Filament Paradigm and Galactic Star Formation

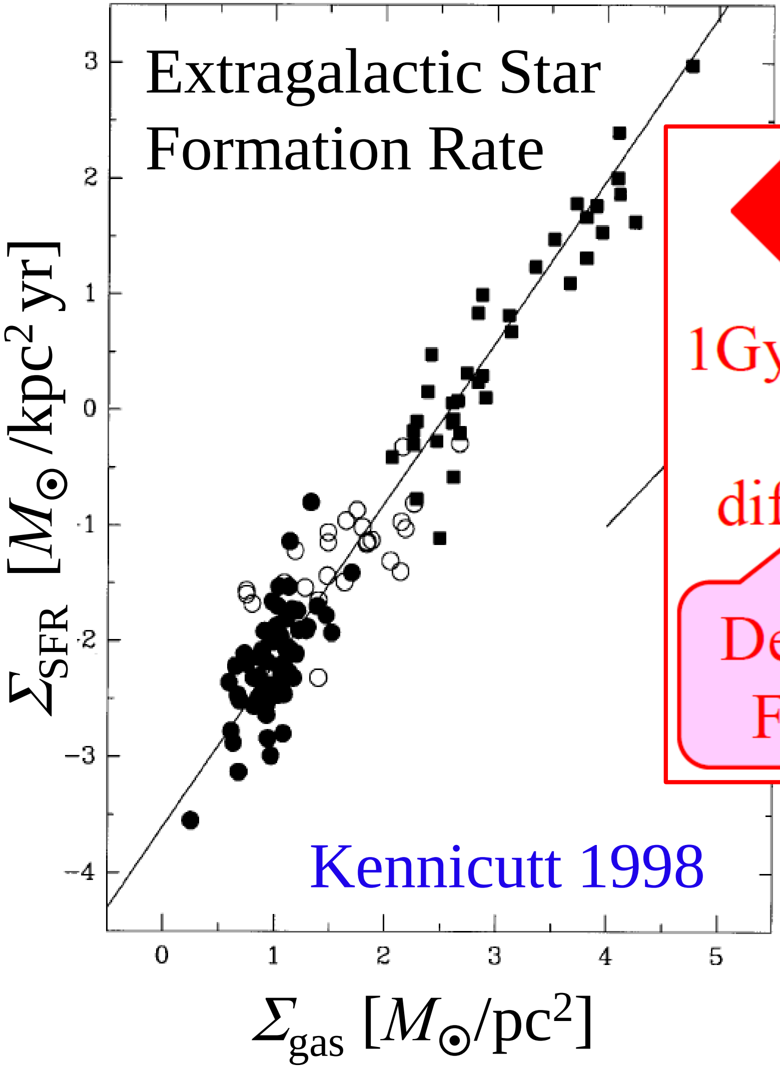
Shu-ichiro Inutsuka (Nagoya University)

1. Characteristic Timescales **1Gyr, 20Myr, 1Myr**
2. Phase Transition Dynamics of ISM
3. **Filament Paradigm** and **Integrated Scenario**

   Core Mass Function, Core Rotation, PP Disks
4. Dispersal of GMC, Mass Function of GMCs
5. Open Questions & Summary

3 December 2019 CEA, Saclay, France

Schmidt-Kennicutt Law of SF



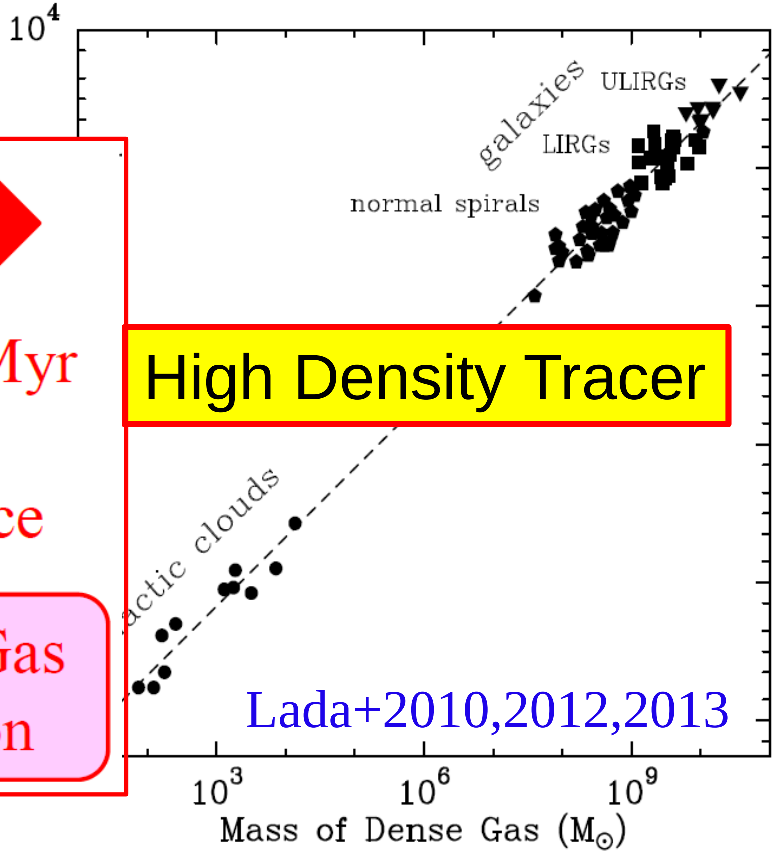
Extragalactic Star Formation Rate

Kennicutt 1998

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

1Gyr/20Myr = 50 difference

Dense Gas Fraction



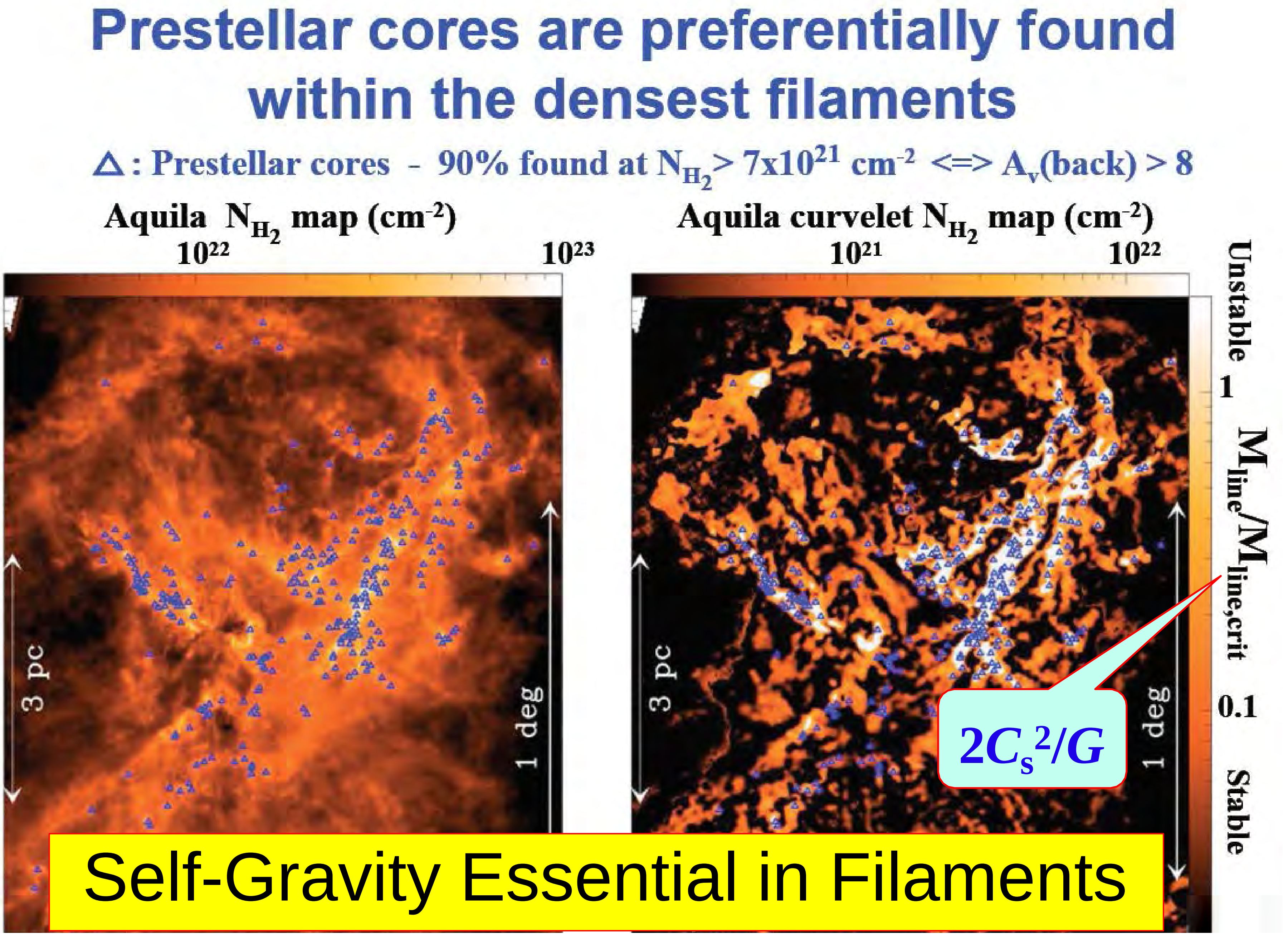
High Density Tracer

Lada+2010,2012,2013

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

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

Highlight of Herschel (e.g., André+2010)



Prestellar cores are preferentially found within the densest filaments

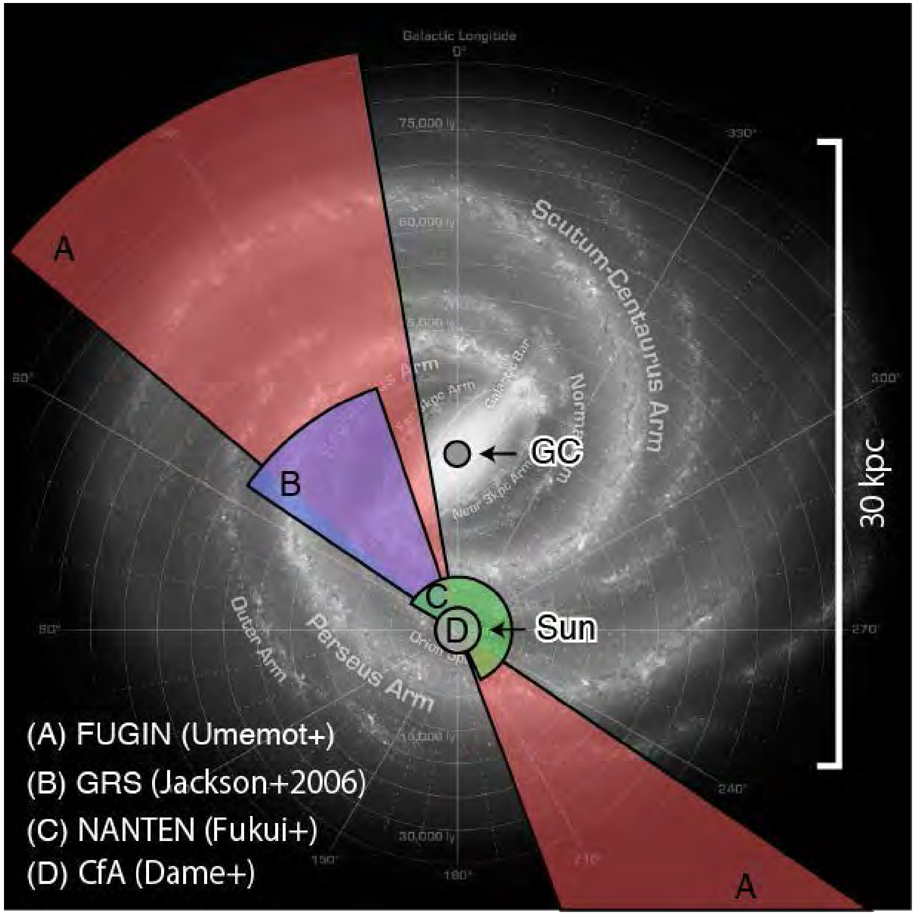
△ : Prestellar cores - 90% found at $N_{H_2} > 7x10^{21}$ cm^{-2} <=> A_v(back) > 8

$2C_s^2/G$

Self-Gravity Essential in Filaments

FUGIN

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

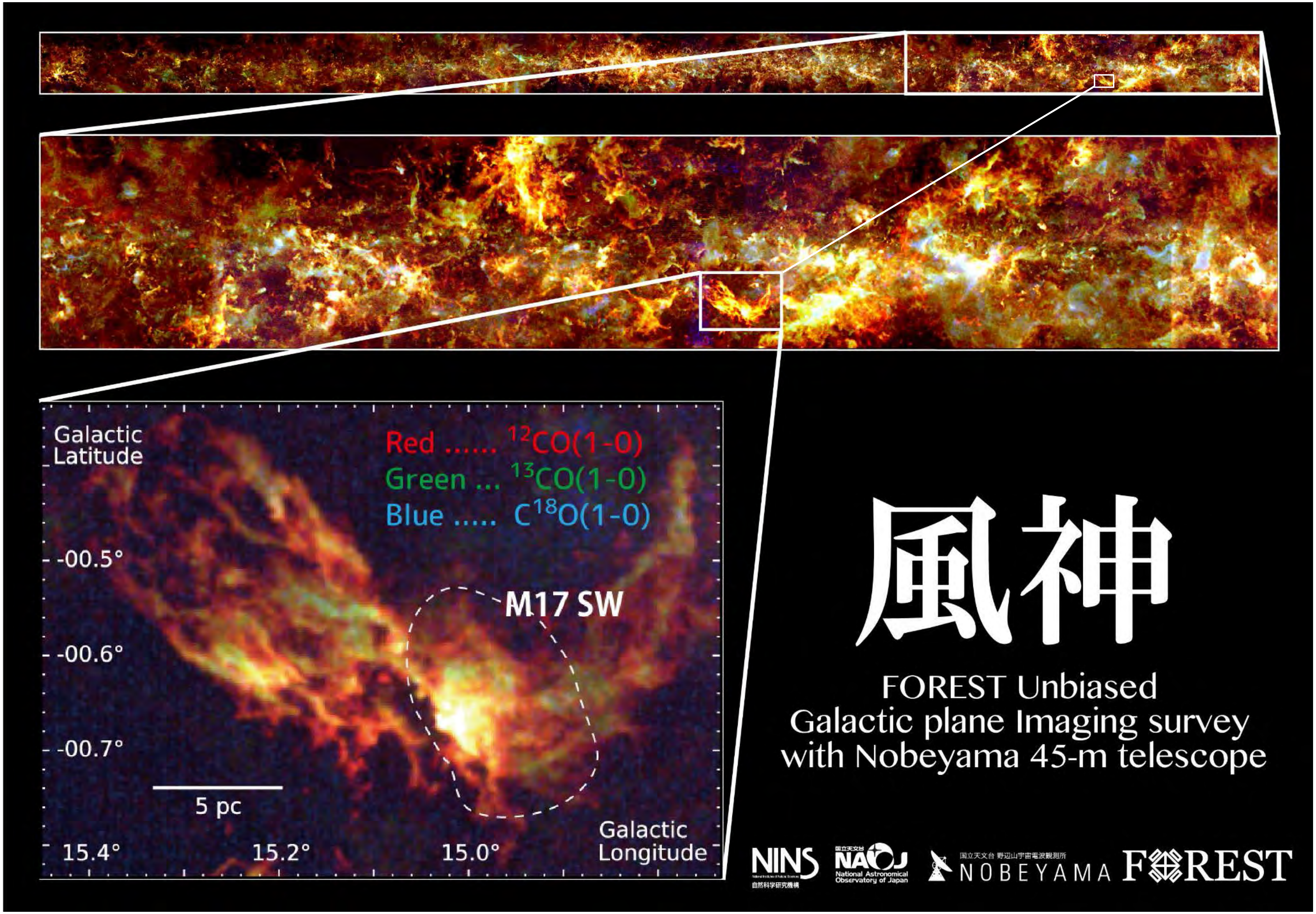


Observed areas of the CO J=1-0 survey projects, where the corresponding spatial resolutions of the surveys are less than 2pc.

