Non-linear collapse phase

As the density continues to increase, linear approximation fails. "non-linear regime"

It does not collapse entirely (into a black hole) because it will gain kinetic energy as it loses potential energy.

dark matter → violent relaxation, reaches equilibrium ("virialized")

gas → potential energy turns to thermal energy, gas heats (to $\sim 10^6$ K in Milky Way-type halo)

.... needs to cool before it can form stars

$> 10^6$ K

at high temperatures, gas cools via free-free interactions

(bremsstrahlung radiation)

(electron-~~proton~~ ion encounters, e^- not bound)

(how we detect hot gas in clusters)

at lower temperatures, gas cools by bound-free or bound-bound transitions

→ recombination or collisional excitation give off emission lines in optical

Depends on metallicity of gas

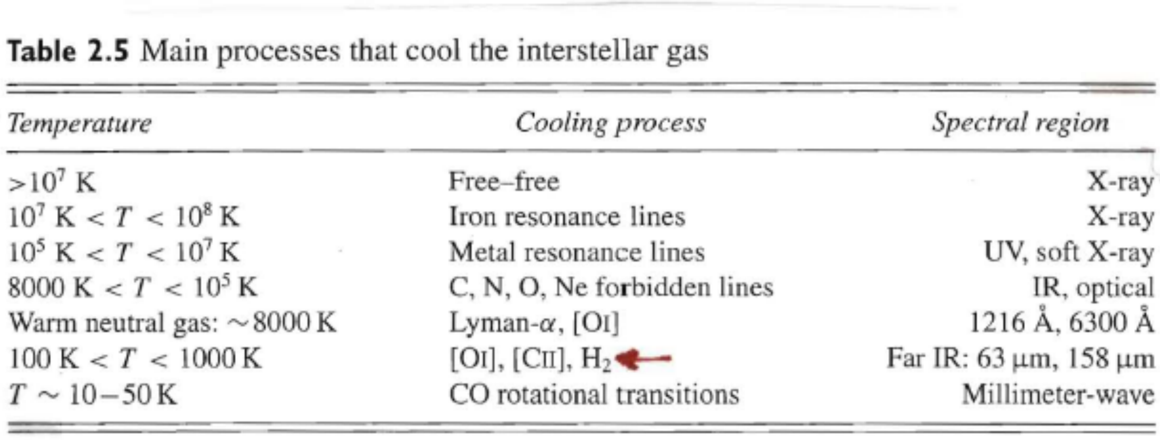


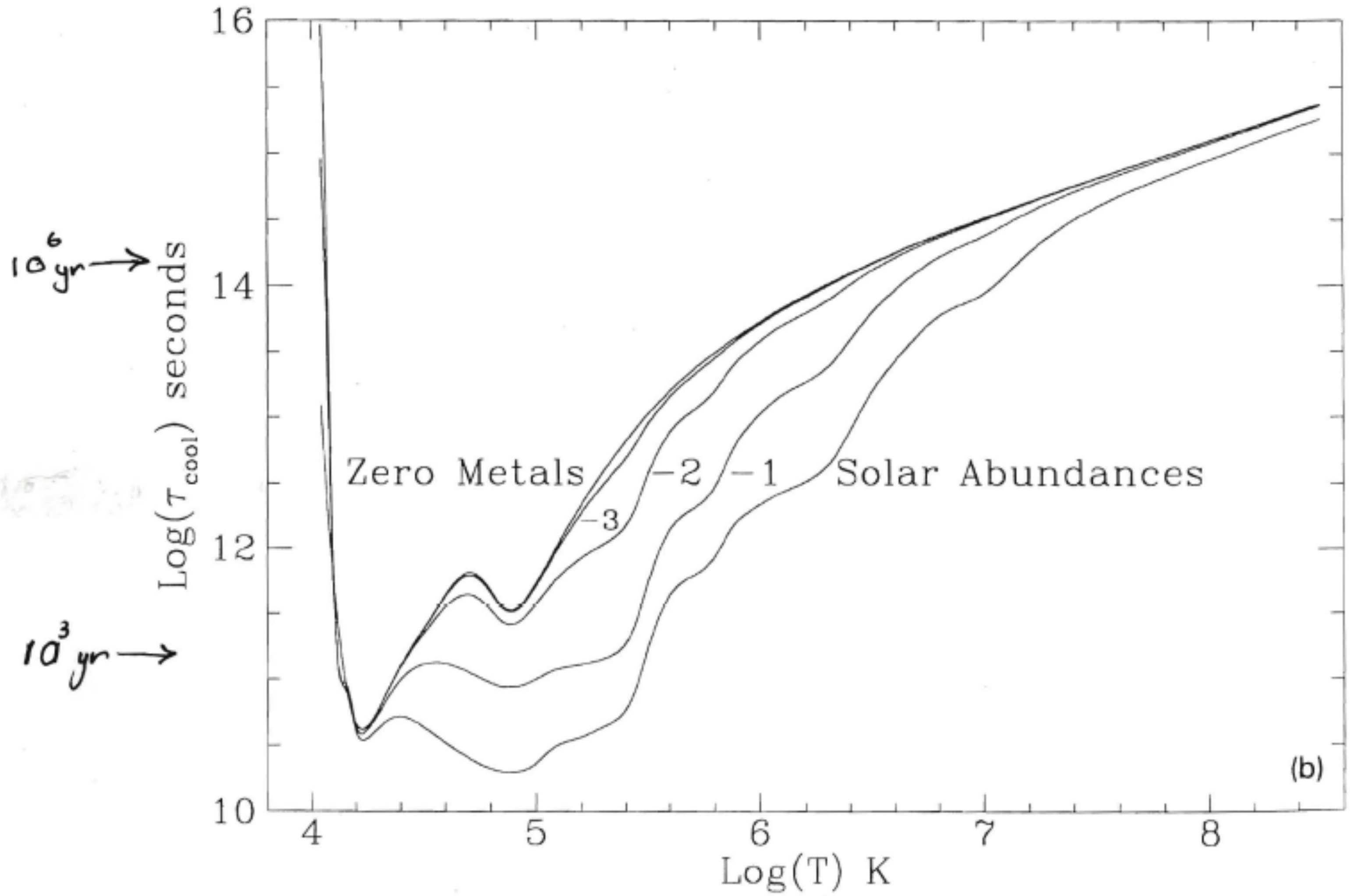
Table 2.5 Main processes that cool the interstellar gas

