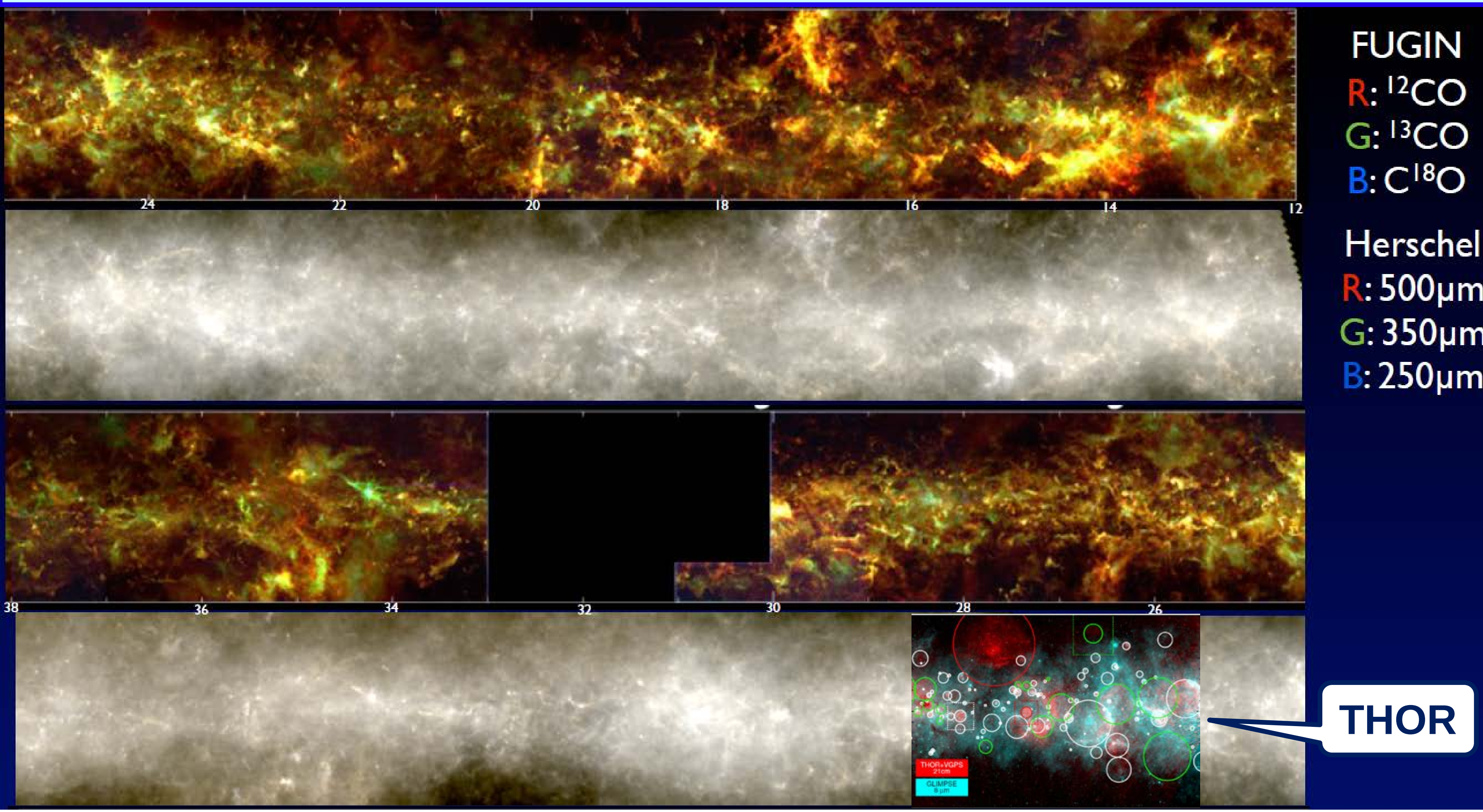
Formation/Evolution of Molecular Clouds

Shu-ichiro Inutsuka (Nagoya University)



Many Surveys: Herschel, THOR, FUGIN, CHIMPS,CHaMP,…

Outline

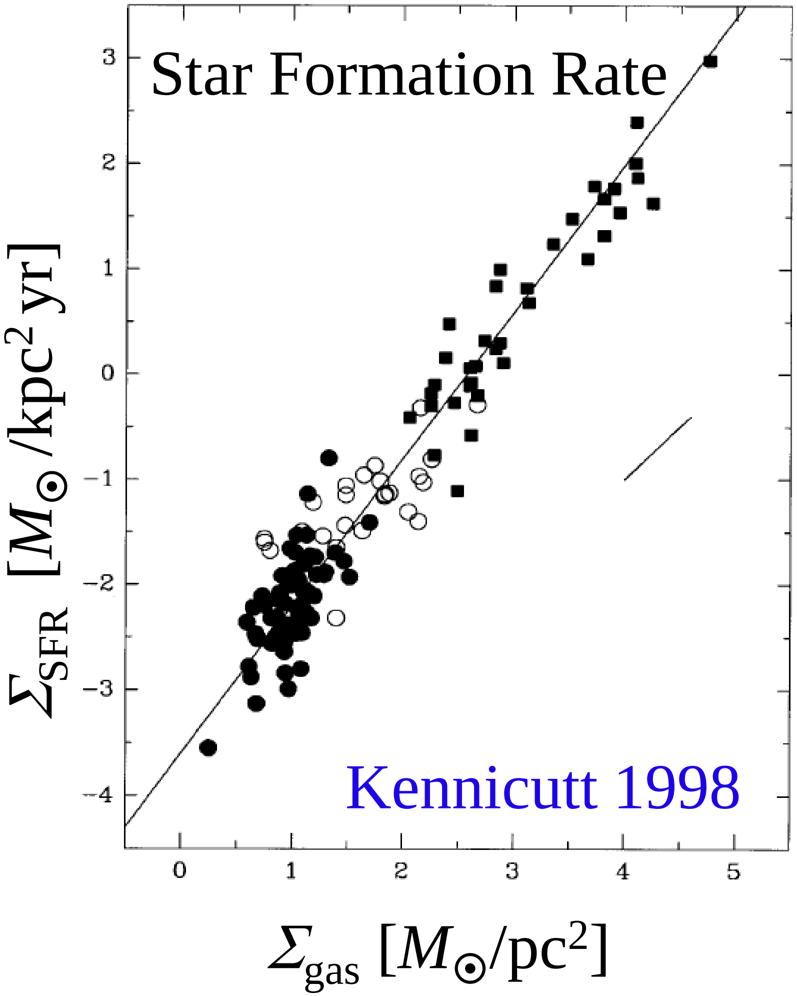
1. Basics & Observational Evidence
2. Characteristic Timescales

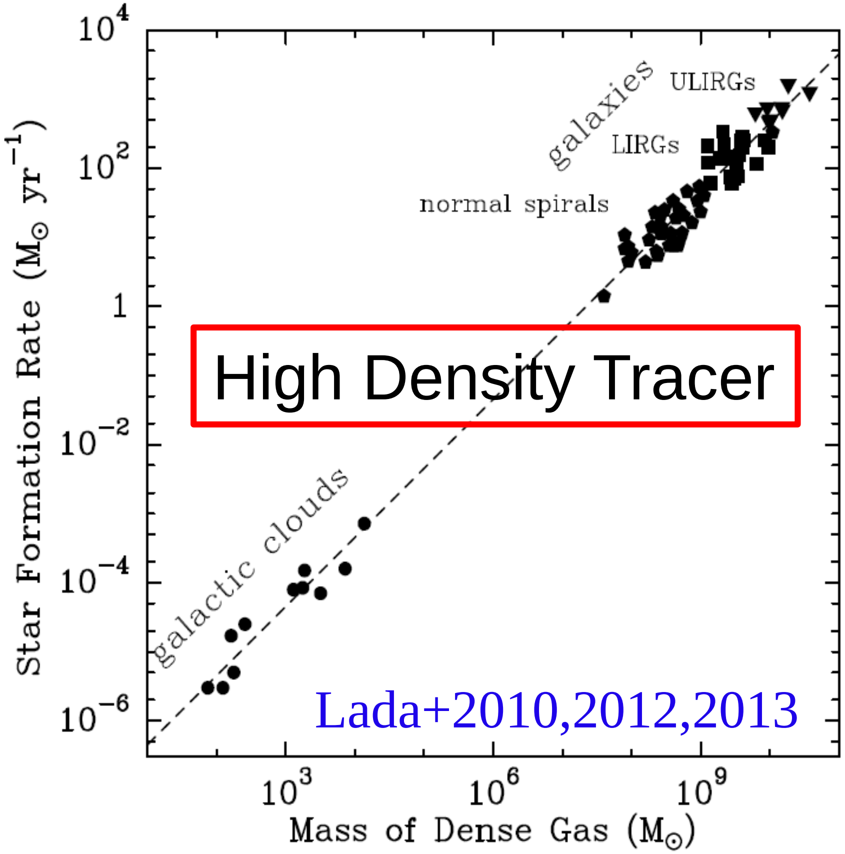
   1Gyr, 20Myr, 1Myr
3. Formation/Evolution of Molec. Clouds

   Phase Transition, Filaments-Sheets-Bubbles, Core Mass Function, Integrated Scenario
4. ~~Dispersal of Molecular Clouds~~

   ~~SF Efficiency, Cloud Mass Function~~
5. Open Questions

Schmidt-Kennicutt Law of SF





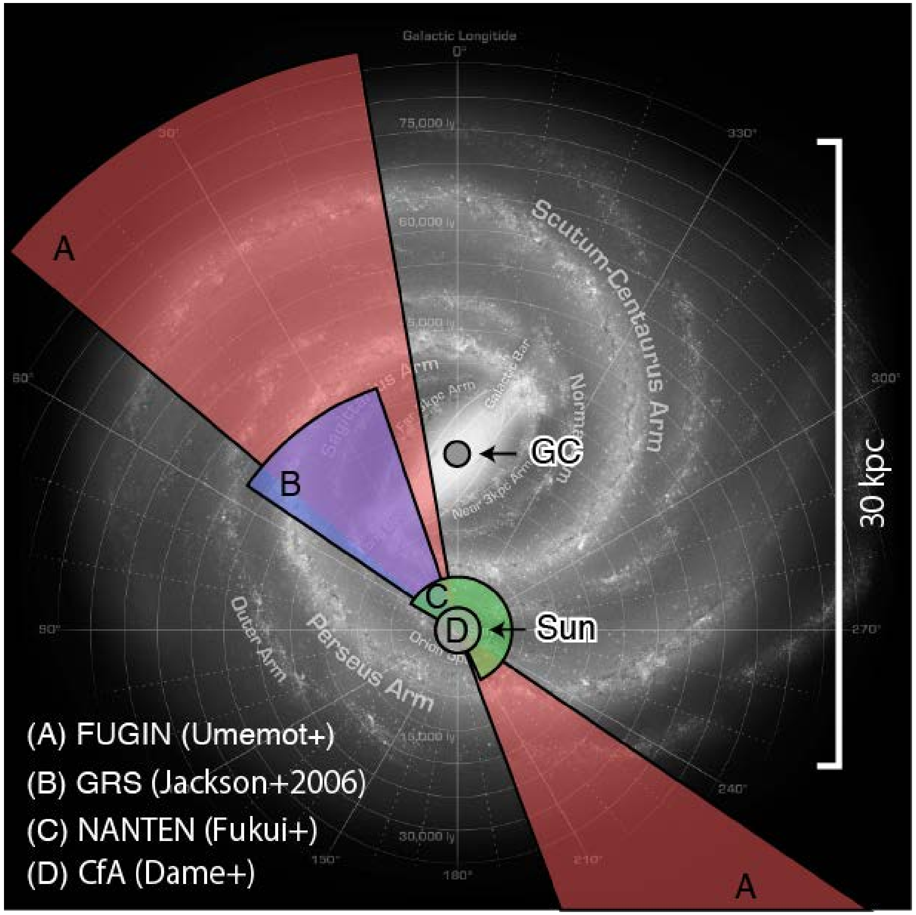
Timescale: Σ_{gas} / Σ_{SFR} ~ Gyr

- Timescale: M/(SFR) ~ 20Myr

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

FUGIN

FOREST Unbiased Galactic plane Imaging survey
with Nobeyama 45-m telescope

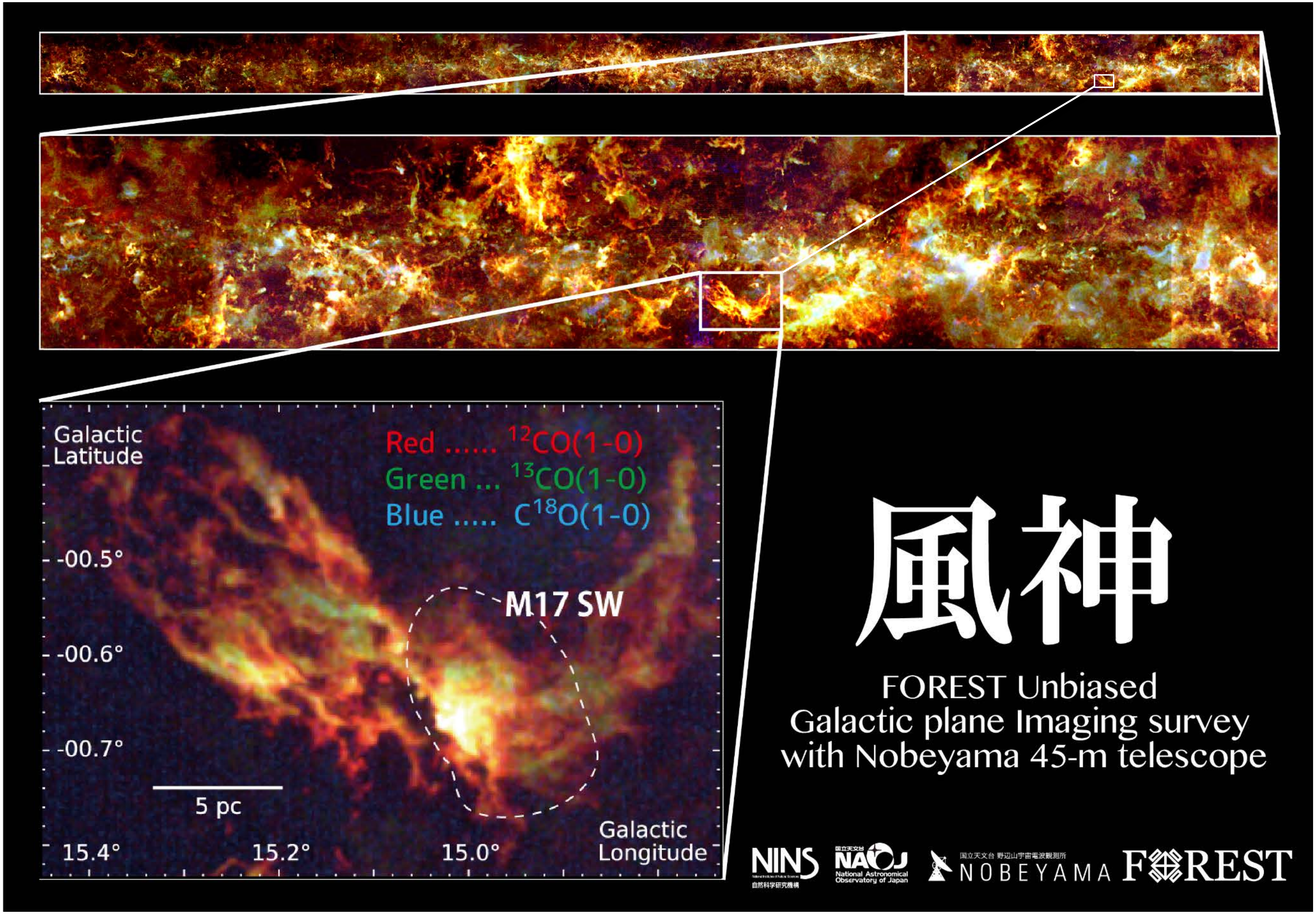


Observed areas of the CO J=1-0 survey projects, where the corresponding spatial resolutions of the surveys are less than 2pc.

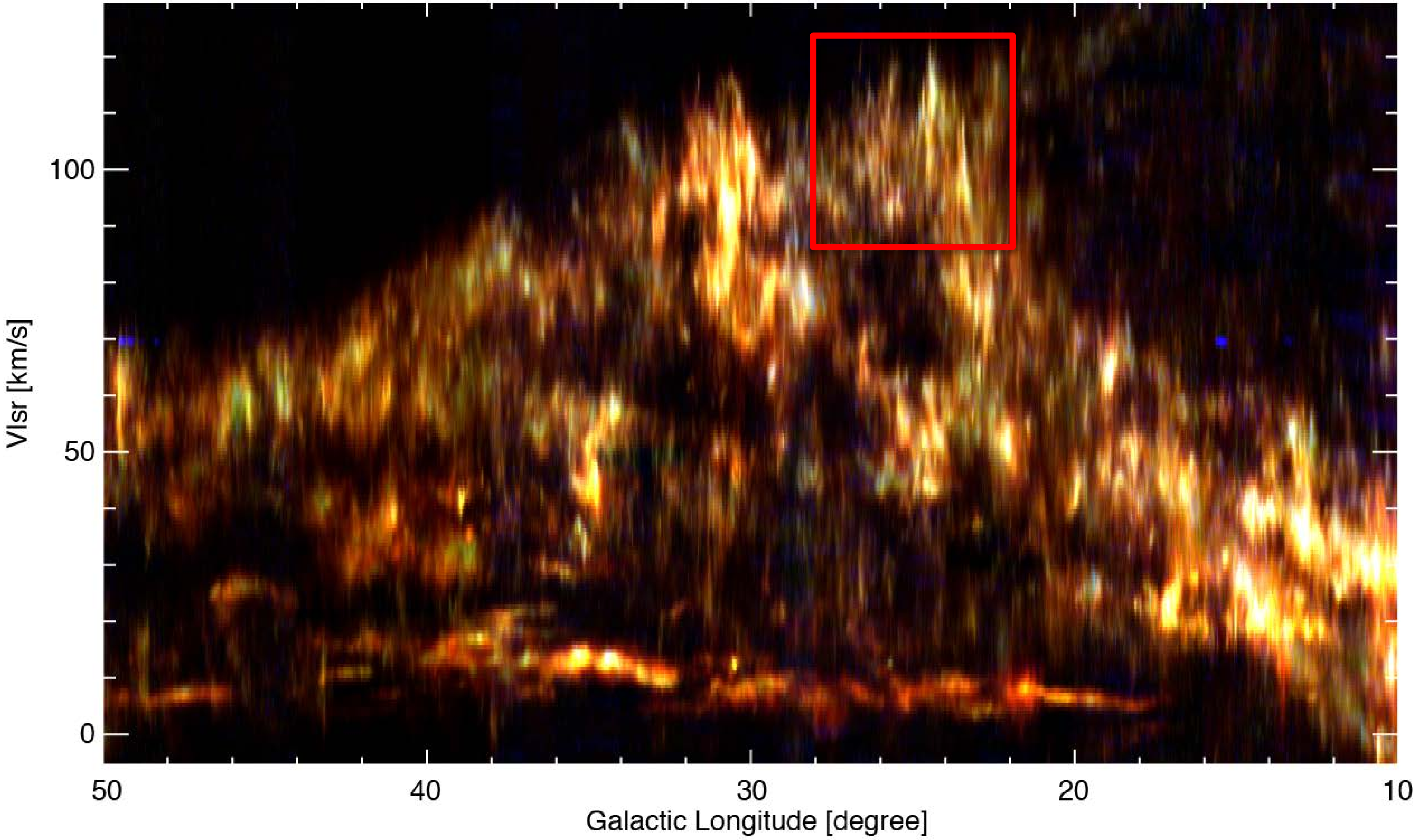
- ^{12}CO, ^{13}CO, $C^{18}O$ survey
- Period: 2014~2017
- Data will be open at JVO

