A formation scenario for primordial Galactic stars based upon equilibrium fractions of primordial chemical network and cosmological simulations

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September 18, 2025

Various Reactions Occurring in the Universe

- Collisional ionization and recombination
  - Optically thin (low-density plasma)
  - Interstellar/intergalactic medium
  - Cooling through UV emission
  - Often assumed to be in equilibrium
- Nuclear reactions
  - Stellar core, neutron star surface, supernovae, merging neutron stars, etc.
  - Source of energy generation
  - Often assumed to be in non-equilibrium or steady state in energy equation
- Chemical reactions
  - Far more complicated than the above two
  - High density and low temperature: star forming region

A Simple Case: Primordial Chemistry

Network for primordial chemistry (AAZN97: Abel+, 1997, NewA)

- 19 Collisional + 9 PD/PI
- 7+1 species (H, He species)
- $k = k(T)$ for collisional
- $k = \int_{UV} \frac{i(\nu)}{h\nu} \sigma(\nu) d\nu$ for photochemistry

Collisional-k: fitting on T

(4) $He^{+} + e^{-} \rightarrow He + \gamma$ Cen (1992) and Aldrovandi & Pequignot (1973)

Radiative: $k_{4r} = 3.925 \times 10^{-13} T^{-0.6353}$ cm^3 s^{-1}

Dielectronic: $k_{4d} = 1.544 \times 10^{-9} T^{-3/2} \exp(-\frac{48.596\ \mathrm{eV}}{T})[0.3 + \exp(\frac{8.10\ \mathrm{eV}}{T})]$ cm^3 s^{-1}

Cross-section for PD/PI

(21) $He + \gamma \rightarrow He^{+} + e^{-}$ Osterbrock (1974)

$\sigma^{\nu}_{21} = 7.42 \times 10^{-18}(1.66(\frac{\nu}{\nu_{th}})^{-2.05} - 0.66(\frac{\nu}{\nu_{th}})^{-3.05})$ cm^2, for $\nu > \nu_{th}$.

A Simpler Approach: Equilibrium Assumption

Chemical System of Quadratic Equations (CSQE)

Rate equations:

$$\frac{dn_i}{dt} = \sum_{i;a,b} k_{ab}^{(2)} n_a n_b + \sum_{i;a} k_a^{(1)} n_a$$

At chemical equilibrium:

$$\sum_{i;a,b} k_{ab}^{(2)} n_a n_b + \sum_{i;a} k_a^{(1)} n_a = 0$$

Equivalent QE system:

$$\sum_{i;a,b} k_{ab}^{(2)} X_a X_b + \frac{1}{n_{tot}} \sum_{i;a} k_a^{(1)} X_a = 0$$

$$\sum_{i} \left(\sum_{i;a} X_a \right) = \sum_{i} X_i = 1$$

When the system reaches chemical equilibrium earlier before its physical properties change, ODE for the chemical processes can be replaced with the system of QE.

Models

Physical conditions & Photochemistry

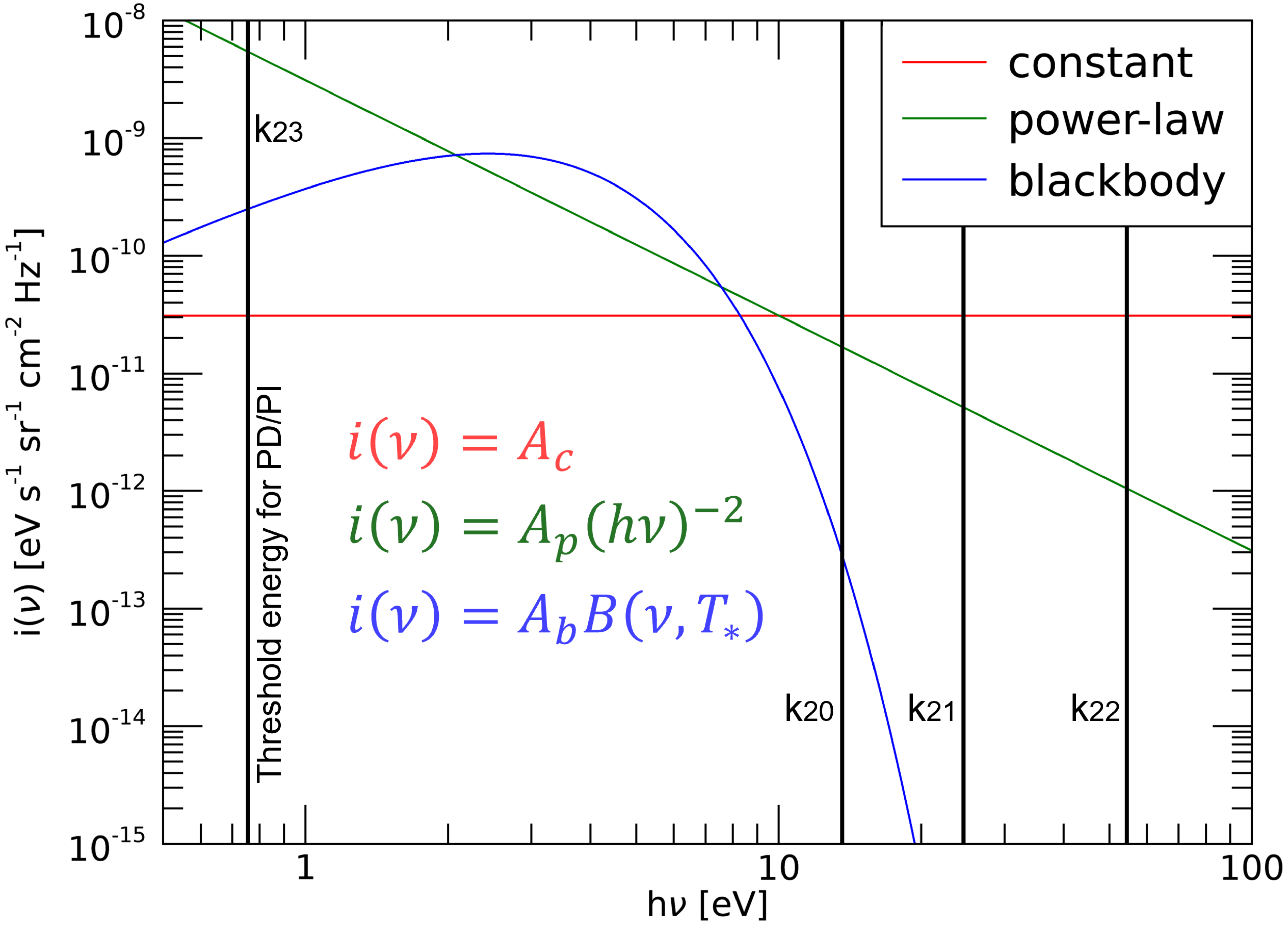
Table 1. Physical properties of primordial cloud model

