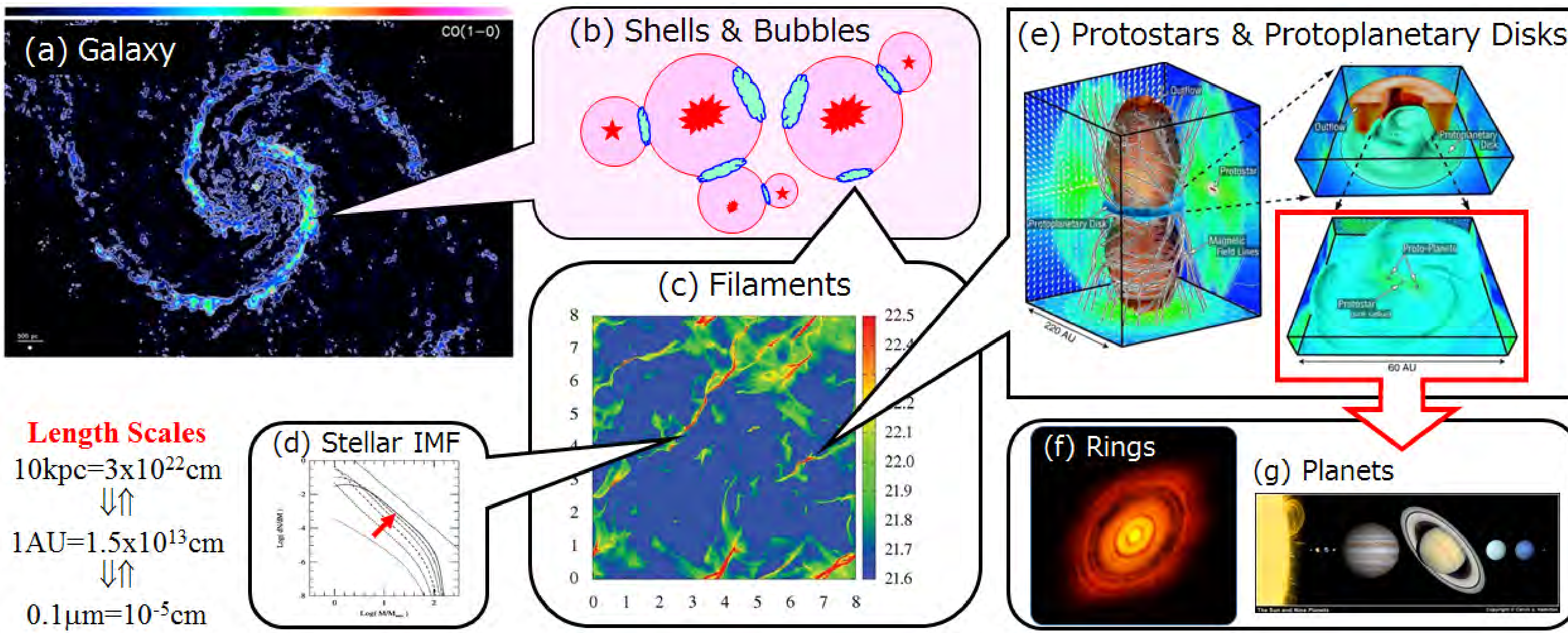
Phase Transition Dynamics of ISM: The Formation of Molecular Clouds and Galactic Star Formation

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

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

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

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
- EoM
- 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

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

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

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

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

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

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

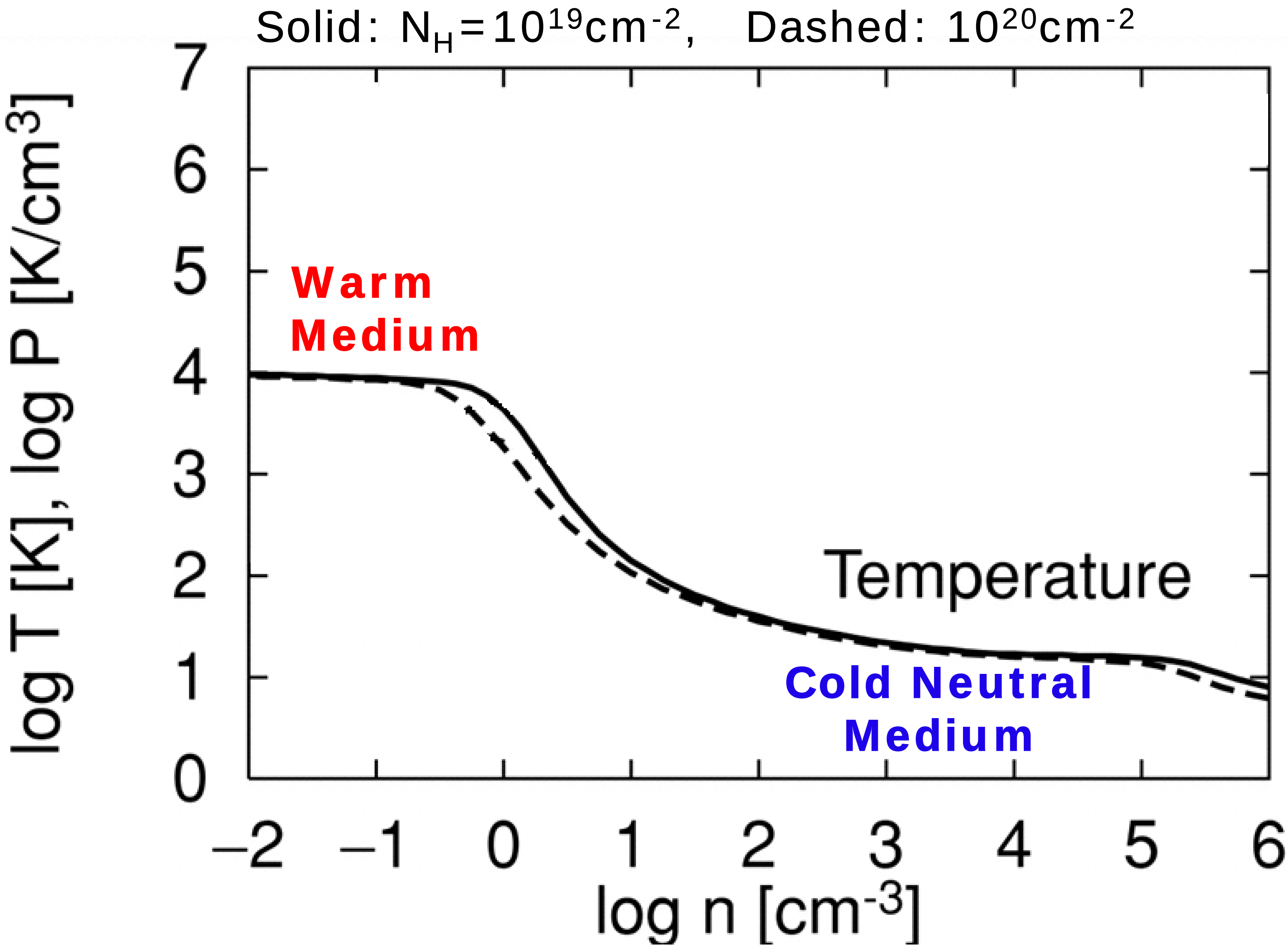
Numerical Simulation of (Isothermal) MHD Turbulence ⇒ Rapid Shock Dissipation or Cascade

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

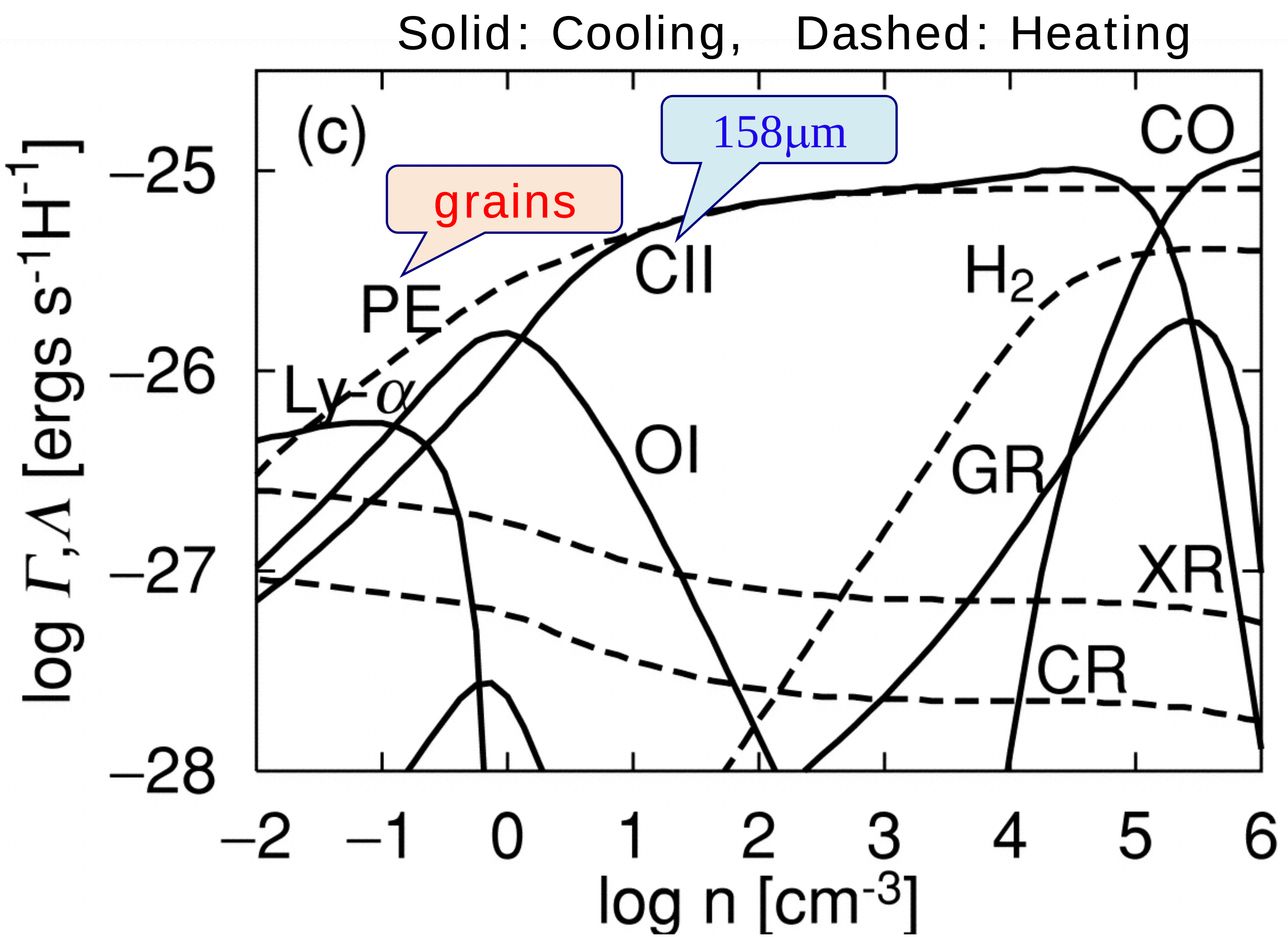
Studies on Origin of Supersonic Motions

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

Radiative Equilibrium for a given density

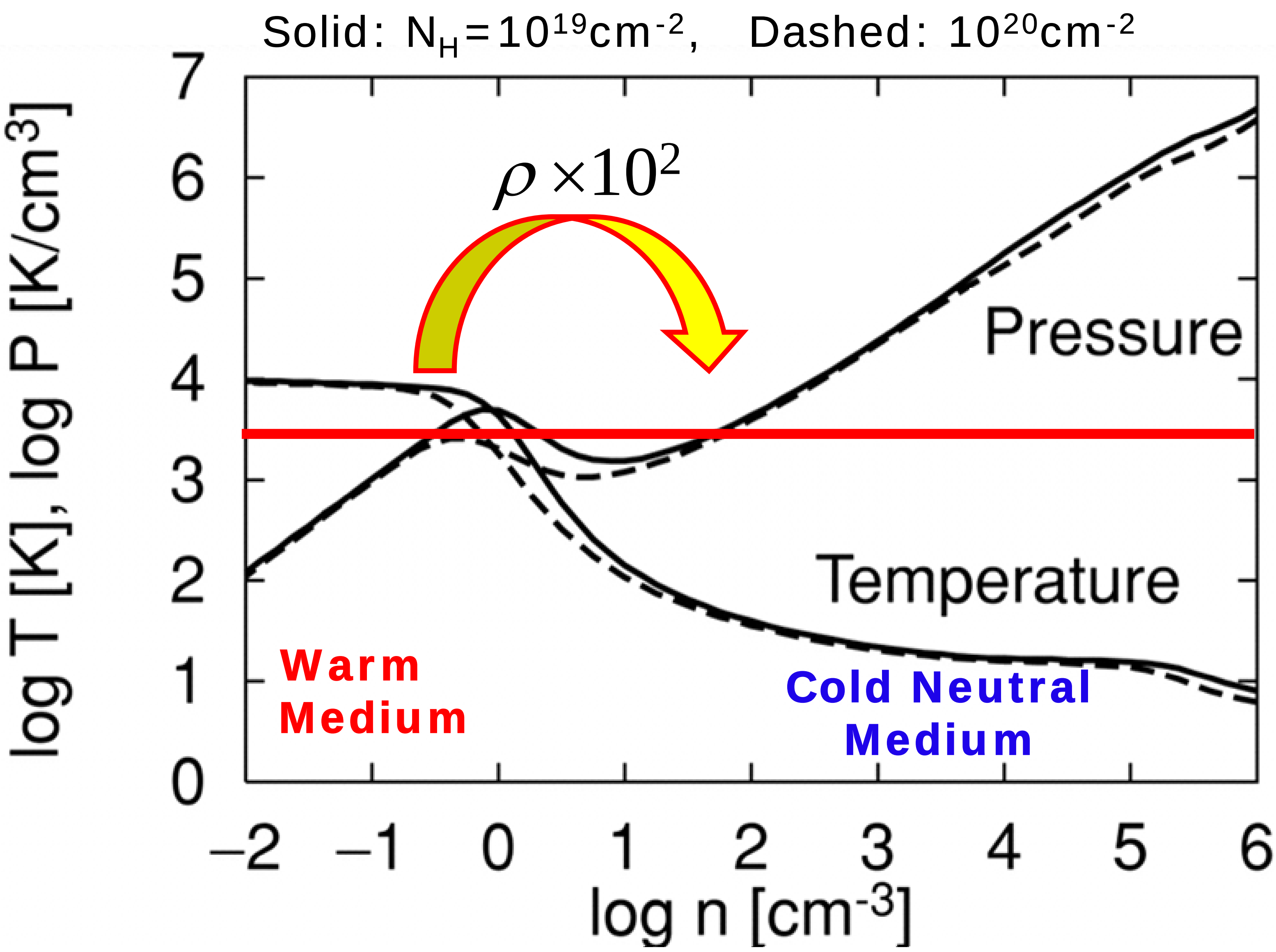


Radiative Cooling & Heating



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

Dispersion Relation of Thermal Instability

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

Thermal Instability

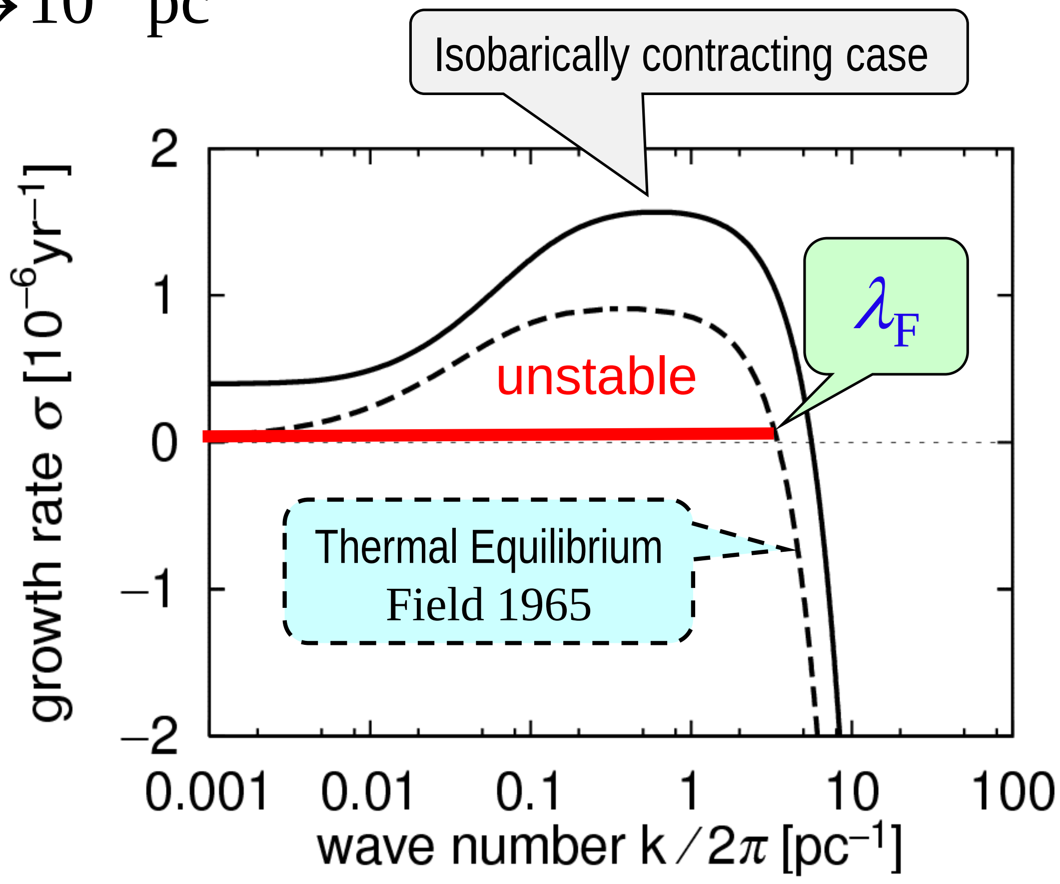
for $\lambda > \lambda_F$

If $\kappa = 0$, then $\lambda_{crit} = 0$

In two-phase medium,

the width of transition layer

$= \lambda_F$.



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

Warning to Numerical Simulation

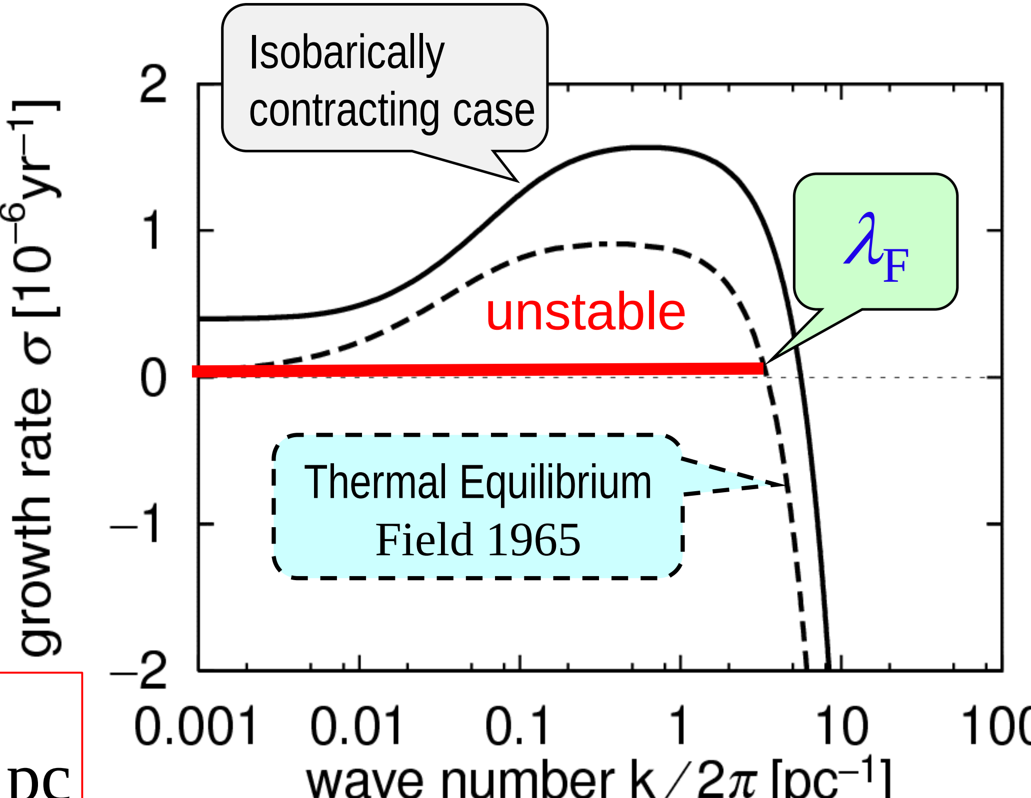
The Astrophysical Journal, 602:L25–L28, 2004 February 10

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

Hiroshi Koyama[1,2] and Shu-ichiro Inutsuka[3]
Received 2003 February 6; accepted 2004 January 2; published 2004 January 30

Requirement for Spatial Resolution "Field Condition"

We should resolve the structure of transition layer: λ_F



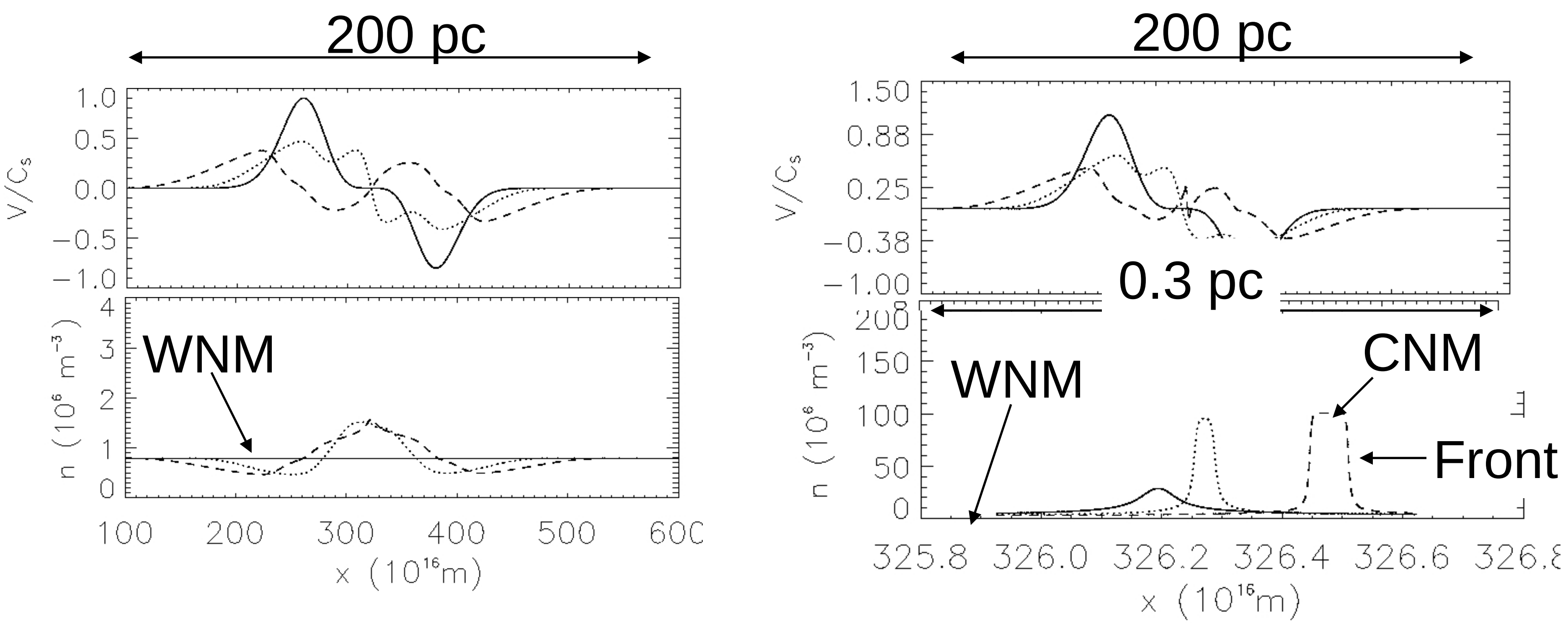
$$\text{Field length}: \lambda_F \equiv \sqrt{\frac{KT}{\rho^2 \Lambda}} \approx 10^{-2}\,\text{pc}$$

Dynamical Triggering of Thermal Instability

Hennebelle & Pérault 1999; Koyama & Inutsuka 2000

A converging flow which does not trigger thermal transition:

A **slightly** stronger converging flow does trigger thermal transition:



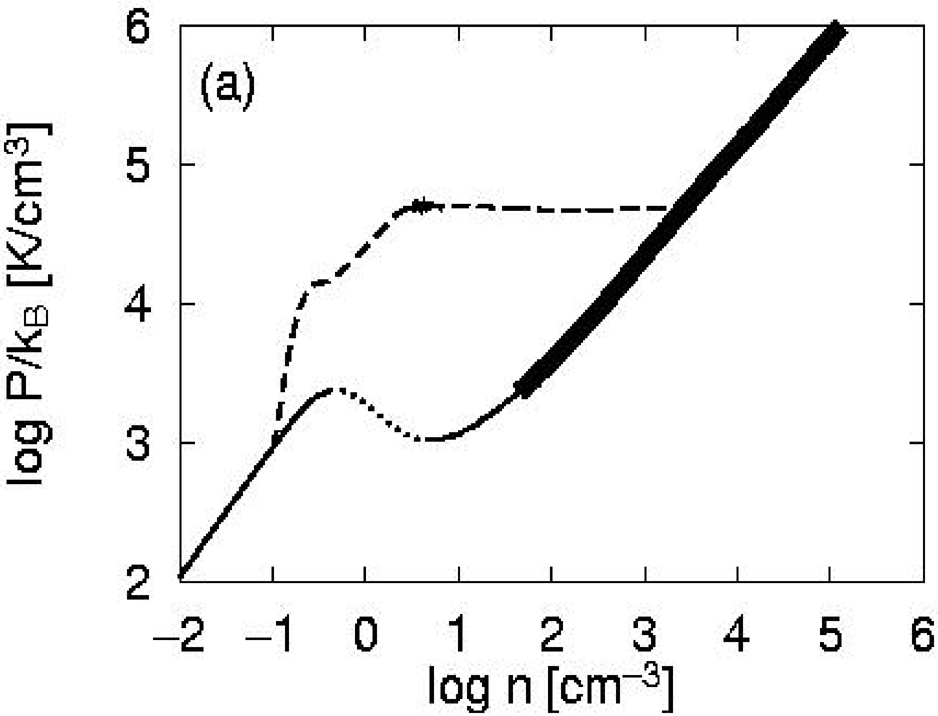
Hennebelle & Pérault 1999

➔ WNM is linearly stable but non-linearly unstable.