Slide by Torii

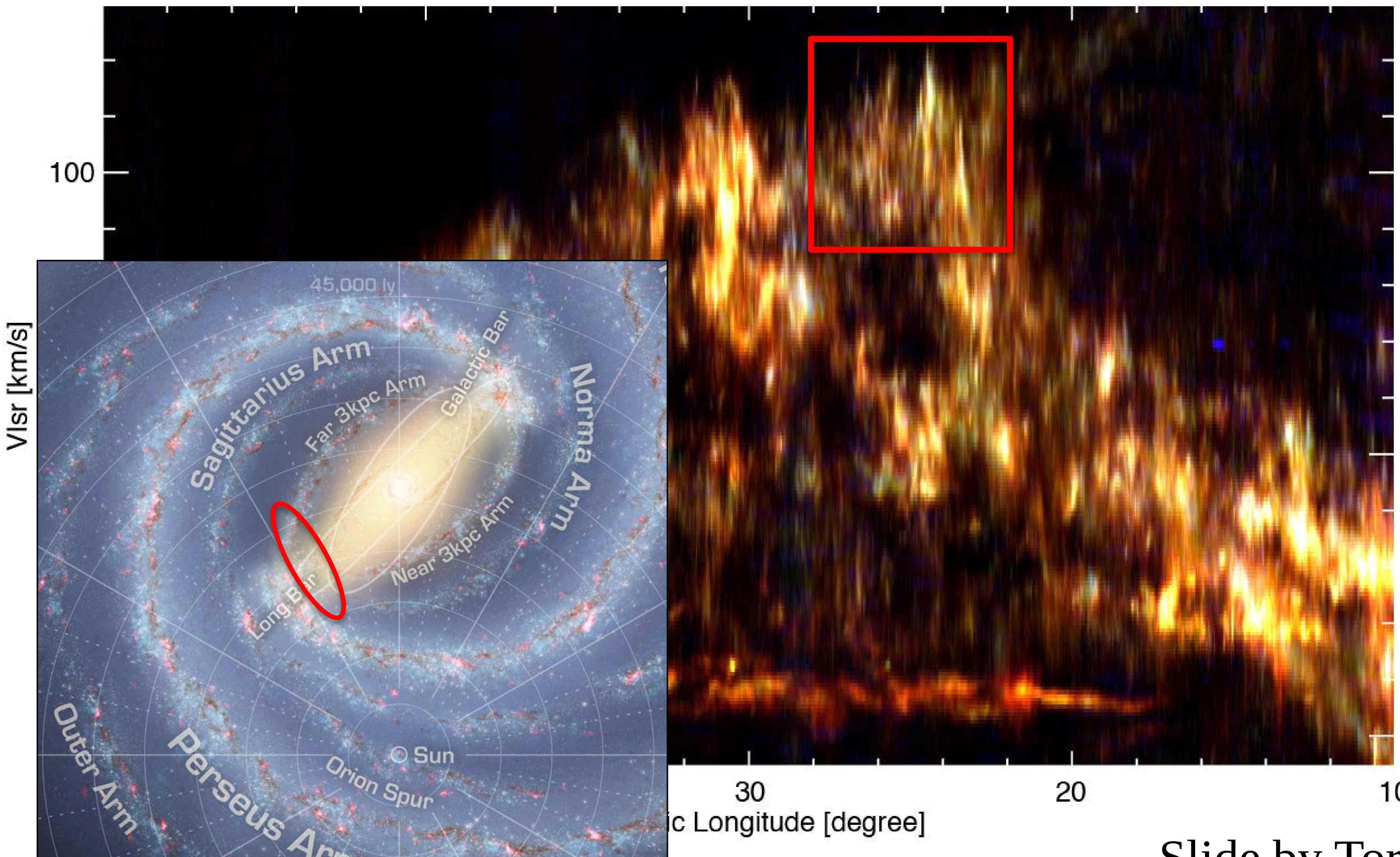
FUGIN


Galactic Latitude
Red ...... $^{12}CO(1-0)$
Green ... $^{13}CO(1-0)$
Blue ..... $C^{18}O(1-0)$
-00.5°
-00.6°
-00.7°
M17 SW
5 pc
15.4°
15.2°
15.0°
Galactic Longitude
風神
FOREST Unbiased
Galactic plane Imaging survey
with Nobeyama 45-m telescope
NINS
NAOJ
National Astronomical Observatory of Japan
NOBEYAMA
FOREST

Test region (3-color pv map)

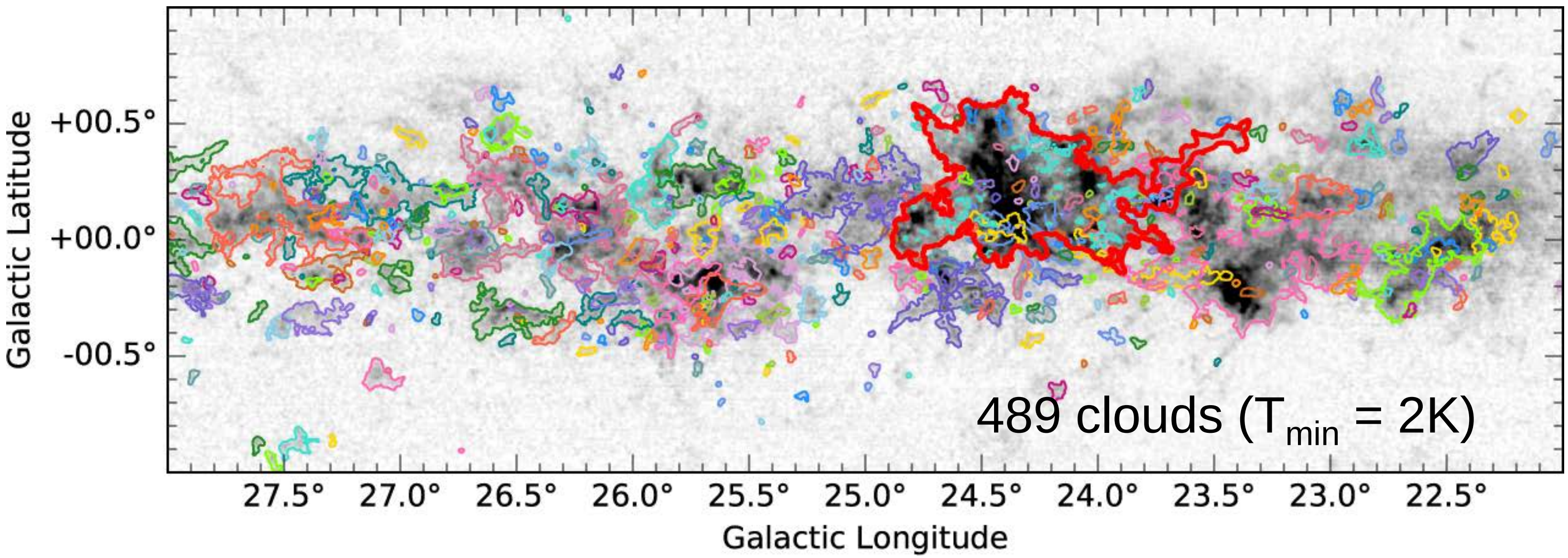


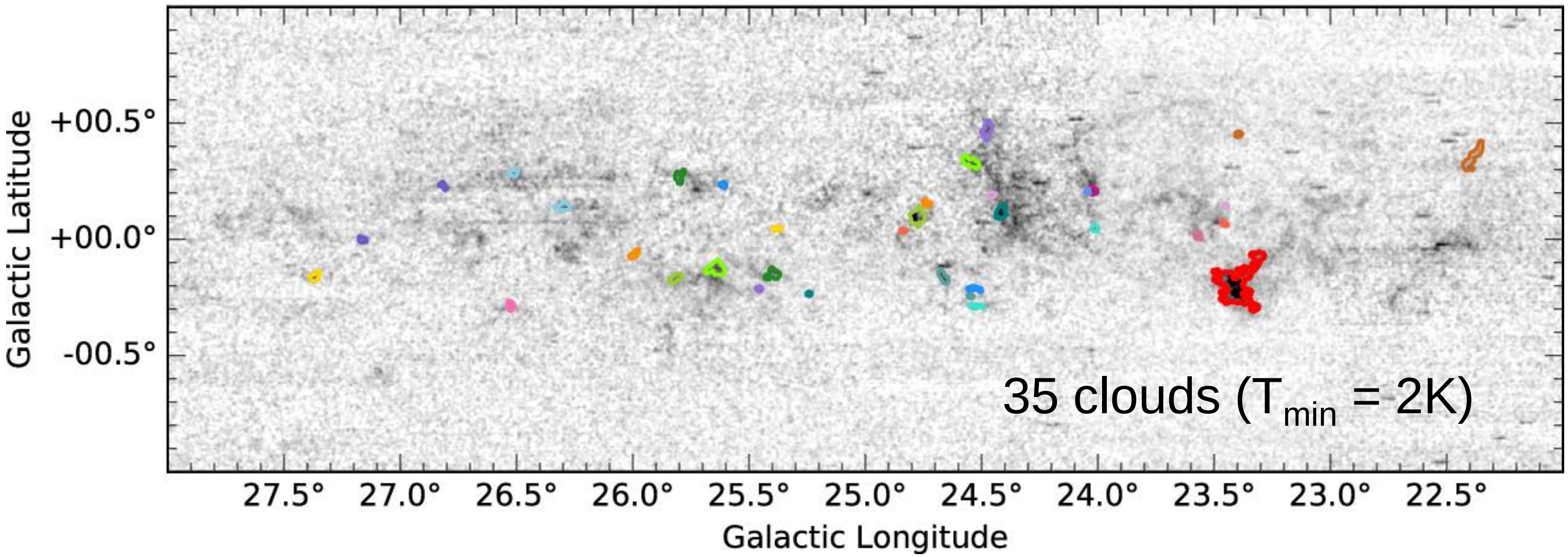
Test region (3-color pv map)



Slide by Torii

Results (^{13}CO and $C^{18}O$ cloud IDs)





Mass Fractions of ^{12}CO, ^{13}CO, & $C^{18}O$

1) Total M_{H2} of the ^{12}CO clouds ~ 2.7×10^7 Mo

– The ^{12}CO stream accounts for 98%.

2) Total M_{H2} of the ^{13}CO clouds ~ 8.5×10^6 Mo

– (2) / (1) ~ 31% (Data pixel volume fraction = 9%)

3) Total M_{H2} of the ^{13}CO clouds with $C^{18}O$ ~ 6.3×10^6 Mo

– (3) / (1) ~ 23%

4) Total M_{H2} of the $C^{18}O$ clouds ~ 4.7×10^5 Mo

– (4) / (1) ~ 2% (Data pixel volume fraction = 0.1%)

Torii et al. (2018) to be submitted

$C^{18}O$-Mass/ ^{12}CO-Mass ~ 0.02 ←→ $t_{\text{dense gas}} / t_{\text{gas}}$ ~ 0.02

Characteristic Timescales

Gas Consumption: $t_{gas} = \Sigma_{gas} / \Sigma_{SFR} \sim 10^3$ Myr

Dense Gas Consumption: $t_{dense\ gas} \sim 20$ Myr

Dynamical Timescale: t_{dyn}=1Myr << $t_{Gal.Rot} \sim 10^2$Myr

Dynamical Timescale (e.g., McKee & Ostriker 1977)

- SN Explosion Rate in Galaxy… 1/(100yr)
- Expansion Time…1Myr
- Expansion Radius… 100pc

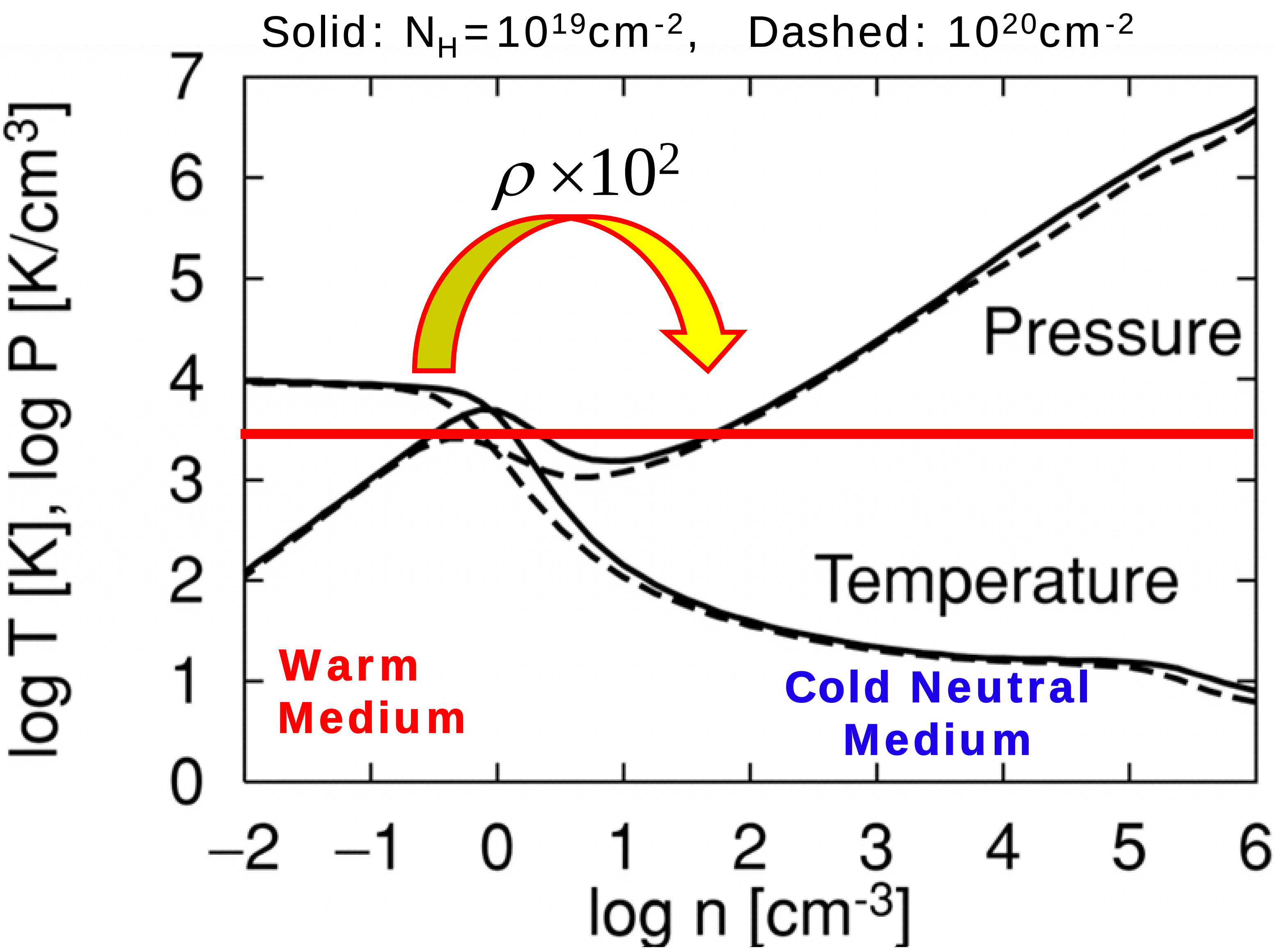
$(10^{-2}\,yr^{-1}) \times (10^6\,yr) \times (100pc)^3 = 10^{10}\,pc^3 \sim V_{Gal.Disk}$

$(10kpc)^2 \times 100pc$

Expanding HII regions can also be important!

