Formation of Compact Stellar Clusters by High-Redshift Galaxy Outflows

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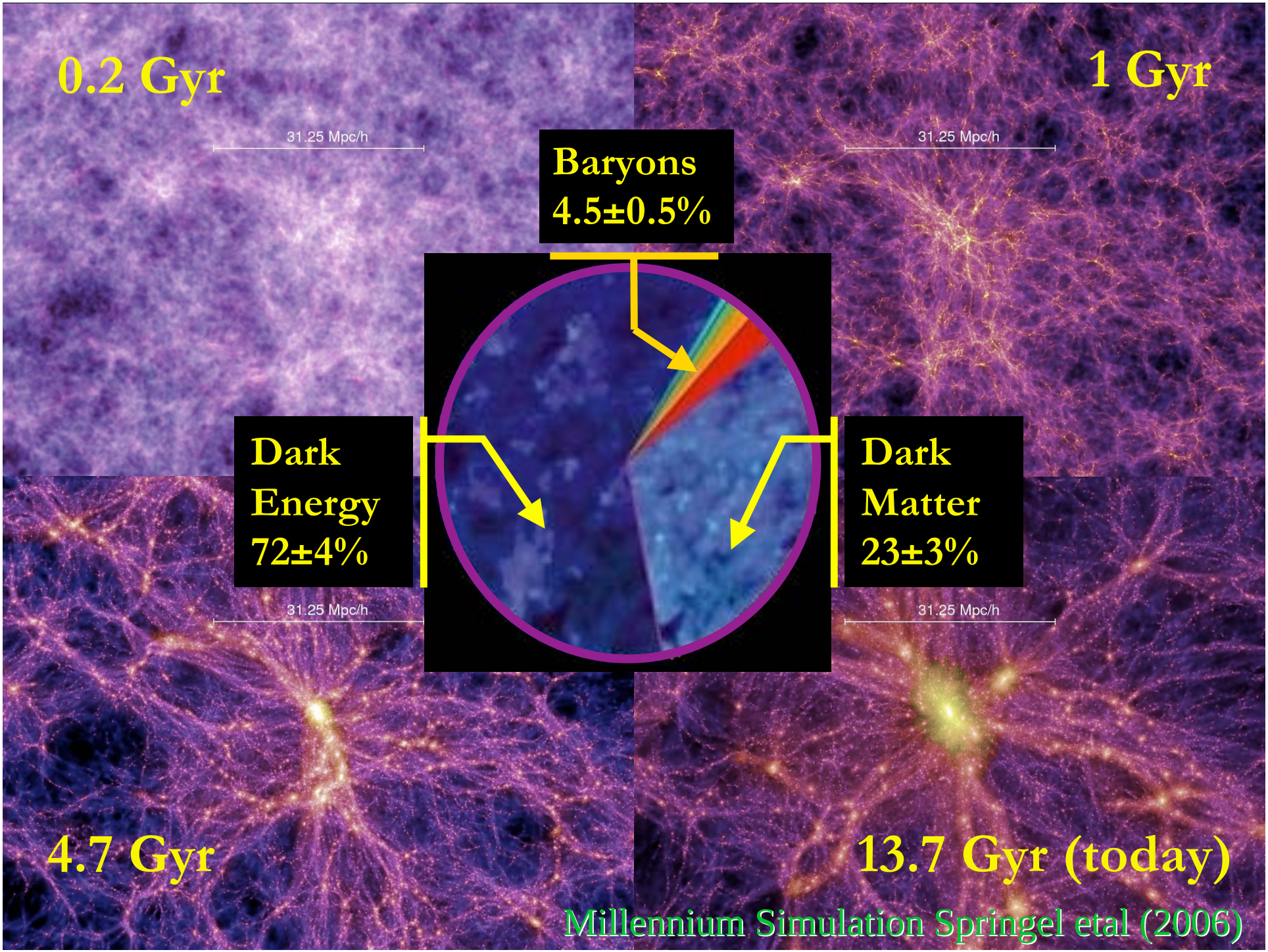
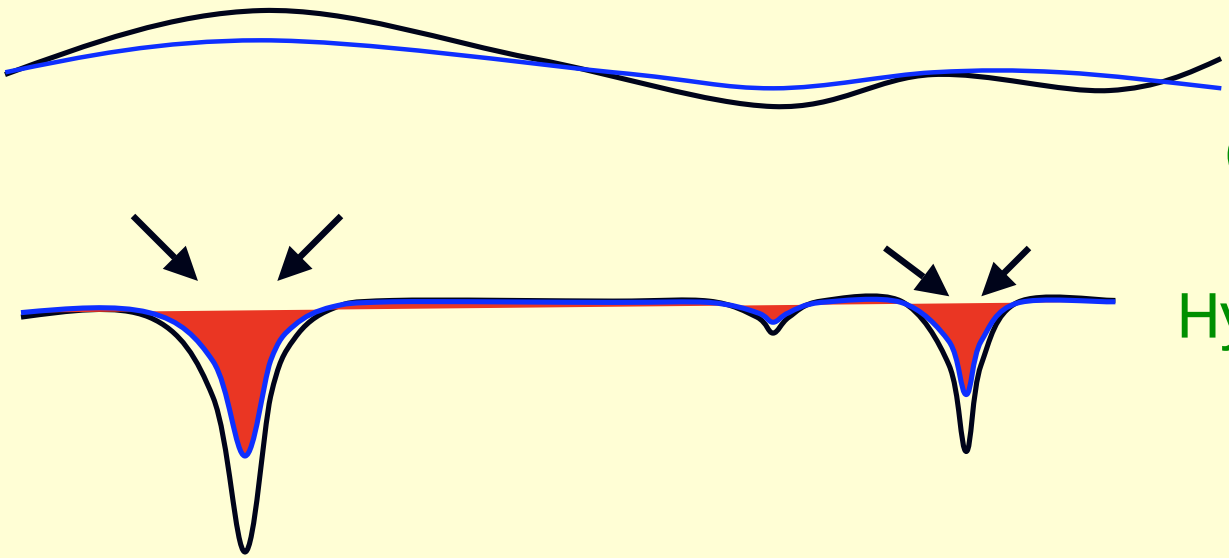
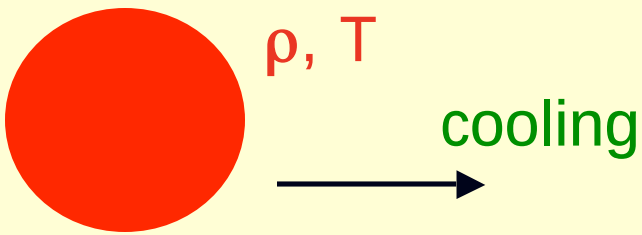

0.2 Gyr
31.25 Mpc/h
1 Gyr
31.25 Mpc/h
Baryons
4.5±0.5%
Dark
Energy
72±4%
Dark
Matter
23±3%
31.25 Mpc/h
31.25 Mpc/h
4.7 Gyr
13.7 Gyr (today)
Millennium Simulation Springel etal (2006)

Galaxy Formation



Gravity

Hydrodynamics



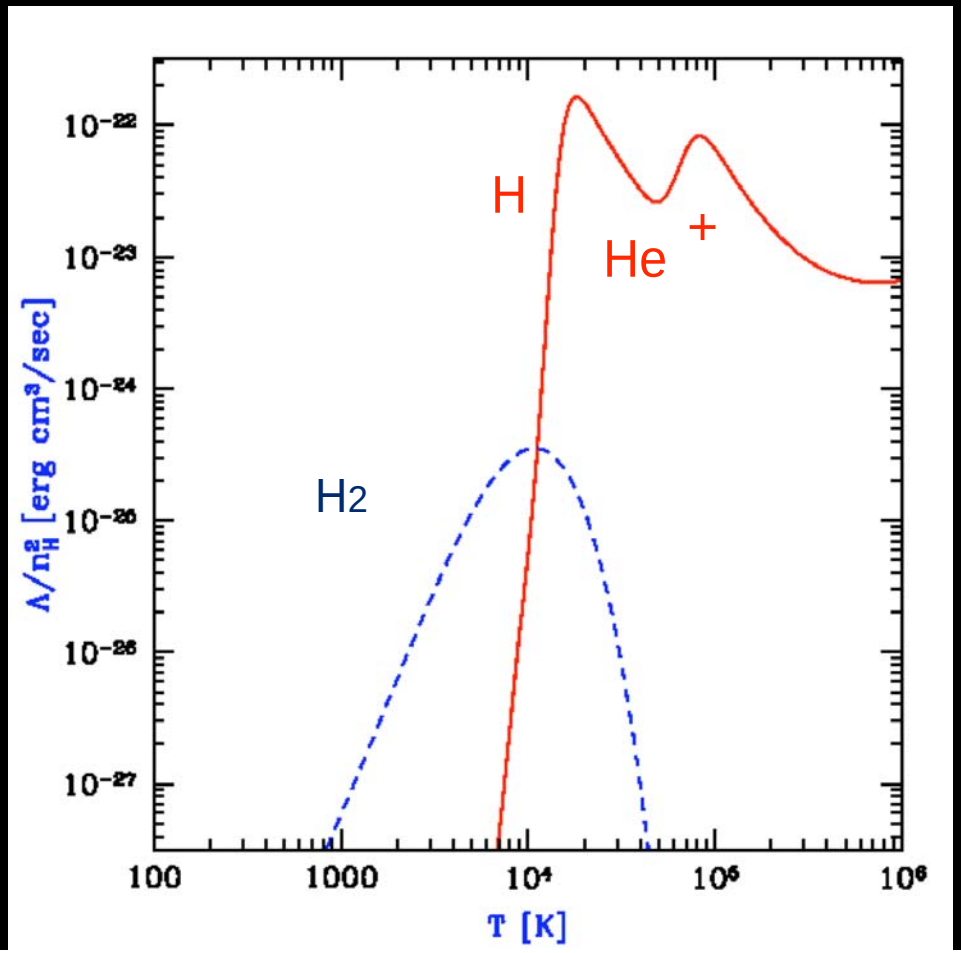
$$\frac{\text{Energy per gas particle}}{\Lambda\ \text{Density}^2}$$

Slide after Yoshida et al.

