The Formation of Molecular Clouds and Galactic Star Formation

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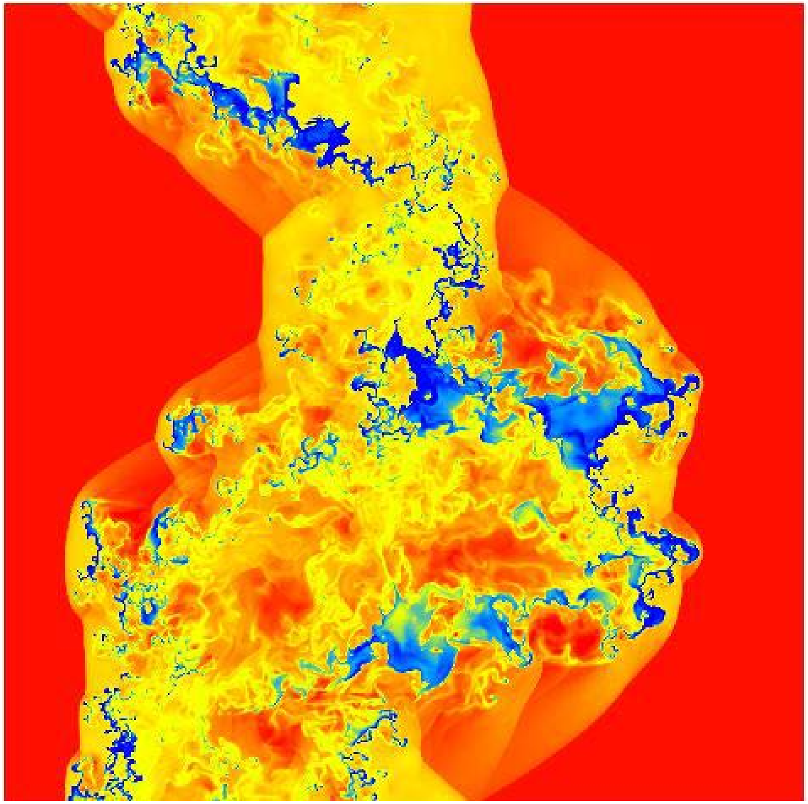
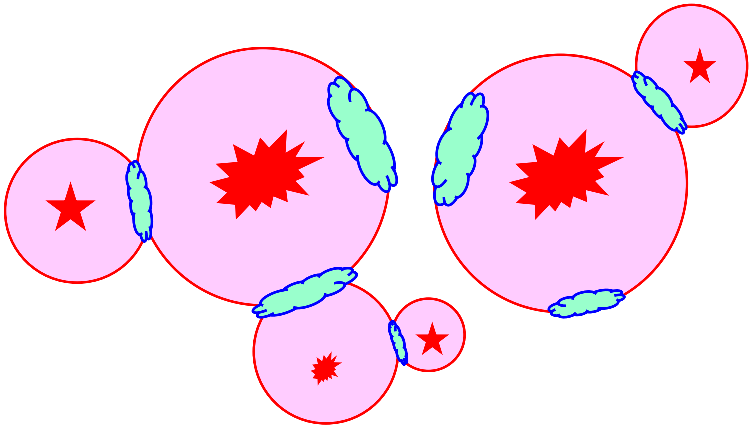
(*SI, Inoue & Iwasaki 2014, submitted*)

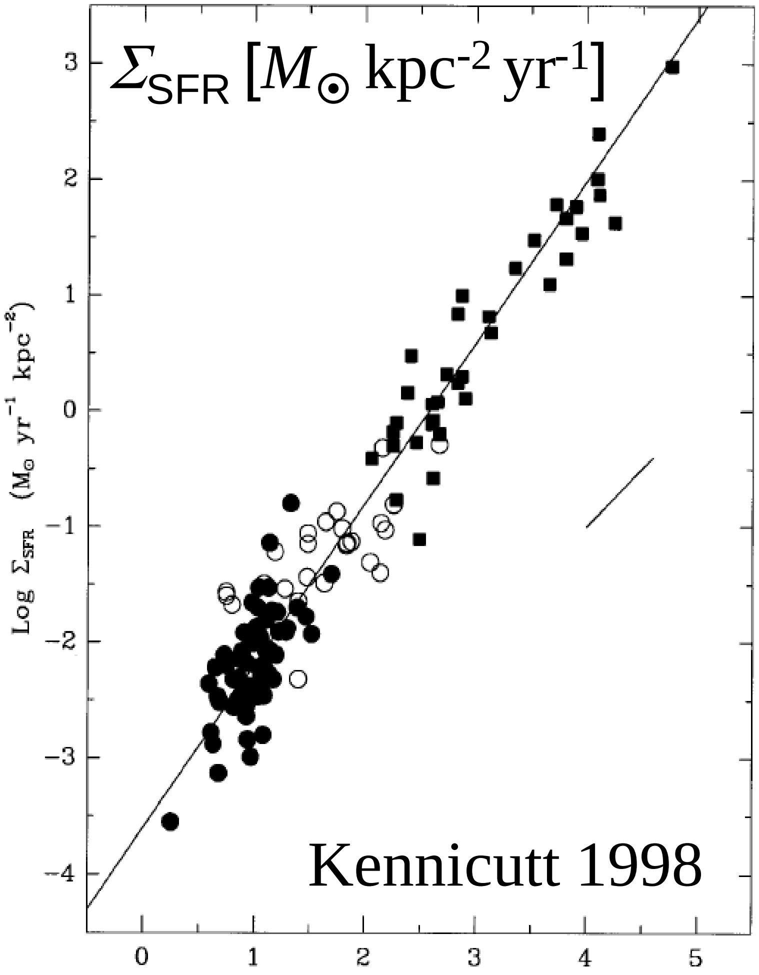




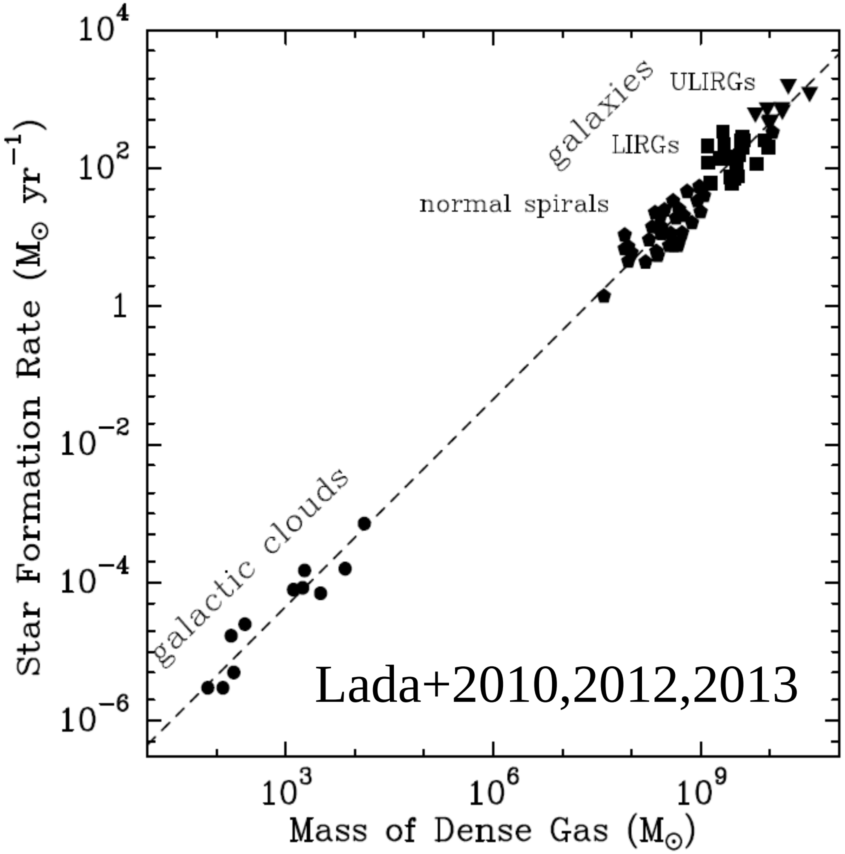
Outline

- Observations: Herschel, ALMA, etc.
  - Filaments, Mass Function of Dense Cores
- Phase Transition Dynamics
  - Thermal Instability, Sustained Turbulence
  - Effect of Magnetic Field
- Galactic Picture of Cloud Formation
  - Accelerated Star Formation
  - SF Efficiency & Schmidt-Kennicutt Law
  - Mass Function of Molecular Clouds
    - Spiral Arm vs Inter-Arm
- Summary

Schmidt-Kennicutt Law of SF

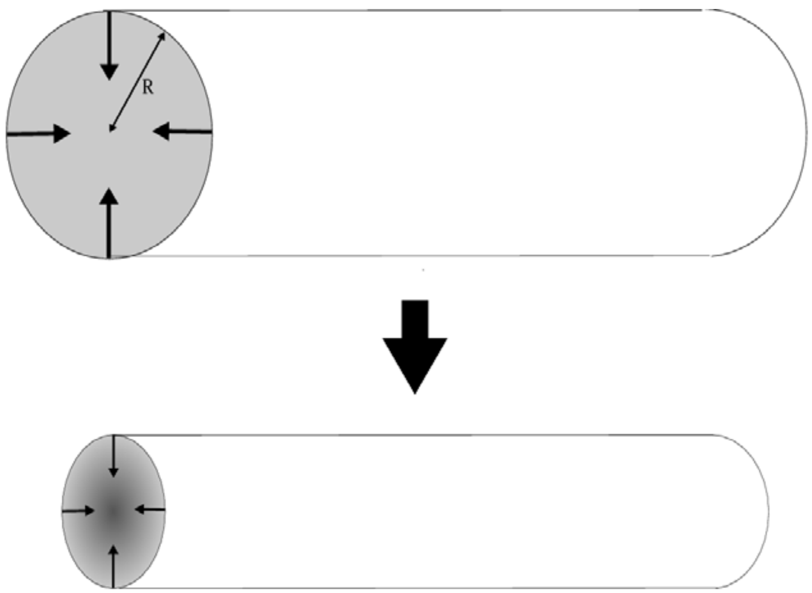


Σ_{gas} [$M_\odot$/pc^2]



- Column Density: Σ_{gas} [$M_\odot$/pc^2]
- SF Rate: Σ_{SFR} [$M_\odot$ /kpc^2 yr]
- Timescale: Σ_{gas} / Σ_{SFR} ~ 10^9 yr

Character of Self-Gravity of Filaments



Cylindrical Symmetry

$$\frac{1}{R}\frac{\partial}{\partial R}R\frac{\partial\Phi}{\partial R}=4\pi G\rho \Rightarrow \frac{\partial}{\partial R}R\frac{\partial\Phi}{\partial R}=2\cdot 2\pi G\rho R$$

$$-\frac{\partial\Phi}{\partial R} \propto \frac{2GM_{\mathrm{L}}}{R}, \quad M_{\mathrm{L}}=2\pi\int\rho R dR$$

Mass per Unit Length

$$-\frac{1}{\rho}\frac{\partial P}{\partial R} \propto \frac{C_{\mathrm{S}}^2}{R}$$

No isothermal pressure support against collapse ➔ $\gamma_{crit}=1$ for cylinder

⟷ $\gamma_{crit}=4/3$ for sphere, $\gamma_{crit}=0$ for sheet

Critical Line-Mass for Filaments

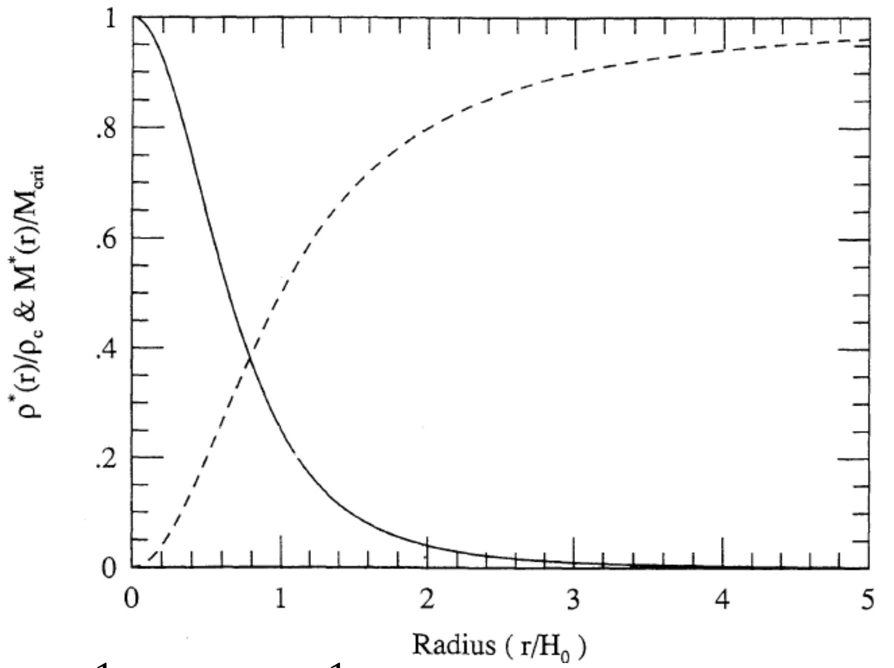
Isothermal Equilibrium Filament

(Stodolkiewicz 1963; Ostriker 1964)

$$\rho_{\rm eq}(r) = \rho_c \left[1 + \left(\frac{r}{H_0} \right)^2 \right]^{-2},$$

where H_0 is the scale height and is defined by

$$H_0 \equiv \sqrt{\frac{2C_s^2}{\pi G \rho_c}}.$$



$$M_{\rm L,crit} \equiv 2\pi \int_0^\infty \rho_{\rm eq}(r) r dr = \frac{2C_S^2}{G} \approx 2 \times 10^1 M_\odot\ {\rm pc}^{-1}$$

If $M_{\rm L} < M_{\rm L,crit}$, isothermal filament can be pressure-confined.

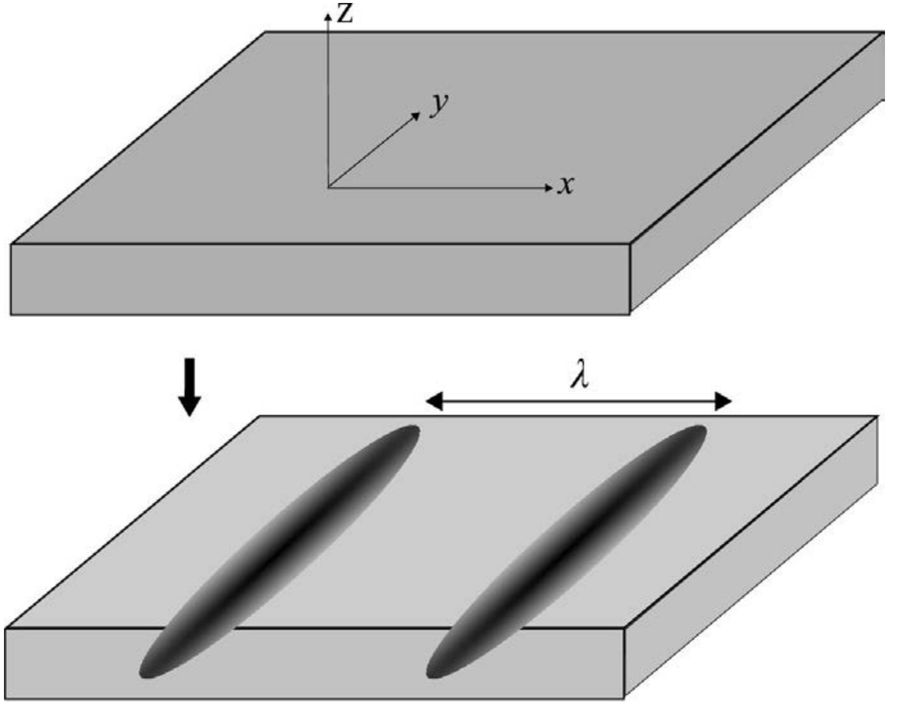
If $M_{\rm L} > M_{\rm L,crit}$, isothermal filament collapses indefinitely!

