星間プラズマの熱的不安定性と短寿命崩壊核の太陽系形成環境への供給

(Kobayashi+ 2017, Kobayashi+ 2023, Kobayashi+ 2026a in prep)

小林将人
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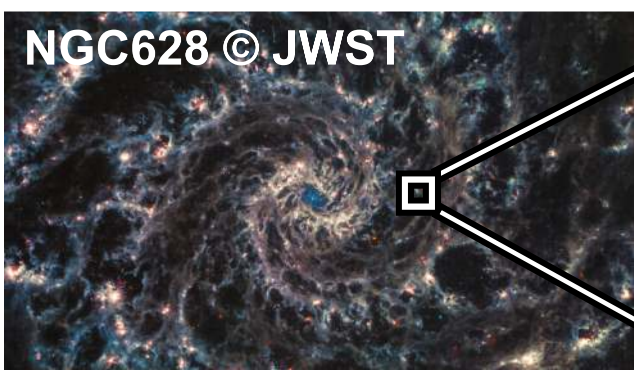
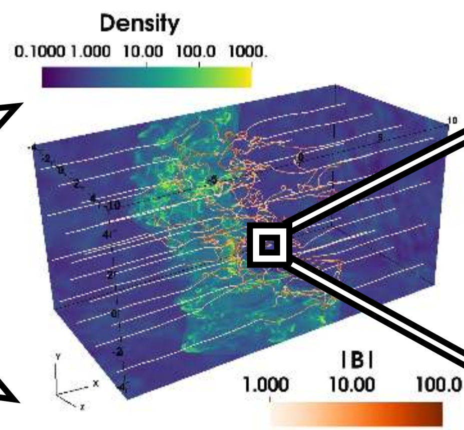
UNIVERSITÄT ZU KÖLN → NIFS

衝撃波に満ちあふれた星間プラズマ



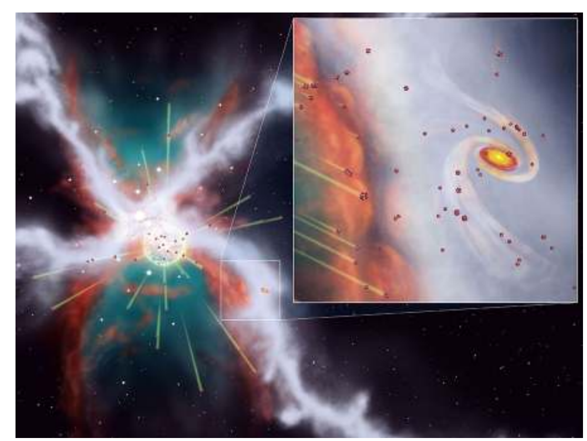
$\gtrsim 10^{22}$ cm

熱的不安定性に支配された分子雲の誕生



$\sim 10^{19}$ cm

短寿命崩壊核に暴露された太陽系の形成期



$\lesssim 10^{16\text{-}18}$ cm

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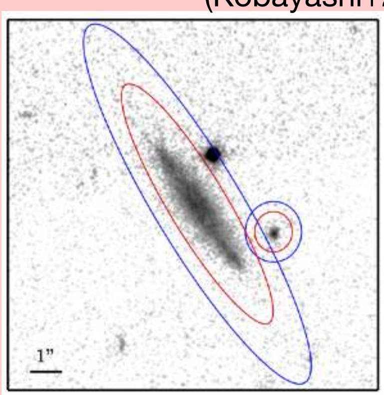
I期棟 825号室

Key goal: cosmic star formation history

- **Observational** analysis of gravitational lensing (HST, HSC)

(Kobayashi+2015)



SKA-JP Square Kilometre Array Japanese Consortium

Gravitational Wave Physics and Astronomy Genesis

COMING, CHIMPS2&3, ngVLA-Japan SWG2/3, LST ISM group, ULTIMATE Subaru WG, Team BISTRO-J, PRIMA-J, PHANGS

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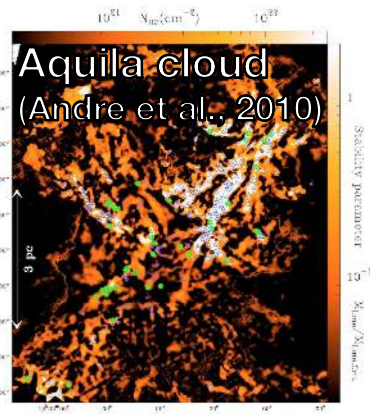
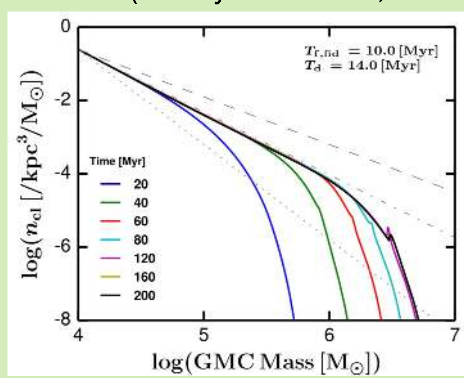
Observed molecular cloud structures

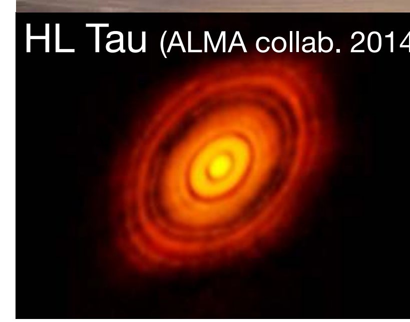


▶ **Semi-analytic** molecular cloud evolution

(Kobayashi+2017, 2018)



Observed protoplanetary disks



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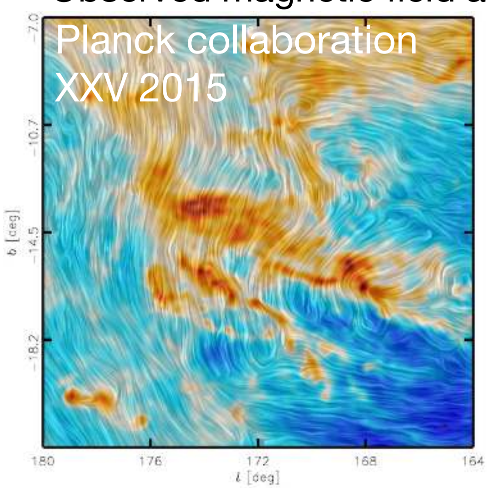
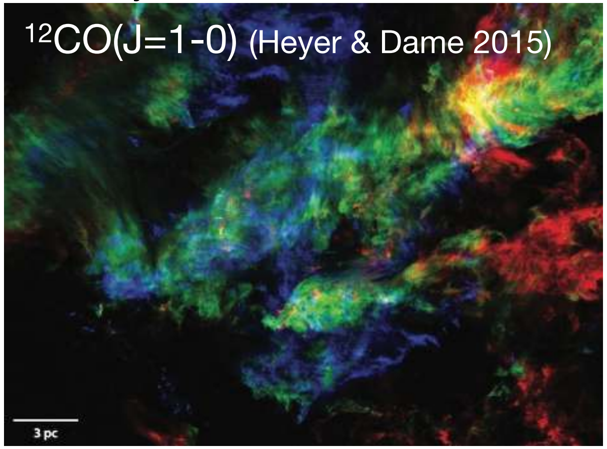
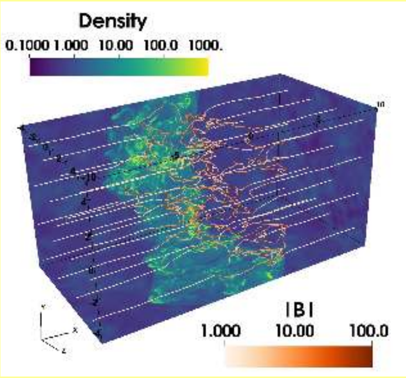
Observed magnetic field and velocity structures in Taurus cloud





▶ Molecular cloud formation **simulation / synthetic obs.**

(Kobayashi+2020, 2022, 2023)



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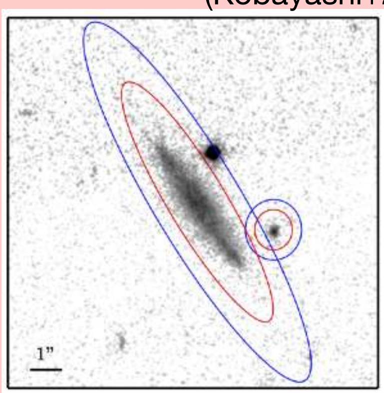

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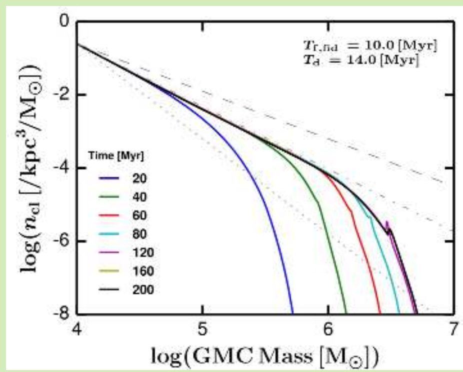

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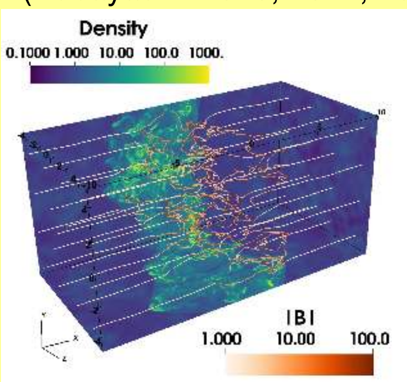

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Interdisciplinary project with fusion plasma

Outline

▶ Background

- Hierarchical structure of the Universe
- Star formation efficiency problem

▶ Thermal instability

- Thermal sates in the interstellar plasma
- The interstellar plasma is filled with “**bubbles**”

