Non-Equilibrium Dynamics in Astrophysics and Material Science

Dynamics of Self-Sustained Turbulence in Astrophysics: Phase Transition Dynamics

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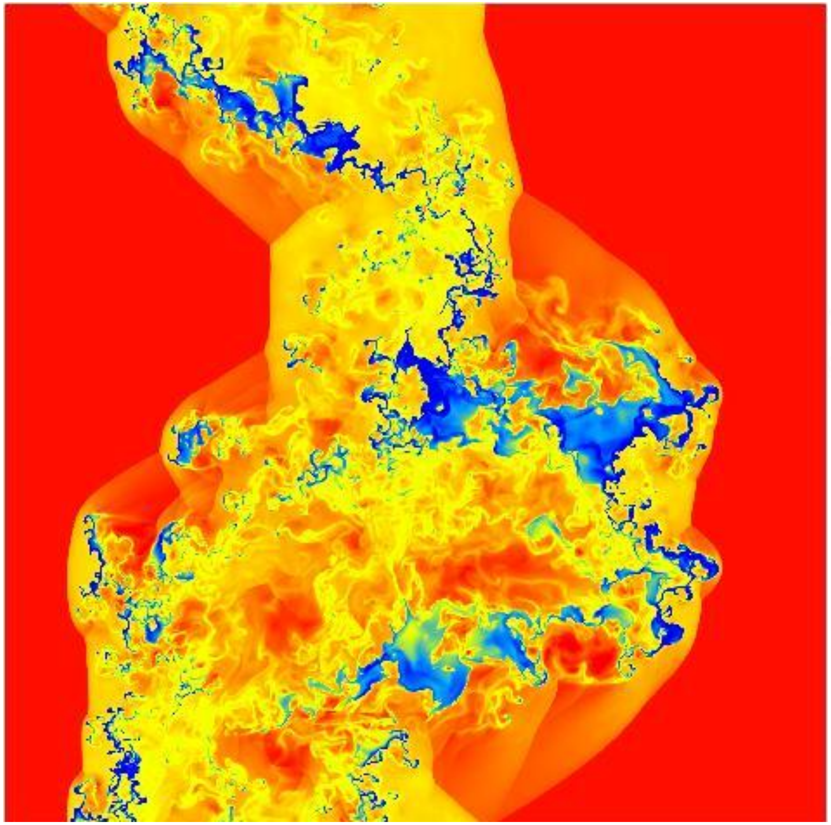
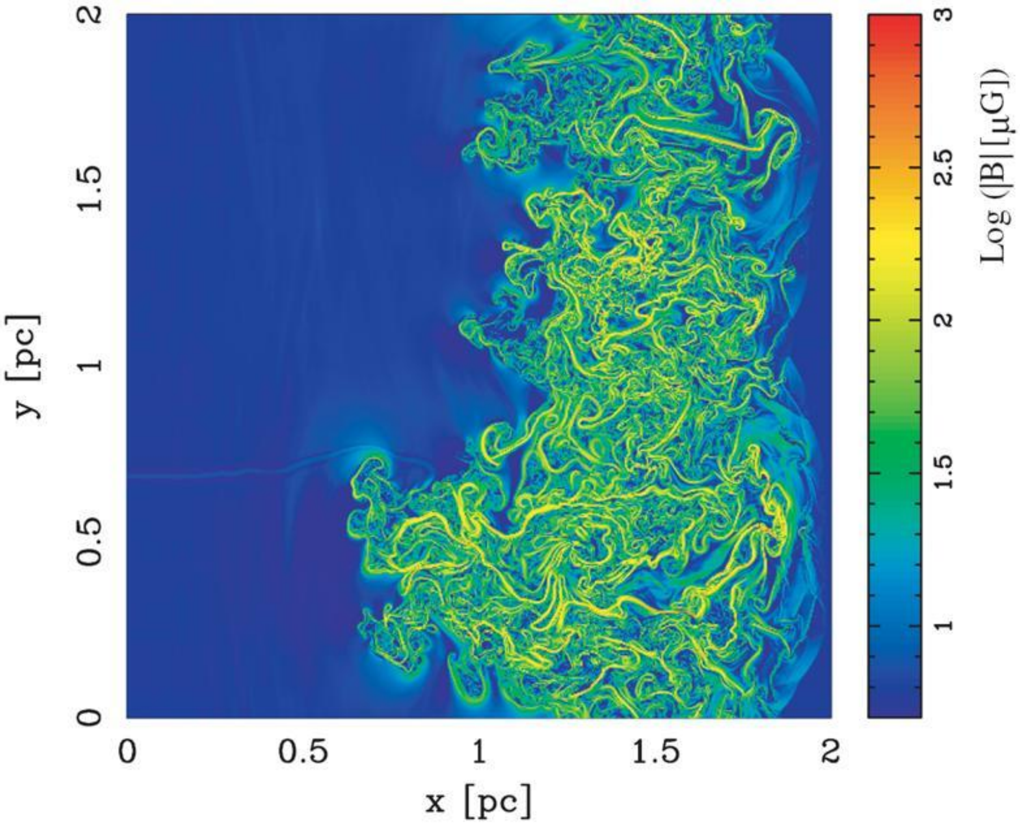


