, depending on angular momentum of the cloud
  - Produce IMBH and little chemical enrichment
- Including radiative feedback, Pop III.1 stars die as CVMS in the range 60-320 Ms, depending on angular momentum of the cloud
  - Produce IMBH and some chemical enrichment
- Pop III.2 stars die as core-collapse supernova with mass ~ 40 Ms
  - Produce stellar BH and some chemical enrichment

Fragmentation by chemo-thermal instability?

- Silk (1983) predicted that onset of 3-body H2 formation would trigger chemo-thermal instability and fragment primordial cloud into small objects
- This has never been observed in ultra-high resolution 3D simulations (Yoshida et al. 2006, Turk et al. 2008)

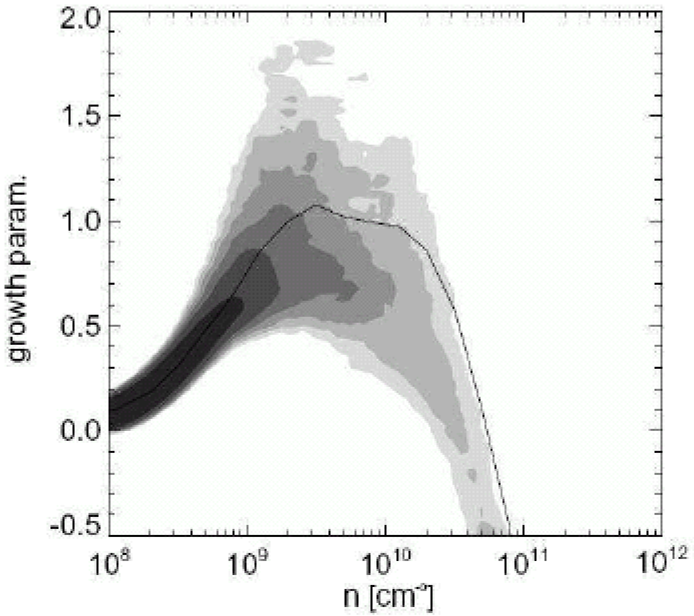
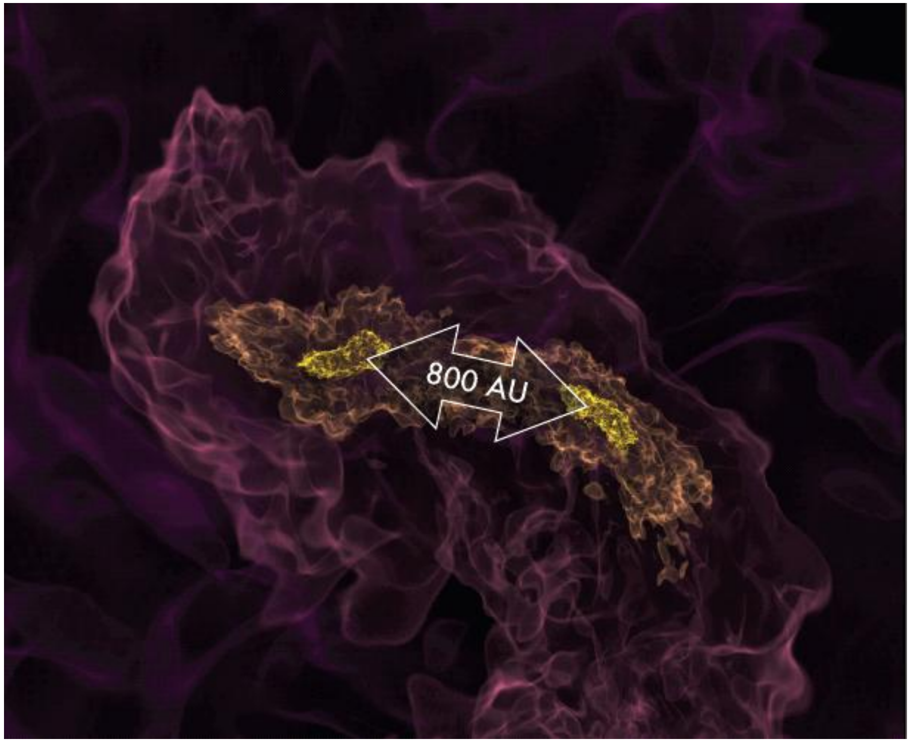


FIGURE 5. Evolution of chemo-thermal instability in the collapsing Pop III cloud core. A growth parameter >2 is required for the core to fragment into multiple pieces. The core does not fragment, but produces a single protostellar seed which accretes the massive envelope. See Yoshida et al. (2006) for more details.

