The Role of Magnetic Field in Star Formation in the Disk of Milky Way Galaxy

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Outline

- Observational Introduction
- Formation of Molecular Clouds
- Dynamics of Filaments
  - Mass Function of Dense Cores → IMF
- Cloud/Star Formation in the Galactic Disk
  - Accelerated Star Formation
  - SF Efficiency & Schmidt-Kennicutt Law
  - ~~Mass Function of Molecular Clouds~~
- Implication for Observation
  - Cloud-to-Cloud Velocity Dispersion, Ridge,
  - Intermediate Mass SF
- Conclusion & Remaining Questions

Star Formation is Inefficient!

- Mass of Molecular Clouds (~10K): $M_{\rm MC} \sim 10^9\, M_\odot$
- Typical Density observed by ^{12}CO: $n_{\rm CO} \sim 10^2\,/{\rm cm}^3$
- Free-Fall Time for $10^2\,{\rm cm}^{-3} \sim 10^6\,{\rm yr}$
- Star Formation Rate (if at Free-Fall Rate)

too large!

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

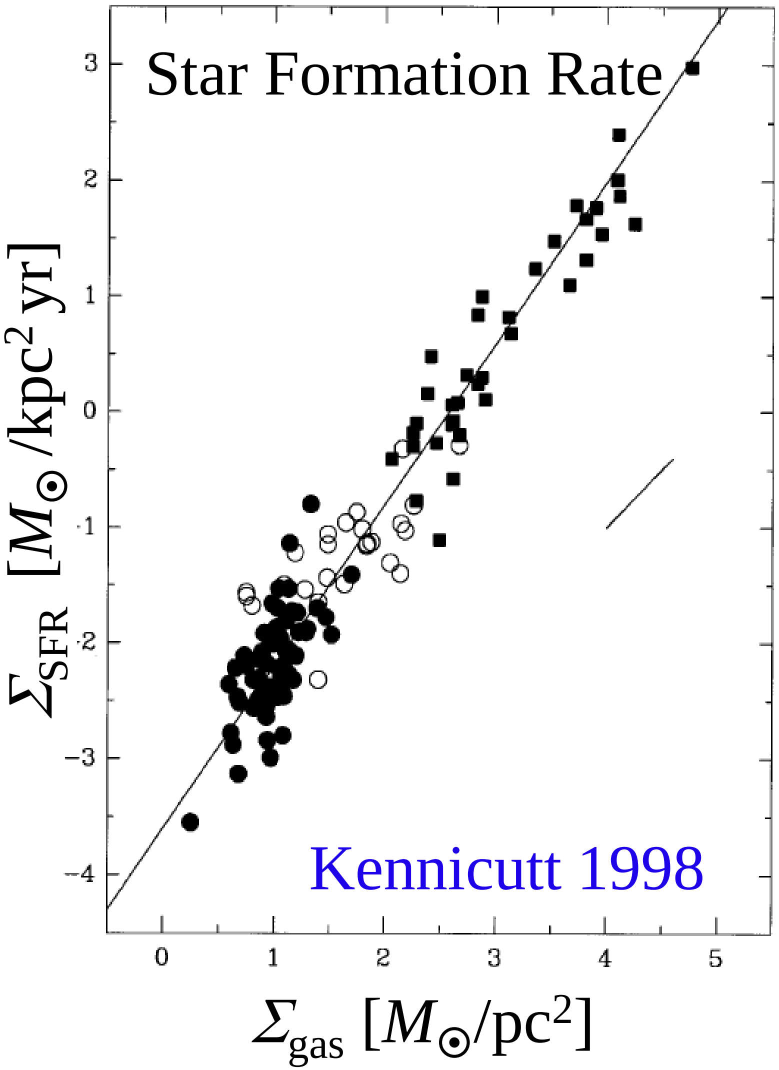
$\Updownarrow$

Observed SF Rate, $R_{\rm SFR,\,obs} \sim 10^0\, M_\odot/{\rm yr}$

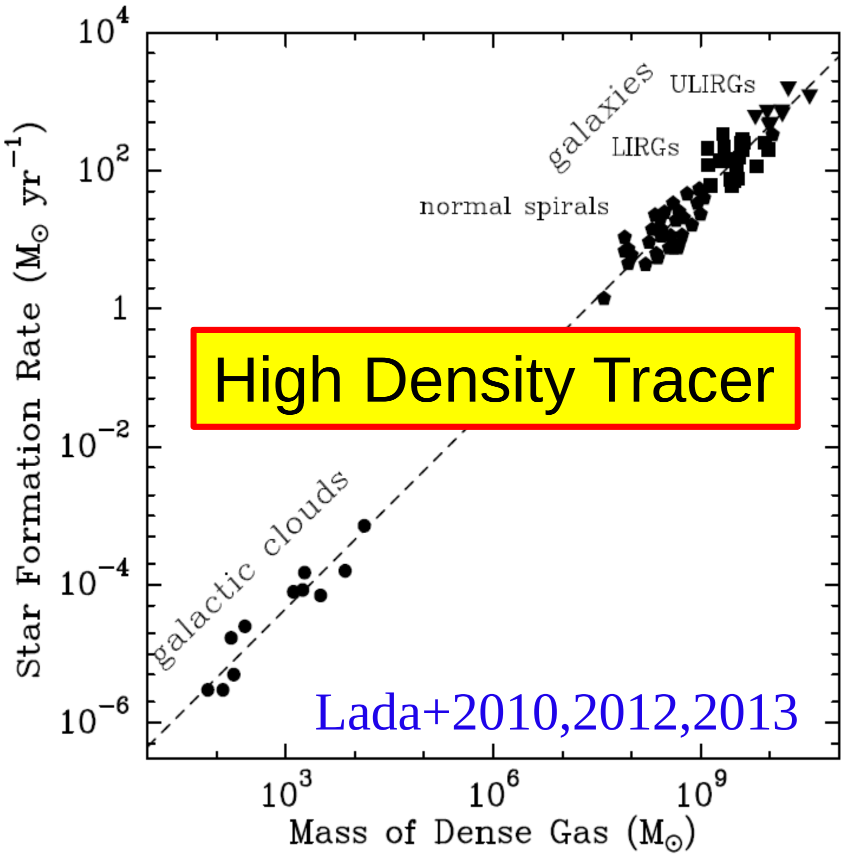
→ Either Slow or Very inefficient (~10^{-3})!

$$t_{\rm Gas} = M_{\rm gas} / R_{\rm SFR,\,obs} \sim 10^0\,{\rm Gyr}$$

Schmidt-Kennicutt Law of SF



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



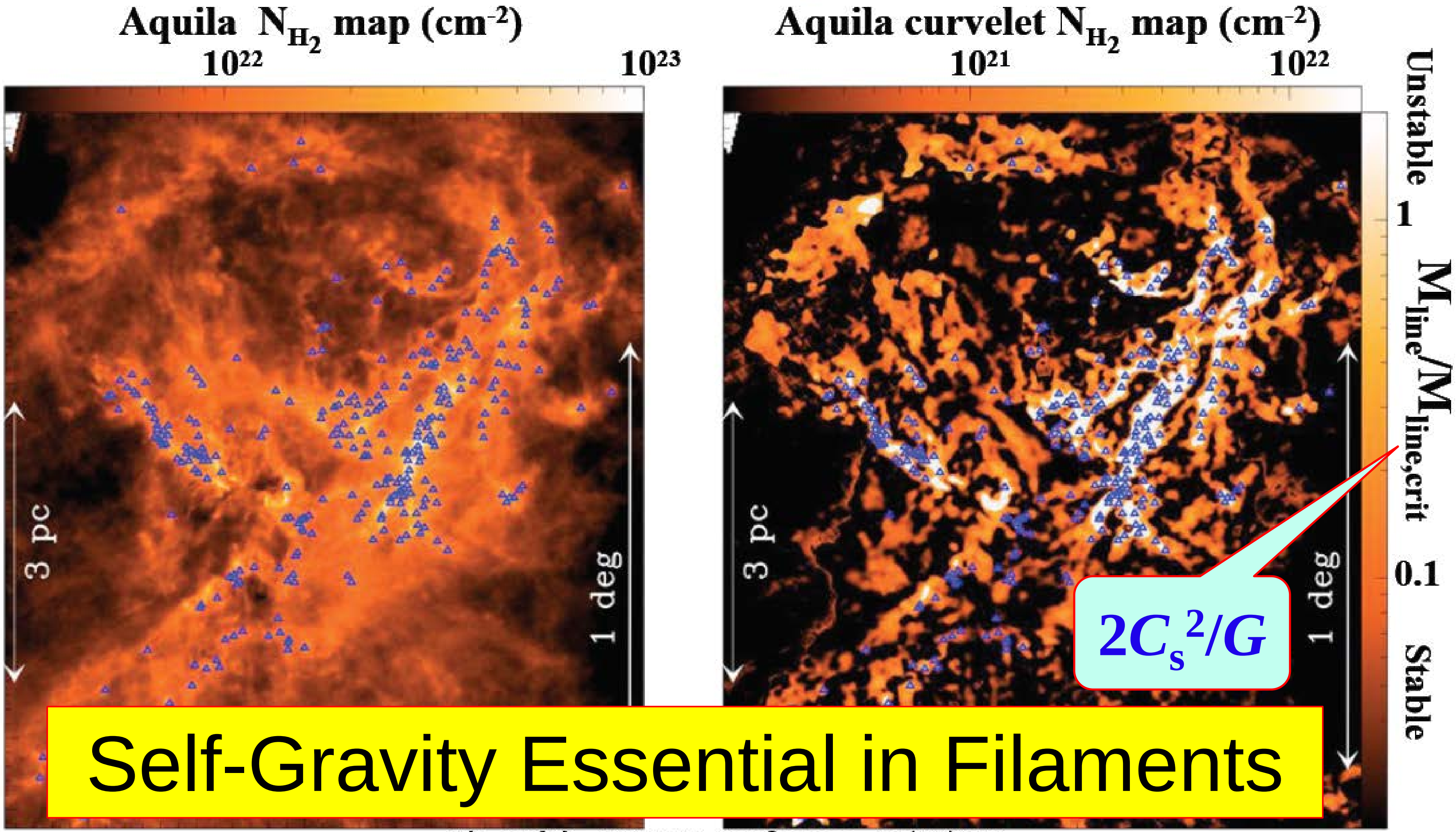
- Column Density: Σ_{gas} [$M_\odot$/pc^2]
- SF Rate: Σ_{SFR} [$M_\odot$ /kpc^2 yr]
- Timescale: M/(SFR) ~ 20Myr

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

Highlight of Herschel Result (André+2010)

Prestellar cores are preferentially found within the densest filaments

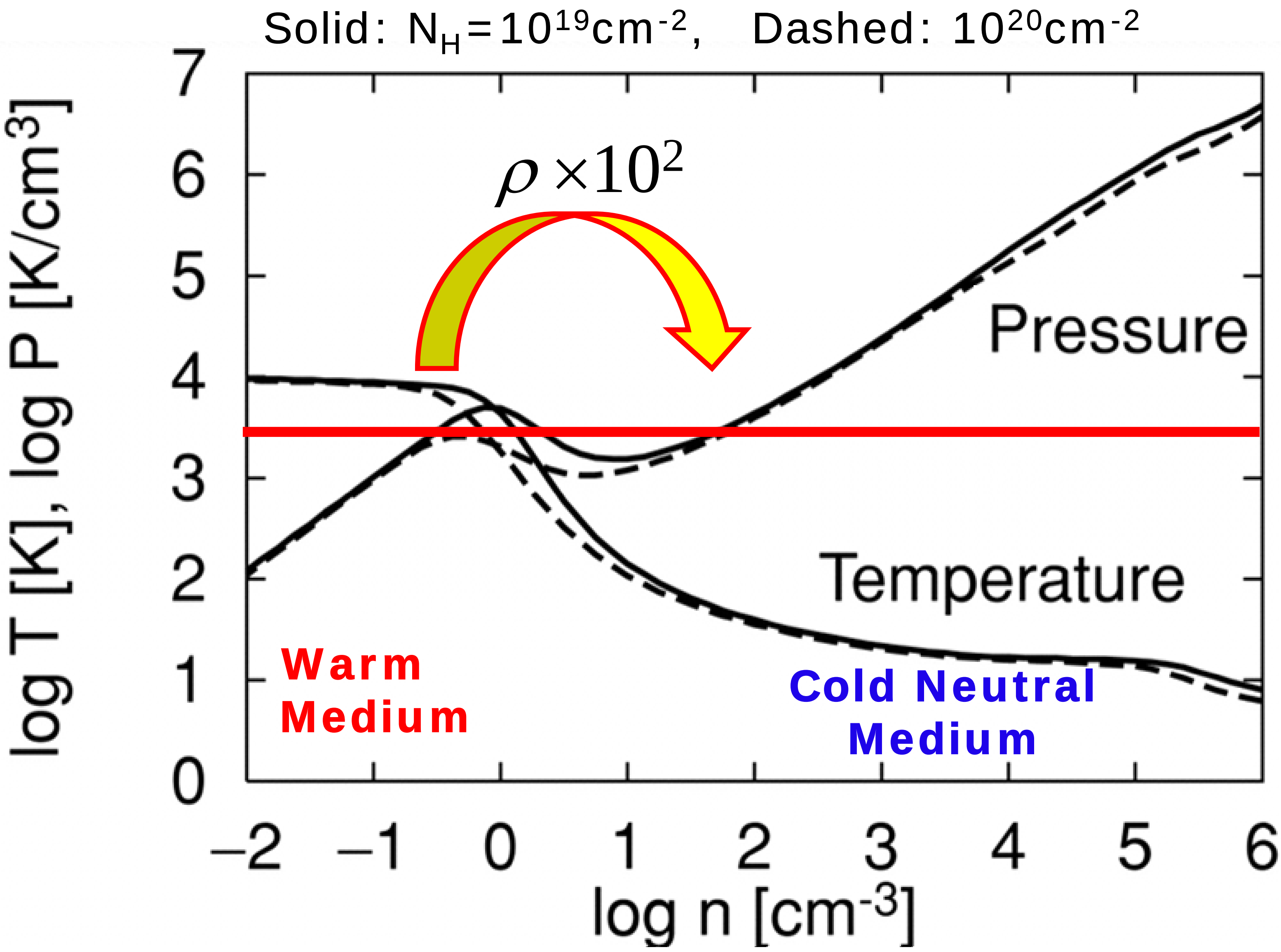
△ : Prestellar cores - 90% found at $N_{H_2} > 7x10^{21}$ cm^{-2} <=> A_v(back) > 8



Self-Gravity Essential in Filaments

Formation of Molecular Clouds

Radiative Equilibrium for a given density



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

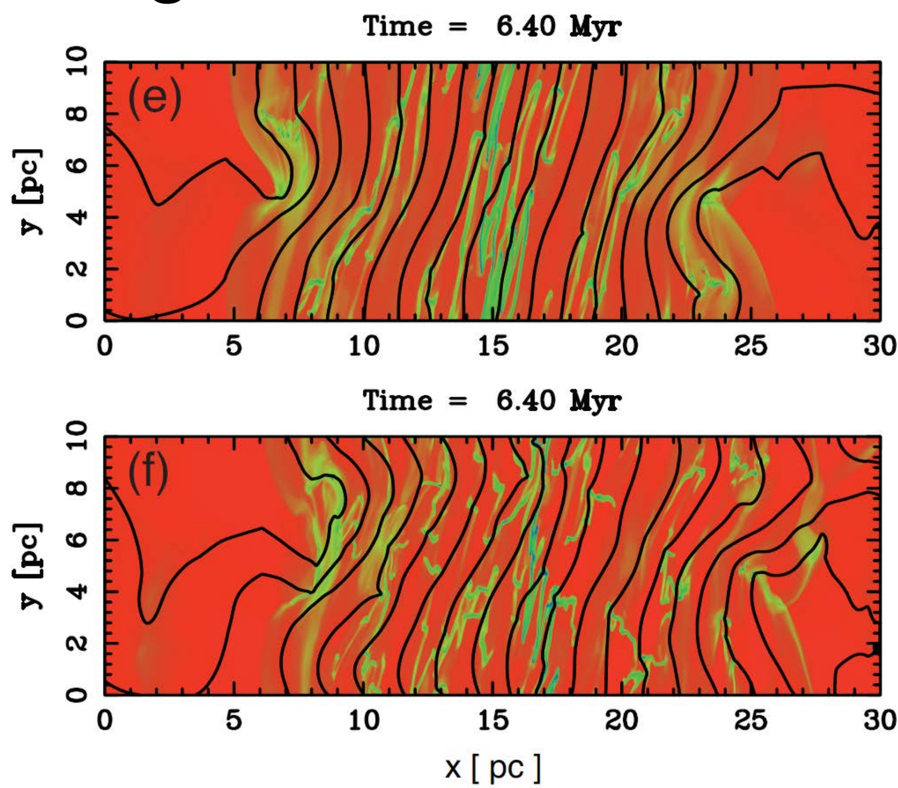
Compression of Magnetized WNM

Can direct compression of magnetized WNM create molecular clouds?

