Formation of the Oldest Stars in the Milky Way Halo

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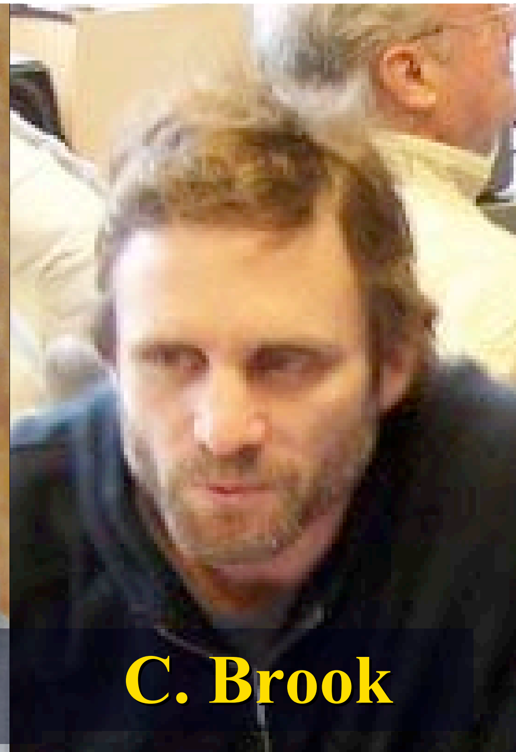
COLLEGE OF **LIBERAL ARTS AND SCIENCES**

I. Spatial Distribution of the First Stars

II. Halo Globular Clusters

III. Simulation Early Star Formation


D. Kawata


C. Brook

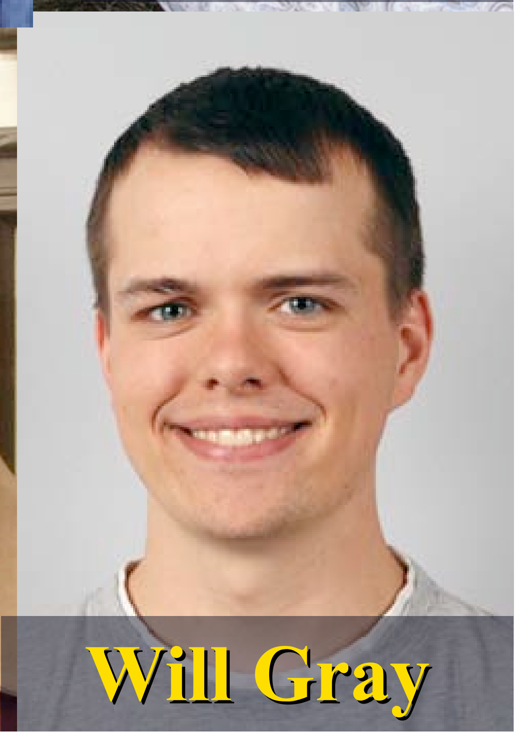

A. Ferrara


B. Gibson


R. Schneider

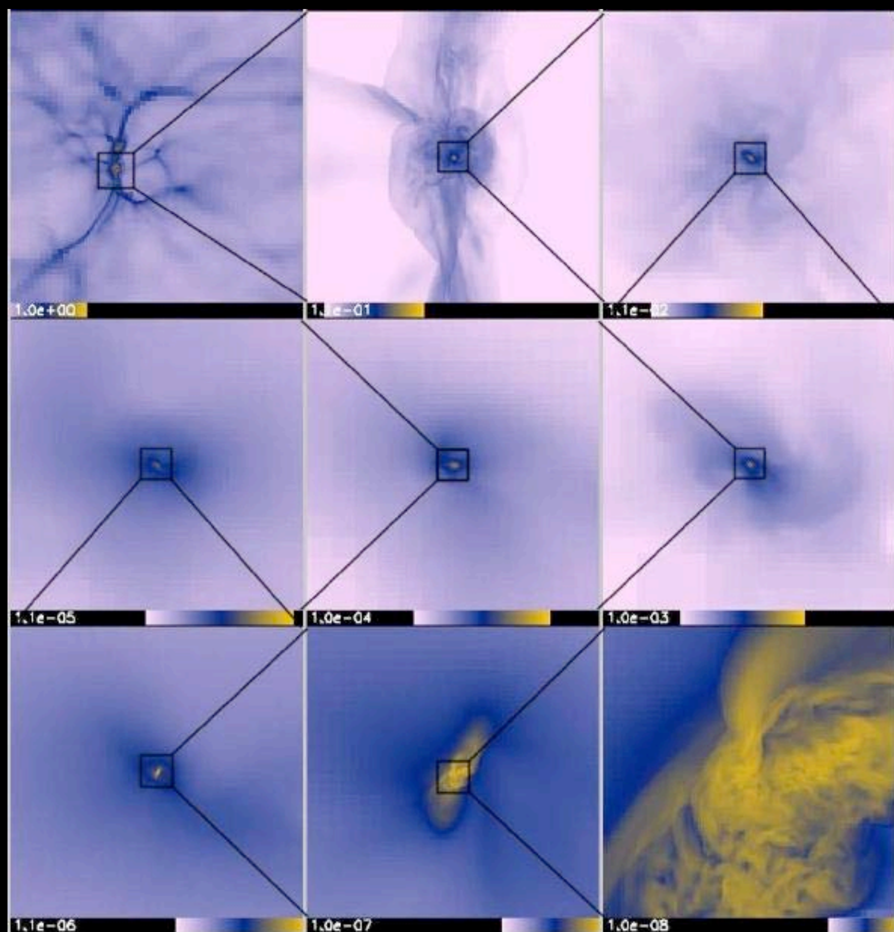

J. Weiseit


F. Harlow


Will Gray

I. Where are the First Stars?

The 1st Objects: Very Massive?



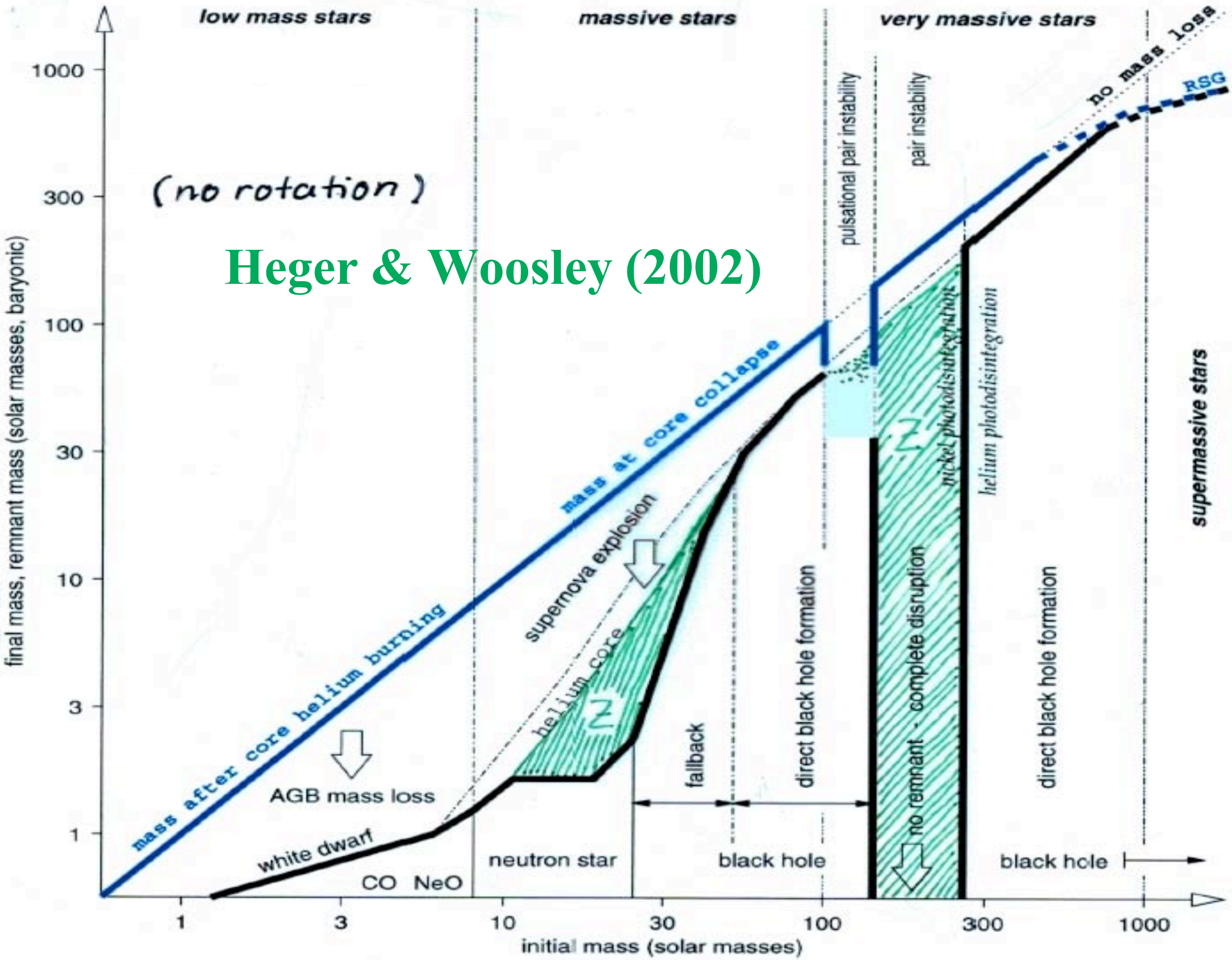
H_2 cooling takes you to a typical density of 10^4 cm^{-3} & T of 100 K

…. LTE

$M_{jeans} \sim 1000\ M_{sun}$

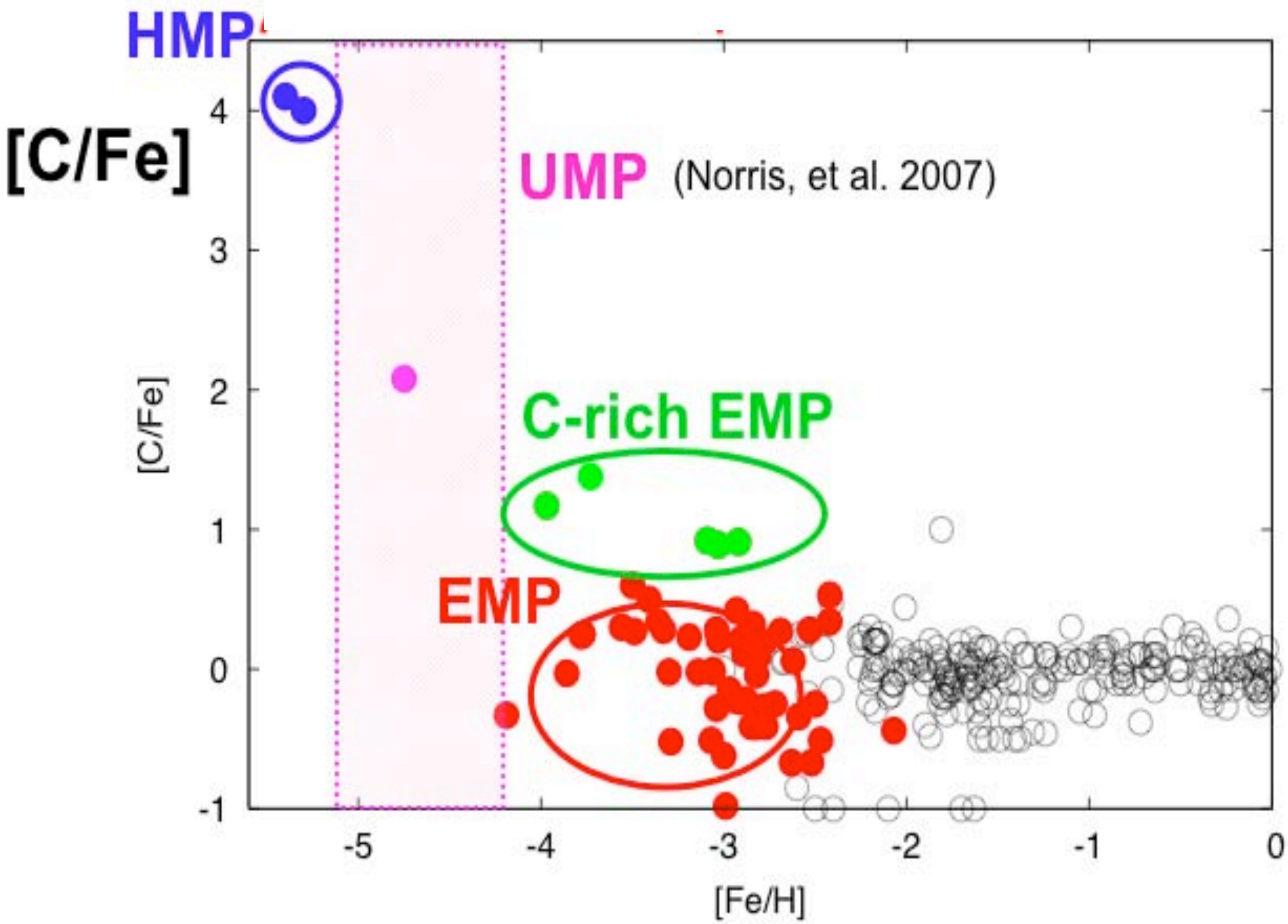
Abel, Byran, Norman (2001)

Heger & Woosley (2002)



Metal-Poor Stars

Beers, Christrieb (2005)



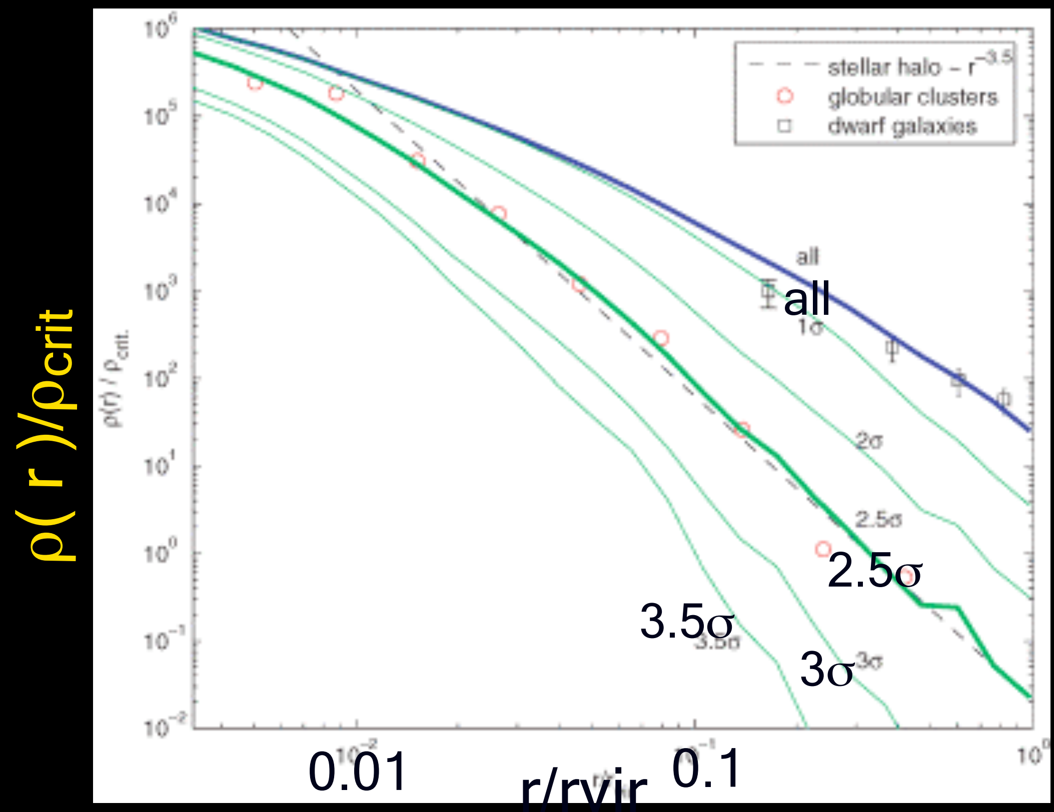
Theoretical prediction of the distribution of first generation stars

Diemand, Madau & Moore (2005); Moore et al. (2006)

(see also White & Springel 2005)

Particles in high-σ collapsed halos are centrally concentrated.

high-σ (>3) building blocks = the birthplace of the oldest stars

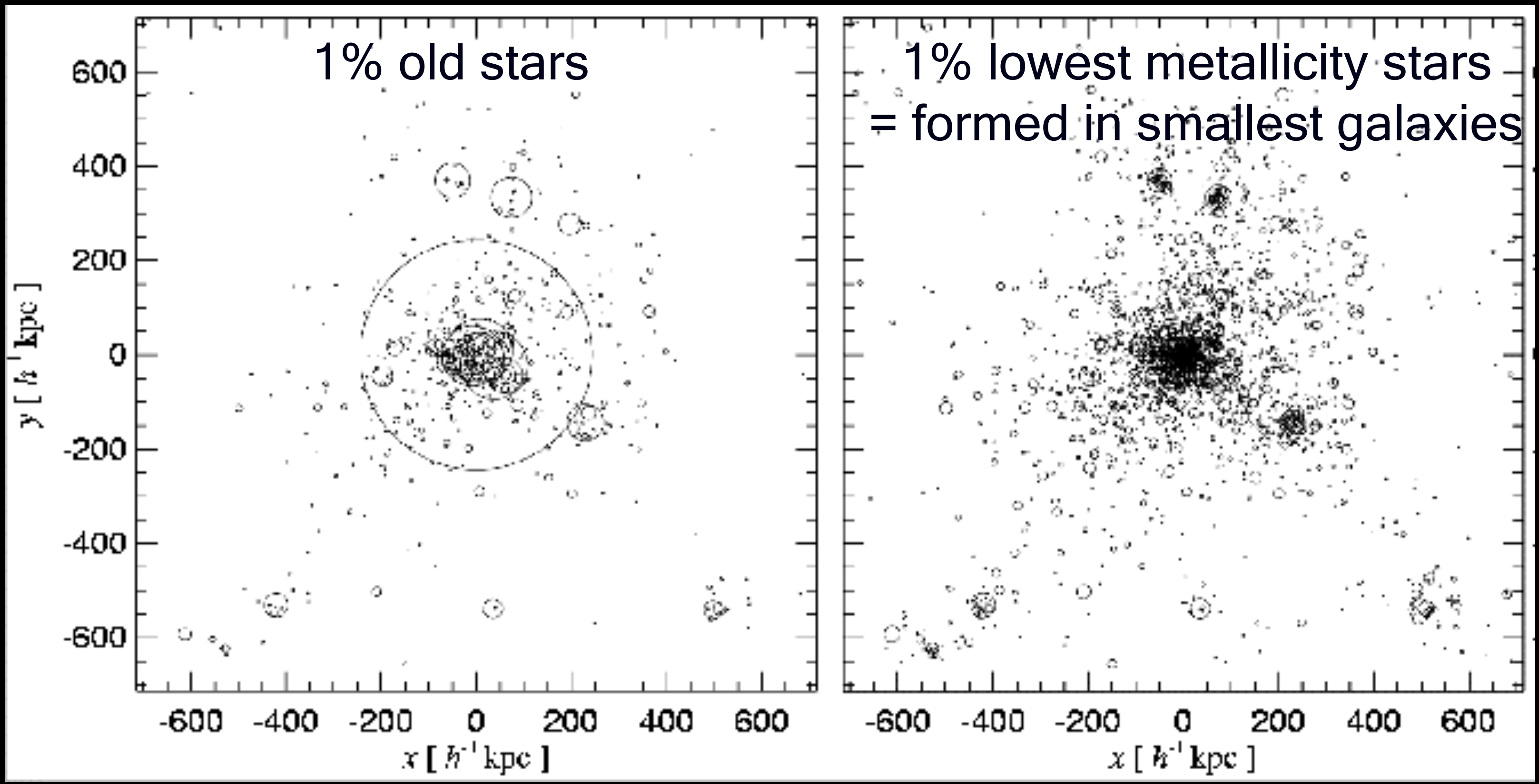


The bulge is the best place to look for the old stars!

The oldest stars = the first generation (metal-free) stars?

<u>White & Springel (2005):</u>

N-body + Semi-analytic model



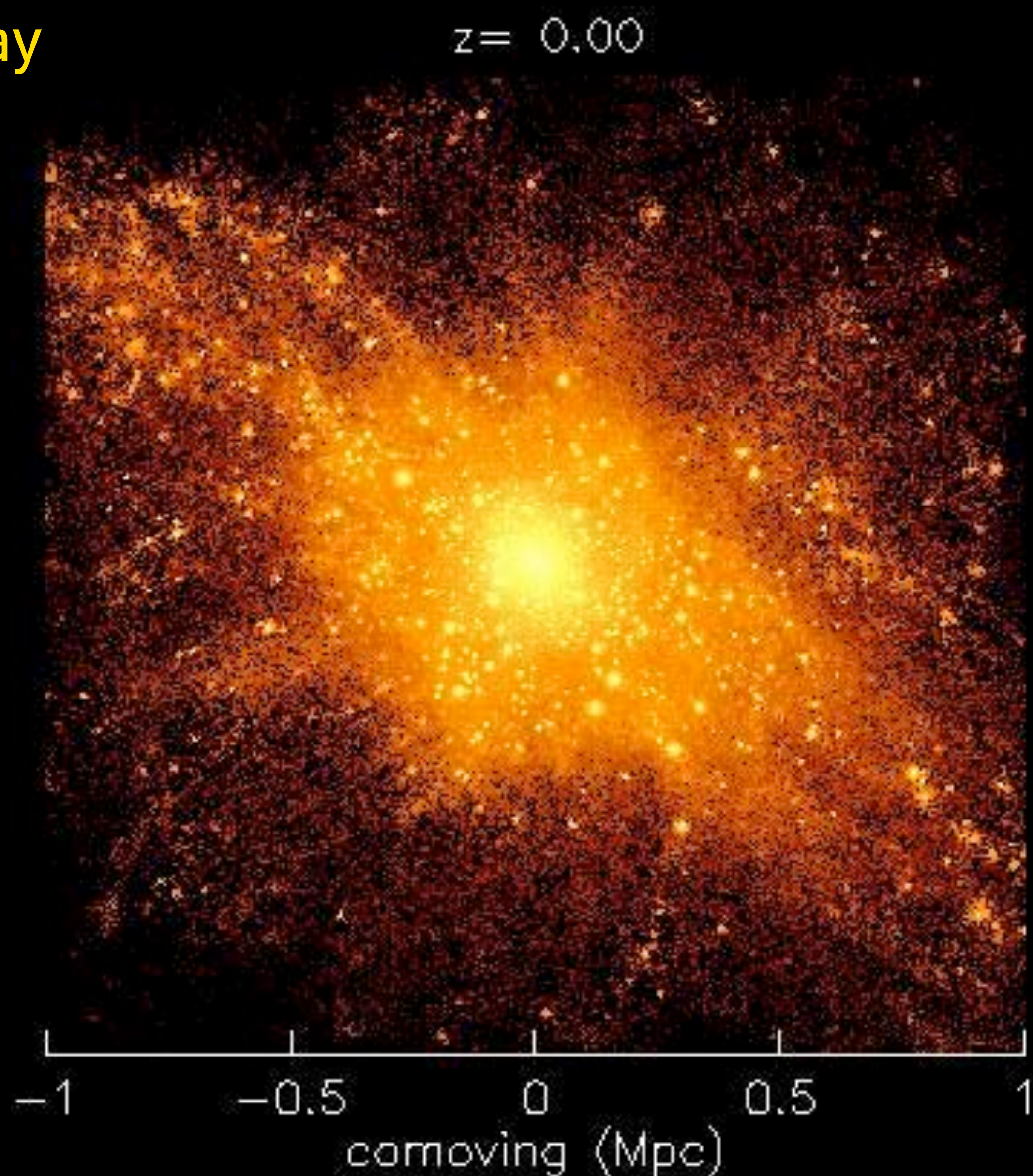
60% within 10 kpc

16% within 10 kpc

The oldest stars are preferentially at small radii, while…
the low metallicity stars lie preferentially at larger radii?