Cooling

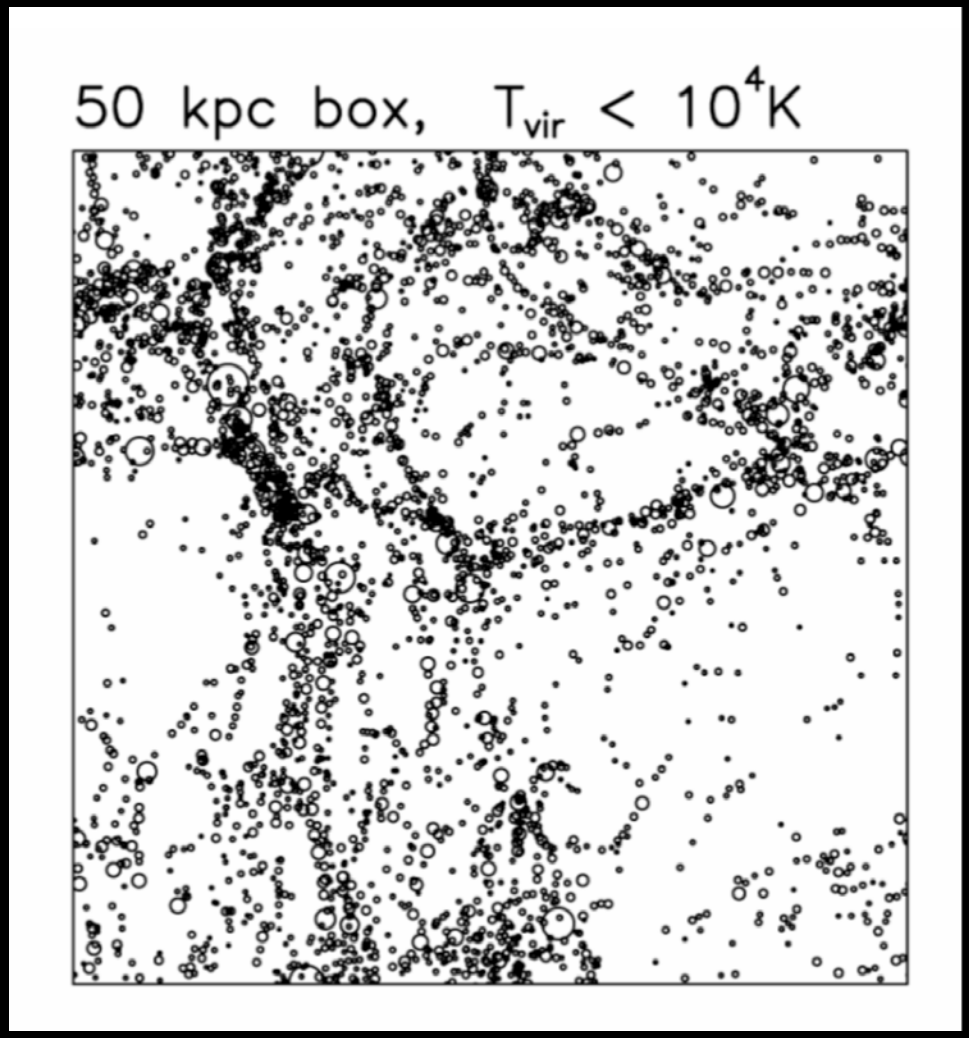
$T_{vir} \geq 10^4$ K

Gass masses >~ $10^7 M_{sun}[(1+z)/10]^{-3/2}$



Sutherland & Dopita (1993)

“Minihalos”

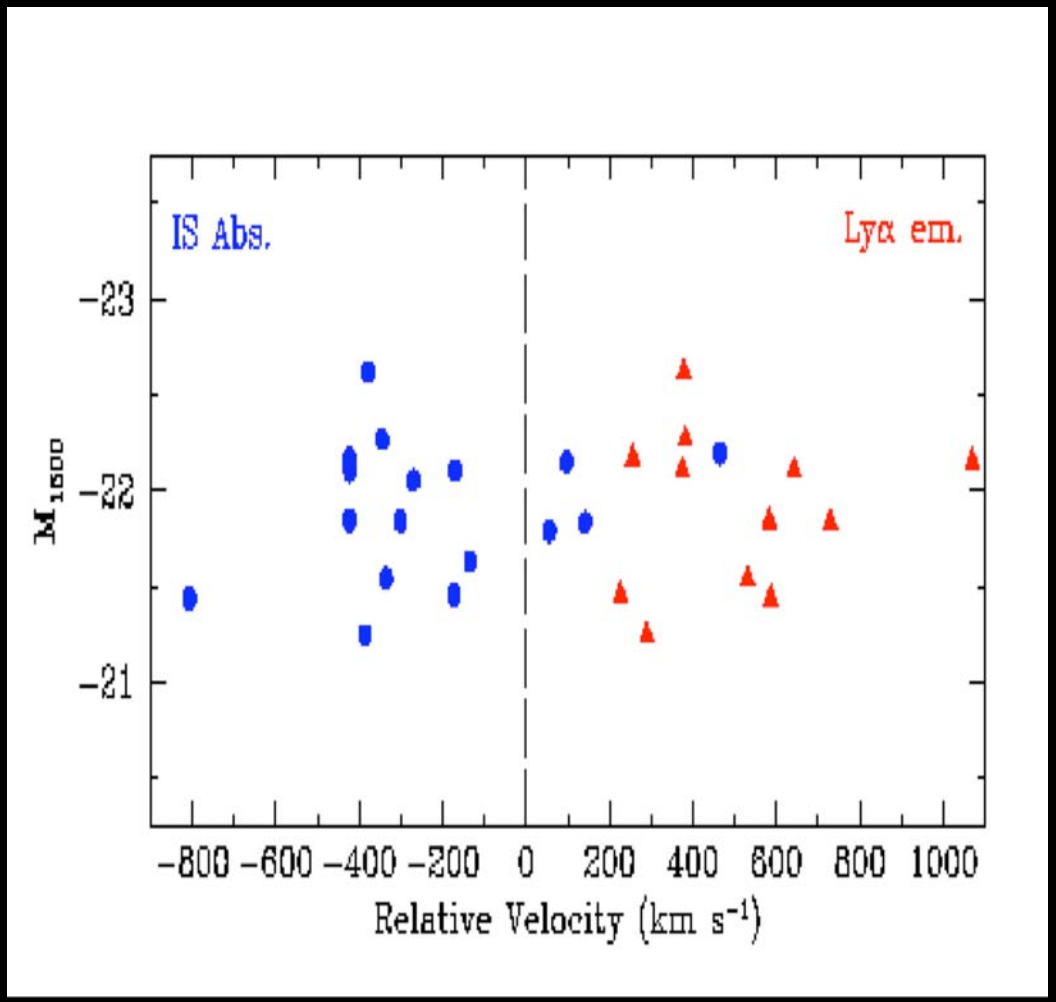


$T_{vir} \leq 10^4$ K at z ~ 10

Shapiro et al (2005)

#2: Galaxy Outflows

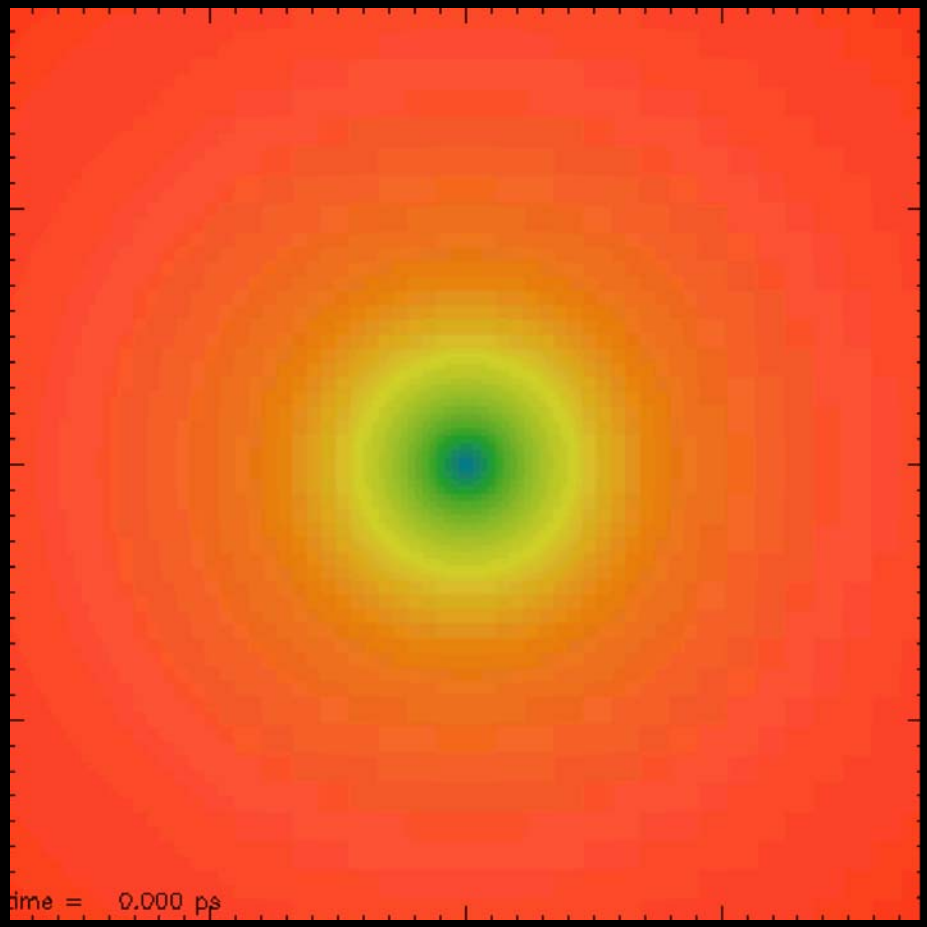
- In a sample of 19 Ly-break z~3 starbursting galaxies, winds were found in all objects.
- Velocities ~200 km/s
- Lyα-nebular emmi.+ metal absorption-nebular emission.
- SFR ~ 20 Msolar /yr



