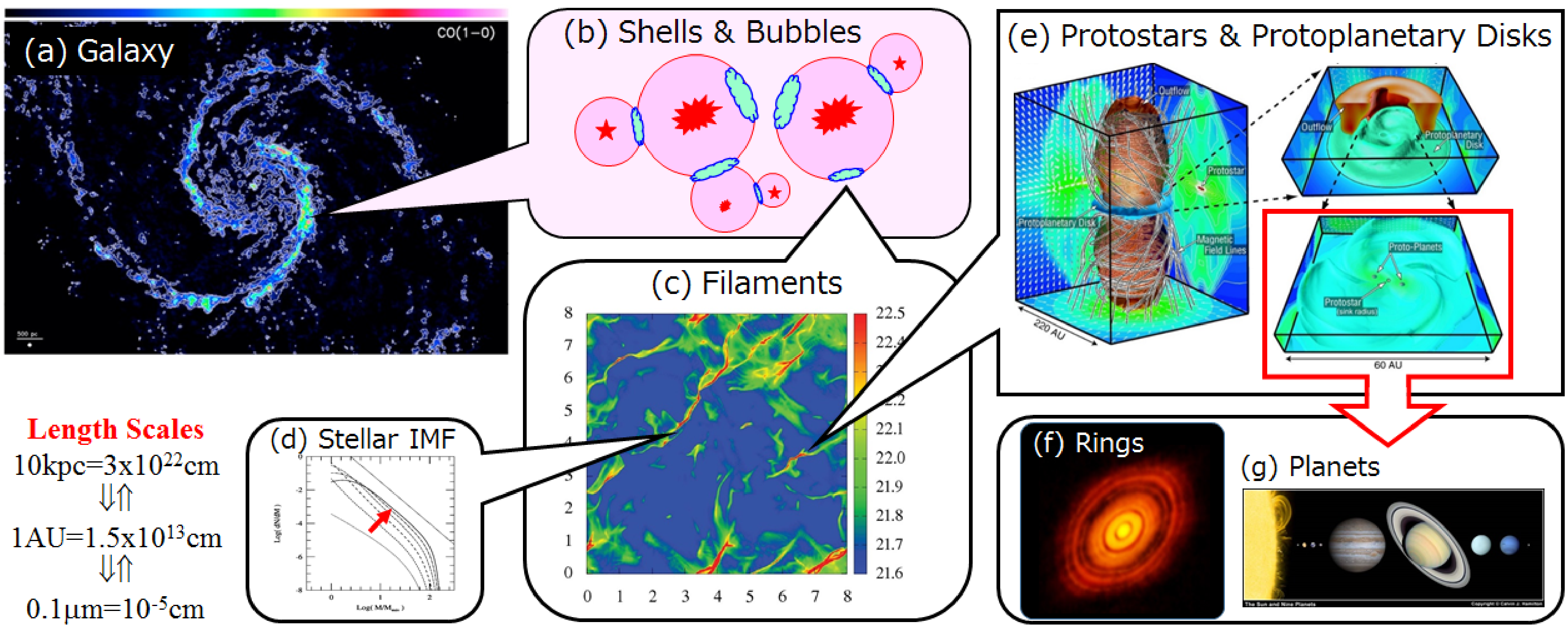
The Milky Way and its environment:
gaining insights into the drivers of galaxy formation and evolution

Phase Transition Dynamics of ISM: A Unified Picture of Galactic Star Formation

Shu-ichiro Inutsuka (Nagoya University)



19-23 September 2016 Institut d'Astrophysique de Paris, Paris, France

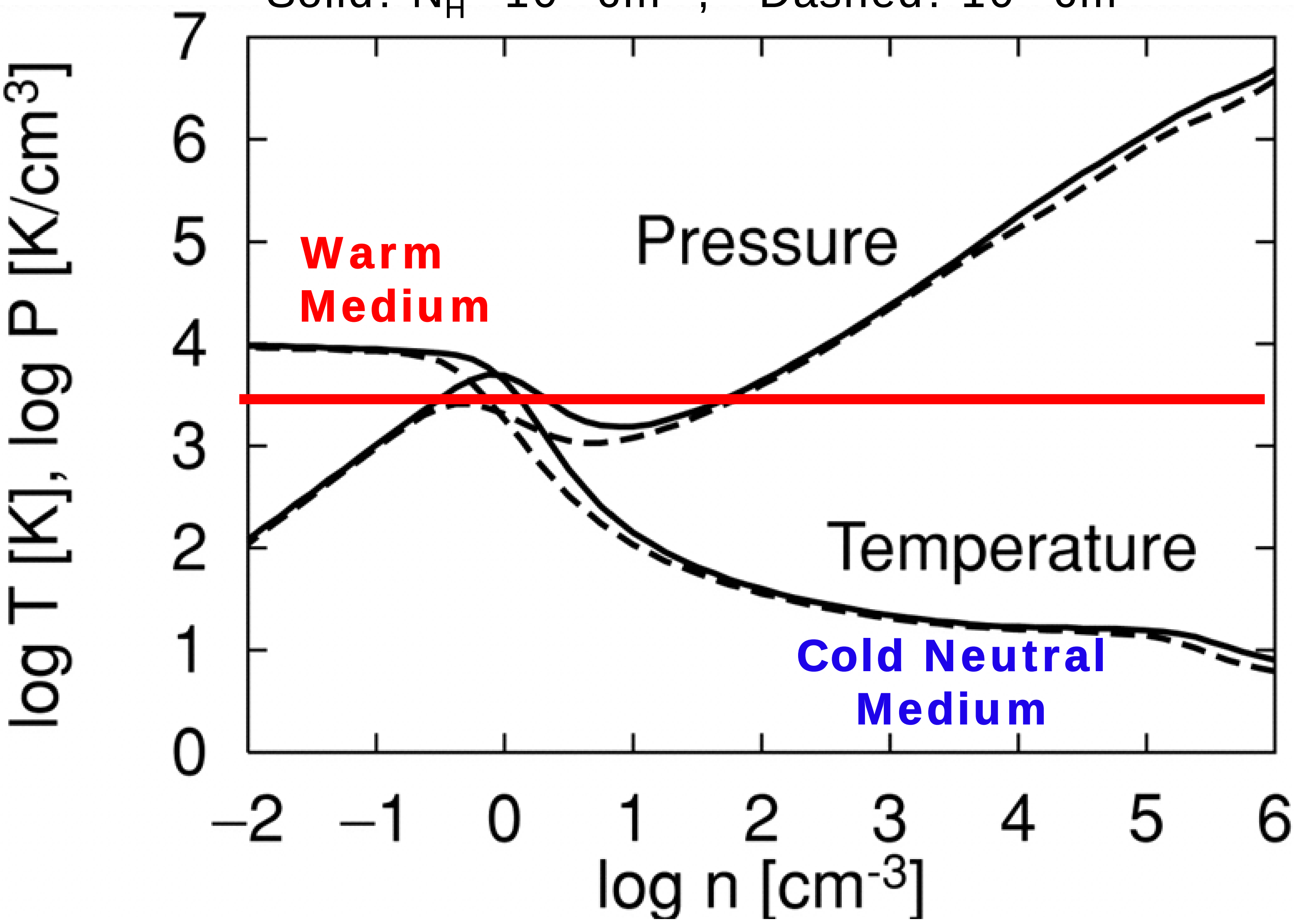
Outline

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

Formation of Molecular Clouds

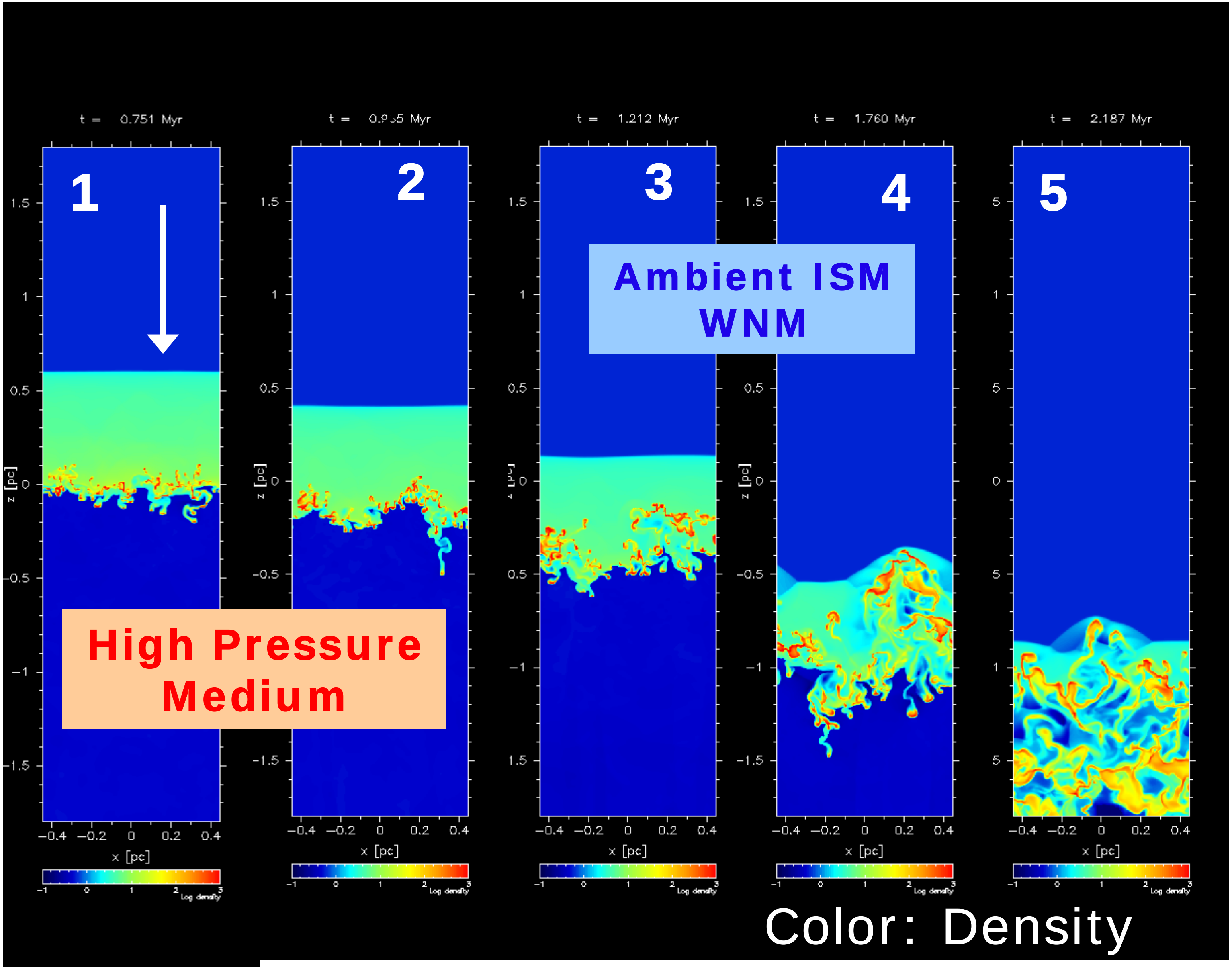
Radiative Equilibrium for a given density

