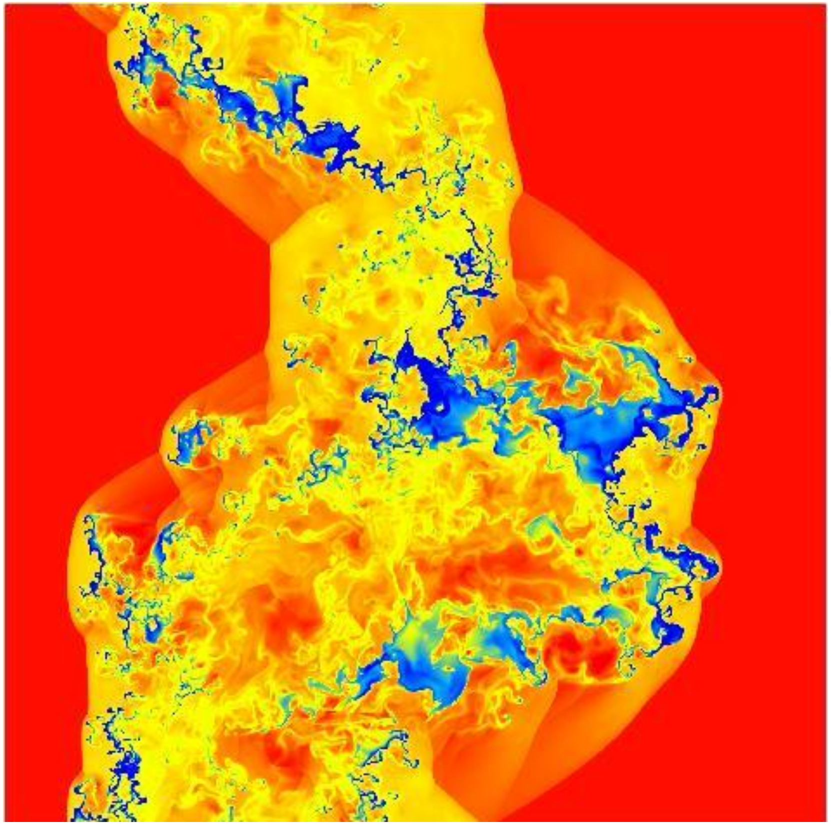
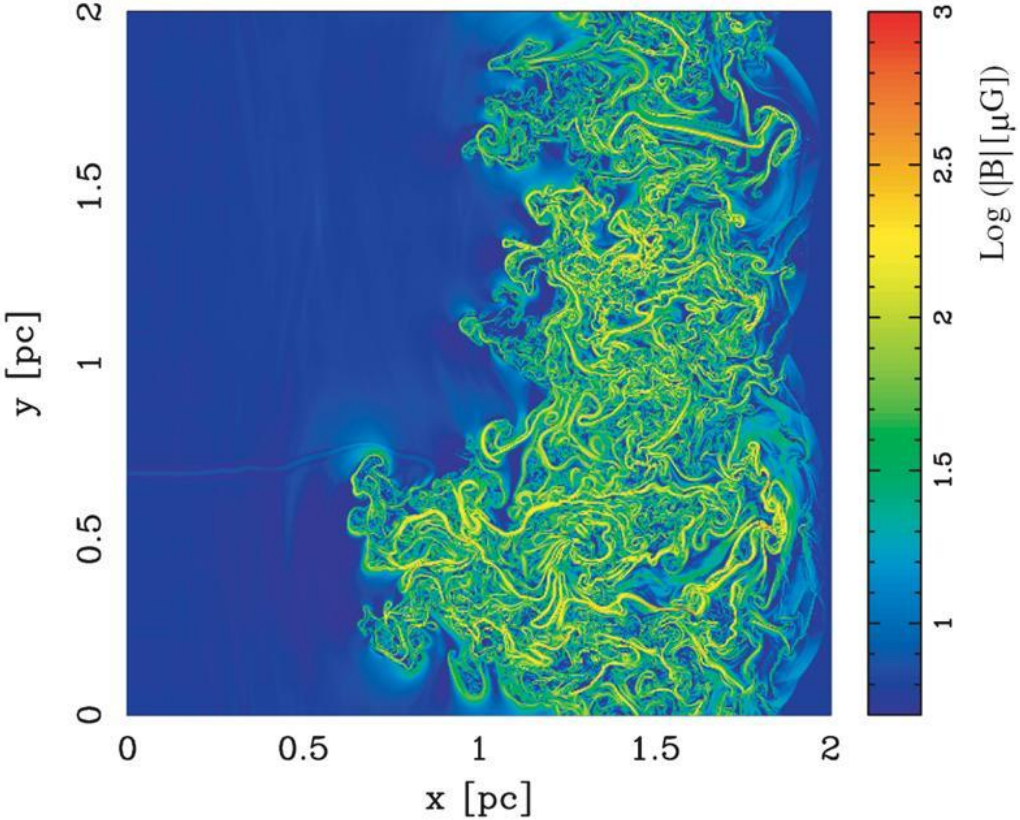
6th Korean Astrophysics Workshop on Fundamental Processes of Astrophysical Turbulence

Phase Transition Dynamics of Multi-Phase Interstellar Medium

Shu-ichiro Inutsuka (Nagoya Univ.)





16 - 19 November, 2011Asia Pacific Center for Theoretical Physics (APCTP), Pohang, Korea

Outline

- Timescale
- 1 Phase Equilibrium
  - Thermal Instability
- 2 Phase Equilibrium
  - Saturation Pressure
- 2 Phase Dynamics ➔ Sustained Turbulence
- Further Analyses w/o shock
  - Evaporation, Condensation, New Instability, Magnetic Field
- Conclusion

Dynamical Timescale of ISM

Dynamical Three Phase Medium

- e.g., McKee & Ostriker 1977

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

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

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

Dynamical Timescale of ISM ~ 1Myr

≪ Timescale of Galactic Density Wave ~ 100Myr

Expanding HII regions are also important.

Basic Equations

- Eq. of Continuity

$$\frac{\partial \rho}{\partial \mathrm{t}} + \frac{\partial}{\partial x}(\rho \mathrm{v}) = 0$$

- EoM

$$\frac{\partial}{\partial t}(\rho v) + \frac{\partial}{\partial x}\left(P + \rho v^2\right) = 0$$

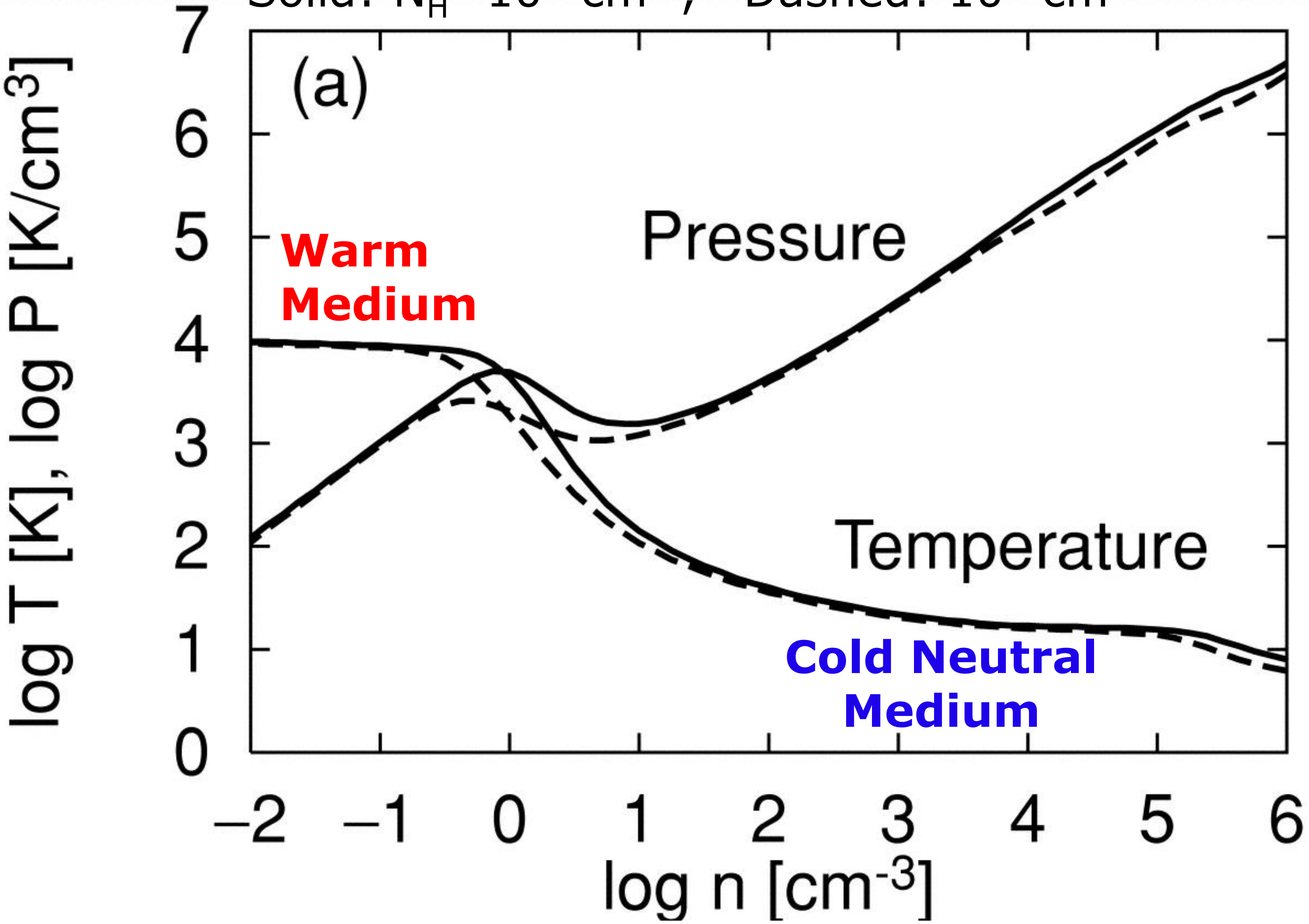
- Eq. of Energy
  - Radiative Heating & Cooling: Γ, Λ
    - H, C^+, O, Fe^+, Si^+, H_2, CO
  - Chemical Reaction
    - HII, HI, H_2, CII, CO
  - Thermal Conduction
    - conduction coefficient: κ

$$\frac{\partial E}{\partial t} + \frac{\partial}{\partial x}\left((E+P)\mathrm{v} - \kappa \frac{\partial T}{\partial x}\right) = \rho\Gamma - \rho^2\Lambda$$

