Formation of Turbulent and Magnetized Molecular Clouds

Inoue & Inutsuka 2012, ApJ, 759, 35

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Introduction

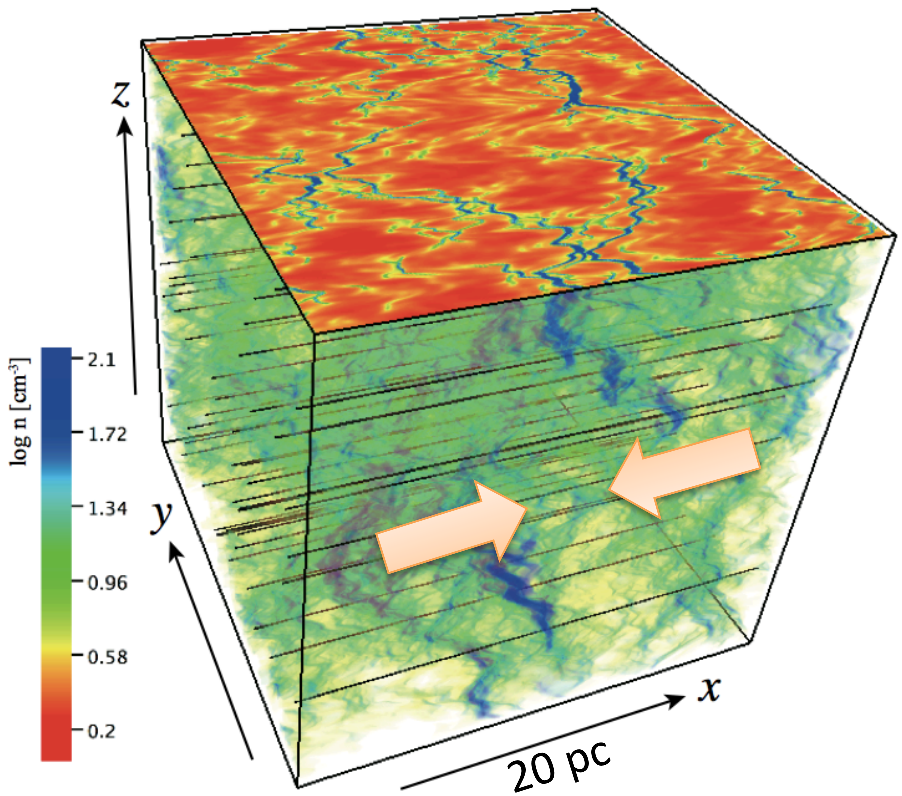
- Molecular clouds (MC): site of all present-day star formation.
  - However, physical conditions of MCs (e.g., $\boldsymbol{B}$ and δv) are poorly understood.
  - Physical conditions are crucial to determine initial condition of SF (PPD), IMF …
- Simulating MCs from their formation: promising way to understand physical conditions.
  - To perform simulations, we need scenario or model of MC formation.
- Recent observations of MCs in nearby galaxies suggest that (Britz+07, Kawamura+09, Fukui+09)
  - MCs evolve by accretion of HI clouds with $\langle n \rangle \sim 10$ cm^{-3}.
  - Estimated accretion velocity: v $\sim$ 10 km/s

- We expect that MCs are formed by shock compression of HI clouds
  - Possible scenarios: (i) massive HI super-shell swept up by galactic spiral shock
    (ii) collision of HI super-shells
    (iii) gravitational contraction of HI super-shell

HI clouds as a building block of MCs

- In this study, we generate HI clouds (building block of MC) also by MHD simulation.
  - Basic eqs.: Ideal MHD + optically thin ISM cooling/heating + thermal conduction.
  - Resolution: $(20\ \mathrm{pc})^3$ domain are divided into 1024^3 cells ($\delta x \sim 0.02$ pc)

Density map of resulting HI medium.

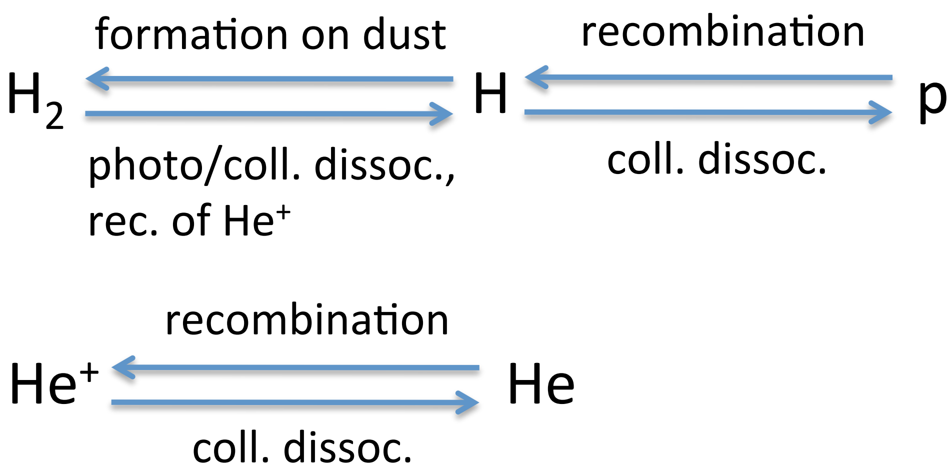


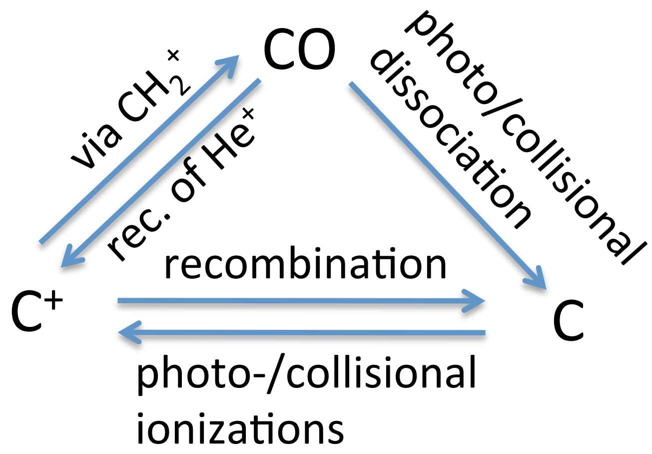
- typical HI clouds are formed by thermal insta. from thermally unstable equilibrium state (Inoue & Inutsuka 08, 09, see also Audit & Hennebelle 10)
- Thermal instability generates HI clouds ($n \sim 30\ \mathrm{cm}^{-3}$, $T \sim 100$ K) that are embedded in diffuse warm medium ($n \sim 1\ \mathrm{cm}^{-3}$, $T \sim 6000$ K).
- Initially homogeneous $\boldsymbol{B}$ with $\langle B \rangle = 5\ \mu$G.
- n, T, B and configuration of HI clouds agree well with 21cm observations (Heiles&Troland 03,05).
- $\langle n \rangle = 5\ \mathrm{cm}^{-3}$ is also consistent with observed HI medium accreting to MCs (Fukui+09).

