Formation of Compact Stellar Clusters by High-redshift Galaxy Outflows

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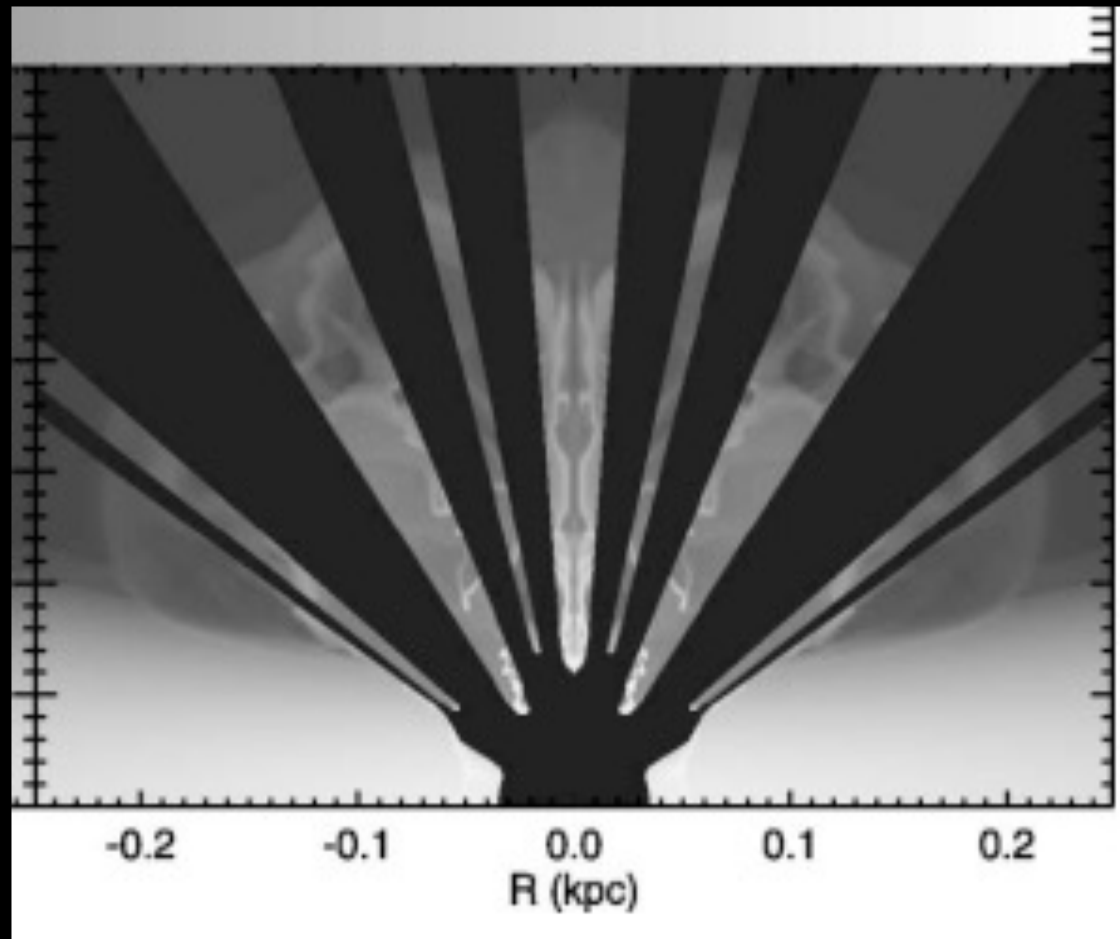
Feedback in the Early Universe

- In a sample of 19 Ly-break z~3 starbursting galaxies, winds were found in all objects.
- Velocities ~200 km/s
- Lya-nebular emmi.+ metal absorption-nebular emission.
- SFR ~ 20 $M_{\odot}$ /yr

- Ionizing photons get trapped behind outflows

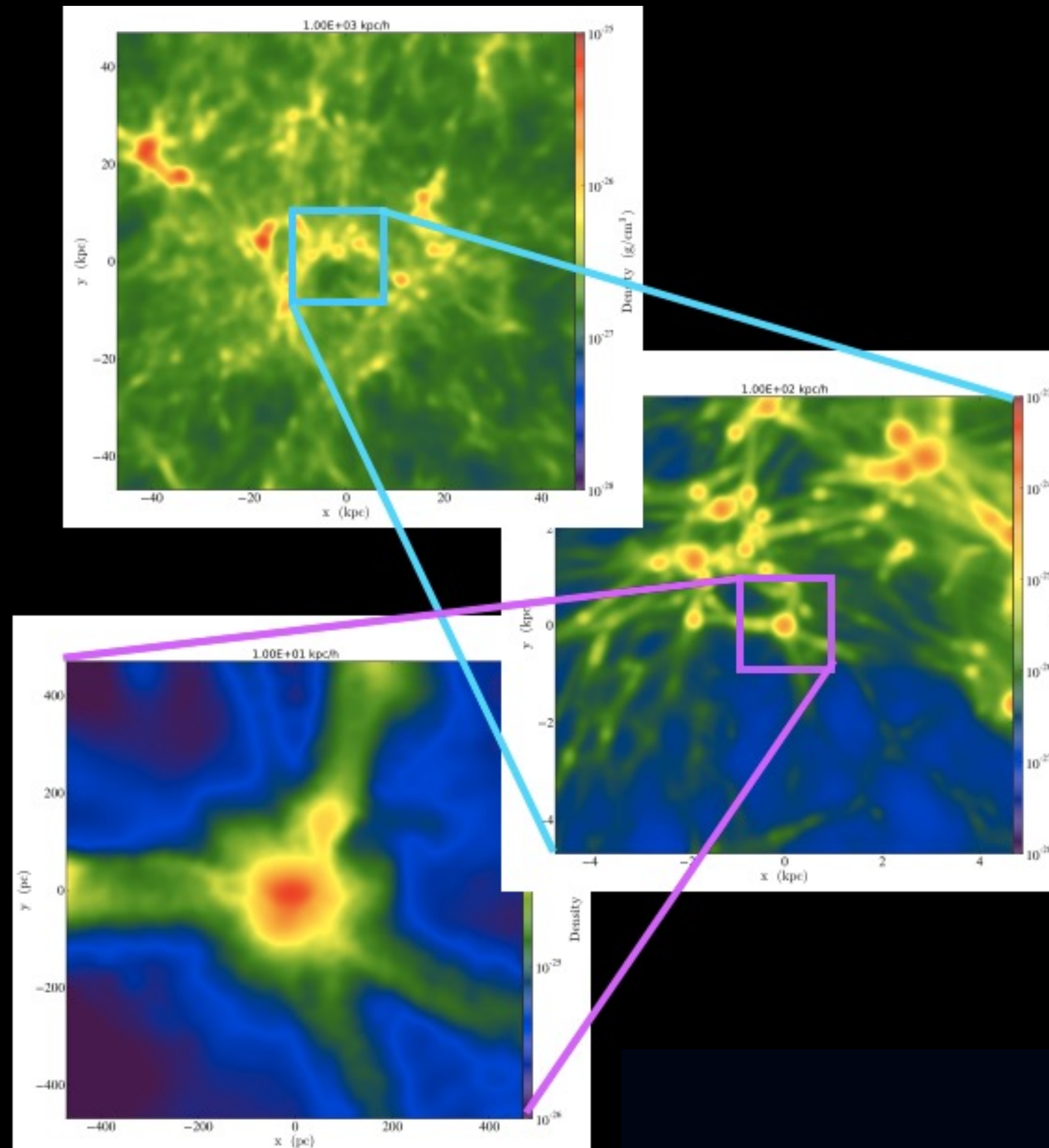


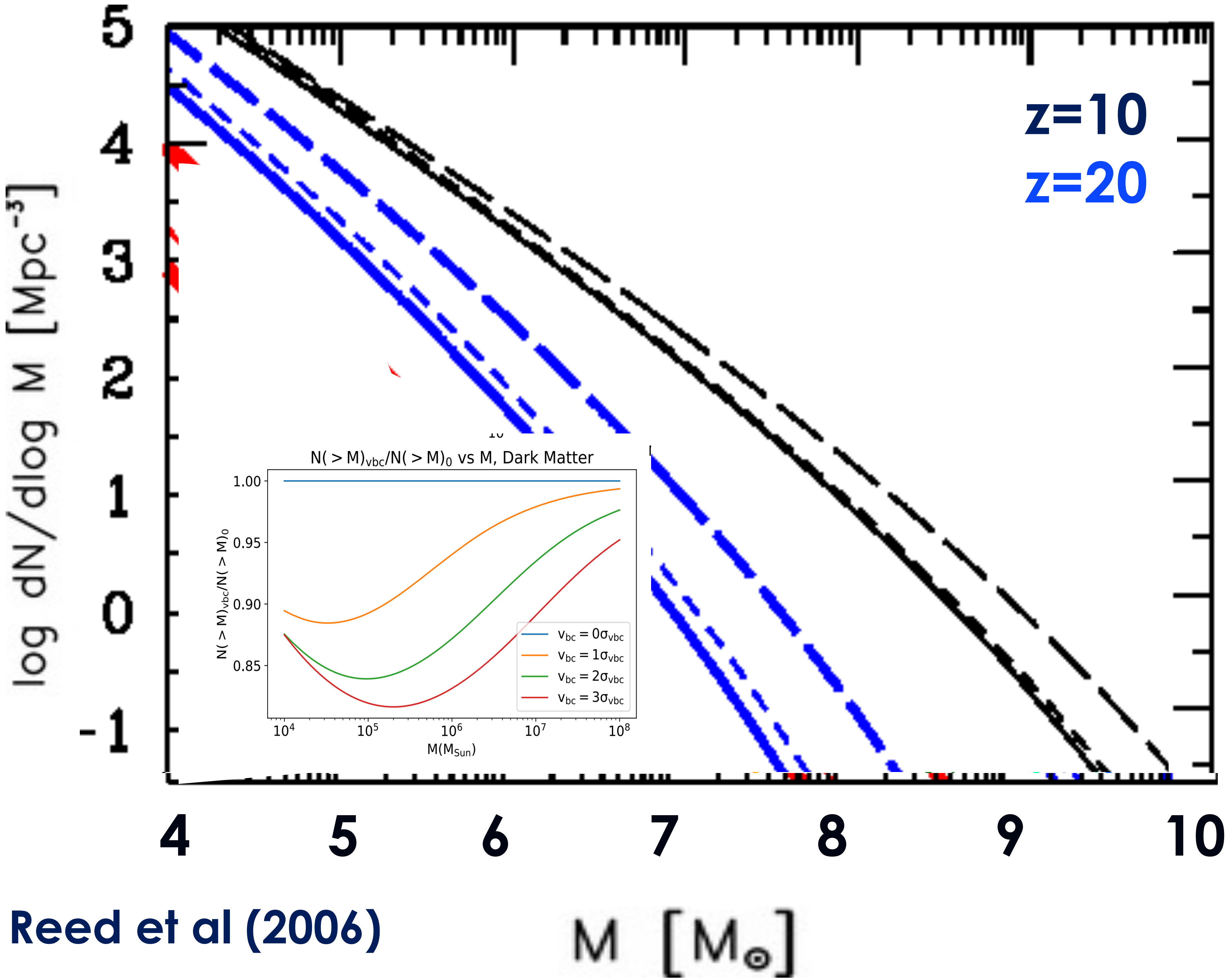
Fujita et al (2003)

Minihalos

- Full of Primordial "Minihalos":
  - Virialized clumps of dark and baryonic matter
  - Virial temperature below atomic cooling limit ($T < 10^4$ K)
  - Small masses ($\sim 10^6 M_\odot$)
  - Primordial chemistry (76% H; 24% He)

Can't form stars after LW background becomes significant.





