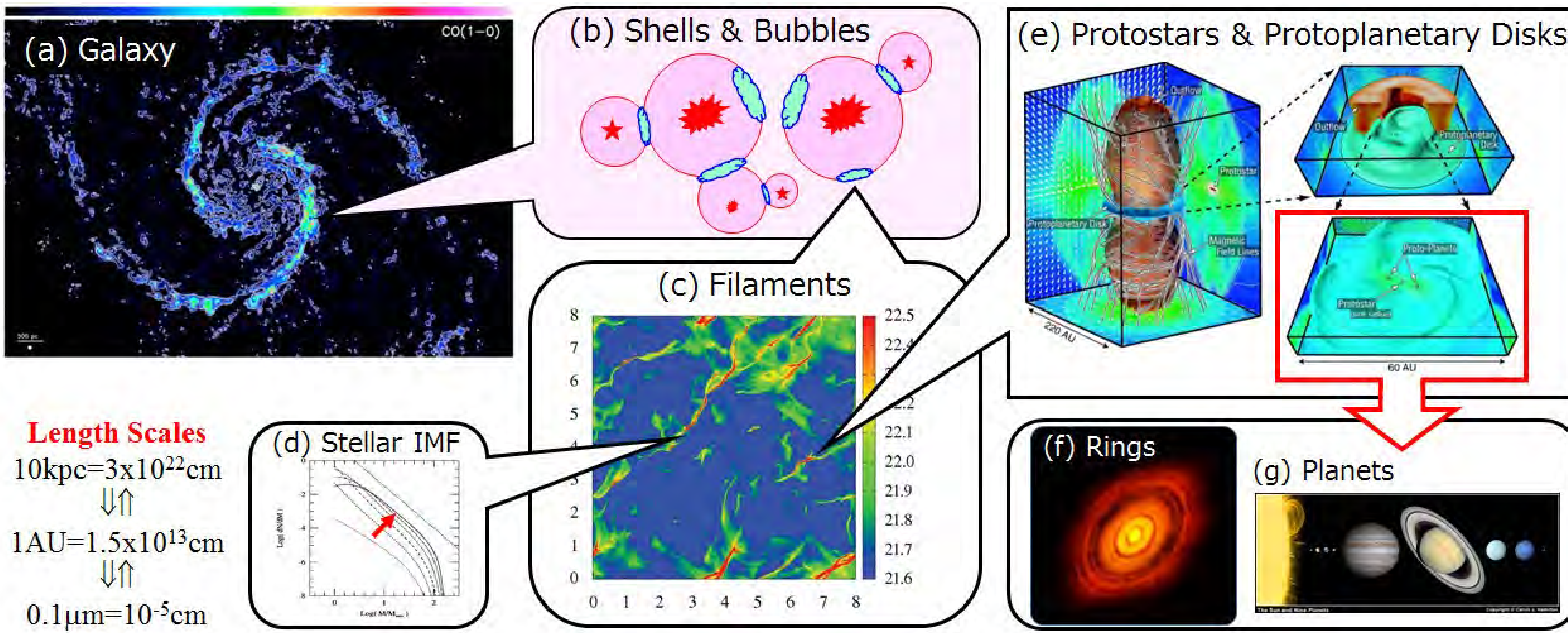
Phase Transition Dynamics of ISM: The Formation of Molecular Clouds and ~~Galactic~~ Star Formation

Shu-ichiro Inutsuka (Nagoya University)



Outline

- Formation of Molecular Clouds
  - Phase Transition Dynamics
  - Thermal Instability, Sustained Turbulence
  - Effect of Magnetic Field
- Self-Gravitational Dynamics of Filaments
  - Mass Function of Dense Cores ➔ IMF
- Galactic Picture of Cloud/Star Formation
  - Destruction of Molecular Clouds
  - SF Efficiency & Schmidt-Kennicutt Law
  - Mass Function of Molecular Clouds
- Summary

Dynamical Timescales of ISM

Dynamical Three Phase Medium

- e.g., McKee & Ostriker 1977

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

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

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

Dynamical Timescale of ISM ~ 1Myr

« Timescale of Galactic Density Wave ~ 100Myr

<u>Expanding HII regions can be more important!</u>

Basic Equations for ISM Dynamics

- Eq. of Continuity

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

- EoM

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

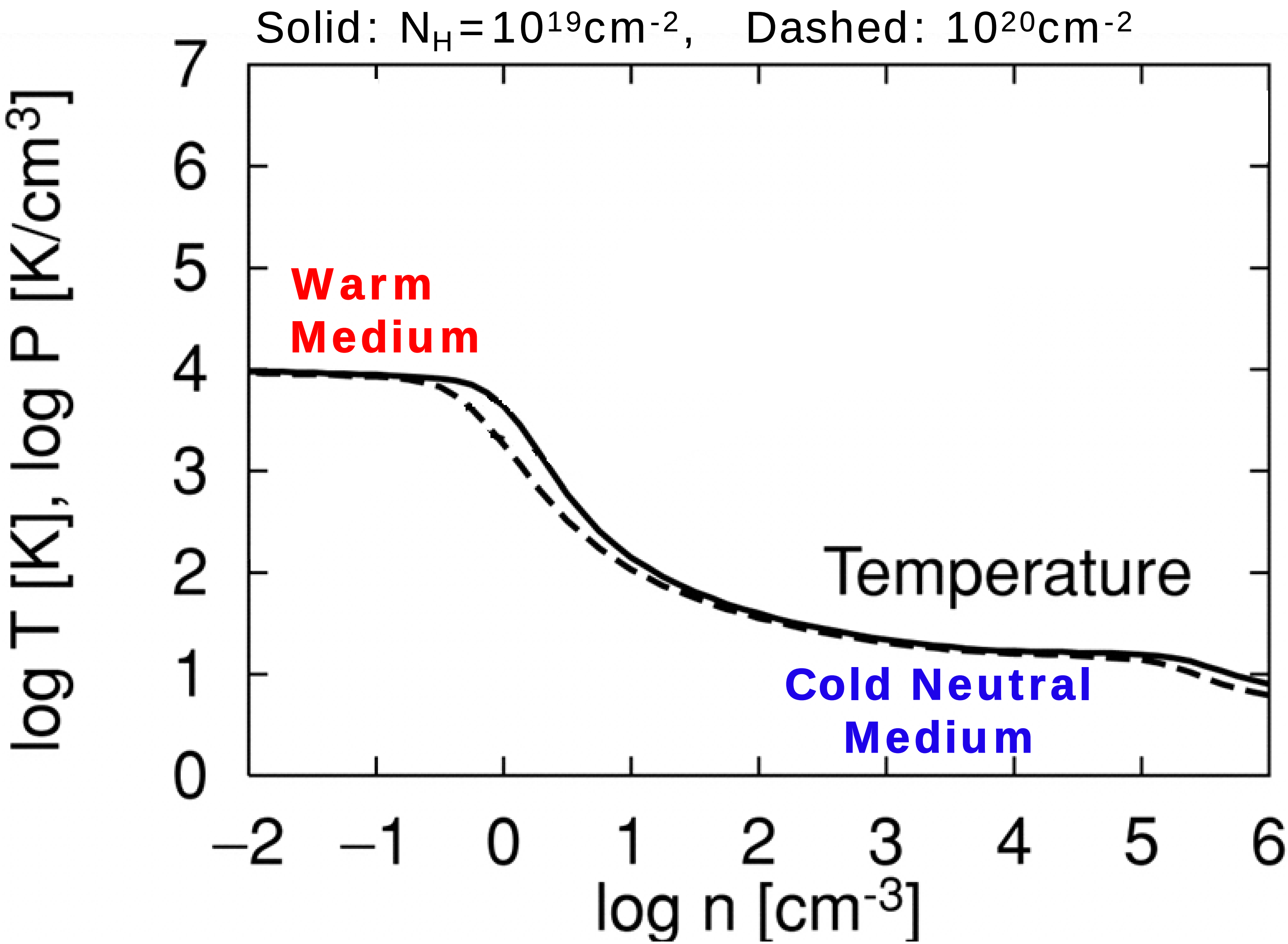
- Eq. of Energy
  - Radiative Heating & Cooling: Γ, Λ
    - H, C^+, O, Fe^+, Si^+, H_2, CO
  - Chemical Reaction
    - HII, HI, H_2, CII, CO
  - Thermal Conduction
    - conduction coefficient: κ

