Dynamics of Multi-Phase Interstellar Medium with and without Magnetic Field

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Keywords:

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

"Turbulence" in Molecular Clouds

Linewidth-Size Relation

(Larson's Law)

$$\delta \mathrm{v} \propto L^{0.5}$$

$10^{21}\ \mathrm{cm}^{-2}$. N_{H2} . $10^{23}\ \mathrm{cm}^{-2}$

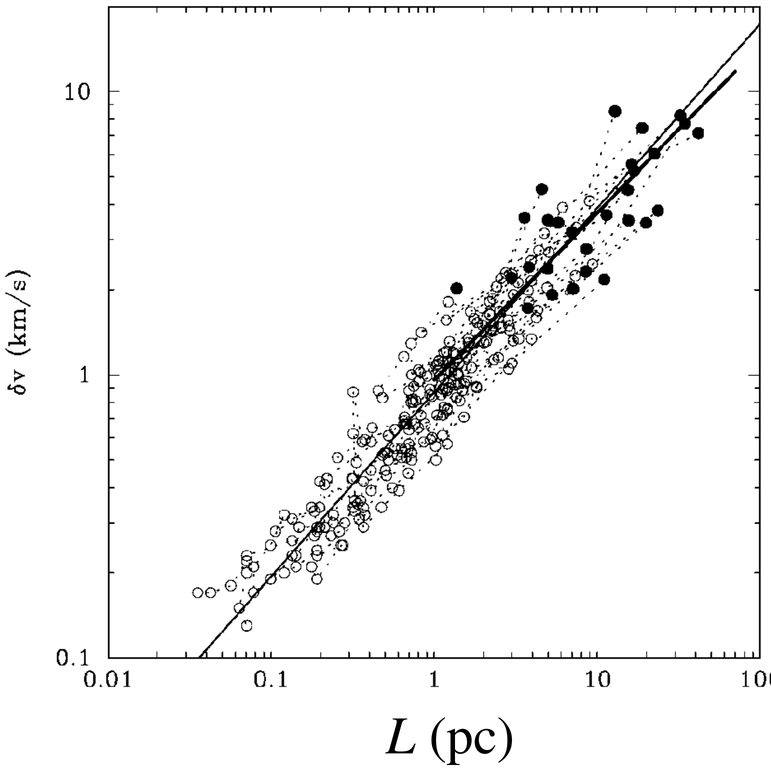


FIG. 1.—Composite $\delta v, l$ relationship from PCA decompositions of ^{12}CO $J = 1$–0 imaging observations of 27 individual molecular clouds. The small scatter of points attests to the near invariance of interstellar turbulence within molecular clouds that exhibit a large range in size, environment, and star formation activity. The large filled circles are the global velocity dispersion and size for each cloud derived from the first principal component. These are equivalent to the global velocity dispersion and size of the cloud as would be measured in the cloud-to-cloud size/line width relationship (Larson 1981; Solomon et al. 1987). The light solid line shows the bisector fit to all points from all clouds. The heavy solid line shows the bisector fit to the filled circles exclusively. The similarity of these two power laws explains the connection of Larson's cloud-to-cloud scaling law to the structure functions of individual clouds.

Heyer & Brunt 2004

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 be due to star formation activity

Numerical Simulation of (Isothermal) MHD Turbulence ⇒ Rapid Shock Dissipation or Cascade

– Dissipation time « Lifetime of Molecular Clouds

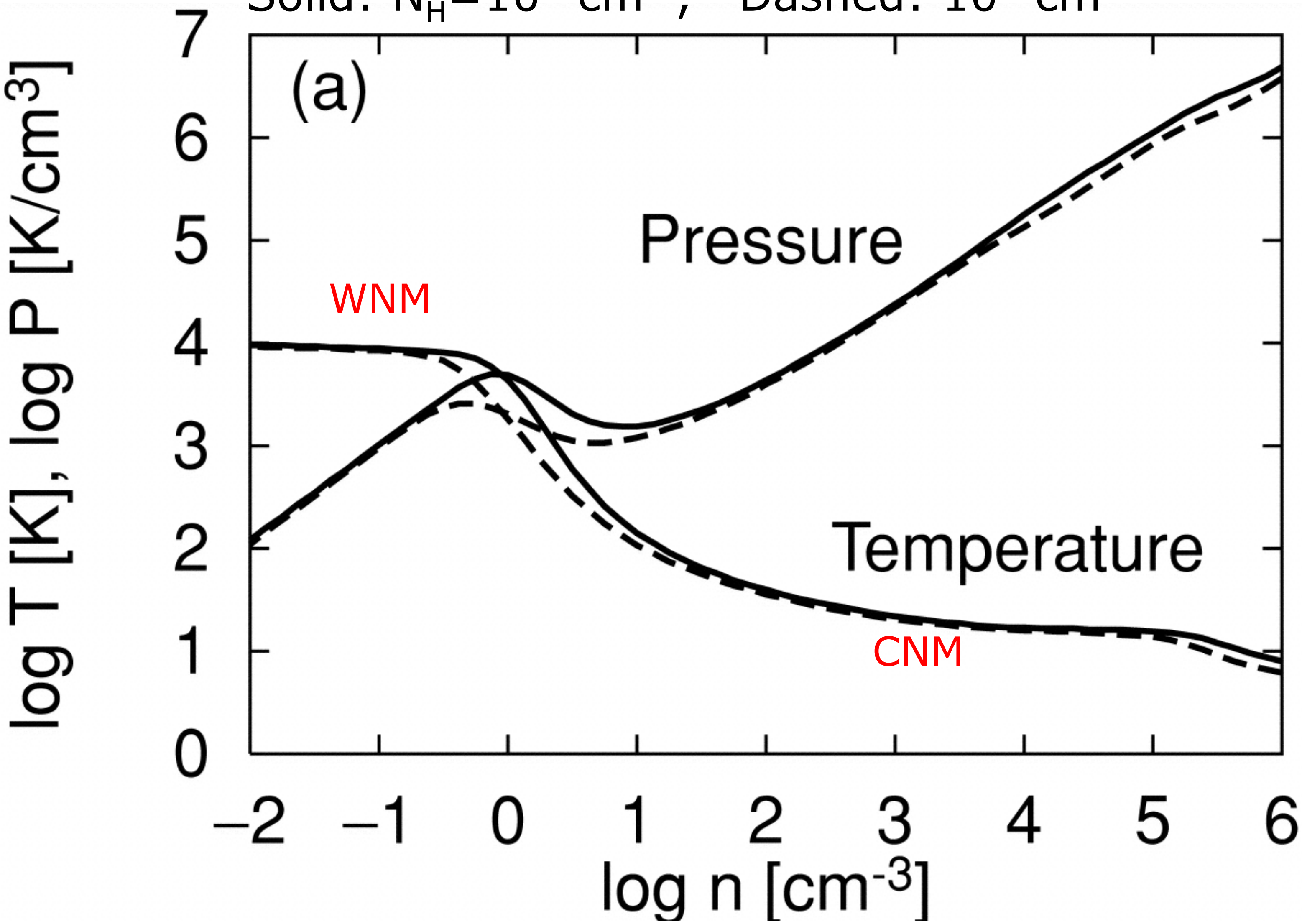
- Gammie & Ostriker 1996, Mac Low 1997, Ostriker et al. 1999, Stone et al. 1999, etc…

Recent Studies on Origin of Supersonic Motions

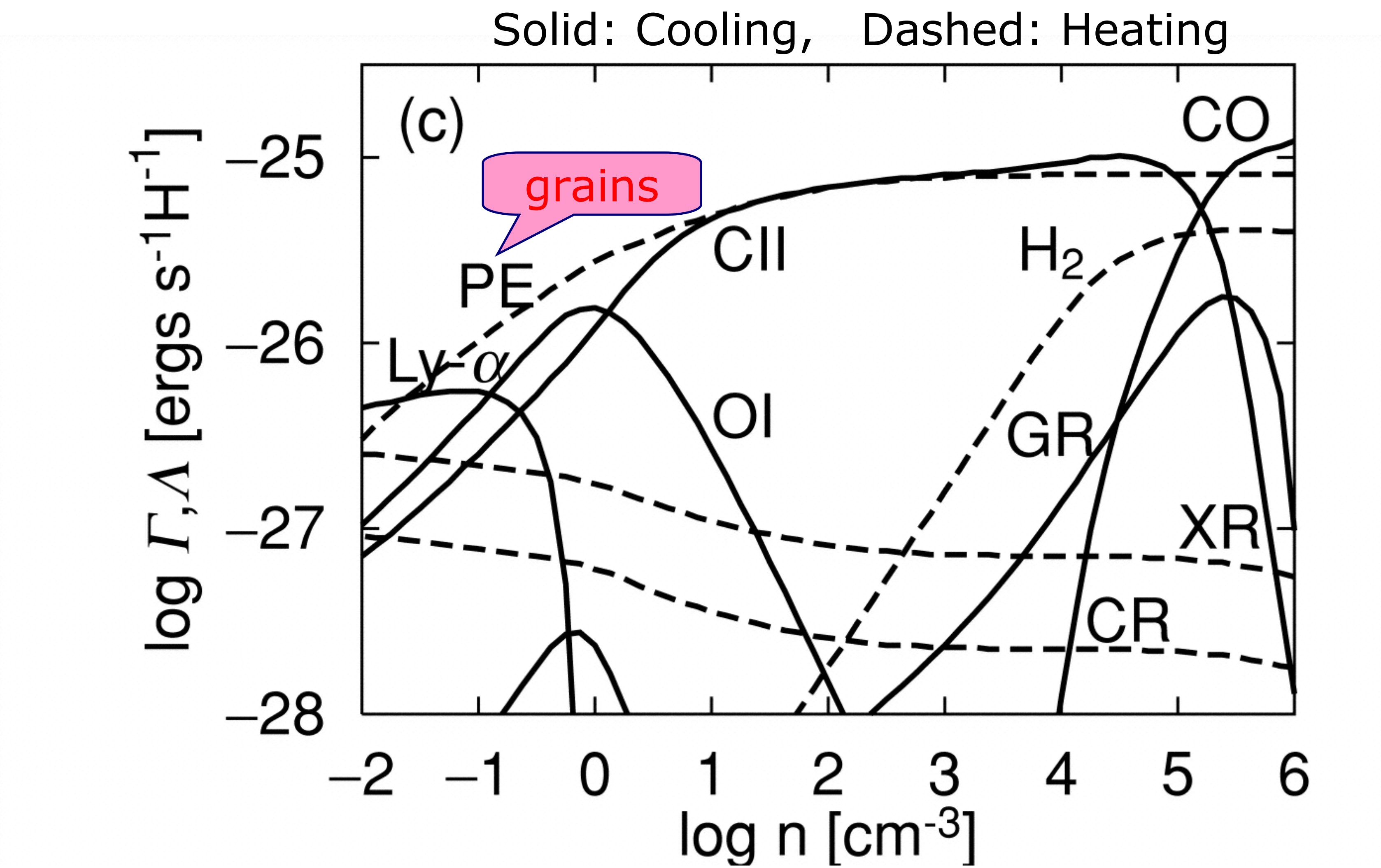
– Koyama & Inutsuka, ApJL **564**, L97 , 2002
– Kritsuk & Norman 2002a, ApJ **569**, L127; 2002b ApJ **580**, L51
– Audit & Hennebelle 2005, A&A **433**, 1
– Heitsch, Burkert, Hartmann et al. 2005, ApJ **633**, L113, Vazquez-Semadeni et al. 2006, etc...

