Physics of Extreme Massive Stars

Marie-Curie-RISE project funded by the European Union

Cloud-Cloud Collision: Formation of Hub-Filament Systems and Associated Gas Kinematics

Arup Kumar Maity

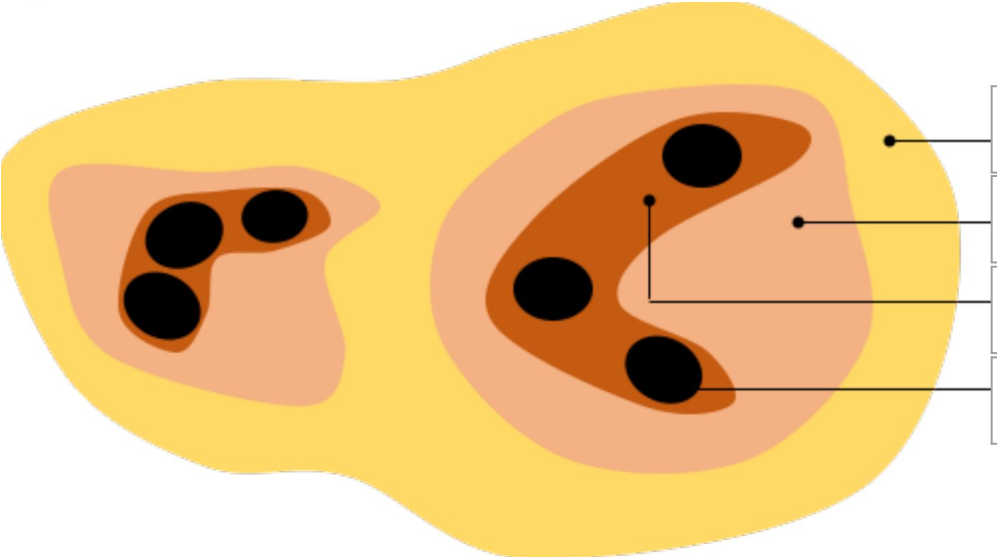
Physical Research Laboratory

List of co-authors

Dr. L. K. Dewangan, Dr. N. K. Bhadari, Prof. Y. Fukui, Dr. H. Sano, Dr. K. Tachihara, Prof. T. Inoue, Mr. O. Jadhav, and Mr. R. I. Yamada

Introduction and Motivation

Stars form in the molecular clouds

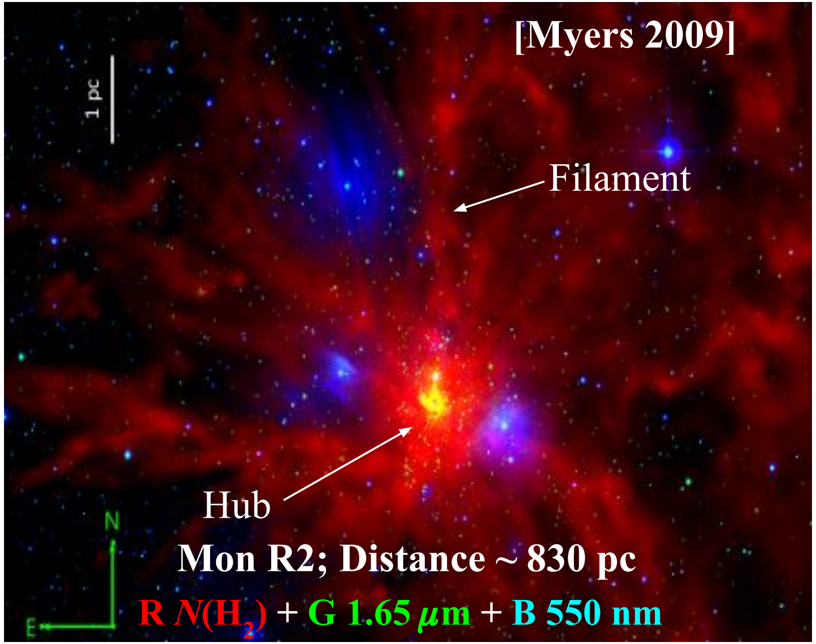


	Size [pc]	Density [cm $^{-3}$]
Cloud	~1 – 10	~10^2–10^3
Clump	~1	~10^3–10^4
Filament	~0.1 (Width)	~10^4–10^5
Core	~0.05 – 0.1	> 10^5

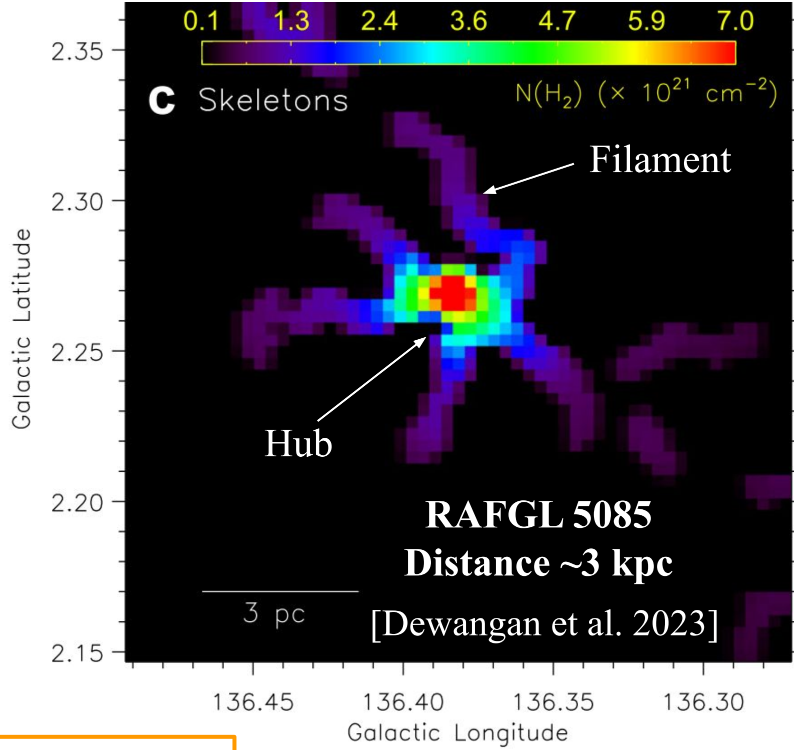
[Owen et. al 2023]

The hierarchical density structure of molecular cloud
[Owen et al. 2023]

Hub-filament system (HFS)



[Treviño-Morales et al. 2019]

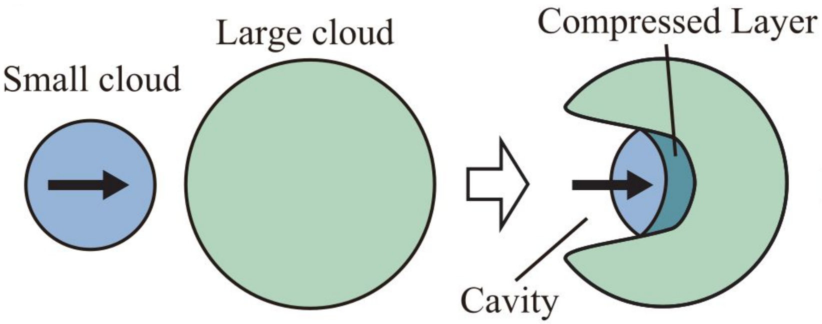


Hub: $N(H_2) > 10^{22}$ cm^{-2}

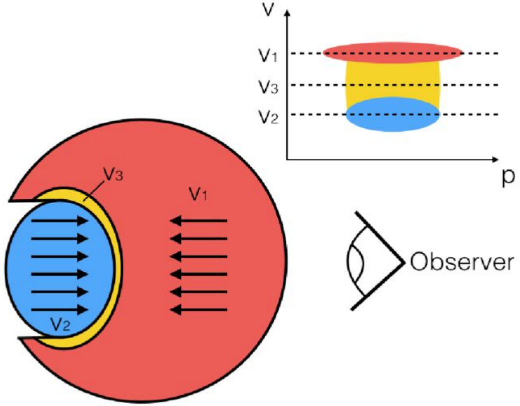
[Kumar et al. 2020]

Cloud-cloud collision (CCC)

[Habe & Ohta 1992]



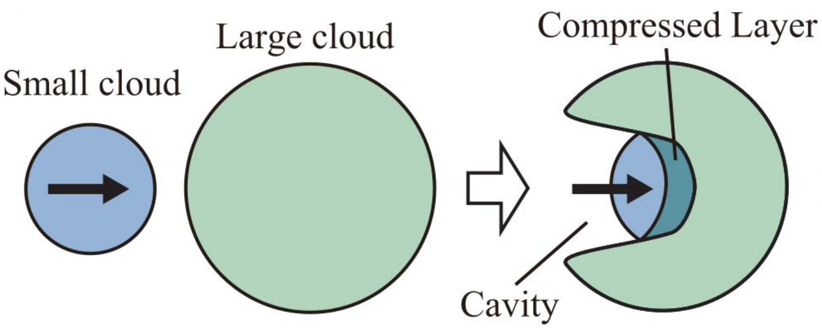
[Fukui et al. 2021]



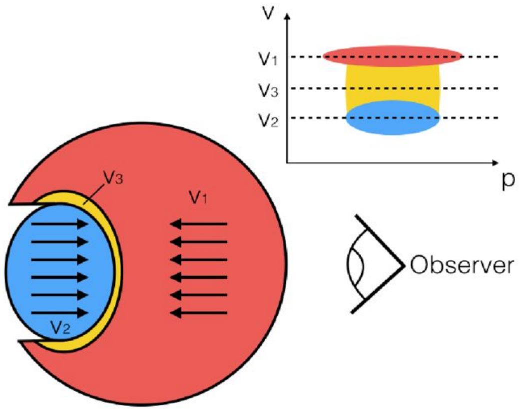
[Haworth et al. 2015]

Cloud-cloud collision (CCC)

[Habe & Ohta 1992]



[Fukui et al. 2021]



[Haworth et al. 2015]

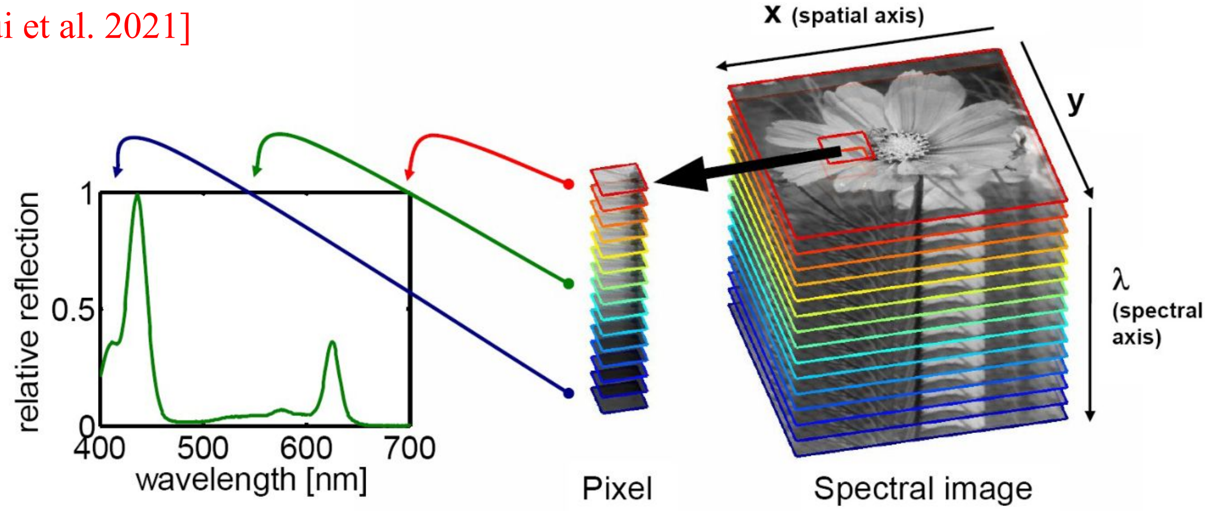
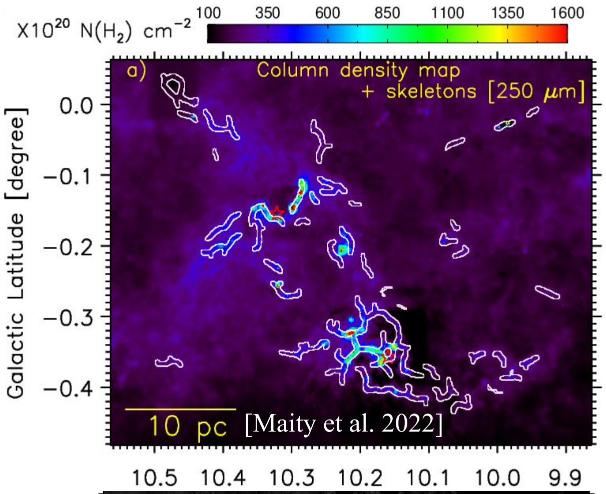
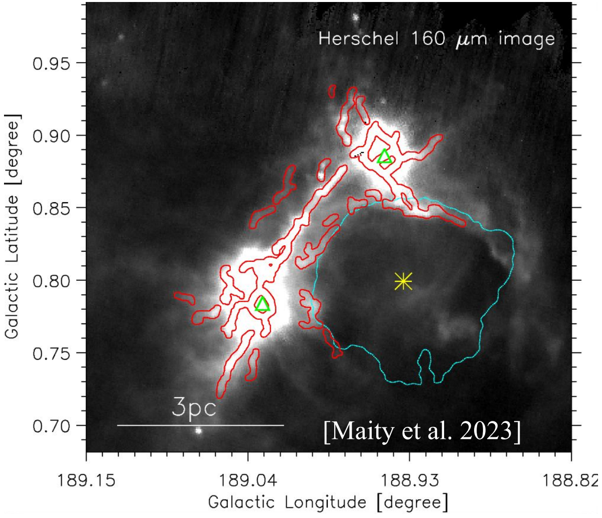


