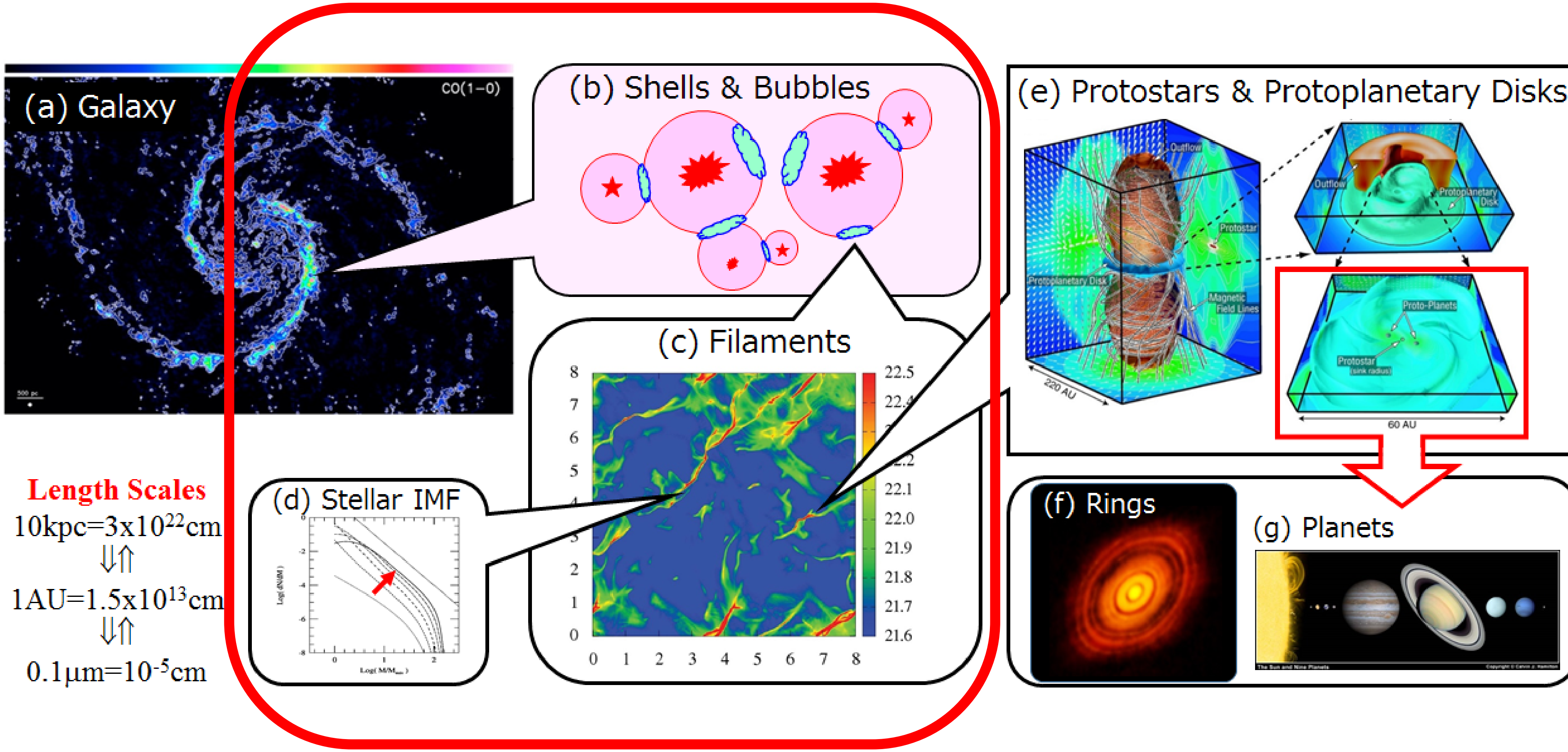
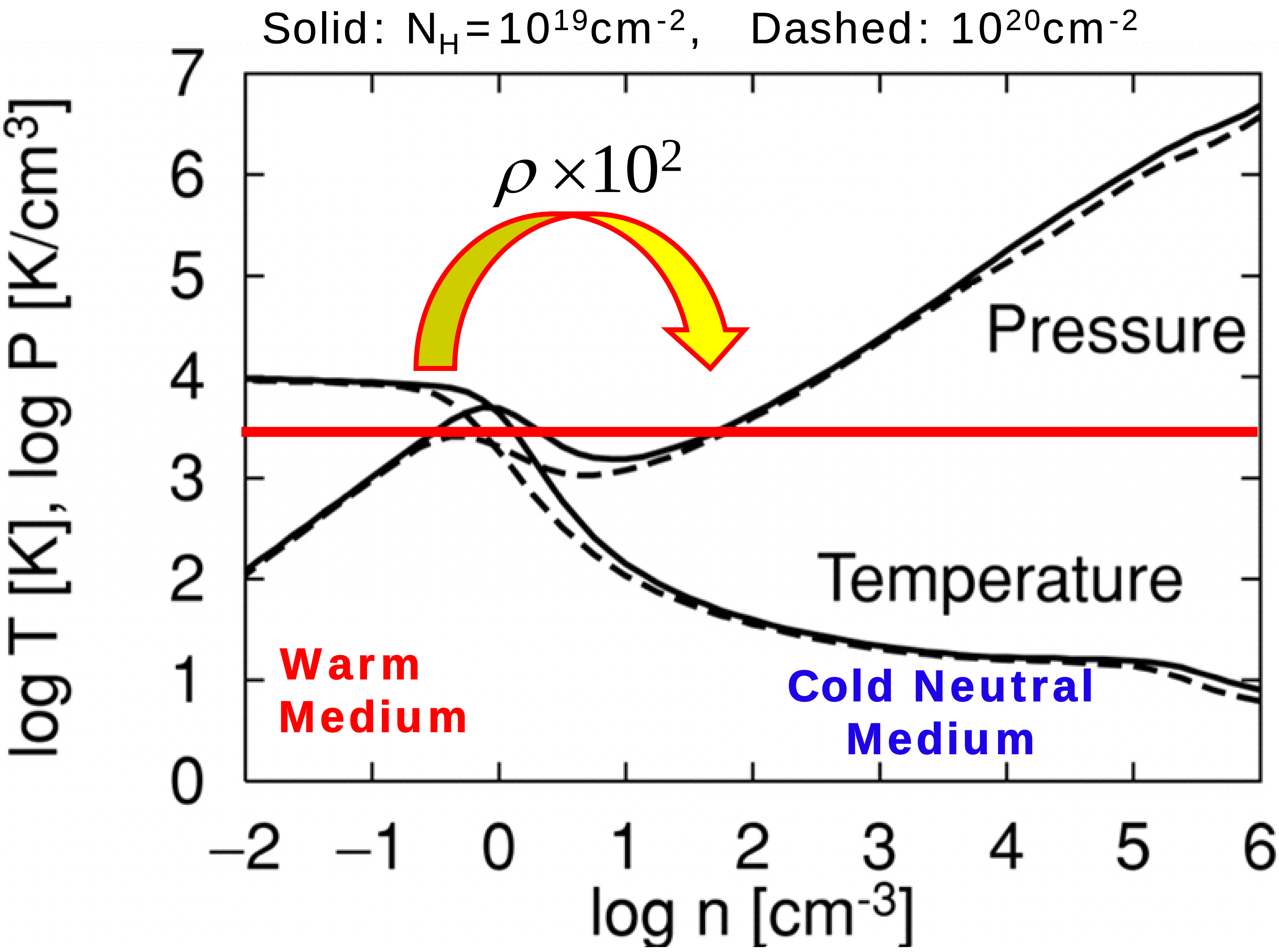
Toward Galactic View of Star Formation

