The Semi-Analytic Model
for
Early Galaxy Formation

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２００６年１２月４日　セミアナ研究会＠長崎

SIMULATIONS OF EARLY STRUCTURE FORMATION: PRIMORDIAL GAS CLOUDS

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Accepted for publication in ApJ, April 5

ABSTRACT

We use cosmological simulations to study the origin of primordial star-forming clouds in a ΛCDM universe, by following the formation of dark matter halos and the cooling of gas within them. To model the physics of chemically pristine gas, we employ a non-equilibrium treatment of the chemistry of 9 species (e^-, H, H^+, He, He^+, He^{++}, H_2, H_2^+, H^-) and include cooling by molecular hydrogen. By considering cosmological volumes, we are able to study the statistical properties of primordial halos and the high resolution of our simulations enables us to examine these objects in detail.

In particular, we explore the hierarchical growth of bound structures forming at redshifts $z \approx 25 - 30$ with total masses in the range $\approx 10^5 - 10^6 M_\odot$. We find that when the amount of molecular hydrogen in these objects reaches a critical level, cooling by rotational line emission is efficient, and dense clumps of cold gas form. We identify these "gas clouds" as sites for primordial star formation. In our simulations, the threshold for gas cloud formation by molecular cooling corresponds to a critical halo mass of $\approx 5 \times 10^5 h^{-1} M_\odot$, in agreement with earlier estimates, but with a weak dependence on redshift in the range $z > 16$. The complex interplay between the gravitational formation of dark halos and the thermodynamic and chemical evolution of the gas clouds compromises analytic estimates of the critical H_2 fraction. Dynamical heating from mass accretion and mergers opposes relatively inefficient cooling by molecular hydrogen, delaying the production of star-forming clouds in rapidly growing halos.

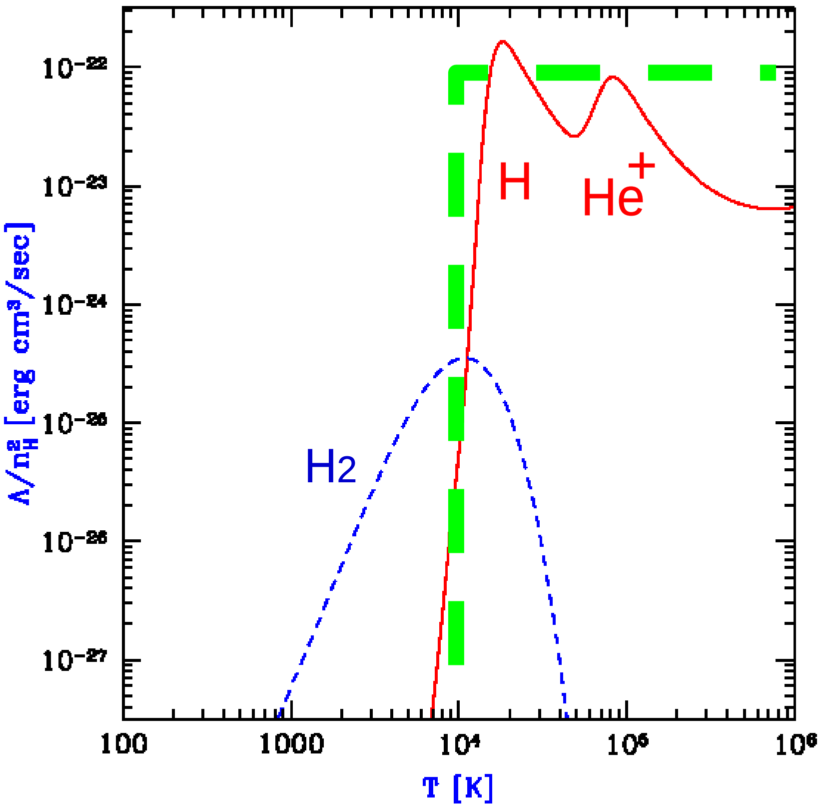
We also investigate the impact of photo-dissociating ultra-violet (UV) radiation on the formation of primordial gas clouds. We consider two extreme cases by first including a uniform radiation field in the optically thin limit and secondly by accounting for the maximum effect of gas self-shielding in virialized regions. For radiation with Lyman-Werner band flux $J > 10^{-23}$ erg s^{-1} cm^{-2} Hz^{-1} str^{-1}, hydrogen molecules are rapidly dissociated, rendering gas cooling inefficient. In both the cases we consider, the overall impact can be described by computing an equilibrium H_2 abundance for the radiation flux and defining an effective shielding factor.

Based on our numerical results, we develop a semi-analytic model of the formation of the first stars, and demonstrate how it can be coupled with large N-body simulations to predict the star formation rate in the early universe.

Subject headings: cosmology:theory - early universe - stars:formation - galaxies:formation

銀河形成のセミアナリティックモデル　は簡単！

途中まで



銀河形成には非常に分かりやすい質量スケールがある。

水素原子冷却の指数関数的特徴により、Tvir~10000Kが明確な境界になる

一方、始原ガス雲形成

z=25:

t_dyn　～3000万年

t_cool　～3000万年

t_chem　～3000万年

t_hubble～１億年

階層的構造形成モデル

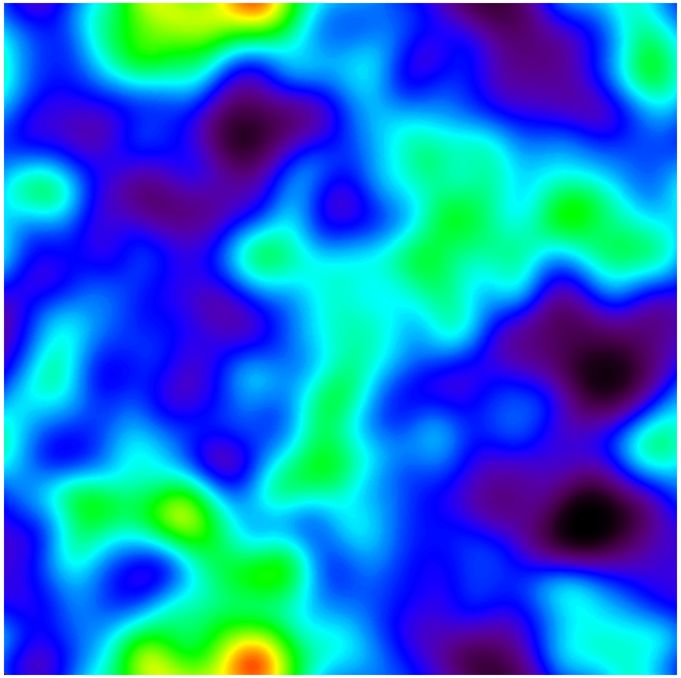
CDMモデルのように小さい物体から先に
形成される宇宙モデルでは、
「銀河形成の最小ユニット」
とは、
「宇宙で初めにできる天体」

やってみればすぐ分かる

実は、宇宙で初めにできる天体は
Tvir ~ 10000Kのシステムではない。

Cosmological Simulations of Primordial Gas Cloud Formation

初期条件：　断熱的密度ゆらぎ（CDM + バリオン + 背景放射）



z = 1000

重力

　ダークマター

流体力学

　水素、ヘリウムガス

化学反応

　9種非平衡

　e, H, H+, H−, H2, H2+,

　He, He+, He++

化学反応リスト

e, H, H+, H−, H2, H2+, He, He+, He++

始原ガス : 76% 水素, 24% ヘリウム

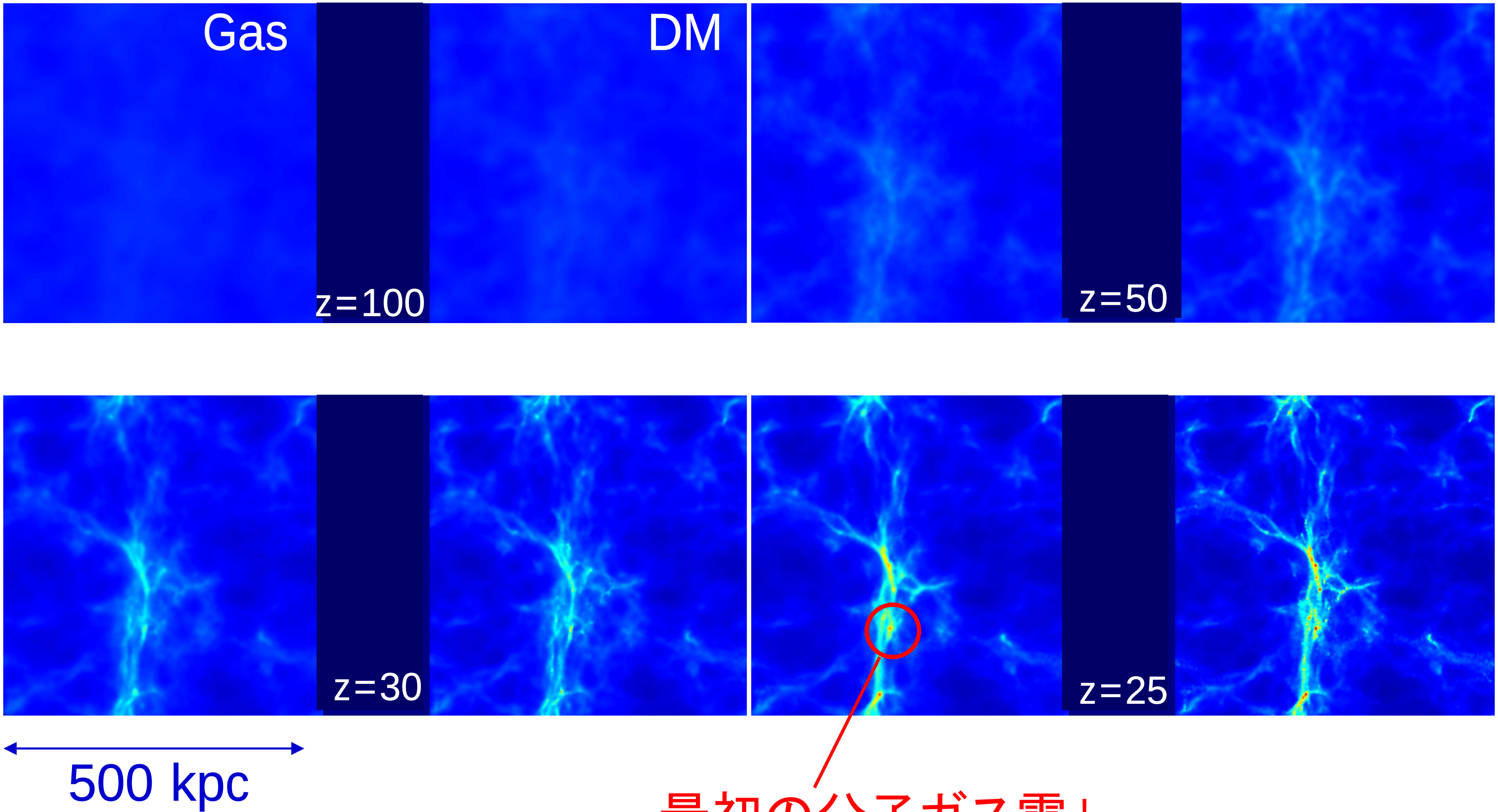
- 衝突電離、再結合
- 水素分子の形成 （$H + e \rightarrow H^- + h\nu$; $H + H^- \rightarrow H_2 + e$）
- 光電電離、解離
- 気体の冷却プロセス:
  衝突励起，衝突電離，再結合，制動輻射, コンプトン過程
  水素分子の回転振動遷移 (Galli & Palla 1998)

低密度では31反応式で十分

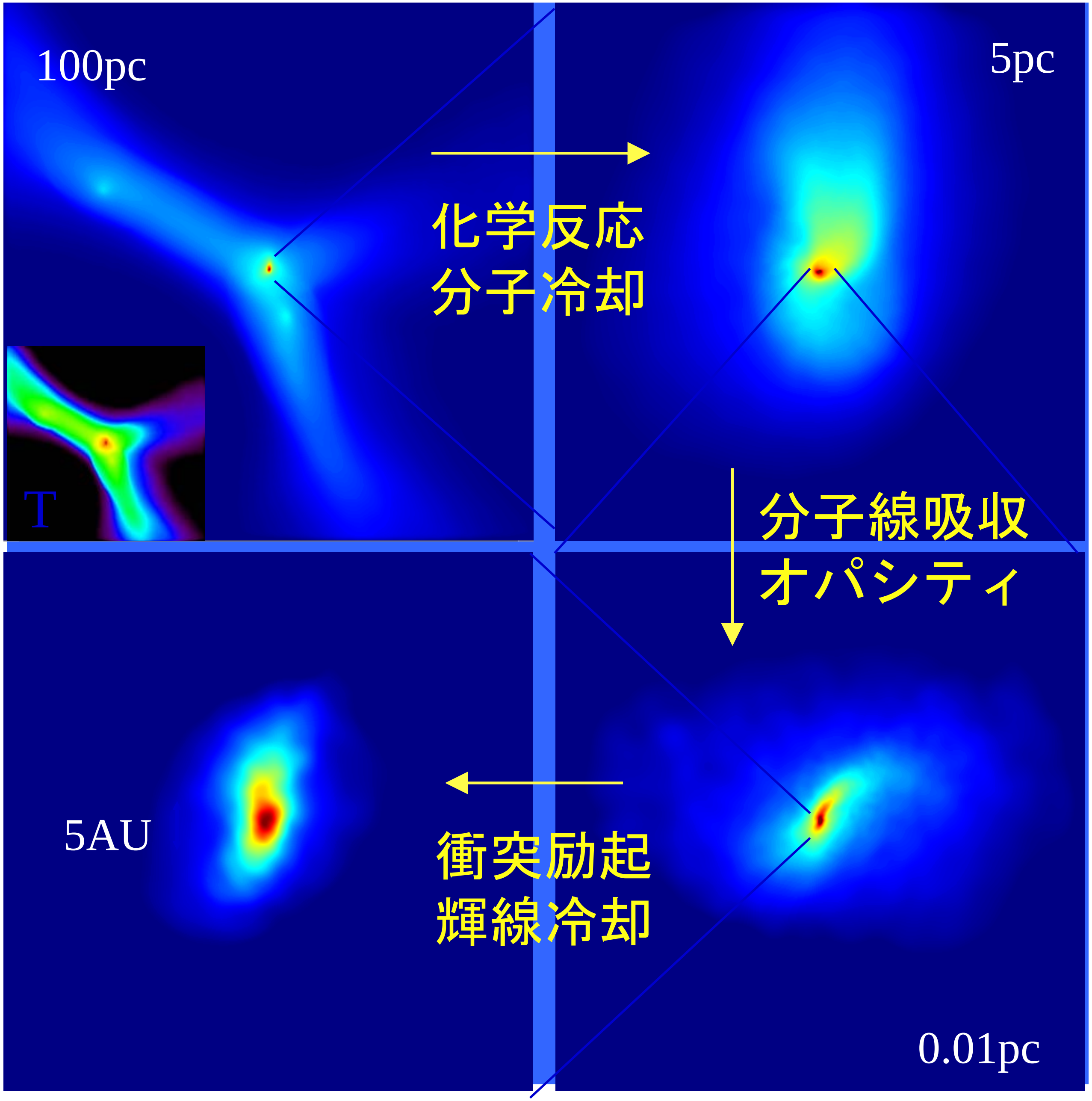
初期構造の形成

ガスとダークマターの密度分布

NY, Abel, Hernquist, Sugiyama (2003)