<u>Self-Gravity Negligible</u> for Low Density Gas

Radiative Equilibrium for a given density

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

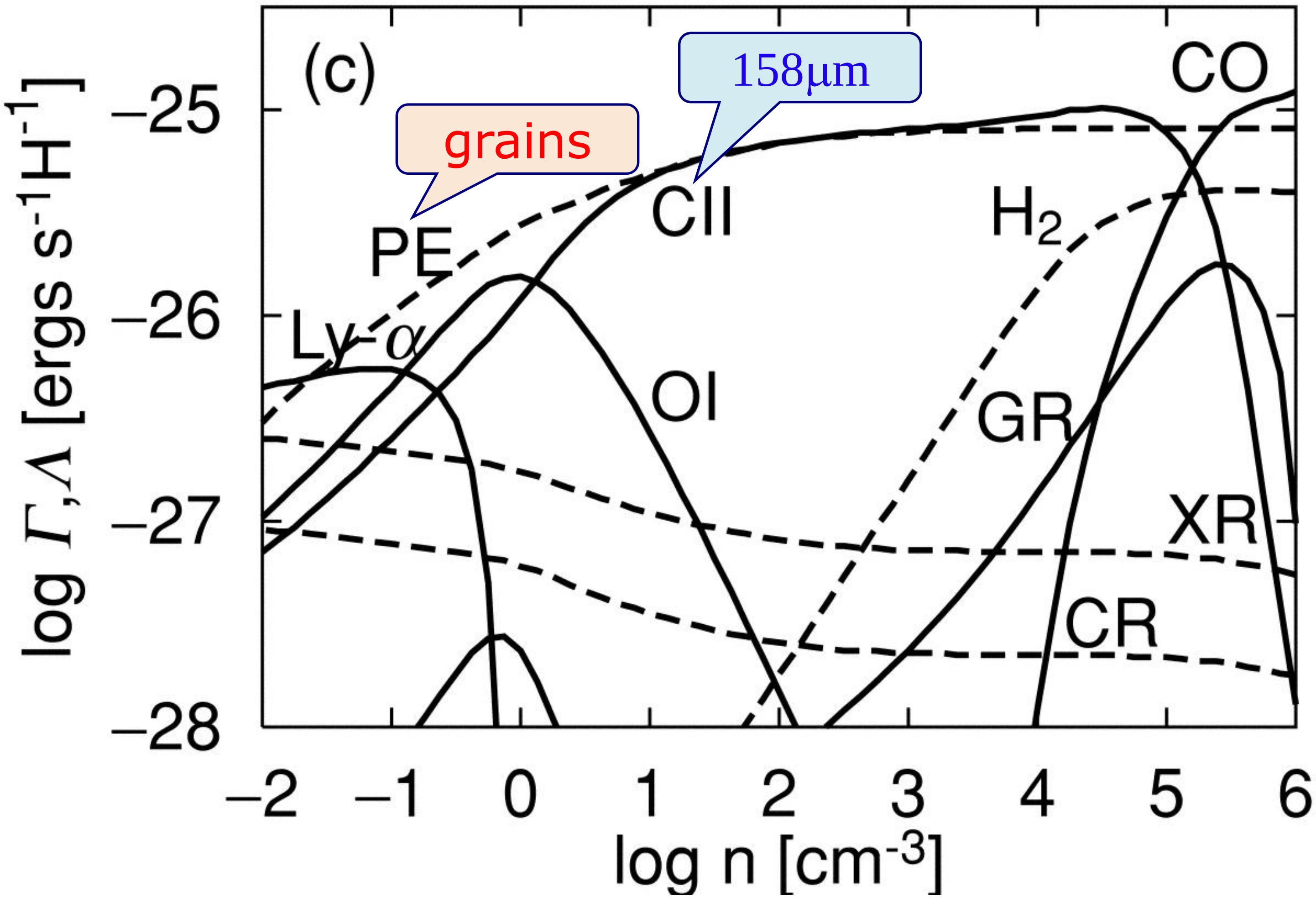


Warm Medium

Cold Neutral Medium

Radiative Cooling & Heating

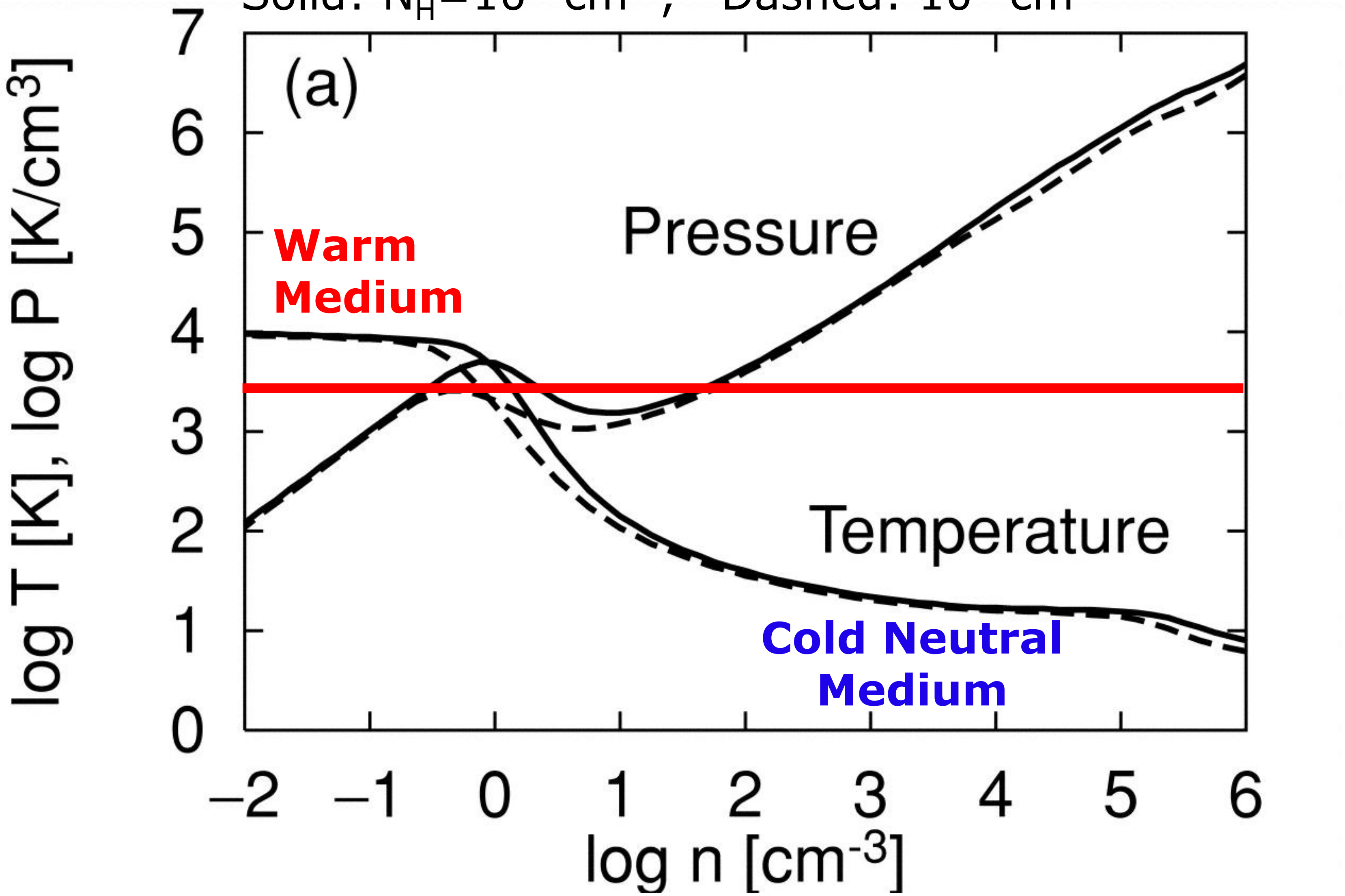
Solid: Cooling, Dashed: Heating



Koyama & SI (2000) ApJ **532**, 980 , (adding CO to Wolfire et al. 1995)

Radiative Equilibrium for a given density

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



Textbook Example of Phase Equilibrium

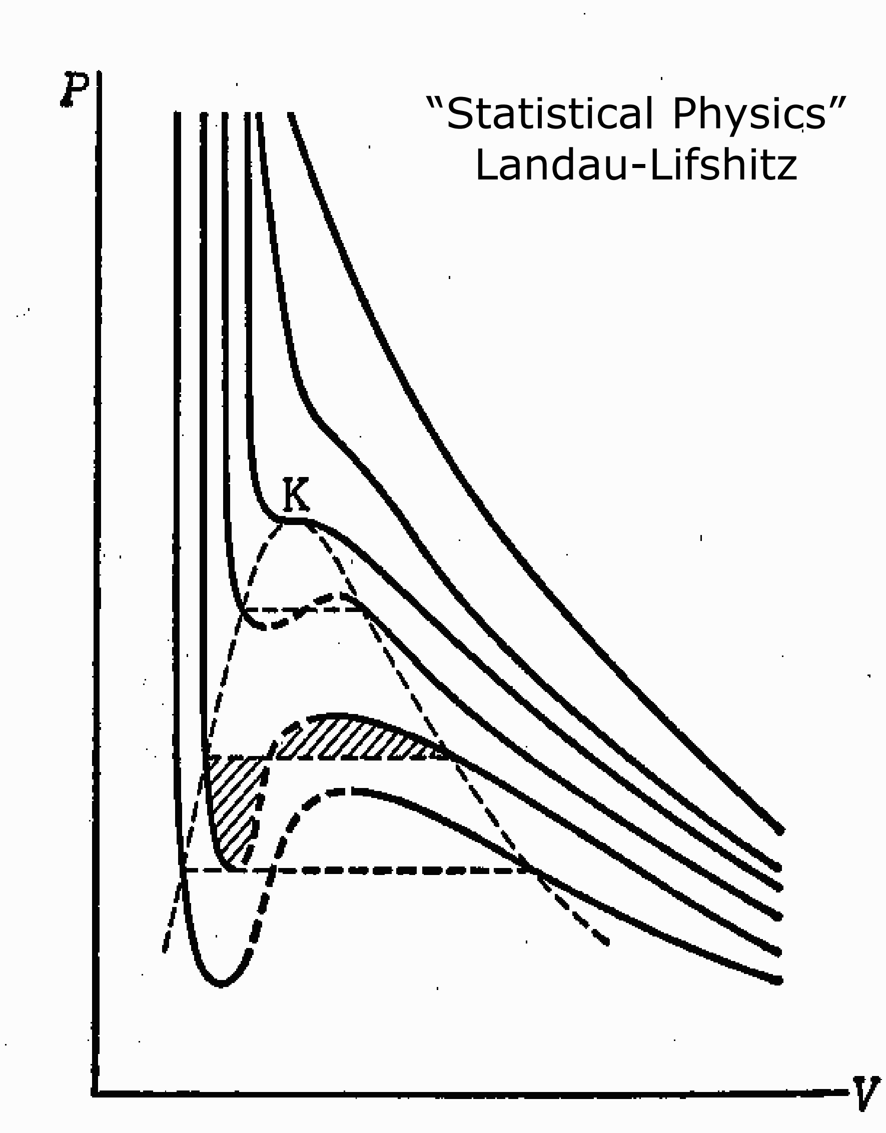
EoS of van der Waals Gas

$$P = \frac{NT}{V - nb} - \frac{N^2 a}{V^2}$$

$$\mu_1 = \mu_2 \Leftrightarrow 0 = \int_1^2 \, d\mu$$

$$= \int_1^2 \, V(P, T = \text{const}) dP$$

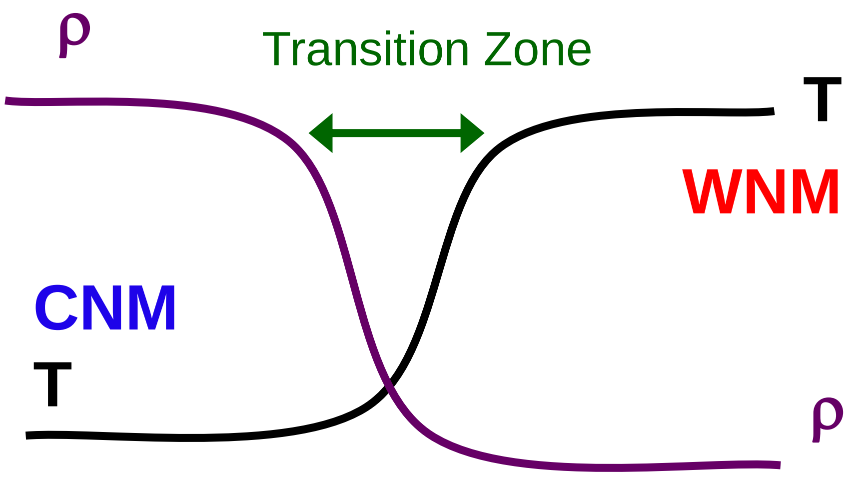
Equal Areas of shaded regions
(Maxwell's rule)