Shu-ichiro Inutsuka (Nagoya University)

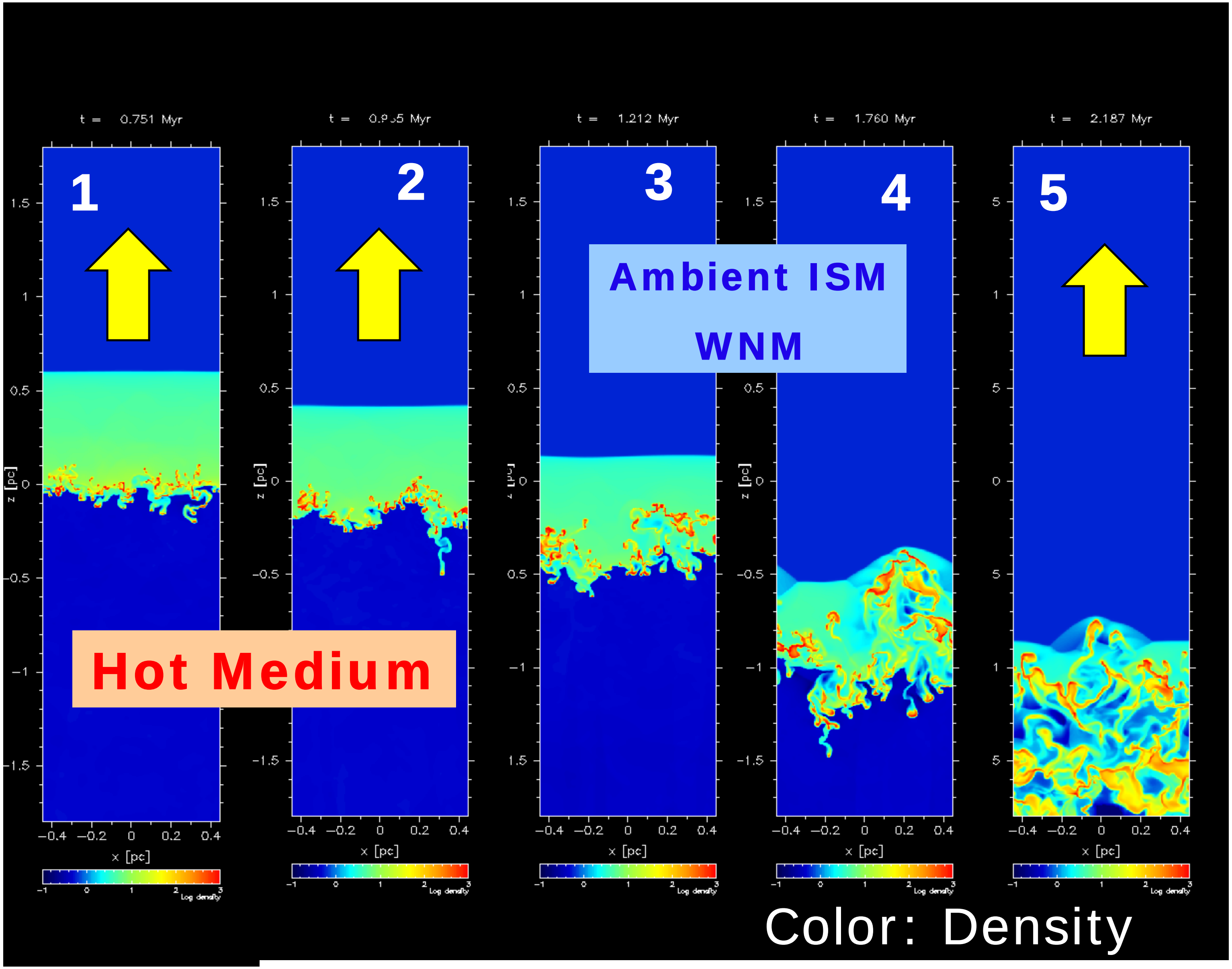


Radiative Equilibrium for a given density



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

Shock Propagation into WNM



Koyama & Inutsuka (2002) ApJ 564, L97

Summary of TI-Driven Turbulence

Koyama & SI (2002): 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)

Hennebelle & Audit (2007):

Turbulence Spectrum = Kolmogorov (Slope ~ 5/3)

