Dynamics of Multi-Phase Interstellar Medium

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Keywords:
radiative cooling/heating,
thermal instability, MHD,
supersonic velocity dispersion, etc.

Observed "Turbulence" in ISM

Observation of Molecular Clouds

line-width $\delta v > C_S$

Universal Supersonic Velocity Dispersion

even in the clouds without star formation activity

⇒ should not due to star formation activity

Numerical Simulation of (Isothermal) MHD

Turbulence ⇒ Rapid Shock Dissipation or Cascade

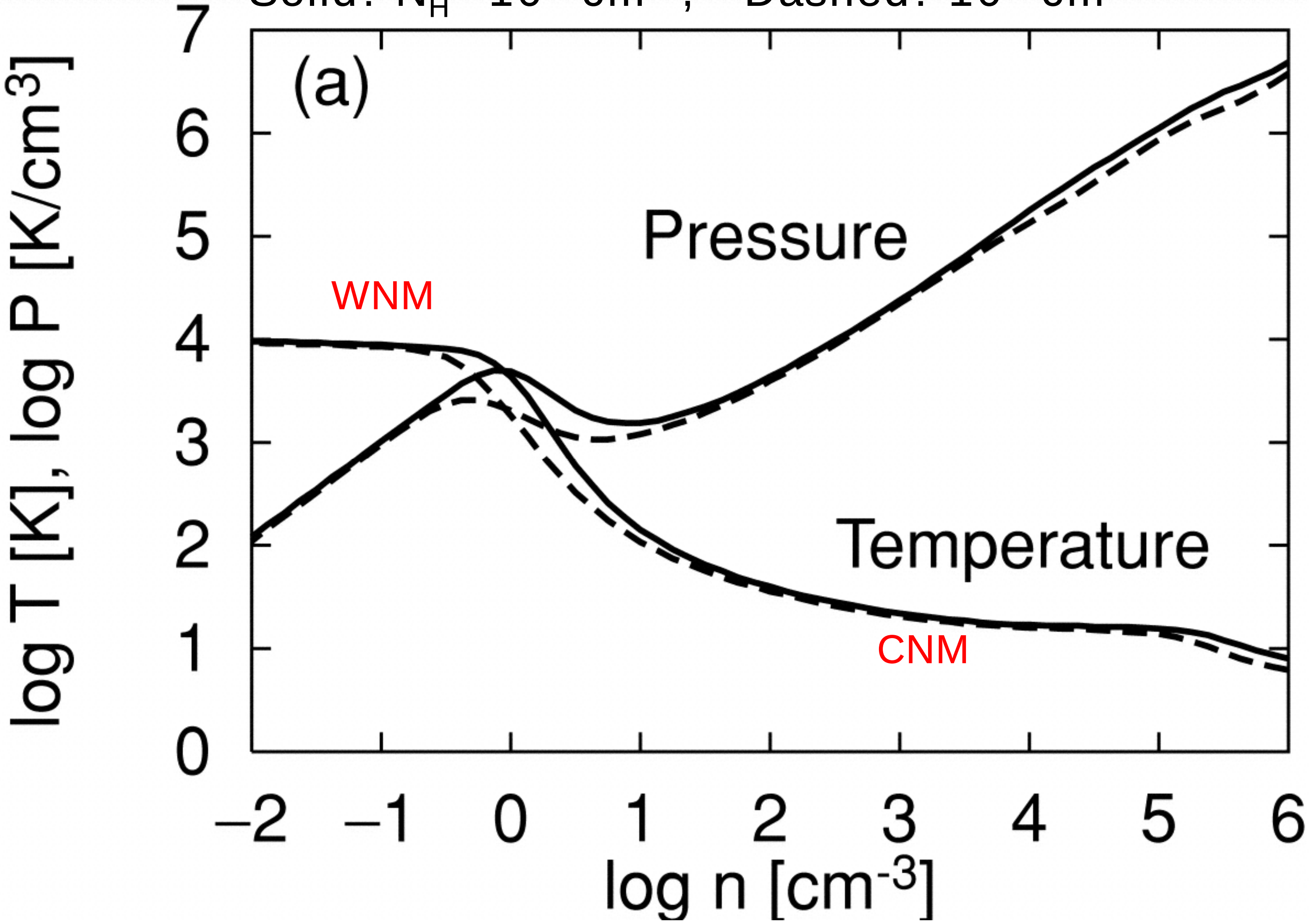
- Dissipation time « Lifetime of Molecular Clouds
  - Gammie & Ostriker 1996, Mac Low 1997, Ostriker et al. 1999, Stone et al. 1999, etc…

Recent Study on Origin of Supersonic Motion

- Koyama & Inutsuka, ApJ **532**, 980, 2000; ApJL **564**, L97 , 2002
- Kritsuk & Norman 2002a, ApJ **569**, L127; 2002b ApJ **580**, L51
- Audit & Hennebelle 2005, A&A **433**, 1
- Heitsch, Burkert, Hartmann et al. 2005, ApJ **633**, L113, Vazquez-Semadeni et al. 2006, etc...

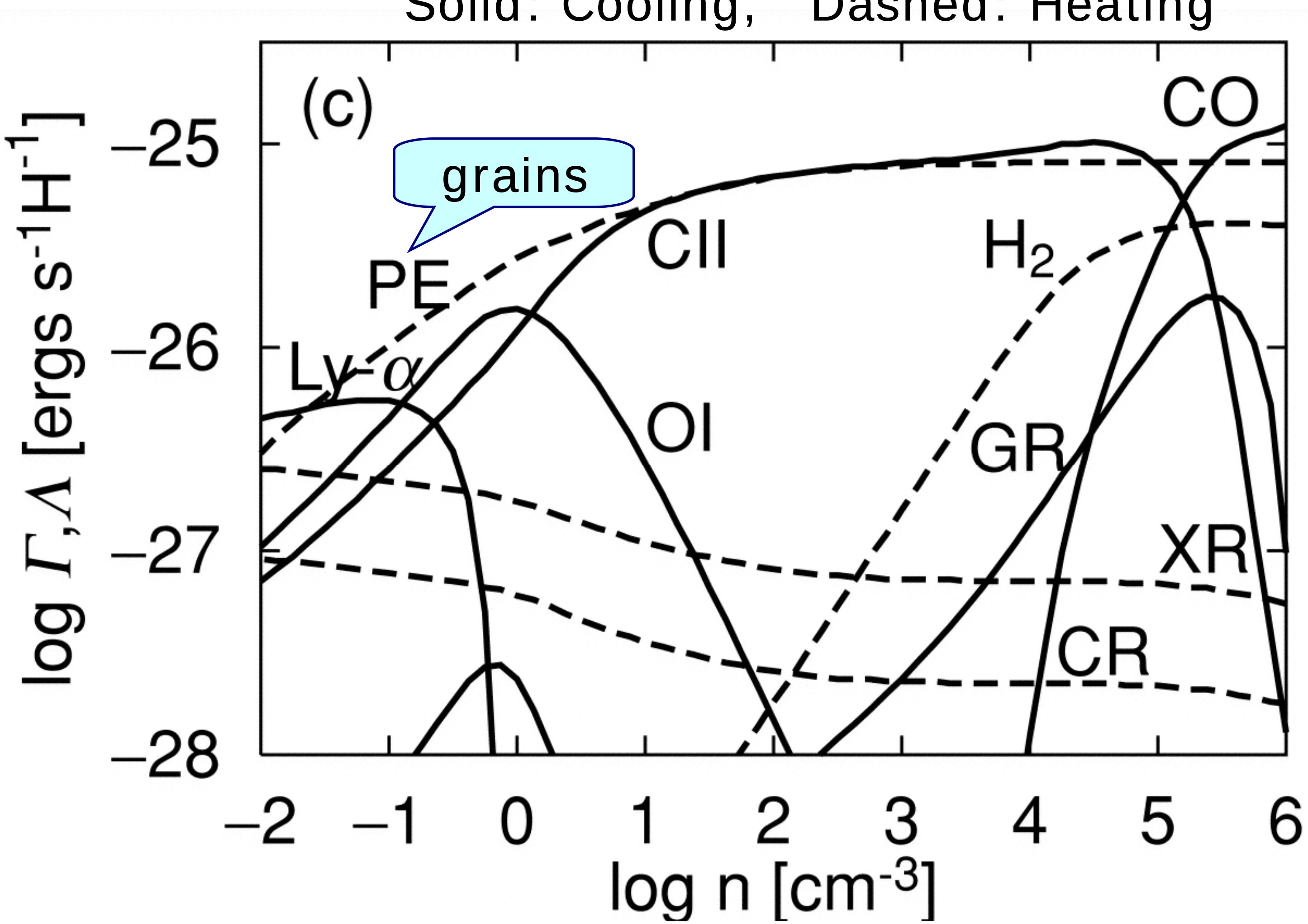
Radiative Equilibrium

Solid: $N_H = 10^{19} cm^{-2}$,   Dashed: $10^{20} cm^{-2}$



Radiative Cooling & Heating

Solid: Cooling, Dashed: Heating



Koyama & Inutsuka (2000) ApJ **532**, 980 , based on Wolfire et al. 1995

Basic Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho v\right) = 0,$$

$$\frac{\partial v}{\partial t} + v \cdot \nabla v = -\frac{1}{\rho} \nabla P + \frac{\left(\nabla \times B\right) \times B}{4\pi\rho},$$