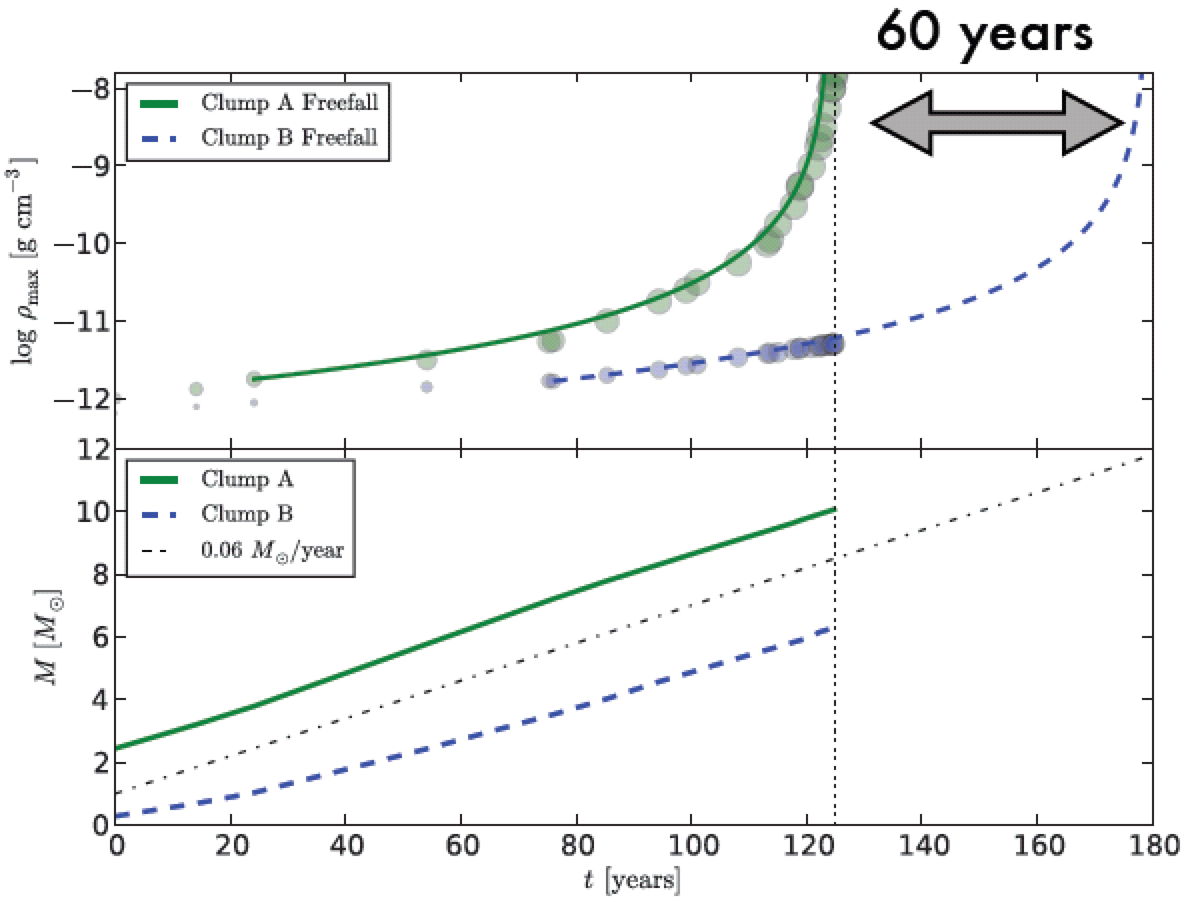
Growth parameter = t_{dyn}/t_{chem}

Binary Fragmentation

- Turk, Abel, & O’Shea (2009) found one in five AMR Pop III.1 simulations to fragment into a binary system
- Central 50 Ms has two clumps separated by 800 AU with mass ratio 2:1
- Seems due to rotation (bar instability) and not chemo-thermal instability
- Stacy, Greif & Bromm (2010) see similar results

