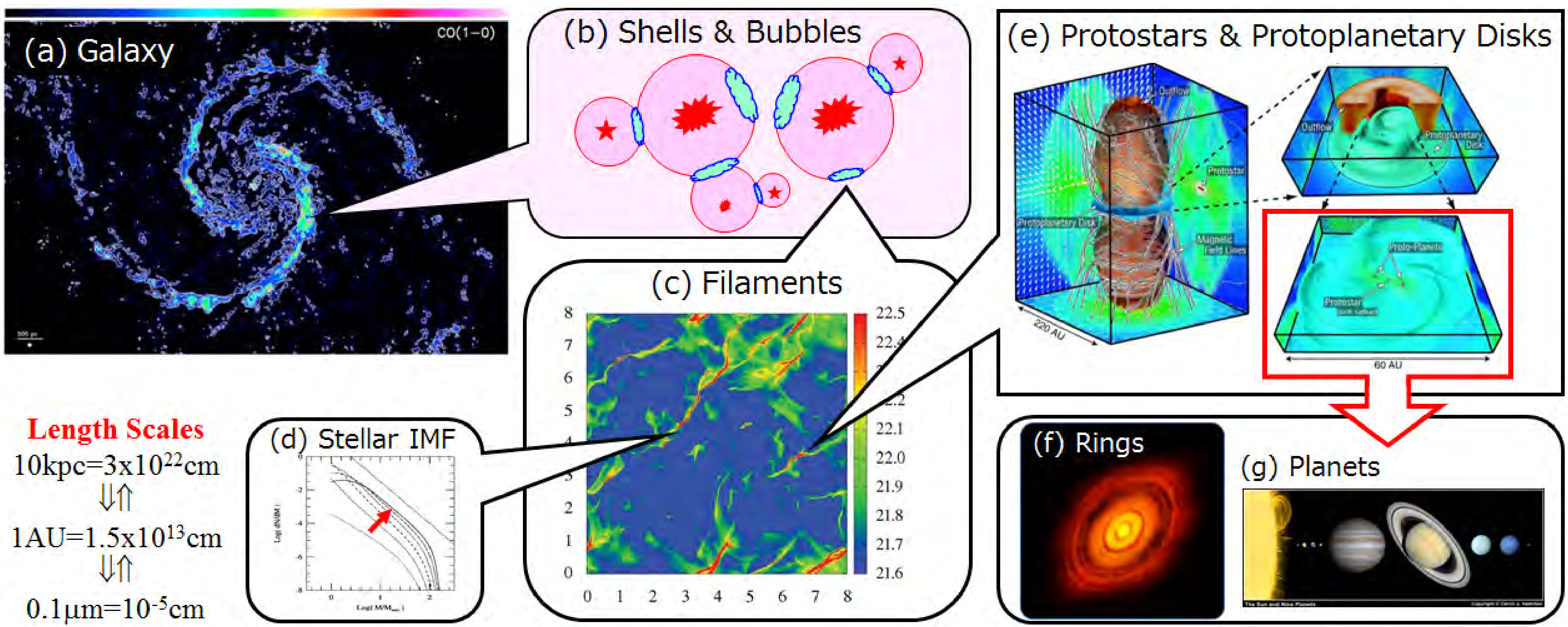
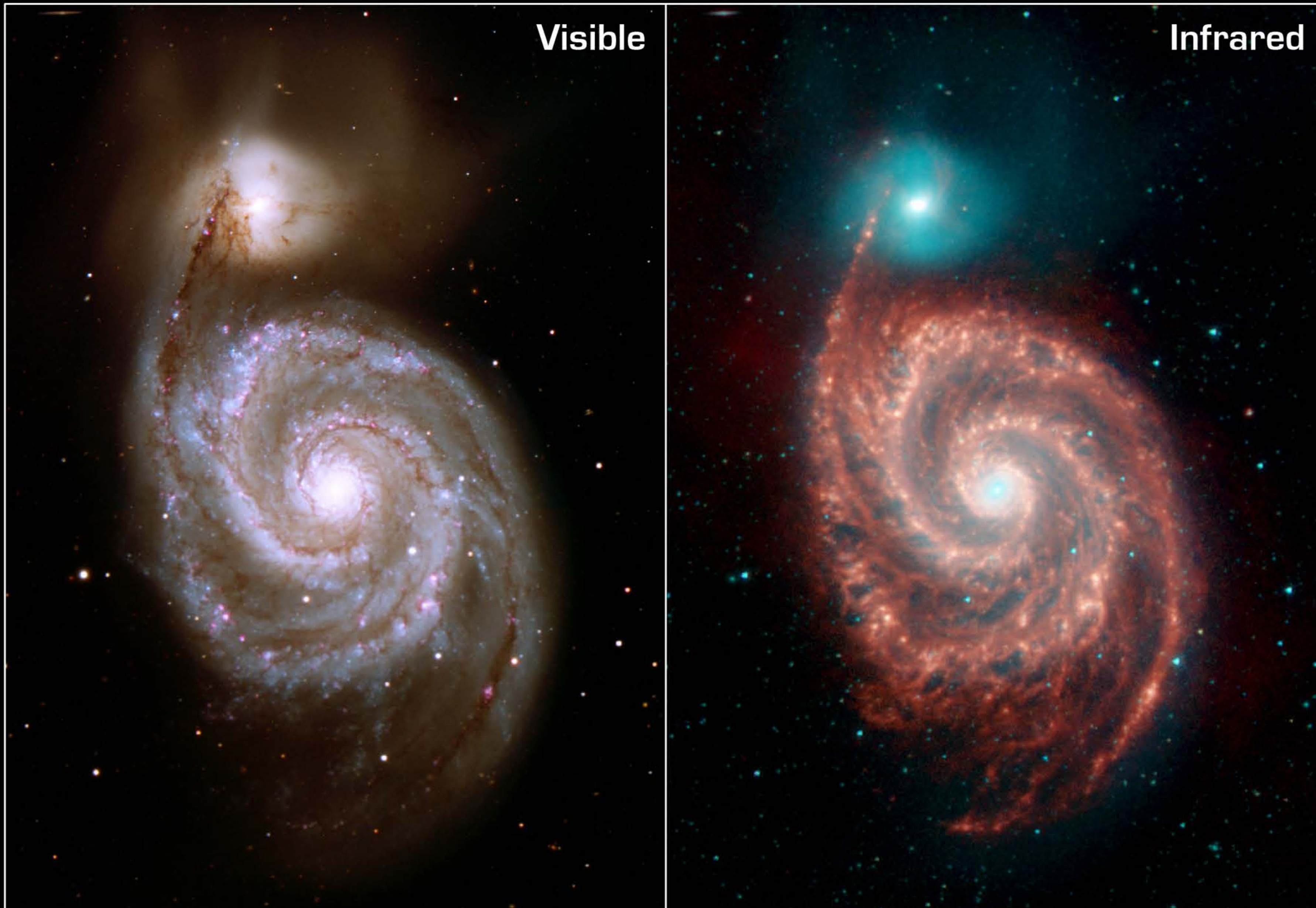
Magnetically Controlled Star Formation in the Galactic Disk

Shu-ichiro Inutsuka (Nagoya University)



Length Scales
10kpc=3x10^{22}cm
⇓⇑
1AU=1.5x10^{13}cm
⇓⇑
0.1μm=10^{-5}cm



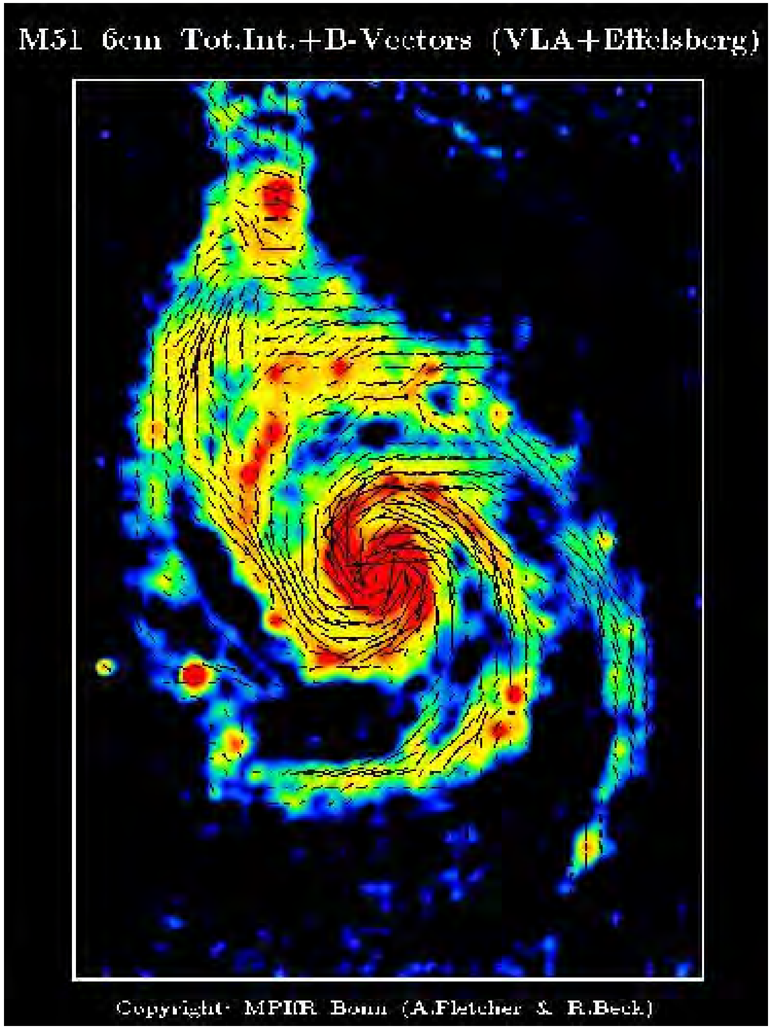
Spiral Galaxy M51 (“Whirlpool Galaxy”)

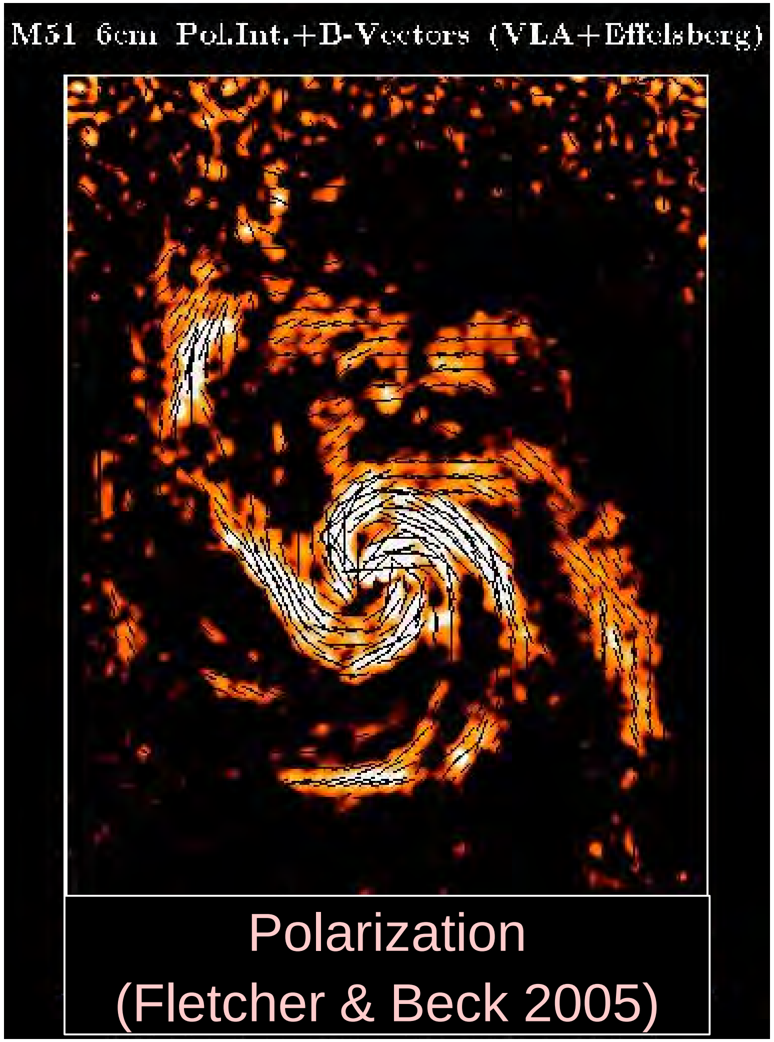
Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / R. Kennicutt (Univ. of Arizona)

ssc2004-19a

M51 Synchrotron

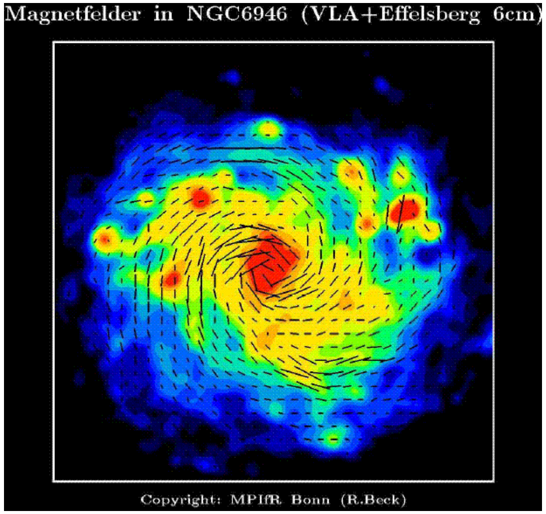


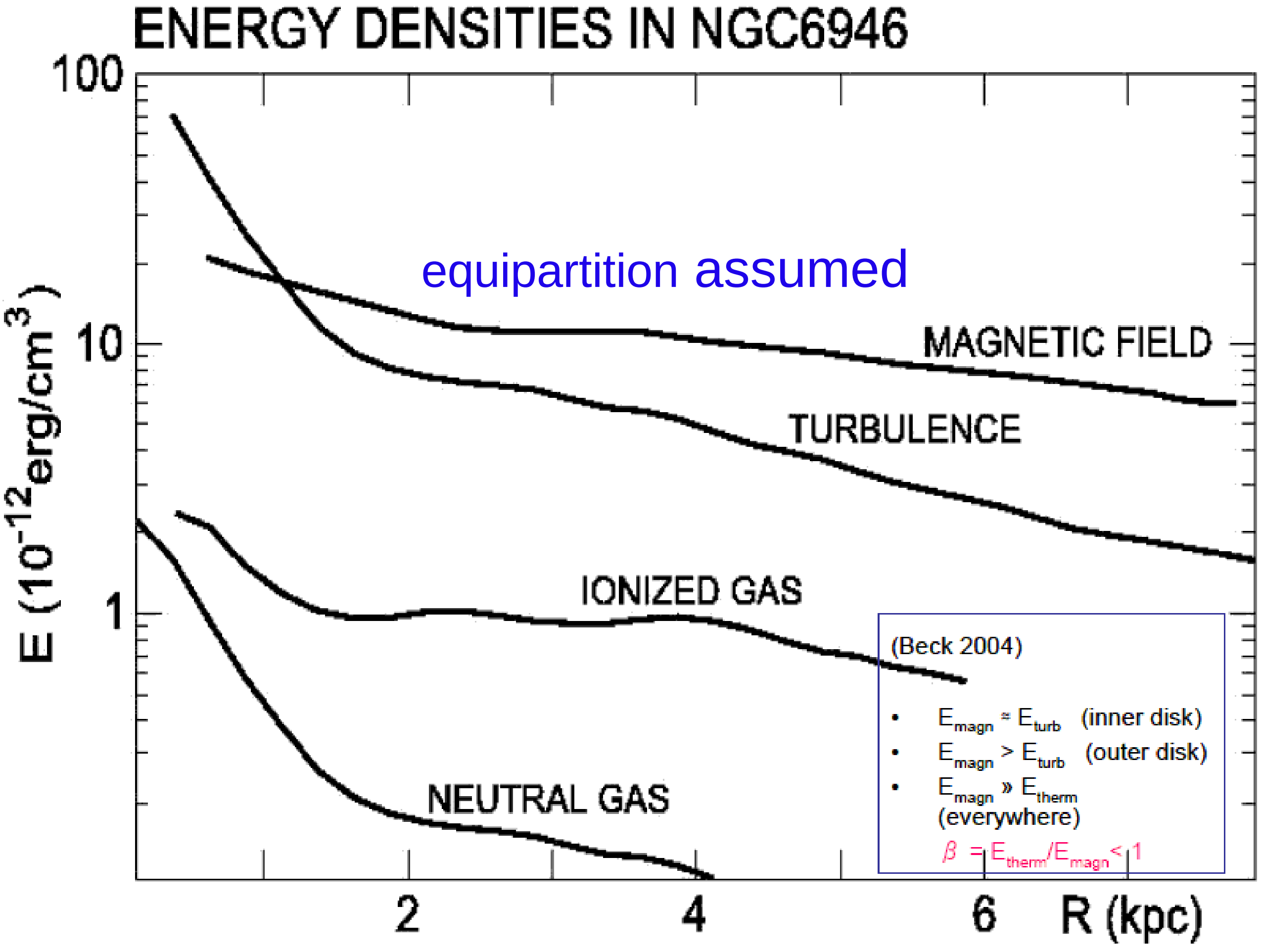


Various Energy Densities

NGC6946

Beck 2004





Star Formation is Inefficient!

- Typical Density observed by CO: $n_{\mathrm{CO}} \sim 10^2\,/\mathrm{cm}^3$
- Mass of Molecular Clouds (~10K): $M_{\mathrm{MC}} \sim 10^9\,M_\odot$
- Free-Fall Time for $10^2\,/\mathrm{cm}^3 \sim 10^6\,\mathrm{yr}$
- Star Formation Rate (if at Free-Fall Rate)

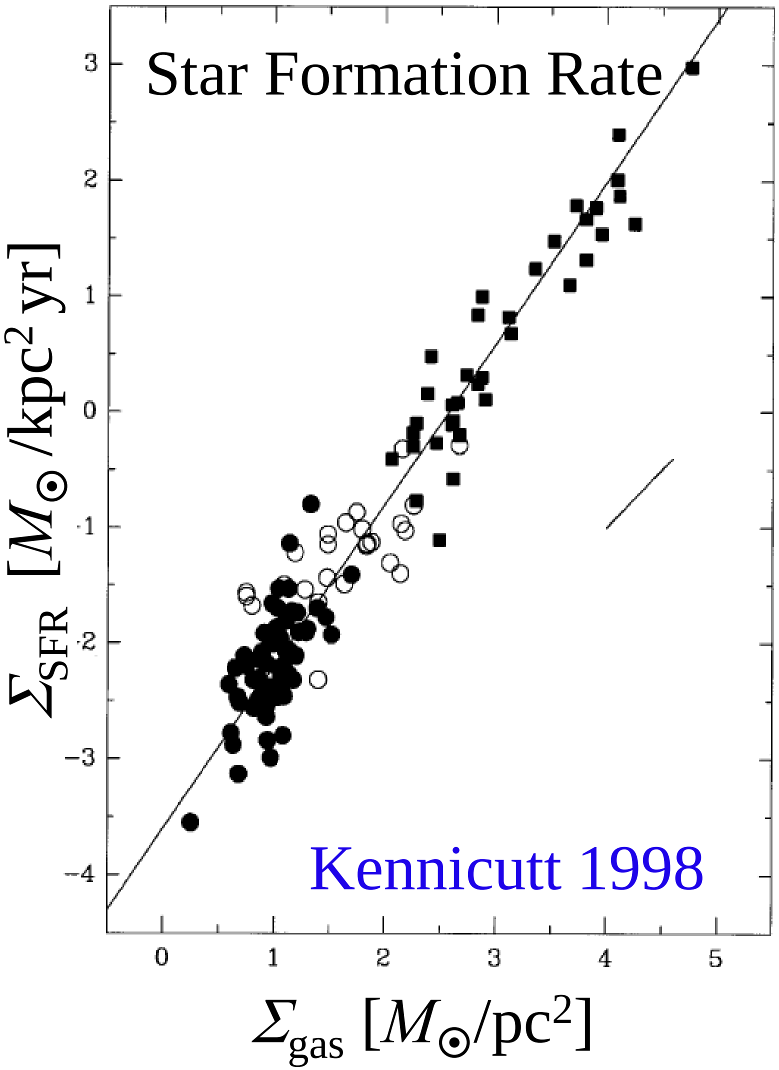
$$R_{\mathrm{SF}} = 10^9\,M_\odot/10^6\mathrm{yr} = 10^3\,M_\odot/\mathrm{yr}$$

Wrong!