➔**Self-gravity is essential for filament with $M_{\rm L} \approx M_{\rm L,crit}$.**

(SI & Miyama 1992, 1997)

What is the resultant line-mass?

Fragmentation of Isothermal Sheet-Like Cloud



Linear Analysis➔

$\lambda_{\mathrm{fastest}} \approx 4\pi H = 4C_s^2/(G\Sigma)$

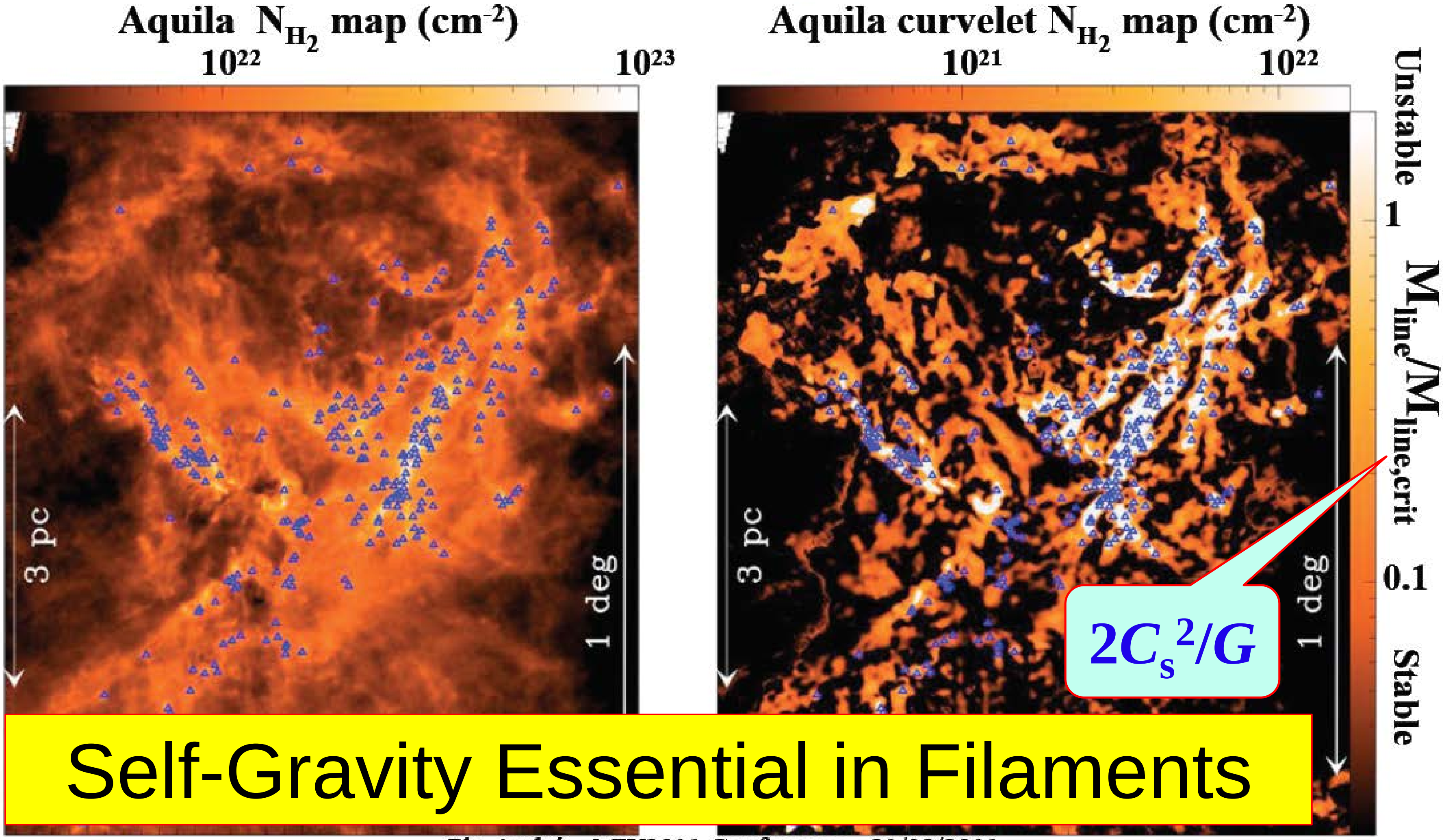
➔ $M_L \approx \Sigma\lambda_{\mathrm{fastest}} = 4C_s^2/G = 2M_{L,\mathrm{crit}}$

Nagai, SI, & Miyama 1998

Highlight of Herschel Result (André+2010)

Prestellar cores are preferentially found within the densest filaments

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



Self-Gravity Essential in Filaments

Mass Function of Cores in a Filament

Inutsuka 2001, ApJ **559**, L149

Perturbation of Line-Mass of a Filamentary Cloud using Press-Schechter Formalism

Initial Power Spectrum

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

Mass Function

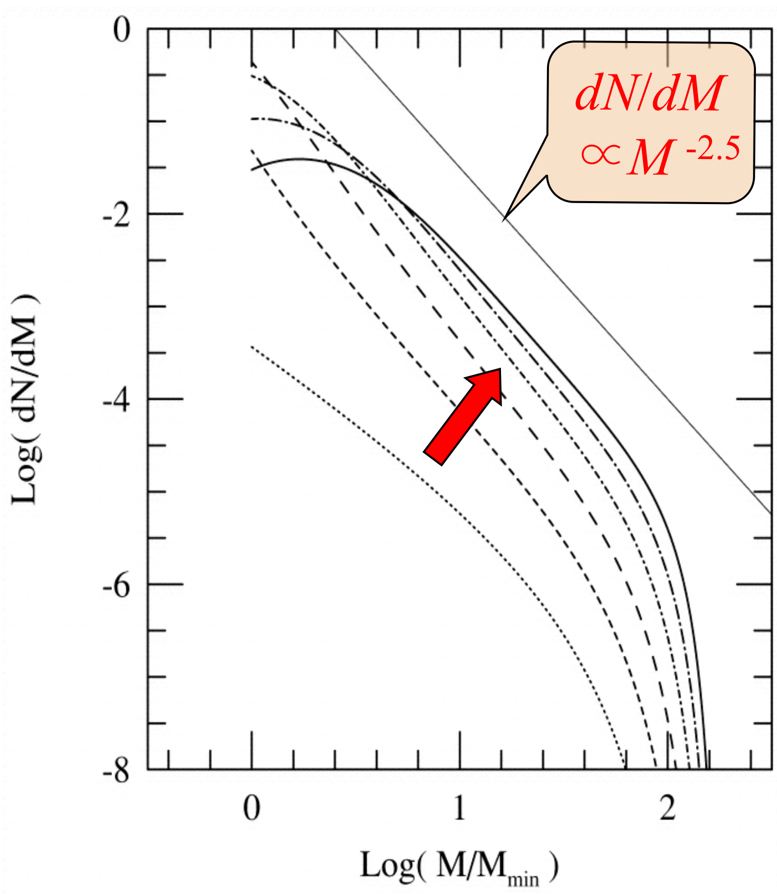
$$\frac{dN}{dM} = -2\frac{M_{\rm line}}{M}\frac{df(M,\ \delta > \delta_c)}{dM}$$

$$= -\frac{M_{\rm line}}{M}\frac{\delta_c}{\sqrt{\pi}}\exp\left(-\frac{\delta_c^2}{2\sigma_M^2}\right)\frac{1}{\sigma_M^3}\frac{d\sigma_M^2}{dM}$$

Observation of Both Perturbation Spectrum and Mass Function

➔direct test !

cf. Hennbelle & Chabrier



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

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

Mass Function of Cores in a Filament

Inutsuka 2001, ApJ **559**, L149

Perturbation of Line-Mass of a Filamentary Cloud using Initial Power Spectrum

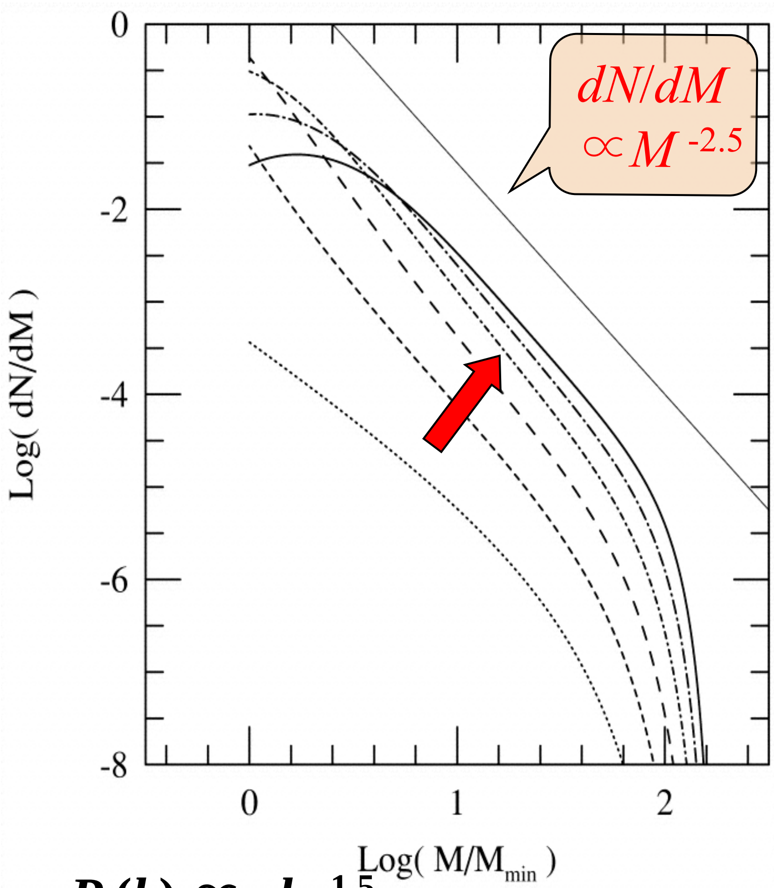
$$P(k) \propto k^{-1.5}$$

Mass Function

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

Observation of Both Perturbation Spectrum and Mass Function

➔direct test !



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

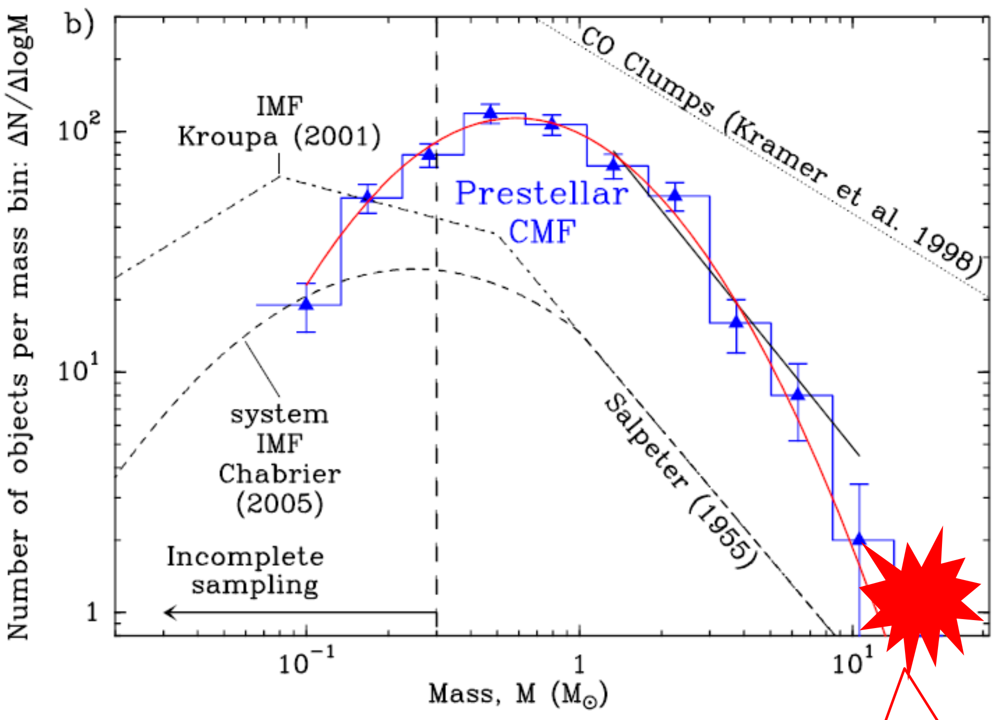
t/t_{ff} = 0 (dotted) , 2, 4, 6, 8, 10 (solid)

≈5/3: Kolmogorov!

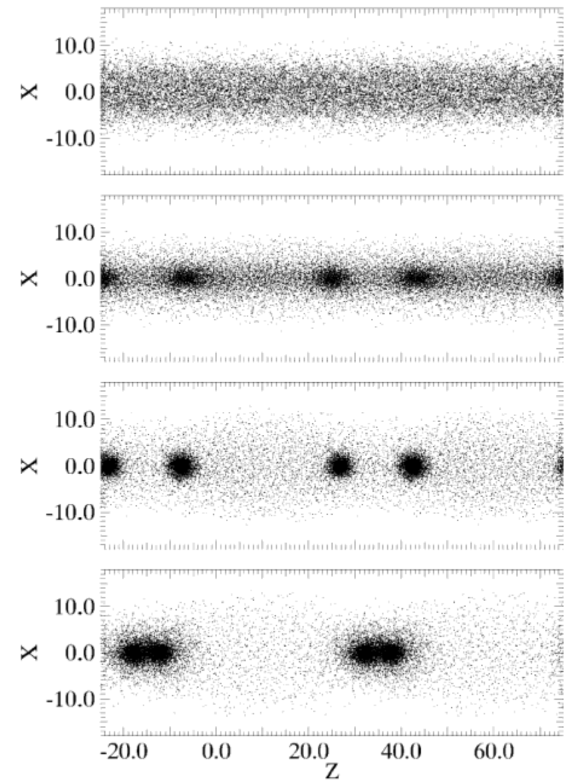
Obs $P(k) \propto k^{-1.6}$ (*André*+2014 PPVI; *Roy*+2014)

Applicability of Filament Paradigm for Massive Stars?

