現代の星形成と星間媒質進化

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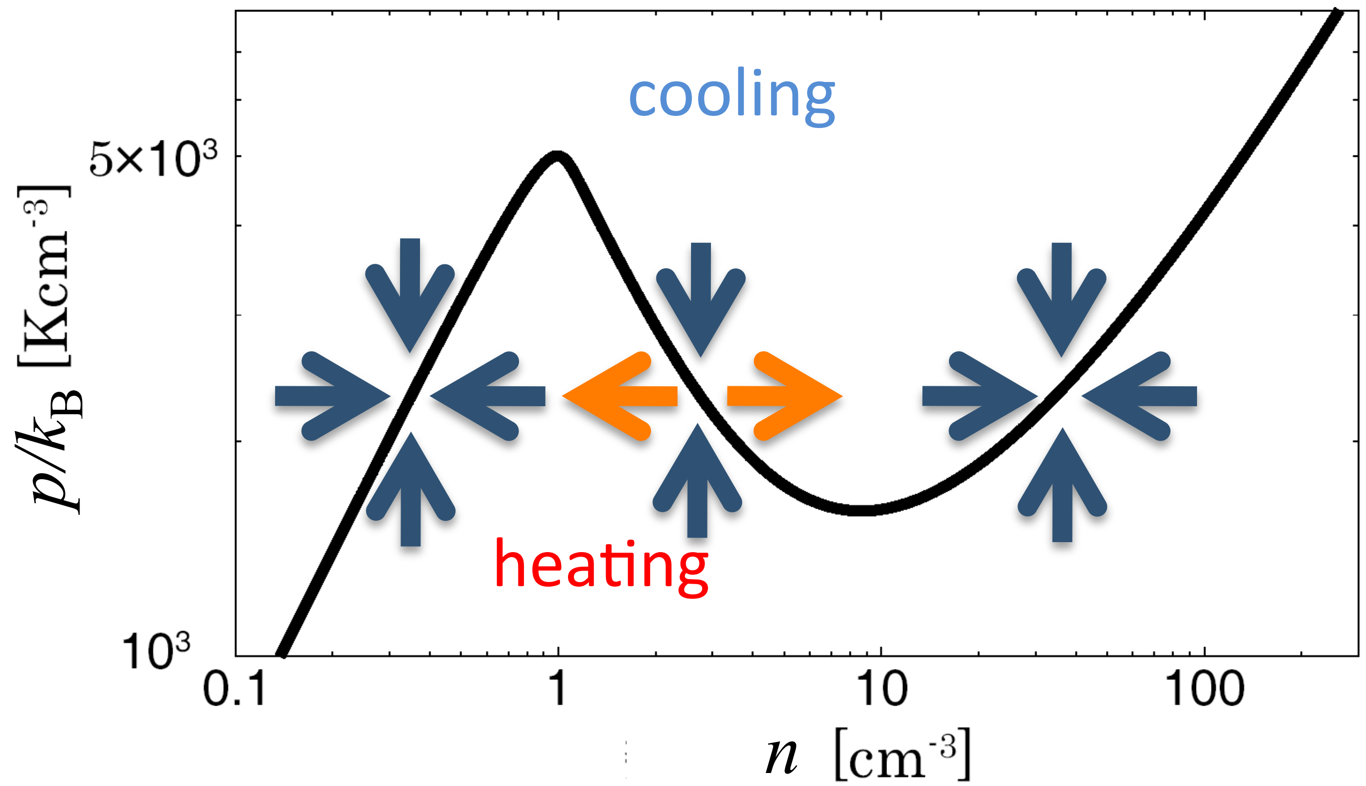
ISM is Thermally Bistable

- Stability of equilibrium against perturbation.



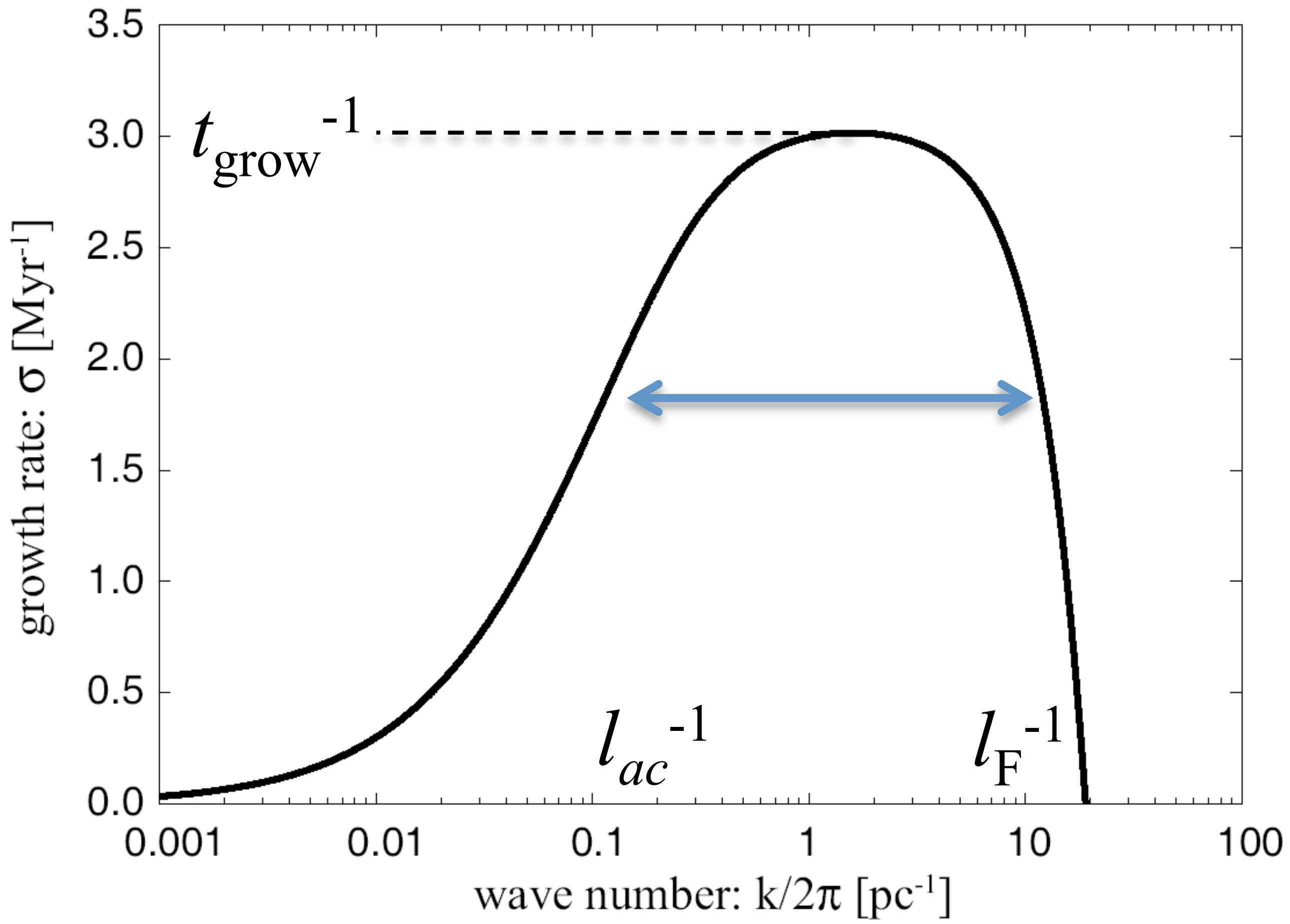
- 加熱源：星からの背景UV光
  - ✓ PAHによる光電加熱
- 冷却源：輝線放射
  - ✓ T ~ 10,000 K では Ly-α
  - ✓ T < 1,000 K では CII 微細構造
    分子相では CO 回転

- The WNM and CNM are stable against perturbations.
- Intermediate phase is unstable against isobaric perturbation.
  - ✓ Thermal instability (Field 65).
  - ✓ Criterion: $\left(\frac{\partial \mathcal{L}}{\partial T}\right)_p > 0$ where $\mathcal{L}$ is net cooling rate per unit mass.

↑ Unstable if cooling rate is enhanced by temperature drop.

Dispersion Relation

- Dispersion relation for the thermal instability (Field 65, Schwarz+72, Koyama & Inutsuka 01).



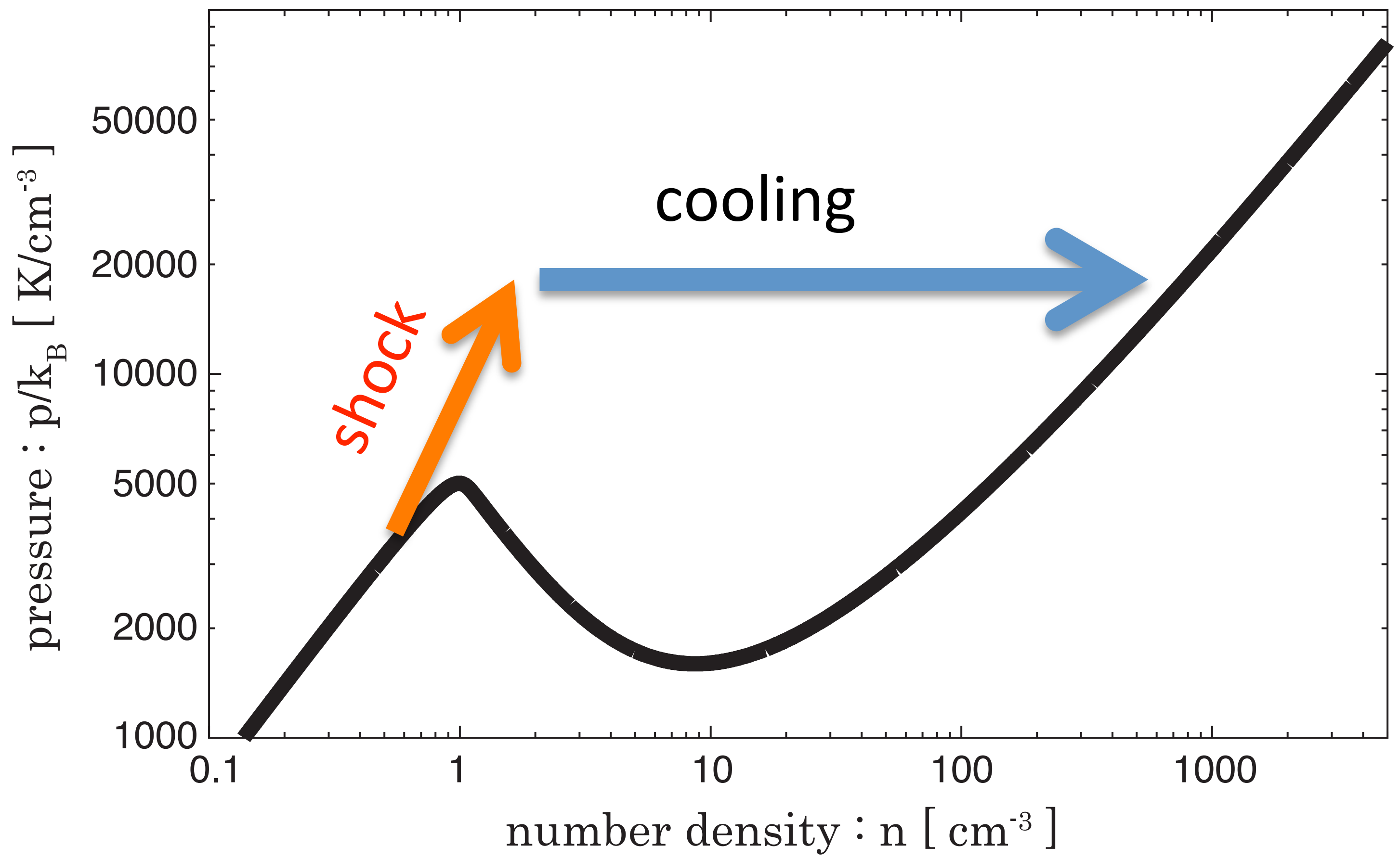
- Timescale scale: $t_{grow} = t_{cool} \sim 1$ Myr
- Spatial scales:
  - ✓ Field length: $l_F = \sqrt{\dfrac{\rho \mathcal{L}}{\kappa T}} \sim 0.1$ pc
  - ✓ Acoustic length: $l_{ac} = c_s\, t_{cool} \sim 10$ pc

- Thermal instability grow in wide spatial scales from l_{ac} to l_F.
- Nonlinear growth generates small scale fragments due to condensation.
- Metallicity dependence on typical scales (Inoue & Omukai 15)

$$l_{ac} \simeq 4\,\mathrm{pc}\left(Z/Z_\odot\right)^{-1} \qquad l_F \simeq 0.013\,\mathrm{pc}\left(Z/Z_\odot\right)^{-1/2} \qquad t_{cool} \simeq 0.4\,\mathrm{Myr}\left(Z/Z_\odot\right)^{-1}$$