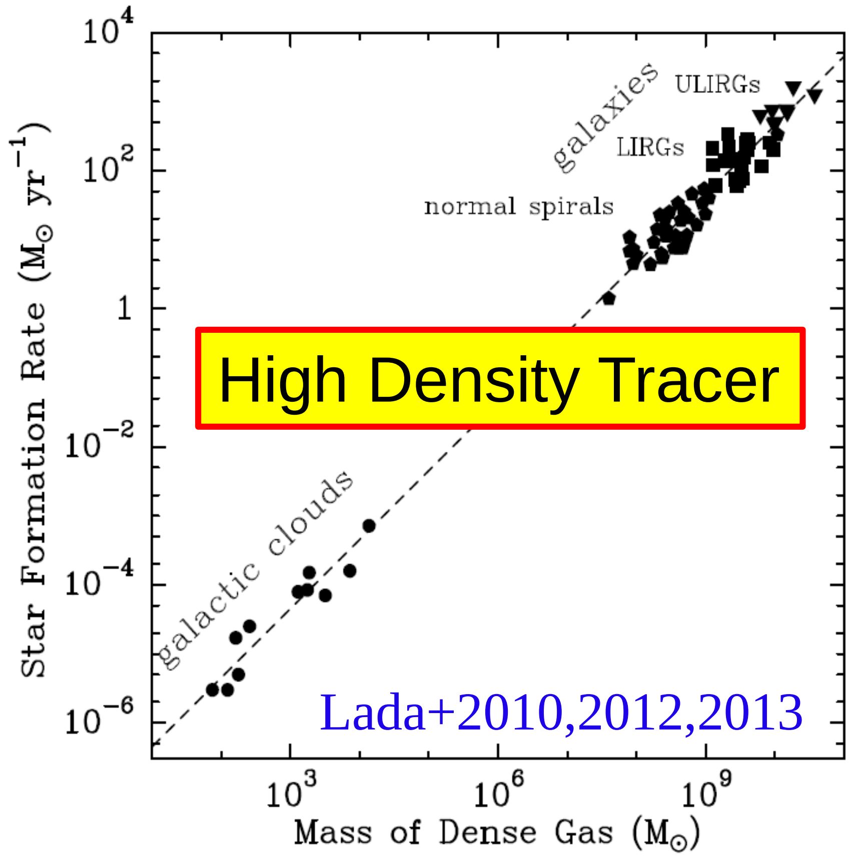
Observed Star Formation Rate ~ $10^0\,M_\odot/\mathrm{yr}$

➔ Either Slow or Very inefficient (~10^{-3})!

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…

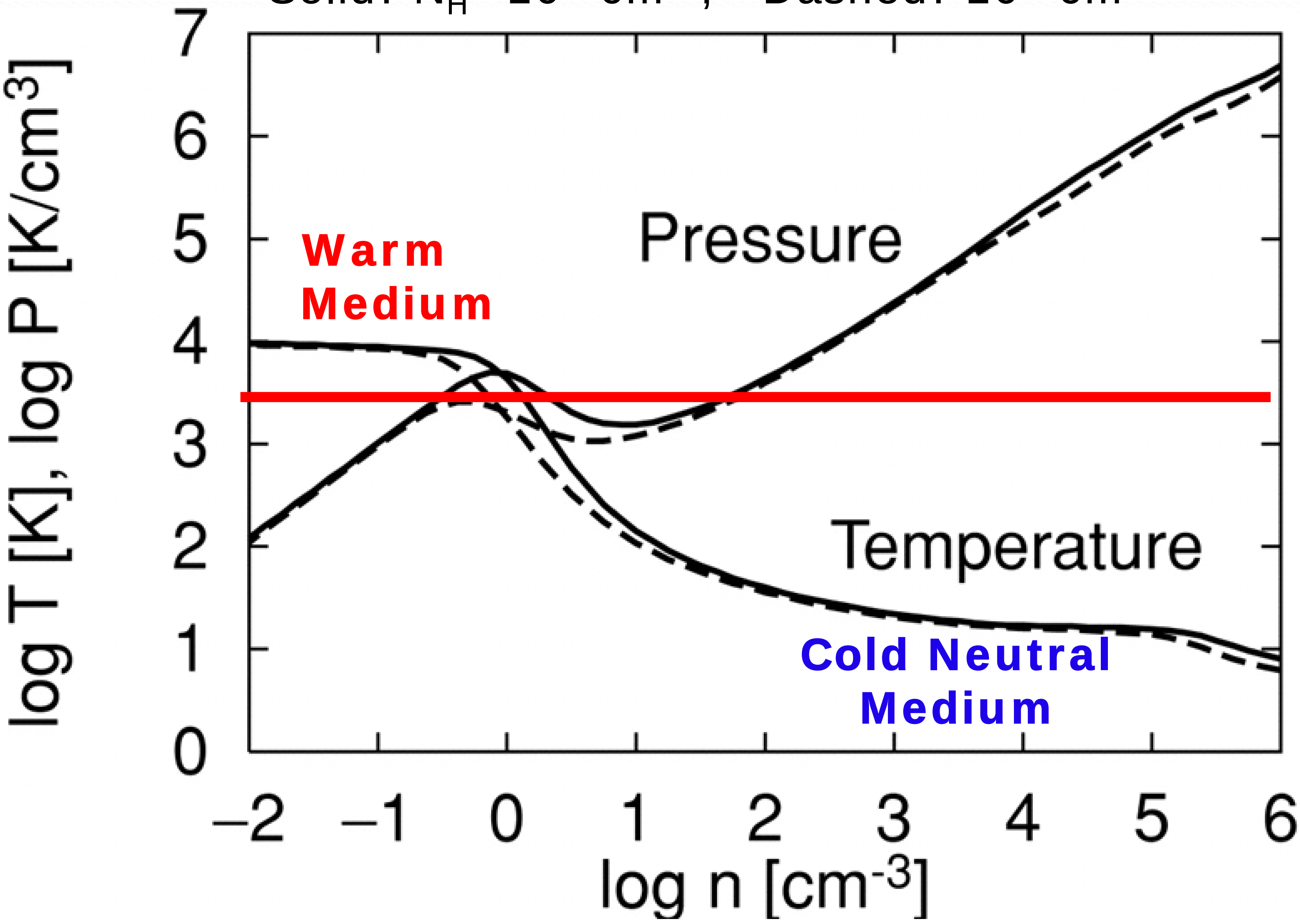
Outline

- 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~~
- Possible Mission of BISTRO

Formation of Molecular Clouds

Radiative Equilibrium for a given density

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

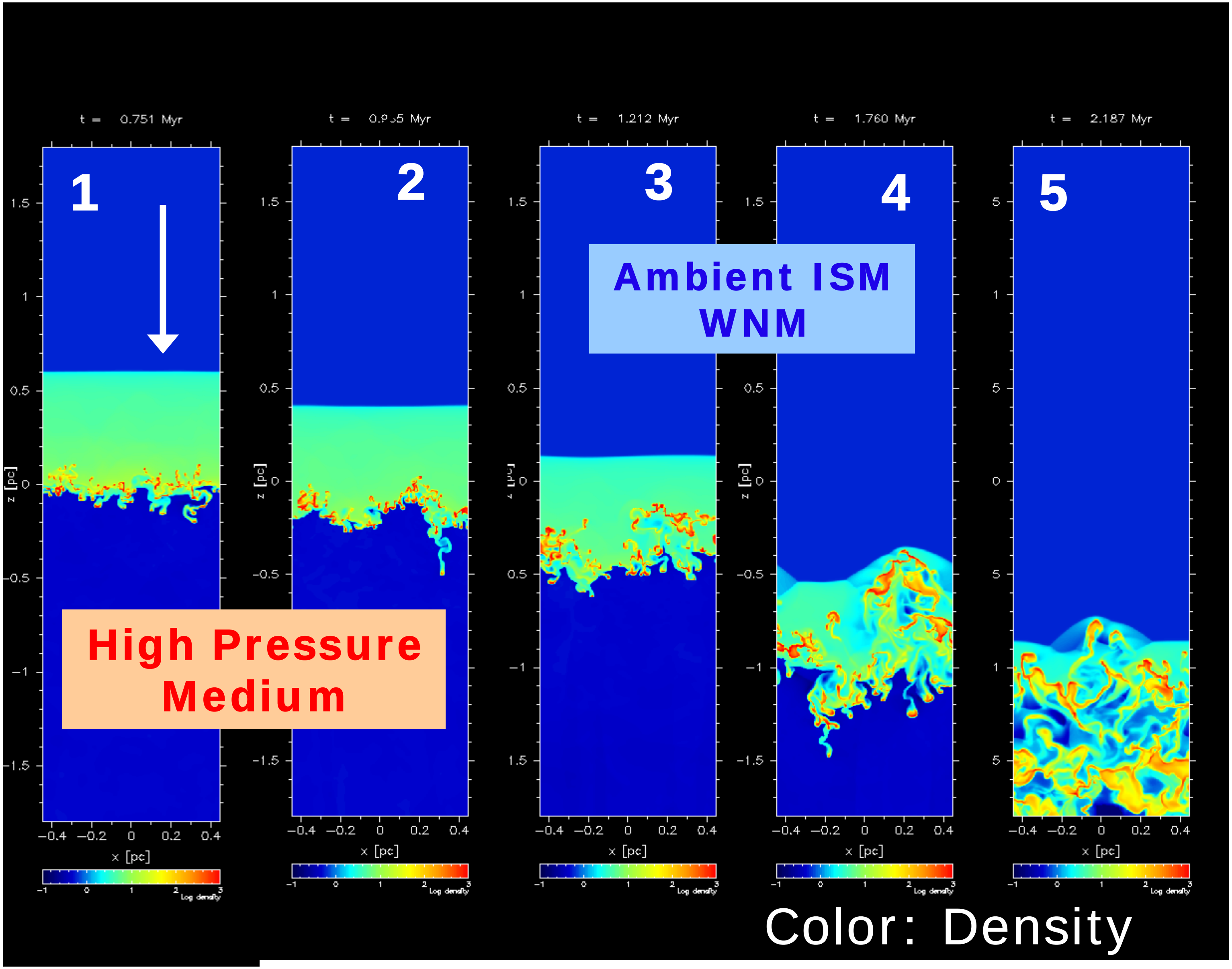


e.g., Wolfire et al. 1995, Koyama & SI 2000

20km/s Shock Propagation into WNM

No forcing! Koyama & SI (2002) ApJ 564, L97

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

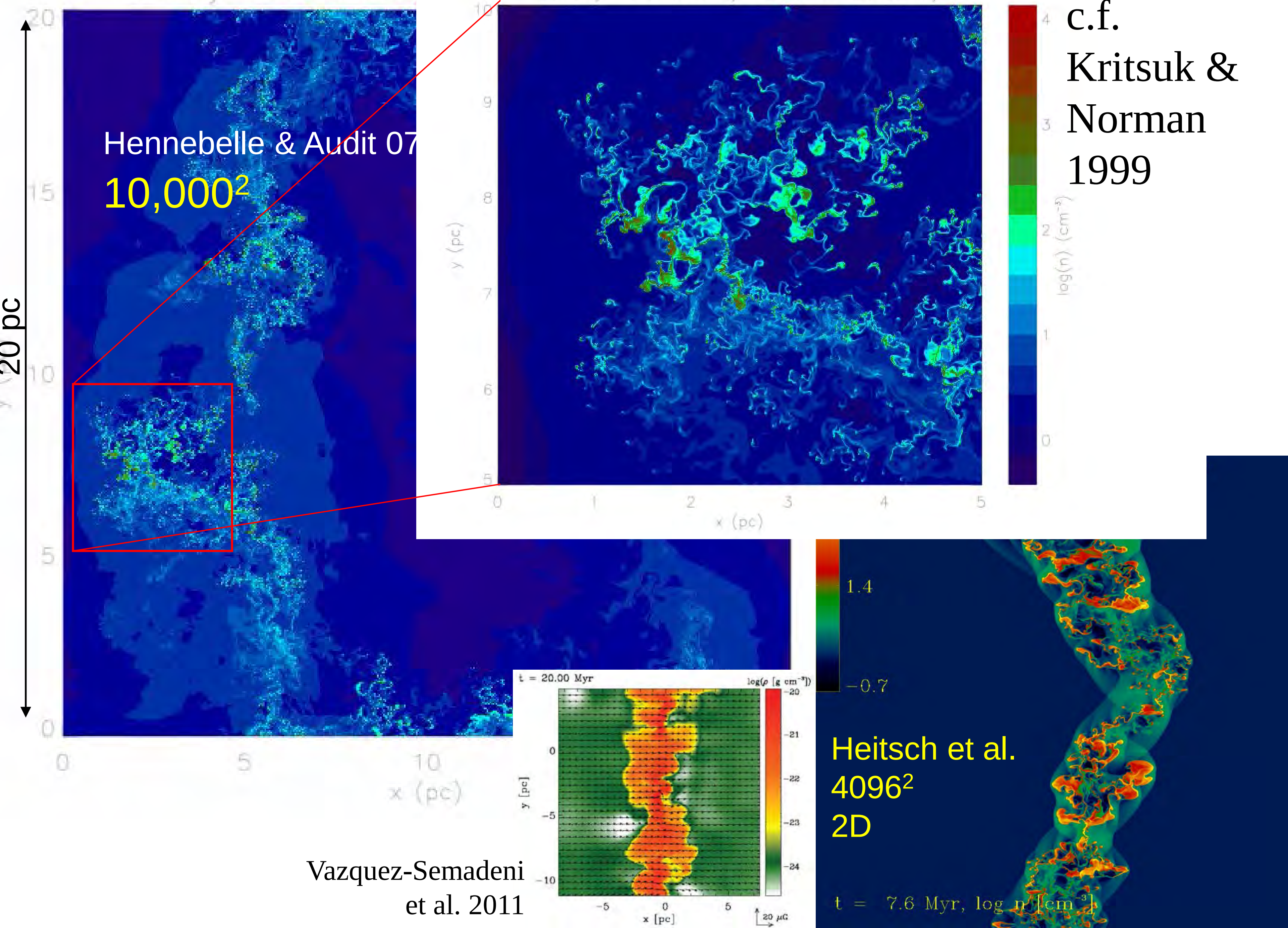
δv ~ a few km/s < $C_{S,WNM}$ =10km/s

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

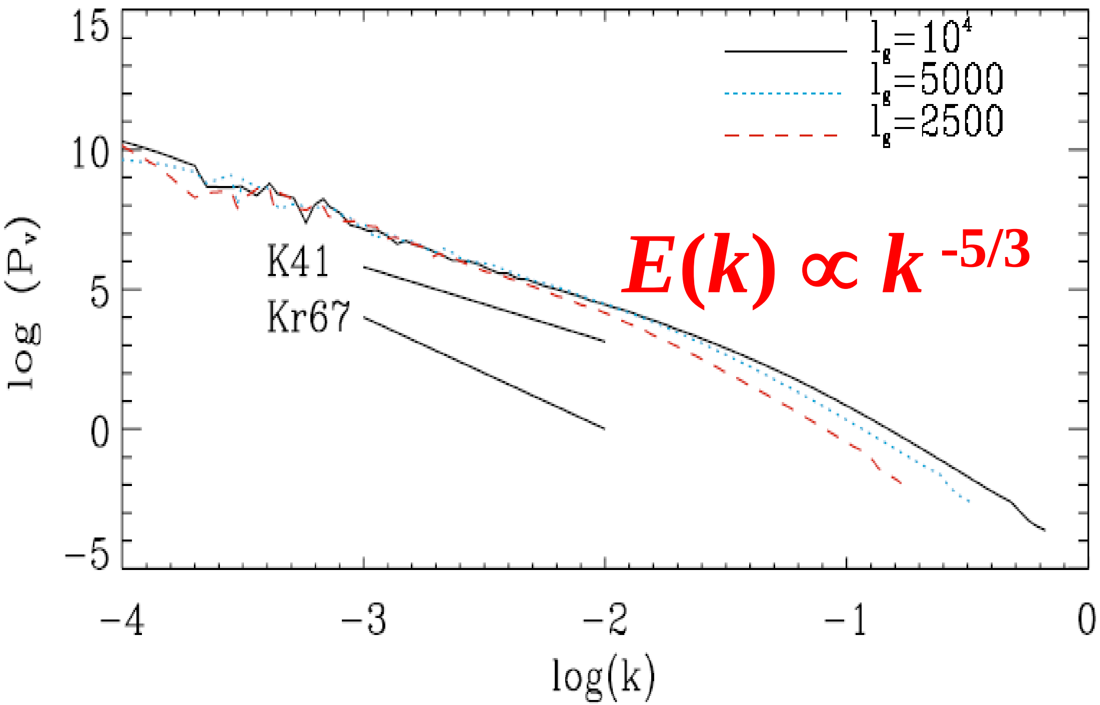
T_{CNM} ~10^2K ⬅ C^+158μm (~92K)

Koyama & SI (2002) ApJ 564, L97

xels


density and velocity fields, t= 26.82 My
20 pc
Hennebelle & Audit 07
10,000^2
x (pc)
y (pc)
log(n) (cm^{-3})
c.f. Kritsuk & Norman 1999
t = 20.00 Myr
log(ρ [g cm^{-3}])
x [pc]
y [pc]
20 μG
Vazquez-Semadeni et al. 2011
Heitsch et al.
4096^2
2D
t = 7.6 Myr, log n [cm^{-3}]