最初の分子ガス雲！



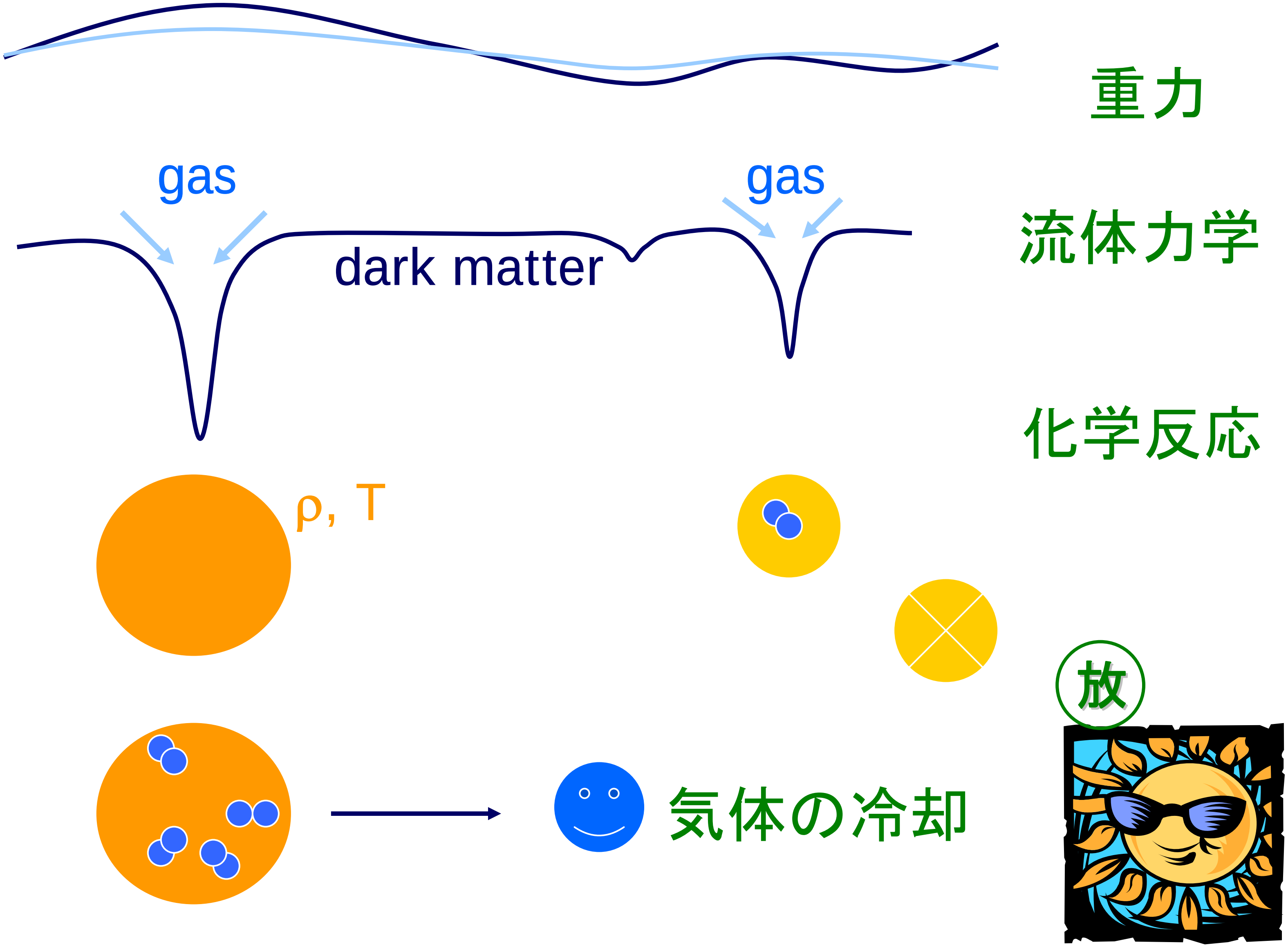
化学反応
分子冷却

分子線吸収
オパシティ

衝突励起
輝線冷却

NY, Omukai, Hernquist, Abel (2006, ApJ)

簡単に説明すると、、、



重力

gas

gas

dark matter

流体力学

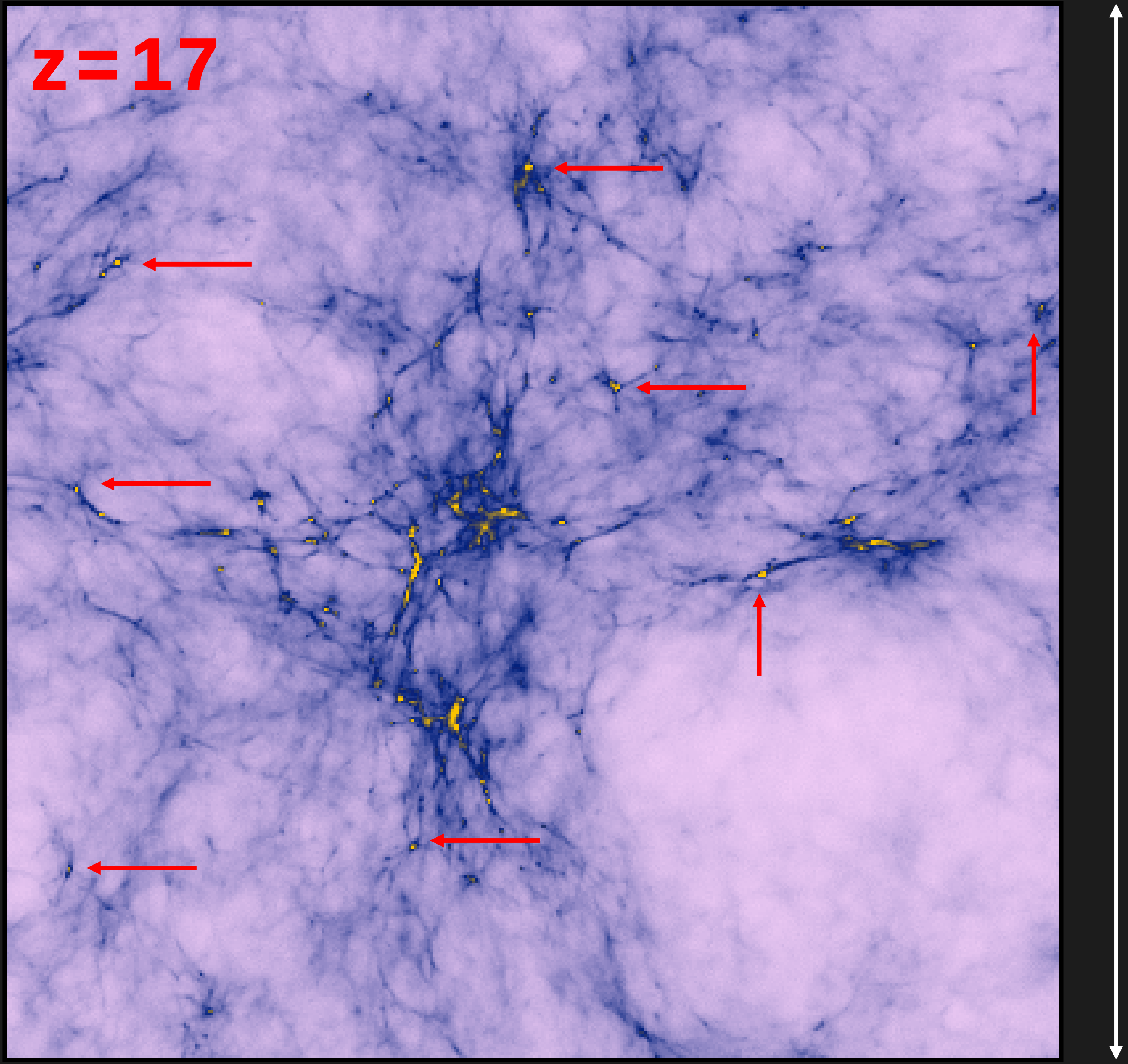
化学反応

ρ, T

放

気体の冷却

初期天体の分布



1 Mpc

6000万個
の粒子

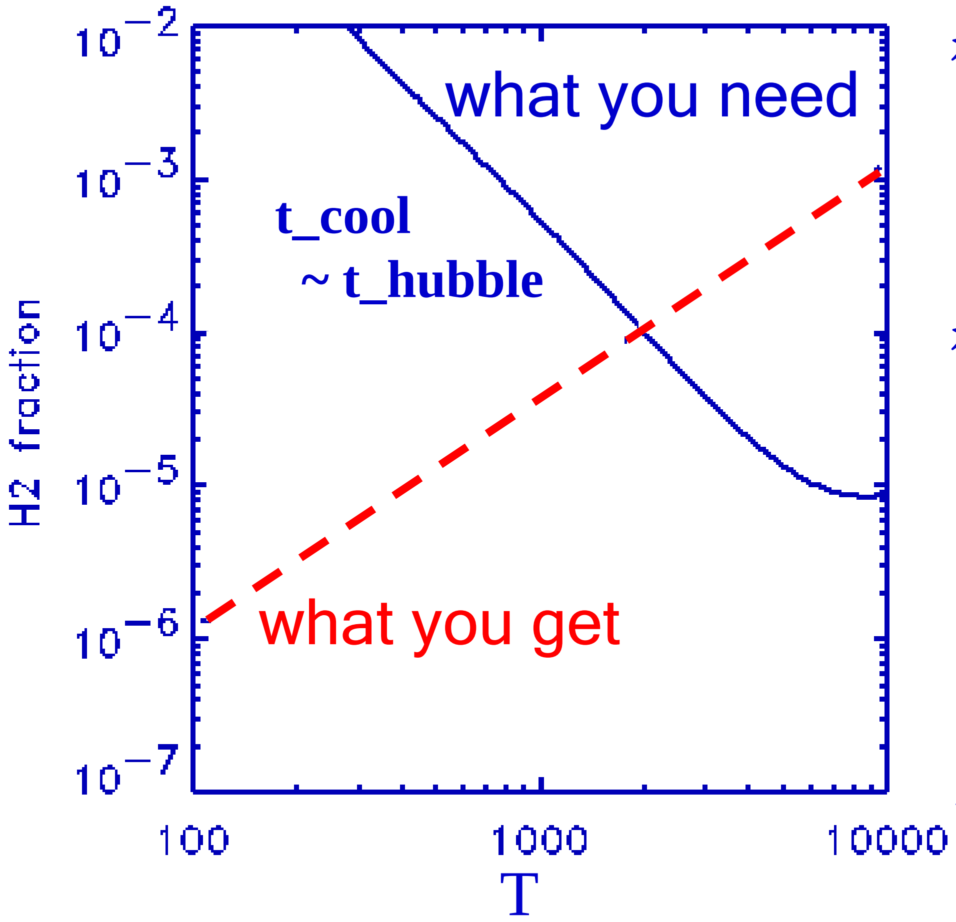
ガス粒子あたり
100 太陽質量

Yoshida, Abel, Hernquist, Sugiyama (2003, ApJ)

ガス雲中の水素分子の量

What you get must be more than what you need

Tegmark et al. (1997)