Strong Disturbance in the ISM

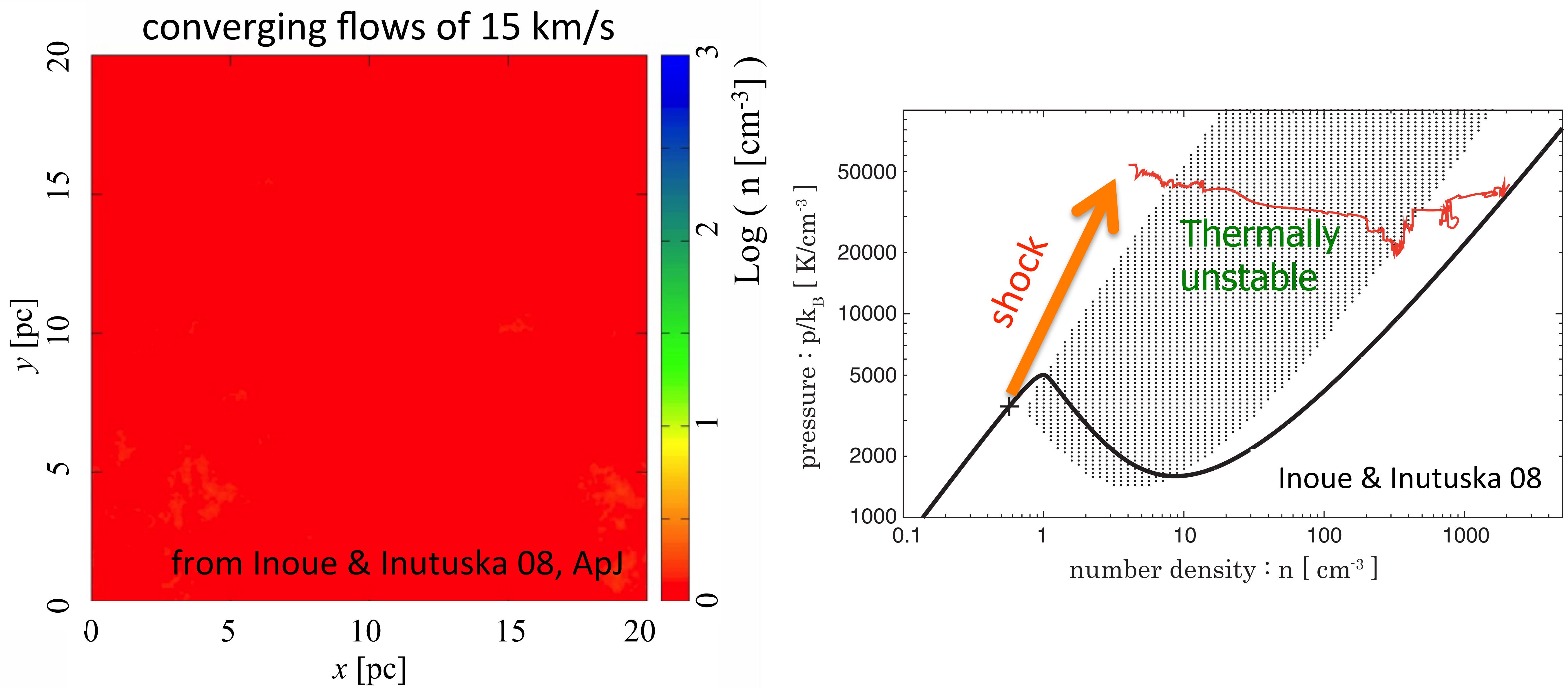
- The WNM is stable against perturbation.
  - The ISM cannot evolve in static environment.
  - Supernovae compress the ISM typically once per Myr (McKee & Ostriker 77).
- What happen if the WNM is shocked ?
  - The WNM destabilized by shock compression and successive cooling create cold clumps (1D simulations by Hennebelle & Perault 99, Koyama & Inutsuka 00).



- During cooling process, gas is influenced by thermal instability → cold fragments.

HD Simulation of Phase Transition

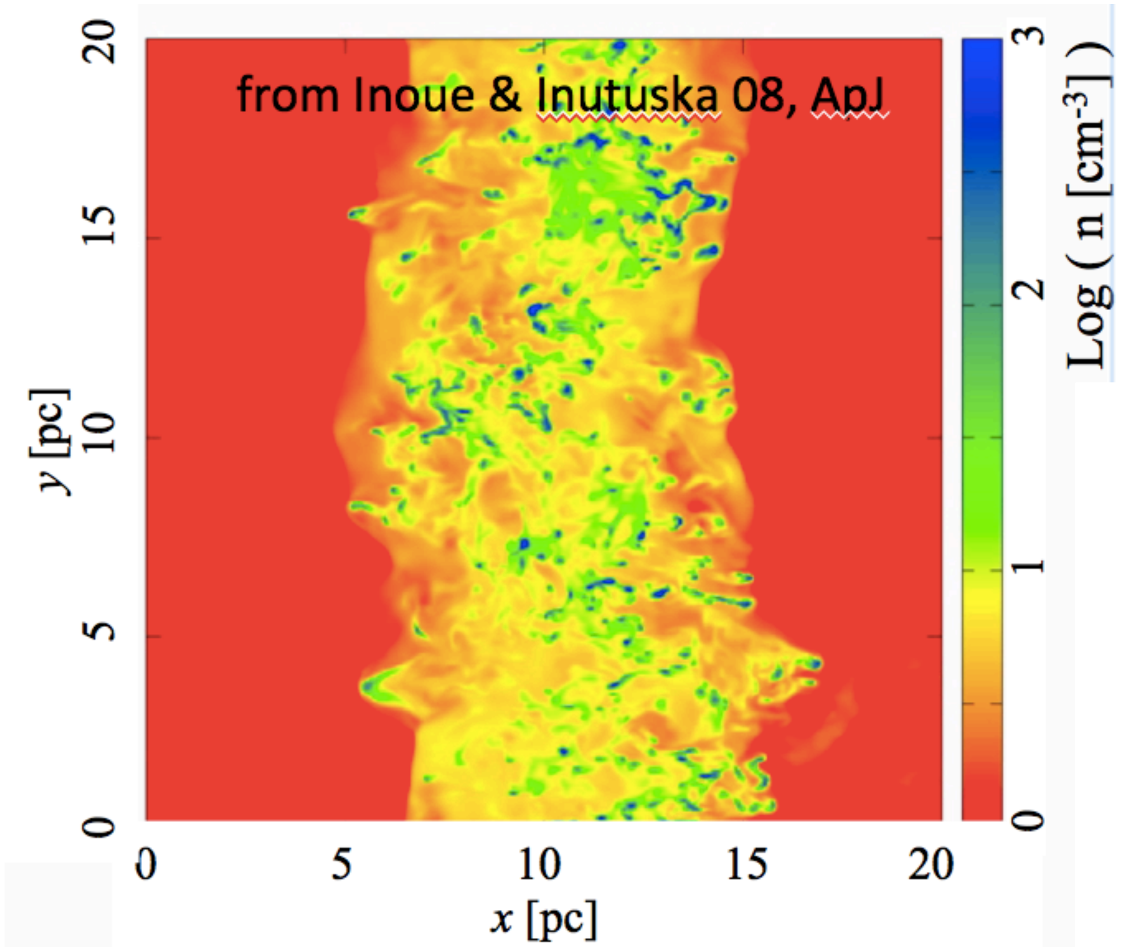
- How thermal instability affects dynamics of cold gas formation?
  - Multi-dimensional simulations by Koyama & Inutsuka 02; Audit & Hennebelle 05; Heitsch+06; Vazquez-Semadeni+07; Hennebelle & Audit 07; Inoue & Inutsuka 08, 16



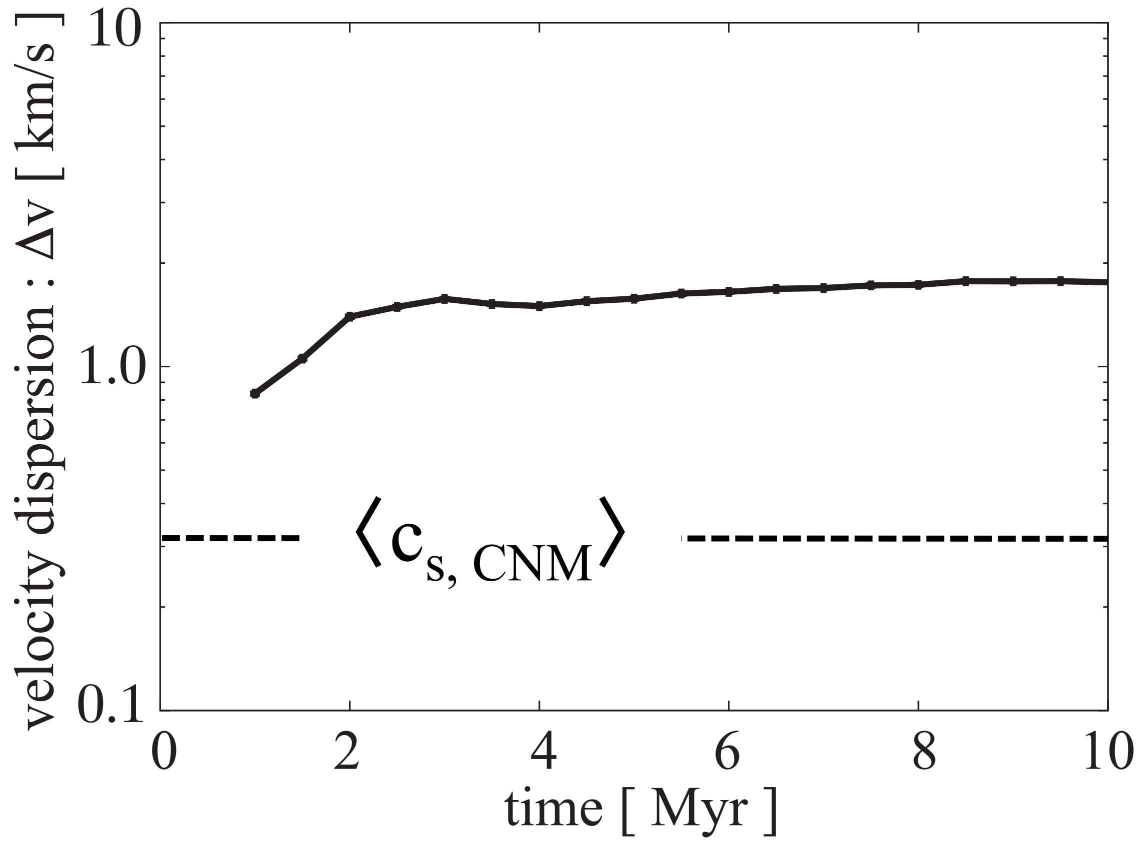
- Nonlinear growth of thermal instability cause small scale cold fragments.
- Cold clumps get random “turbulent” velocity.

Supersonic Turbulence

- Thermal instability mediate turbulence can be "supersonic" (Koyama & Inutuska 02).



Δv of the region with $n > 10^2$ cm^{-3}



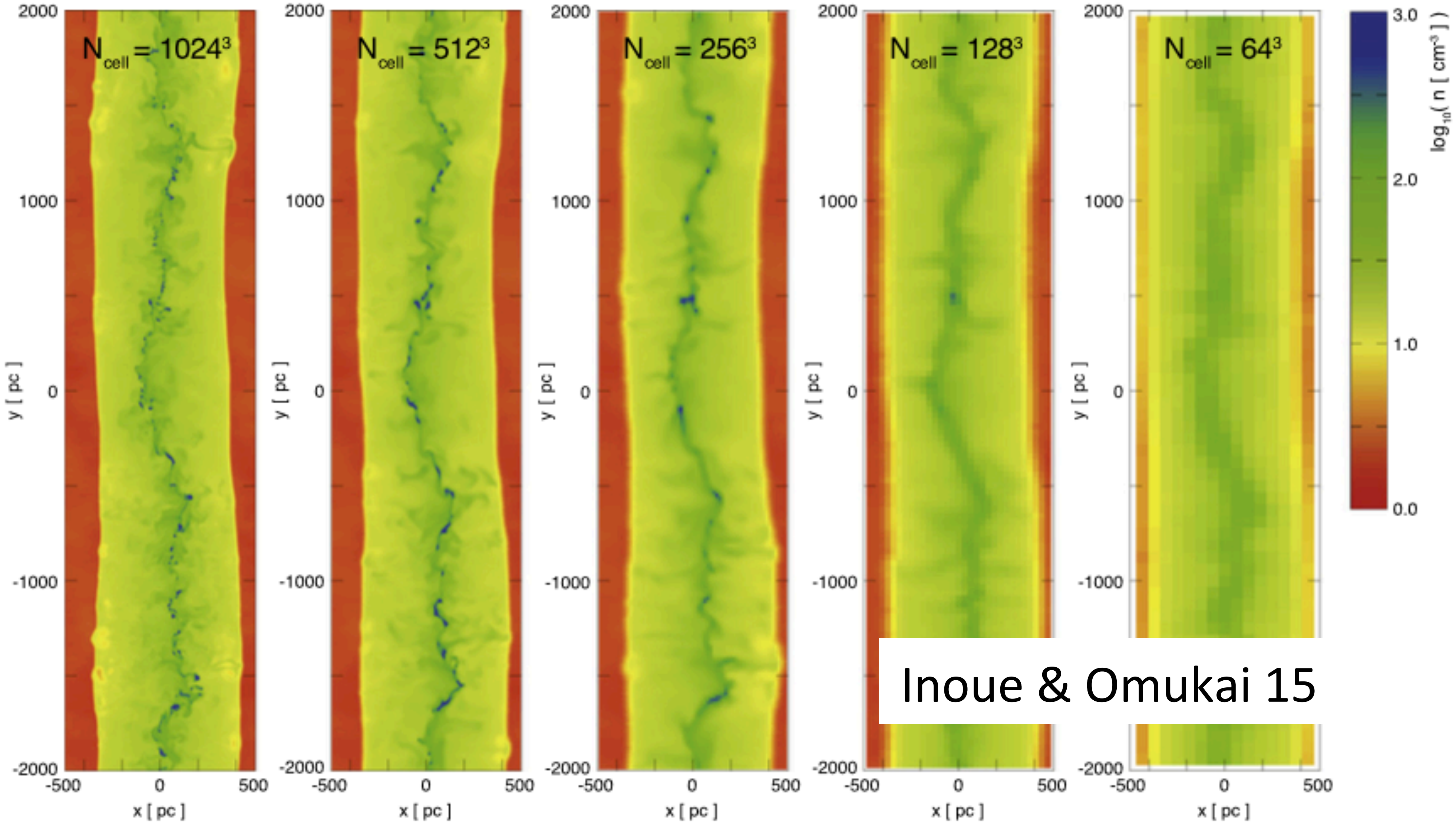
- Subsonic turbulence is involved in preshock gas as seed fluctuation.
- Cooling drastically reduce sound speed of postshock cold clump.

  → Subsonic seed turbulence becomes supersonic.
- If no cooling, we never expect supersonic turbulence in postshock (TI+13).

分解能問題

Inoue & Omukai 15

- Filed length を4点以上で分解した完璧なシミュレーションは無理(Koyama & Inutsuka 04)
- Clump 質量関数は浅いベキ分布： $dN/dM \propto M^{-1.7}$ (Hennebelle & Audit 07)
  - → 質量は大きな clump (長波長モード)が担う
- Acoustic length: $l_{ac} \simeq 4\ \mathrm{pc}(Z/Z_{\odot})^{-1}$ を60点以上で分解すると major clump は再現可能



Magnetic Field

- Magnetic field is very important ingredient of the ISM, because…

  - $e_B \sim e_{th} \sim 1$ ev/cc ($B \sim 5$ μG) in both the WNM and CNM (Beck 00, Heiles & Troland 05).

