Abe et al. (2025)

A Novel Mechanism to Drive Turbulence in Massive and Magnetized Star-Forming Filaments

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Tsuyoshi INOUE[2,3], Shu-ichiro INUTSUKA[3], & Doris ARZOUMANIAN[4]

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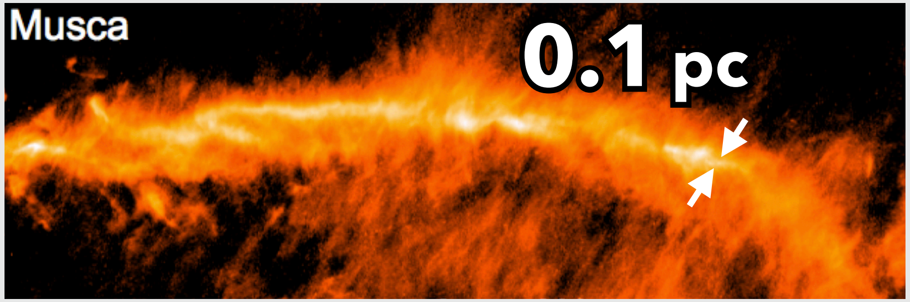
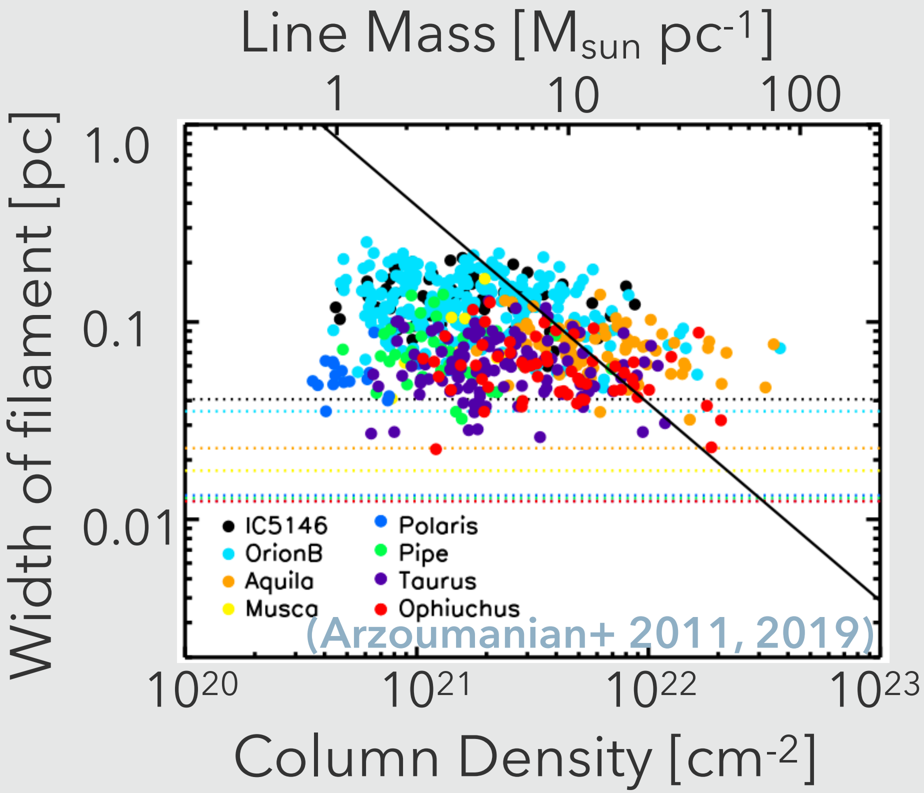
JSPS Research Fellow-PD [Tohoku University (Japan) / CEA Paris-Saclay

Star-forming Filaments



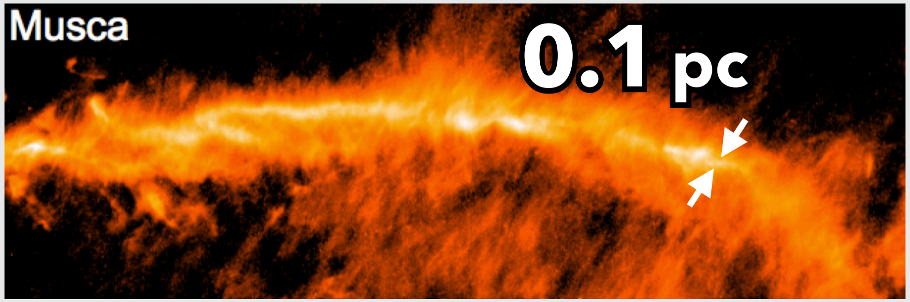
Filaments play an important role in setting the initial conditions.



Observed filaments typically have a width of ~ **0.1 pc**

Questions: What controls the initial condition of star formation?

Star-forming Filaments



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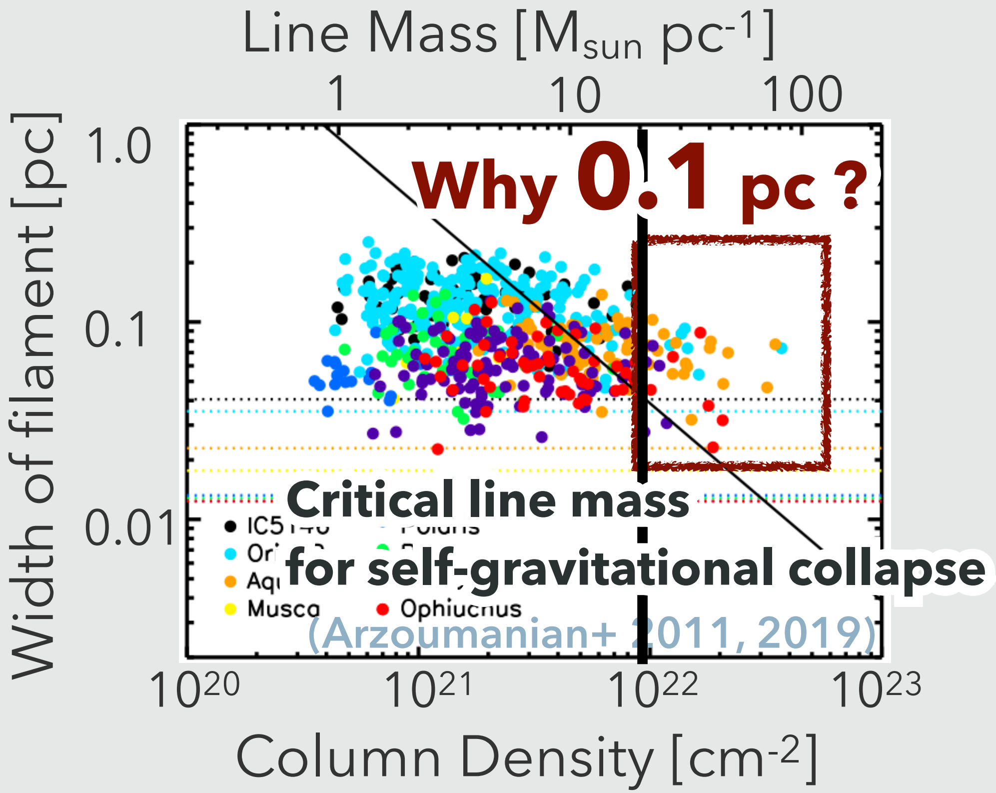


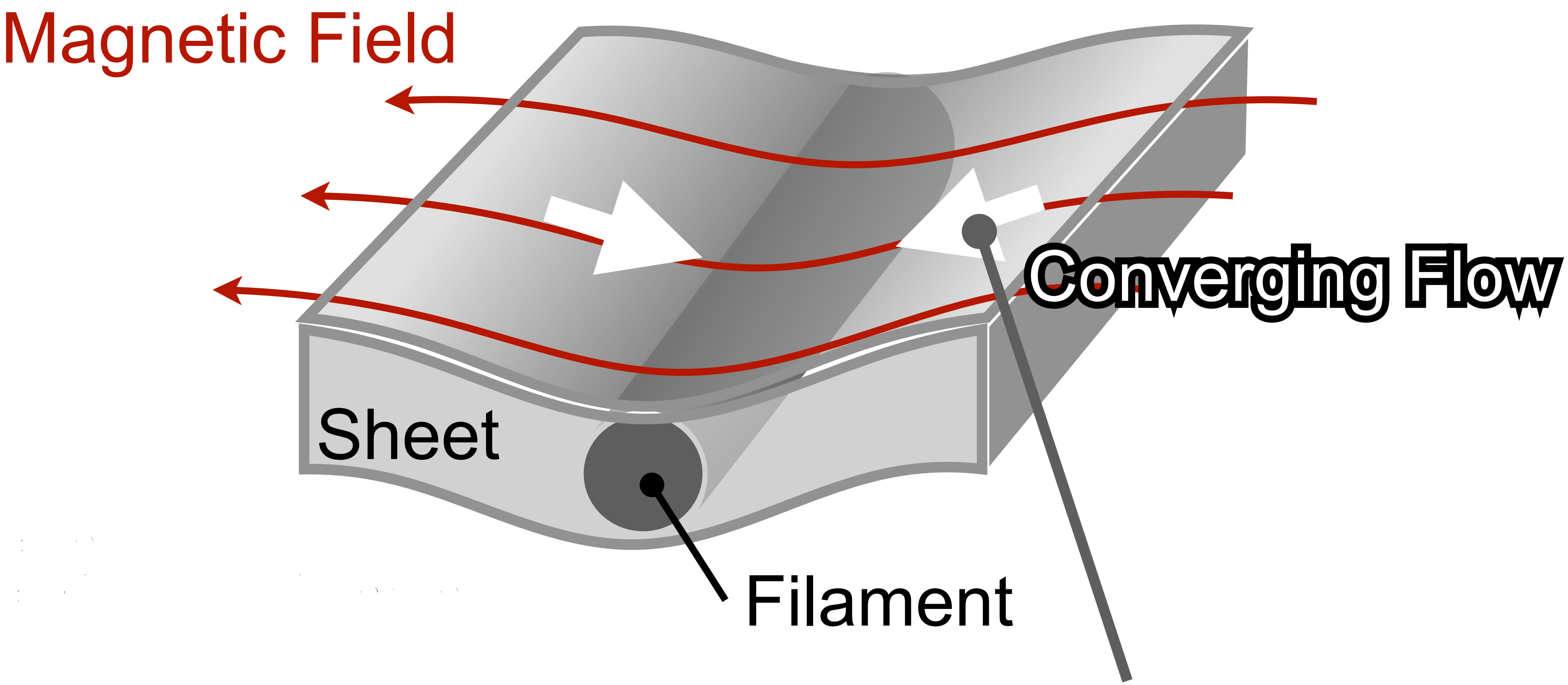
Observed filaments typically have a width of ~ **0.1 pc**

However, most simulations show **much narrower width due to strong gravity**.

–> ***We are missing something.***

Theoretical Picture of Filament Evolution

e.g., Tomisaka & Ikeuchi (1983); Kitsionas & Whitworth (2007); Balfour et al. (2015). Inoue & Fukui (2013); Vaidya et al. (2013); Inoue et al. (2018); Chen & Ostriker (2014); Padoan & Nordlund (1999), ***Abe***+(2021), Pineda et al. (PPVII 2023)



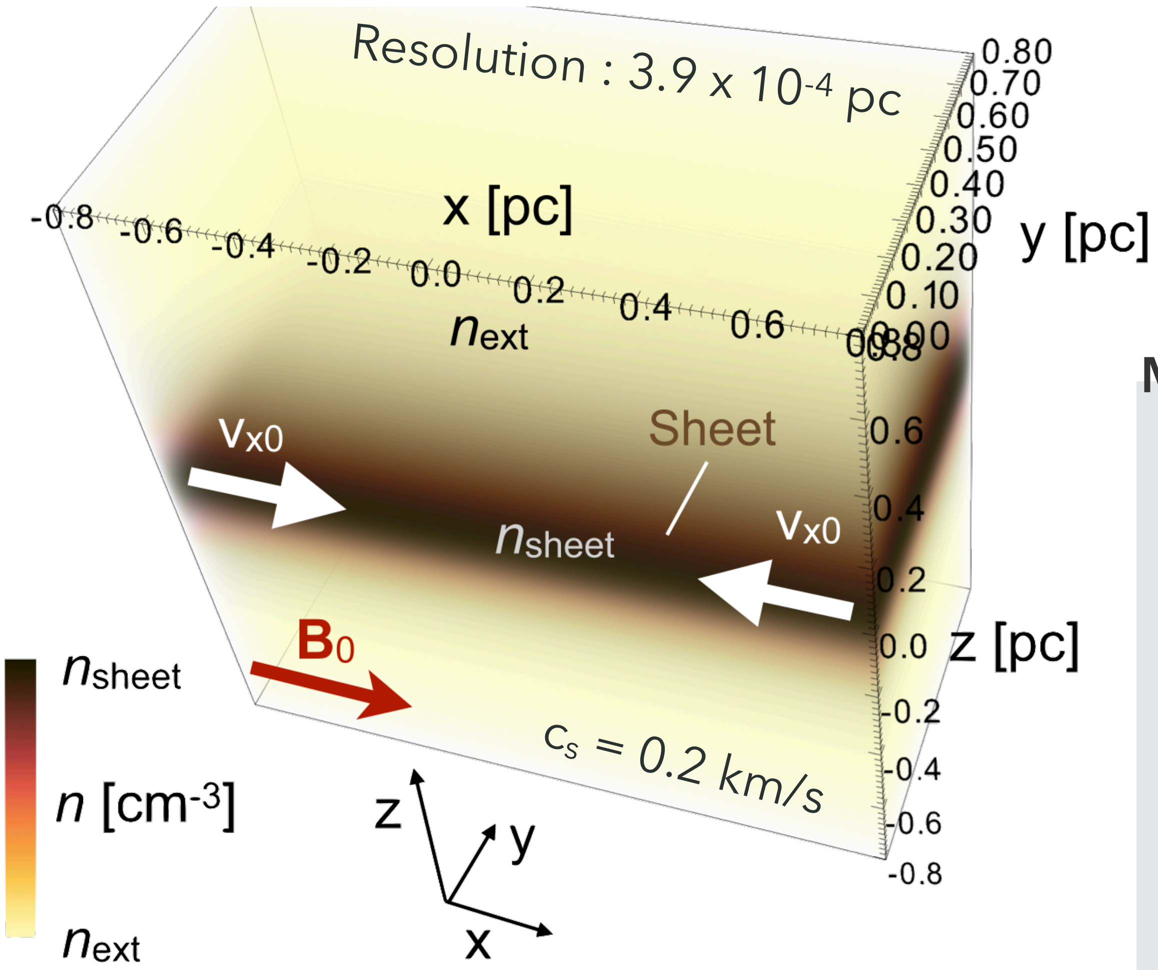
Filaments evolve via gas inflow along magnetic field lines.

We performed a simulation of this situation (Abe+ 2025).

Initial Condition for the Simulation

Simulations using Athena++ code (Stone+ 2020, Tomida & Stone 2023)

Initial Condition: Gas inflows along the B field –> filament formation



Boundary Condition

- x –> gas continue to flow in
- y,z–> Periodic

MHD including ambipolar diffusion

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\frac{\partial \rho v}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + P + B^2/2\right) = -\rho \nabla \Phi$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times \left[(\boldsymbol{v} \times \boldsymbol{B}) - \frac{\eta_{\rm AD}}{|\boldsymbol{B}|^2} \boldsymbol{B} \times ((\nabla \times \boldsymbol{B}) \times \boldsymbol{B}) \right] = 0$$

$$\nabla^2 \Phi = 4\pi G \rho \qquad P = \rho c_s^2 \qquad \eta_{\rm AD} = \frac{B^2}{4\pi \gamma_{\rm in} \rho_{\rm n} \rho_{\rm i}}$$

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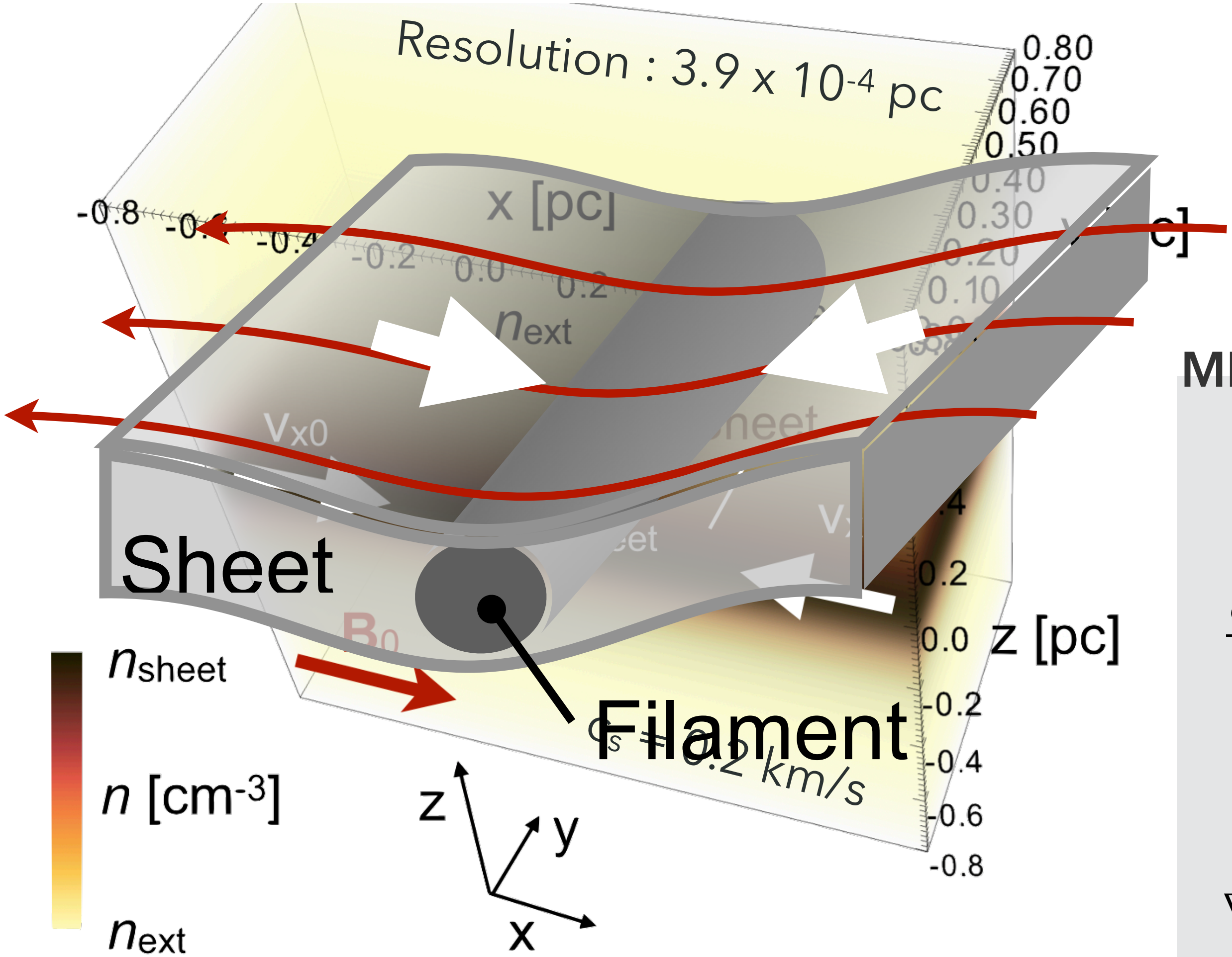

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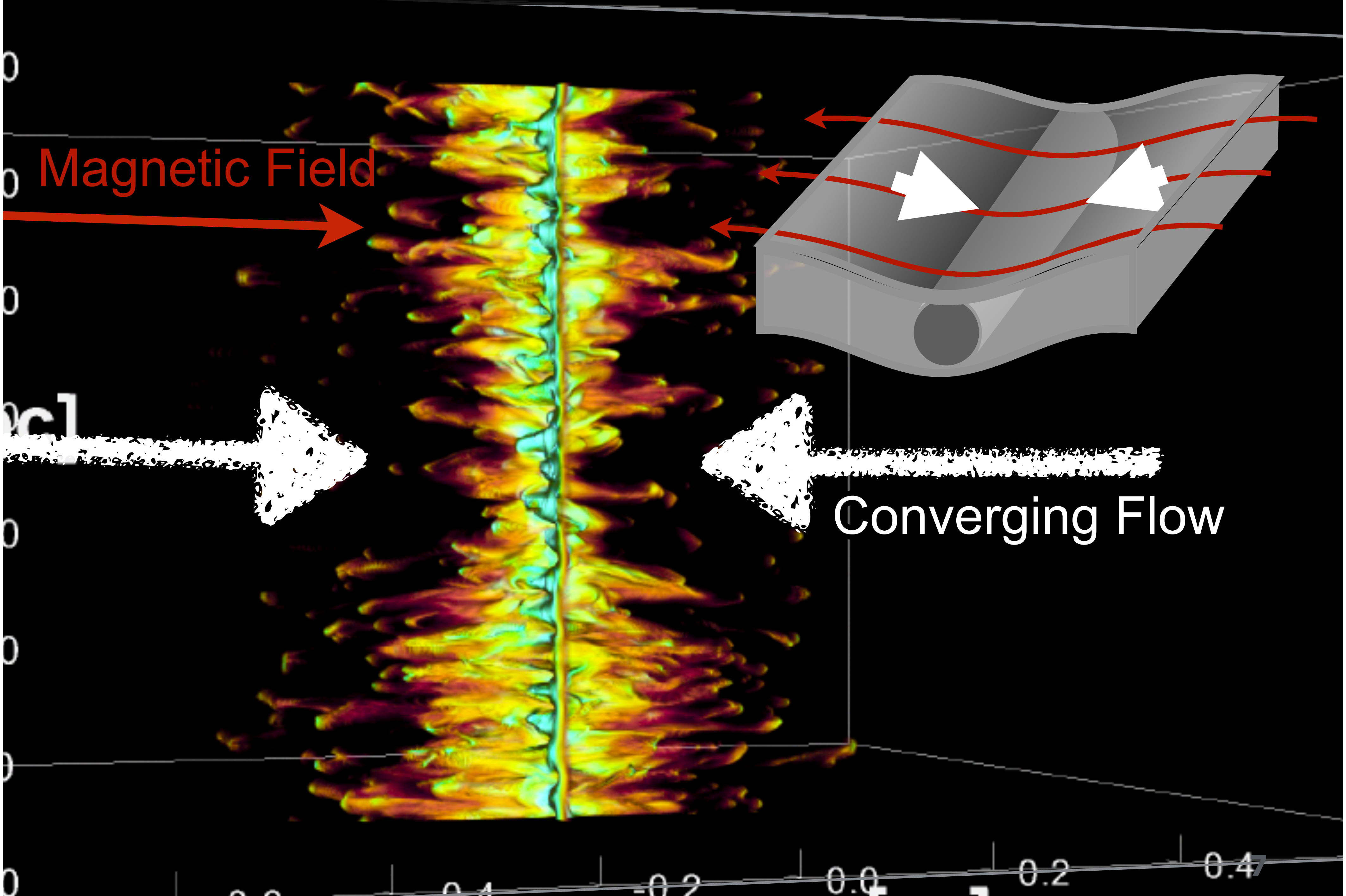
3D Simulation of Filament Evolution (Abe et al. 2025)