Property	Range
Density (n_{tot}, cm^{-3})	[1,1000]
Temperature (K)	[10,10000]
Number density ratio ($n_H : n_{He}$)	0.65:0.35

Table 4. List of background UV models for the cloud model

Blackbody	Constant	Power-law
$A_b = 10^{-32}$ "B-weak"	$A_c = 3.1 \times 10^{-11}$ "C-weak"	$A_p = 3.1 \times 10^{-9}$ "P-weak"
$A_b = 10^{-28}$ "B-strong"	$A_c = 3.1 \times 10^{-7}$ "C-strong"	$A_p = 3.1 \times 10^{-5}$ "P-strong"

$i(\nu)$ used for this work ("weak" models)



Chemical equilibrium in cosmological timescale

Table 6. Table of the maximum equilibrium timestamps by densities and temperatures

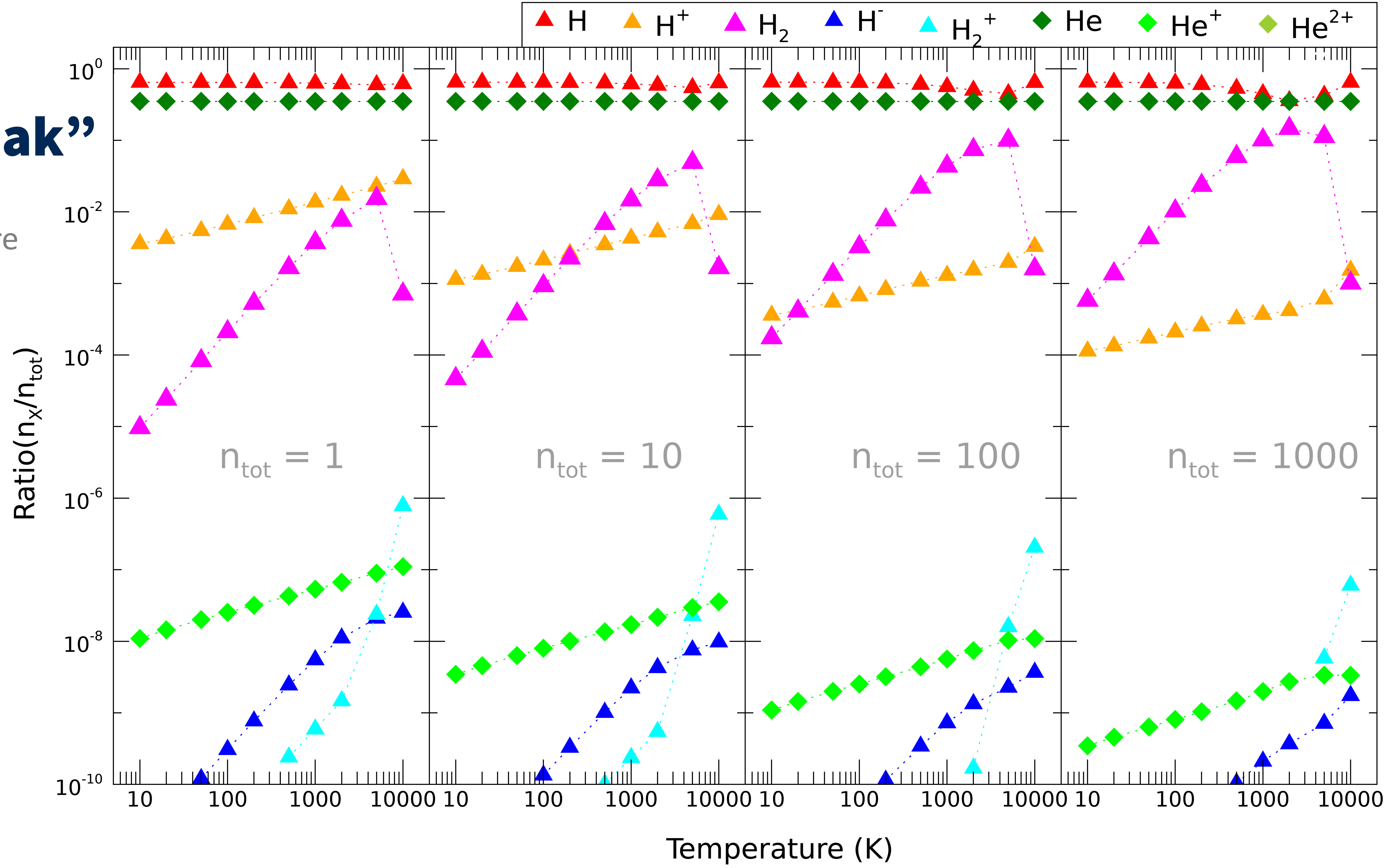
Eq. timestamp (yr)	$n = 1\ \mathrm{cm}^{-3}$	$10\ \mathrm{cm}^{-3}$	$100\ \mathrm{cm}^{-3}$	$1000\ \mathrm{cm}^{-3}$
$T = 10$ K	4.37(8)	4.08(8)	3.76(8)	3.44(8)
100 K	3.42(8)	3.09(8)	2.79(8)	2.40(8)
1000 K	2.98(8)	2.48(8)	1.95(8)	9.93(7)
10000 K	5.57(7)	1.97(7)	5.38(6)	$<$ 2.25(6)

- Key assumption: Chemical evolution already reaches equilibrium before the galaxy formation got physically stable.

➔ Agree with primordial clouds in $z \leq 10$. (⇔ ≤ 0.48 Gyr after BB.)