High-resolution Milky-Way N-body simulation

- LCDM multi-resolution simulation of $8 \times 10^{11}\ M_\odot$ galaxy.
- DM simulation with $7 \times 10^5\ M_\odot$ particles.
- star formation threshold $T_{vir}=10^4$ K limit.



ES, D. Kawata, C. Brook, R. Schneider, A. Ferrara, B. K. Gibson (2006)

Semi-analytic model + outflow model (Fiducial Model)

Star formation in a collapsed halo.

10 % of baryon mass ⇒ stars ⇒ inner 10 % of particles

➡ Outflow bubble ⇒ enrich the IGM

metal-free stars : free parameters. 3 models

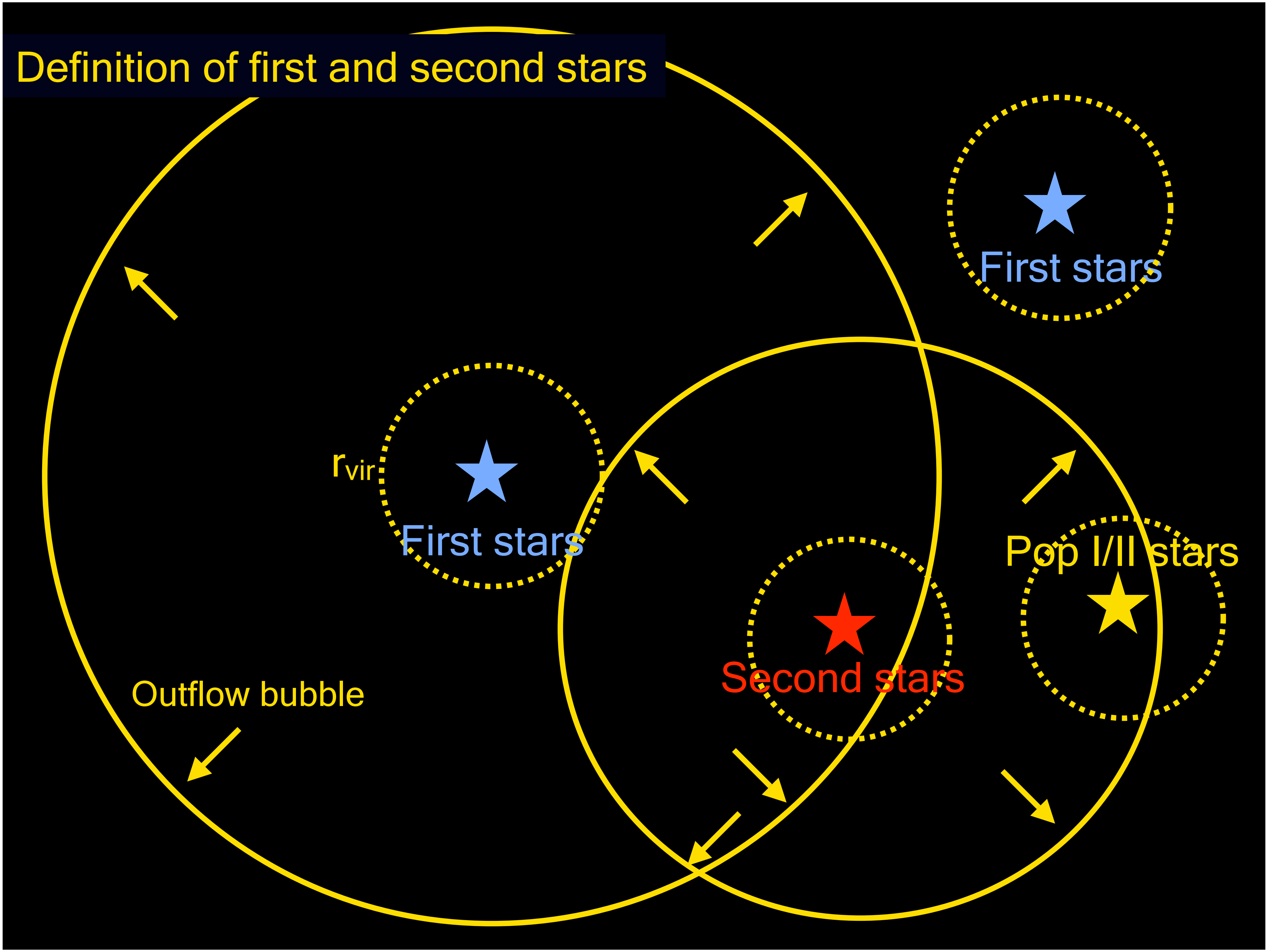
strong ($Eg_{III}=10^{-2}$) outflow,

moderate ($Eg_{III}=10^{-3}$) outflow,

weak ($Eg_{III}=10^{-4}$) outflow

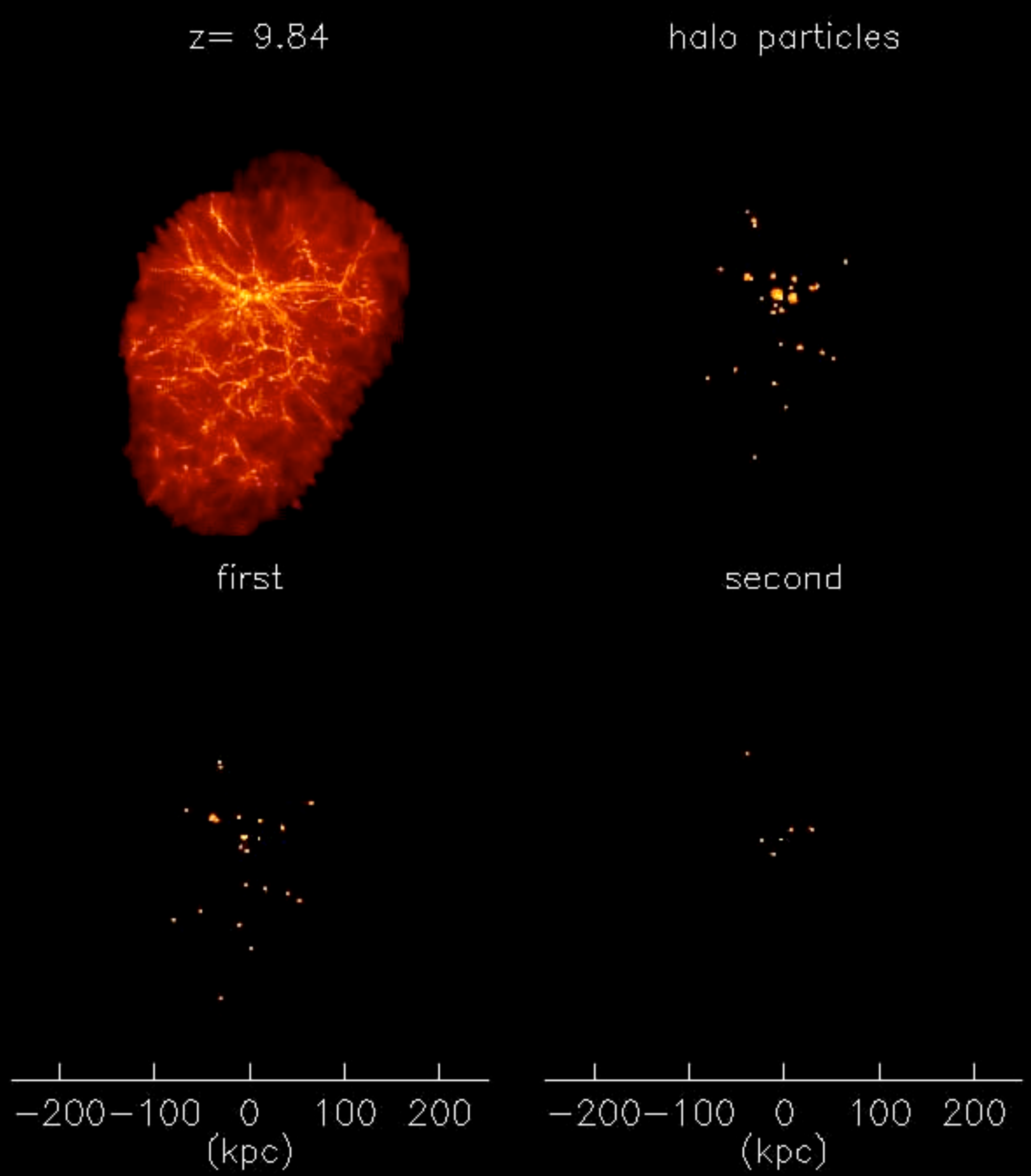
the other parameters

= Scannapieco, Schneider, Ferrara (2003)



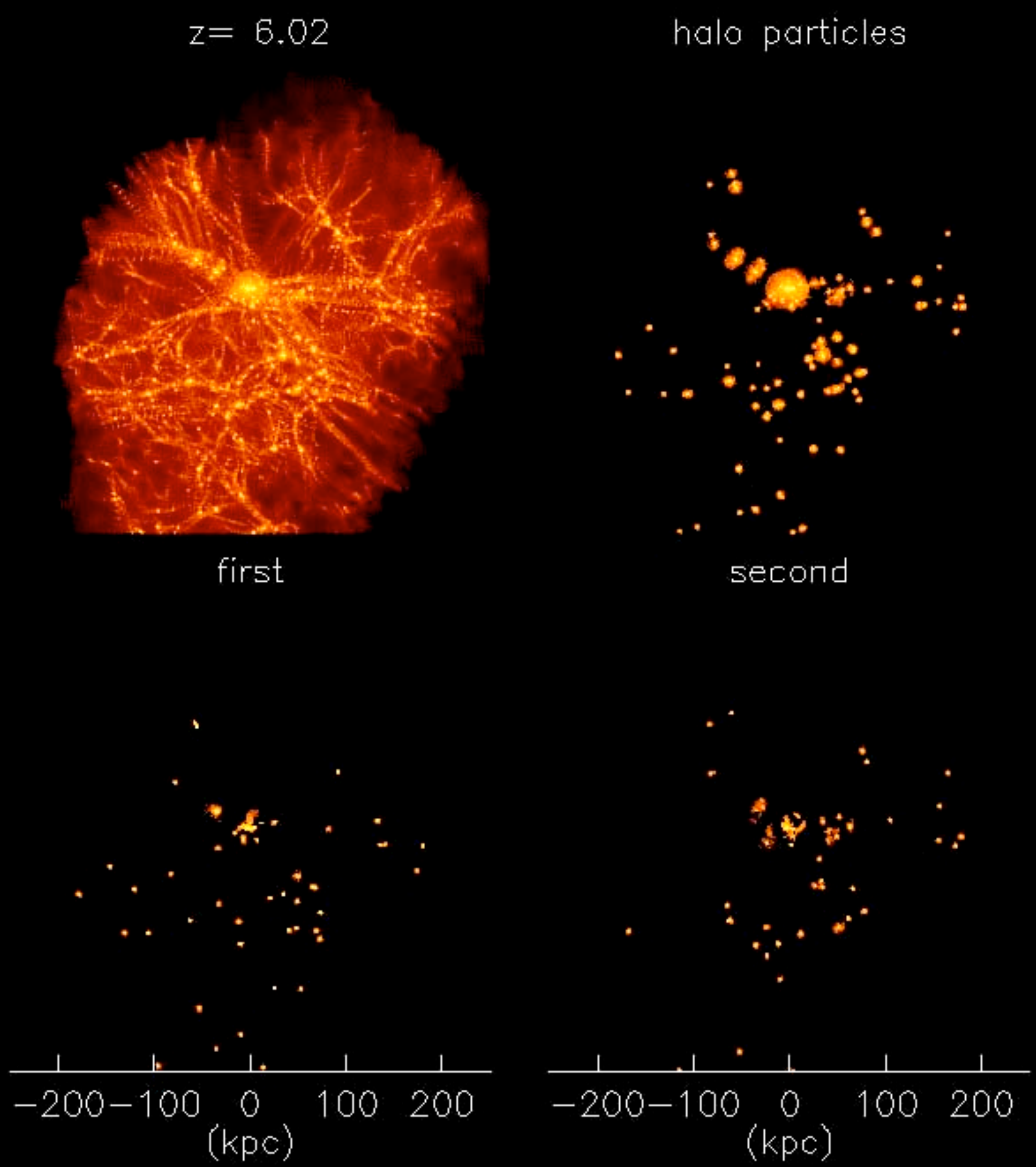
Definition of first and second stars
First stars
r_vir
First stars
Pop I/II stars
Second stars
Outflow bubble

Milky Way Implications



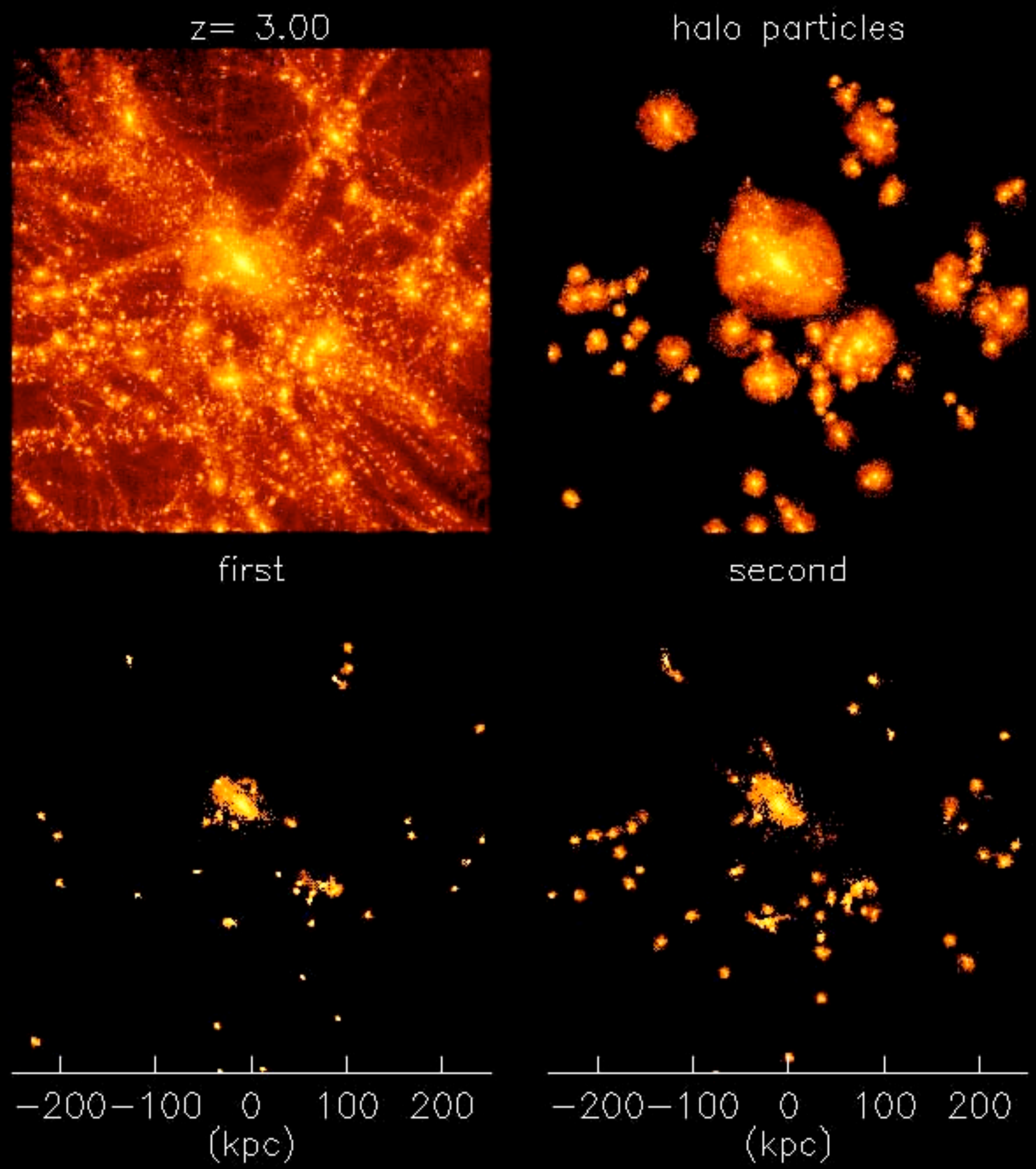
ES etal (2006)

Milky Way Implications



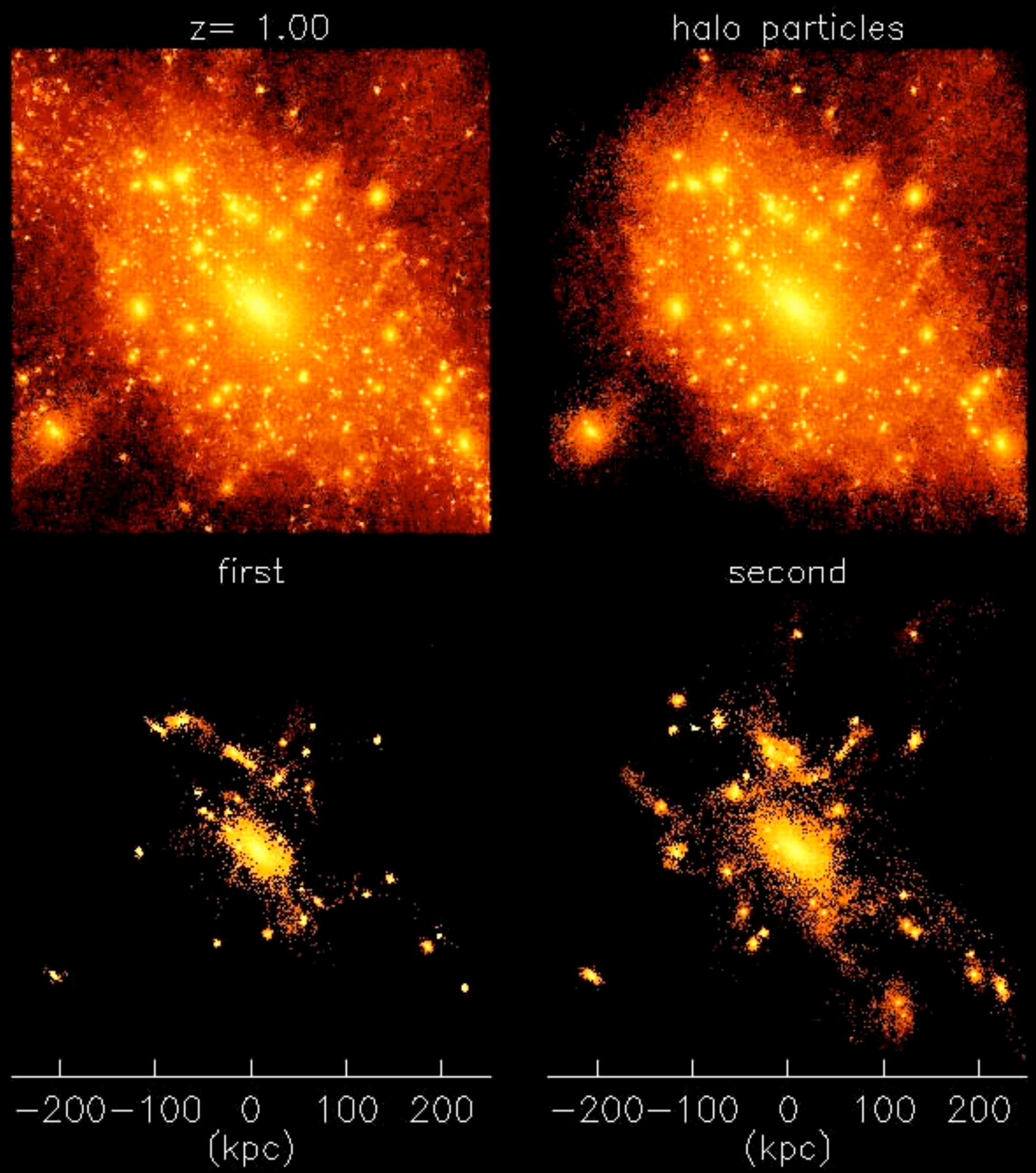
ES etal (2006)

Milky Way Implications



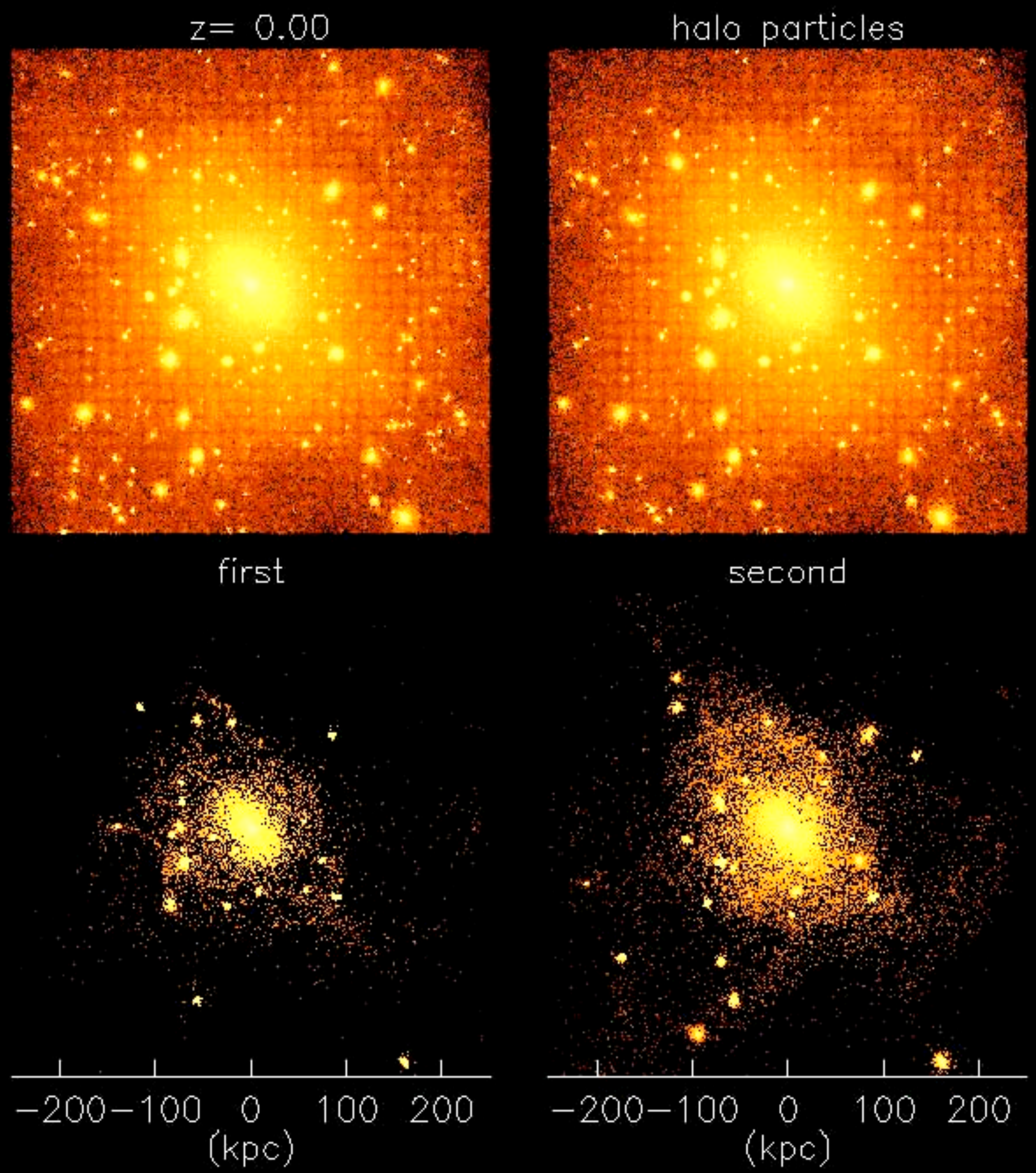
ES etal (2006)