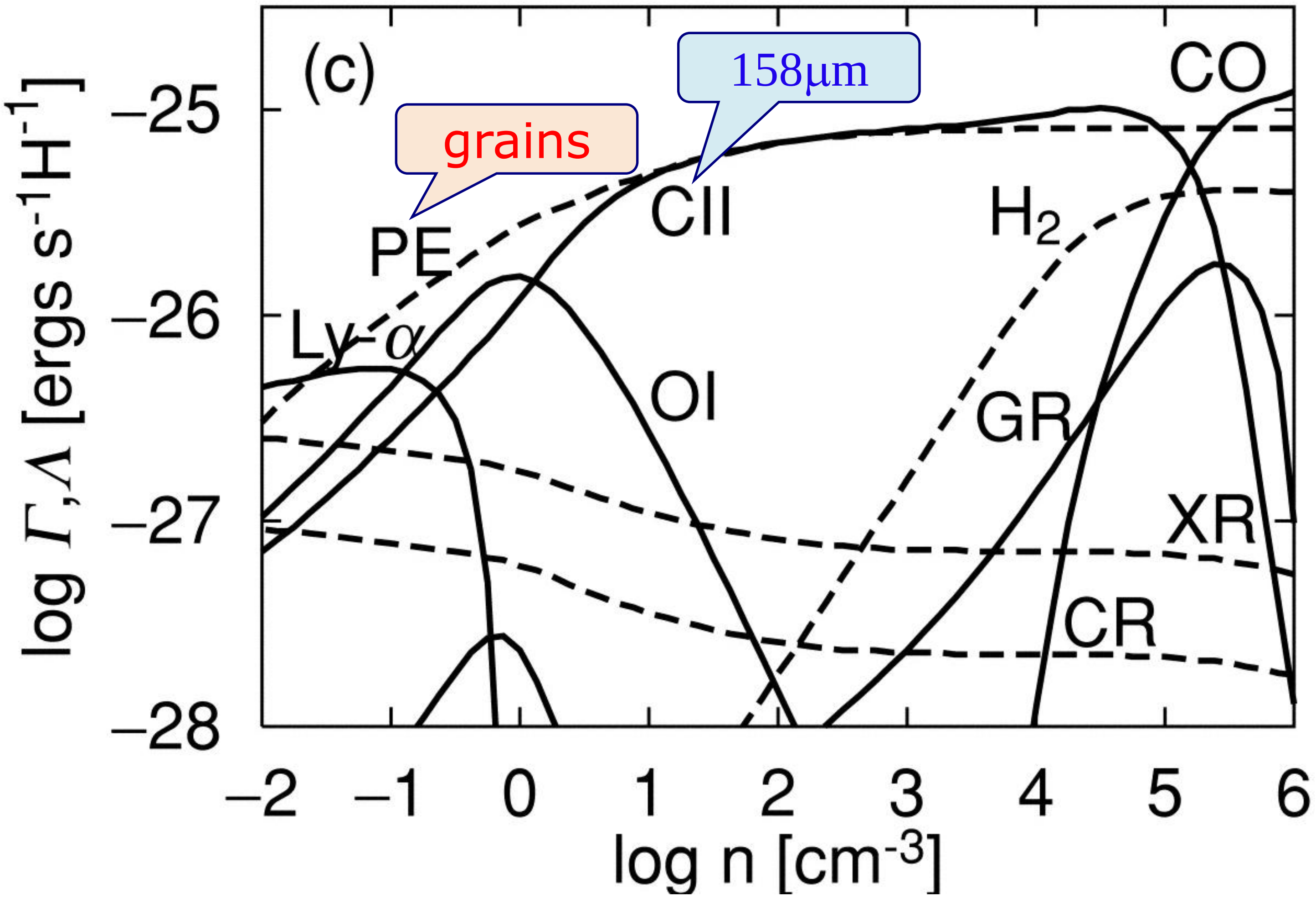


November 3, 2011

YITP, Kyoto, Japan

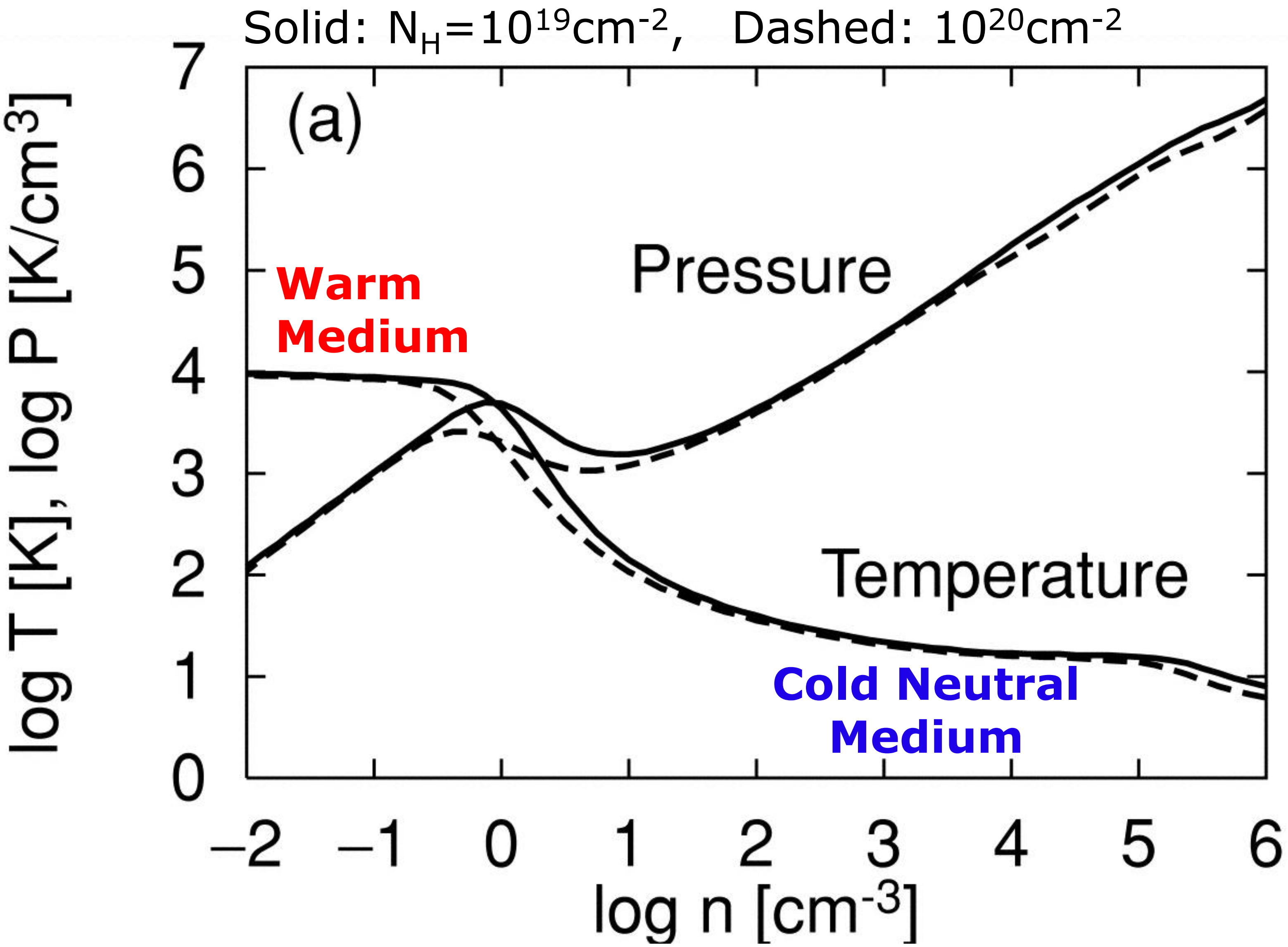
Radiative Cooling & Heating

Solid: Cooling,   Dashed: Heating



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

Radiative Equilibrium for a given density



Equilibrium of 2 Phases

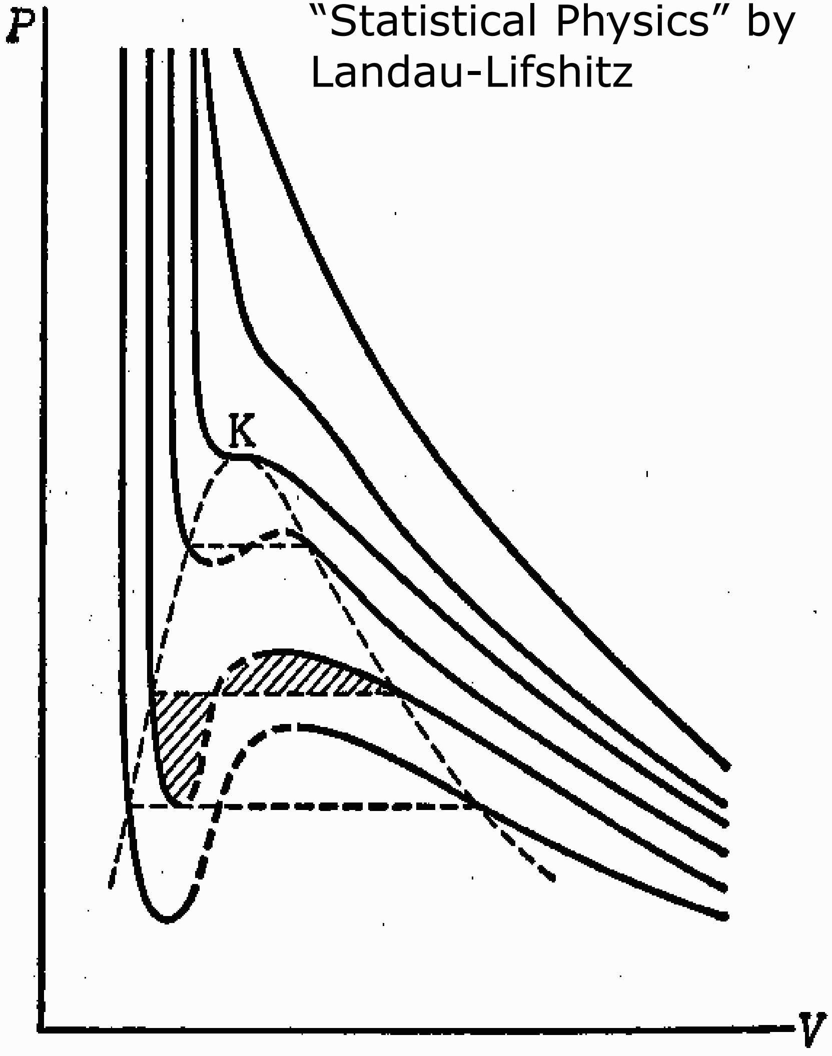
EoS of Van der Waals Gas

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

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

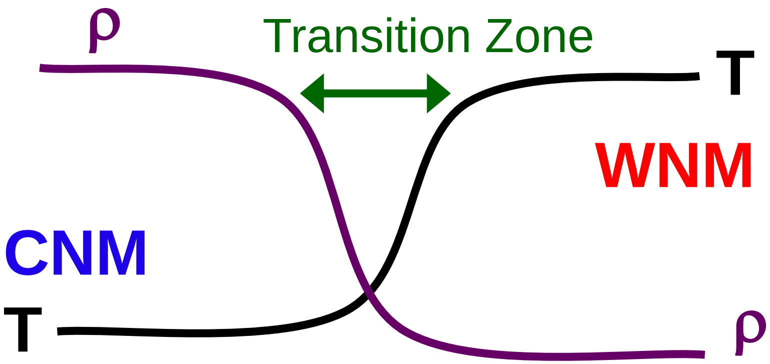
$$= \int_1^2 V(P, T = \text{const})dP$$

Equal Areas of shaded regions
(Maxwell's rule)