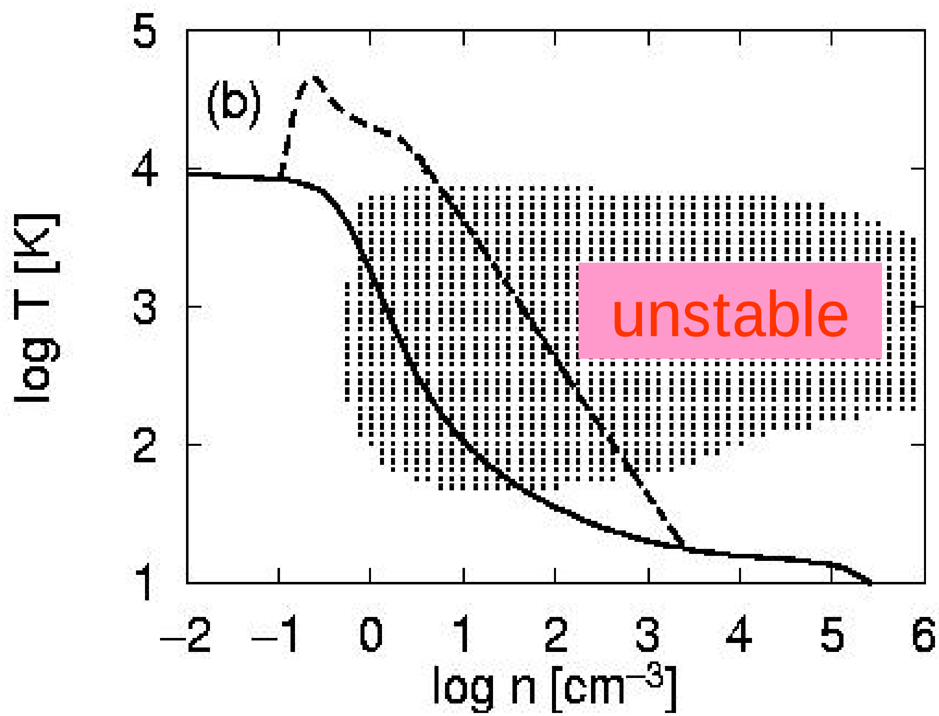
1D Shock Propagation into WNM

Realistic Cooling/Heating + Chemistry (H_2, CO)

Density-Pressure Diagram



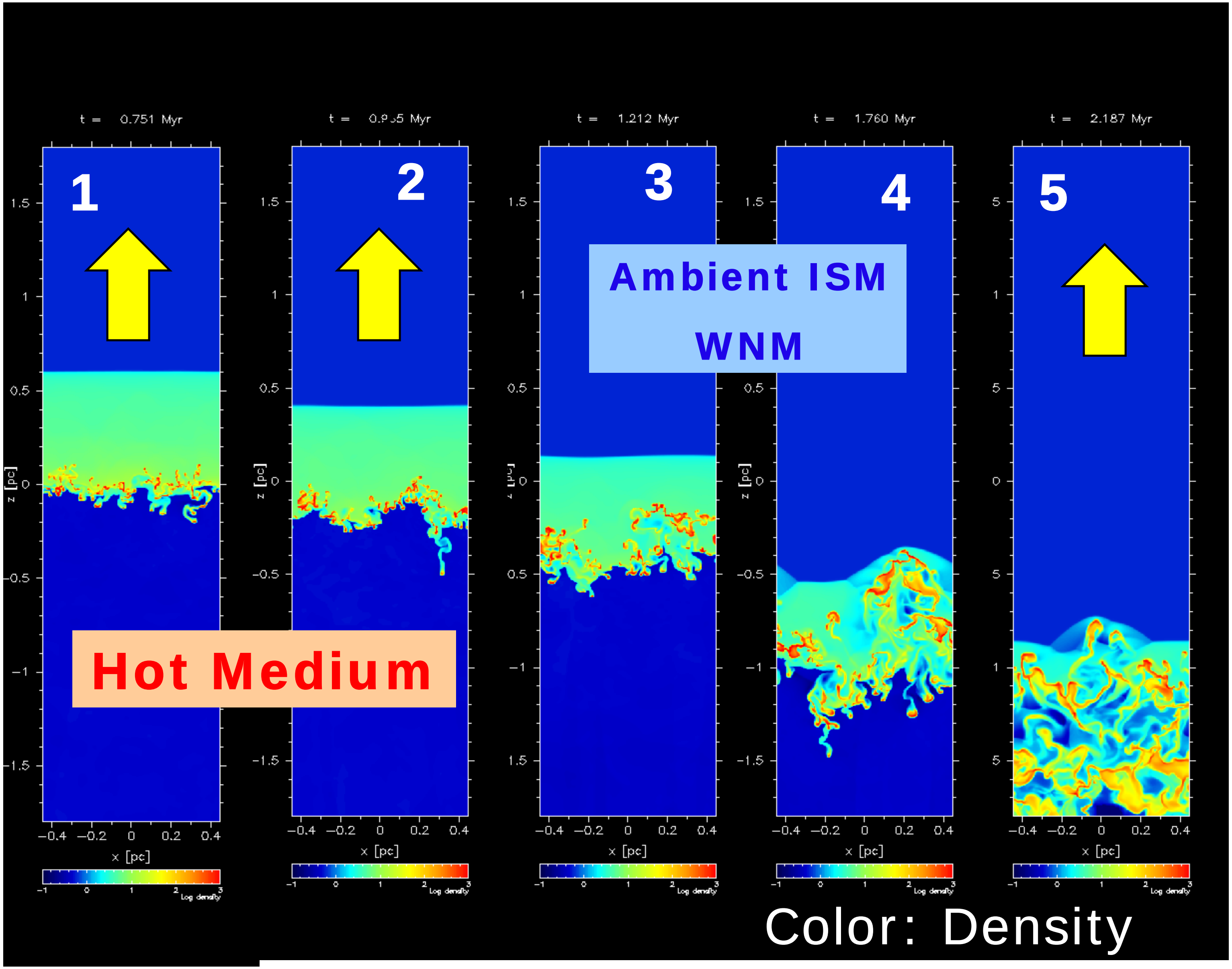
Density-Temperature Diagram



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

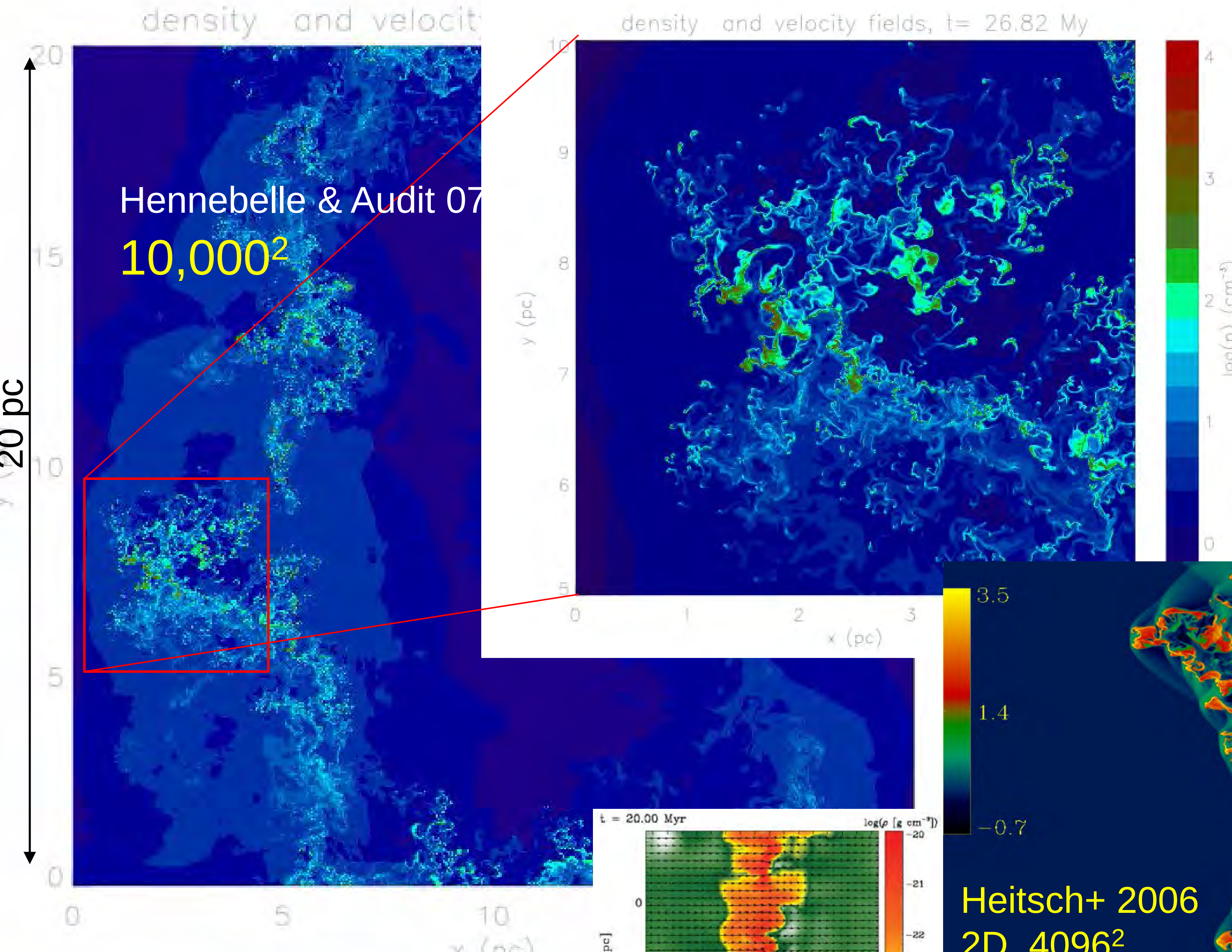
2D&3D: Shock $\Rightarrow E_{th} \Rightarrow E_{rad} + E_{kin}$

δv ~ a few km/s < $C_{S,WNM}$ =10km/s

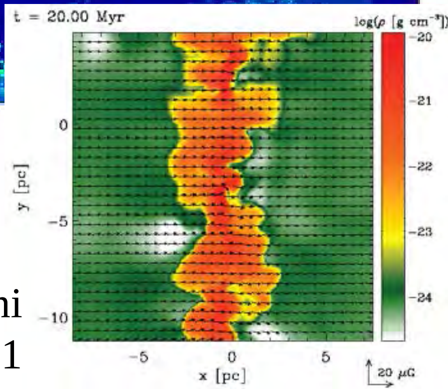
← 10^4K due to Lyα line: Universality!

T_{CNM} ~10^2K ← C^+158μm (~10^2K)

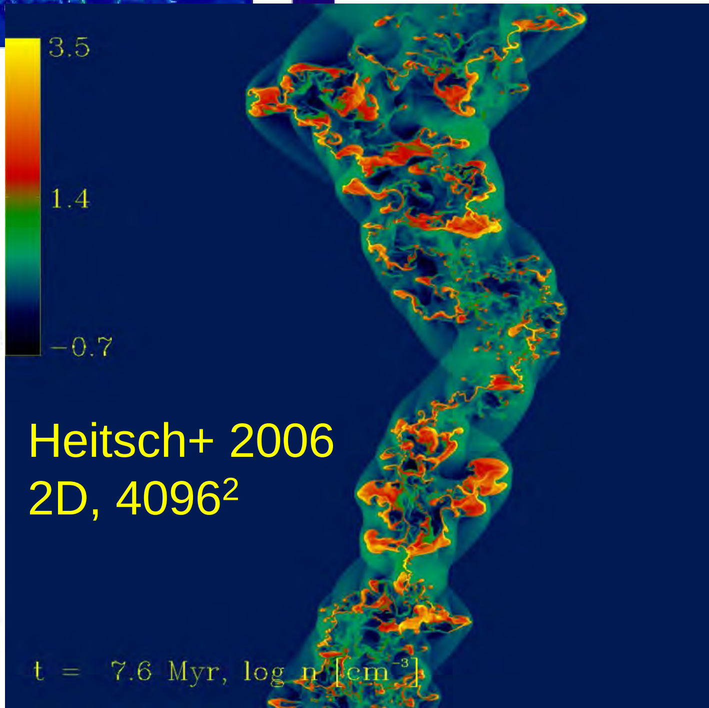
Koyama & SI (2002) ApJ 564, L97



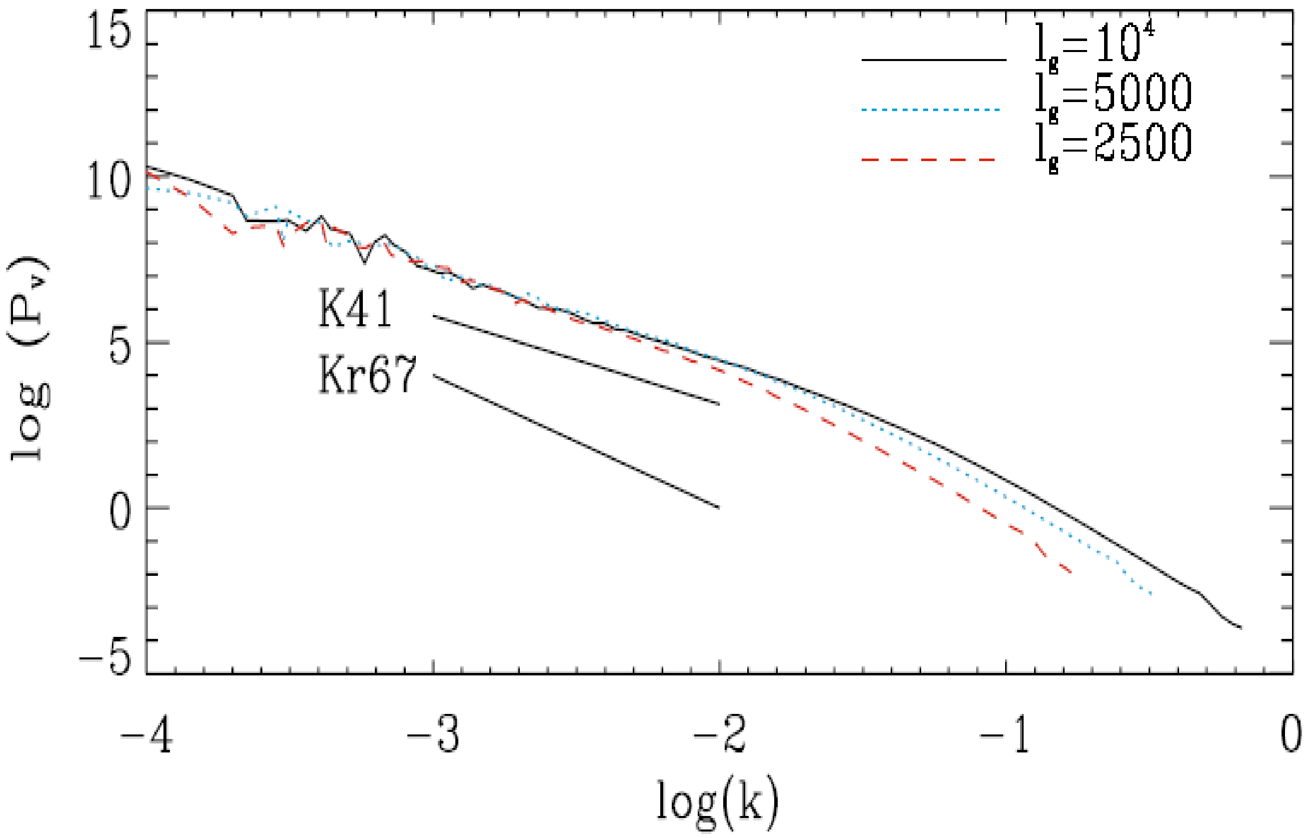
c.f.
Kritsuk &
Norman 1999



Vazquez-Semadeni
et al. 2011



Property of "Turbulence"…Subsonic

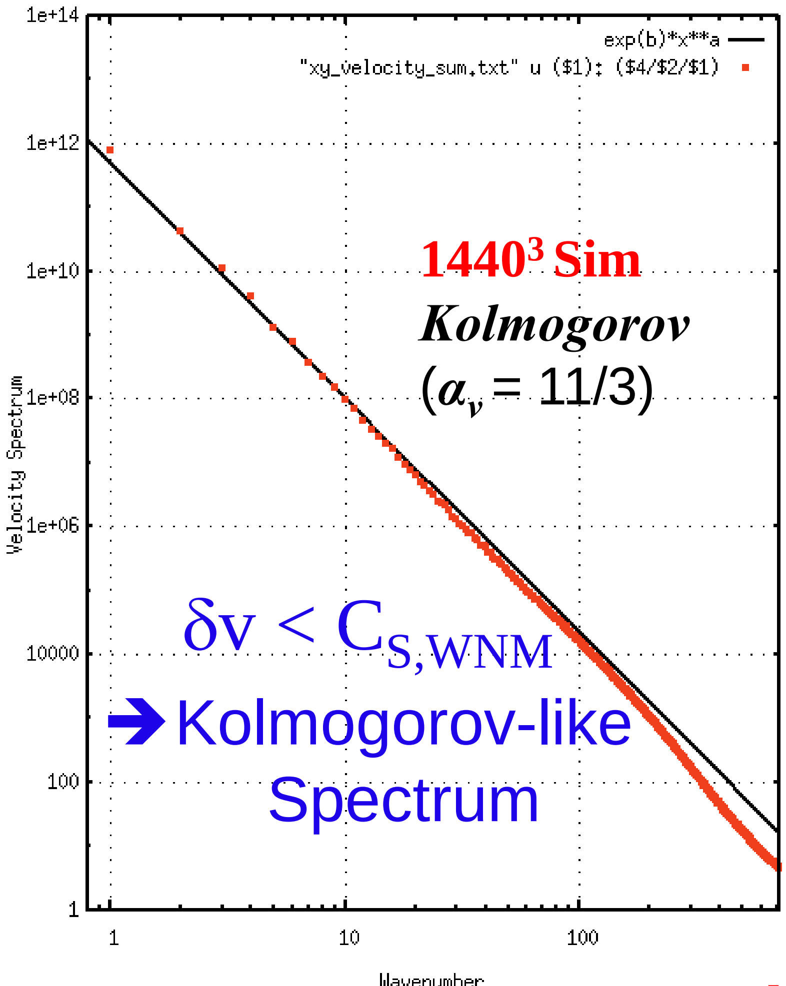


$\delta v < C_{S,WNM}$ ➔ Kolmogorov Spectrum

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

Property of 3D "Turbulence"

Muranushi, Inoue & SI (unpublished)



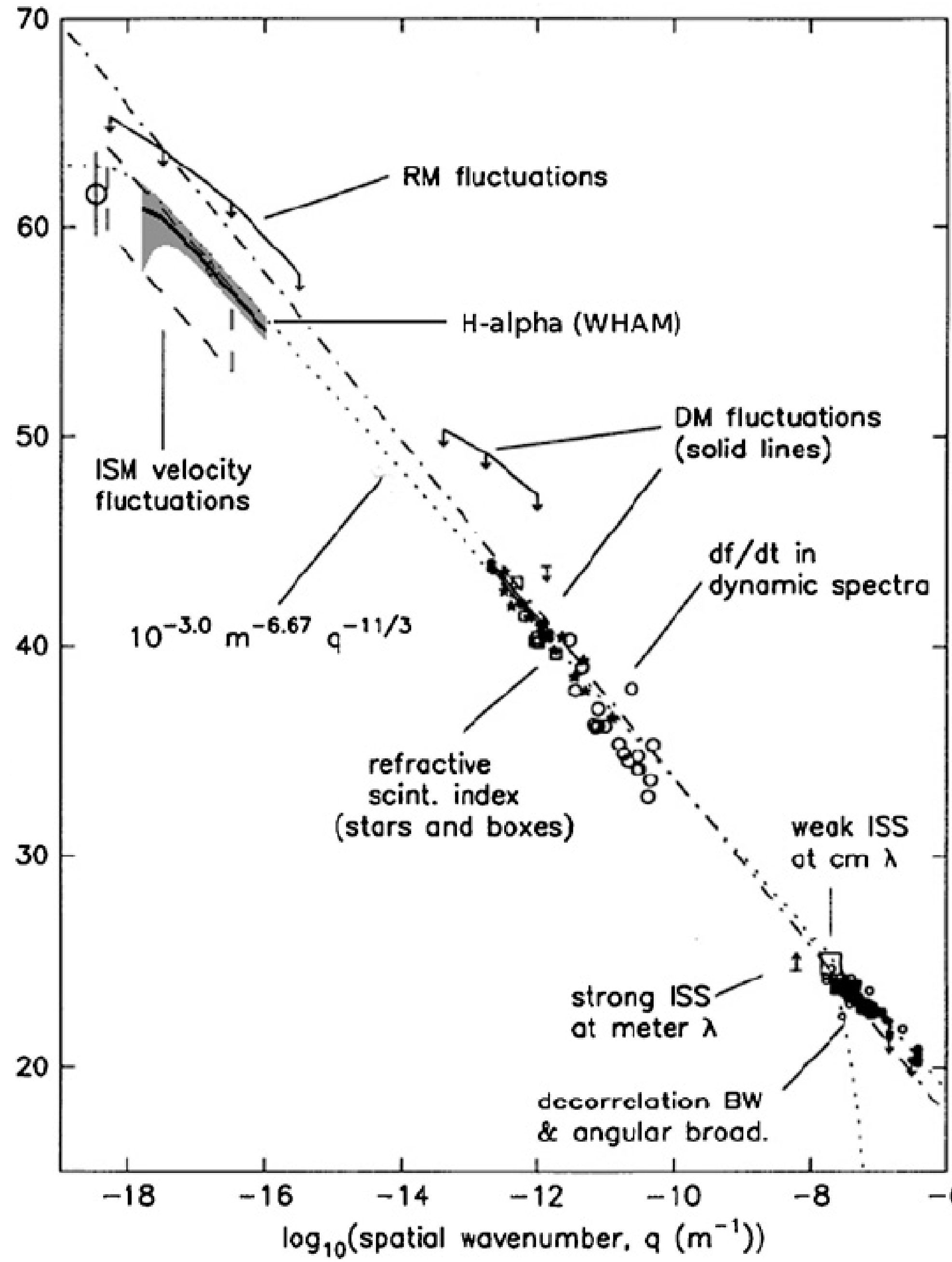
1440^3 Sim

Kolmogorov

(α_v = 11/3)

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

➔ Kolmogorov-like Spectrum



Good Agreement!