Milky Way Implications



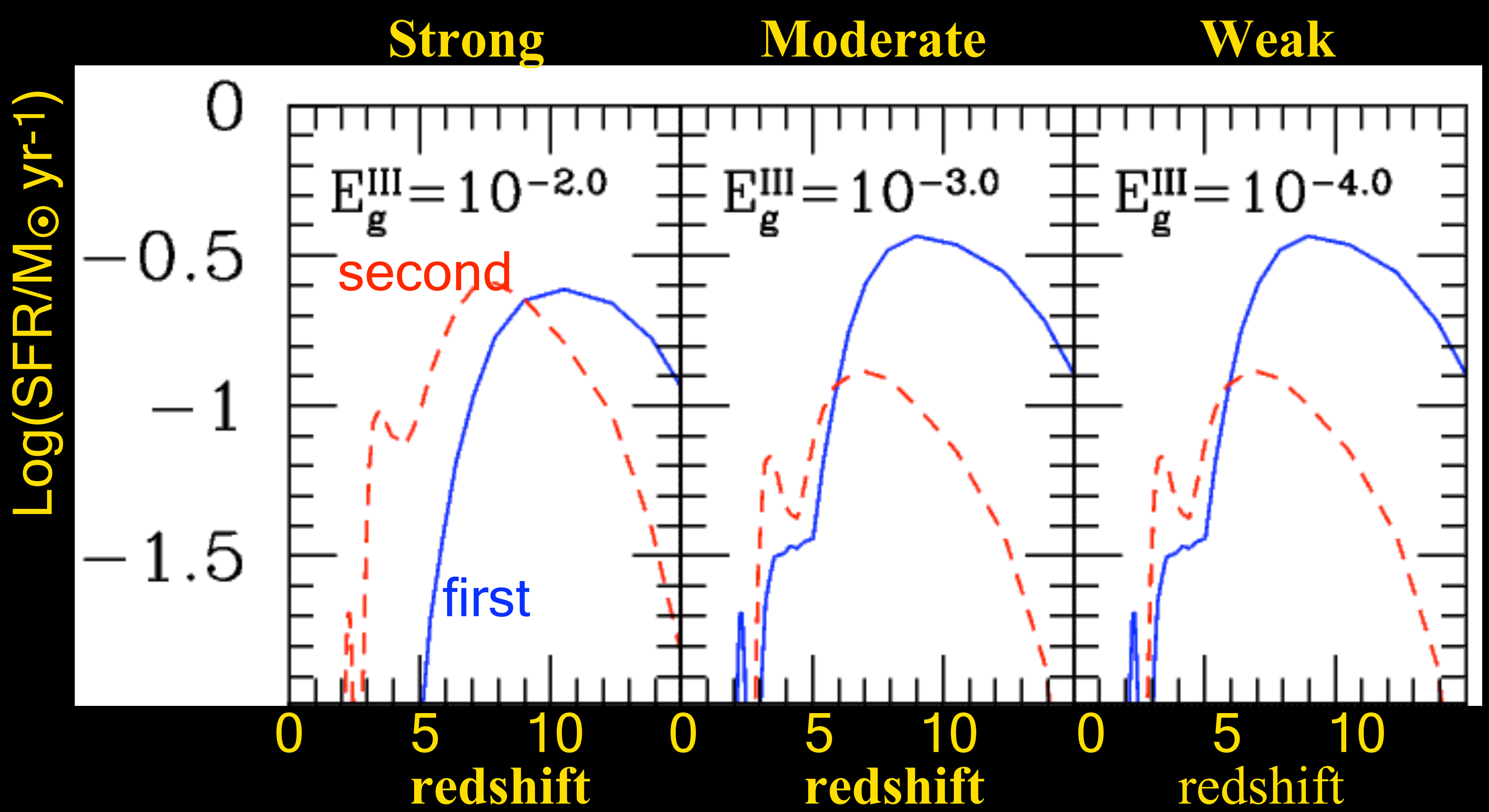
ES etal (2006)

Milky Way Implications



ES etal (2006)

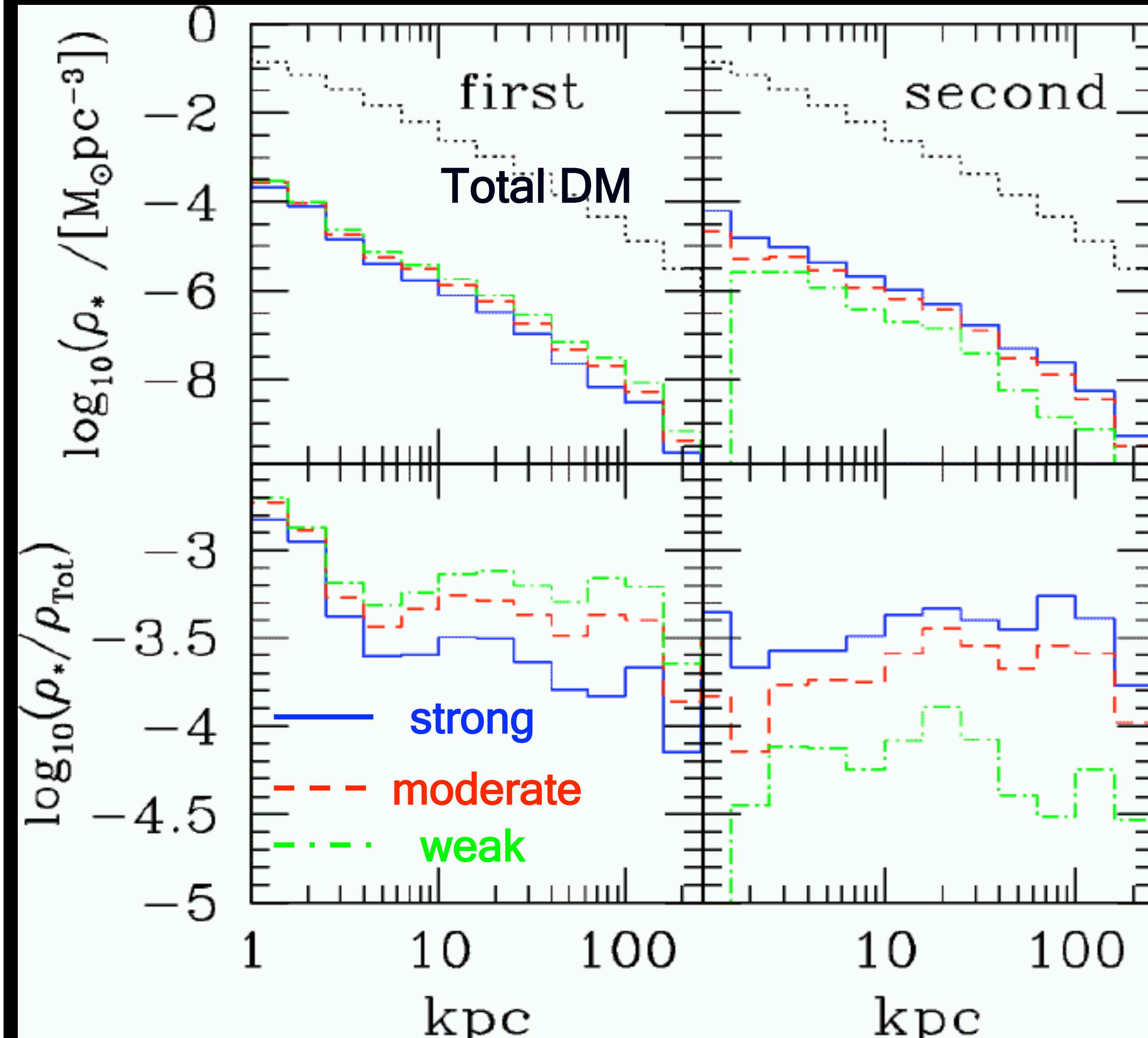
Star Formation History



First stars: peak around z=10 and continue till z~5

Weaker outflow (inefficient IGM enrichment) allows first stars to form at lower redshift

The radial distribution of first and second stars at z=0



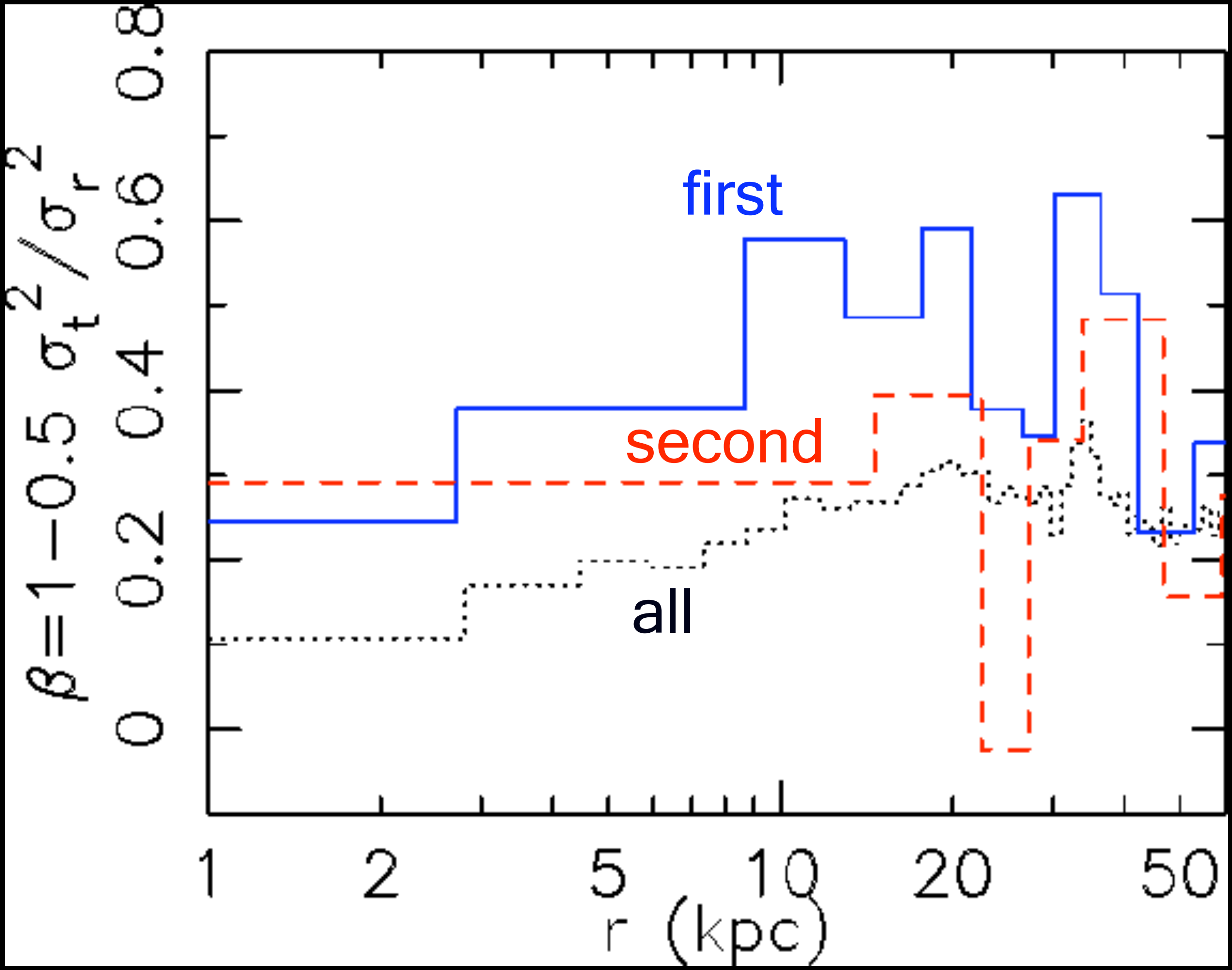
Density profile centrally concentrated, but the profile is similar to total DM

Fraction: first or second stars/total only small difference between inner and outer region

Weaker outflow flatter profile

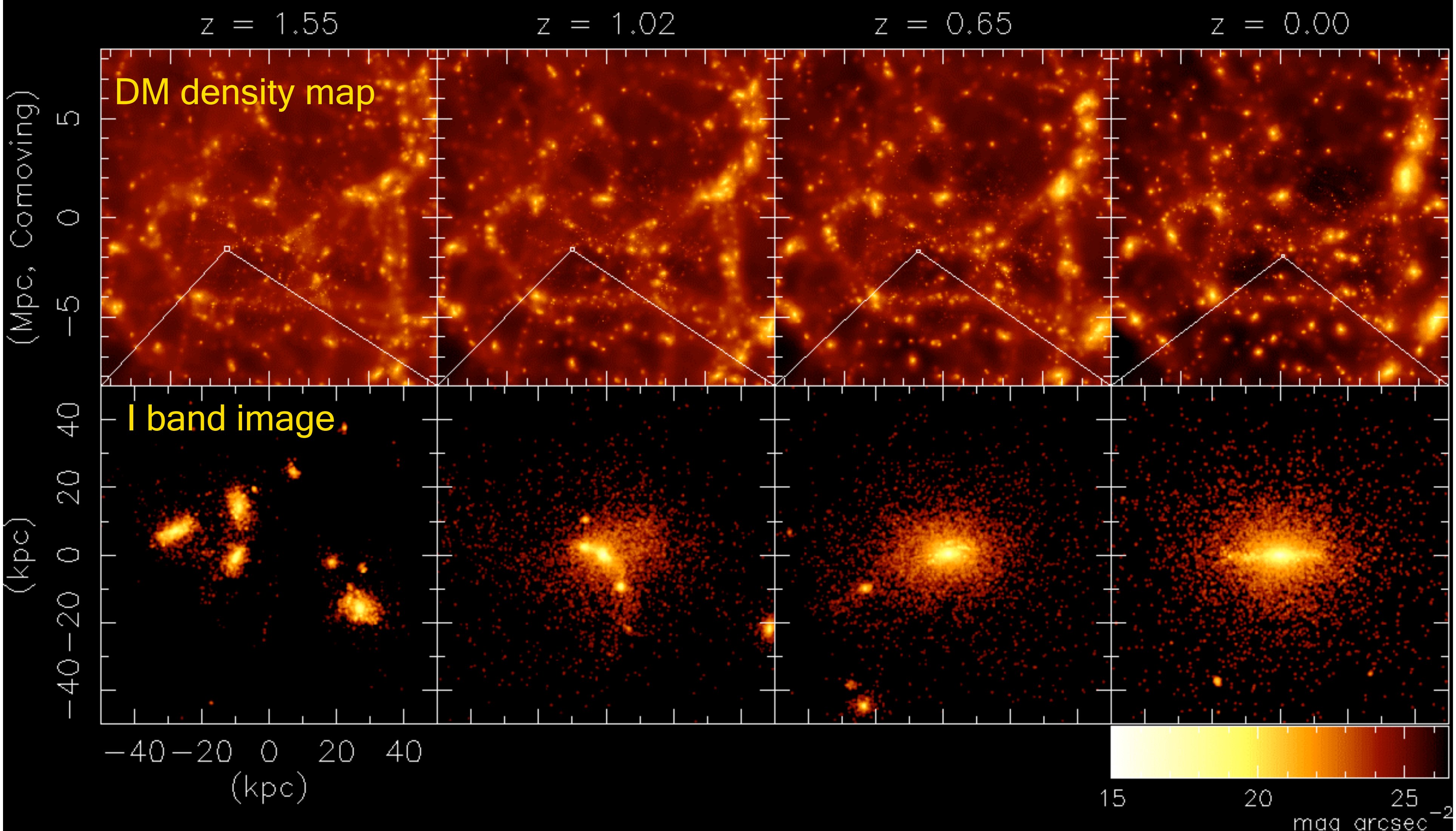
First and second stars end up everywhere!

Kinematics of first and second stars (moderate outflow)
anisotropy ($\beta=1-0.5\sigma_t^2/\sigma_r^2$) vs. radius



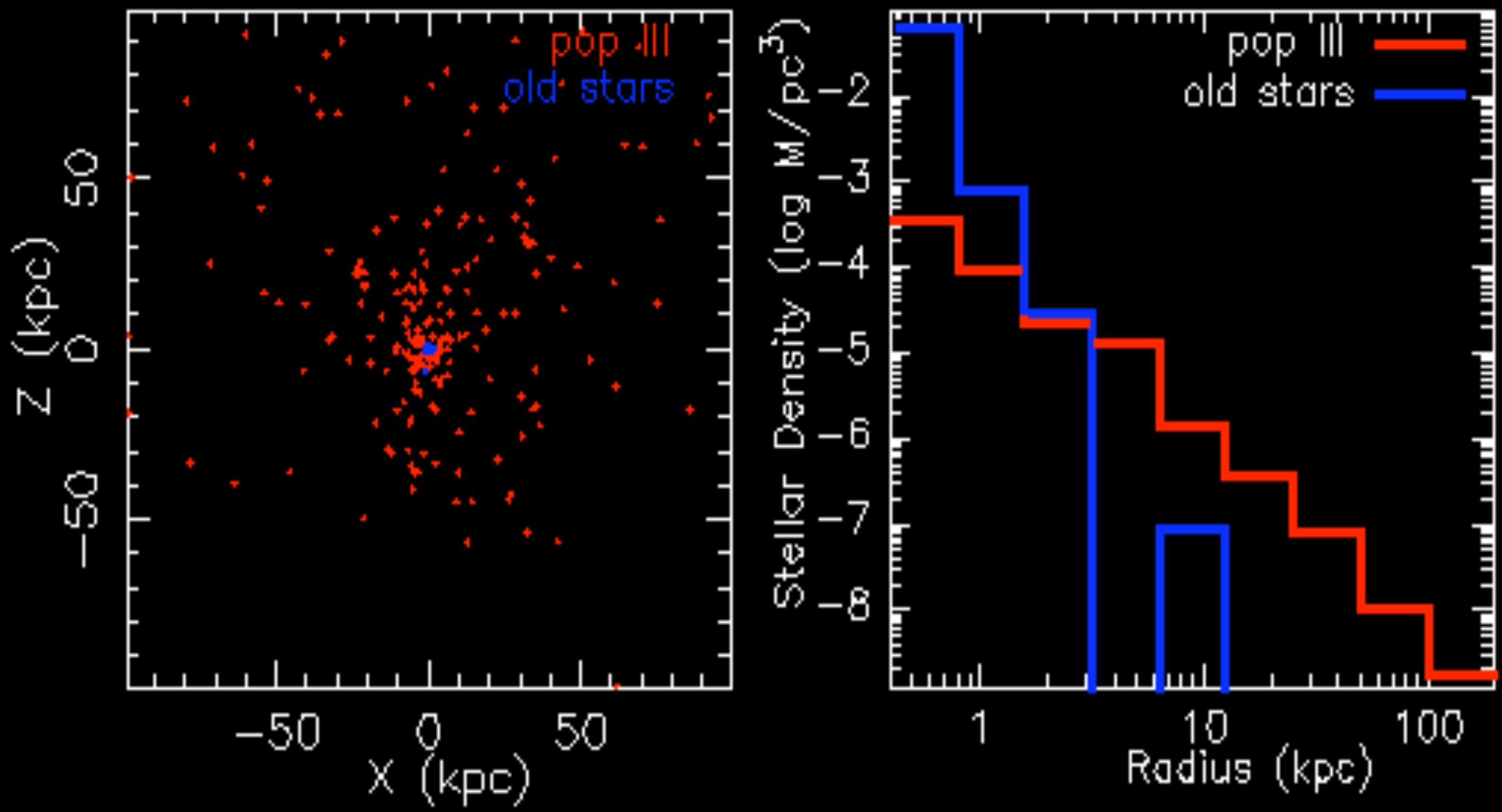
First stars have higher β, the radial velocity dispersion dominant

4. Chemodynamics cosmological simulations of disk galaxies
Brook et al. ApJ submitted



Simply identify the place of metal free and old stars

Full SPH calculations DM: $8 \times 10^6\ M_\odot$



Limits on Mass function:

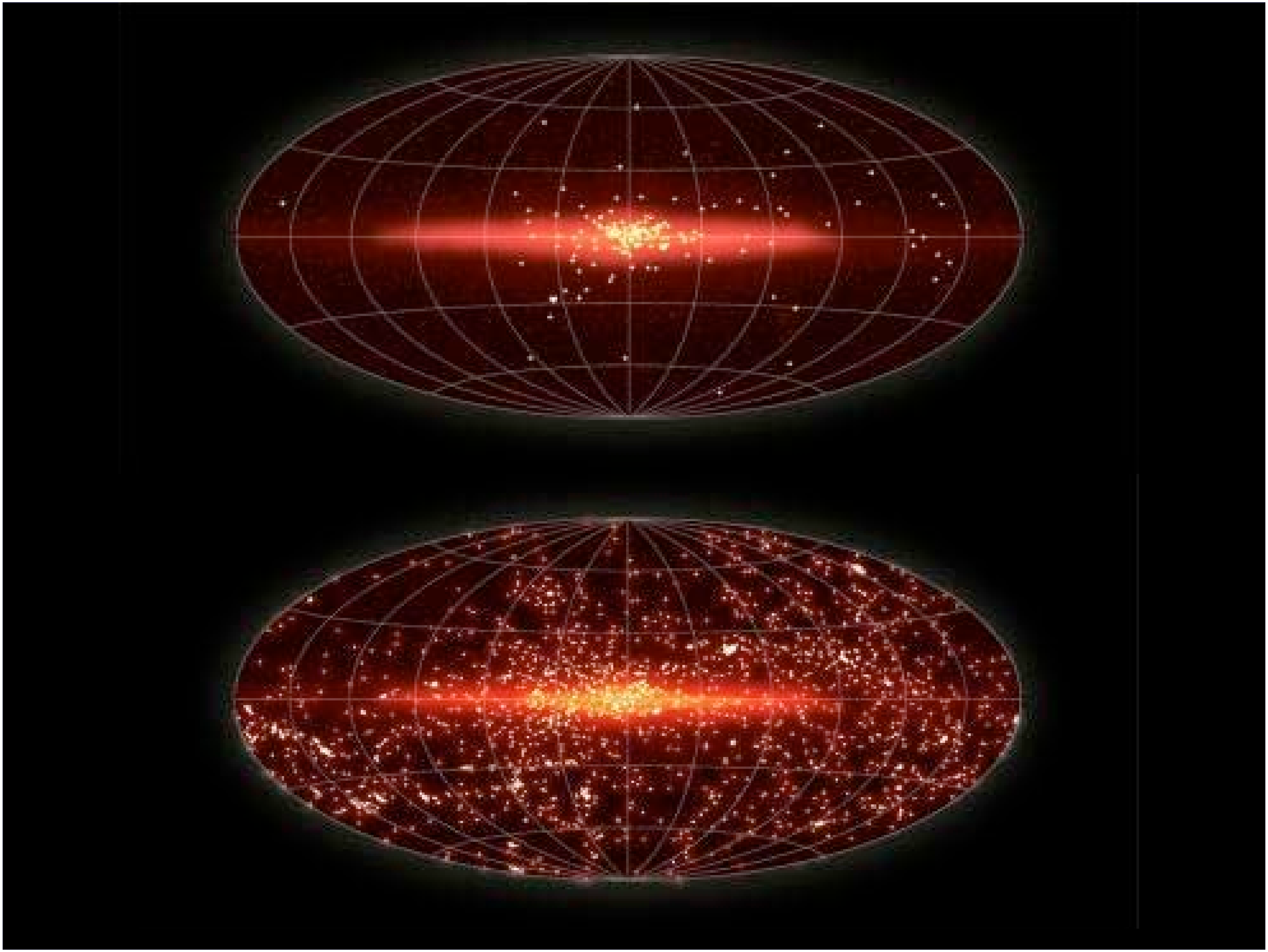
No Metal free observed stars: M_{min} 0.8 M