水素の再結合期

ほんの少し残った電子

H, H-

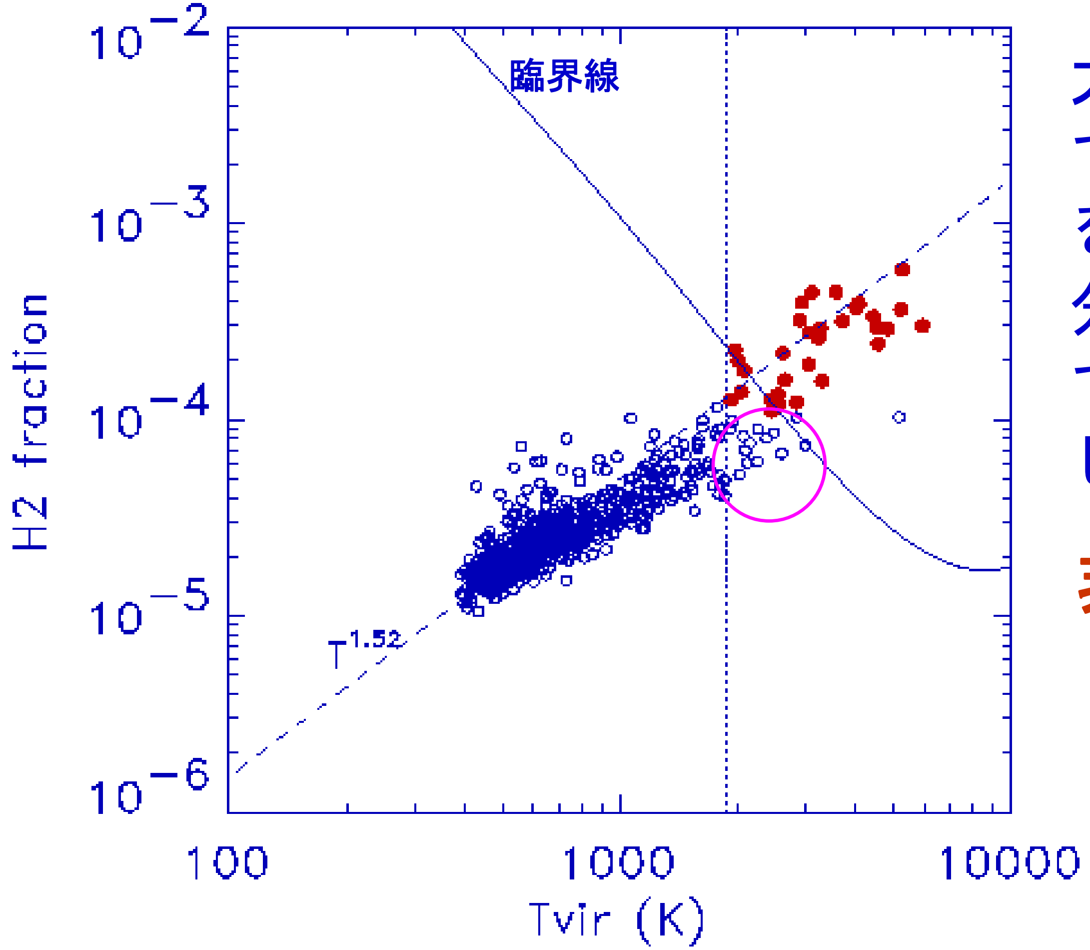
水素分子の形成

電子の供給減

H^+, e-

ガスの冷却

水素分子の量：シミュレーション結果



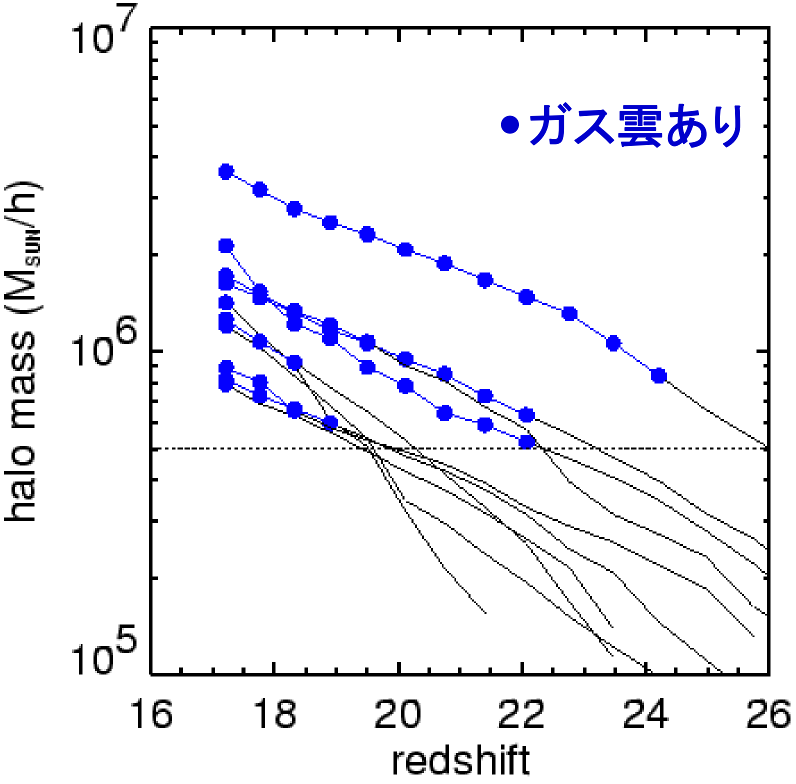
大規模シミュレーションで見つかった分子ガス雲をf-Tにプロットすると、分布はまさに理論曲線で分けられるようになる。しかし、、、

非常によく合う理論？

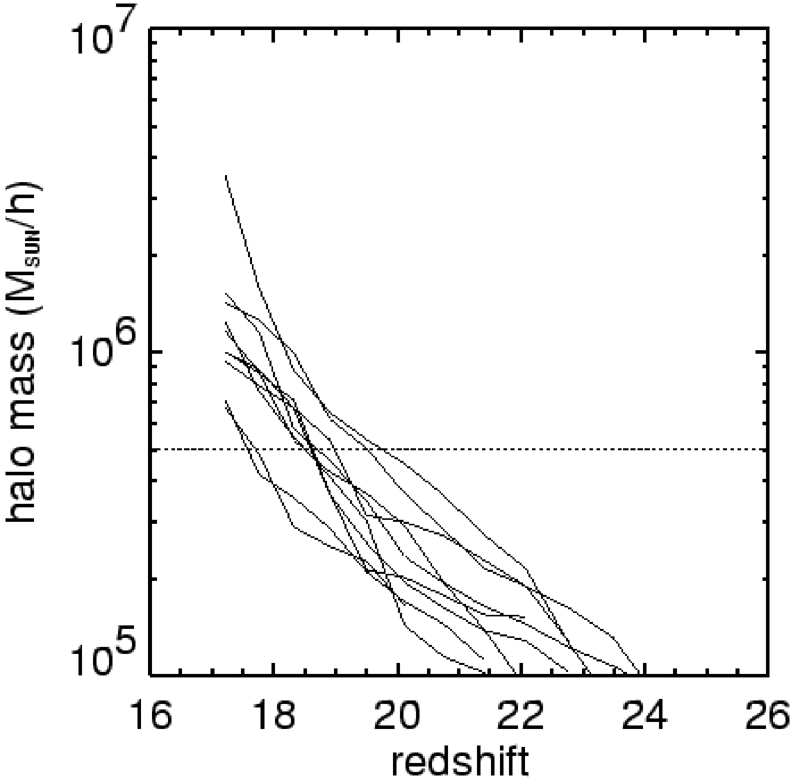
CDMハローの形成

ハローの形成史

グループ A

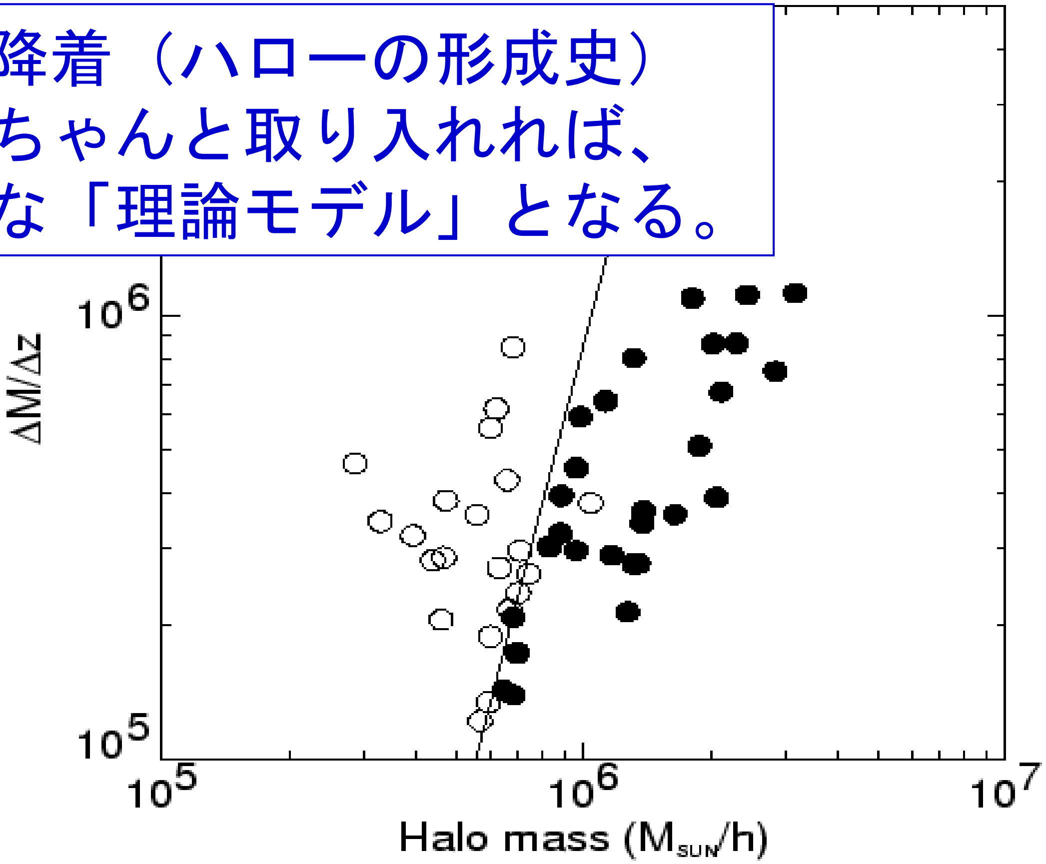


グループ B



質量降着による“じゃま”