Property of “Turbulence”…Subsonic



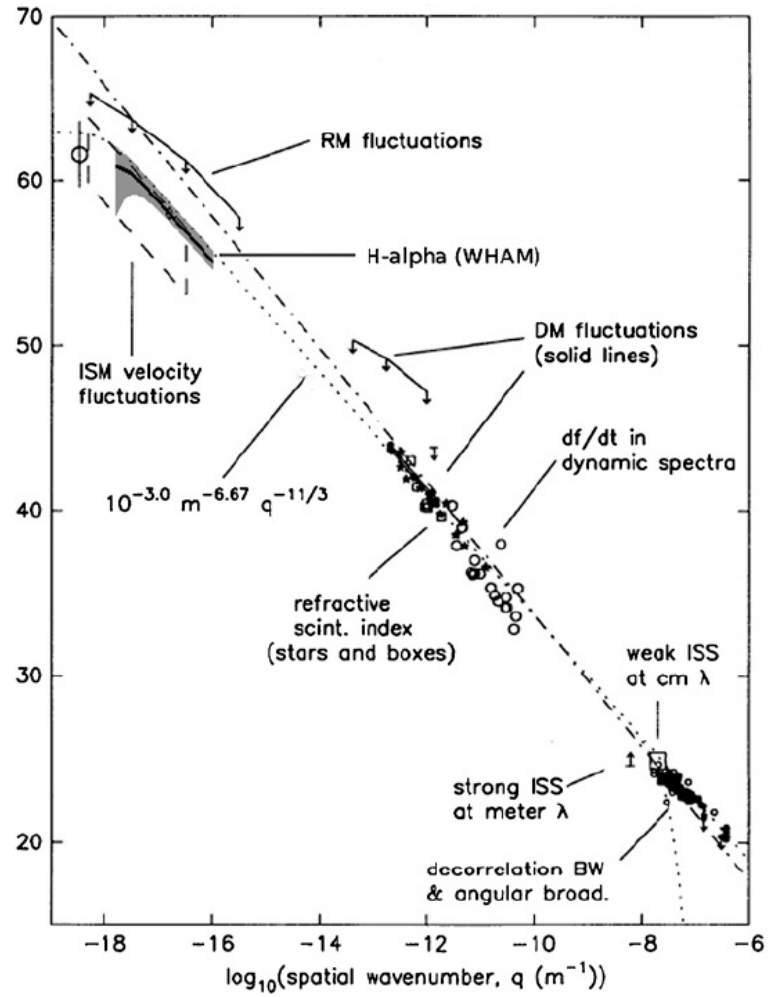
$E(k) \propto k^{-5/3}$

$\delta v < C_{S,WNM}$ ➔

Kolmogorov Spectrum

2D: Hennebelle & Audit 2007;

See, e.g., Gazol & Kim 2010

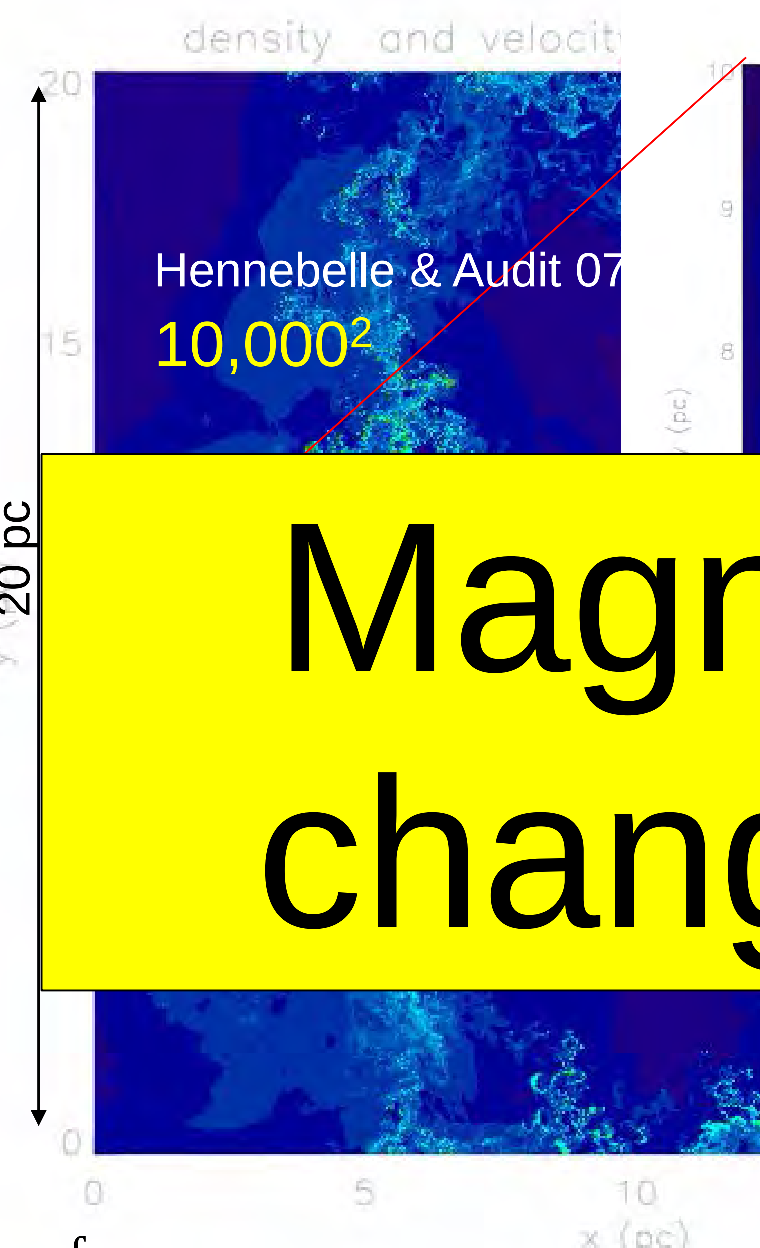


Spectrum Observed in ISM

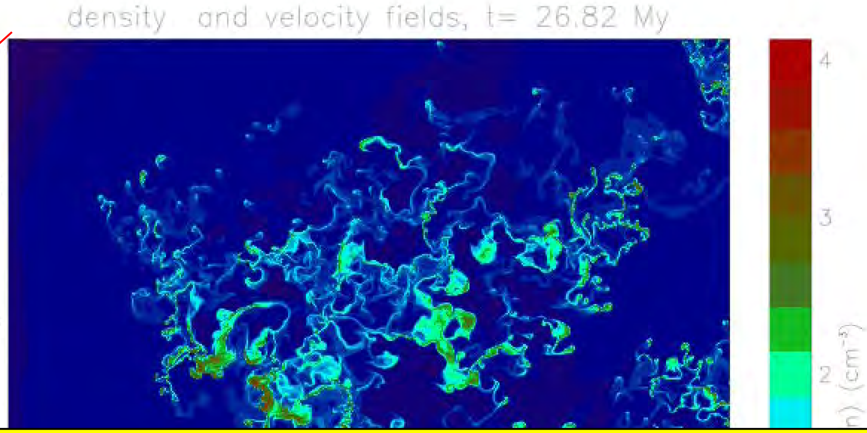
Chepurnov & Lazarian 2010

Armstrong et al. 1995

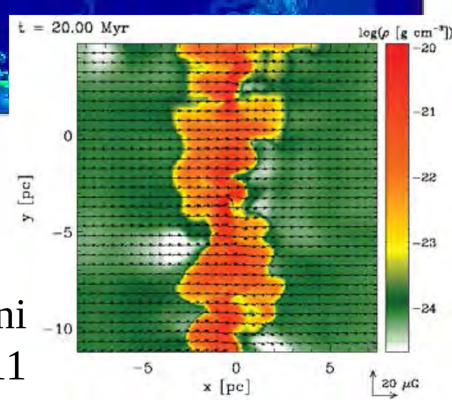
Magnetic Field changes Story!



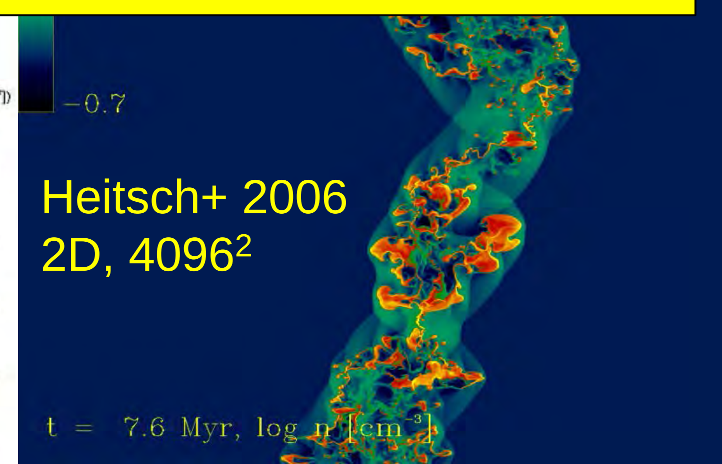
Hennebelle & Audit 07
10,000^2



c.f.
Kritsuk & Norman 1999



Vazquez-Semadeni et al. 2011



Heitsch+ 2006
2D, 4096^2

Colliding WNM with B_0=3μG

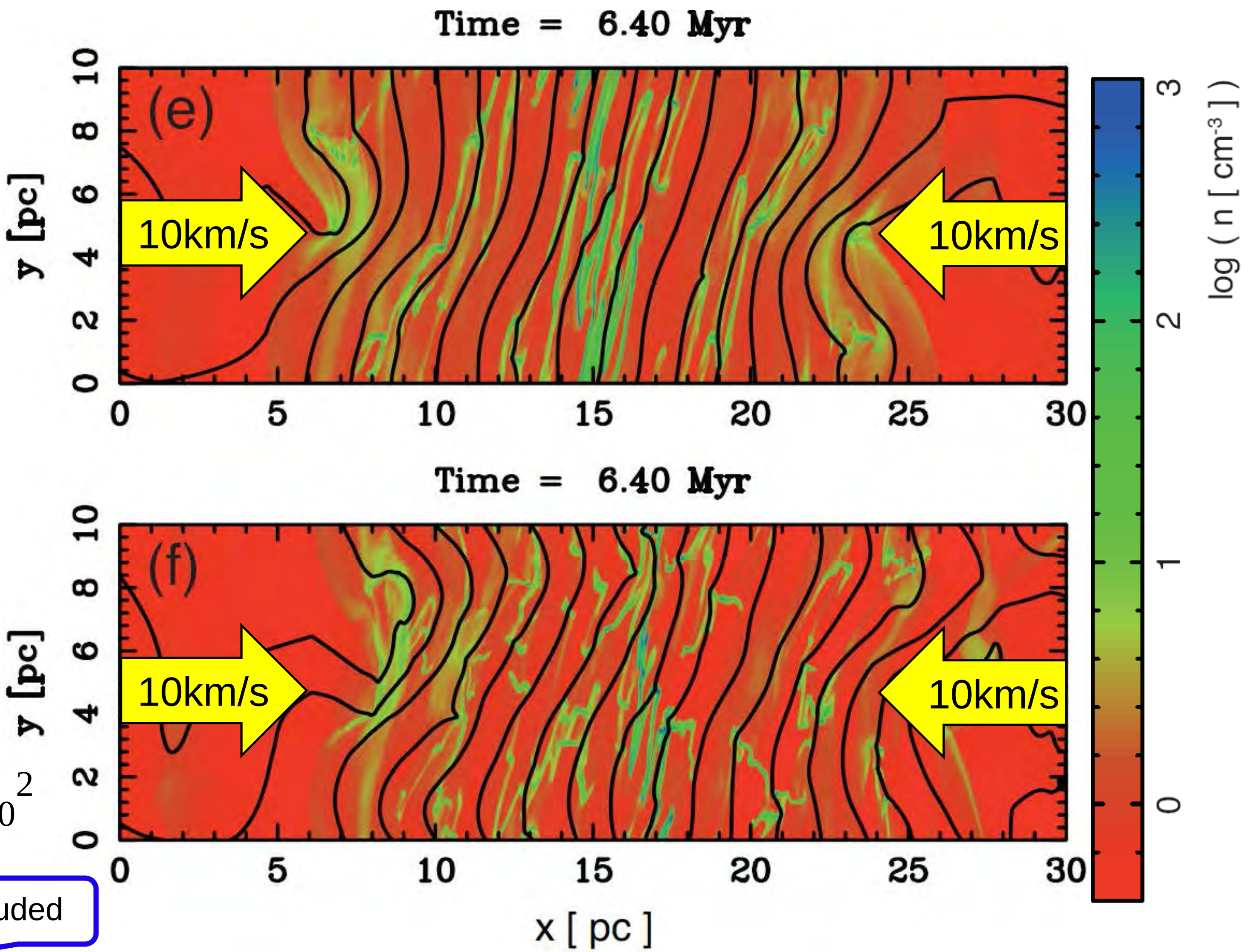
v=10km/s

(a) 15deg

$<\delta B^2>_{init} = B_0^2$

(a) 40 deg

$<\delta B^2>_{init} = 4B_0^2$



Ambipolar Diffusion Included

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

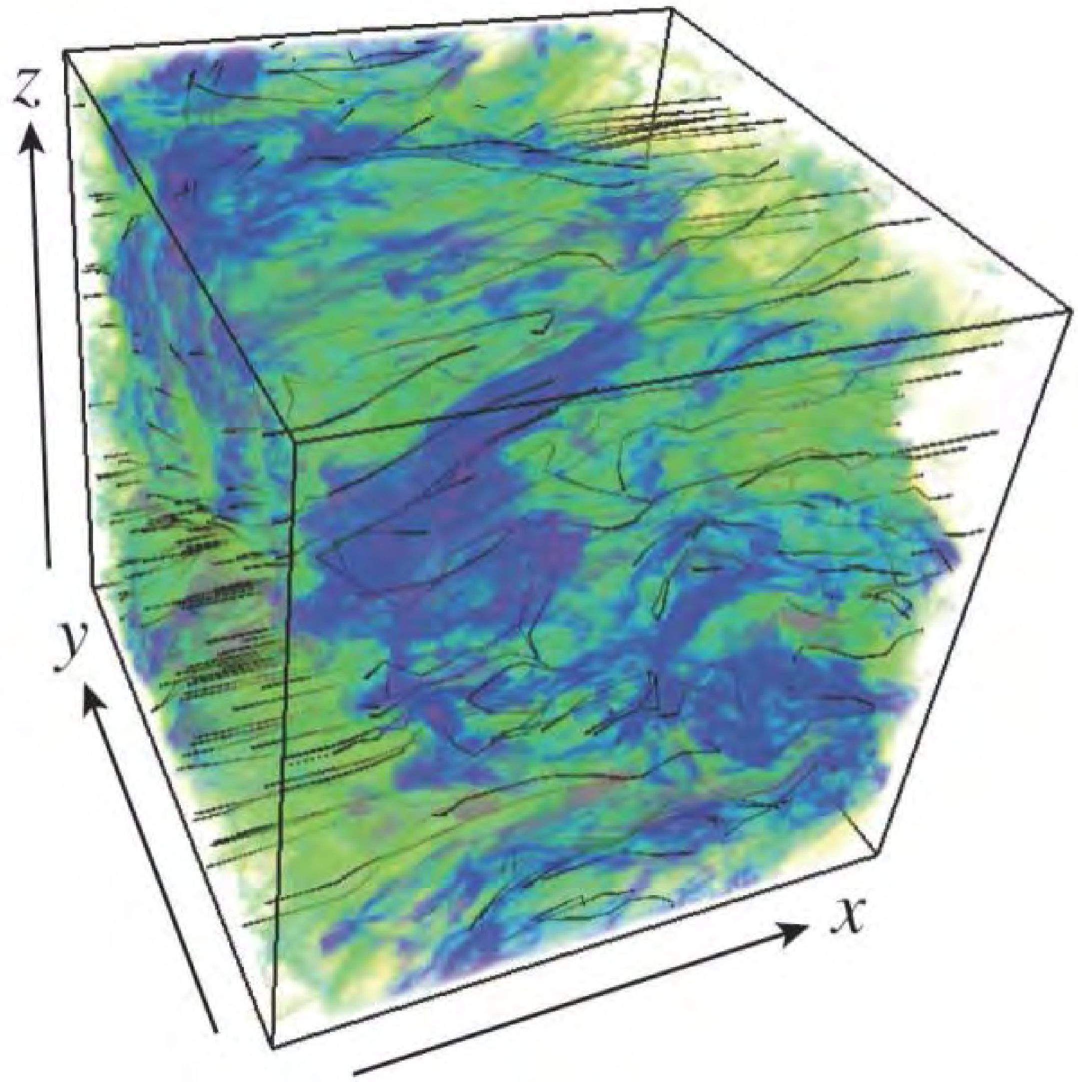
We need multiple episodes of compression.

Compression of CNM (HI) ➔ H_2

Compression <u>along Magnetic Field</u> lines, + H_2,CO

➔

Formation of Magnetized Molecular Clouds



Transformation of HI to H_2

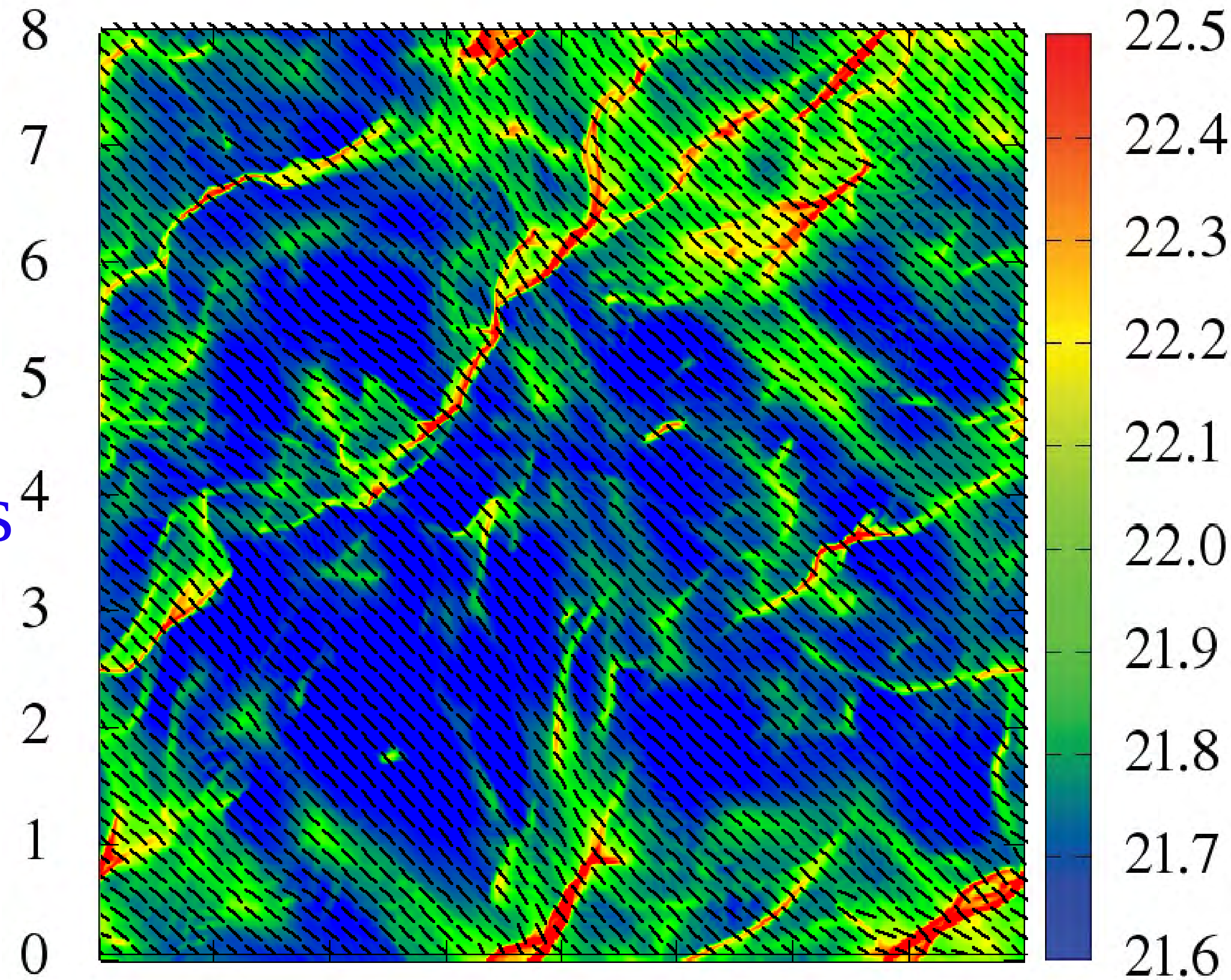
Inoue & SI (2012) **759**, 35

Further Compress. of Mole. Clouds

Multiple Compressions of Molecular Cloud

➔Magnetized Massive Filaments & Striations

Agree with Observations!