Colliding WNM with B_0=3μG

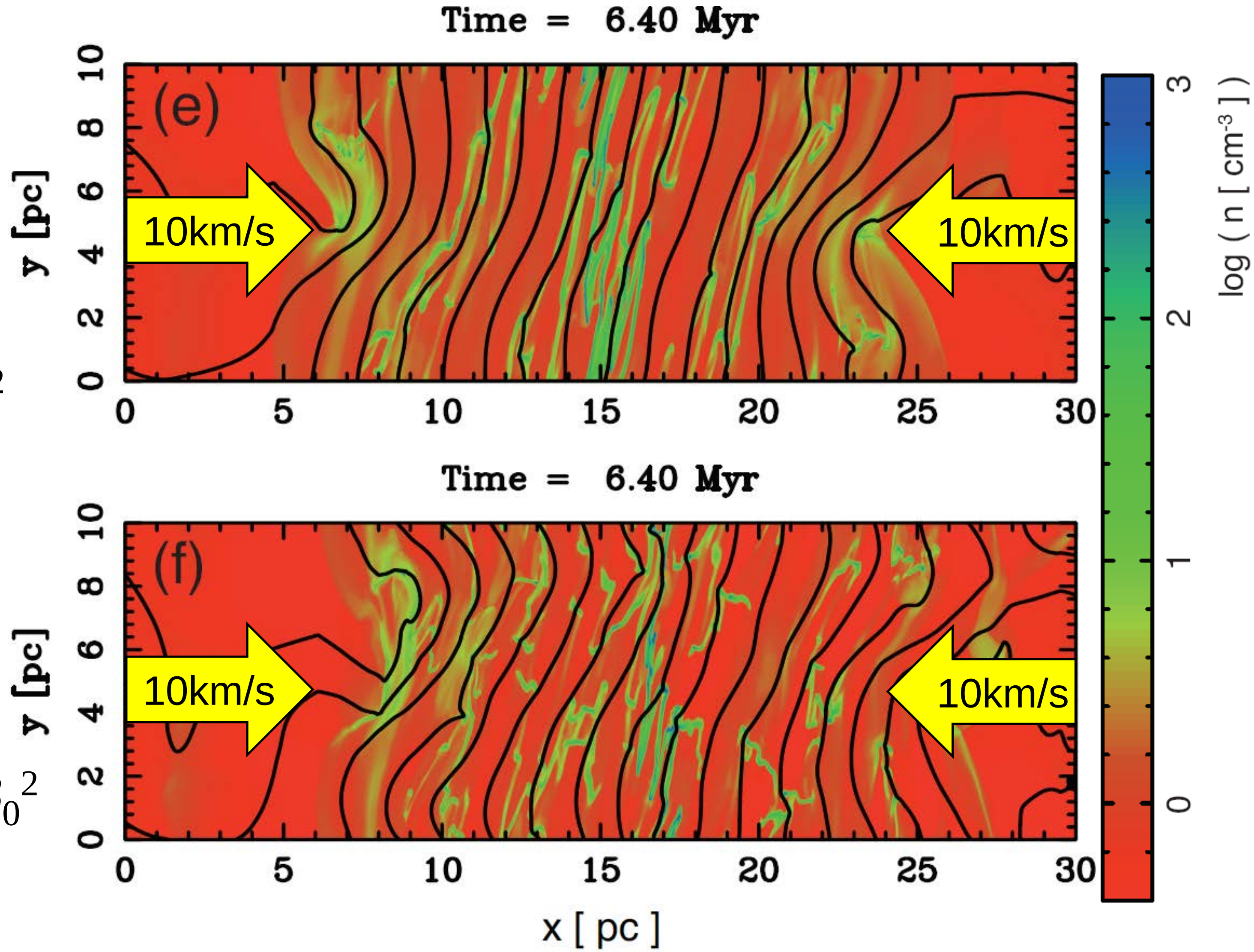
v=10km/s

(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

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