Temperature	*Cooling process*	*Spectral region*
$>10^7$ K	Free–free	X-ray
$10^7\ \mathrm{K} < T < 10^8\ \mathrm{K}$	Iron resonance lines	X-ray
$10^5\ \mathrm{K} < T < 10^7\ \mathrm{K}$	Metal resonance lines	UV, soft X-ray
$8000\ \mathrm{K} < T < 10^5\ \mathrm{K}$	C, N, O, Ne forbidden lines	IR, optical
Warm neutral gas: ~ 8000 K	Lyman-α, [OI]	1216 Å, 6300 Å
$100\ \mathrm{K} < T < 1000\ \mathrm{K}$	[OI], [CII], H_2 ←	Far IR: 63 μm, 158 μm
$T \sim 10-50$ K	CO rotational transitions	Millimeter-wave

Cooling rate depends on density of gas, and on metallicity

Q Why? Which cools faster, zero metal gas or metal-rich gas?

Cooling time as f(metallicity)

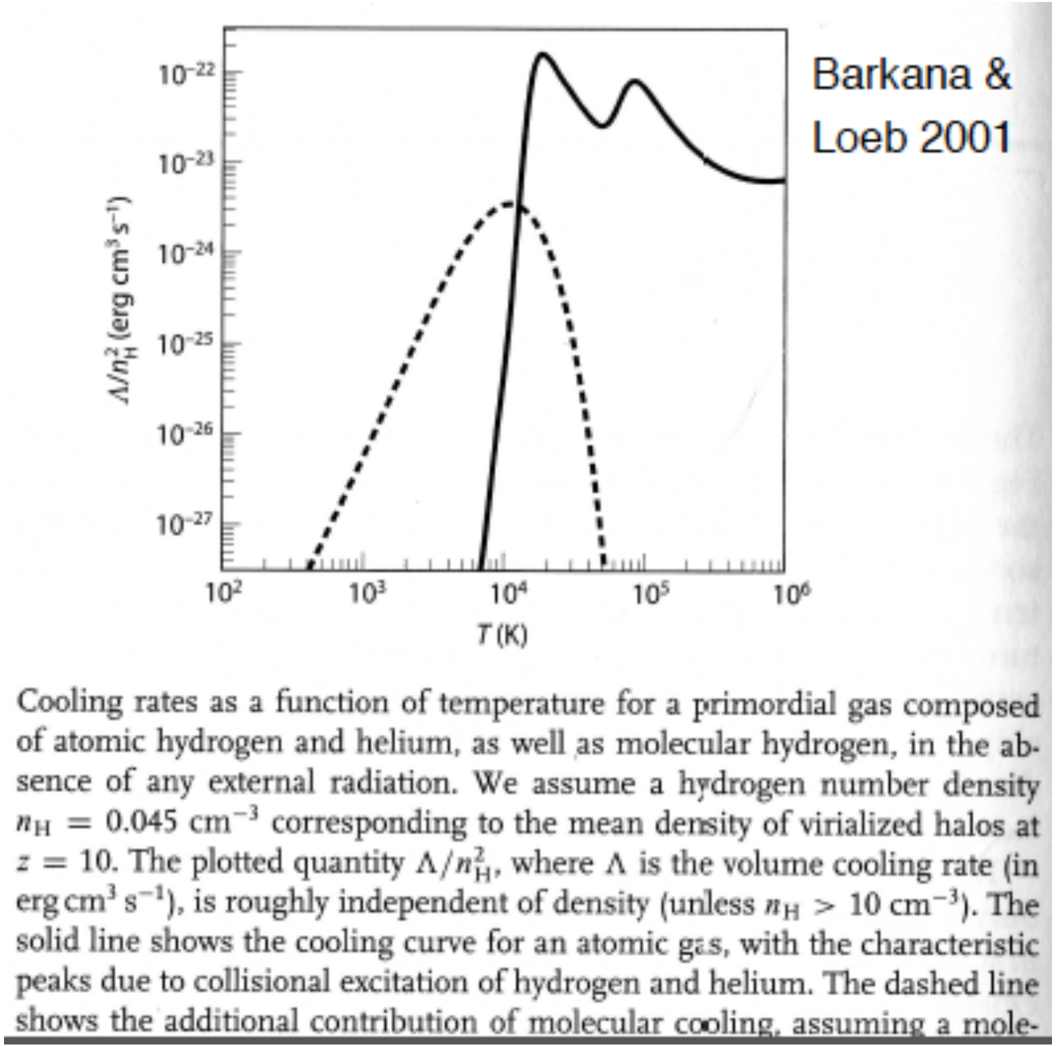


10^6 yr →

10^3 yr →

Cooling rate for an astrophysical plasma of unit density, for various abundances that range from s