Image Credit: Gerrit Polder

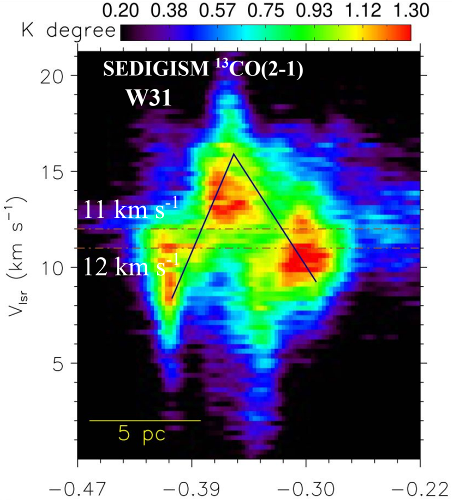
W31 Complex

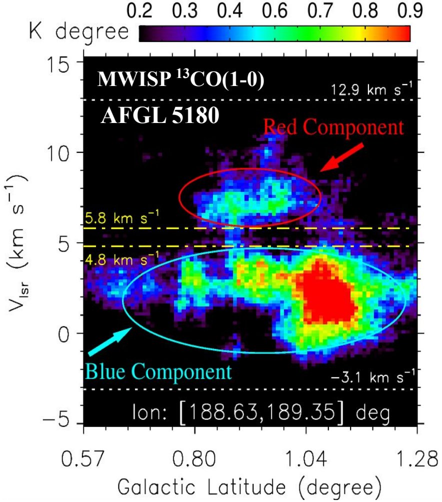


AFGL 5180 & 6366

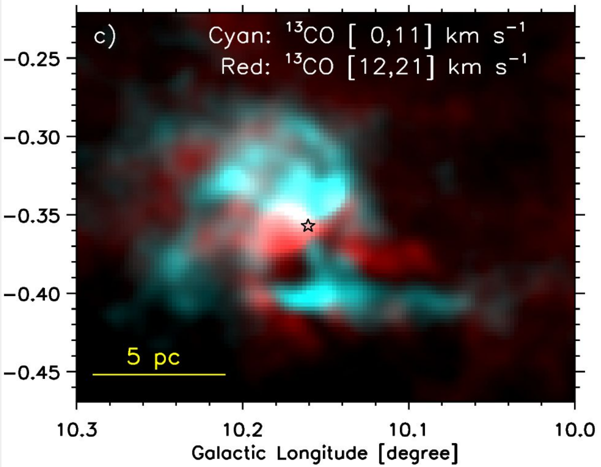


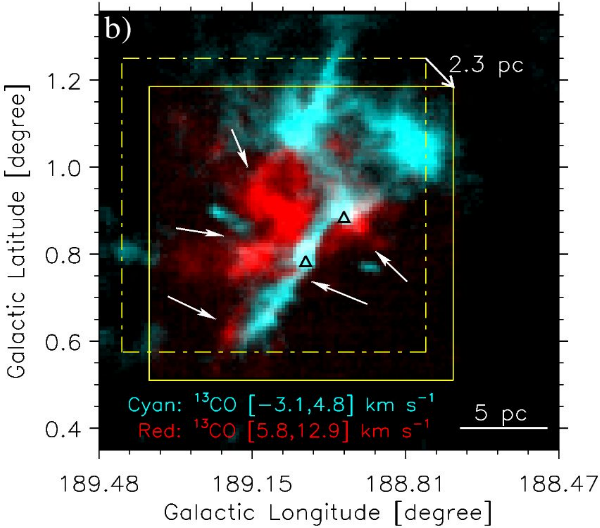
The position-velocity (*PV*) diagrams

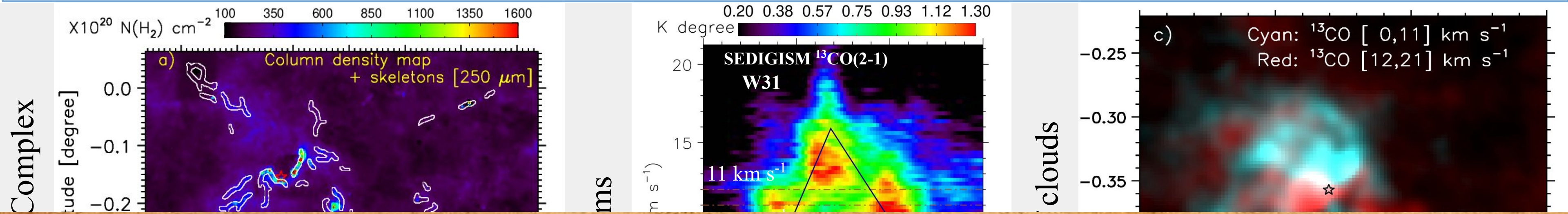




Complementary spatial distribution of clouds

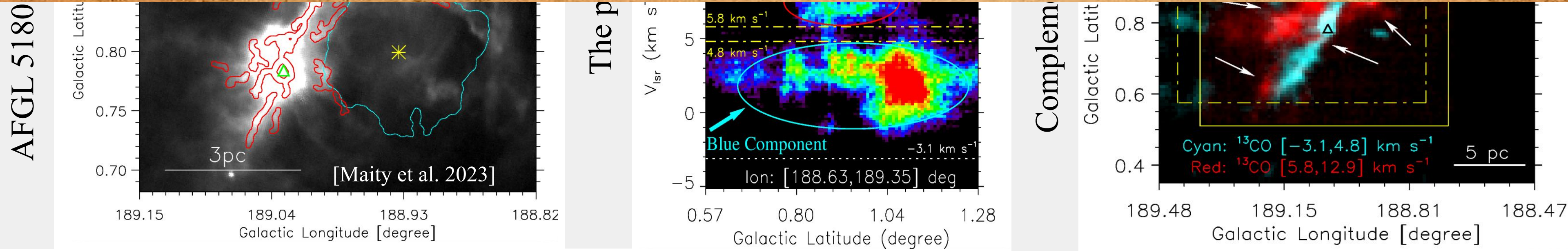




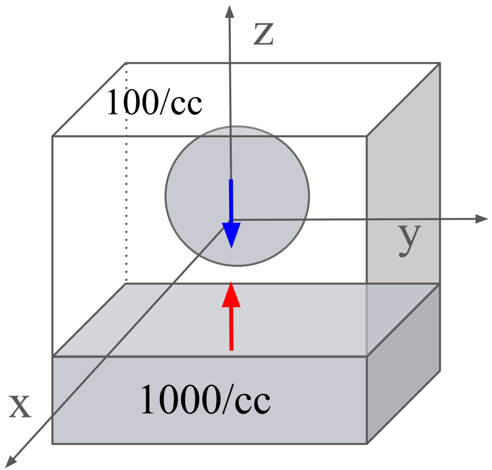


Questions

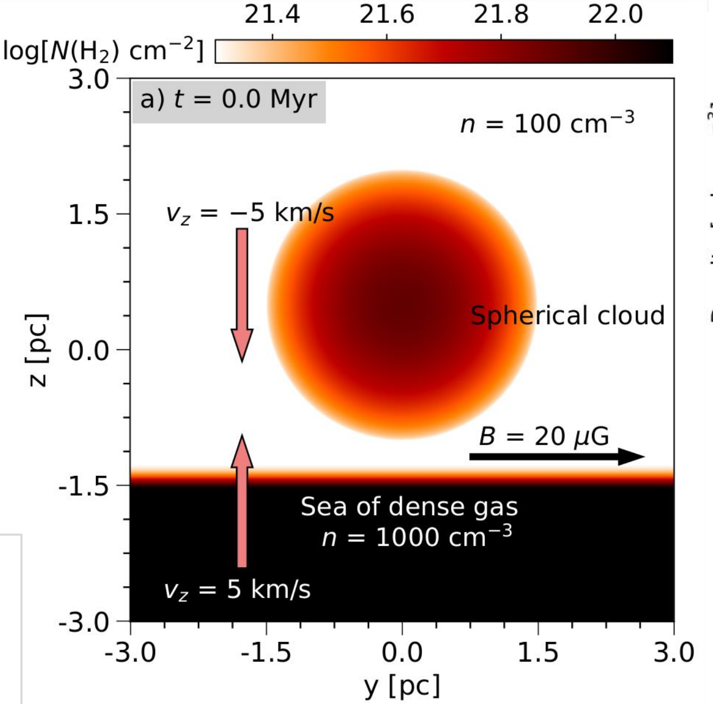
1. ***Can CCC lead to the formation of HFSs?***
2. ***How do filaments converge to form HFSs in CCC sites?***
3. ***What are the difficulties in the detection of CCC sites?***

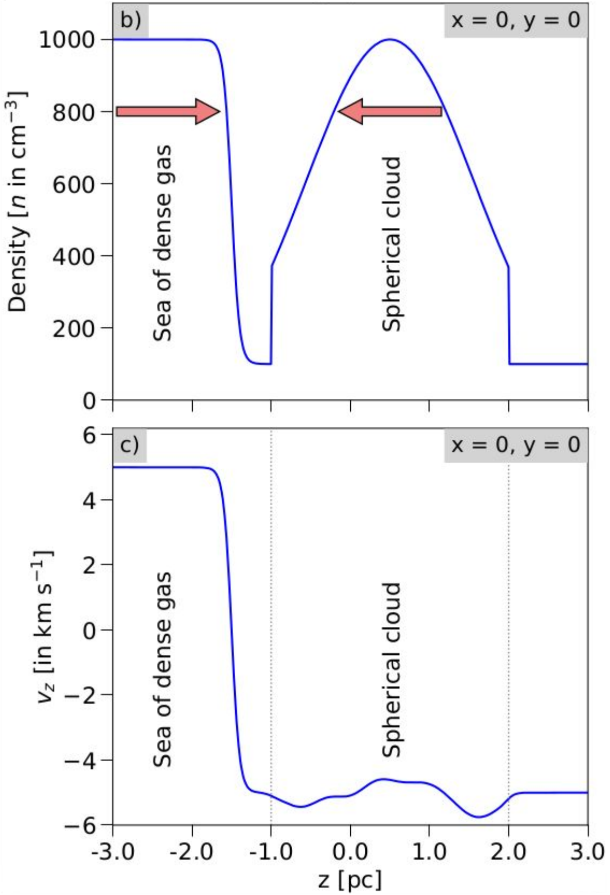


Numerical Setup



[Lx, Ly, Lz] = [6, 6, 6] pc
Resolution = 6/512 pc ~2400 AU
c_s = 0.3 km/s, $\boldsymbol{B}$ = [0, 20 μG, 0]
m = 2.4 Proton Mass*

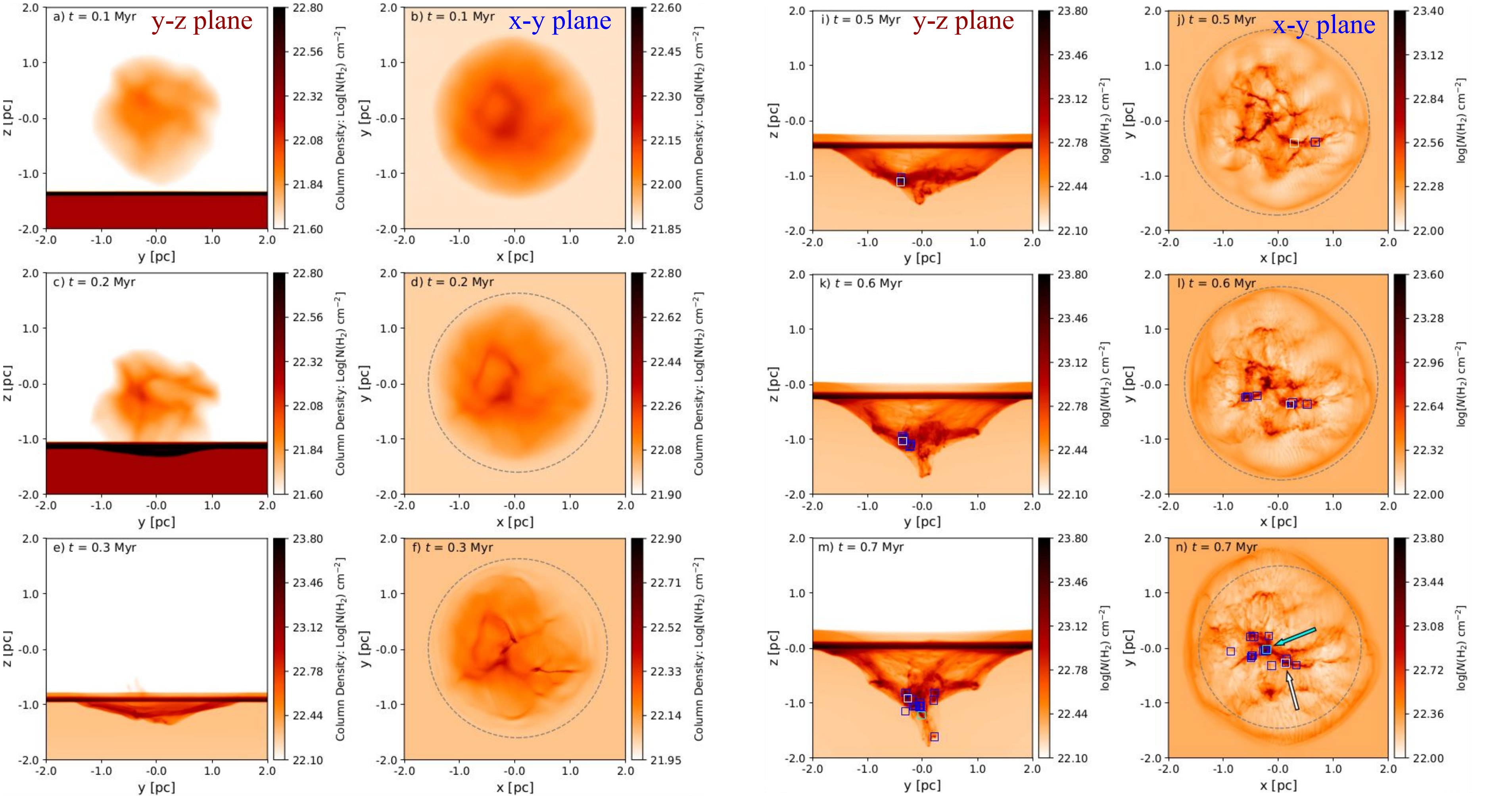




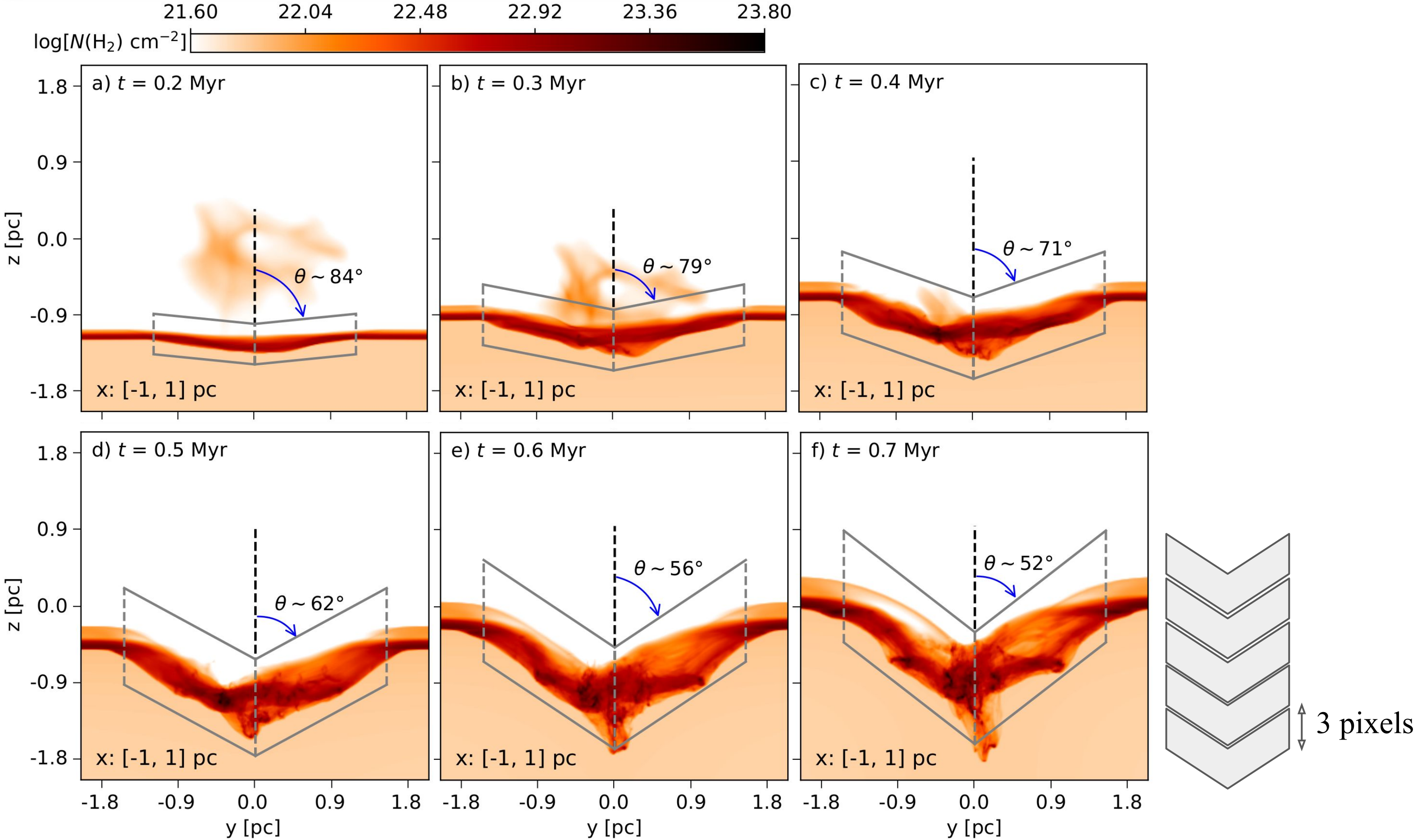
<u>Spherical Cloud</u>
R = 1.5 pc,
M = 477 Msun
Turbulence velocity FWHM ~1 km/s