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

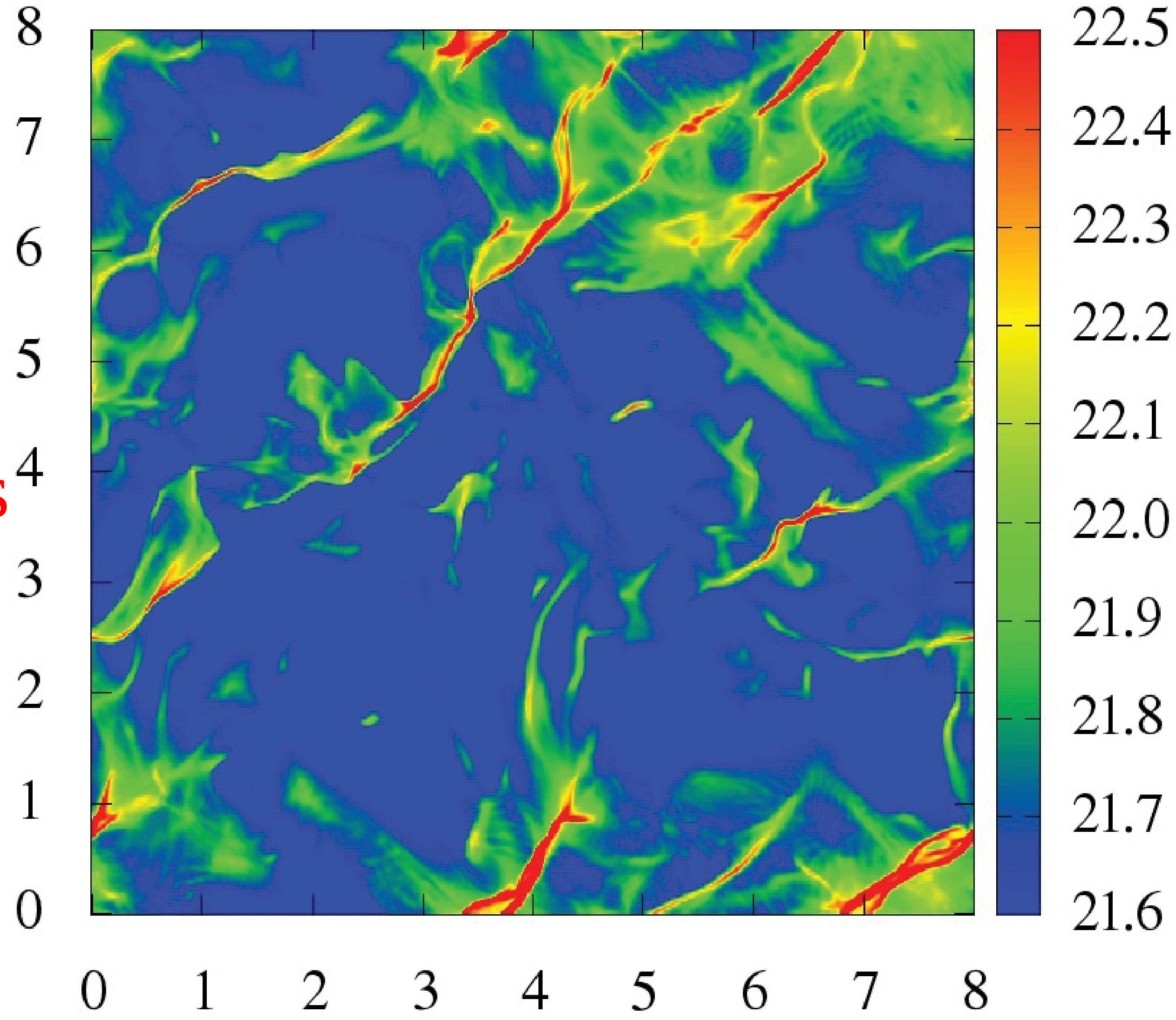
Next Question: What happens for further compressions?