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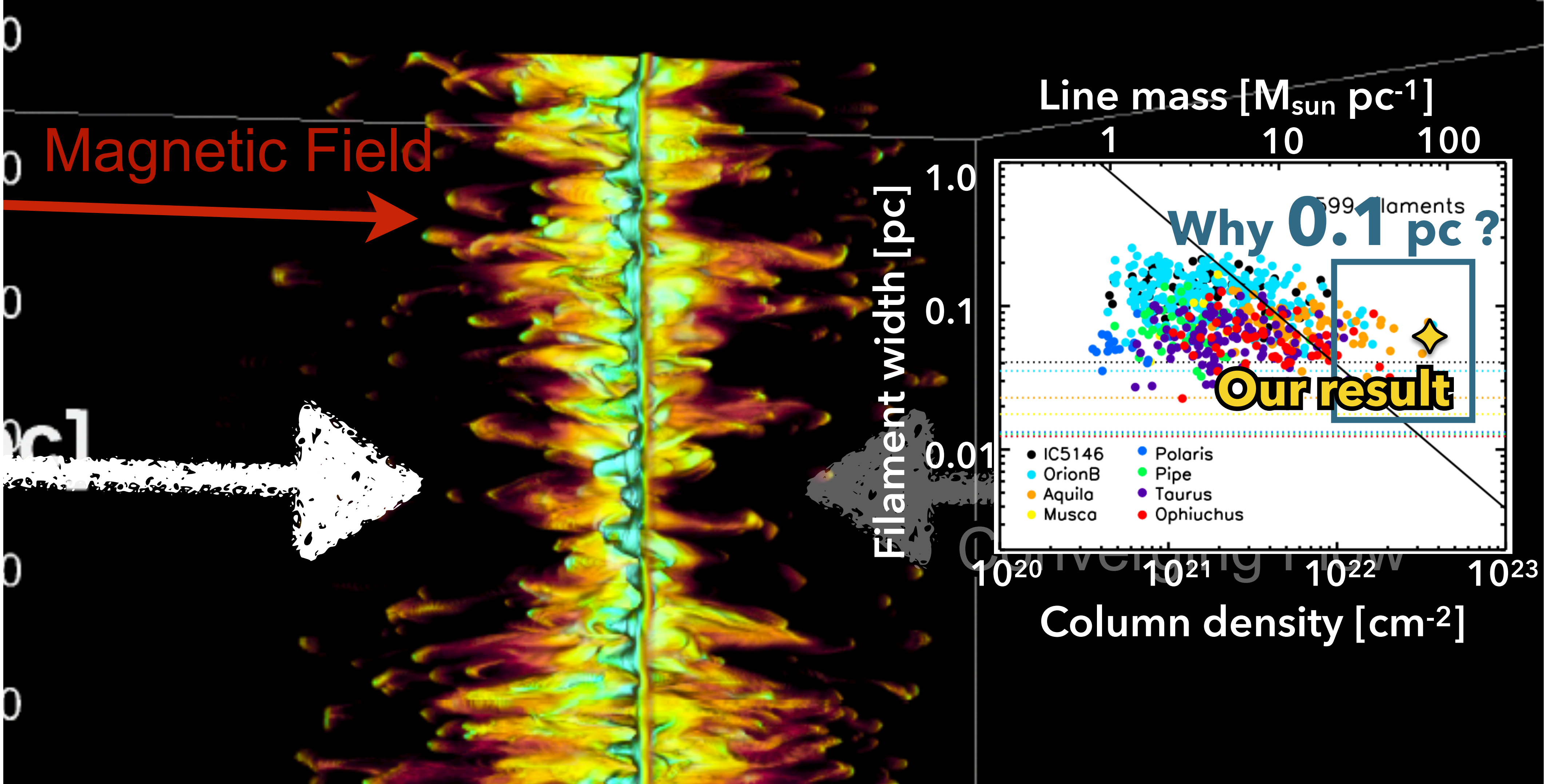
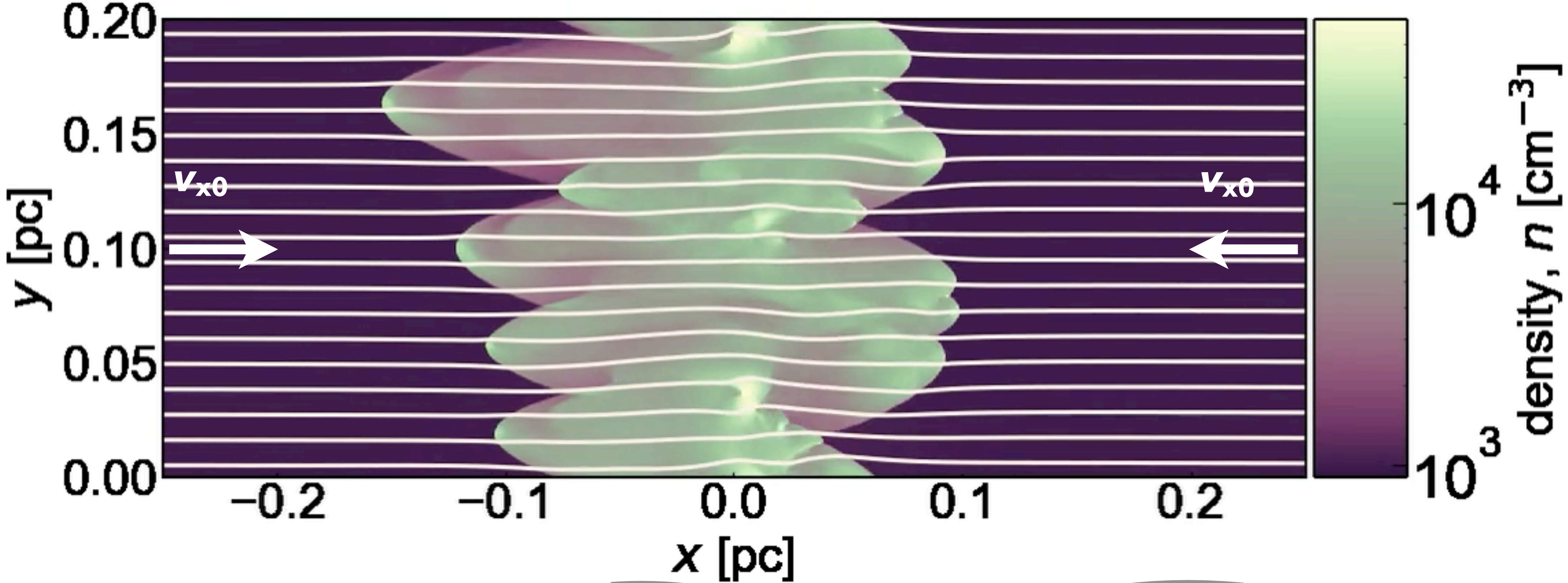
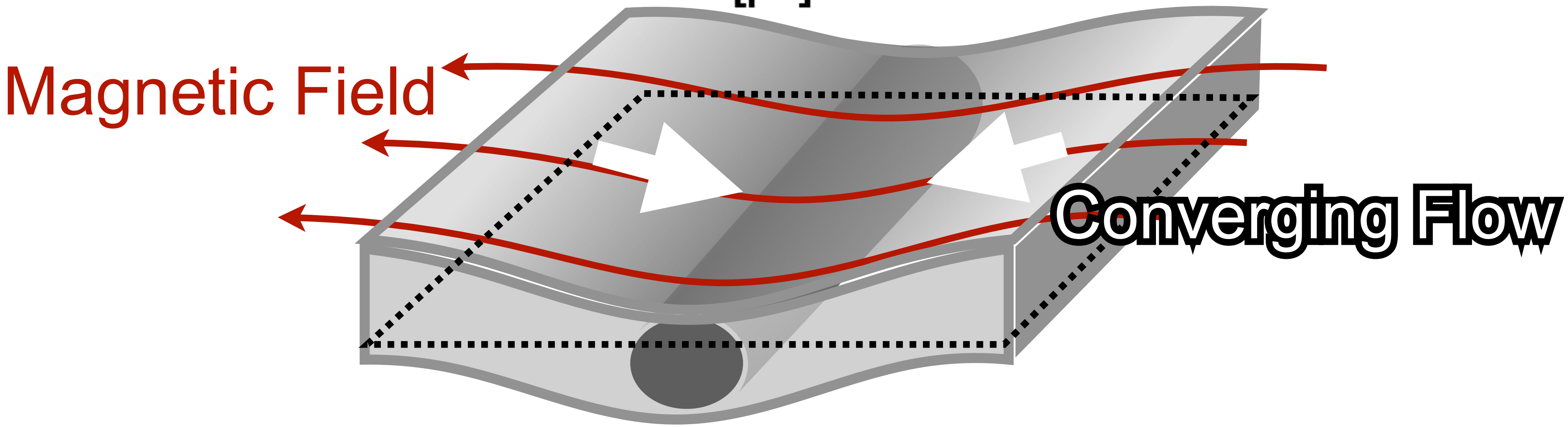


We found a mechanism that drives turbulence and supports filaments against radial collapse.

What is the Mechanism?: Finding of "STORM"

t = 0.770 Myr   **Test simulation (2D, w/o self-gravity)**





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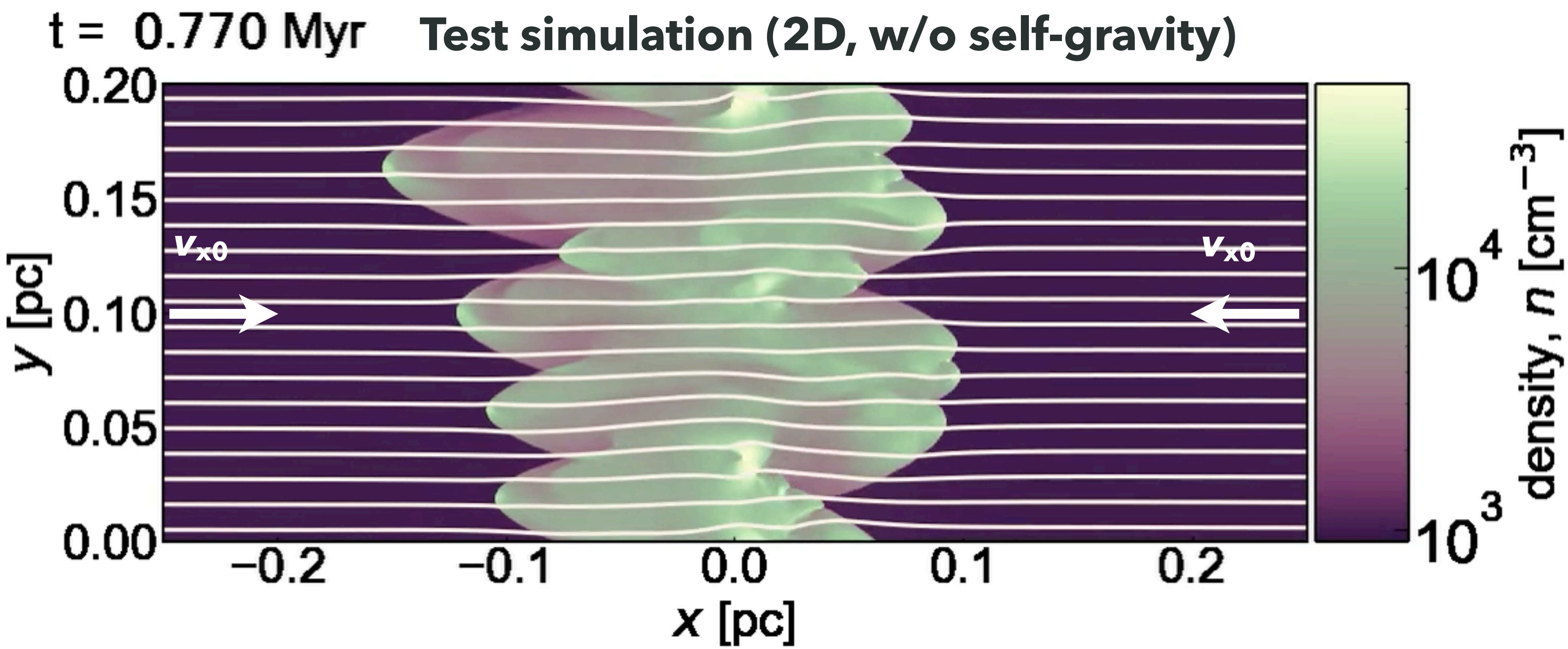

✔ Slow-shock Instability

Magnetic fields play an important role
in this instability.
Perturbation of the shock front grows.

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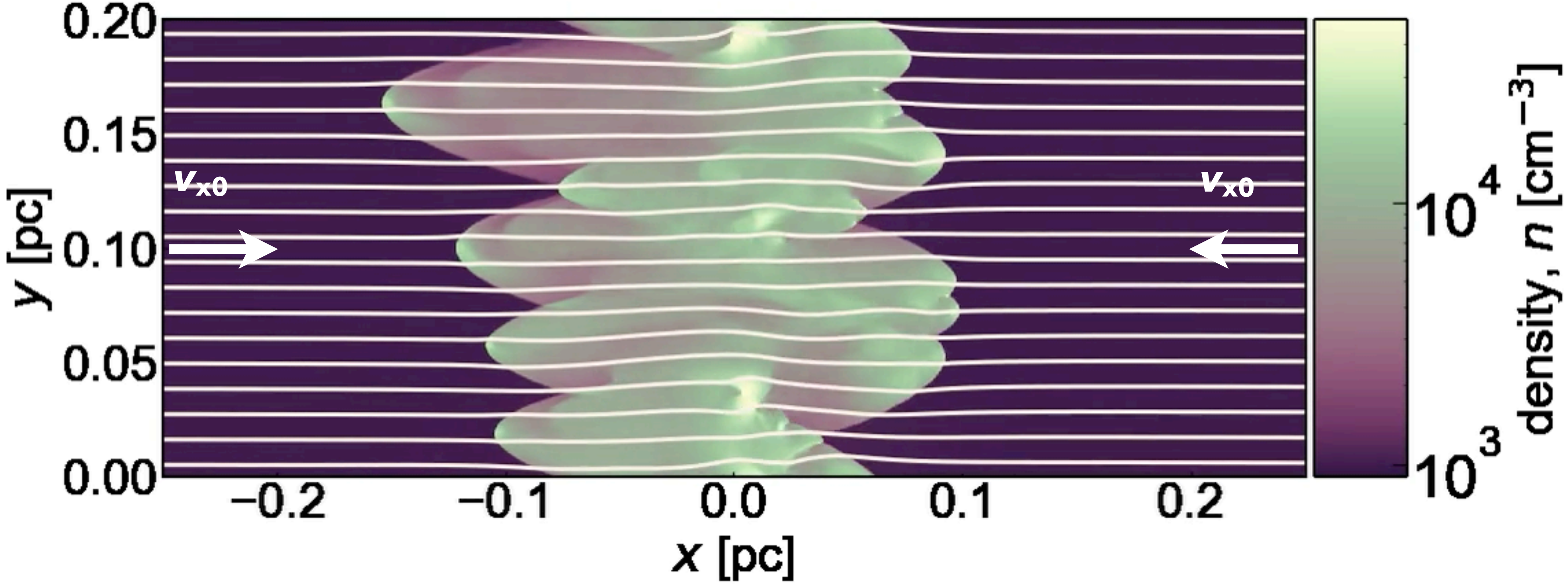

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✔ Partially ionized plasma (Ambipolar Diffusion)

Neutral gas can move freely without being frozen into the magnetic field.

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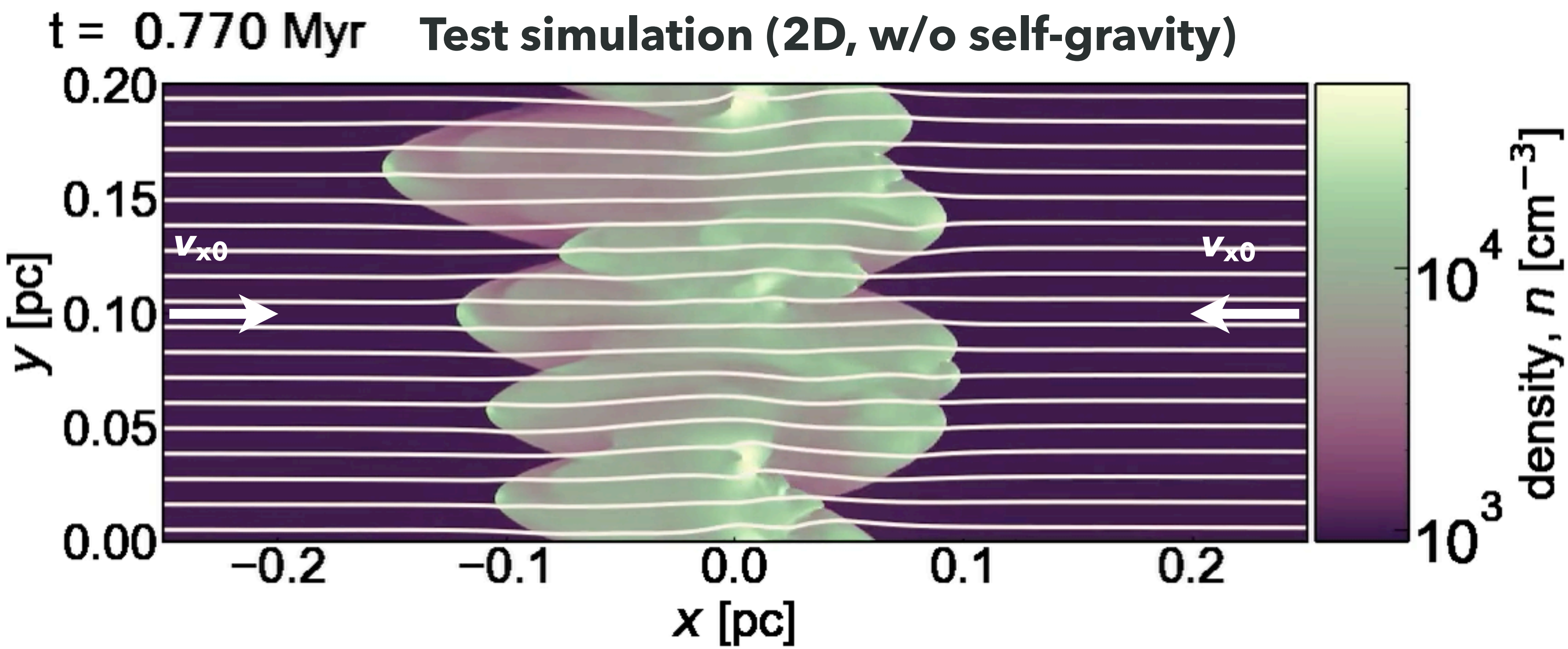

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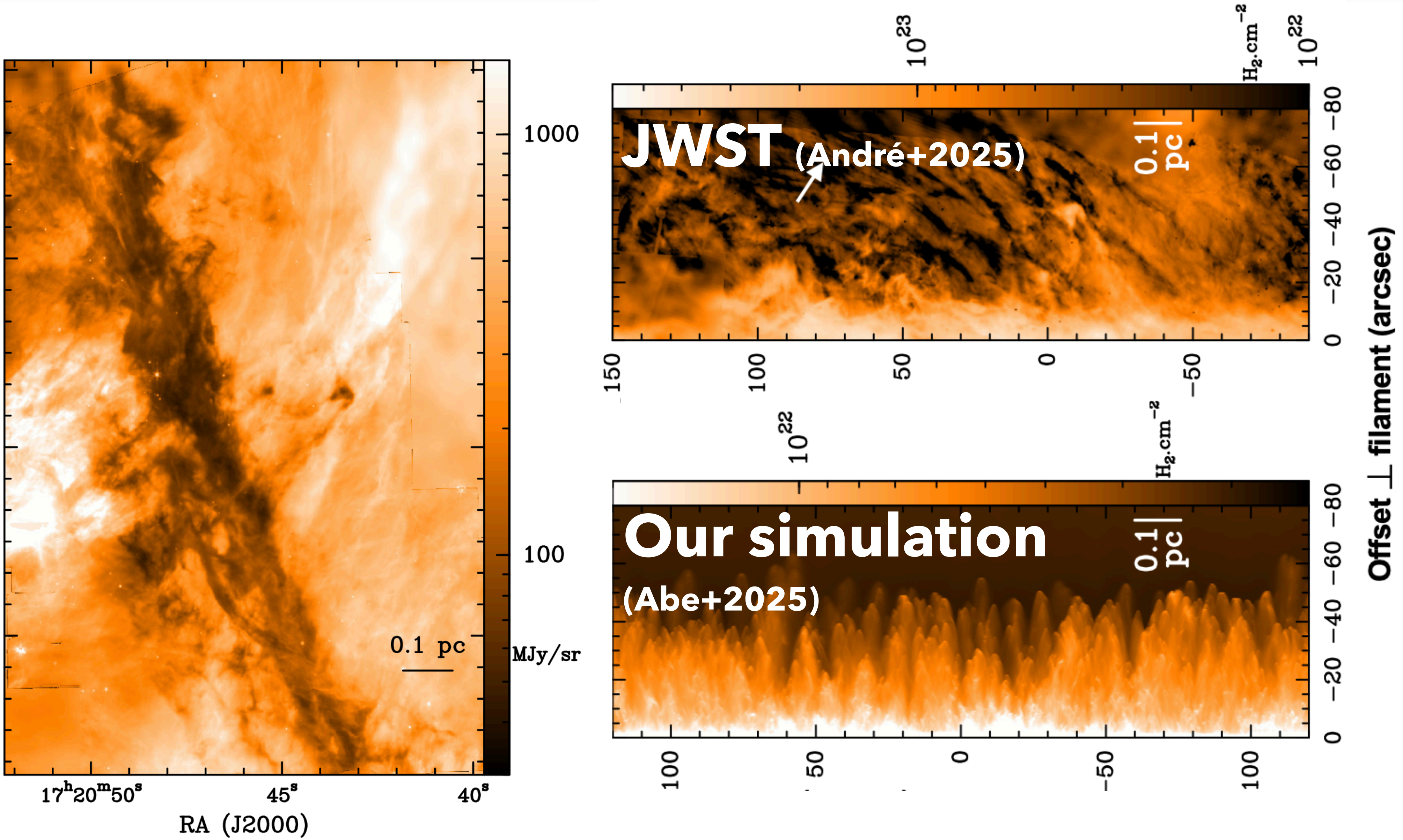
"**STORM** (**S**low-shock-mediated **T**urbulent fl**O**w **R**einforced by **M**agnetic diffusion)"

Comparison with Observation



<u>**The spacing of the "fingers"**</u> & <u>**the column density power spectrum**</u> are **consistent with the JWST observation.**

Summary

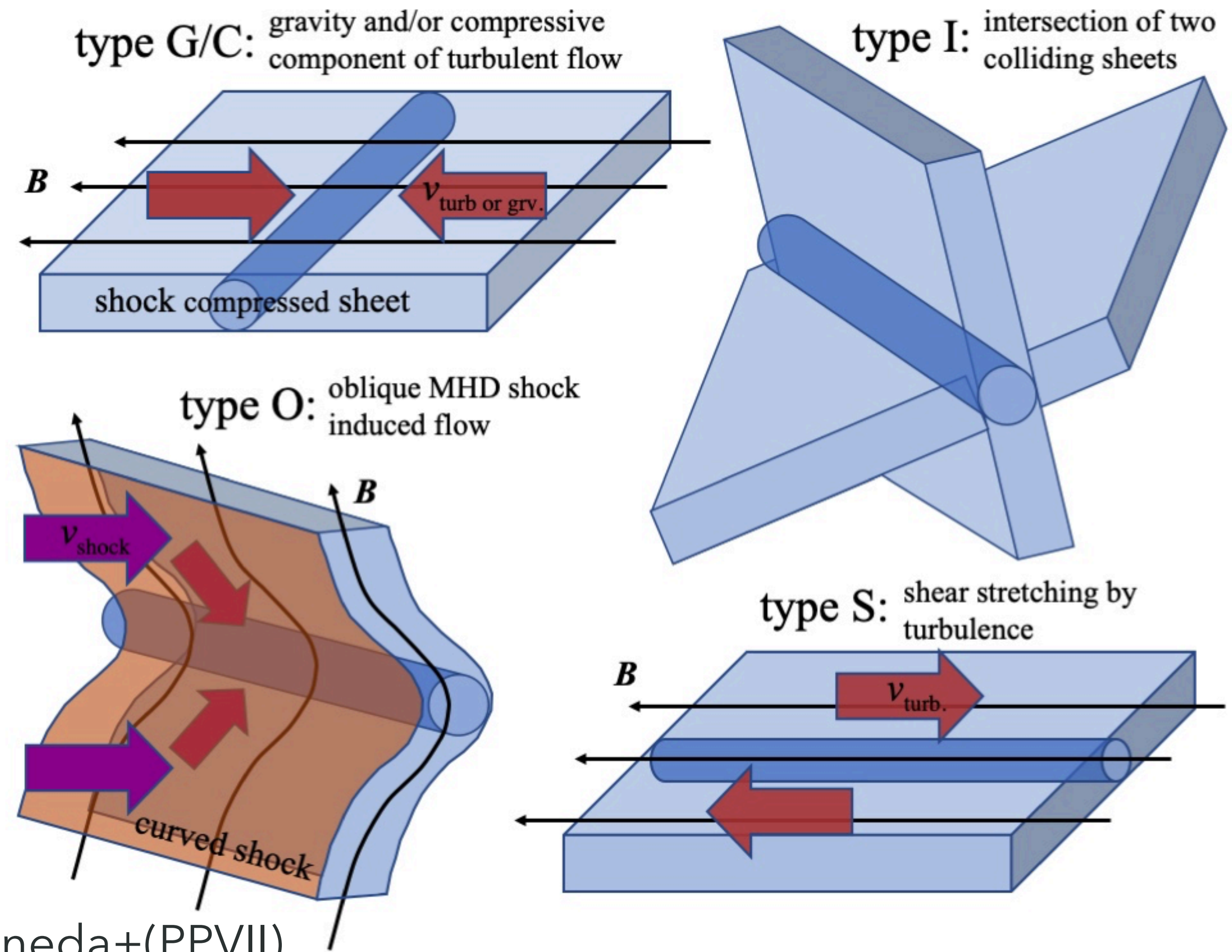
STORM

Slow-shock-mediated Turbulent flOw Reinforced by Magnetic diffusion

can be important in determining the initial conditions for star formation.

Filament Formation

There are 5 types of formation mechanisms

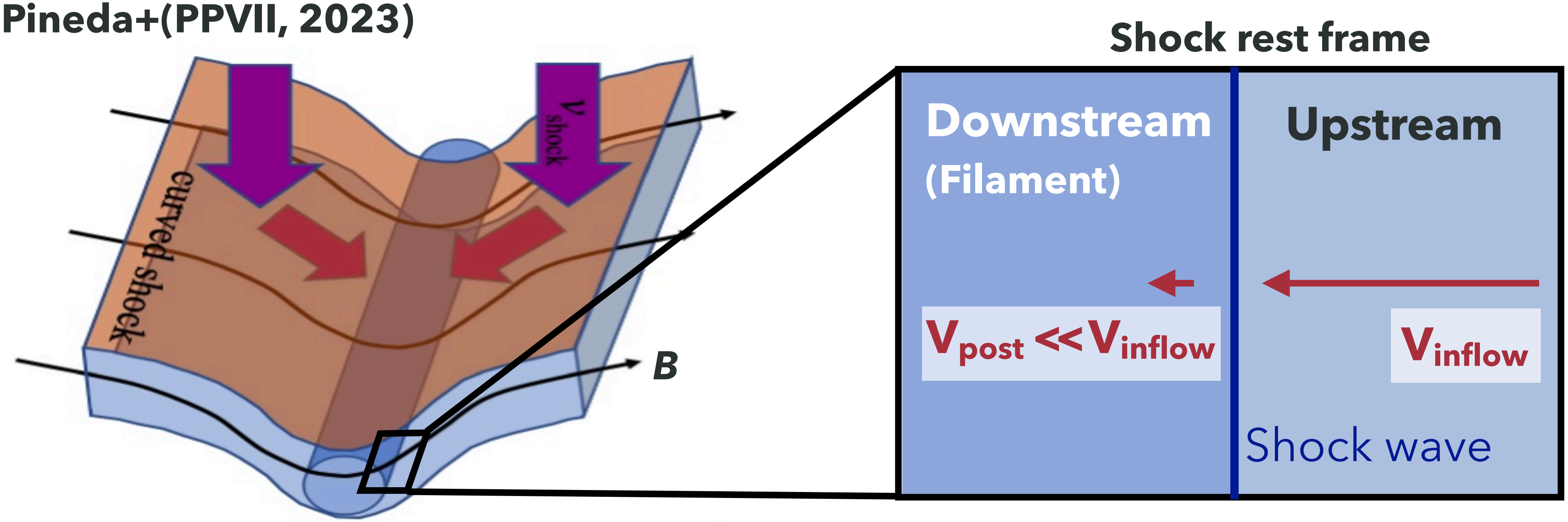


Abe+(2021), Pineda+(PPVII)

Formation process is well understood!