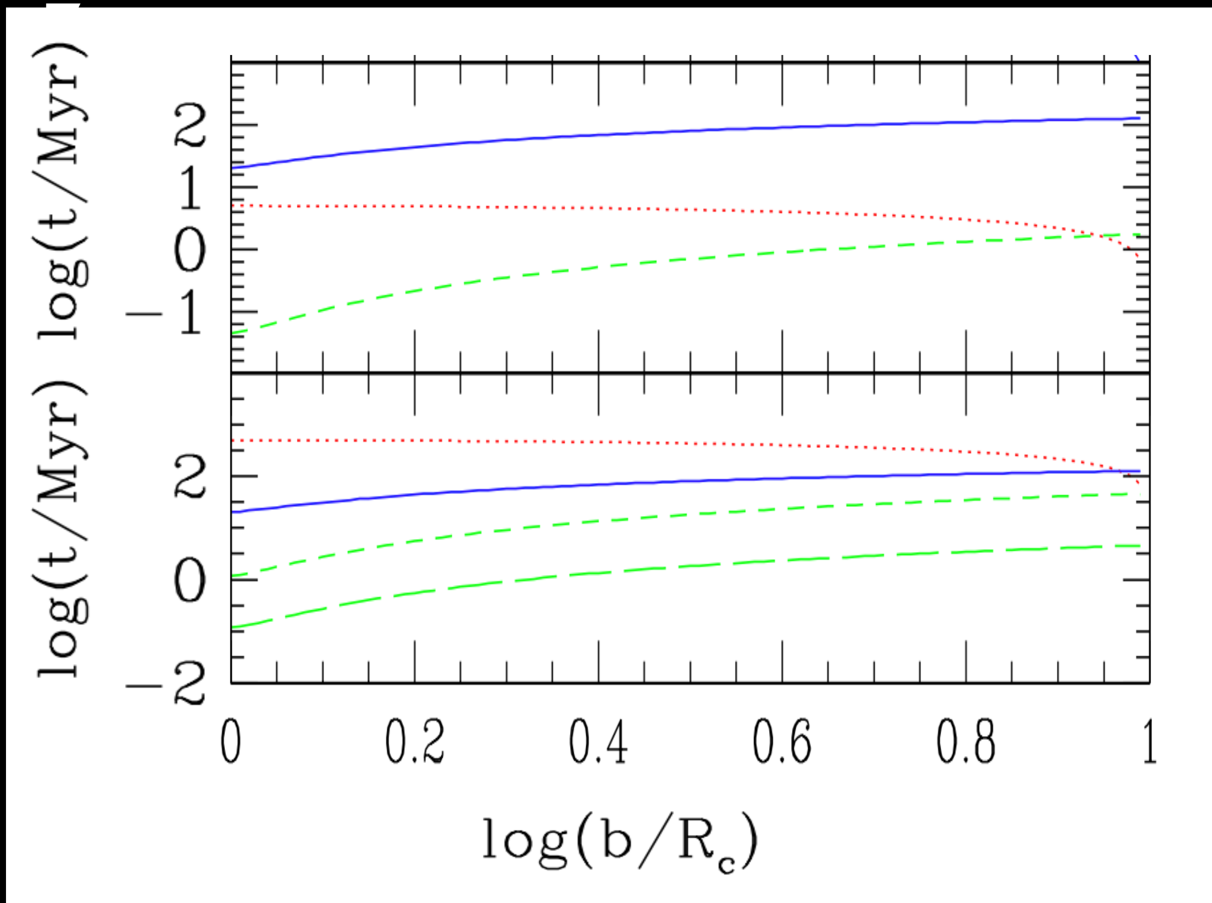
Reed et al (2006)

Fiducial Interaction

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

Initial Interaction

Further Cooling



Free-fall time

Sound Xing time

Cooling time

Further cooling by:
nonequilibrium
H_2, HD formation,
C II, FeII, SiII

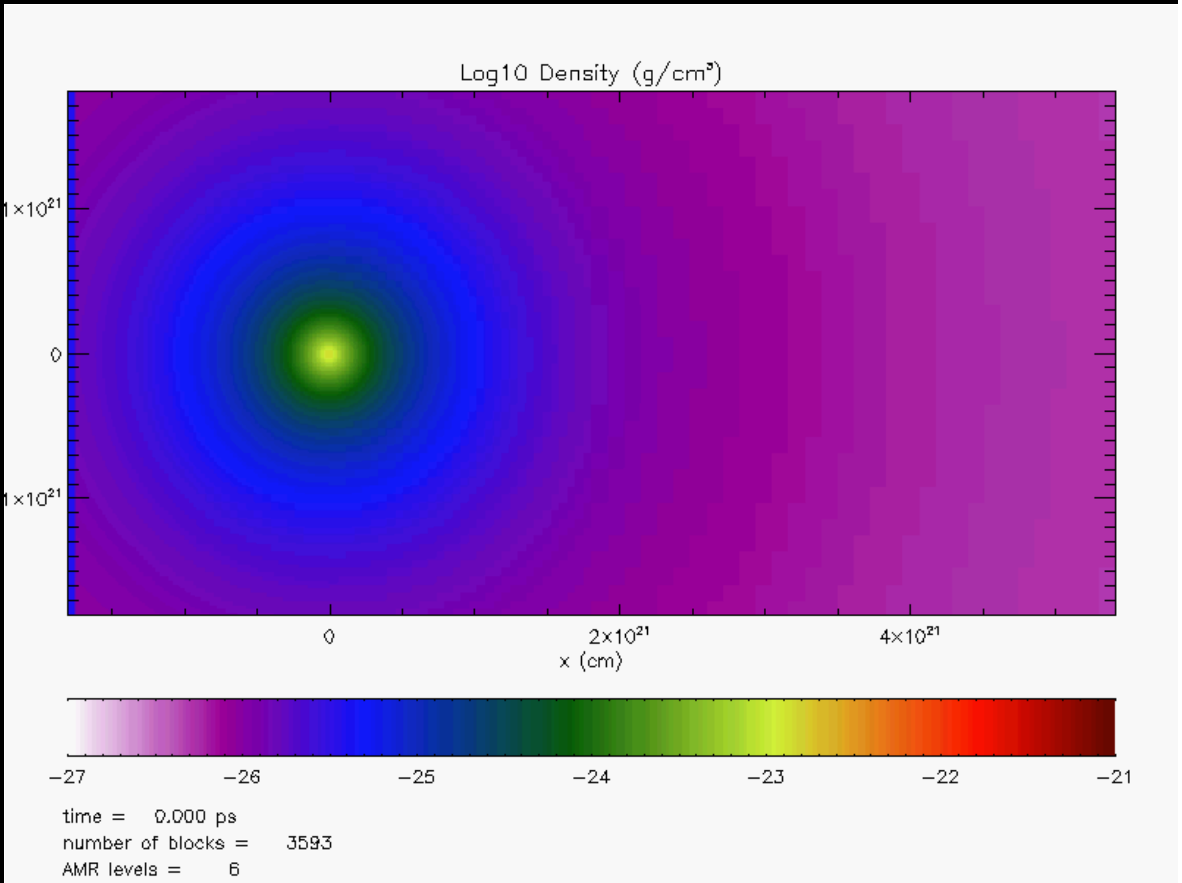
ES, Weisheit, & Harlow (2004)

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

$(H + H^+ \rightarrow H_2^+ + \gamma;\ H_2^+ + H \rightarrow H_2 + H^+)$

Idealized Flash Simulations

- initially hydrostatic cluster, fully neutral, static gravity
- 1 kpc^2 x 2.0 kpc box 5 levels of refinement, 4 pc effective resolution,
- NFW halo ($M_{tot}=3\times10^6\ M_\odot$)
- 150 km/s 5 Myr shock
- Chemistry and Cooling



Gray & ES (2010, 2011a, b)

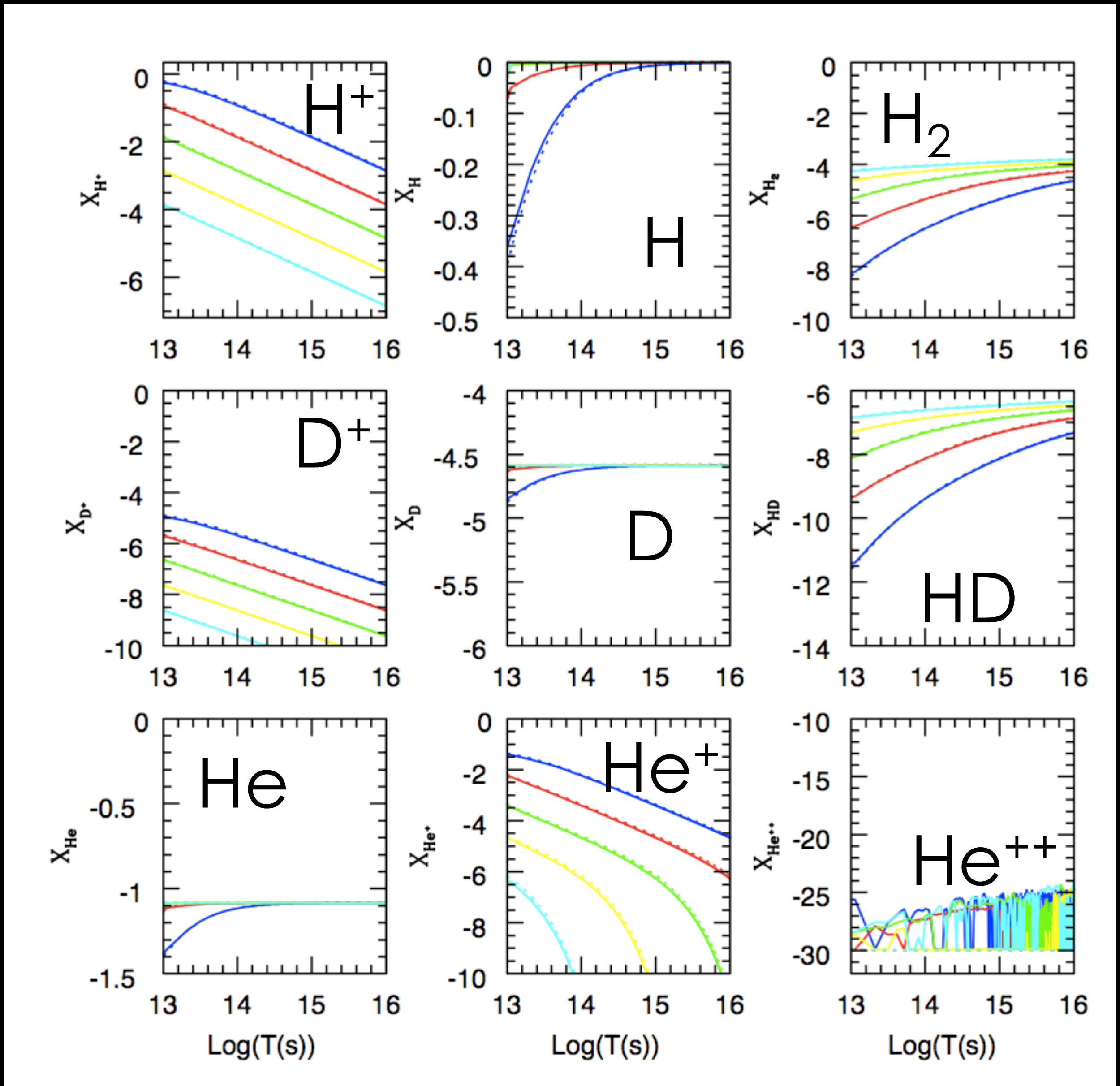
Test Results

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

T = 100 K

Blue: n=0.01 cm^{-3}
Red: n=0.1 cm^{-3}
Green: n=1.0 cm^{-3}
Yellow: n=10.0 cm^{-3}
Teal : n=100.0 cm^{-3}

Gray & ES (2010)