Further Compress. of Mole. Clouds

Further Compression of Molecular Cloud

➔ Magnetized Massive Filaments ($M_{\rm line} > 2C_s^2/G$)

& Striations



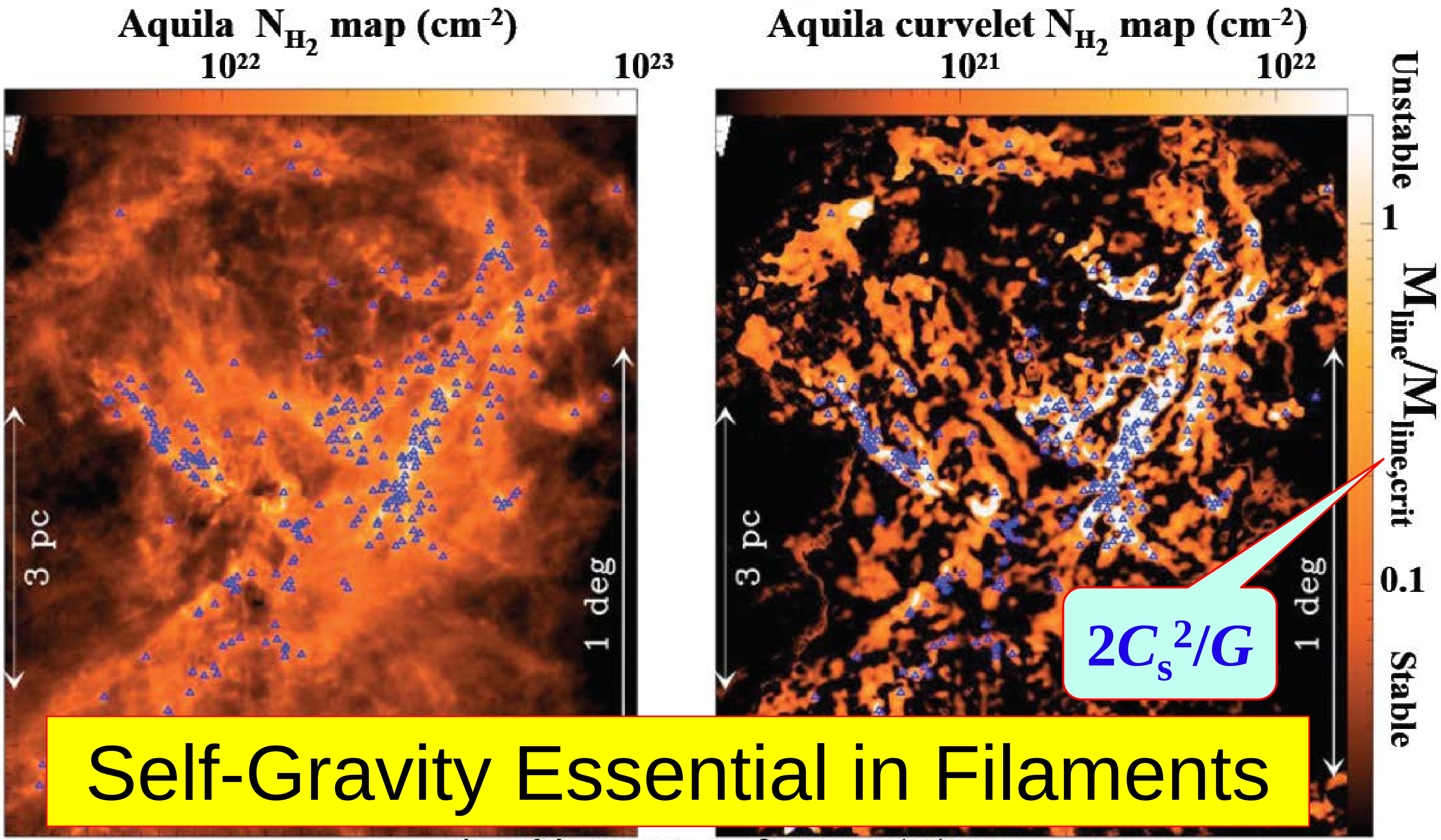
Self-Gravity Included, *SI, Inoue, Iwasaki, & Hosokawa 2015*

