初代銀河における熱不安定性

井上 剛志 (国立天文台)

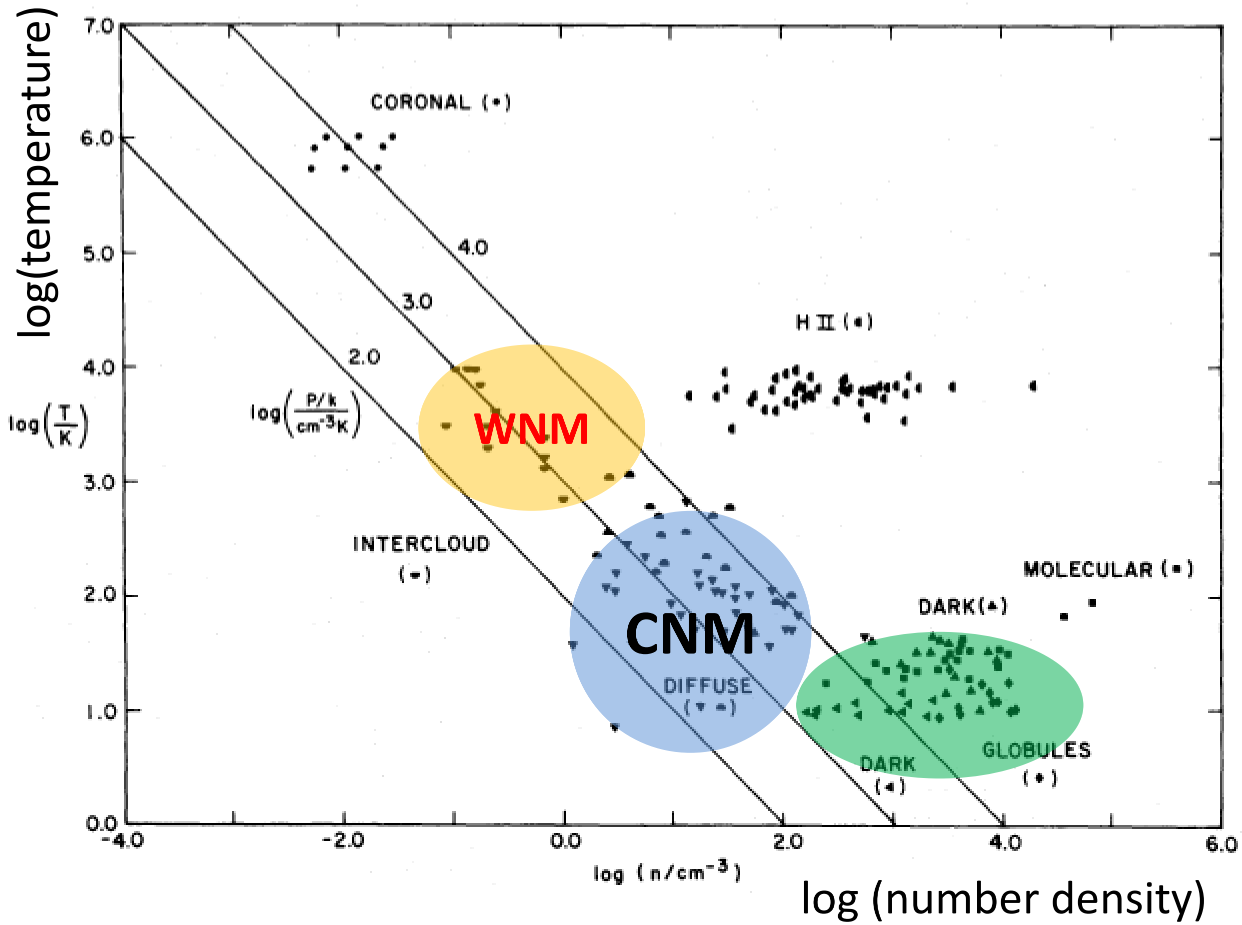
大向一行 (東北大)

Inoue & Omukai (2015), arXiv:1412.5699

TOHOKU UNIVERSITY

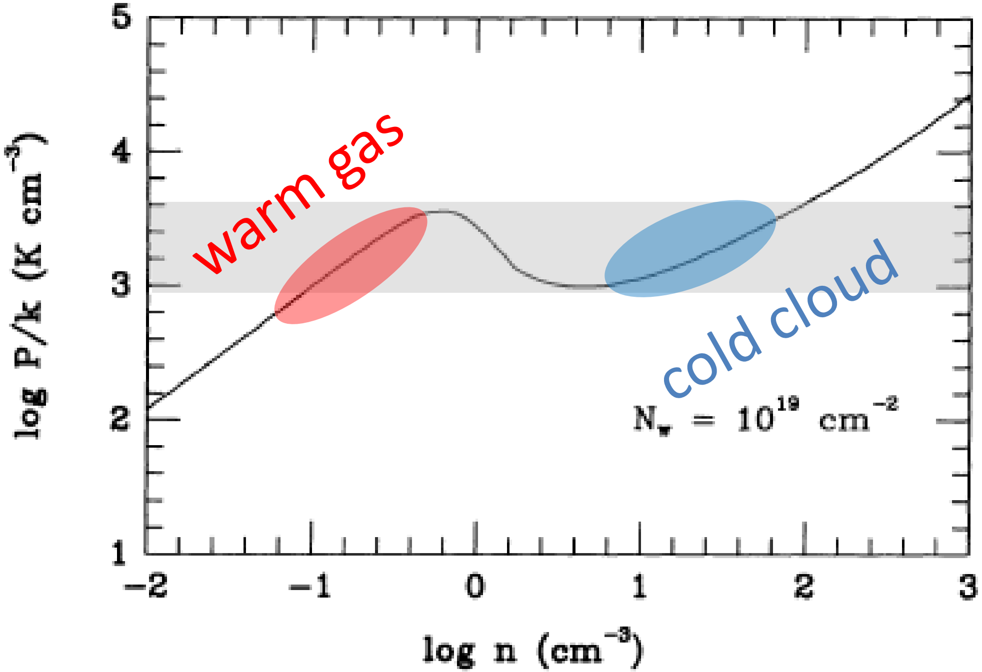
Theoretical Astrophysics Tohoku University