ガスの冷却　対　力学的加熱

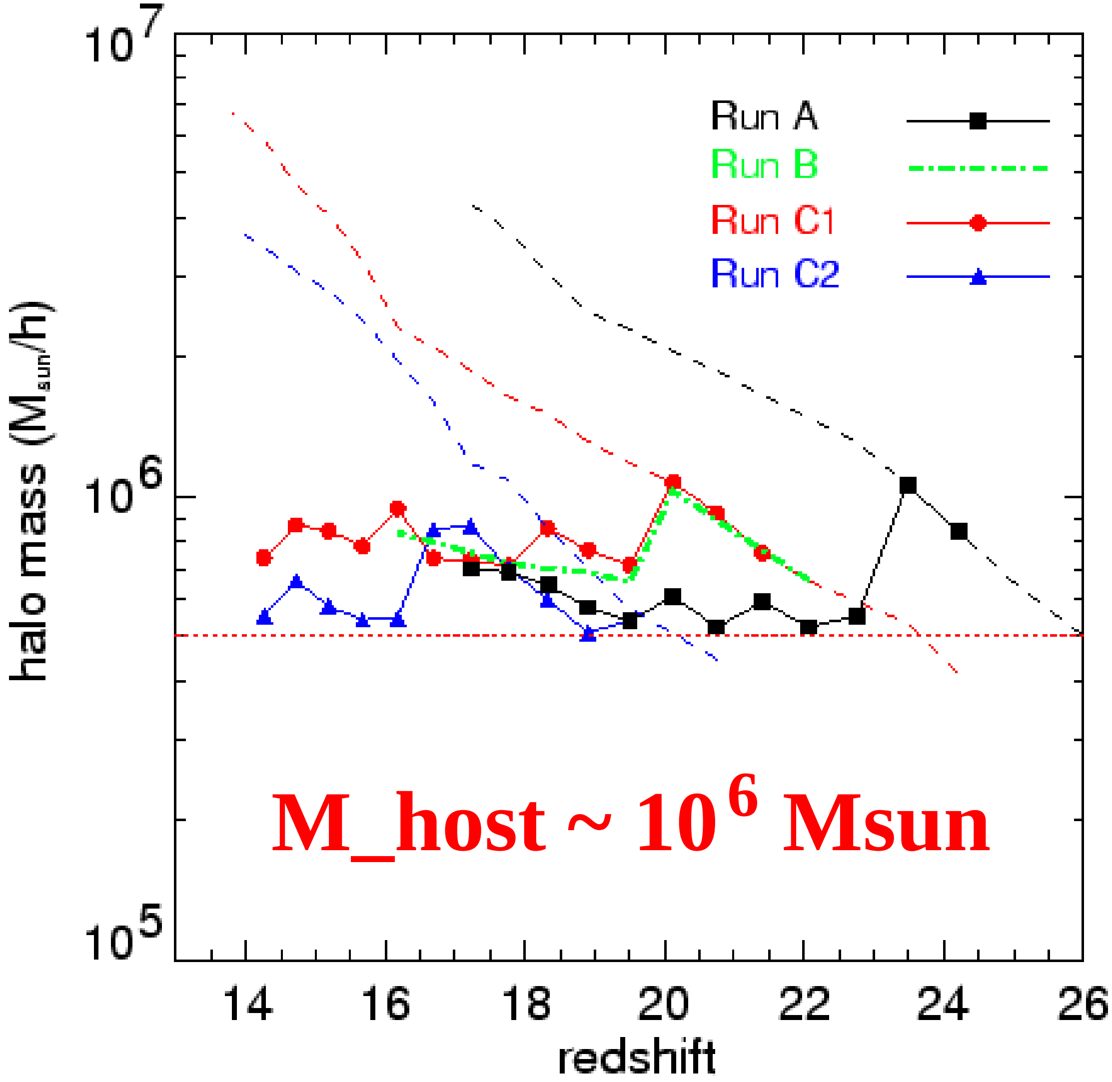


質量降着（ハローの形成史）
までちゃんと取り入れれば、
正確な「理論モデル」となる。

静かな環境

⇦　都会の喧騒は避けたい

天体形成をおこす最小質量



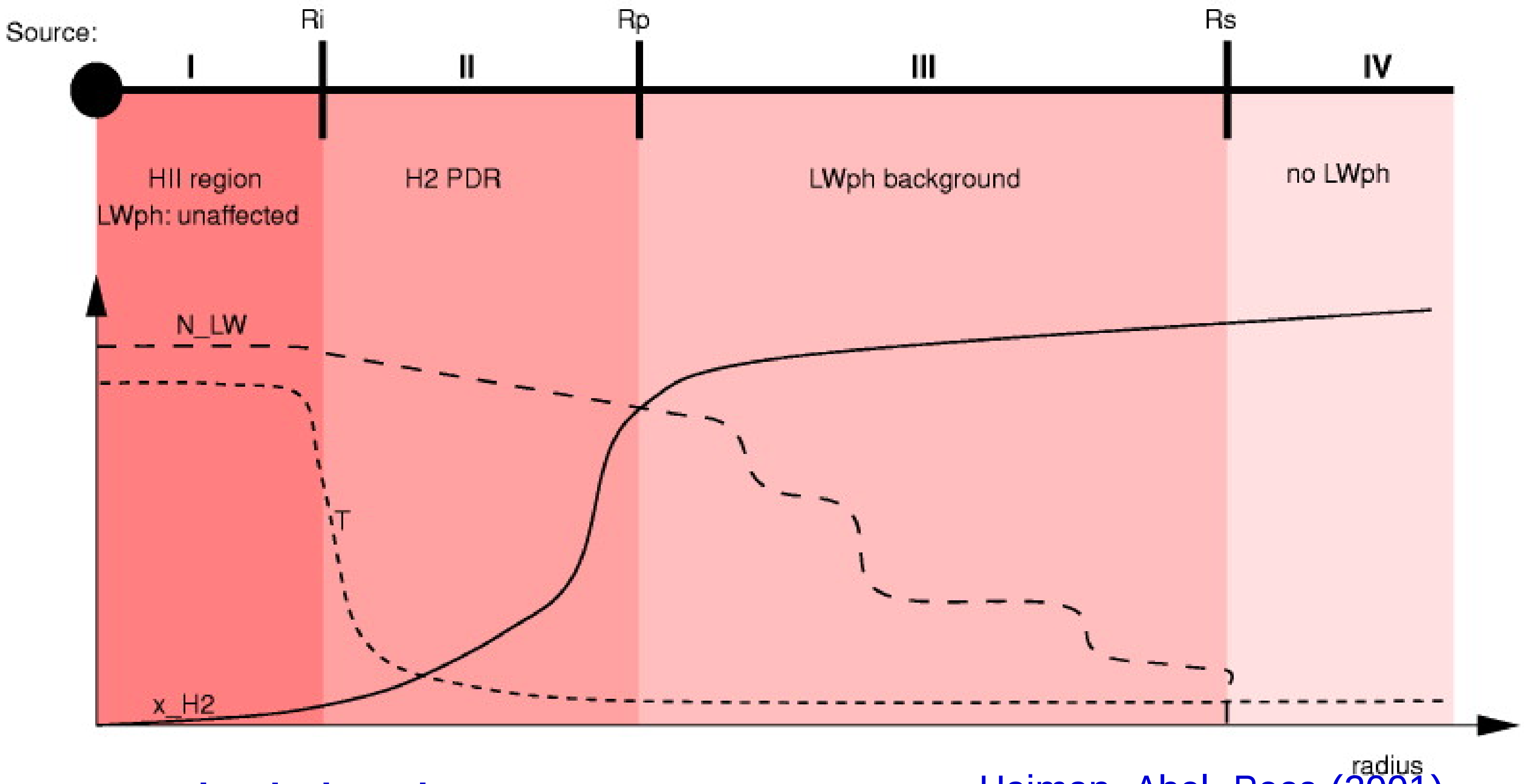
M_host ~ 10^6 Msun

Yoshida, Abel, Hernquist, Sugiyama (2003a)

初期構造形成の準解析モデル

1. ハローの形成・進化：N体計算のアウトプット
2. 気体密度・温度（ビリアル関係）、その後の冷却と凝縮：
   解析モデル　（流体化学反応計算の結果を利用）
3. 大質量星の形成 (小質量星はnegligible):
   ガス雲中で~100太陽質量の星誕生 (仮定)
4. 背景放射のビルドアップ

星が光ると、、、

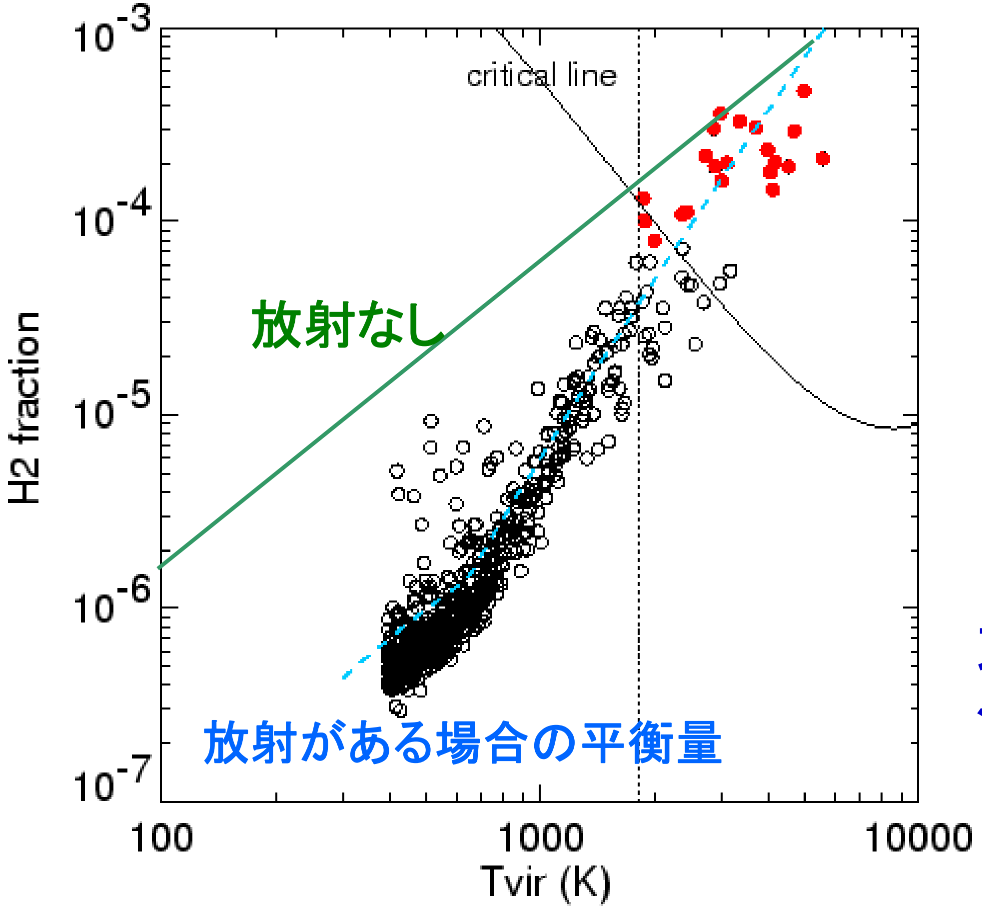


Optical depth　τ_H　>>　τ_H2

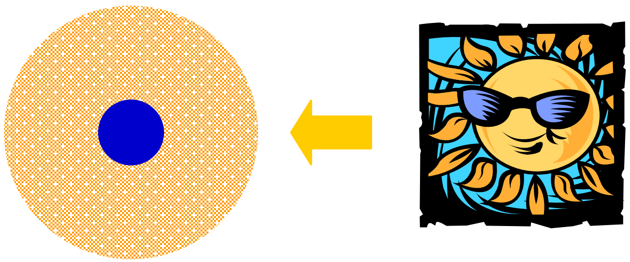
Haiman, Abel, Rees (2001)

放射による水素分子の解離

Lyman-Werner photons (11.18-13.6eV)
with $J=10^{-23}$ erg sec^{-1} cm^{-2} Hz^{-1} str^{-1}