"Statistical Physics"
Landau-Lifshitz

Exact Equilibrium of 2-Phases

1D Case



Saturation Pressure

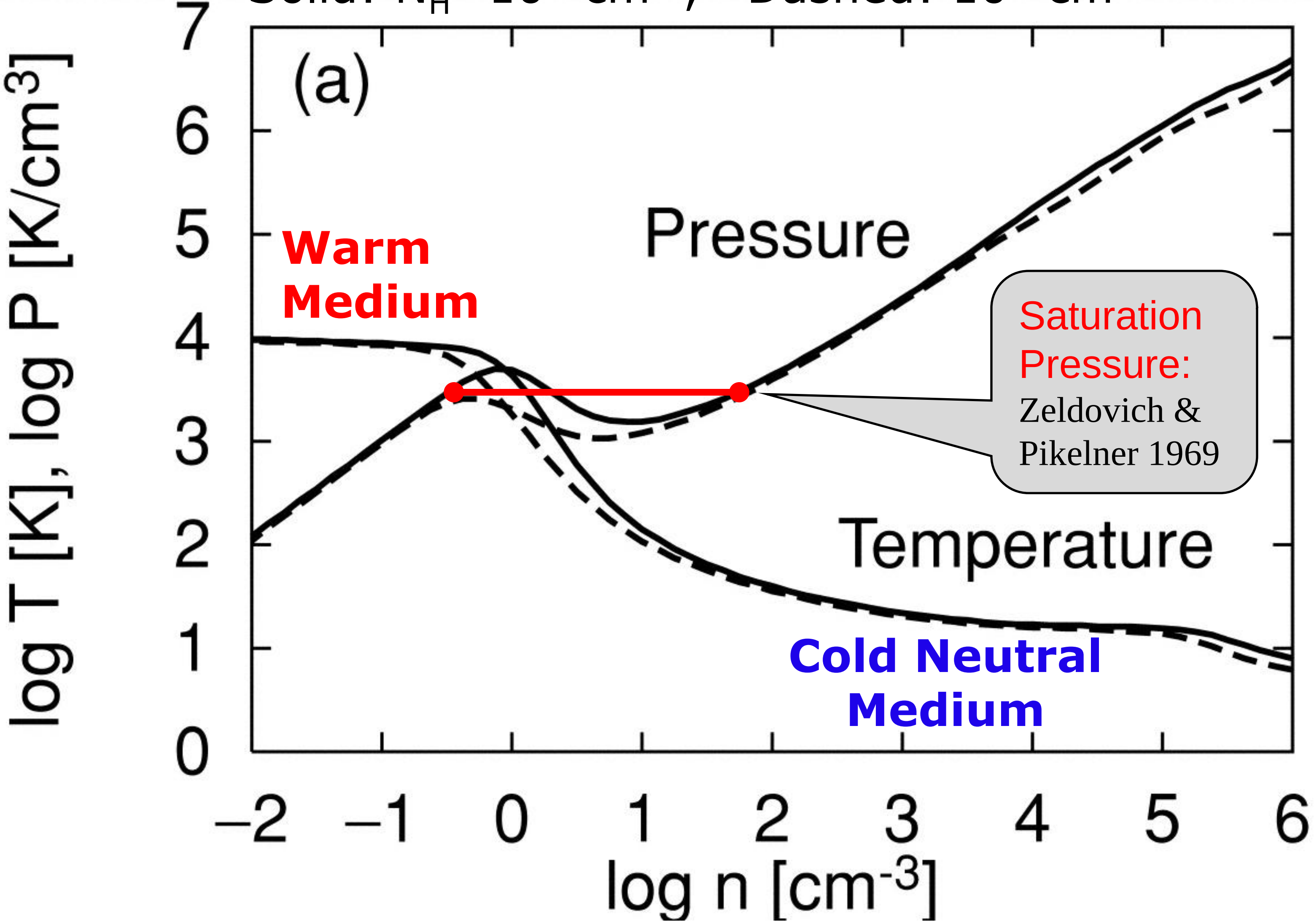
$$\int(\rho\Gamma-\rho^{2}\Lambda)dV=0\Rightarrow\ \text{only at}\ P{=}P_{\text{sat}}$$

- 1D Plane-Parallel Case: Zeldovich & Pikelner 1969
- 2D Cylindrical Symmetry: Graham & Langer 1973
- 3D Spherical Symmetry: Nagashima, SI, Koyama 2005

No Unique P_{sat} ➔ 2-Phase with various P

2 Phase in Equilibrium

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



Warm Medium

Saturation Pressure: Zeldovich & Pikelner 1969

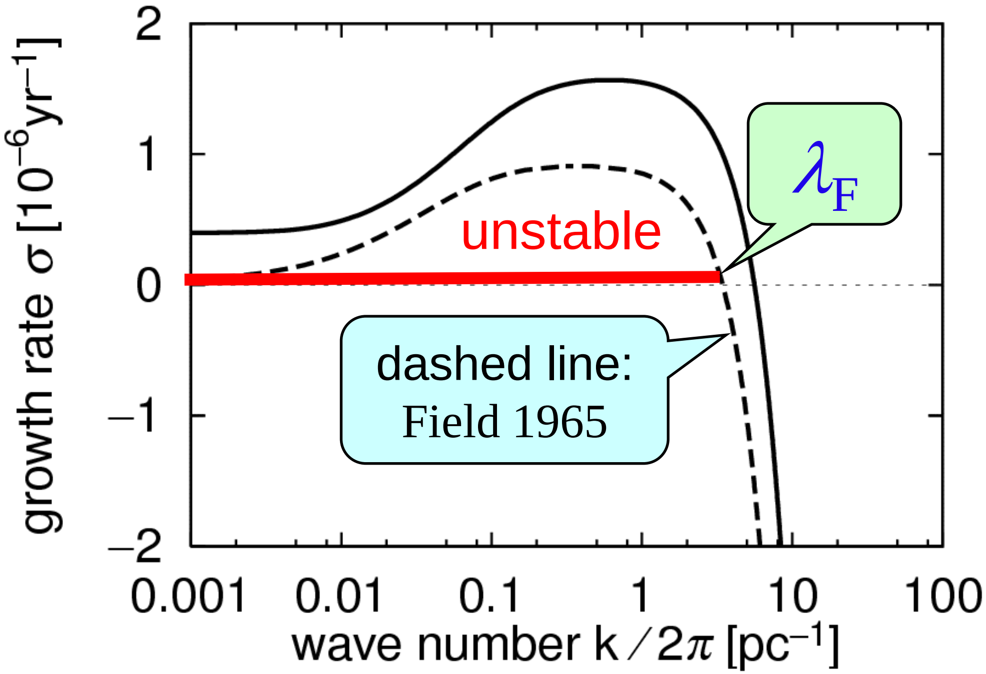
Cold Neutral Medium

Dispersion Relation of Thermal Instability

“Field length” : $\lambda_F \equiv \sqrt{\frac{\kappa T}{\rho^2 \Lambda}} \rightarrow 10^{-2}\,\mathrm{pc}$

Thermal Instability

for $\lambda > \lambda_F$



dashed line:
Field 1965

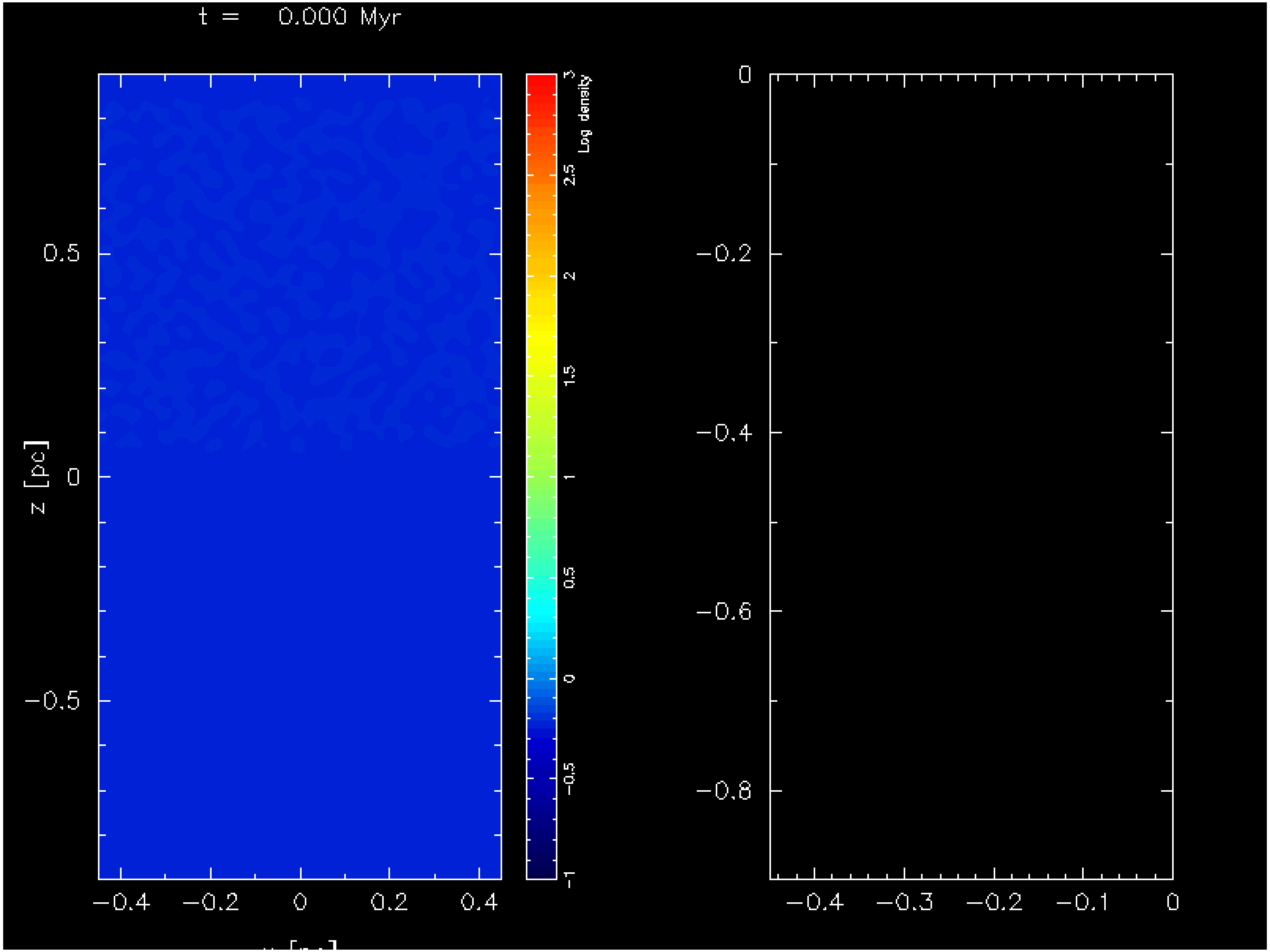
In 2-phase medium,

the width of transition layer

= λ_F .