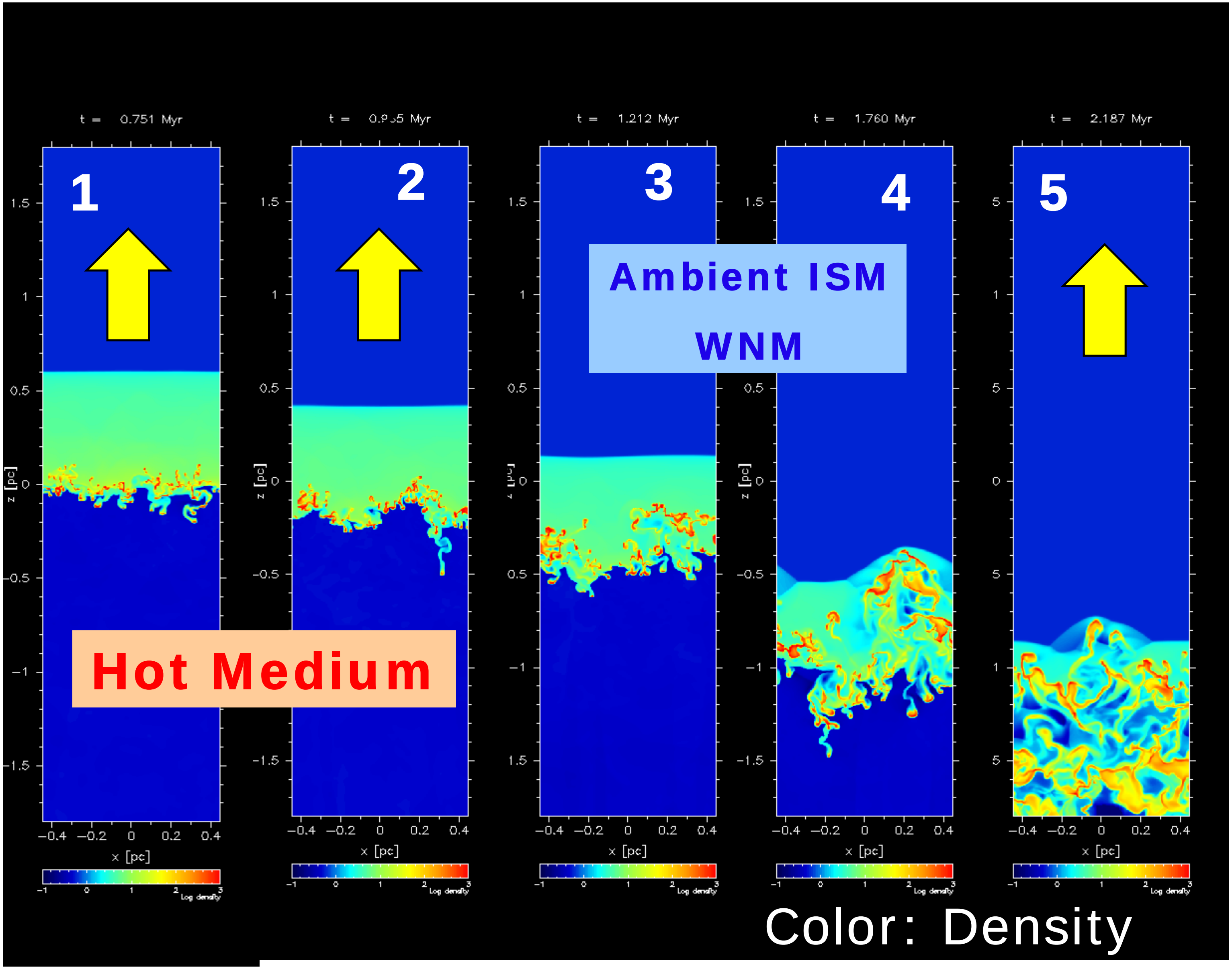
Formation of Molecular Clouds

Radiative Equilibrium for a given density



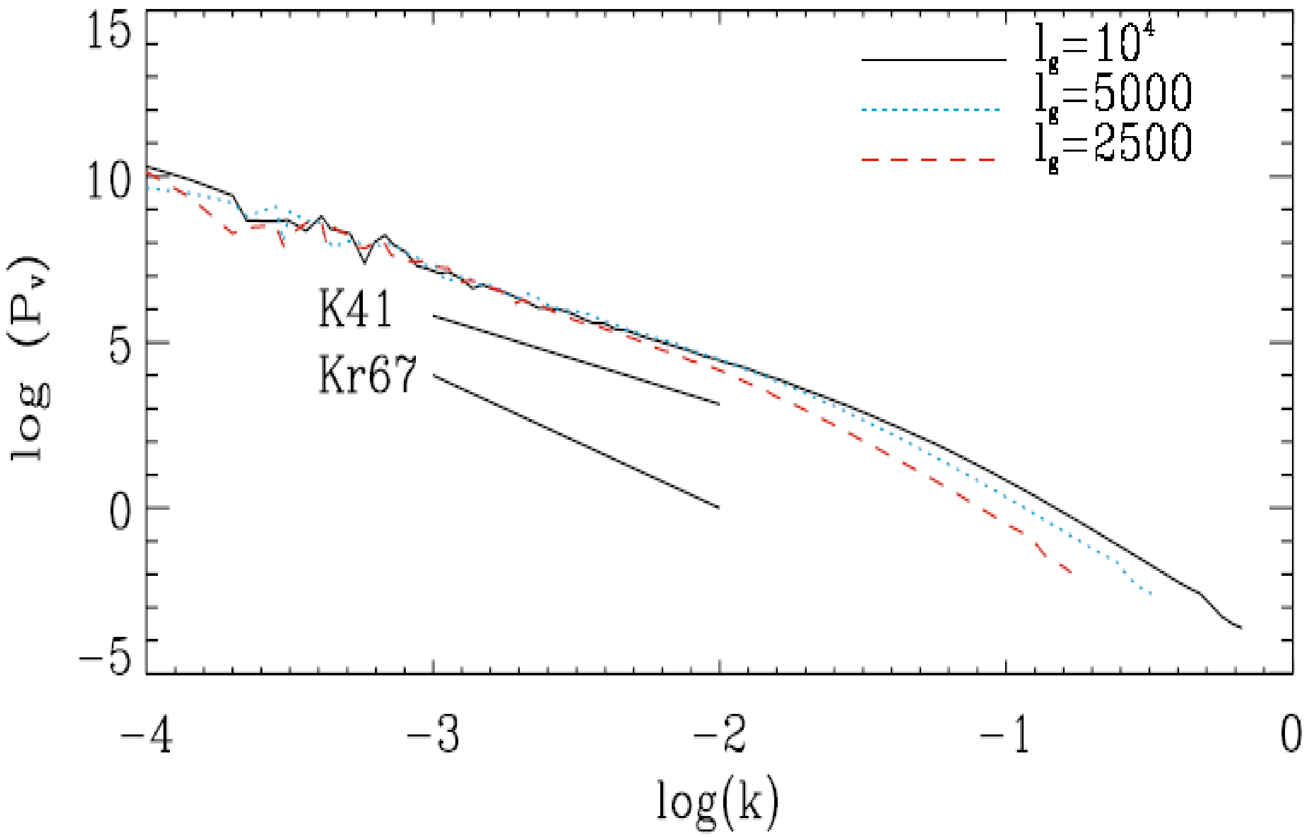
e.g., Wolfire et al. 1995, Koyama & SI 2000

Shock Propagation into WNM



Koyama & Inutsuka (2002) ApJ 564, L97

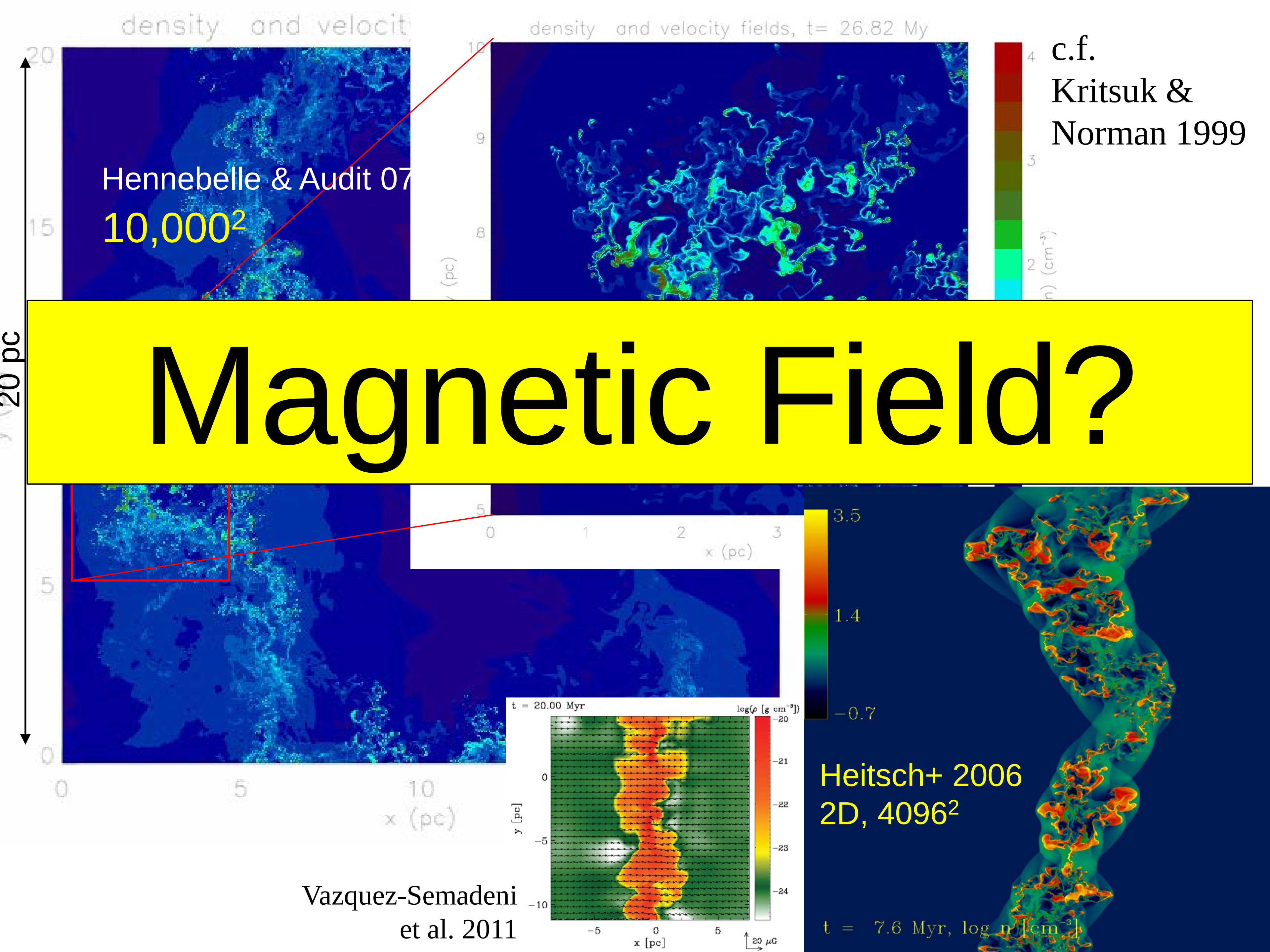
Property of "Turbulence"…Subsonic



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

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

Magnetic Field?



Cloud Formation in Magnetized WNM

Can compression of magnetized WNM create molecular clouds?

Ambipolar diffusion included

Ref. Inoue & SI 2008, 2009, 2012;

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

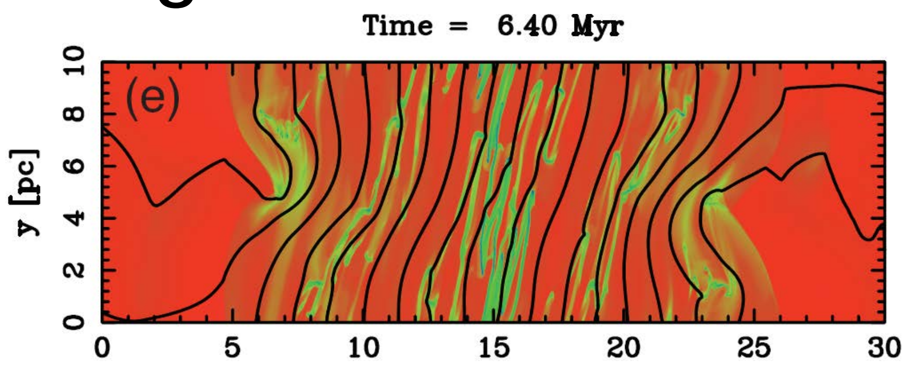
Inoue & SI (2012) ApJ **759**, 35

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

See also *van Loo*+2007, 2008, 2012

Compression of Magnetized WNM

Can direct compression of magnetized WNM create molecular clouds?



➔ No, It only creates multi-phase HI clouds!

Inoue & SI (2008) ApJ **687**, 303; *Inoue & SI* (2009) ApJ **704**, 161

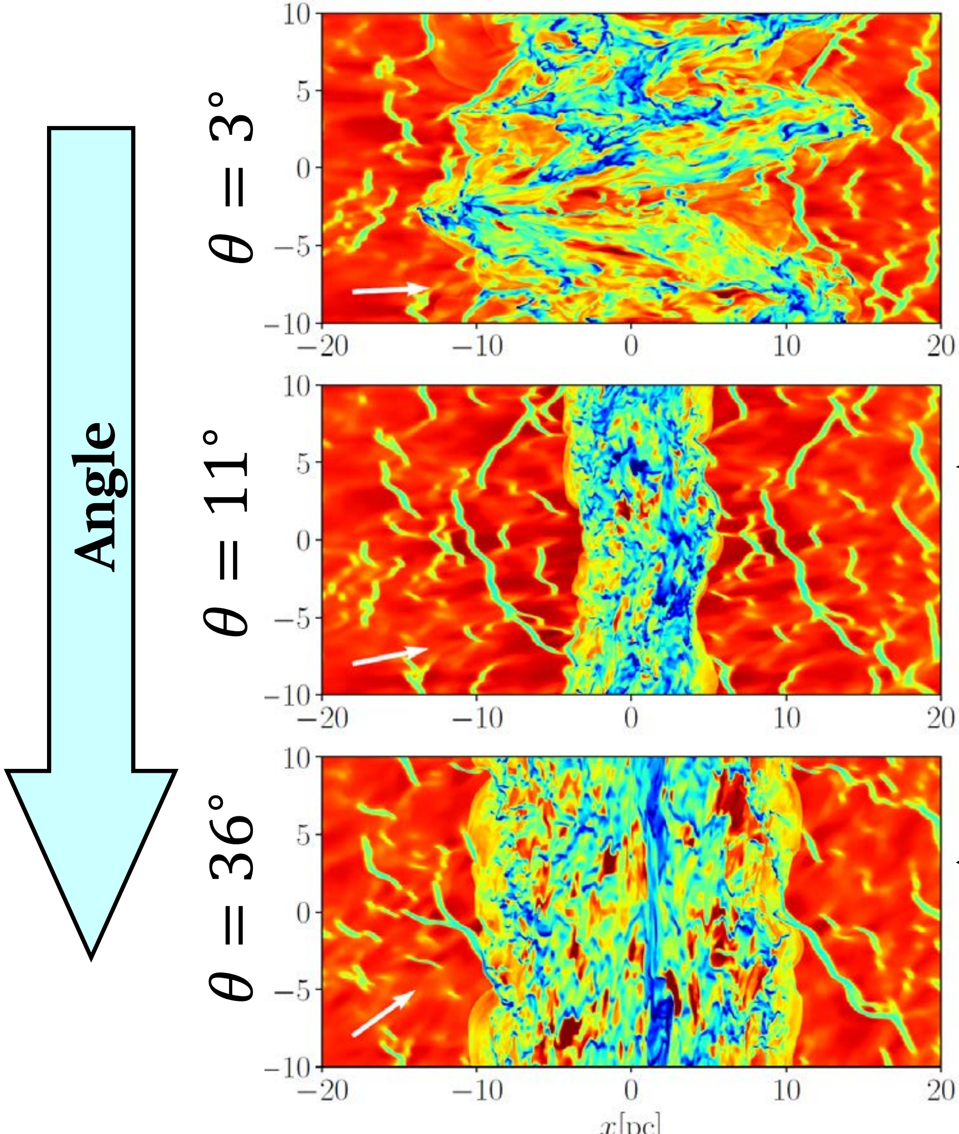
Essentially same result by

van Loo+2007; *Heitsch*+2009; *Körtgen & Banerjee* 2015; *Valdivia*+2016; *Iwasaki*+2018

➔ Further compression of HI clouds required!

Compression of a HI Cloud

Iwasaki+2018



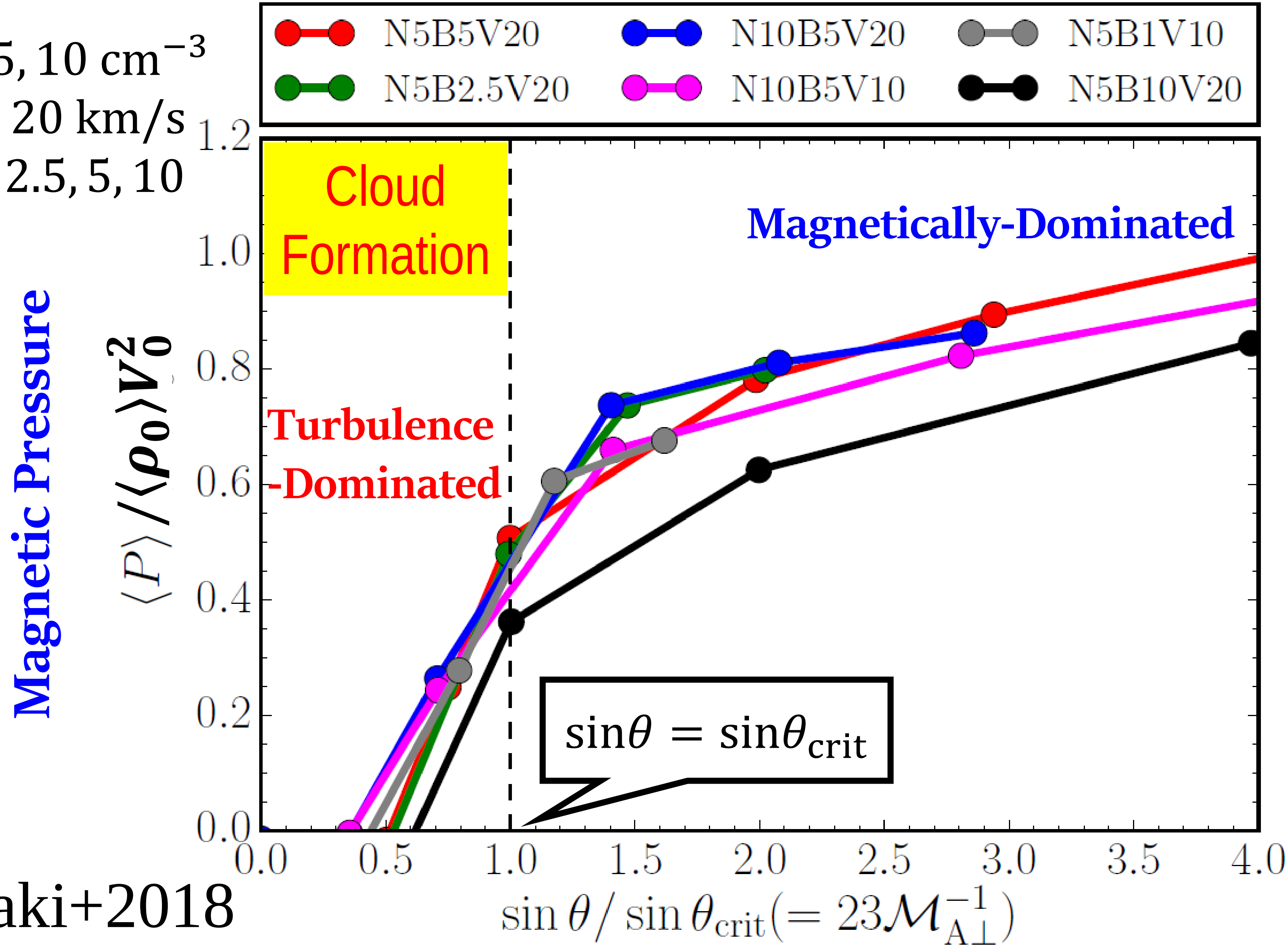
Super-Alfvenic Anisotropic Turbulence: $\delta v_{//} > \delta v_{\perp}$
(Inoue & Inutsuka 2012)

Trans-Alfvenic Turbulence by Increased Magnetic Field

Layer Supported by Increased Magnetic Field: Sub-Alfvenic Turbulence

Dependence on $\langle n_0 \rangle, V_0, |B_0|$

$\langle n_0 \rangle = 5, 10\ \mathrm{cm}^{-3}$
$V_0 = 10, 20\ \mathrm{km/s}$
$B_0 = 1, 2.5, 5, 10$



Iwasaki+2018

Formation of Molecular Clouds

We need multiple episodes of compression.