“B-weak”

Plots by Temperature



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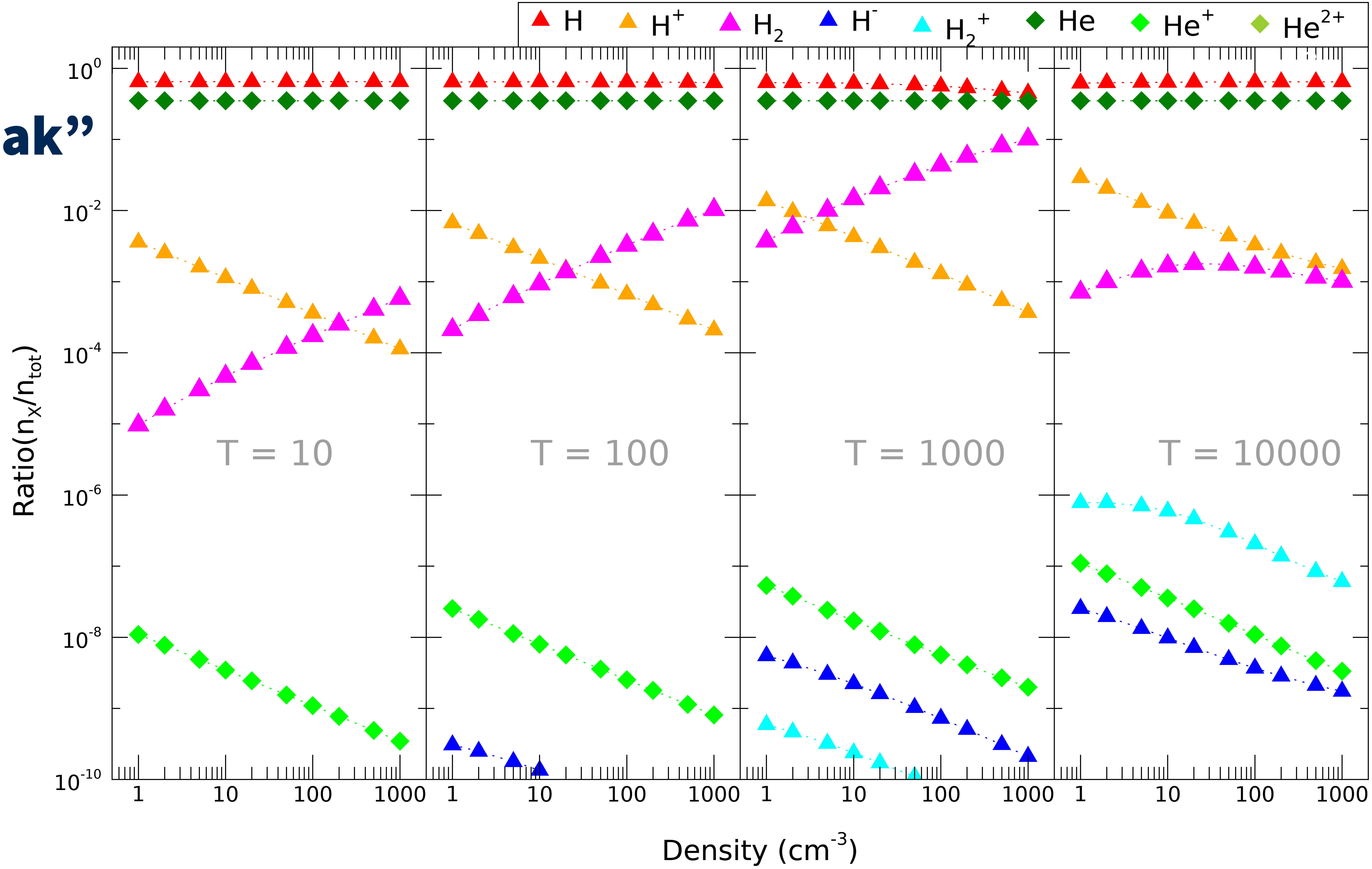
“B-weak”

Plots by Density



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He chemistry

a (b) = a×10^b

Reaction	Type	No.	k at 10 K	100 K	1000 K	10000 K	100000 K
1st ion. (He ⇌ He^+)	Coll. ion.	3	0	0	5.1003 (-105)	1.5655 (-21)	4.7897 (-10)
	Coll. recom	4	3.4737 (-11)	8.0445 (-12)	1.8629 (-12)	4.3142 (-13)	5.8911 (-13)
	Photoion.	21	3.8961 (-21)	3.8961 (-21)	3.8961 (-21)	3.8961 (-21)	3.8961 (-21)
2nd ion. (He+ ⇌ He^{++})	Coll. ion.	5	0	0	2.2038 (-171)	1.3662 (-33)	4.5101 (-12)
	Coll. recom	6	1.2747 (-12)	8.6362 (-13)	5.7964 (-13)	3.8477 (-13)	2.5204 (-13)
	Photoion.	22	4.2887 (-36)	4.2887 (-36)	4.2887 (-36)	4.2887 (-36)	4.2887 (-36)

$$\mathrm{He} \underset{k_4}{\overset{k_3,\, k_{21}}{\rightleftharpoons}} \mathrm{He}^{+} \underset{k_6}{\overset{k_5,\, k_{22}}{\rightleftharpoons}} \mathrm{He}^{++}$$

[He] ≫ [He+] ≫ [He++] at T ≤ 10000 K:
- $k_3 \ll k_{21} \ll k_4 \,//\, k_5 \ll k_{22} \ll k_6$
- coll. ion. << photoion. << coll. recom.

[He++] ≫ [He+] ≫ [He] at T = 100000 K:
- $k_{21} \ll k_4 \ll k_3 \,//\, k_{22} \ll k_6 < k_5$
- photoion. << coll. recom. << coll. ion.
- He almost ionized as He^{++}

H_2 chemistry

a (b) = a×10^b

Reaction	Type	No.	*k* at 10 K	100 K	1000 K	10000 K	100000 K
$H + H^-$	Association ($\mathbf{R} \rightarrow H_2$)	8	1.4280 (-9)	1.4280 (-9)	1.4280 (-9)	1.8605 (-9)	3.5476 (-9)
$H_2^+ + H$		10	6.4000 (-10)	6.4000 (-10)	6.4000 (-10)	6.4000 (-10)	6.4000 (-10)
$H_2^+ + H^-$		19	1.5811 (-06)	5.0000 (-7)	1.5811 (-7)	5.0000 (-8)	1.5811 (-8)
$H_2^+ + H$	Coll. Diss ($H_2 + R \rightarrow \mathbf{P}$)	11	0	0	1.0388 (-50)	1.6159 (-11)	9.9817 (-11)
$2H + e^-$		12	0	0	7.8759 (-54)	2.0559 (-13)	6.3778 (-9)
3H		13	0	1.8264 (-241)	4.6277 (-37)	2.9262 (-15)	3.4412 (-21)
$H_2^+ + e^-$	Photodiss. ($H_2 + \gamma \rightarrow \mathbf{P}$)	24	5.6049 (-17)	5.6049 (-17)	5.6049 (-17)	5.6049 (-17)	5.6049 (-17)
$H_2^* \rightarrow 2H$		27	1.2516 (-15)	1.2516 (-15)	1.2516 (-15)	1.2516 (-15)	1.2516 (-15)
2H		28	8.6123 (-17)	8.6123 (-17)	8.6123 (-17)	8.6123 (-17)	8.6123 (-17)

at $T \leq 1000$ K:

- coll. diss. ≪ photodiss. ≪ Association
- More ingredients (H_2^+, H^-) at high-T ⇒ high [H2]

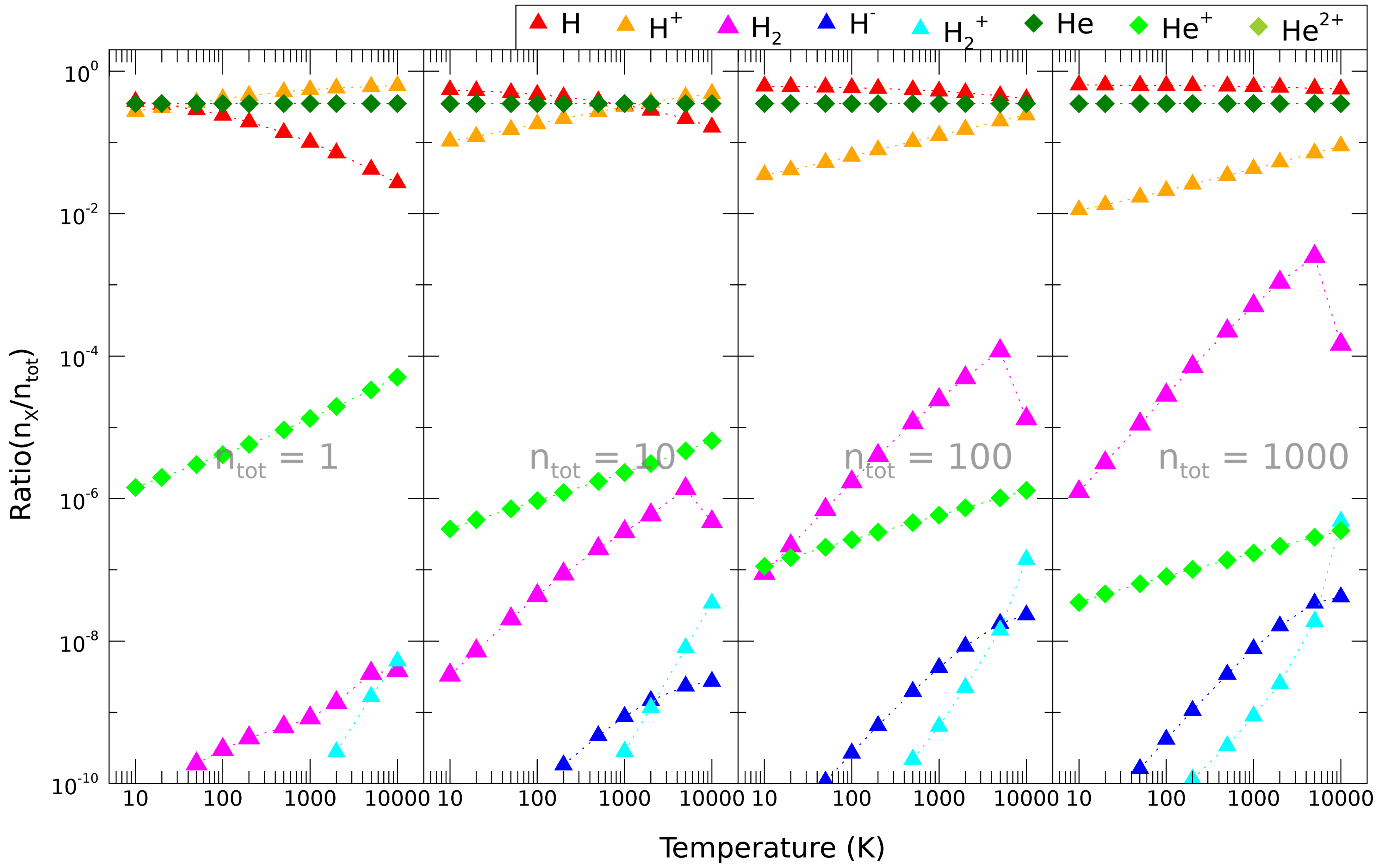
at $T > 1000$ K:

- photodiss. ≪ coll. diss. ≲ Association
- H_2 rapidly dissociated: as expected

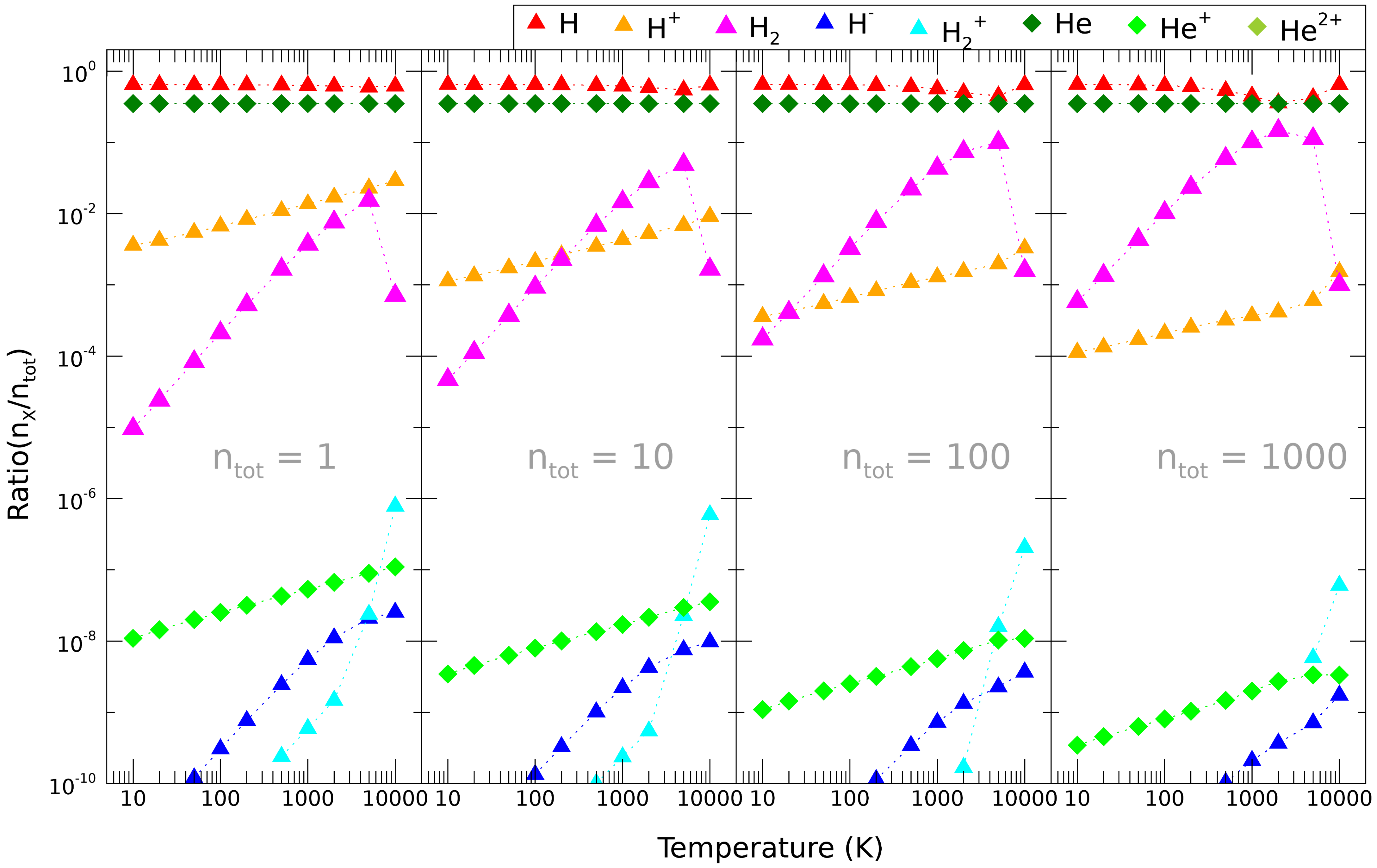
Other background UV models

With "Strong" background UV

▼"B-strong": x10^4 stronger UV field than "B-weak"

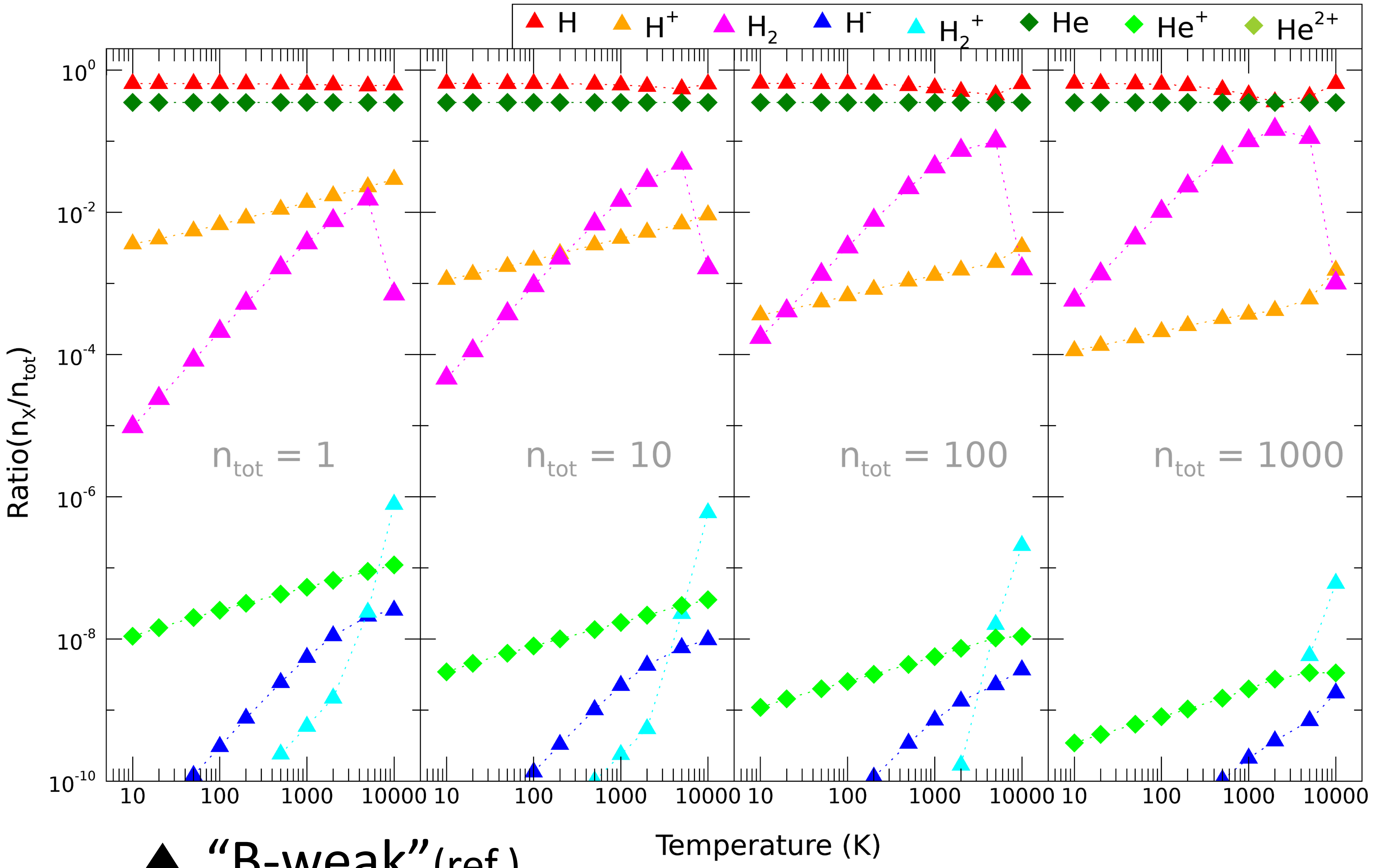


▼"B-weak"



