

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 \rightarrow violent relaxation, reaches equilibrium ("vialized")

gas \rightarrow 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

at high temperatures, $> 10^6$ K, 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 ~~de~~ excitation
give off emission lines in optical

Depends on metallicity of gas

Table 2.5 Main processes that cool the interstellar gas

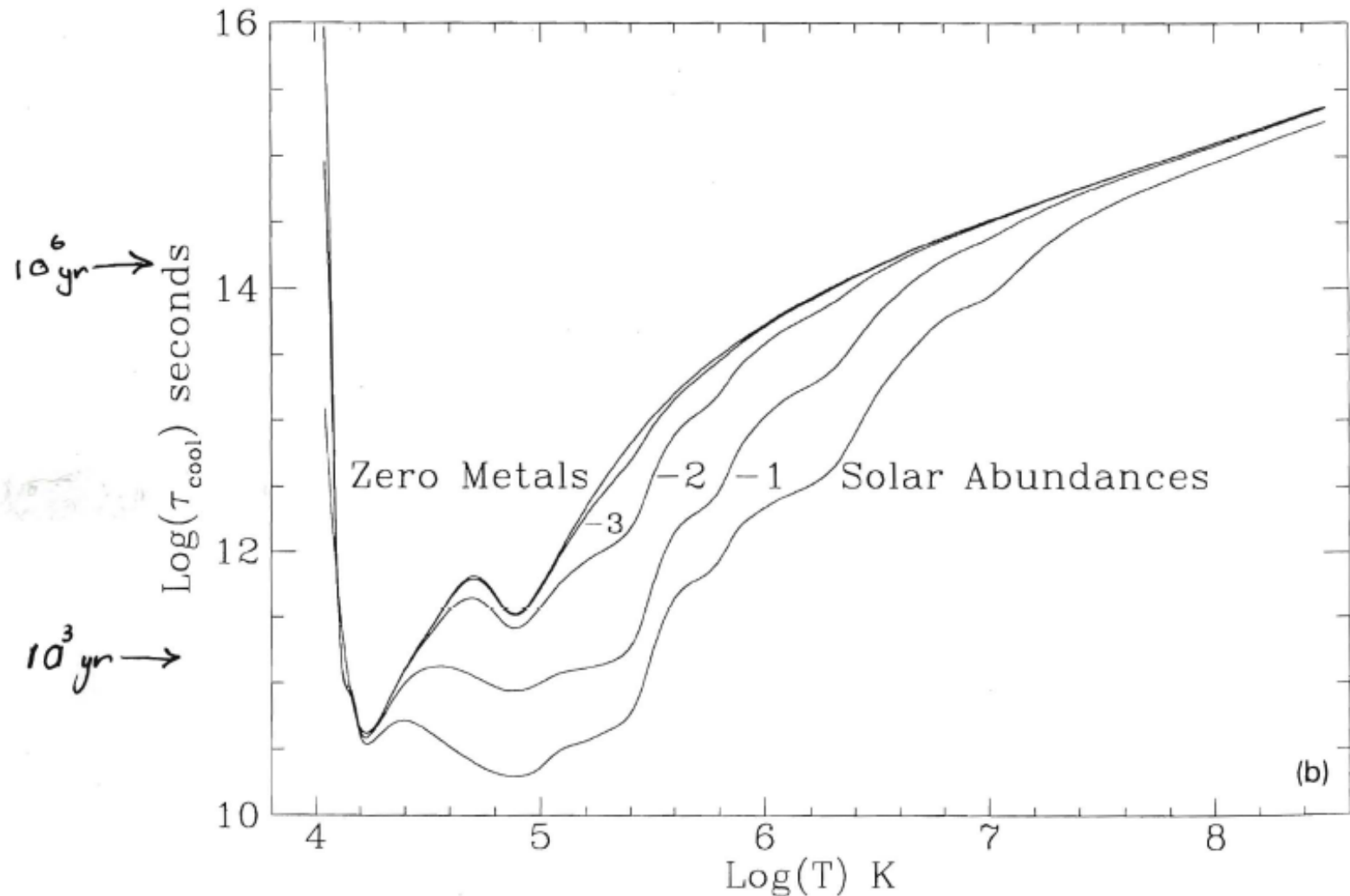
Temperature	Cooling process	Spectral region
$>10^7$ K	Free-free	X-ray
10^7 K $< T < 10^8$ K	Iron resonance lines	X-ray
10^5 K $< T < 10^7$ K	Metal resonance lines	UV, soft X-ray
8000 K $< T < 10^5$ K	C, N, O, Ne forbidden lines	IR, optical
Warm neutral gas: ~ 8000 K	Lyman- α , [O I]	1216 Å, 6300 Å
100 K $< T < 1000$ K	[O I], [C II], H ₂ ←	Far IR: 63 μ m, 158 μ m
$T \sim 10-50$ K	CO rotational transitions	Millimeter-wave