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



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

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

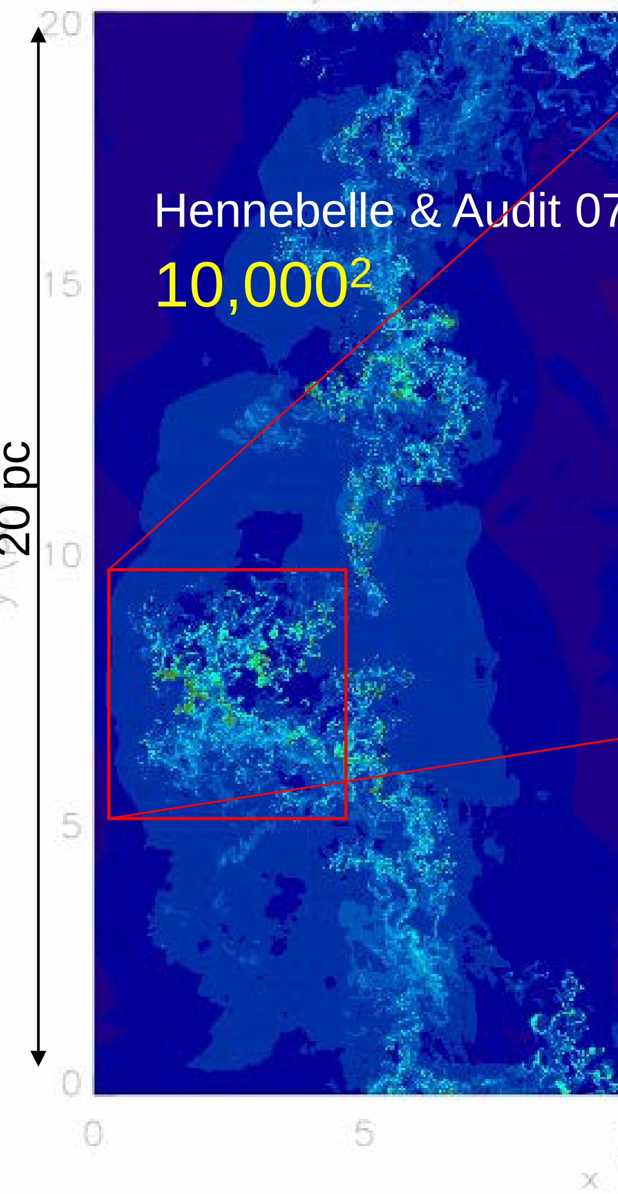
δv ~ a few km/s < $C_{S,WNM}$ =10km/s

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

T_{CNM} ~10^2K 🡐 C^+158μm (~92K)

