A Reply to Palla & Stahler 2000: An Origin of Accelerating Star Formation

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THE ASTROPHYSICAL JOURNAL, 540: 255-270, 2000 September 1

ACCELERATING STAR FORMATION IN CLUSTERS AND ASSOCIATIONS

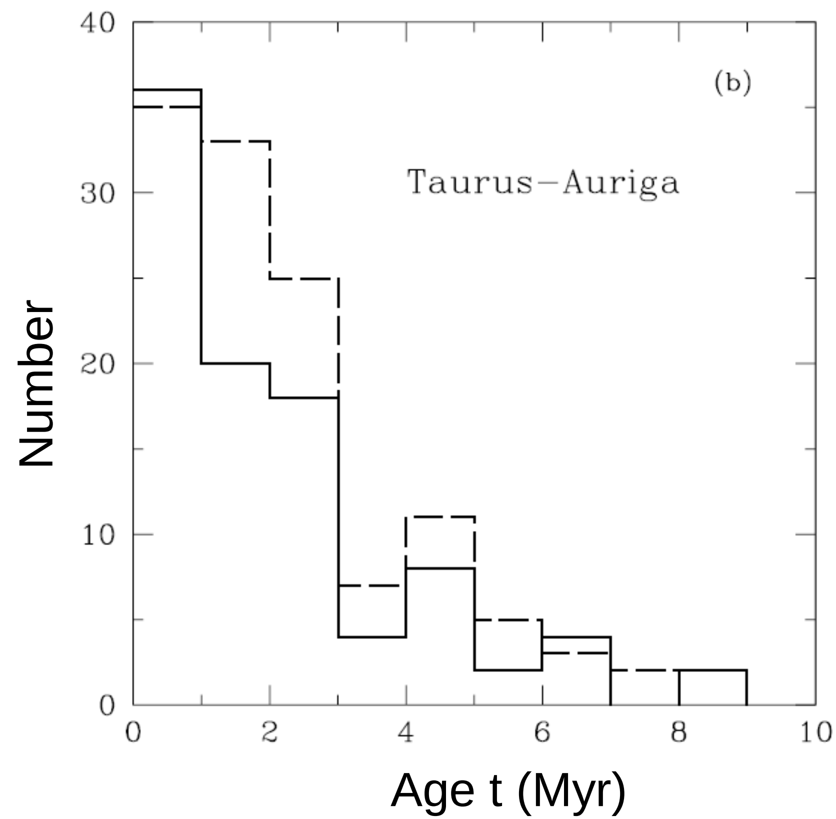
FRANCESCO PALLA AND STEVEN W. STAHLER

Received 1999 November 29; accepted 2000 April 7

Section 4. DISCUSSION

"The present study therefore reinforces our view that both the production and collapse of dense cores occur in response to global evolution of the parent cloud."

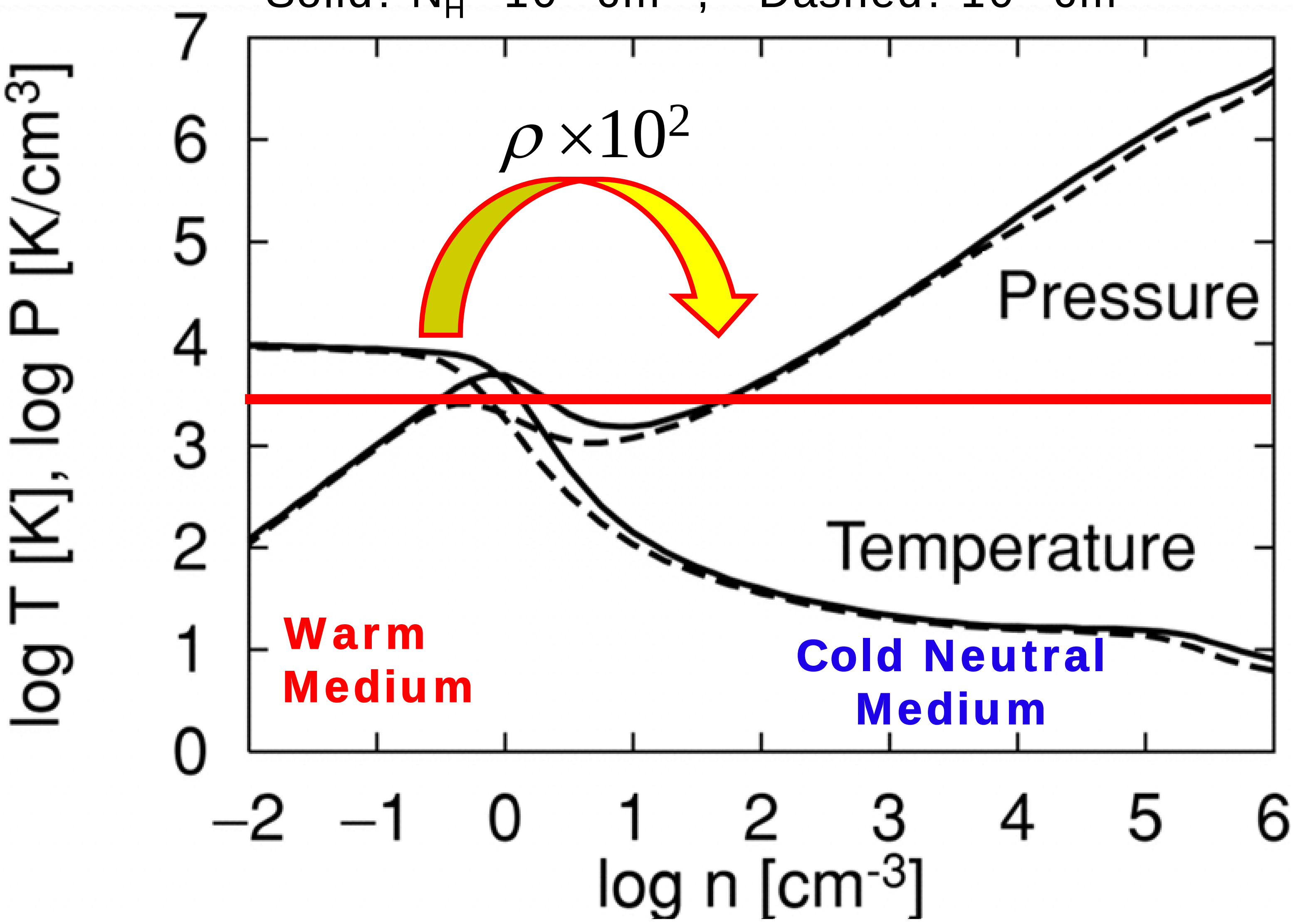
"What is the nature of this evolution?"