"Statistical Physics" by Landau-Lifshitz

Saturation Pressure

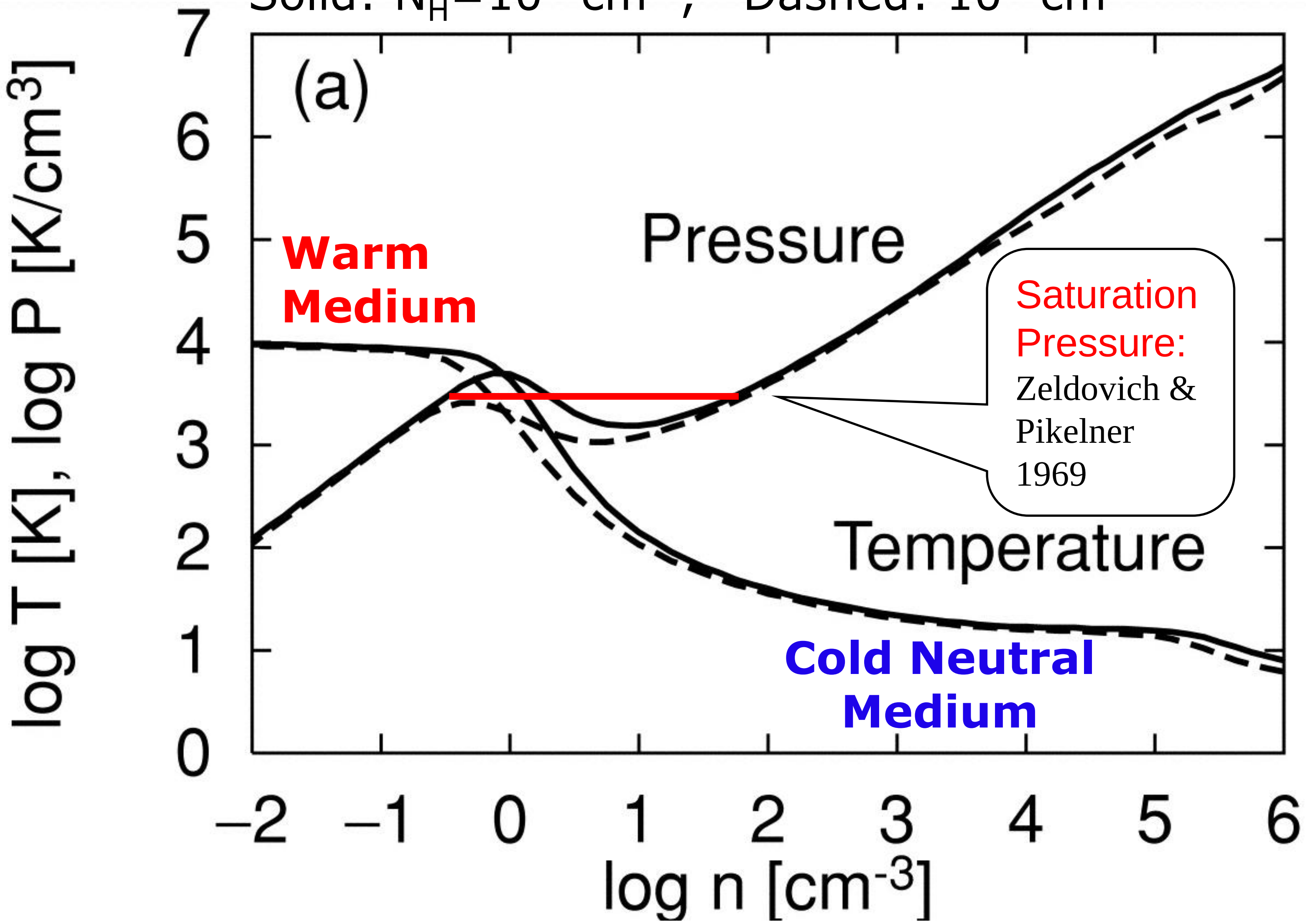


$$\int (\rho\Gamma + \rho^2\Lambda)\,dV = 0 \Rightarrow \text{ only at } P = P_{\text{sat}}$$

1D Plane-Parallel Case: Zeldovich & Pikelner 1969

2 Phase in Equilibrium

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



Warm Medium

Cold Neutral Medium

Saturation Pressure:
Zeldovich & Pikelner 1969

Basic Equations

- Eq. of Continuity
- EoM

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

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

- 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: K

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

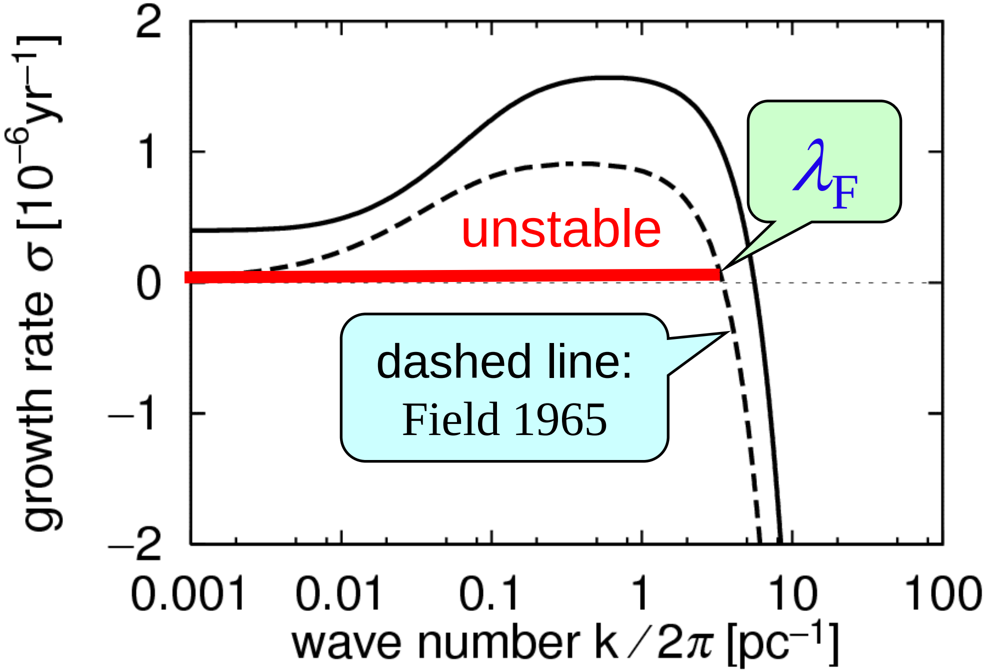
<u>Self-Gravity Negligible</u> for Low Density Gas