  - The ISM is tightly coupled to B field.
    - ✓ Ion-neutral drift timescale: $t_{AD} = \dfrac{4\pi\, A\, \rho_n\, \rho_i}{B^2} L^2$, $\quad A = \dfrac{\langle \sigma\, v_{rel} \rangle}{m_n + m_i}$

      ~ 10 Myr for typical atomic ISM (e.g., Hennebelle & Perault 00, Inoue+07).

      $> t_{cool}$

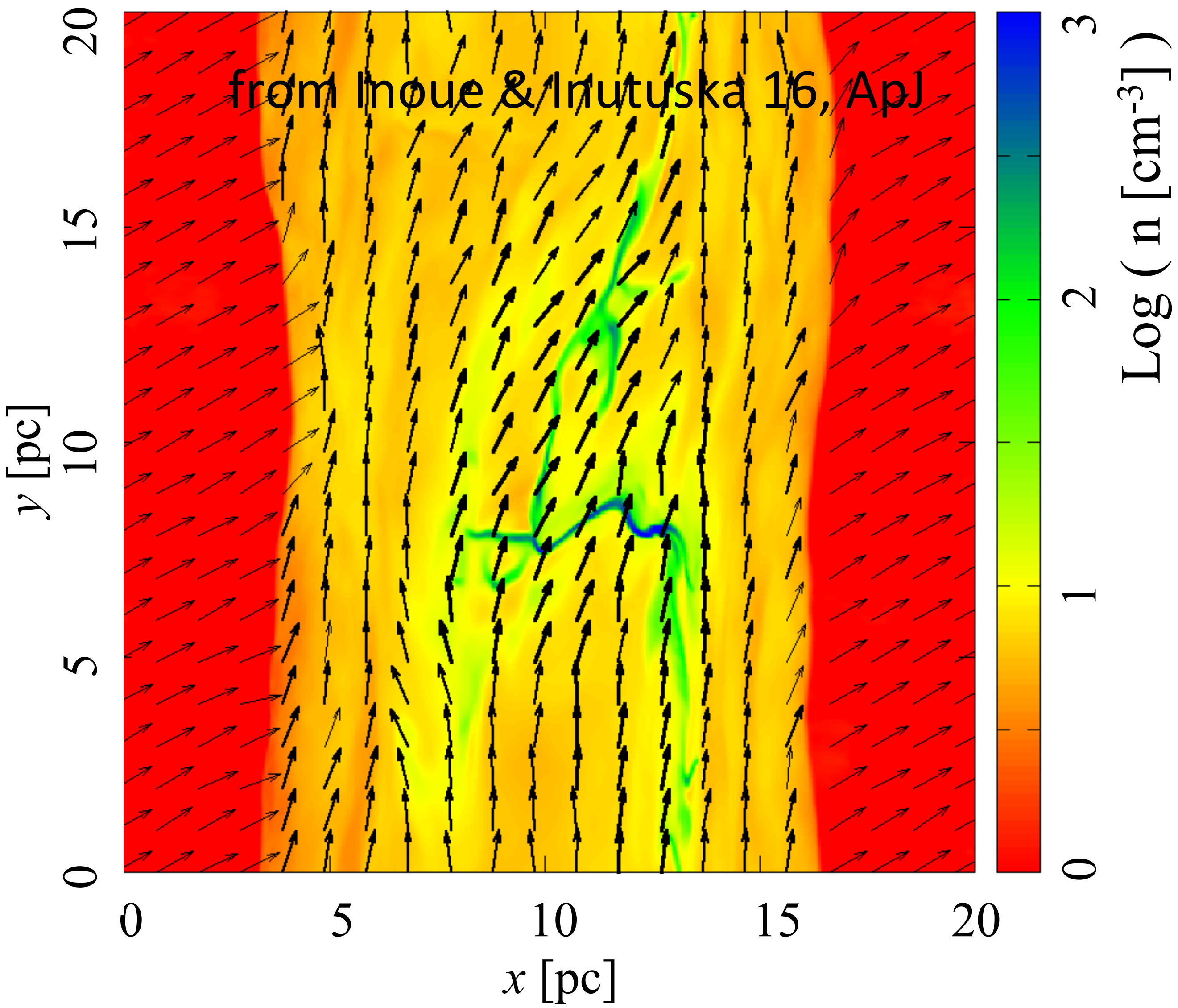
    → MHD treatment of the ISM is necessary.

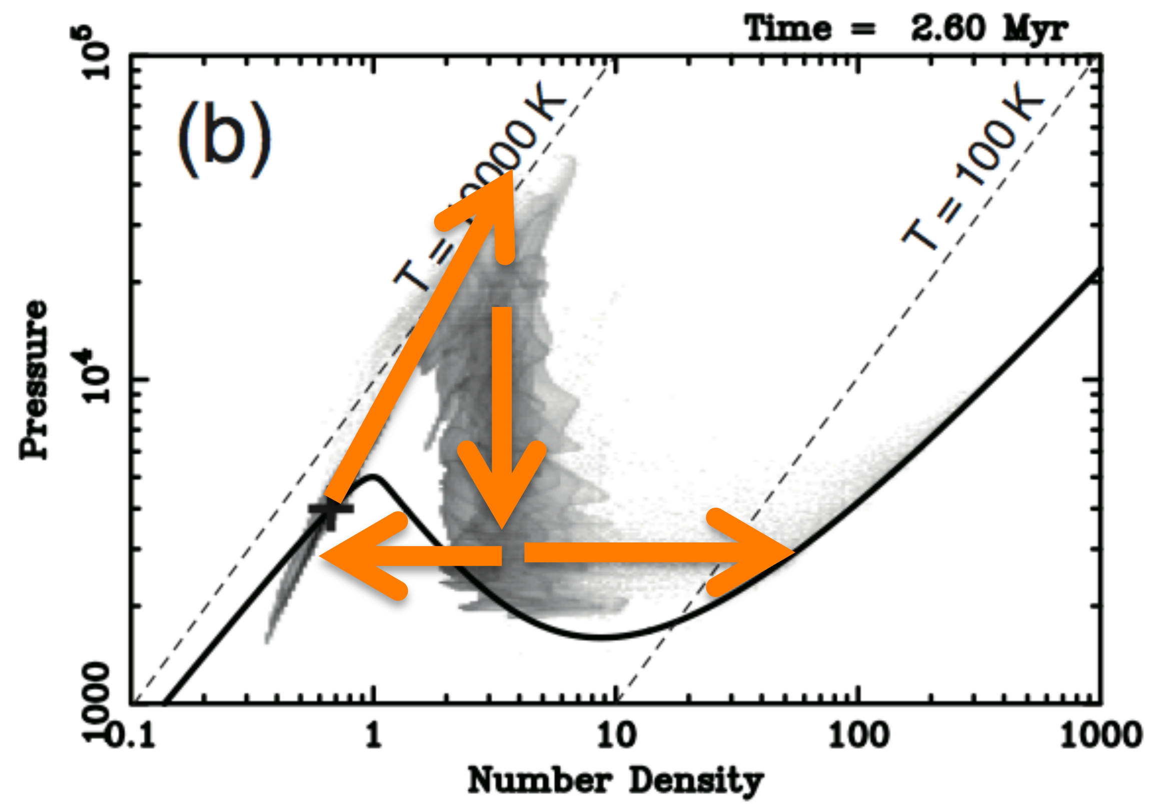
  - B field is much harder than gas.
    - ✓ If the ISM contract with B field ($B \propto \rho$), then $p_{mag} = B^2/8\pi \propto \rho^2$.

    → effect of B field enhanced rapidly in compressed gas.

Realistic Evolution of WNM

- Evolution of shocked WNM with ***B*** field（Inoue & Inutuska 08, 09, 16）
  - Evolutionally track is drastically changed due to the effect of magnetic pressure.

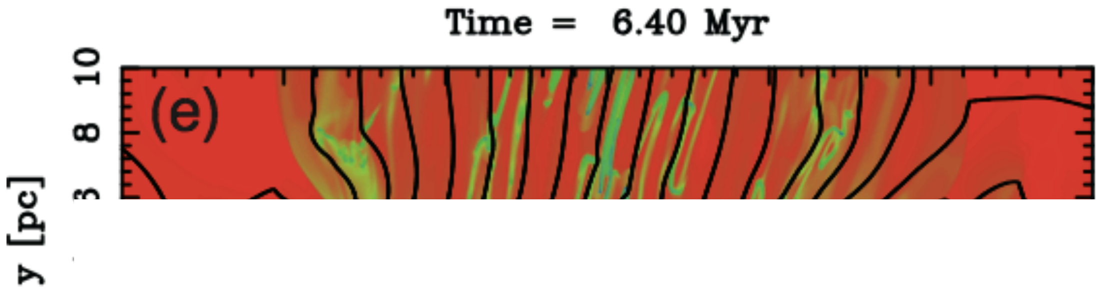




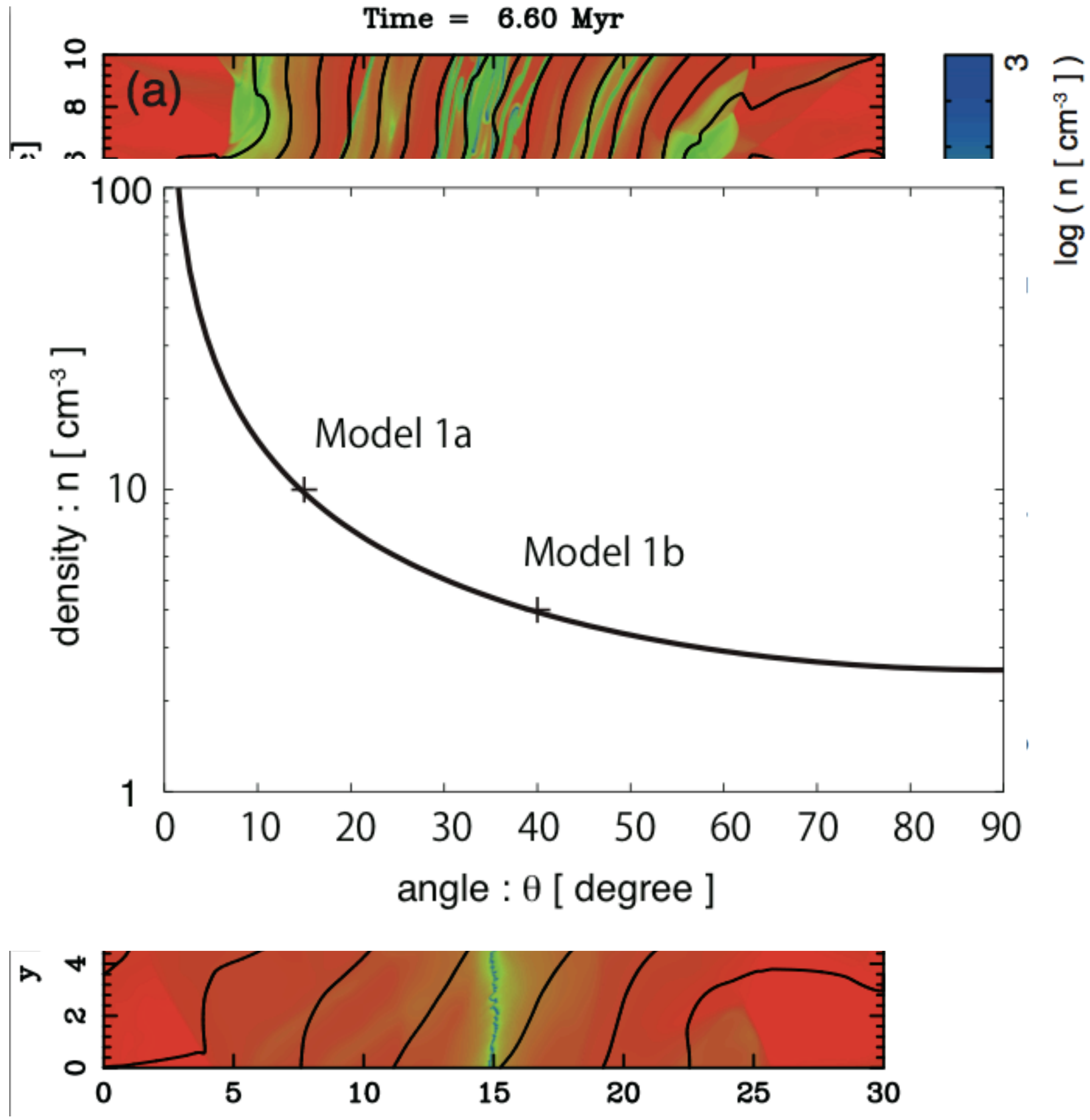
- Many observed characteristics of HI clouds（Heiles & Troland 03）are reproduced.
  i) morphology (r_{aspect}~50), ii) strength of *B*($\beta < 1$), iii) moderate turbulence(M~2)
- Cold HI filament と磁場の向きは大体一致！(Clark+14, Inoue & Inutsuka 16)

Effects of Magnetic Field

- In most initial condition, B field prevents direct formation of molecular cloud from the WNM (Inoue & Inutsuka 09)



$$\langle n \rangle \approx n_{WNM} \times \sqrt{\frac{\rho_{WNM} v_{WNM}^{\;2}}{(B\sin\theta)^2/8\pi}}$$