Cooling rate depends on density of gas, and on metallicity



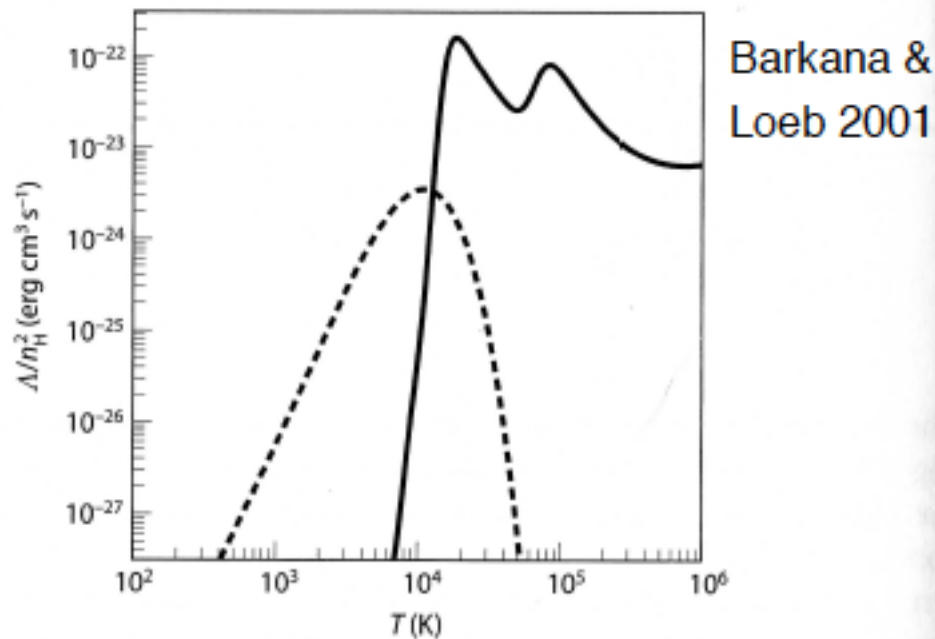
Why? Which cools faster, zero metal gas or metal-rich gas?

Cooling time as f(metallicity)



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

Atomic and molecular cooling for zero metal gas



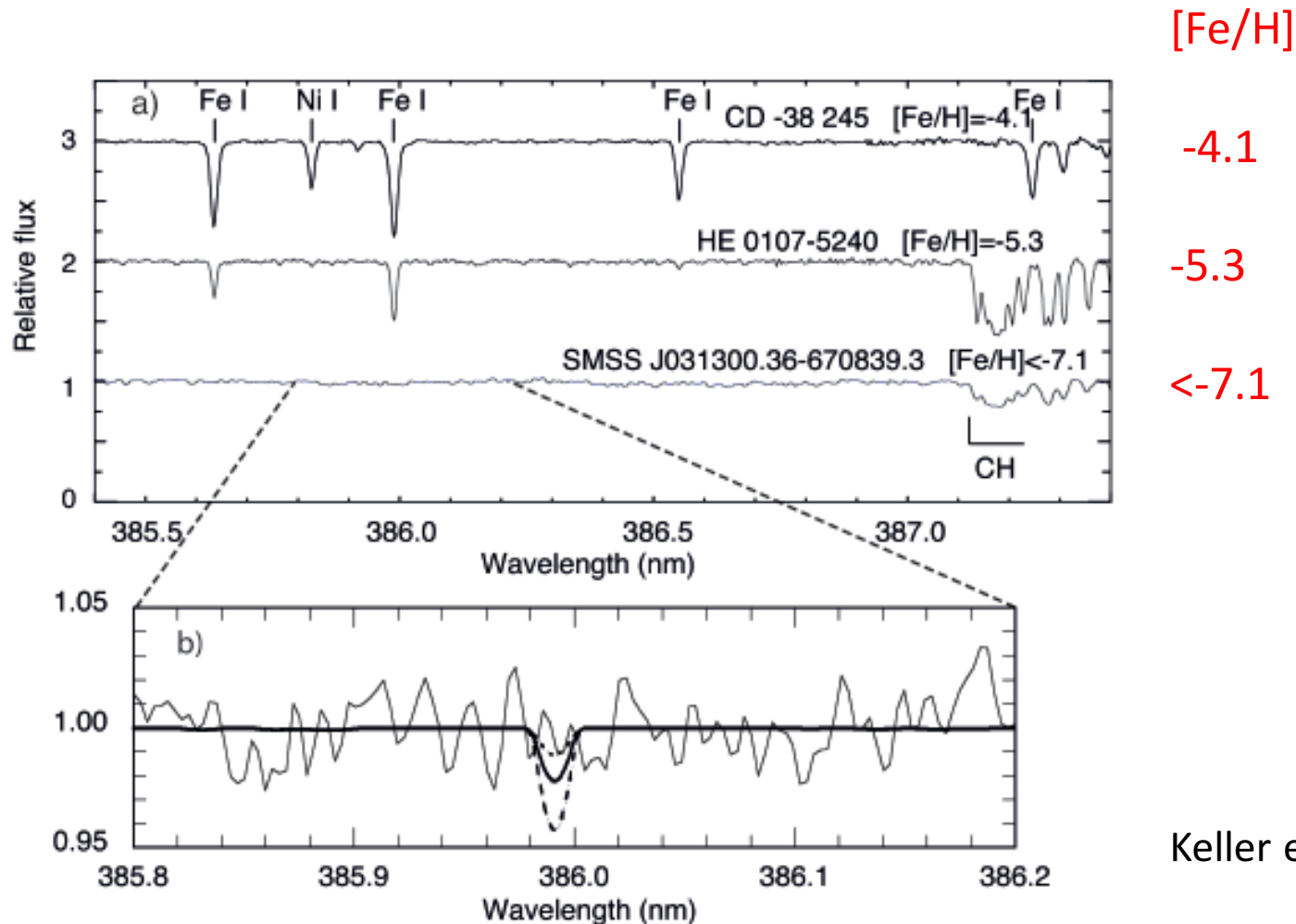
Cooling rates as a function of temperature for a primordial gas composed of atomic hydrogen and helium, as well as molecular hydrogen, in the absence of any external radiation. We assume a hydrogen number density $n_{\text{H}} = 0.045 \text{ cm}^{-3}$ corresponding to the mean density of virialized halos at $z = 10$. The plotted quantity Λ/n_{H}^2 , where Λ is the volume cooling rate (in $\text{erg cm}^3 \text{ s}^{-1}$), is roughly independent of density (unless $n_{\text{H}} > 10 \text{ cm}^{-3}$). 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 ($Z=0$)