- To start MC formation, we set converging flows of the HI medium with $v_{\mathrm{coll}} = 20$ km/s.
  - copy of initial HI medium continuously flow from x-boundary planes.

Microphysics: Chemical Reactions

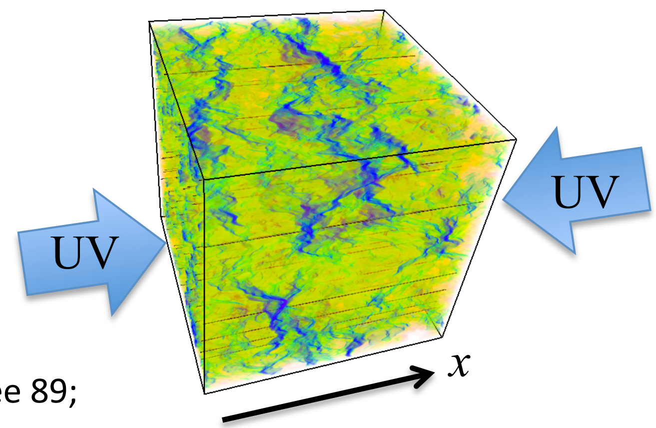
- Formation of molecules is taken into account including UV shielding effects, in order to calculate ``molecular” cloud formation appropriately (see also Glover+10).
  - 28 chemical reactions between species of H, H_2, p, He, He^+, C^+, C, and CO





✓ UV irradiation from x = ± ∞ with strength G_0=1.0

✓ H_2 & CO photo-dissociation: self & dust UV shielding



Refs: Tilelens & Hollenbach 85; Draine & Bertoldi 96; Hollenbach & McKee 89; Millar+ 97; Shapiro & Kang 87; Nelson & Langer 97)

Microphysics: Cooling/Heating

- Following cooling/heating are taken into account.
  - Cooling/Heating: 8 processes

