Simulating the Transition from the First Stars to the Second Stars

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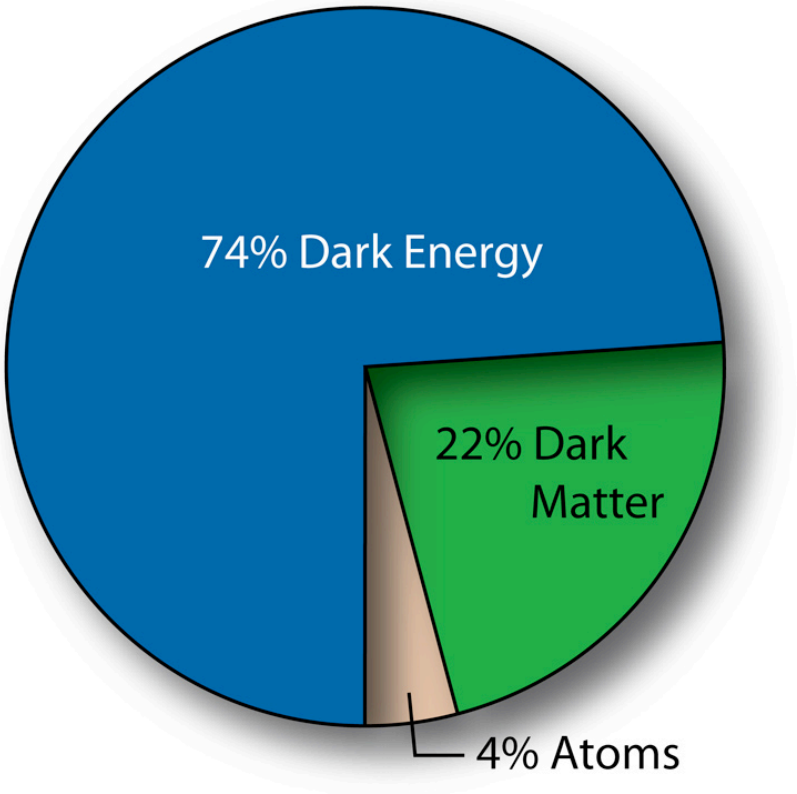
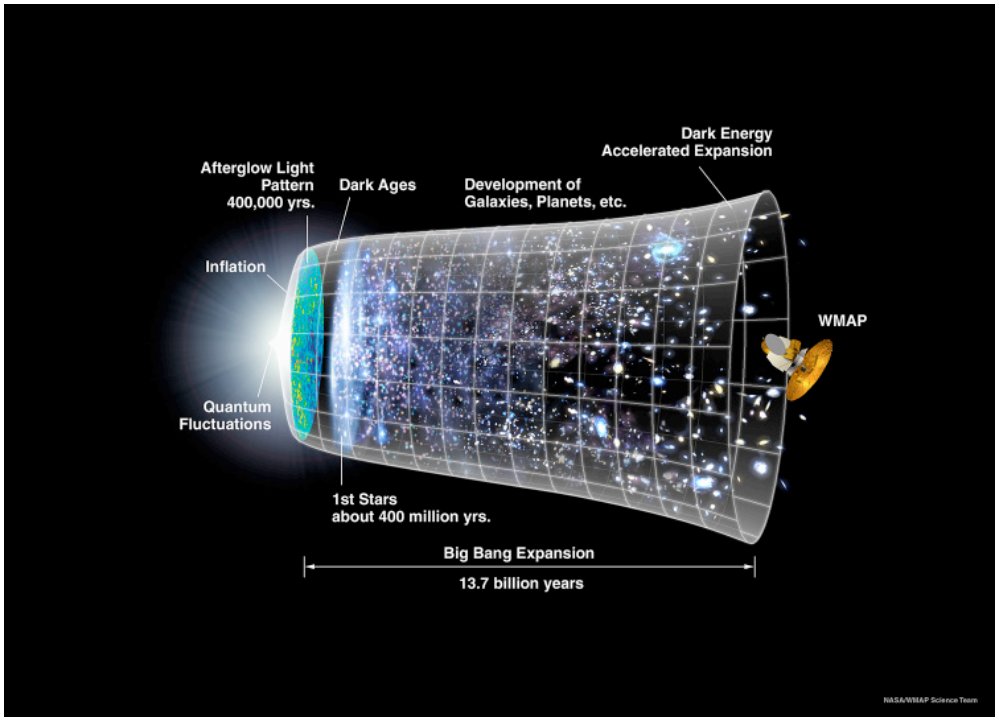
Aspen 2-15-08

The First Stars:
a well posed problem

- Initial conditions courtesy of The Big Bang





Thanks, WMAP.

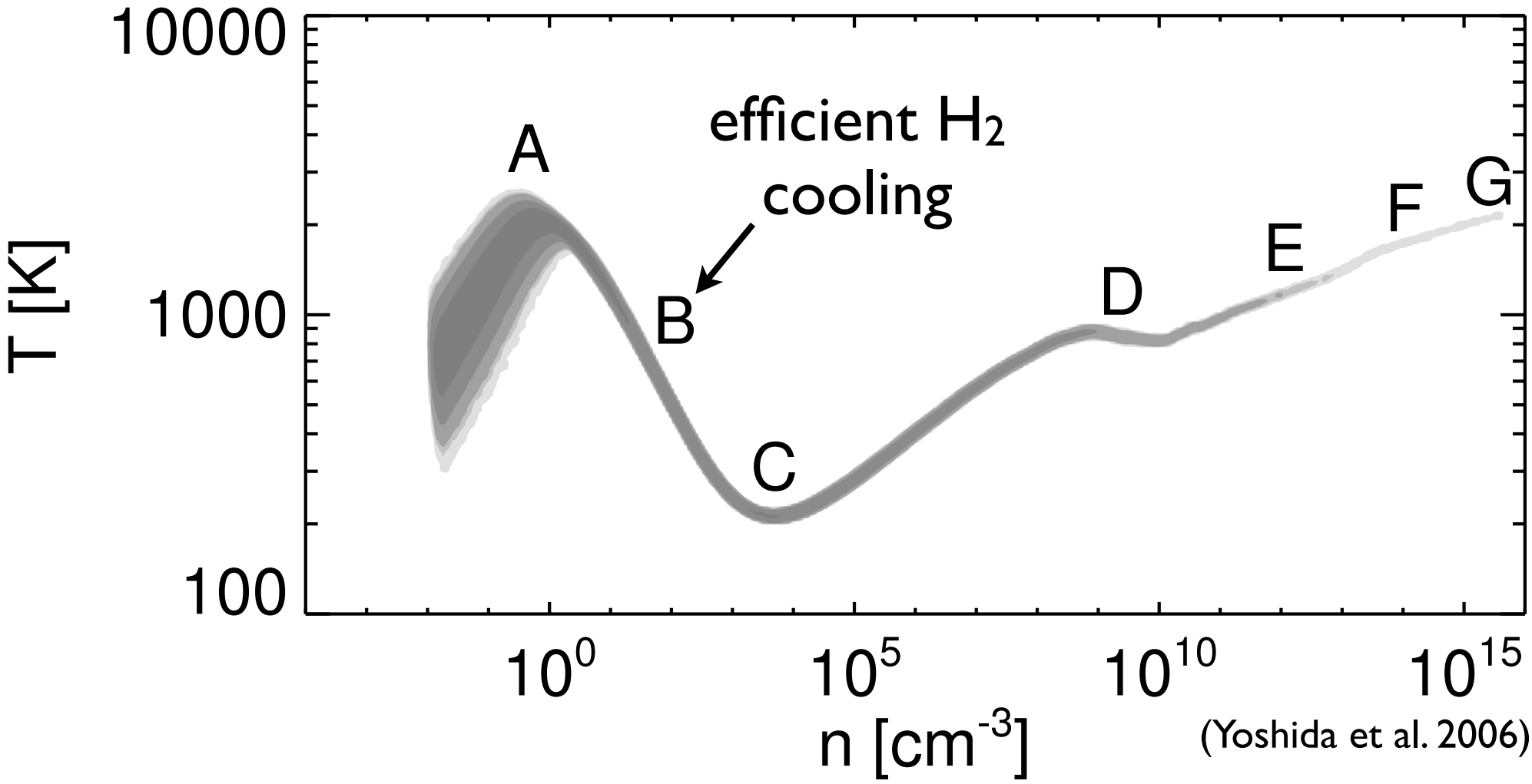
The First Stars:
a well posed problem

- Gas Chemistry: Big Bang Nucleosynthesis
  - H, He, and a little D and Li (metal-free)
  - D and Li relatively unimportant
  - Radiative cooling
    - $T > 10^4$ K: atomic H, He
    - $T < 10^4$ K: H_2

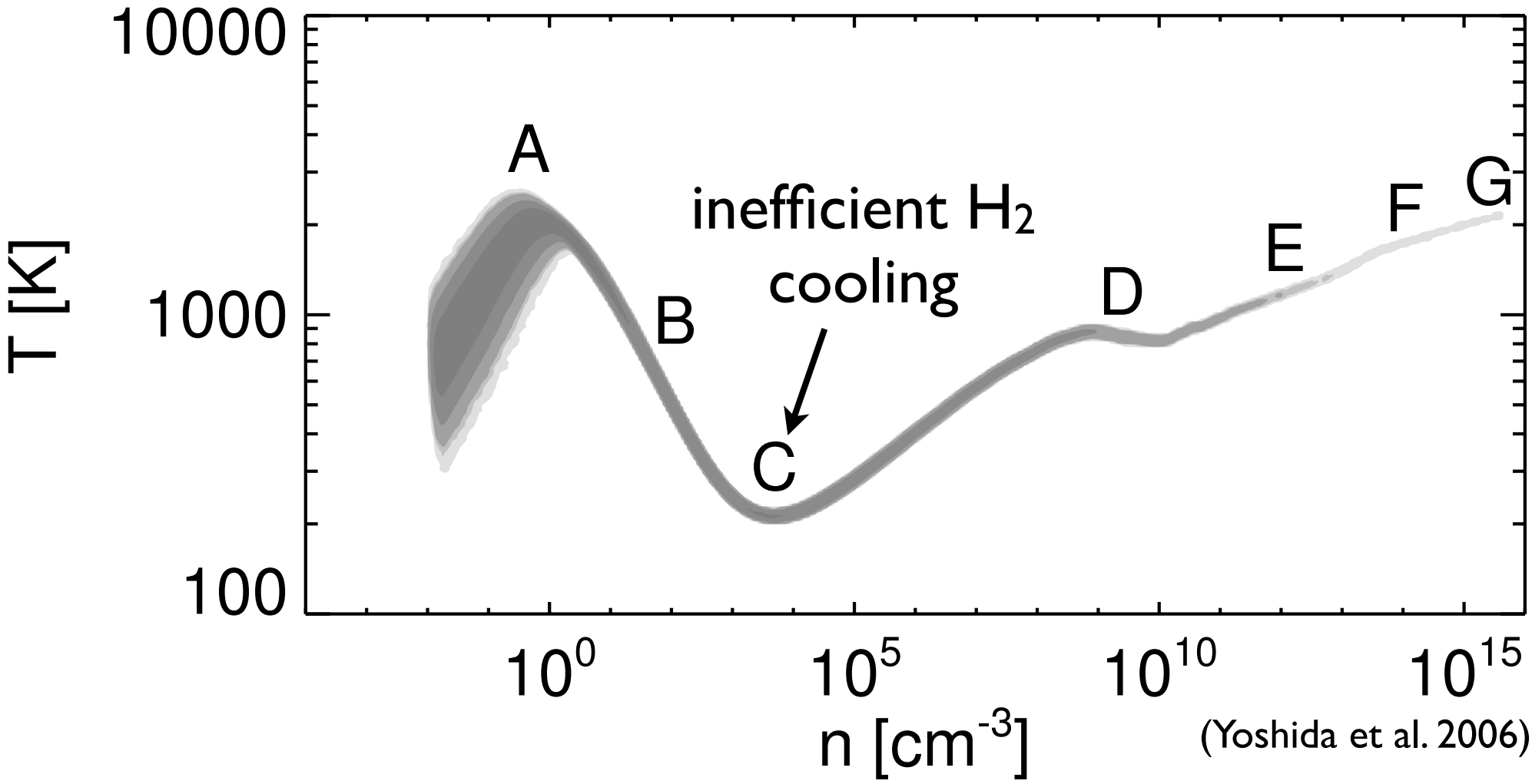
The First Stars

- **Formation controlled by H_2 physics**
  (Bromm et al. 2002; Abel et al. 2002)
  - H_2 only low-temperature coolant
  - lowest rot. trans. ~512 K → T_{min} ~ 200 K
  - states in LTE at n ~ 10^4 cm^{-3}
    - NLTE: $\Lambda \propto n^2$ (efficient)
    - LTE: $\Lambda \propto n$ (inefficient)