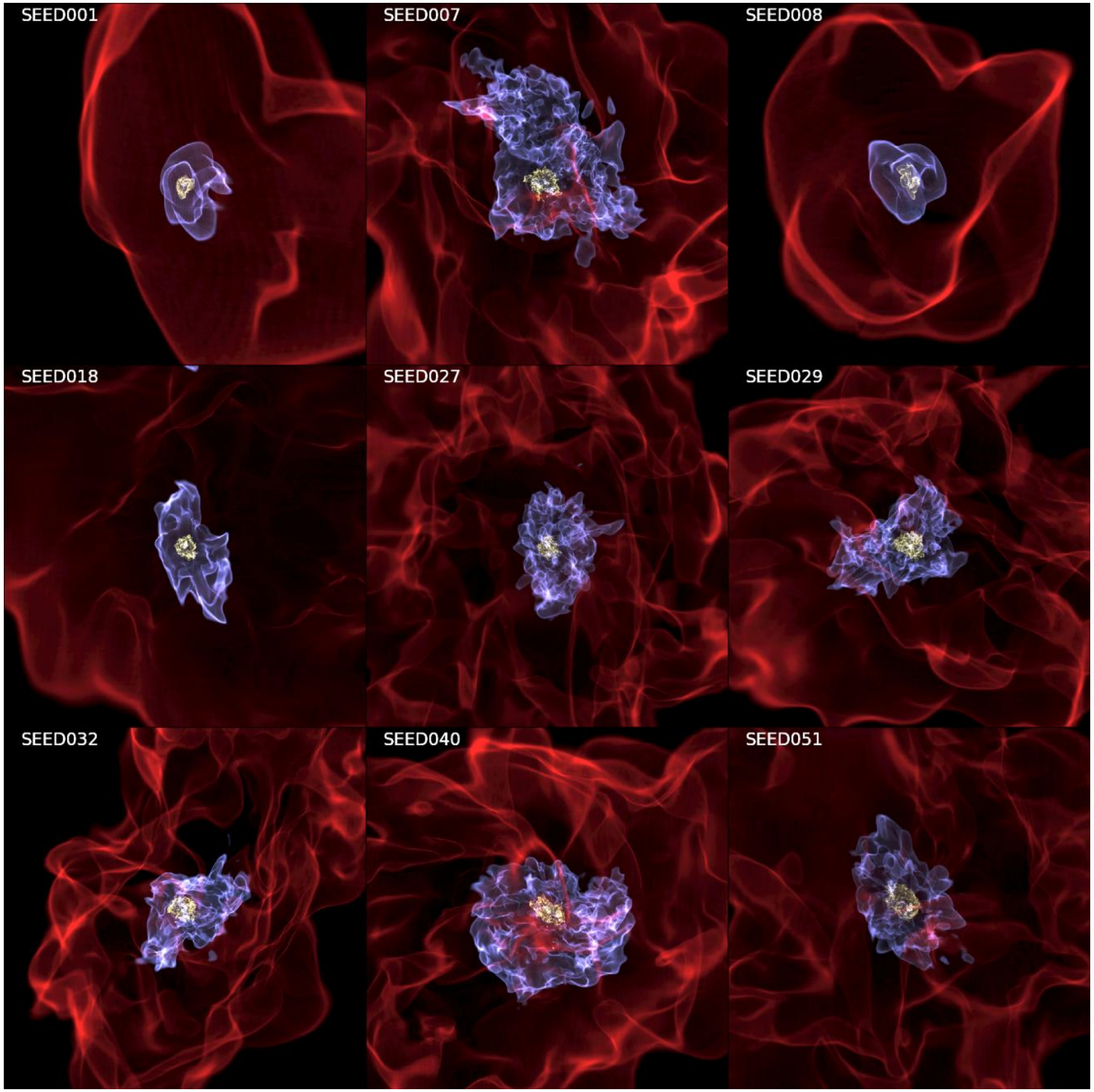


“runaway collapse” bias against finding