Radiative Equilibrium

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



Radiative Cooling & Heating



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

Basic Equations

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

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

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

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

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

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

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

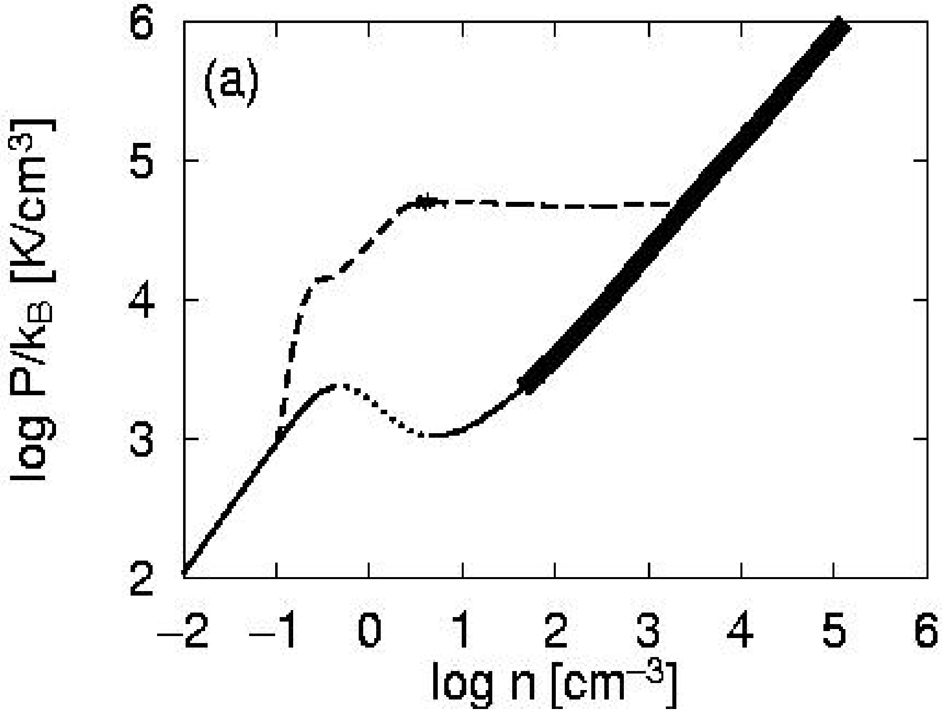
$$n(e) = n(HII) + n f_{CII}.$$

radiative heating/cooling

thermal conduction

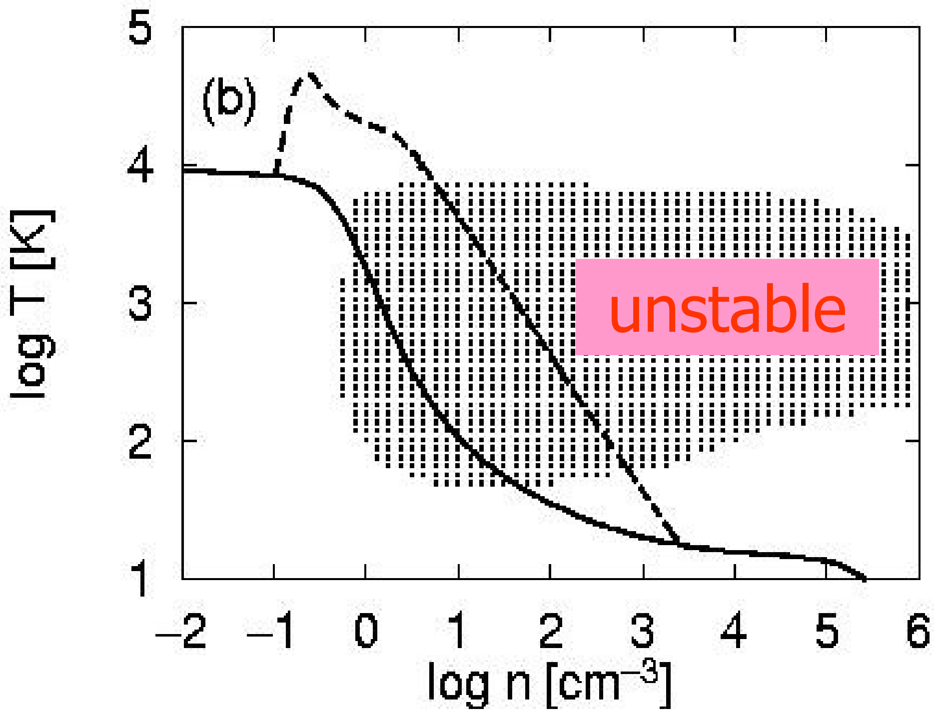
1D Shock Propagation into WNM

Density-Pressure Diagram



Density-Temperature Diagram

– through unstable region

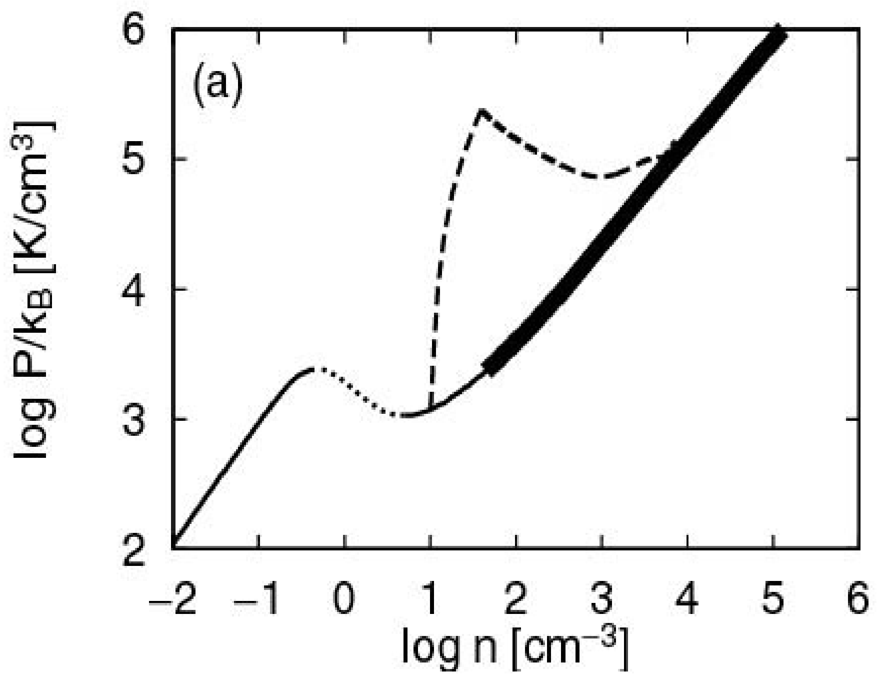


Koyama & Inutsuka 2000, ApJ **532**, 980

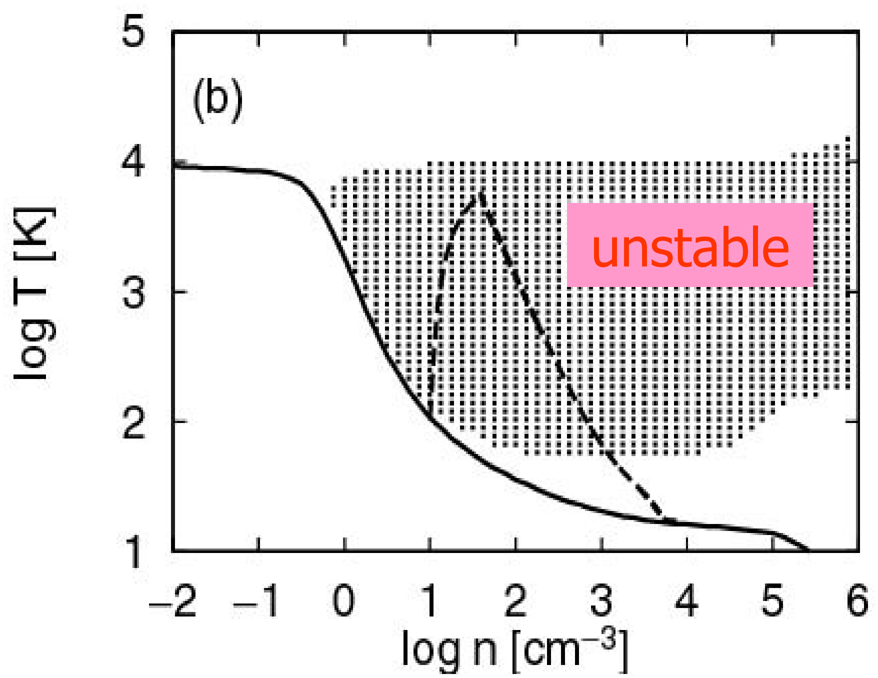
See also Hennebelle & Pérault 1999

1D Shock Propagation into CNM

Density-Pressure Diagram



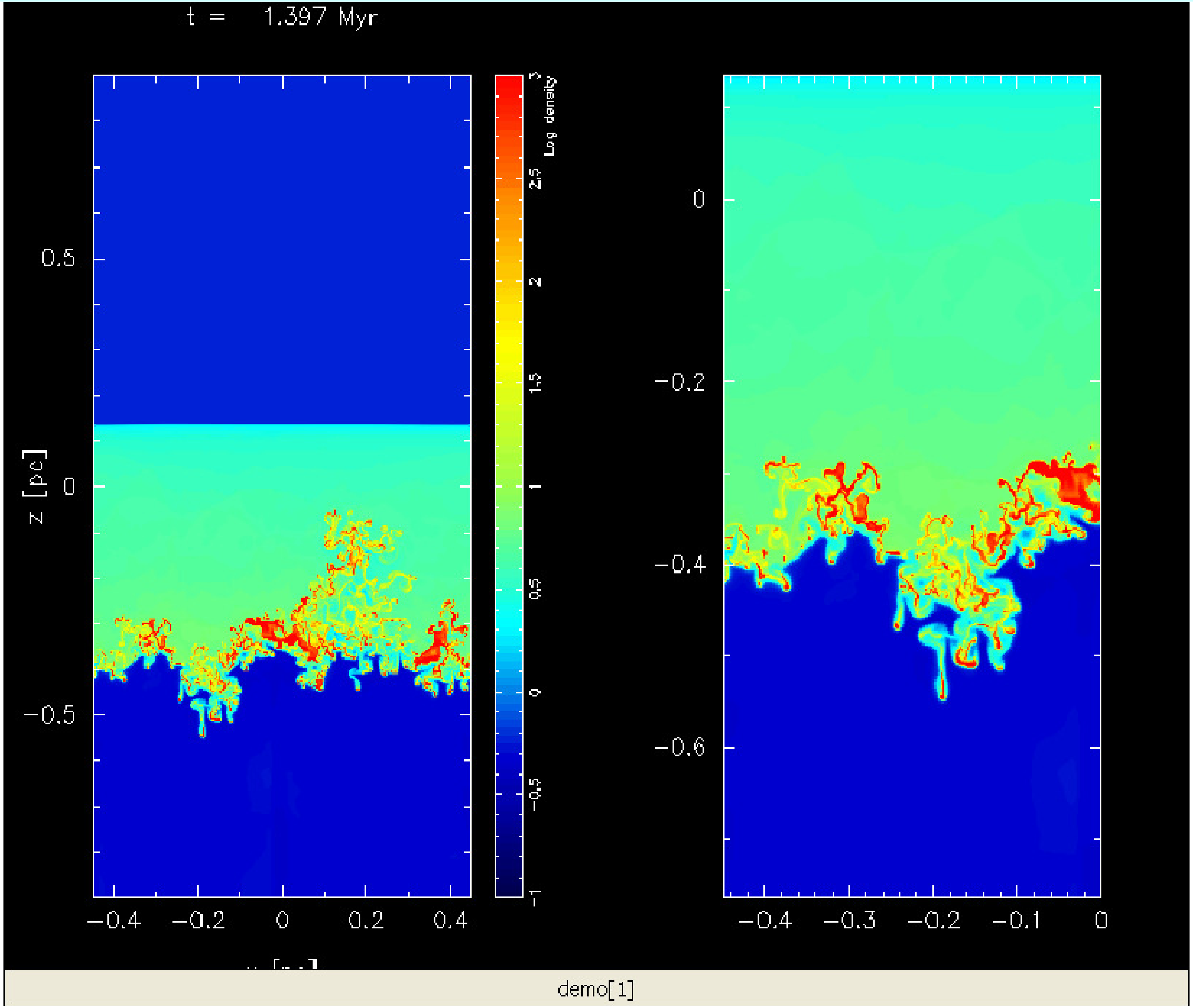
Density-Temperature Diagram



CNM becomes thermally unstable with shock.