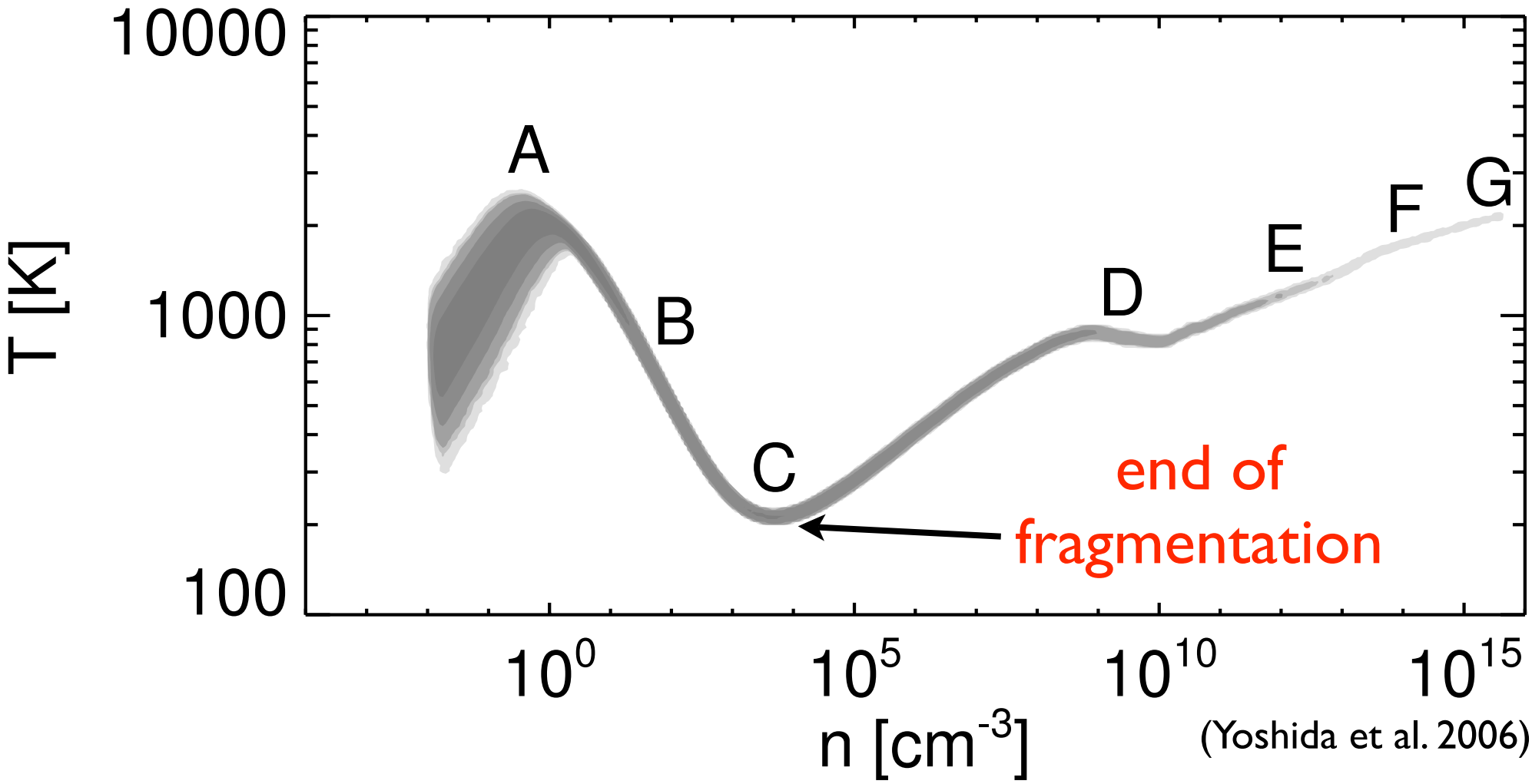
The First Stars



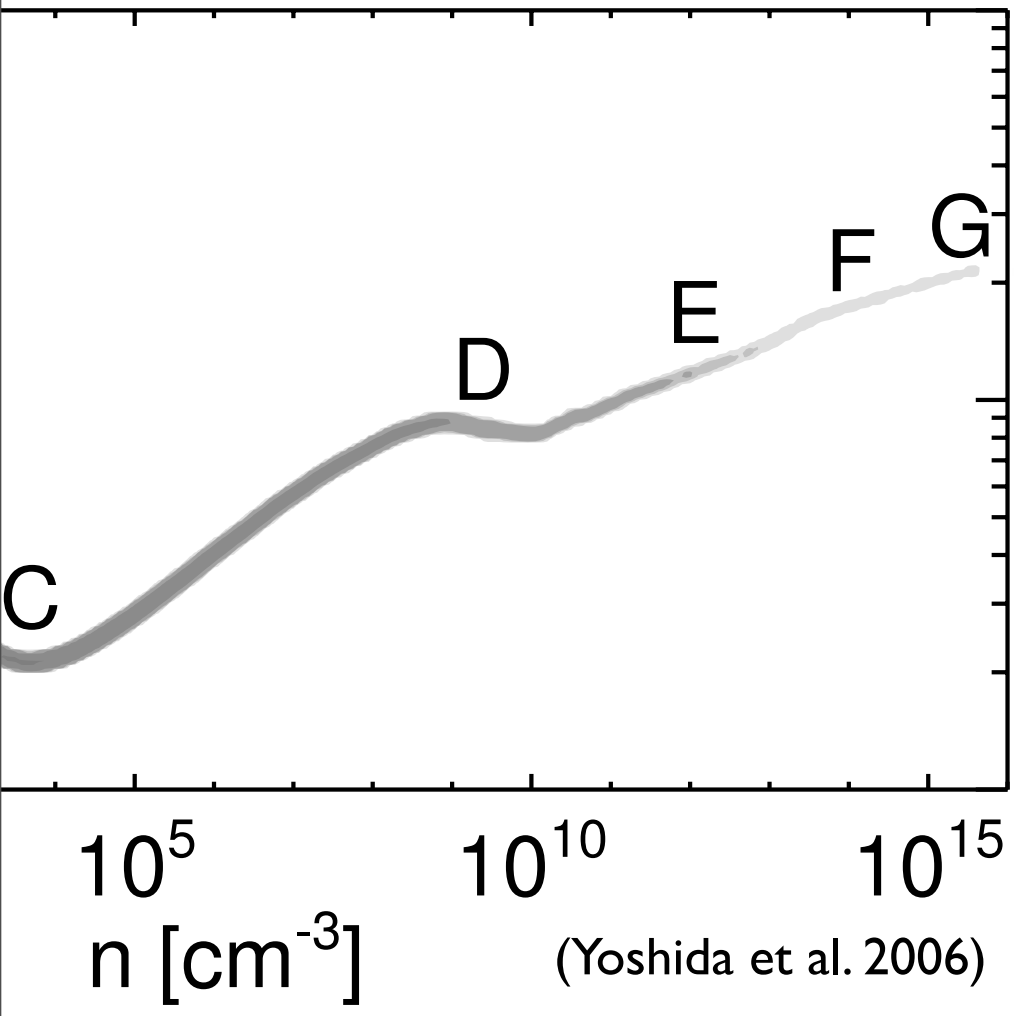
The First Stars



The First Stars



The First Stars:



(Yoshida et al. 2006)

?

1 star:
10s to 100s $M_\odot$

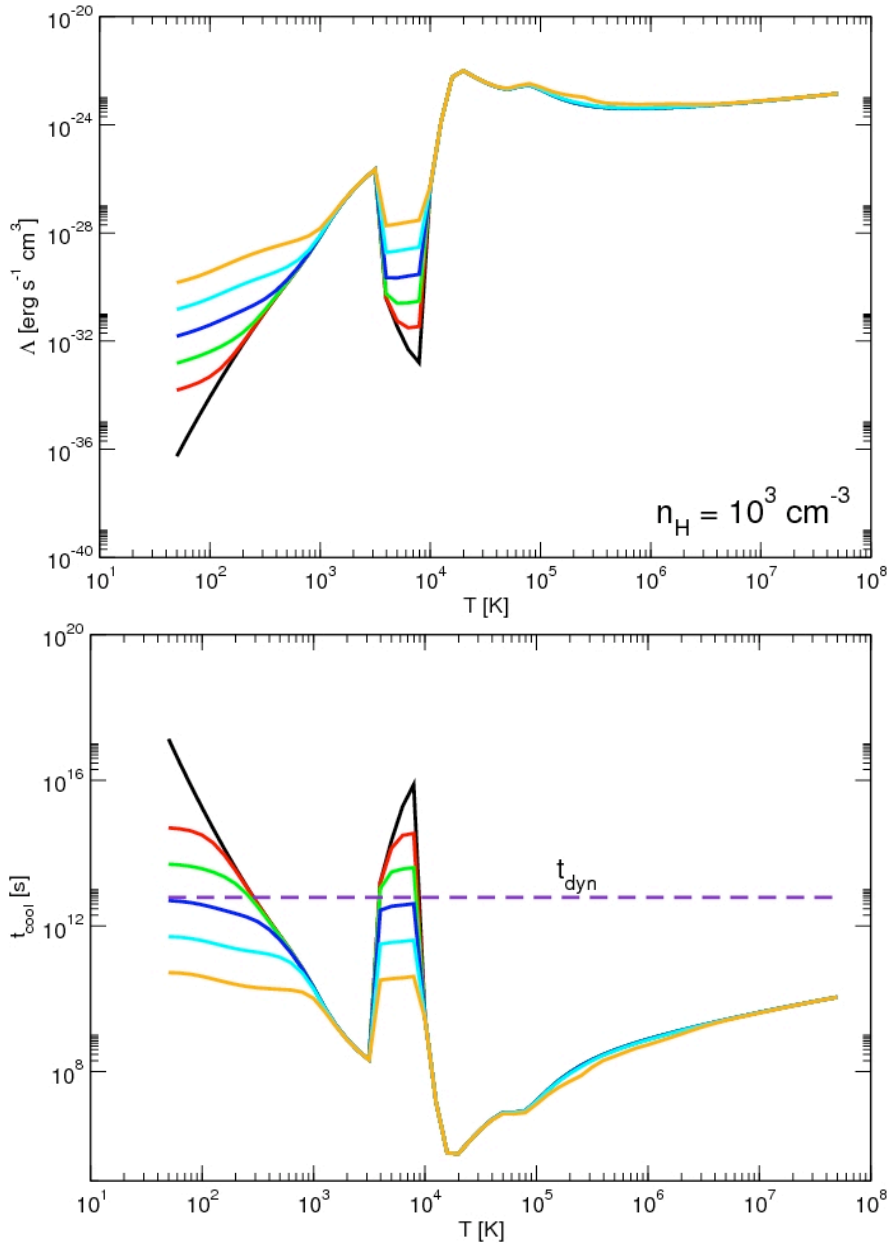
metals

Key Questions:

