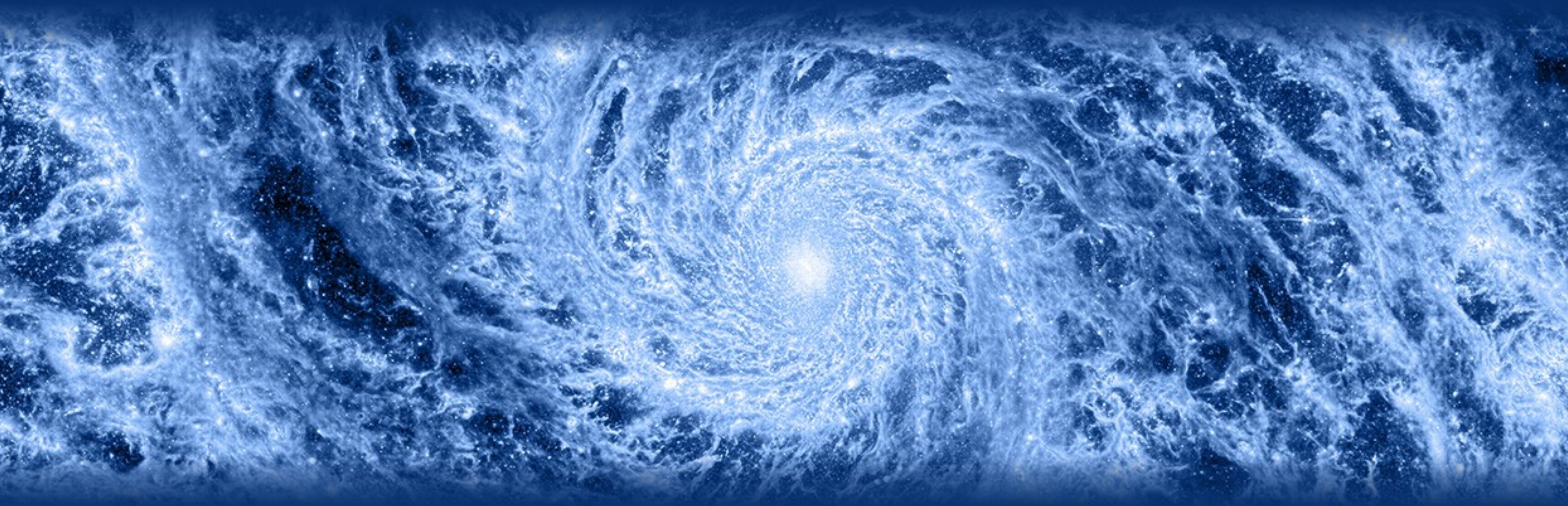
Galaxies

Prof. Benedikt Diemer



Chapter 6 • Gas accretion and cooling

Background: Hydrodynamics and shocks

The Euler Equations

Changes at fixed position + Fluid motion along gradients = Changes experienced by fluid elem.

Density

$$\frac{\partial \rho}{\partial t} + \boldsymbol{u} \cdot \nabla \rho = \frac{\mathrm{D}\rho}{\mathrm{D}t} = -\rho \nabla \cdot \boldsymbol{u}$$

Inflow of density into fluid element

Velocity

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = \frac{\mathrm{D}\boldsymbol{u}}{\mathrm{D}t} = -\frac{\nabla P}{\rho} - \nabla \Phi$$

Pressure gradient

Gravitational force

Energy

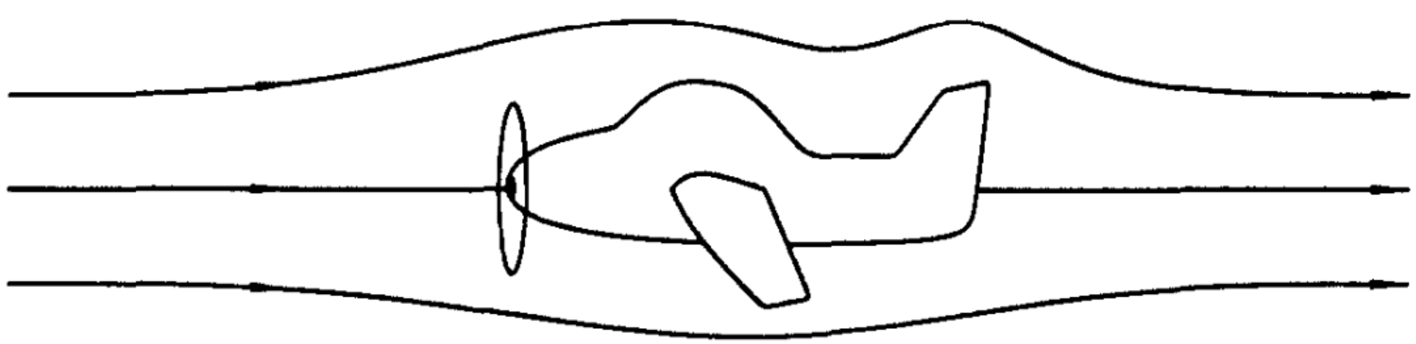
$$\frac{\partial \varepsilon}{\partial t} + \boldsymbol{u} \cdot \nabla \varepsilon = \frac{\mathrm{D}\varepsilon}{\mathrm{D}t} = -\frac{P}{\rho} \nabla \cdot \boldsymbol{u} + \frac{\Gamma}{\rho} - \frac{\Lambda}{\rho}$$