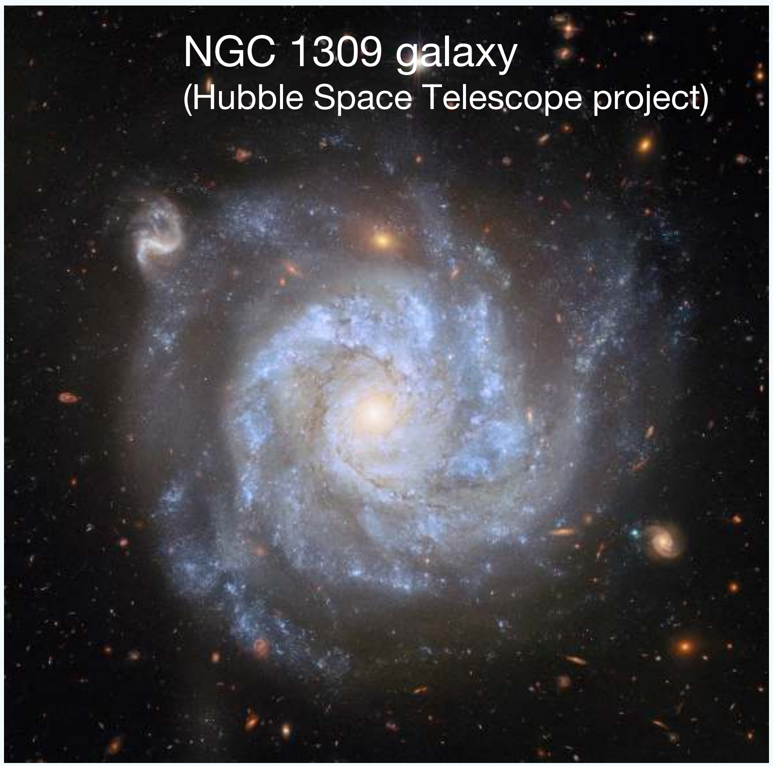
▶ Colliding HI flow simulations

- **Shear flows** suppress the growth of thermal instability
- **Impurity fraction** (= different epoch of the Universe)
- Comparison with thermal instability in **fusion plasma (LHD)**

▶ Solar system formation with short-lived radio nuclei?

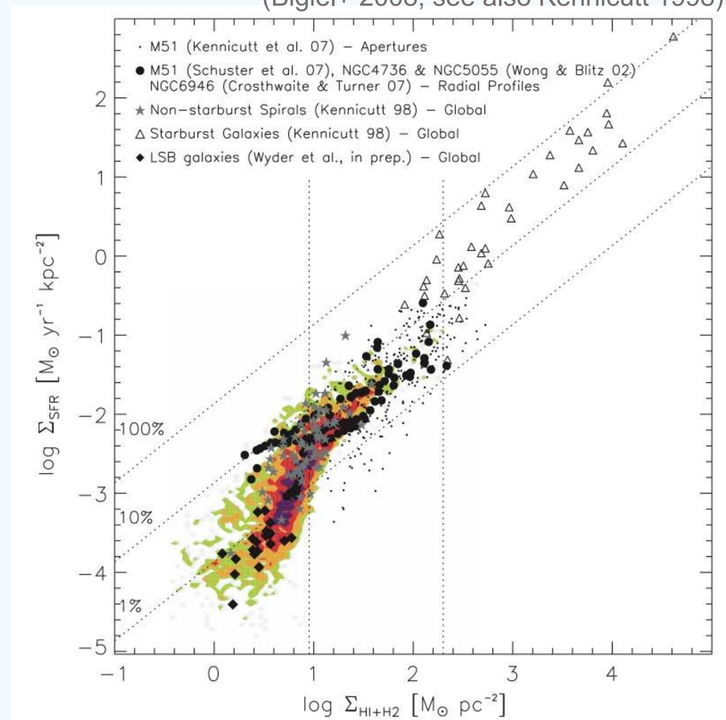
Background

1) Hierarchical structure of the Universe



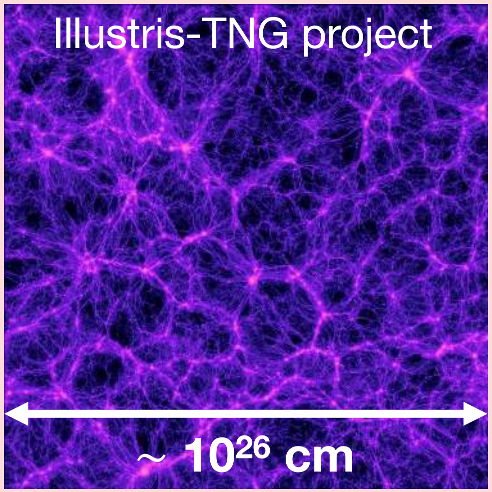
2) Star formation efficiency problem

(Bigiel+ 2008; see also Kennicutt 1998)

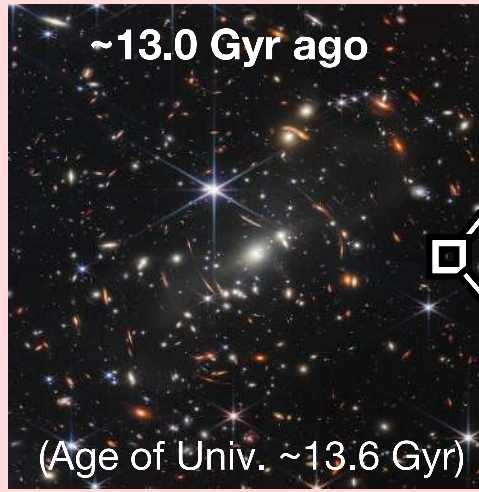


Hierarchical structure of the Universe

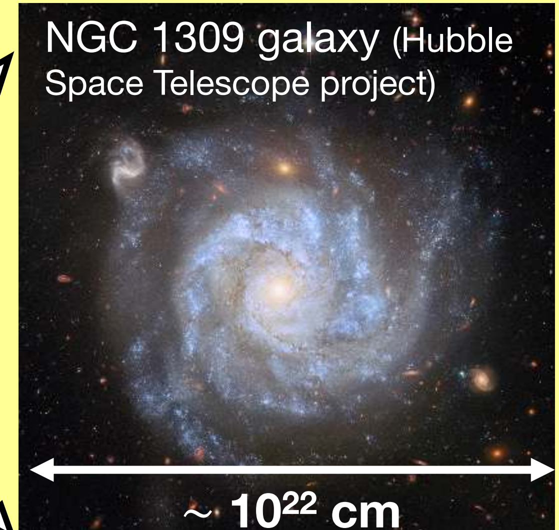
Simulate cosmological large-scale structures

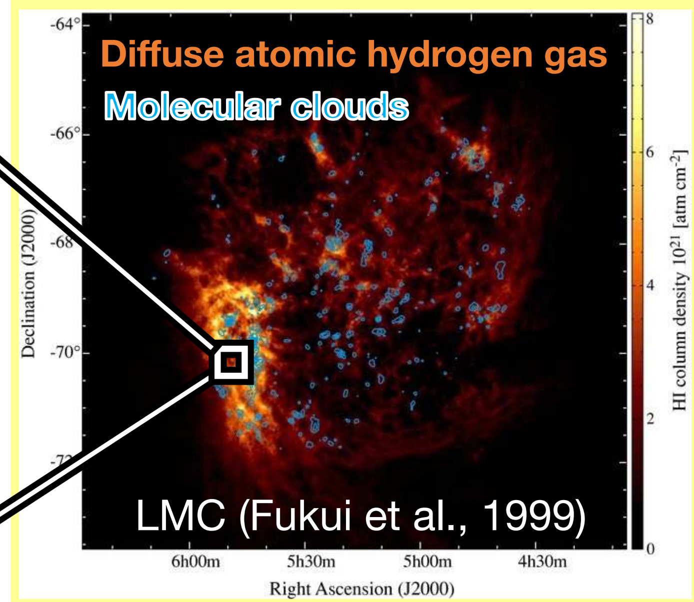


(The) most ancient galaxies (JWST telescope)

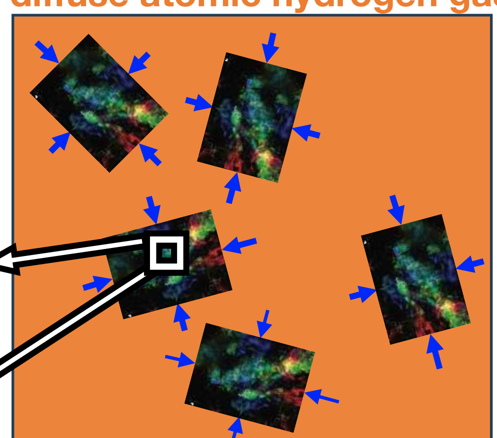


A galaxy = 10^{11} stars





- **Mass / volume dominately in diffuse atomic hydrogen gas**
- **Limited mass condense into molecular clouds**
- **Stars are born in molecular clouds**

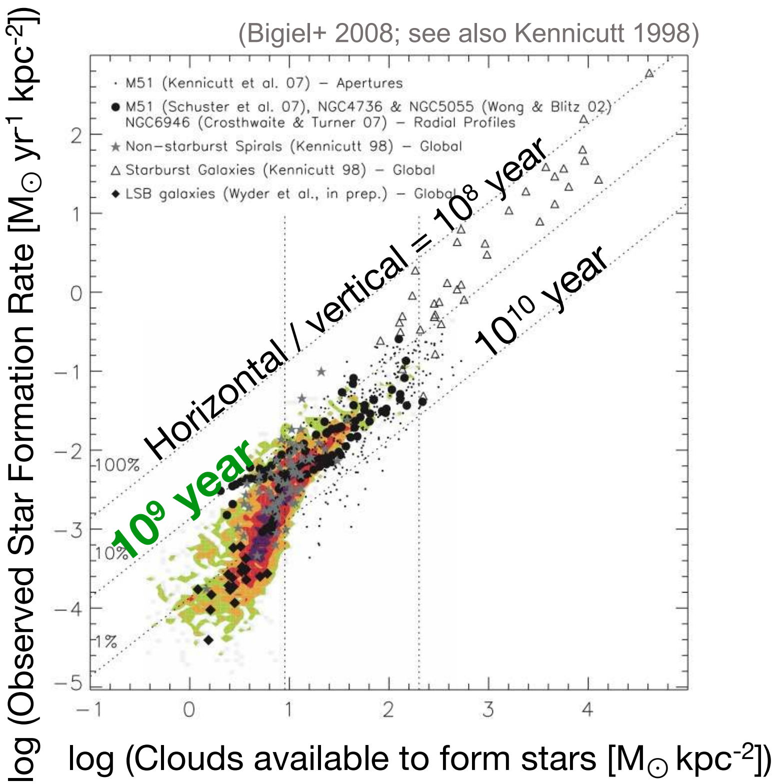


~ 10^{20} cm

~ 10^{14} cm

Star formation efficiency problem (星形成効率問題)

One of the largest open questions in astrophysics



(1) Theory: Expected contraction timescale of a molecular cloud due to self-gravity.