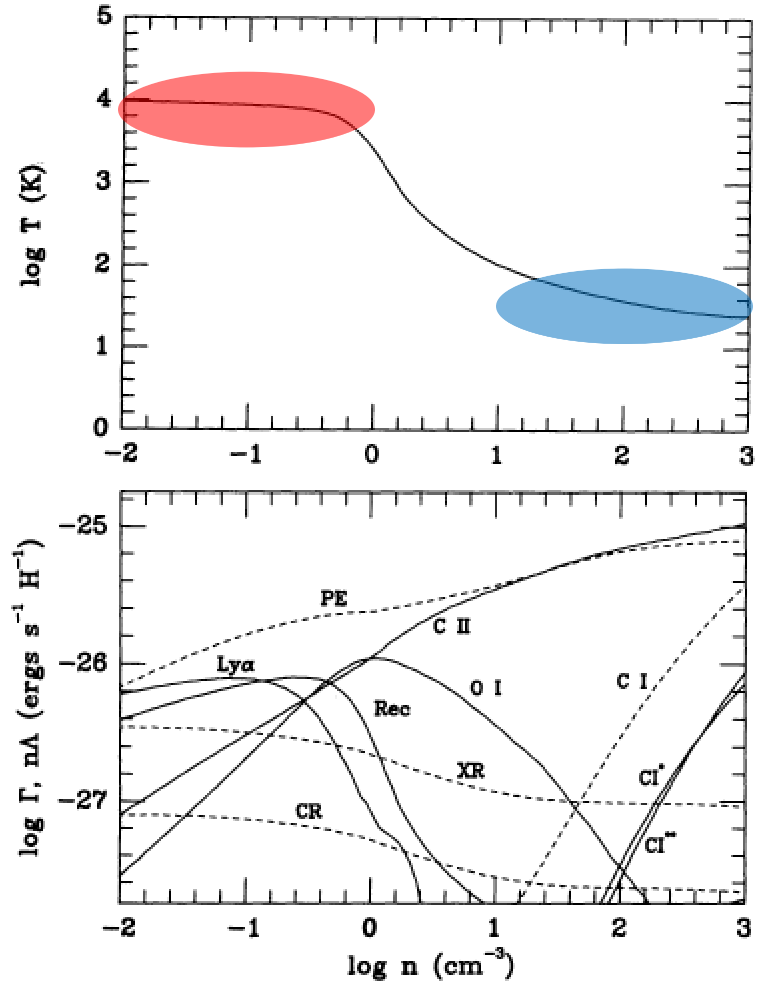
Multi-phase interstellar medium (ISM)



- (Diffuse) neutral media are close to pressure equilibrium
- Molecular gas has higher pressure and Self-gravitating.