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: The 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)

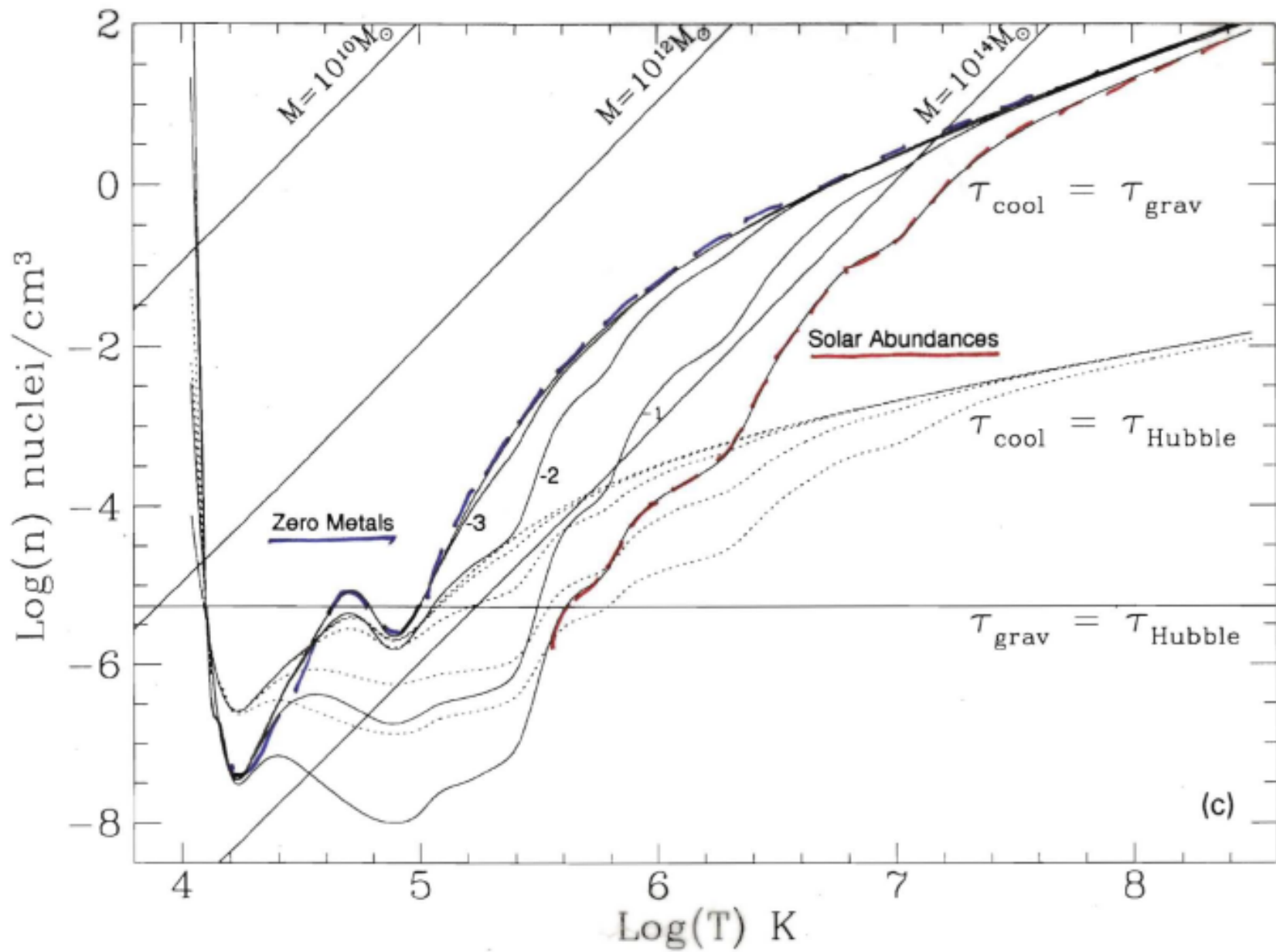
$$\propto \frac{1}{\sqrt{G\rho}}$$