Chepurnov & Lazarian 2010
Armstrong et al. 1995

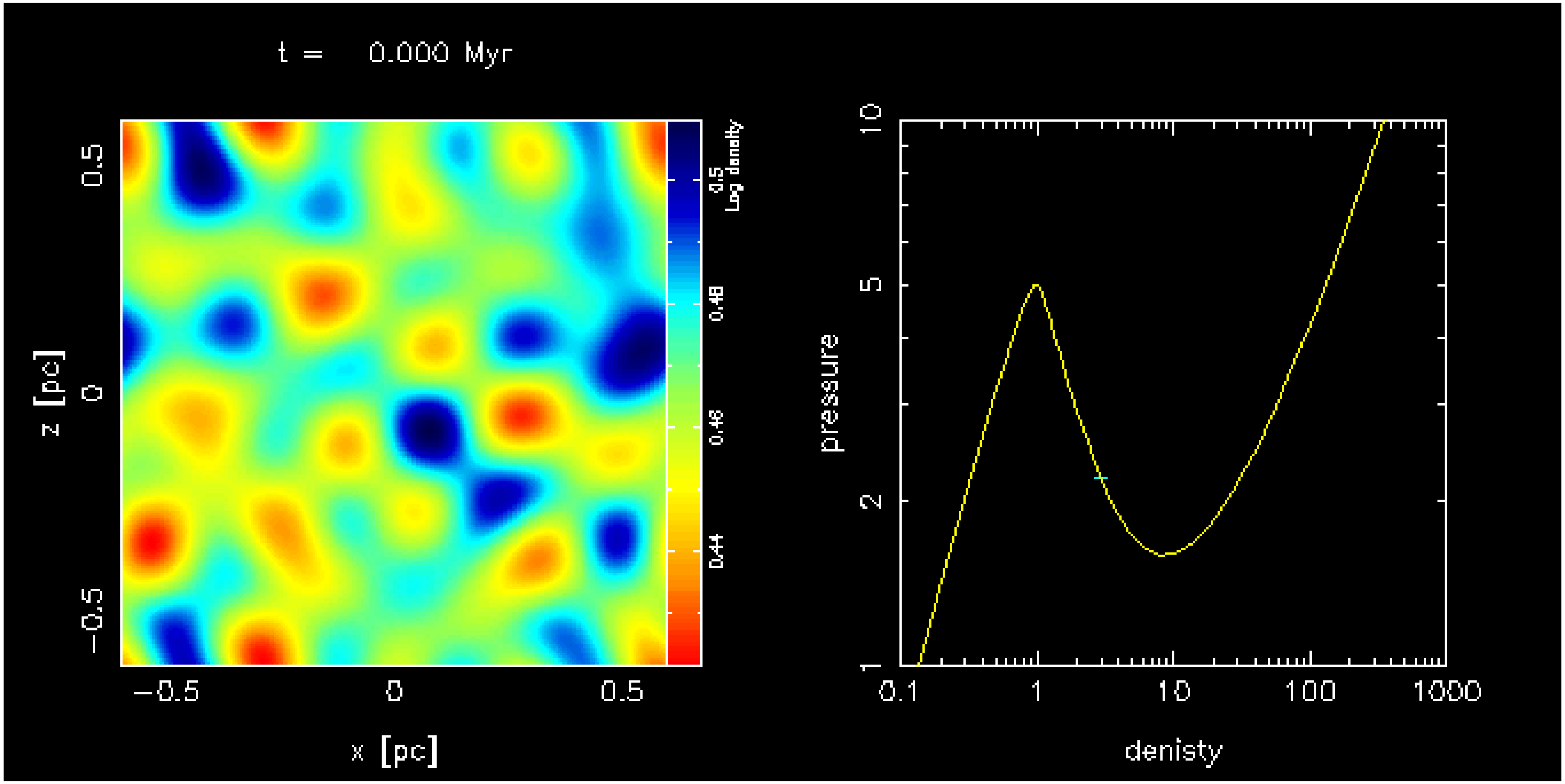
Two Aspects in Multi-Phase Dynamics

2: Phase Transition Dynamics without Shock Waves

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

The Answer is NO!

Sustained "Turbulence" in Periodic Box



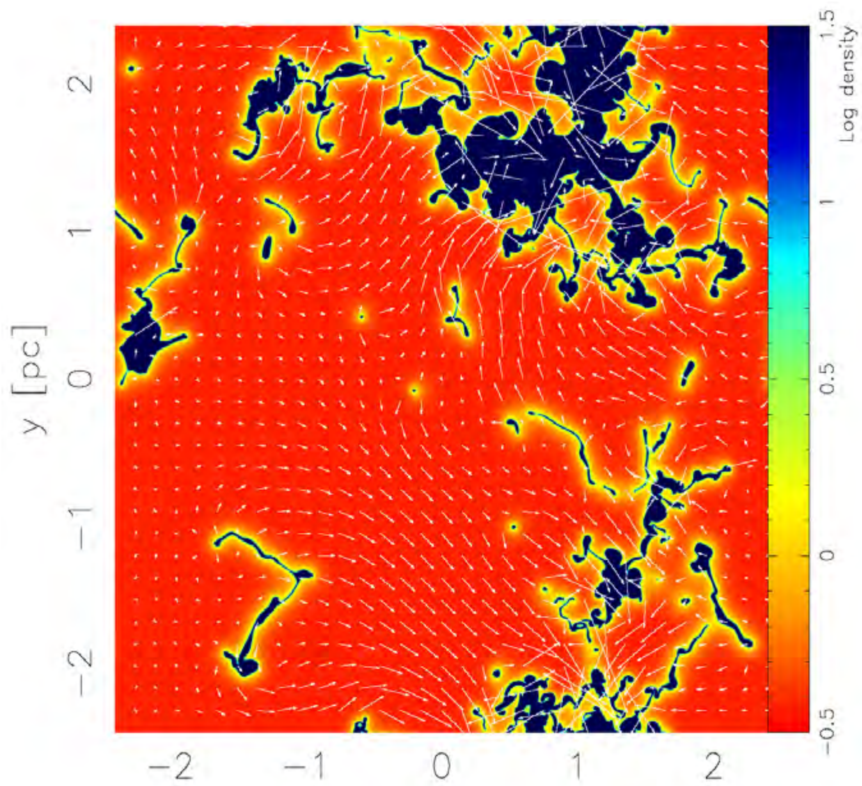
Periodic Box Evolution <u>without Shock Driving</u>

With Cooling/Heating and Thermal Conduction

Without Physical Viscosity (*Prandtl* # = 0)

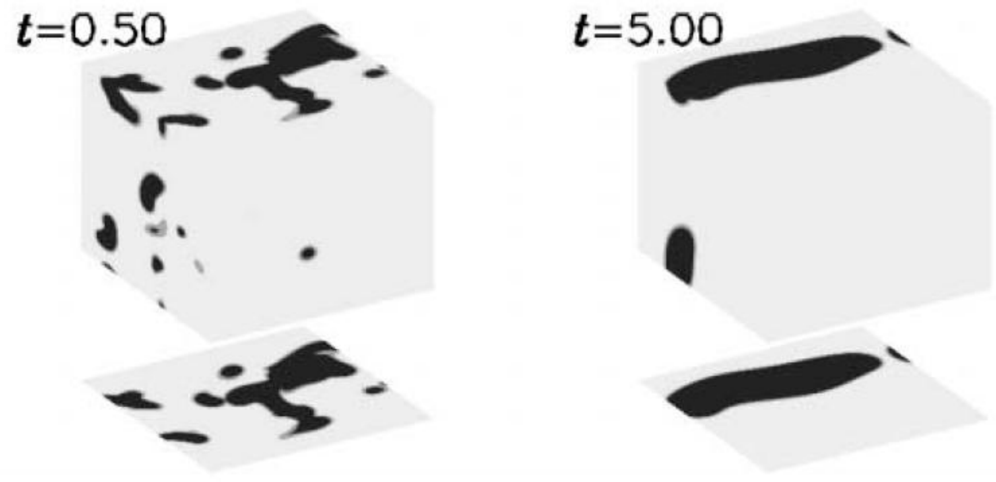
Non-Linear Development of TI without External Forcing

Sustained Turbulence for realistic conduction κ



Koyama & Inutsuka 2006;
Iwasaki & Inutsuka 2014 ApJ 784,115

Decaying Turbulence for $\kappa \propto n$



Brandenburg et al. 2007

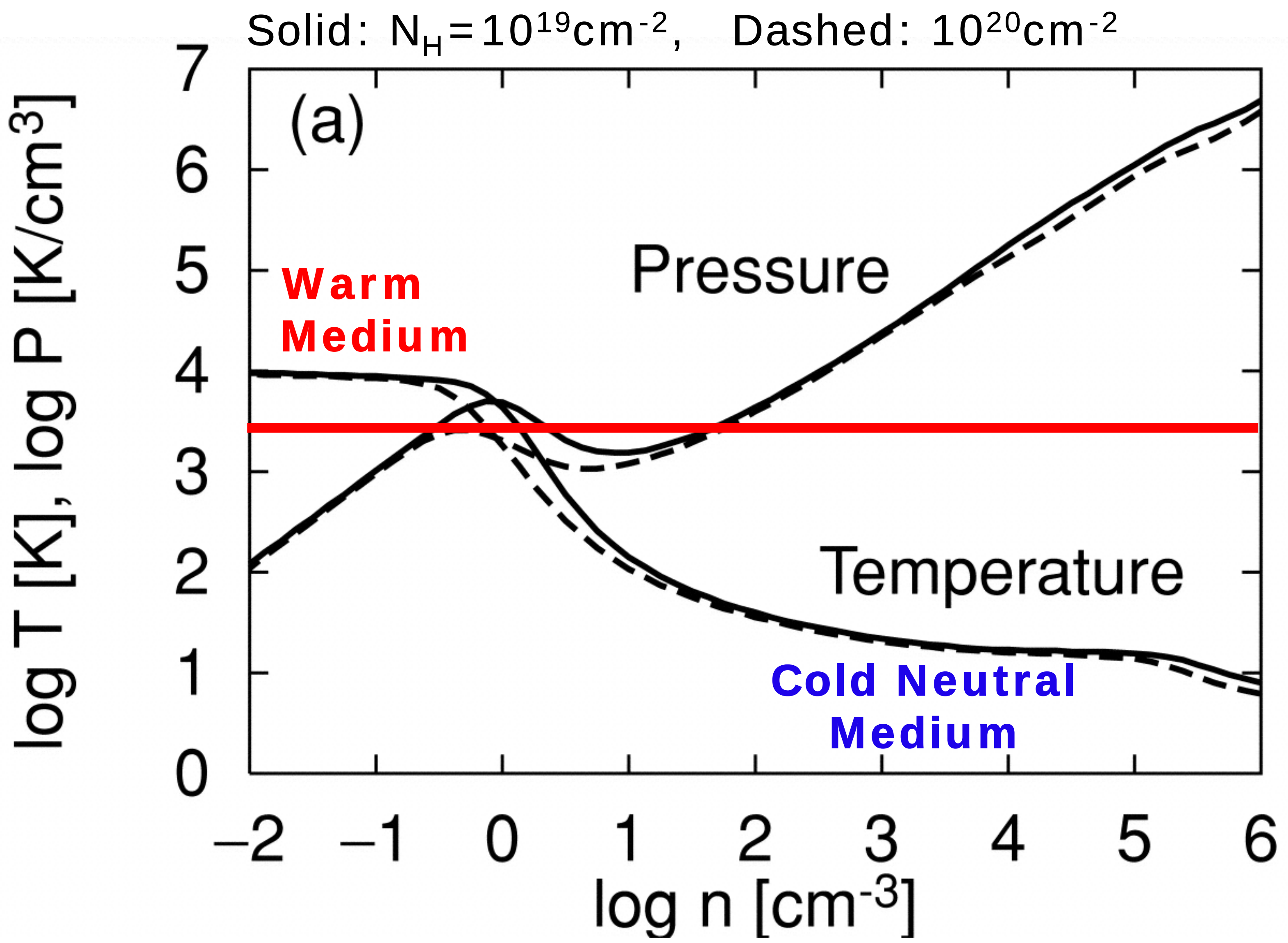
In reality, κ =*const.*

$\kappa \propto n\mathrm{v}l \propto \underline{n}\mathrm{v}/(\underline{n}\sigma)$

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



Textbook Example of Phase Equilibrium

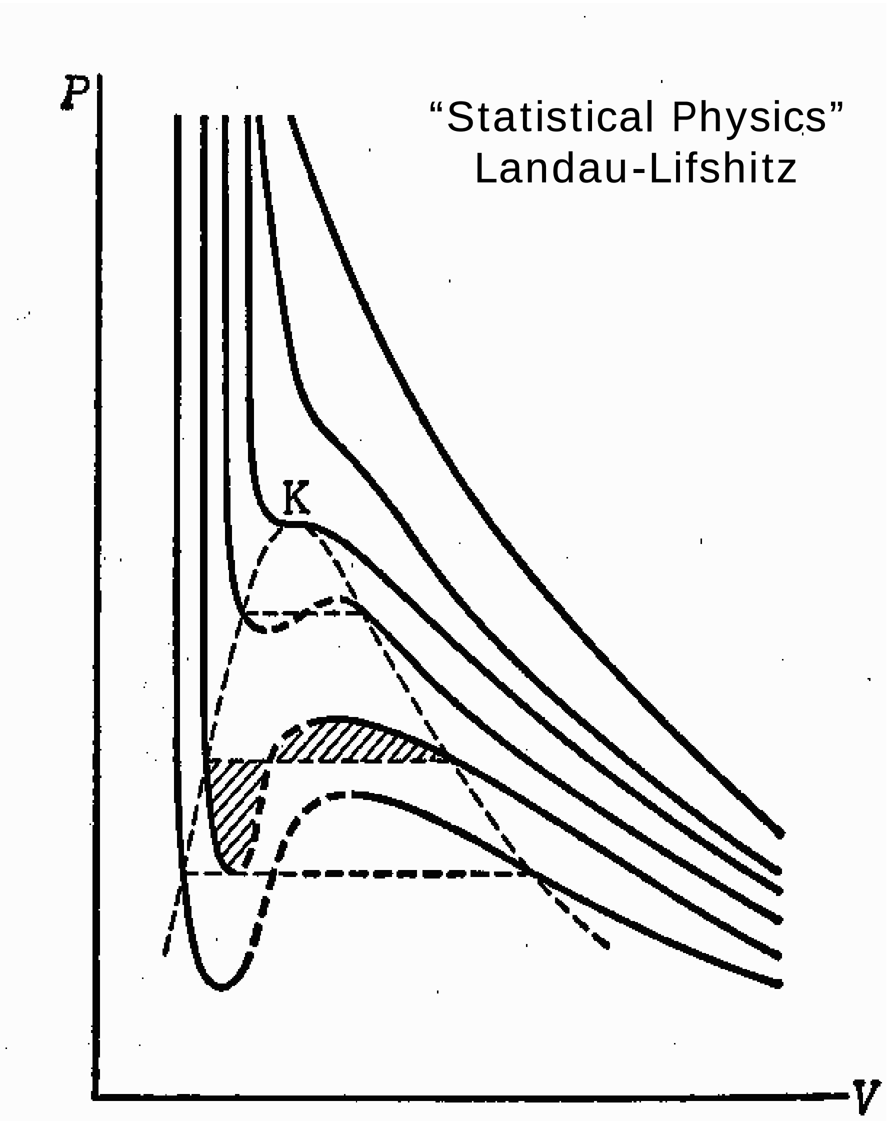
EoS of van der Waals Gas

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

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

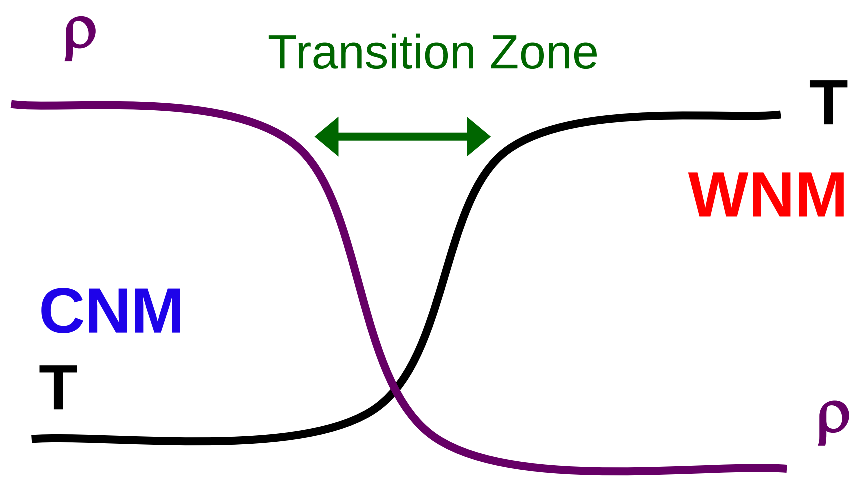
$$= \int_1^2 V(P, T = \text{const})dP$$

Equal Areas of shaded regions
(Maxwell's rule)



Exact Equilibrium of 2-Phases

1D Case



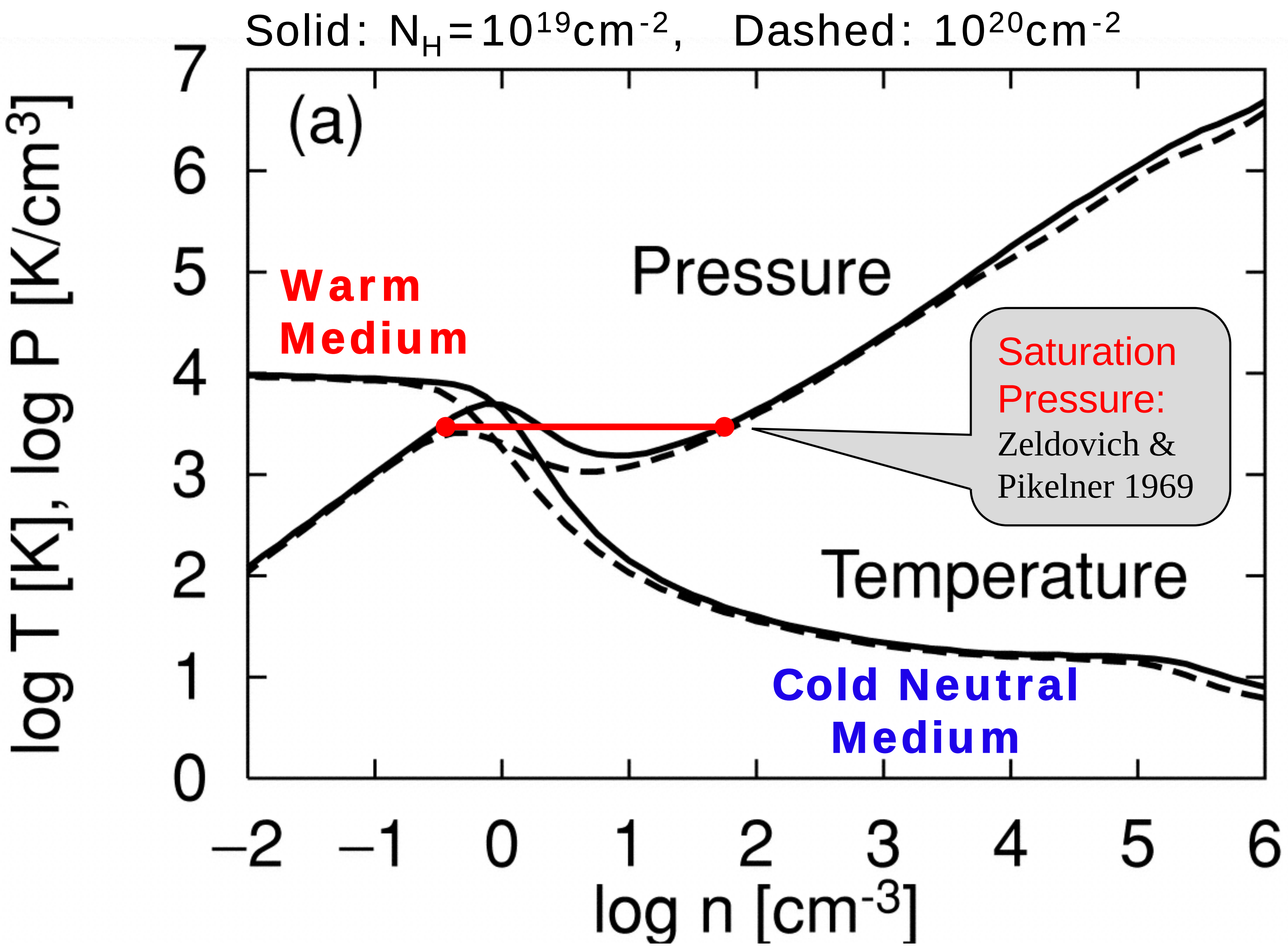
Saturation Pressure

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

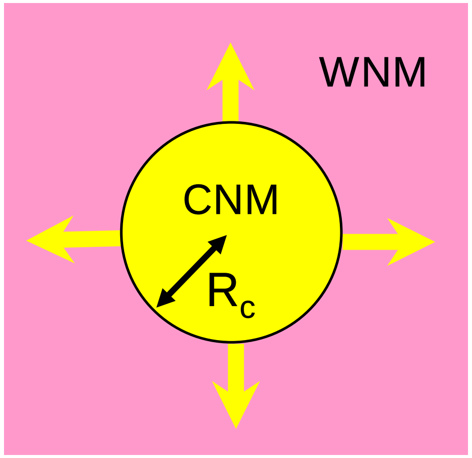
- 1D Plane-Parallel Case: Zeldovich & Pikelner 1969
- 2D Cylindrical Symmetry: Graham & Langer 1973
- 3D Spherical Symmetry: Nagashima, SI, Koyama 2005