thermal stability of ISM

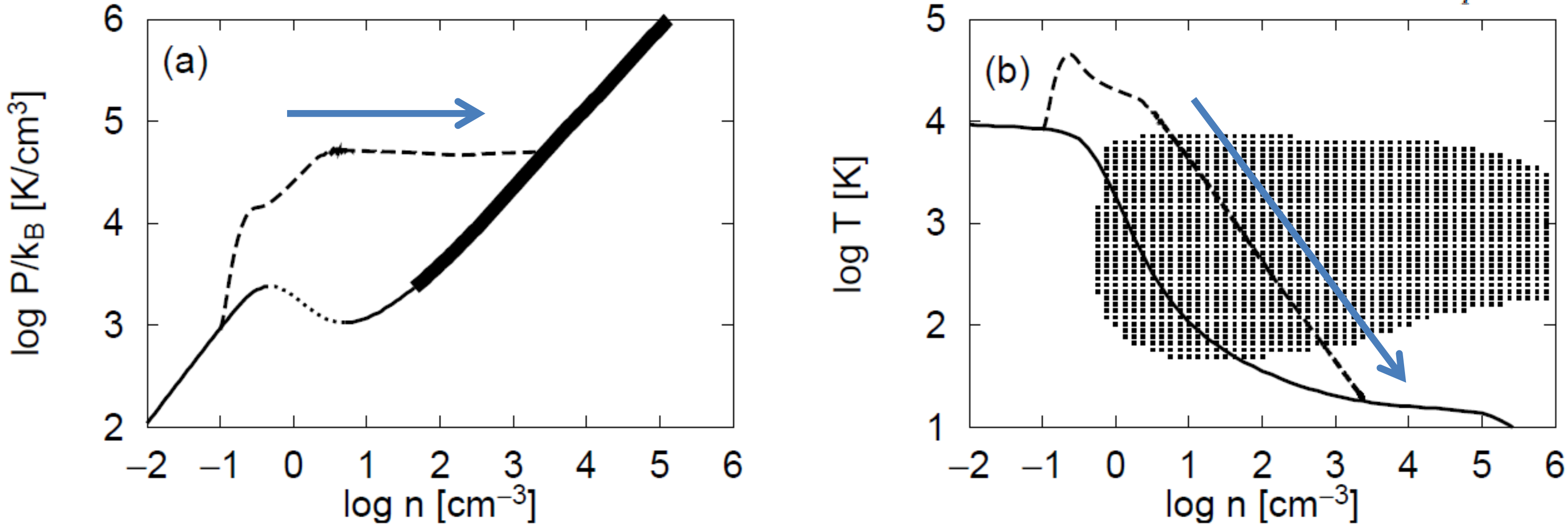




- Multi-phase ISM is a result of thermal stability

Thermal instability by shocks

instability criterion $\left(\frac{\partial \Lambda}{\partial T}\right)_p < 0$

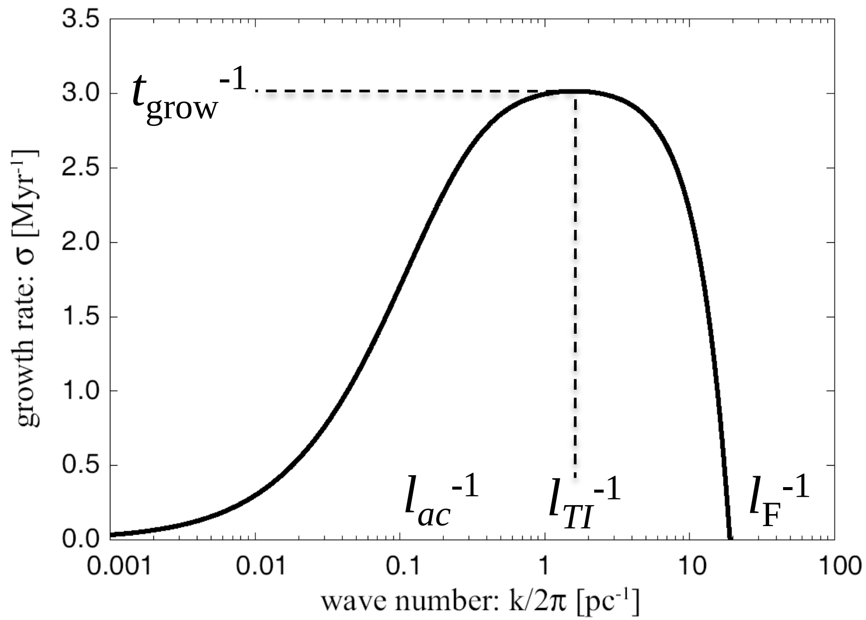


Two phase medium is developed during its (isobaric) cooling.

Basics of Thermal Instability

- Thermal Intability (TI): runaway cooling that causes inhomogeneous condensation.
- Linear analyses (Field 65, Schwarz+ 72, Koyama & Inutsuka 01)

Dispersion relation



Timescale scale: $t_{\rm grow} = t_{\rm cool} \lesssim 1$ Myr

Most unstable scale: $l_{\rm TI} = \sqrt{l_c l_F} \lesssim 1$ pc

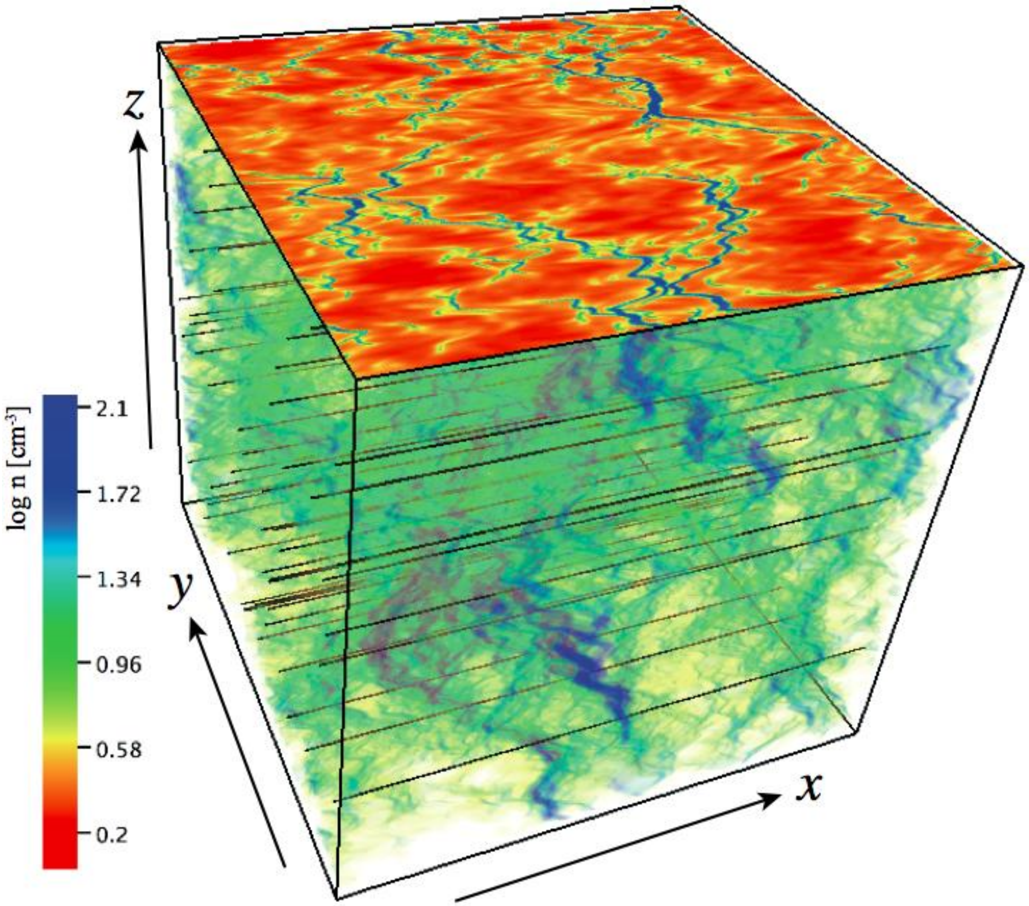
Field length: $l_F = \sqrt{\kappa T/\Lambda} \lesssim 0.1$ pc

Acoustic length: $l_{ac} = c_s t_{cool} \lesssim 10$ pc

- $t_{\rm grow} = t_{\rm cool}$ indicates that TI generate fragmented CNM, even if unperturbed state is uniformly condensing gas.
- Nonlinear growth generates cloud much smaller than $l_{\rm TI}$ due to condensation.

3D MHD simulation

Inoue & Inutsuka (2012)