M. Pettini et al (2001)

Wind-Minihalo Interaction

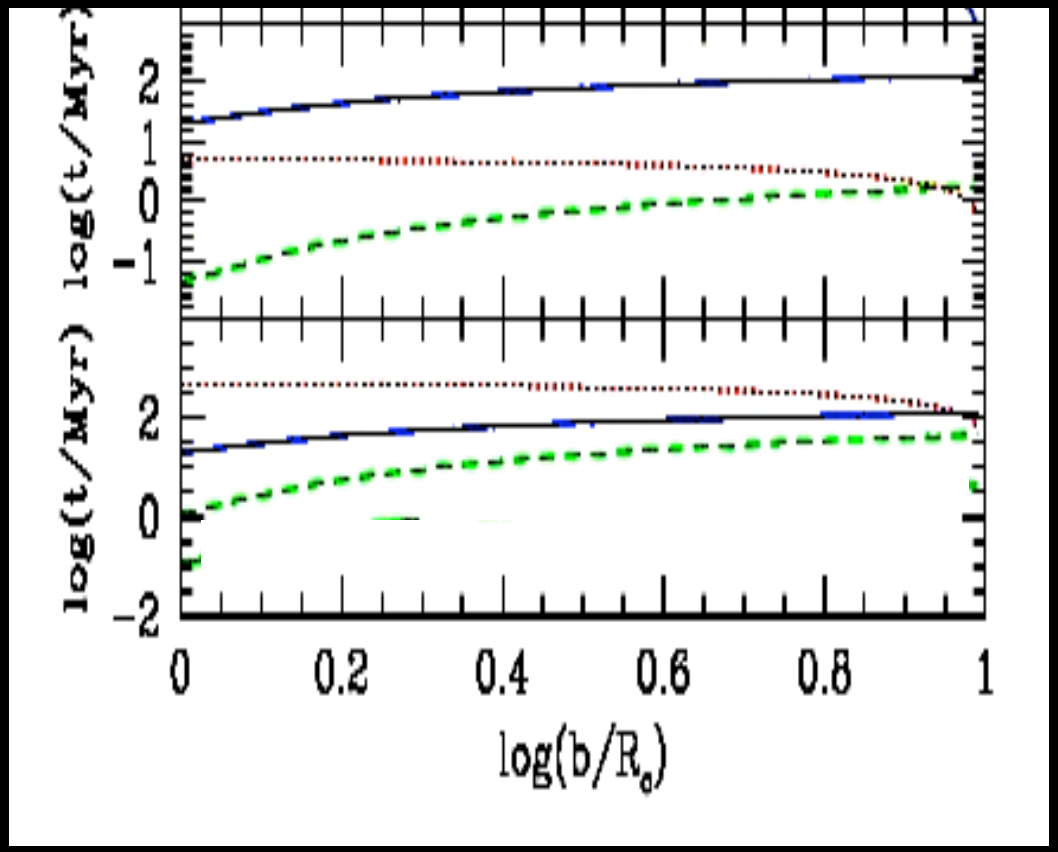
Ewind is = 10^{56} ergs ;
NFW halo => $M=10^{6.5}\ M_{sun}$;
$Z \sim 10^{-1.5}\ Z_{sun}$



ES, Weisheit, & Harlow (2004)

Fiducial Interaction

$E = 10^{56}$ ergs ; $M=10^{6.5}\,M_{sun}$; $Z\sim10^{-1.5}\,Z_{sun}$



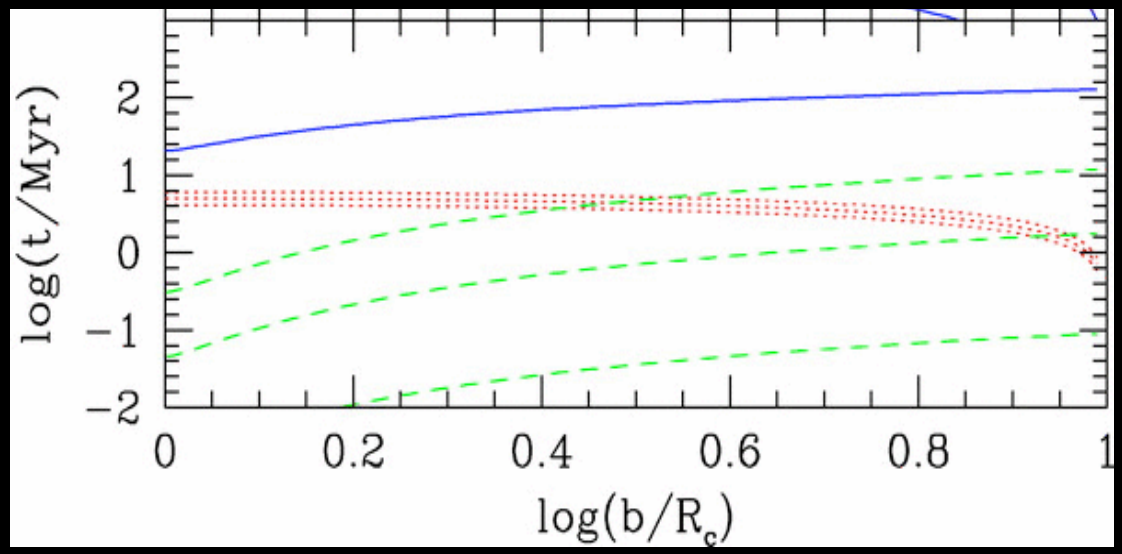
Free-fall time
Sound Xing time
Cooling time

Cooling by:
nonequilibrium H2, HD formation

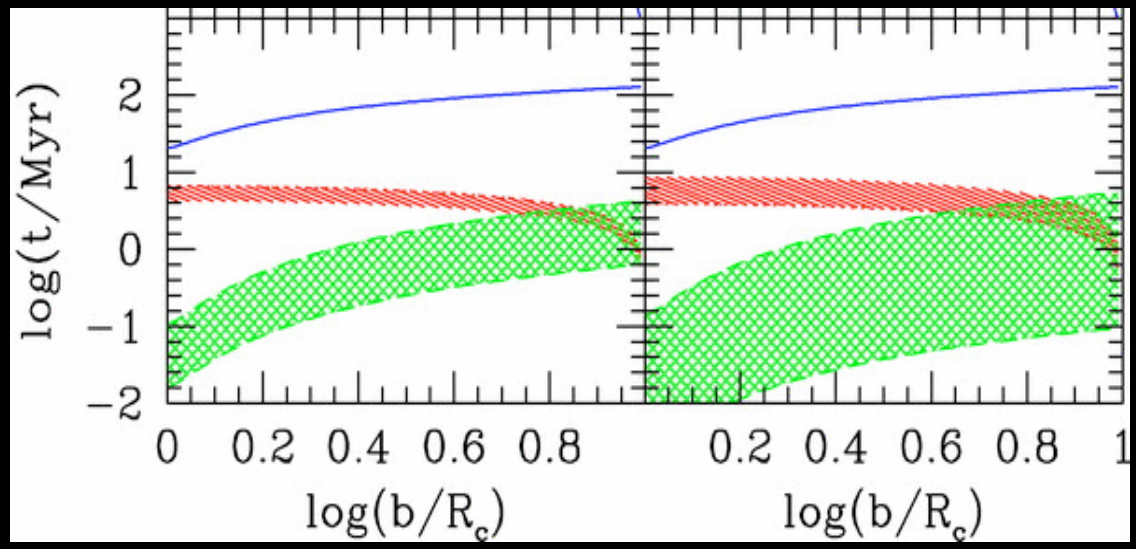
ES, Weisheit, & Harlow (2004)

$(H + e \rightarrow H^- + h\nu;\ H^- + H \rightarrow H_2 + e)$
$(H + H^+ \rightarrow H_2^+ + h\nu;\ H_2^+ + e \rightarrow H_2 + H^+)$

Minihalo mass



Starburst energy



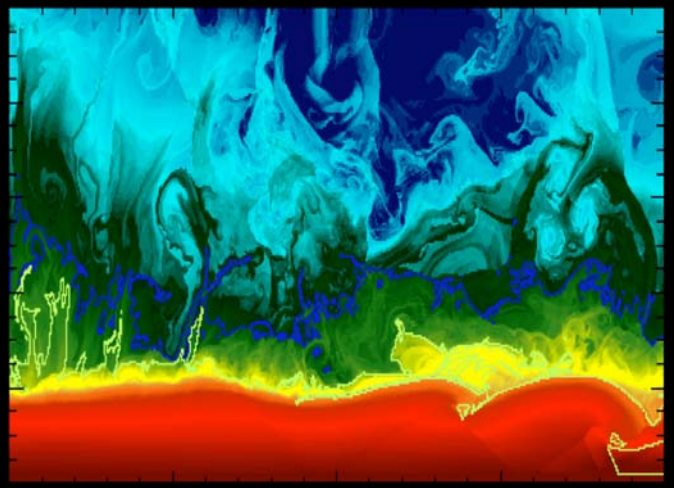
ES, Weisheit, & Harlow (2004)

FLASH3 (AMR) Simulations

- CHEMISTRY + COOLING
- Taken from Glover & Abel (2008)
- 14 species:

  $H, H^+, H^-, D, D^+, D^-, He, He^+, He^{++}, H_2, H_2^+, HD, HD^+$ and e^-
- 84 total reactions

Will Gray, ES (in prep)



