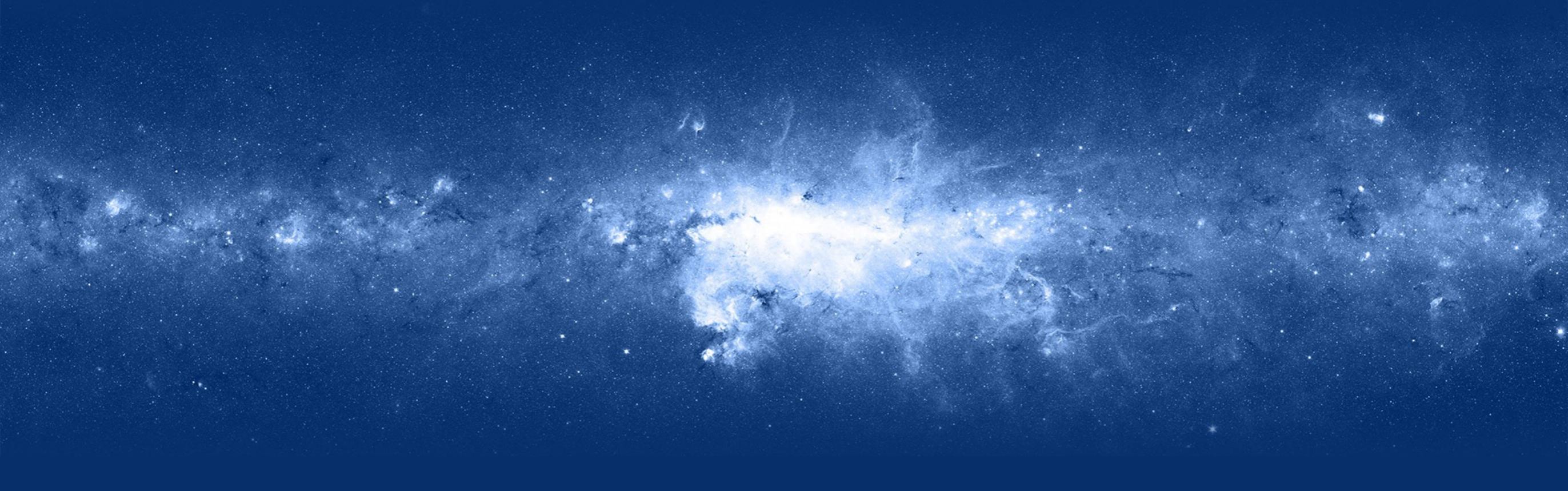


# **ASTR 670: Interstellar medium and gas dynamics**

Prof. Benedikt Diemer

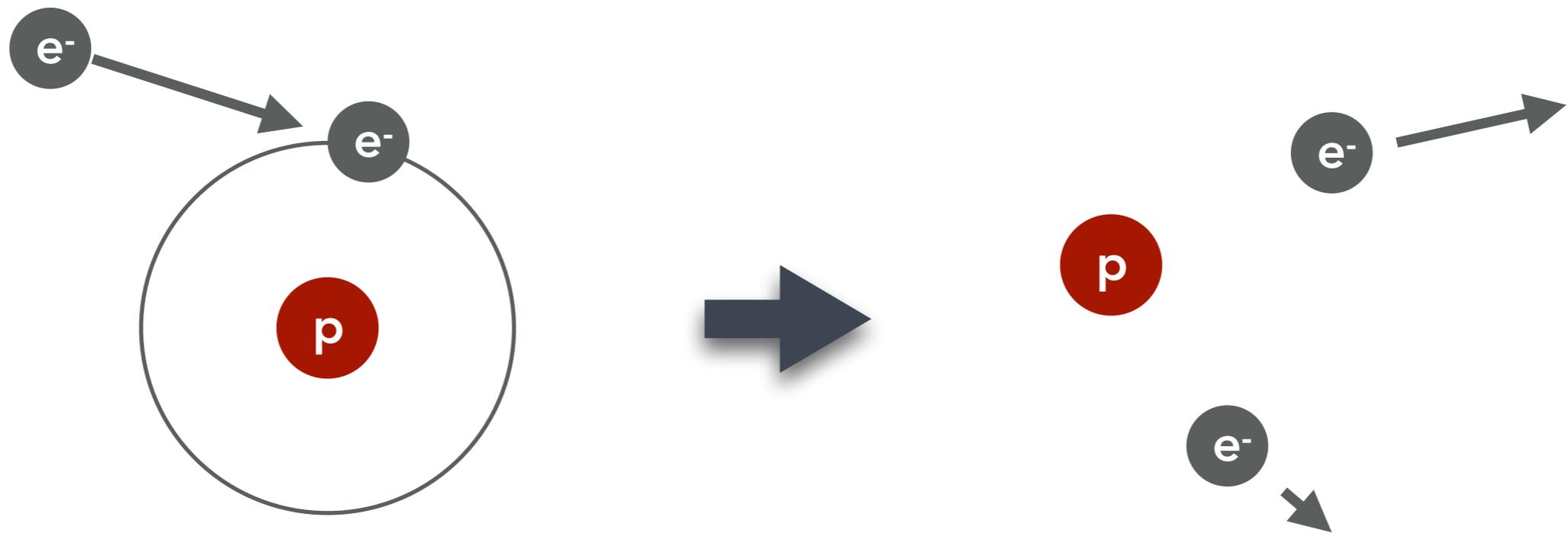


**Chapter 2 • The hot ionized medium**

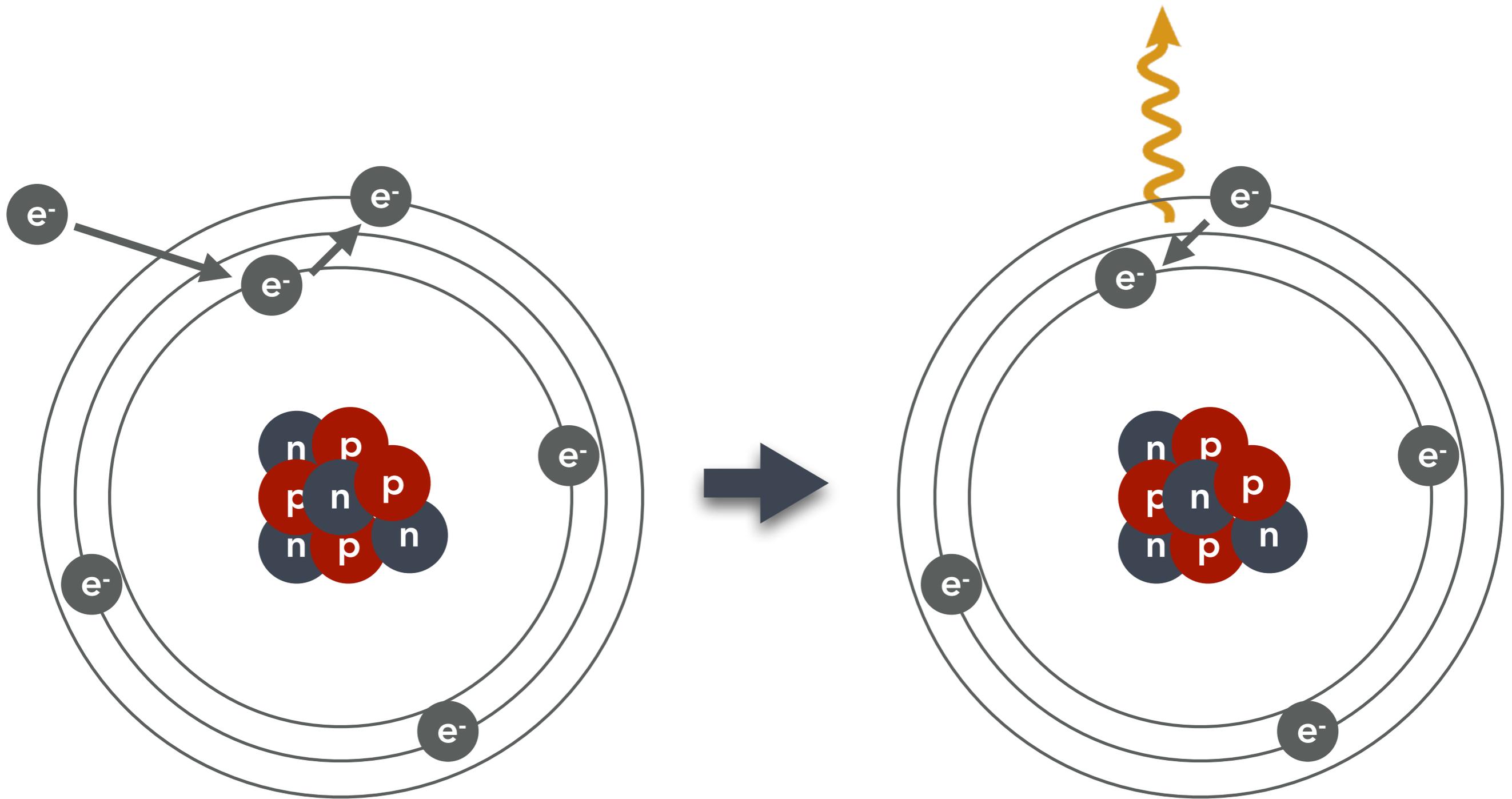
## §2.1 • Collisional ionization equilibrium

# What does "hot" mean?

- **Collisional excitation and ionization**
  - as opposed to photo-ionization



# Collisional excitation

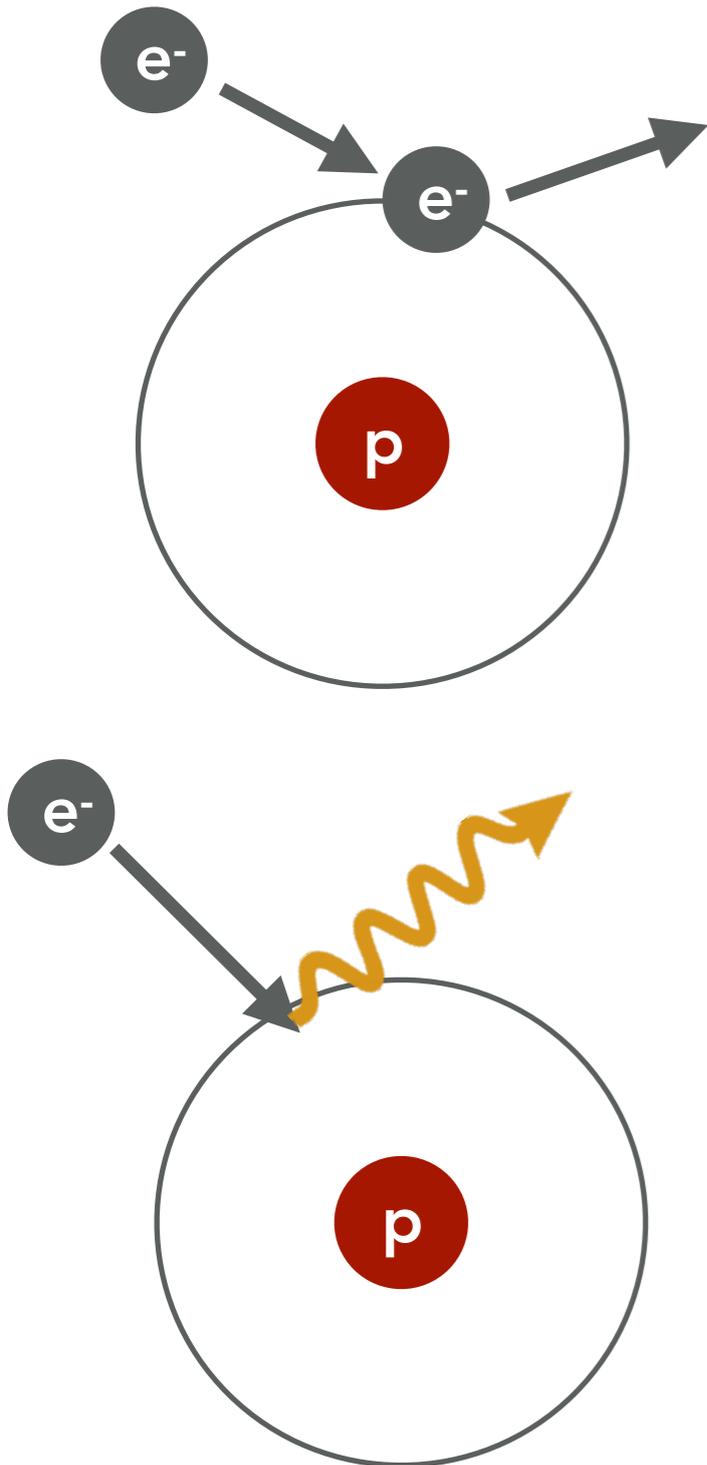


# Ionization of hydrogen

$$E_{\text{ion,H}} = 13.6 \text{ eV} = 2.2 \times 10^{-11} \text{ erg}$$

$$\langle E \rangle = \frac{3}{2} k_B T$$

$$\Rightarrow T_{\text{ion,H}} \approx 10^5 \text{ K}$$



- However, this calculation uses the **average** energy at a given temperature
- Even a small number of particles that have enough energy can ionize lots of atoms
- The real temperature where **hydrogen gets efficiently ionized** is about **10<sup>4</sup> K**