See talk by *Arzoumanian, Chung,...*

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



Self-Gravity Essential in Filaments

Mass Function of Cores in a Filament

Inutsuka 2001, ApJ **559**, L149

Line-Mass Fluctuation of Filaments

Initial Power Spectrum

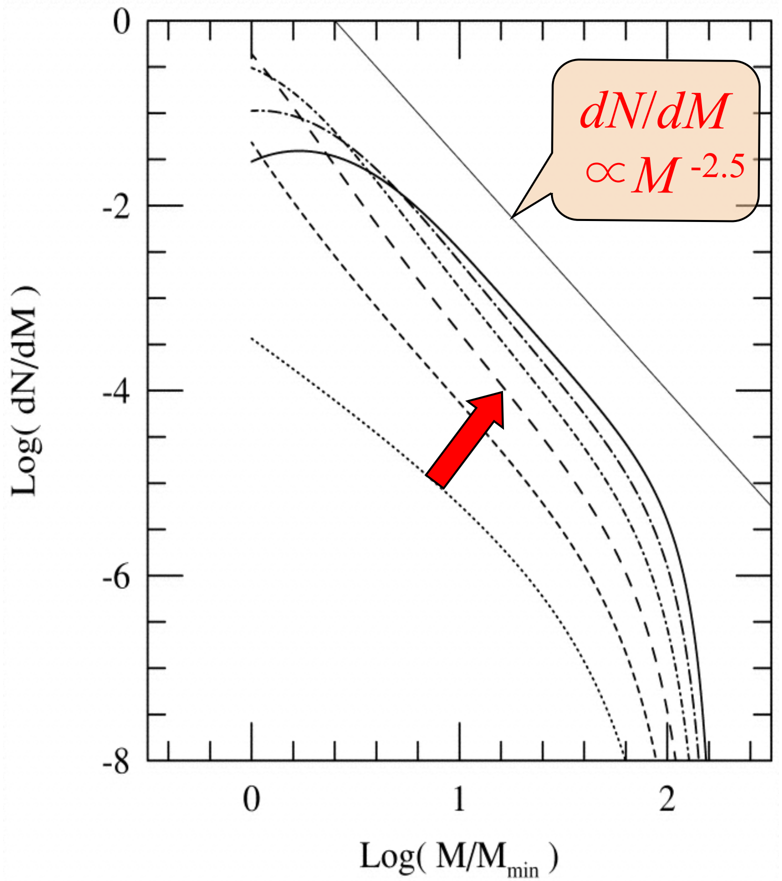
$$P(k) \propto k^{-1.5}$$

Mass Function

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

Observation of Both Perturbation Spectrum and Mass Function

➔ Clear and Direct Test!

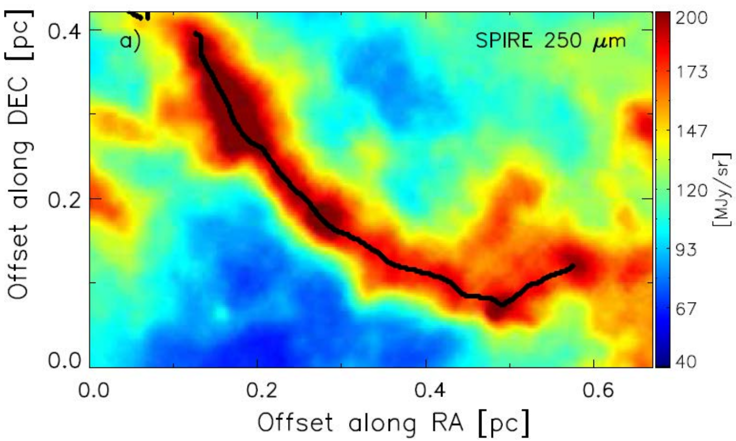


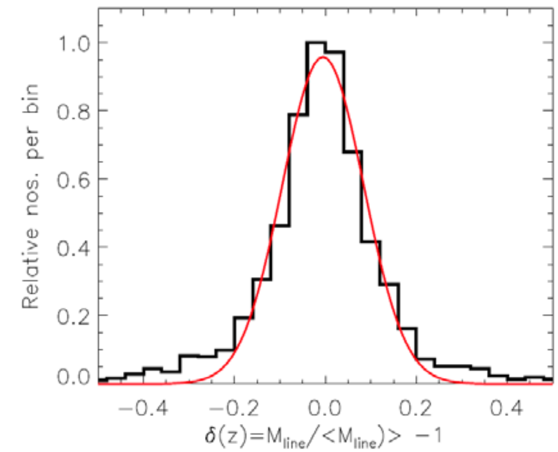
$P(k) \propto k^{-1.5}$

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”

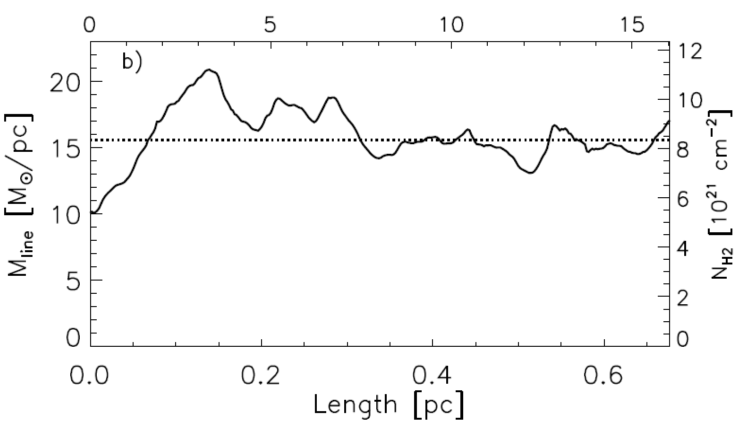
Roy, André, Arzoumanian et al. (2015) A&A **584**, A111