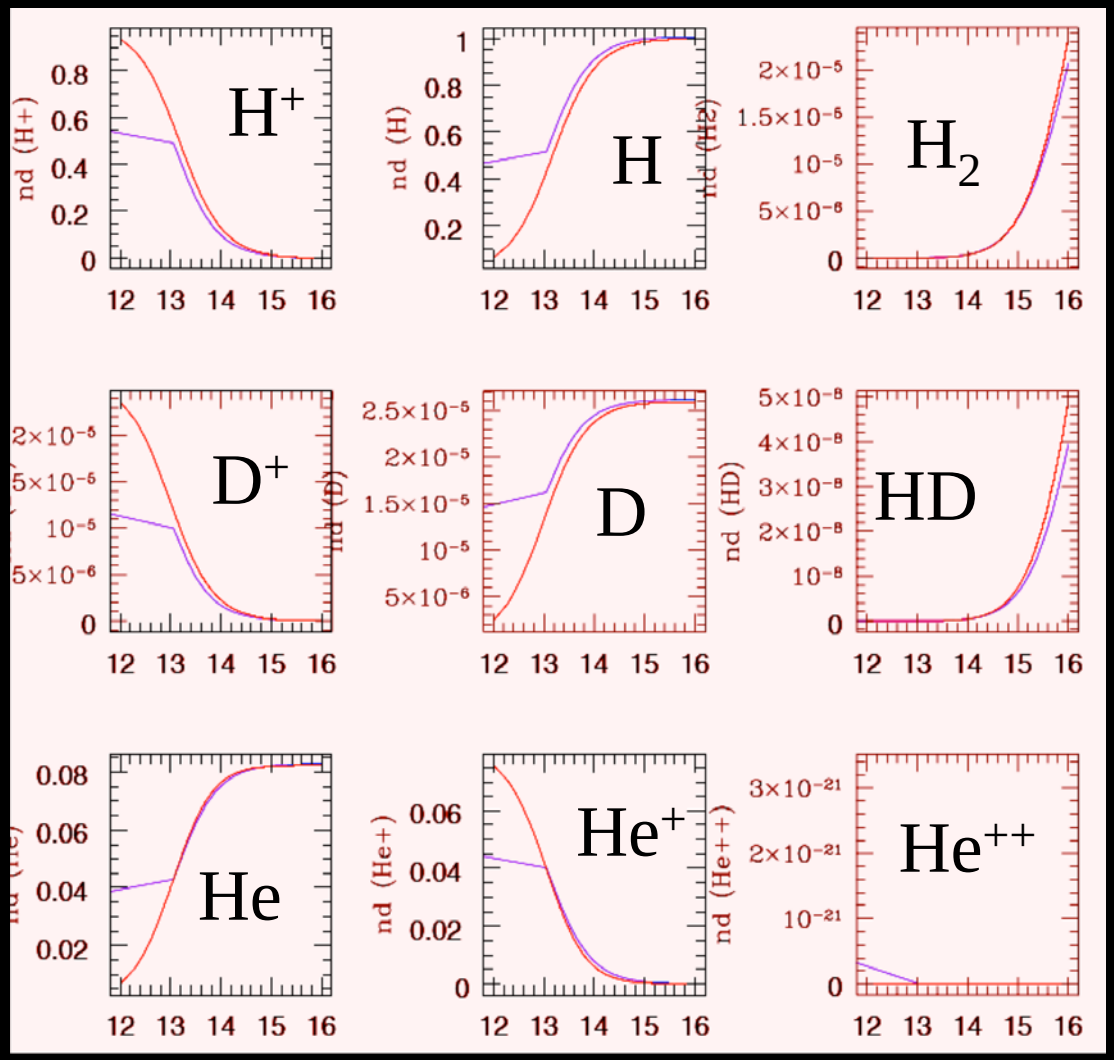
Chemistry

- Rate Matrix is Dense, Stiff Equations:
  - Have to use general implicit solver
  - Bader-Deuflhard Method, with LU decomposition
  - You still have to subcycle when any abundance changes than 10%

Test Results

--Fixed T and n
--Primordial Composition
--H and He initially (singly) ionized

n_H=0.01 cm^{-3}
T = 100 K



Gray & ES (in prep)

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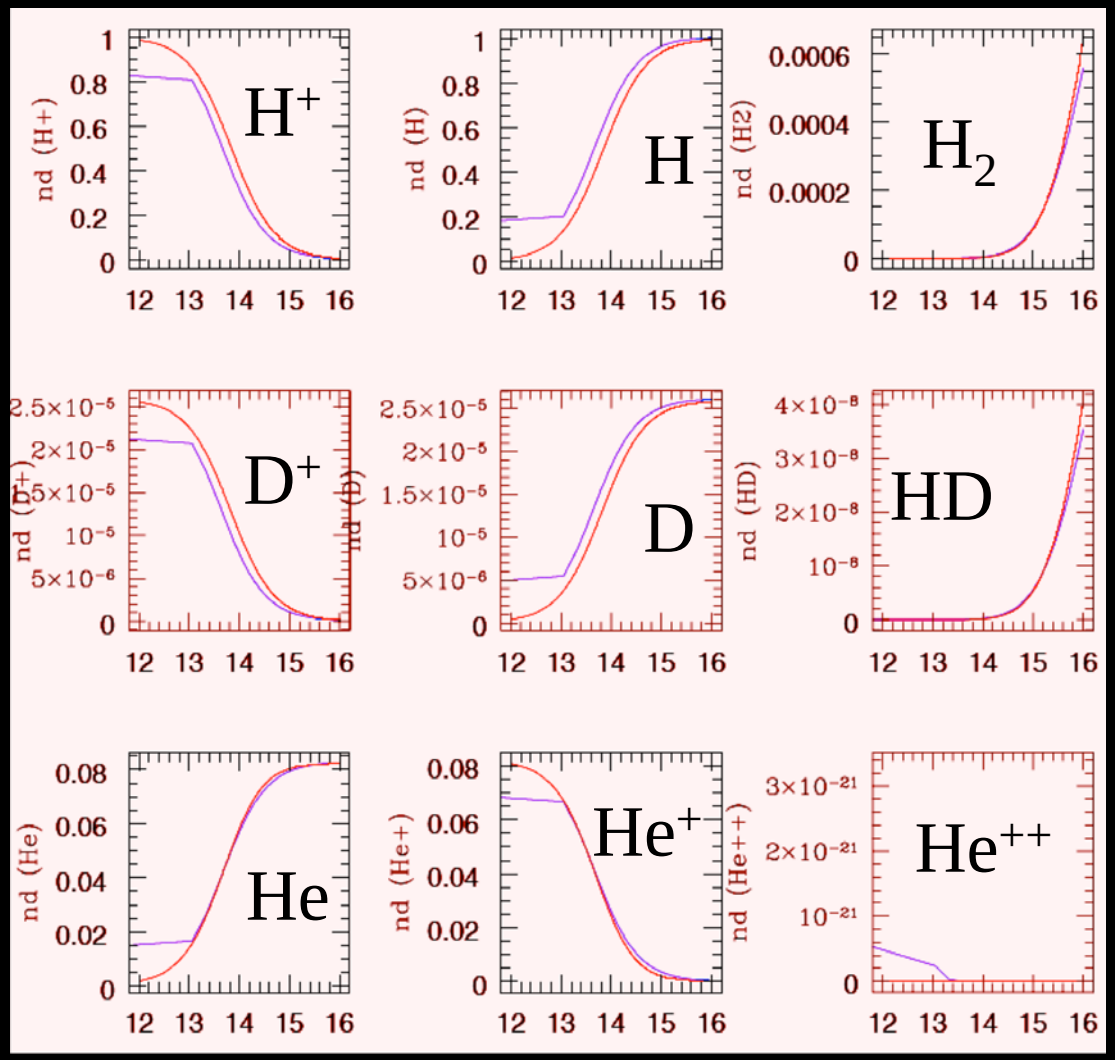


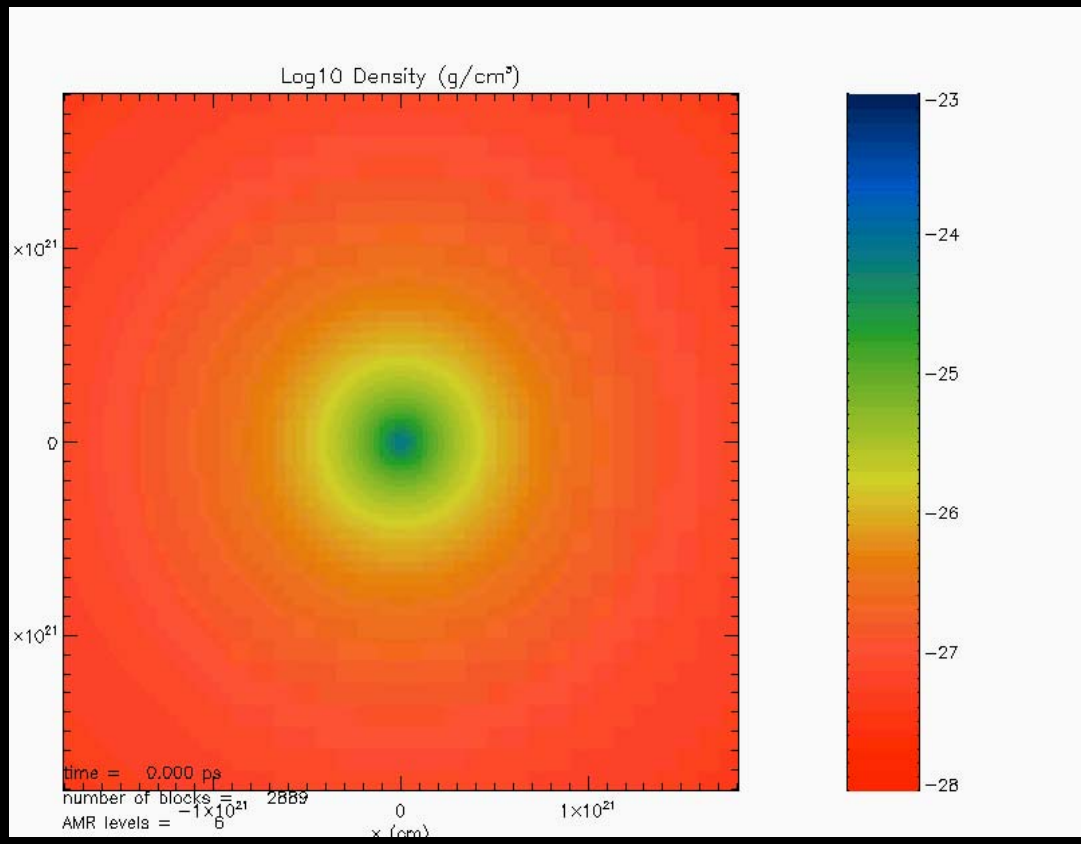
Gray & ES (in prep)