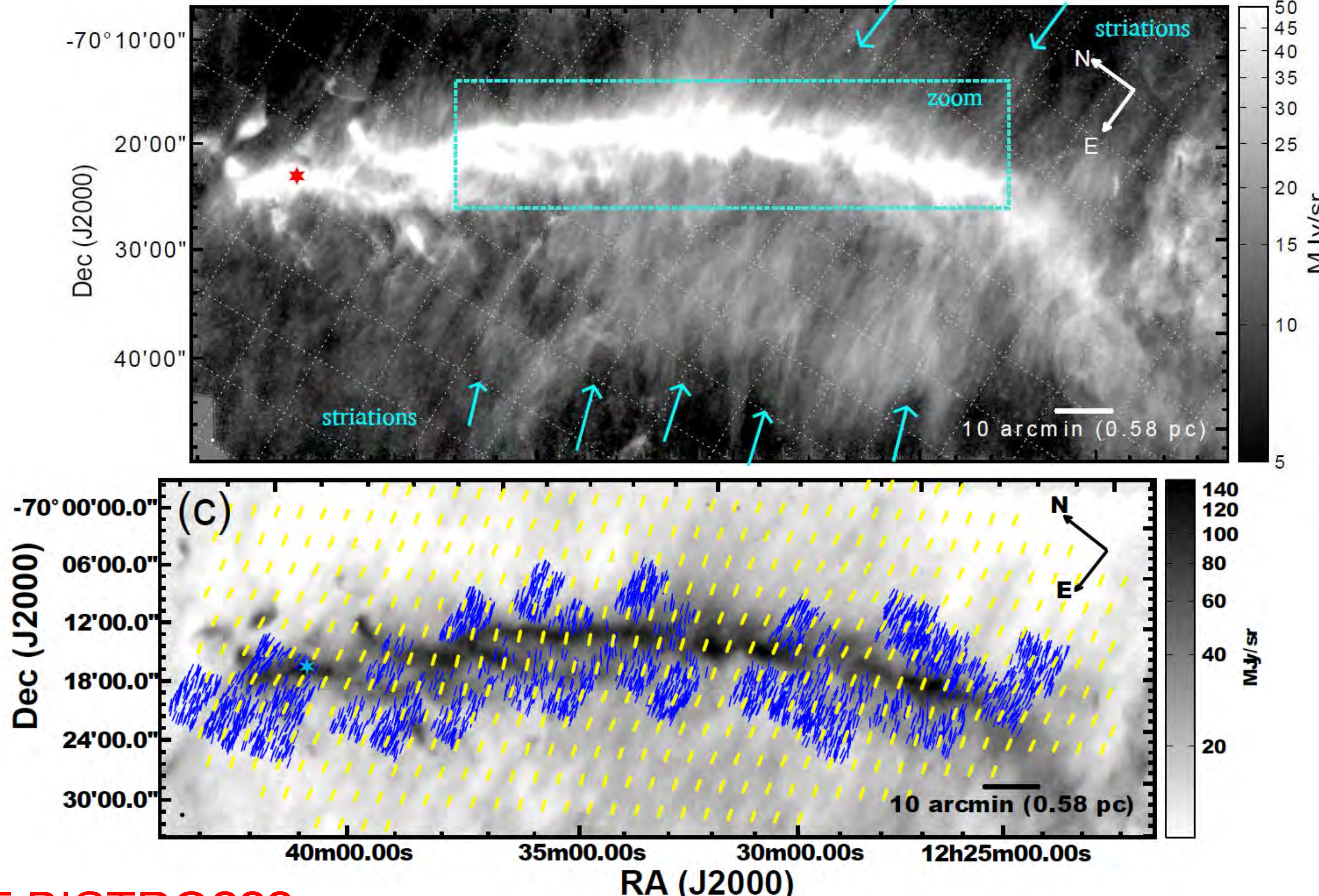


Black Lines: Magnetic Field Lines

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

Observed Molecular Clouds

Cox, Arzoumanian, André+2016



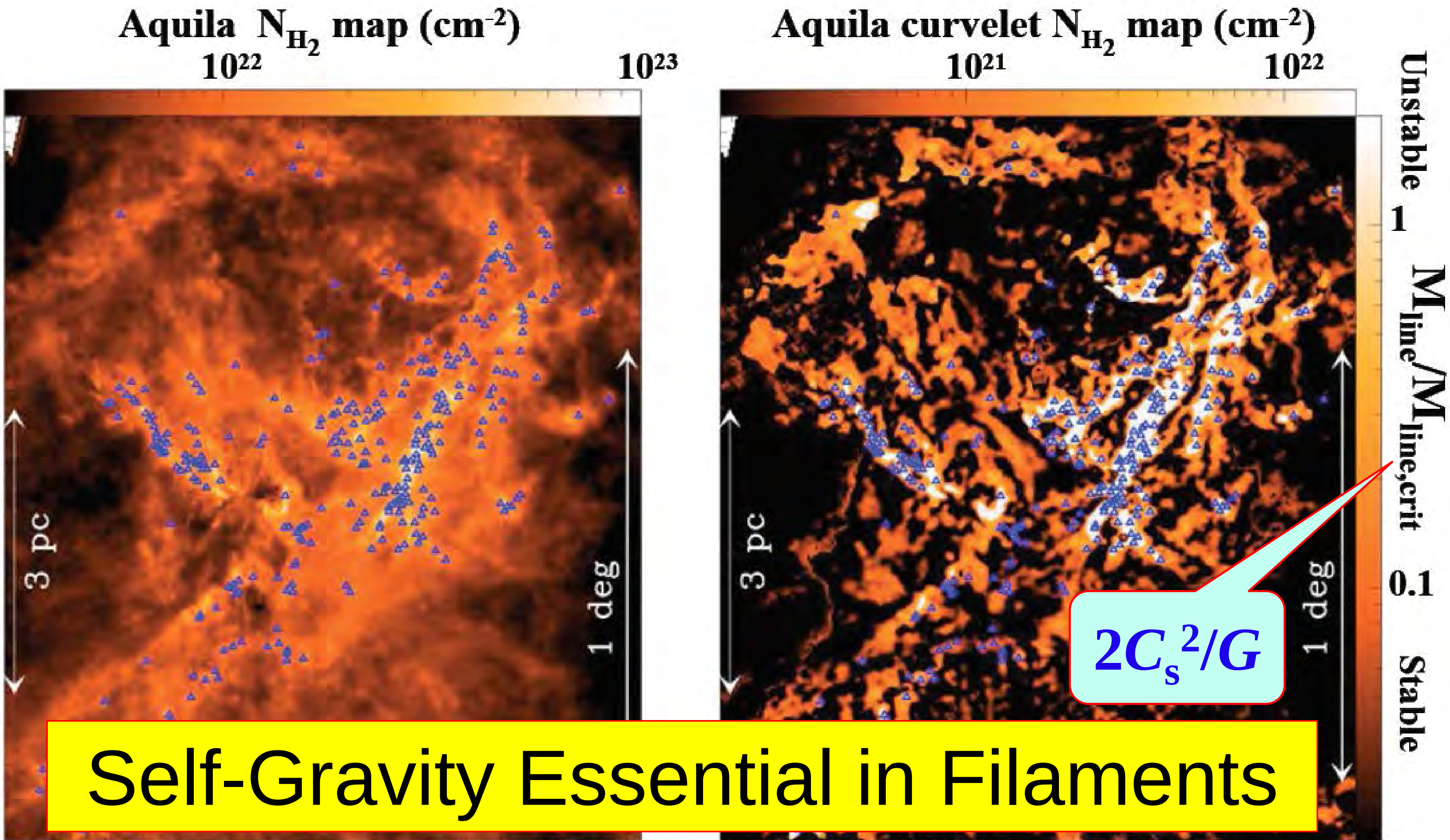
JCMT-BISTRO???

Yellow and Blue Lines: Magnetic Field Lines

Highlight of Herschel Result (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

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

Dynamical Timescales of Star Formation

Observational Demography of YSOs (e.g., Fuller&Myers1985)

- $N_{\rm TTauri} / N_{\rm protostar} \sim 10^{1.5\text{-}2}$ ➔ $T_{\rm protostar} \sim 10^5$ yr
- # of Dense Cores: $N_{\rm +IR} / N_{\rm noIR} \sim 10^1$ ➔ $T_{\rm core} \sim 10^6$ yr

c.f. $T_{\rm ambipolar} \sim 10^7$ yr & $T_{\rm freefall} \sim 10^5$ yr for $n=10^4$/cc

➔ Gravitational collapse of a core is not quasi-steady!

➔ Dynamical Gravitational Collapse in Dense Cores!

⇕

Dynamical Evolution in Self-Gravitating Filament with

$M_{\rm line} \sim 2C_s^2/G$

Star Formation Efficiency

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

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

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

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

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

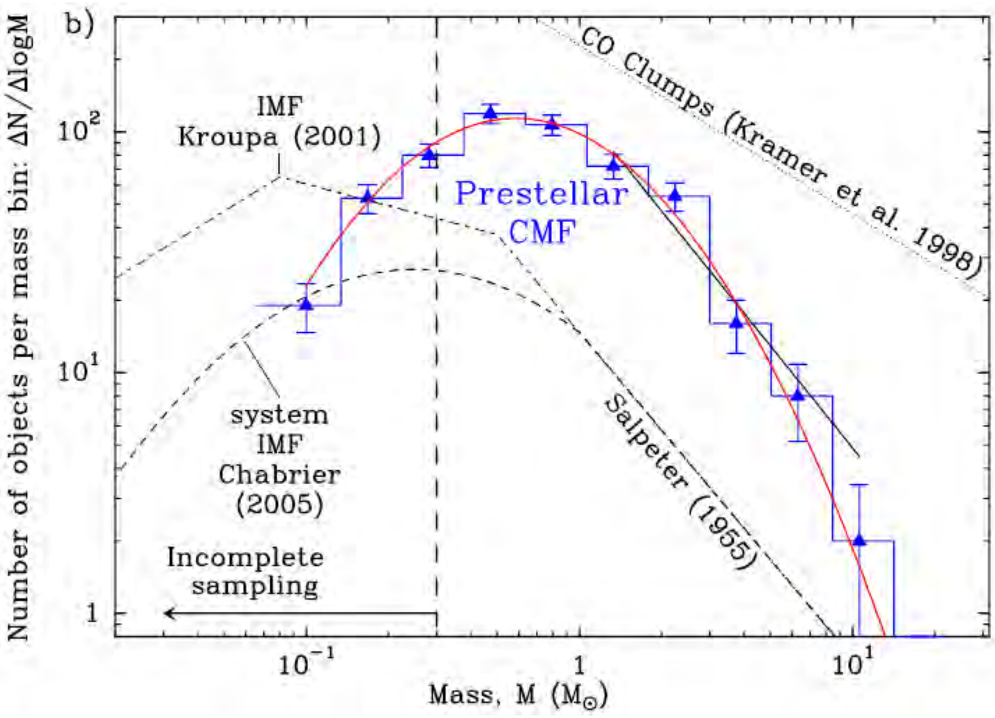
Star Formation Efficiency of Dense Gas: $\varepsilon_{\rm dense\ gas}$

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

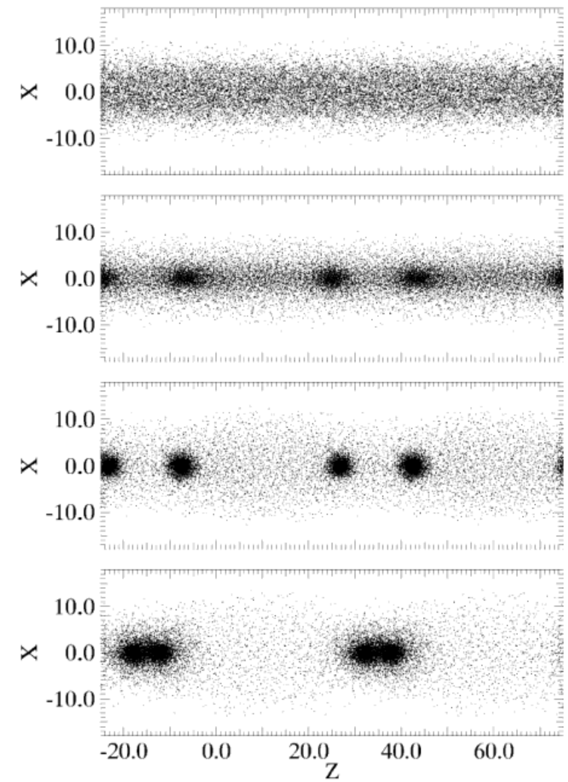
$$\Rightarrow \ t_{\rm dense\ gas} \sim 20{\rm Myr}$$

Mass Function of Dense Core?

Aquila CMF from Herschel



André+2010; Könyves+2010



SI & Miyama 1997

Larger Wavelength
→ Massive Core

Mass Function of Cores in a Filament

Inutsuka 2001, ApJ **559**, L149

Line-Mass Fluctuation of Filaments

Initial Power Spectrum

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

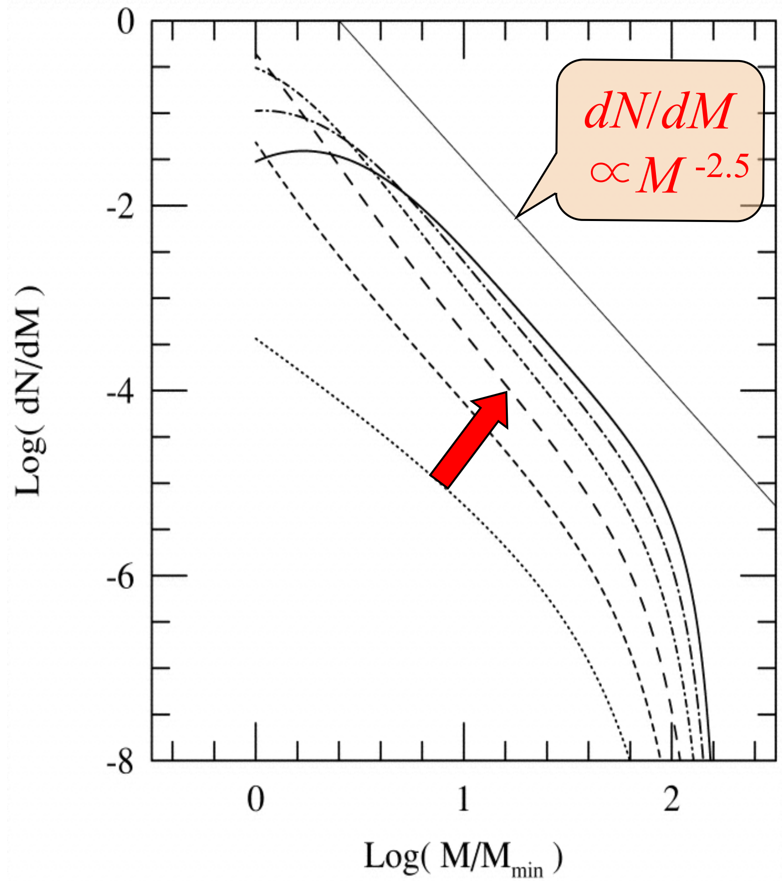
Mass Function

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

Observation of Both Perturbation Spectrum and Mass Function

➔direct test !

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



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

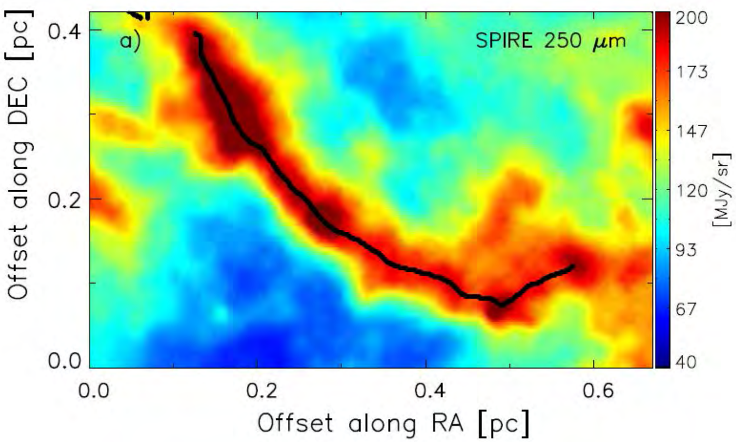
t/t_{ff} = 0 (dotted) , 2, 4, 6, 8, 10 (solid)

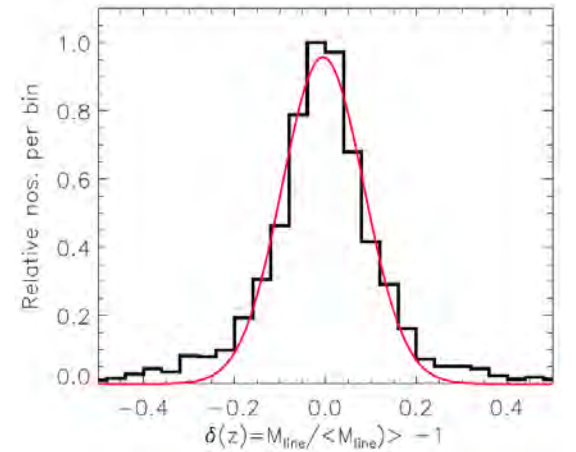
≈ 5/3: Kolmogorov!