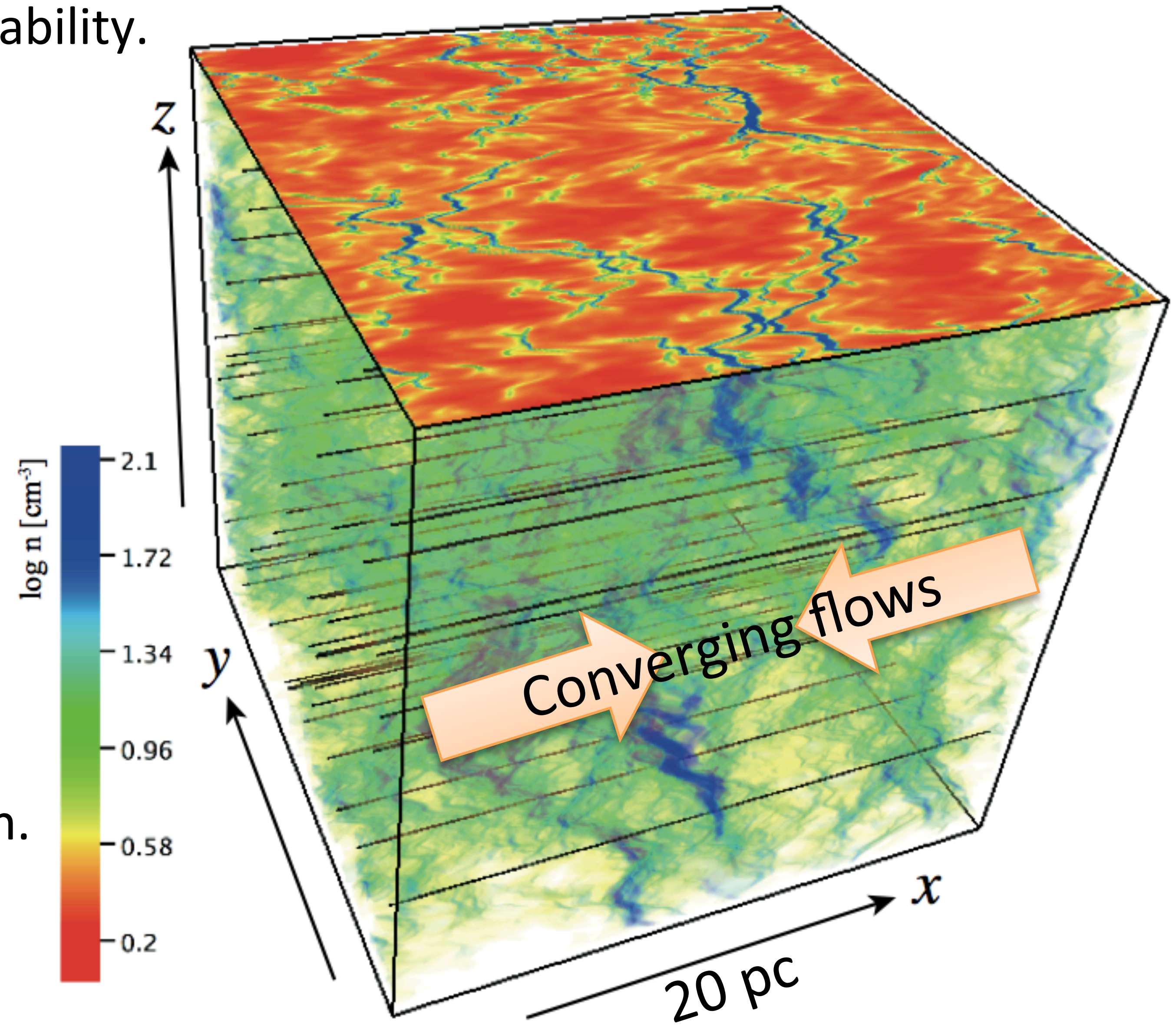
Simulation of Molecular Cloud Formation

Inoue & Inutsuka 12

- Setting of molecular cloud formation 3DMHD simulation by dense HI gas accretion.
  - Initial two-phase HI gas is created by thermal instability.
    - ✓ blue: HI clouds ($n \sim 50$ cm^{-3}, $T \sim 100$ K)
    - ✓ red: diffuse WNM ($n \sim 1$ cm^{-3}, $T \sim 6000$ K)
    - ✓ $\langle n \rangle \sim 5$ cm^{-3} consistent with obs. by Fukui+09.
    - ✓ $B = 5\ \mu$G parallel to converging flow
  - Converging flow velocity of $v_{\rm coll}$=20km/s
    - ✓ Shock sweeping of dense HI region by super-shell or spiral shock.
  - We solve radiation transfer by 2-ray approximation.
    - ✓ Evolution from atomic to molecular gas.

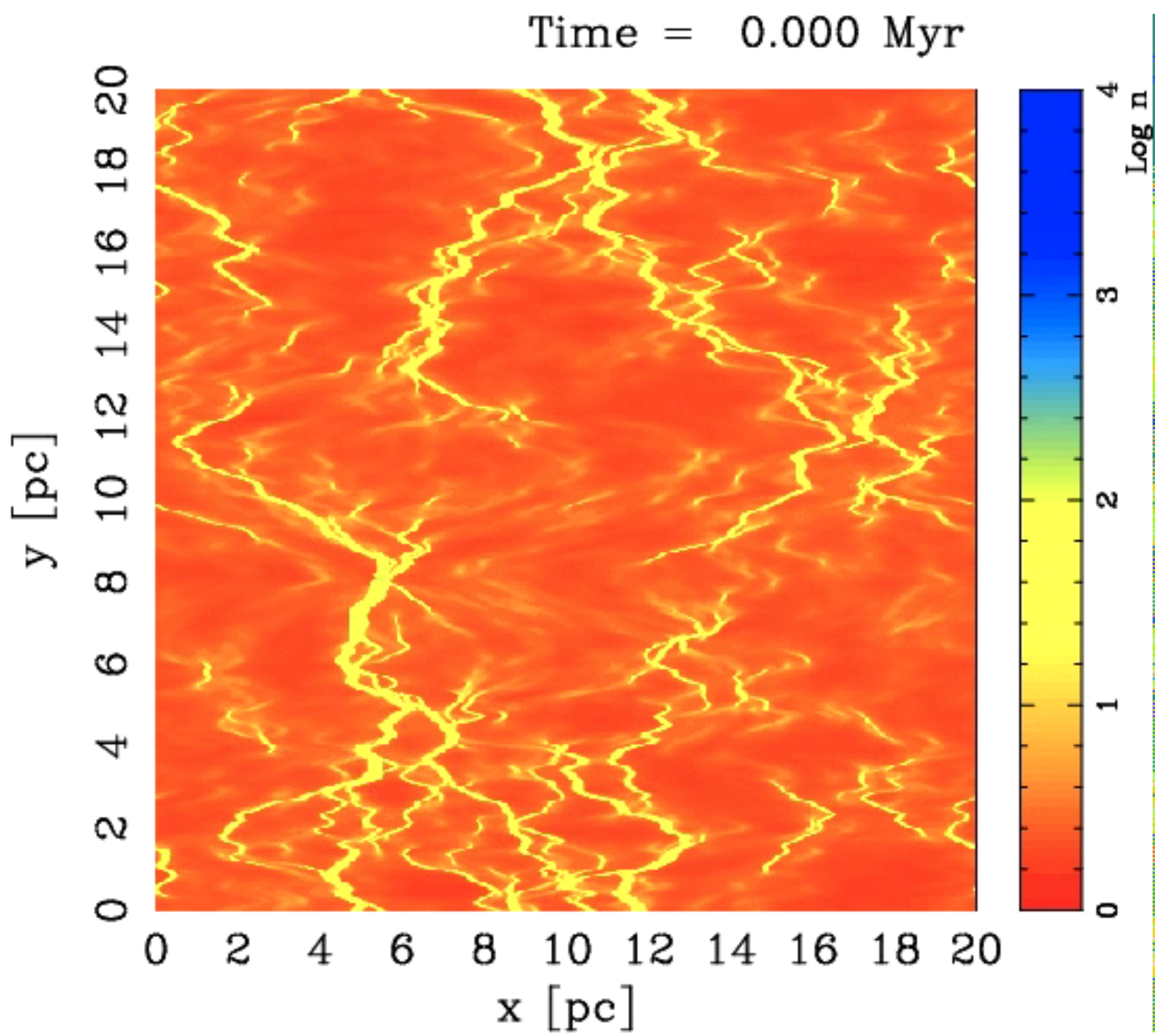
      H → H_2, C^+ → CO
    - ✓ Transition of C^+ cooling to CO cooling.

(see, Valdivia & Hennebelle 2014 for more sophisticated method).



Density Cross-section

Inoue & Inutsuka 12

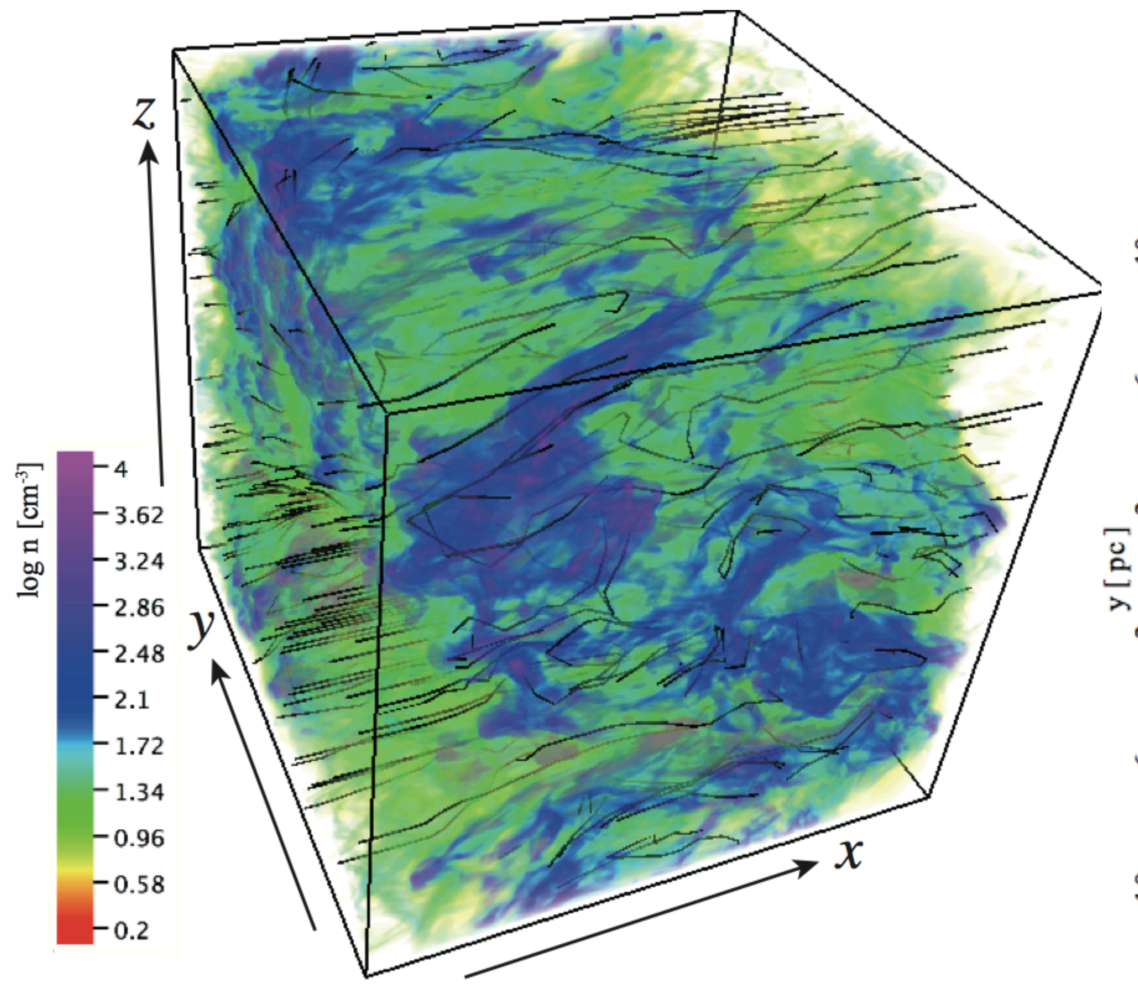


- 運良く磁力線に沿って衝撃波圧縮が起きれば超音速乱流をともなった分子雲が生成
  - ✓ 乱流の諸性質まで解明された訳ではない
- In dense molecular gas： $\Delta v \sim 3$ km/s >> $c_s \sim 0.2$ km/s.

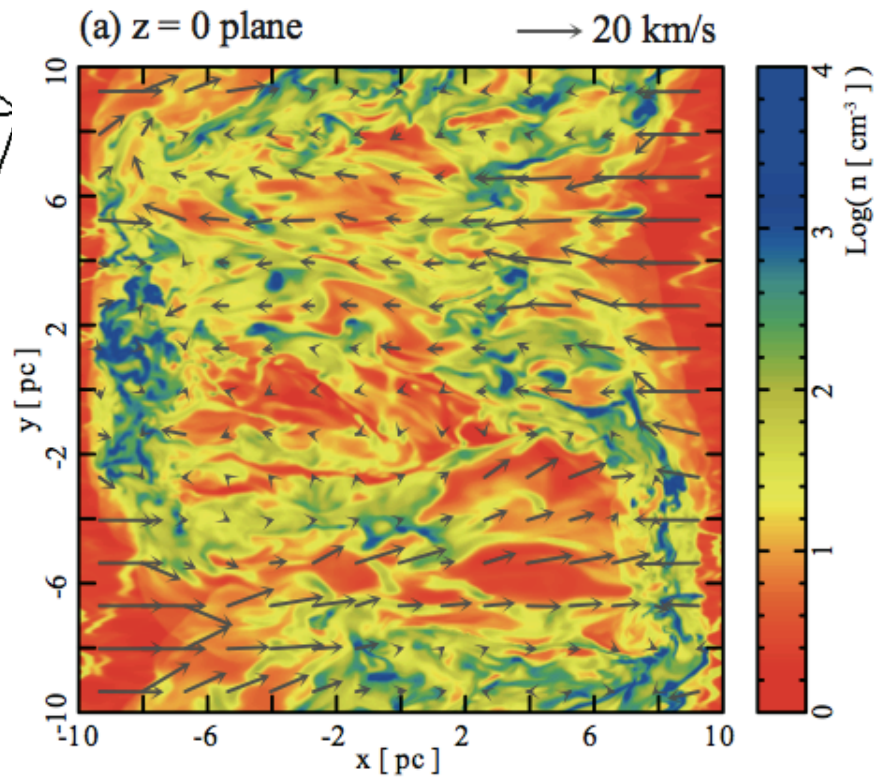
Result

Inoue & Inutsuka 12

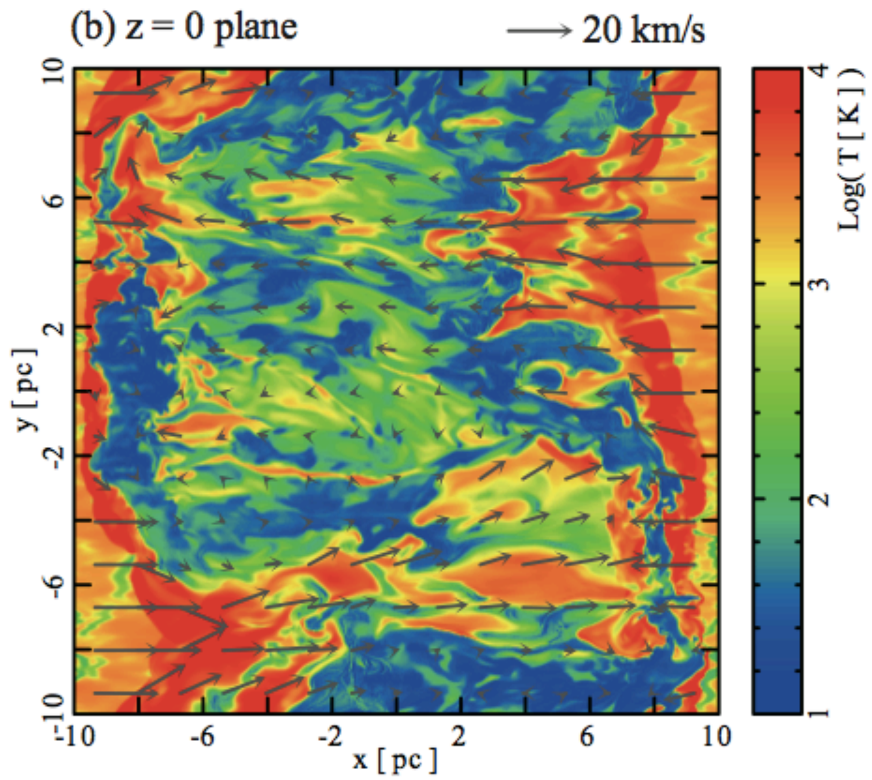
- 3D density map at 10 Myr



Structure of n



Structure of T



- 形成される分子雲は多くの理論モデルで過程される等温１相にはならない
- 磁力線に完全に沿わなくても $\theta < 10°$ であればやはり分子雲はできる(Iwasaki+18 in prep.)