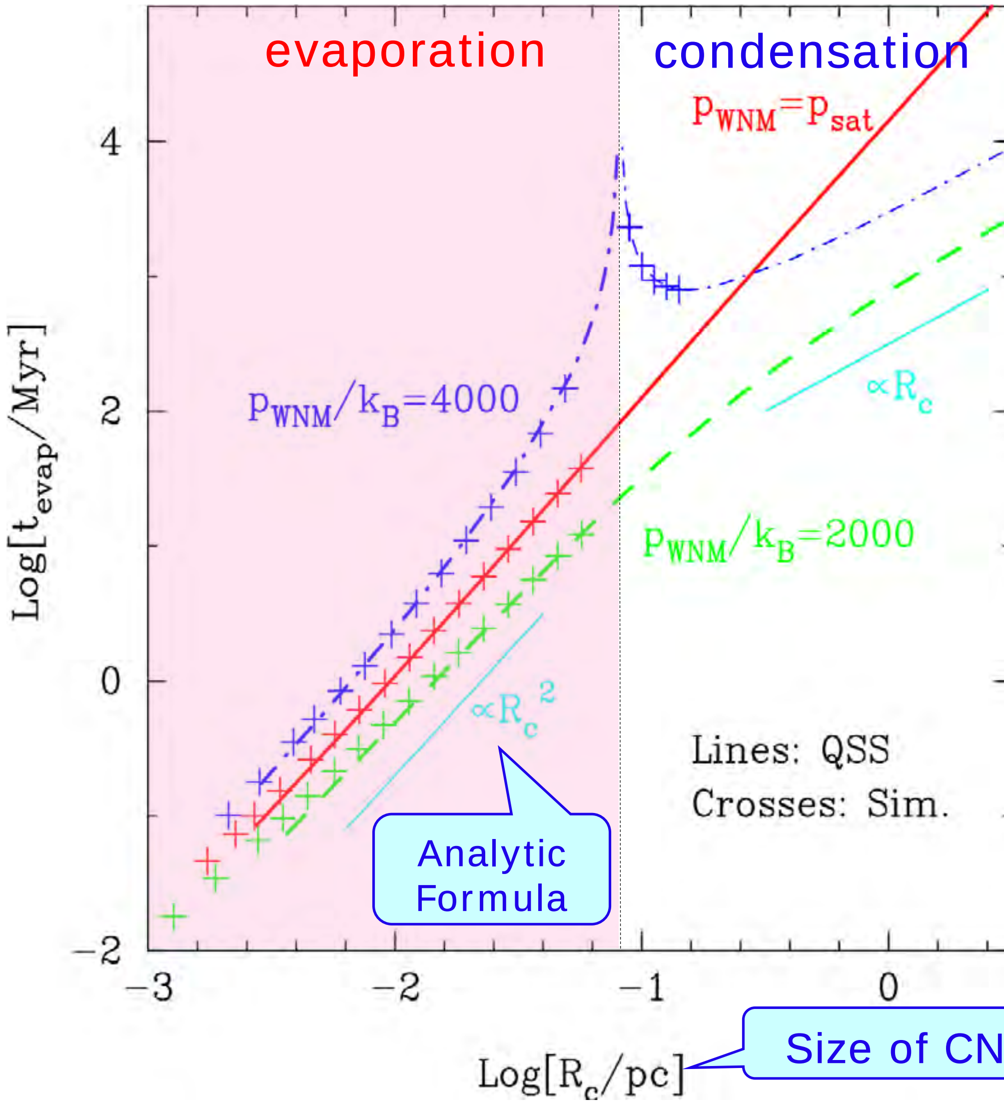
No Unique $\boldsymbol{P}_{\mathrm{sat}}$ ➔ 2-Phase with various $\boldsymbol{P}$

Saturation Pressure in 1D Geometry



Evaporation of Spherical CNM in WNM





Evaporation Timescale

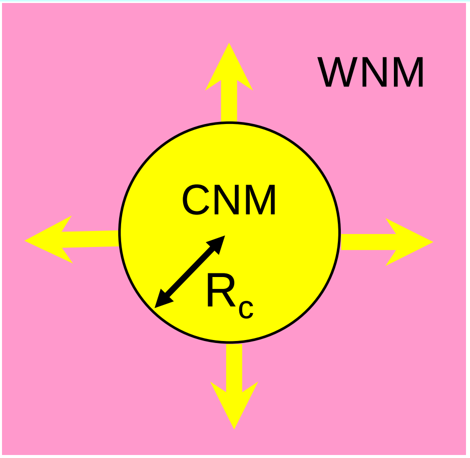
Size of CNM cloud

Smaller CNM cloud evaporates:

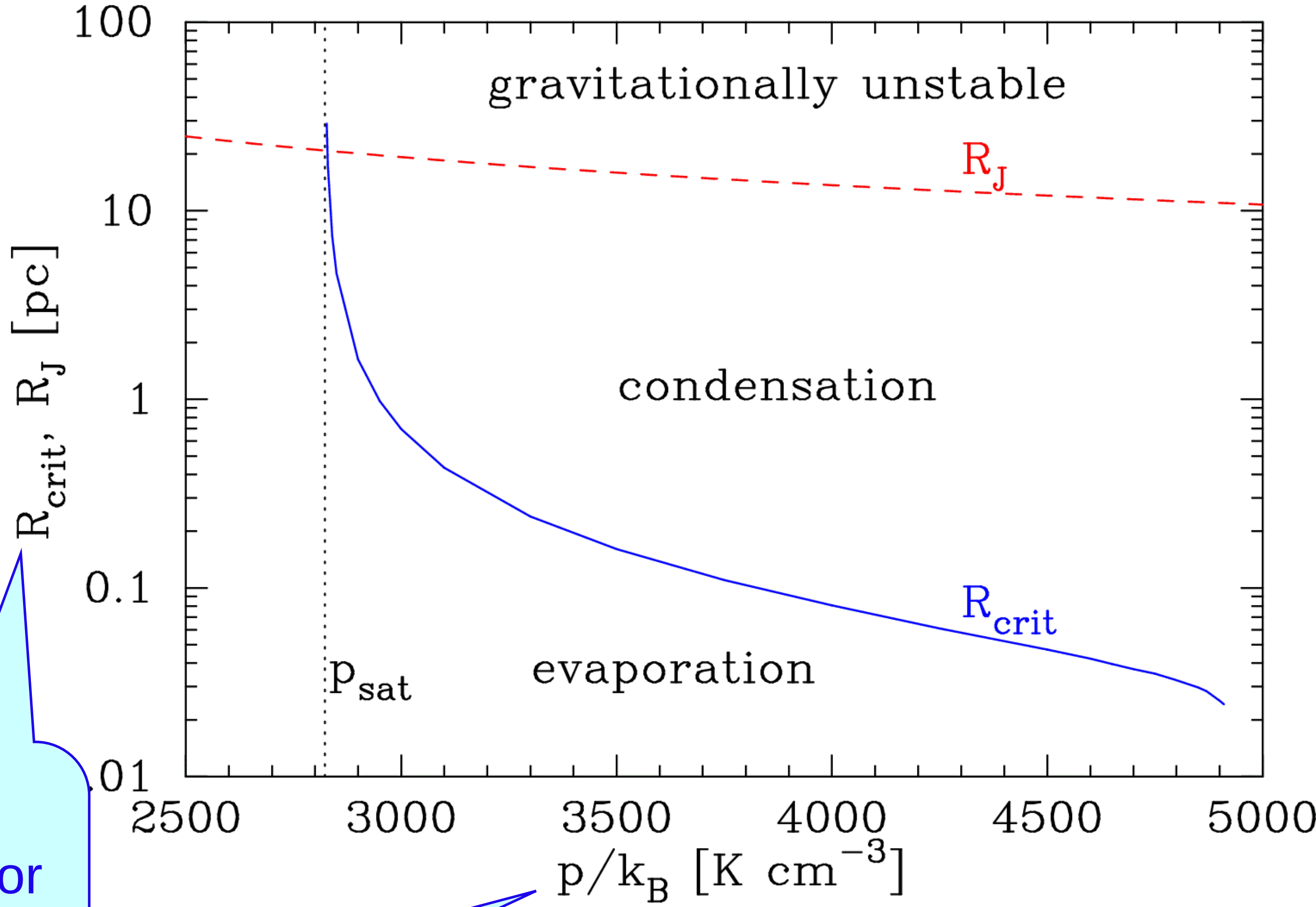
R~0.01pc clouds evaporate in ~Myr

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

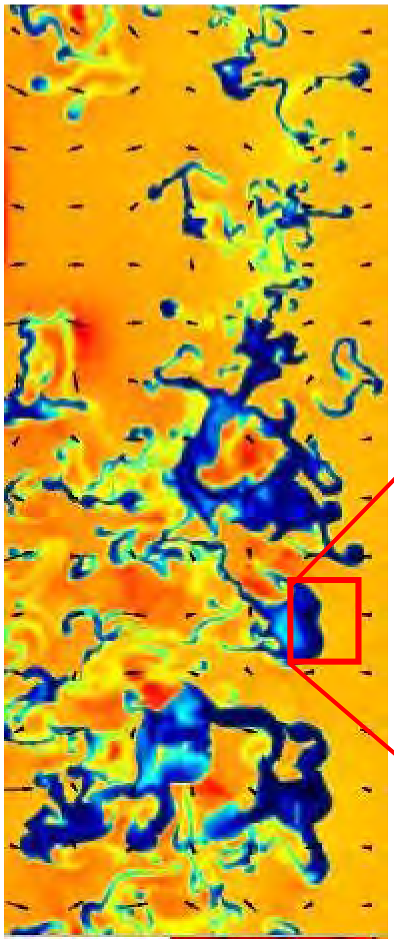
Nagashima, SI, & Koyama 2006, ApJL **652**, L41

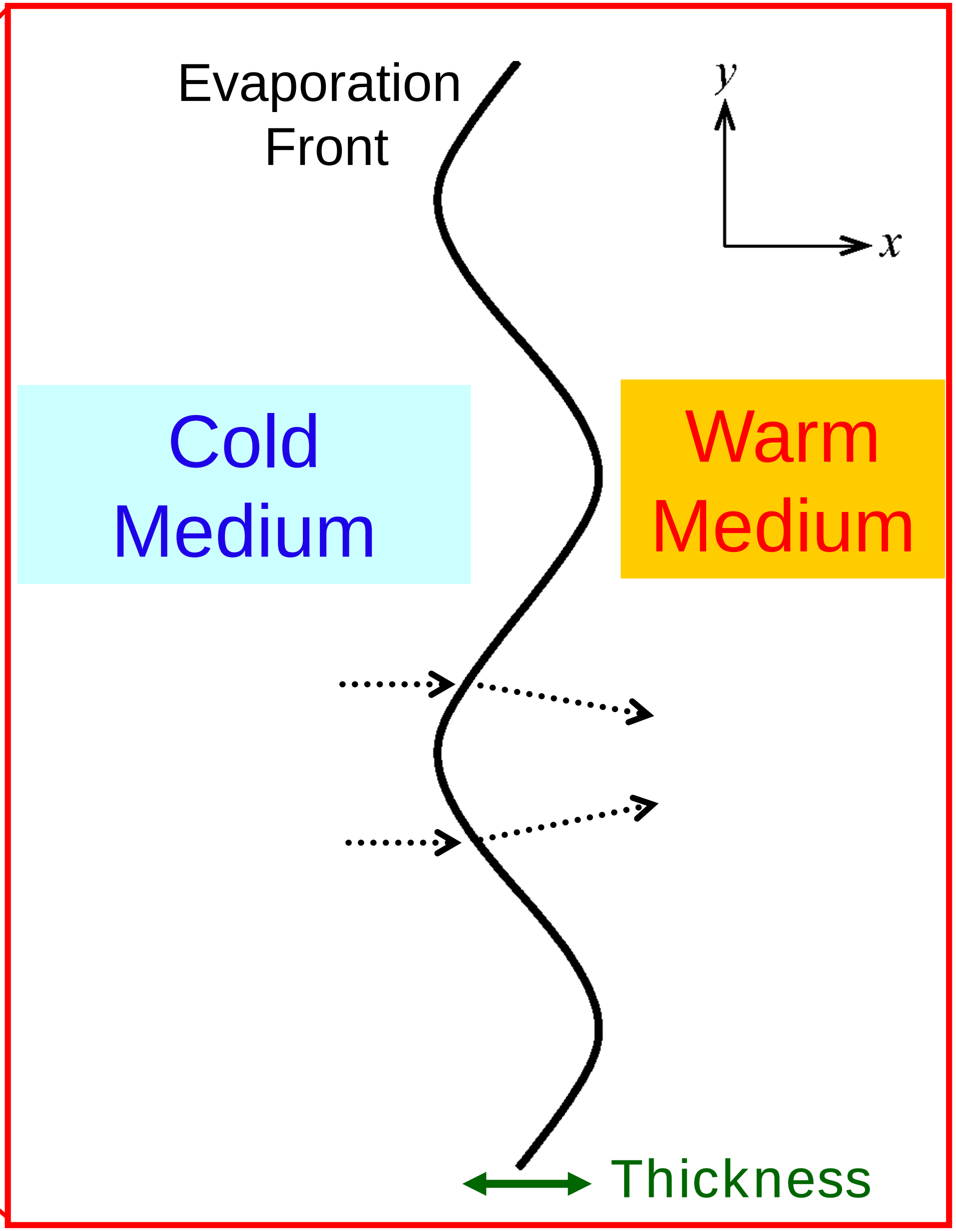
cf. "Tiny Scale Atomic Structure" Braun & Kanekar 2005, Stanimirovic & Heiles 2005

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

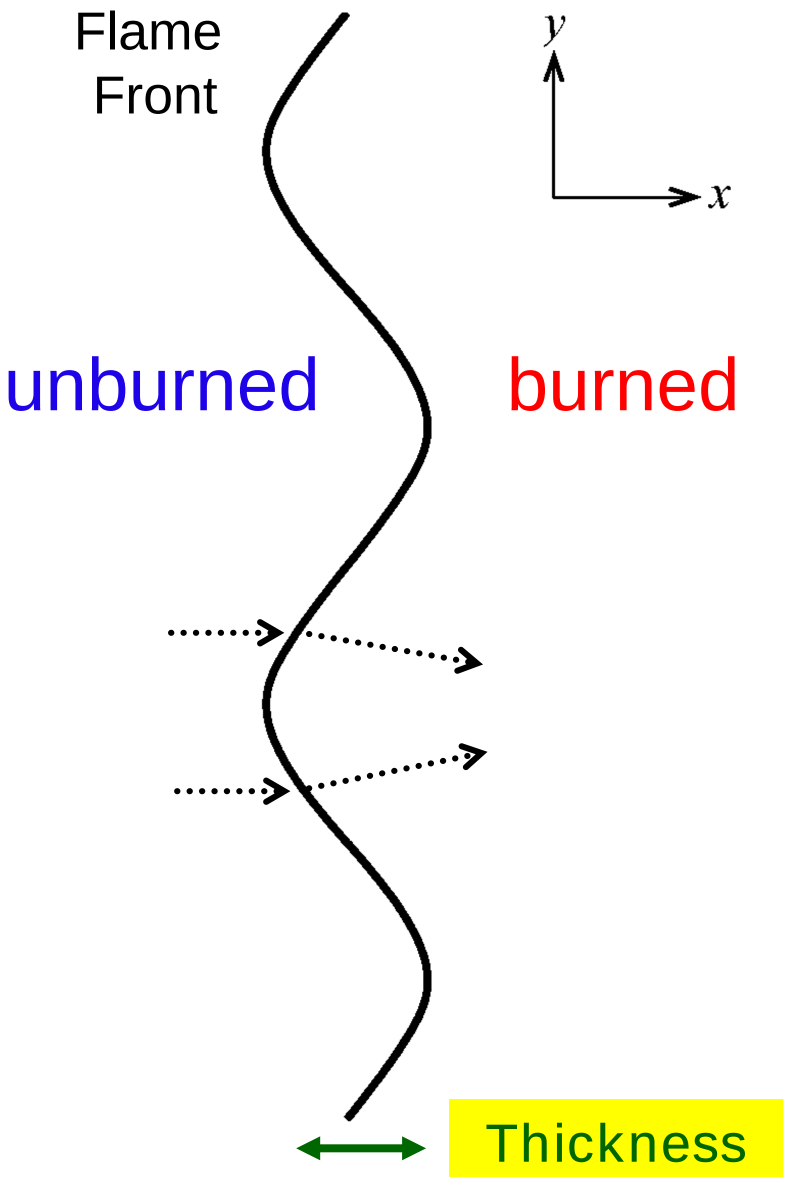
Effect of Magnetic Field

See Dursi (2004)

2) Corrugation Instability in MHD Slow Shock

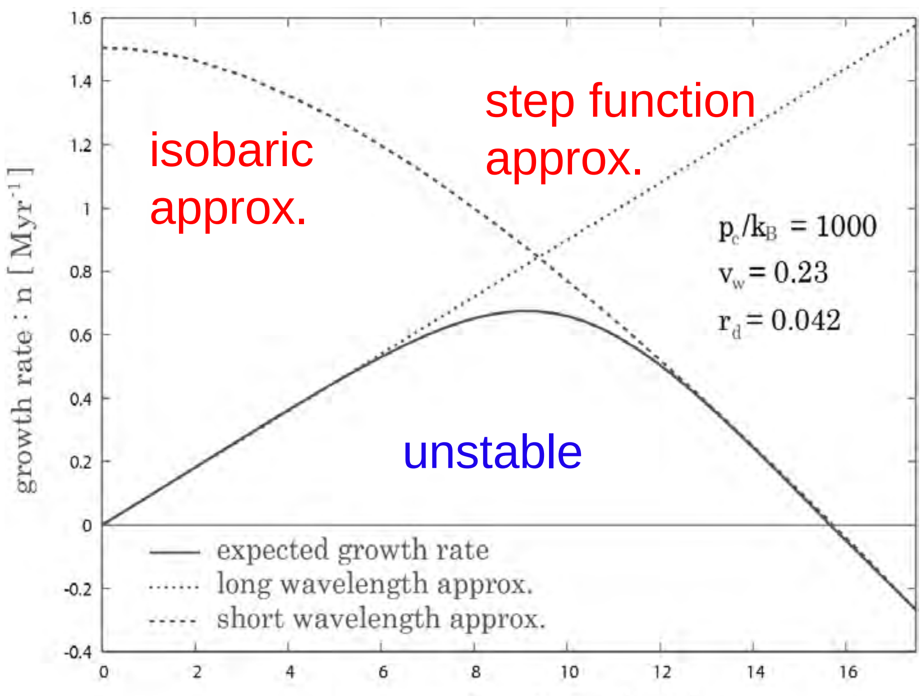
– Edelman 1990

– Stone & Edelman 1995



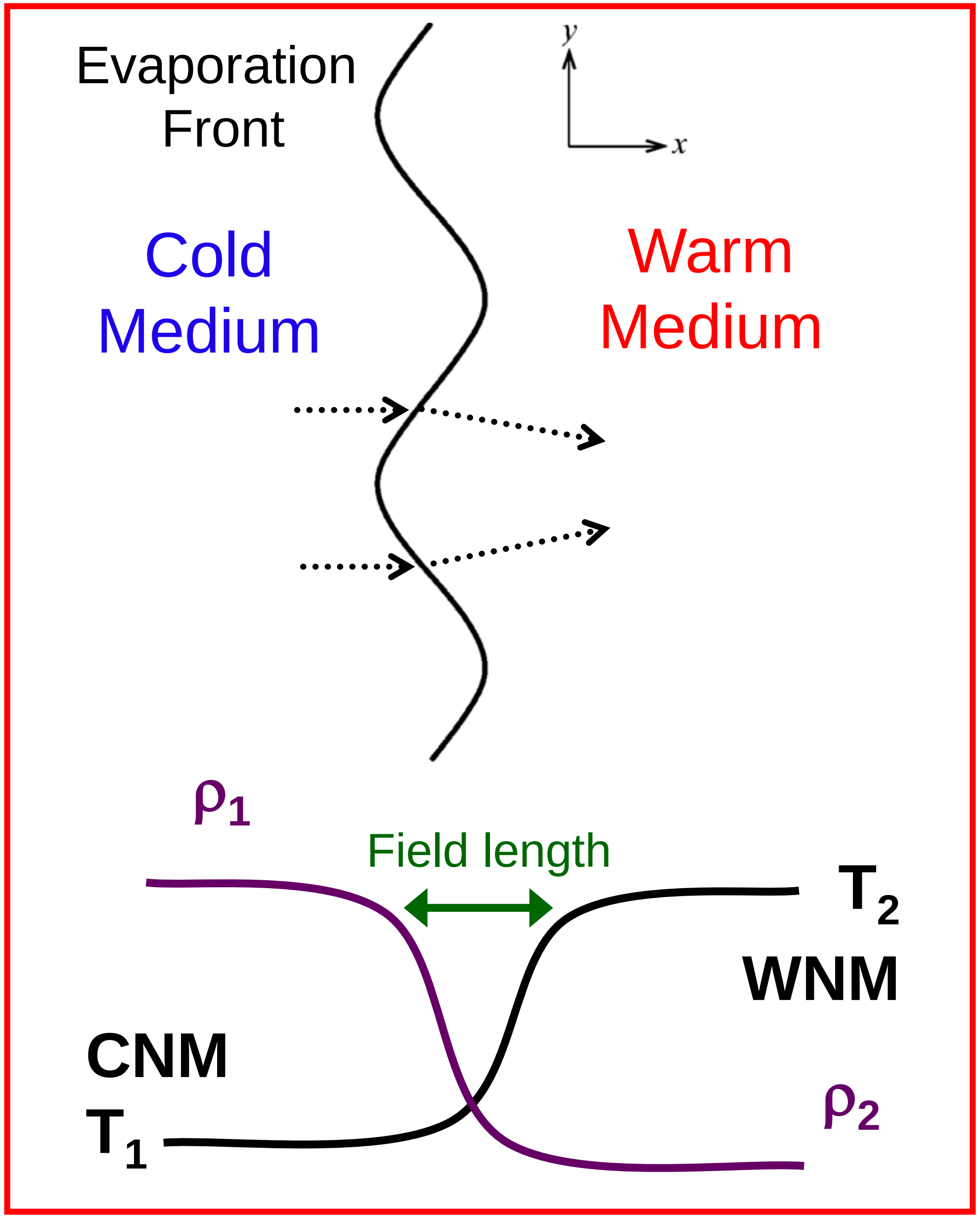
Linear Analysis of New Instability

Growth Rate (Myr[-1])



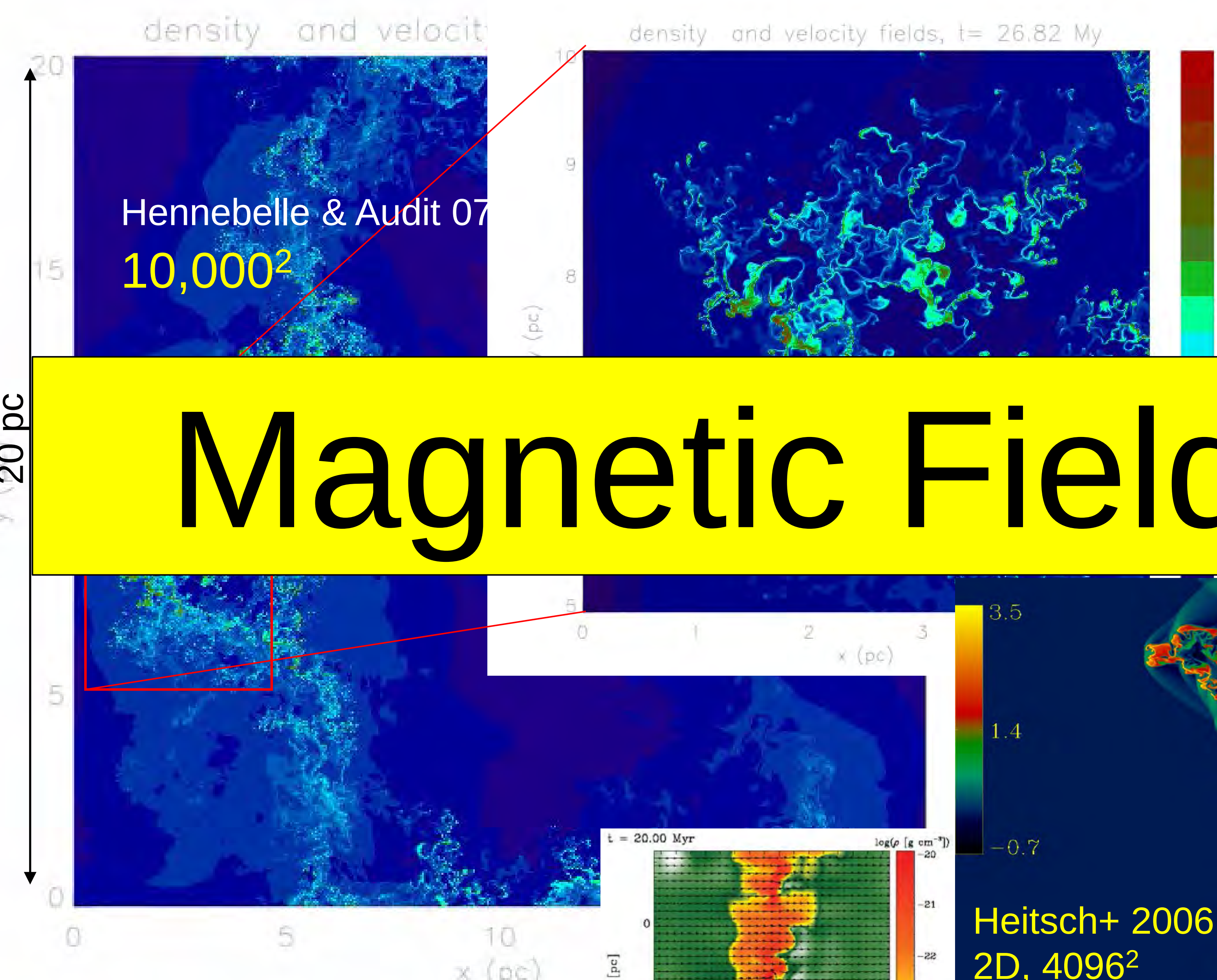
wavenumber $k_y/2\pi$ [pc^{-1}]

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



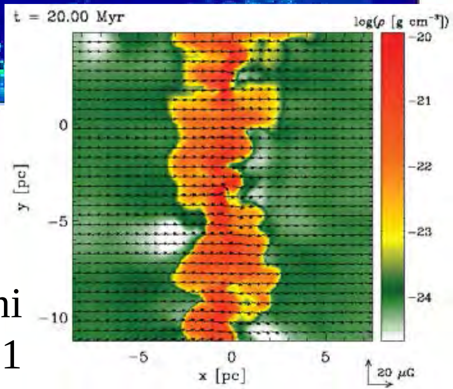
Effect of ***B***:

Stone & Zweibel 2009, ApJ 696, 233

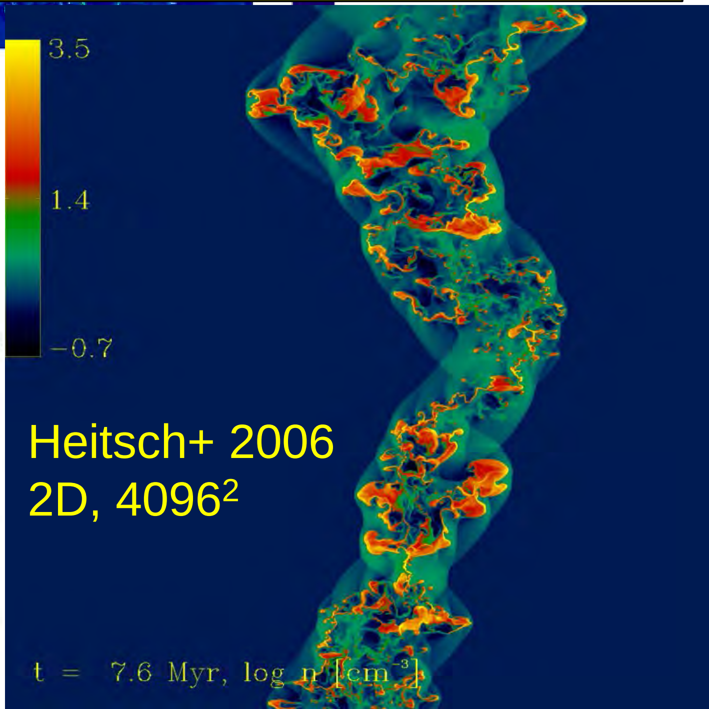


c.f.
Kritsuk &
Norman 1999

Magnetic Field?