Aquila CMF from Herschel



André+2010; Könyves+2010

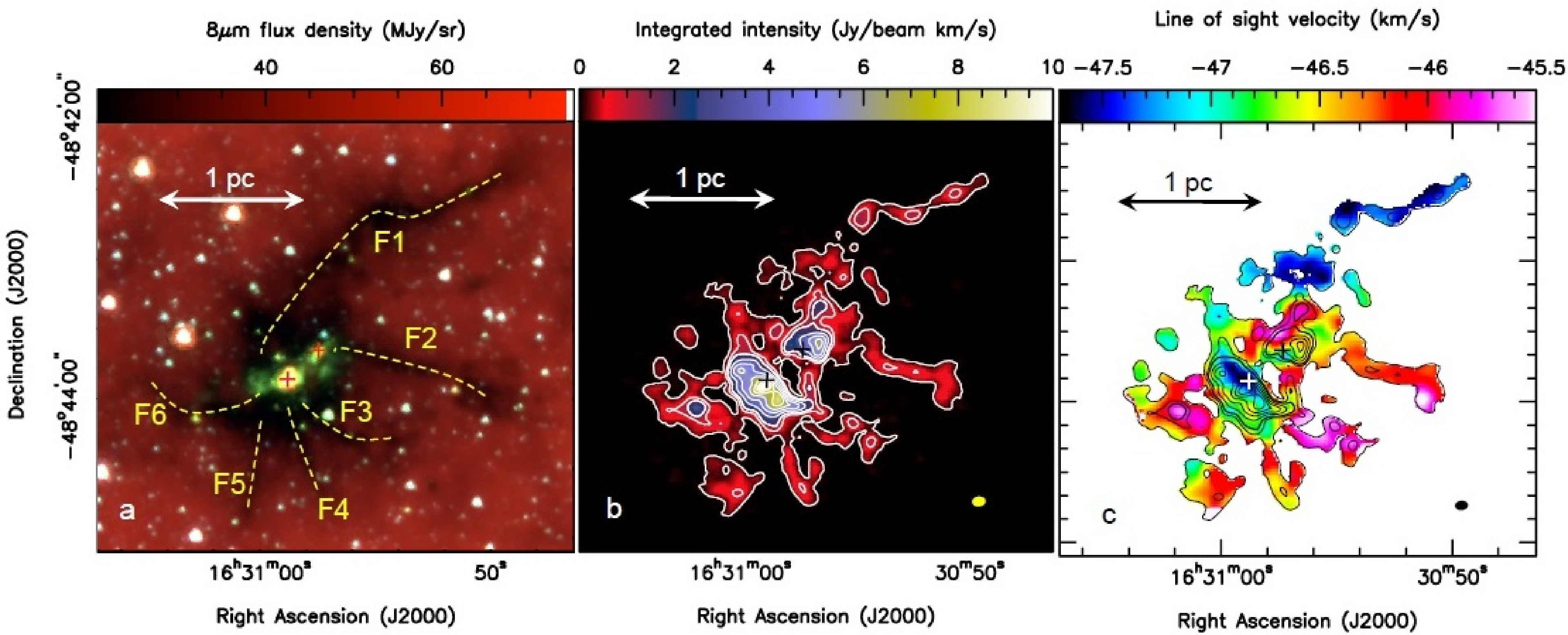


SI & Miyama 1997

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 ~ $10^{-3}\, M_{\odot}/\mathrm{yr}$

Nicely Understood in Filament Paradigm

Filament Paradigm Completely Successful?!

Other Modes of Star Formation?

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

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

Formation of Molecular Clouds

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

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

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

Dynamical Timescale of ISM ~ 1Myr

« Timescale of Galactic Density Wave ~ 100Myr

Expanding HII regions are also important.

Basic Equations for ISM Dynamics

- Eq. of Continuity

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

- EoM

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

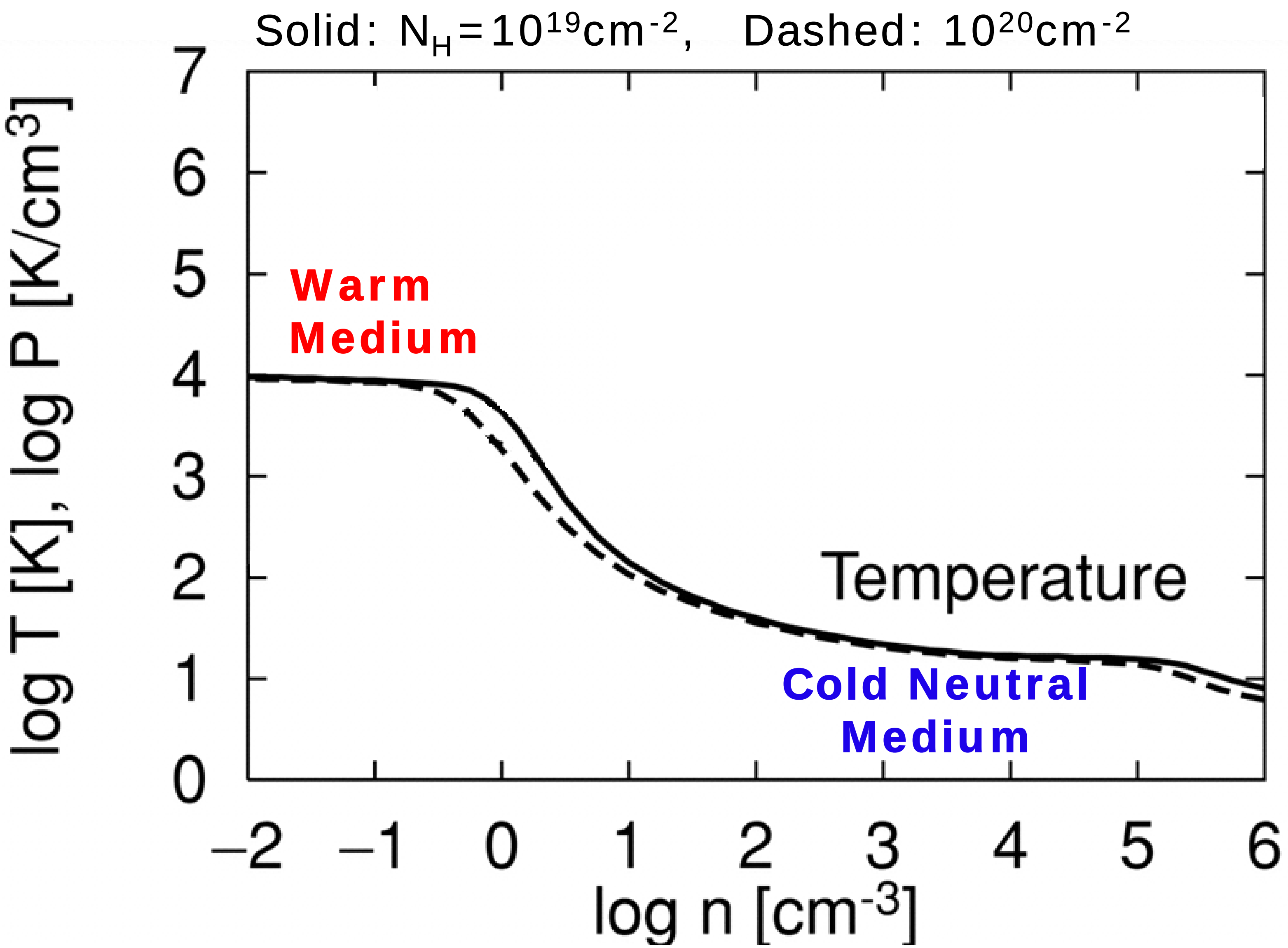
- Eq. of Energy
  - Radiative Heating & Cooling: *Γ, Λ*
    - H, C^+, O, Fe^+, Si^+, H_2, CO
  - Chemical Reaction
    - HII, HI, H_2, CII, CO
  - Thermal Conduction
    - conduction coefficient: *κ*

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

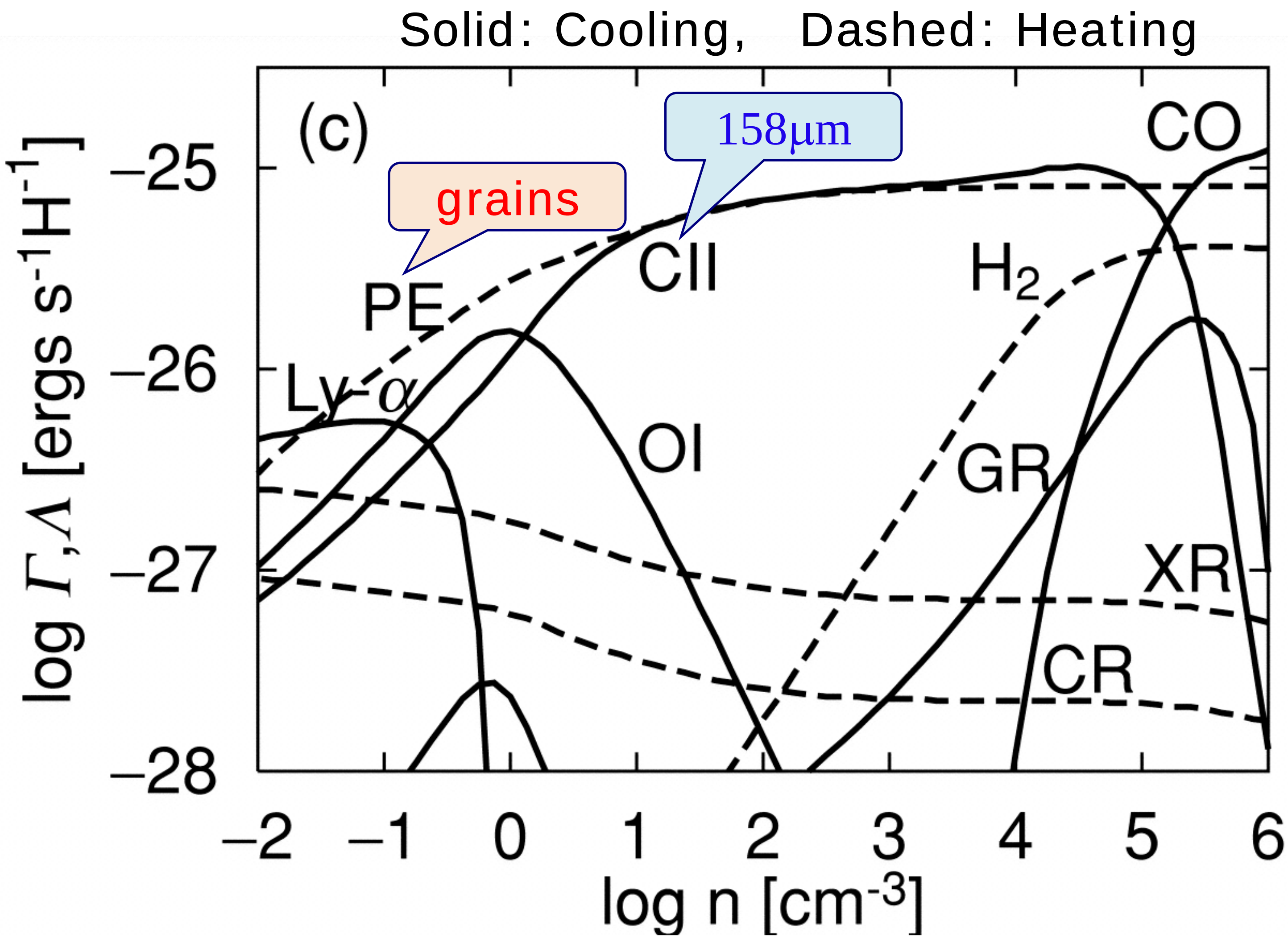
Self-Gravity Negligible for Low Density Gas

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

Radiative Equilibrium for a given density

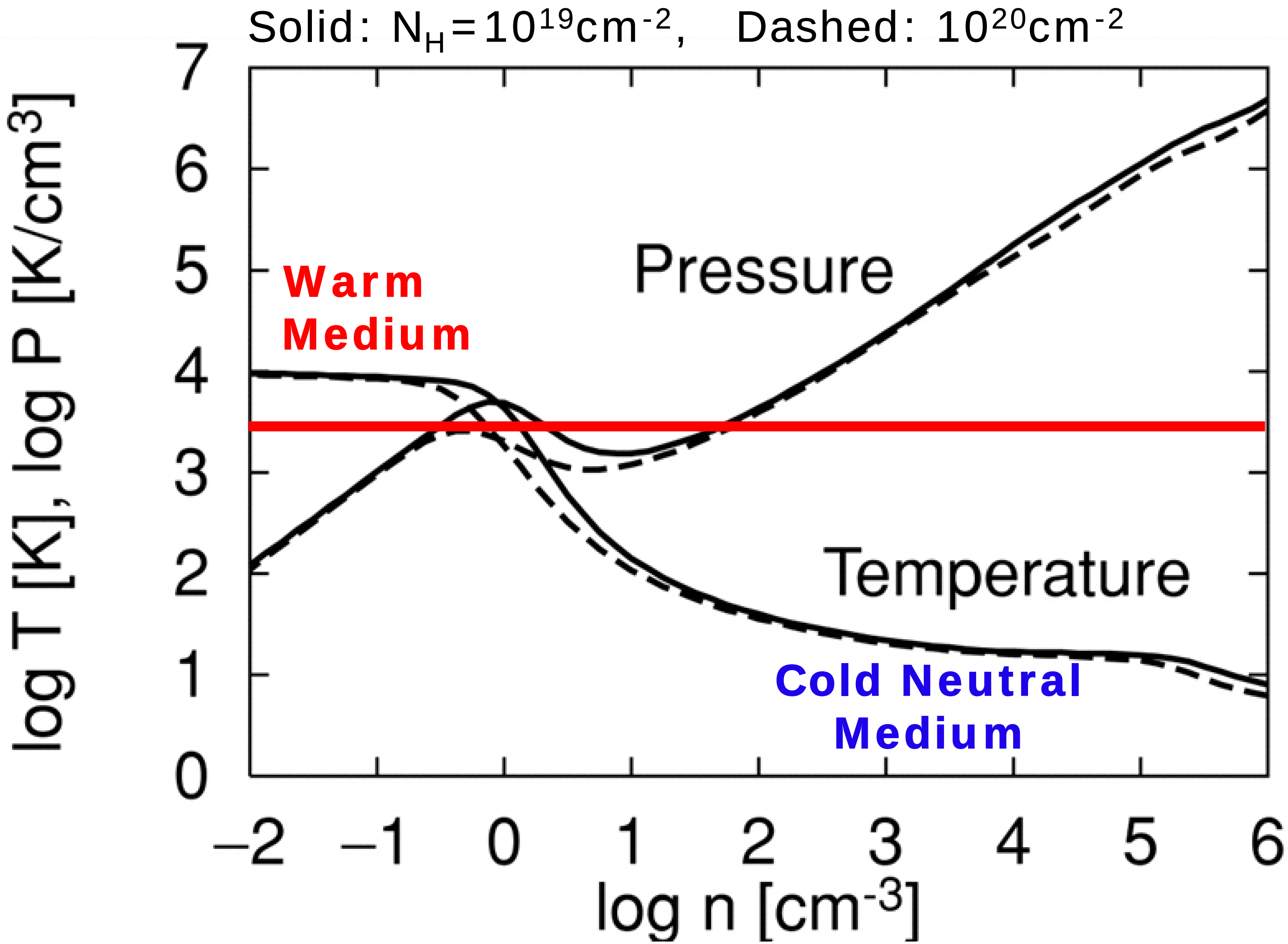


Radiative Cooling & Heating



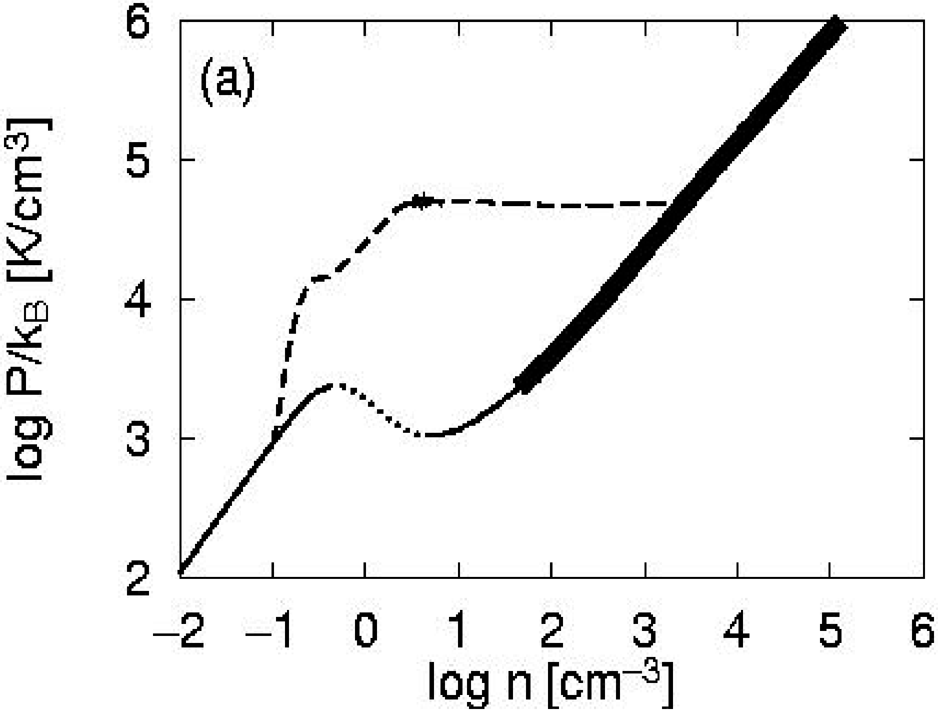
Koyama & SI (2000) ApJ **532**, 980 , (adding CO to Wolfire et al. 1995)