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot (\rho e v) + P \nabla \cdot v - \frac{\left|\left(\nabla \times B\right) \times B\right|^2}{16\pi^2 A \rho \rho_i} = \rho \Gamma - \rho^2 \Lambda(T) + \nabla \cdot \left(K \nabla T\right),$$

$$\frac{\partial B}{\partial t} = \nabla \times (v_i \times B),$$

$$v_i - v = \frac{\left(\nabla \times B\right) \times B}{4\pi A \rho \rho_i},$$

$$\rho_i = m_H n(HII) + 12 m_H n f_{CII},$$

$$0 = \zeta n(HI) - n(HII) n(e) \alpha(T),$$

$$n(e) = n(HII) + n f_{CII}.$$

radiative heating/cooling

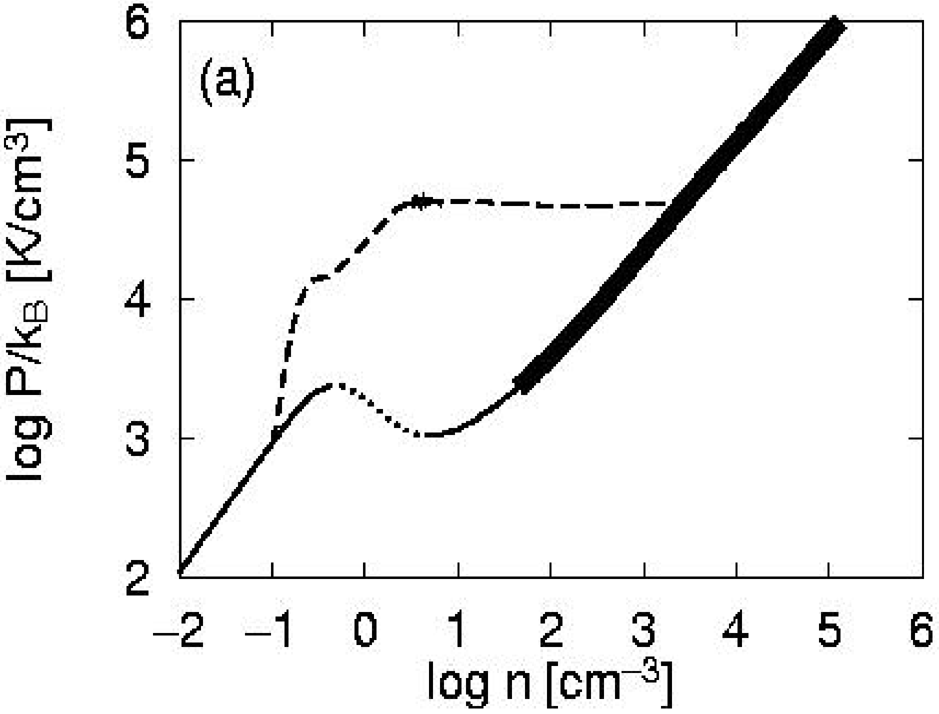
thermal conduction

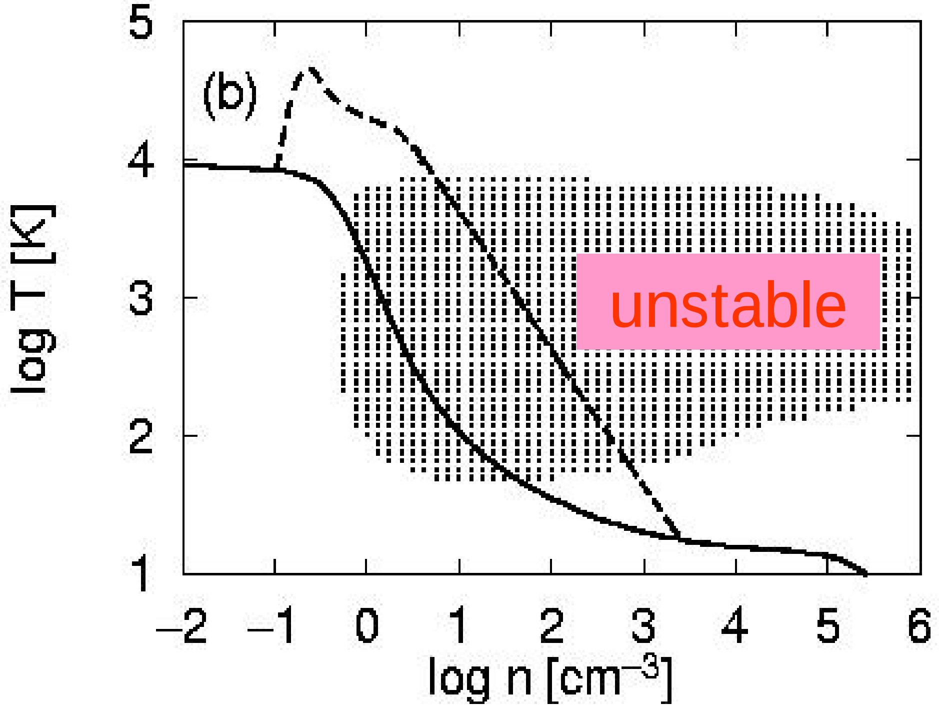
1D Shock Propagation into WNM

Density-Temperature Diagram

– through unstable region

Density-Pressure Diagram

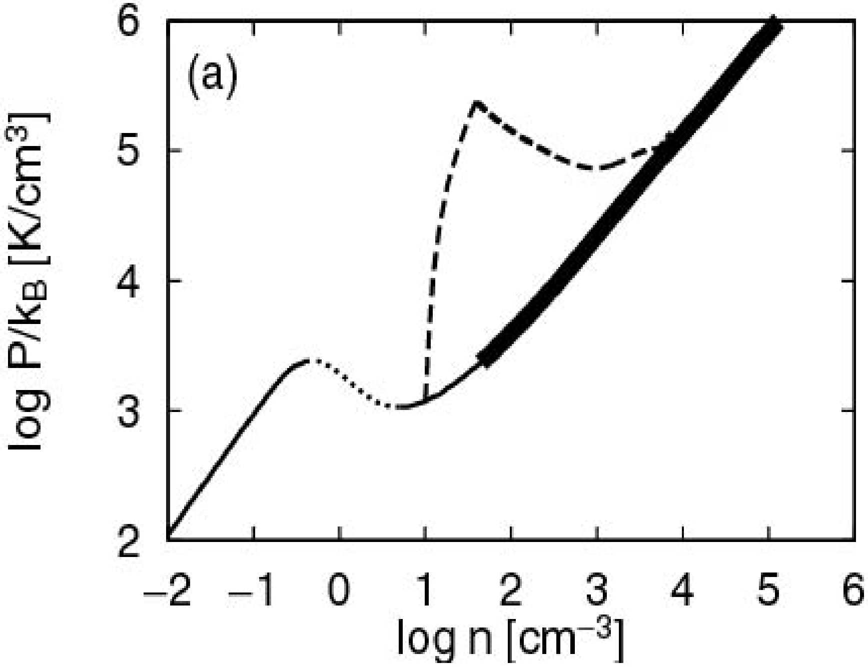




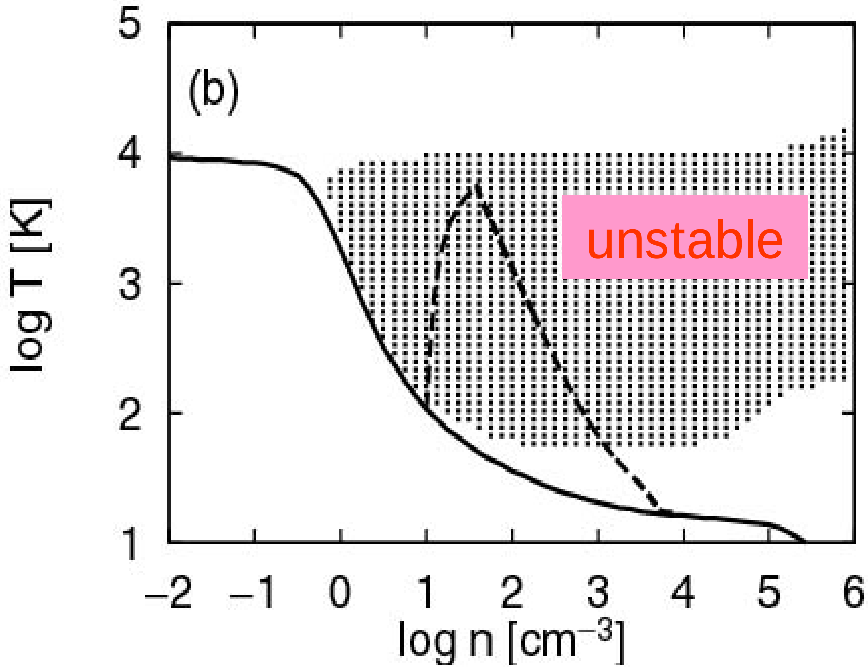
Koyama & Inutsuka 2000, ApJ **532**, 980