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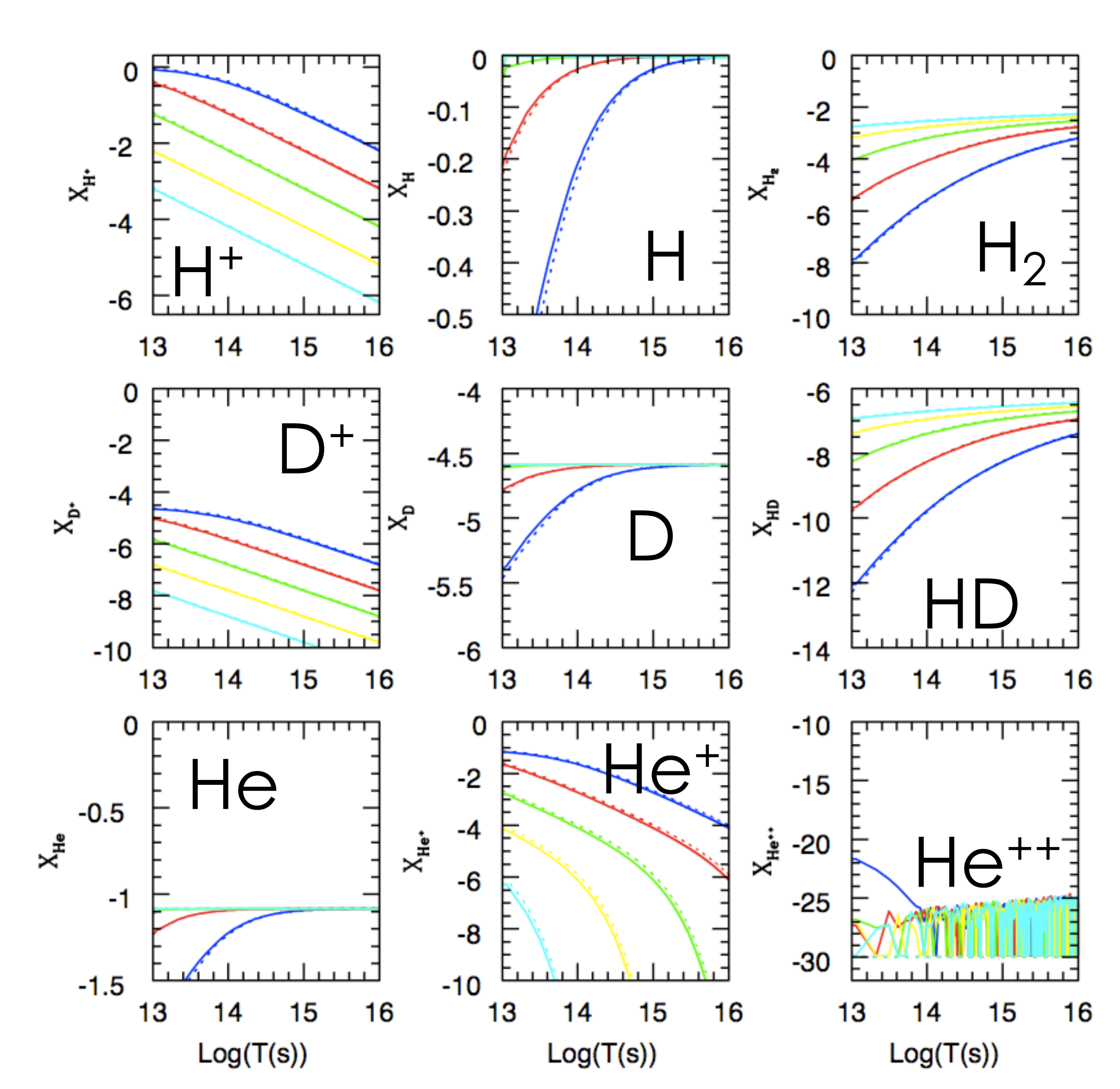
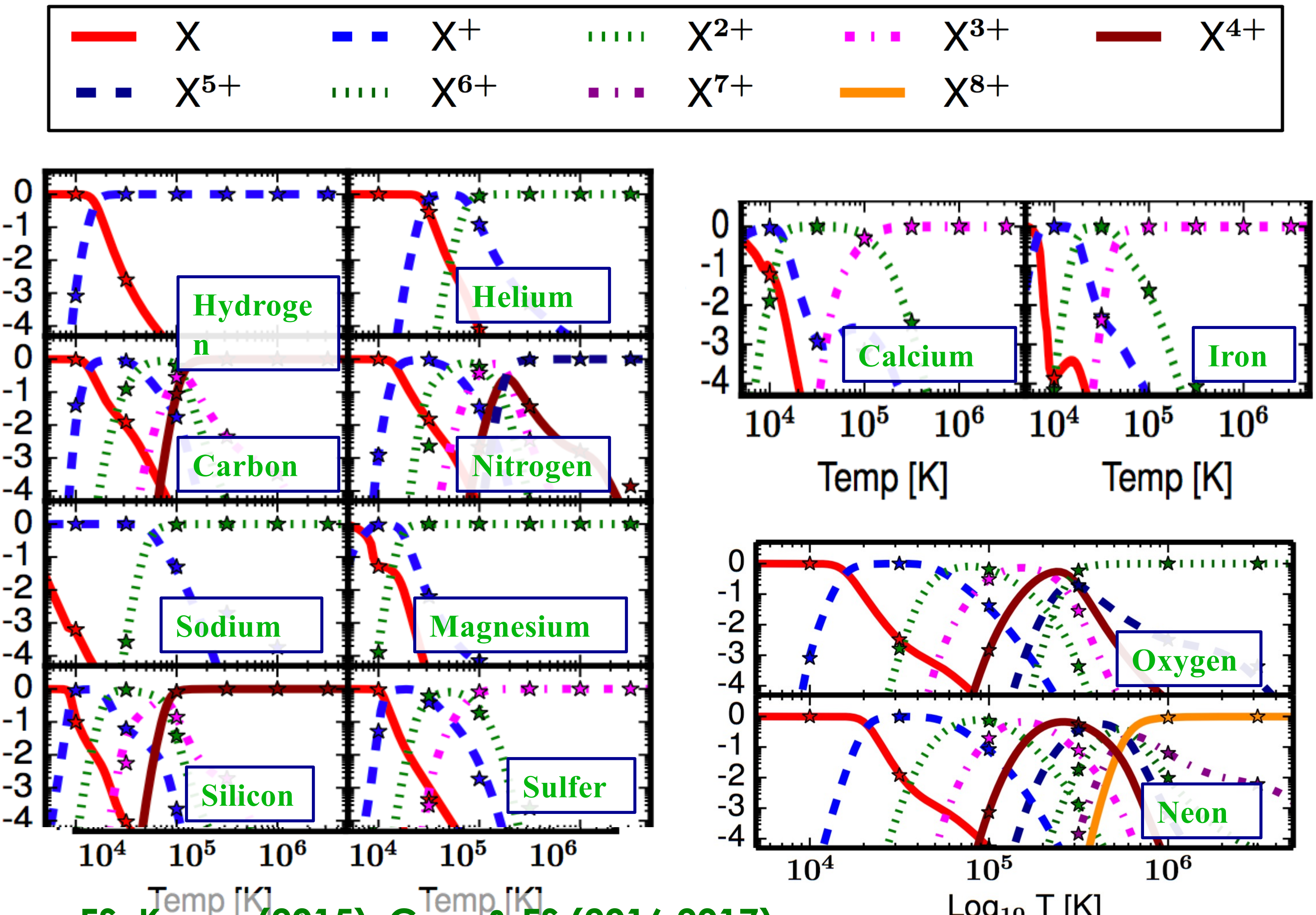
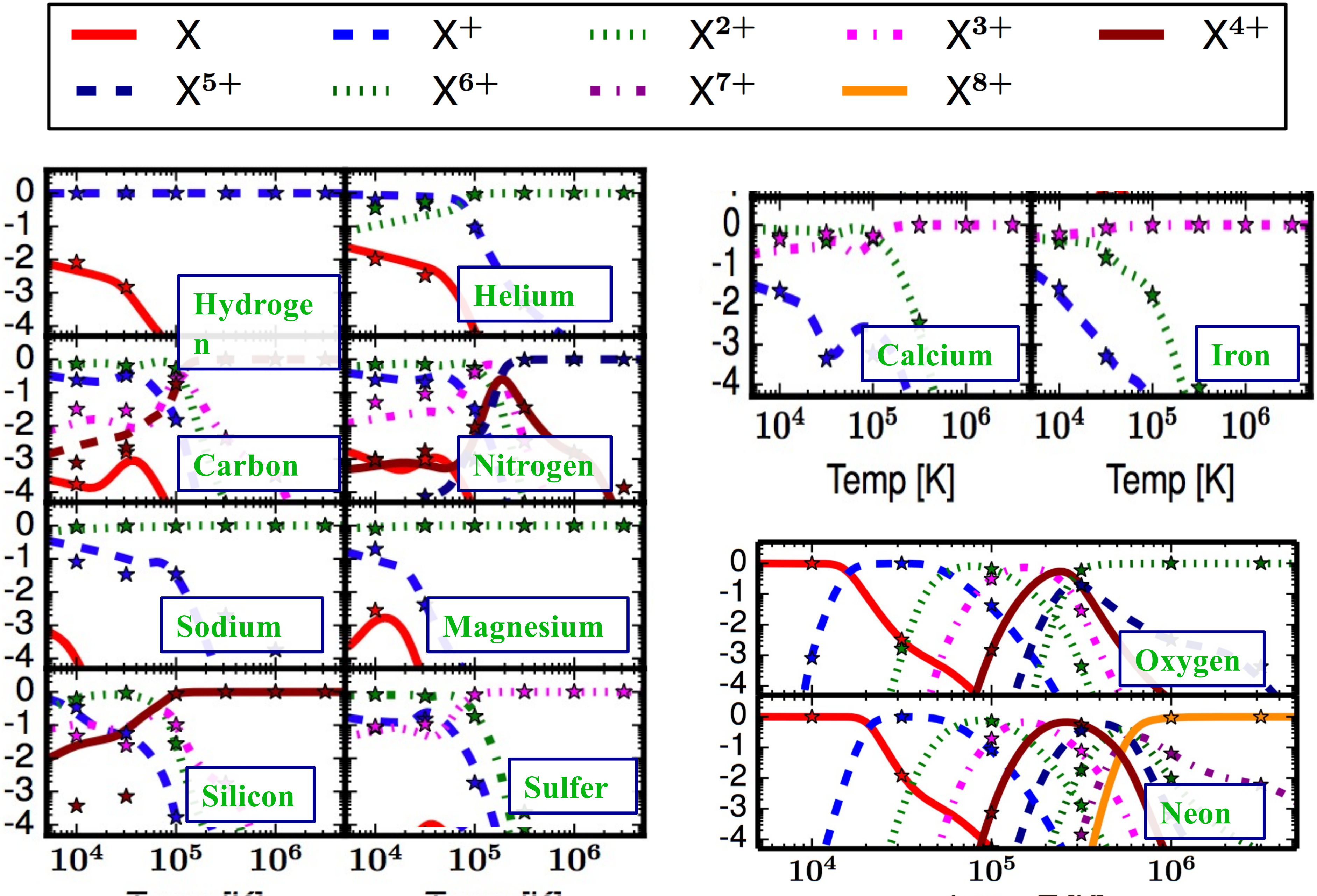


No Ionizing Background

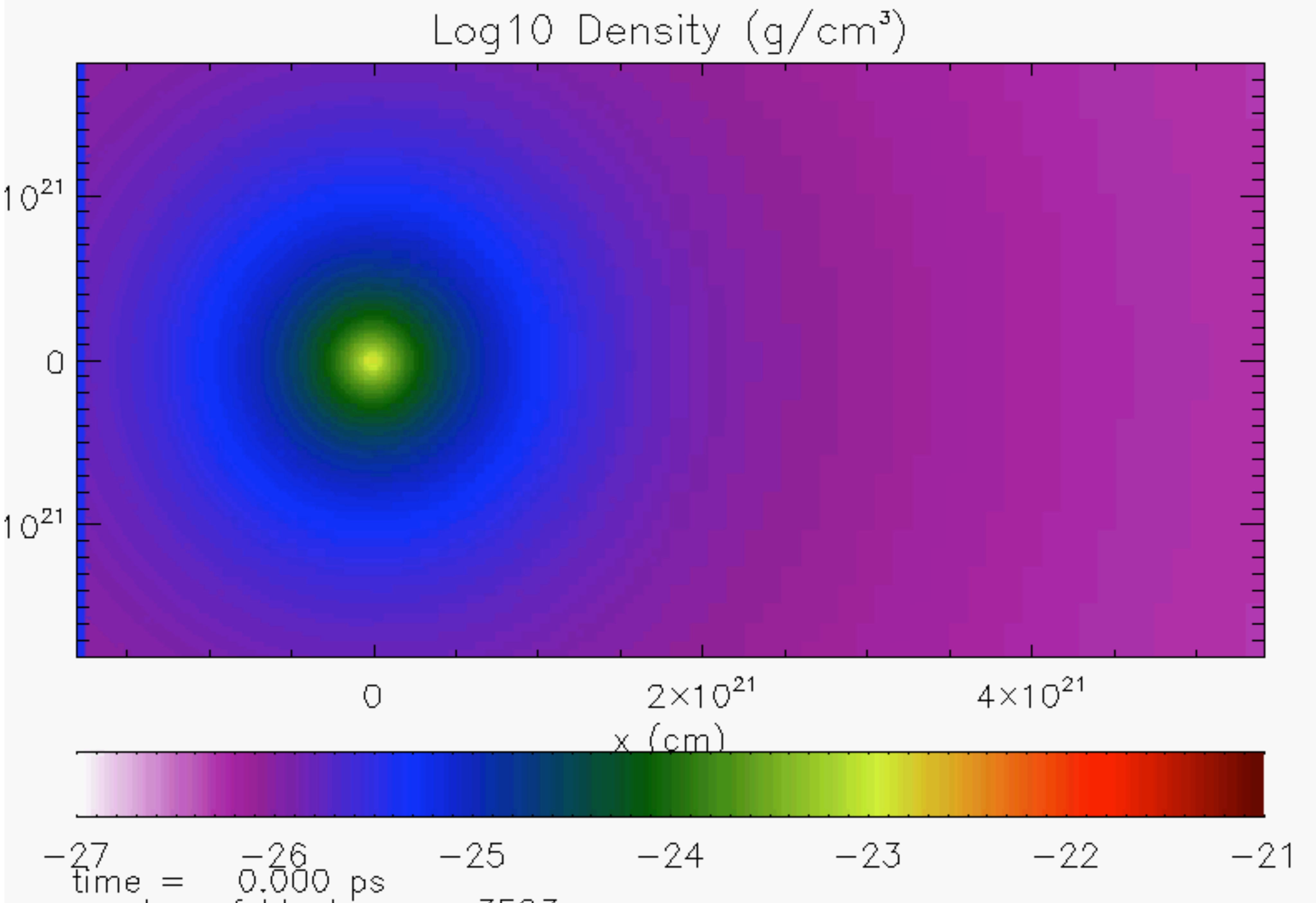


Gray, ES, Kasen (2015), Gray & ES (2016,2017)