Radiative Equilibrium for a given density



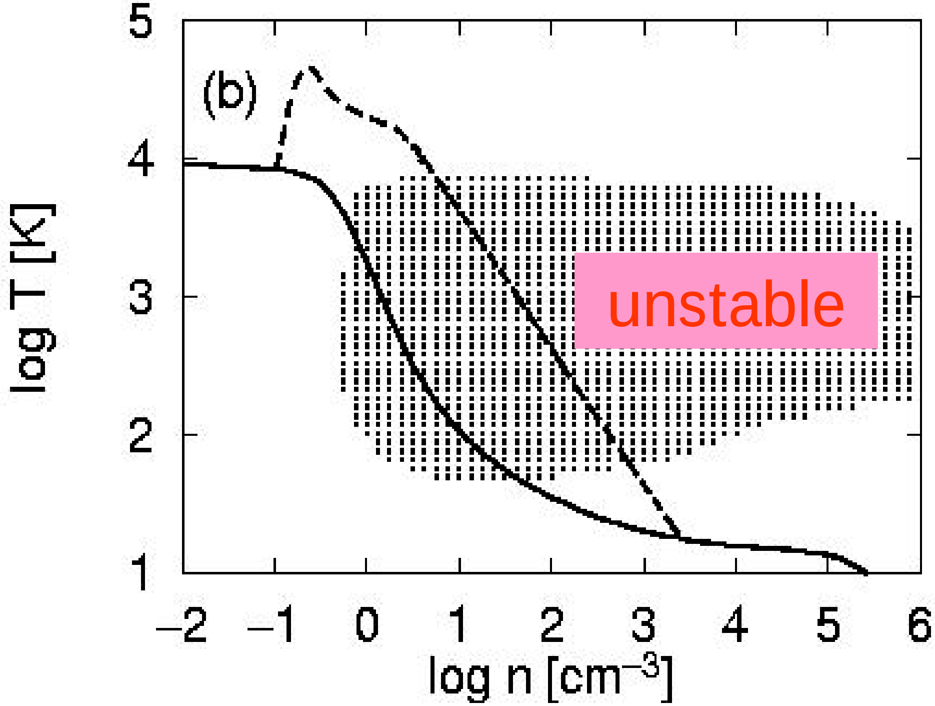
1D Shock Propagation into WNM

Density-Pressure Diagram



Density-Temperature Diagram

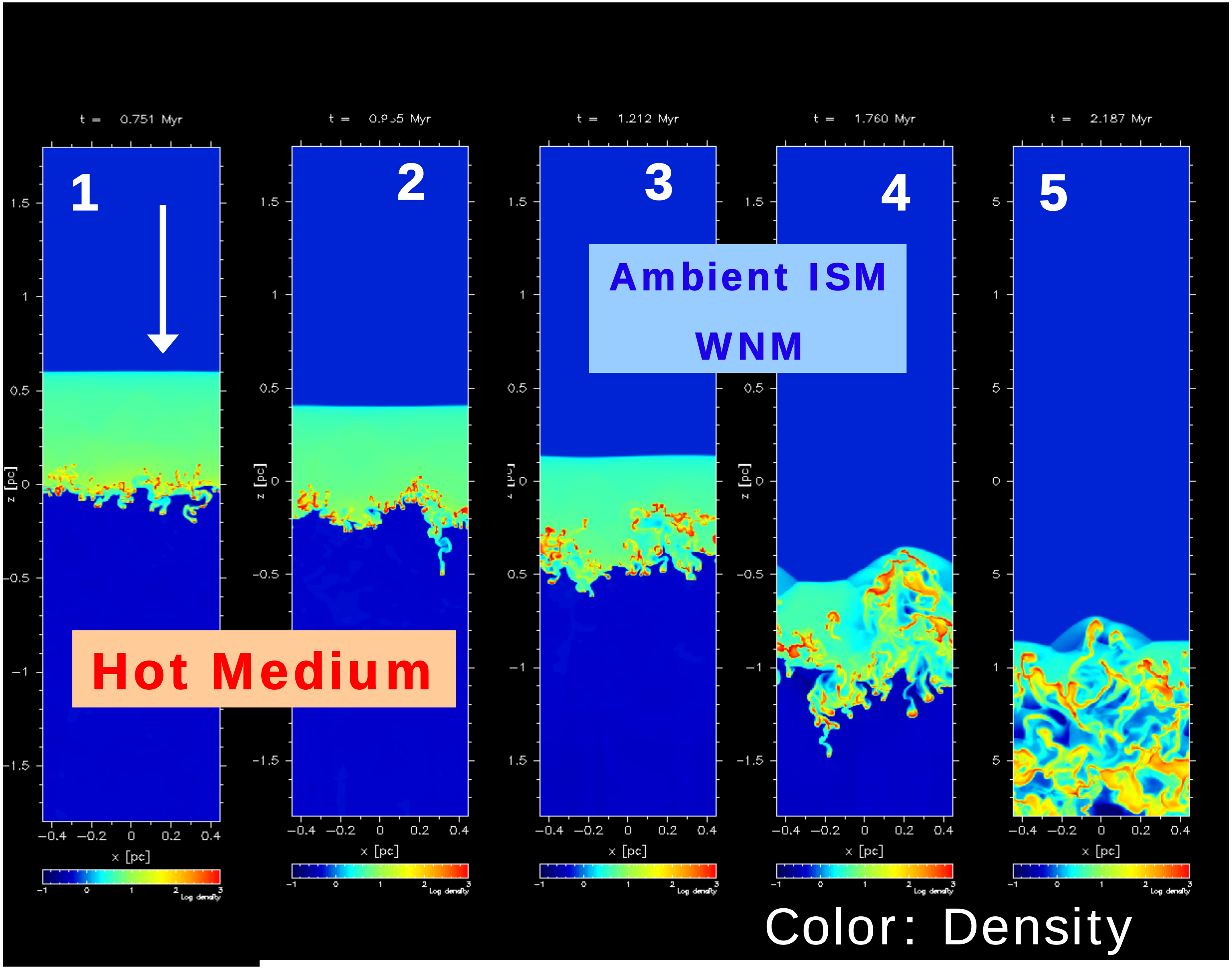
– through unstable region



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

See also Hennebelle & Pérault 1999

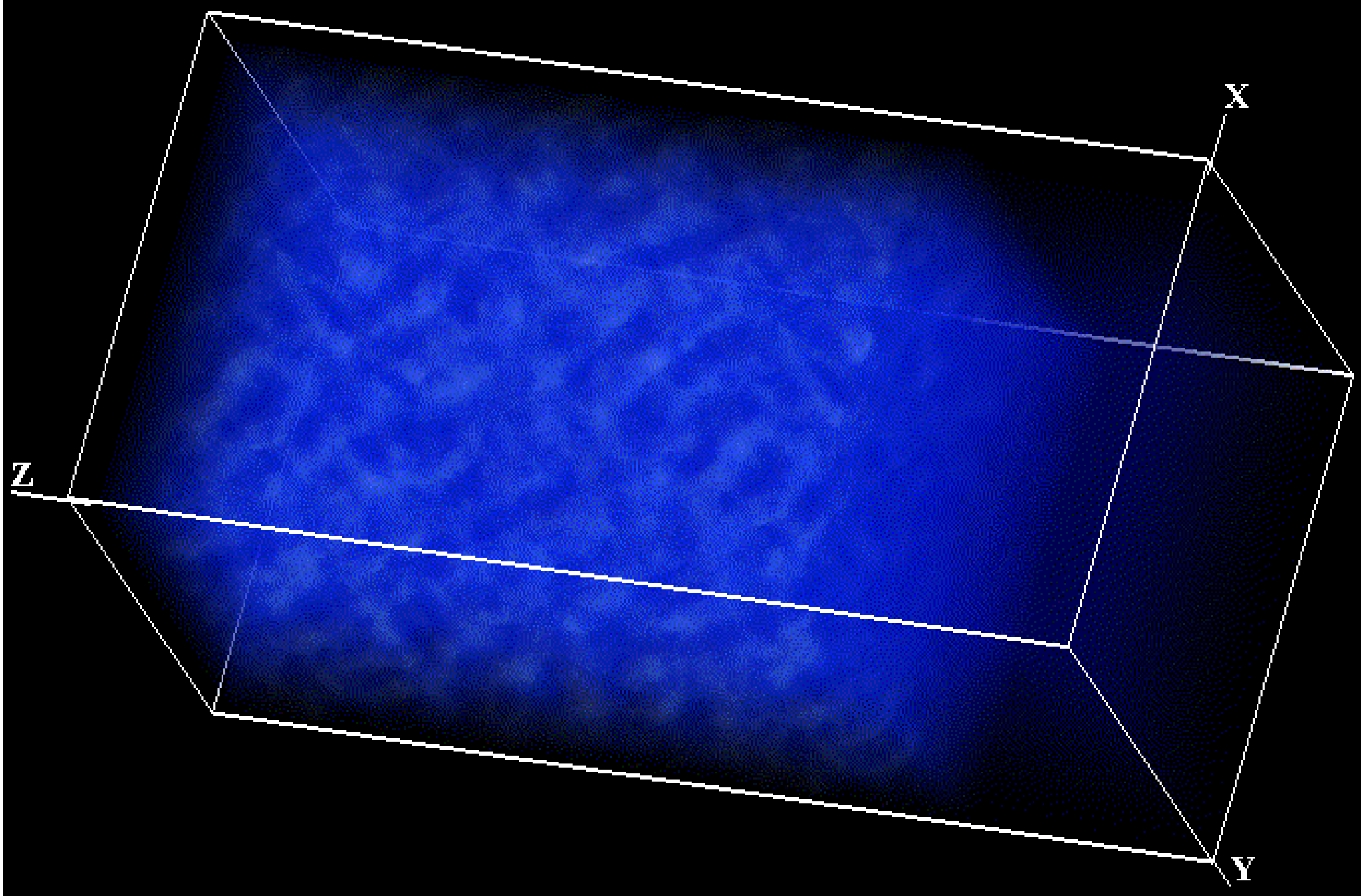
Shock Propagation into WNM



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)

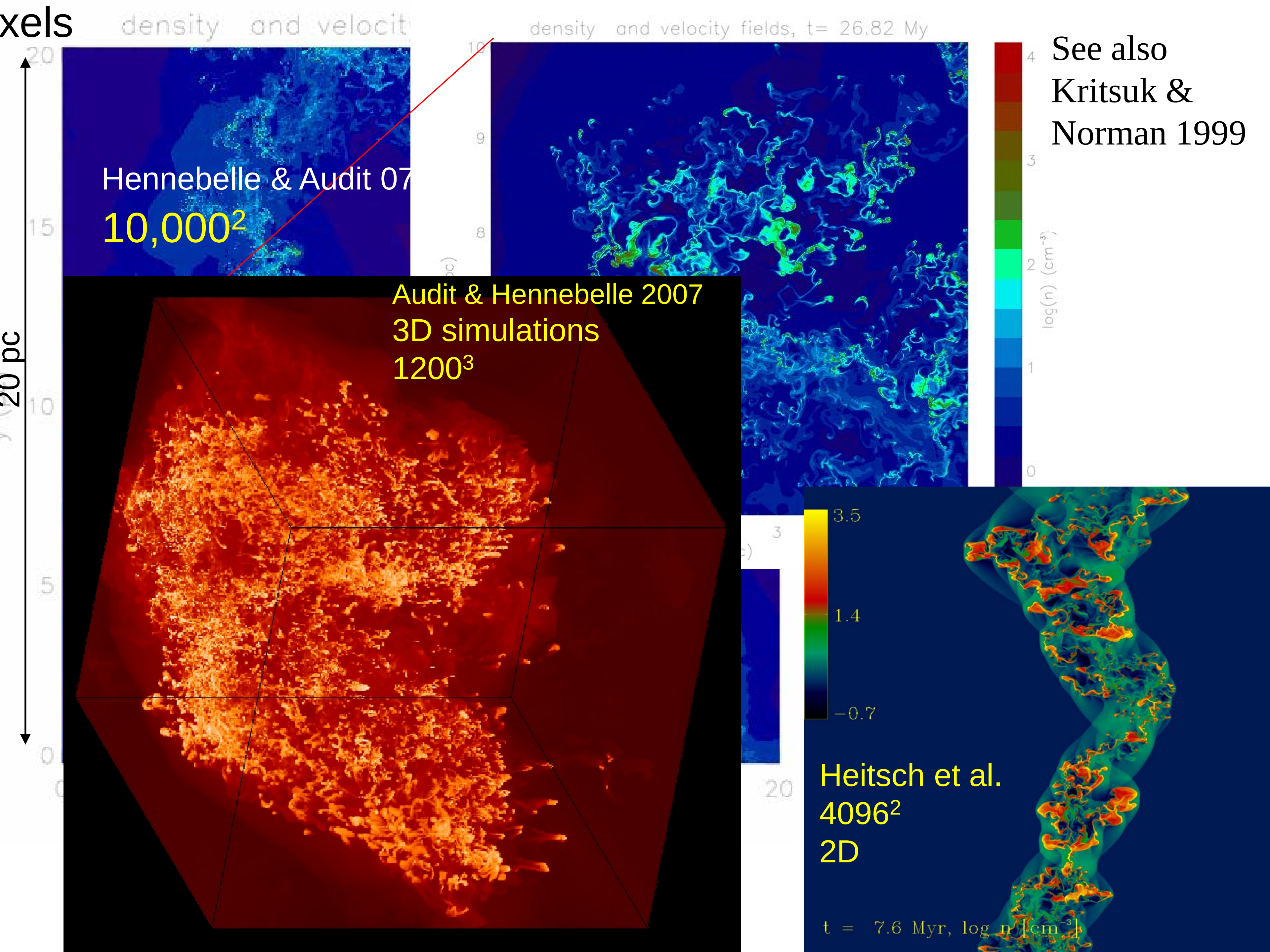
  1D: Shock $\Rightarrow E_{th} \Rightarrow E_{rad}$