*Proton Mass = 1.67 x 10^{-27} kg

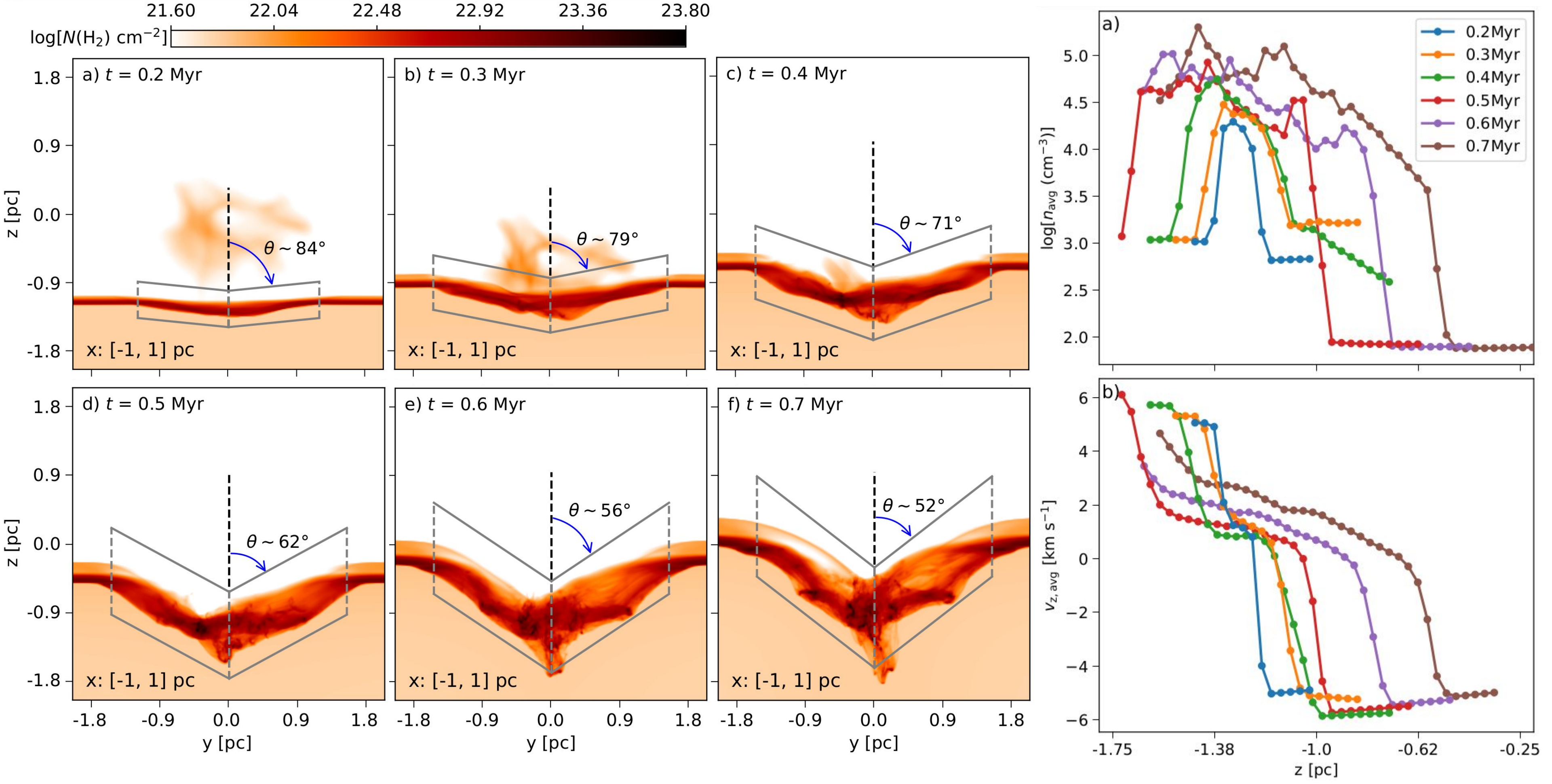
The column density maps



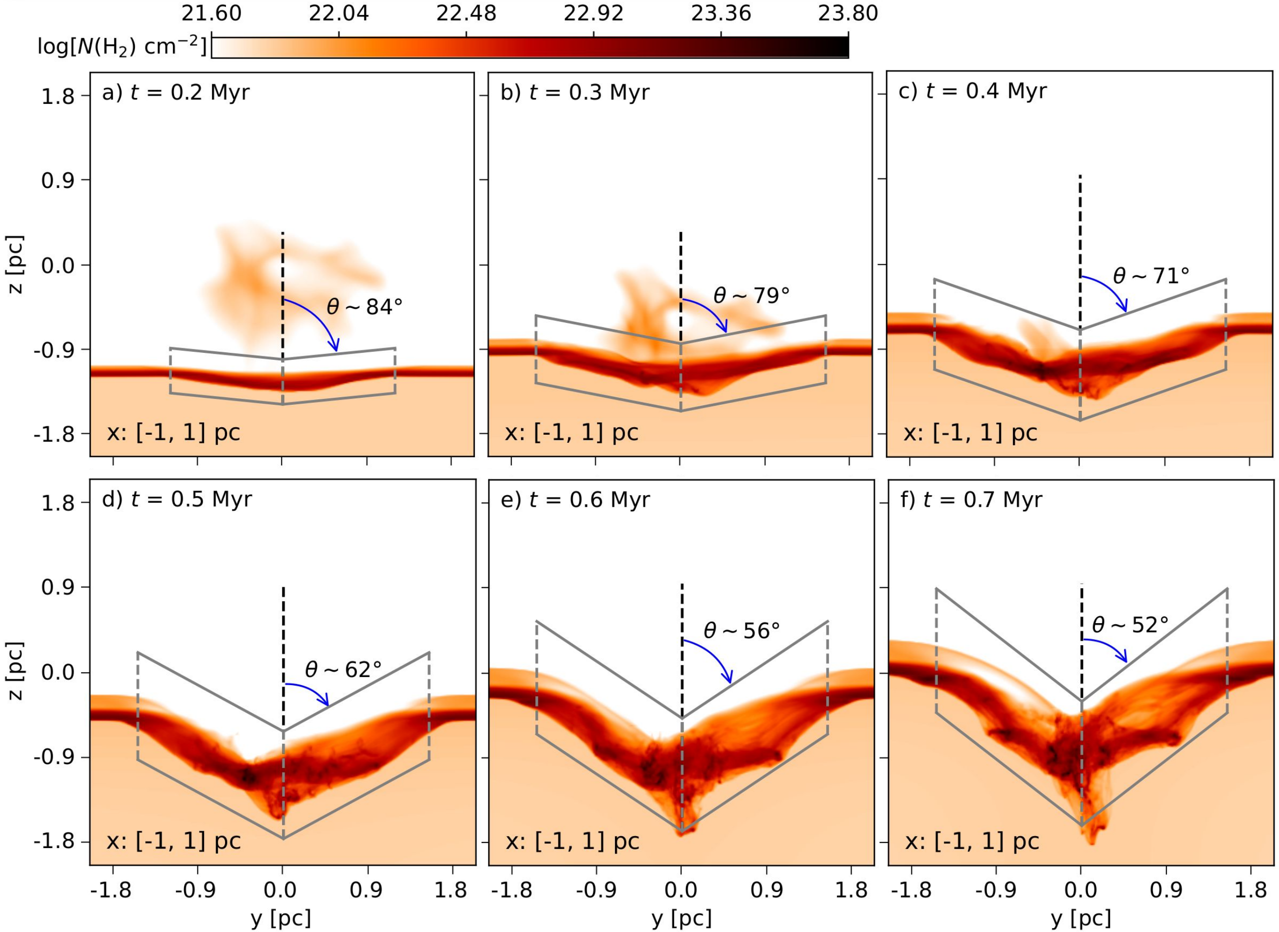
The compressed layer

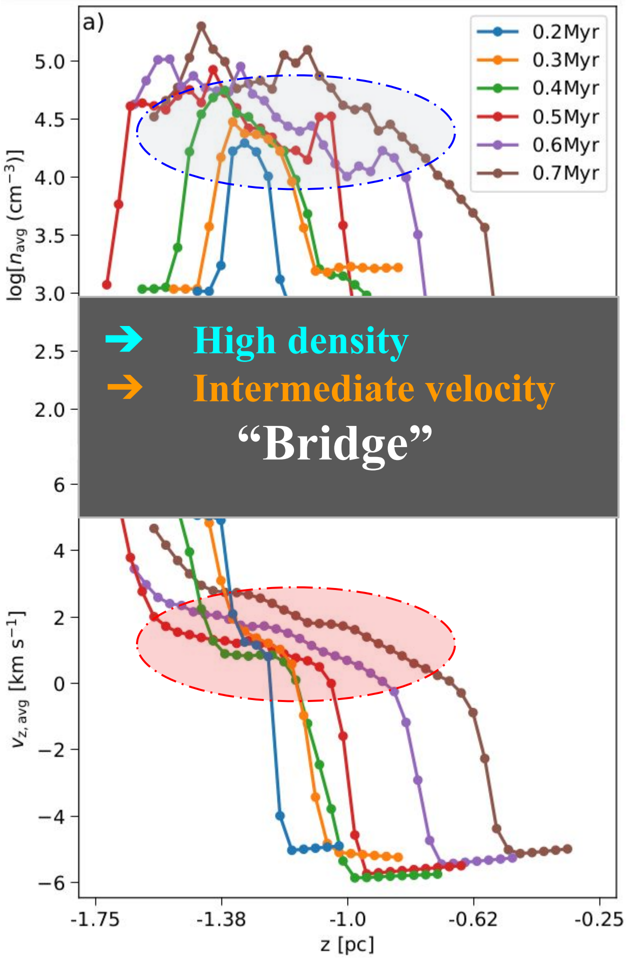


The compressed layer



The compressed layer



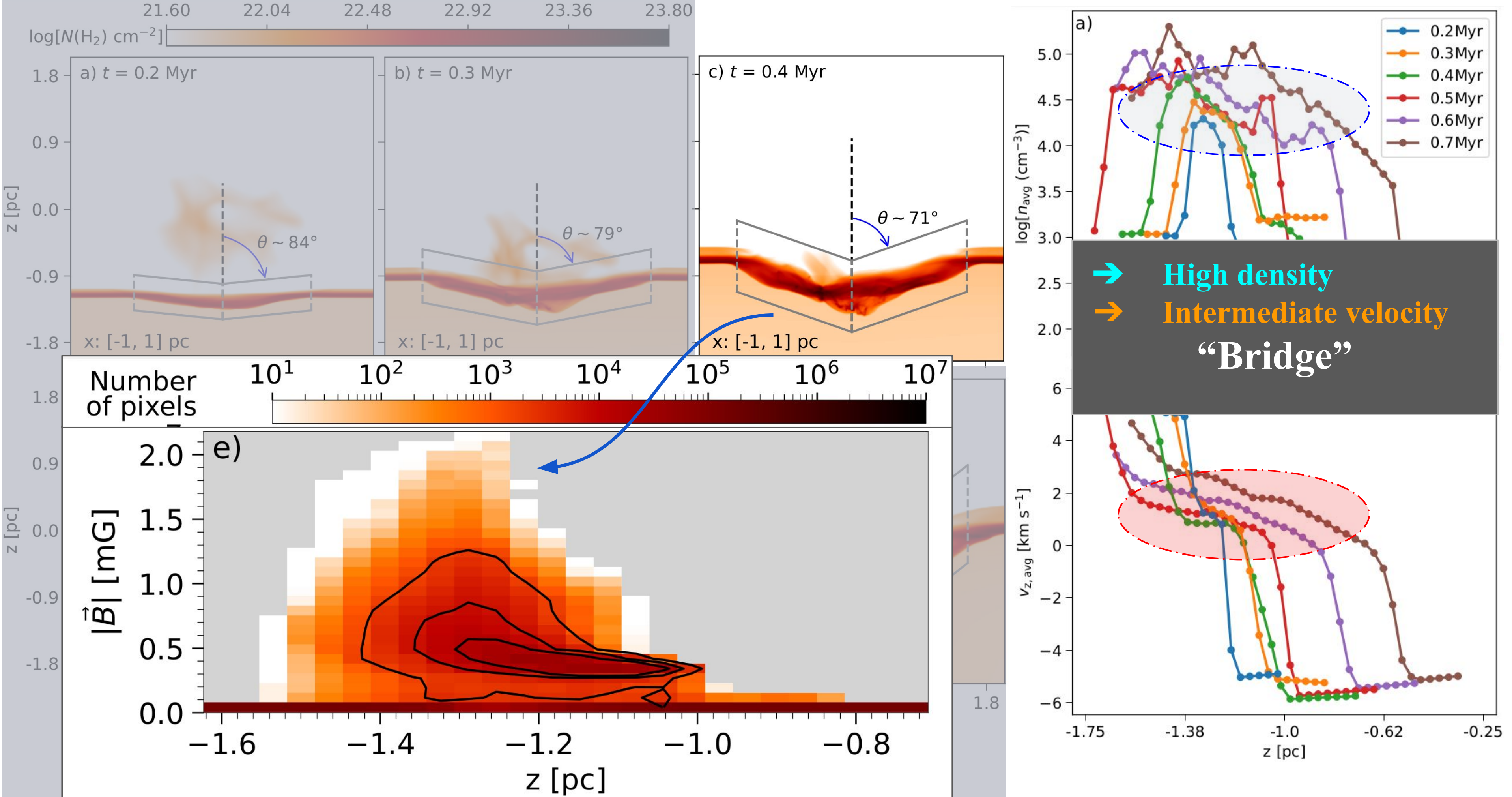


➔ **High density**

➔ **Intermediate velocity**

"Bridge"

The compressed layer



Detection of the filaments and cores using *getsf*

Astronomical Images

getsf

[Men'shchikov, A. 2021]

Cores

Filaments

Detection of the filaments and the cores using *getsf*

Astronomical Images

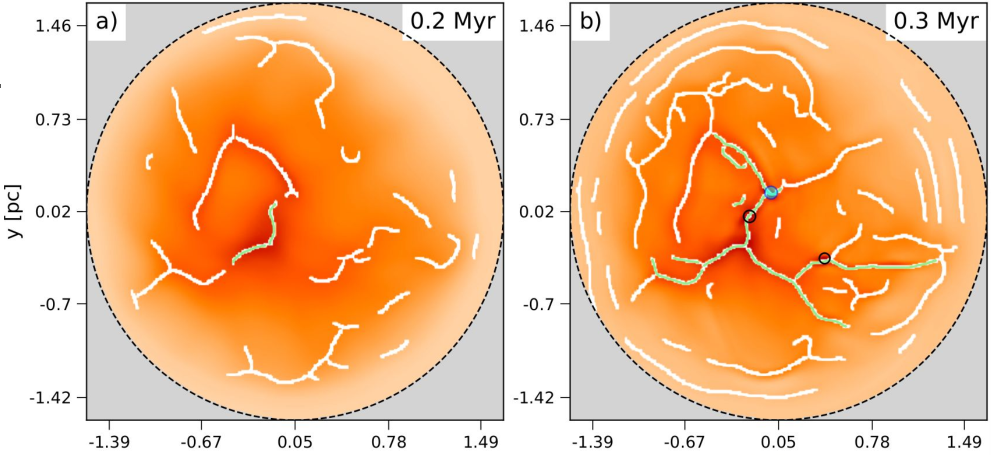
↓

getsf

[Men'shchikov, A. 2021]

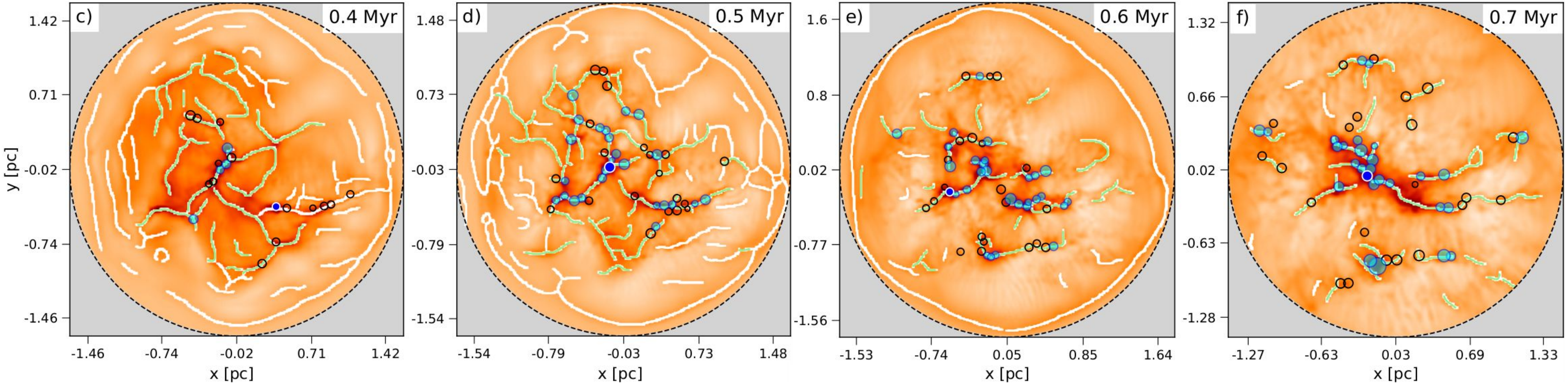
↙ ↘

Cores **Filaments**



$N(\mathrm{H_2})^{\mathrm{crest}}_{\mathrm{med}} \geq 10^{21.7}\ \mathrm{cm}^{-2}$

t (Myr)	$\mathrm{M_{max}}$ ($M_\odot$)	Total Mass ($M_\odot$)
0.2	—	—
0.3	1.06	2.58
0.4	3.88	17.05
0.5	7.72	80.17
0.6	9.81	104.74
0.7	15.39	123.78



Detection of the filaments and the cores using *getsf*

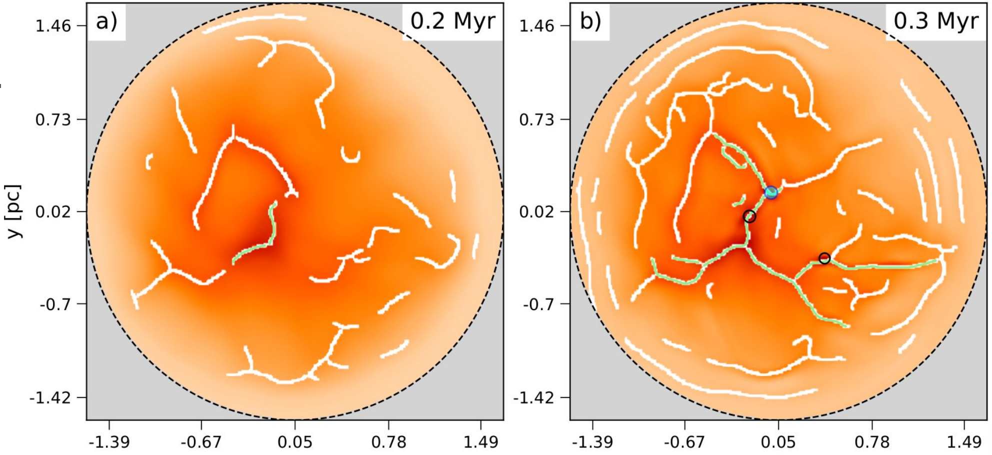
Astronomical Images

↓

getsf

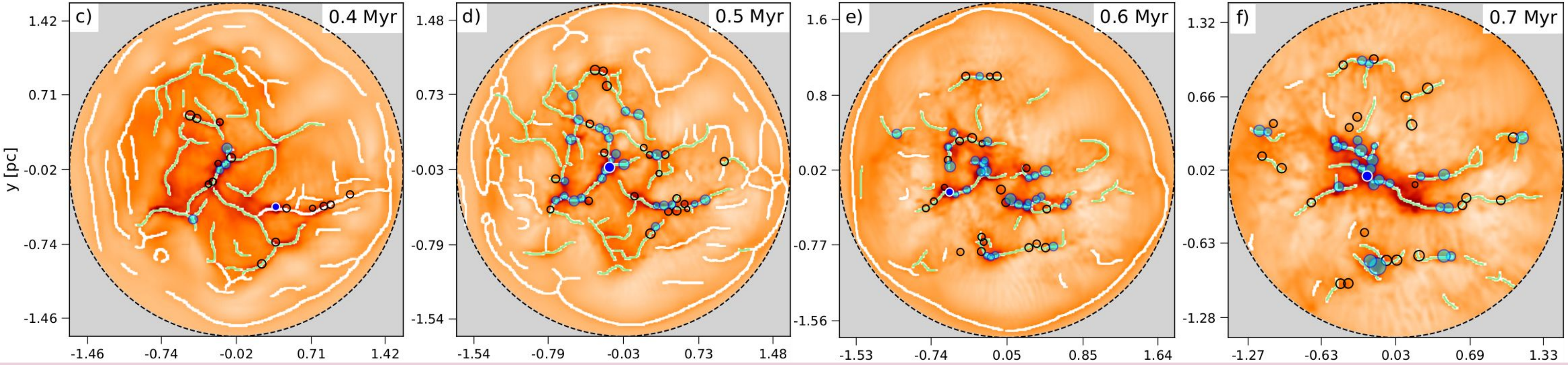
[Men'shchikov, A. 2021]

Cores | **Filaments**



$N(H_2)^{crest}_{med} \geq 10^{21.7}\ cm^{-2}$

t (Myr)	M_{max} ($M_\odot$)	Total Mass ($M_\odot$)
0.2	—	—
0.3	1.06	2.58
0.4	3.88	17.05
0.5	7.72	80.17
0.6	9.81	104.74
0.7	15.39	123.78



CCC can lead to the formation of HFS

Formation of filaments in CCC sites

Astronomical Images

getsf

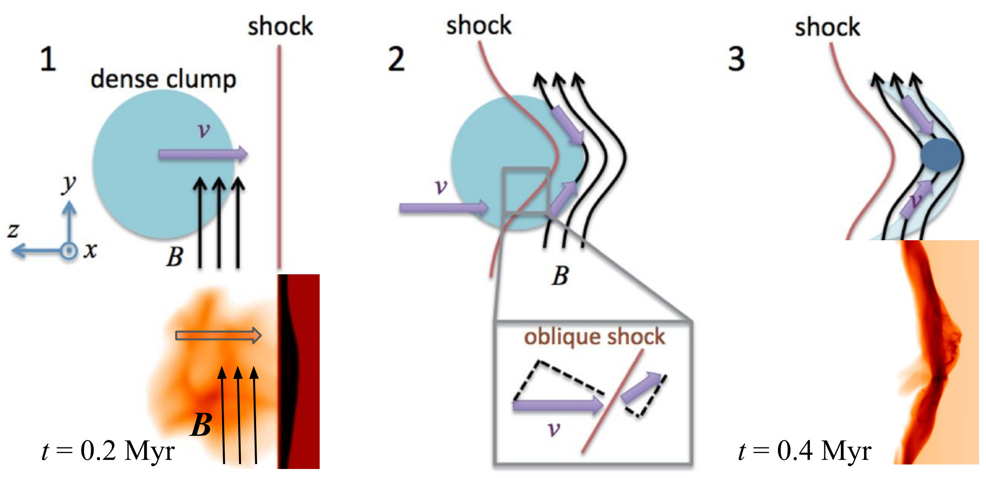
[Men'shchikov, A. 2021]