Shock Propagation into WNM

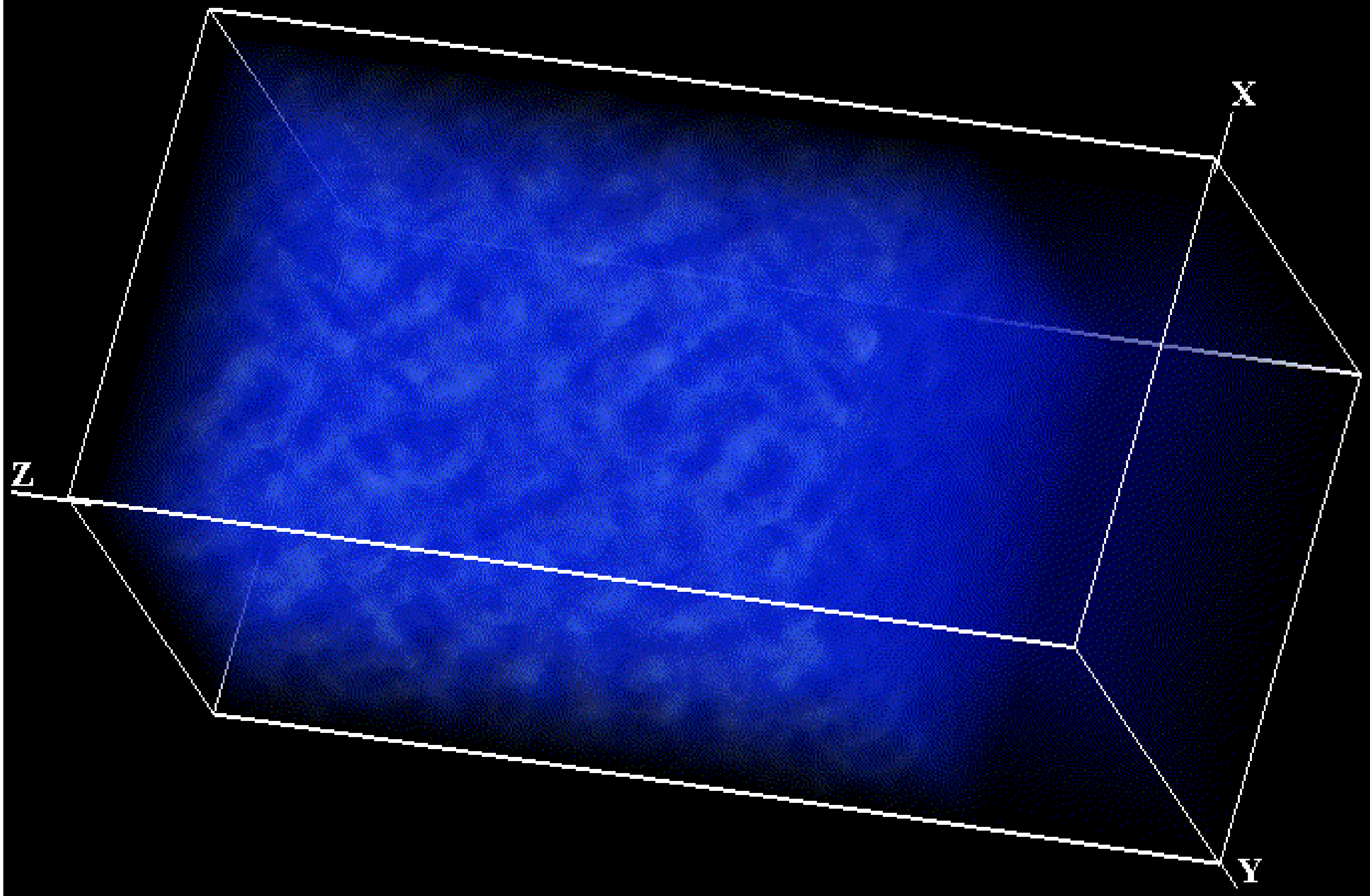
shock wave



Koyama & SI (2002) ApJ 564, L97

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

Koyama & Inutsuka 2002



Summary of TI-Driven Turbulence

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

  via Thermal Instability

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

  1D: Shock $\Rightarrow E_{th} \Rightarrow E_{rad}$

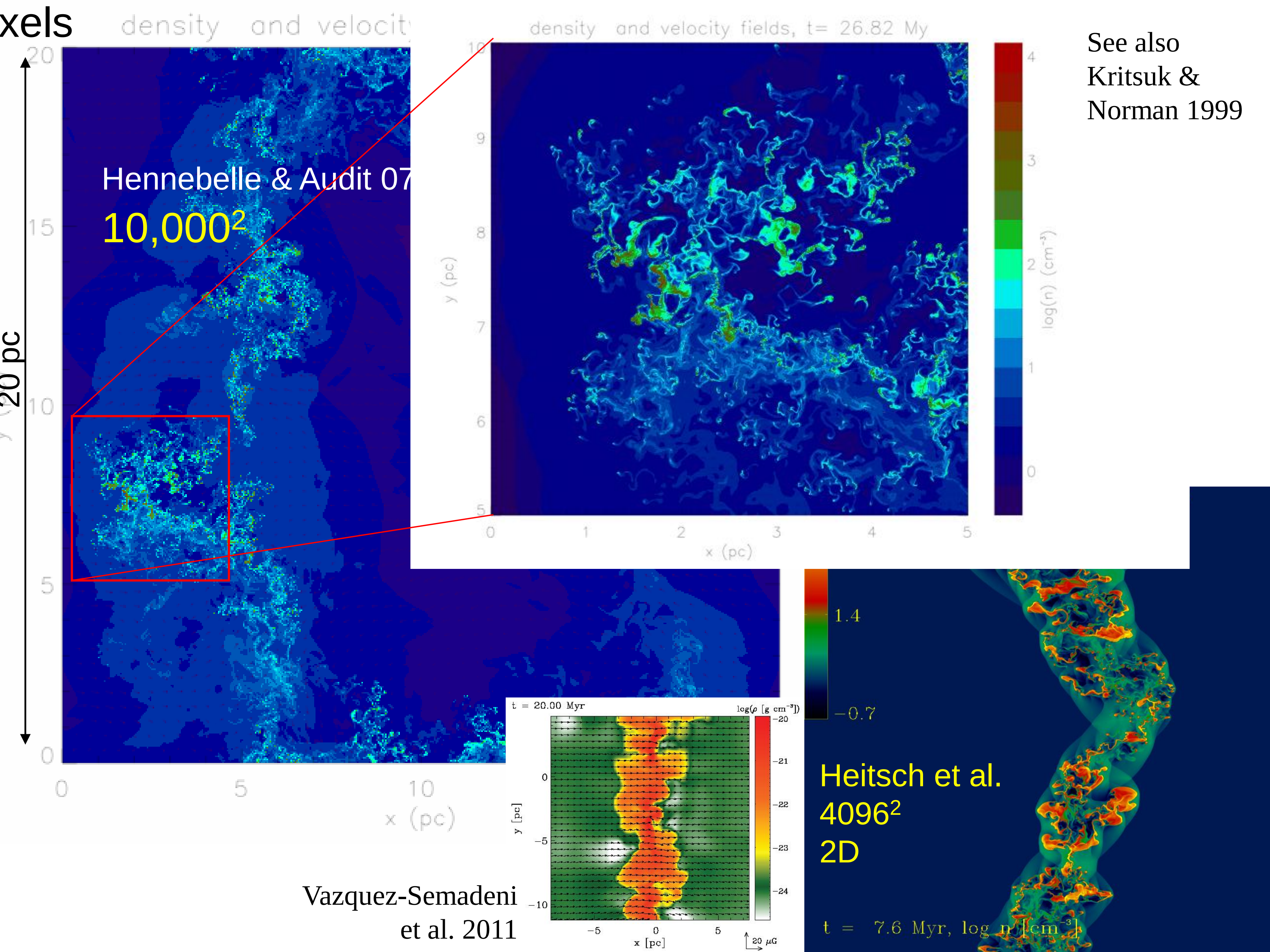
  2D&3D: Shock $\Rightarrow E_{th} \Rightarrow E_{rad} + E_{kin}$

  δv ~ a few km/s < $C_{S,WNM}$ =10km/s

  ⇐ 10^4K due to Lyα line: Universality?

Koyama & SI (2002) ApJ 564, L97

xels



See also Kritsuk & Norman 1999

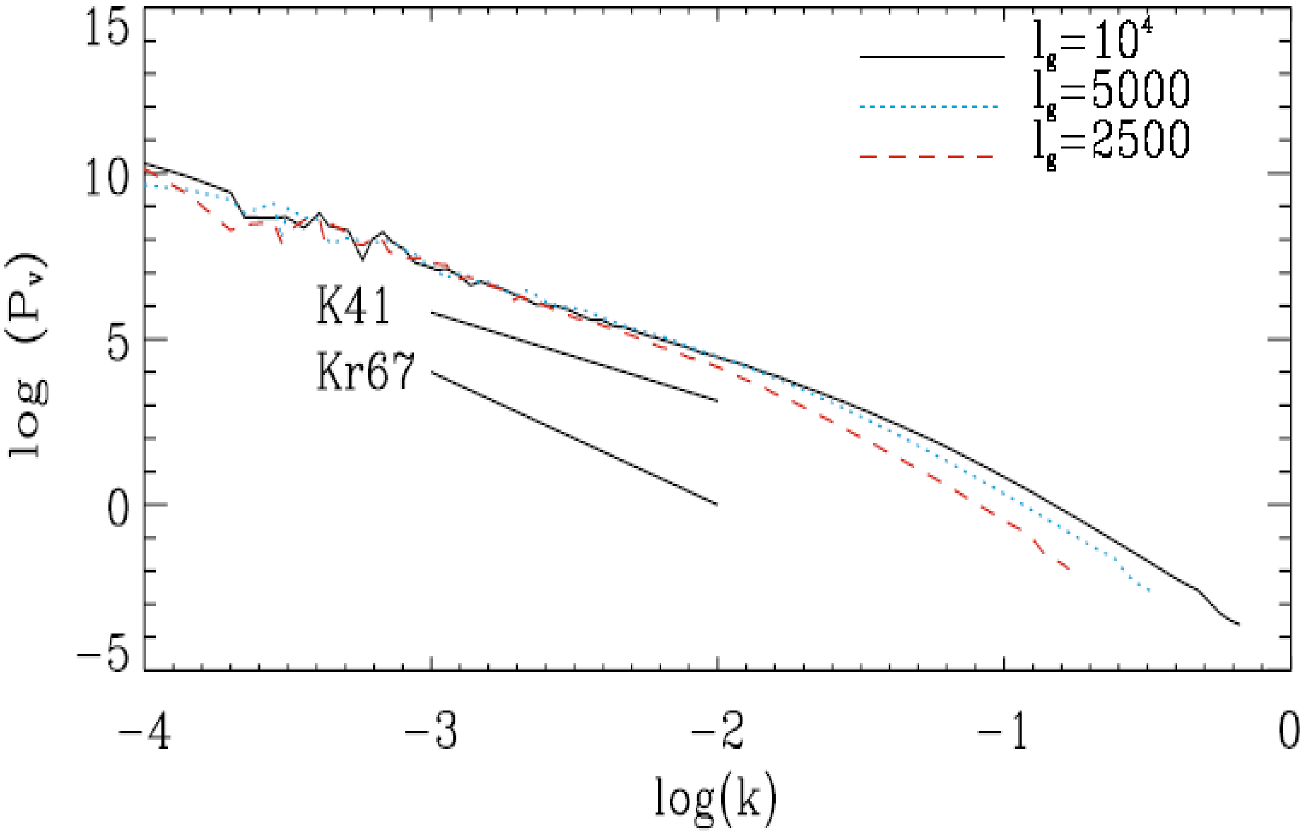
Hennebelle & Audit 07

$10{,}000^2$

Heitsch et al.
4096^2
2D

Vazquez-Semadeni
et al. 2011

Property of 2D "Turbulence"

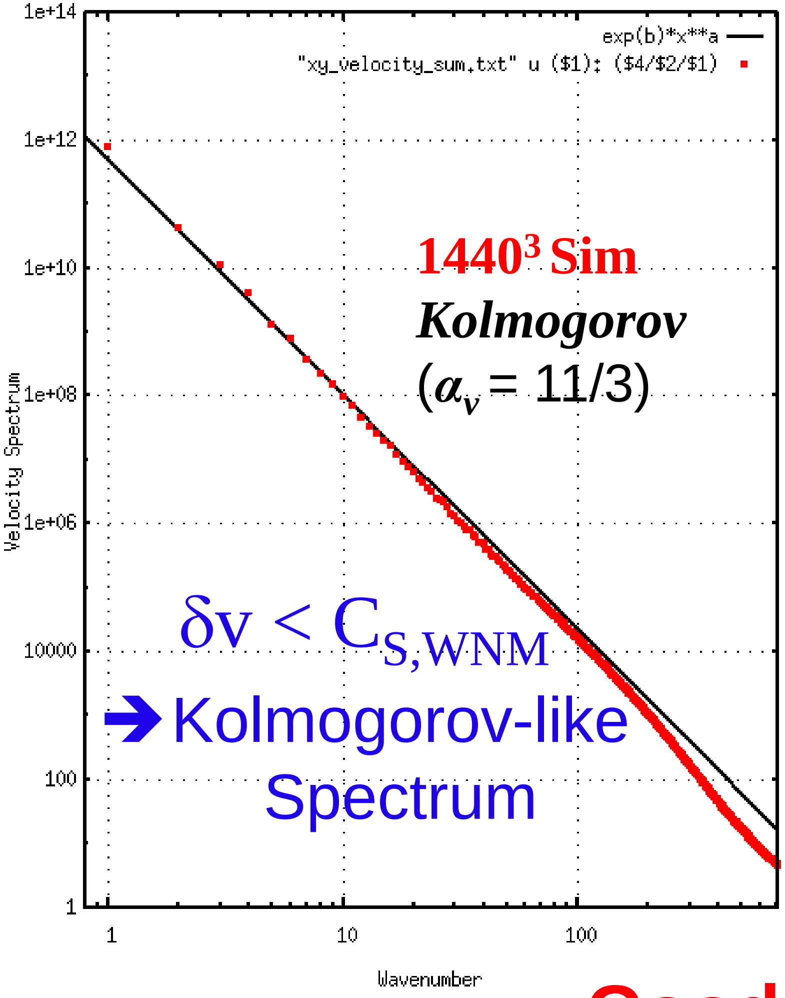


$\delta v < C_{S,WNM}$ ➔ Kolmogorov Spectrum

Hennebelle & Audit 2007; see also Gazol & Kim 2010

Property of 3D "Turbulence"

Muranushi, Inoue & SI 2011 in prep.