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

δv ~ a few km/s < $C_{S,WNM}$ =10km/s

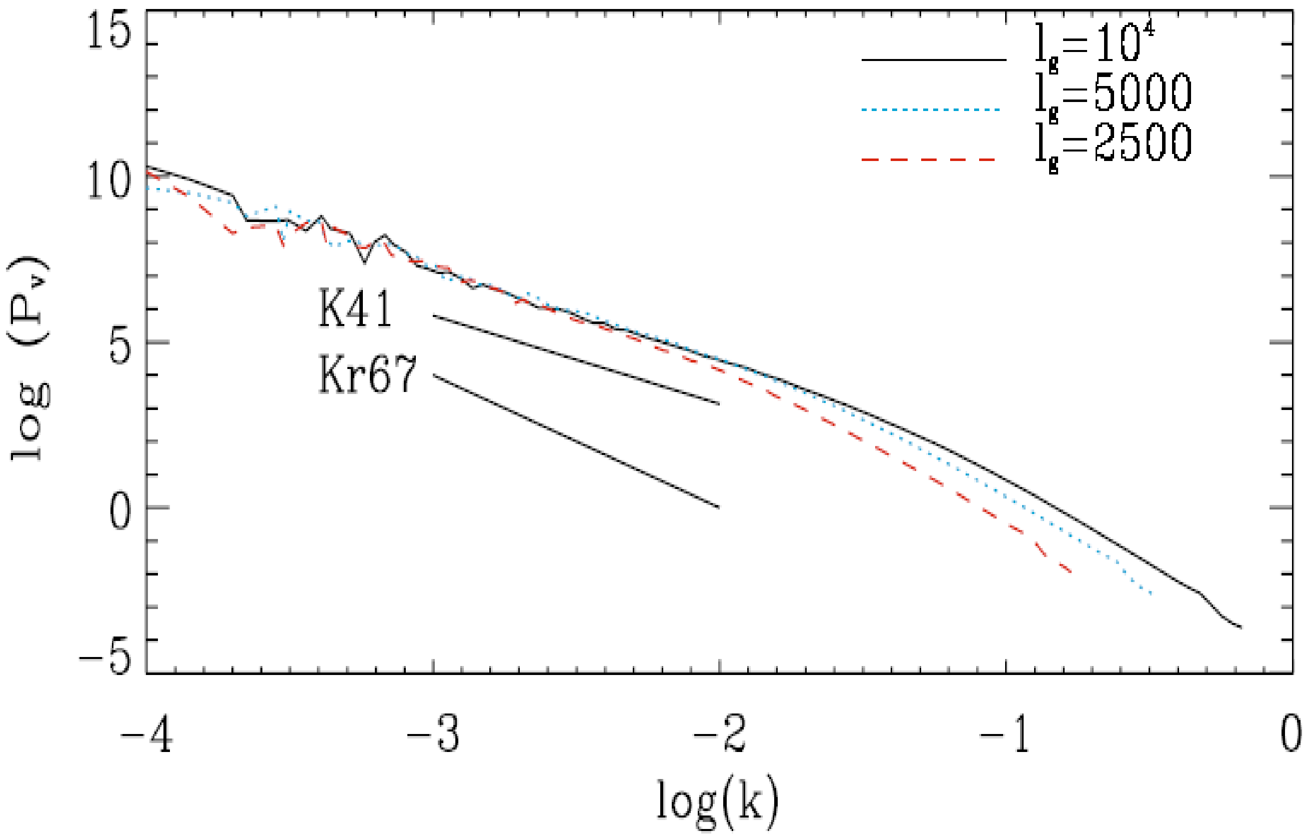
🡐 10^4K due to Lyα line: Universality?

Koyama & SI (2002) ApJ 564, L97



xels
density and velocit
density and velocity fields, t= 26.82 My
See also
Kritsuk &
Norman 1999
Hennebelle & Audit 07
10,000²
20 pc
Audit & Hennebelle 2007
3D simulations
1200³
log(n) (cm⁻³)
3.5
1.4
−0.7
Heitsch et al.
4096²
2D
t = 7.6 Myr, log n [cm⁻³]

Property of "Turbulence"

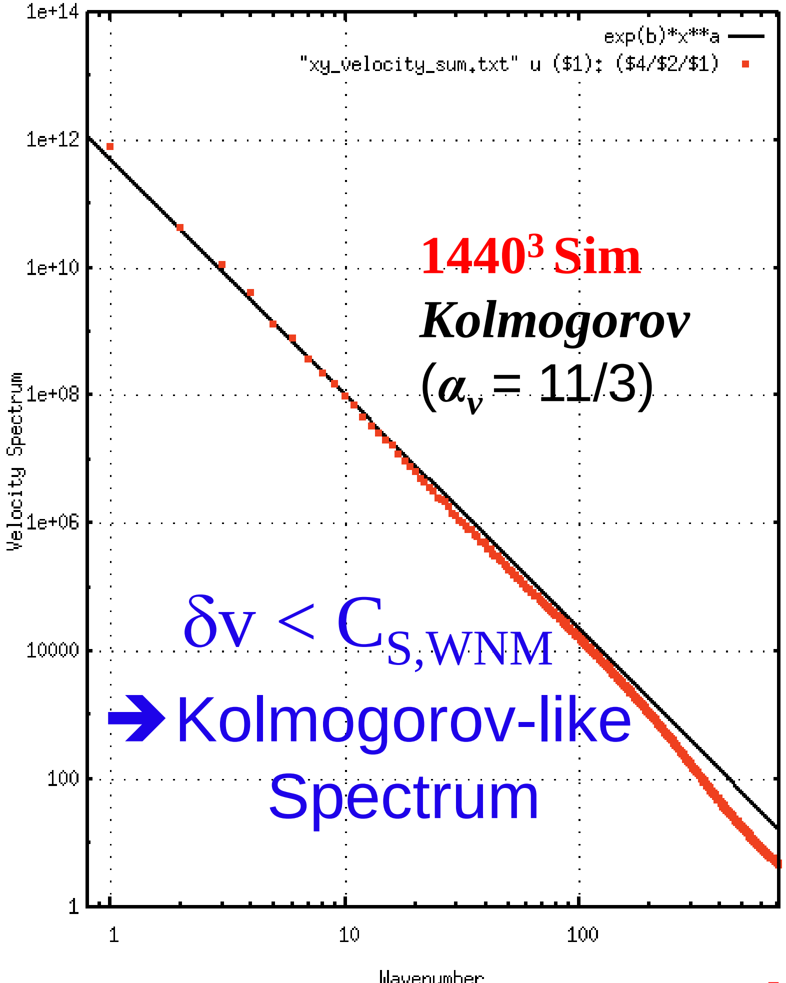


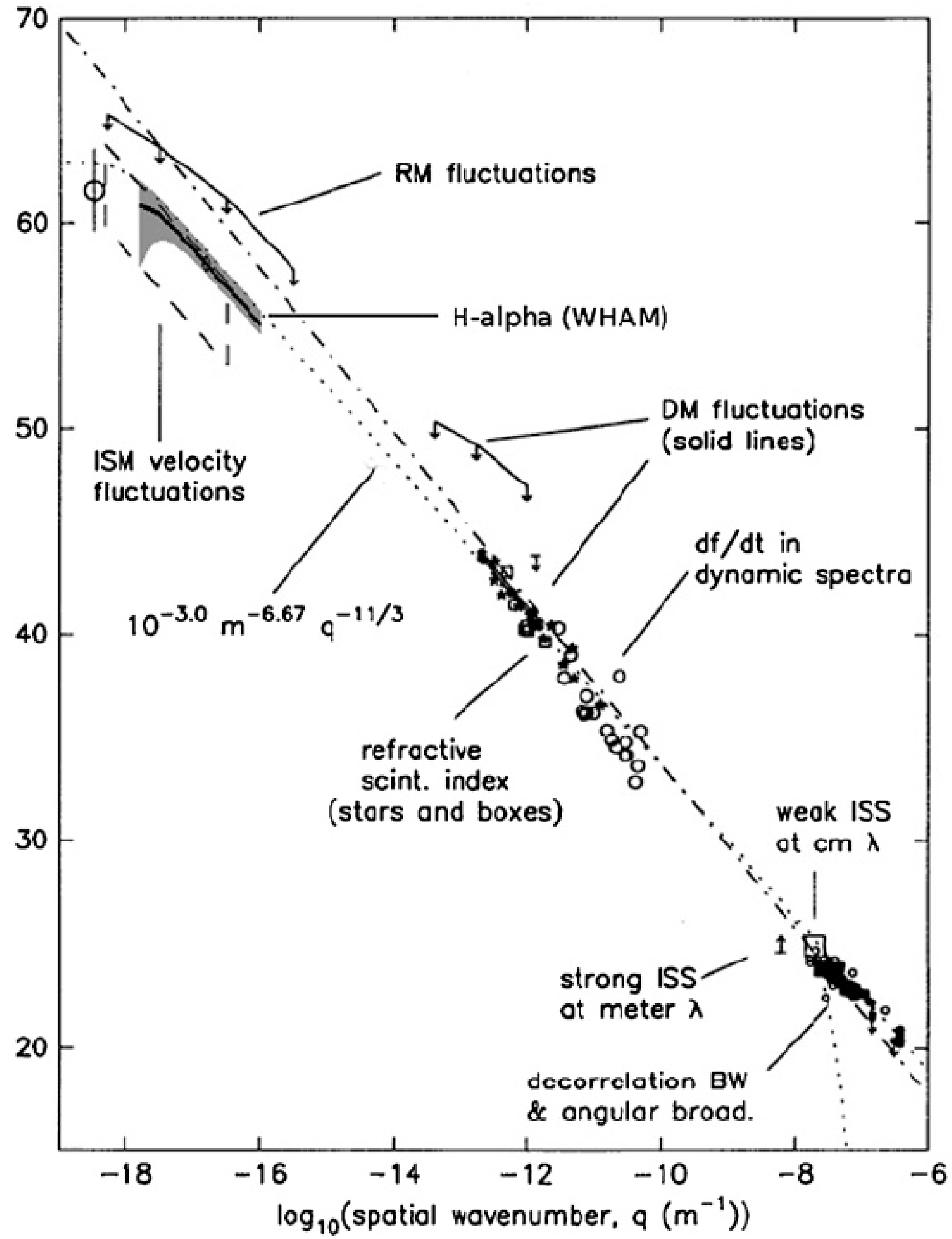
$\delta v < C_{S,WNM}$ ➔ Kolmogorov Spectrum

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

Property of 3D "Turbulence"

Muranushi, Inoue & SI 2014 in prep.

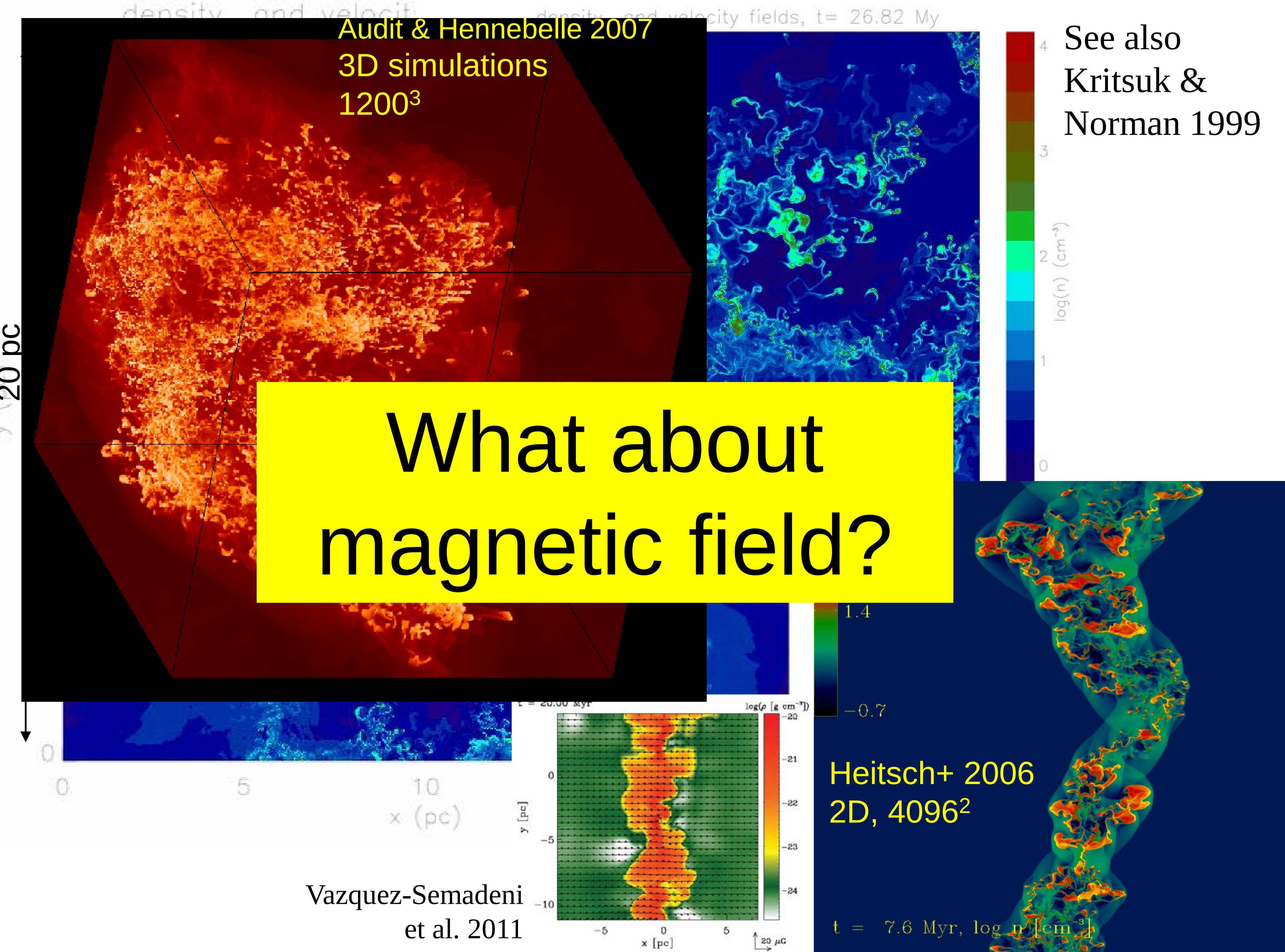




Good Agreement!

Chepurnov & Lazarian 2010
Armstrong et al. 1995

What about magnetic field?



See also Kritsuk & Norman 1999

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 2014 submitted

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

Ambipolar diffusion included

Colliding WNM with B_0=3μG

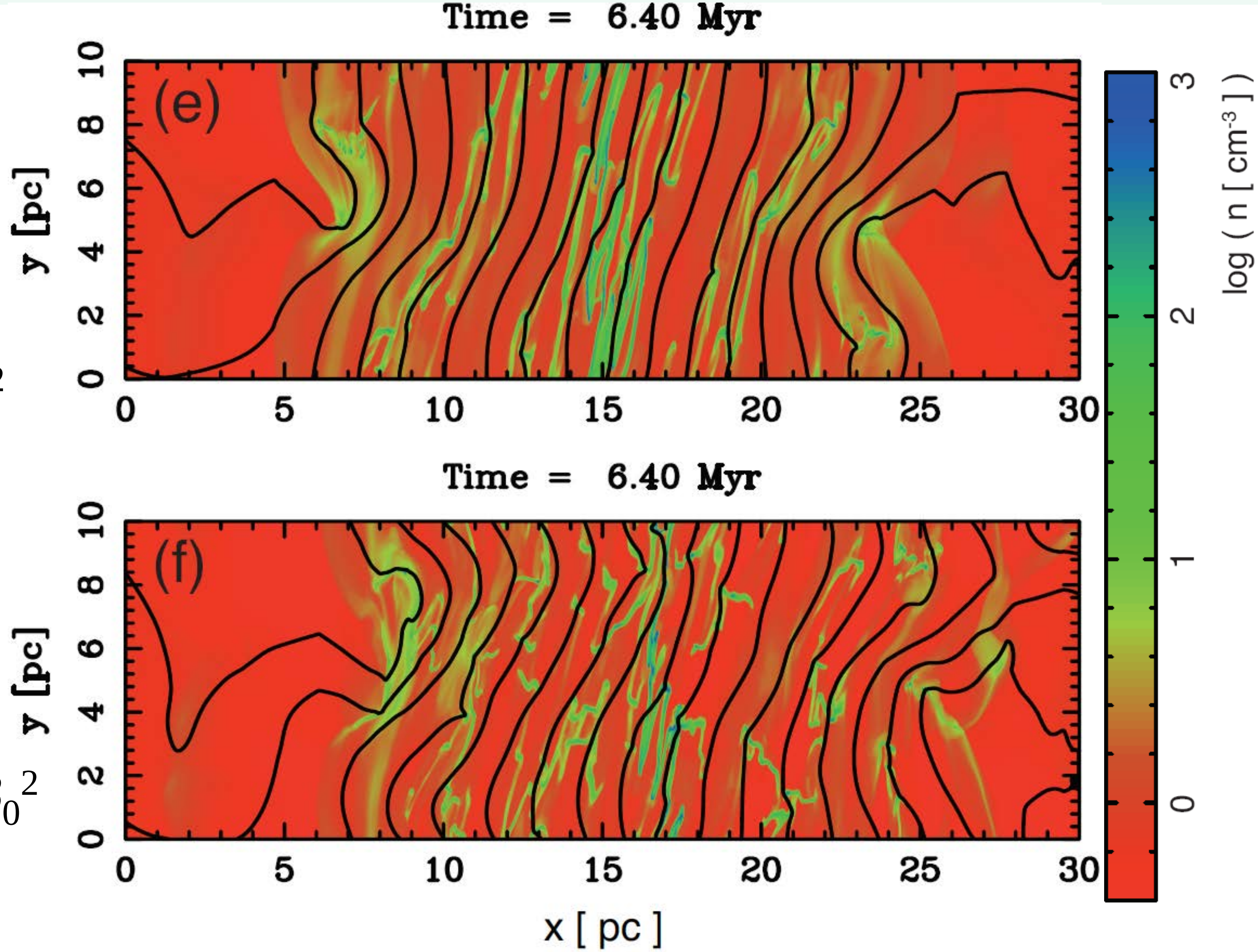
v=10km/s

(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)

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

We need multiple episodes of compression.