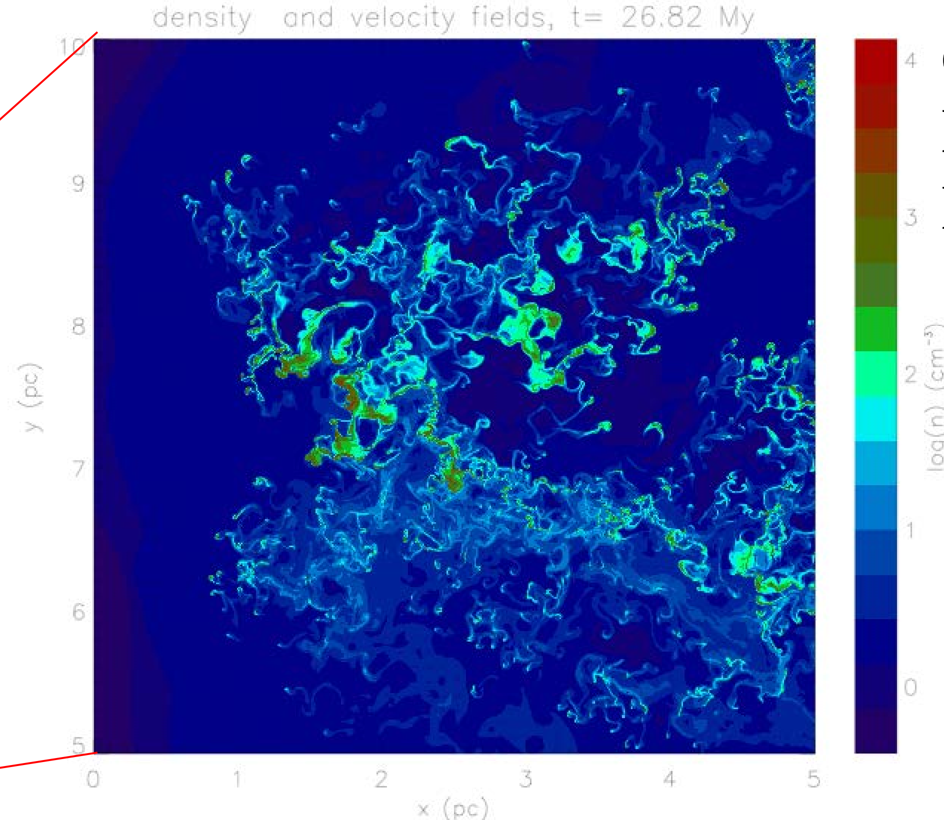
Koyama & SI (2002) ApJ 564, L97

xels

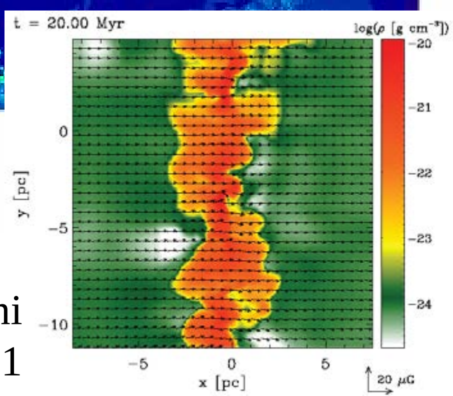


Hennebelle & Audit 07

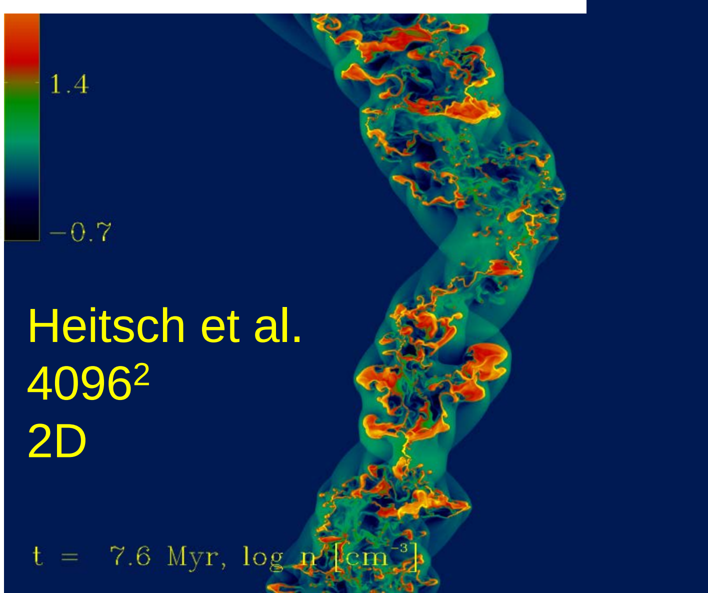
10,000²



c.f.
Kritsuk &
Norman
1999

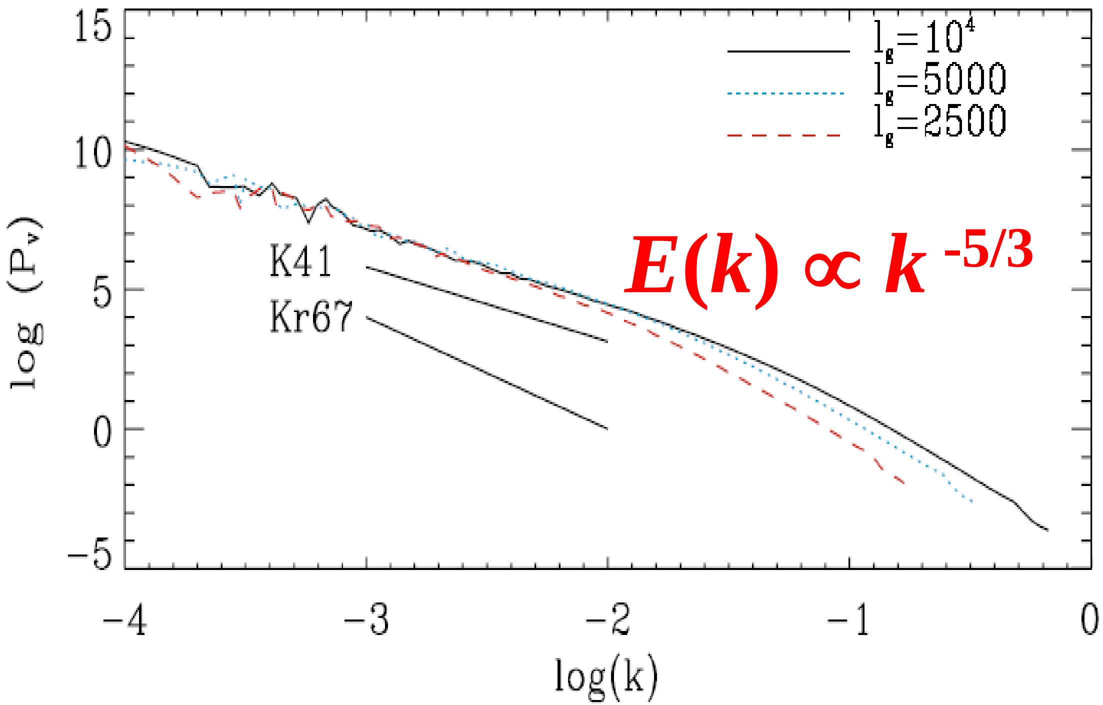


Vazquez-Semadeni
et al. 2011



Heitsch et al.
4096²
2D

Property of “Turbulence”…Subsonic



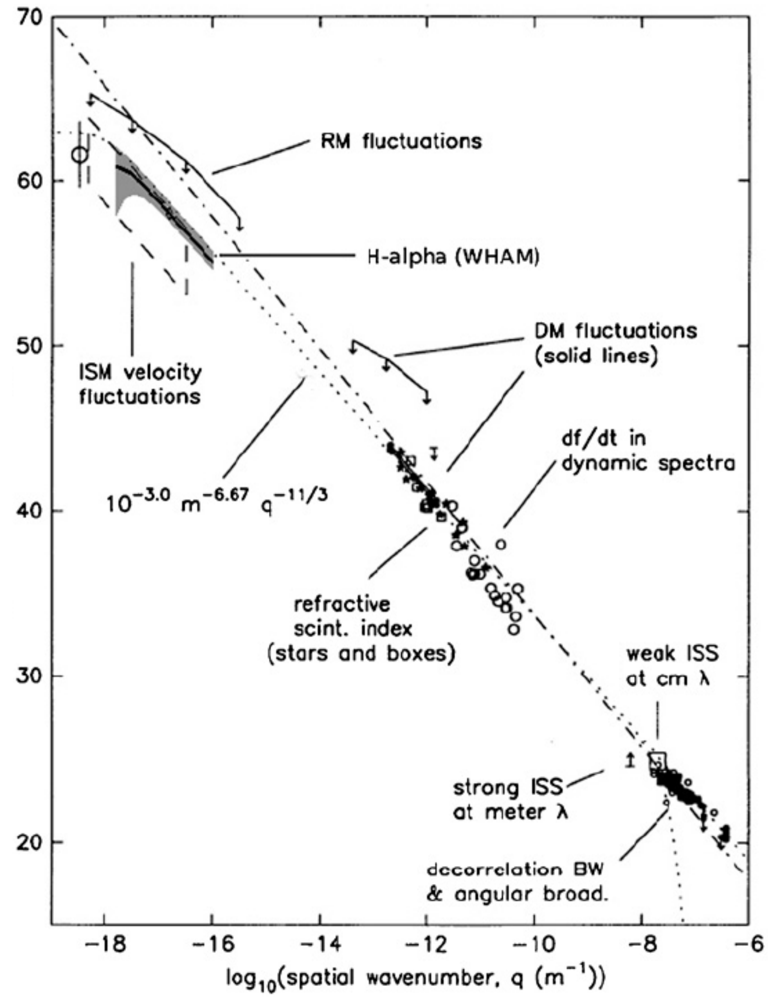
$E(k) \propto k^{-5/3}$

$\delta v < C_{S,WNM}$ ➔

Kolmogorov Spectrum

2D: Hennebelle & Audit 2007;

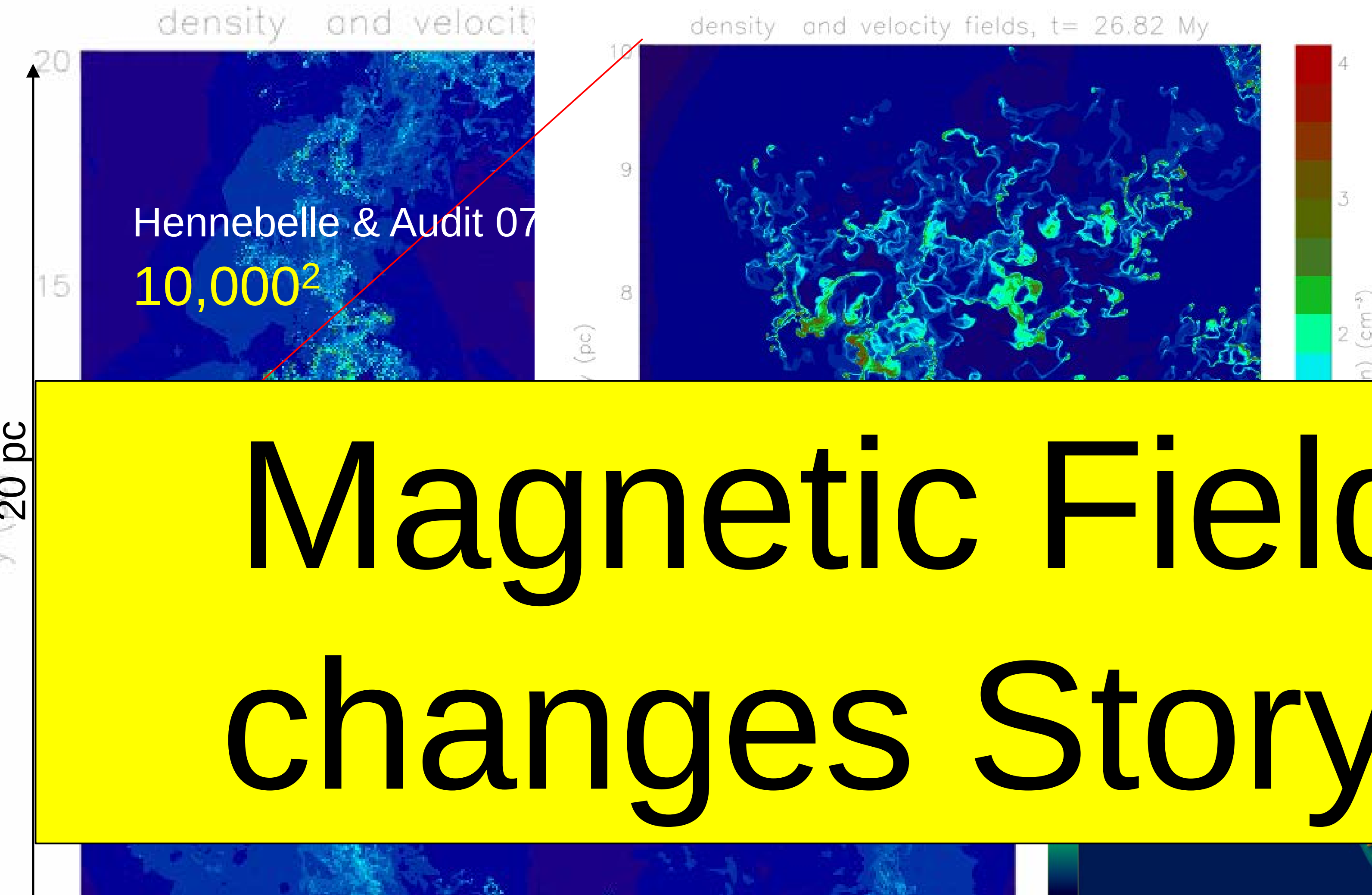
See, e.g., Gazol & Kim 2010



Spectrum Observed in ISM

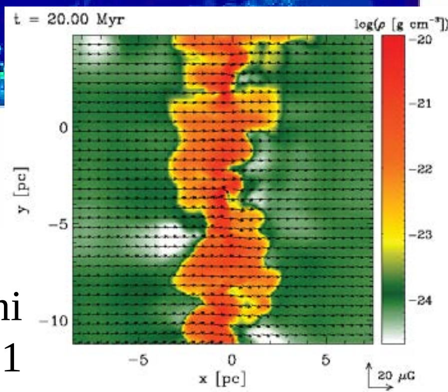
Chepurnov & Lazarian 2010

Armstrong et al. 1995



Magnetic Field changes Story!