$$\propto \frac{1}{\sqrt{n}}$$

n is number density of particles

So, high density regions cool & collapse fast

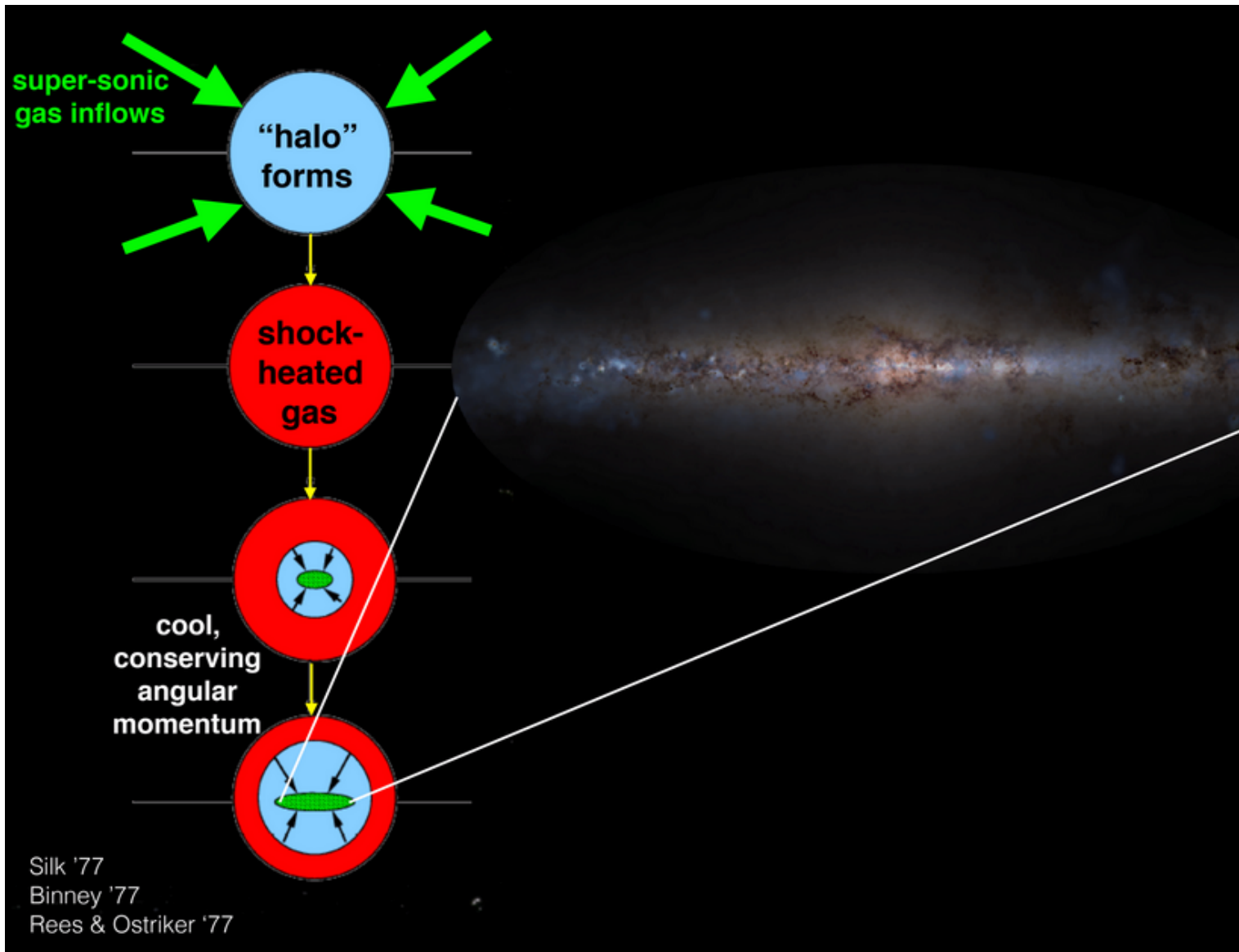
Very low density regions will neither cool nor collapse.