➔ No, 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.

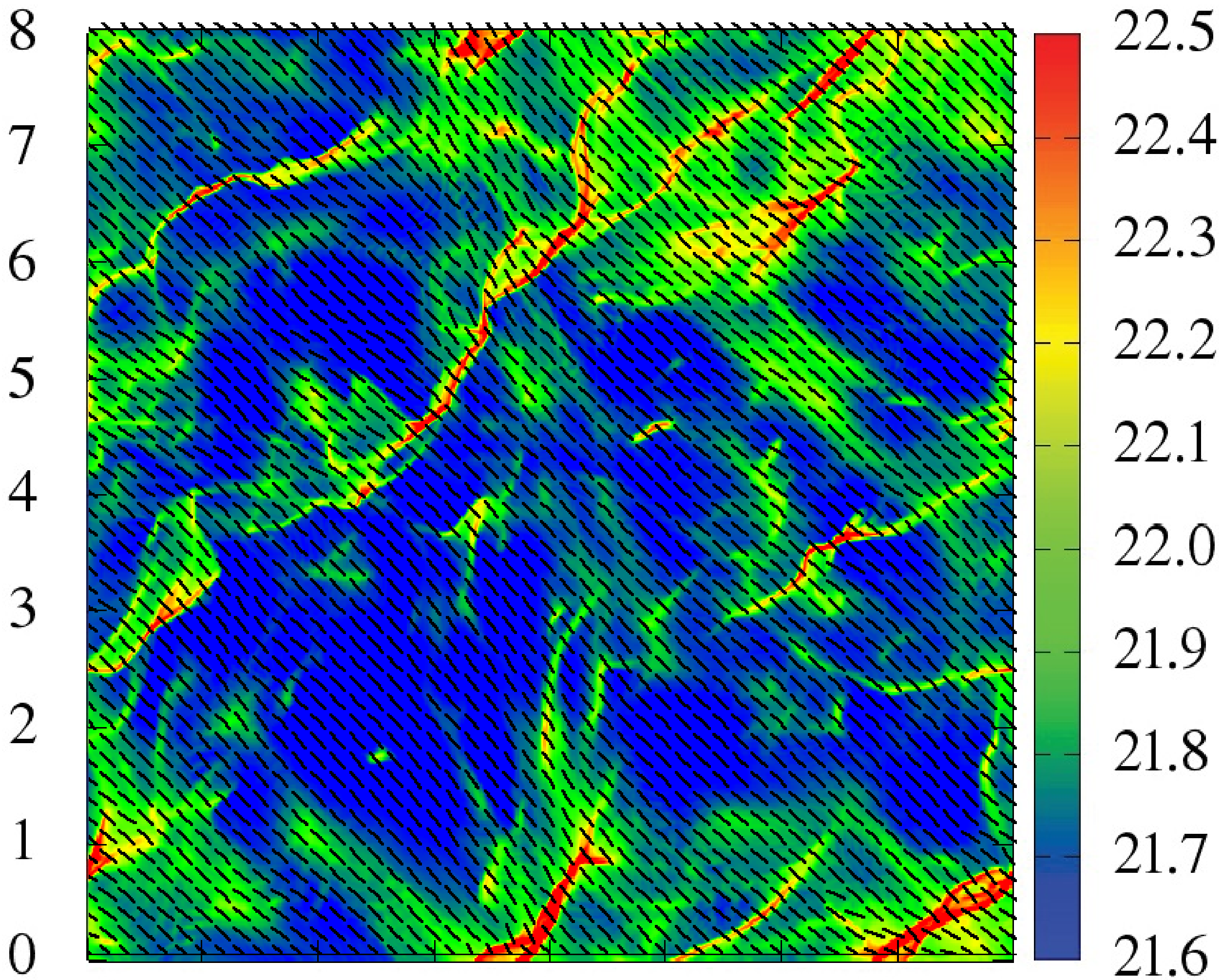
Further Compress. of Mole. Clouds

Multiple Compressions of Molecular Cloud

➔

Magnetized Massive Filaments & Striations

Agree with Many Observations!



Black Lines: Magnetic Field Lines

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

Formation of Molecular Clouds

Can direct compression of magnetized WNM create molecular clouds? ➔ Not at once.

We need multiple episodes of compression.

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

Inoue & SI (2012) ApJ **759**, 35 Transformation of HI to H_2

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

Further Compression of Molecular Clouds

➔Magnetized Massive Filaments & Striations

= "Herschel Filaments"

Dynamical Timescales of Star Formation

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

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

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

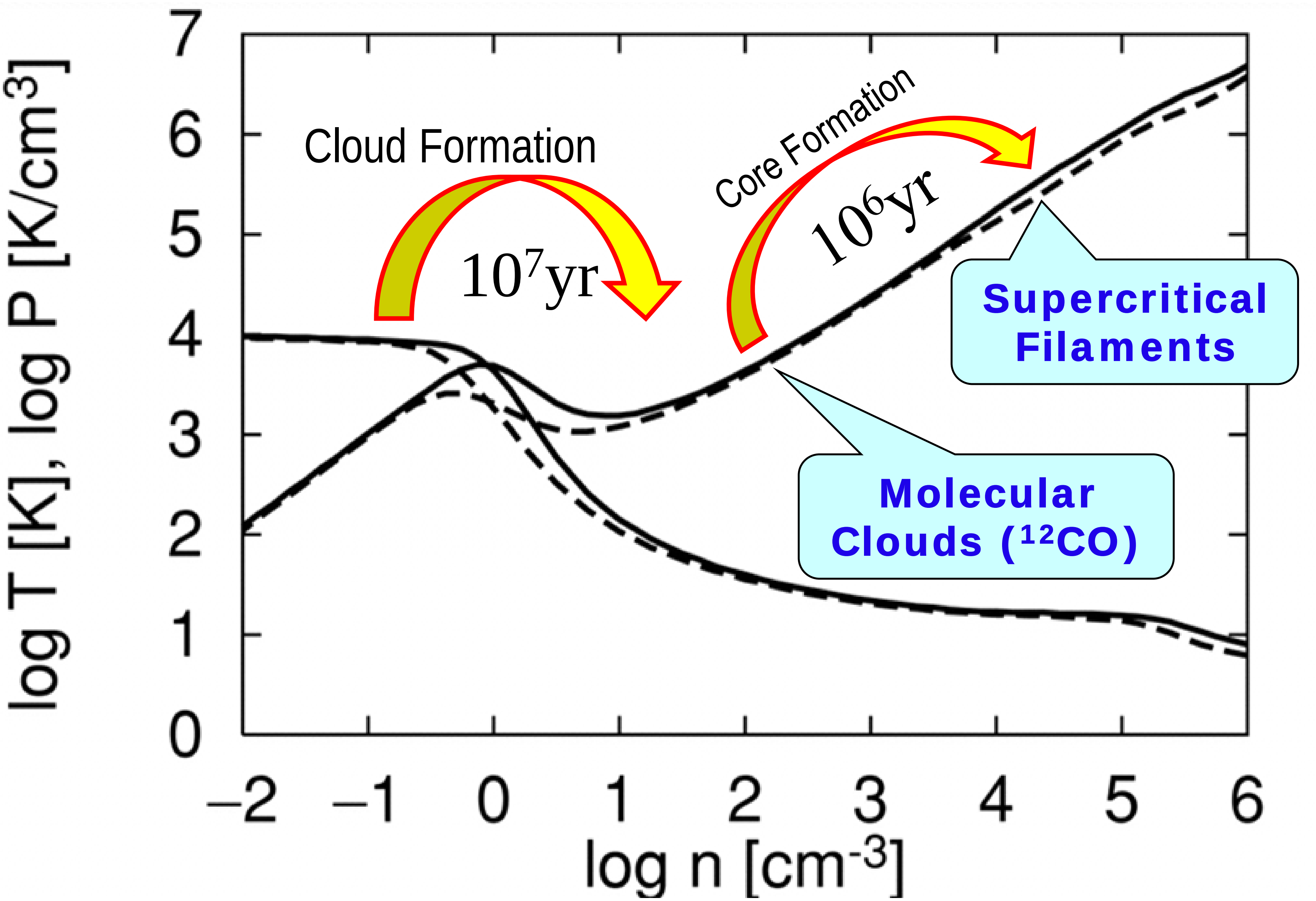
➔ Gravitational collapse of a core is not quasi-steady!
➔ Dynamical Gravitational Collapse in Dense Cores!

⬍

Dynamical Evolution in Self-Gravitating Filament with

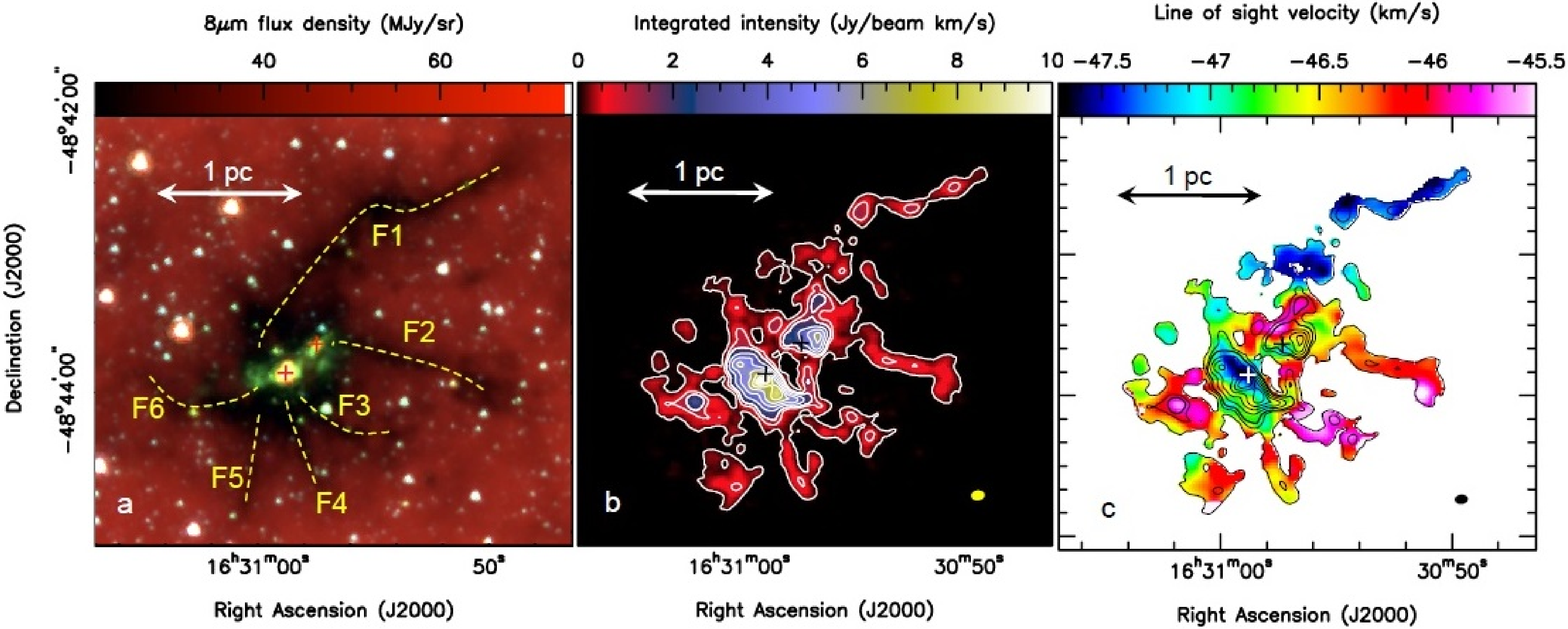
$M_{\mathrm{line}} \sim 2C_s^2/G$

Evolutionary Timescales



Mass Function of Molecular Cloud Cores and IMF

Massive Stars through Filaments



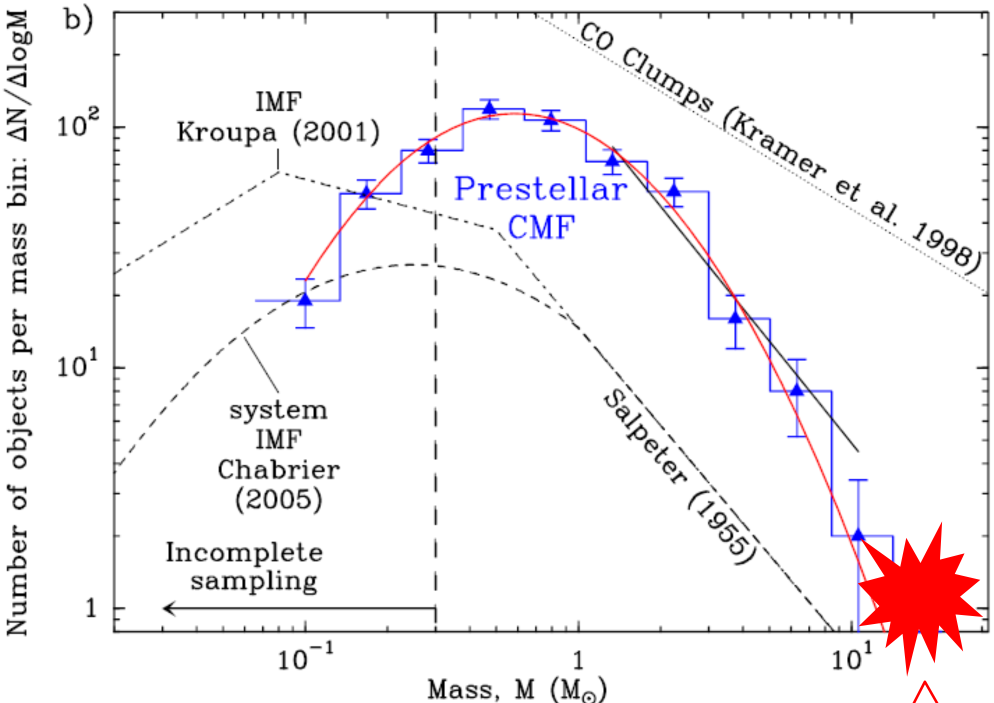
(Peretto+2013)

- Uniform but Different Velocity in Each Filament
- Infall through Filament ~ $10^{-3}\ M_\odot/\mathrm{yr}$

