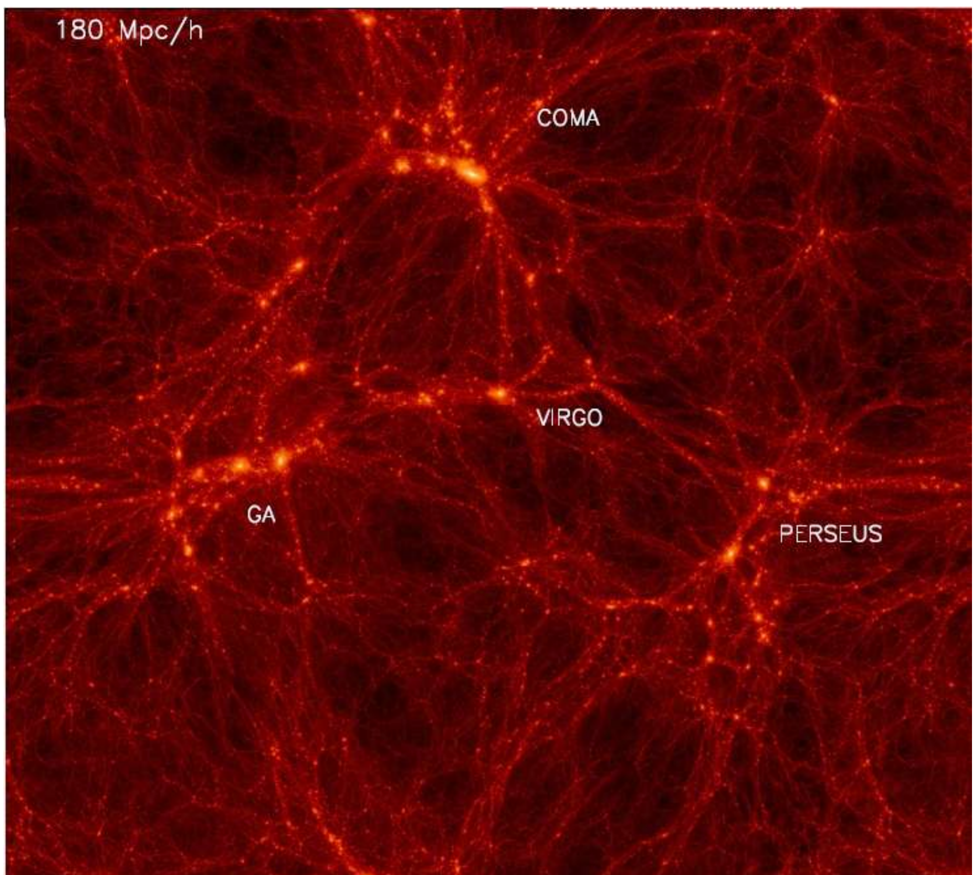
PART II

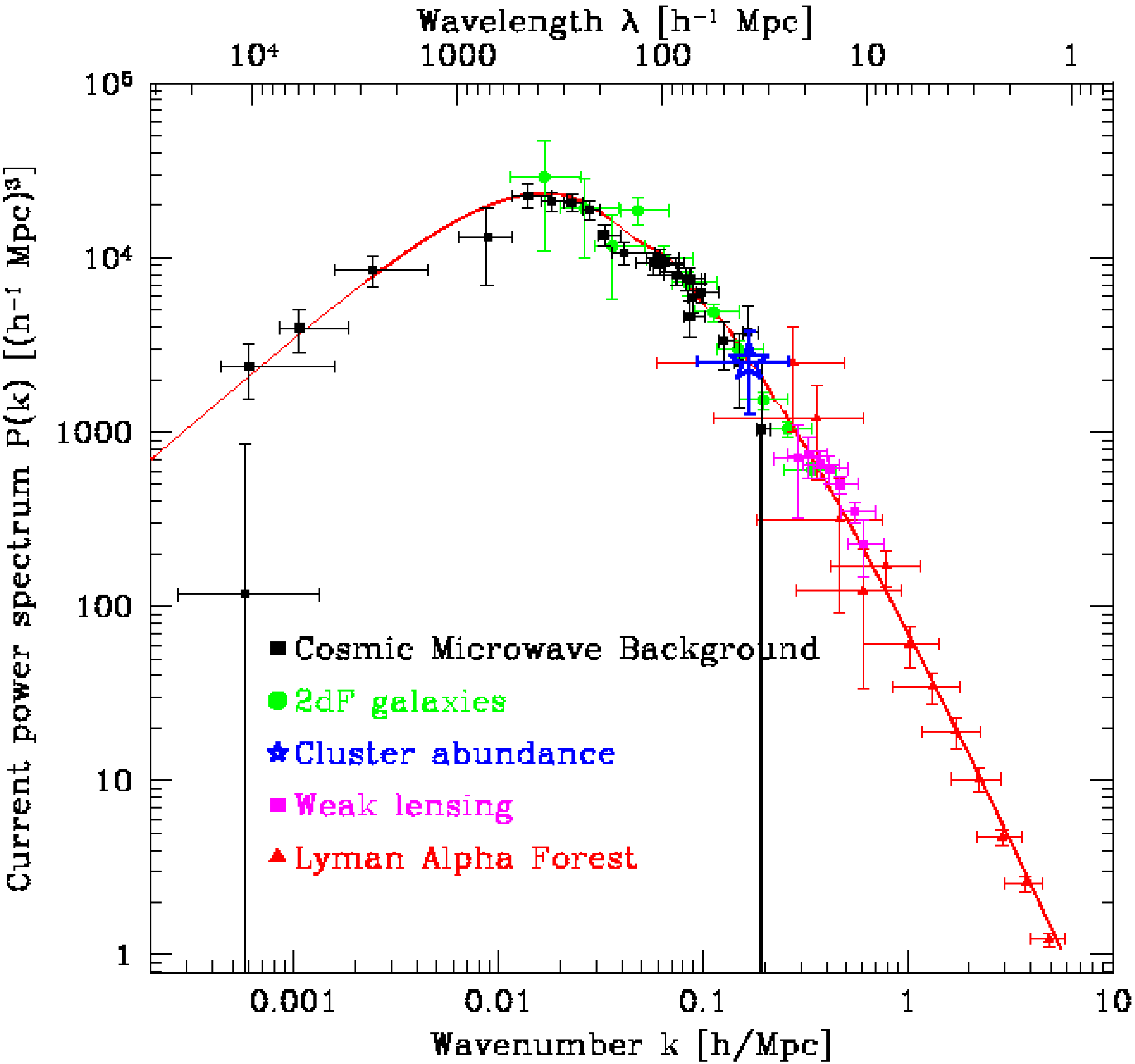
From IGM to CGM

Theory of LSS On 1 Slide

- LSS includes voids, filaments, and clusters/group at the intersection of filaments.

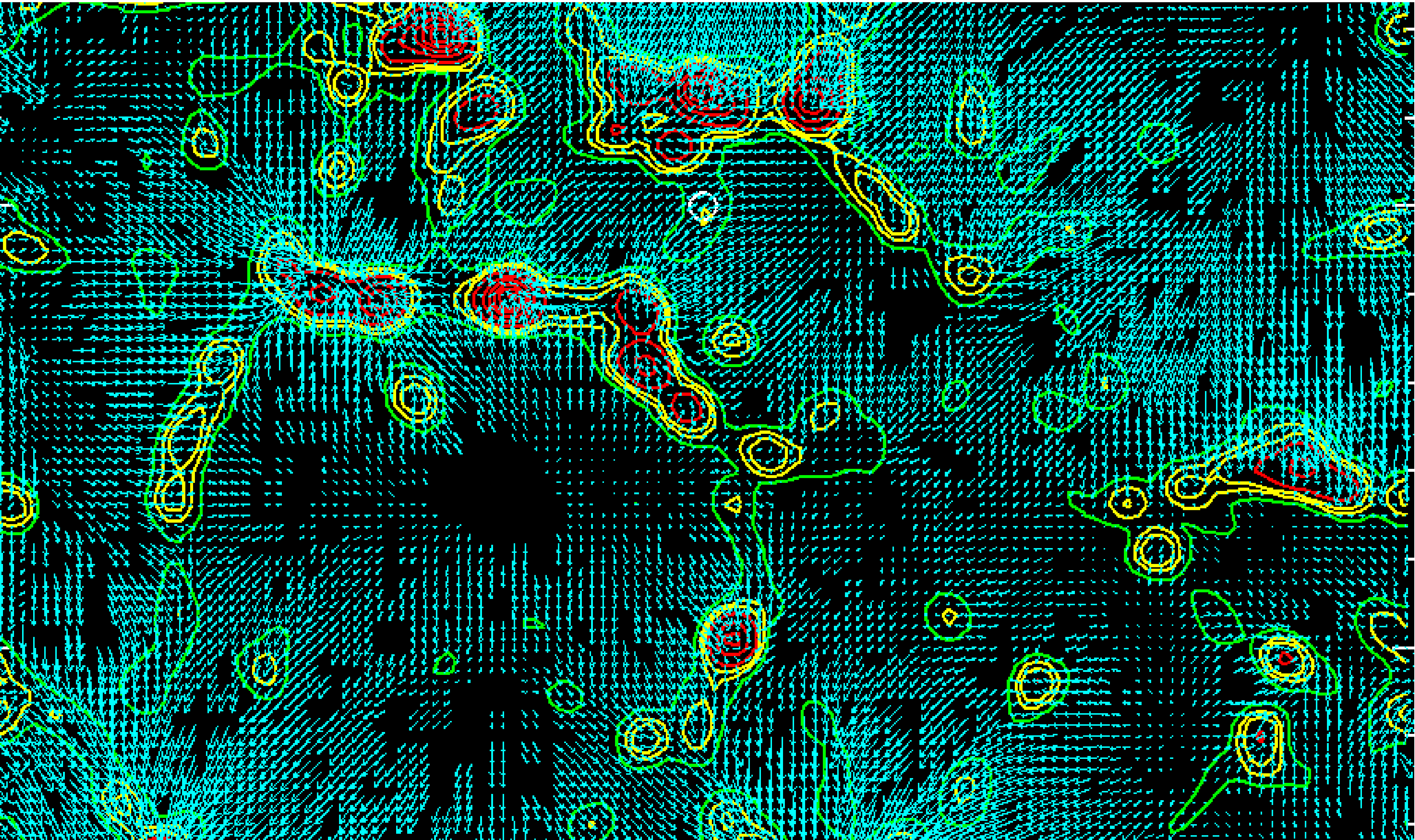


- Size of void ~ ½ peak of matter PS (100 CHIMP, the same at all times!)
- Filament width ~ nonlinear scale (5 CHIMP)
- Cluster mass/size ~ virial mass/size size of a region (nonlinear scale)^3.



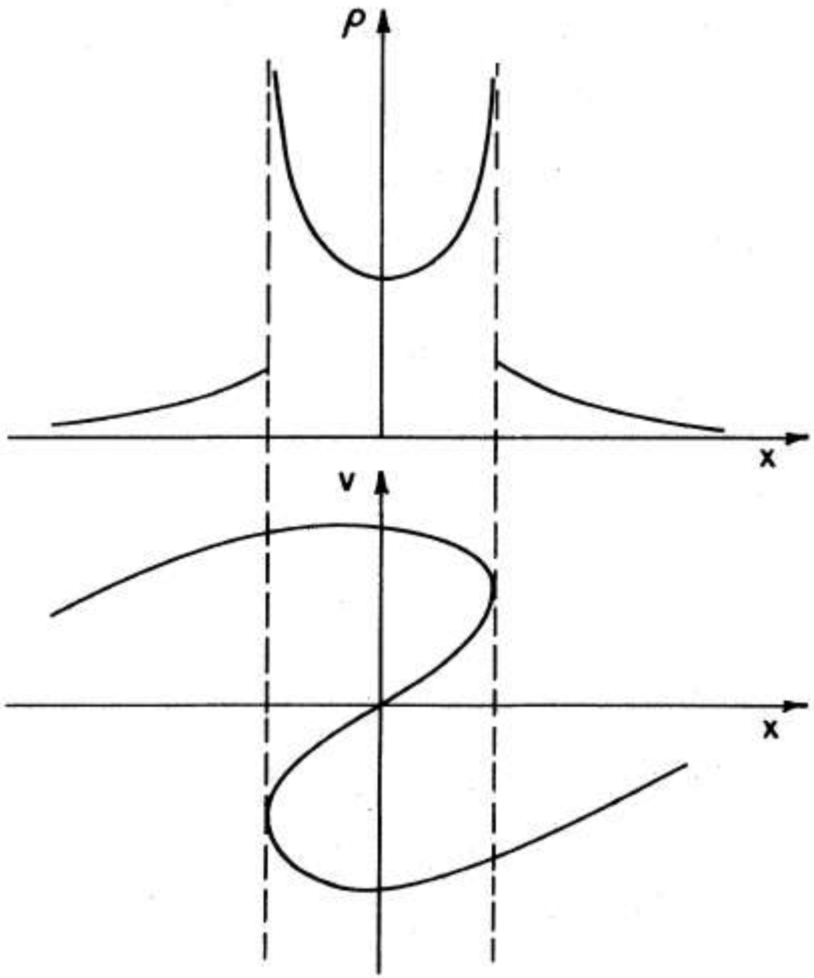
Wavelength λ [h⁻¹ Mpc]
10⁴
1000
100
10
1
10⁵
10⁴
1000
100
10
1
Current power spectrum P(k) [(h⁻¹ Mpc)³]
Cosmic Microwave Background
2dF galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
0.001
0.01
0.1
1
10
Wavenumber k [h/Mpc]