Dispersion Relation of Thermal Instability

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

Thermal Instability

for $\lambda > \lambda_F$



unstable

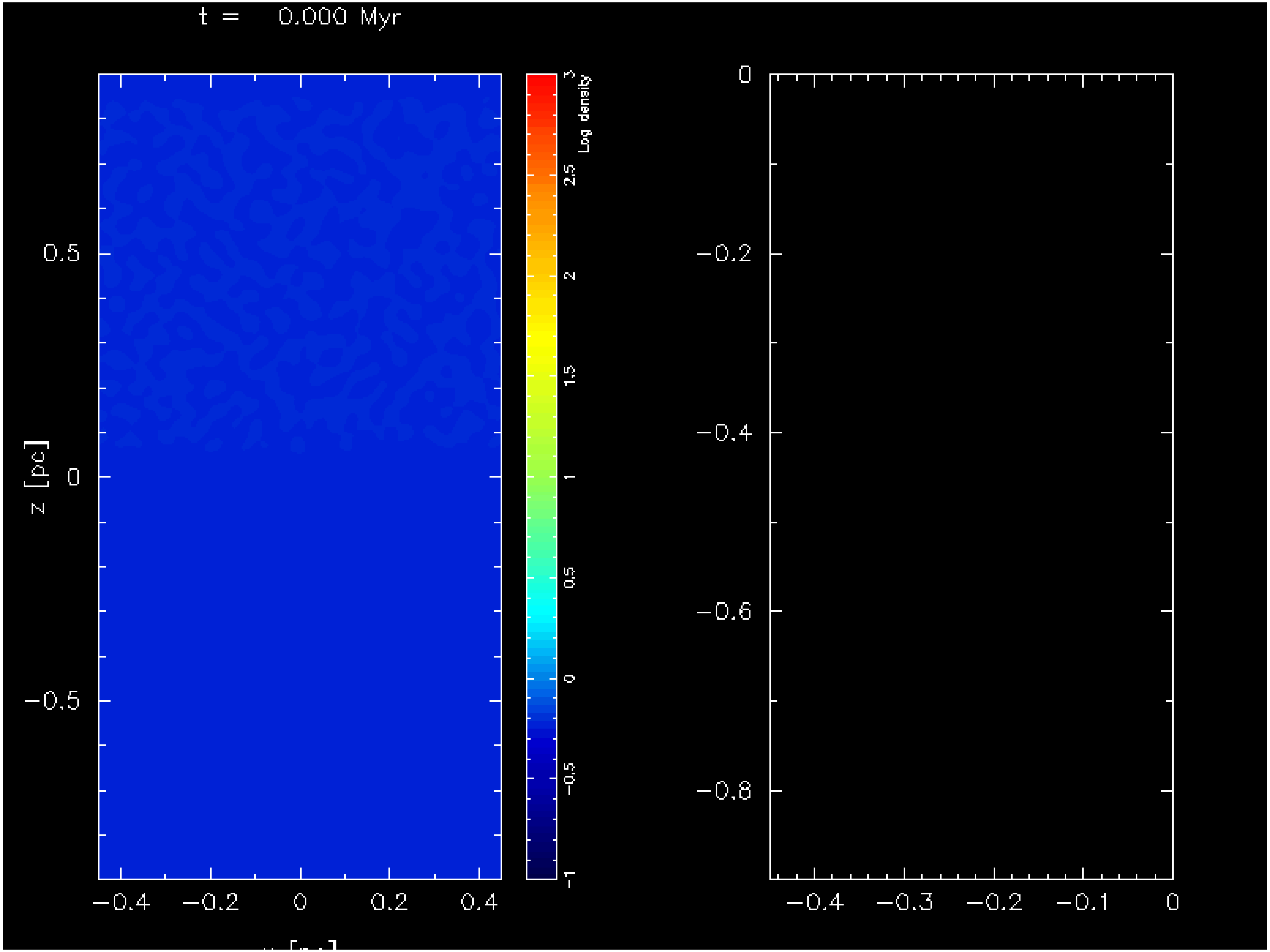
λ_F

dashed line:
Field 1965

In 2-phase medium,

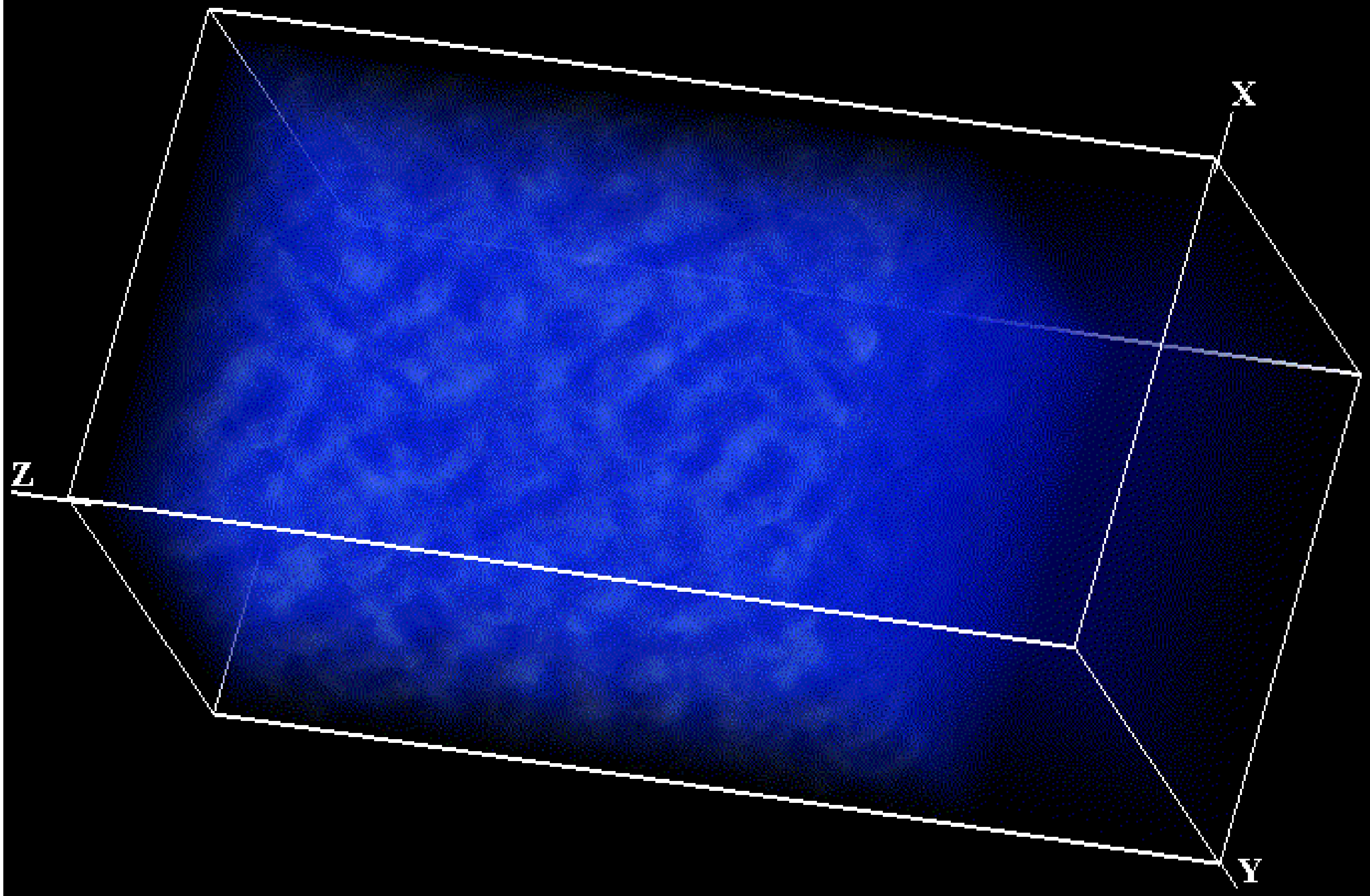
the width of transition layer = λ_F .

Shock Propagation into WNM



Koyama & Inutsuka (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 $\Rightarrow E_{th} \Rightarrow E_{rad}$

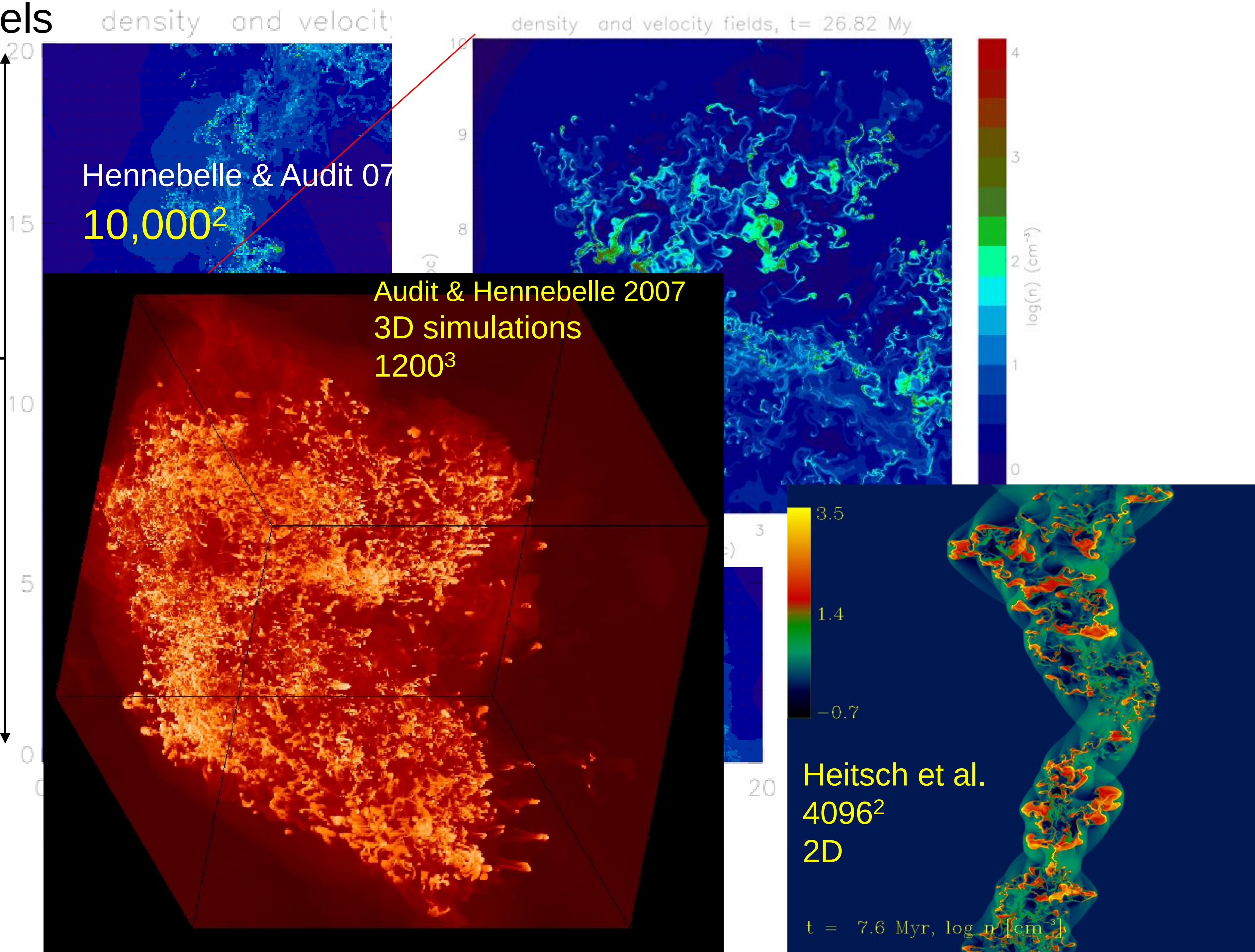
2D&3D: Shock $\Rightarrow E_{th} \Rightarrow E_{rad} + E_{kin}$