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32\rho G}} = 10^6 \text{ year}$$

(2) Observation: (left panel)

Cloud mass / observed new born stars = 10^9 year

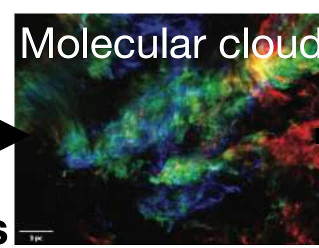
Stars form at only < 1 % efficiency. Why?

- Turbulence & magnetic fields counteract self-gravitational contraction.
- **From where did turbulence & magnetic fields of molecular clouds originate?**

Diffuse atomic hydrogen gas

?

Phase-transition dynamics driven by "thermal instability"

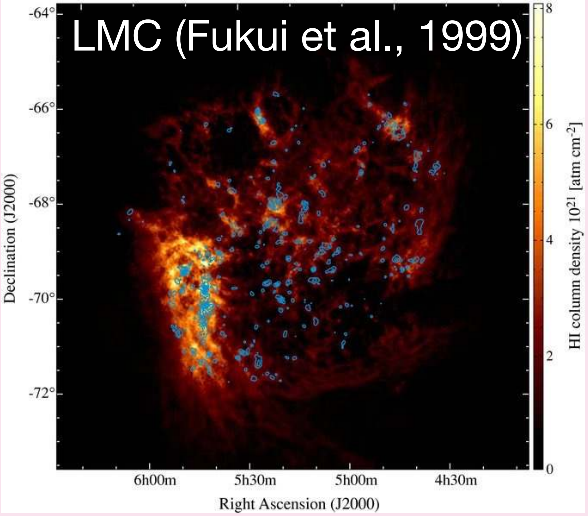


Stars & planets

Turbulence & magnetic fields v.s. self-gravity

Plasma parameters

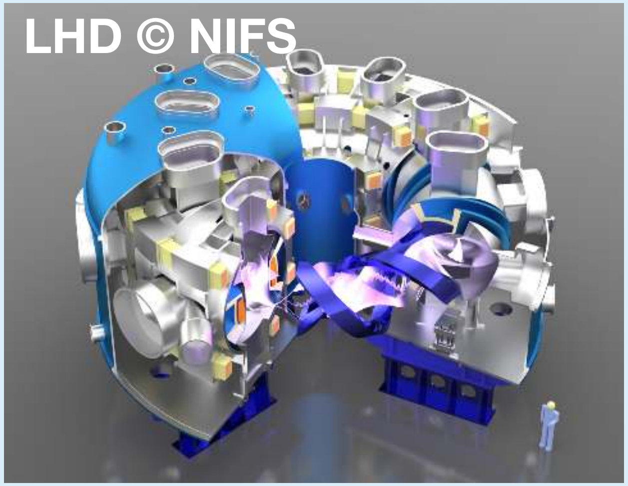
Interstellar plasma



$n_H = 10^{0\text{-}3}$ cm^{-3}
$T = 10^{1\text{-}4}$ K
$B = 10^{-6}$ G (= 10^{-10} T)
Ionization frac.: $n_p/n_H = 10^{-4} \sim 10^{-1}$
Impurity frac.: $n_C/n_H < 10^{-4}$
(almost in the form of C^+)

- VERY weakly ionized
- Typically high plasma β

Fusion plasma



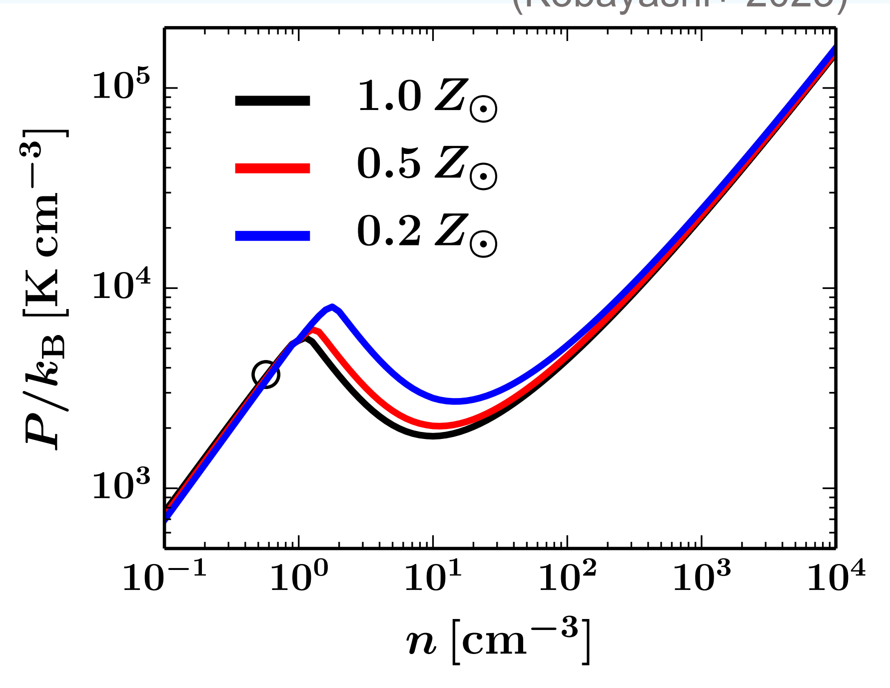
$n_H = 10^{13}$ cm^{-3}
$T = 10^{4\text{-}7}$ K
$B = 10^4$ G (>= 1 T)
Ionization frac.: $n_p/n_H > 10^{-1}$
Impurity frac.: $n_C/n_H \sim 10^{-2}$

- Highly ionized
- Low plasma β

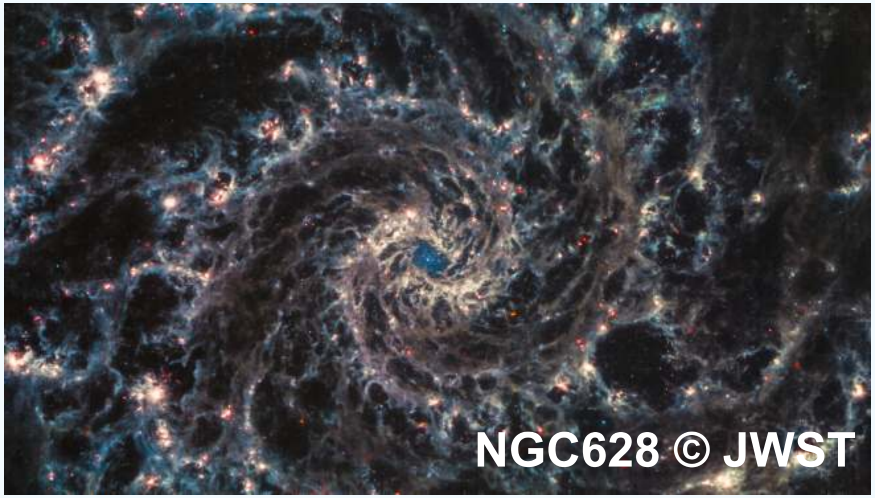
Thermal instability

1) Phase diagram

(Kobayashi+ 2023)



2) Ubiquitous "bubble" structures

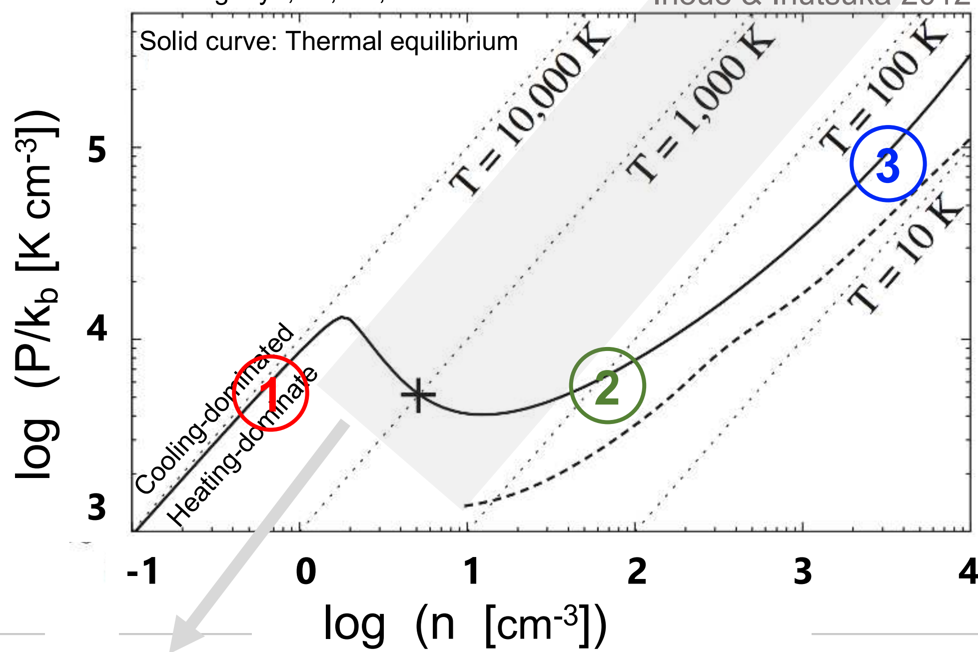


The thermal states of the ISM @ present-day

(e.g., Field 1965, McKee & Ostriker 1977, Wolfire+ 1995)

The "multi-phase" ISM and the thermal instability

Heating: photo-electric
Cooling: Lyα, OI, CII, CO



1 Warm Neutral Medium (WNM)

HI gas, 10^{-2-0} cm^{-3}, 10^4 K
Most volume in the MW disk

2 Cold Neutral Medium (CNM)

HI gas, 10^{1-2} cm^{-3}, 10^2 K

3 Molecular Gas (MCs)

H_2 gas, >10^2 cm^{-3}, <10^2 K, progenitor of stars

Condition for the thermal instability (100K < T < 6000K)