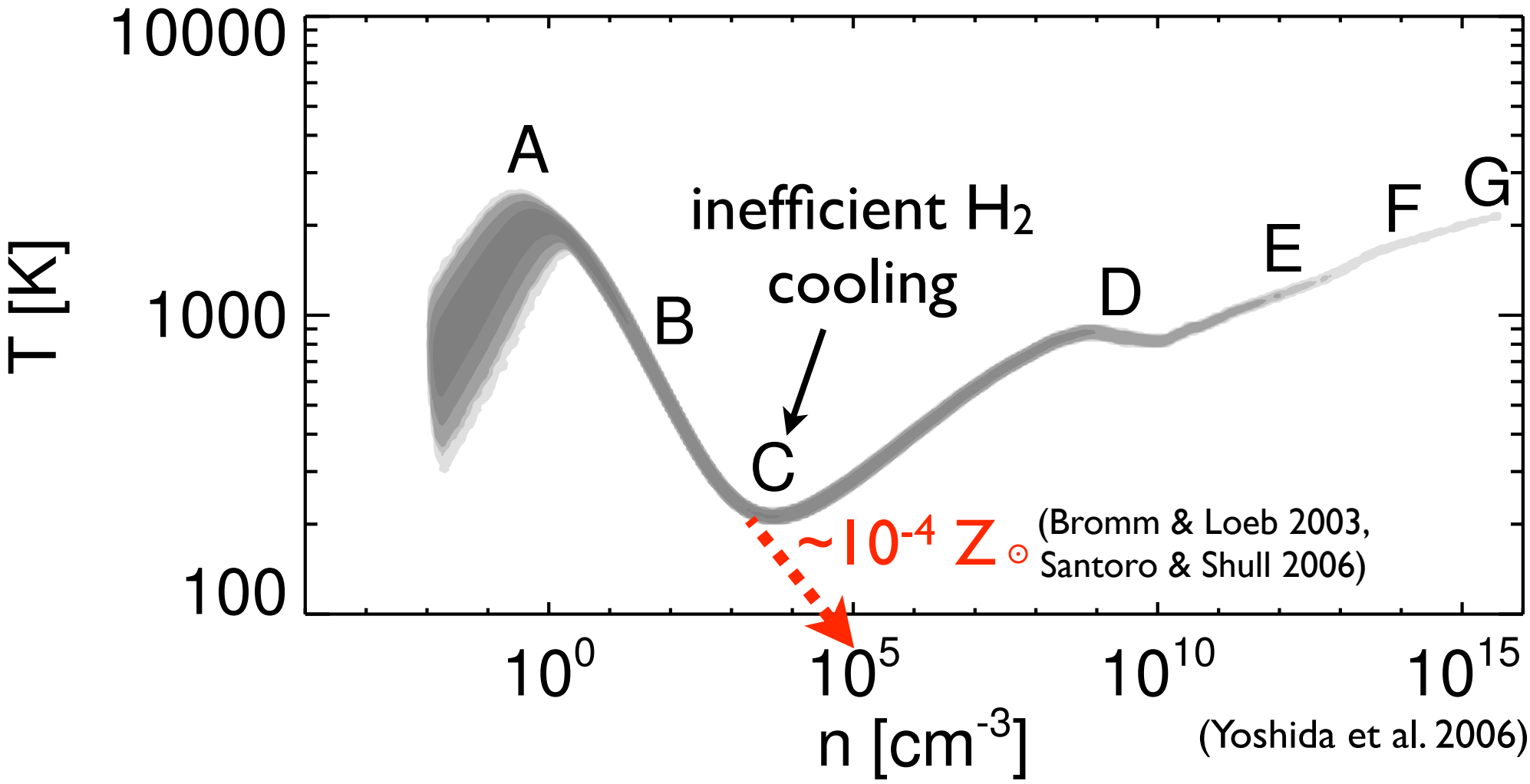
- How does the addition of metals alter the star-formation process?
- What chemical abundance is required to form the first low-mass stars?
- How rapid was the transition from Pop III to Pop II?
- What was the IMF of the first generation of Pop II stars? Is the IMF metallicity dependent?

The First Metals

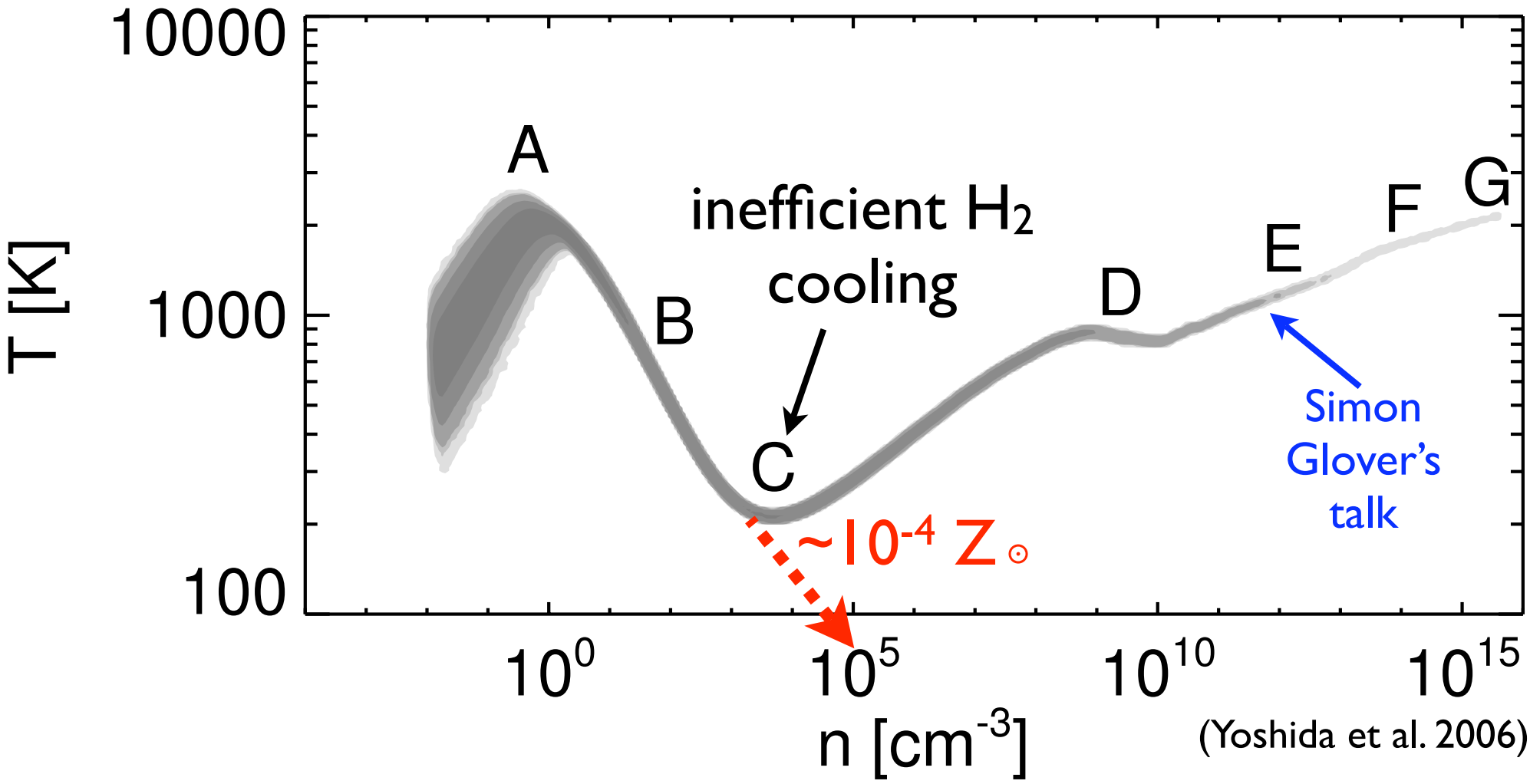
- Cooling
  - fine-structure
  - molecules
  - dust (also helps form H_2)



The Transition to Pop II



The Transition to Pop II



Simulations with Enzo

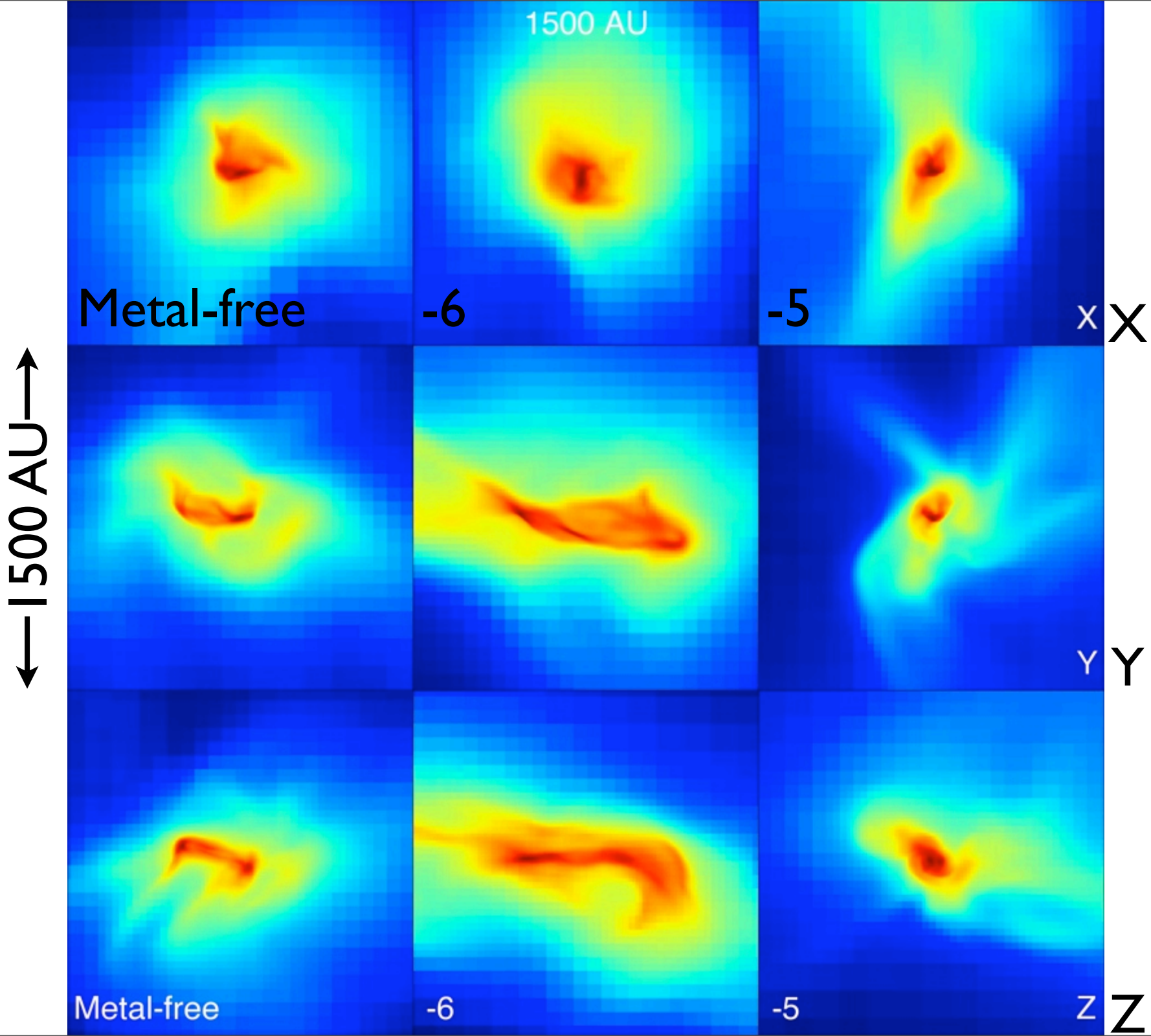
(Bryan & Norman 1997, O'Shea et al. 2004)

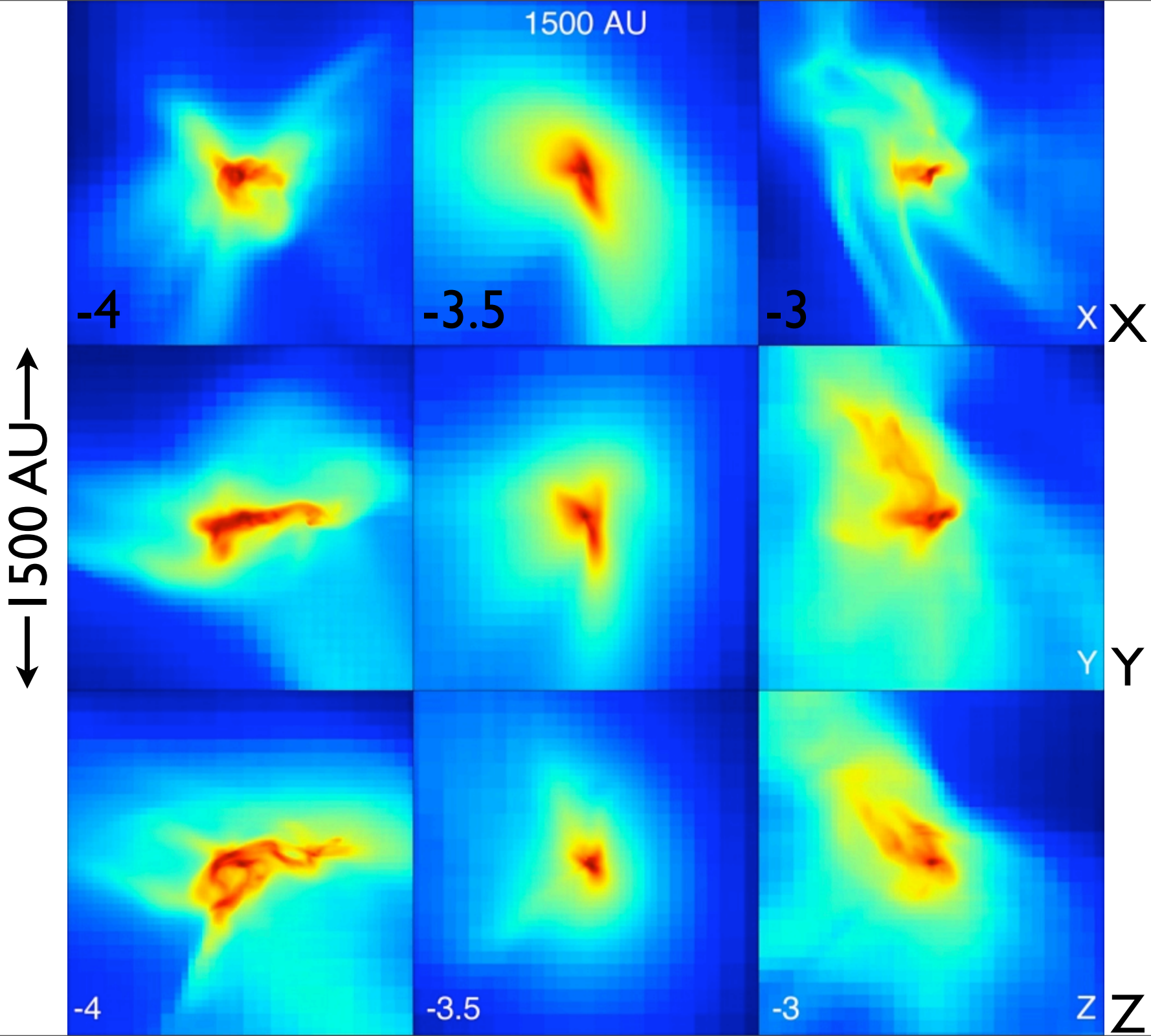
- Pre-enriched first star simulations
  - identical cosmological initial conditions ($300h^{-1}$ kpc box)
  - $Z = 0, 10^{-6}, 10^{-5}, 10^{-4}, 10^{-3.5}, 10^{-3}\ Z_{\odot}$
  - solar abundance patterns
  - non-eq H/He chemistry + tabulated metal cooling from Cloudy (all metals through Zn) (BDS, Sigurdsson, & Abel 2008)