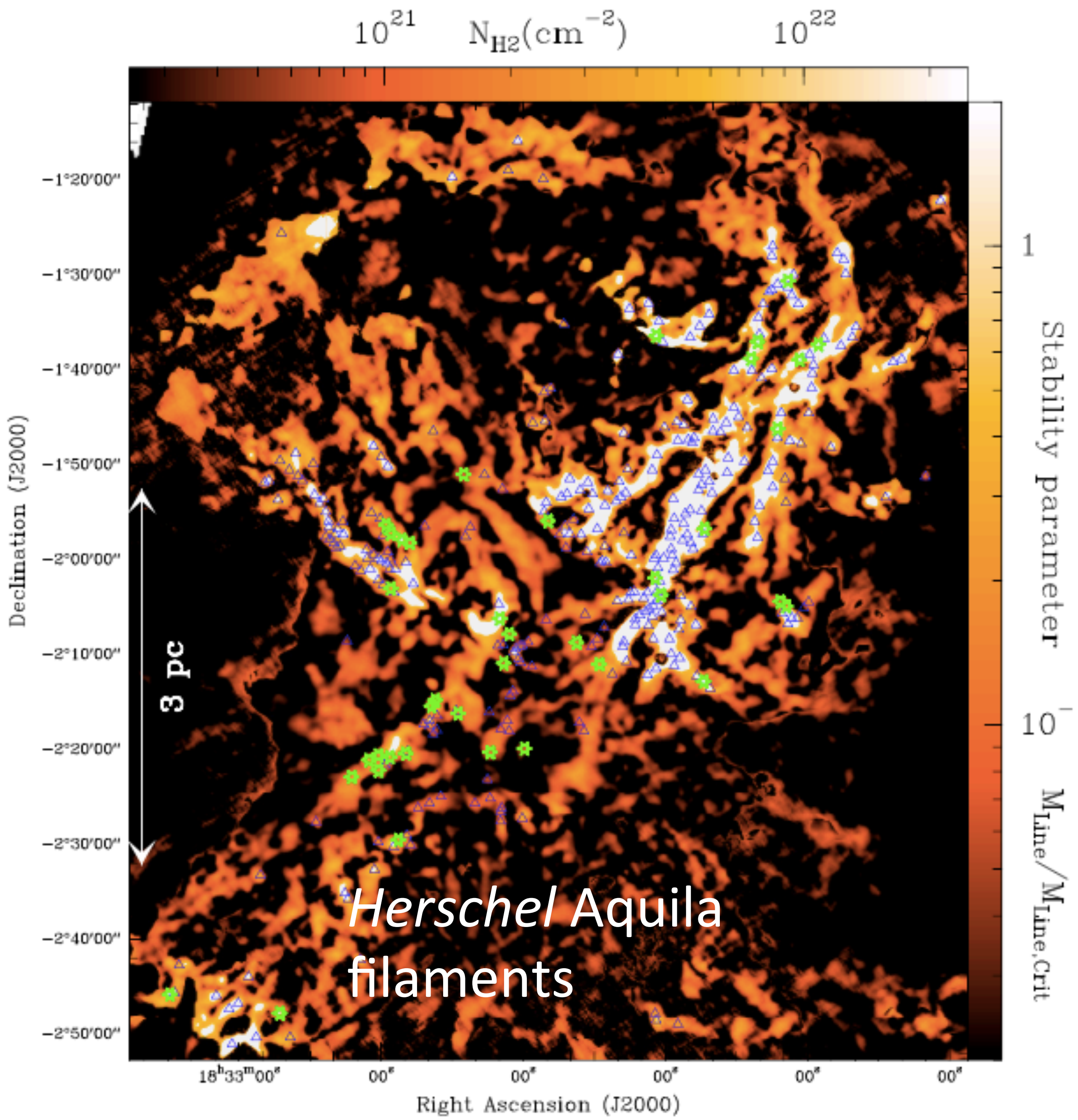
→ 分子雲形成、成長は（何度も圧縮される必要があり）時間がかかる: t_{form}>> 10 Myr.

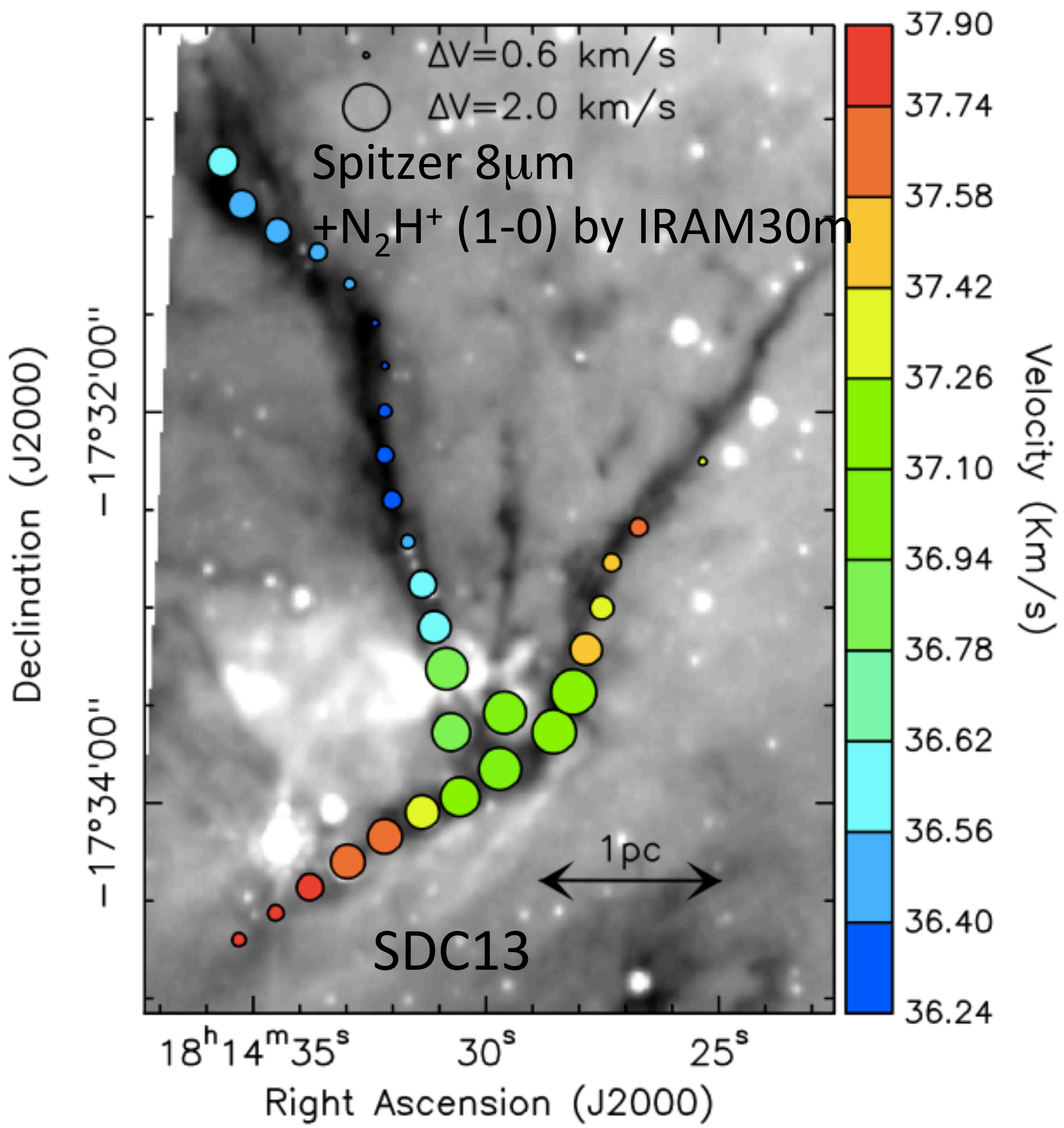
→ 一時期流行した速い星形成シナリオ（Hartmann+01; t_{form}< 10 Myr）は厳しい

＊LMCの雲と星団の相関から年齢を推定した Kawamura+09 の t ~ 30 Myr が現在はスタンダード

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).

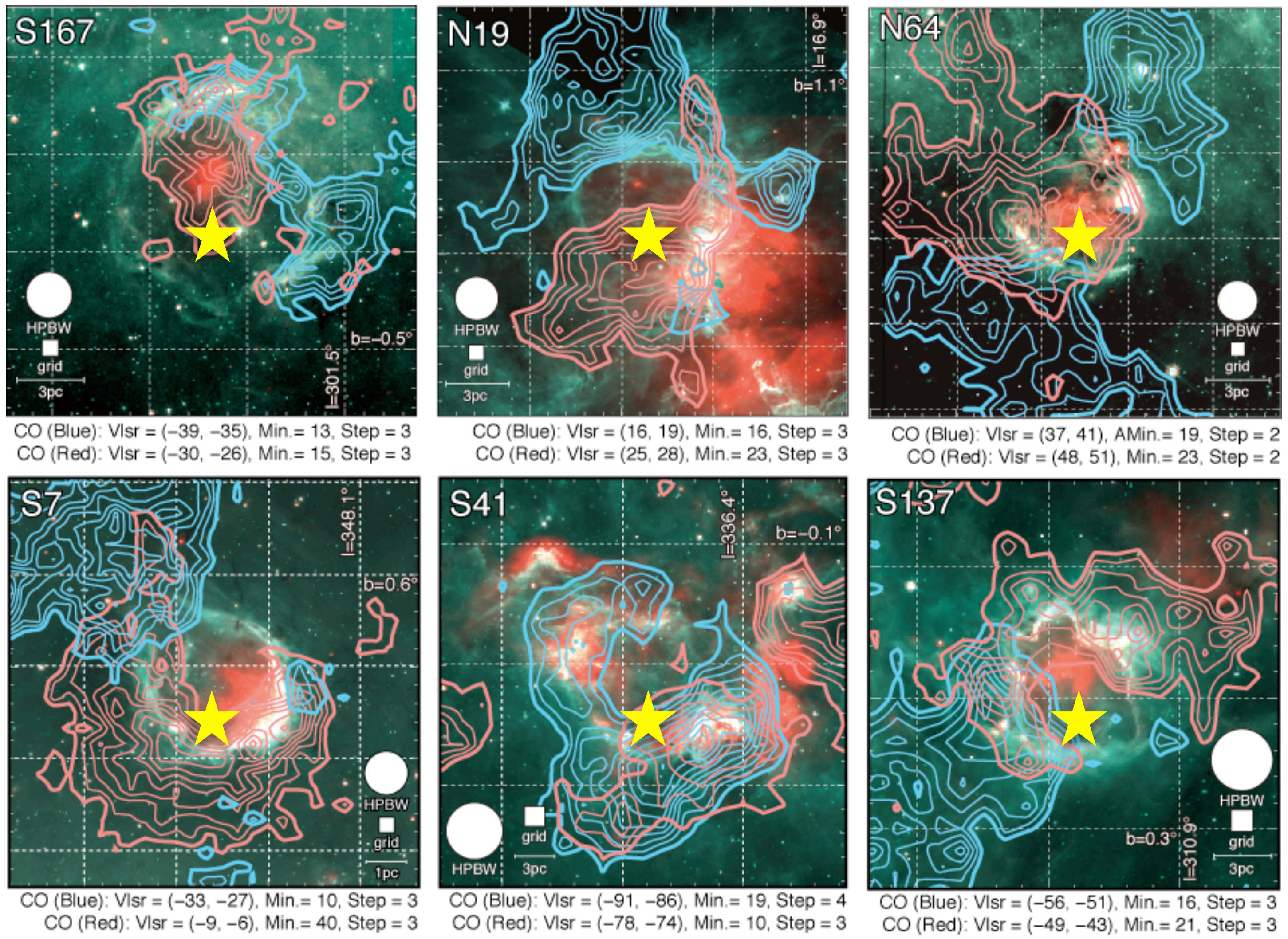




Strong Shock as Trigger of Massive Star Formation

- 大質量星や大質量星団は分子雲衝突が引き金？

（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+15 in prep.)