PdV work

Heating

Cooling

Subsonic vs. supersonic



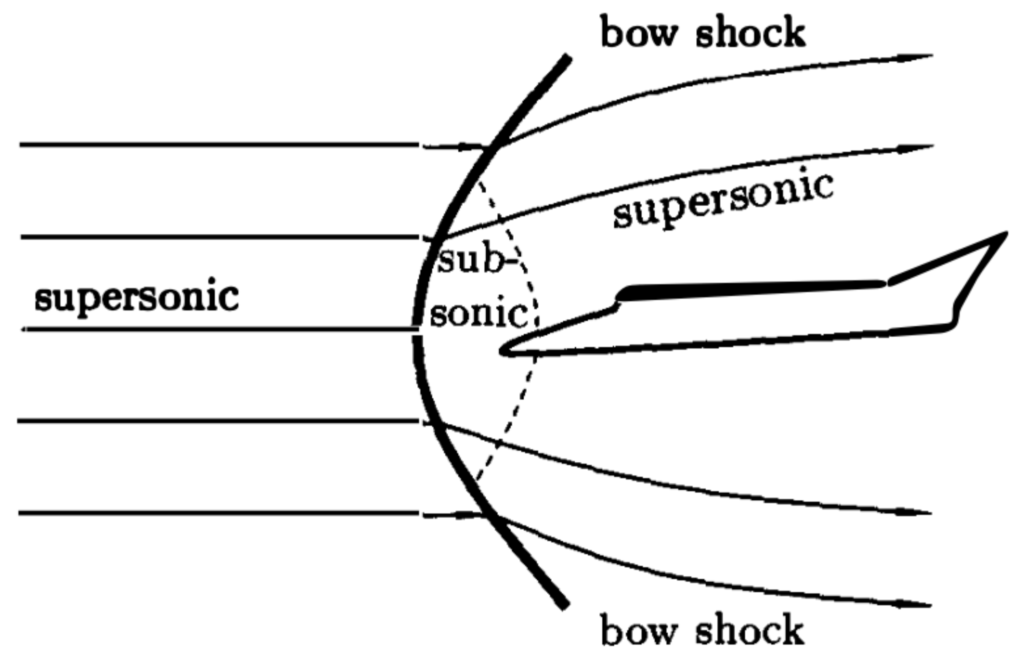


Figure from Shu

Shocks

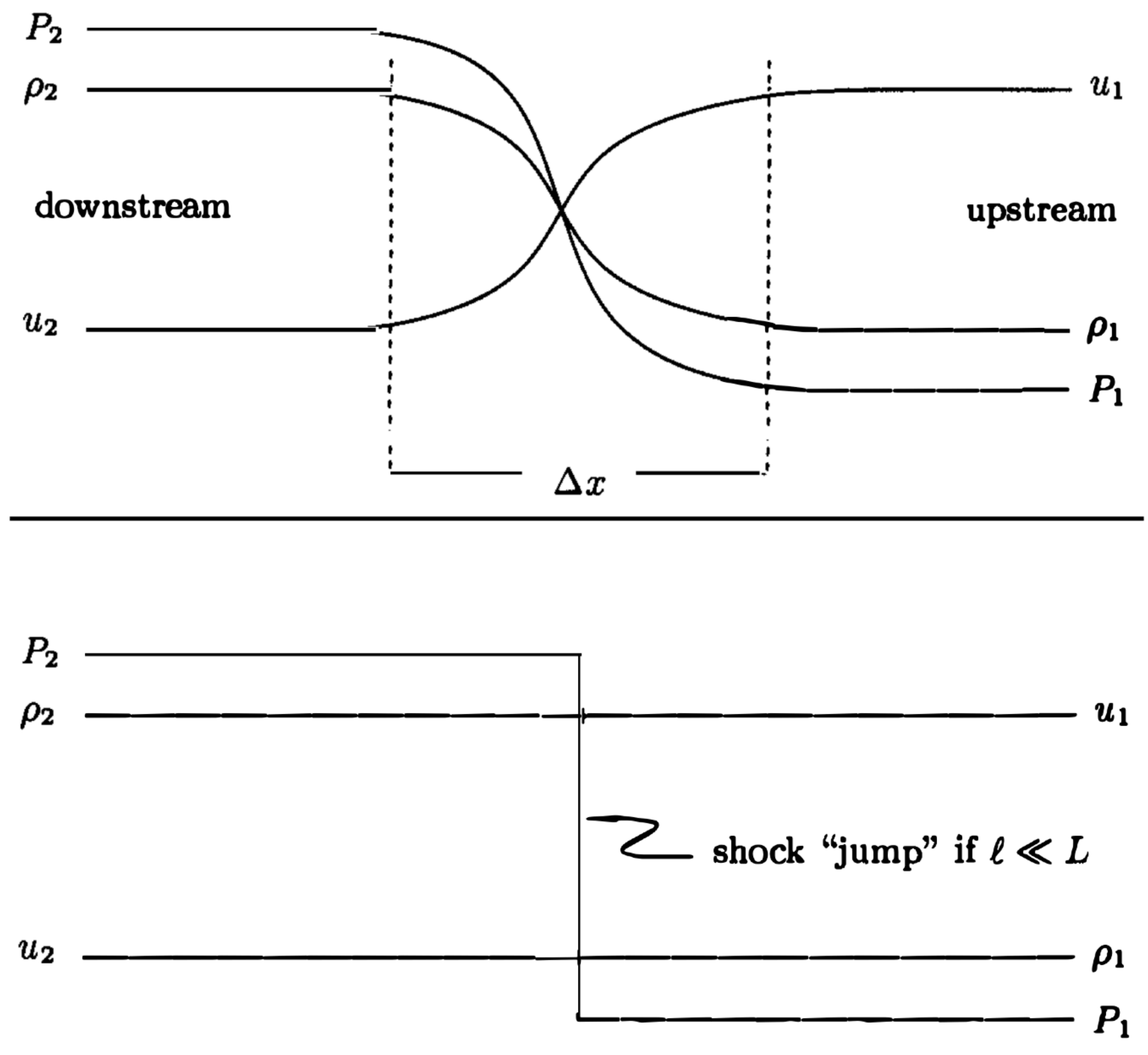
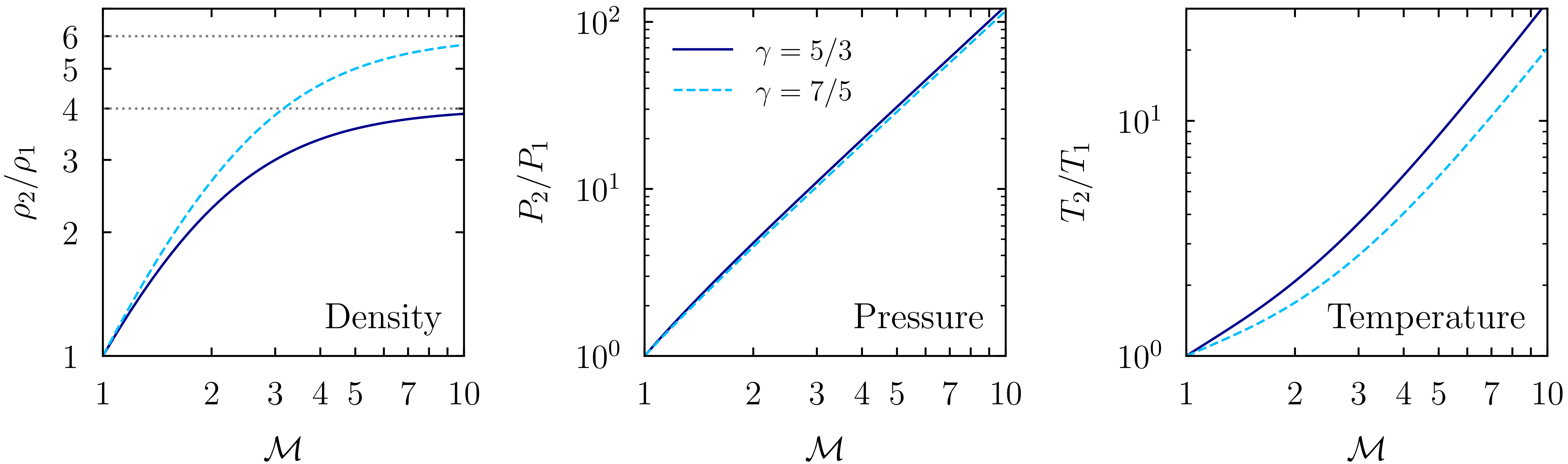