1D Shock Propagation into CNM

Density-Pressure Diagram



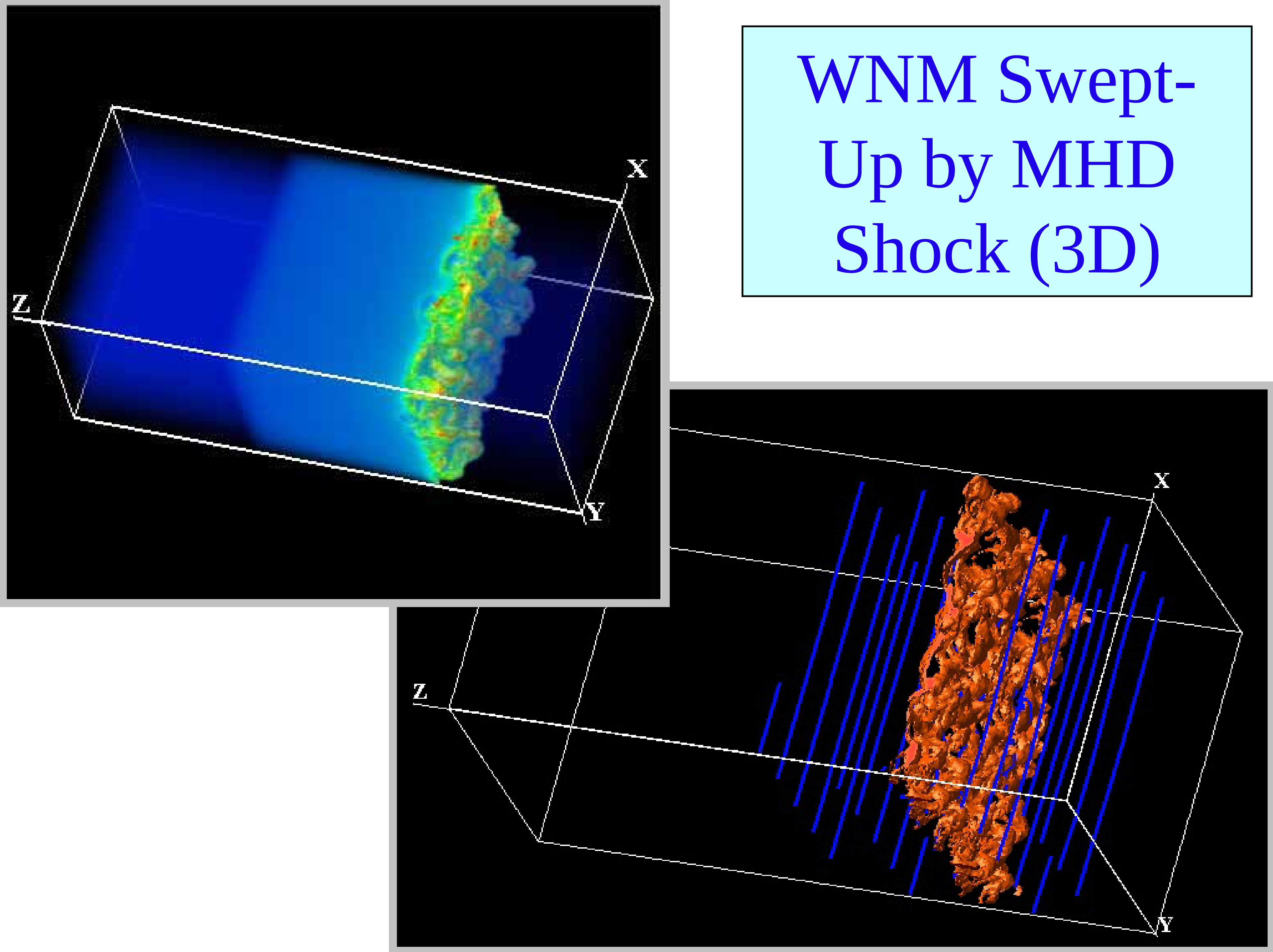
Density-Temperature Diagram



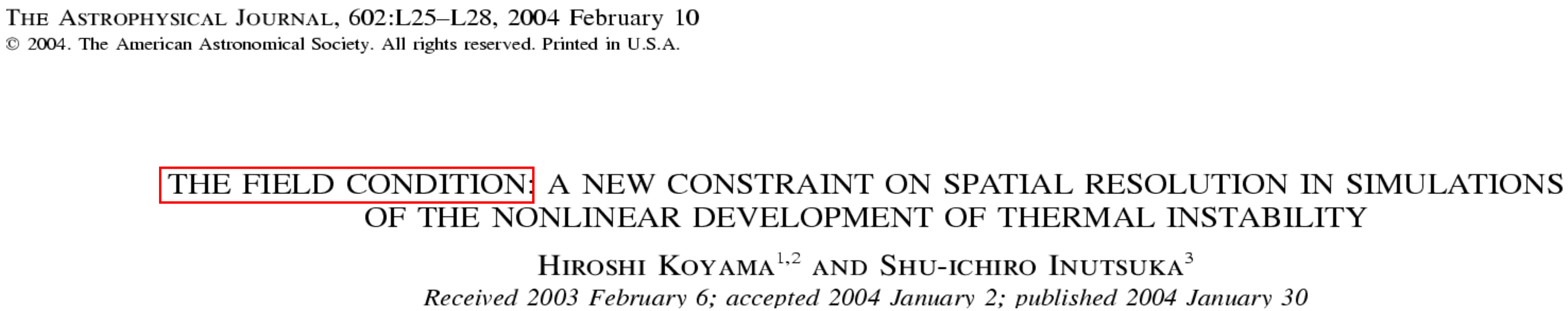
CNM becomes thermally unstable with shock.

Koyama & Inutsuka,2000,ApJ **532**,980

WNM Swept-Up by MHD Shock (3D)



Warning to Numerical Simulation



THE ASTROPHYSICAL JOURNAL, 602:L25–L28, 2004 February 10

THE FIELD CONDITION: A NEW CONSTRAINT ON SPATIAL RESOLUTION IN SIMULATIONS
OF THE NONLINEAR DEVELOPMENT OF THERMAL INSTABILITY

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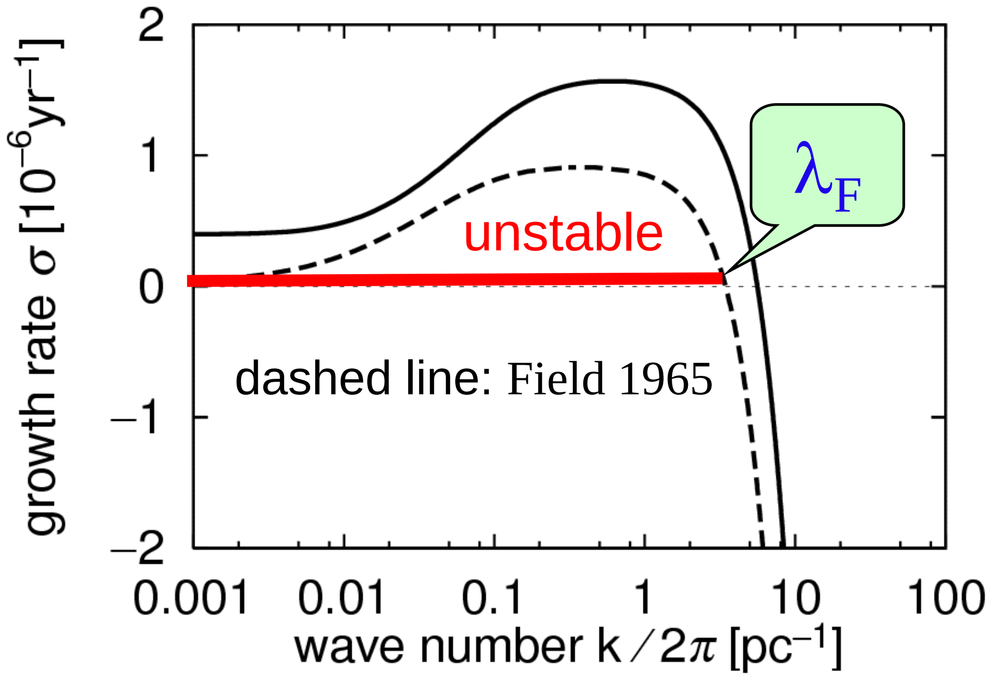
Requirement for
Spatial Resolution
"Field Condition"

We should resolve the structure of transition layer: λ_F



dashed line: Field 1965

$$\text{“Field length”}: \lambda_F \equiv \sqrt{\frac{KT}{\rho^2 \Lambda}} \approx 10^{-2}\,\text{pc}$$

No convergence for
$\Delta x > \lambda_F/3$

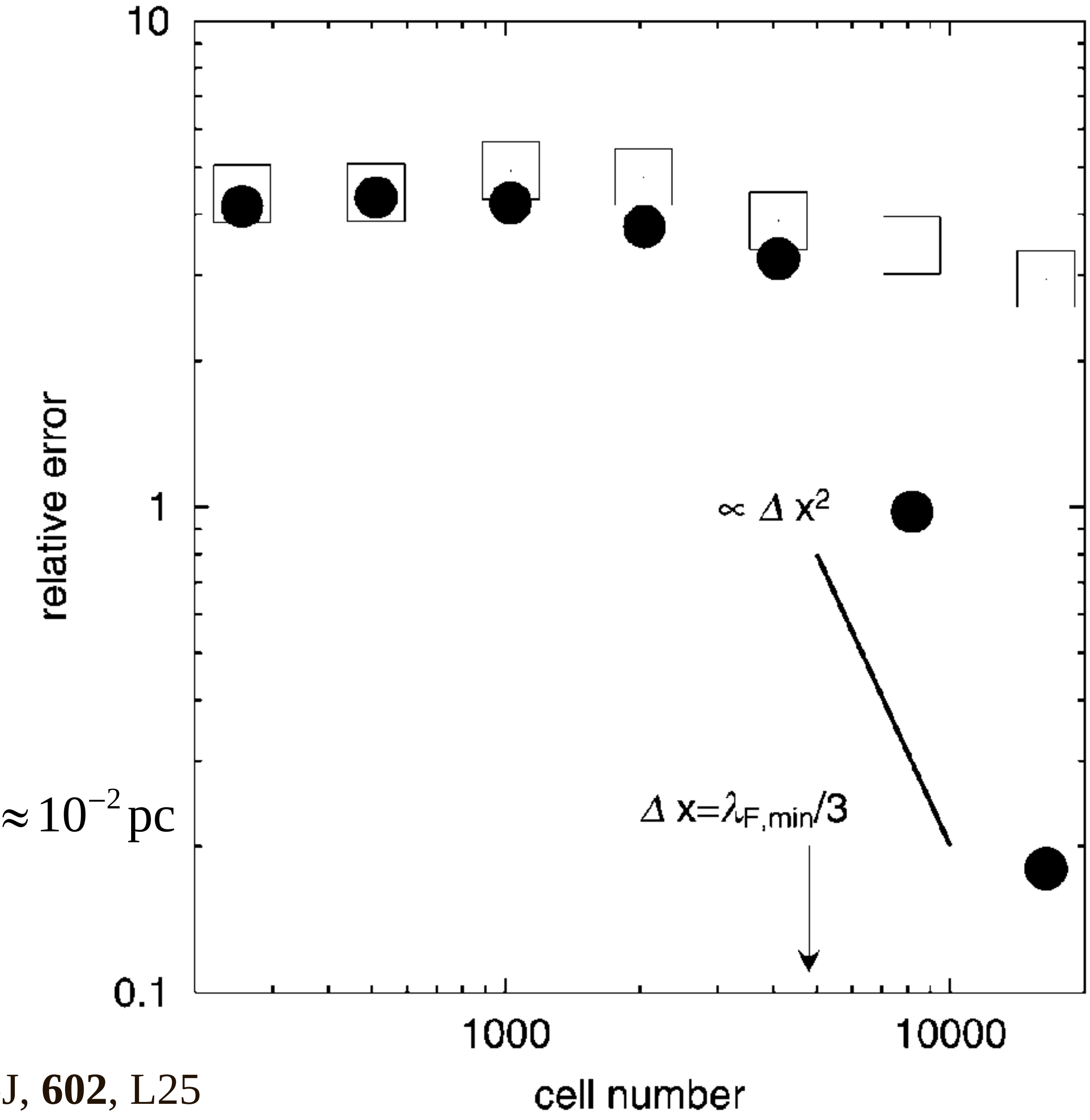
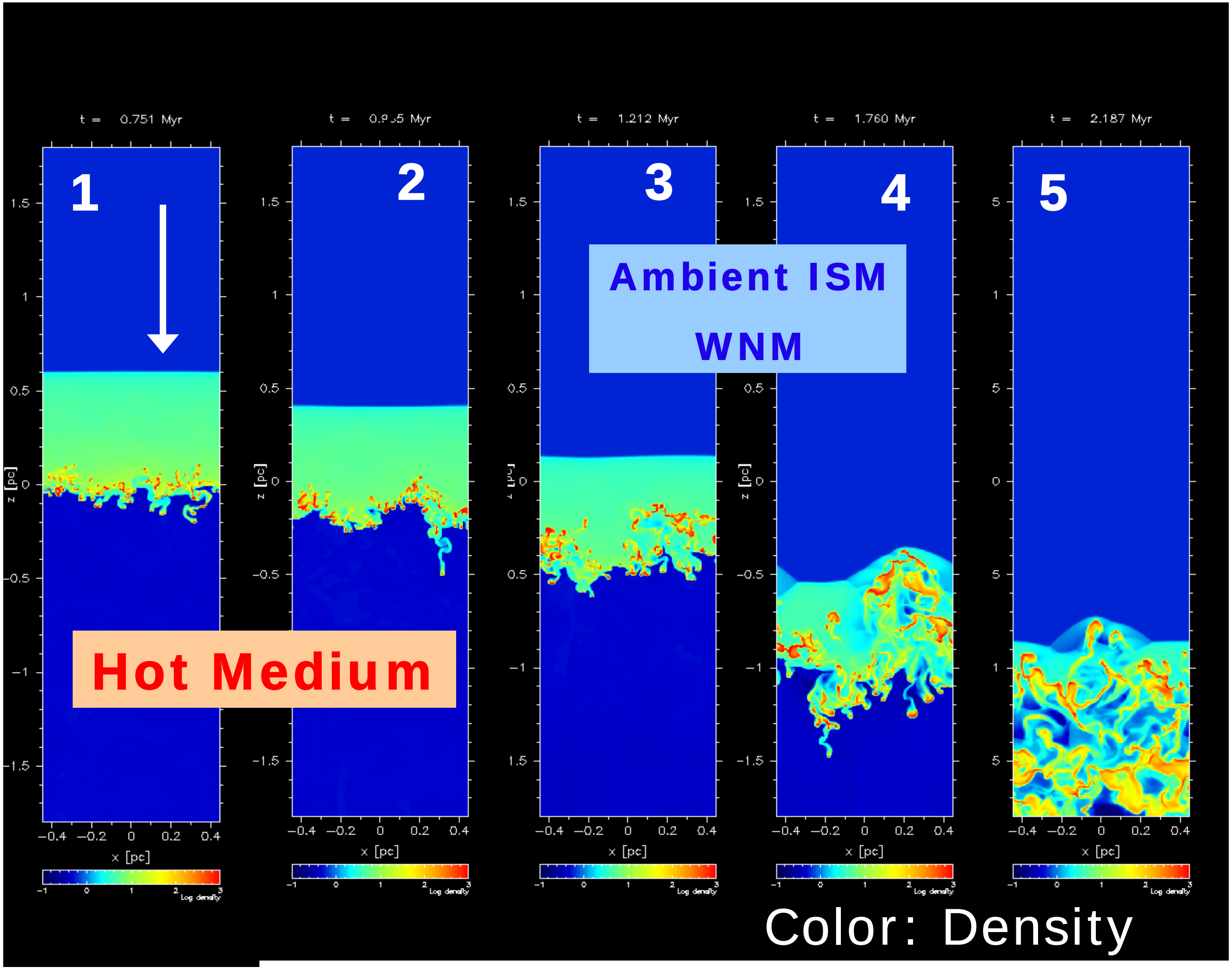