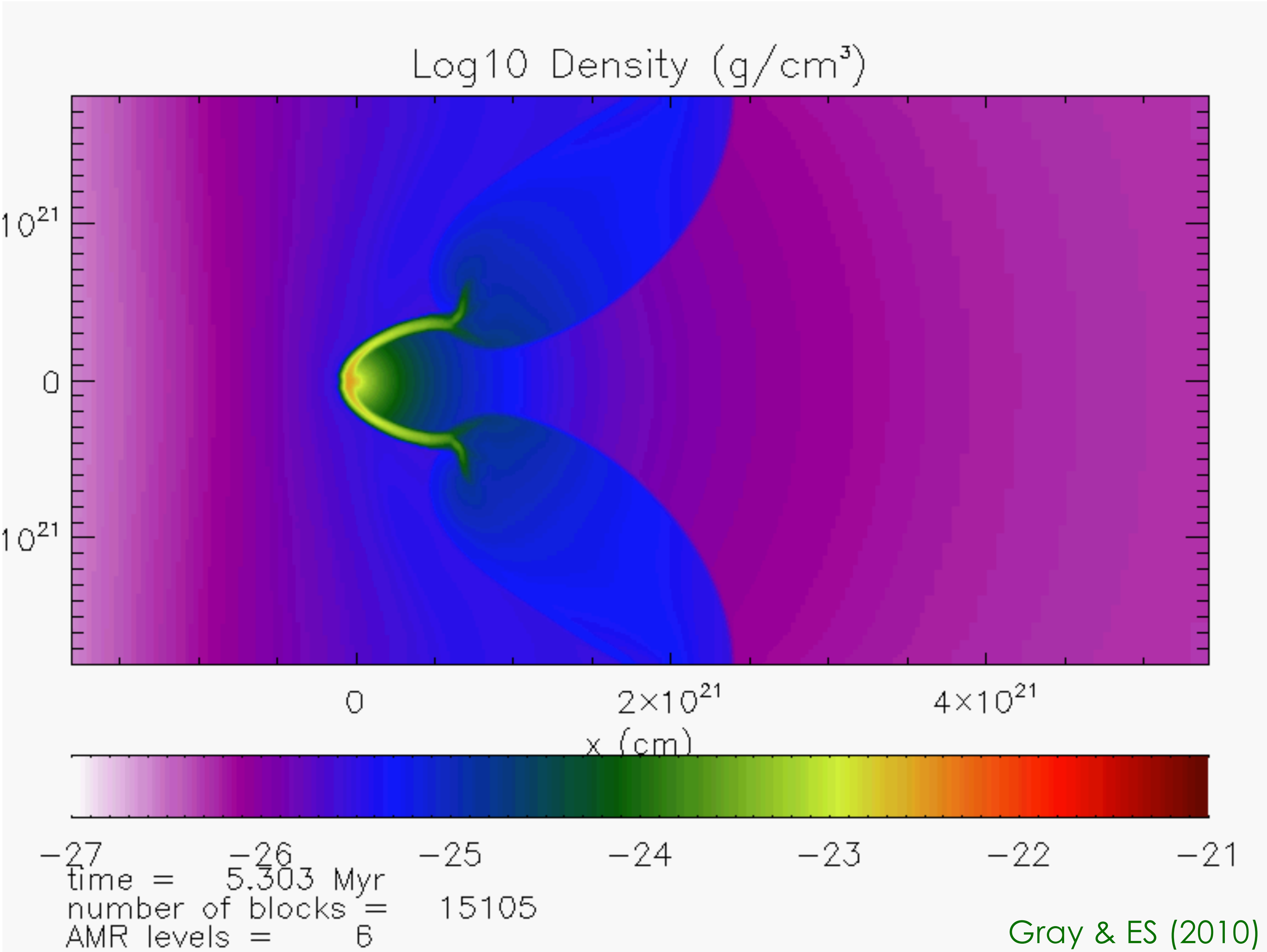
$U=10^{-3}$



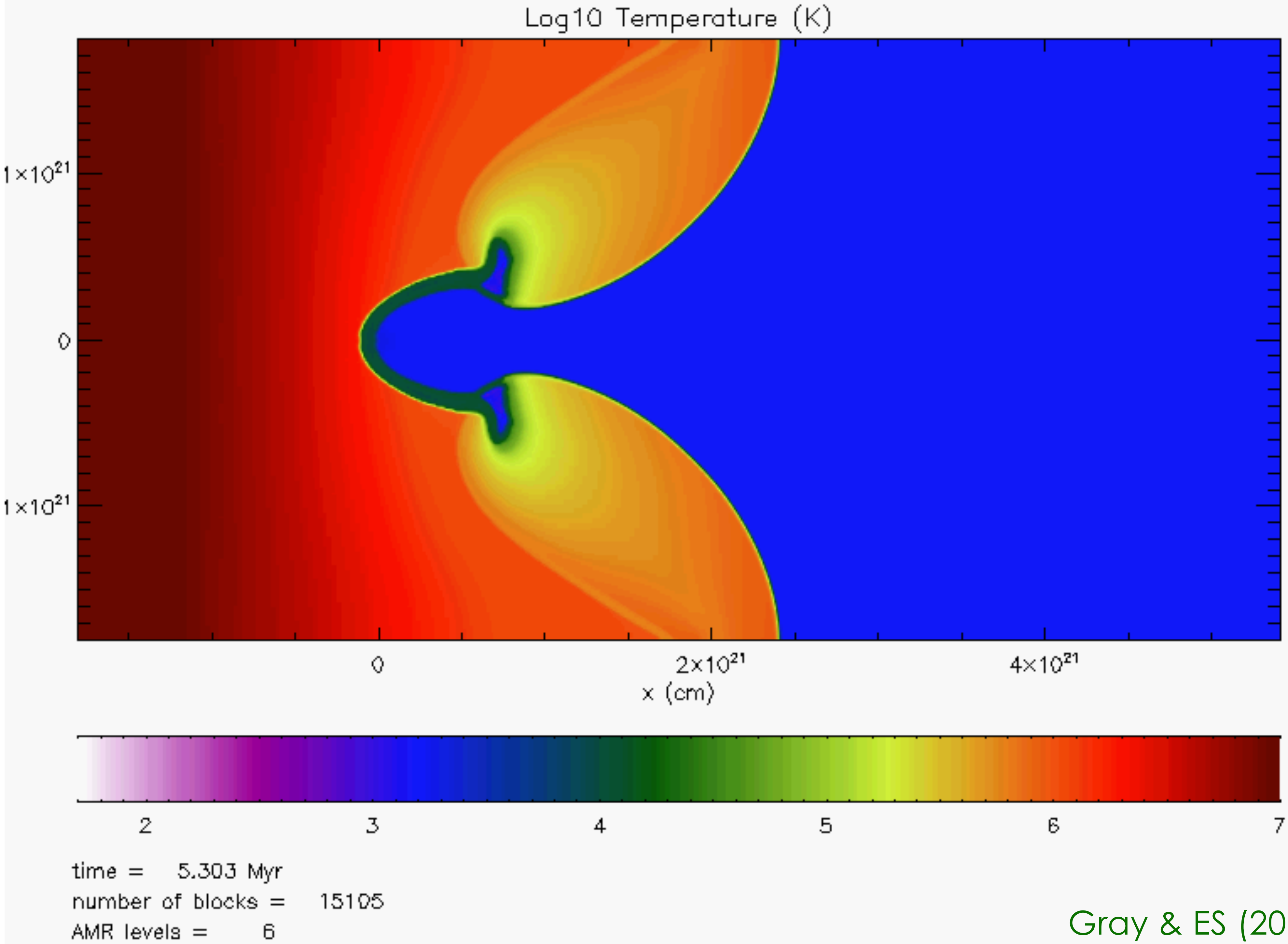
Gray, ES, Kasen (2015), Gray & ES (2016,2017)


Log10 Density (g/cm³)
10²¹
0
10²¹
0
2×10²¹
4×10²¹
x (cm)
−27
−26
−25
−24
−23
−22
−21
time = 0.000 ps
number of blocks = 3593
AMR levels = 6

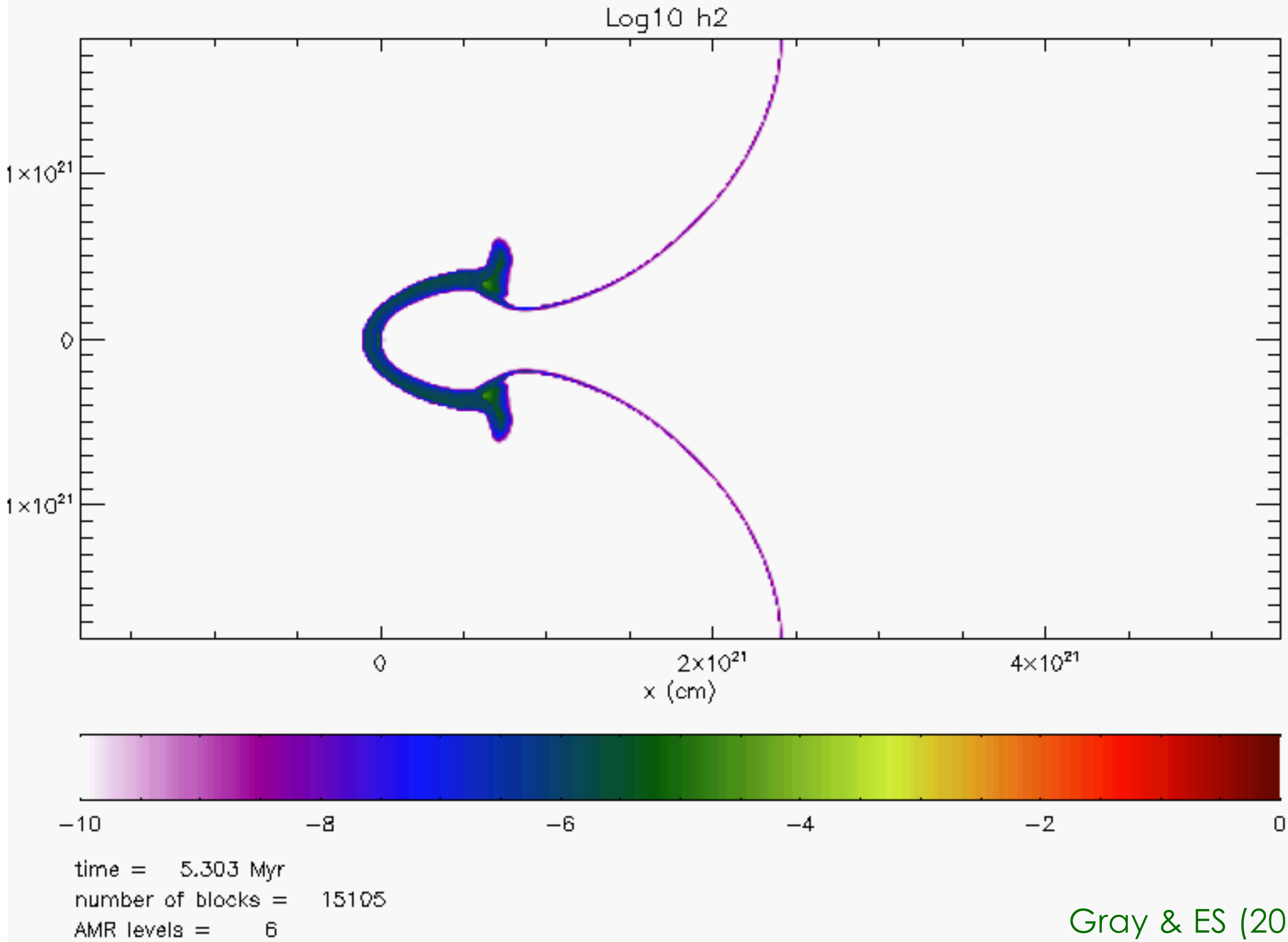
Gray & ES (2010)