✓ Photo-electric heating by PAH:
UV shielding by dust is included

✓ CR heating

✓ H_2 photo-dissoc. heating:
self & dust UV shielding is included

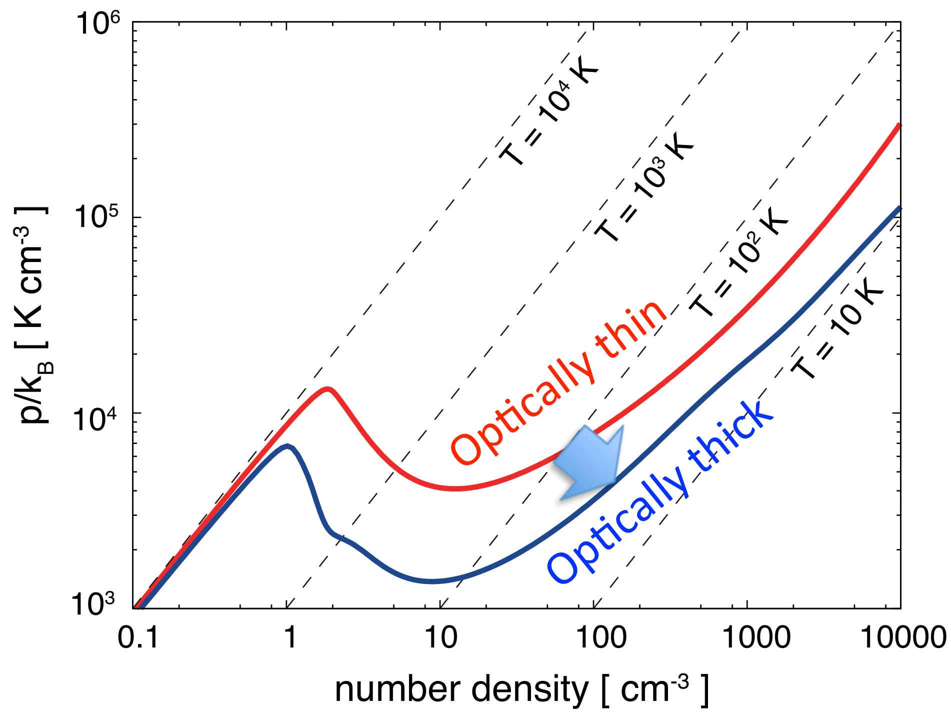
✓ Ly-α emission

✓ C^+ fine-structure (158μm):
escape probability is calculated

✓ O fine-structure (63μm):
escape probability is calculated

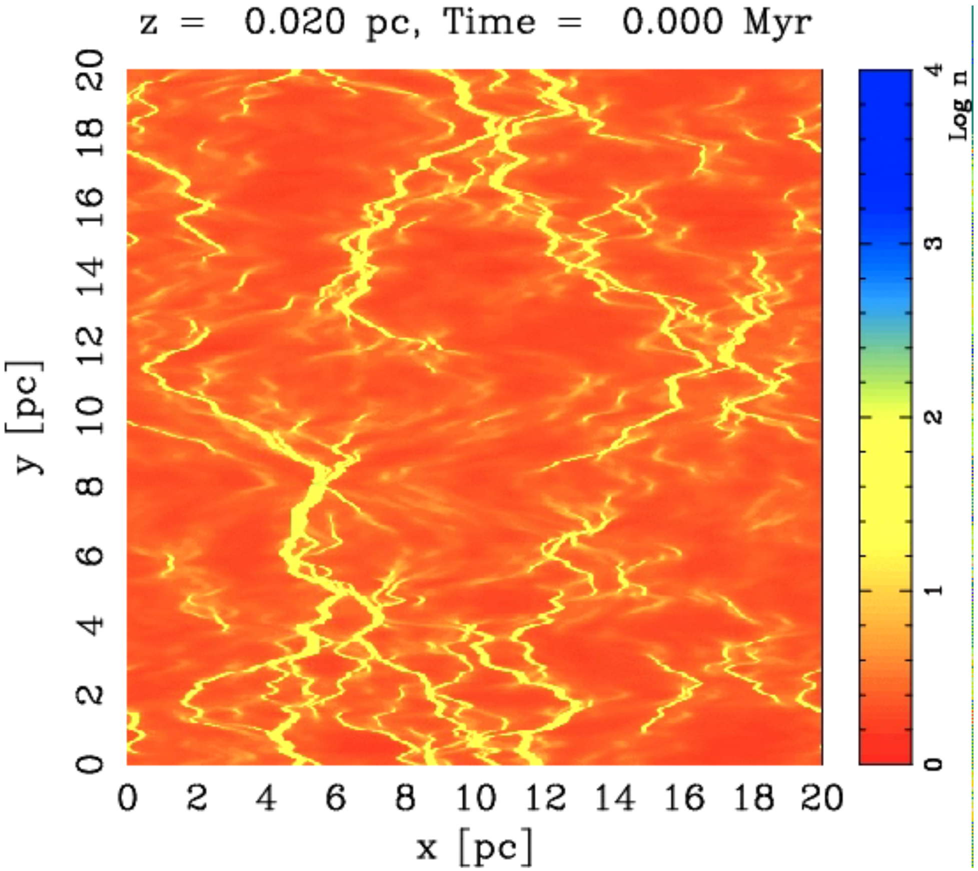
✓ CO ro-vibration lines:
escape probability is calculated

✓ Electron recombination cooling on dust



Refs: Bakes & Tielens 94; Glover & MacLow 07; Goldsmith & Langer 78; Black & Dalgano 77; Spitzer 78; de Jong+ 80; Wolfire+ 03; McKee+ 82; Hollenbach & MacKee 79; Hosokawa & Inutsuka 06; Tilelens & Hollenbach 85; Draine & Bertoldi 96)

Result: 2D slice of density



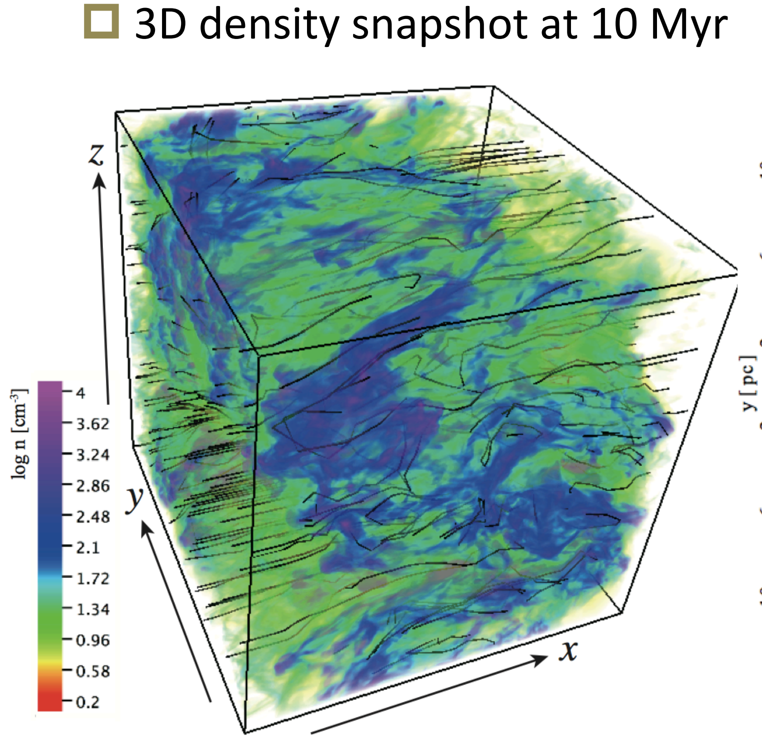
Yellow: cold HI gas
(n ~ 10-100 cm^{-3}, T ~ 100 K)

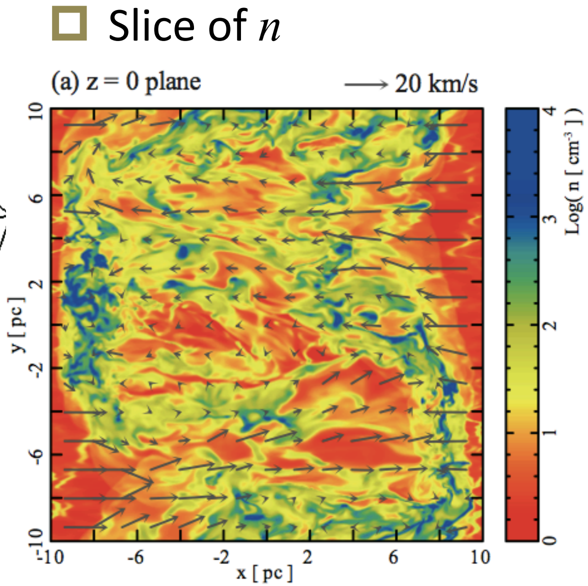
red: diffuse warm gas
(n ~ 1 cm^{-3}, T > 1000 K)

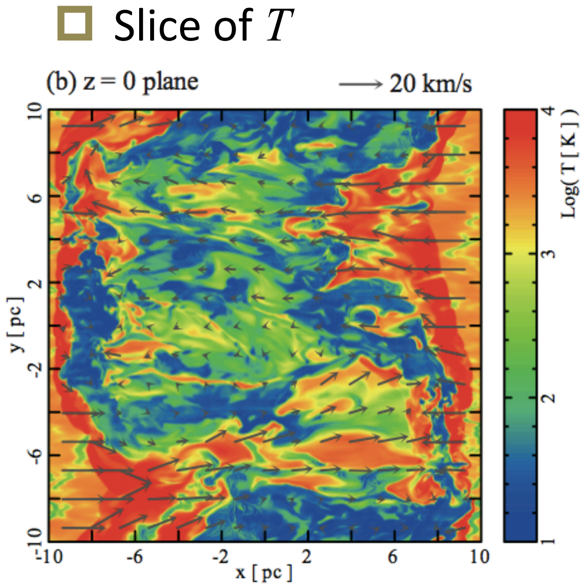
Brue: dense gas
(n > 10^3 cm^{-3}, T ~ 10 K)