Interpreting the cooling plot

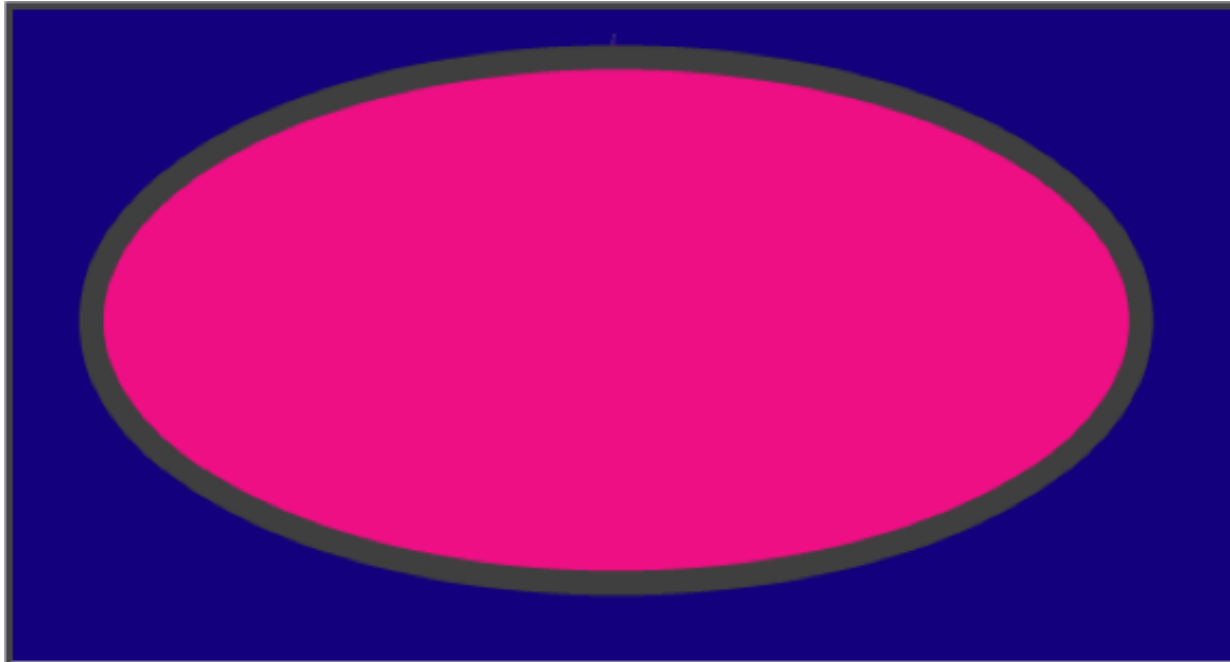
- Q The above plot (from Silk & Wyse 1993) shows gas number density vs Temperature, and also shows the loci where the cooling time = grav. collapse time and where both equal the Hubble time. Lines have const virial mass. (how object would collapse & stay virialized)
- (i) what regions of density & Temperature 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?