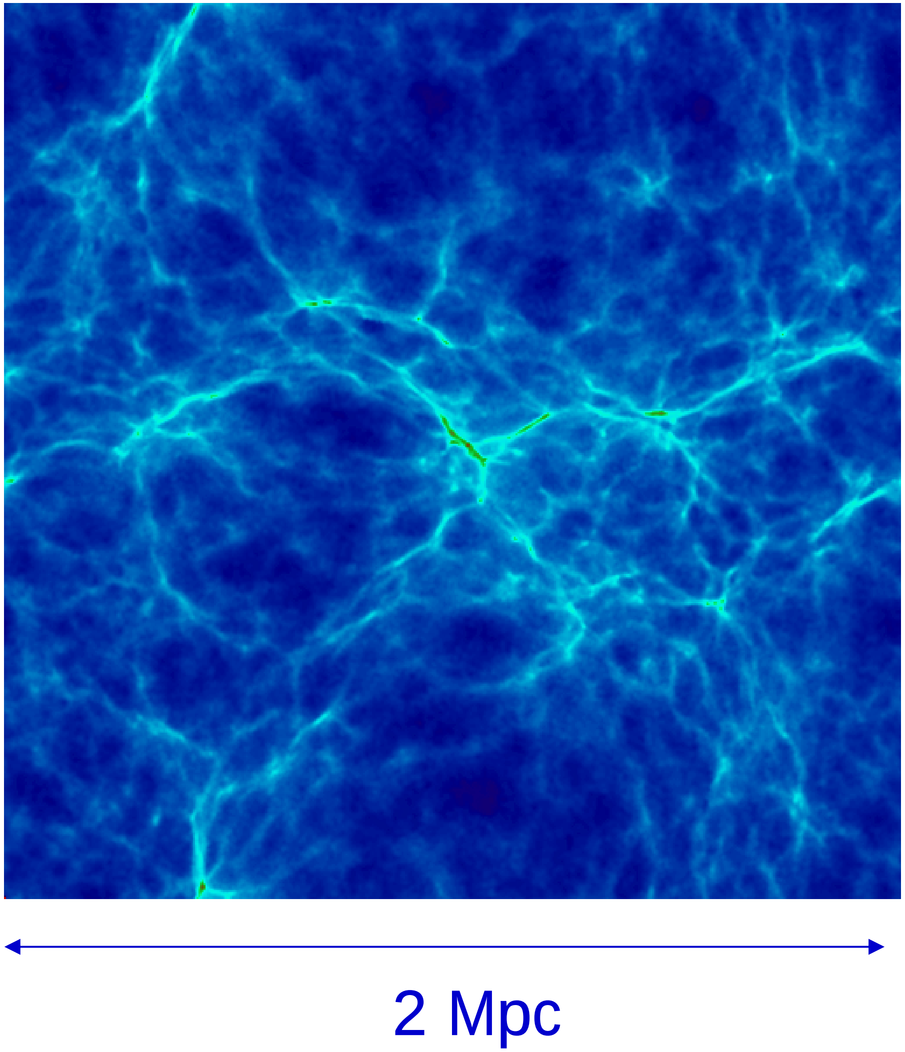


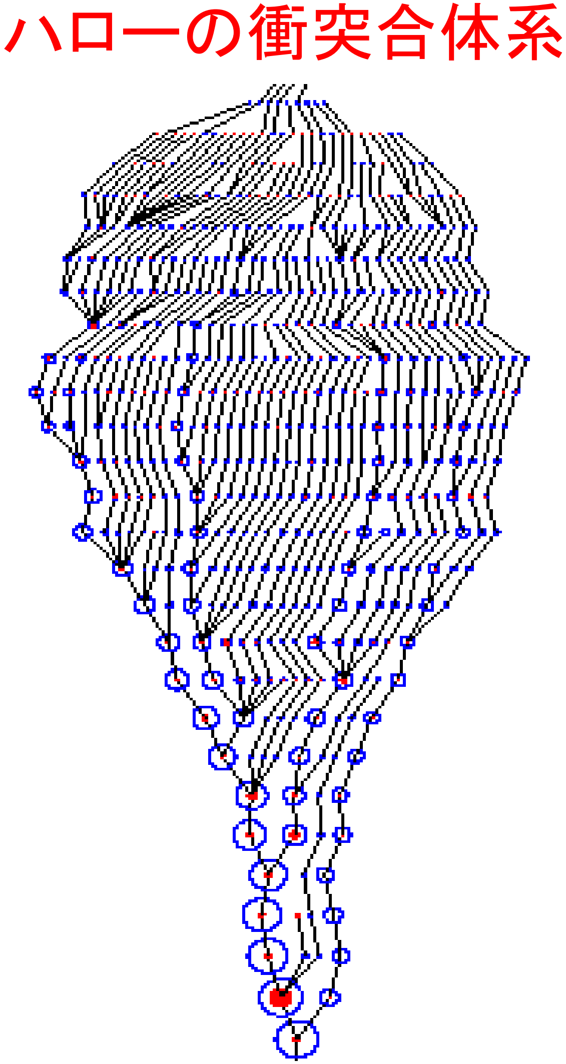
背景紫外放射
＋　シールディング効果



大きなハローは
シールディングが効く
⟶　放射の影響が小さい

N体計算の結果に”the”解析モデルを適用


2 Mpc


ハローの衝突合体系譜

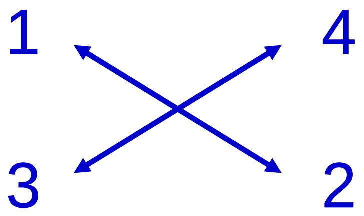
初期構造形成の準解析モデル

1. ハローの形成・進化：**N体計算のアウトプット**

2. 気体密度・温度（ビリアル関係）、その後の冷却と凝縮：
   解析モデル　（流体化学反応計算の結果を利用）

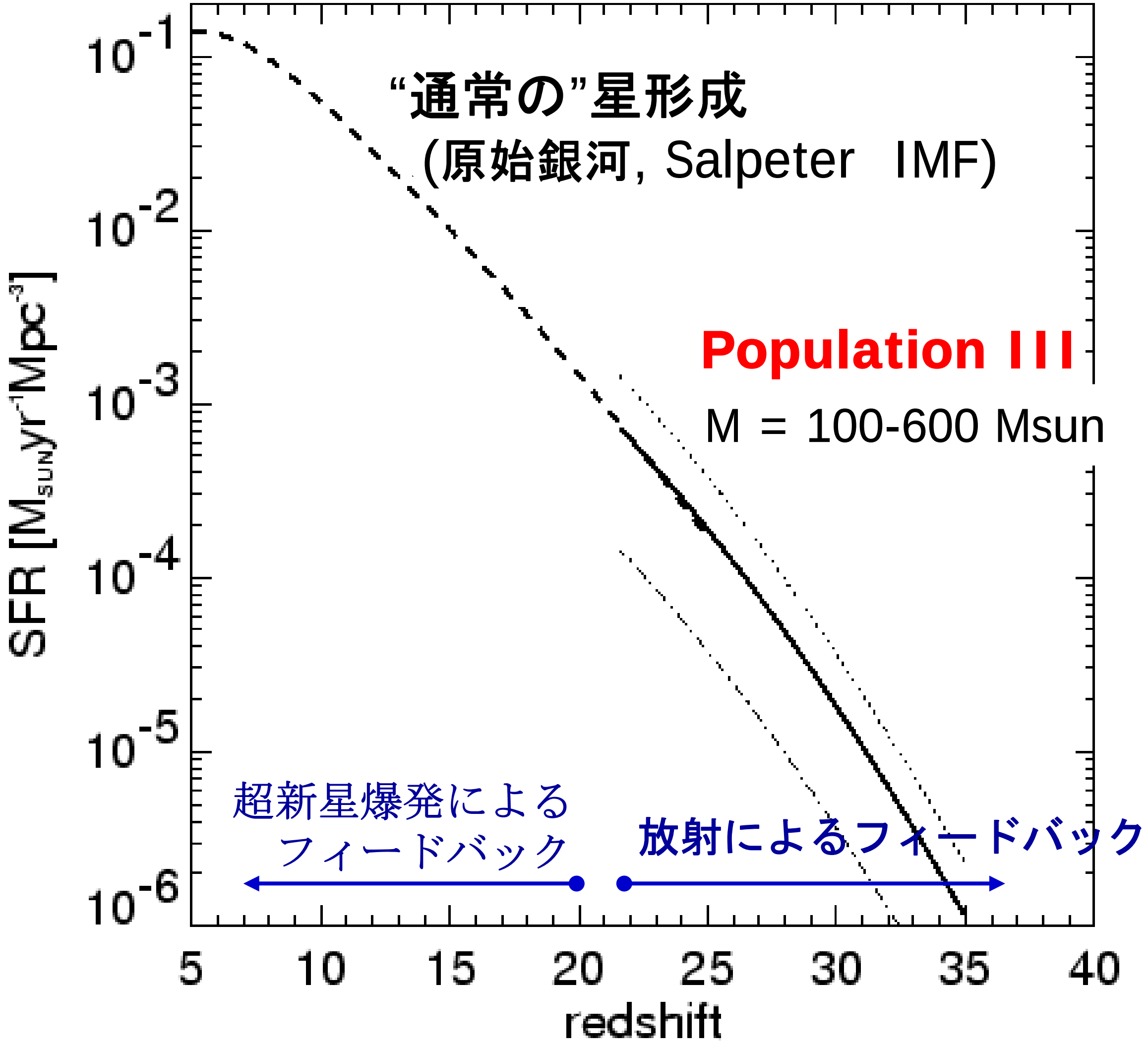
3. 大質量星の形成：
   ガス雲中で100－600太陽質量の星誕生 (仮定)

4. 背景放射のビルドアップ



各プロセス間の複雑な相互作用

宇宙全体の星形成率



“通常の”星形成

(原始銀河, Salpeter IMF)

Population III

M = 100-600 Msun

超新星爆発による
フィードバック

放射によるフィードバック

NY, Abel, Hernquist, Sugiyama astro-ph/0301645

世界に広がるマイモデル

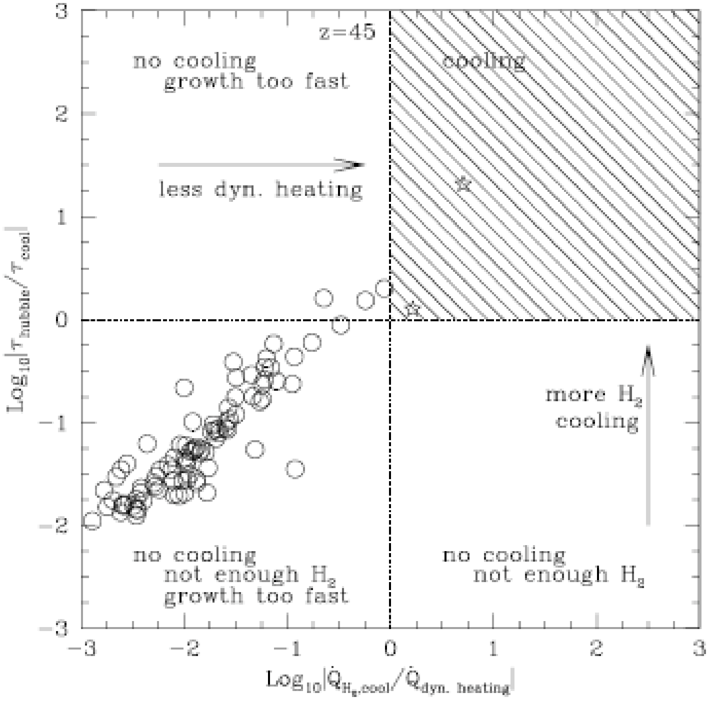
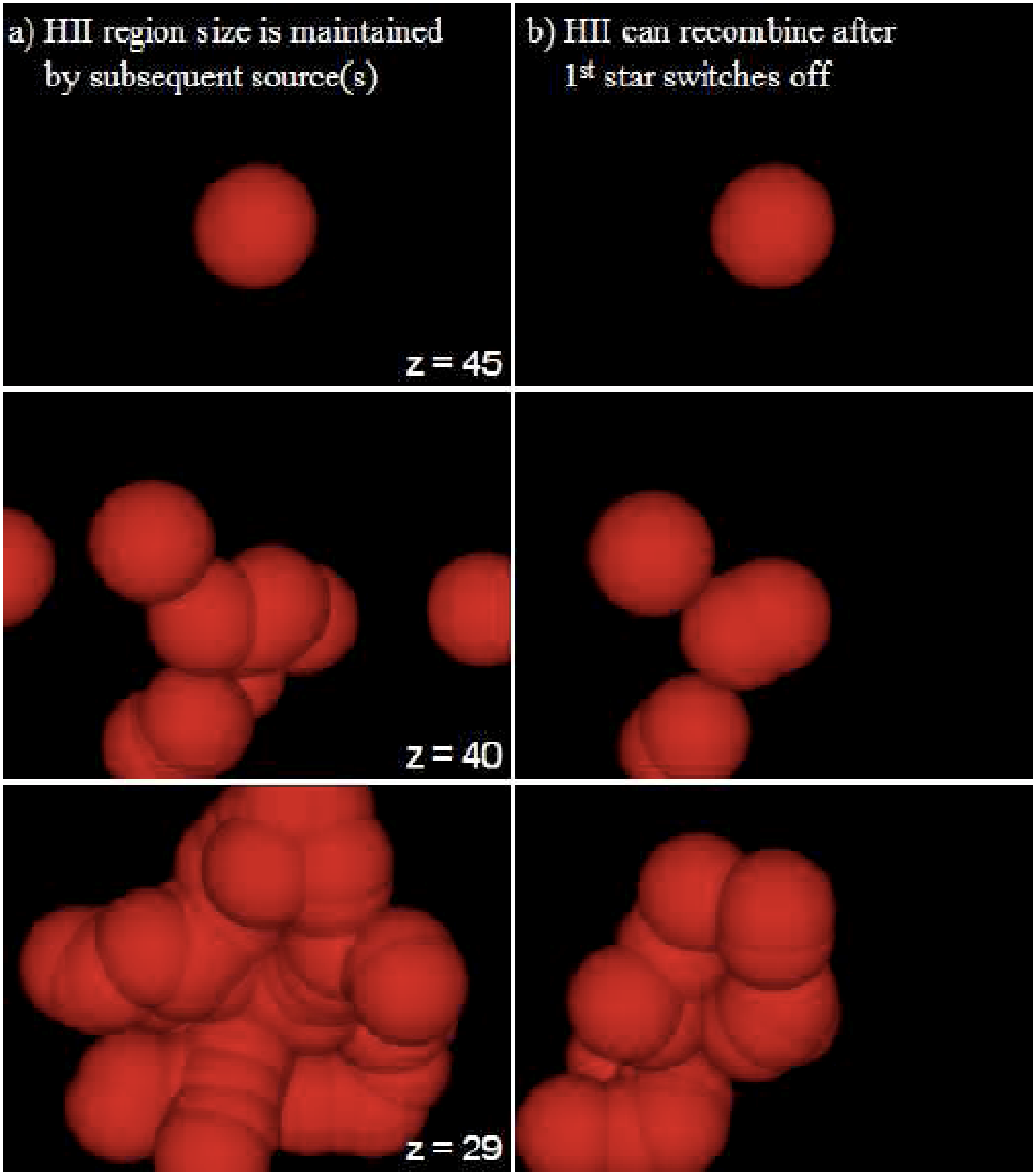


Figure 4. The two criteria for baryonic cooling, $\tau_{\rm Hubble}/\tau_{\rm H_2,cool} > 1$ (Eqn. 5) and $|\dot{Q}_{\rm H_2,cool}/\dot{Q}_{\rm dyn.heat}| > 1$ (Eqn. 6), for the 100 most massive haloes at redshift 45. Haloes in the upper right quadrant satisfy both cooling criteria and are thus expected to undergo baryonic collapse. Haloes in the upper half have enough H_2 such that their baryonic cooling time is less than the age of the universe. Haloes in the right half have H_2 cooling rates that are larger than their dynamical heating rates and thus experience nett cooling. Dynamical heating delays baryonic collapse (haloes in upper left panel) such that only 2 haloes are capable of cooling by redshift 45, even though 5 haloes have sufficiently short H_2 cooling times.

Reed, Gao, Frenk, Bower, White (2005)

宇宙論的体積の中での~6sigma ピークを選び、ダークマターハローの形成史をY03にならって使って初期☆形成ガス雲の進化をおった。

Reed+ 2005



a) HII region size is maintained by subsequent source(s)

b) HII can recombine after 1st star switches off

Neutrino Signatures from the First Stars

Frédéric Daigne[1], **Keith A. Olive**[2], **Pearl Sandick**[3], and **Elisabeth Vangioni**[1]

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[2] *William I. Fine Theoretical Physics Institute, School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455 USA*

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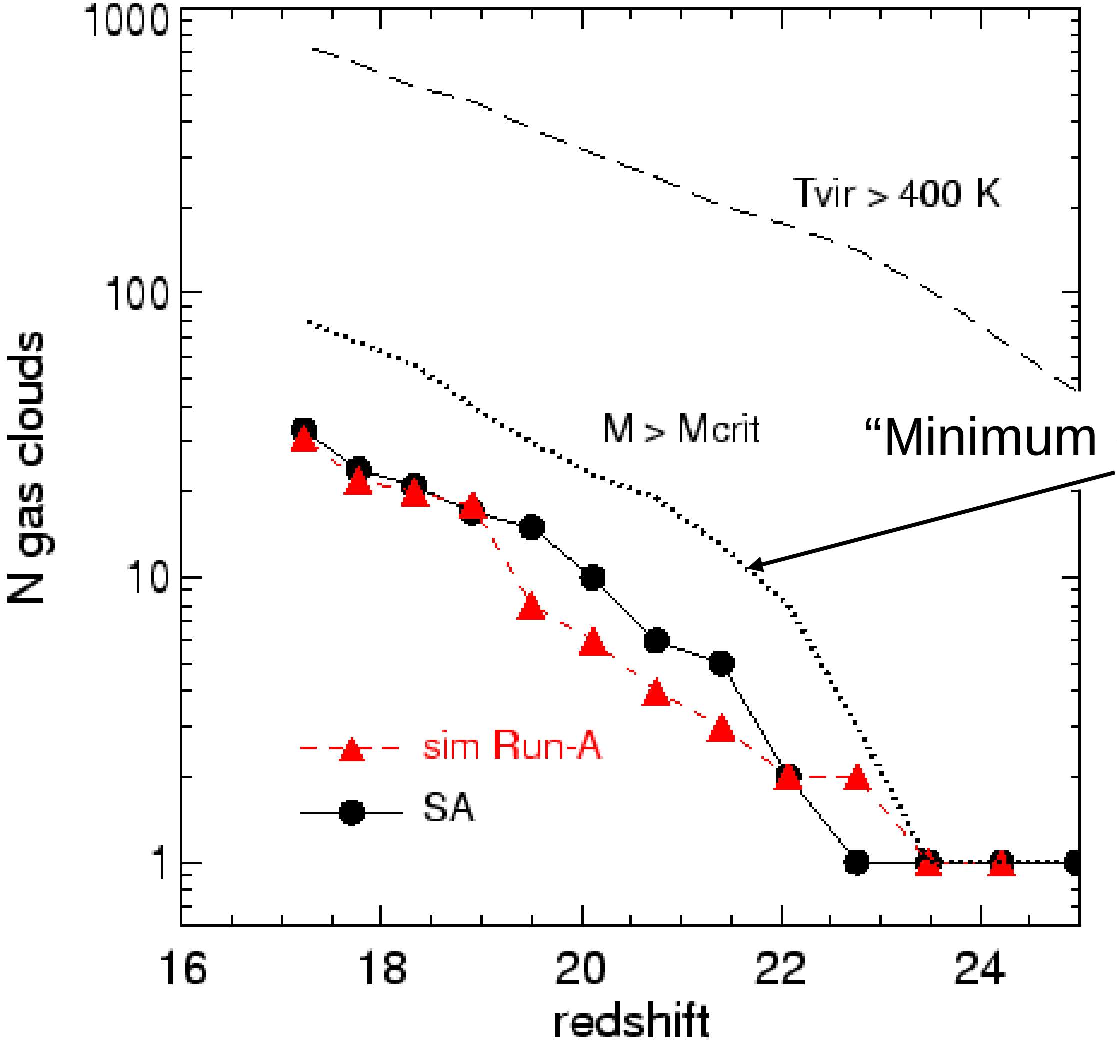
Abstract

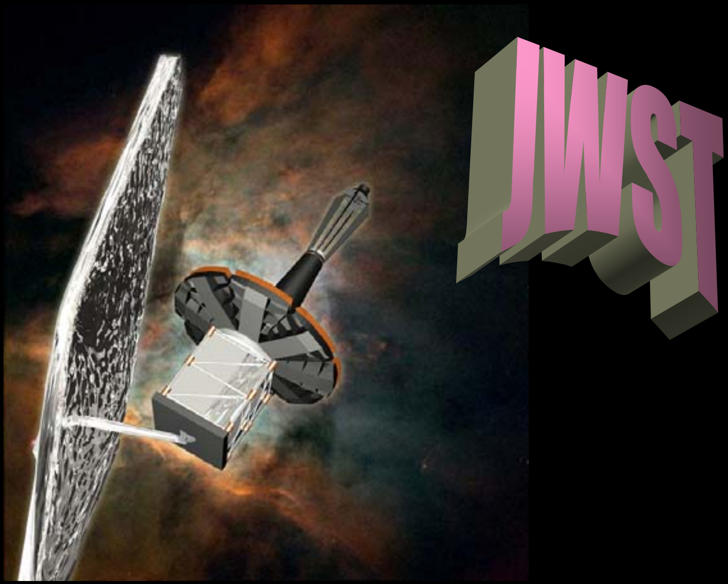
Evidence from the WMAP polarization data indicates that the Universe may have been reionized at very high redshift. It is often suggested that the ionizing UV flux originates from an early population of massive or very massive stars. Depending on their mass, such stars can explode either as type II supernovae or pair-instability supernovae, or may entirely collapse into a black hole. The resulting neutrino emission can be quite different in each case. We consider here the relic neutrino background produced by an early burst of Population III stars coupled with a normal mode of star formation at lower redshift. The computation is performed in the framework of hierarchical structure formation and is based on cosmic star formation histories constrained to reproduce the observed star formation rate at redshift $z \lesssim 6$, the observed chemical abundances in damped Lyman alpha absorbers and in the intergalactic medium, and to allow for an early reionization of the Universe at $z \sim 10-20$. We find that although the high redshift burst of Population III stars does lead to an appreciable flux of neutrinos at relatively low energy ($E_\nu \approx 1$ MeV), the observable neutrino flux is dominated by the normal mode of star formation. We also find that predicted fluxes are at the present level of the SuperK limit. As a consequence, the supernova relic neutrino background has a direct impact on models of chemical evolution and/or supernova dynamics.