c.f.
Kritsuk & Norman 1999



Vazquez-Semadeni et al. 2011

Heitsch+ 2006
2D, 4096^2

Colliding WNM with B_0=3μG

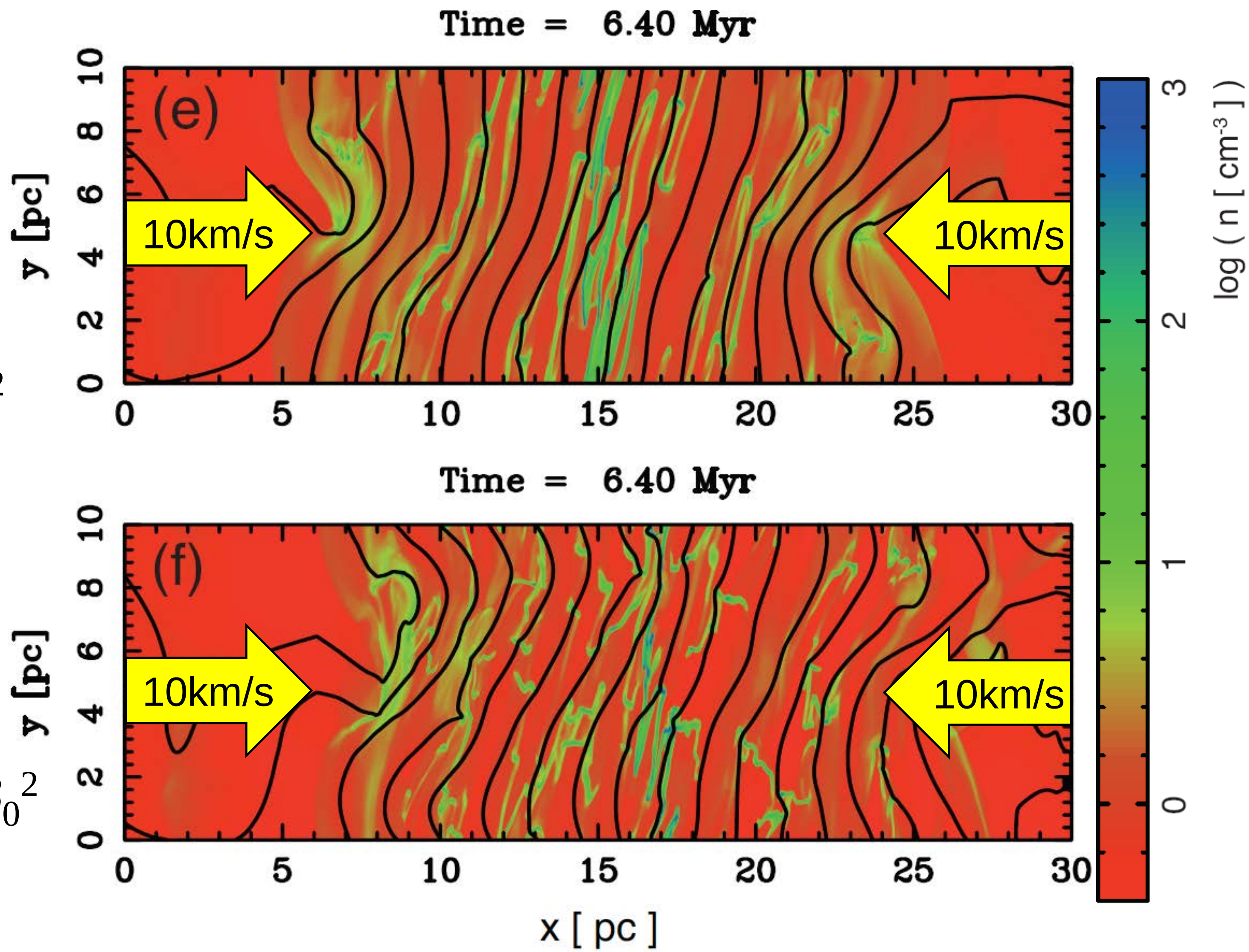
v=10km/s

(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

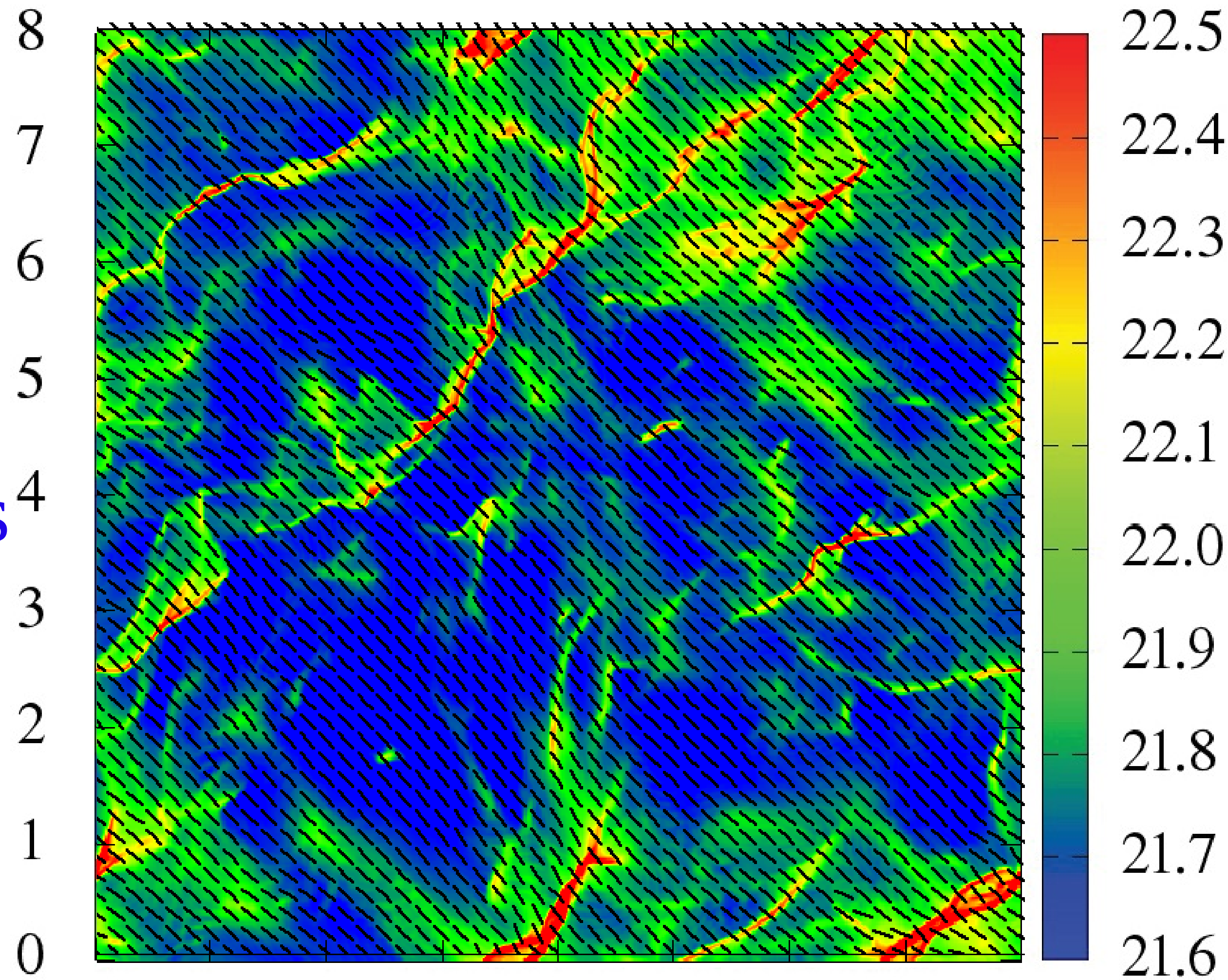
We need multiple episodes of compression.

Further Compress. of Mole. Clouds

Multiple Compressions of Molecular Cloud

➔Magnetized Massive Filaments & Striations

Agree with Observations!



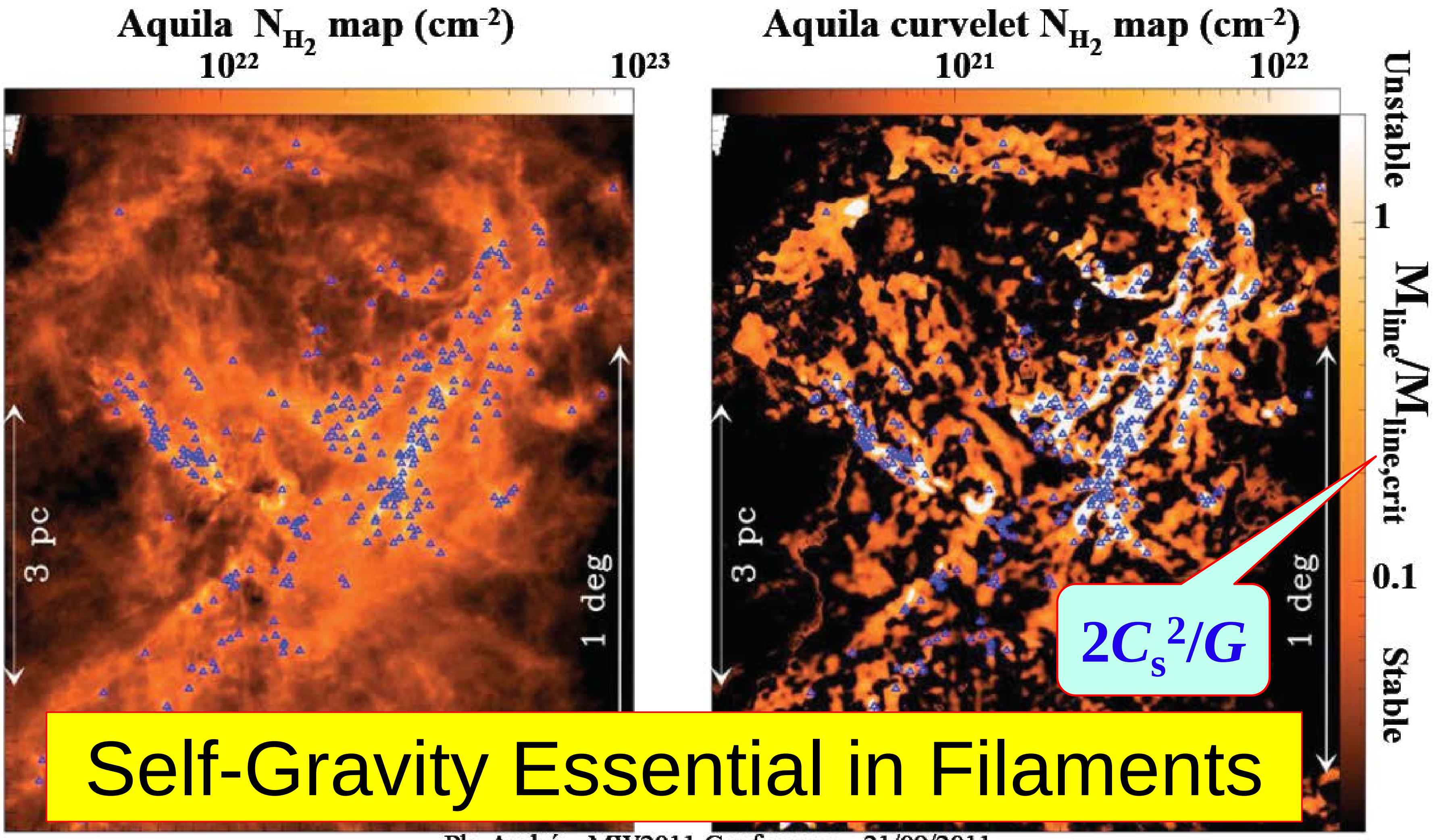
Black Lines: Magnetic Field Lines

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 $N_{H_2} > 7\times10^{21}$ cm^{-2} <=> A_v(back) > 8