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

Slide by Torii

FUGIN

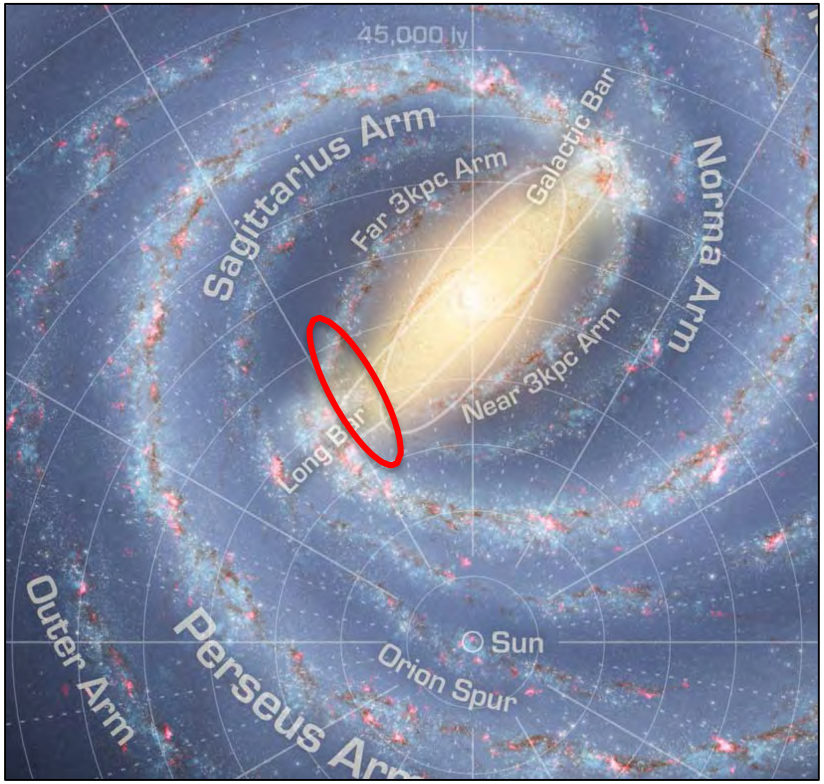

Galactic Latitude
Red ...... ^{12}CO(1-0)
Green ... ^{13}CO(1-0)
Blue ..... C^{18}O(1-0)
-00.5°
-00.6°
-00.7°
M17 SW
5 pc
15.4°
15.2°
15.0°
Galactic Longitude
風神
FOREST Unbiased
Galactic plane Imaging survey
with Nobeyama 45-m telescope
NINS 自然科学研究機構
国立天文台 NAOJ National Astronomical Observatory of Japan
国立天文台 野辺山宇宙電波観測所 NOBEYAMA
FOREST

FUGIN: Mass Fractions of ^{12}CO & C^{18}O

(1) Total M_{H2} of the ^{12}CO clouds ~ $\boxed{2.7 \times 10^7\ \mathrm{Mo}}$

(2) Total M_{H2} of the C^{18}O clouds ~ $\boxed{4.7 \times 10^5\ \mathrm{Mo}}$

- (2) / (1) ~ <u>2%</u> (Data pixel volume fraction = 0.1%)



C^{18}O-Mass/ ^{12}CO-Mass ~ 0.02

↔ $t_{\mathrm{dense\ gas}}$ / t_{gas} ~ 0.02

Torii et al. (2019) PASJ

Characteristic Timescales

Gas Consumption: $\boldsymbol{t}_{\rm gas} = \Sigma_{\rm gas} / \Sigma_{\rm SFR} \sim 10^{3}$ Myr

Dense Gas Consumption: $\boldsymbol{t}_{\rm dense\ gas} \sim 20$ Myr

Dynamical Timescale: $\boldsymbol{t}_{\rm dyn} = 1{\rm Myr} \ll t_{\rm Gal.Rot} \sim 10^{2}{\rm Myr}$

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

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

$(10{\rm kpc})^{2} \times 100{\rm pc}$

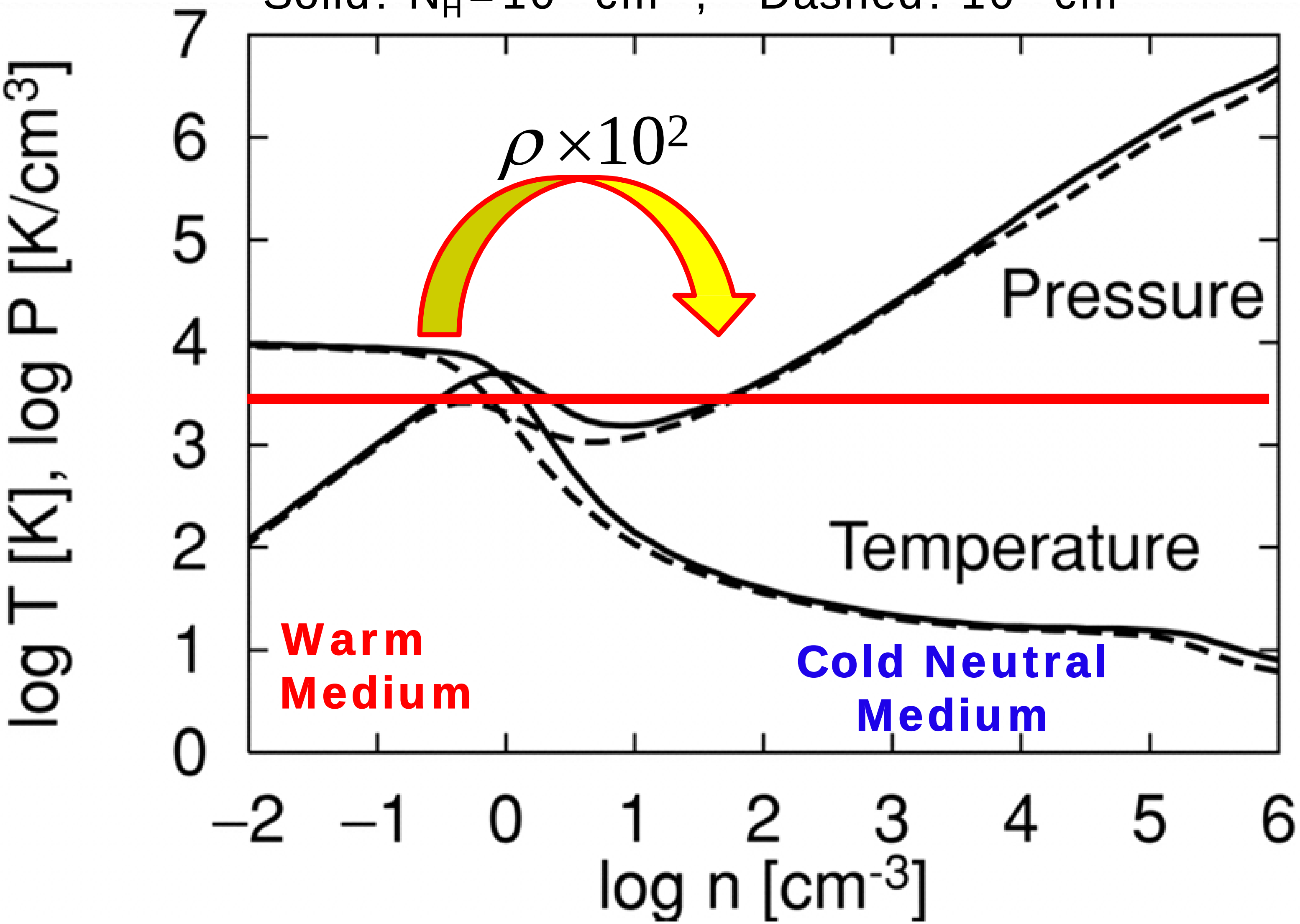
$$(10^{-2}\,{\rm yr}^{-1}) \times (10^{6}\,{\rm yr}) \times (100{\rm pc})^{3} = 10^{10}\,{\rm pc}^{3} \sim V_{\rm Gal.Disk}$$

Expanding HII regions can also be important!

Formation of Molecular Clouds

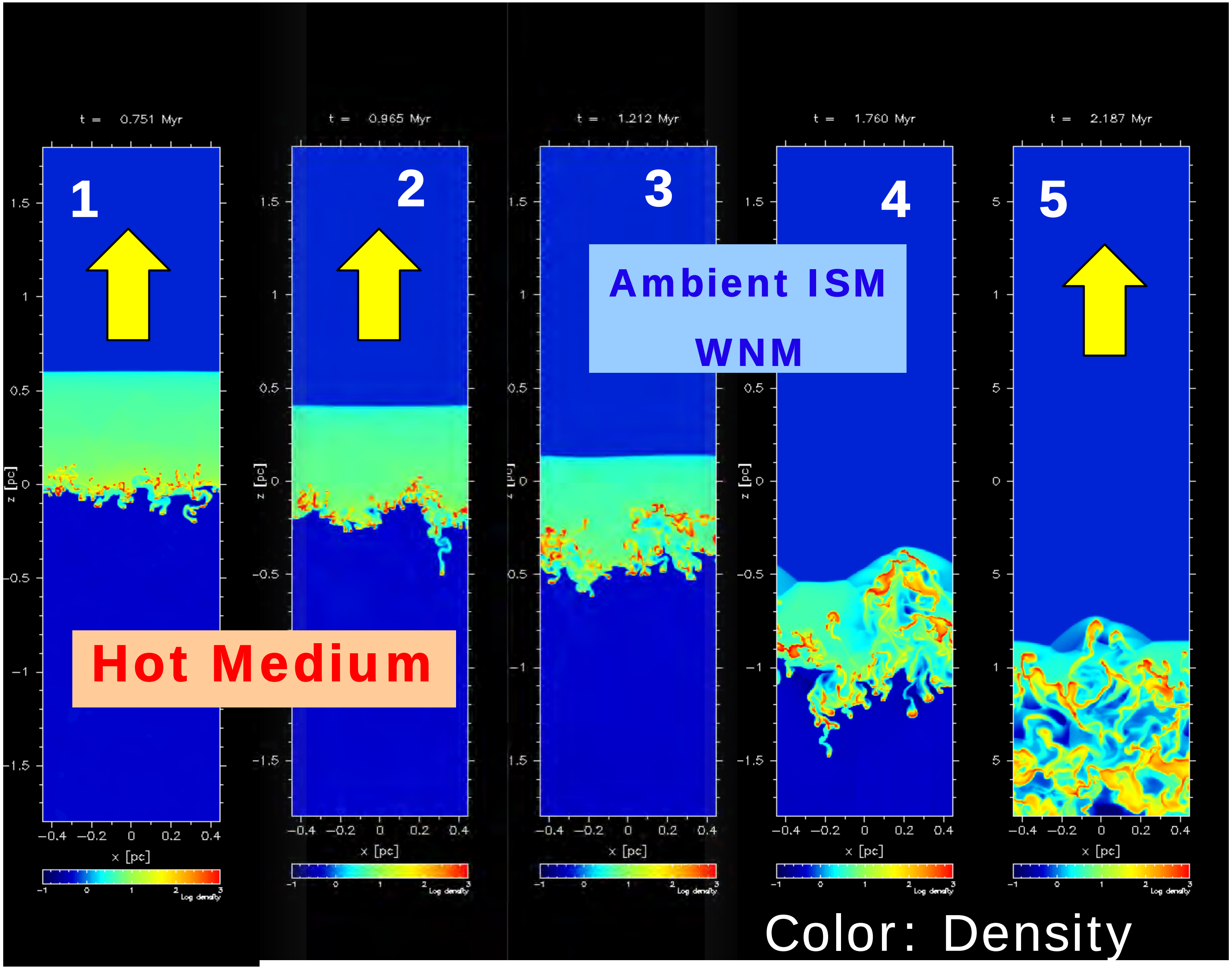
Radiative Equilibrium for a given density