Obs $P(k) \propto k^{-1.6}$ (*André*+2014 PPVI; *Roy*+2015)

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

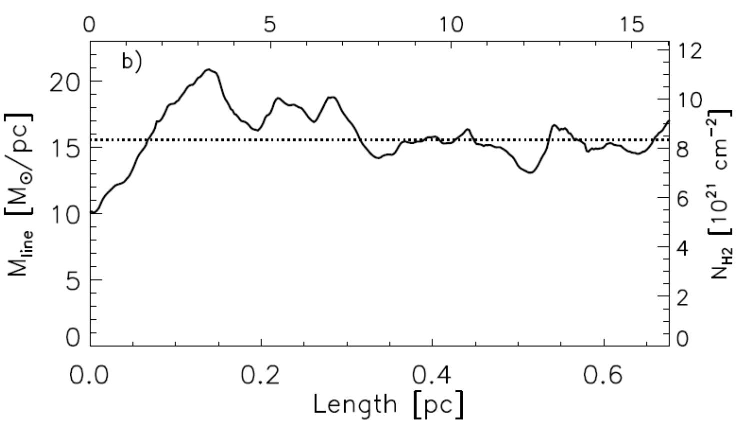
Roy, André, Arzoumanian et al. (2015) A&A **584**, A111





δ …

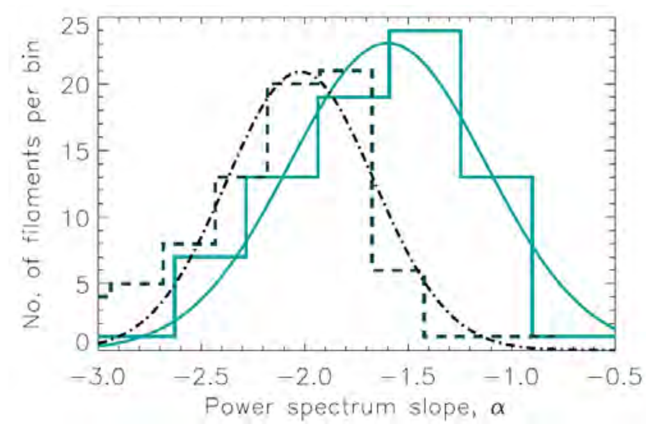
Gaussian



P **(*k*)**

$\propto k^{n}$

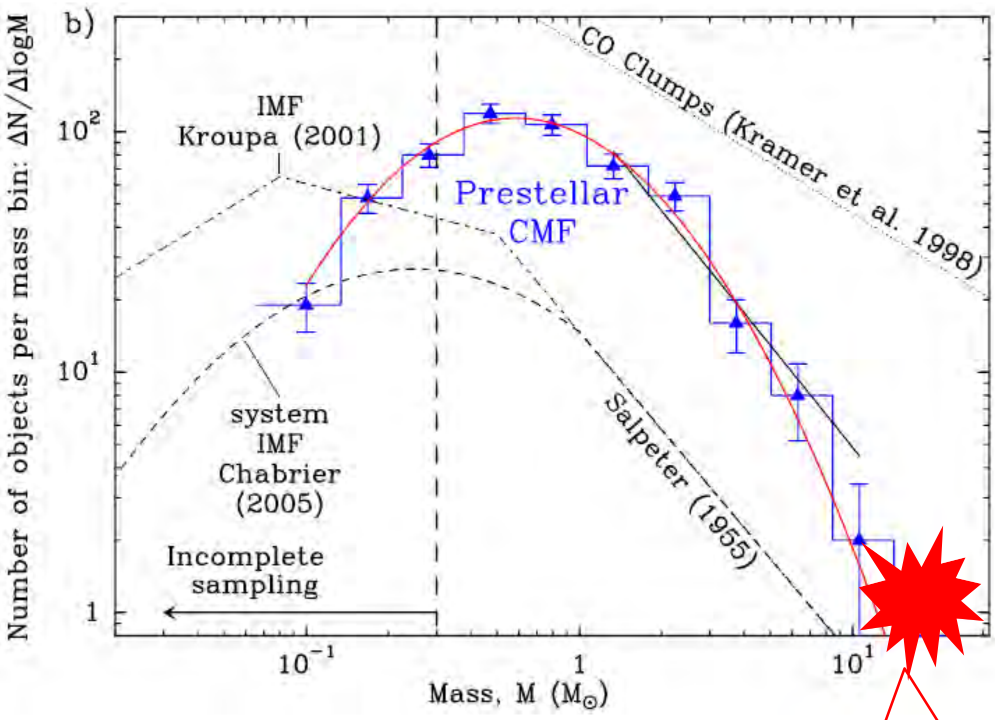
n= −1.6±0.3



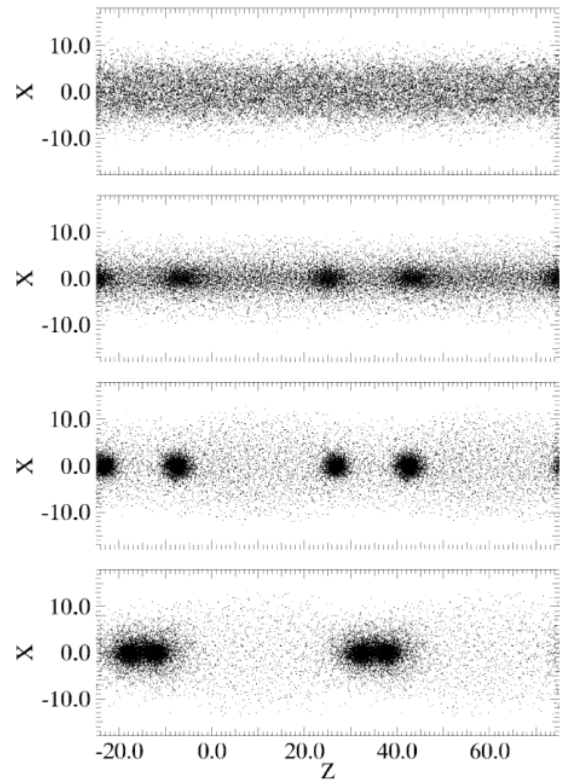
Supporting Inutsuka 2001

Applicability of Filament Paradigm for Massive Stars?

Aquila CMF from Herschel



André+2010; Könyves+2010

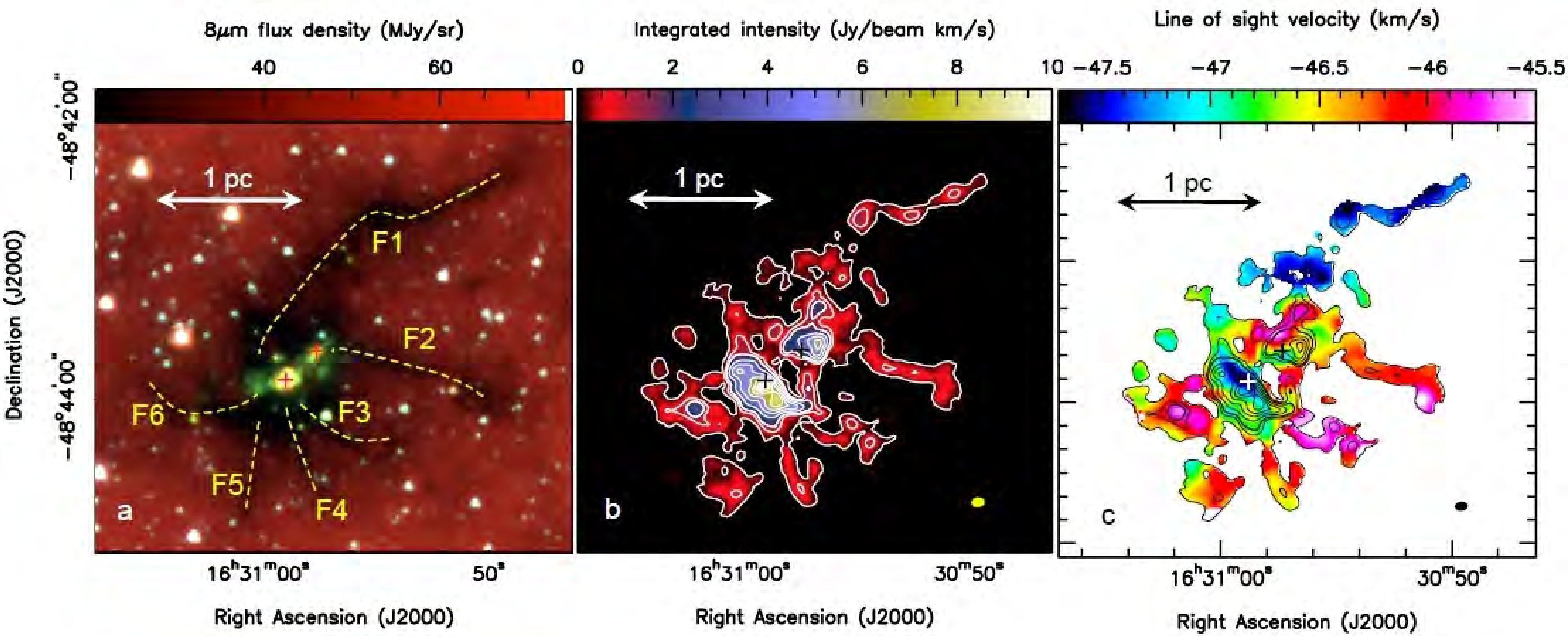


SI & Miyama 1997

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,…*)

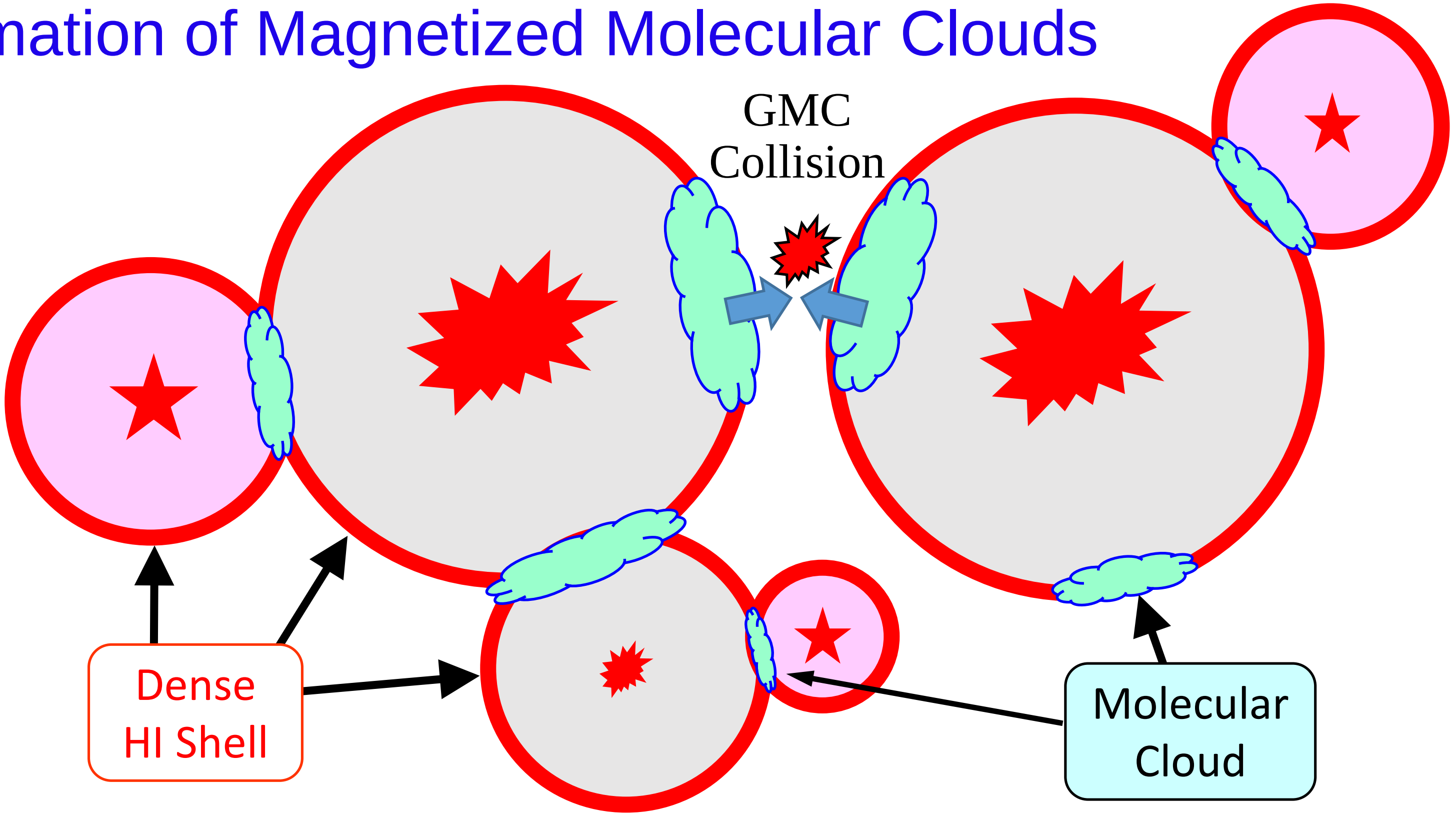
Toward Global Picture of Star Formation

Multiple Compressions Needed for Molecular Cloud Formation

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

Network of Expanding Shells

Multiple Episodes of Compression ➔ Formation of Magnetized Molecular Clouds



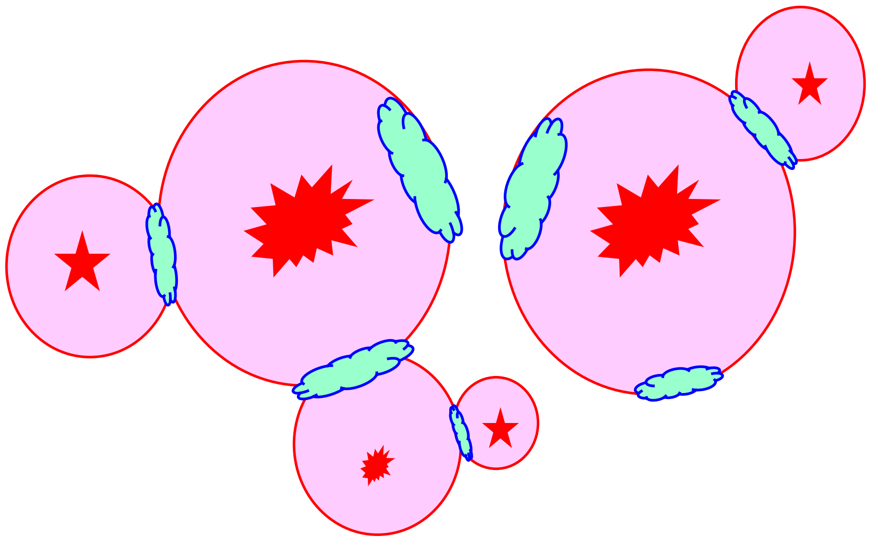
Long (>10Myr) Exposure Picture!

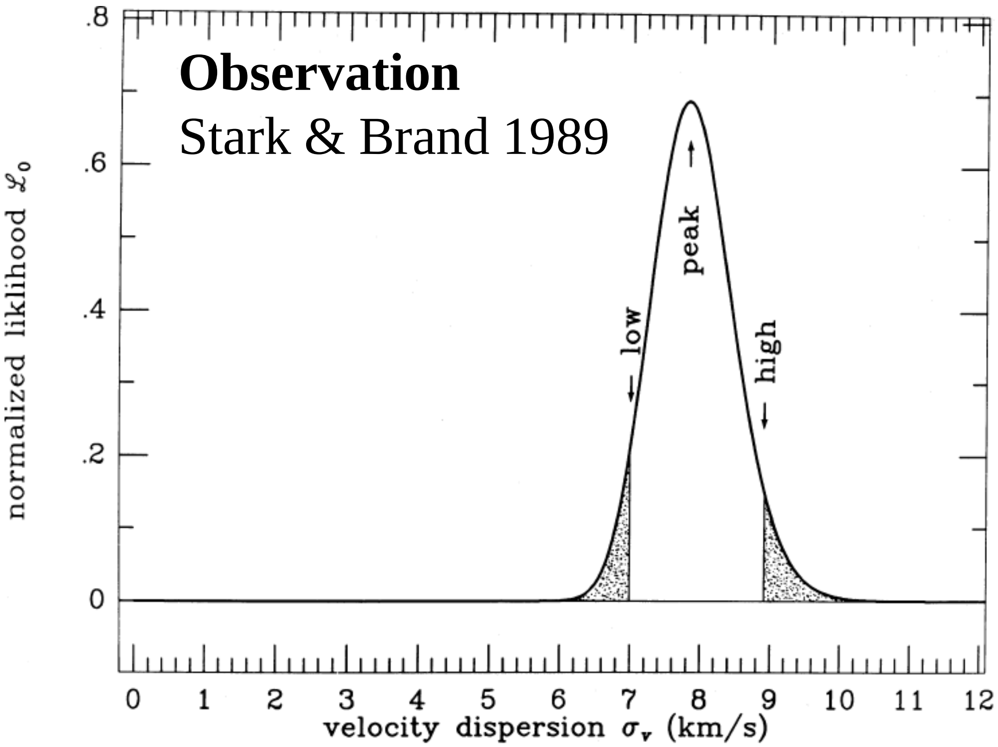
Each bubble disappears quickly (<Myr).

SI+2015; cf. Elmegreen 2007

Velocity Dispersion of Clouds

Multiple Episodes of Compression → Formation of Magnetized Molecular Clouds

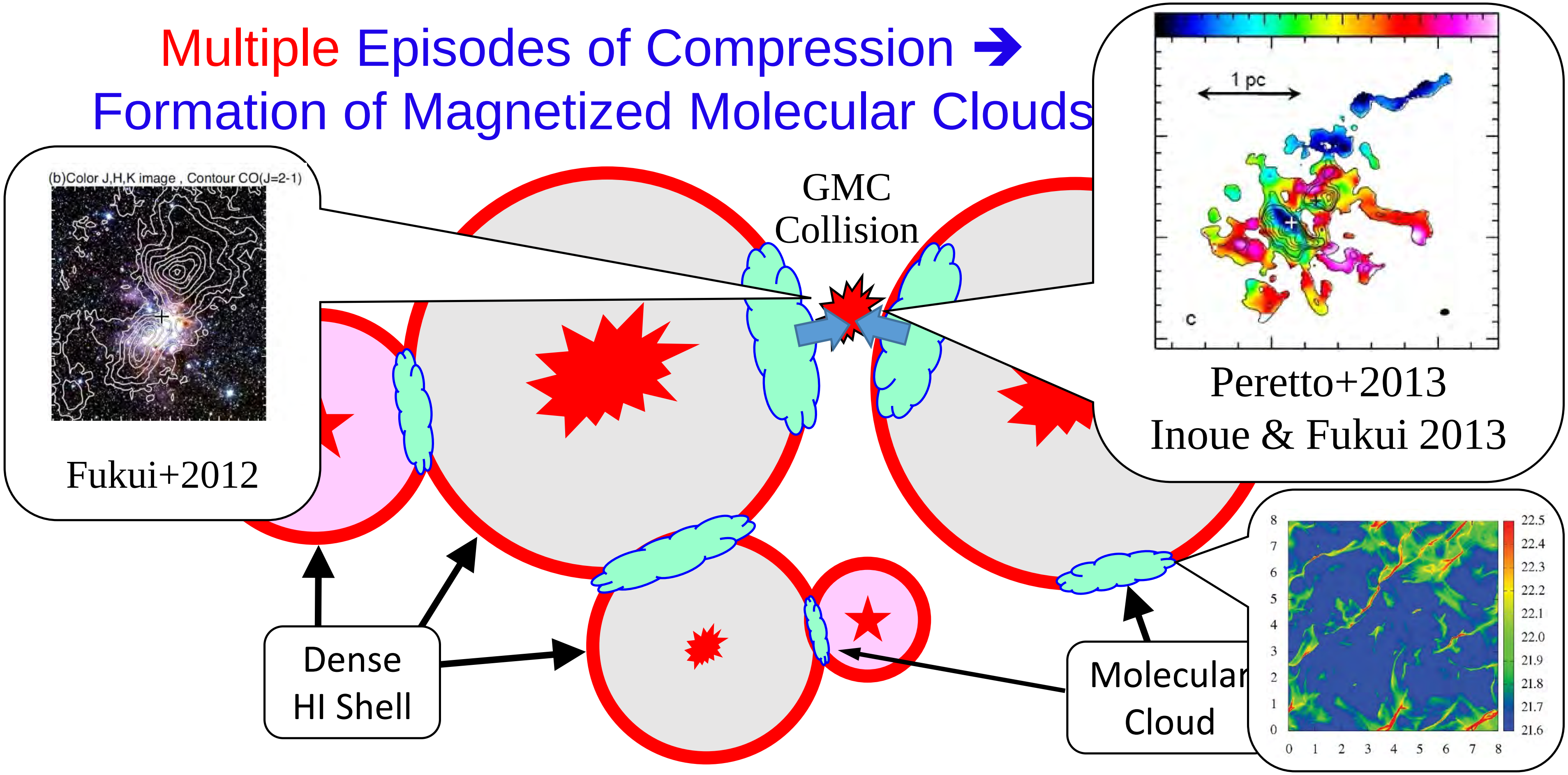




Shell Expansion Velocities ~ 10^1 km/s → Cloud-to-Cloud Velocity Dispersion

Network of Expanding Shells

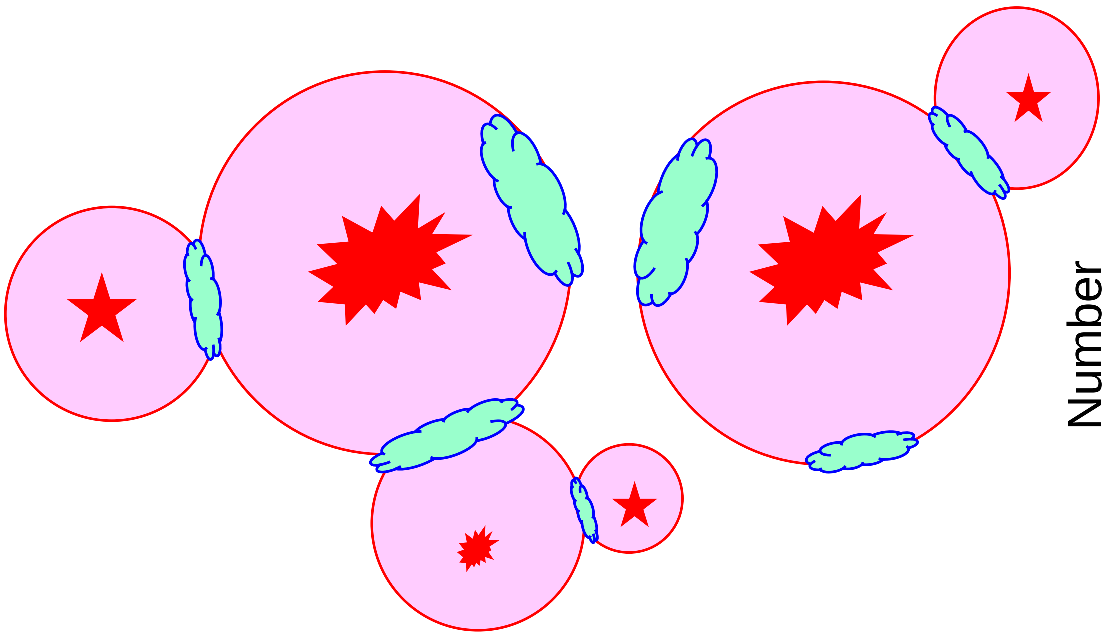
Multiple Episodes of Compression ➔
Formation of Magnetized Molecular Clouds

