Formation of Filamentary HI/Molecular Clouds and Role of Magnetic Fields

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Inoue & Inutsuka 2016, ApJ, 833, 10

Inoue, Hennebelle, Fukui, Matsumoto, Iwasaki & Inutsuka 2018, PASJ accepted.

Outline

- Formation of filamentary HI clouds (HI fibers) our of shocked diffuse ISM

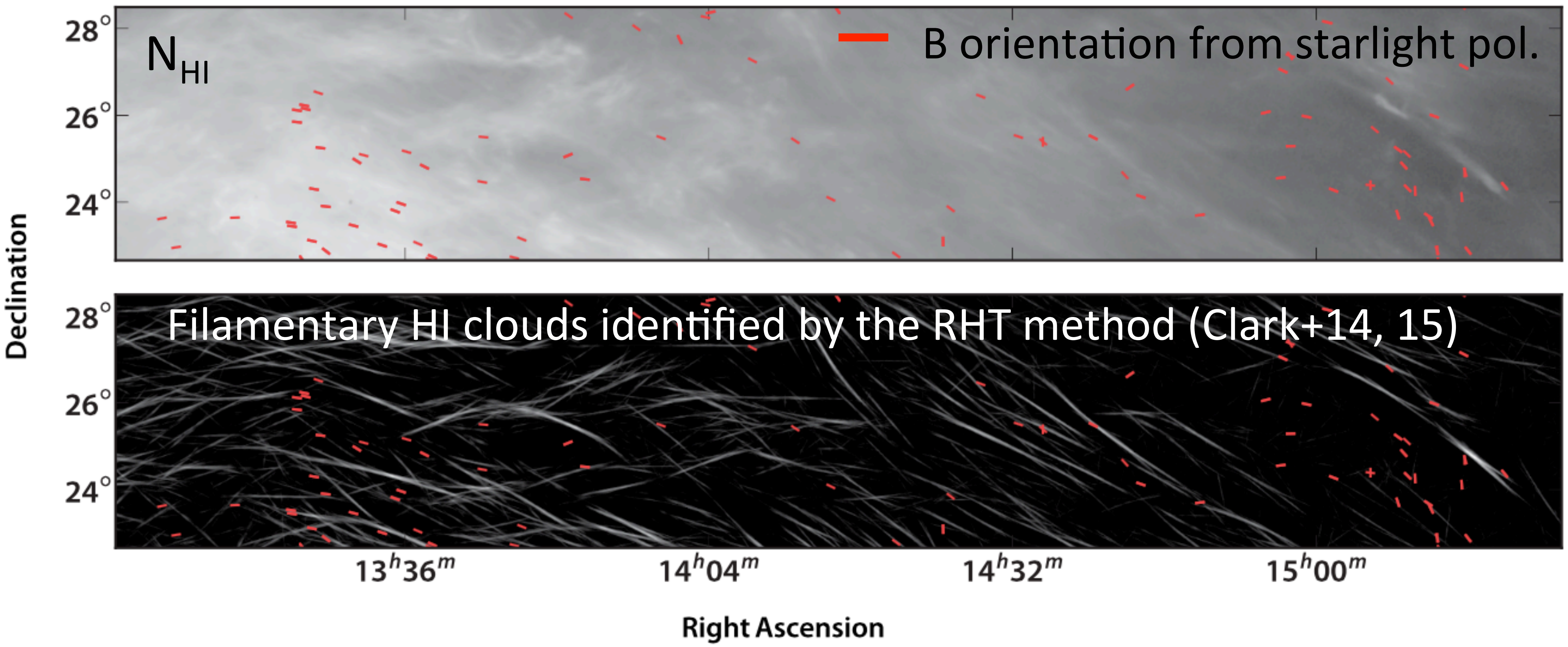
  (Inoue & Inutsuka 08, 09, 16)

- Formation of star forming filaments our of shocked molecular gas clumps

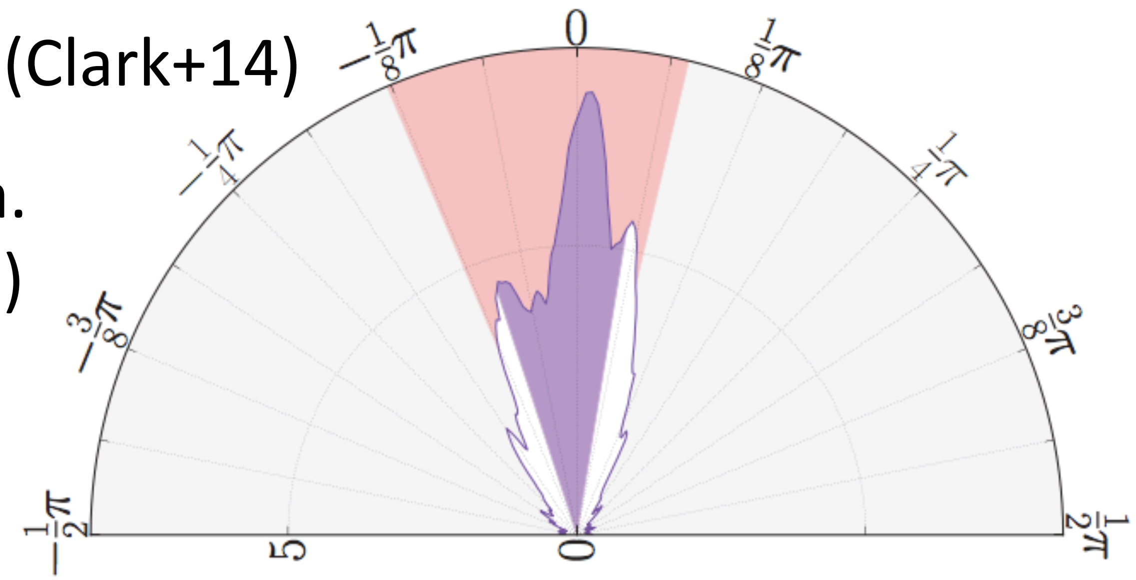
  (Inoue+18)

HI Fibers

- The Galactic Arecibo L-Band Feed Array HI (GALFA-HI) Survey.



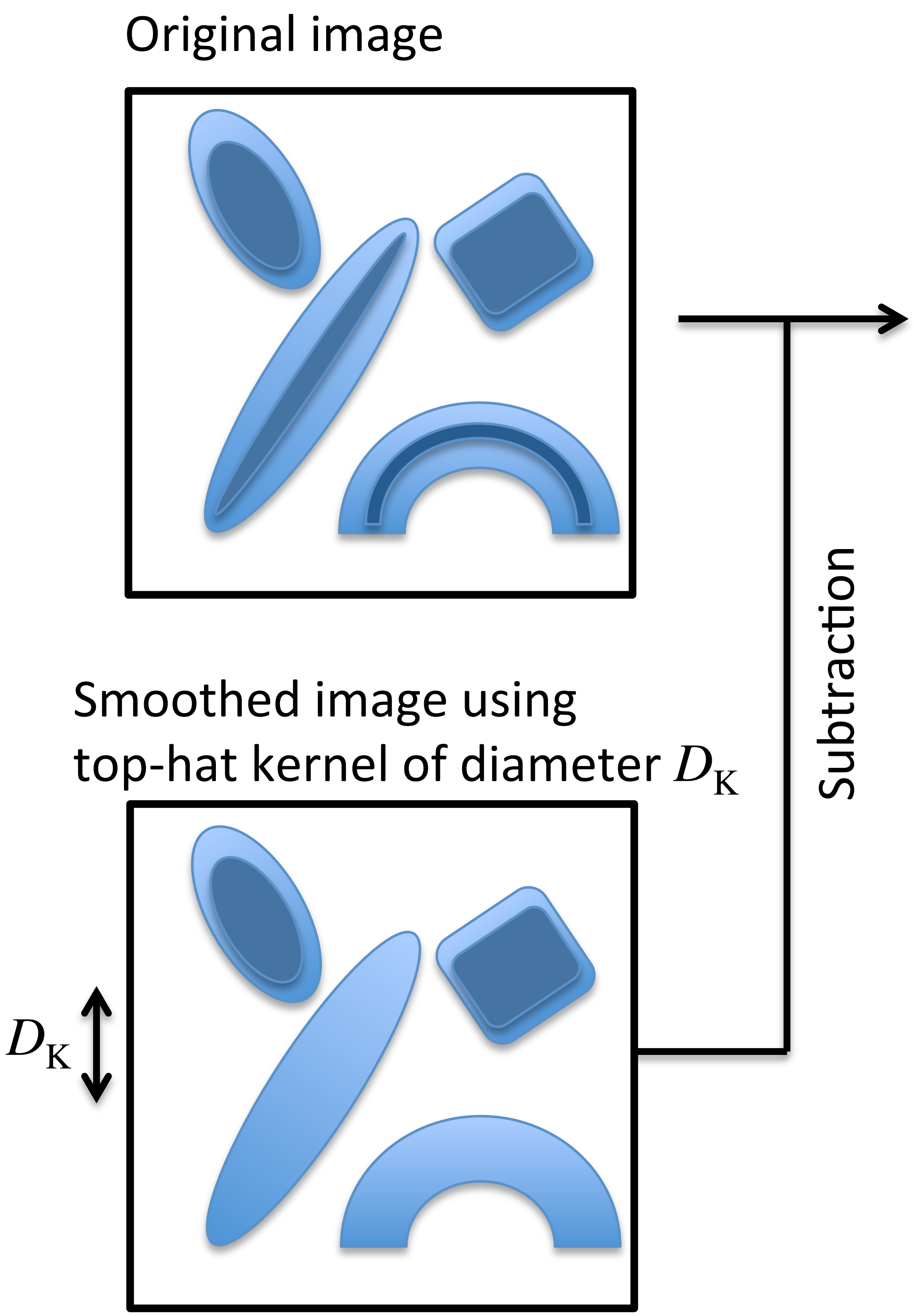
- Angular correlation between fibers and B-field (Clark+14)
  - Good correlation with Plank Polarization data. (Clark+15)
  - B-field orientation is measured only from gas structures!?

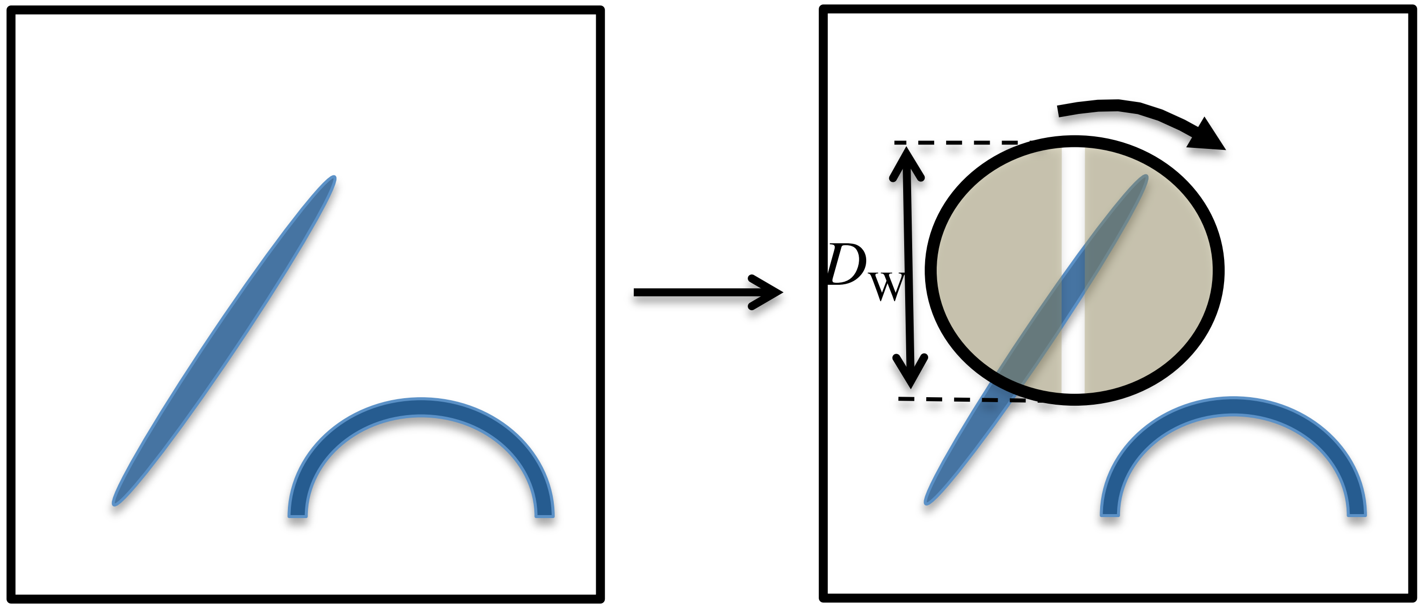


- These HI fibers are embedded in shell of Local bubble（see also McClure-Griffiths+ 06）.

The Rolling Hough Transform

- A machine vision transformation technique to extract linear structures（Clark+14）





Putting rolling slit of size D_W to find linear structures of length larger than D_W. Angle to local B field is measured when the linear structure is detected.