Mass Function of Cores in a Filament

Inutsuka 2001, ApJ **559**, L149

Line-Mass Fluctuation of Filaments

Initial Power Spectrum

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

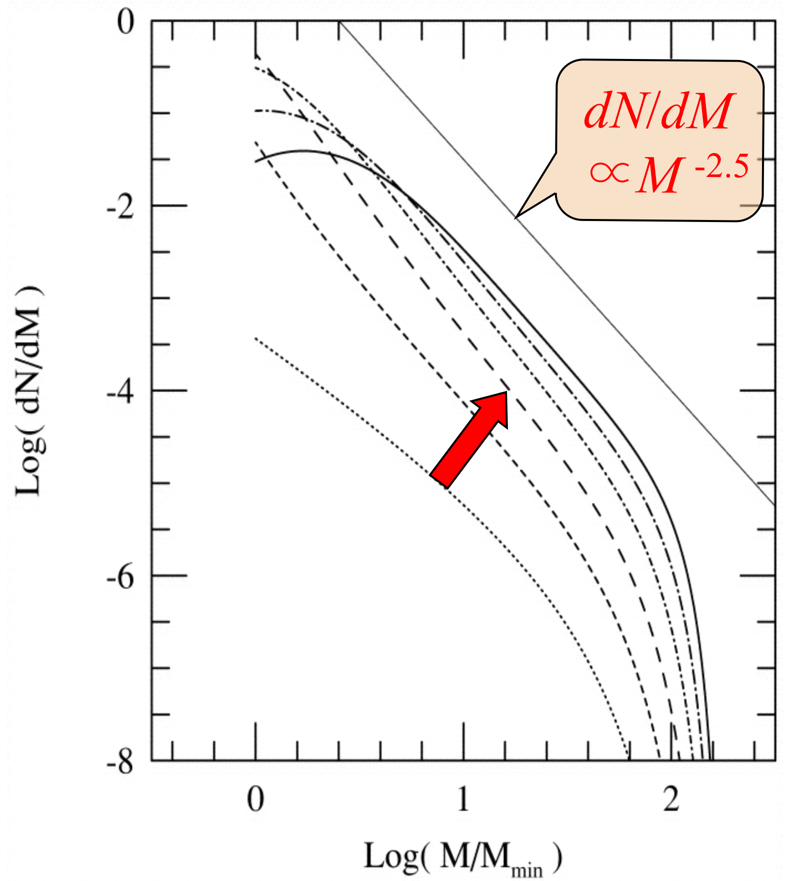
Mass Function

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

Observation of Both Perturbation Spectrum and Mass Function

→direct test !

(cf. Hennebelle & Chabrier 2008; Shadmehri & Elmegreen 2011)



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

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*+2015)

Filament Paradigm

Completely Successful?!

Other Modes of Star Formation?

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

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

See also talk by *Diehl*!

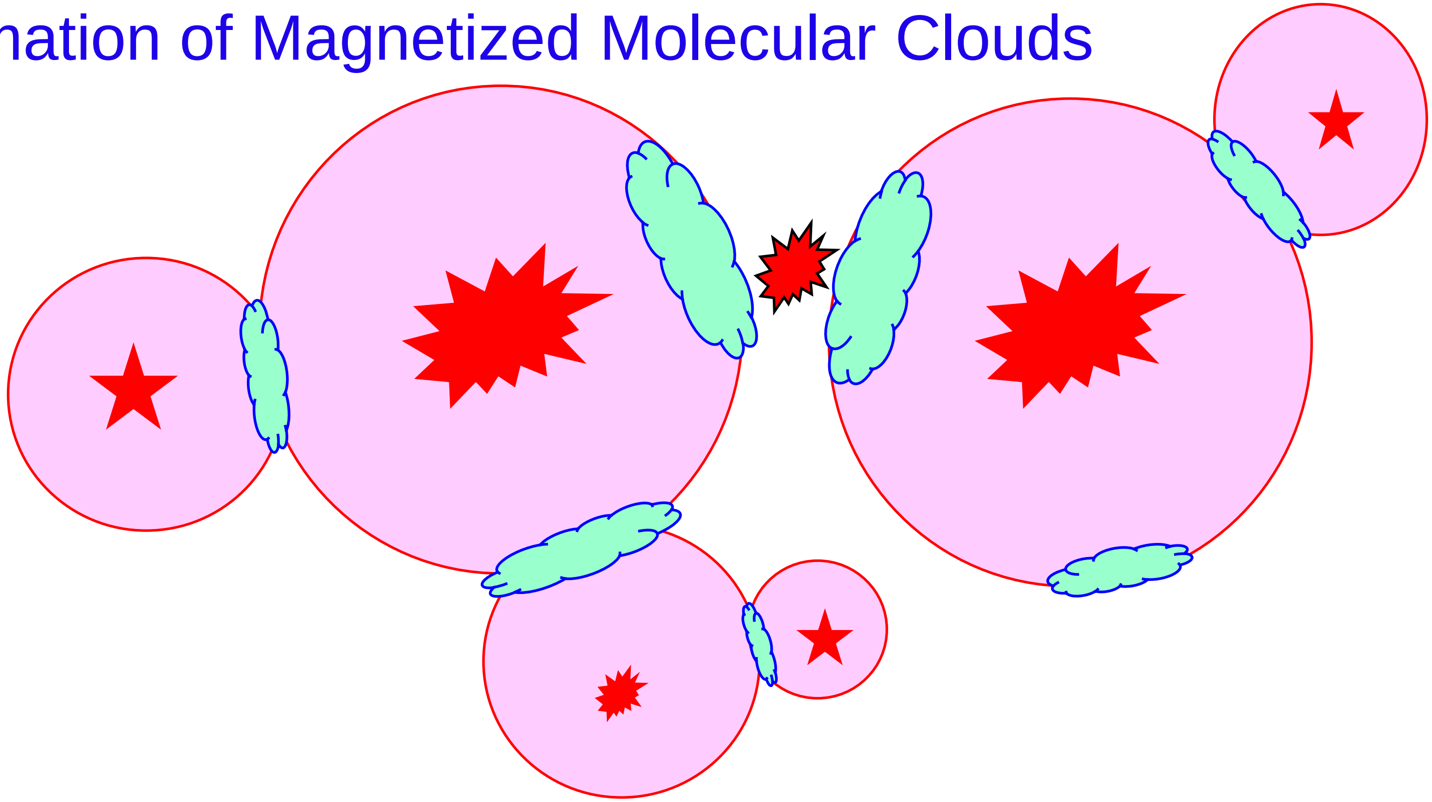
Toward Global Picture of Star Formation

Multiple Compressions Needed
for Molecular Cloud Formation

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

Network of Expanding Shells

Multiple Episodes of Compression ➔
Formation of Magnetized Molecular Clouds



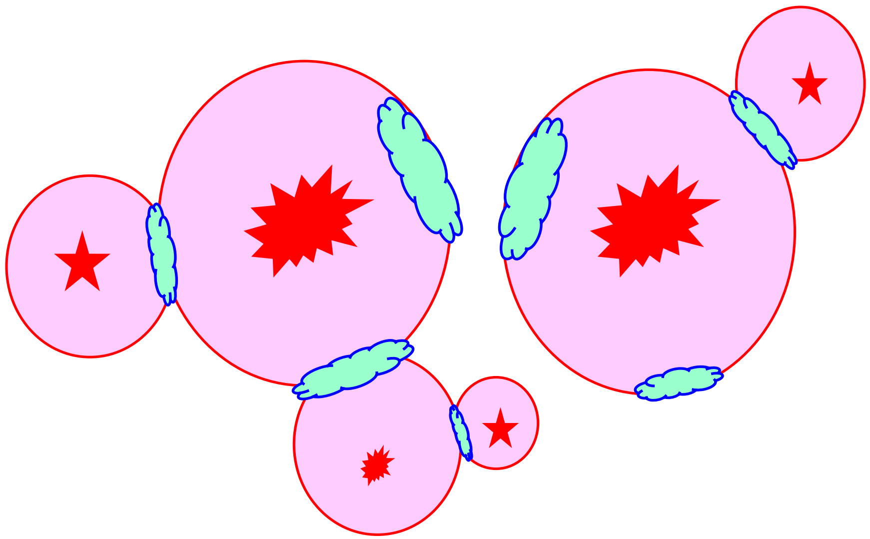
Long (>10Myr) Exposure Picture!