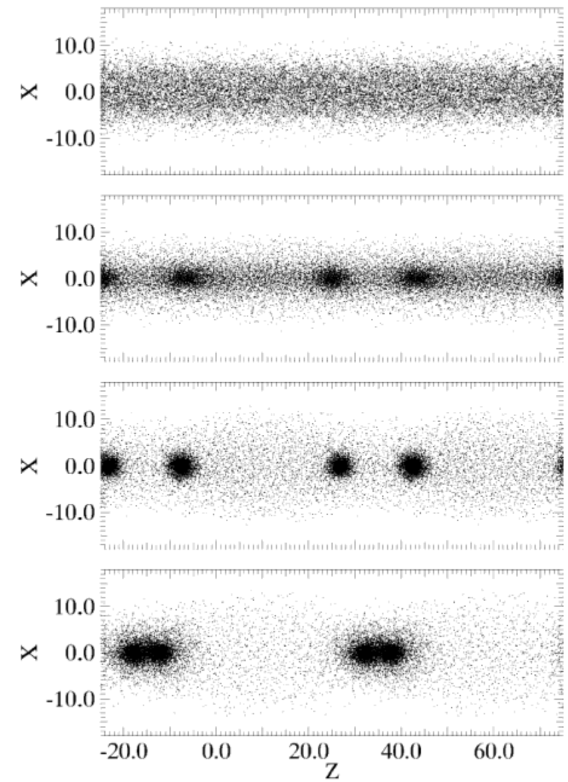
Nicely Understood in Filament Paradigm

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

Mass Function of Cores in a Filament

Inutsuka 2001, ApJ **559**, L149

Line-Mass Fluctuation of Filaments

Initial Power Spectrum

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

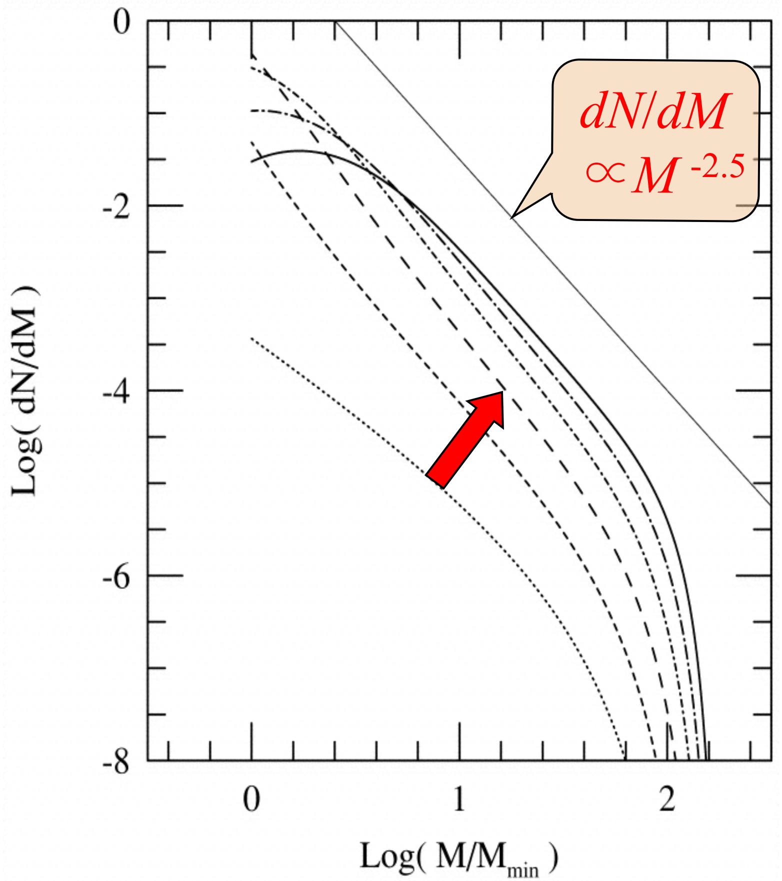
Mass Function

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

Observation of Both Perturbation Spectrum and Mass Function

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

➔direct test!

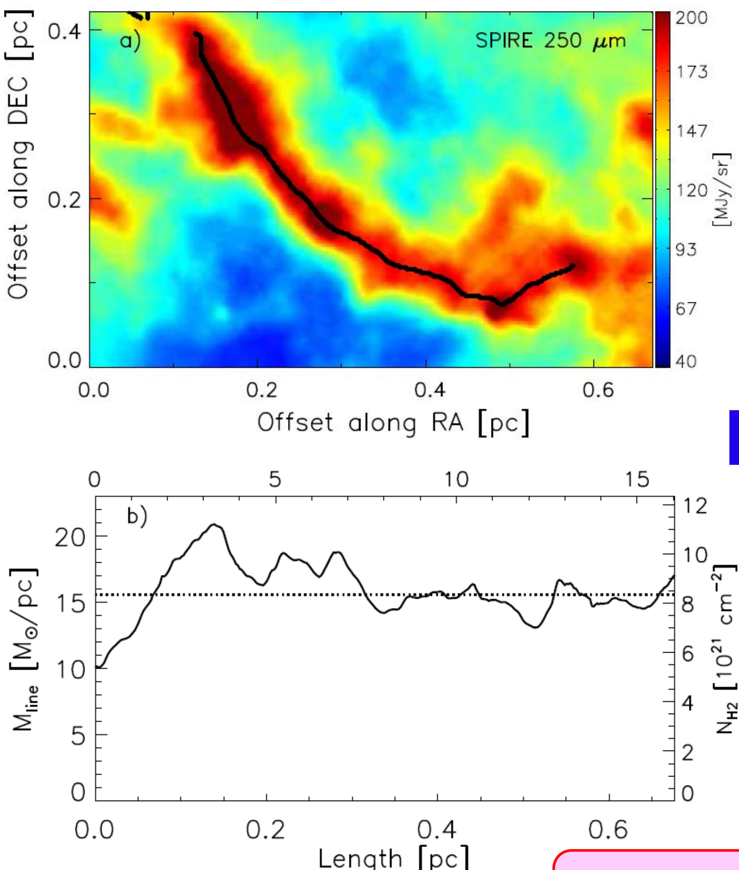


$P(k) \propto k^{-1.5}$

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"

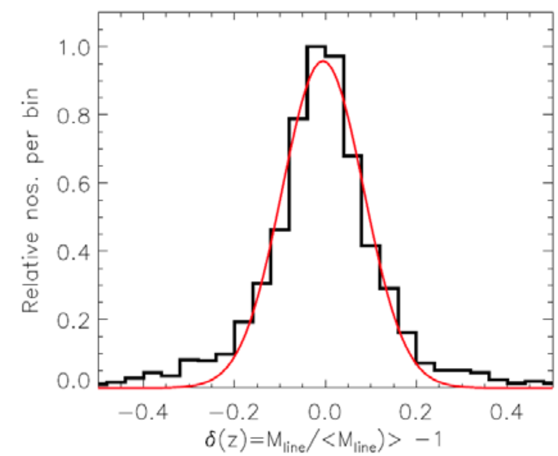
Roy, André, Arzoumanian et al. (2015) A&A **584**, A111



δ ...

Gaussian

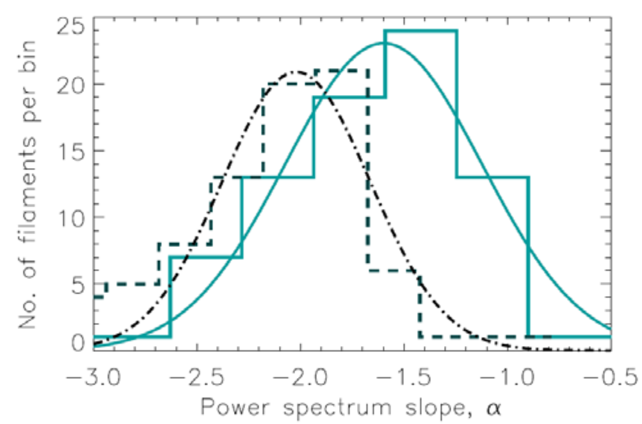
➔ **Press-Schecter**



$$P(k) \propto k^{n}$$

$$n = -1.6 \pm 0.3$$

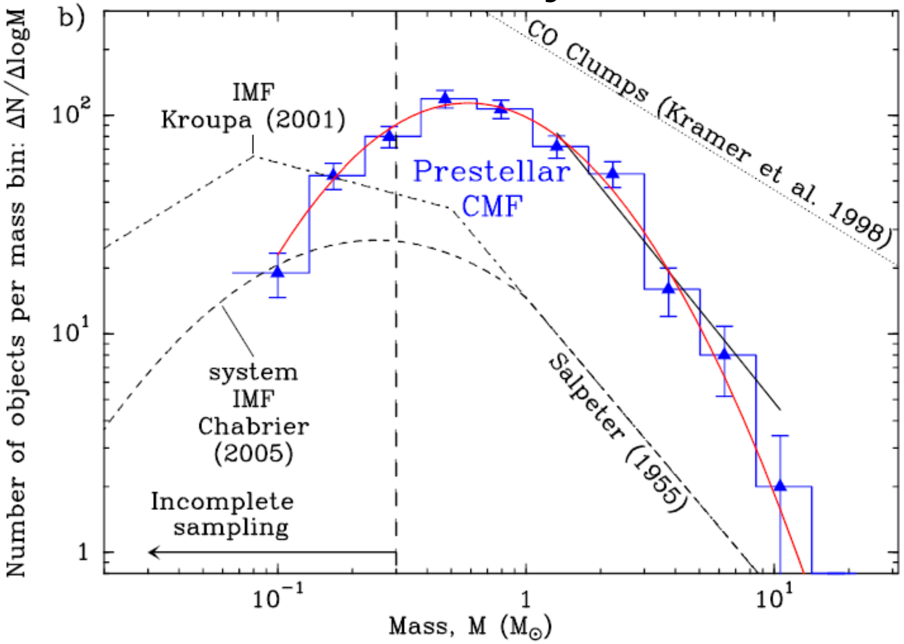
≈5/3: Kolmogorov!

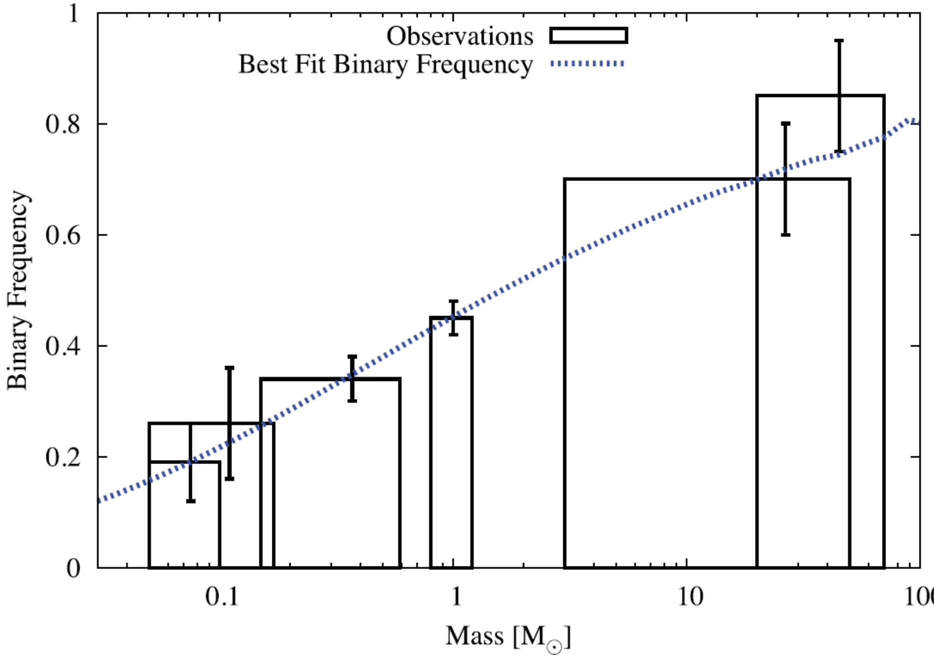


Supporting Inutsuka 2001

How About Binary Statistics?

André+2010; Könyves+2010



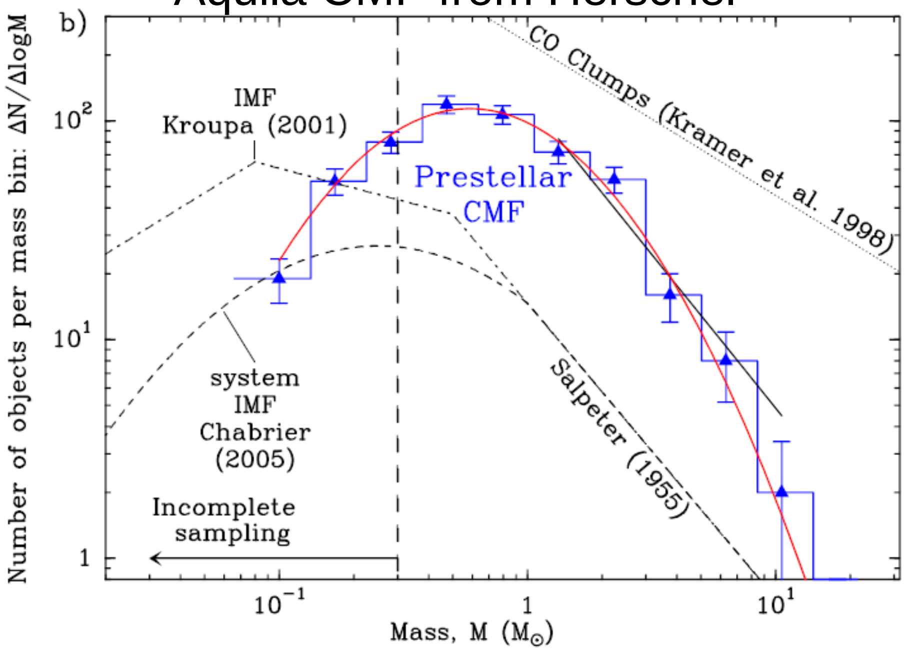


"Mapping the core mass function on to the stellar initial mass function: multiplicity matters", *Holman, Walch, Goodwin & Whitworth 2013, MNRAS*

Need for Non-Self-Similar Mapping???

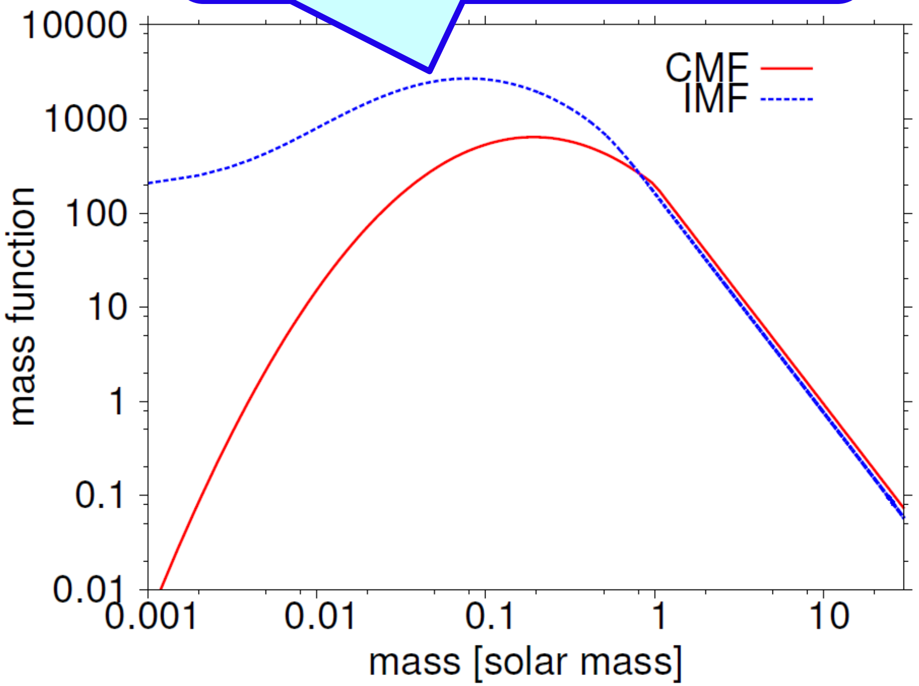
CMF to Stellar IMF with Binary SF

Aquila CMF from Herschel



André+2010; Könyves+2010

~2 Stars Created in a Core
& Binary Frequency ∝ M_*



Self-Similar Mapping from Log-Normal + Power Law

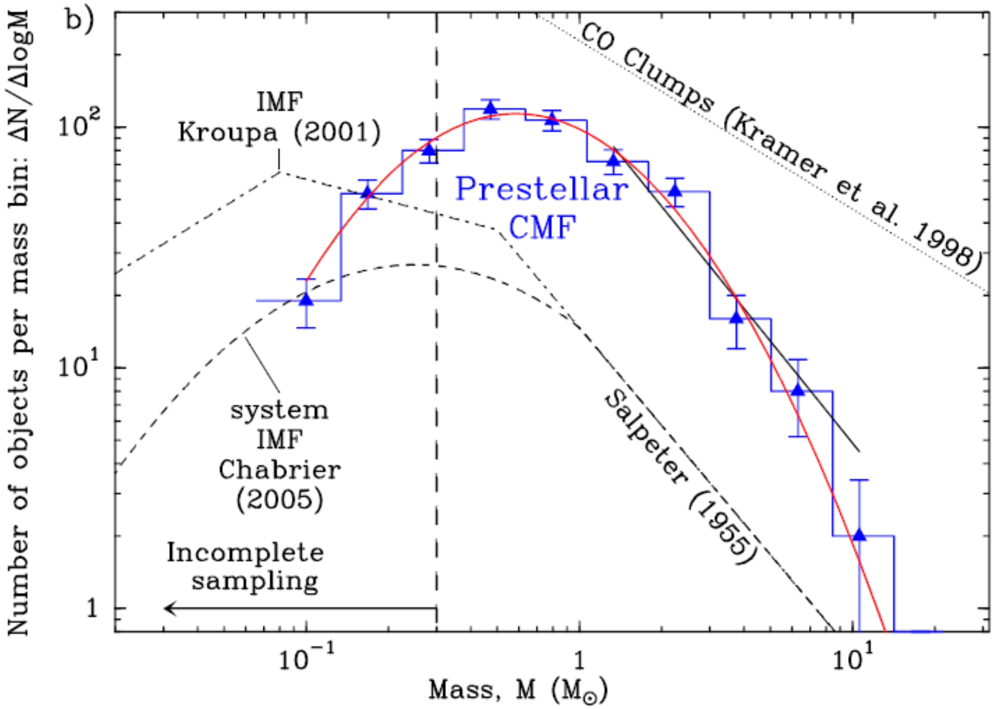
Applicable for any SF Efficiency ($M_*=\eta M_{core}$)

and any Power Law Slope (*Misugi & SI 2018, in prep*)