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

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

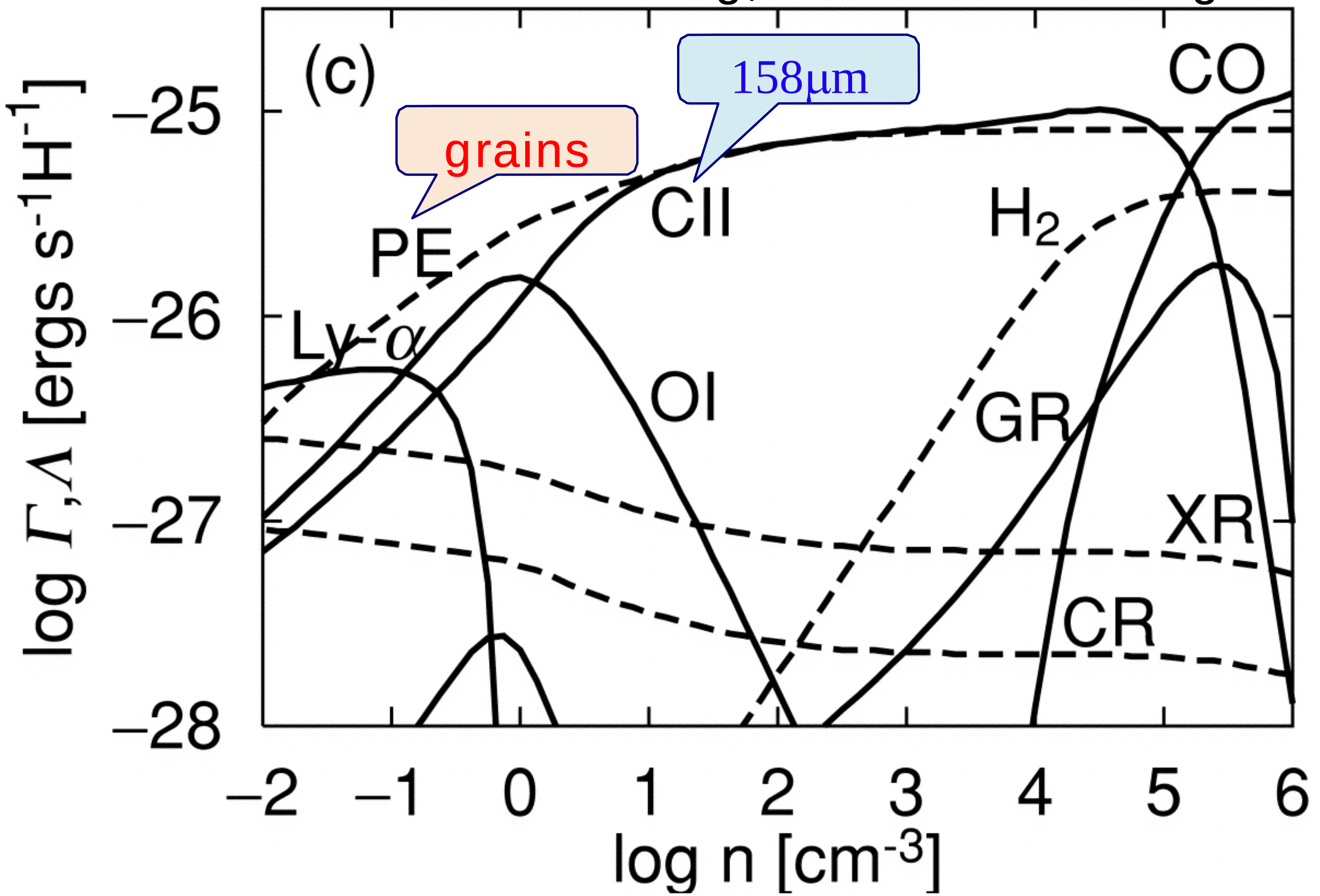
for $M < M_{\text{Jeans}}$

Radiative Equilibrium for a given density



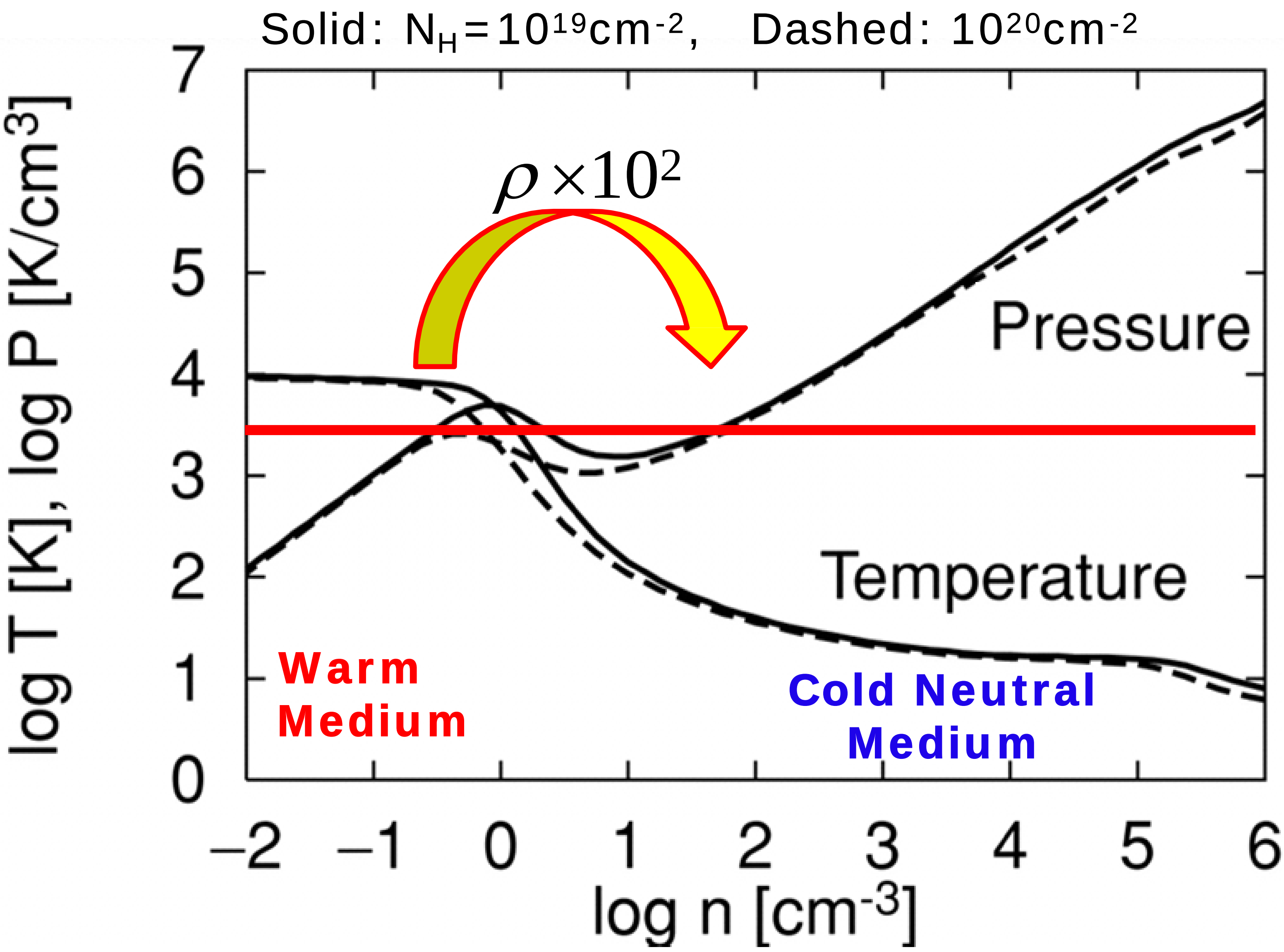
Radiative Cooling & Heating

Solid: Cooling,   Dashed: Heating



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

Radiative Equilibrium for a given density

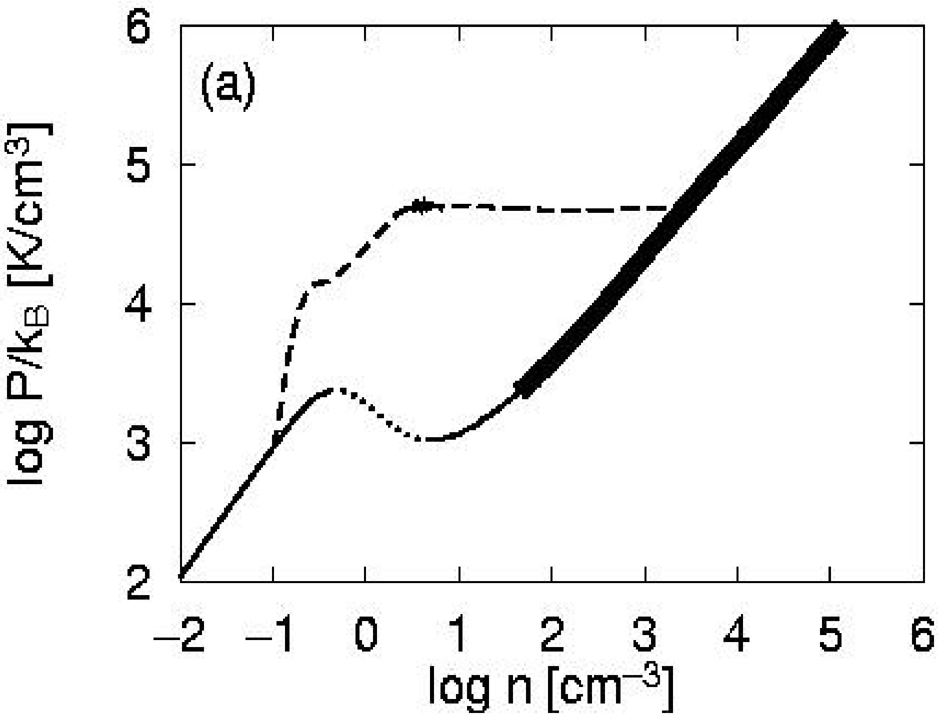


e.g., Wolfire et al. 1995, Koyama & SI 2000

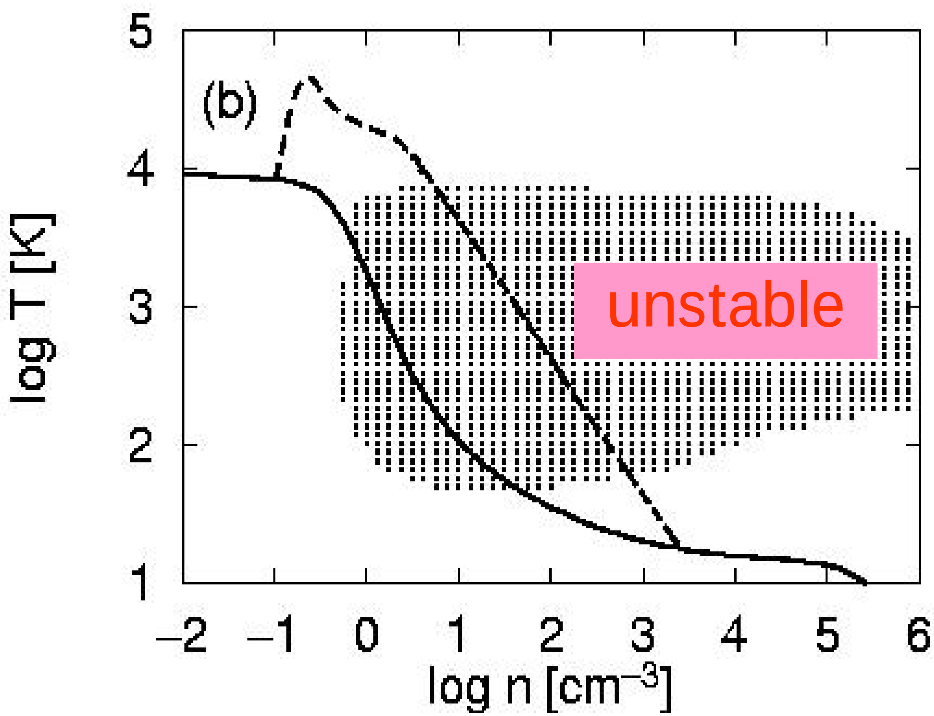
1D Shock Propagation into WNM

Realistic Cooling/Heating + Chemistry (H_2, CO)

Density-Pressure Diagram



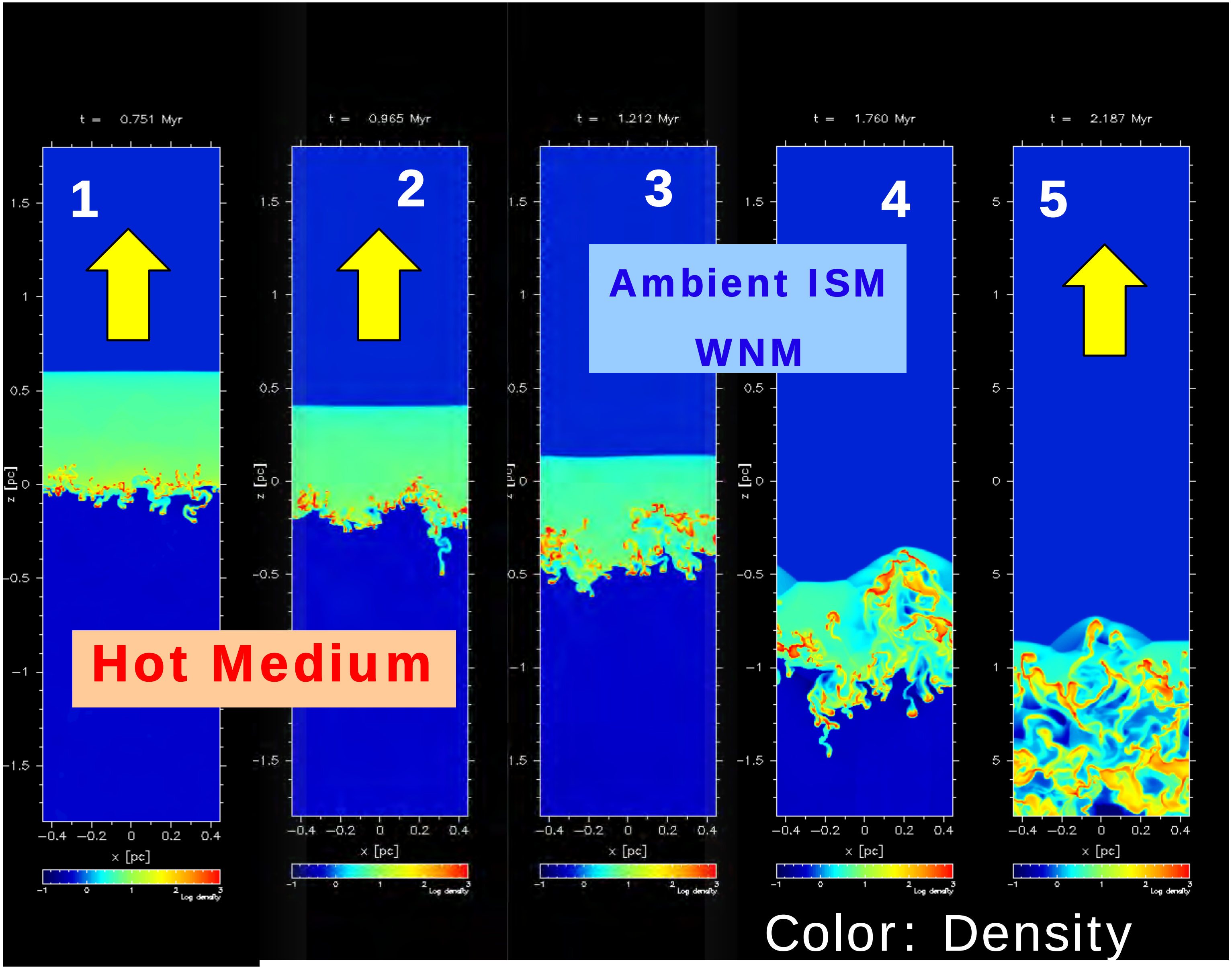
Density-Temperature Diagram



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

See also Hennebelle & Pérault 1999

Shock Propagation into WNM



Koyama & Inutsuka (2002) ApJ 564, L97

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

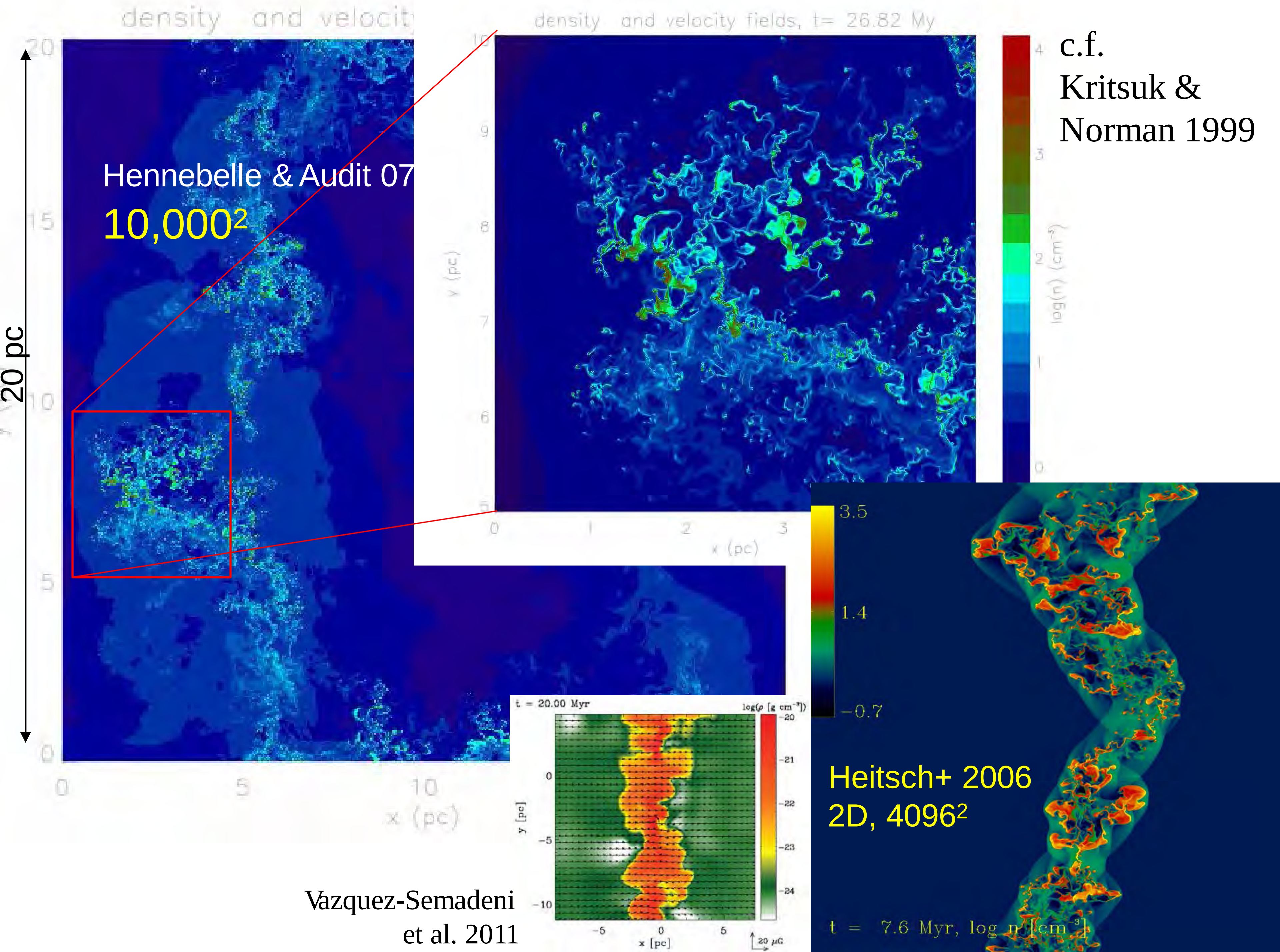
2D&3D: Shock $\Rightarrow E_{th} \Rightarrow E_{rad} + E_{kin}$

δv ~ a few km/s < $C_{S,WNM}$ =10km/s

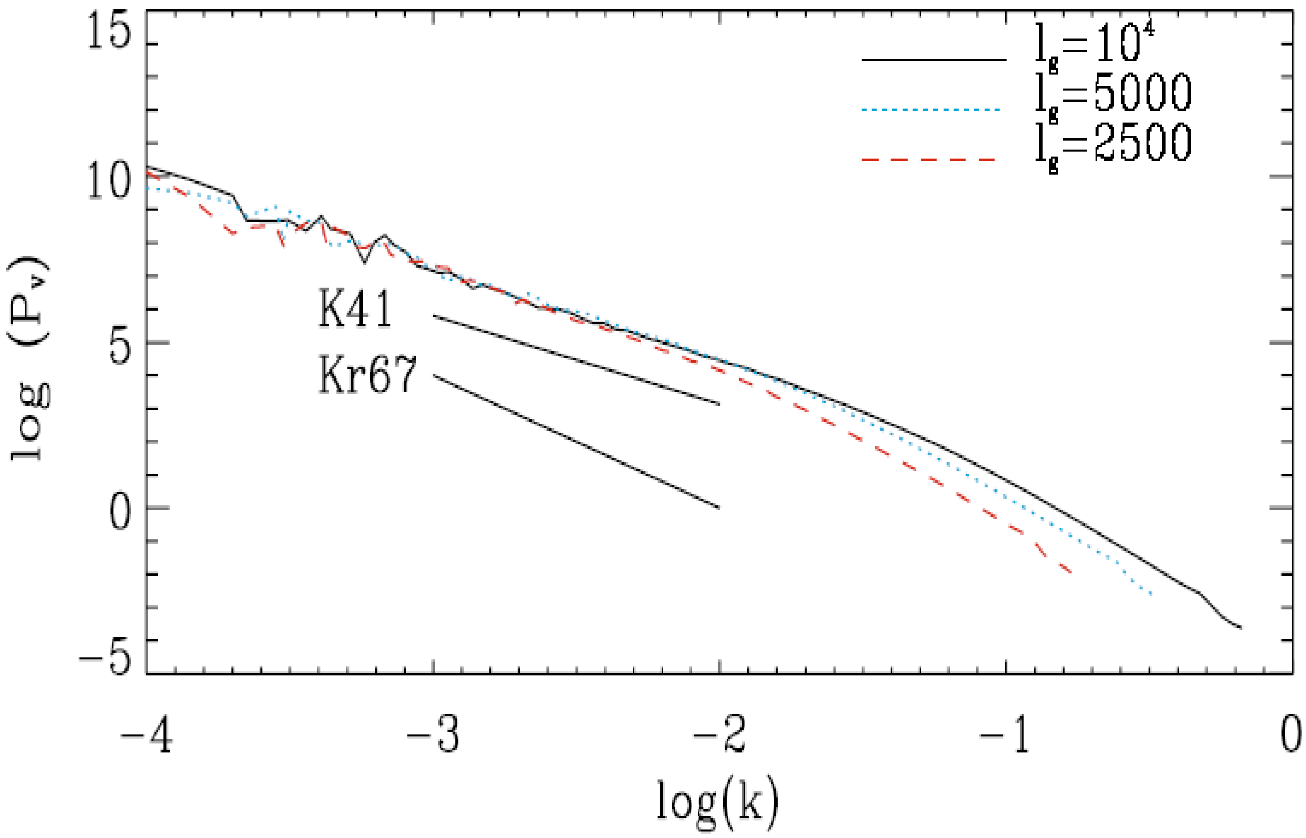
🡐 10^4K due to Lyα line: Universality!

T_{CNM} ~10^2K 🡐 C^+158μm (~10^2K)

Koyama & SI (2002) ApJ 564, L97


density and velocity fields, t= 26.82 My
c.f.
Kritsuk &
Norman 1999
Hennebelle & Audit 07
10,000²
20 pc
x (pc)
y (pc)
log(n) (cm⁻³)
3.5
1.4
−0.7
Heitsch+ 2006
2D, 4096²
t = 7.6 Myr, log n [cm⁻³]
t = 20.00 Myr
log(ρ [g cm⁻³])
x [pc]
y [pc]
20 μG
Vazquez-Semadeni
et al. 2011