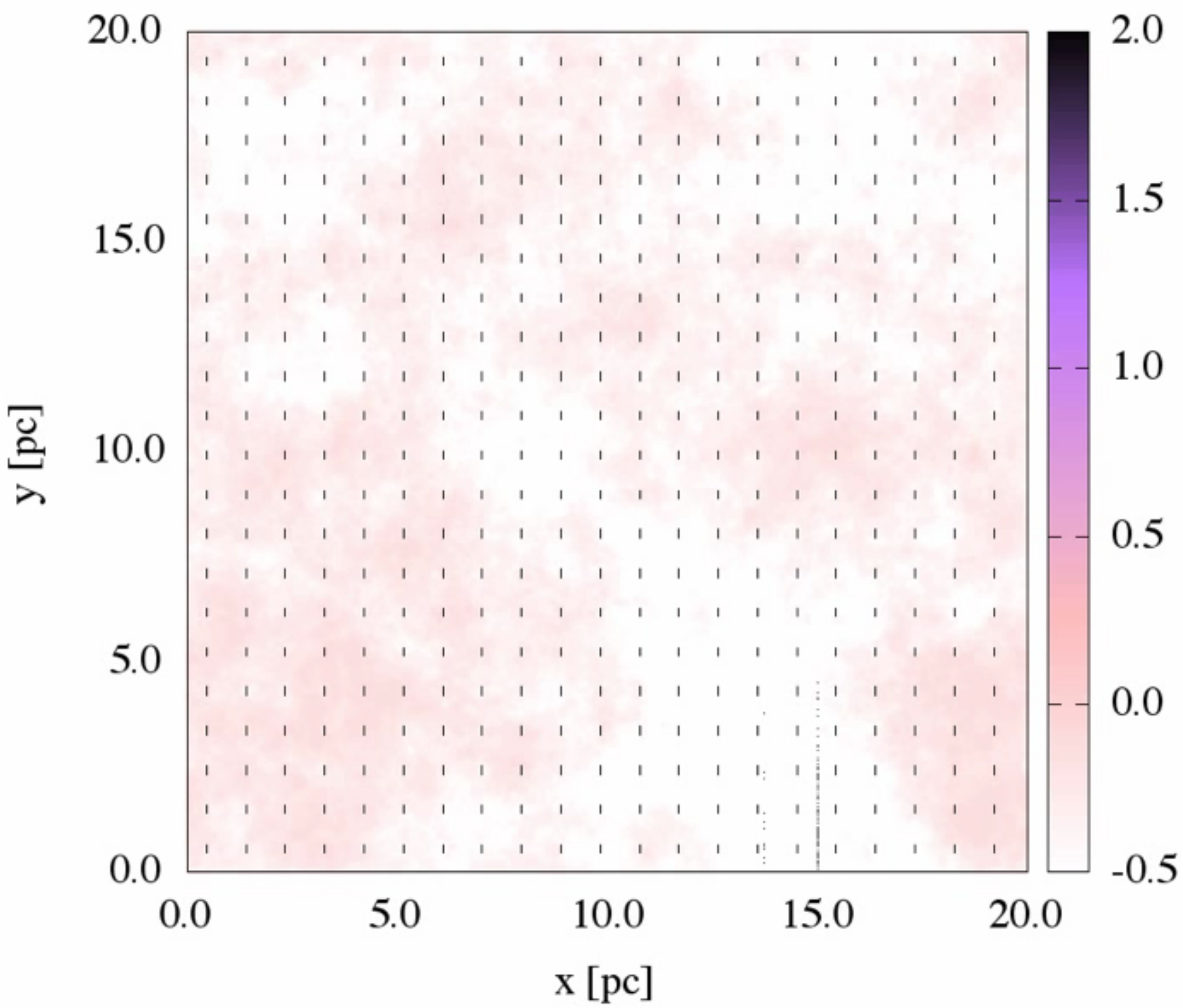
- $D_K \sim 0.1$ pc, $D_W \sim 1$ pc is applied

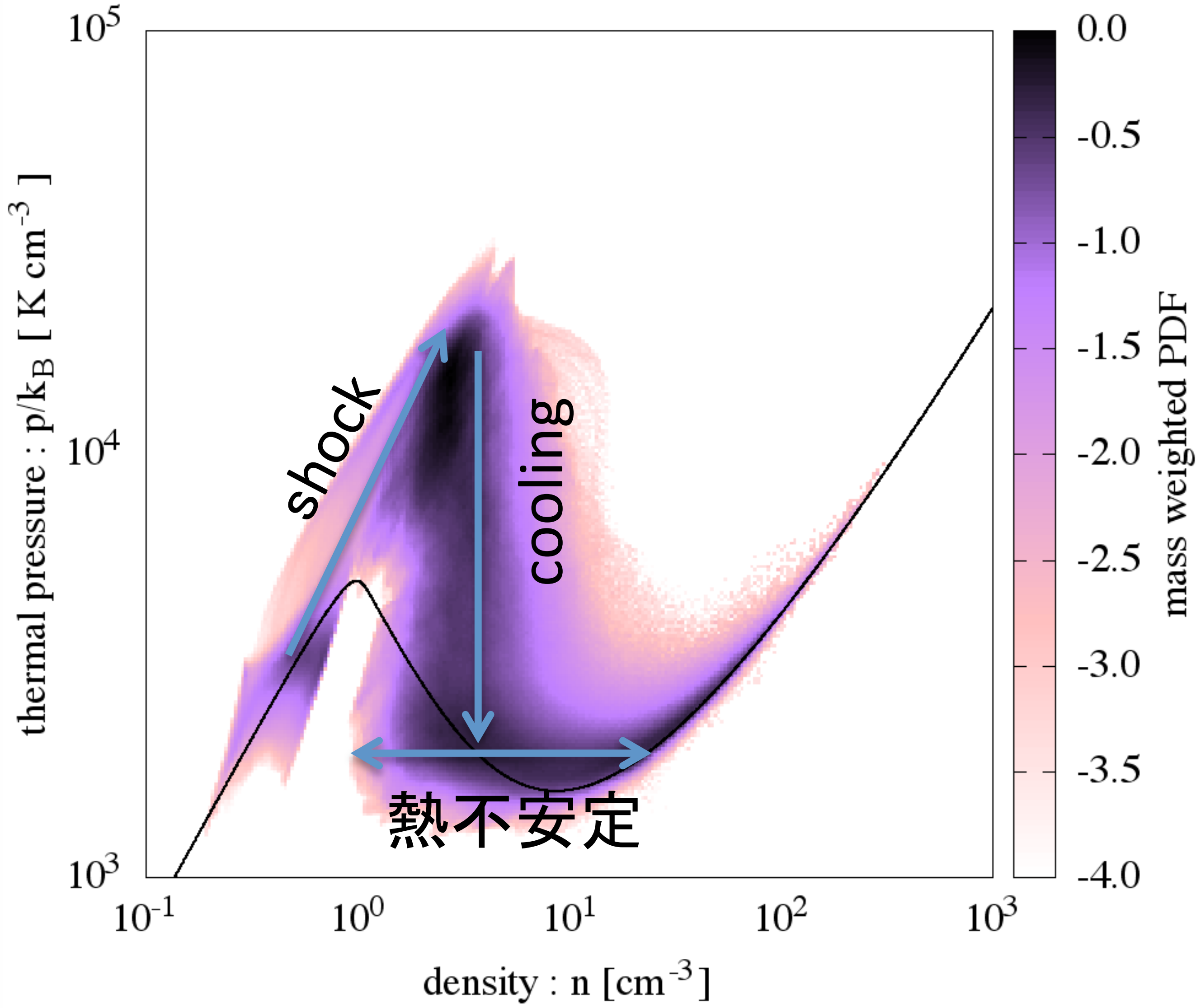
  → Linear structures of width $\lesssim 0.1$ pc and length $\gtrsim 1$ pc are extracted.

Impact of Magnetic Field

- Evolutionally track is drastically changed due to the effect of magnetic pressure.

(Inoue & Inutsuka 08, 09)



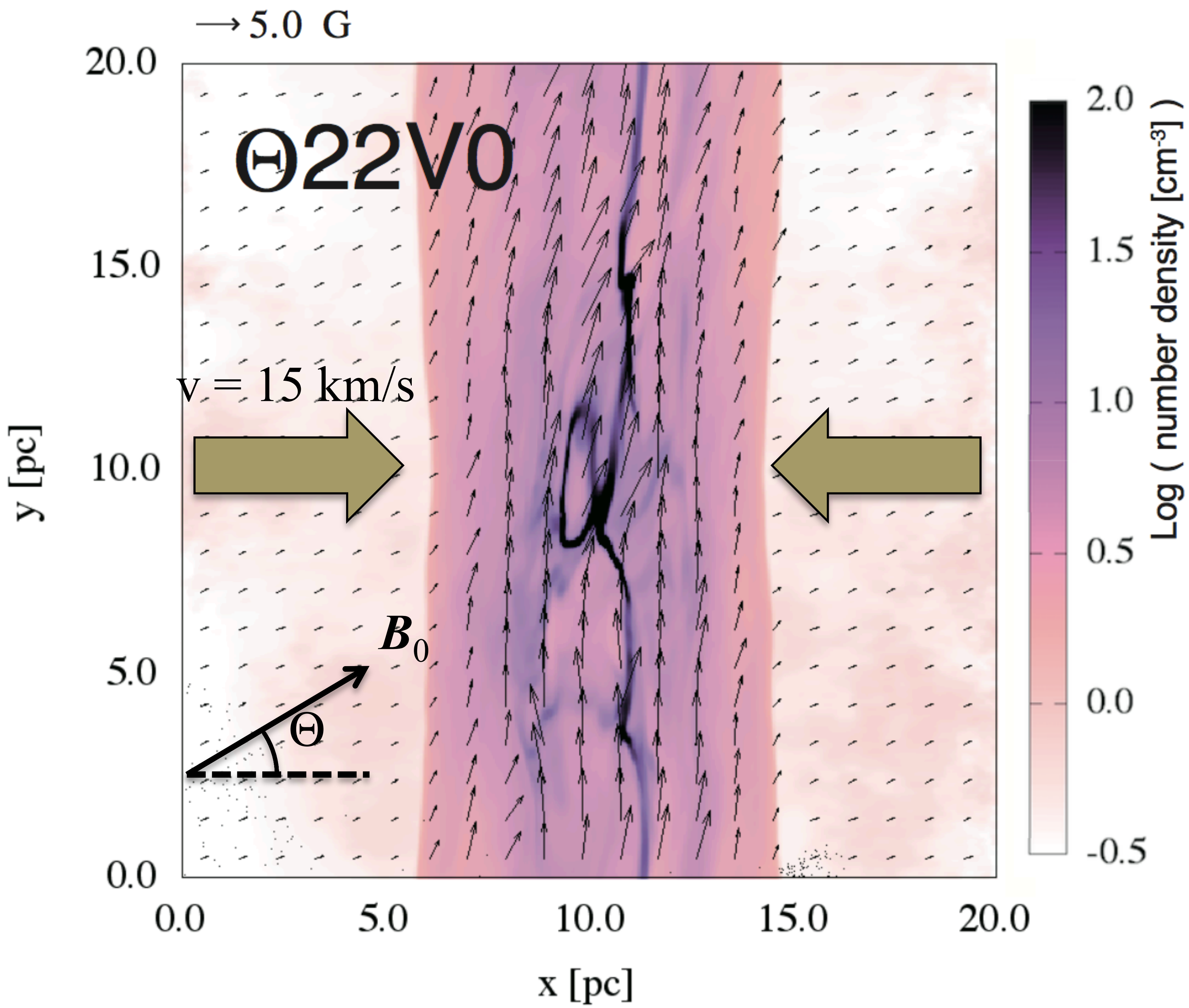


- Many observed characteristics of HI clouds（Heiles & Troland 03）are reproduced.
  i) morphology (r_{aspect}~50), ii) strength of B($\beta < 1$), iii) moderate turbulence(M~2)

3D MHD Simulation of HI Cloud Formation

Inoue & Inutsuka 16, ApJ

- We have updated simulations to 3D to study morphological properties of HI clouds.