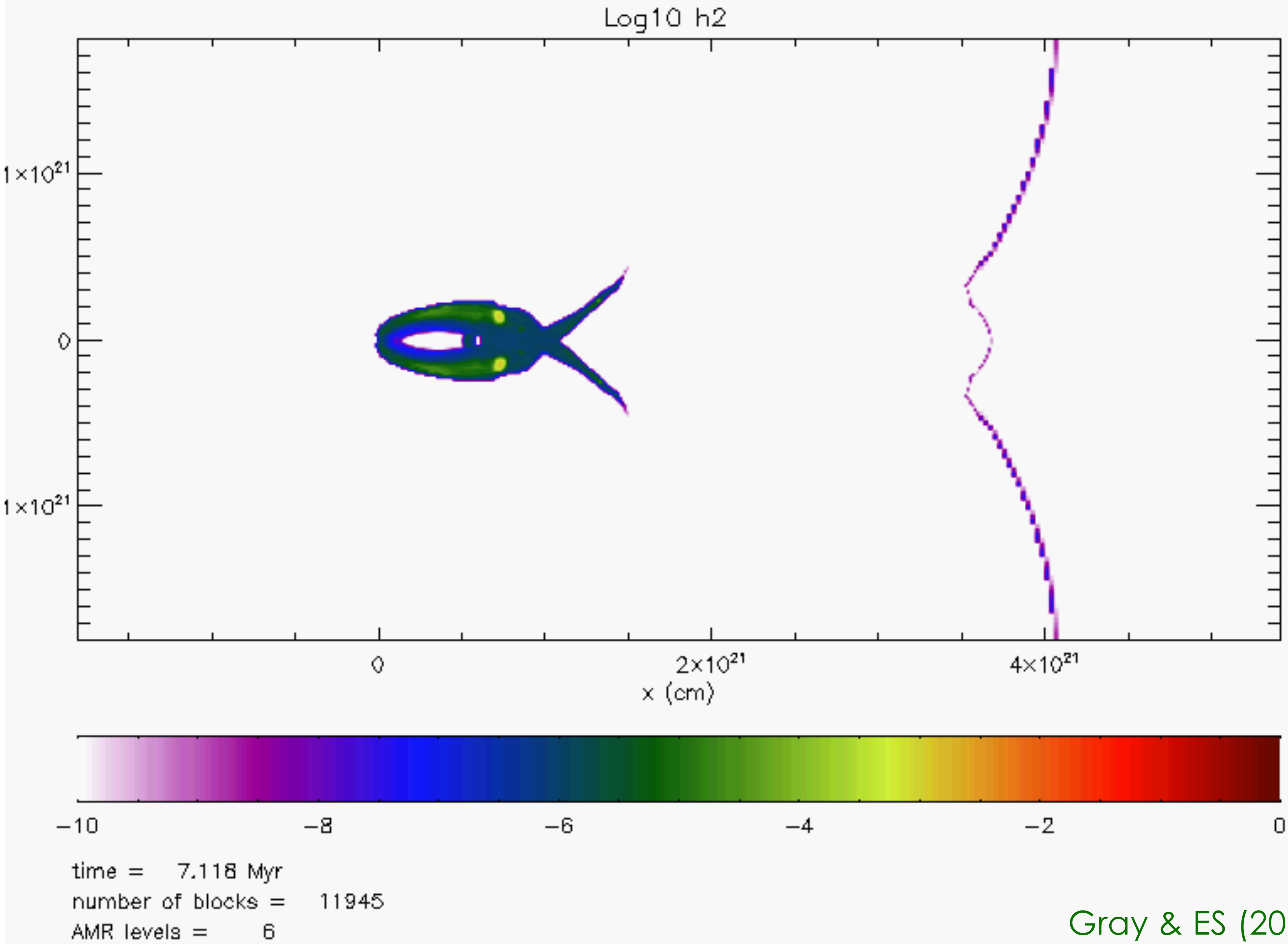
Log10 Density (g/cm³)
10²¹
0
10²¹
0
2×10²¹
4×10²¹
x (cm)
−27
−26
−25
−24
−23
−22
−21
time = 5.303 Myr
number of blocks = 15105
AMR levels = 6
Gray & ES (2010)


Log10 Temperature (K)
1×10²¹
0
1×10²¹
0
2×10²¹
4×10²¹
x (cm)
2
3
4
5
6
7
time = 5.303 Myr
number of blocks = 15105
AMR levels = 6

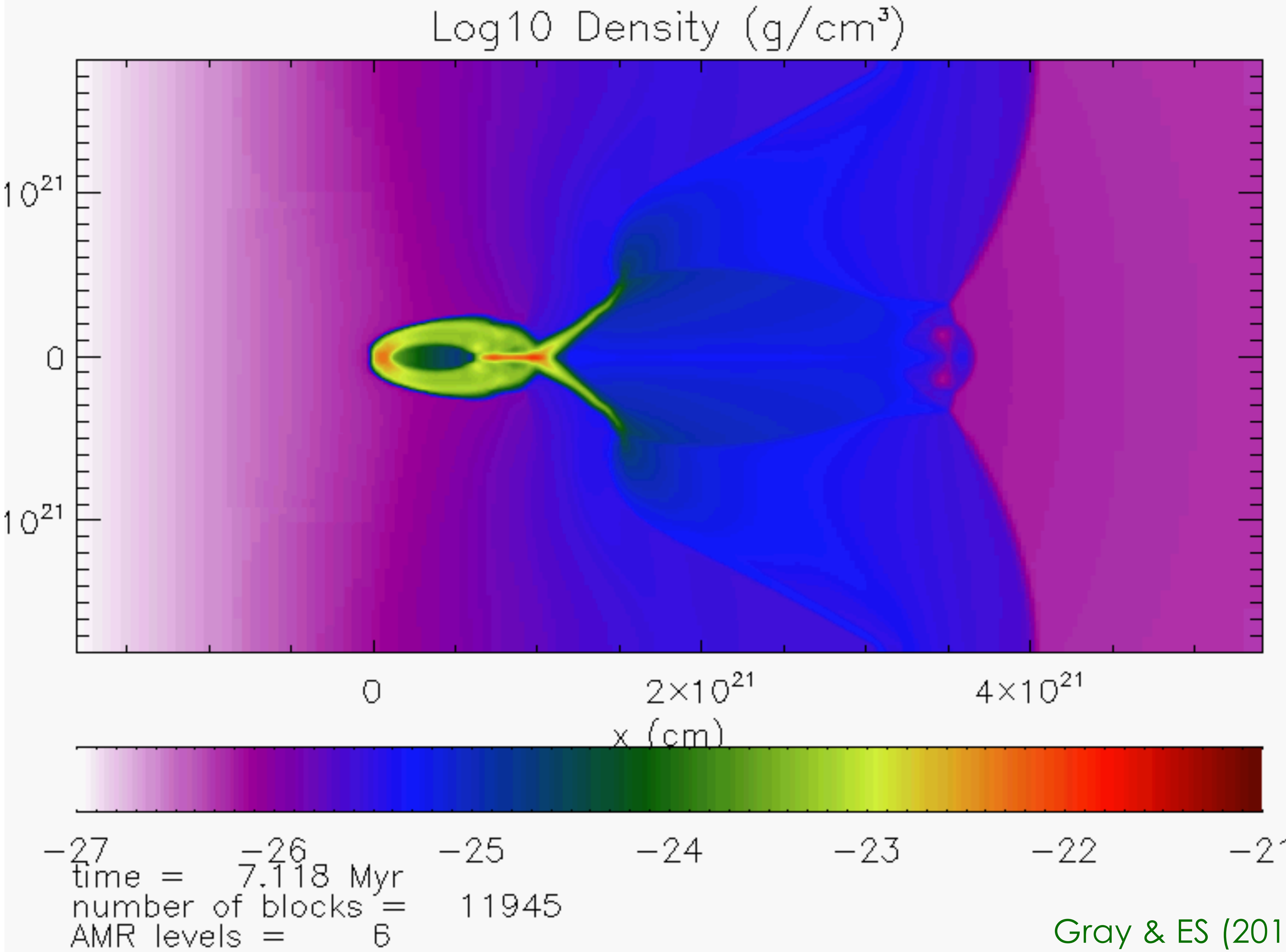
Gray & ES (2010)


Log10 h2
1×10^21
0
1×10^21
0
2×10^21
4×10^21
x (cm)
−10
−8
−6
−4
−2
0
time = 5.303 Myr
number of blocks = 15105
AMR levels = 6

Gray & ES (2010)

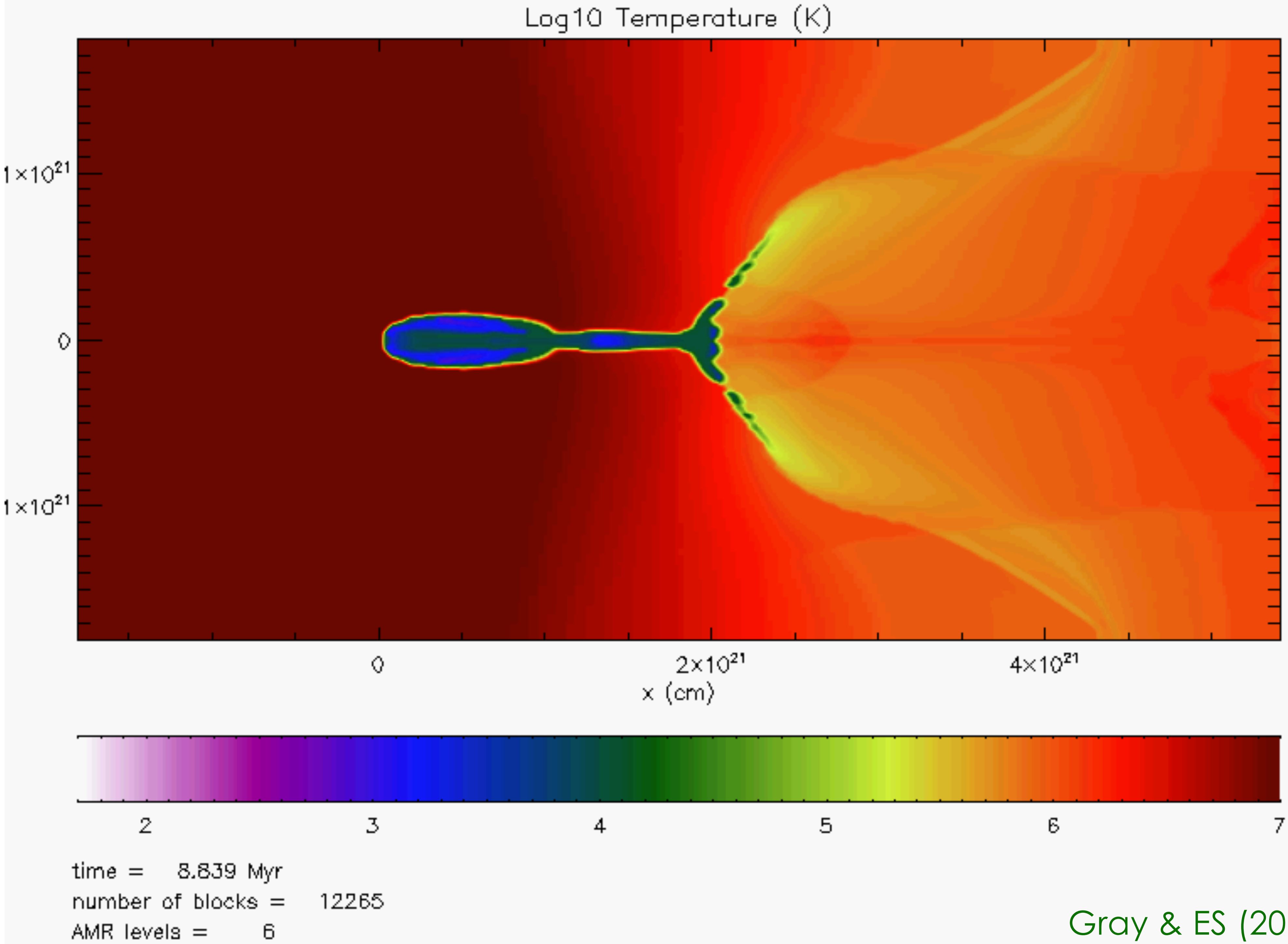

Log10 h2
1×10^21
0
1×10^21
0
2×10^21
4×10^21
x (cm)
−10
−8
−6
−4
−2
0
time = 7.118 Myr
number of blocks = 11945
AMR levels = 6

Gray & ES (2010)