Formation of Molecular Clouds

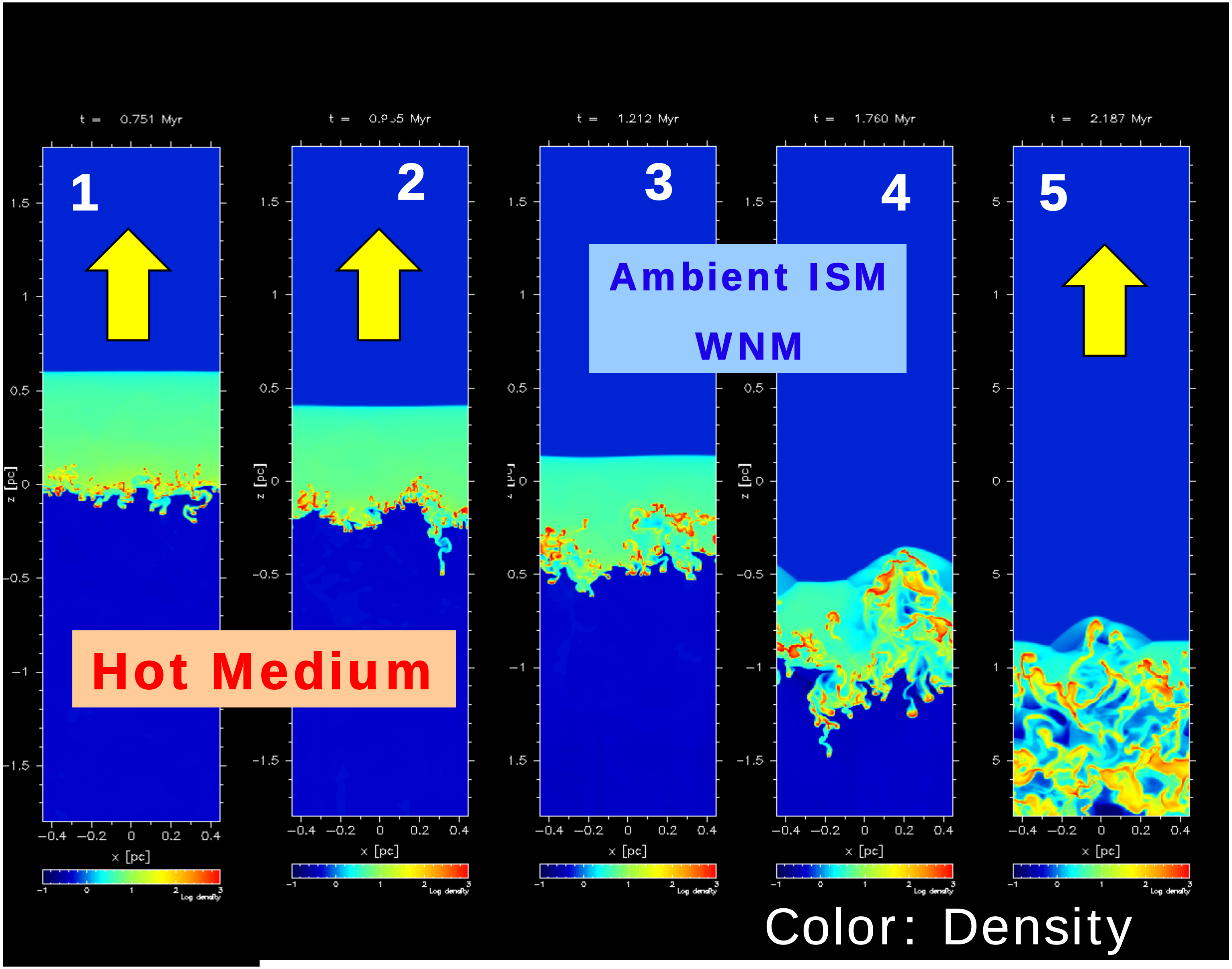
Radiative Equilibrium for a given density

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

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

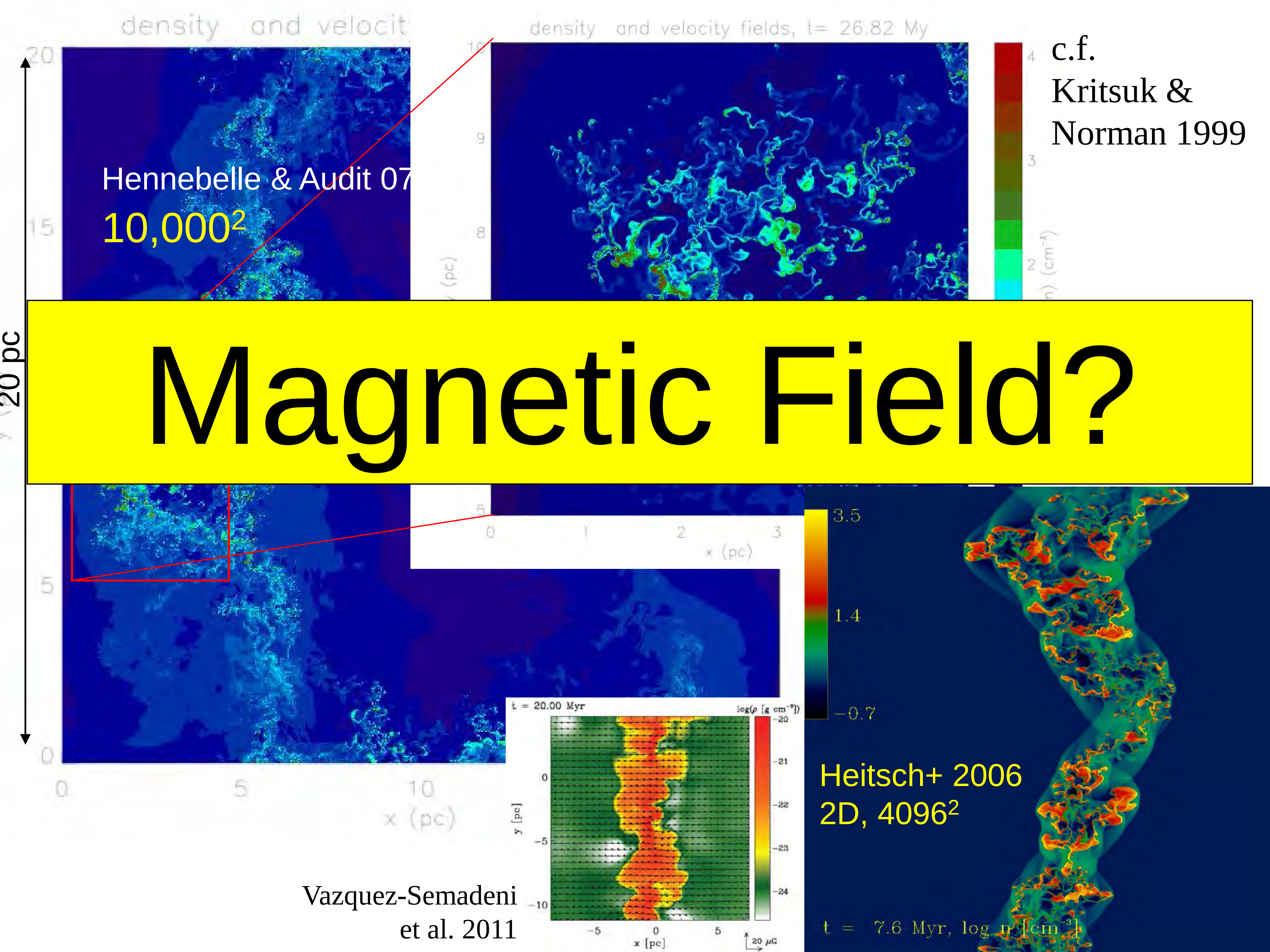
⬅ 10^4K due to Lyα line: Universality!

T_{CNM} ~10^2K ⬅ C^+158μm (~92K)

Hennebelle & Audit (2007):

Turbulence Spectrum ~ Kolmogorov

Magnetic Field?