Limits for nucleosynthesis:

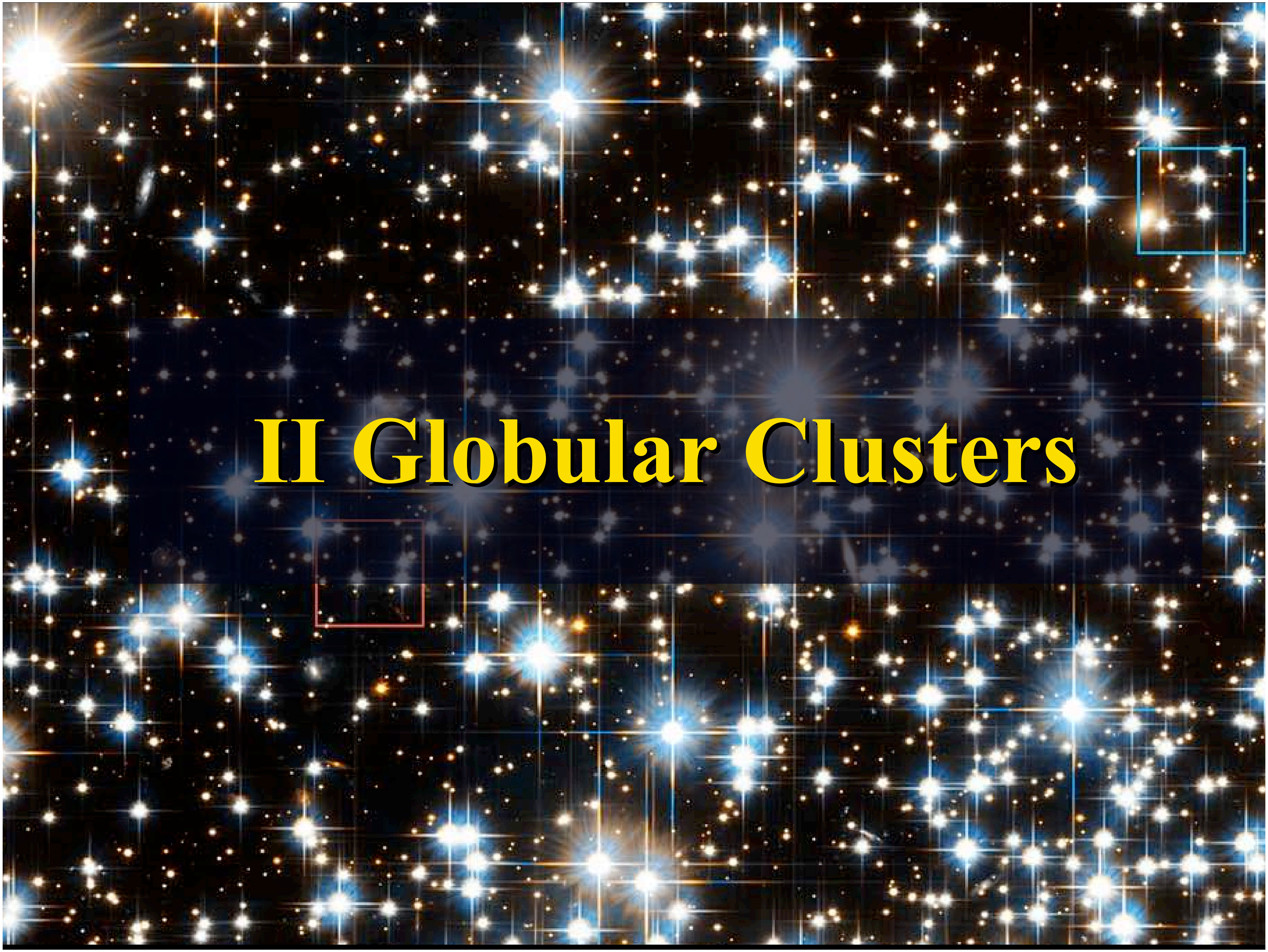
Odd even effect not observed

<1/2 Fe from Pop III is from PPSN

Metallicity distribution function of halo stars, etc… have important implications for PopIII star formation.

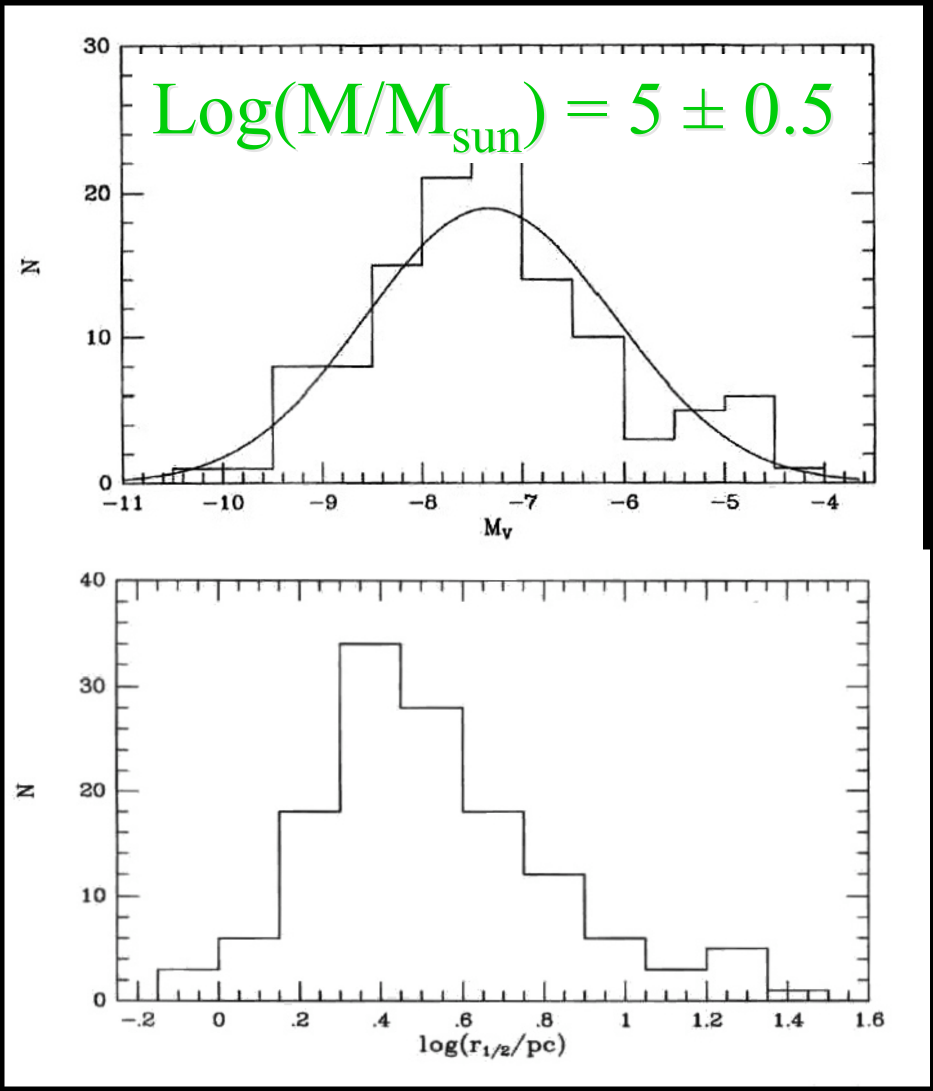


II Globular Clusters



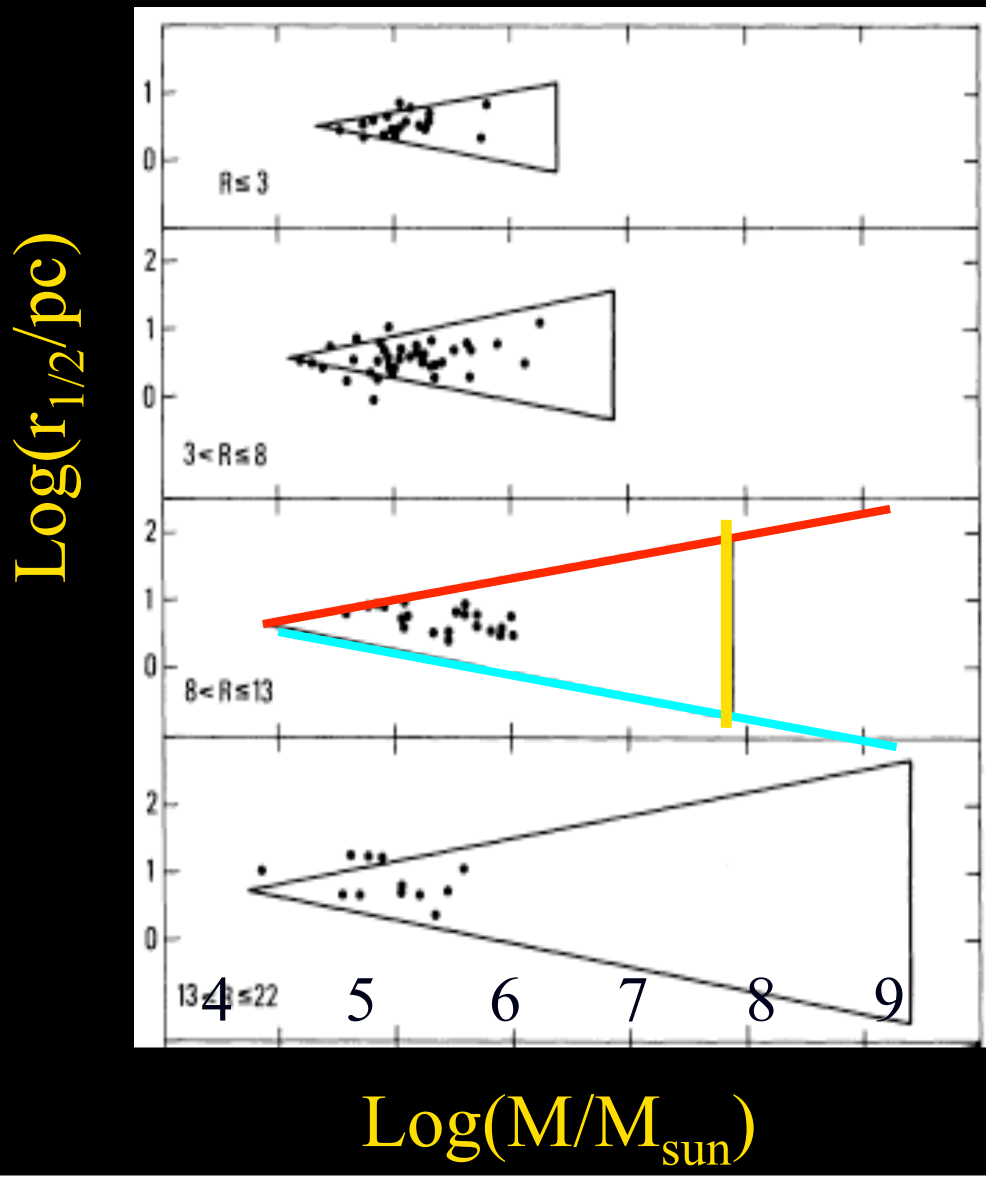
Globular Clusters

M92, Hillary Mathis REU(NOAO/AURA/NSF)



Ashman & Zepf (1998)

Issue # 1: Globular Cluster Sizes



Disk shocking

$t \sim r_{1/2}^{-3}\ M\ R$

Evaporation

$t \sim r_{1/2}^{3/2}\ M^{1/2}$

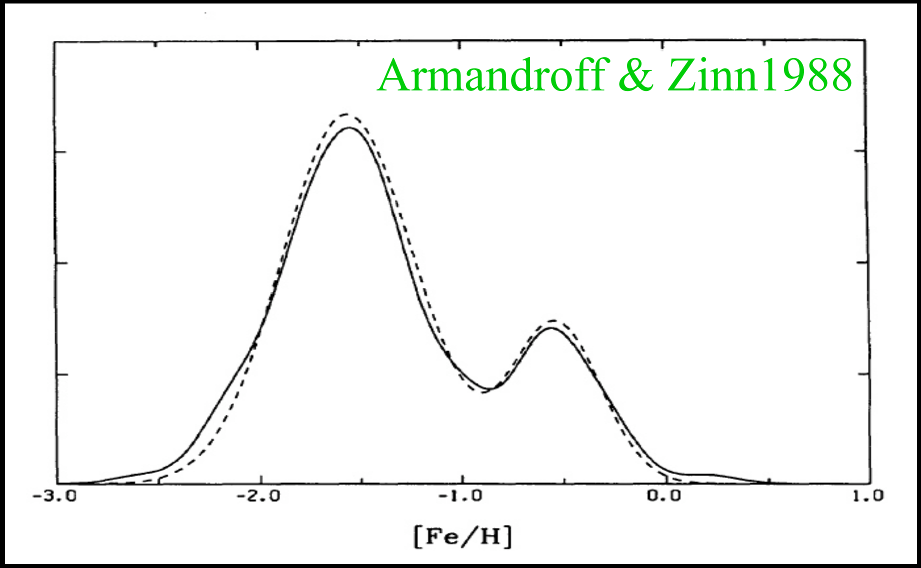
Dynamical Friction

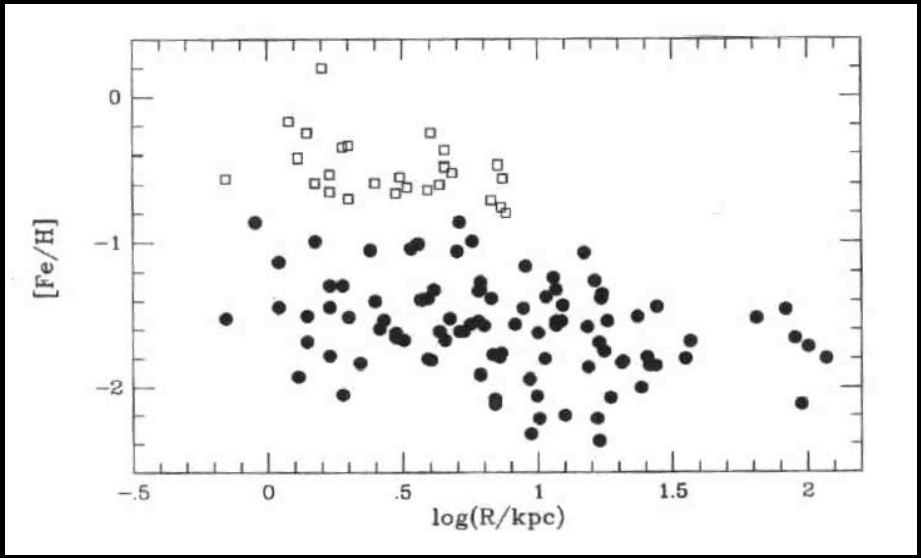
$t \sim M^{-1}\ R^{2}$

Maximum mass is an intrinsic property of the ***initial*** GC population

Castellani & Caputo 1984

#2: Globular Cluster Metallicities





Double-peaked

[Fe/H] ~ -0.5 ± .25

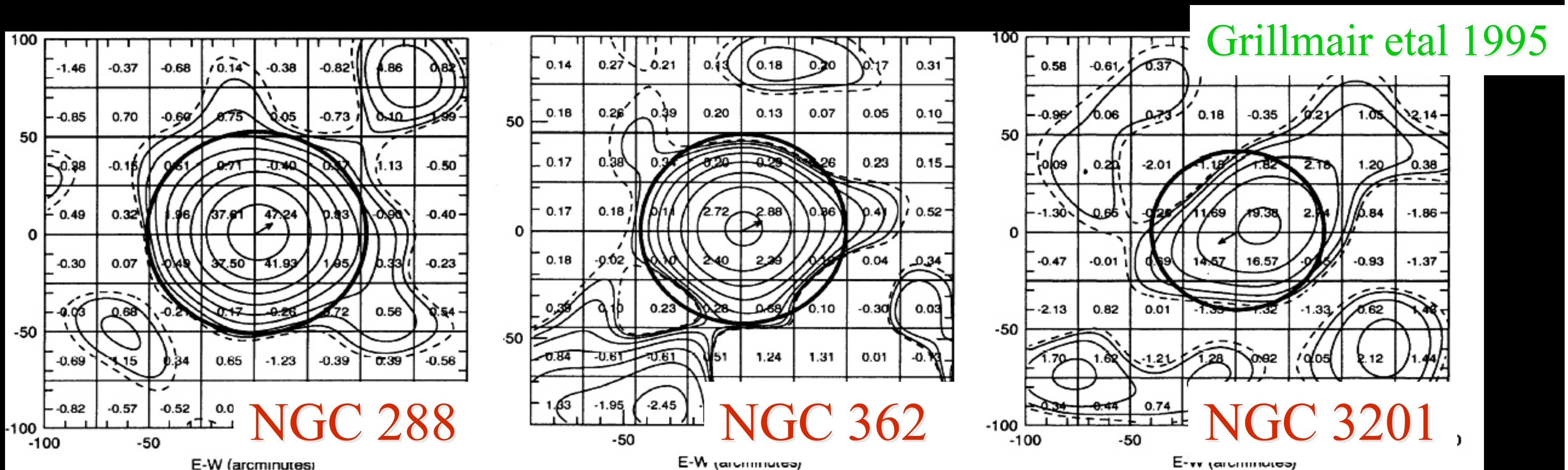
[Fe/H] ~ -1.6 ± .35

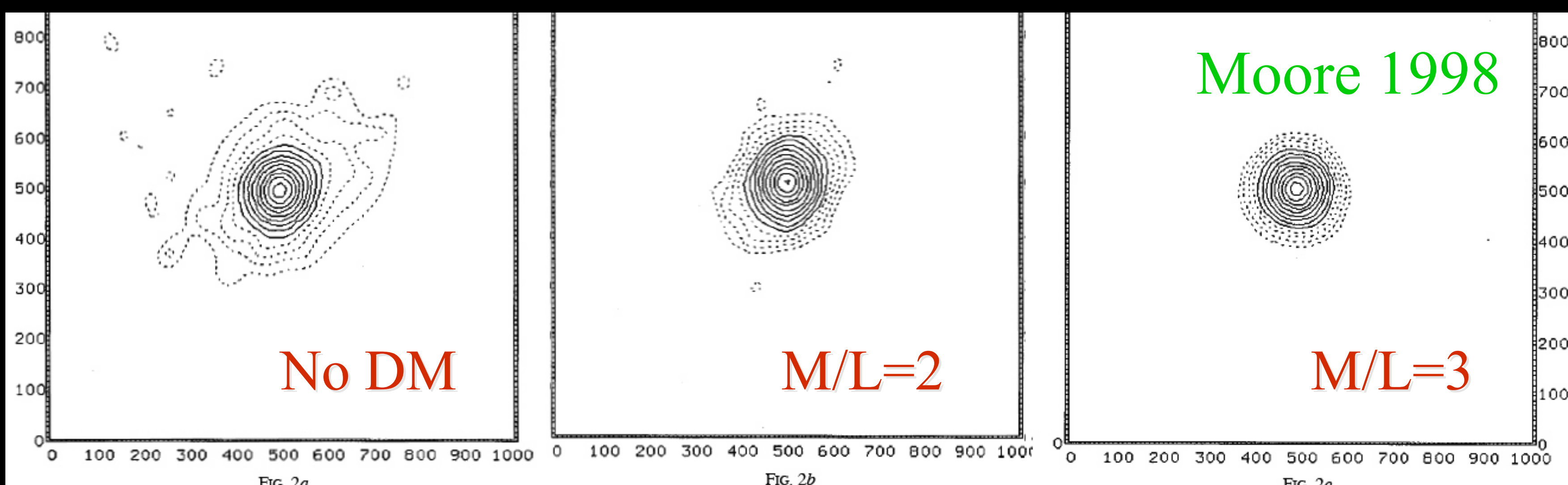
Dynamically Different "Halo" and "Disk," Also seen in other galaxies (eg Forbes Brodie Huchra 1997)

Narrow range < ΔZ± 0.1 In each GC (eg Sunzeff 1993)