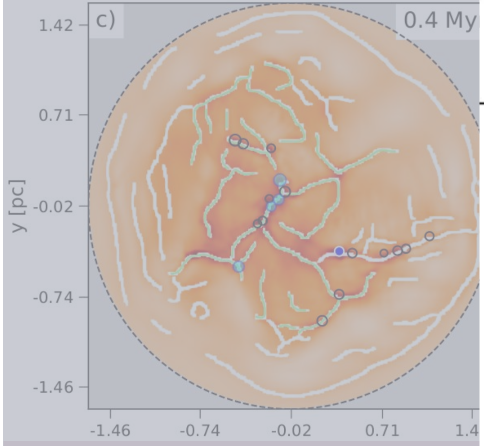
Cores

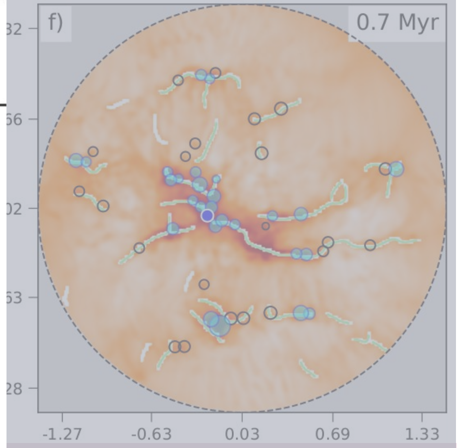
Filaments

t (Myr)	M_{max} ($M_\odot$)	Total Mass ($M_\odot$)
0.2	—	—
0.3	1.06	2.58
0.4	3.88	17.05
0.5	7.72	80.17
0.6	9.81	104.74
0.7	15.39	123.78

$N(H_2)^{crest}_{med} \geq 10^{21.7}$ cm^{-2}

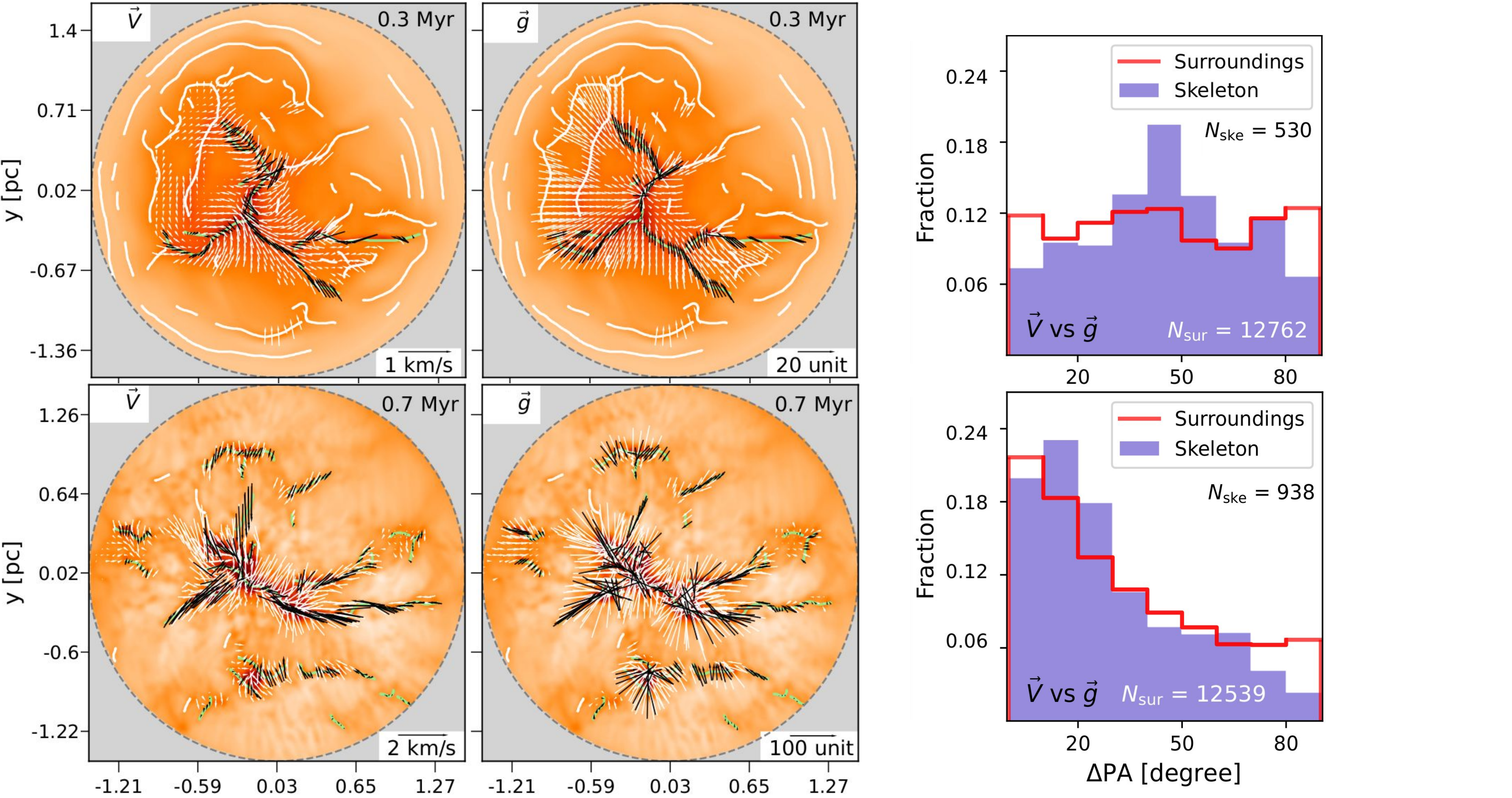


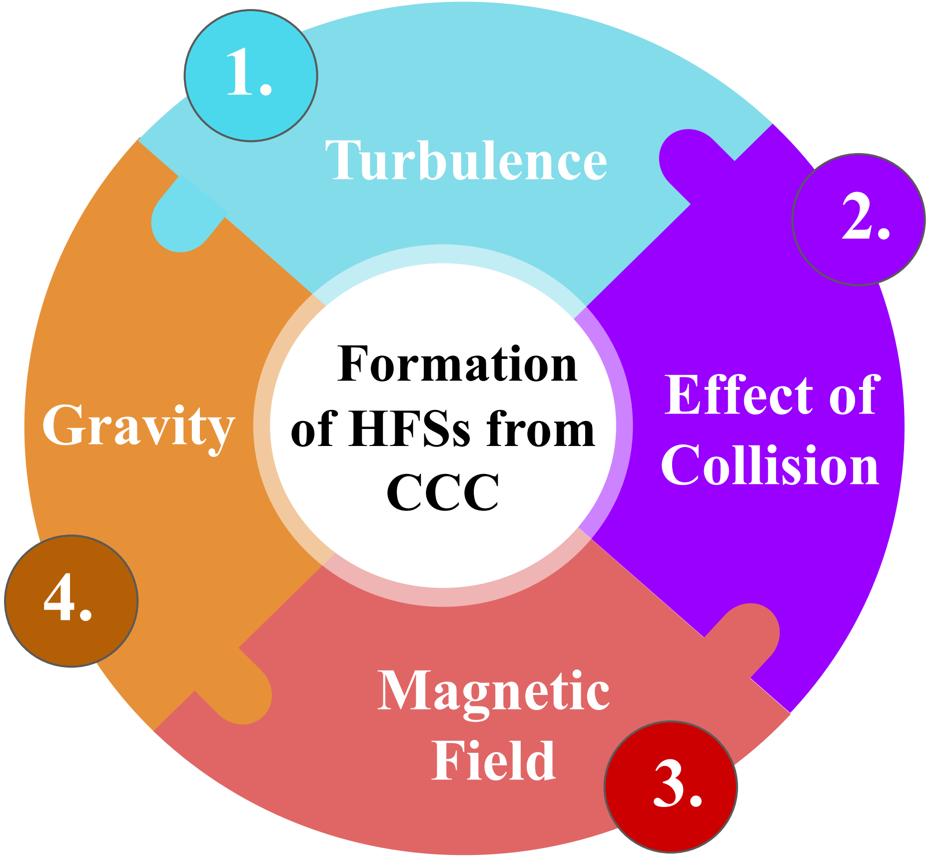




t (Myr)	$\text{Length}^{\text{Fil}}_{\text{tot}}$ (pc)	$\text{Mass}^{\text{Fil}}_{\text{tot}}$ ($M_\odot$)	$\frac{\text{Length}^{\text{Fil}}_{\text{x}}}{\text{Length}^{\text{Fil}}_{\text{y}}}$
0.2	0.62	51	0.80
0.3	4.74	466	1.51
0.4	10.35	864	1.03
0.5	13.15	1189	1.17
0.6	8.81	780	1.54
0.7	8.50	983	1.60

How do filaments converge?

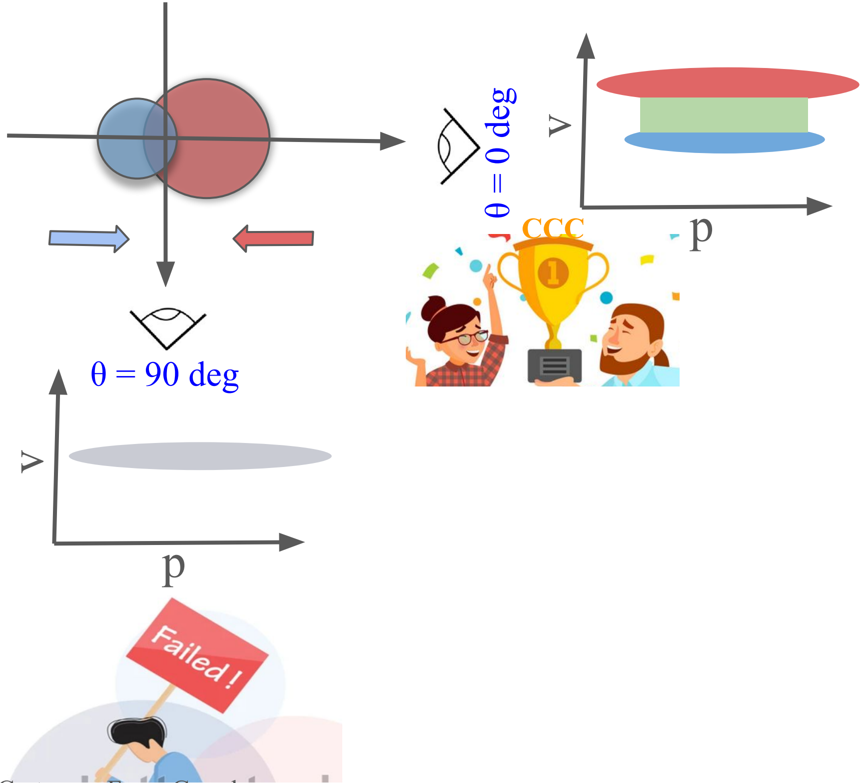



1.
Turbulence
2.
Effect of Collision
3.
Magnetic Field
4.
Gravity
Formation of HFSs from CCC

Observational difficulties in CCC detection

Estimated CCC rate in our Galaxy is ~ 1 per 100 years
[Dobbs et al. 2015]

Detected CCC sites ~ 90 !!!
[Fukui et al. 2021]



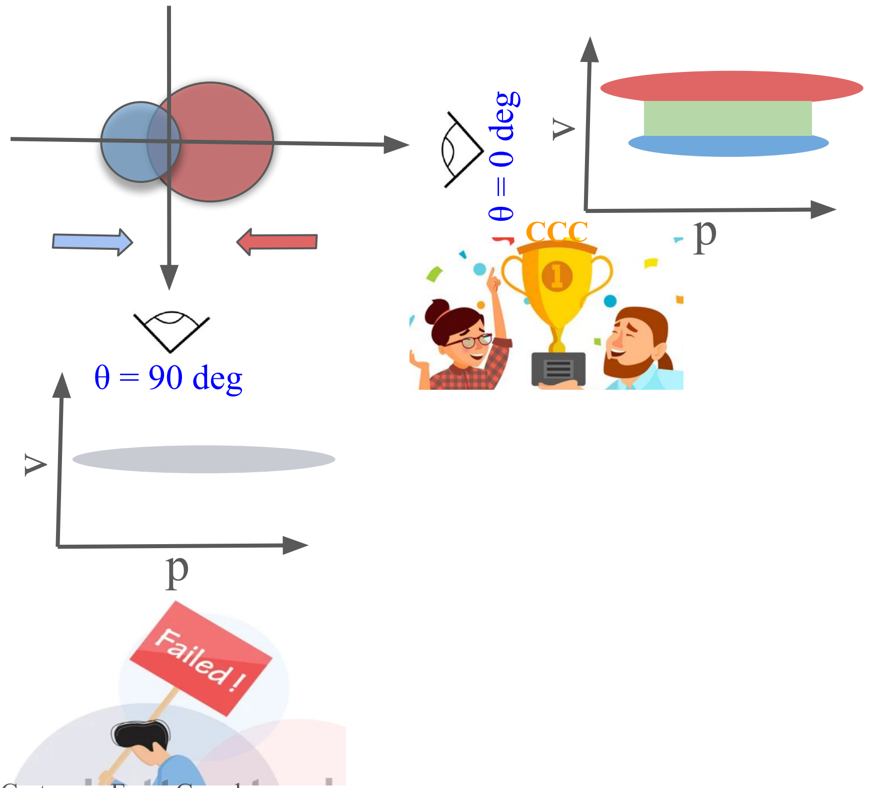
Cartoons: From Google.com

Estimated CCC rate in our Galaxy is ~ 1 per 100 years

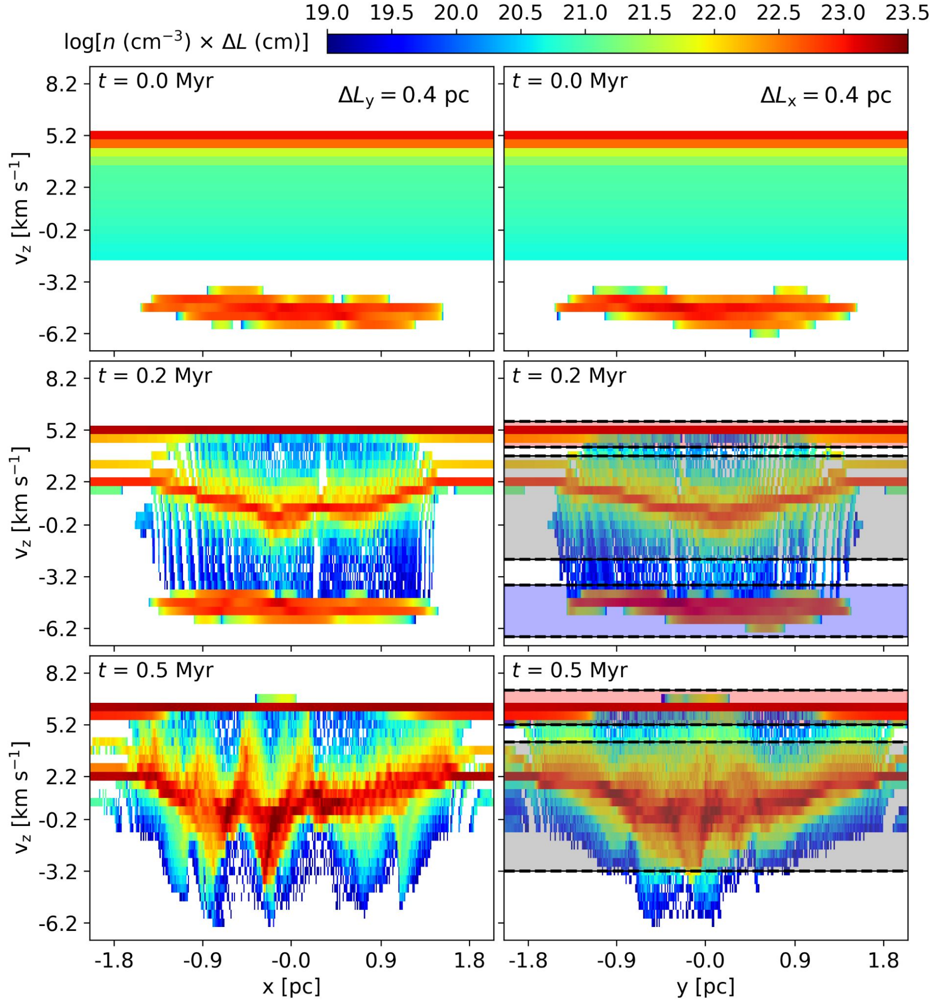
[Dobbs et al. 2015]

Detected CCC sites ~ 90 !!!

[Fukui et al. 2021]



Cartoons: From Google.com



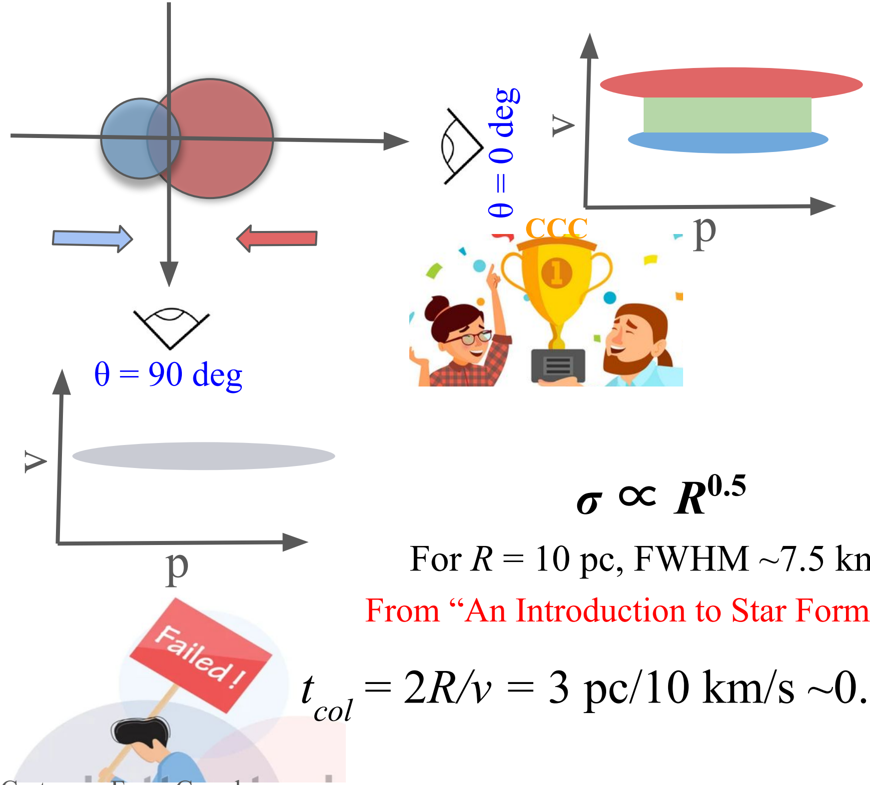
Observational difficulties in CCC detection

Estimated CCC rate in our Galaxy is ~ 1 per 100 years

[Dobbs et al. 2015]

Detected CCC sites ~ 90 !!!