See also *Whitworth & Lomax 2015, MNRAS*

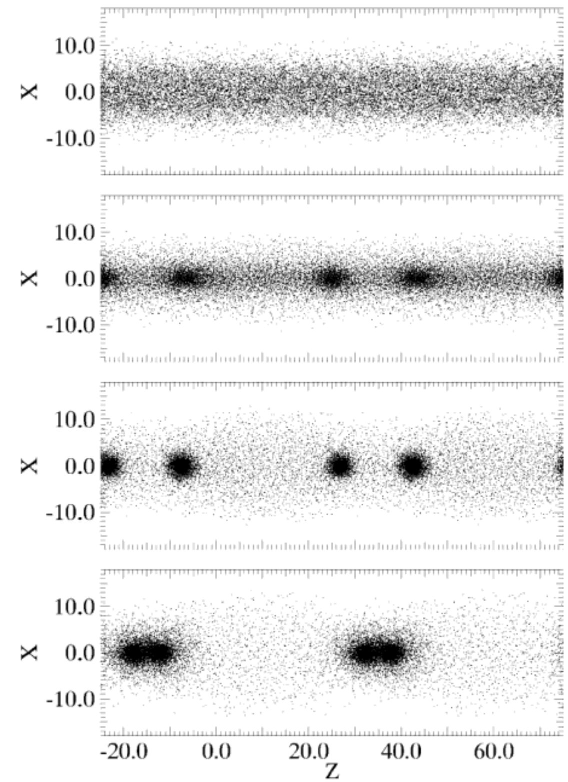
Core MF ➔ Stellar System MF

Mass Function of Dense Cores



Aquila CMF from Herschel

André+2010; Könyves+2010

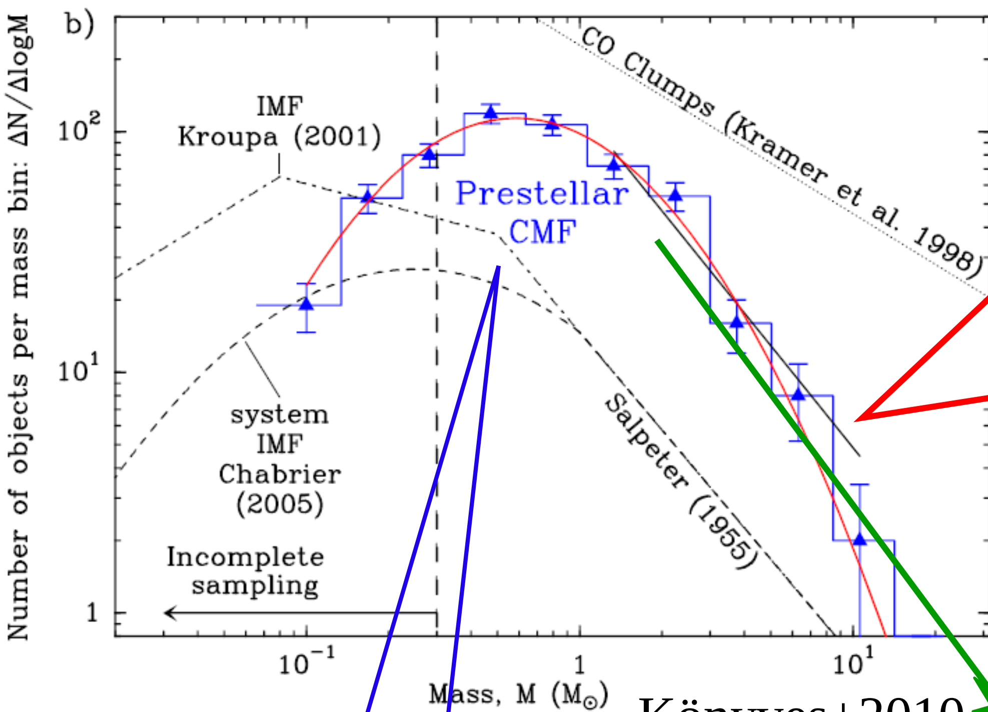


SI & Miyama 1997

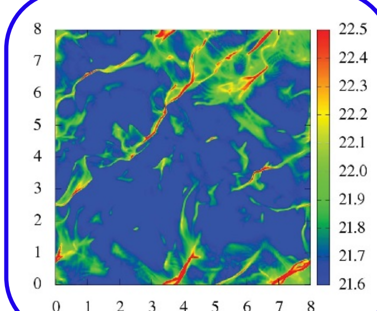
Slope of System MF = Slope of IMF

Possible Mission of JCMT-BISTRO

Aquila CMF from Herschel



Könyves+2010

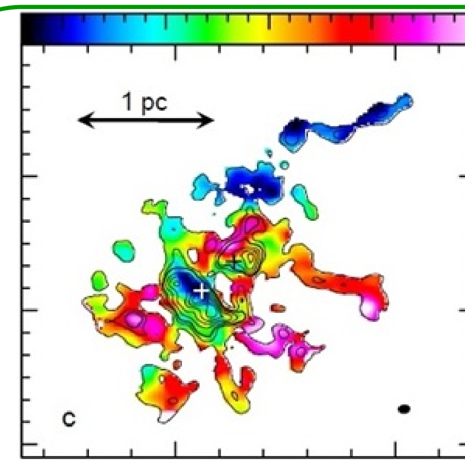


BISTRO Obs

filament ⊥ B?

filament // filament?

Intermediate Mass SF in Filament Paradigm



Peretto+2013

Massive Star Formation

Filament Paradigm

Completely Successful???

Other Modes of Star Formation?

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

Collect & Collapse (by Expanding HII Regions)

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

Toward Global Picture of Star Formation

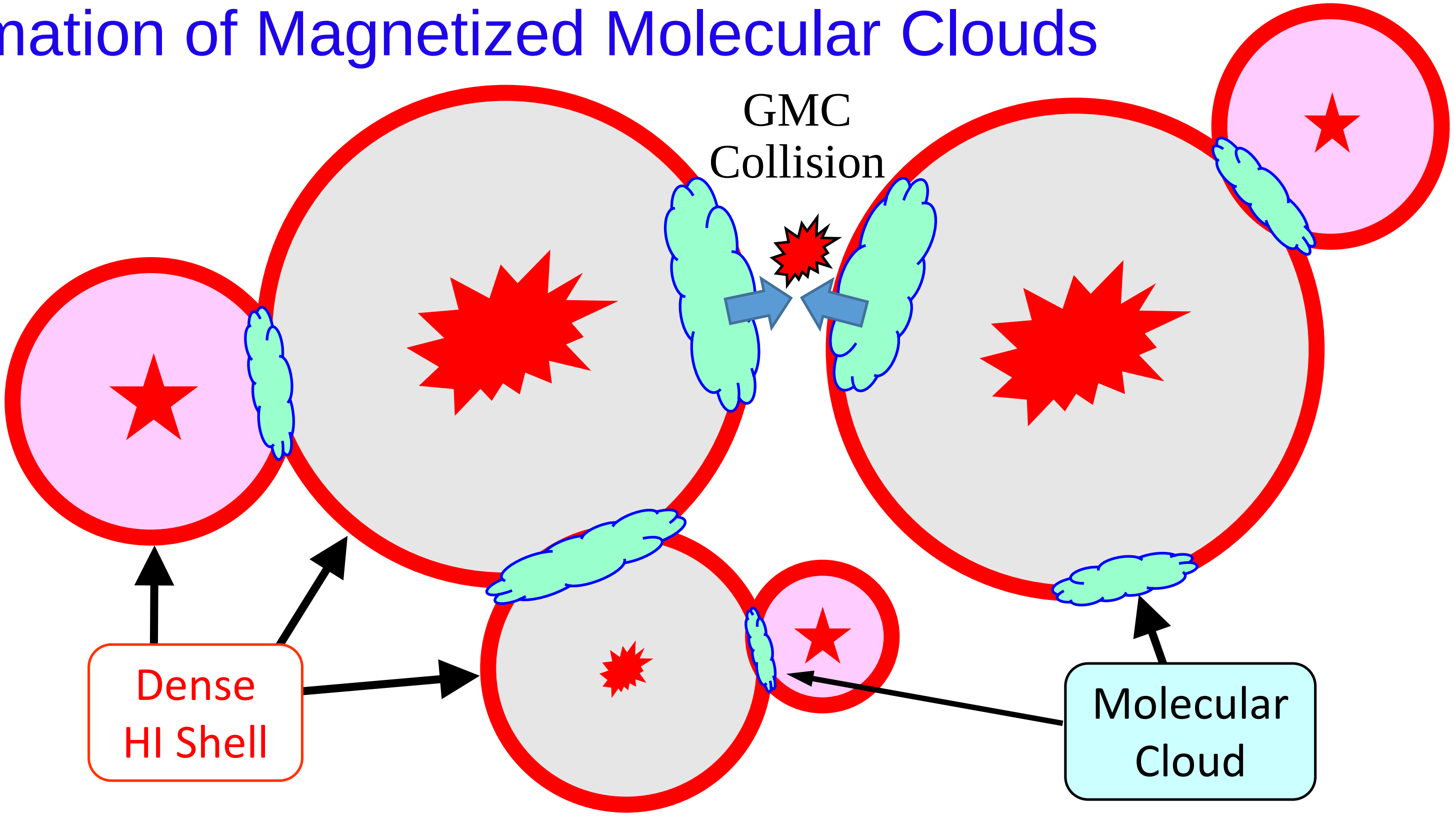
Multiple Compressions Needed
for Molecular Cloud Formation

t_{form} = a few 10^7yr

(1 Compression in 1Myr)

Network of Expanding Shells

Multiple Episodes of Compression ➔
Formation of Magnetized Molecular Clouds



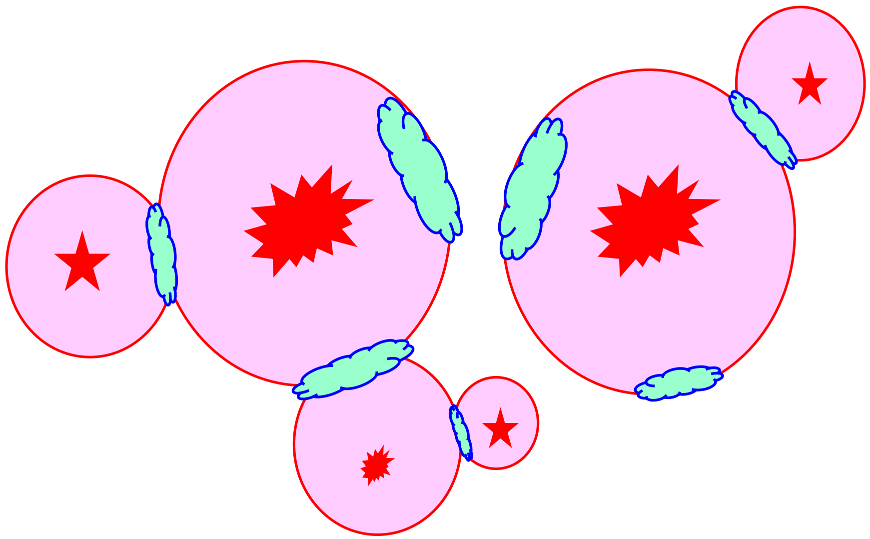
Long (>10Myr) Exposure Picture!

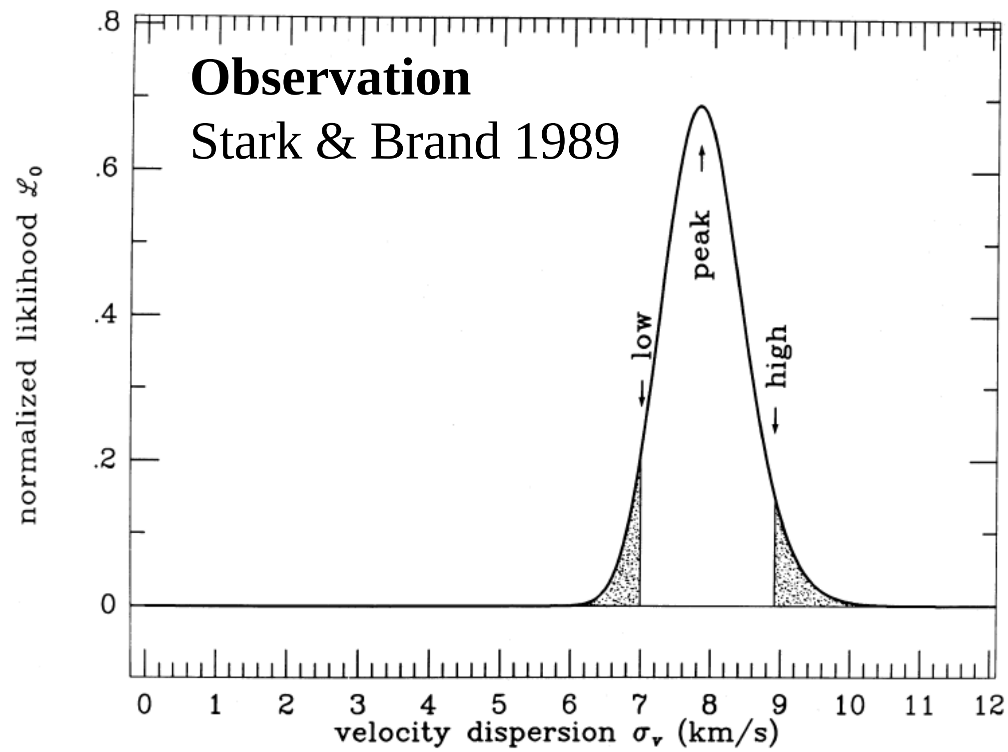
Each bubble clearly visible only for short time (<Myr).