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

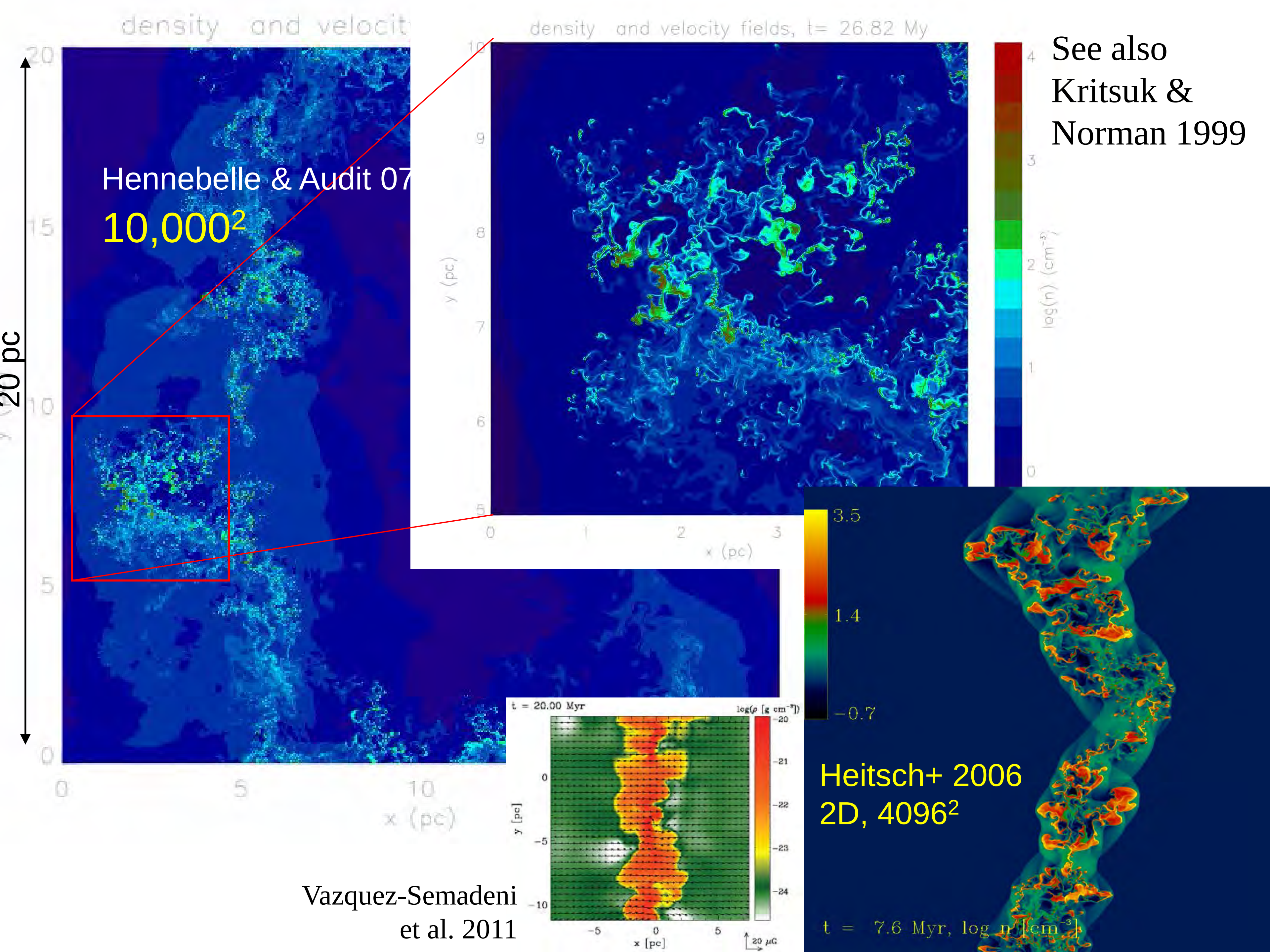


e.g., Wolfire et al. 1995, Koyama & SI 2000

Shock Propagation into WNM



Koyama & Inutsuka (2002) ApJ 564, L97



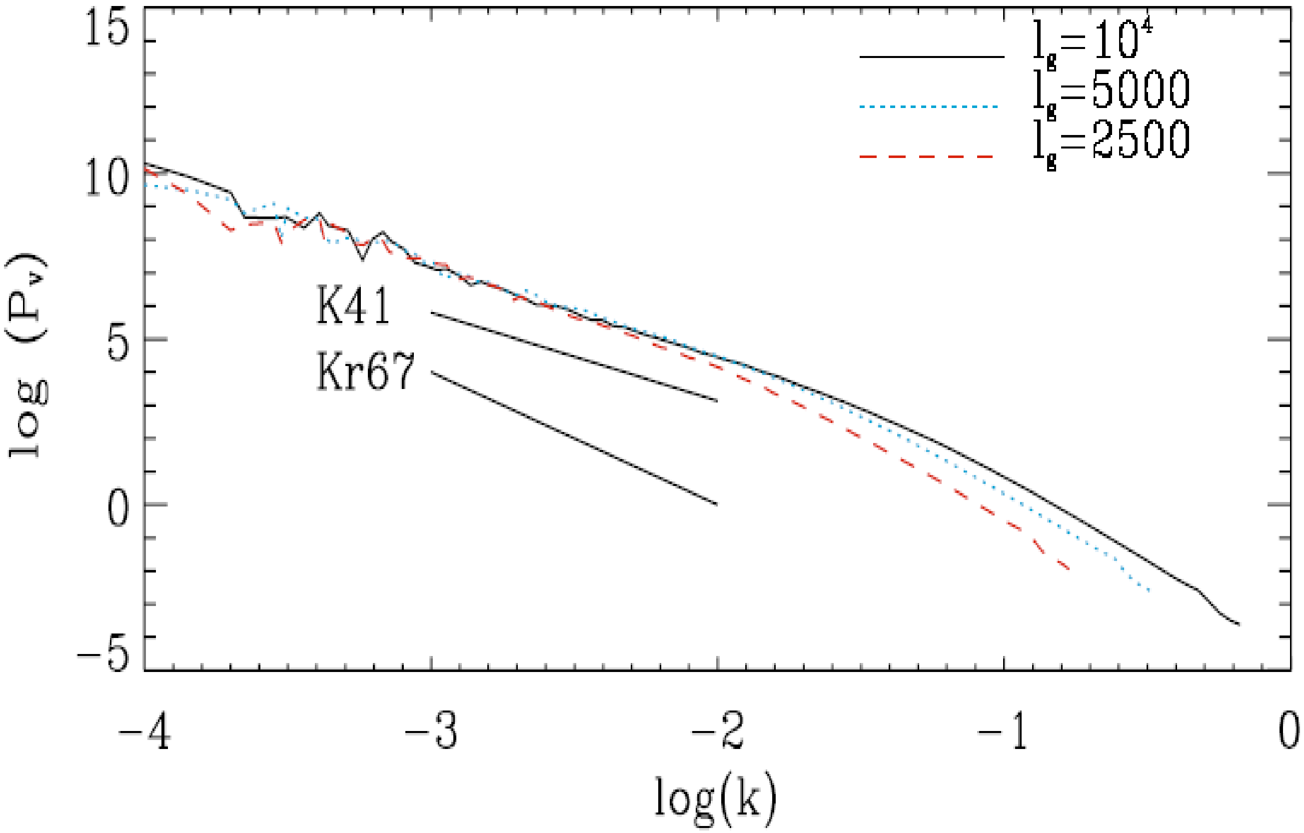
Hennebelle & Audit 07
10,000^2

See also
Kritsuk &
Norman 1999

Heitsch+ 2006
2D, 4096^2

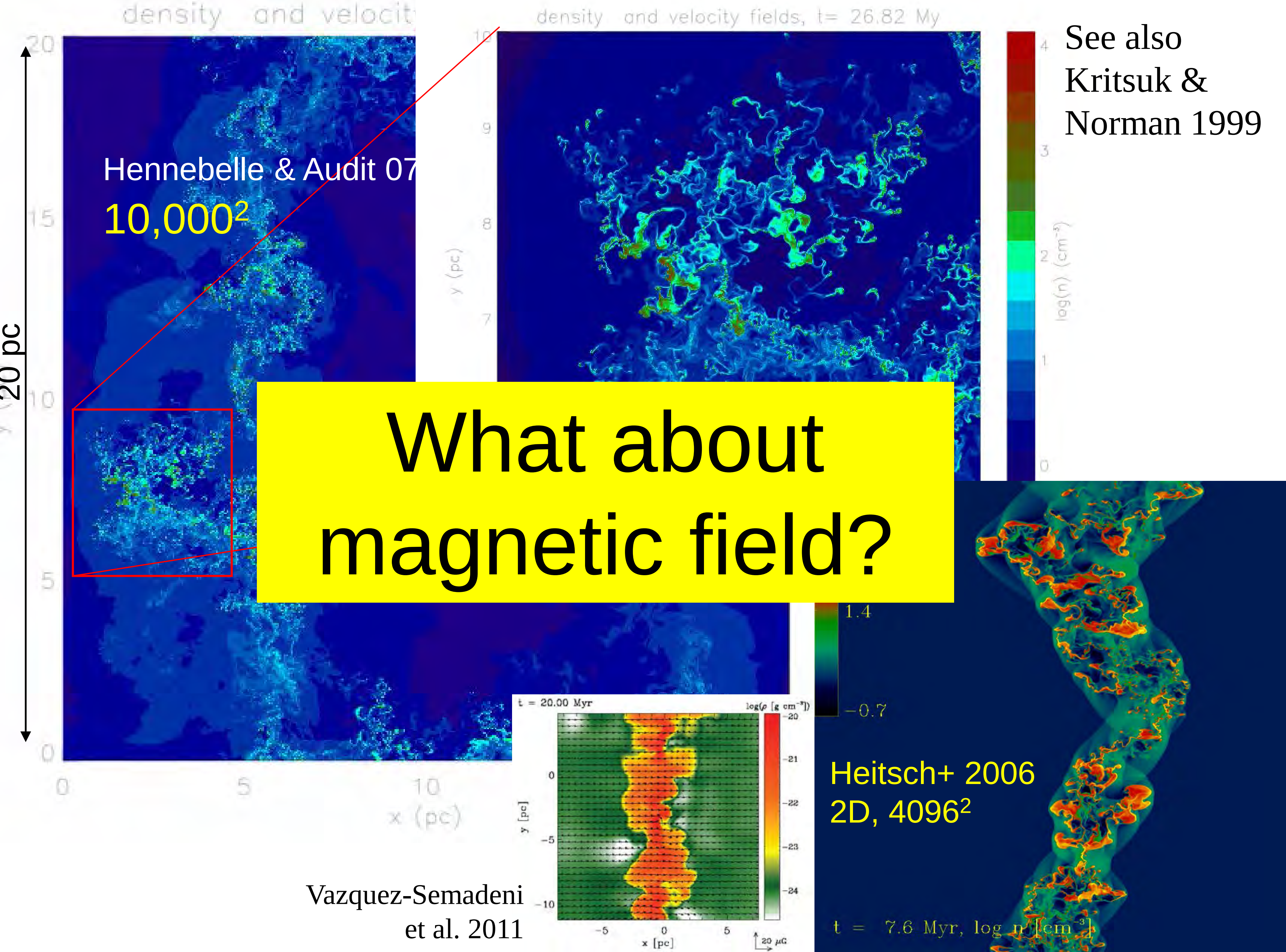
Vazquez-Semadeni
et al. 2011

Property of “Turbulence”…Subsonic



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

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



Hennebelle & Audit 07

10,000^2

See also Kritsuk & Norman 1999

What about magnetic field?

Vazquez-Semadeni et al. 2011

Heitsch+ 2006

2D, 4096^2

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

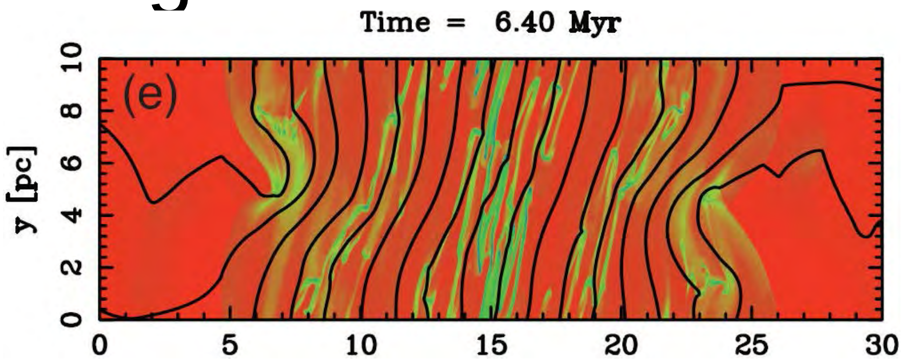
Two-Fluid Resistive MHD + Cooling/Heating + Thermal Conduction + Chemistry (H_2, CO,…)

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

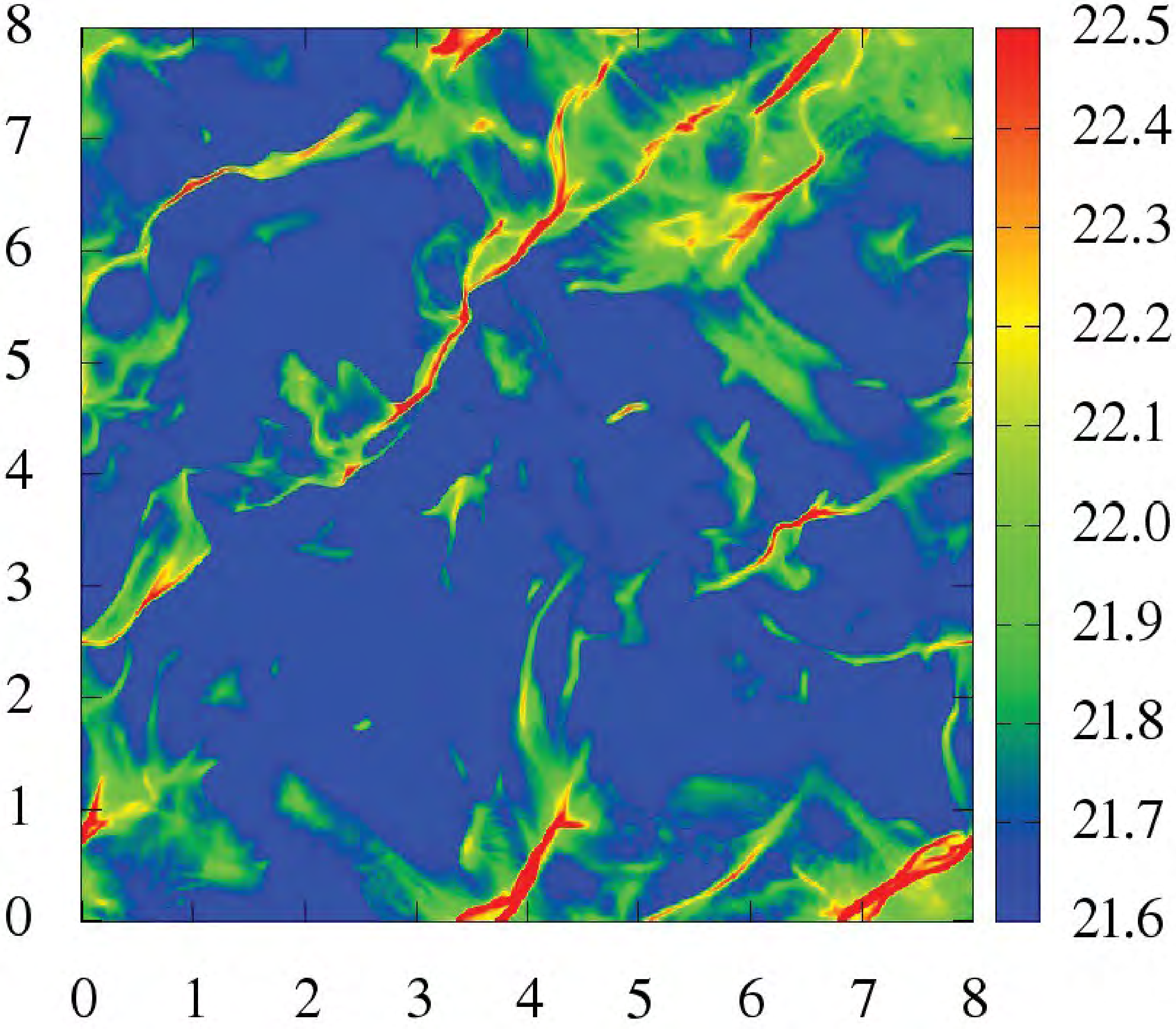
van Loo+2007; *Heitsch*+2009; *Körtgen & Banerjee* 2015; *Valdivia*+2016; *Iwasaki*+2018

➔ Further compression of HI clouds required!

Further Compress. of Mole. Clouds

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

➔Magnetized Massive Filaments & Striations

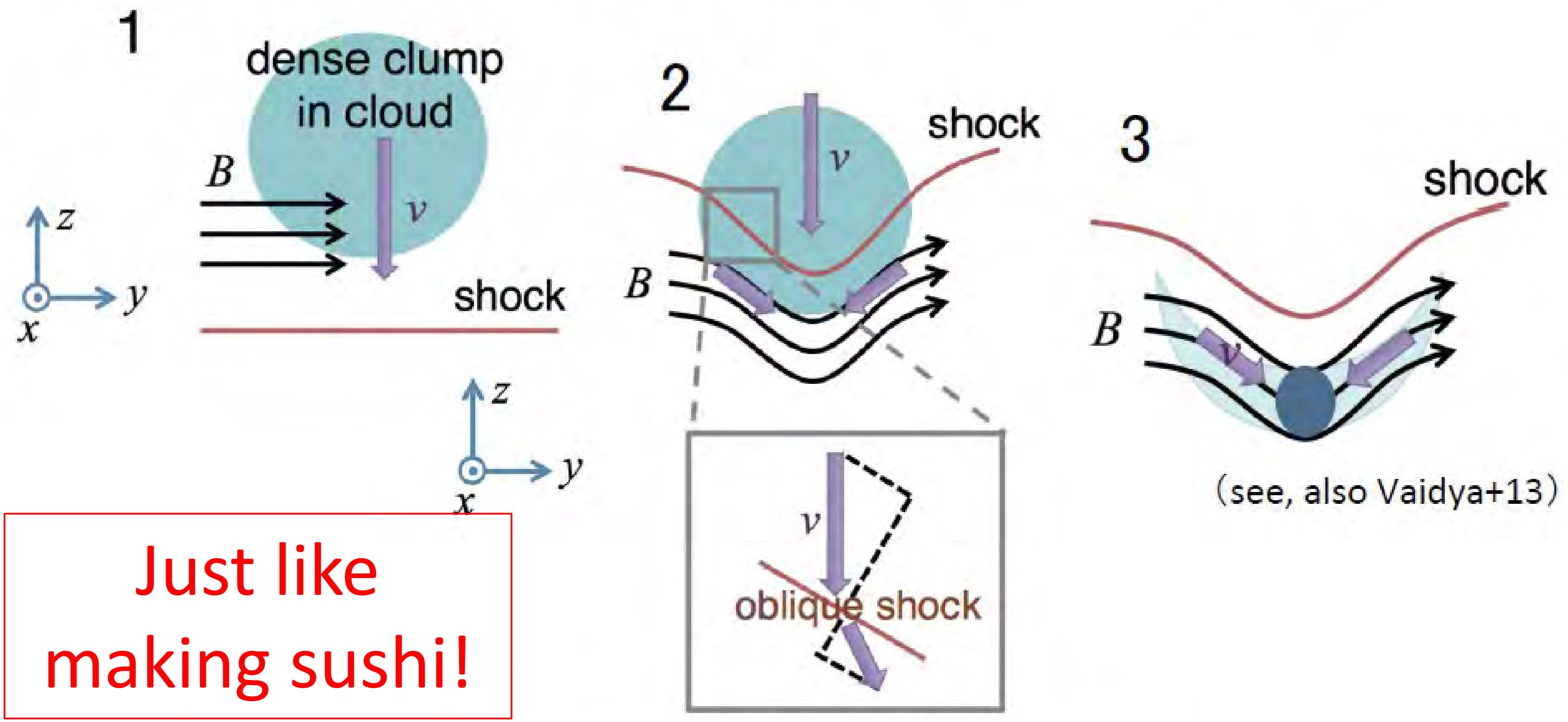


Self-Gravity Included, *SI, Inoue, Iwasaki, & Hosokawa 2015*

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)

Just like making sushi!