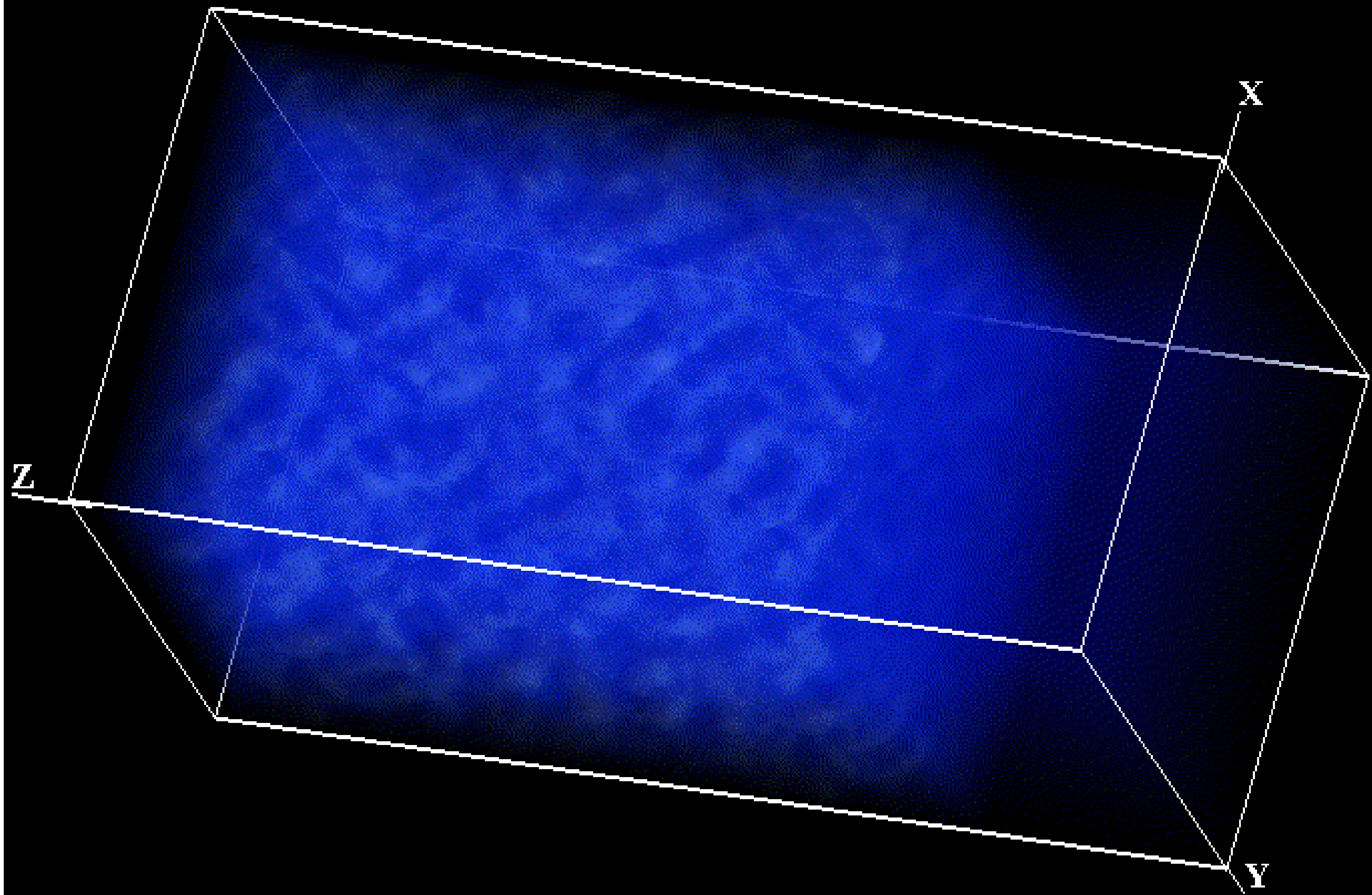
Koyama & Inutsuka 2000,ApJ **532**,980

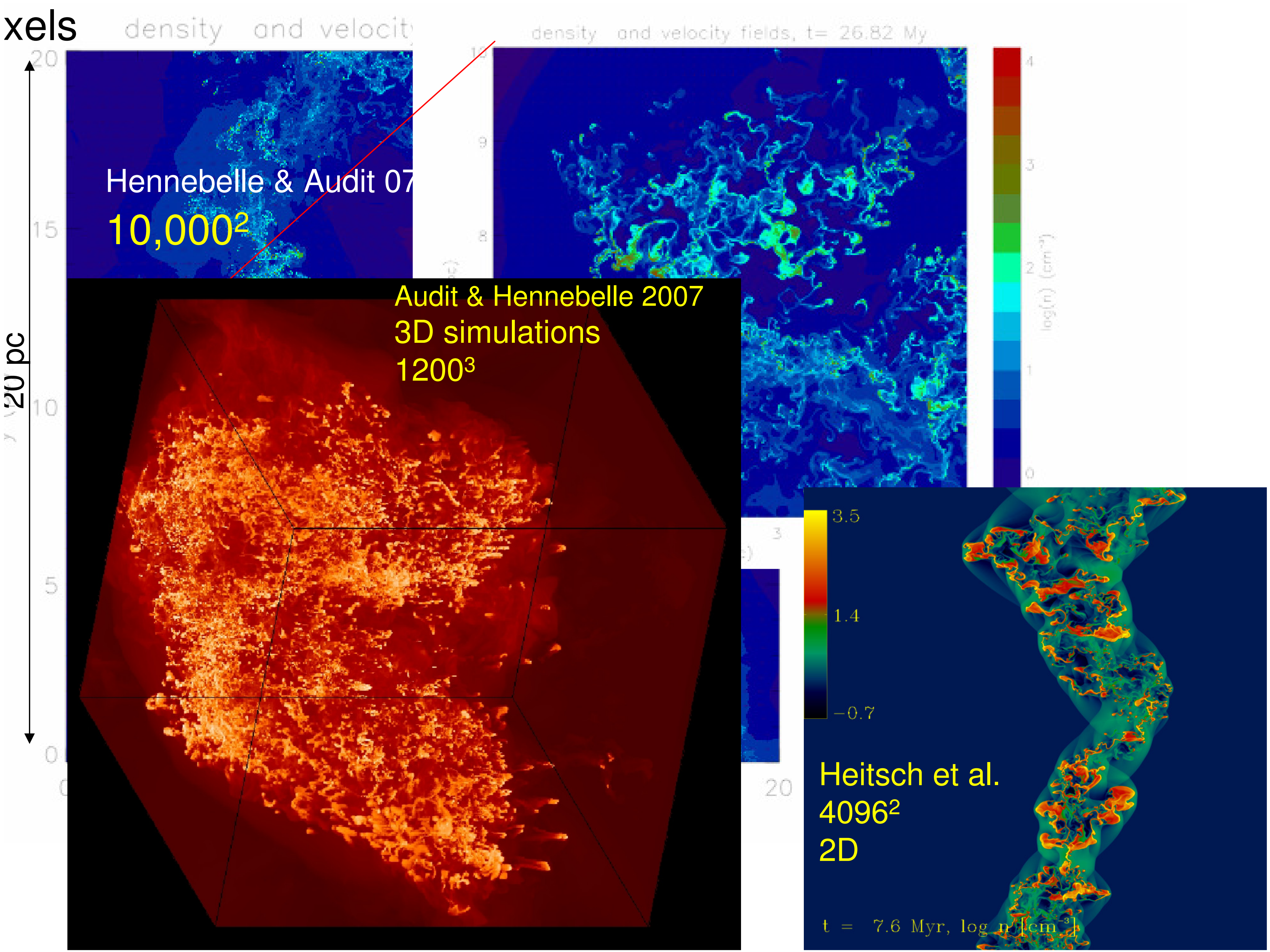
Shock Propagation into WNM



WNM Swept-Up by 14.4km/s Shock (3D)

Koyama & Inutsuka 2002





xels
density and velocit
density and velocity fields, t= 26.82 My
20 pc
Hennebelle & Audit 07
$10,000^2$
Audit & Hennebelle 2007
3D simulations
1200^3
Heitsch et al.
4096^2
2D
t = 7.6 Myr, log n [cm^{-3}]

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 $\Rightarrow E_{th} \Rightarrow E_{rad}$

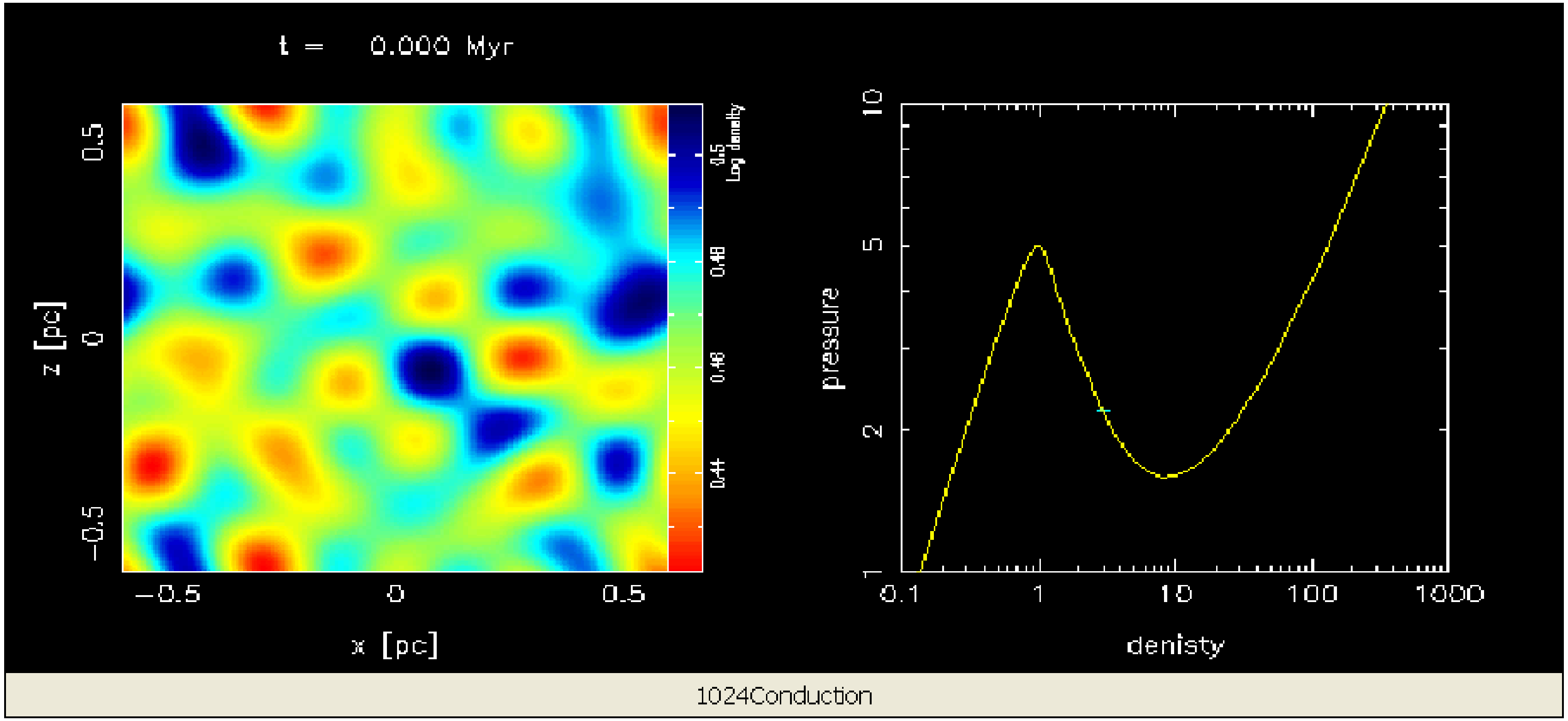
2D&3D: Shock $\Rightarrow E_{th} \Rightarrow E_{rad} + E_{kin}$

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

Further Analysis

- Driving Mechanism
- Evaporation & Condensation
- Instability of Transition Layer
- Effect of Magnetic Field

2D Evolution from Unstable Equilibrium

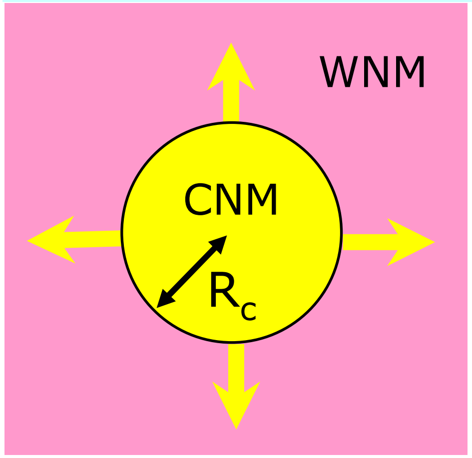


Periodic Box Evolution without Shock Driving

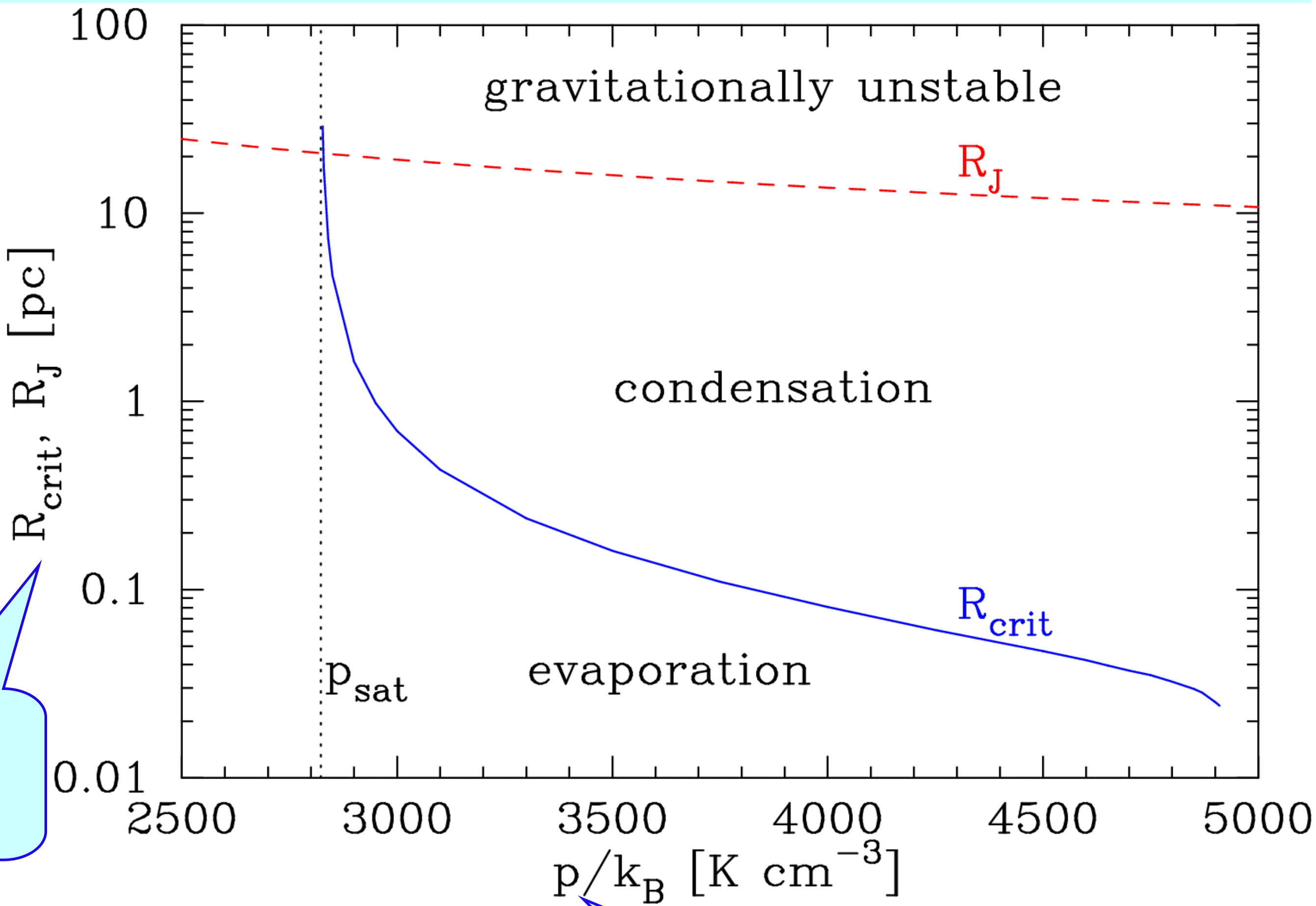
With Cooling/Heating and Thermal Conduction