FIG. 3.—Convergence test for density distribution at $t = 8$ Myr. The error function is defined by eq. (6). Model CV (*open squares*) and model CCV (*filled circles*) are presented.

$$\text{“Field length”}: \lambda_F \equiv \sqrt{\frac{KT}{\rho^2\Lambda}} \approx 10^{-2}\,\mathrm{pc}$$

Koyama & Inutsuka (2004) ApJ, **602**, L25

Shock Propagation into WNM



Ambient ISM

WNM

Hot Medium

Color: Density

Koyama & Inutsuka, 2001

Summary of TI-driven Turbulence

- 2D/3D Calculation of The Propagation of Shock Wave into WNM

via Thermal Instability

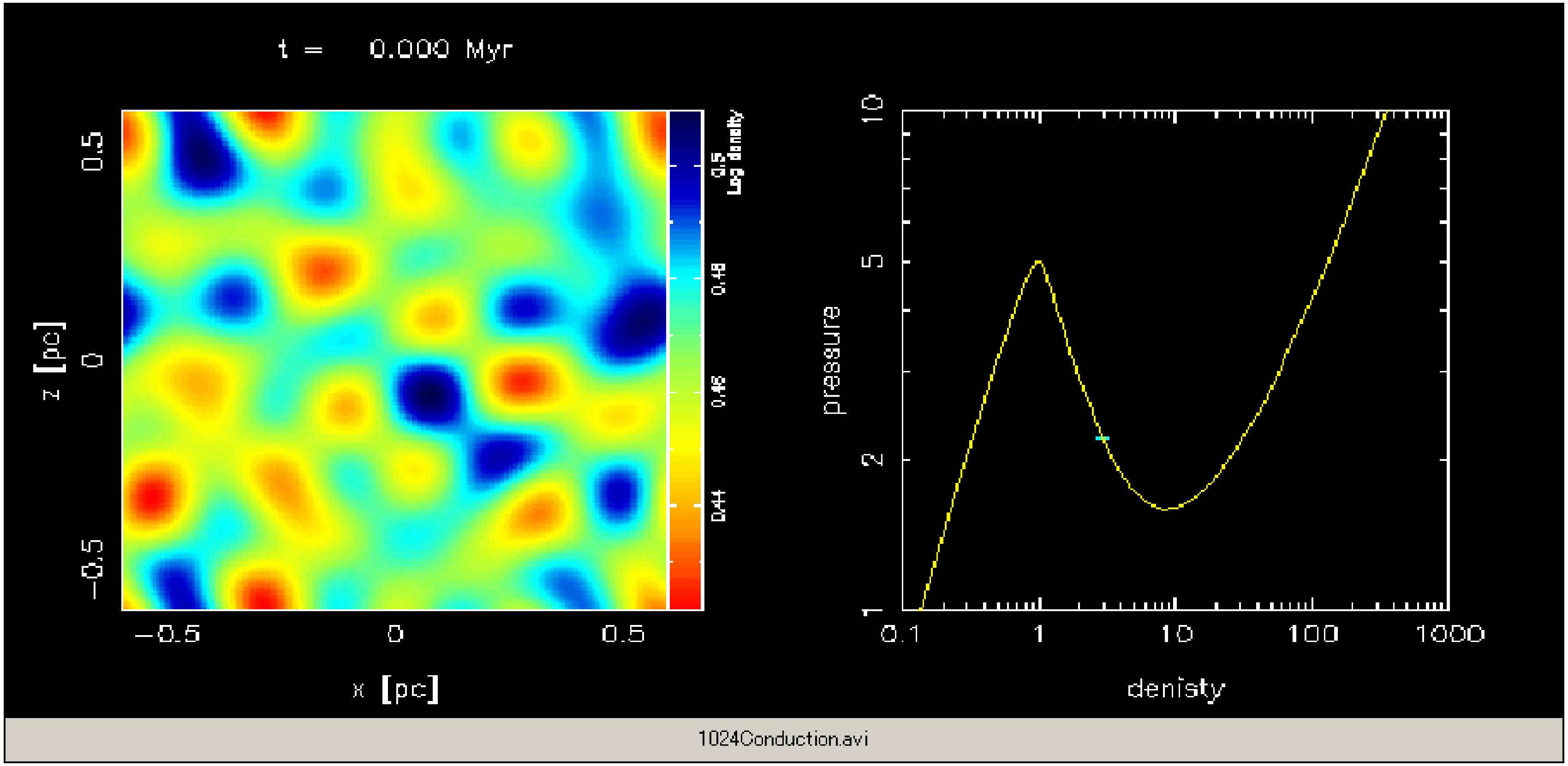
⇒ fragmentation of the cold layer into cold clumps with long-sustained supersonic velocity dispersion (~km/s)