Log10 Density (g/cm³)
10²¹
0
10²¹
0
2×10²¹
4×10²¹
x (cm)
−27
−26
−25
−24
−23
−22
−21
time = 7.118 Myr
number of blocks = 11945
AMR levels = 6

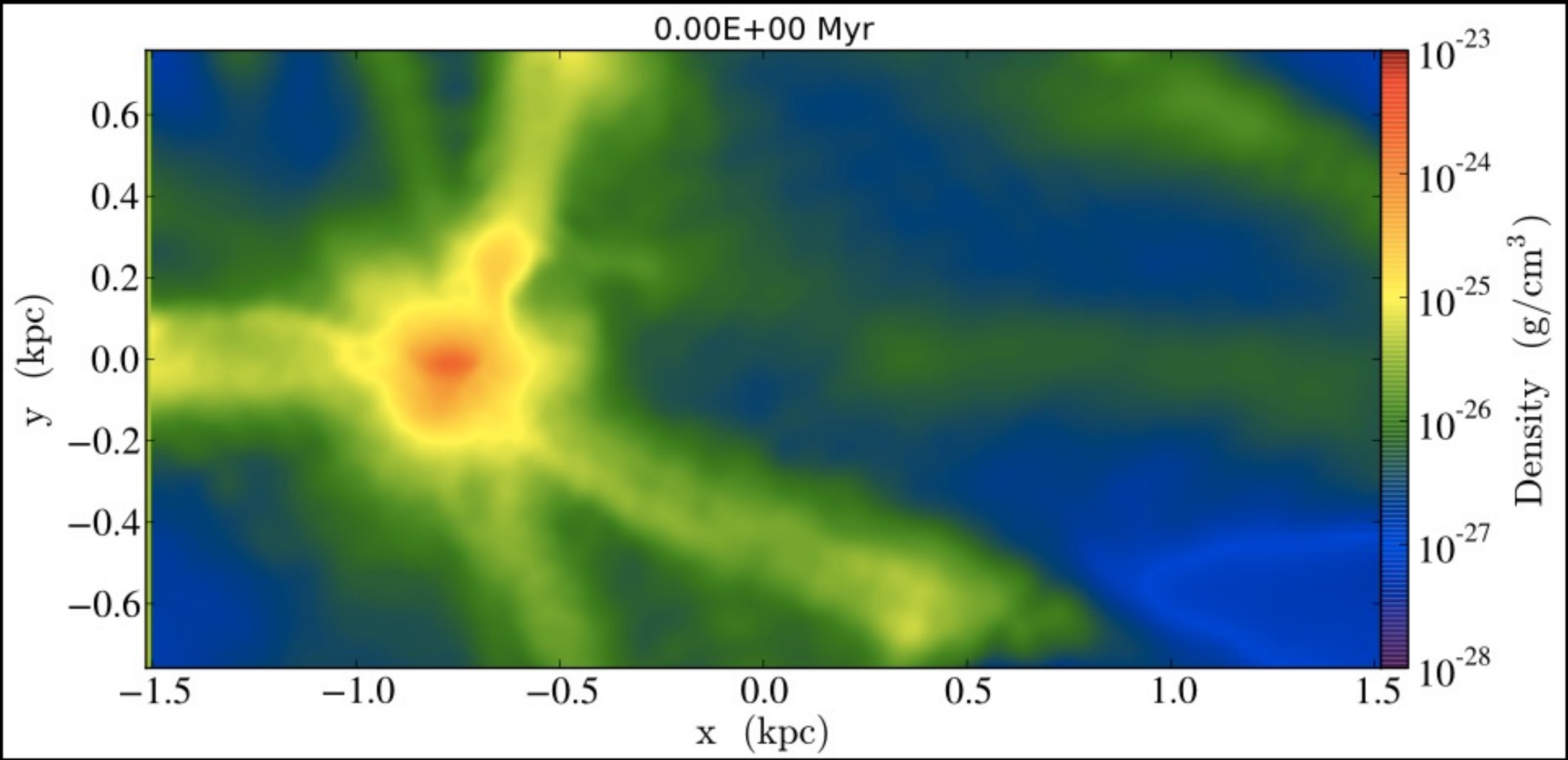
Gray & ES (2010)


Log10 Temperature (K)
1×10²¹
0
1×10²¹
0
2×10²¹
4×10²¹
x (cm)
2
3
4
5
6
7
time = 8.839 Myr
number of blocks = 12265
AMR levels = 6

Gray & ES (2010)

Minihalos Extracted From Cosmological Simulations

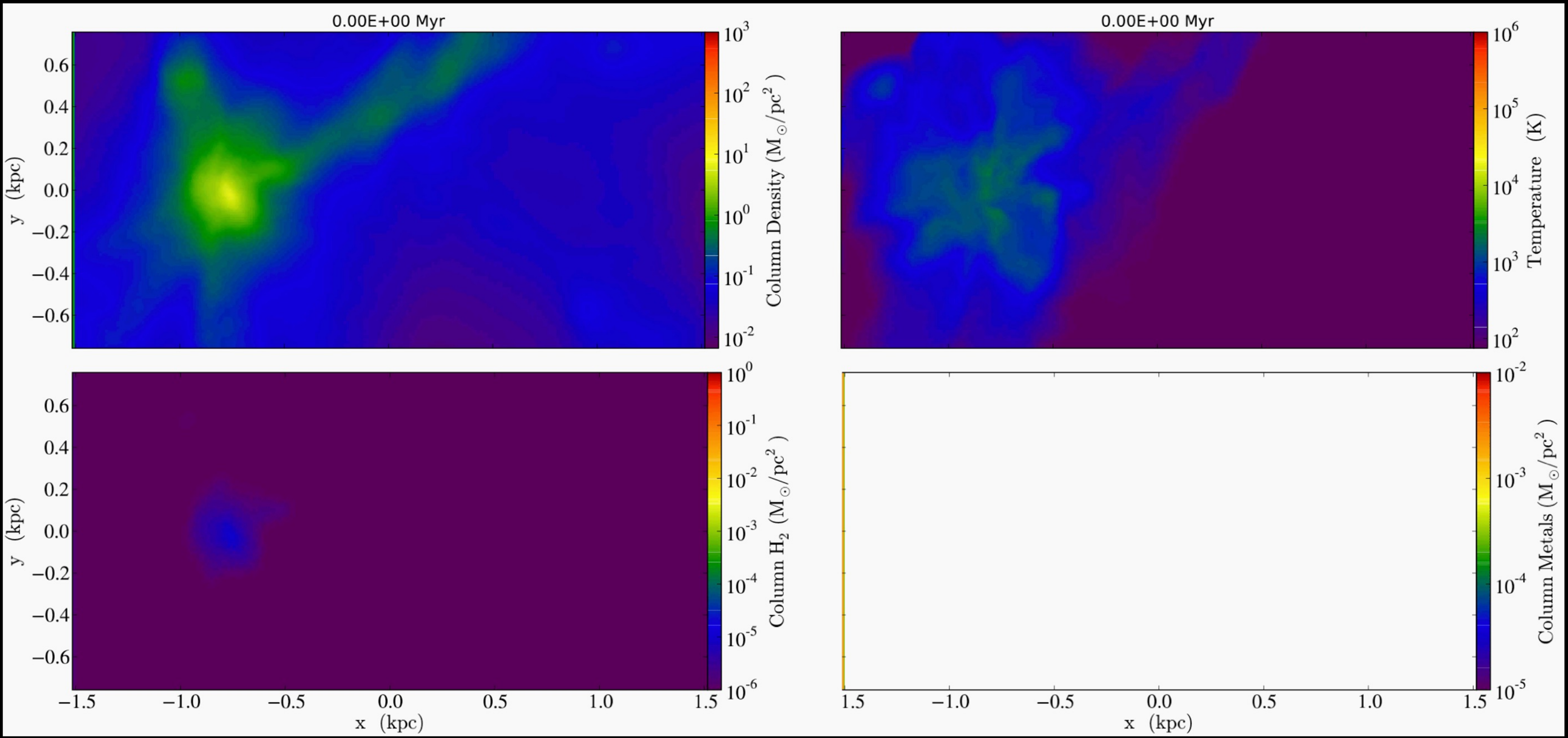
- **Minihalos are not actually perfectly spherical, in a perfectly isolated environment, with a static dark matter field.**



Richardson, Gray, & ES (2013)

Table 1
Simulations Summary

SPH Parameters:		SPH z_{init} 199	SPH z_f 14	SPH $m_{\rm DM}$ 144 $M_\odot$	SPH $m_{\rm gas}$ 29.3 $M_\odot$	Box Size 2.57 Mpc					
AMR Model	M_6	$r_{\rm vir}$ (pc)	Δx (pc)	Orientation	v_s (km s^{-1})	μ_s	E_{55}	σ_5	z	$Z(Z_\odot)$	J_{21}
FID	2.72	505	5.92	Filament	226	60.4	10.0	2.62	8	0.12	0.0
LR	2.72	505	11.8	Filament	226	60.4	10.0	2.62	8	0.12	0.0
HR	2.72	505	2.96	Filament	226	60.4	10.0	2.62	8	0.12	0.0
PO1	2.72	505	5.92	IGM	226	60.4	10.0	2.62	8	0.12	0.0
PM07	0.716	320.	3.75	Filament	226	60.4	10.0	2.62	8	0.12	0.0
PM1	1.38	402	4.71	Filament	226	60.4	10.0	2.62	8	0.12	0.0
PM2	2.33	470.	5.51	Filament	226	60.4	10.0	2.62	8	0.12	0.0
PM7	7.17	693	8.12	Filament	226	60.4	10.0	2.62	8	0.12	0.0
PM19	18.7	967	11.3	Filament	226	60.4	10.0	2.62	8	0.12	0.0
Pv75	2.72	505	5.92	Filament	75.0	60.4	30.2	7.91	8	0.12	0.0
Pv125	2.72	505	5.92	Filament	125	60.4	18.1	4.74	8	0.12	0.0
Pv340	2.72	505	5.92	Filament	340.	60.4	6.66	1.74	8	0.12	0.0
Pv510	2.72	505	5.92	Filament	510.	60.4	4.44	1.16	8	0.12	0.0
Pμ3	2.72	505	5.92	Filament	226	32.5	1.54	1.14	8	0.12	0.0
Pμ8	2.72	505	5.92	Filament	226	77.5	4.59	3.35	8	0.12	0.0
Pμ9	2.72	505	5.92	Filament	226	90.0	5.33	3.89	8	0.12	0.0
Pz10	2.72	413	4.84	Filament	226	90.7	10.0	3.92	10	0.12	0.0
Pz14	2.72	303	3.55	Filament	226	169	10.0	7.30	14	0.12	0.0
PZ005	2.72	505	5.92	Filament	226	60.4	10.0	2.62	8	0.005	0.0
PZ05	2.72	505	5.92	Filament	226	60.4	10.0	2.62	8	0.05	0.0
PZ5	2.72	505	5.92	Filament	226	60.4	10.0	2.62	8	0.5	0.0
PJ01	2.72	505	5.92	Filament	226	60.4	10.0	2.62	8	0.12	0.1



0.00E+00 Myr
Column Density ($M_\odot/pc^2$)
0.00E+00 Myr
Temperature (K)
Column H_2 ($M_\odot/pc^2$)
Column Metals ($M_\odot/pc^2$)
y (kpc)
x (kpc)