Cooling and Heating

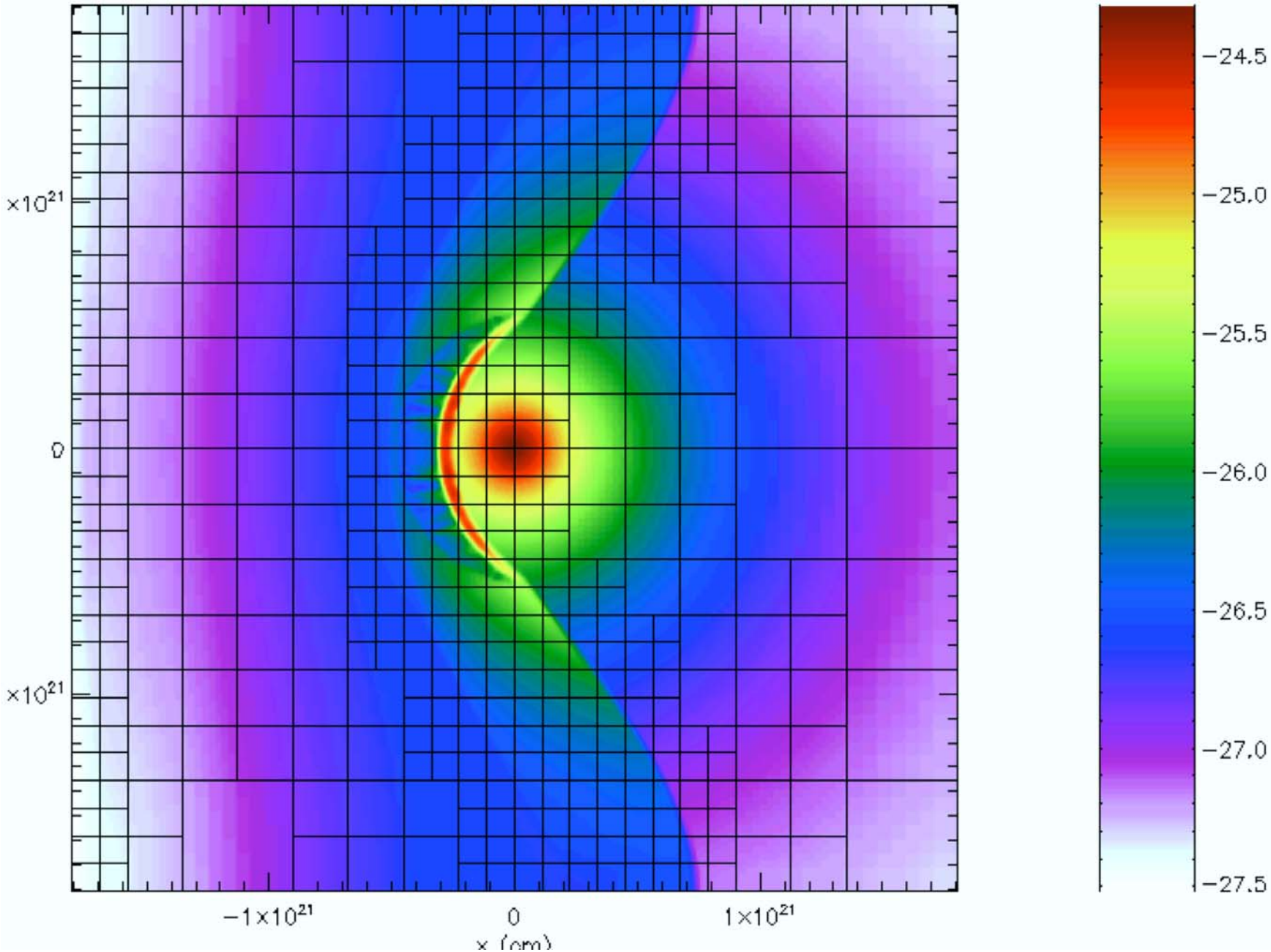
- Within each chemistry subcycle
  - Account for internal energy change due to Recombination/ionization
  - Implement radiative cooling. (at low T, H_2, HD are the major coolants).

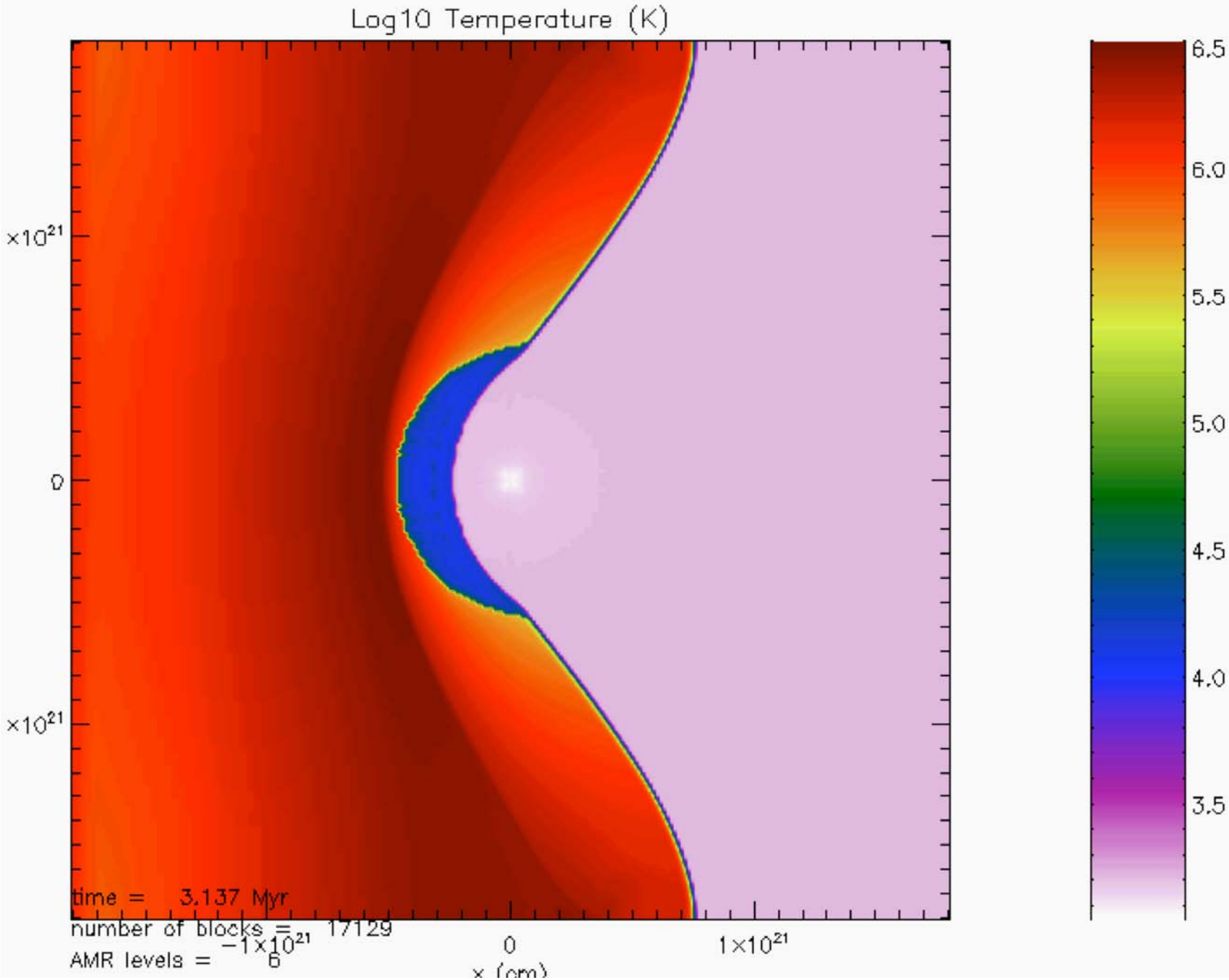
FLASH3 (AMR) Simulations

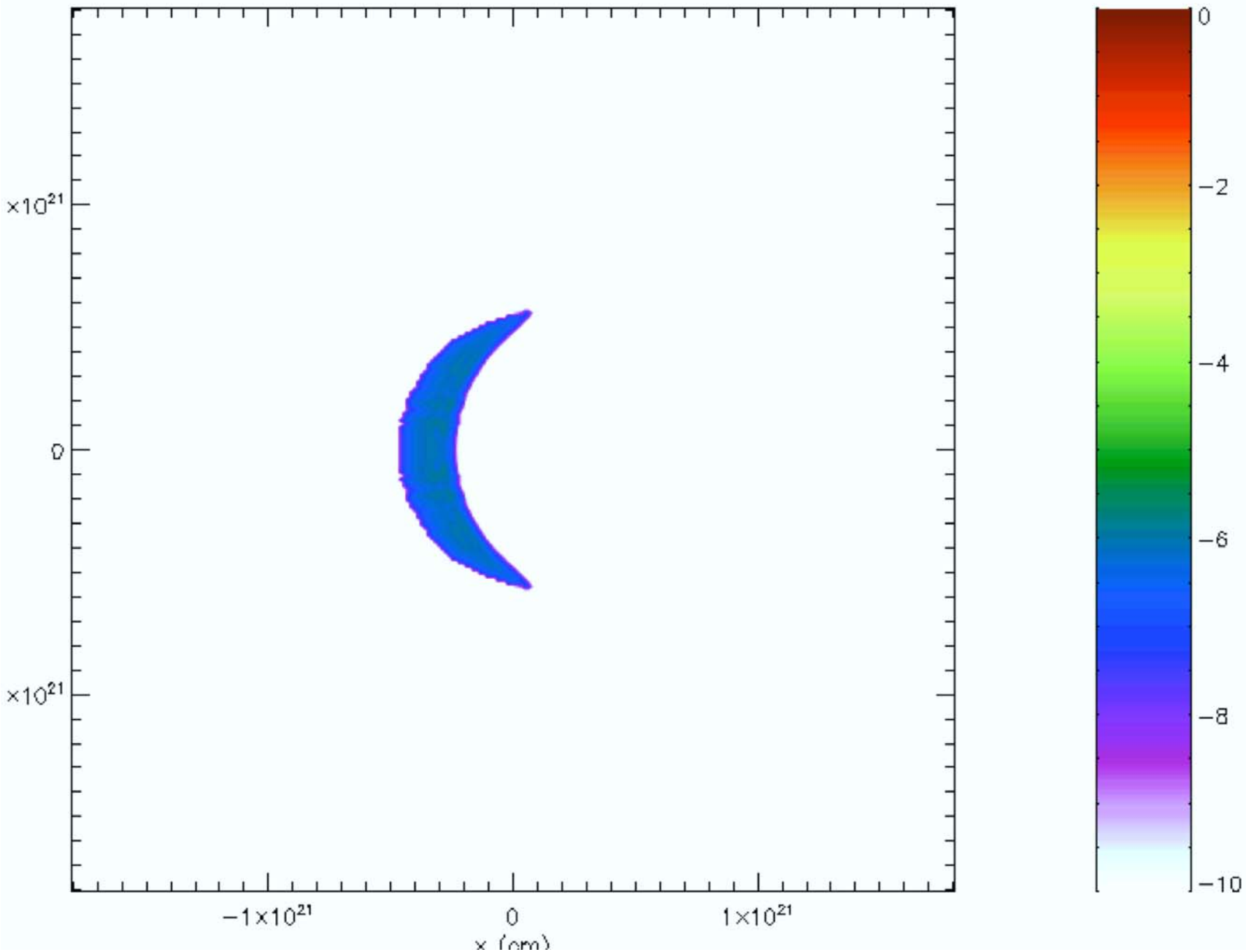
- initially hydrostatic cluster, static gravity
- 5 levels of refinement, 512^3 effective resolution, 1 kpc^3 box
- NFW halo ($M_{tot}=10^{6.5}$ M_{sun})
- Saguaro computer cluster (4096 core cluster at ASU)
- Chemistry and Cooling