Shock by colliding flows

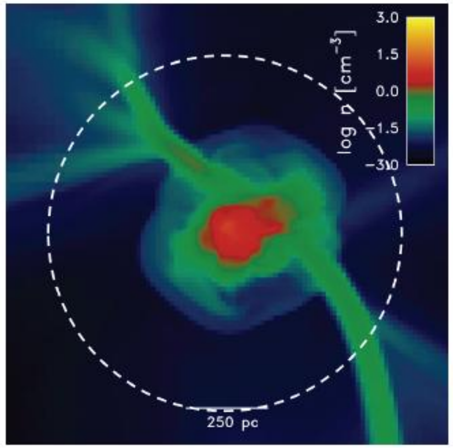
⬇

Two-phase medium is reproduced

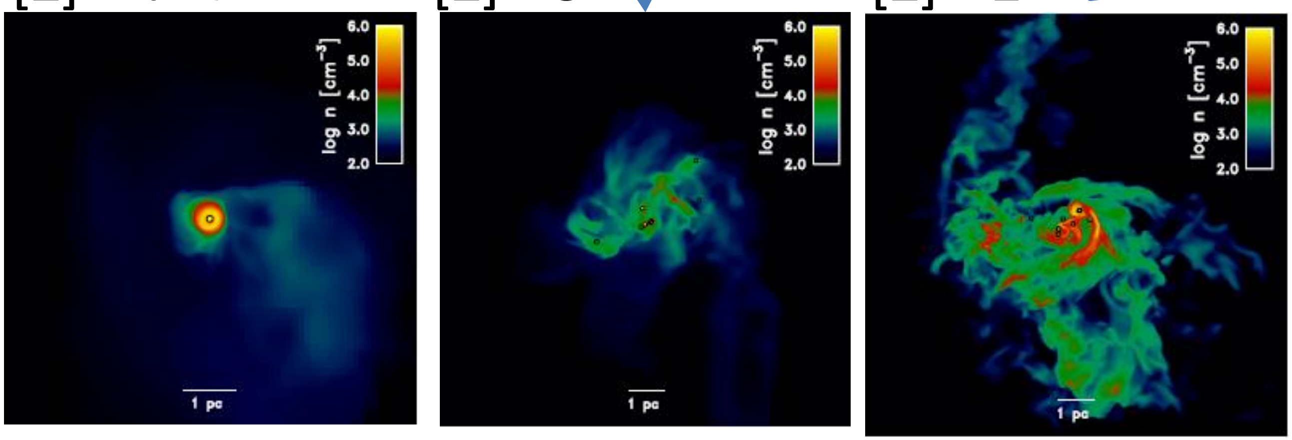
How about in low-Z gas?

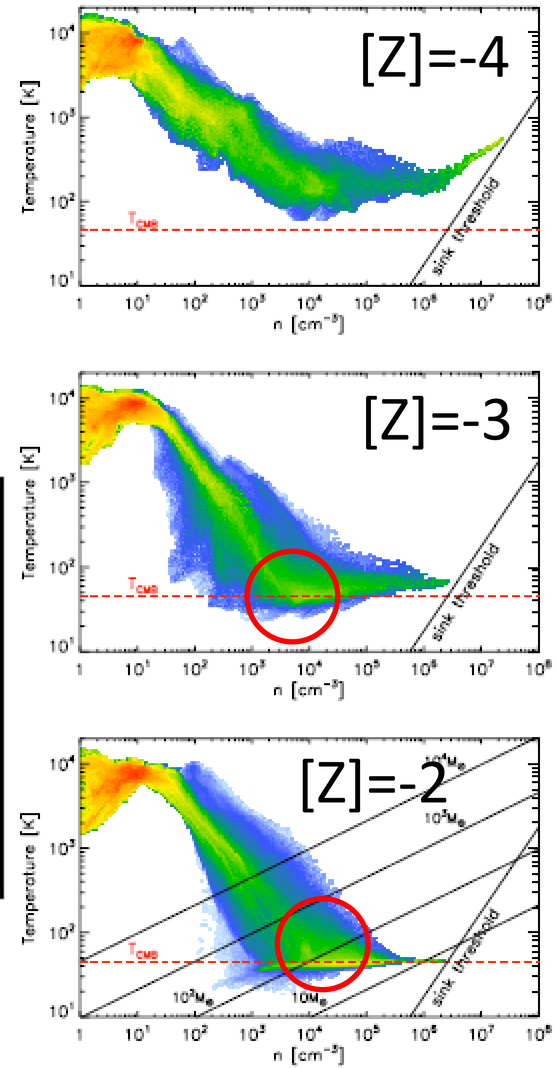
Safranek-Shrader et al. 2013

Add metals to a halo in cosmological simulation



[Z]=-4 [Z]=-3 [Z]=-2



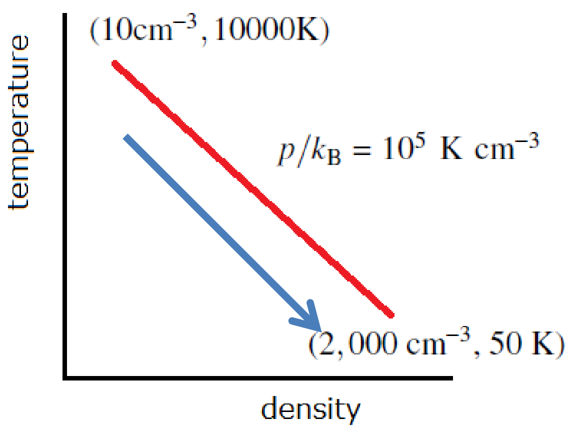


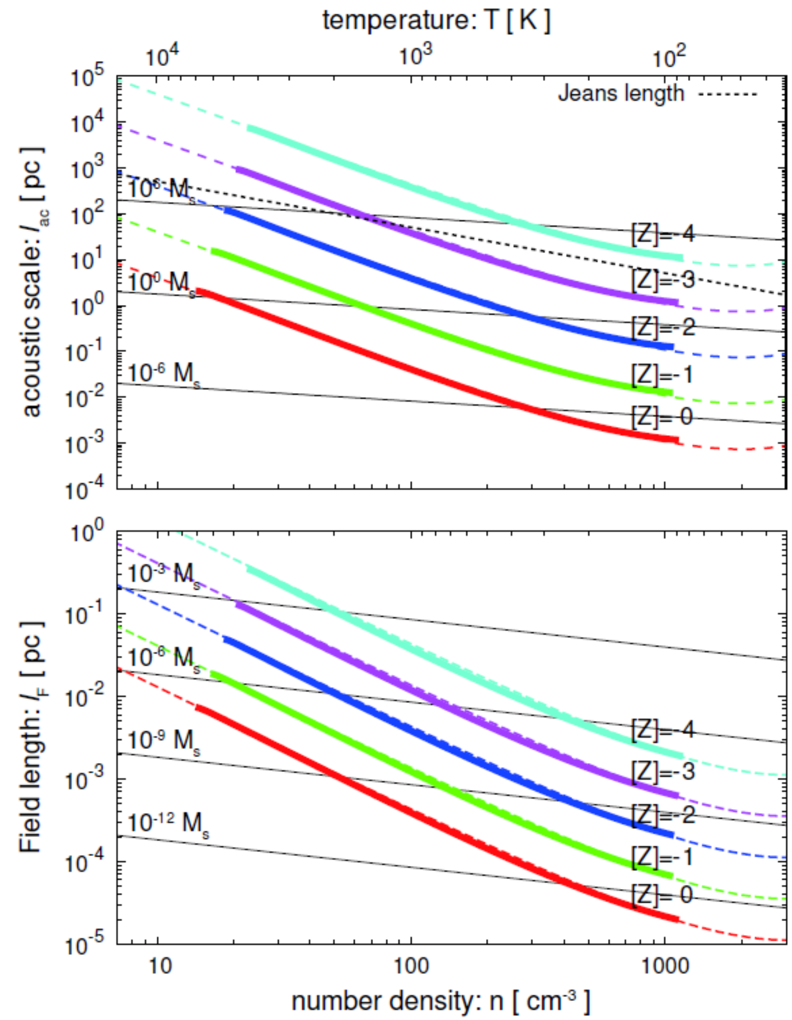
For [Z]>= -3, almost isobaric contraction and fragmentation at T_{CMB}