Vazquez-Semadeni
et al. 2011



Cloud Formation in Magnetized Medium

Can compression of magnetized WNM create molecular clouds?

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

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

Inoue & SI (2012) ApJ **759**, 35

SI, Inoue, Iwasaki, Hosokawa 2015 A&A **580**, A49

Ambipolar diffusion included

Two-Fluid Resistive MHD + Cooling/Heating + Thermal Conduction + Chemistry (H_2, CO,…)

Colliding WNM with B_0=3μG

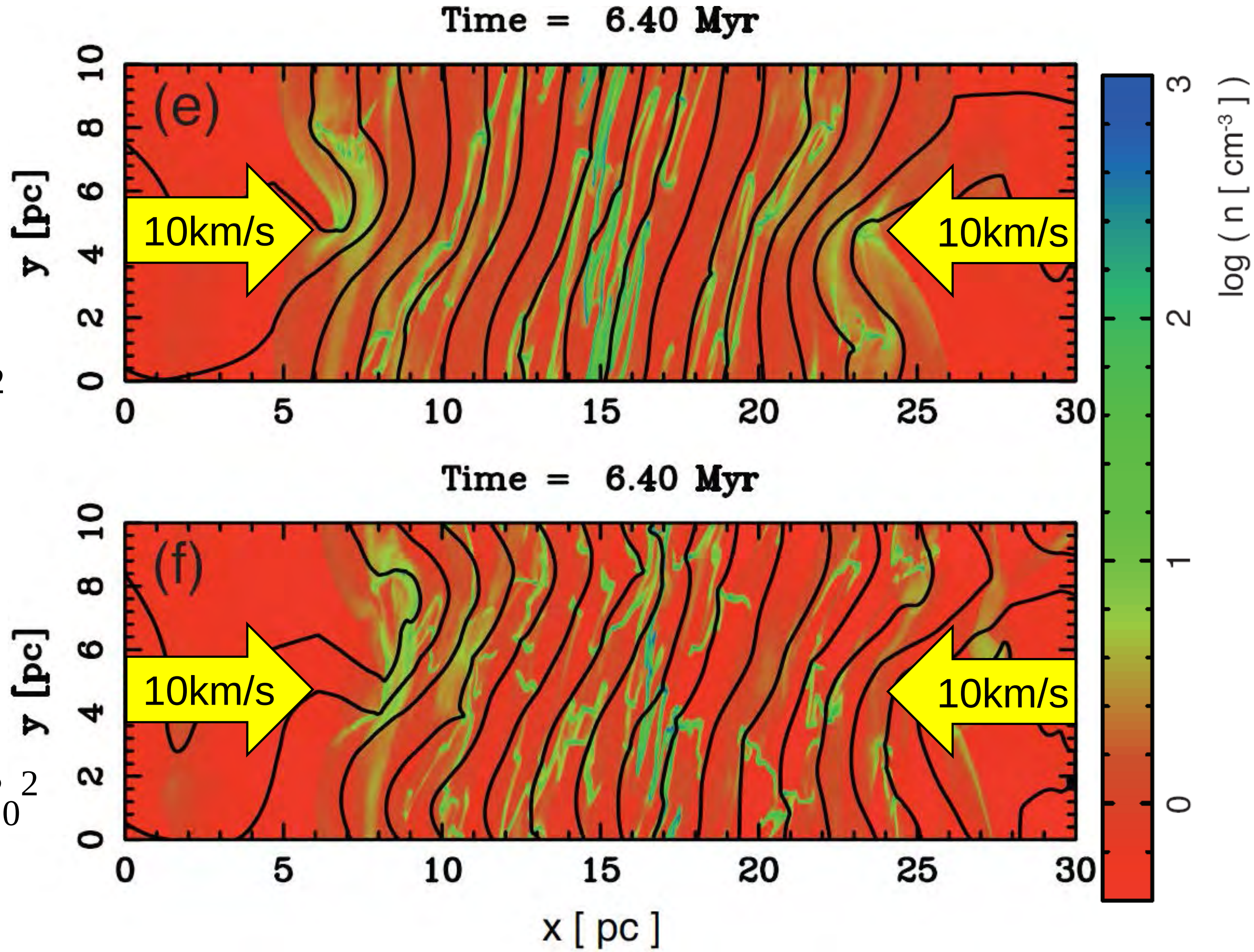
v=10km/s

(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?

Compression of CNM (HI) ➔ H_2

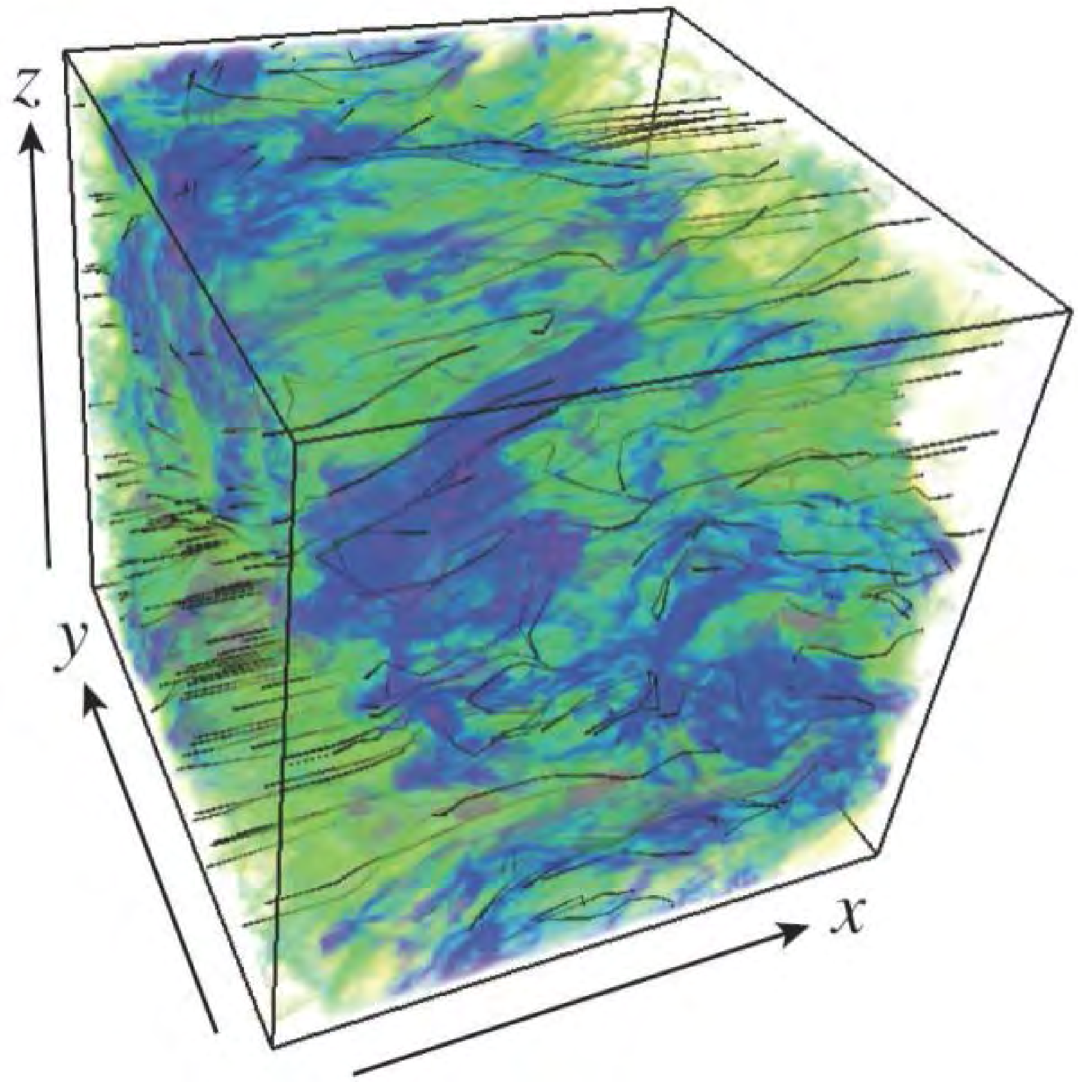
Compression <u>along Magnetic Field</u> lines, + H_2,CO

➔

Formation of Magnetized Molecular Clouds

Transformation of HI to H_2

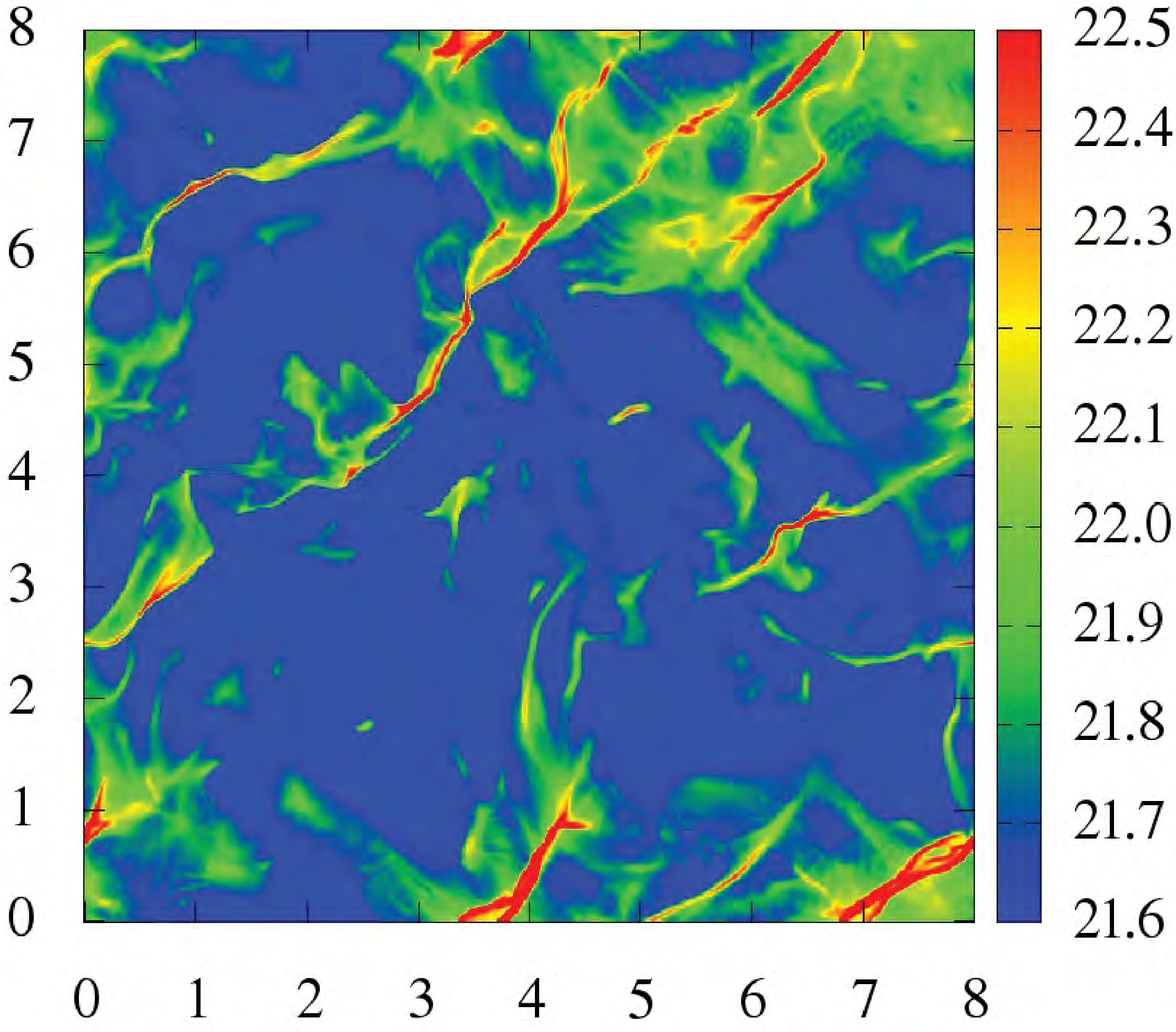
<u>*Inoue & SI* (2012) **759**, 35</u>



Further Compress. of Mole. Clouds

Further Compression of Molecular Cloud

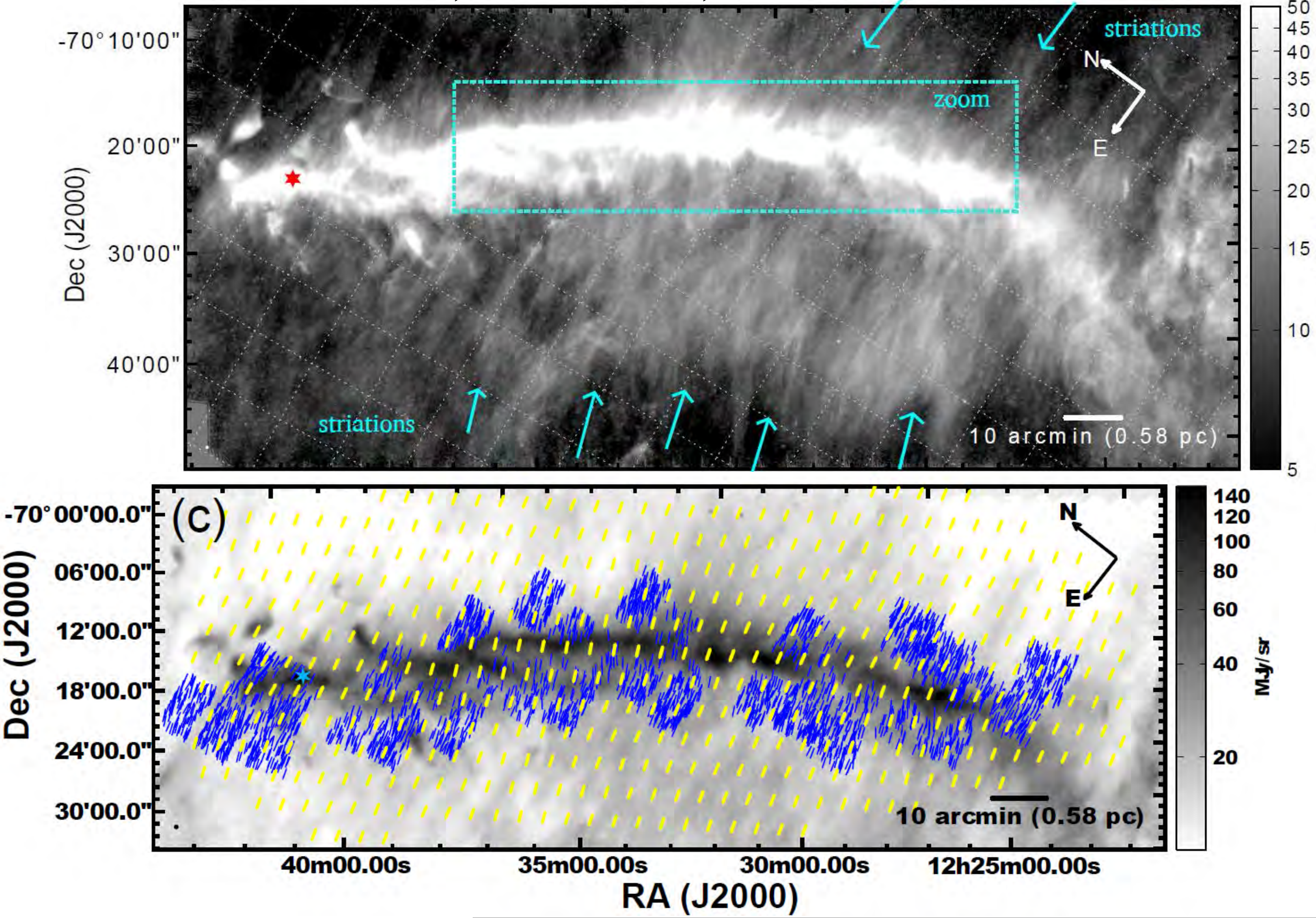
➔Magnetized Massive Filaments & Striations



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

Observed Molecular Clouds

Cox, Arzoumanian, André+2016



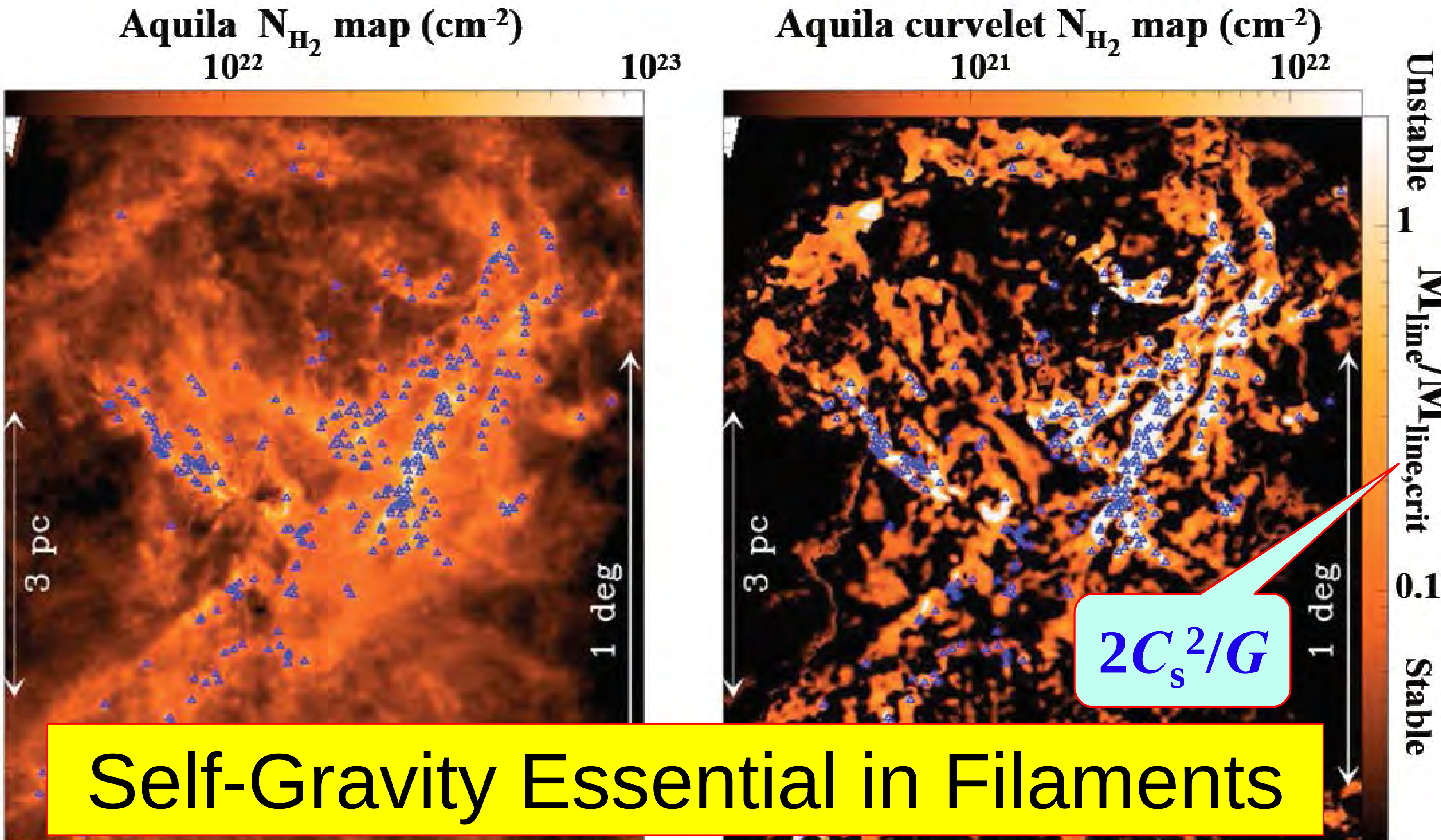
See also Soler+, Fissel+

Yellow and Blue Lines: Magnetic Field Lines

Highlight of Herschel Result (André+2010)

Prestellar cores are preferentially found within the densest filaments

△ : Prestellar cores - 90% found at $N_{H_2} > 7 \times 10^{21}$ cm^{-2} <=> A_v(back) > 8



Self-Gravity Essential in Filaments

Outline

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Mass Function of Cores in a Filament

Inutsuka 2001, ApJ **559**, L149

Line-Mass Fluctuation of Filaments

Initial Power Spectrum

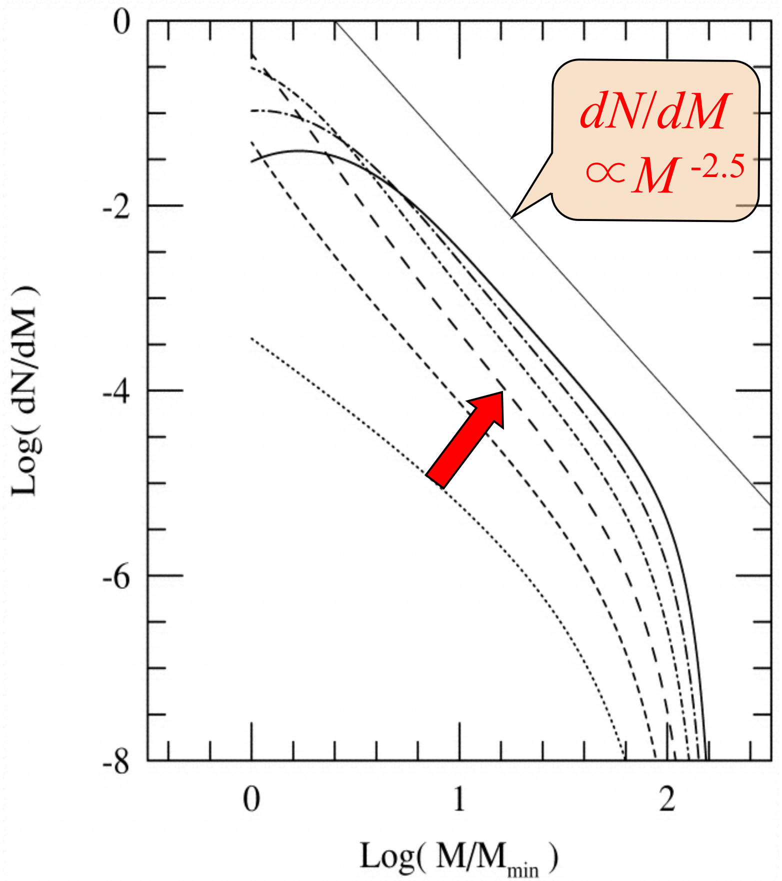
$$P(k) \propto k^{-1.5}$$

Mass Function

$$dN/dM \propto M^{-2.5}$$

Observation of Both Perturbation Spectrum and Mass Function

➔ Clear and Direct Test!