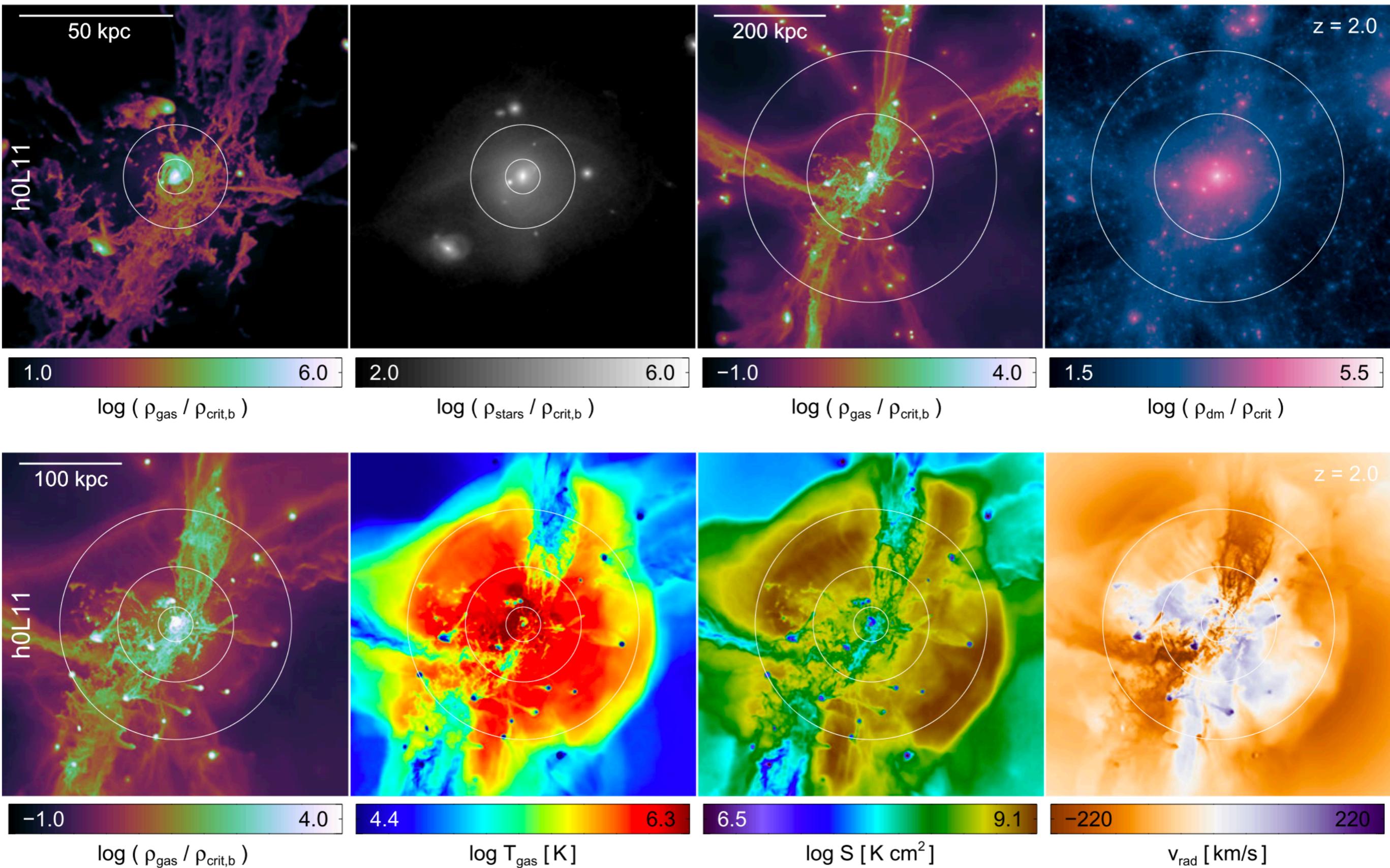
# Collisional ionization equilibrium (CIE)

- Assumptions necessary for CIE:
  - Photo-ionization is not important
  - Enough time to reach equilibrium
  - Known abundance pattern
- If CIE, both ionization and recombination are proportional to  $n_e \times n_i$ ; thus, the **ionization fractions** depend **only on the temperature**
- At  $T > 10^4$  K, there are enough electrons freed from hydrogen atoms to dominate the collisions

# Energy sources for HIM

- Accretion (or virial) shock heating
- Type Ia Supernovae (white dwarf)
- Core-collapse supernovae (massive stars)
- Stellar winds

# Hot vs. cold mode accretion



# Energy sources: supernova bubbles

- Henize 70 superbubble
- $\sim 10^6$  K at center of bubbles
- $\sim 10^5$  K at edges



# Energy sources: Stellar winds

- Bubble Nebula
- Blown by wind from central star
- About 2 pc across



# Energy sources: Stellar winds

- M27 planetary nebula
- Final stage of massive stars



# Diagnostics of hot gas

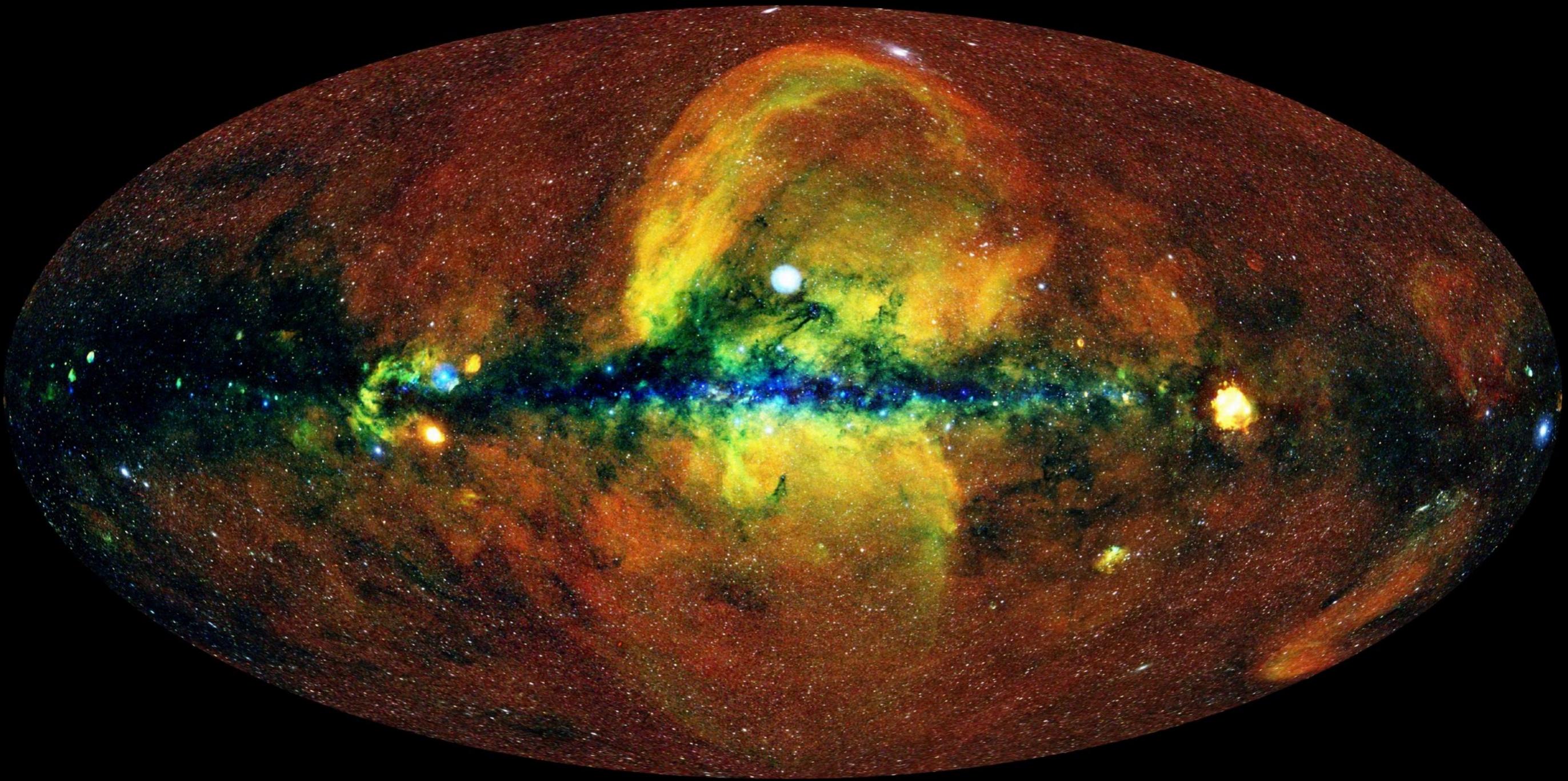
- **Soft X-ray**

- For  $T \geq 7 \times 10^5$  K
- Opacity of ISM limits distance at which we can see X-rays
- Soft X-ray background known only at our position in the ISM, but not in general
- At  $T < 3 \times 10^7$  K, emission is dominated by resonant lines from heavy elements; thus, cannot determine gas temperature without detailed spectrum modeling

- **UV lines**

- For slightly cooler gas
- Each ion has a temperature where its abundance is maximized (e.g.,  $T = 10^5$  K for C IV)
- Ionization fraction is independent of density (in CIE)

# X-rays (eROSITA)



# Local ISM (120 pc)

- How do we know about walls?
- Slightly cooler ( $10^5$  K) gas in walls does not seem to be moving fast based on lines
- That indicates interfaces between bubbles rather than shock fronts



## §2.2 • Cooling rates

# Cooling processes

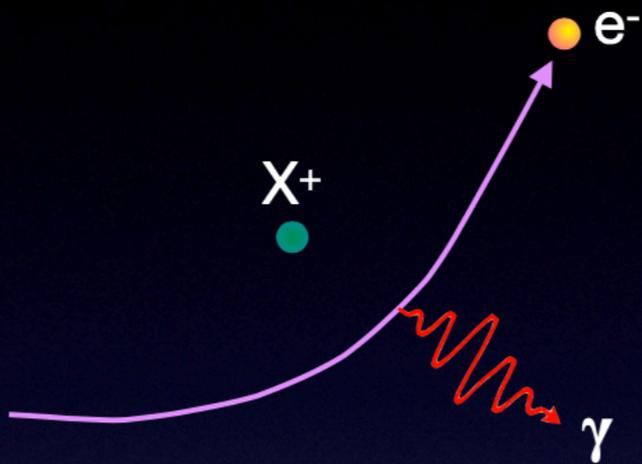
- One-particle processes:
  - Electrons Compton-scatter off CMB photons, giving them energy (most relevant at high  $z$ )
- Two-particle processes:

	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

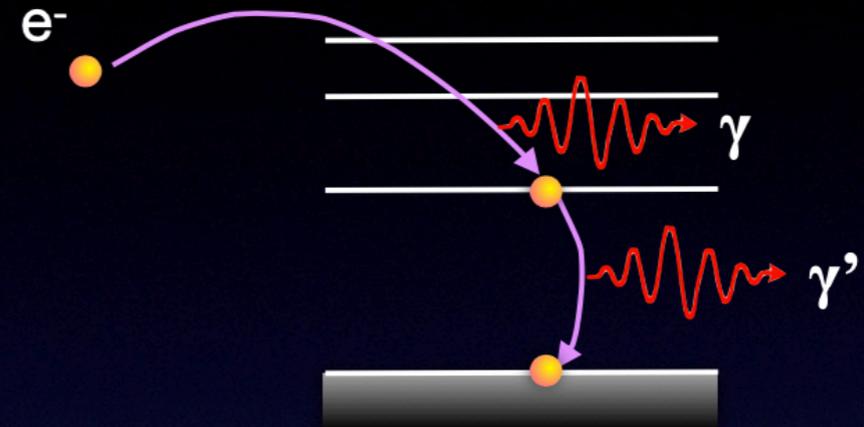
# Cooling processes

## 1) free-free (bremsstrahlung)



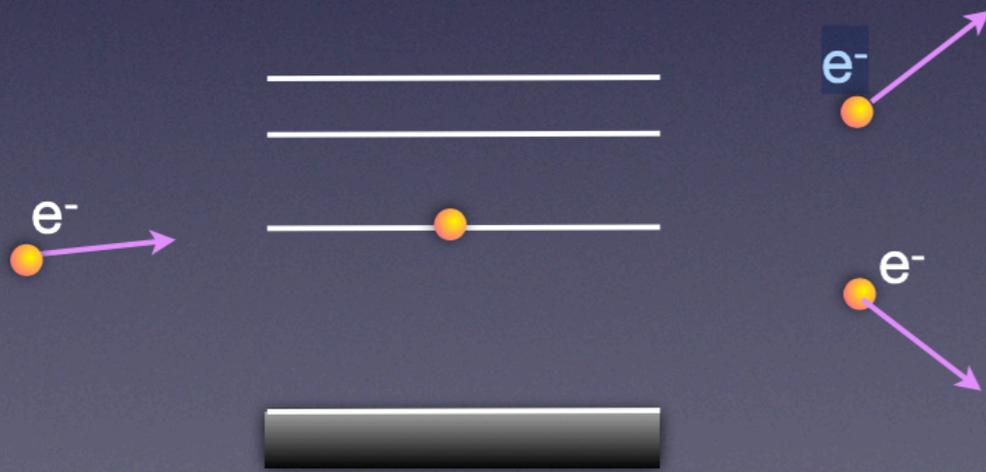
Free electron is accelerated by ion. Accelerated charges emit photons, resulting in cooling. For bremsstrahlung,  $\Lambda \propto T^{1/2}$

## 2) free-bound (recombination)



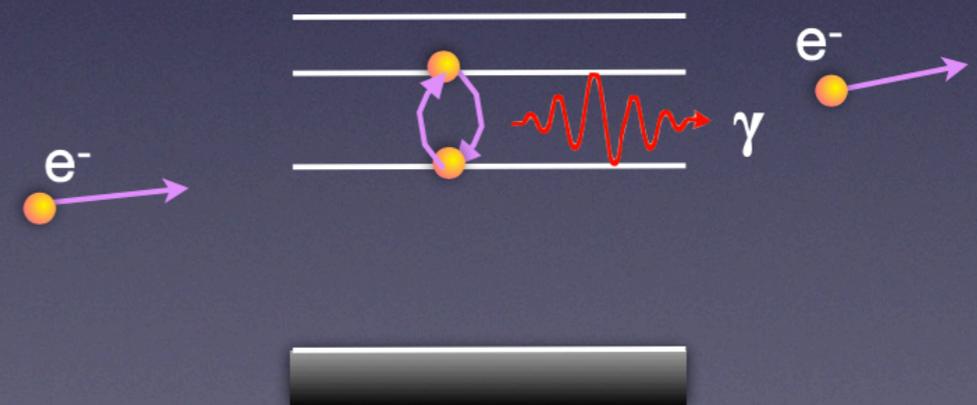
Free electron recombines with ion. Binding energy plus free electron's kinetic energy are radiated away. If capture into an excited state, subsequent (line) emission may result as electron cascades down to ground level.

## 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)



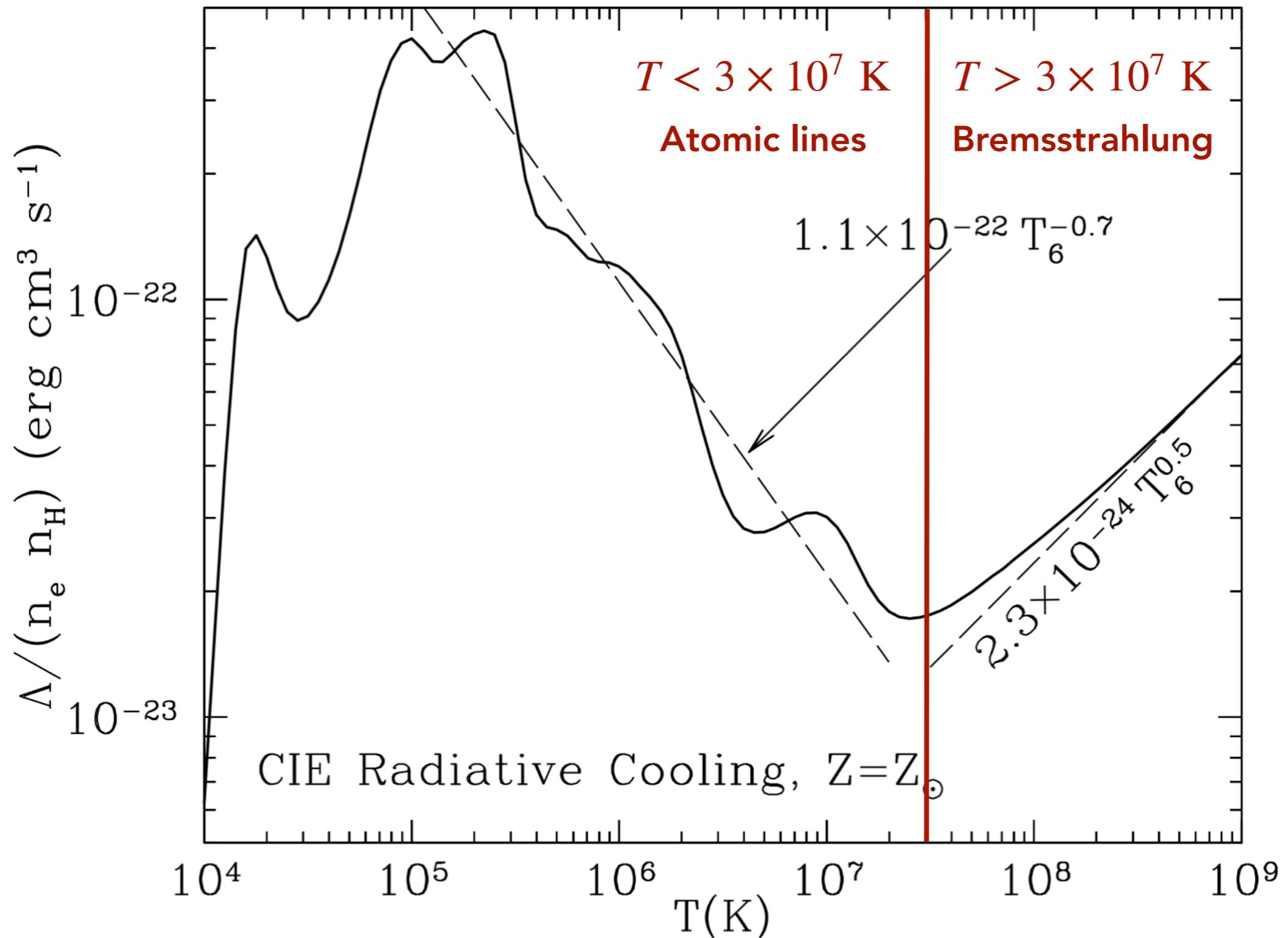
Impact of free electron knocks bound electron to excited state. As it decays, it emits a photon. Note, in case of collisional de-excitation, no photon is emitted (no net cooling)

# Cooling

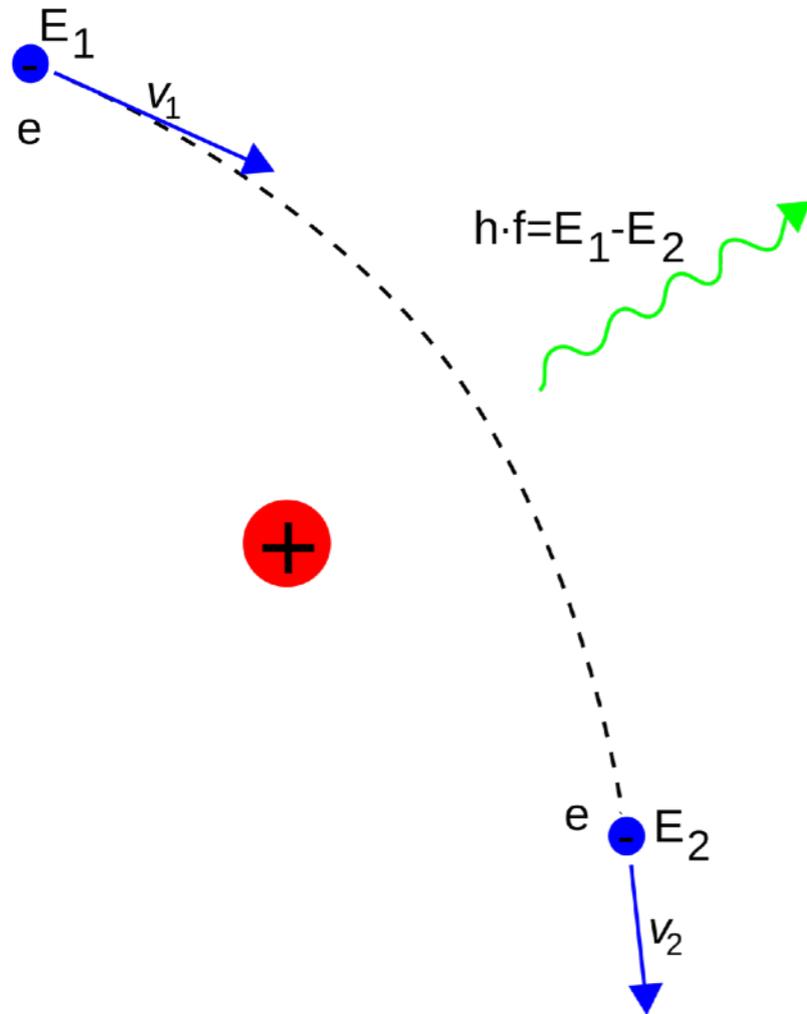
- As long as the density is not too high, we can assume that every collisional excitation is followed by a de-excitation before the next collision
- The respective energy is radiated away
- Thus, we can write down a **cooling function** that is independent of density:

$$\mathcal{C} = \left( \frac{\Lambda}{n_e n_i} \right) \times n_e n_i \left[ \frac{\Lambda}{n_e n_i} \right] = \text{erg cm}^3/\text{s}$$

# Cooling curves



# Bremsstrahlung



- As T increases, larger and larger atoms are fully ionized and do not contribute to line cooling any more
- At highest T, only nuclei and free electrons
- They interact via free-free emission (Bremsstrahlung), where an electron loses kinetic energy to a photon

# Bremsstrahlung

## Emissivity

(energy / time / unit volume /  
unit frequency / steradian)

$$j_{\text{ff},\nu} = \frac{8}{3} \left( \frac{2\pi}{3} \right)^{1/2} g_{\text{ff},i} \frac{e^6}{m_e^2 c^3} \left( \frac{m_e}{kT} \right)^{1/2} e^{-h\nu/kT} n_e Z_i^2 n_i$$
$$= 5.444 \times 10^{-41} g_{\text{ff}} T_4^{-1/2} e^{-h\nu/kT} Z_i^2 n_i n_e \text{ erg cm}^3 \text{ s}^{-1} \text{ sr}^{-1} \text{ Hz}^{-1}$$

## Cooling function

(energy / time / unit volume)

$$\Lambda_{\text{ff}} = 4\pi \int_0^\infty j_{\text{ff},\nu} d\nu = \frac{32\pi}{3} \left( \frac{2\pi}{3} \right)^{1/2} \frac{e^6}{m_e^2 h c^3} (m_e kT)^{1/2} \langle g_{\text{ff}} \rangle_T Z_i^2 n_i n_e$$