Without Physical Viscosity $\rightarrow\ Pr = 0$

Evaporation of Spherical CNM in WNM



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



Critical Radius

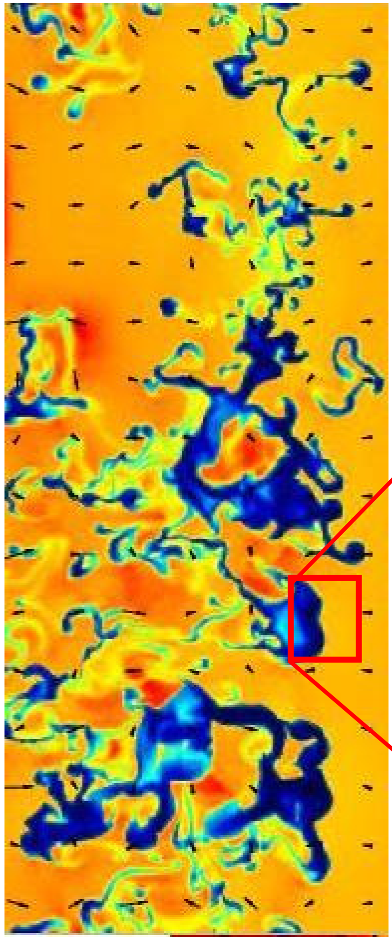
Ambient Pressure

"Tiny Scale Atomic Structure"?

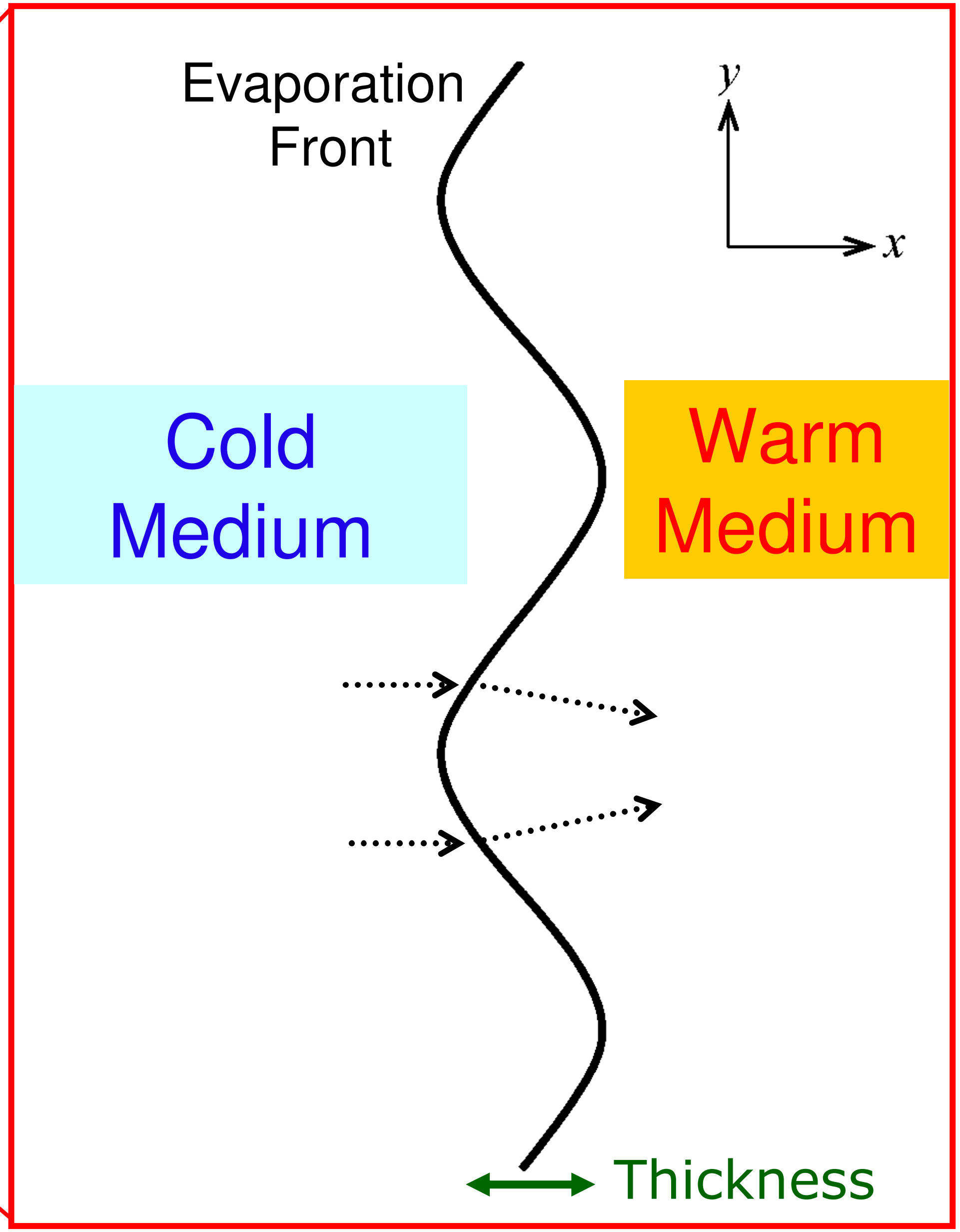
Braun & Kanekar 2005

Nagashima, Inutsuka, & Koyama 2006, ApJL **652**, L41

Instability of Transition Layer



important in maintaining the “turbulence”



Instability of Transition Layer

Similar Mechanisms…

1) Darrieus-Landau (DL) Instability

Flame-Front Instability

Important in SNe Ia

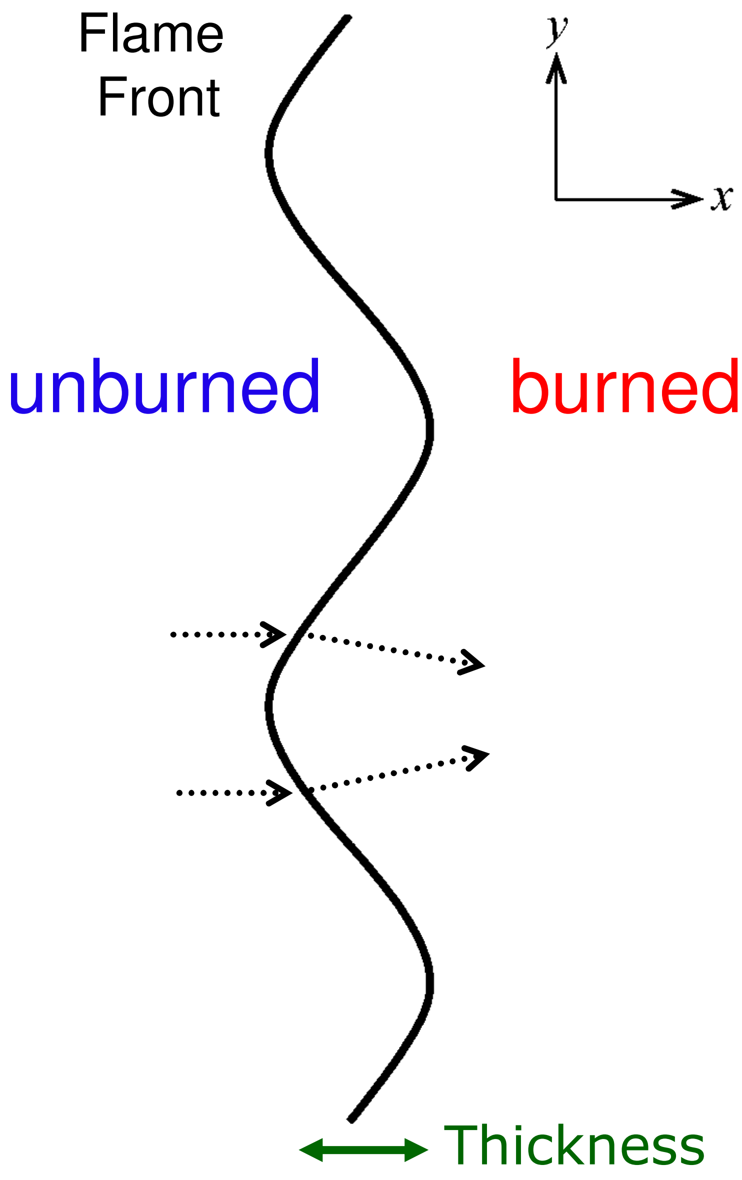
Effect of Magnetic Field

See Dursi (2004)