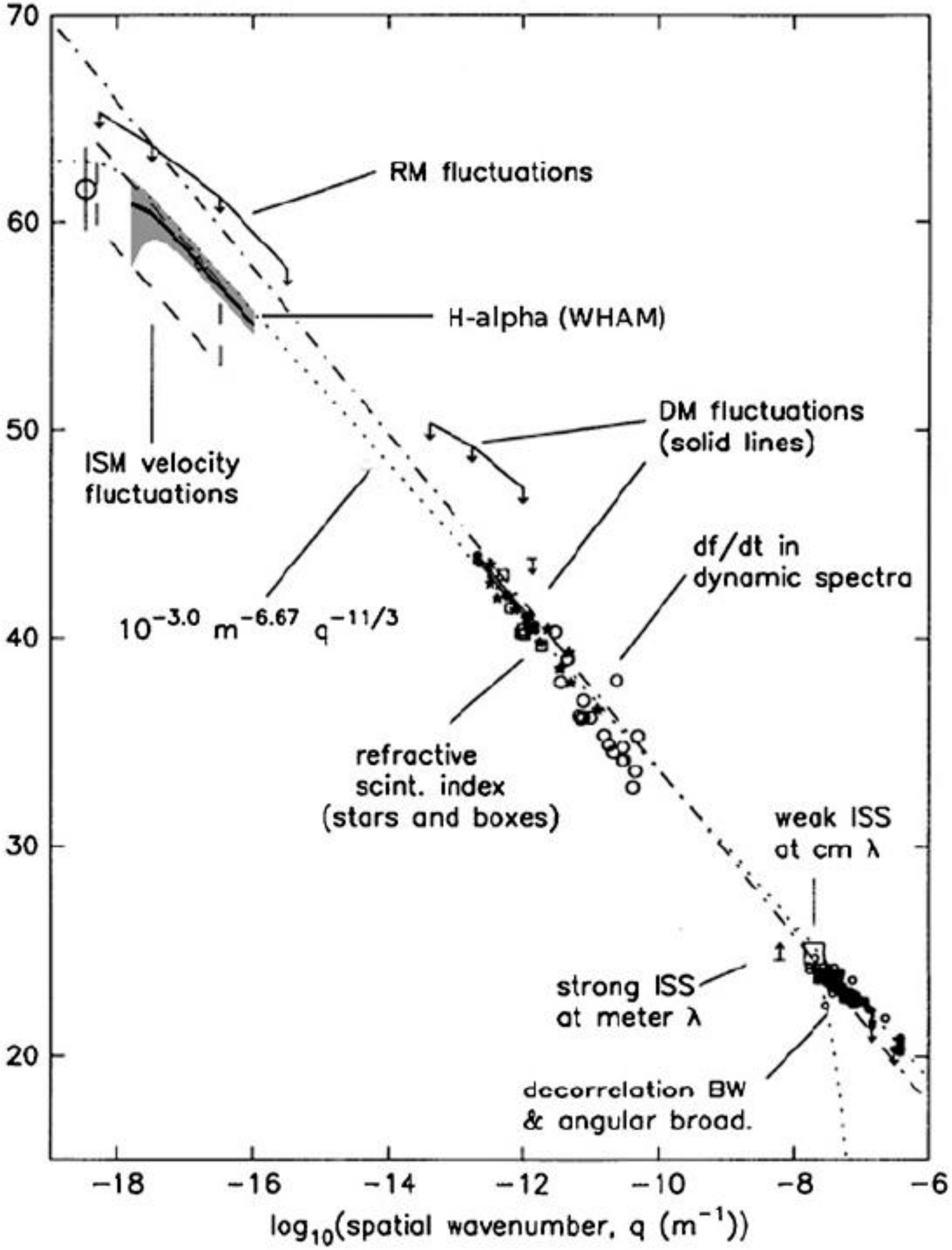
1440^3 Sim

Kolmogorov

($\alpha_v = 11/3$)

$\delta v < C_{S,WNM}$

➔Kolmogorov-like Spectrum



Good Agreement!

Chepurnov & Lazarian 2010
Armstrong et al. 1995

Further Analyses

Two Aspects in Multi-Phase Dynamics:

1. Effect of Inhomogeneous Pre-Shock Density for Propagation of Shock
2. Turbulence Driven by Thermal Instability without Shock

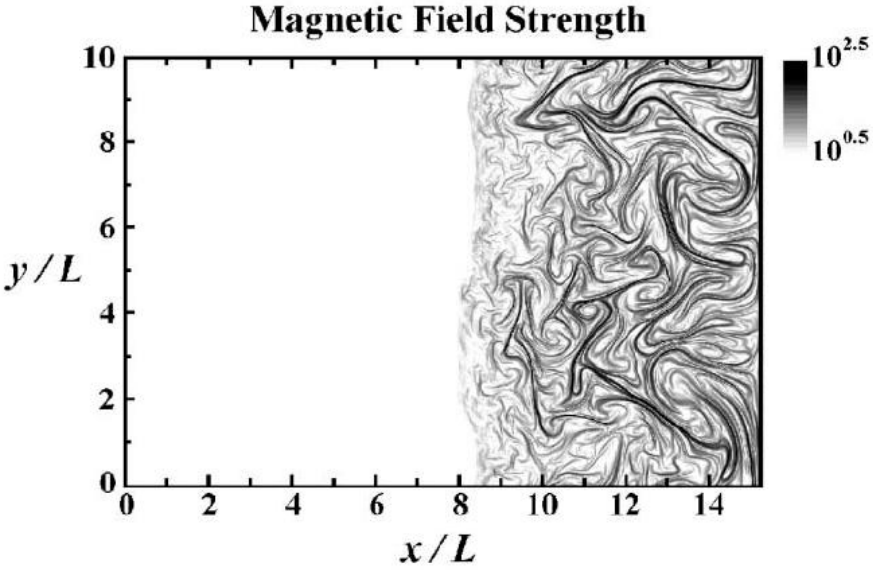
Two Aspects in Multi-Phase Dynamics

#1. Effect of Inhomogeneous Pre-Shock Density

Shock waves can create turbulence in inhomogeneous pre-shock gas even without cooling!

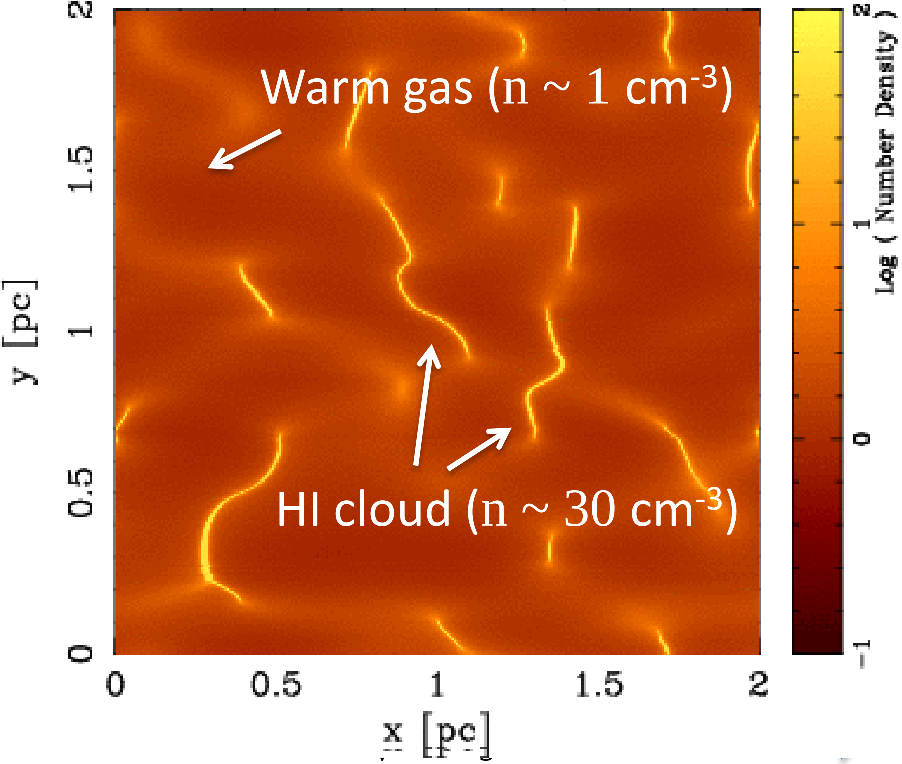
Giacalone & Jokipii 2007

$$t_{\text{growth}} < t_{\text{cooling}}$$

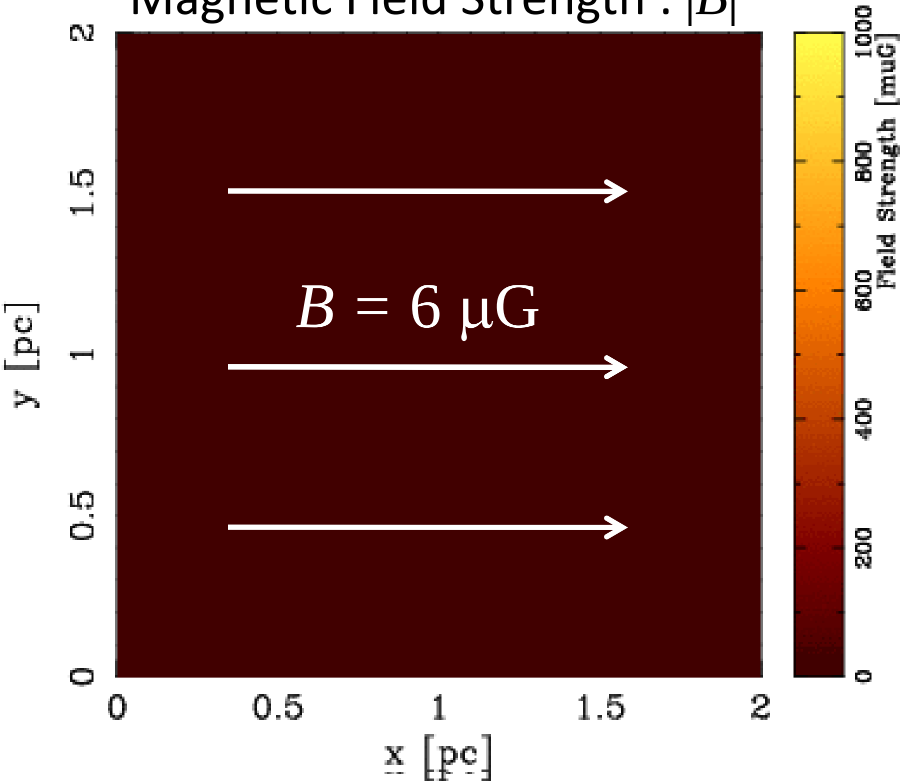


Supernova Shock in Multi-Phase ISM

Number Density : n



Magnetic Field Strength : $|B|$



$$\nabla\rho \times \nabla p \neq 0 \rightarrow \text{Vorticity Creation } (\delta v \sim c_s)$$

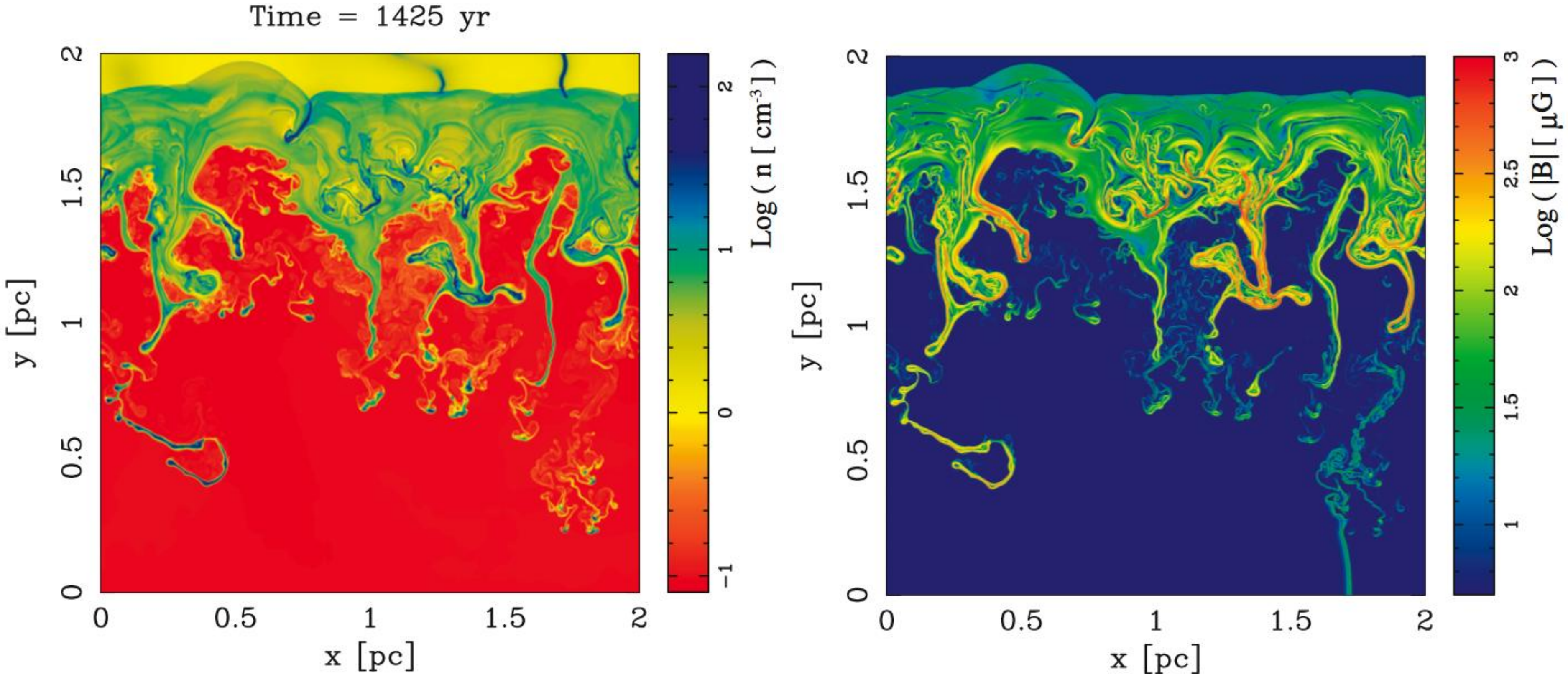
Magnetic Field Amplification via Turbulent Dynamo

$$B_{\max} \sim 1\text{mG} \quad (\beta \sim 1 \text{ @post shock})$$

Mach # > 10^4

Inoue, Yamazaki, & SI (2009) ApJ 695, 825

B~mG important for CRs



Inoue, Yamazaki, & SI (2009) ApJ 695, 825;   (2010) ApJ 723, L108

➔X-ray Observations of Supernova@age~10^{3}yr

$B \sim$ 1mG (Bamba+2002, Uchiyama+ 2008, etc.)