1D: Shock ⇒ E_{th} ⇒ E_{rad}

2D&3D: Shock ⇒ E_{th} ⇒ $E_{rad} + E_{kin}$

$\delta v \sim$ a few km/s $< C_{S,WNM}$

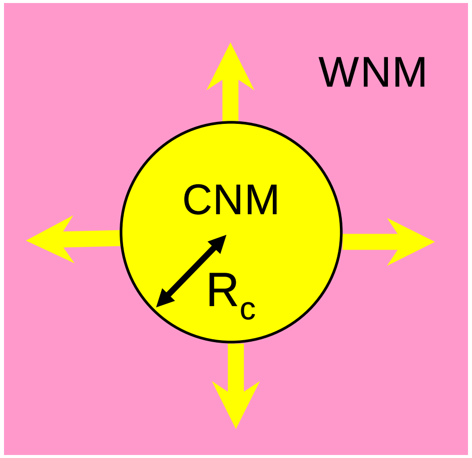
2D Evolution from Unstable Equilibrium

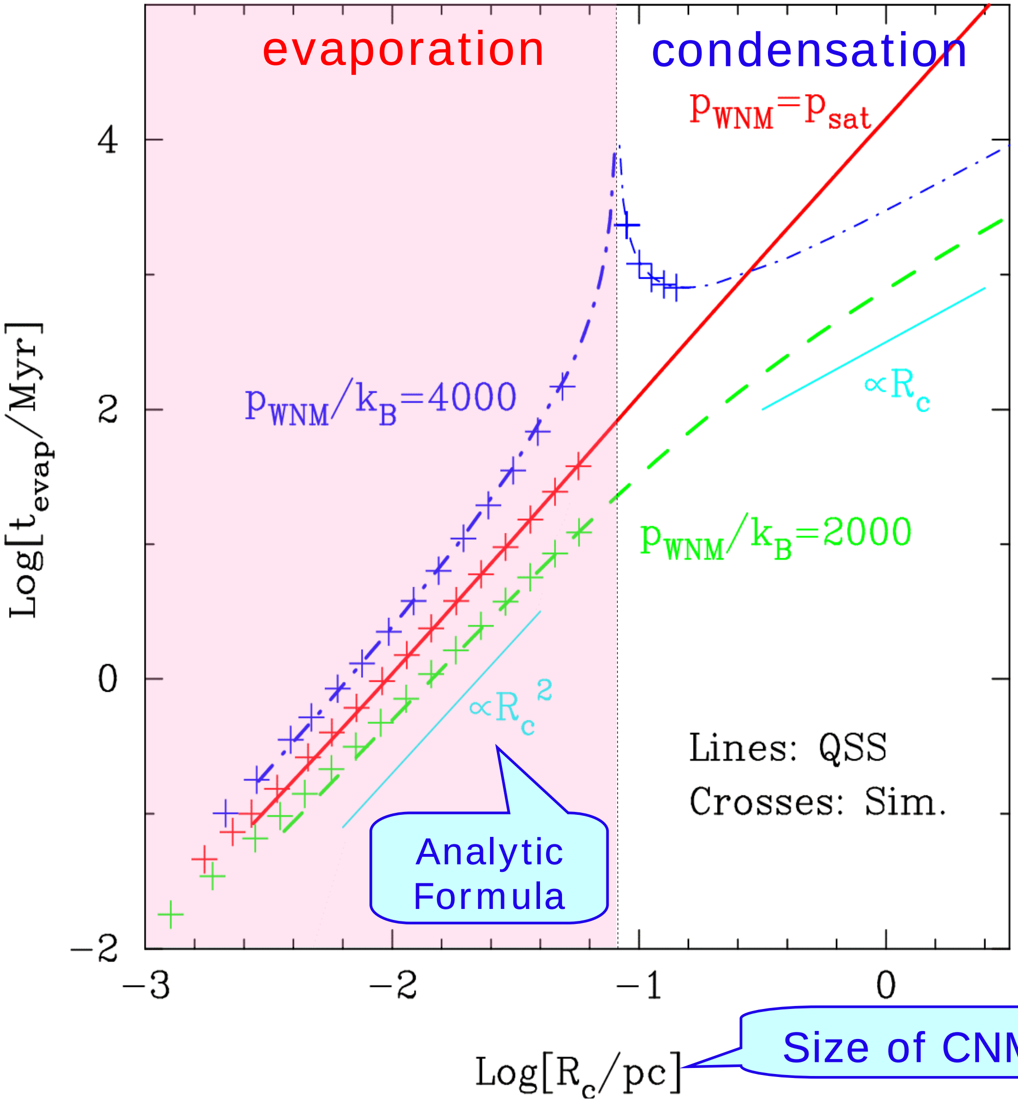


With Cooling/Heating and Thermal Conduction

Without Physical Viscosity → $Pr = 0$

Evaporation of Spherical CNM in WNM





Evaporation Timescale

Analytic Formula

Size of CNM cloud

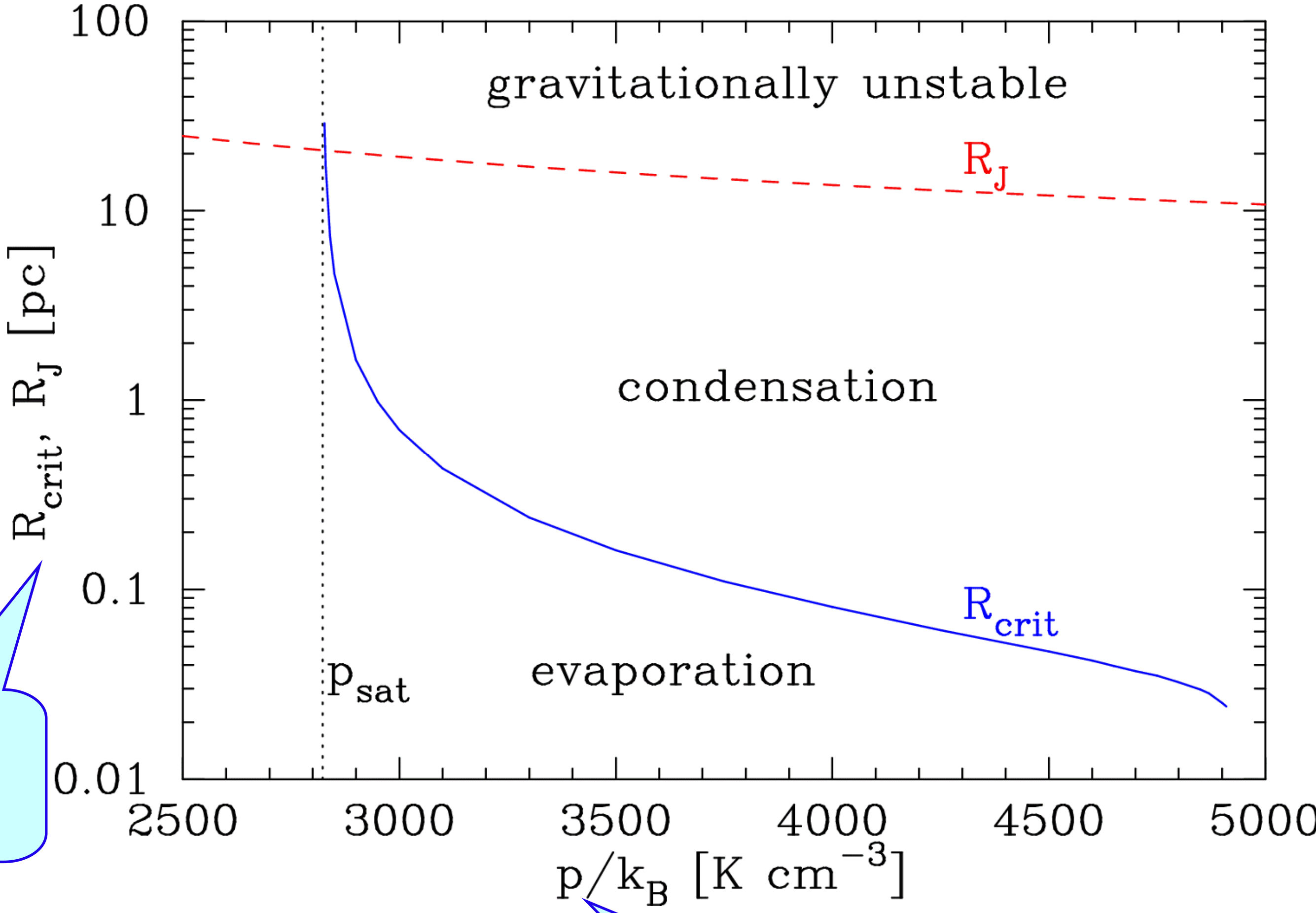
Smaller CNM cloud evaporates:

R~0.01pc clouds evaporate in ~Myr

Nagashima, Koyama, Inutsuka & 2005, MN **361**, L25
Nagashima, Inutsuka, & Koyama 2006, ApJL **652**, in press (astro-ph/0603259)

Evaporation of Spherical CNM in WNM

If the ambient pressure is larger, the critical size of the stable cloud is smaller.

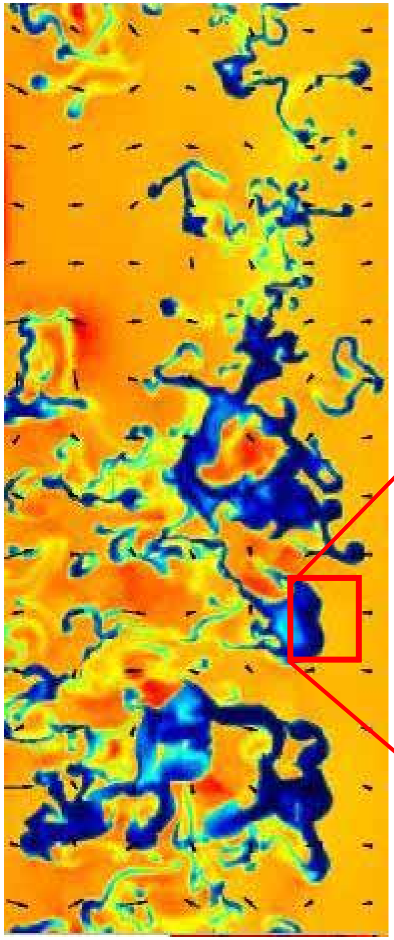


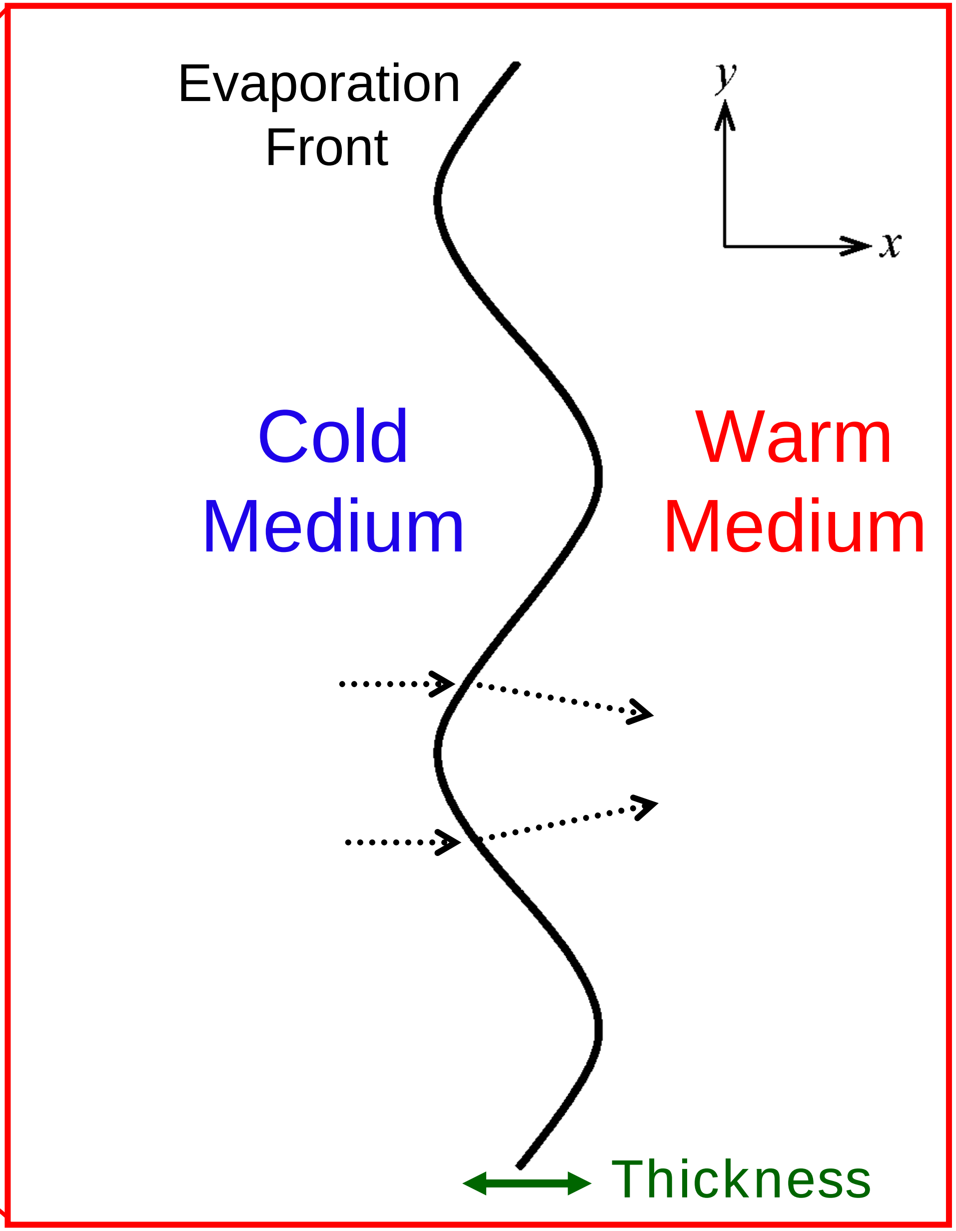
Critical Radius

Ambient Pressure

Nagashima, Inutsuka, & Koyama 2006, ApJL **652**, in press

Instability of Transition Layer





Evaporation Front

Cold Medium

Warm Medium

Thickness

important in maintaining the “turbulence”