Property of “Turbulence”…Subsonic

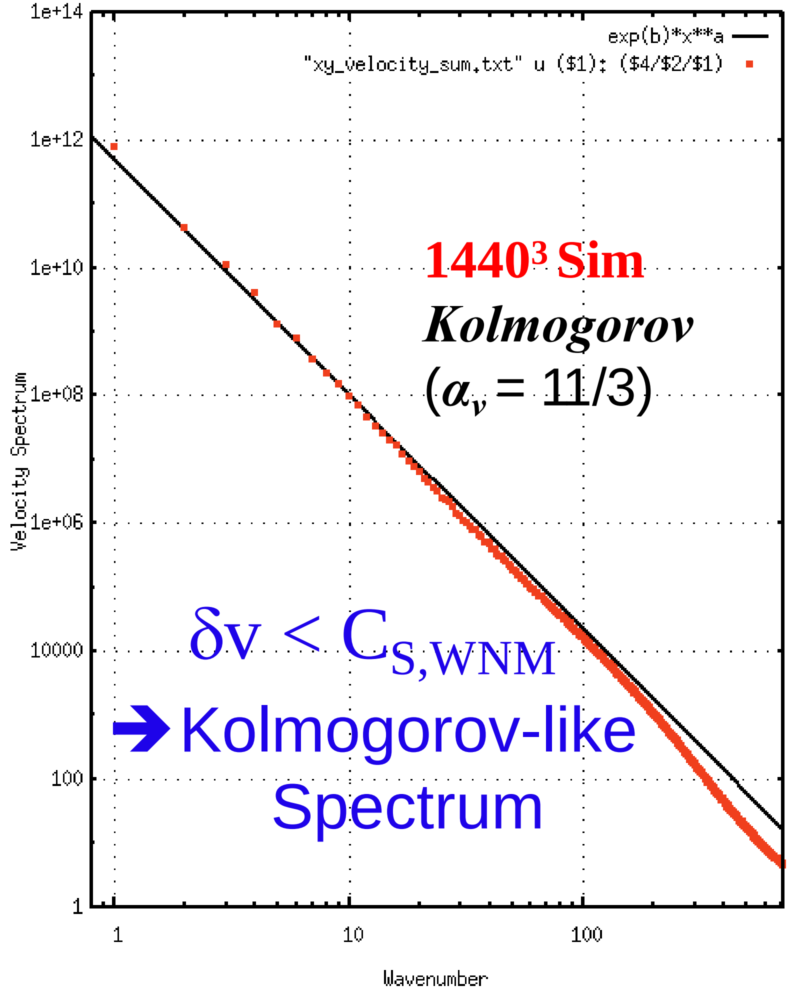


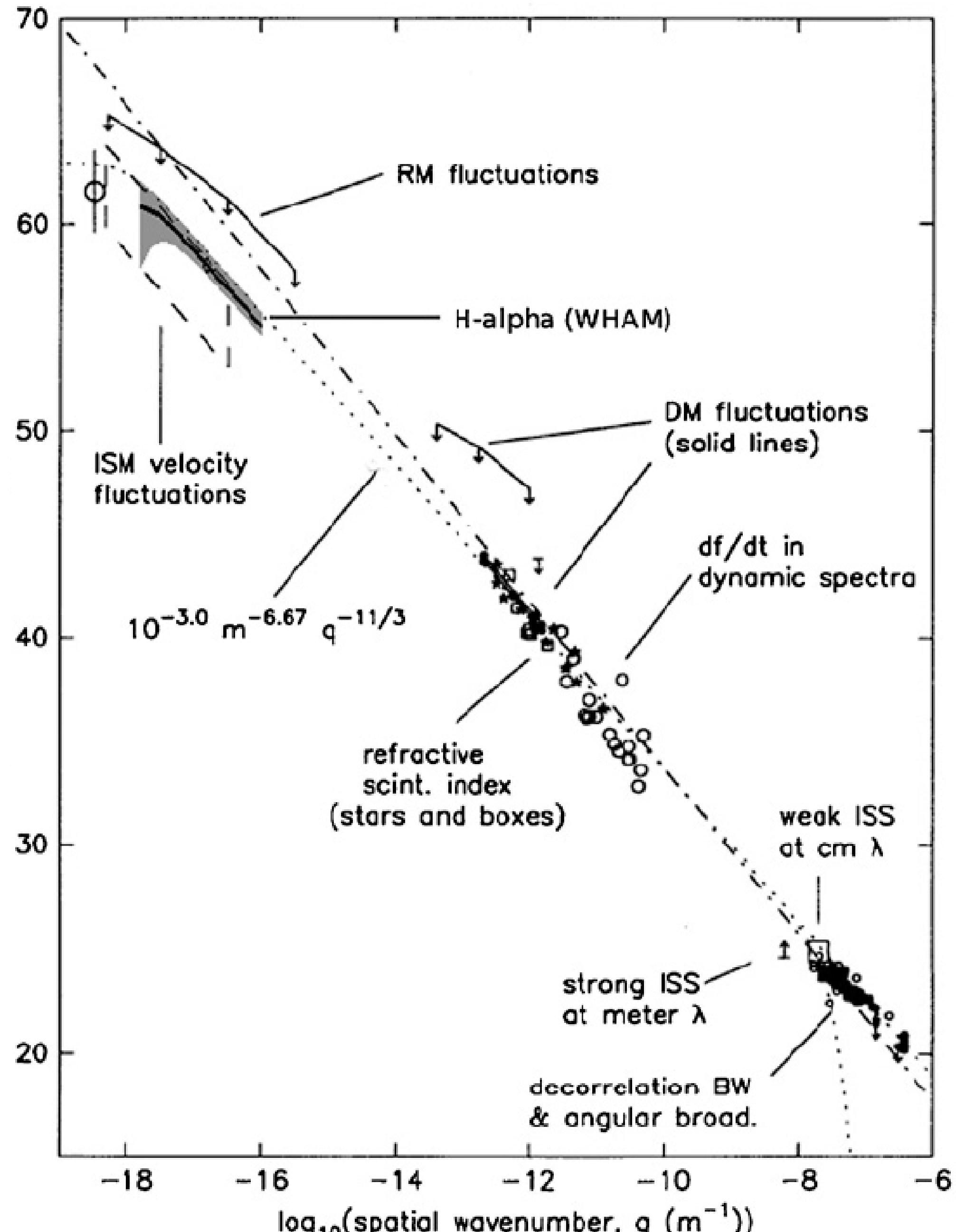
$\delta v < C_{S,WNM}$ ➔ Kolmogorov Spectrum

2D: Hennebelle & Audit 2007; see also Gazol & Kim 2010

Property of 3D "Turbulence"

Muranushi, Inoue & SI (unpublished)





Good Agreement!

Chepurnov & Lazarian 2010
Armstrong et al. 1995

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?

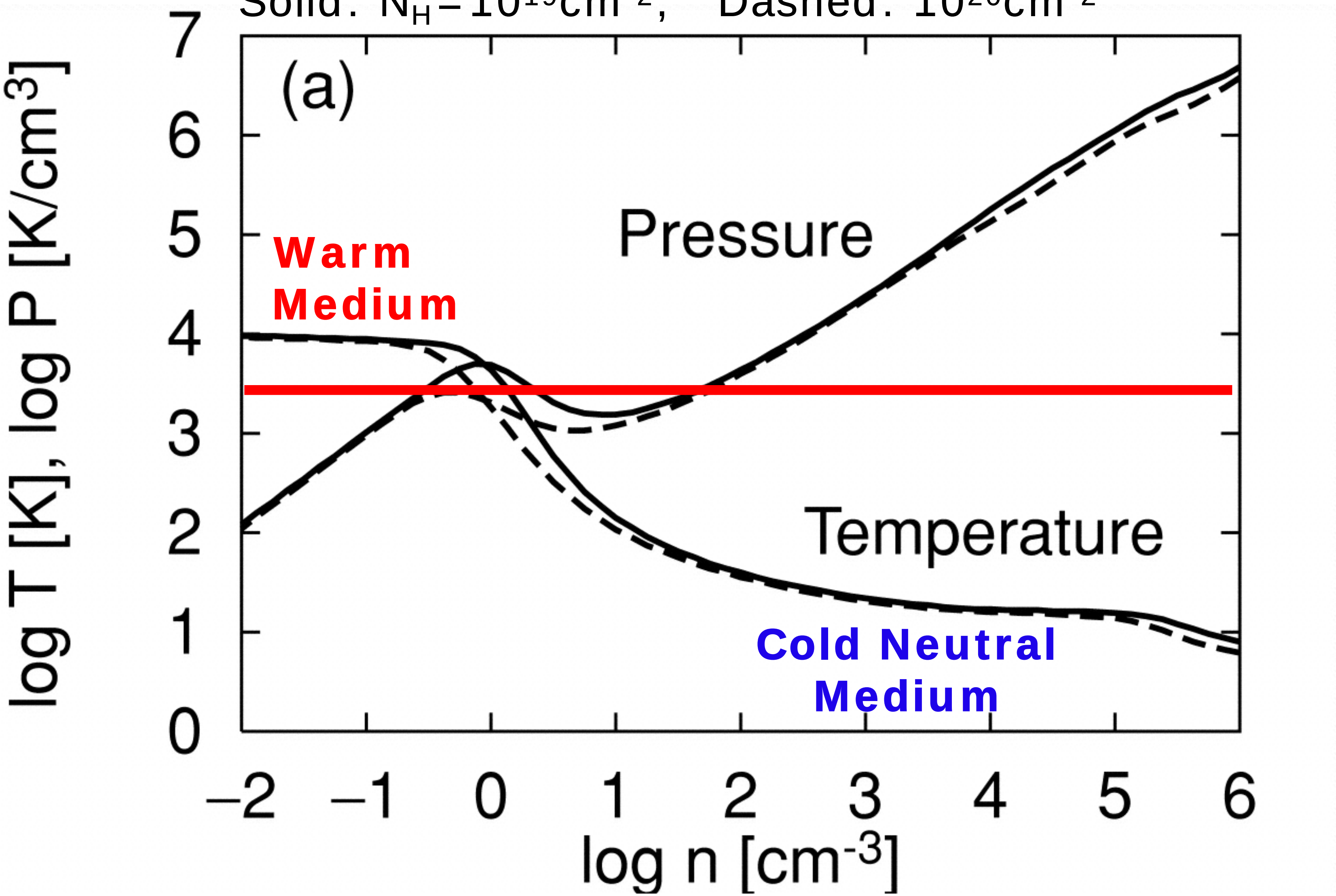
The Answer is NO!

Further Analysis on Phase Transition Dynamics

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

Radiative Equilibrium for a given density

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



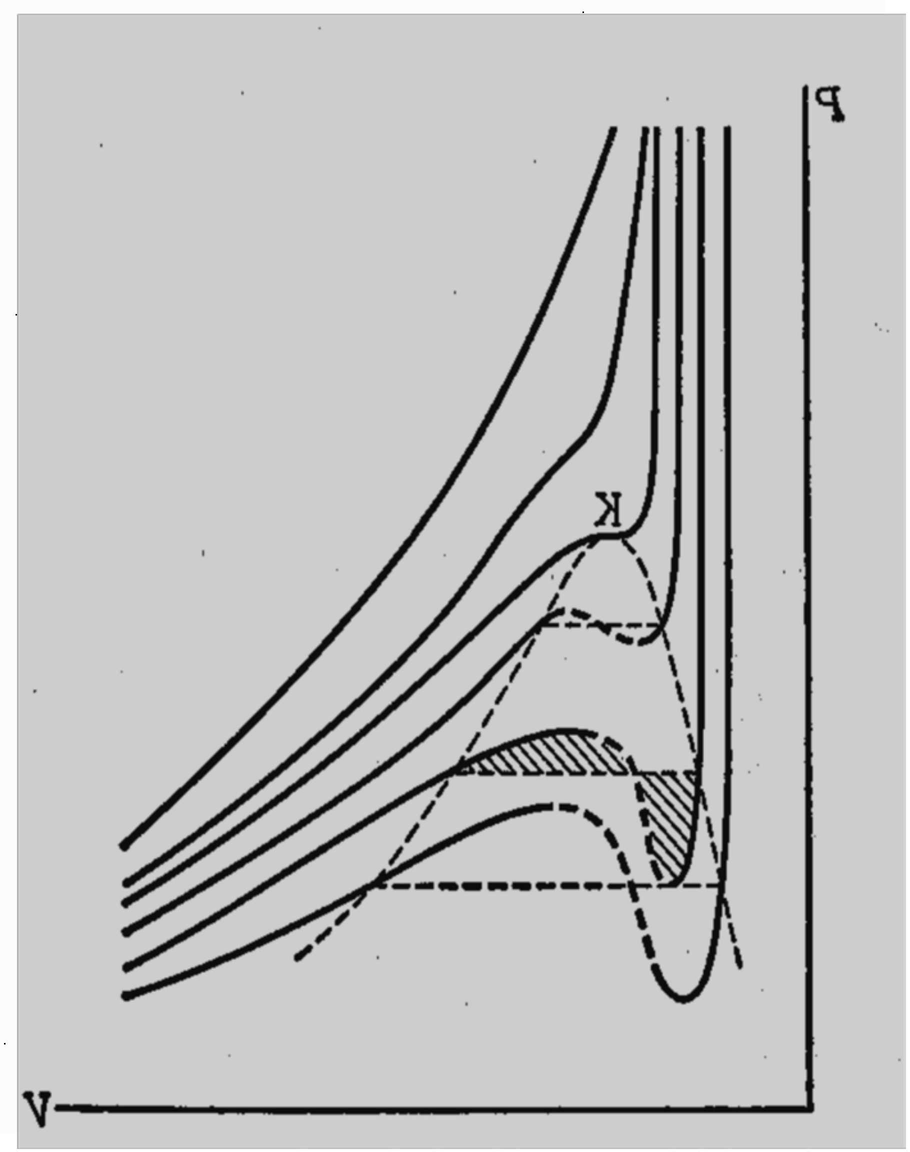
Textbook Example of Phase Equilibrium

EoS of van der Waals Gas

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

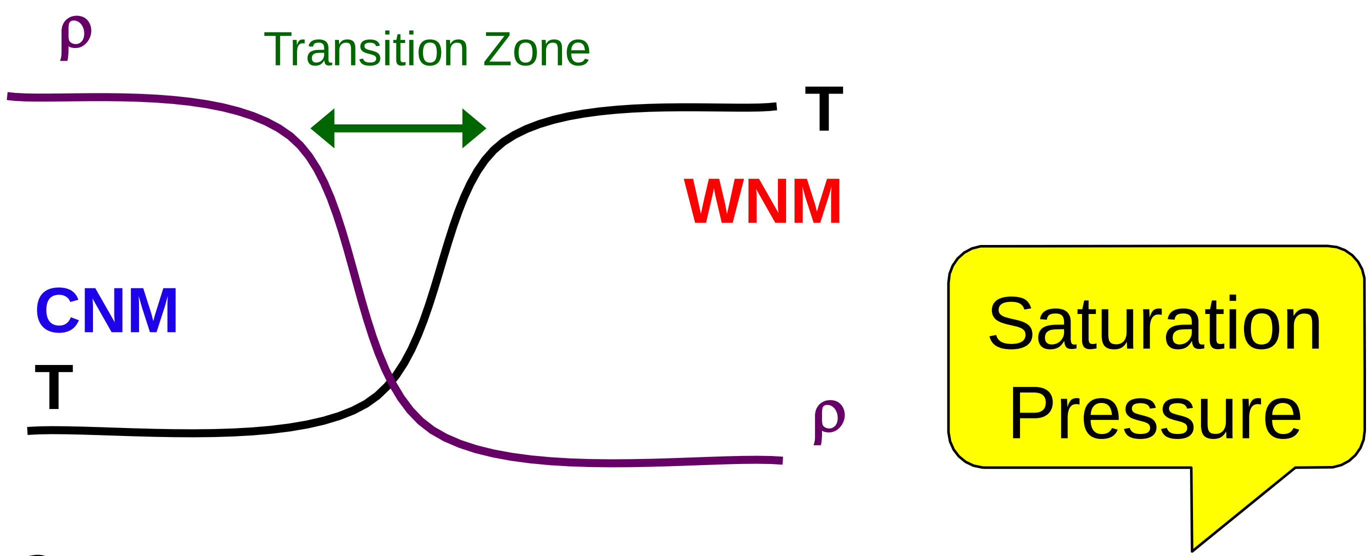
$$\mu_1 = \mu_2 \Leftrightarrow 0 = \int_1^2 d\mu$$
$$= \int_1^2 V(P, T = \mathrm{const})dP$$

Equal Areas of shaded regions
(Maxwell's rule)



Exact Equilibrium of 2-Phases

1D Case

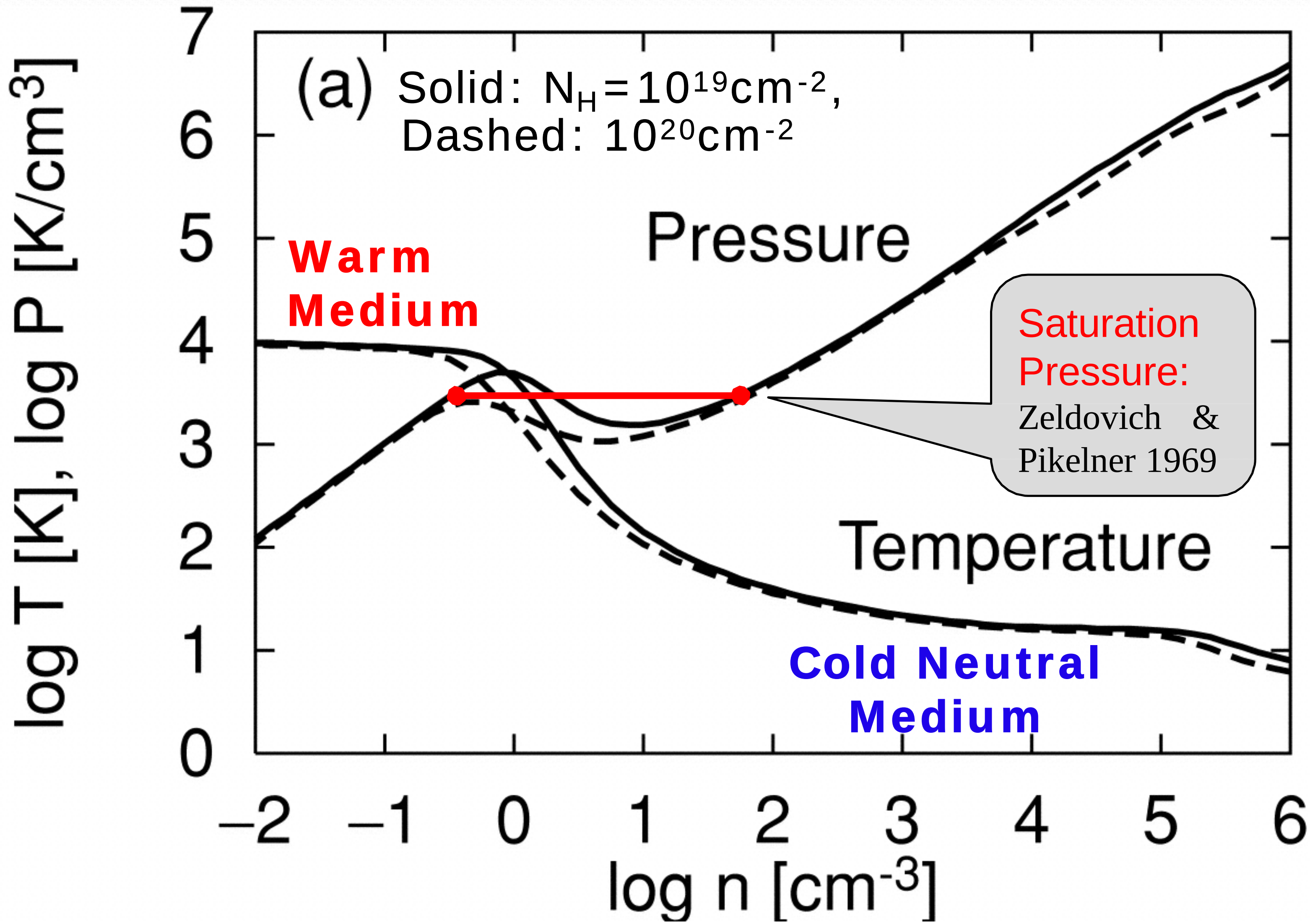


$$\int(\rho\Gamma - \rho^2\Lambda)dV = 0 \Rightarrow \text{ only at } P = P_{\rm sat}$$

