清華大學 Tsinghua University

Calculate Cooling Function of ISM Using cloudy

Xiaohong Tang, Tao Jing, Jixuan Yang, Anning Gao

Contents

Introduction to cloudy and example

Speaker: Xiaohong Tang

Cloudy - Introduction

Designed to simulate physical conditions within clouds

Ranging from the intergalactic medium to the high-density LTE limits

Predicts the thermal, ionization, and chemical structure of a cloud according to given conditions, and predicts its observed spectrum

Cloudy - Calculation

Divide a given cloud into a set of thin concentric shells (zones)

Solve radiative transfer, iteratively adjust to find a self-consistent solution

- Ionization / recombination balance
- Heating / cooling balance

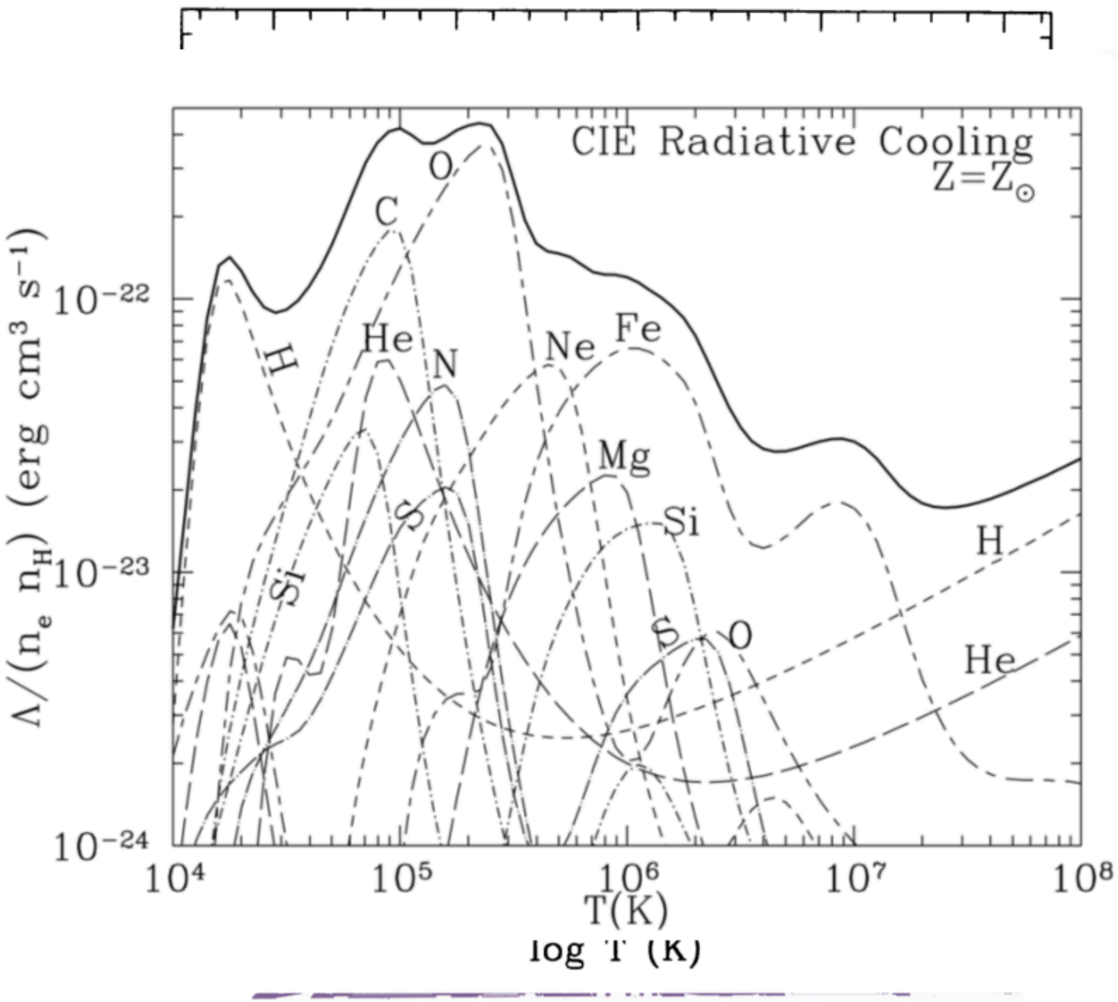
Report the results

Cloudy - Calculation of the cooling

Key cooling processes

- Collisional excitation
- Coliisional ionization
- Recombination
- Bremsstrahlung
- Molecules

Intensity of emission lines recorded



Calculate the cooling function – An example

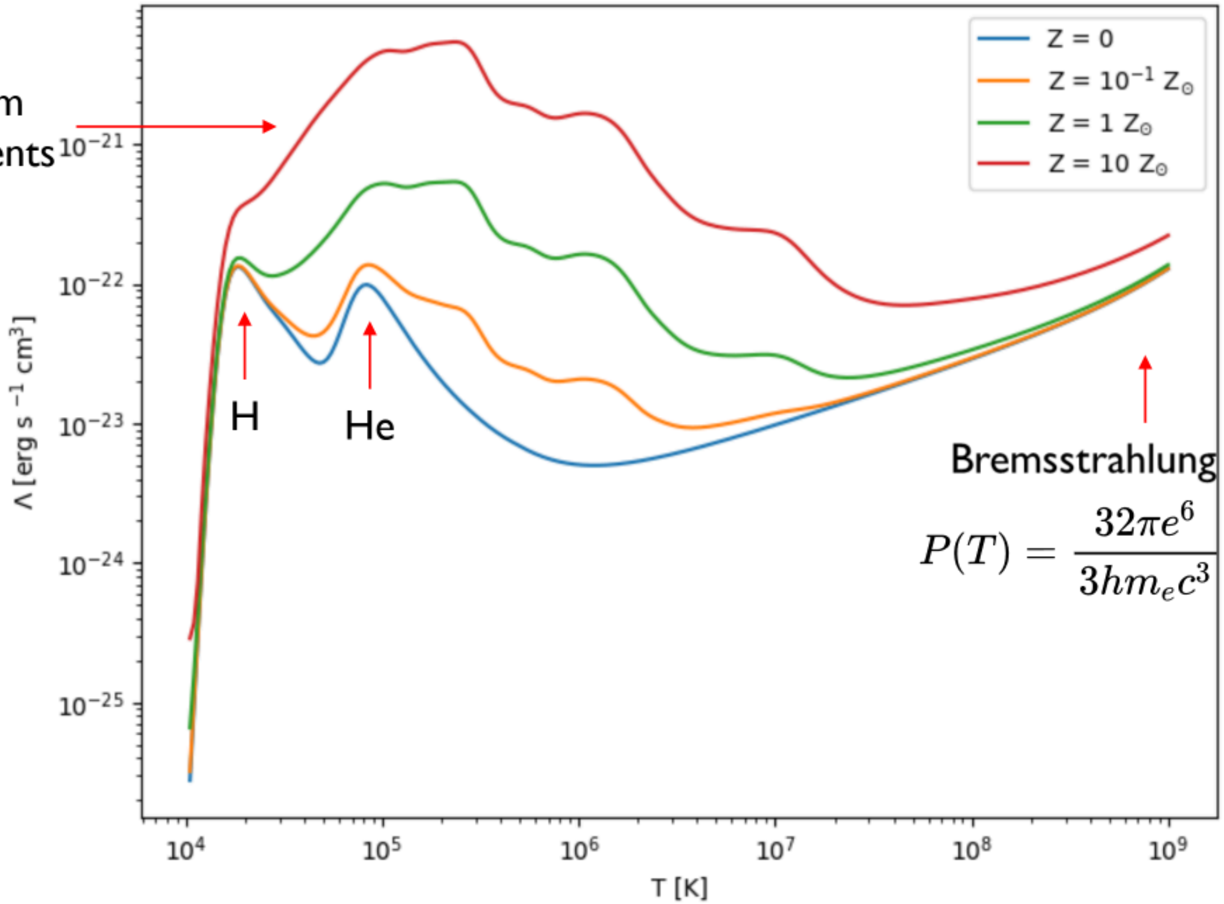
```
iterate to convergence
stop zone 1
set dr 0
hden 0
metals 0
constant temperature 4.0 vary
grid 4.0 to 9.0 step 0.02
save cooling last "cooling.out"
```

- Calculate only one zone (time-saving)
- Set geometry (shape & size)
- Set hydrogen density
- Set metallicity ($\log(Z/Z_\odot)$)
- Set temperature as a varying parameter
- Perform a simulation for every temperature
- Save the cooling rate ($\mathrm{erg\,s^{-1}\,cm^{-3}}$)

No external radiation field: collisional ionization equilibrium

Calculate the cooling function – An example

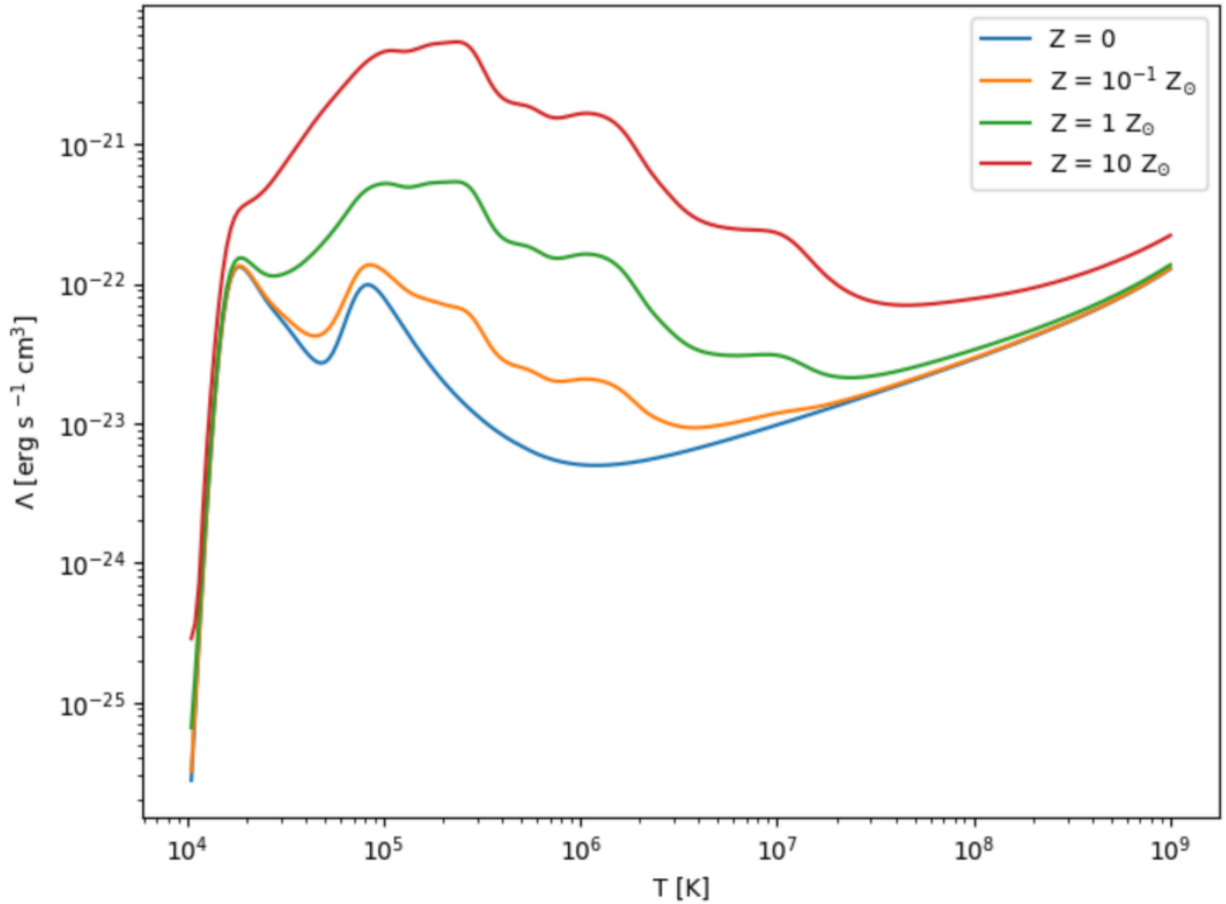
Cooling from metal elements

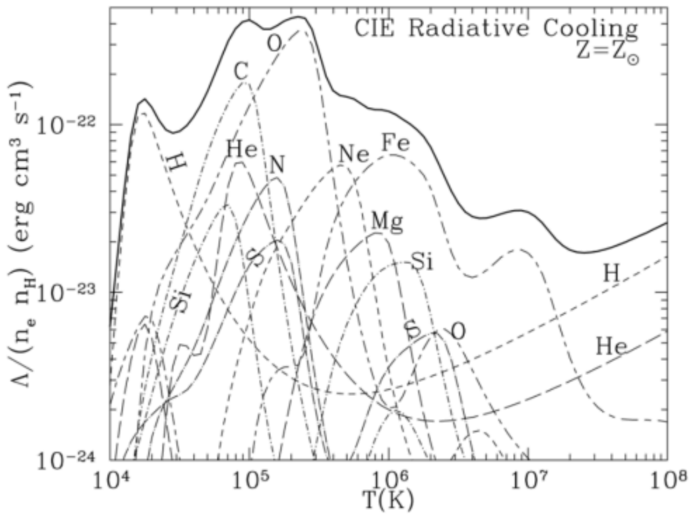


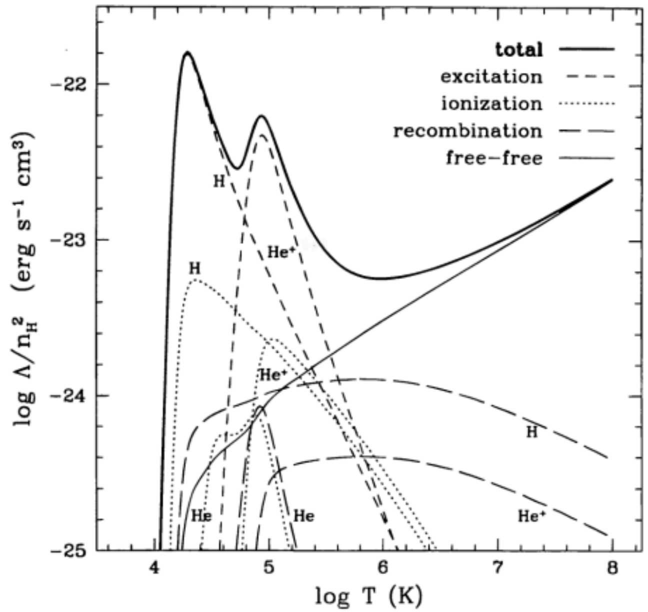
Bremsstrahlung ($\Lambda \propto T^{0.5}$)

$$P(T) = \frac{32\pi e^6}{3hm_e c^3}\left(\frac{2\pi k}{3m_e}\right)^{1/2} T^{1/2} Z^2 \langle g_{ff}\rangle n_e n_i$$