Gas Flows Onto Filaments

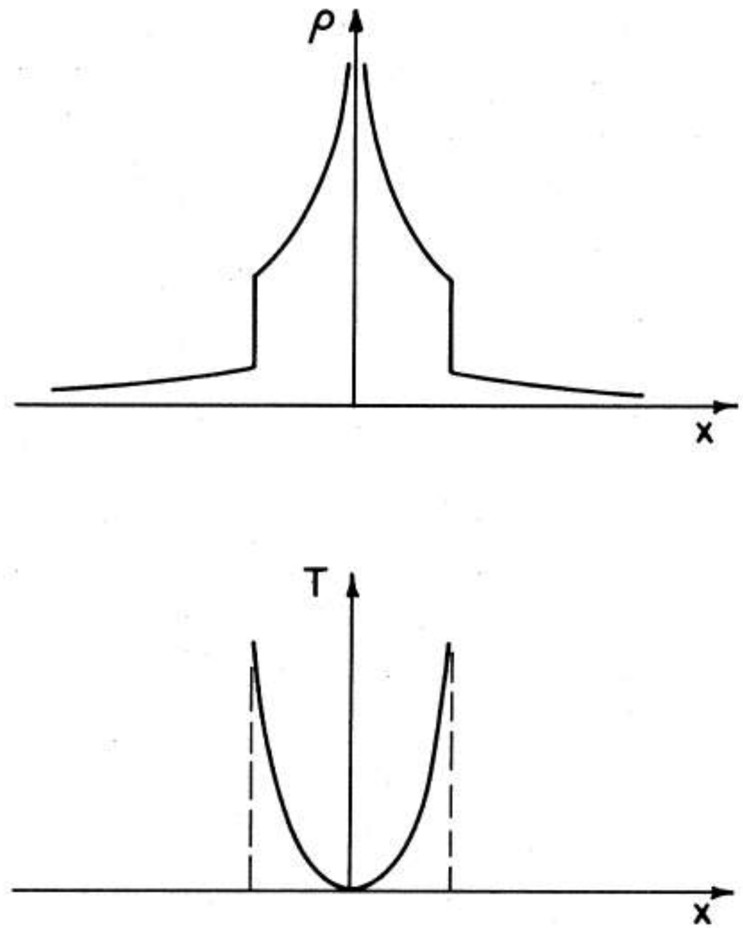


Structure Of Filaments

Dark Matter

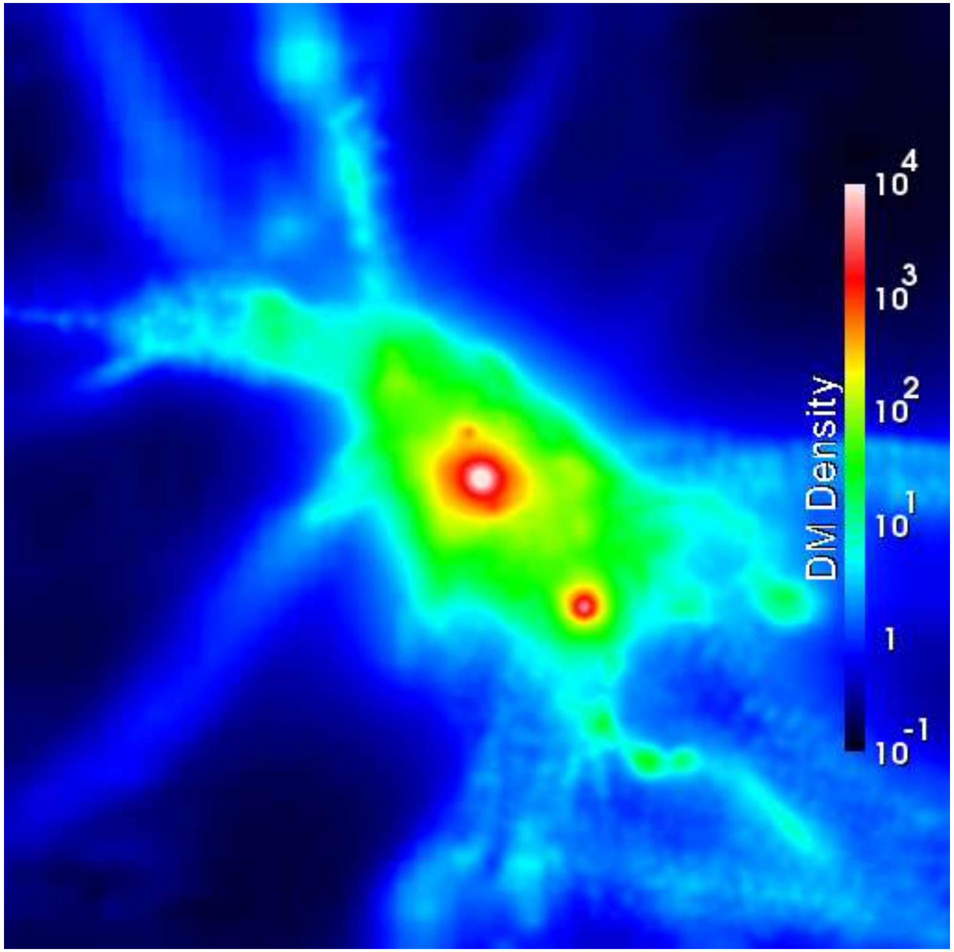


Gas

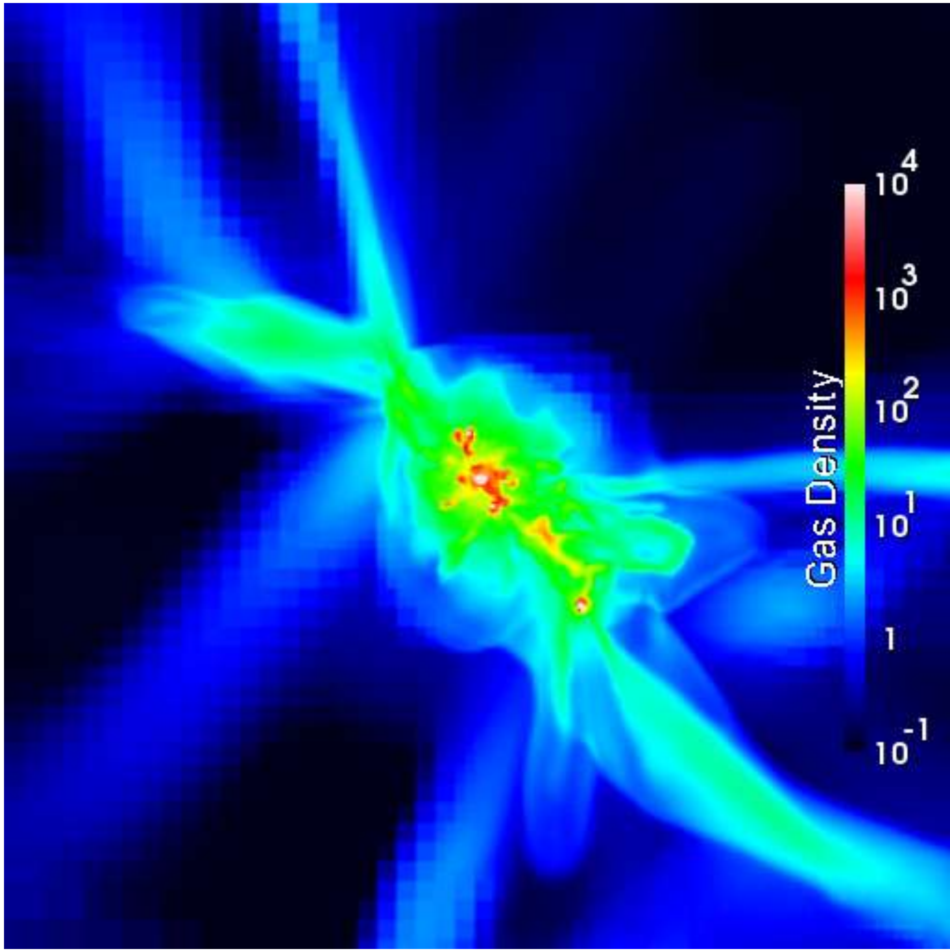


Structure Of Filaments

Dark Matter



Gas



Structure Of Filaments

Quiz: ***Why do gas filaments have less structure than DM filaments?***

A. Gas can flow from a high density region into a low density region.
B. Structure in filaments is suppressed by the force of gravity.
C. Structure in filaments is suppressed by the force of pressure.
D. Angular momentum is conserved.
E. Fluctuations in dark matter grow with time.

2. How Gas Gets Onto Galaxies

- Dense enough regions will collapse and virialize (=reach virial equilibrium).

- The simplest collapse model is a *top-hat*.

$$\rho(\vec{x}) = \begin{cases} \bar{\rho}(1+\delta_i), & r < r_i \\ \bar{\rho} & r > r_i \end{cases}$$

- The evolution of the radius of the sphere can be solved analytically (in the matter-dominated regime):

$$r = \frac{GM}{\delta_i \dot{r}_i^2}(1-\cos\theta) \qquad t = \frac{GM}{\delta_i^{3/2}\dot{r}_i^3}(\theta - \sin\theta)$$

Top-Hat Collapse

- Perturbation collapses ($r = 0$) at

$$\theta = 2\pi \qquad\qquad t_f = 2\pi \frac{GM}{\delta_i^{3/2} \dot{r}_i^3}$$

- This solution is independent of the initial conditions if expressed in the following form. Let $\delta_L(t)$ be the linear growing perturbation,

$$\delta_L(t) = \frac{D_+(t)}{D_+(t_i)} \delta_i$$

- then

$$\delta_L(t_f) = \frac{3}{5} \left(\frac{9\pi^2}{4} \right)^{1/3} = 1.69$$

Virial Overdensity

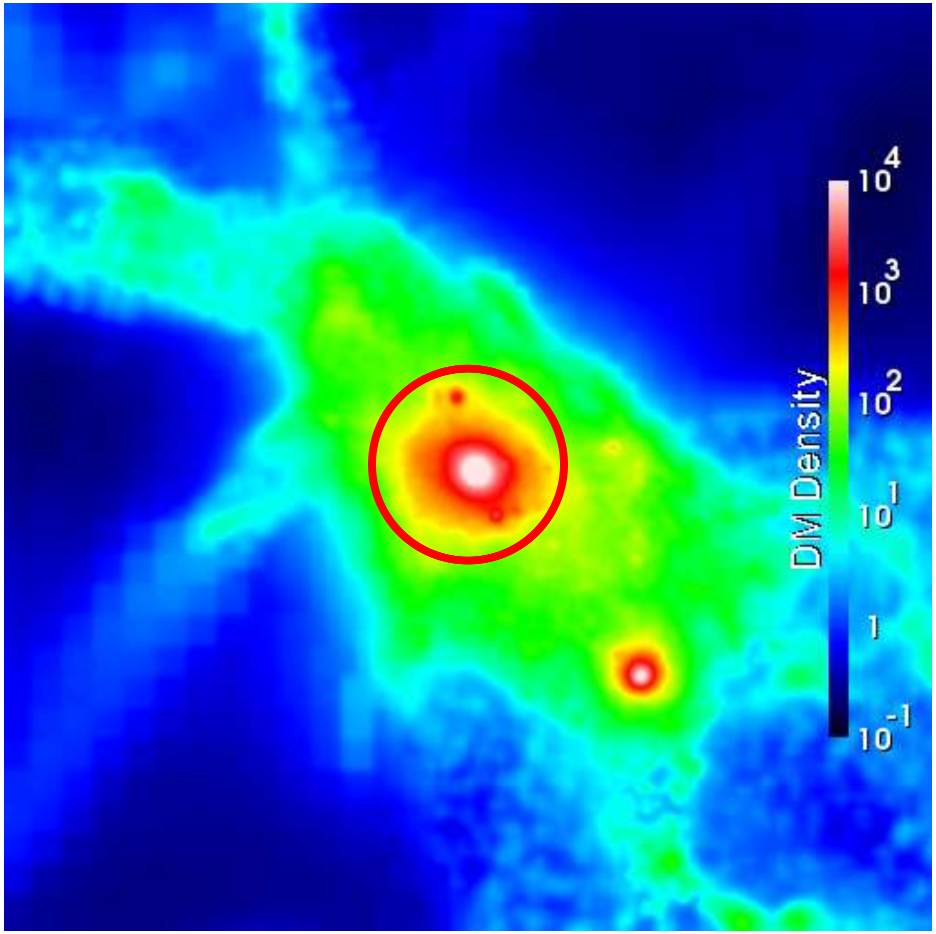
- Of course, a perturbation cannot collapse to a point ($r = 0$). It is assumed that at t_f the perturbation reaches virial equilibrium ($2K + W = 0$). Then the mean overdensity of the virialized object is

$$1 + \delta_v = 18\pi^2 = 178 \approx 180 \approx 200$$

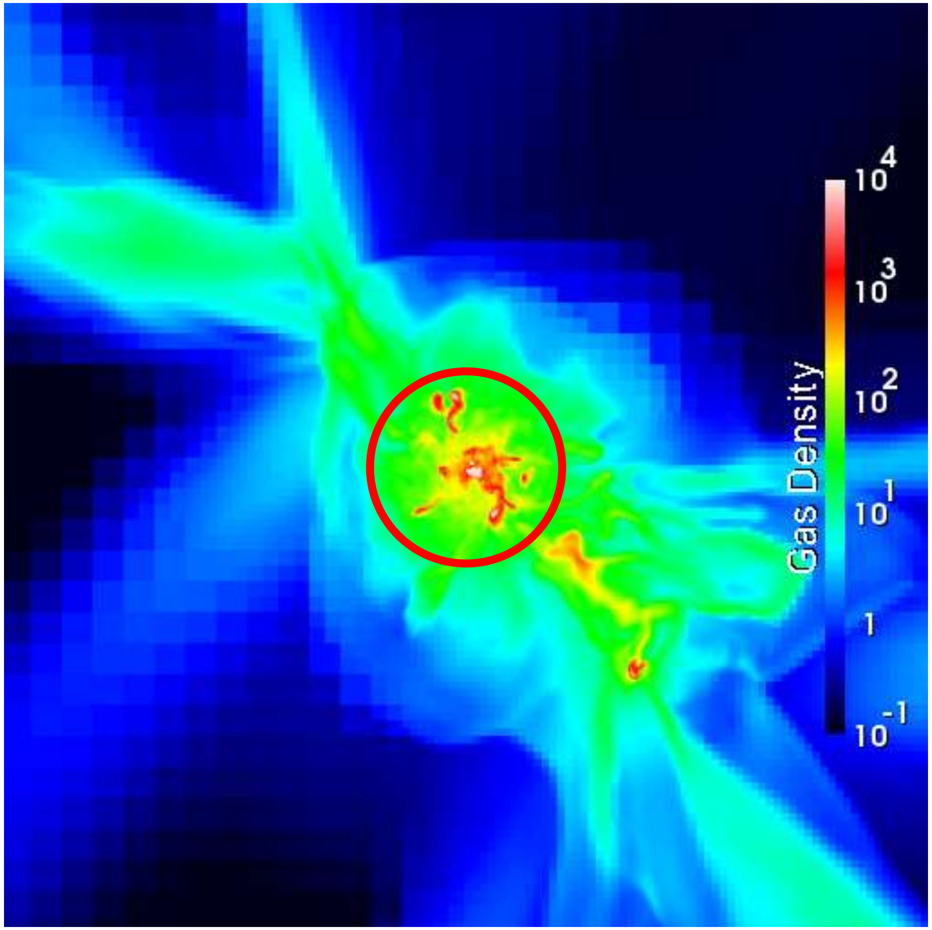
- At low redshifts (when Λ dominates), δ_v becomes redshift-dependent.

Galactic Halos Look Virialized!

Dark Matter

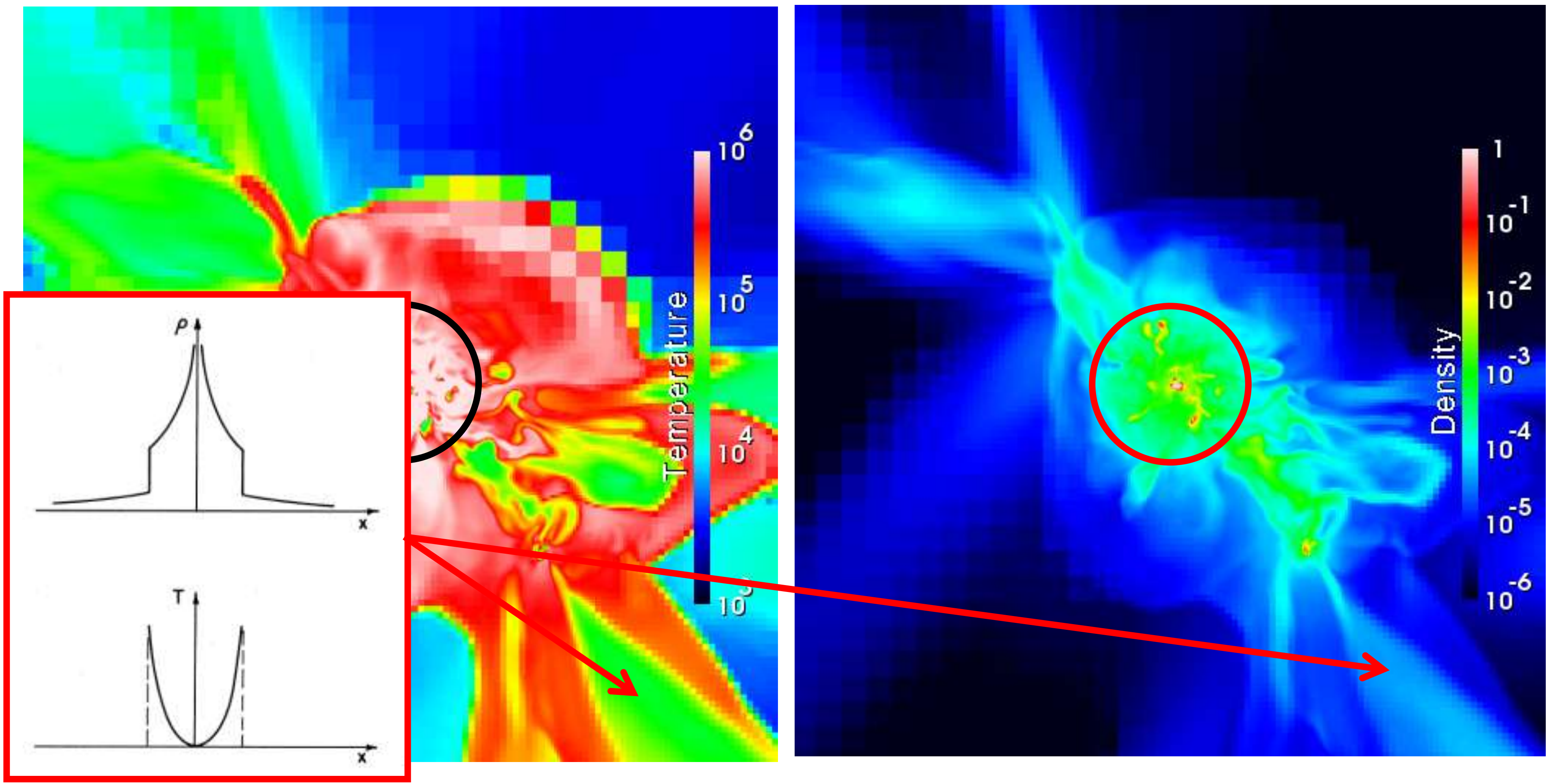


Gas



Galactic Halos Look Virialized!

Gas Temperature   Gas Density

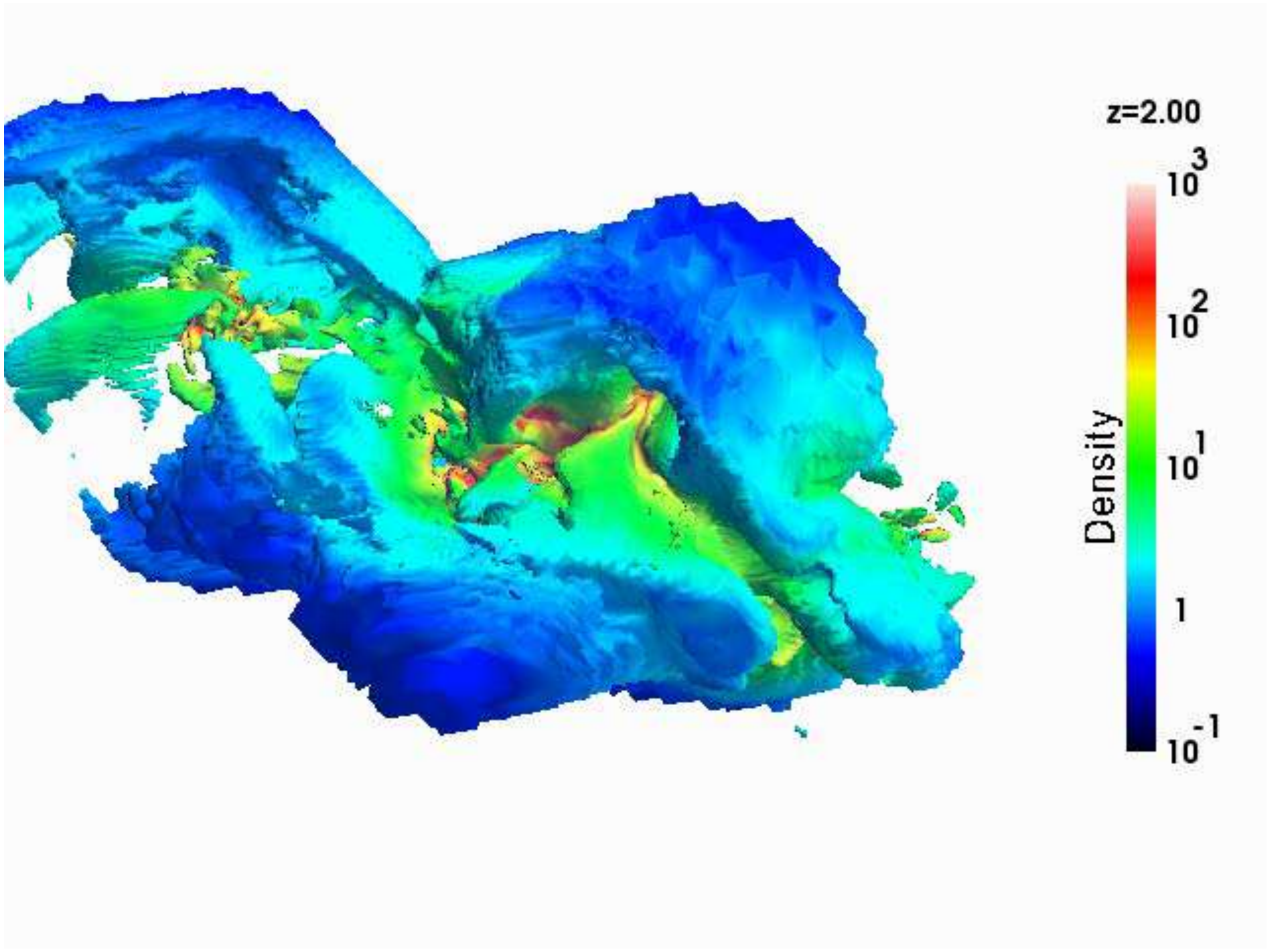


Accretion Shock

- Virial radius is a good approximation of a boundary beyond which any, even imaginable, resemblance of spherical symmetry totally vanishes!
- As gas falls into potential wells of halos, it gets shocked and heated to ~virial temperature. The ***accretion shock*** propagates outward.
- It is not uncommon to find the accretion shock at ~3 virial radii.
- While occasionally assumed to be spherical by some theorists, it is one of most non-spherical objects in the whole universe!