Compression of CNM (HI)

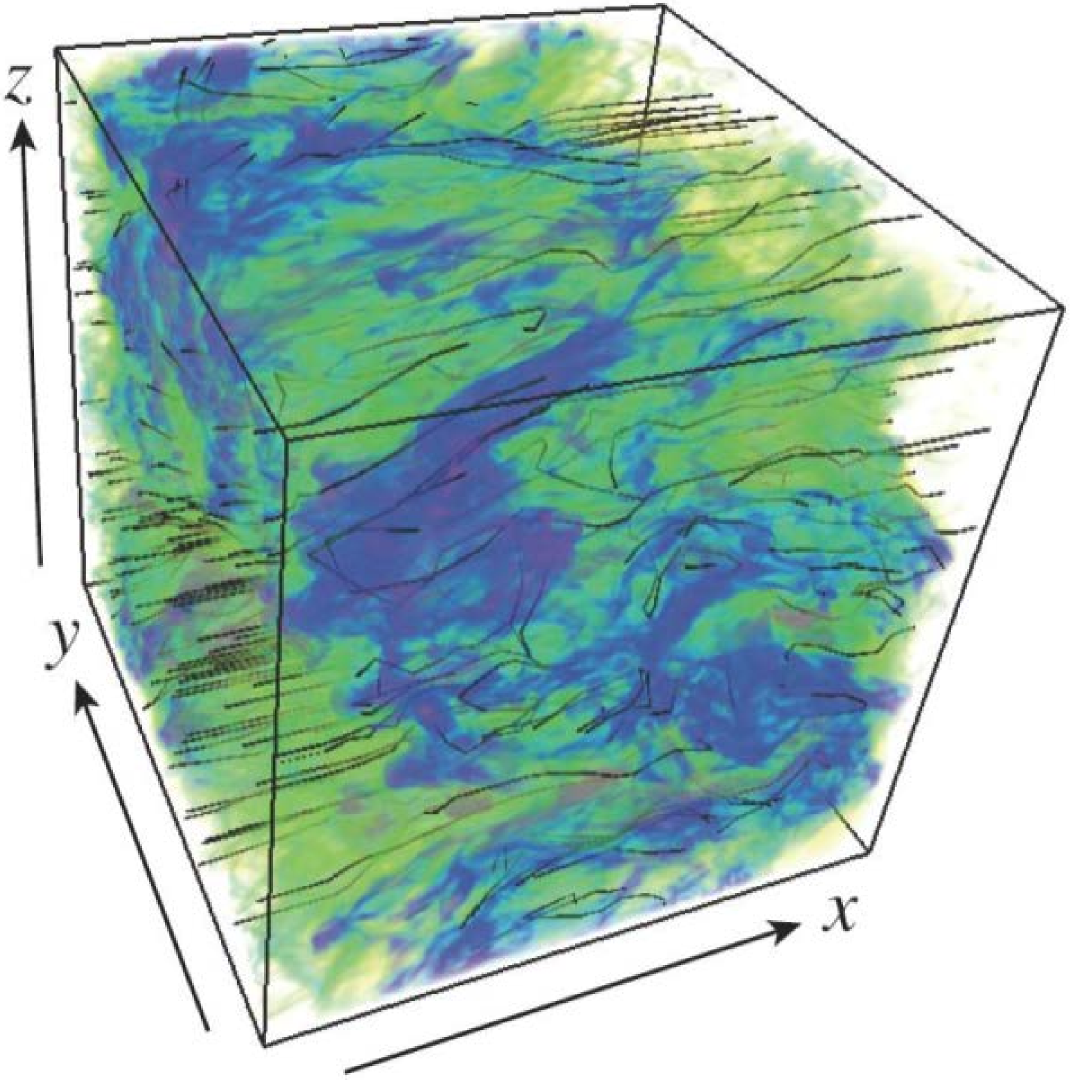
Compression along Magnetic Field lines, + H_2,CO

➔

Formation of Magnetized Molecular Clouds

Transformation of HI to H_2

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



Further Compress. of Mole. Clouds

Compression of Molecular Clouds
➔ Magnetized
Massive Filaments
& Striations

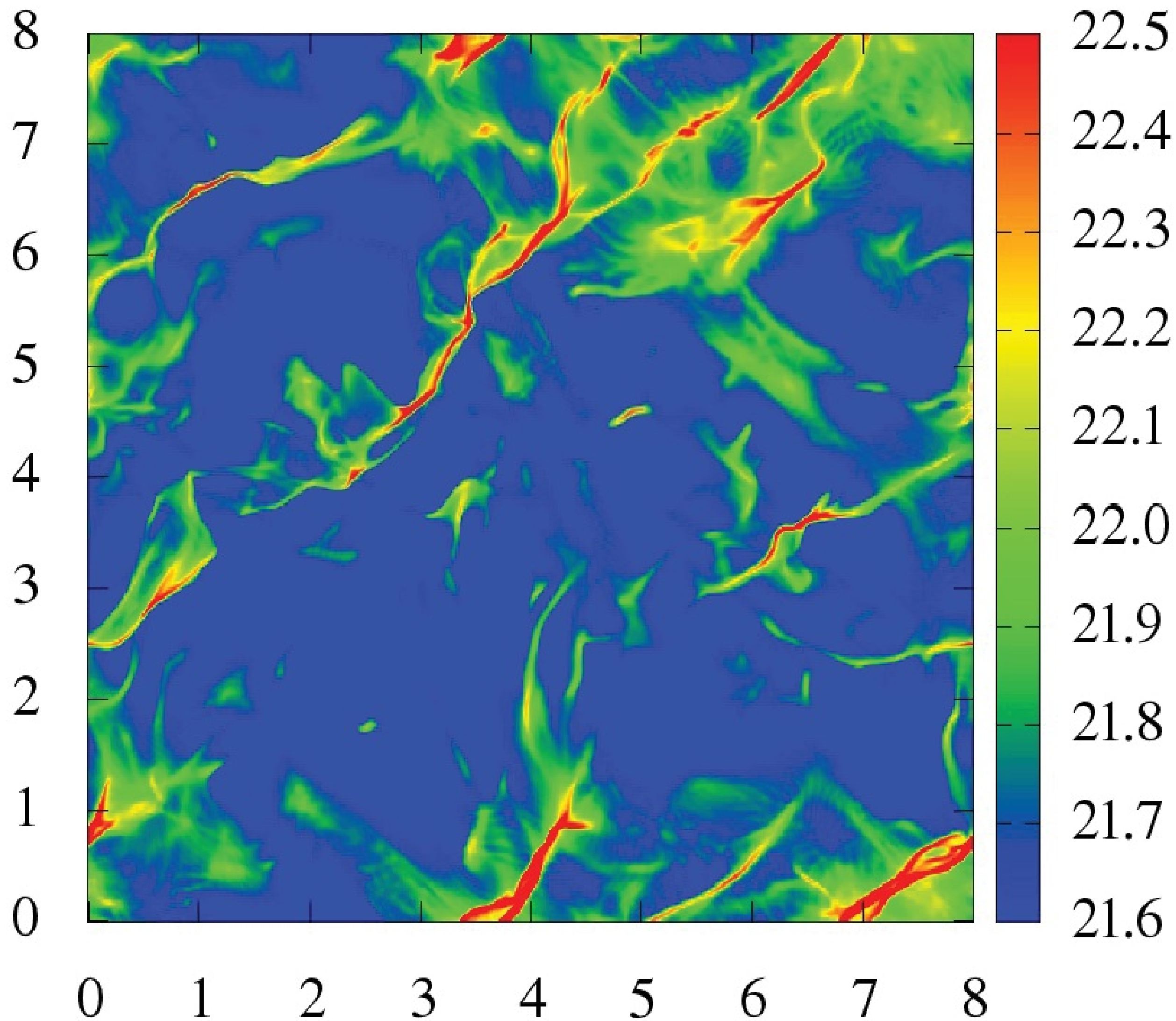
(Goldsmith+2008; Palmeirim+2013)

➔ *Herschel Obs.*

by Arzoumanian+

and

"*Planck*" arXiv:1409.6728



Self-Gravity Included, *SI, Inoue & Iwasaki 2014*

An Origin of Fibers in Filament

Collision at 10km/s of 2 Identical MCs ($n=10^2$/cc, $B=4\mu G$)

➔

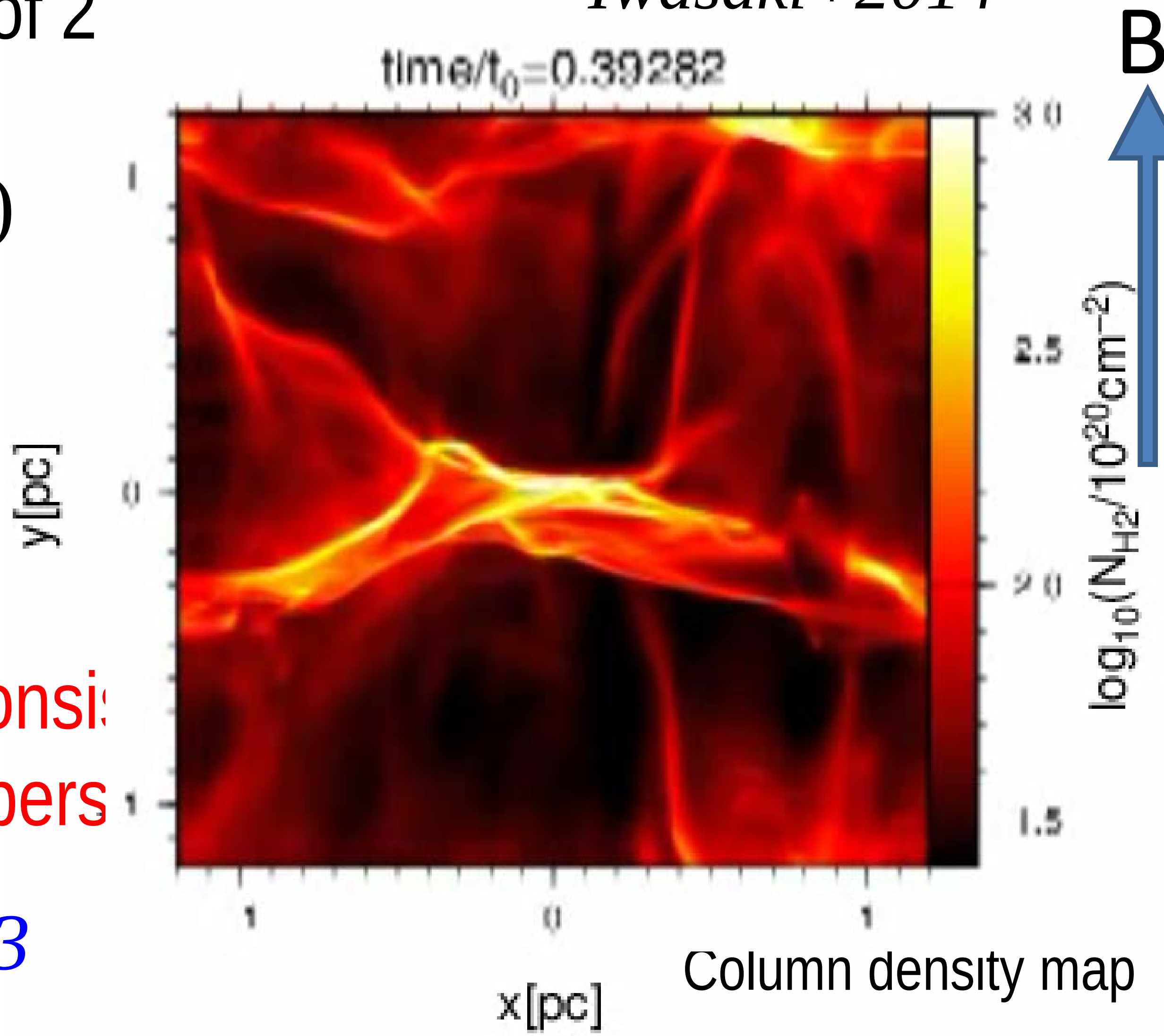
Massive Magnetized Filaments ⊥ B & Striations // B