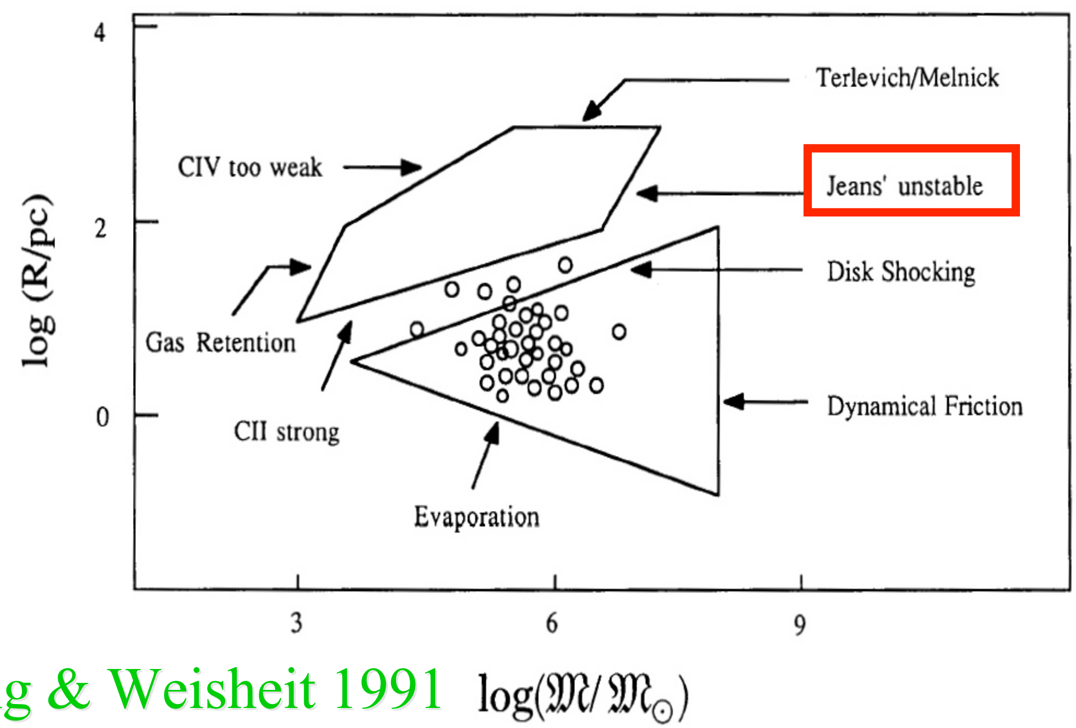
One generation

#3: (No) Dark Matter In GCs





Explanation #1: Minihalos



Peng & Weisheit 1991

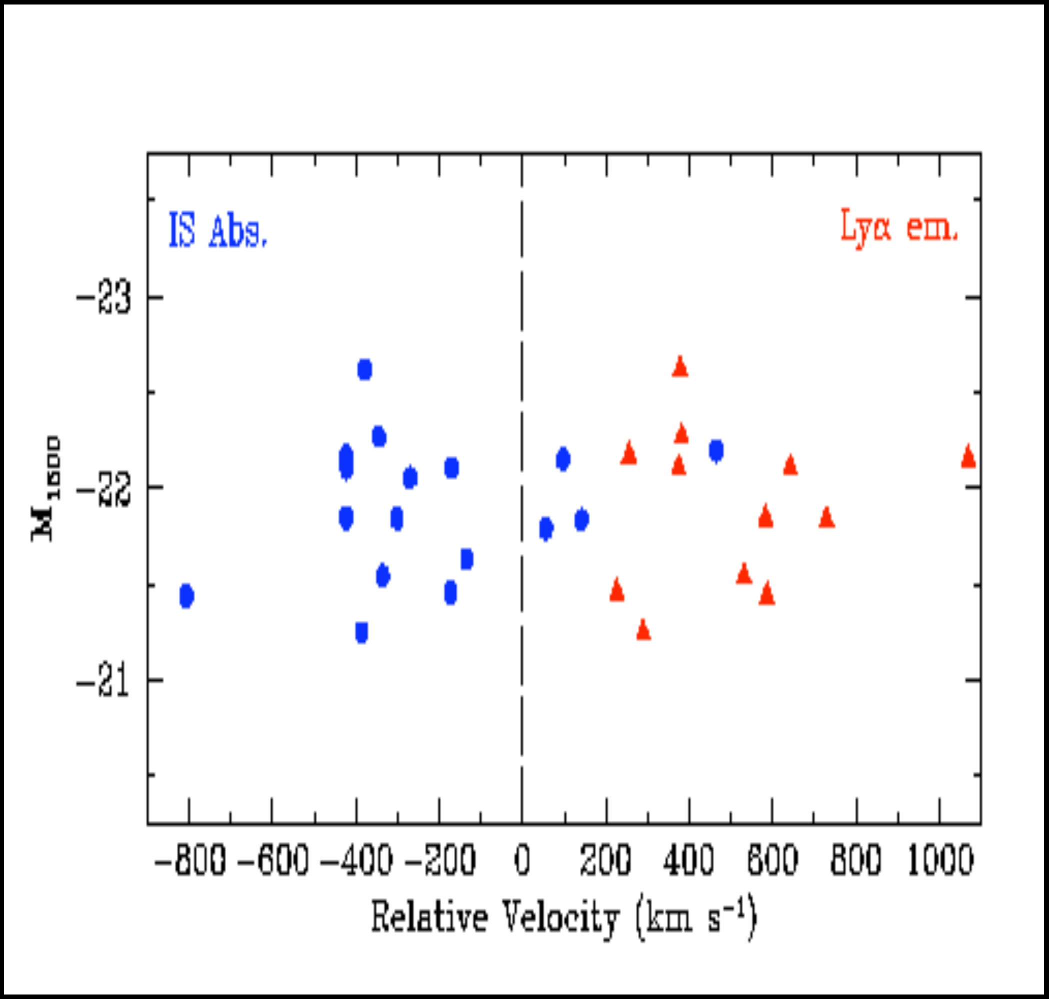
$T_{vir} \leq 10^4$ K at
z ~ 10

Below this temperature you need dust or H_2 to cool.

Primordial clouds, after the very first stars form may not be able to form stars on their own: Minihalos (total masses <~ 5×10^7 M_{sun})

#2: Galaxy Outflows

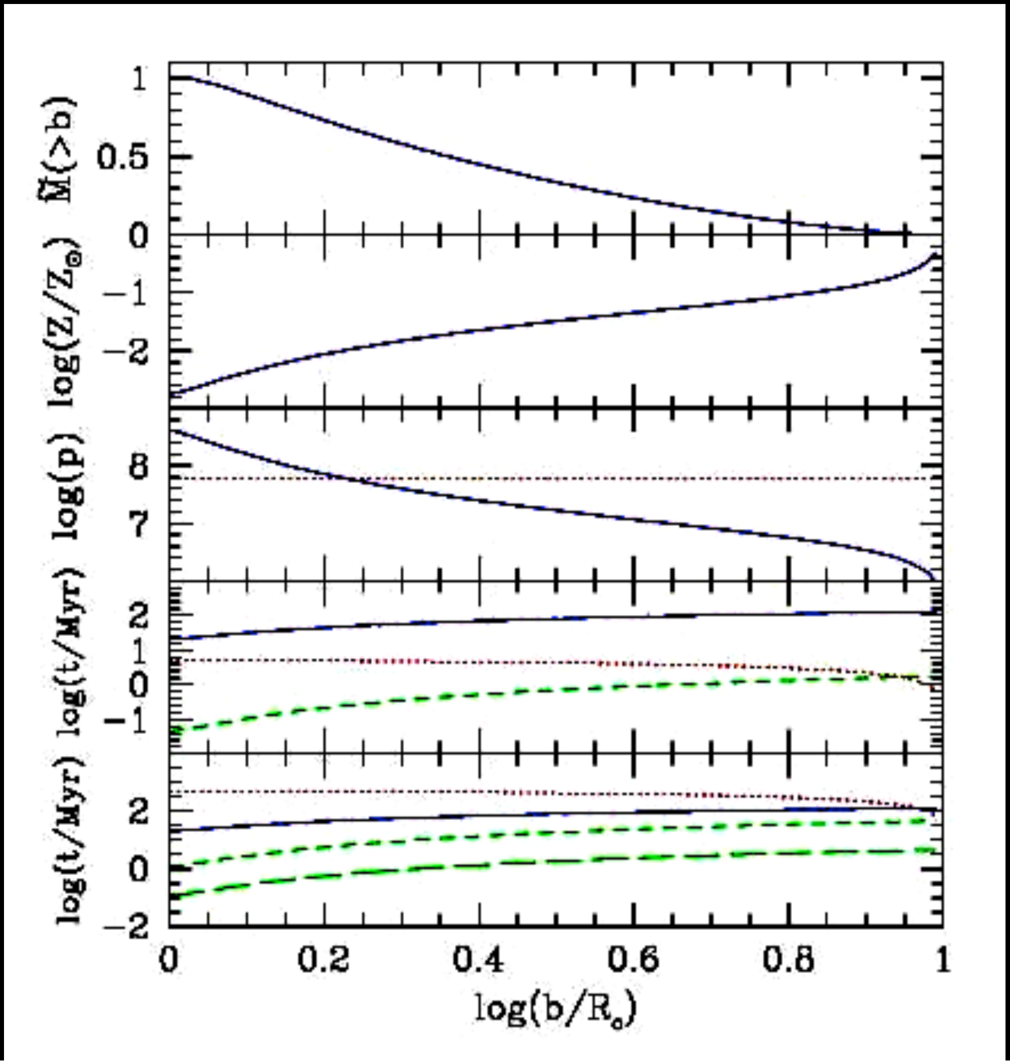
- In a sample of 19 Ly-break z~3 starbursting galaxies, winds were found in all objects.
- Velocities ~200 km/s
- Lyα-nebular emmi.+ metal absorption-nebular emission.
- SFR ~ 20 Msolar /yr



M. Pettini et al 2001

Fiducial Interaction

$E = 10^{56}$ ergs ; $M = 10^{6.5}\ M_{sun}$; $Z \sim 10^{-1.5}\ Z_{sun}$



Gas is stripped from the potential

Free-fall time

Sound Xing time

Cooling time

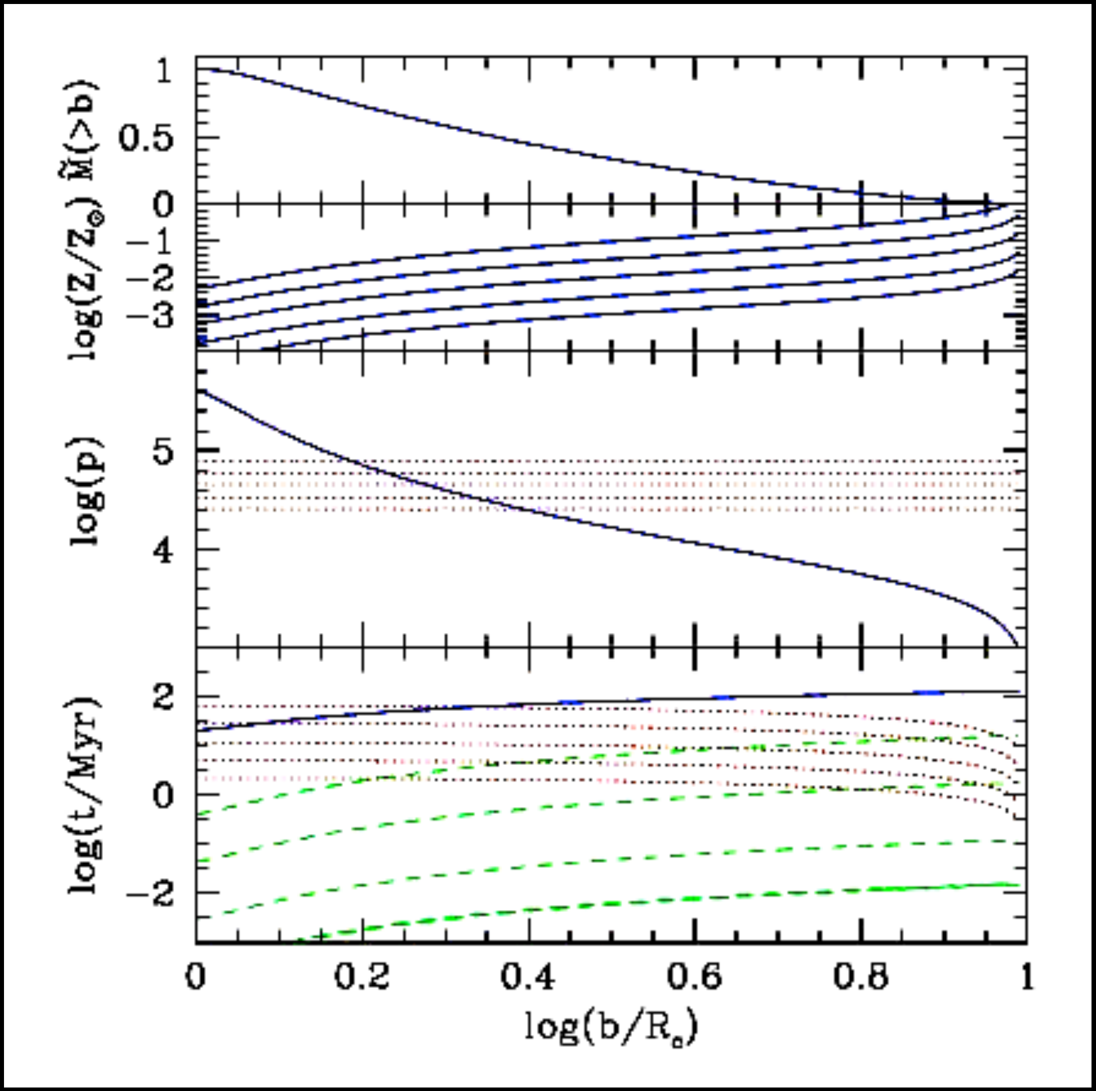
Cooling by:

nonequilibrium proc.

Infrared CII,FeII,SiII (<13.6eV)

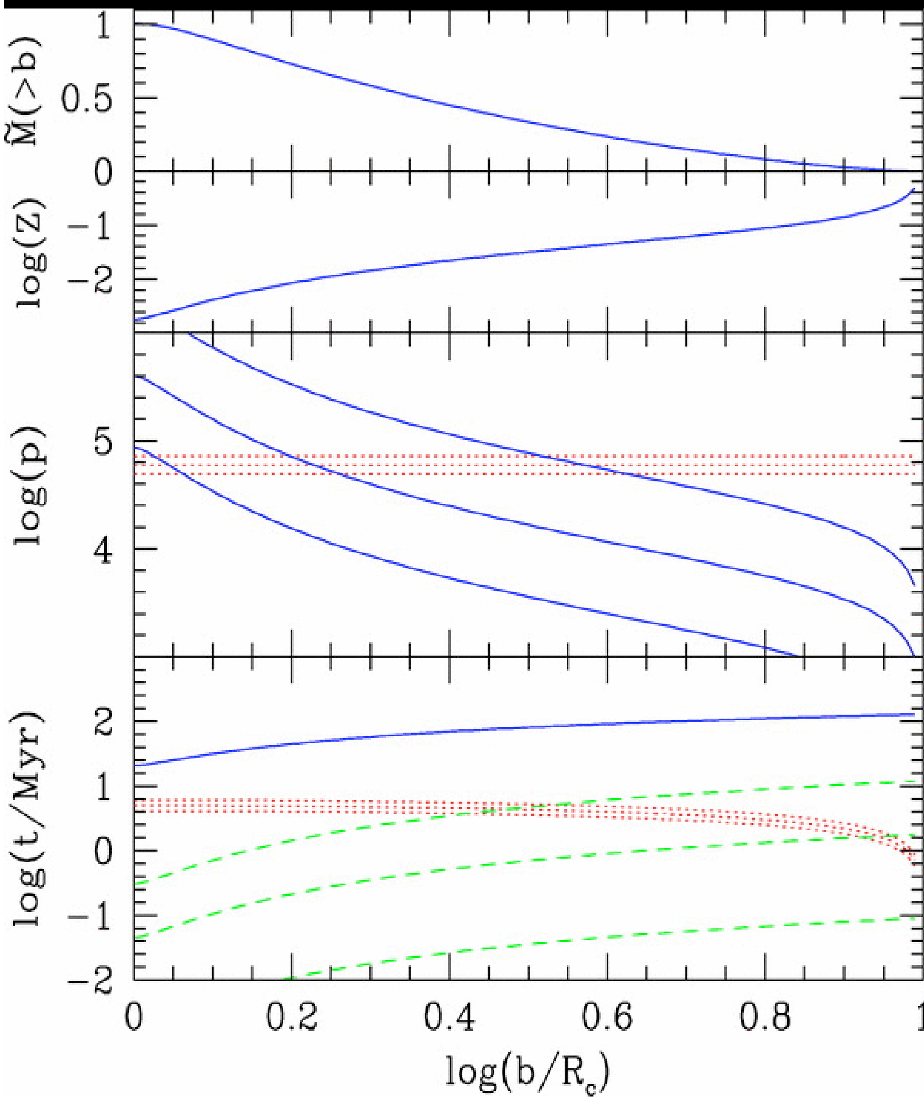
Parameter Dependencies

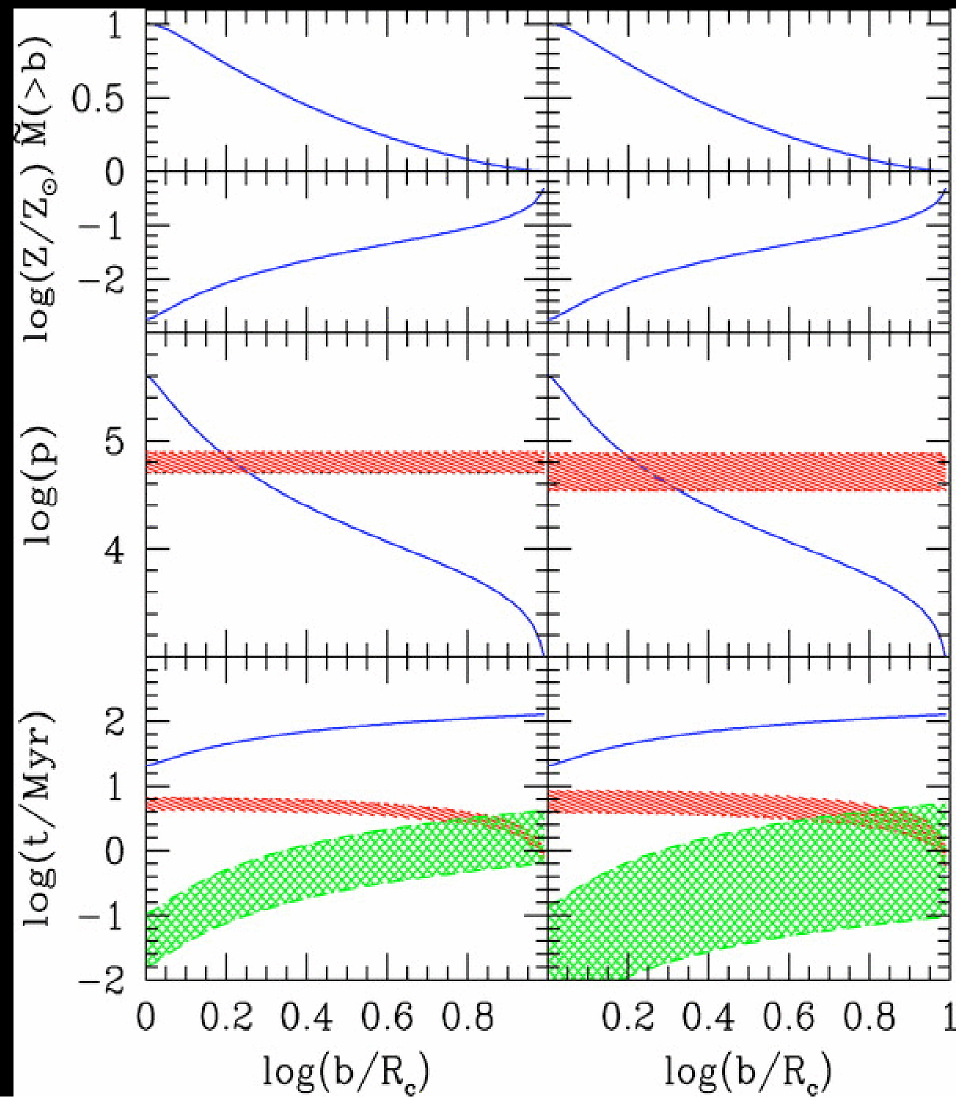
Distance
(-3<logZ<-1)



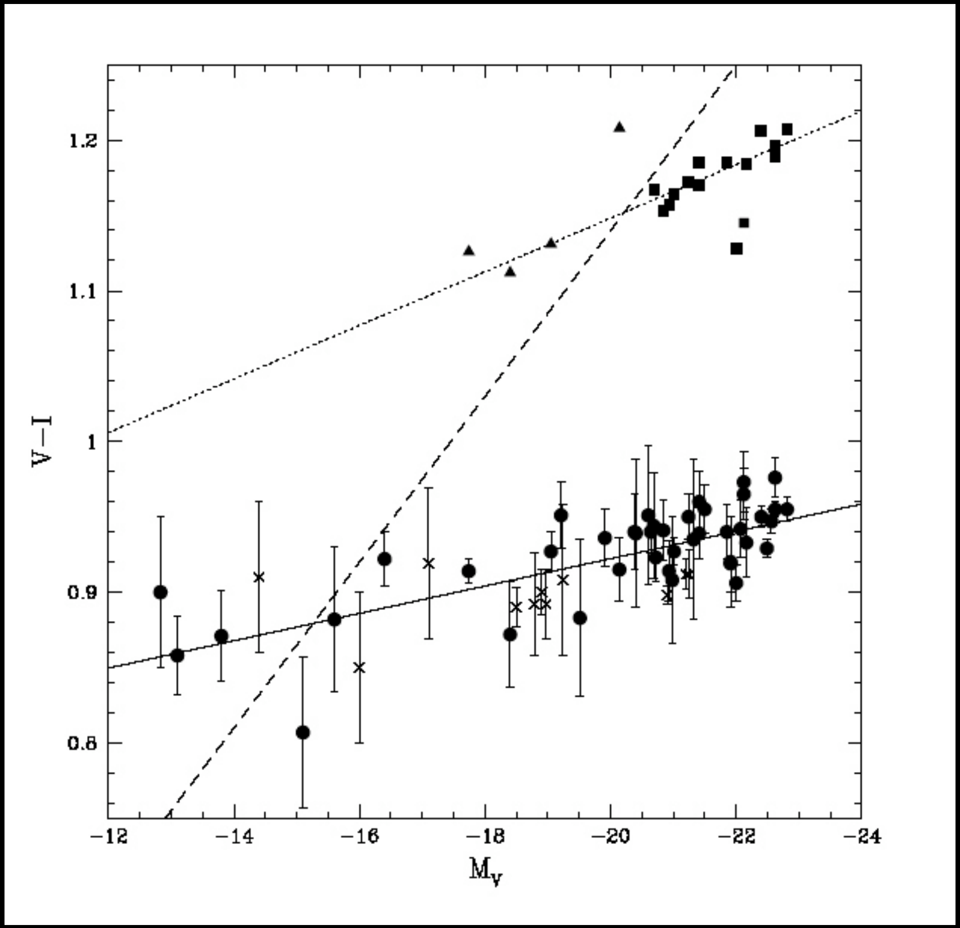
Minihalo mass

Starburst energy





Other Observables



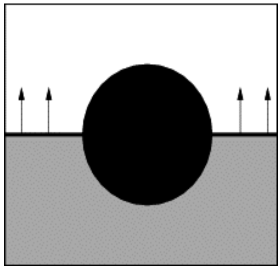
Strader, Brodie, & Forbes 2004

$Z \propto L^{1/6}$

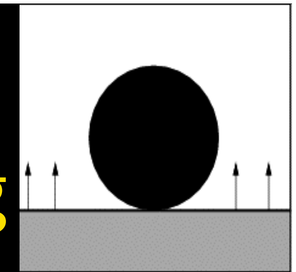
Fix v_s:
$R \propto E^{1/3} (1+z)^{-1}$

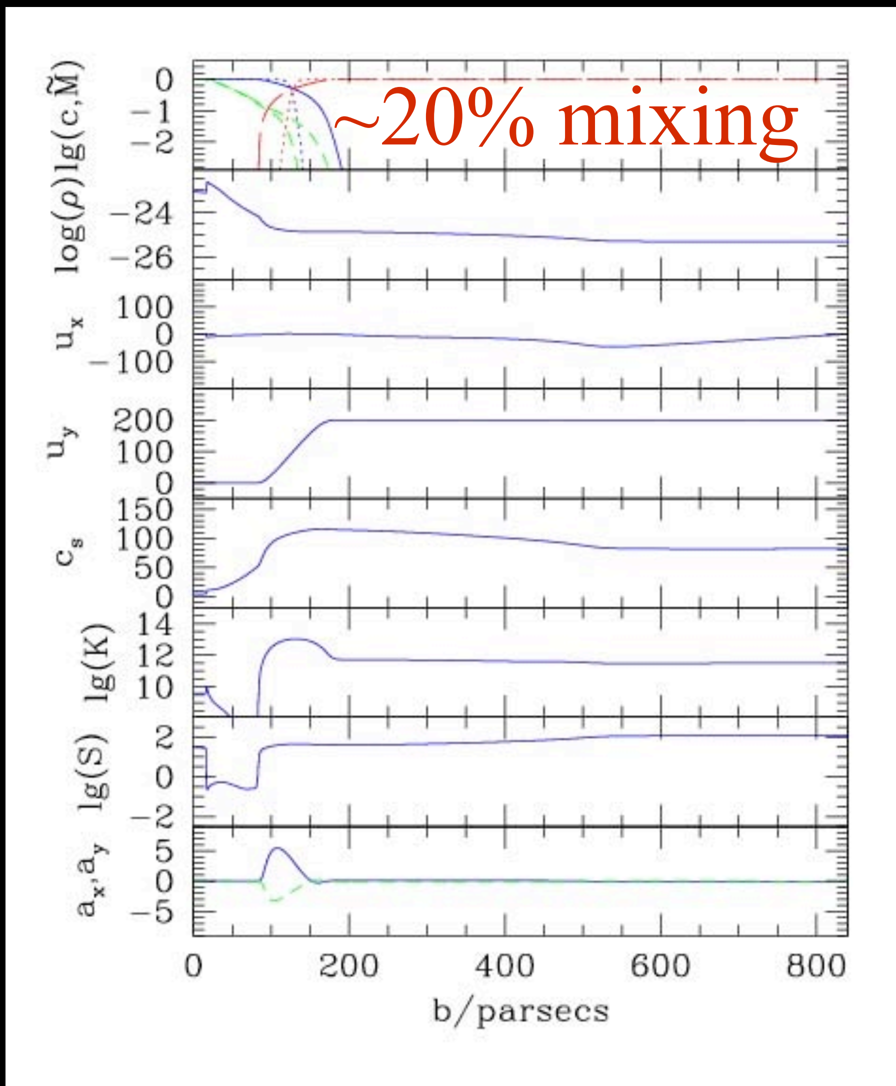
Assume ejected Z
E of starburst $\propto$ L
$Z \propto L^{1/3} (1+z)^{2}$