To Solve the 0.1 pc Problem

Pineda+(PPVII, 2023)



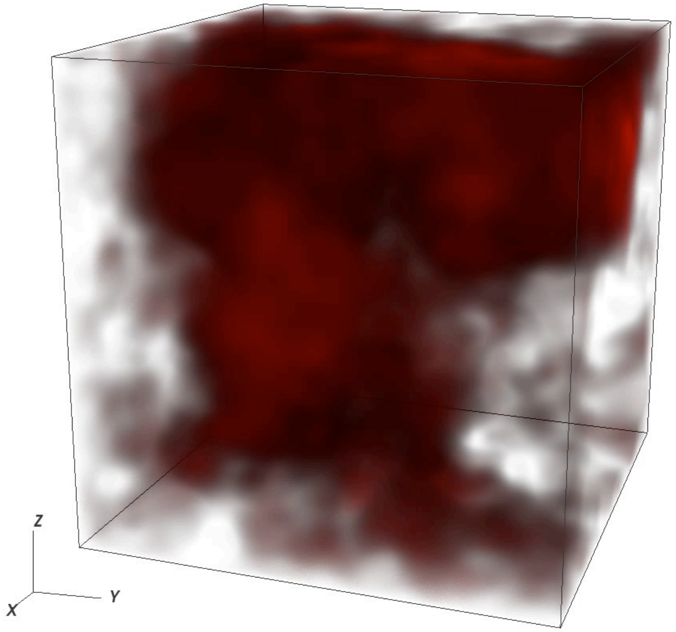
Shock waves bound the filament –> **dissipation** of the kinetic energy

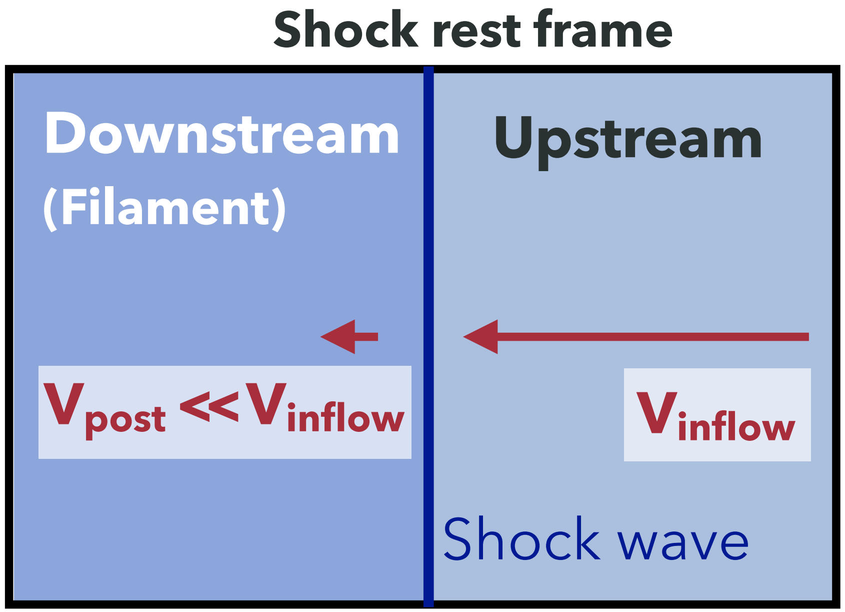
Non-thermal pressure is necessary to keep the filament width.

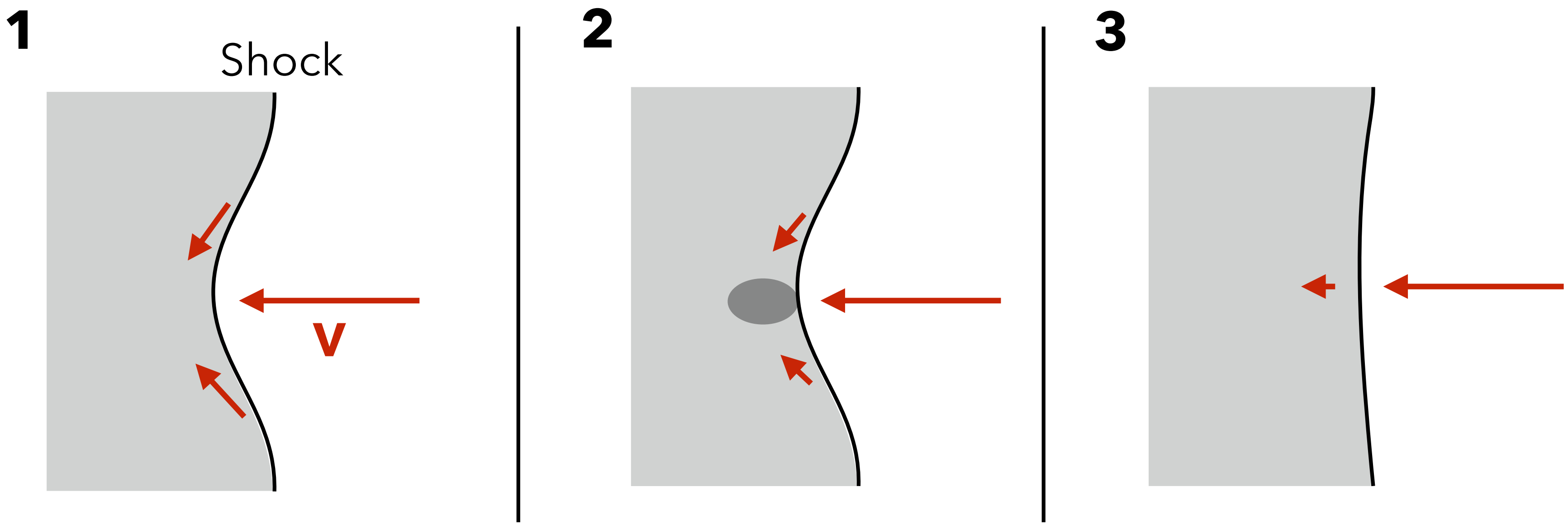
$$M_{\rm line,crit} = 2c_{\rm s}^2/G \ \rightarrow 2(c_{\rm s}^2 + \sigma_{\rm NT}^2)/G$$

Non-thermal velocity dispersion

Remarks: Stability of Shock Fronts

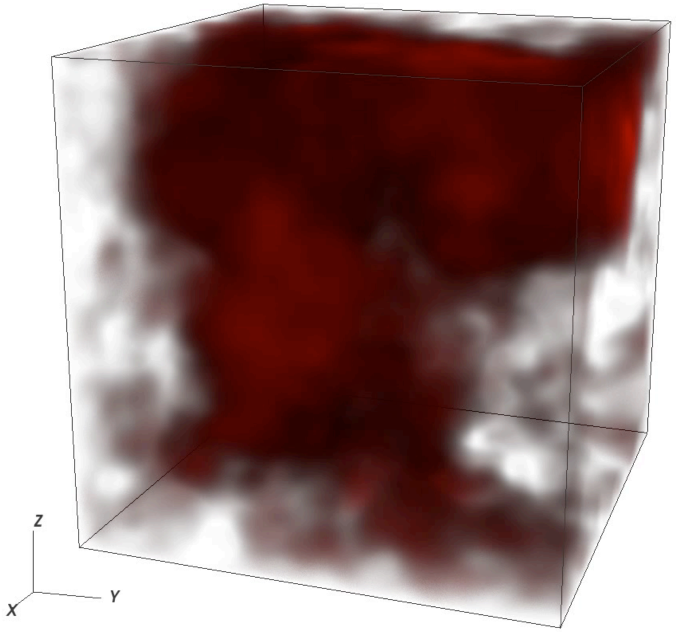


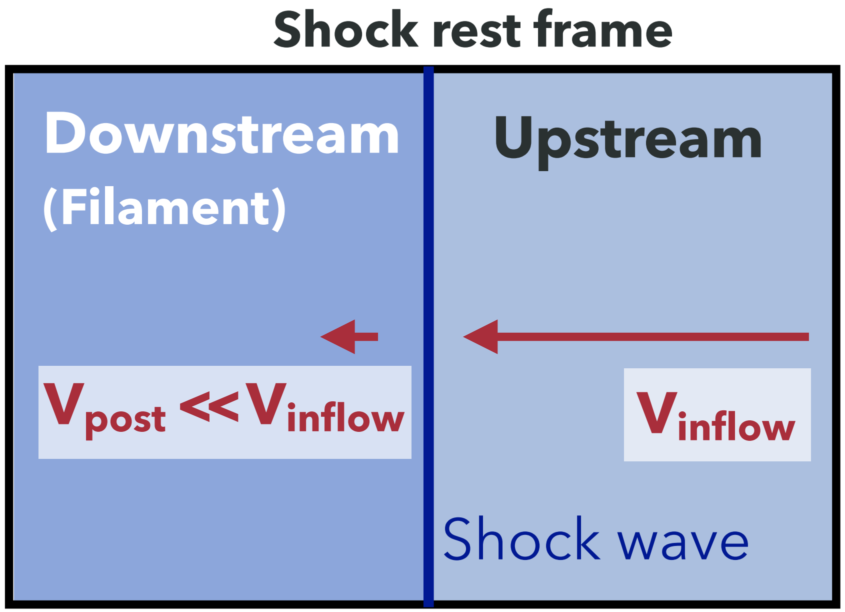


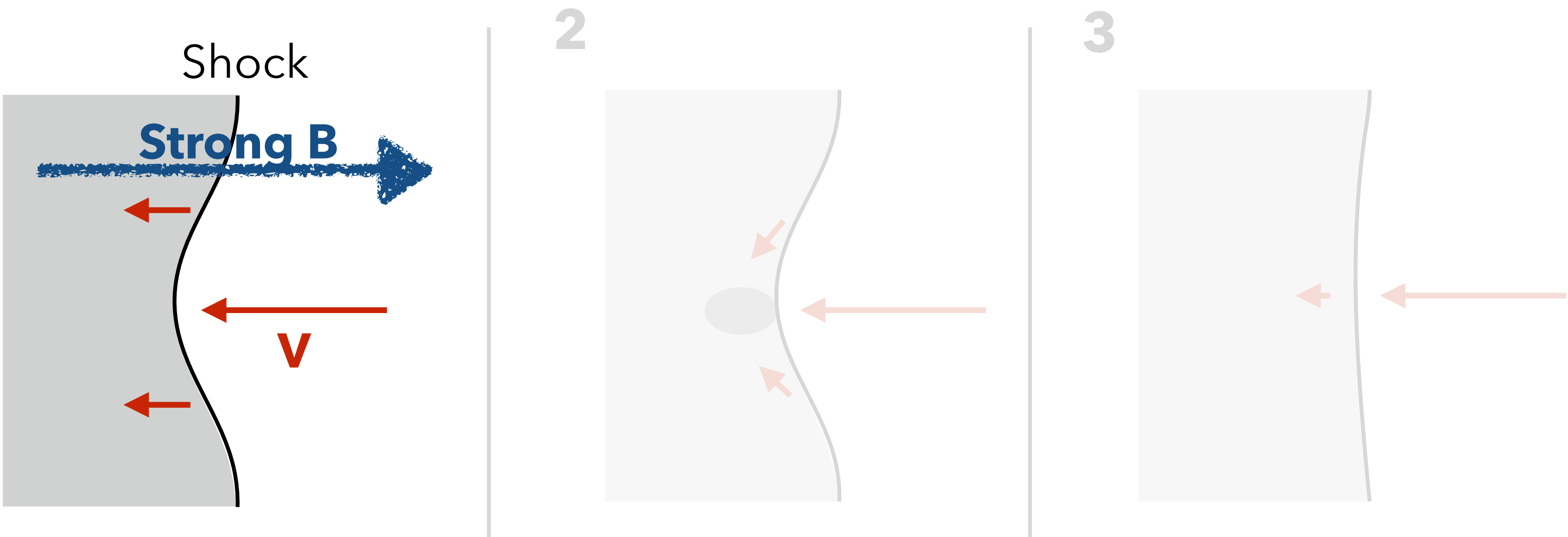


(Usual) Shock fronts are stable to perturbations in their shape.

Brief Explanation of Slow-shock Instability



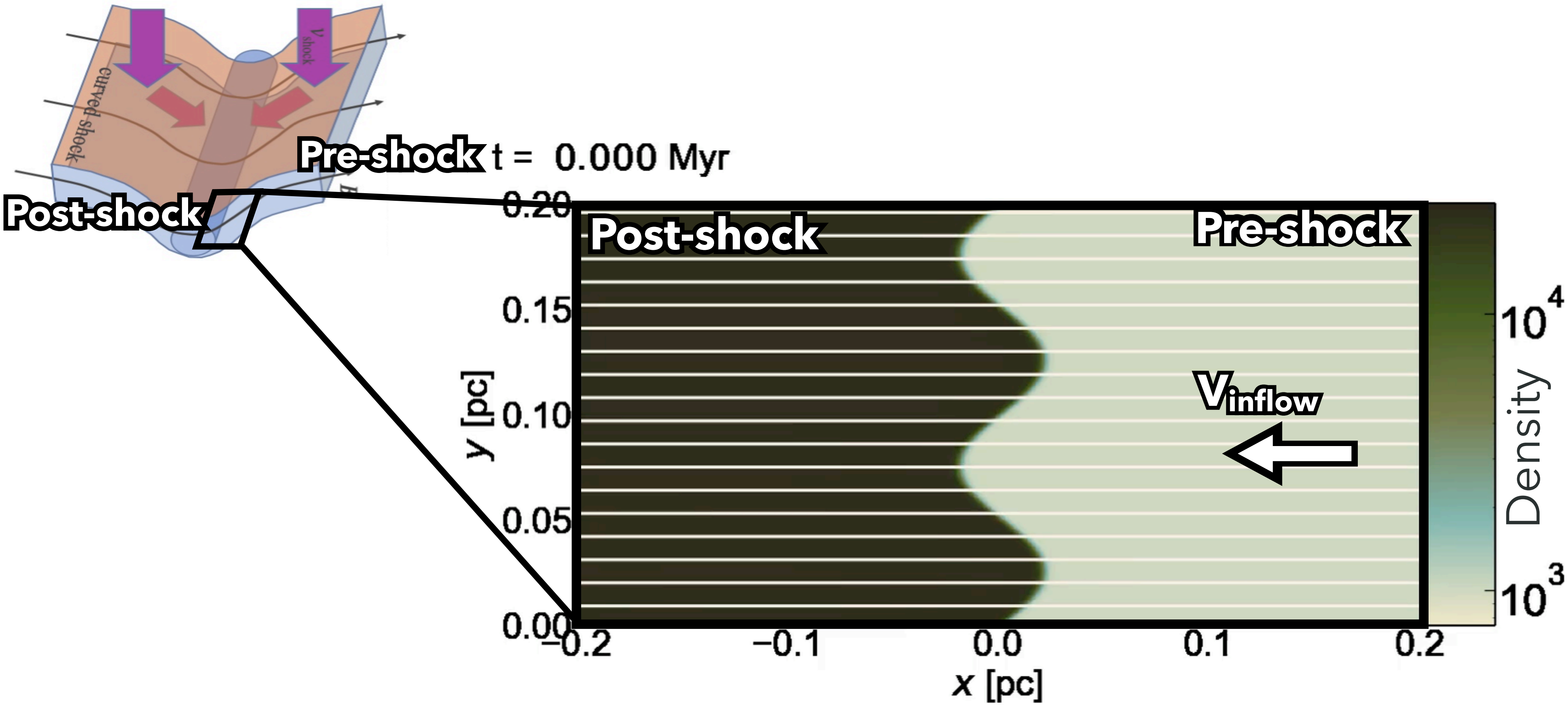




Accurate mechanism is different but brief understanding is OK with this.

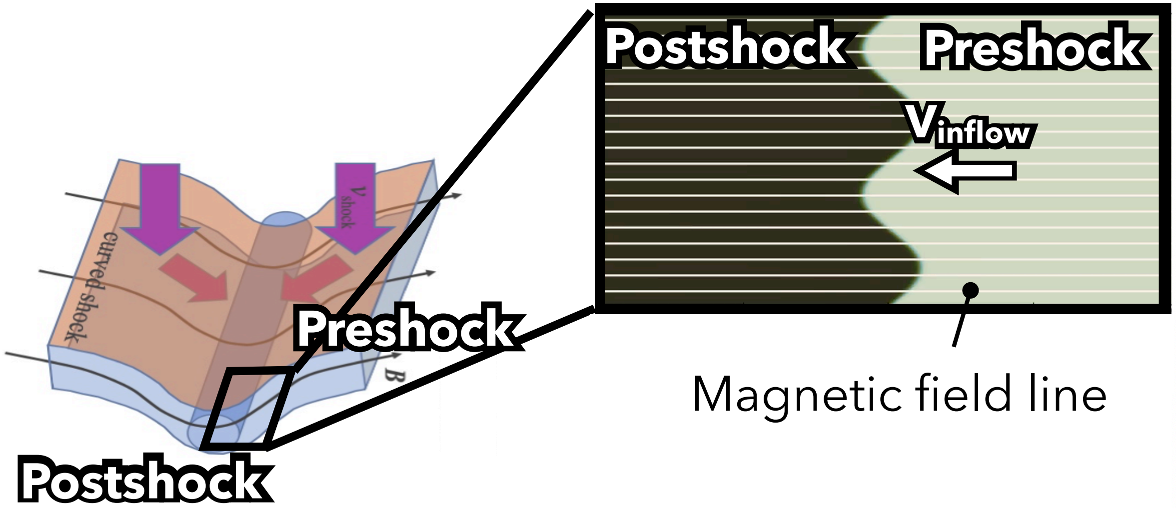
Key Process: Instability at Filament Boundaries

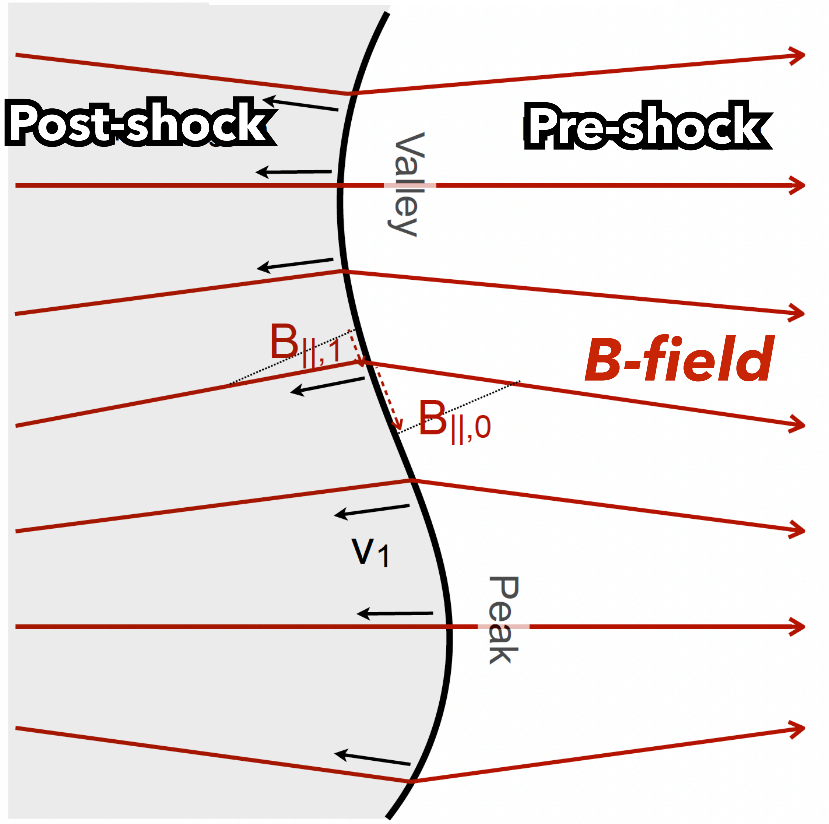
Slow-shock Instability (SSI) (e.g., Lesson & Deshpande 1967)



Linear Growth of the SSI

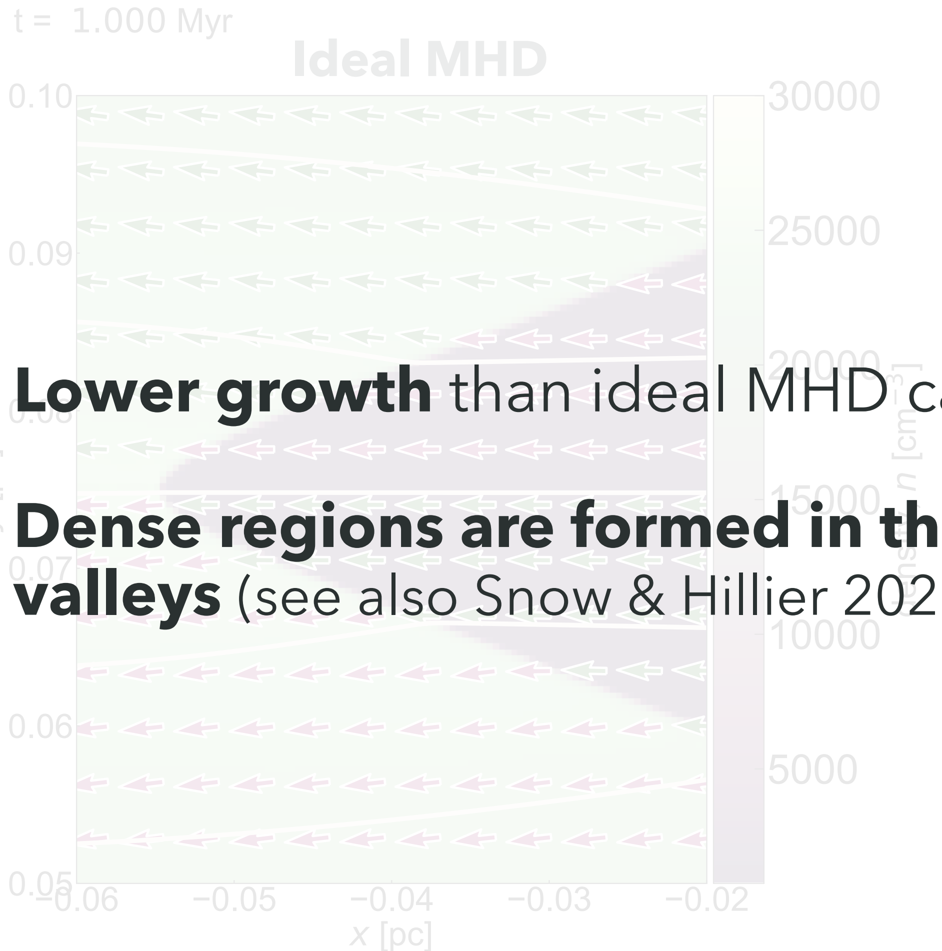
Slow-shock Instability (SSI) (e.g., Lesson & Deshpande 1967)



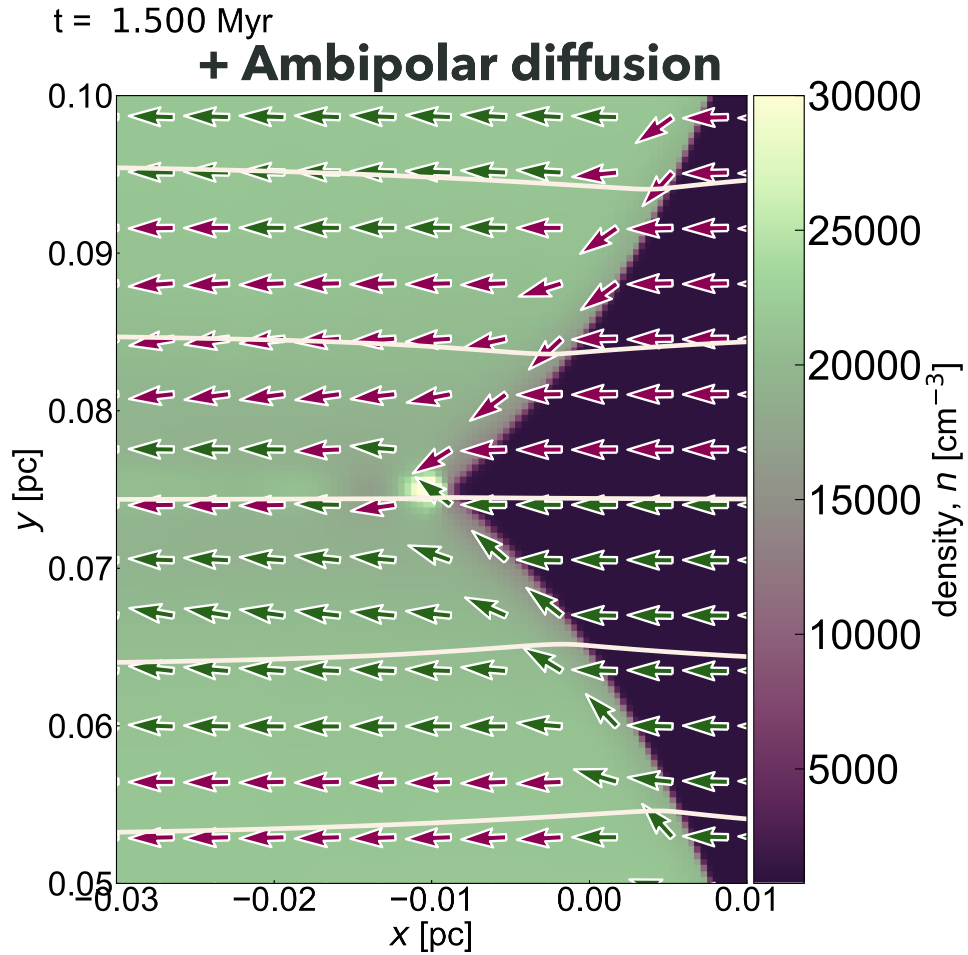


$B_{||}$ becomes small

Nonlinear evolution of SSI + ambipolar diffusion

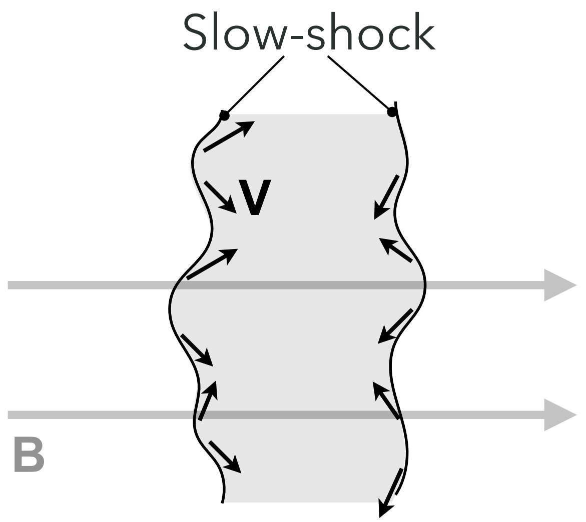


- **Lower growth** than ideal MHD case
- **Dense regions are formed in the valleys** (see also Snow & Hillier 2022)