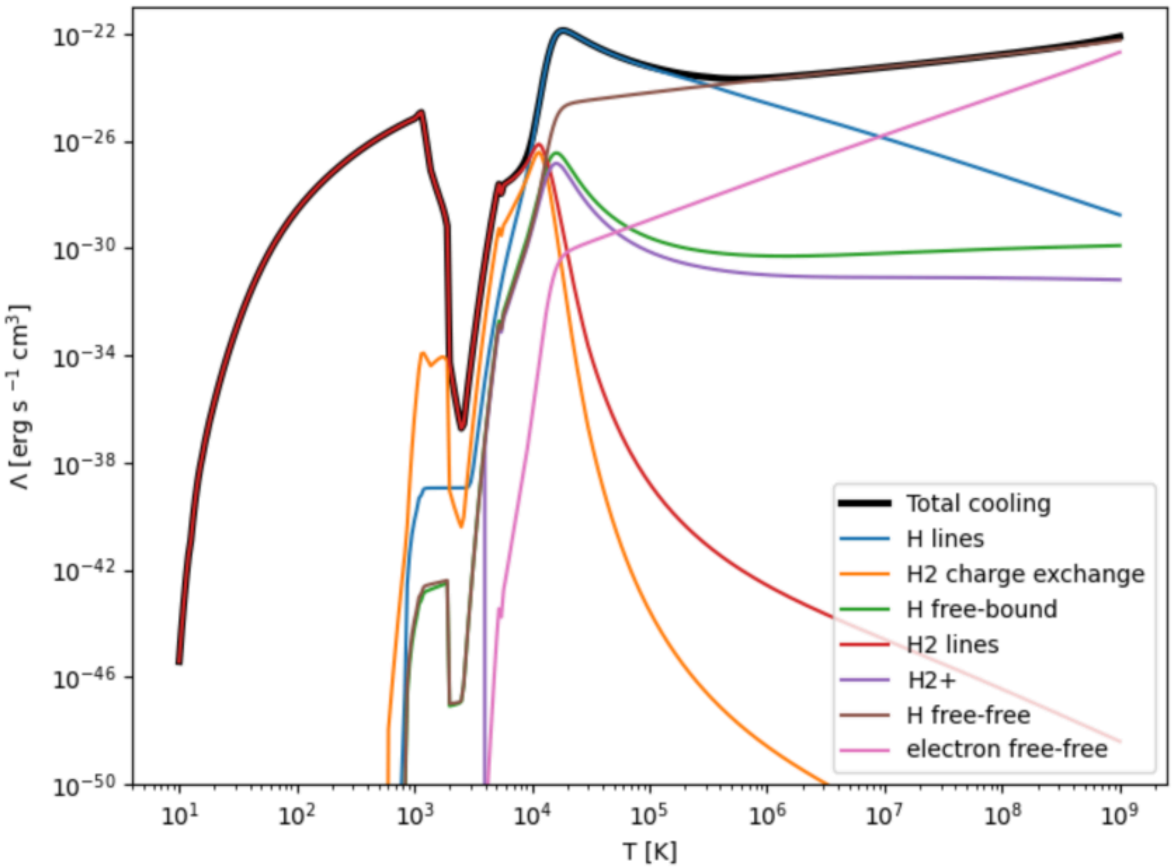
Calculate the cooling function – An example







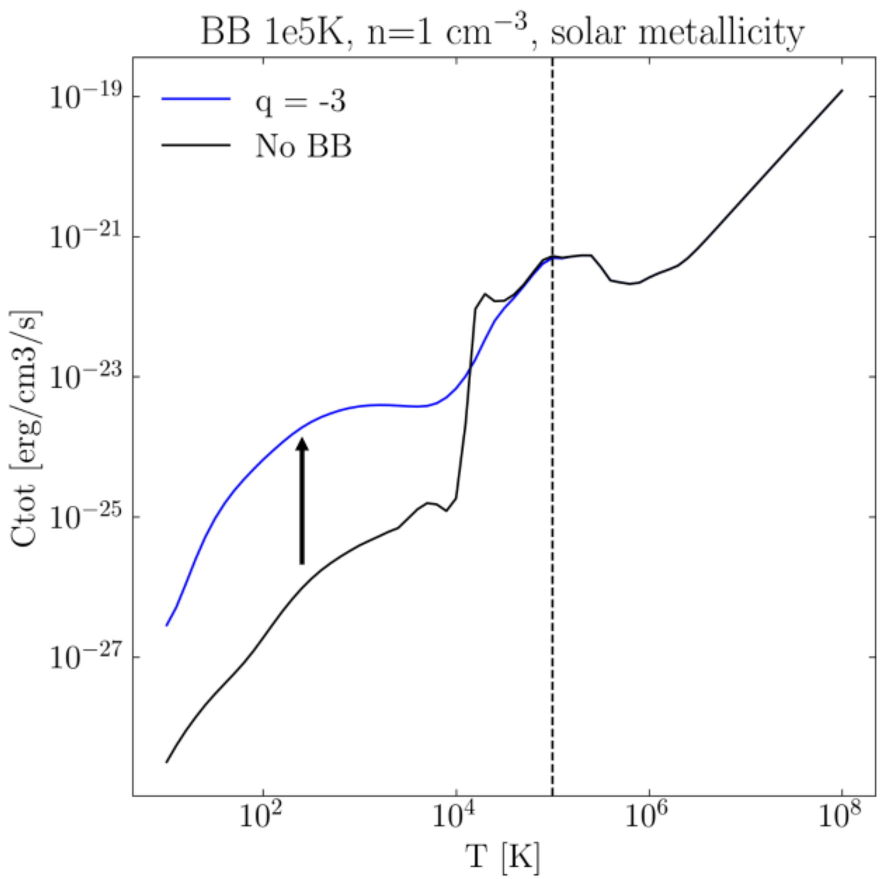
Pure hydrogen - distribution of cooling components



Effect of Radiation Feild

Speaker: Tao Jing

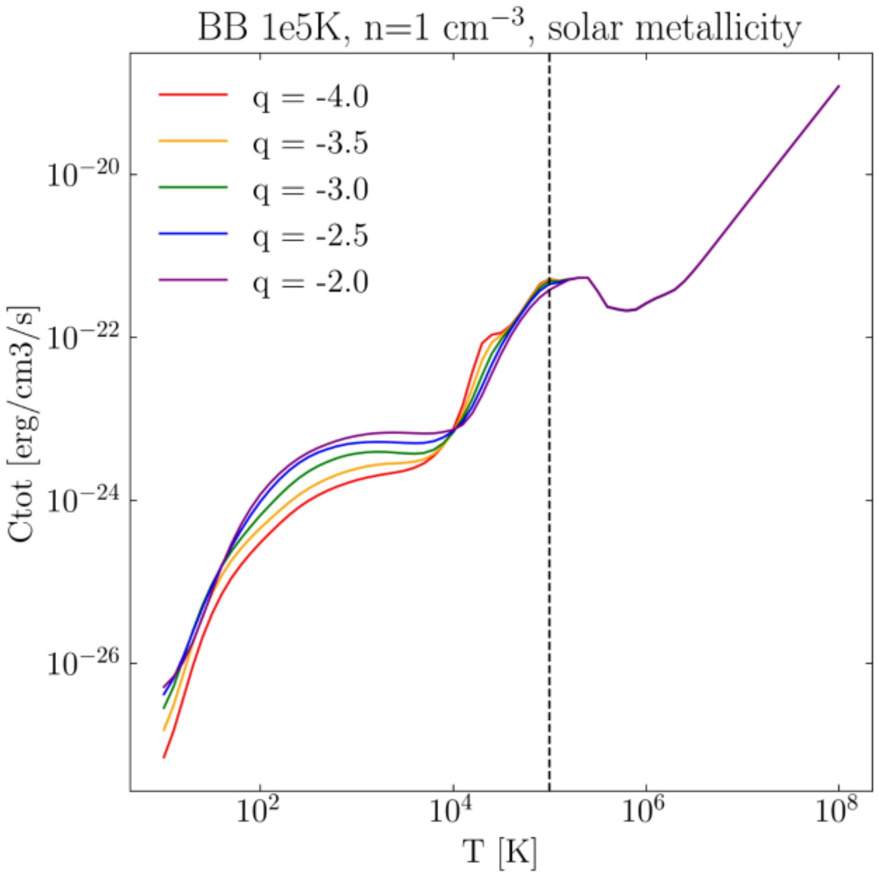
Effect of Radiation Feild: H II Region Like, 1e5K Blackbody



$$q \equiv \log U$$

Low temperature end (< 1e5 K) is significantly enhanced.

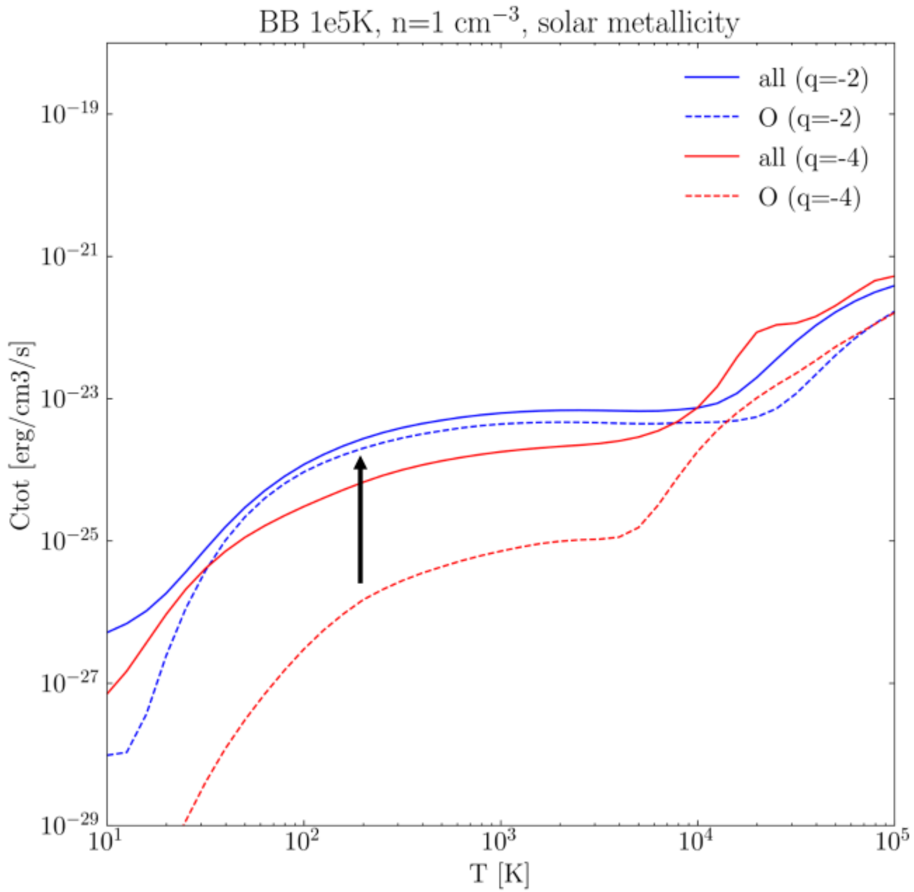
1e5K Blackbody, Effect of Ionization Parameter



$$q \equiv \log U$$

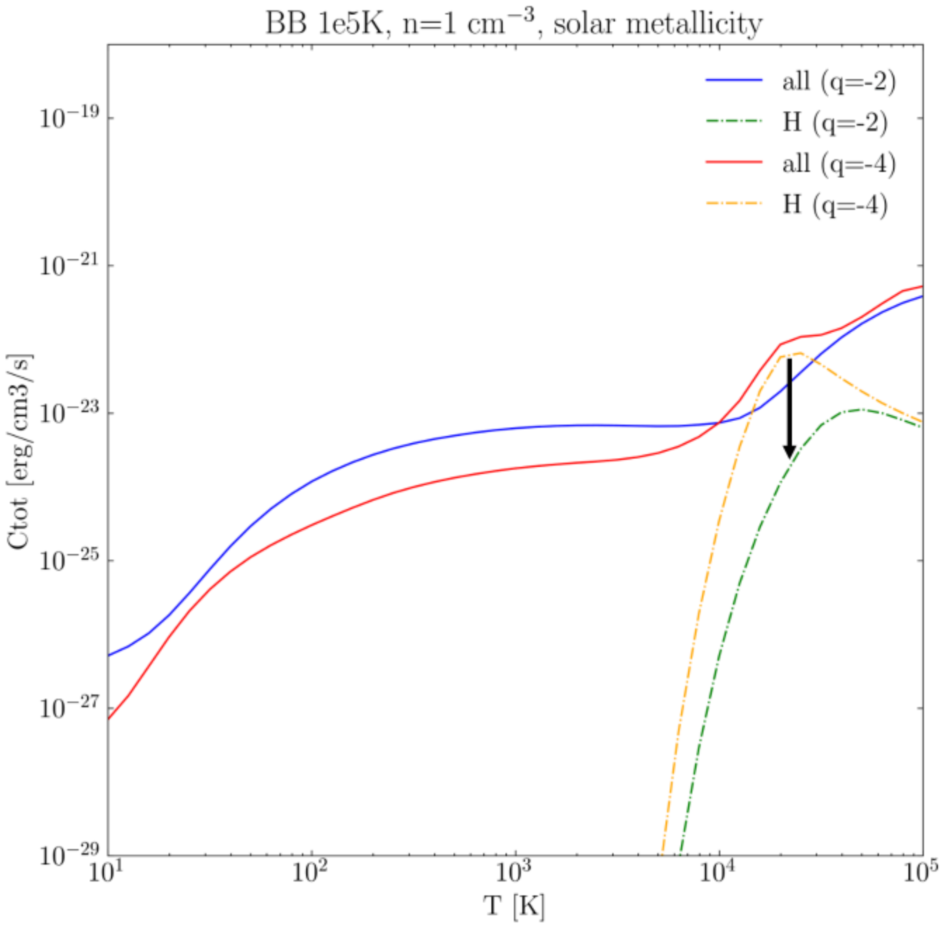
Only low temperature end (< 1e5 K) is affected by ionization parameter.