They are thermally unstable, too

if FUV radiation is present

G_0=1 is assumed



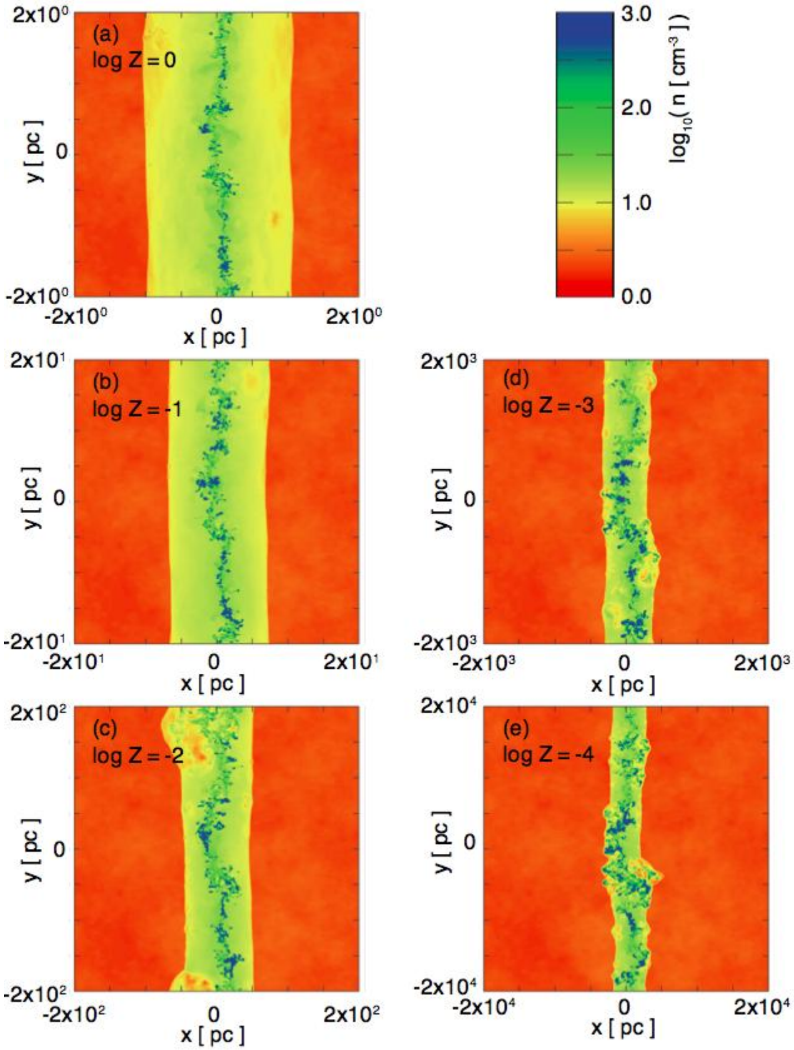


Acoustic scale is below the Jeans scale for [Z] > -3.

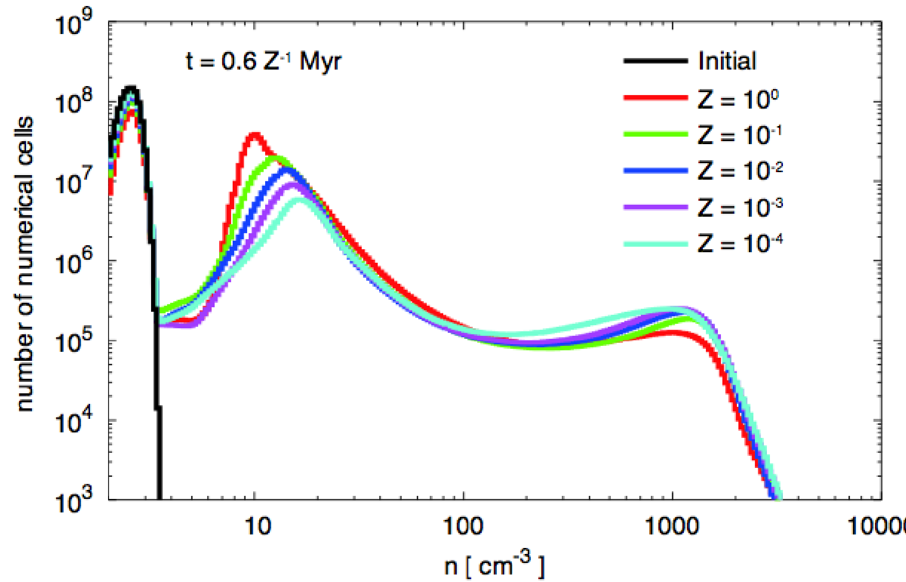
局所3次元シミュレーション

- Converging flow で等圧冷却収縮ガスを生成させて熱不安定の成長を見る(G0 = 1)