[Fukui et al. 2021]

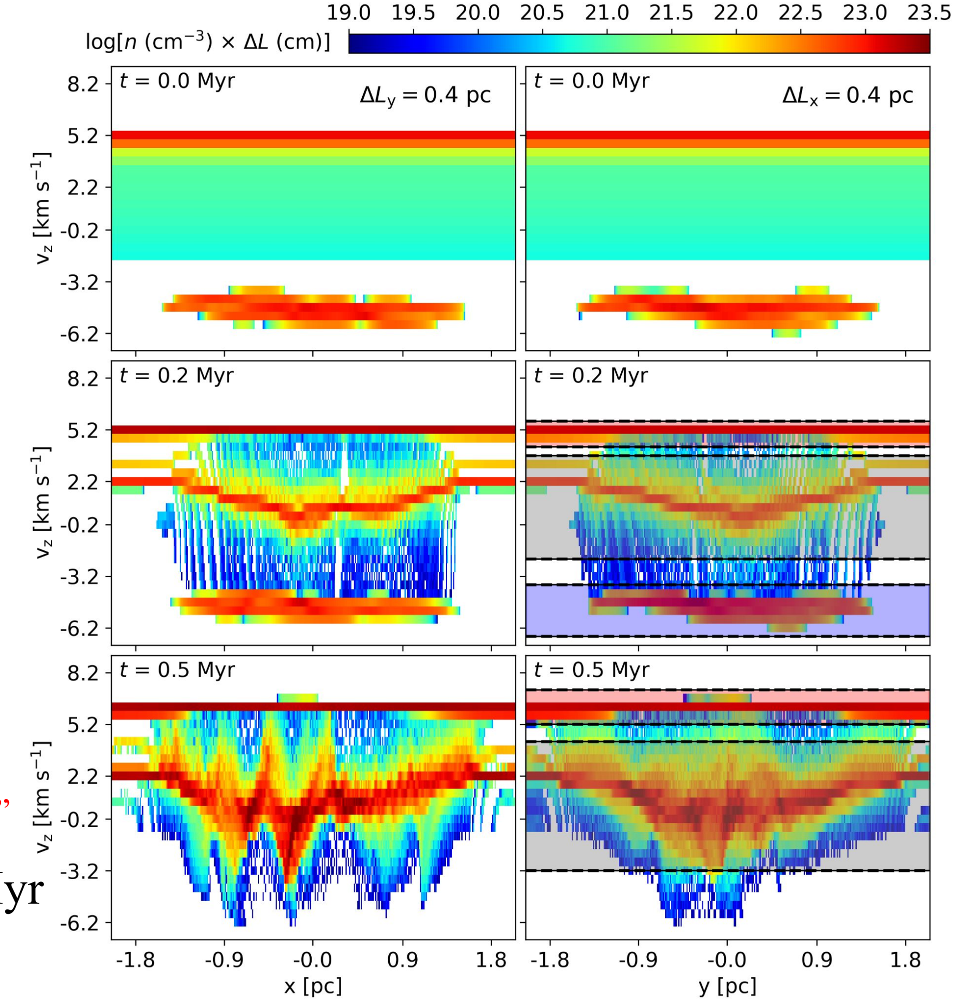


$$\sigma \propto R^{0.5}$$

For R = 10 pc, FWHM ~7.5 km/s

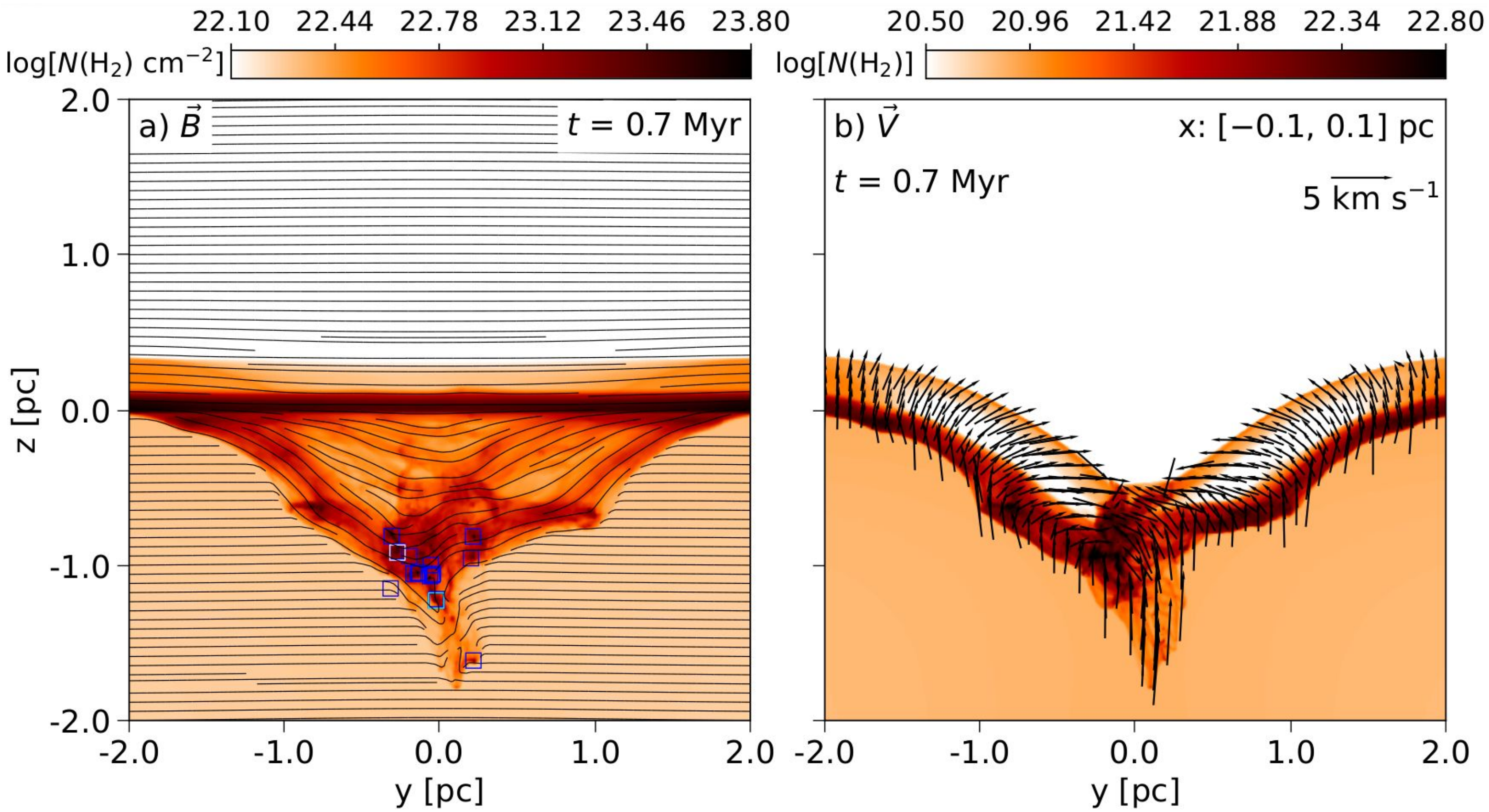
From “An Introduction to Star Formation”

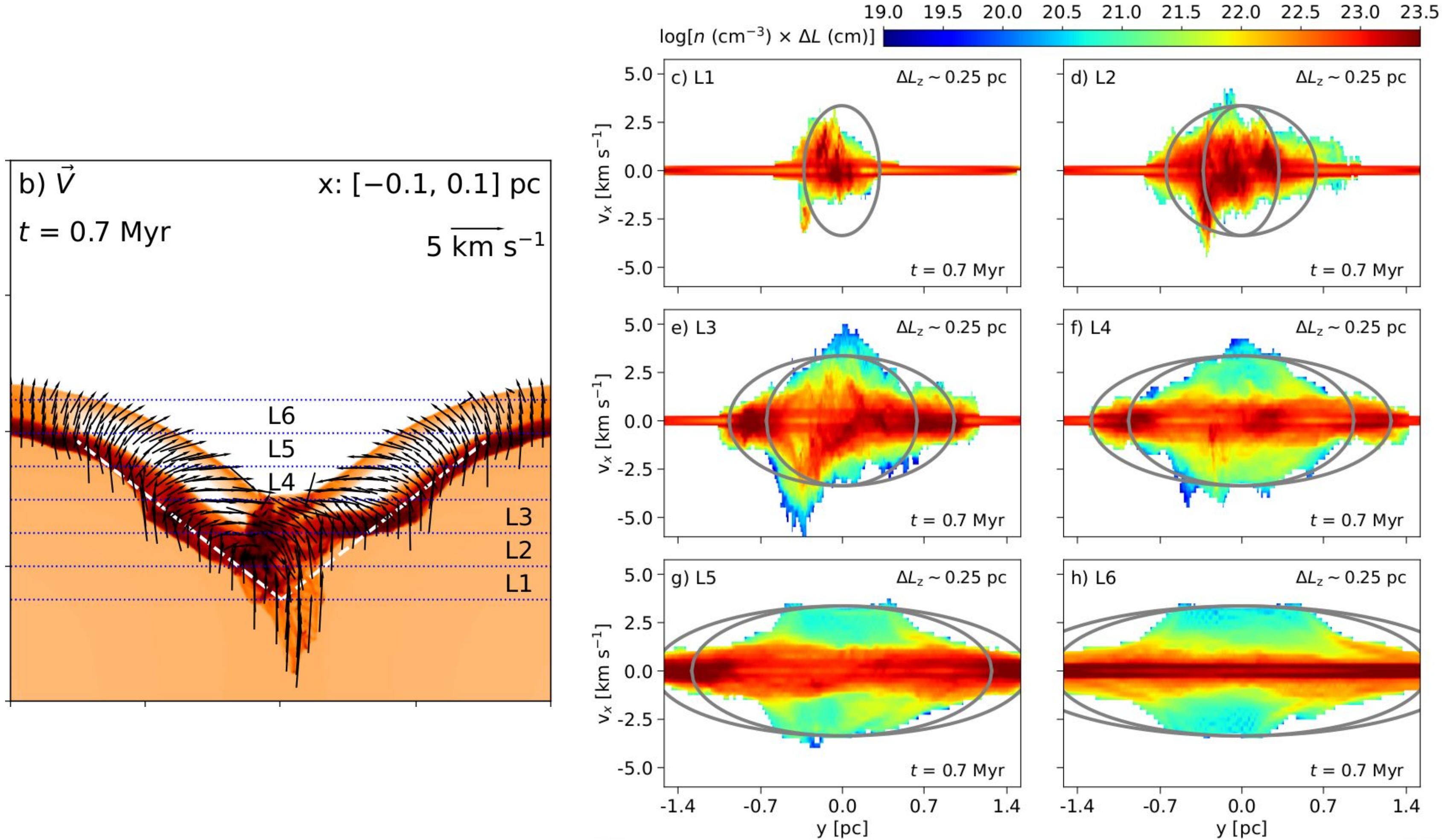
$$t_{col} = 2R/v = 3 \text{ pc}/10 \text{ km/s} \sim 0.3 \text{ Myr}$$

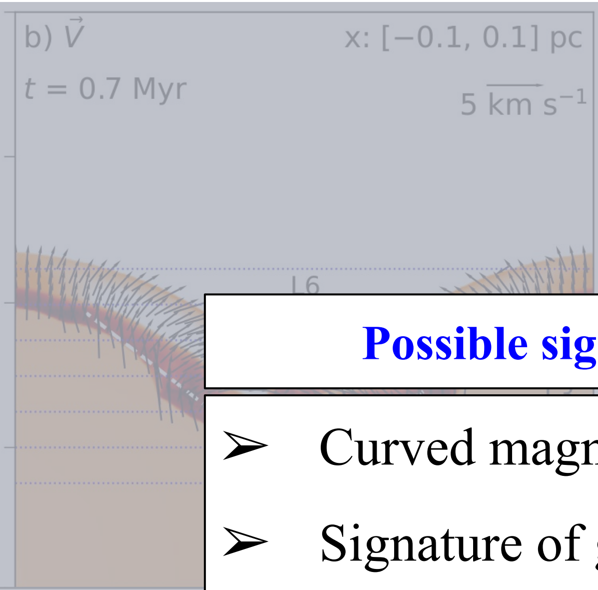


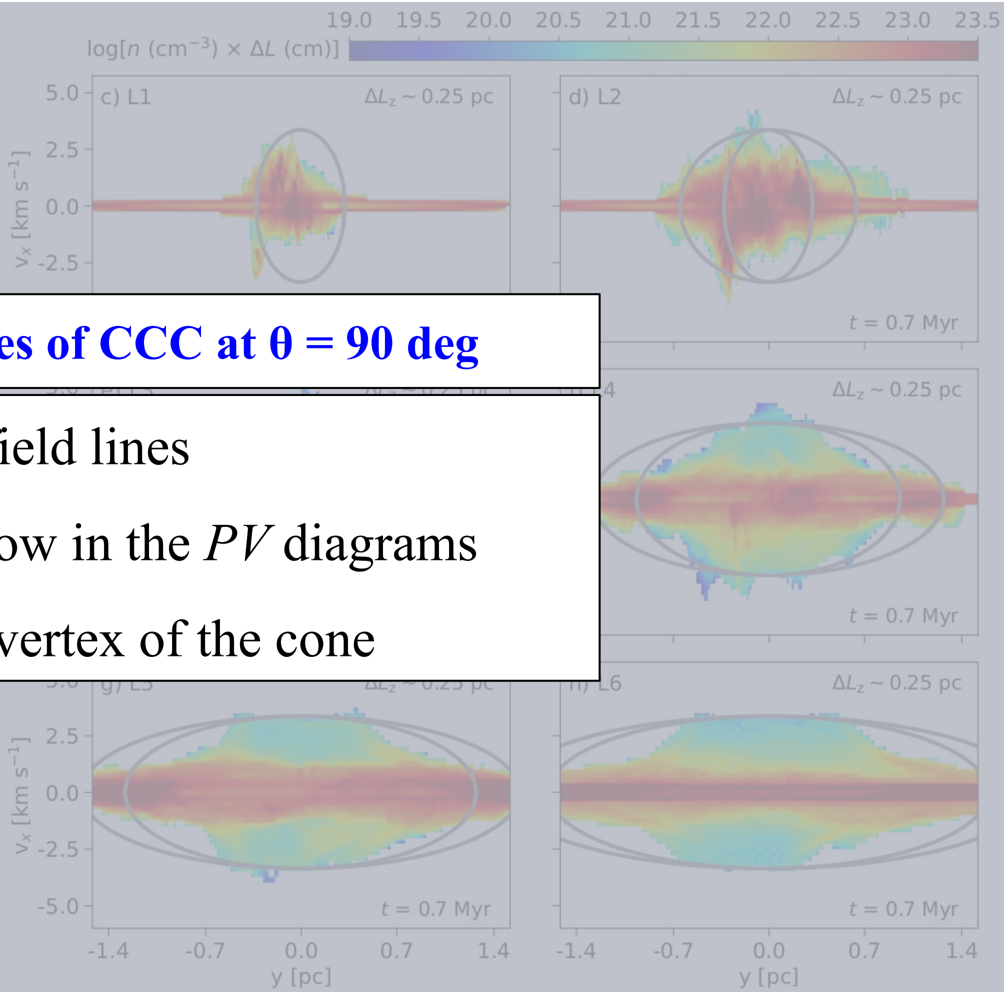
Cartoons: From Google.com

New signatures of CCC



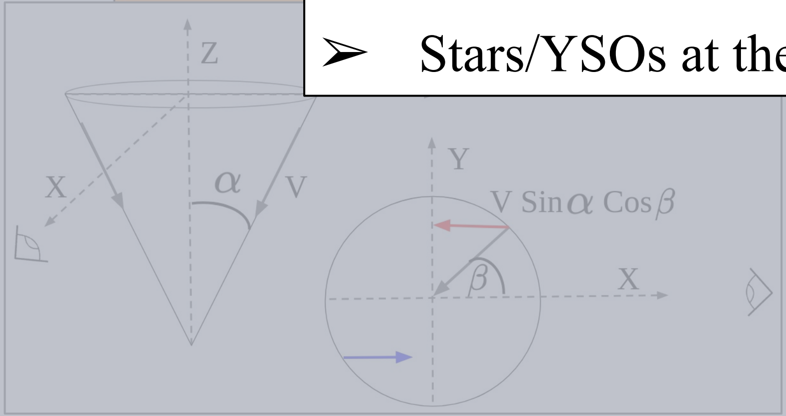

b) $\vec{V}$
x: [−0.1, 0.1] pc
t = 0.7 Myr
5 km s⁻¹
L6
L5
L4
L3
L2
L1
log[n (cm⁻³) × ΔL (cm)]
19.0 19.5 20.0 20.5 21.0 21.5 22.0 22.5 23.0 23.5
c) L1
d) L2
e) L3
f) L4
g) L5
h) L6
ΔLz ~ 0.25 pc
t = 0.7 Myr
vx [km s⁻¹]
5.0 2.5 0.0 -2.5 -5.0
-1.4 -0.7 0.0 0.7 1.4
y [pc]





Possible signatures of CCC at θ = 90 deg

- Curved magnetic field lines
- Signature of gas flow in the *PV* diagrams
- Stars/YSOs at the vertex of the cone



Summary

- CCC can lead to formation of HFSs.
- **CCC to HFSs:** A combined effect of turbulence, collision, magnetic field and gravity.
- Detecting two cloud components can be challenging when the clouds have a significant difference in size.
- **The curved magnetic field morphology, gas flow signatures in a cone, and spatial distribution of stars/YSOs** can be used to detect CCC sites.

Summary

- CCC can lead to formation of HFSs.
- **CCC to HFSs:** A combined effect of turbulence, collision, magnetic field and gravity.
- Detecting two cloud components can be challenging when the clouds have a significant difference in size.
- **The curved magnetic field morphology, gas flow signatures in a cone, and spatial distribution of stars/YSOs** can be used to detect CCC sites.