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

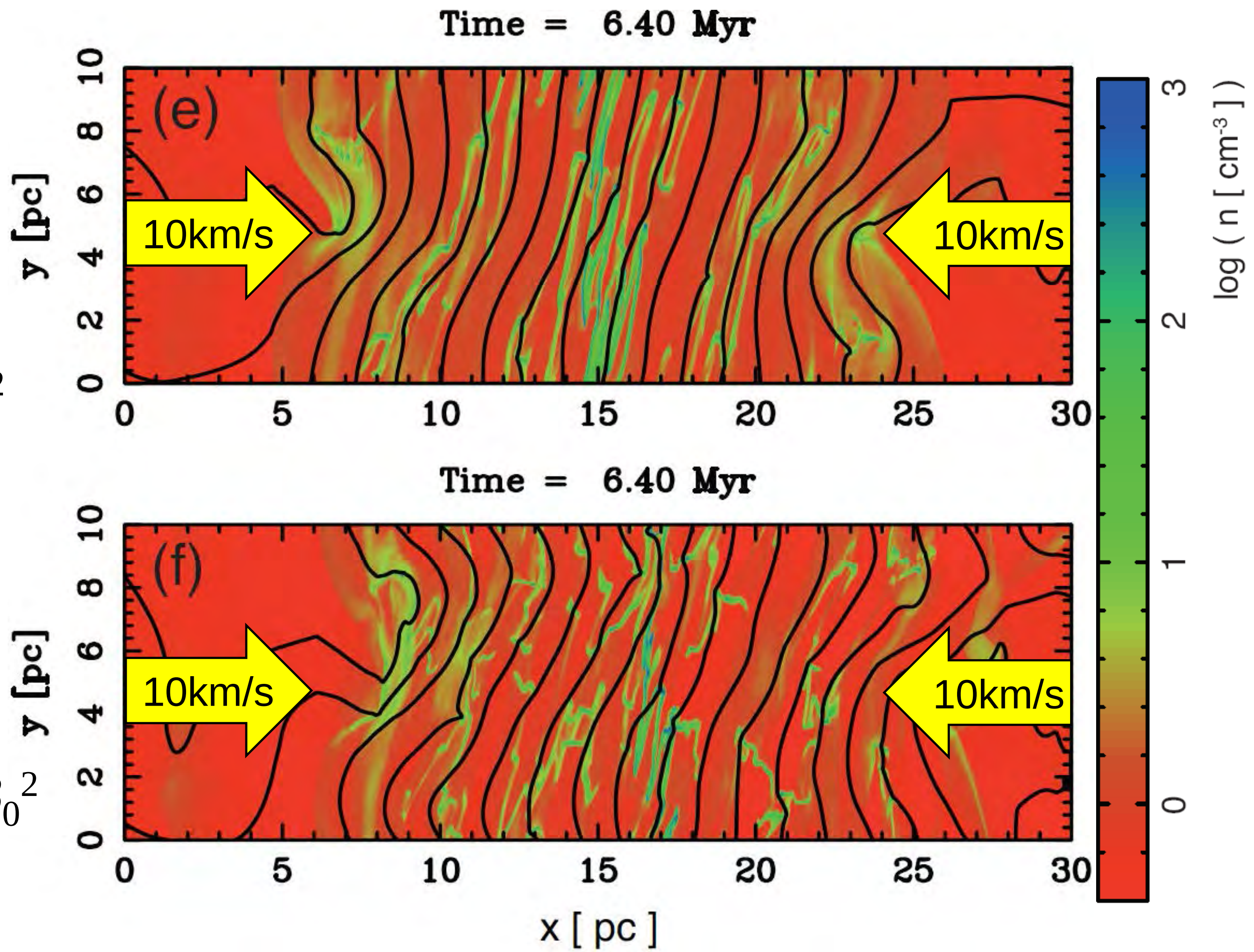
v=10km/s

(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; (*Iwasaki*+2017 in prep)

We need multiple episodes of compression.

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

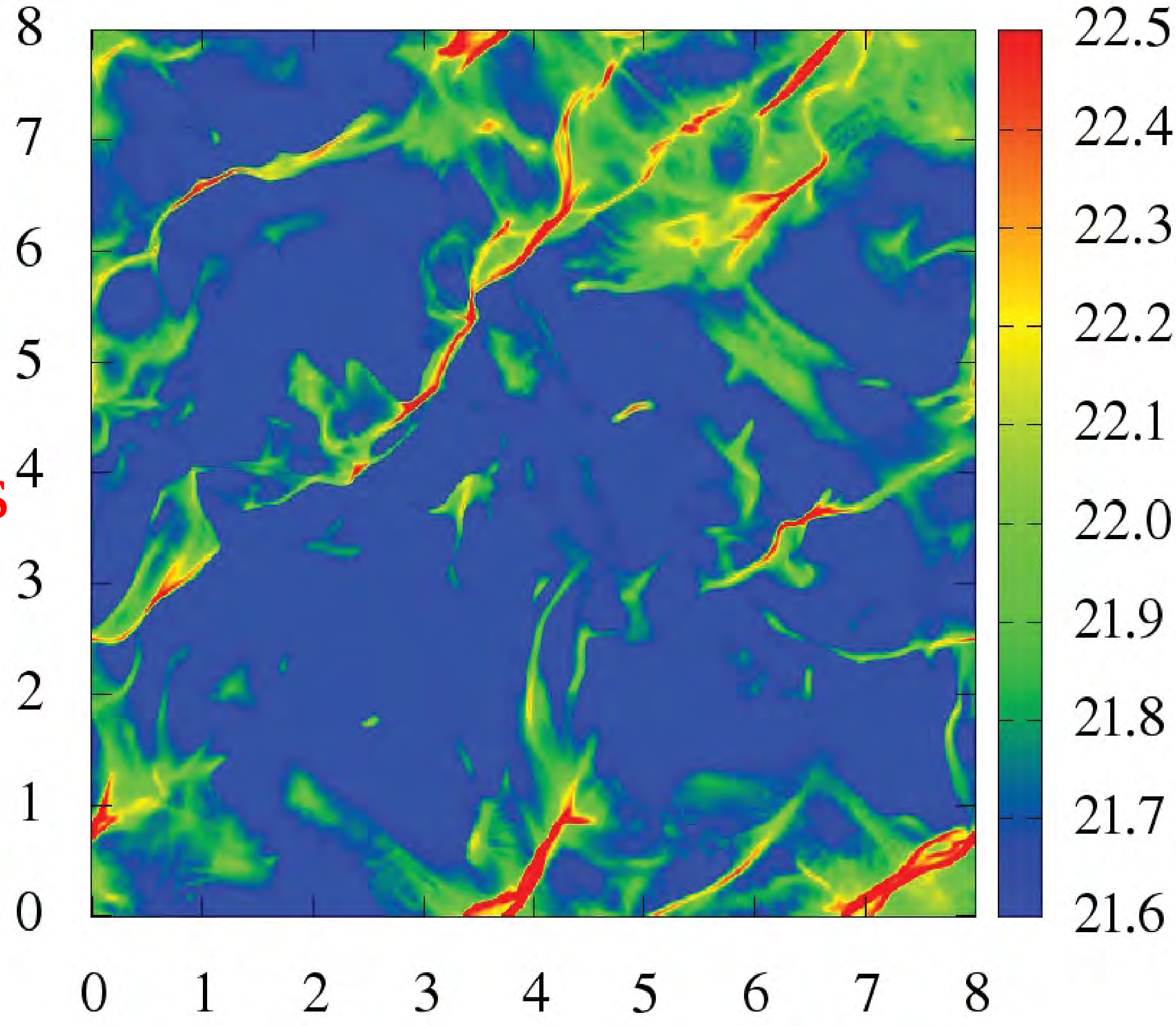
Next Question: What happens for further compressions?