SI+2015

Cloud-to-Cloud Velocity Dispersion

Multiple Episodes of Compression ➔ Formation of Magnetized Molecular Clouds

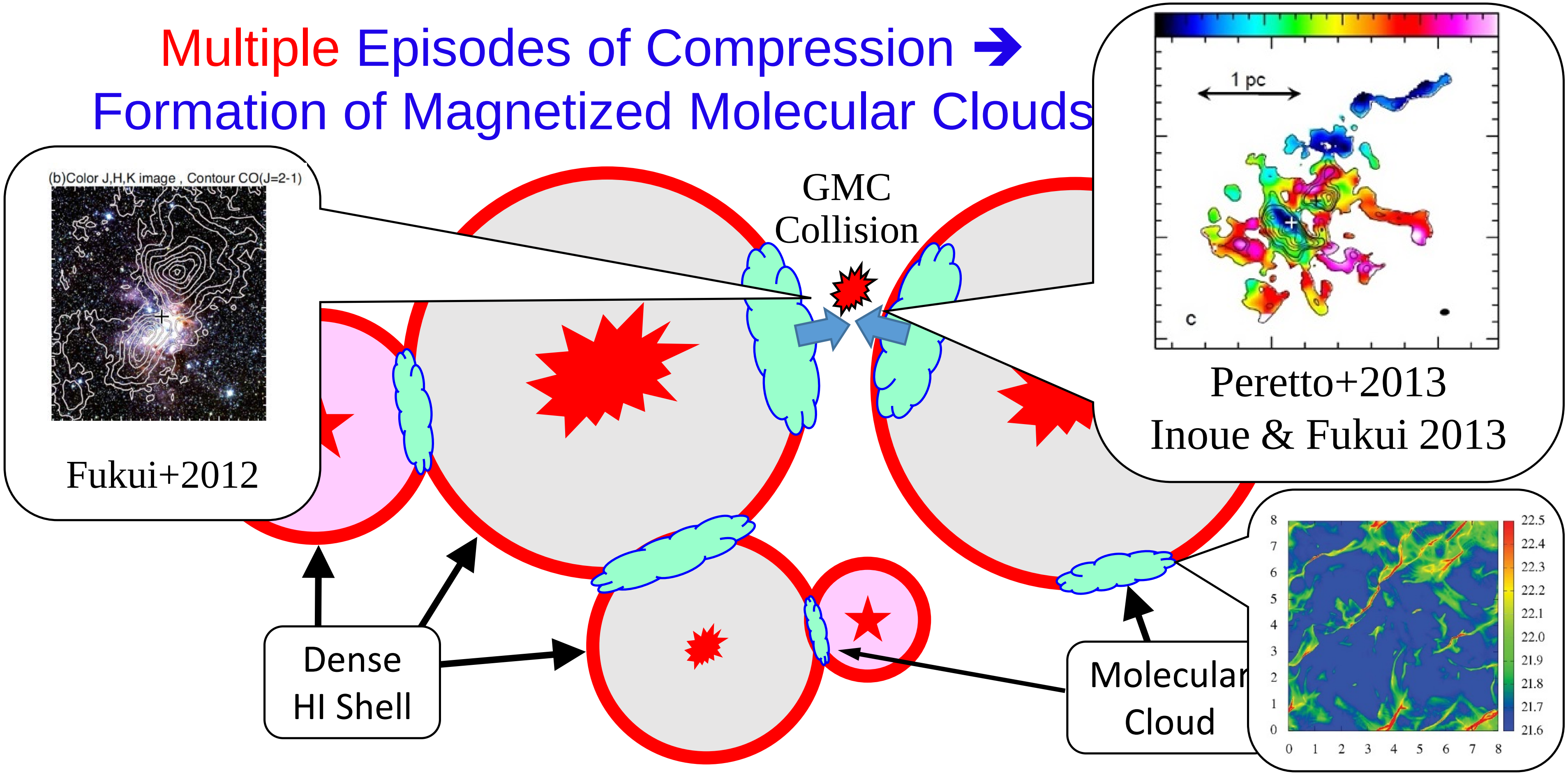




Shell Expansion Velocities $\lesssim 10^1$ km/s ➔ Cloud-to-Cloud Velocity Dispersion

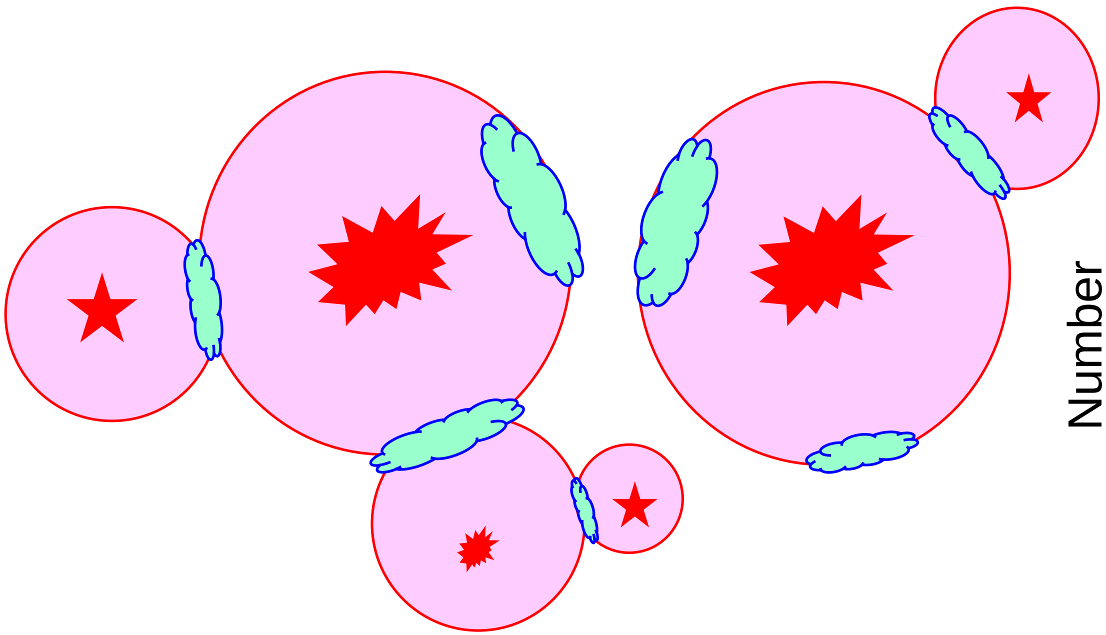
Network of Expanding Shells

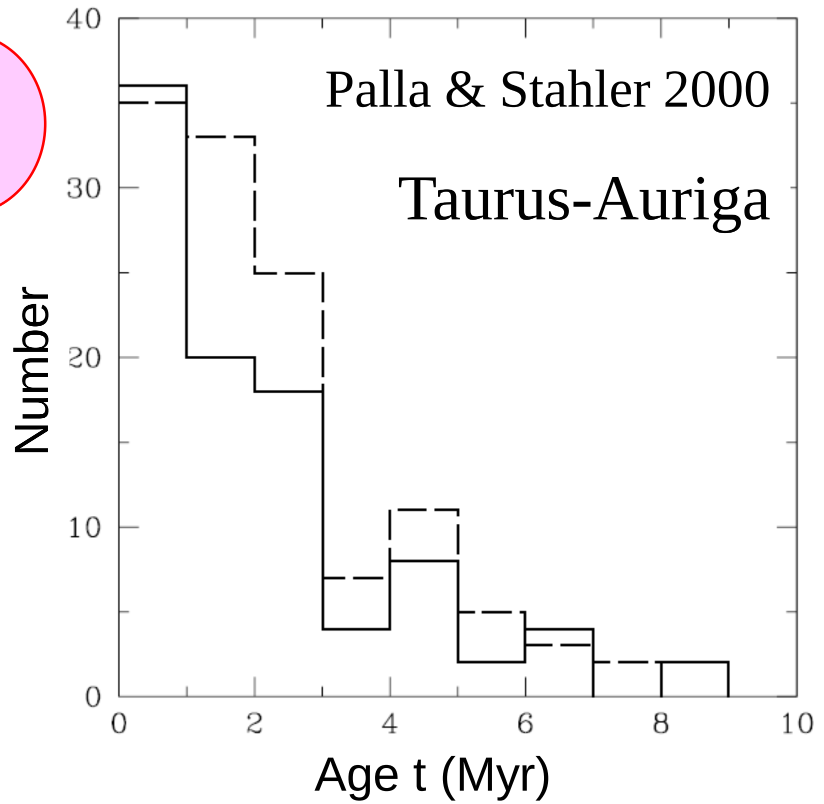
Multiple Episodes of Compression ➔
Formation of Magnetized Molecular Clouds



SF starts in filaments once $M_L \sim M_{L,crit} = 2C_s^2/G$
and may intensify with increasing M_{cloud} !

Accelerated Star Formation





Molecular Cloud Growth

➔Gradual Activation of SF

➔Multiple Episode of SF in OB-Association

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

Star Formation Efficiency in Dense Gas

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

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

Theory?

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

$$\varepsilon_{\rm core} \sim 33\%$$

Ex) Theory by 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: $t_{\rm dense\ gas}$

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

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

(eg. Lada+2010, Andre+2014)

How Many Generations of Filaments?

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

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

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:

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

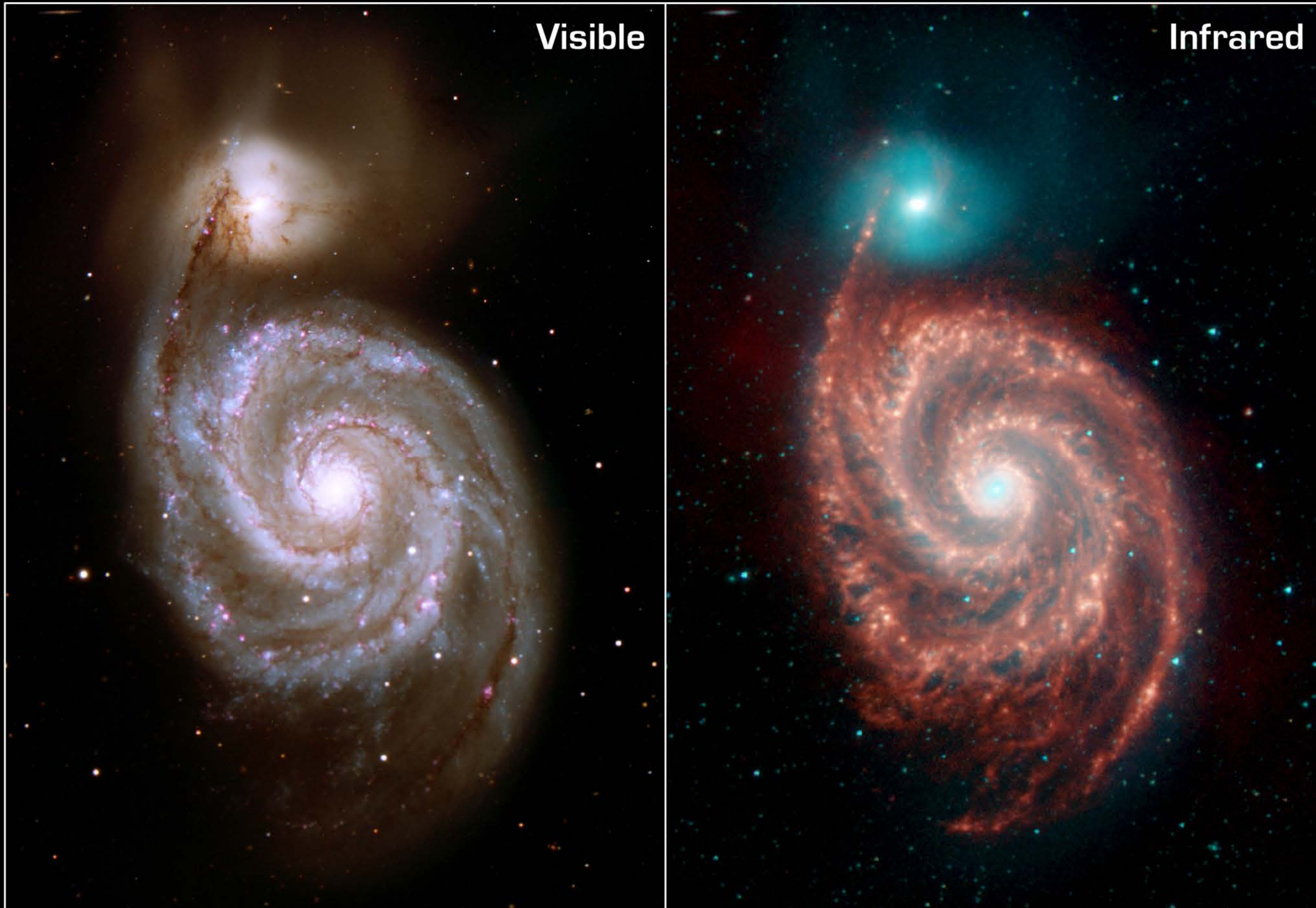
→ Total Mass of YSOs: $M_{*\text{total}}$

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

→ Multiple Generations of Filaments Needed!