δ …

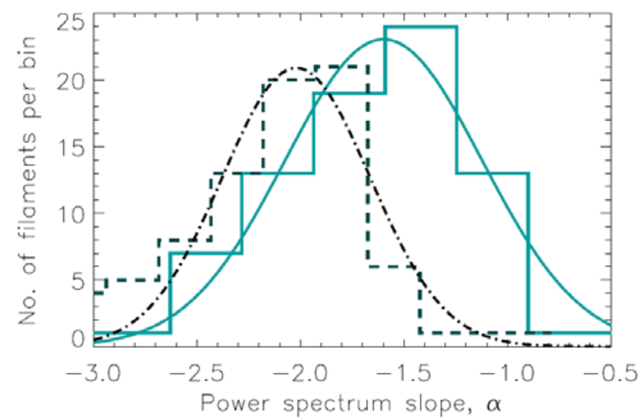
Gaussian



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

$\propto k^{n}$

n= −1.6±0.3



Supporting Inutsuka 2001

Filament Paradigm

Completely Successful?!

SF Threshold, Morphology, CMF, etc.

?

Other Modes of Star Formation?

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

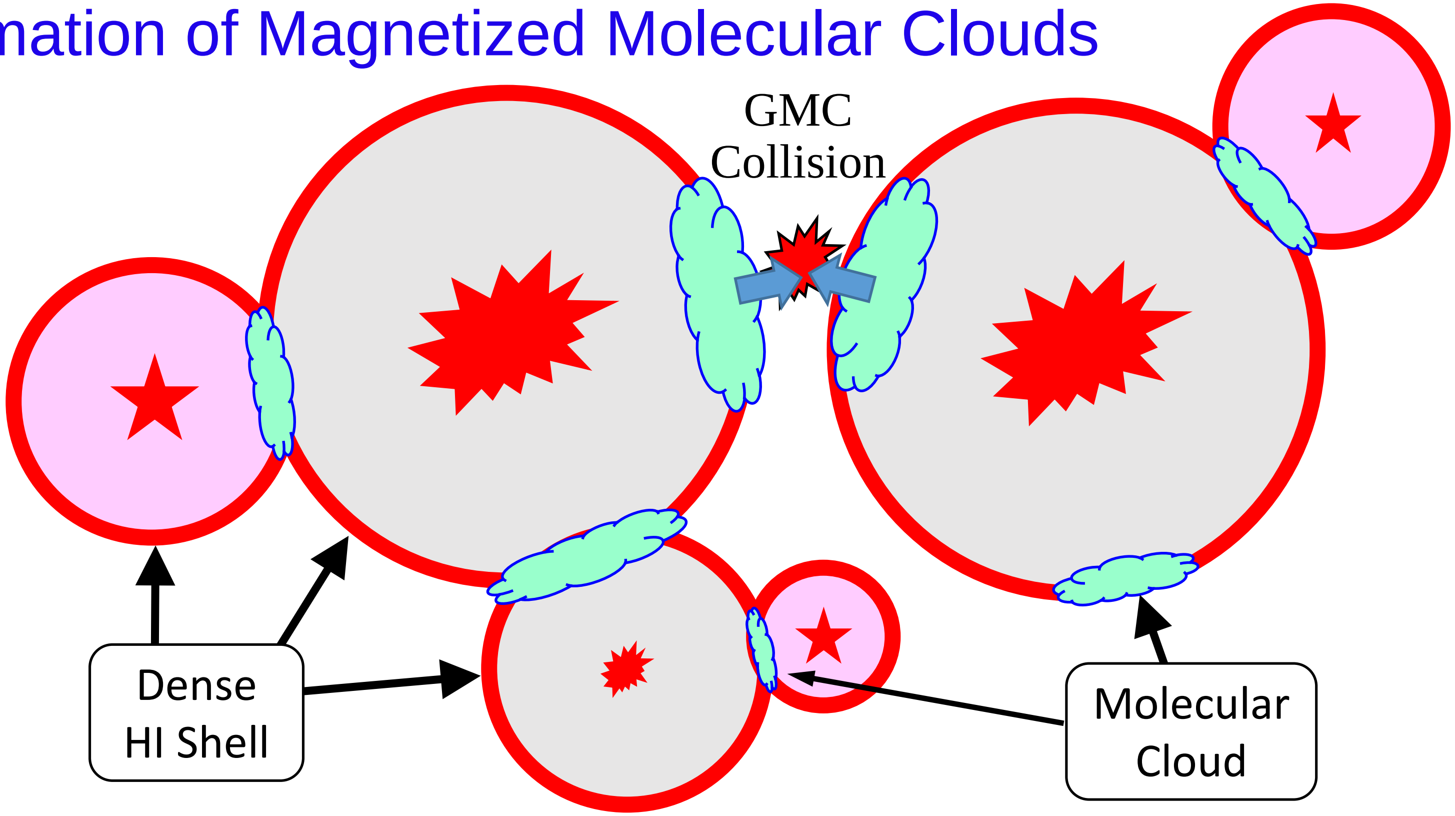
Collect & Collapse (*Elmegreen-Lada, Whitworth, Palouš, Deharveng, Zavagno,…*)