fragmentation

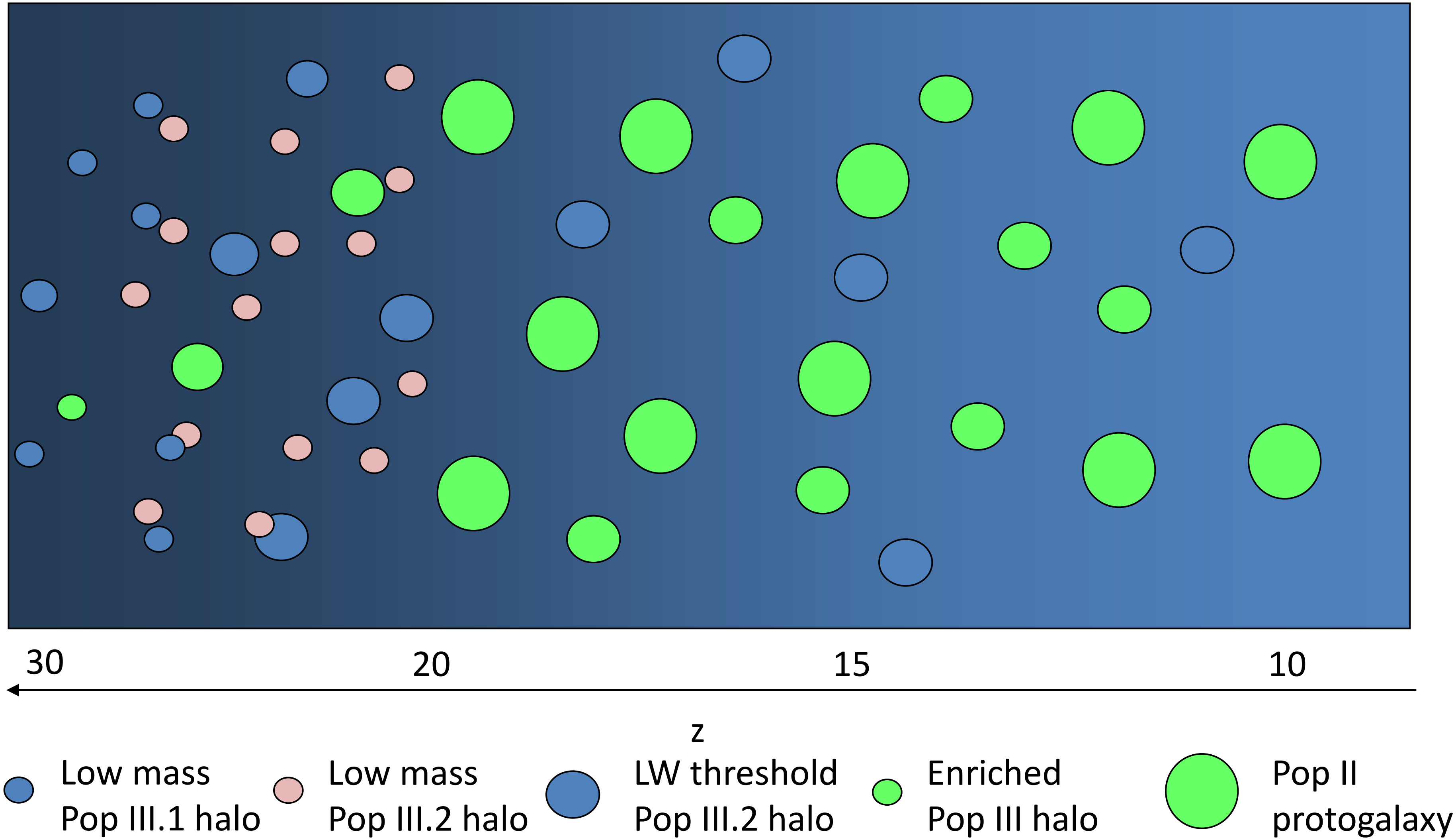


Turk, Abel & O’Shea (2009)