Further Compress. of Mole. Clouds

Further Compression of Molecular Cloud

➔Magnetized Massive Filaments & Striations

c.f. obs. by *Soler, Pillai, Arzoumanian, Fissel, etc.*

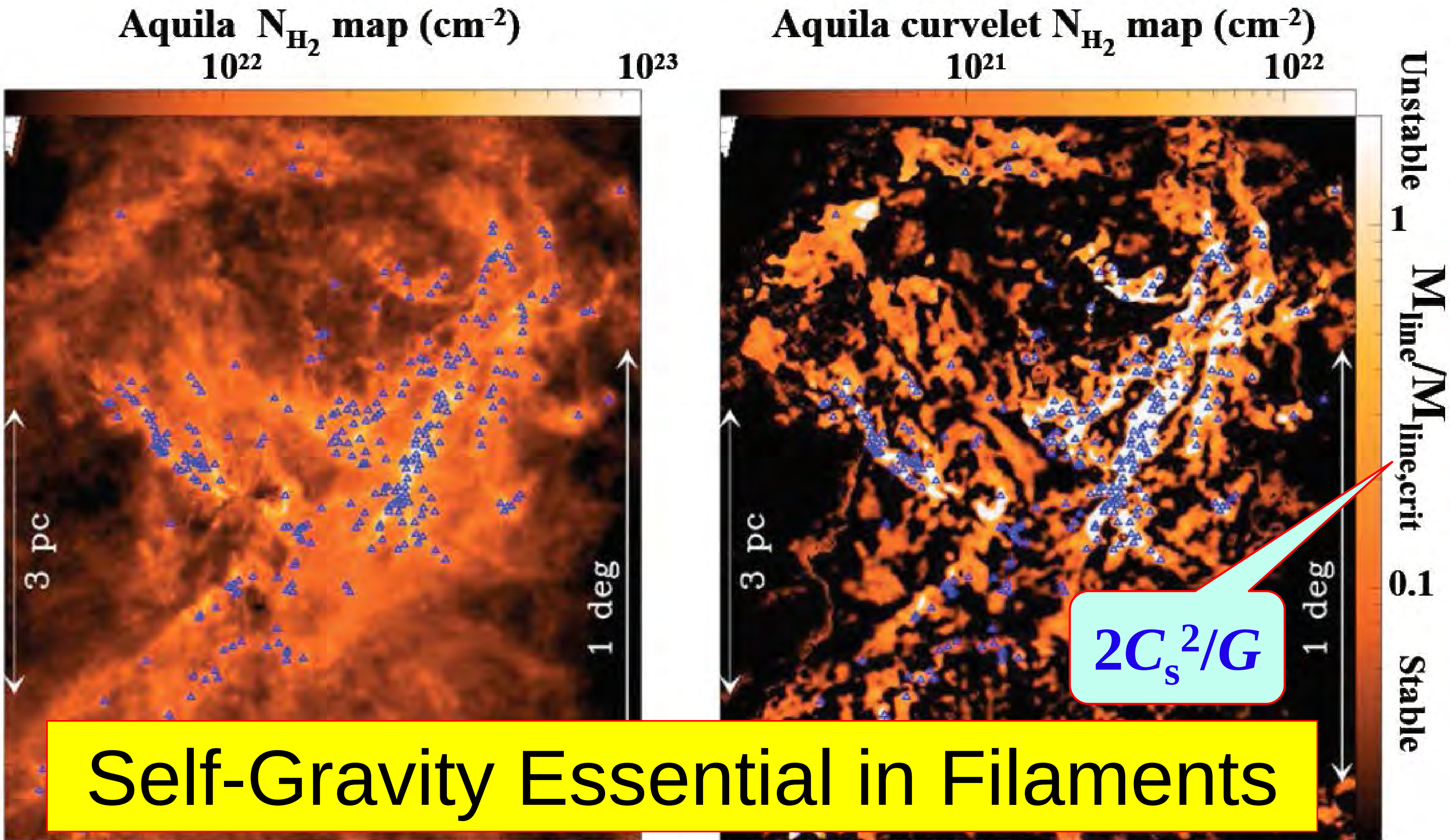


Self-Gravity Included, *SI, Inoue, Iwasaki, & Hosokawa 2015*

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



Ph. André – MW2011 Conference – 21/09/2011

Mass Function of Cores in a Filament

Inutsuka 2001, ApJ **559**, L149

Line-Mass Fluctuation of Filaments

Initial Power Spectrum

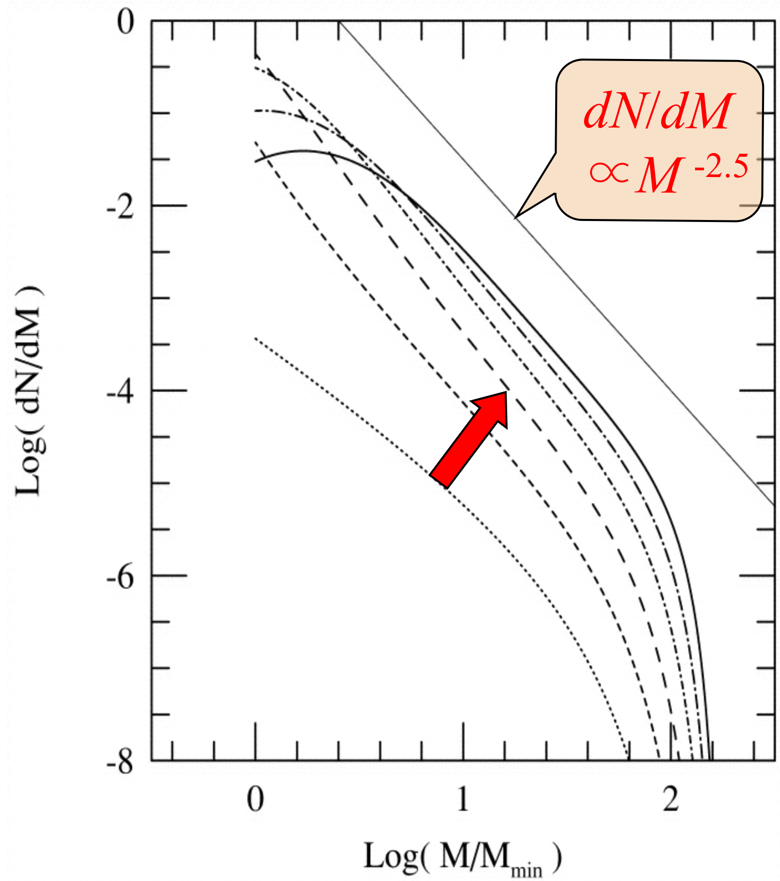
$$P(k) \propto k^{-1.5}$$

Mass Function

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

Observation of Both Perturbation Spectrum and Mass Function

➔ Clear and Direct Test!