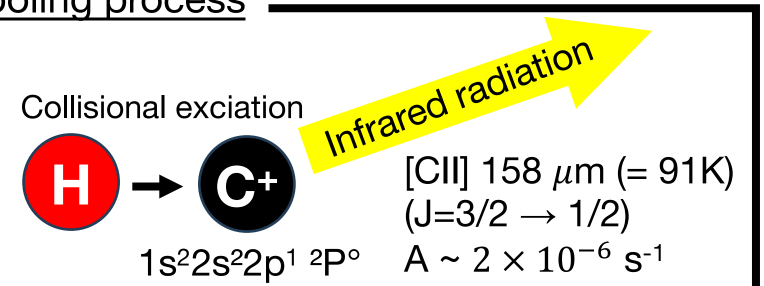
$$\left(\frac{\partial(\mathcal{L}/T)}{\partial T}\right)_P < 0$$

(Run-away cooling e.g., Schwarz 1972, Balbus 1995; c.f., Field 1965)

Typical growing scale: Cs × cooling time
= **0.01 - 0.1 pc << Molecular cloud**

1 pc = 3×10^{18} cm

Cooling process



- 158 μm radiates far away = cooling
- Dominant at T < 6000 K
- H is the most abundance

Thermal instability

Basice equations

$$\frac{\partial \rho}{\partial t} + \nabla_i(\rho v_i) = 0\,,$$

$$\frac{\partial(\rho v_i)}{\partial t} + \nabla_j(P\delta_{ij} + \rho v_j v_i) = 0\,,$$

$$\frac{\partial e}{\partial t} + \nabla_i\left[(e+P)\delta_{ij}v_j\right] = \nabla_i\left[\kappa(T)\nabla_i T\right] - \rho\mathcal{L}(T,Z)$$

Thermal conduction   Net cooling

$$\gamma = C_{\rm P}/C_{\rm V}$$

$$k_\rho = \frac{\mu m_{\rm H}(\gamma-1)}{k_{\rm B}C_{\rm s}}\frac{\rho_0}{T_0}\left(\frac{\partial\mathcal{L}}{\partial\rho}\right)_T$$

$$k_T = \frac{(\gamma-1)\mu m_{\rm H}}{k_{\rm B}c_{\rm s}}\left(\frac{\partial\mathcal{L}}{\partial T}\right)_\rho$$

$$k_\kappa = \frac{k_{\rm B}c_{\rm s}}{\gamma-1}\frac{\rho_0}{\mu m_{\rm H}}\frac{1}{\kappa}$$

$$\delta a = a_1\exp(\sigma t + i\boldsymbol{kx})$$ (for rho, T, v)

Dispersion relation with net cooling + thermal conductivity

$$\sigma^3 + \sigma^2 c_{\rm s}\left(k_T\frac{k^2}{k_\kappa}\right) + \sigma c_{\rm s}^2 k^2 + \frac{c_{\rm s}^3 k^2}{\gamma}\left(k_T - k_\rho + \frac{k^2}{k_\kappa}\right) = 0$$

Growth rate (up to its first order)

$$\sigma = (C_{\rm S}/\gamma)(k_\rho - k_T)$$

Maximum growth

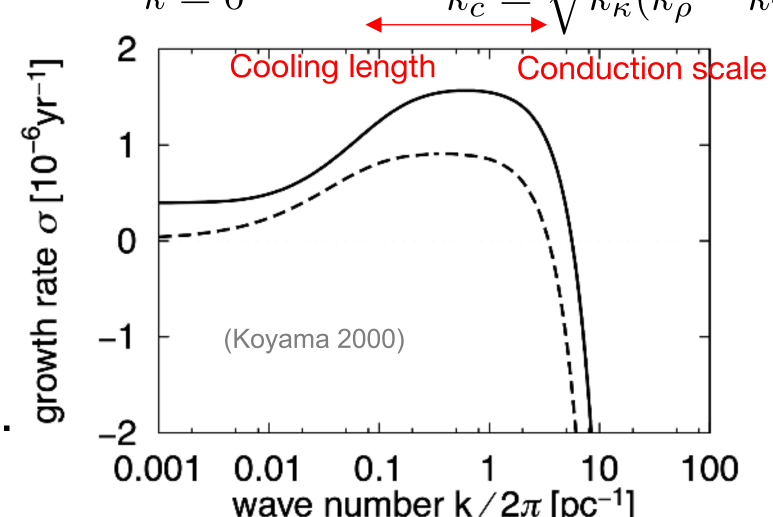
$$k_m = \sqrt{k_\rho k_c}$$

0.2pc @Z⊙ - 1.0 pc @ 0.2 Z⊙

⇨ Convergence requires <~0.02 pc resol.
(Kobayashi+2020)

k-range for growing

$k = 0$ $k_c = \sqrt{k_\kappa(k_\rho - k_T)}$



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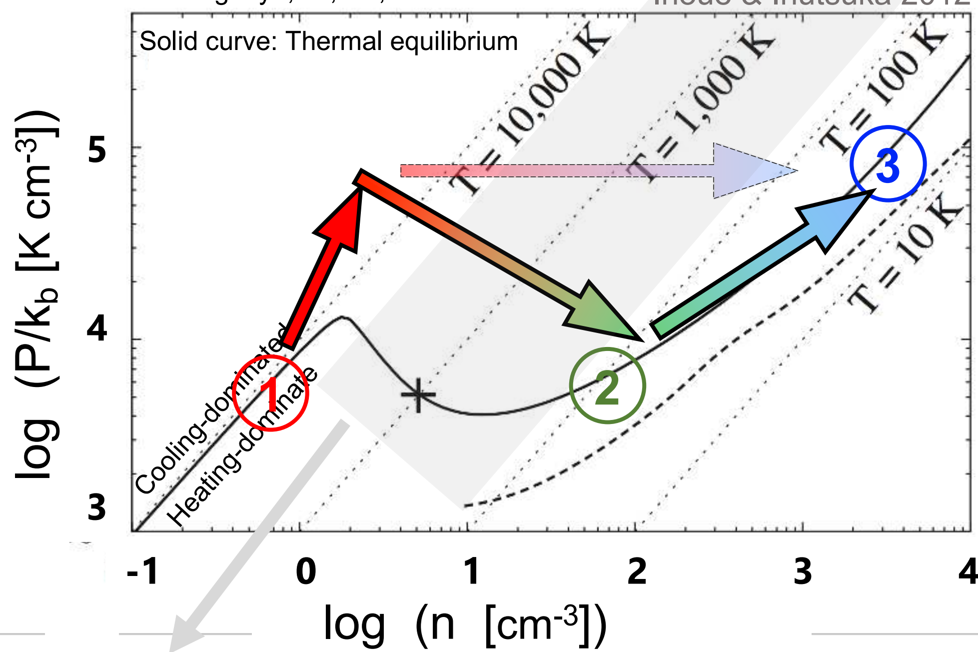

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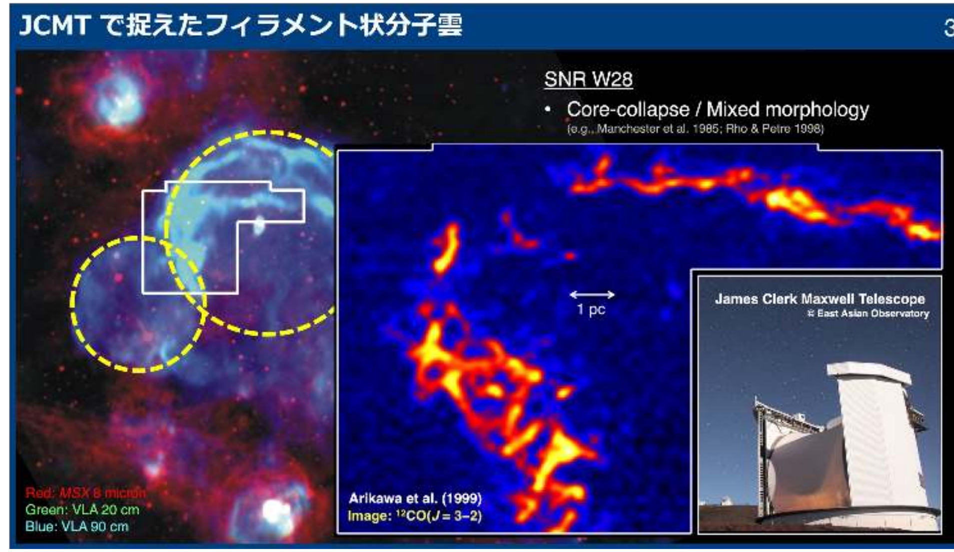
Shocks compress WNM to destabilize

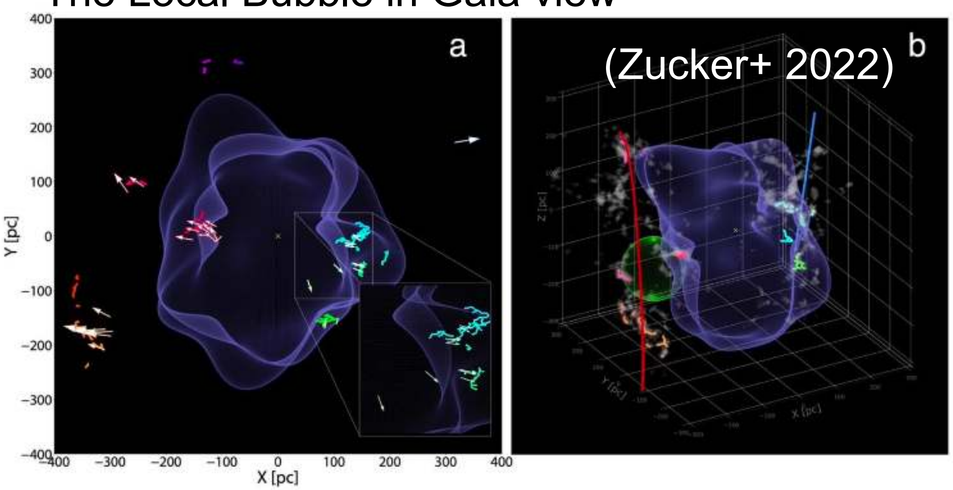
1 WNM
↓
Thermal instability
↓
2 CNM / 3 Molecular cloud

The ISM is ubiquitously “bubbly” (= bubble-dominated)

Courtesy of Hidetoshi Sano (Gifu Univ.)