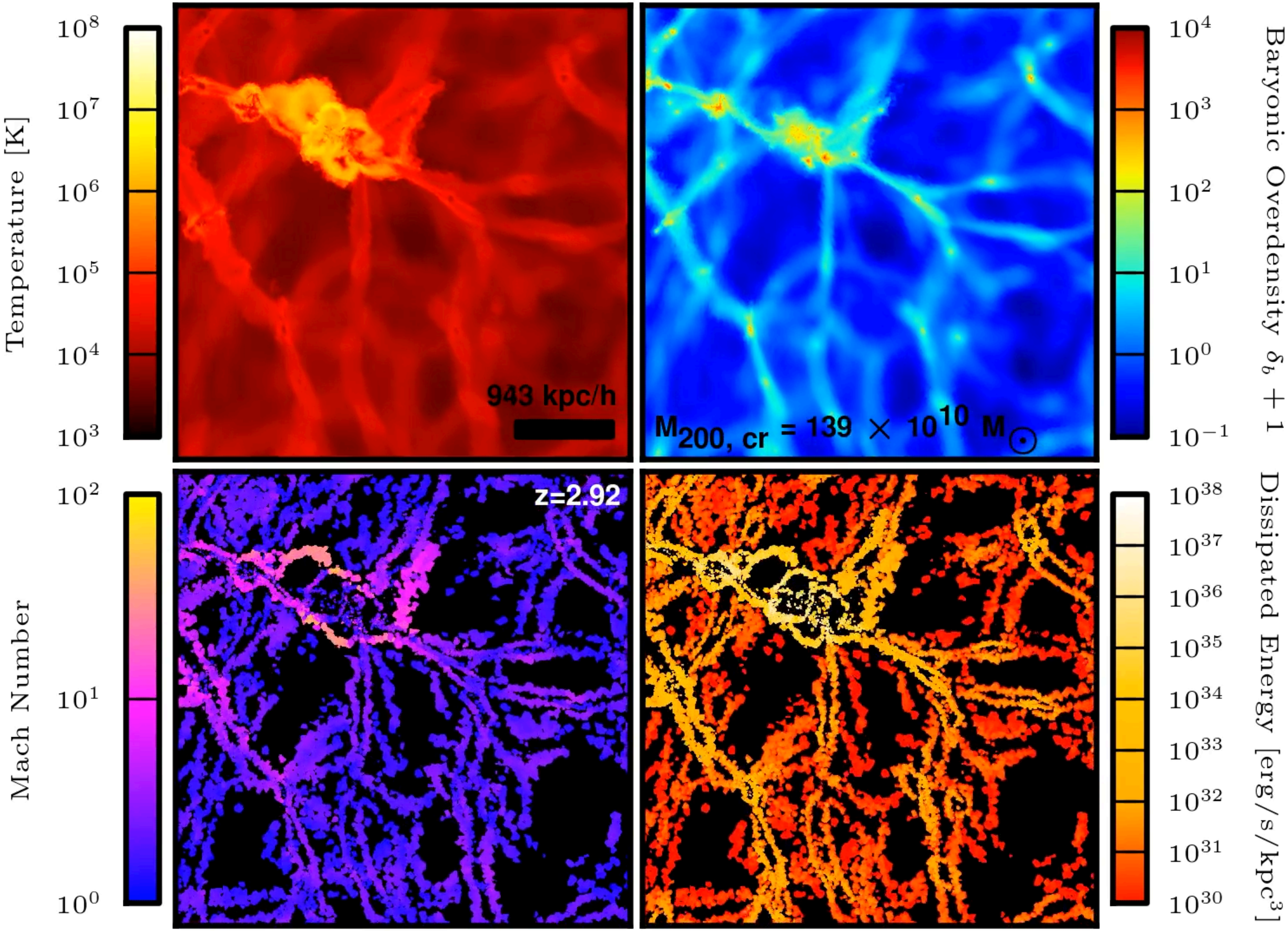
Figure from Shu

Ideal gas shocks

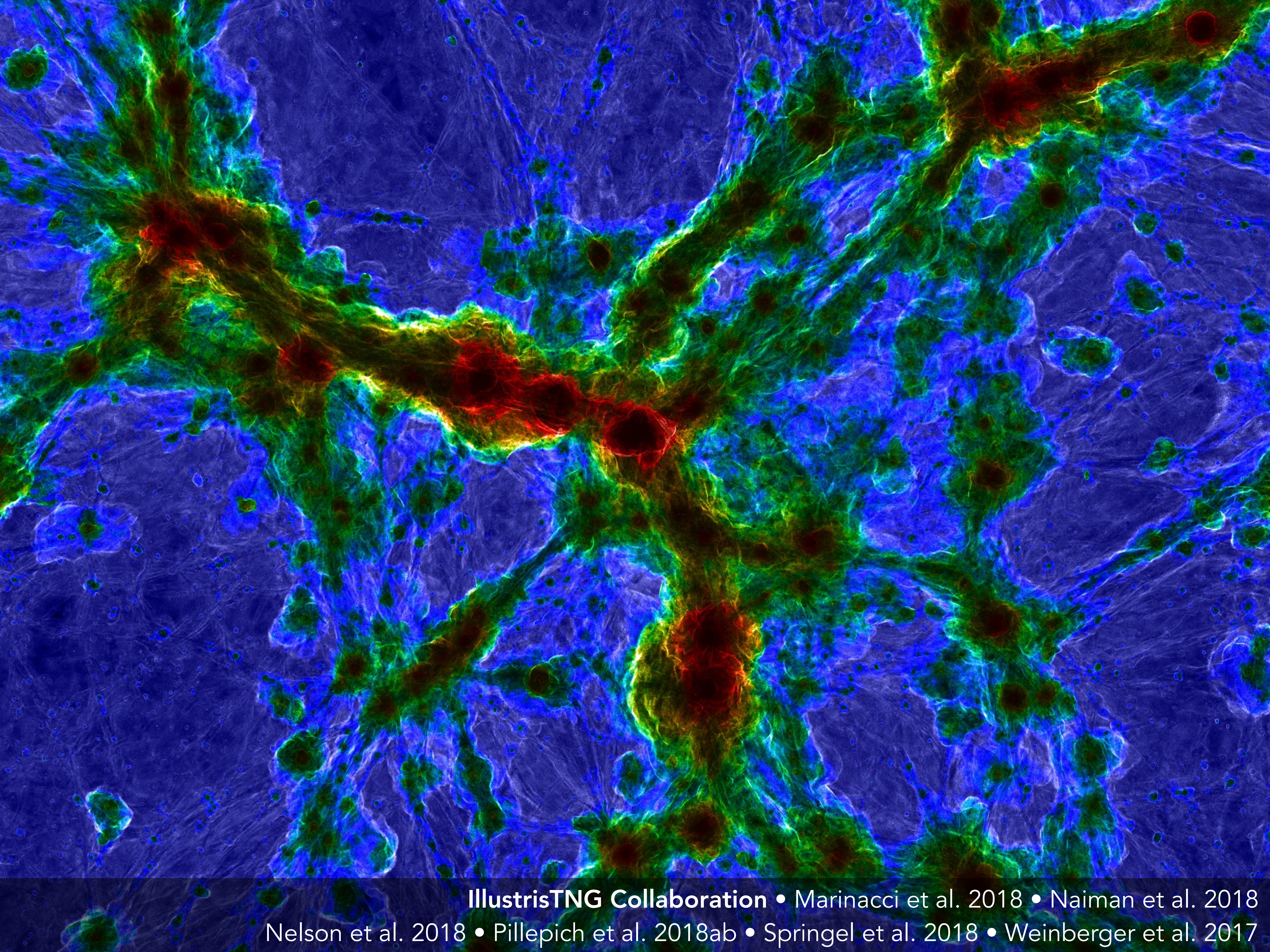


§6.1 • Accretion shocks and the virial temperature

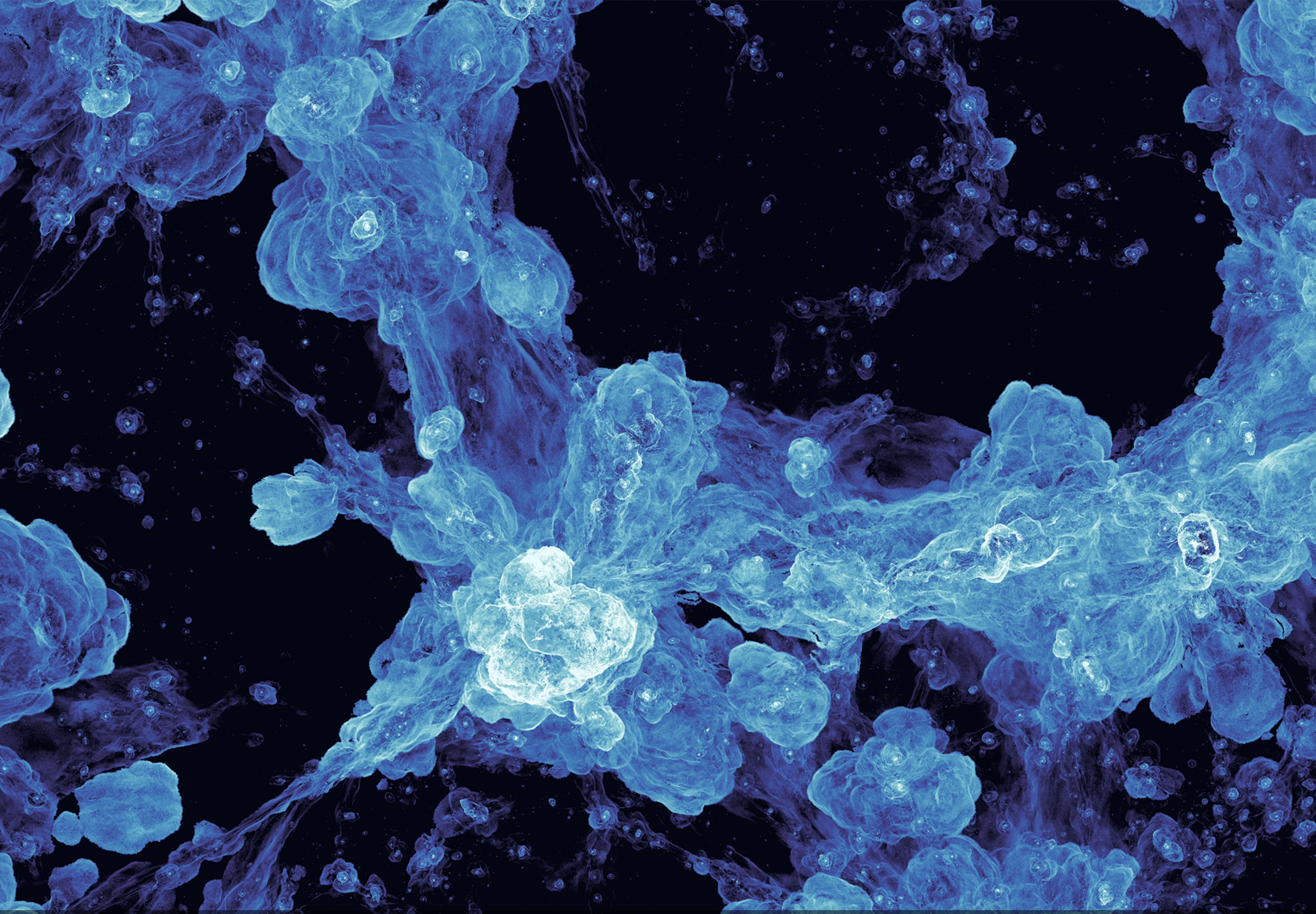
Accretion shocks



Kevin Schaal (youtube)

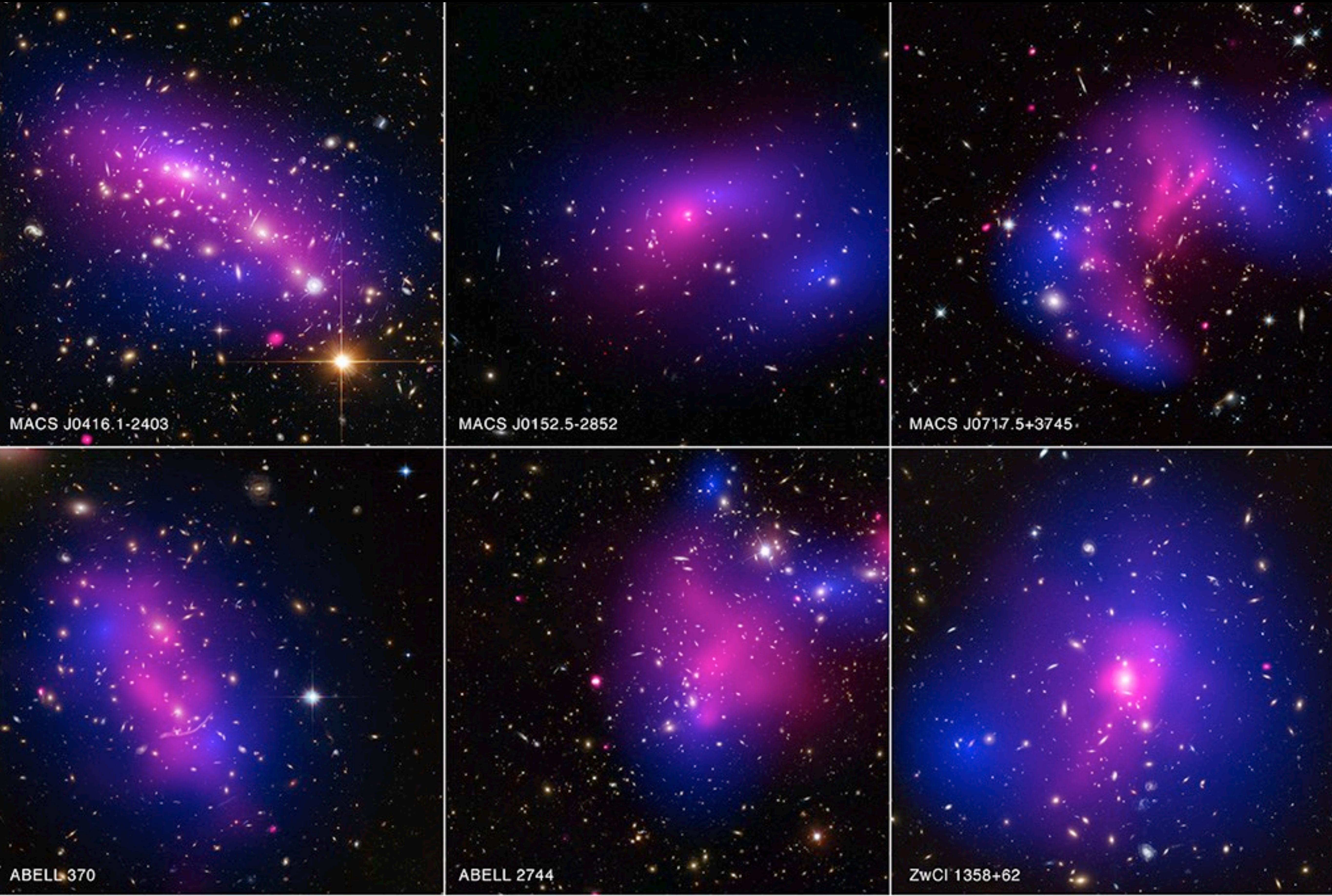


IllustrisTNG Collaboration • Marinacci et al. 2018 • Naiman et al. 2018
Nelson et al. 2018 • Pillepich et al. 2018ab • Springel et al. 2018 • Weinberger et al. 2017