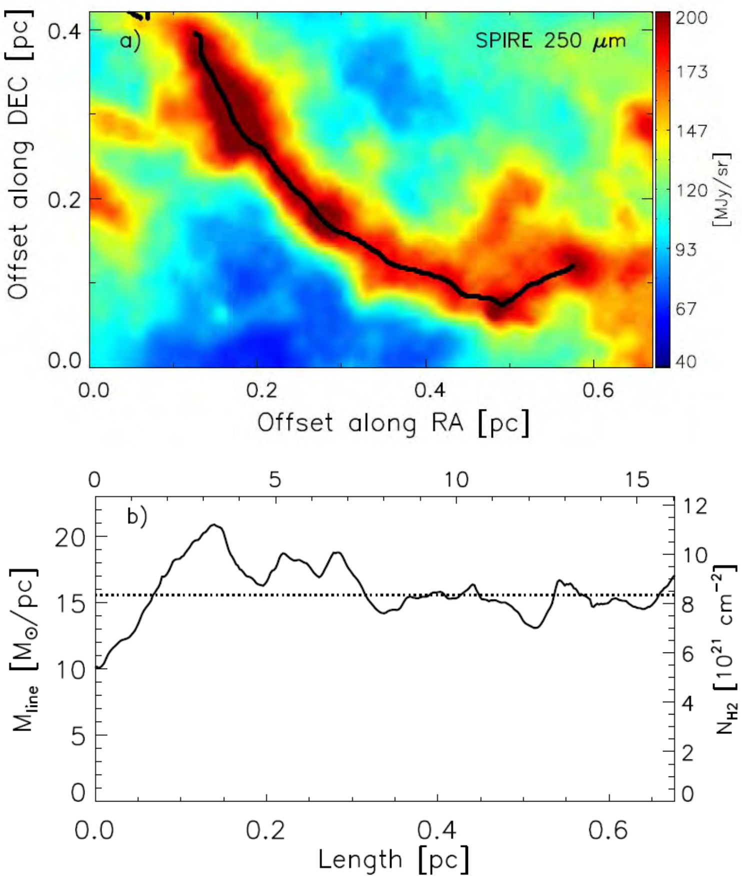


$P(k) \propto k^{-1.5}$

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

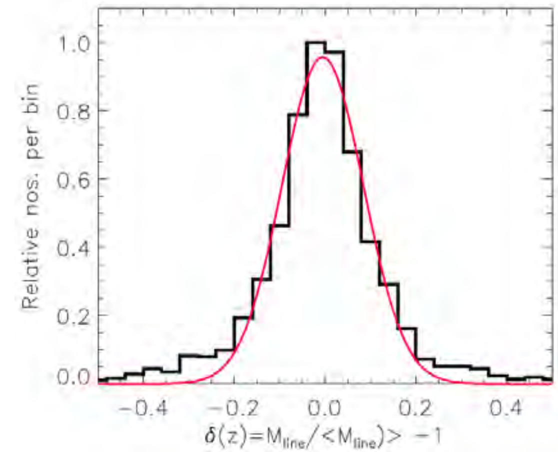
"A possible link between the power spectrum of interstellar filaments and the origin of the prestellar core mass function"

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



δ ...

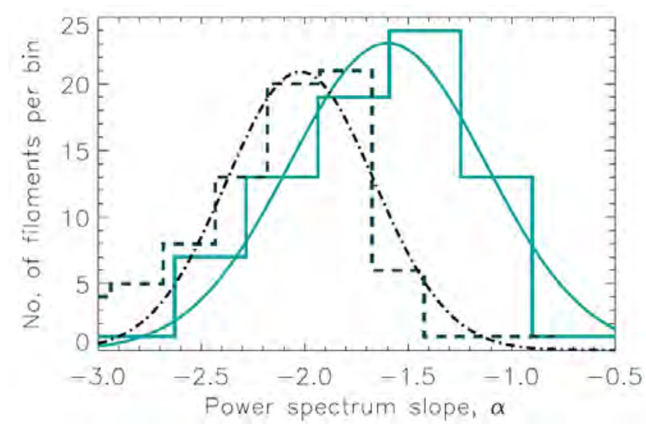
Gaussian



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

$\propto k^{n}$

n$= -1.6 \pm 0.3$



Supporting Inutsuka 2001; *Li, Hennebelle & Chabrier* 2017

Filament Paradigm

Completely Successful?!

?

Other Modes of Star Formation?

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

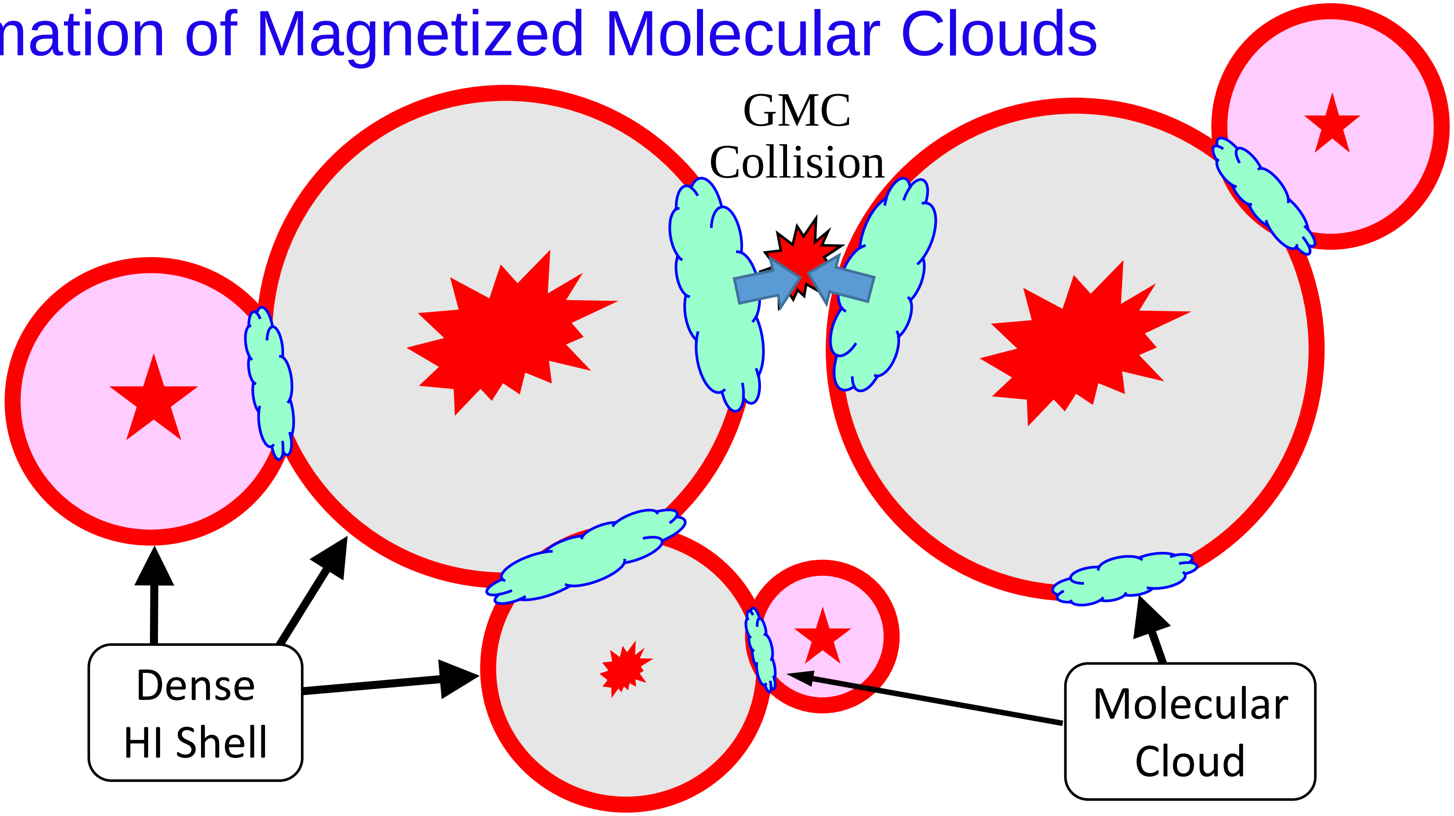
Collect & Collapse (*Elmegreen-Lada*, *Whitworth*, *Palouš*, *Deharveng*, *Zavagno*,…)