Parameters

Mass: Final Mass roughly proportional to initial mass

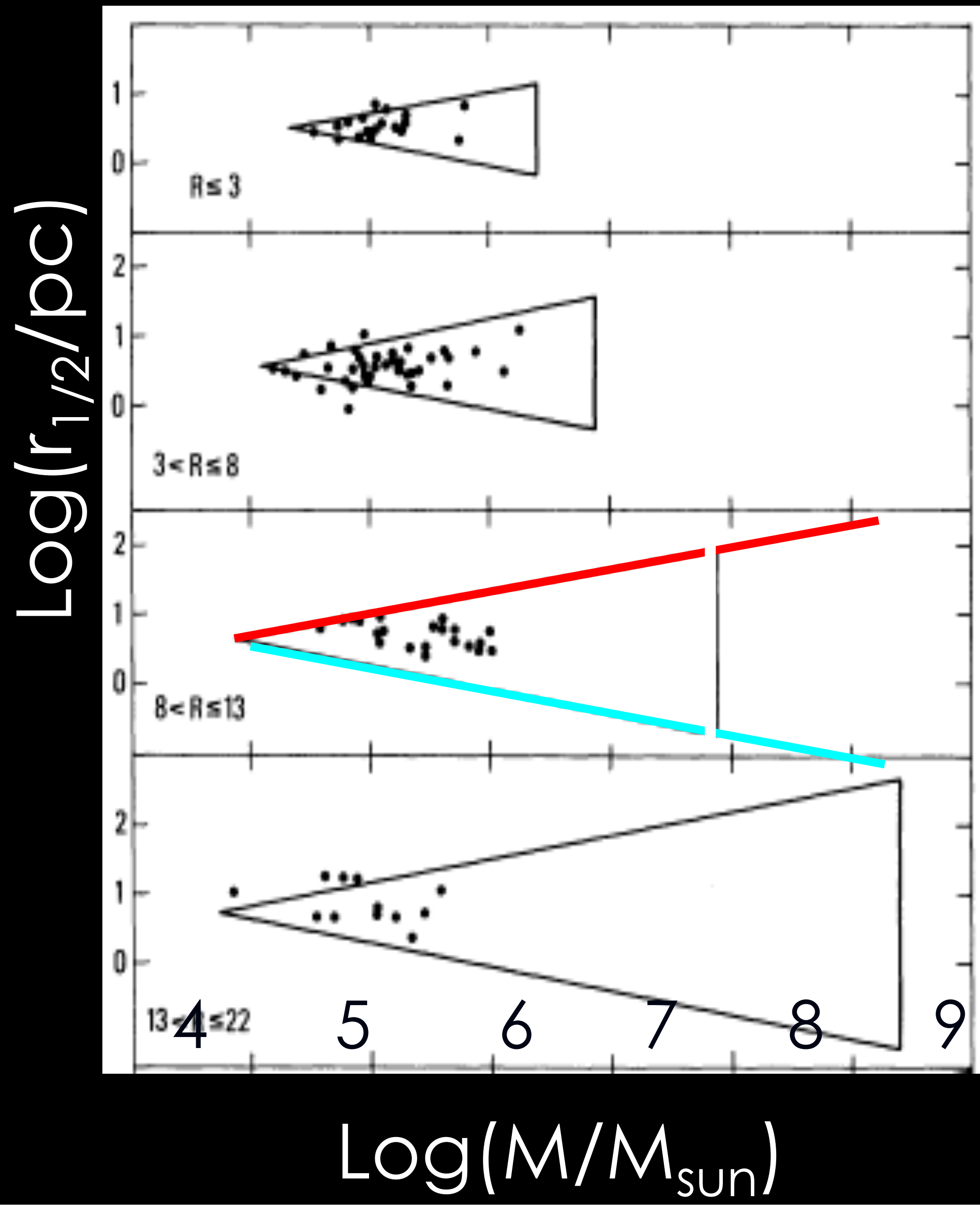
Dissociating Background: No impact, H_2 is formed much too quickly

Shock energy: in general, the higher the shock energy, the lower mass clusters are formed

Distance: The closer to the host, the more efficiently SF is induced. Very far away > 5-6 kpc little impact.

Concentration & Formation Redshift: Minor impact

Where are they now?



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

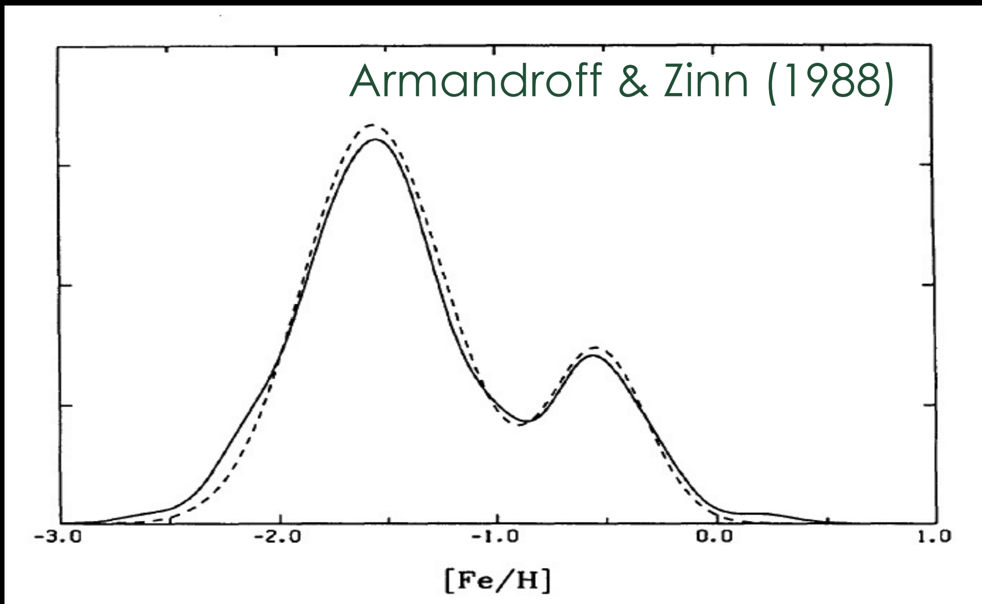
Evaporation
$t \sim r_{1/2}^{3/2}\ M^{1/2}$