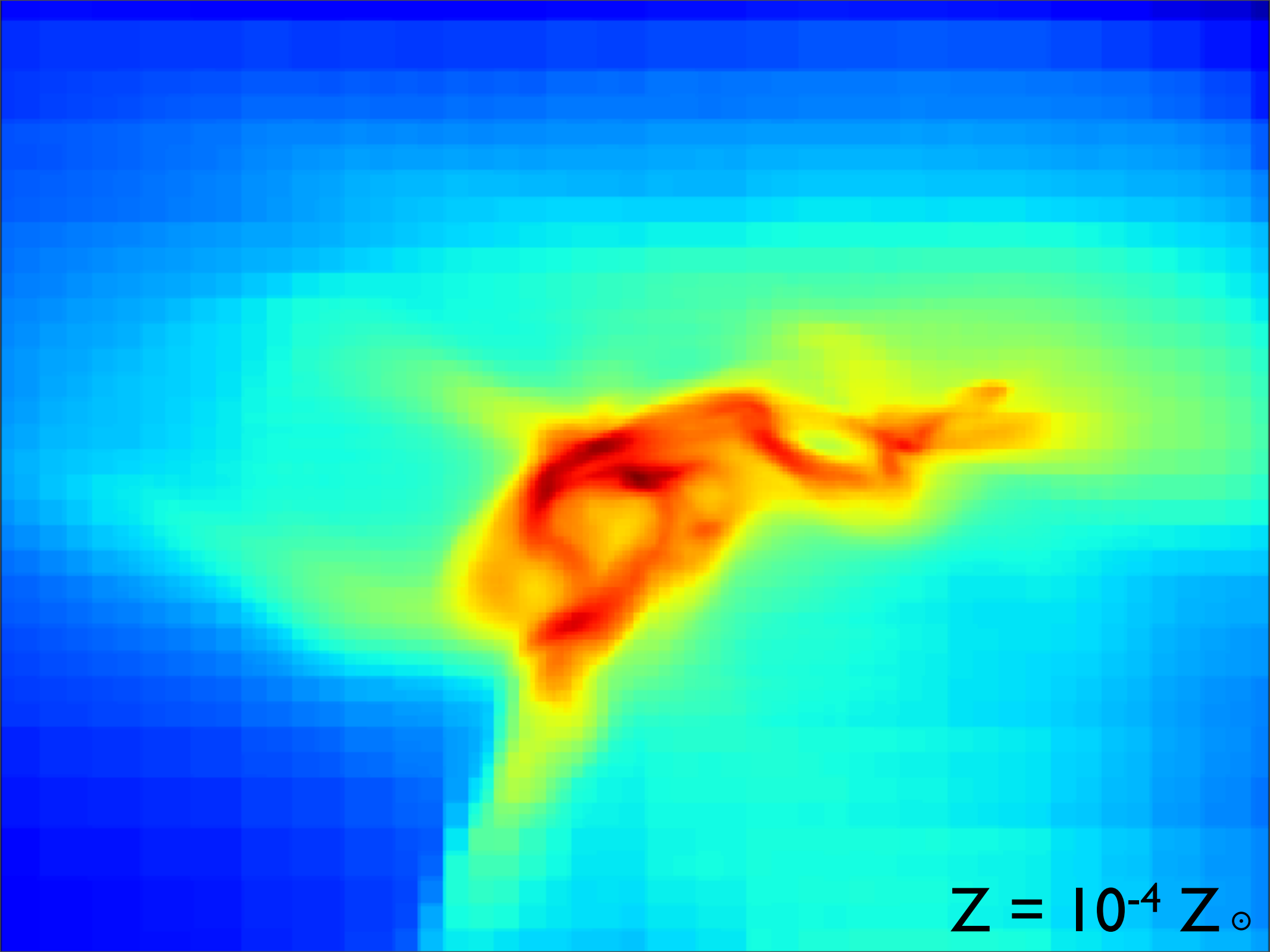
Simulations with Enzo

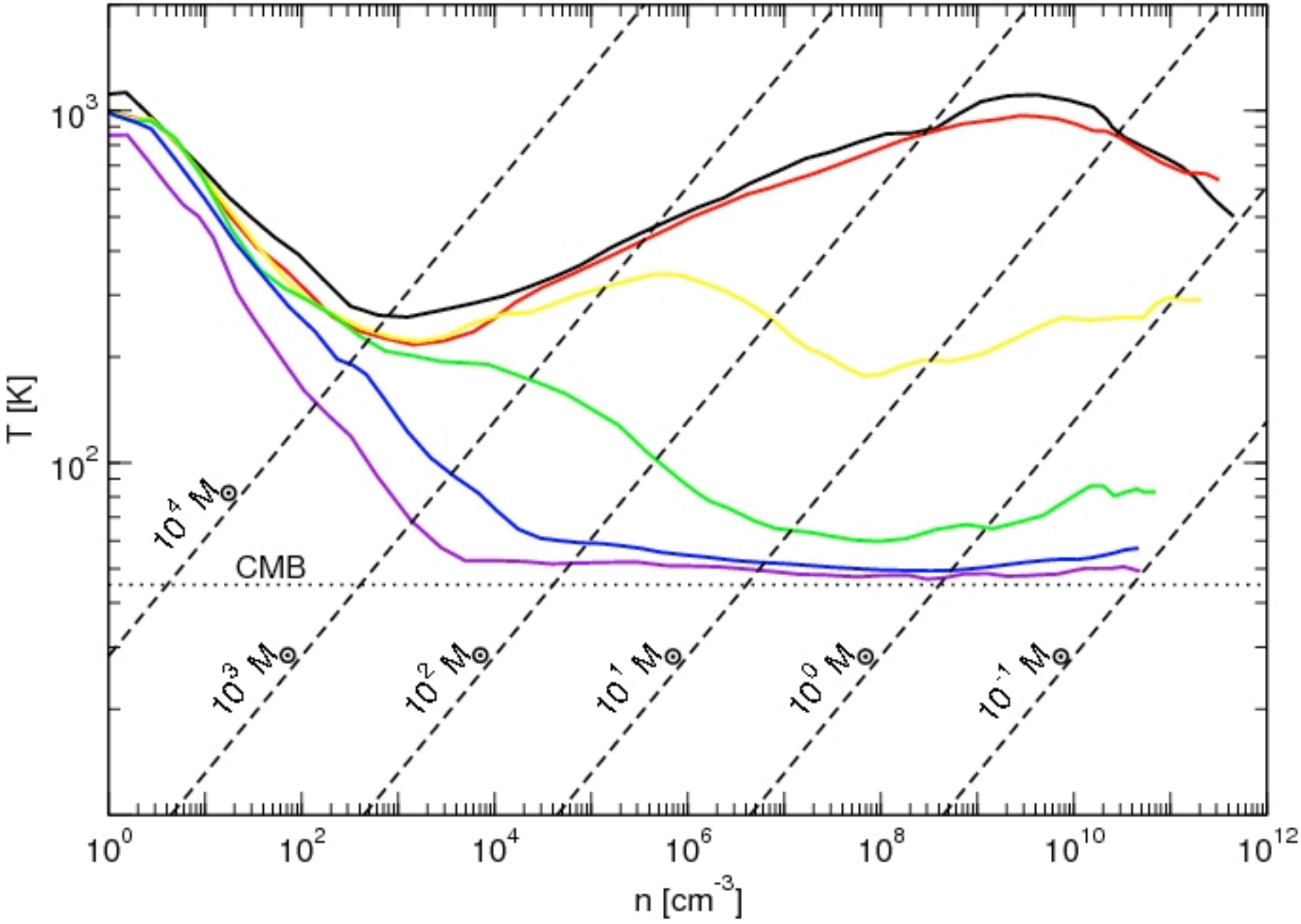
(Bryan & Norman 1997, O'Shea et al. 2004)

- refinement:
  - baryon/DM overdensity: 4/8
  - jeans length: 16 cells
  - time-step < t_{cool}
- stop after 24 levels of refinement (10^{10} dynamic range)
- $z_{col} \sim 15$


1500 AU
Metal-free
-6
-5
X
X
1500 AU
Y
Y
Metal-free
-6
-5
Z
Z

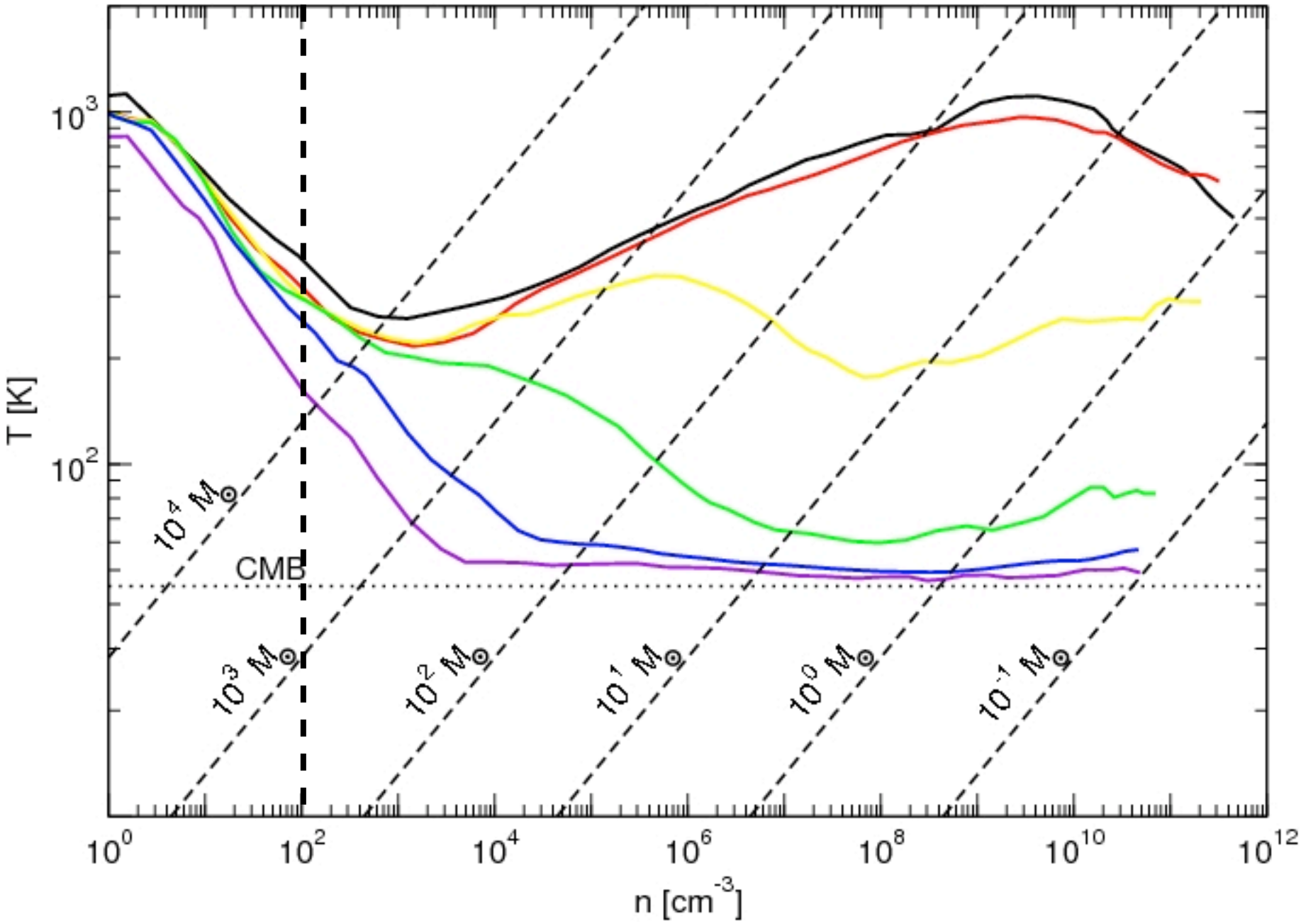

1500 AU
1500 AU
-4
-3.5
-3
X
X
Y
Y
-4
-3.5
-3
Z
Z


$Z = 10^{-4}\ Z_{\odot}$



Fragmentation continues as long as T↓ as n↑.