- Representative sites of cloud-cloud collision where massive stars are located at center of each panels. (Fukui+15 in prep.)
- Large collision velocity for massive star formation:

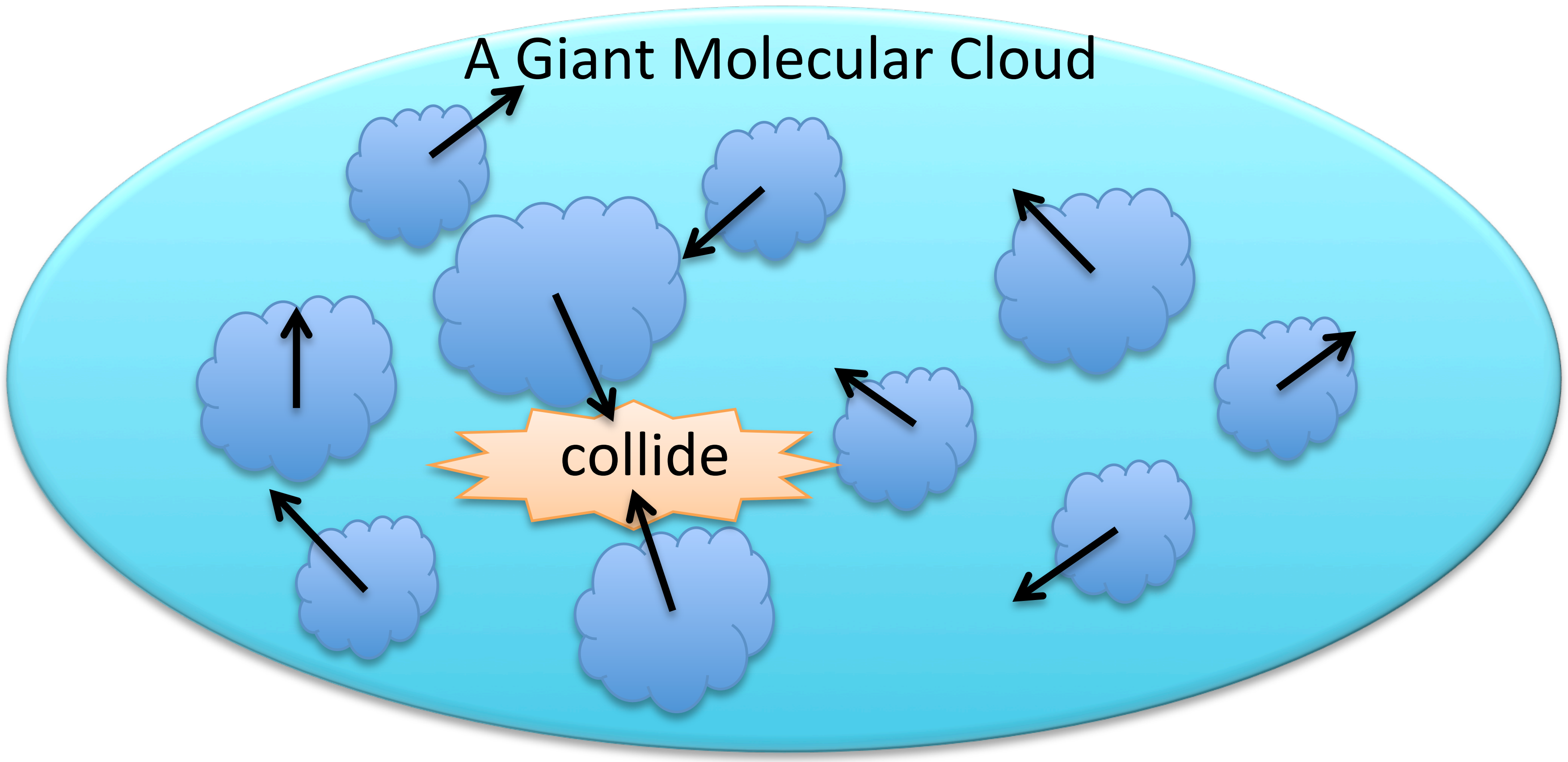
  ✓ $v_{rel} \sim 20$ km/s $>> c_s \sim 0.2$ km/s

→ Strong shock triggers massive star formation?

Cloud Collision の一般性

- 独立な形成過程で生まれた雲同士の衝突頻度は単純な見積もりではそれほど高くない
  e.g., Kobayashi+18
- 分子雲の内部構造は極めてclumpyでかつ超音速の乱流状態（e.g., Inoue+12）

  Larson's law : $\Delta v = 10$ km/s $(L/100$ pc$)^{0.5}$

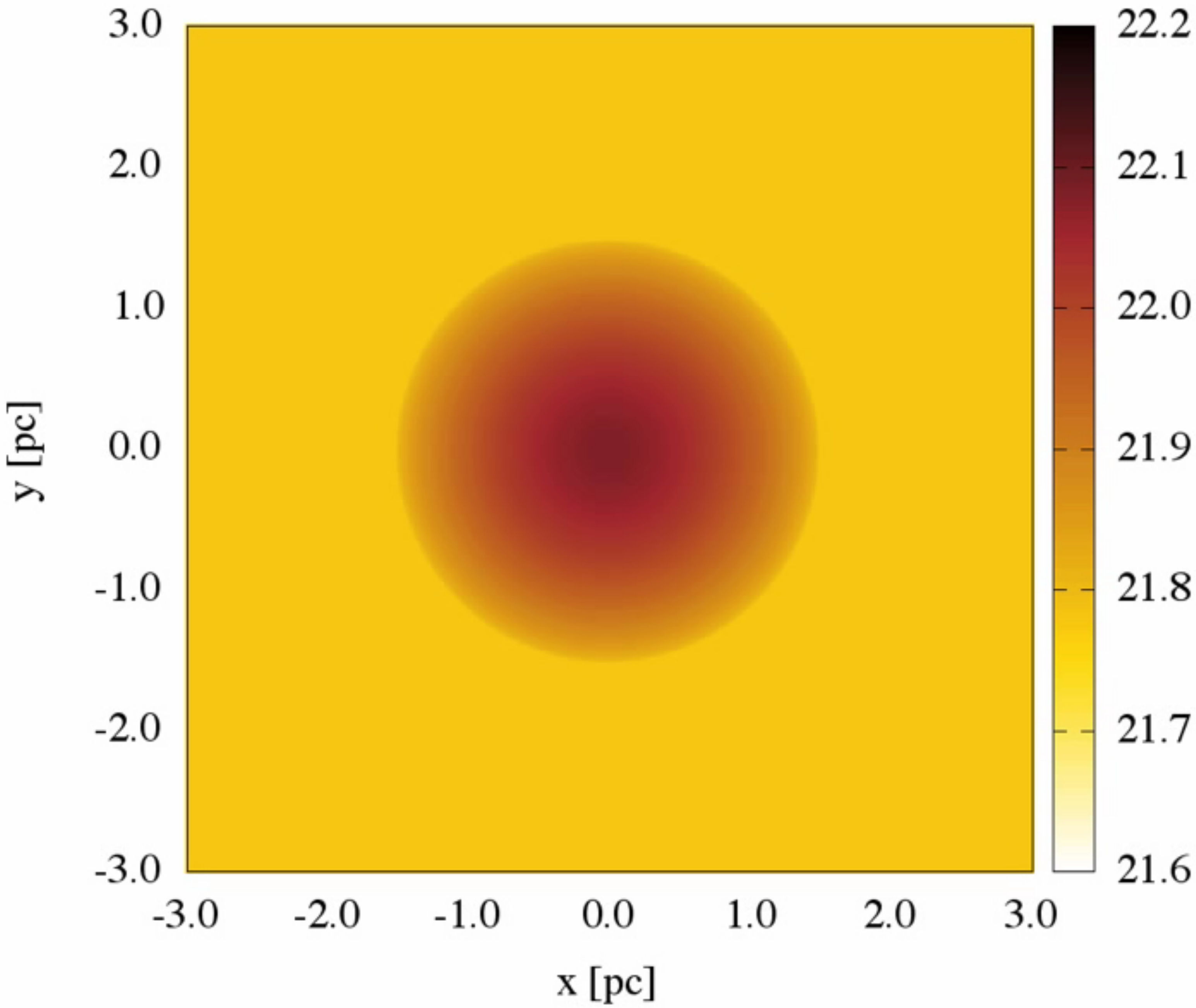


- 巨大分子雲(L~100pc)では 10 km/s レベルの雲衝突は一般的に期待出来る
- 「雲衝突 = 特異な現象」ではなく、天文学用語でいう「乱流星形成」の素過程が「雲衝突」として観測されている（井上の個人的見解）

Postshock Focusing Flow

Inoue & Fukui 13, Inoue+18

- 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.

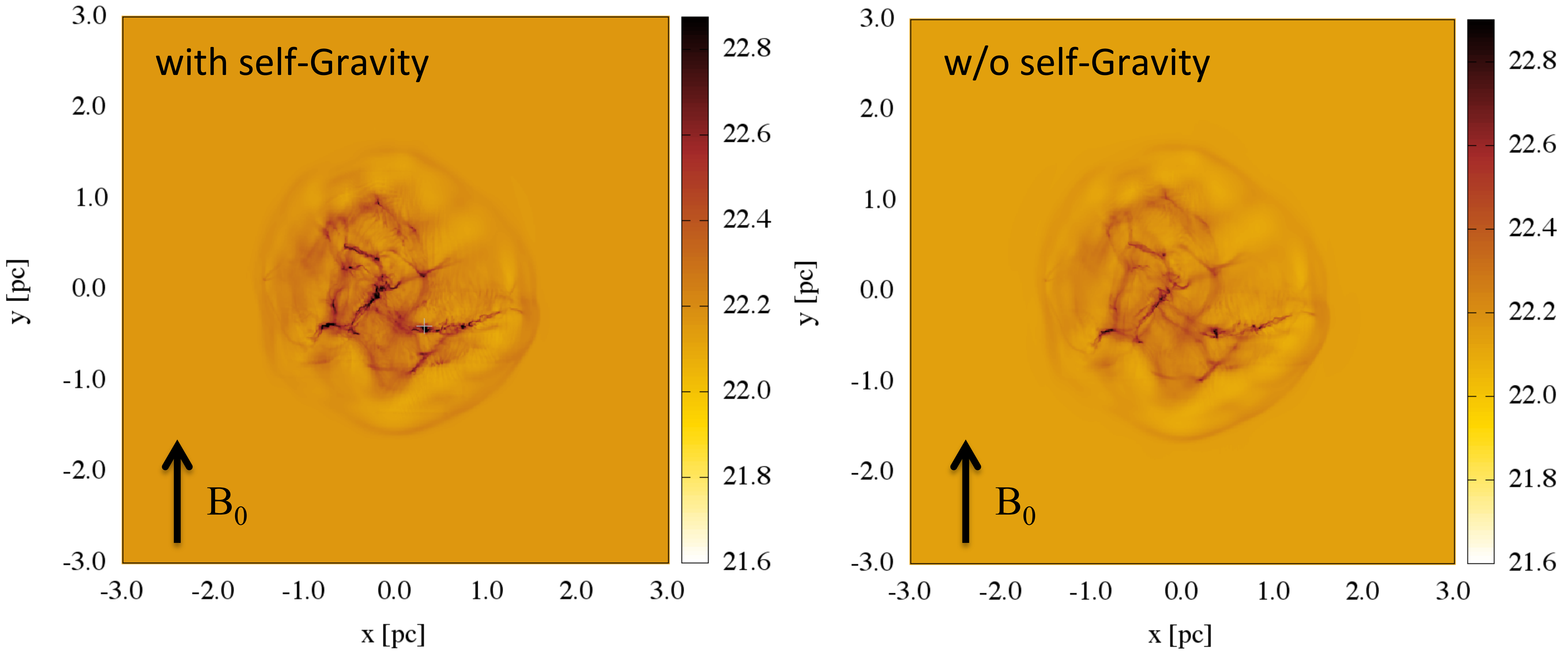


- The small cloud is clashed as if it is imploded → Gas of small cloud is focused into a small region.

Filament Formation by Clump Crushing

Inoue & Fukui 13, Inoue+18

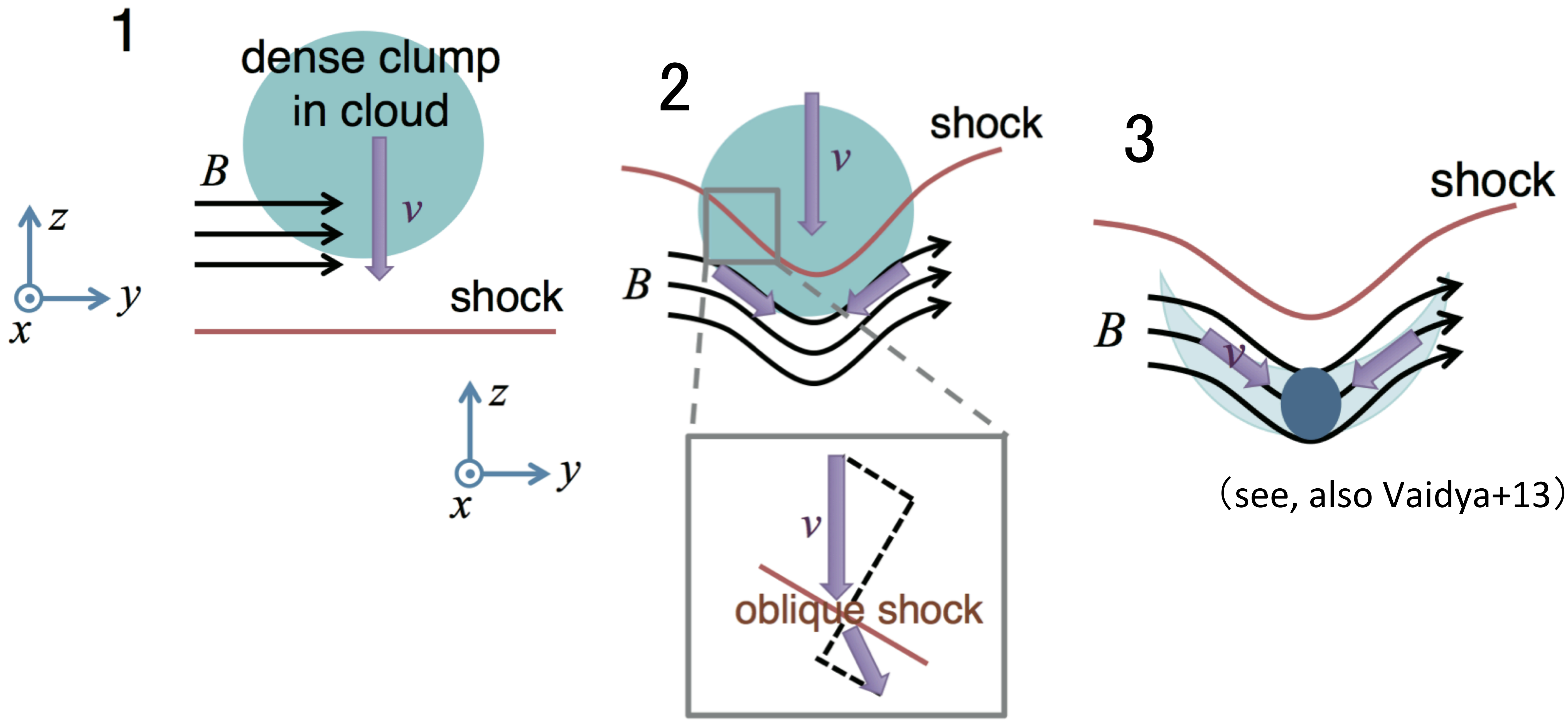
- Filaments are NOT formed by self-gravity.