The Local Bubble in Gaia view



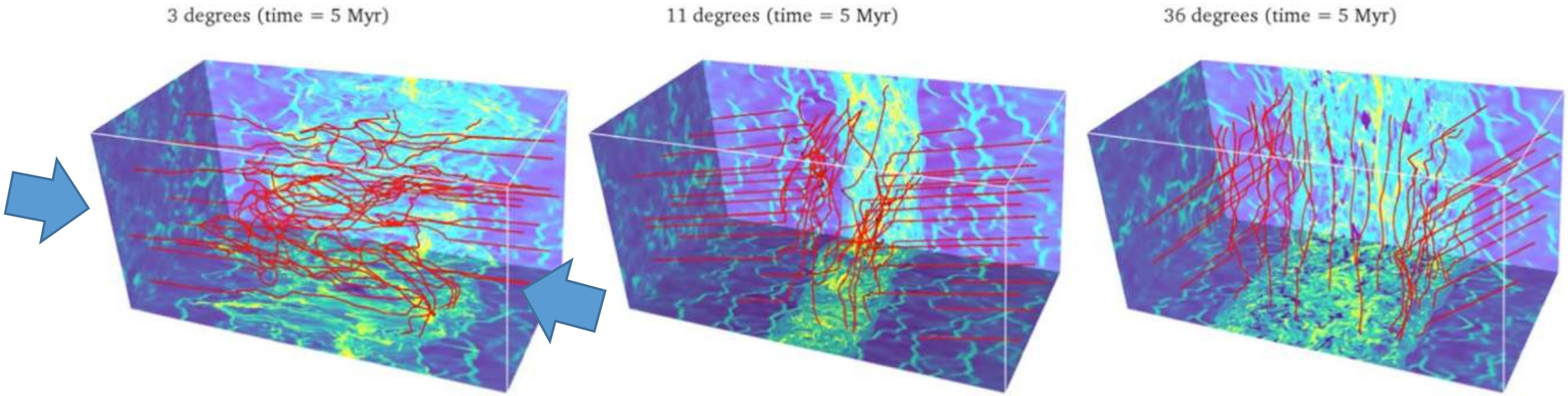
Almost all known star forming regions in the Solar neighborhood is **on the surface of the Local Bubble!** **(~14 supernovae?)**

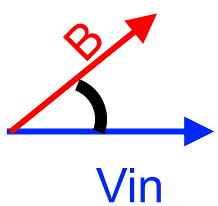
HI gas accumulation by supersonic flows

(c.f., Koyama & Inutsuka 2000, 2002
Hennebelle & Perault 1999,
Audit & Hennebelle 2005, 2008,
Heitsch 2005,
Vazquez-Semadeni 2006, 2007, etc.)

▶ **Molecular cloud formation is regulated by "B-fields"**

Red lines: B-fields (Iwasaki+ 2019; e.g., Inoue & Inutsuka 2009)





< 15 deg: HI(WNM) → HI(CNM) → **Molecular cloud**

> 15 deg: HI(WNM) → HI(CNM)

$$\frac{B_\perp^2}{8\pi} = \rho_0 V_0^2 \longrightarrow \sin\theta'_{\rm cr} \sim 0.3\left(\frac{\epsilon}{0.1}\right)\left(\frac{\langle n_0\rangle}{5\ {\rm cm}^{-3}}\right)^{1/2}\left(\frac{V_0}{20\ {\rm km\ s}^{-1}}\right)\left(\frac{B_0}{5\ \mu{\rm G}}\right)^{-1}$$ ~15 deg

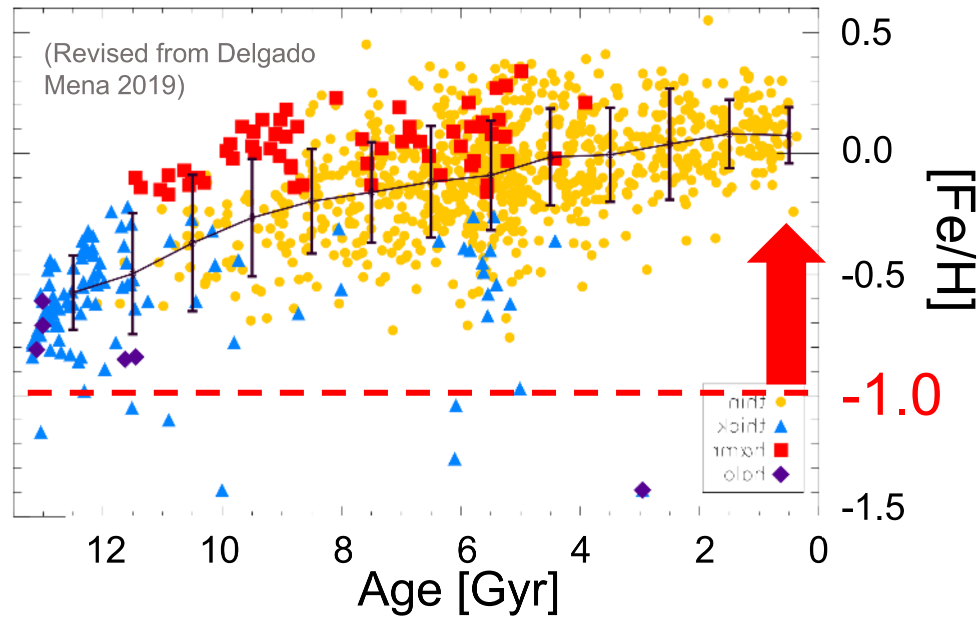
⇨ Present-day: Cloud formation / growth after "multiple" compression.
Past Universe: ?

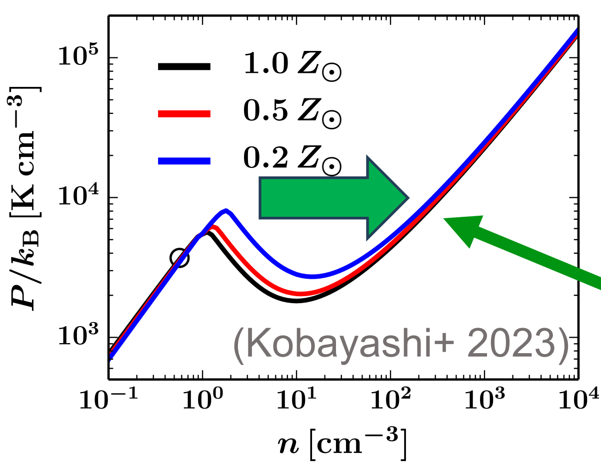
(Inutsuka et al. 2015)

Galactic Archiology: SF history of the MW galaxy

Gaia data: age of stars in the Solar neighborhood < 2 kpc

- In the past 12 Gyr, stars were born in 0.1 $Z_\odot$ - 1.0 $Z_\odot$ ($Z_\odot$: Solar value)
  (c.f., Ivezic 2008, Péroux & Howk 2020, Sahlholdt 2021, Huang 2022)

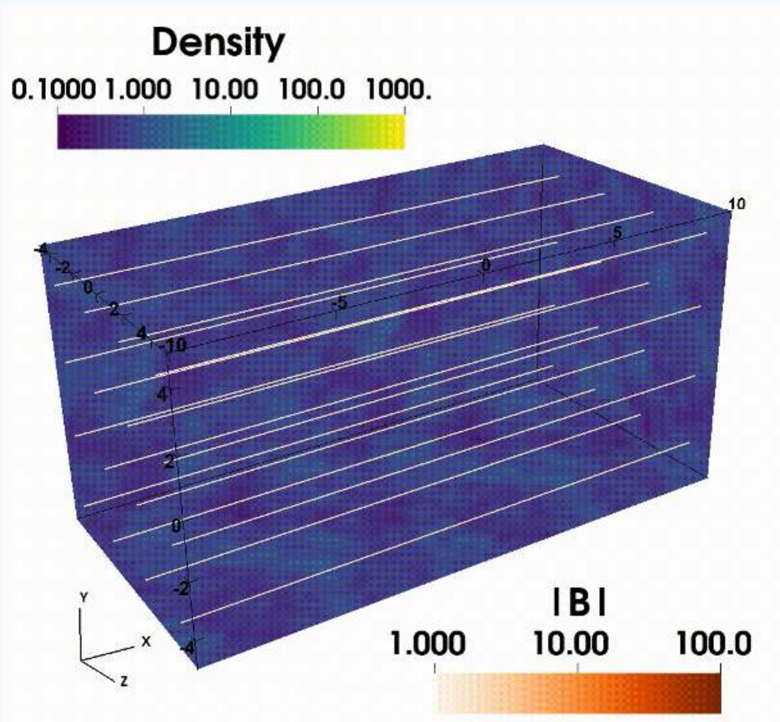




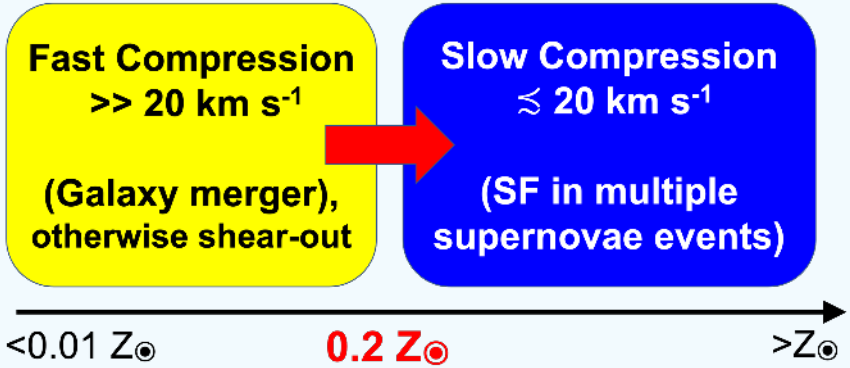
- Thermally stable branches and unstable regions exist, but **the evolution timescale becomes longer in lower metallicity environments (= lower impurity fraction)**.