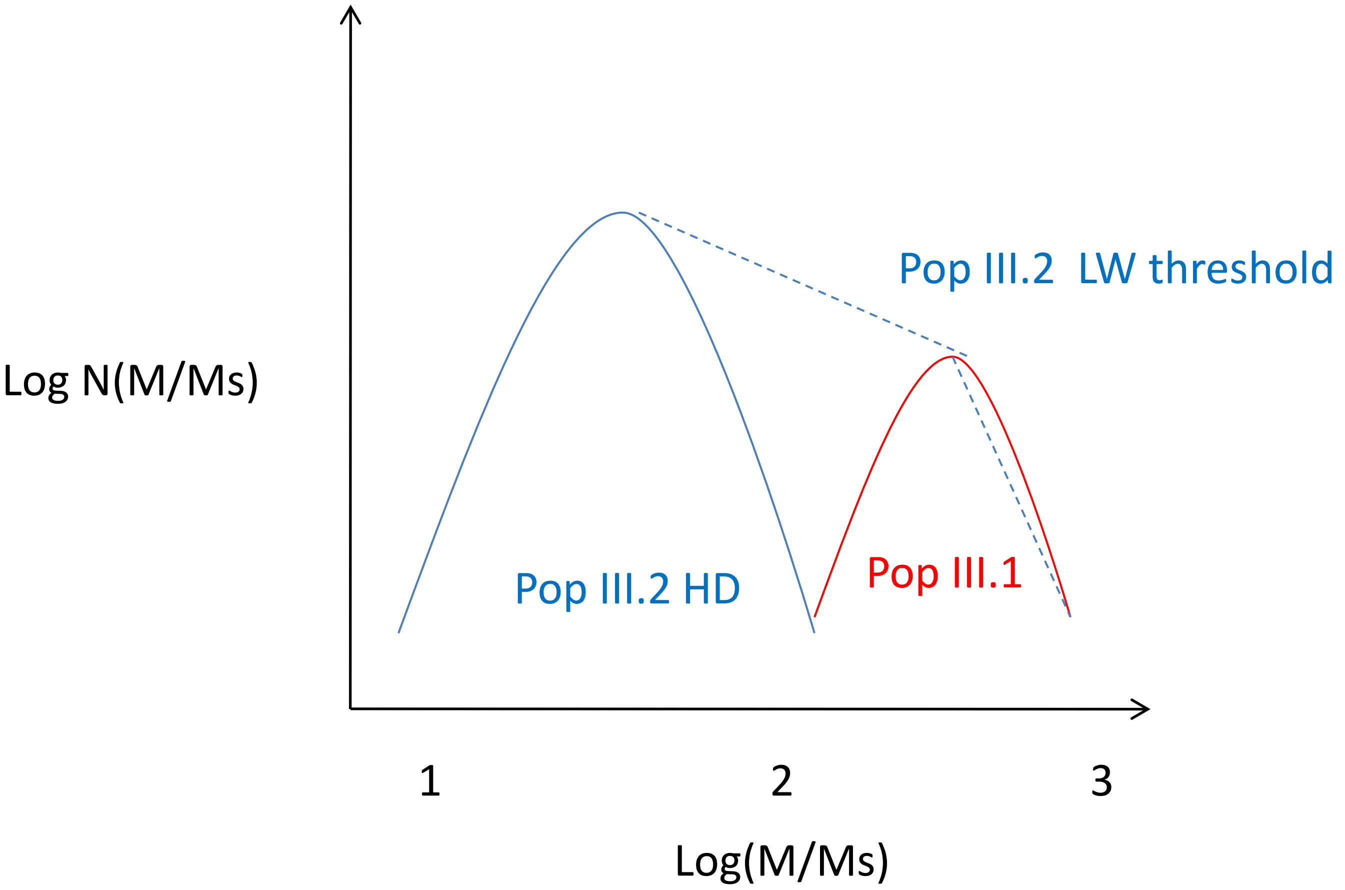
Princeton Twist Survey (Turk et al.)