Filament Formation behind MHD Shock

Inoue & Fukui 13, ApJL

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



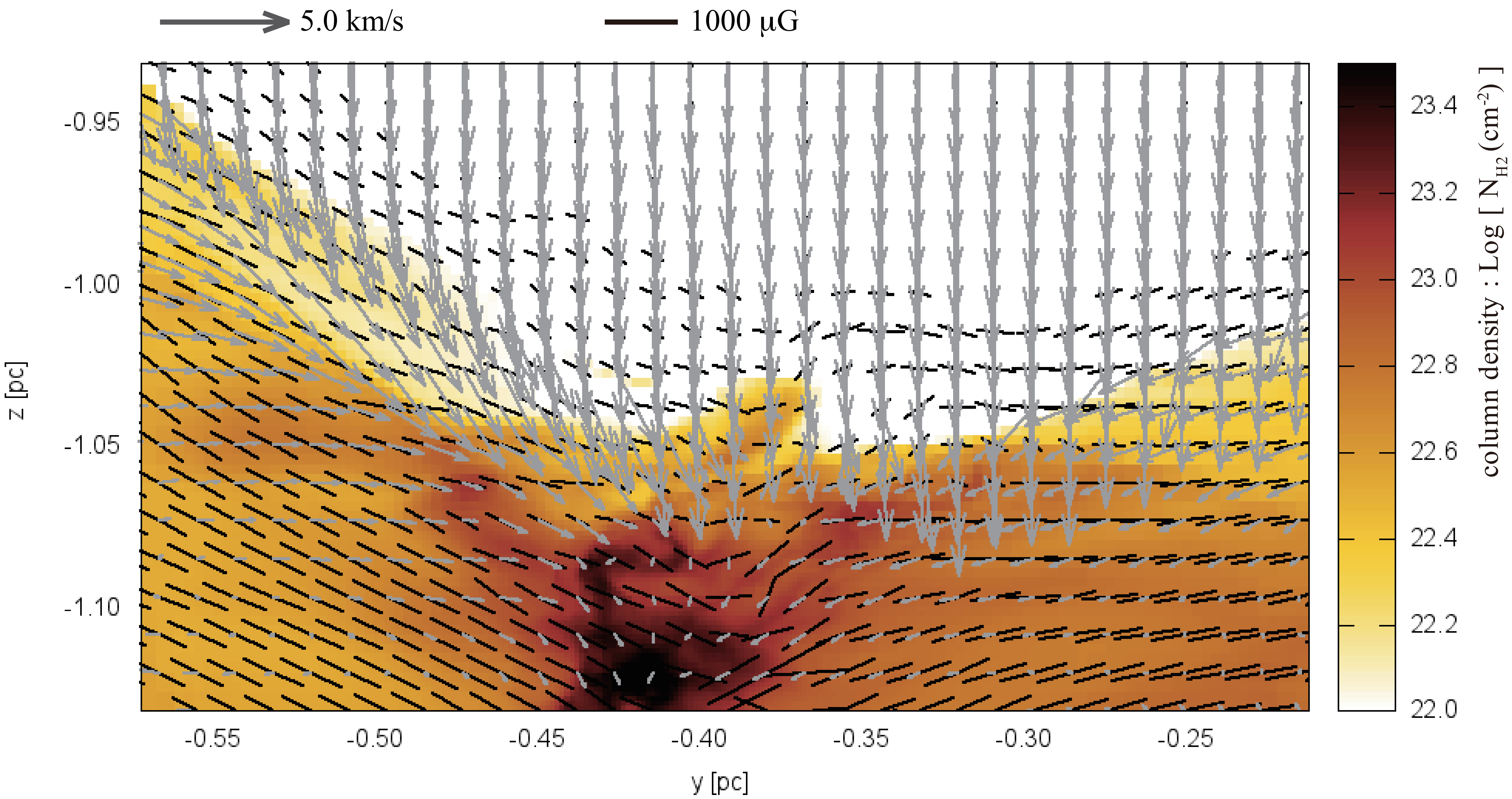
(see, also Vaidya+13)

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

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

Focused Flow by Oblique Shock

Inoue+18

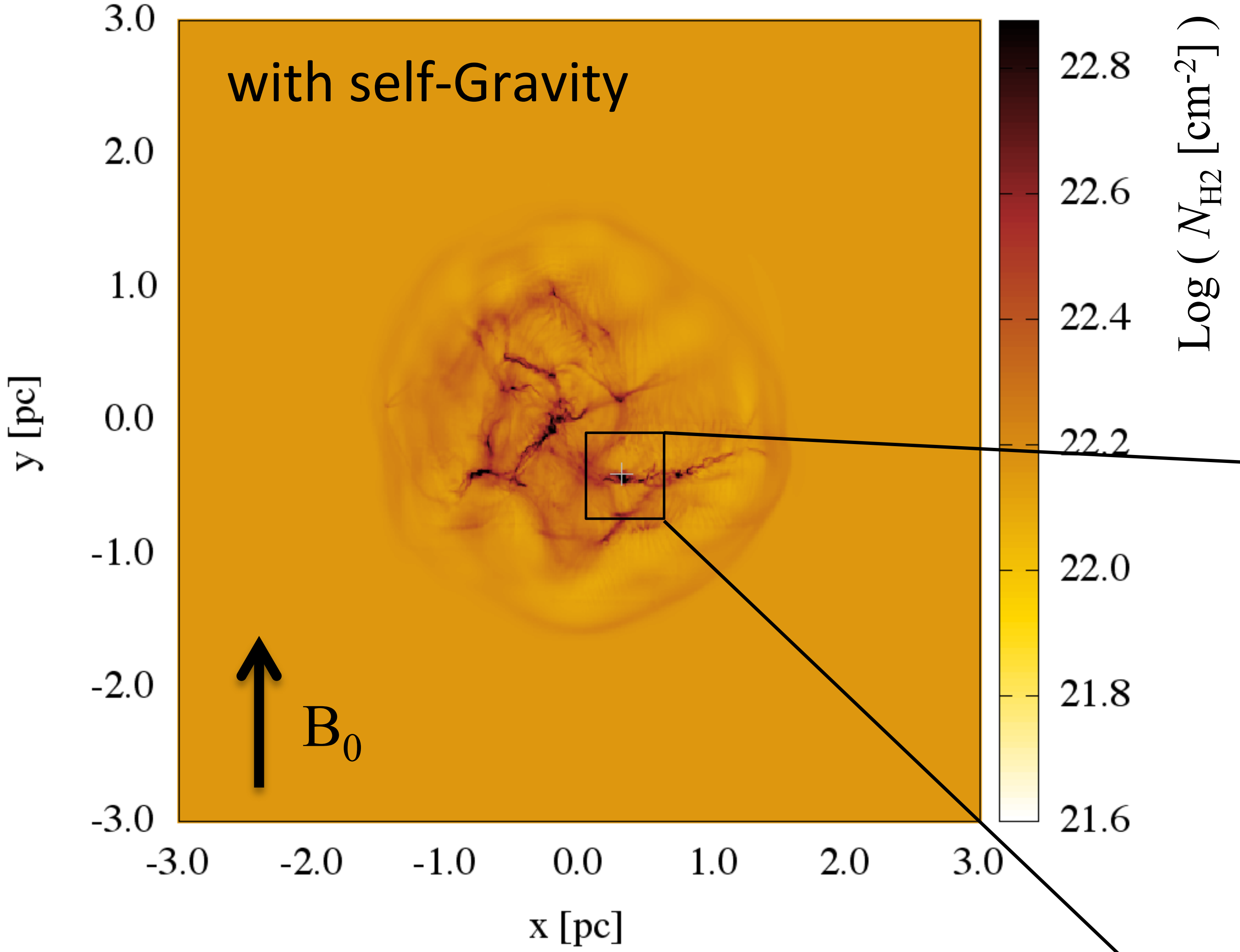


Massive Star Formation

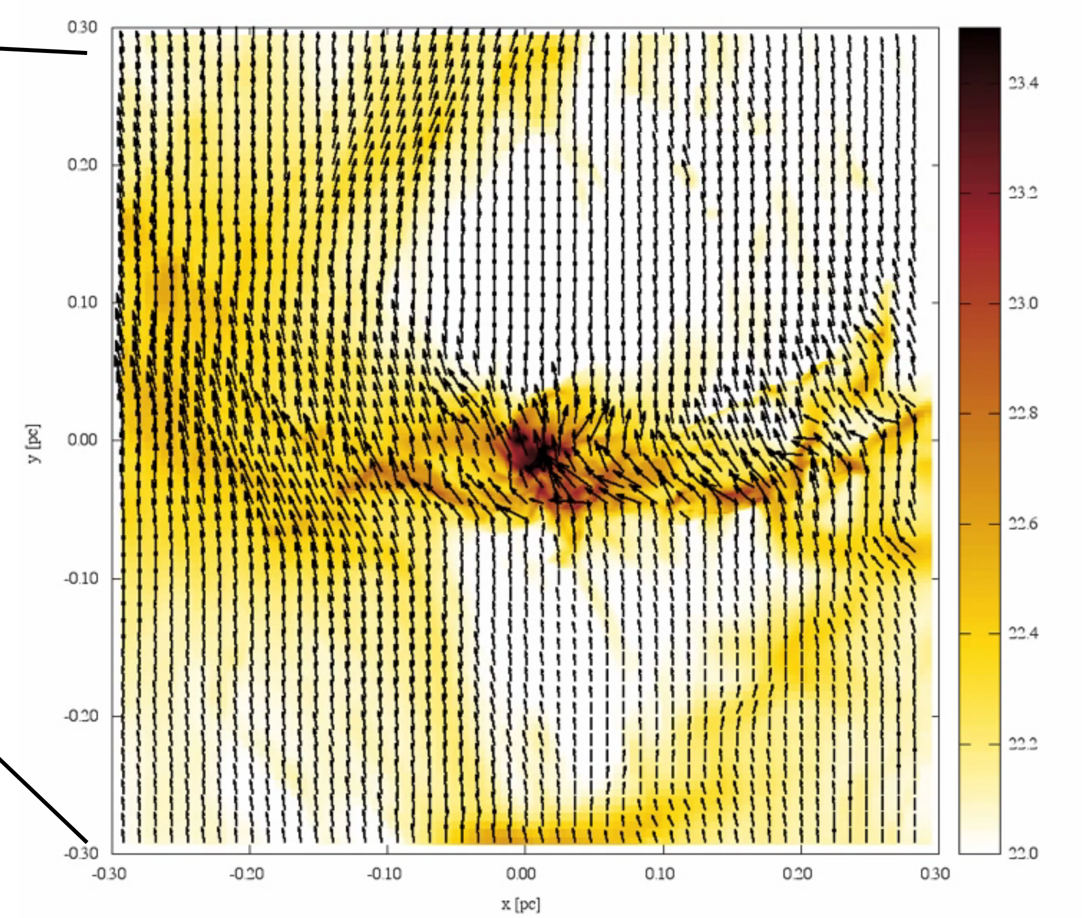
Inoue+18

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

duration = 0.7 Myr



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

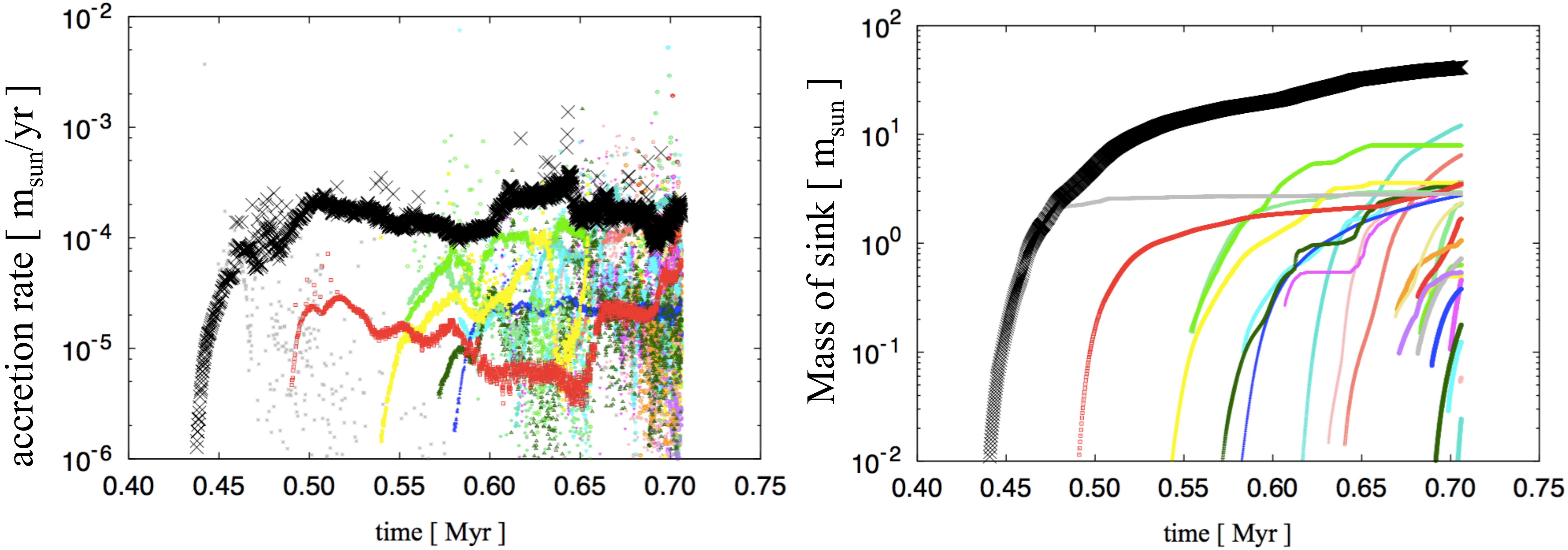


- The most massive sink mass ~ 50 m_{sun}

Accretion Rate

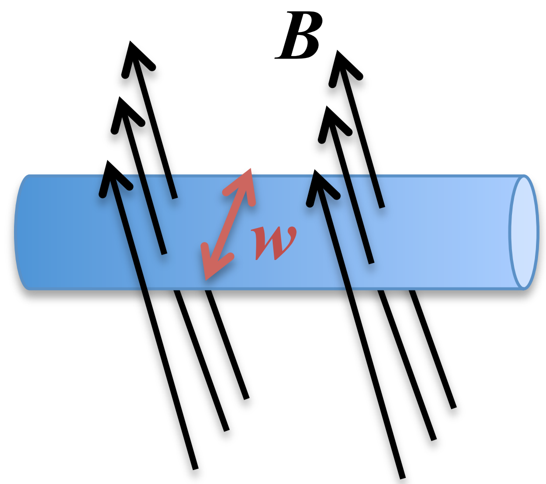
Inoue+18

- 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 contraction continues.