熱不安定でガスは分裂

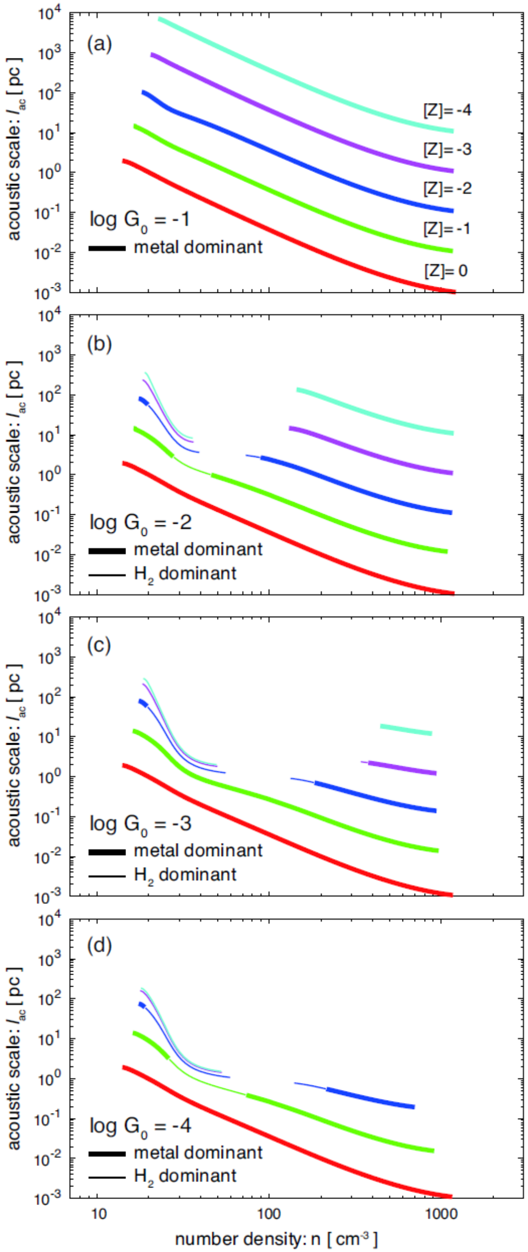


ρ PDF

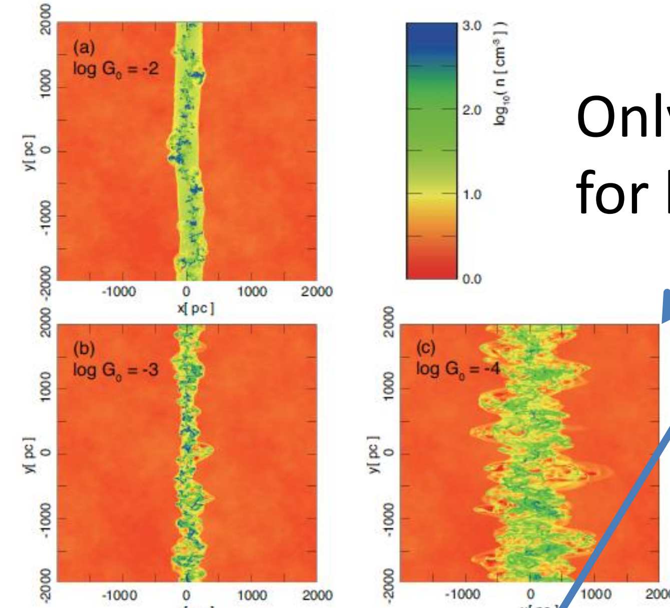


＊熱的不安定の結果 bimodal PDF

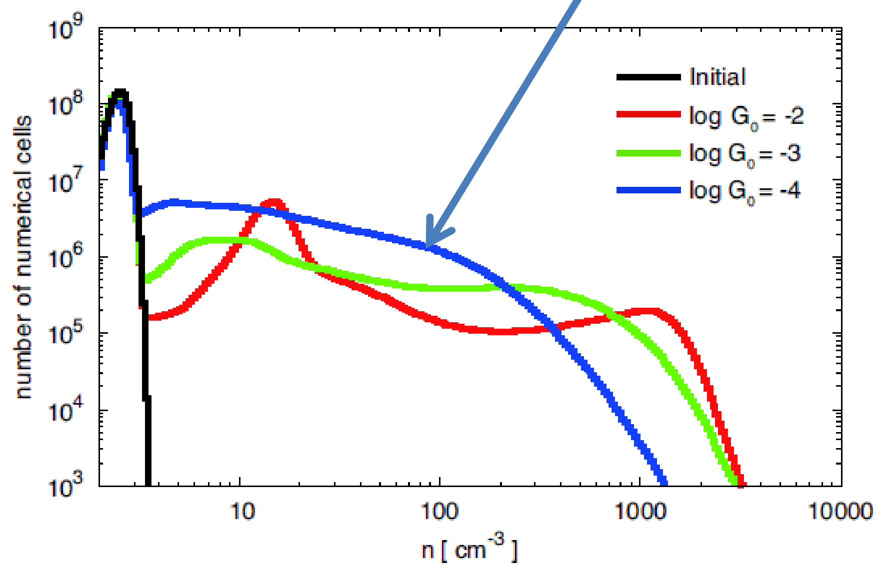
For lower G_0



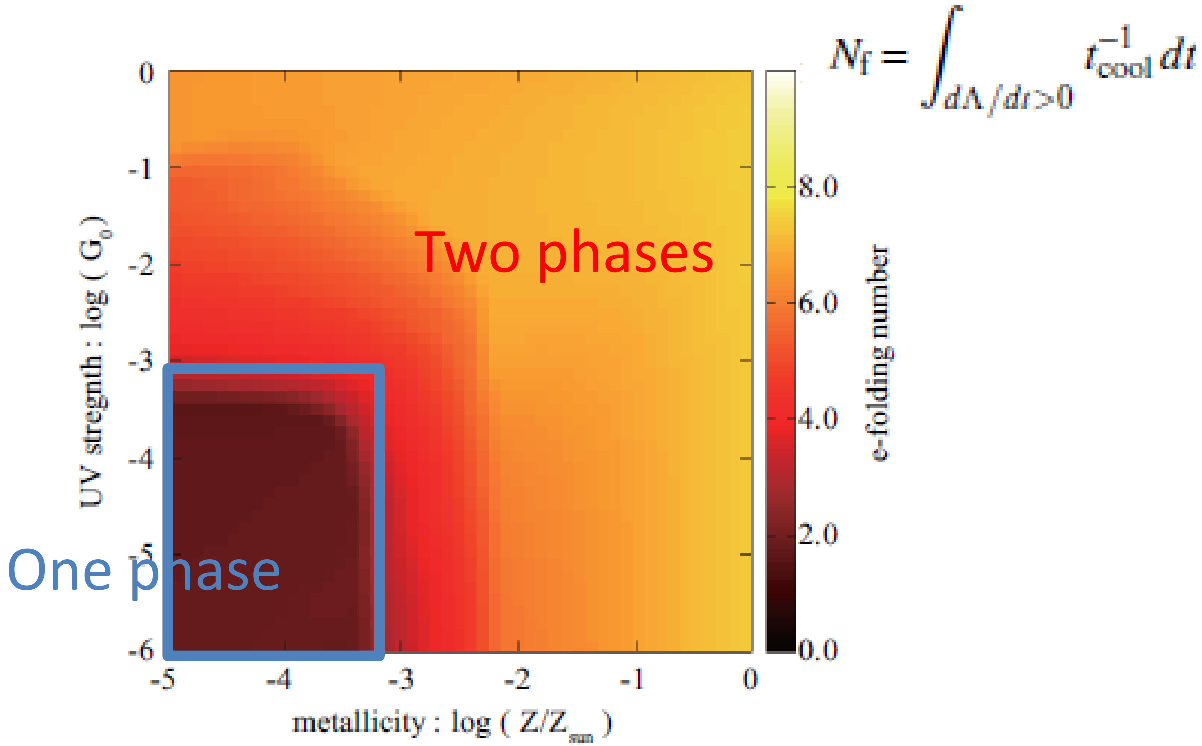
Thermal instability range shrinks



Only one phase for log G_0=-4



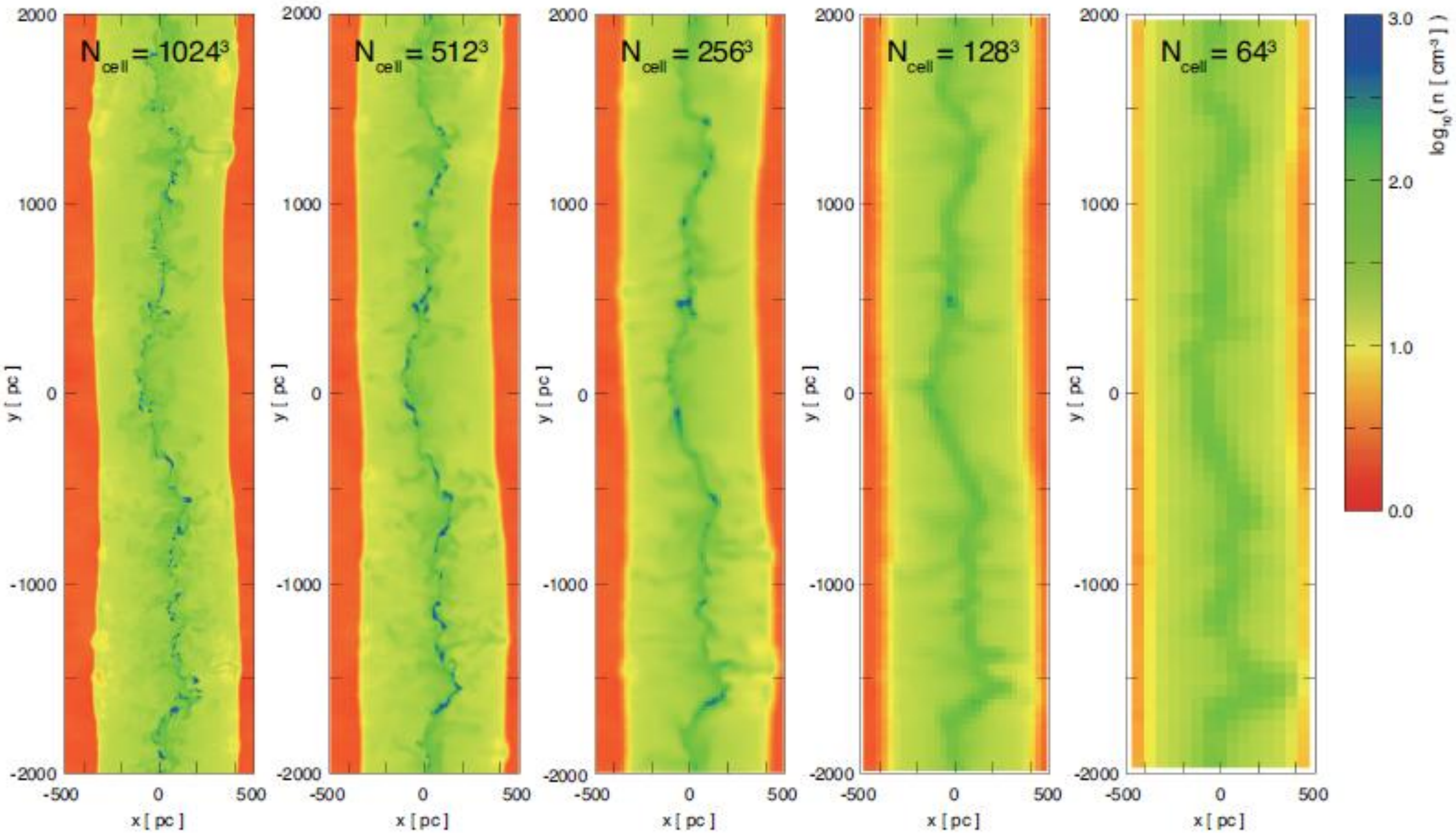