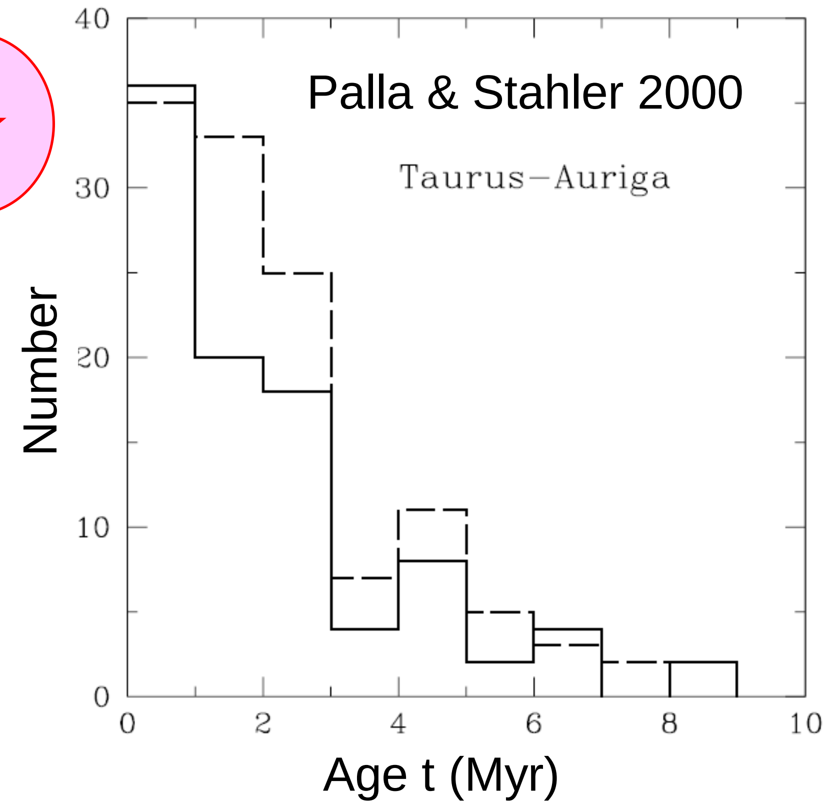


Each Bubble Visible Only for Short Time (~1Myr)!

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

Accelerated Star Formation





Molecular Cloud Growth

➔ Collisions of Clouds

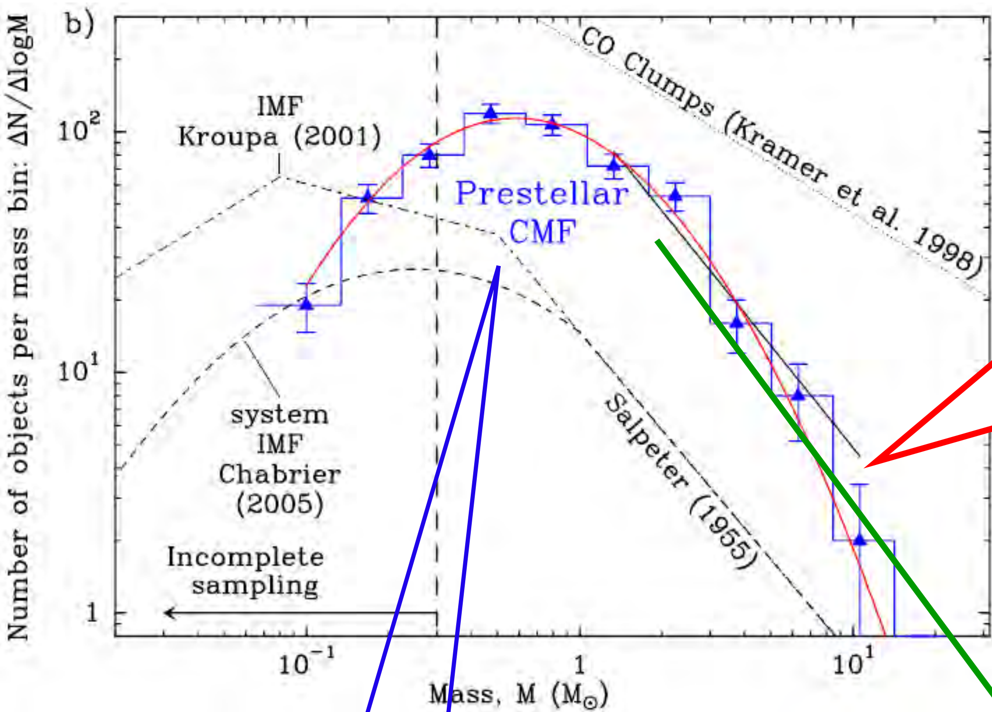
➔ Accelerated SF

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

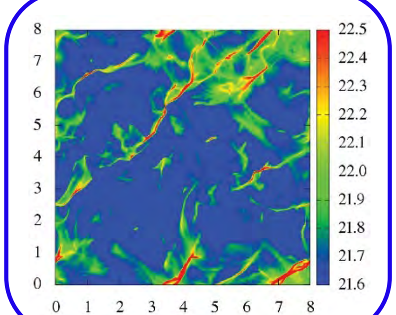
c.f., Vazquez-Semadeni+2007

Possible Mission of JCMT-BISTRO

Aquila CMF from Herschel



Könyves+2010

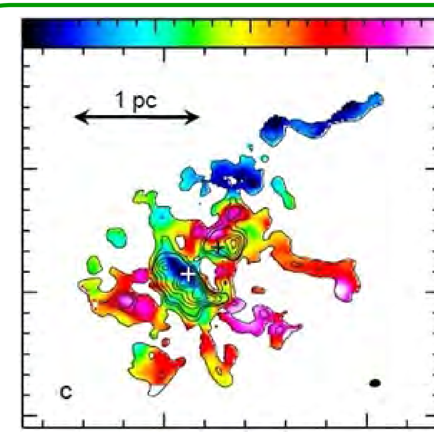


BISTRO Obs

filament ⊥ B?

filament // filament?

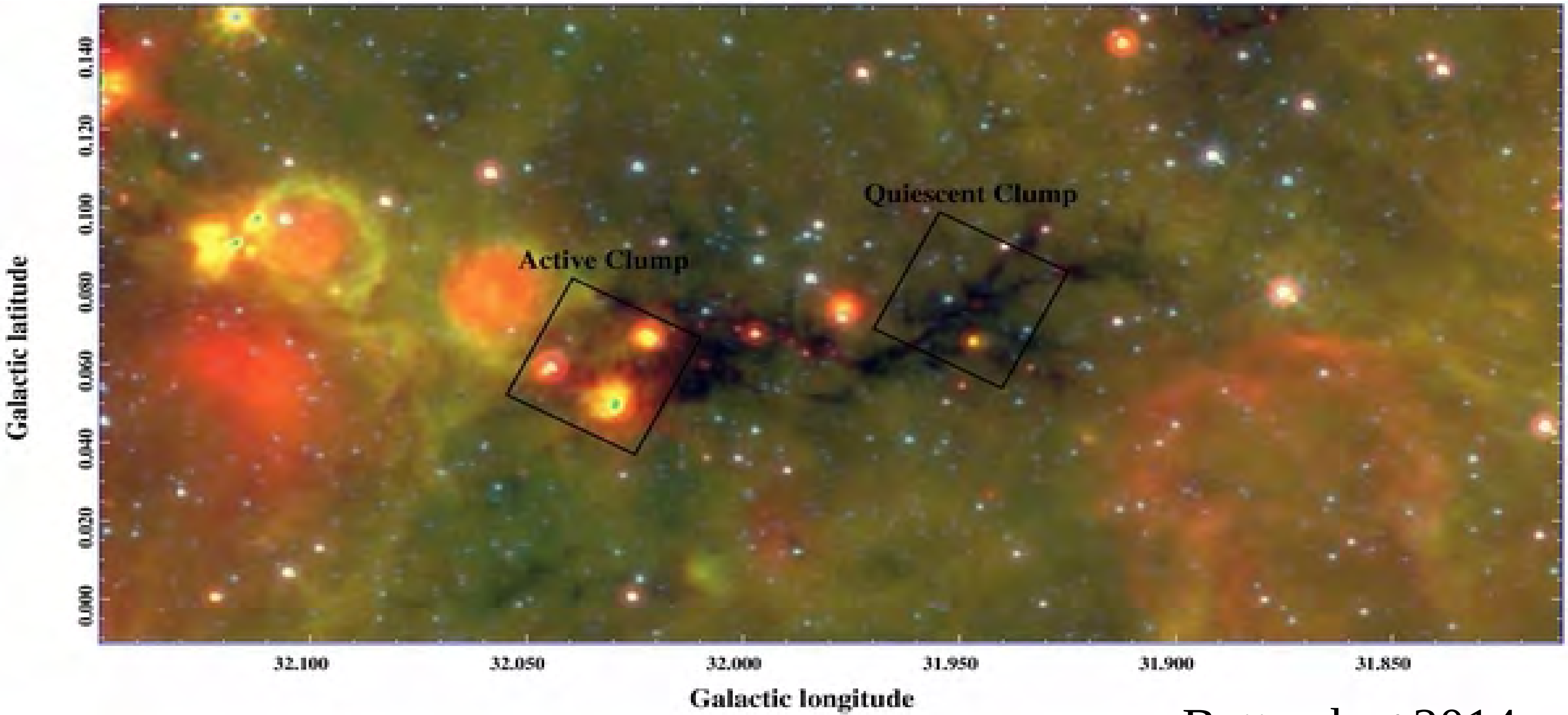
➔ Intermediate Mass Star Formation



Peretto+2013

Massive Star Formation

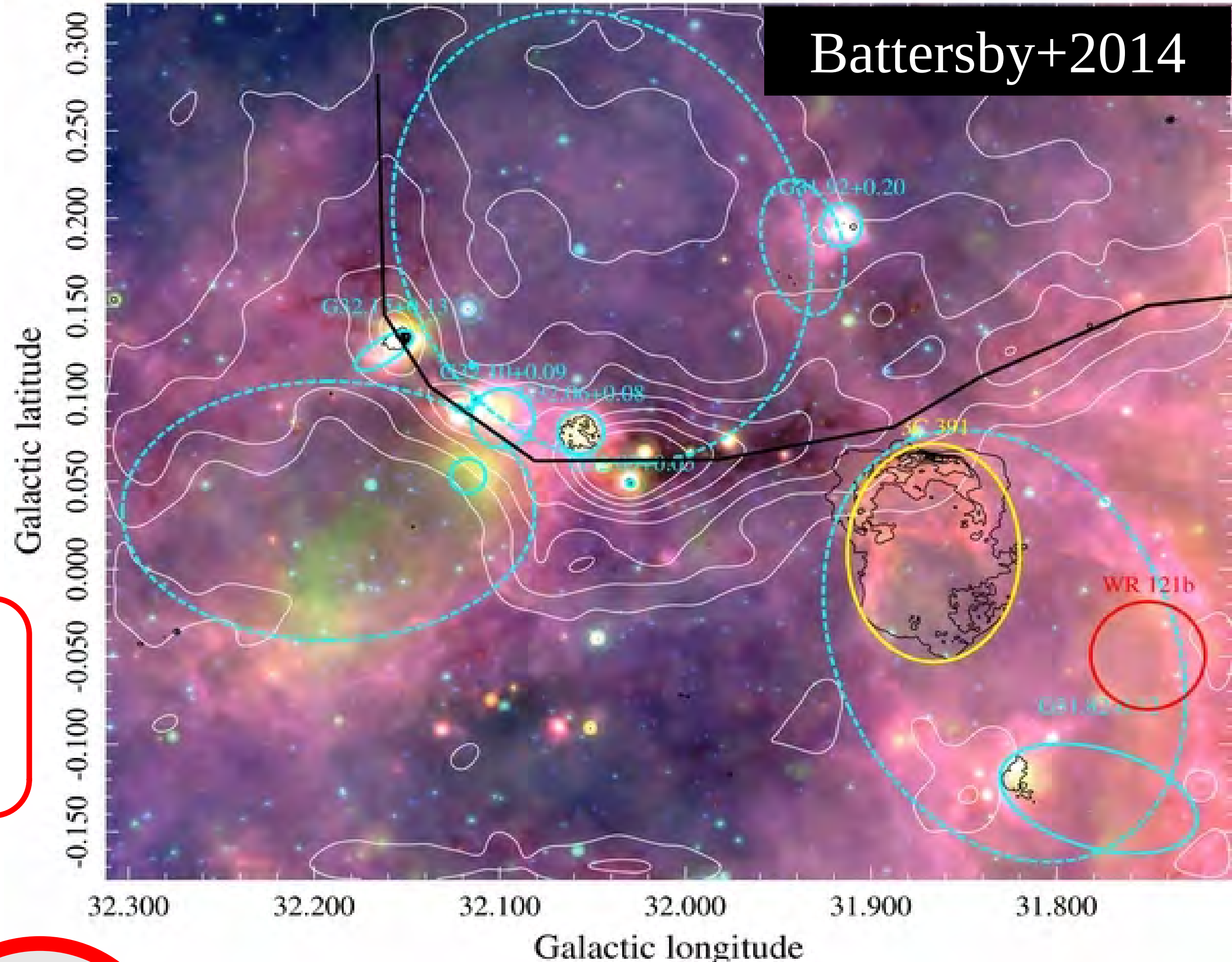
Massive Star Formation in Ridge



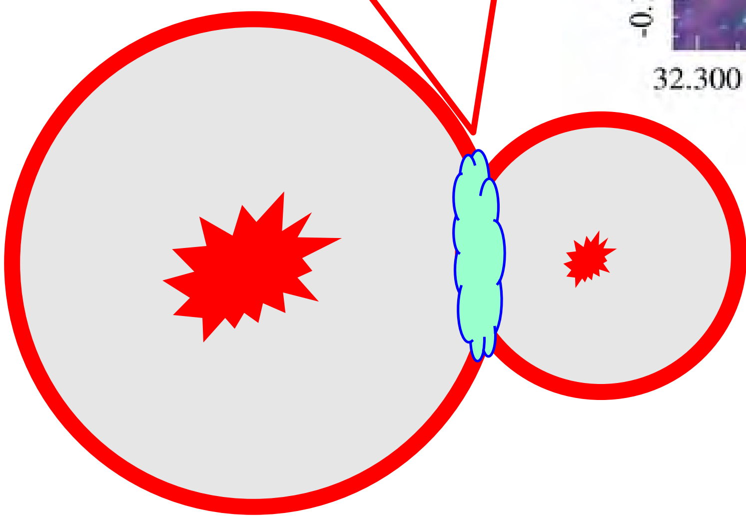
Battersby+2014

Extensive Herschel Studies on Massive Star Formation in “**Ridges**”

Ridge or Edge-On Shell?

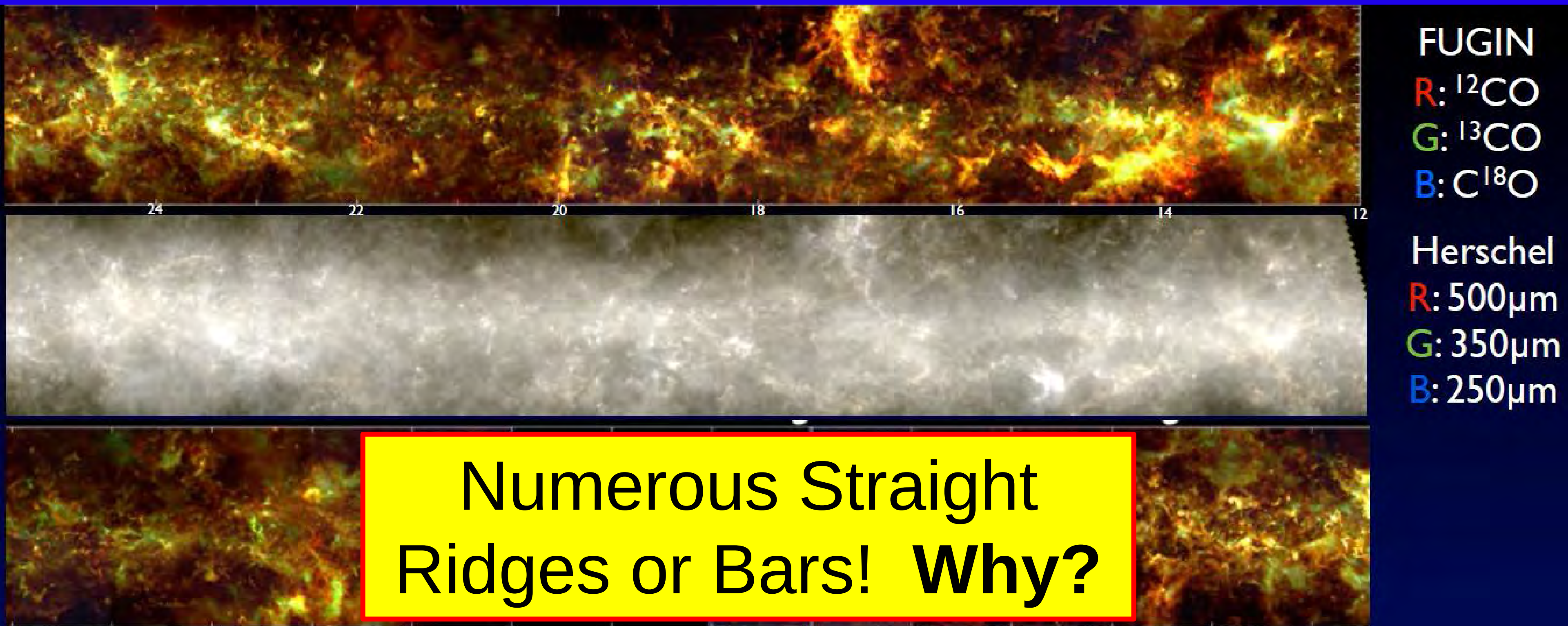


Edge-On View of Compressed Shell
➔ Ridge or Bar!