Massive filaments consi
of finer filaments (Fibers

➔ *Hacar+2013*

See Talk by Hacar

Iwasaki+2014



Column density map

See Poster by Iwasaki

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

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

Further Compression of Molecular Clouds

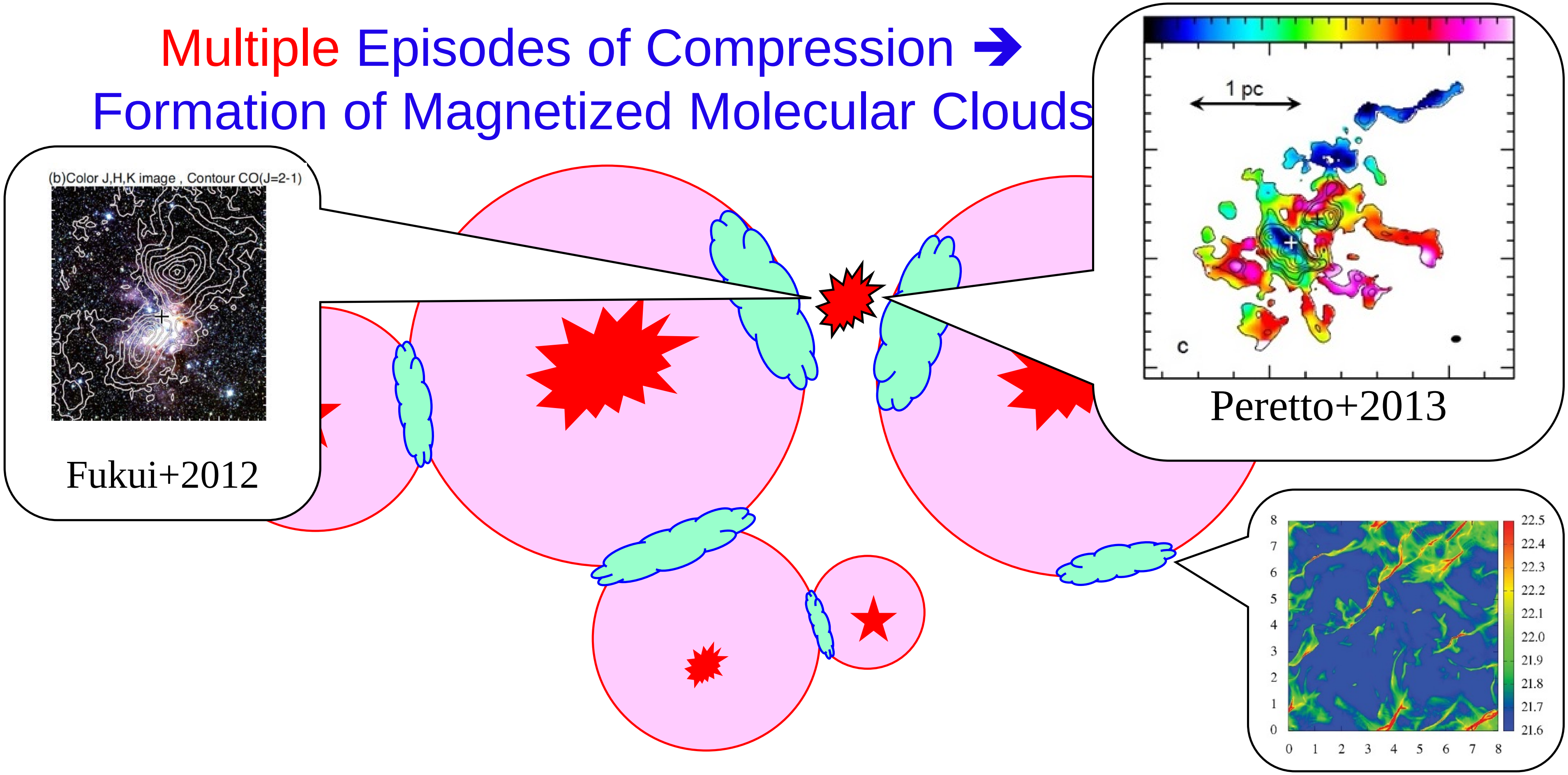
➔Magnetized Massive Filaments & Striations

= "Herschel Filaments"

Toward Global Picture of Cloud Formation

Network of Expanding Shells

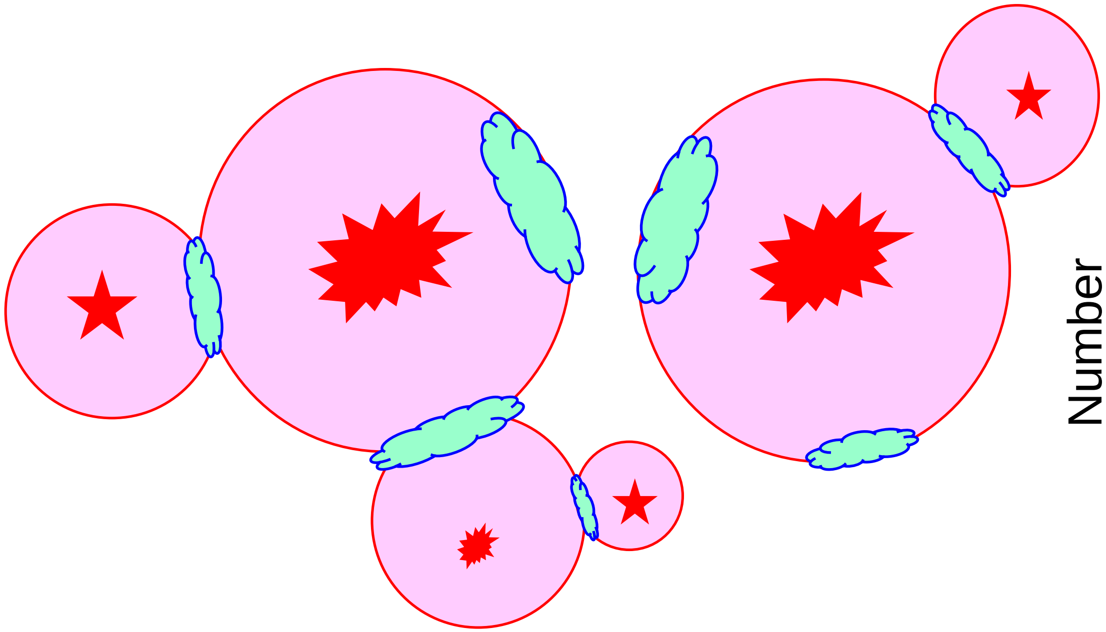
Multiple Episodes of Compression →
Formation of Magnetized Molecular Clouds

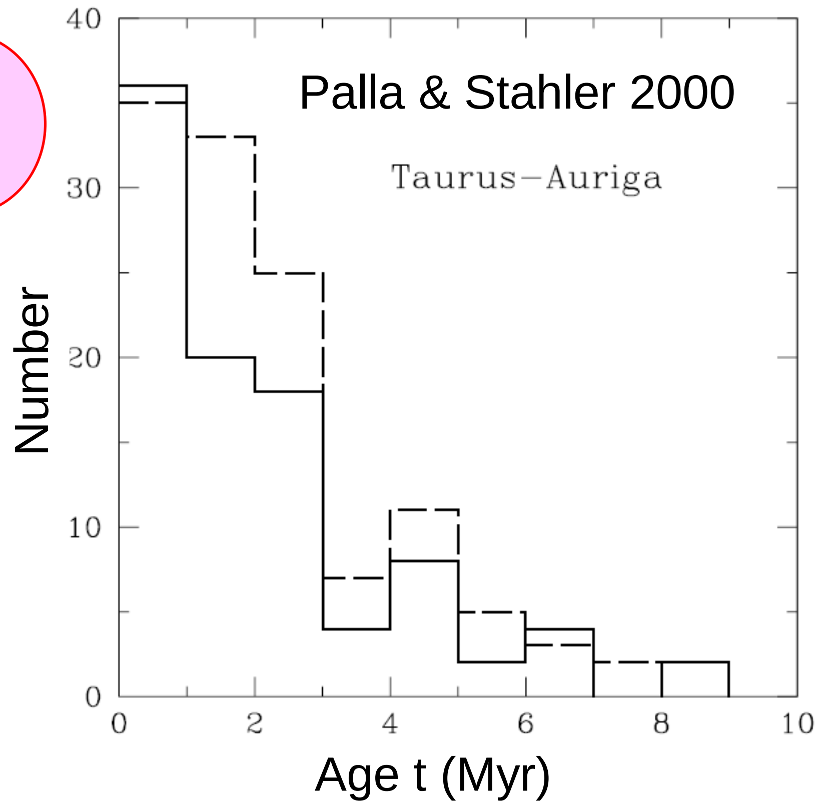


Each Bubble Visible Only for Short Time (~1Myr)!

δv of Mole Clouds ~ v_{exp} of Shells ~ 10km/s

Network of Expanding Shells





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

Mass Function of Molecular Clouds

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

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

$\frac{M_{\rm cl}}{\tau_{\rm form}}$

const.
➔KS Law

In steady state

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

If $\tau_{\rm dis} \sim \tau_{\rm form} + 5{\rm Myr} \rightarrow \alpha = 1.67$

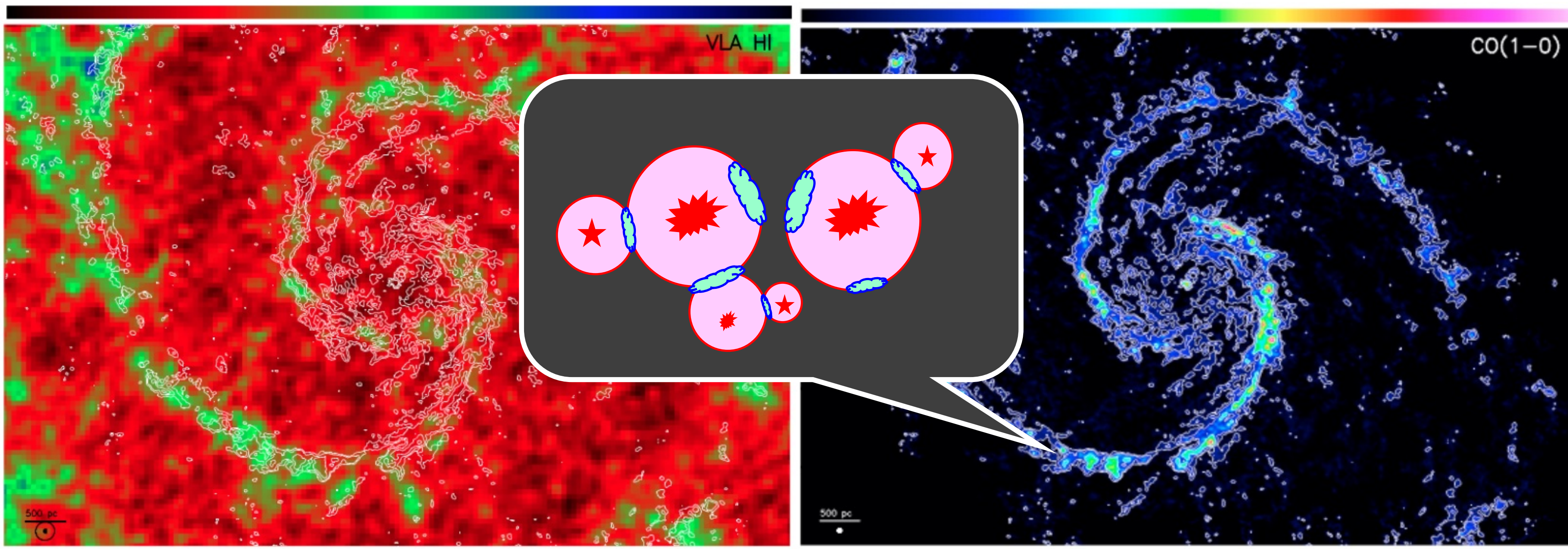
10Myr

(*SI, Inoue & Iwasaki 2014*)

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

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

Typically, $\tau_{\rm dis} \sim \tau_{\rm form} + 5{\rm Myr} \rightarrow \alpha = 1.67$

In low density region (Inter-Arm Region)

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

In high density region (Arm Region)

Smaller $\tau_{\rm form}$ ➔ Smaller α

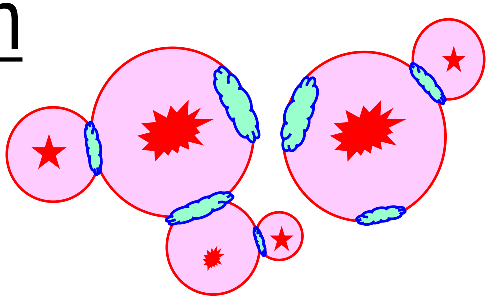
➔ GMCs in M51 (Colombo+2014)

Summary

- Fragmentation of Filaments ➔ Core Mass Function
- <u>Massive Stars in Tail of Core Mass Function</u>

  ← Collision of Clouds formed on Shells

  $\delta V_{\text{inter-cloud}} \sim 10^1$ km/s



- <u>Shell-Dominated Formation of Molecular Clouds</u>

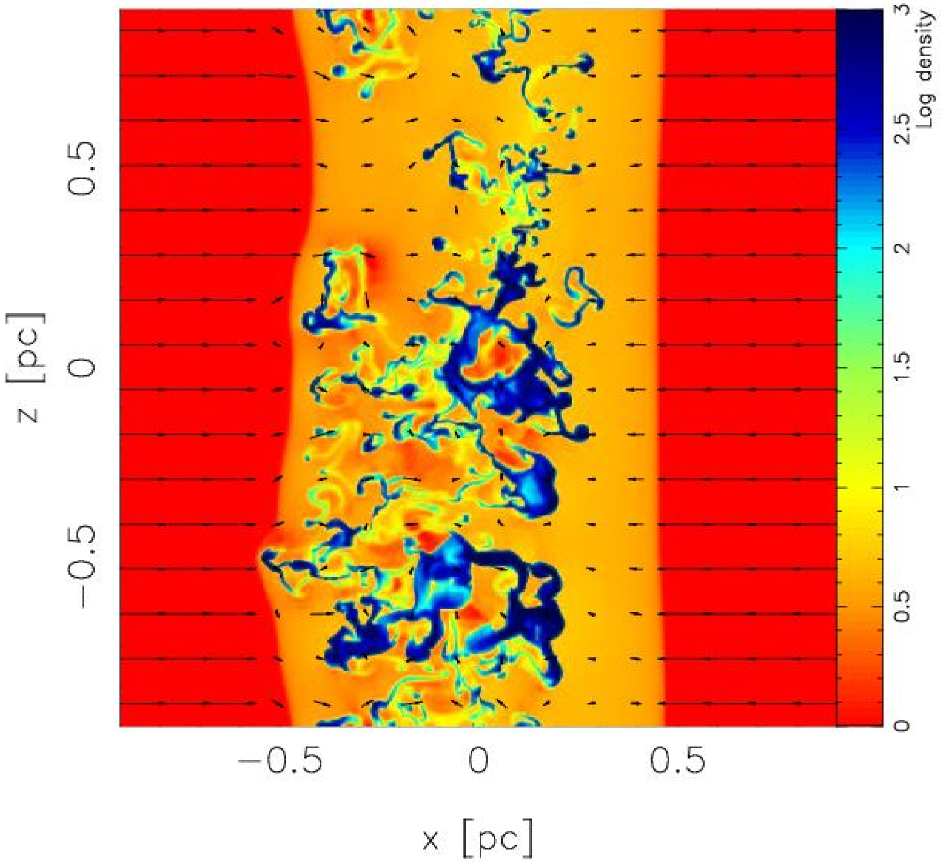
➔ Unified Picture of Star Formation

- ε_{SF}~0.03, Schmidt-Kennicutt Law (t_{dis}~Gyr)
- Accelerated Star Formation
- Slope of Cloud Mass Func $= 1 + \tau_{form}/\tau_{dis} \sim 1.67$