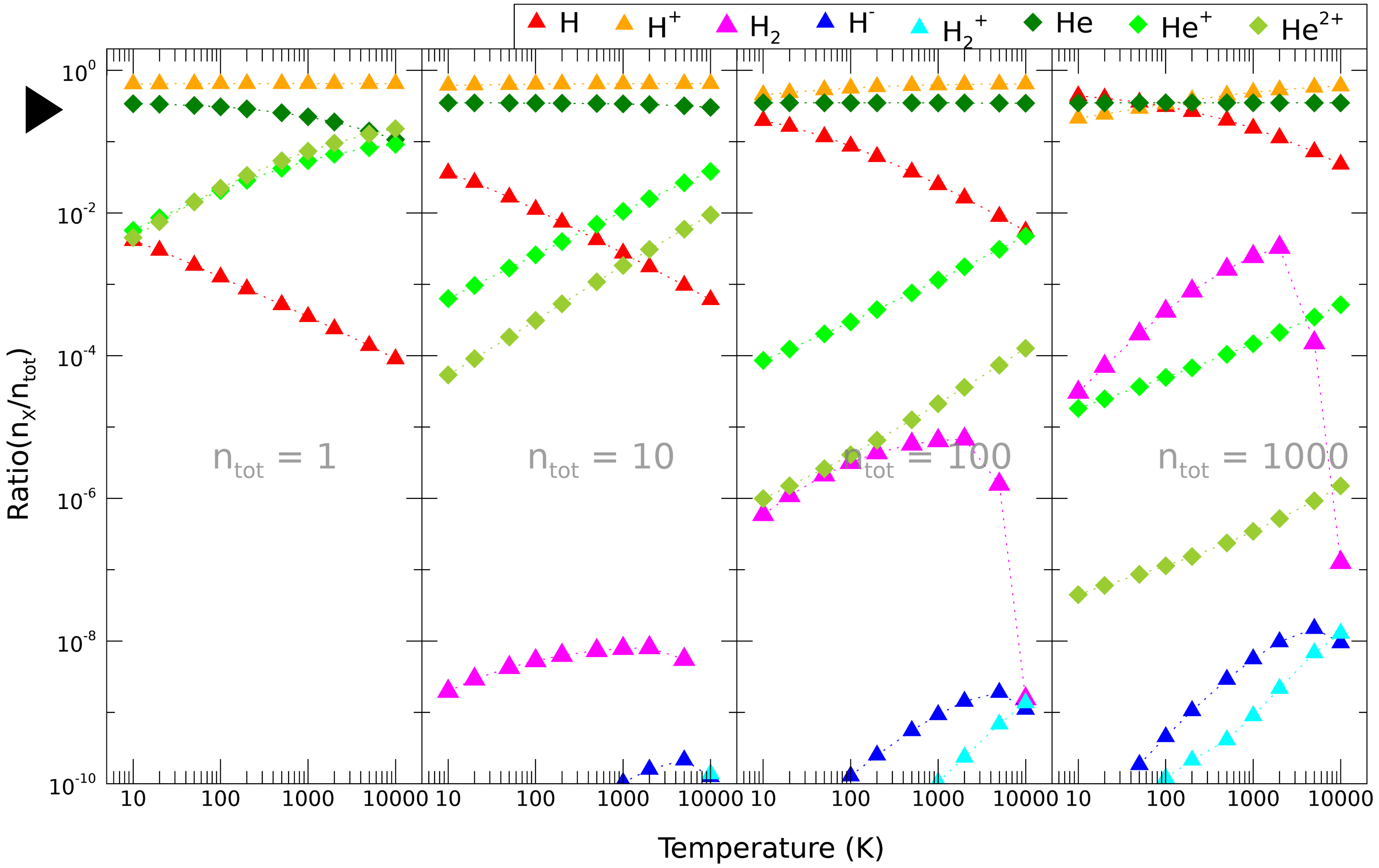
Other background UV models

With different background UV profile

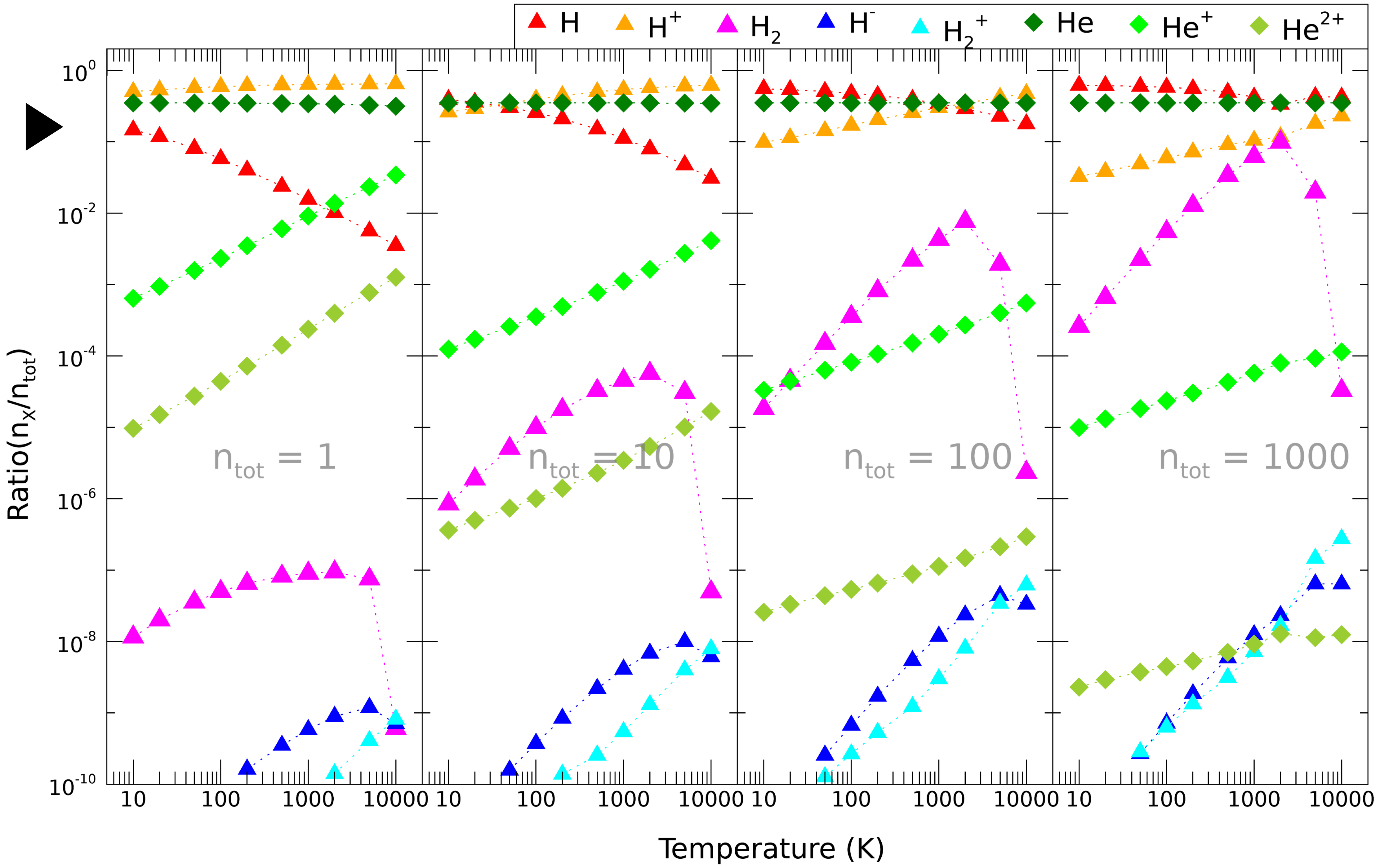


▲ "B-weak"(ref.)

"C-weak" ▶



"P-weak" ▶



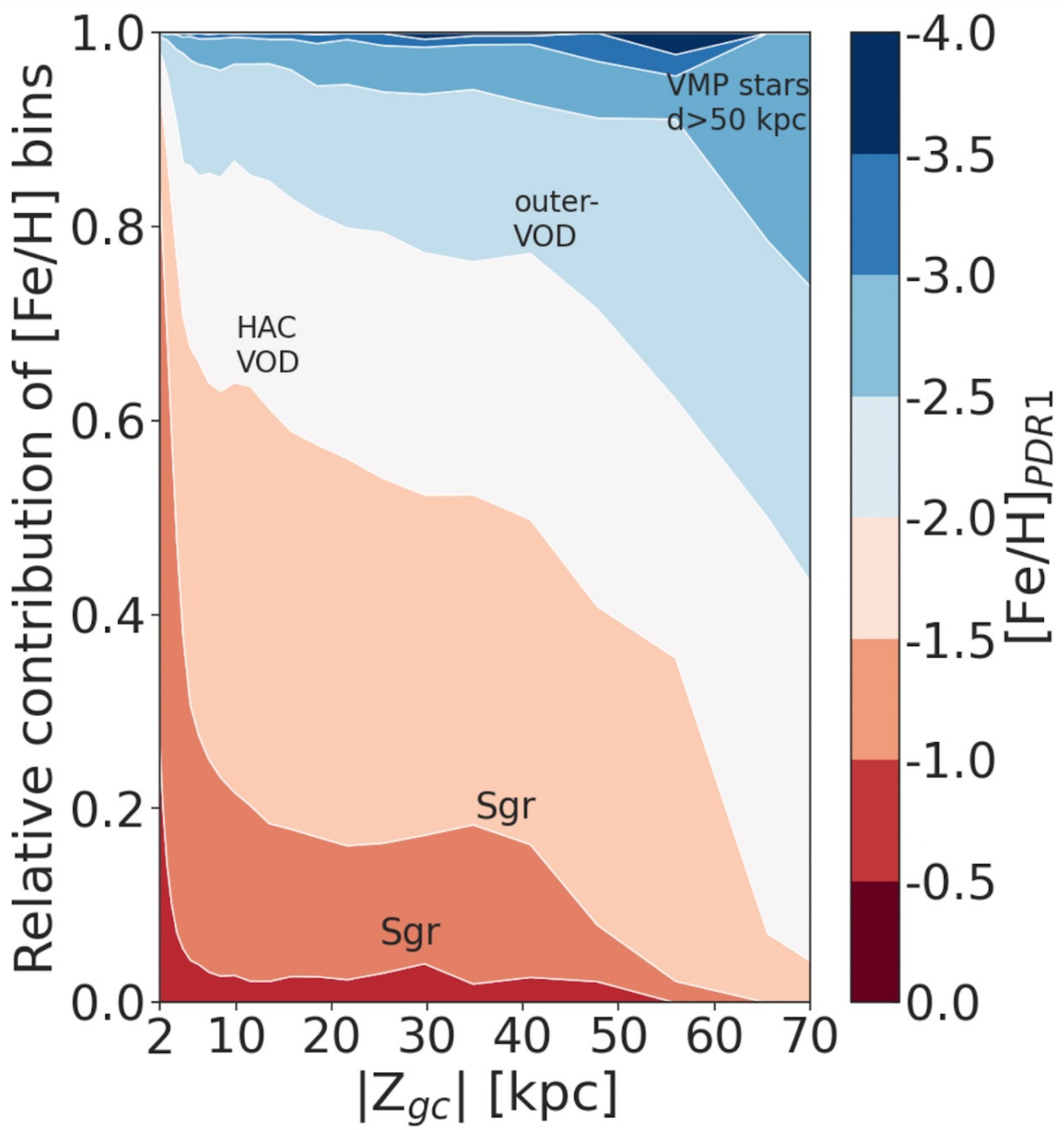
Metal-poor stars in Milky Way

- *Pristine* survey (2017 - present)
  - Publish Catalog of stars in Milky way with [Fe/H] < -2.0

- Ultra metal-poor (UMP) star discovered (Schlaufman, ApJ, 2018)
  - 2MASS J18082002–5104378 B
  - M = 0.14 $M_{\odot}$, [Fe/H] = -4.1
  - age ≒ 13.5 Gyr