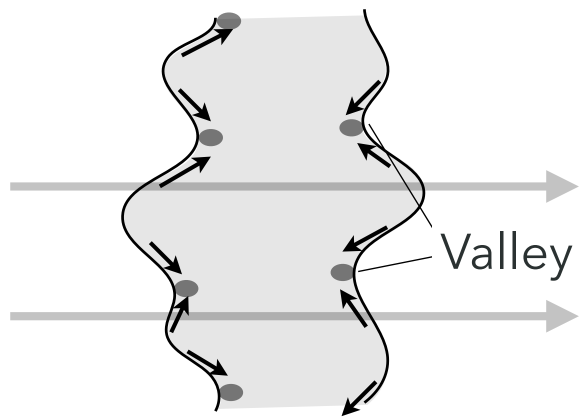


The Origin of Additional Pressure: ``STORM"

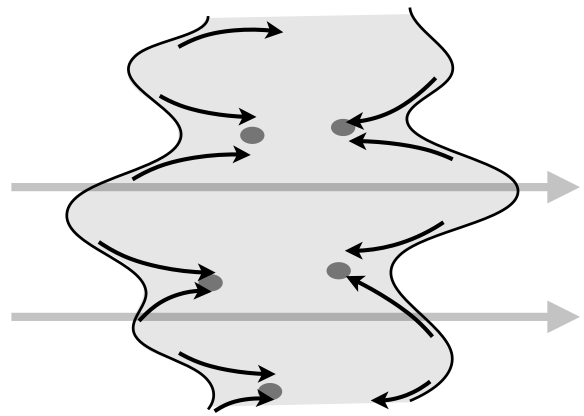
STORM (**S**low-shock-mediated **T**urbulent fl**O**w **R**einforced by **M**agnetic diffusion)



1. AD permits **flow across the magnetic field** lines



2. Gas accumulates in the valleys

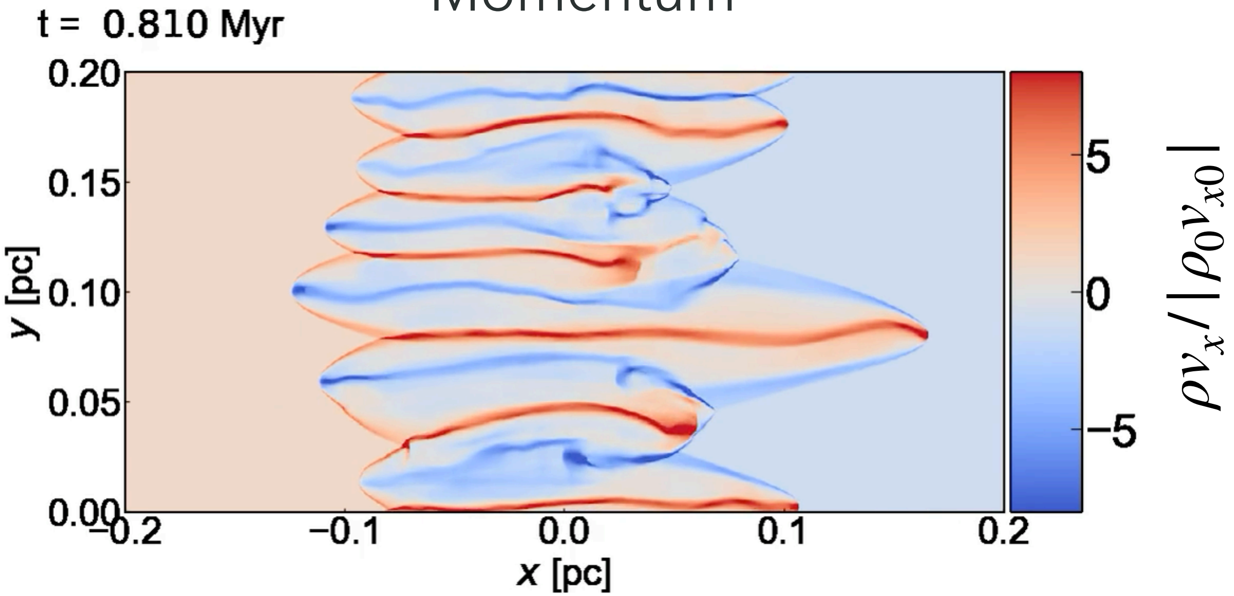


3. **Momentum injection** induces expansion of the shock-bound region

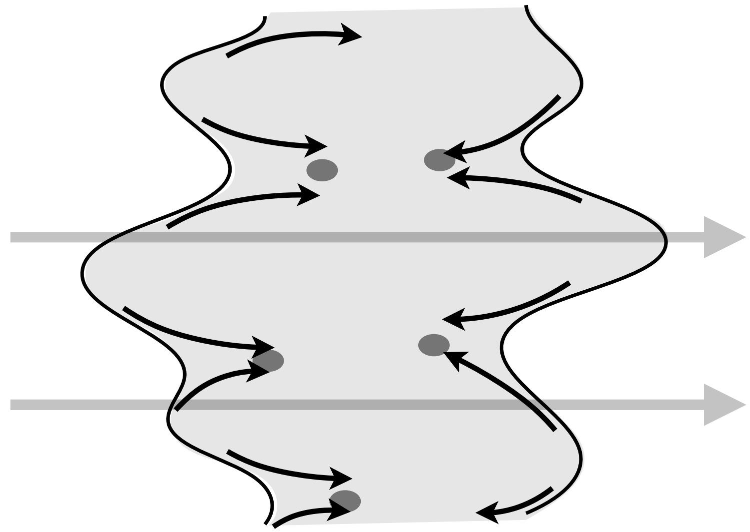
The corrugation of shock fronts continues to grow under the effect SSI.

The Origin of Additional Pressure: ``STORM"

Momentum



The blobs stir the filament gas like ``hailstorm".

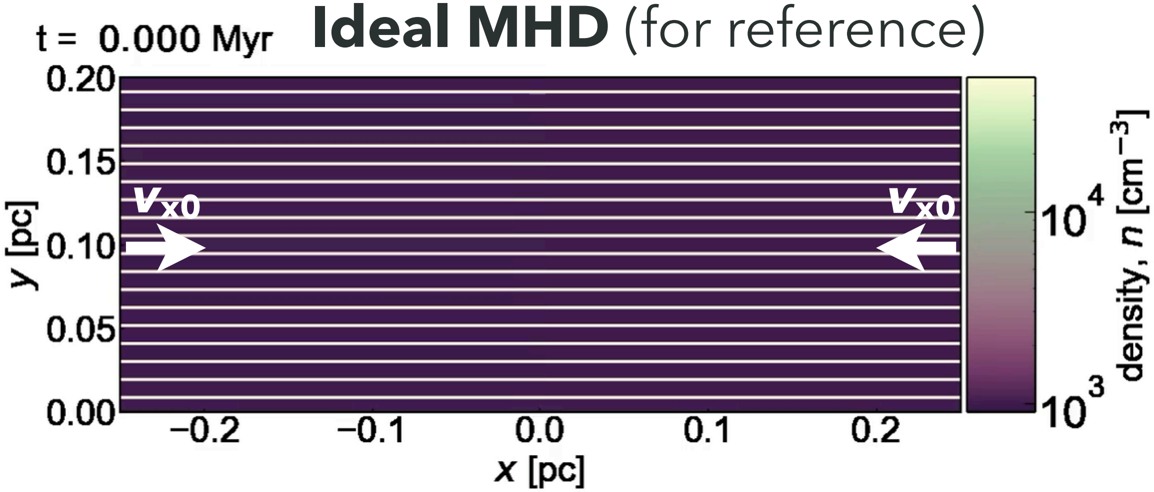


***``STORM"* provides ram pressure** to increase filament width

Result: Simulation of Filament Evolution with Ambipolar Diffusion

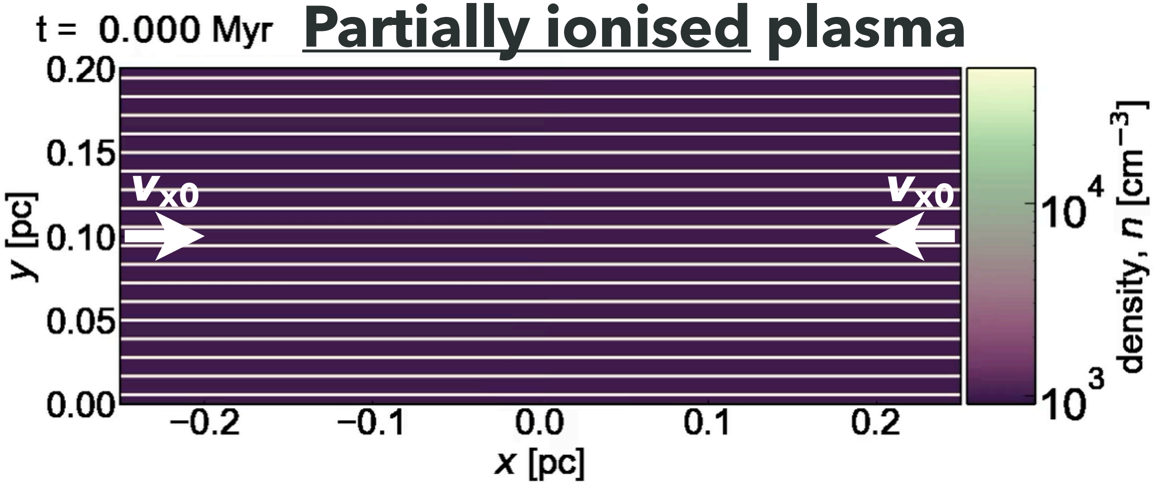
Evolution of density field

Ideal MHD (for reference)