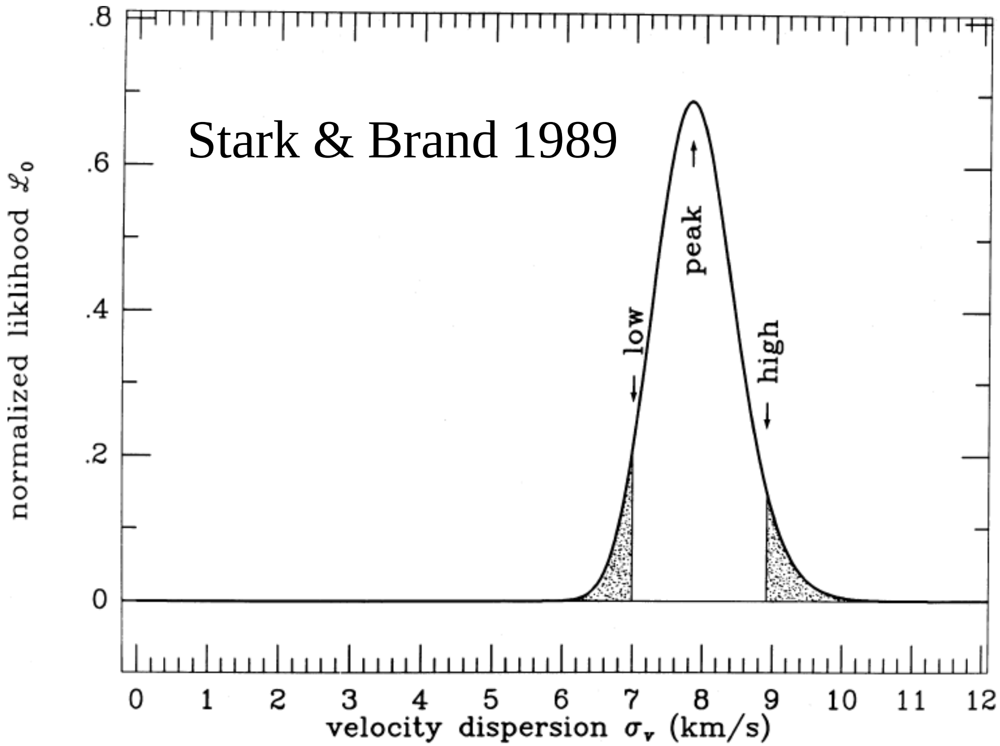
Each bubble disappears quickly (<Myr).

SI+2015; cf. Elmegreen 2007

Velocity Dispersion of Clouds

Multiple Episodes of Compression ➔ Formation of Magnetized Molecular Clouds



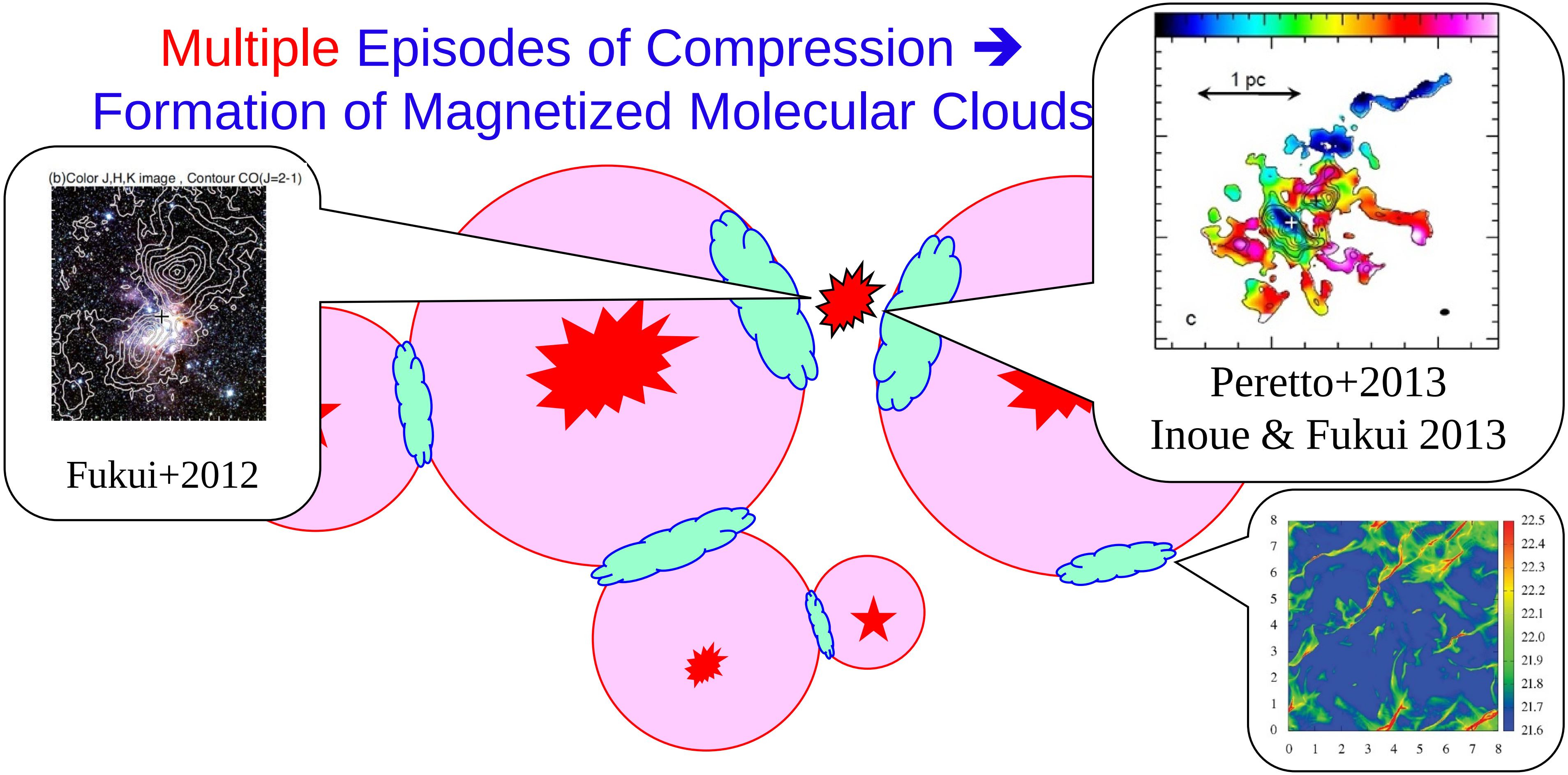


Shell Expansion Velocities ~ 10^1 km/s

Cloud-to-Cloud Velocity Dispersion

Network of Expanding Shells

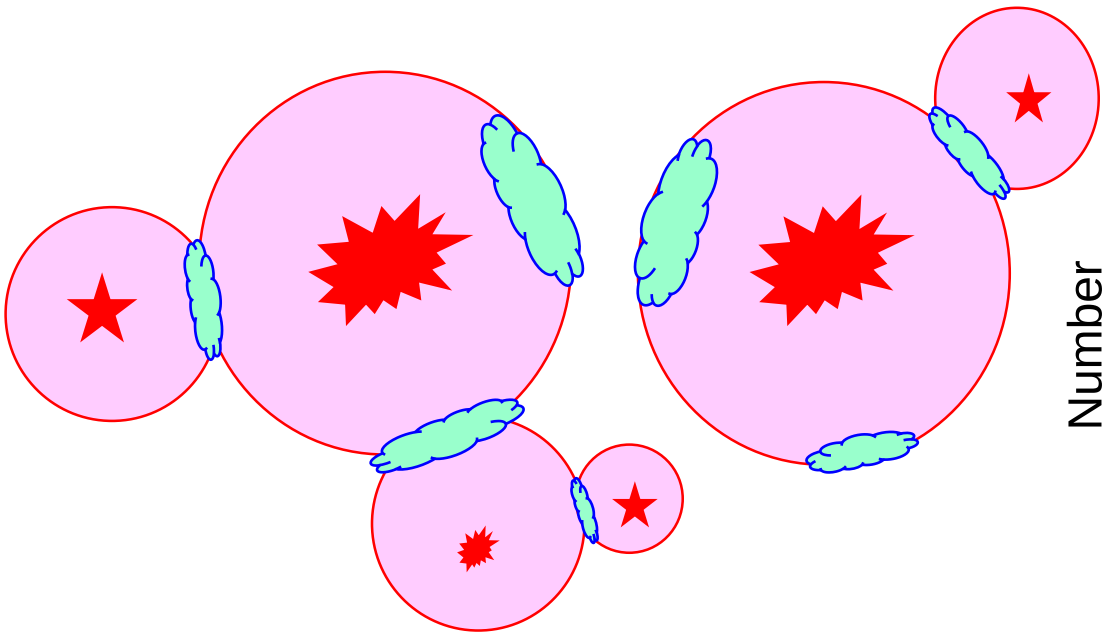
Multiple Episodes of Compression ➔
Formation of Magnetized Molecular Clouds

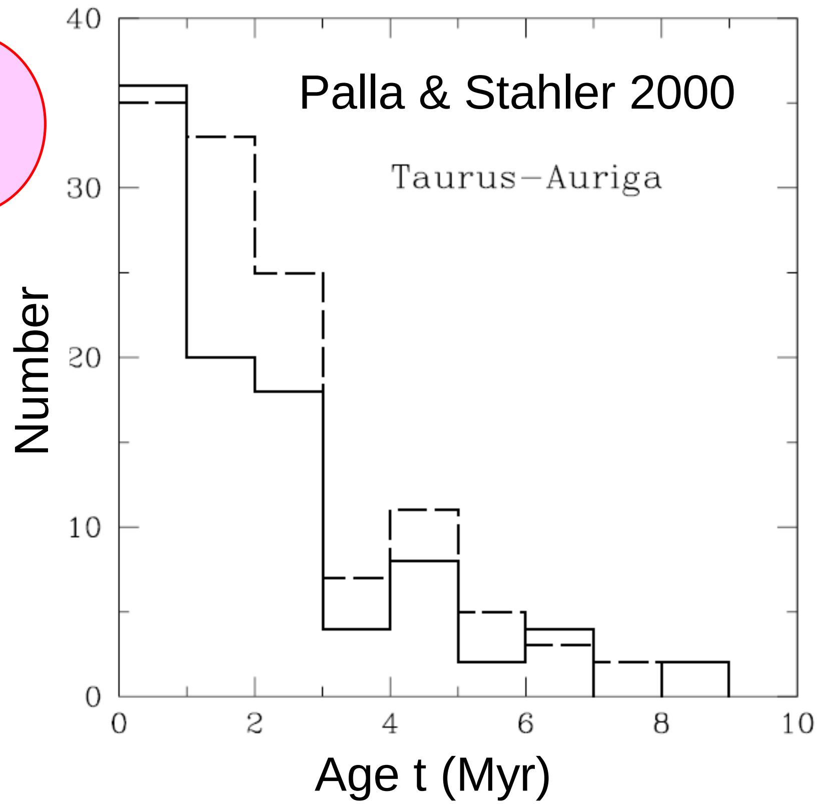


Each Bubble Visible Only for Short Time (~1Myr)!