Filament ⊥ Compressed Magnetic Field

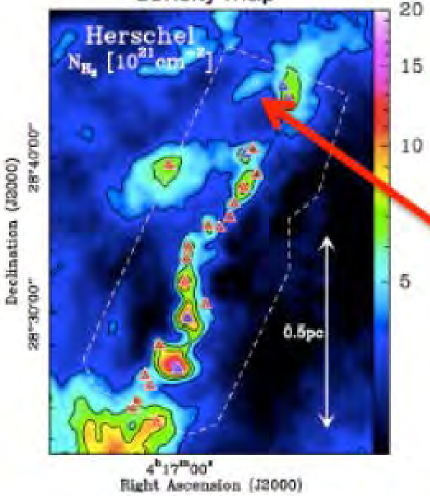
See observational Study in Arzoumanian+2018!

P-V Structure of Observed Baby Filament

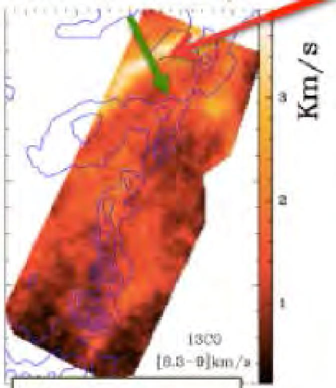
Arzoumanian+2018

- ☐ A young filament observed in Taurus MC has the P-V structure that is very similar to the simulated young filament!

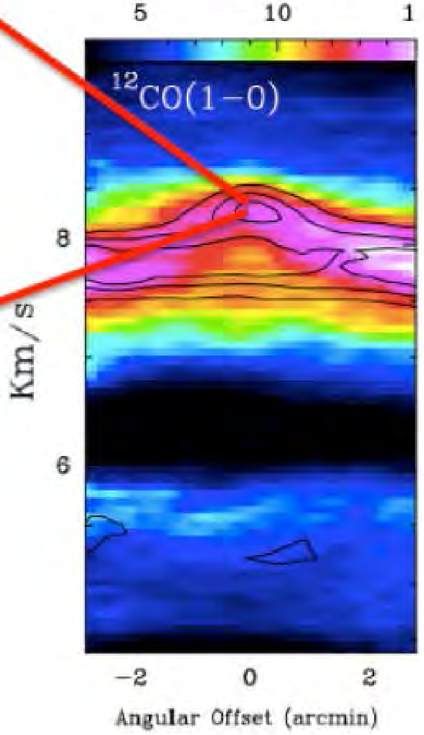
Herschel column density map



Channel map



^{13}CO
[~8-9] km/s

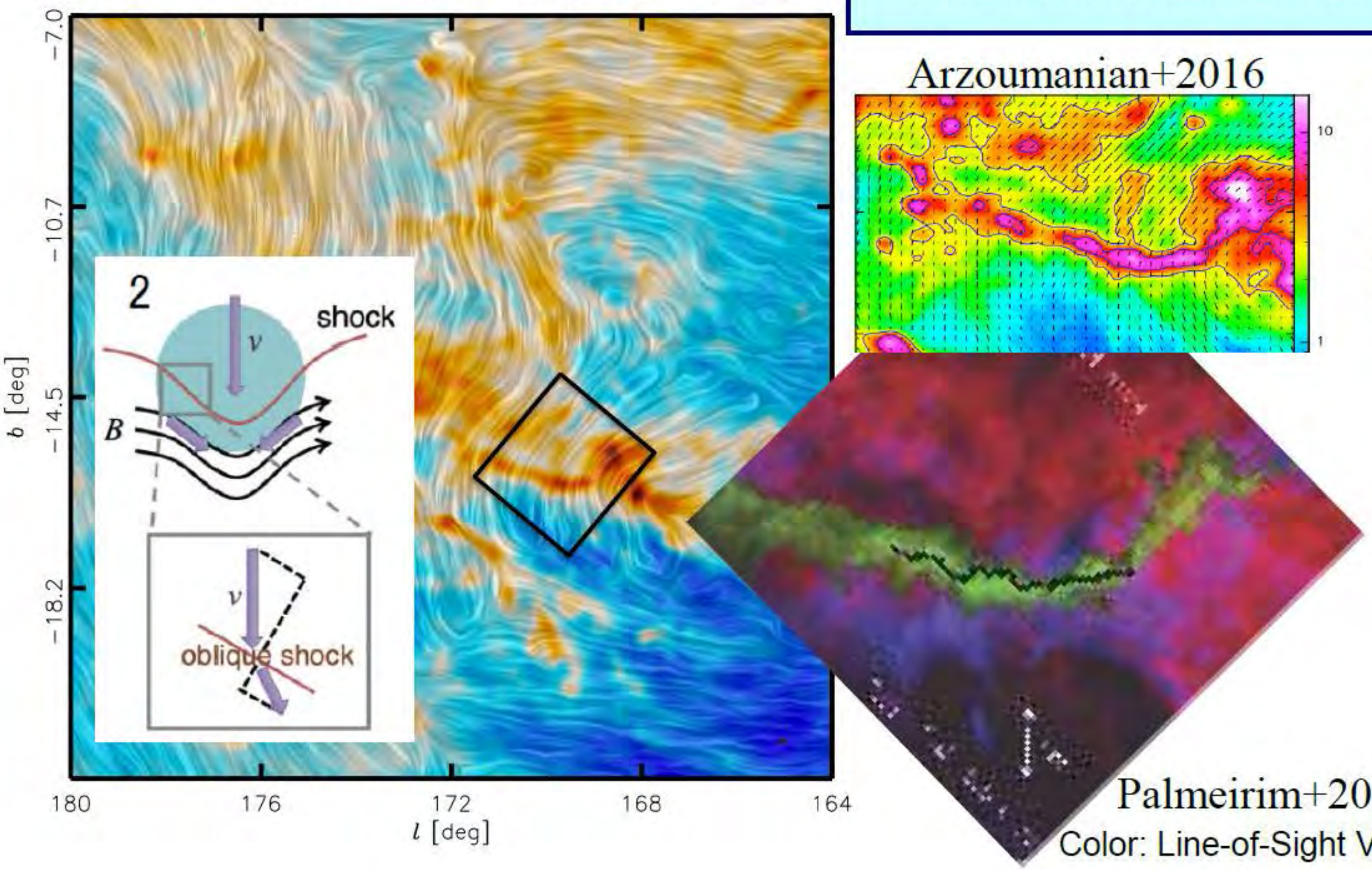


Nobeyama 45m telescope

Observational Evidence for Sheet?

Planck Col. Int. XXXV 2016 (Soler+2016)

Arzoumanian+2016



Palmeirim+2013

Color: Line-of-Sight Velocity

2 points!

1) Thickness = *N* / *n*

2) Coherent Flows around a Filament

🡐

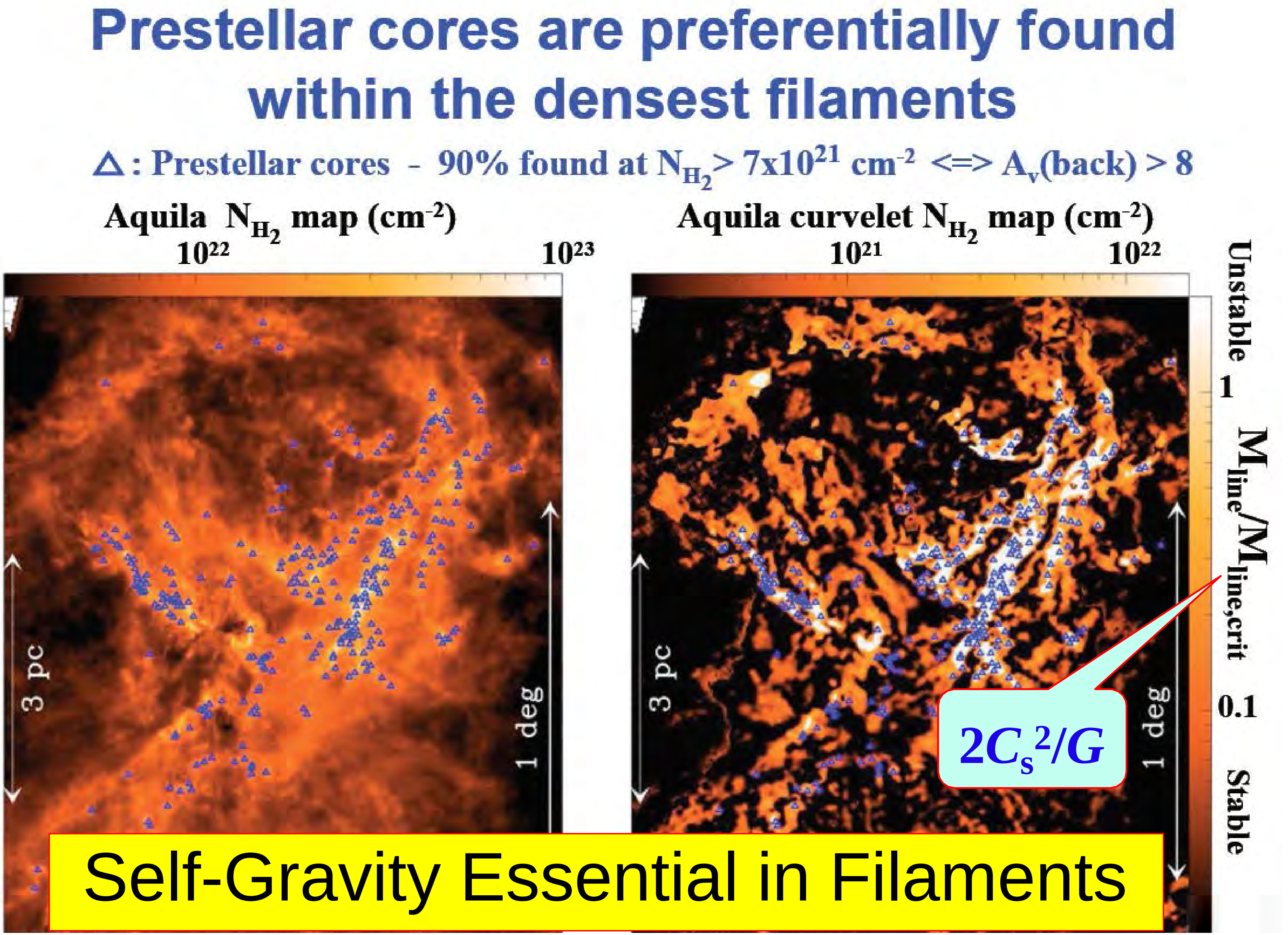
Accretion along a sheet?

Andre 2017
(arXiv:1710.01030)
Shimajiri+2018

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

See also Tahani+2018 for
Line-of-Sight Magnetic Field Reversal across Filament!

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

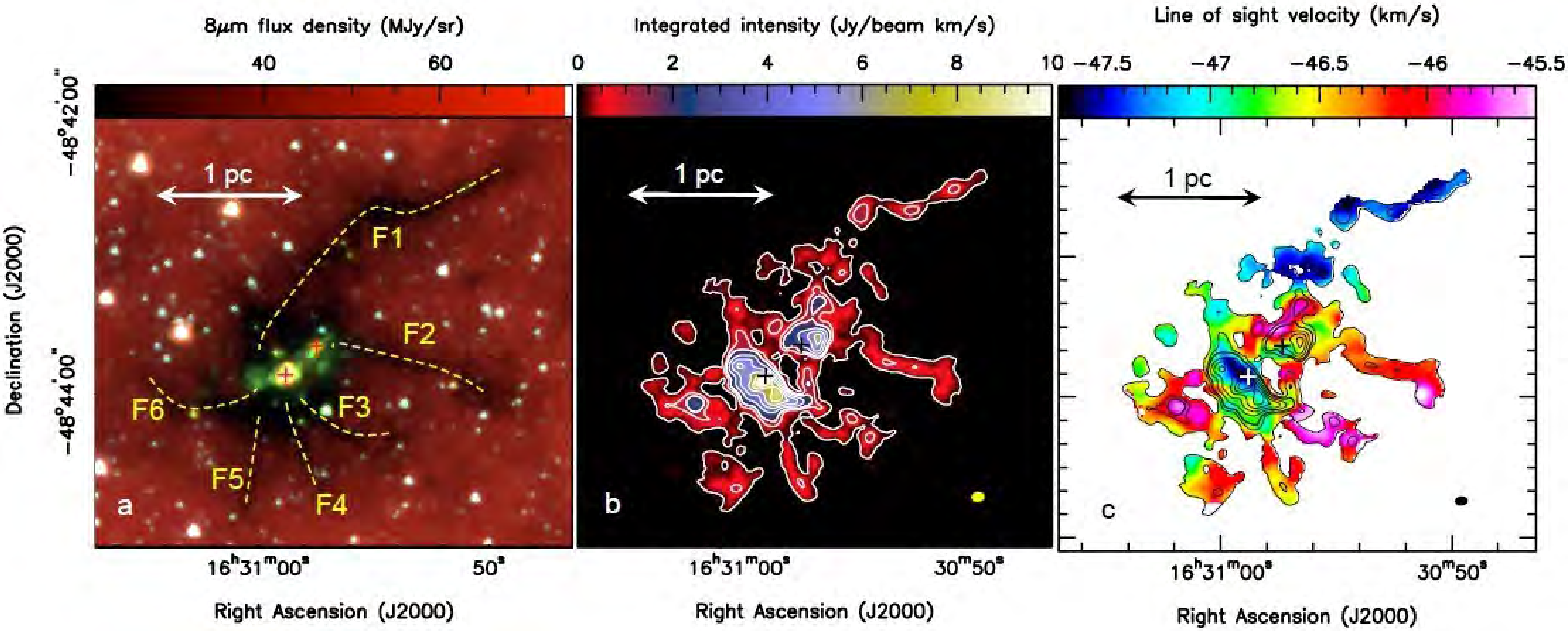
Aquila N_{H_2} map (cm^{-2})

Aquila curvelet N_{H_2} map (cm^{-2})

$2C_s^2/G$

Self-Gravity Essential in Filaments

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?