The ideal MHD Equations with self gravity

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{F}_x}{\partial x} + \frac{\partial \boldsymbol{F}_y}{\partial y} + \frac{\partial \boldsymbol{F}_z}{\partial z} = \boldsymbol{S}$$

→ MHD Equations

$$\boldsymbol{U} = (\rho, \rho v_x, \rho v_y, \rho v_z, B_x, B_y, B_z, \rho E)^T$$

Variable

$$\boldsymbol{F}_x = \begin{pmatrix} \rho v_x \\ \rho v_x^2 + P + |\boldsymbol{B}|^2/8\pi - B_x^2/4\pi \\ \rho v_x v_y - B_x B_y/4\pi \\ \rho v_x v_z - B_x B_z/4\pi \\ 0 \\ v_x B_y - v_y B_x \\ -v_z B_x + v_x B_z \\ (\rho E + P + |\boldsymbol{B}|^2/8\pi) v_x - B_x (\boldsymbol{B} \cdot \boldsymbol{v})/4\pi \end{pmatrix}$$

Flux

$$\boldsymbol{S} = (0, \rho g_x, \rho g_y, \rho g_z, 0, 0, 0, \rho \boldsymbol{g} \cdot \boldsymbol{v})^T$$

Source

Poisson's Equation

$$\nabla^2 \Phi = 4\pi G \rho$$

Φ: Gravitational potential

ρ: Density

Gravitational field

$$\boldsymbol{g} = (g_x, g_y, g_z)^T = -\nabla \Phi$$

Velocity

$$\boldsymbol{v} = (v_x, v_y, v_z)^T$$

Magnetic field

$$\boldsymbol{B} = (B_x, B_y, B_z)^T$$

$$E = |\boldsymbol{v}|^2/2 + P/\rho + |\boldsymbol{B}|^2/8\pi\rho$$

[Matsumoto 2007]

Values of important constants

GENERAL CONSTANTS:

Charge on electron	$-e$	$=$	$-1.60217733 \times 10^{-19}\ C$
Mass of electron	m_e	$=$	$9.1093897 \times 10^{-31}\,\mathrm{kg}$ $(\equiv\ 0.510998902\,\mathrm{Mev/c^2})$
Mass of proton	m_p	$=$	$1.6726231 \times 10^{-27}\,\mathrm{kg}$ $(\equiv\ 938.27200\,\mathrm{Mev/c^2})$
Mass of neutron	m_n	$=$	$1.6749286 \times 10^{-27}\,\mathrm{kg}$ $(\equiv\ 939.56533\,\mathrm{Mev/c^2})$
Permeability of vacuum	μ_0	$=$	$4\pi \times 10^{-7}\,\mathrm{H\,m^{-1}}$
Permittivity of vacuum	ϵ_0	$=$	$8.854187817 \times 10^{-12}\,\mathrm{F\,m^{-1}}$
Fine structure constant	α	$=$	$1/137.035989$
Gravitation constant	G	$=$	$6.67259 \times 10^{-11}\,\mathrm{N\,m^2\,kg^{-2}}$
Boltzmann's constant	k_B	$=$	$1.3806503 \times 10^{-23}\,\mathrm{J\,K^{-1}}$
Atmospheric pressure	1 atm.	$=$	$1.01325 \times 10^5\,\mathrm{N\,m^{-2}}$ (Pa)
Stefan-Boltzmann constant	σ	$=$	$5.6704 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$
Avogadro's number	N	$=$	6.0221367×10^{23}
Velocity of light	c	$=$	$2.99792458 \times 10^8\,\mathrm{m\,s^{-1}}$
Bohr radius	a_0	$=$	$5.2917721 \times 10^{-11}\,\mathrm{m}$
Bohr magneton	μ_B	$=$	$9.274006 \times 10^{-24}\,\mathrm{J\,T^{-1}}$
Planck's constant	h	$=$	$6.62607544 \times 10^{-34}\,\mathrm{J\,s}$
Planck's constant/2π	$\hbar$	$=$	$1.05457266 \times 10^{-34}\,\mathrm{J\,s}$

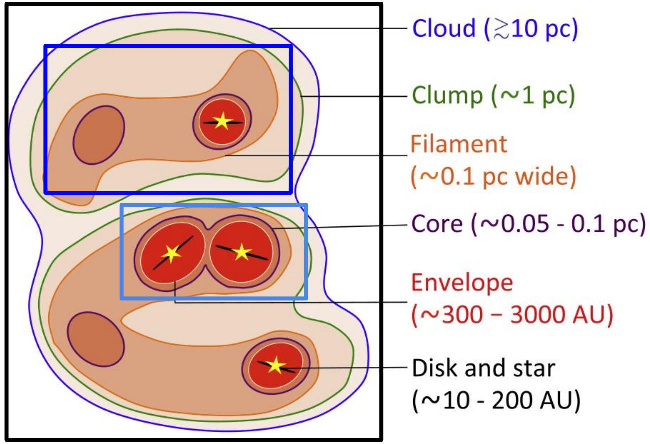
ASTRONOMICAL CONSTANTS

Astronomical unit:	1AU	$=$	$1.49597871 \times 10^{11}\,\mathrm{m}$
Parsec:	1pc	$=$	$3.08567758 \times 10^{16}\,\mathrm{m}$
Mass of the Earth	$M_\oplus$	$=$	$5.97 \times 10^{24}\,\mathrm{kg}$
Radius of the Earth	$R_\oplus$	$=$	$6.37814 \times 10^6\,\mathrm{m}$
Mass of the Sun	$M_\odot$	$=$	$1.99 \times 10^{30}\,\mathrm{kg}$
Radius of the Sun	$R_\odot$	$=$	$6.96 \times 10^8\,\mathrm{m}$
Luminosity of the Sun	$L_\odot$	$=$	$3.85 \times 10^{26}\,\mathrm{W}$
Thomson cross-section	σ_T	$=$	$6.652459 \times 10^{-29}\,\mathrm{m^2}$

Source: School of physics and Astronomy, University of Southampton

Mass accumulation processes

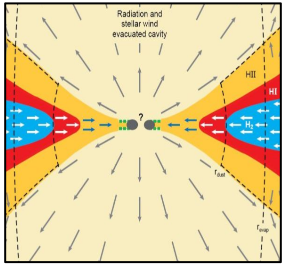
Massive stars $\geq 8M_{\odot} \Rightarrow 10^3 L_{\odot}$



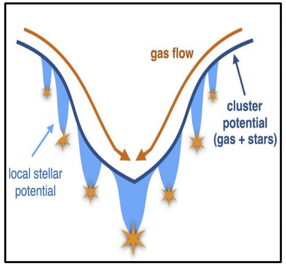
In Core Scale

How does core accumulate mass?

- ➢ Monolithic collapse [McKee & Tan 2002]
- ➢ Competitive accretion [Bonnel & Bate 2006]



[Zinnecker & Yorke 2007]

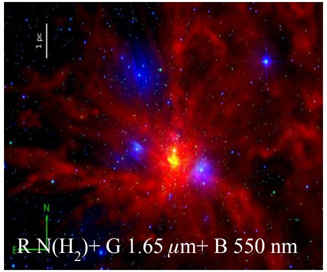


[Figure credit: Paul Clark]

In Intermediate Scale

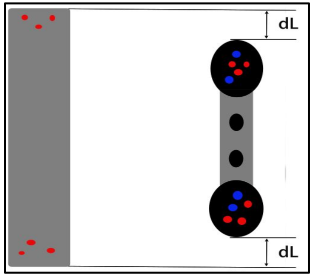
What is the role of filaments in mass accumulation?

- ➢ Hub-filament systems [HFS; Myers 2009]
- ➢ Edge-collapse in isolated Filament [EDC; Bastien (1983); Pon et al. (2012)]



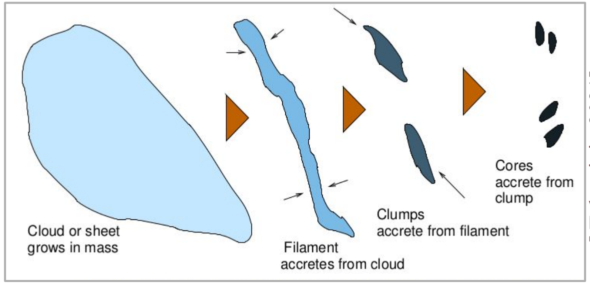
[Treviño-Morales et al. 2019]

[Yuan et al. 2020]



In Cloud Scale (Spontaneous)

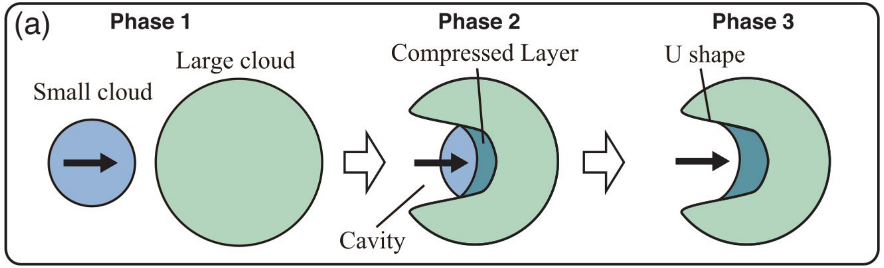
- ➢ Global Hierarchical collapse [Semadeni et al. 2007, 2017]



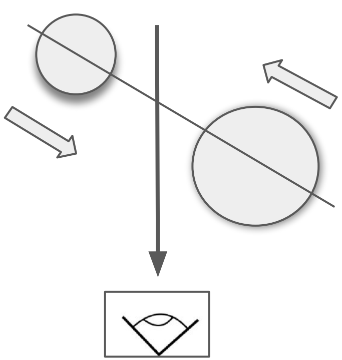
[Tokovinin 2021]

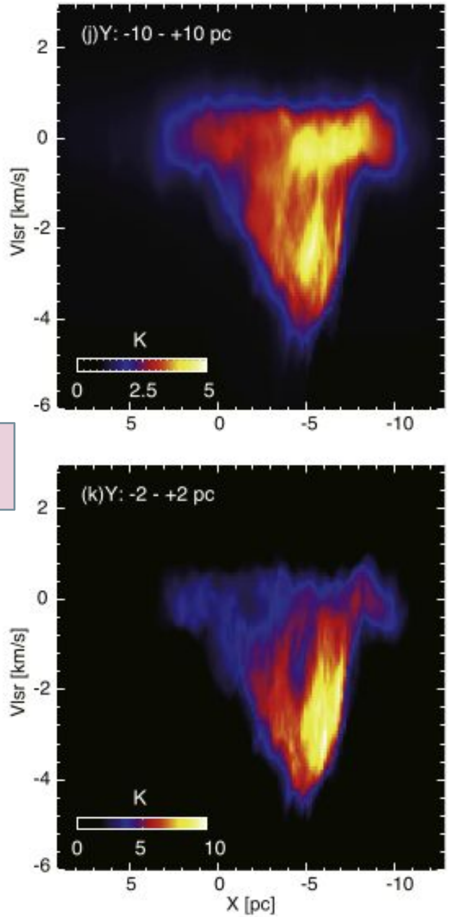
In Cloud Scale (Triggered)

- ➢ Cloud-cloud collision (CCC) [Habe & Ohta1992; Inoue & Fukui 2013]



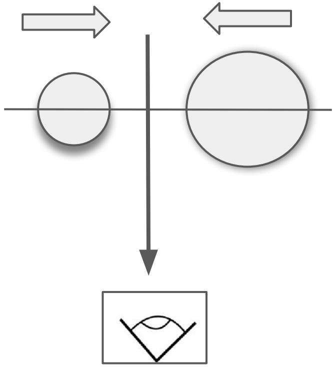
Observational Signatures of CCC

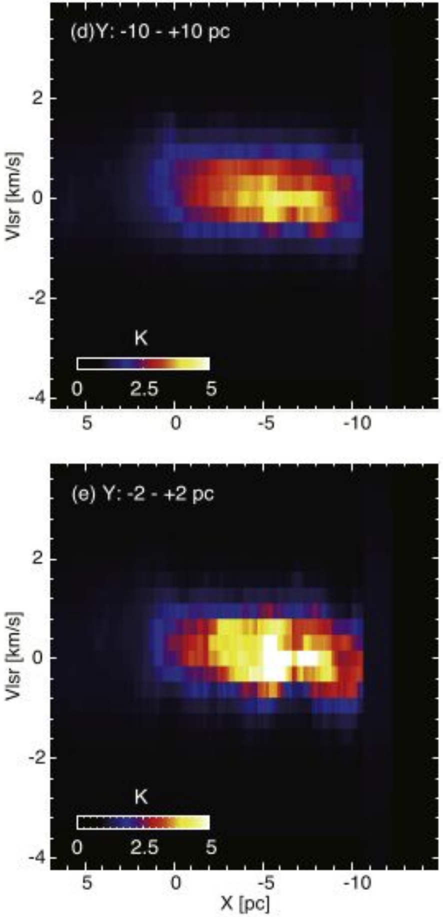




Bridge Feature (θ = 45 deg)

[From Tikahara et al. 2014]





Bridge Feature (θ = 90 deg)

[From Tikahara et al. 2014]

Formation of the SDC13 Hub-filament System: A Cloud–Cloud Collision Imprinted on the Multiscale Magnetic Field [Wang et al. 2022]

Distance ~3.6 kpc

Three velocity components: [5, 20] km/s, [32, 40] km/s, and [42, 58] km/s

1. IRAM 30m $C^{18}O$ (1–0) data: Resolution ~24.6 arcsec, σ ~0.17 K
2. SEDIGISM ^{13}CO (2–1) data: Resolution ~30 arcsec, σ ~1 K
3. JCMT 850 μm Stokes I image, Resolution ~14 arcsec, σ ~4 mJy/beam > To detect filaments

Formation of hub–filament structure triggered by a cloud–cloud collision in the W33 complex [Zhou et al. 2023]

Distance ~2.4 kpc

Three velocity components: [29.6, 43.3] km/s and [47.2, 60.2] km/s

1. FUGIN $^{13}CO/C^{18}O$(1 –0) data: Resolution ~20 arcsec, σ ~0.7/0.7 K, respectively
2. SEDIGISM ^{13}CO (2–1) data: Resolution ~30 arcsec, σ ~1 K
3. Integrated intensity map >>> To detect filaments

Set up the velocity dispersion

Observed velocity scaling relation for the molecular clouds

$$\Delta v_l \propto l^{1/2}$$

$$v_k^2 \propto k^{-4}$$

Assumption: Flow is divergence free

$$\nabla \cdot \boldsymbol{v} = 0$$

$$\boldsymbol{v} = \nabla \times \boldsymbol{A}$$

$$\langle | A_k |^2 \rangle \sim k^{-6}$$

$$\langle | A_k |^2 \rangle = C(k^2 + k_{\min}^2)^{-3}$$

a small k cutoff to assure convergence

$$k_{\min} = 2\pi/L$$

Size of the cloud

$$\sigma_v^2 = \frac{1}{2\pi^2} \int_0^\infty k^2\, dk\, P_v(k) = \frac{C}{8\pi} k_{\min}^{-1}$$

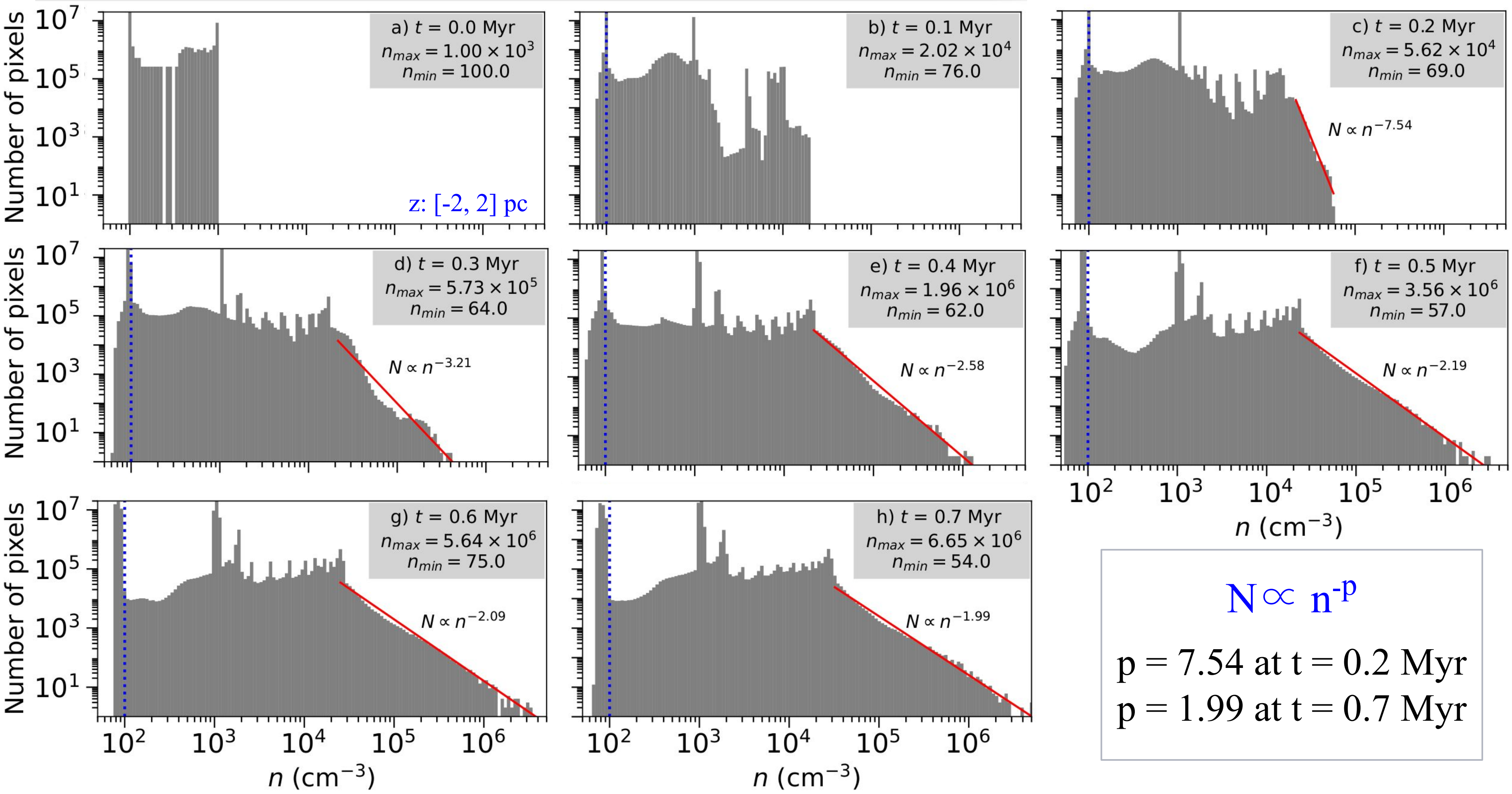
Virial equilibrium condition for a known mass and radius of molecular cloud

$$\boldsymbol{v}_k = i\boldsymbol{k} \times \boldsymbol{A}_k$$

Now take a IFT to get the velocity field

[From Dubinski et al. 1995]