1e5K Blackbody, Effect of Ionization Parameter



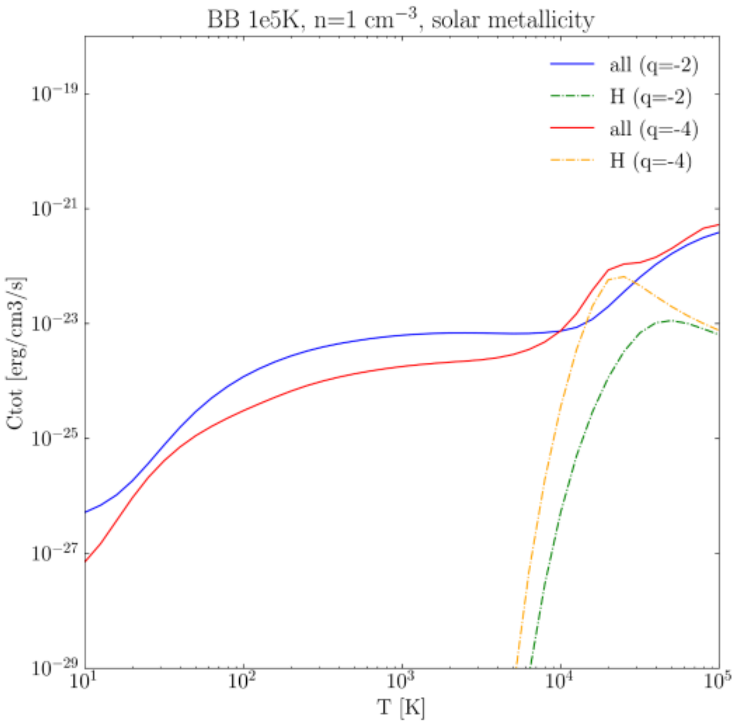
Cooling by Oxygen is significanly enhanced due to radiation feild.

1e5K Blackbody, Effect of Ionization Parameter



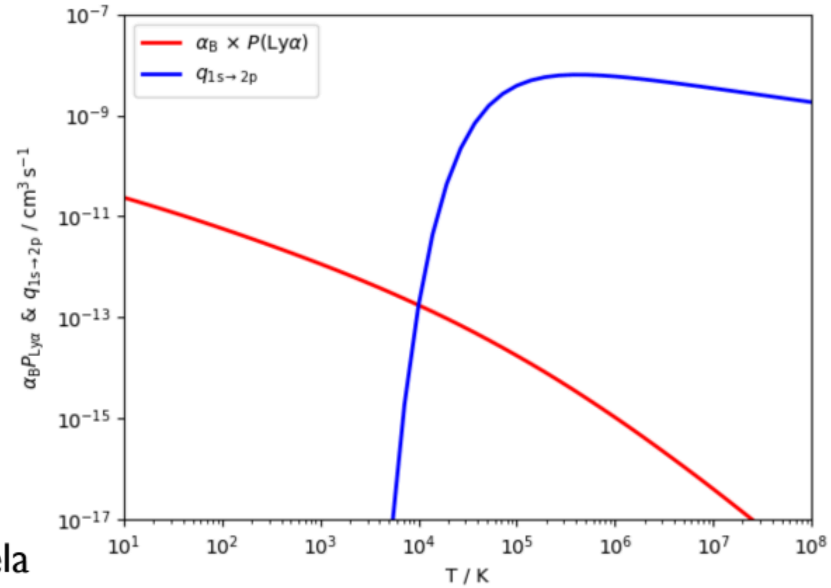
But cooling by Hydrogen is significanly suppressed around 2e4K

1e5K Blackbody, Effect of Ionization Parameter



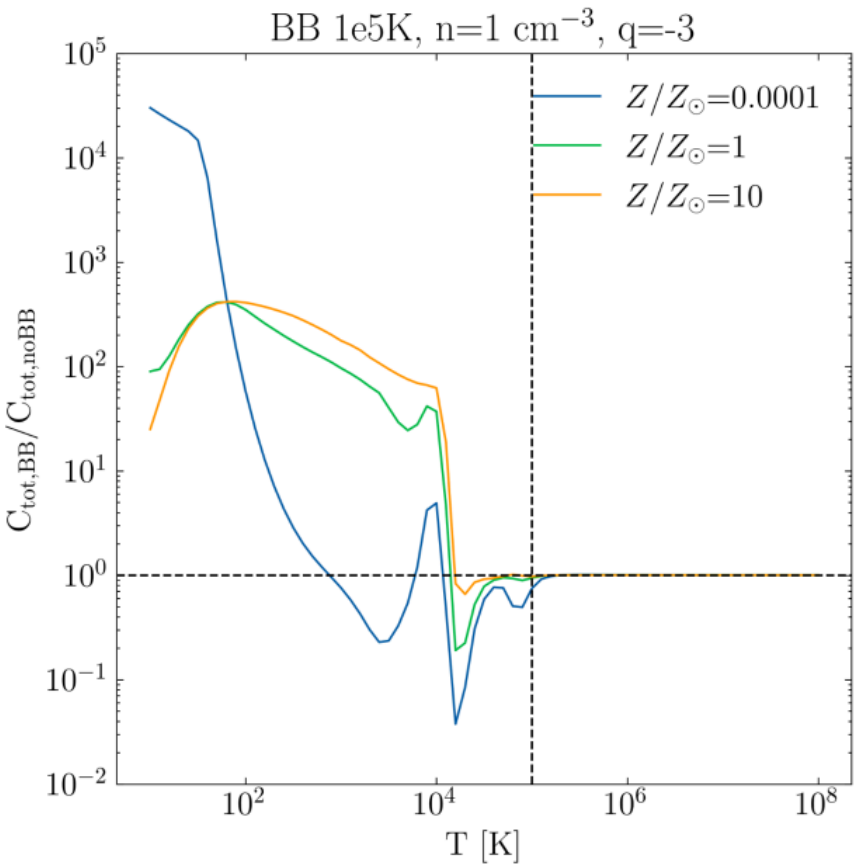
But cooling by Hydrogen is significanly suppressed around 2e4K

$$\begin{aligned}\varepsilon_{\mathrm{Ly}\alpha} &= \varepsilon_{\mathrm{rec}} + \varepsilon_{\mathrm{coll}} \\ &= P(\mathrm{Ly}\alpha) h\nu_0\, n_{\mathrm{e}} n_{\mathrm{HII}}\, \alpha_{\mathrm{B}}(T) + h\nu_0\, n_{\mathrm{e}} n_{\mathrm{HI}}\, q_{1\mathrm{s}\to 2\mathrm{p}}(T),\end{aligned}$$