(Larson 2005)



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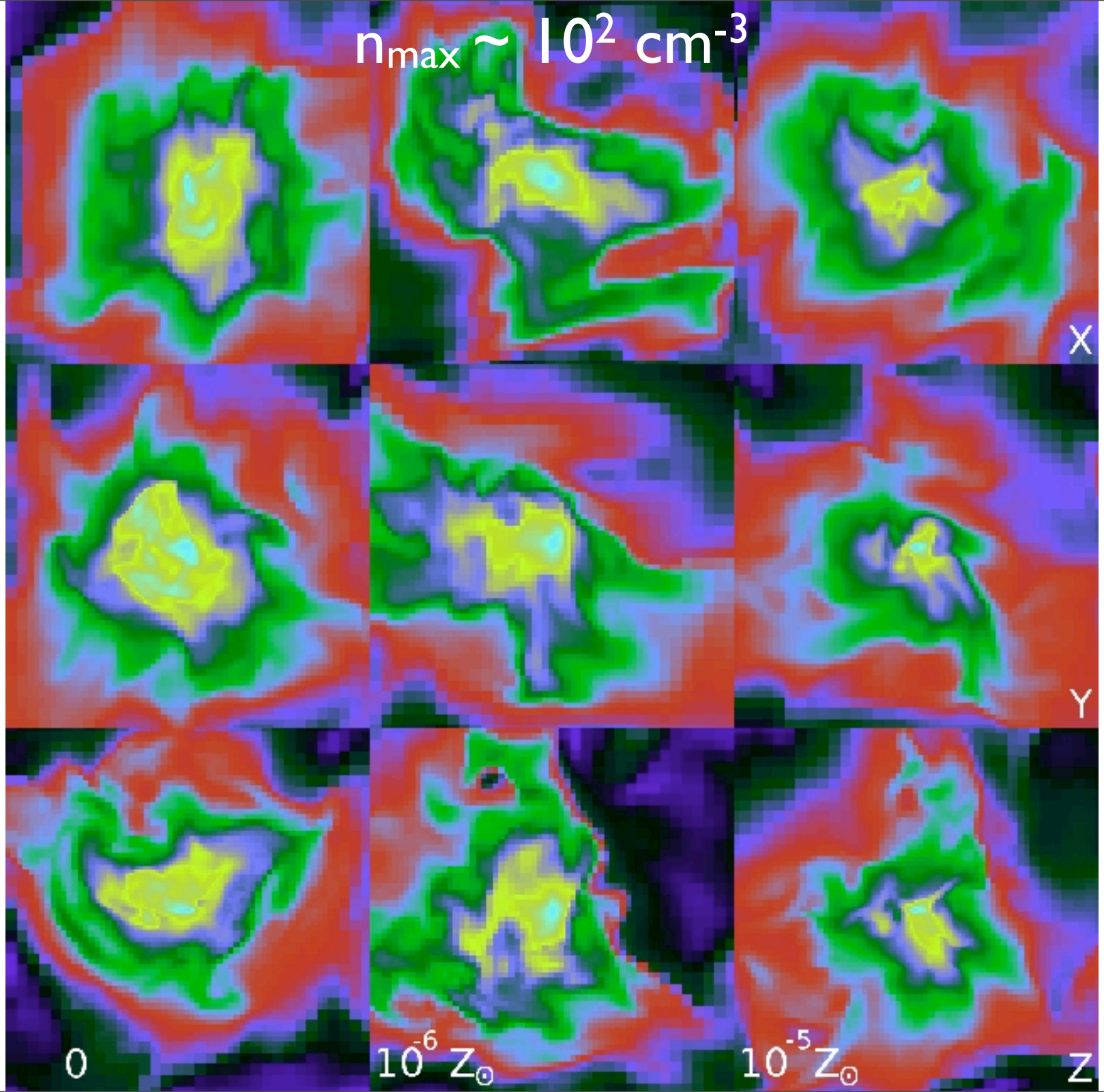
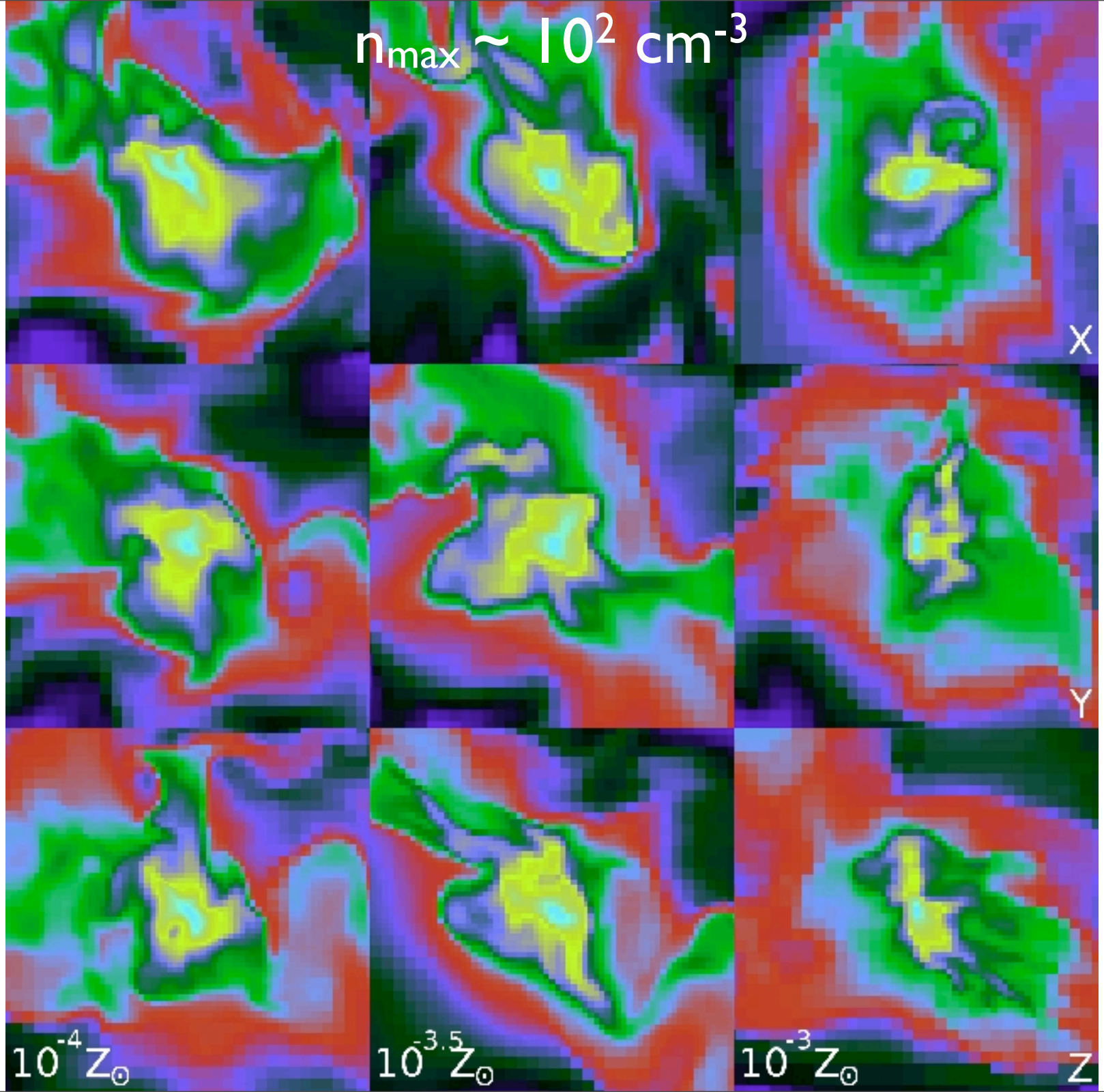
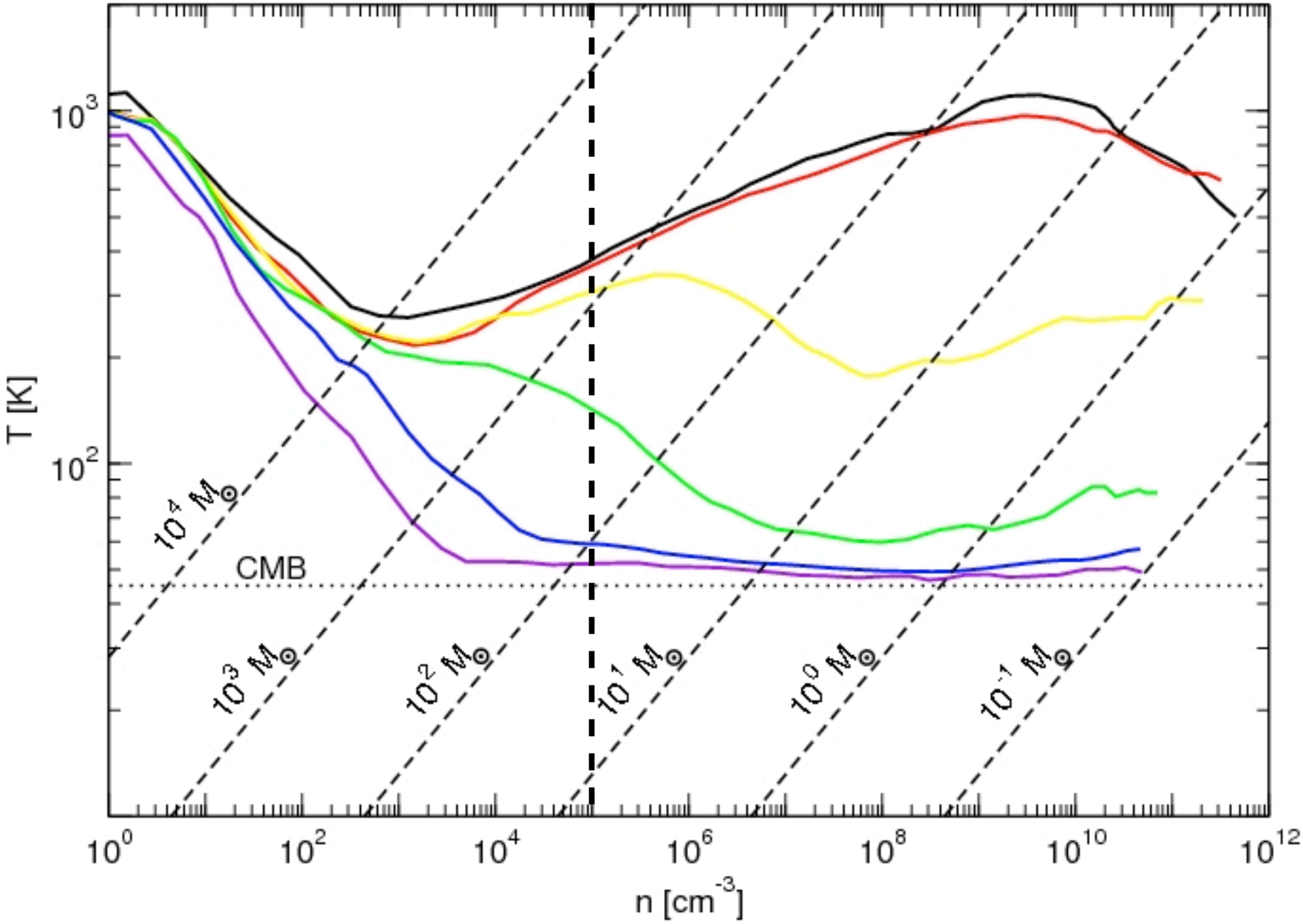
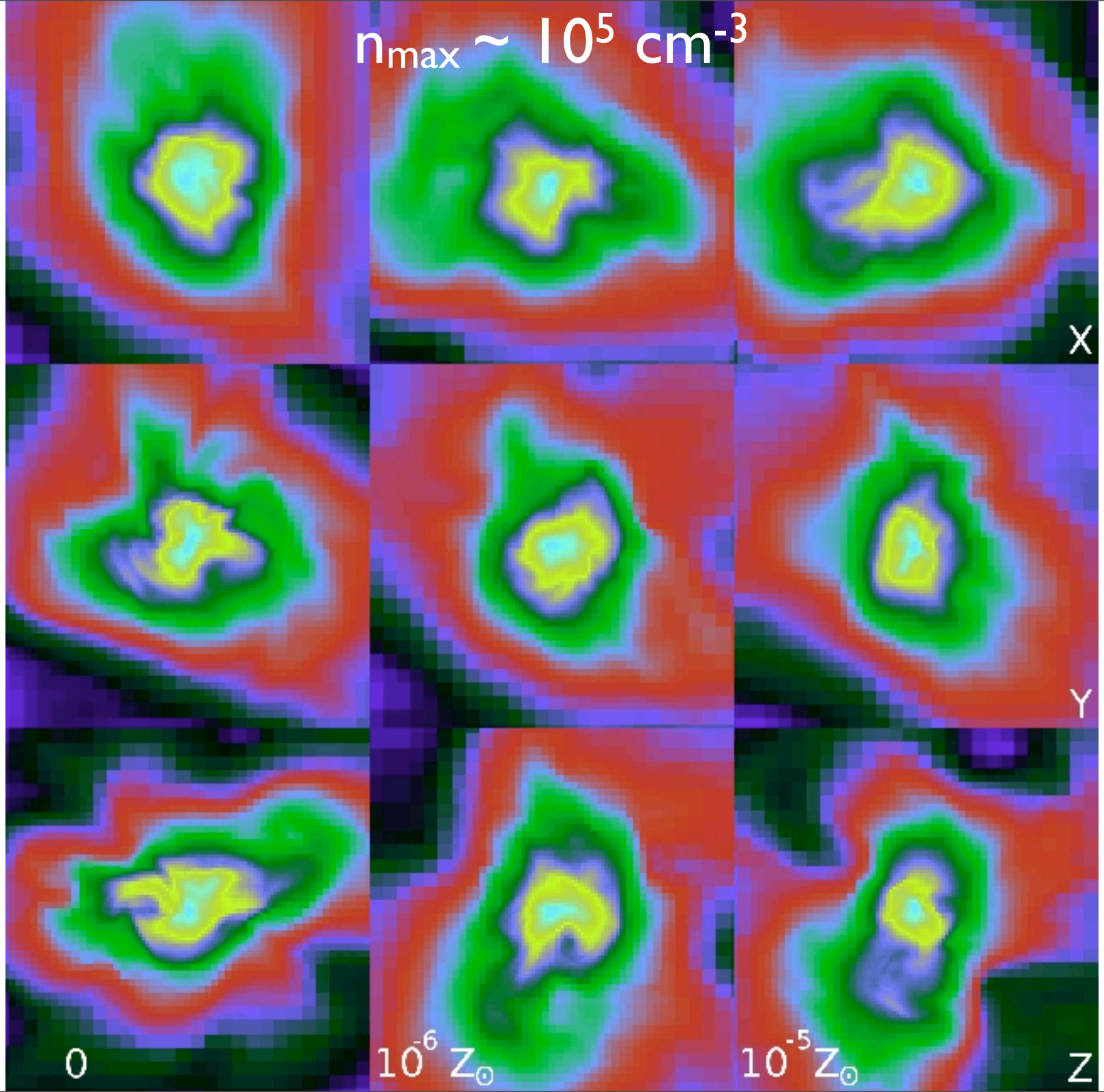