$\delta v \sim$ a few km/s $< C_{S,WNM} = 10$km/s

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

Koyama & SI (2002) ApJ 564, L97

xels



20 pc

Hennebelle & Audit 07

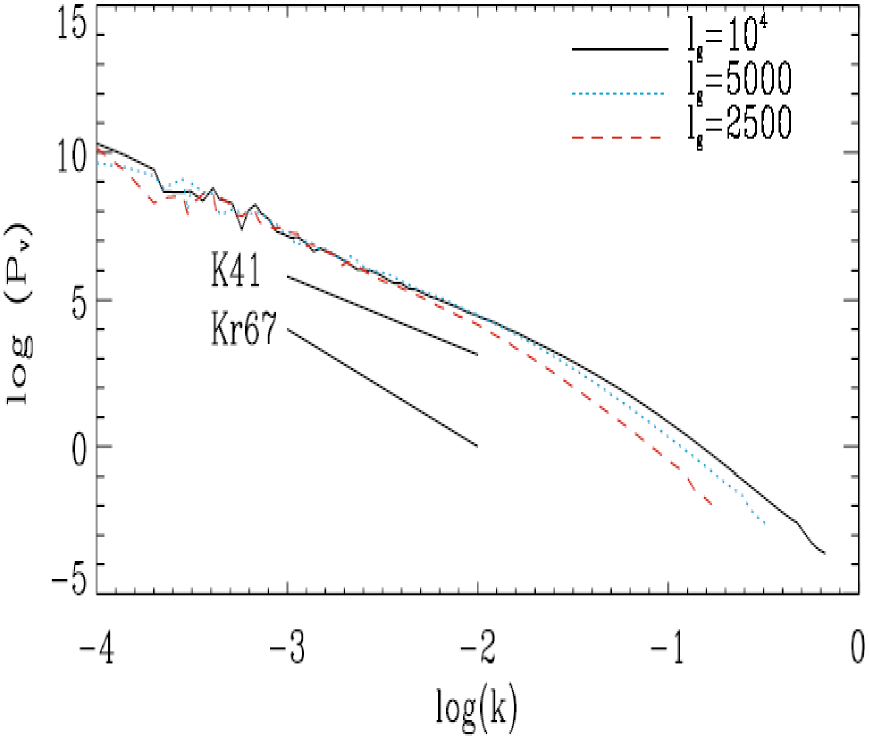
$10{,}000^2$

Audit & Hennebelle 2007
3D simulations
1200^3

Heitsch et al.
4096^2
2D

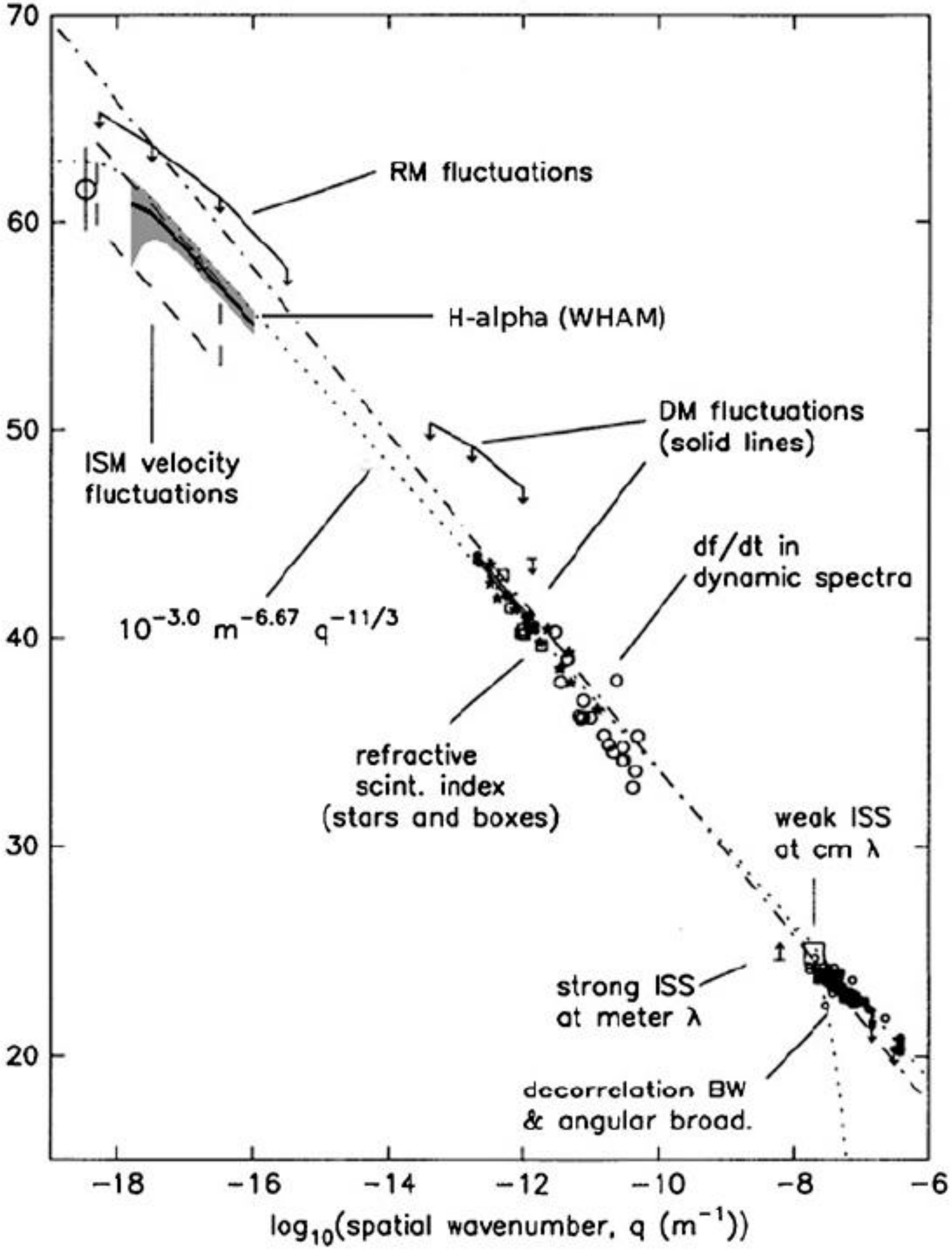
Property of "Turbulence"

Hennebelle & Audit 2007



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

➔Kolmogorov-like Spectrum



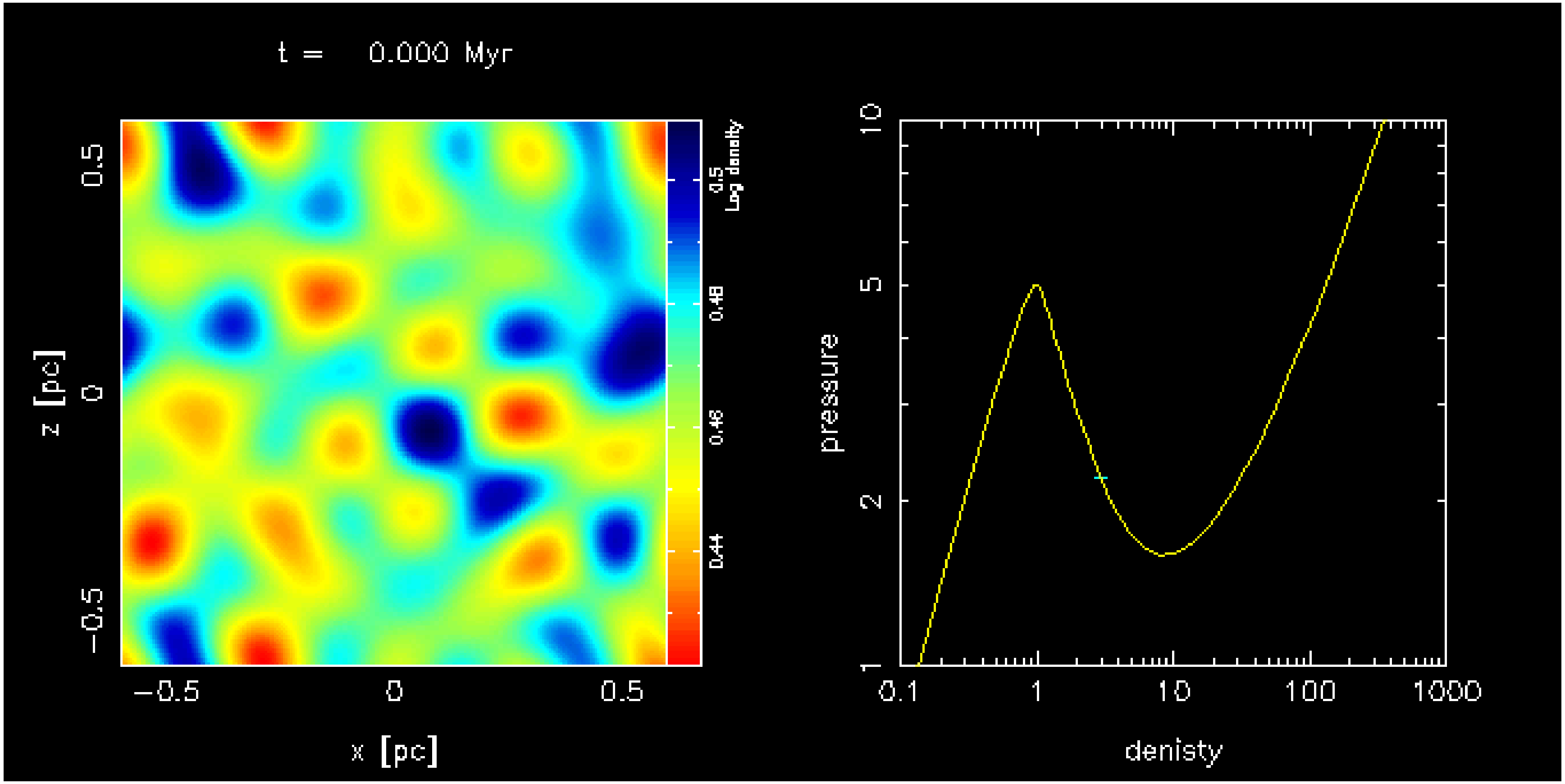
Good Agreement!

Chepurnov & Lazarian 2010
Armstrong et al. 1995

Further Analysis on Phase Transition Dynamics

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

2D Evolution from Unstable Equilibrium



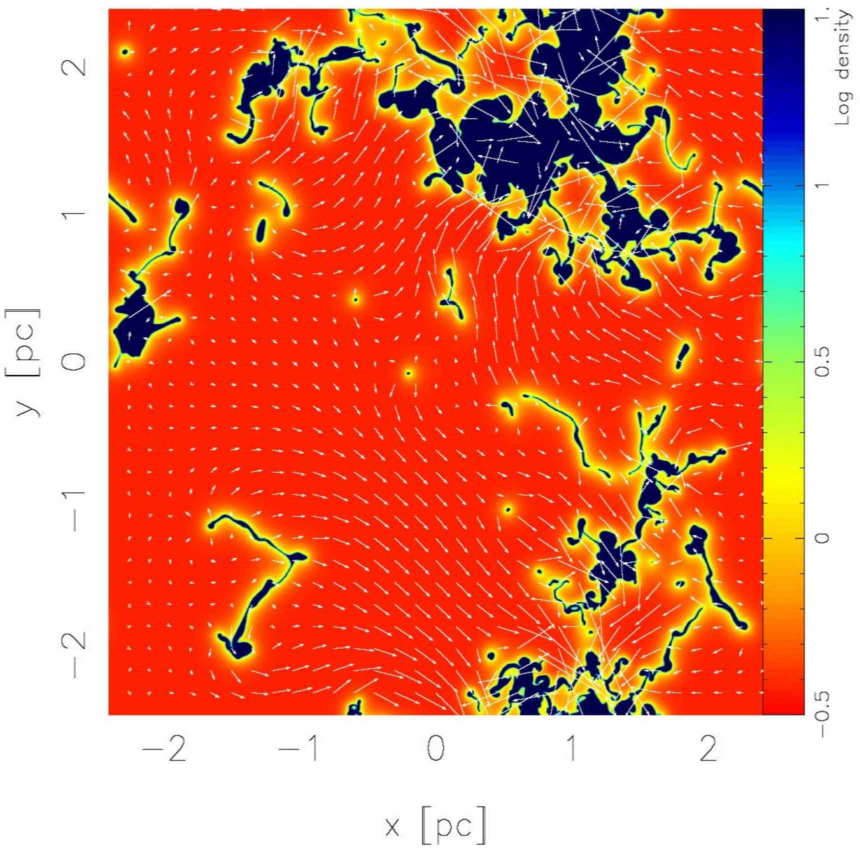
Periodic Box Evolution <u>without Shock Driving</u>