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

No Unique $\boldsymbol{P}_{\rm sat}$ ➔ 2-Phase with various $\boldsymbol{P}$

Saturation Pressure in 1D Geometry

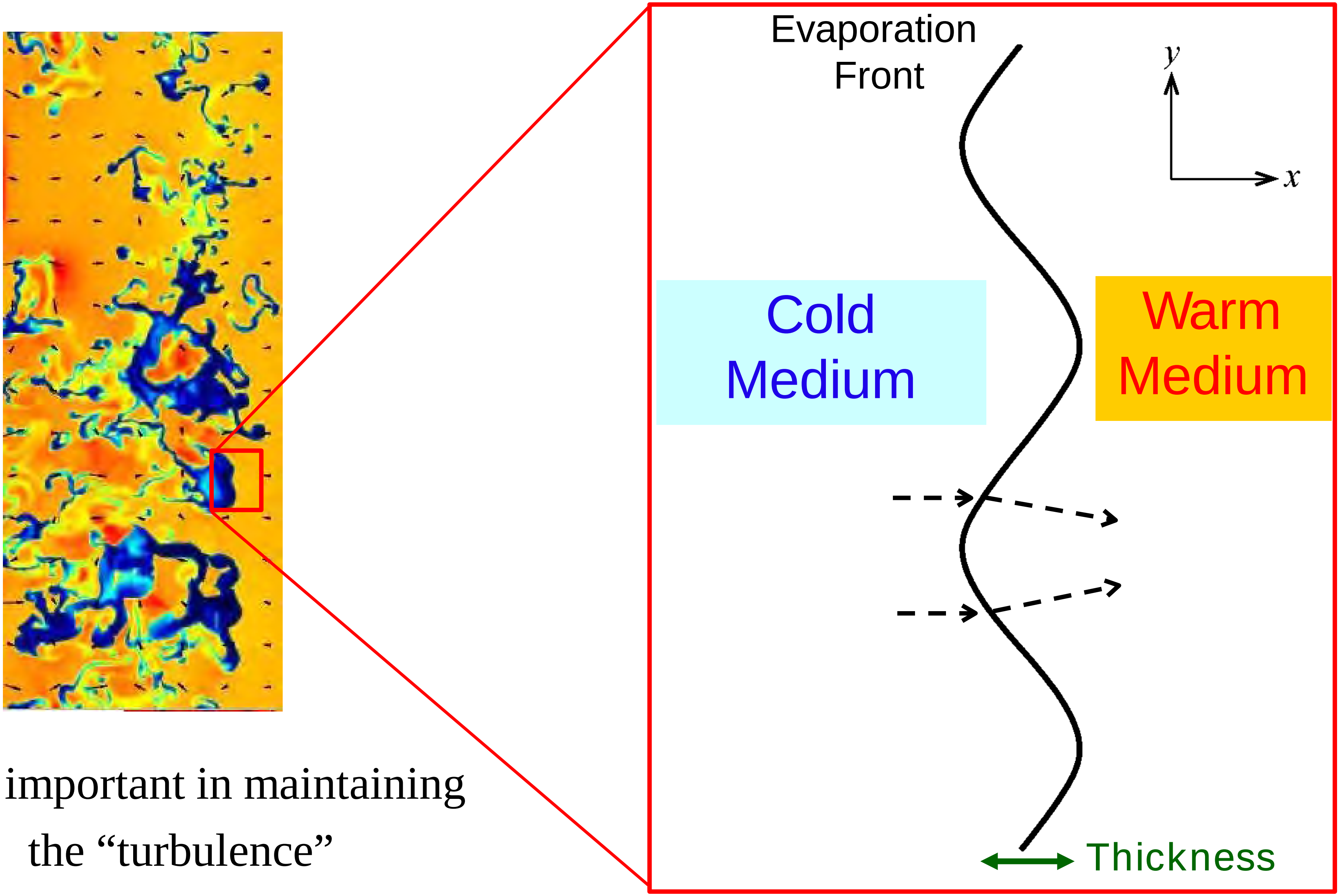


This actually depends on Geometry: Nagashima, Koyama, Inutsuka & 2005, MNRAS **361**, L25; Nagashima, Inutsuka, & Koyama 2006, ApJL **652**, L41

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

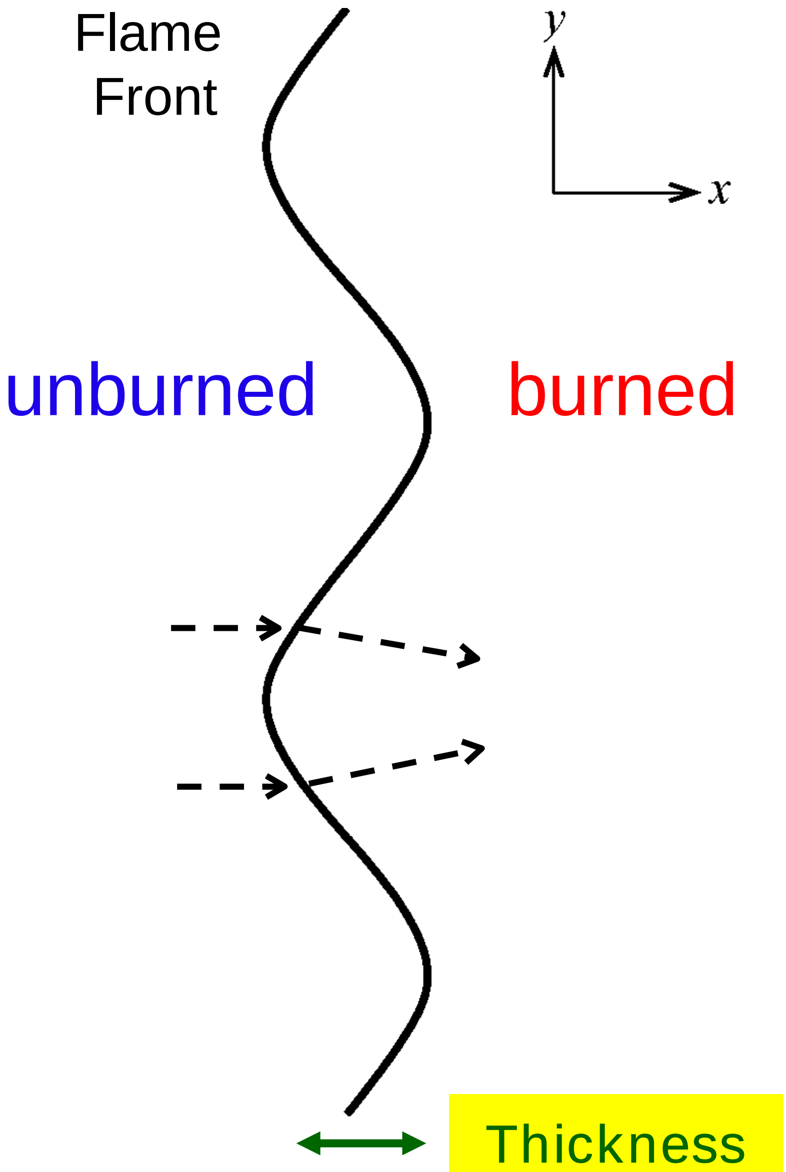
Effect of Magnetic Field

See Dursi (2004)

2) Corrugation Instability in MHD Slow Shock

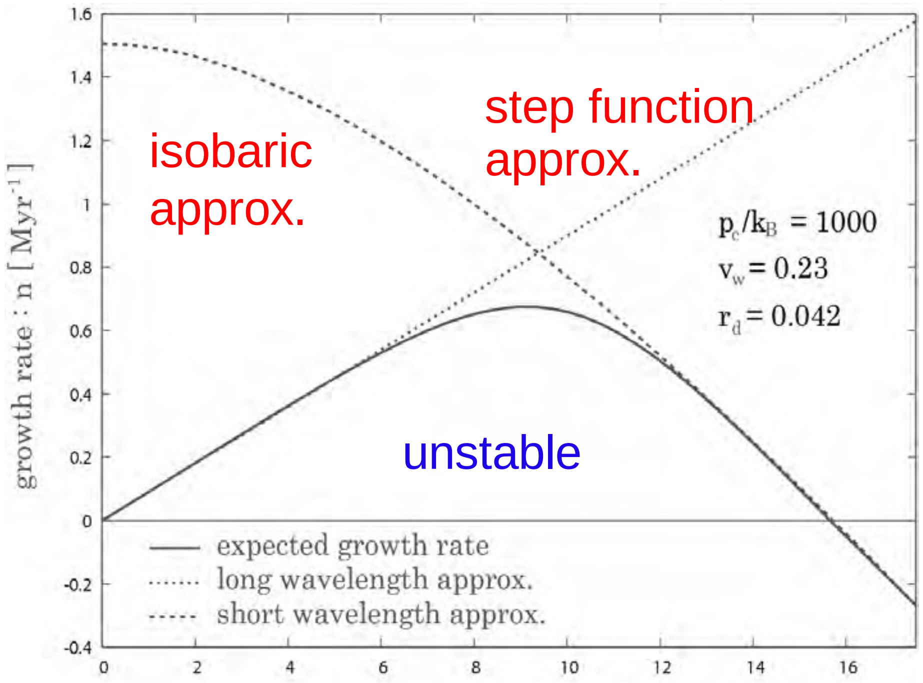
– Edelman 1990

– Stone & Edelman 1995



Linear Analysis of New Instability

Growth Rate (Myr^{-1})

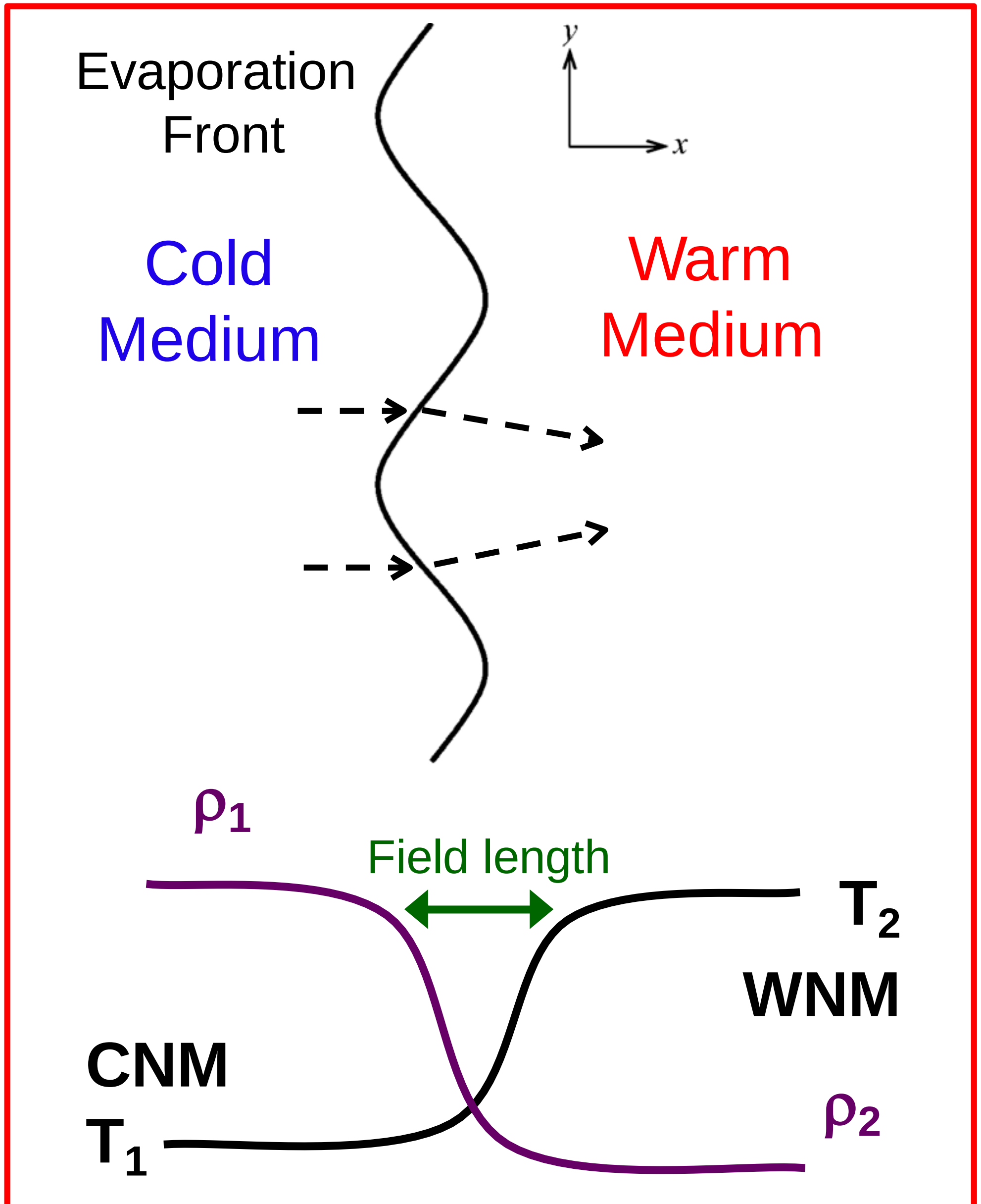


wavenumber $k_y/2\pi$ [pc^{-1}]

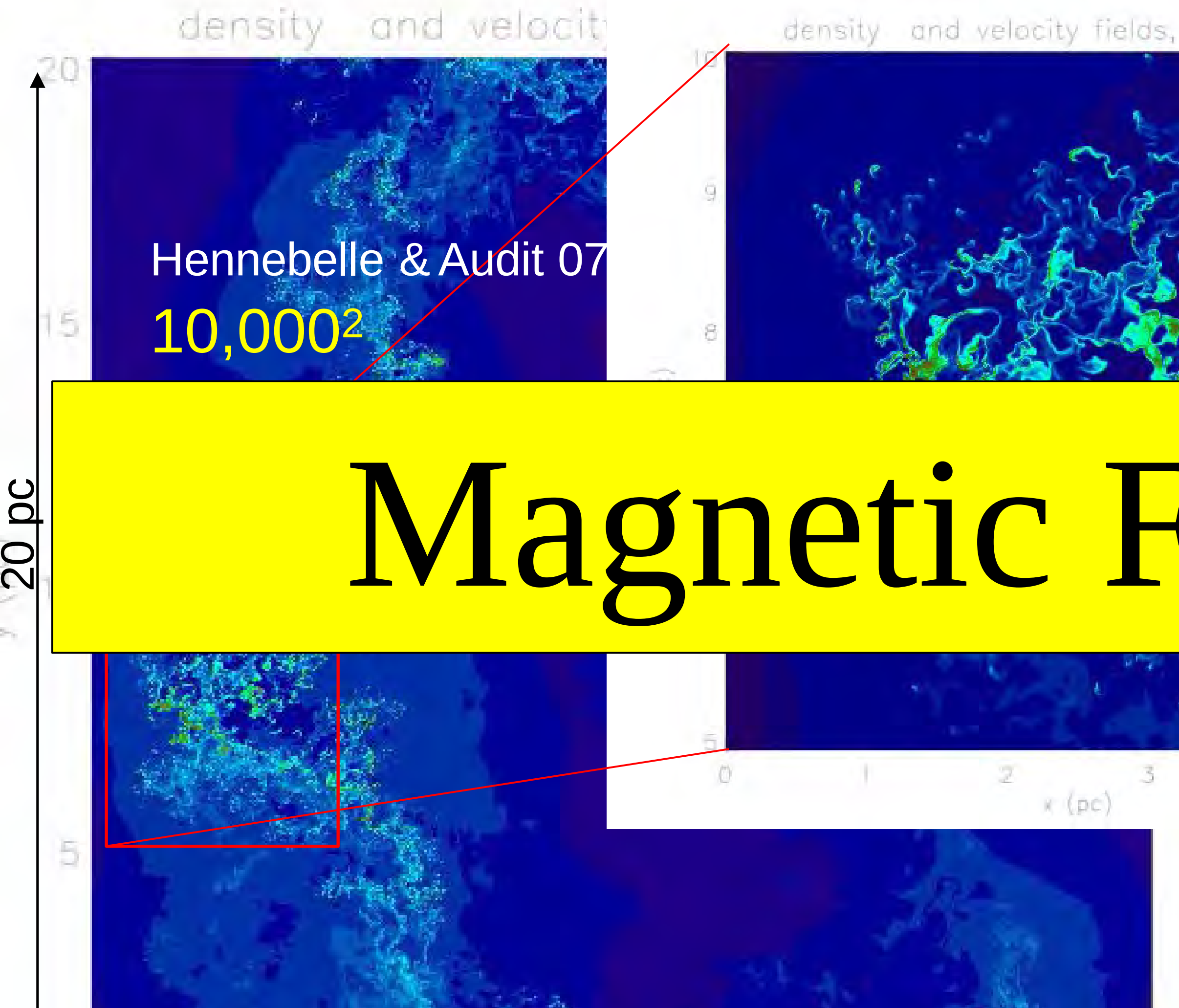
Inoue, SI, & Koyama 2006, ApJ **652**, 1131

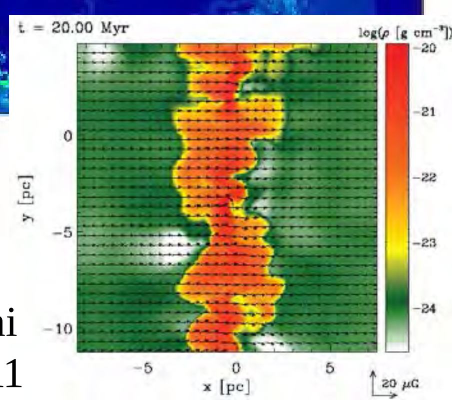
Effect of ***B***:

Stone & Zweibel 2009, ApJ 696, 233

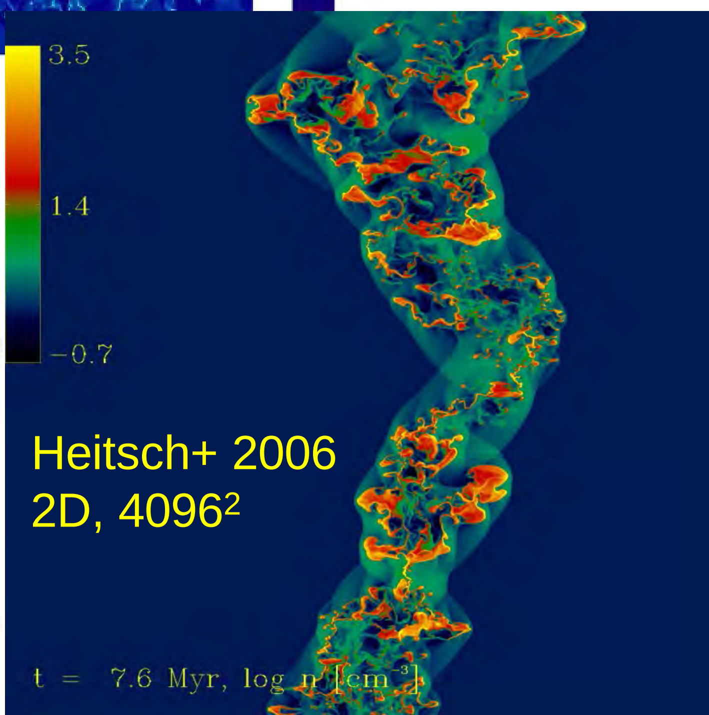


Magnetic Field?