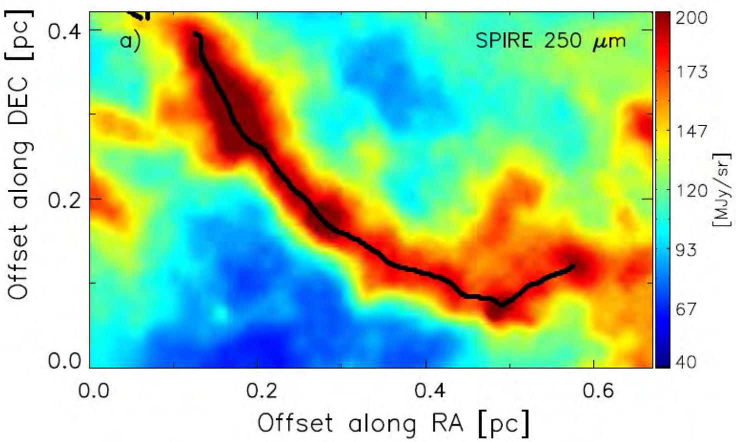


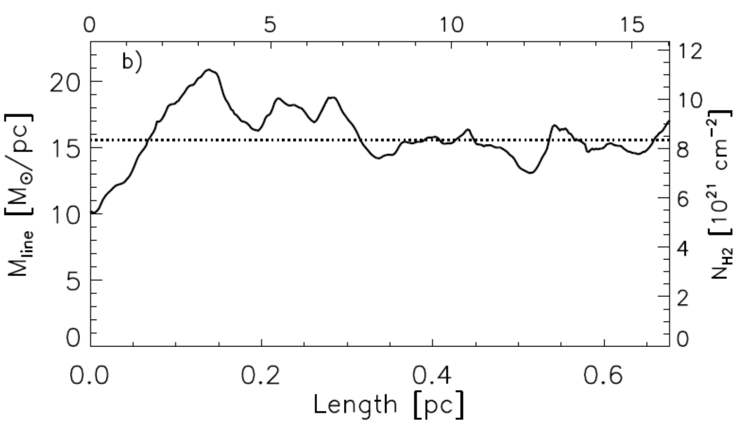
$P(k) \propto k^{-1.5}$

t/t_{ff} = 0 (dotted) , 2, 4, 6, 8, 10 (solid)

“A possible link between the power spectrum of interstellar filaments and the origin of the prestellar core mass function”

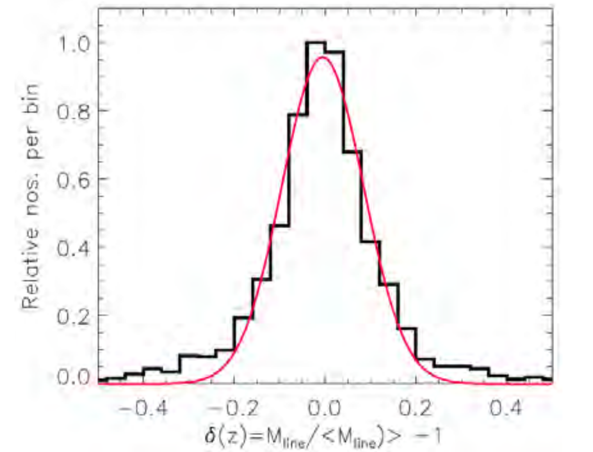
Roy, André, Arzoumanian et al. (2015) A&A **584**, A111





δ ...

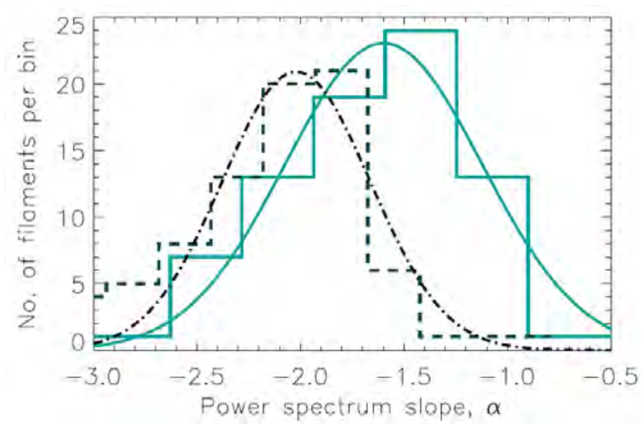
Gaussian



***P* (*k*)**

$\propto k^{n}$

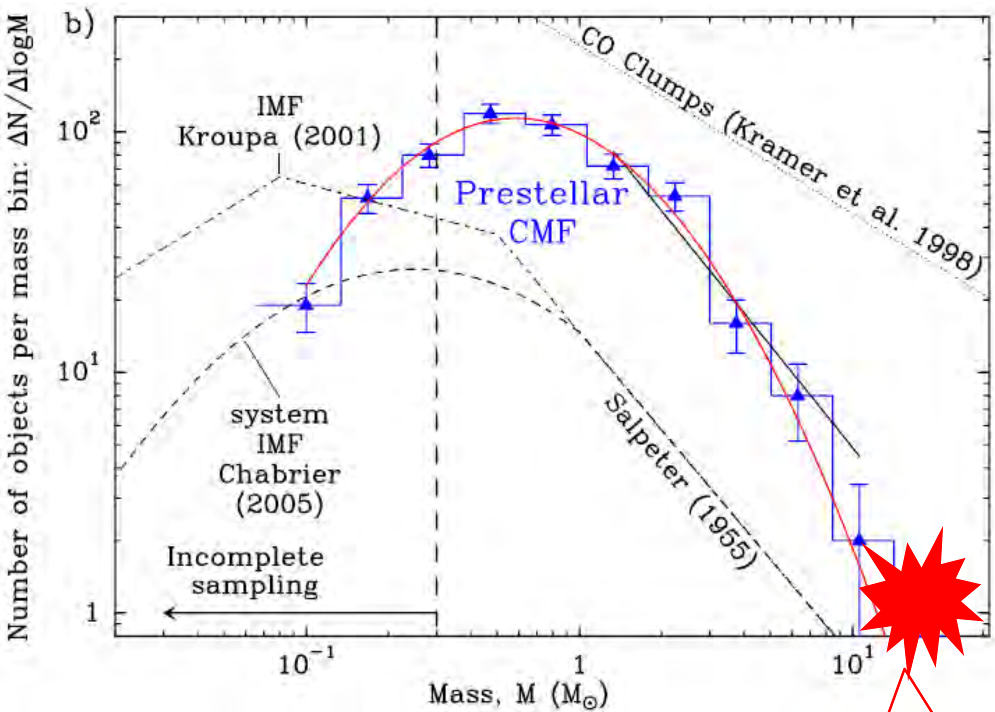
n$= -1.6 \pm 0.3$



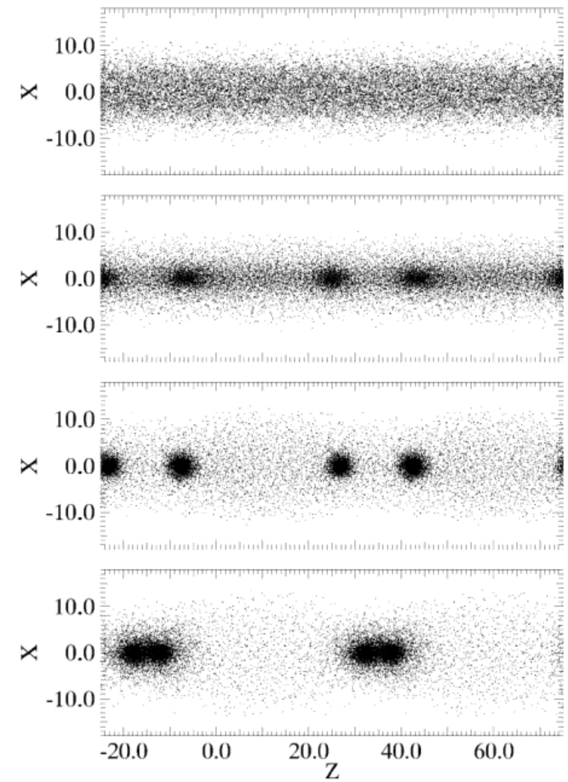
Supporting Inutsuka 2001

Applicability of Filament Paradigm for Massive Stars?

Aquila CMF from Herschel



André+2010; Könyves+2010

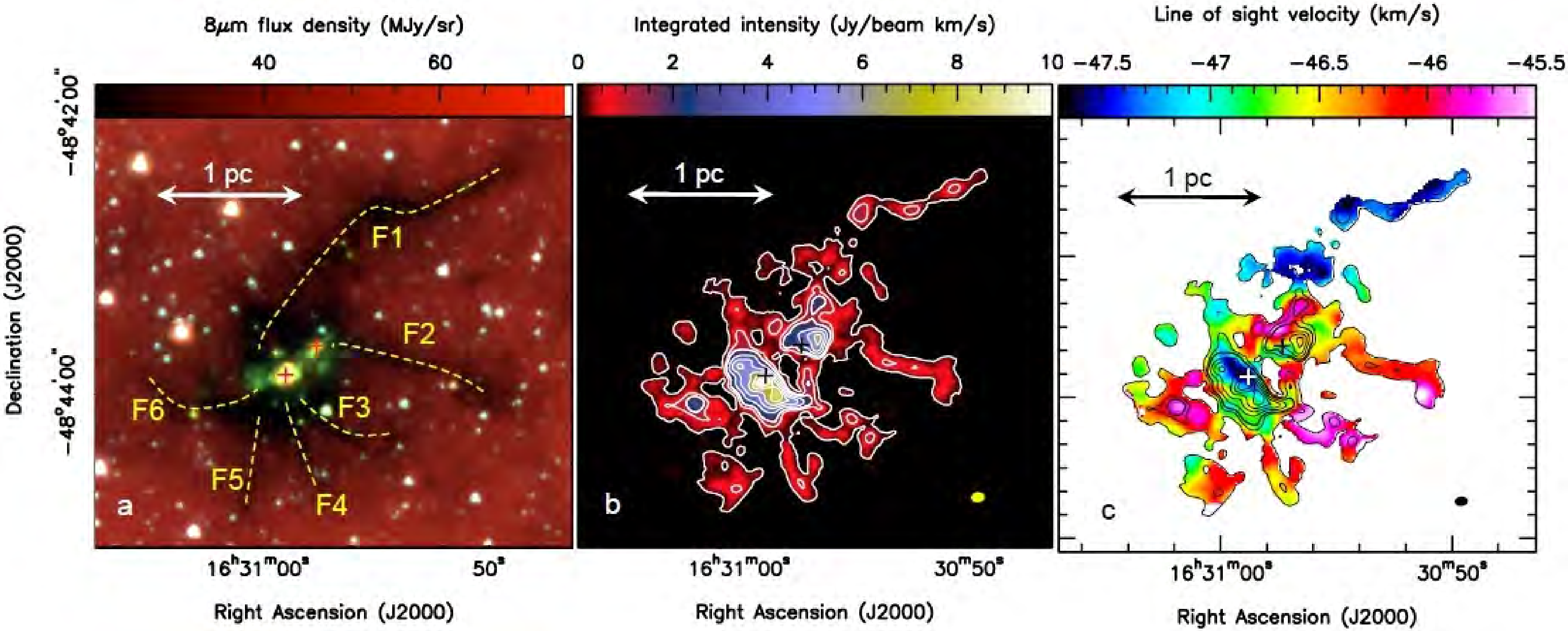


SI & Miyama 1997

Massive stars can be formed in filaments?

Larger Wavelength → Massive Core

Massive Stars through Filaments



(Peretto+2013)

- Uniform but Different Velocity in Each Filament
- Infall through Filament ~ $10^{-3}\, M_{\odot}$/yr

Nicely Understood in Filament Paradigm

Toward Global Picture of Cloud Formation

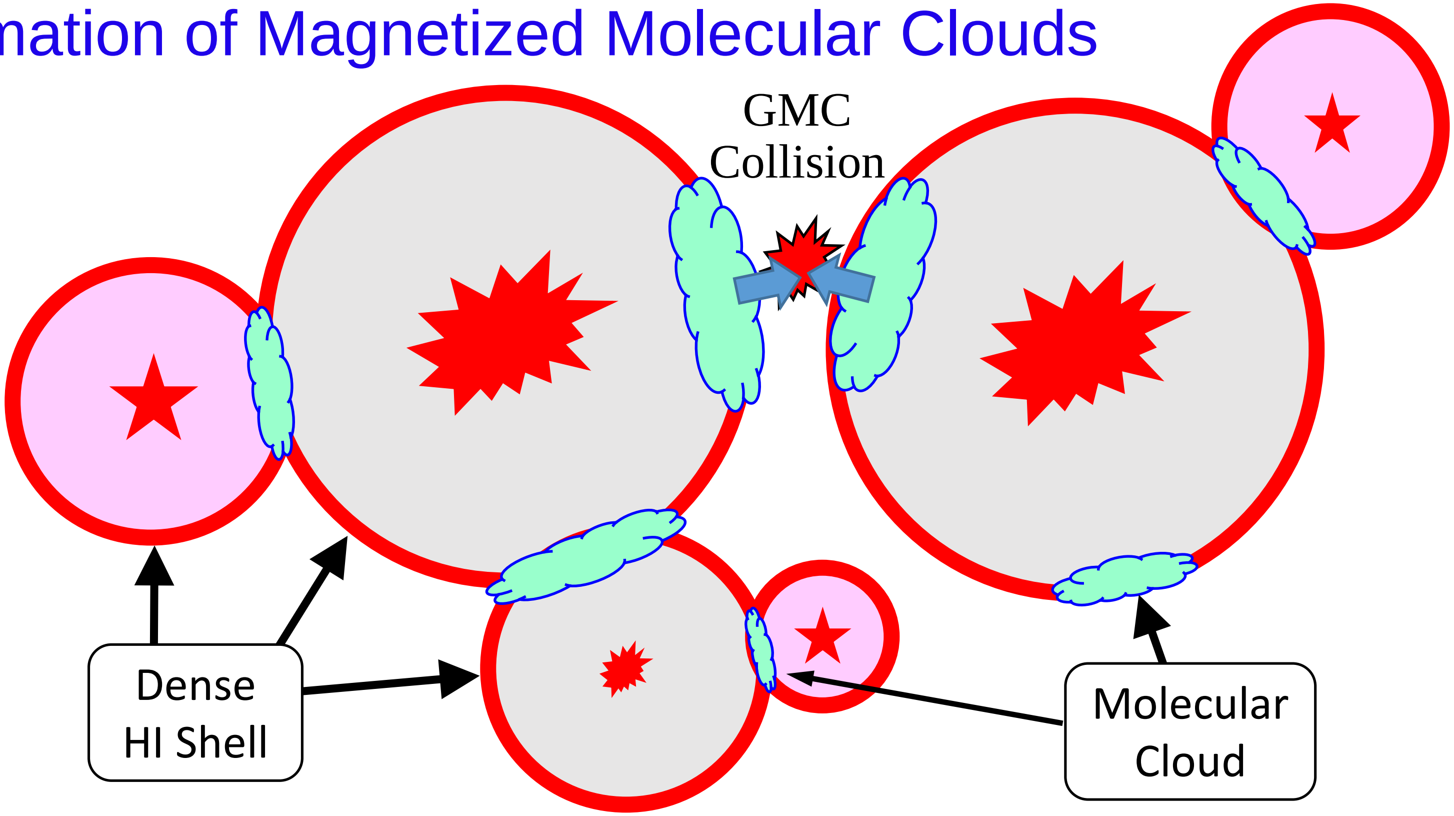
$$t_{\mathrm{form}} = \text{a few} \times 10^{7}\mathrm{yr}$$

$$N_{\mathrm{H}} \sim 10^{21}\mathrm{cm}^{-2} = 1\mathrm{cm}^{-3} \times 300\mathrm{pc}$$

$$300\mathrm{pc} \sim 10\mathrm{km/s} \times 30\mathrm{Myr}$$

Network of Expanding Shells

Multiple Episodes of Compression ➔
Formation of Magnetized Molecular Clouds



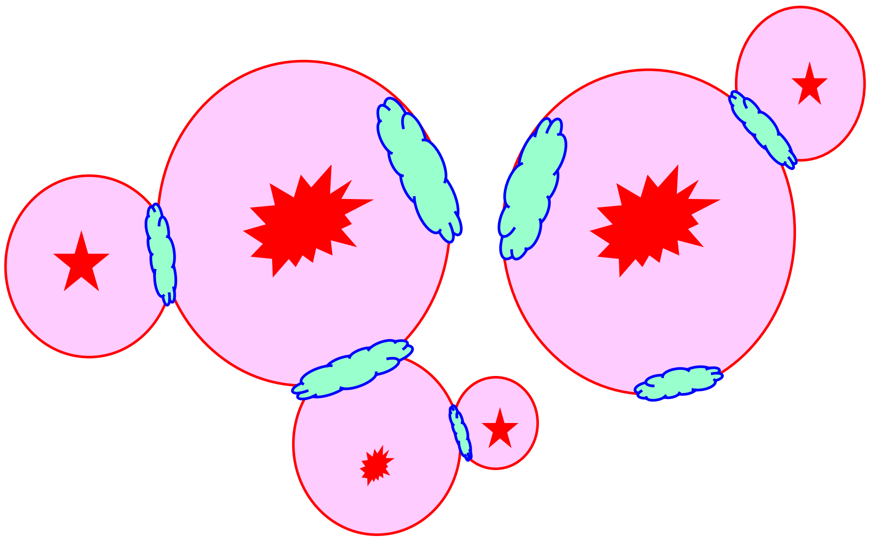
Long (>10Myr) Exposure Picture!

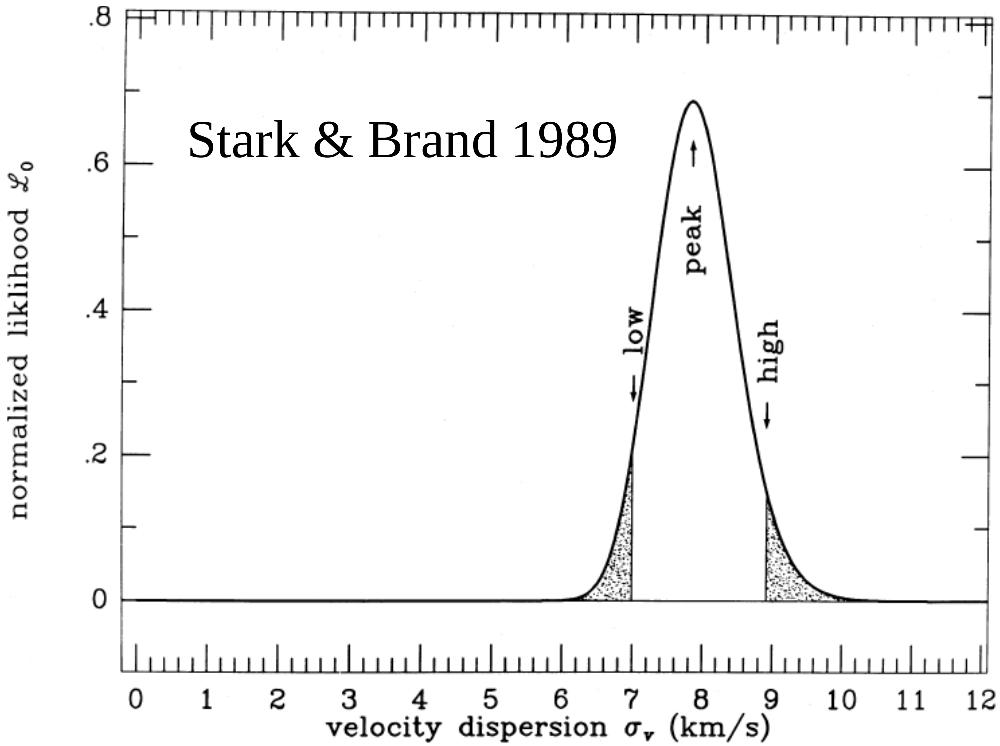
Each bubble disappears quickly (<Myr).

SI+2015; cf. Elmegreen 2007

Velocity Dispersion of Clouds

Multiple Episodes of Compression ➔ Formation of Magnetized Molecular Clouds





Shell Expansion Velocities ~ 10^1 km/s

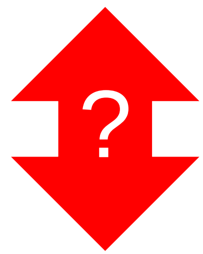
Cloud-to-Cloud Velocity Dispersion

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

Filament Paradigm

Completely Successful?!



Other Modes of Star Formation?

Cloud Collision (*Fukui, Tan, Tasker, Dobbs*,...)