Applicability of Present Scenario

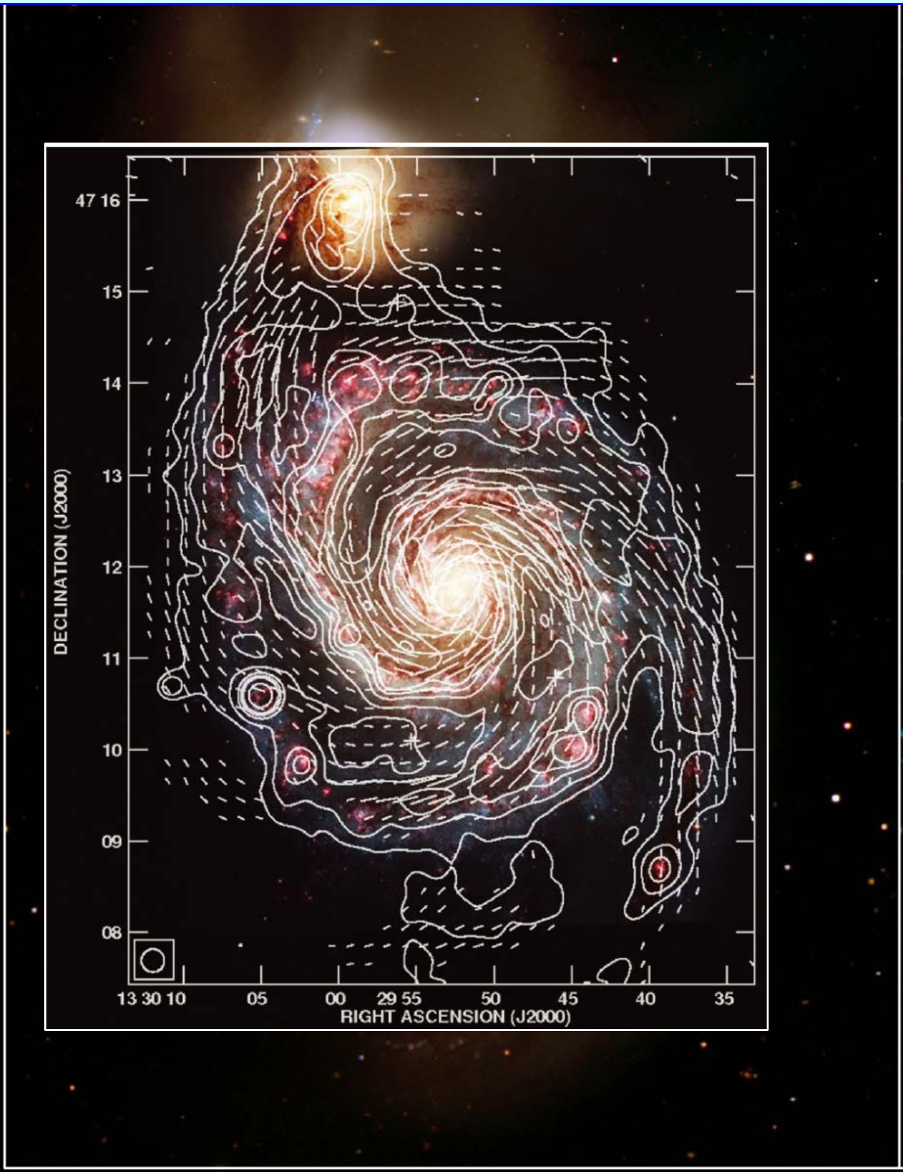
Implication to Observation

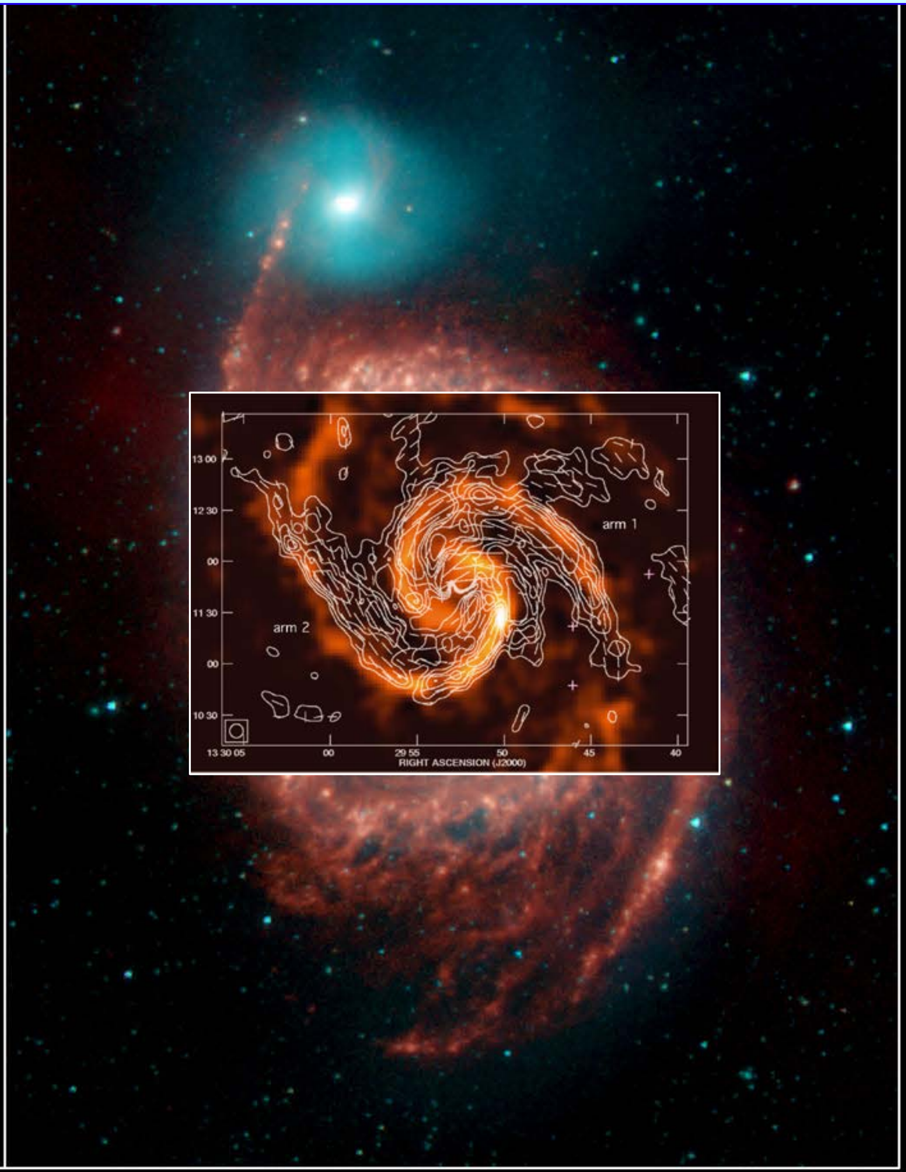


Spiral Galaxy M51 ("Whirlpool Galaxy") Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / R. Kennicutt (Univ. of Arizona) ssc2004-19a

M51 Synchrotron





λ =6 cm radio emission at 15 arcsec resolution from VLA and Effelsberg

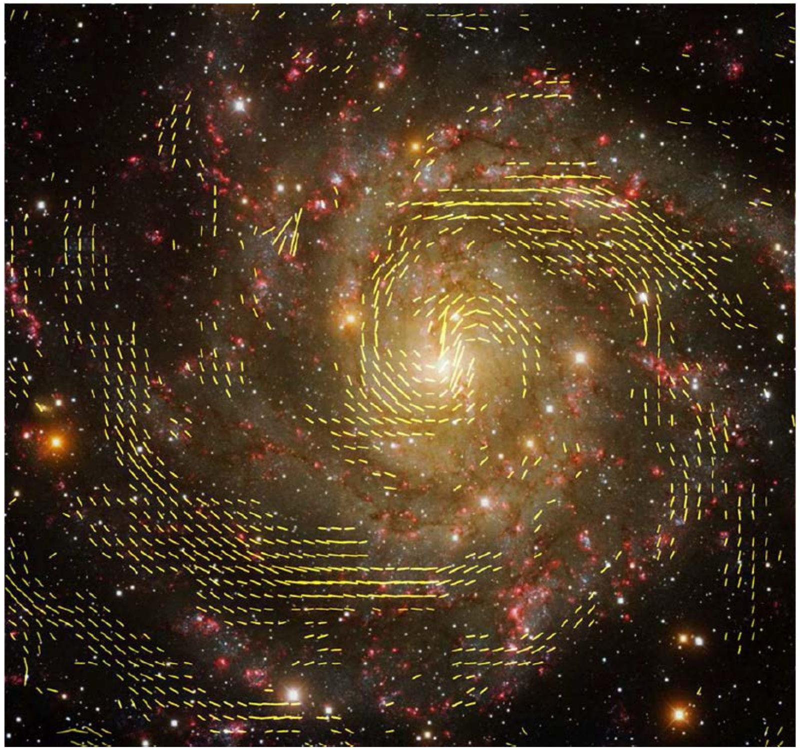
Polarized Intensity (Fletcher+ 2011)

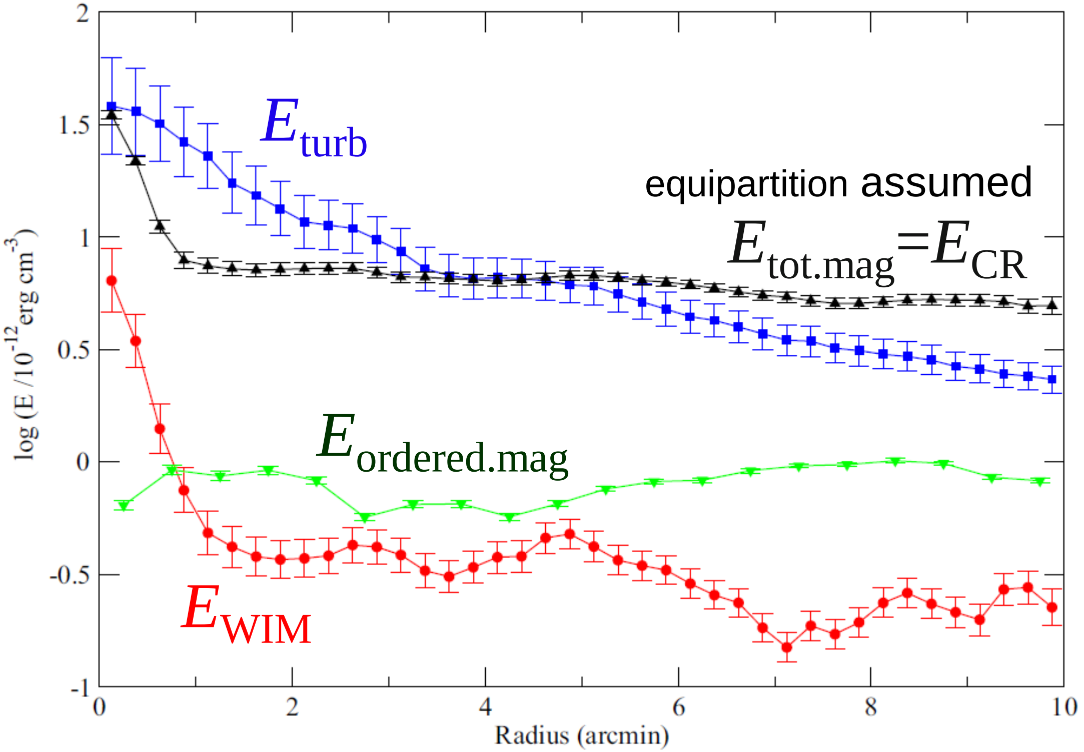
Various Energy Densities

Polarization B-vectors of **IC 342**

6cm VLA and Effelsberg telescopes

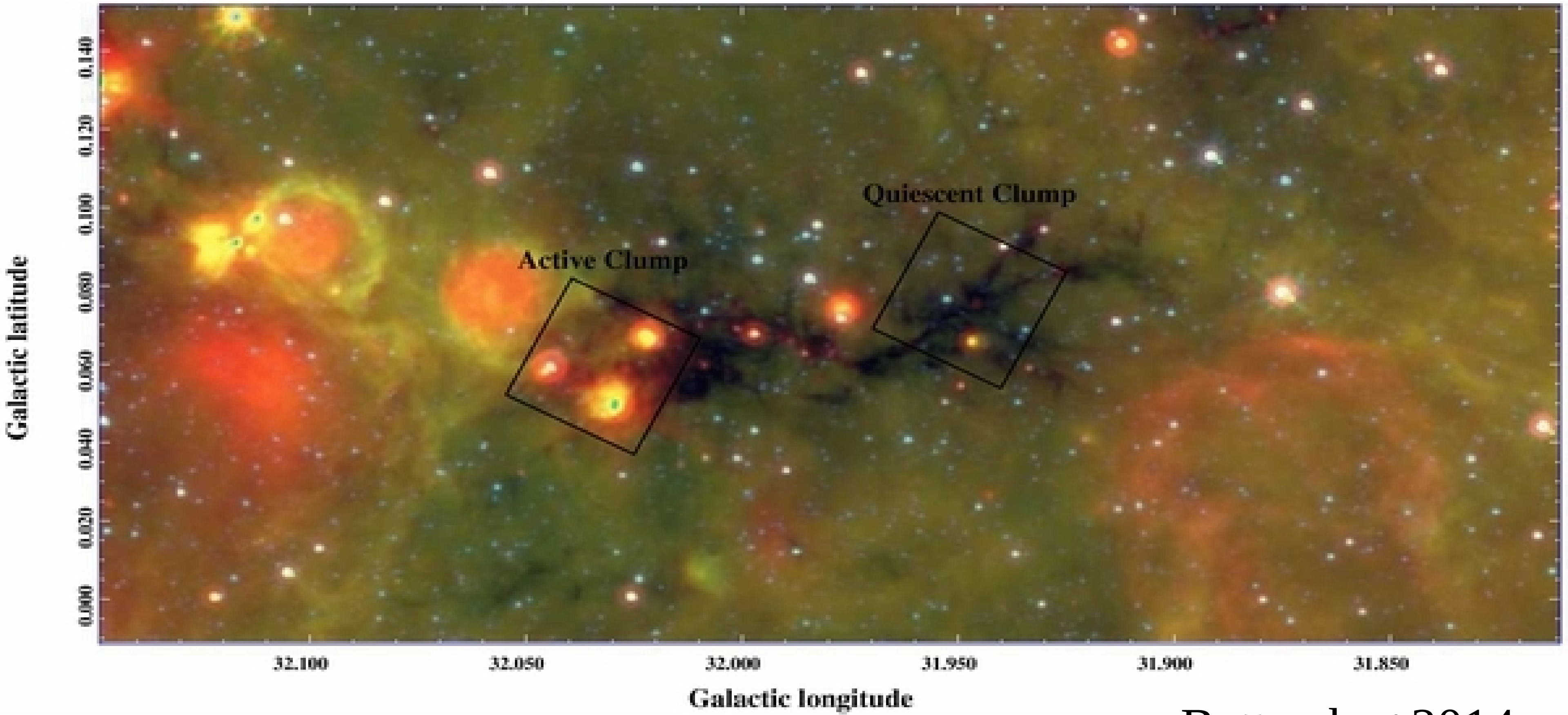
Beck 2015





Magnetic energy dominates thermal energy!

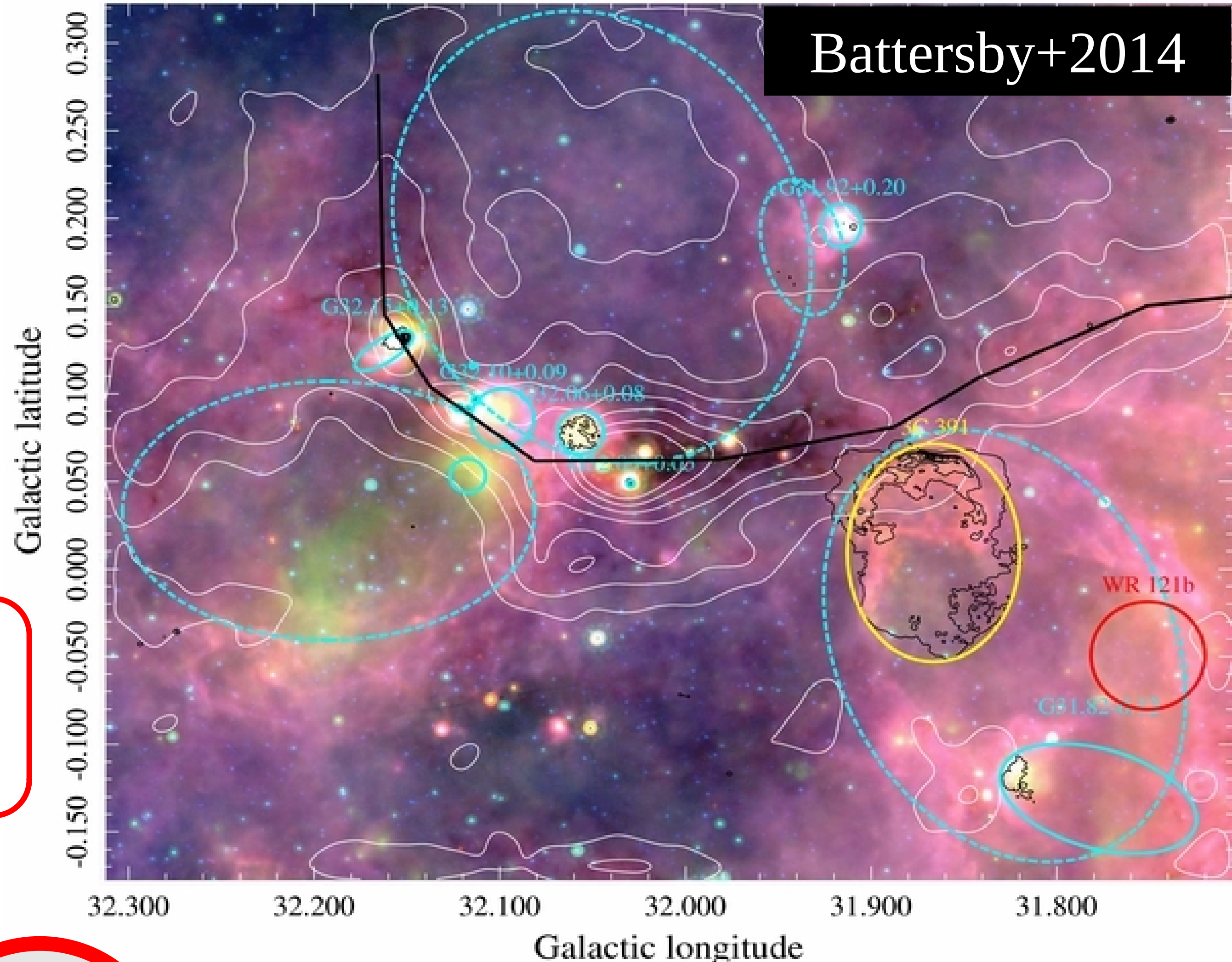
Massive Star Formation in Ridge



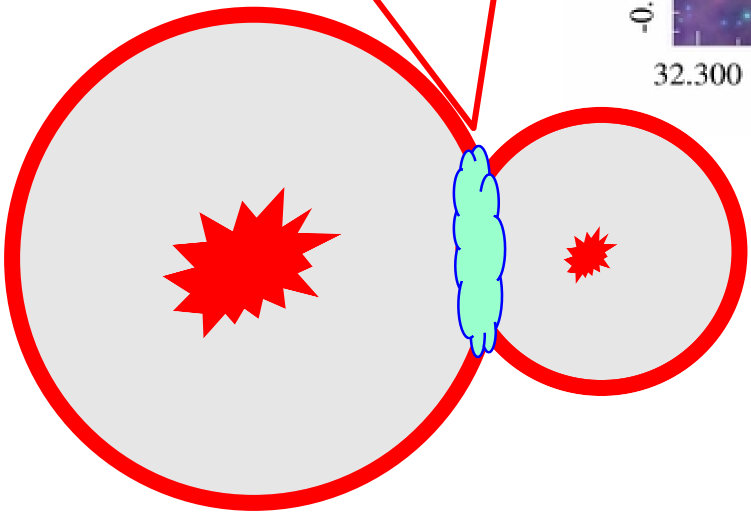
Battersby+2014

Extensive Herschel Studies on Massive Star Formation in "**Ridges**"

Ridge or Edge-On Shell?