↕ ?

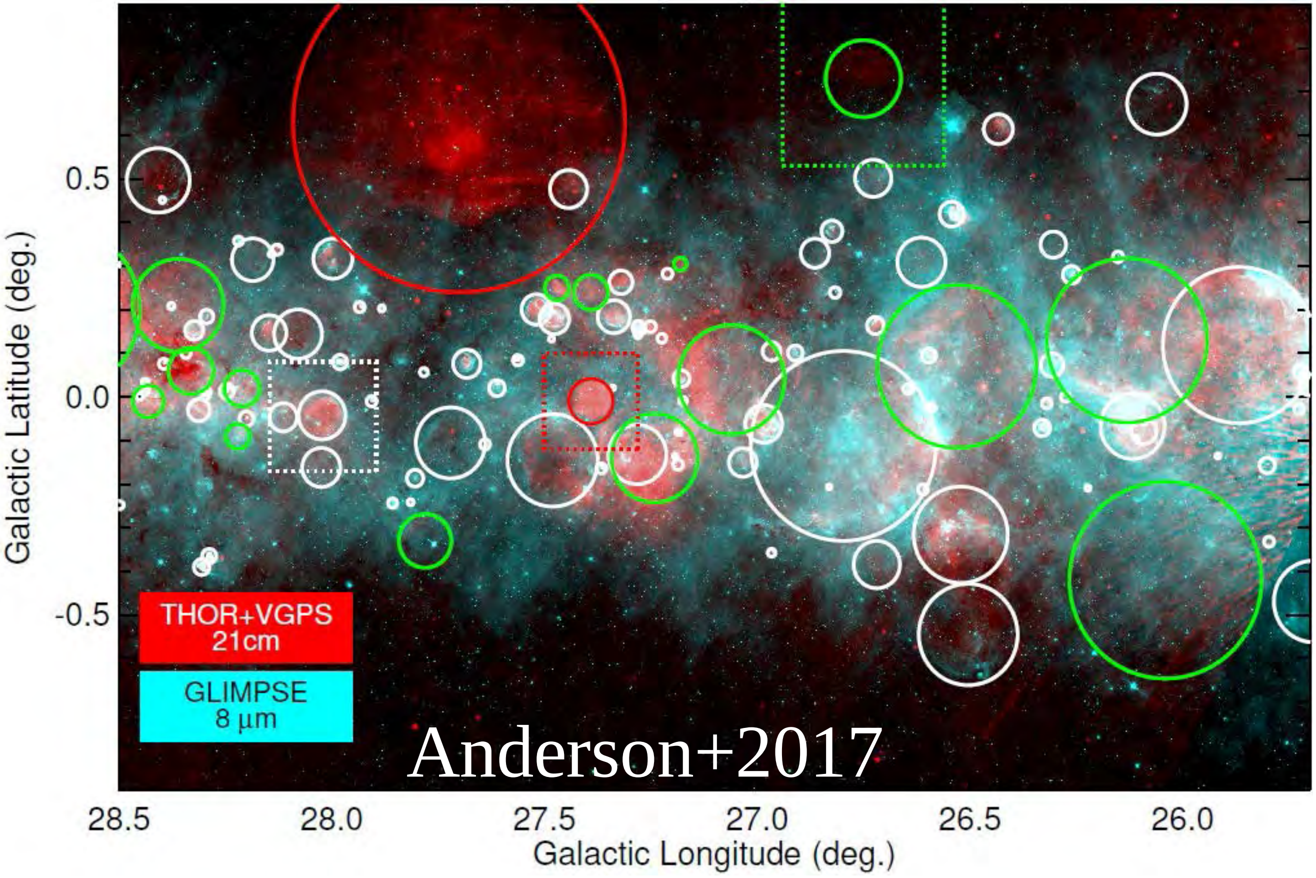
Other Modes of Star Formation?

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

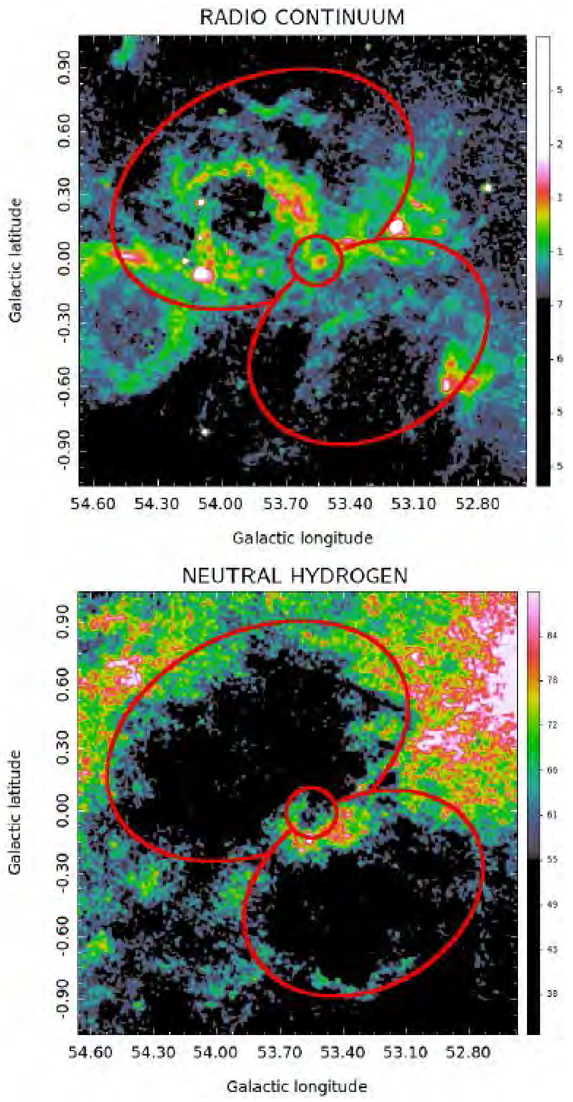
Collect & Collapse (*Elmegreen-Lada, Whitworth, Palouš, Deharveng, Zavagno,…*)

Observed (Colliding) Bubbles

THOR Survey (Beuther+)



Anderson+2017



RADIO CONTINUUM

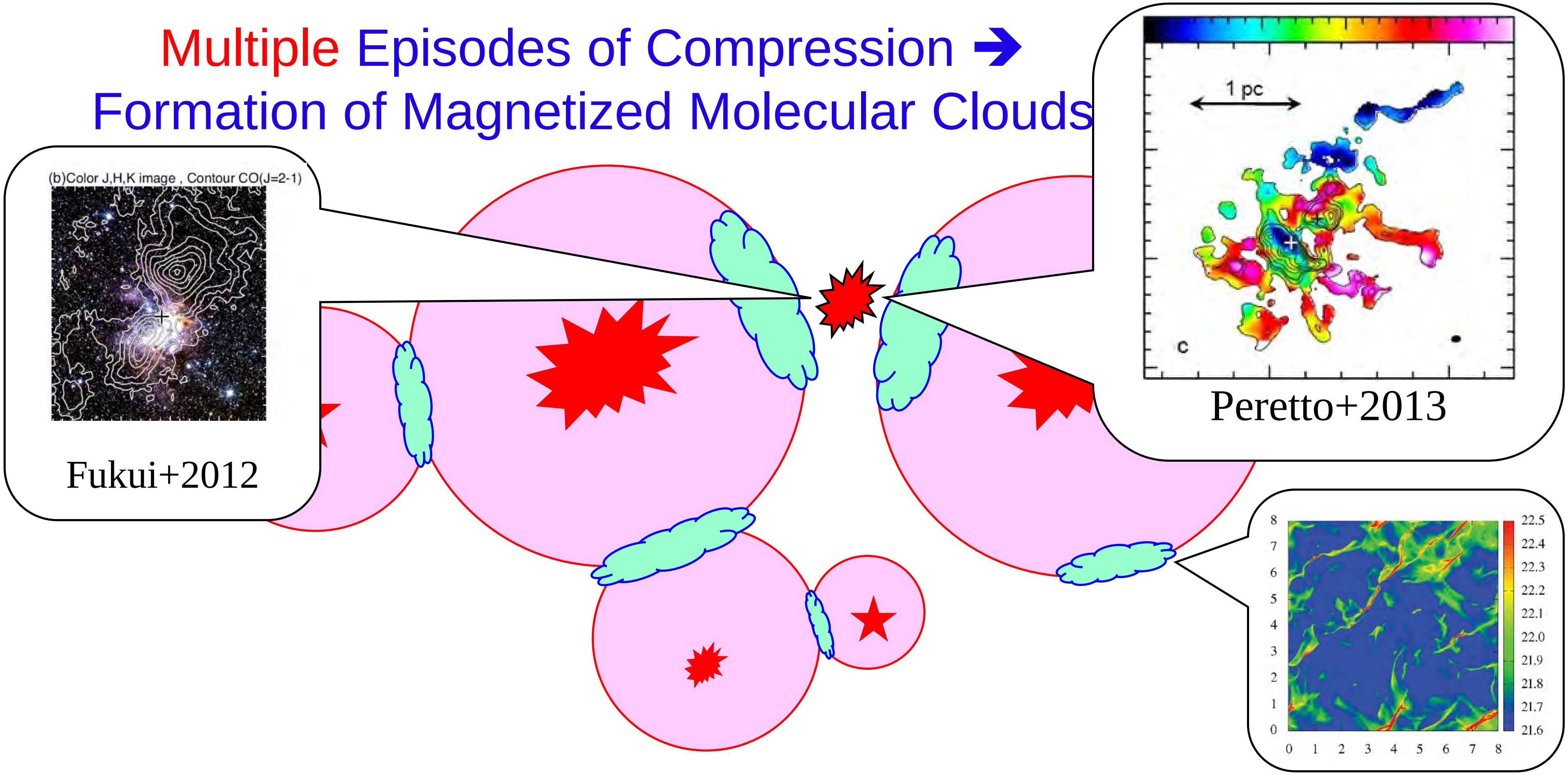
NEUTRAL HYDROGEN

Zychová & Ehlerová 2016

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

Network of Expanding Shells

Multiple Episodes of Compression ➔
Formation of Magnetized Molecular Clouds



Fukui+2012

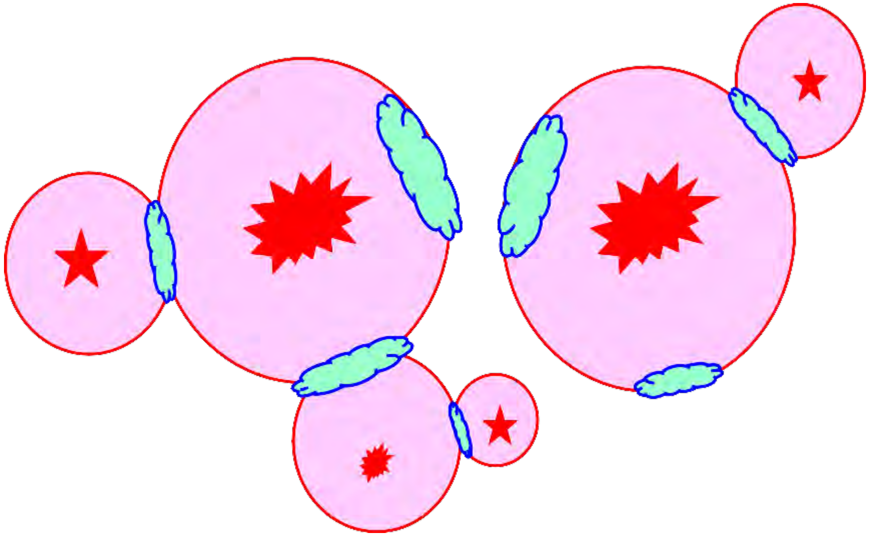
Peretto+2013

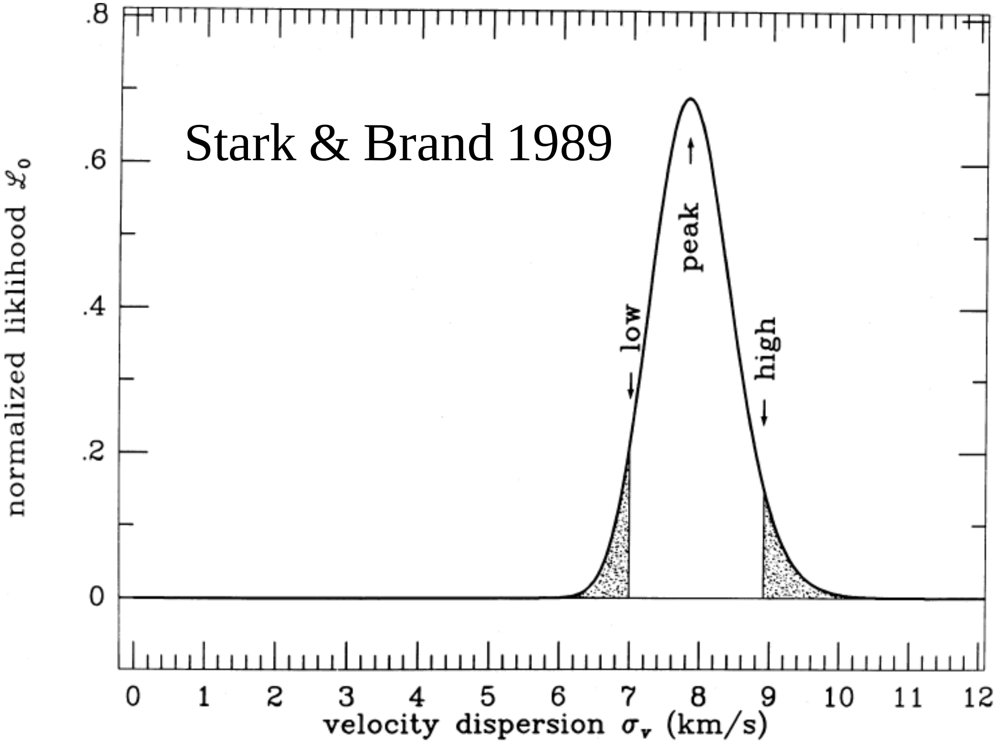
Each Bubble Visible Only for Short Time (~1Myr)!