- Converging flows induce two shock fronts.
- Shock fronts are deformed when clouds hit the fronts (Richtmyer-Meshkov Insta.).
- Because vorticity is not a conserved variable across a shock, turbulence is generated behind the curved shock (Crocco's theorem).
  - ✓ for molecular gas component: δv ~ 3 km/s (cs ~ 0.3 km/s)

Result after 10 Myr Accretion







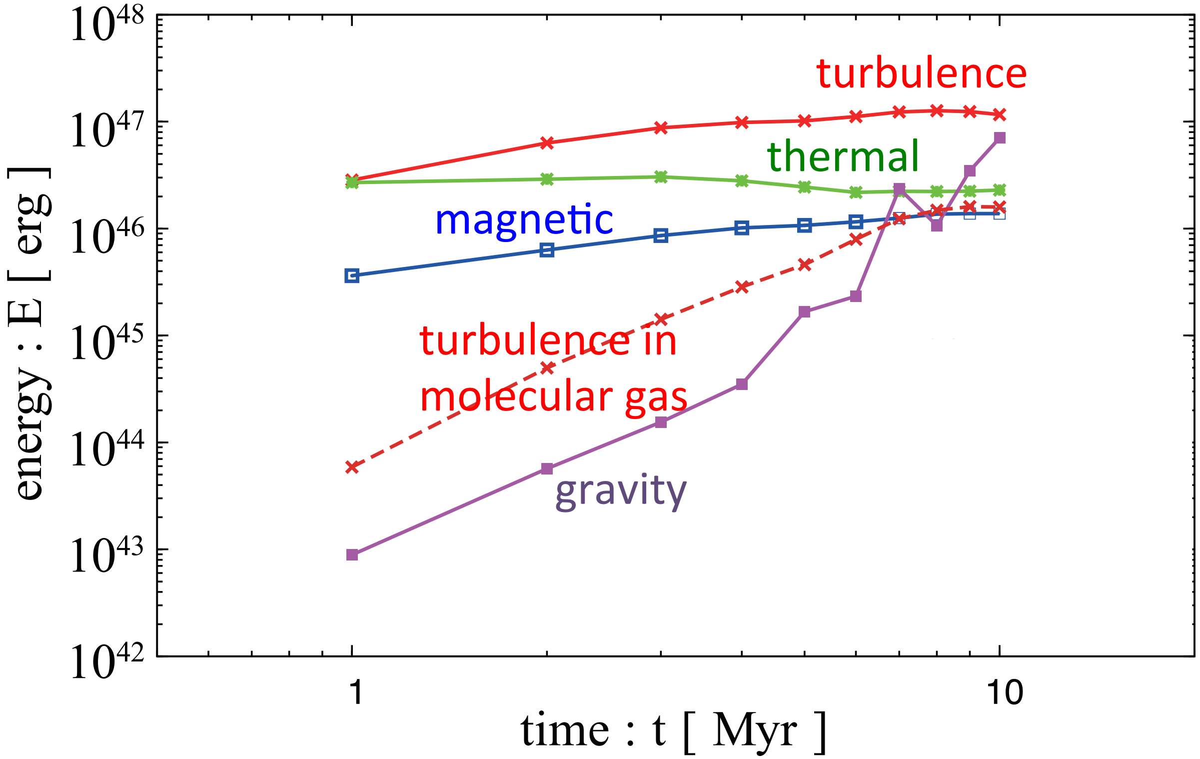
- Structure is very inhomogeneous ($n \sim 1\text{-}10^4\ \mathrm{cm^{-3}}$) and non-isothermal ($T \sim 10$ - 10^4 K).
- Diffuse warm gas ($n \sim 1\text{-}10\ \mathrm{cm^{-3}}$, $T > 10^3$ K) survives even deep inside MC, despite cooling timescale < 1 Myr.

  ✓ Turbulent mixing can provide warm gas before it is cooled.

  Velocity dispersion of diffuse gas component: $\Delta v \sim 10$ km/s
  → Mixing length in cooling time: $l \sim 10$ pc

Temporal Evolution

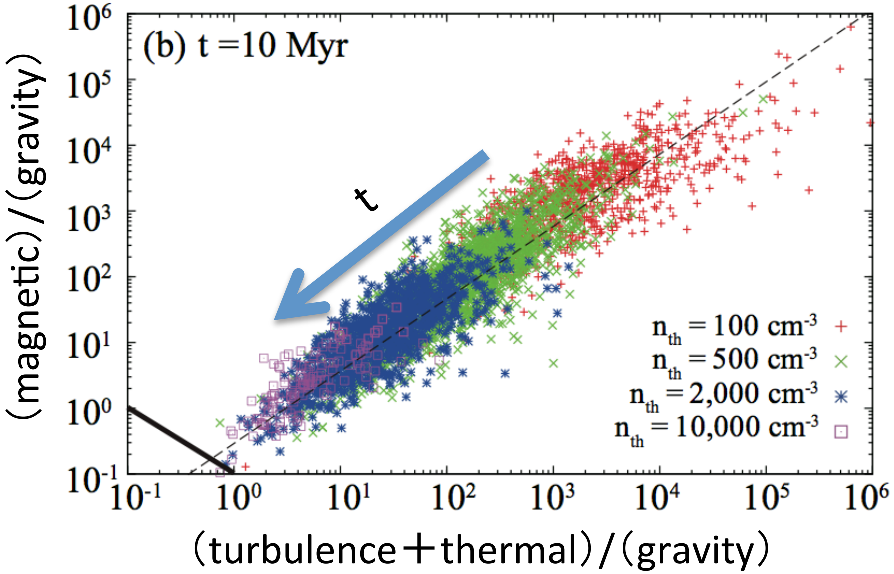
- Evolution of energies in numerical domain except accreting HI gas.



- dotted red: CO fraction weighted turbulent kinetic energy → E_{turb} in cold gas
- $E_{\mathrm{turb,\ CO}}$ is roughly an order of magnitude smaller than total energy of turbulence E_{turb}.
  - → Most of turbulent energy is in diffuse warm gas
  - → Estimation of E_{turb} by molecular emission linewidth underestimate true energy.