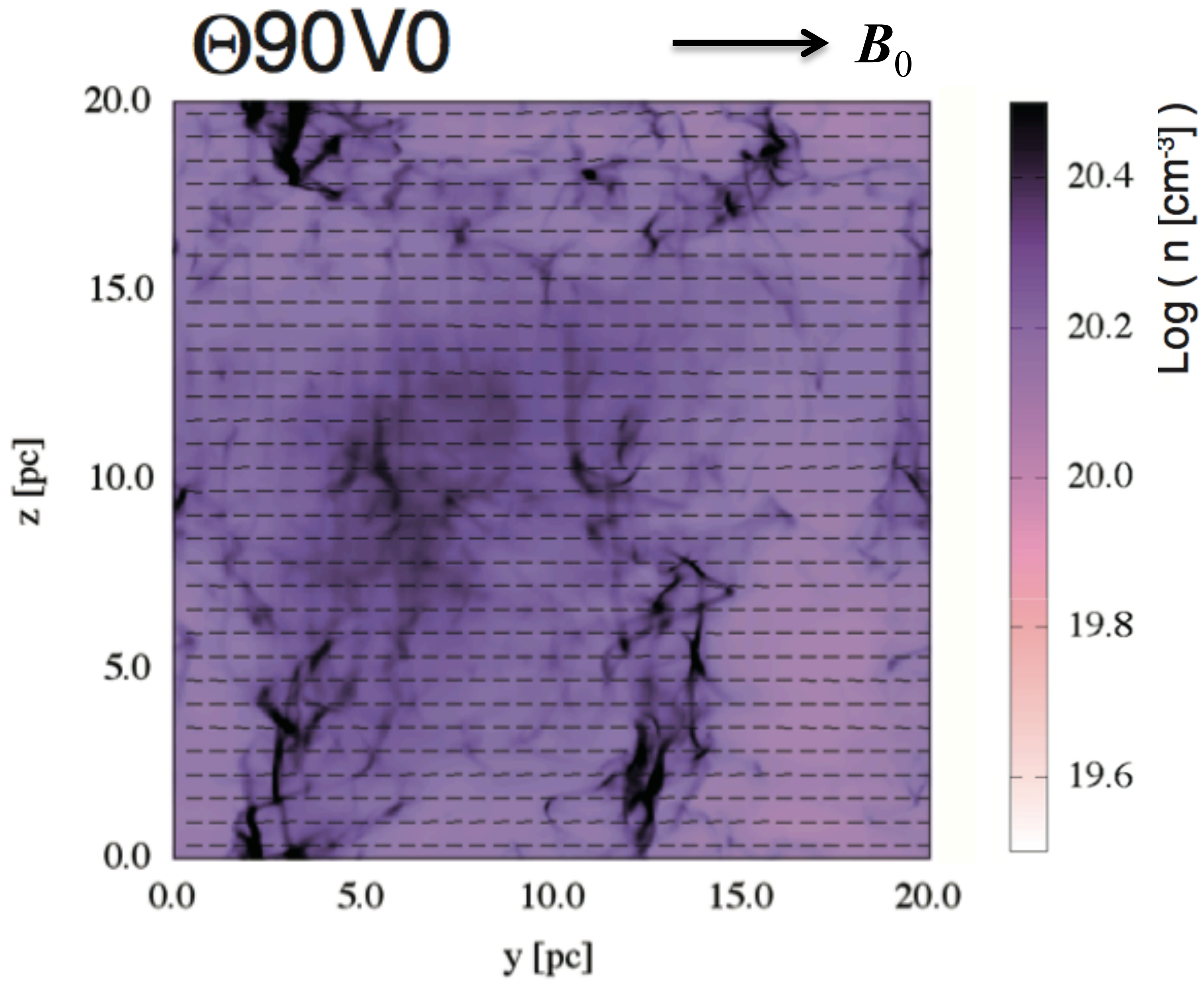


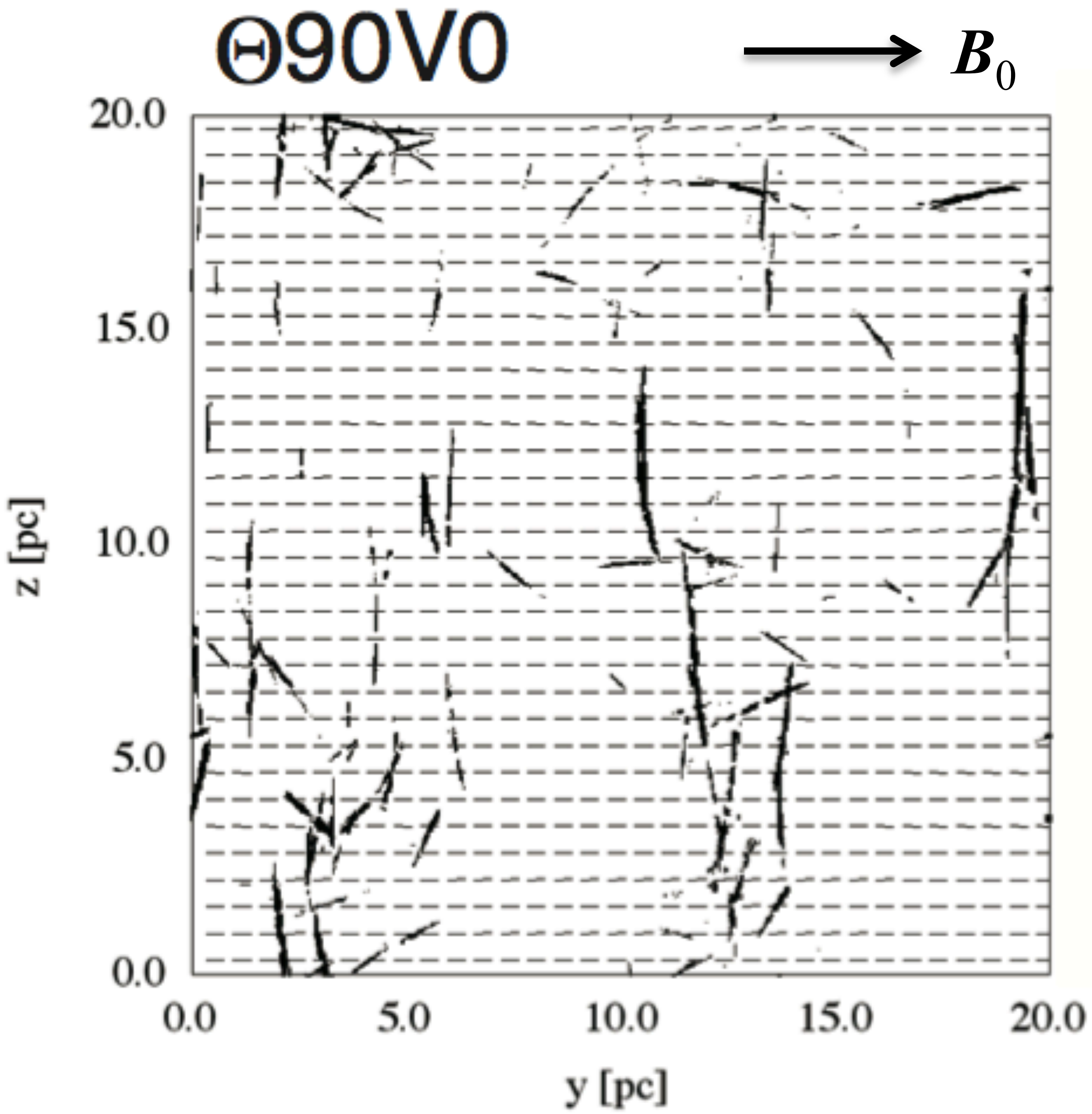
Model Parameters

Model ID	Θ [deg.] [a] (Initial B angle)	Δv [km s^{-1}] [b] (Initial level of turbulence)
Θ22V0	22.5	0.0
Θ45V0	45.0	0.0
Θ67V0	67.5	0.0
Θ90V0	90.0	0.0
Θ22V5	22.5	5.0
Θ45V5	45.0	5.0
Θ67V5	67.5	5.0
Θ90V5	90.0	5.0

Fibers Identified by RHT

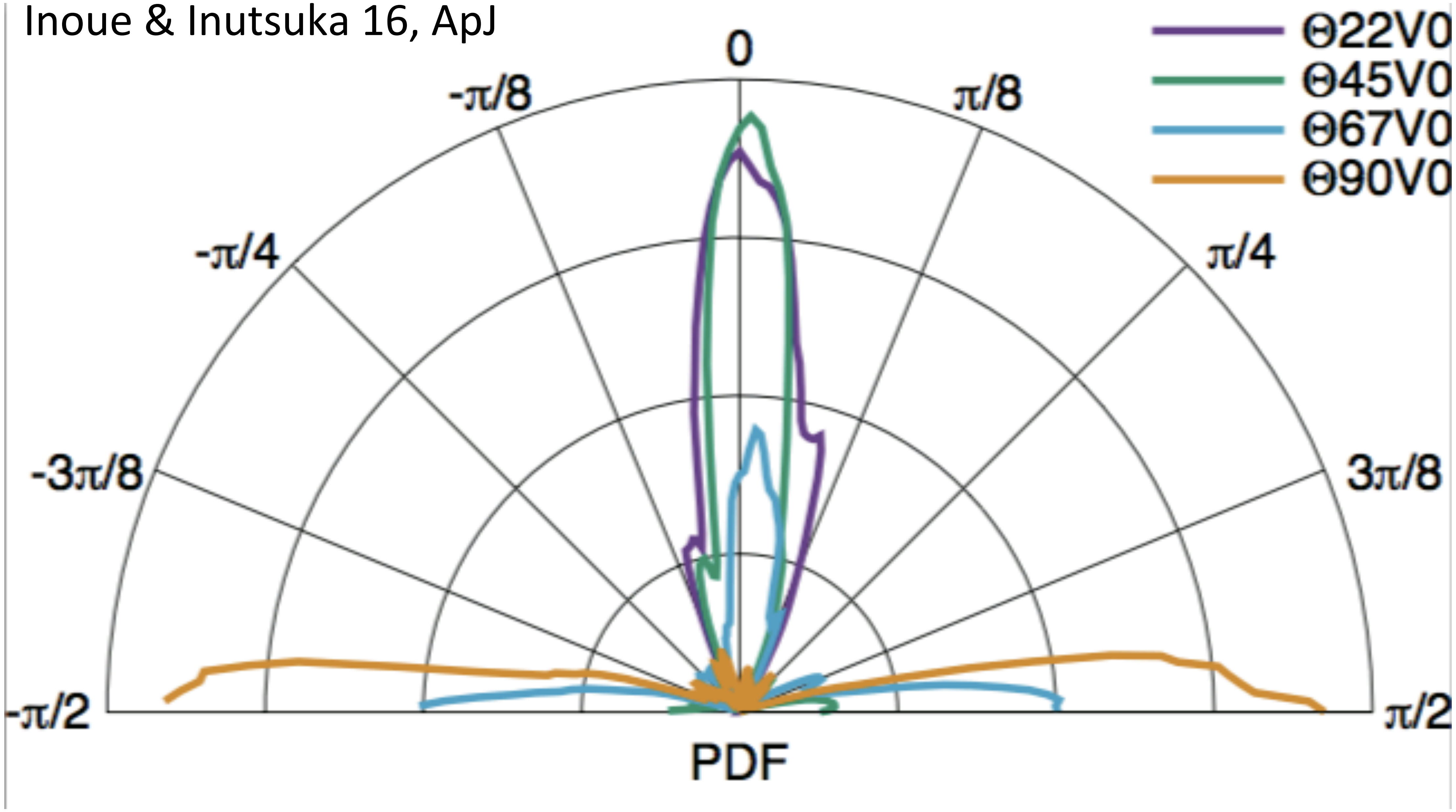
- W/O initial turbulence, orientation of fibers tend to be parallel to B-field for low Θ, while it becomes perpendicular for large Θ.