Toward Global Picture of 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



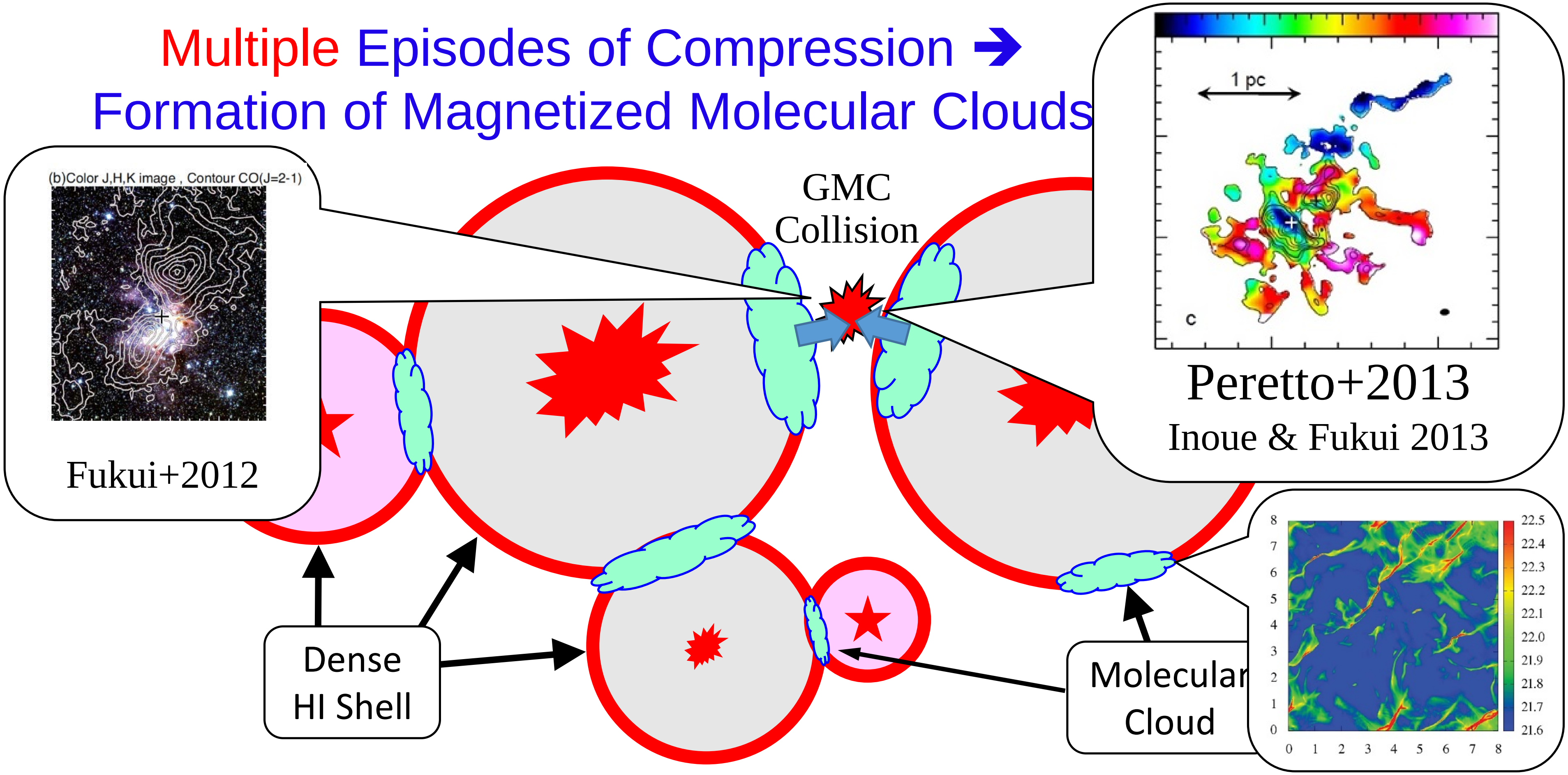
Long (>10Myr) Exposure Picture!

Each bubble disappears quickly (<Myr).

SI+2015; cf. Elmegreen 2007; Dawson+2013,2015

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

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

Zuckerman & Evans 1974

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

Star Formation Time ~10Myr

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

Schmidt-Kennicutt Law

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

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

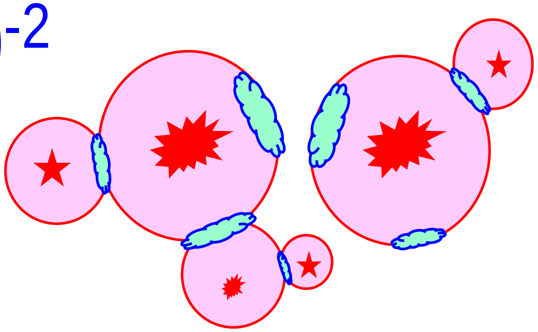
➔Origin of Kennicutt-Schmidt Law (SI+2015)

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



- Mass Func. of GMC ← Talk by *Kobayashi* on Friday!

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

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