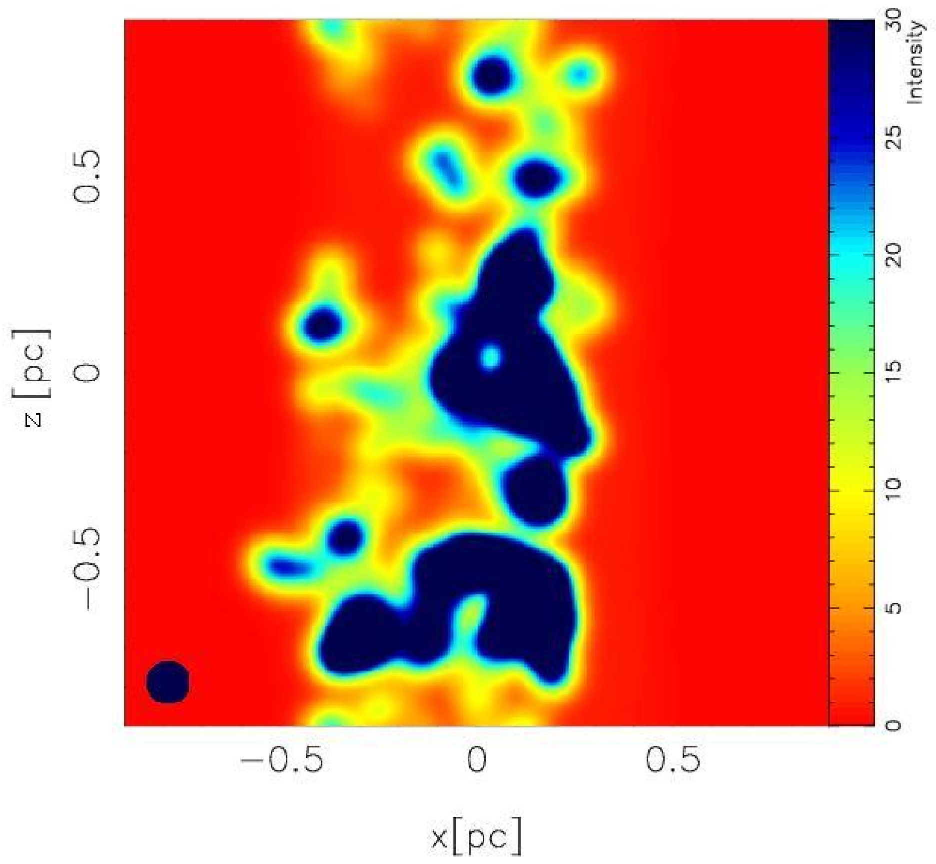
SI, Inoue & Iwasaki 2014, submitted

Simulated "Observation" of Structure Generated by TI

Result of Hydro Calc

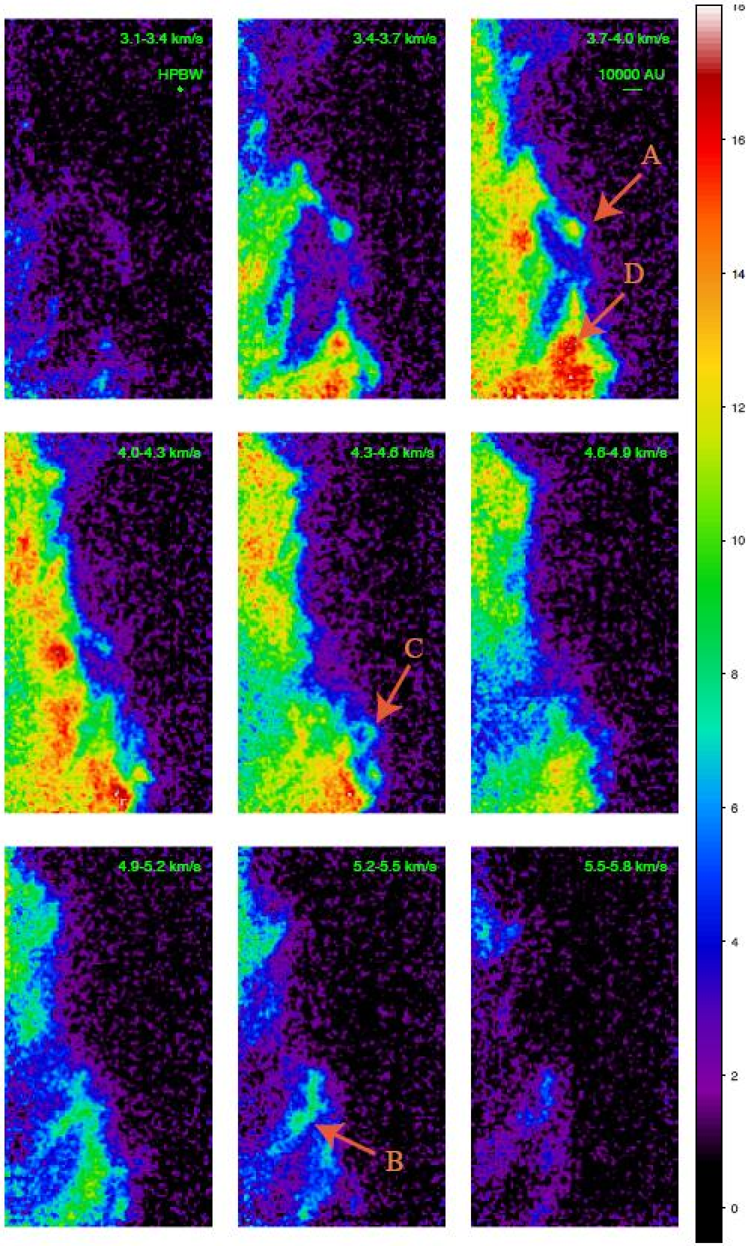


Convolution by Telescope Beam Pattern

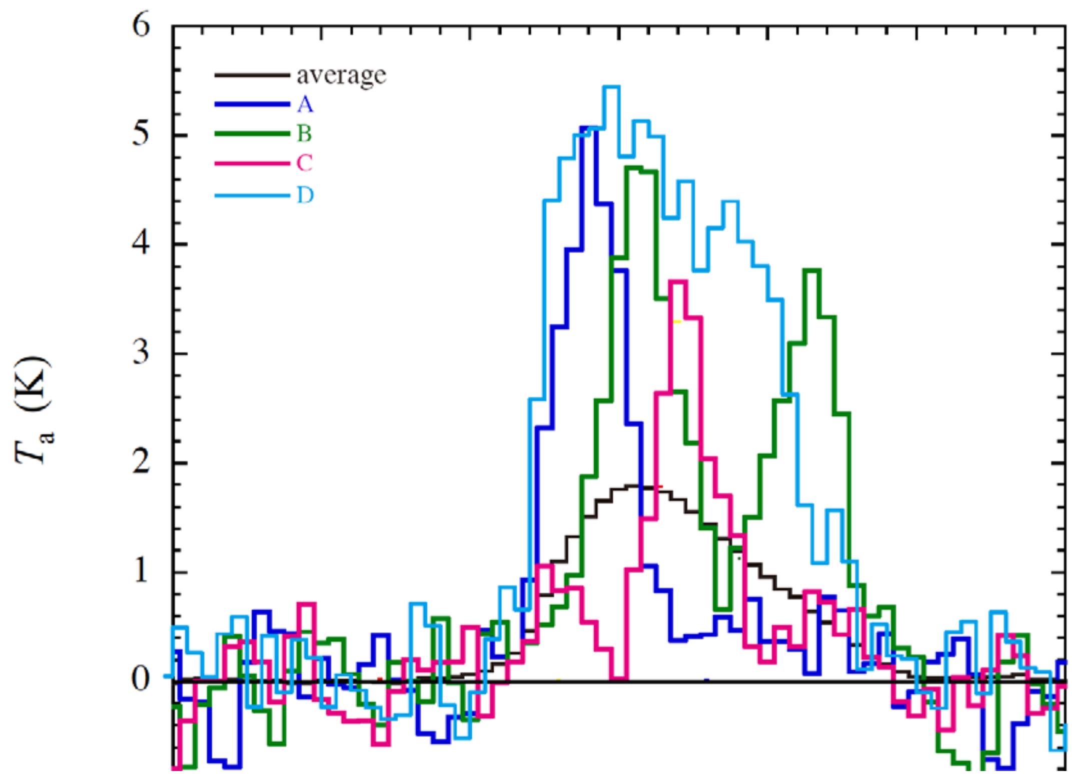


Inutsuka, Koyama, & Inoue 2005

“Resolved” Molecular Clouds



LDN 204 is a cloud complex
facing the Sh 2-27 H II region (d~5pc)

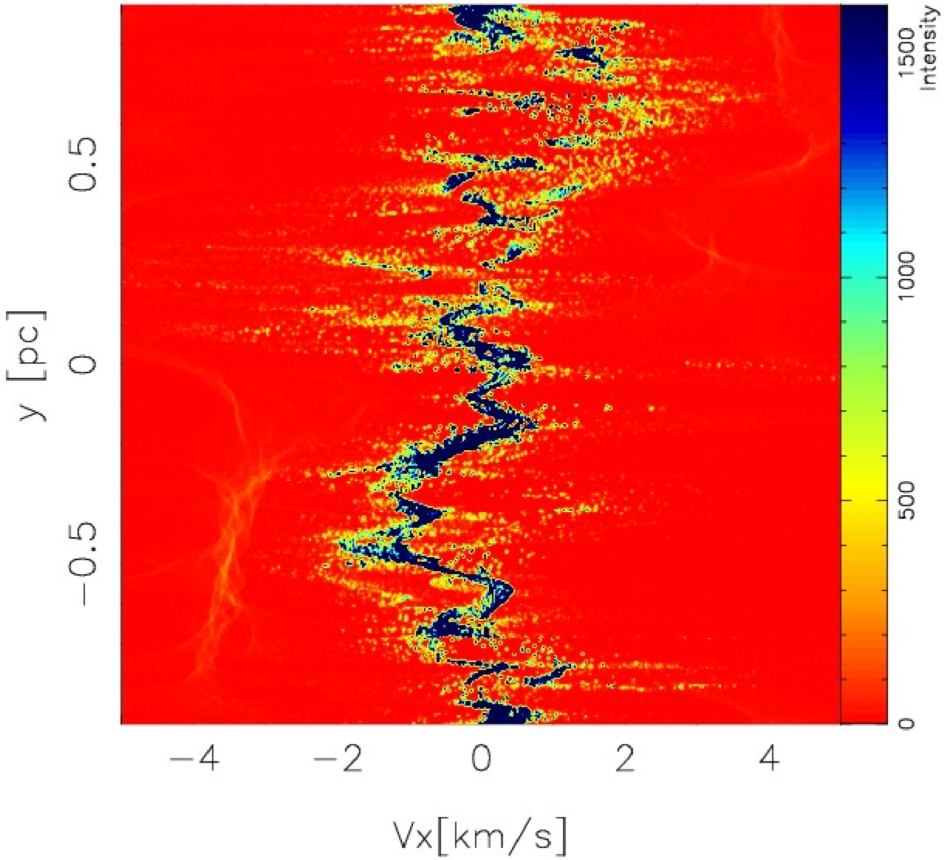


The main cloud line-width can be decomposed into small clouds with thermal line-widths.

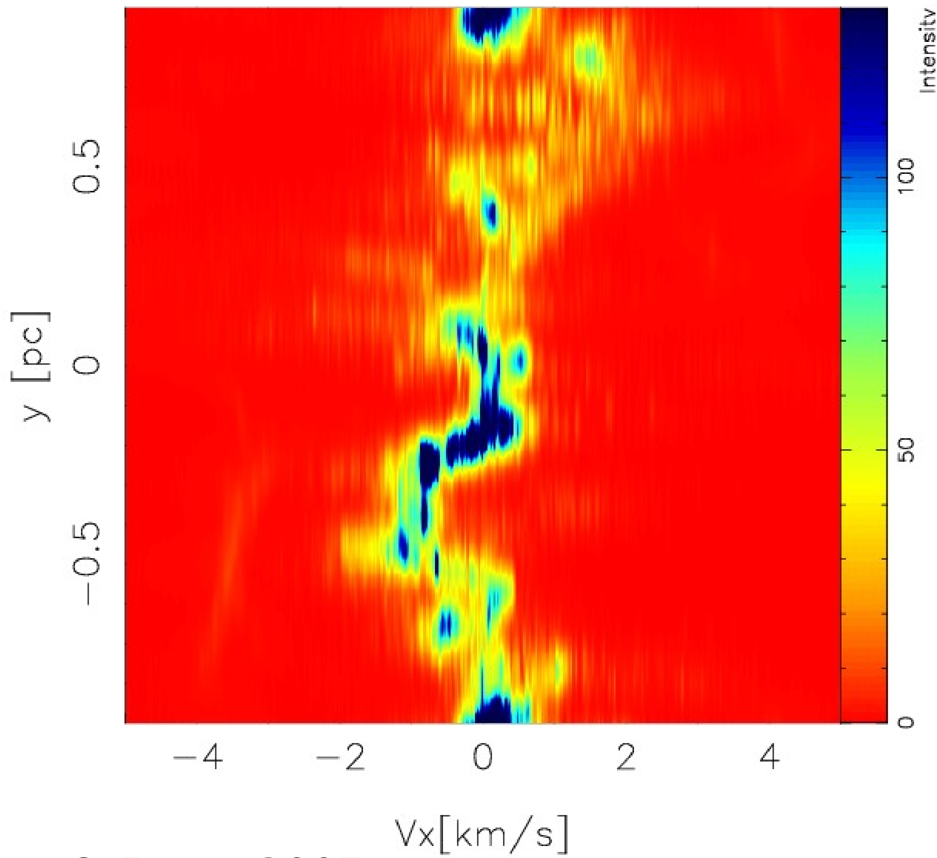
Tachihara et al. (2011)

Simulated "P-V Diagram" of Turbulence Generated by TI

P-V map from Hydro Calc

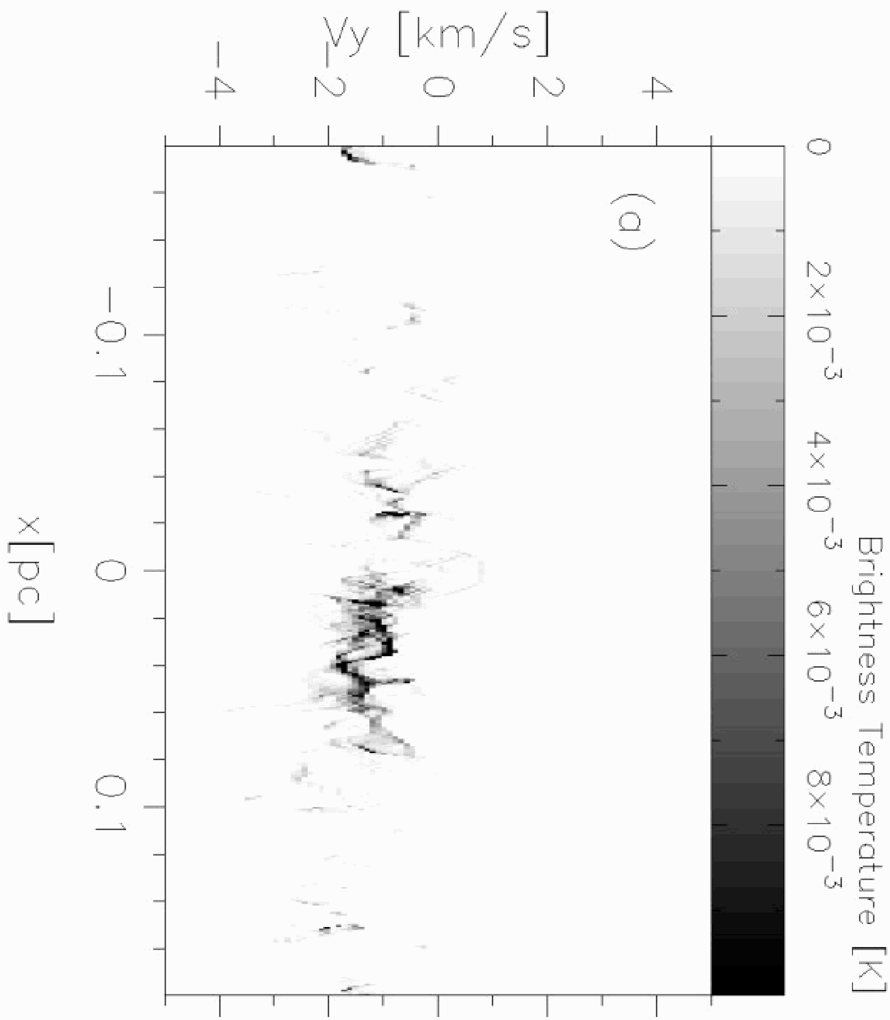


Convolution by Telescope Beam Pattern



Inutsuka, Koyama, & Inoue 2005

P-V map generated from simulation



Koyama & Inutsuka 2002, ApJL **564**, L97

High-Latitude Cloud MBM 55 $^{12}CO(J=1\text{-}0)$

(Sakamoto 2002, ApJ **565**, 1050)