Atomic and molecular cooling for zero metal gas



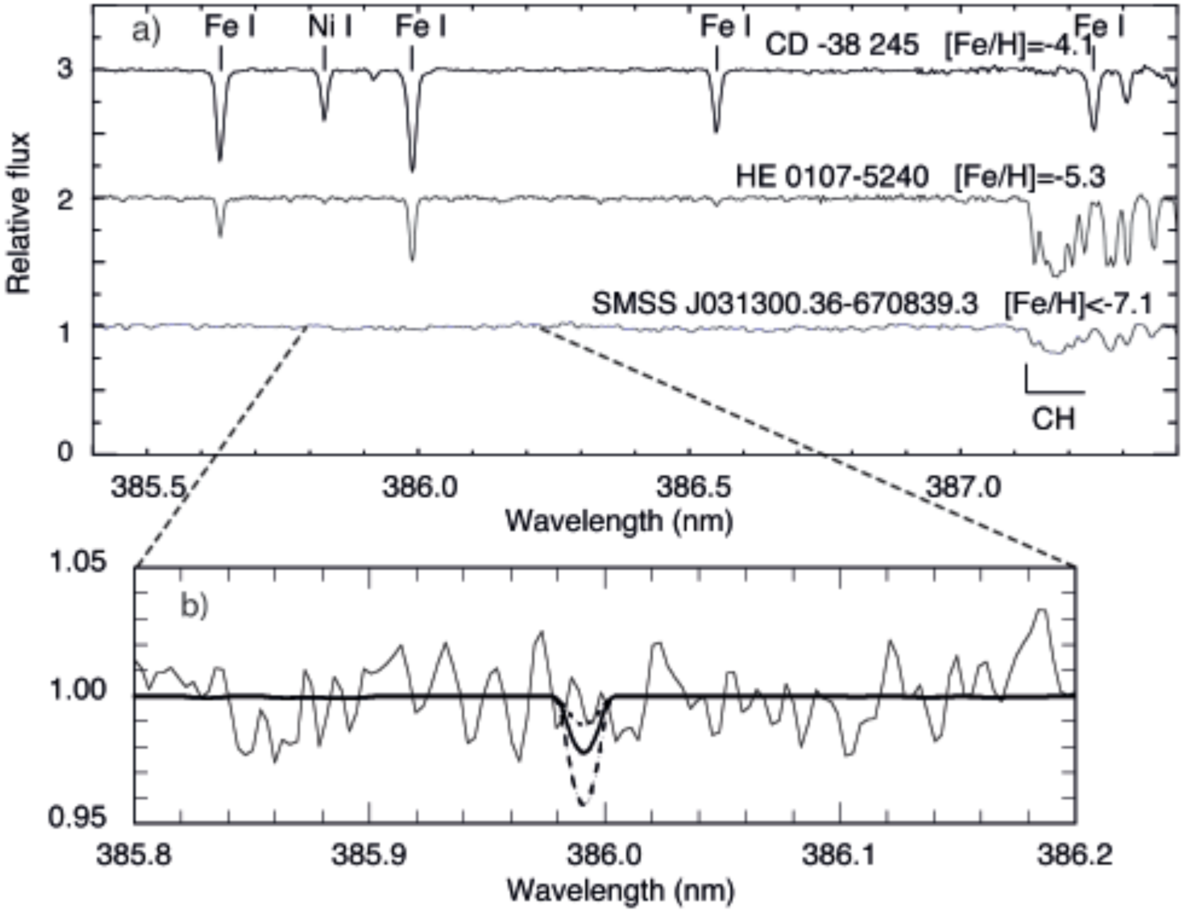
Cooling rates as a function of temperature for a primordial gas composed of atomic hydrogen and helium, as well as molecular hydrogen, in the absence of any external radiation. We assume a hydrogen number density $n_H = 0.045\ \mathrm{cm}^{-3}$ corresponding to the mean density of virialized halos at $z = 10$. The plotted quantity Λ/n_H^2, where Λ is the volume cooling rate (in erg cm^3 s^{-1}), is roughly independent of density (unless $n_H > 10\ \mathrm{cm}^{-3}$). The solid line shows the cooling curve for an atomic gas, with the characteristic peaks due to collisional excitation of hydrogen and helium. The dashed line shows the additional contribution of molecular cooling, assuming a mole-