IllustrisTNG Collaboration • Marinacci et al. 2018 • Naiman et al. 2018
Nelson et al. 2018 • Pillepich et al. 2018ab • Springel et al. 2018 • Weinberger et al. 2017

Clusters in X-rays (Chandra)



§6.2 • Cooling

Cooling processes

- One-particle processes:
  - Electrons Compton-scatter off CMB photons, giving them energy (most relevant at high z)
- Two-particle processes:

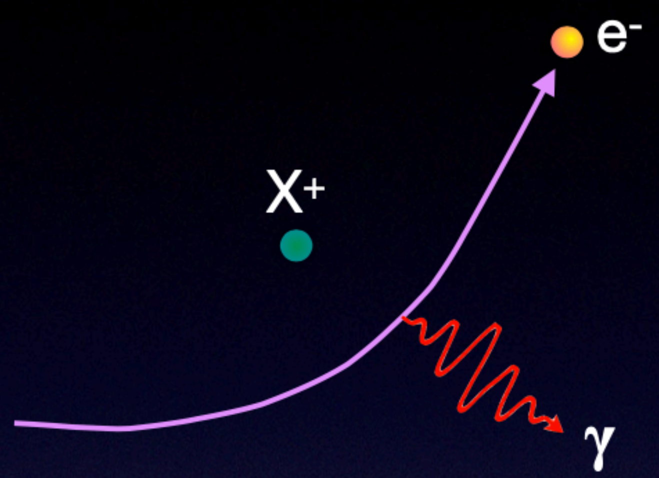
	type	reaction	name
1	free-free	$e^- + X^+ \rightarrow e^- + X^+ + \gamma$	bremsstrahlung
2	free-bound	$e^- + X^+ \rightarrow X + \gamma$	recombination
3	bound-free	$e^- + X \rightarrow X^+ + 2e^-$	collisional ionization
4	bound-bound	$e^- + X \rightarrow e^- + X'$ $\rightarrow e- + X + \gamma$	collisional excitation

- Note that all of these processes involve free electrons

Slide by Frank van den Bosch

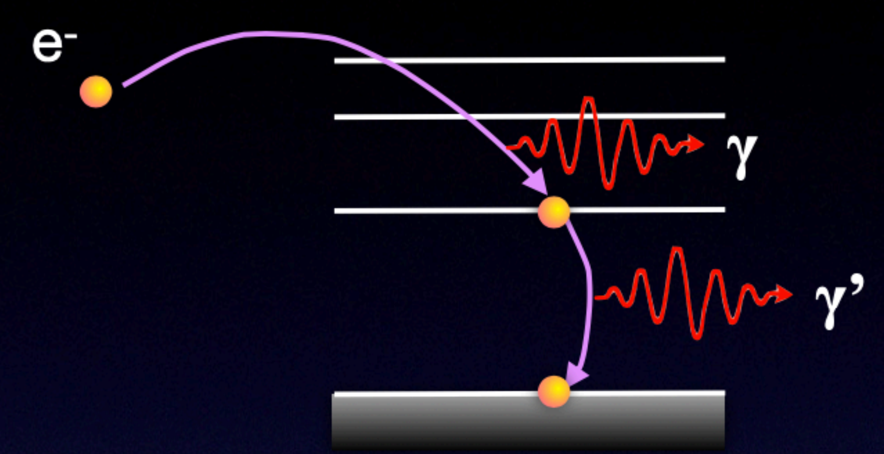
Cooling processes

1) free-free (bremsstrahlung)



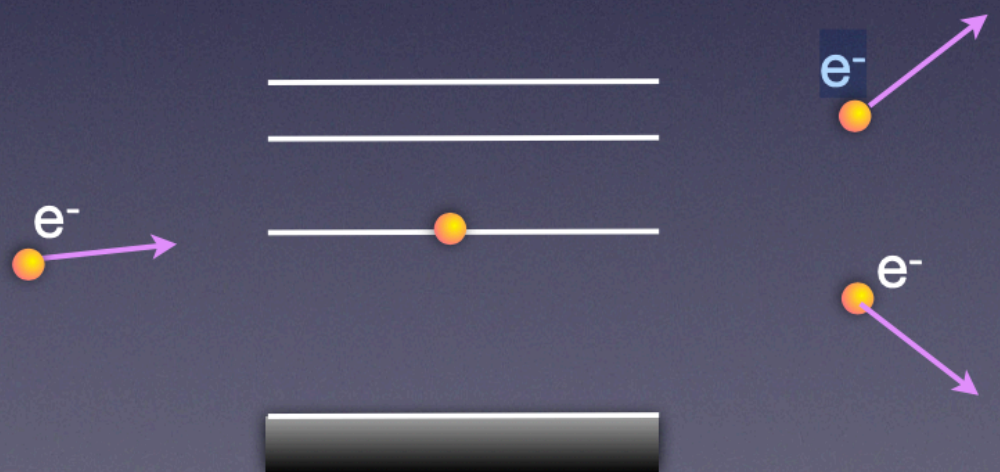
Free electron is accelerated by ion. Accelerated charges emit photons, resulting in cooling. For bremsstrahlung, $\Lambda \propto T^{1/2}$

2) free-bound (recombination)



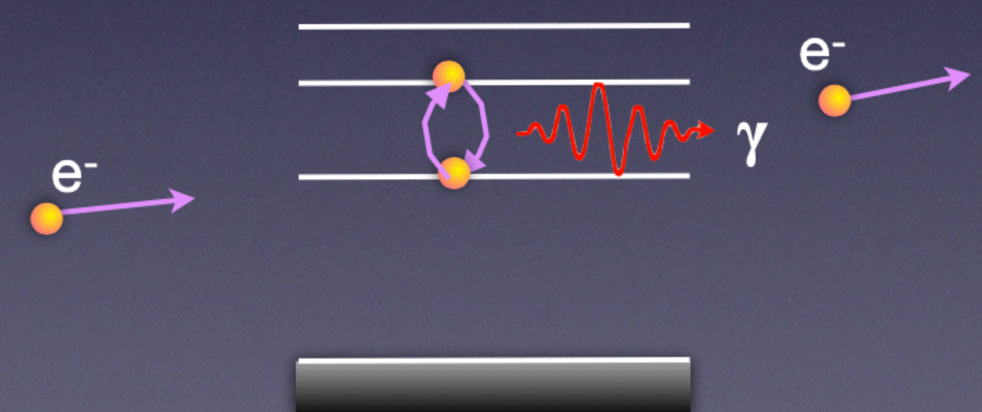
Free electron recombines with ion. Binding energy plus free electron's kinetic energy are radiated away. If capture into an excited state, subsequent (line) emission may result as electron cascades down to ground level.

3) bound-free (collisional ionization)



Impact of free electron ionizes a formerly bound electron, taking (kinetic) energy from the free electron

4) bound-bound (collisional excitation)



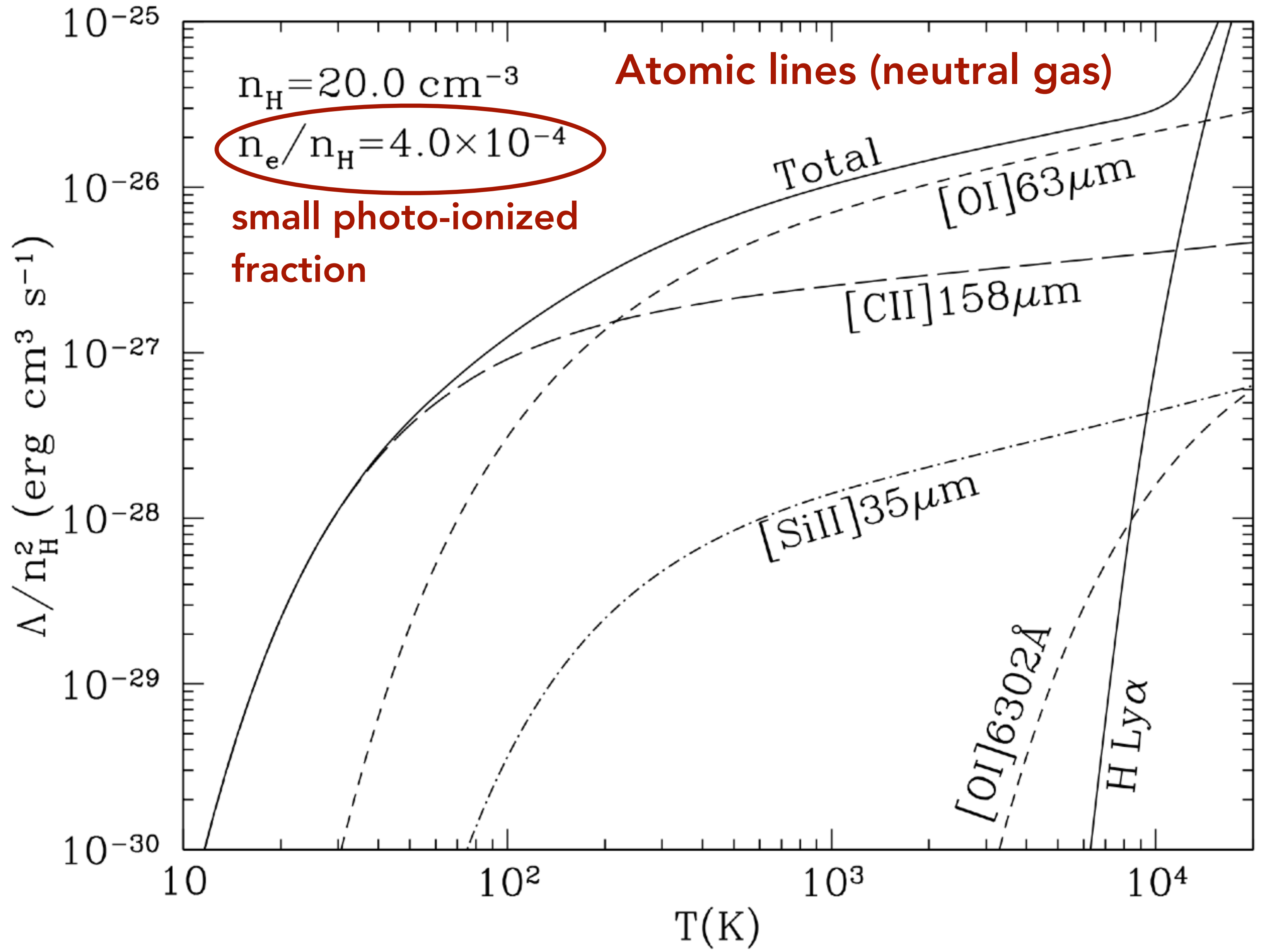
Impact of free electron knocks bound electron to excited state. As it decays, it emits a photon. Note, in case of collisional de-excitation, no photon is emitted (no net cooling)