Instability of Transition Layer

Similar Mechanisms…

1) Darrieus-Landau (DL) Instability

Flame-Front Instability

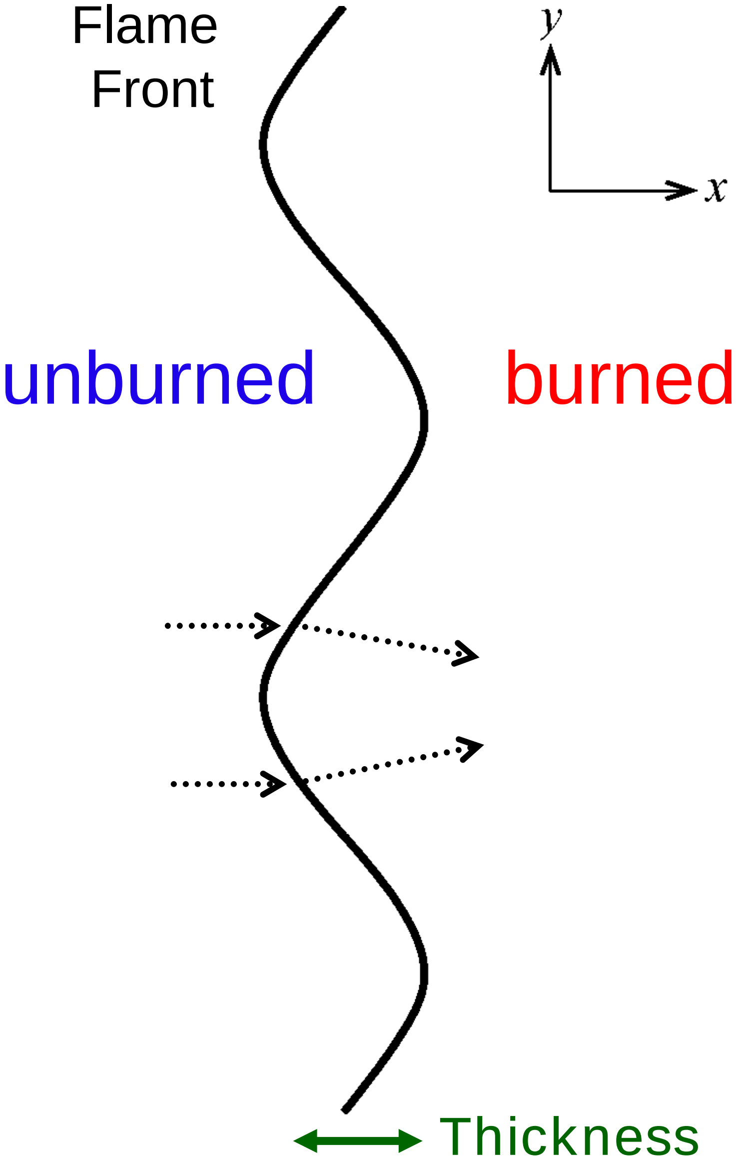
\# Important in SNe Ia

\# Effect of Magnetic Field

See Dursi (astroph/0312135)

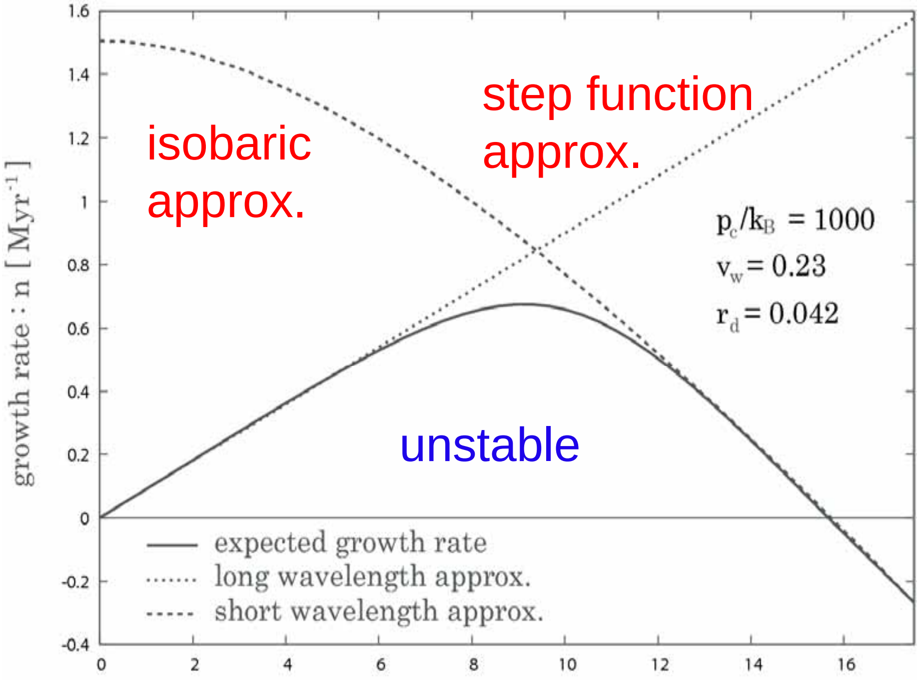
2) Corrugation Instability in MHD Slow Shock

- Edelman 1990
- Stone & Edelman 1995



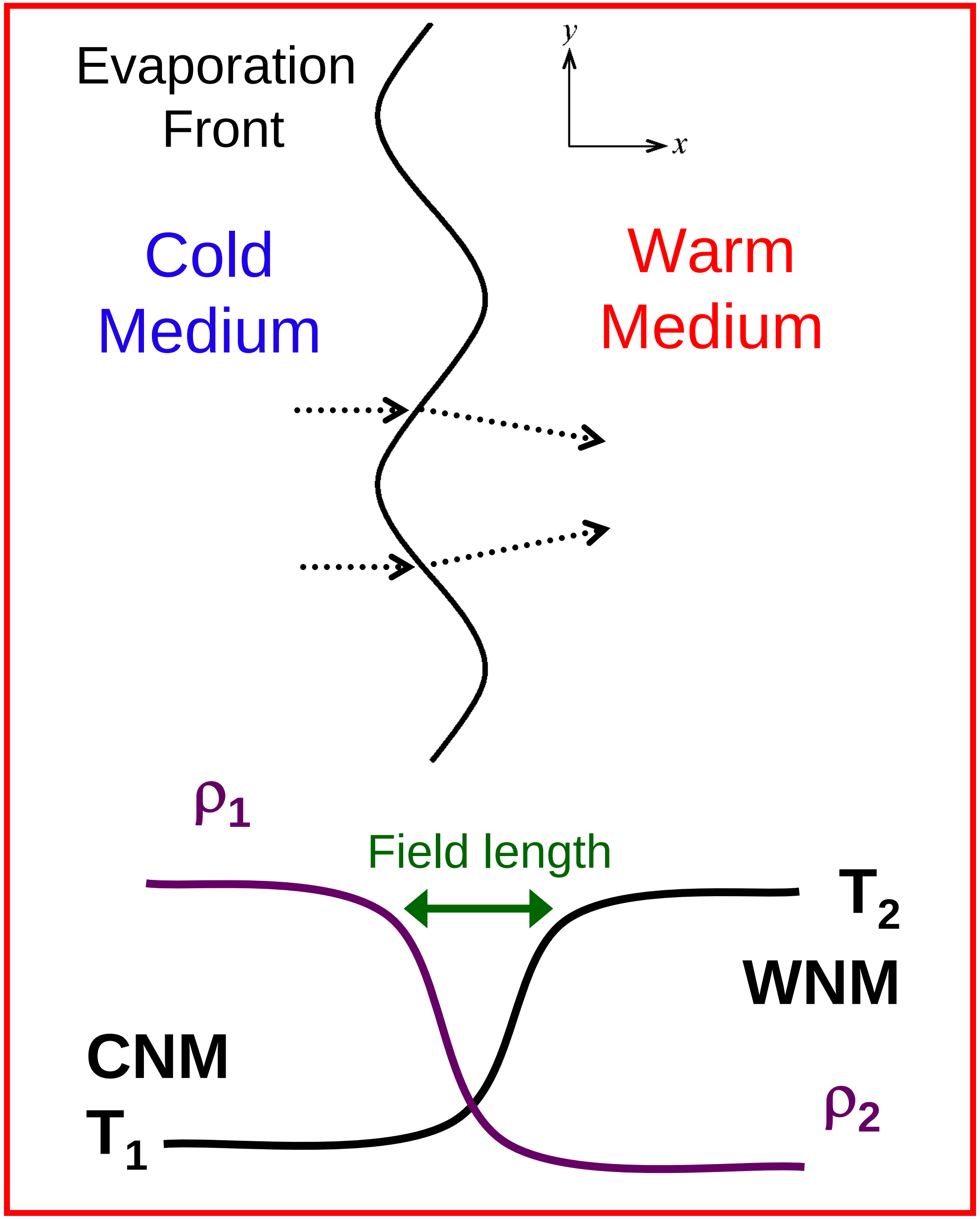
Linear Analysis of New Instability

Growth Rate (Myr^{-1})



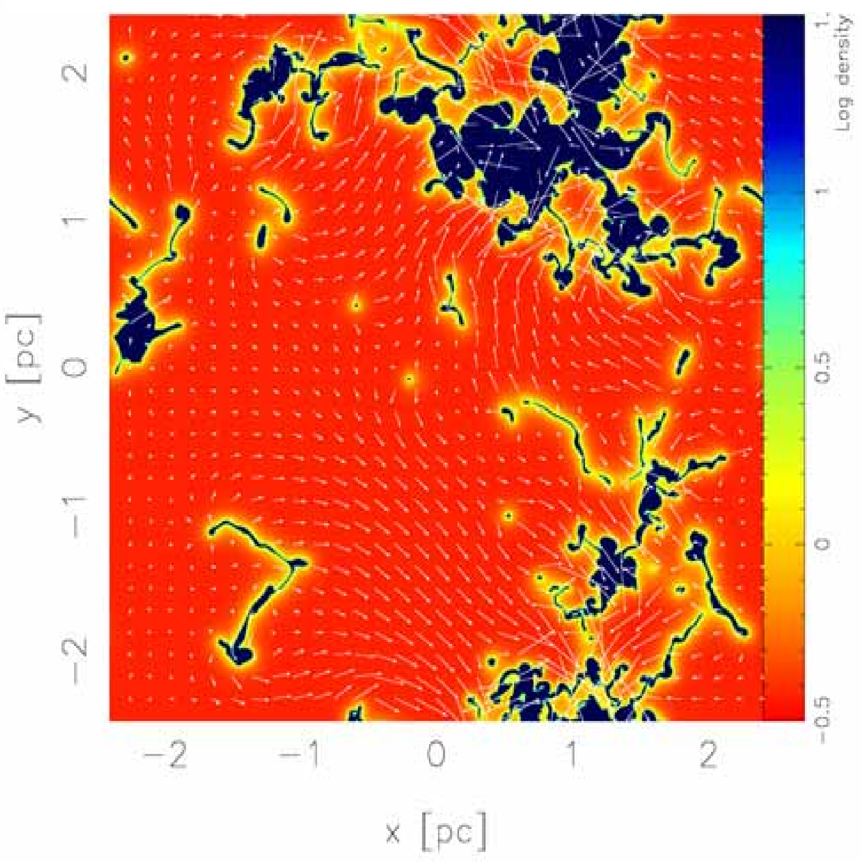
wavenumber $k_y/2\pi\ [\mathrm{pc}^{-1}]$