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



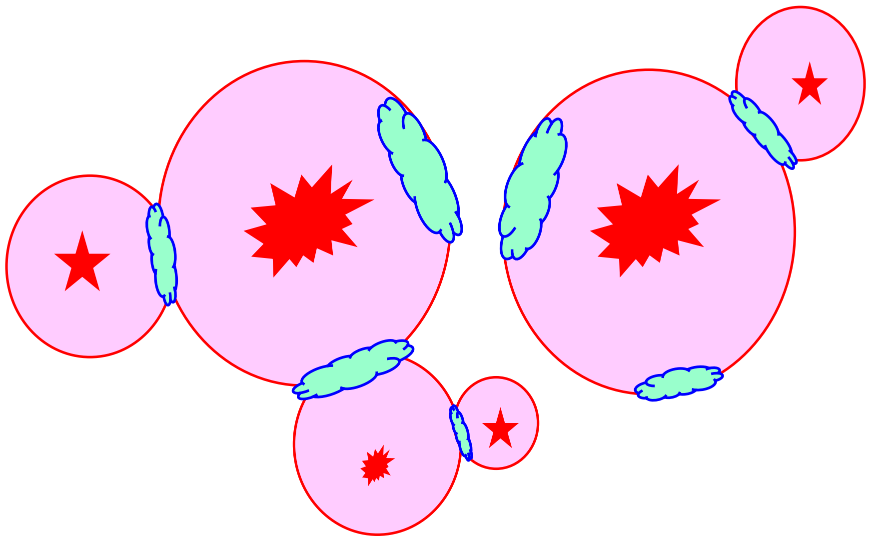
Long (>10Myr) Exposure Picture!

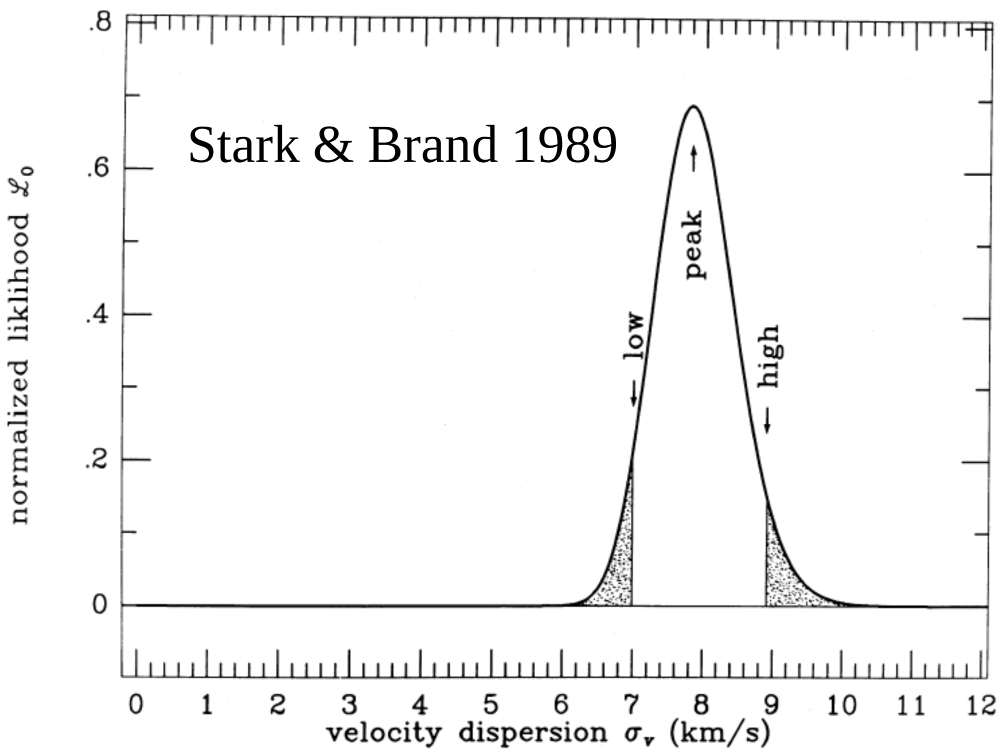
Each bubble disappears quickly (<Myr).

SI+2015; cf. Elmegreen 2007

Velocity Dispersion of Clouds

Multiple Episodes of Compression → Formation of Magnetized Molecular Clouds

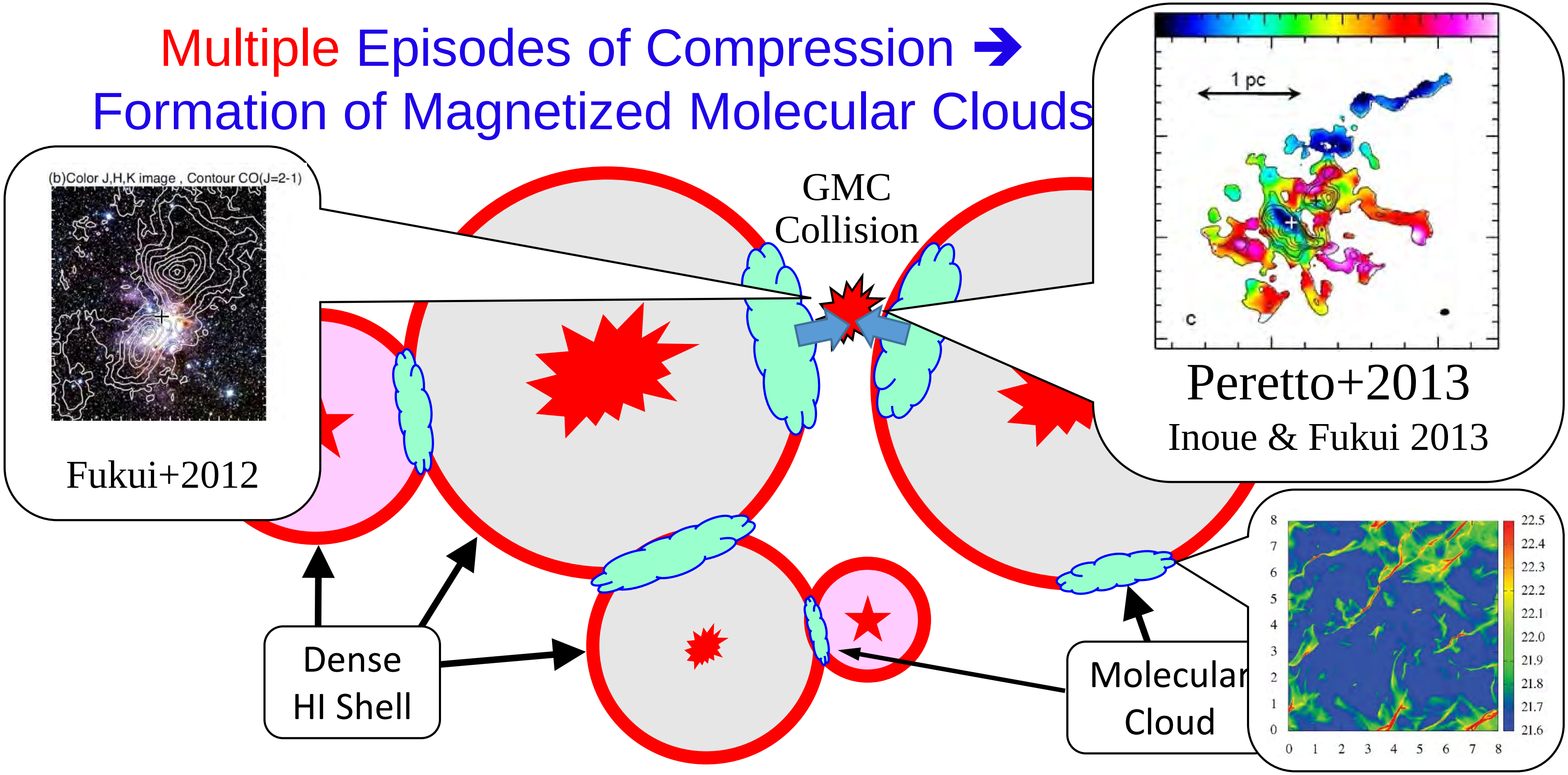




Shell Expansion Velocities ~ 10^1 km/s → Cloud-to-Cloud Velocity Dispersion

Network of Expanding Shells

Multiple Episodes of Compression → Formation of Magnetized Molecular Clouds



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

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

Star Formation Efficiency in Dense Gas

Herschel Observation (e.g., Andre+2014, Könyves+2015)