The cooling function

- As long as the density is not too high, we can assume that every collisional excitation is followed by a de-excitation before the next collision; the respective energy is radiated away
- For other processes such as Bremsstrahlung, there is no reason they should not scale as n^2
- Thus, we can write down a **cooling function** that is independent of density:

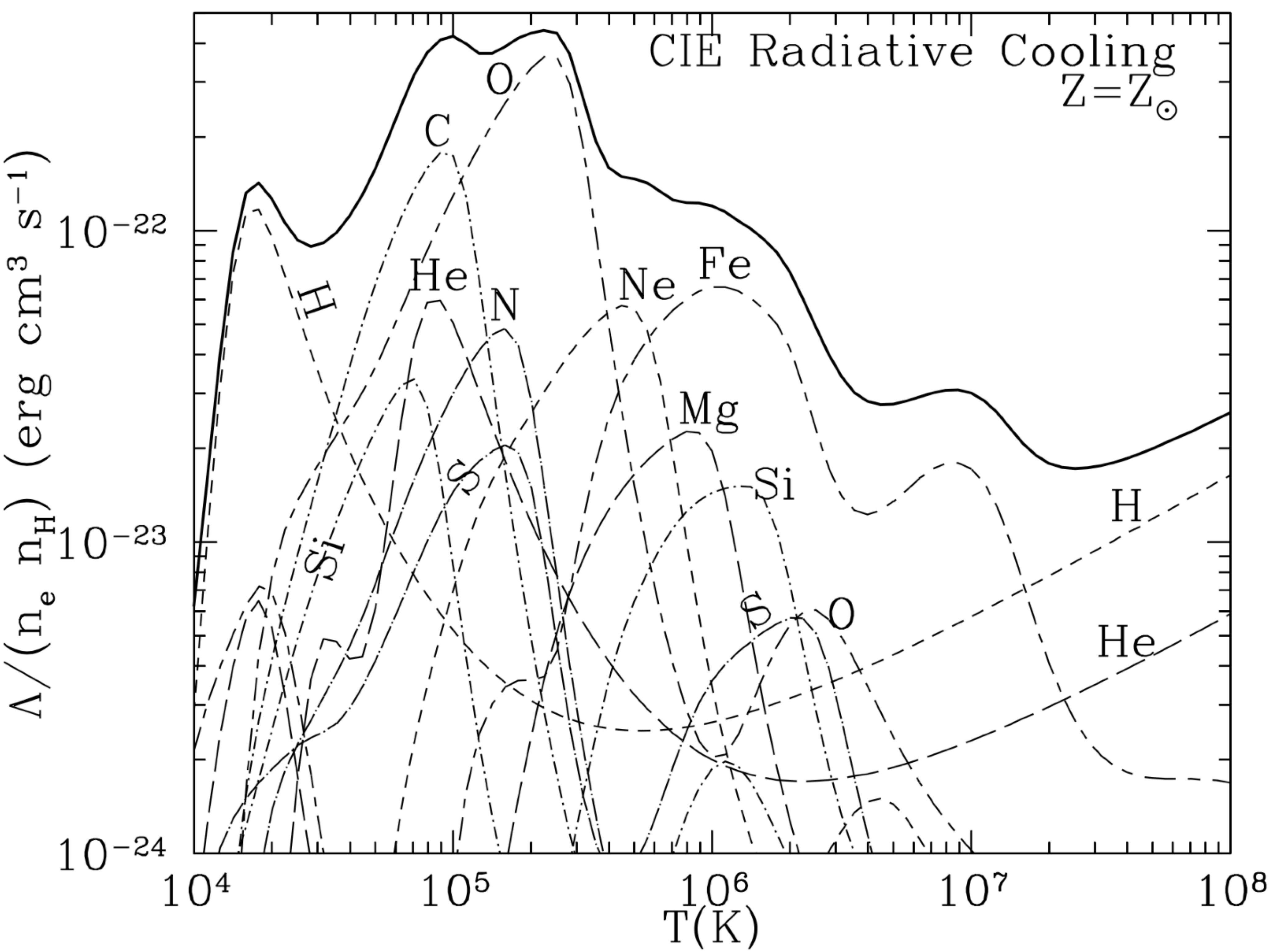
$$\mathscr{C} = \left(\frac{\Lambda}{n^2}\right) \qquad \left[\frac{\Lambda}{n^2}\right] = \mathrm{erg\ cm^3/s}$$

Low temperature: collisional excitation



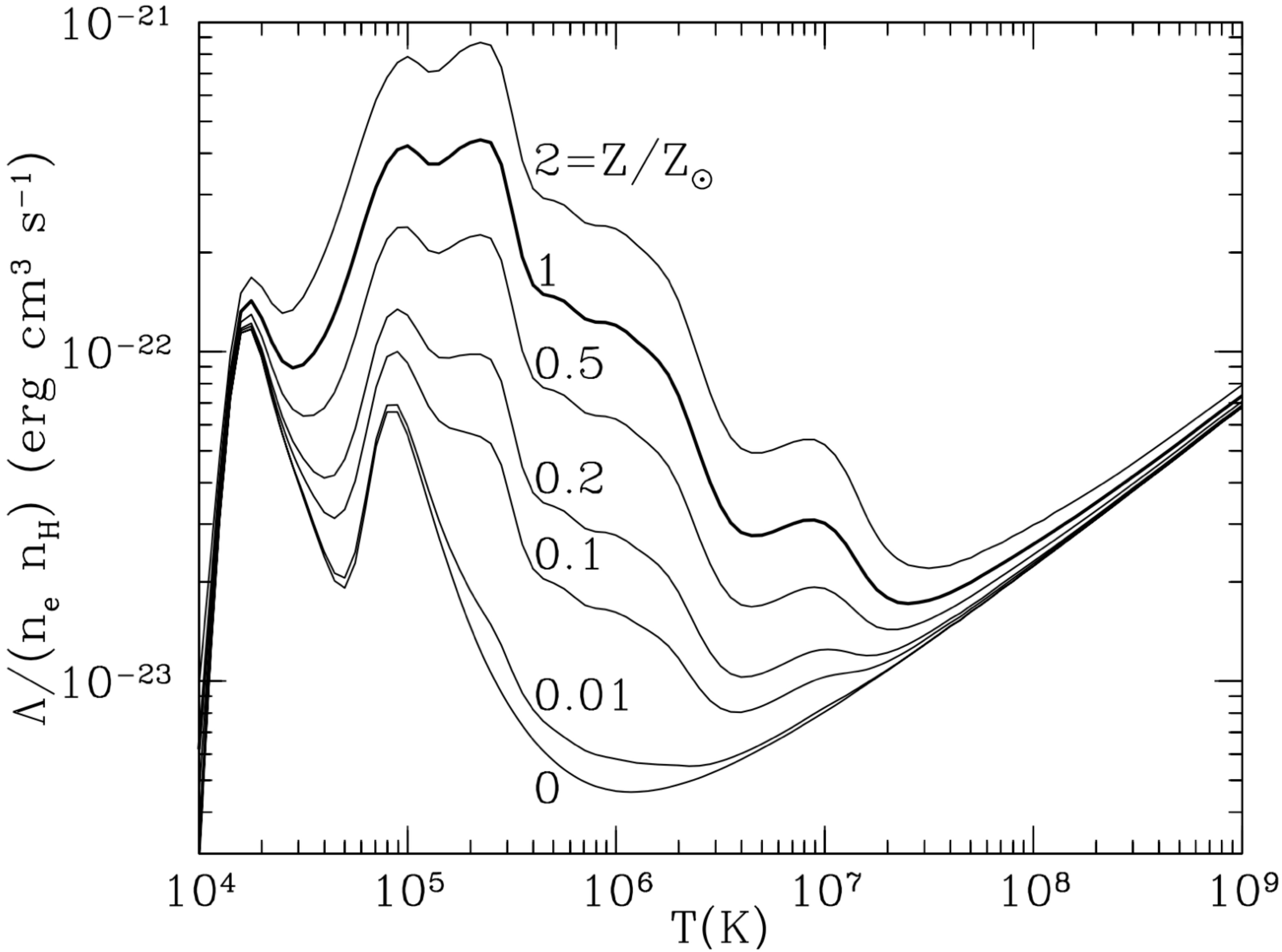
Draine §30.4, §34.1

Intermediate temperature: collisional exc./ion.