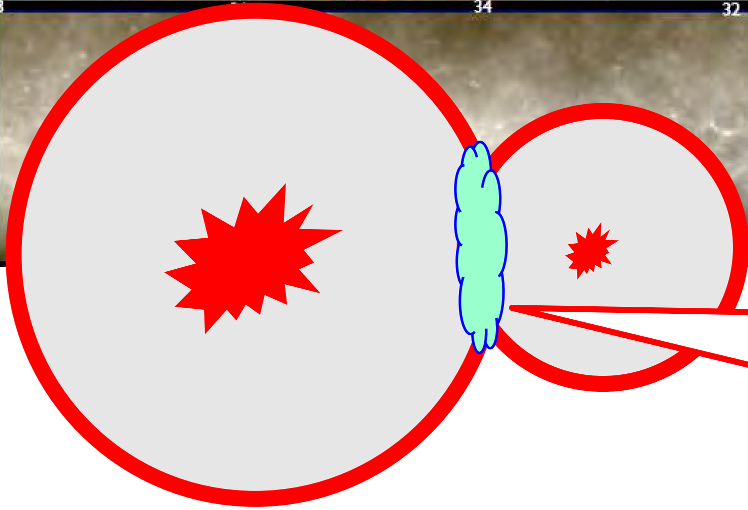


Bubbles (cyan dashed circles)
HII regions (cyan solid circles)
SNR 3C 391 (yellow oval)
Wolf–Rayet star WR 121b (red oval)

Advent of Large Surveys such as **FUGIN**



Numerous Straight Ridges or Bars! **Why?**



Edge-On View of Compressed Shells = Ridges or Bars! ➔ **Bar // *B***

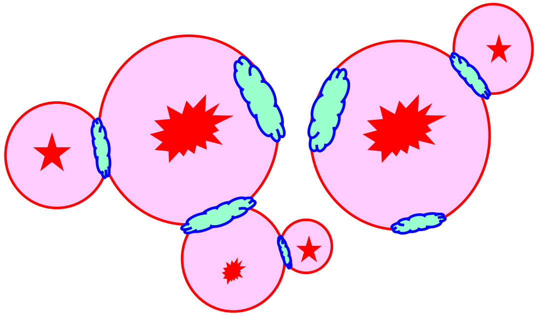
➔ Obs Proof of Cloud Formation Theory!!!

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



- Intermediate Mass Star Formation ← BISTRO
- Colliding Bubbles ➔ Ridges/Bars ← FUGIN

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

Kobayashi+2016 submitted

Destruction of Molecular Clouds

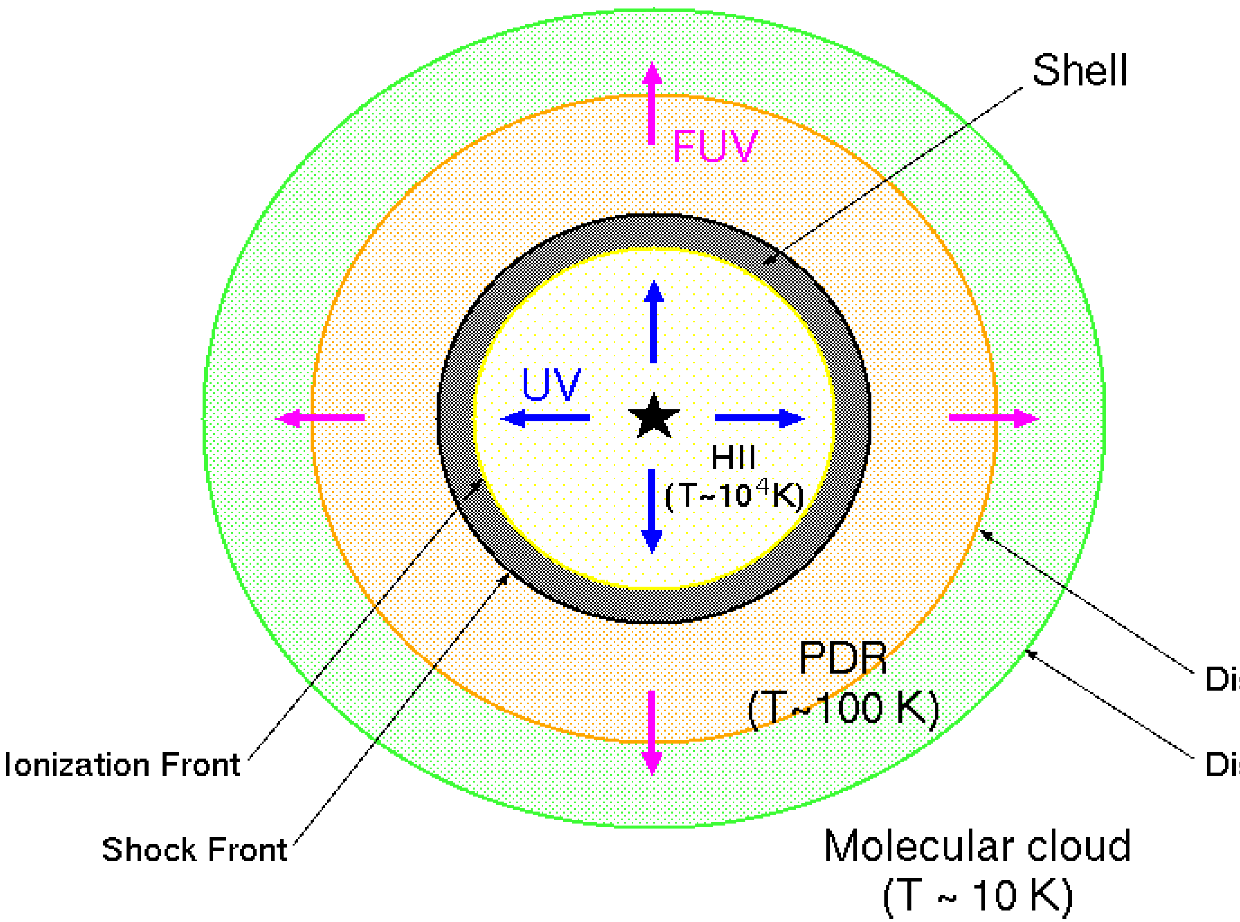
How to Stop Star Formation?

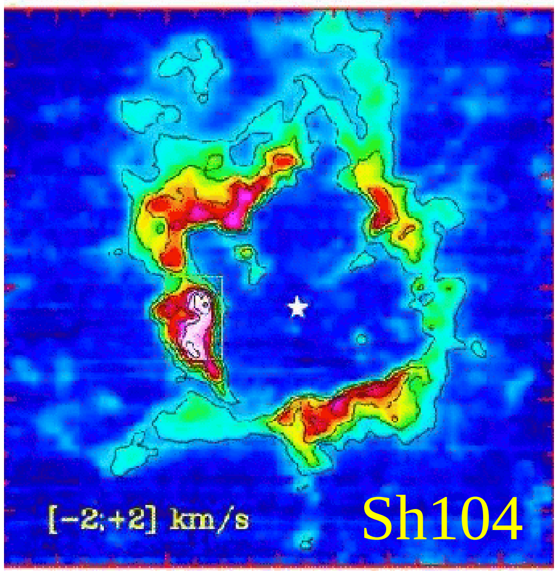
Radiative Feedback

Photodissociation Critical!

c.f. *Dale, Walch,…*

Expanding HII Region in Magnetized Molecular Cloud





Deharveng et al. 2003

Radiation Magnetohydrodynamics Calculation

UV/FUV + H_2 + CO Chemistry (Hosokawa & SI 2005, 2006ab, 2007)

Disruption of <u>Magnetized</u> Molecular Clouds

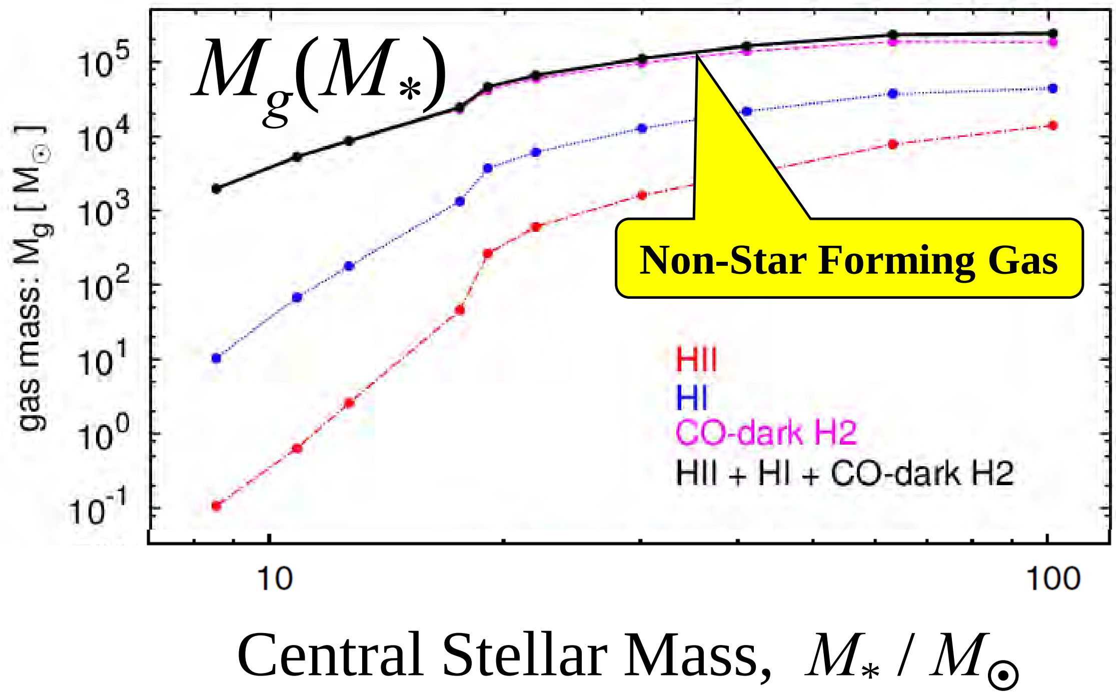
Feedback due to UV/FUV in a Magnetized Cloud by MHD version of *Hosokawa & SI* (2005,2006ab)

➔

$30M_\odot$ 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: $T_{\rm d} = 4{\rm Myr} + T_*$

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

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

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

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

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

observation ⟷ β of IMF

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

Galactic Population of Molecular Clouds

Mass Function of Molecular Clouds

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

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

$\frac{dM_{\rm cl}}{dt} = \frac{M_{\rm cl}}{T_{\rm form}}$

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

In steady state

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

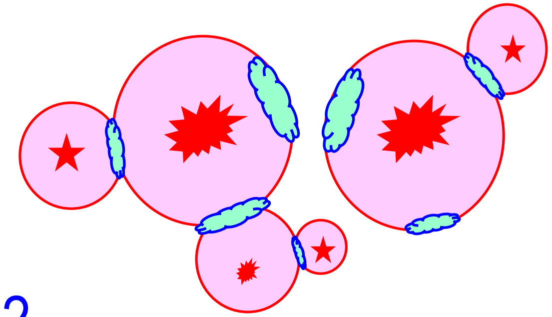
$$T_{\rm dis}\sim 14\,{\rm Myr}\ \&\ T_{\rm form}\sim 10\,{\rm Myr} \rightarrow \alpha = 1.7$$

(*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

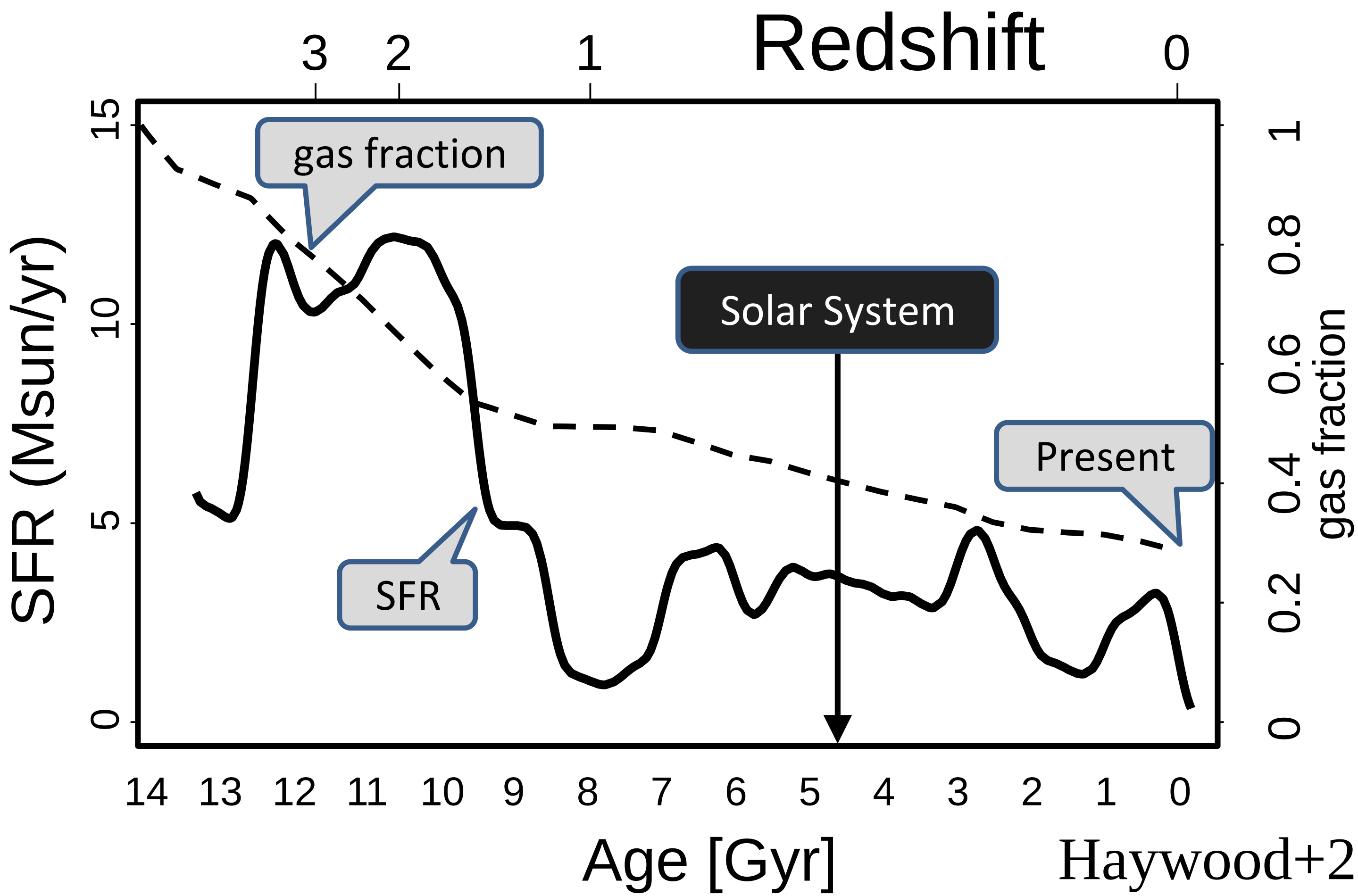


- $\delta v_{\text{cloud-cloud}} \sim 10^1$ km/s
- Accelerated Star Formation
- Star Formation Efficiency: $\varepsilon_{SF} \sim 10^{-2}$
- Schmidt-Kennicutt Law
- Slope of Cloud Mass Func $= 1 + T_{\mathrm{form}}/T_{\mathrm{dis}} \sim 1.7$

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

Kobayashi+2016 submitted

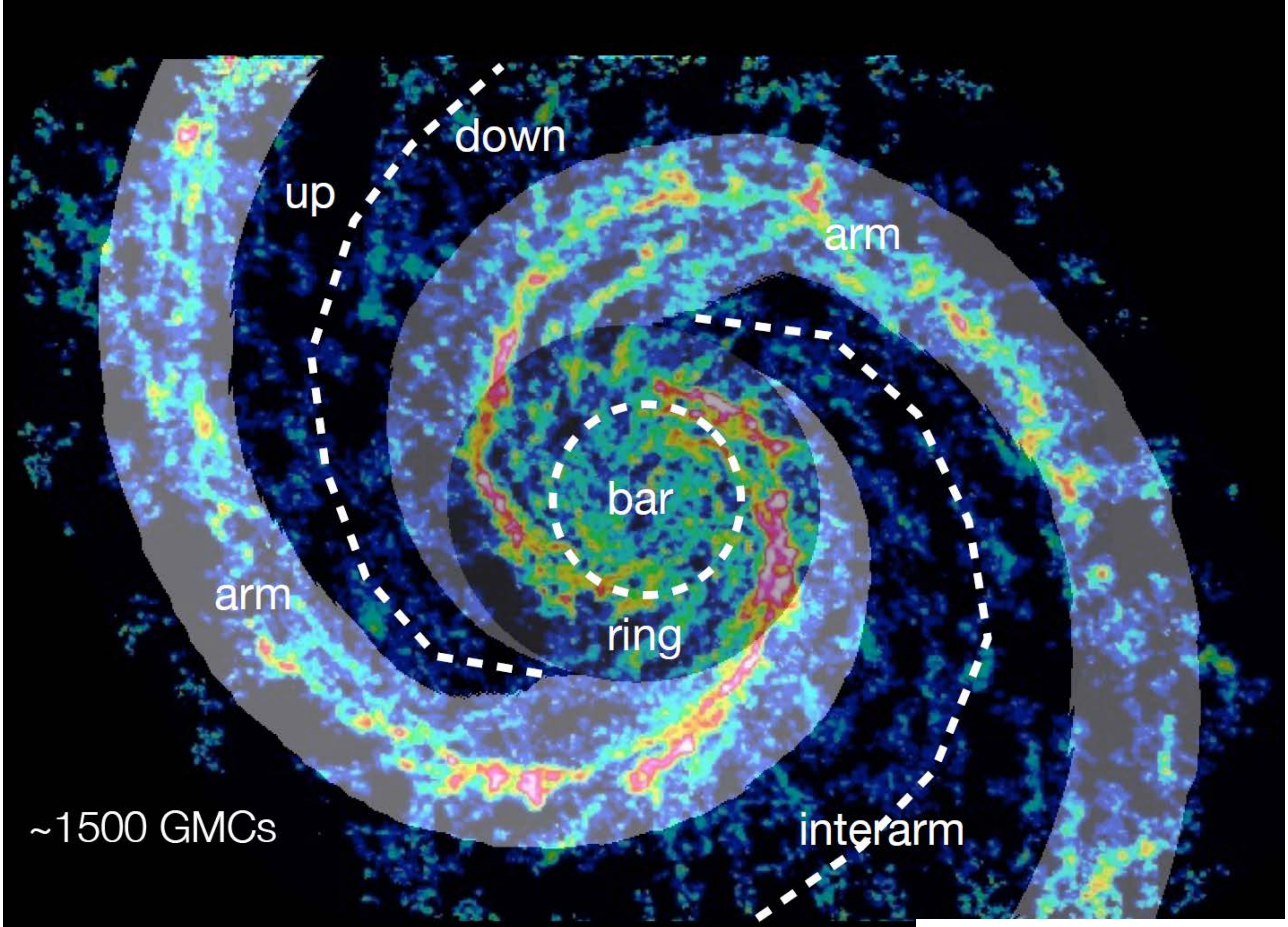
How far can we trace back?