Rise and Fall of Pop III: A schematic



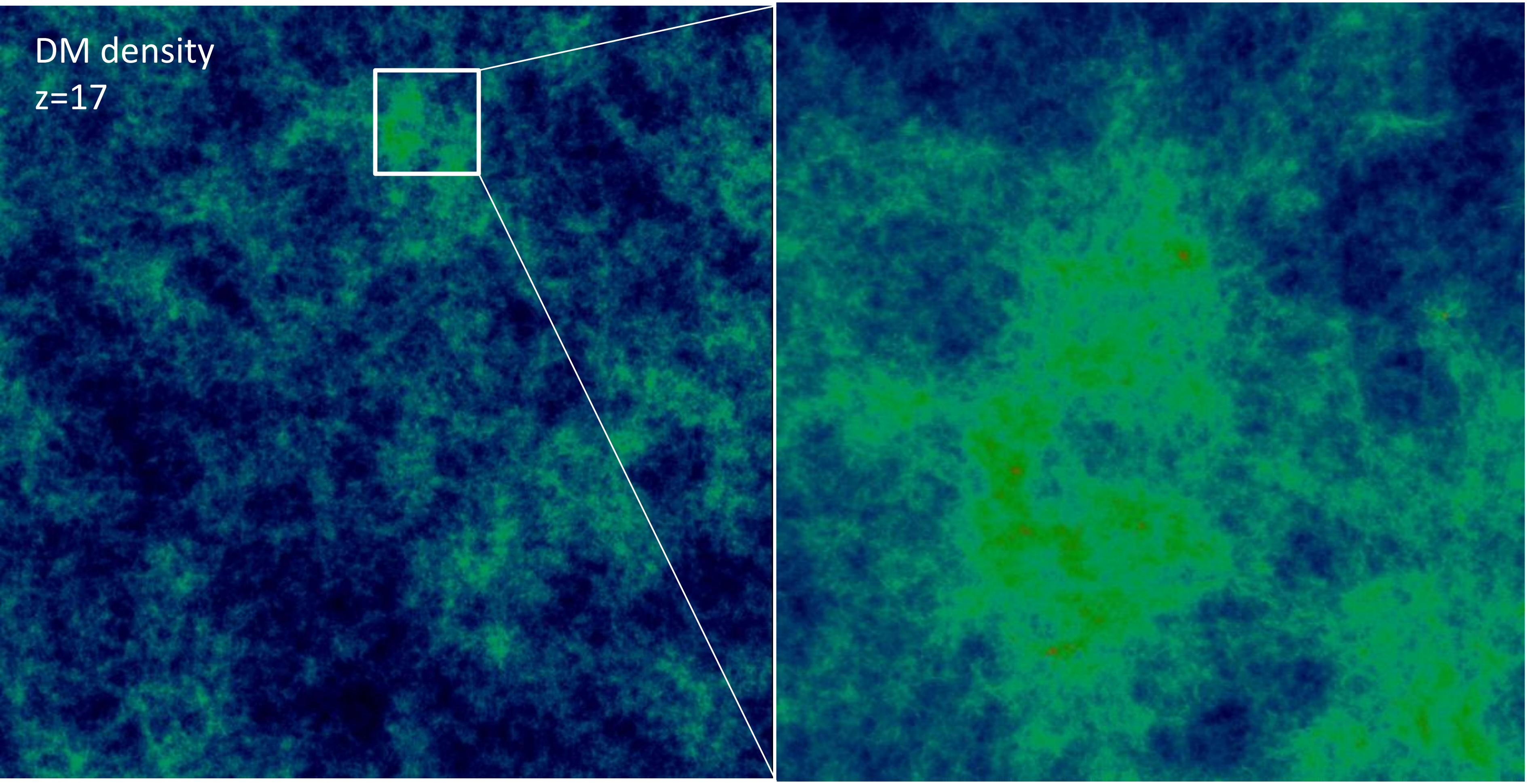
Possible Evolution of Pop III IMF (very speculative!)