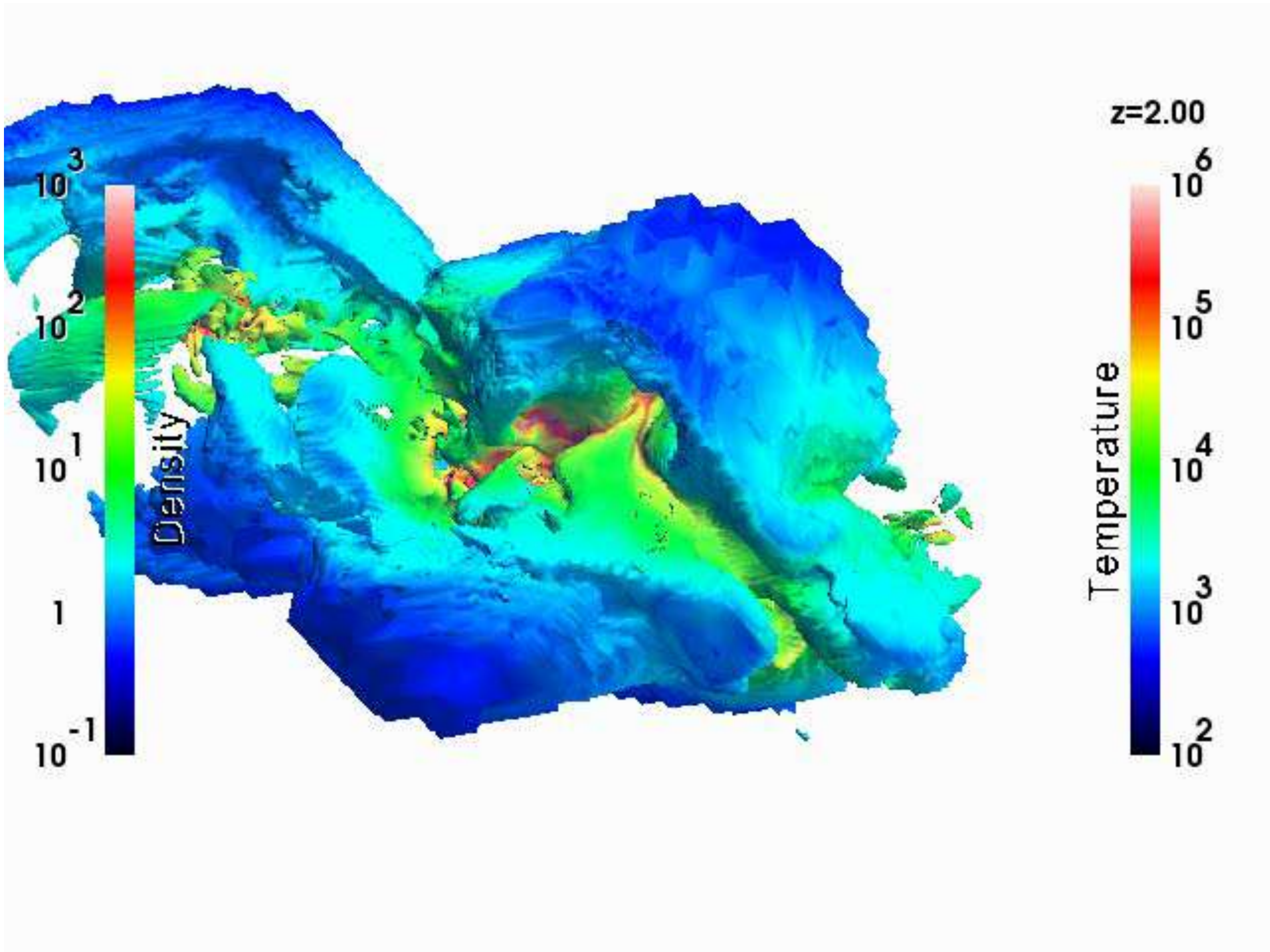
Accretion Shock
(A Poster Child Of Non-sphericity)

- Isosurface of $T=\frac{1}{2} T_{VIR}$ for a MW progenitor at z=2



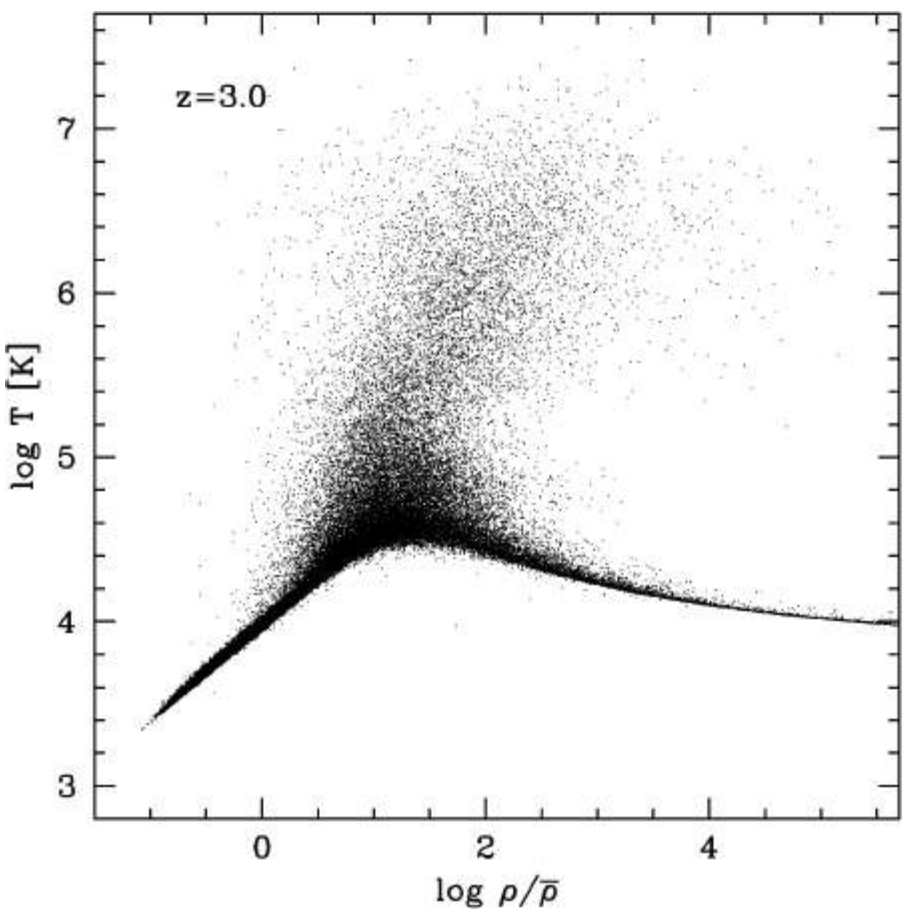
Cold (Or, Rather, Cool) Streams

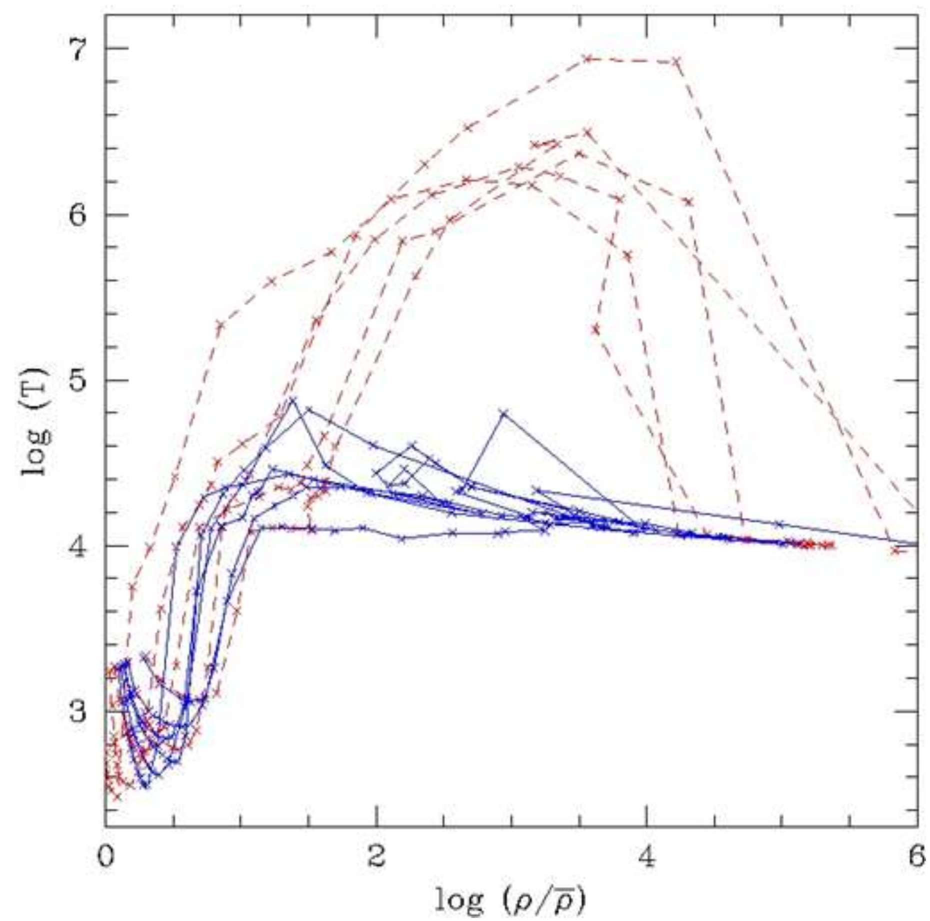
- Cool streams of gas penetrate well inside the halo.



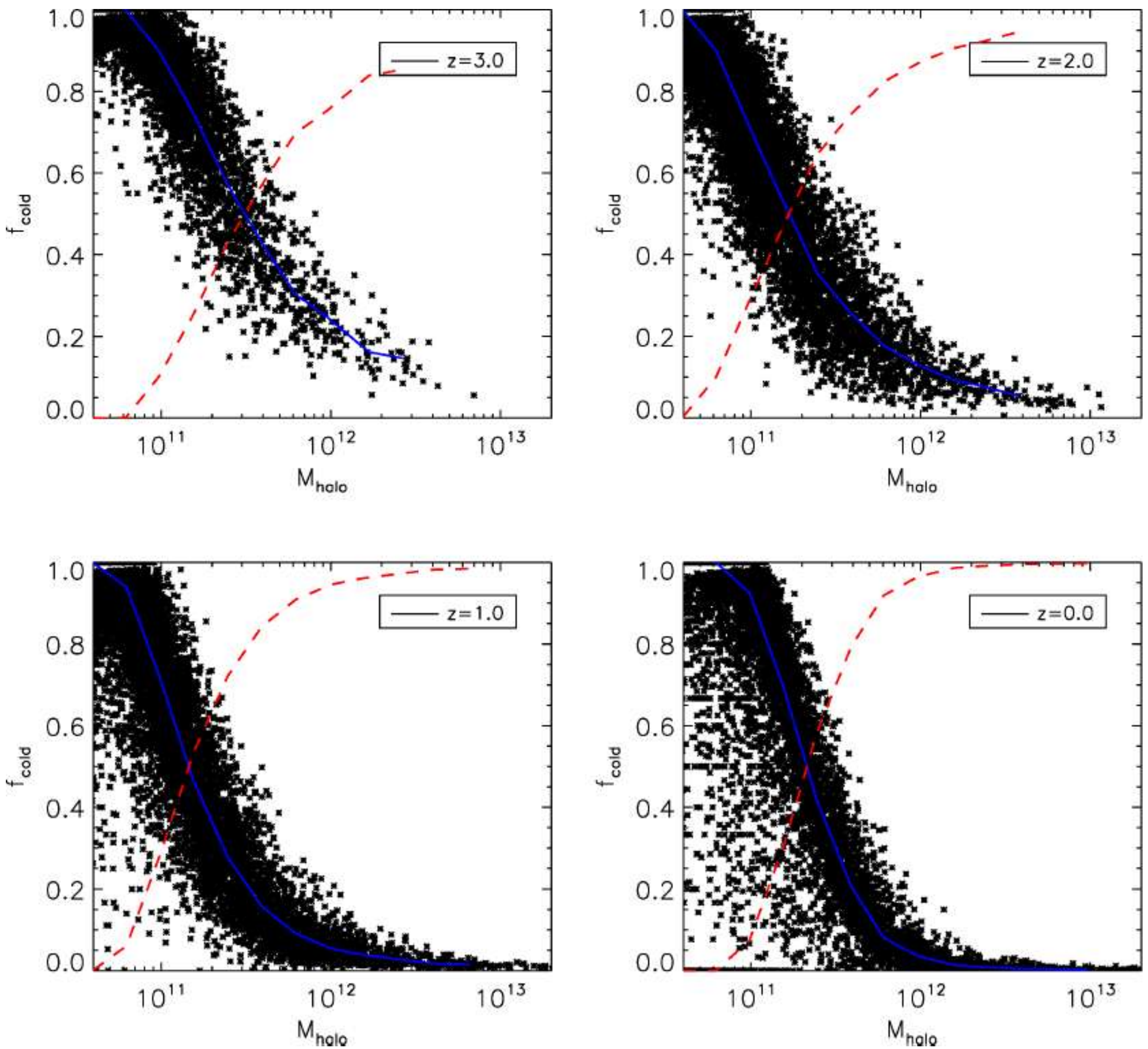
Cool Streams

- A substantial fraction of the gas was never heated to the virial temperature.



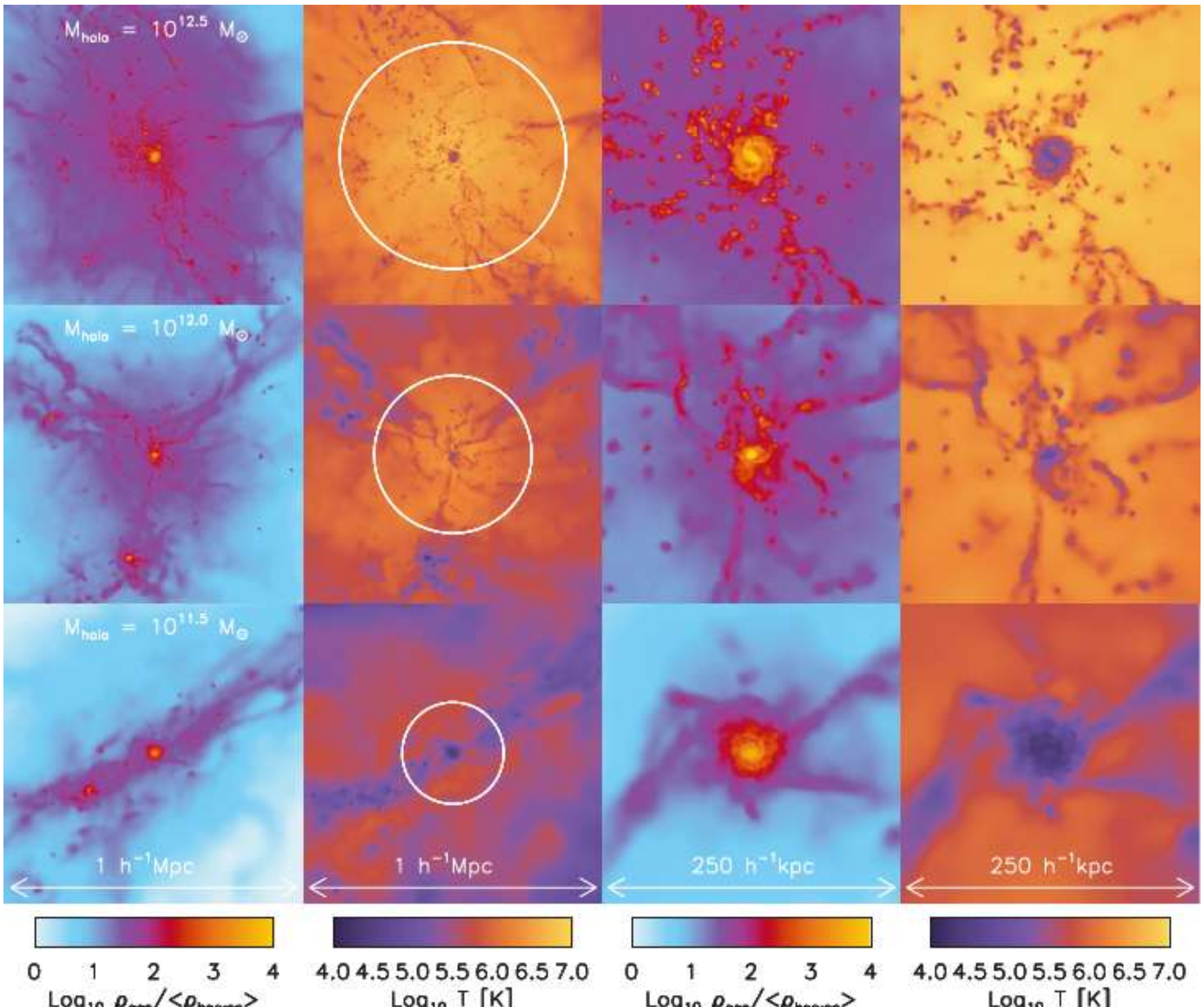


Hot vs Cool



- Big guys like it hot.
- Small guys take it cool.