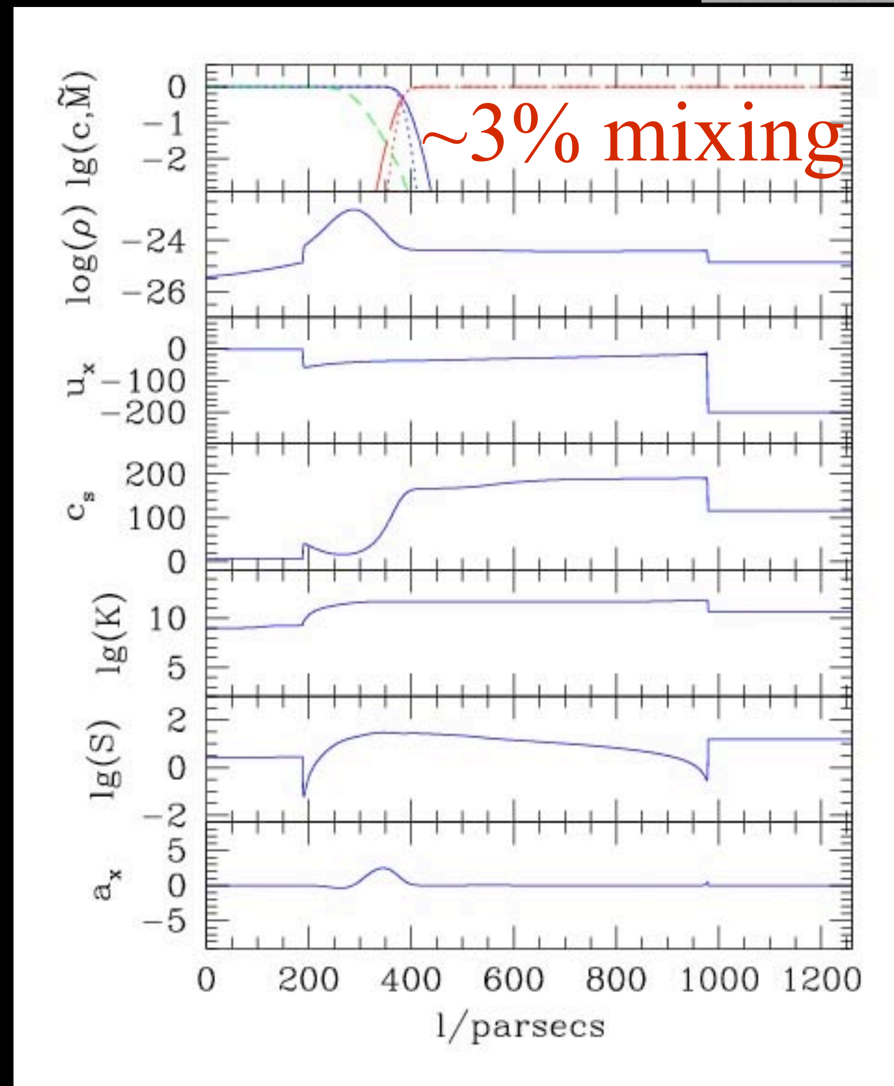
Fixed sigma
peaks (CDM):
$Z \propto L^{1/3-0}$



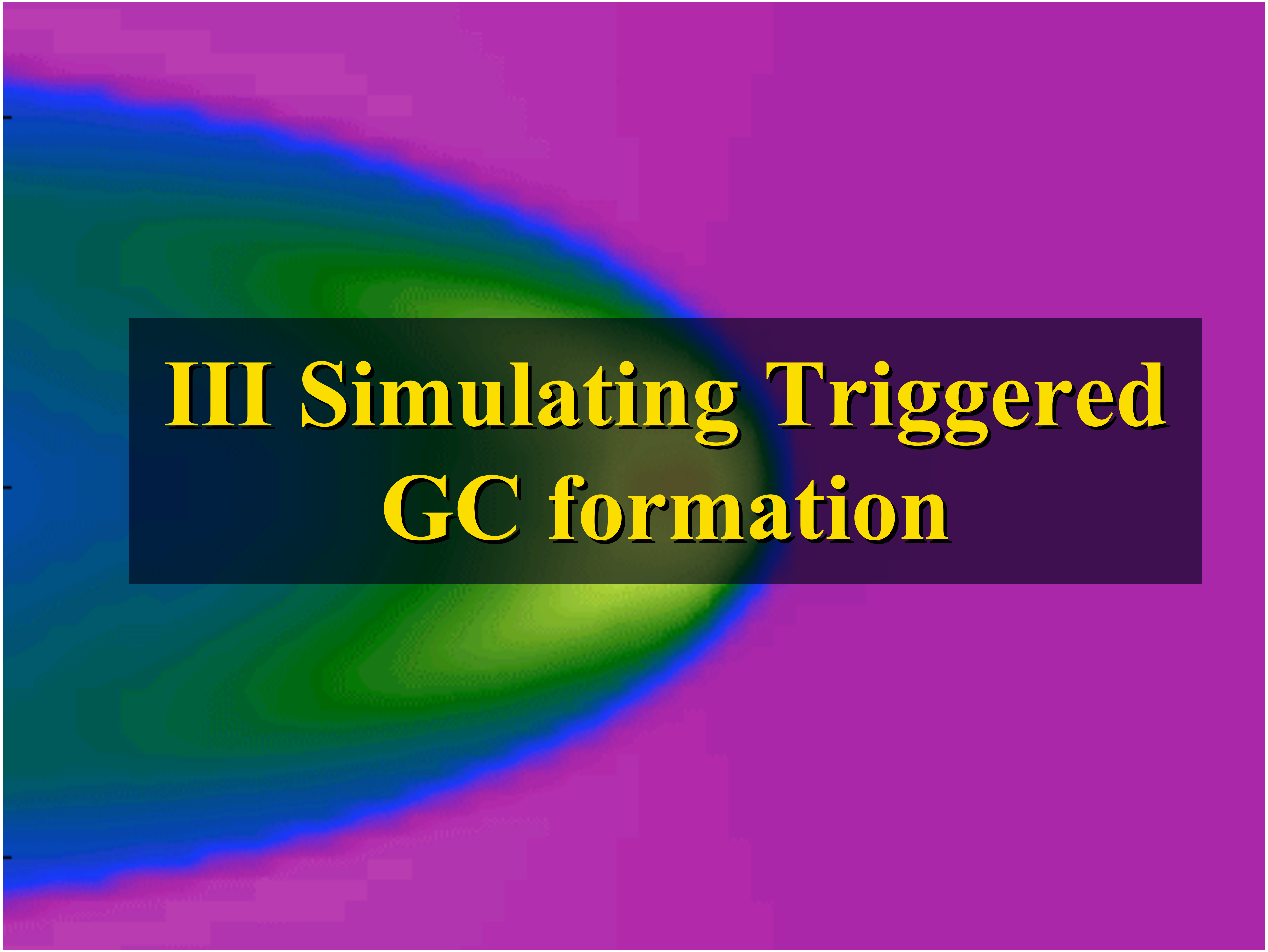
1D Simulation of (Turbulent) Mixing



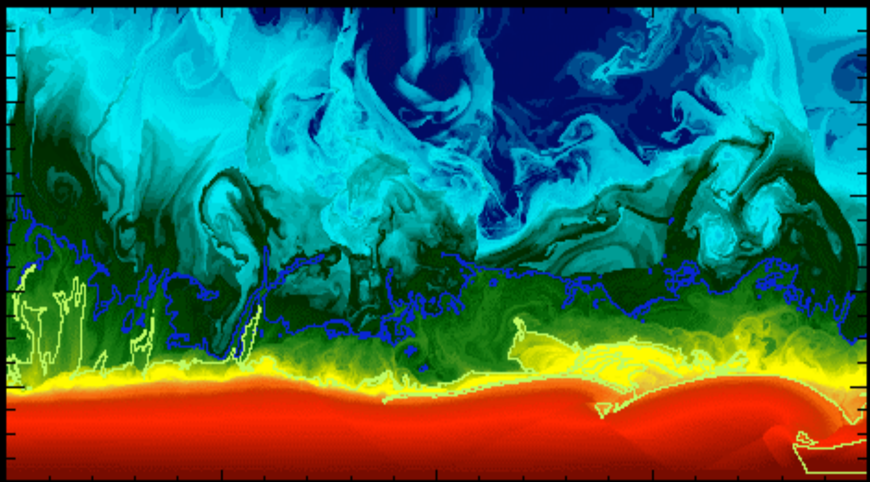




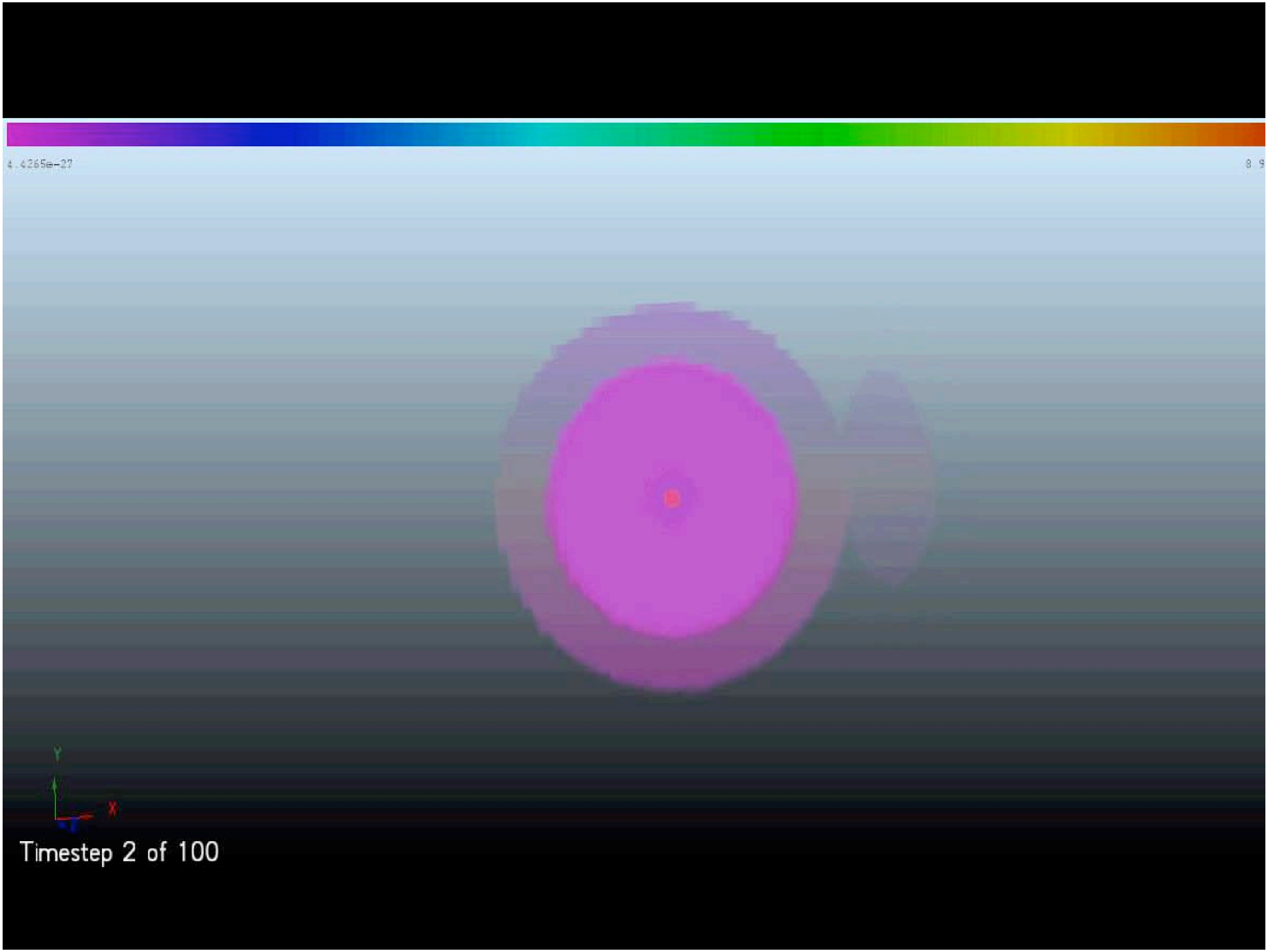
III Simulating Triggered GC formation

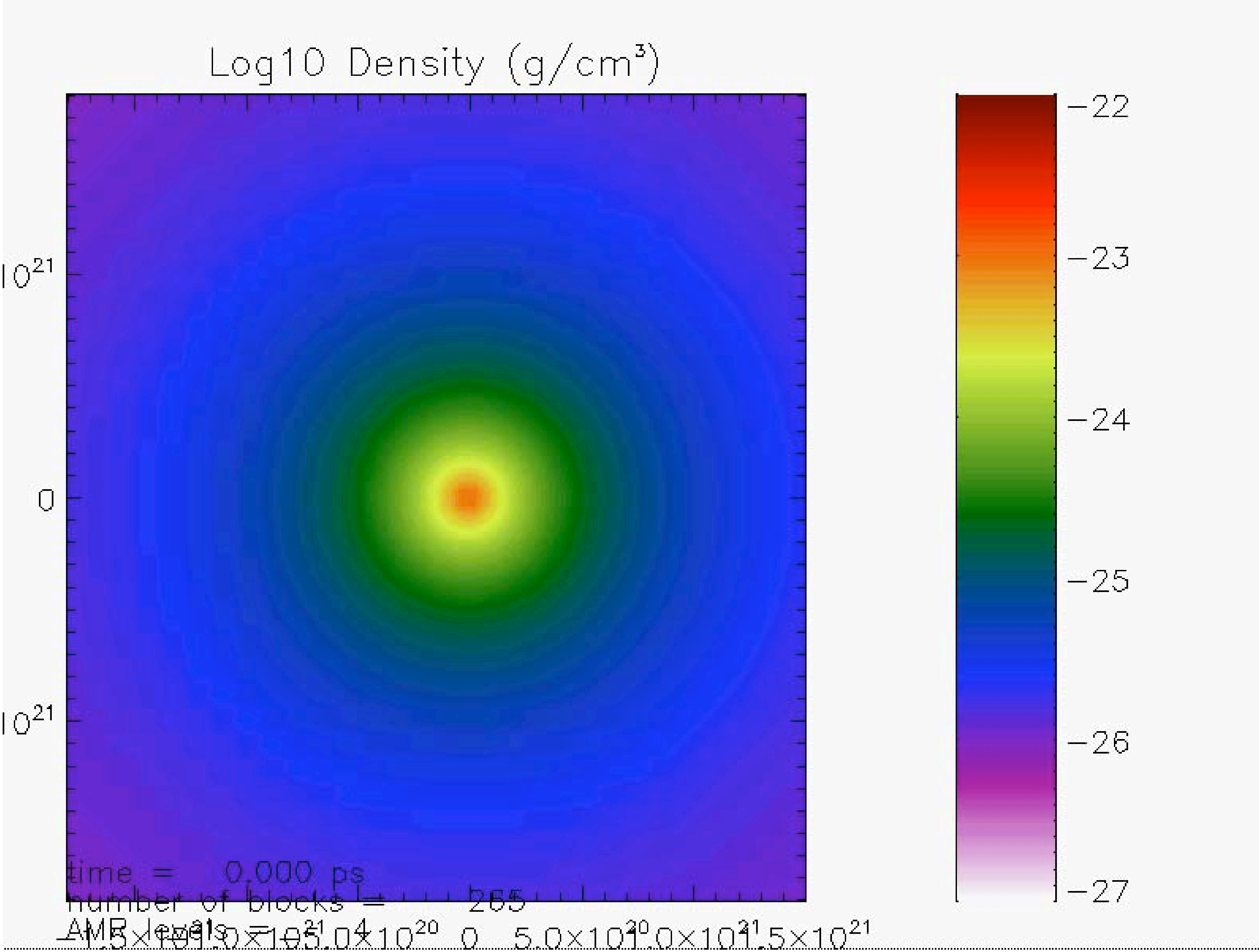


FLASH3 (AMR) Simulations

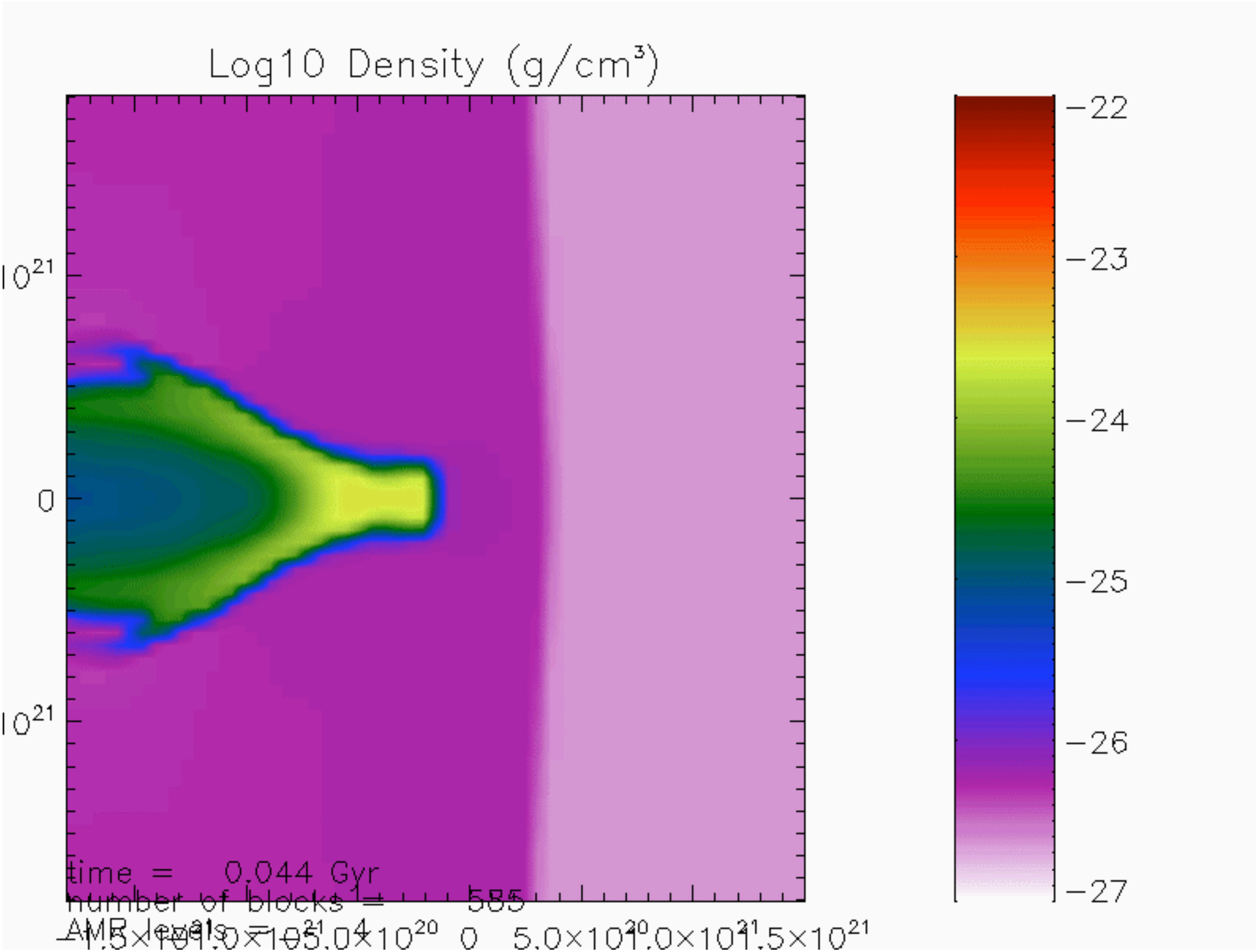


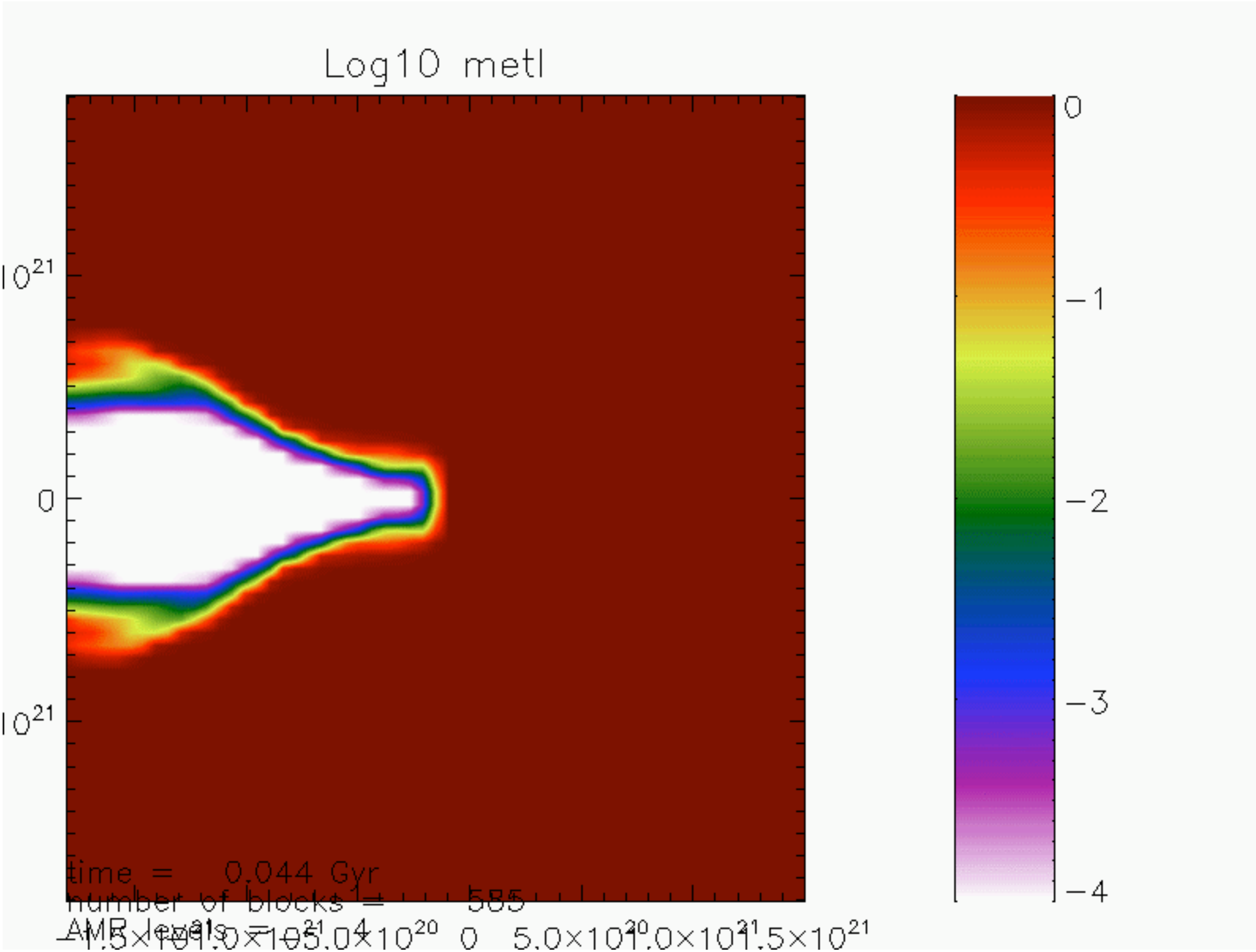
- initially hydrostatic cluster, static gravity
- 4 levels of refinement, 256^3 effective resolution, 1 kpc^3 box
- NFW halo
- Saguaro computer cluster (4096 core cluster at ASU)
- Multigrid Self Gravity
- NO COOLING!