How Numerical Simulations Need to Evolve

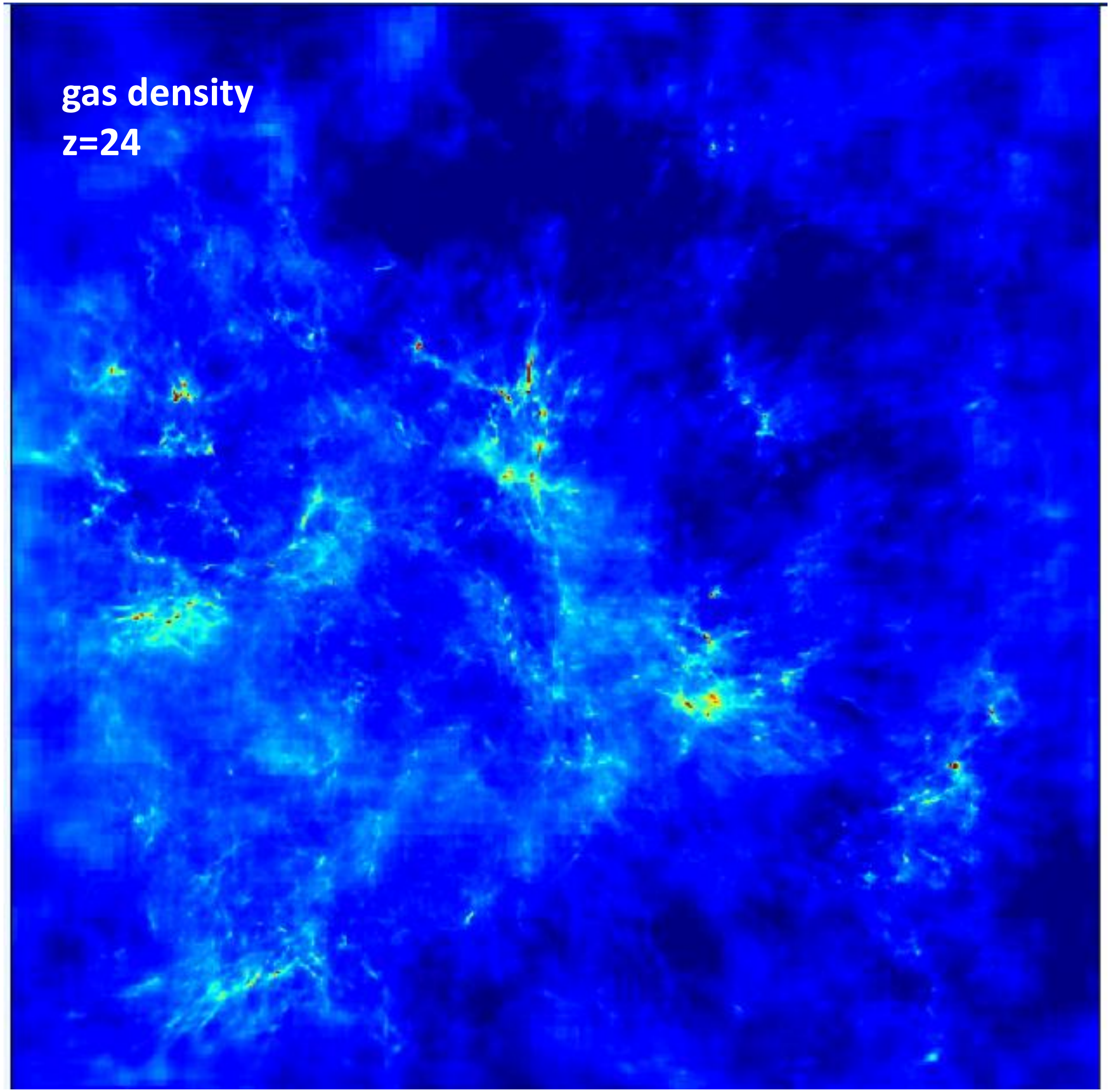
- Individual halo scale
  - Simulate radiative feedback during accretion phase (e.g., Yorke & Sonnhalter 2002; Krumholz, Klein & McKee 2007)
    - 3D radiation hydrodynamics+ionization+chemistry
    - accreting evolving protostar "particle"
    - ➔implicit numerical methods
  - Simulate chemical enrichment and transition to Pop II
- Cosmic scale
  - Large boxes; high resolution in rare peaks to study local and global radiative feedbacks
    - 3D radiation hydrodynamics+ionization+chemistry
    - Calibrated source population subgrid model (FUV, EUV, X)
    - ➔petascale computational platforms

A Huge Unigrid: 6400^3 *Enzo*



6400^3 cells/particles, 80 Mpc box, DM+Gas+SF/FB

93,000 cores, Kraken



7.5 Mpc

Deep AMR simulation of highly biased region inside 30 Mpc box

Wise, Norman, Abel, O'Shea in prep

$M_{dm} = 3 \times 10^4$ Ms

Min(Δx)= 11pc@z=6

Pop II SF/FB model of Wise & Cen (2009)