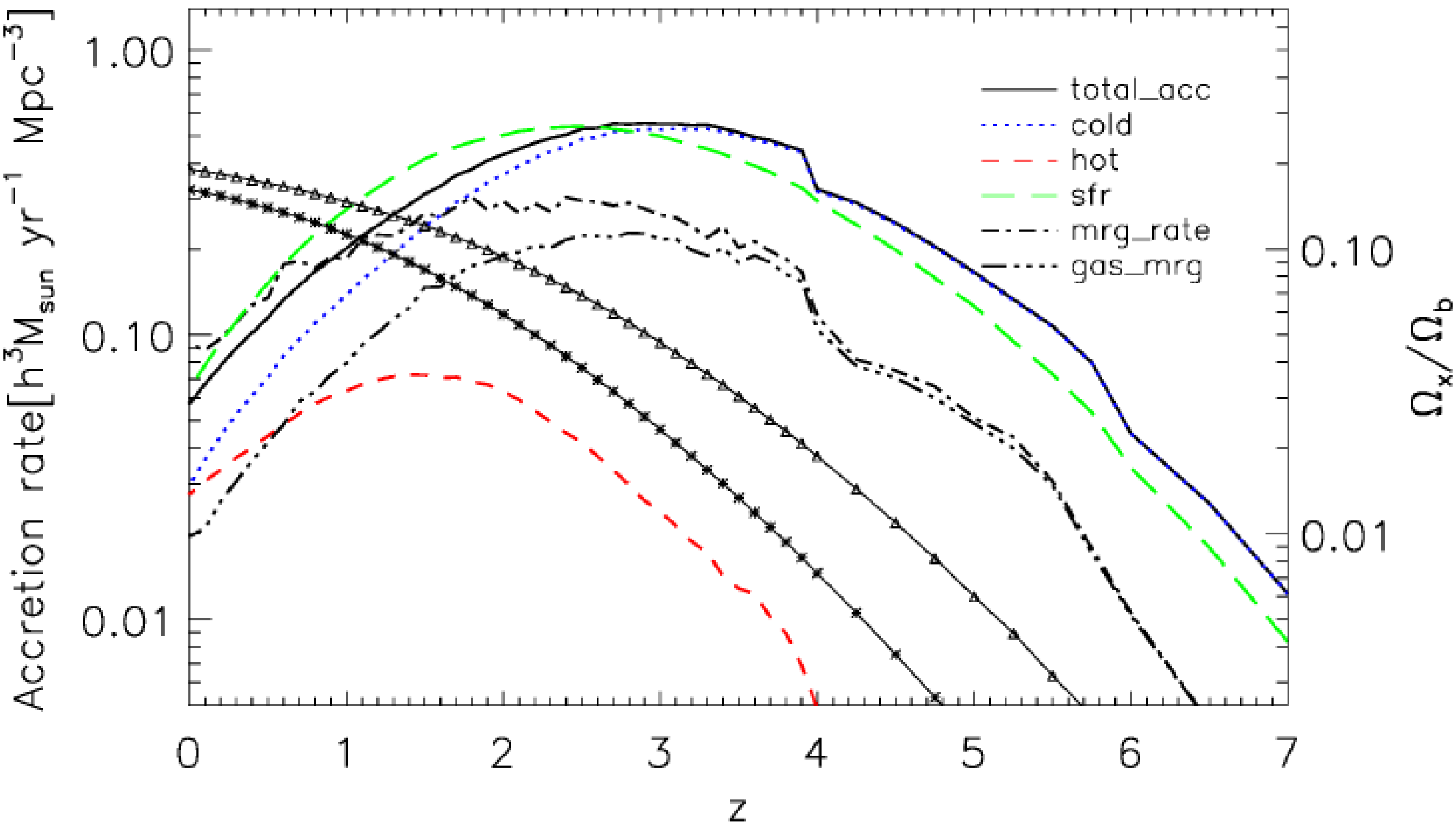
Hot vs Cool



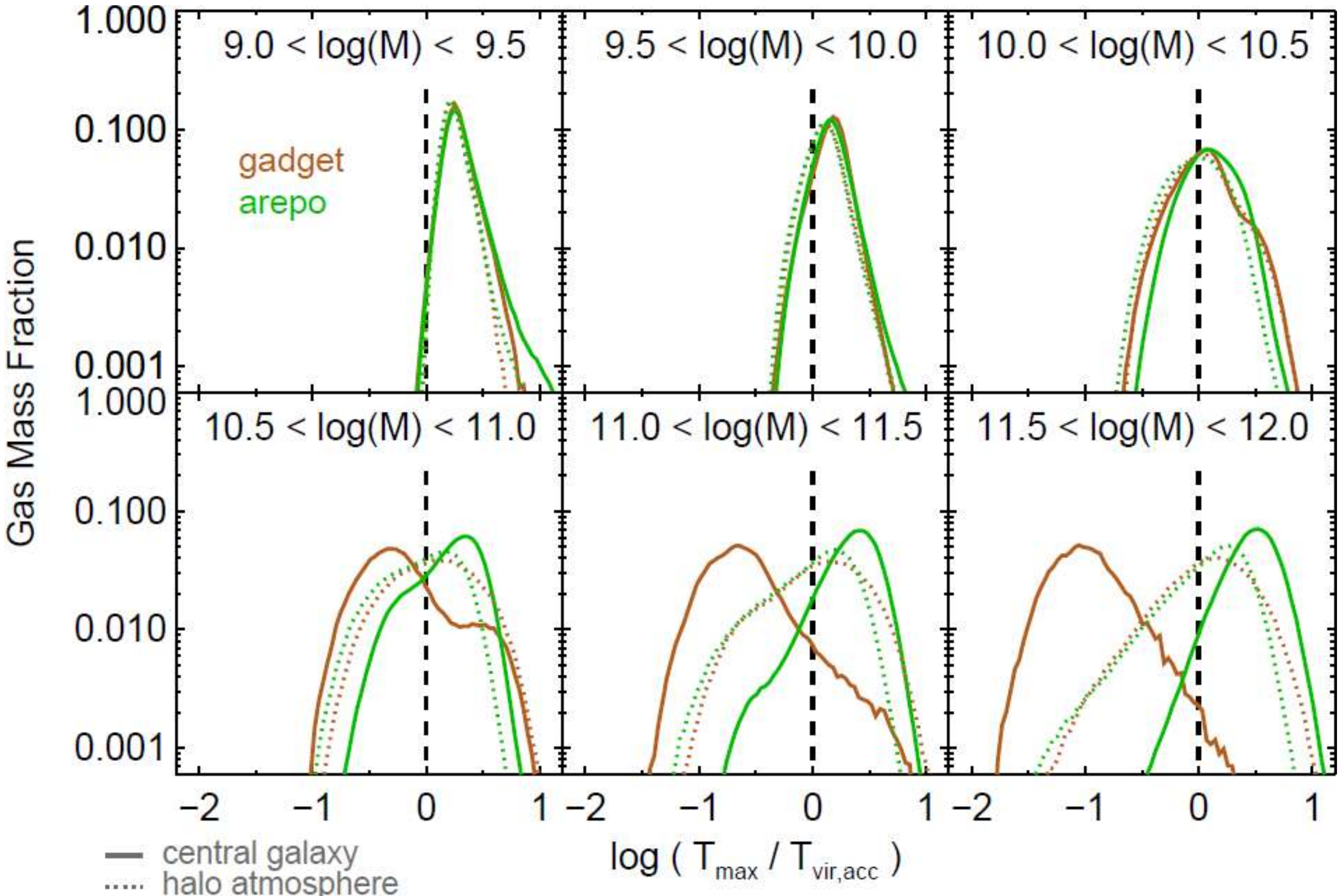
$M_{halo} = 10^{12.5} M_\odot$
$M_{halo} = 10^{12.0} M_\odot$
$M_{halo} = 10^{11.5} M_\odot$
1 h^{-1}Mpc
1 h^{-1}Mpc
250 h^{-1}kpc
250 h^{-1}kpc
0 1 2 3 4
$Log_{10}\ \rho_{gas}/\langle\rho_{baryon}\rangle$
4.0 4.5 5.0 5.5 6.0 6.5 7.0
Log_{10} T [K]
0 1 2 3 4
$Log_{10}\ \rho_{gas}/\langle\rho_{baryon}\rangle$
4.0 4.5 5.0 5.5 6.0 6.5 7.0
Log_{10} T [K]

Hot vs Cool

- Most of gas in galaxies accreted cool!



Are We There Yet?

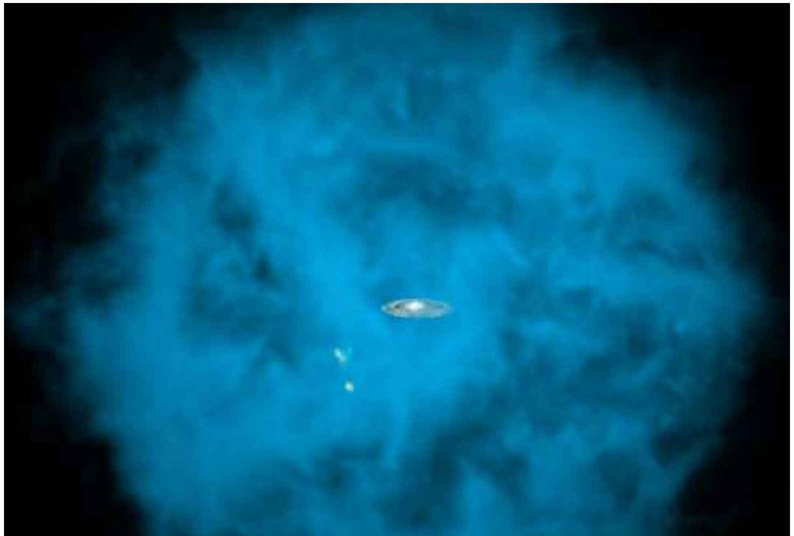


Are We There Yet?

- Most of gas that ends up in the galactic disks enter the halo as “cool” – significantly below the virial temperature. It may still be well above the “ISM cool” of 10^4 K.
- Its further history is not yet fully understood – SPH codes predict rapid cooling of that gas, while in grid codes it can get heated way above the virial temperature very close to the disk.
- It is possible to identify numerical artifacts in both approaches, hence it remains to be seen who (if anyone) is closer to reality.

3. Galactic Halos

- Cosmological simulations generically predict that galaxies like the Milky Way should be surrounded by hot gaseous halos in quasi-virial equilibrium.
- For 2 decades the actual existence of hot halos was an even more hotly debated topic.
- Hot gas emits X-rays, hence hot halos may be detectable in X-rays.

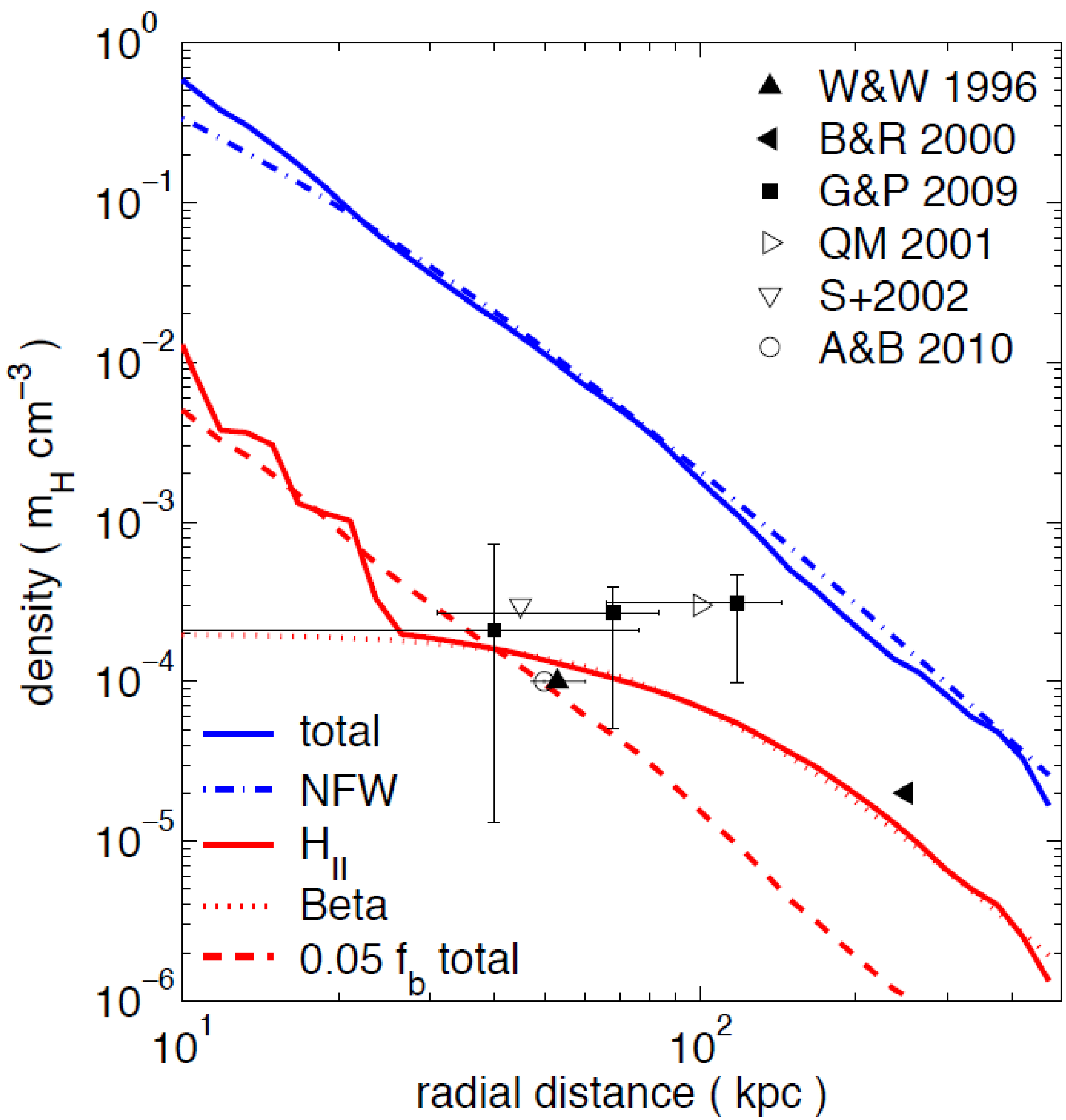


X-ray halo of the MW detected by Chandra
(from the official Chandra site)

Mass Budget of the MW

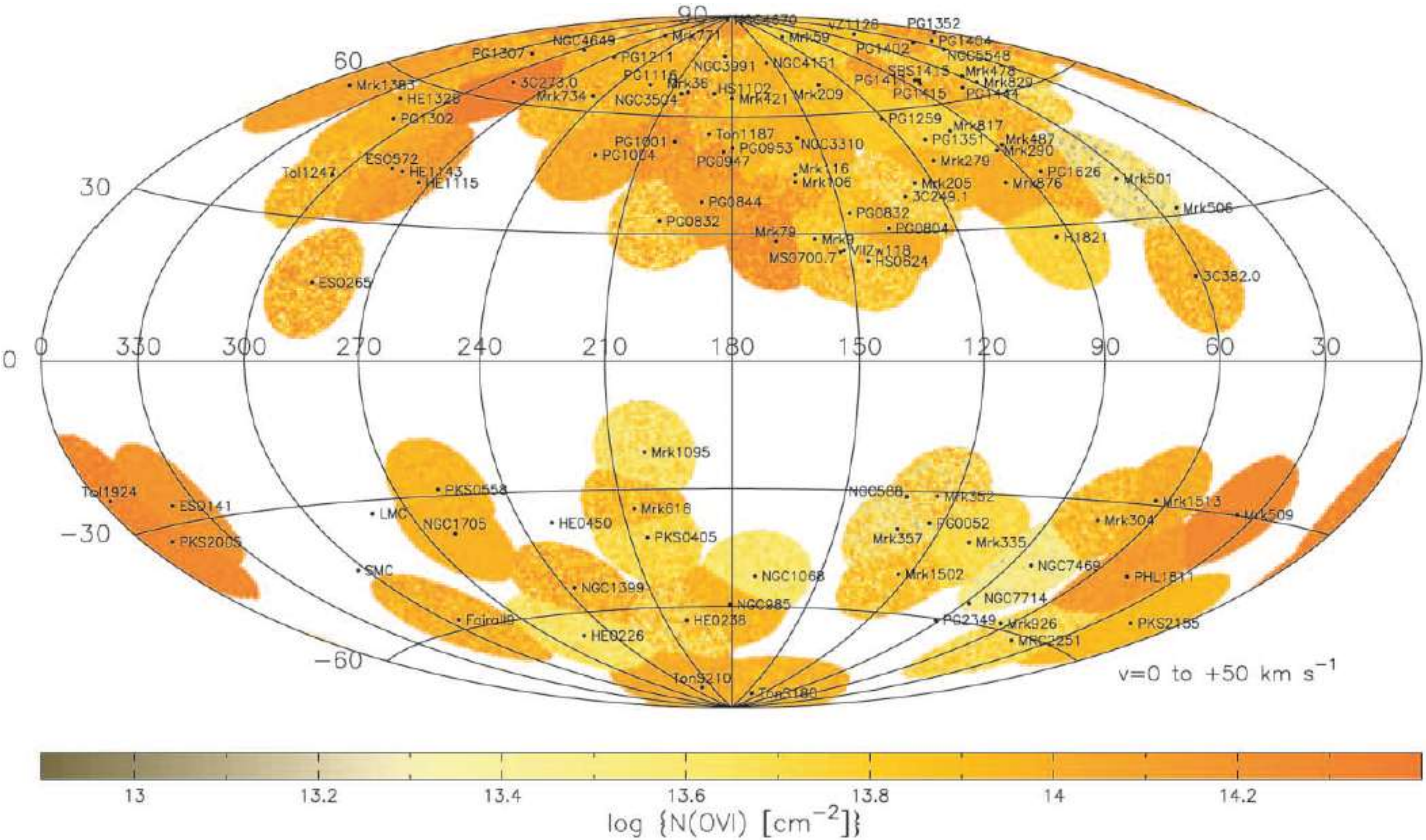
- The mass of the MW halo is hard to estimate. Proposed values range from ~5×10^{11} $M_\odot$ to ~2×10^{12} $M_\odot$. Values outside this range are considered extremist and will provoke a French military intervention and an American bombing campaign.
- For the fiducial value of 10^{12} $M_\odot$ the cosmic share of baryons in the MW is 1.8×10^{11} $M_\odot$.
- The stellar mass of the MW is about 5×10^{10} $M_\odot$ and the disk gas mass is about 1×10^{10} $M_\odot$.
- Hence, the gaseous halo may contain up to ~10^{11} $M_\odot$.