Inoue, Inutsuka, & Koyama
2006, ApJ **652**, in press
(astro-ph/0604564)

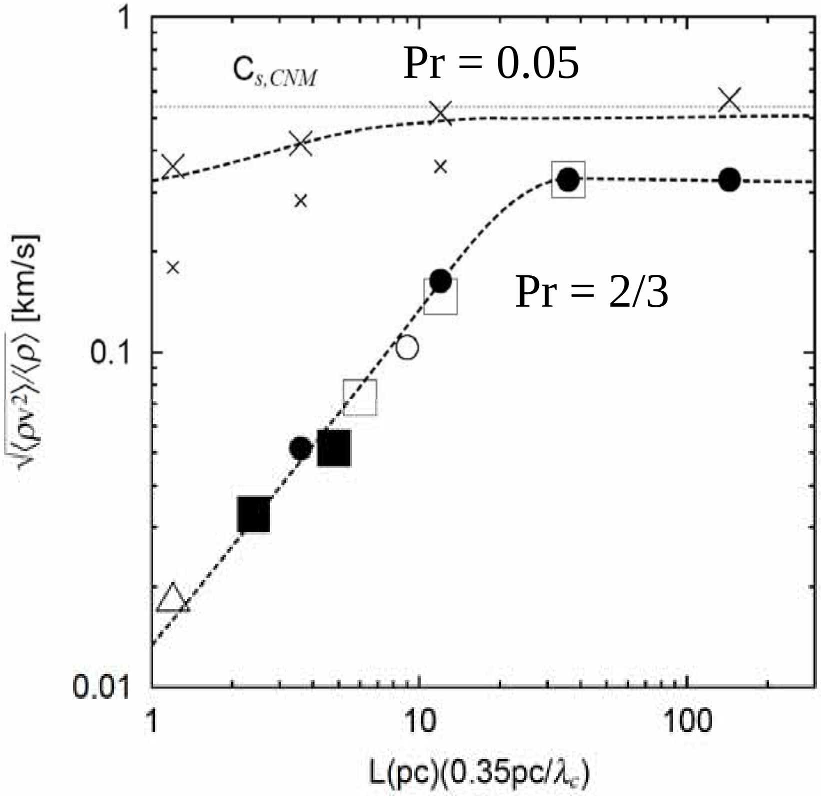


Non-Linear Development of TI without External Forcing

Turbulent Motions Driven by Thermal Instability

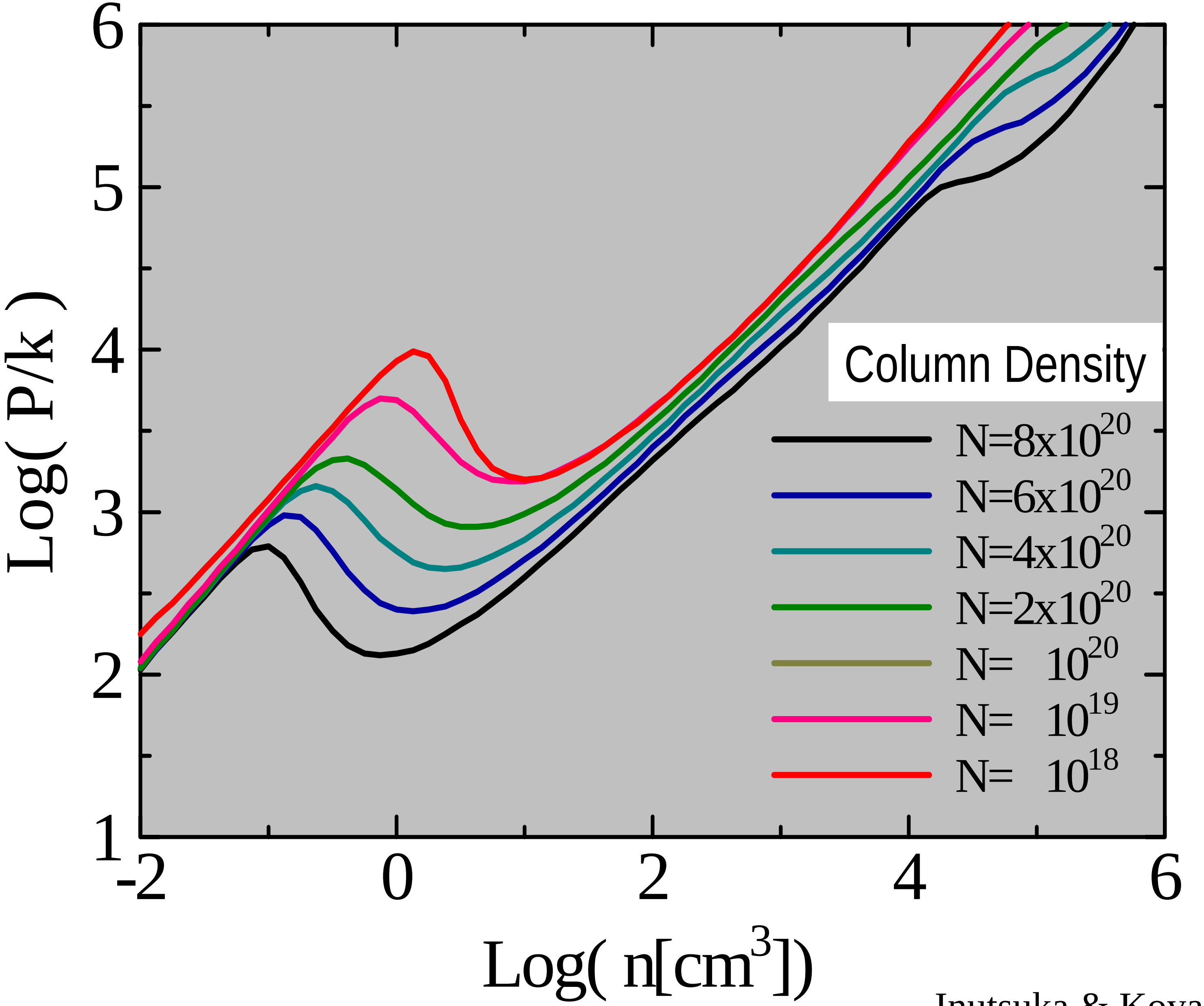


Amplitude of Turbulent Velocity vs. Domain Length



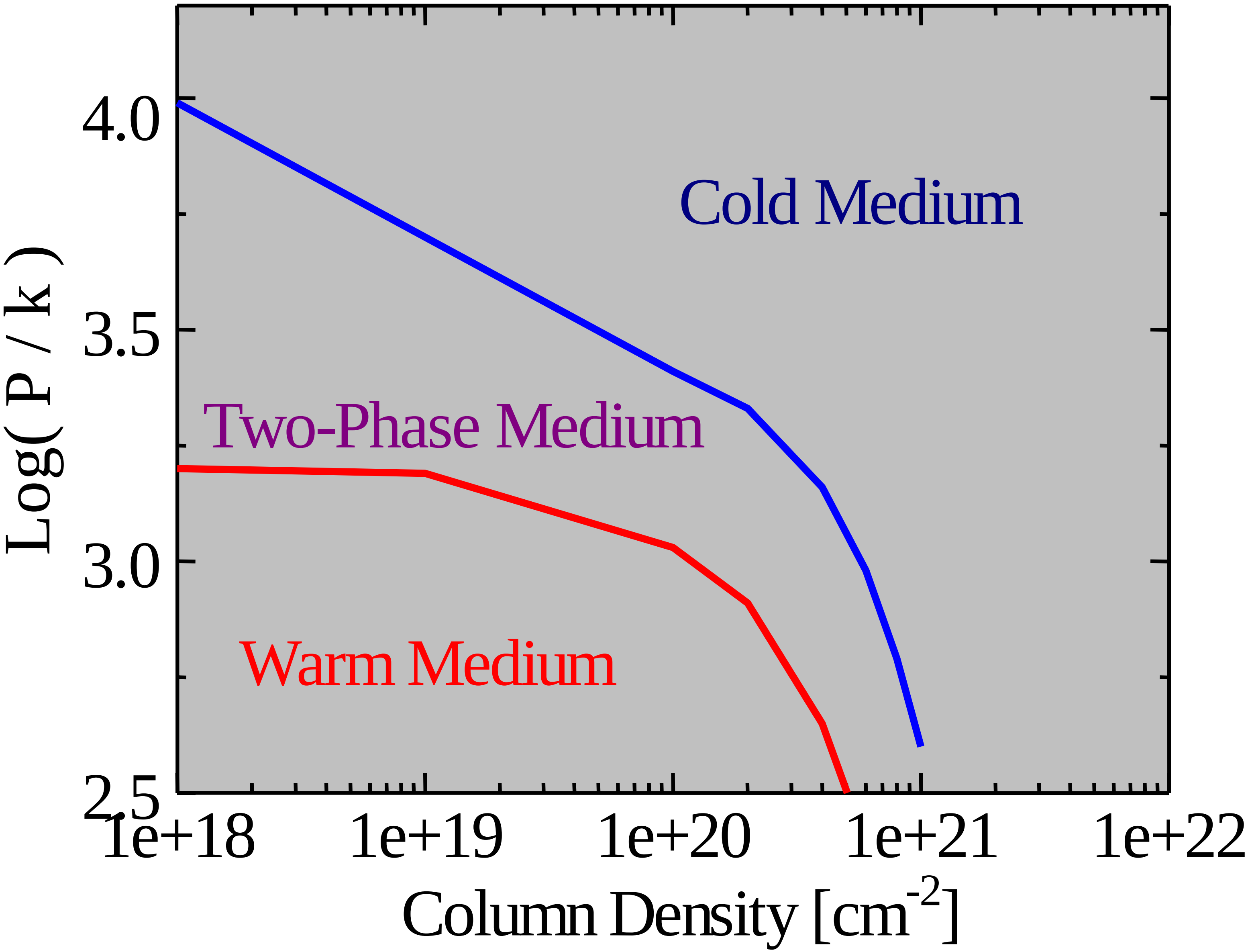
Koyama & Inutsuka 2006, astro-ph/0605528