Role of B Field



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

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

~ 15 Ms/pc (thermal critical line mass)

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

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

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

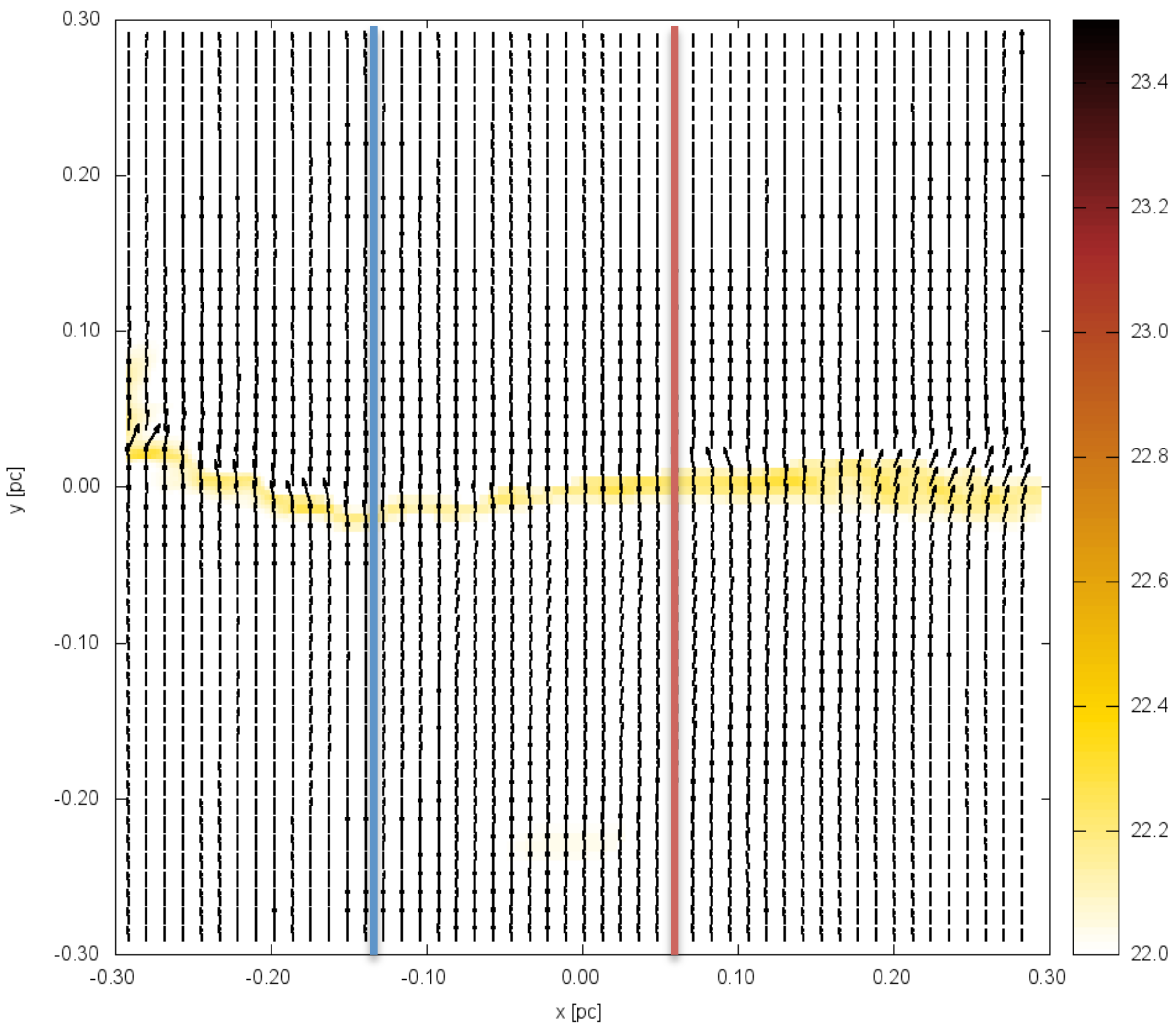
→ $\lambda \sim 100$ Ms/pc

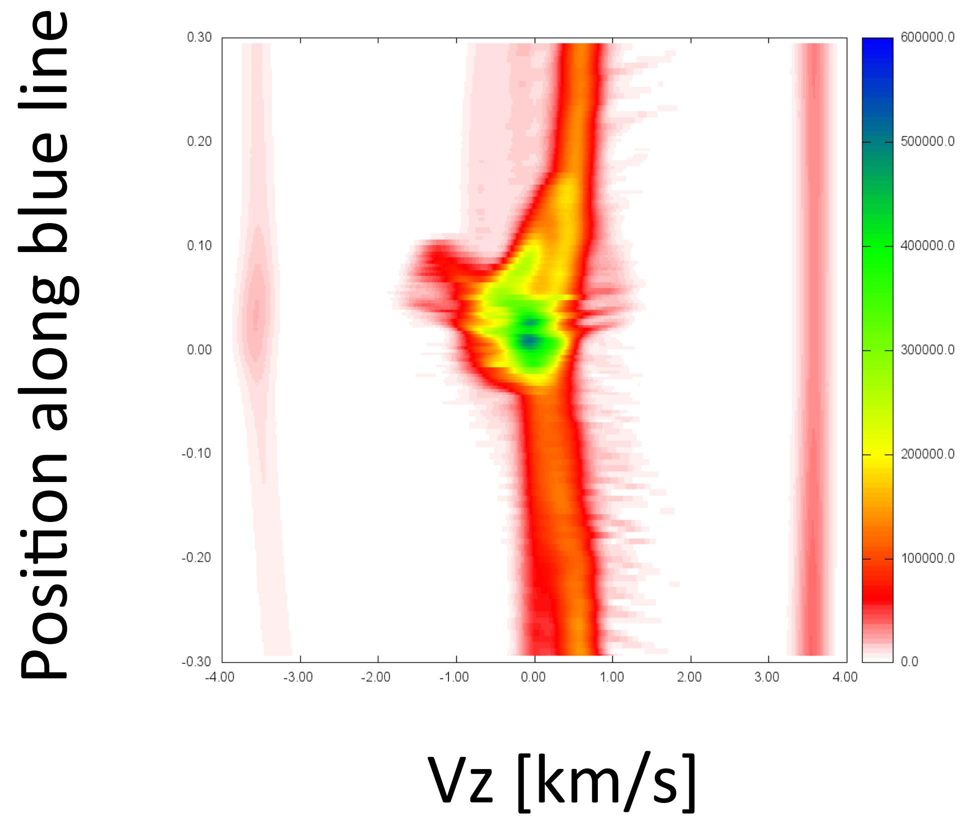
→ The critical line-mass of the shock induced filament can be much larger than the thermally supported filament.

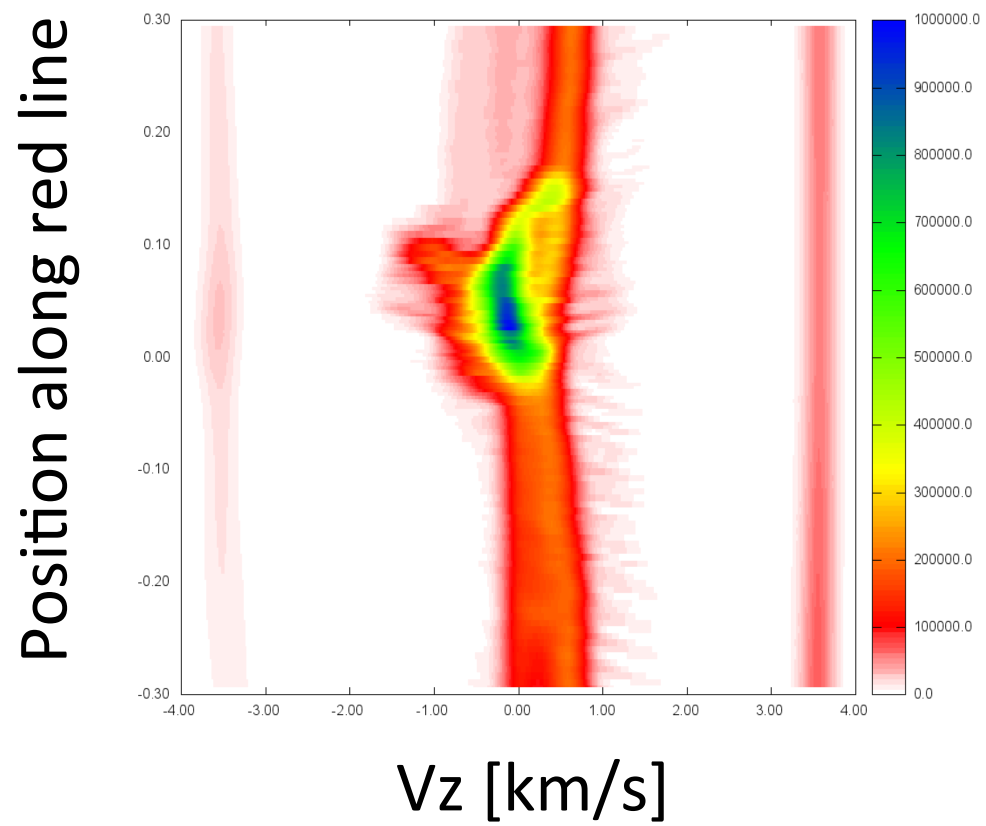
P-V Structure of Simulated Baby Filament

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

Colmn density map



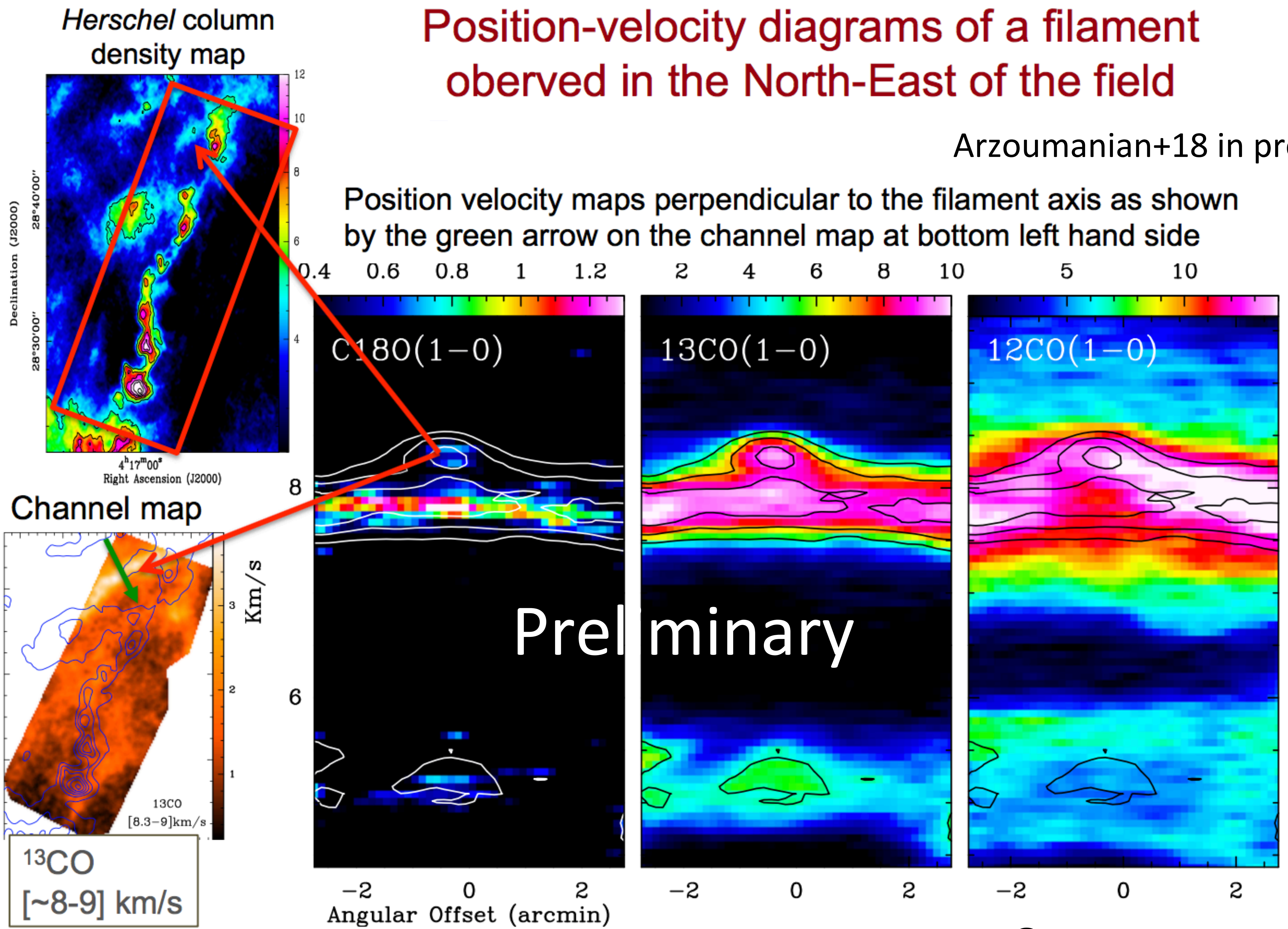




Position-velocity diagrams of a filament oberved in the North-East of the field

Arzoumanian+18 in prep.

Position velocity maps perpendicular to the filament axis as shown by the green arrow on the channel map at bottom left hand side



Summary

- Shock wave plays crucial role for evolution of the ISM
  - Shocked WNM becomes thermally unstable gas which evolve into turbulent CNM.
  - ***B*** field drastically affect the formation process of HI clouds.
  - Molecular cloud can be formed by accretion flows of the two-phase ISM.
  - Accretion of clumpy HI clouds drives supersonic turbulence in molecular clouds.
  - Shock-clump interaction leads to formation of star forming molecular filament.
  - Massive star can be formed by collapse of massive filament created by cloud collision.