Q: how do we form molecules in the ISM today, given the very low gas densities?

At high redshift, H_2 forms via H^- ion (rare process)

The first stars

We have never observed a star with no heavy metals (Z=0)



[Fe/H]

-4.1

-5.3

<-7.1

Keller et al 2014

IMF of first stars

Q: think of the Jeans criterion for gravitational collapse. What might cause the Jeans mass to be higher at redshift ~10 than now?

IMF of first stars

Q: think of the Jeans criterion for gravitational collapse. What might cause the Jeans mass to be higher at redshift ~9 than now?

A: CMB temperature would be about 30K then, not 3K. So no gas cloud could be as cool as current day molecular clouds

This would explain absence of Z=0 stars today if no low mass stars were formed then

Keller et al star consistent with contamination from only one zero-metal 60 Msun star going supernova

For rapid collapse (to make stars before we all lose interest)

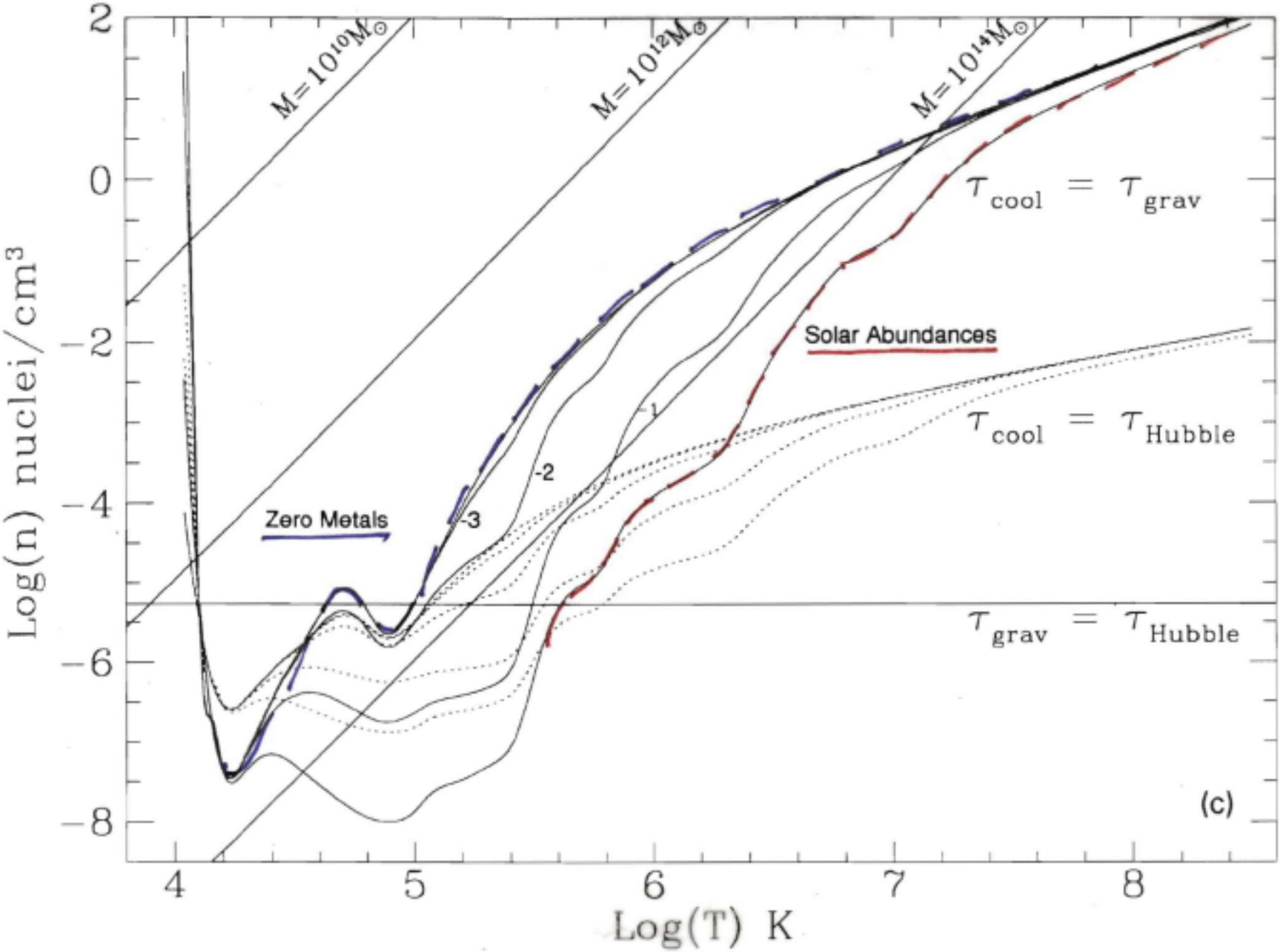
cooling time < free fall time
(gravitational collapse time)

$$\propto \frac{1}{\sqrt{G\rho}}$$ [illegible]

$$\propto \frac{1}{\sqrt{n}}$$ n is number density of particles

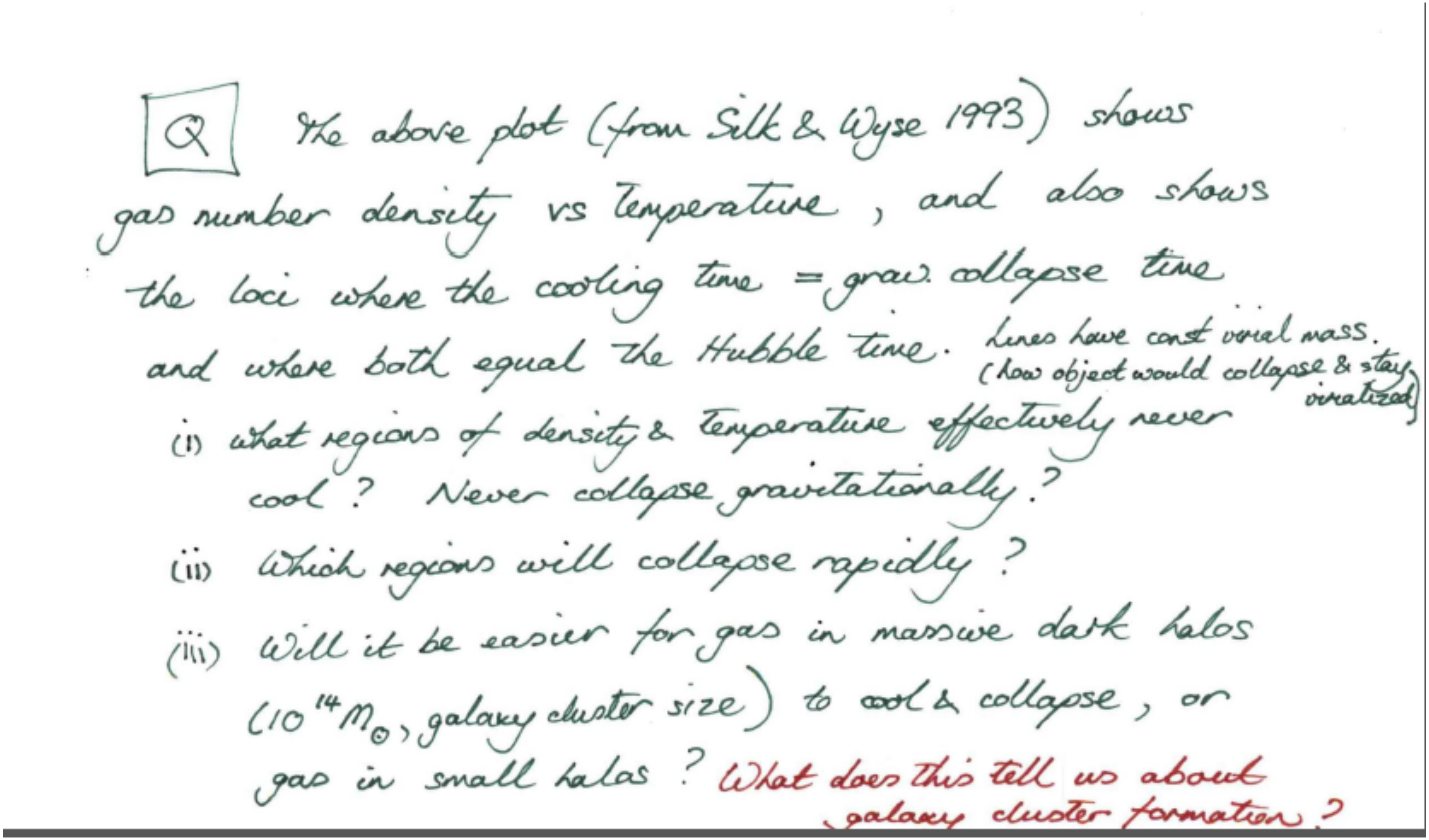
So, high density regions cool & collapse fast