Hot Gas Around Virtual MW



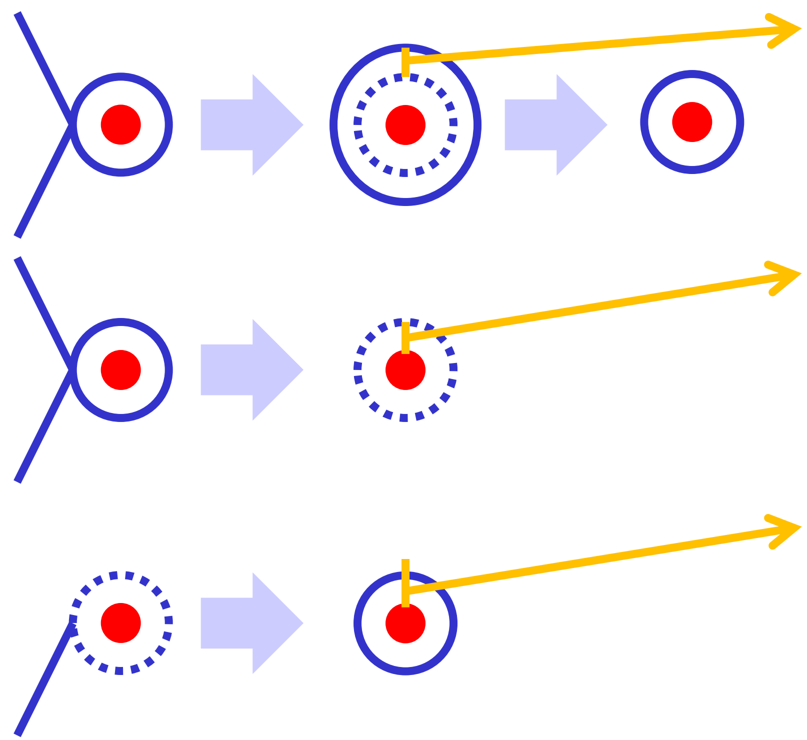
- Radial profile of the gas density for the ***same*** galaxy as shown before on all color plots at z=0.
- The gaseous halo has a ***core***!

MW Halo in OVI



Diversion: Cooling Of Rarefied Gases

- Radiative cooling is the loss of gas thermal energy by emitting radiation.
  - Line exitation
  - Collisional ionization
  - Recombination



Cooling Function

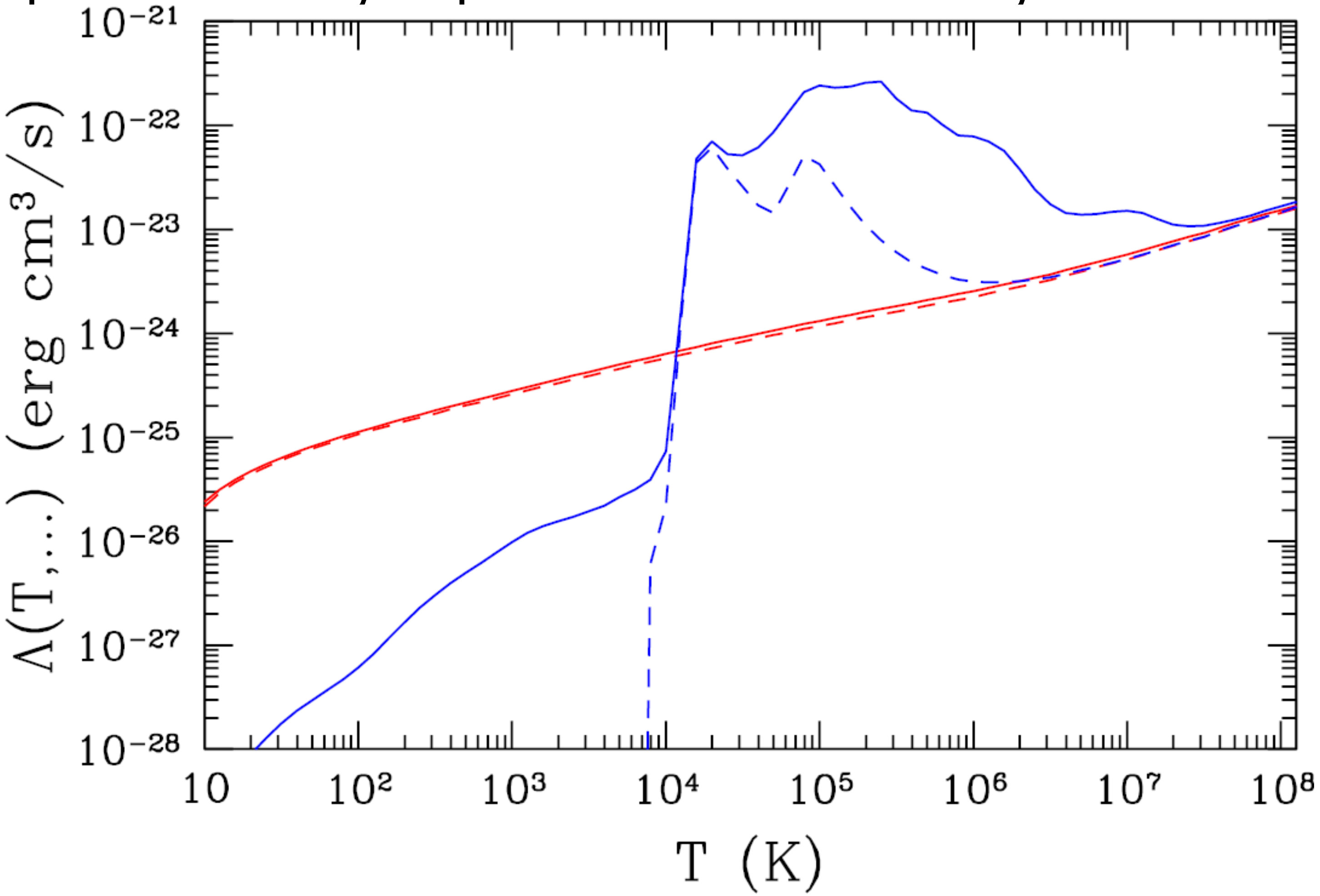
- All these collisional processes depend on density^2, hence:

$$\frac{3}{2}\frac{d}{dt}(nk_BT)\Big|_C = -n_b^2\Lambda(T,...)$$

- In the simplest case we only has gas in collisional ionization equilibrium (no external radiation of any kind –CIE). This is often called a ***standard cooling function/curve***.

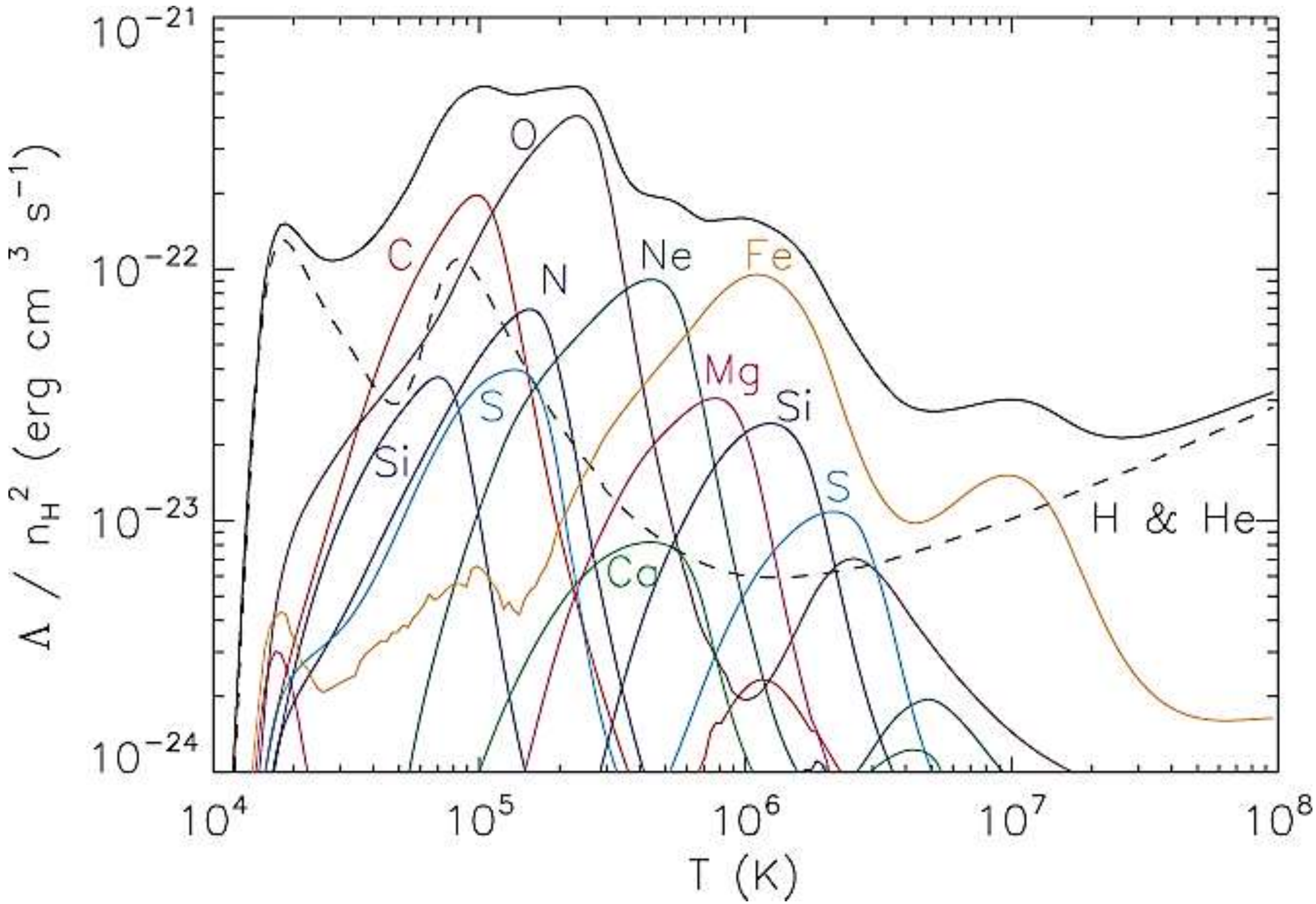
"Standard Cooling Function"

- It depends on abundances of chemical elements; for a fixed composition it only depends on the metallicity Z.



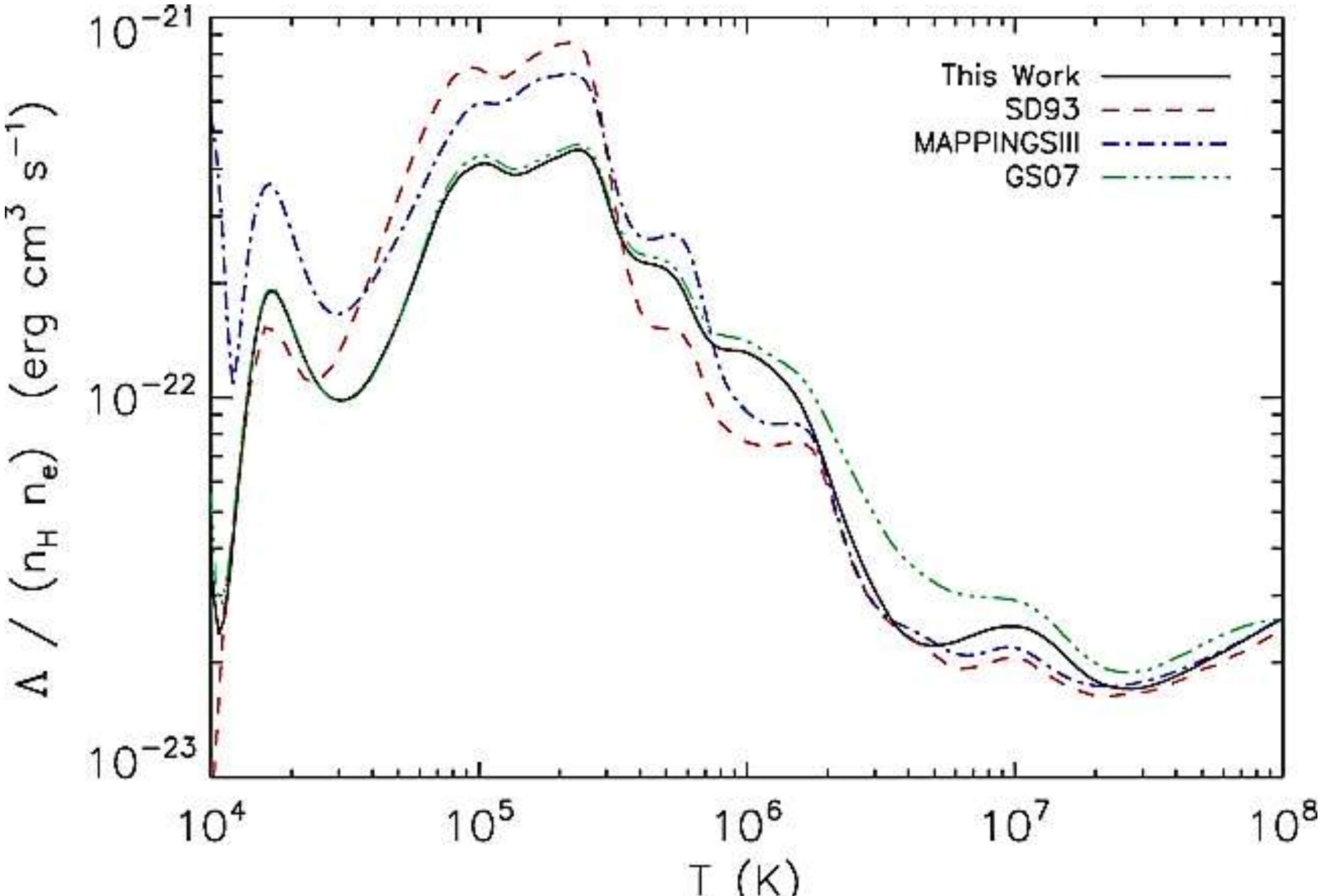
Pairs Of All Creatures...

- Many (~15) different elements contribute non-trivially.