2) Corrugation Instability in MHD Slow Shock

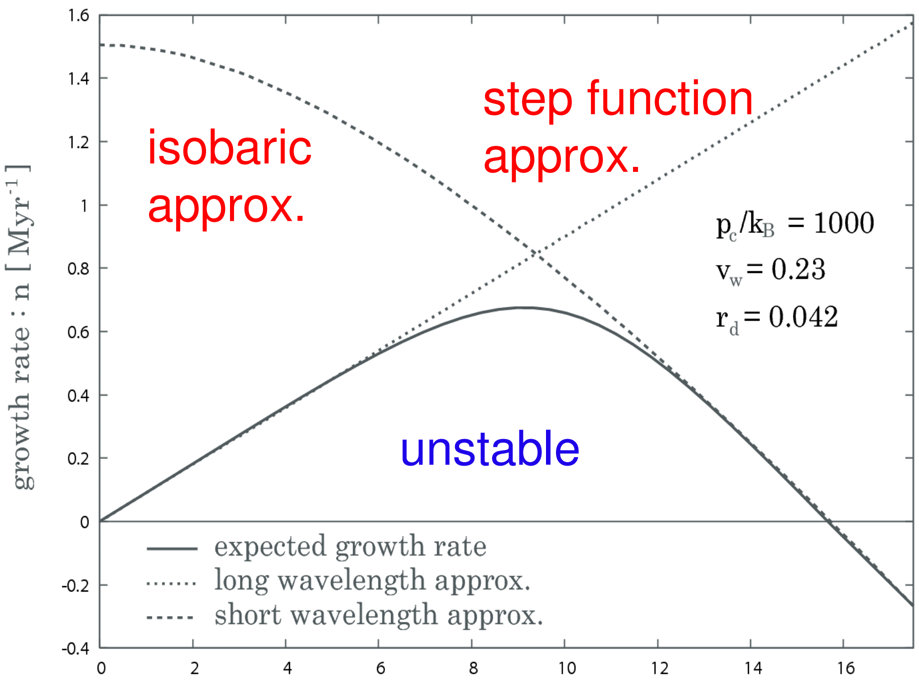
– Edelman 1990

– Stone & Edelman 1995



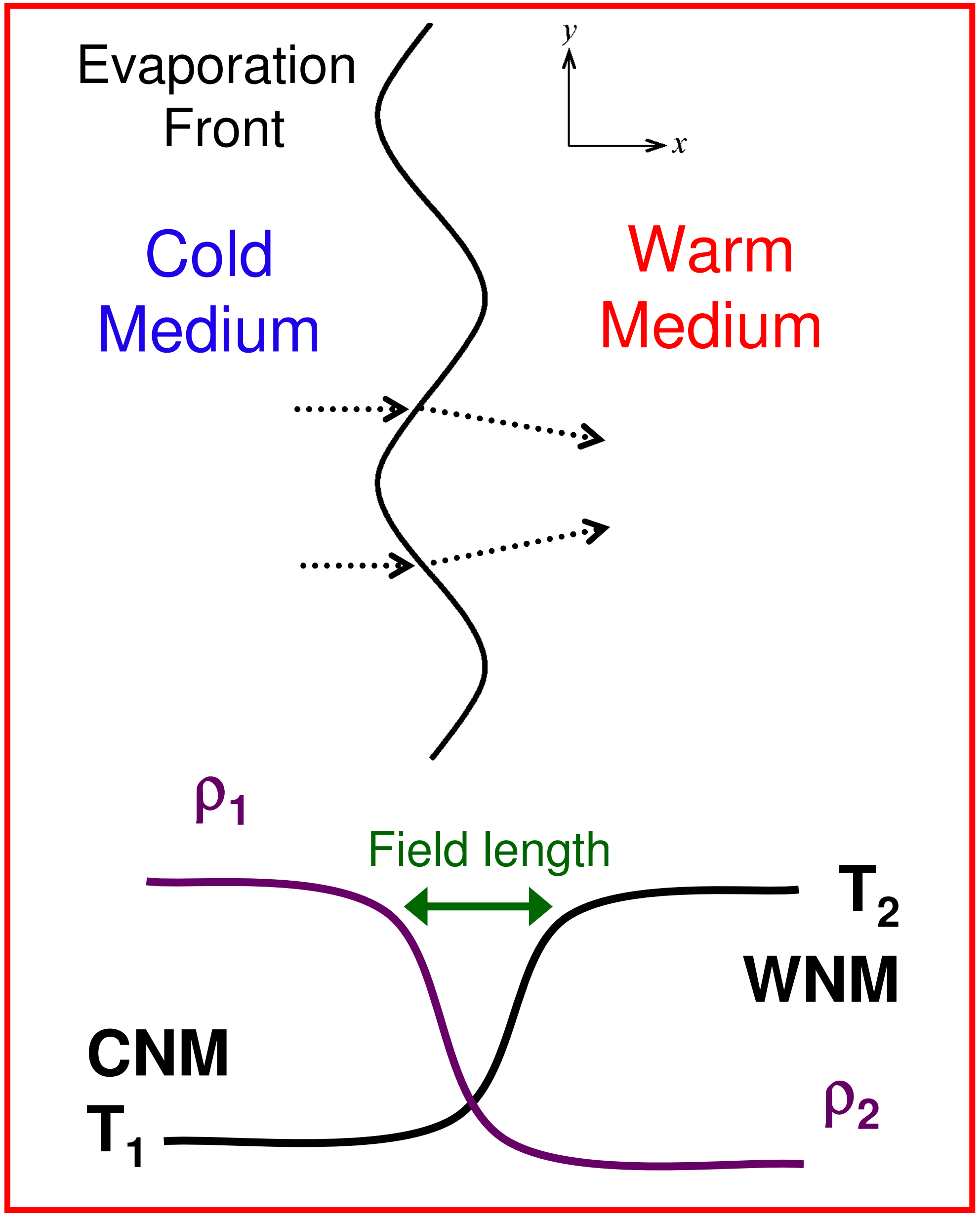
Linear Analysis of New Instability

Growth Rate (Myr^{-1})

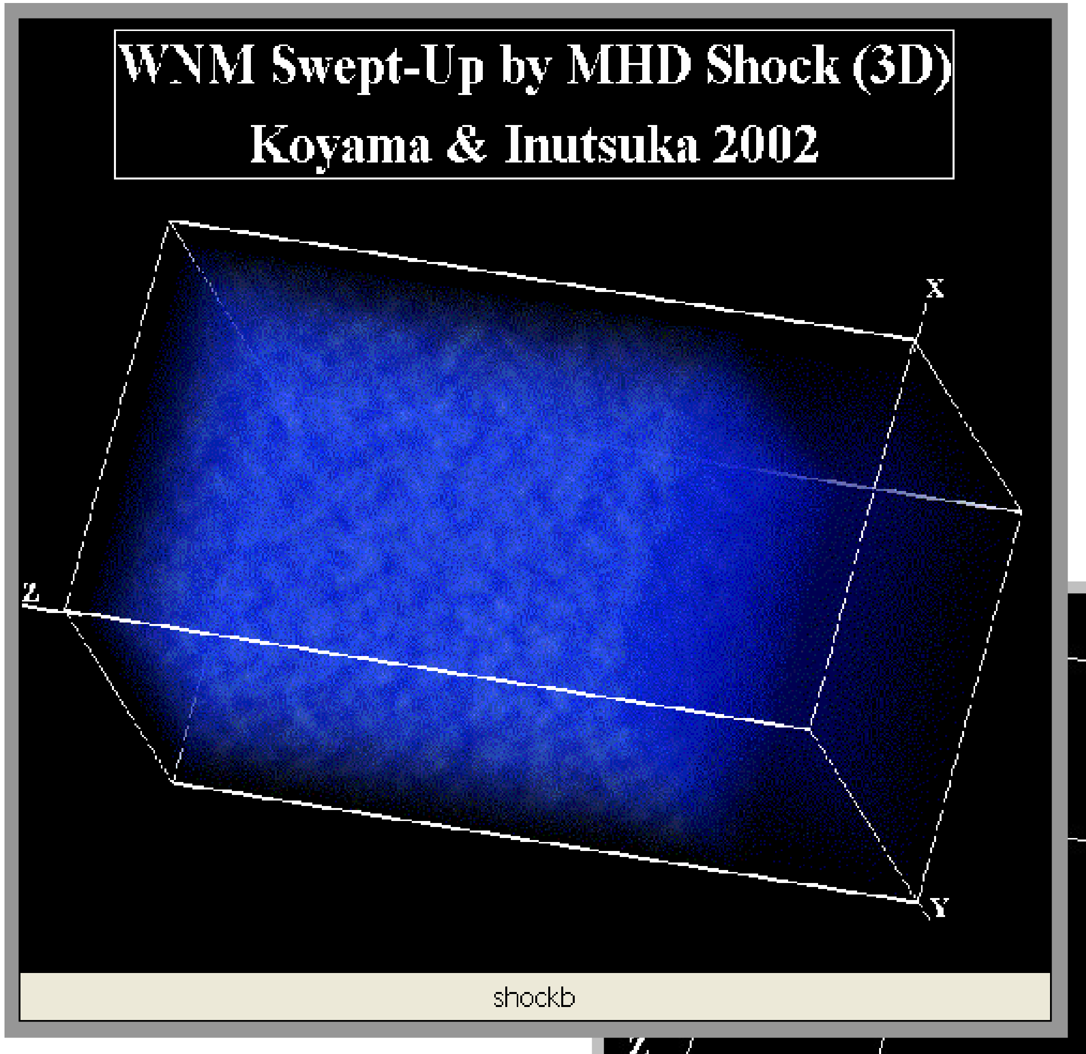


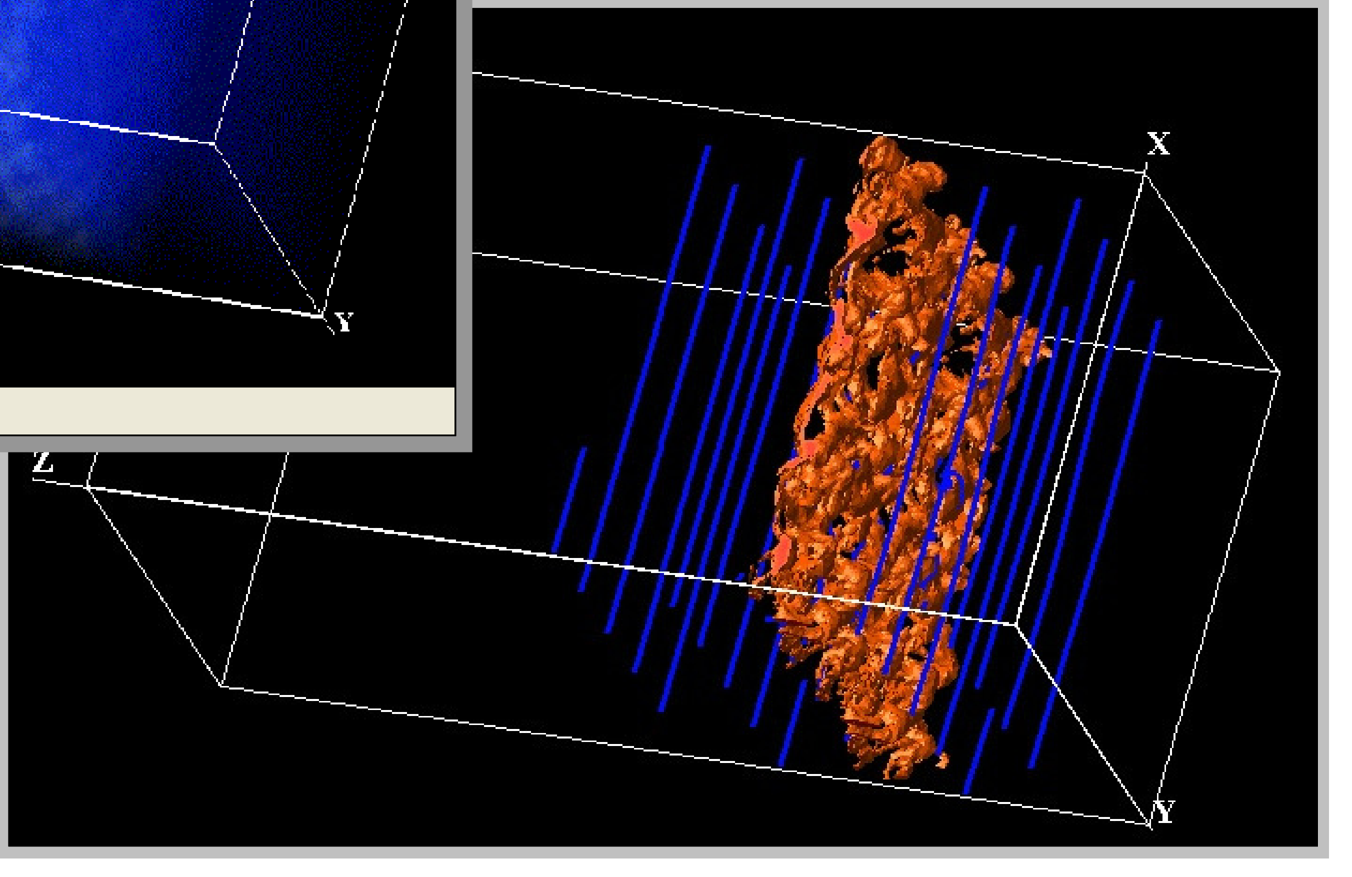
wavenumber $k_y/2\pi$ [pc^{-1}]

Inoue, Inutsuka, & Koyama 2006, ApJ **652**, 1131



WNM Swept-Up by MHD Shock (3D)





Effect of Magnetic Field on TI

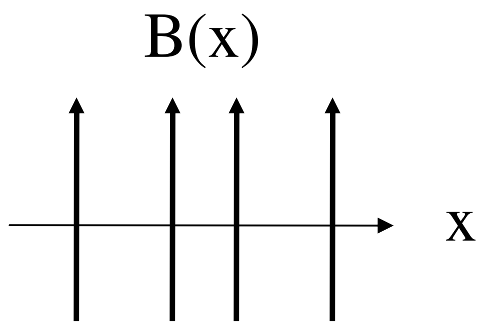
TI growth until gas reaches stable phase.

But, Magnetic field can prevent TI.

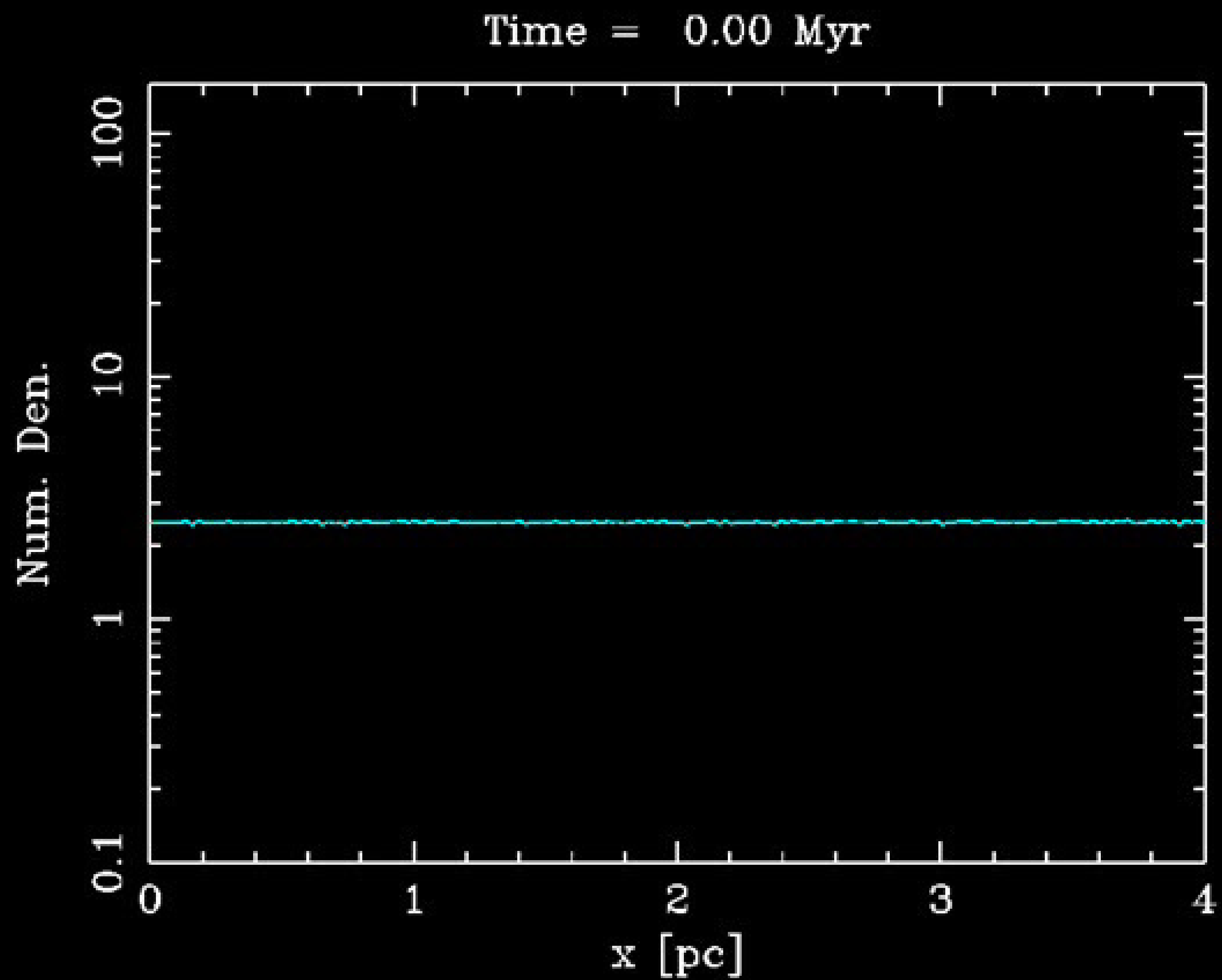
Actually, ISM is a partially ionized medium.