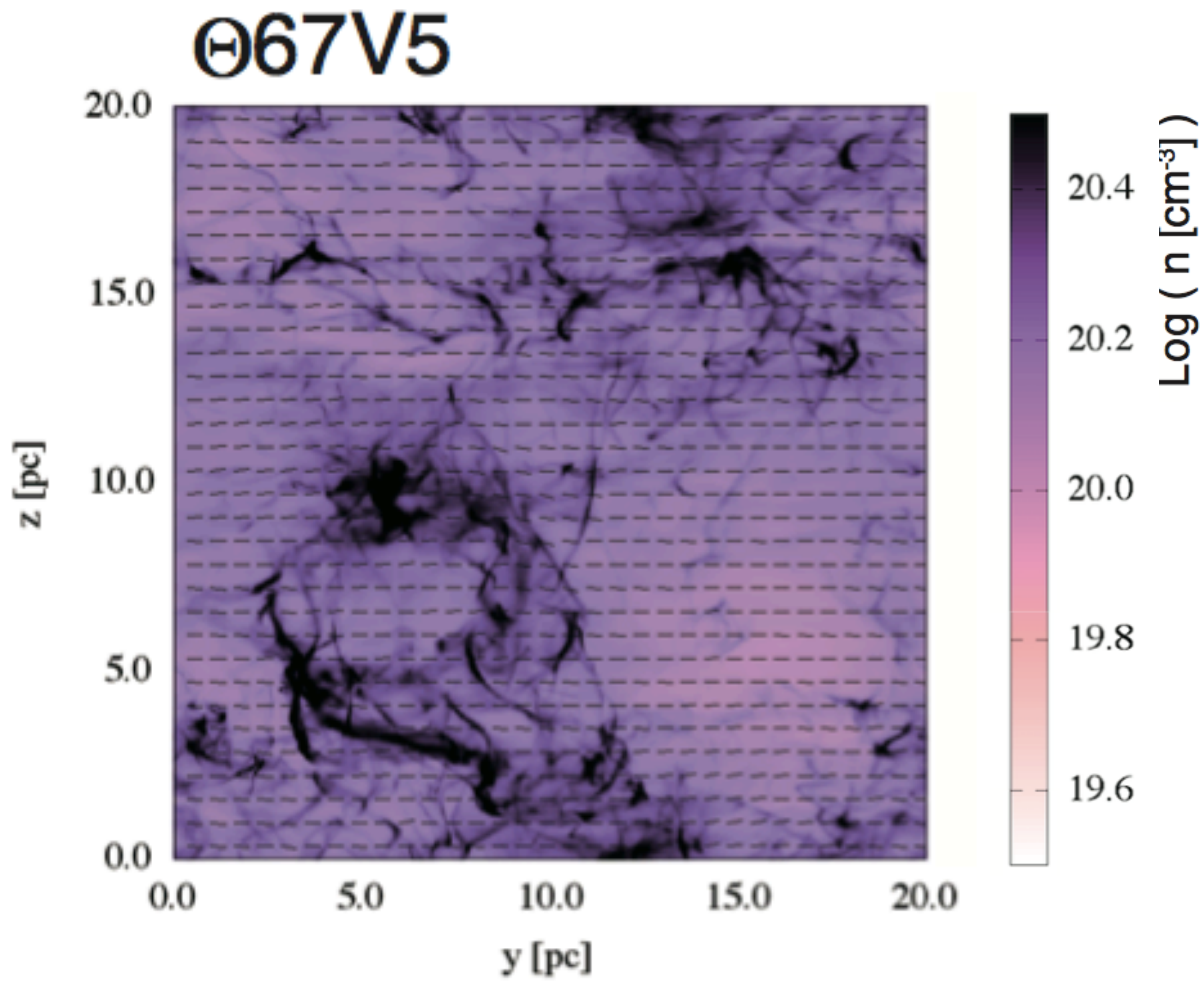
Angular PDF of Fiber Orientation

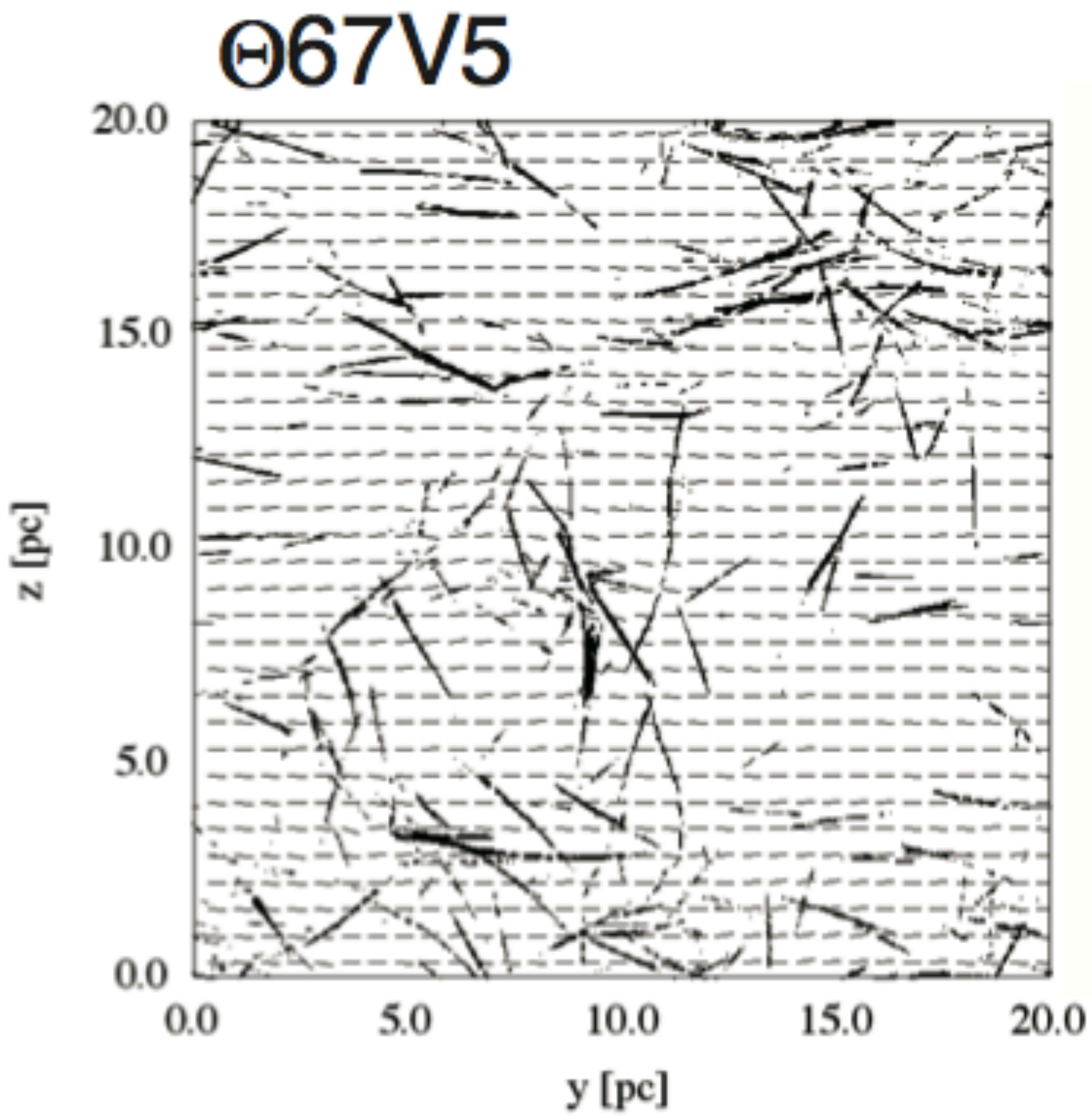
Inoue & Inutsuka 16, ApJ



Fibers Identified by RHT

- With initial turbulence, orientation of fibers is parallel to B-field independent of Θ, though dispersion is large.





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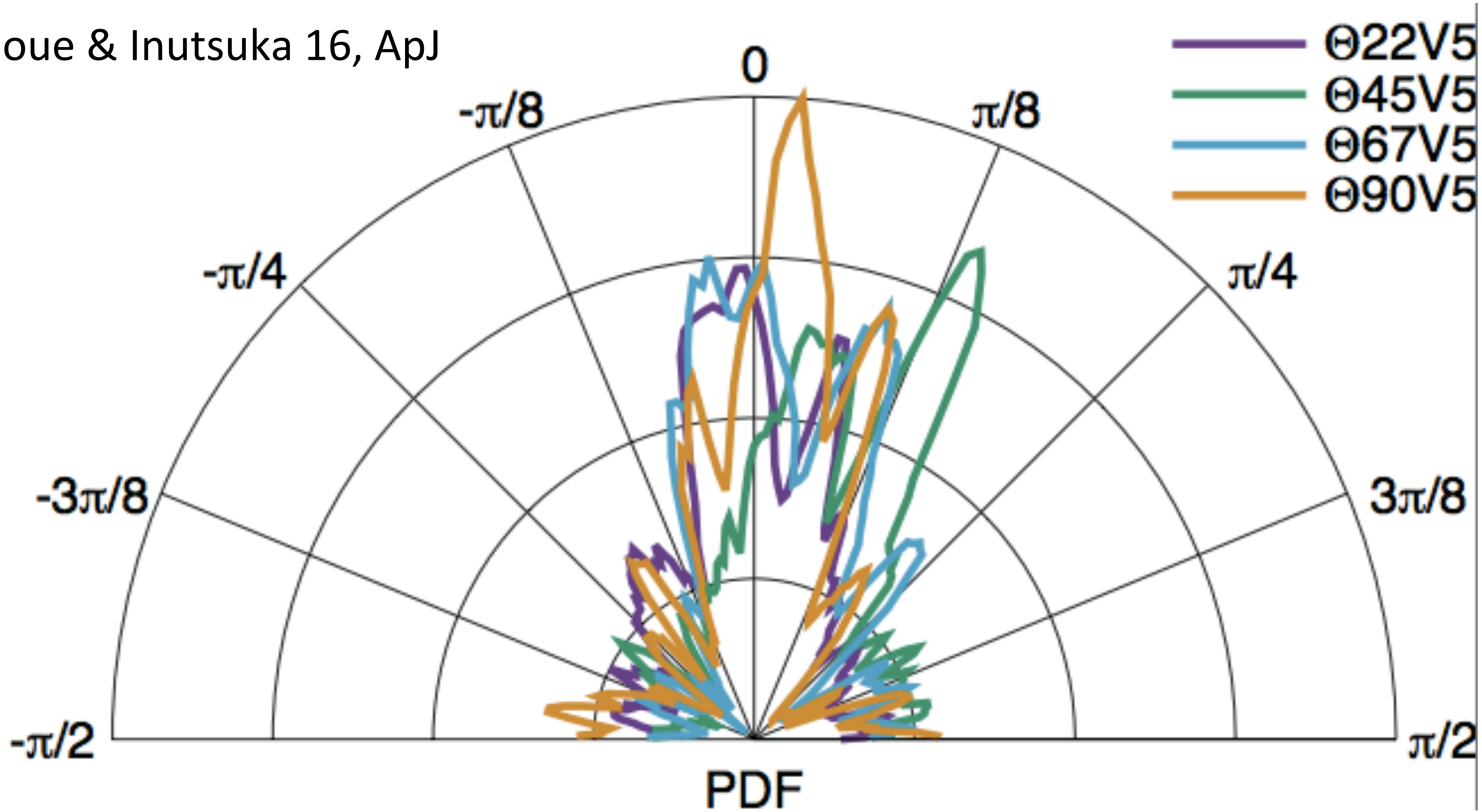
Inoue & Inutsuka 16, ApJ

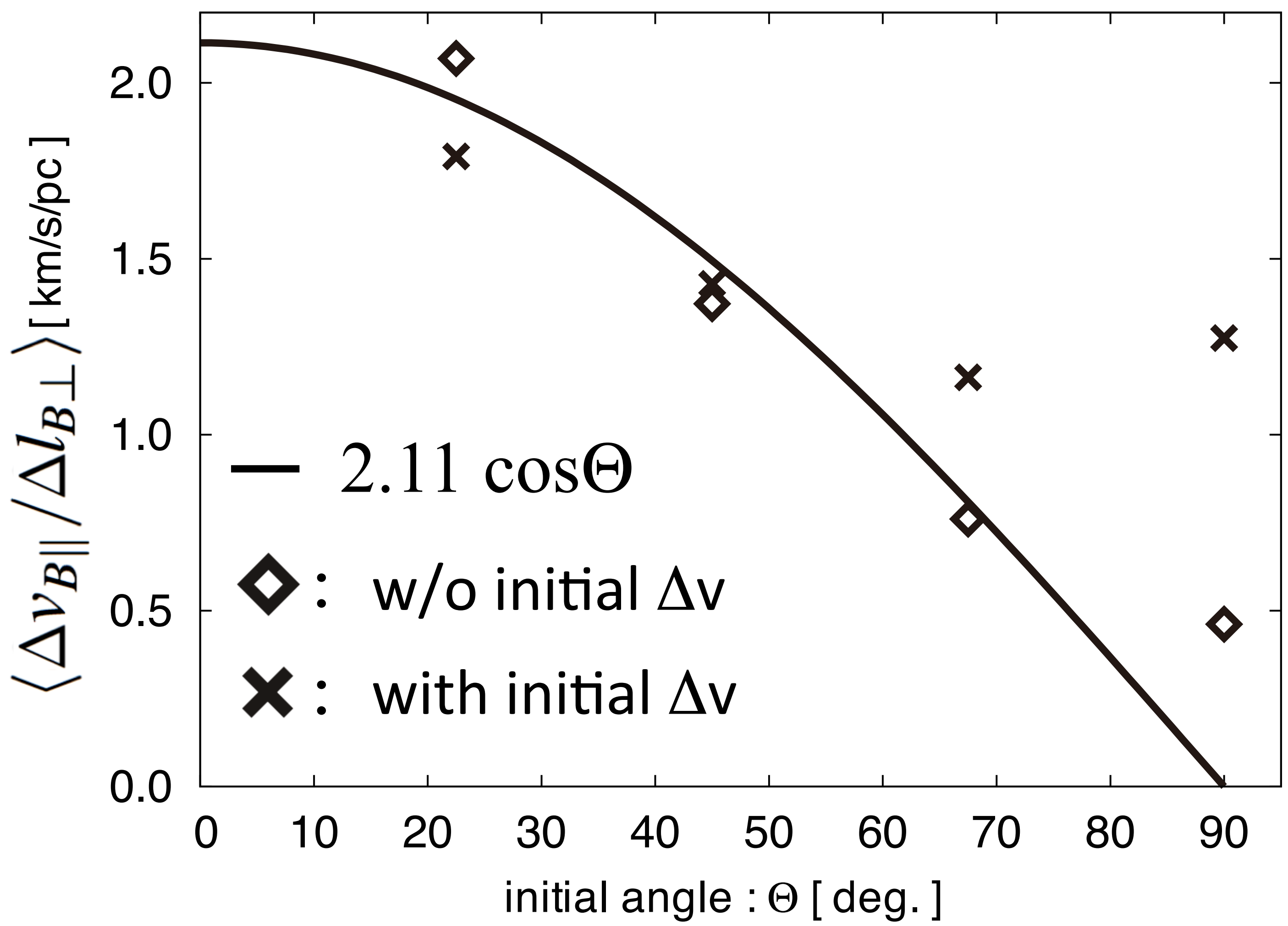


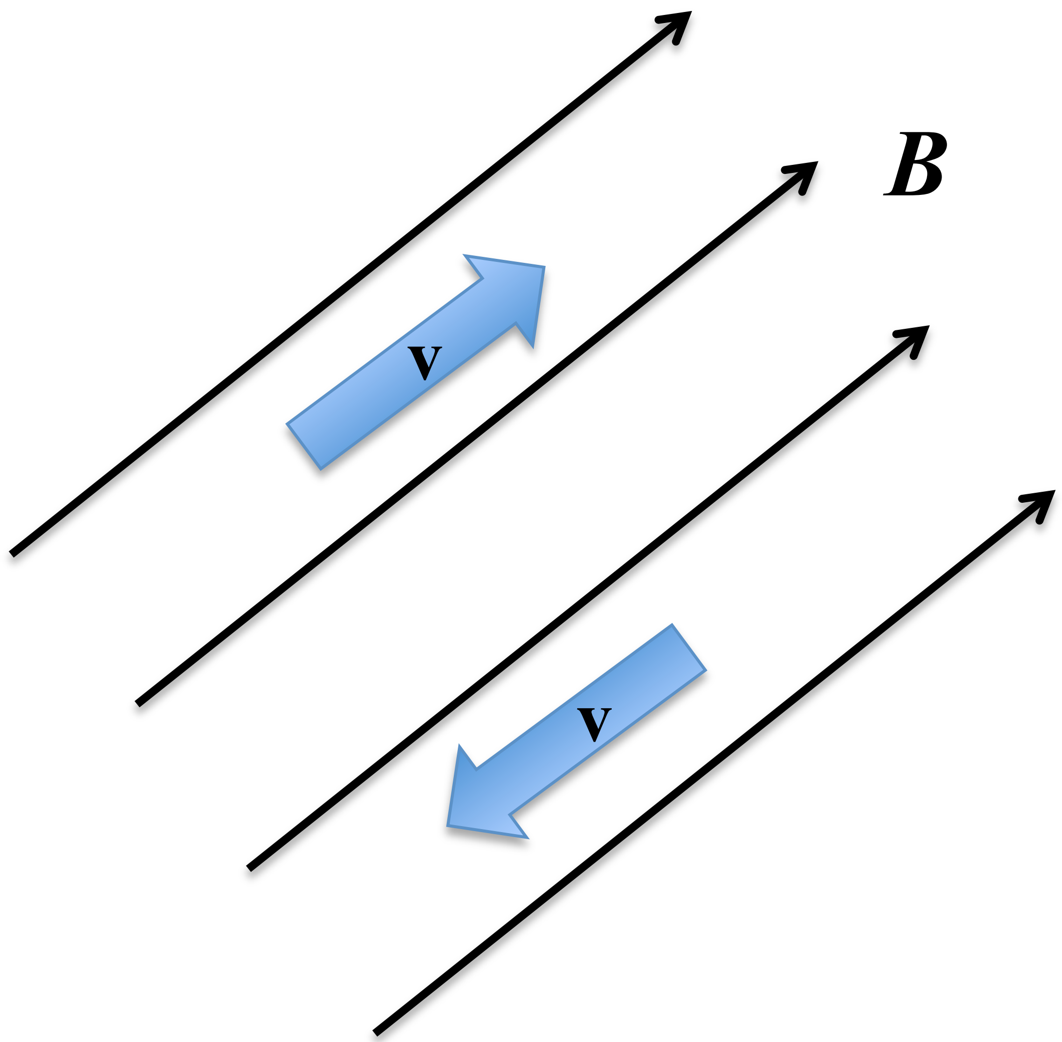
- Angular dispersion ~ 40° is consistent with Planck observation (Solar+16).

Why？

Inoue & Inutsuka 16, ApJ

- Shear of velocity along B-field plays key role.