Physical State of Clumps

- Evolution of dense clumps in simple virial diagram

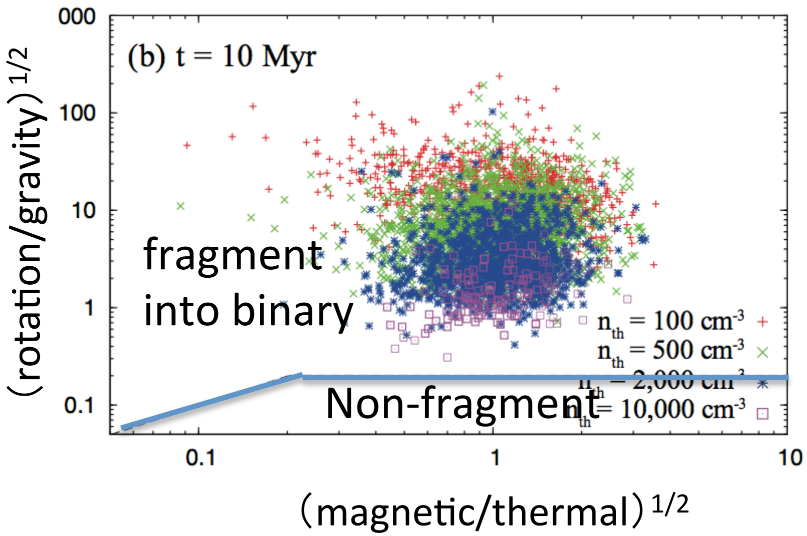


- dense clumps evolve towards gravitationally bound (supercritical) cores through a similar path in virial diagram.

Typical initial condition of star formation?

$$E_{mag} \sim E_{turb} + E_{th}$$

- Rotation



- ——— : threshold for core fragmentation into binary stars derived by Machida+04
- Clumps seem to evolve into cores that form binary stars

* rotation is apparently faster than observed cores. However, observation is known to underestimate it in turbulent core (Dib+10)

Mass Function of Clumps

- Mass function of clumps depends on density

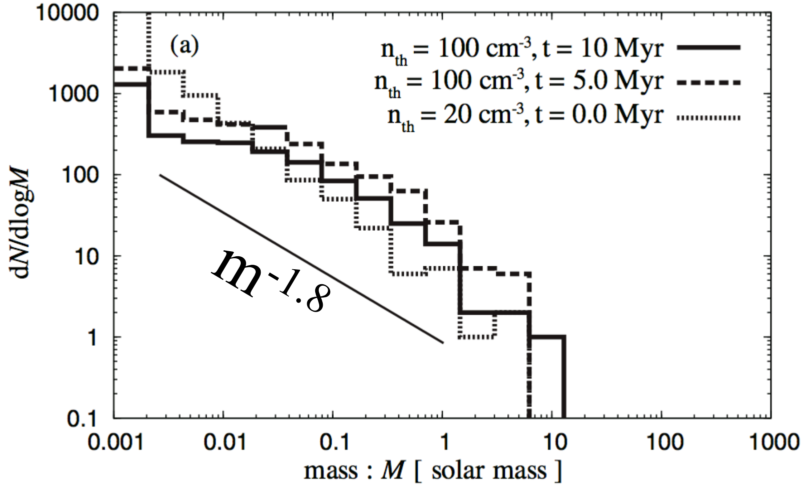
  - $n \sim 100\ \mathrm{cm}^{-3}$: $dN/dm \propto m^{-1.8}$
  - $n \gtrsim 1{,}000\ \mathrm{cm}^{-3}$: $dN/dm \propto m^{-2.3}$

✓ Spectral index of low density clumps can be understood by fragmentation by thermal instability（Hennebelle & Audit 07）.

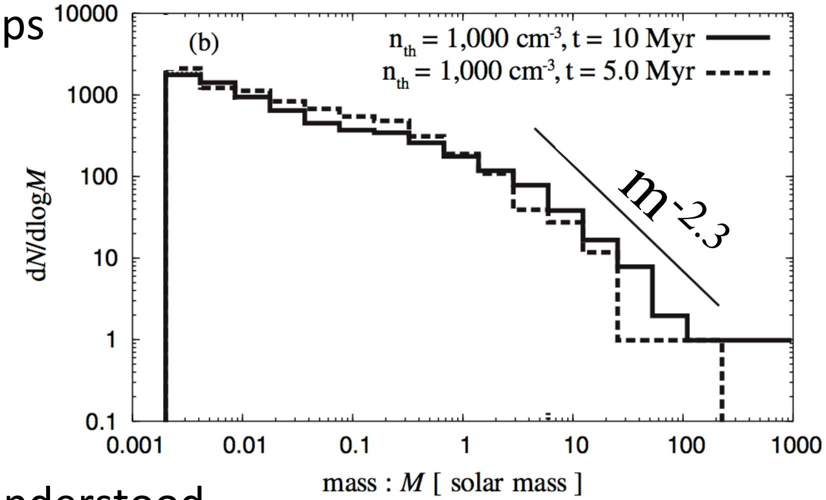
✓ Spectral index of high mass tail for dense clumps ~ Salpeter IMF index (why?, Andre+10)

Consistent with observations that suggest CMF is already determined in lower density gas of $n \sim 1000\ \mathrm{cm}^{-3}$（Ikeda+07, 09）

low density clumps ($n \lesssim 100\ \mathrm{cm}^{-3}$)



high density clumps ($n \gtrsim 1000\ \mathrm{cm}^{-3}$)