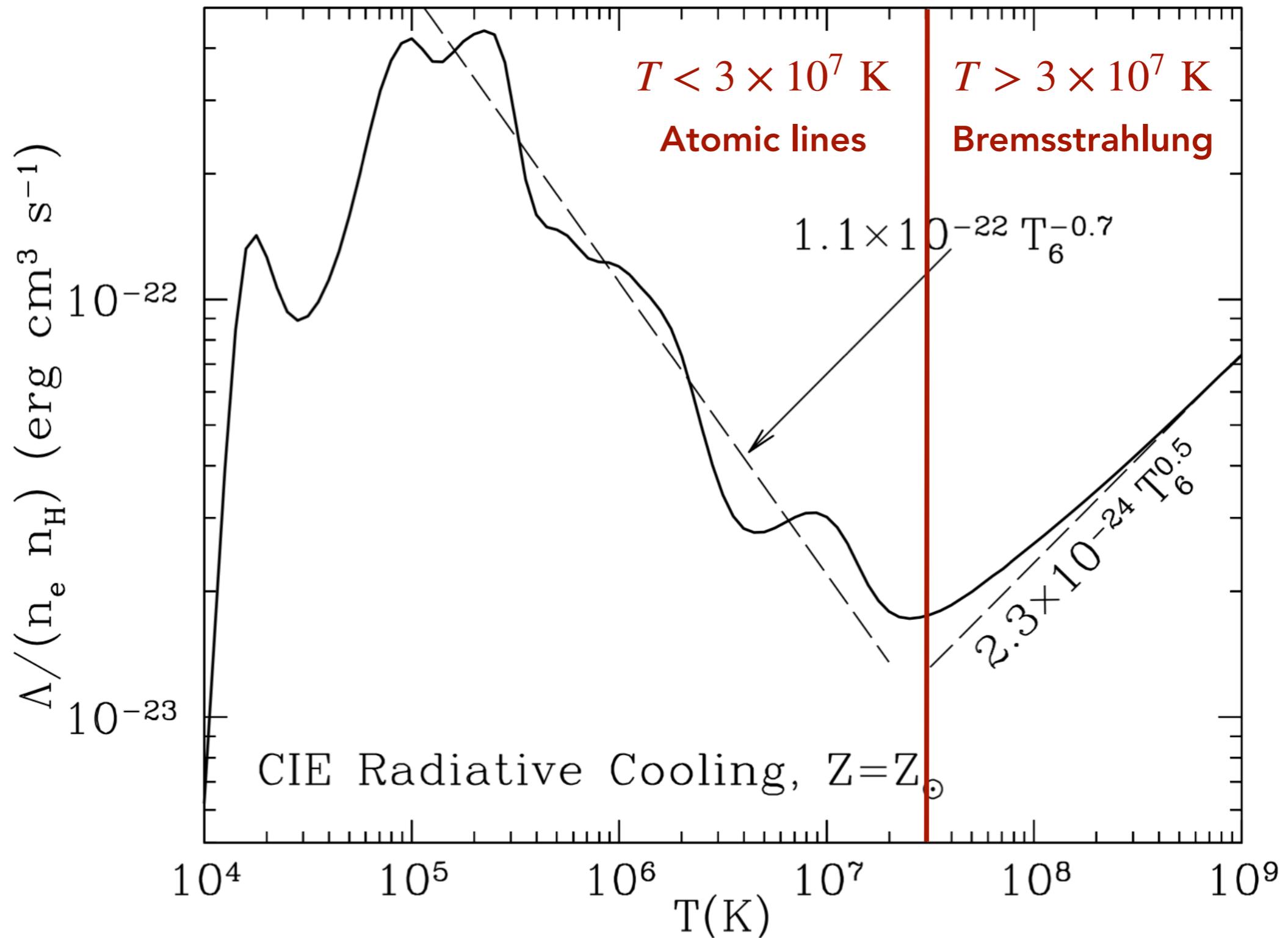
## Average Gaunt factor

(QM corrections)

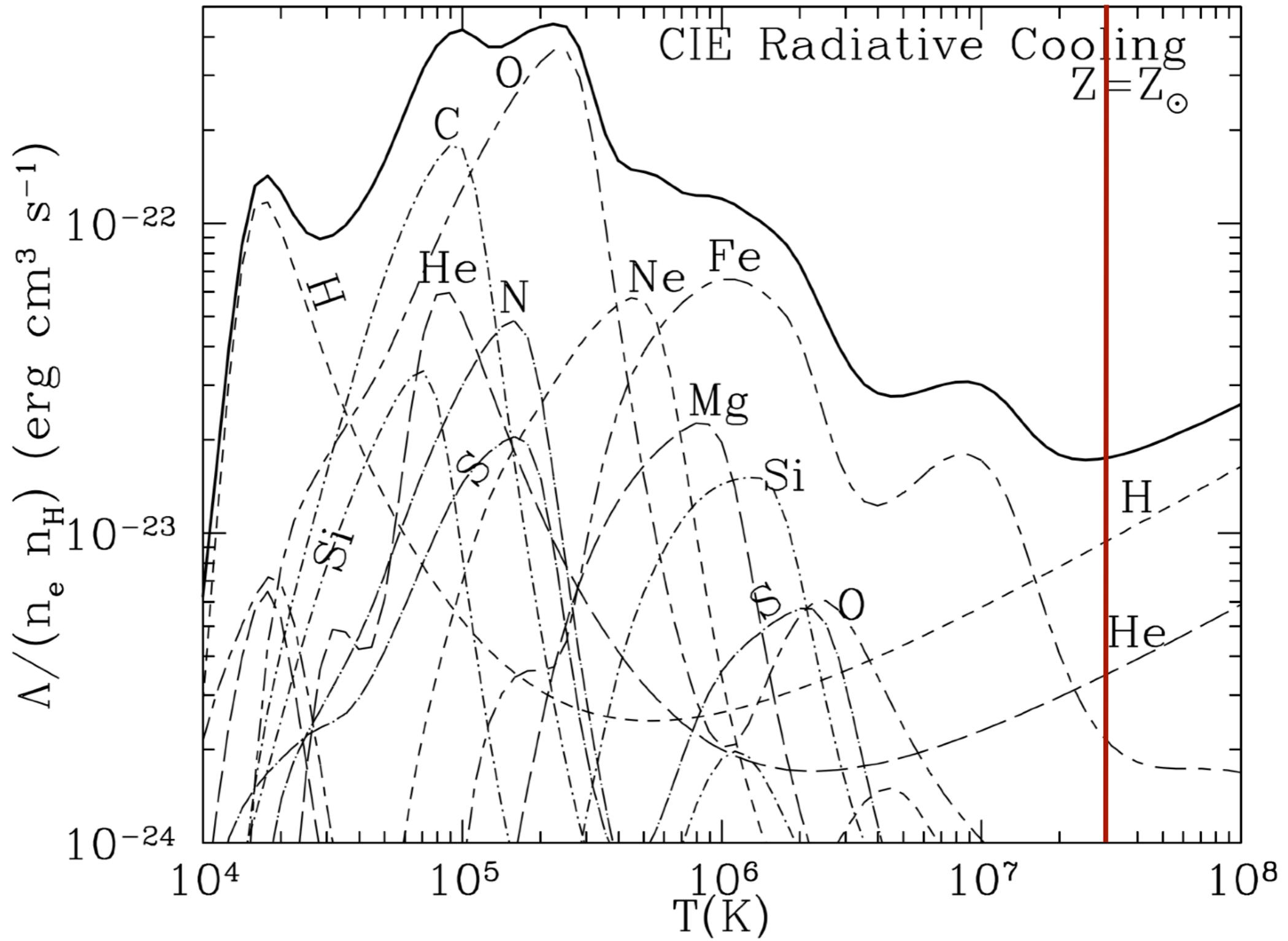
$$\langle g_{\text{ff}} \rangle_T \equiv \int_0^\infty \frac{dh\nu}{kT} e^{-h\nu/kT} g_{\text{ff}}(\nu, T) \quad (\text{almost independent of } T)$$