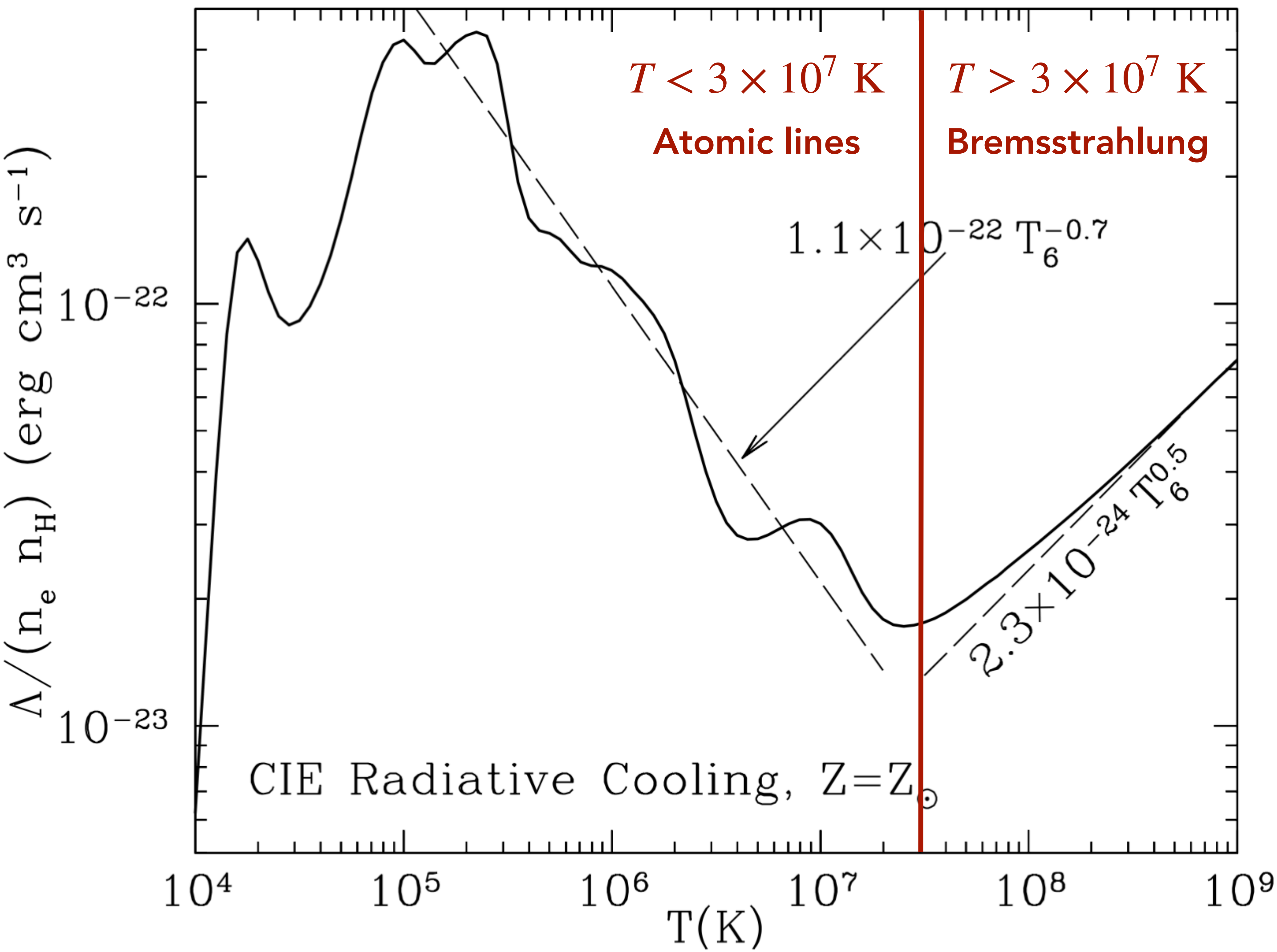
Draine §34.1

Intermediate temperature: collisional exc./ion.



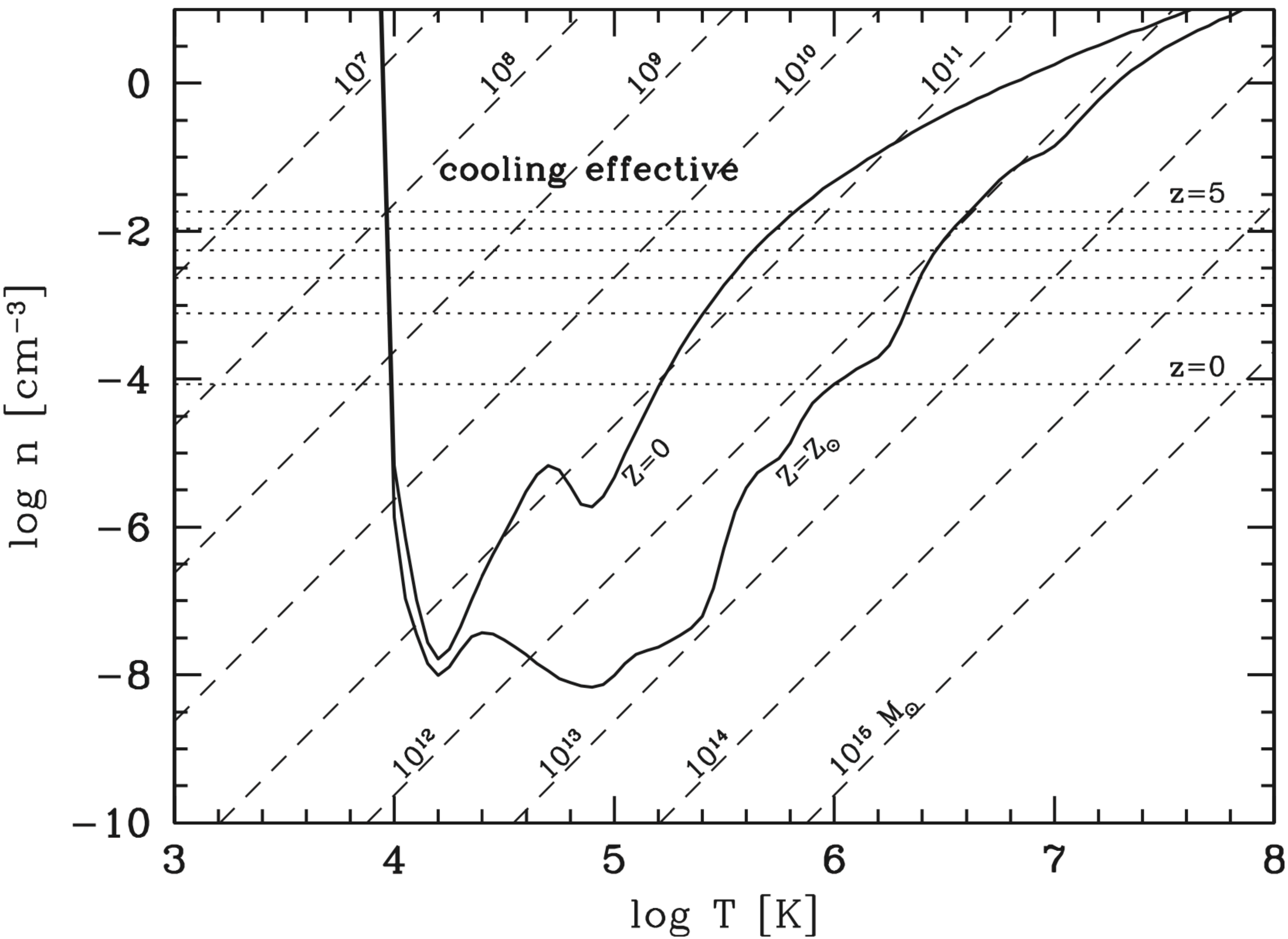
Draine §34.1

High temperature: Bremsstrahlung



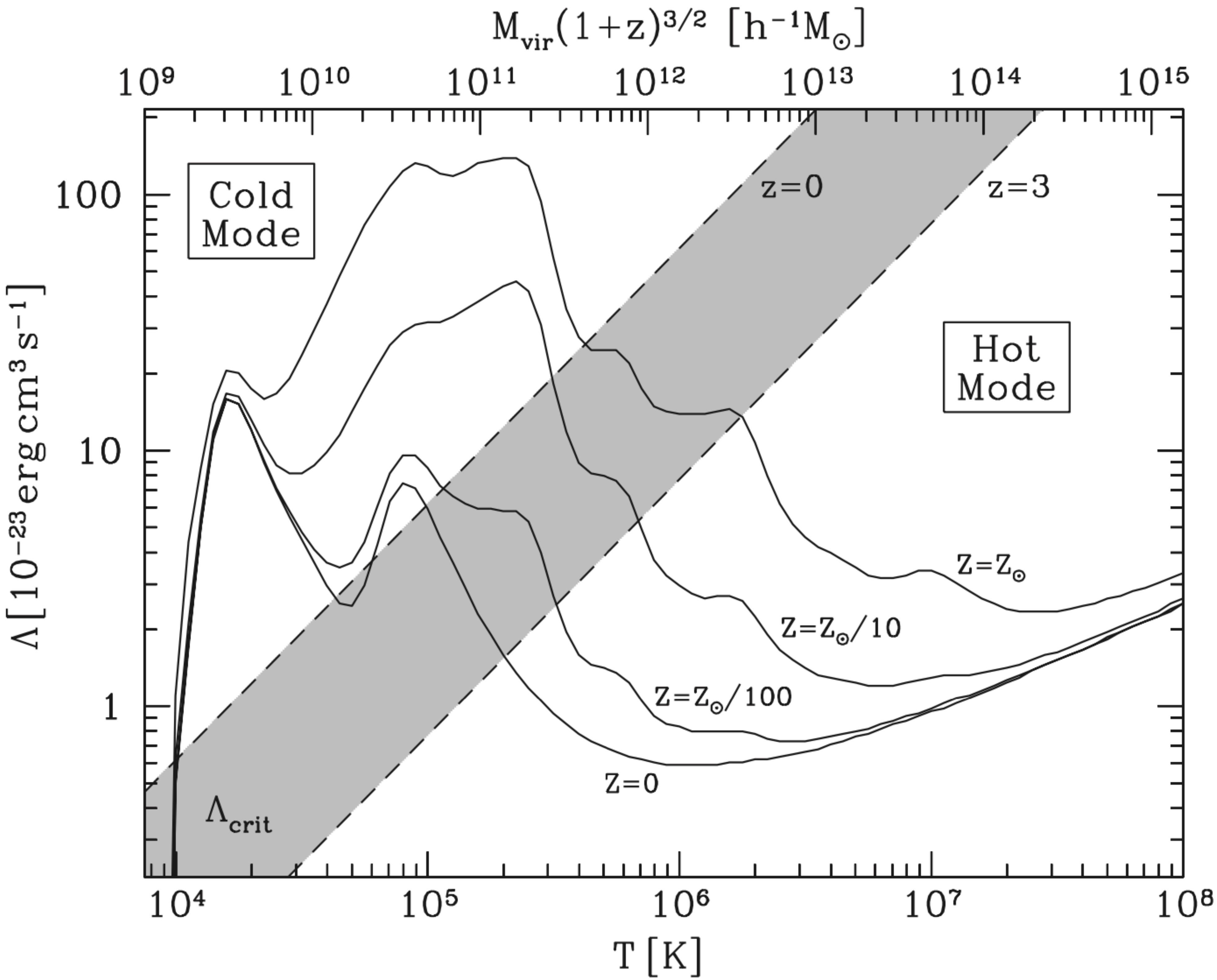
Draine §34.1

When is cooling effective?