Vazquez-Semadeni
et al. 2011



Colliding WNM with B_0=3μG

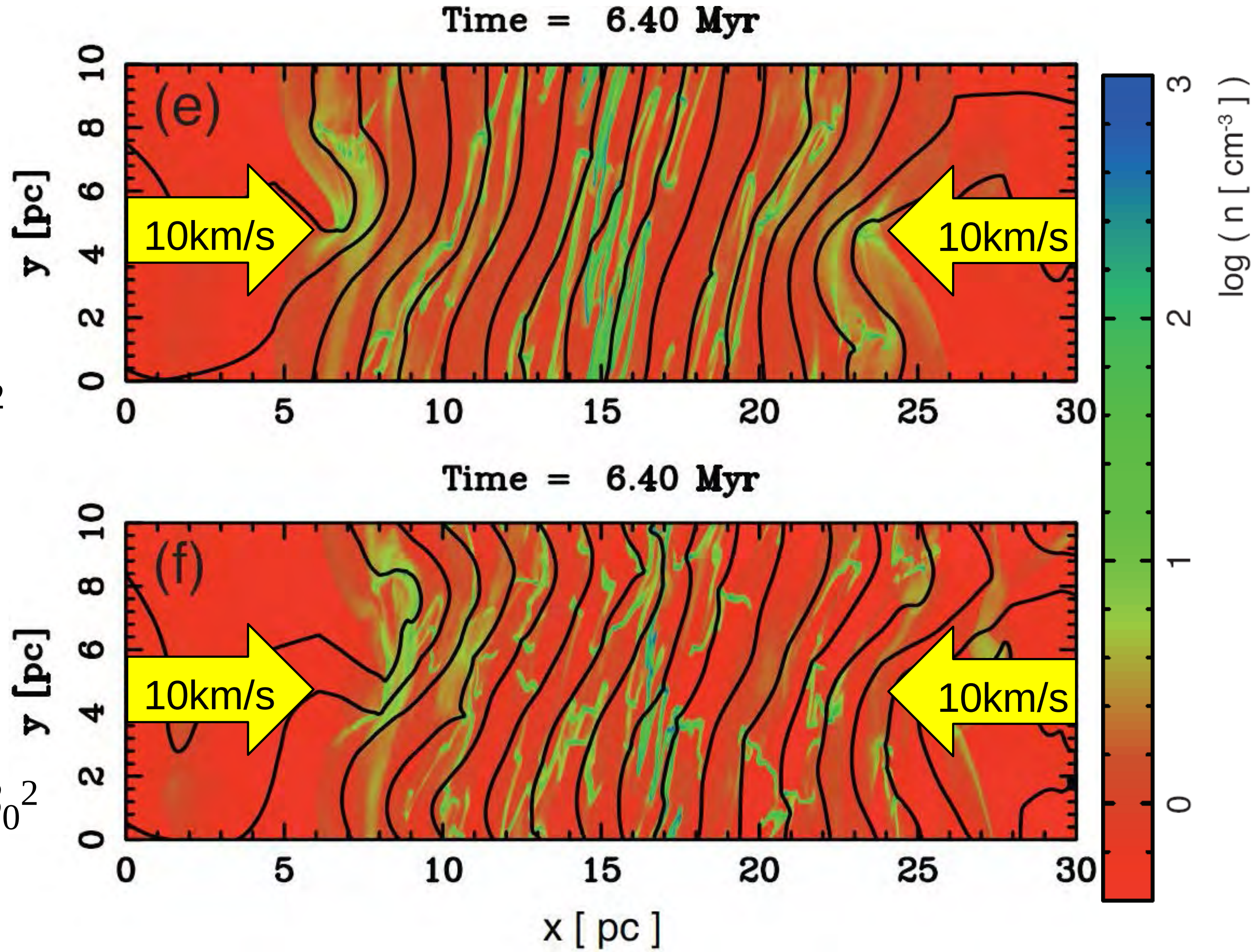
v=10km/s

(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)

Inoue & SI (2008) ApJ **687**, 303

Compression of Magnetized WNM

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

Inoue & SI (2008) ApJ **687**, 303

Inoue & SI (2009) ApJ **704**, 161

Essentially same result by

Heitsch+2009; *Körtgen & Banerjee* 2015; *Valdivia*+2016

We need multiple episodes of compression.

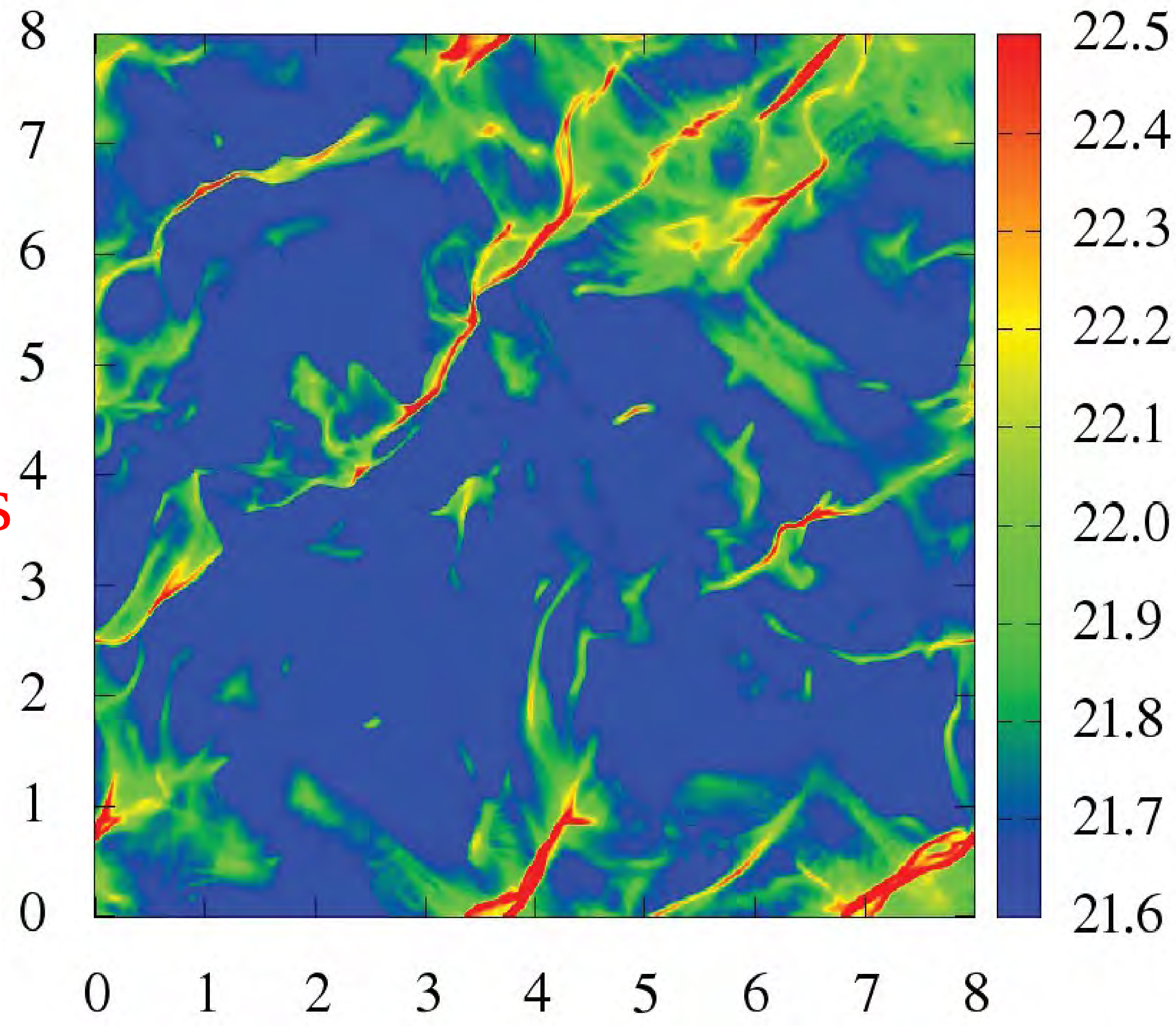
➔Timescale of Molecular Cloud Formation ~ a few 10^7yr

Next Question: What happens for further compressions?

Further Compress. of Mole. Clouds

Further Compression of Molecular Cloud

→Magnetized Massive Filaments & Striations

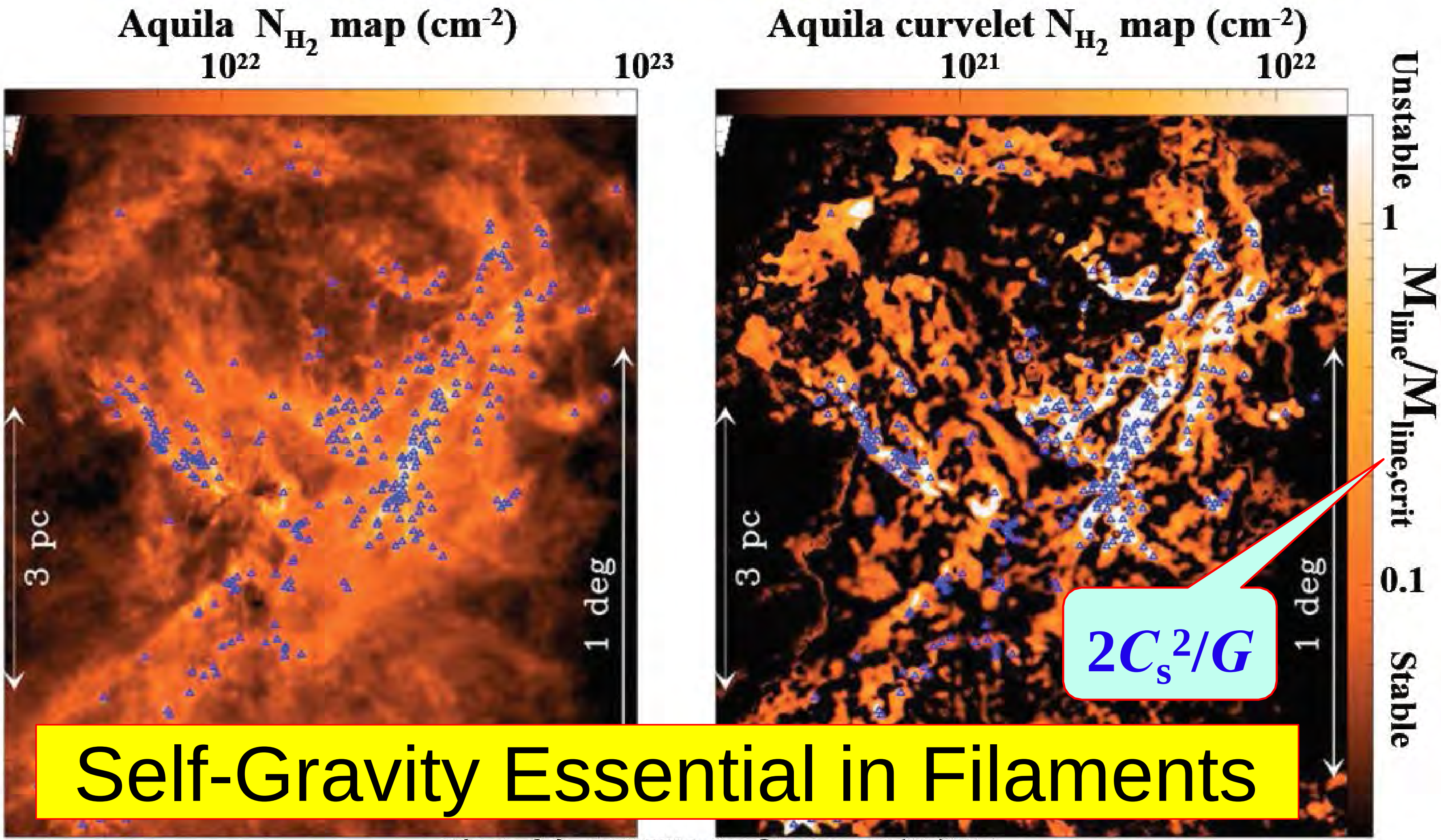


Self-Gravity Included, *SI, Inoue, Iwasaki, & Hosokawa 2015*

Highlight of Herschel Result (André+2010)

Prestellar cores are preferentially found within the densest filaments

△ : Prestellar cores - 90% found at $N_{H_2} > 7x10^{21}$ cm^{-2} <=> A_v(back) > 8



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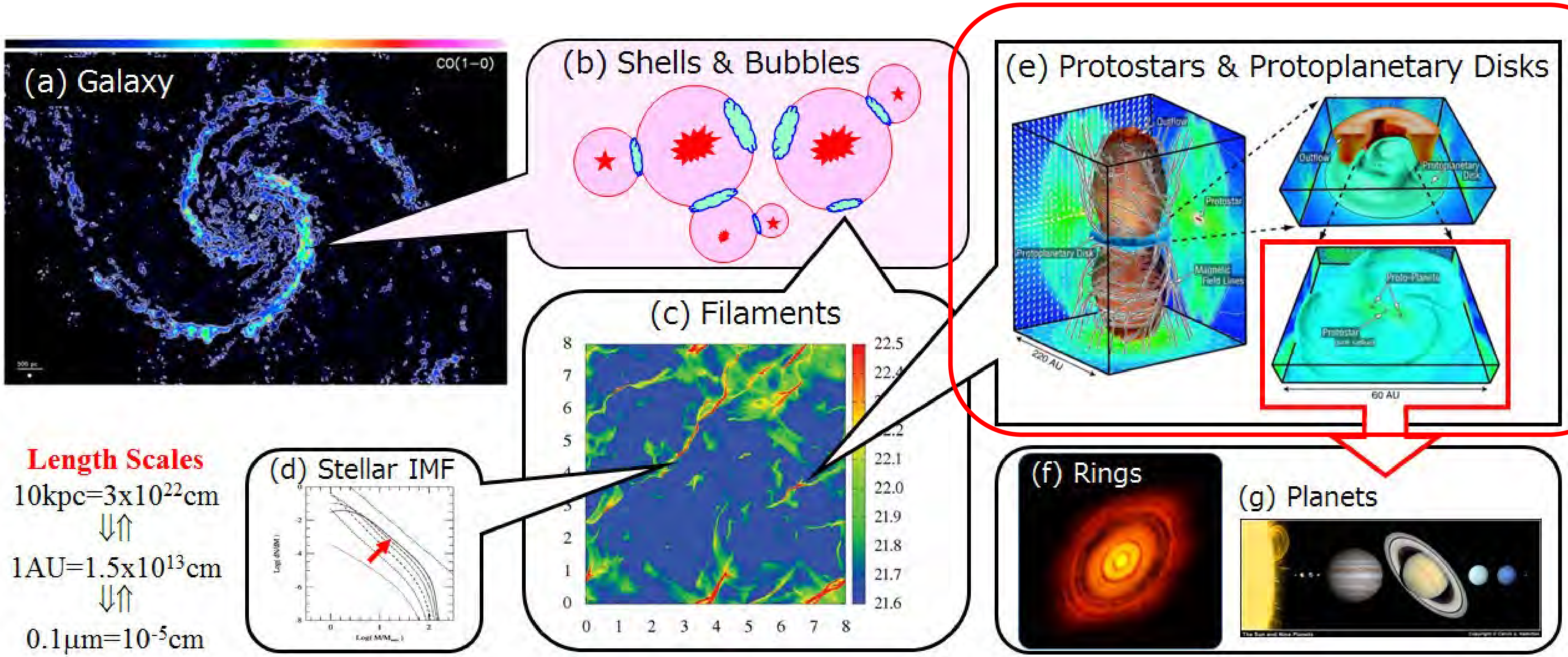
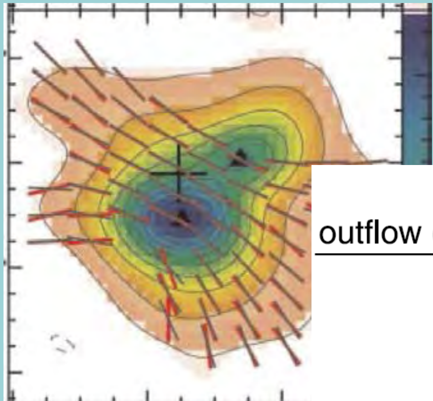
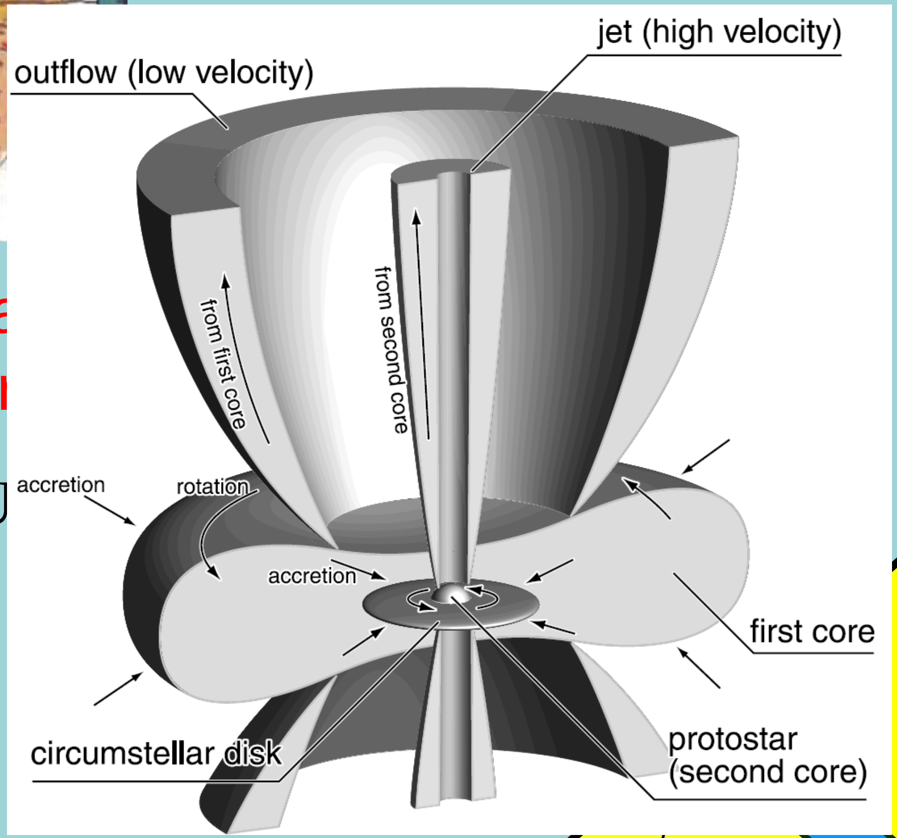