Can ambipolar diffusion reduce magnetic field in CNM?

We perform 1D simulations of TI with transverse MF & Ambipolar diffusion.



Model 2 : B_{ini}=1 μ G



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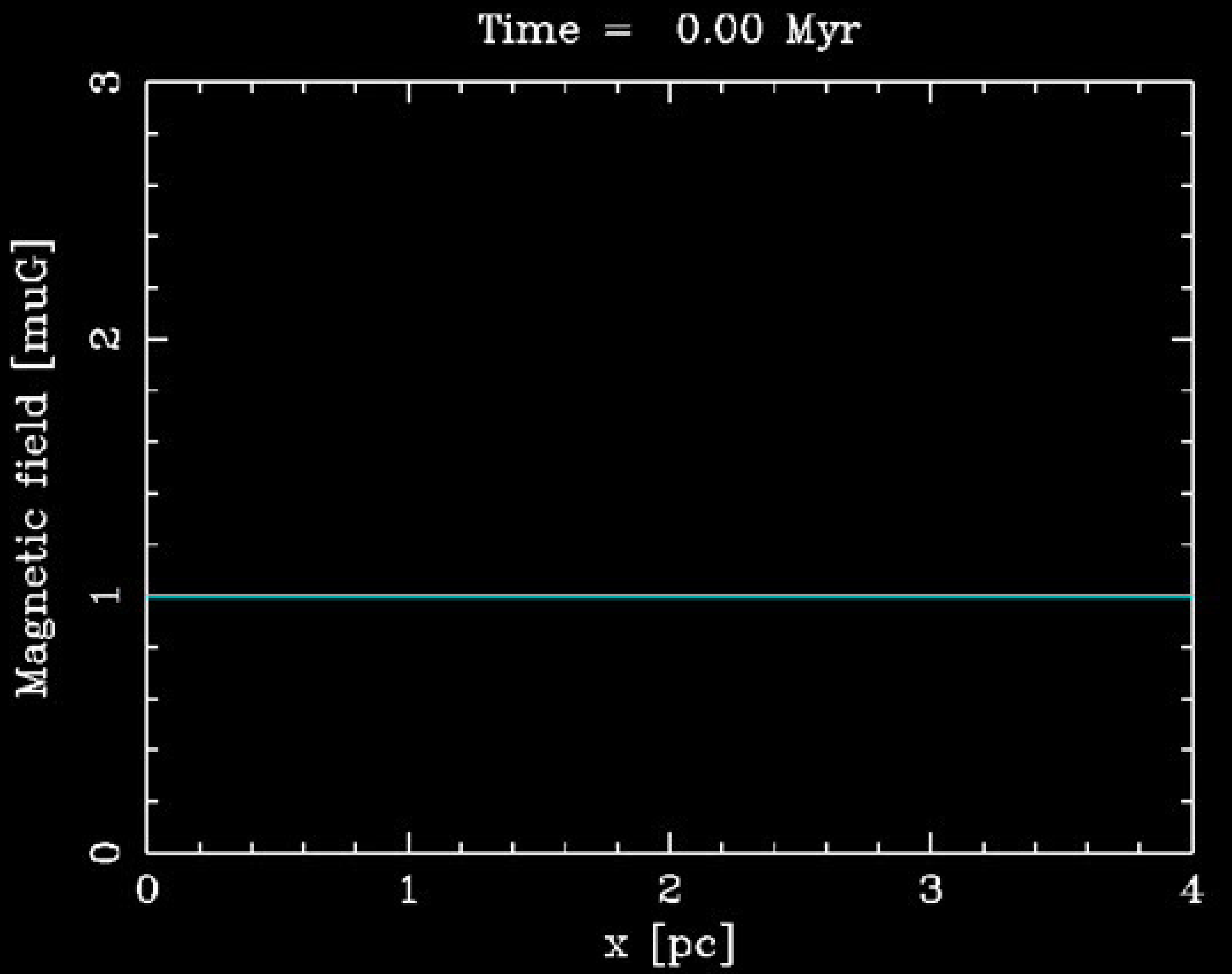
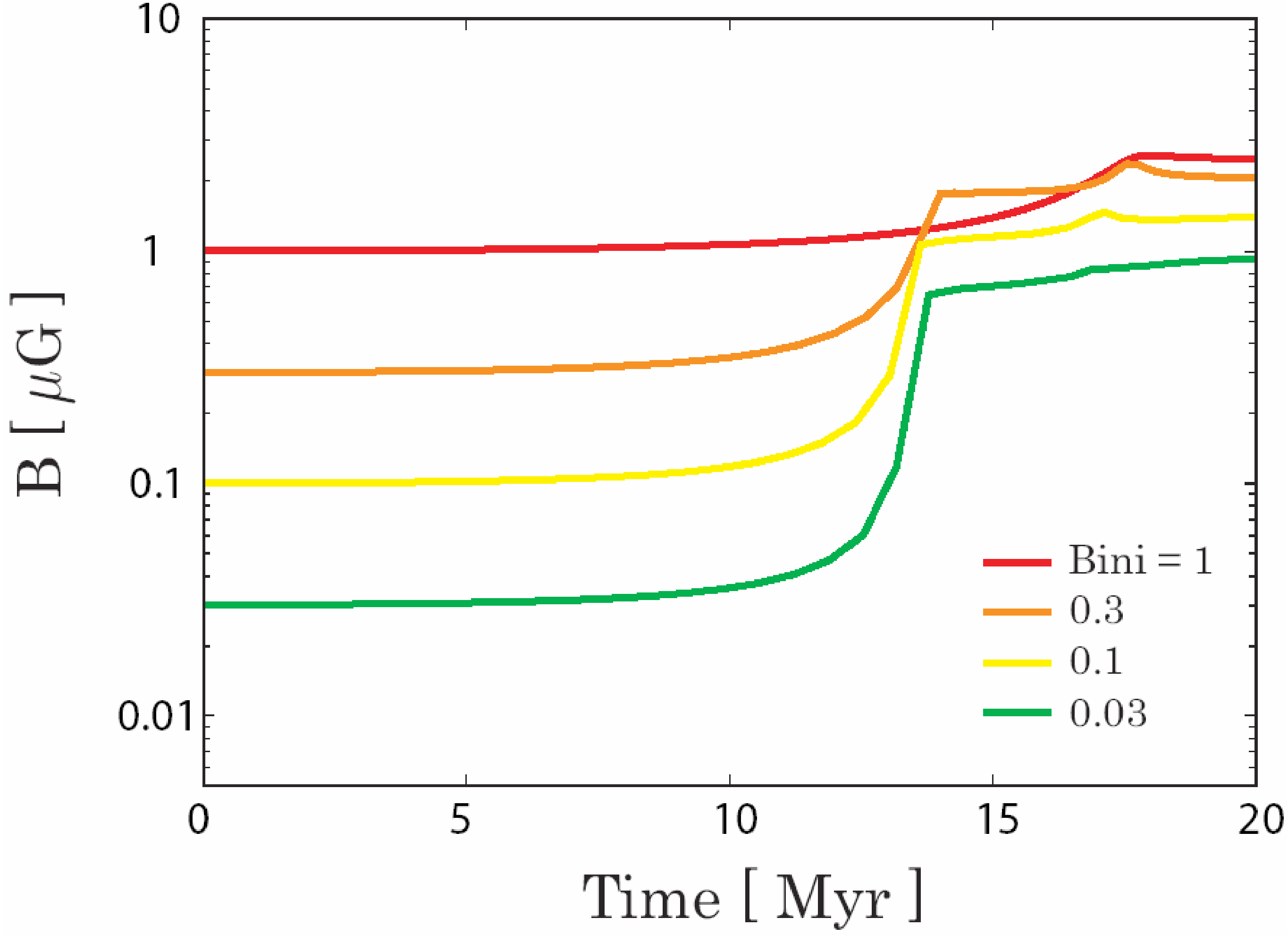


Evolution of Magnetic Intensity

Magnetic intensity growth to a few μG irrespective of initial intensity!



Inoue, Inutsuka, & Koyama (2006) ApJ **658**, L99

Magnetic Intensity in CNM

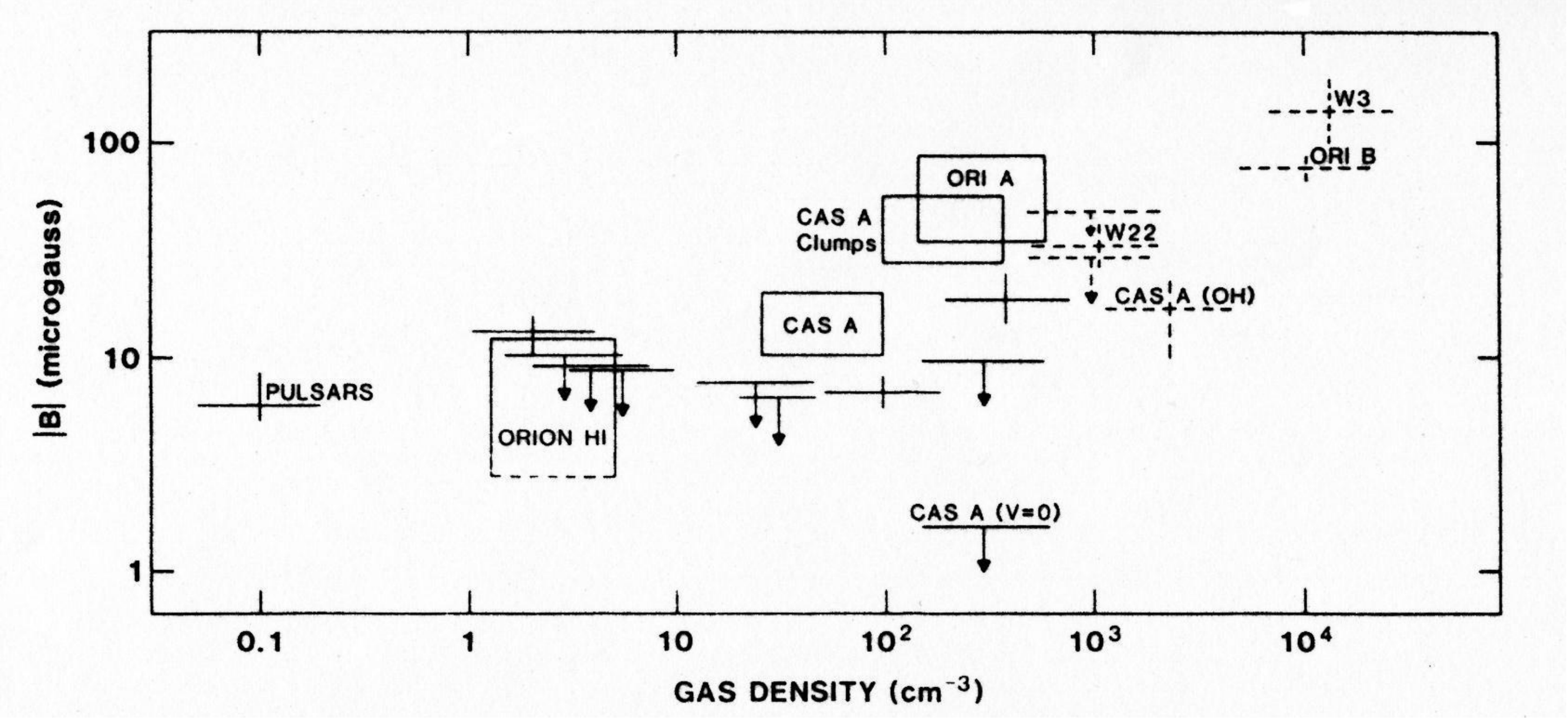
- Condensation speed of TI: $v_{TI} = \lambda_F / t_{cool}$
- If $v_{TI} < v_{drift}$, magnetic field lines do not accumulate. ➔ TI is easy.
- If $v_{TI} > v_{drift}$, magnetic field lines accumulate.