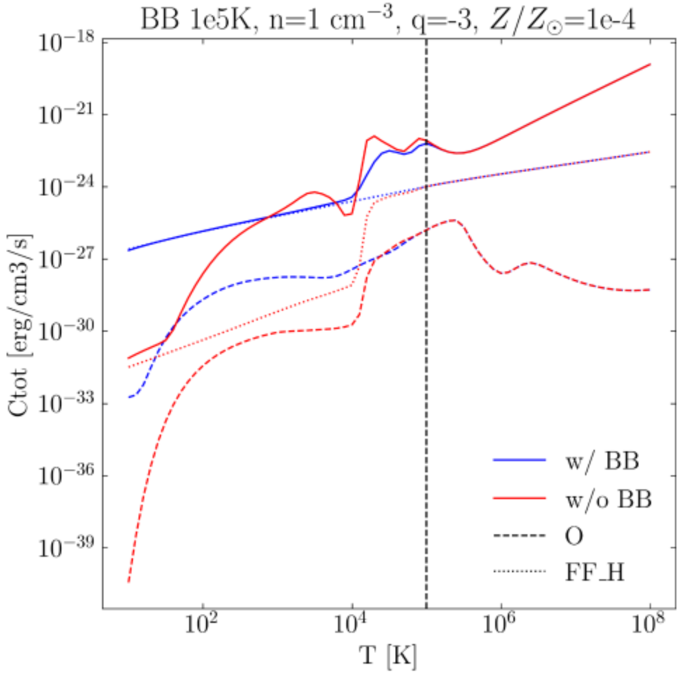
credits: pela

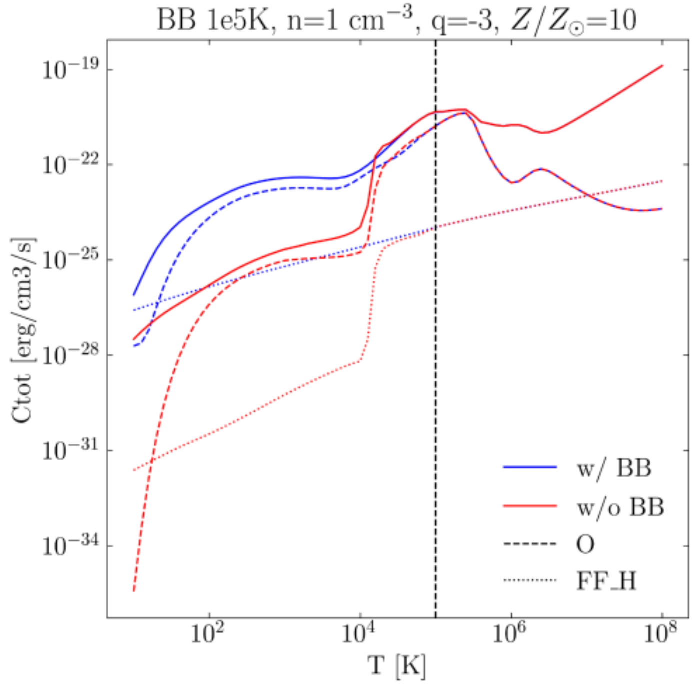
1e5K Blackbody, Effect of Metallicity



Effect of Radiation is different for ISM with different metallicities

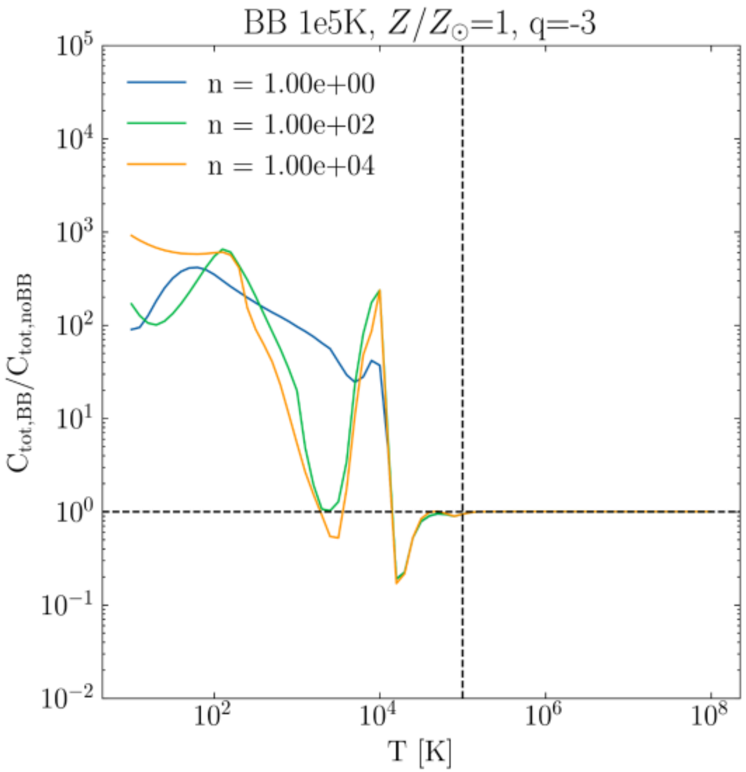
1e5K Blackbody, Effect of Metallicity

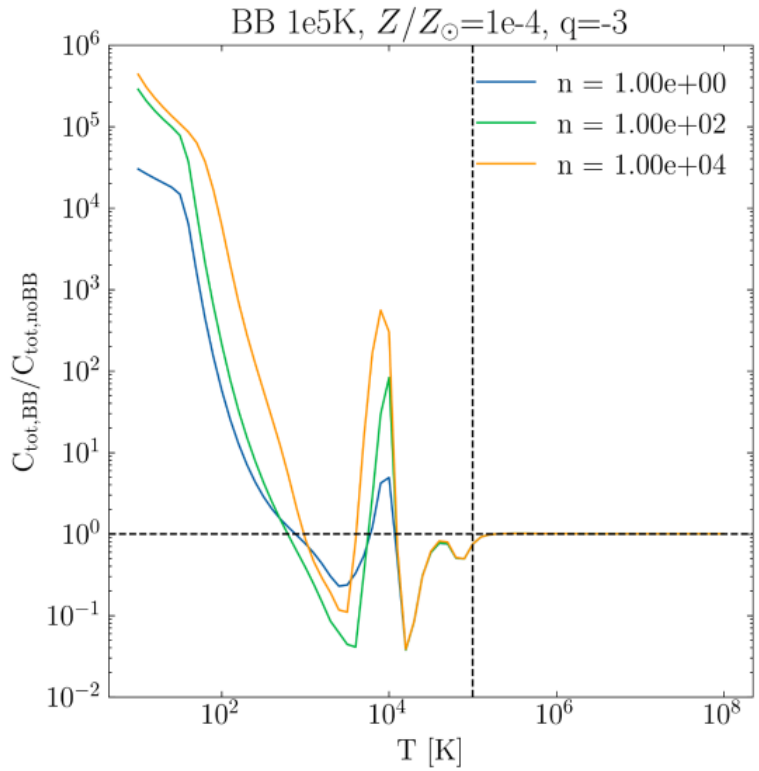




- Low Z: enhance free-free emission
- High Z: enhance Oxygen emission

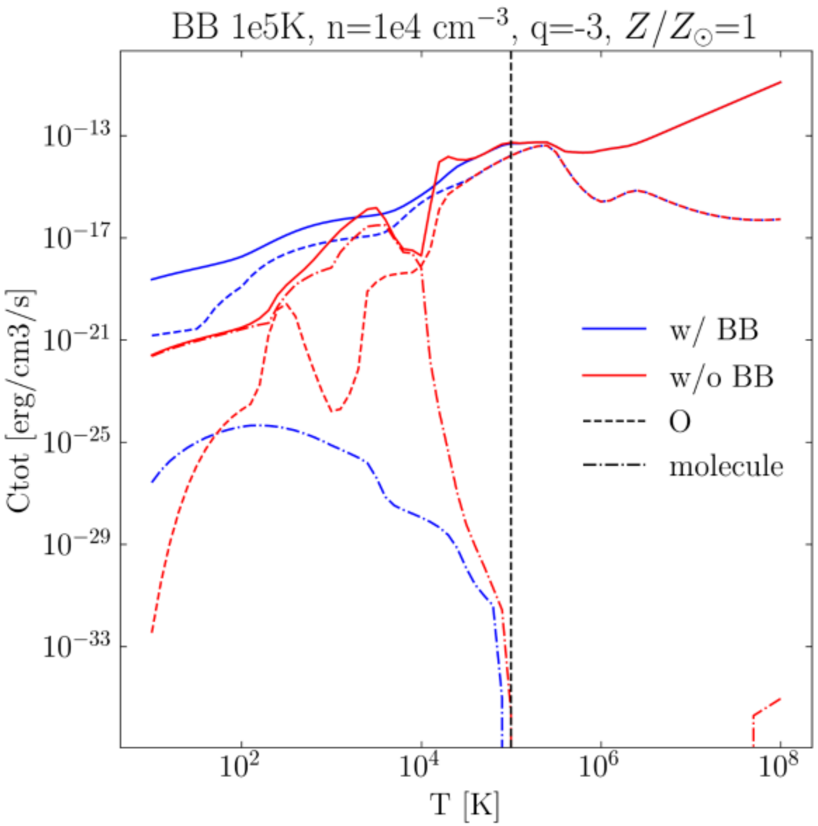
1e5K Blackbody, Effect of Density

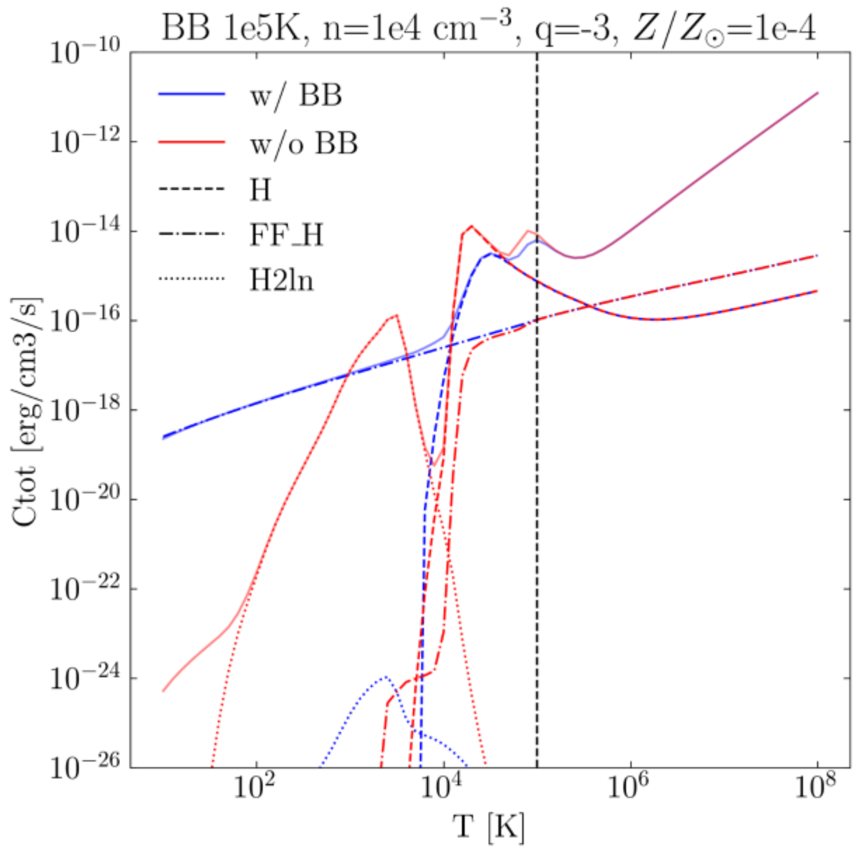




1e5K Blackbody, Effect of Density

H2ln - line cooling within simple H2 molecule (rotation)





Cooling at Low Temperature

Speaker: Jixuan Yang

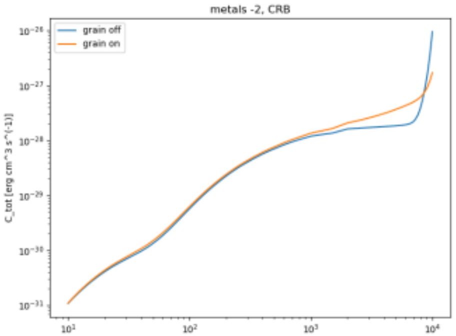
Effect of dust on the total cooling rate

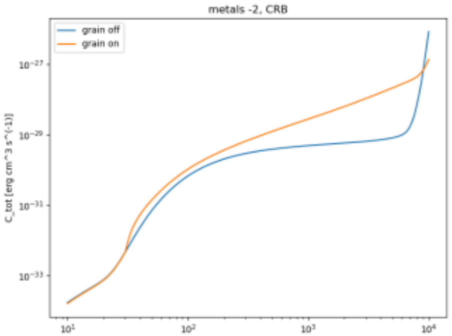
- Use command "grains ISM"
  - Grain sizes range: $5 \times 10^{-3} \sim 0.15\ \mu\mathrm{m}$
  - Distribution: $p(a)da \propto a^{-3.5}da$
  - Abundances per H (for solar metallicity): $10^{-9.811}$ for graphite, $10^{-9.748}$ for silicates
- Use command "no H2 molecules"
  - To better compare the cooling contribution between gas and grains.

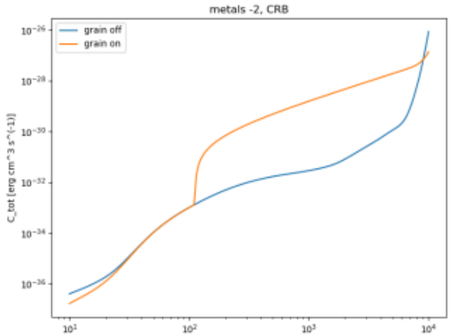
- Parameters in simulation:
  - $Z = 10^{-2} Z_{\odot},\ n_H = 10^3, 10^6, 10^9\ \mathrm{cm}^{-3}$
  - $n_H = 10^3\ \mathrm{cm}^{-3},\ Z = 10^{-2}, 10^{-4}, 10^{-6}\ Z_{\odot}$

Effect of dust on the total cooling rate

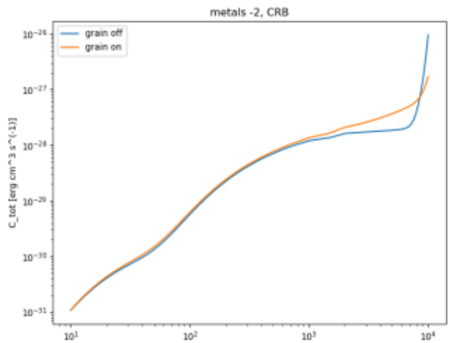
- $Z = 10^{-2} Z_{\odot},\ n_H = 10^3, 10^6, 10^9\ \mathrm{cm}^{-3}$

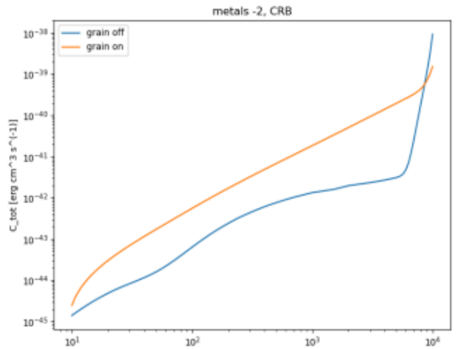


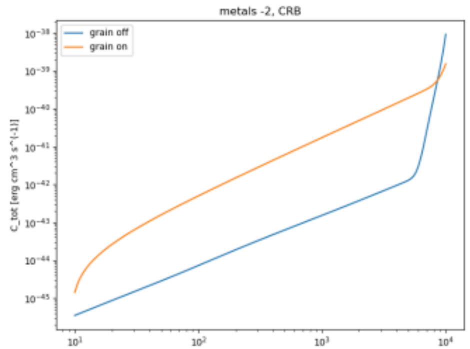




- $n_H = 10^3\ \mathrm{cm}^{-3},\ Z = 10^{-2}, 10^{-4}, 10^{-6}\ Z_{\odot}$

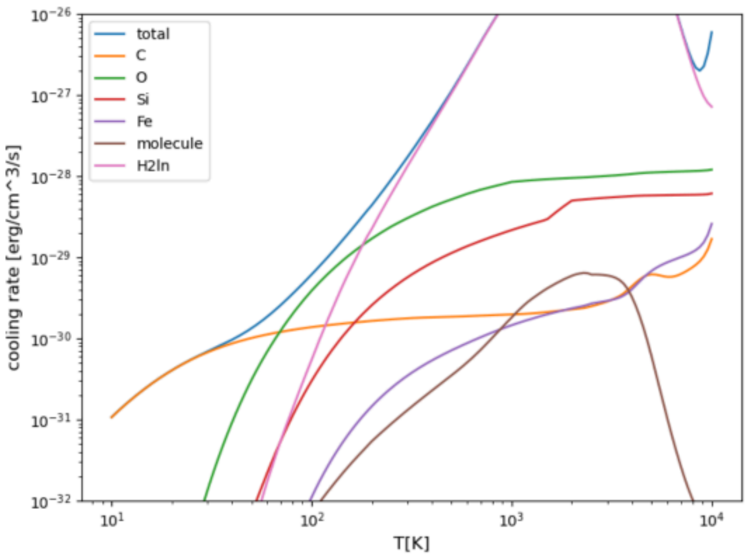


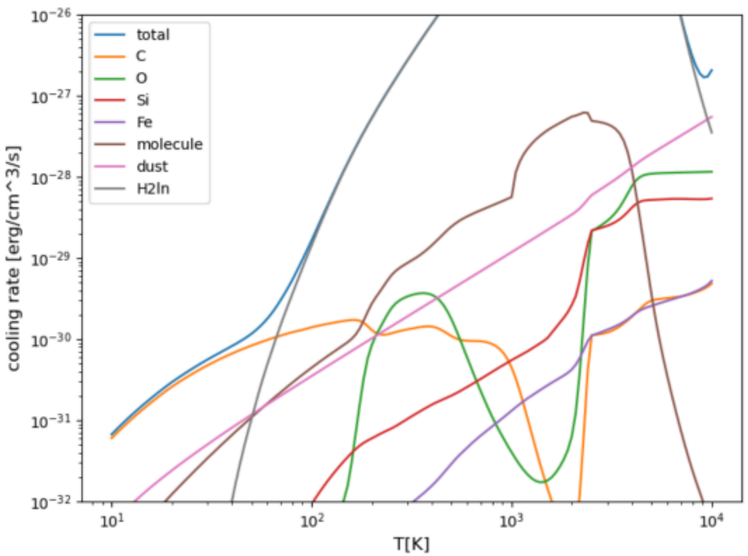




Components in low temperature

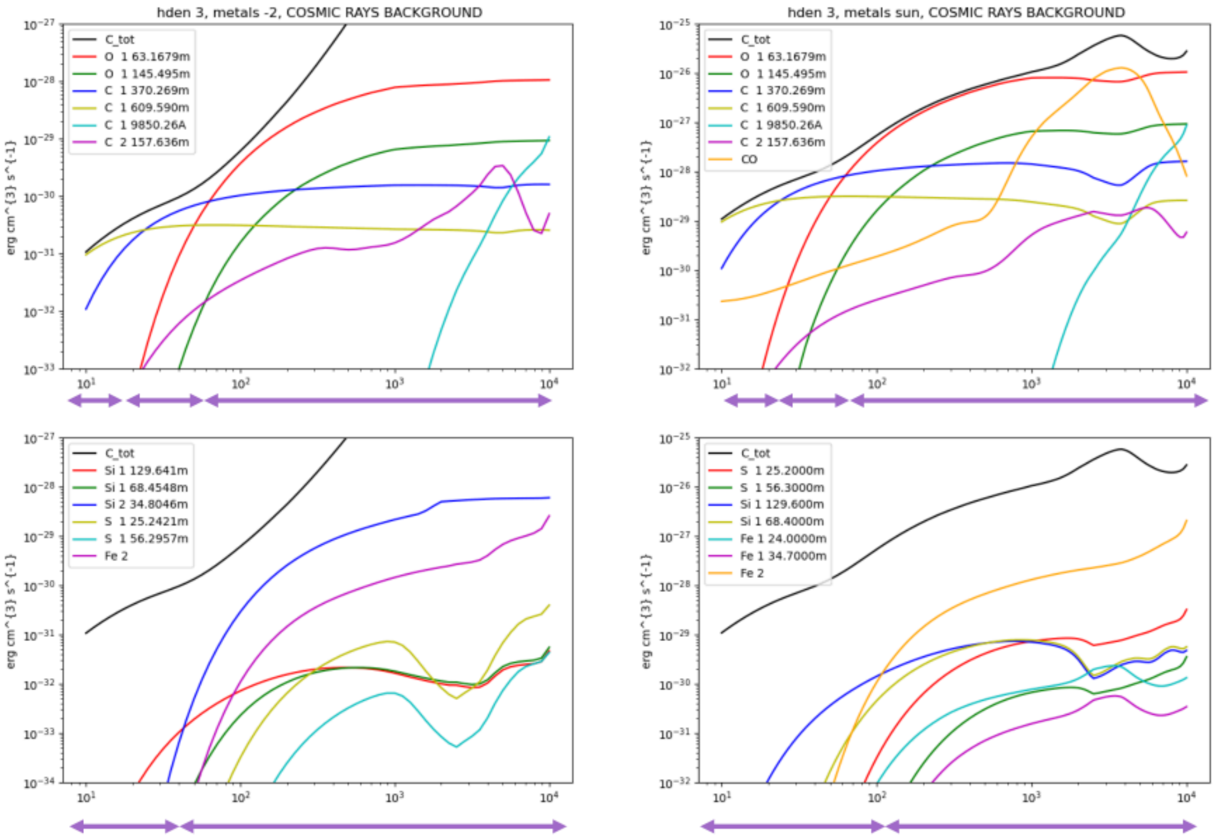
- Our default condition:
  - cosmic rays background; $n_H = 10^3\ \mathrm{cm}^{-3}$; $Z = 10^{-2}\ Z_\odot$
  - upper: without dust; bottom: with dust——have more molecules via grain catalysis
- Cooling rate by H2 molecule:
  - >85.4 K: rotational transitions.
  - $> 6.10 \times 10^3$ K : vibrational transitions.
  - T>5000K: limited by molecular hydrogen dissociation.