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

Velocity Dispersion of Clouds

Multiple Episodes of Compression ➔ Formation of Magnetized Molecular Clouds





Stark & Brand 1989

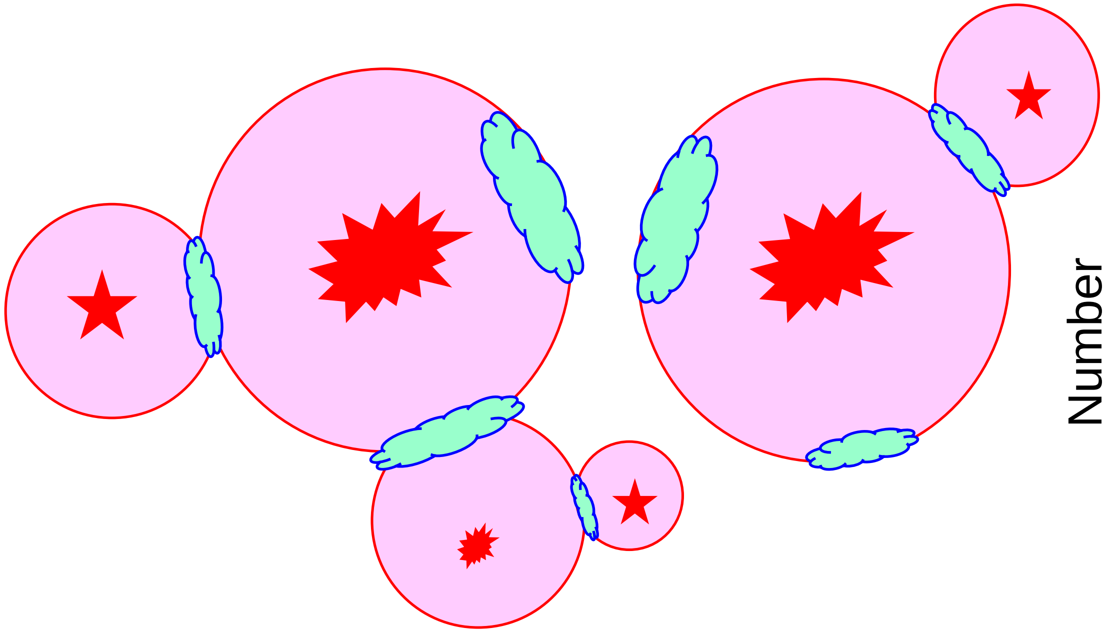
Shell Expansion

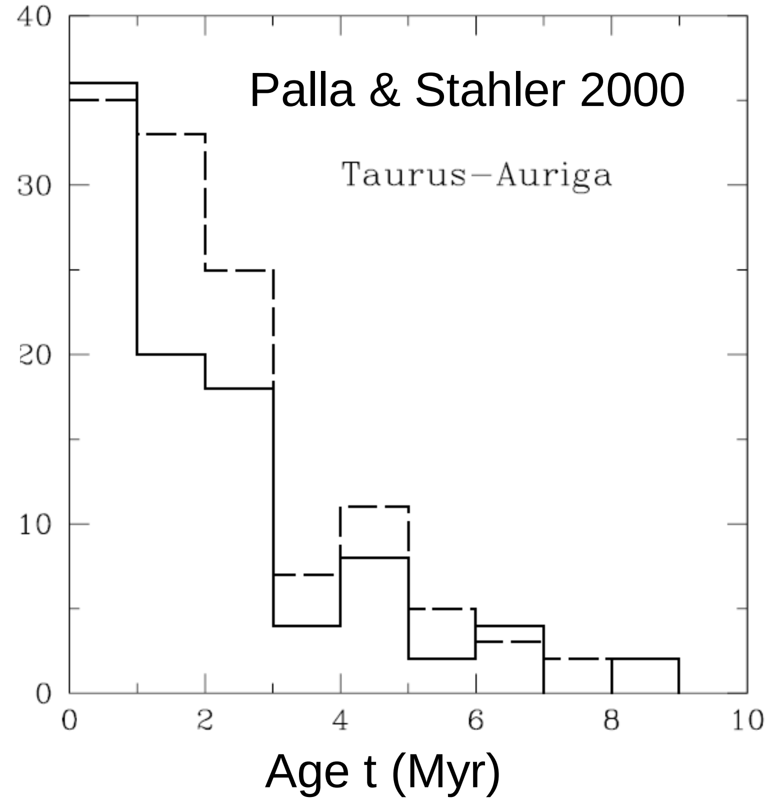
Velocities ~ 10^1 km/s

Cloud-to-Cloud Velocity Disp.

But need for more obs!

Natural Acceleration of SF





Molecular Cloud Growth

➔ <u>Collisions of Clouds</u>

➔ Accelerated SF

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

c.f., Vazquez-Semadeni+2007

Further Implication:
Stellar Initial Mass Function

An Origin of Mass Function
of Molecular Cloud Cores

Mass Function of Cores in a Filament

Inutsuka 2001, ApJ **559**, L149

Line-Mass Fluctuation of Filaments

<u>Initial Power Spectrum</u>

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

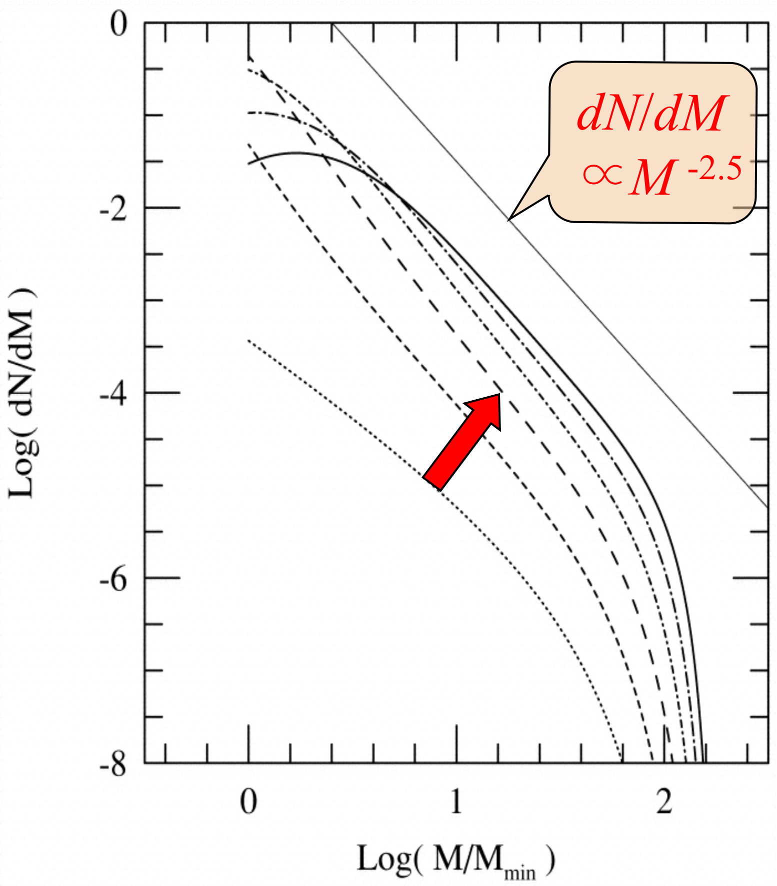
Mass Function

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

(cf. Hennebelle & Chabrier)

Observation of Both Perturbation Spectrum and Mass Function

➔direct test !

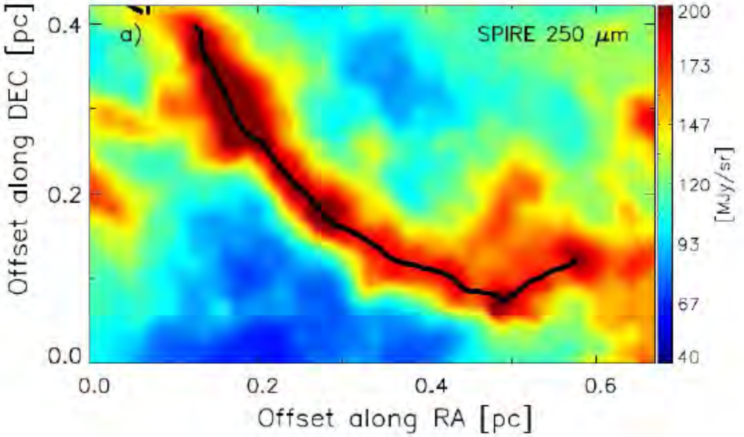


$P(k) \propto k^{-1.5}$

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"

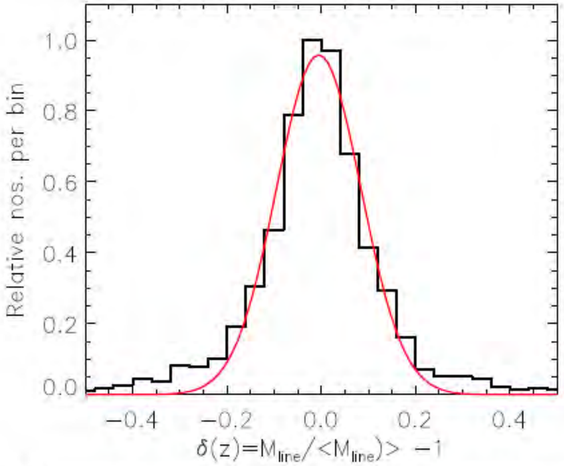
Roy, André, Arzoumanian et al. (2015) A&A **584**, A111

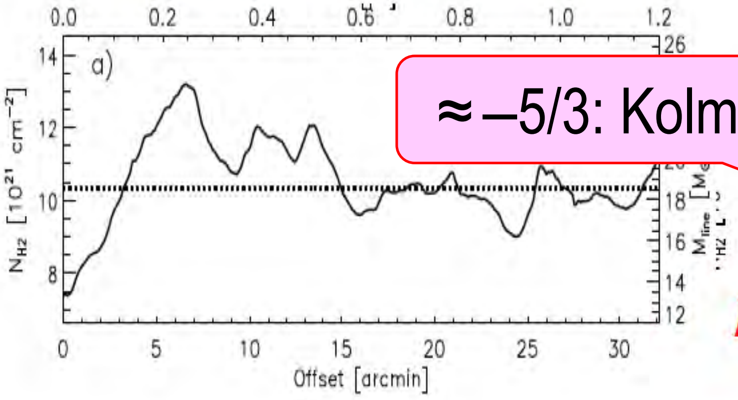


Measurement of 80 Filaments

δ ...

Gaussian

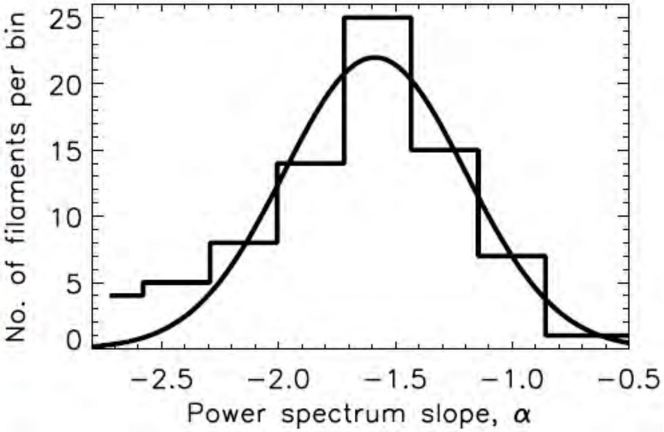




≈ –5/3: Kolmogorov!

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

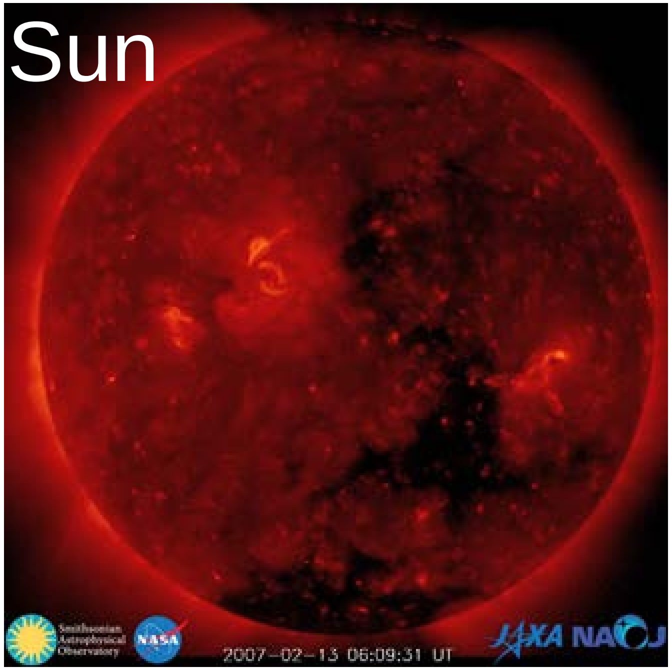
$$n = -1.6 \pm 0.3$$

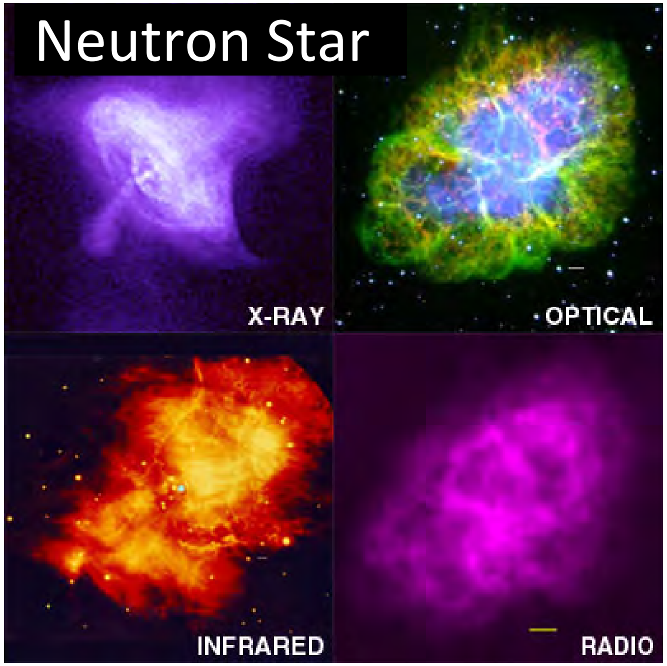


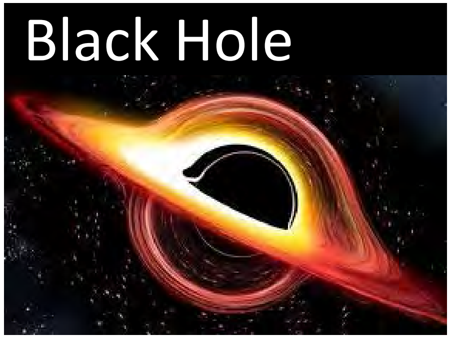
***Strong Support** to Inutsuka* 2001; See also *Lee*+2017, *André*+2019

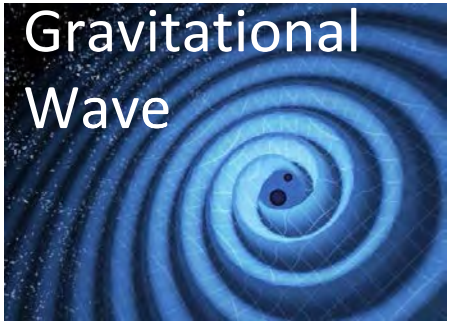
Yet Another Implication: the Origin of Rotation of Stars and Disks