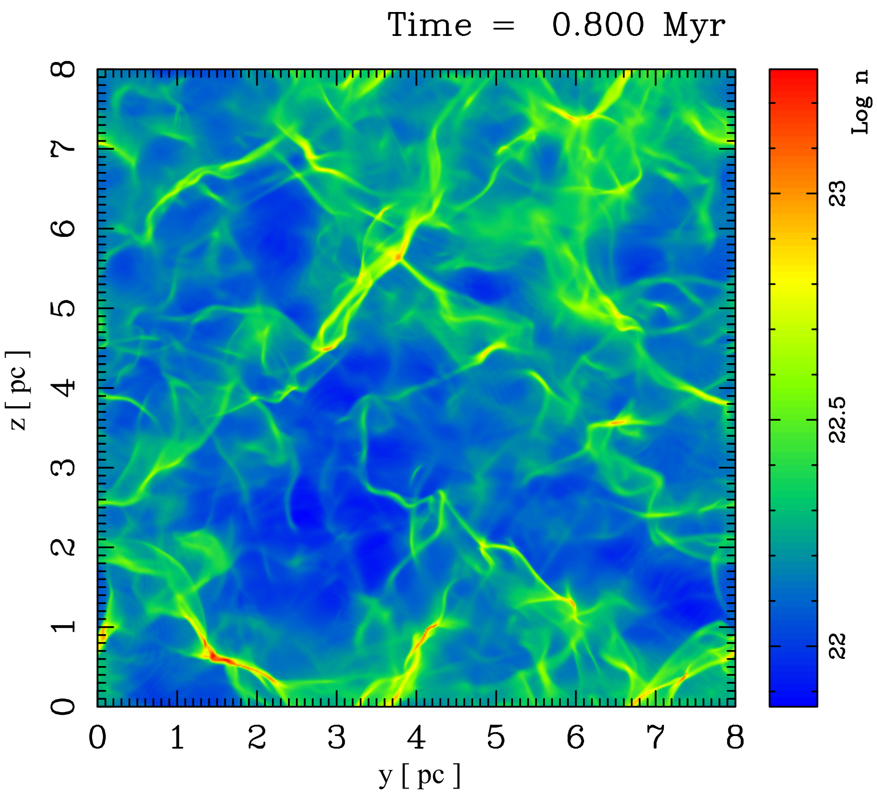
- Clumps evolve by clump-clump collision
  → Origin of CMF (and hopefully IMF) may be understood by studying clump evolution by clump-clump collision.

Summary

- We have studied molecular cloud formation via accretion of HI clouds.
- Newly-formed molecular cloud is highly inhomogeneous and non-isothermal.
  - roughly 50% of volume is filled by diffuse warm gas due to efficient turbulent mixing.
- Turbulence is generated behind deformed accretion shocks.
  - Δv in molecular gas ~ 3 km/s, Δv in diffuse gas ~ 10 km/s.
  - Total energy of turbulence in the sysytem is determined by turbulent diffuse warm gas.
- Molecular clumps evolve through certain path in virial diagram towards gravitationally bound, magnetically supercritical cores.
  - typical initial condition for star formation? : $E_{mag} \sim E_{turb} + E_{th}$
- Mass function of clumps depends on density:
  - $dN/dm \propto m^{-1.7}$ for $n \sim 100$ cm^{-3} (consisitent with Hennebelle & Audit 07 and Kramer+96).
  - $dN/dm \propto m^{-2.3}$ for $n > 1000$ cm^{-3} (consisitent with Andre+ 07 and Ikeda+07, 09).

Formation of Filaments by Clump-clump Collision

柱密度



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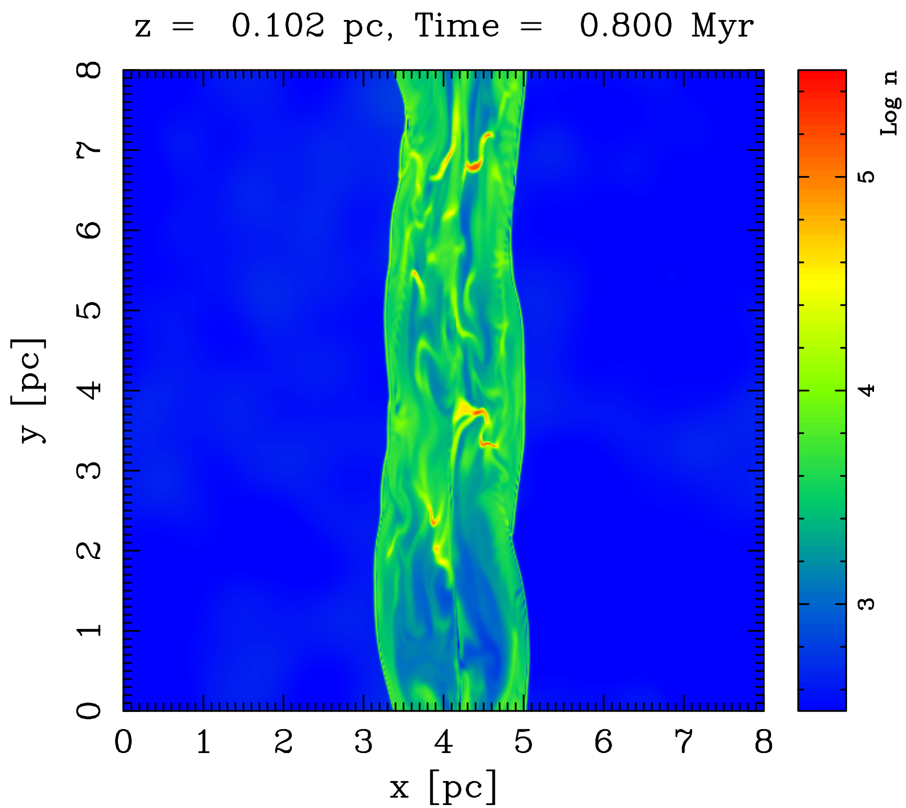
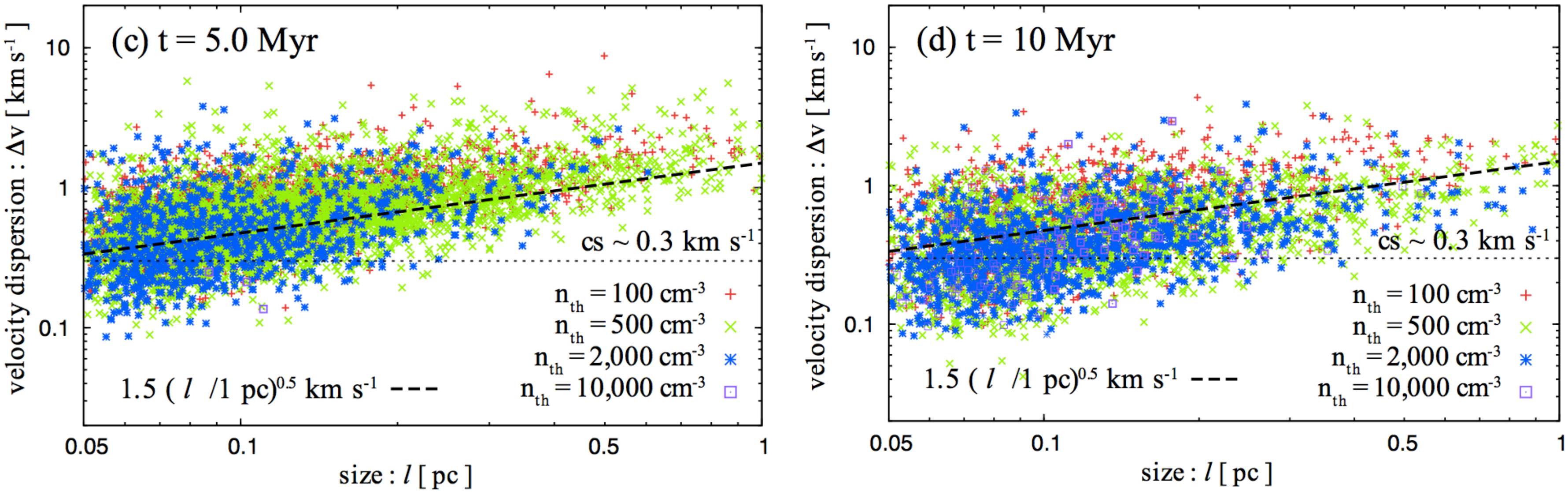