$n_{max} \sim 10^2$ cm^{-3}
X
Y
Z
0
10^{-6} $Z_\odot$
10^{-5} $Z_\odot$

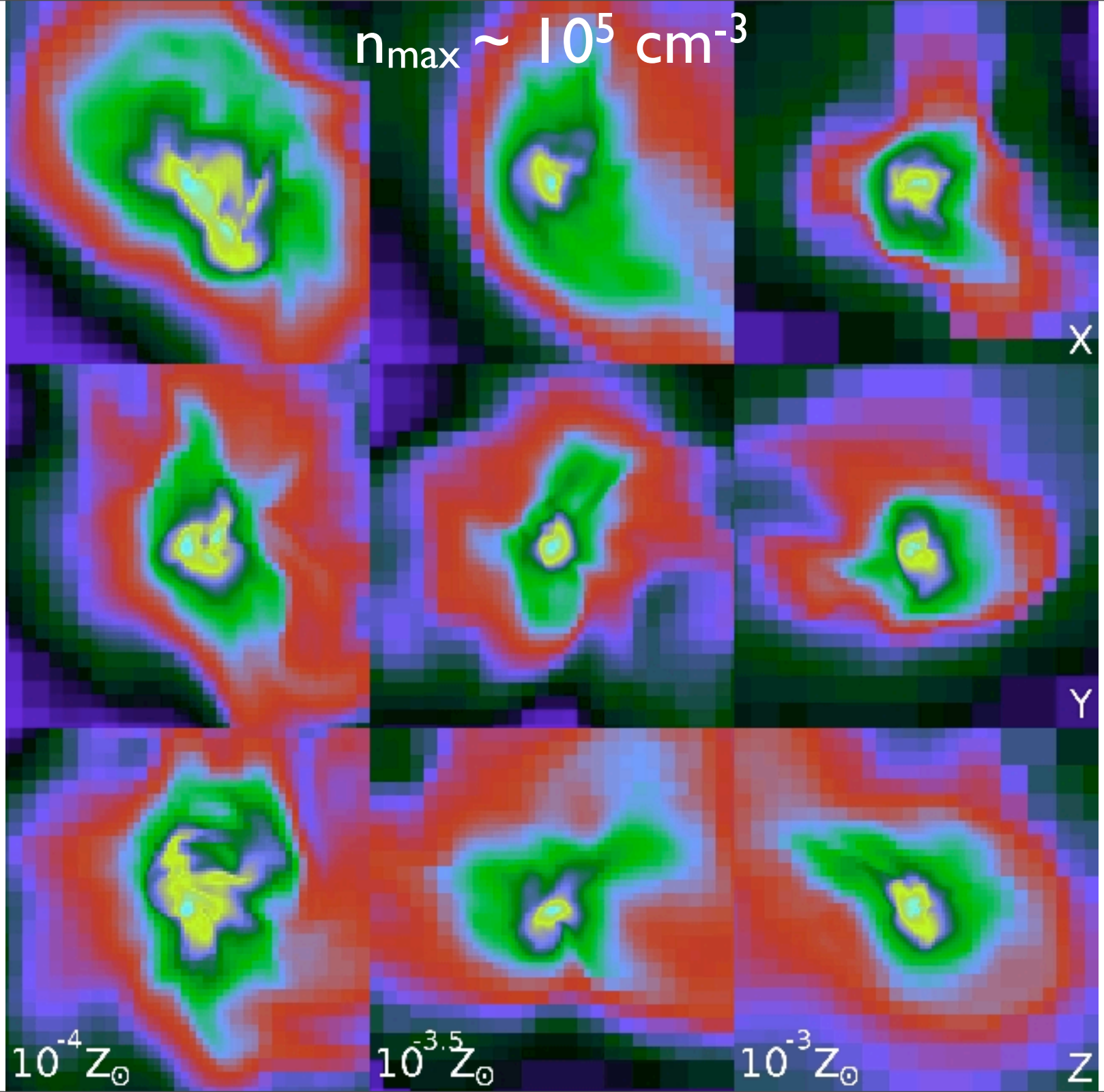

$n_{max} \sim 10^2$ cm^{-3}
X
Y
Z
10^{-4} $Z_\odot$
$10^{-3.5}$ $Z_\odot$
10^{-3} $Z_\odot$

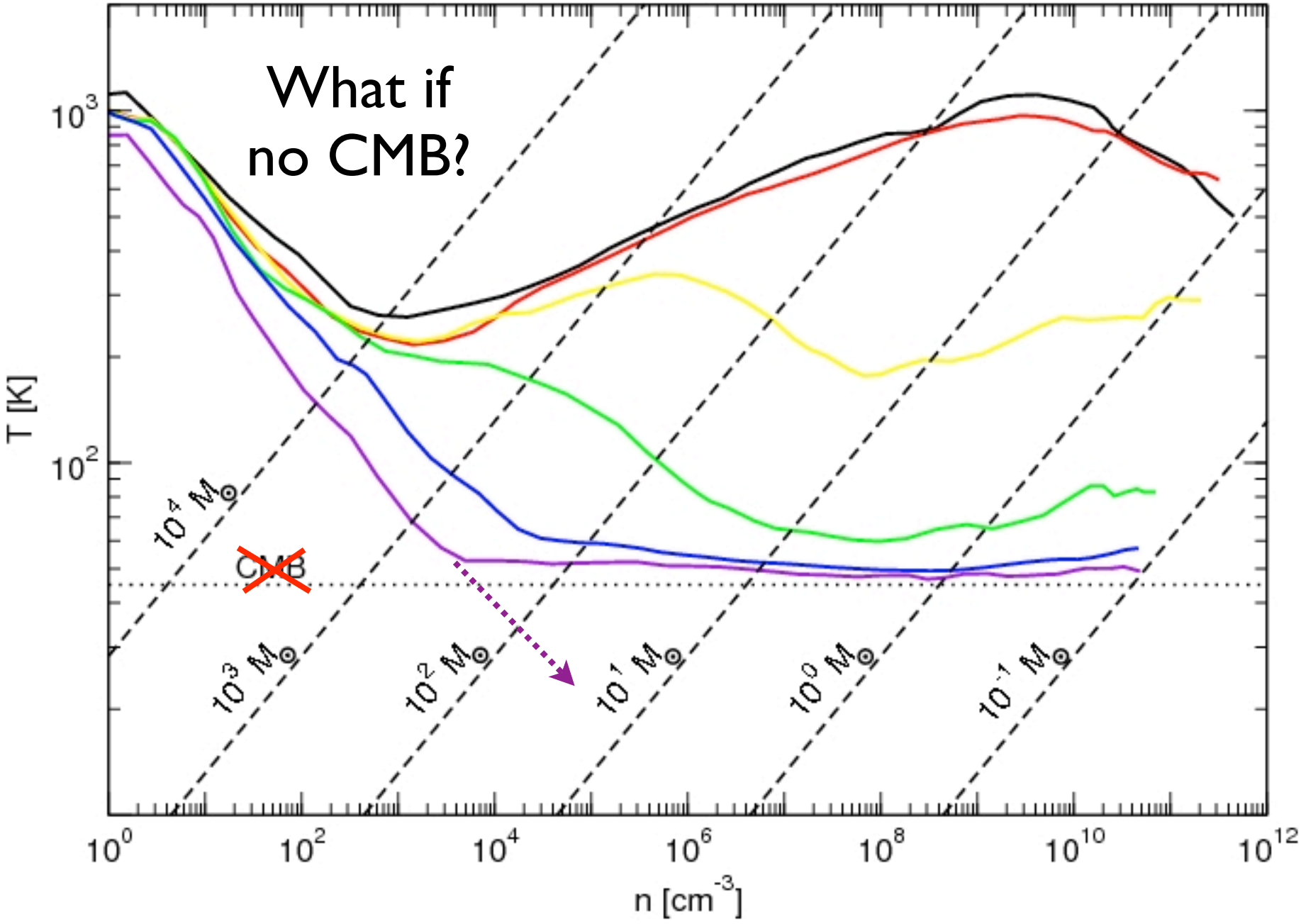


Fragmentation continues as long as T↓ as n↑.