Very low density regions will neither cool nor collapse.



2
0
−2
−4
−6
−8
4
5
6
7
8
Log(n) nuclei/cm^3
Log(T) K
M=10^{10}M$_\odot$
M=10^{12}M$_\odot$
M=10^{14}M$_\odot$
$\tau_{cool} = \tau_{grav}$
$\tau_{cool} = \tau_{Hubble}$
$\tau_{grav} = \tau_{Hubble}$
Solar Abundances
Zero Metals
-3
-2
-1
(c)

Interpreting the cooling plot



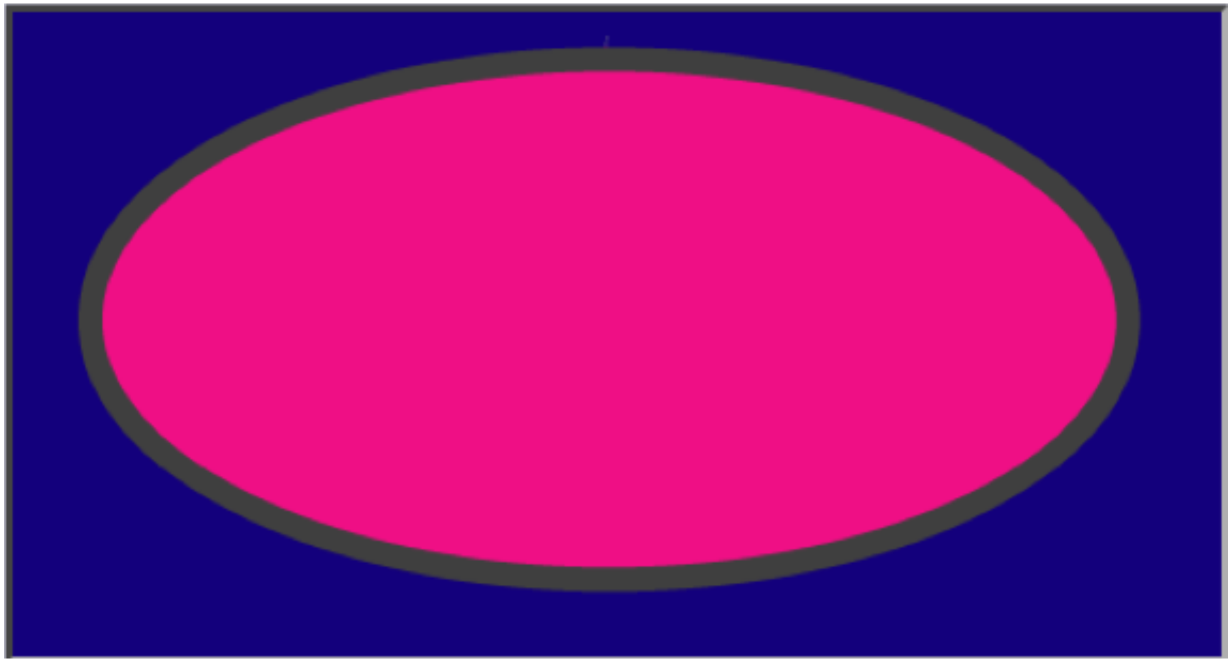
$\boxed{Q}$ The above plot (from Silk & Wyse 1993) shows gas number density vs Temperature, and also shows the loci where the cooling time = grav. collapse time and where both equal the Hubble time. Lines have const virial mass. (how object would collapse & stay virialized)