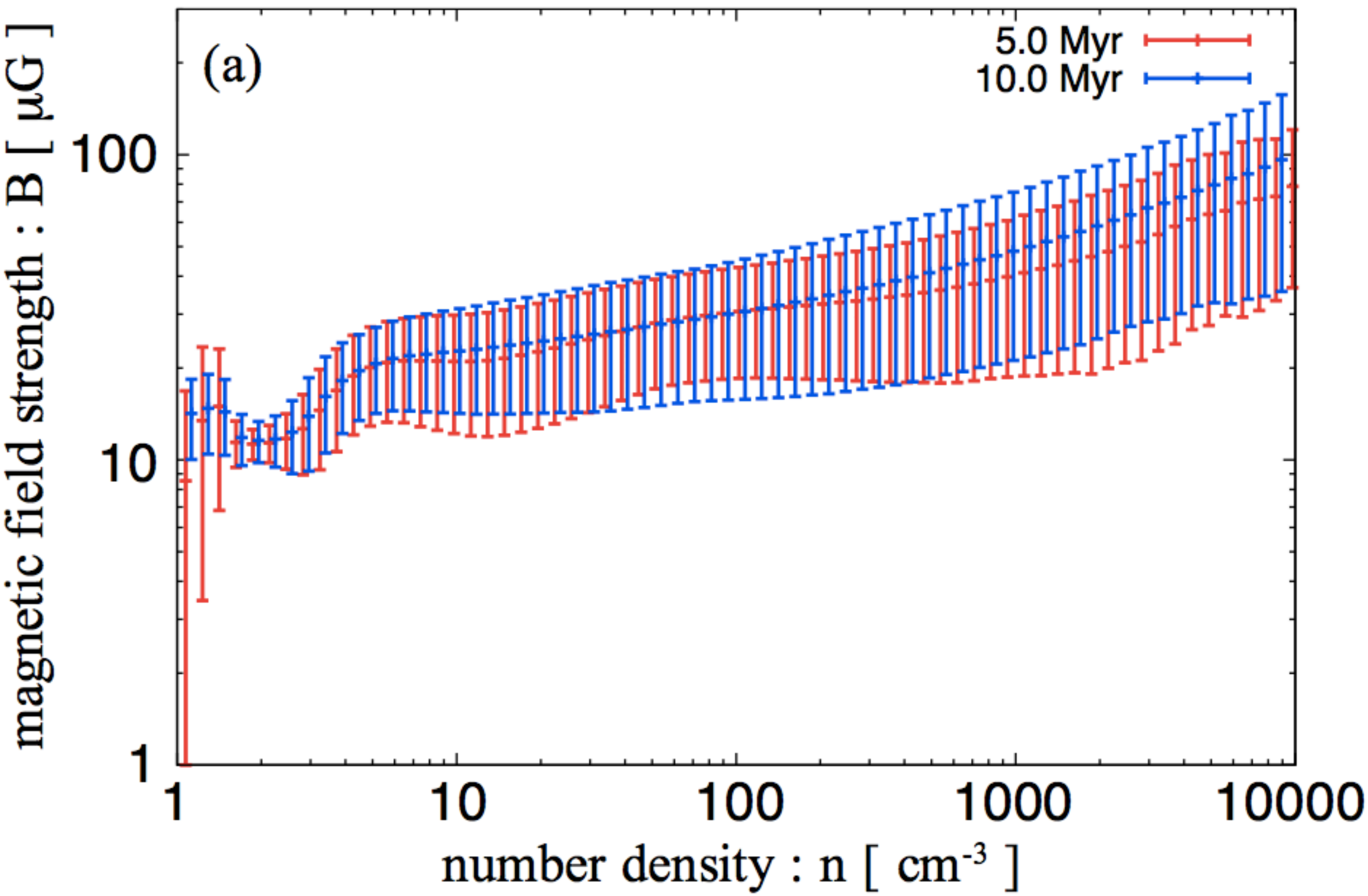
Size-Velocity Dispersion Relation

- size-velocity dispersion relation



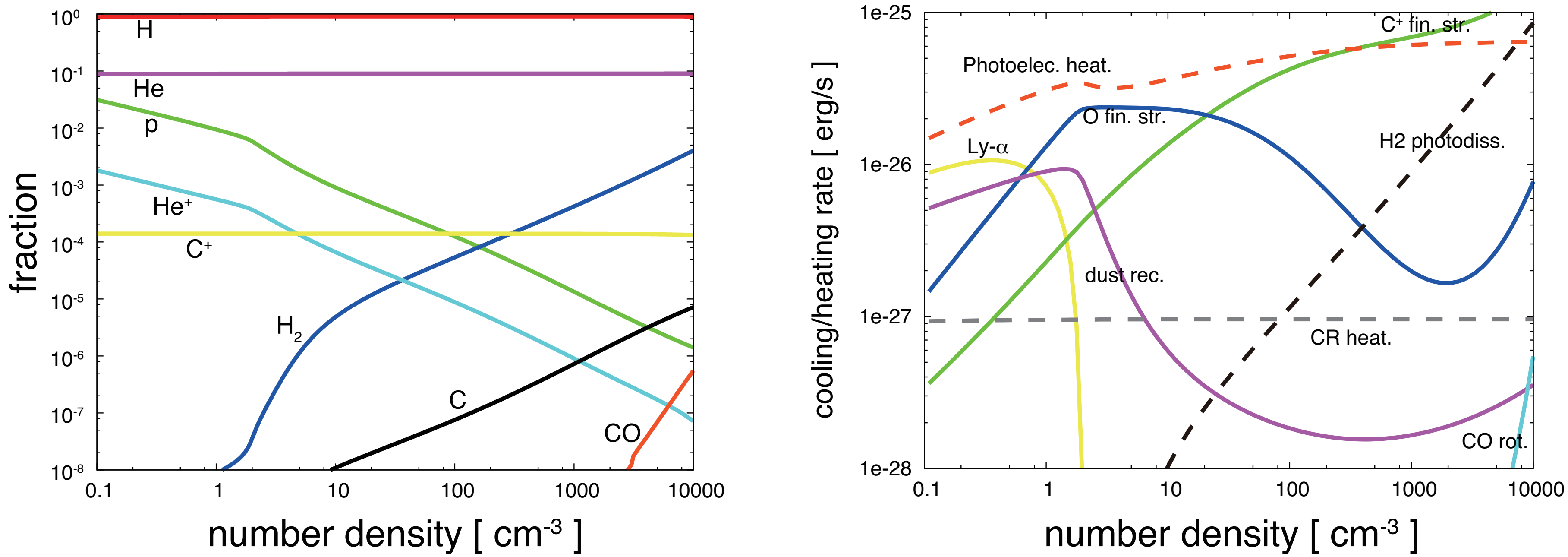
- $\Delta v \sim 1.5\ (\,l\ /1\ \mathrm{pc})^{0.5}\ \mathrm{km\ s^{-1}}$
- Relation does NOT depend on density.

Distribution of B Strength



Microphysics: Equilibrium

- Chemical, thermal, radiative equilibrium in optically thin case ($N_H = 0$).