モデルのテスト: SA vs simulation



"Minimum collapse mass" model

Prospects for observation



~nJy sensitivity@NIR

Direct imaging

21 cm emission

Infrared background

モデルは未完成

～今後の発展へ向けて～

構築したモデルは宇宙最初期の星形成についてはある程度うまくいく。

しかし以下の２点でさらなる発展が必要

１　ローカルな放射の影響

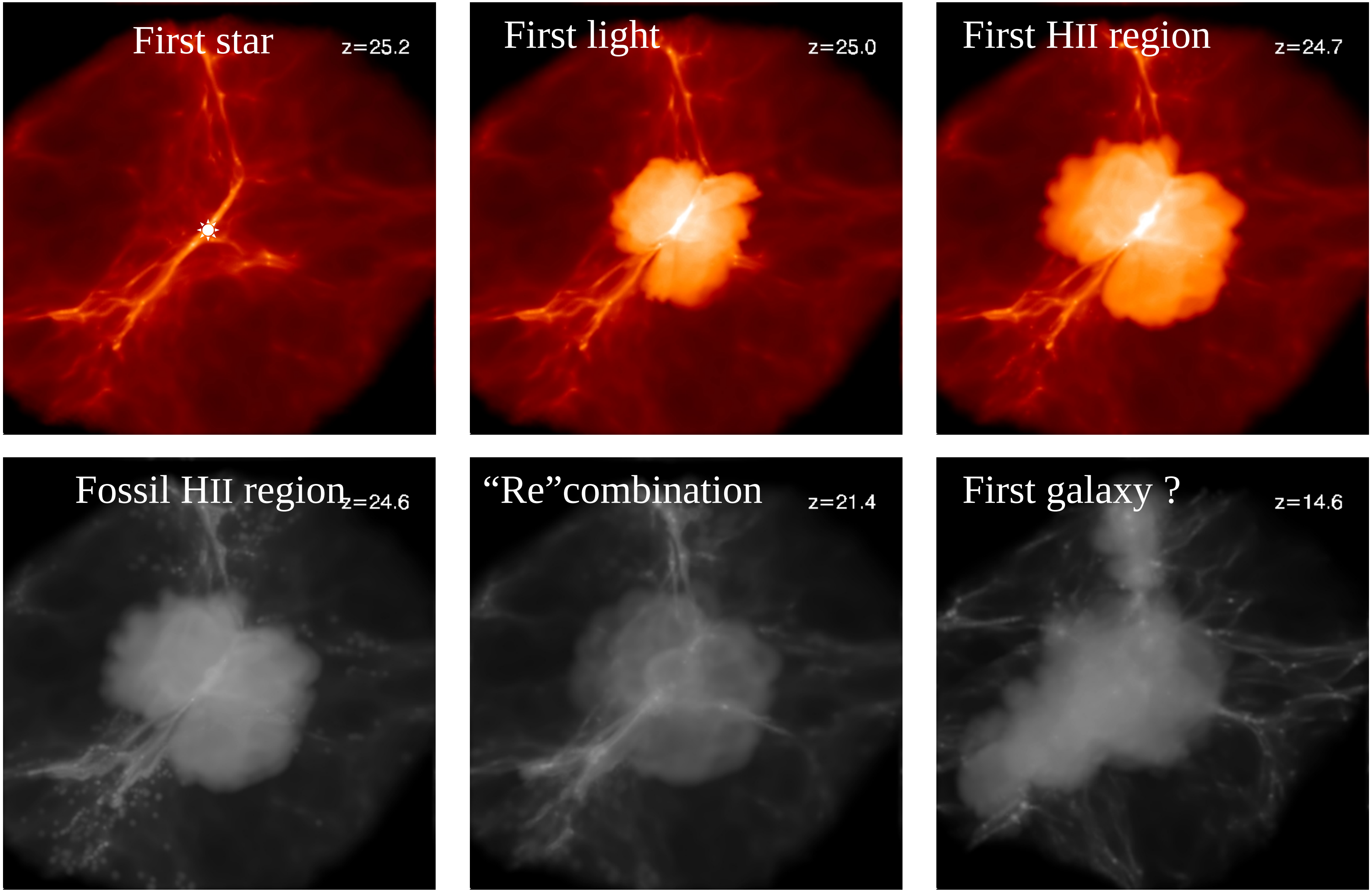
２　その後の（原始）銀河形成への影響

そして
セミアナ初代天体＋セミアナ銀河
Grand Unified Modelへ…

How did the first galaxies form ?