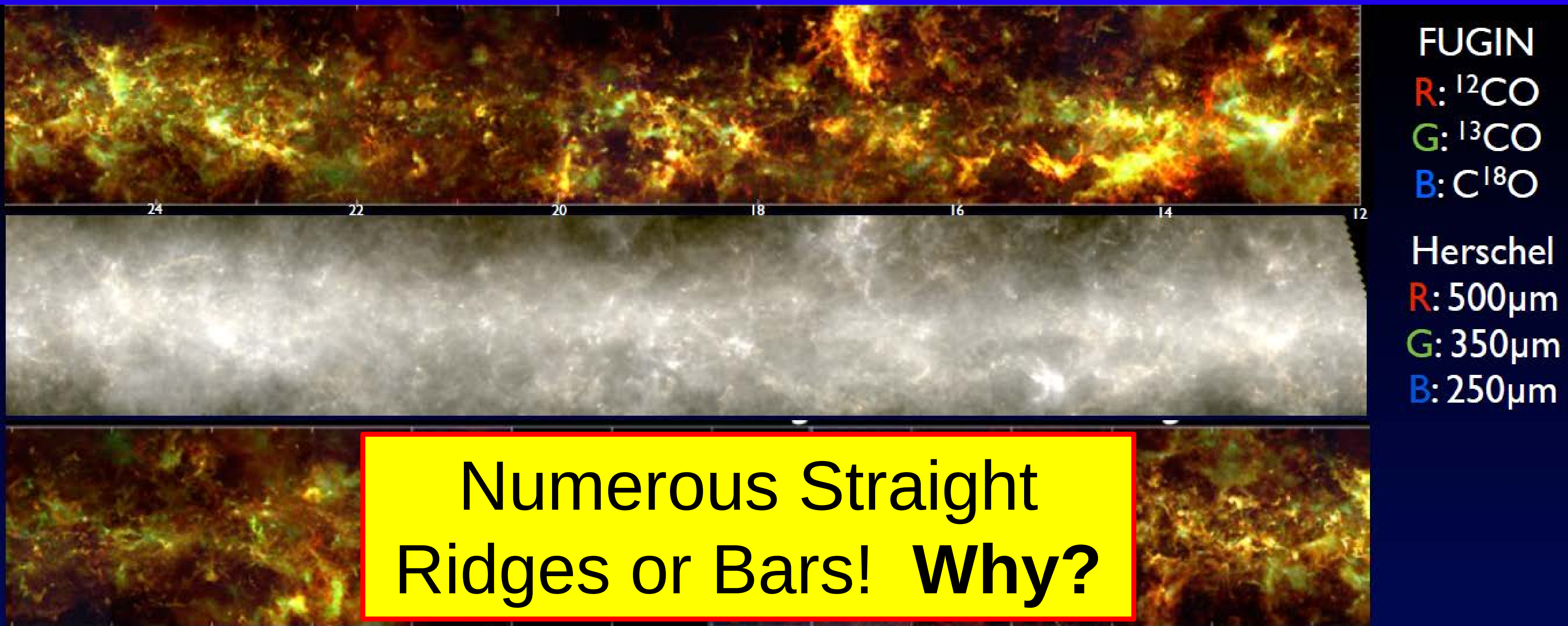


Edge-On View of
Compressed Shell
➔ Ridge or Bar!

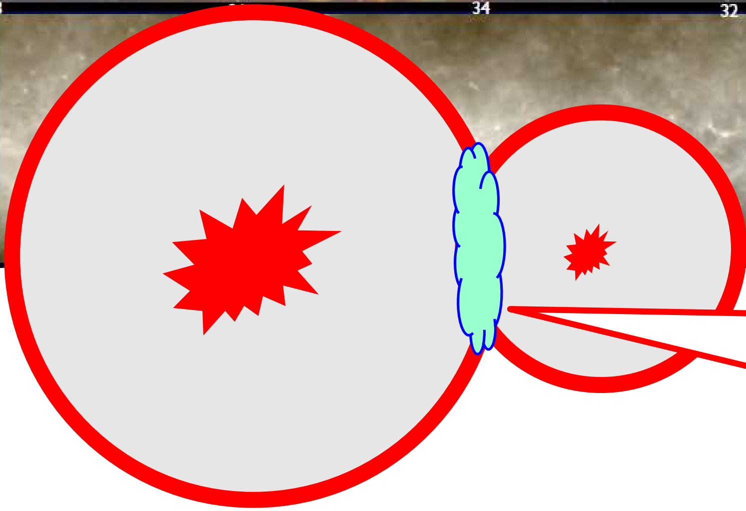


Bubbles (cyan dashed circles)
HII regions (cyan solid circles)
SNR 3C 391 (yellow oval)
Wolf–Rayet star WR 121b (red oval)

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!!!

Destruction of Molecular Clouds

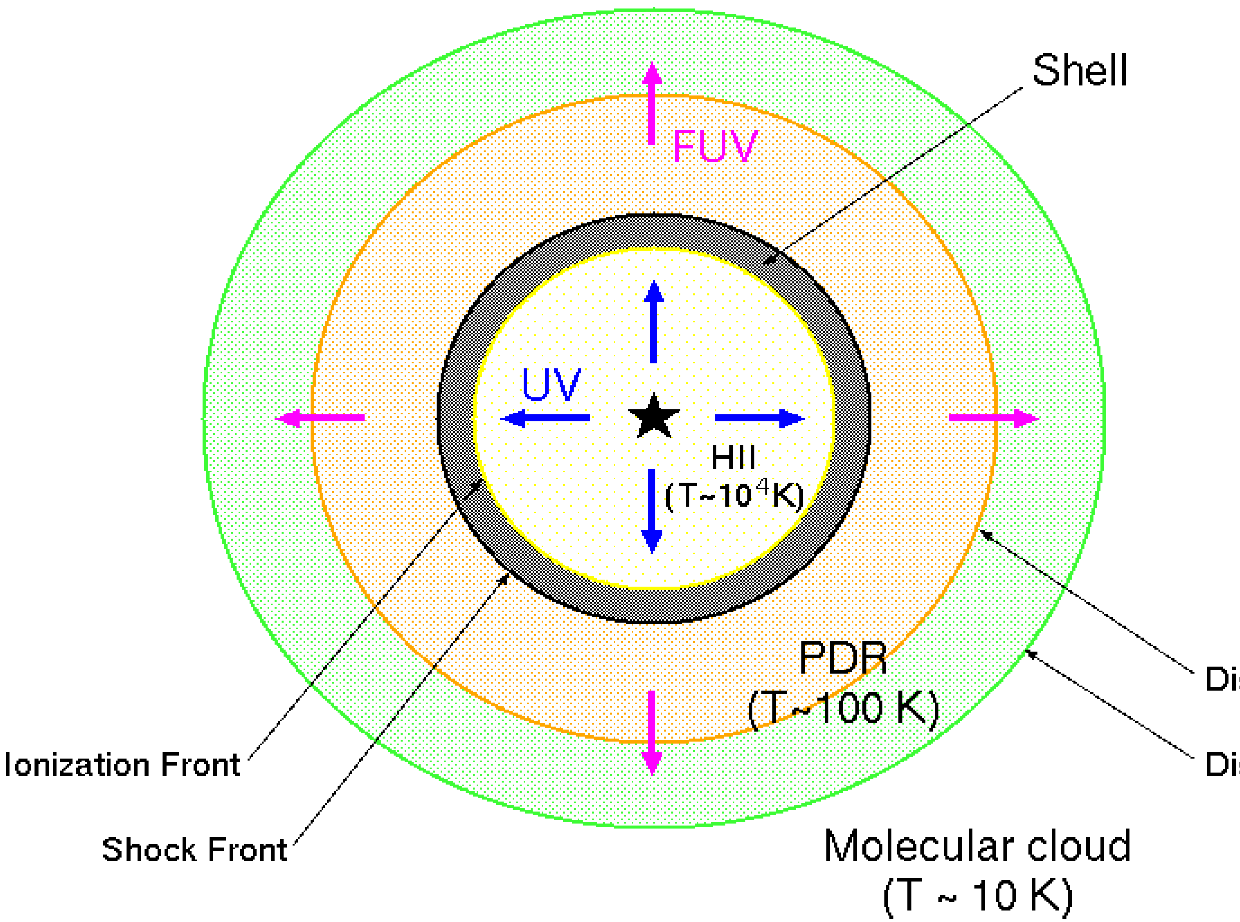
How to Stop Star Formation?

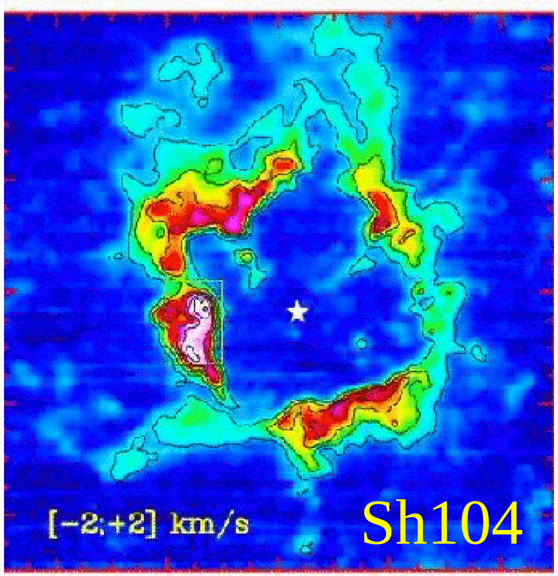
Radiative Feedback

Photodissociation Critical!

c.f. *Dale, Walch,…*

Expanding HII Region in **Magnetized** Molecular Cloud





Deharveng et al. 2003

Radiation Magnetohydrodynamics Calculation

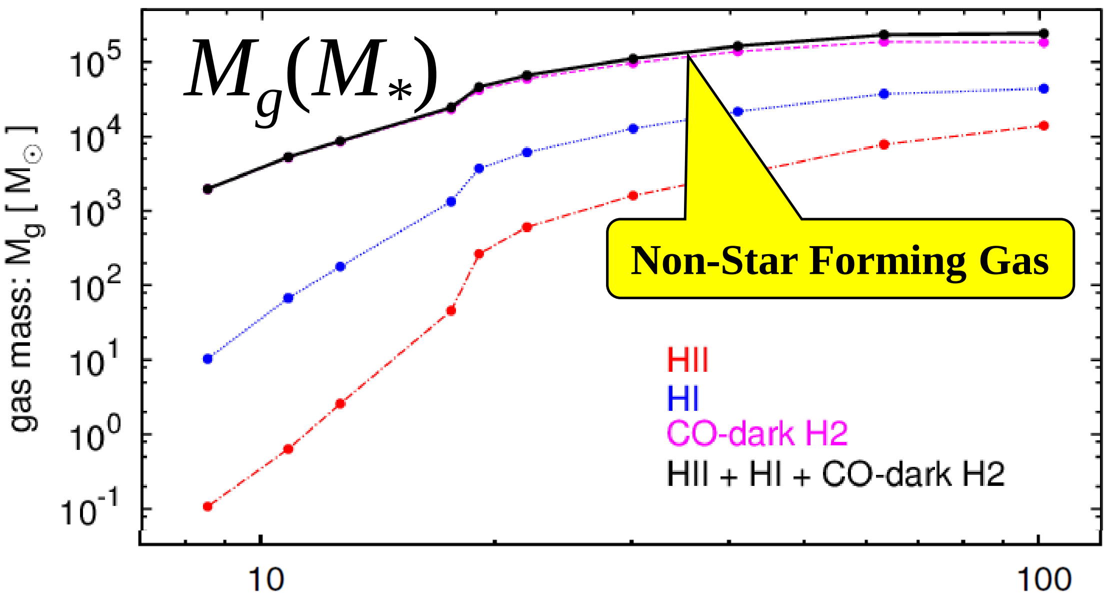
UV/FUV + H_2 + CO Chemistry (Hosokawa & SI 2005, 2006ab, 2007)

Disruption of 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!



Central Stellar Mass, $M_* / M_\odot$

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

Disruption of Magnetized Molecular Clouds

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

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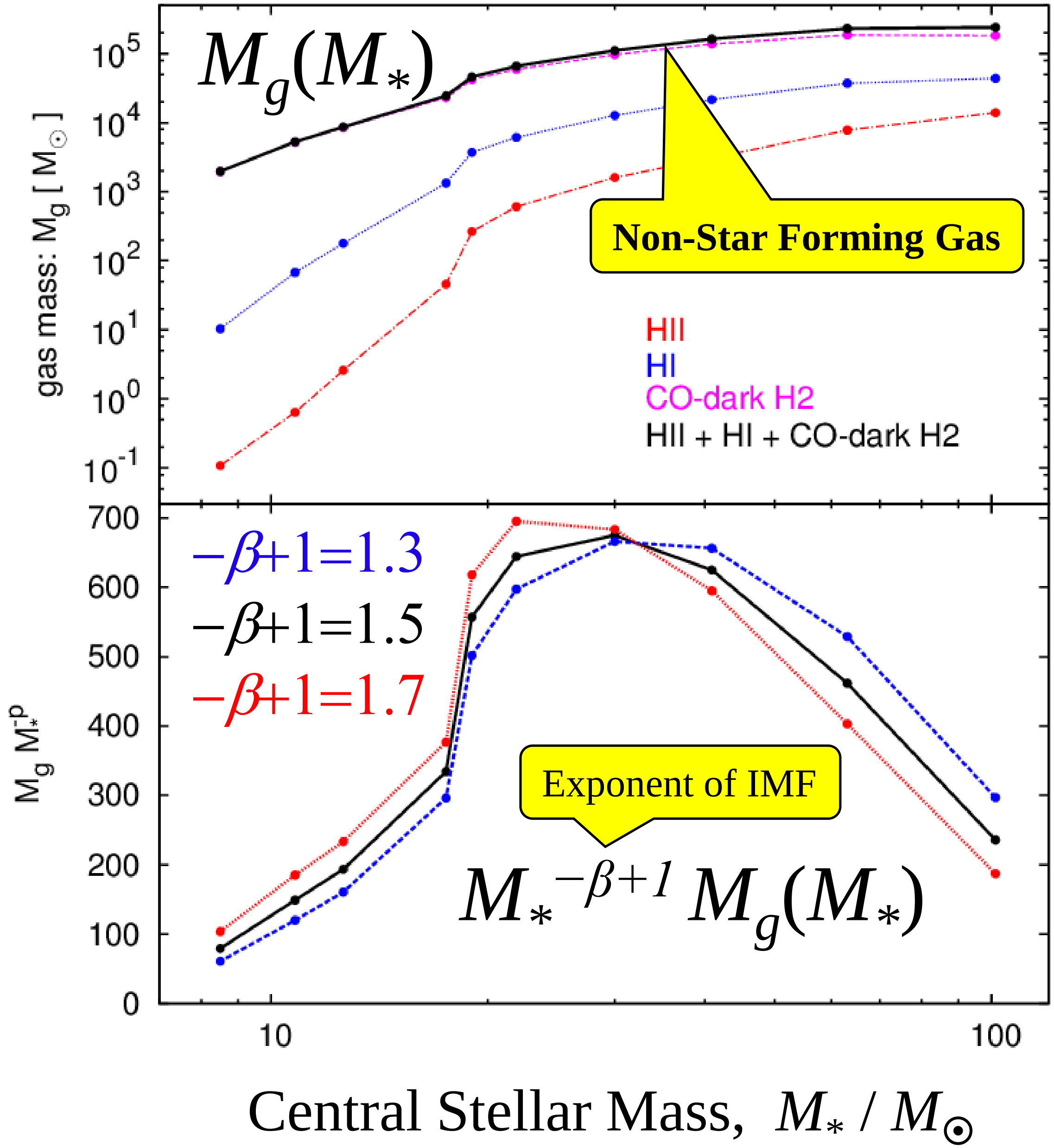