(i) what regions of density & Temperature effectively never cool? Never collapse gravitationally?

(ii) Which regions will collapse rapidly?

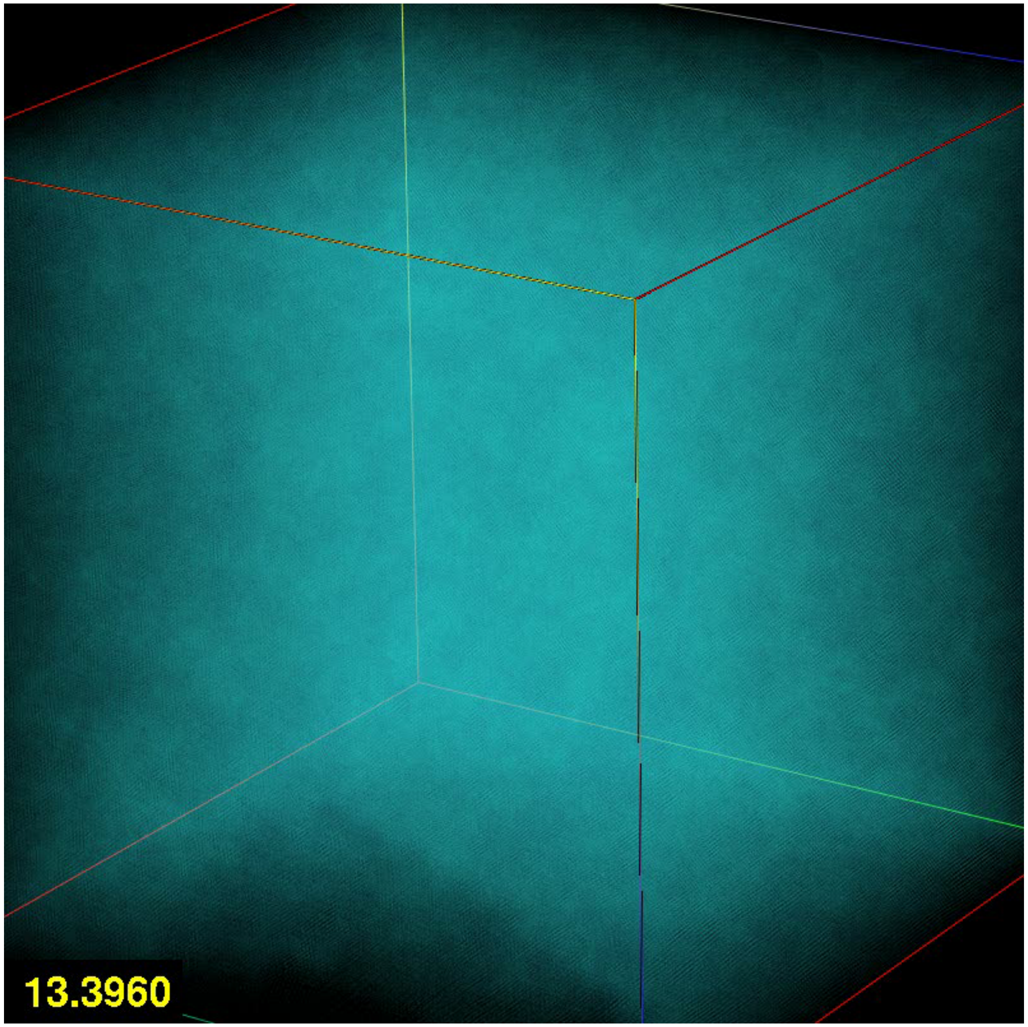
(iii) Will it be easier for gas in massive dark halos ($10^{14} M_\odot$, galaxy cluster size) to cool & collapse, or gas in small halos? What does this tell us about galaxy cluster formation?