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

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

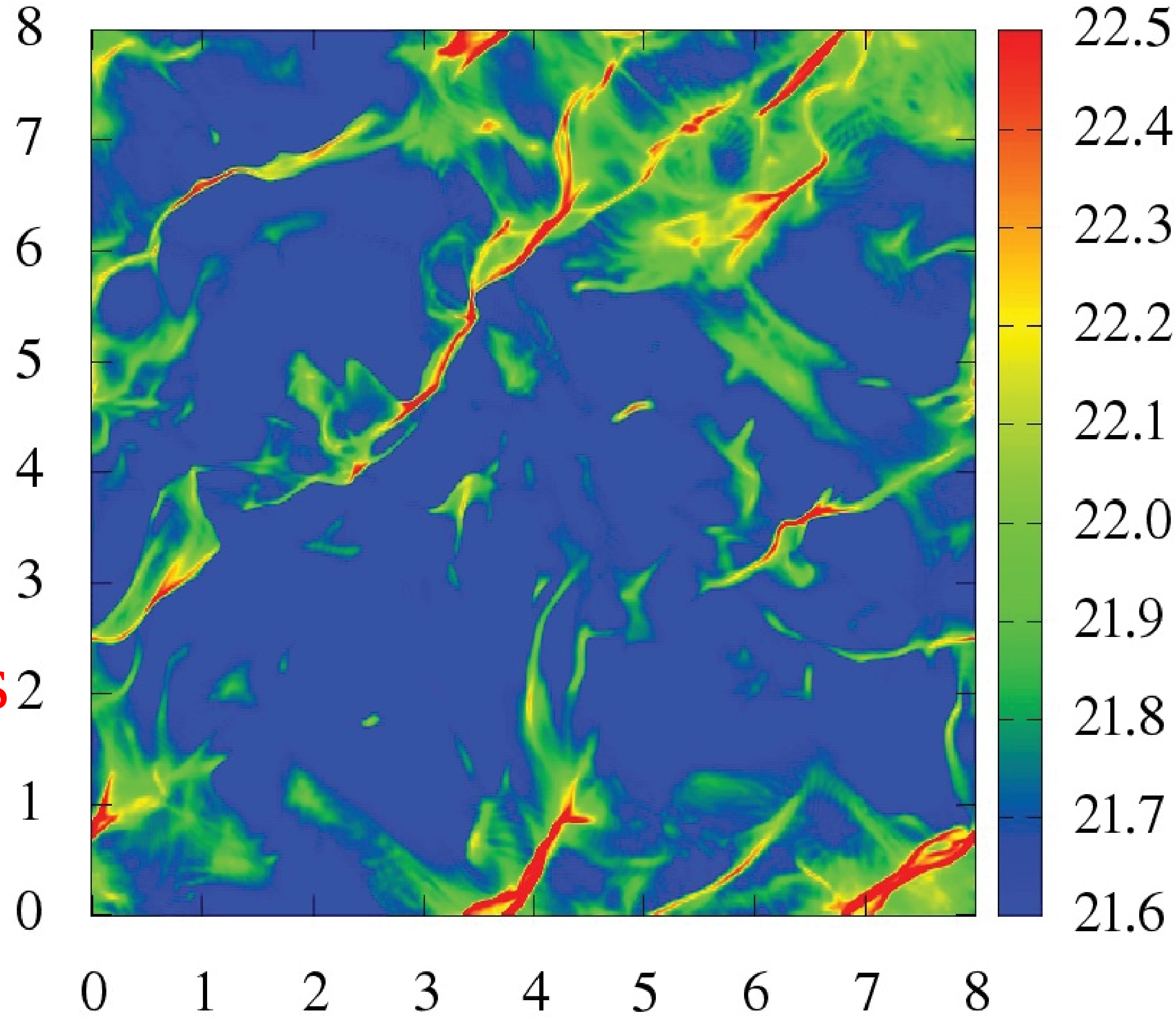
Next Question:

What happens at further compression after a significant fraction of gas become molecular?

Further Compress. of Mole. Clouds

Further Compression of Molecular Cloud (face-on view of compressed layer)

➔Magnetized Massive Filaments & Striations

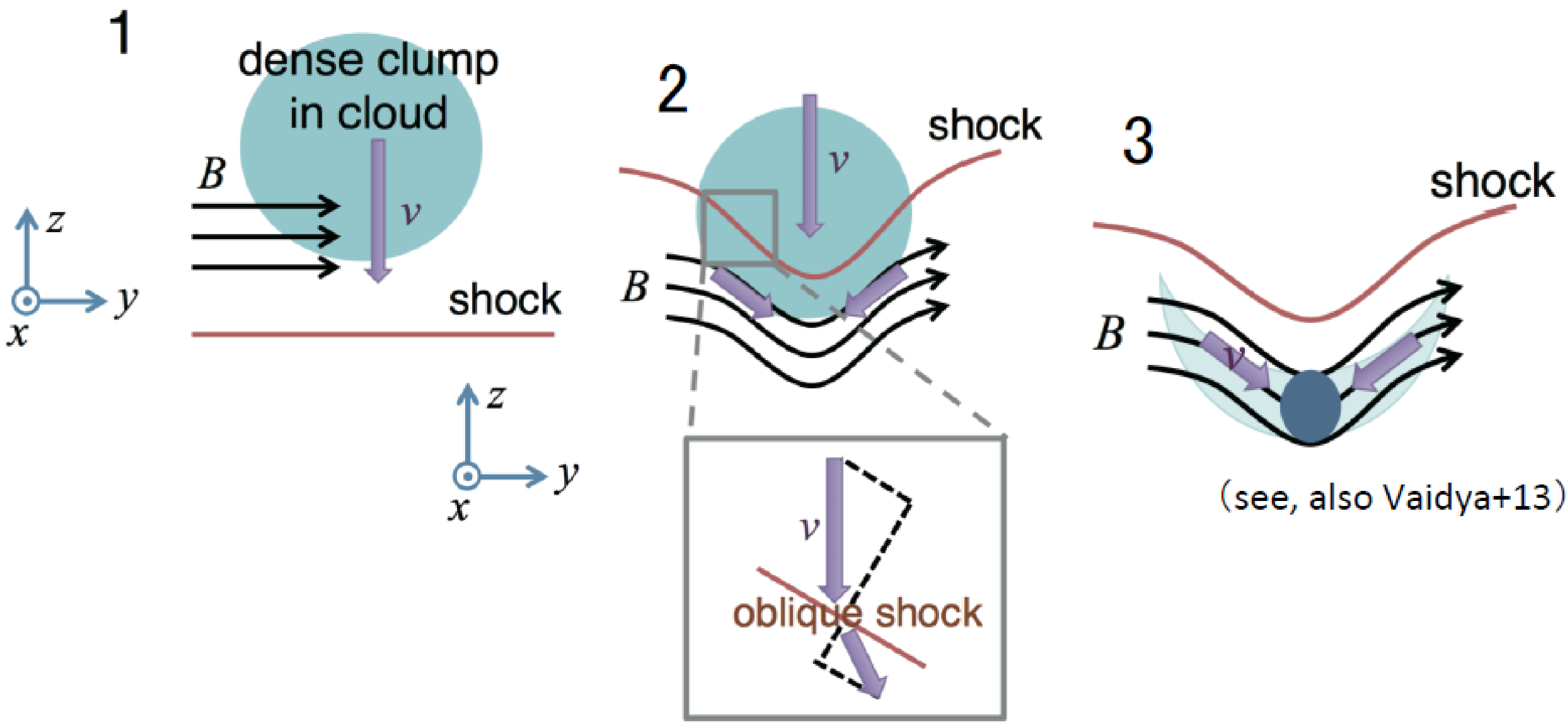


Self-Gravity Included, *SI, Inoue, Iwasaki, & Hosokawa 2015*

Filament Formation Behind MHD Shock

Inoue & Fukui 13, ApJL
Inoue+18, PASJ

- What happens when a dense clump is swept by a shock?



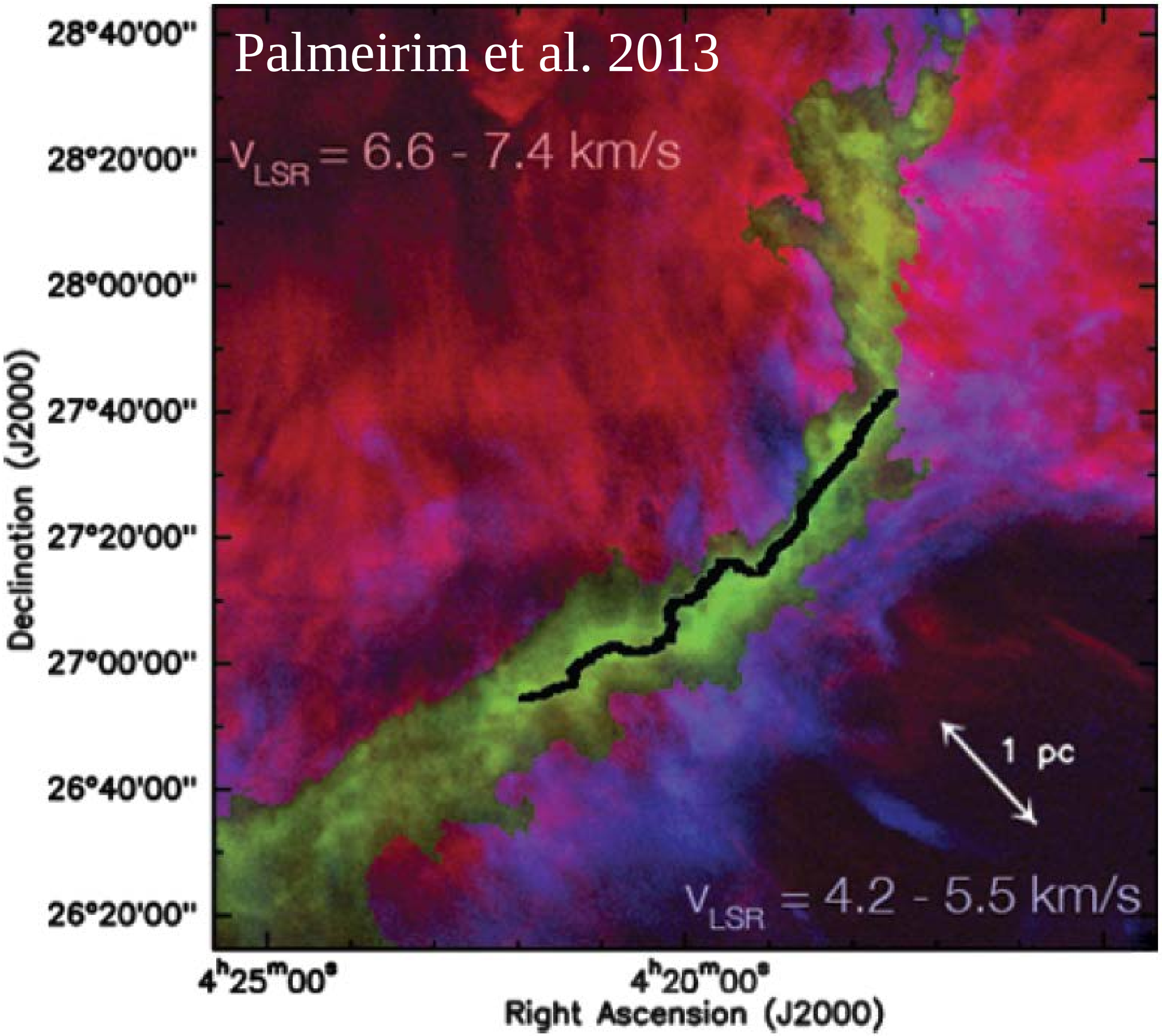
(see, also Vaidya+13)

* Compression is weak in the z-direction due to magnetic pressure.

→ A MHD shock compression of a dense blob leads to a filament formation.

Filament ⊥ Compressed Magnetic Field

Observational Evidence for Sheet?



1) Thickness = *N* / *n*

2) Coherent Flows around a Filament
🡐
Accretion along a sheet?

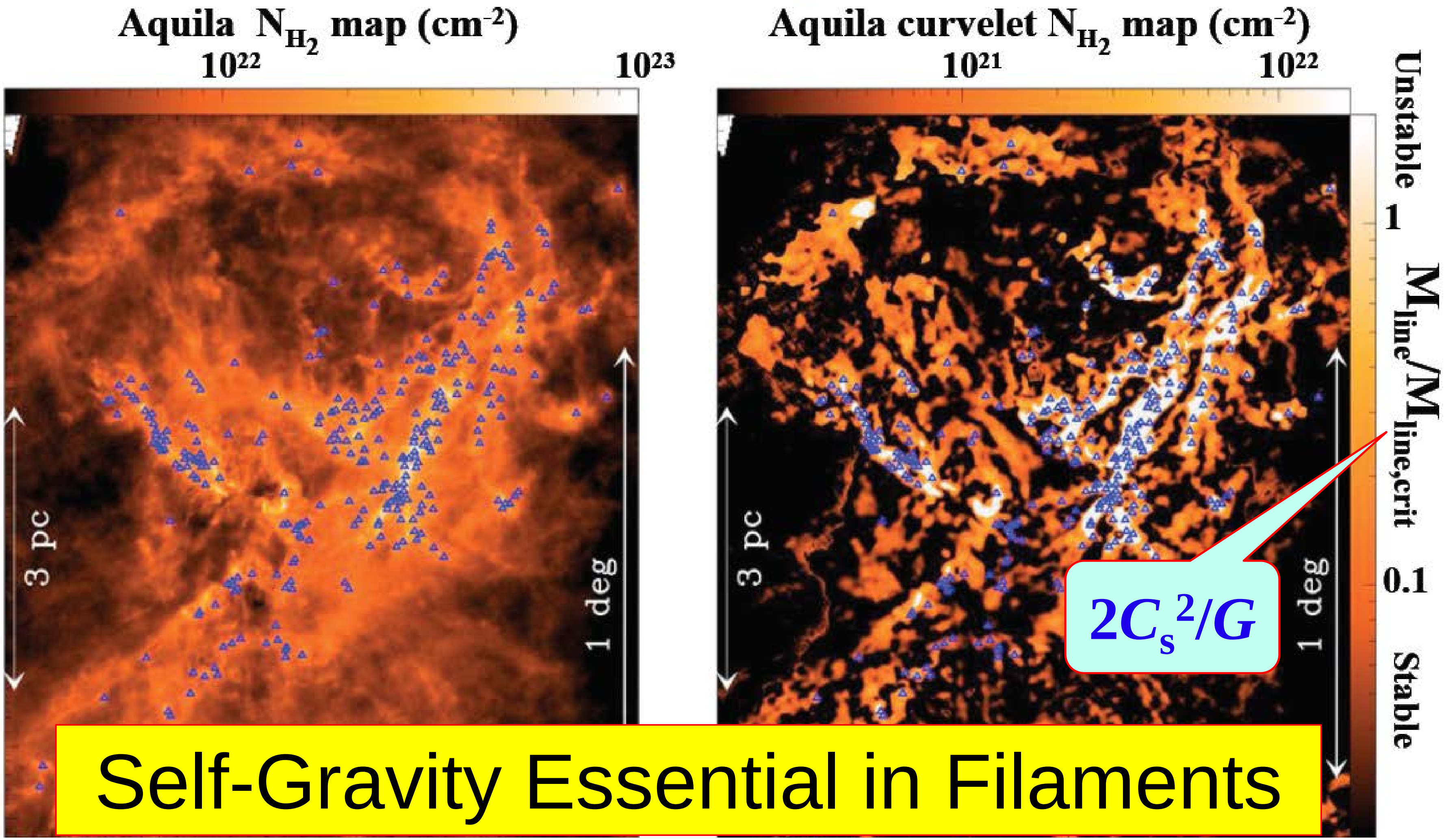
Andre 2017
(arXiv:1710.01030)
Shimajiri+2018

See also "CVD" by Qian, Li, Offner, & Pan 2015

Highlight of Herschel (e.g., 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

Mass Function of Cores in a Filament

Inutsuka 2001, ApJ **559**, L149

Line-Mass Fluctuation of Filaments

Initial Power Spectrum

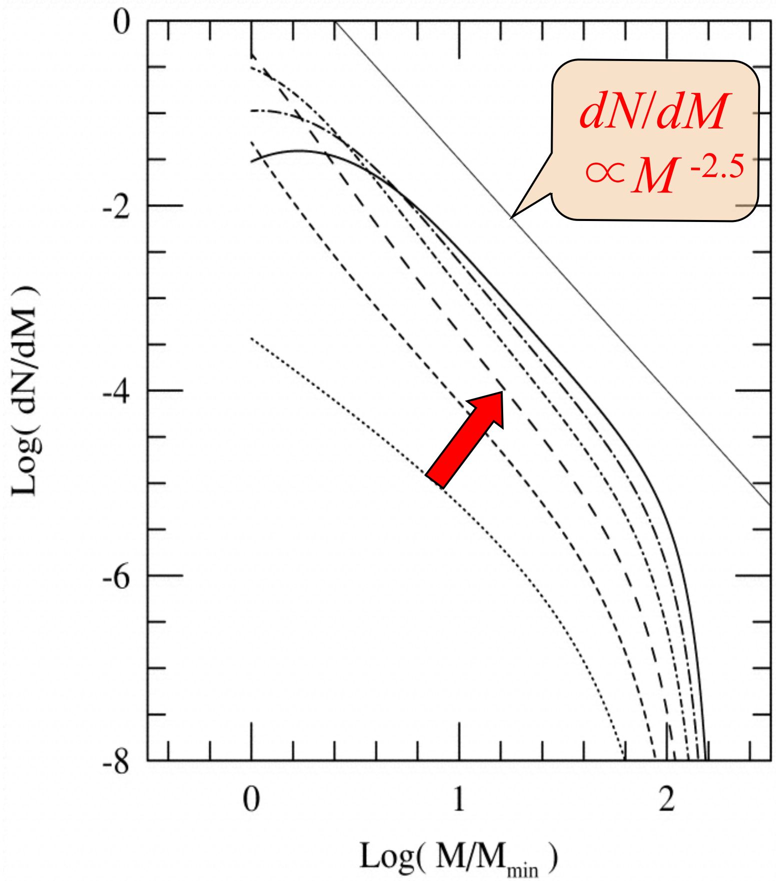
$$P(k) \propto k^{-1.5}$$

Mass Function

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

Observation of Both Fluctuation Spectrum and Mass Function

➔ Clear and Direct Test!

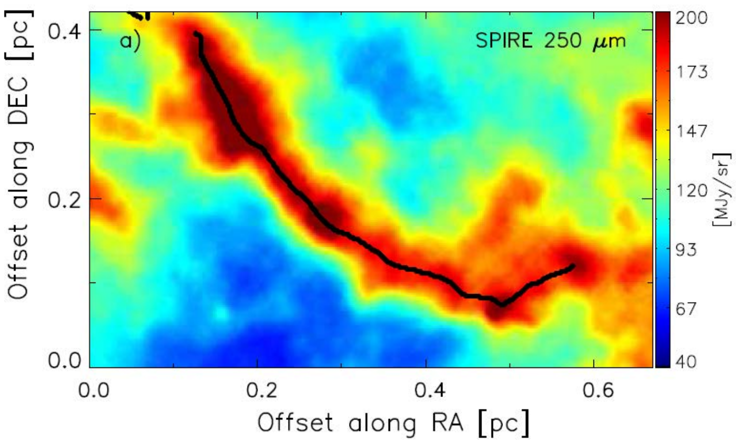


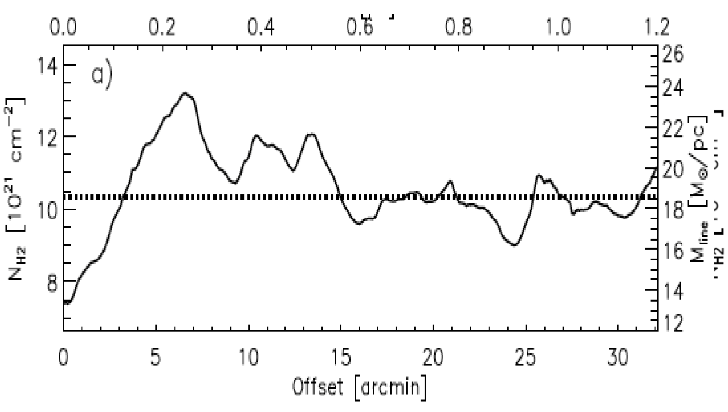
$$P(k) \propto k^{-1.5}$$

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





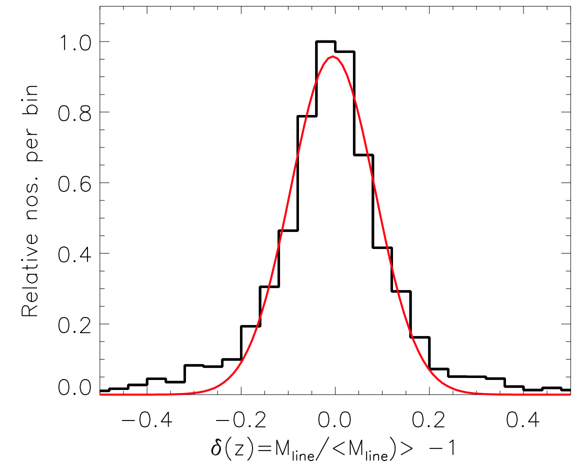
δ ...