Density Histograms

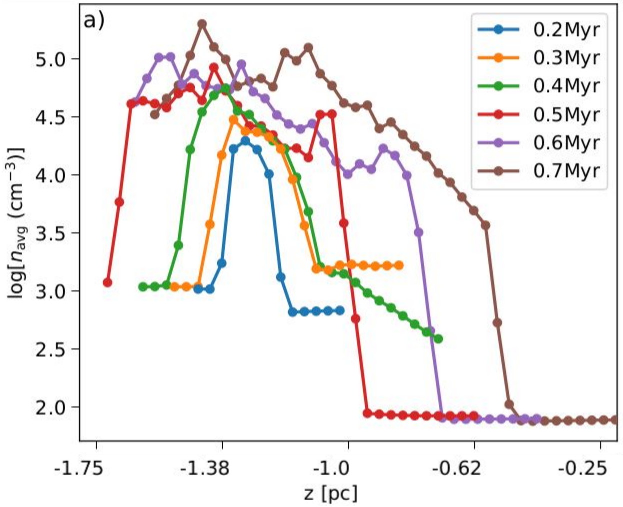


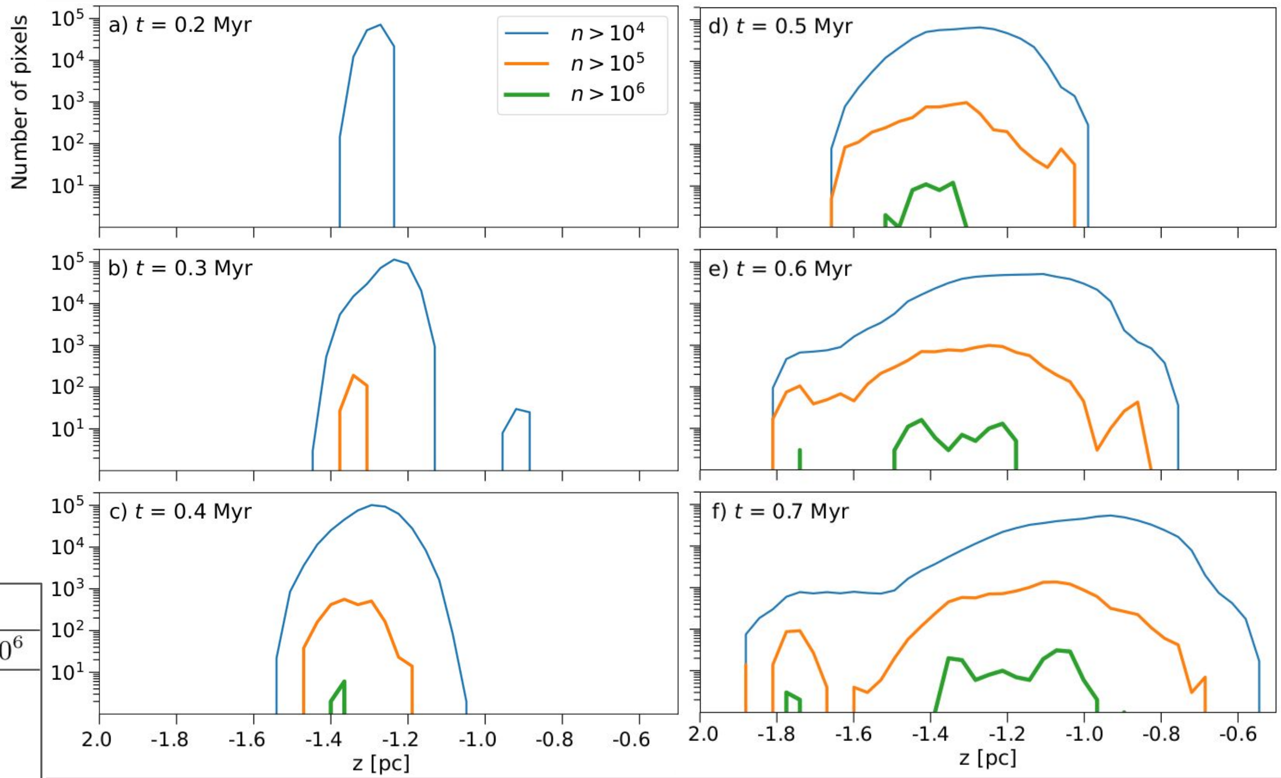
$N \propto n^{-p}$

p = 7.54 at t = 0.2 Myr

p = 1.99 at t = 0.7 Myr

The compressed layer

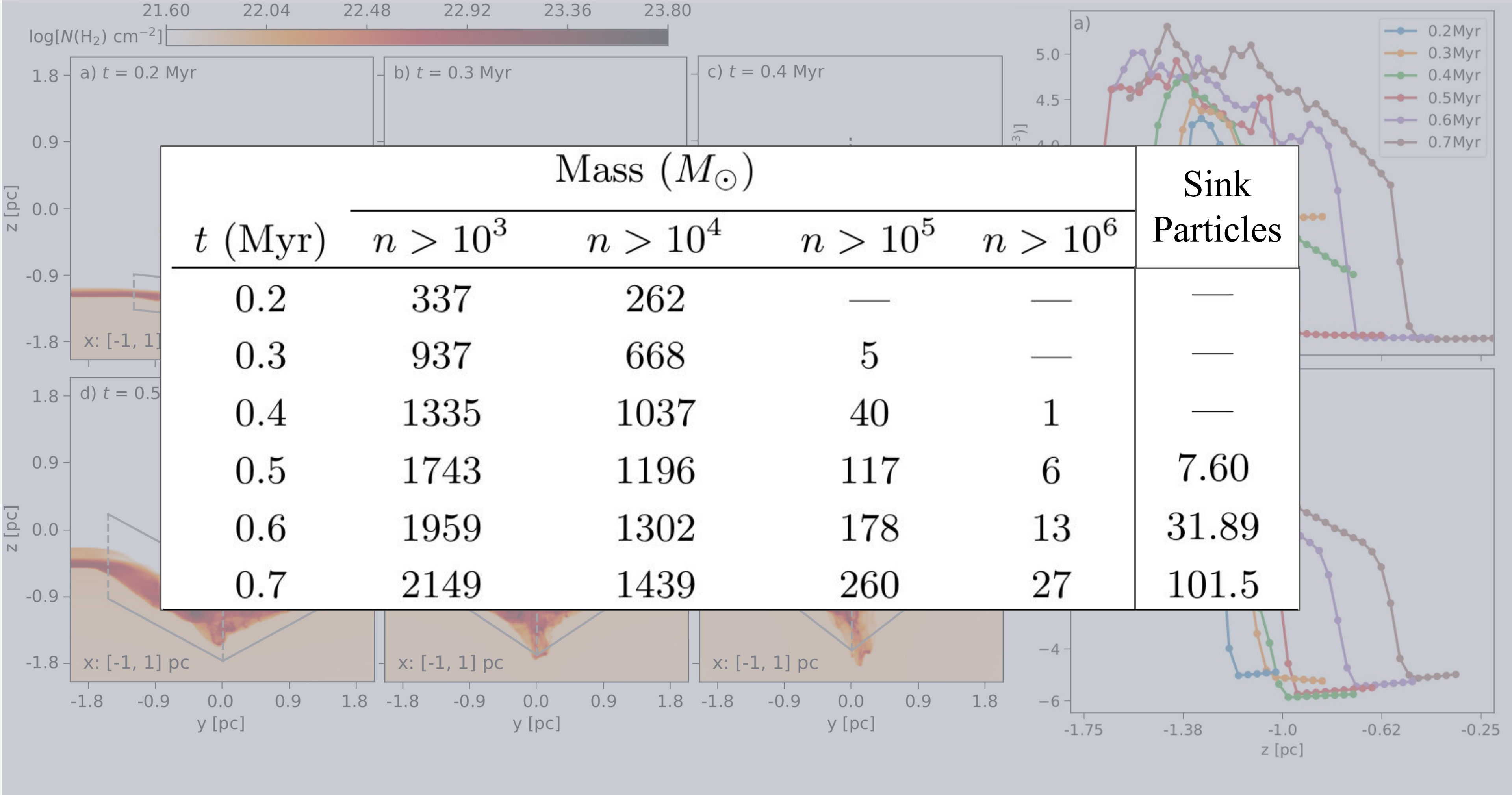




	Mass ($M_\odot$)			
t (Myr)	$n > 10^3$	$n > 10^4$	$n > 10^5$	$n > 10^6$
0.2	337	262	—	—
0.3	937	668	5	—
0.4	1335	1037	40	1
0.5	1743	1196	117	6
0.6	1959	1302	178	13
0.7	2149	1439	260	27

The fluctuation in the distribution of the high-density gas indicates the formation of structural components

The compressed layer



t (Myr)	Mass ($M_\odot$)				Sink Particles
	$n > 10^3$	$n > 10^4$	$n > 10^5$	$n > 10^6$	
0.2	337	262	—	—	—
0.3	937	668	5	—	—
0.4	1335	1037	40	1	—
0.5	1743	1196	117	6	7.60
0.6	1959	1302	178	13	31.89
0.7	2149	1439	260	27	101.5

Details of the getsf-identified cores and the sink particles

t (Myr)	$N^{\rm core}$	$M^{\rm core}_{\rm min}$ ($M_\odot$)	$M^{\rm core}_{\rm max}$ ($M_\odot$)	$M^{\rm core}_{\rm total}$ ($M_\odot$)	$N^{\rm sink}$	$M^{\rm sink}_{\rm min}$ ($M_\odot$)	$M^{\rm sink}_{\rm max}$ ($M_\odot$)	$M^{\rm sink}_{\rm total}$ ($M_\odot$)	$M^{\rm core}_{\rm total} + M^{\rm sink}_{\rm total}$ ($M_\odot$)
0.2	—	—	—	—	—	—	—	—	—
0.3	3	0.71	1.06	2.58	—	—	—	—	2.58
0.4	19	0.24	3.88	17.05	—	—	—	—	17.05
0.5	46	0.21	7.72	80.17	3	0.16	5.04	7.60	87.77
0.6	50	0.36	9.81	104.74	9	0.28	20.25	31.89	136.63
0.7	50	0.19	15.39	123.78	25	0.04	40.25	101.5	225.28

Shock compression of the interface layer

[From Inoue & Fukui 2013]

Zero magnetic field

Shock compression ratio; $r = \frac{\rho_2}{\rho_1} = M_s^2$, where, $M_s = \frac{v_{coll}}{c_s}$

For, $v_{coll} = 10\, km/s, c_s = 0.2\, km/s$, $M_s = 50$

Initial density, $n_1 \sim 10^3\ cm^{-3}$; Shocked layer density, $n_2 \sim 10^6\ cm^{-3}$

[From Inoue & Fukui 2013]

Non-zero magnetic field

$r = \frac{\rho_2}{\rho_1} = \sqrt{2}\, M_A = \frac{B_2}{B_1}$, where, $M_A = \frac{v_{coll}}{c_A}$

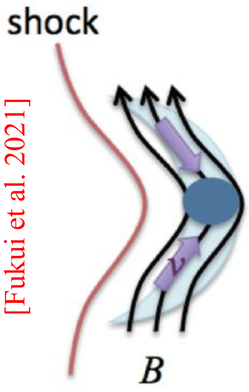
For, $v_{coll} = 10\, km/s, n_1 = 300\, cm^{-3}, B_1 = 10\, \mu G$

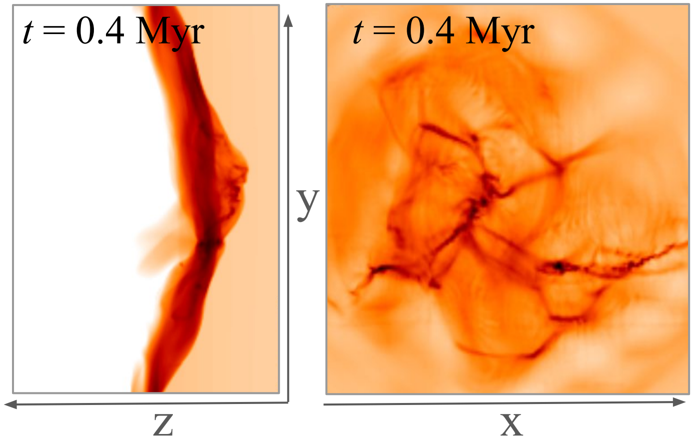
$$\frac{\rho_2}{\rho_1} \sim 17$$

Magnetic field plays a crucial role in massive star formation in CCC

Formation of filaments in CCC sites

[Fukui et al. 2021]





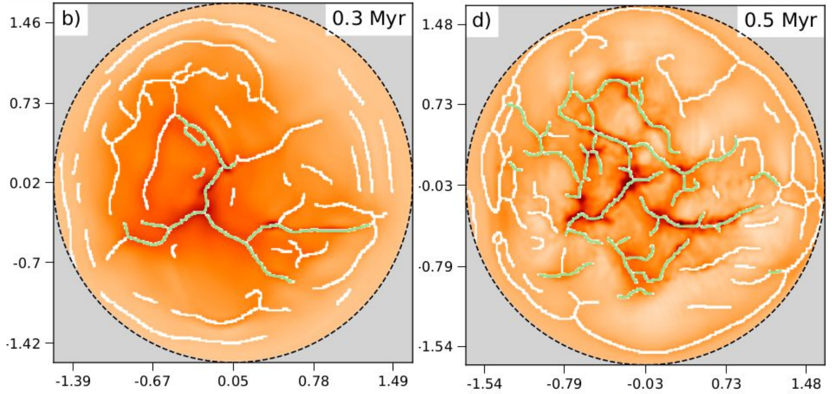
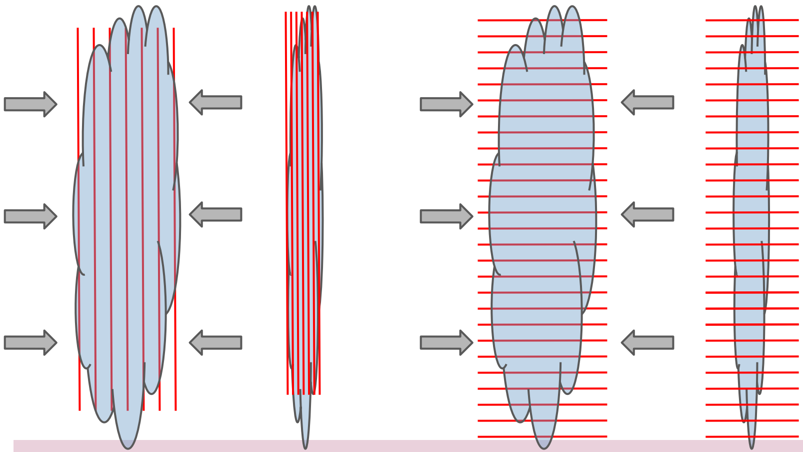


Table 2. Physical parameters for the high-density filaments with $N(\mathrm{H_2})^{\mathrm{crest}} \geq 10^{21.7}$ cm^{-2}.

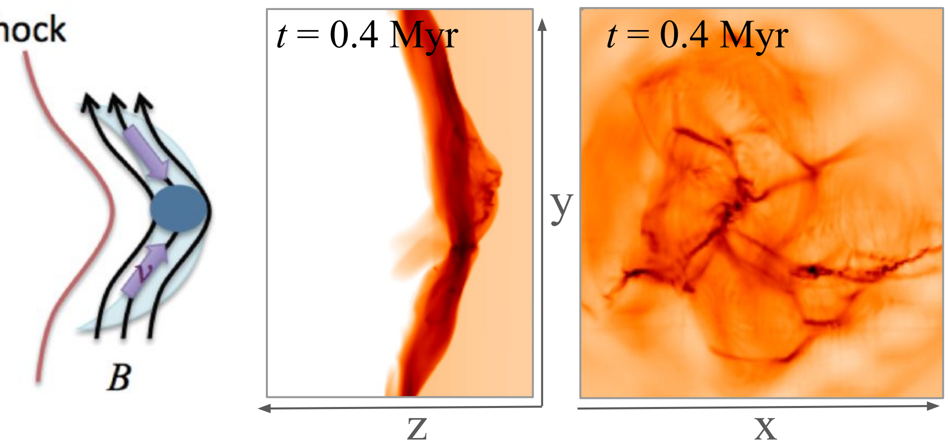
t (Myr)	N^{Fil}	$\mathrm{Length}^{\mathrm{Fil}}_{\mathrm{tot}}$ (pc)	$\mathrm{Mass}^{\mathrm{Fil}}_{\mathrm{tot}}$ ($M_\odot$)	$\frac{\mathrm{Length}^{\mathrm{Fil}}_{\mathrm{x}}}{\mathrm{Length}^{\mathrm{Fil}}_{\mathrm{y}}}$
0.2	2	0.62	51	0.80
0.3	8	4.74	466	1.51
0.4	19	10.35	864	1.03
0.5	31	13.15	1189	1.17
0.6	24	8.81	780	1.54
0.7	23	8.50	983	1.60



This gives rise to the filament parallel to the magnetic field, with an increased magnetic field strength.