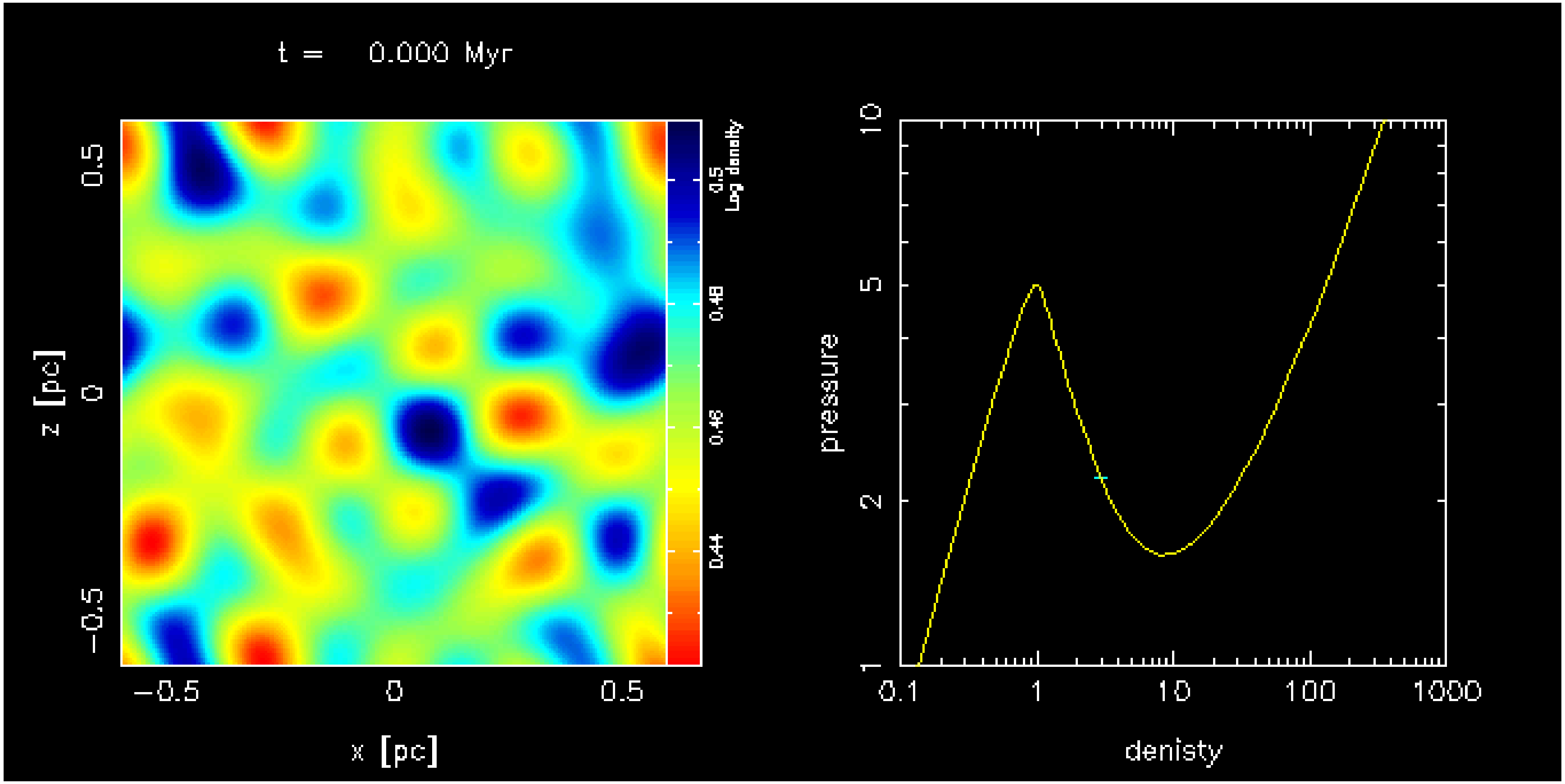
Two Aspects in Multi-Phase Dynamics

2: Phase Transition Dynamics without Shock Waves

Does turbulence decay without external mechanical driving such as due to shock waves?

The Answer is NO!

Sustained “Turbulence” in Periodic Box



Periodic Box Evolution <u>without Shock Driving</u>

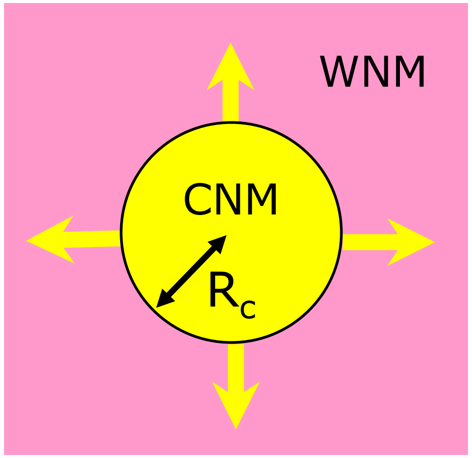
With Cooling/Heating and Thermal Conduction

Without Physical Viscosity (*Prandtl* # = 0)

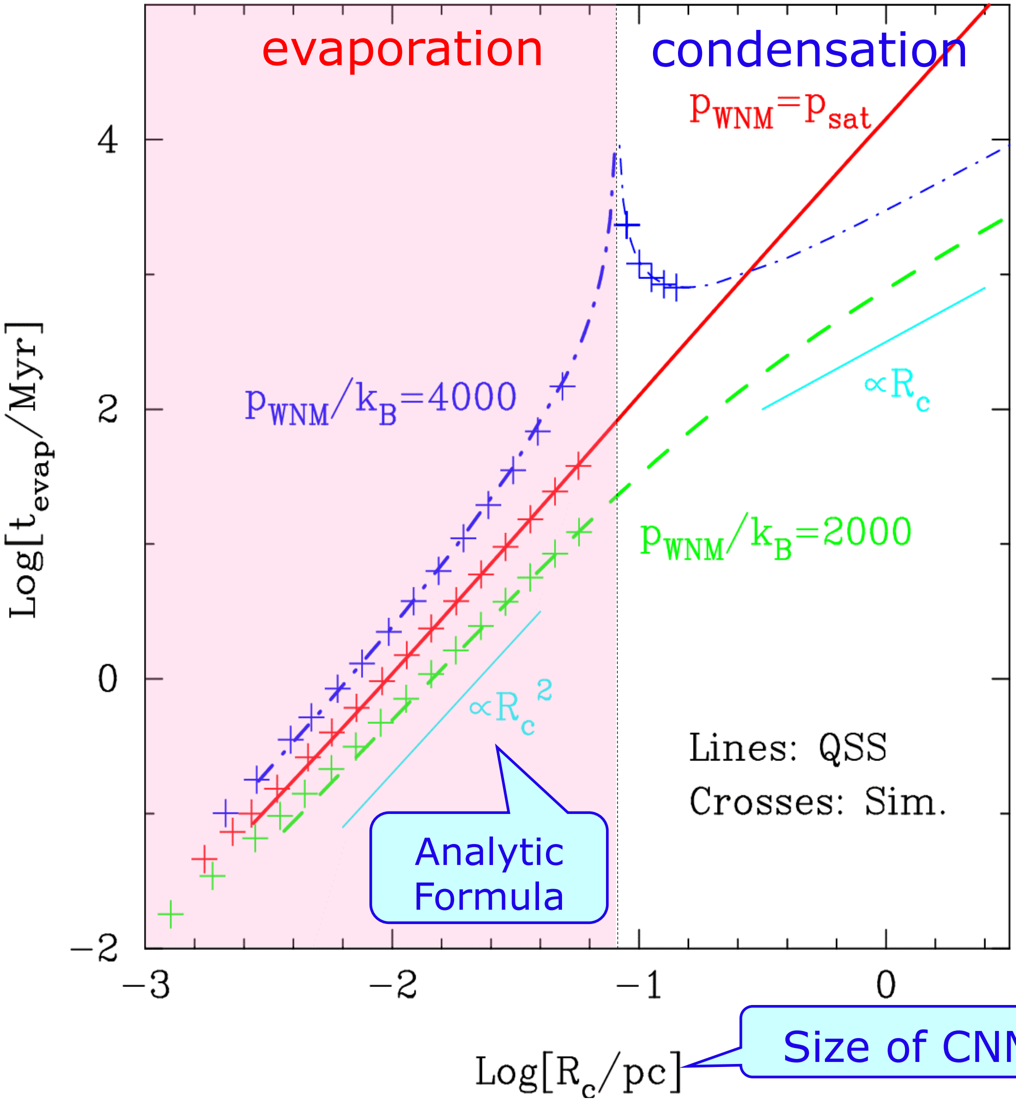
Further Analysis on Phase Transition Dynamics

1. Evaporation & Condensation
2. New Instability of Transition Layer
3. Effect of Magnetic Field

Evaporation of Spherical CNM in WNM



Evaporation Timescale



Analytic Formula

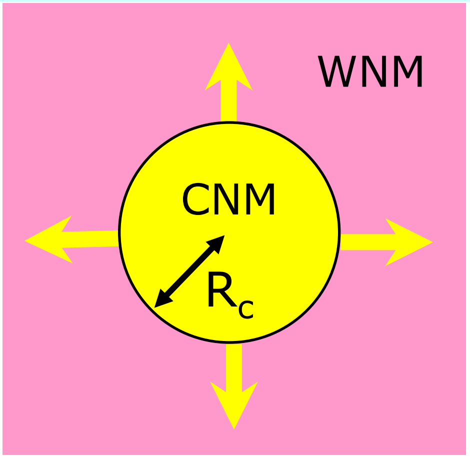
Size of CNM cloud

Smaller CNM cloud evaporates:

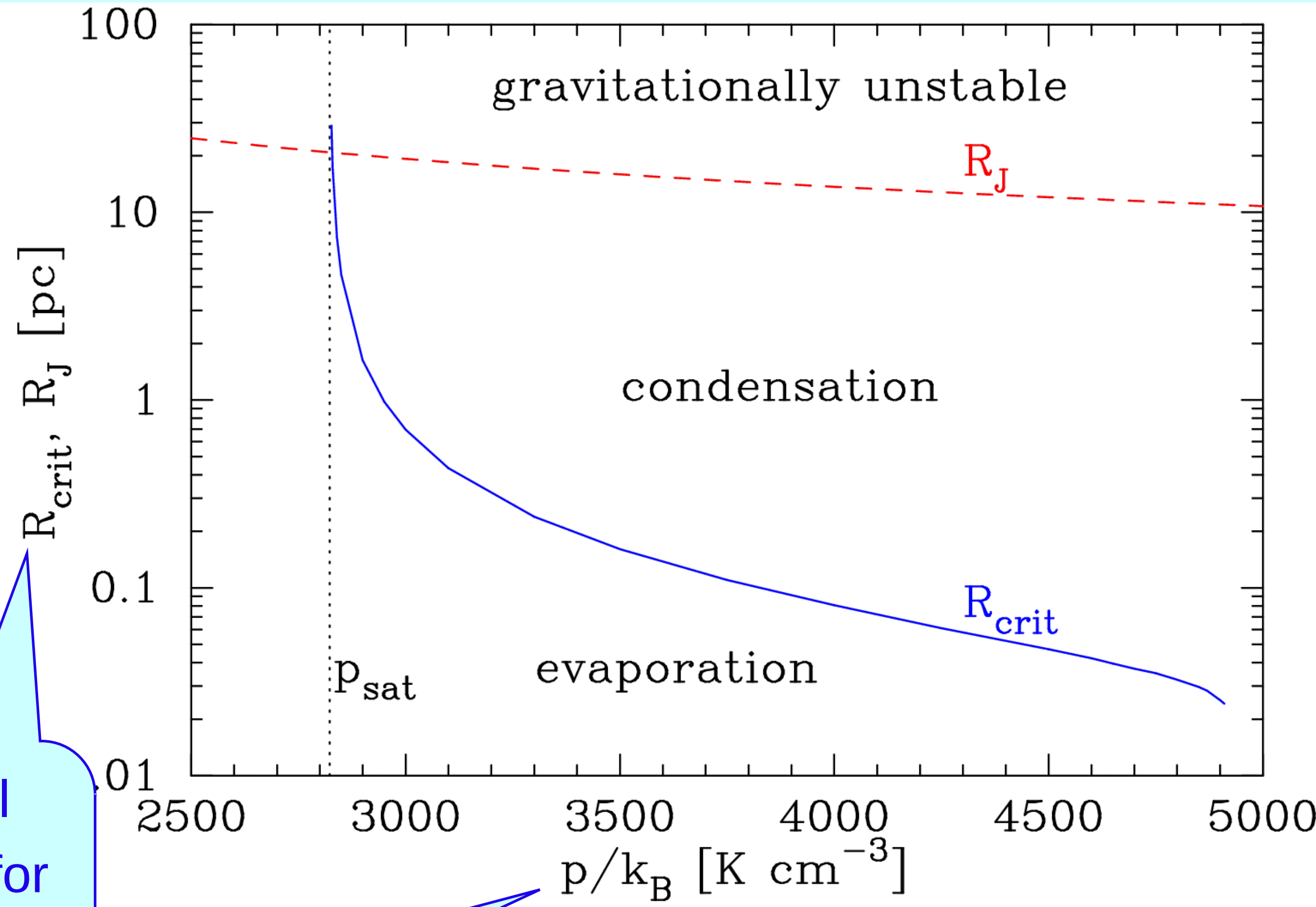
<u>R~0.01pc</u> clouds evaporate in ~Myr