4.4265e-27
Y
X
Timestep 2 of 100



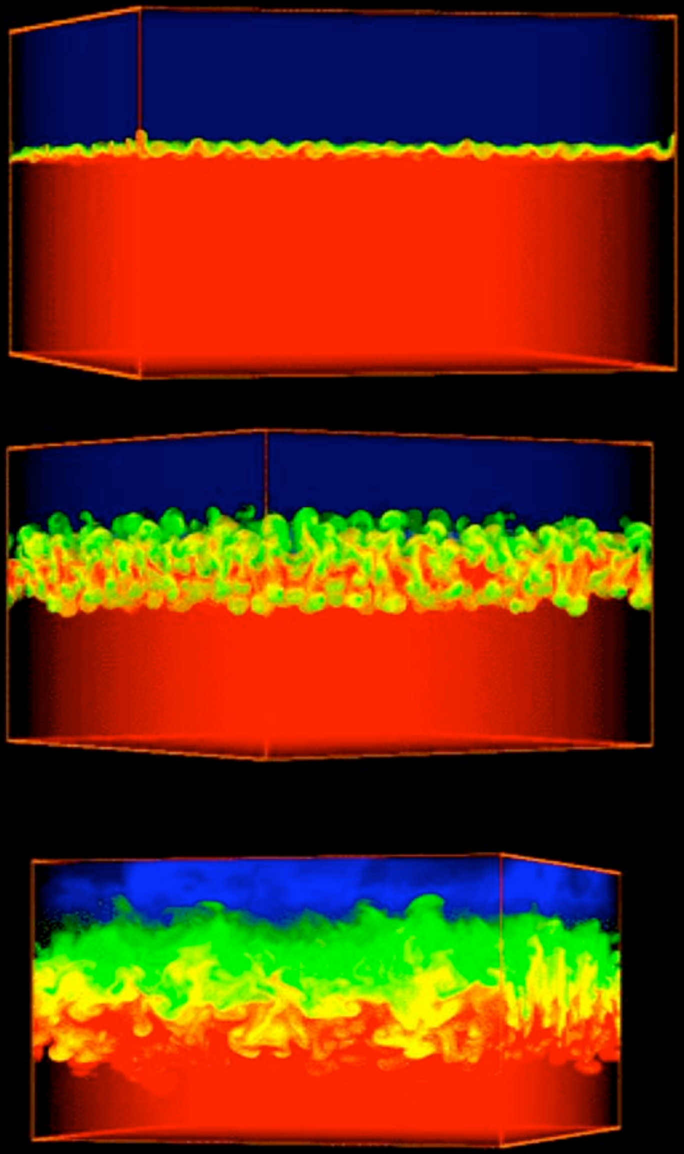
Log10 Density (g/cm^3)
−22
−23
−24
−25
−26
−27
0
time = 0.000 ps


Log10 Density (g/cm³)
time = 0.044 Gyr
number of blocks = 585
AMR levels = 4
−22
−23
−24
−25
−26
−27


Log10 metl
time = 0.044 Gyr
number of blocks = 585
AMR levels = 4
0
−1
−2
−3
−4

Rayleigh Taylor Instability

$$h_b = \alpha_b A_o g t^2$$



Cook et al. (2004)

Dimonte & Tipton '06 Turbulence Model

based on buoyancy-drag models for RT and RM instabilities: **self-similar, conserves energy, preserves Galilean invariance, works with shocks**

K = Turbulent KE , L= Turbulent Length Scale

$$\frac{\partial \bar{\rho} K}{\partial t} + \frac{\partial \bar{\rho} K \tilde{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{N_K}\frac{\partial K}{\partial x_j}\right) - R_{i,j}\frac{\partial \tilde{u}_i}{\partial x_j} + S_K$$

turb. diffusion — work associated with turbulent stress — source term with RM and RT contributions

$$\frac{\partial \bar{\rho} L}{\partial t} + \frac{\partial \bar{\rho} L \tilde{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{N_L}\frac{\partial L}{\partial x_j}\right) + \bar{\rho} V + C_C \bar{\rho} L \frac{\partial \tilde{u}_i}{\partial x_i},$$

turb. diffusion — growth of eddies through turb. motion — growth of eddies through motion in mean flow

$$S_K = \bar{\rho} V \left[C_B A_i g_i - C_D \frac{V^2}{\boldsymbol{L}} \right], \qquad \mu_T = C_\mu \bar{\rho} L V, \qquad V \equiv \sqrt{2K}$$

buoyancy — drag — turb. viscosity — turb. velocity

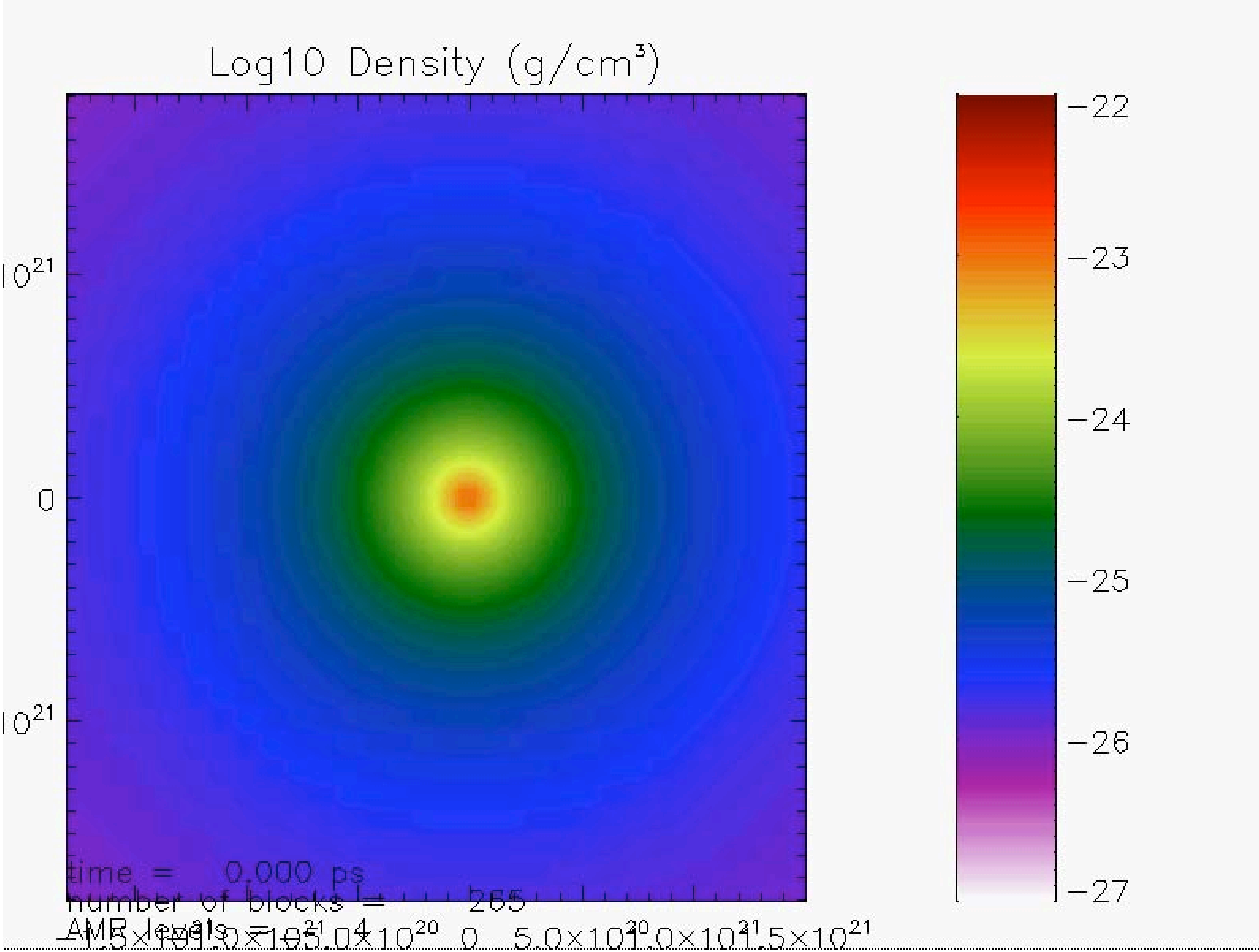
Modified Fluid Equations

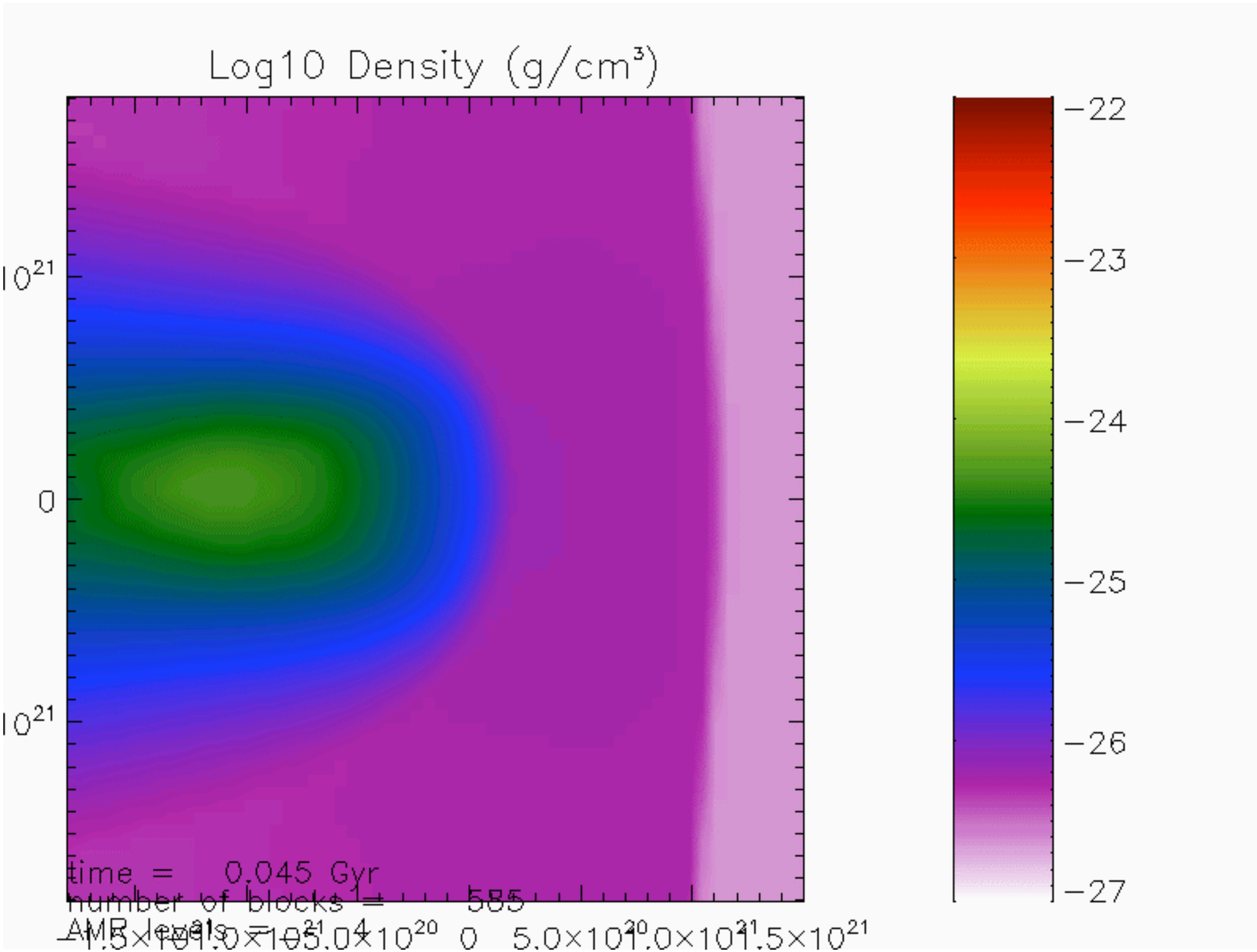
Leading order in expansion around mean velocity: mean quantities are modified by presence of

1. Reynolds stress $R_{i,j}$
2. Turbulent viscosity, μ_t
3. Source term S_K

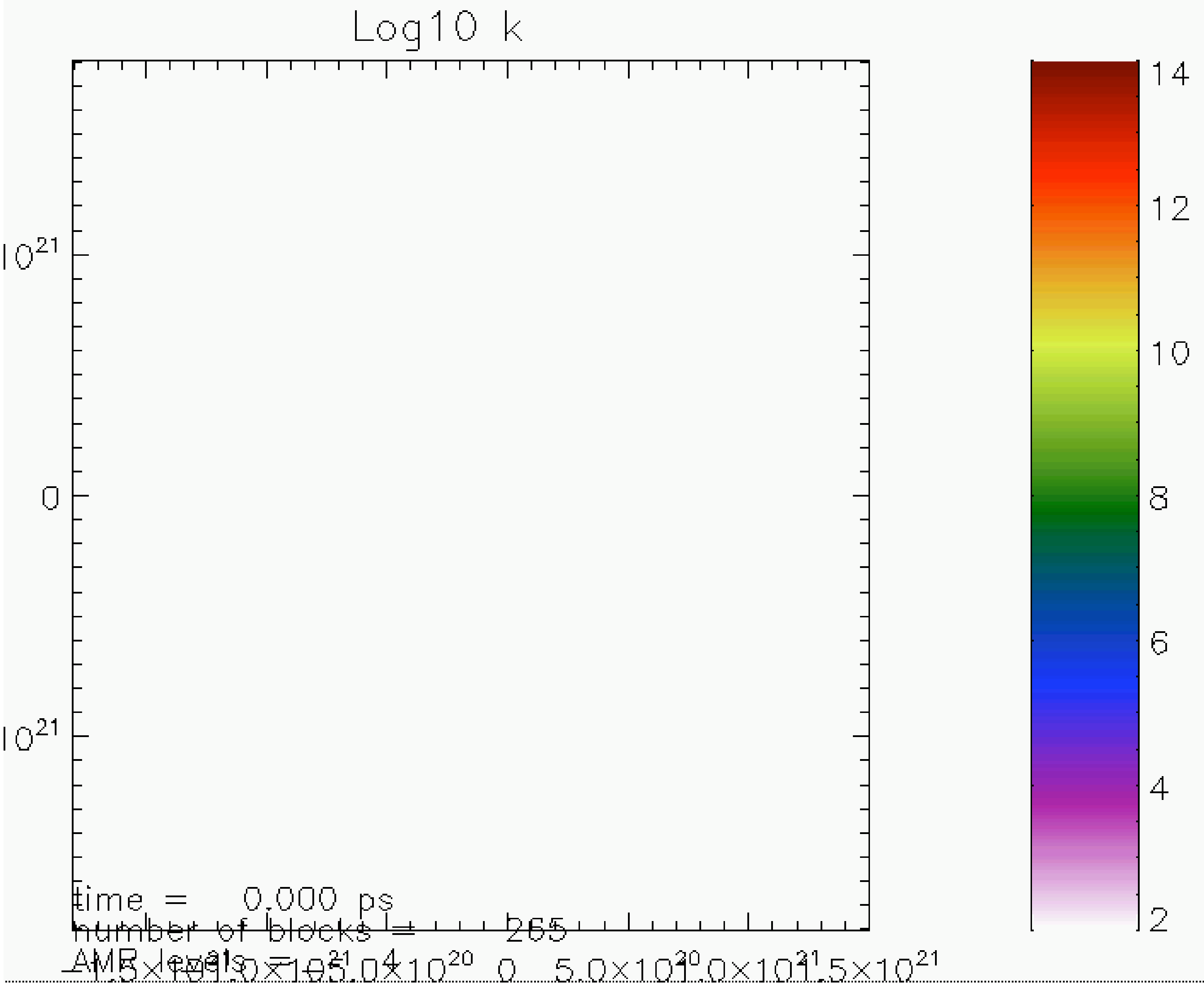
$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial P}{\partial x_i} - \frac{\partial R_{i,j}}{\partial x_j}$$

$$\frac{\partial \rho E}{\partial t} + \frac{\partial \rho E u_j}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{N_E}\frac{\partial E}{\partial x_j}\right) - \frac{\partial P u_j}{\partial x_j} - S_K$$

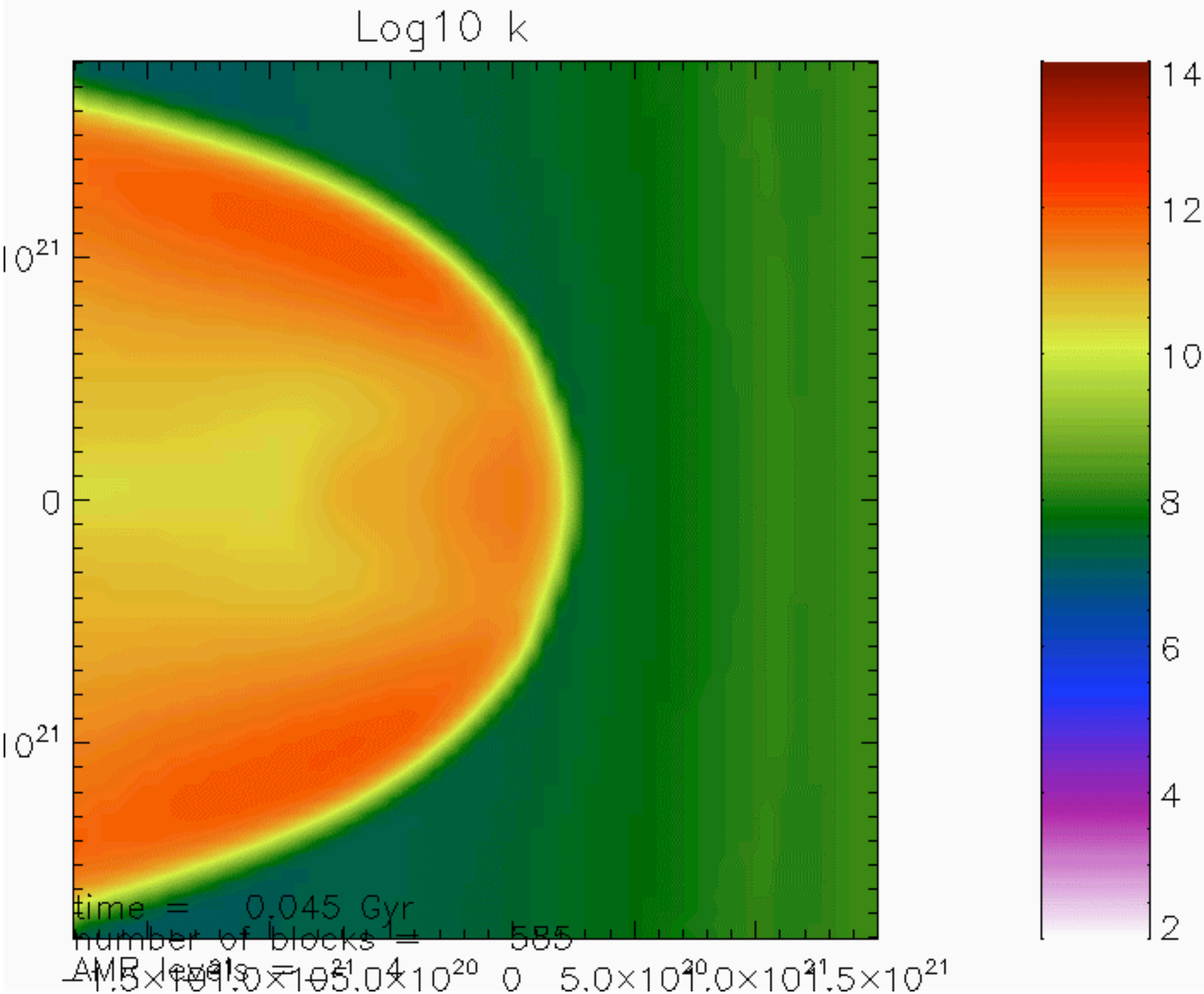

Log10 Density (g/cm³)
-22
-23
-24
-25
-26
-27
0
time = 0.000 ps
number of blocks = 265
AMR levels = 4
0
5.0×10^20