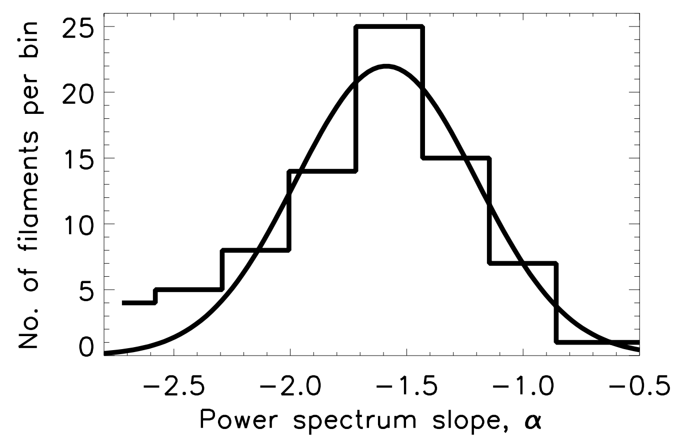
Gaussian

P **(*k*)**

$\propto \boldsymbol{k^{n}}$

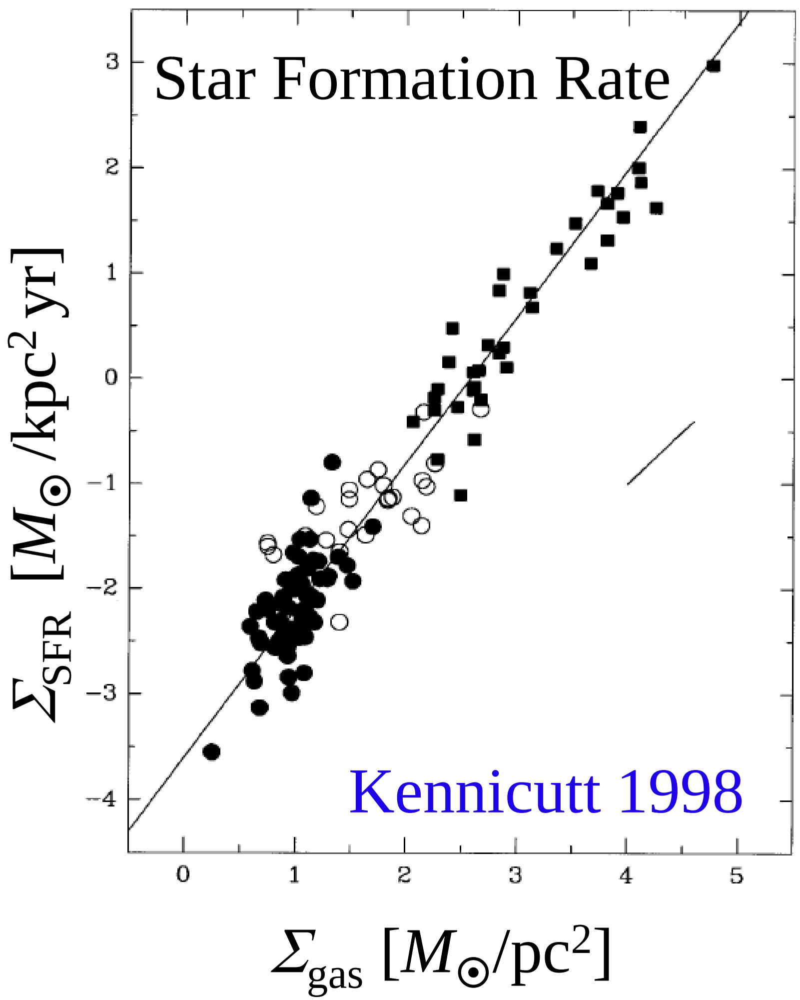
$\boldsymbol{n} = -1.6 \pm 0.3$

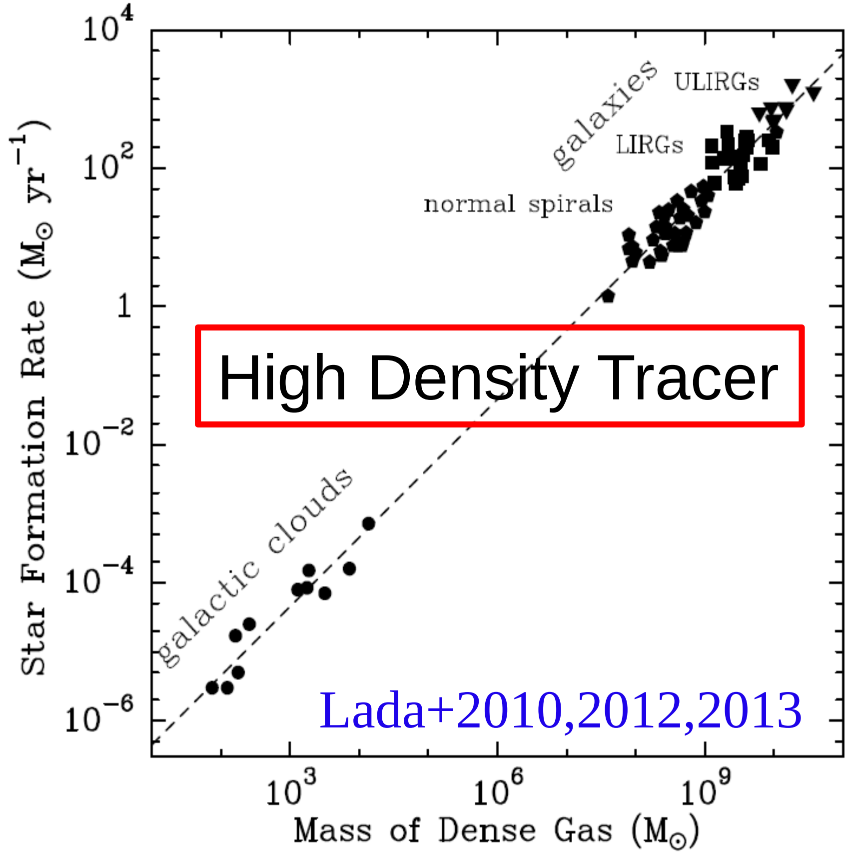




Supporting Inutsuka 2001; c.f., *Li, Hennebelle & Chabrier* 2017

Schmidt-Kennicutt Law of SF





Timescale: $\Sigma_{gas} / \Sigma_{SFR}$ ~ Gyr

- Timescale: $M/(\mathrm{SFR}) \sim$ 20Myr

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

Star Formation Efficiency in Dense Gas

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

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

Why?

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

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

Star Formation Efficiency in a Filament: $\varepsilon_{\rm dense\ gas}$

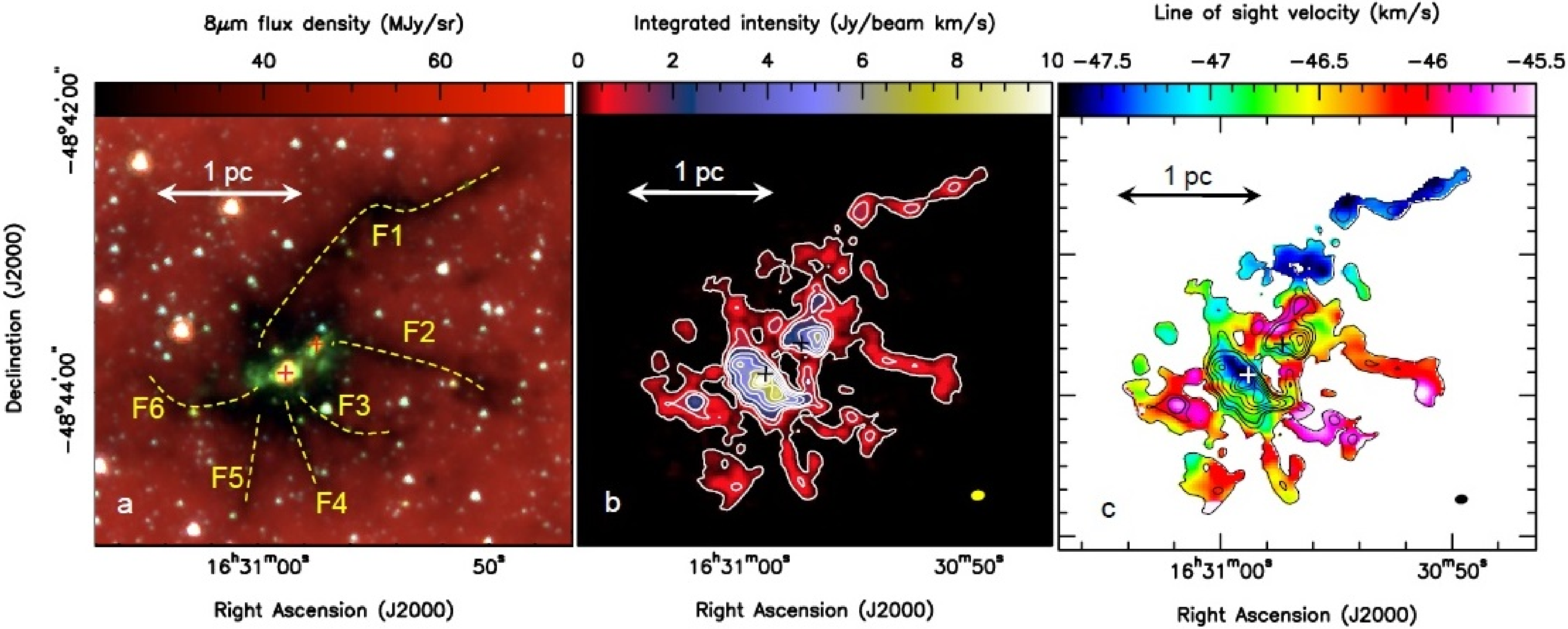
$$\Rightarrow \varepsilon_{\rm dense\ gas} = M_{\rm core} / M_{\rm filament} \times \varepsilon_{\rm core} \sim 5\%$$

Consumption Timescale of Dense Gas: $t_{\rm dense\ gas}$

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

$$\Rightarrow t_{\rm dense\ gas} \sim 20{\rm Myr} \quad \text{(eg. Lada+2010, Andre+2014)}$$

Massive Stars through Filaments: Archetype?



(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?

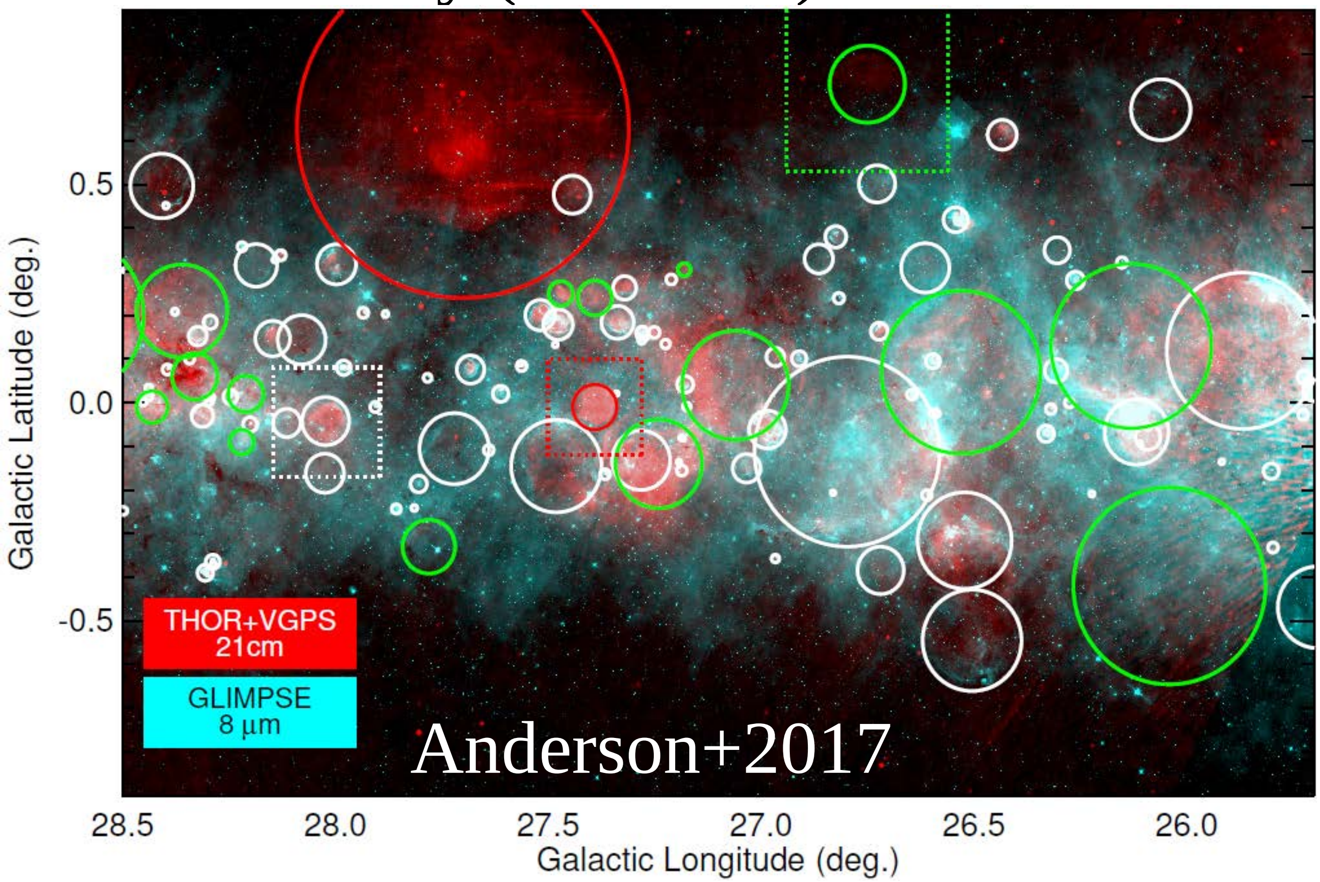
Other Modes of Star Formation?

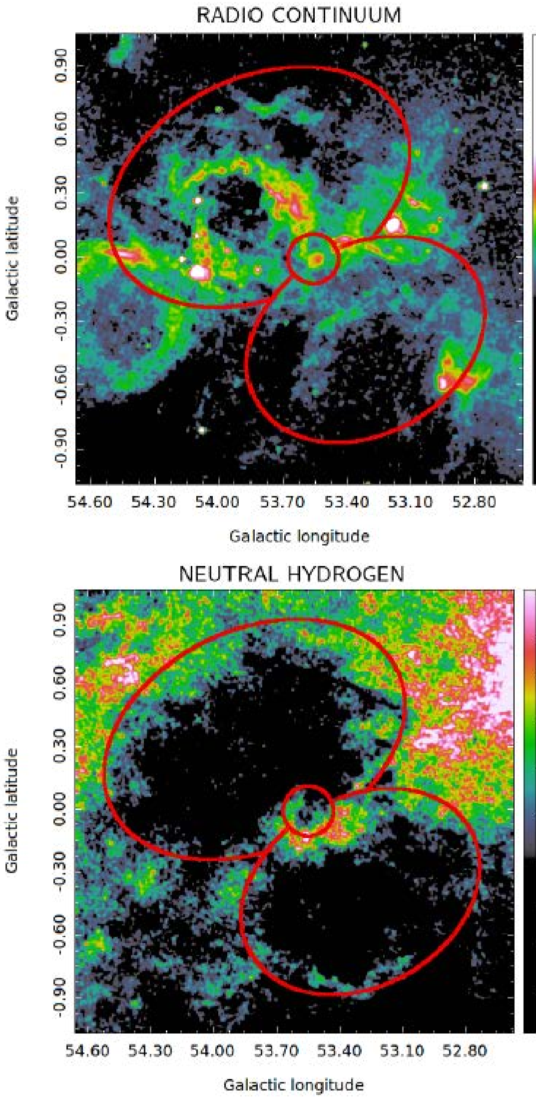
Cloud Collision (*Fukui*, *Tan*, *Dobbs*,...)

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

Observed (Colliding) Bubbles

THOR Survey (Beuther+)



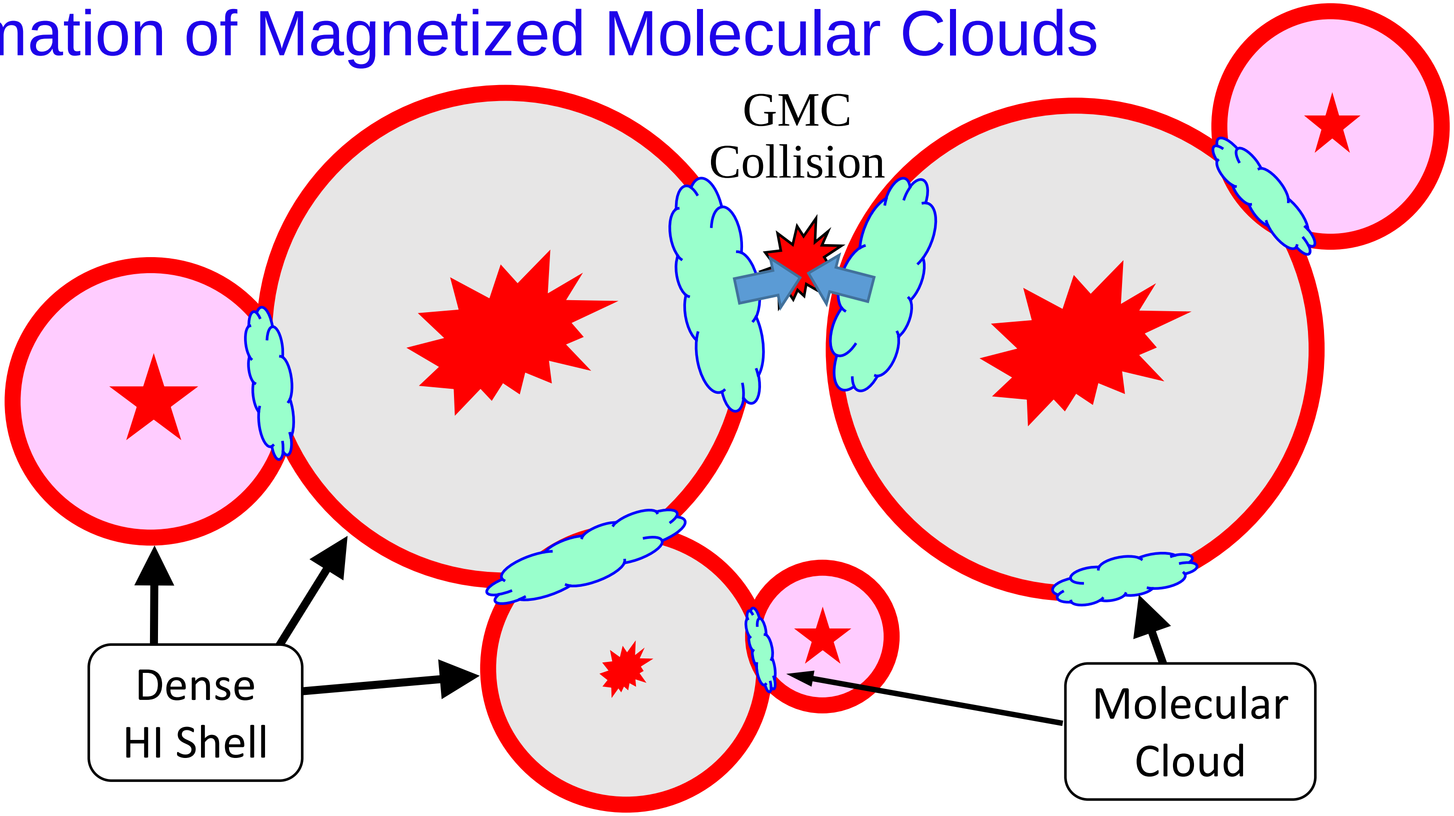


See also 10^3 HII region statistics by Palmeirim+2017!