- maybe not the way you might have thought

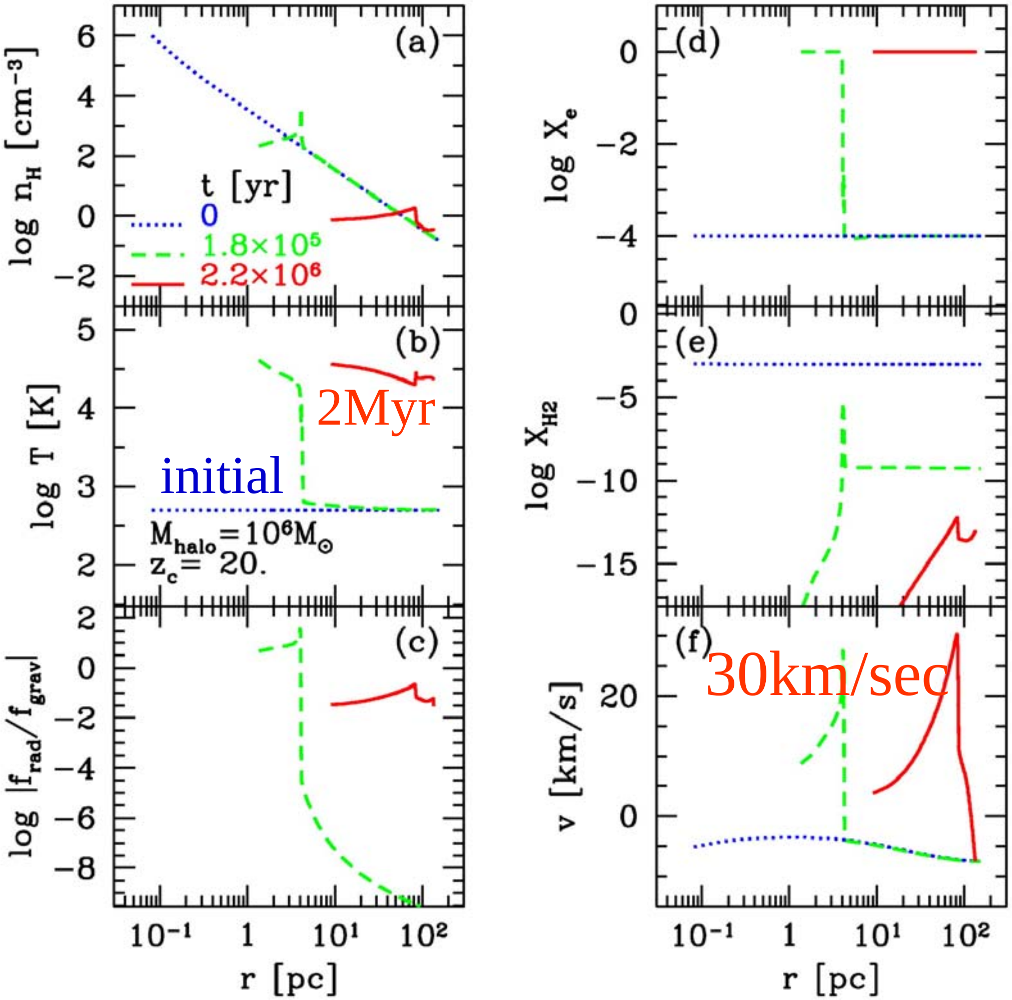
The Dark Ages…



Evolution of early HII regions

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

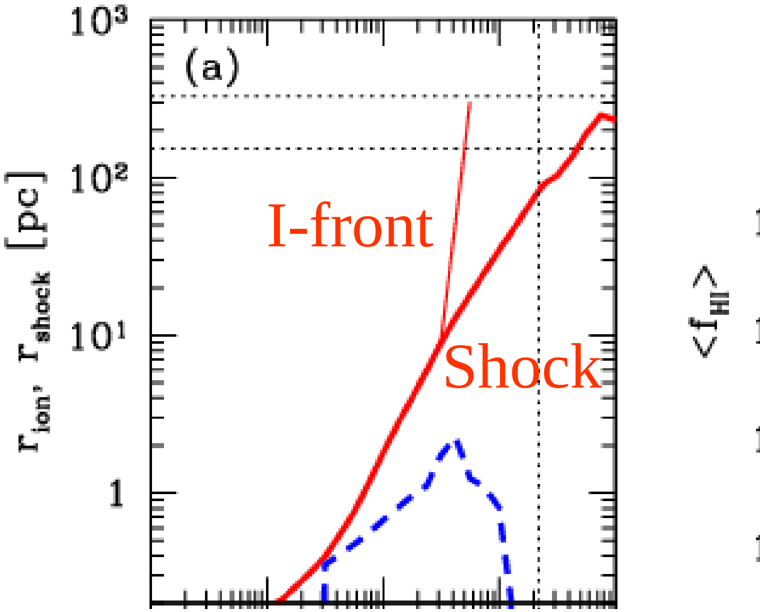
D-type →R-type



2Myr

initial

30km/sec

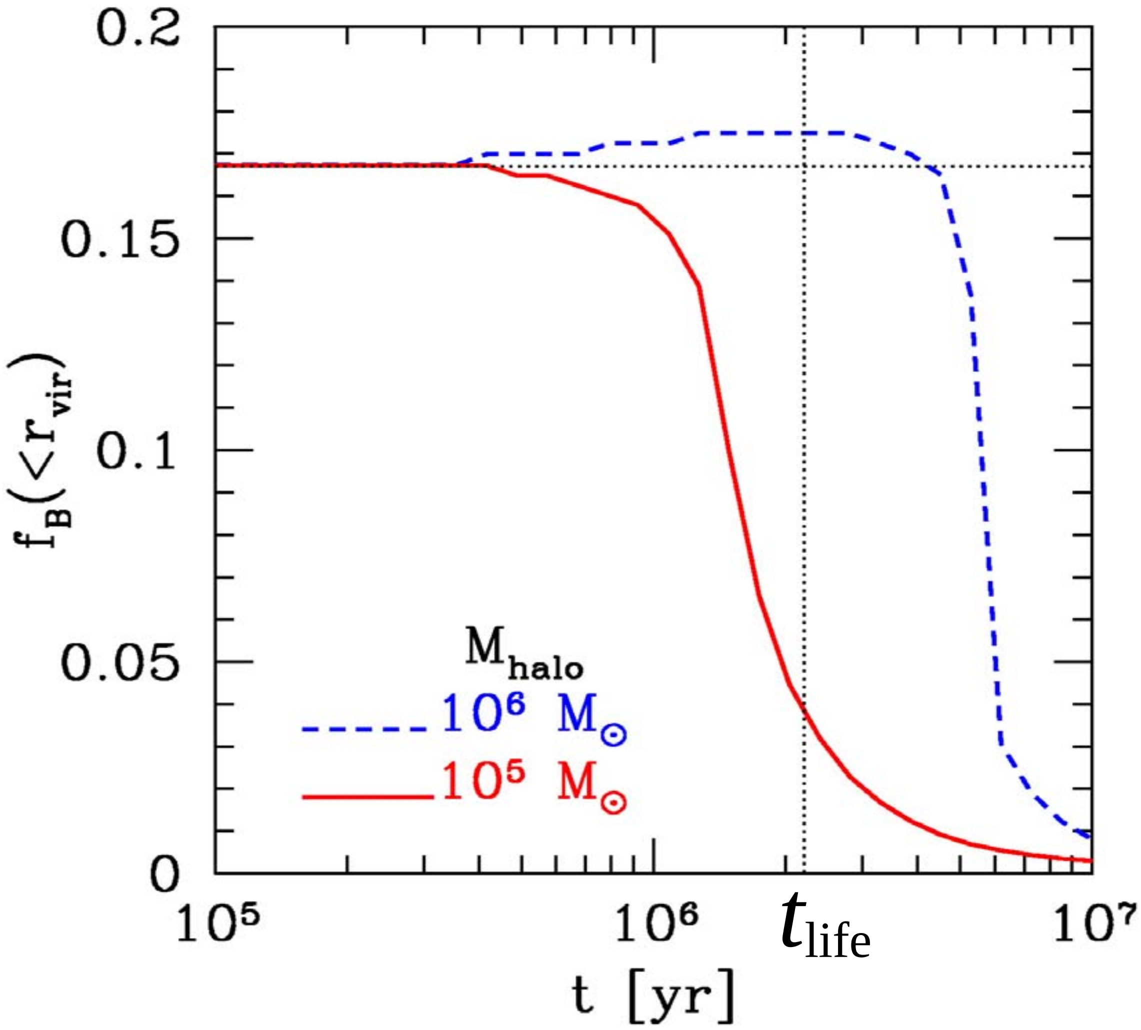


I-front

Shock

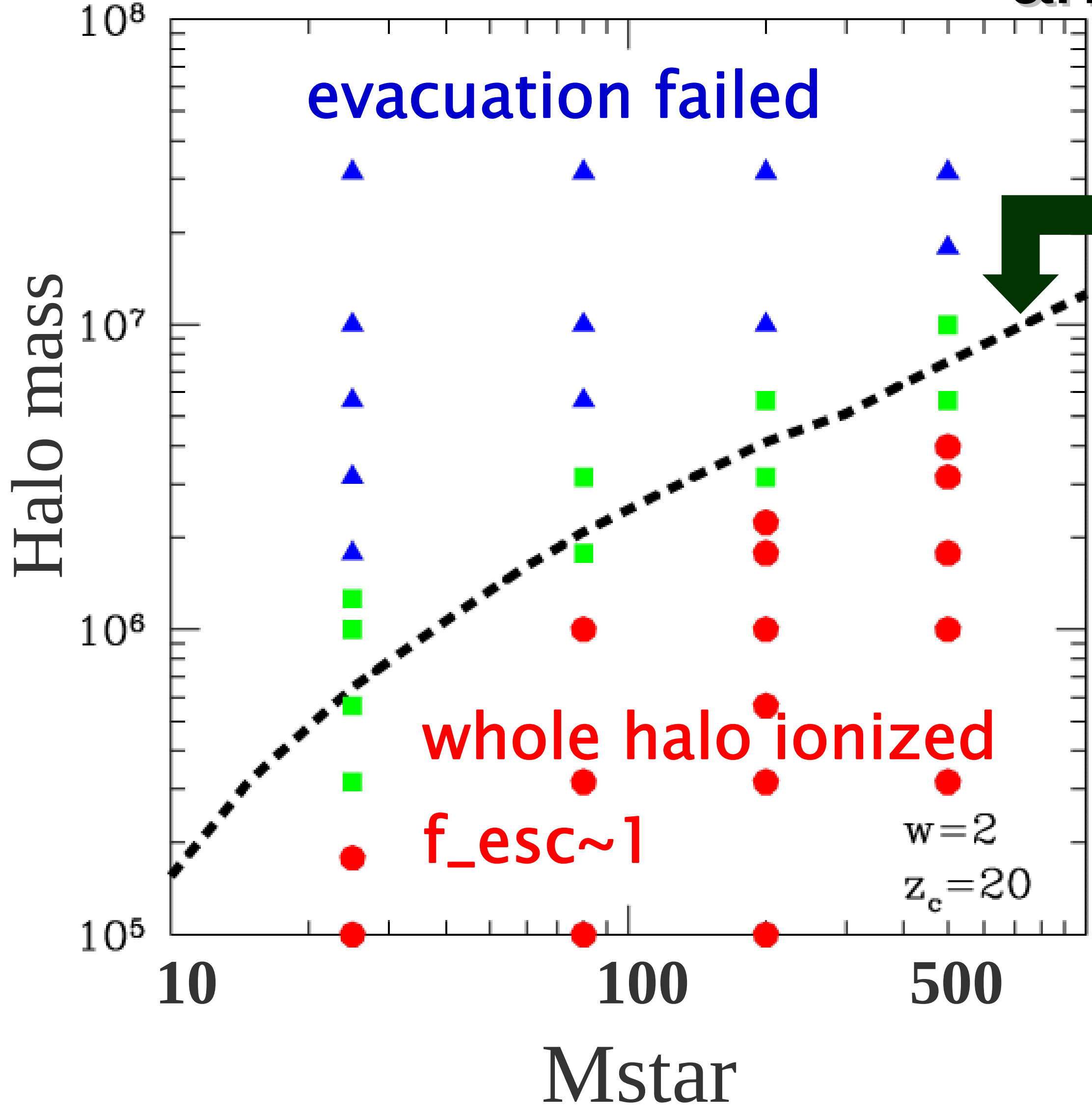
Radiation-hydro. sim. by Kitayama, NY, Susa, Umemura (2004, ApJ)

Hot gas in a small halo - gone with the wind...



Vhalo=3km/sec
Vgas =30km/sec

Critical halo mass for complete ionization and gas evacuation

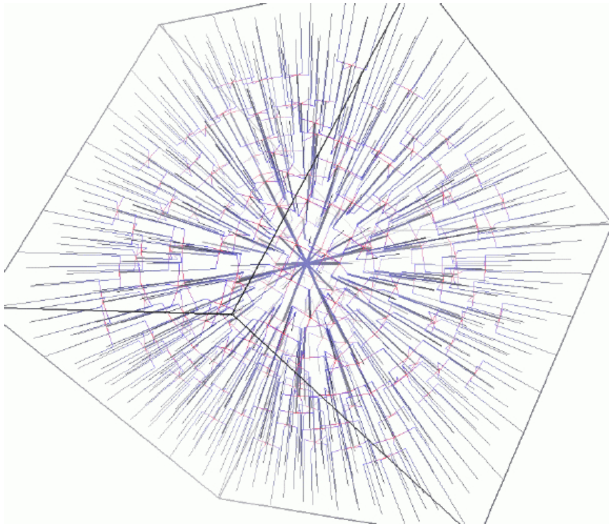


Necessary condition

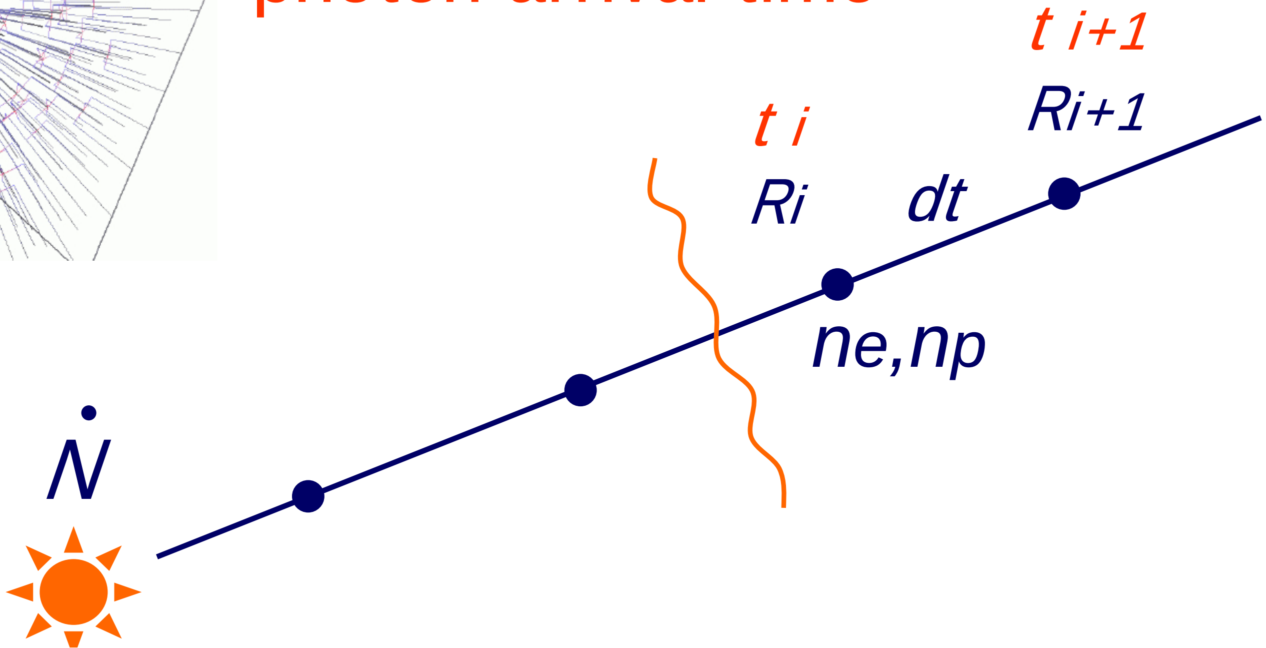
$$R_{\mathrm{shock}} > R_{\mathrm{St}}$$

$$R_{\mathrm{St}} = 68 \left(\frac{\dot{N}}{10^{49}}\right)^{1/3} n_{\mathrm{in}}^{-2/3}$$

3D radiative transfer scheme



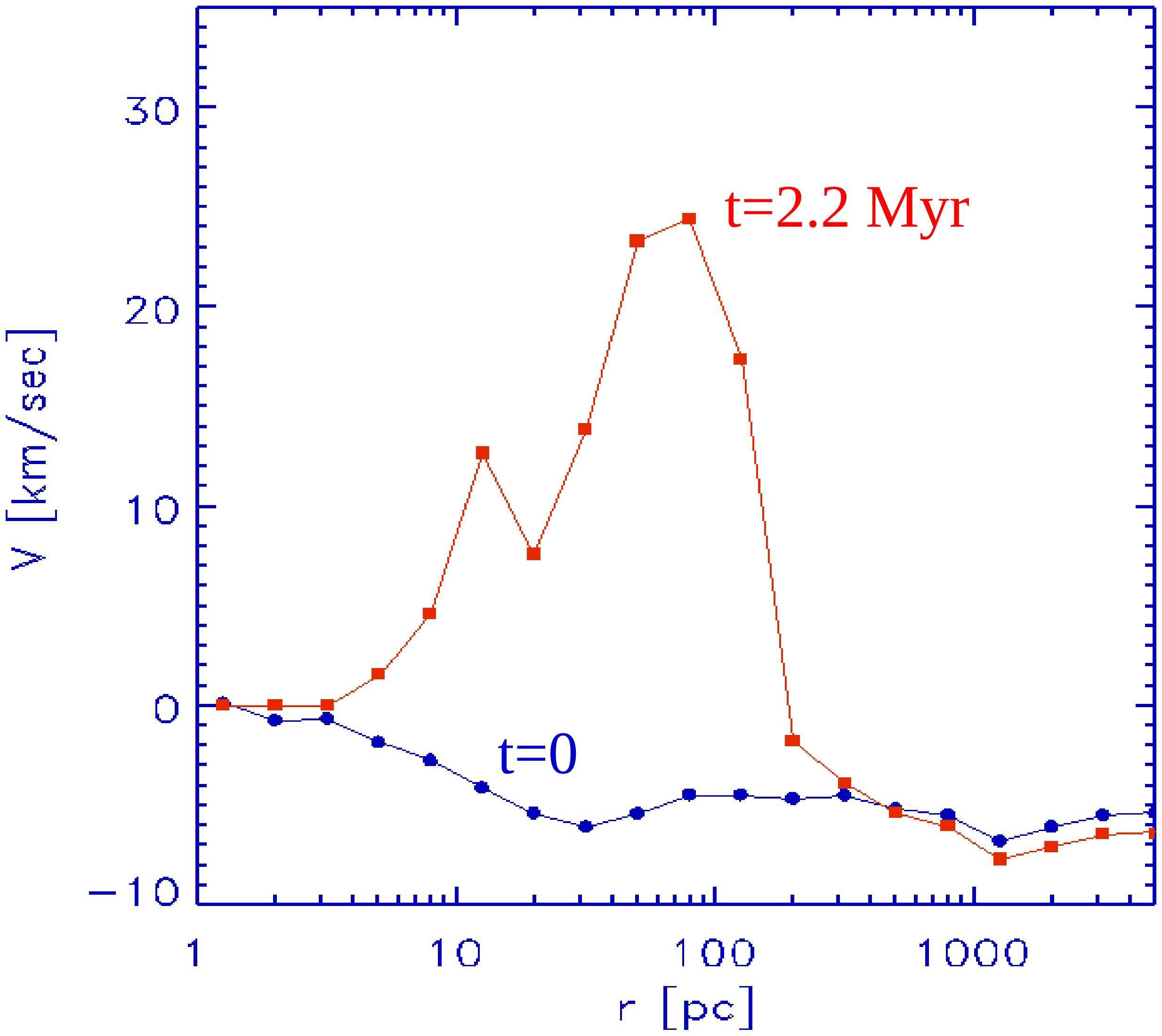
Ray-tracing to
all the gas particles (~ millions particles) to compute
photon arrival time