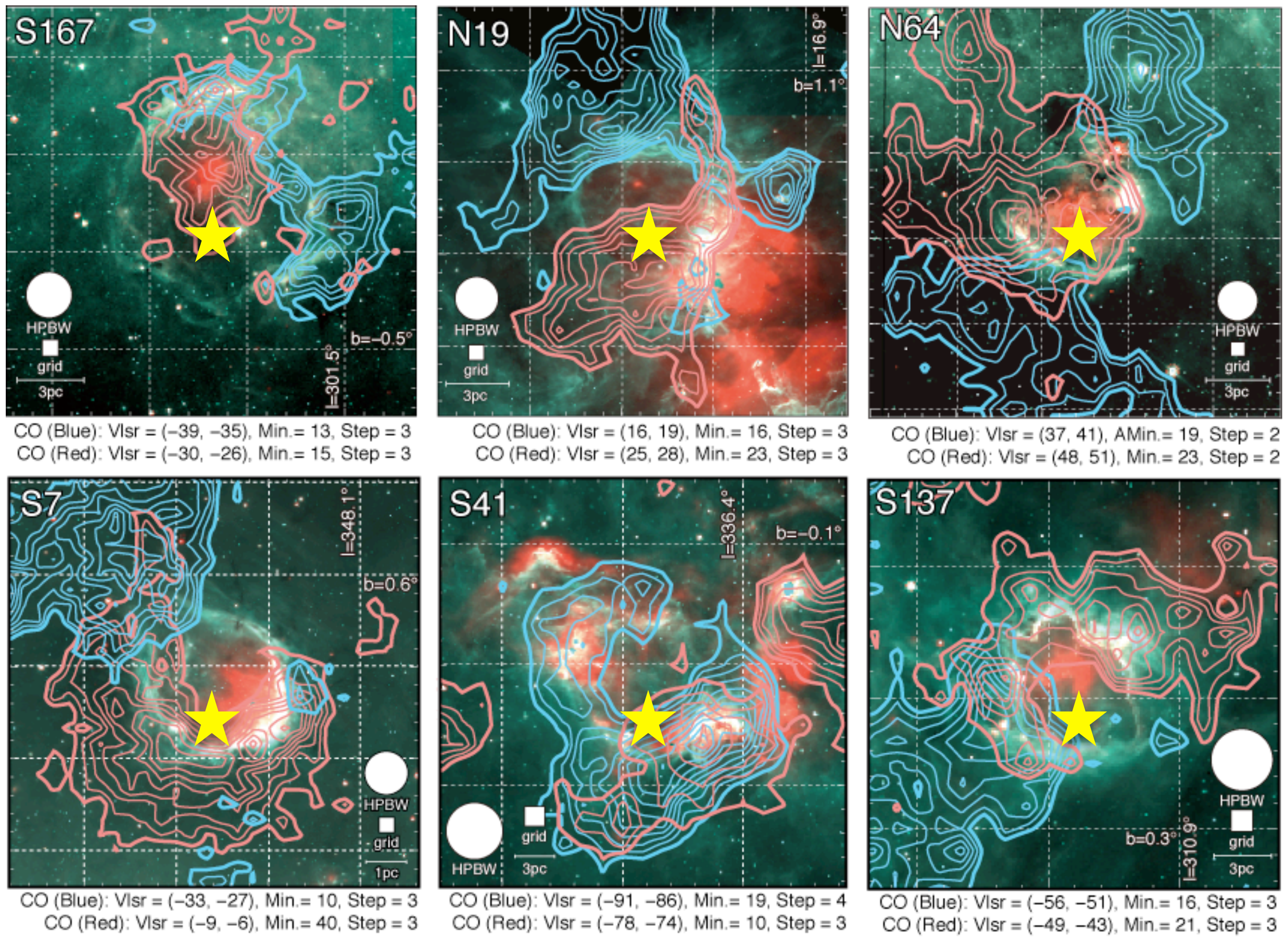
- Fibers that align with B-field is created when the shear along B-field is larger than the critical value of ~ 1 km/s/pc.
- W/o initial turbulence, it is known that velocity shear is created at shock front whose strength is decrease with Θ (∝ cos Θ) (e.g., Inoue et al. 2013, ApJ, 772, L20)

→ In realistic ISM with turbulence, we can always expect fibers along B-field.

Strong Shock as Trigger of Massive Star Formation

- Recent observations suggest massive star/cluster formation is triggered by cloud collision

  (e.g., Furukawa+09, Ohama+10 for Westerlund2, Torii+11, 15 for M20 & RCW120, Fukui+14 for NGC3603, Nakamura+14 for Serpens South).



Color: Spitzer 8, 24μm (Benjamin+03, Carey+09)

Contour: NANTEN2 ^{12}CO J=1-0 (Fukui+)

- Representative sites of cloud-cloud collision where massive stars are located at center of each panels.

- Large collision velocity for massive star formation:

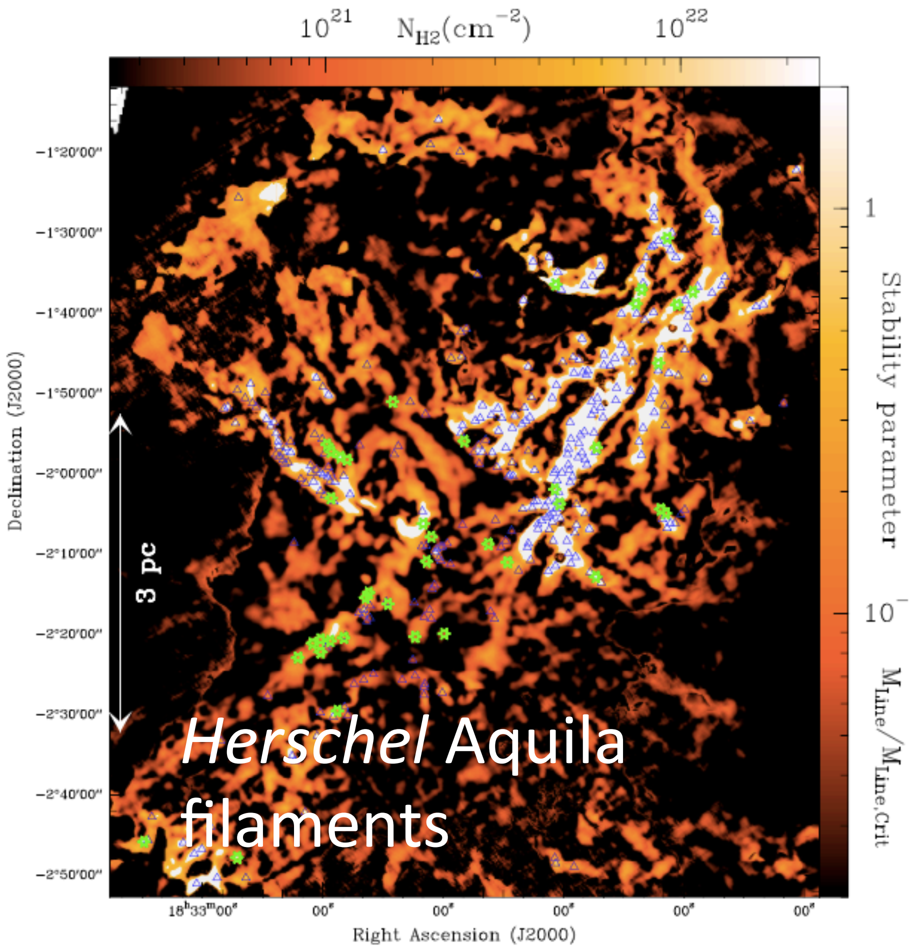
  ✓ $v_{rel} \sim 20$ km/s

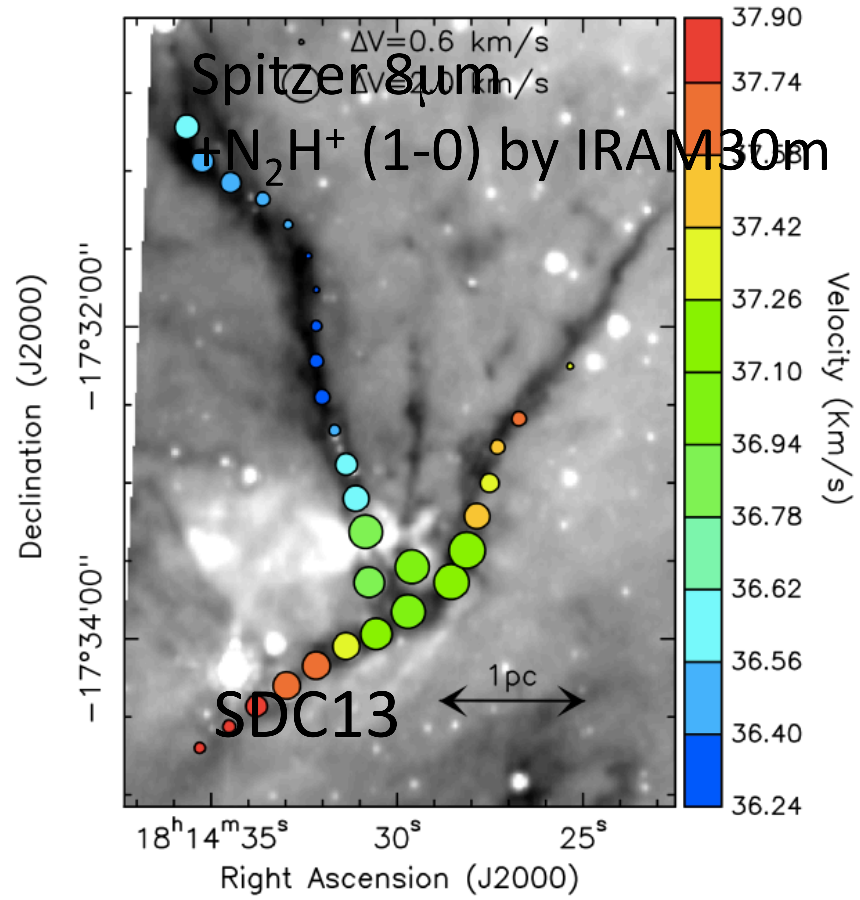
  $\gg c_s \sim 0.2$ km/s

  → Strong shock triggers massive star formation?

Filaments

- Recent observations established that dense filament is the terminal of ISM evolution.
  - Low mass stars are formed from filament with $m_{line} > m_{crit}$ for GI (Andre+10).
  - Global collapse of massive filament drives massive-star formation (Pretto+13).