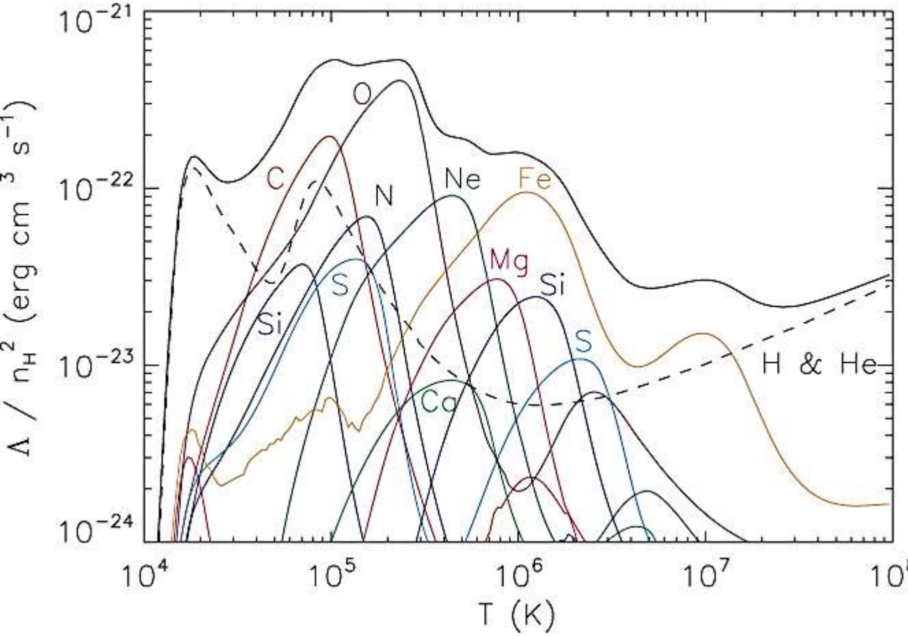
A Word Of Caution

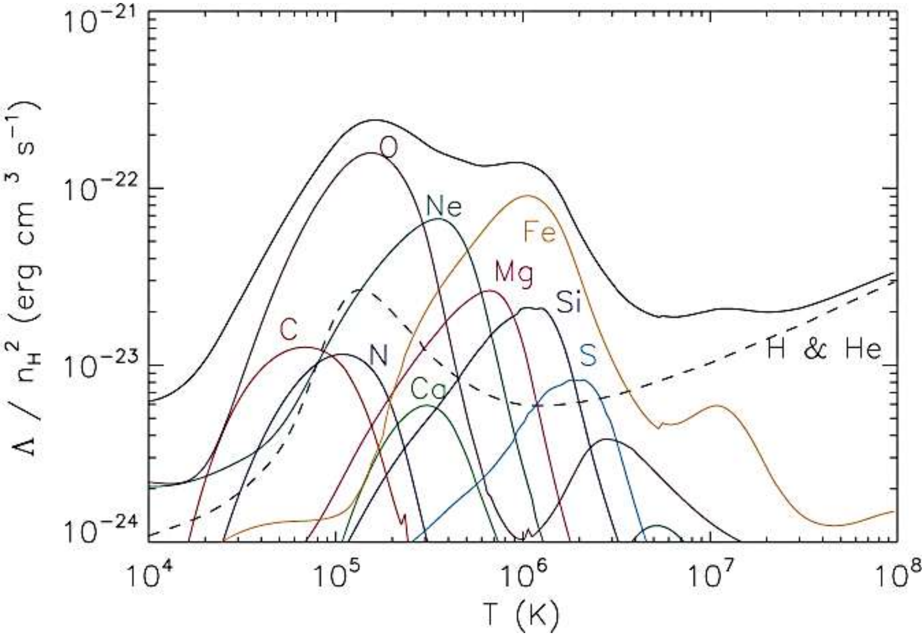
- Some of the atomic rates are surprisingly poor known.



"Standard Cooling Function"

- The problem with the "standard cooling function" is that assumes CIE, i.e. no radiation, and that is almost never true.
- The "standard cooling function" is *highly non-standard*!





Cooling Function 101

- Most general cooling and heating functions:

$$\left.\frac{dU}{dt}\right|_{\mathrm{rad}} = n_b^2(\Gamma - \Lambda)$$

$$\Lambda = \Lambda(T, n_b, Xij, J_\nu, \tau_{ij})$$

One needs a sophisticated radiative transfer code to compute Λ in its full g(l)ory.

Cooling Function 101

$$\Lambda = \Lambda(T, n_b, \cancel{X_{ij}}, J_\nu, \cancel{\tau_{ij}})$$

- Simplification #1: optically thin
- Simplification #2: ionization/excitation balance

$$\Downarrow$$

$$\Lambda = \Lambda(T, n_b, Z, J_\nu)$$

- Often, this is what is actually called a “cooling function”.

Cooling Function 101

$$\Lambda = \Lambda(T, n_b, Z, J_\nu)$$

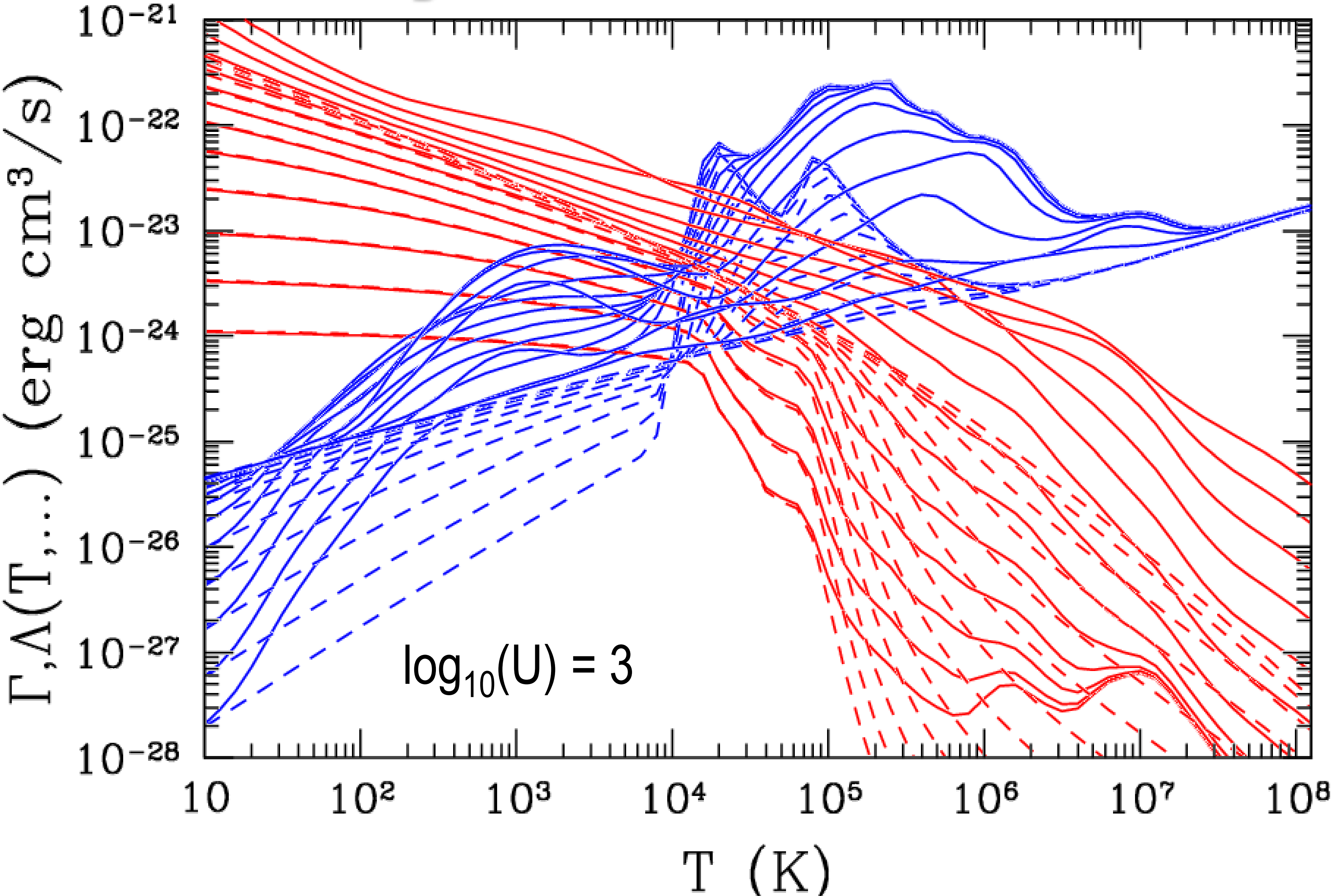
- A trick that is useful:

$$\Lambda = \Lambda\left(T, Z, \frac{J_\nu}{n_b}, n_b\right)$$

Takes care of all 2-body processes

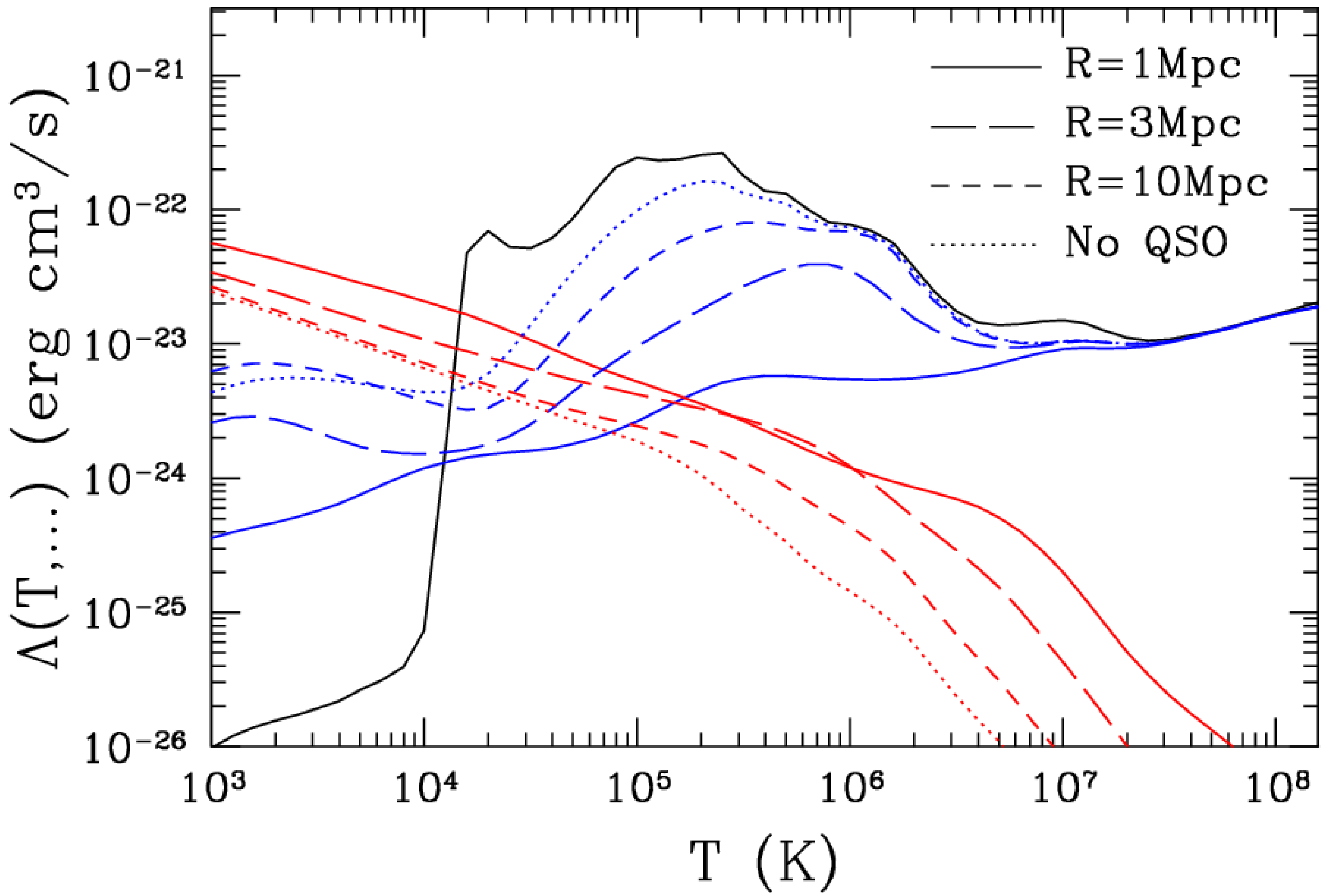
Only needed for 3-body processes, critical densities, etc; i.e. that dependence is ***weak***.

Sunny Places are Warm



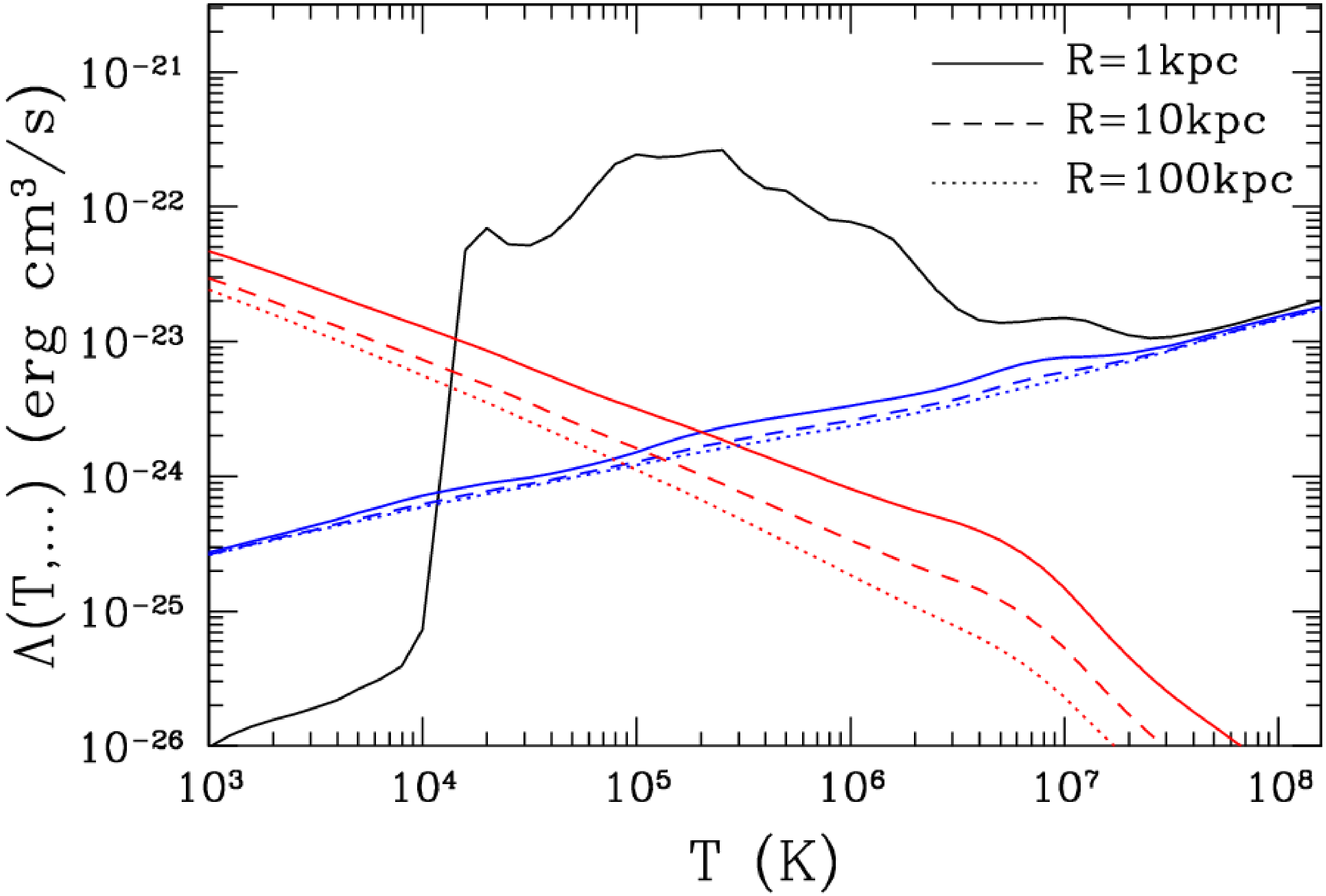
Cute Example #1

- A halo next to a quasar: no cooling in $T_{VIR} < 10^5$K halos within 1Mpc!



Cute Example #2

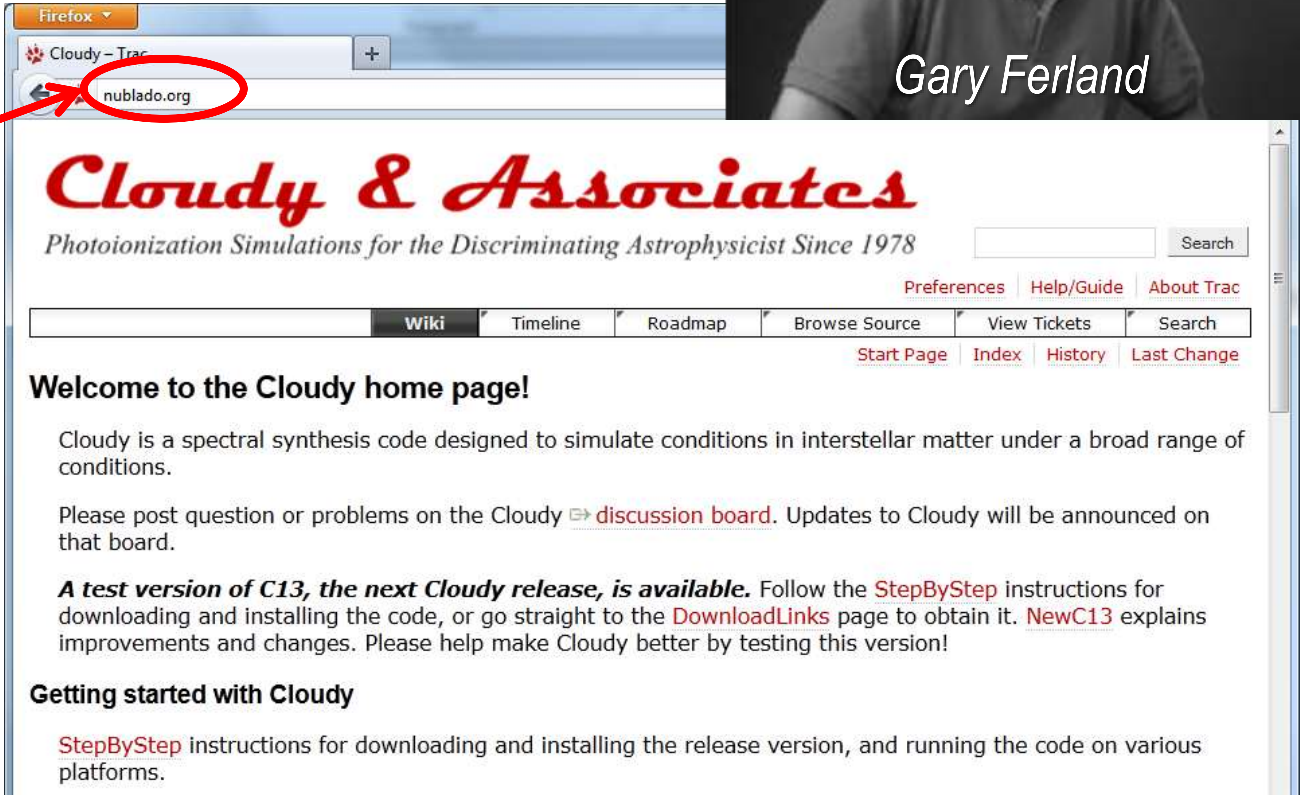
- A host halo of a quasar: no cooling at all – novel feedback mechanism!