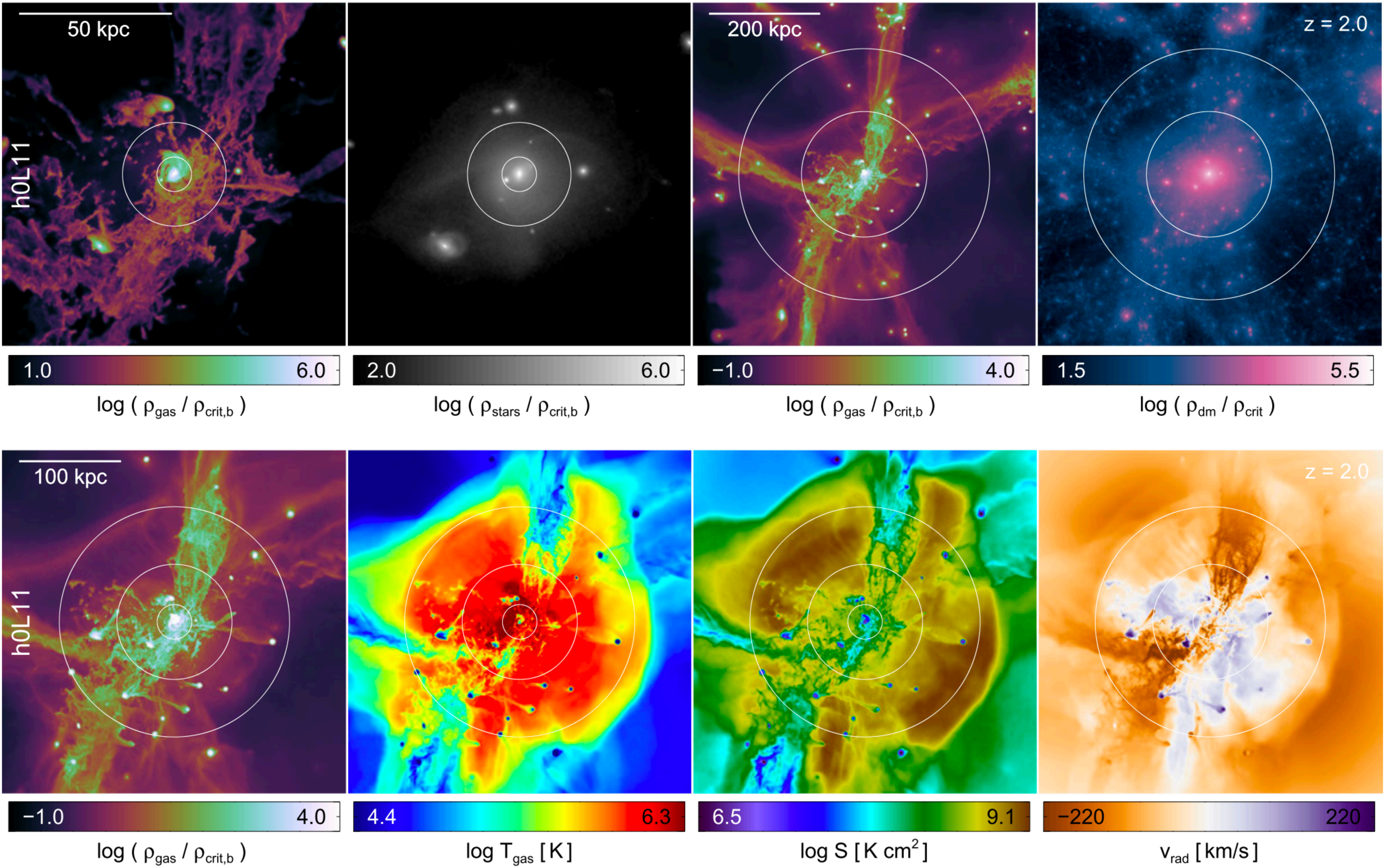
MvdBW §8.4.1

Hot vs. cold mode accretion



MvdBW §8.4.4

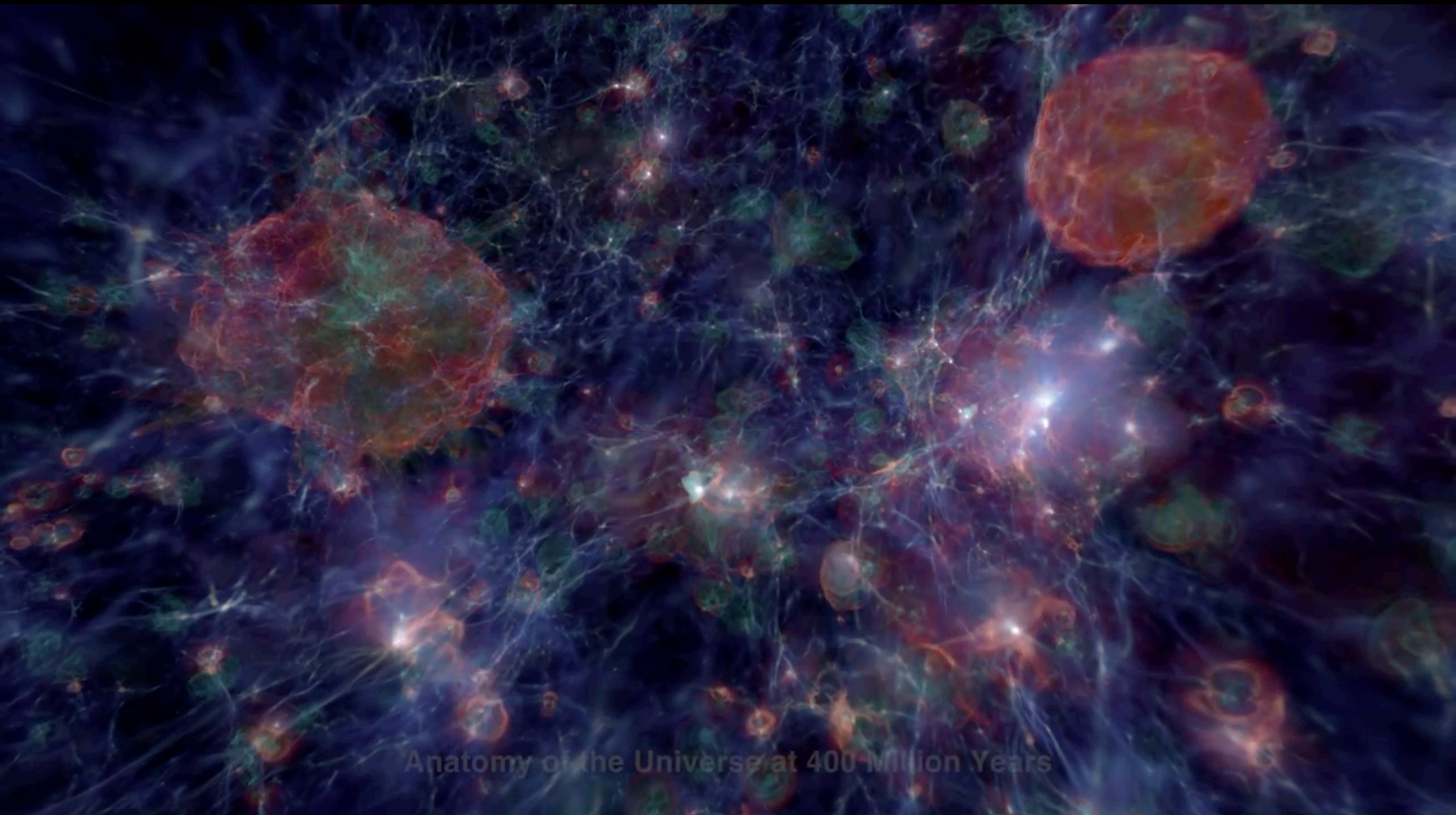
Hot vs. cold mode accretion



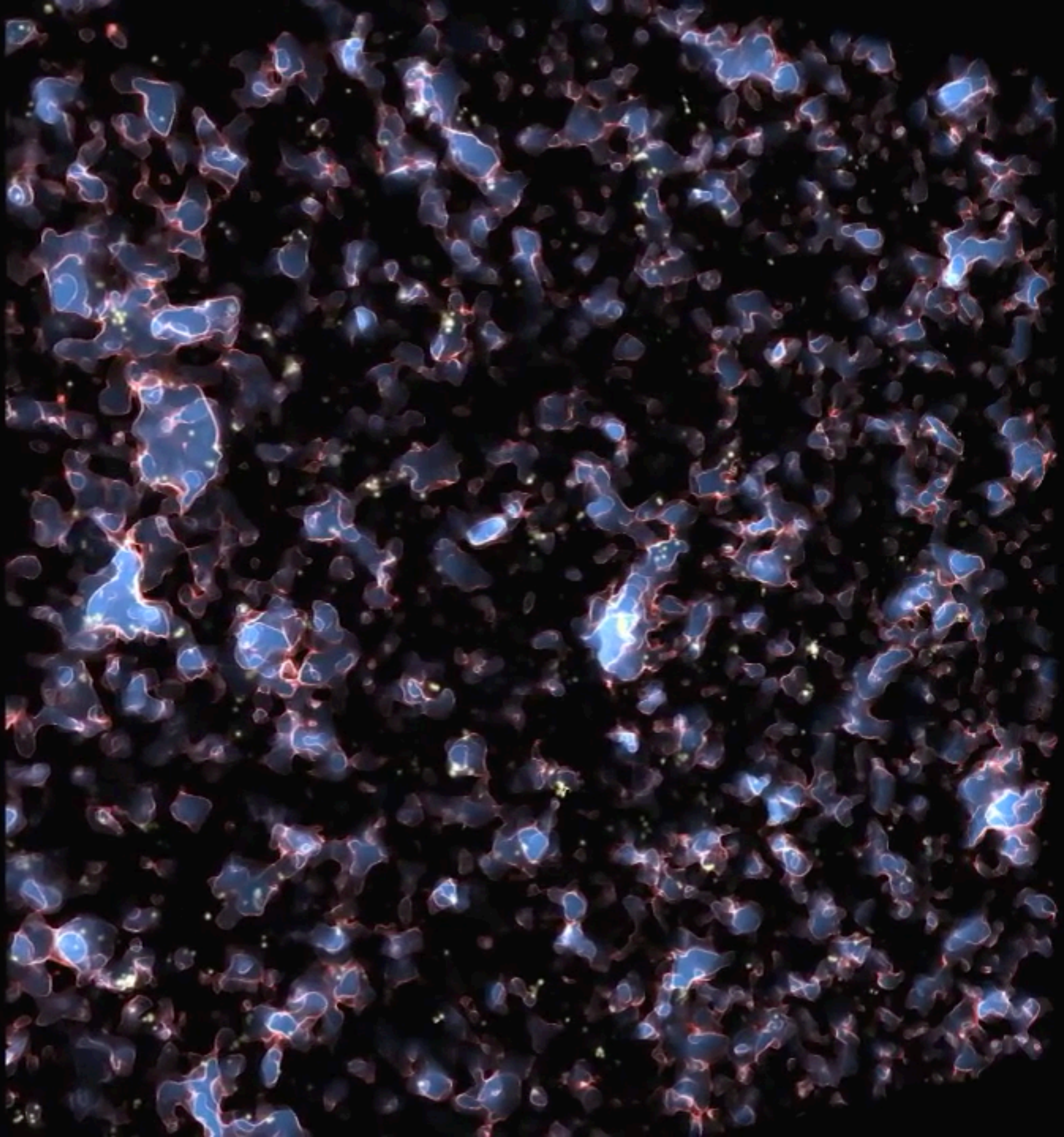
Nelson et al. 2015

§6.3 • Reionization and a mass limit for baryon accretion