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

Accelerated Star Formation





Molecular Cloud Growth

➔ Collisions of Clouds

➔ Accelerated SF

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

c.f., Vazquez-Semadeni+2007

Destruction of Molecular Clouds

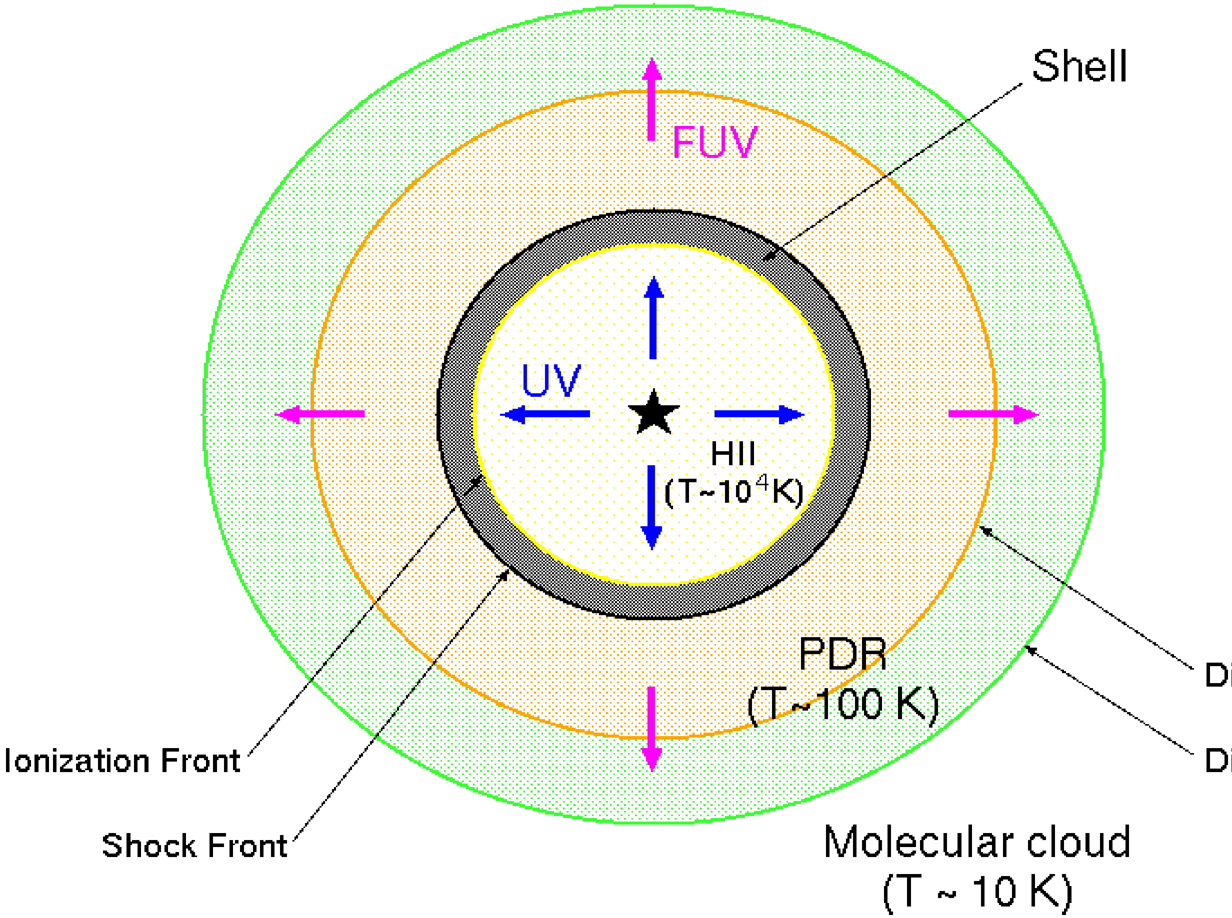
How to Stop Star Formation?

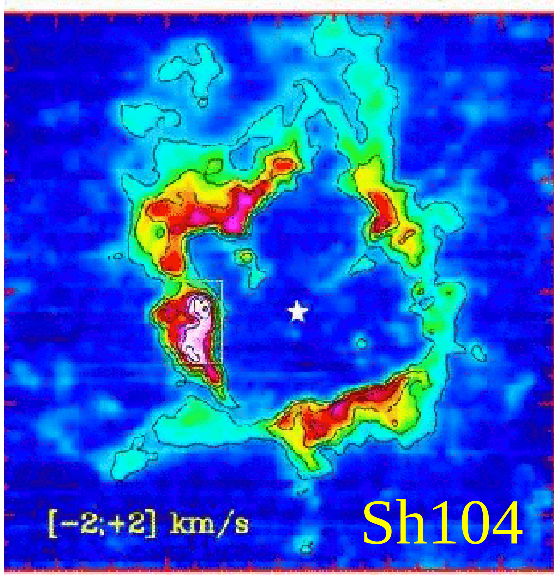
Radiative Feedback

Photodissociation Critical!

c.f. *Dale, Walch,…*

Expanding HII Region in Magnetized Molecular Cloud





Deharveng et al. 2003

Radiation Magnetohydrodynamics Calculation

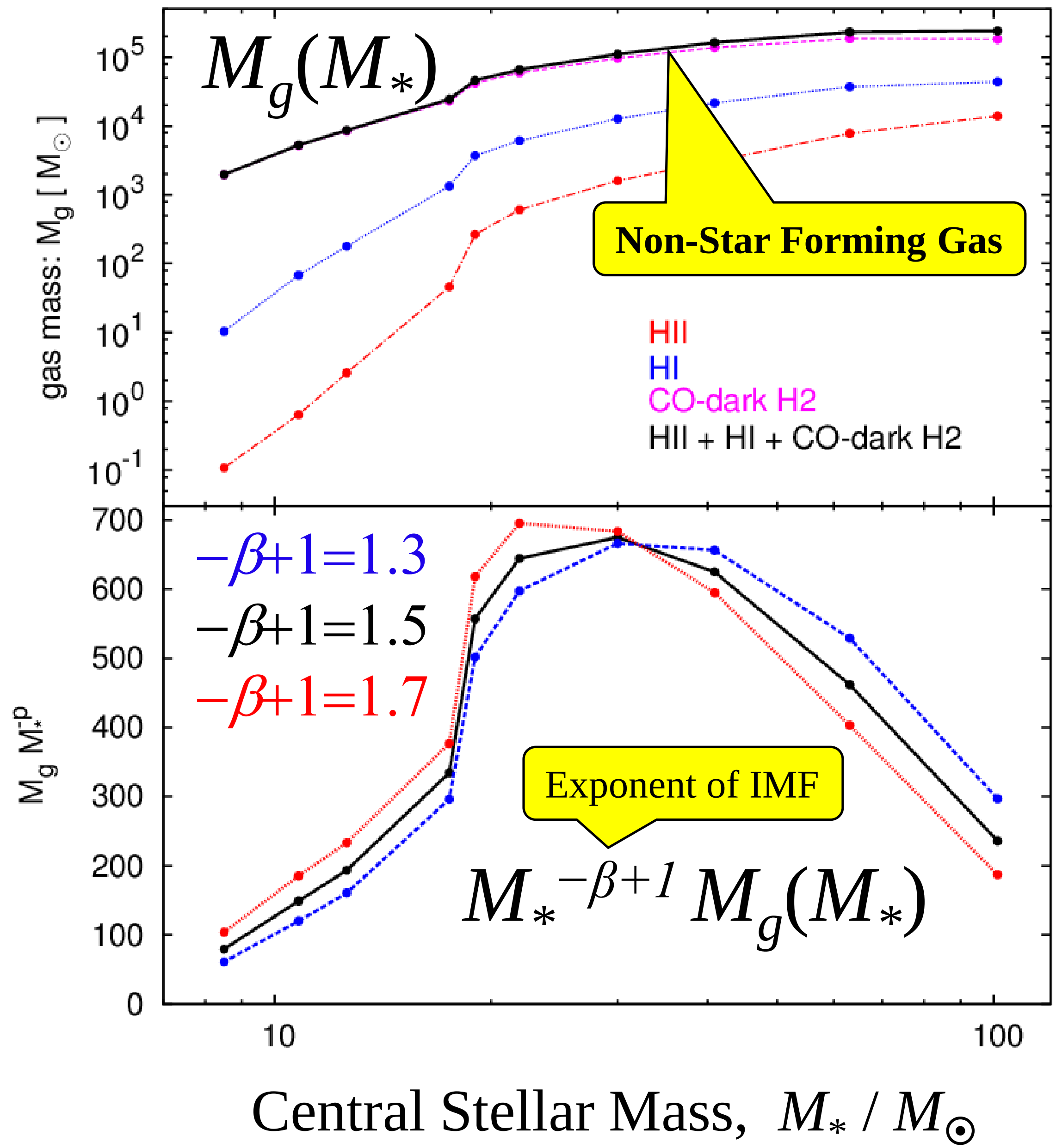
UV/FUV + H2 + CO Chemistry (Hosokawa & SI 2005, 2006ab, 2007)

Disruption of Magnetized Molecular Clouds

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

➔

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



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

Star Formation Efficiency & Schmidt-Kennicutt-Law

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

Suppose $M_{\rm total} \sim 10^3 M_\odot$ stars formed in $10^5 M_\odot$

➔ ~1 massive ($>30 M_\odot$) star for std IMF

Zuckerman & Evans 1974

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

Star Formation Time

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

$$\text{Gas Dissipation time: } \tau_{\rm dis} = \frac{T_{\rm d}}{\varepsilon_{\rm SF}} \sim 1.4\text{Gyr}$$