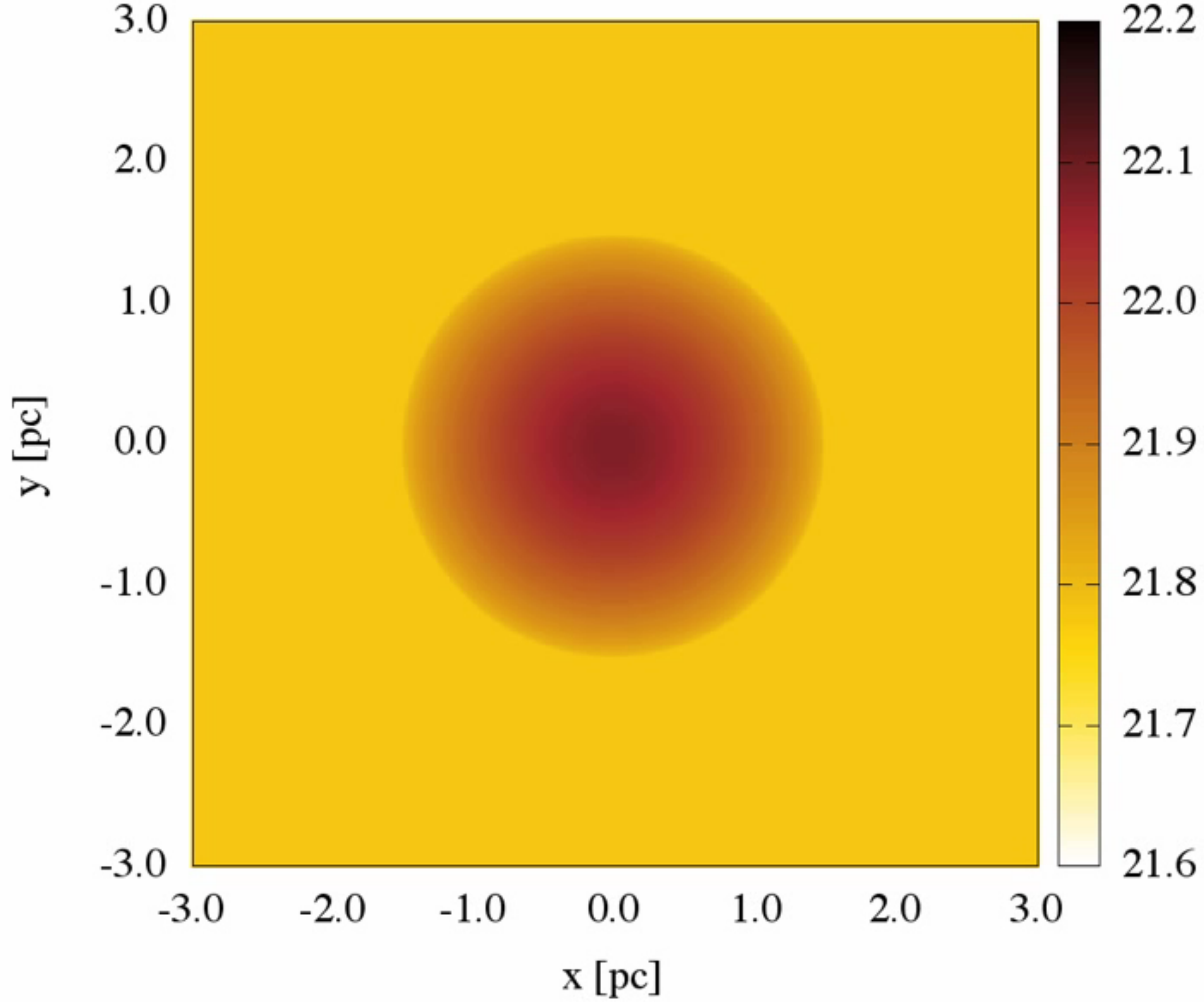


- Cloud collision と フィラメントからの大質量形成がつながると面白い。

Shock Crushing of Turbulent Cloud

Inoue & Fukui 13, Inoue+18 PASJ special issue

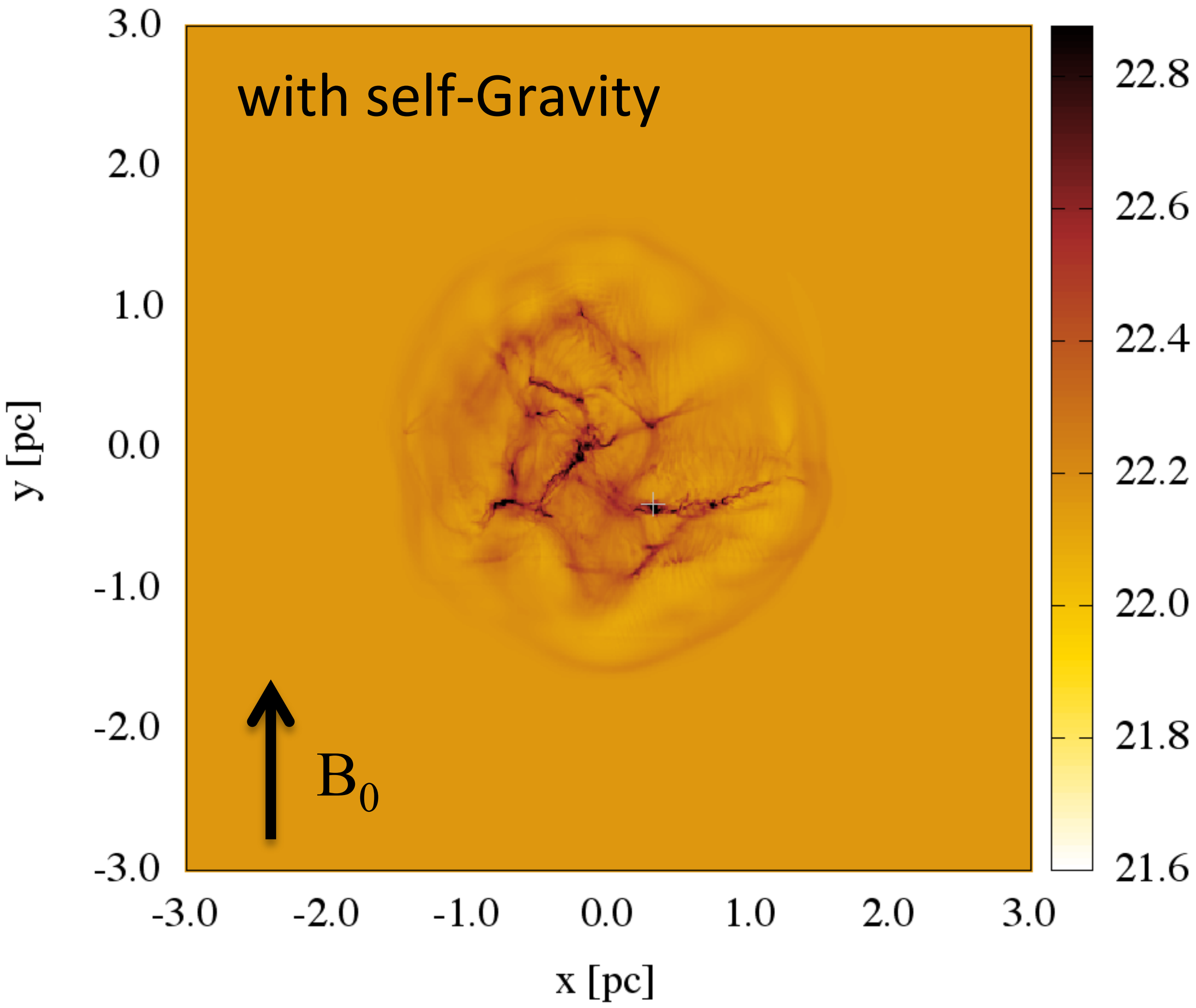
- AMR MHD simulation of cloud collision by SFUMATO code (Matsumoto 07).
  - Collision of a turbulent cloud and a bigger cloud with effective resolution 4096^3 cells ($\Delta x \sim 0.0015$ pc).
  - $\langle n \rangle = 1000$ cm^{-3}, $B_y = 10$ μG, $v_{rel} = 10$ km/s.
  - $M = 500$ m_{sun}, $\delta v = 1.5$ km/s for small cloud.

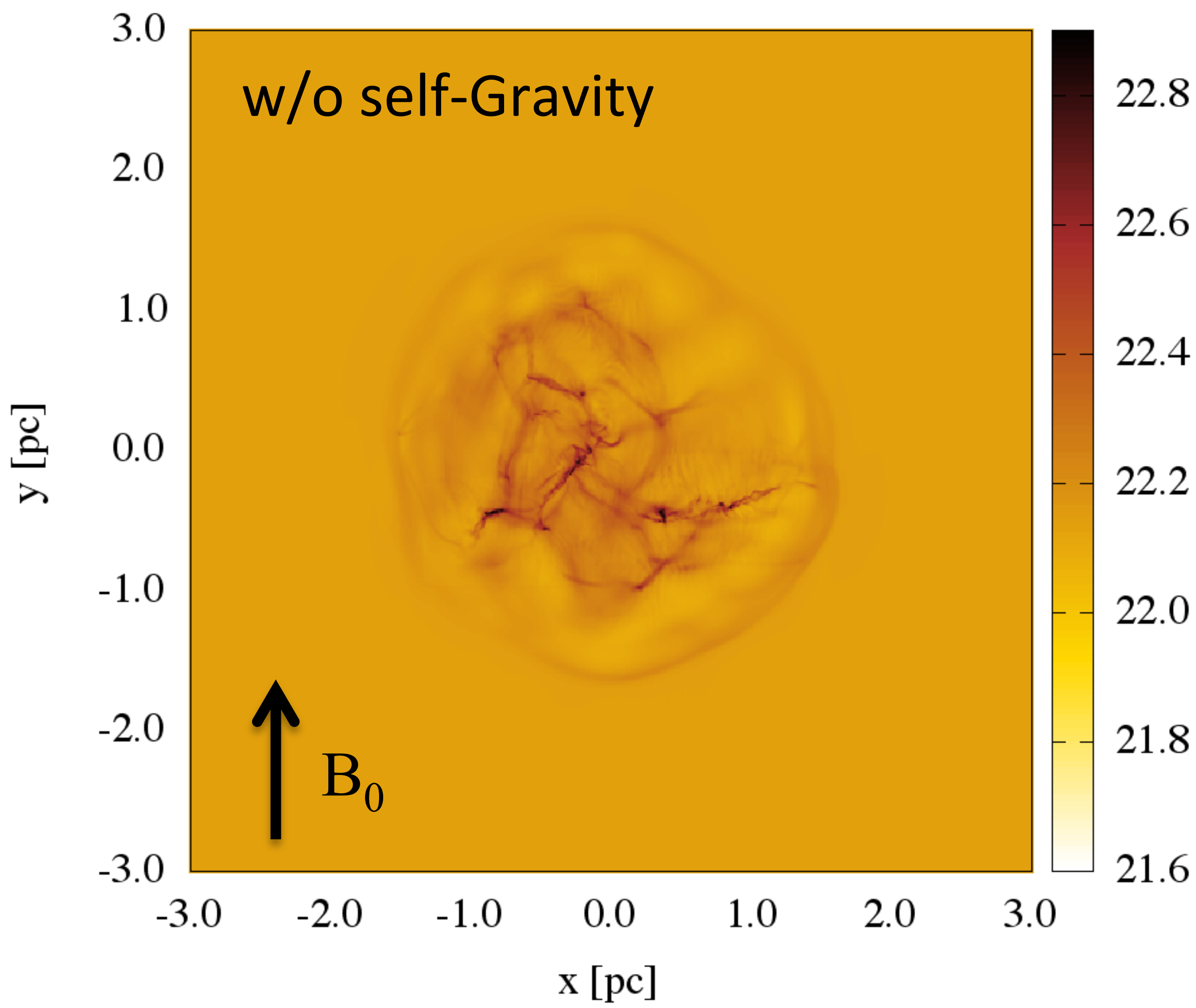


Filament Formation by Clump Crushing

Inoue & Fukui 13, Inoue+17 in prep.

- Filaments are formed even if self-gravity is switched off.



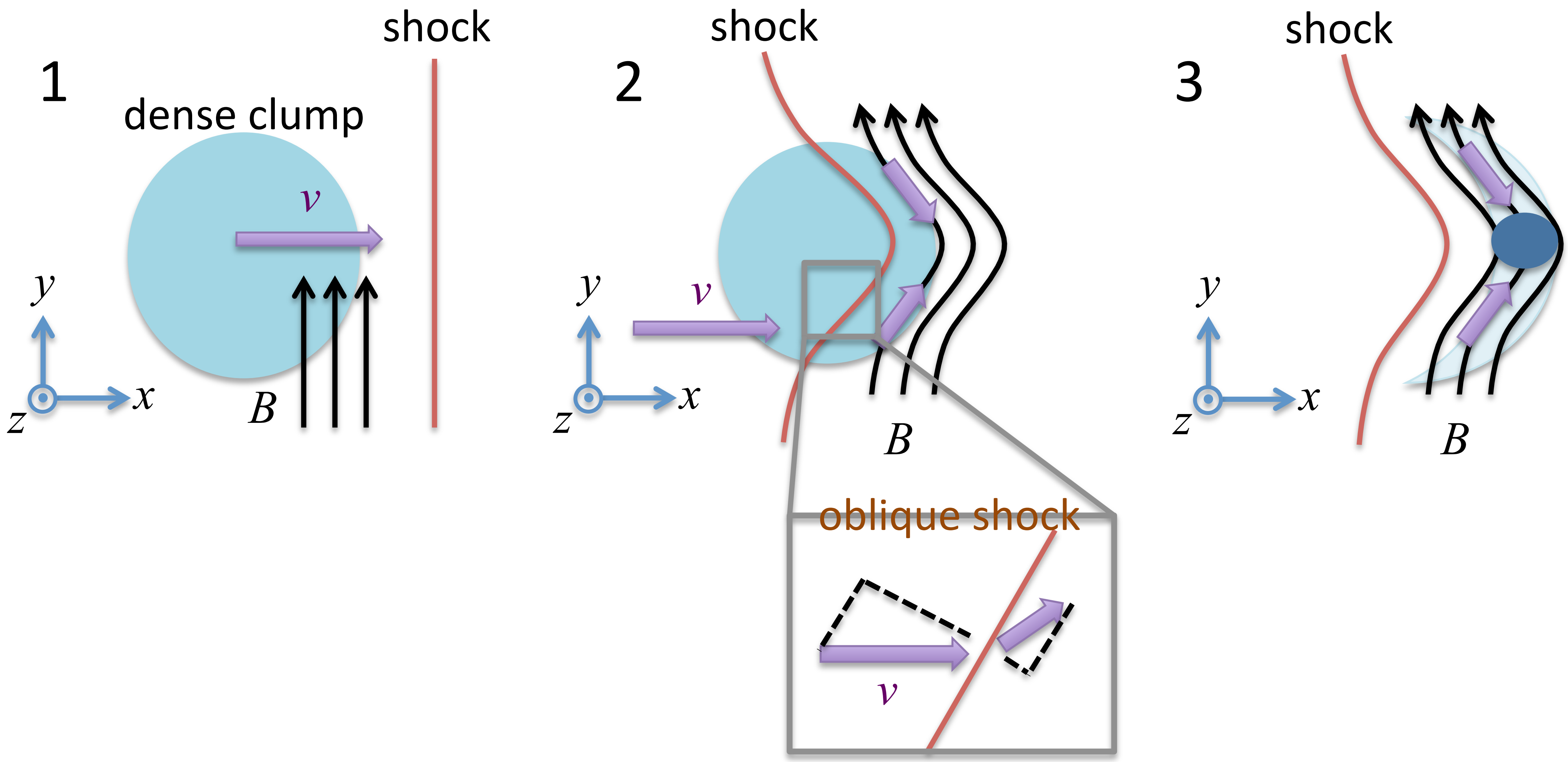


- Filaments are formed by magneto-hydrodynamic process.

Filament Formation behind MHD Shock

Inoue & Fukui 13, Vaidya+13

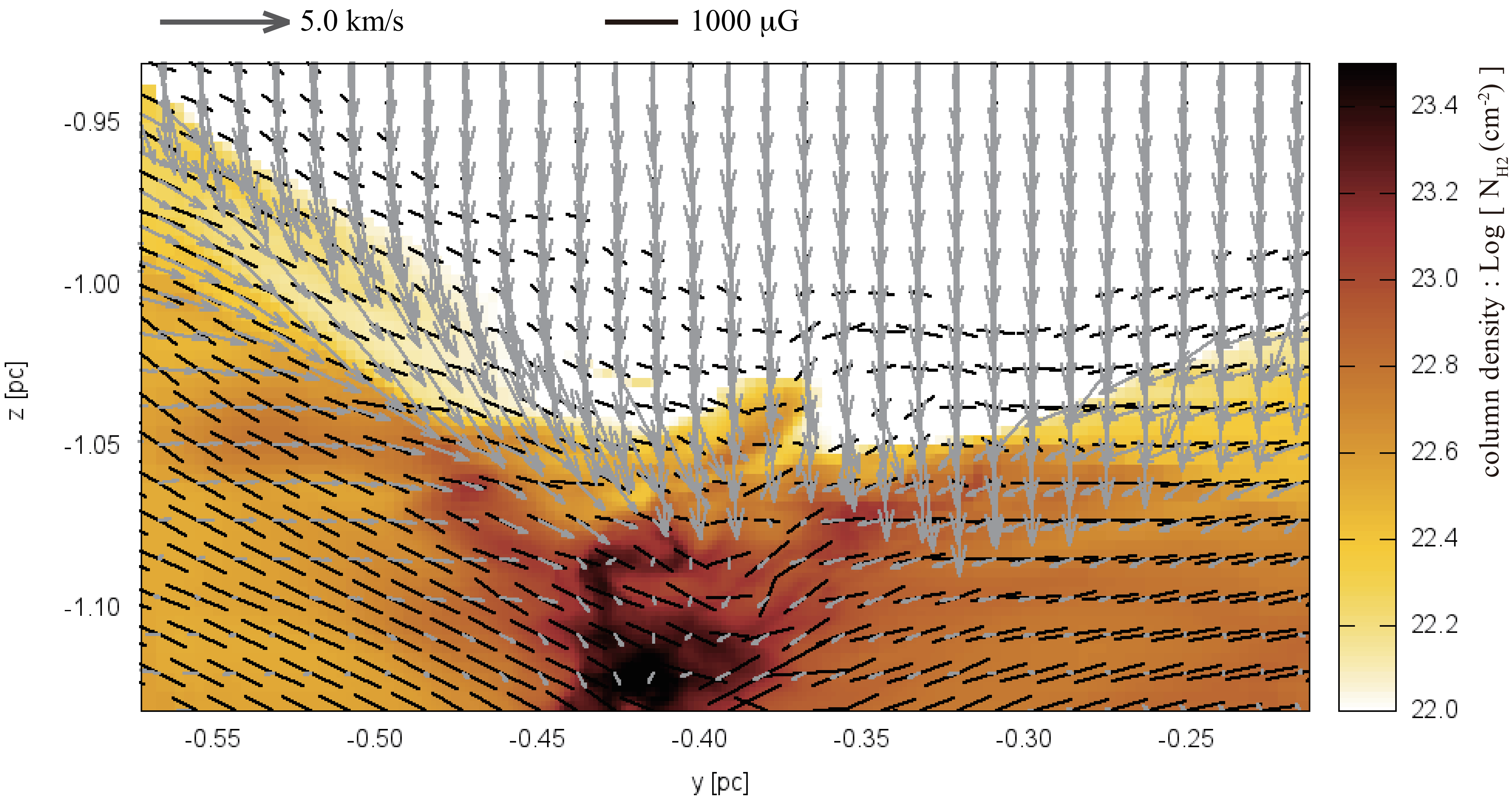
- What happens when a dense clump is swept by a shock?