- $v_{TI} \approx v_{drift}$ determine critical Magnetic intensity B_{AD}:

$$B_{AD} \simeq 3.2 \left(\frac{p_n/k_B}{4000\ \mathrm{K\ cm^{-3}}} \right)^{1.475} \left(\frac{n_n}{50\ \mathrm{cm^{-3}}} \right)^{-0.4875} \mu\mathrm{G}$$

Inoue, Inutsuka, & Koyama (2006) ApJ **658**, L99

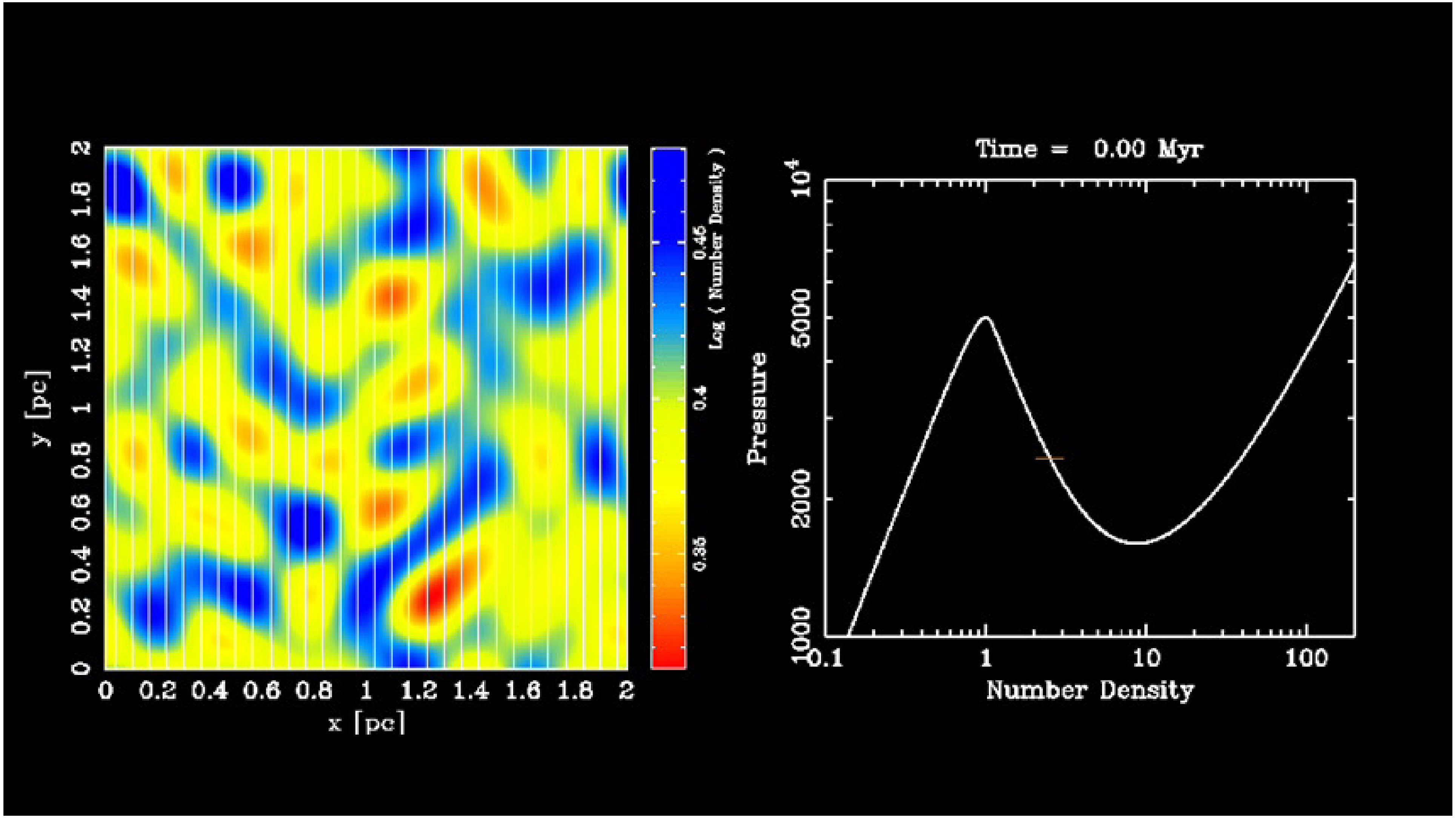
Observed Magnetic Field Intensity vs. Density



Troland & Heiles 1986

2D 2-Fluid MHD Simulations

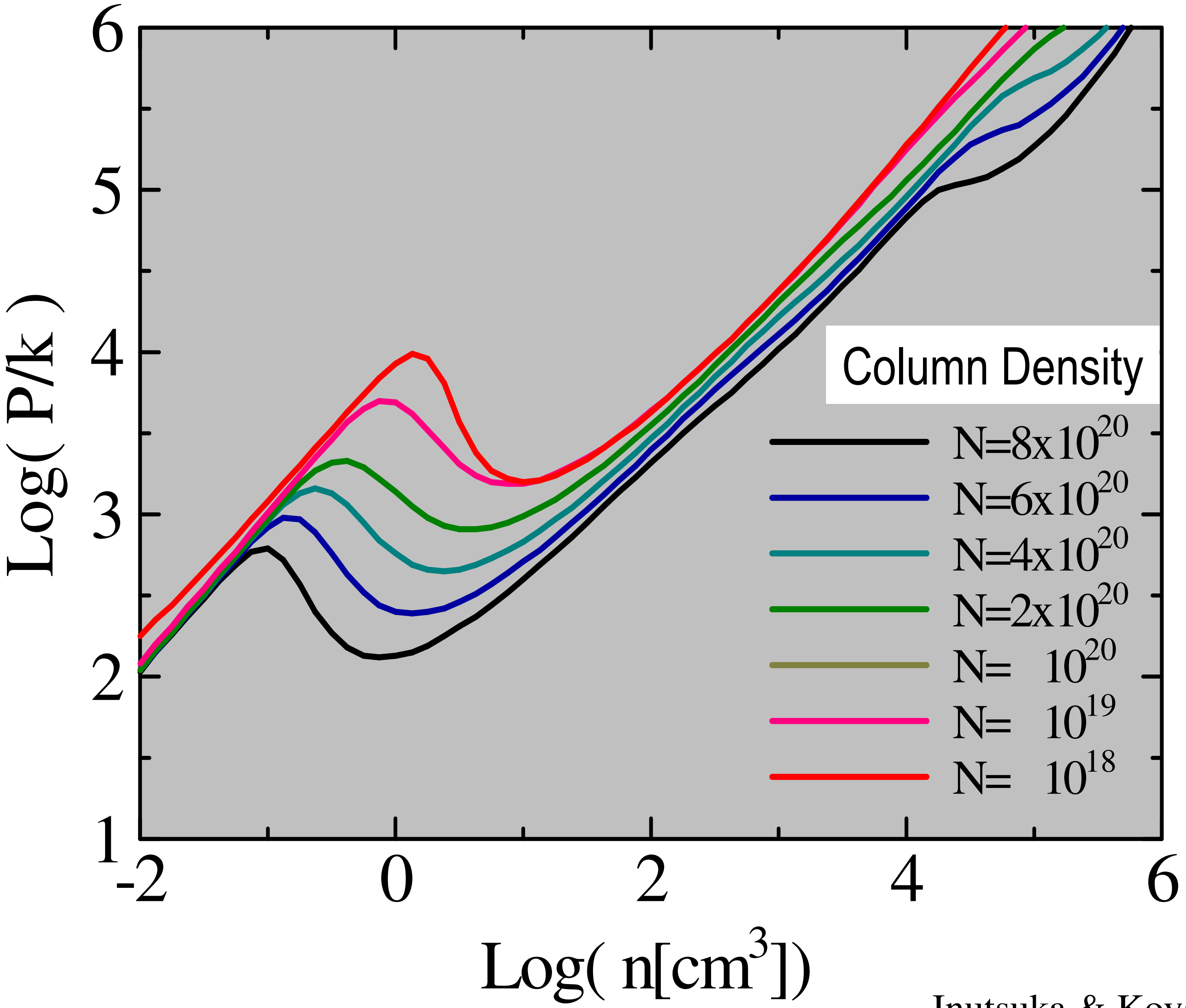
Preliminary!



Further Evolution into Molecular Clouds?

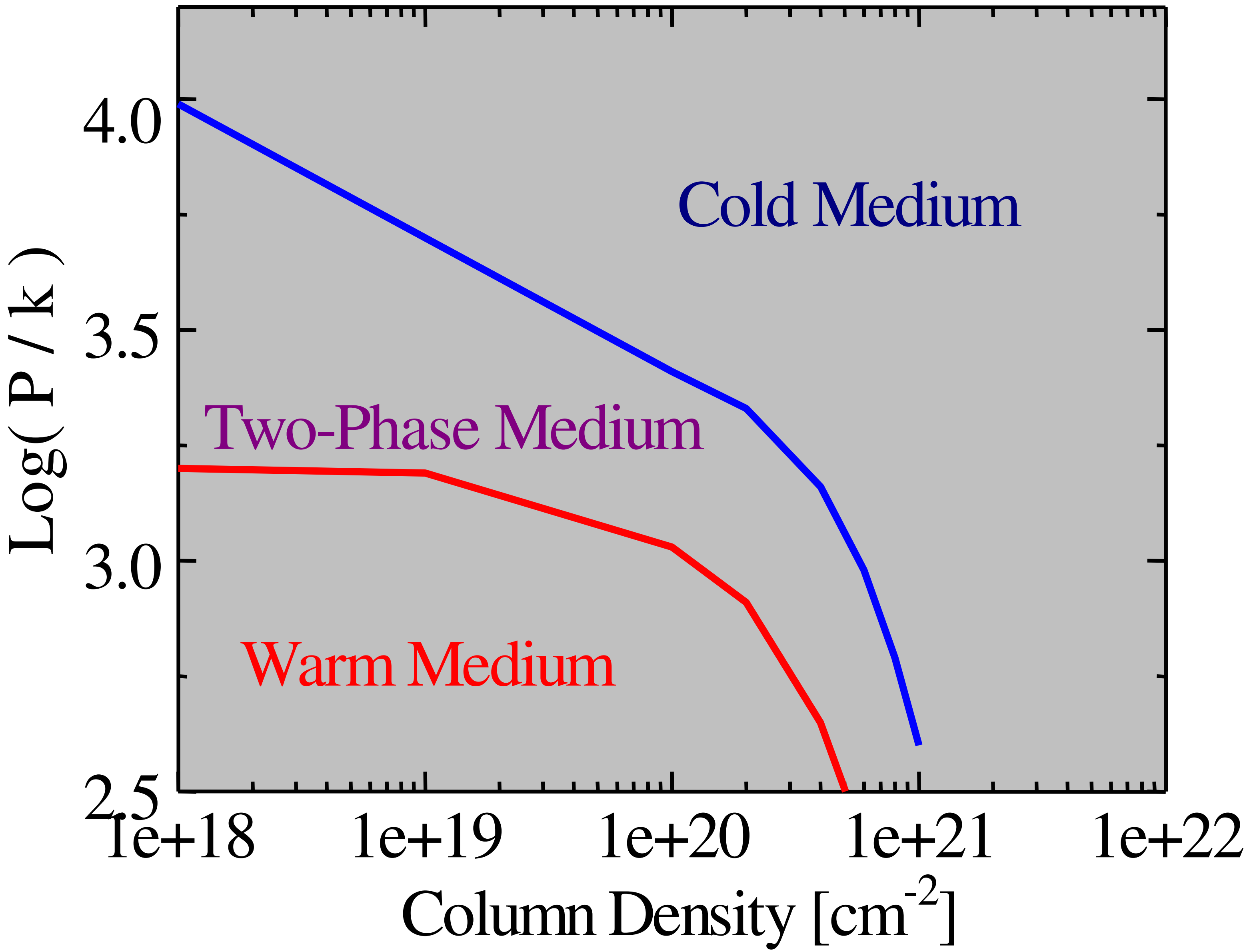
- Higher Column Density?
- Higher Density?