- SSI causes shock front corrugation.
- **No turbulence**

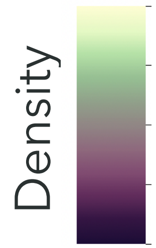
Partially ionised plasma



More turbulent than in ideal MHD

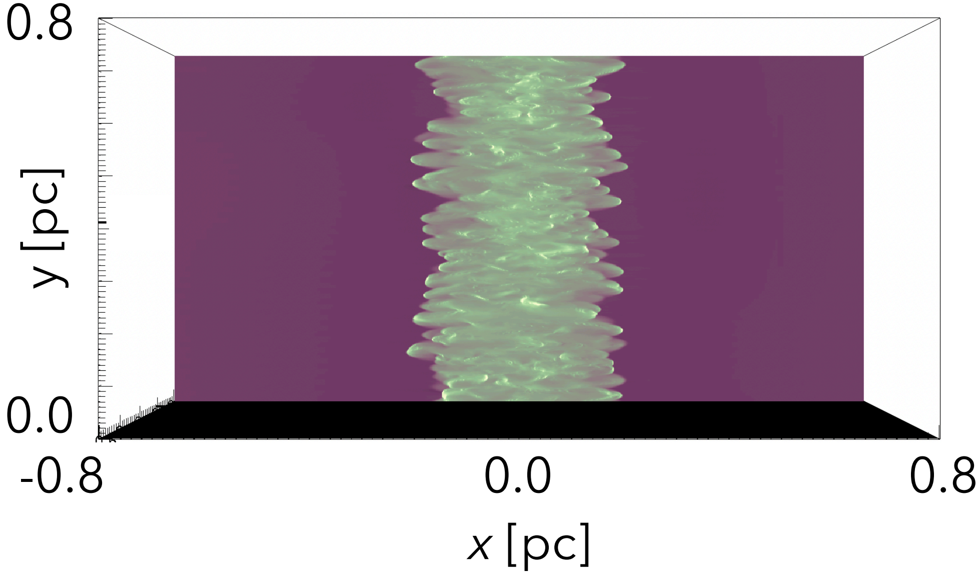
Importance of Resolution

Density Slice



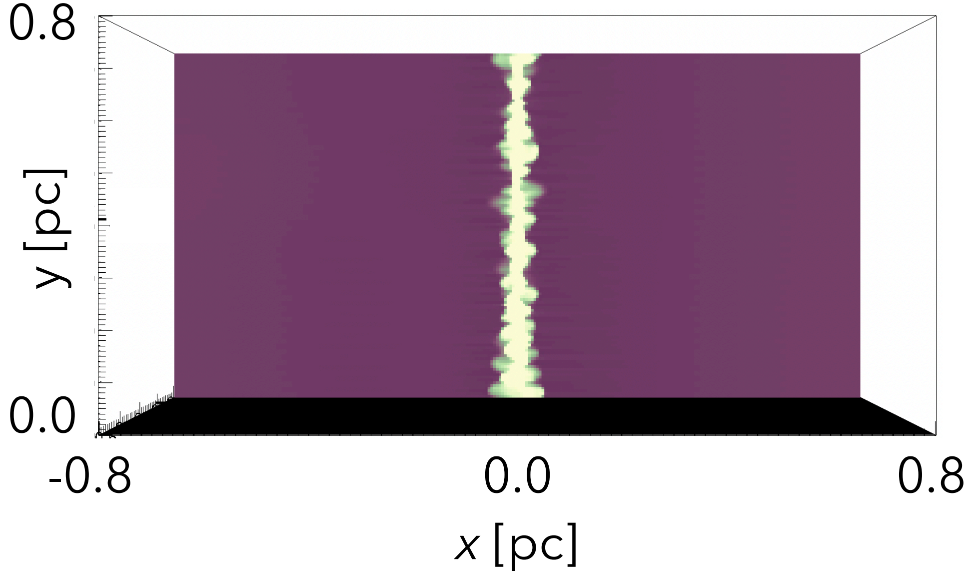
High resolution

Finest resolution: $\Delta x \sim 1.5 \times 10^{-3}$ pc



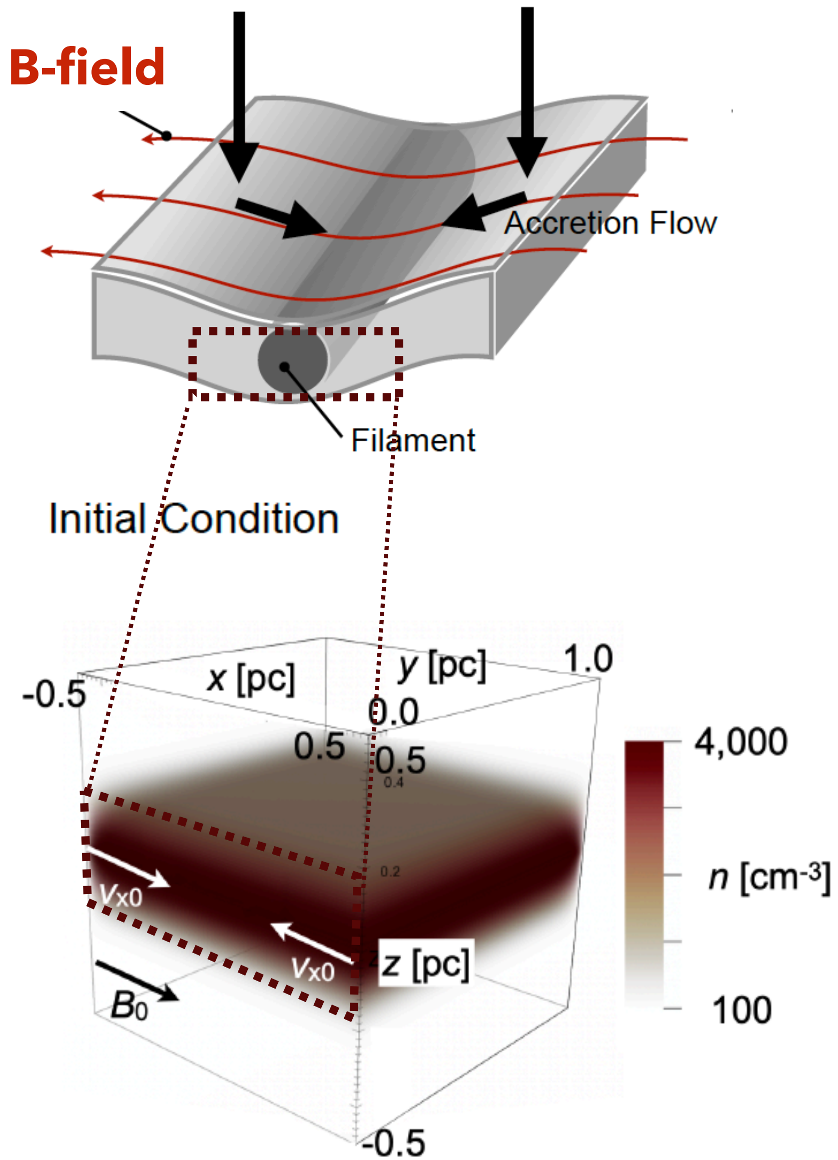
Low resolution

$\Delta x \sim 6.2 \times 10^{-3}$ pc

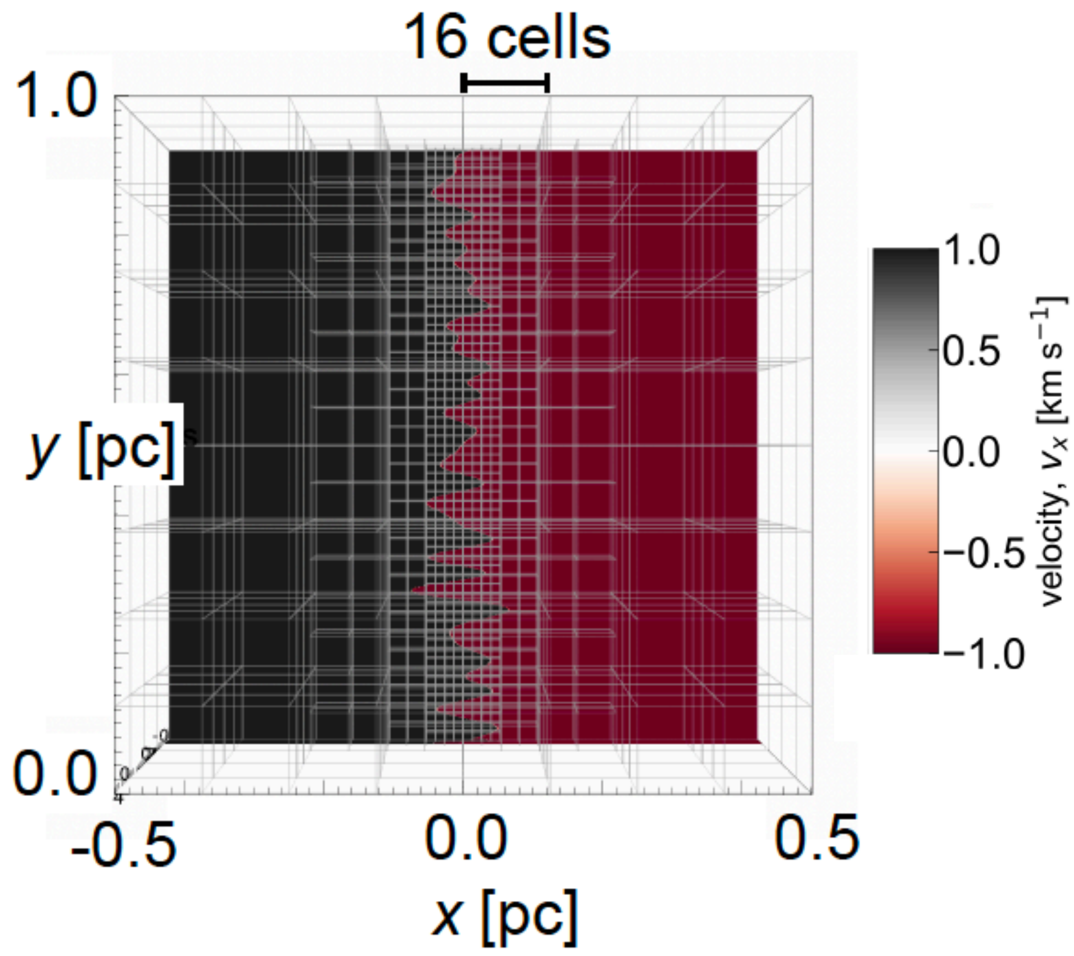


We need high resolution
to appropriately solve the filament evolution

Setup for 3D Simulation



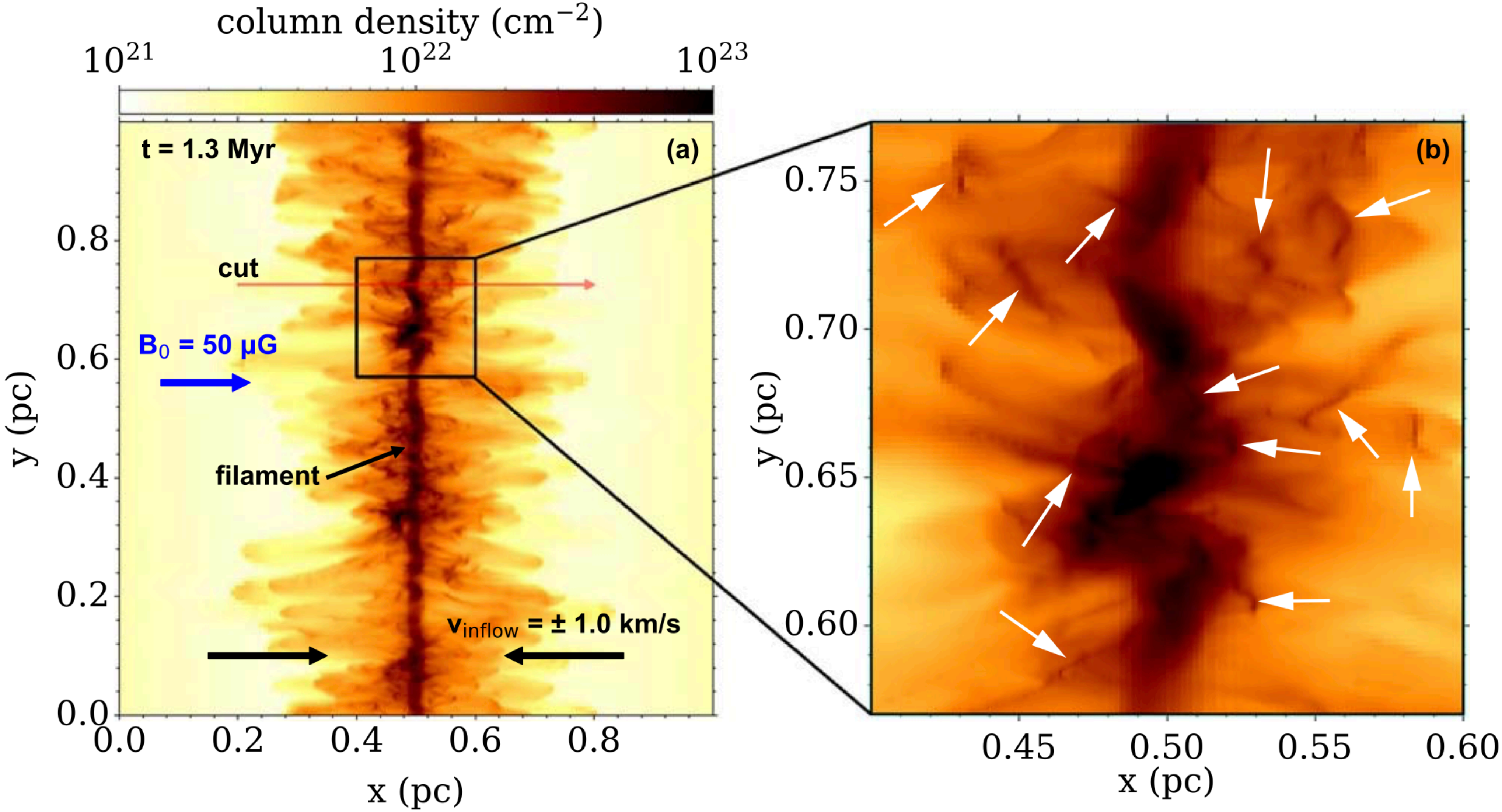
Velocity and grid structure



Use hierarchical grids

Finest resolution: ~0.001 pc

Internal 1000 au Scale Structures of the R CrA Cluster-forming Cloud



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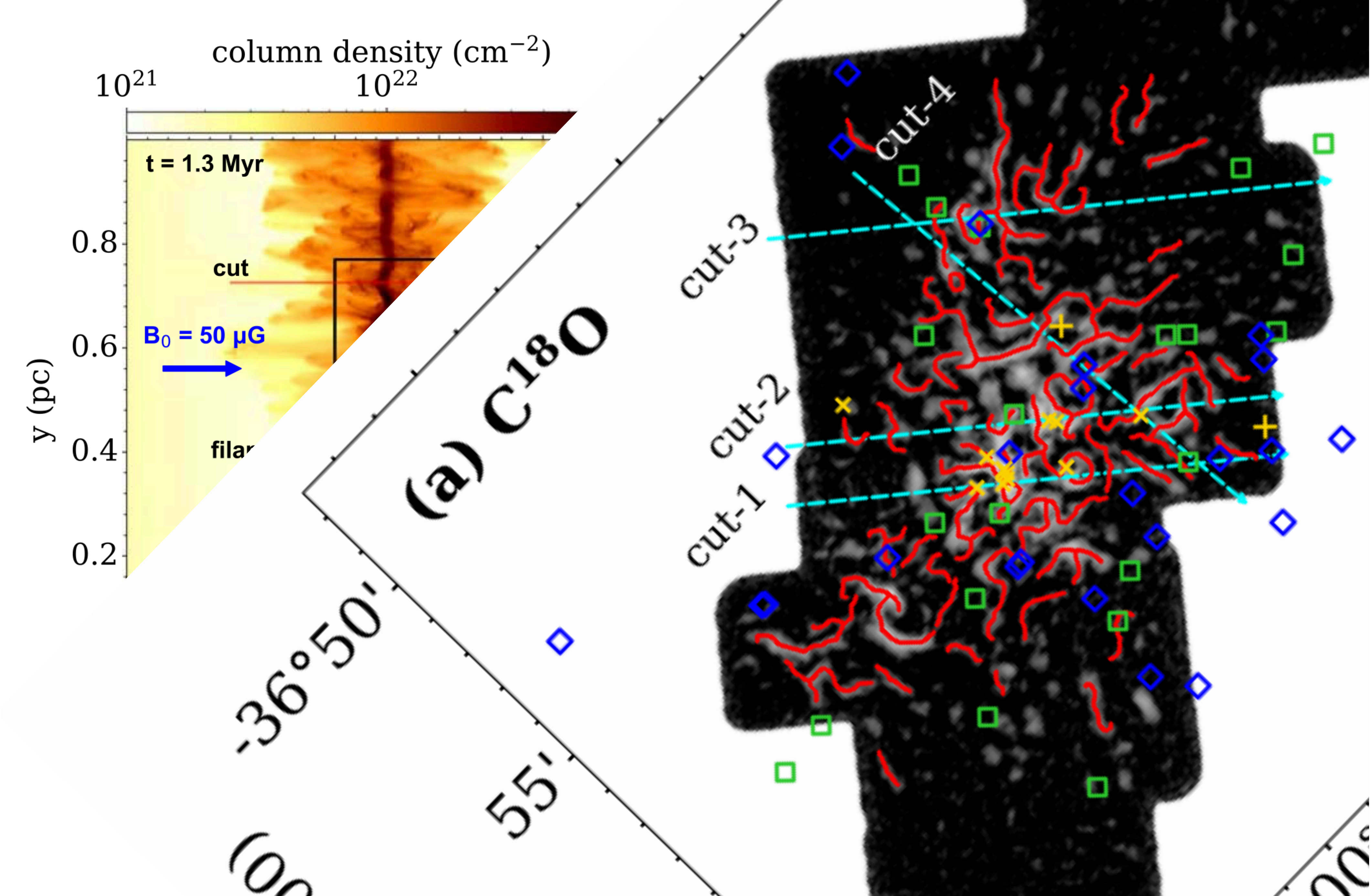
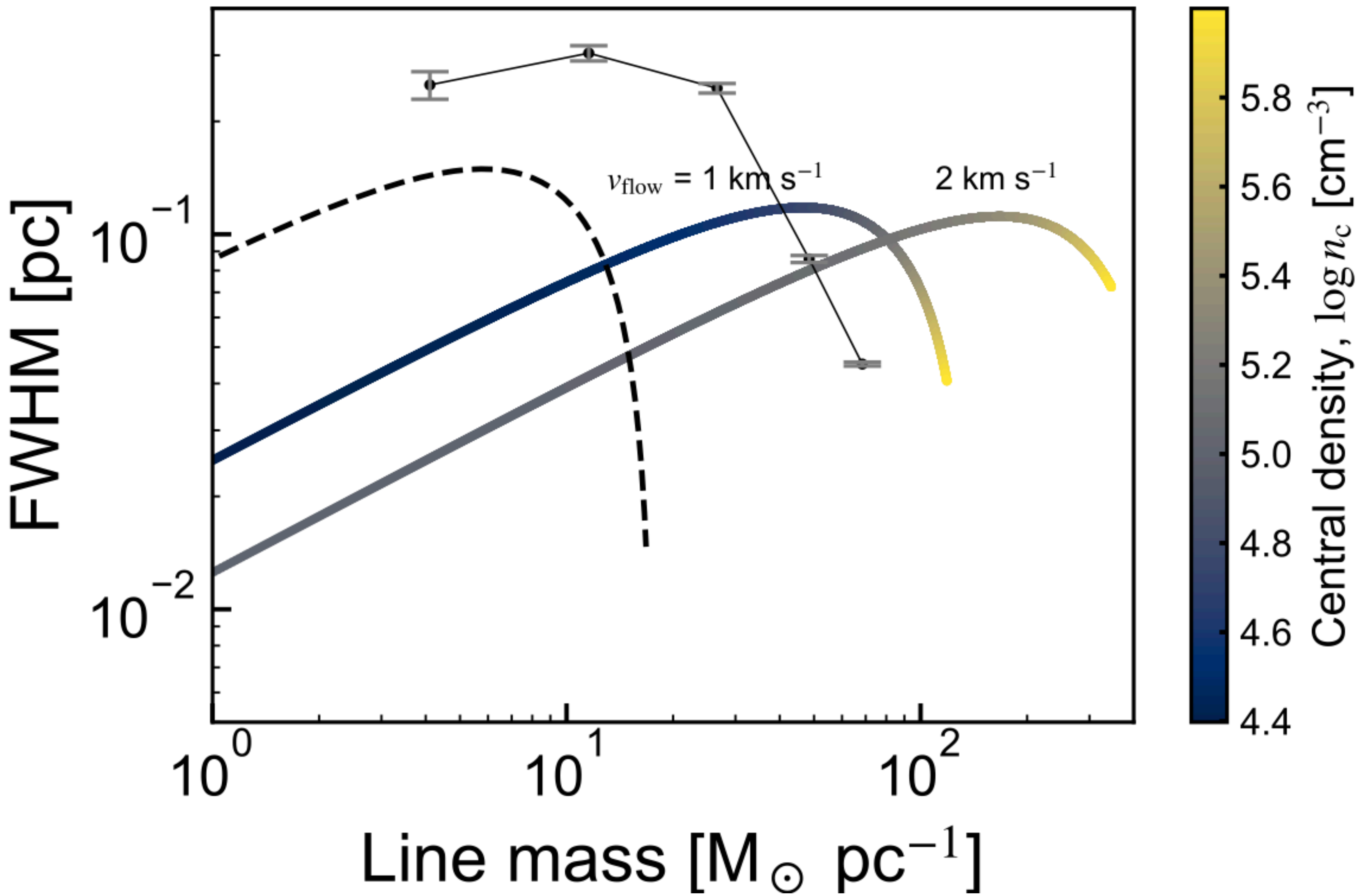
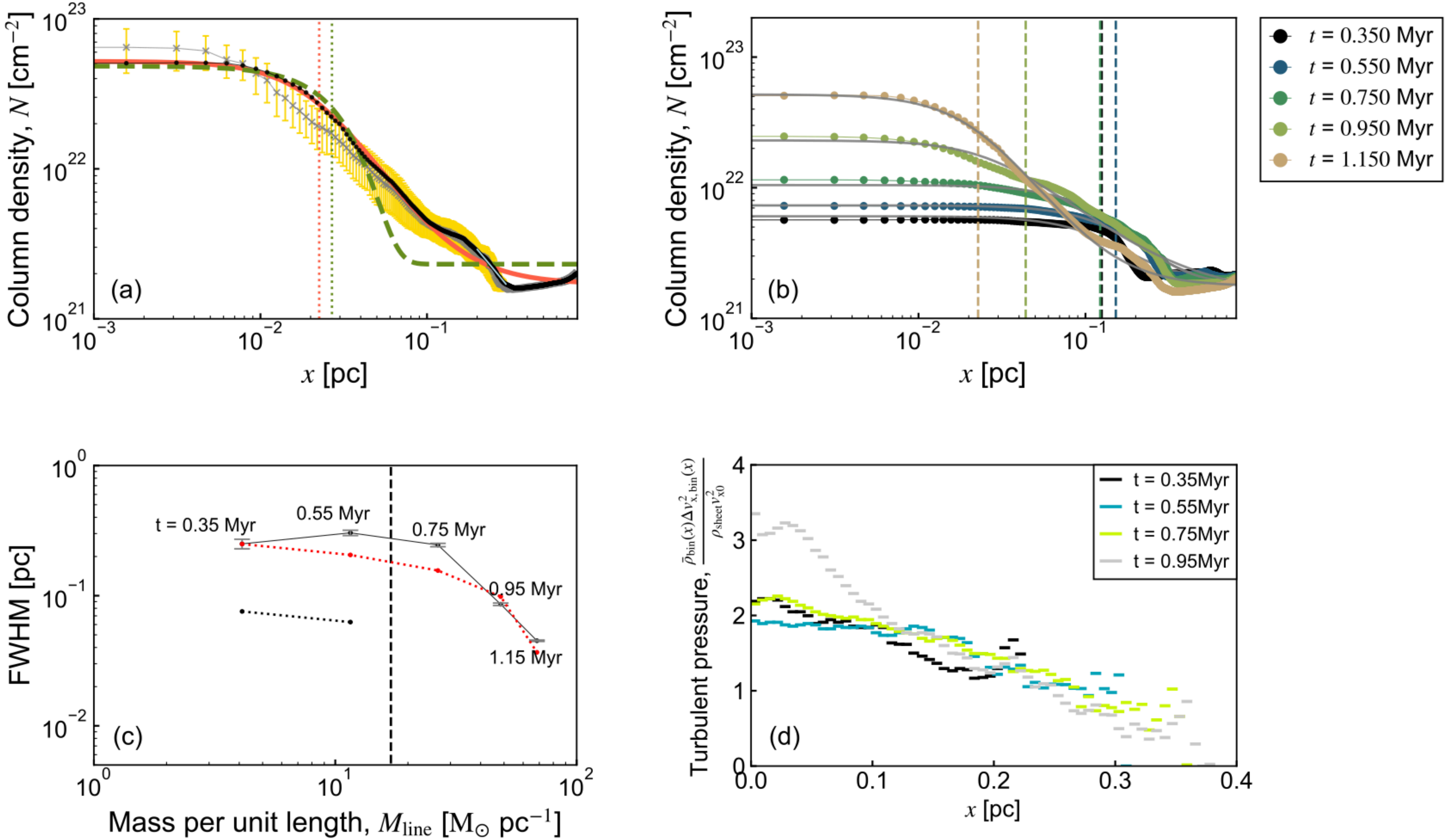


Analytic Model considering the STORM mechanism



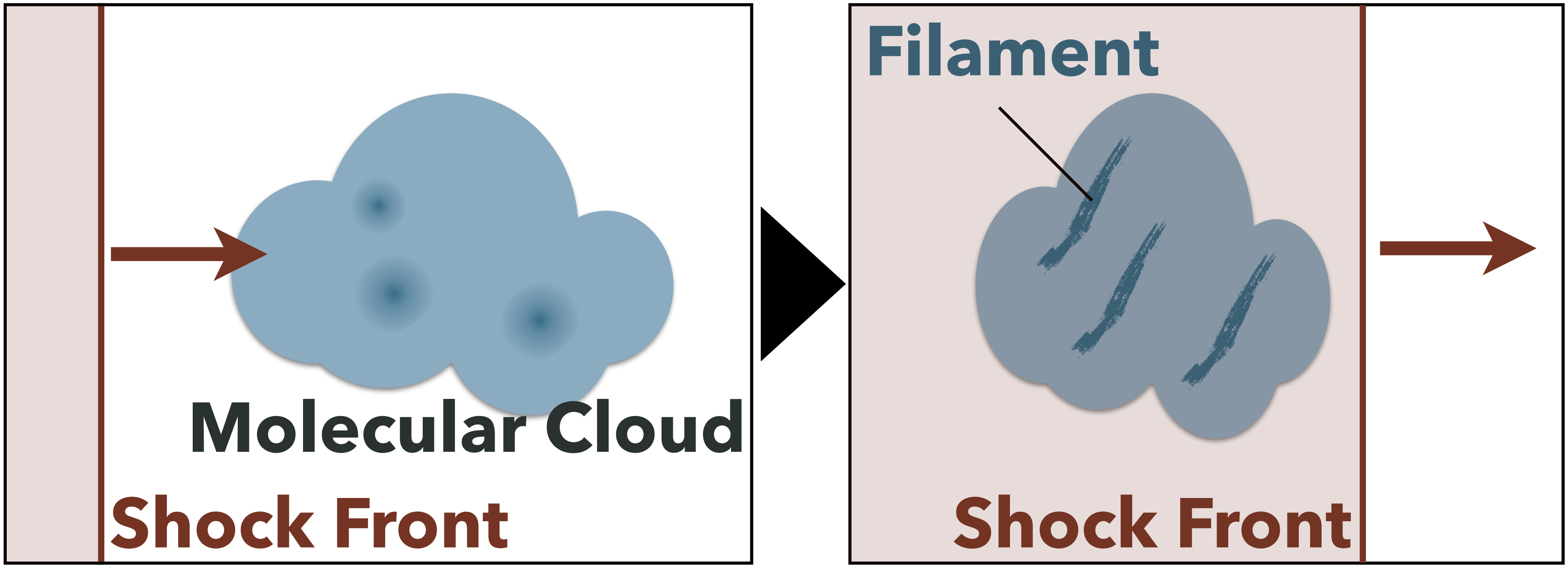
Properties of the STORM filament



Trigger of Filament Formation

Molecular clouds are **frequently** (~1 Myr^{-1}) swept by **shock waves.**

(ex. Super Novae, Cloud-cloud Collision, Expansion of HII regions etc.)

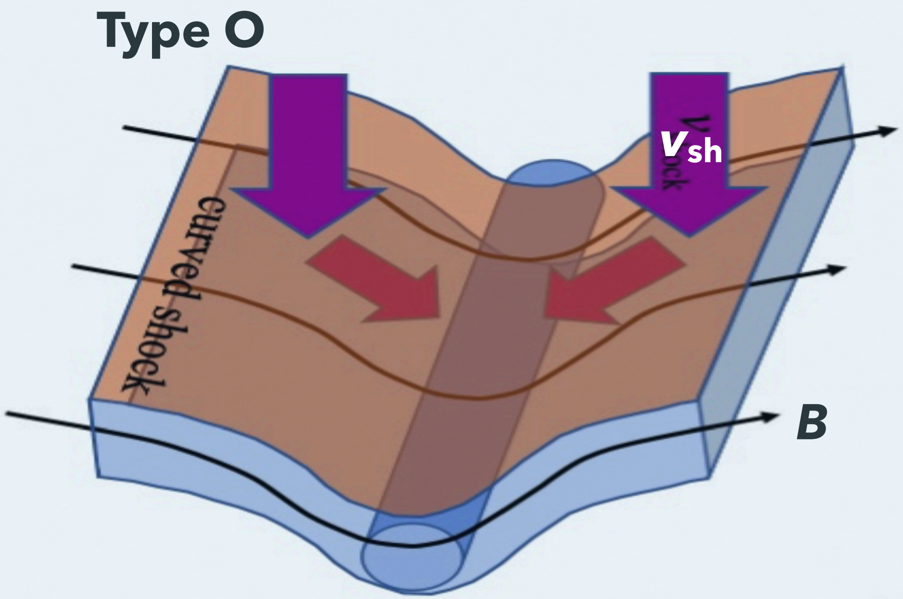


Shock waves trigger **filament formation**.

Formation Mechanisms of Filaments

Main filament formation mechanisms

- Type G: Gravitational fragmentation of shocked sheet
  (e.g., Nagai+ 1998)
- Type C: Compressive component of turbulent flow
  (e.g., Matsumoto+ 2015)
- **Type O**: Oblique MHD shock induced flow
  (Inoue & Fukui 2013)

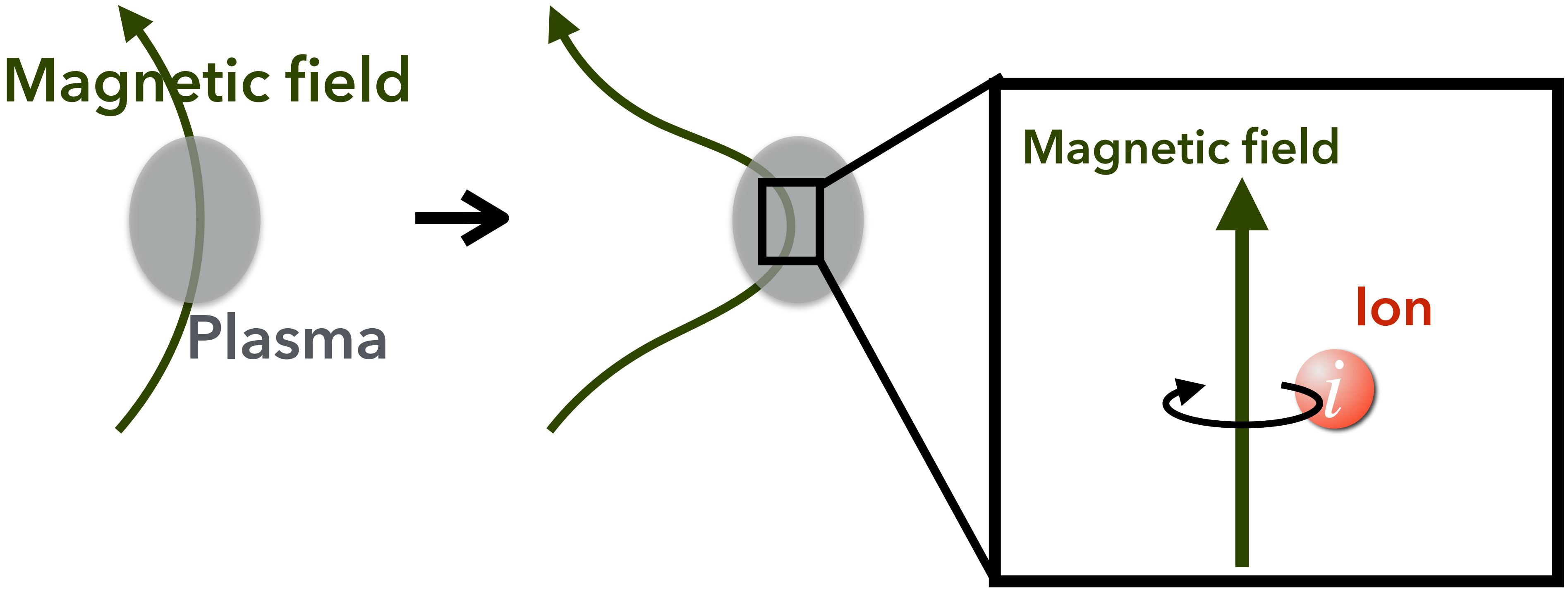


Abe+2021,
see also PPVII review (Pineda+ 2023)

Filament formation is well understood!

(Abe, Inoue, Inutsuka & Matsumoto 2021)

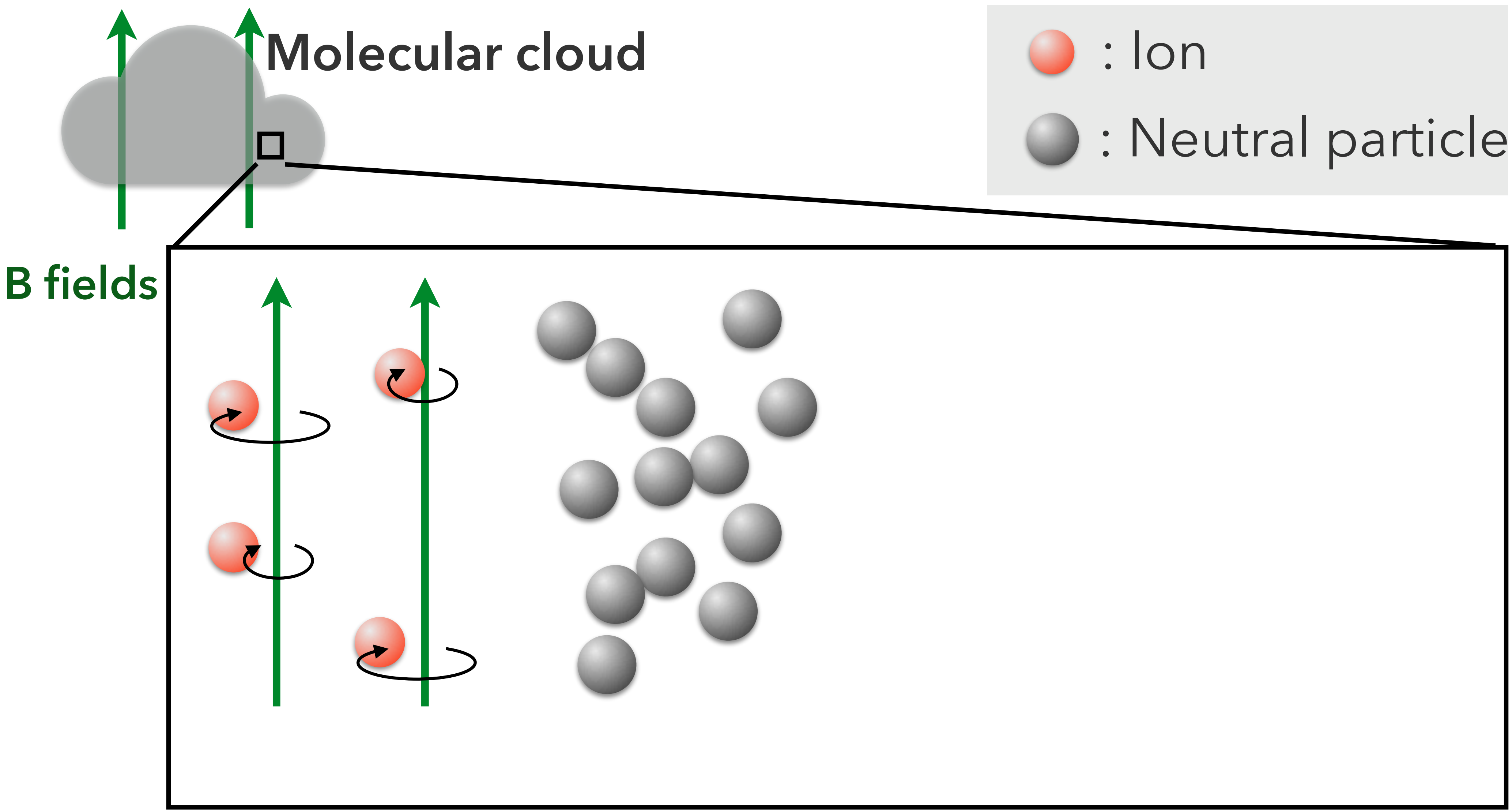
Properties of Magneto-Hydro Dynamics (MHD)



- Plasma can move easily along magnetic fields.
- Plasma drags magnetic field
- Plasma cannot move across magnetic fields.

"Magnetic frozen-in"

MHD Approximation for Molecular Clouds Dynamics



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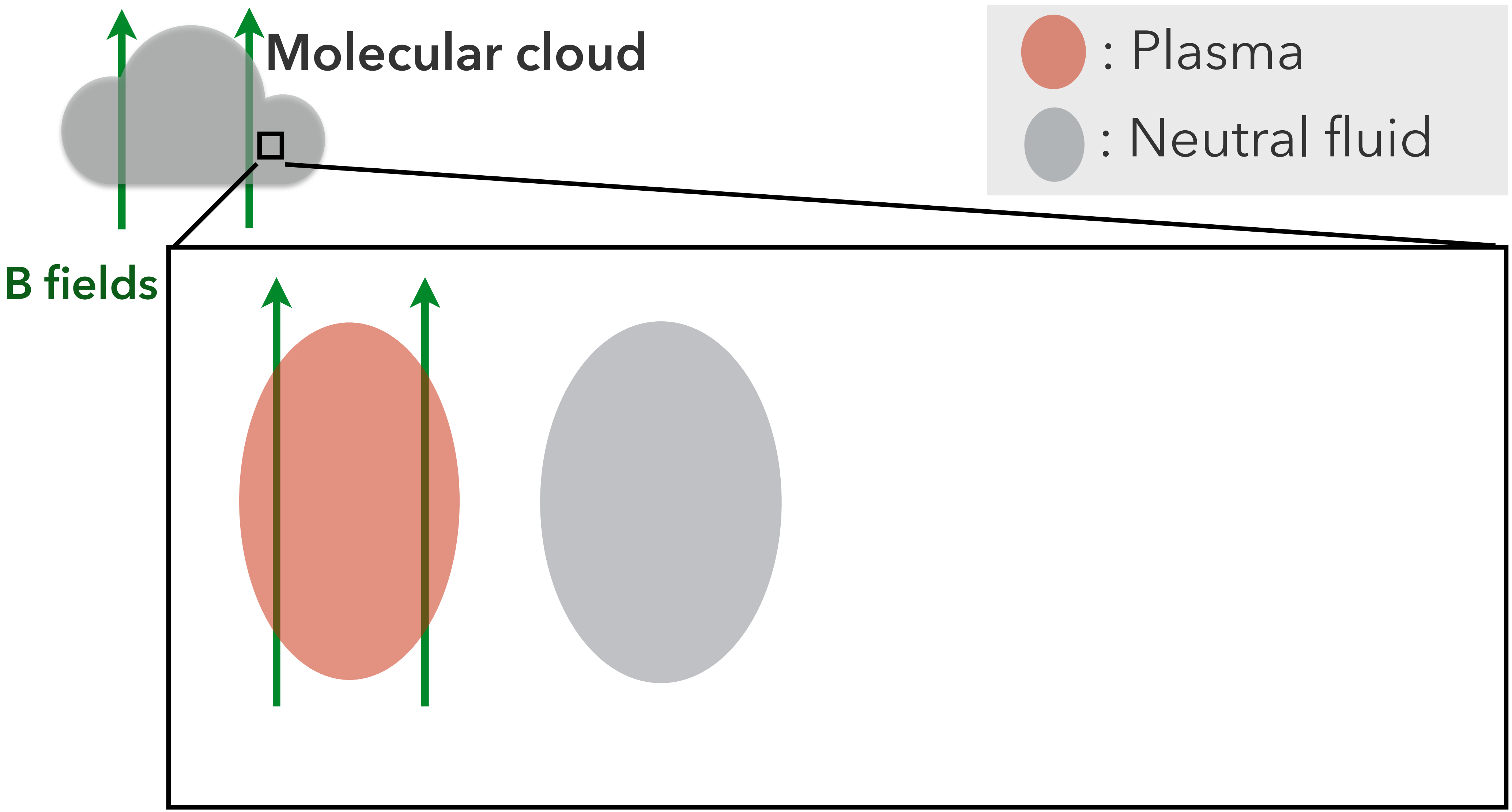