What To Do: #1

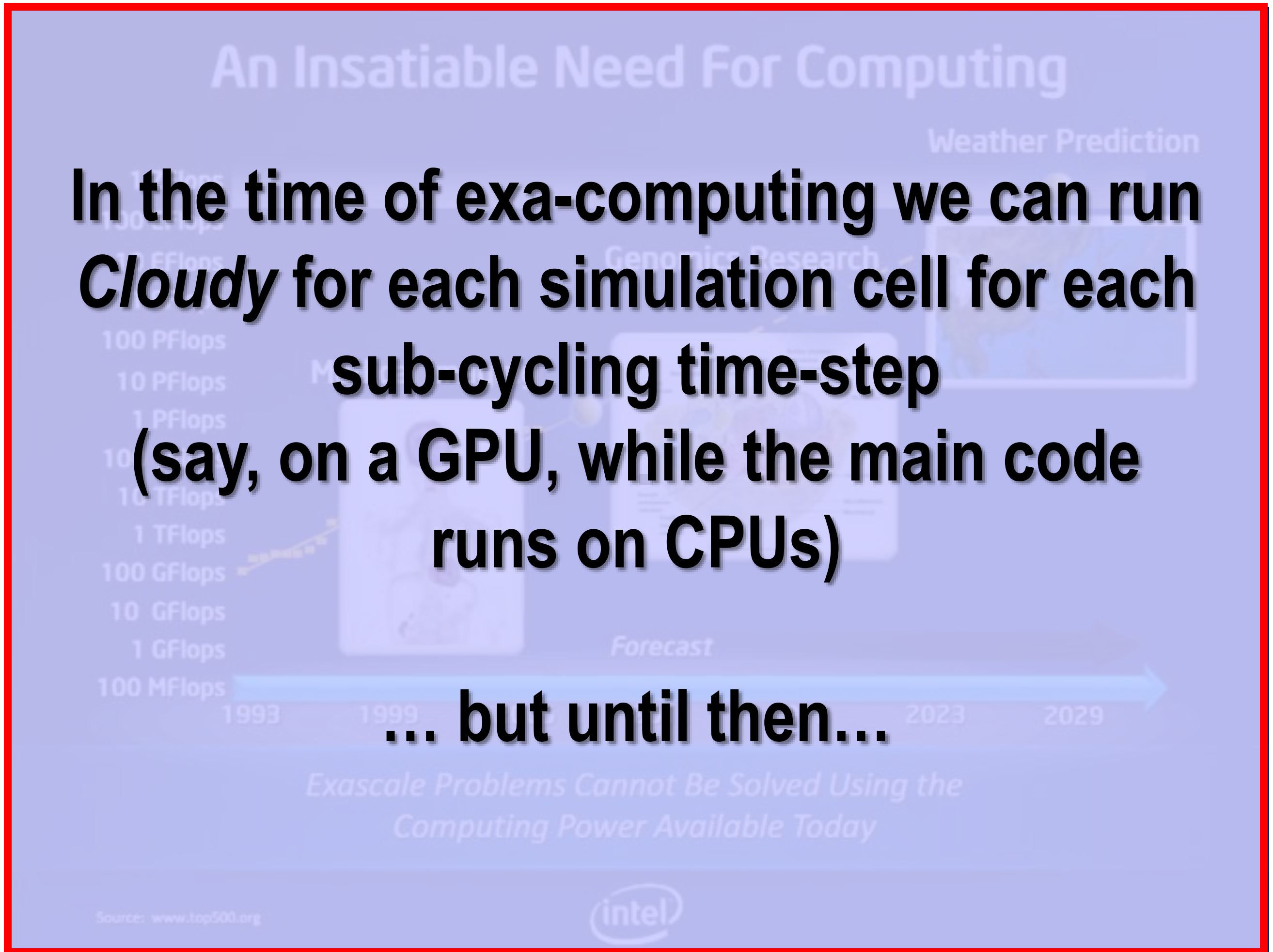
- There are people who enjoy writing sophisticated radiative transfer codes.
- ***Cloudy*** is the code of choice for computing the *full* CHF.

nublado.org



An Exa-Dream

$$\Lambda = \Lambda(T, n_b, Xij, J_\nu, \tau_{ij})$$



In the time of exa-computing we can run *Cloudy* for each simulation cell for each sub-cycling time-step (say, on a GPU, while the main code runs on CPUs)

… but until then…

What To Do: #2

- In modeling IGM the radiation field is dominated by the Cosmic Ionizing Background (with a few exceptions).

- Reference: ***Wiersma et al 2009MNRAS.393...99W***
- Pros:
  - Simple tables from full *Cloudy* calculation.
- Cons:
  - Only valid in the IGM, not suitable for ISM, CGM is kind of marginal…
  - CIB is *not* measured, it is *modeled*. There exist several competing, somewhat different models.

What To Do: #3

- Idea: use several photo-ionization rates P_j to economically represent the radiation field.
- Adopt an approximate ansatz:

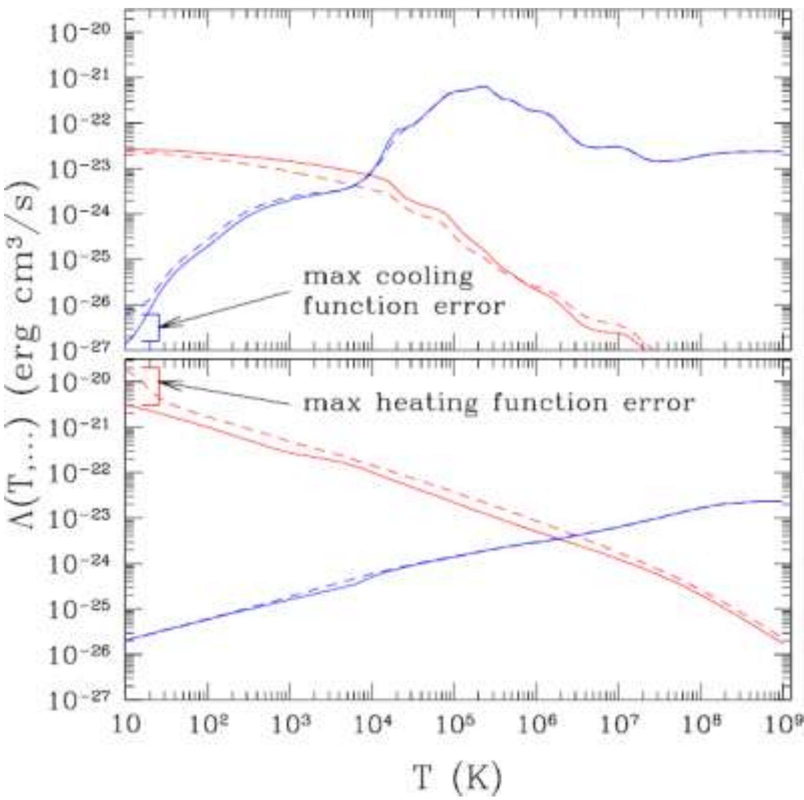
$$\Lambda_i\left(T, \frac{J_\nu}{n_b}, n_b\right) \approx \Lambda_i\left(T, \frac{P_j}{n_b}, n_b\right)$$

for some set of photo-ionization rates P_j.

- Compute Λ_i by tabulating P_j dependence on a multi-dimensional grid of values.

What To Do: #3

- Reference: ***Gnedin & Hollon 2012ApJS..202...13G***
- Pros:
  - Works for any radiation field and for high density.
  - Valid everywhere (IGM, CGM, ISM, …)
- Cons:
  - Not exact, an *approximation*.
  - Subject to catastrophic errors.

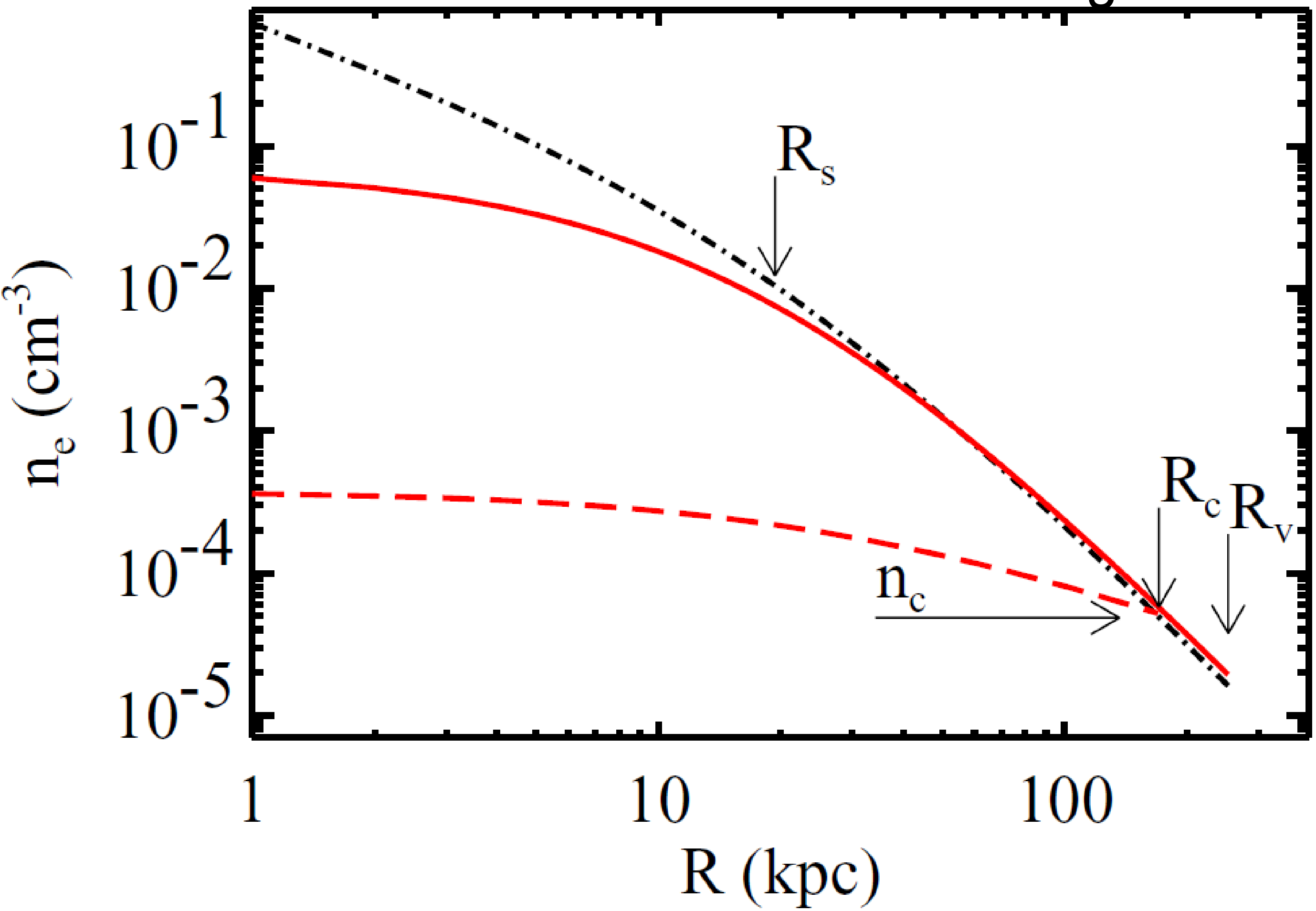


3. Back To Galactic Halos

- As gaseous halos are expected to become denser at the center, the cooling time will decrease towards the center. Hence, there must exist a *cooling radius* R_C at which the cooling time = age of the halo.
- Gas inside R_C is able to cool efficiently and condense towards the halo center.
- Gas outside R_C is unable to cool and will remain in (quasi-) hydrostatic equilibrium.

“Maller & Bullock” Model

- The gas in the inner halo is dense enough to cool efficiently.
- Gas that remains after most of the gas cools towards the center forms a cored profile.



What Happens To The Cooled Gas?

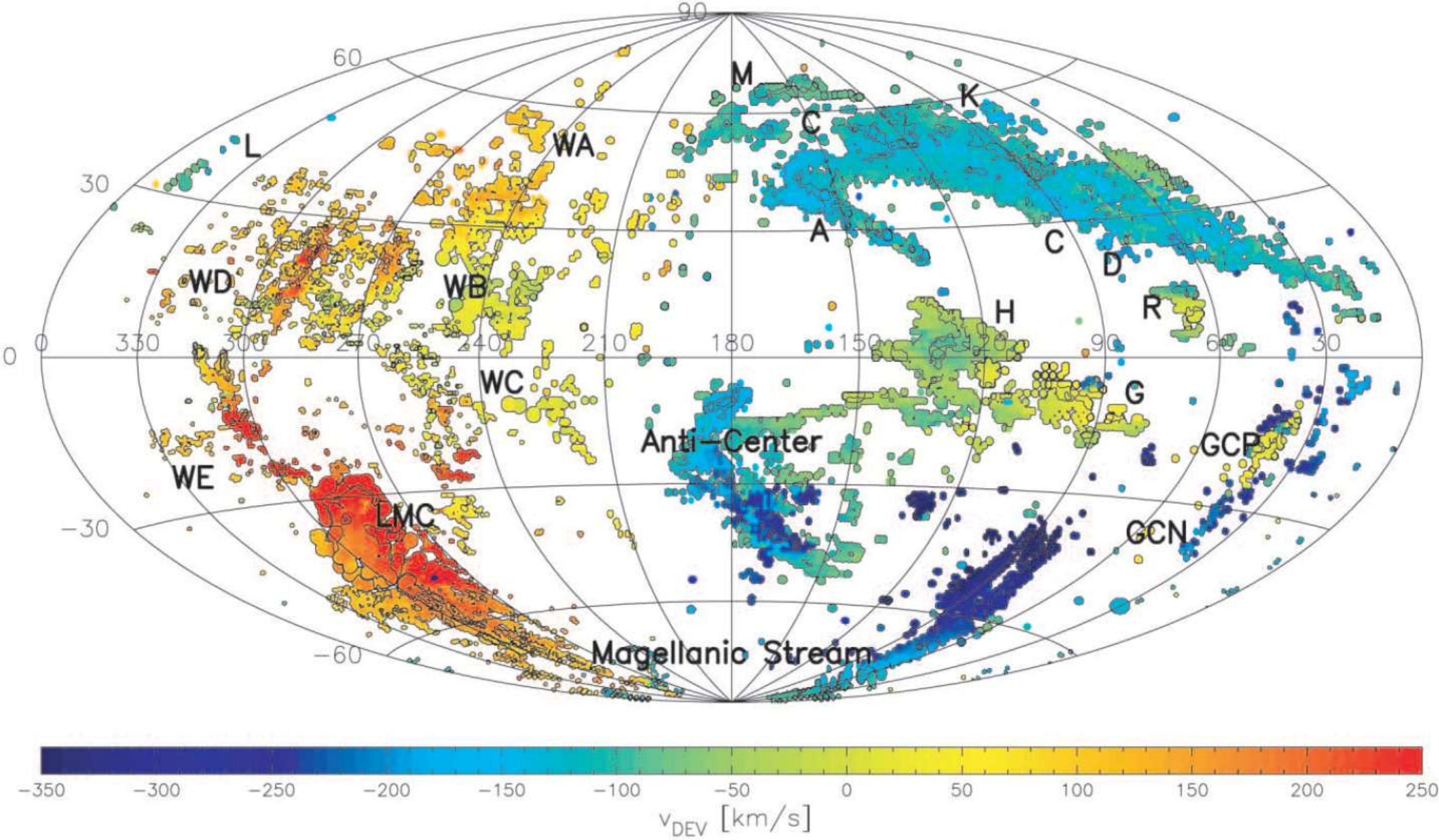
- There may be two ways for the cooling gas to stream towards the center.

  A. It can develop a “cooling flow” and smoothly flow in a quasi-spherical way.

  B. It can experience thermal instability, split into individual dense clouds, which then fall along parabolic orbits.

- Make your choice!

MW Halo in HI



90
60
30
0
-30
-60
0
330
300
270
240
210
180
150
120
90
60
30
M
K
C
L
WA
A
C
D
WD
WB
H
R
WC
G
Anti-Center
GCP
WE
LMC
GCN
Magellanic Stream
-350
-300
-250
-200
-150
-100
-50
0
50
100
150
200
250
v_{DEV} [km/s]

MW Halo in HI

- Our sky is certainly “clouded”!