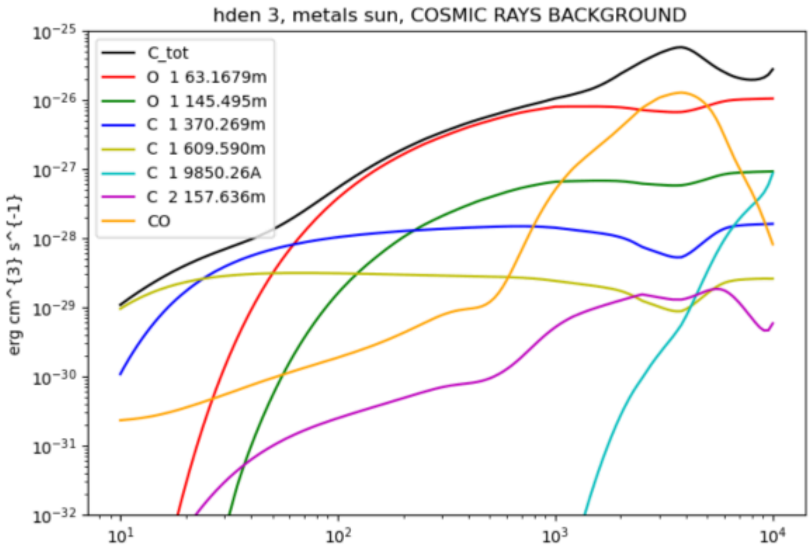


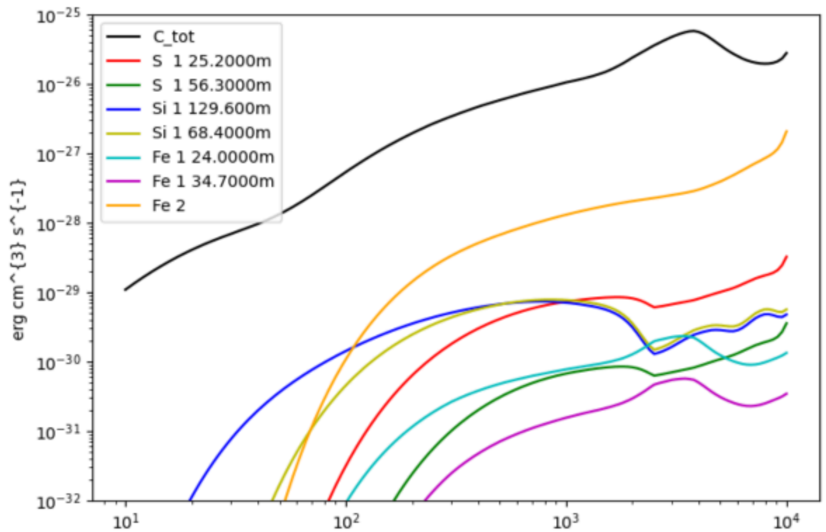
Main emissivity in low temperature (without dust)

- Simulation condition:
  - $n_H = 10^3\ \mathrm{cm}^{-3}$
  - $Z = 10^{-2}, 10^{0}\ Z_\odot$
  - have molecules, cosmic rays background
- Dominate component:
  - low metallicity:
    - C I 609.6 um -- C I 370.3 um -- O I 63.2 um
    - Si I 129.6 um -- Si II 34.8 um
  - high metallicty:
    - C I 609.6 um -- C I 370.3 um -- O I 63.2 um+ **CO**
    - Si I 129.6 um -- Fe II



Main emissivity in low temperature (without dust)

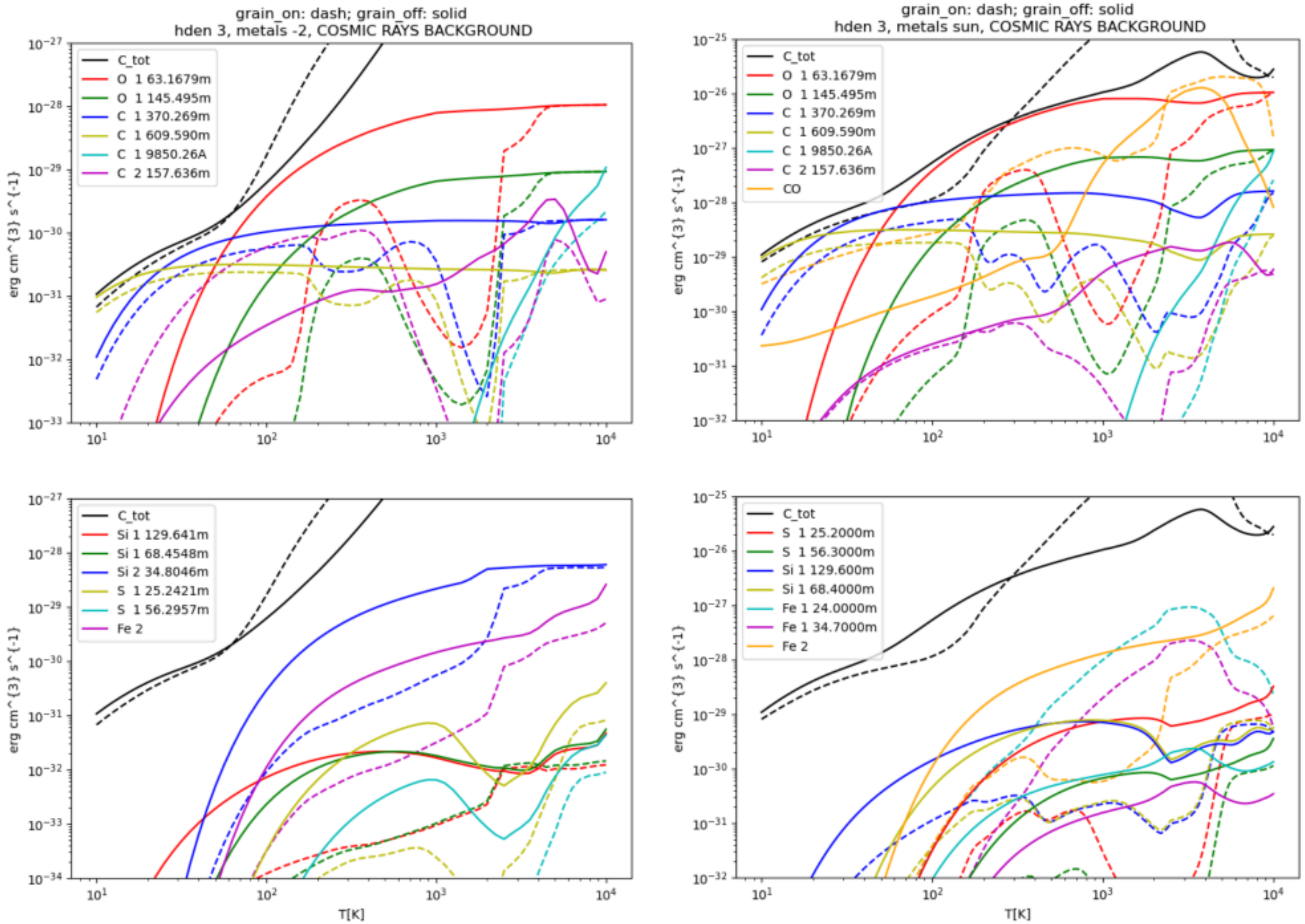




- C I : ${}^3P_0 - {}^3P_1 \rightarrow {}^3P_1 - {}^3P_2 \rightarrow {}^3P_2 - {}^1D_2$
- O I: ${}^3P_0 - {}^3P_1 < {}^3P_1 - {}^3P_2$
- Si I: ${}^3P_0 - {}^3P_1 \rightarrow {}^3P_1 - {}^3P_2$
- Fe I: ${}^5D_2 - {}^5D_3 < {}^5D_3 - {}^5D_4$

Main emissivity in low temperature (with dust)

- The code does not now solve for ^{12}C and ^{13}C abundances and ionic fractions. The $^{12}C/^{13}C$ ratio depends on both location in the galaxy and age. It is ≈ 90 in the solar system (Asplund et al., 2009) .



Cooling at High Temperature

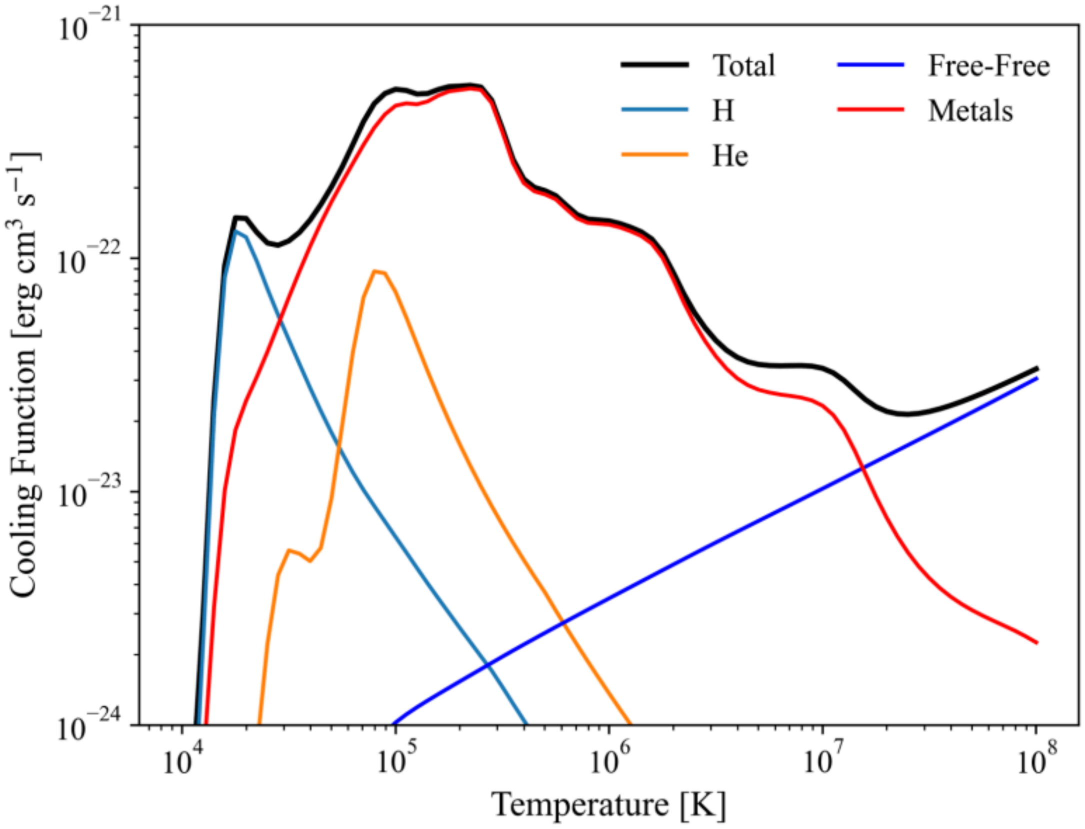
Speaker: Anning Gao

Cooling at High Temperature

Our default condition:

- Solar metallicity
- Low density ($n_{\mathrm{H}} = 1\,\mathrm{cm}^{-3}$)
- No dust, no molecules
- No radiation field

Collisional Ionization Equilibrium (CIE)

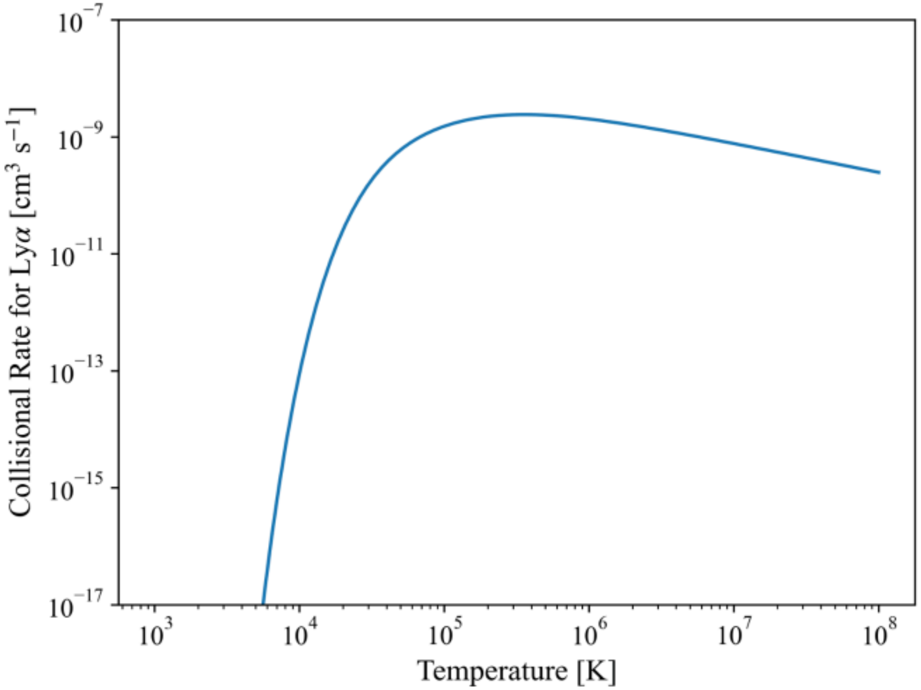


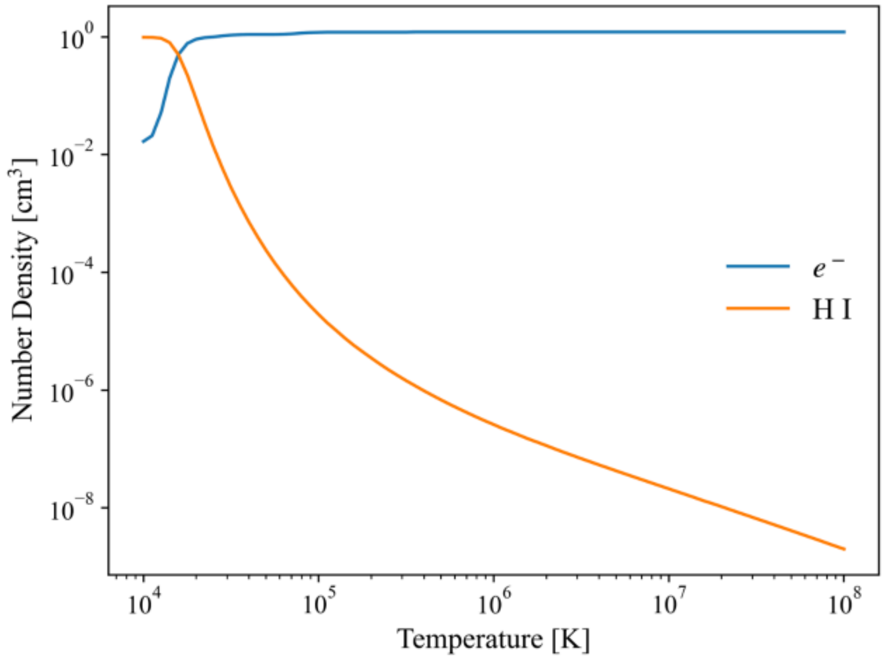
Cooling at High Temperature

H Cooling:

- Dominated by collisional excitation

$$\varepsilon_{ul} = h\nu_{ul} k_{lu} n_e n_{\mathrm{HI}}$$



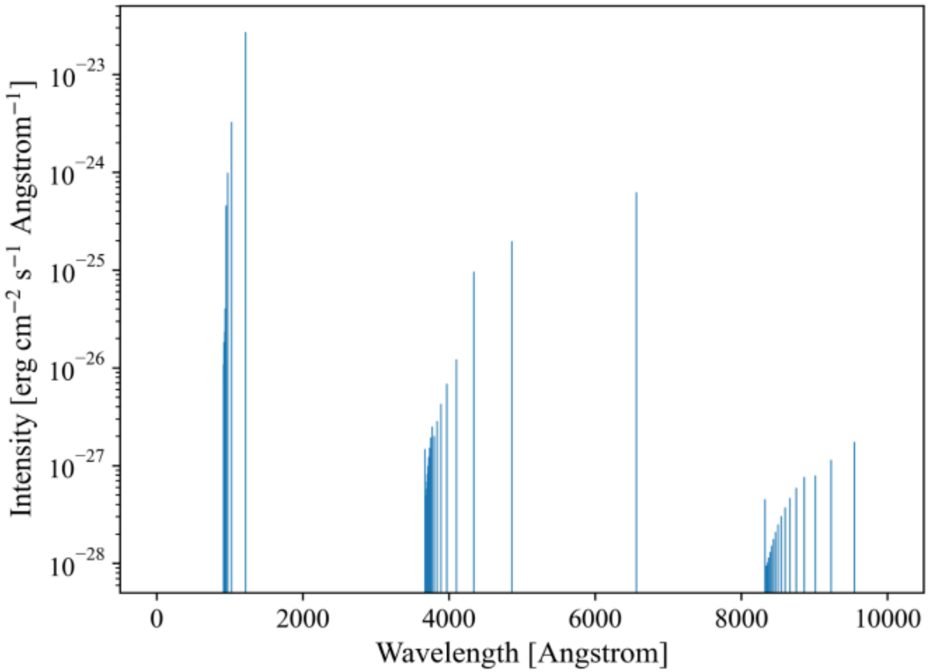


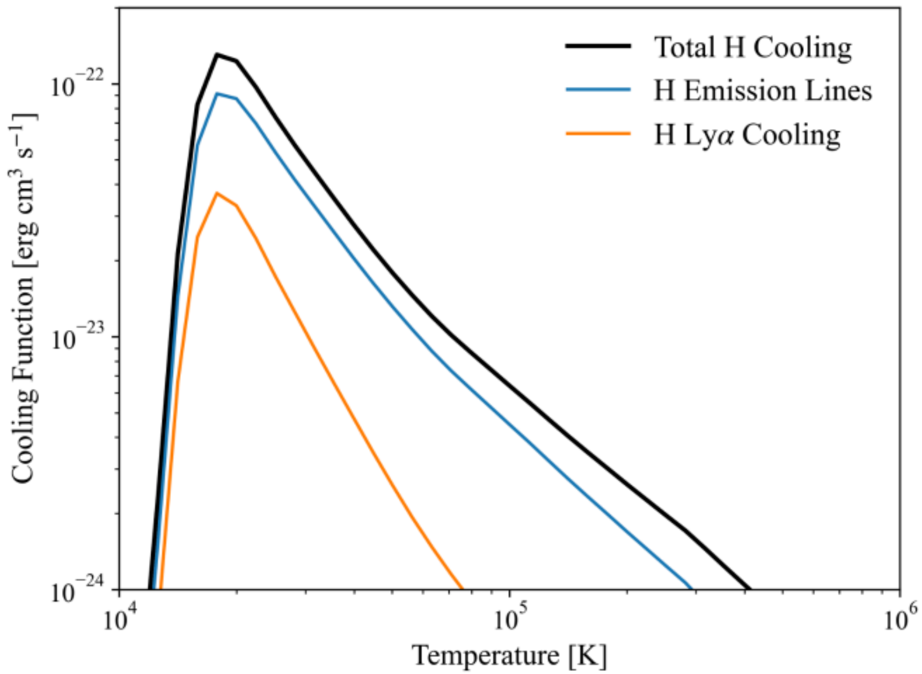
Cooling at High Temperature

H Cooling:

- Dominated by collisional excitation

$$\varepsilon_{ul} = h\nu_{ul} k_{lu} n_e n_{\mathrm{HI}}$$



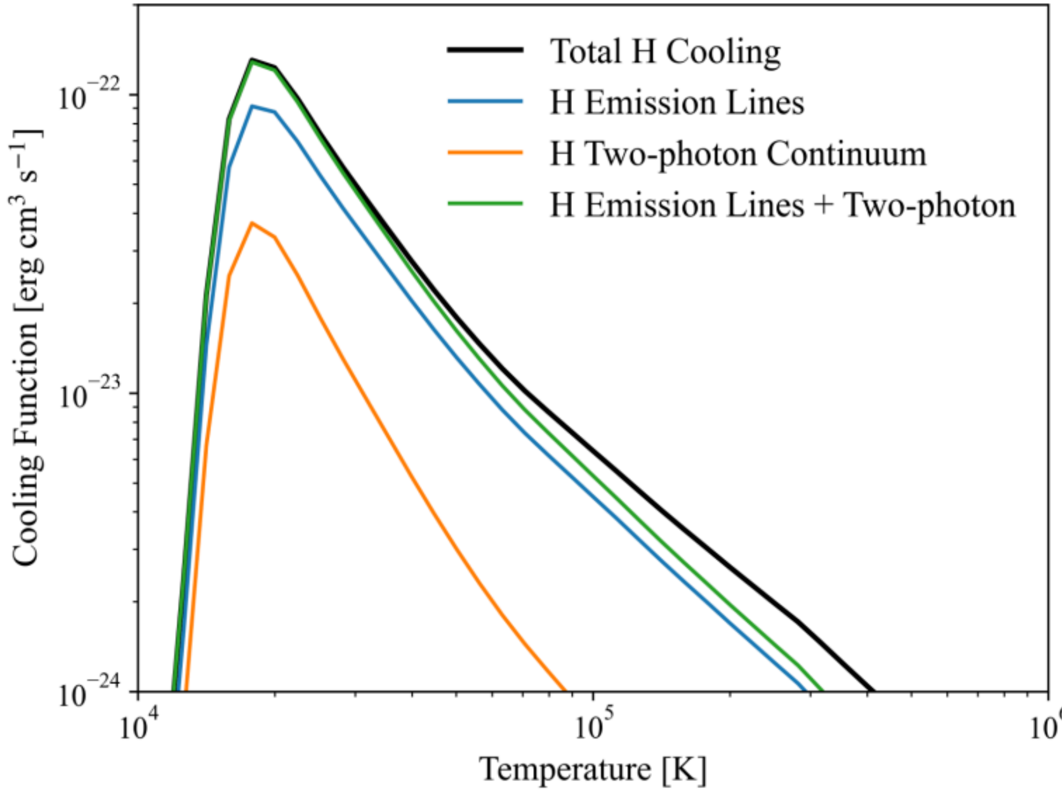


Cooling at High Temperature

H Cooling:

- Two photon decay:

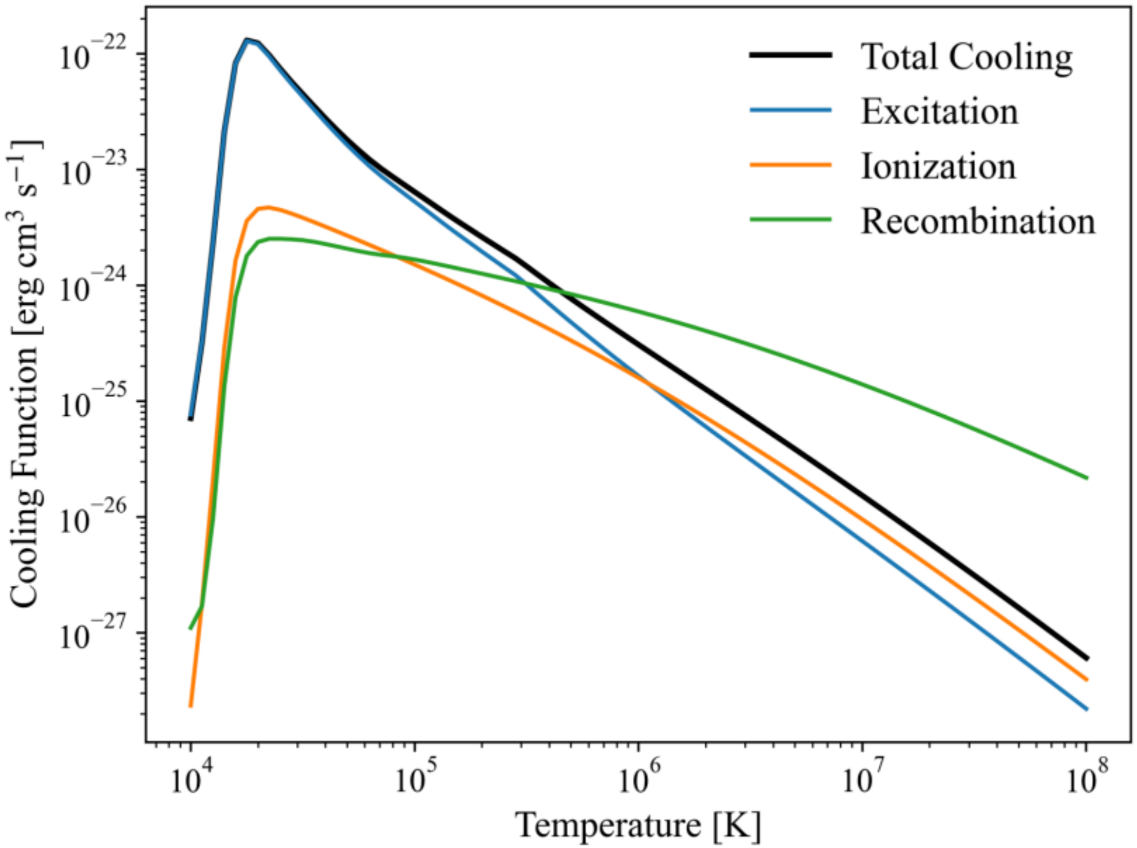
$$\mathrm{H_{2s}} \rightarrow \mathrm{H_{1s}} + 2\gamma$$



Cooling at High Temperature

H Cooling:

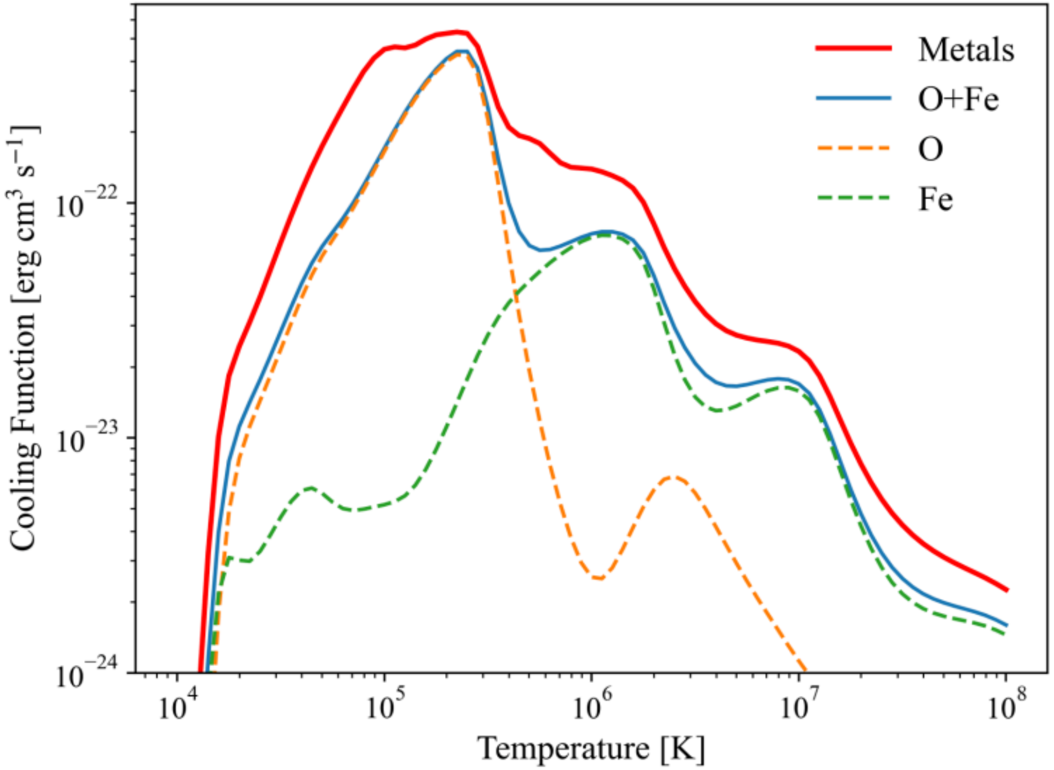
- Collisional Ionization
- Recombination



Cooling at High Temperature

Metal Cooling:

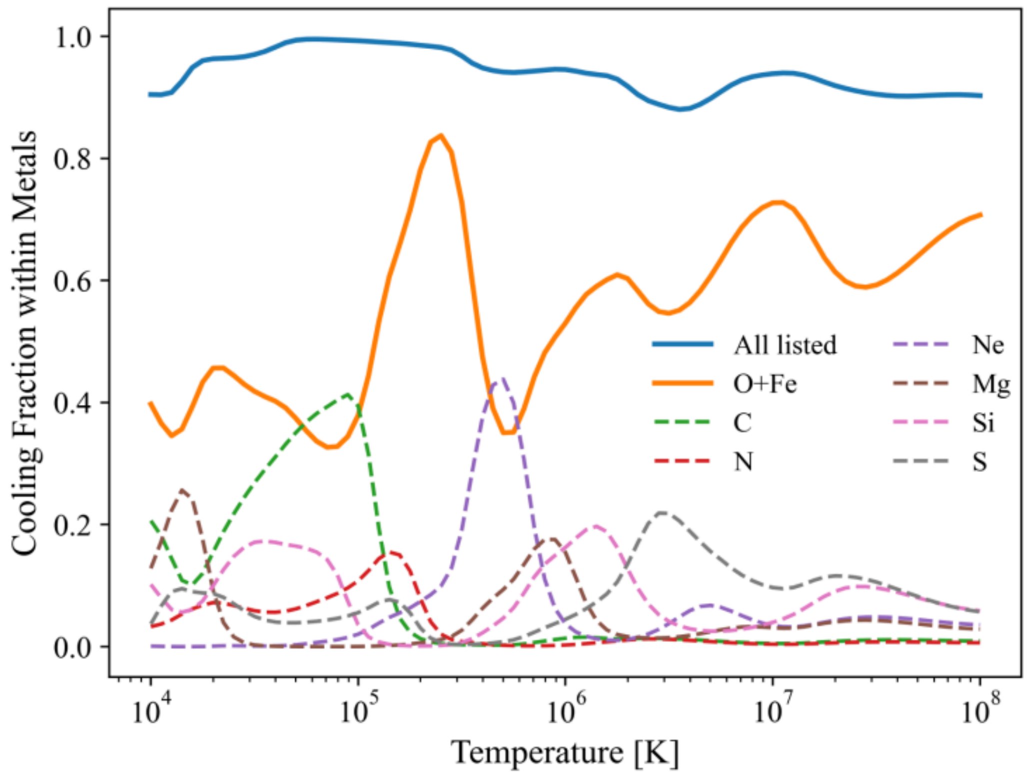
- O and Fe contribute the most!



Cooling at High Temperature

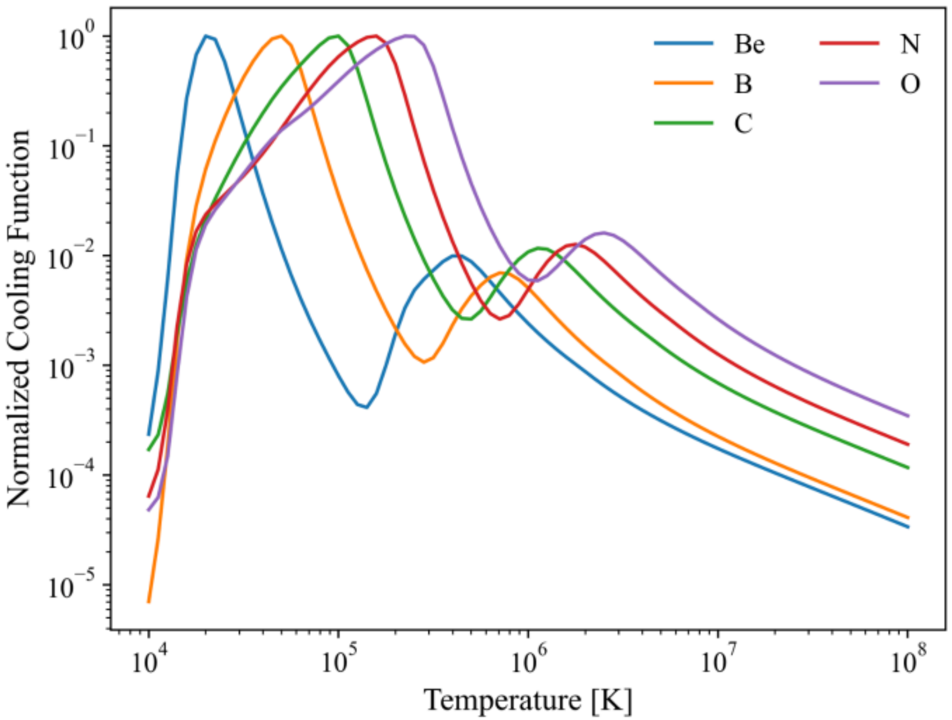
Metal Cooling:

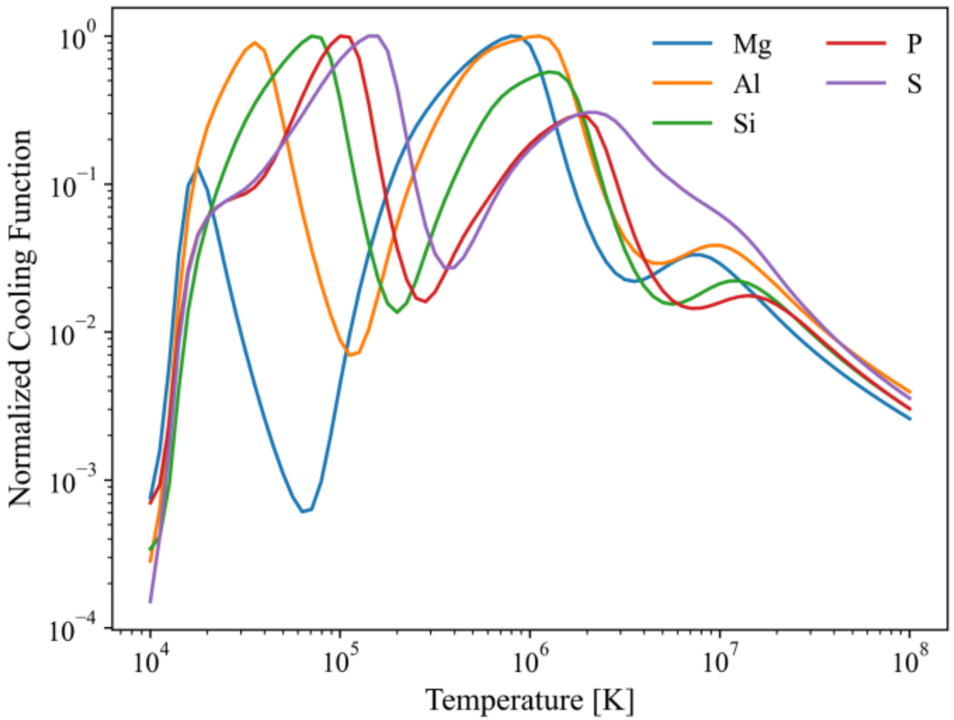
- O and Fe contribute the most!
- $T \sim 10^6\,\mathrm{K}$: Ne, Mg, Si
- $T \sim 10^4\,\mathrm{K}$: C, Si, Mg



Cooling at High Temperature

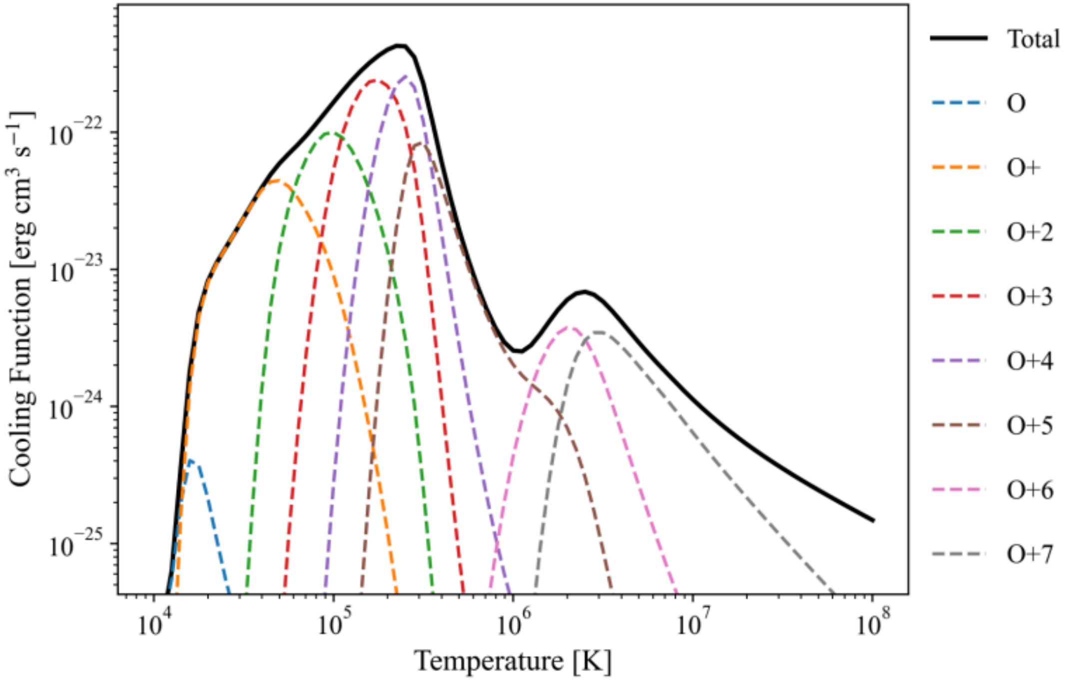
Cooling of Single Species:

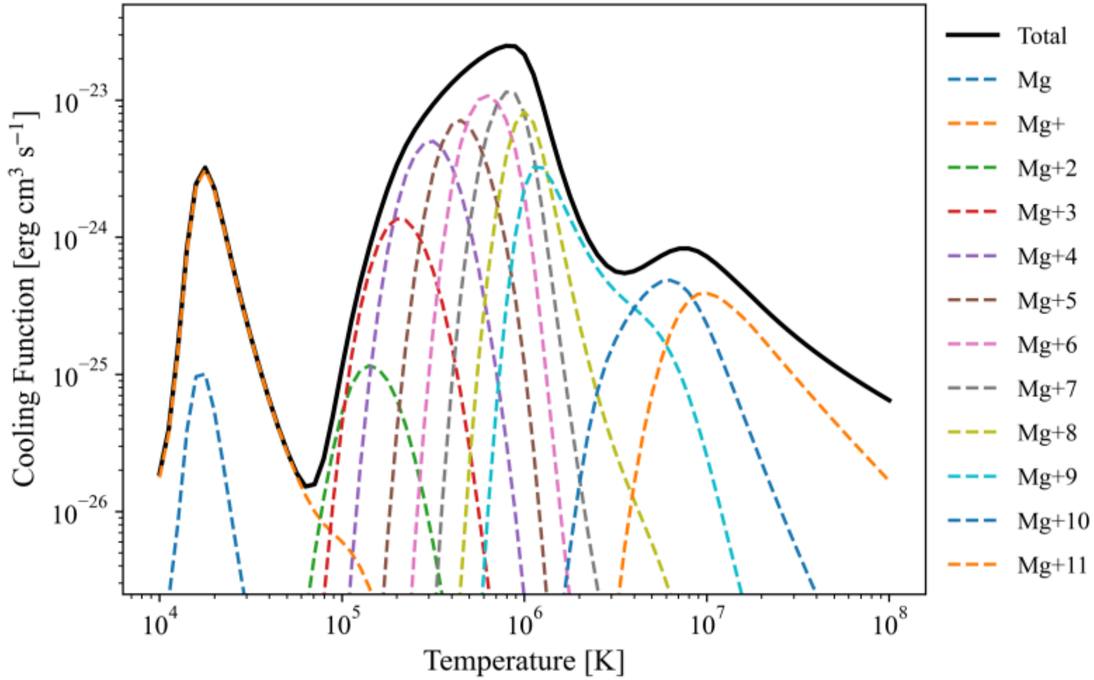




Cooling at High Temperature

Cooling of Single Species:

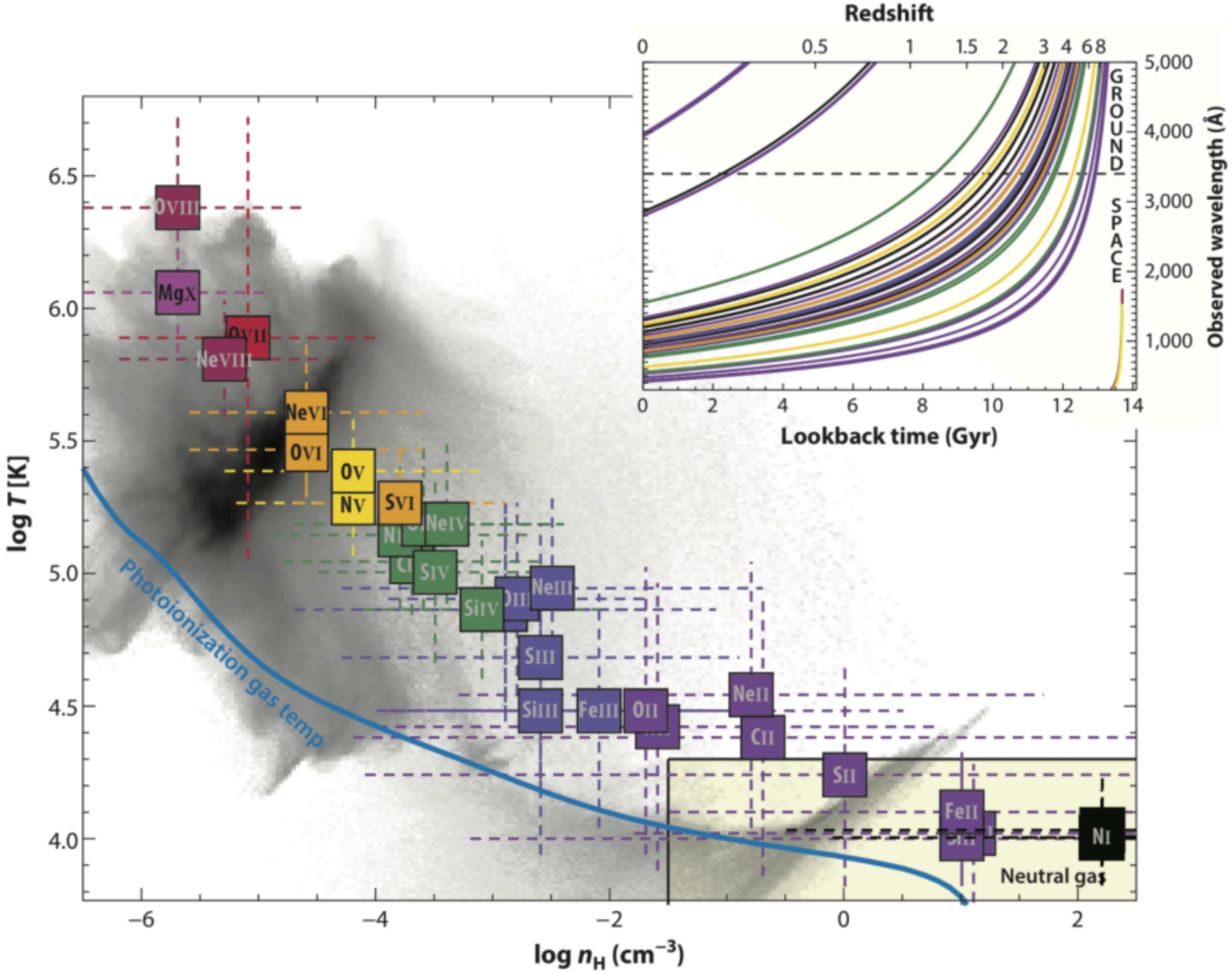




Cooling at High Temperature

Metal Lines in CGM Observation:

Tumlinson et al. 2017

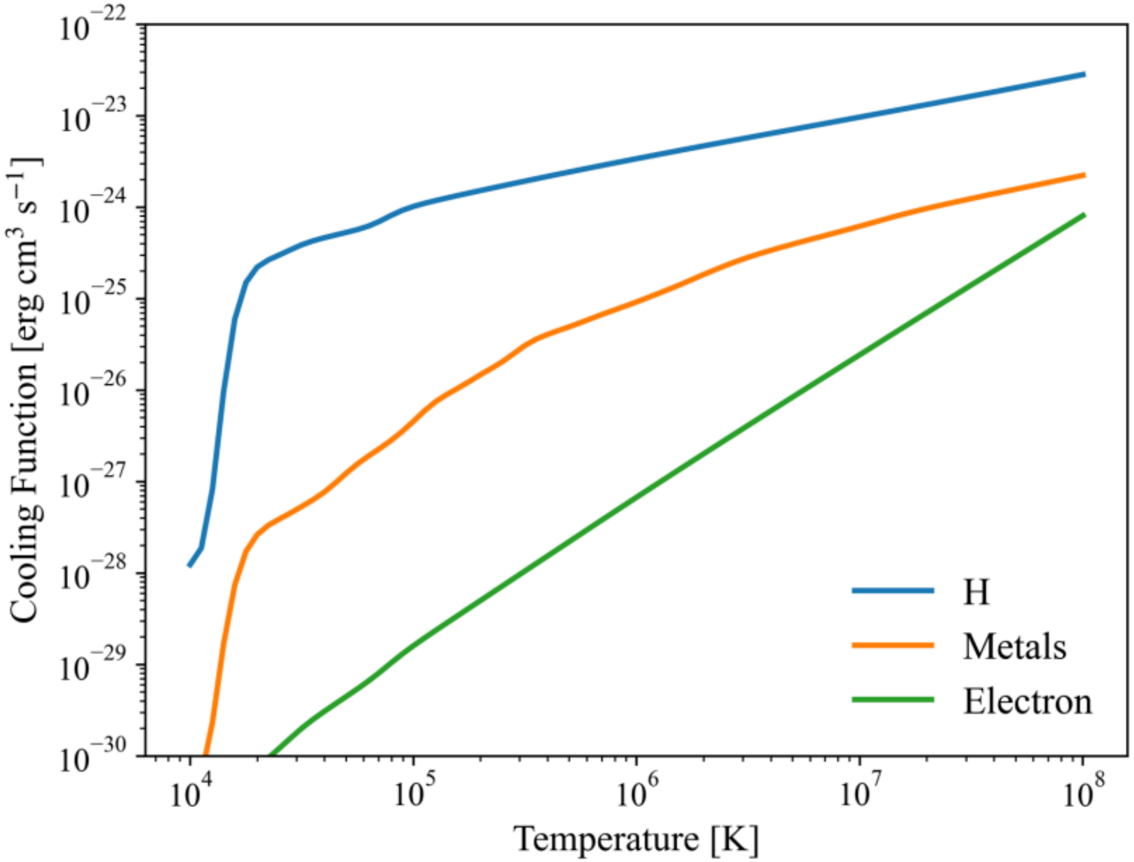


Cooling at High Temperature

Free-Free Cooling (**bremsstrahlung**):

- Efficient at $T \gtrsim 10^7\,\mathrm{K}$
- Radio emission

$$P(T) = \frac{32\pi e^6}{3hm_e c^3}(\frac{2\pi k}{3m_e})^{1/2} T^{1/2} Z^2 \langle g_{ff} \rangle n_e n_i$$



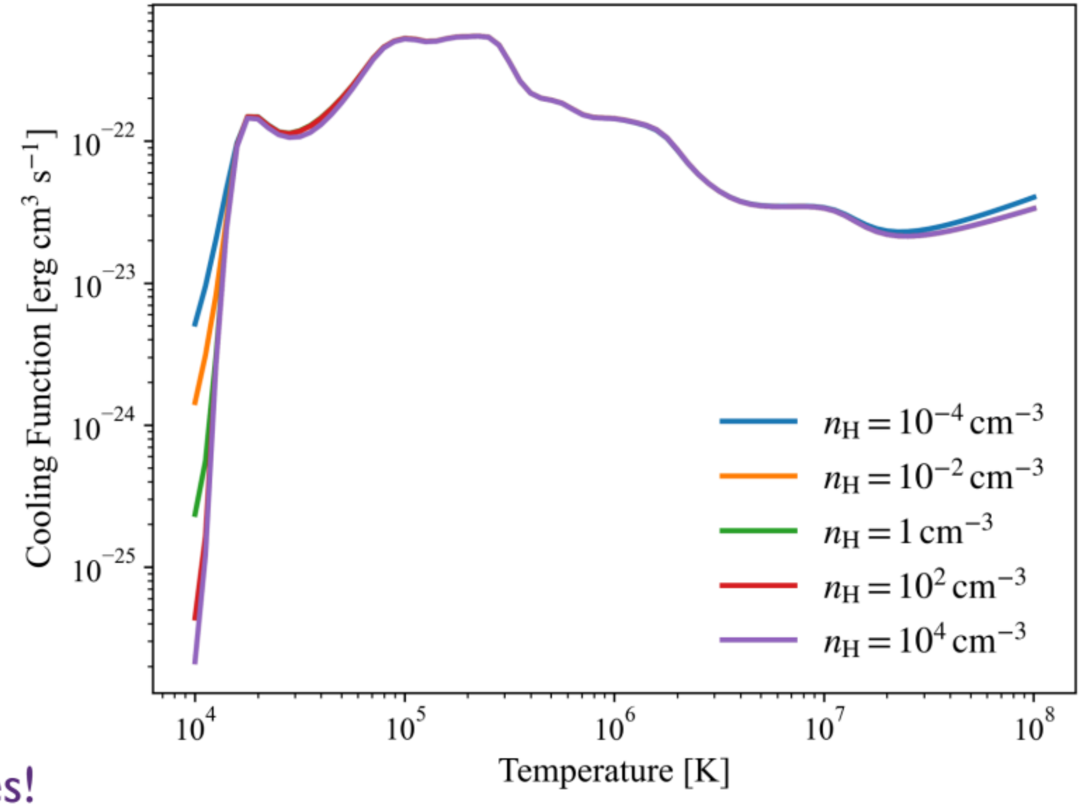
Cooling at High Temperature

Cooling Function v.s. Density:

Table 4.1 Main contributors to line cooling in H II regions[a]

Transition	λ [Å]	$A_{u\ell}$ $[10^{-3}\,s^{-1}]$	n_{crit} $[10^4\,cm^{-3}]$
O II $^4S - ^2D$	3726	0.164	0.406
	3729	0.041	0.130
N II $^3P - ^1D$	6548	0.985	8.86
	6583	2.91	8.86
O III $^3P - ^1D$	4959	6.97	69.1
	5007	20.46	69.1

Ryden & Pogge, Interstellar and Intergalactic Medium



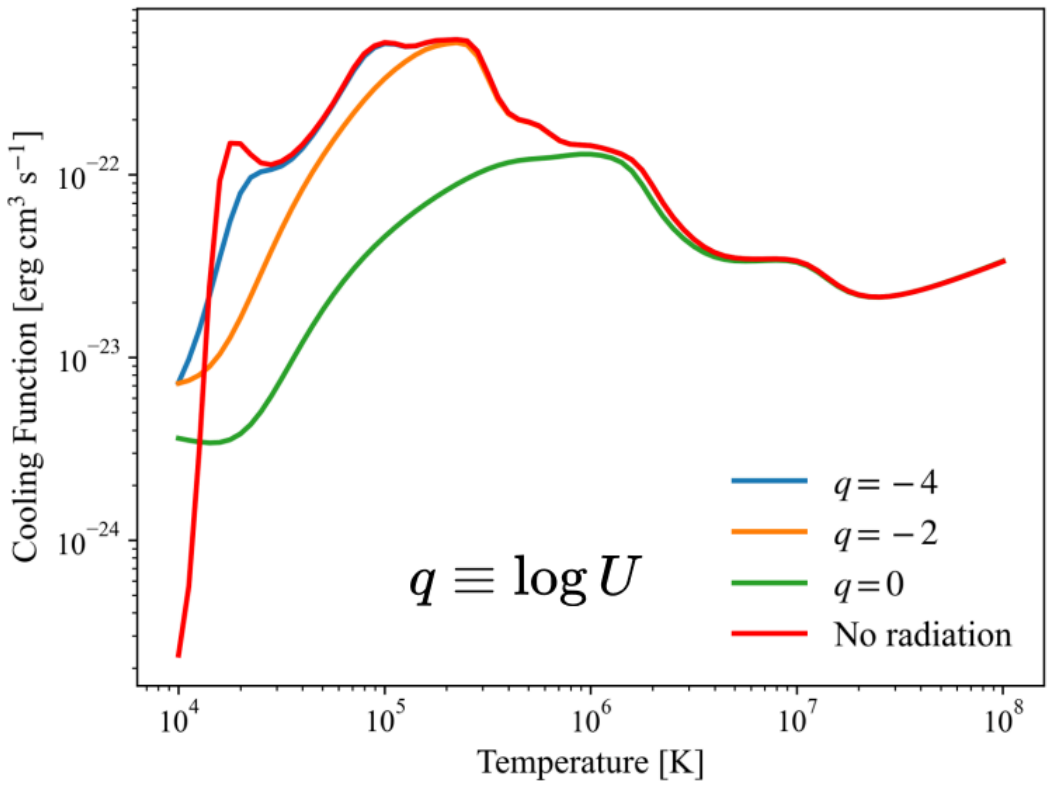
Radiative de-excitation dominates in most cases!

Cooling at High Temperature

Cooling Function v.s. Radiation Field:

AGN radiation with different ionization parameter:

- Radiation field supresses cooling!
- Ionization equilibrium is forced to deviate from the most cooling-efficient point

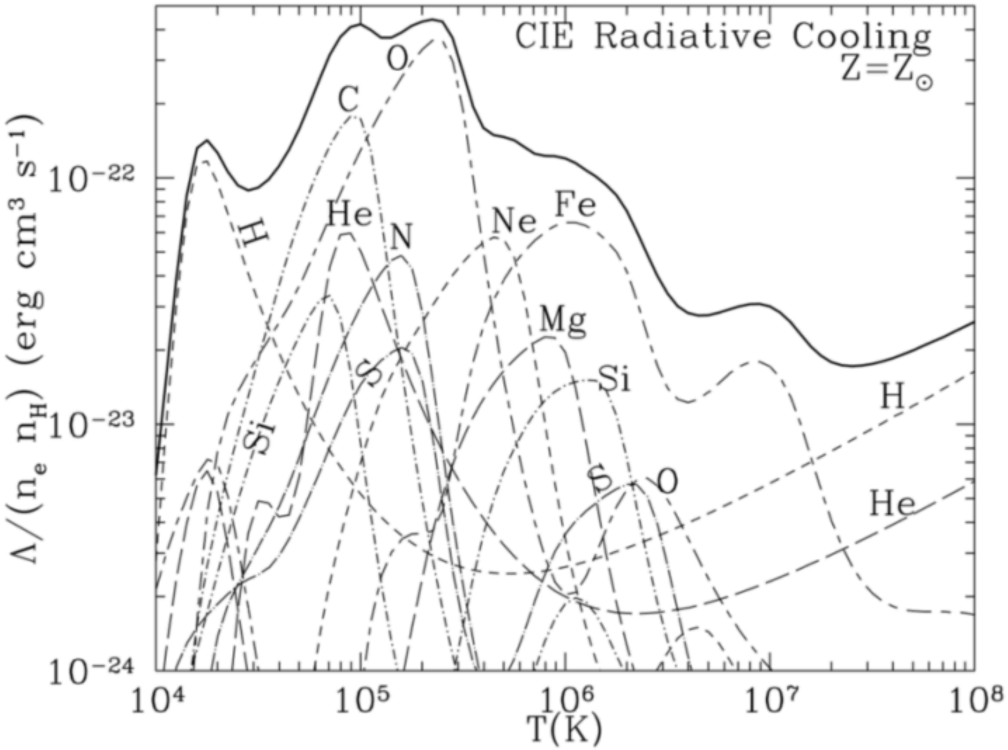


Summary

- 1e5 K blackbody radiation affect the cooling below 1e5 K: enhance 1e1-1e4 K, suppress 1e4 -1e5K

- At low temperature, the higher the H density and the lower the metal abundance, the more significant the effect of dust on the cooling function. The dust can also increase the cooling of molecules.

- At high temperature, cooling is dominated by collisional excitation of different ions. While H is the most efficient coolant at T~1e4K, metals dominate the cooling at most temperature ranges.



Thanks !

Xiaohong Tang, Tao Jing, Jixuan Yang, Anning Gao

2024, Dec. 27