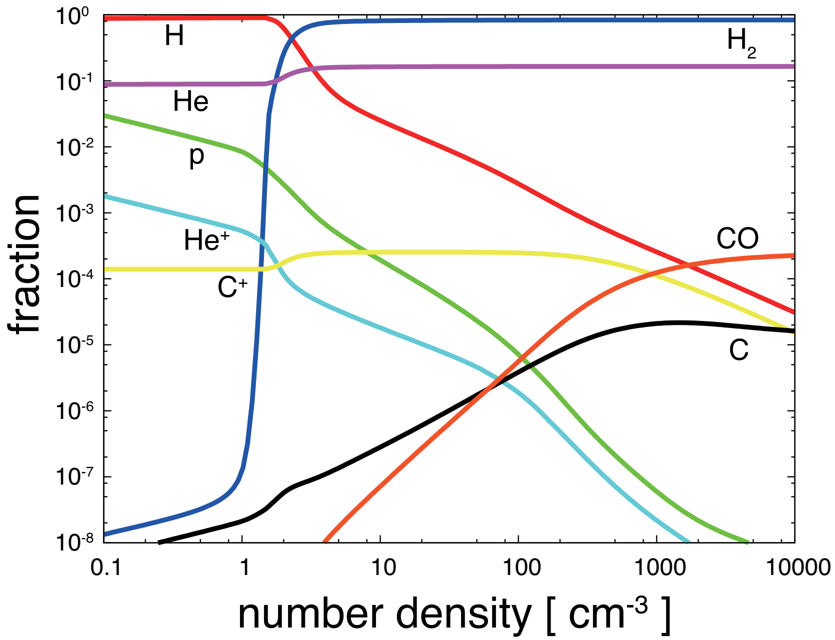


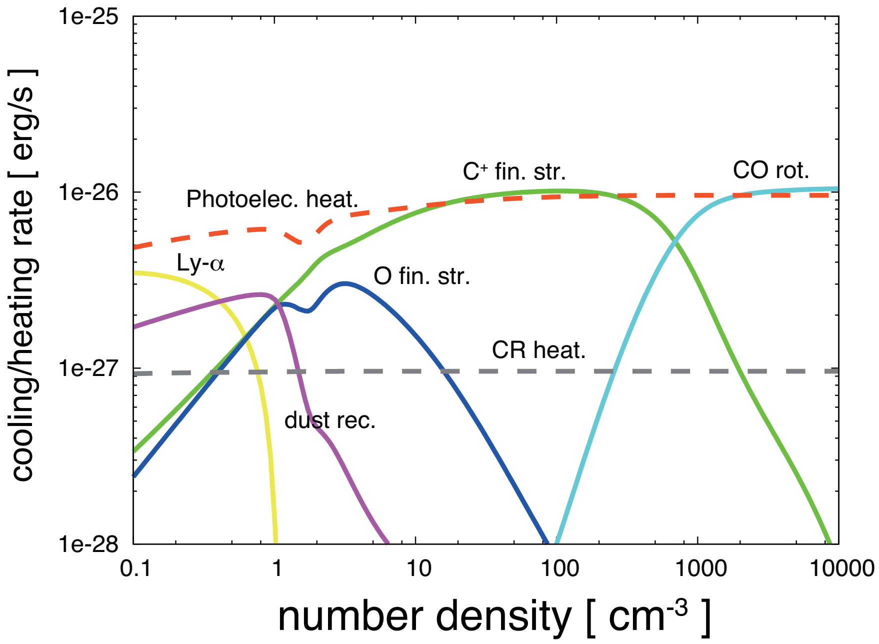
Molecules are not formed due to photo-dissociation.

Dominant cooling process in CNM is C^+ 158 μm emission.

Microphysics: Equilibrium

- Chemical, thermal, radiative equilibrium in optically thick case ($N_H = 2 \times 10^{21}$ cm^{-2}).





Molecules are formed owing to shielding effect.

Dominant cooling process in dense gas is CO emission.