Colliding HI Flows

1) Shock-compressed cloud formation

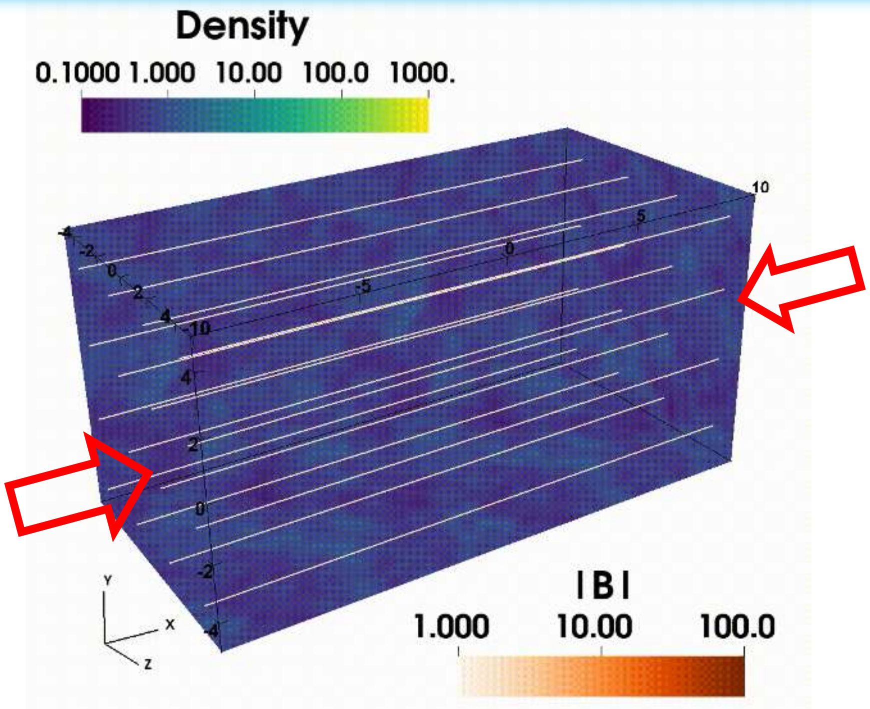


2) Transition of star formation



Supersonic converging flow of WNM

(c.f., Hennebelle & Perault 1999, Audit & Hennebelle 2005, 2008, Heitsch 2005, Vazquez-Semadeni 2006, 2007, etc.)



$$\frac{\partial \rho}{\partial t} + \nabla_i(\rho v_i) = 0\,,$$

$$\frac{\partial(\rho v_i)}{\partial t} + \nabla_j(T_{ij} + \rho v_j v_i) = -\rho \nabla_i \Phi\,,$$

$$T_{ij} = \left(P + \frac{B^2}{8\pi}\right)\delta_{ij} - \frac{B_i B_j}{4\pi}$$

$$\frac{\partial e}{\partial t} + \nabla_i\left((e\delta_{ij} + T_{ij})v_j\right) = \nabla_i(\kappa(T)\nabla_i T) - \rho v_i \nabla_i \Phi - \rho \mathcal{L}(T, Z)$$

$$\frac{\partial B_i}{\partial t} + \nabla_j\left(v_j B_i - v_i B_j\right) = 0\,,$$

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

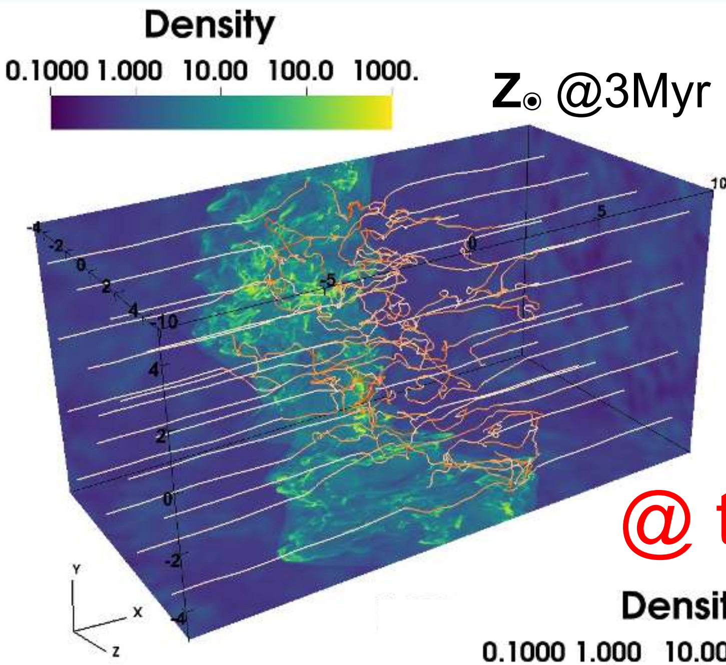
0.57 cm^{-3}, 1uG, 20 km s^{-1} (with density inhomogeneity)
x,y,z = 20 pc, 10 pc, 10 pc

Code	Athena++ (Stone+ 2020)
Thermal conduction	H+H collision (Parker 1953)
Heating / Cooling	Photo-electric heating / Lyα, OI, CII, CO modified with metallicity (Koyama & Inutsuka 2002 + Sutherland & Dopita 1993 modified)
Seed density inhomogeneity	Kolmogorov spectrum (Kolmogorov 1941) $\Delta\rho_0 = \sqrt{\langle\delta\rho_0^2\rangle}/\rho_0 \sim 1$
Spatial resolution	0.04 pc, **0.02 pc**, 0.01pc (1024 x 512 x 512 cells)
Self-gravity	Multi-grid method (Tomida & Stone 2023)
Metallicity	**$Z_\odot$, 0.5 $Z_\odot$, 0.2 $Z_\odot$** MW, LMC , SMC
B-field angle	**0, 15, 30 deg**

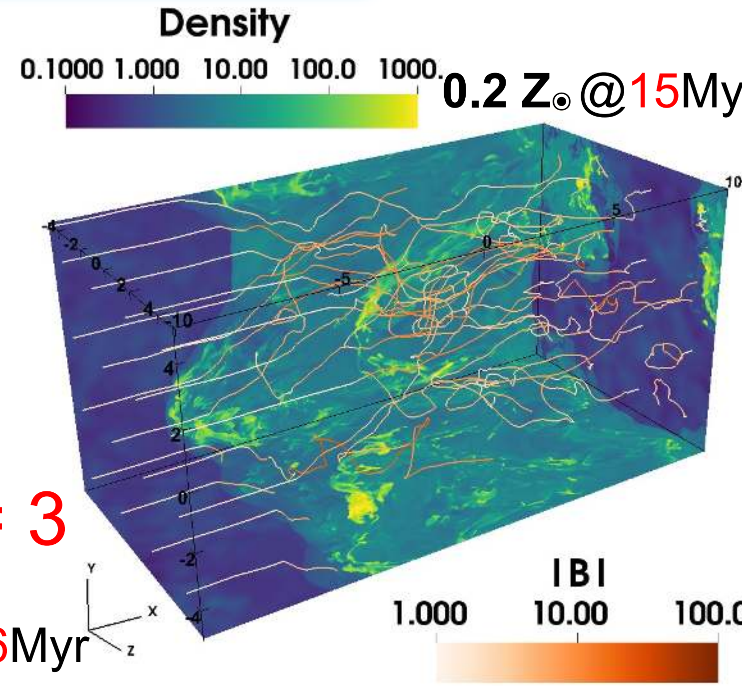
Metallicity dependence down to the SMC level