(*SI, Inoue, Iwasaki, & Hosokawa 2015* A&A **580**, A49)

Star Formation Efficiency & Schmidt-Kennicutt-Law (SI+2015)

$10^5 M_\odot$ 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_*

No Dependence on Mass ➔ Schmidt-Kennicutt Law

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

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

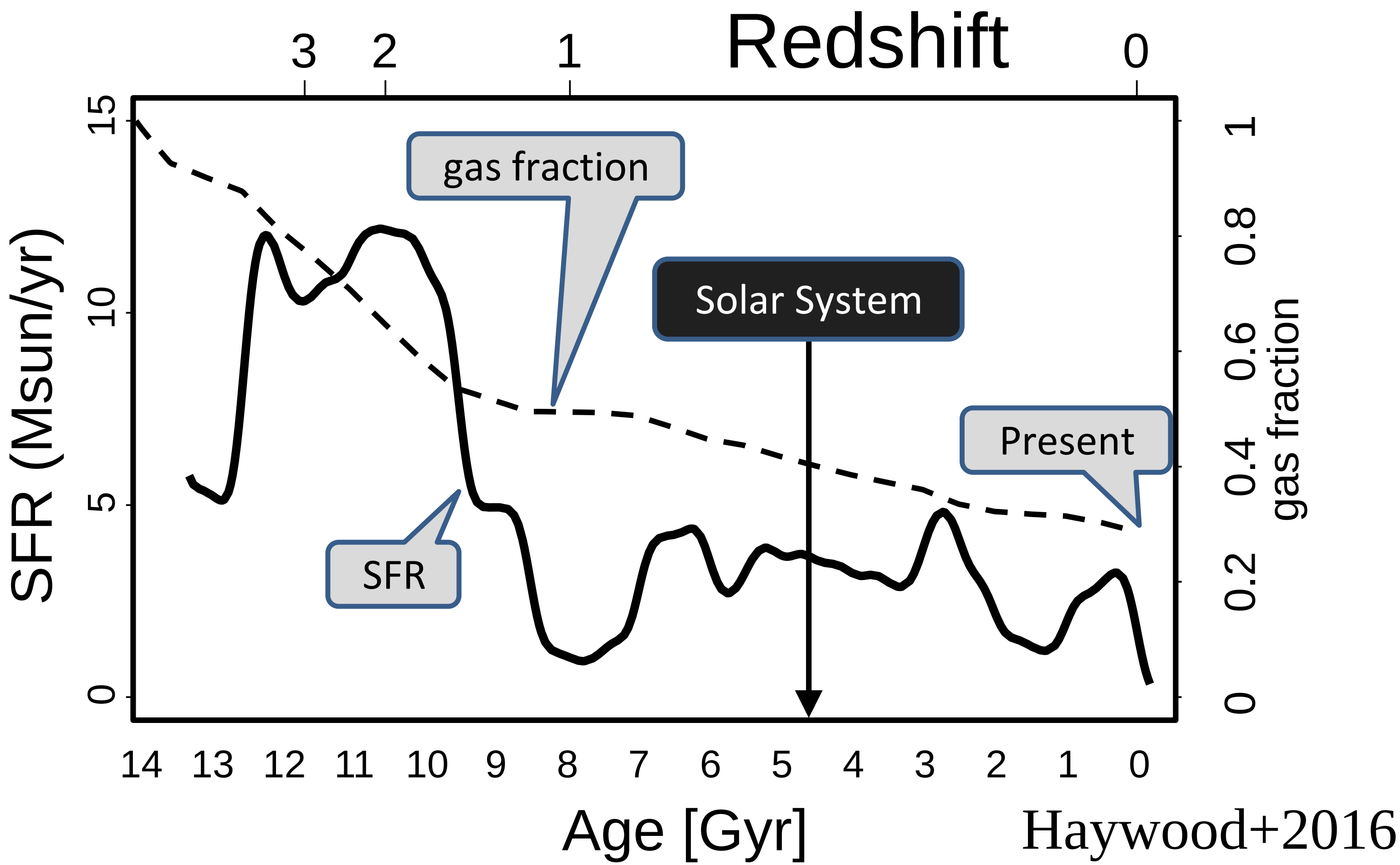
$$\varepsilon_{SF} = \frac{10^3 M_\odot}{10^5 M_\odot} = 0.01$$

observation

β of IMF

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

How far can we trace back?



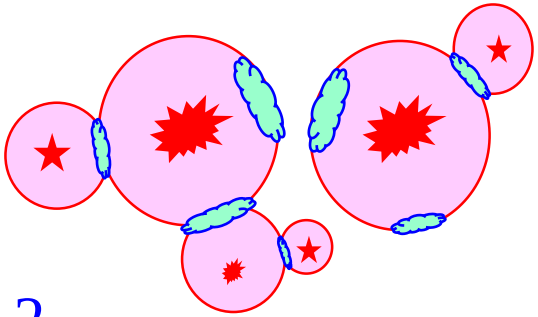
Present SF mode responsible for z < 2

in Our Galaxy!

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: t_{disp}(total gas)~1Gyr

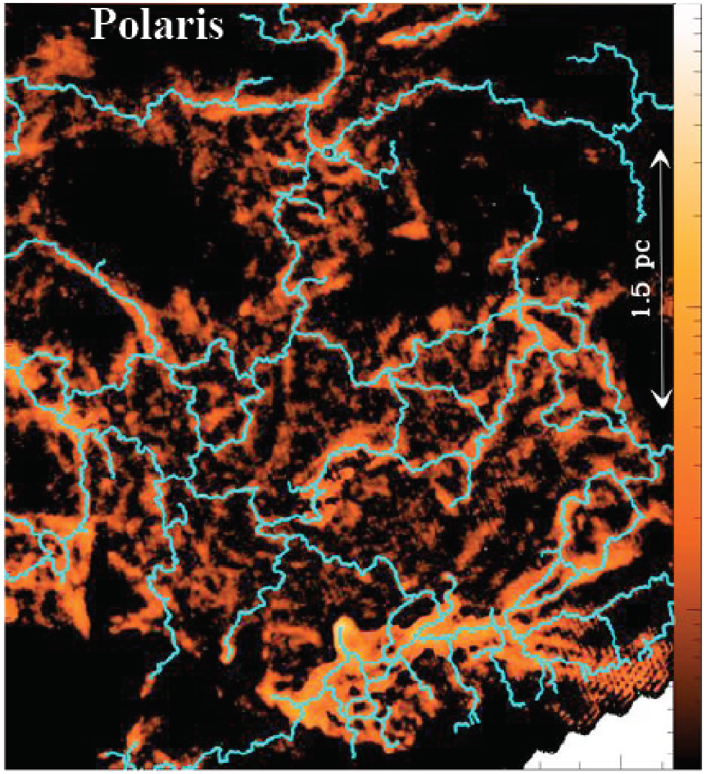
  t_{disp}(dense gass) ~ 20Myr

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

Kobayashi+2017, ApJ **836**, 175; *Kobayashi*+2017, PASJ submitted

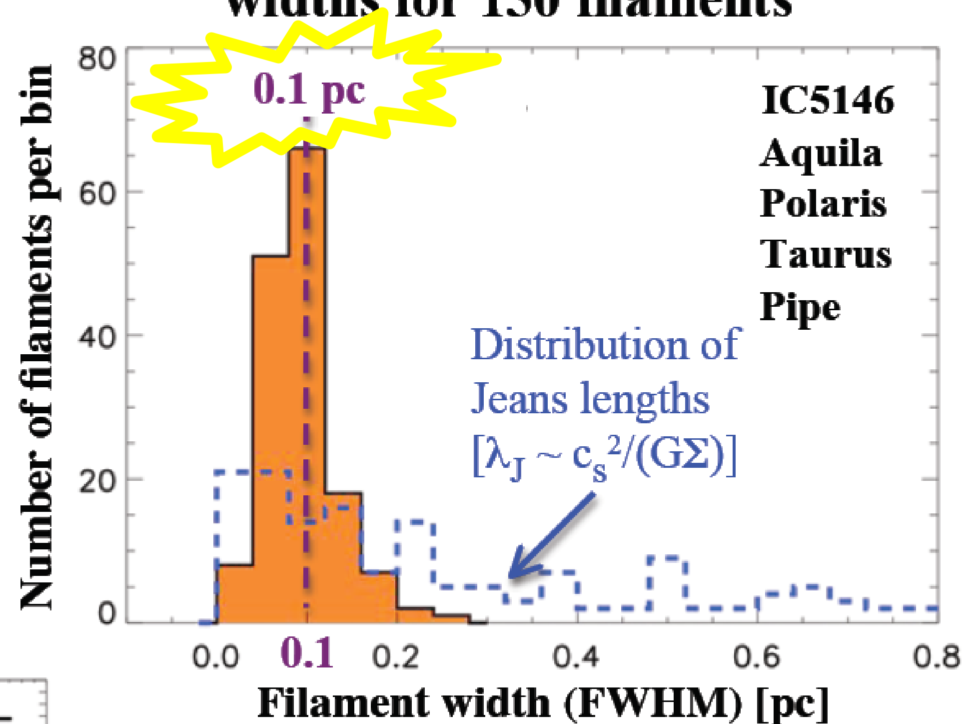
Open Question: Characteristic Widths of Filaments

Filaments have a characteristic width ~ 0.1 pc

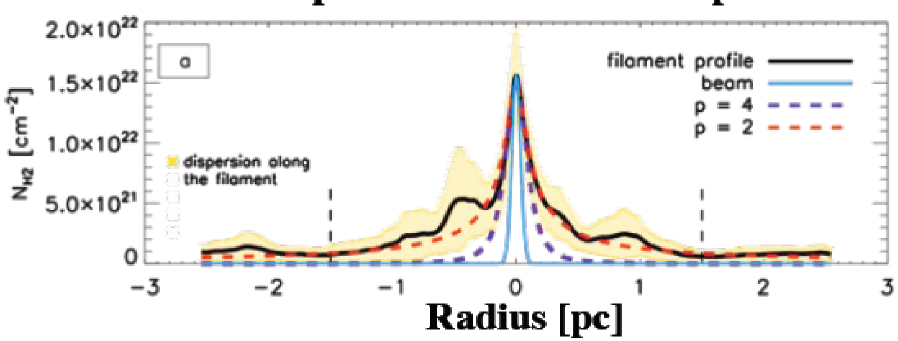


D. Arzoumanian et al. 2011, A&A, 529, L6

Statistical distribution of widths for 150 filaments

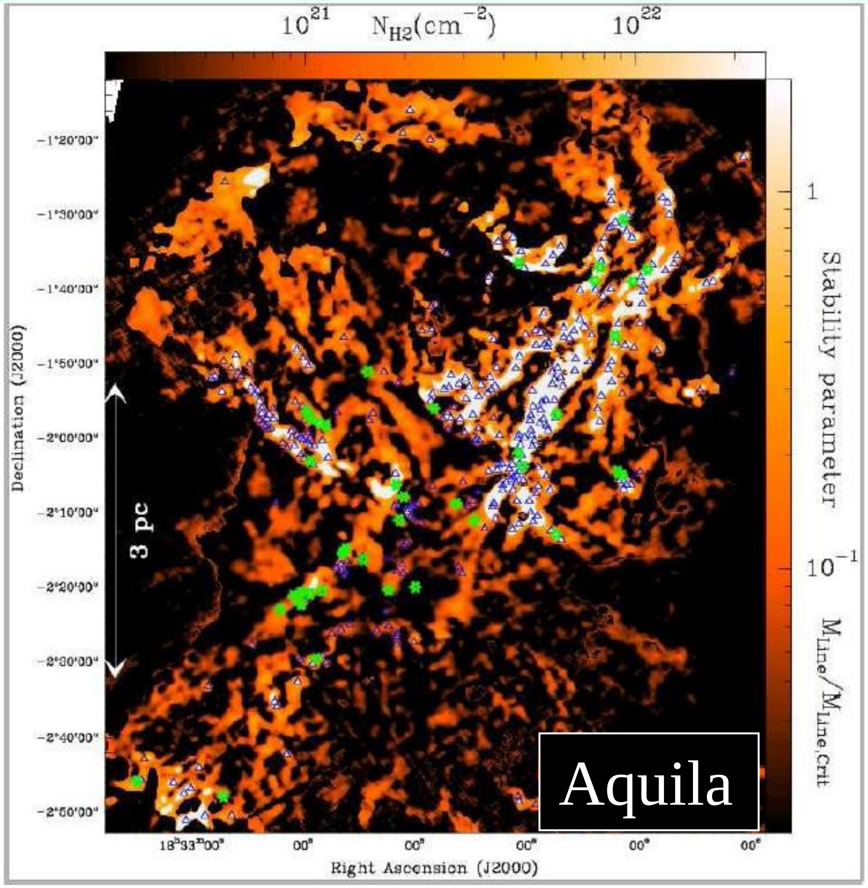


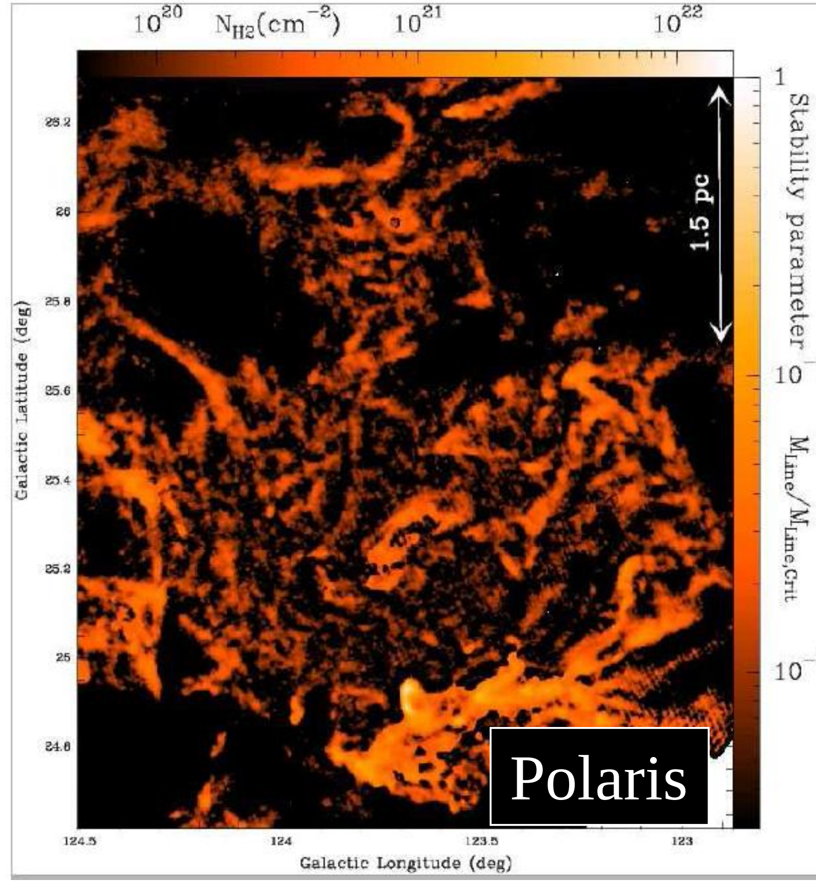
Example of a filament radial profile



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?

Open Questions (Personal)

- Why 0.1pc Width?
- Herschel Observation (e.g., Andre+2014, Könyves+2015)

$$M_{\rm core} / M_{\rm filament} < 15\% \quad \text{Why?}$$

- Gas Dissip. time: $\tau_{\rm dis} = \frac{T_{\rm d}}{\varepsilon_{\rm SF}} \sim$ 1.4Gyr ➔ KS Law

if SF Efficiency $\varepsilon_{\rm SF} \sim 10^{-2}$ & $T_{\rm d} \sim$ 10Myr

Timescale of Massive SF