Angular Momenta of Molecular Cloud Cores


Sun


Neutron Star

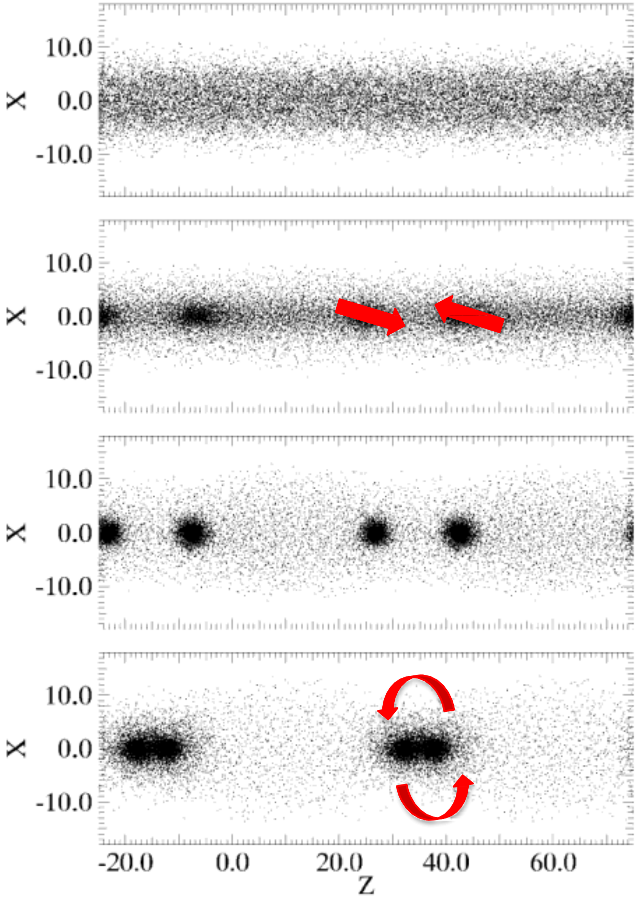

Black Hole


Gravitational Wave

An Origin of Core Angular Momentum

Misugi, SI, & Arzoumanian 2019, ApJ **881**, 11

Episodic Merging
➔ Random Accretion of
Angular Momentum



Mathematical Formulation
Subsonic Velocity
Fluctuation on Filament

⬍

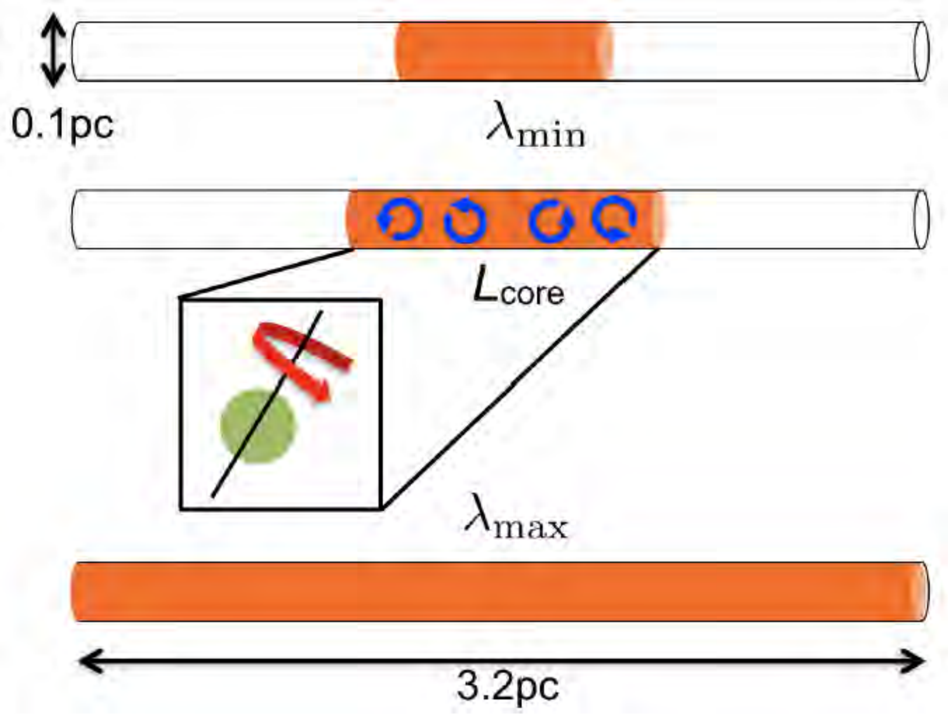
Resultant Core Angular
Momenta

Method of Calculations

Misugi, SI, & Arzoumanian 2019, ApJ **881**, 11

Line mass : $\boldsymbol{M}_{\mathbf{line}}$ **=16** $\boldsymbol{M}_{\mathbf{sun}}$ pc^{-1}

Constant density for Simplicity

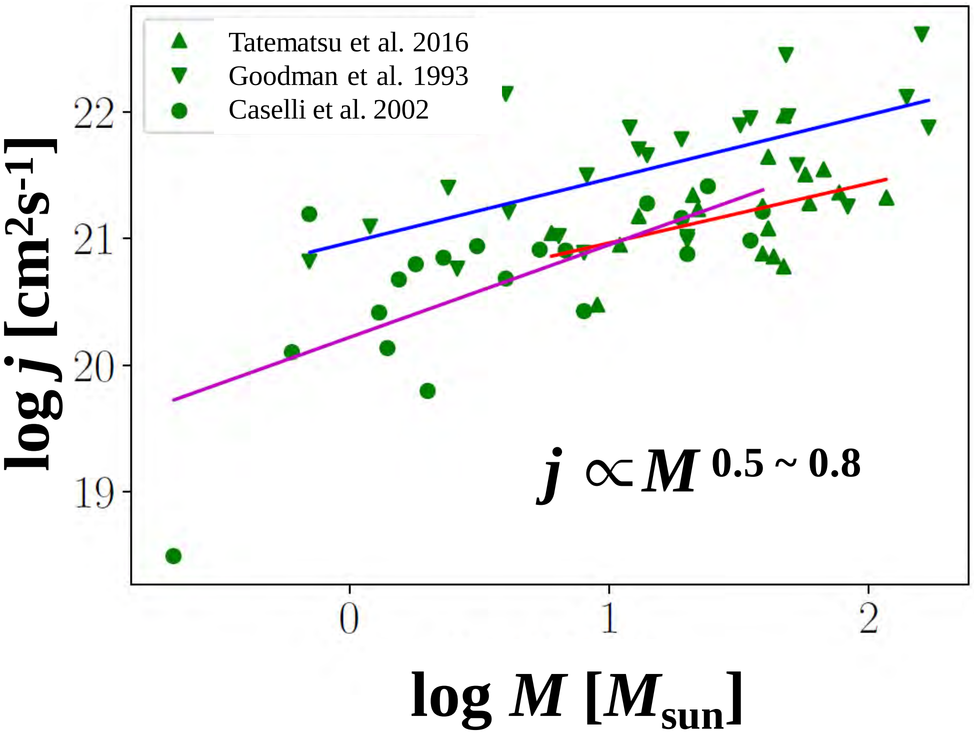


Solenoidal Velocity Field with power spectrum $P(k) \propto k^{-n}$

Subsonic Velocity Dispersion: $\sigma_{3D} = \sqrt{\langle \delta v^2 \rangle} = C_s$

(e.g., Hacar & Tafalla 2011)

Observed Angular Momenta of Molecular Cloud Cores



Almost Consistent with Larson’s law

—Goodman+1993, NH_3

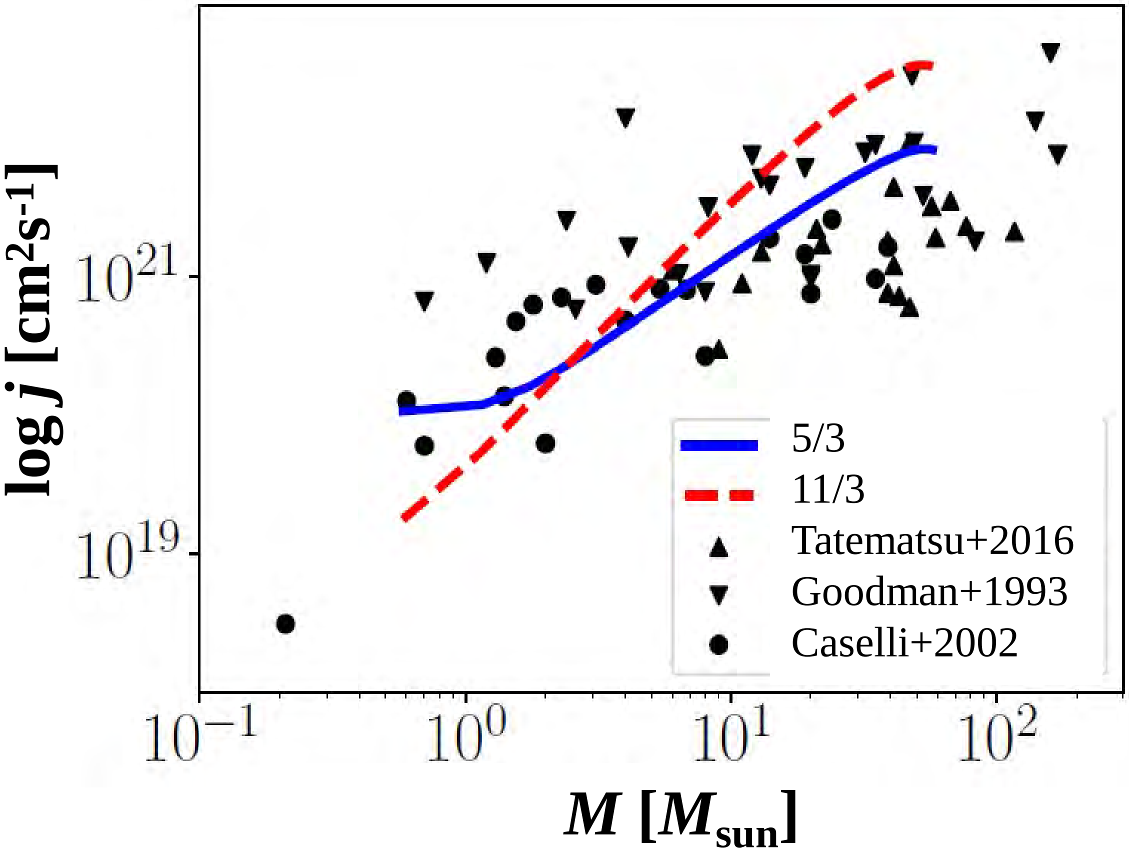
—Caselli+2002, N_2H^+

—Tatematsu+2016, N_2H^+

- Can we explain the angular momenta of observed cores by the velocity fluctuation of the filament?

Angular Momenta of Cores from Filament Fragmentation

Misugi, SI, & Arzoumanian (2019) ApJ **881**, 11



1D Kolmogorov:
$P(k) \propto k^{-5/3}$

c.f.
3D Kolmogorov: $P(k) \propto k^{-11/3}$

Surprisingly Good Fit from 1D Kolmogorov-like Spectrum $P(k) \propto k^{-5/3}$ with $\sigma_{3D} = \sqrt{<\delta v^2>} = C_s$

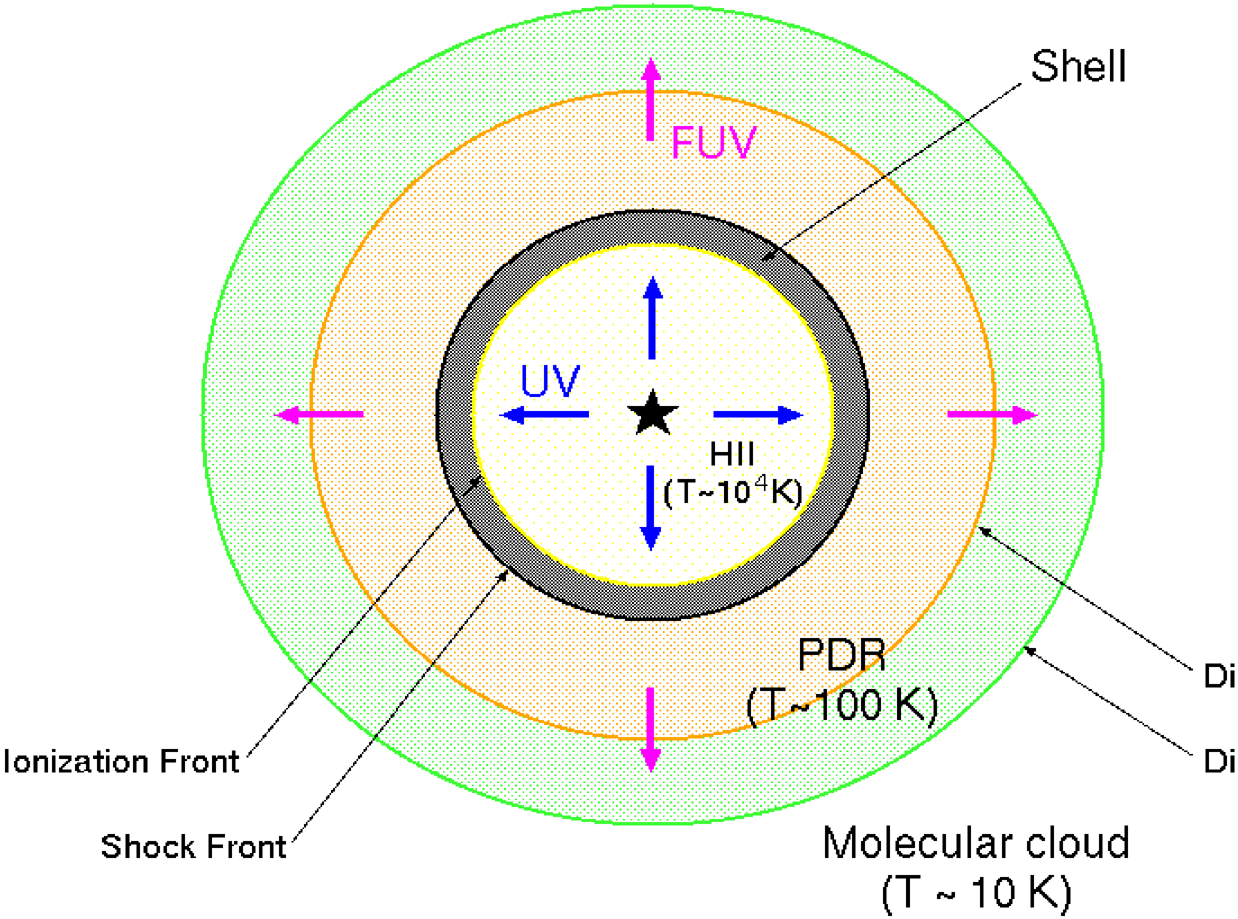
Dispersal of Molecular Clouds

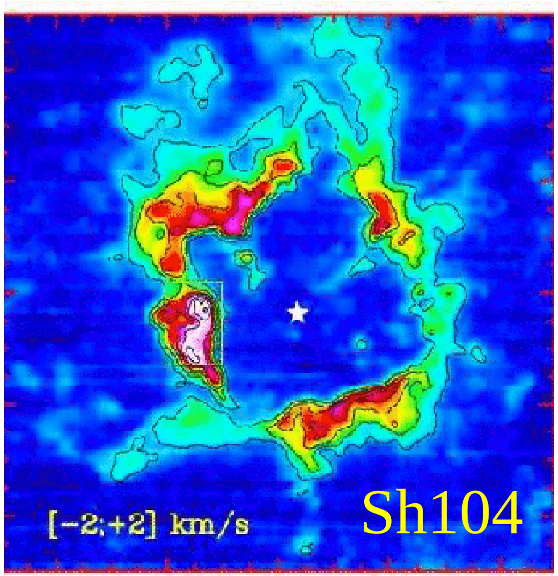
How to Stop SF?