$$M_{\rm core} / M_{\rm filament} \lesssim 15\%$$

Star Formation Efficiency in Dense Core: $\varepsilon_{\rm core}$

$$\varepsilon_{\rm core} \sim 33\% \quad \text{(ex. Machida+)}$$

Star Formation Efficiency in Dense Gas: $\varepsilon_{\rm dense\ gas}$

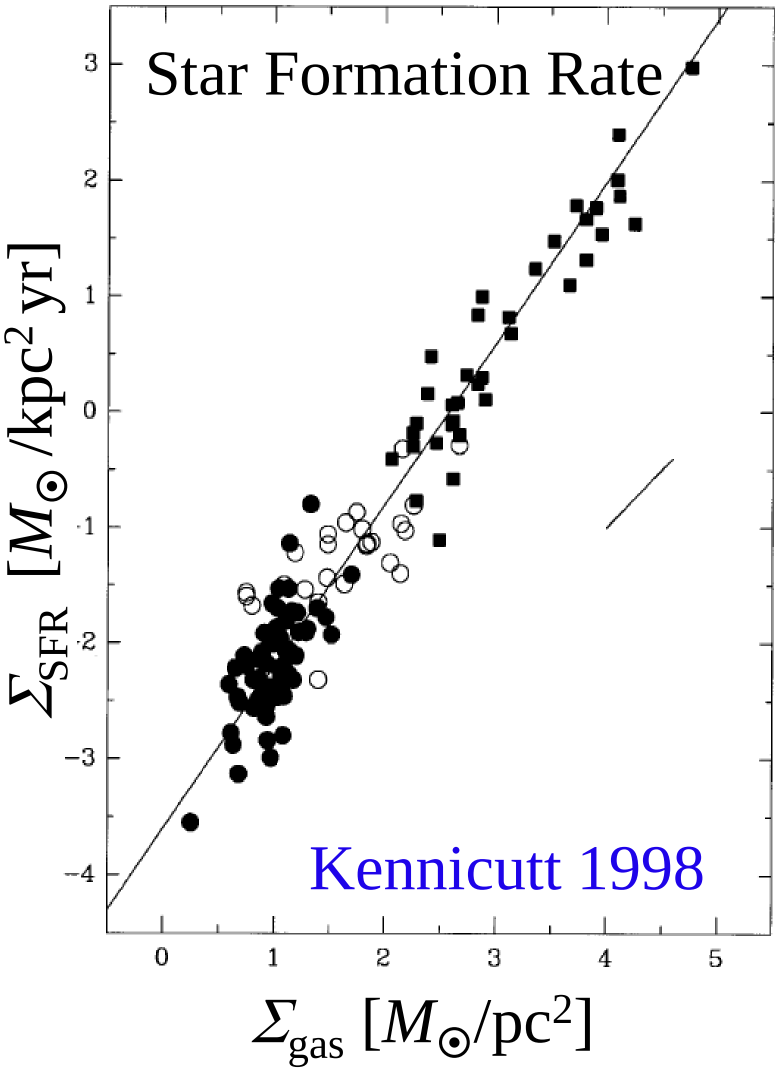
$$\rightarrow \varepsilon_{\rm dense\ gas} = M_{\rm core} / M_{\rm filament} \times \varepsilon_{\rm core} \sim 5\%$$

Consumption Timescale of Dense Gas: $\boldsymbol{t}_{\rm dense\ gas}$

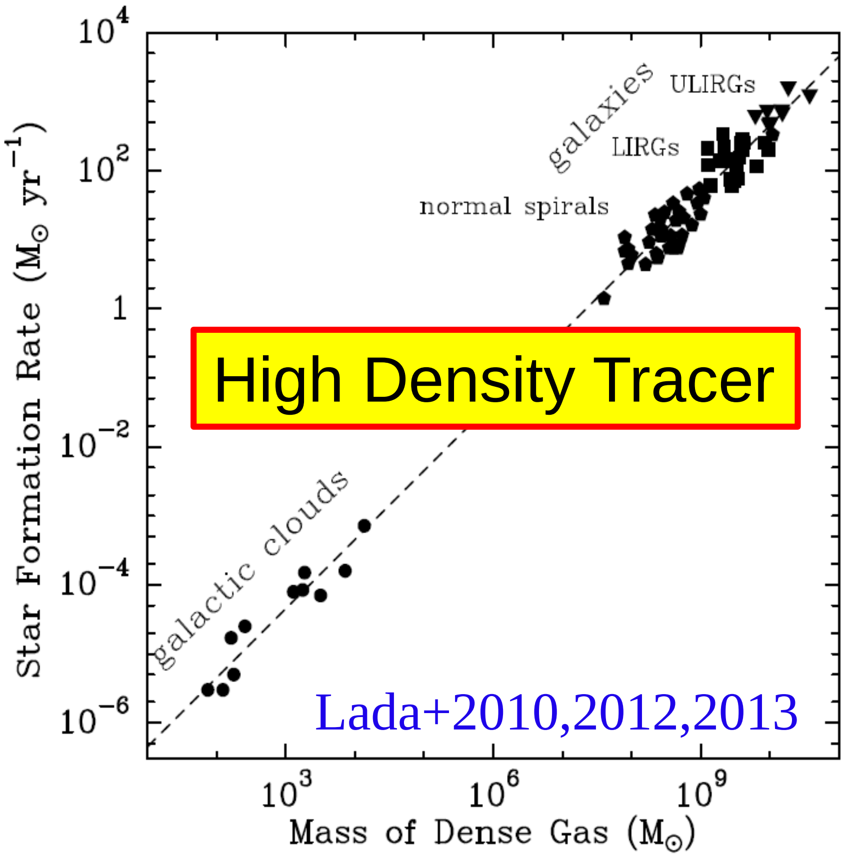
$$\boldsymbol{t}_{\rm dense\ gas}{}^{-1} = (10^6\,{\rm yr})^{-1} \times \varepsilon_{\rm dense\ gas} = (20{\rm Myr})^{-1}$$

$$\rightarrow \boldsymbol{t}_{\rm dense\ gas} \sim 20{\rm Myr} \quad \text{(eg. Lada+2010, Andre+2014)}$$

Schmidt-Kennicutt Law of SF



Timescale: Σ_{gas} / Σ_{SFR} ~ Gyr



- Column Density: Σ_{gas} [$M_\odot$/pc^2]
- SF Rate: Σ_{SFR} [$M_\odot$ /kpc^2 yr]
- Timescale: M/(SFR) ~ 20Myr

See also Gao & Solomon 2004; Wu+2005; Bigiel et al. 2008,2010,2011, Shimajiri+2017

How Many Generations of Filaments?