(Larson 2005)


$n_{max} \sim 10^5$ cm^{-3}
X
Y
Z
0
10^{-6} $Z_\odot$
10^{-5} $Z_\odot$

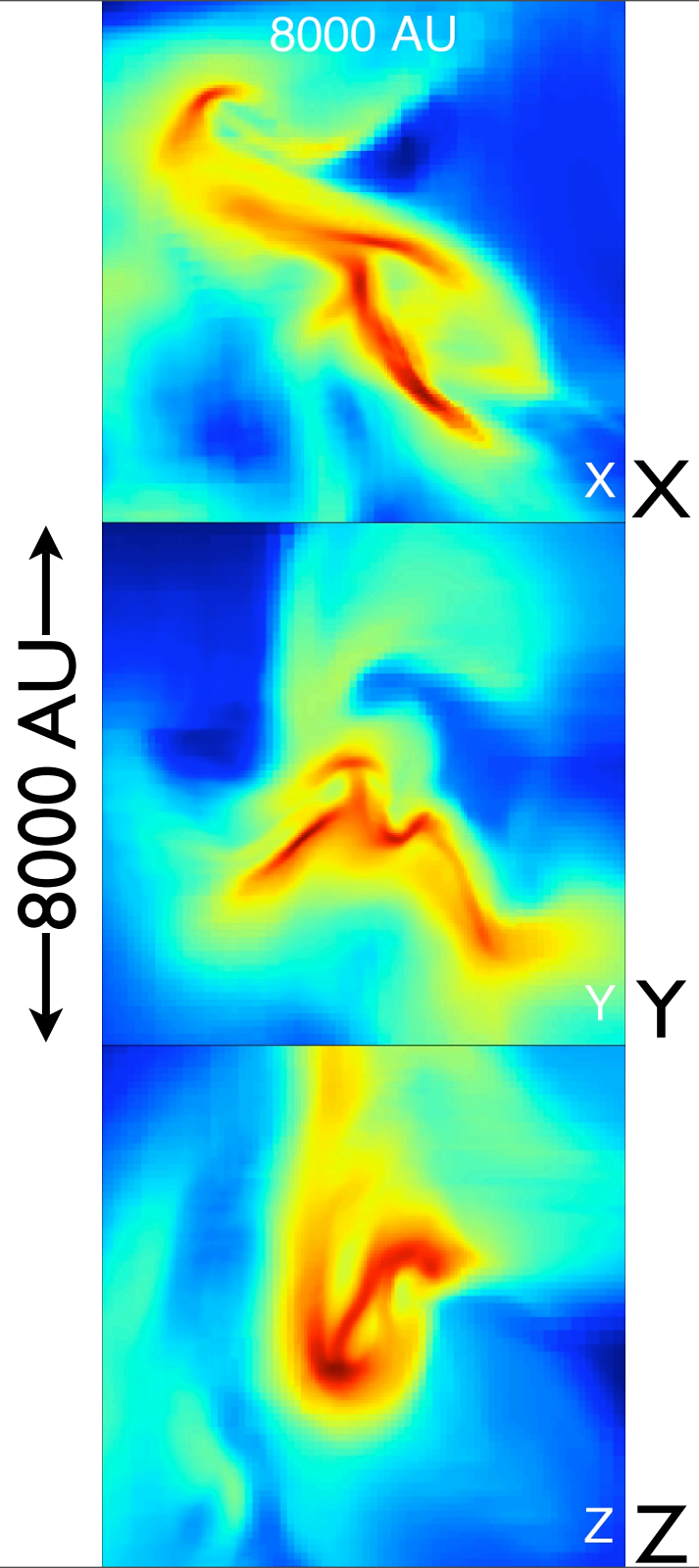

$n_{max} \sim 10^5$ cm^{-3}
X
Y
Z
10^{-4} $Z_\odot$
$10^{-3.5}$ $Z_\odot$
10^{-3} $Z_\odot$

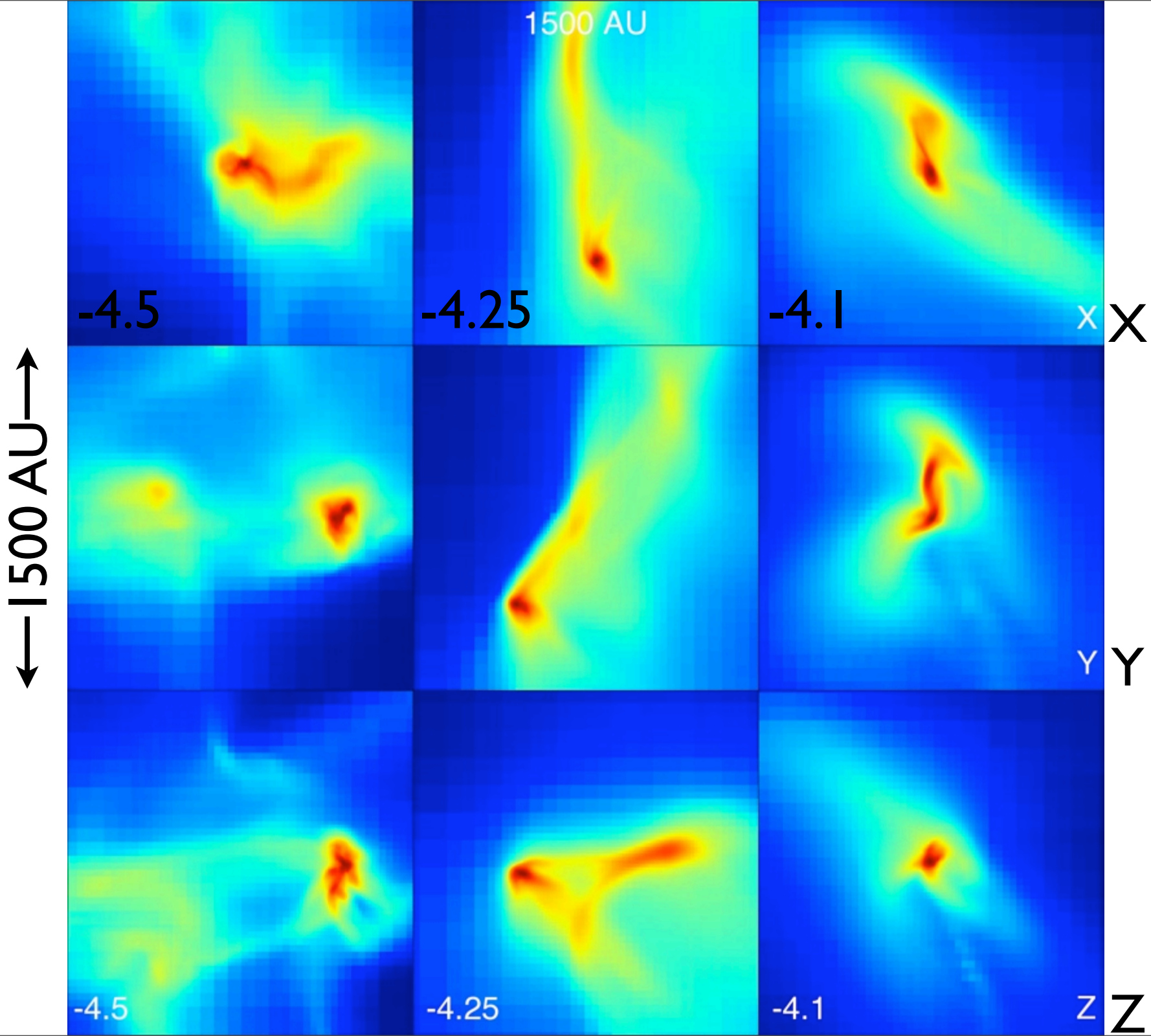


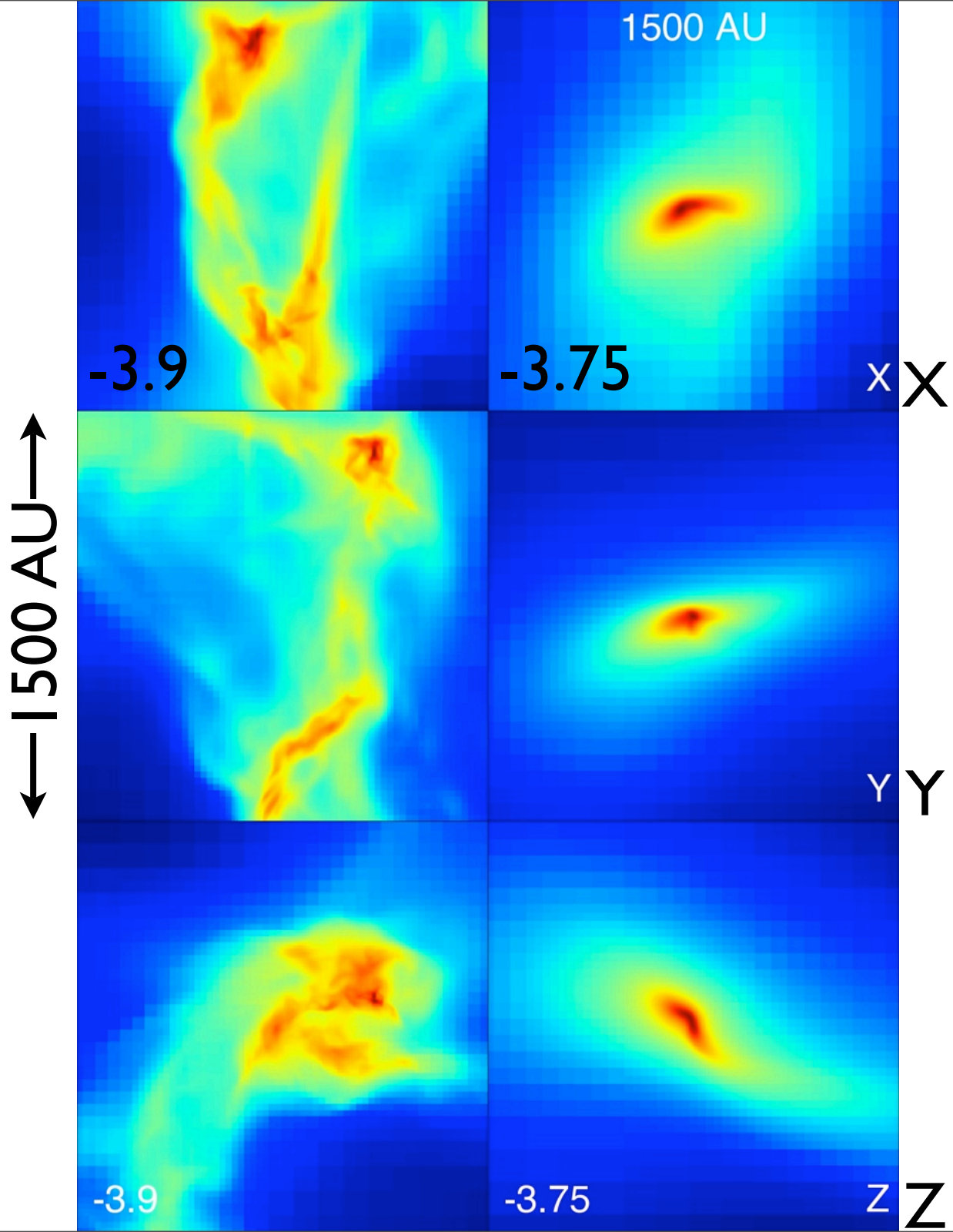
Fragmentation continues as long as T↓ as n↑.

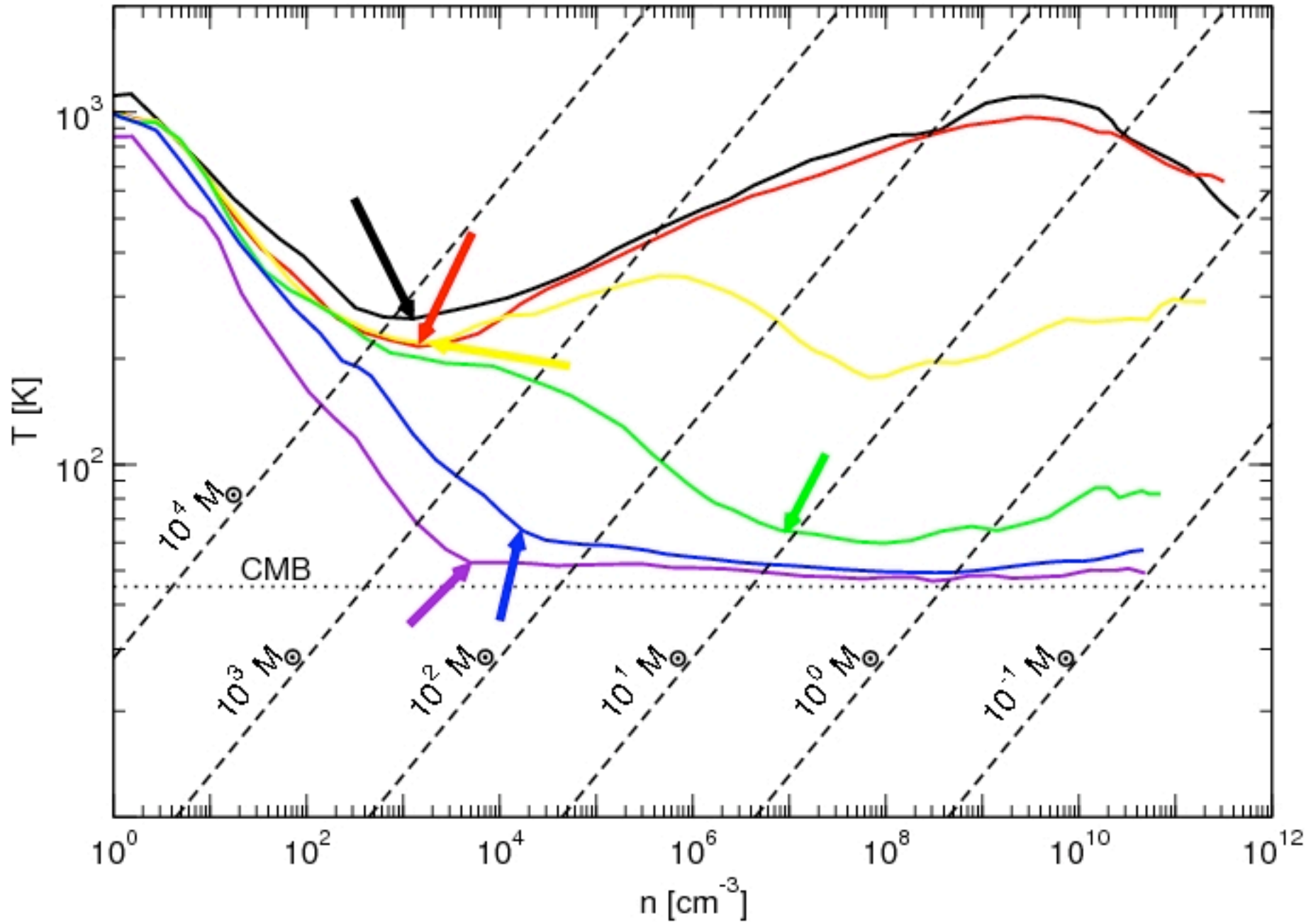
(Larson 2005)

$Z = 10^{-3}\ Z_{\odot}$
without CMB!