Equilibrium with Various Column Density



Inutsuka & Koyama 1999

Allowed Region of 2-Phase Medium



Inutsuka & Koyama 1999

When column density is sufficiently large,

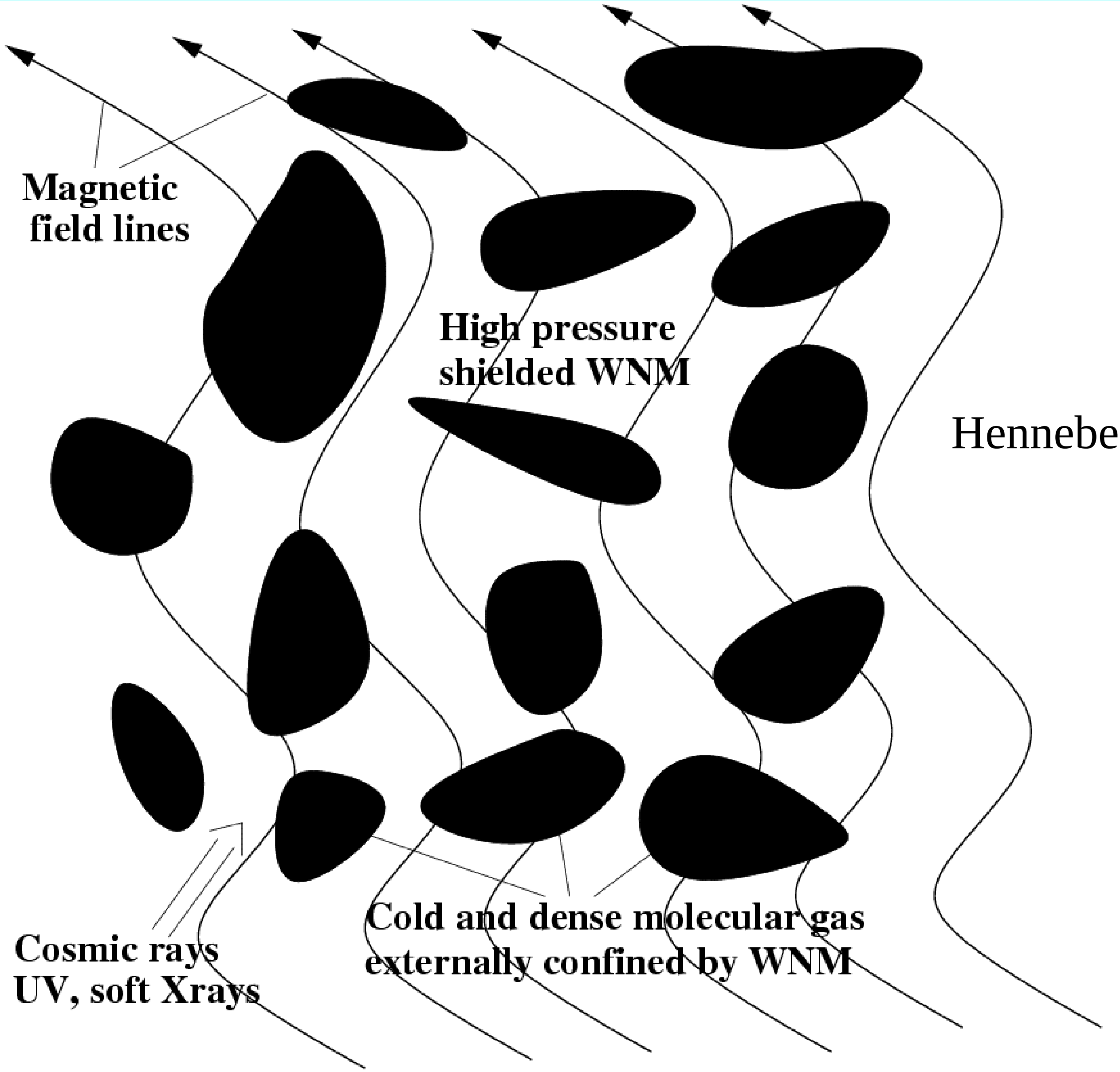
$$N_H > 10^{21}\ \mathrm{cm}^{-2} \text{ or } A_v > 1 \text{ mag}$$

ambient radiation field does not provide sufficient radiative heating for WNM.

Without any heating WNM simply cools down very quickly.

Is there any heating to WNM inside Molecular Clouds?

Schematic Picture



Hennebelle & Inutsuka 2006
ApJ **647**, 404

Heating due to Dissipation of MHD Waves

$\delta B \approx B$ ➔ $E_{\rm wave} \approx B^2/8\pi$

Assume $B \approx 10\mu{\rm G}\,(n_{\rm WNM}\,/\,1{\rm cm}^{-3}\,)^{0.5}$ (e.g., Heiles & Troland)

Damping Timescale: $t_{\rm damp} = 2\gamma\rho_{\rm i}/(V_{\rm A}{}^2k^2)$

$\gamma \approx 5.7\times10^{14}\,({\rm v_{rms}/km\,s^{-1}})^{0.75}\,{\rm cm^3\,g^{-1}s^{-1}}$

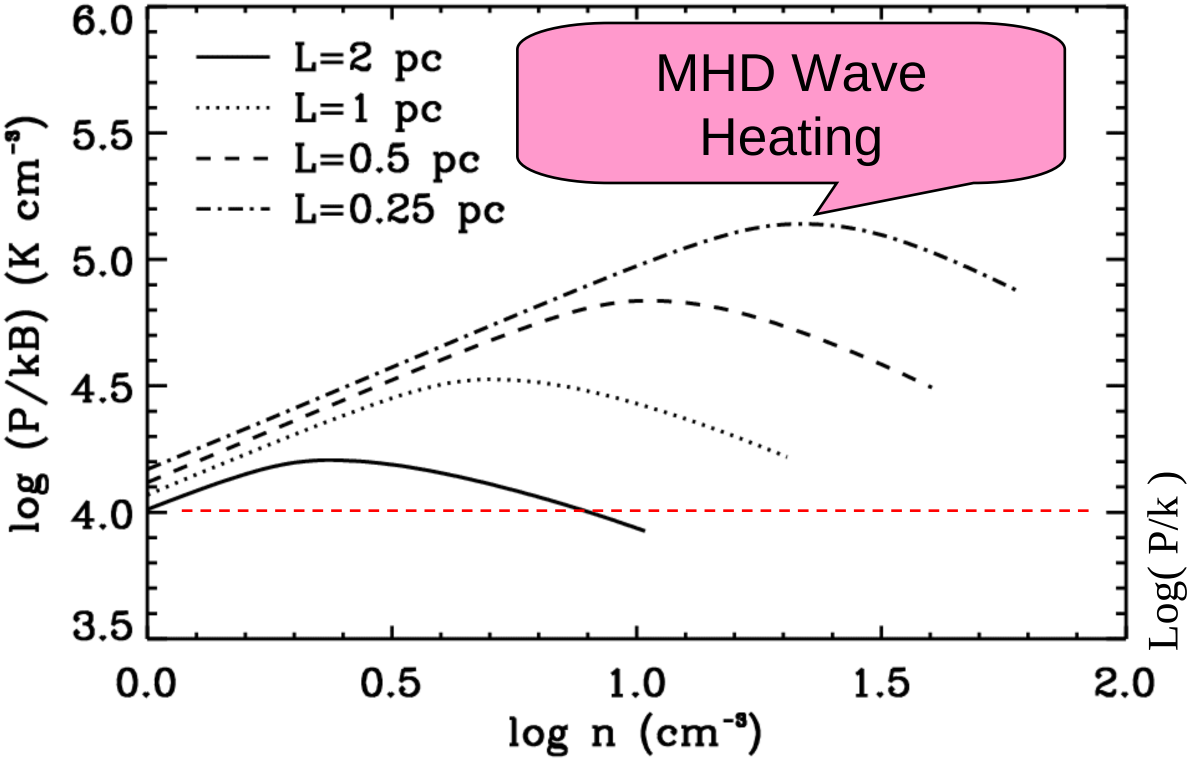
Glassgold et al. 2005

Heating Rate: $\Gamma \approx E_{\rm wave}\,/{\rm t_{damp}}$

$\approx 3\times10^{-24}\,(1{\rm cm}^3/n_{\rm WNM})^{0.5}(1{\rm pc}/\lambda)^2\ {\rm erg^{-1}s^{-1}}$

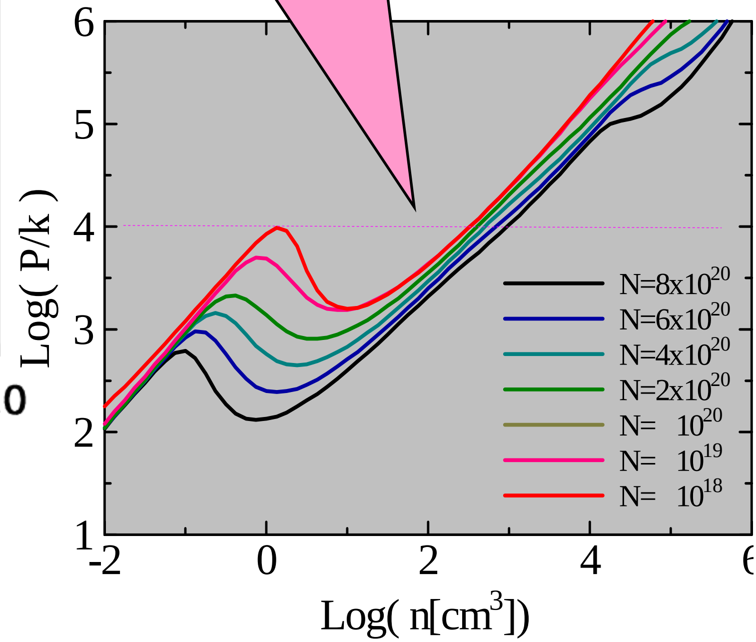
& Cooling Rate: $\Lambda_{\rm WNM} \approx 10^{-25}\ {\rm erg\ cm^{-3}\ s^{-1}}$

WNM in Molecular Clouds: Thermal Equilibrium with MHD Wave Heating



MHD Wave Heating

Interstellar Thermal Radiation Case



$P_{MC}=nT=10^4(n/10^3)(T/10K)$

Heating is sufficient for WNM to survive in MC.

Hennebelle & Inutsuka 2006
ApJ **647**, 404

Summary

- Shock waves in ISM create
  turbulent CNM embedded in WNM.
- In TI-driven turbulence in Multi-Phase ISM
  - Evaporation/Condensation of CNM clouds
  - New Instability in Evaporation Front
- Can WNM Survive in Molecular Clouds?
  - Possible: Dissipation of MHD Waves

Future Work

- RHD calculation of the evolution of two phase medium…
- When self-gravity becomes important?