Equilibrium with Various Column Density



Inutsuka & Koyama 1999

Allowed Region of 2-Phase Medium



Inutsuka & Koyama 1999

When column density is sufficiently large,

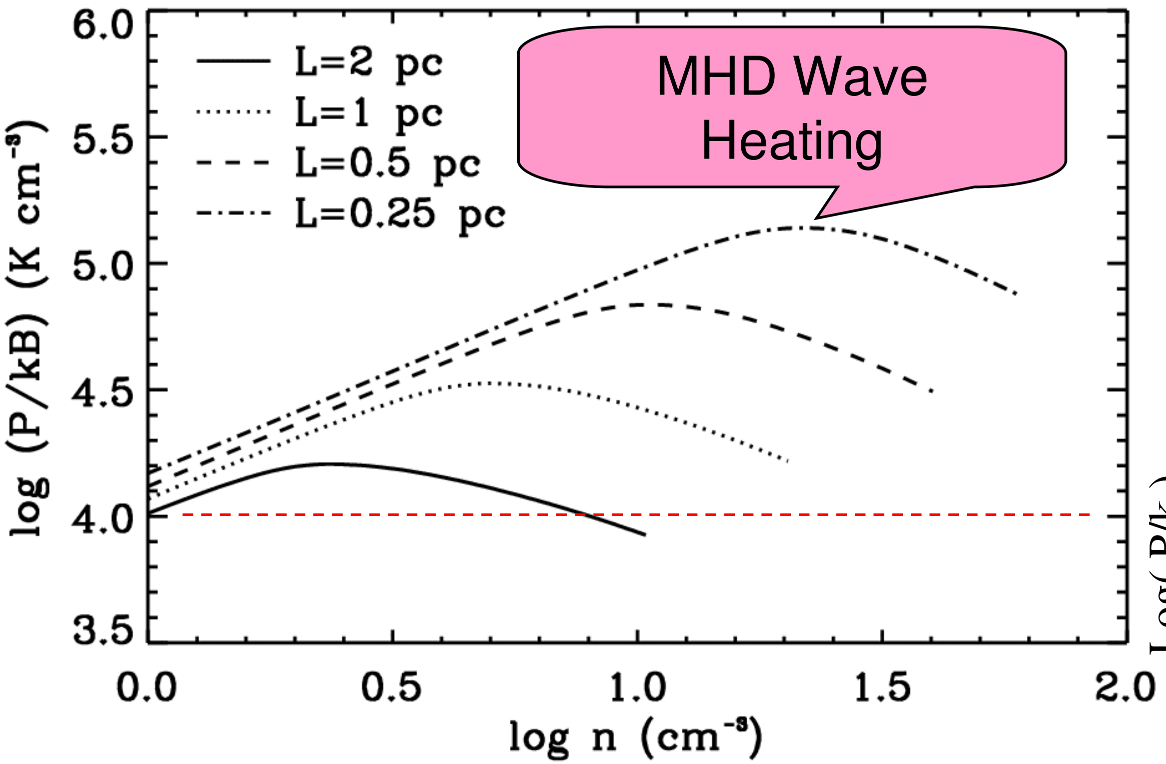
$$N_H > 10^{21}\ cm^{-2}\ \text{or}\ A_v > 1\ mag$$

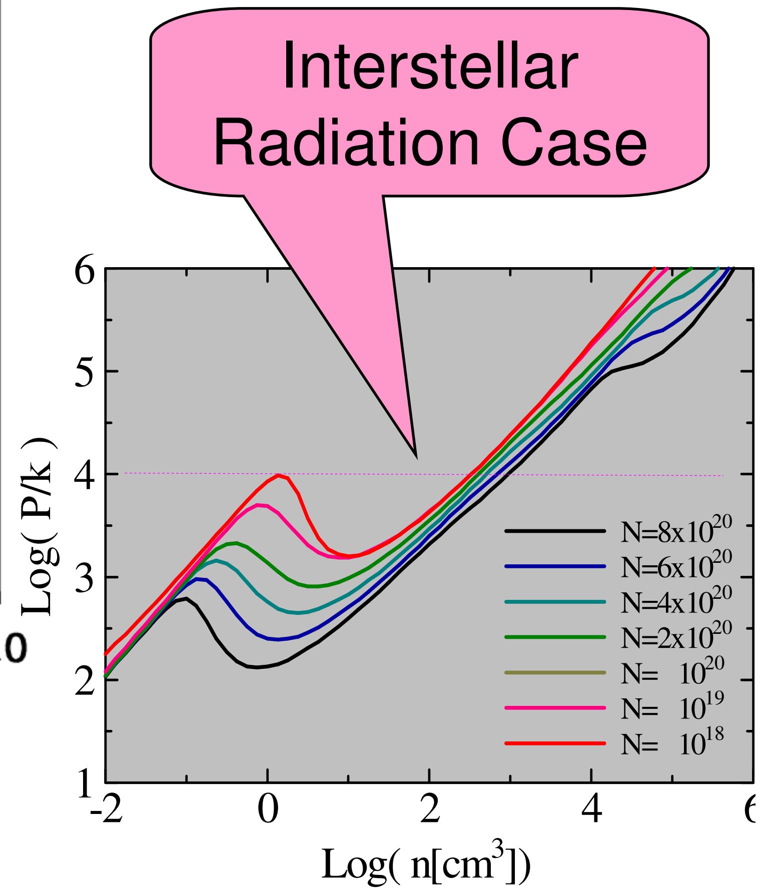
ambient radiation field does not provide sufficient radiative heating for WNM.

Without any heating WNM simply cools down very quickly.

Is there any heating to WNM inside Molecular Clouds?

WNM in Molecular Clouds: Thermal Equilibrium with MHD Wave Heating





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

Heating is sufficient for WNM to survive in MC.

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

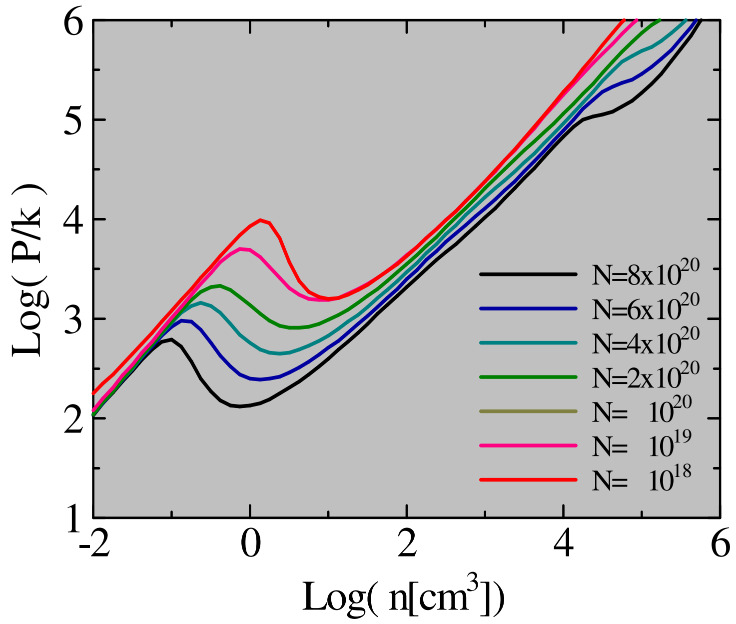
Summary

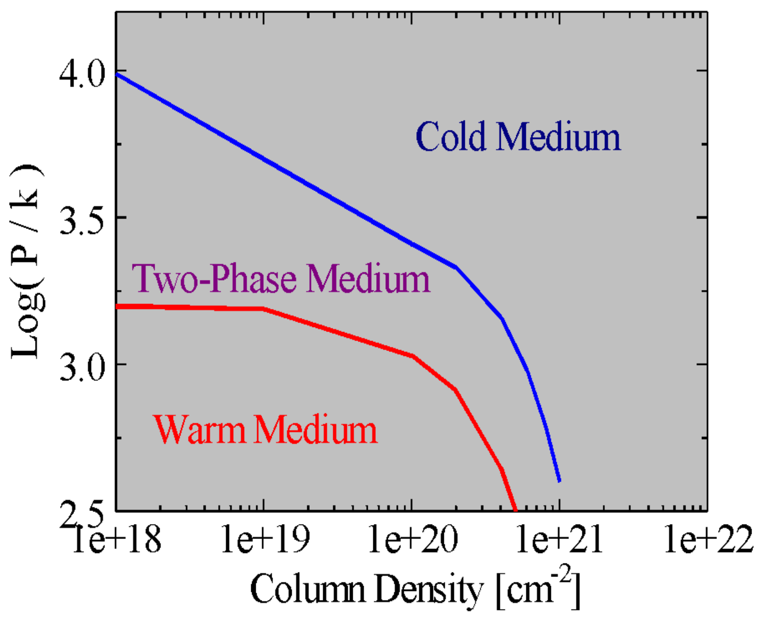
- Shock waves in ISM create
  turbulent CNM embedded in WNM.
- In TI-driven turbulence in Multi-Phase ISM
  - Evaporation/Condensation of CNM clouds
  - New Instability in Evaporation Front
- Can WNM Survive in Molecular Clouds?
  - Possible: Dissipation of MHD Waves

Future Work

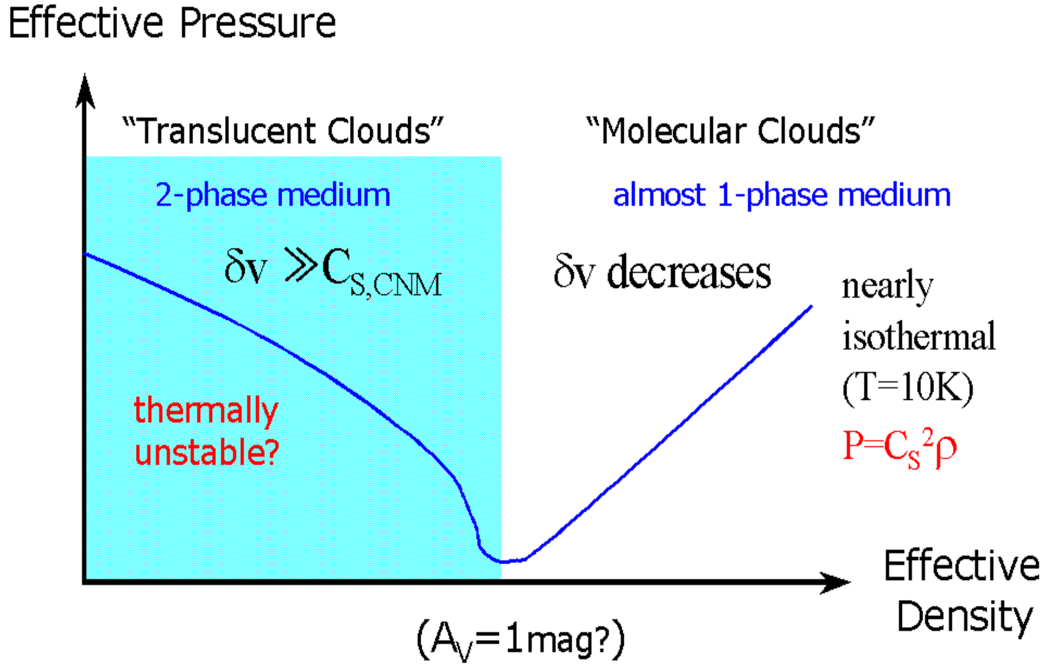
- RHD calculation of the evolution of two phase medium…
- When self-gravity becomes important?

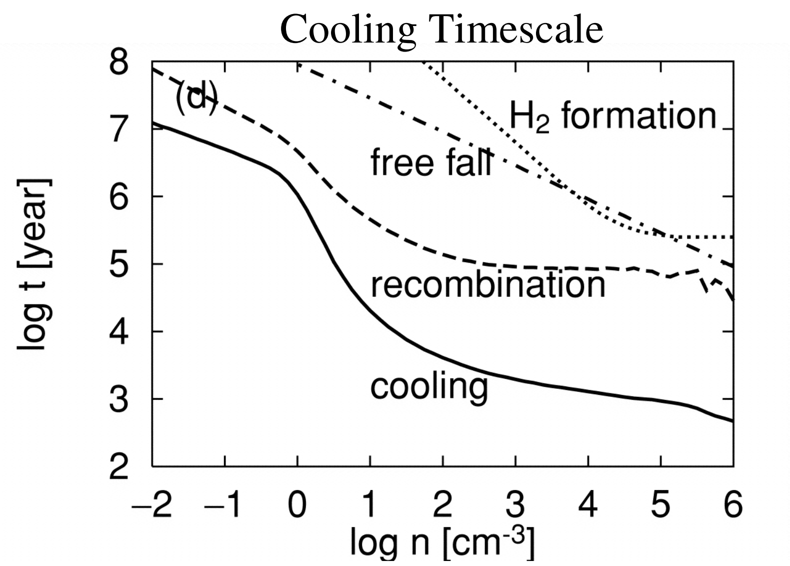
Radiative Equilibrium: Column Density Dependence





Inutsuka & Koyama 2000





Dynamical Timescale of ISM

Dynamical Three Phase Medium

– McKee & Ostriker 1977

- SN Explosion Rate in Galaxy… 1/(100yr)
- Expansion Time…1Myr
- Expansion Radius… 100pc

$(10^{10}\,\mathrm{kpc})^2 \times 100\,\mathrm{pc}$

$$(10^{-2}\,\mathrm{yr}^{-1}) \times (10^{6}\,\mathrm{yr}) \times (100\mathrm{pc})^{3} = 10^{10}\,\mathrm{pc}^{3} \sim V_{Gal.Disk}$$

Dynamical Timescale of ISM ~ 1Myr

« Timescale of Galactic Density Wave ~ 100Myr