Formation of filaments in CCC sites

[Fukui et al. 2021]



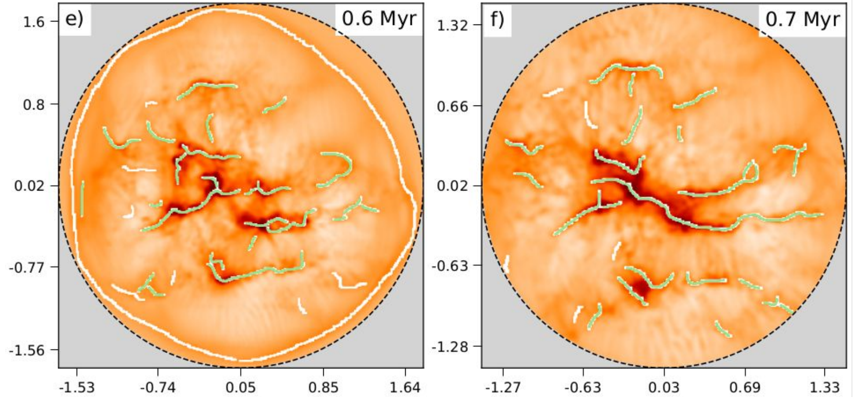
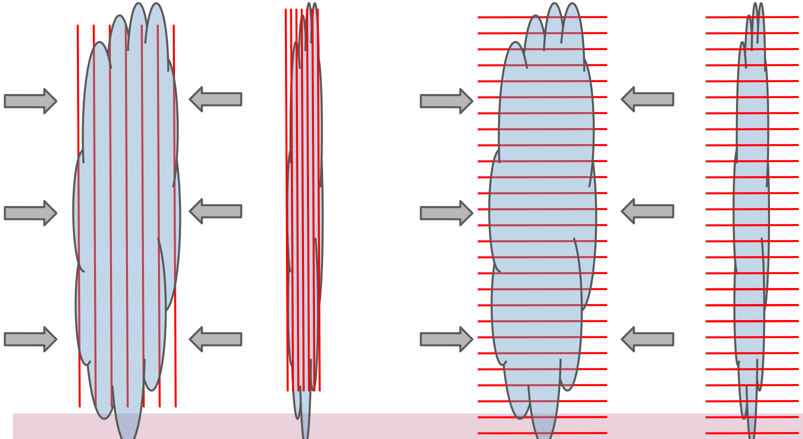


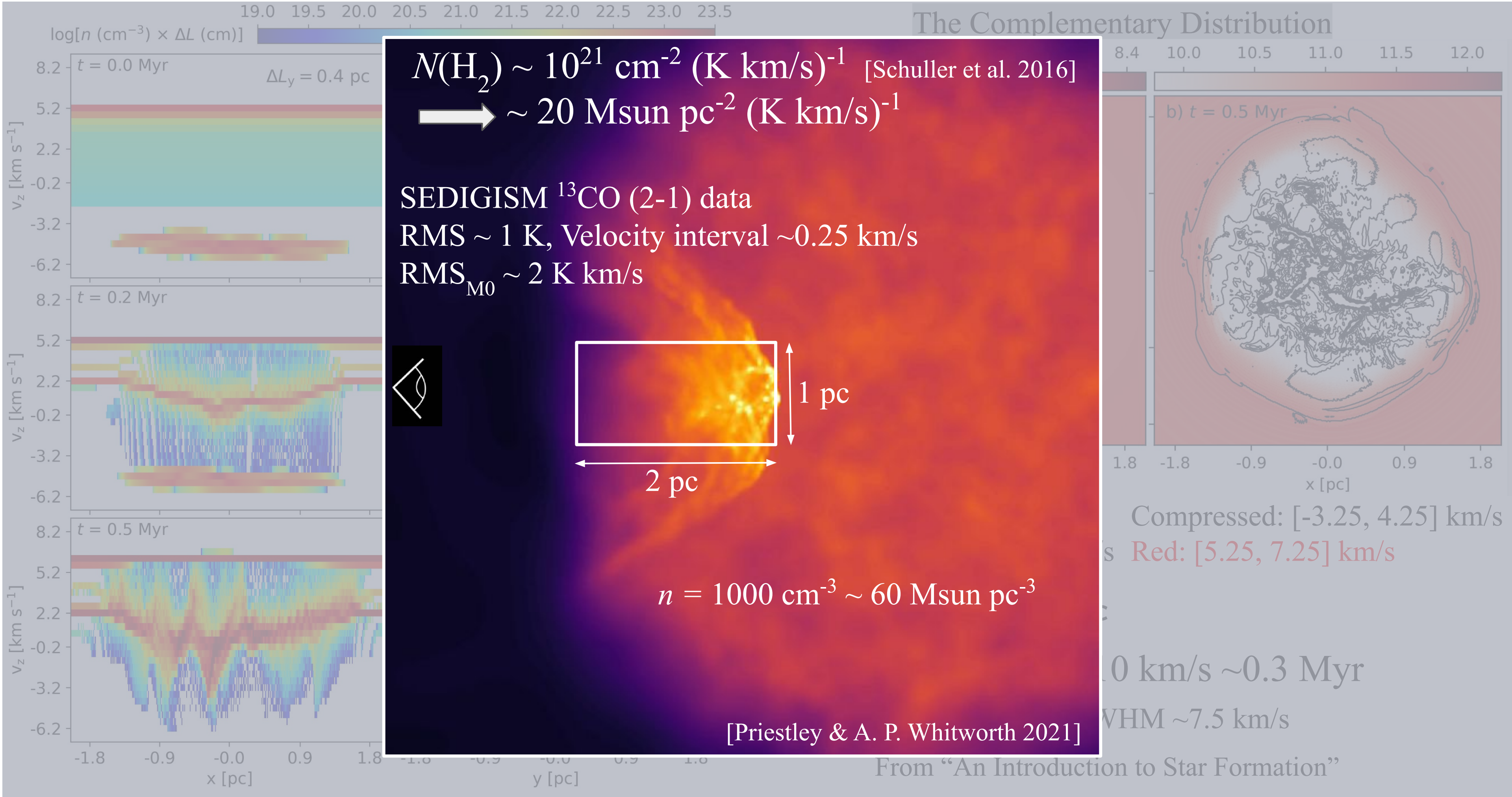
Table 2. Physical parameters for the high-density filaments with $N(H_2)^{crest} \geq 10^{21.7}$ cm^{-2}.

t (Myr)	N^{Fil}	$Length^{Fil}_{tot}$ (pc)	$Mass^{Fil}_{tot}$ ($M_\odot$)	$\frac{Length^{Fil}_x}{Length^{Fil}_y}$
0.2	2	0.62	51	0.80
0.3	8	4.74	466	1.51
0.4	19	10.35	864	1.03
0.5	31	13.15	1189	1.17
0.6	24	8.81	780	1.54
0.7	23	8.50	983	1.60

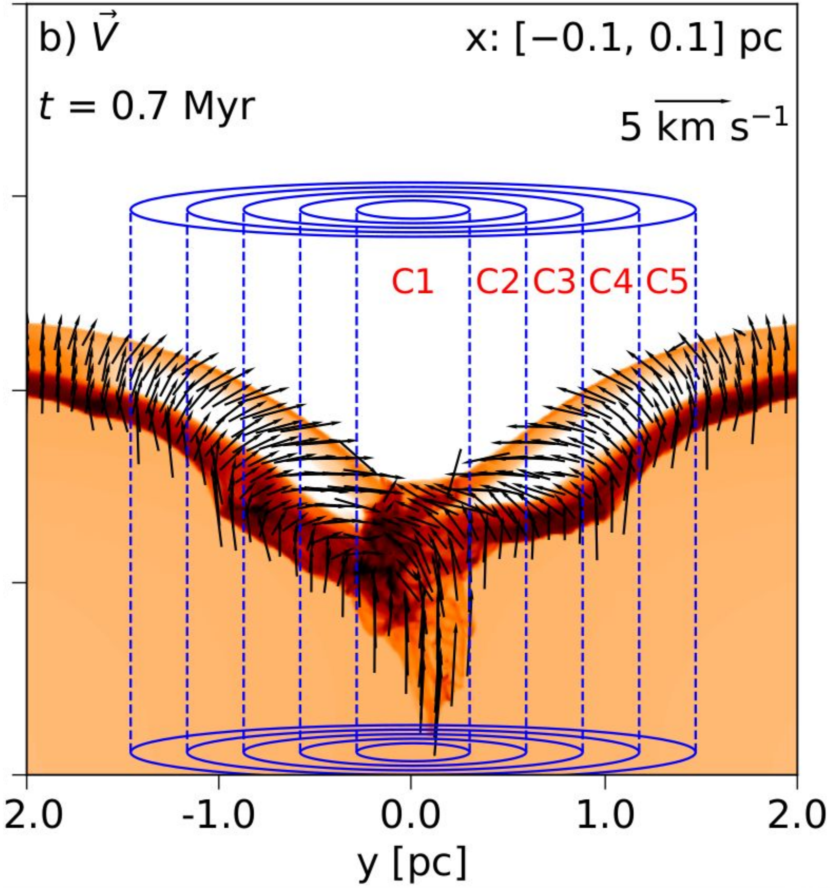


Rise in the projected length ratio and drop in the total mass and length of the high-density filaments after $t = 0.5$ Myr.

Observational difficulties in CCC detection



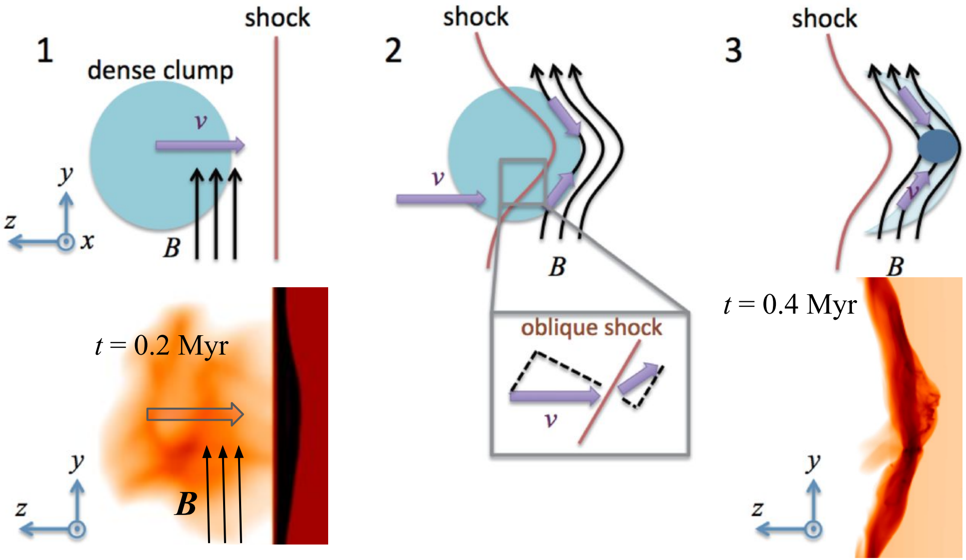
The Cone: A mass-collecting machine



Cylindrical shell	M^{gas} ($M_\odot$)	Volume fraction (%)	M^{sink} ($M_\odot$)	$\frac{M^{\mathrm{gas}}+M^{\mathrm{sink}}}{M_{\mathrm{total}}}$
C1	233	8.1	69	0.17
C2	355	15.6	25	0.21
C3	327	20.0	8	0.19
C4	353	25.2	–	0.19
C5	436	31.1	–	0.24

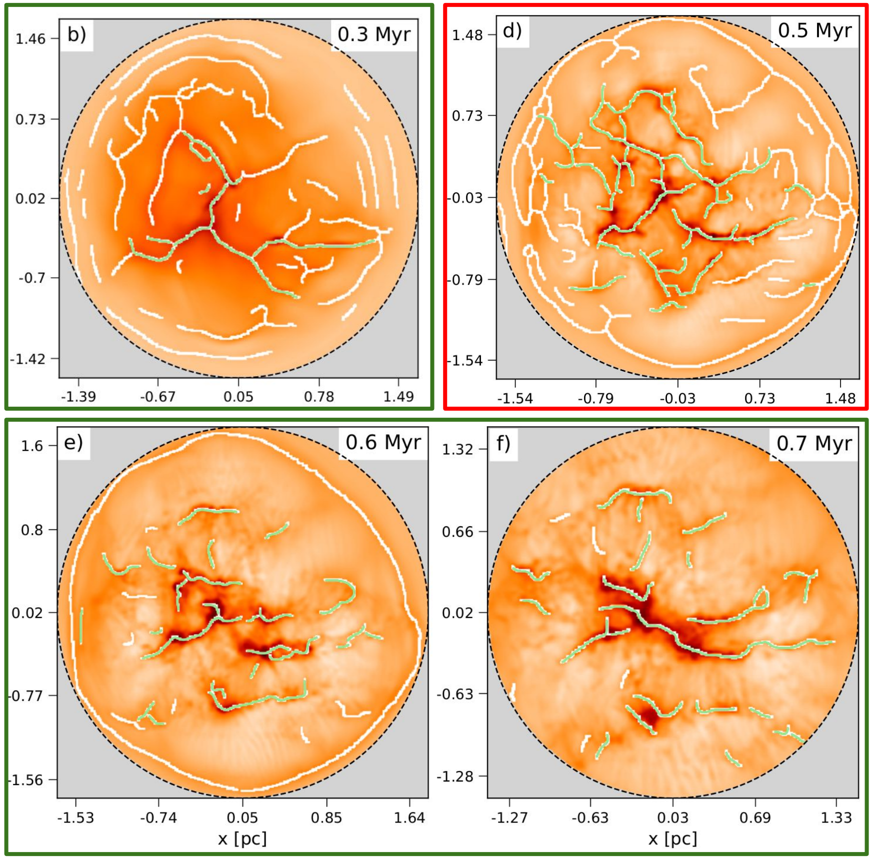
Collects huge amount of gas rapidly in a small volume

Formation of filaments in CCC sites



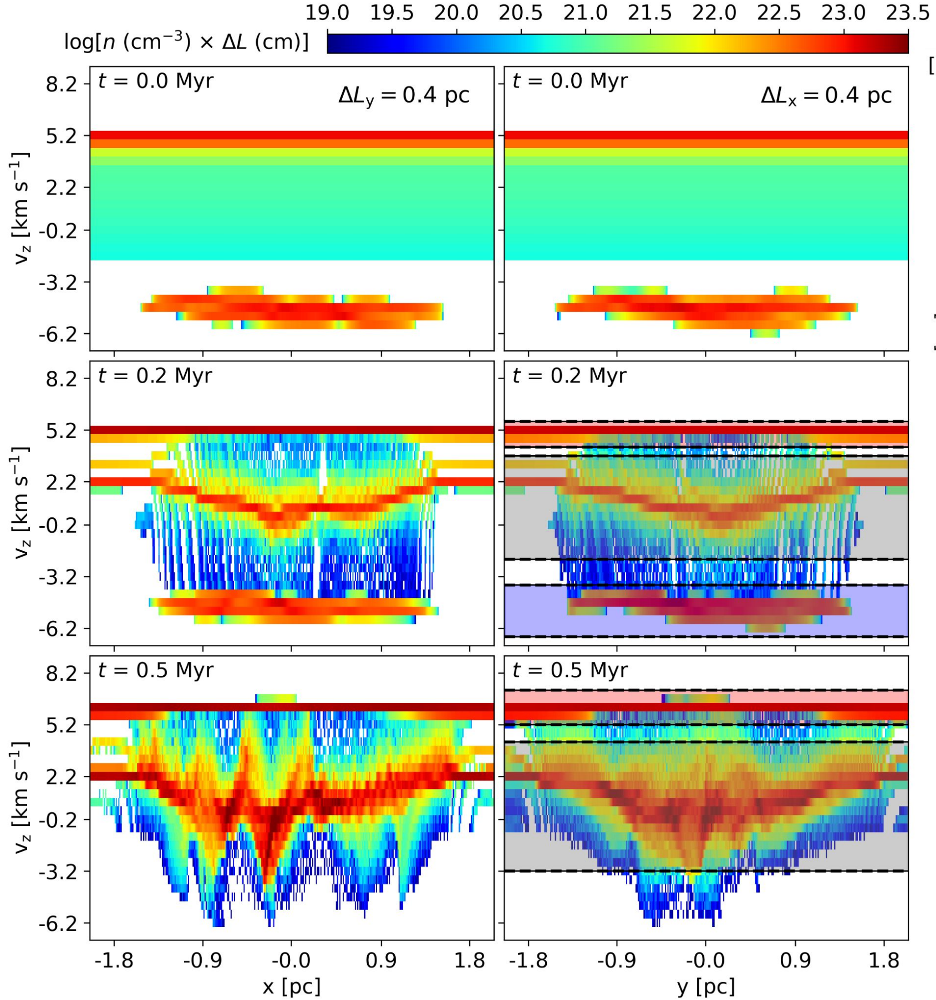
[Fukui et al. 2021]

Rise in the projected length ratio and drop in the total mass and length of the high-density filaments after $t = 0.5$ Myr.

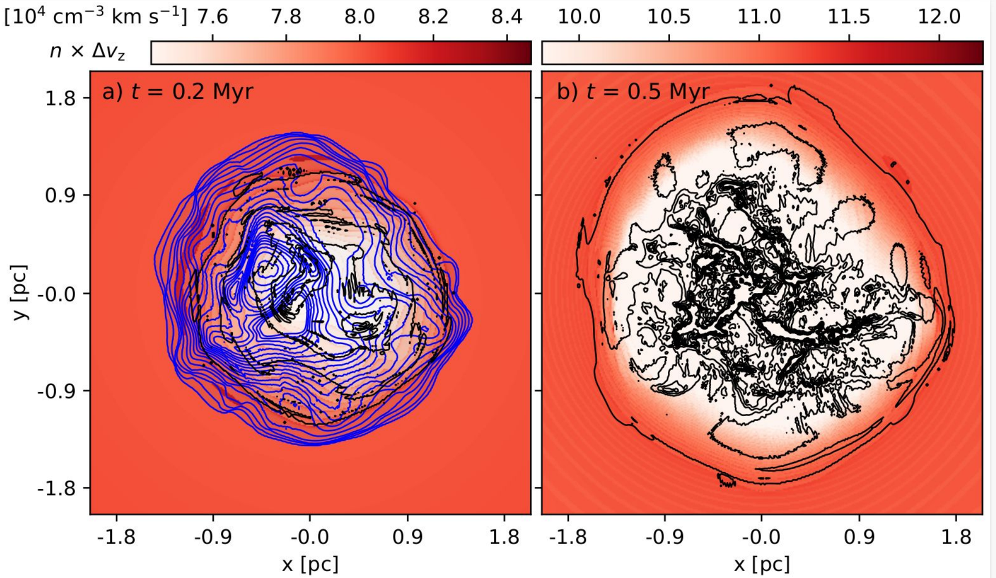


t (Myr)	$\mathrm{Length}^{\mathrm{Fil}}_{\mathrm{tot}}$ (pc)	$\mathrm{Mass}^{\mathrm{Fil}}_{\mathrm{tot}}$ ($M_{\odot}$)	$\frac{\mathrm{Length}^{\mathrm{Fil}}_{\mathrm{x}}}{\mathrm{Length}^{\mathrm{Fil}}_{\mathrm{y}}}$
0.2	0.62	51	0.80
0.3	4.74	466	1.51
0.4	10.35	864	1.03
0.5	13.15	1189	1.17
0.6	8.81	780	1.54
0.7	8.50	983	1.60

Observational difficulties in CCC detection



The Complementary Distribution



Blue: [-6.75, -3.75] km/s

Compressed: [-2.25, 3.75] km/s

Red: [4.25 5.75] km/s

Compressed: [-3.25, 4.25] km/s

Red: [5.25, 7.25] km/s

$$t_{col} = 2R/v = 3 \text{ pc}/10 \text{ km/s} \sim 0.3 \text{ Myr}$$

$$\boldsymbol{\sigma \propto R^{0.5}}$$

For R = 10 pc, FWHM ~7.5 km/s

From “An Introduction to Star Formation”

Outline

- Introduction and Motivation
- Objectives
- Data set
- Results
- Summary