Phases of Star Formation



Molecula
Cloud Co

$\sim 10^4$AU

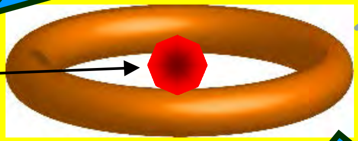


Collapse Phase

Accretion Phase

$\sim 10^{4\text{-}5}$ yr

Protoplanetary Disk



Protostar

$t = t_*$

$\sim 10^{6\text{-}7}$ yr

TTauri, MS

Planet Formation

Basic Problems in Star Formation

1. Angular Momentum Problem:

Protostar:

$$h_* = \Omega_* R_*^2 \sim (10^{11}\text{cm})^2/(10^5\text{s}) \sim 10^{17}\ \text{cm}^2/\text{s}$$

Molecular Cloud:

$$h_{core} = \delta v_{core} R_{core} \sim 0.1\text{km/s} \times 10^{17}\text{cm} \sim 10^{21}\ \text{cm}^2/\text{s}$$

$$\Rightarrow \quad h_* \sim 10^{-4}\ h_{core}$$

When?

2. Magnetic Flux Problem

Protostar: $\Phi_* \sim B_* R_*^2 \sim \text{kG}\times(10^{11}\text{cm})^2$

Molecular Cloud: $\Phi_{core} \sim B_{core} R_{core}^2 \sim 10\mu\text{G}\times(10^{17}\text{cm})^2$

$$\Rightarrow \quad \Phi_* \sim 10^{-4}\ \Phi_{core}$$

Self-Gravitational Collapse

Homologous Collapse

$P \propto \rho^{\gamma}$, $C_S^2 \propto \rho^{\gamma-1}$

$\rho \propto 1/R^3$, $M = \text{const.}$

$F_P \equiv (1/\rho)dP/dR \propto C_S^2/R$

$F_G \equiv GM/R^2 \propto 1/R^2$

$F_P / F_G \propto R^{-(3\gamma-4)}$

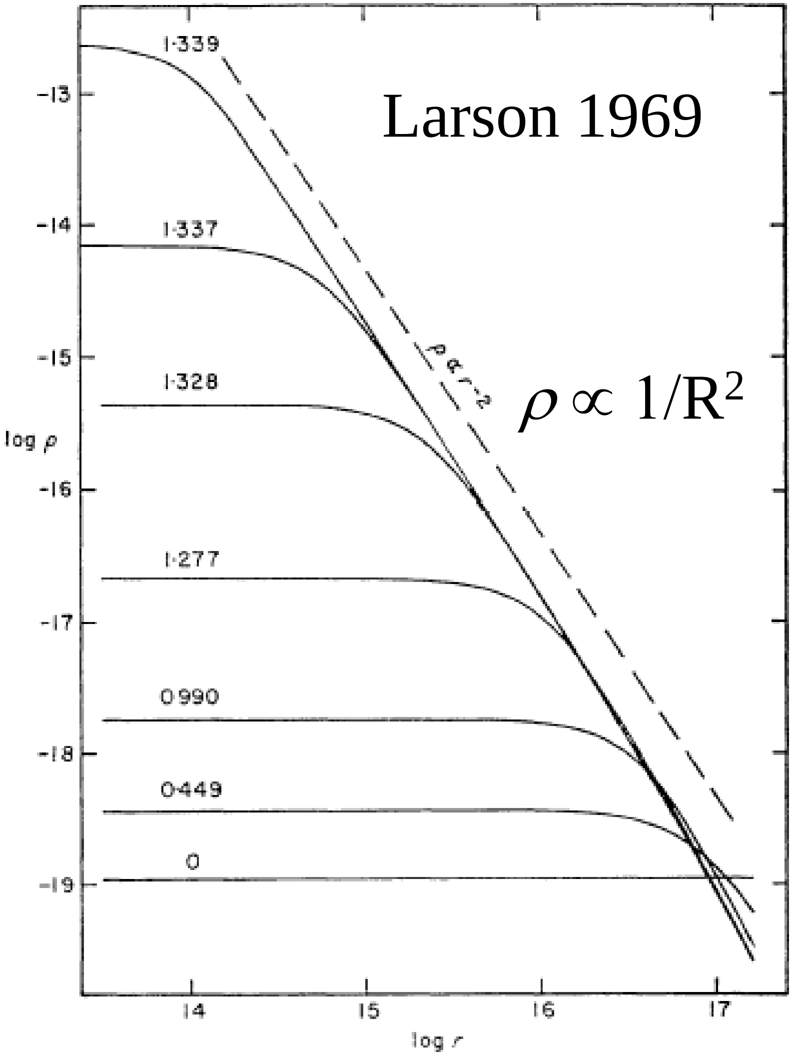
$$\gamma_{crit} = 4/3$$

if $\gamma < 4/3$ ➔ unstable

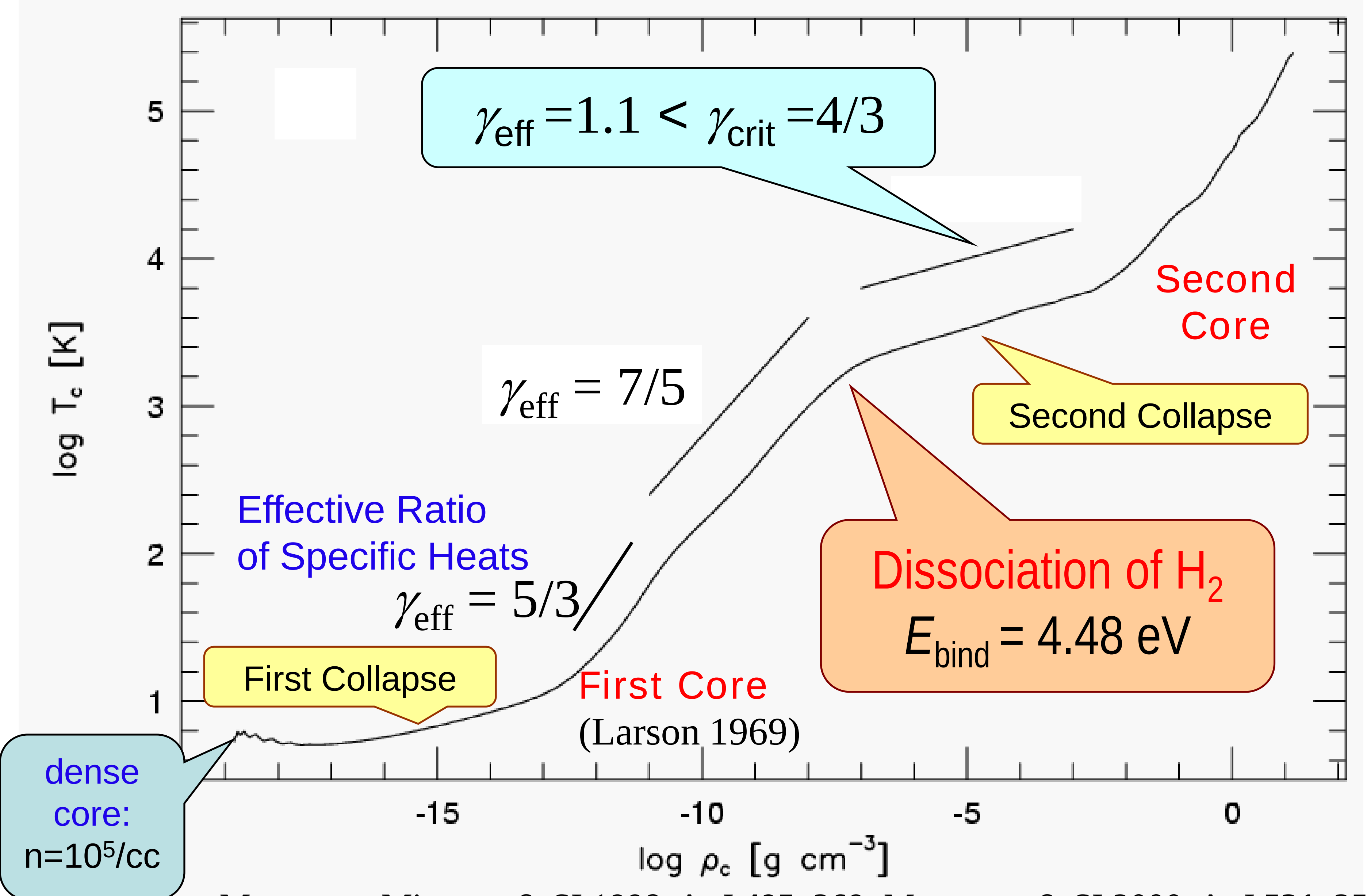
($\gamma \approx 1$ in Molecular Clouds)

$t_{ff} \sim (G\rho)^{-0.5}$ ➔ Run-Away

Run-Away Collapse

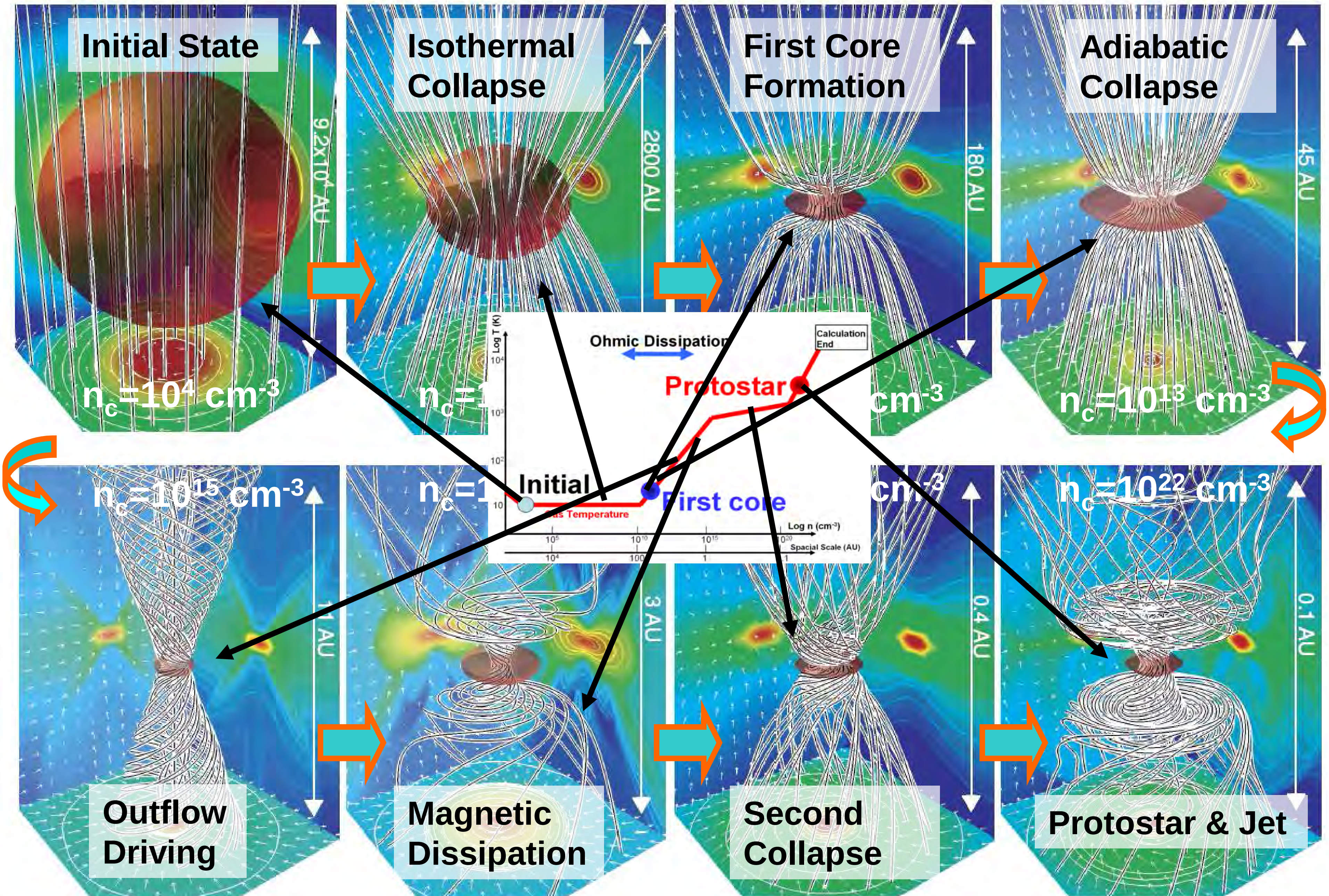


Temperature Evolution at Center

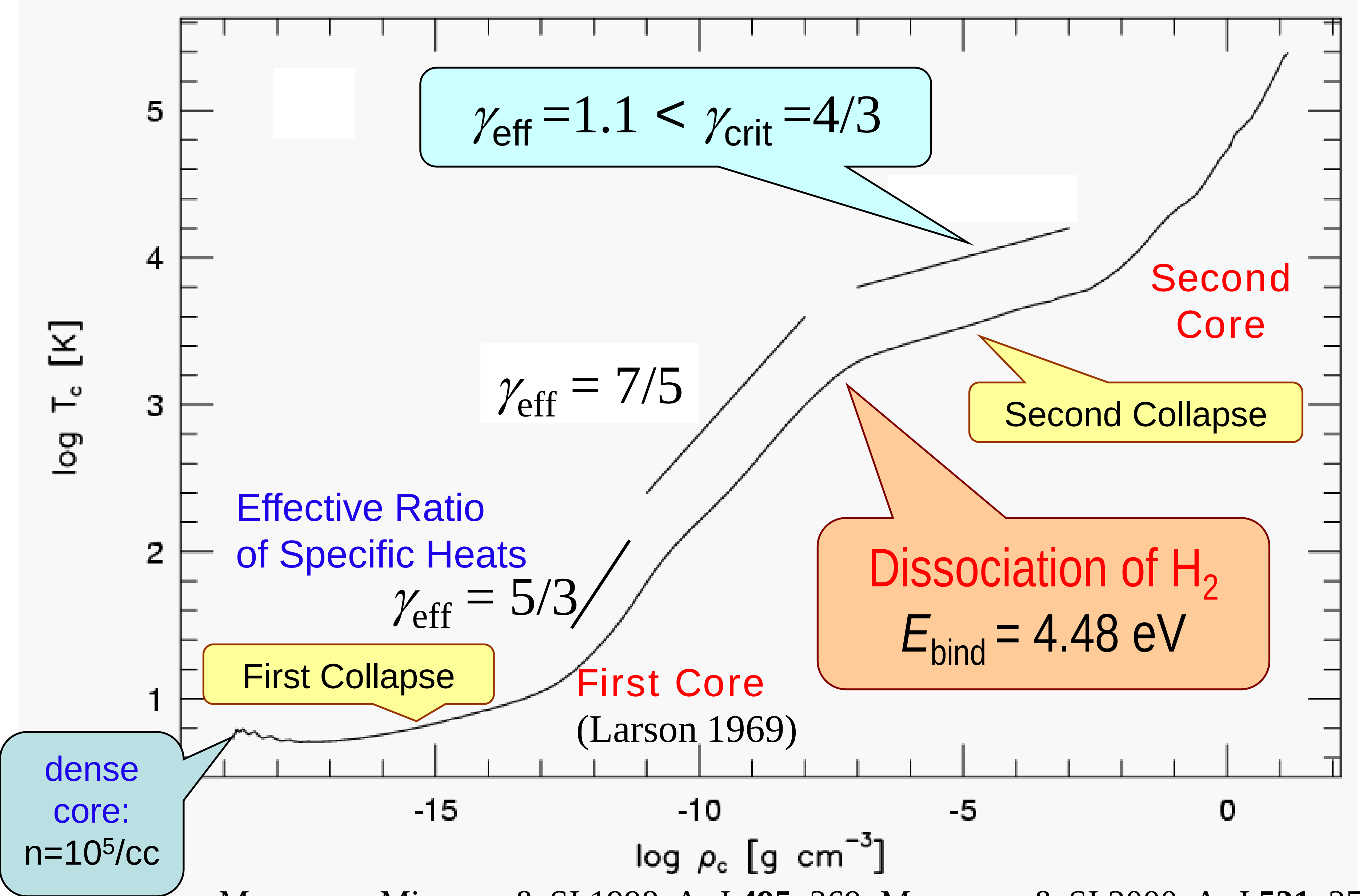


Masunaga, Miyama, & SI 1998, ApJ **495**, 369; Masunaga & SI 2000, ApJ **531**, 350