Condition for two phase medium



$N_f > 2$ for two phase medium
from numerical experiment

Required resolution

Clumps resolved ← → not resolved



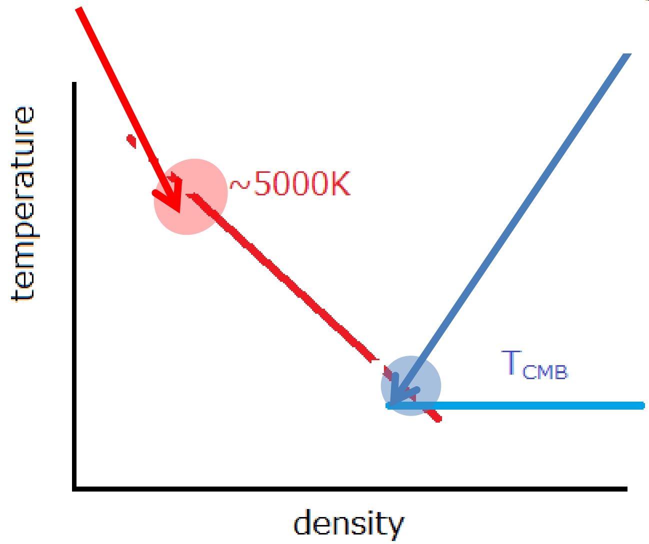
- ✓Acoustic scale need to be resolved with >60 cells.
- ✓Most simulations with Jeans criterion fail in resolving clumps