Metal enrichment and metal-dependent cooling

adaptive ray tracing radiative transfer

WATCH THIS SPACE

Nonstandard Models: WDM

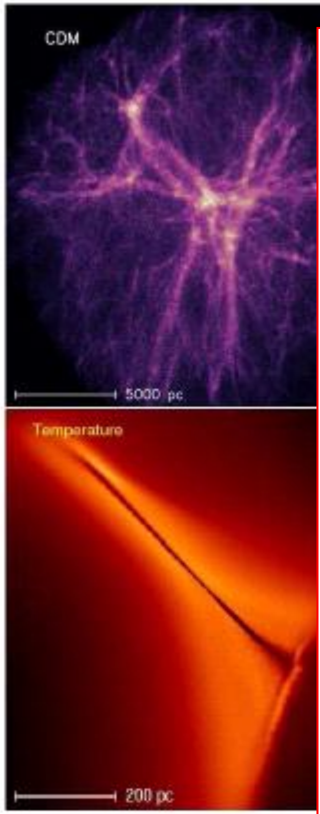
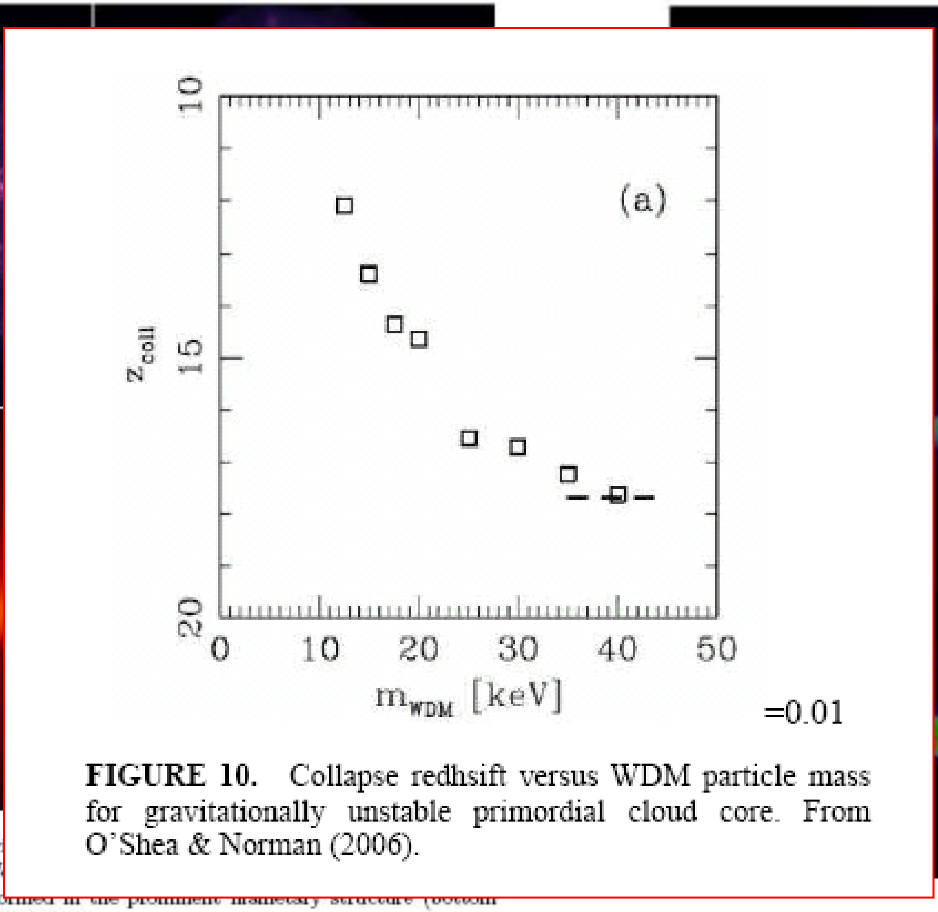


Figure 4: The projected gas distr
and for a WDM model (right). W
model, in which gas clouds are fo
panels). From Gao & Theuns 2007, Science.



=0.01

FIGURE 10. Collapse redhsift versus WDM particle mass for gravitationally unstable primordial cloud core. From O'Shea & Norman (2006).

Gao & Theuns (2007)

O'Shea & Norman (2006)