Evolution from Molecular Cloud Core to Protostar



Temperature Evolution at Center



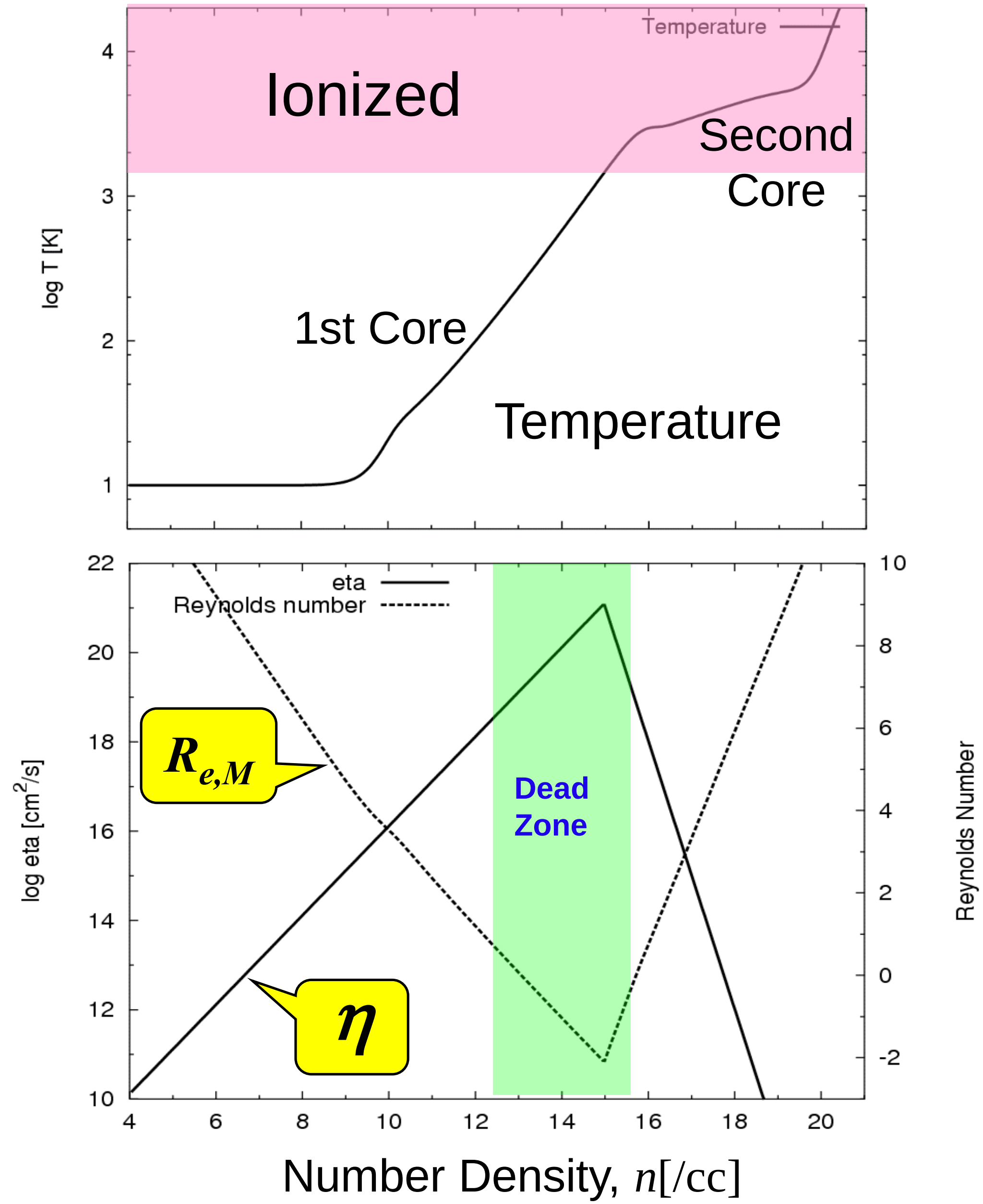
Masunaga, Miyama, & SI 1998, ApJ **495**, 369; Masunaga & SI 2000, ApJ **531**, 350

Effect of ***Non-Ideal*** **MHD**

Weakly Ionized Gas

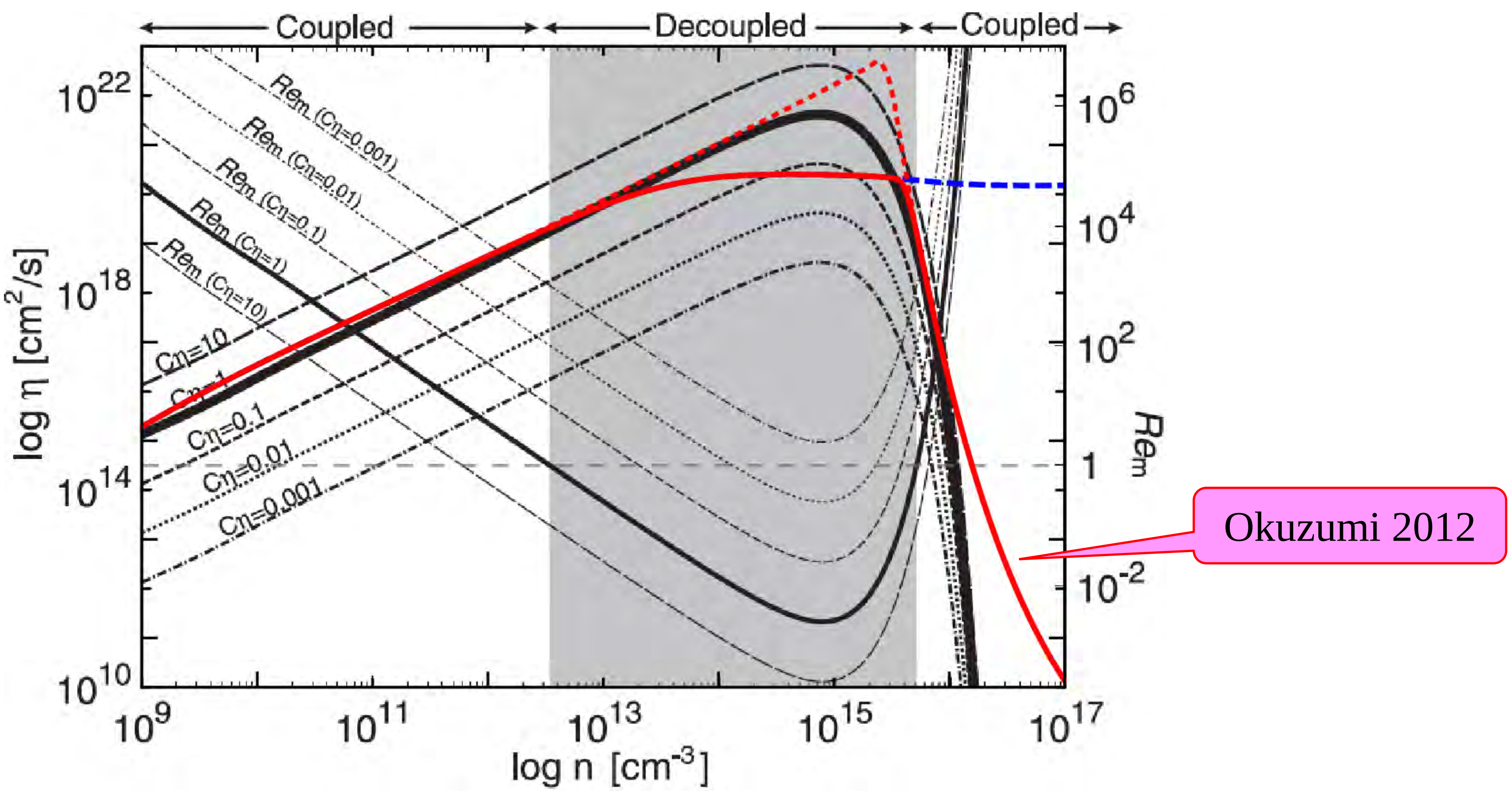
- Low density…
  <u>Ambipolar Diffusion</u>
- Intermediate…
  <u>Hall Current Effect</u>
- High density…
  <u>Ohmic Dissipation</u>

e.g., *Nakano, Mouchouvias, Wardle, Tassis, Galli,…*



Evolution of Ionization Degree

Because of uncertainty of dust grain properties, we have parameterized resistivity.



Machida, SI, & Matsumoto (2007) ApJ **670**, 1198

Stage 1: **Outflow** driven from the **first core**

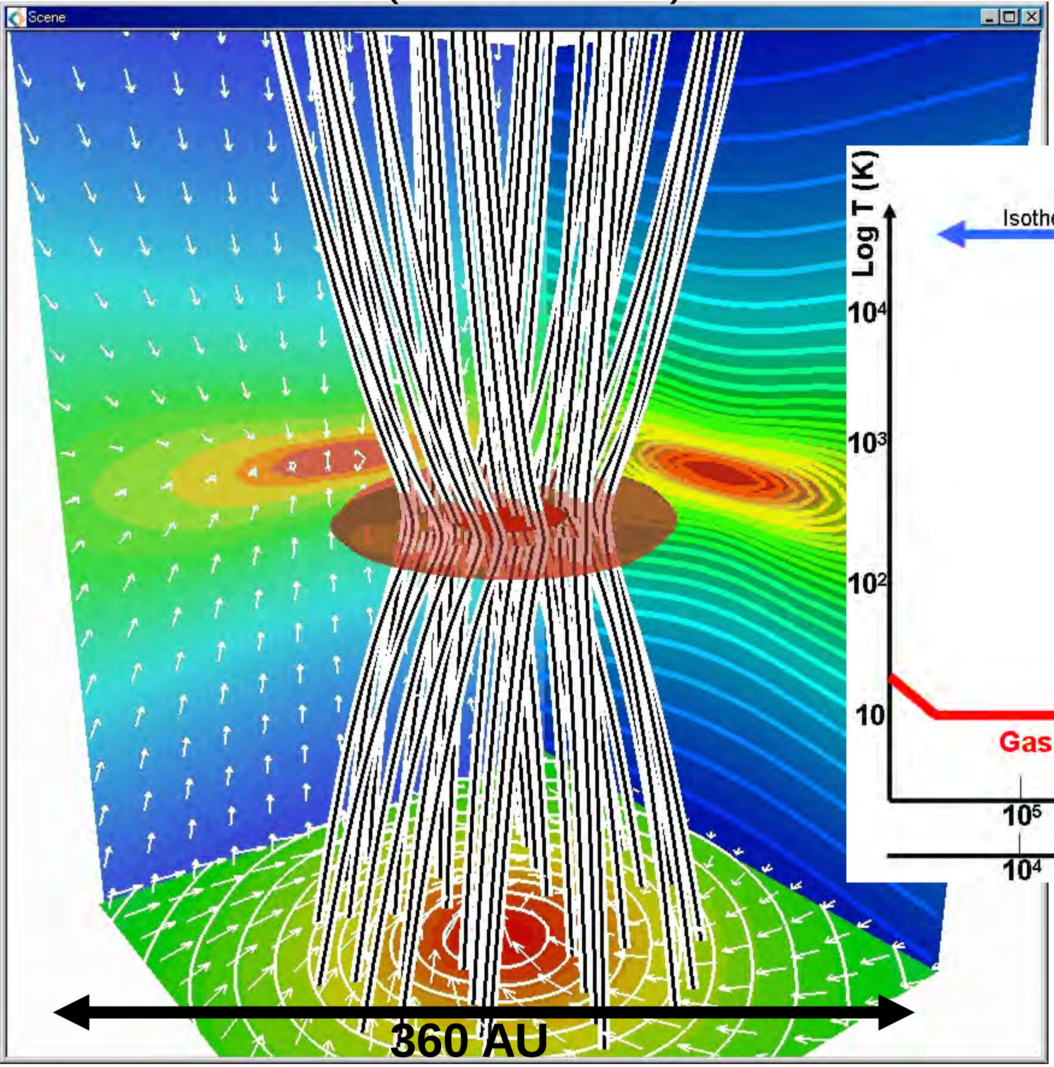
The evolution of the Outflow around the first core

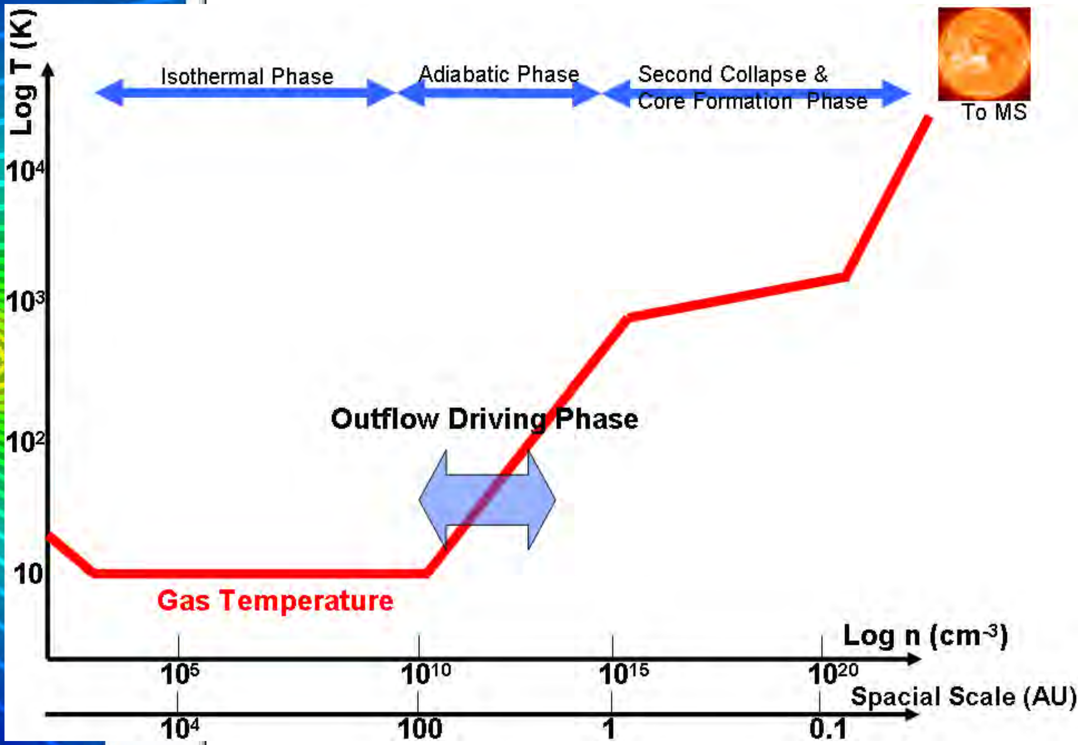
- This animation start after the first core is formed at n~10^{10} cm^{-3}

Model for
(α, ω)=1, 0.3

Grid level L=12 (Side on view)

Grid level L=12 (Top on view)