$$\implies \Lambda_{\text{ff}} \propto n_e n_i T^{1/2}$$

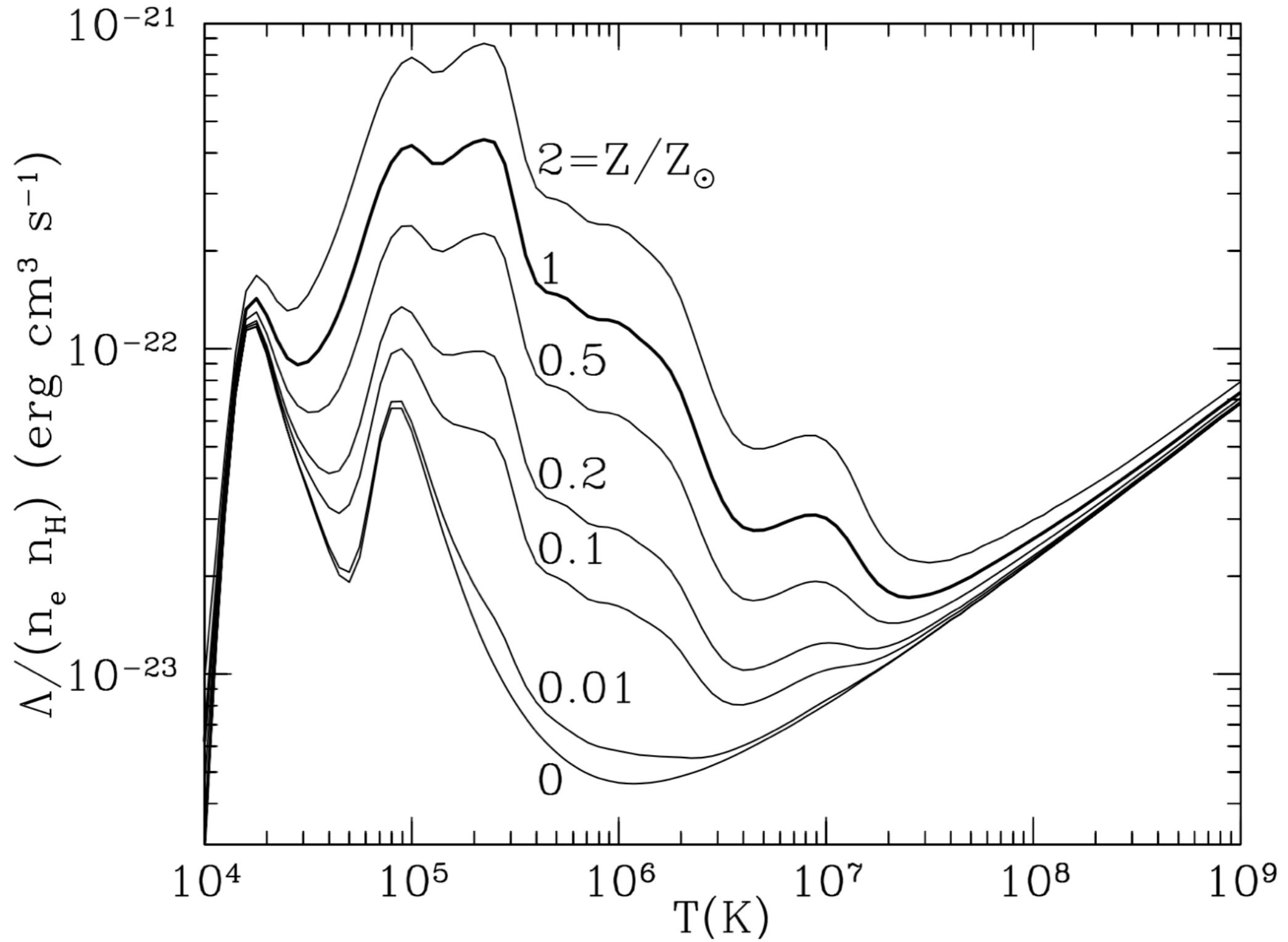
# Cooling curves



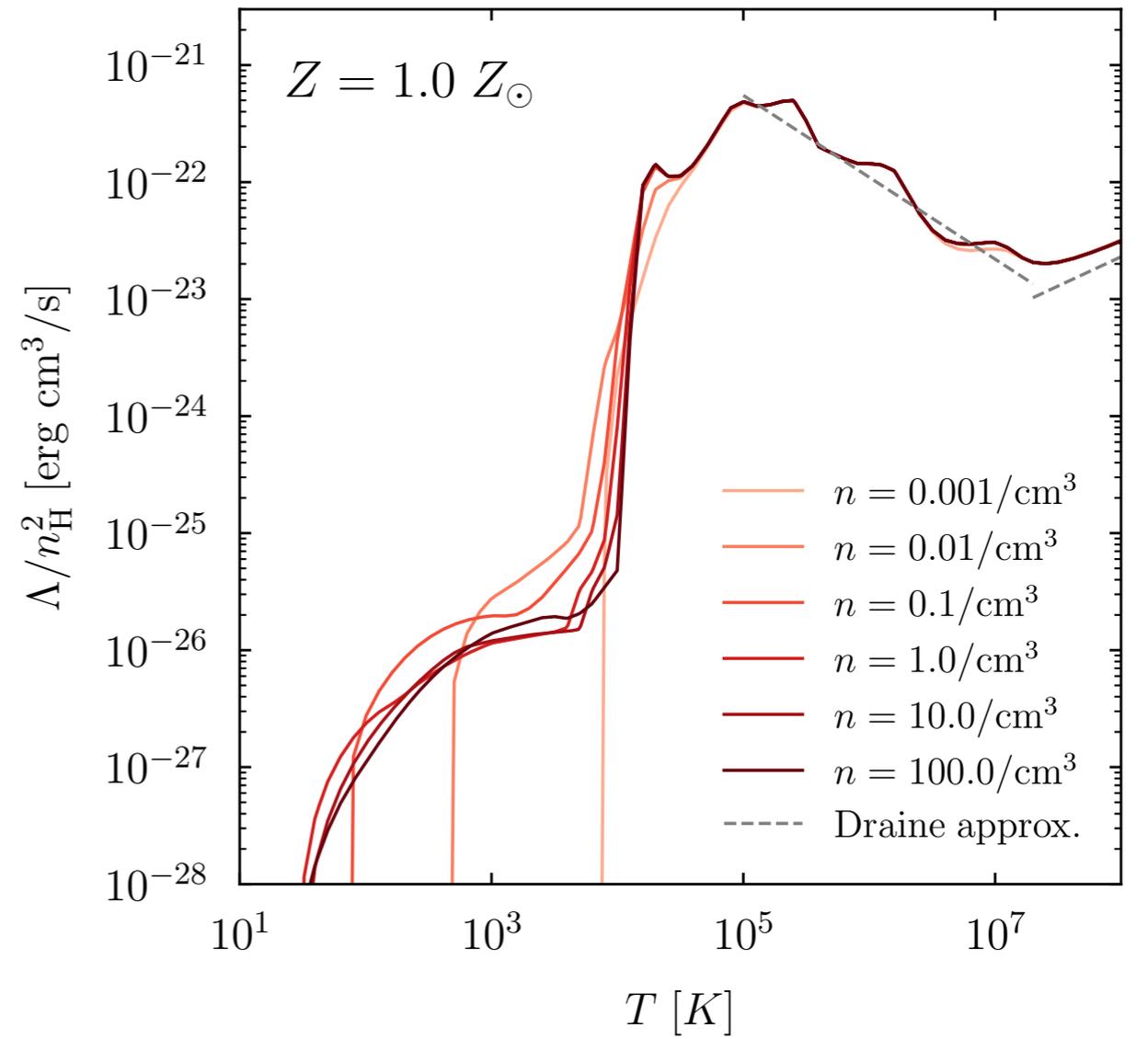
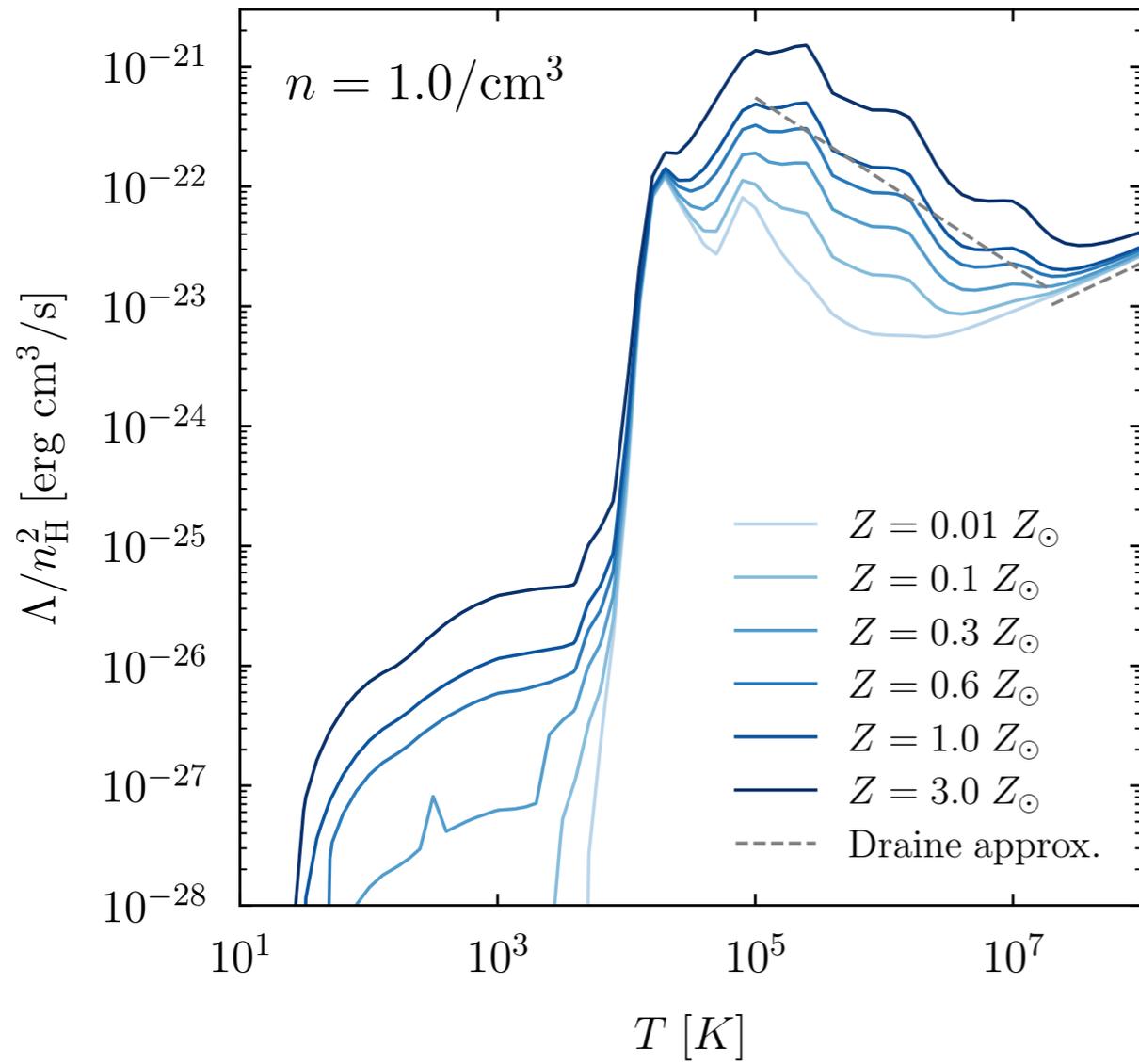
# Cooling curves



# Cooling curves



# Cooling curves



## §2.3 • Cooling times

# Cooling time

- We define the cooling time as the time it takes for the gas to cool to  $T = 0$  at the current (!) rate,

$$t_{\text{cool}} \equiv \frac{T}{|DT/Dt|}$$

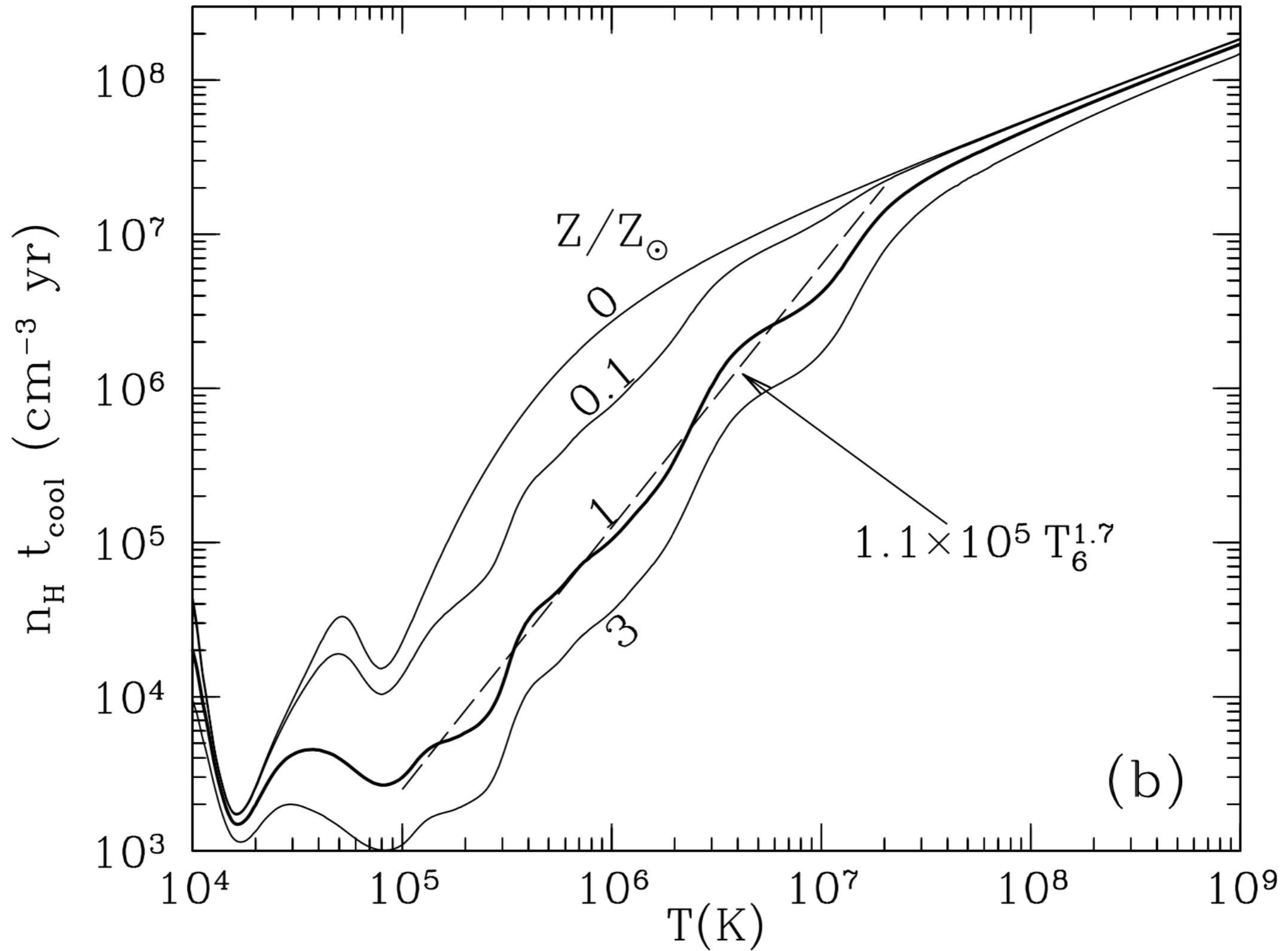
- We get the expression for  $DT / Dt$  by converting the internal energy equation,

$$\frac{D\epsilon}{Dt} = -\frac{P}{\rho} \nabla \cdot u - \frac{\Lambda}{\rho} \quad \Longrightarrow \quad \frac{DT}{Dt} = \frac{(\gamma - 1)}{\gamma n k_B} \left( \frac{DP}{Dt} - \Lambda \right)$$

- As the temperature drops, either density or pressure has to decrease as well. Depending on which we keep constant, we get (for  $\gamma = 5/3$ ):

$$t_{\text{cool, isobaric}} = \frac{5}{2} \frac{n k_B T}{\Lambda} \quad \text{and} \quad t_{\text{cool, isochoric}} = \frac{3}{2} \frac{n k_B T}{\Lambda}$$