Thin disk formation



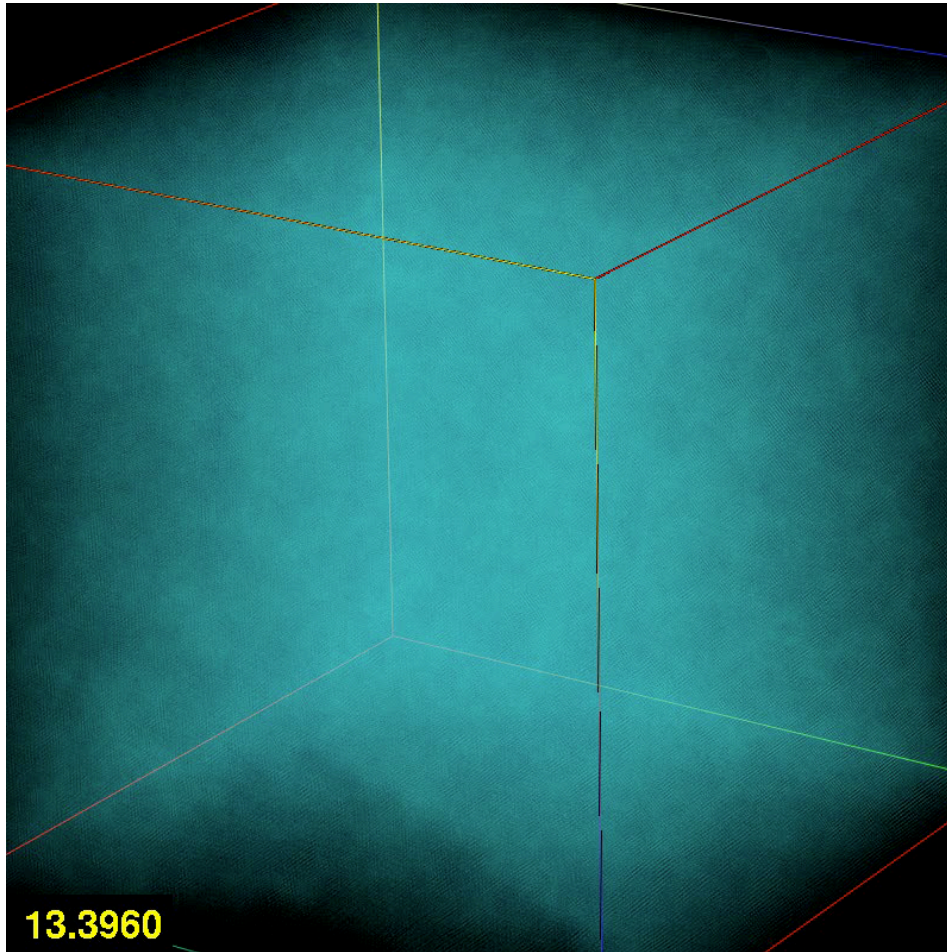
Phil Hopkins

Angular momentum in galaxies



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

Angular momentum in galaxies

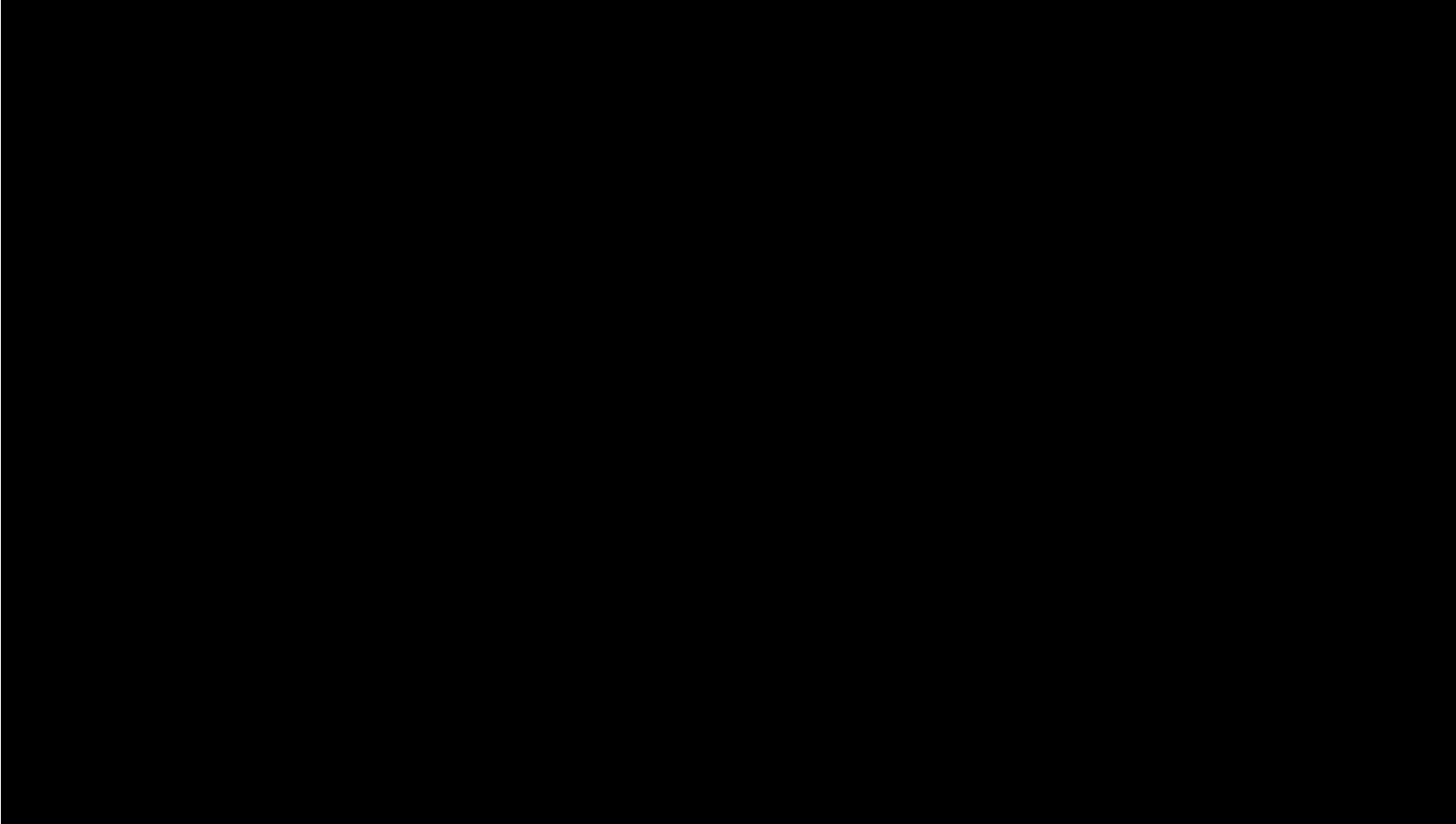


Q: The situation is quite different now. What do you think might have given disk galaxies their angular momentum?