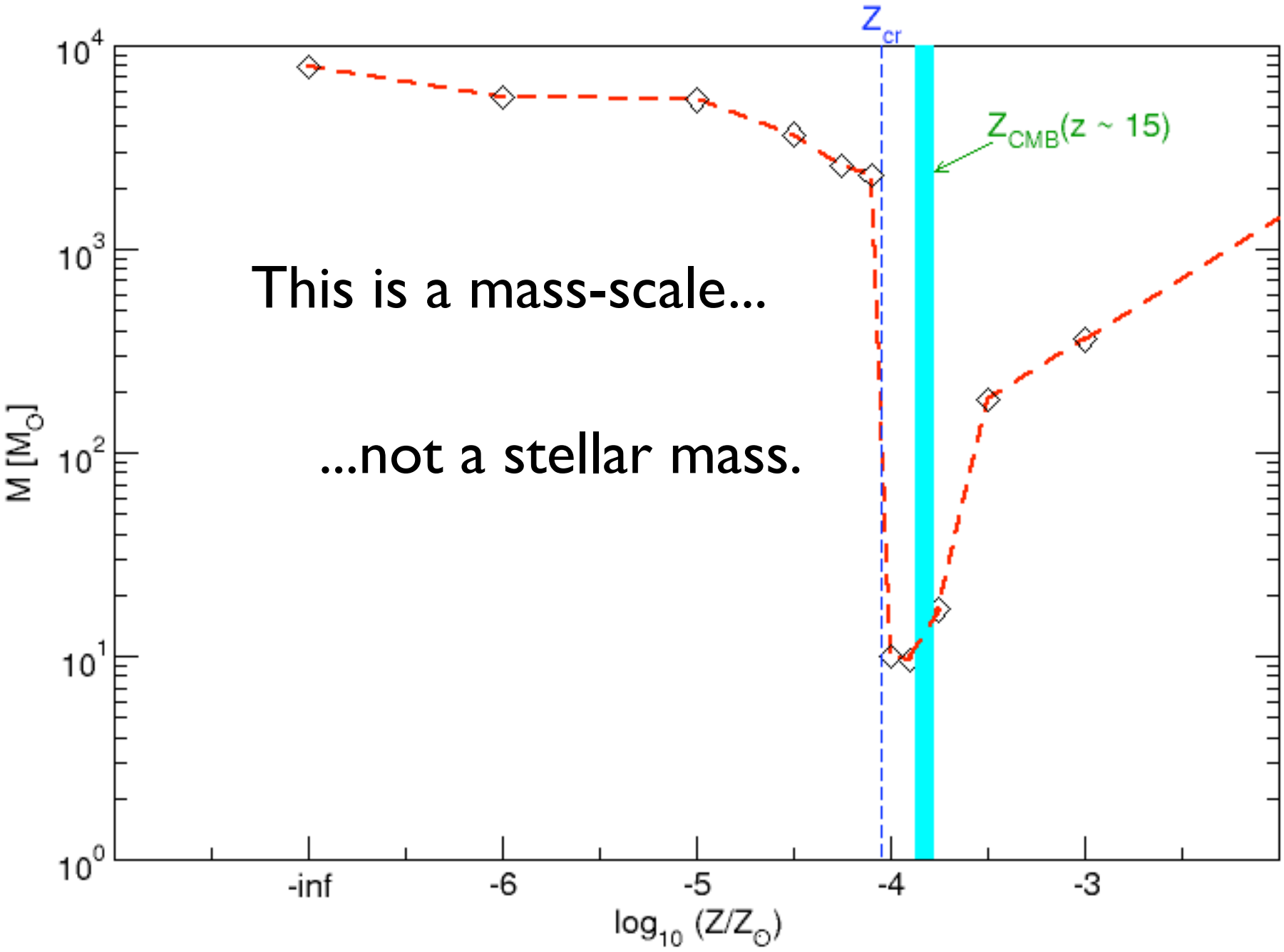



1500 AU
-4.5
-4.25
-4.1
X
X
1500 AU
Y
Y
-4.5
-4.25
-4.1
Z
Z


1500 AU
-3.9
-3.75
X
X
1500 AU
Y
Y
-3.9
-3.75
Z
Z

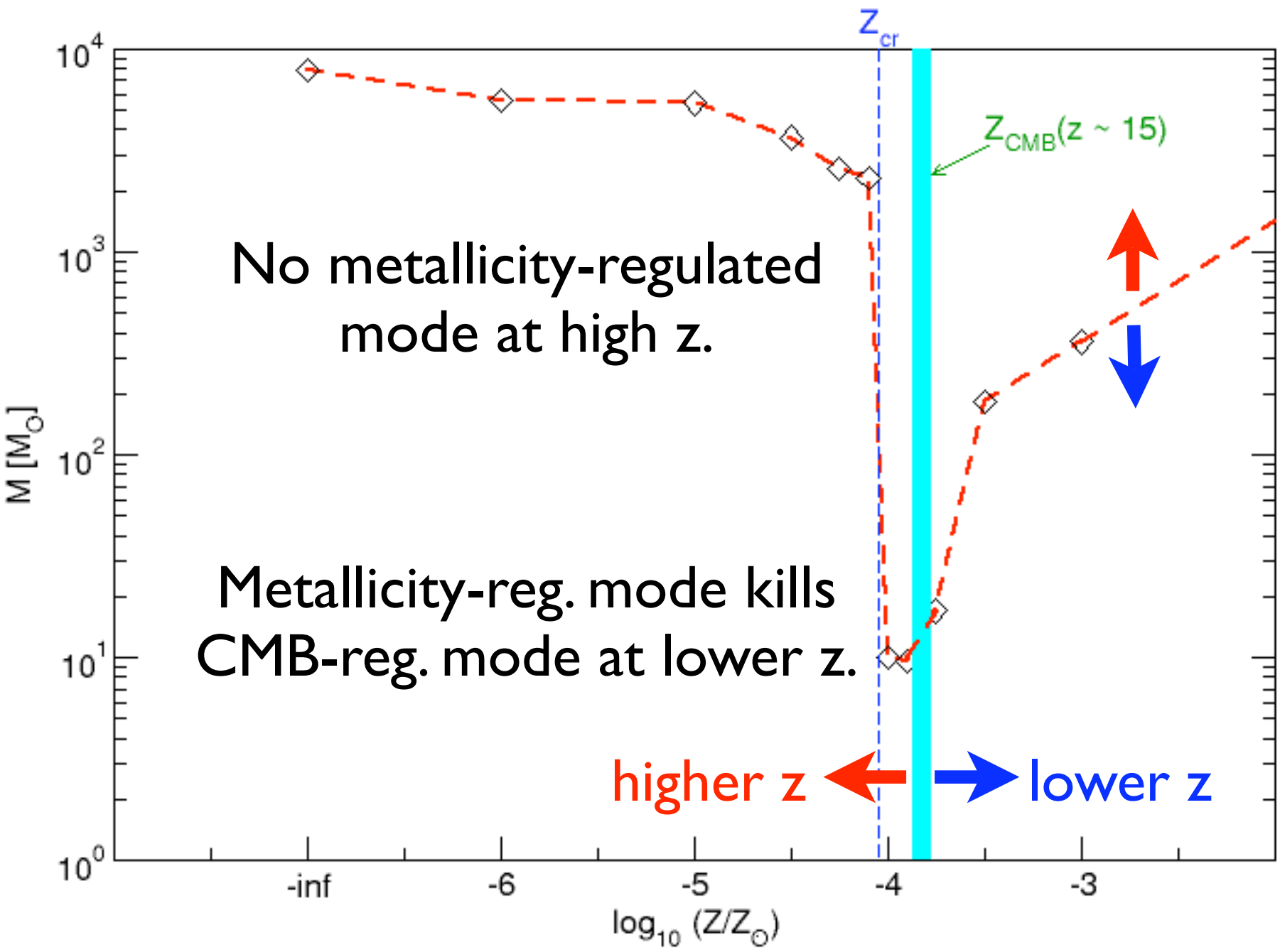


Define mass-scale as Jeans mass at first temperature minimum. (Larson 2005)


Z_{cr}
$Z_{CMB}(z \sim 15)$
This is a mass-scale...
...not a stellar mass.
10^4
10^3
10^2
10^1
10^0
M [$M_\odot$]
-inf
-6
-5
-4
-3
$\log_{10}(Z/Z_\odot)$

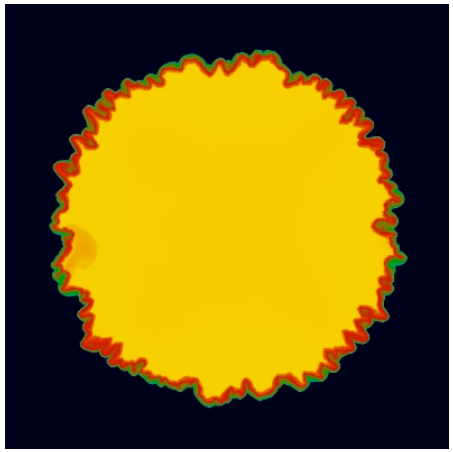
Three Modes of Star Formation

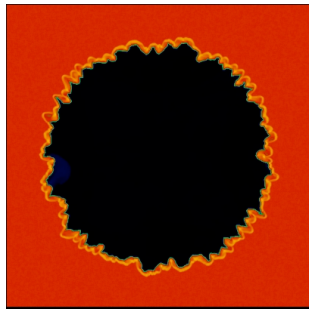
- $Z < Z_{cr}$: primordial (M_{char} = few x 10^3 $M_\odot$) - cooling cannot prevent loitering phase, collapse proceeds like metal-free case.
- $Z_{cr} \leq Z < Z_{CMB}$: metallicity-regulated (M_{char} = few $M_\odot$) - cools past loitering phase, does not reach T_{CMB}.
- $Z \geq Z_{CMB}$: CMB-regulated (M_{char} = few x 10^2 $M_\odot$) - cools rapidly to T_{CMB} where frag. stops.


Z_{cr}
$Z_{CMB}(z \sim 15)$
No metallicity-regulated mode at high z.
Metallicity-reg. mode kills CMB-reg. mode at lower z.
higher z
lower z
M [$M_\odot$]
10^4
10^3
10^2
10^1
10^0
-inf
-6
-5
-4
-3
$\log_{10}(Z/Z_\odot)$

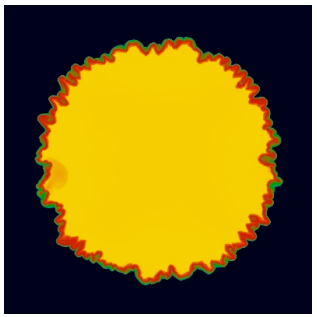
Caveats

- $M_{char} \neq M_{star}$: stellar mass depends on accretion and feedback
- rotation: less rotation → less fragmentation
- SN ejecta will not have solar pattern
- metal mixing important
- dust not included
- radiation field unknown
- the real ICs? - need Pop III supernovae





Summary



- fragmentation suppressed by CMB
- 2 threshold metallicities: Z_{cr} and Z_{CMB}
- 3 modes of star formation: primordial, metallicity-regulated, and CMB regulated
- star formation modes time dependent - top heavy IMF in distant past
- when was star formation 'normal?'
  - GMCs: T ~ 10 K (easy answer)
  - T_{CMB} = 10 K at z ~ 2.6 (2.6 Gyr after BB)

Metal Cooling: The Method

- Before the simulation:
  - assume ionization equilibrium
  - pre-compute cooling rates over n, T, Z, etc.
  - subtract H/He cooling: only metals left
- During the simulation:
  - follow H/He chemistry: H, H^+, H^-, H_2, H_2^+, He, He^+, He^{++}, e^-
  - calculate H/He cooling directly (H_2!)
  - interpolate metal cooling from data-grid