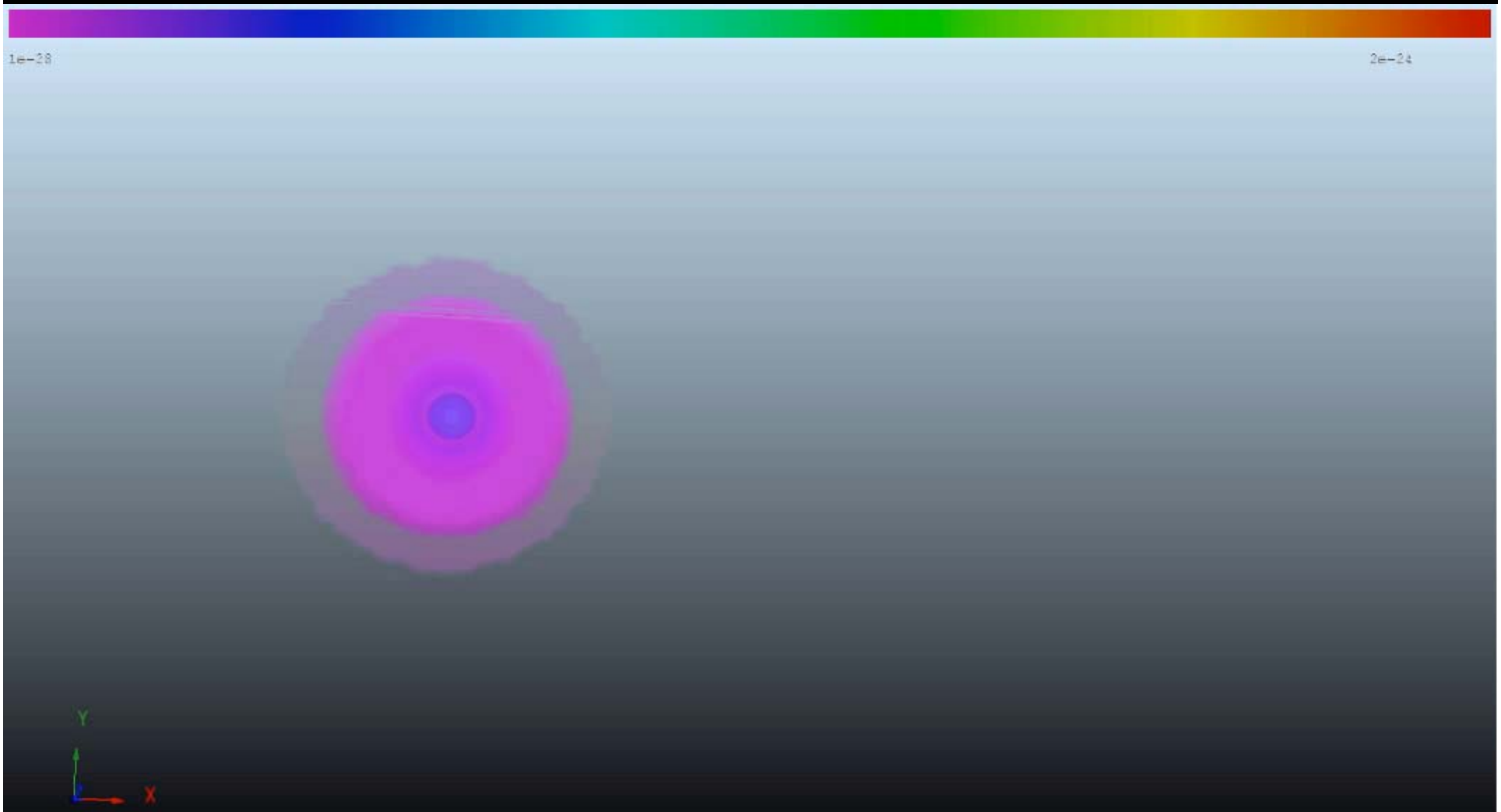


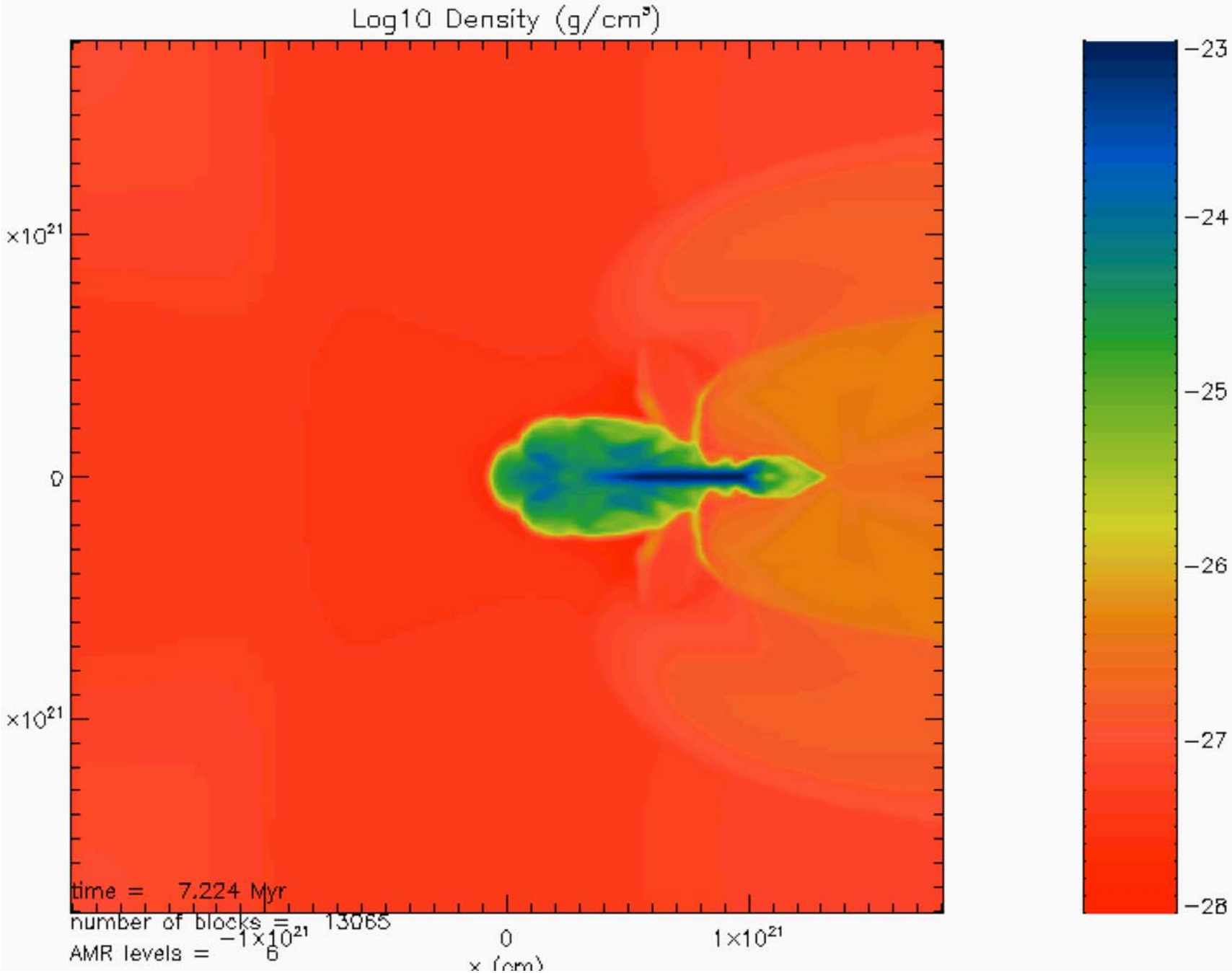
Gray & ES (in prep)