Kobayashi+ 2023

$Z_\odot$ @3Myr

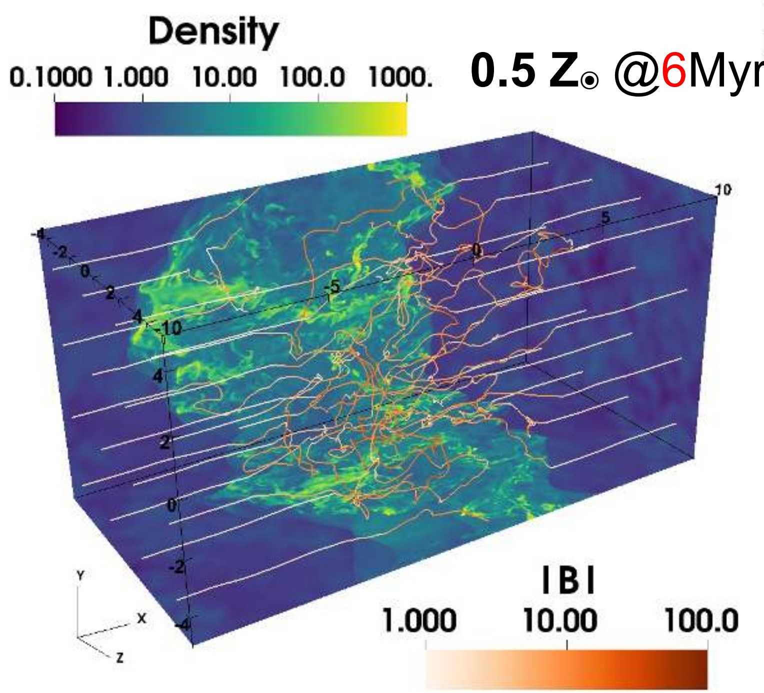


0.2 $Z_\odot$ @15Myr



@ t / t_cool(Z) = 3

0.5 $Z_\odot$ @6Myr



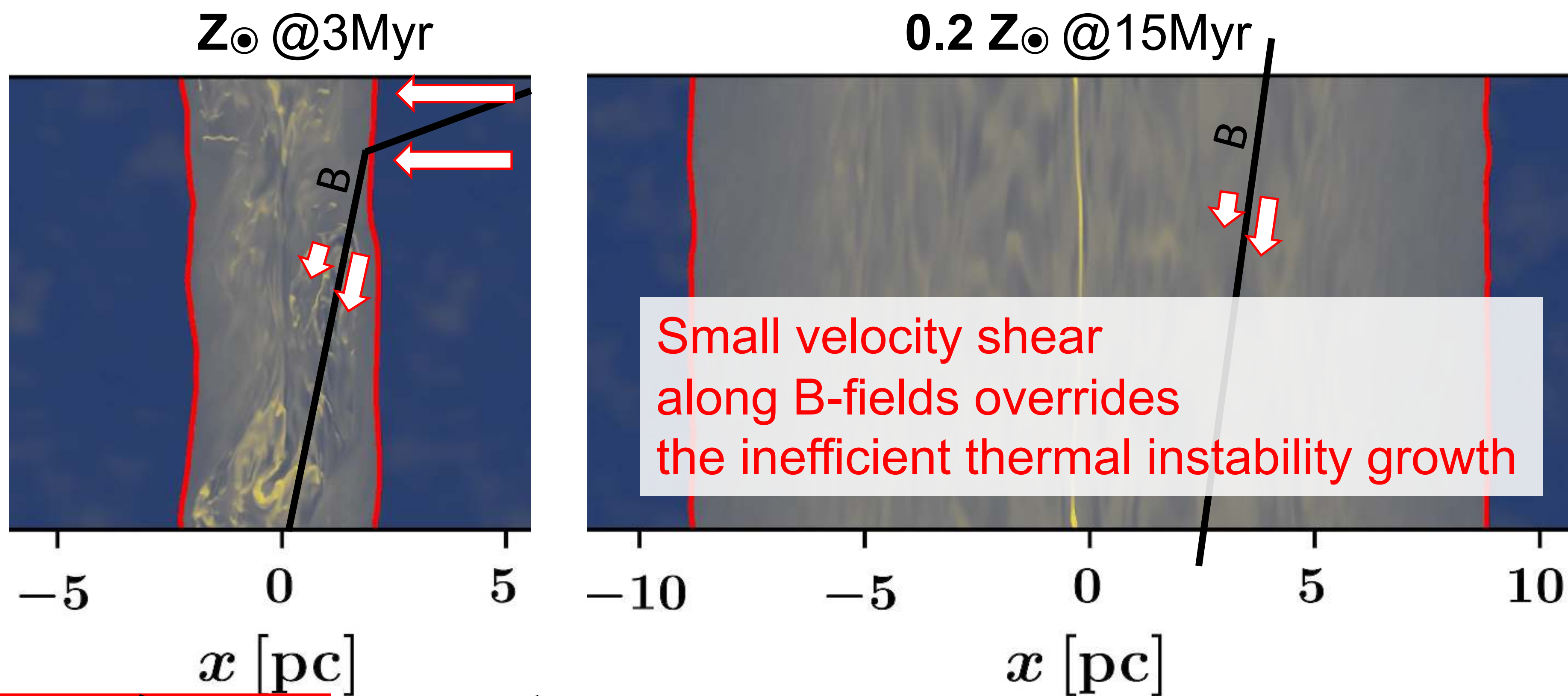
(Turbulence is solenoidal mode dominated.)

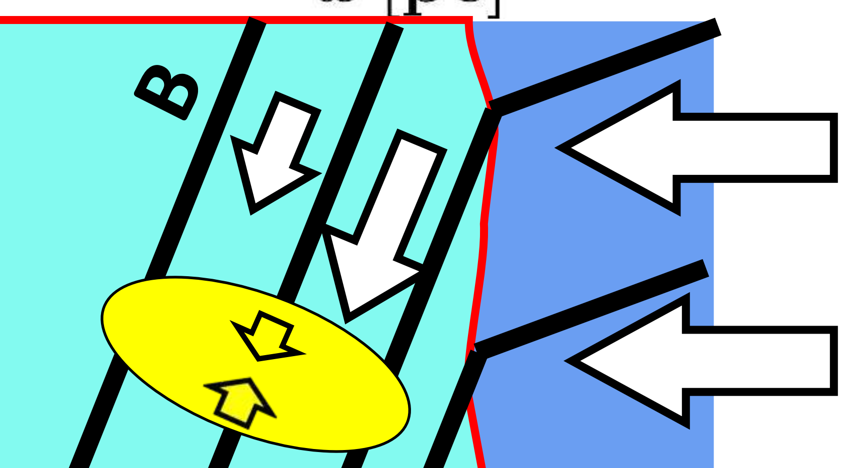
Discussion: B-field angle against HI gas flow

(Kobayashi et al. 2026 in prep.)

	$Z_\odot$ @3Myr	0.5 $Z_\odot$ @6Myr	0.2 $Z_\odot$ @15Myr
0 deg			
15 deg			
30 deg			

Discussion: B-field angle against HI gas flow 15 deg





Thermal instability in LHD experiments

with Masahiro Kobayashi, Ryohtaro Ishikawa, Kennichi Nagaoka, and many others

Astro: Lagrangian time-evolution from WNM to CNM when β <1

log (P/kB [K cm^{-3}])

Preliminary

log (n [cm^{-3}])

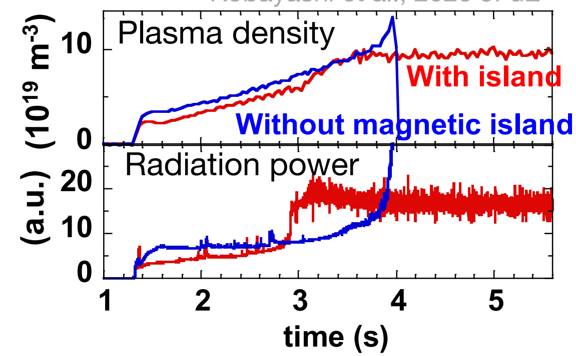
LHD: Eulerian time-evolution (with Carbon)

$T_e n_e$ [kJ/m^3]

Preliminary

n_e [10^{19} m^{-3}]

Kobayashi et al., 2025 JFuE



- Thermal instability seems to grow predominantly **"along" magnetic fields.**
- **Magnetic island stabilize** the instability to achieve stable detached phase.
- Thermal instability growth scale << torus loop (i.e., instability grows **locally**).

We performed further LHD experiments in FY2025 cycle; for example,

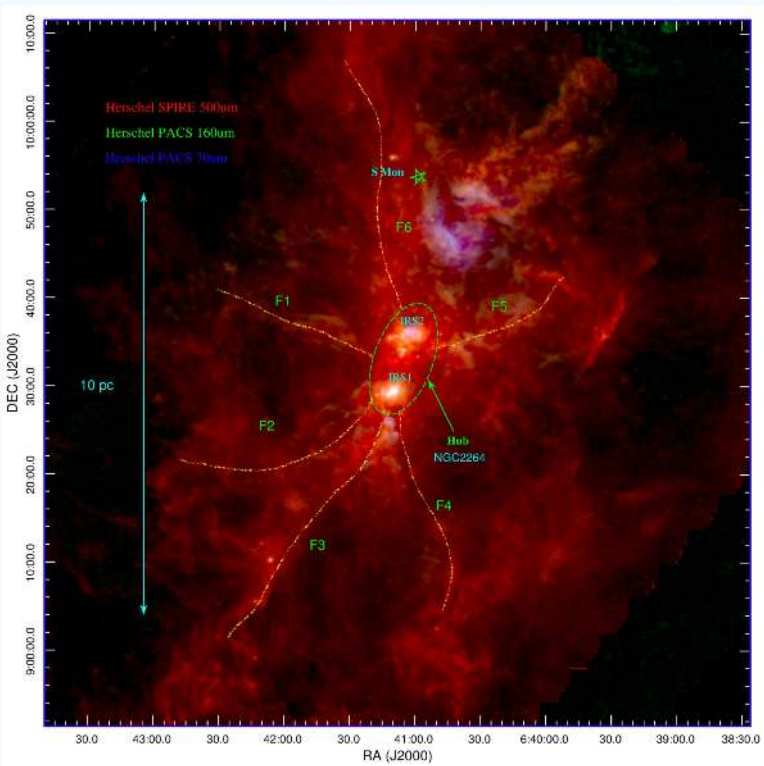
- Varying impurity fraction similar to cosmic evolution of the interstellar plasma
- Heating comparable to Solar Corona
- Revealing hysteresis conditions

We will invite Dr. Patrick Antolin to discuss Solar thermal instability during the last week of Feb.

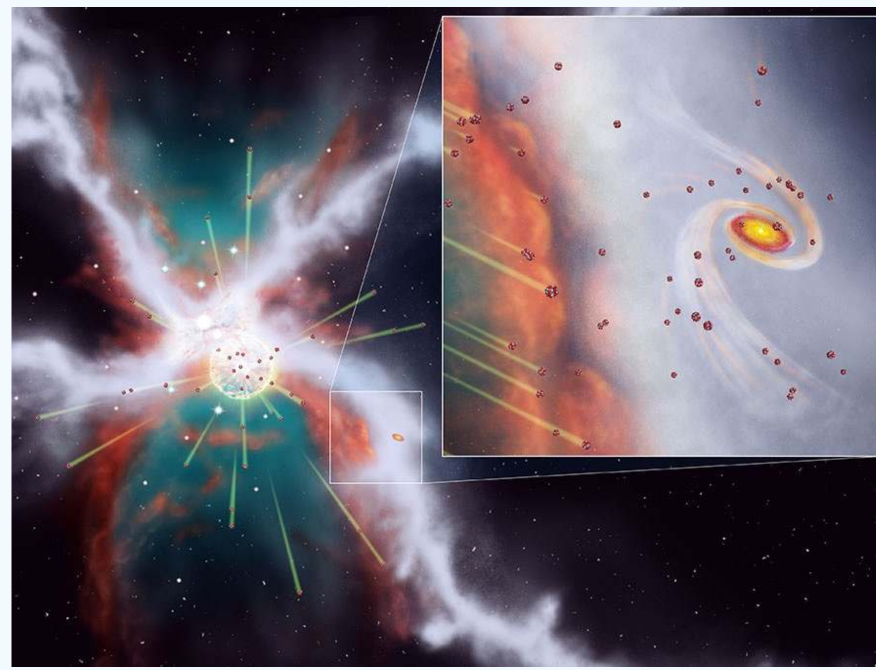
^{26}Al and the birth of Solar System

Arzoumanian, Arakawa, Kobayashi et al 2023

1) Hub-filament system

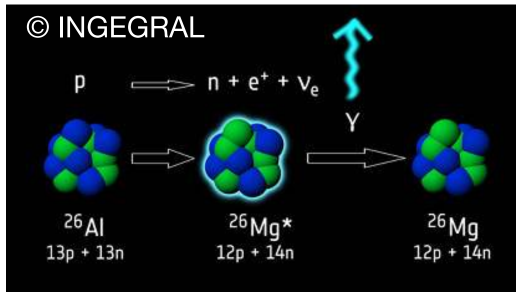


2) Birth of the Solar system with ^{26}Al

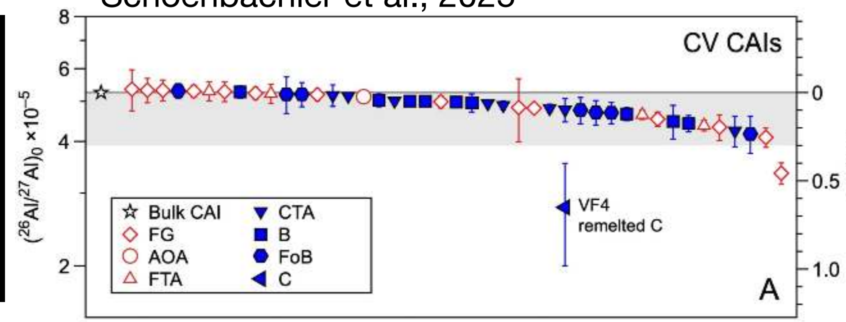


^{26}Al as the heating source in proto-Sun disk / planetesimals

- ✓ Meteorites contain calcium–aluminum-rich Inclusions (CAIs),
  which formed at the beginning of Solar system formation (4.6 Gyr ago).