No Dependence on Mass ➔ Schmidt-Kennicutt Law

Star Formation Efficiency, KS-Law

M_g molecular gas (H_2) dispersed by M_{d*}

β: exponent of IMF

M_{*m} : Effective Minimum Stellar Mass

$$\Rightarrow \epsilon_{SF} = \frac{M_{*,\mathrm{total}}}{M_g(M_{*d})} = \left(\frac{\beta - 1}{\beta - 2}\right)\left(\frac{M_\odot}{M_{*m}}\right)^{\beta-2}\left(\frac{M_{*d}}{M_\odot}\right)^{\beta-1}\left(\frac{M_g}{M_\odot}\right)^{-1}$$

If $M_g = 10^5$, $M_{d*} = 30M_\odot$, $M_{*m} = 0.1M_\odot$, $\beta = 2.5$,

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

$\Leftrightarrow$ observation $\Leftrightarrow$ β of IMF

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

Galactic Population of Molecular Clouds

➔Poster by Masato Kobayashi

Mass Function of Molecular Clouds

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

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

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

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

In steady state

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

$$T_{\rm dis} \sim 14\,{\rm Myr}\ \&\ T_{\rm form} \sim 10\,{\rm Myr} \rightarrow \alpha = 1.7$$

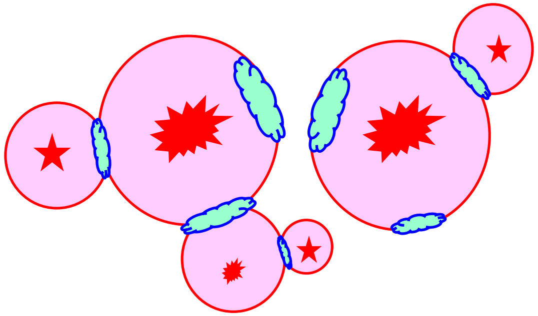
(*SI, Inoue, Iwasaki, & Hosokawa 2015* A&A **580**, A49; *Kobayashi+2016* submitted)

Summary

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

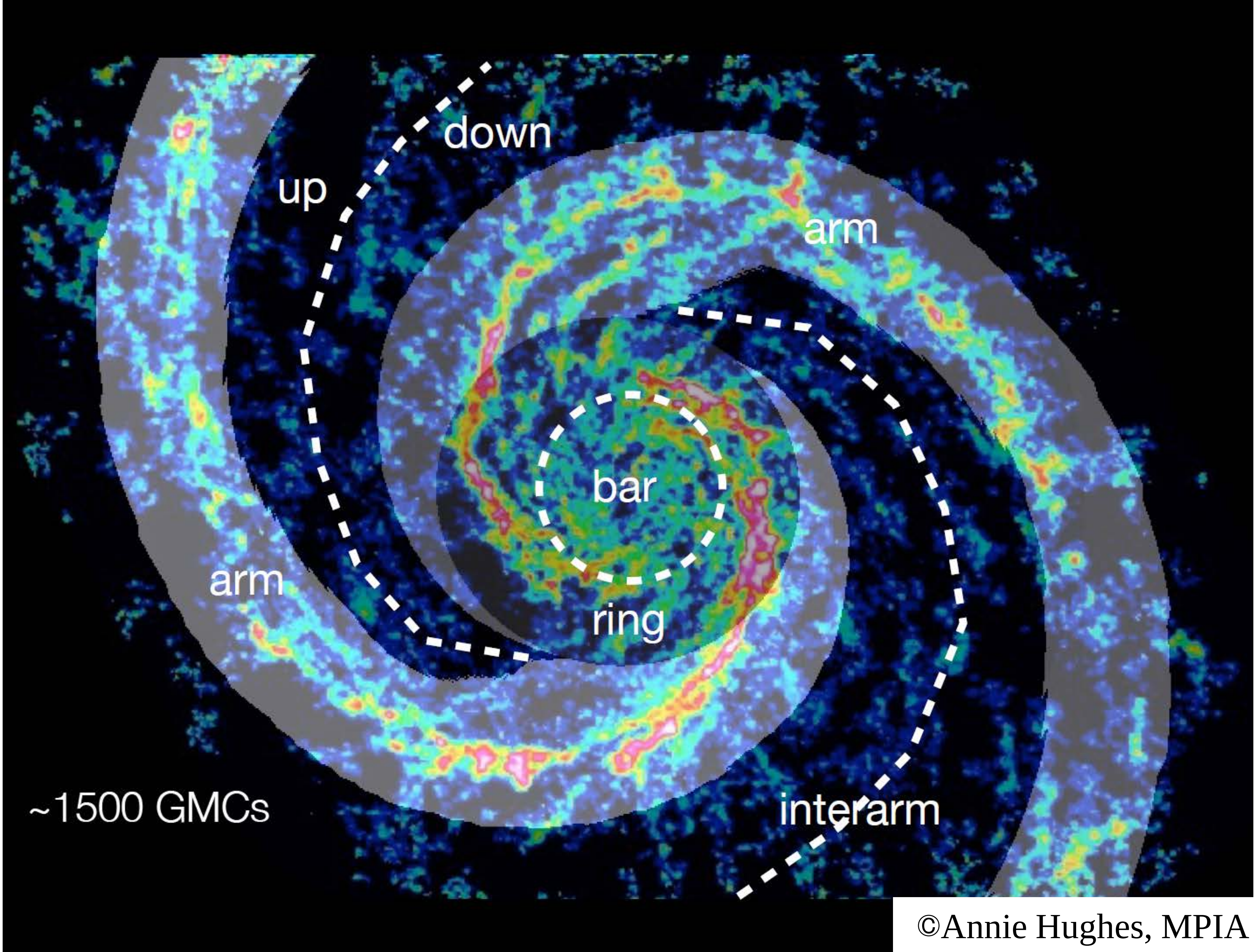
➔ Unified Picture of Star Formation

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

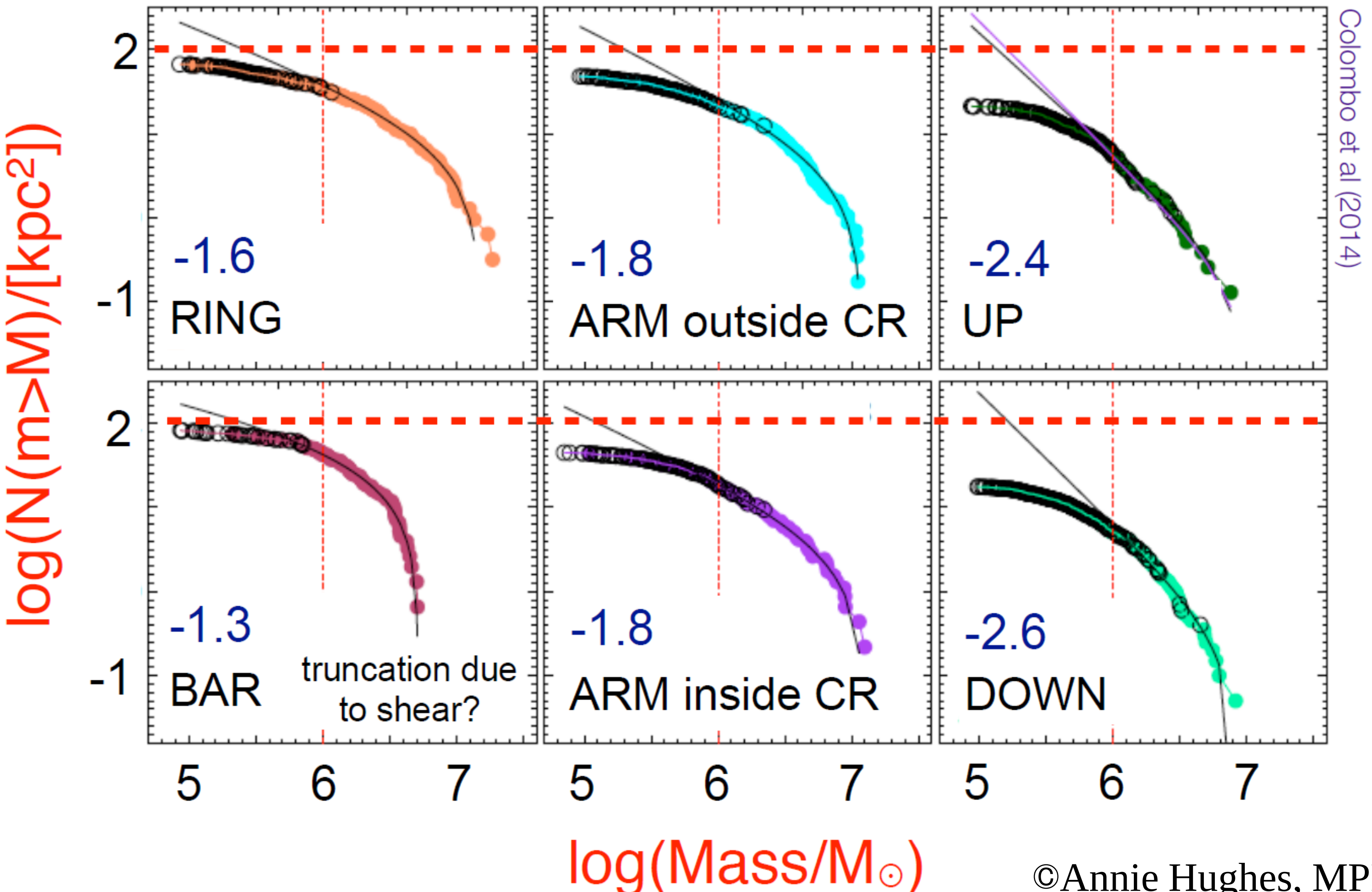


SI, Inoue, Iwasaki, & Hosokawa 2015, A&A **580**, A49

Kobayashi+2016 submitted


down
up
arm
bar
arm
ring
~1500 GMCs
interarm

GMC Mass Spectra: M51 environments



Slope of Cloud Mass Function

Steady State Mass Function of Molecular Clouds

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

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

In low density region (Inter-Arm Region)

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

In high density region (Arm Region)

Smaller T_{form} ➔ Smaller α

➔ GMCs in M51 (Colombo+2014)