Collect & Collapse (*Elmegreen-Lada, Whitworth, Palouš, Deharveng, Zavagno,…*)

Formation of Molecular Clouds

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

Inoue & SI (2012) ApJ **759**, 35 Transformation of HI to H_2

$$t_{\mathrm{form}} = \text{a few} 10^7 \mathrm{yr}$$

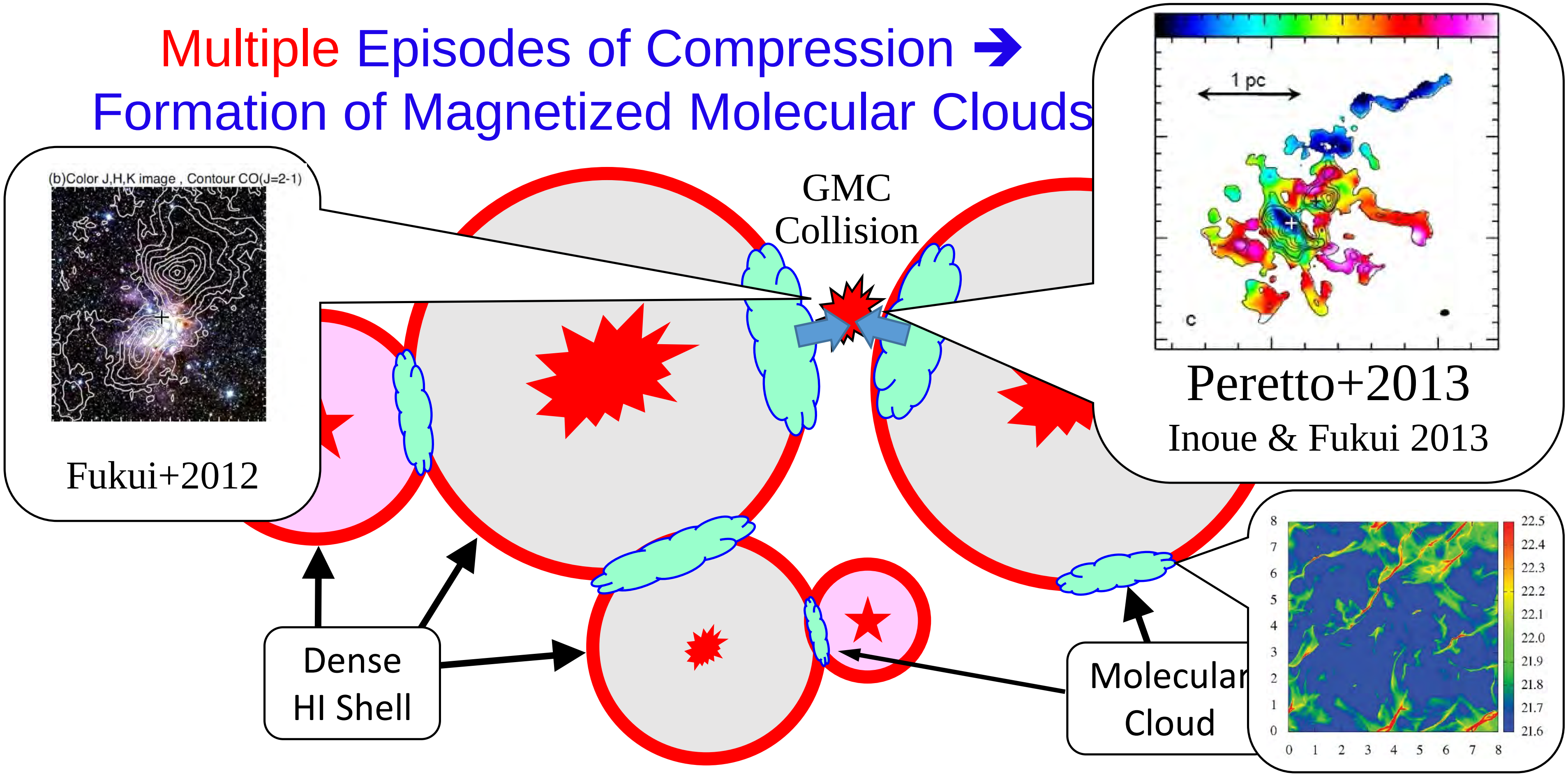
Further Compression of Molecular Clouds

➔Magnetized Massive Filaments & Striations

= "Herschel Filaments"

Network of Expanding Shells

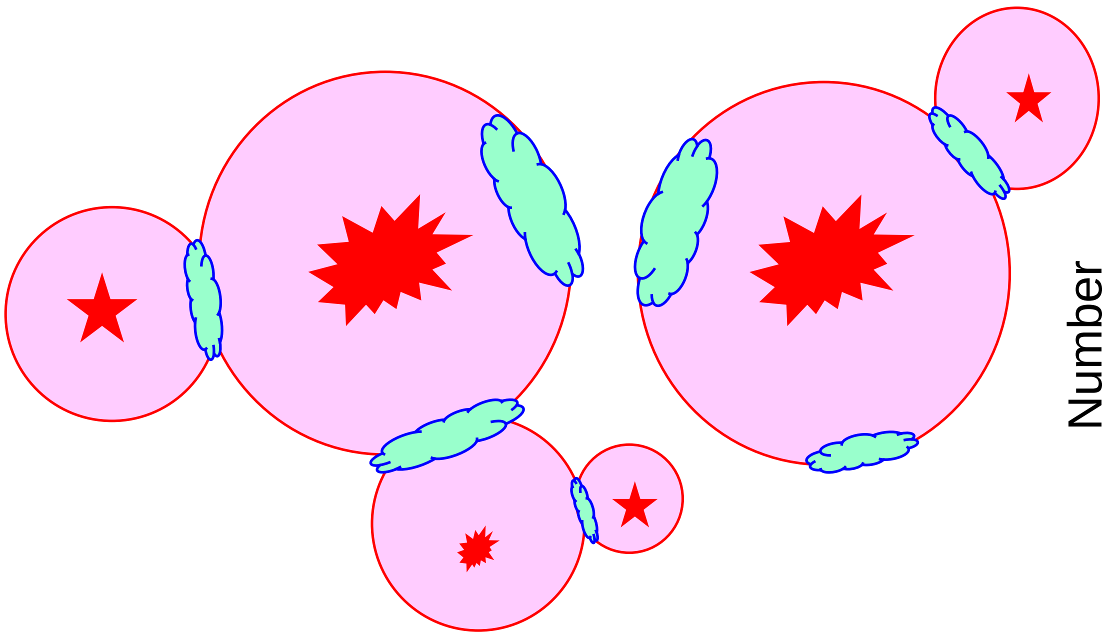
Multiple Episodes of Compression ➔
Formation of Magnetized Molecular Clouds

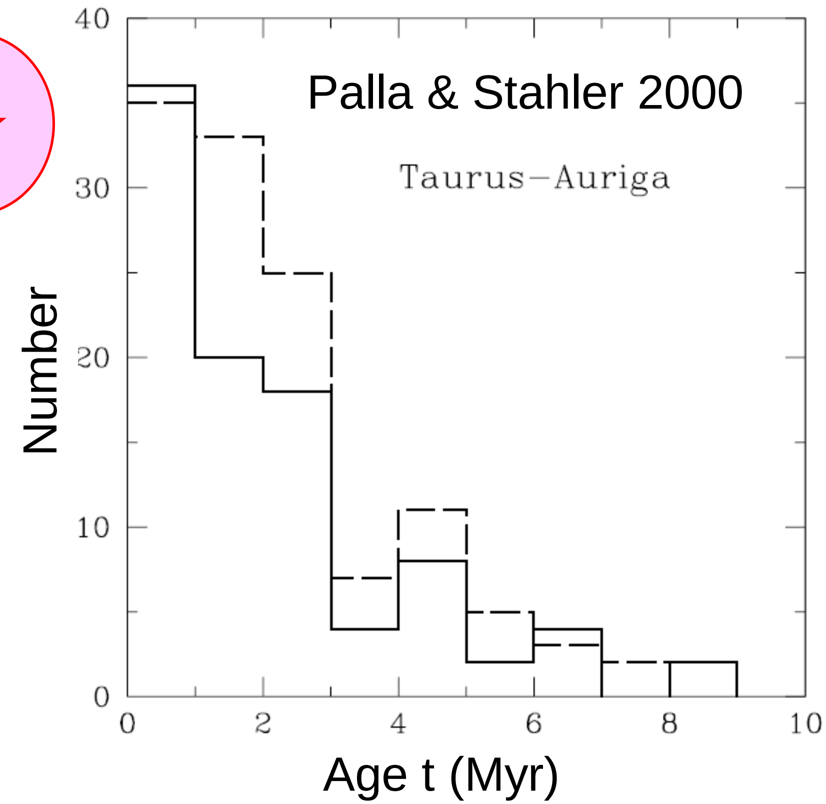


Each Bubble Visible Only for Short Time (~1Myr)!

δv of Clouds ~ Cloud-Cloud Col. Velocity ~ 10km/s

Natural Acceleration of Star Formation





Molecular Cloud Growth

➔ <u>Collisions of Clouds</u>

➔ Accelerated SF

Also in *Lupus, Chamaeleon, ρ Ophiuchi, Upper Scorpius, IC 348, and NGC 2264*

c.f., Vazquez-Semadeni+2007

Destruction of Molecular Clouds

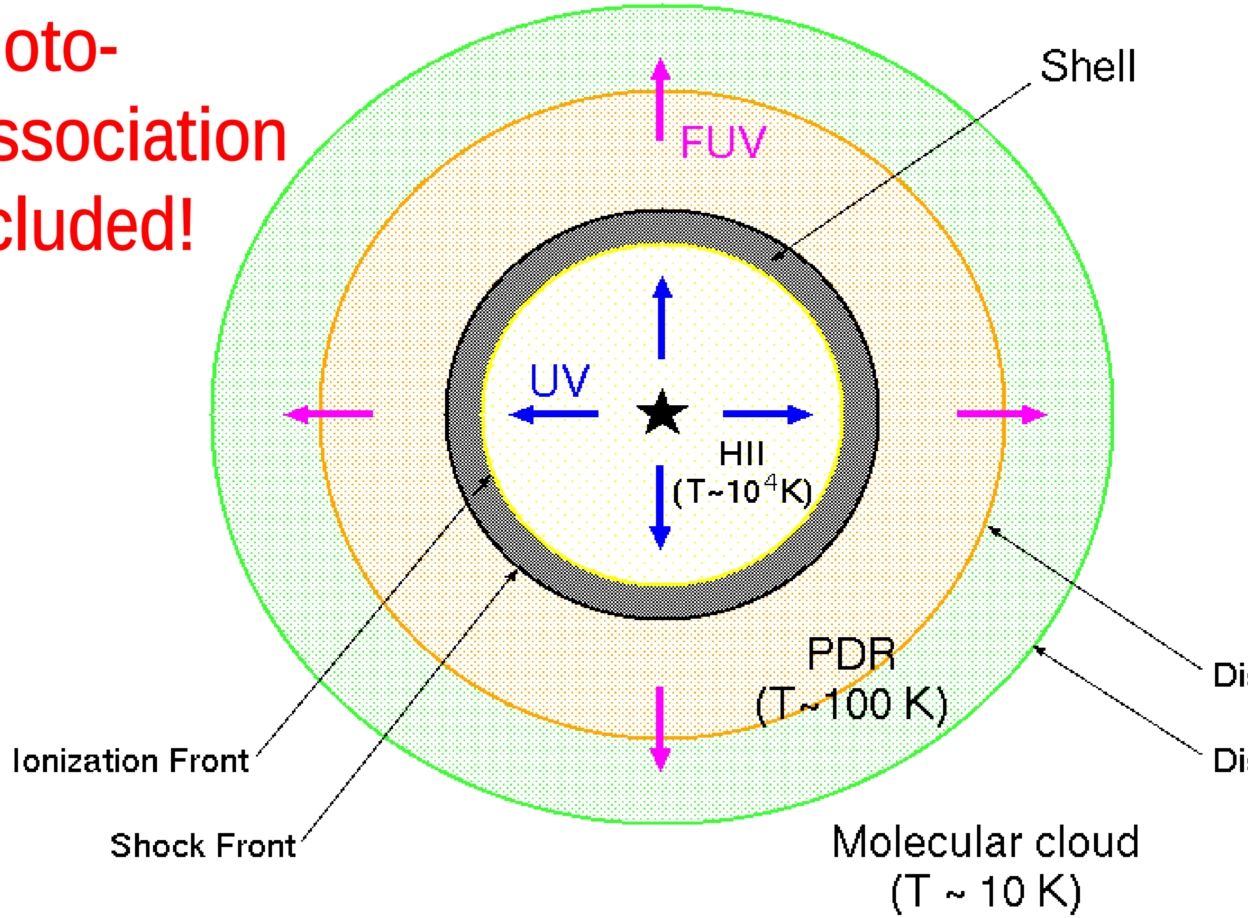
How to Stop Star Formation?

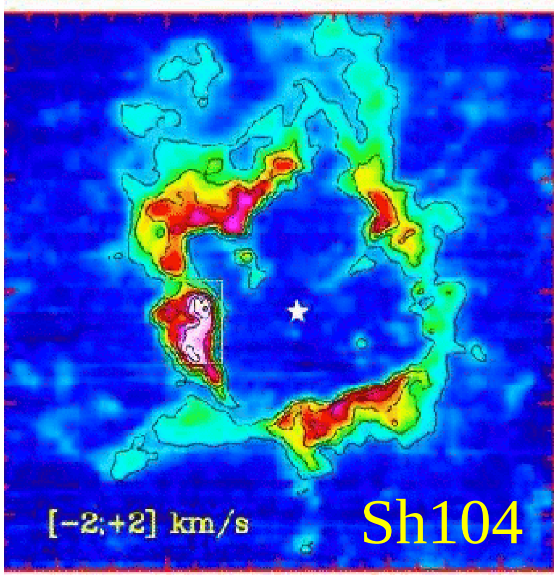
Radiative Feedback

See also *Kuiper*+, *Walch*+, *Hennebelle*+

Expanding HII Region in Magnetized Molecular Cloud

Photo-Dissociation Included!





Deharveng et al. 2003

Radiation Magnetohydrodynamics Calculation

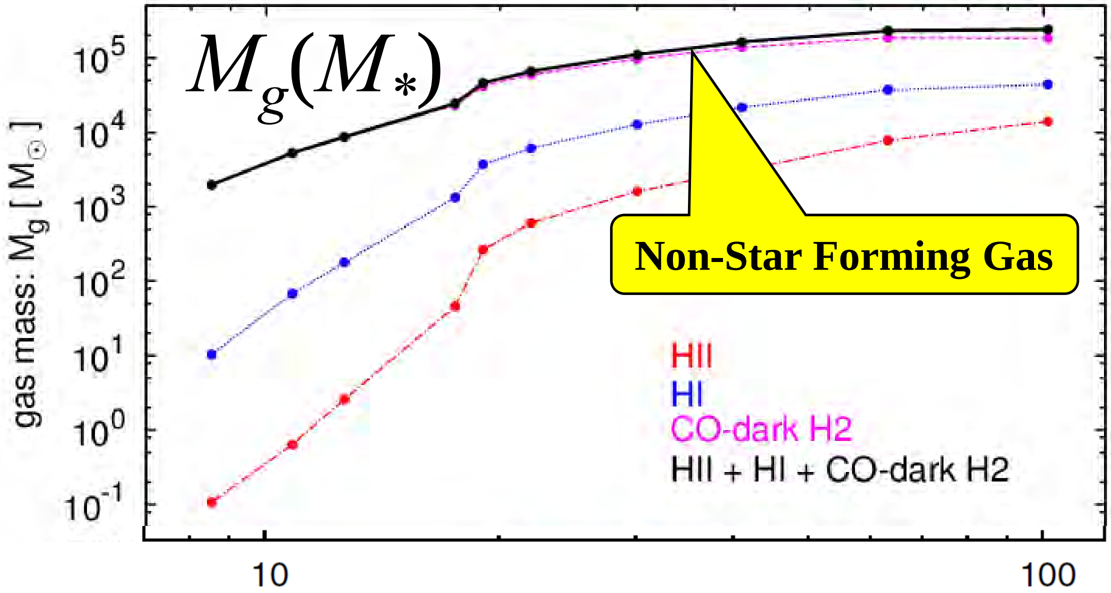
UV/FUV + H_2 + CO Chemistry (Hosokawa & SI 2005, 2006ab, 2007)

Disruption of <u>Magnetized</u> Molecular Clouds

Feedback due to UV/FUV in a Magnetized Cloud by MHD version of *Hosokawa & SI* (2005,2006ab)

➔

<u>$30M_\odot$</u> star destroys <u>$10^5 M_\odot$</u> H_2 gas in <u>4Myrs</u>!



Central Stellar Mass, $M_* / M_\odot$

(*SI, Inoue, Iwasaki, & Hosokawa 2015* A&A **580**, A49)

Star Formation Efficiency, KS-Law

$10^5 M_\odot$ H_2 destroyed by $M_* > 30 M_\odot$ in 4Myrs!

If $M_{\rm total} \sim 10^3 M_\odot$ stars

➔ ~1 Massive ($>30 M_\odot$) Star for Standard IMF

$$\varepsilon_{SF} = \frac{10^3 M_\odot}{10^5 M_\odot} = 0.01$$

Zuckerman & Evans 1974

Star Formation Time ~10Myr

Cloud Disruption Time: $T_{\rm d}$=4Myr+T_*

Schmidt-Kennicutt Law

Gas Depletion time: $\tau_{\rm depl} = \frac{T_{\rm d}}{\varepsilon_{\rm SF}} \sim 1.4\,{\rm Gyr}$

No Dependence on Cloud Mass! (e.g., Bigiel+2011)

Galactic Population of Molecular Clouds ???

Mass Function of Molecular Clouds

$$dn = N_{\rm cl}(M_{\rm cl})dM_{\rm cl}$$

$$\frac{\partial N_{\rm cl}}{\partial t} + \frac{\partial}{\partial M_{\rm cl}}\left(N_{\rm cl}\frac{dM_{\rm cl}}{dt}\right) = -\frac{N_{\rm cl}}{T_{\rm depl}}$$

Self-Growth $\frac{M_{\rm cl}}{T_{\rm form}}$

$T_{\rm depl}$=const.
"KS Law"

In steady state

$$\rightarrow N_{\rm cl}(M_{\rm cl}) = \frac{N_0}{M_0}\left(\frac{M_{\rm cl}}{M_0}\right)^{-\alpha}, \alpha = 1 + \frac{T_{\rm form}}{T_{\rm dis}}$$

$T_{\rm dis}$~14Myr & $T_{\rm form}$~10Myr → $\alpha = 1.7$

(*SI, Inoue, Iwasaki, & Hosokawa 2015* A&A **580**, A49)

Effect of Cloud-Cloud Collision on Mass Function of Molecular Clouds

Formulation of Coagulation Equation

$$\frac{\partial n_{\rm cl}}{\partial t} + \frac{\partial}{\partial M}\left(n_{\rm cl}\frac{{\rm d}M}{{\rm d}t}\right) = -\frac{n_{\rm cl}}{T_{\rm d}}$$

$T_{\rm d}$=const. "KS Law"

$\frac{M_{\rm cl}}{T_{\rm f}}$

$$+\frac{1}{2}\int_0^\infty\int_0^\infty K(m_1,m_2)n_{{\rm cl},1}n_{{\rm cl},2}\,\delta(m-m_1-m_2){\rm d}m_1{\rm d}m_2 - \int_0^\infty K(m,m_2)n_{\rm cl}n_{{\rm cl},2}{\rm d}m_2\,.$$

Effect of Cloud-Cloud Collision

Kobayashi, SI, Kobayashi, & Hasegawa 2017, ApJ **836**, 175

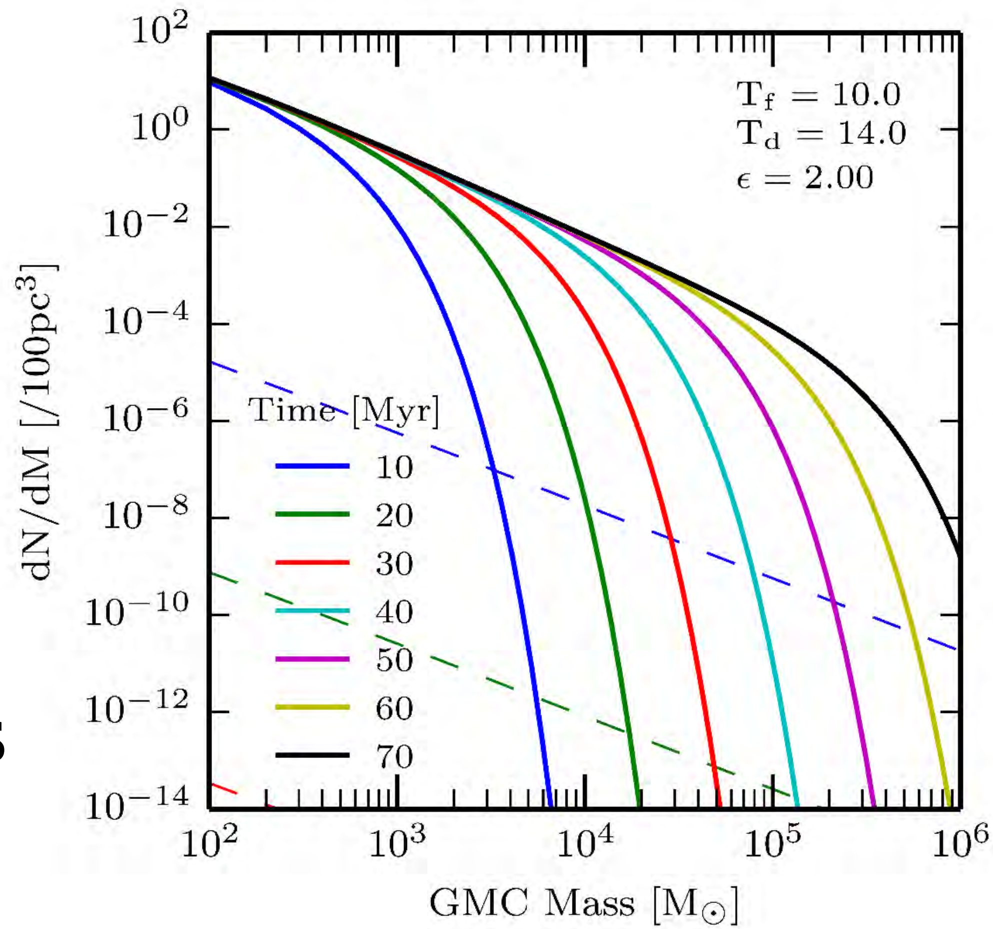
Resultant Mass Functions

Case without Cloud-Cloud Collision

self-growth & self-dispersal only

Assumption:

$\delta v_{\text{cloud-cloud}} = 10\text{km/s}$



Resultant Mass Functions

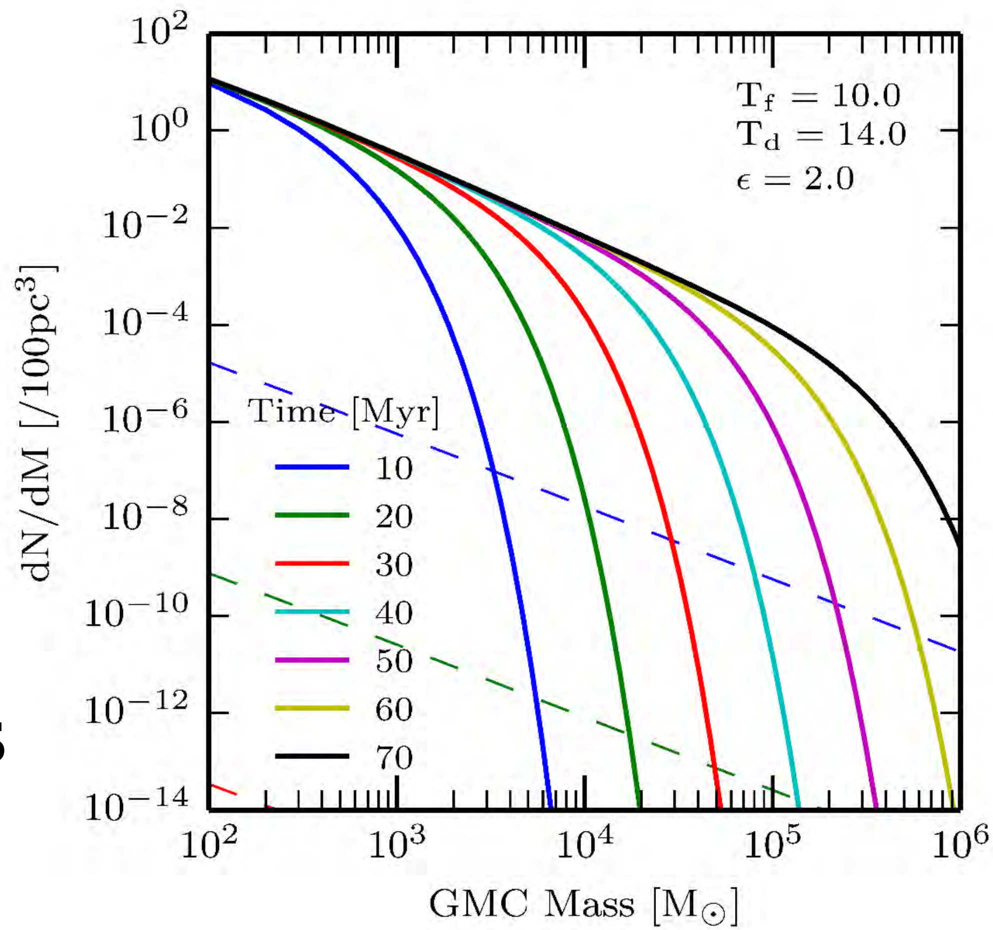
Case with Cloud-Cloud Collision

+ self-growth

& self-dispersal

Assumption:

$\delta v_{\text{cloud-cloud}} = 10\text{km/s}$



CCC does not alter GMC mass function significantly!