Nagashima, Koyama, Inutsuka & 2005, MNRAS **361**, L25
Nagashima, Inutsuka, & Koyama 2006, ApJL **652**, L41

Evaporation of Spherical CNM in WNM



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



Critical Radius for Static Equilibrium

Ambient Pressure

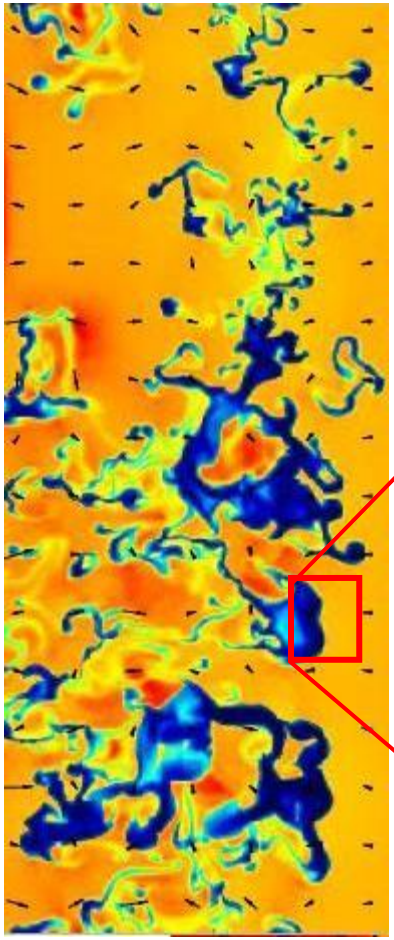
Nagashima, SI, & Koyama 2006, ApJL **652**, L41

cf. "Tiny Scale Atomic Structure" Braun & Kanekar 2005, Stanimirovic & Heiles 2005

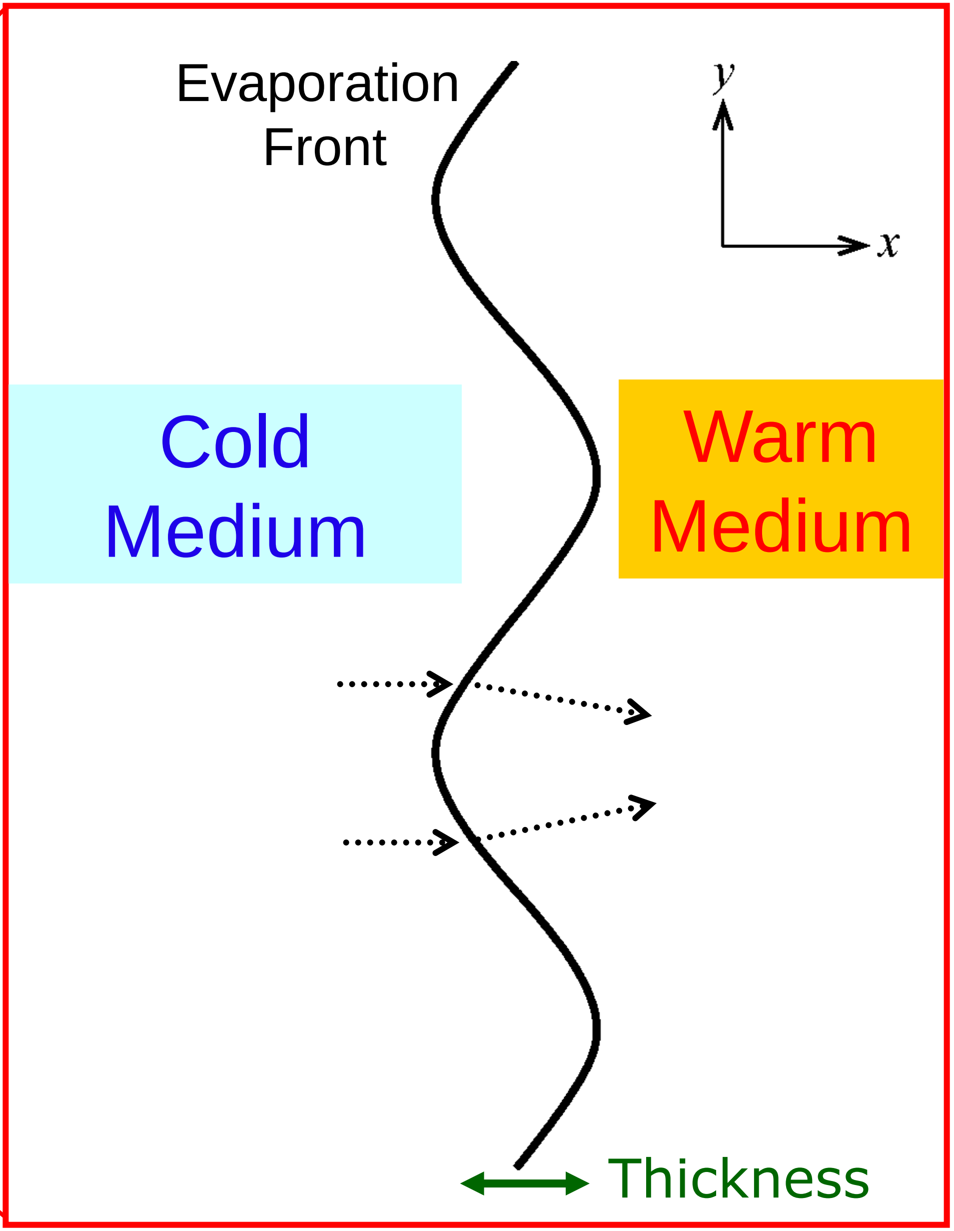
Further Analysis on
Phase Transition Dynamics

1. Evaporation & Condensation
2. New Instability of Transition Layer
3. Effect of Magnetic Field

2) Instability of Phase Transition Layer



important in maintaining
the “turbulence”



Instability of Phase Transition Layer

Similar Mechanisms…

1) Darrieus-Landau (DL) Instability

Flame-Front Instability

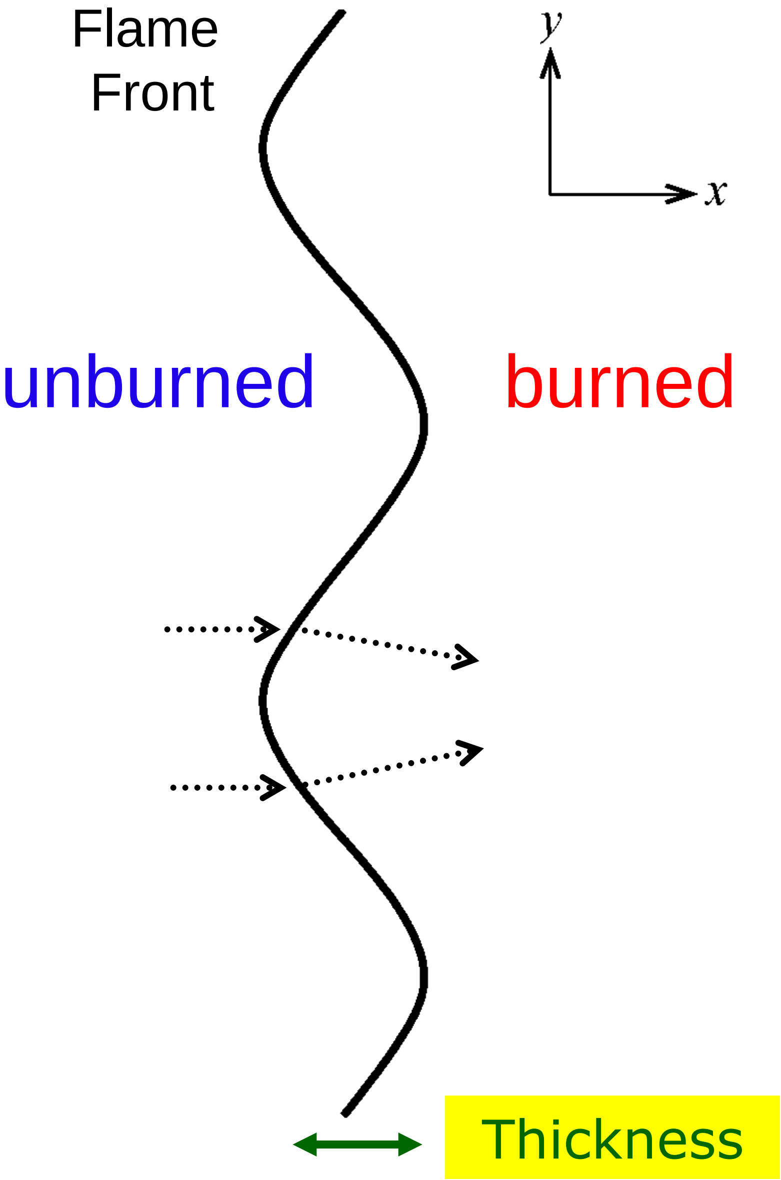
\# Important in SNe Ia

\# Effect of Magnetic Field

See Dursi (2004)

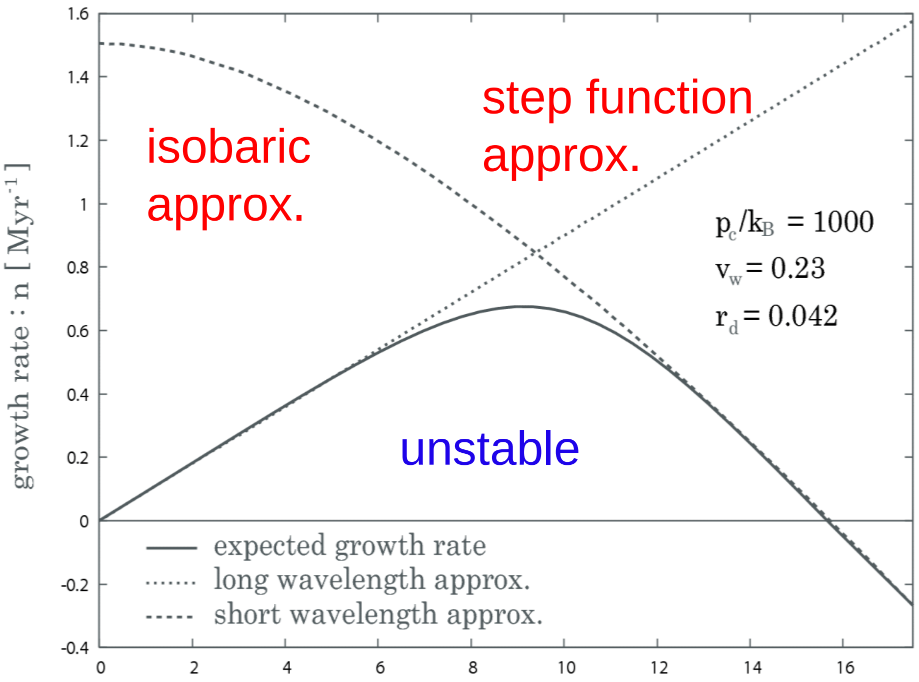
2) Corrugation Instability in MHD Slow Shock

- – Edelman 1990
- – Stone & Edelman 1995



Linear Analysis of New Instability

Growth Rate (Myr^{-1})