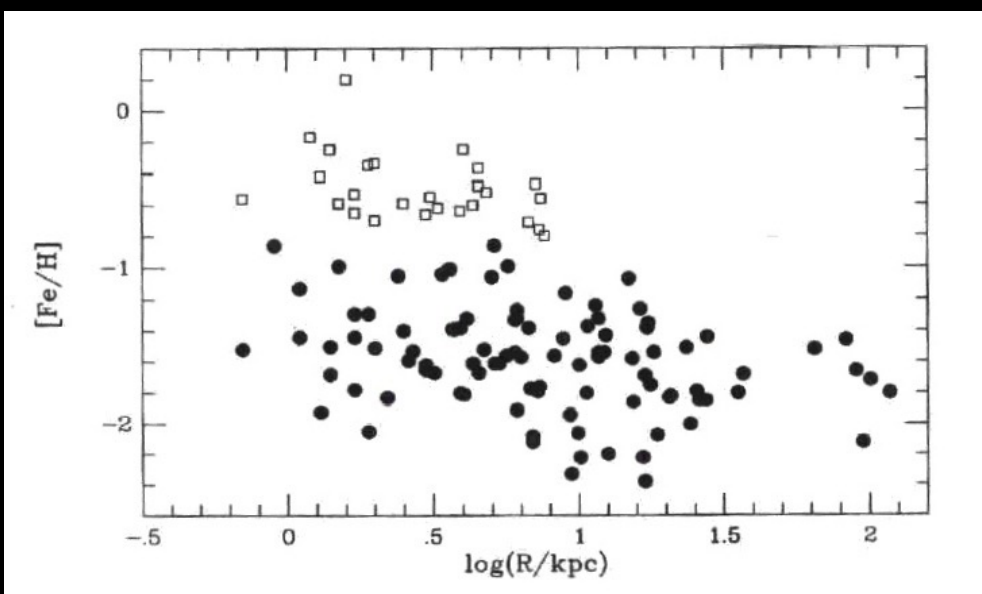
Dynamical Friction
$t \sim M^{-1}\ R^2$

Maximum mass is an intrinsic property of the initial GC population

Castellani & Caputo 1984
Fall & Rees 1977

Globular Cluster Metallicities

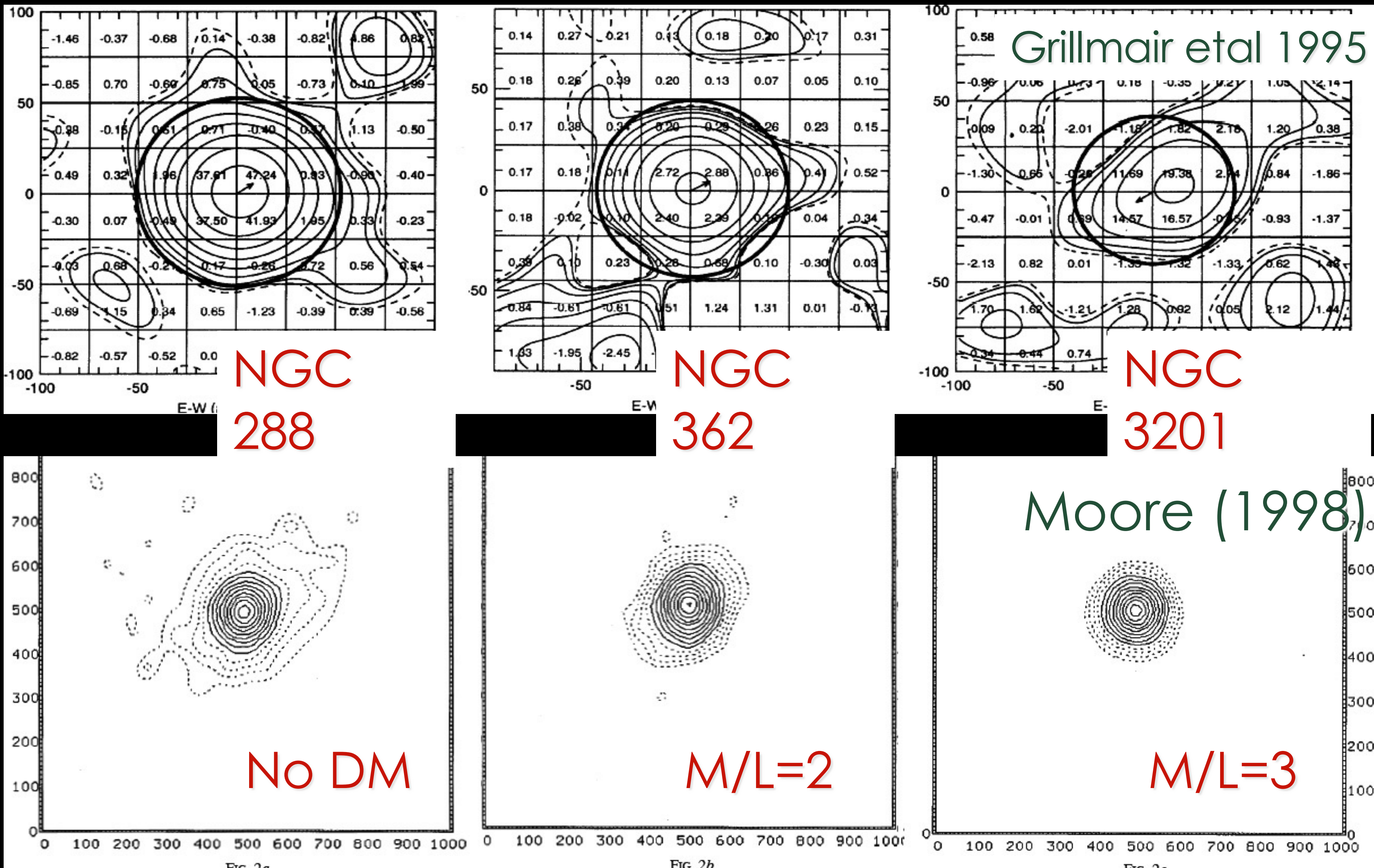


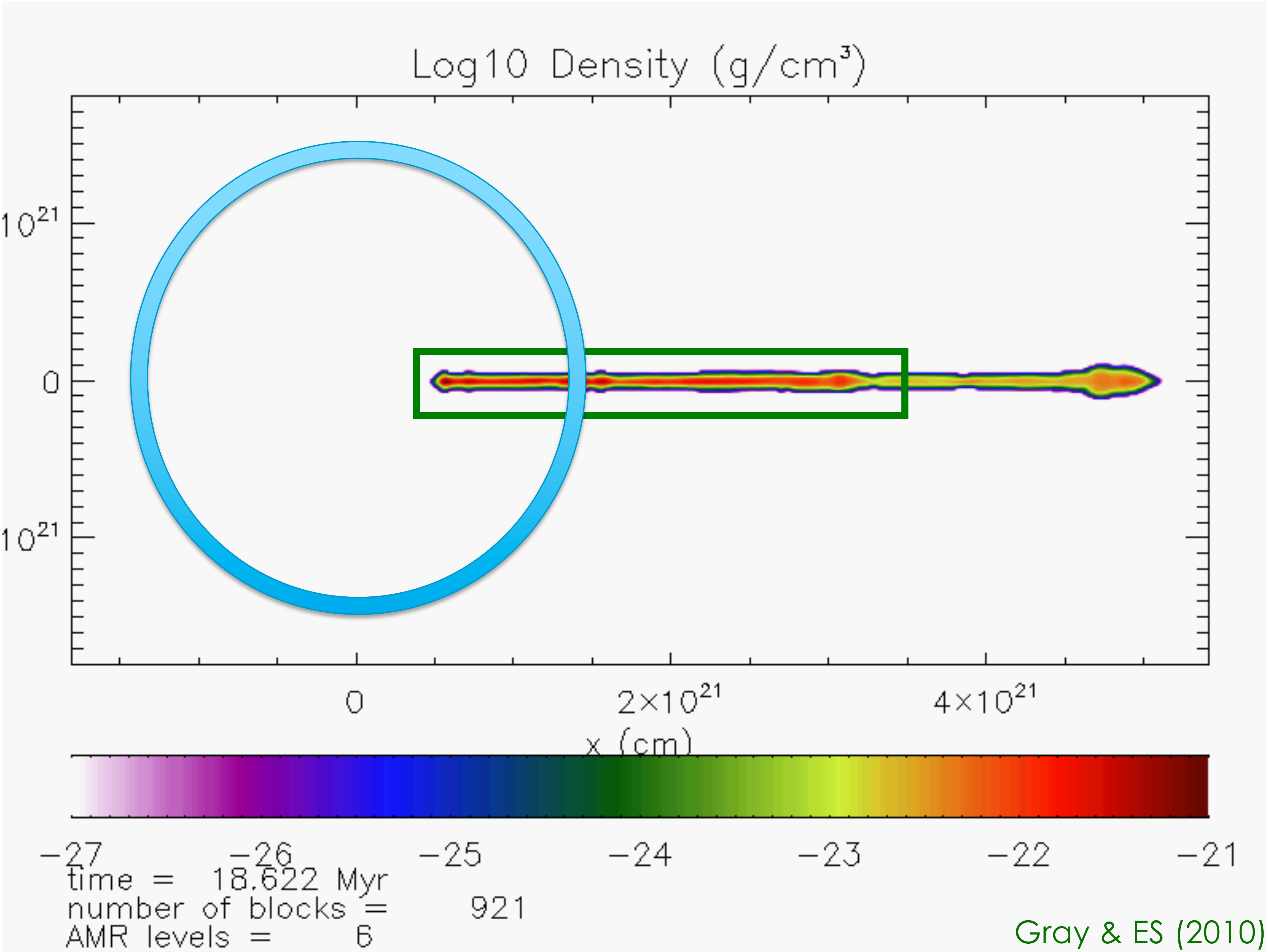


Double-peaked
[Fe/H] ~ -0.5 ± .25
[Fe/H] ~ -1.6 ± .35

Narrow range < $\Delta Z \pm 0.1$
In each GC

No Dark Matter In GCs





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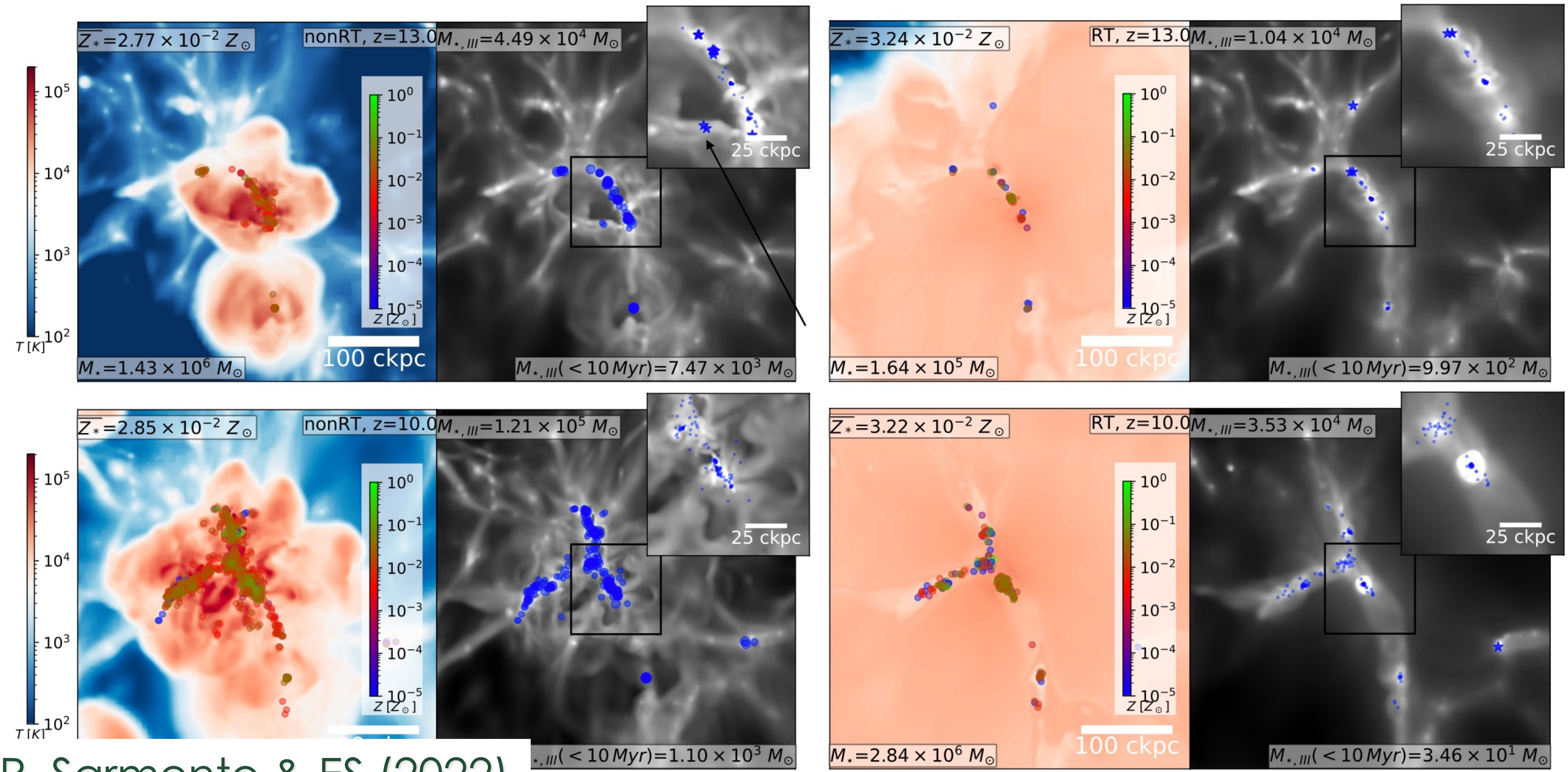
10²¹
0
10²¹
0
2×10²¹
4×10²¹
x (cm)
−27
−26
−25
−24
−23
−22
−21
time = 18.622 Myr
number of blocks = 921
AMR levels = 6
Gray & ES (2010)

Requirements in Cosmological Simulations

Full radiative transfer
Non-LTE chemistry / Cooling
Resolving halos down to <=10^6 total mass at distances of ~100 kpc physical

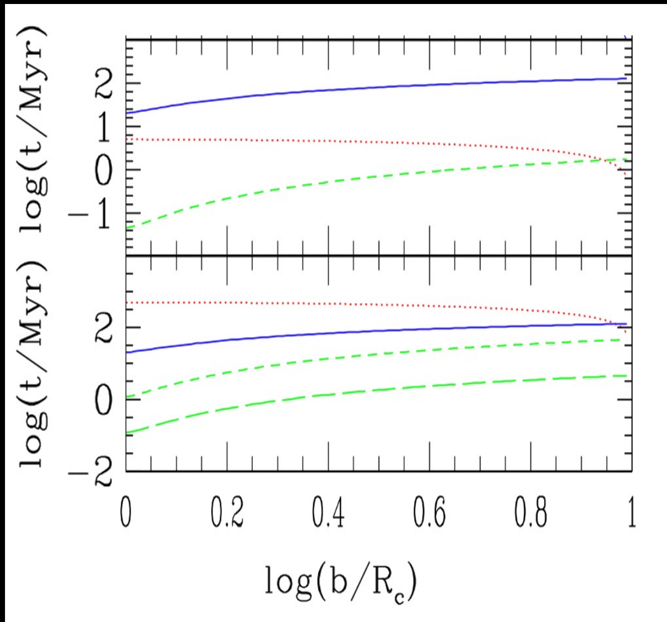
Requirements in Cosmological Simulations

RAMSES radiative transfer + primordial chemistry & cooling
Tracks: Metallicity, Primordial Fraction, Pop III Metals, R-process elements.

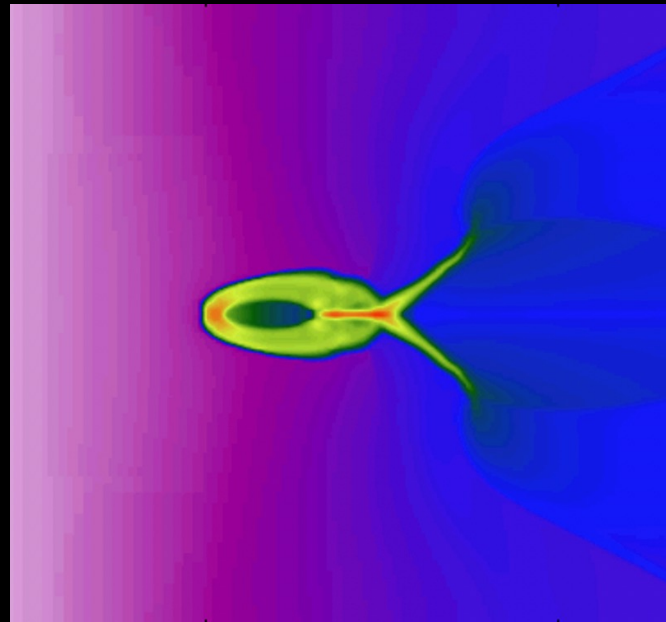


R. Sarmento & ES (2022)

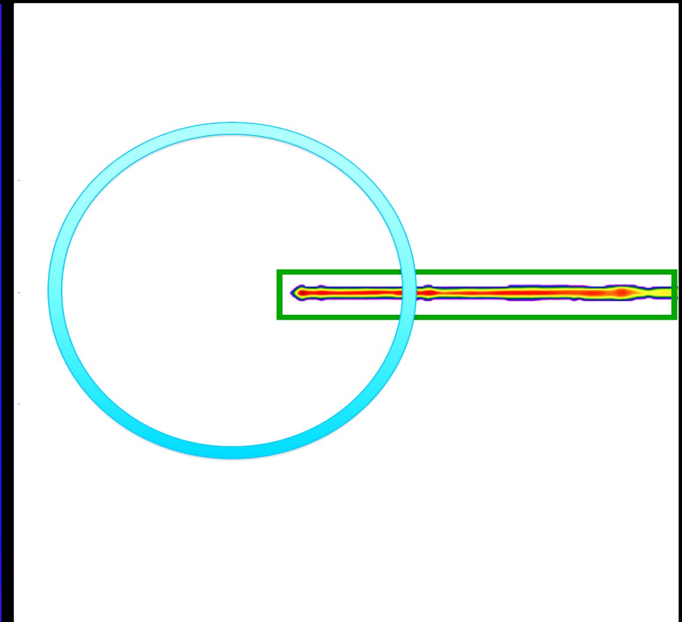
I



II

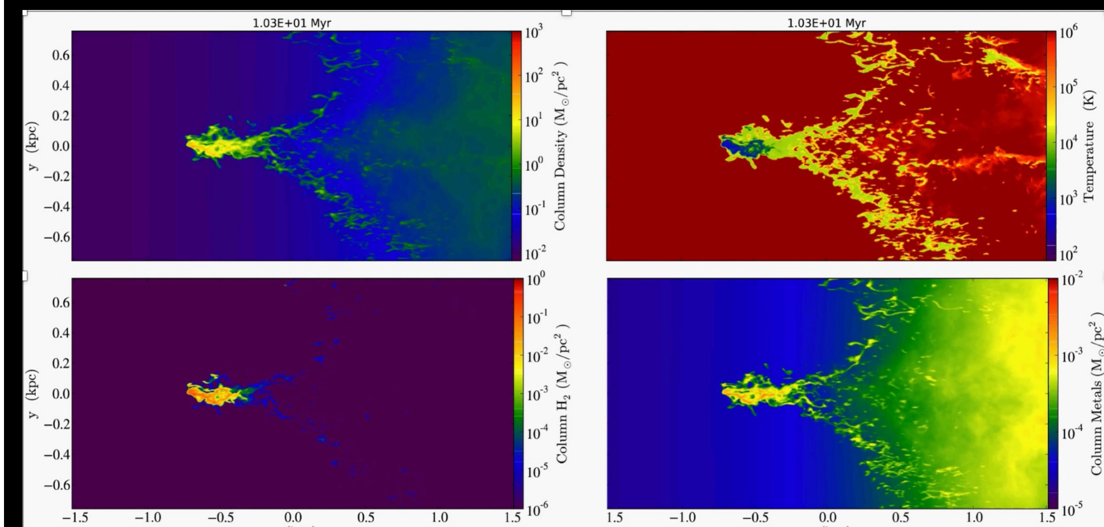


III



Thank you!

IV



V