Zychová & Ehlerová 2016

Network of Expanding Shells

Multiple Episodes of Compression ➔
Formation of Magnetized Molecular Clouds



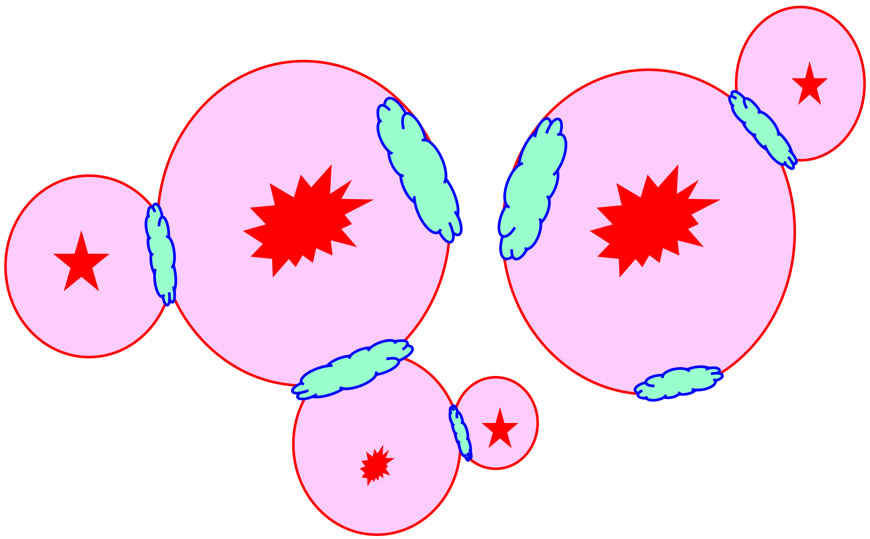
Long (>10Myr) Exposure Picture!

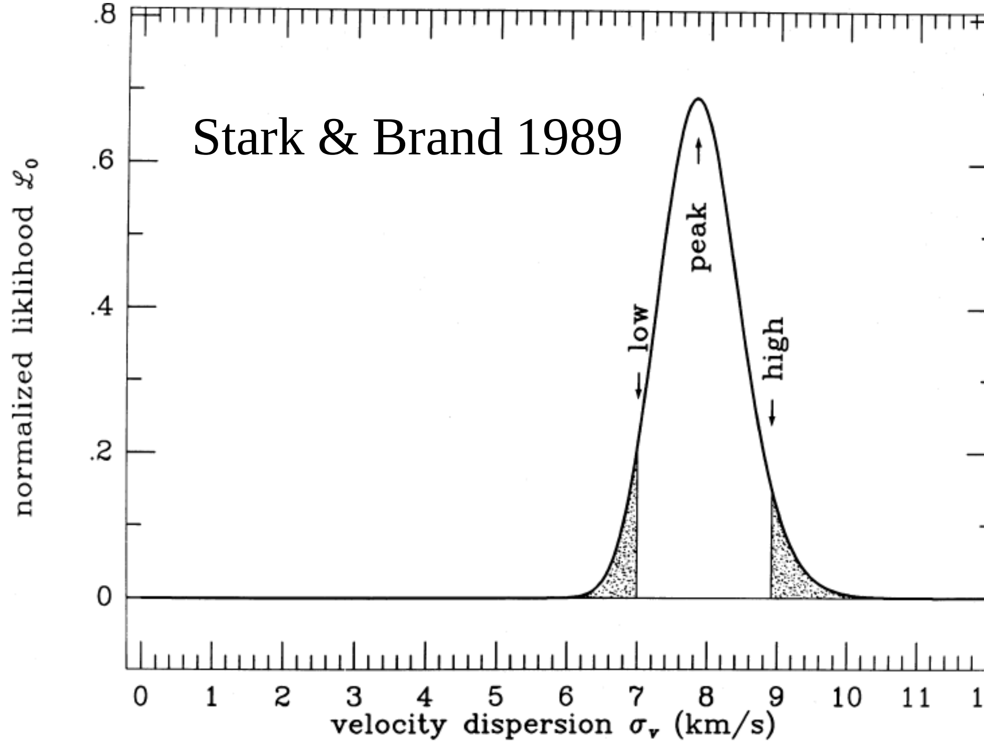
Nb: Each bubble disappears quickly (<Myr).

SI+2015; cf. Elmegreen 2007

Velocity Dispersion of Clouds

Multiple Episodes of Compression ➔ Formation of Magnetized Molecular Clouds



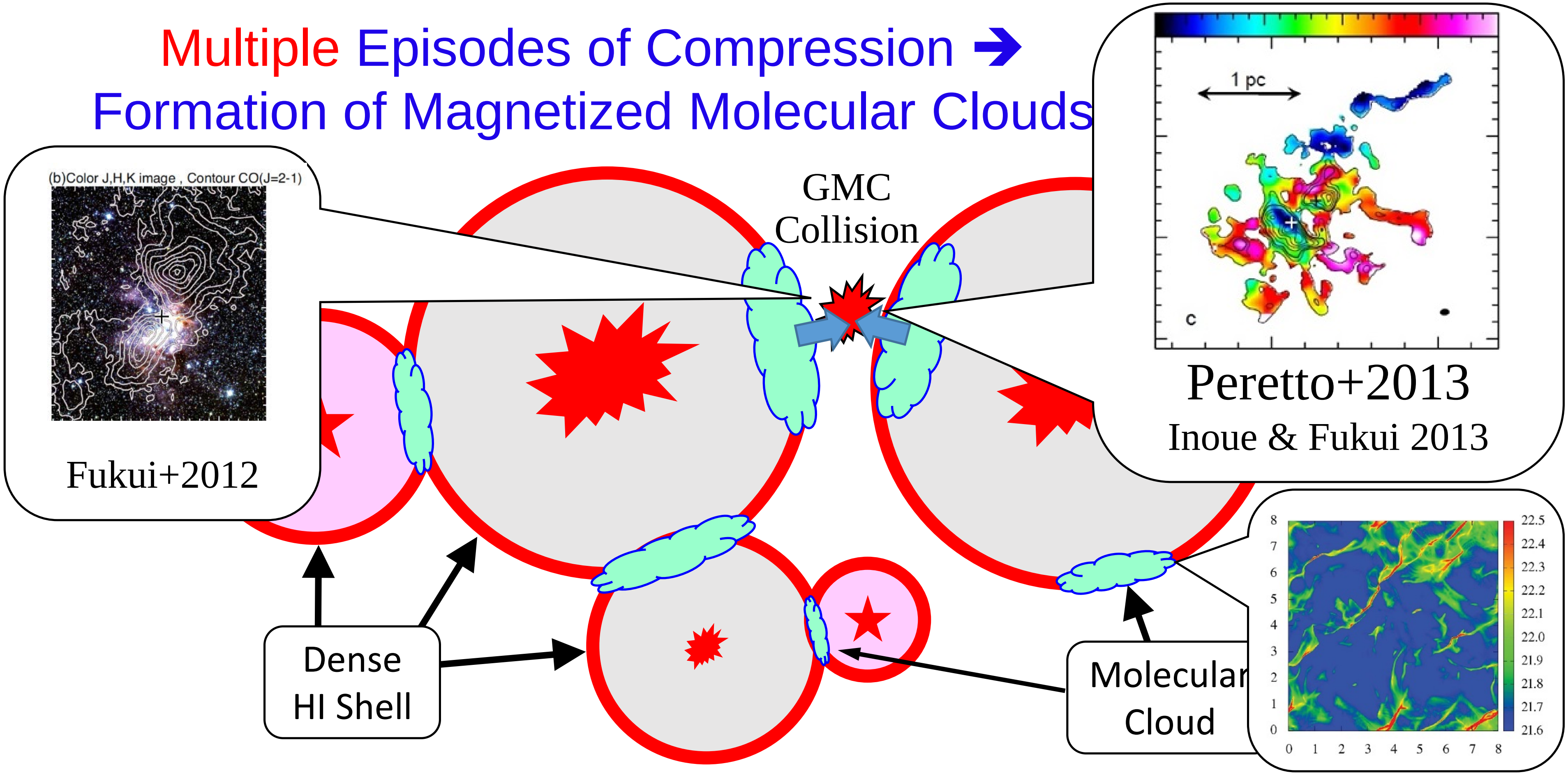


Shell Expansion Velocities ~ 10^1 km/s ➔ Cloud-to-Cloud Velocity Disp.

But need for more obs!

Network of Expanding Shells

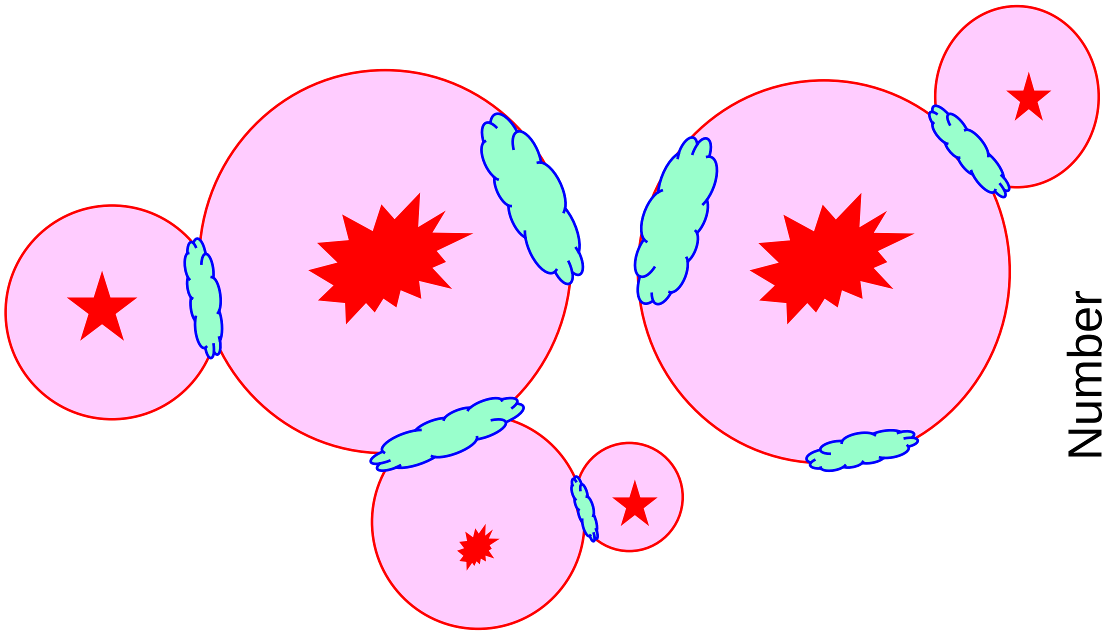
Multiple Episodes of Compression →
Formation of Magnetized Molecular Clouds

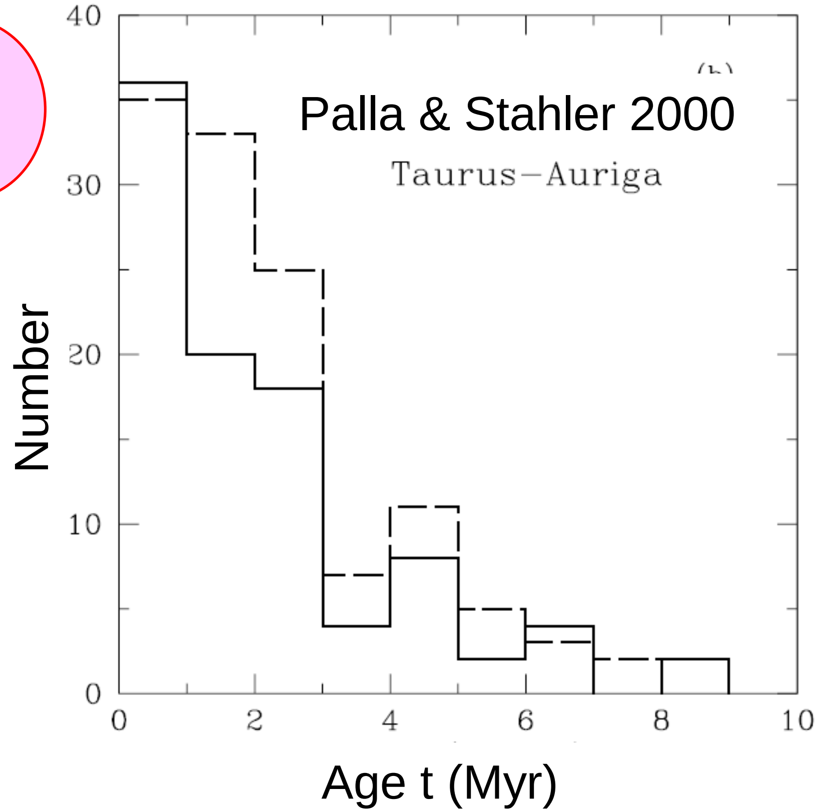


Each Bubble Visible Only for Short Time (~1Myr)!

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

Natural Acceleration of Star Formation





Molecular Cloud Growth

➔ Mass Increase in Supercritical Filaments

➔ Accelerated SF

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

How Many Generations of Filaments?

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

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

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:

$$\rightarrow 60 M_{\text{sun}} \times \varepsilon_{\text{dense gas}} \sim 3 M_{\text{sun}}$$

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

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

➔ Multiple Generations of Filaments Needed!

Open Questions

1) Why Filament Width ~ **0.1pc**? ➔ SF Threshold for N

2) Why Upper Limit for Core Formation Efficiency?

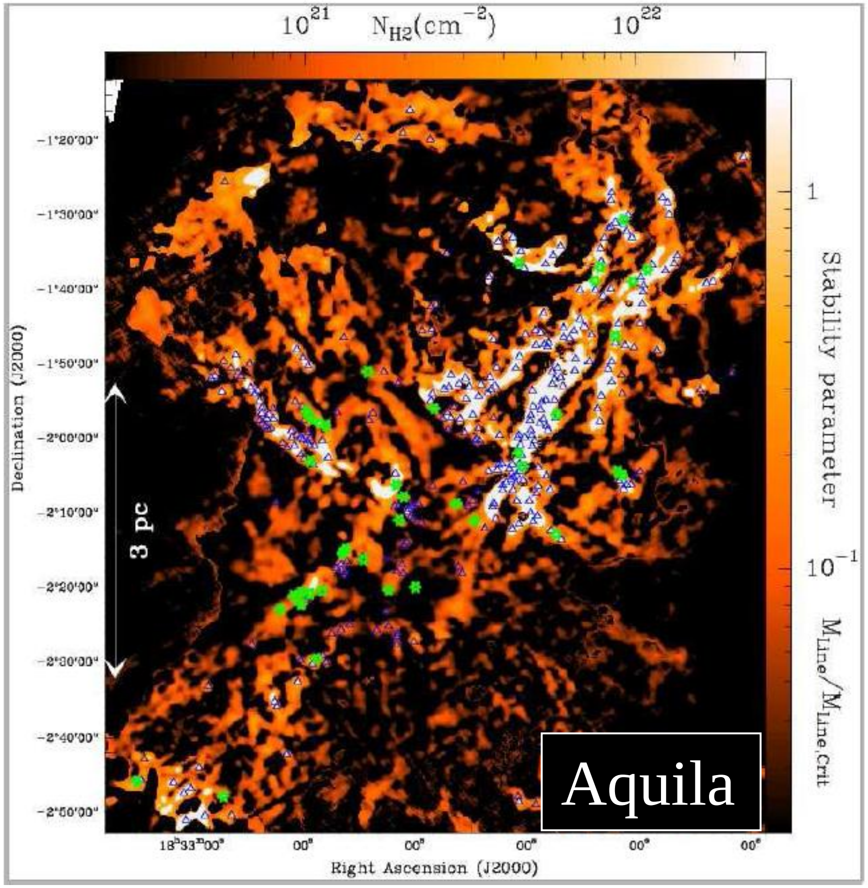
$M_{\rm core} / M_{\rm filament} < 15\%$ ➔ $t_{\rm dense\ gas} \sim$ 20 Myr

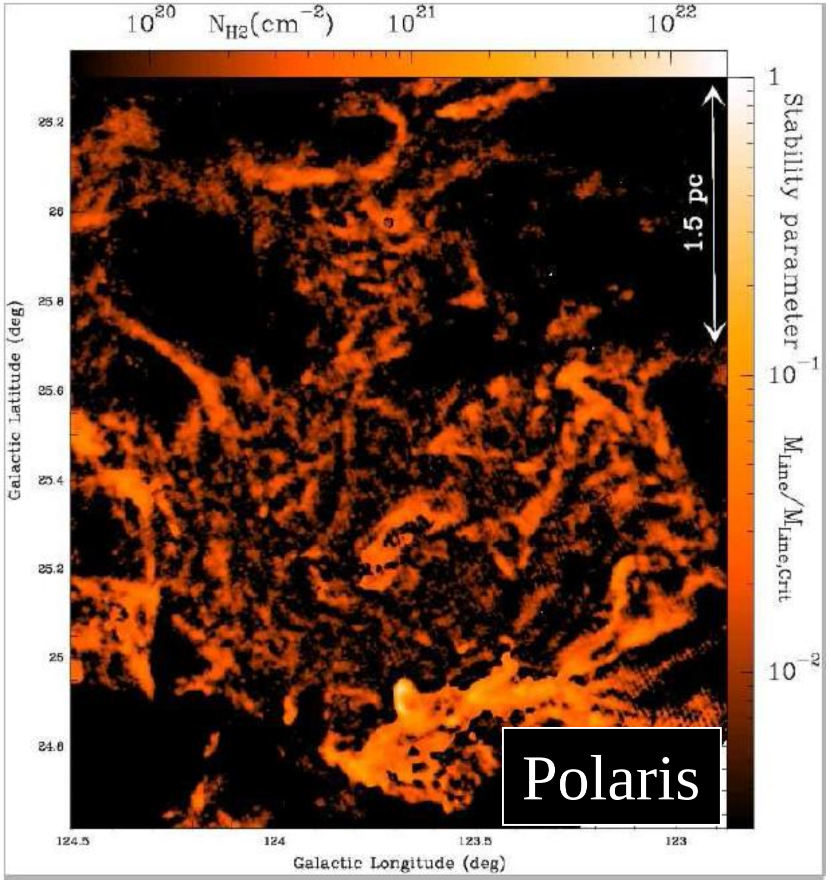
3) Core Mass Function for Massive Cores?

(ex., Motte+2018…)

4) …

Which is determinant, N_H or Filament-Width?





Herschel filaments have almost the same radii!