Schoenbachler et al., 2025



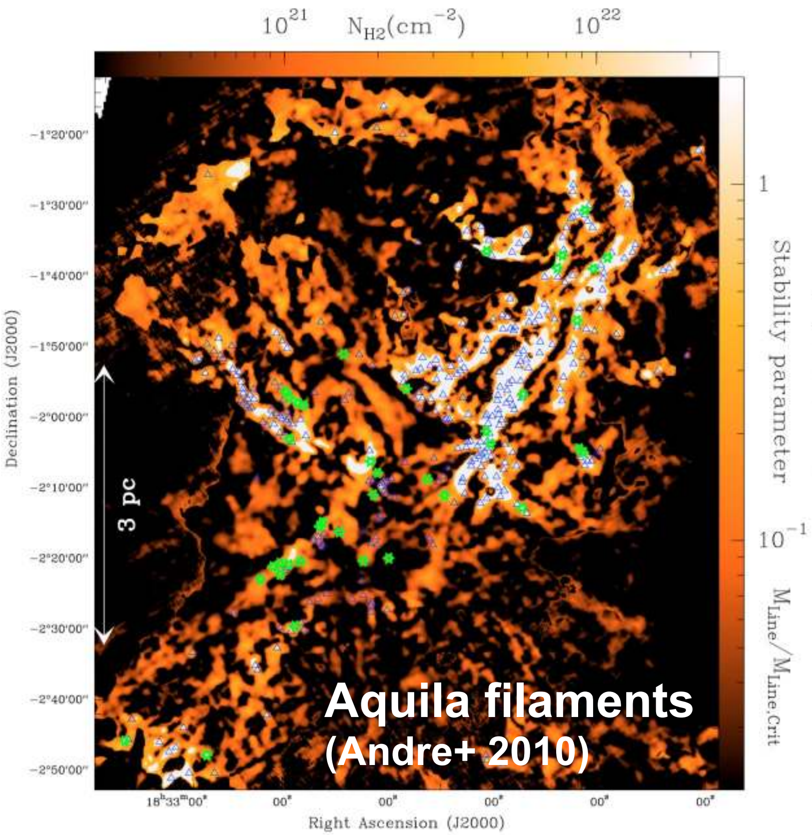
- ✓ CAIs contain short-lived radionuclides (SLRs),
  e.g., ^{26}Al (used to be):
  ^{26}Al → ^{26}Mg beta+ decay with 0.7 Myr timescale to heat disks / planetesimals

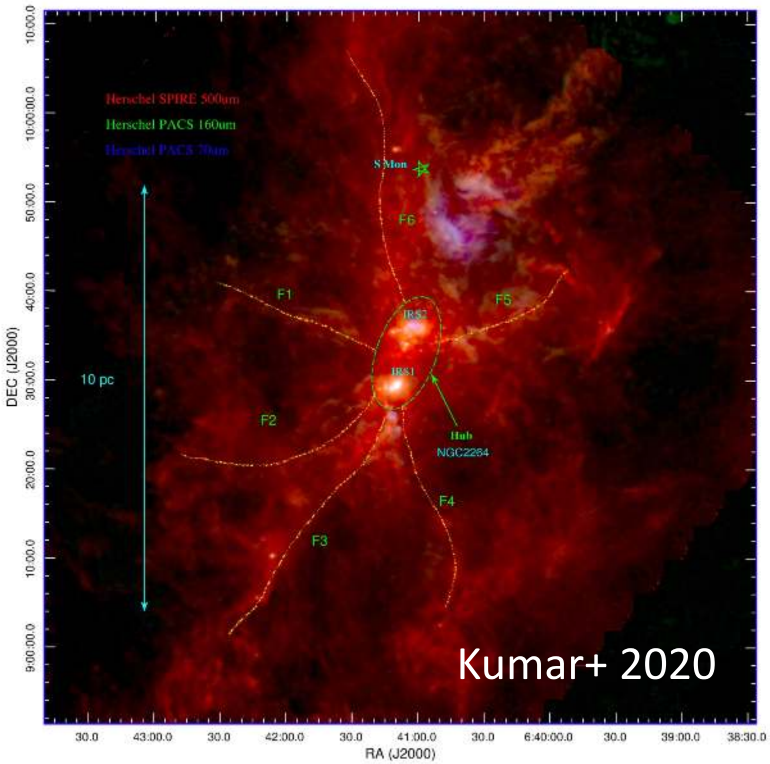
- ✓ Initial fraction at the birth of the Solar system [^{26}Al/^{27}Al] = 5 x 10^{-5}

- ✓ There are theories proposing the source of ^{26}Al and how it was delivered to the Solar System.
  One of the promising mechanisms is **supernovae**, but this involves difficulties:
  (1) too far away to provide enough amount (^{26}Al fully decayed before arriving)
  or
  (2) too close-by to provide enough amount (shock wave destruct the Solar System)

Our alternative solution: Massive stars form in a hub

- ✓ Stars ubiquitously form in filaments in molecular clouds.
- ✓ Massive stars (> 20 Msun) form in intersections of filaments (="hub")





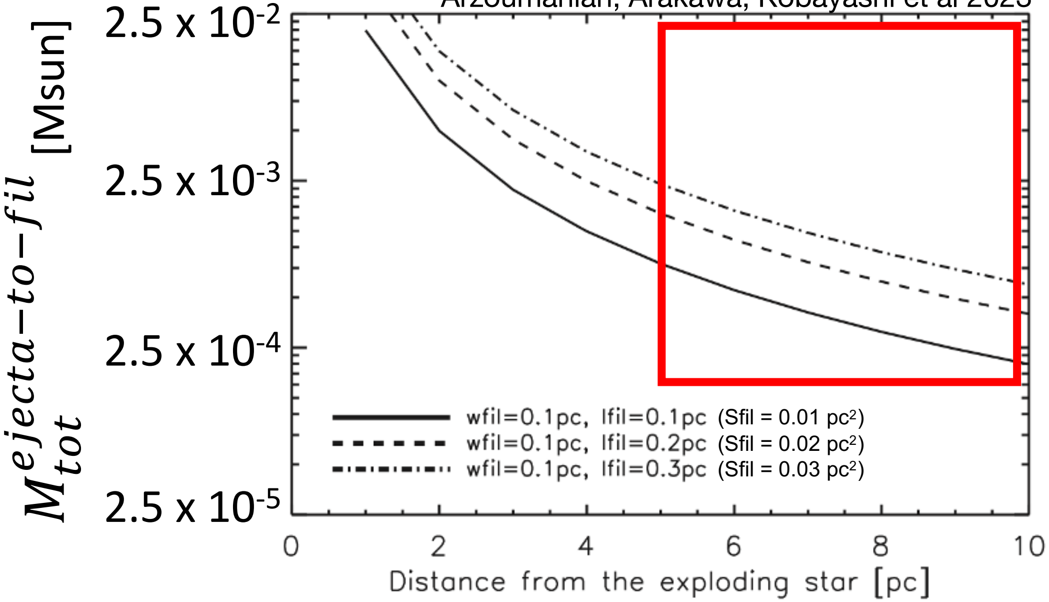
→ Proto-Sun formed in one of such filaments emanating from the hub?

Injection of ^{26}Al through filaments

✓ The mass from SN ejecta to the proto-Sun filament?

$$M_{\rm tot}^{\rm ejecta-to-fil} = M_{\rm ejecta} \frac{S_{\rm fil}}{4\,\pi\,d^2}$$

Arzoumanian, Arakawa, Kobayashi et al 2023



Parameter space for

(1) **the Solar System survives** from the supernovae shock

AND

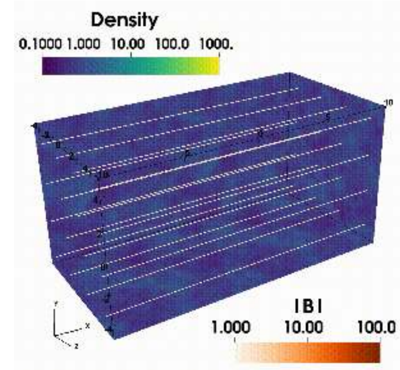
(2) **enough ^{26}Al arrives** $M_{tot}^{ejecta-to-fil} \gg M_{tot}^{SN-to-PPD}$

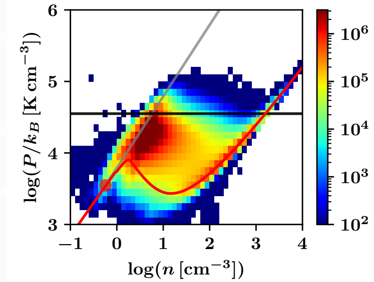
→ Ongoing: Code development for 26Al transport in MHD simulations of molecular cloud evolution.

Summary

✓<u>Backgrounds</u>

- Star formation efficiency problem
- Thermal instability





✓<u>Colliding HI flow simulations</u>

- **At < 0.2 $Z_\odot$, shear flows prevent thermal instability.** Clouds form only in large-scale fast flows.
- Once > 0.2 $Z_\odot$, clouds form in slower compressions.
- **The solar system was also exposed to a supernovae shock, which delivered ^{26}Al.**

✓Future prospects:

- Various environments
  e.g., galaxy merger, SMC-LMC interaction
- Impurity transport
  i.e., flows with different metallicity