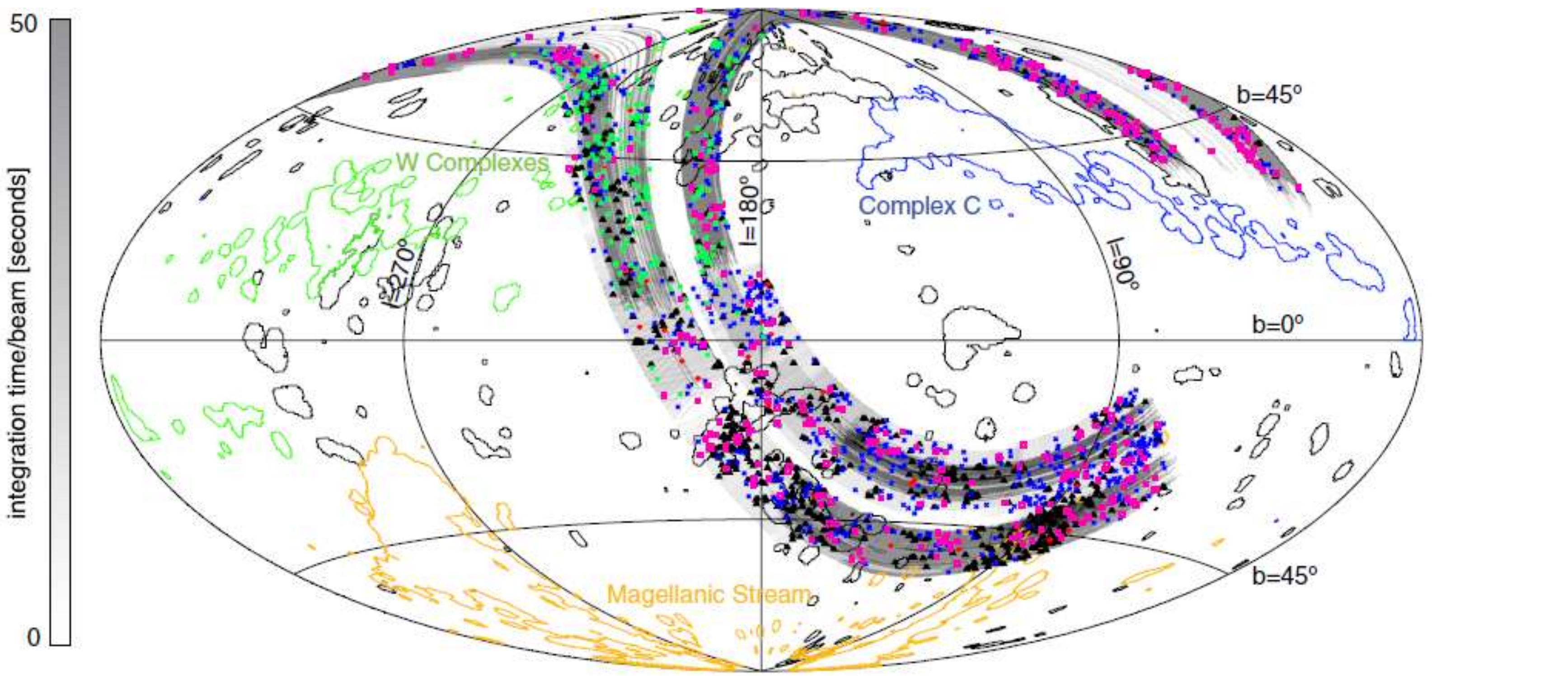
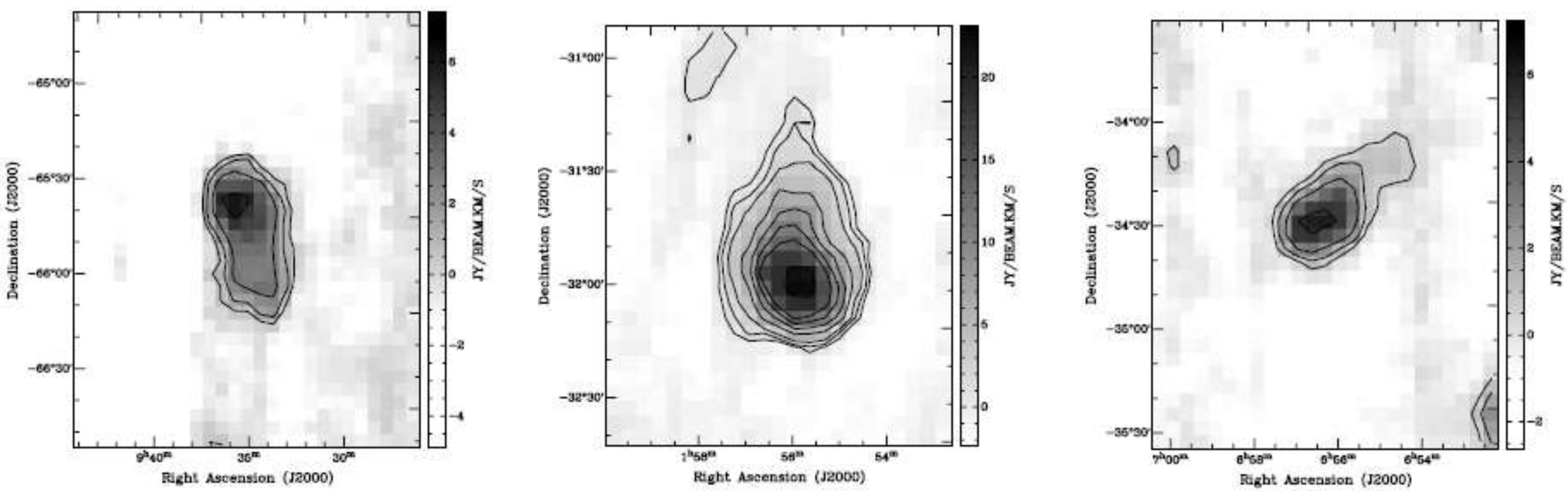


Figure 2. Hammer–Aitoff plot of the positions of all of the cataloged clouds in Galactic coordinates. Cloud type is indicated by color, with black for HVCs, red for galaxy candidates, blue for cold LVCs, pink for warm LVCs (excluding the Q3 clouds), and green for warm, positive-velocity Q3 clouds. The coverage of the survey is indicated in gray scale, with the darkest gray indicating $>50\ \mathrm{s\ beam^{-1}}$ of integration time. High-velocity cloud complexes are shown in outline, with the W complexes shown in green, complex C shown in blue, and the Magellanic Stream shown in orange. Other HVCs are shown in black.

High Velocity Clouds

- (Clouds of) neutral hydrogen are known to exist in the MW halo.
- A few clouds that have been resolved in 21cm observations show head-tail extensions.



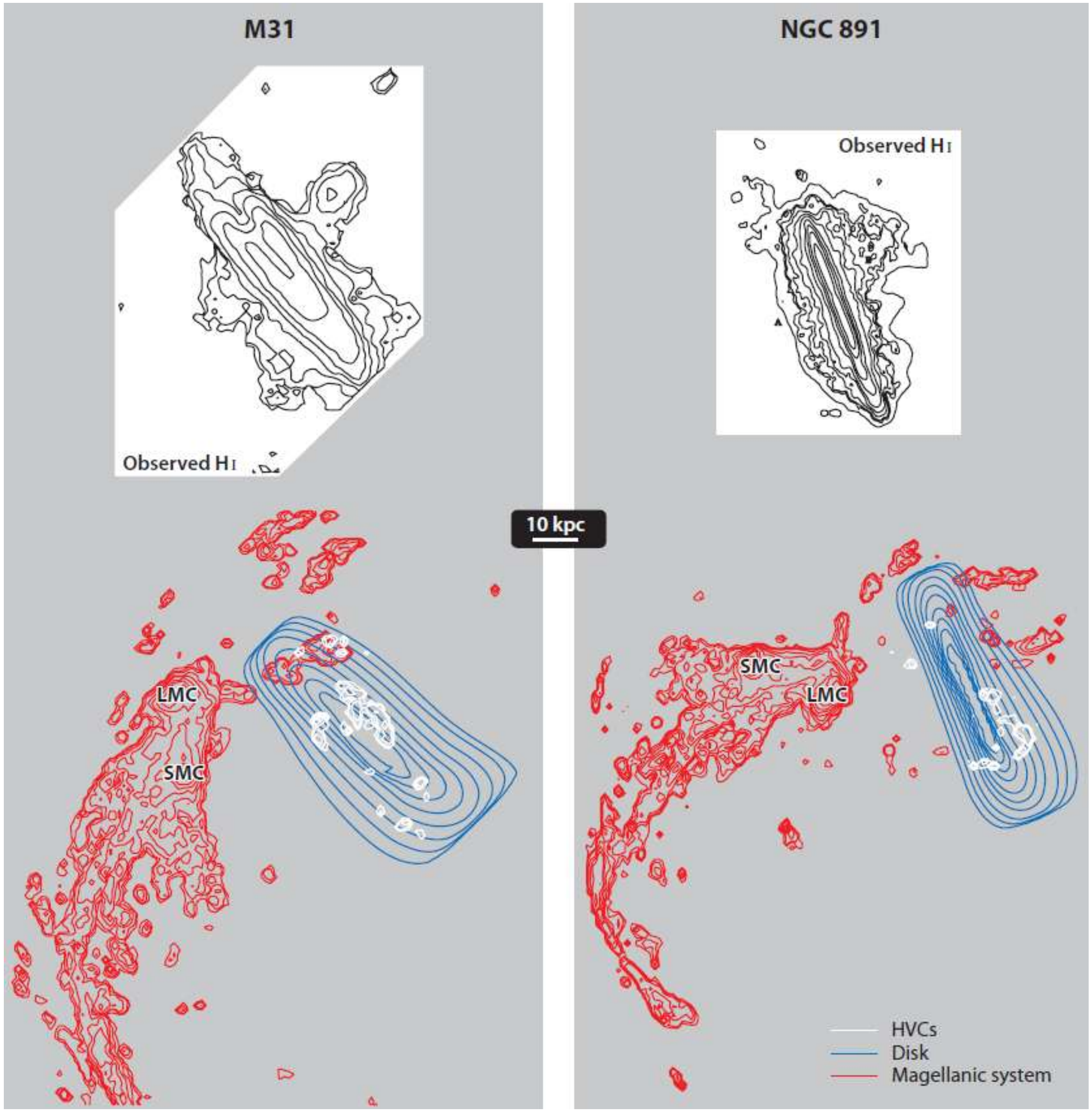
High Velocity Clouds

Quiz: ***Why would halo clouds have extended tails?***

A. They need tails to swim faster.
B. Gas is ejected from the cloud center by the pressure force.
C. Angular momentum is conserved.
D. Clouds are located in the MW halo.
E. Clouds are made out of gas, and gas is always irregularly shaped.

HVCs in Other Galaxies

HVCs in Other Galaxies II

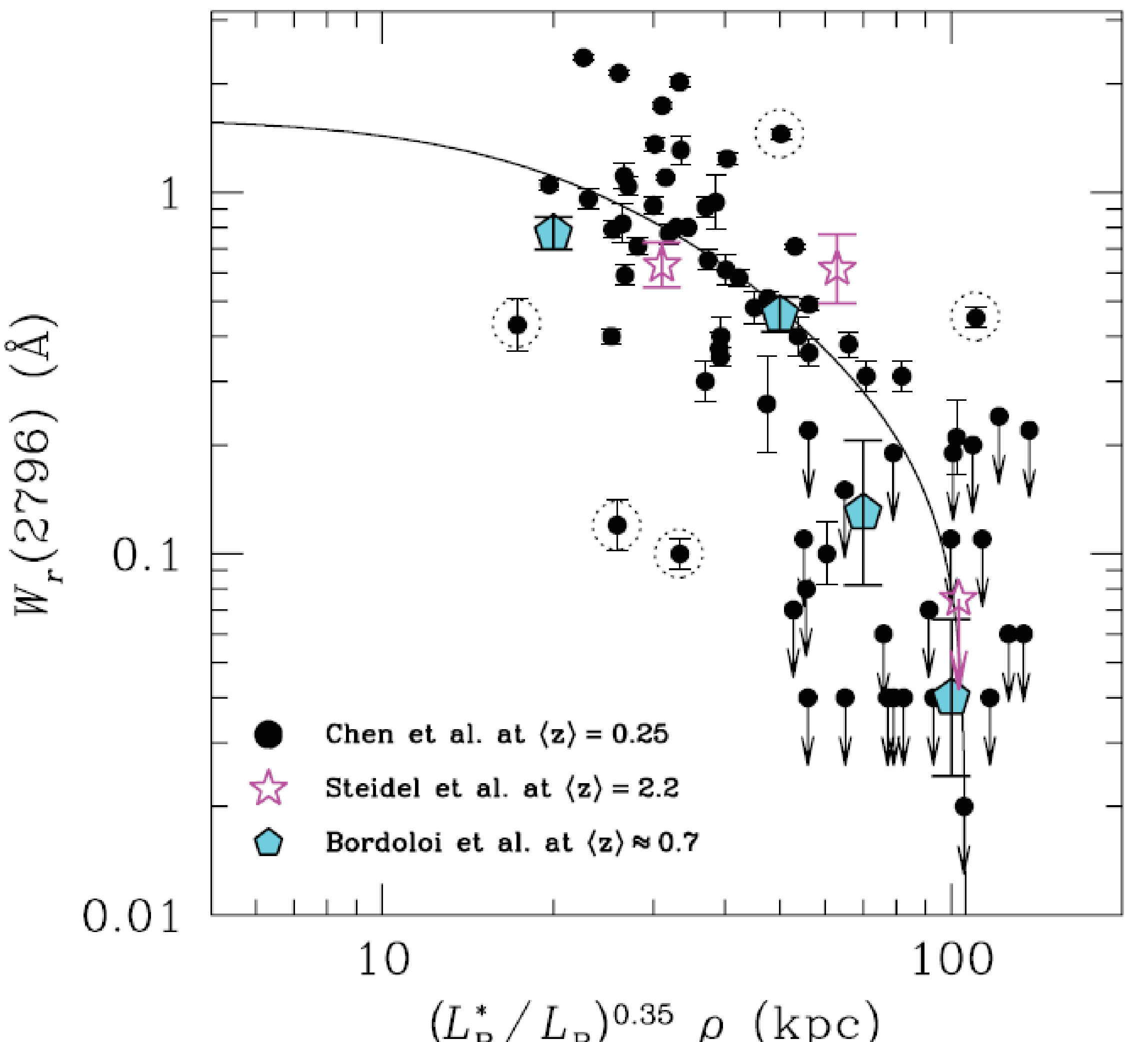


Hunting for Clouds

- The problem with 21cm line is that it is one of the weakest lines in this universe.
- But hydrogen also has one of the strongest lines – Lyman-α. But it is not easy to excite n=2 level, hence Ly-α is usually seen in absorption.
- Another useful ion is MgII, because its ionization threshold is 15eV, very close to hydrogen. In fact, it is even more useful for studying halos of nearby galaxies than Ly-α. ***Why?***
- OI has ionization threshold of 13.62eV. Yet, it is not used to study gaseous halos. ***Why?***

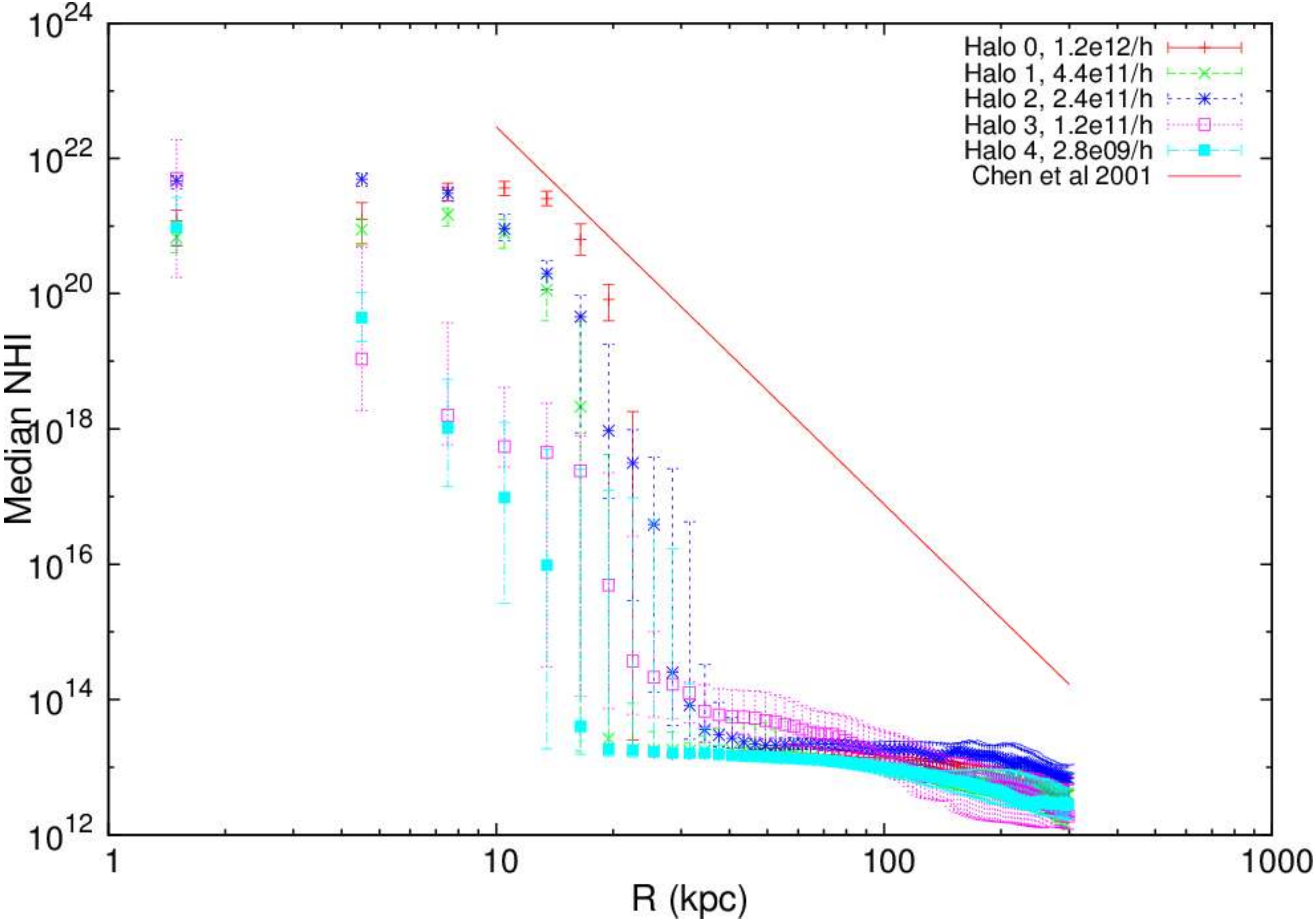
Clouds and Galaxies

- MgII clouds are only found within ~100kpc from galaxies.



Why???

Theory vs Observations



The End