* a filament perpendicular to the screen is formed by this process.

Focused Flow by Oblique Shock

Inoue+18

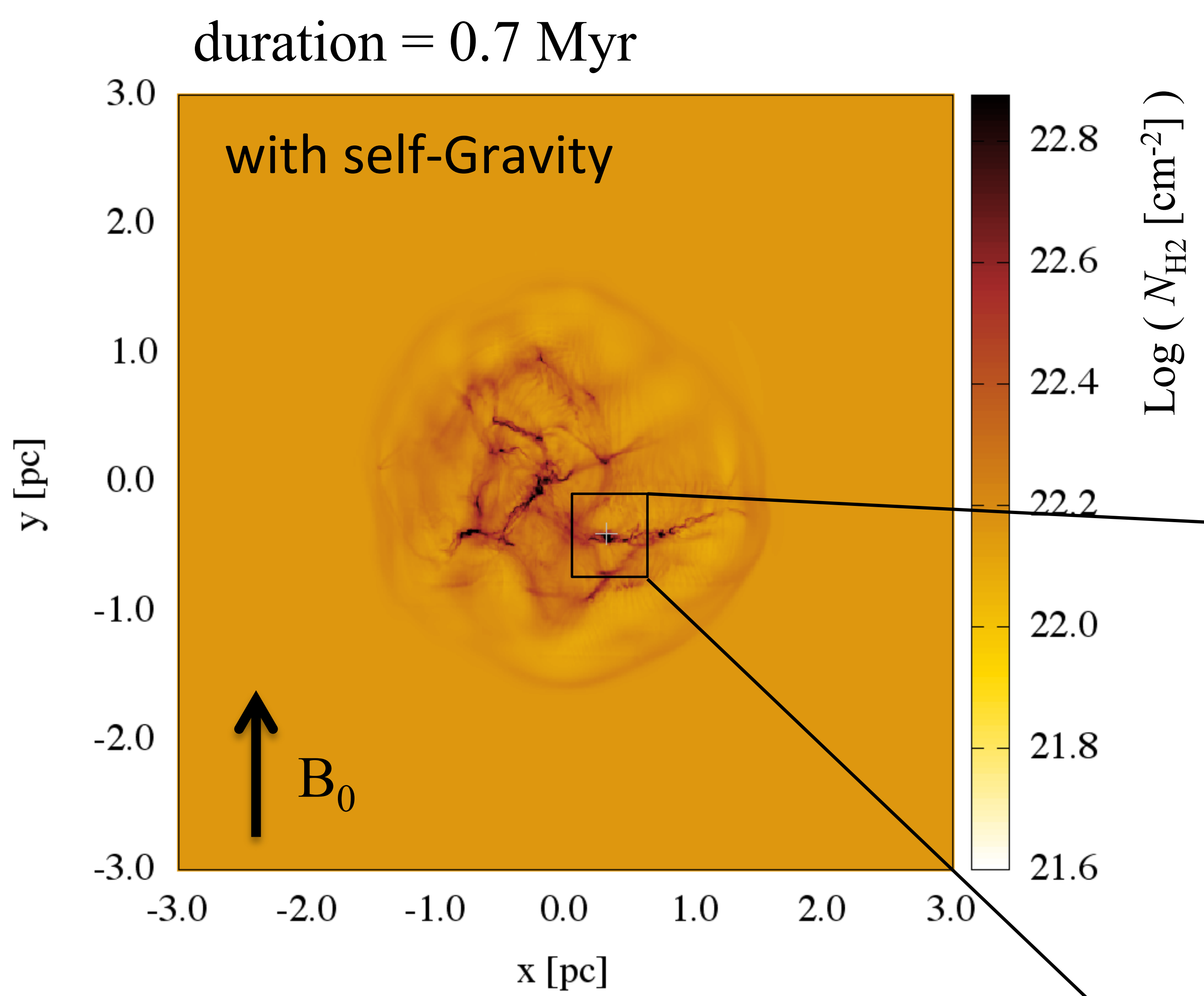


実際のシミュレーションデータでも Inoue & Fukui (2013) 機構を確認

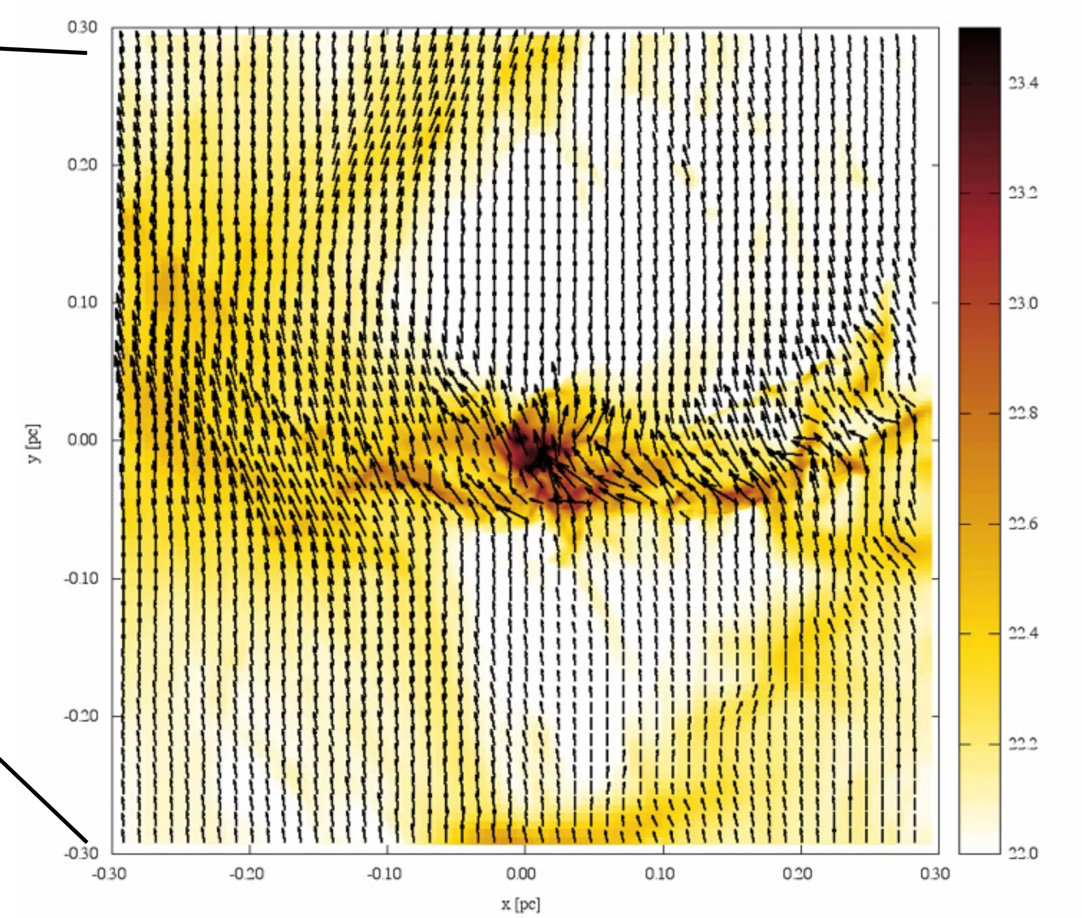
Massive Star Formation

Inoue+18

- Collapse of massive filament leads formation of massive core (sink).



- Up to $n \sim 8 \times 10^6$ cm^{-3}, thermal Jeans length is resolved more than 8 cells (the Jeans criterion; Truelove+97).
- Above $n \sim 8 \times 10^6$ cm^{-3}, sink particle is introduced if the region shows signatures of gravitational collapse (div. v <0, E_{tot}<0, Eigenvalue of grd. v tensor < 0).