With Cooling/Heating and Thermal Conduction

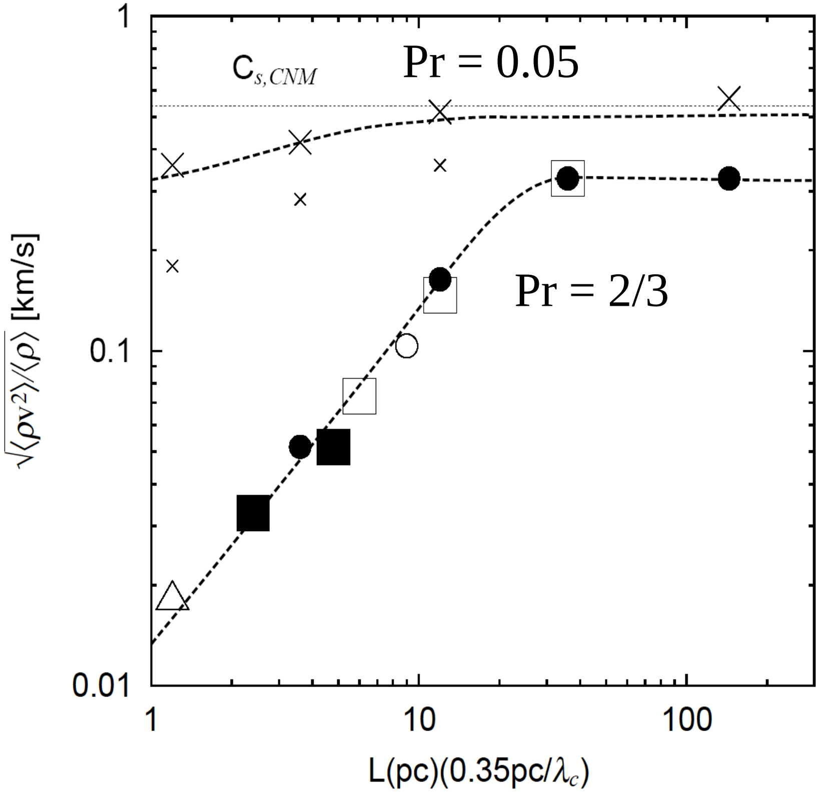
Without Physical Viscosity → $\mathrm{Pr} = 0$

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

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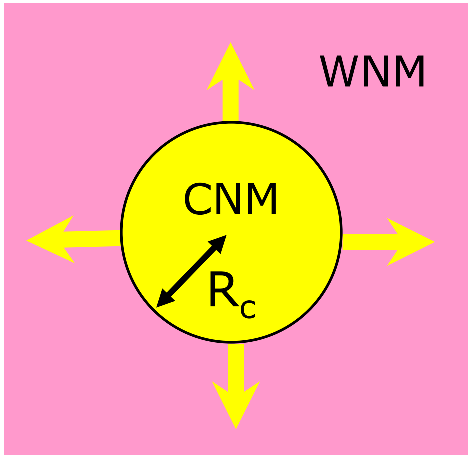
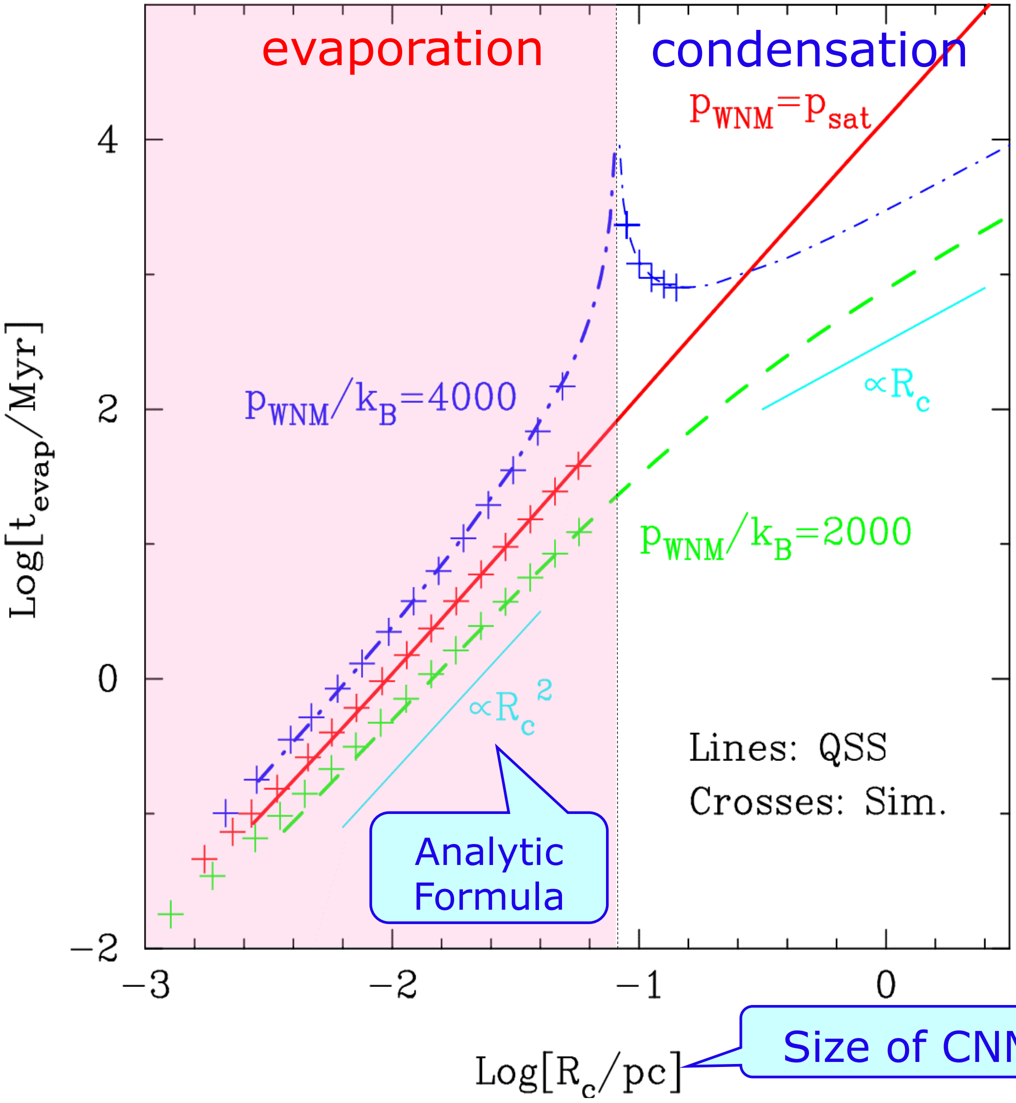
Evaporation of Spherical CNM in WNM





Evaporation Timescale

Analytic Formula

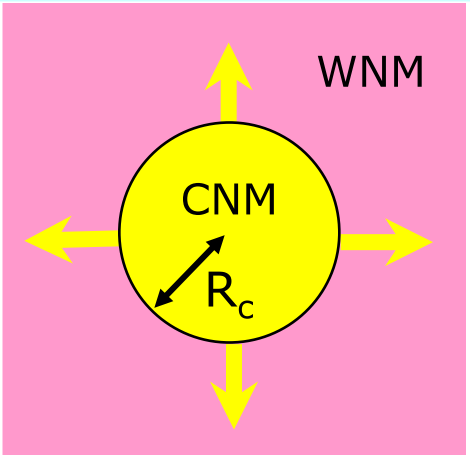
Size of CNM cloud

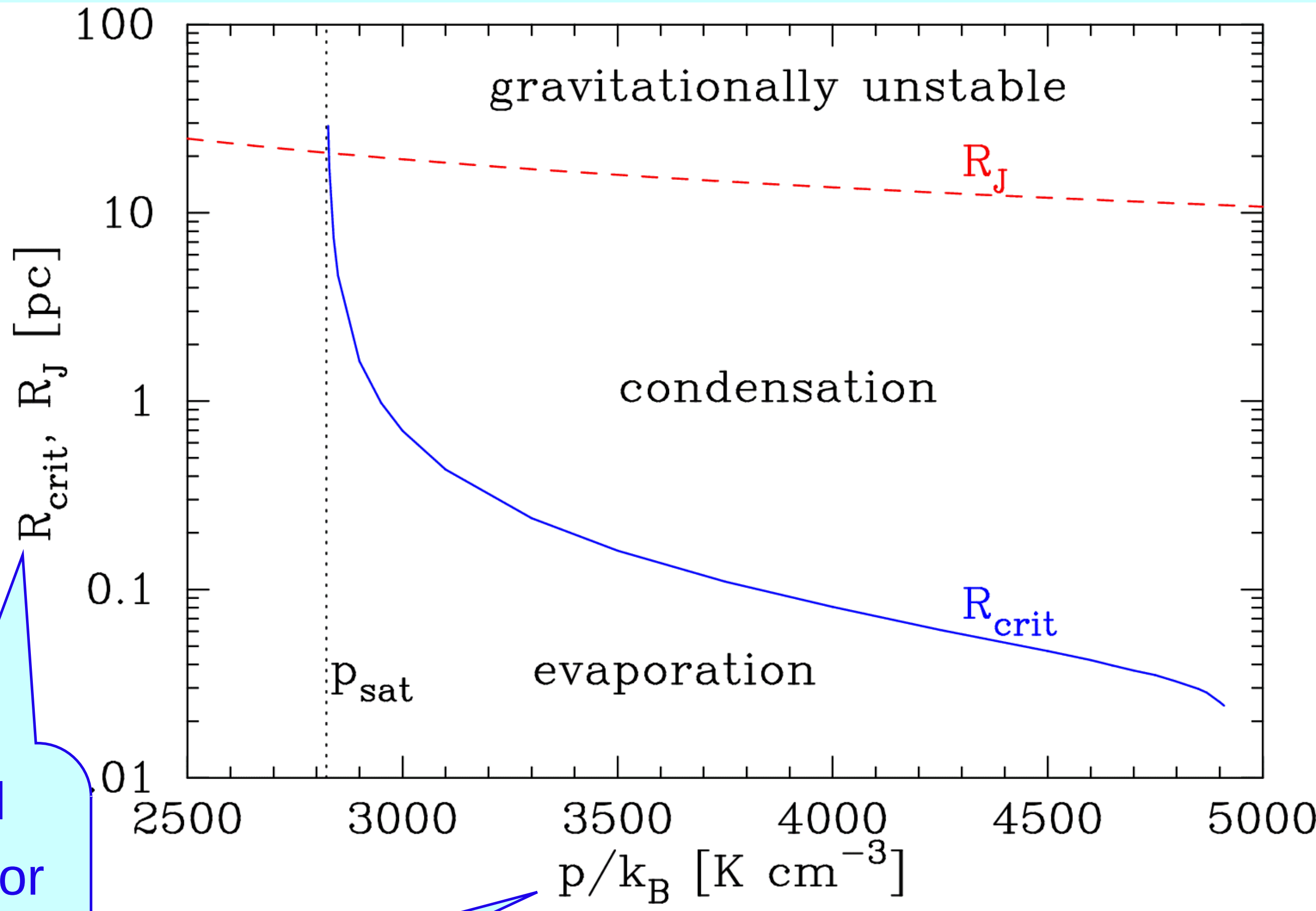
Smaller CNM
cloud evaporates:

<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

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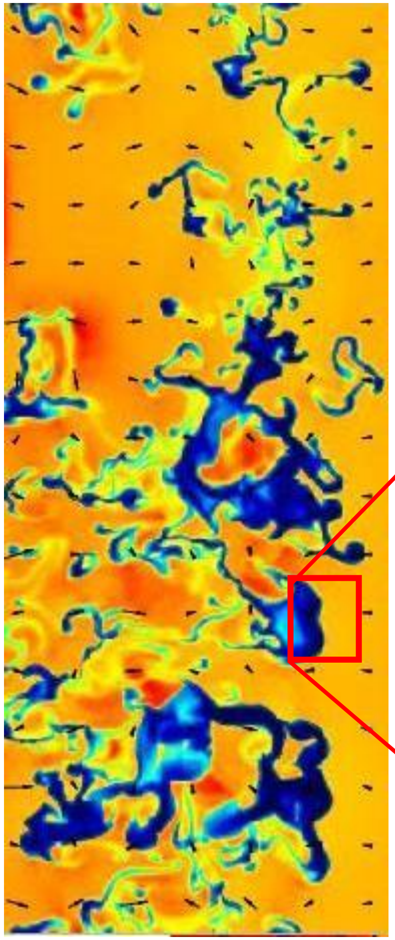
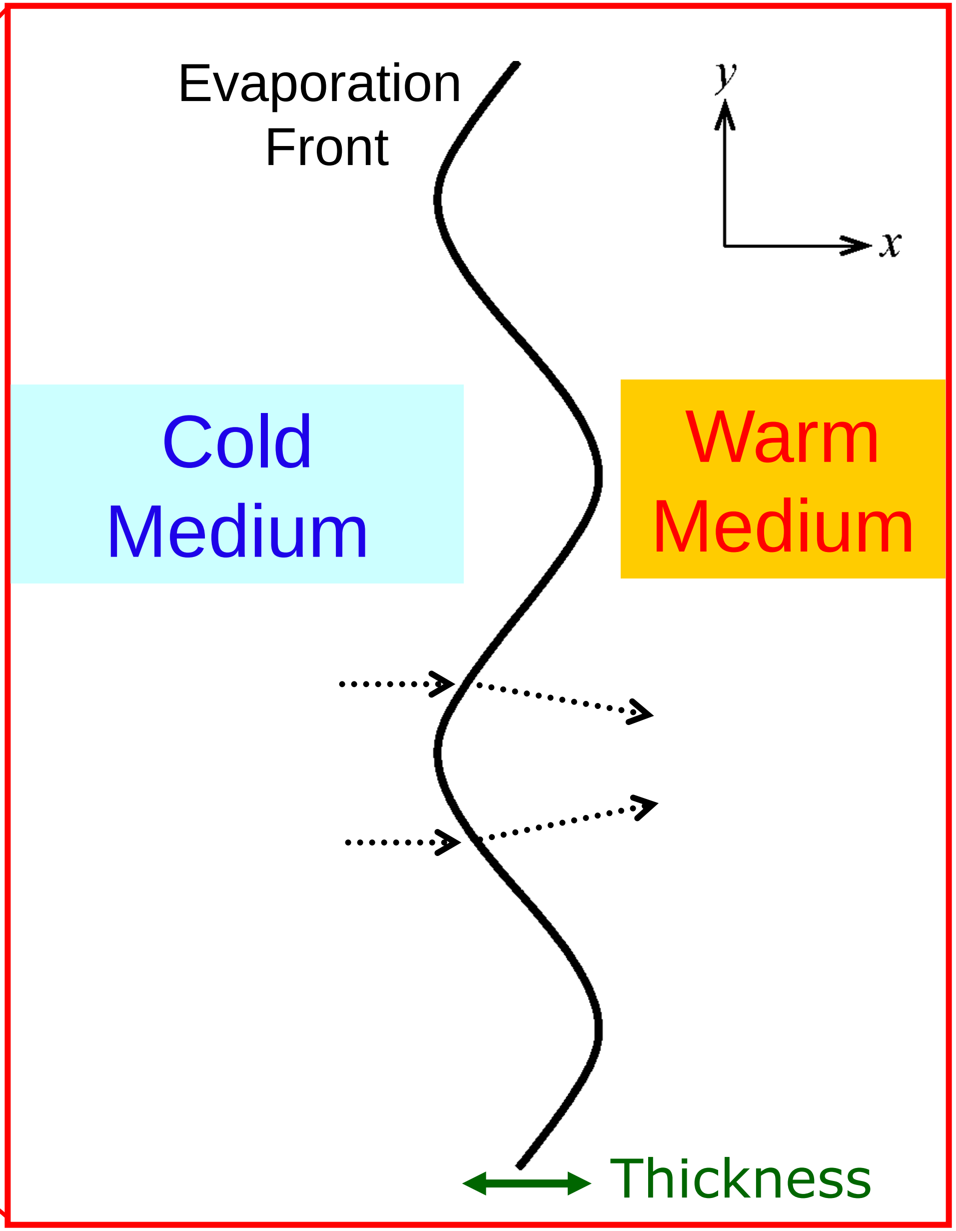
3. Effect of Magnetic Field

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

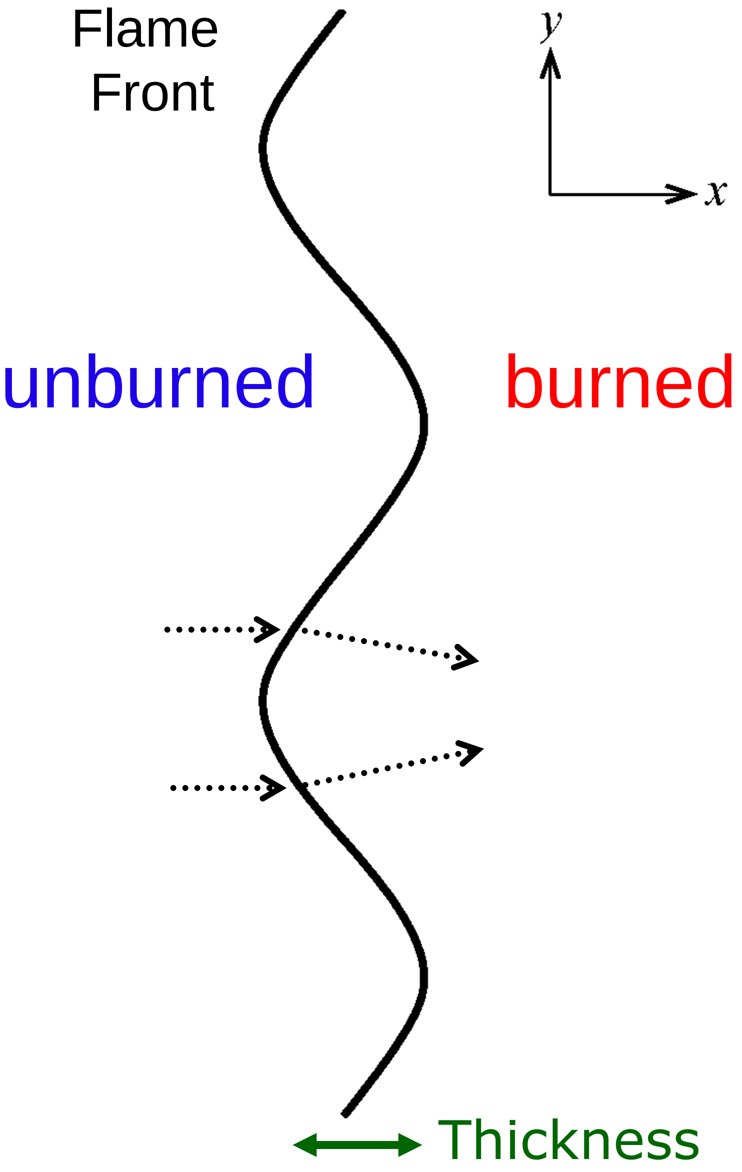
\# Effect of Magnetic Field

See Dursi (2004)