Same as in Tomisaka 2002

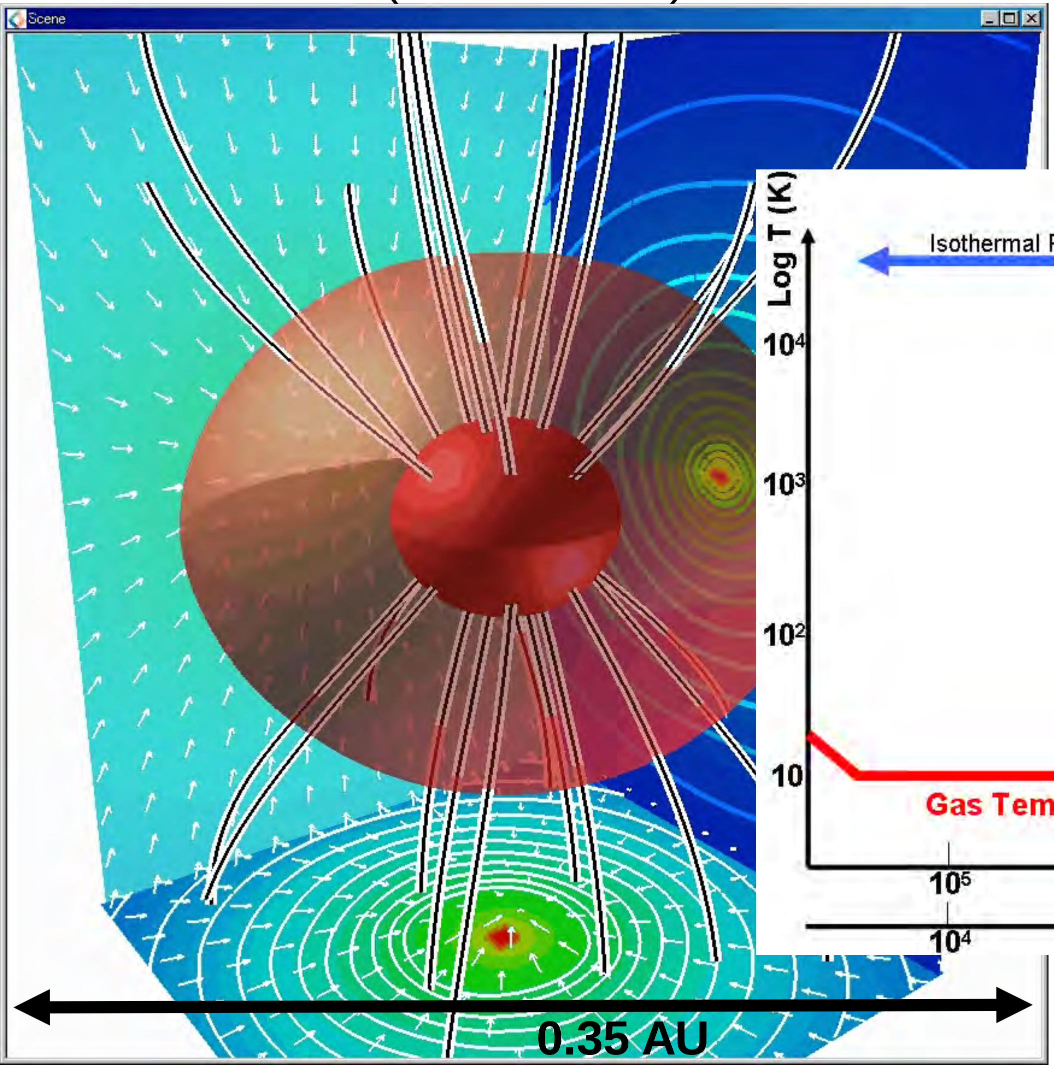
Stage 3: Jet driven from the protostar

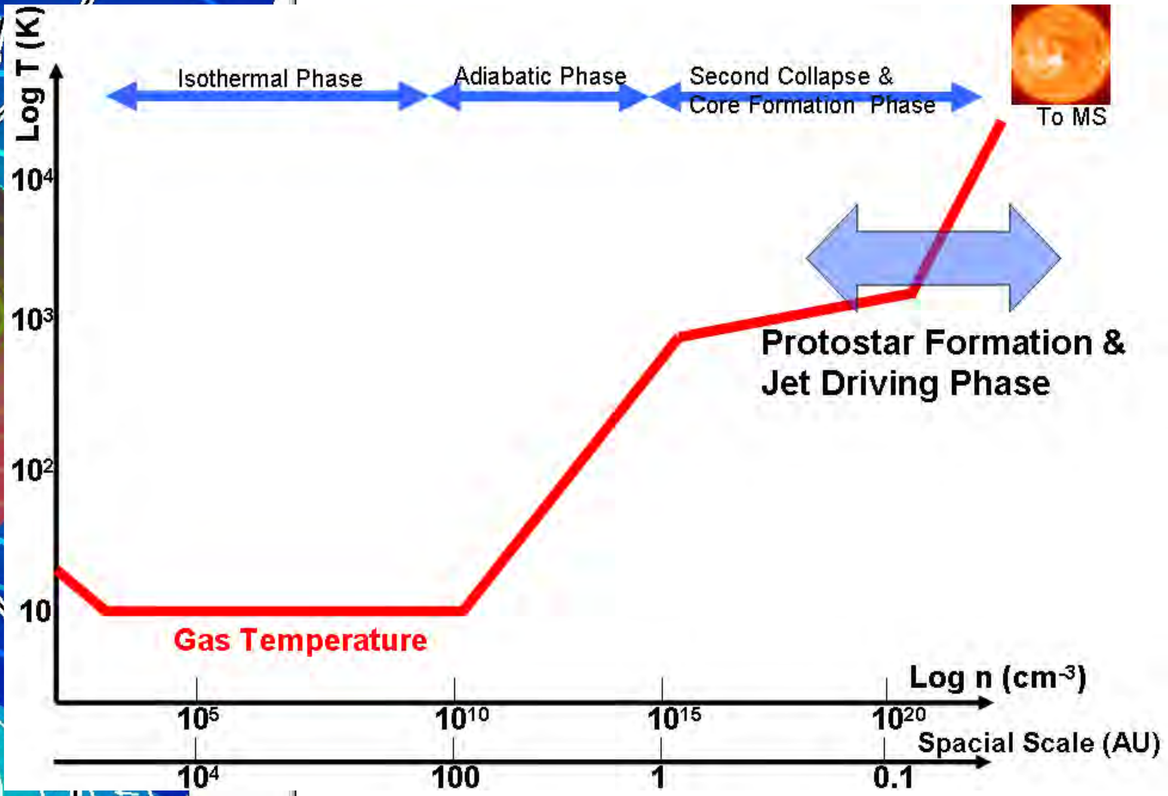
The evolution of the Jet around the protostar

- This animation start before the protostar is formed at $n \sim 10^{19}$ cm^{-3}

Model for
(α, ω)=1, 0.003

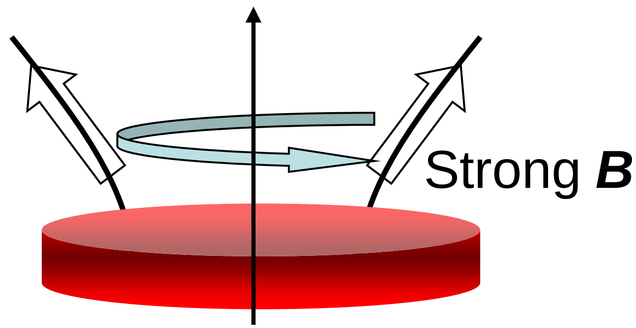
Grid level L=21 (Side on view)





Difference in Driving Mechanism

Magnetocentrifugally driven Wind



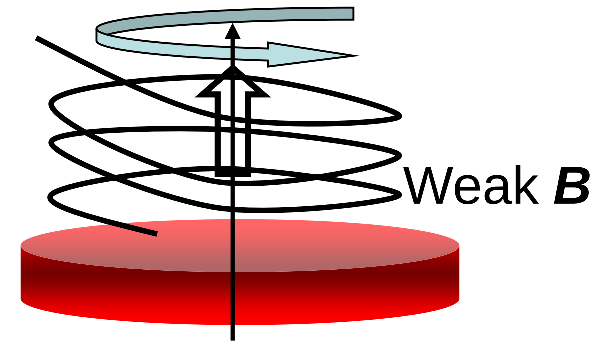
Wide Opening Angle

outflow around first core

$B_r \approx B_z \approx B_\phi$

only at launching region,
not in distant region

Magnetic Pressure driven Wind



Narrow Opening Angle

jet around protostar

$B_z << B_\phi$

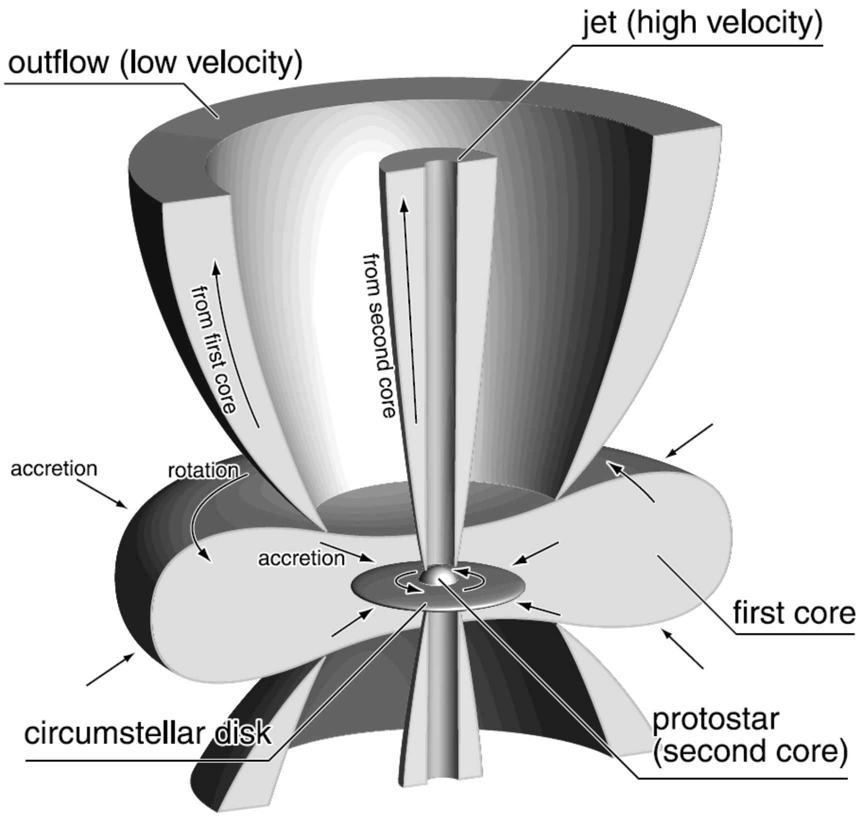
Machida, SI, & Matsumoto (2008) ApJ **676**, 1088

Summary of Machida et al.

Stiffening of EoS ➔ 2 different flows (outflow/jet)

- Outflow driven by the first core has wide opening angle and slow speed.
- Jet driven by the protostar has well-collimated structure and high speed.

Velocities = Escape speeds from the first core & protostar.



Machida, SI, Matsumoto (2008) ApJ **676**, 1088

Observational Proof ➔ Velusamy, T., et al. 2007 ApJ 668, L159,

Velusamy, T. et al. 2011 ApJ 741, 60

Sufficient Flux Loss?

Machida, SI, & Matsumoto (2008)

$\boldsymbol{B}_{\mathrm{protostar}}$ ~ kGauss in standard model of $\boldsymbol{\eta}$

resistivity

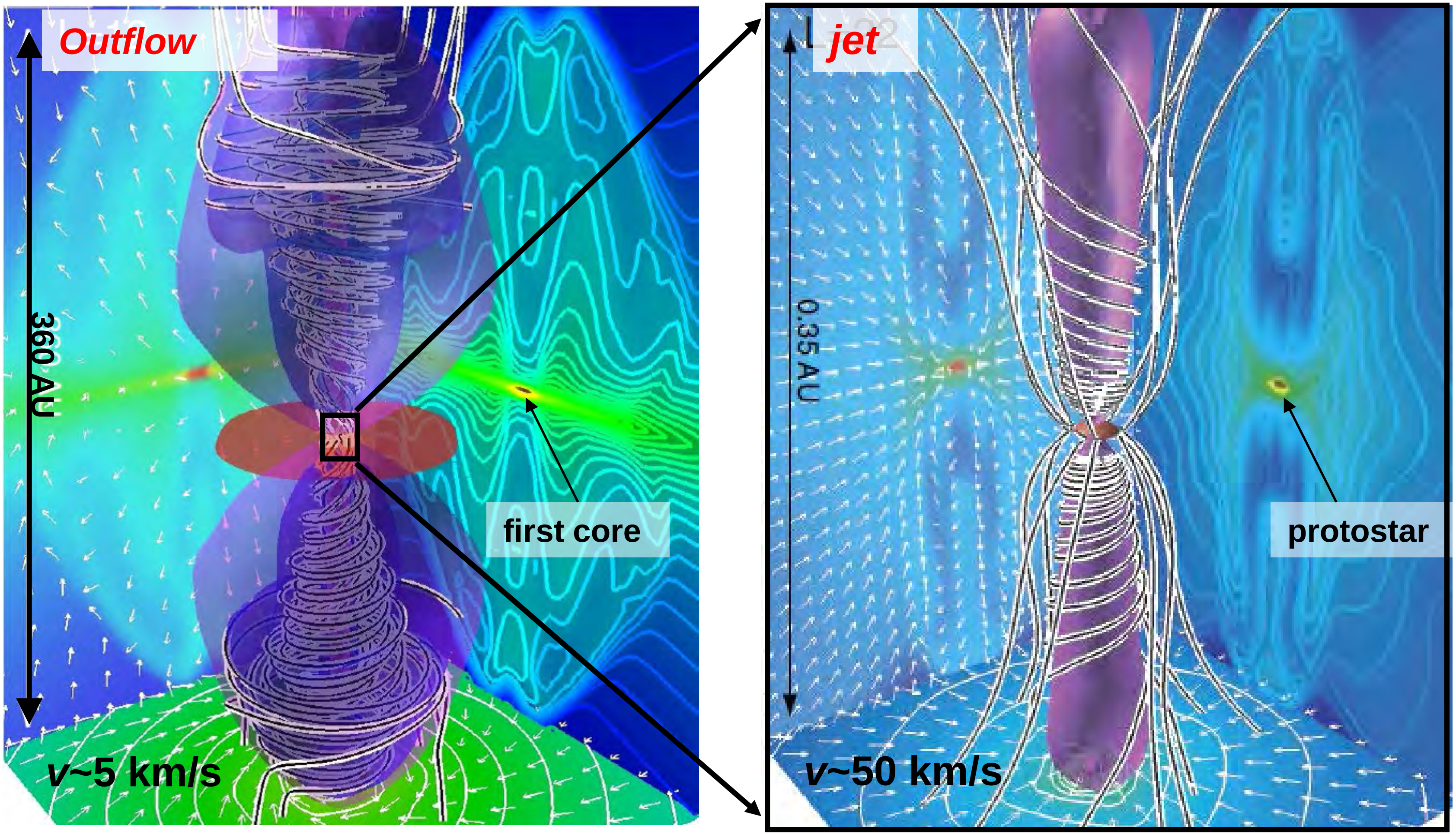
my guess:

Turbulent Diffusion in Convection on Hayashi-Track

➔ Decrease of $\boldsymbol{B}$ in T-Tauri Phase (kG➔G?)

For Turbulent Diffusion, see Lazarian & Vishniac (1999)

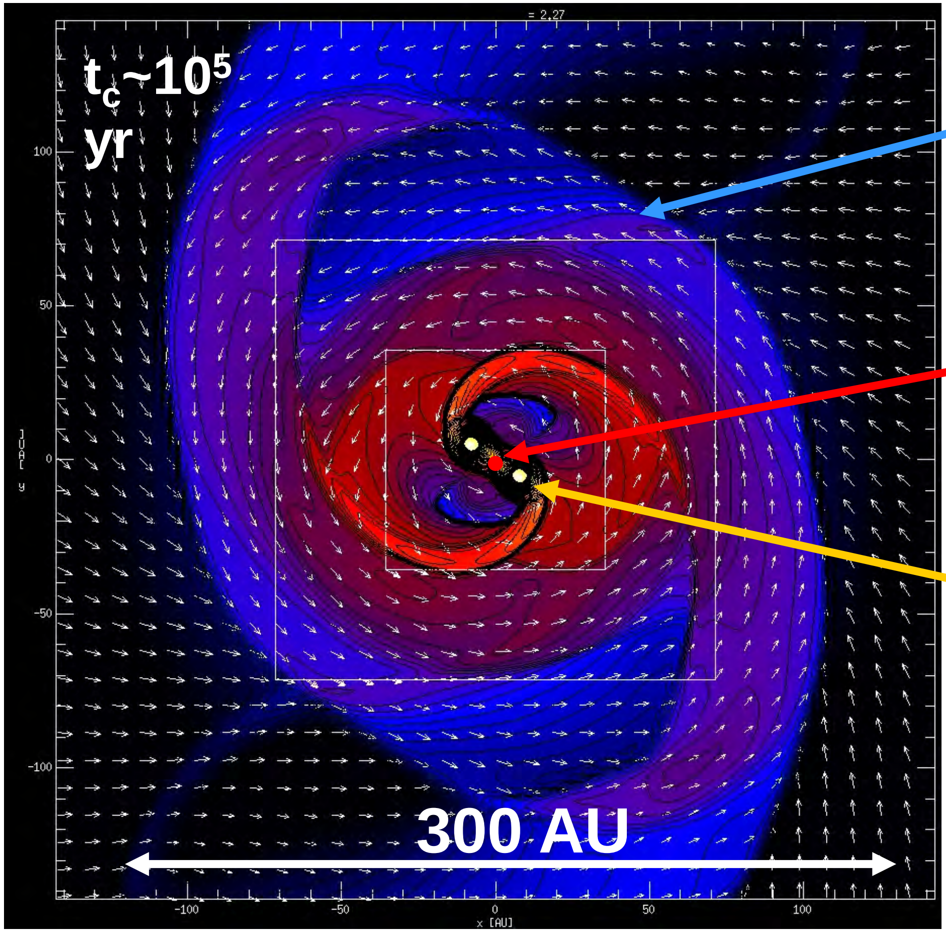
Formation of a Protostar



Machida et al. (2006-2012), Banerjee & Pudritz (2006), Hennebelle et al. (2008), Duffin & Pudritz (2011), Commerçon et al. (2011), Tomida et al. (2011)

Outflows & Jets are Natural By-Products!

Formation of Planetary Mass Companions in Protoplanetary Disk



Protoplanetary Disk

Protostar

- $\sim 0.1\ M_{sun}$

Protoplanet

- $M \sim 8\ M_{Jup}$
- $R_{sep} \sim 10\text{-}20$ AU

Machida, SI, Matsumoto (2009)