Thermal & gravitatinal instability scales

$$m_{\rm TI} \equiv 0.04 \times \frac{4\pi}{3}\rho\left(\frac{l_{\rm ac}}{2}\right)^3$$
$$\sim 1.3\times 10^4\,{\rm M_\odot}\left(\frac{Z}{0.01 Z_\odot}\right)^{-3}\left(\frac{T}{5000{\rm K}^{-3}}\right)^5\left(\frac{p/k_{\rm B}}{10^5\,{\rm K\,cm^{-3}}}\right)^{-2}$$

$$m_{\rm J,CMB} \equiv \frac{4\pi}{3}\rho\left(\frac{l_{\rm J}}{2}\right)^3$$
$$= 190\,{\rm M_\odot}\left(\frac{p/k_{\rm B}}{10^5\,{\rm K\,cm^{-3}}}\right)^{-1/2}\left(\frac{1+z}{10}\right)^2$$

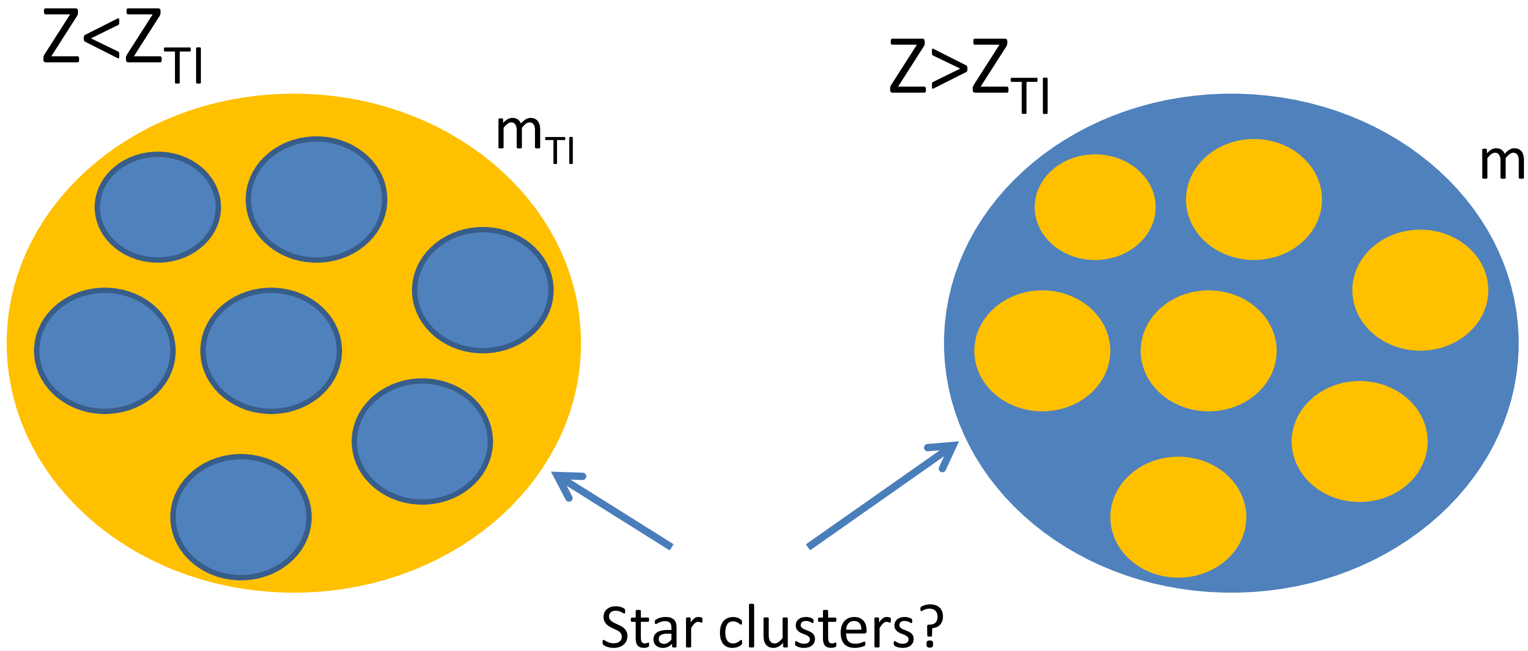
For the expected power-low distribution $N(m) \propto m^{-1.78}$
>50% of mass above m_{TI}



$$Z_{\rm TI} = 0.042\,Z_\odot\left(\frac{T}{5000\,{\rm K}^{-3}}\right)^{5/3}\left(\frac{p/k_{\rm B}}{10^5\,{\rm K\,cm^{-3}}}\right)^{-1/2}\left(\frac{1+z}{10}\right)^{-2/3}$$

If $Z > Z_{TI}$ → $m_{J,CMB} > m_{TI}$
$Z < Z_{TI}$ $m_{J,CMB} < m_{TI}$

Significance of Z_{TI} ?



Single phase/no turbulence
→ starburst?

Two phase/turbulent medium
→ gradual star formation?

まとめ

- 低金属環境下における熱的不安定性の線形/非線形成長を調べた
  - 不安定性の最大/最小スケールの解析的表現

$$l_{\rm ac} \simeq 4\,{\rm pc}\,\left(Z/Z_\odot\right)^{-1}\, n_1^{-2}\,(p/k_{\rm B})_5$$
$$l_{\rm F} \simeq 0.013\,{\rm pc}\,\left(Z/Z_\odot\right)^{-1/2}\, n_1^{-3/2}\,(p/k_{\rm B})_5^{1/2}$$

  - 最大スケールを 60 mesh 以上で分解することがシミュレーションに必須
  - 熱不安定が非線形成長で 2-phasic ISM を生成する条件を導いた:

$G_0 > 10^{-3}$ or $Z > 10^{-3}\ Z_{\rm sun}$

→ 今後の初代銀河形成研究の物理的基盤を整えた