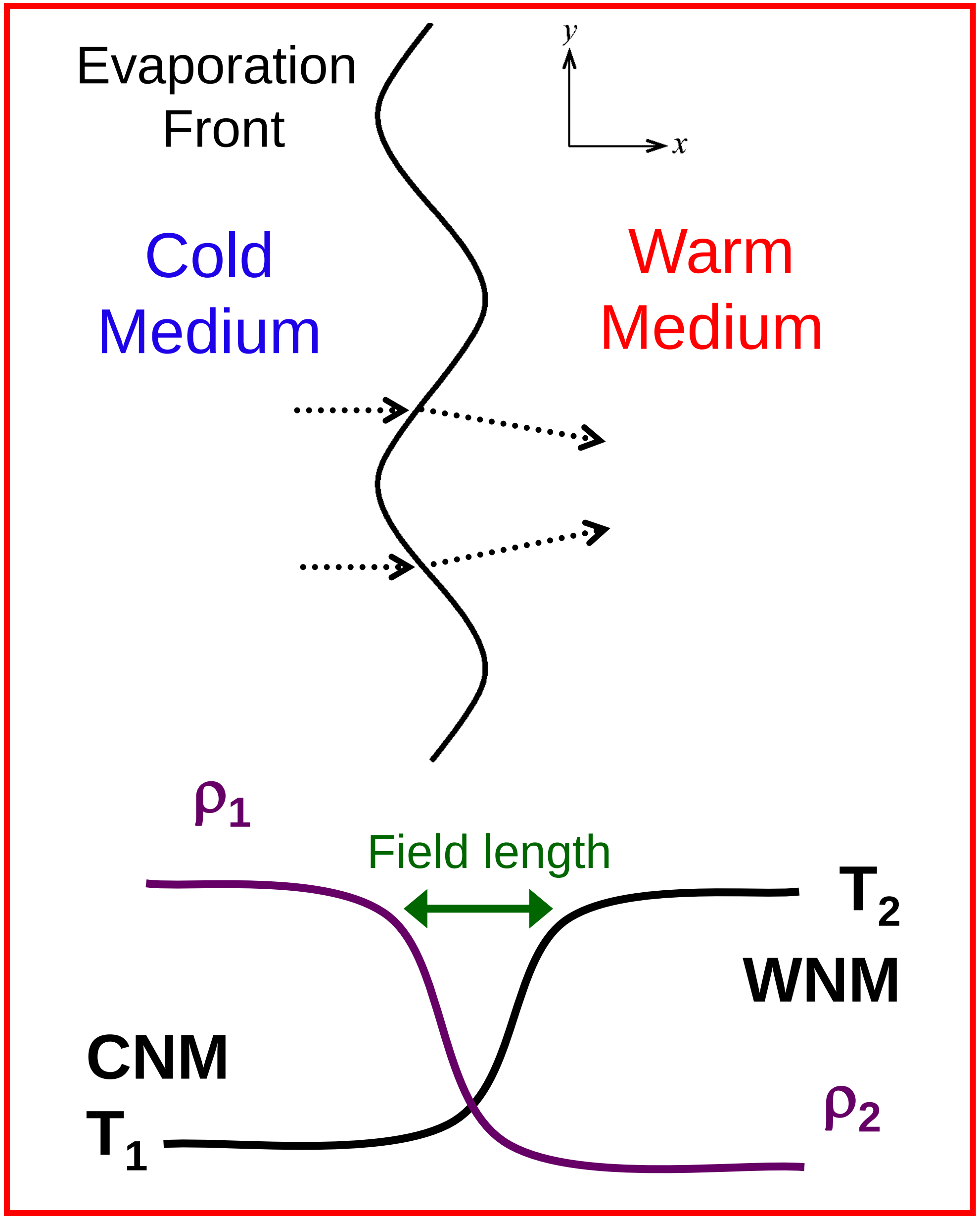


wavenumber $k_y/2\pi$ [pc^{-1}]

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

Effect of ***B***:

Stone & Zweibel 2009, ApJ 696, 233



Evaporation Front

Cold Medium

Warm Medium

ρ_1

Field length

T_2

WNM

CNM

T_1

ρ_2

Further Analysis on Phase Transition Dynamics

1. Evaporation & Condensation
2. New Instability of Transition Layer
3. Effect of Magnetic Field

Front Stability with B

Stone & Zweibel 2009, ApJ **696**, 233

Front Type	Hydrodynamic	Super-Alfvénic	Sub-Alfvénic
Evaporation	Unstable	Unstable	Stable
Condensation	Stable	Stable	Unstable

Detailed Analysis of Non-Linear Growth Needed

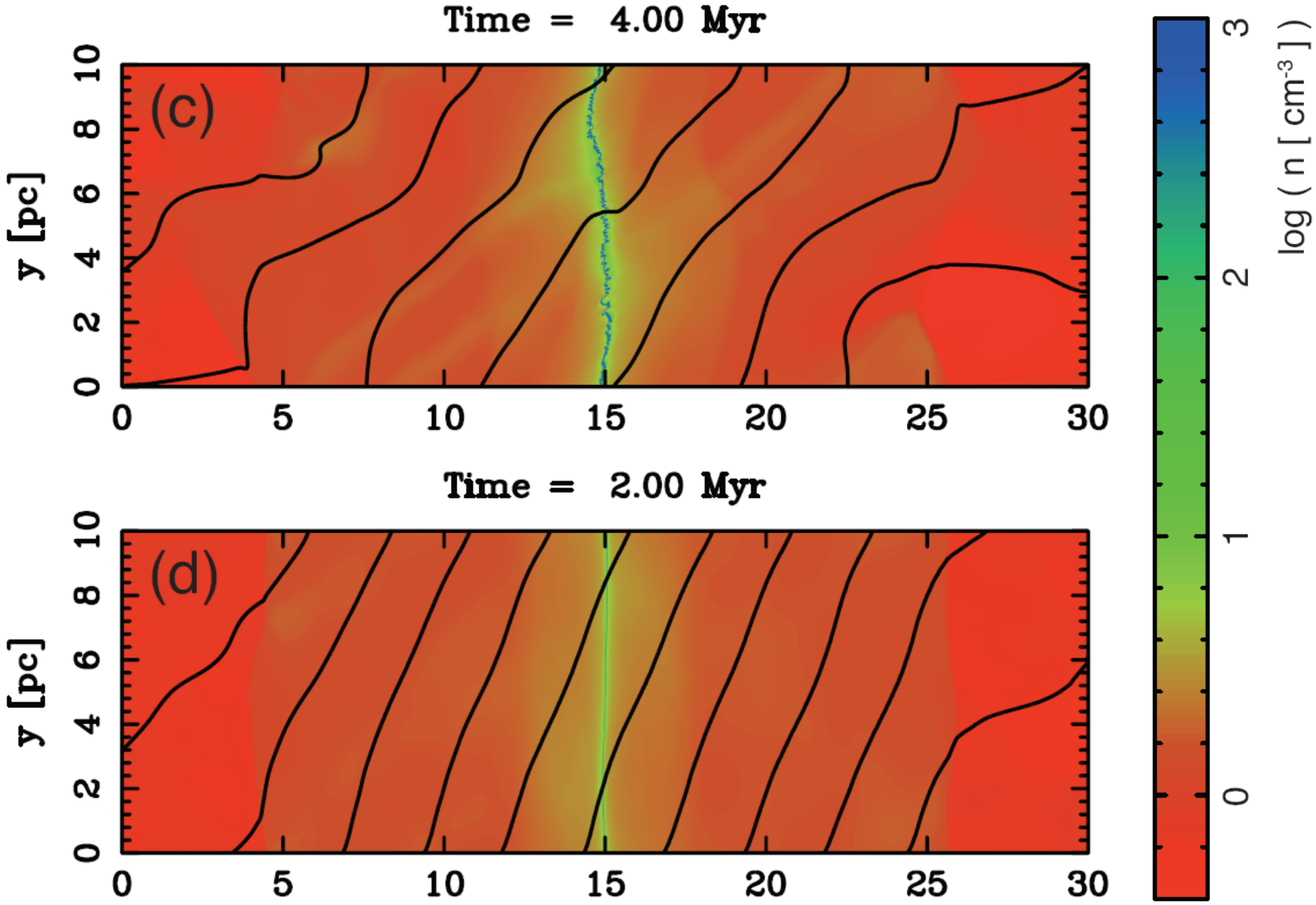
Colliding WNM with B_0=3μG

v=10km/s

B=3μG

(a) 15deg

(b) 40 deg



2-Fluid MHD Simulation (AD included)

Colliding WNM with B_0=3μG

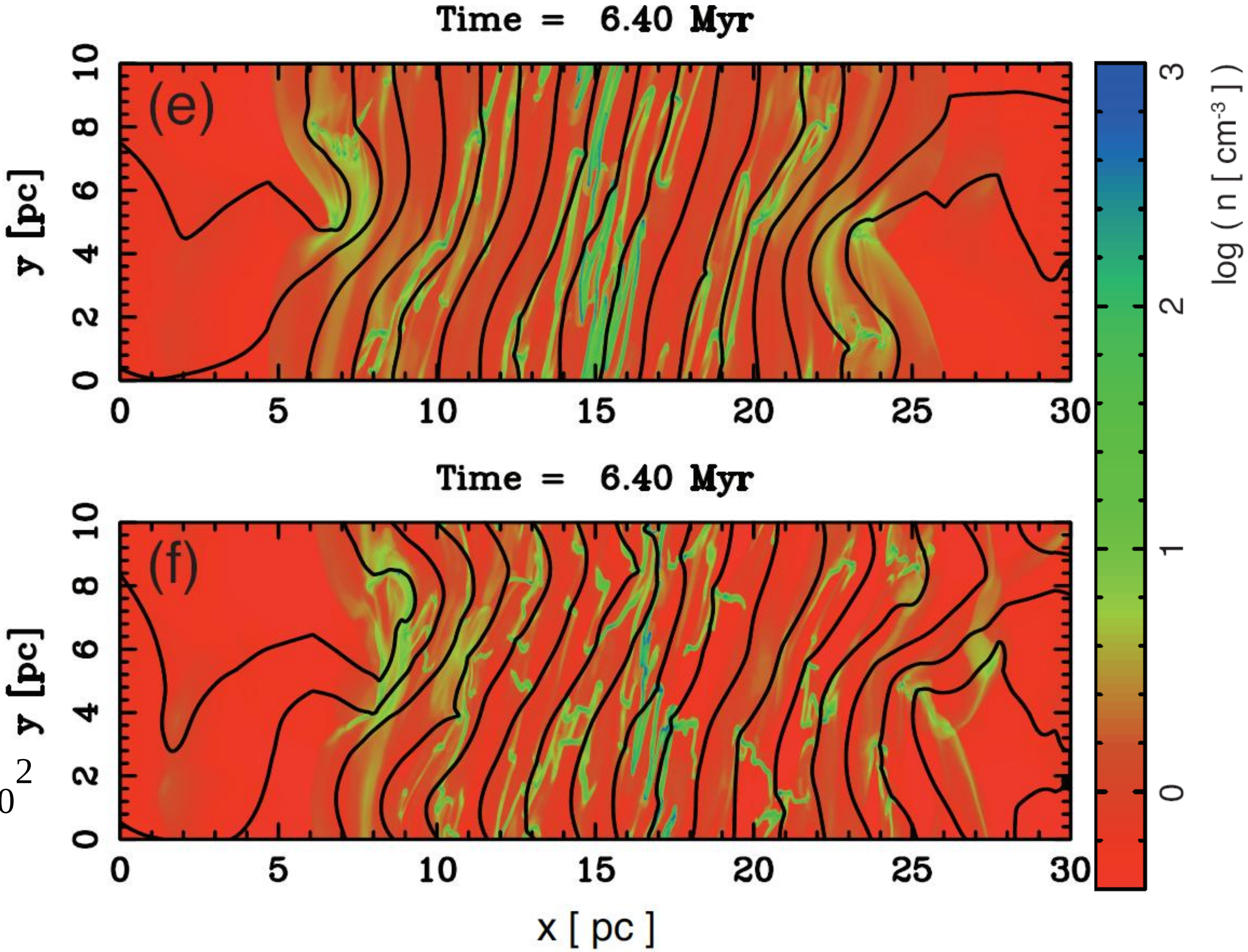
v=10km/s

(a) 15deg

$<\delta B^2>_{init} = B_0^2$

(a) 40 deg

$<\delta B^2>_{init} = 4B_0^2$



2-Fluid MHD Simulation (AD included)

Implication

Can direct compression of magnetized WNM create molecular clouds? ➔ Not at once.

We need multiple episodes of compression.

Inoue & SI (2008) ApJ **687**, 303; Inoue & SI (2009) ApJ **704**, 161

May Explain Inefficient Star Formation…

Summary

- Shock waves in ISM create
  turbulent CNM embedded in WNM.
- TI-driven turbulence in Multi-Phase ISM
  - Evaporation/Condensation of CNM clouds
  - Instabilities in Phase Transition Front
  - Agree with Observed Kolmogorov Law

- We need some mathematics for TI-driven turbulence.