Tidal torque theory

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

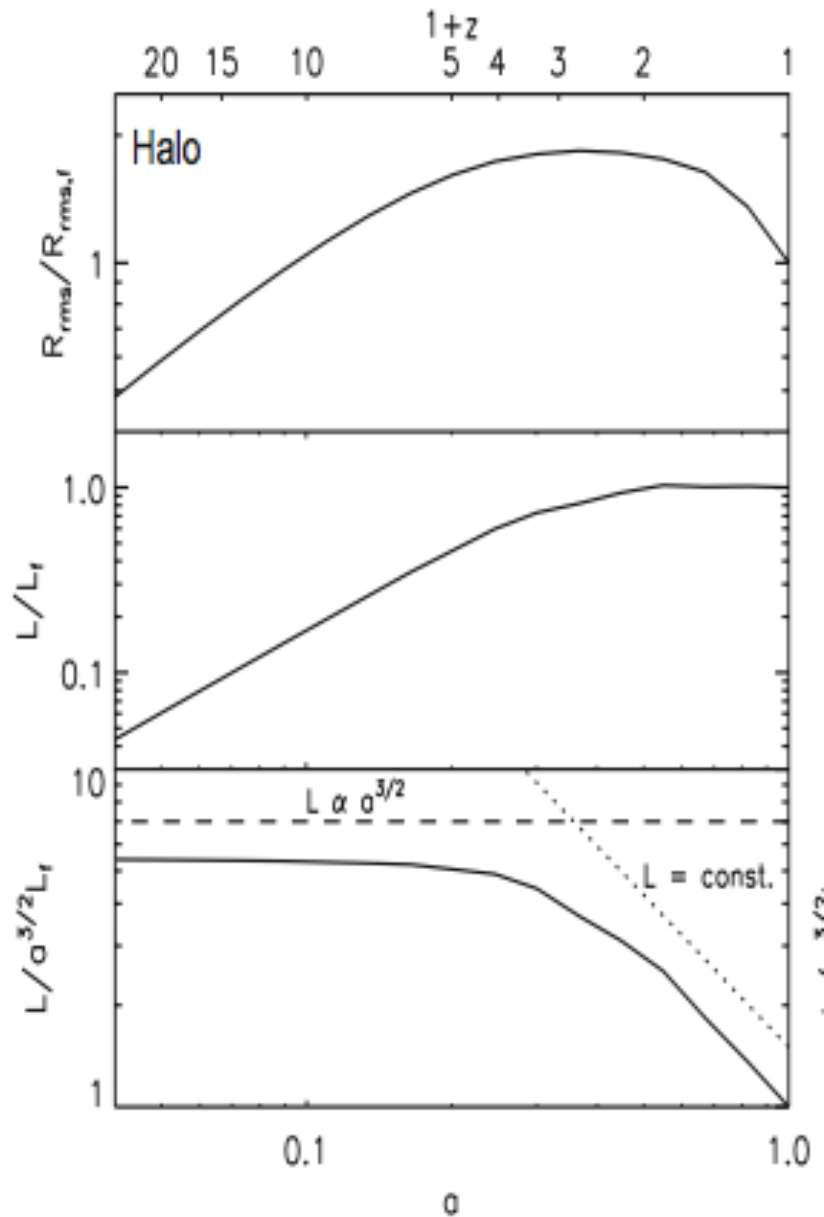
Bolshoi
simulaton,
courtesy
Joel
Primack



Tidal torque theory

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}

Inner halo is different

- Objects that will be in the inner halo suffer intense merging and lose angular momentum via dynamical friction