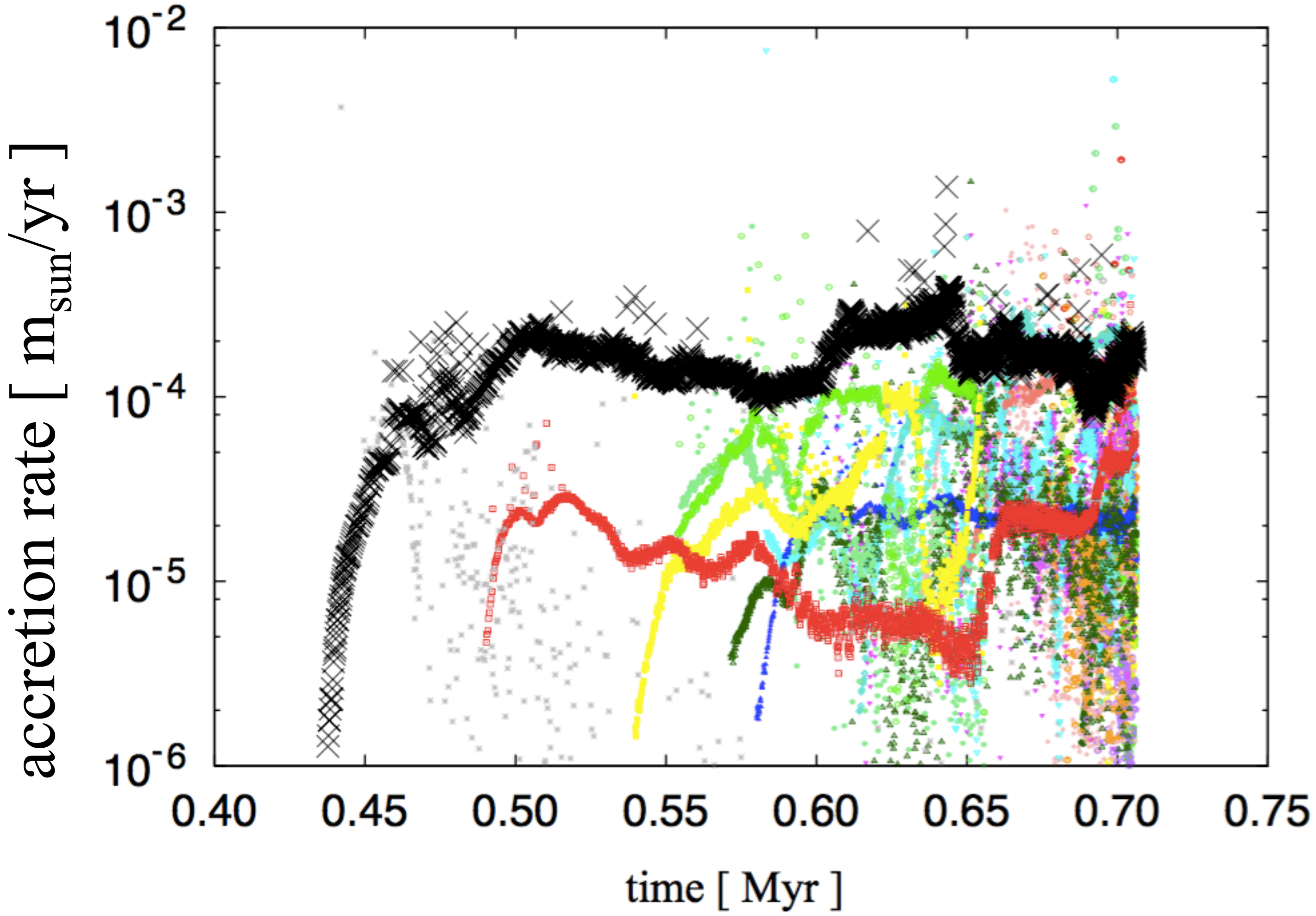


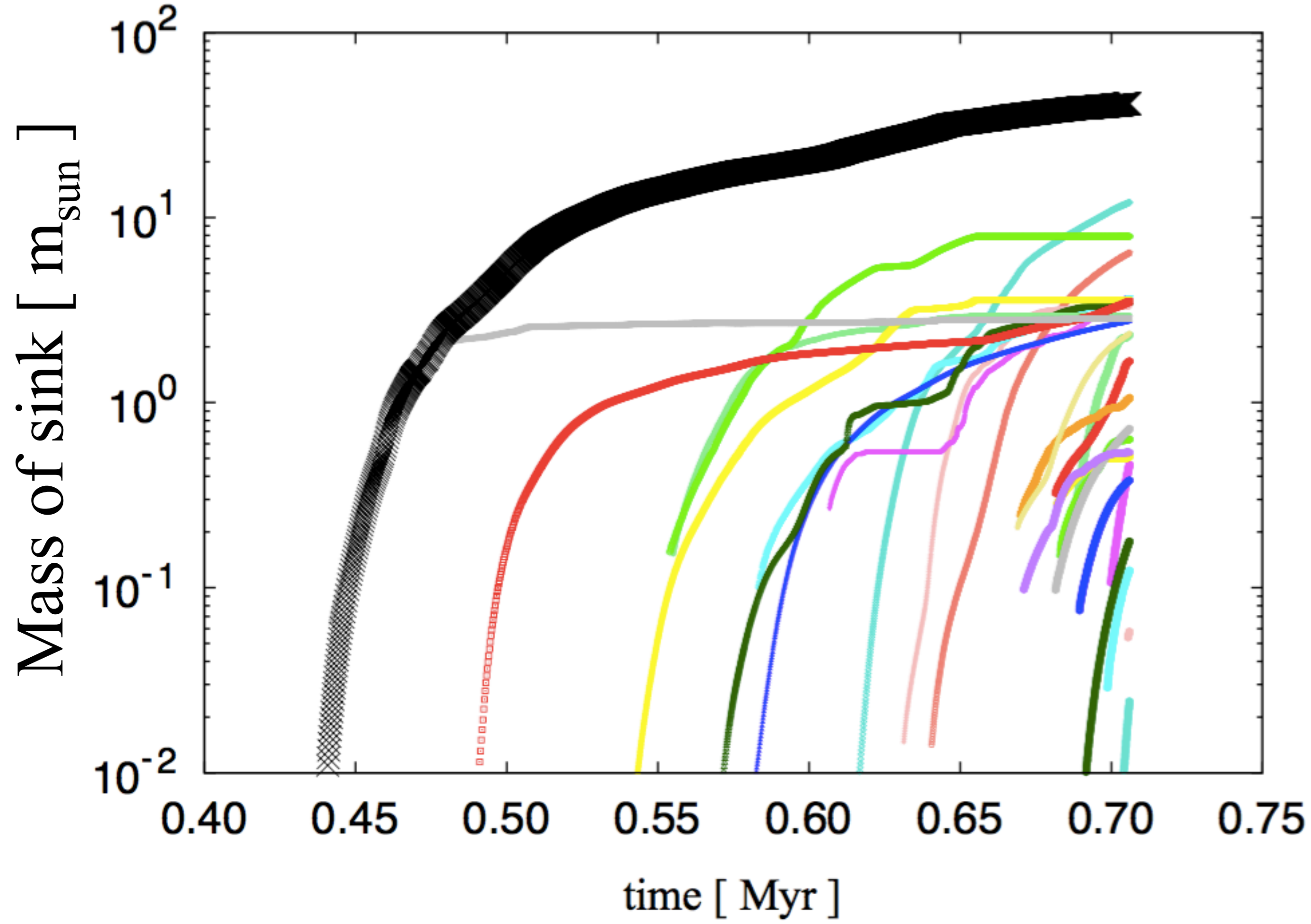
- The most massive sink mass ~ 50 m_{sun}

Accretion Rate

Inoue+17 in prep.

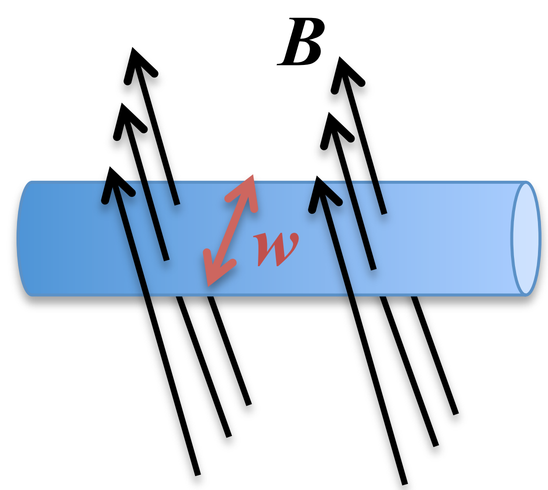
- The most massive sink grow with high accretion rate





- Most massive sink grow with constant, high, accretion rate: $\dot{M}_{acc} > 10^{-4}\ m_{sun}$/yr.
- High accretion rate is kept for a long time so long as the filament collapse continues.

Role of B Field



- Critical line-mass for filament with perp. B field (Tomisaka 14).

$$\lambda_{\rm max} \simeq 0.24\Phi_{\rm cl}/G^{1/2} + 1.66\, c_s^2/G \quad \text{where } \Phi = B\, w.$$

$$\sim 15 \text{ Ms/pc}$$

B field contribution dominate, if $B > 35\ \mu\text{G}\ (c_s/0.2\ \text{km/s})^2\ (w/0.1\text{pc})^{-1}$.

- Typical B field in the shock induced filament (Inoue & Fukui 13):

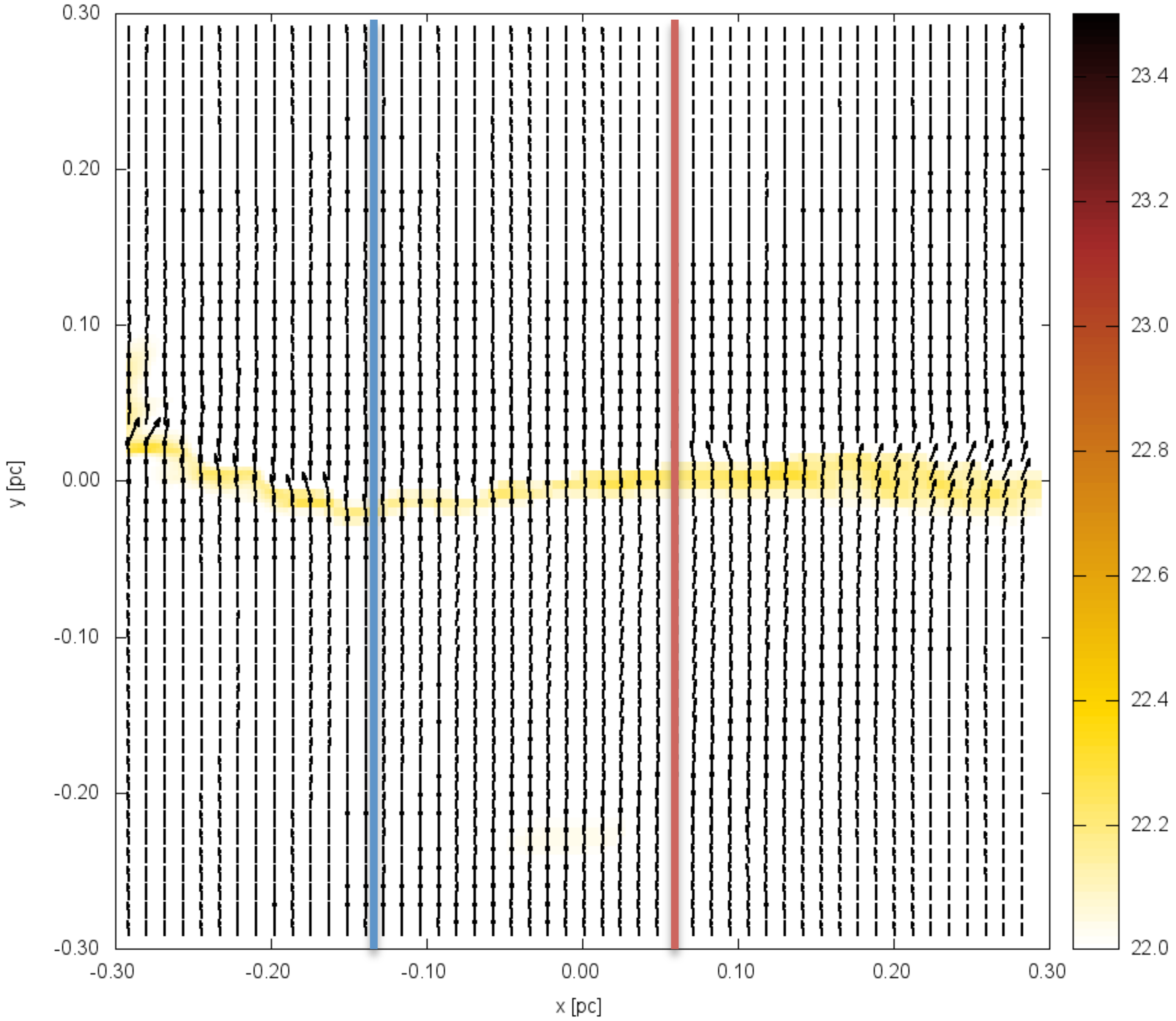
$$B_{\rm filament} \approx \sqrt{2}\,\frac{v_{\rm sh}}{v_{\rm Alf}} B_{\rm ini} = \sqrt{8\pi\rho_{\rm ini}}\, v_{\rm sh} \quad \sim 300\ \mu\text{G}\ (n_{\rm ini}/10^3\ \text{cm}^{-3})^{1/2}\ (v_{\rm sh}/10\ \text{km/s}).$$

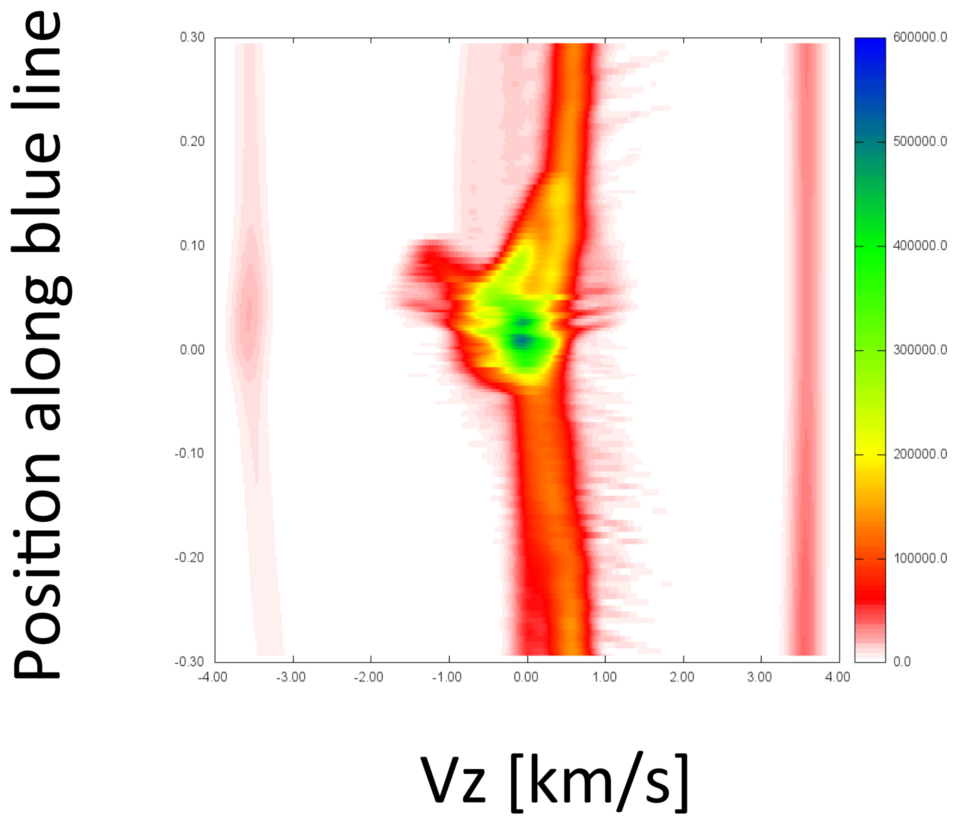
→ The critical line-mass of the shock induced filament can be much larger than the thermally supported filament.

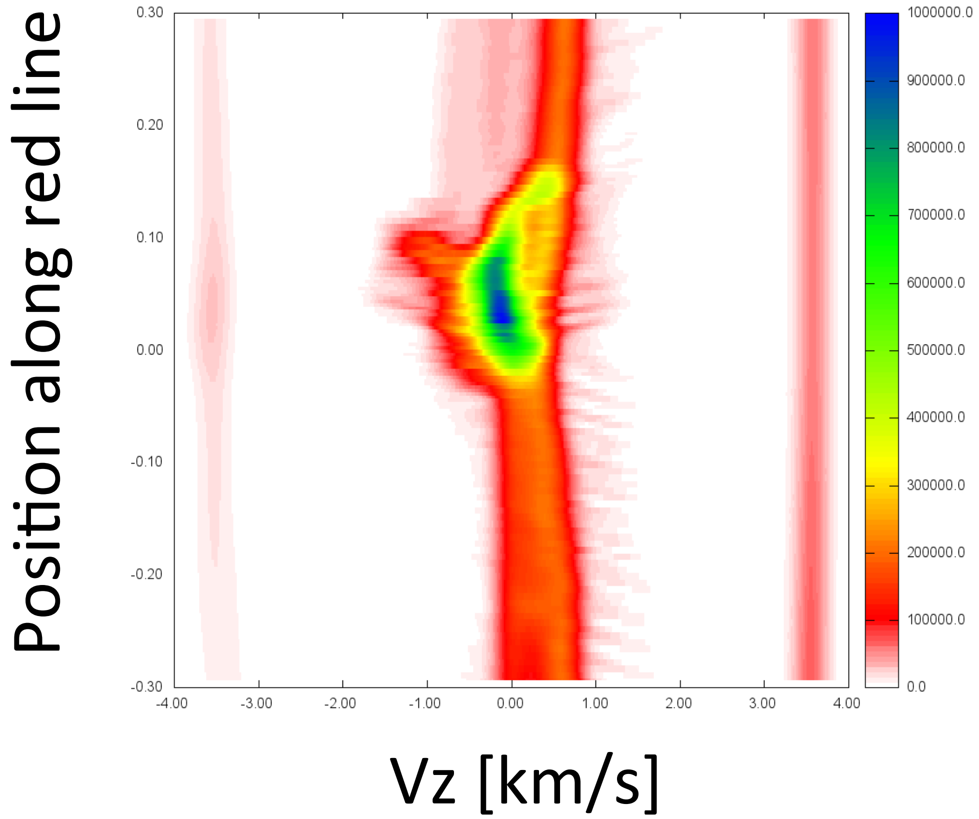
P-V Structure of Simulated Filament

- P-V map of a filament formed in Inoue+18 paper.

Colmn density map







Summary

- Correlation between HI filament (fiber) orientation and B-field is studied. (Inoue & Inutsuka 16)
  - Good correlation HI fibers and B field is due to turbulent stretching.
  - Turbulence does not give perfect alignment, but there is always small misalignment.
    - ✓ Application to the Chandrasekhar-Fermi method is not recommended.

- Formation of (massive) molecular filaments by shock compression are studied. (Inoue+18)
  - Filaments are formed by Inoue & Fukui 12 mechanism.
  - Filament line-mass seems to be determined by B-field estimated from Tomisaka formula.
  - Position-Velocity structure of filament formation cite shows nice similarity to observed young filament (Arzoumanian+ in progress).