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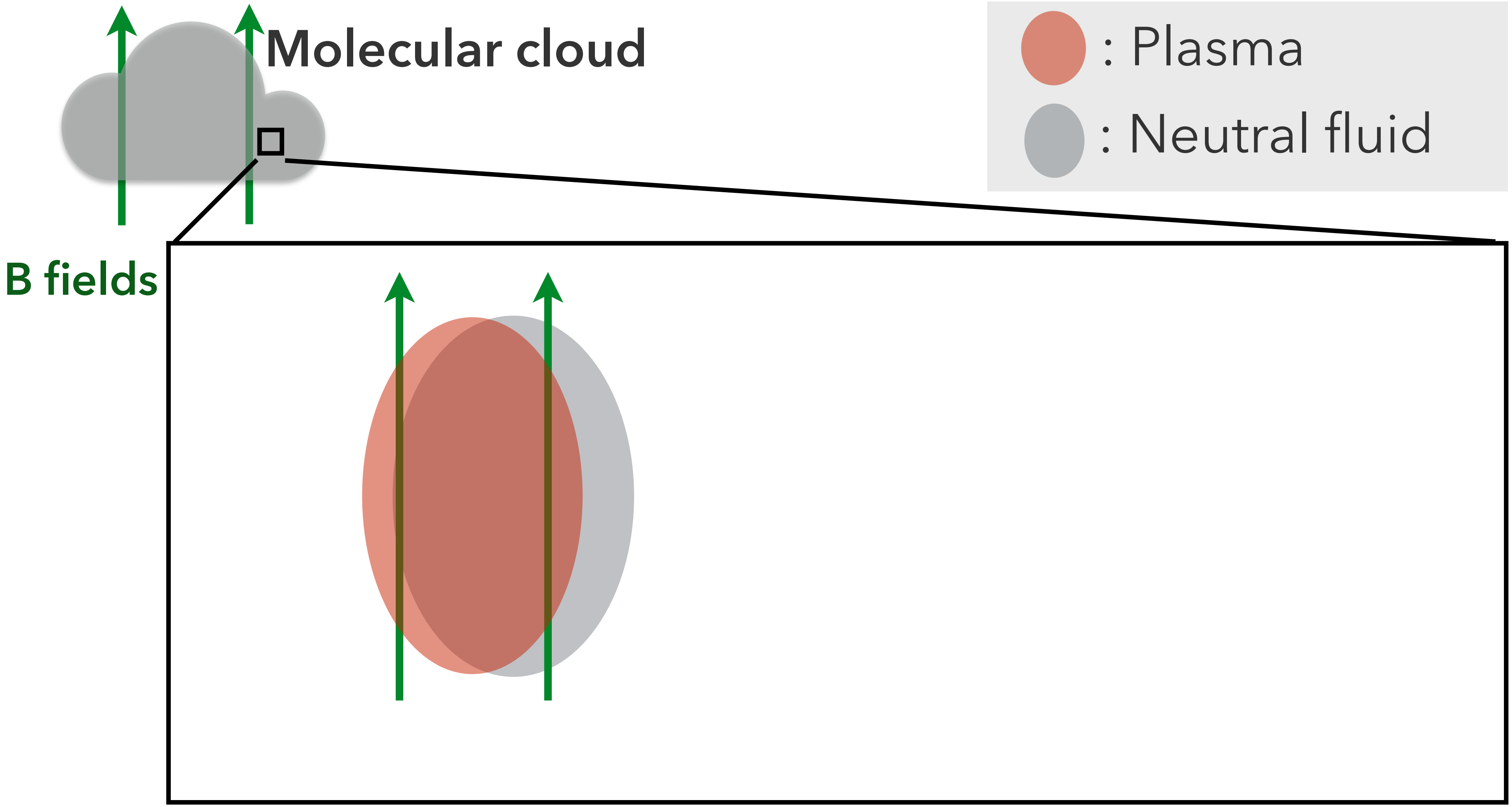
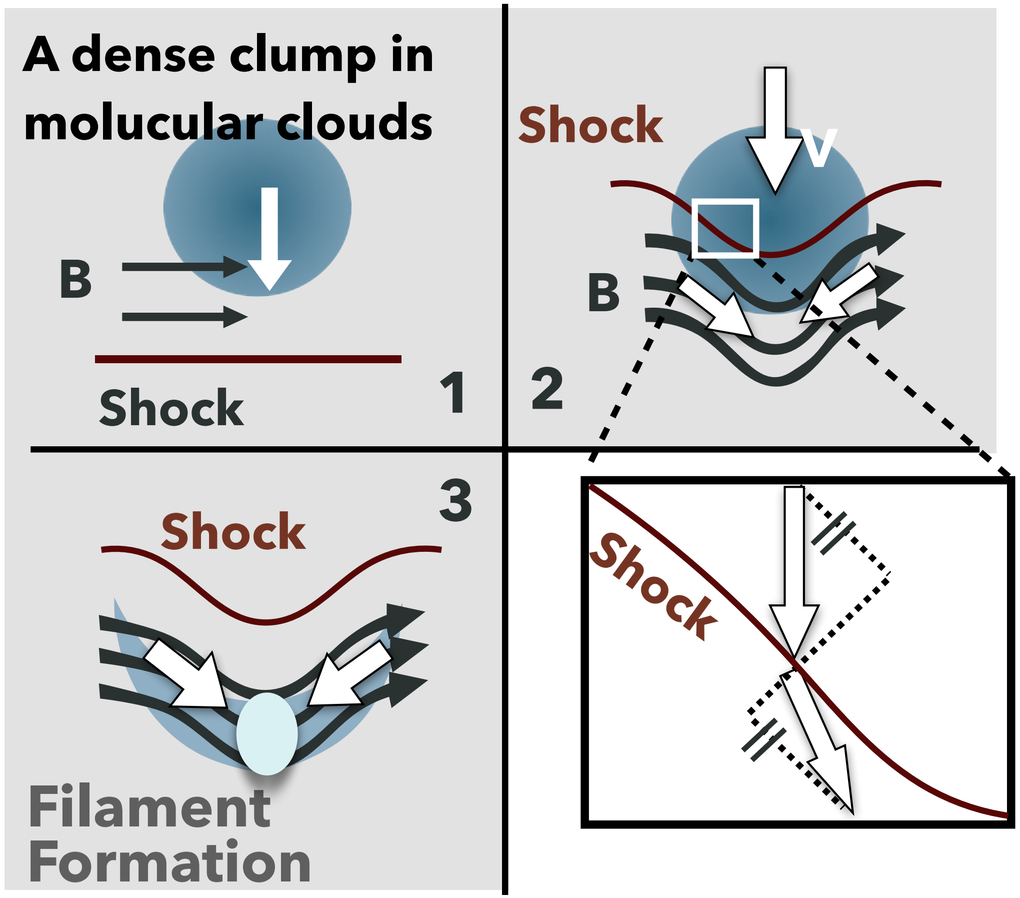
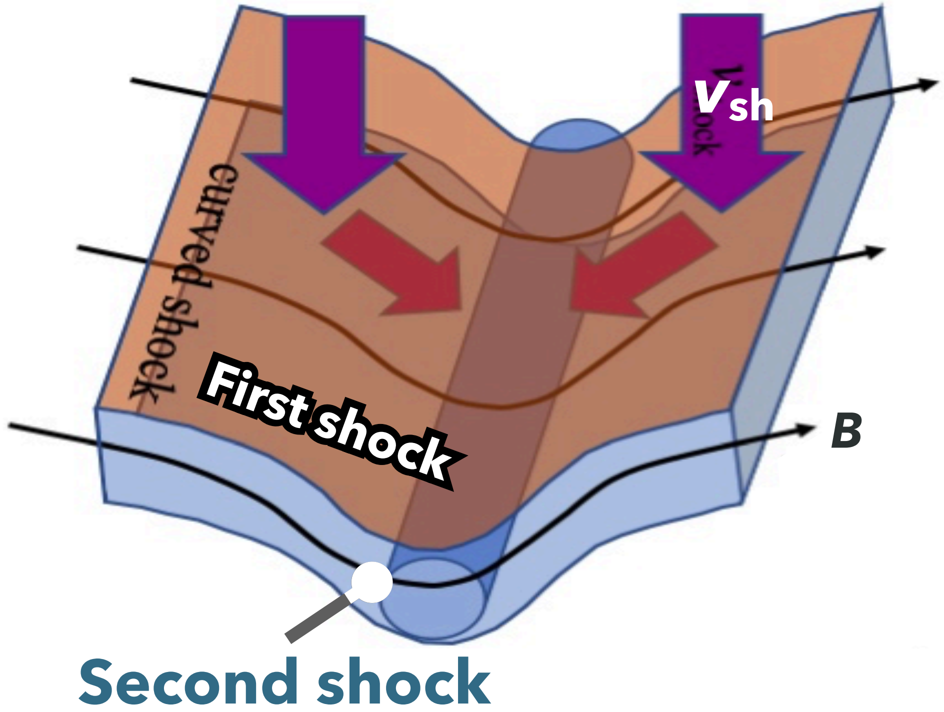


The dynamics of molecular clouds can be described as MHD.

An example of filament formation mechanism (Type O)

Interstellar shock wave with velocity of $\gtrsim$ 5 km/s –> Type O
(Abe+ 2021)





Two stages of compression –> Filament formation

Importance of Filament Width

Condition of Star Formation

Statement in the Filament Paradigm

Stars form in filaments above **critical line mass**
(e.g., André+2010)

Which is correct?

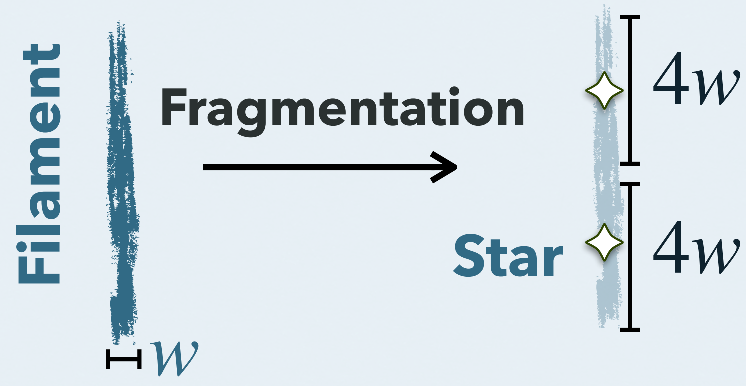
Statement by Lada et al.

There is a threshold column density **(~10^{22} cm^{-2})** for star formation to occur.
(e.g., Lada+2010)

Core Mass

(The most unstable mode of self-gravitational fragmentation) ~ (Filament width).
(Inutsuka & Miyama 1997)

–> The width determines core mass



Physical origin of 0.1 pc width should be clarified

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Stars form in filaments
above **critical line mass**
(e.g., André+2010)

Critical line mass & **Width**

$2c_s^2/G$ & $0.1\ \mathrm{pc}$

–> Column density

$$N \sim 10^{22}\ \mathrm{cm}^{-2}$$

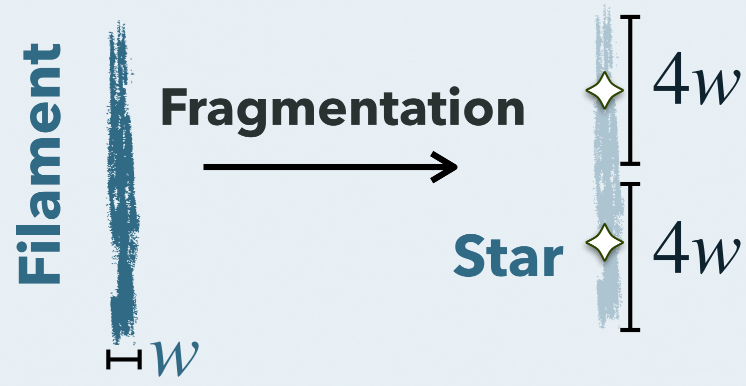
Statement by Lada et al.

There is a threshold column density **(~10^{22} cm^{-2})** for star formation to occur.
(e.g., Lada+2010)

Core Mass

(The most unstable mode of self-gravitational fragmentation)
~ (Filament width).
(Inutsuka & Miyama 1997)

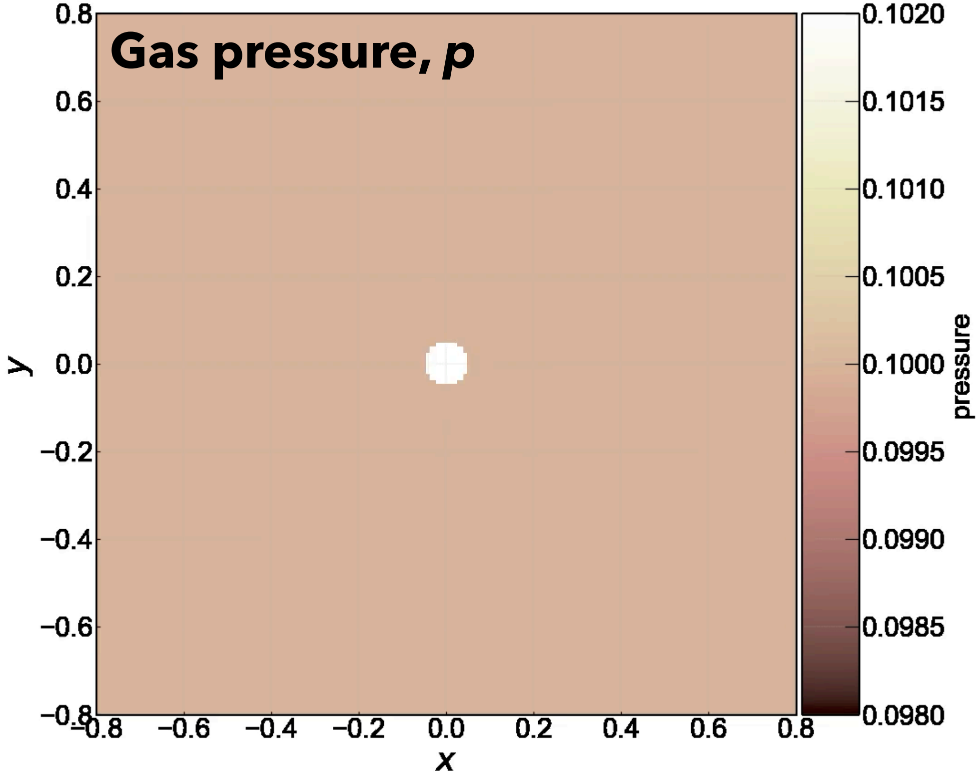
–> The width determines core mass



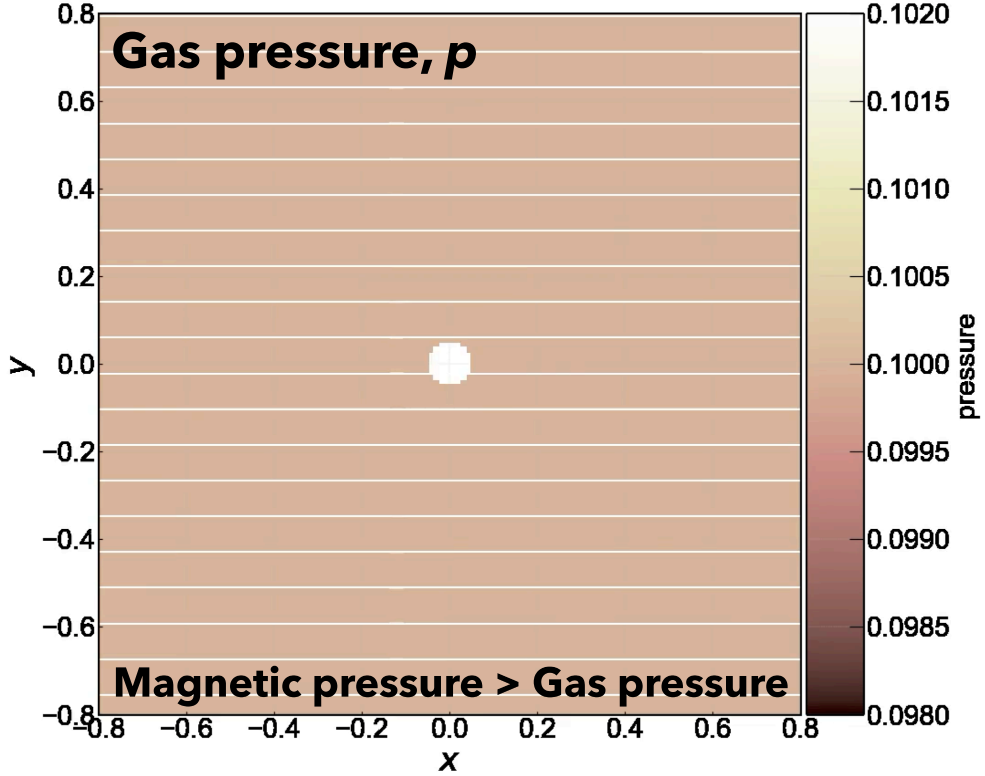
Physical origin of 0.1 pc width should be clarified

Remarks: Slow-mode (Slow Wave)

Ripple in unmagnetized fluid

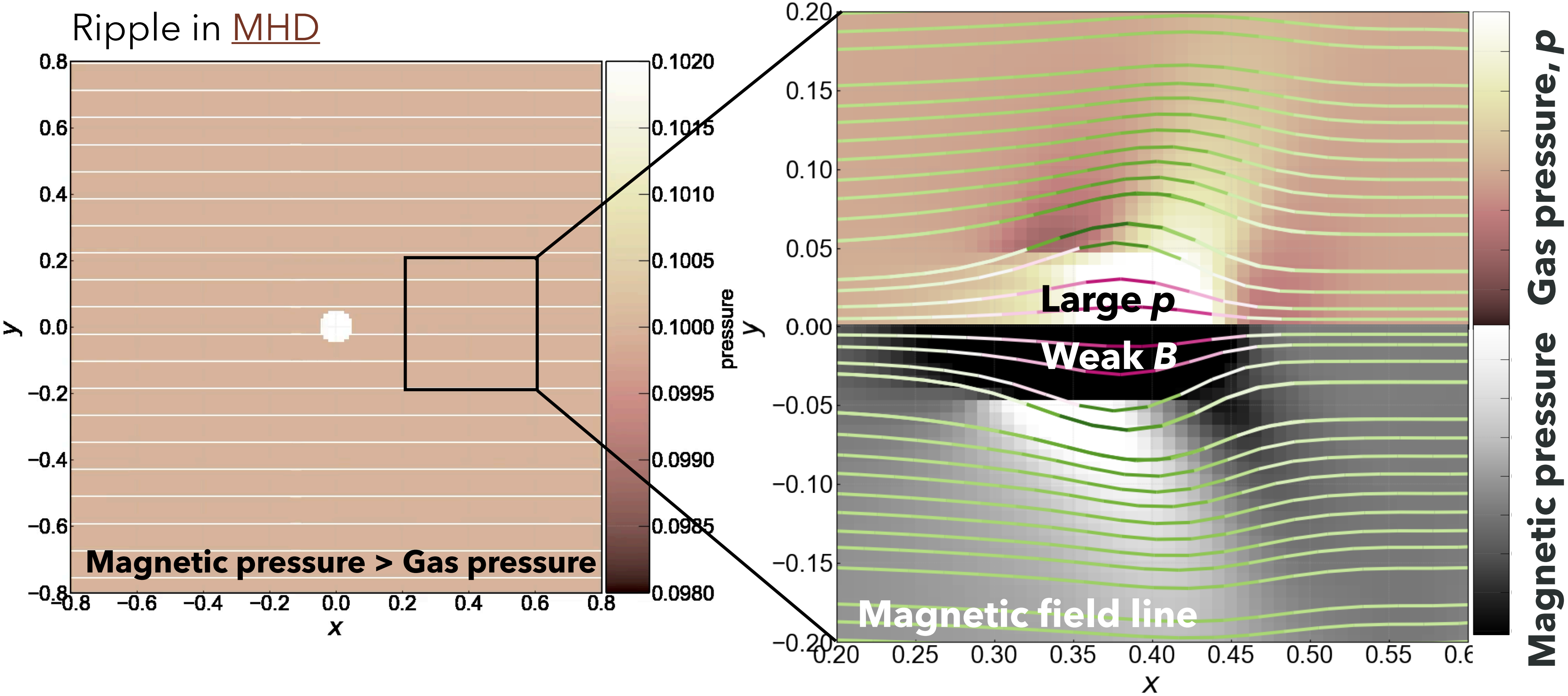


Ripple in MHD



Slow-mode: Compressional wave that gas pressure and magnetic pressure have inverse phase of each other.

Remarks: Slow-mode (Slow Wave)



Slow-mode: Compressional wave that gas pressure and magnetic pressure have inverse phase of each other.

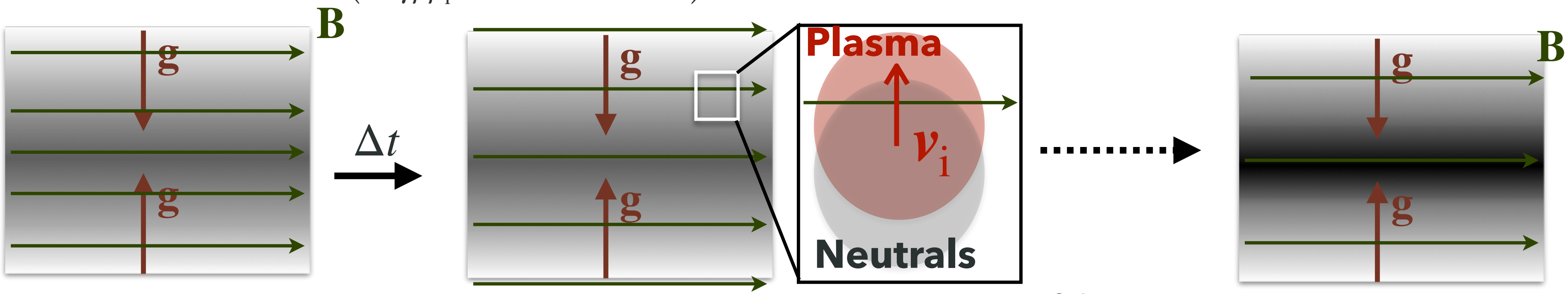
The Ion-Neutral Drift (Ambipolar Diffusion)

The neutral fluid and plasma are **not** perfectly coupled in molecular clouds

Ex. Magnetized self-gravitating slab of lightly ionized gas

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \nabla \times \left(\frac{1}{4\pi\gamma\rho\rho_{\mathrm{i}}} ((\nabla \times \mathbf{B}) \times \mathbf{B}) \times \mathbf{B} \right)$$

Color shows gas density



Initial condition:
Hydrostatic equilibrium

Assuming $v_{\mathrm{n}} \sim 0$ km/s

Collapse

Magnetic Reynolds number for ambipolar diffusion $R_{\mathrm{AD}} = 1$ –> Length scale of AD

$$\ell_{\mathrm{AD}} = 0.09 \text{ pc} \left(\frac{B}{30\ \mu\mathrm{G}} \right)^{2} \left(\frac{n}{10^3\ \mathrm{cm}^{-3}} \right)^{-3/2} \left(\frac{v}{1\ \mathrm{km/s}} \right)^{-1}$$

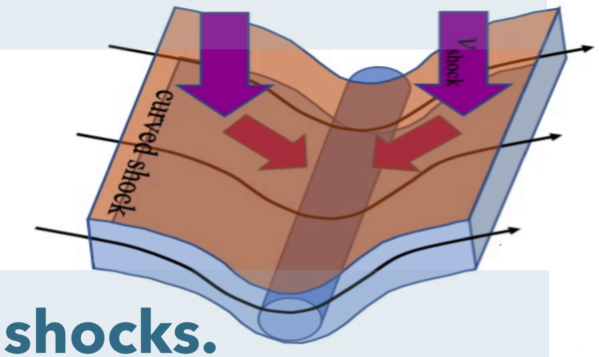
–> AD is effective in filaments (ℓ ~ 0.1 pc)

Purpose

Aim

Discover the mechanism to keep upstream kinetic energy

–> Understand how massive filament width is maintained



This Study

In reality, there are *two* shocks.

Investigate whether turbulent ram pressure can be provided by ***two* slow-shocks simulations with ambipolar diffusion**.