# Cooling time

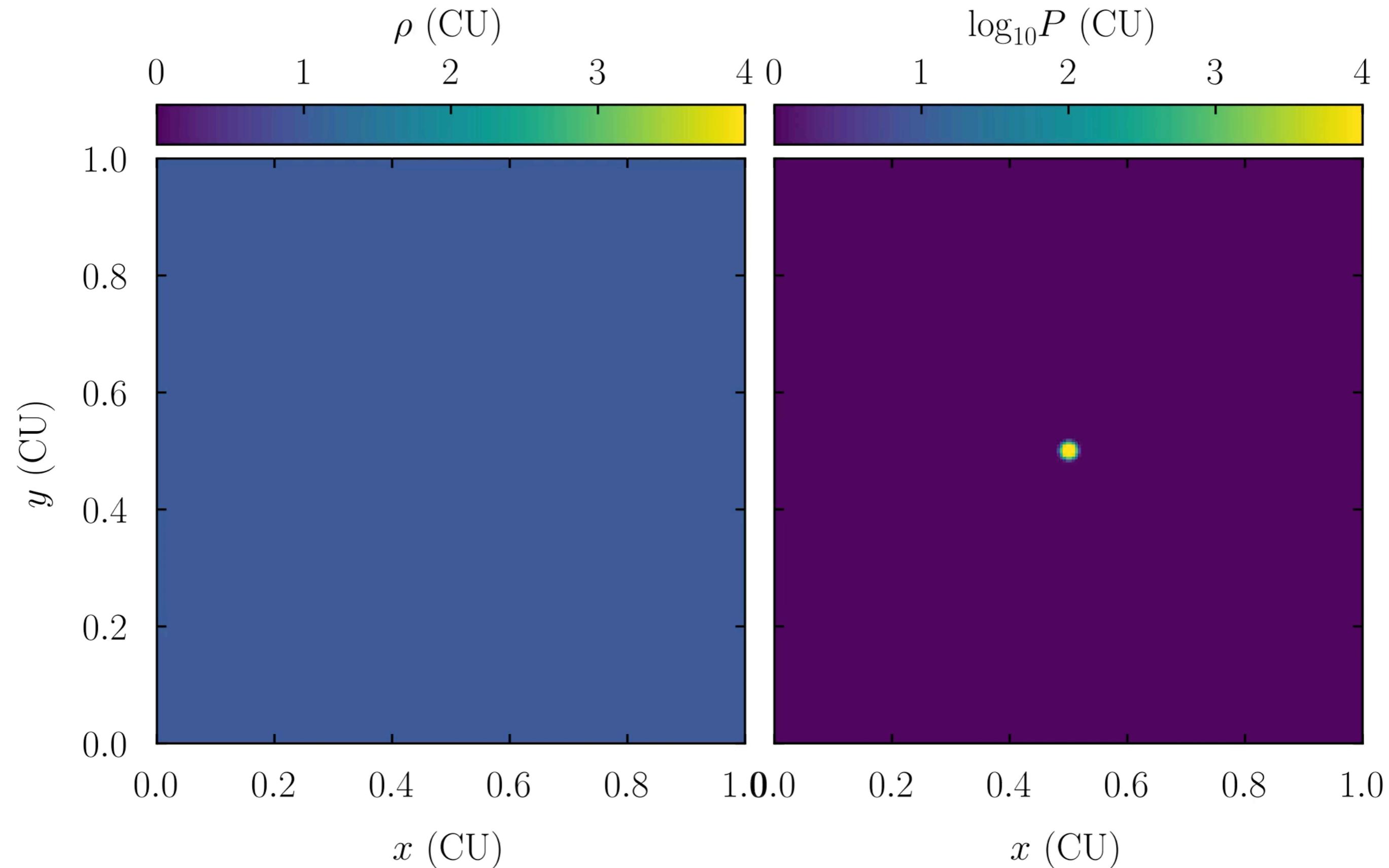


# Other cooling mechanisms

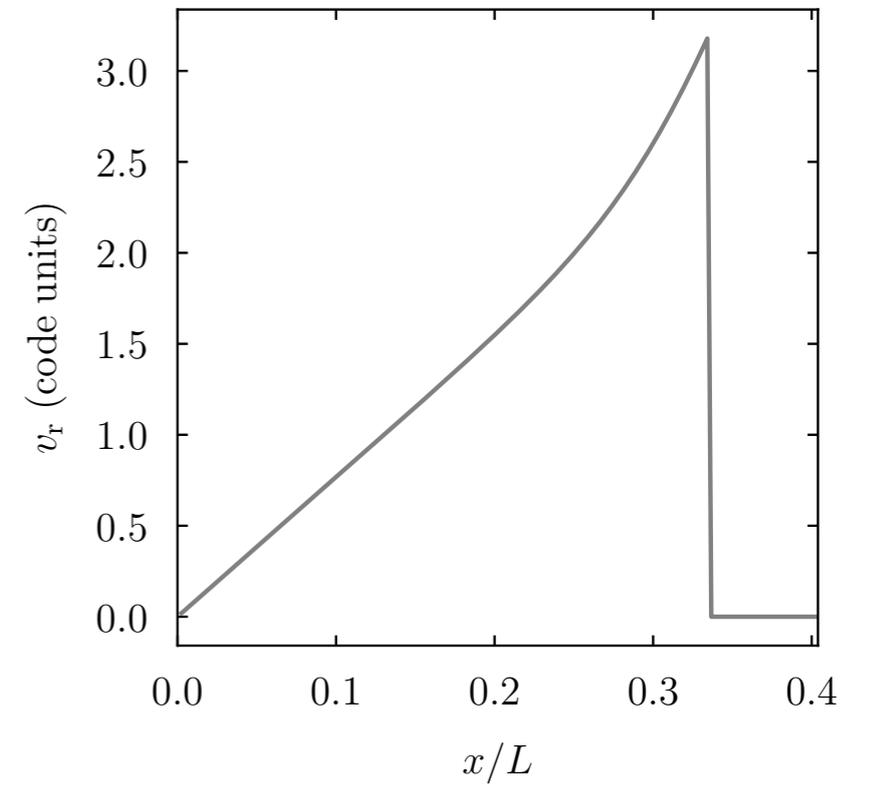
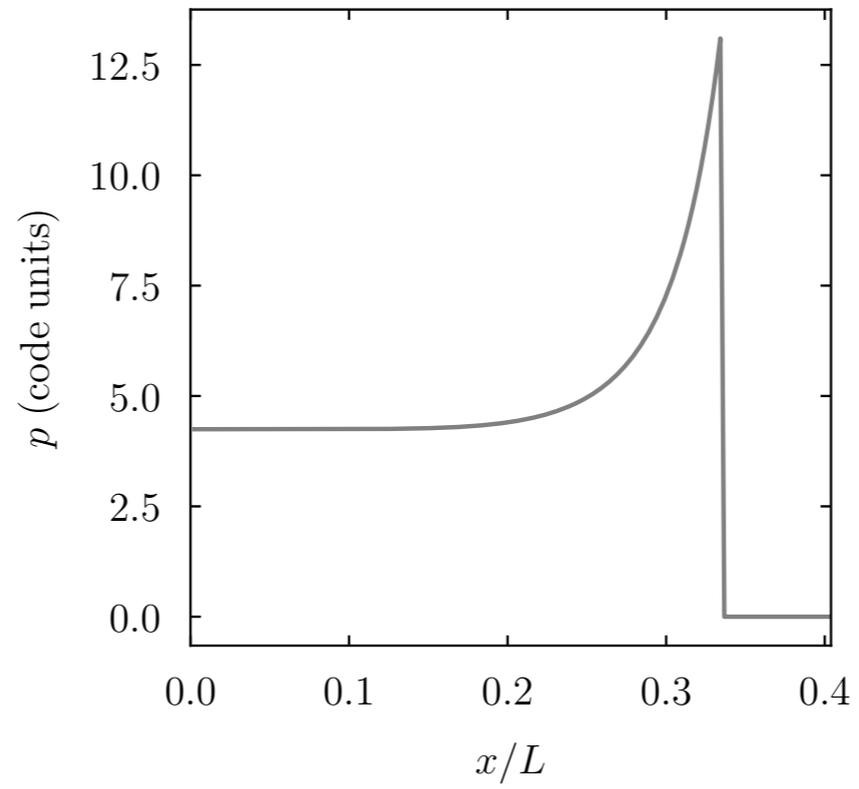
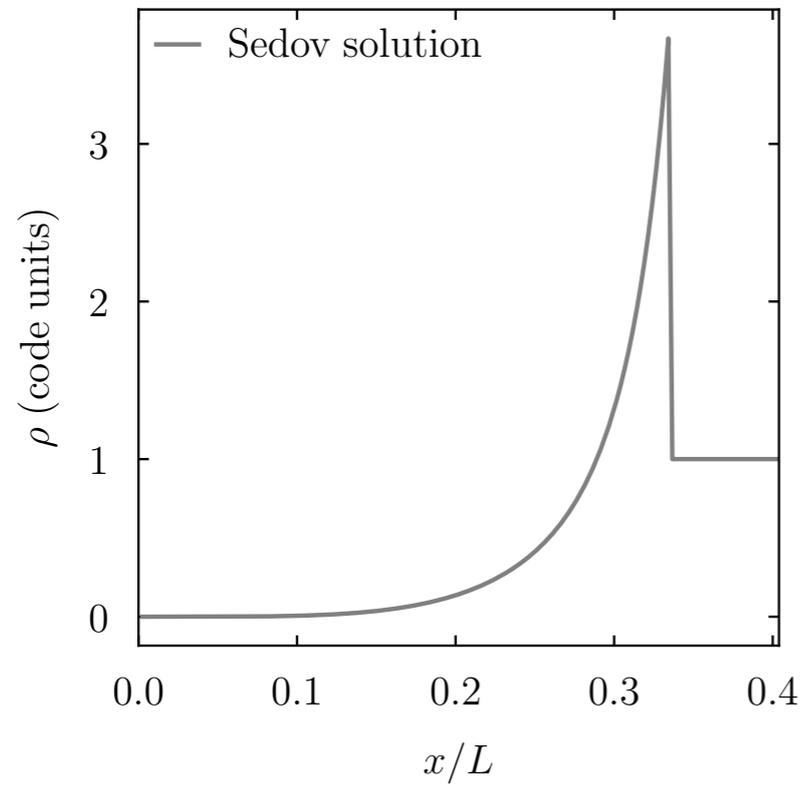
- Conduction (can be relevant for hot gas)
- Dust cooling (inelastic collisions with grains, heat radiated away in the IR)