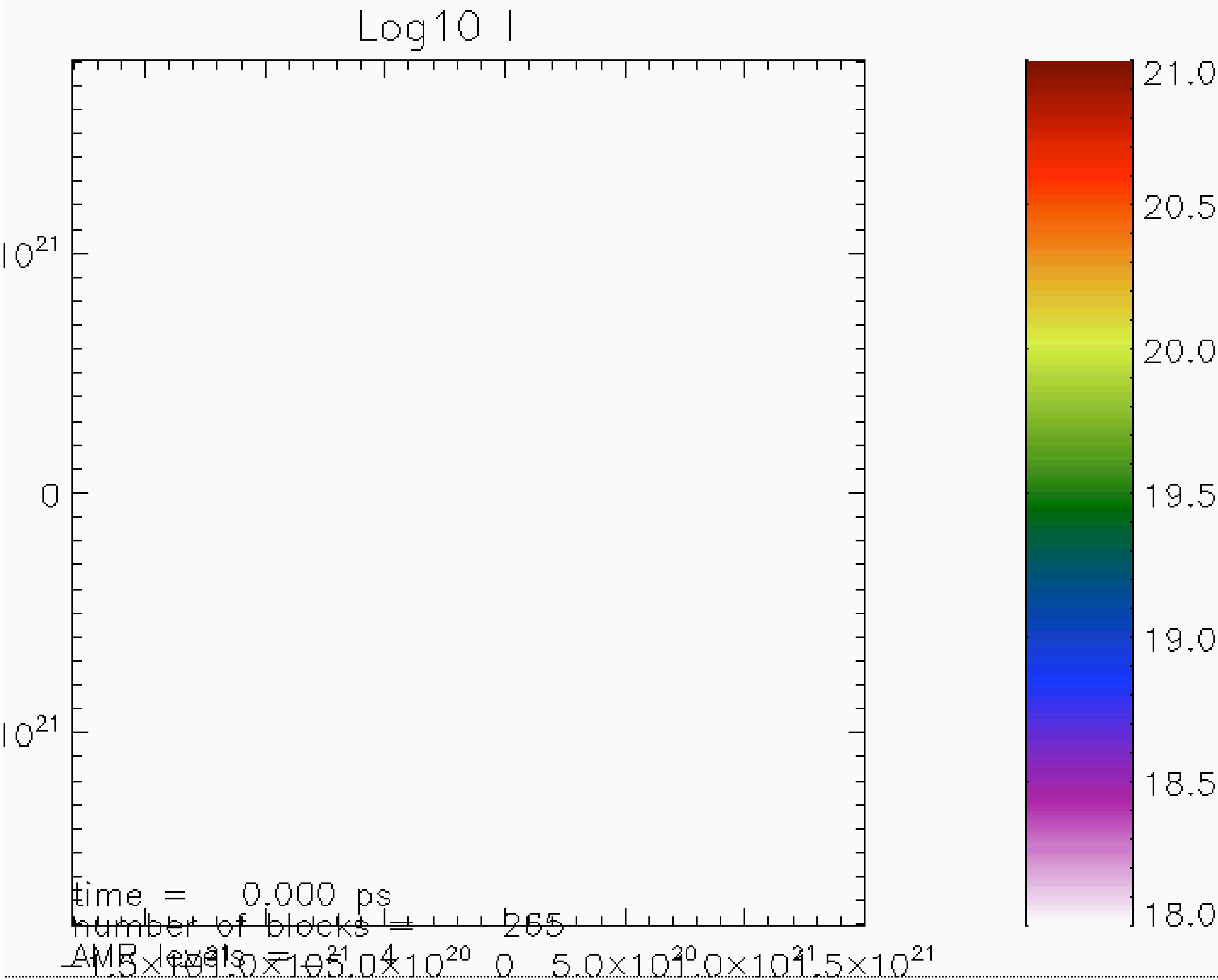


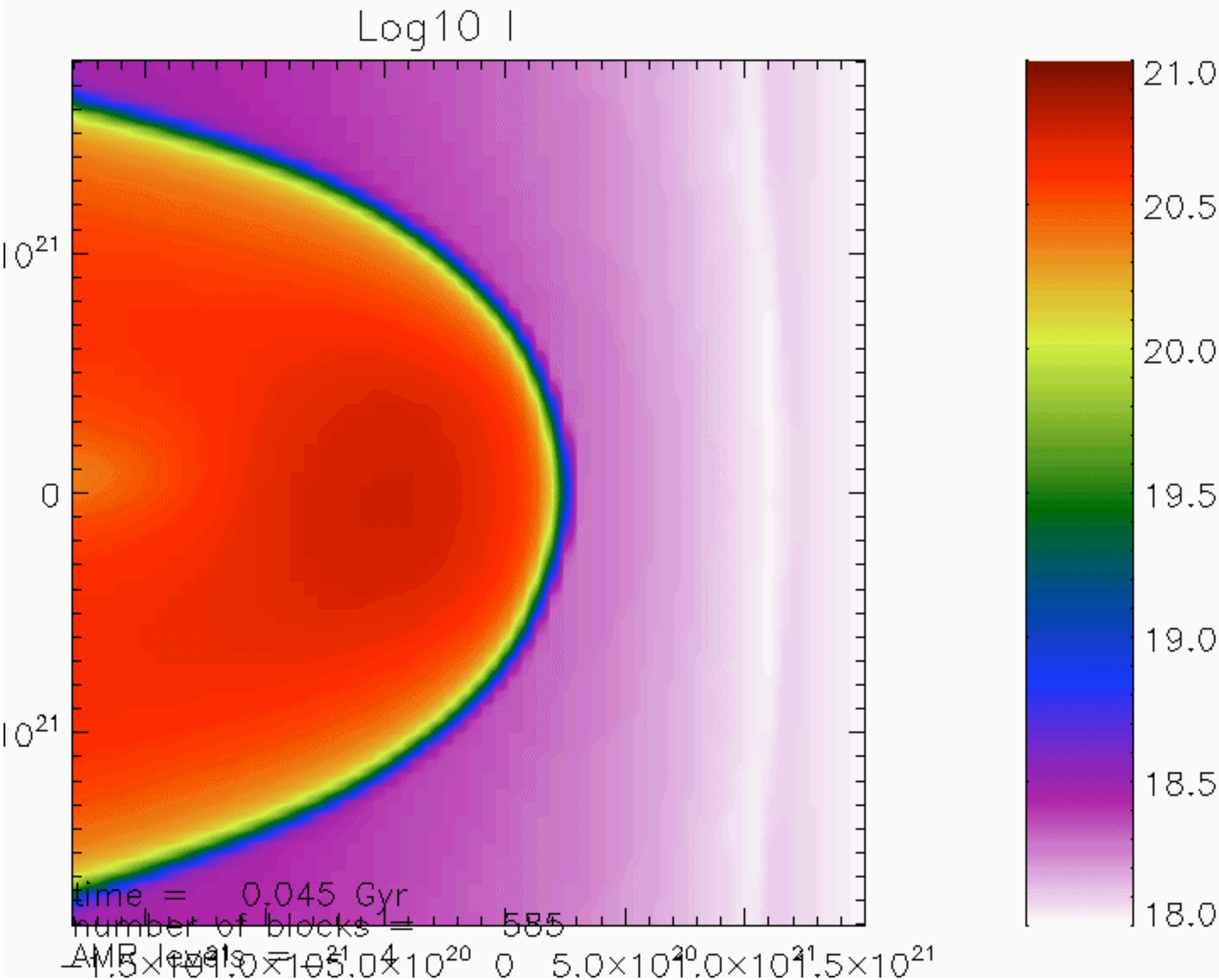
Log10 Density (g/cm³)
time = 0.045 Gyr
number of blocks = 585
AMR levels = 4
0
−22
−23
−24
−25
−26
−27



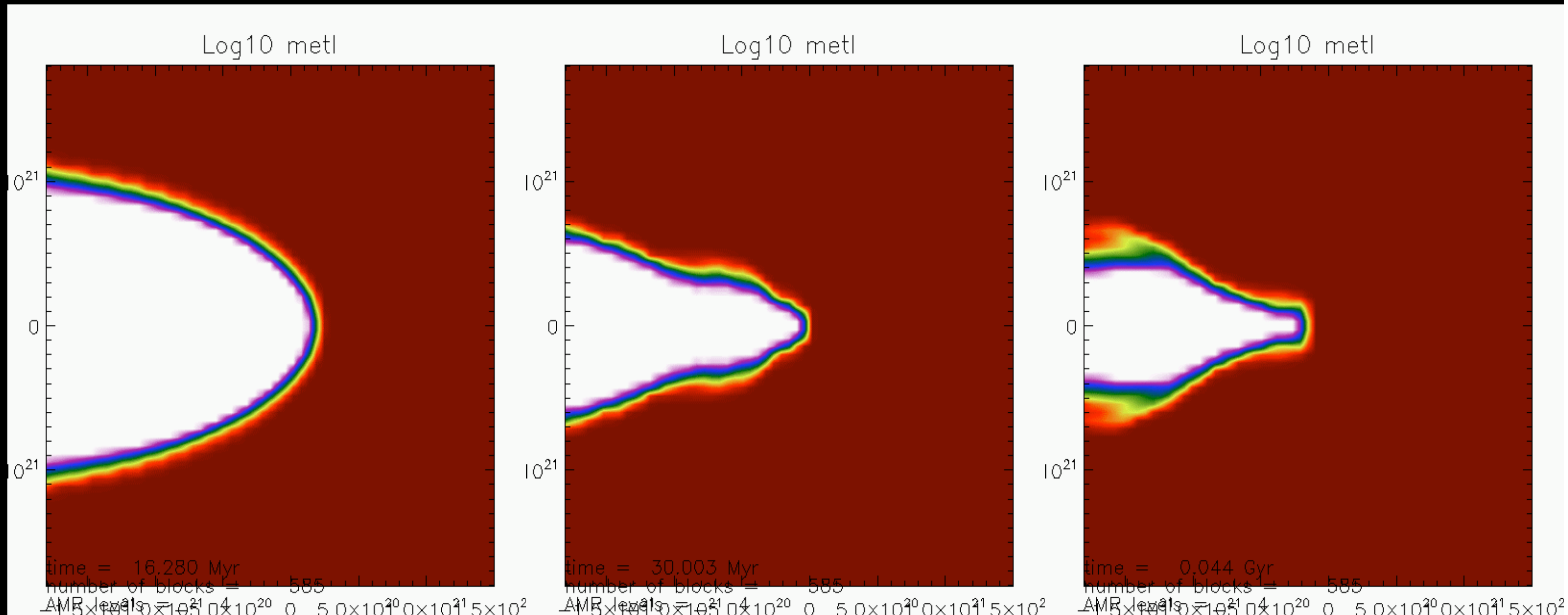
Log10 k
10^21
0
10^21
14
12
10
8
6
4
2
time = 0.000 ps
number of blocks = 265
AMR levels = 4
0


Log10 k
10^21
0
10^21
time = 0.045 Gyr
number of blocks = 585
AMR levels = 4
−1.5×10^21 −1.0×10^21 −5.0×10^20 0 5.0×10^20 1.0×10^21 1.5×10^21
14
12
10
8
6
4
2

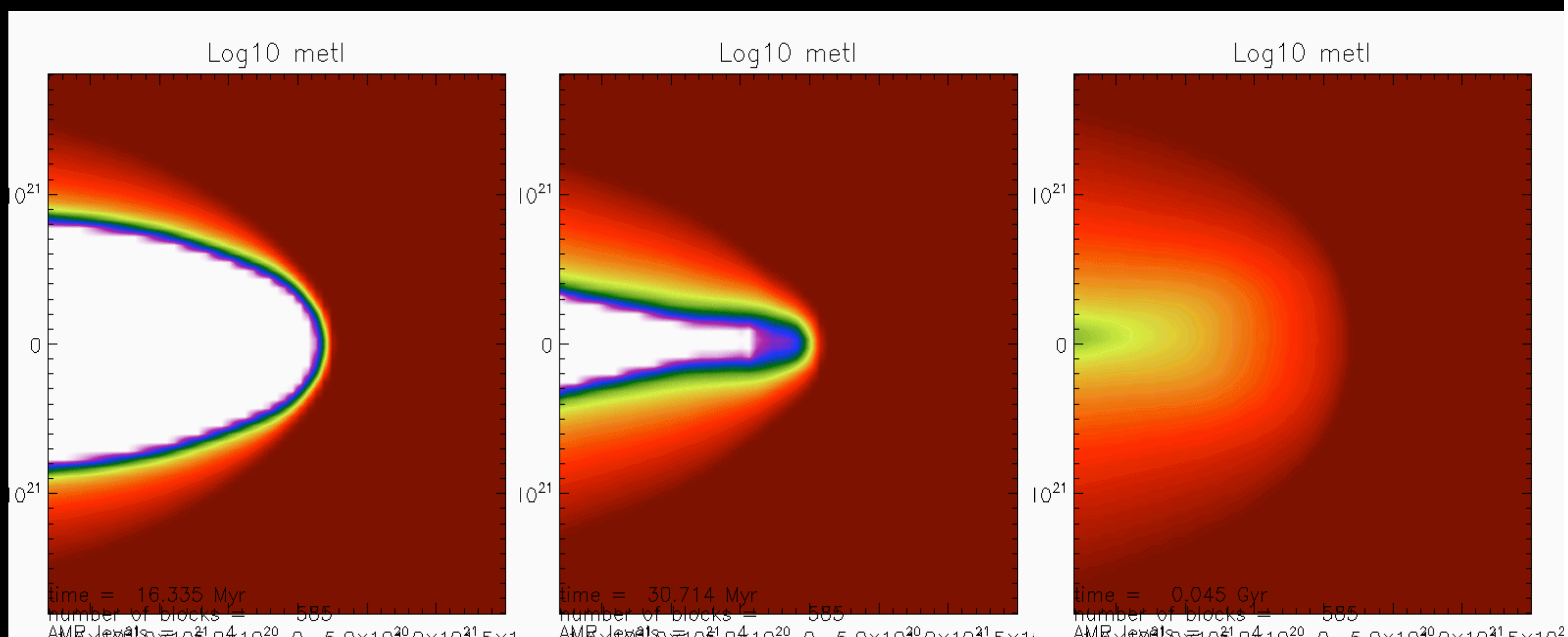

Log10 I
21.0
20.5
20.0
19.5
19.0
18.5
18.0
0
time = 0.000 ps
number of blocks = 265
AMR levels = 4
−1.5×10²¹ −1.0×10²¹ −5.0×10²⁰ 0 5.0×10²⁰ 1.0×10²¹ 1.5×10²¹

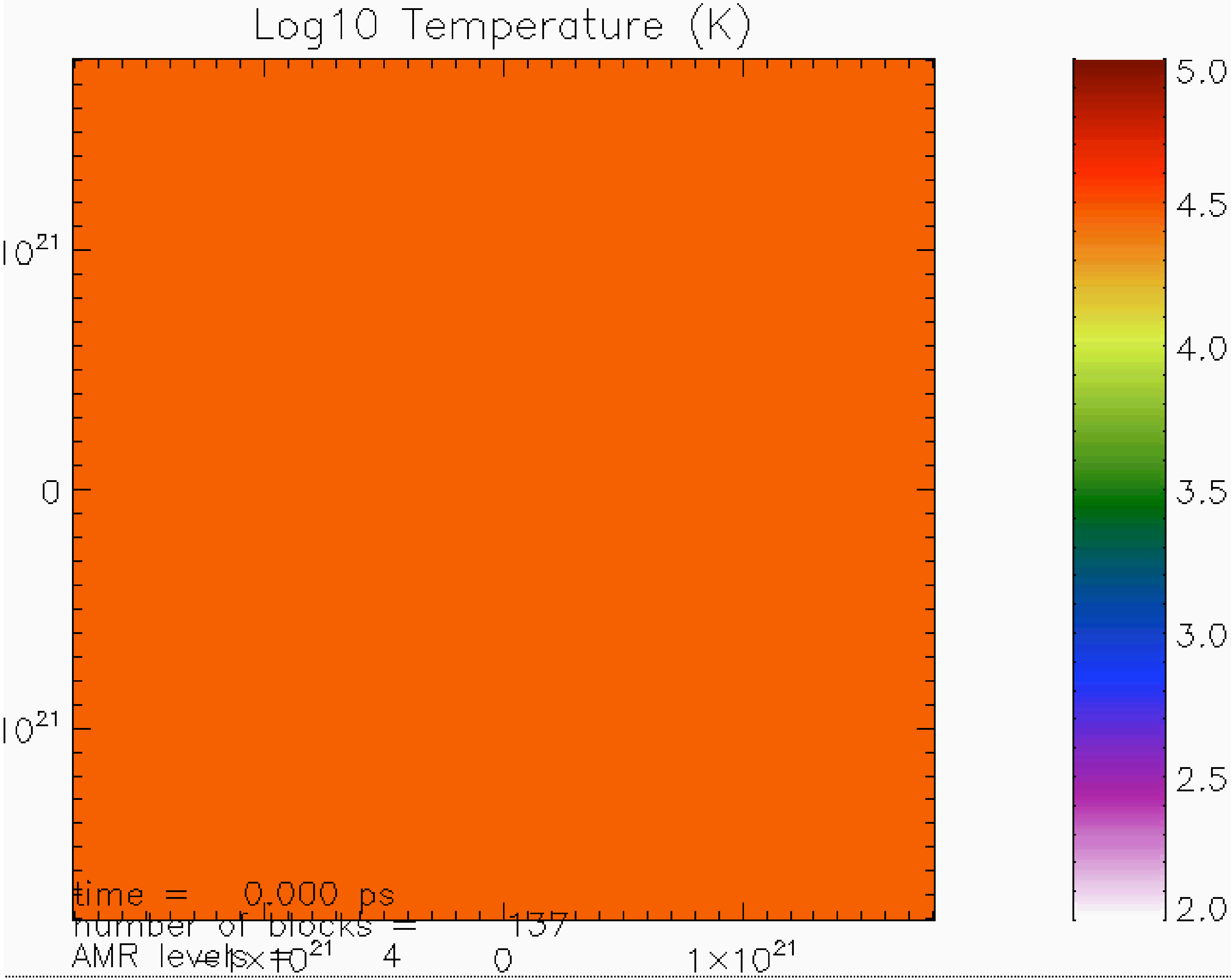

Log10 I
time = 0.045 Gyr
number of blocks = 585
AMR levels = 4
21.0
20.5
20.0
19.5
19.0
18.5
18.0
0

No Turb

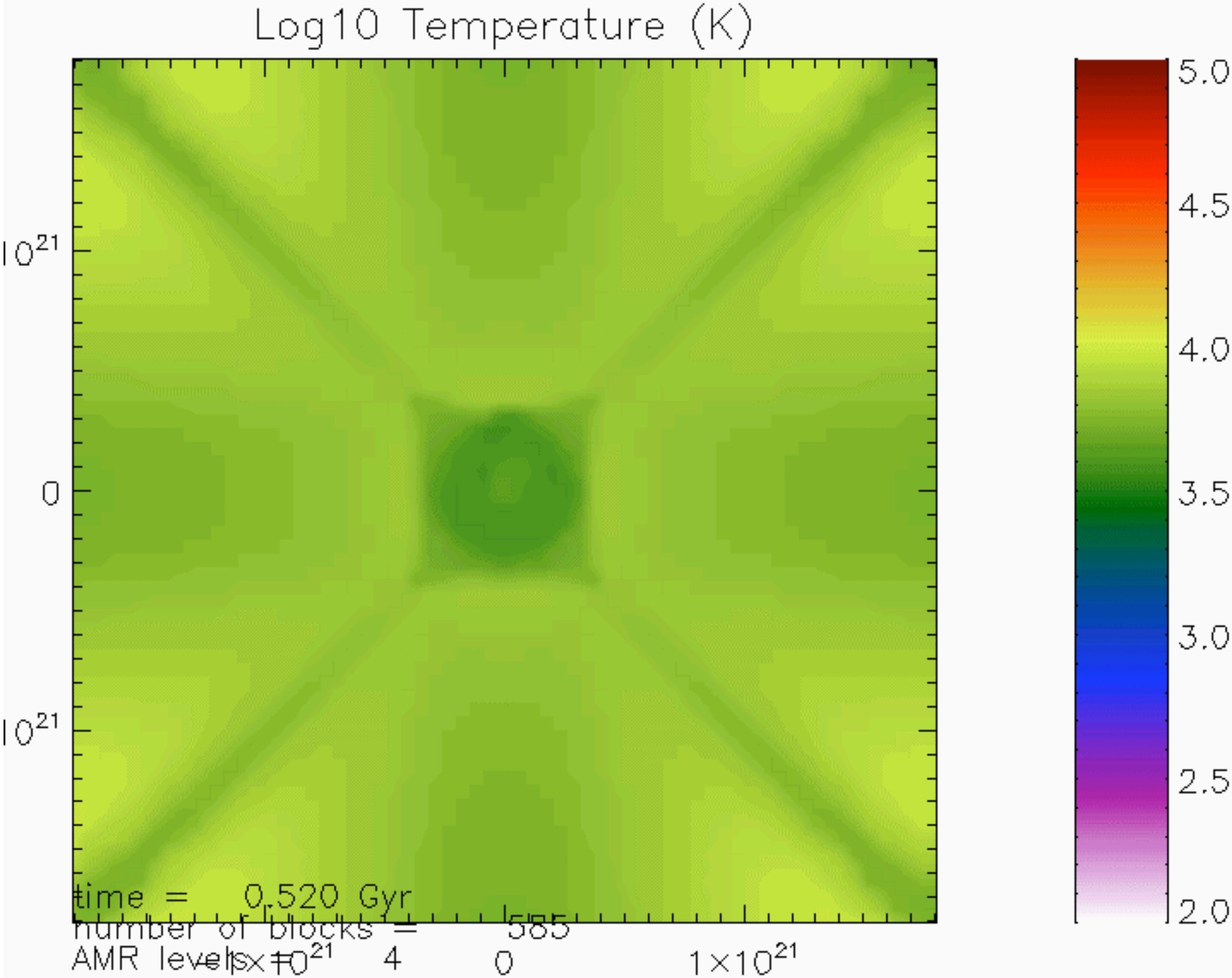

Log10 metl
Log10 metl
Log10 metl
time = 16.280 Myr
number of blocks = 585
time = 30.003 Myr
number of blocks = 585
time = 0.044 Gyr
number of blocks = 585

Turb


Log10 metl
Log10 metl
Log10 metl
time = 16.335 Myr
number of blocks = 585
time = 30.714 Myr
number of blocks = 585
time = 0.045 Gyr
number of blocks = 585



Log10 Temperature (K)
5.0
4.5
4.0
3.5
3.0
2.5
2.0
0
0
1×10^21
time = 0.000 ps
number of blocks = 137
AMR levels = 4



Log10 Temperature (K)
10^21
0
10^21
time = 0.520 Gyr
number of blocks = 585
AMR levels = 4
1×10^21
0
1×10^21
5.0
4.5
4.0
3.5
3.0
2.5
2.0

Conclusions

I First Stars

- Metal-free stars and their products end up everywhere
- Lack of metal-free stars argues for high mass, lack of odd even
  effect constrains PPSNe

II Halo Globular Clusters

- observed maximum mass
- chemical homogeneity
- the lack of dark matter

III Globular Cluster Simulations

- Use subgrid models of mixing which should have many
  applications
- Include primordial chemistry + metal cooling.

STAY TUNED…