Setup for Simulations

2D simulations using Athena++ code (Stone+ 2020)

Isothermal MHD including ambipolar diffusion (w/o self-gravity)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\frac{\partial \rho v}{\partial t} + \nabla \cdot \left(\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + P + B^2/2\right) = 0$$

AD

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + P + B^2/2\right)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B}\cdot\boldsymbol{v}) + \frac{\eta_{\rm AD}}{|\boldsymbol{B}|^2}\{\boldsymbol{B}\times(\boldsymbol{J}\times\boldsymbol{B})\}\times\boldsymbol{B}\right] = 0$$

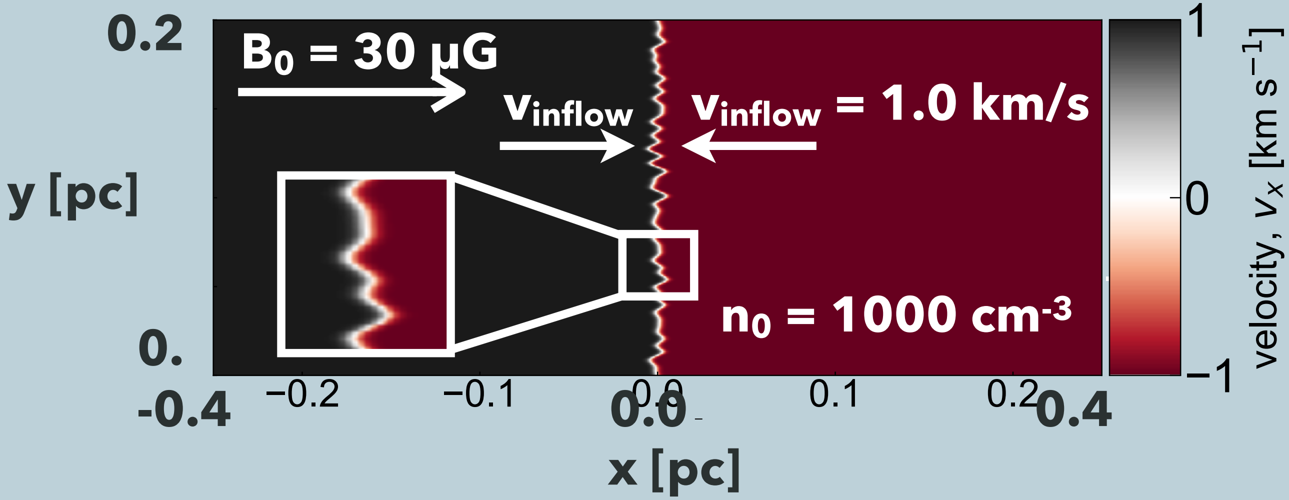
$$E = e + \frac{1}{2}\rho v^2 + \frac{B^2}{2} \qquad P = (\gamma - 1)e \qquad \gamma = 1.01$$

AD

$$\frac{\partial \boldsymbol{B}}{\partial t} - \nabla \times \left[(\boldsymbol{v}\times\boldsymbol{B}) - \frac{\eta_{\rm AD}}{|\boldsymbol{B}|^2}\boldsymbol{B}\times((\nabla\times\boldsymbol{B})\times\boldsymbol{B})\right] = 0$$

$$\eta_{\rm AD} = \frac{B^2}{4\pi\gamma_{\rm in}\rho_{\rm n}\rho_{\rm i}}$$ (Shu 1992)

Initial Condition: Gas inflows along the B field –> filament formation



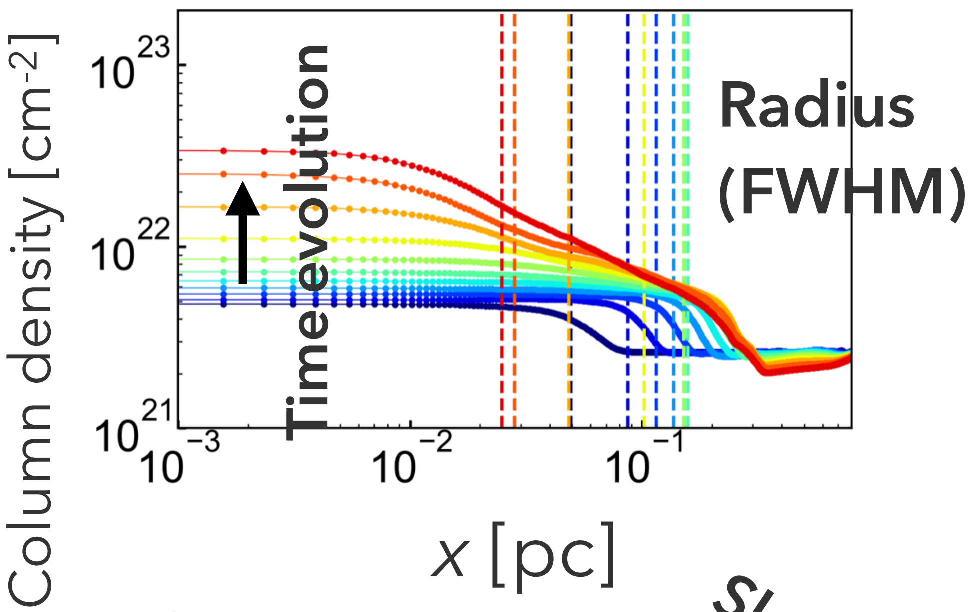
Boundary Condition

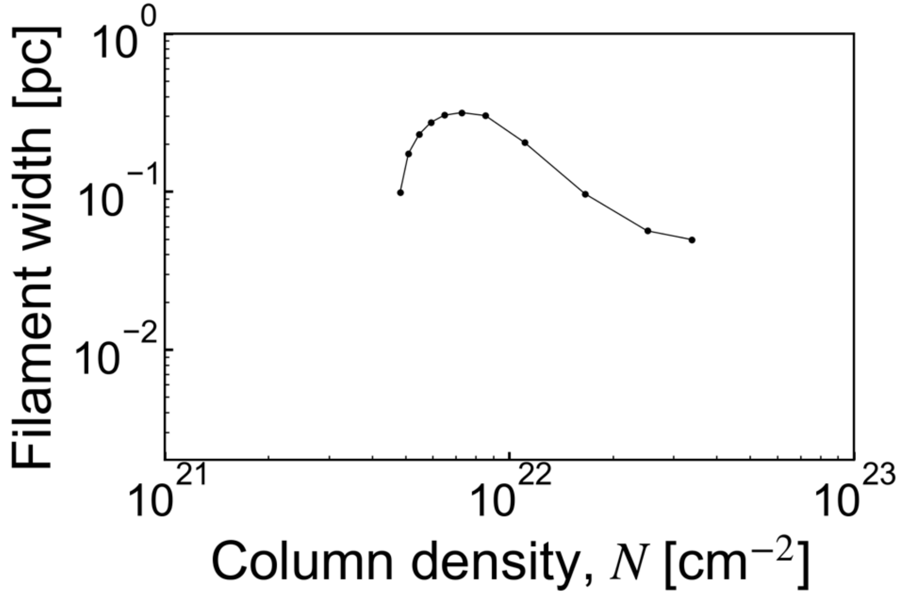
- x–> Free
- y–> Periodic

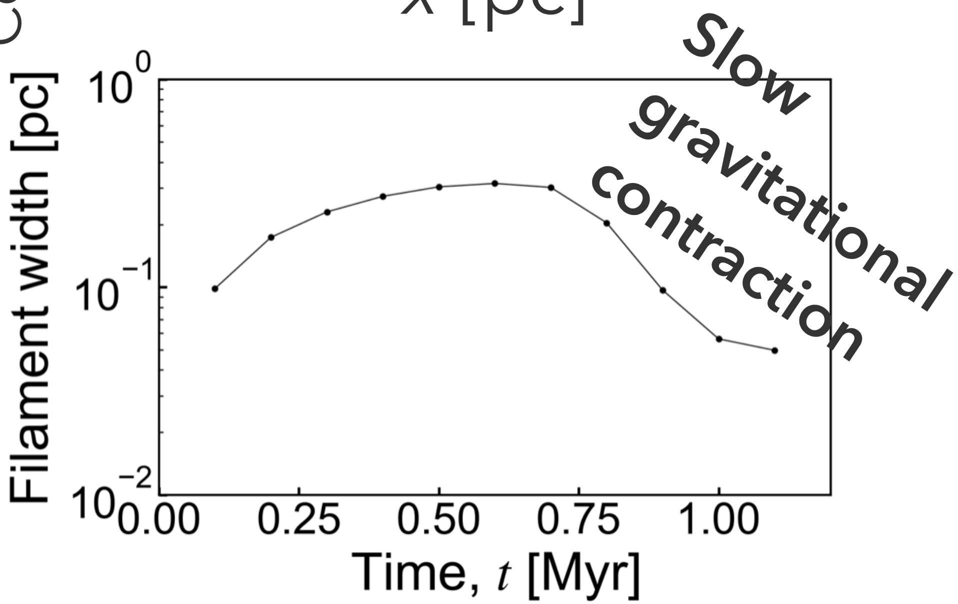
c_s = 0.2 km/s

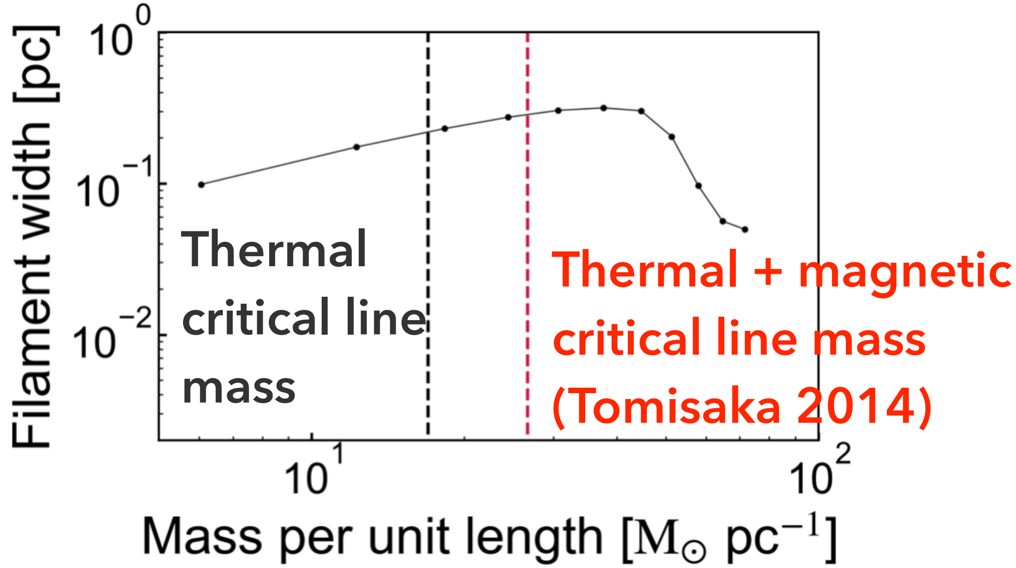
Resolution : 3.9 x 10^{-4} pc

Time evolution of filament width



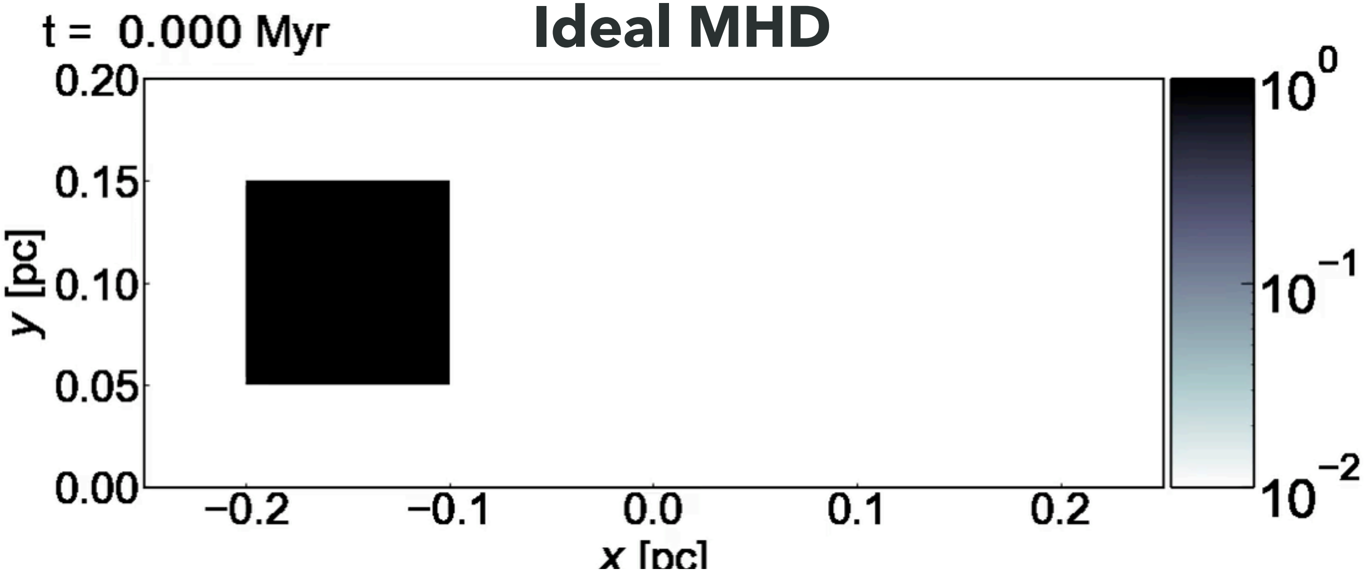






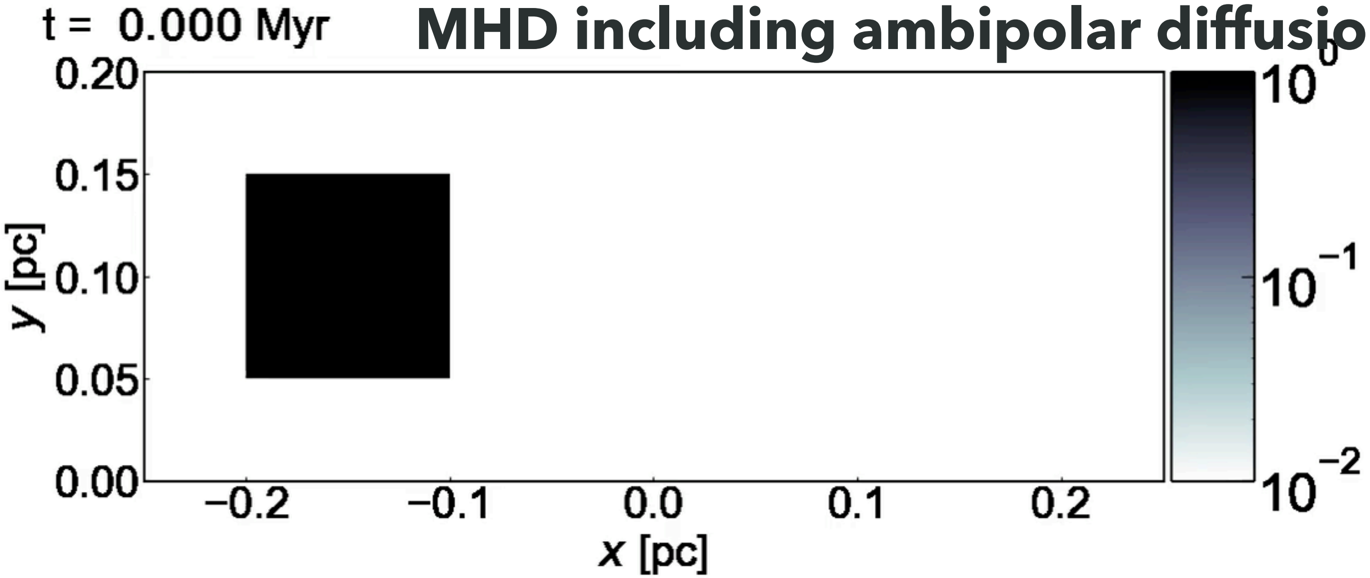
Additional Results: Passive Scalar

Ideal MHD



Gas in the filament cannot move due to magnetic frozen-in.

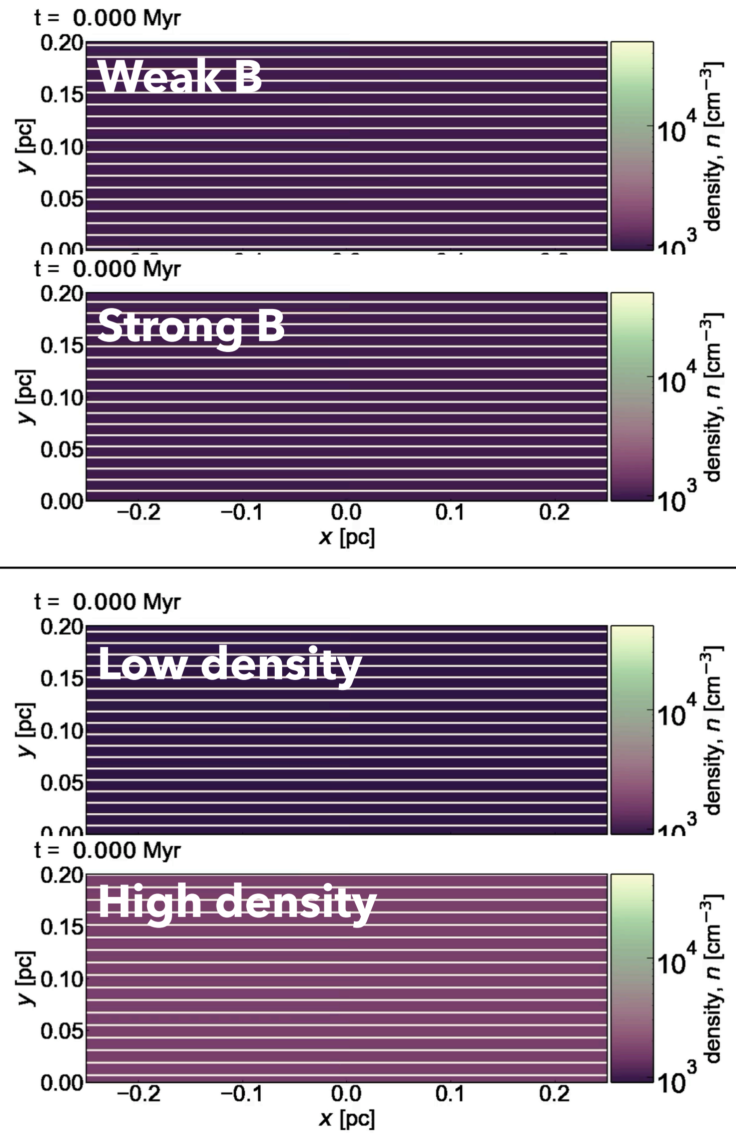
MHD including ambipolar diffusion

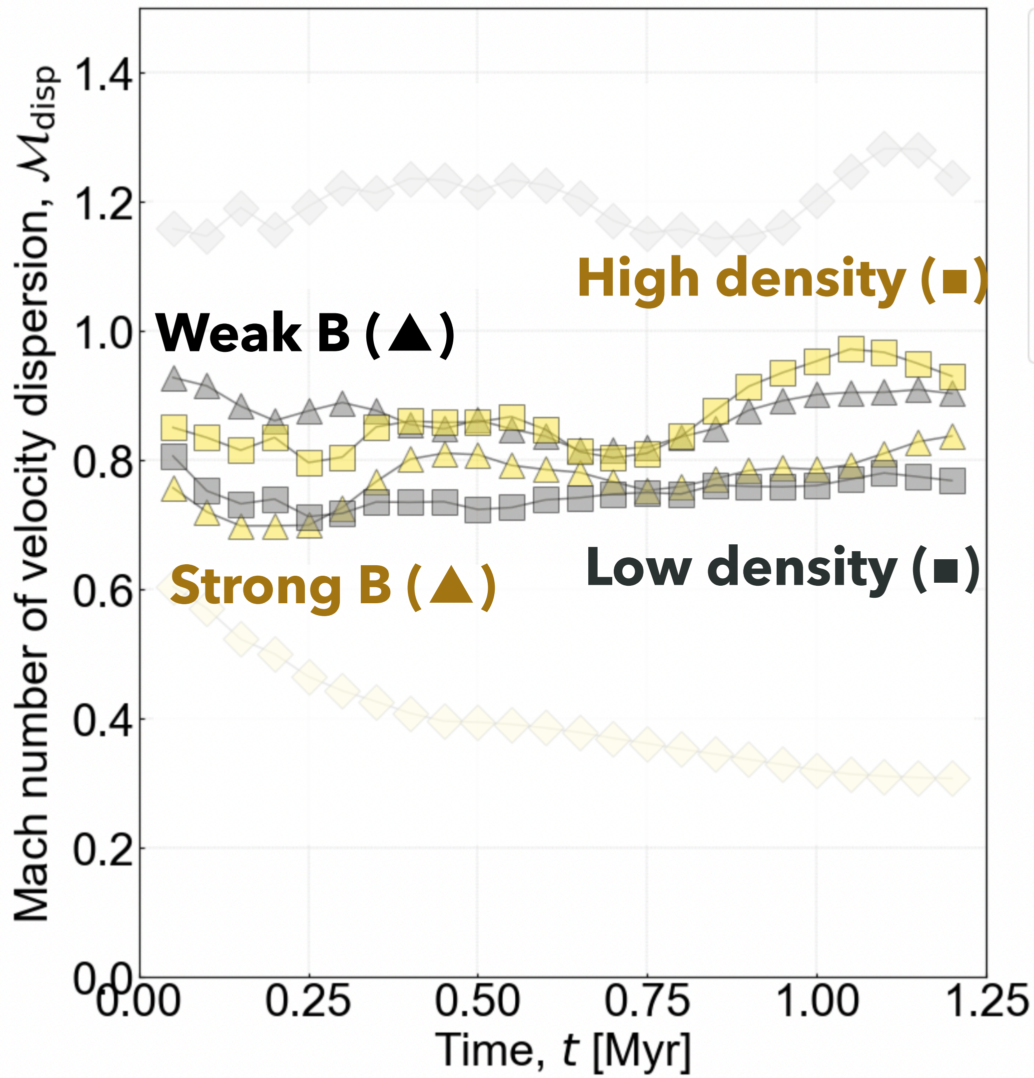


Gas can circulate in the filament.

Confirm that the bullets are physical gas blobs.

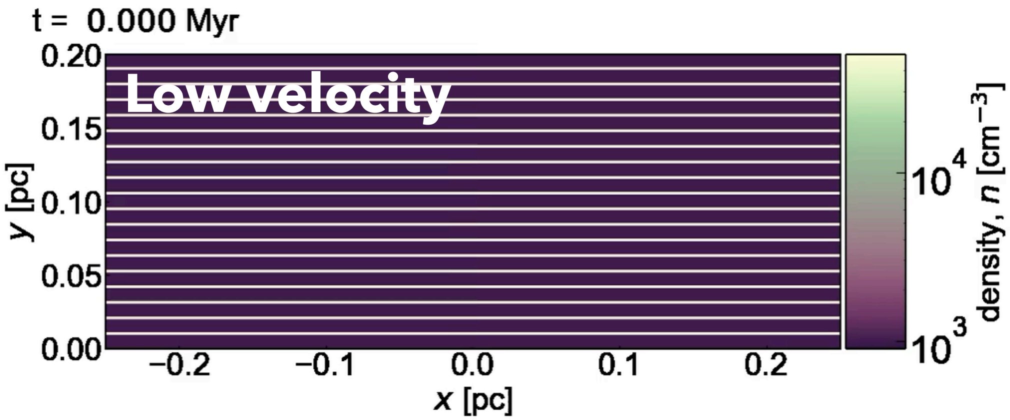
Dependence on Density and Magnetic Field

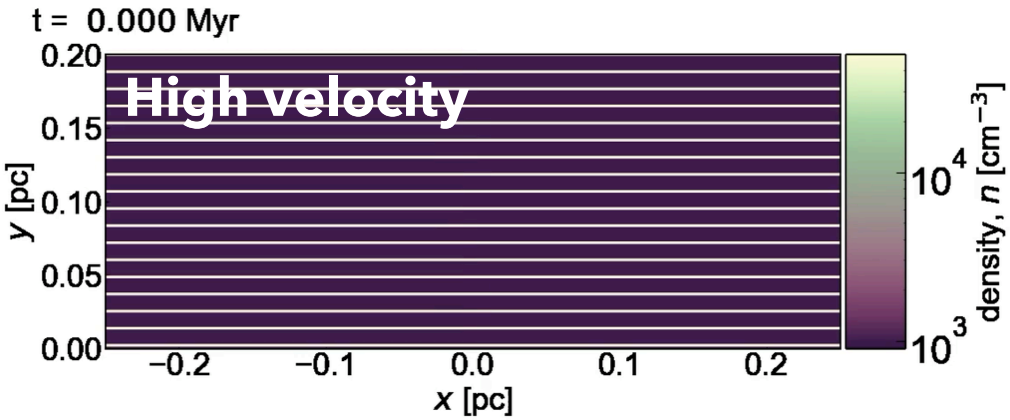


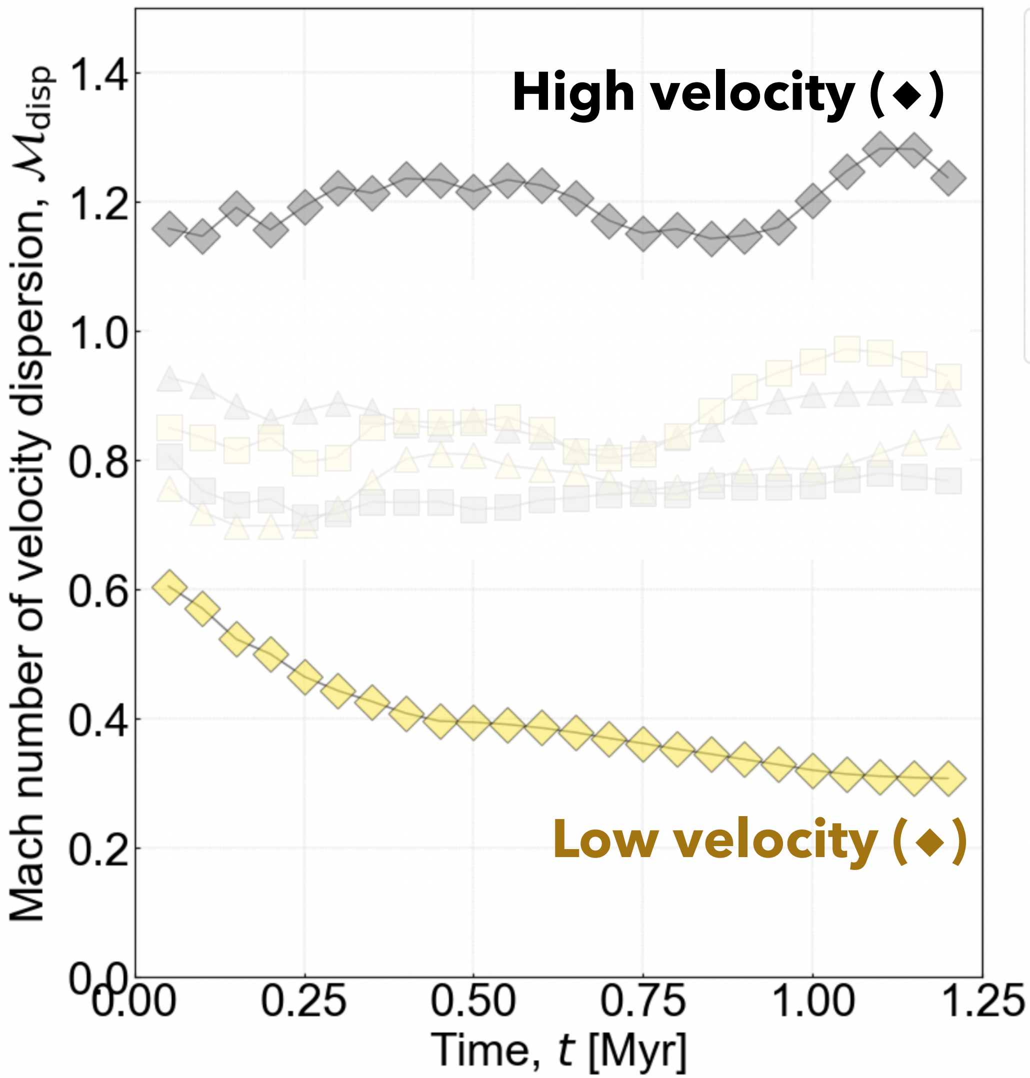


The strength of the generated anisotropic turbulence is independent of the magnetic field and density.