Aquila: 2R=0.1pc & $M_L = 2C_s^2/G$ ➔ $N_H \approx 10^{22}$cm^{-2} (A_v= several)

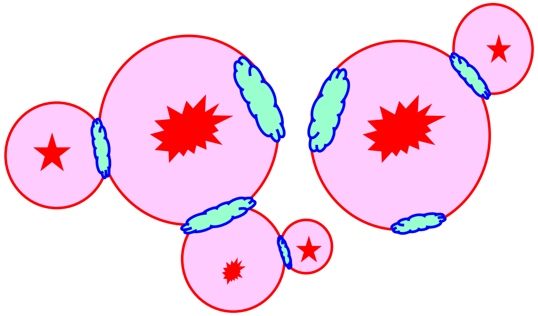
Polaris: 2R=0.1pc & $M_L < 2C_s^2/G$ ➔ $N_H < 10^{22}$cm^{-2} (A_v< several)

"Column Density Threshold" is a consequence?

Summary

- WNM ➔ Multi-Phase HI ➔…➔ Molecular Clouds
- 3 Timescales for Cloud Evolution, 1Myr, 30Myr, 1000Myr
- 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
- Filaments in Sheet-Like Cloud
- Star Formation Efficiency: $\varepsilon_{SF} \sim 10^{-2}$
- Schmidt-Kennicutt Law
- Accelerating 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

Dispersal of Molecular Clouds

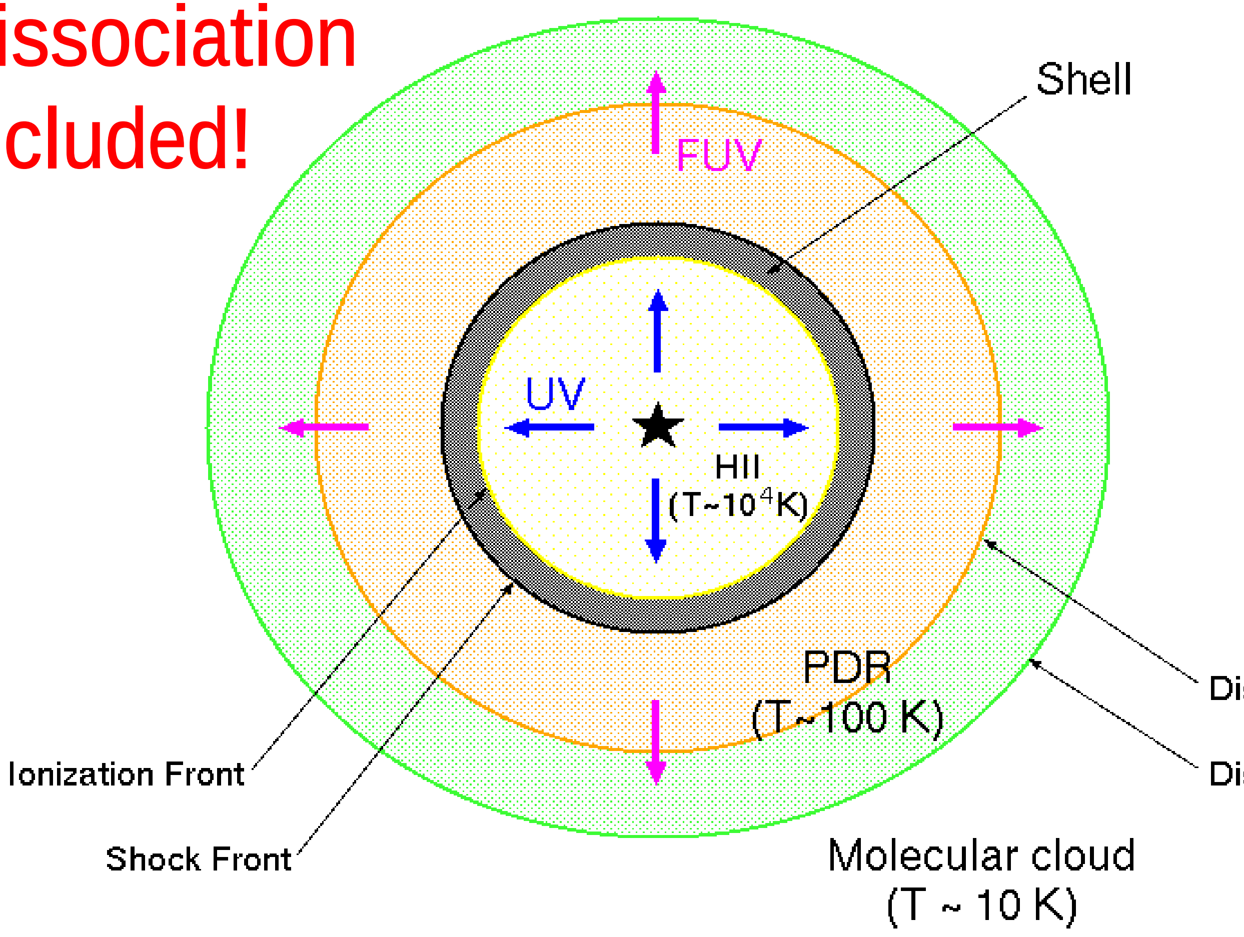
How to Stop SF?

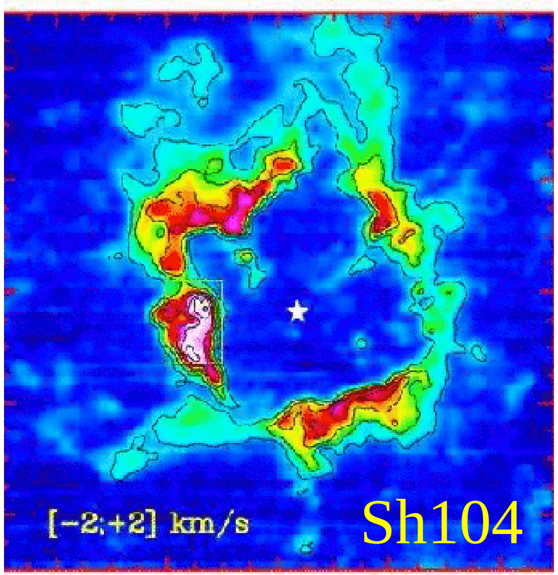
Radiative Feedback to Parental Molecular Clouds

See also *Kuiper*+, *Rosen & Krumholz*, *Walch*+, *Peters*+, *Padoan*+, and many others

Expanding HII Region in a Molecular Cloud

Photo-
Dissociation
Included!





Deharveng et al. 2003

Radiation Magnetohydrodynamics Calculation

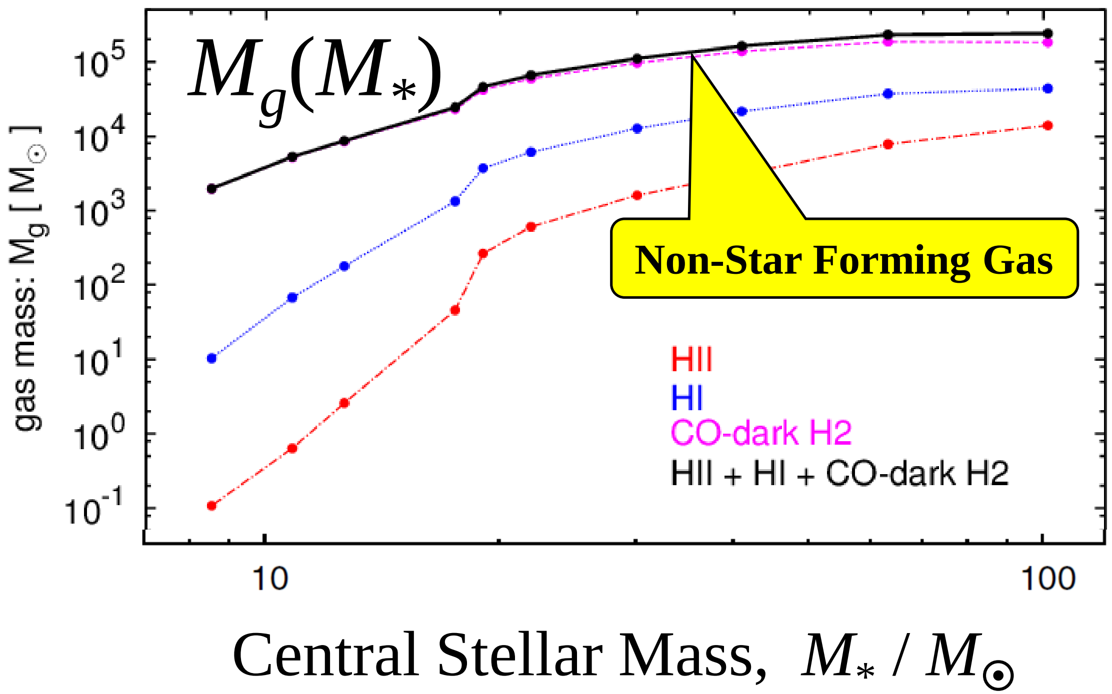
UV/FUV + H2 + CO Chemistry (Hosokawa & SI 2005, 2006ab, 2007)

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



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

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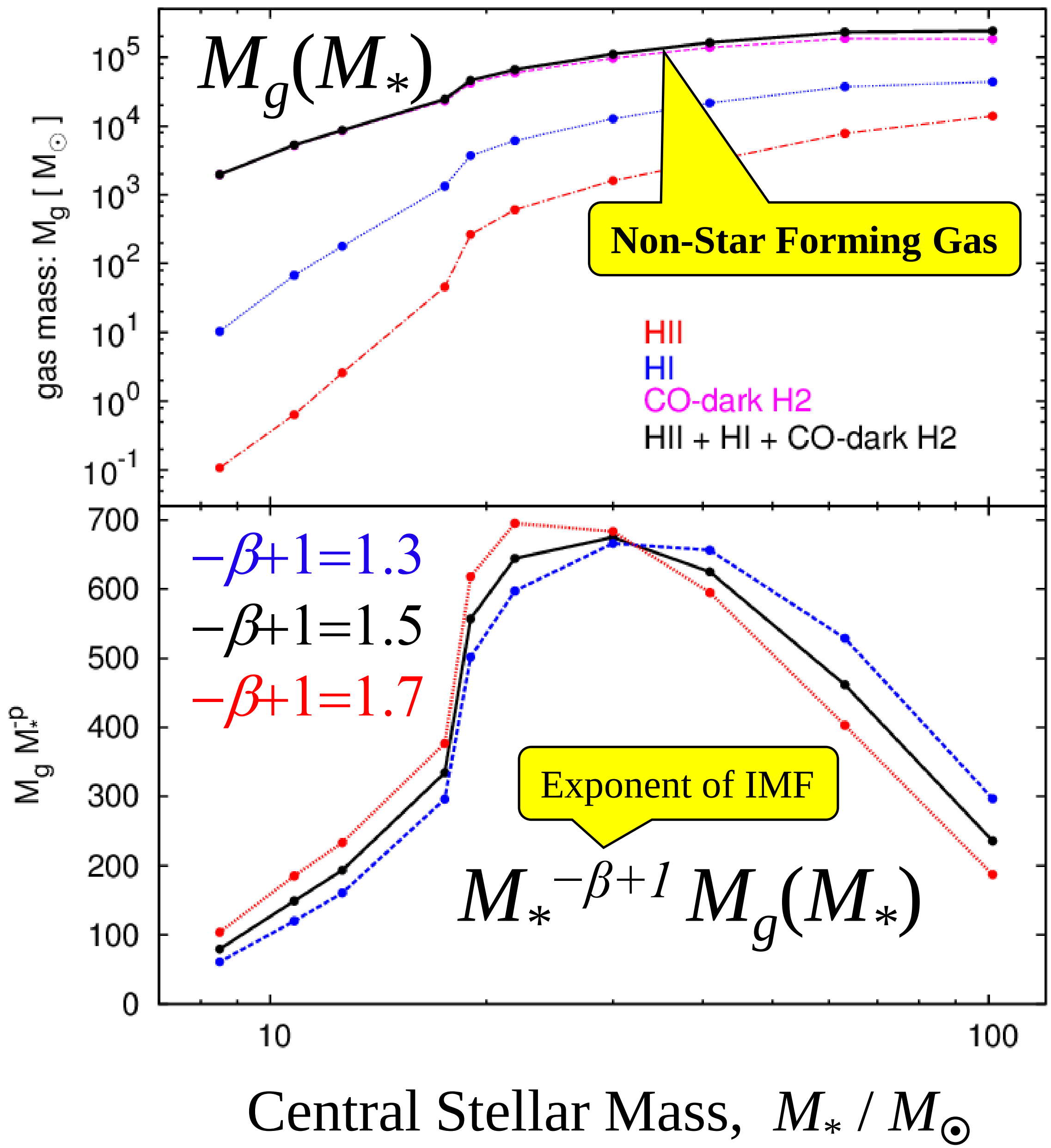


(*SI, Inoue, Iwasaki, & Hosokawa 2015* A&A **580**, A49)

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

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

e.g., 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

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

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

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

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

Formulation of Coagulation Equation

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

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

Effect of Cloud-Cloud Collision

Kobayashi, SI, Kobayashi, & Hasegawa 2017, ApJ **836**, 175
Kobayashi, Kobayashi, & SI 2018, PASJ in press

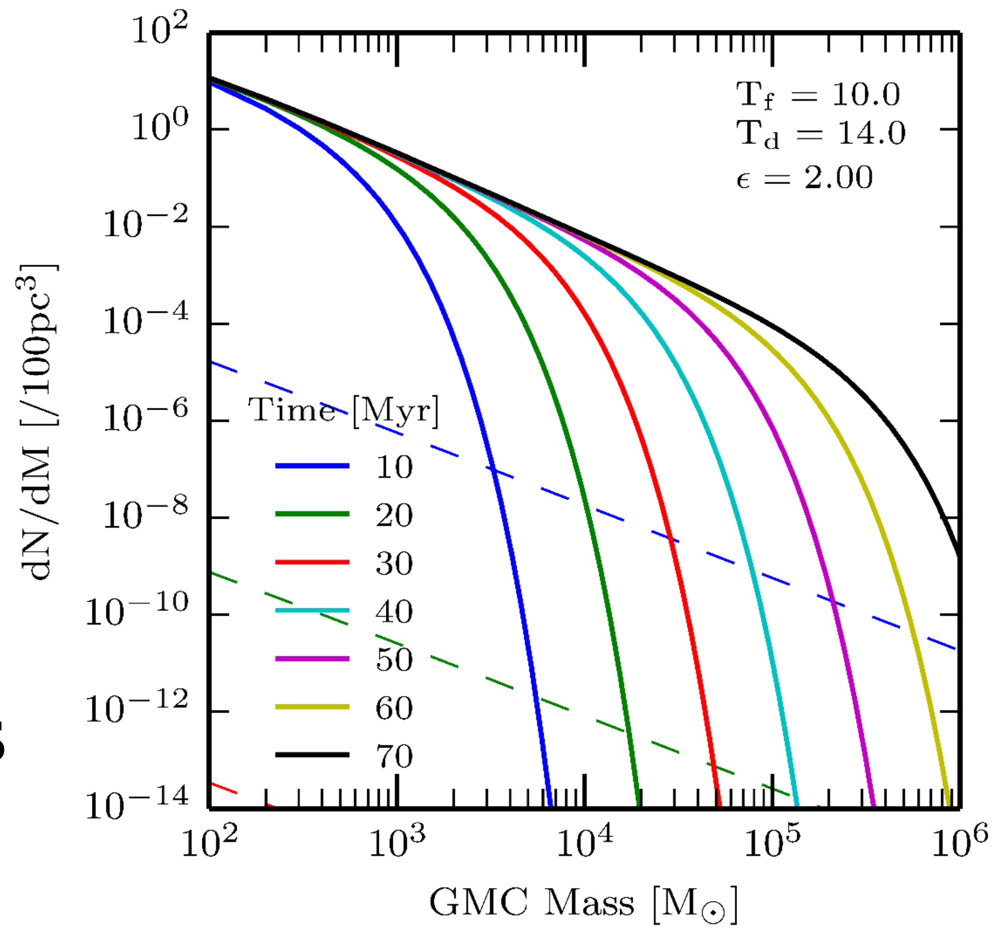
Resultant Mass Functions

Case without Cloud-Cloud Collision

self-growth & self-dispersal only

Assumption:

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

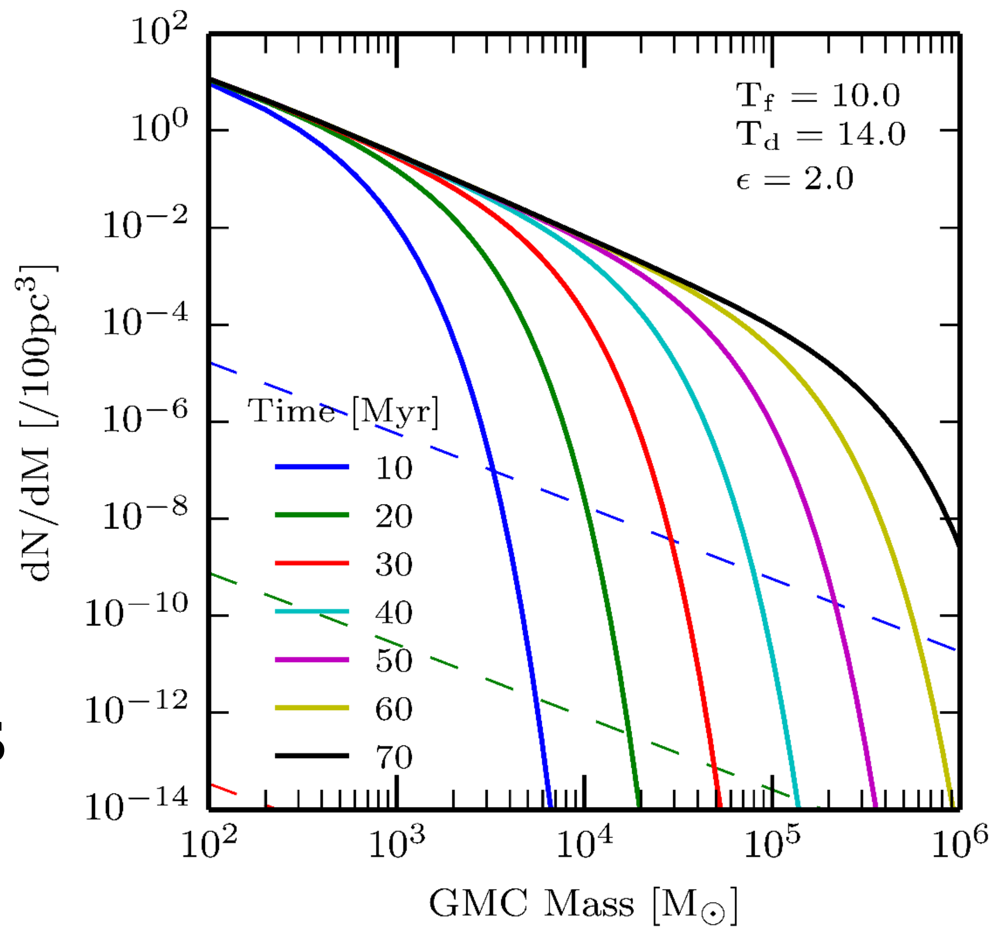


Resultant Mass Functions

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

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

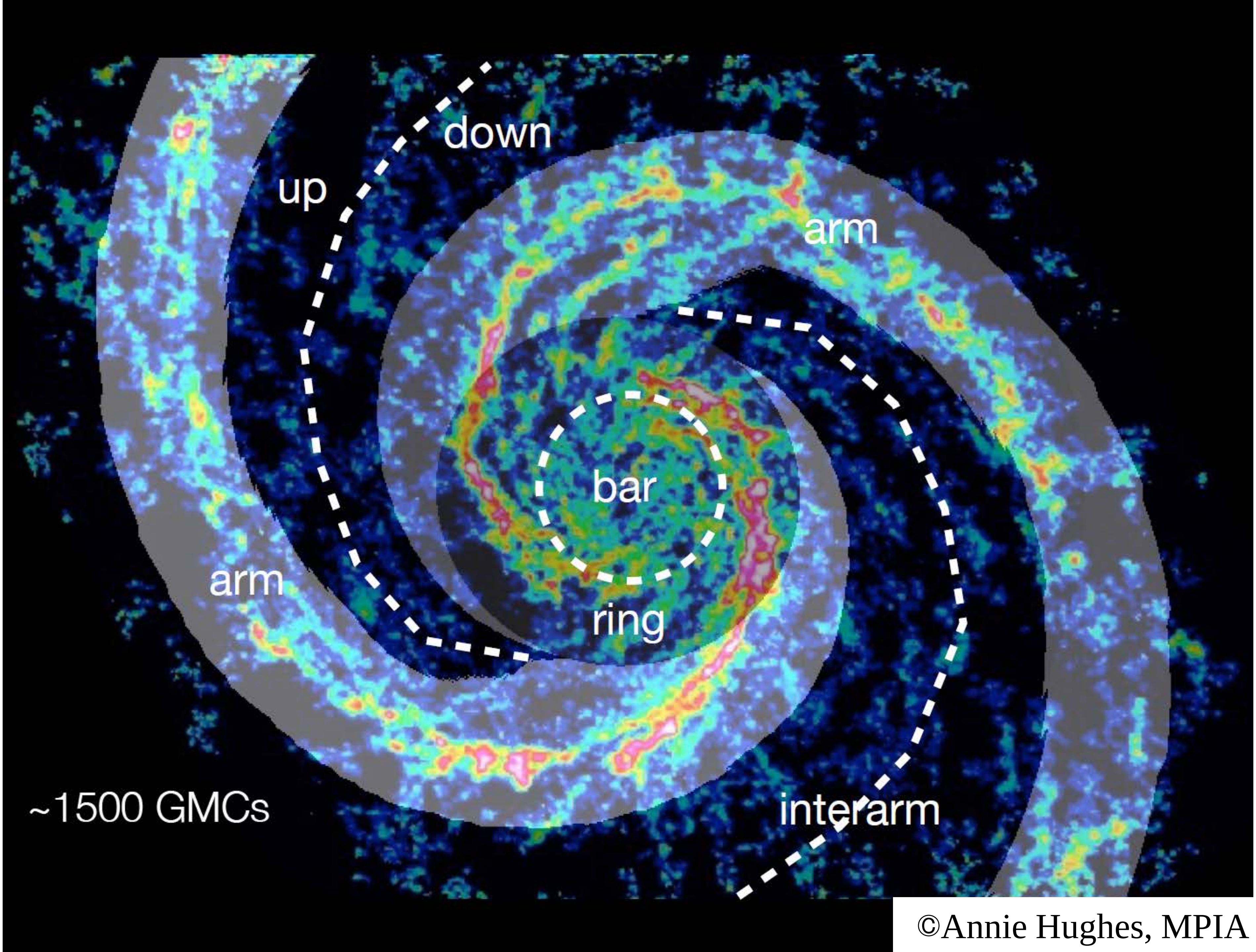
In low density region (Inter-Arm Region)

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

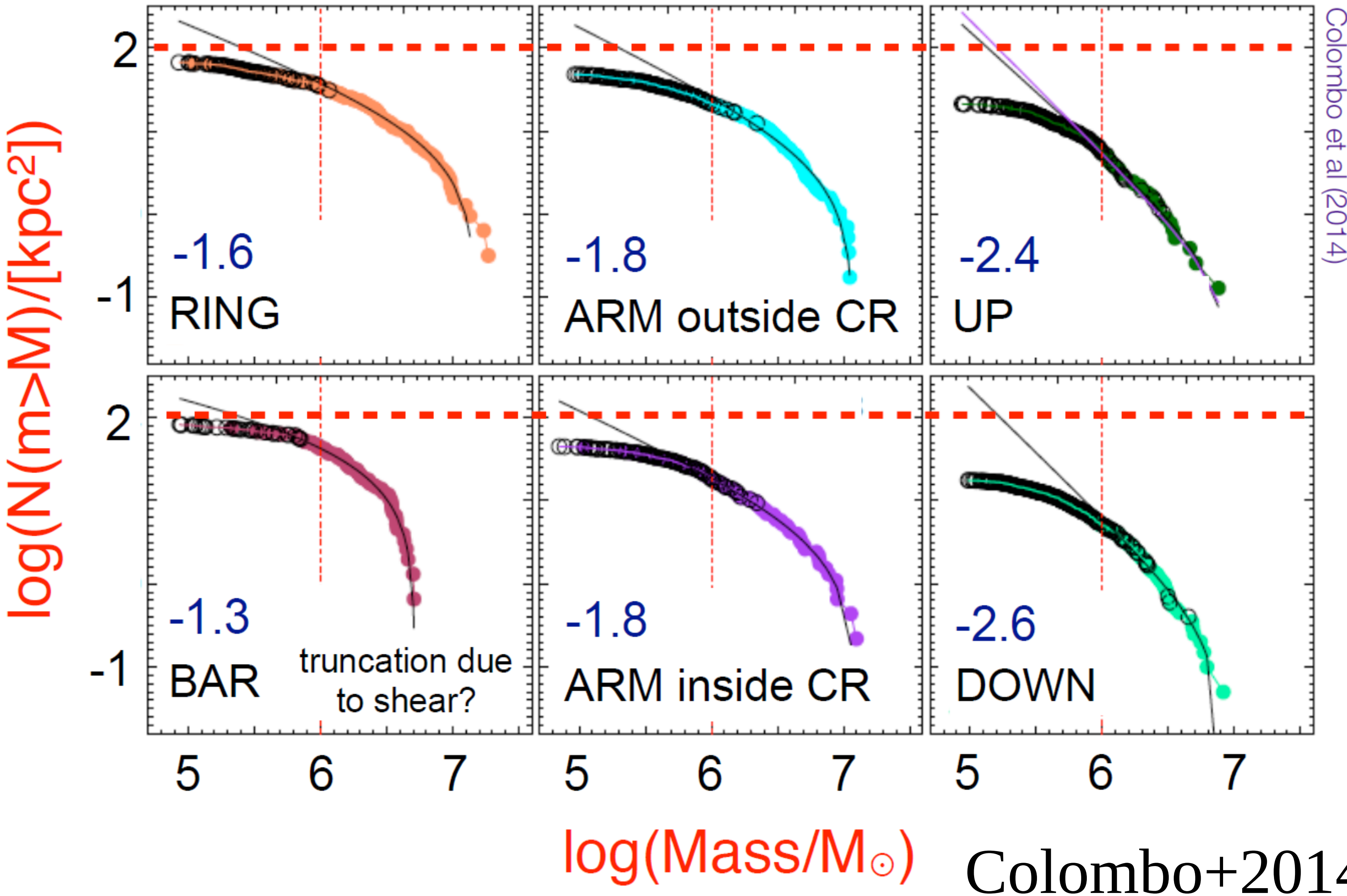
In high density region (Arm Region)

Smaller T_{form} ➔ Smaller α

➔ GMCs in M51 (Colombo+2014)


down
up
arm
bar
arm
ring
~1500 GMCs
interarm

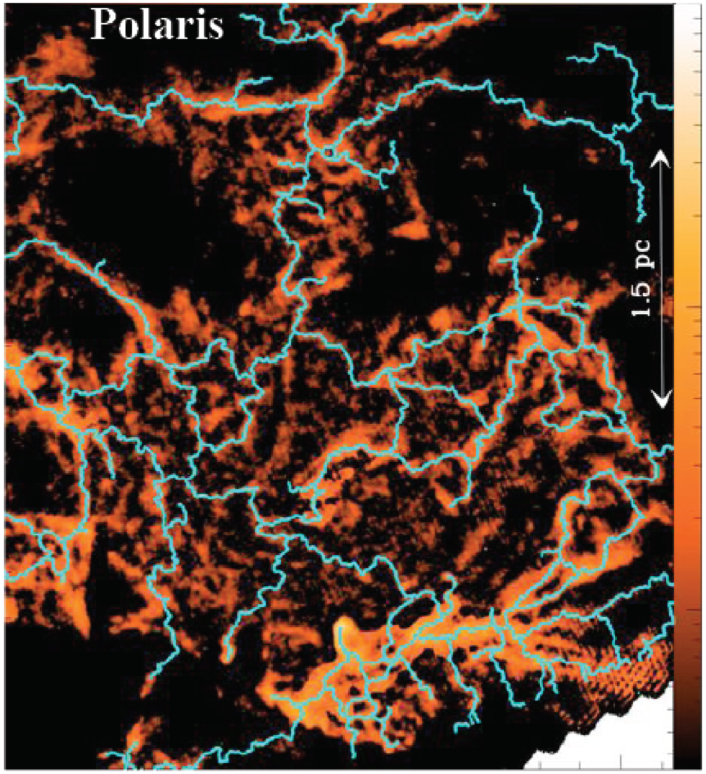
Variation of GMC Mass Function in M51



Colombo+2014

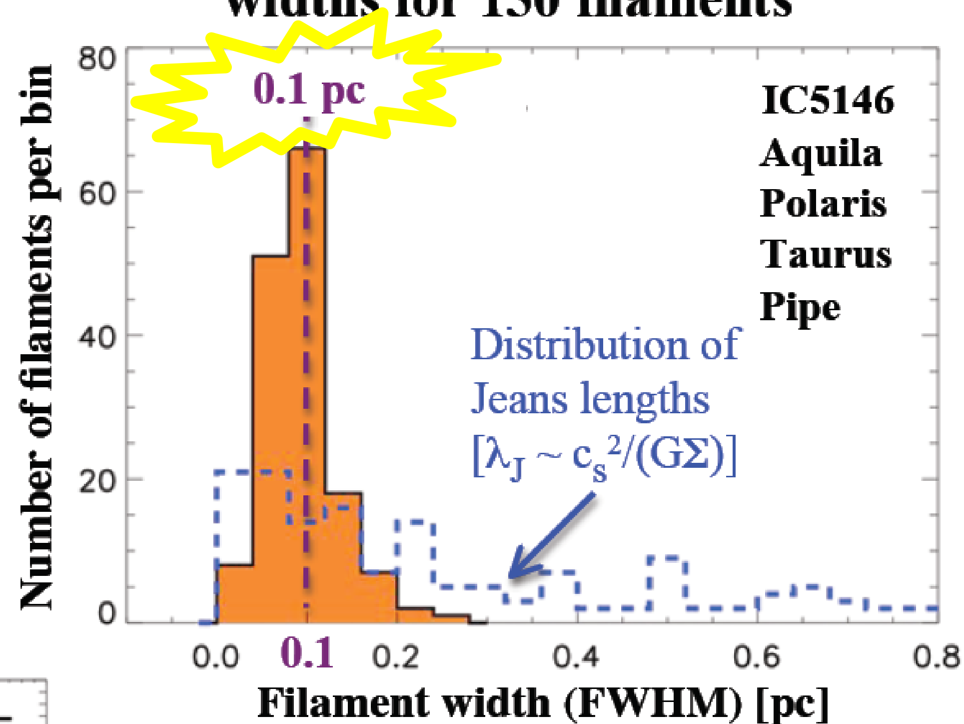
Open Question

Filaments have a characteristic width ~ 0.1 pc

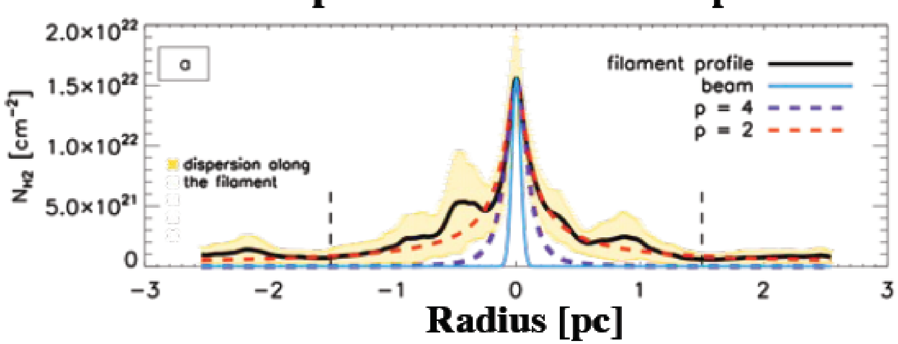


D. Arzoumanian et al. 2011, A&A, 529, L6

Statistical distribution of widths for 150 filaments



Example of a filament radial profile



Using the 'skeleton' or DisPerSE algorithm (Sousbie 2011) to trace the ridge of each filament

Open Questions

1) Why Filament Width ~ **0.1pc**? ➔ SF Threshold for N

2) Why Upper Limit for Core Formation Efficiency?

   $M_{\rm core} / M_{\rm filament} < 15\%$ ➔ $t_{\rm dense\ gas} \sim 20$ Myr

3) $t_{\rm SF} \sim 10$Myr? & Why? ➔ $t_{\rm gas} \sim 1.4$ Gyr

4) Core Mass Function for Massive Cores?

(ex., Motte+2018…)

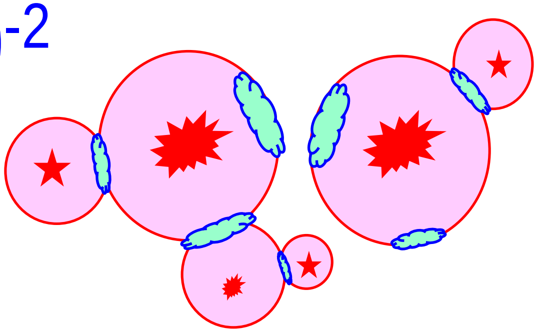
5) …

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 $= 1 + T_{\text{form}}/T_{\text{dis}} \sim 1.7$

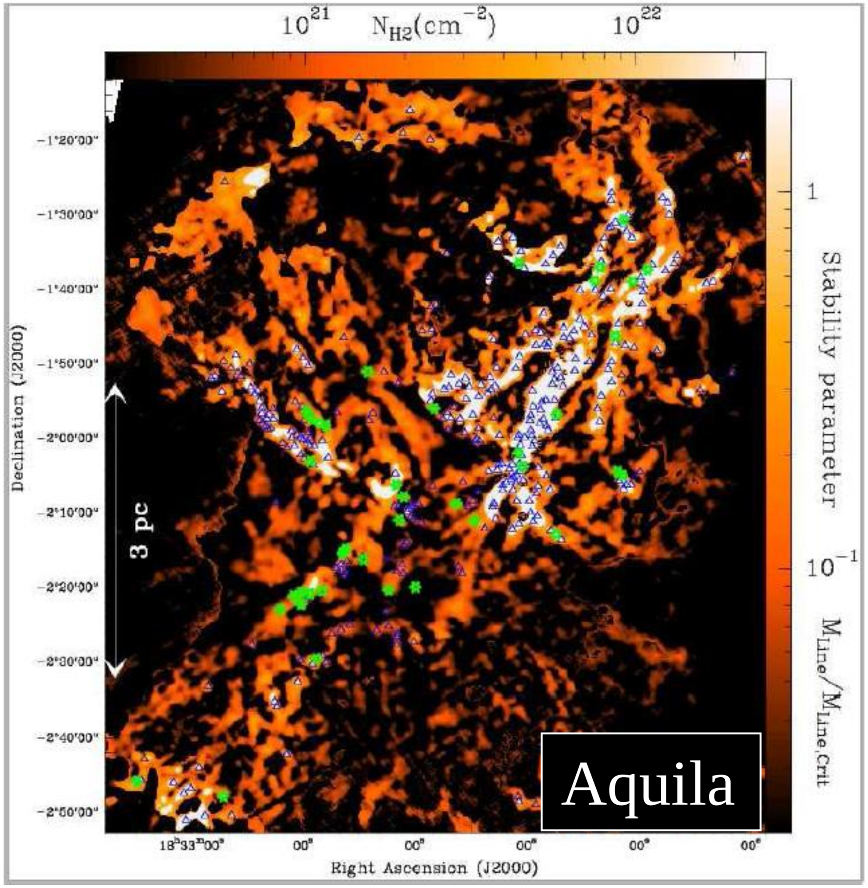


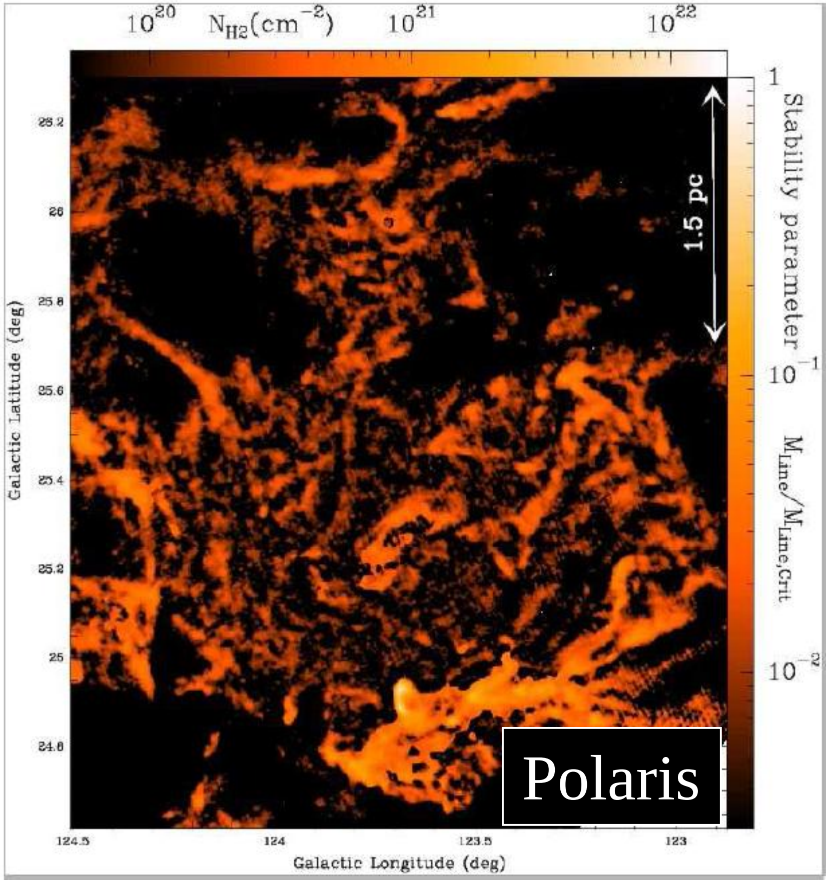
SI, Inoue, Iwasaki, & Hosokawa 2015, A&A **580**, A49

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

Kobayashi, Kobayashi, & SI 2018, PASJ in press

Which is determinant, N_H or Filament-Width?





<u>Herschel filaments have almost the same radii!</u>

Aquila: <u>2R=0.1pc</u> & $\boldsymbol{M}_L = 2C_s^2/G$ ➔ $N_H \approx 10^{22}\mathrm{cm}^{-2}$ (A_v= several)

Polaris: <u>2R=0.1pc</u> & $\boldsymbol{M}_L < 2C_s^2/G$ ➔ $N_H < 10^{22}\mathrm{cm}^{-2}$ (A_v< several)

"Column Density Threshold" is a consequence?