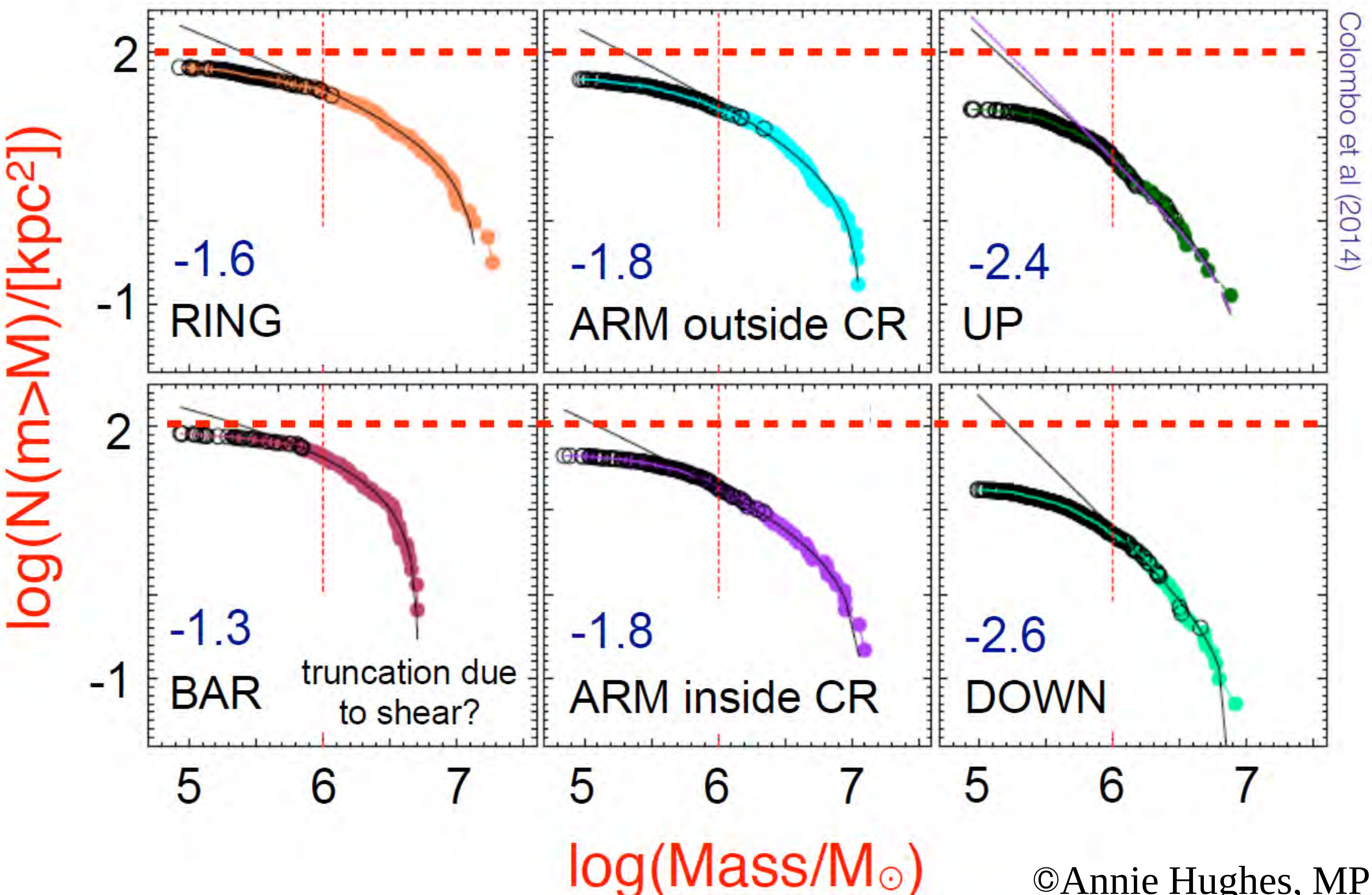
Haywood+2016

Present SF mode responsible for z < 2

in Our Galaxy!


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

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

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

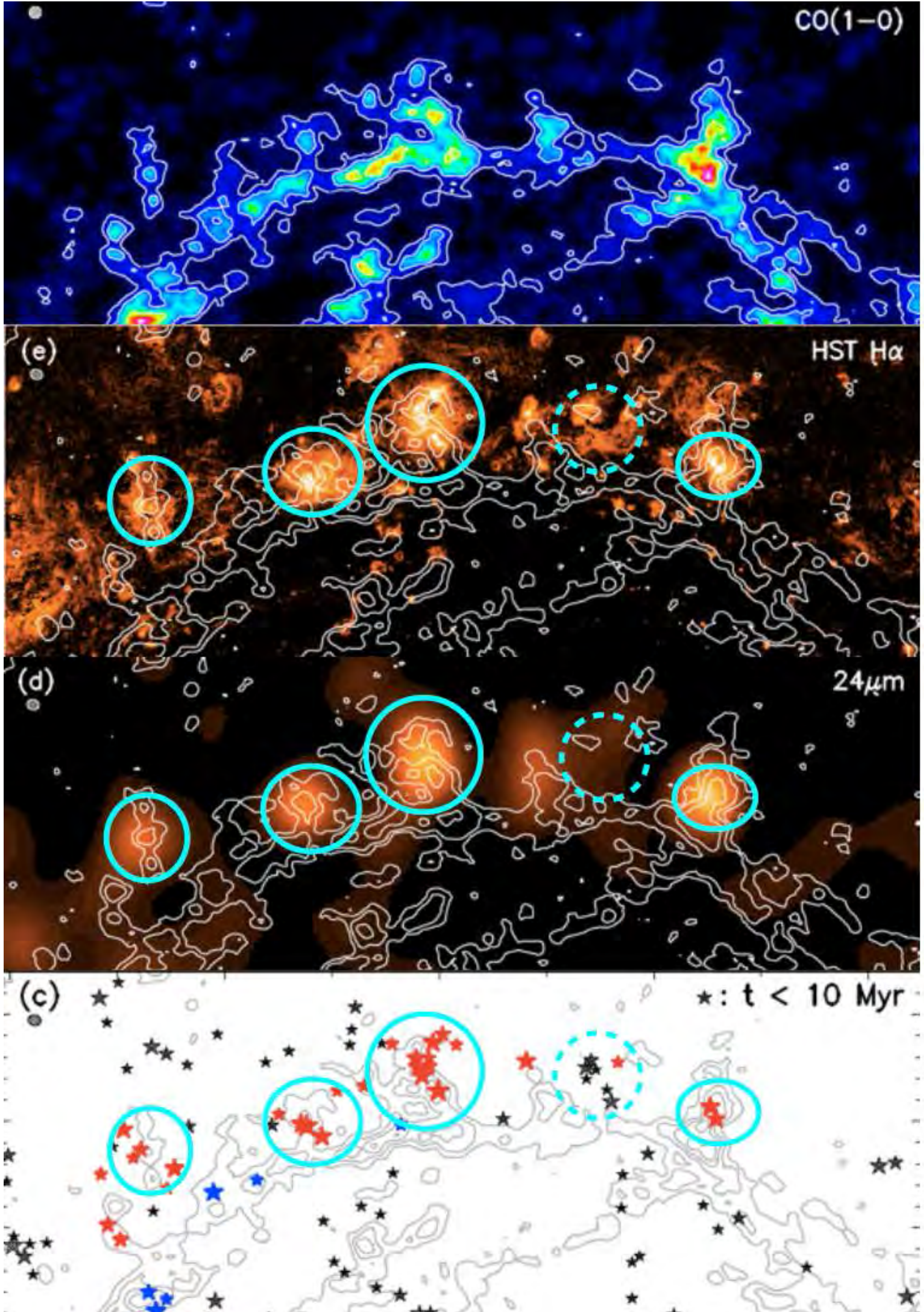
In low density region (Inter-Arm Region)

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

In high density region (Arm Region)

Smaller $T_{\rm form}$ ➔ Smaller α

➔ GMCs in M51 (Colombo+2014)



Star formation occurs along the spurs, not in the arm

Schinnerer et al. (in prep.)

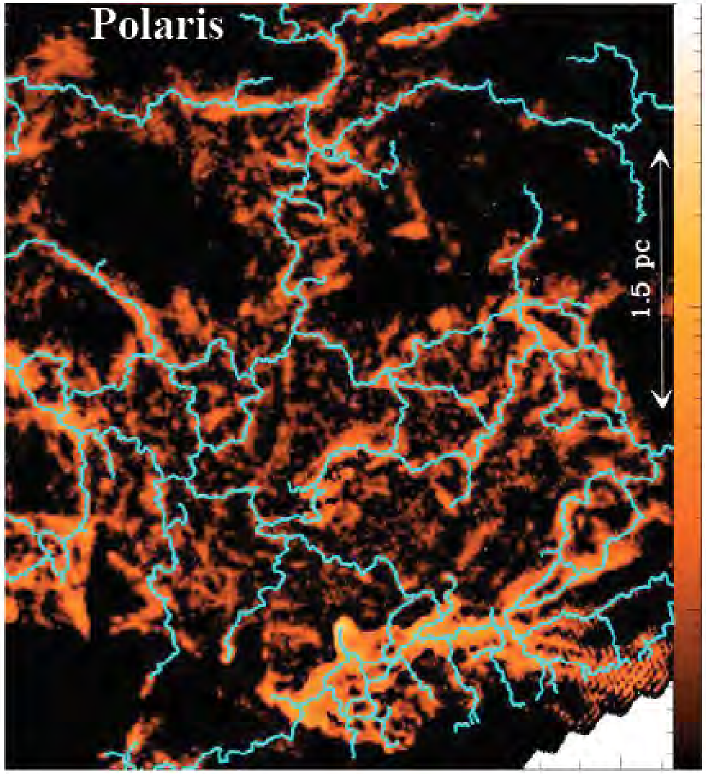
HII regions are offset from arm ridge-line along spurs

warm dust (24 μm) associated with HII regions

young stellar clusters more common off arm, along spurs

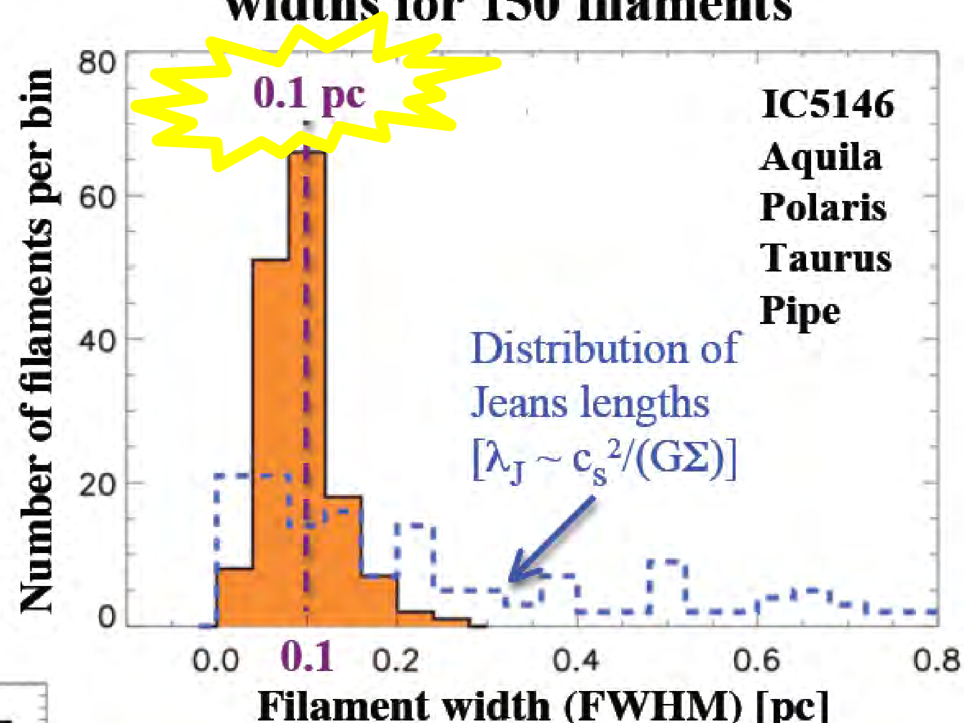
Characteristic Widths of Filaments

Filaments have a characteristic width ~ 0.1 pc

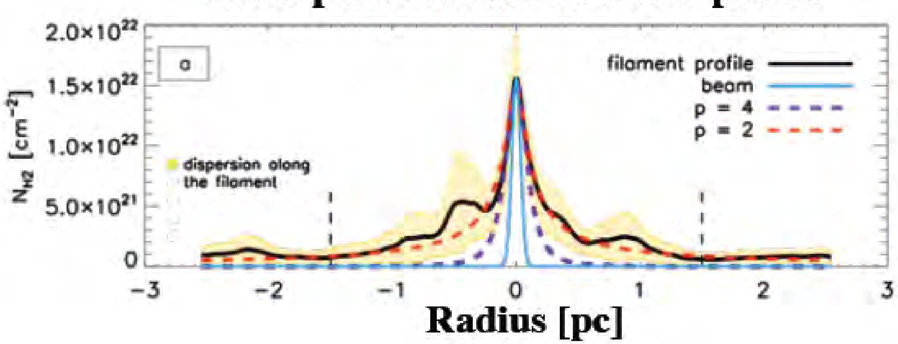


D. Arzoumanian et al. 2011, A&A, 529, L6

Statistical distribution of widths for 150 filaments

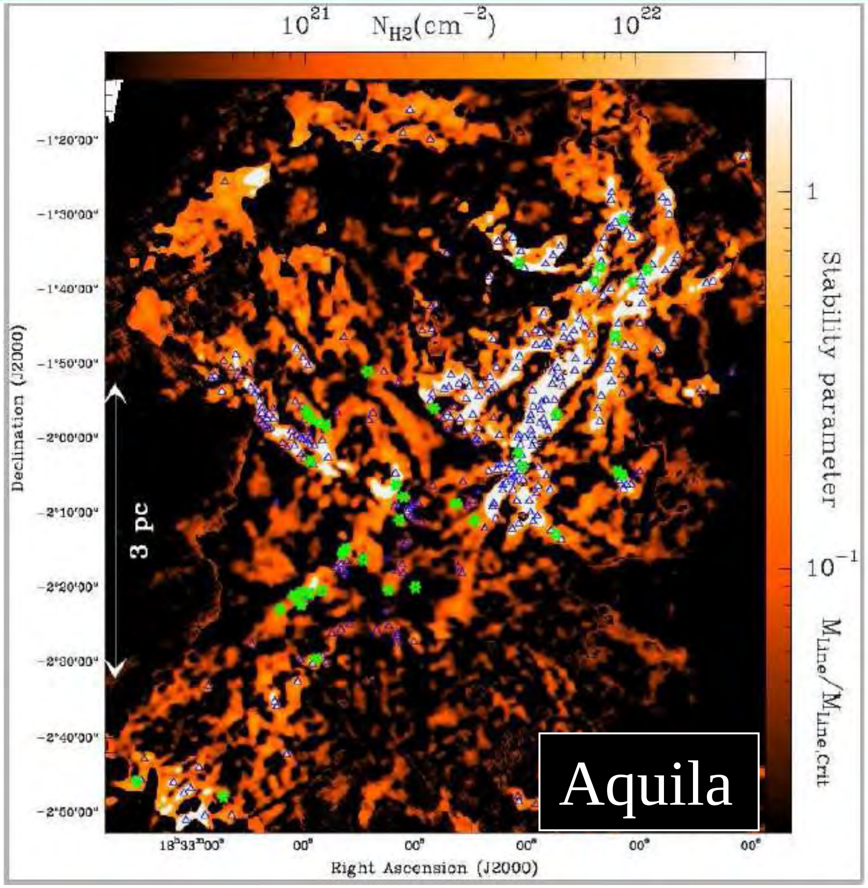


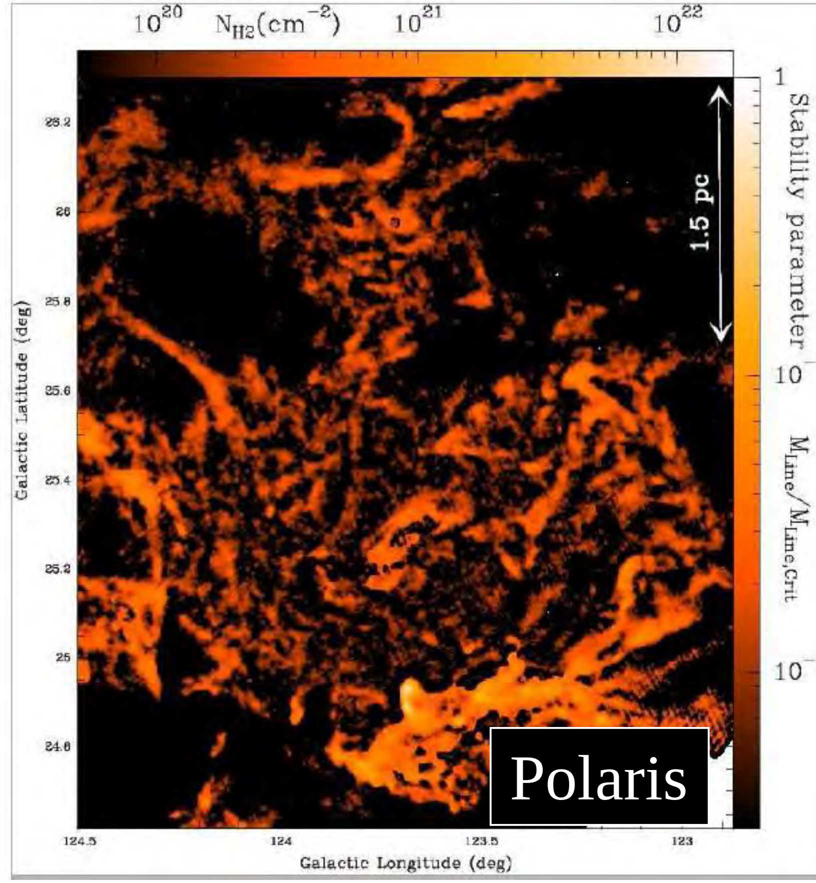
Example of a filament radial profile



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

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?