First galaxies lighting up the Universe (simulation)



Video by M. Norman et al. (youtube)



Alvarez, Kaehler & Abel (youtube)

Reionization

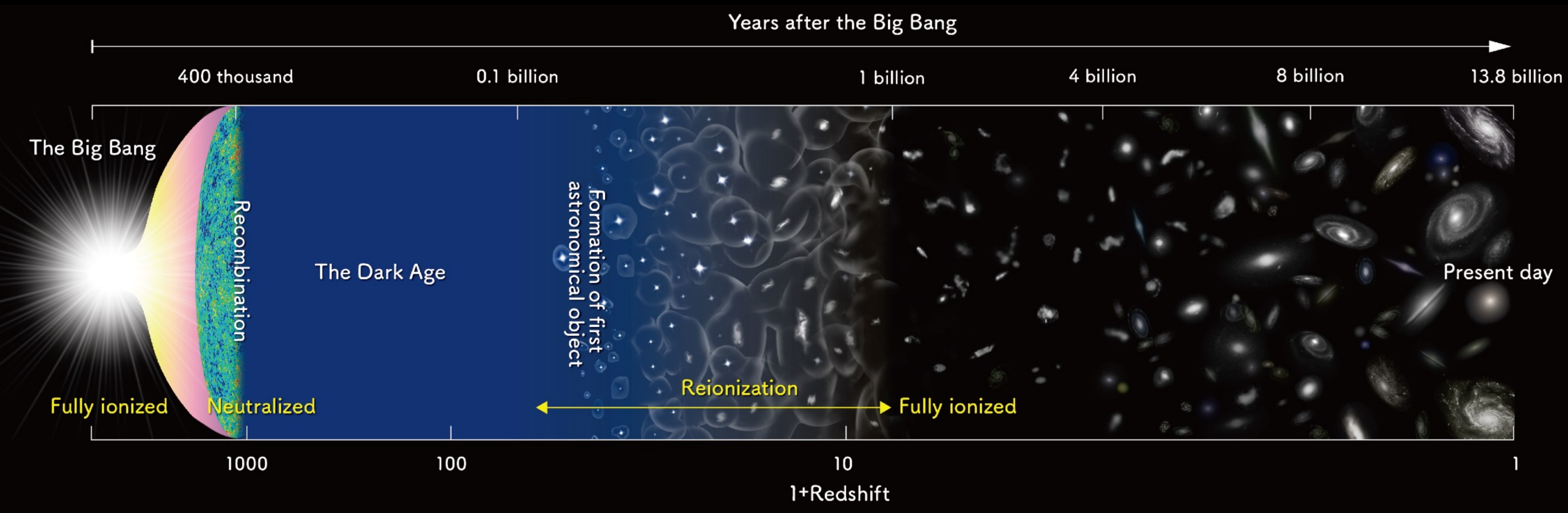
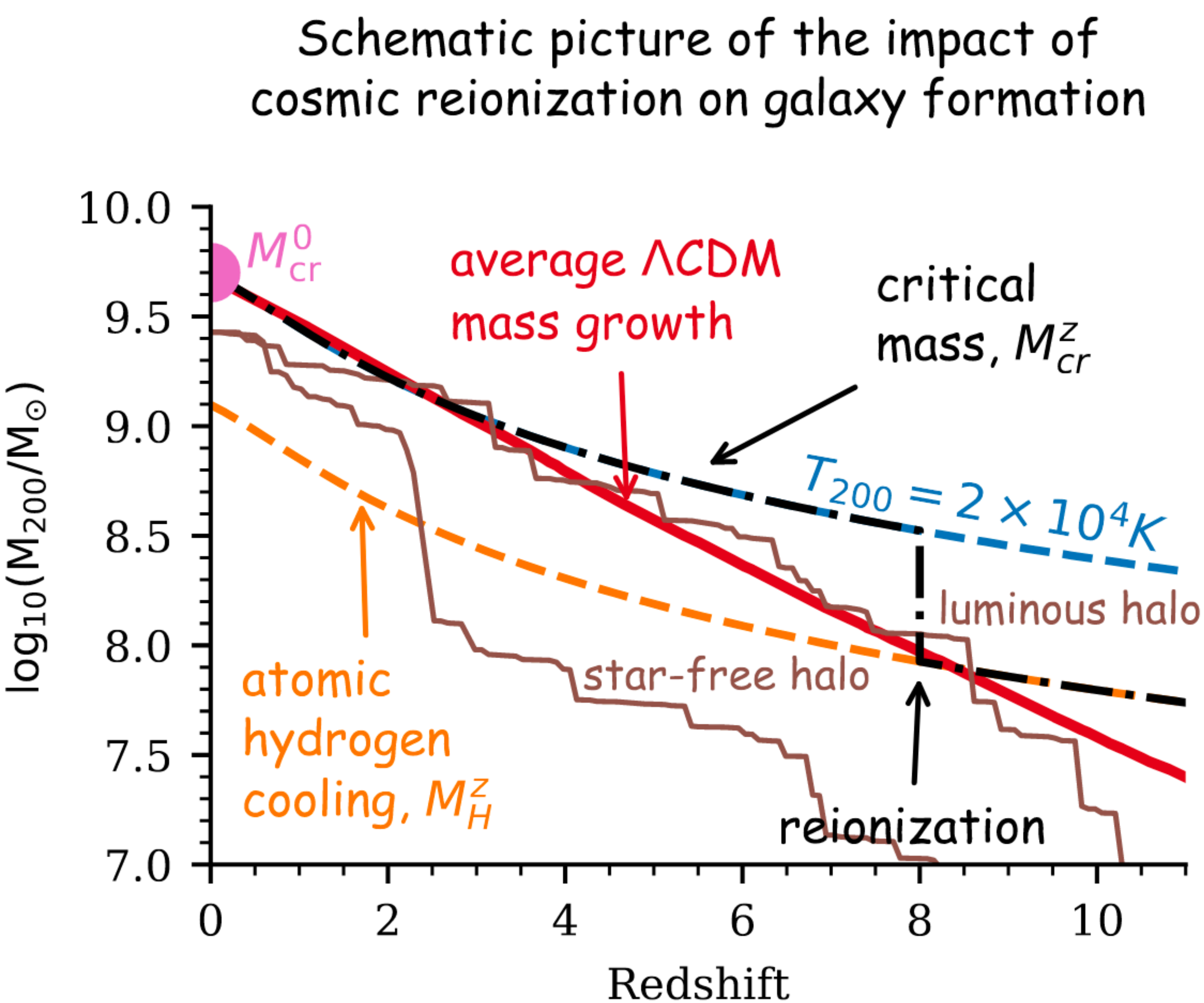


Image by NAOJ

Filtering mass



Benitez-Llambay & Frenk 2020

Reading

- CFN §8.1.1, §8.2, §9.4, §9.9
- MvdBW §8.1-8.5