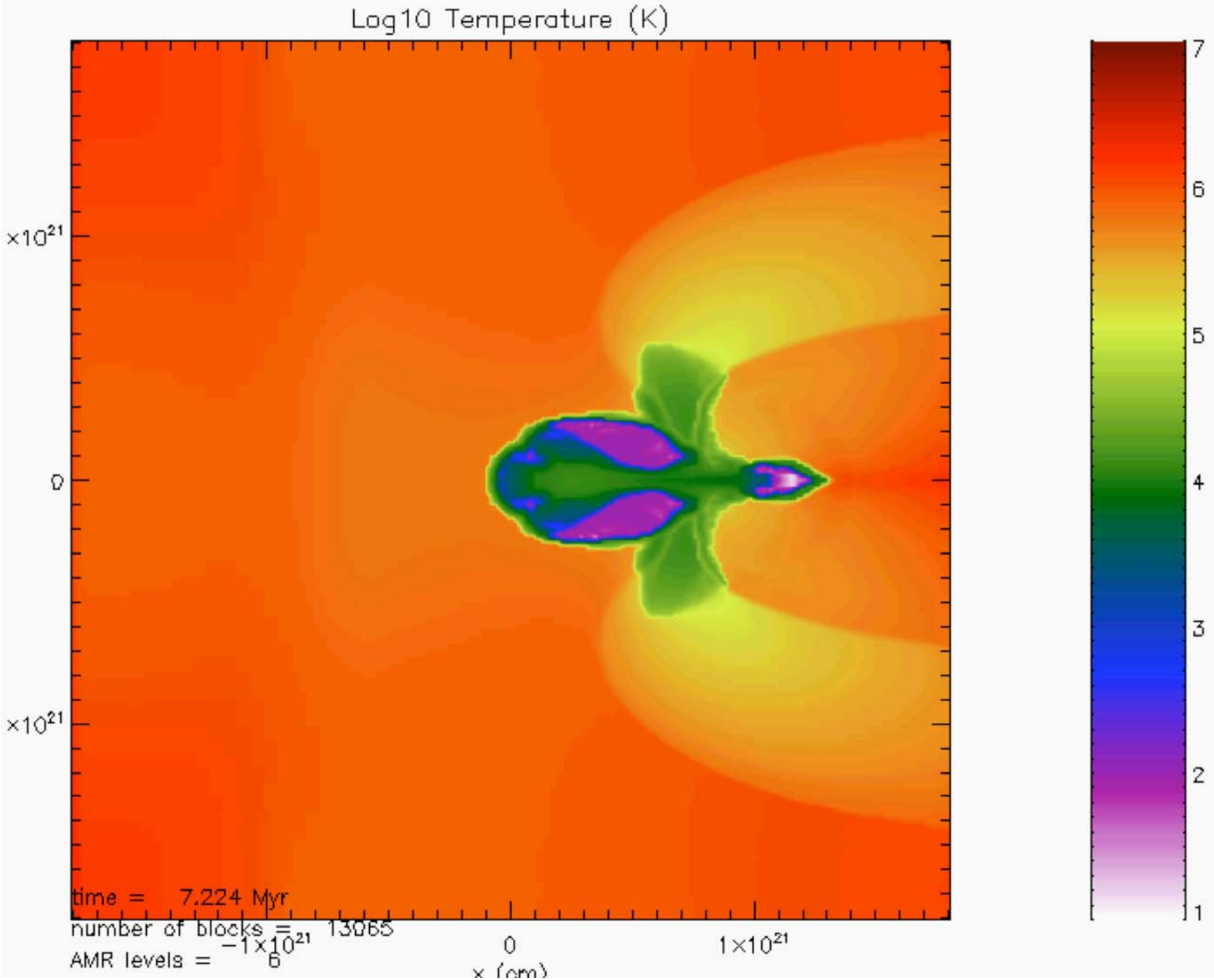

×10^21
0
×10^21
−1×10^21
0
1×10^21
x (cm)
−24.5
−25.0
−25.5
−26.0
−26.5
−27.0
−27.5


Log10 Temperature (K)
6.5
6.0
5.5
5.0
4.5
4.0
3.5
×10^21
0
×10^21
time = 3.137 Myr
number of blocks = 17129
AMR levels = 6
−1×10^21
0
1×10^21
x (cm)

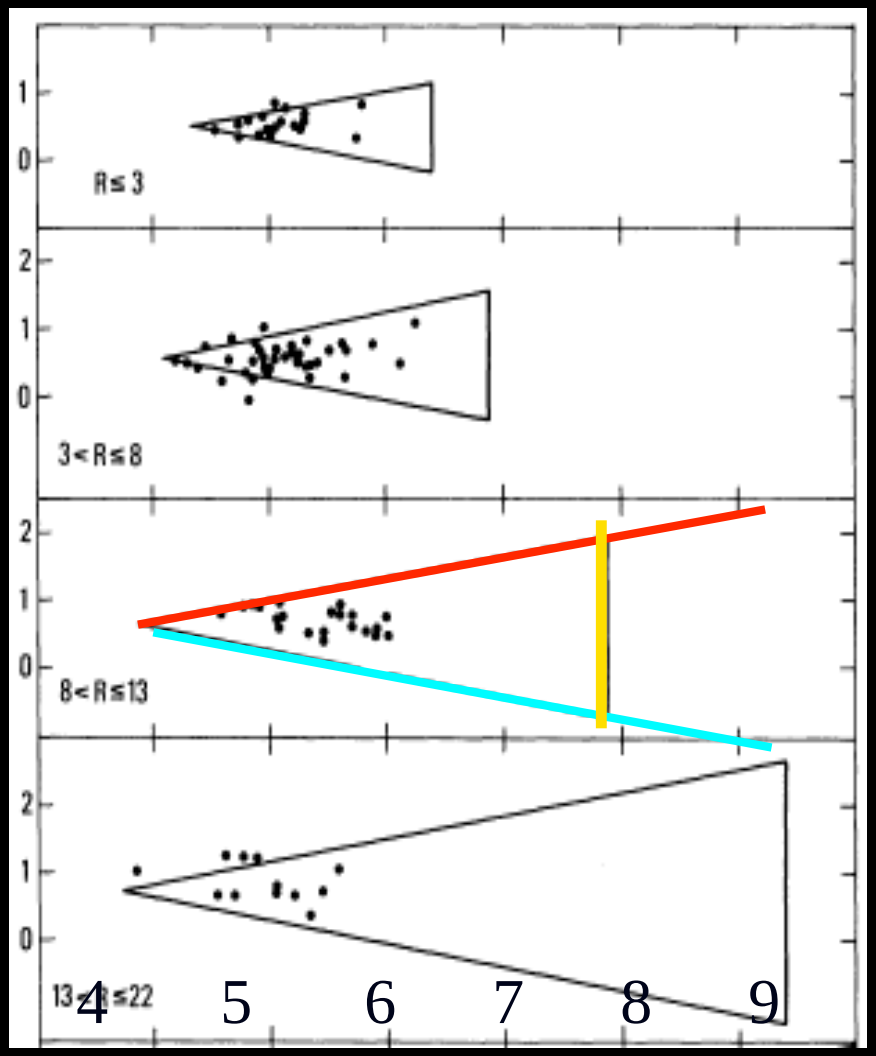

×10^21
0
×10^21
−1×10^21
0
1×10^21
x (cm)
0
−2
−4
−6
−8
−10


1e-28
2e-24
Y
X
Timestep 3 of 108


Log10 Density (g/cm³)
×10²¹
0
×10²¹
time = 7.224 Myr
number of blocks = 13065
AMR levels = 6
−1×10²¹
0
1×10²¹
x (cm)
−23
−24
−25
−26
−27
−28


Log10 Temperature (K)
×10^21
0
×10^21
time = 7.224 Myr
number of blocks = 13065
AMR levels = 6
−1×10^21
0
1×10^21
x (cm)
7
6
5
4
3
2
1

Issue # 1: Globular Cluster Mass/Sizes



Log($r_{1/2}$/pc)

Log(M/M_{sun})

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

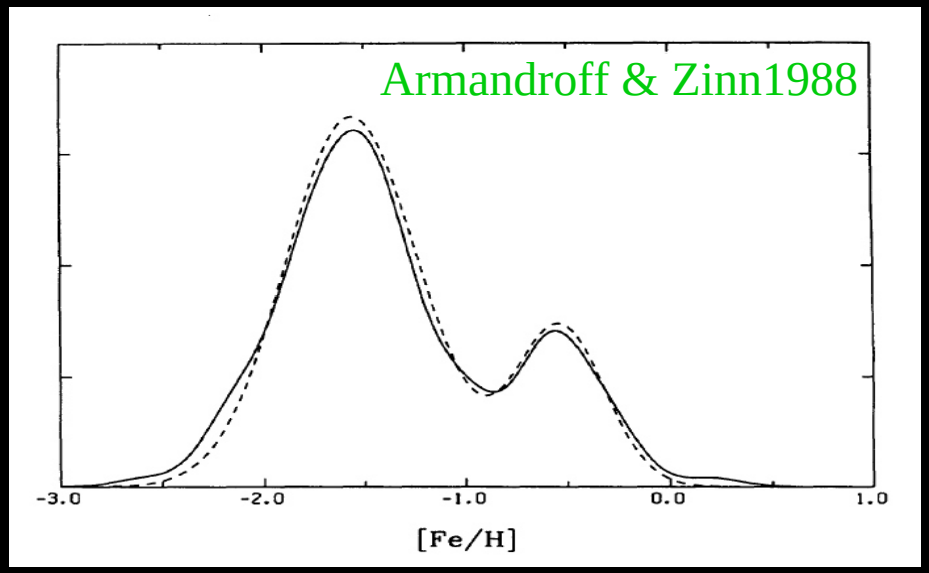
Evaporation
$t \sim r_{1/2}^{3/2}\ M^{1/2}$