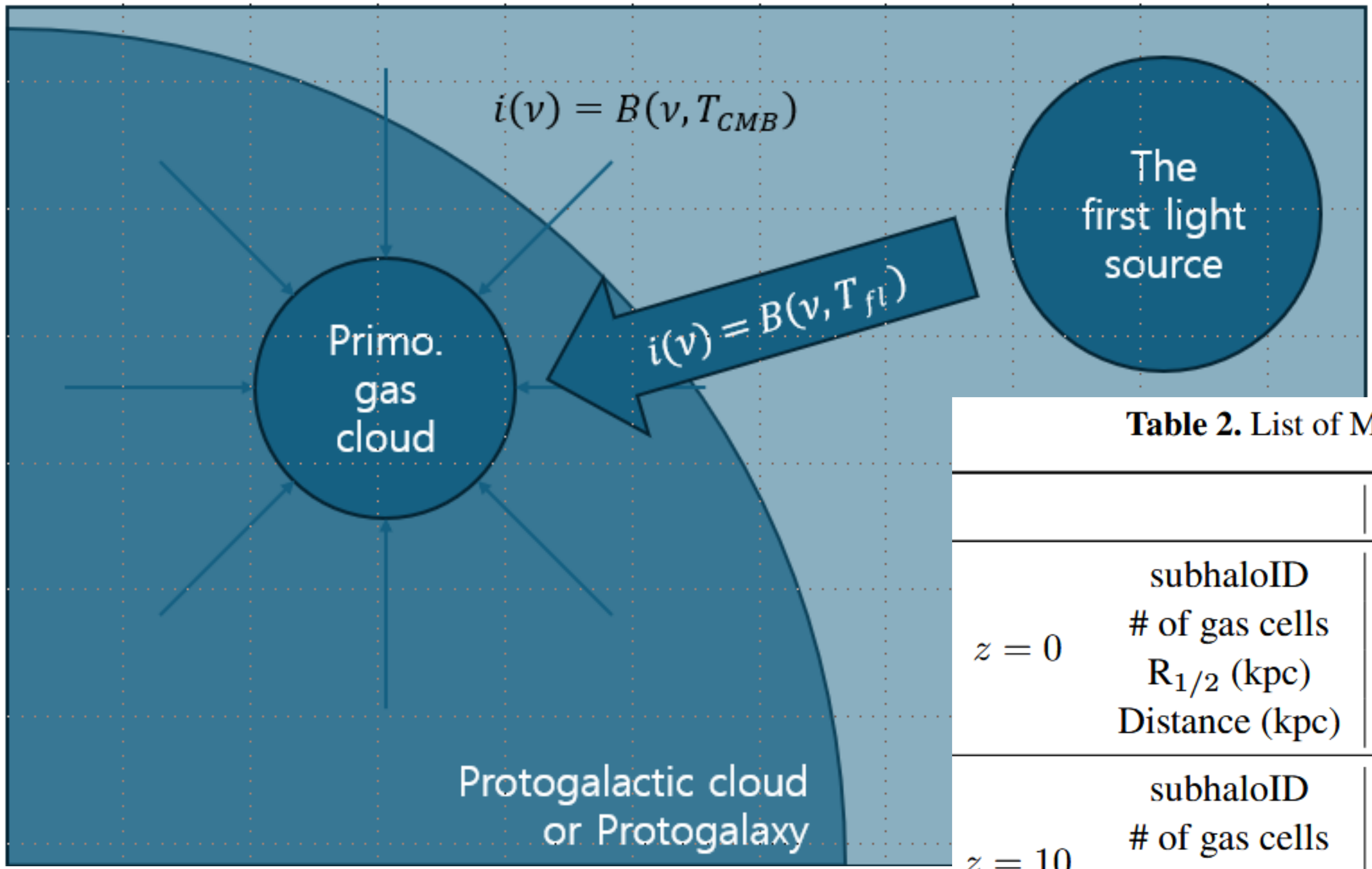
➔ UMP stars Formed in the early phase of MW

➔ **How active is the molecular formation?**



▲ Cumulative distribution of [Fe/H] by distance from disk ($|Z_{gc}|$)
(Viswanathan et al., 2024b via *Pristine*)

Blueprint for primordial star-forming clouds



▲ Brief illustration about the primordial gas clou

- External radiation sources
  - Background radiation B(ν, T_{CMB})
    - ➔ Too weak at z=10
  - "First light sources"
    - Pop.III stars
    - Activated nearby protogalaxies

Table 2. List of MW/M31 analogs in TNG50-1 that imitate the Local Group

		pair #1		pair #2		pair #3	
$z = 0$	subhaloID	400973	400974	425719	580406	454171	454172
	# of gas cells	2029697	373323	2315168	419900	451443	173598
	$R_{1/2}$ (kpc)	139.12	49.09	123.49	52.49	108.83	63.70
	Distance (kpc)	933.66		870.81		565.57	
$z = 10$	subhaloID	86724	22278	42972	15073	2956	93946
	# of gas cells	412	1589	554	1585	8922	260
	$R_{1/2}$ (kpc)	1.13	3.25	1.72	1.91	4.30	1.24
	Distance (kpc)	327.74		470.72		282.31	

Properties of galaxy progenitors

From TNG50-1 (Nelson+, 2019a, ComAC)

- Stats of gas cells consists subhalos (=galaxies) at z=10

SubhaloID ($z = 0$)	SubhaloID ($z = 10$)	Density of gas cells (cm^{-3}) min.	mean	median	max.	Temperature of gas cells (K) min.	mean	median	max.
400973	86724	1.83(-3)	6.90(-2)	1.75(-1)	1.07	9780.6	12392	15110	61070
400974	22278	1.52(-3)	5.79(-2)	9.65(-2)	1.13	6488.4	11848	13979	88222
425719	42972	1.33(-3)	5.14(-2)	1.53(-1)	1.11	8205.9	12565	15987	124435
580406	15073	1.77(-3)	1.09(-1)	1.87(-1)	1.32	9150.3	13397	16173	143201
454171	2956	2.33(-3)	9.11(-2)	2.08(-1)	3.90	8132.2	13370	19434	492528
454172	93946	9.96(-4)	4.67(-2)	1.77(-1)	1.38	8415.4	12417	15093	51974

Dens. = (1e-3 , 4.0) cm^{-3}

Temp. = (8e3 , 5.0e5) K

- Resolution of TNG is larger than typical dense cloud
  ➔ Possible to set denser and/or cooler primordial cloud

Conclusion

- Metal-poor stars in the Milky Way have been discovered & surveyed in recent years, and those primordial stars may have formed in a very young stage of MW.
- To elaborate that scenario, we solved CSQE to estimate H2 fraction that evolve to form primordial stars.
- Its solutions for equilibrium state are collected to “Fractional table” by density / temperature / radiative models.

THANK YOU