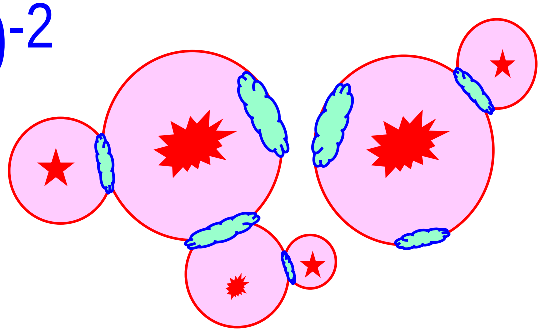
Kobayashi, SI, Kobayashi, & Hasegawa 2017, ApJ **836**, 175

Summary

- Fragmentation of Filaments ➔ Core Mass Function
- Bubble-Dominated Formation of Molecular Clouds

➔ Unified Picture of Star Formation

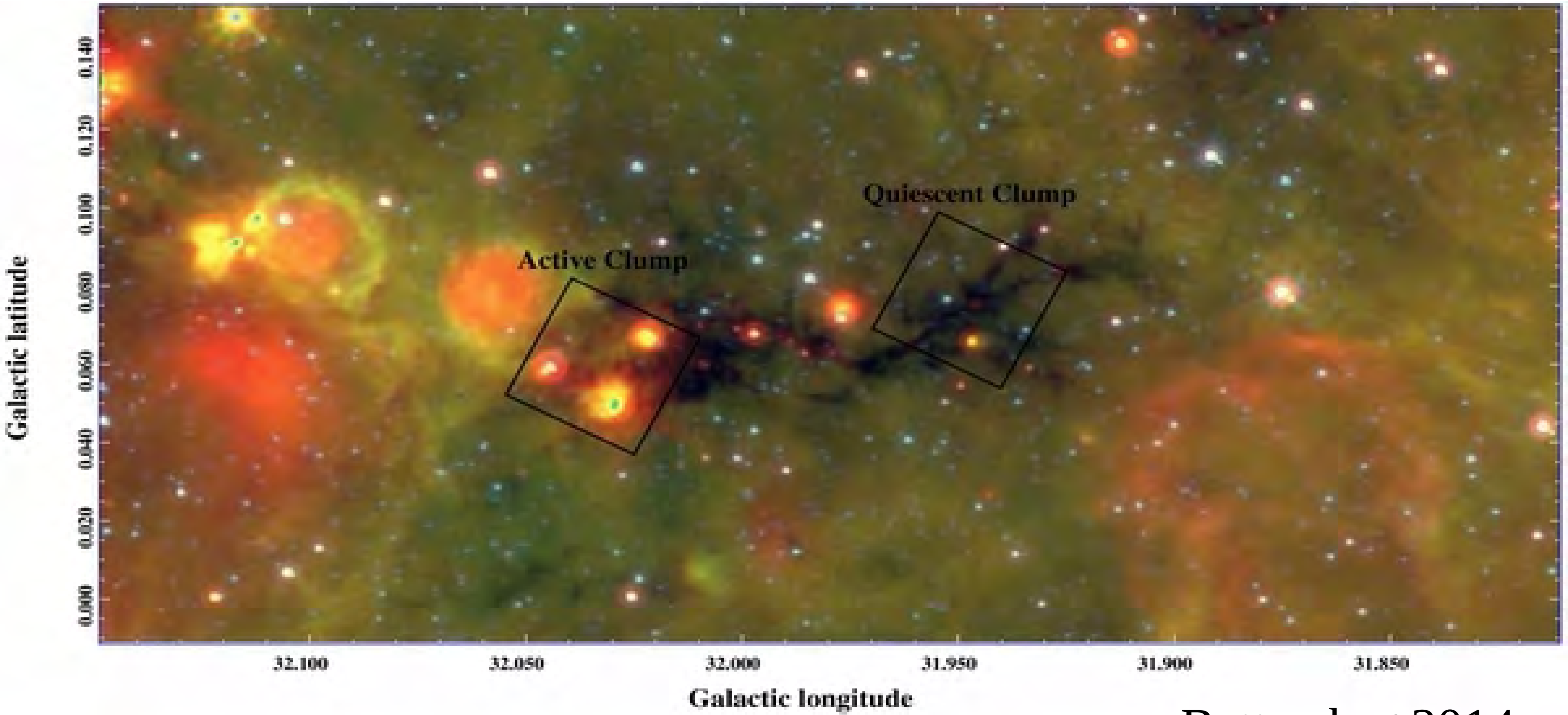
- $\delta v_{\text{cloud-cloud}} \sim 10^1$ km/s
- Star Formation Efficiency: $\varepsilon_{SF} \sim 10^{-2}$
- Schmidt-Kennicutt Law
- Accelerated Star Formation
- Slope of Cloud Mass Func $= 1 + T_{\text{form}}/T_{\text{dis}} \sim 1.7$



SI, Inoue, Iwasaki, & Hosokawa 2015, A&A **580**, A49

Kobayashi, SI, Kobayashi, & Hasegawa 2017, ApJ **836**, 175

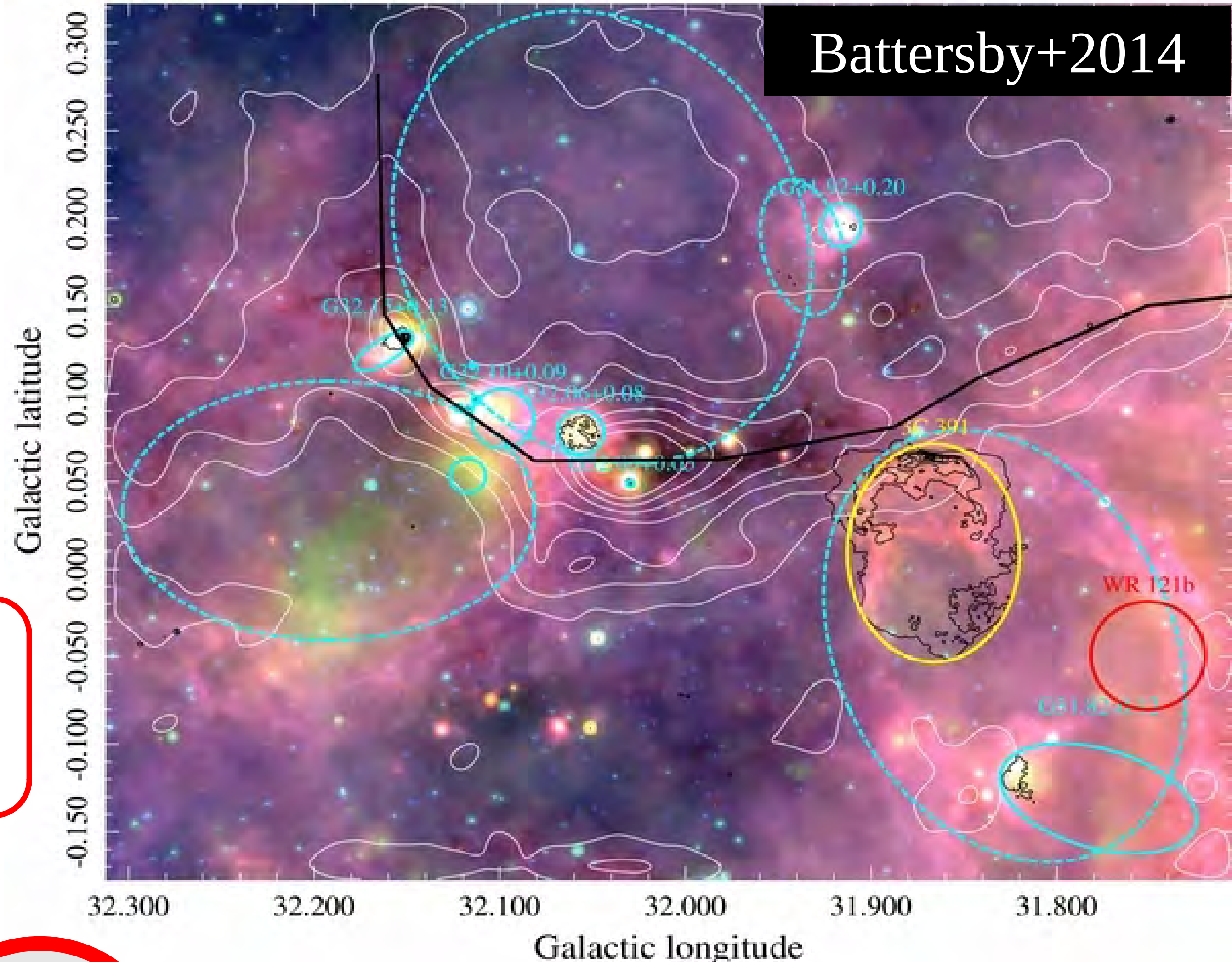
Massive Star Formation in Ridge



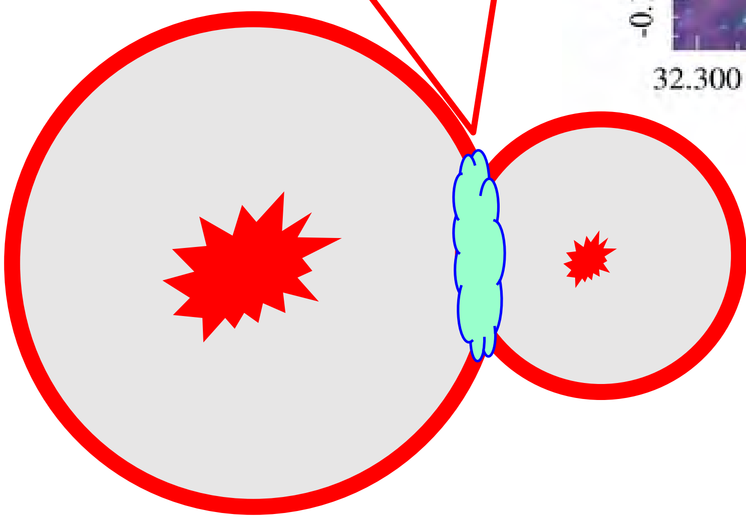
Battersby+2014

Extensive Herschel Studies on Massive Star Formation in “**Ridges**”

Ridge or Edge-On Shell?



Edge-On View of Compressed Shell
➔ Ridge or Bar!



Bubbles (cyan dashed circles)
HII regions (cyan solid circles)
SNR 3C 391 (yellow oval)
Wolf–Rayet star WR 121b (red oval)

Advent of Large Surveys such as **FUGIN**

Numerous Straight Ridges or Bars! **Why?**

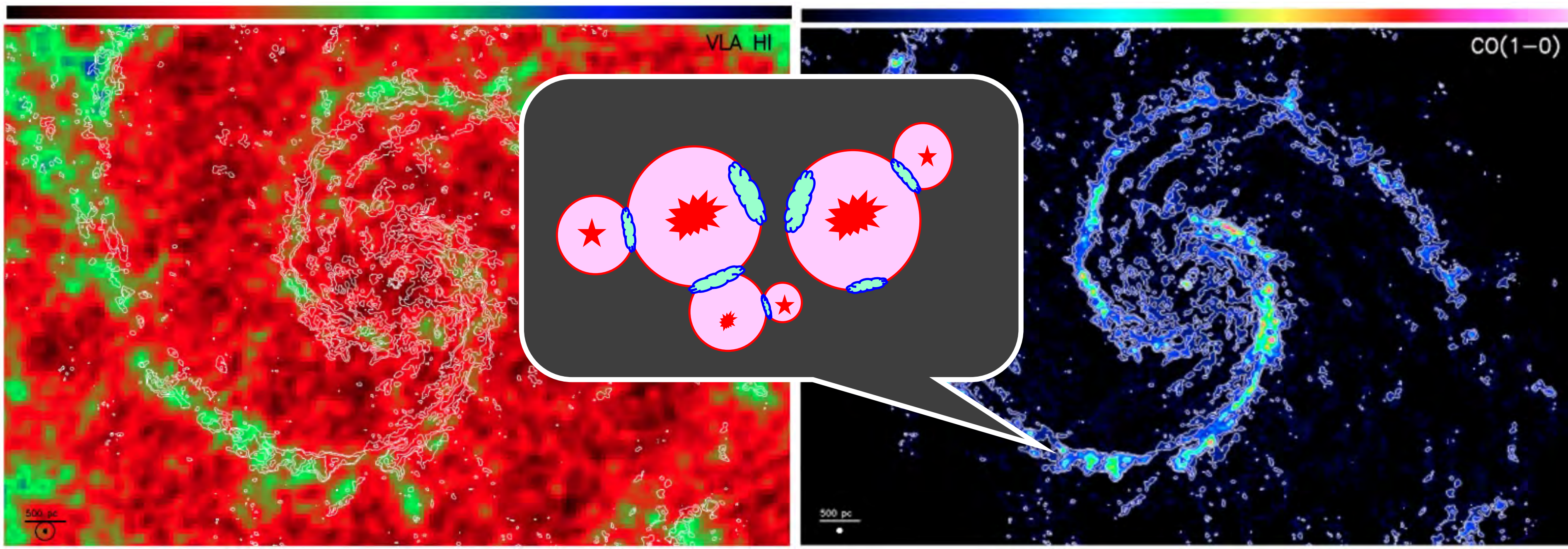
Edge-On View of Compressed Shells = Ridges or Bars! ➔ **Bar // *B***

➔ Obs Proof of Cloud Formation Theory!!!

Galactic Scale View

HI Clouds vs Molecular Clouds

HI (VLA)　　　　CO(1-0)



M51 in PAWS　Schinnerer+ (2013)

Slope of Cloud Mass Function

Steady State Mass Function of Molecular Clouds

$$\rightarrow N_{\rm cl}(M_{\rm cl}) = \frac{N_0}{M_0}\left(\frac{M_{\rm cl}}{M_0}\right)^{-\alpha}, \alpha = 1 + \frac{T_{\rm form}}{T_{\rm dis}}$$

Typically, $T_{\rm dis} \sim T_{\rm form} + 4{\rm Myr} \rightarrow \alpha = 1.7$

In low density region (Inter-Arm Region)

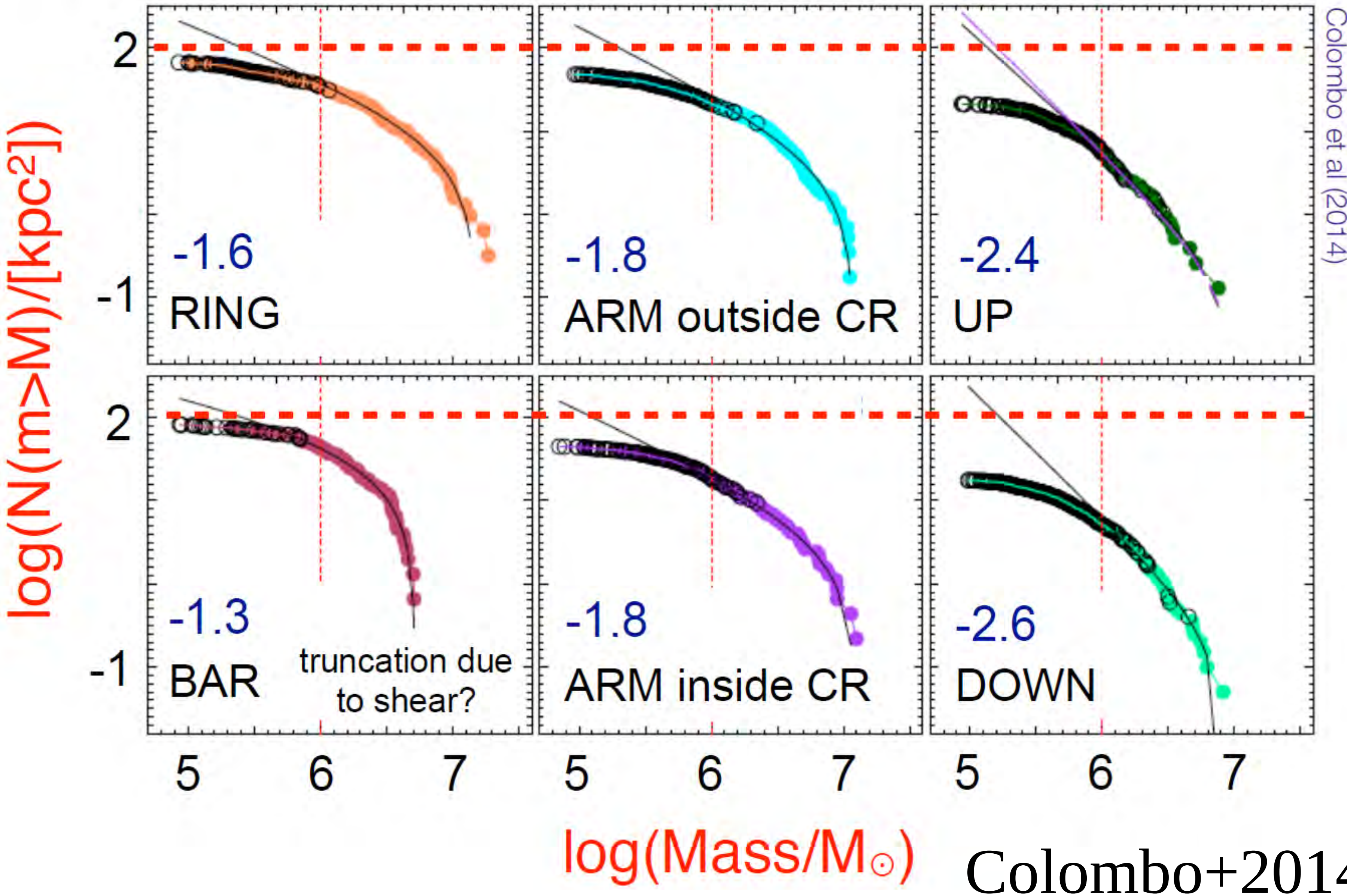
Larger $T_{\rm form} > T_{\rm dis}$ ➔ Larger α

In high density region (Arm Region)

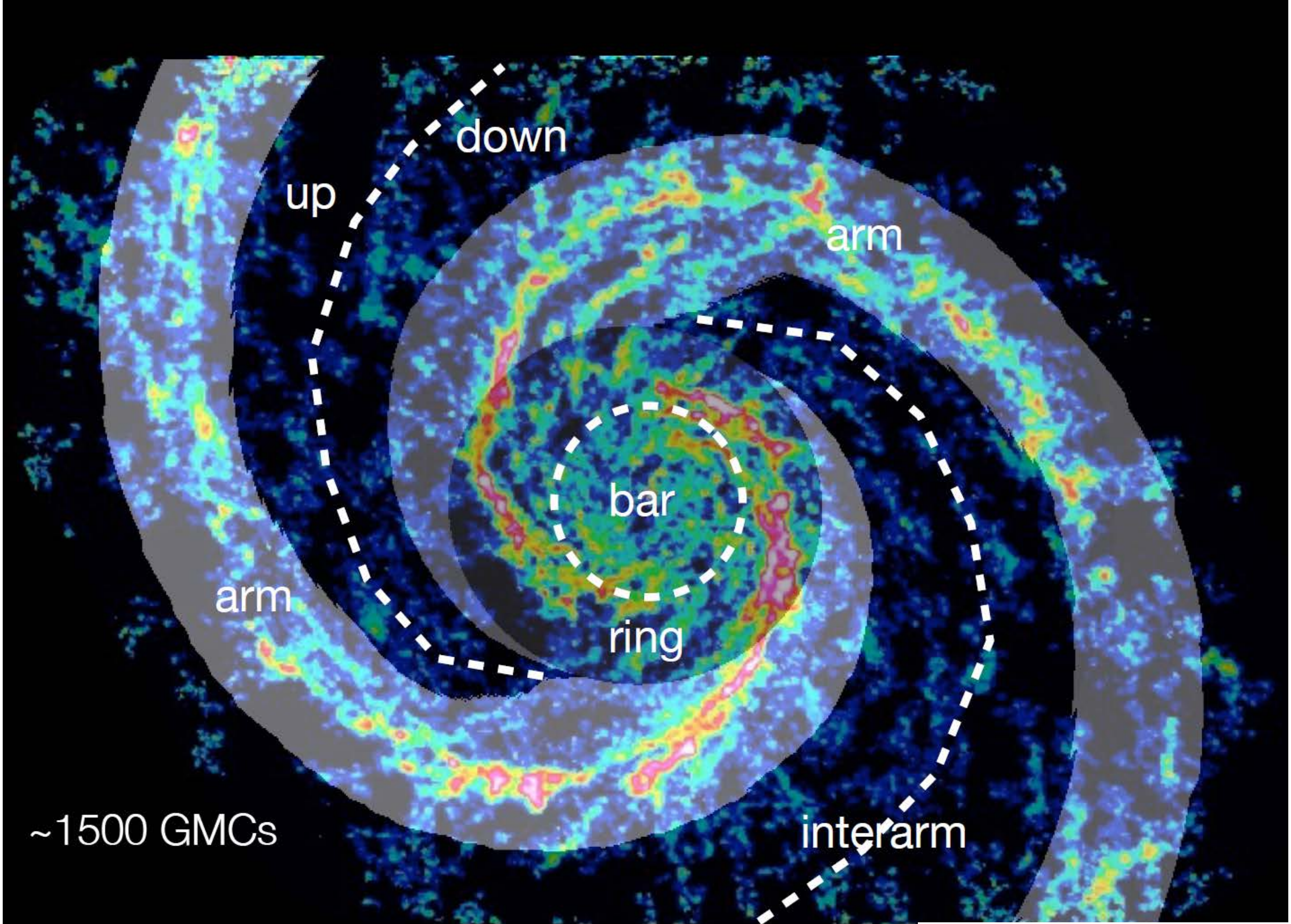
Smaller $T_{\rm form}$ ➔ Smaller α

➔ GMCs in M51 (Colombo+2014)

Variation of GMC Mass Function in M51



Colombo+2014


down
up
arm
bar
arm
ring
~1500 GMCs
interarm

Mass Function of Molecular Clouds

$$dn = N_{\mathrm{cl}}(M_{\mathrm{cl}})dM_{\mathrm{cl}}$$

$$\frac{\partial N_{\mathrm{cl}}}{\partial t} + \frac{\partial}{\partial M_{\mathrm{cl}}}\left(N_{\mathrm{cl}}\frac{dM_{\mathrm{cl}}}{dt}\right) = -\frac{N_{\mathrm{cl}}}{\tau_{\mathrm{dis}}}$$

➔ CO-Dark Gas

In steady state, mass of CO-dark gas can be huge!

➔ Formation of Molecular Clouds should recycle CO-Dark Gas!

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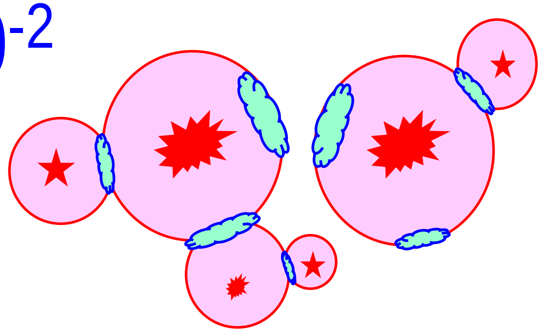
- Accelerated Star Formation
- Slope of Cloud Mass Func $=1+T_{\text{form}}/T_{\text{dis}} \sim 1.7$



SI, Inoue, Iwasaki, & Hosokawa 2015, A&A **580**, A49

Kobayashi, SI, Kobayashi, & Hasegawa 2017, ApJ **836**, 175

Future Work

- Galactic Disk Scale Simulations with GMC Model as a Sub-Grid Physics: Spatial Resolution ~ 100pc
- Galactic Center
- Model of Spur

SI, Inoue, Iwasaki, & Hosokawa 2015, A&A **580**, A49

Kobayashi, SI, Kobayashi, & Hasegawa 2017, ApJ **836**, 175