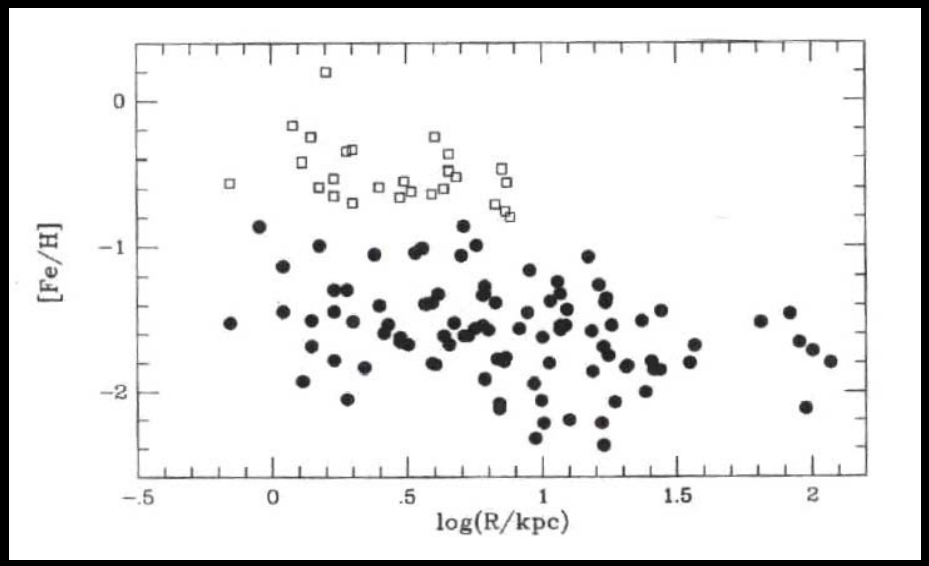
Dynamical Friction
$t \sim M^{-1}\ R^{2}$

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

Castellani & Caputo 1984

#2: Globular Cluster Metallicities





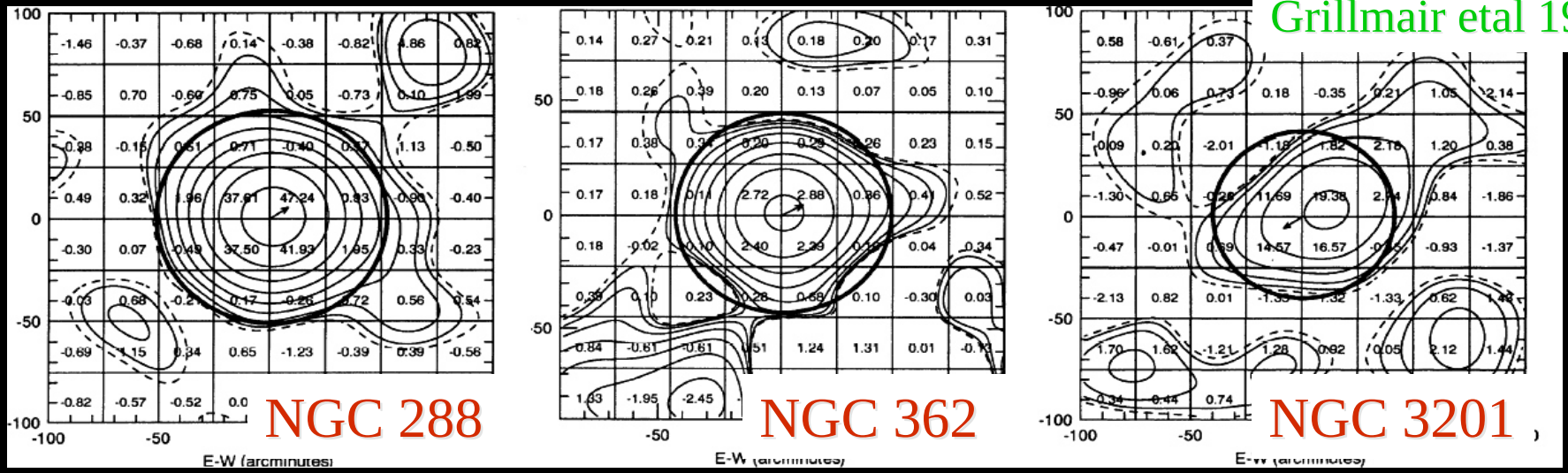
Double-peaked
[Fe/H] ~ -0.5 ± .25
[Fe/H] ~ -1.6 ± .35

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

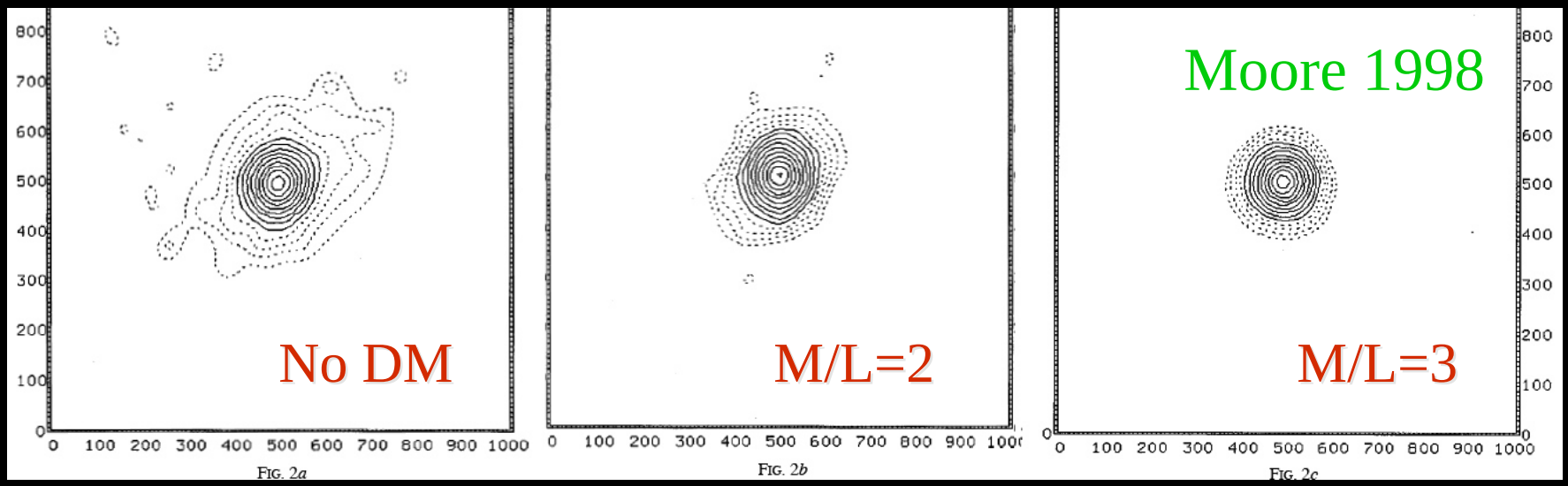
Subgrid models of turbulent mixing

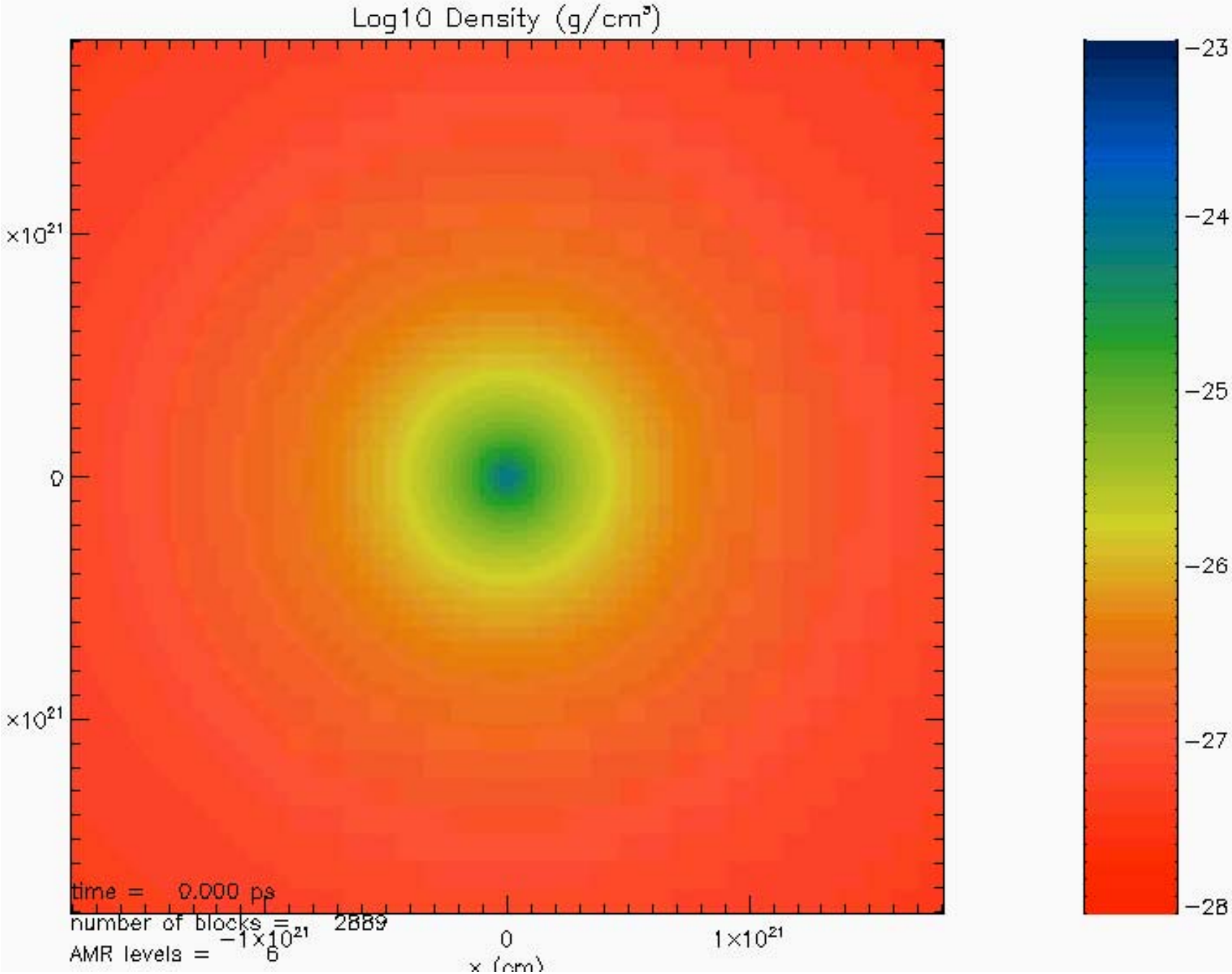
#3: No Dark Matter In GCs

Grillmair etal 1995



Moore 1998




Log10 Density (g/cm³)
×10²¹
0
×10²¹
time = 0.000 ps
number of blocks = 2889
AMR levels = 6
−1×10²¹
0
1×10²¹
x (cm)
−23
−24
−25
−26
−27
−28

Thanks!