**§2.4 • Radiative corrections  
to the Sedov-Taylor phase of supernovae**

# Sedov-Taylor blastwave

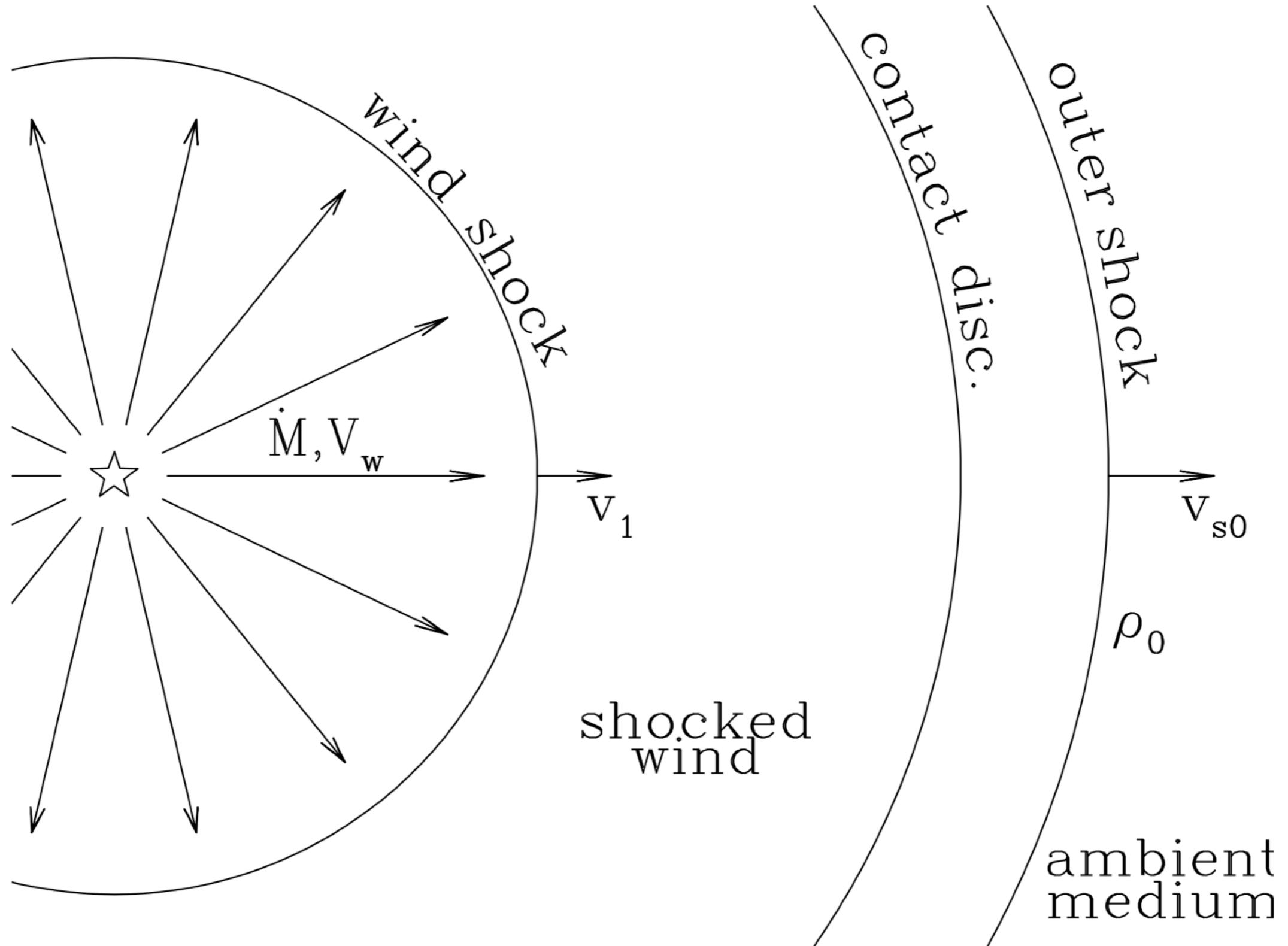


# Sedov solution

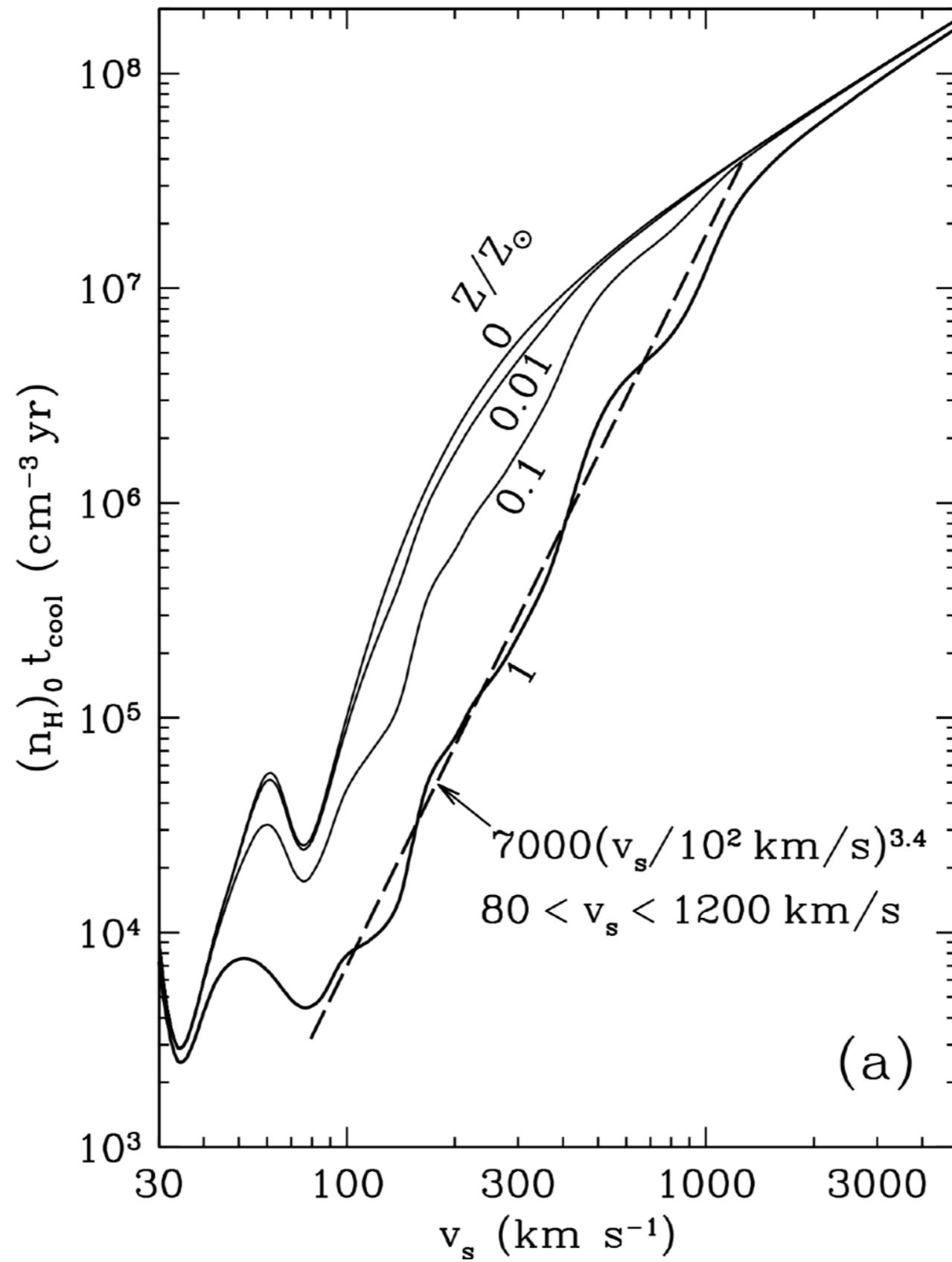


## §2.5 • Stellar winds

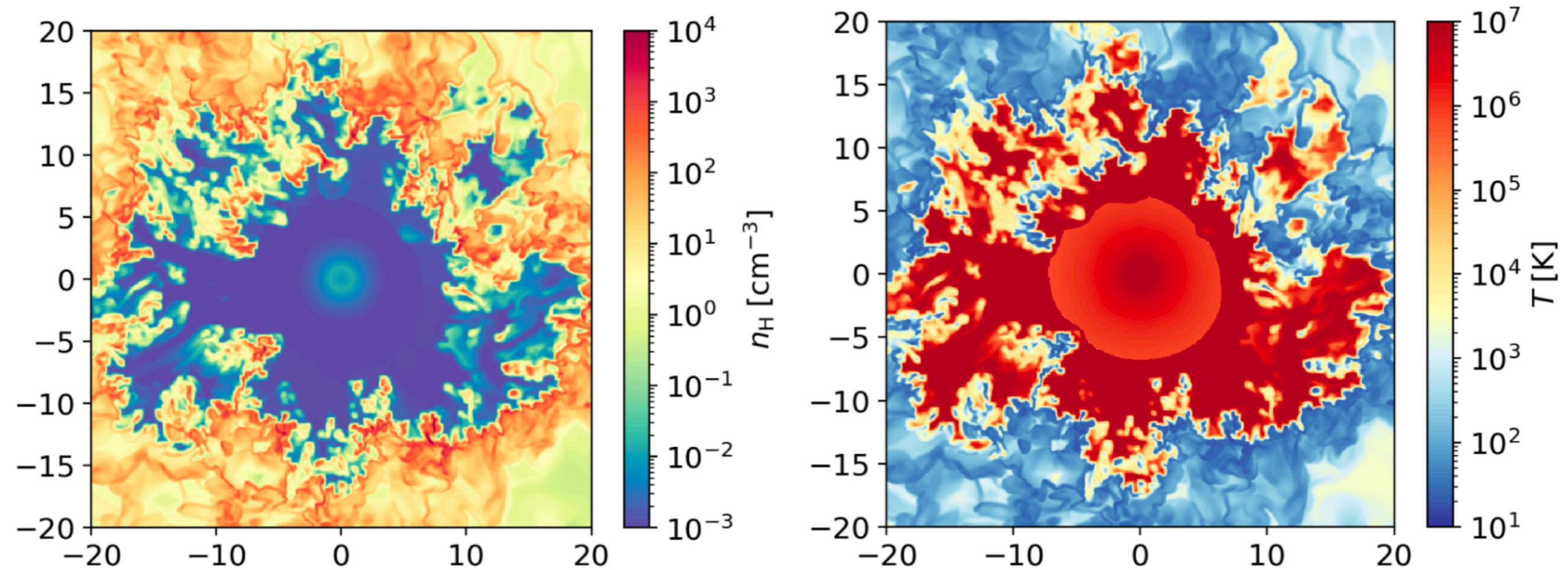
# Stellar winds



# Cooling time



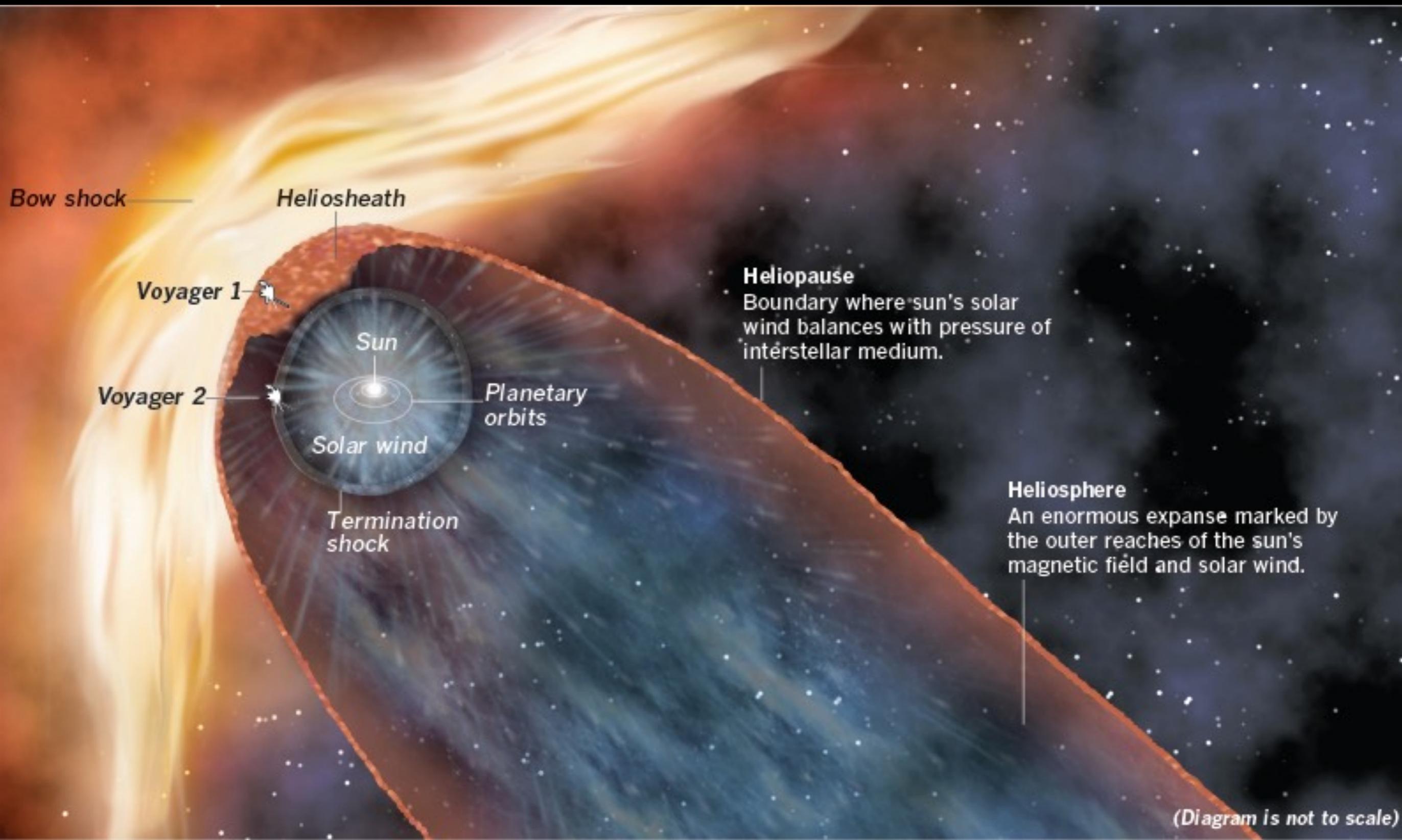
# Stellar wind simulations



# Stellar winds

- If star moves faster than sound speed of ISM, we also get a bow shock
- Wind from star LL Orionis running into surrounding H II region
- Shock is  $\sim 0.1$  pc across





Bow shock

Heliosheath

Voyager 1

Voyager 2

Sun

Solar wind

Termination shock

Planetary orbits

**Heliopause**

Boundary where sun's solar wind balances with pressure of interstellar medium.

**Heliosphere**

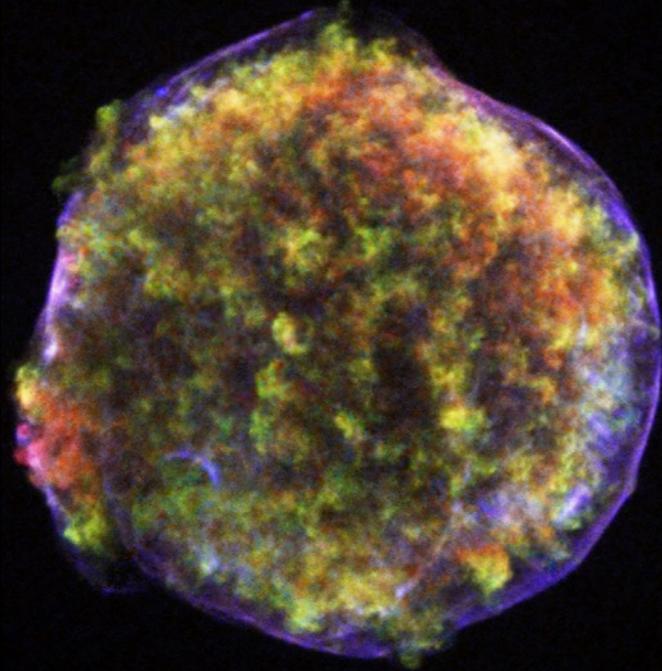
An enormous expanse marked by the outer reaches of the sun's magnetic field and solar wind.