2) Corrugation Instability in MHD Slow Shock

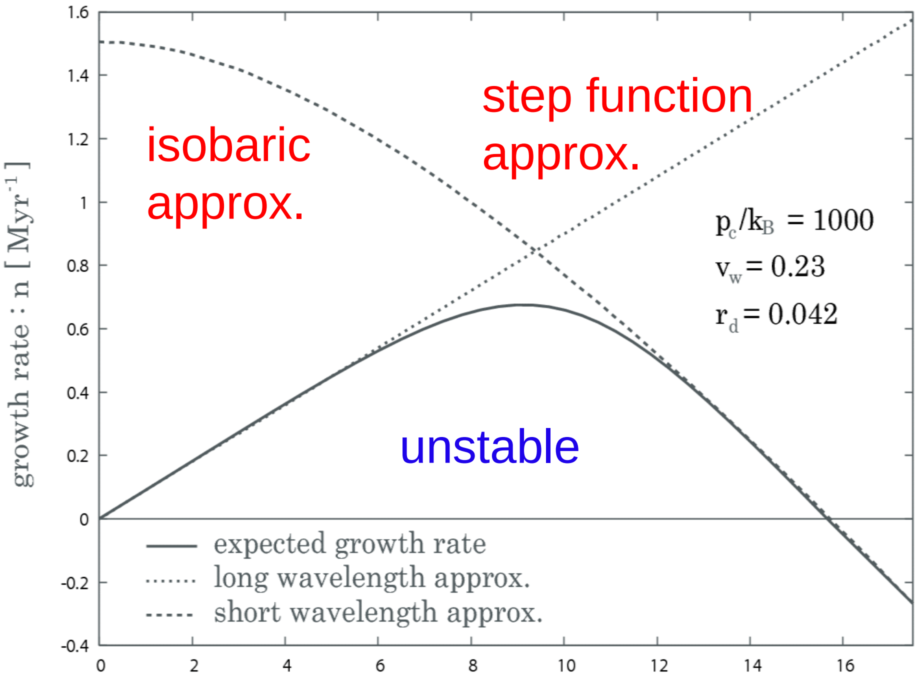
– Edelman 1990

– Stone & Edelman 1995



Linear Analysis of New Instability

Growth Rate (Myr^{-1})

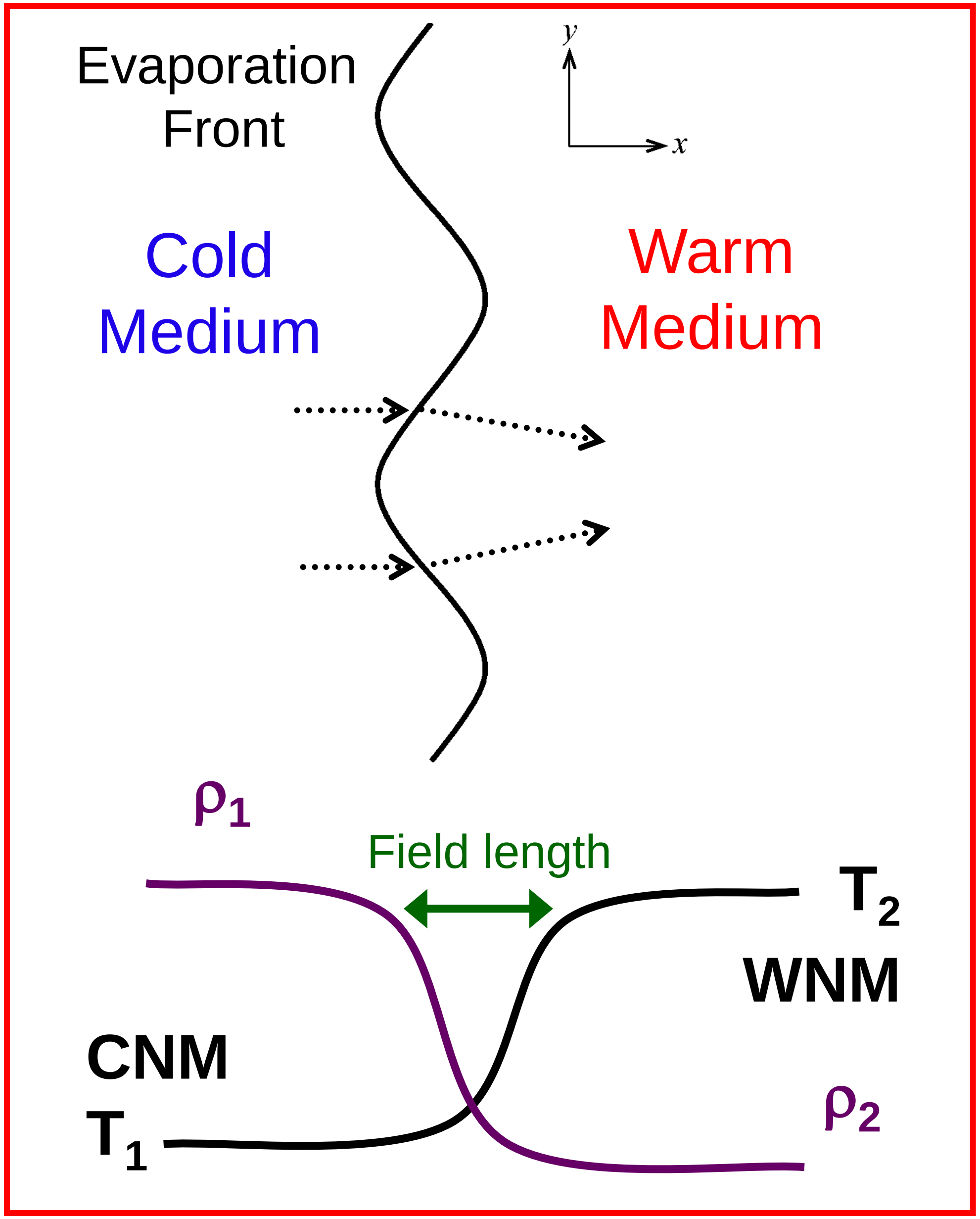


wavenumber $k_y/2\pi$ [pc^{-1}]

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

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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

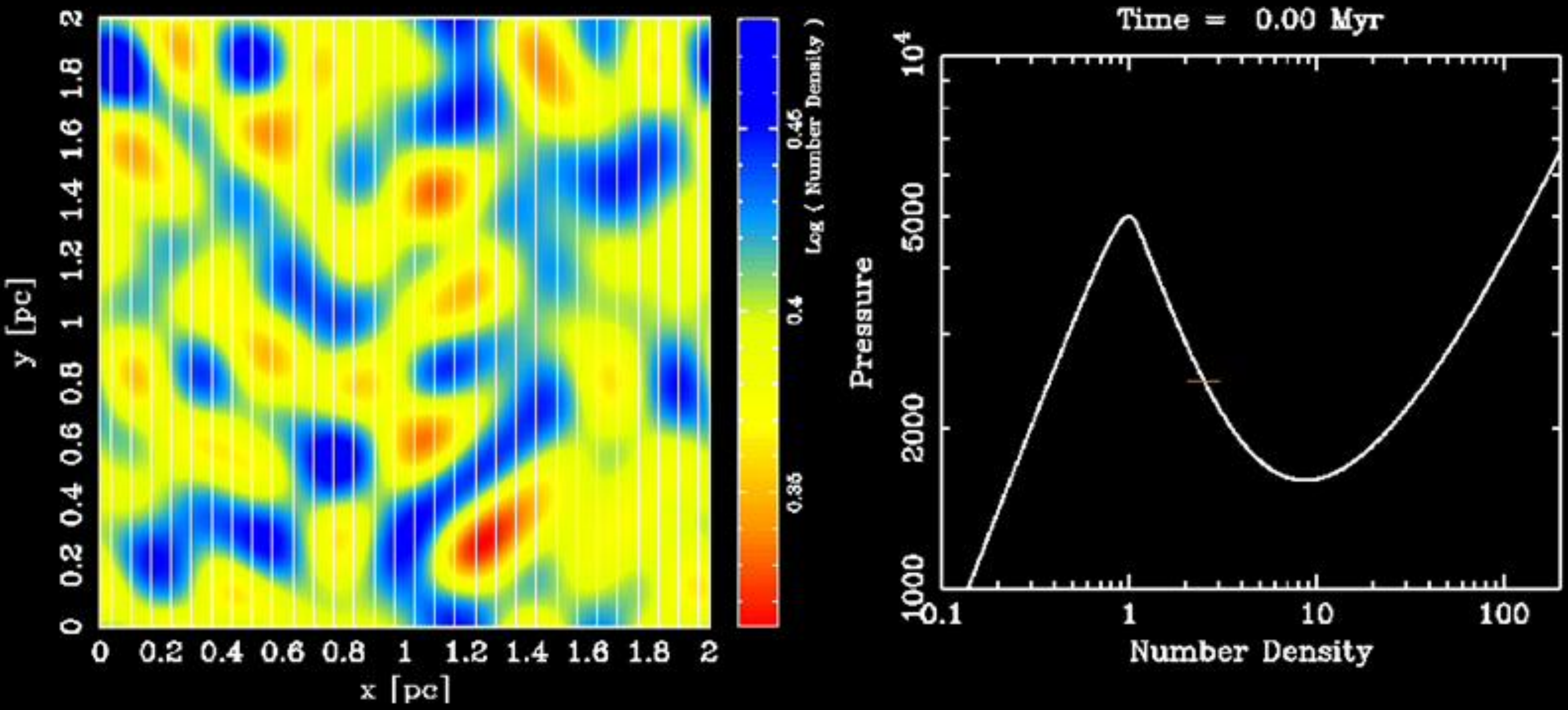
Detailed Analysis of Non-Linear Growth Needed

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.

2D 2-Fluid MHD Simulations



Inoue & Inutsuka (2007) in prep.