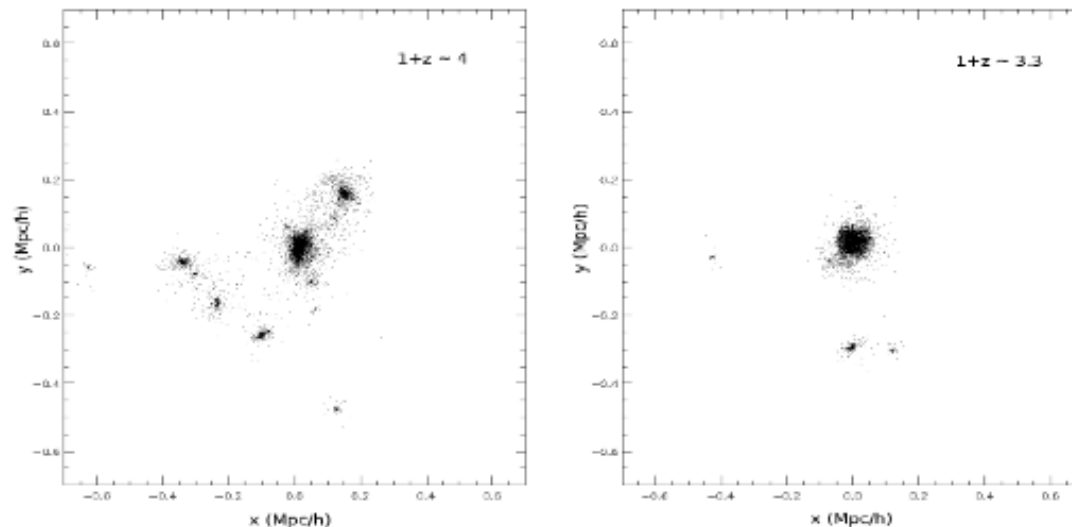
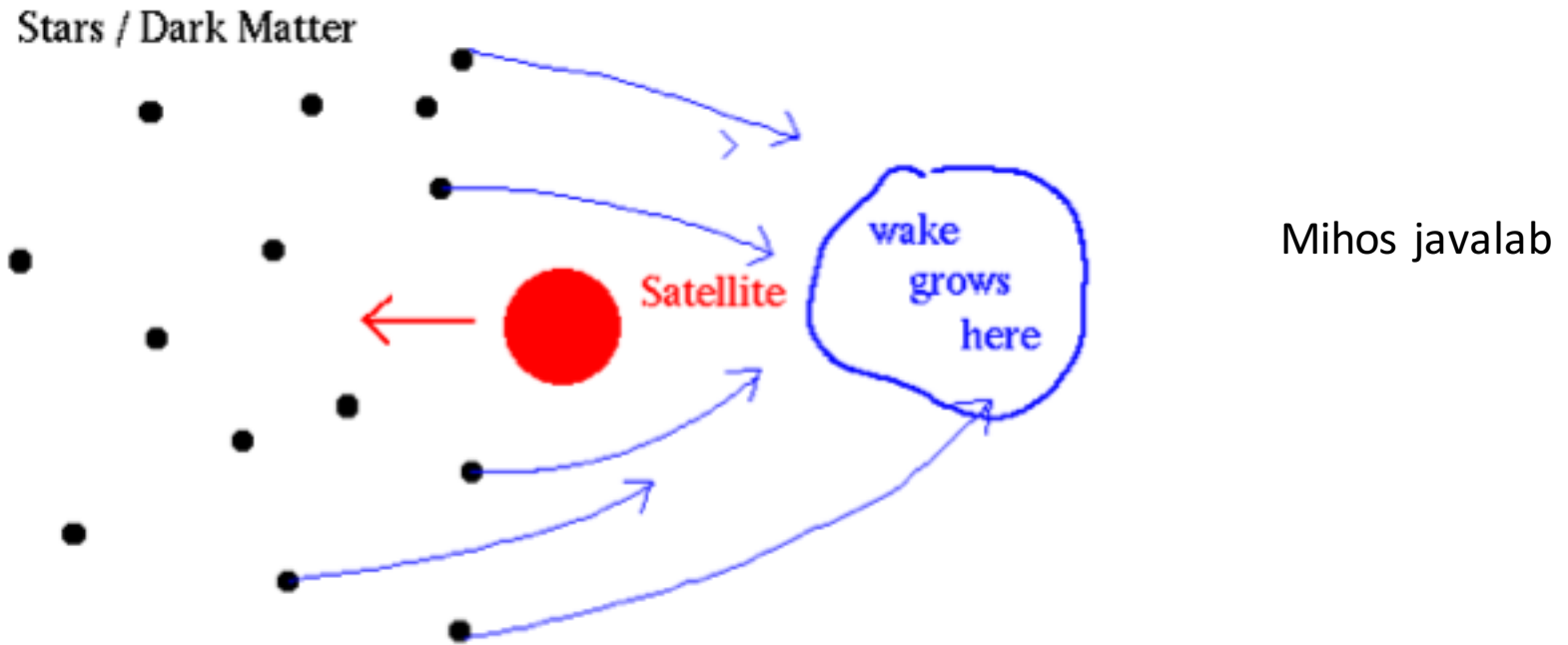


Figure 3. Projected positions of the dark matter particles which will eventually end up in the inner halo at $z = 0$. The left panel shows the distribution at $1 + z \sim 4$ and the right panel at $1 + z \sim 3.3$.

Dynamical friction: just gravity



Mihos javalab

When a massive object moves thru stars or dark matter, it forms a wake which exerts a backward force on the object. Satellite can transfer energy and angular momentum to surroundings

- Strong merger activity in subhalos that form inner halo transfer angular momentum to outer halo and leave inner halo with low a.m.