*(Diagram is not to scale)*

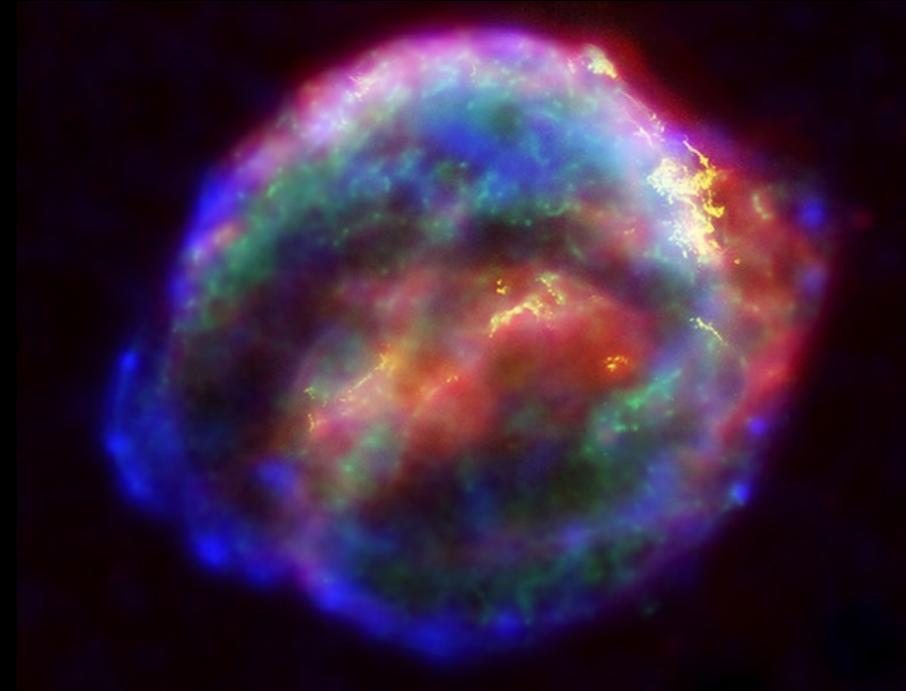
**§2.6 • The supernova rate  
and the pressure of the hot ISM**

# Galactic SN remnants

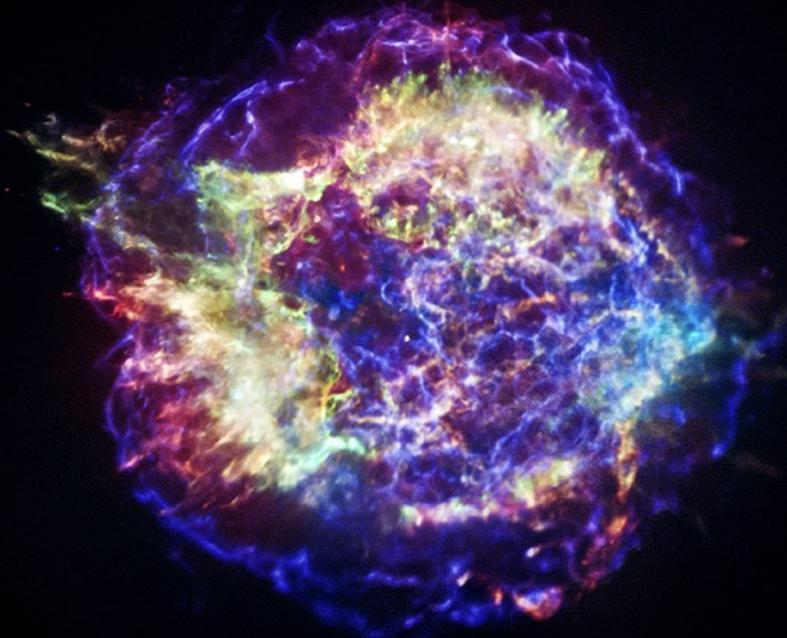
Tycho's SN (1572, B Cas)



Kepler's SN (1604)



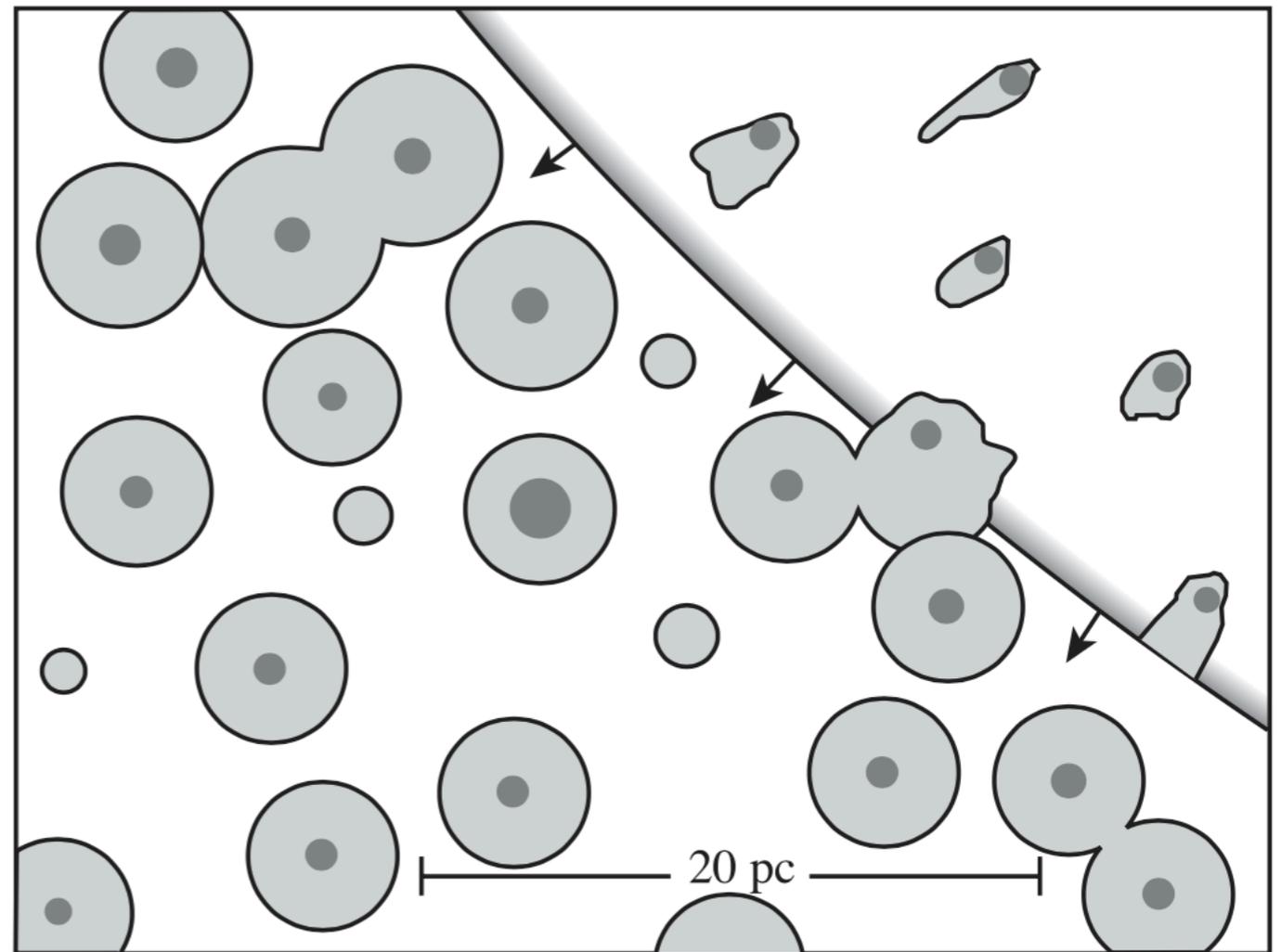
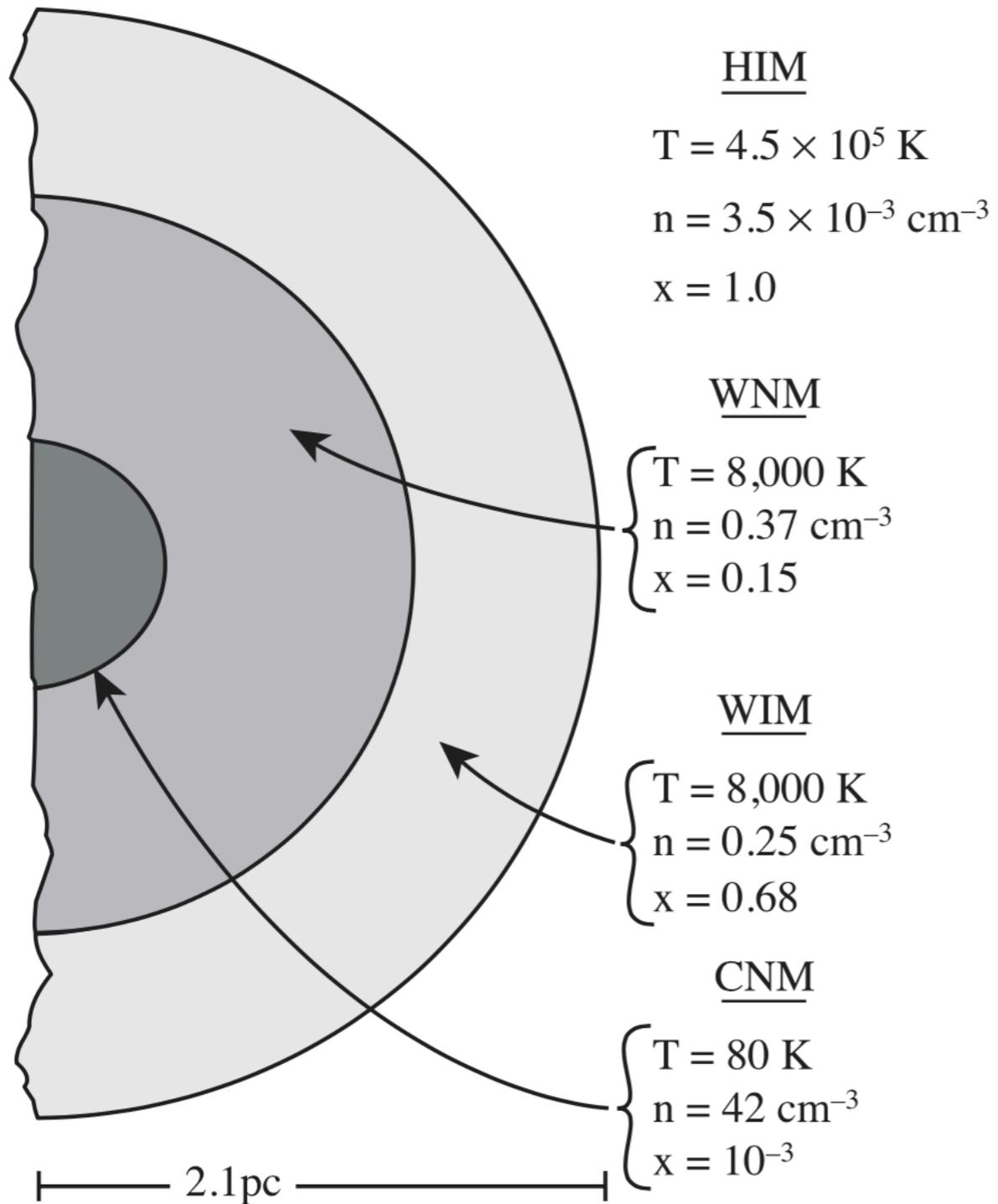
Cas A (1681  $\pm$ 19)



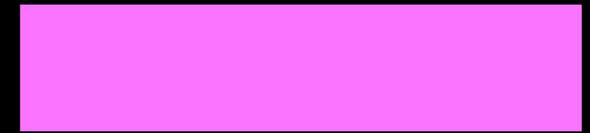
G1.9+0.3 (1880  $\pm$ 30)



# Three-phase model of the ISM



$z=30.0$



**Cold gas**  
 $T < 1000 \text{ K}$



**Warm ionized**  
 $10^4 < T < 10^5 \text{ K}$



**Hot gas**  
 $T > 10^6 \text{ K}$

# Reading

## Draine

- §10.1
- §34.1-2
- §38.1
- §39.1-2