Star Formation Efficiency in Dense Gas: $\varepsilon_{\text{dense gas}}$

➔ $\varepsilon_{\text{dense gas}} = M_{\text{core}} / M_{\text{filament}} \times \varepsilon_{\text{core}}$ ~ 5%

Typical Mass of Star Forming Filaments: $L \sim 3\text{pc}$, $M_{\text{Line}} \sim \mathbf{2}\boldsymbol{C}_{\mathbf{s}}^{\mathbf{2}}/\boldsymbol{G}$

$$M = M_{\text{Line}} \times L \sim 60 M_{\text{sun}}$$

Total Mass of Stars Created in a Filament:

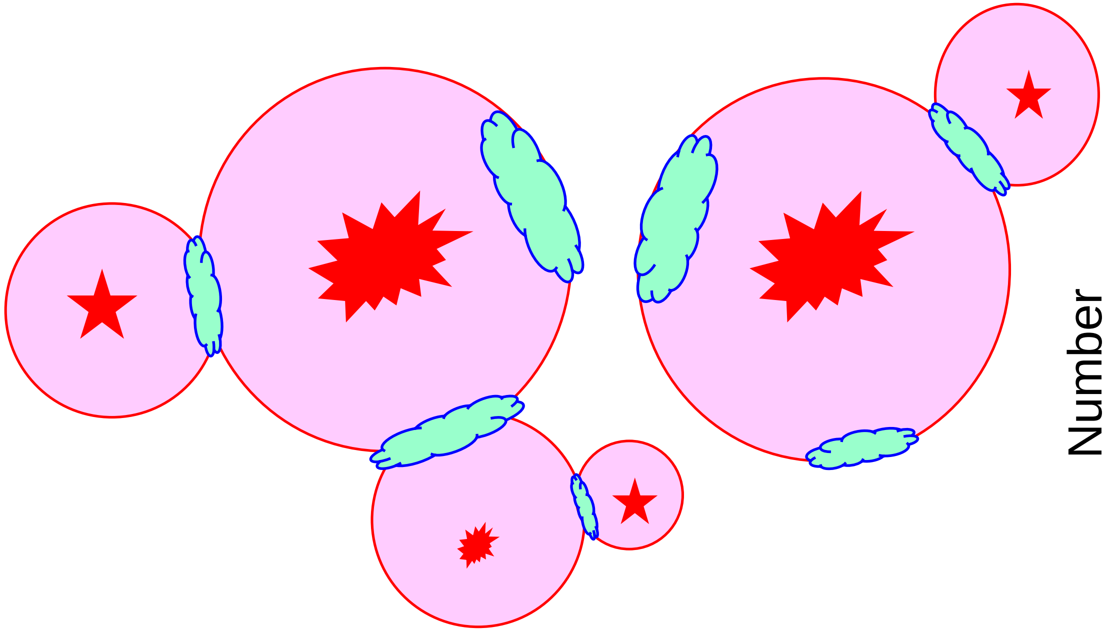
➔ $60 M_{\text{sun}} \times \varepsilon_{\text{dense gas}}$ ~ $3 M_{\text{sun}}$

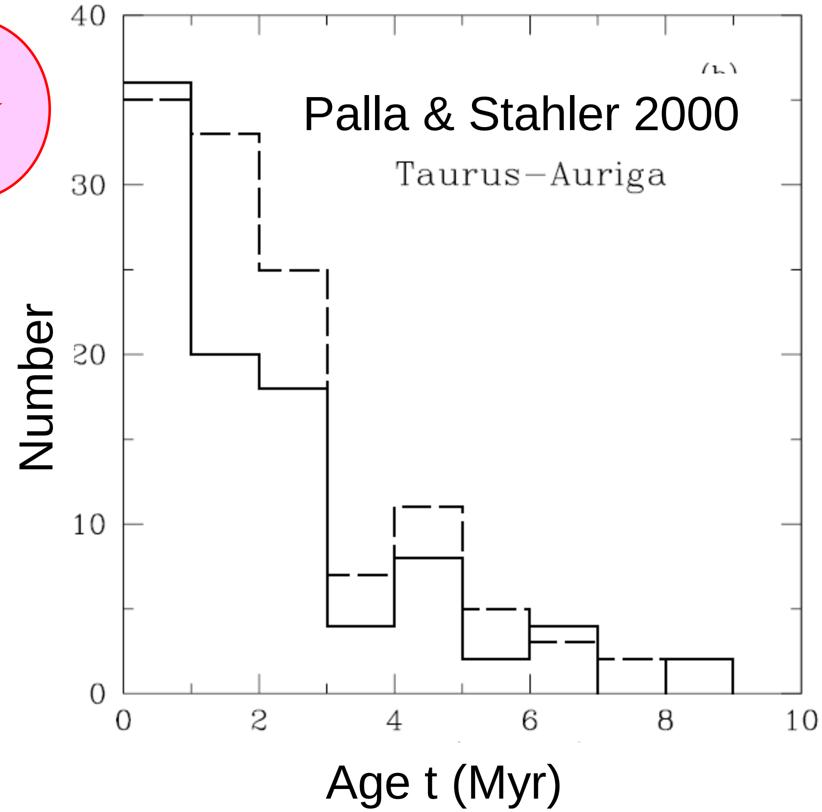
➔ Total Mass of YSOs: $M_{*\text{total}}$

# of Filaments to Form Stars = $M_{*\text{total}}/3M_{\text{sun}}$

➔ Multiple Generations of Filaments Needed!

Natural Acceleration of Star Formation





Molecular Cloud Growth

➔Mass Increase in Supercritical Filaments

➔Accelerated SF

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

See also Poster 52 by Kunitomo

My Last Exchange with Francesco Palla

Dear Francesco and Steven,

18 May 2015

I would like to introduce our recent paper on a scenario of Galactic star formation. This is based on our time-consuming (~15yrs) work on the formation of molecular clouds and their destruction, and accepted for Astronomy & Astrophysics.

I think we found a clue in understanding "Accelerating Star Formation" you found in the year I started this line of work. I hope you would have some interest. Thank you.

With my best regards, Shu-ichiro Inutsuka

27 Jan 2016, RIP

Dear Shu-Ichiro,

19 May 2015

good to hear form you and many thanks for your paper. I will read it with great pleasure!

It also comes at the right time since in my course I'm now teaching the formation and evolution of molecular clouds. So, in addition to my personal interest, it will provide me with important material for the students.

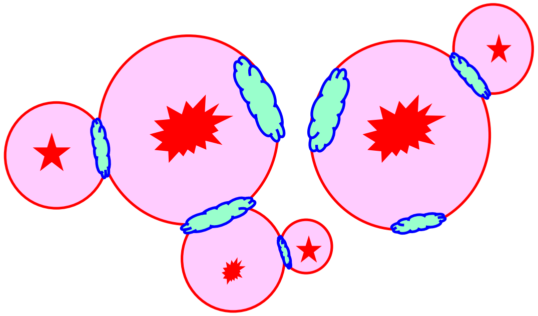
All the best, Francesco

Summary

- Fragmentation of Filaments ➔ Core Mass Function
- <u>Bubble-Dominated Formation of Molecular Clouds</u>

➔ Unified Picture of Star Formation

- $\delta v_{\text{cloud-cloud}} \sim 10^1$ km/s
- Accelerated Star Formation
- Schmidt-Kennicutt Law



- Star Formation Efficiency: $\varepsilon_{SF} \sim 10^{-2}$
- Slope of Cloud Mass Func $= 1 + T_{\text{form}}/T_{\text{dis}} \sim 1.7$

Poster 12

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

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