Angular momentum



- Q: think back to the conditions at z~1000 when the CMB was observed. Was there much net angular momentum in the universe?

Angular momentum in galaxies



Q: The situation is quite different now. What do you think might have given disk galaxies their angular momentum?

Tidal torque theory

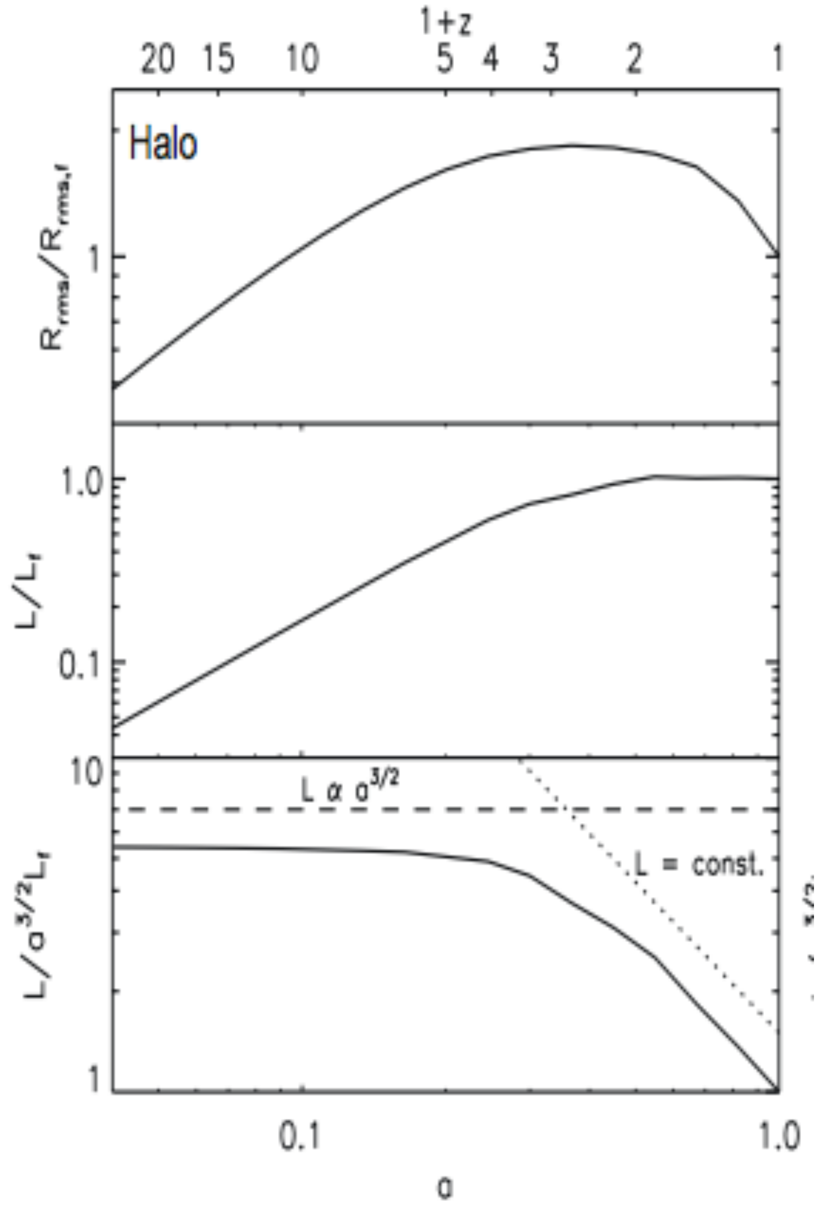
The matter distribution in the universe is not uniform: galaxies on filaments, clusters where filaments cross

Bolshoi
simulaton
courtesy
Joel
Primack

Tidal torque theory

This means that the surroundings of galaxies will exert a torque on them, creating angular momentum in the gas and dark matter which will go on to form the galaxy

Then the gas (but not the dark matter) radiates, cools, and collapses, conserving angular momentum during a decrease in size of around a factor of 10, leading to the rapidly rotating disks we see today (Fall and Efstathiou 1980)



Zavala et al 2008

- The top panel shows the size of the dark matter halo: growing then collapsing to half Rmax
- Middle panel shows angular momentum growing as the halo does, then staying constant during halo collapse
- Tidal torque theory predicts that L grows as (scale factor)$^{3/2}$