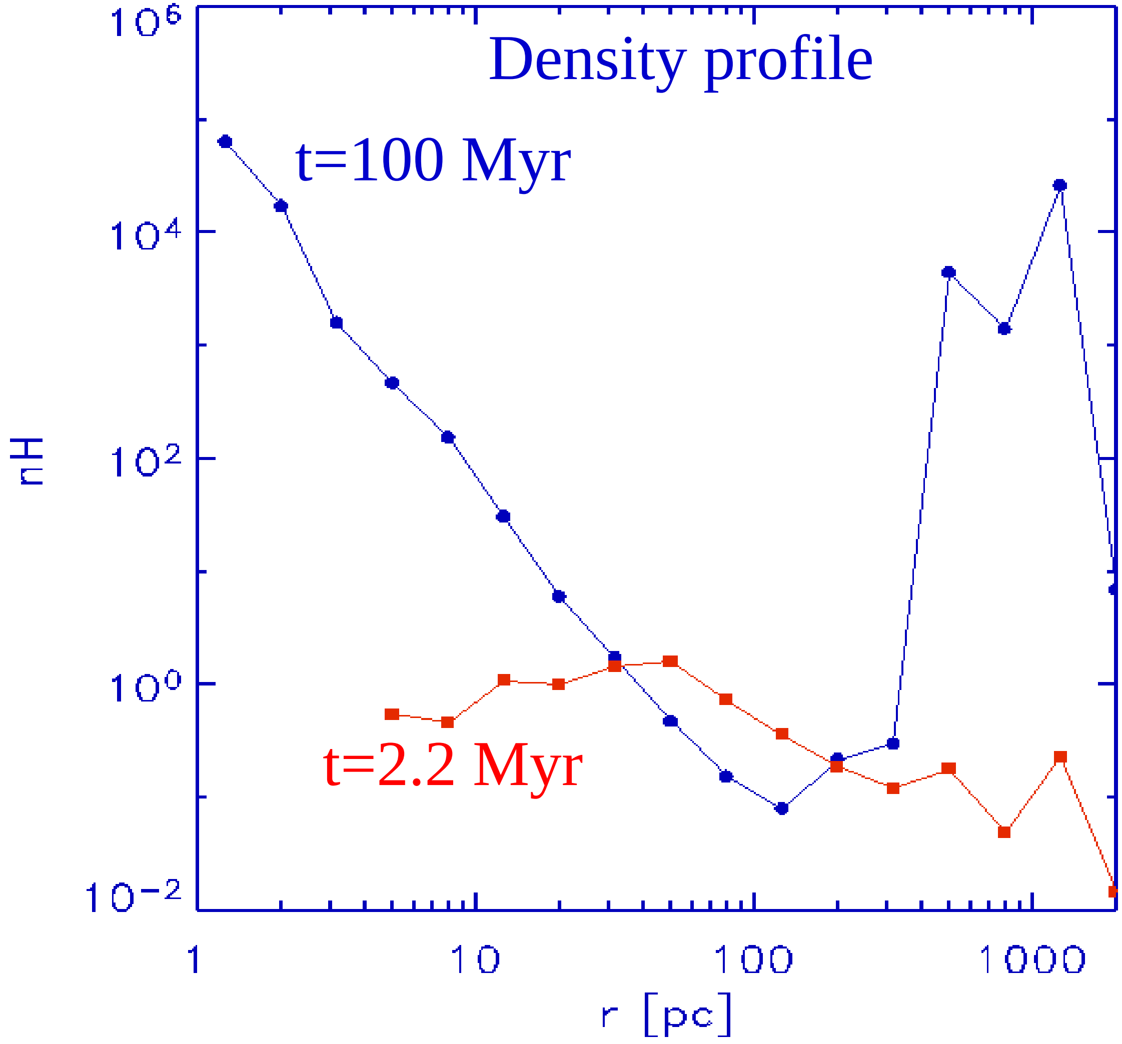
$$4\pi r_i^2 n \frac{dr_i}{dt} = \dot{N}_{\rm ph} - 4\pi\alpha \int_0^{r_i} n_e n_p r^2 dr$$

A three-dimensional
cosmological simulation
with gravity, hydrodynamics,
primordial gas chemistry,
and radiative transfer

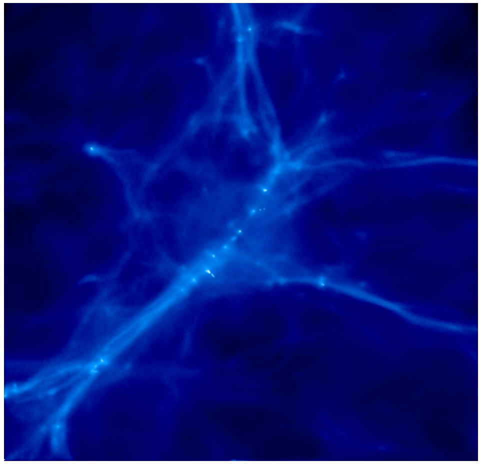
Radial velocity profile



Evolution of the baryon fraction



Initially outward motion is reverted due to gravity by the growing dark halo and infalling gas

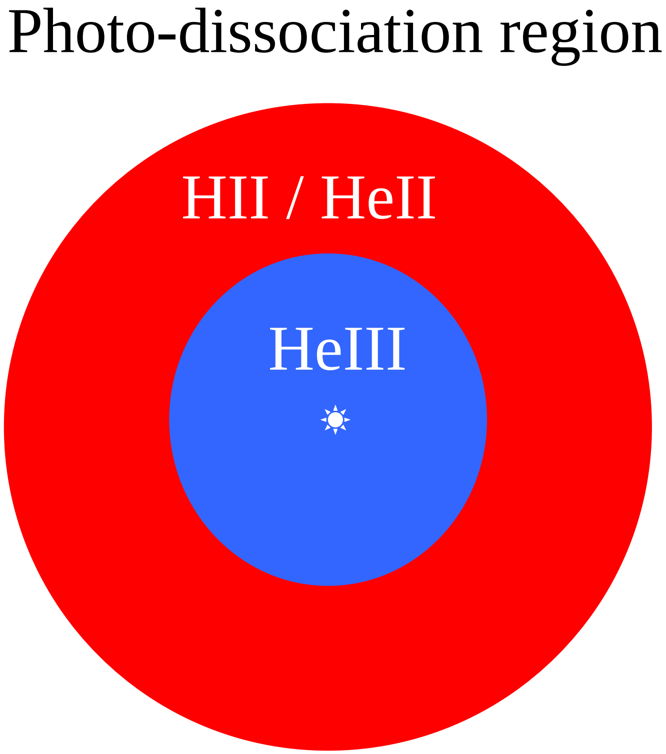


Helium ionization

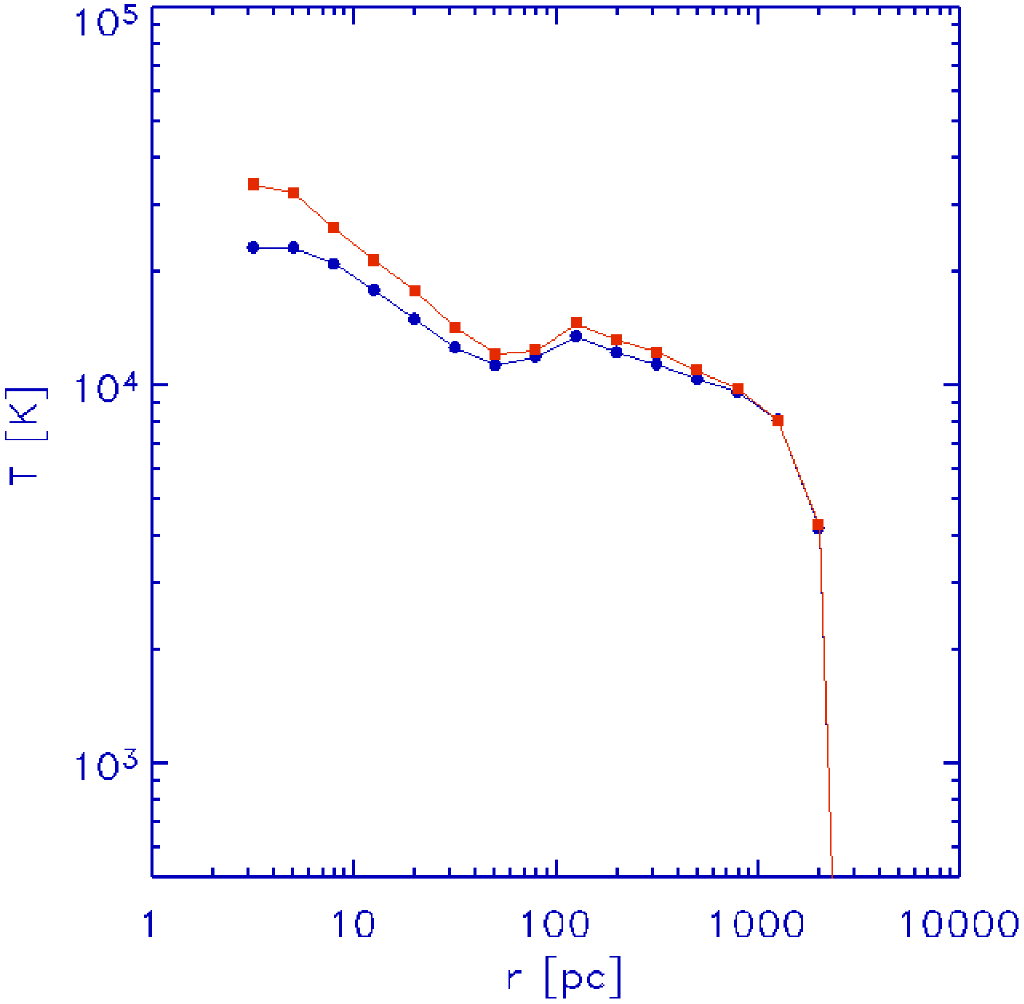
A 120 Msun PopIII star

$Q_{LW} = 1.6\ 10^{50}$ /s
$Q_{H} = 1.4\ 10^{50}$ /s
$Q_{He} = 7.8\ 10^{49}$ /s
$Q_{He+} = 5.0\ 10^{48}$ /s

Ionized region could be similar to planetary nebula rather than to local HII regions



Early HeIII region



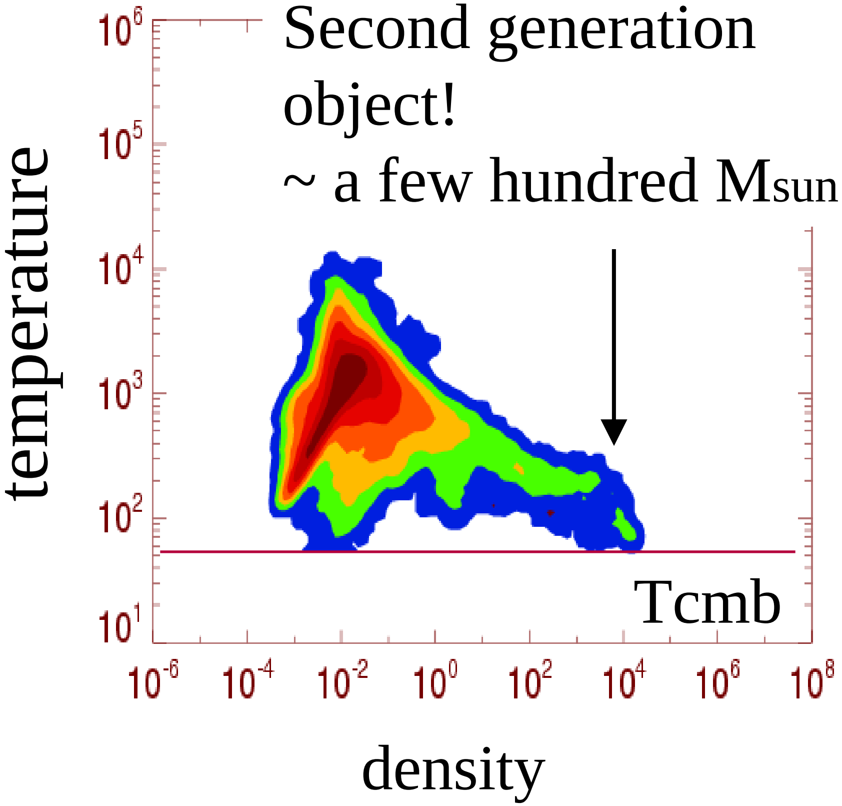
Almost fully ionized within the HeIII region.

H in HeIII region kept ionized by recombination (HeII Ly-a, HeII-Balmer, HeII two-photon) photons (Osterbrook 1989)

HII/HeII regions have (almost) the same extent.

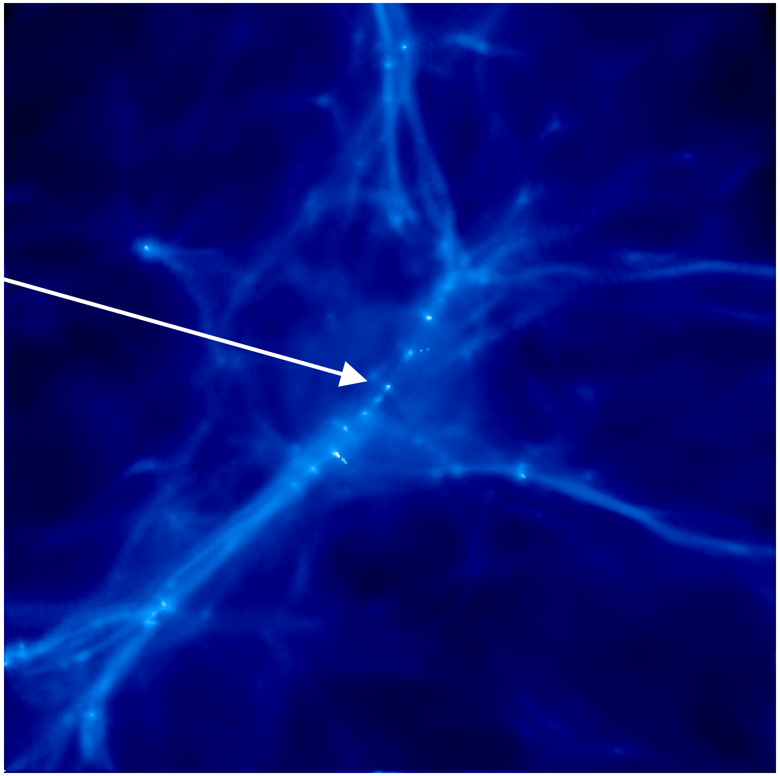
Final state

z=17



Second generation object!
~ a few hundred Msun

Tcmb



During the 100 Myrs…

1. Radiation from the central star drives a wind and evacuates the halo gas.
2. The star dies off. ~a few Myrs
3. The surrounding gas starts cooling and recombining. (Plenty of electrons.) ~10^4 yrs
4. Dark halo grows continuously. ~20-30 Myrs
5. The outgoing gas is eventually (re-)captured by the halo's gravity. ~20-30 Myrs
6. The primordial gas cools more efficiently, and condenses at the center of the halo.
7. A single small (~a few hundred solar masses) gas clump is formed, in which 2nd generation stars are being formed ~10 Myrs

Chemo-radiation-hydrodynamics simulations – so, what’s new ?

1. Photon escape fractions are now consistently calculated. (not just input parameters).

   Gas clumping factor better (directly) estimated, and star-forming gas clouds are explicitly located.

$$Q_{\text{we want}} = \xcancel{f}(N, \dot{N}_{\text{ph}}, C, f_{\text{esc}}, c_*)$$

2) The results have significant implications for early (proto-)galaxy formation, and provide initial conditions.

Halo mass evolution in the CDM model