Dependence on Accretion Velocity

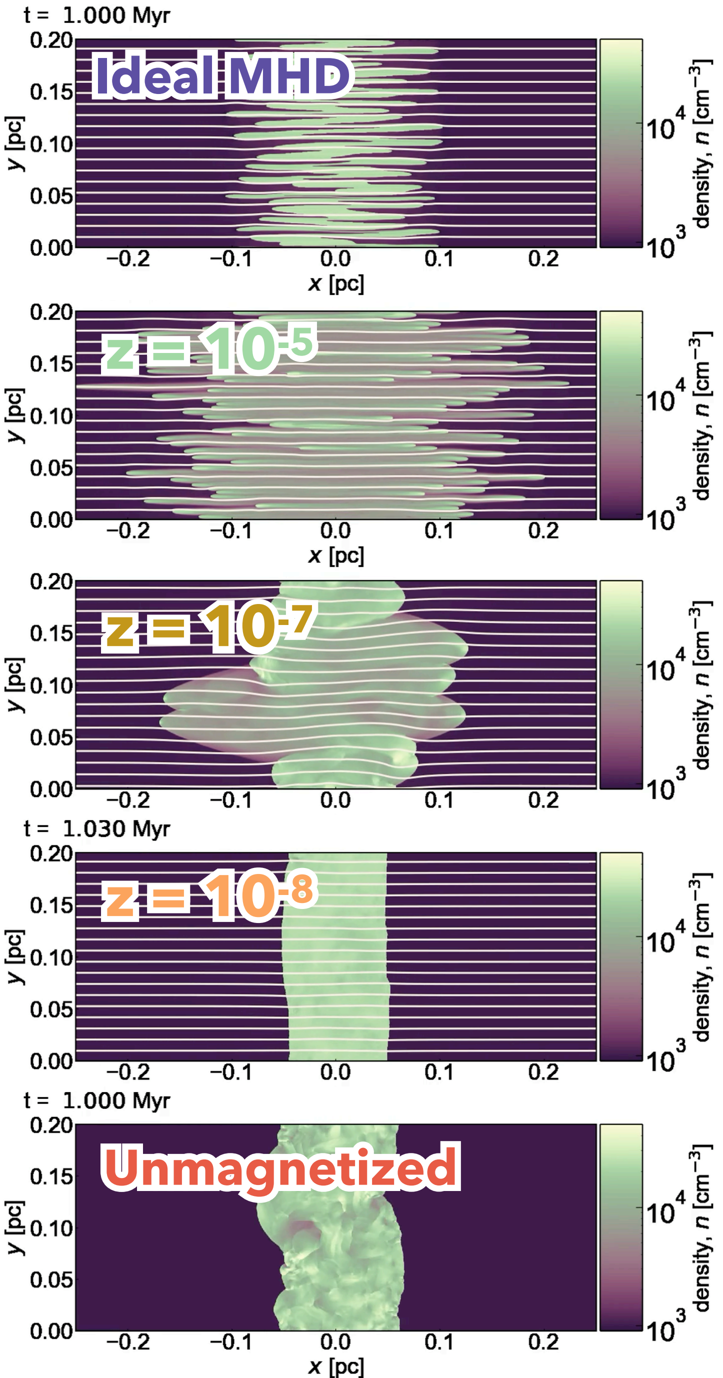


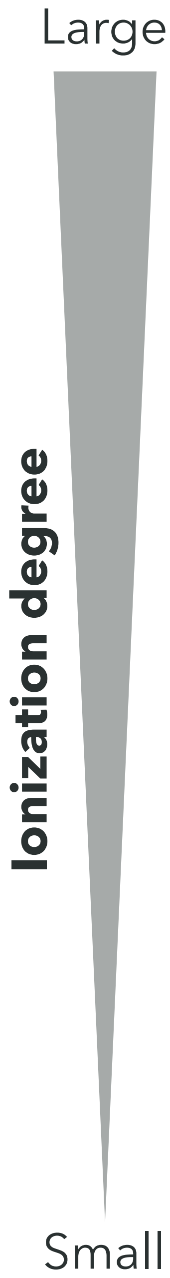


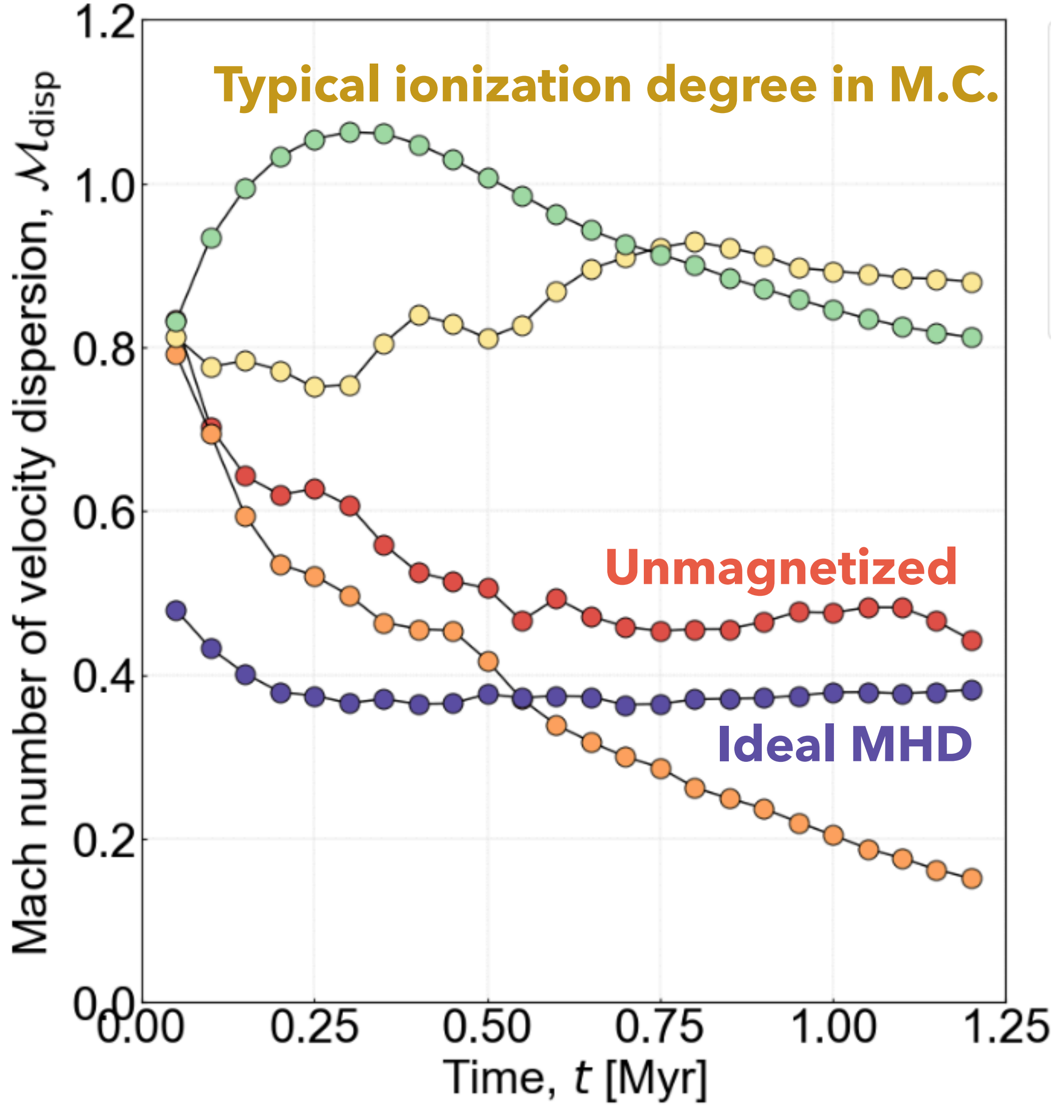


The strength of the generated anisotropic turbulence depends on the accretion velocity.

Dependence on Ionization Degree







Bullet mechanism exists even if the ionization degree changes by one or two orders of magnitude.

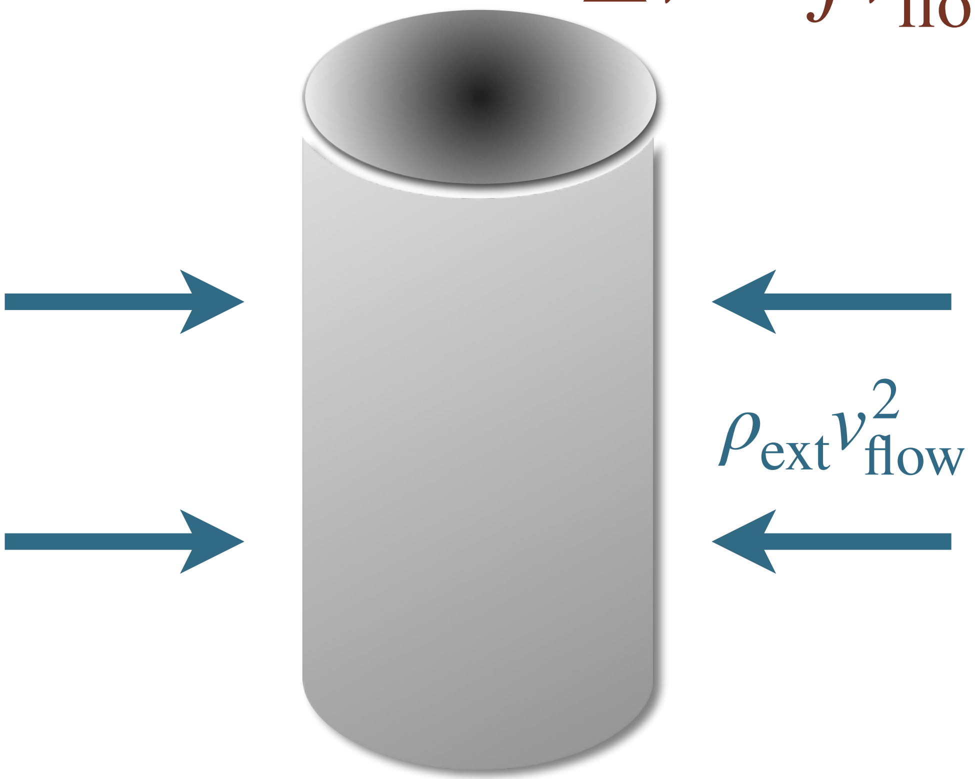
Discussion: Line mass v.s. FWHM (Theoretical Model)

Does flow-driven turbulence explain the observed line mass independent width?

Outline of our model

Velocity dispersion within the filament:

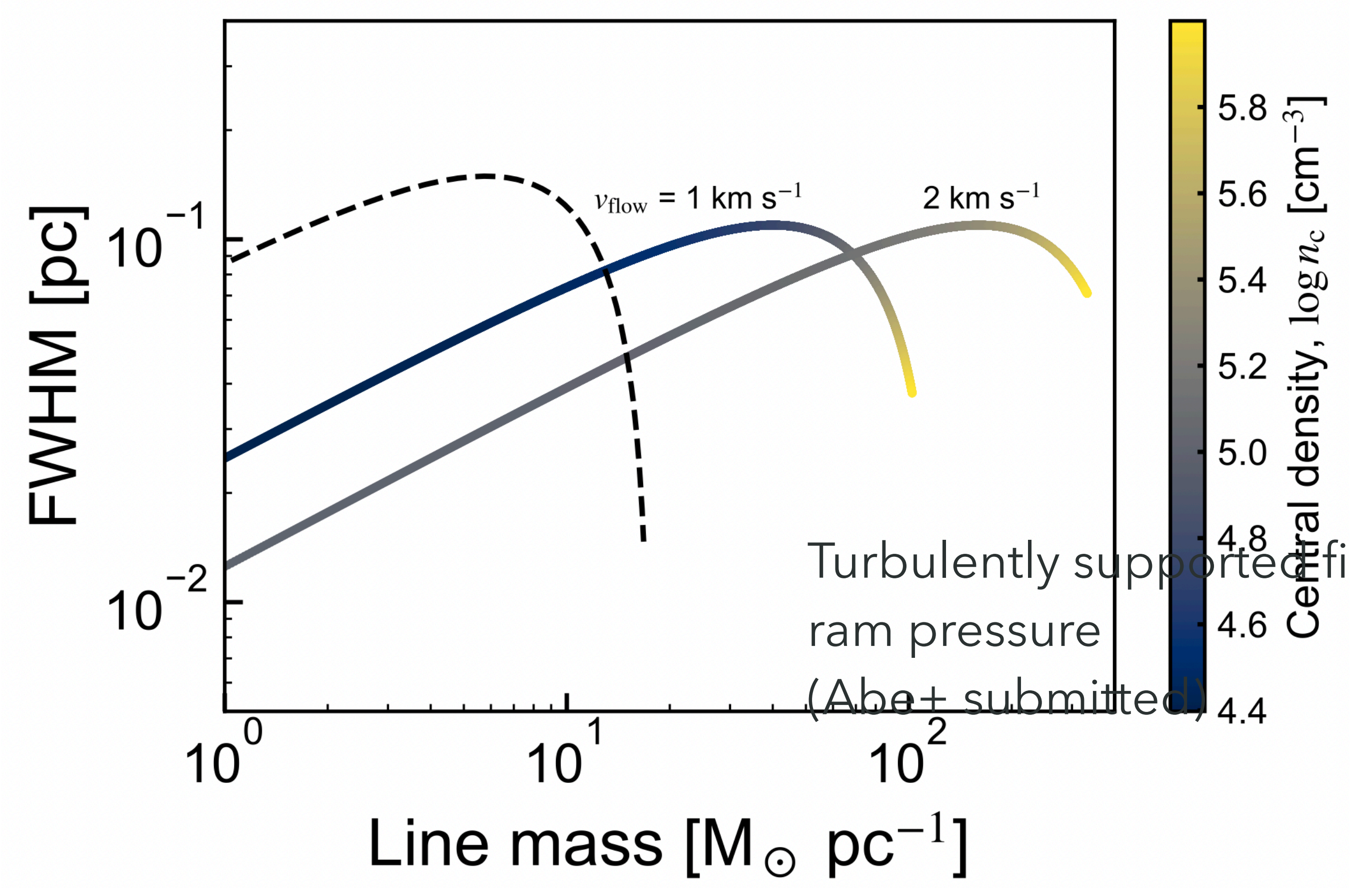
$$\Delta v = f v_{\rm flow}, \ (f \simeq 0.5)$$



Discussion: Line mass v.s. FWHM (Theoretical Model)

Does flow-driven turbulence explain the observed line mass independent width?

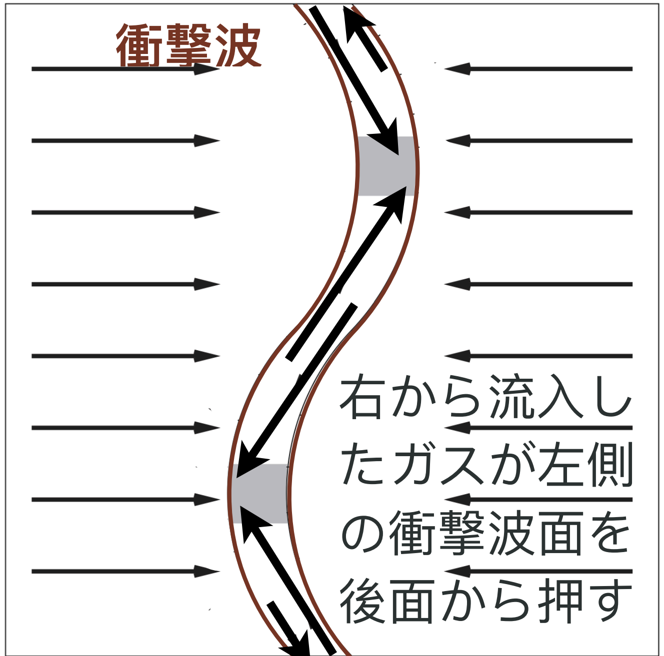
Thermally supported filament w/ external gas pressure
Fischera & Martin (2012)



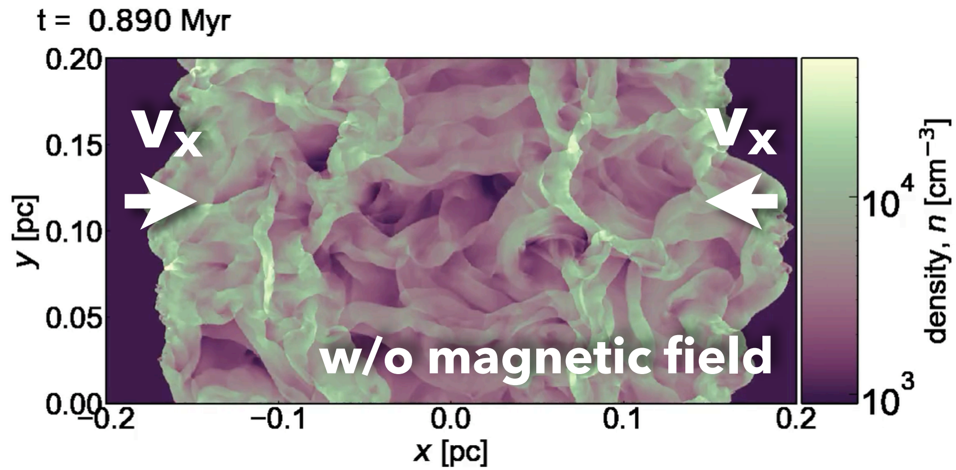
Turbulently supported filament confined by inflow ram pressure
(Abe+ submitted)

Nonlinear Thin-Shell Instability (NTSI)

Nonlinear Thin Shell Instability (NTSI): 磁場なし等温衝撃波2枚に挟まれた薄いシートにおける衝撃波面の揺らぎは不安定 **(e.g., Vishniac 1994)**



McLeod & Whitworth (2013)



反対側の衝撃波面への運動量輸送が本質

強磁場 (Slow shock) ではNTSIの成長を抑制する **(Heitsh+ 2007)**

※ NTSIには飽和があり乱流は維持できないので**フィラメントの幅の維持には向かない話**

Future Works

Star Formation Rate Problem

Contradiction between the observation & the theoretical estimation

The observed star formation rate (SFR)
~ 1 M_{sun}/yr

≪

Simple estimation of SFR

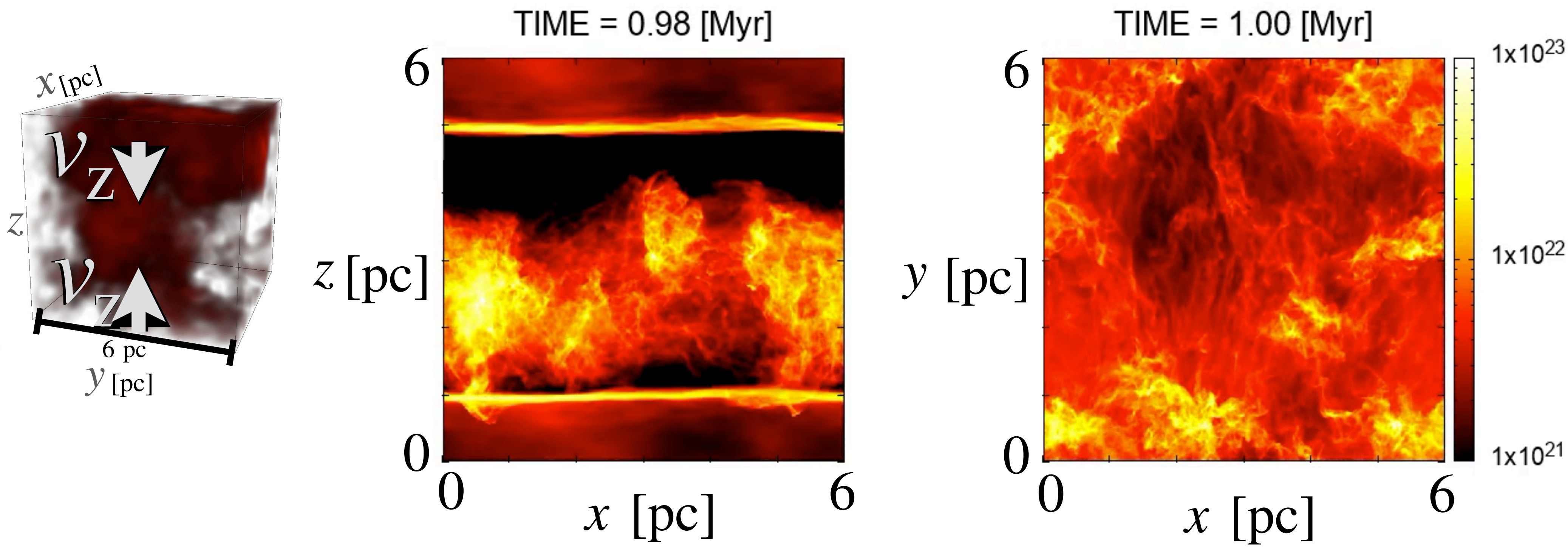
Molecular clouds mass in MW ~ **10^9 M_{sun}.**
Free-fall time scale of ~ **10^6 yr**,
–> The **SFR** ~ **1,000 M_{sun}/yr**.

An example of solutions
–> Only a small fraction of the molecular cloud becomes stars.

How can such a situation to be realized?

Our Strategy: Filament “Resetting”

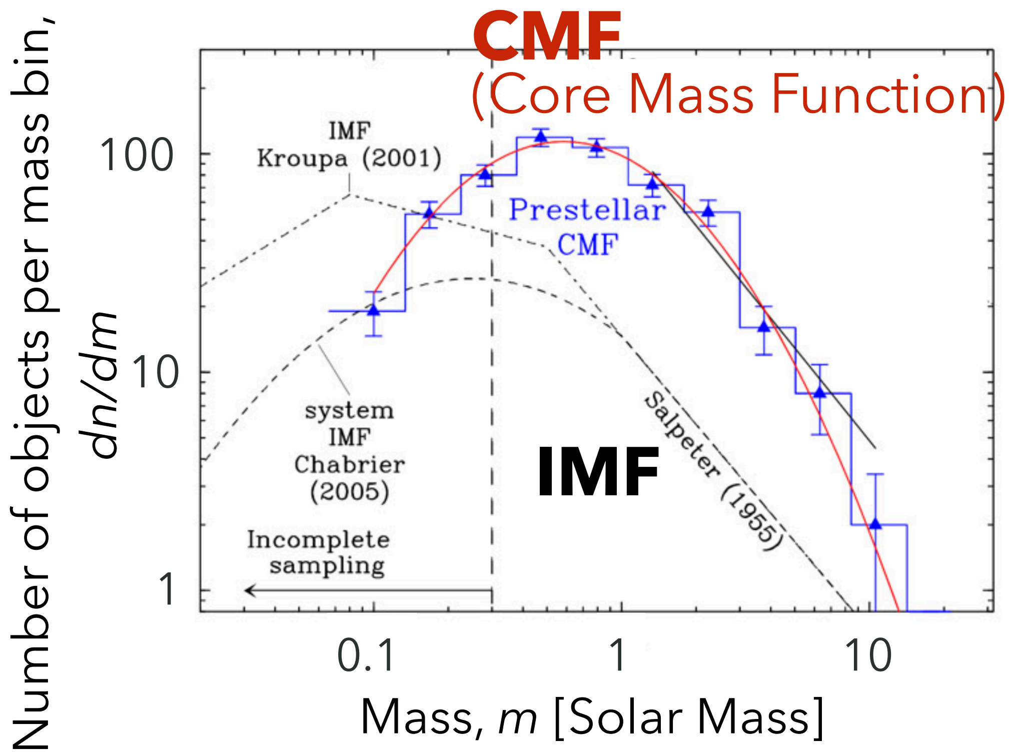
Idea: The effect of multi-compression causes filament **destruction** & formation
—> Filament mass fraction keeps low value?

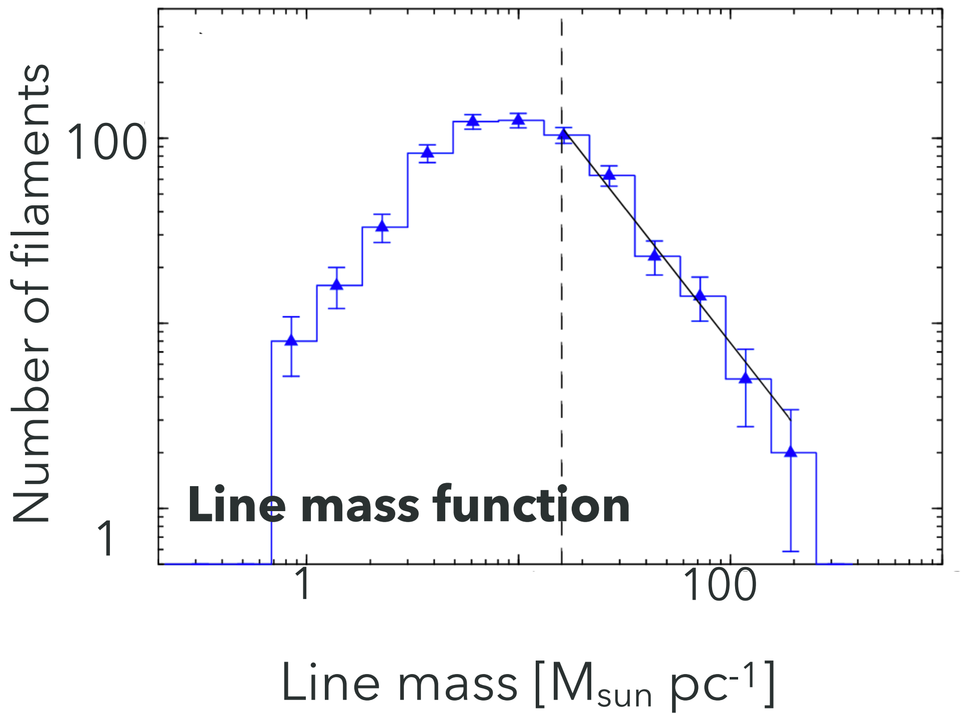


First, I would like to reveal the conditions of the destruction.

Other Future Work

Link between CMF and Line Mass Function?





I would like to clarify the origins of the IMF through an understanding of filaments.

Summary & Future Works

We perform non-ideal MHD simulations and investigate filament evolution simulations.

"Anisotropic turbulence driven by the Bullet mechanism (SSI + ambipolar diffusion)**" can maintain the width of massive filaments.**

Future Works

- Solve the 0.1 pc problem
- Understanding the "filament resetting." –> Solve the SFR problem
- Clarifying the origin of filament line mass function and relation with IMF