Radiative Feedback to Parental Molecular Clouds

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

Expanding HII Region in <u>Magnetized</u> Molecular Cloud





Radiation Magnetohydrodynamics Calculation

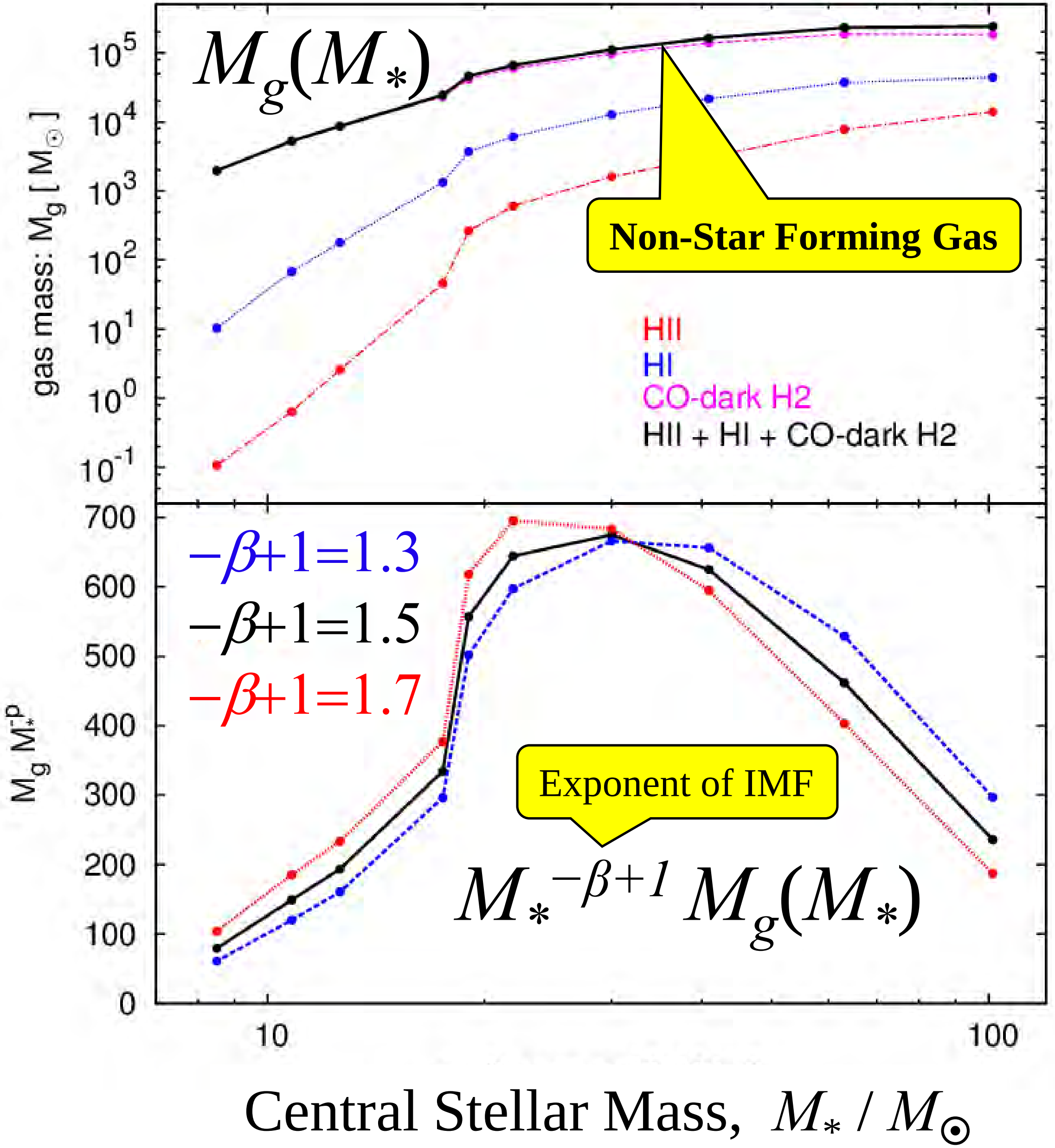
UV/FUV + H2 + CO Chemistry

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!



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

Star Formation Efficiency, KS-Law

Calculations → $10^5 M_\odot$ molecules (H_2) destroyed by $M_* > 30 M_\odot$ in 4Myrs!

$M_{\rm total} \sim 10^3 M_\odot$ stars

→ ~1 Massive (>$30 M_\odot$) Star for std IMF

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

Zuckerman & Evans 1974

Star Formation Time

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

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

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

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

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

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

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

Galactic Population of Molecular Clouds

Formation and Destruction of GMC

↓

Mass Function of Molecular Clouds

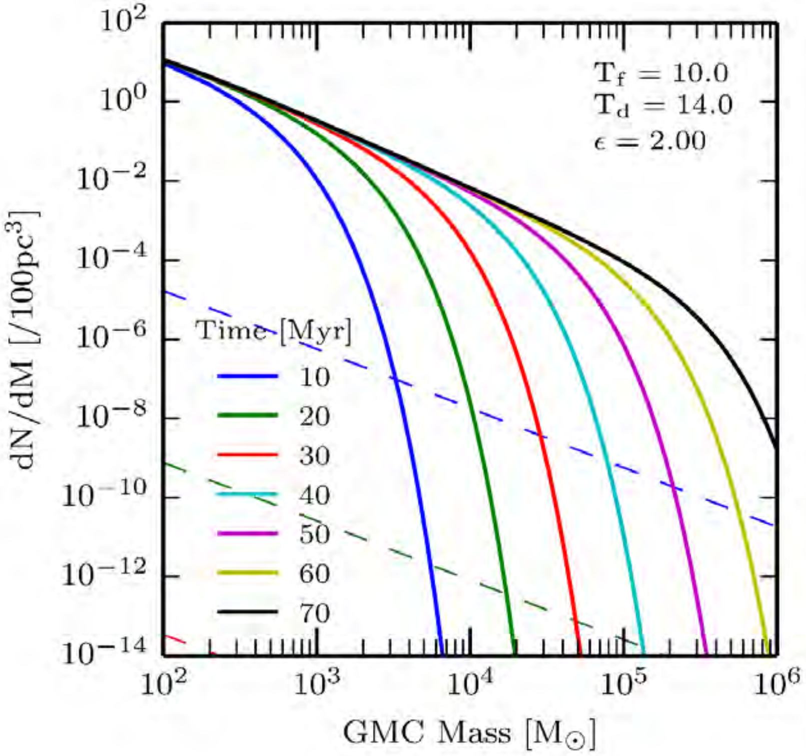
Mass Function of Molecular Clouds

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

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

$$\frac{M_{\rm cl}}{T_{\rm form}}$$

$T_{\rm dis}$=const.
“KS Law”



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

$$_{\rm orm} \sim 10{\rm Myr} \rightarrow \alpha = 1.7$$

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

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)

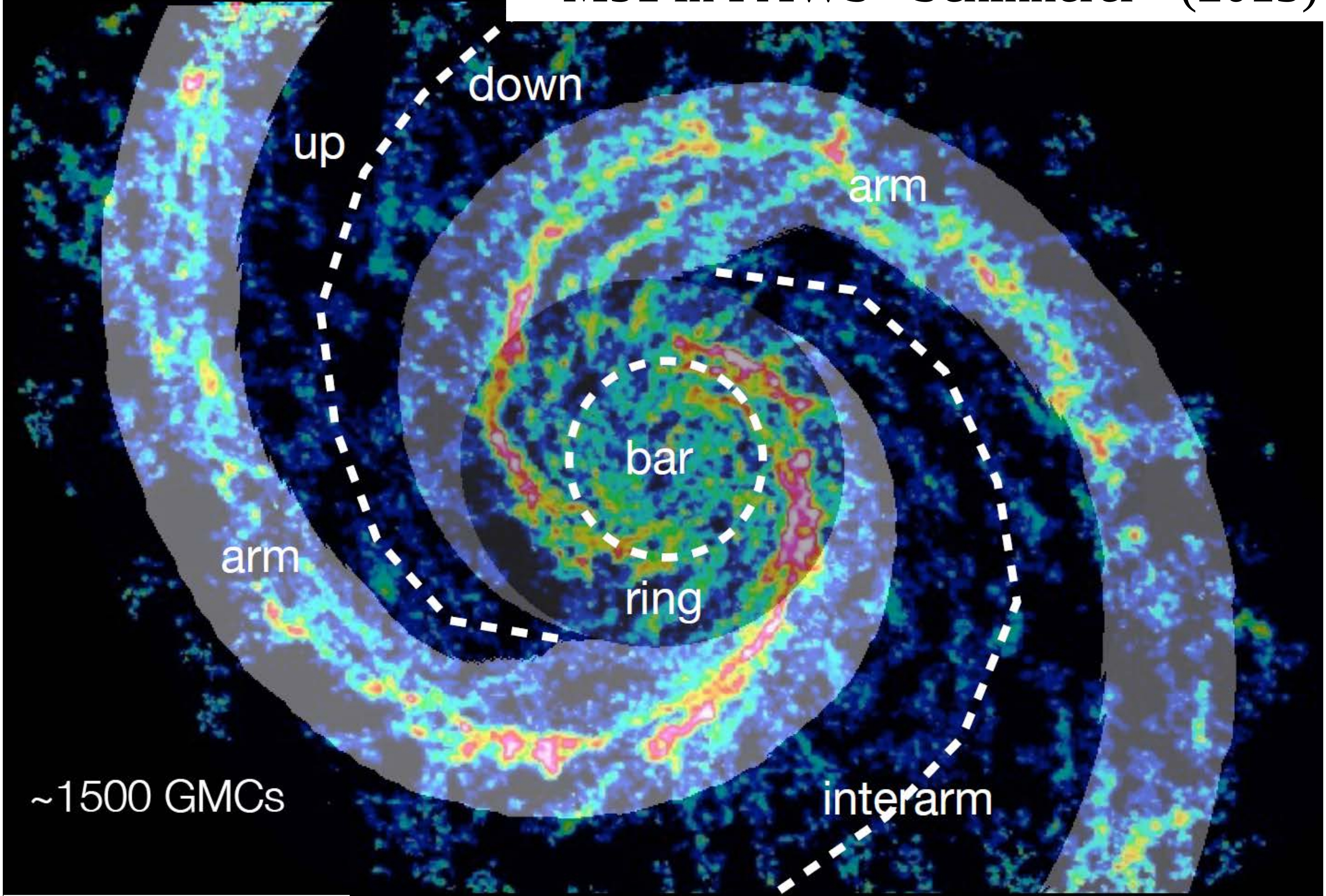
Larger $T_{\mathrm{form}} > T_{\mathrm{dis}}$ ➔ Larger α

In high density region (Arm Region)

Smaller T_{form} ➔ Smaller α

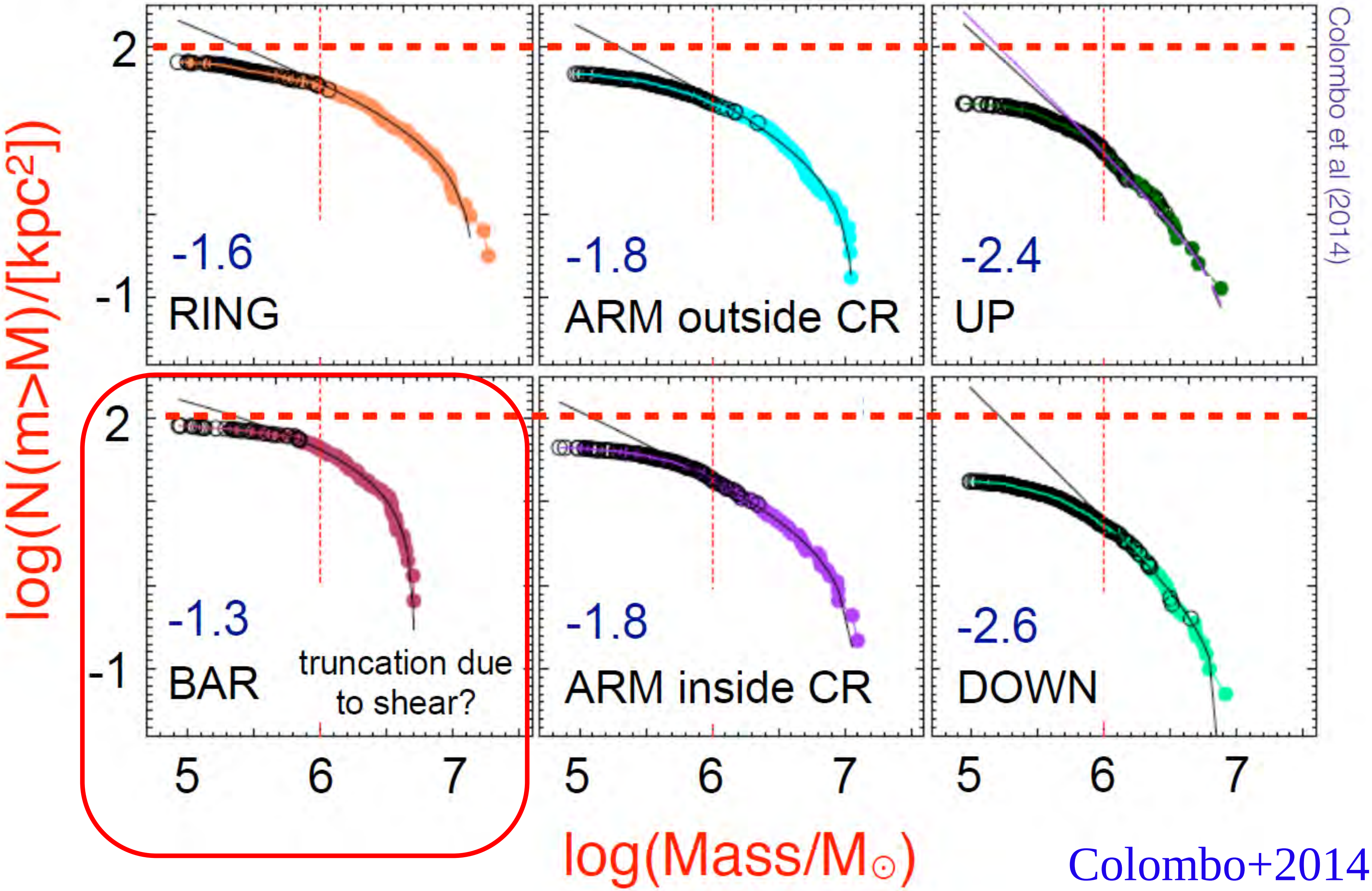
➔ GMCs in M51 (Colombo+2014)

M51 in PAWS Schinnerer+ (2013)



©Annie Hughes, MPIA

M51 GMC Mass Functions



Colombo+2014

Open Questions

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

2) Mass Fraction of Filaments in GMC? a few %?

   ➔ Relation between Gyr vs 20 Myr

3) Why Upper Limit for Core Formation Efficiency?

$$M_{\text{core}} / M_{\text{filament}} < \mathbf{15\%} \Rightarrow \boldsymbol{t}_{\text{dense gas}} \sim 20\text{Myr}$$

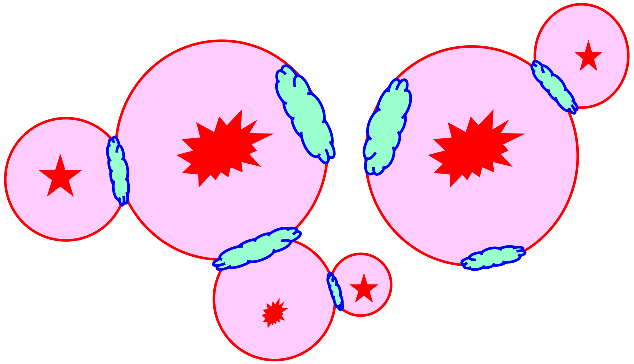
Summary: Unified Picture of Star Formation

Fragmentation of Filaments with Kolmogorov

−5/3

➔ Core Mass Function, Core Rotations

- $\delta v_{\text{cloud-cloud}} \sim 10\,\text{km/s}$
- $\varepsilon_{\text{SF}} \sim 10^{-2}$, Schmidt-Kennicutt Law ($t_{\text{dis}} \sim \text{Gyr}$)
- Accelerating Star Formation
- Mass Function of GMCs 🡐 Obs Test in Ext. Gal.



SI, Inoue, Iwasaki, & Hosokawa 2015, A&A **580**, A49
Inoue et al. 2018 PASJ **70**, S53
Iwasaki et al. (2019) ApJ **873**, 6
Kobayashi, SI, Kobayashi, & Hasegawa 2017, ApJ **836**, 175
Kobayashi, Kobayashi, SI, et al.2018, PASJ **70**, S59