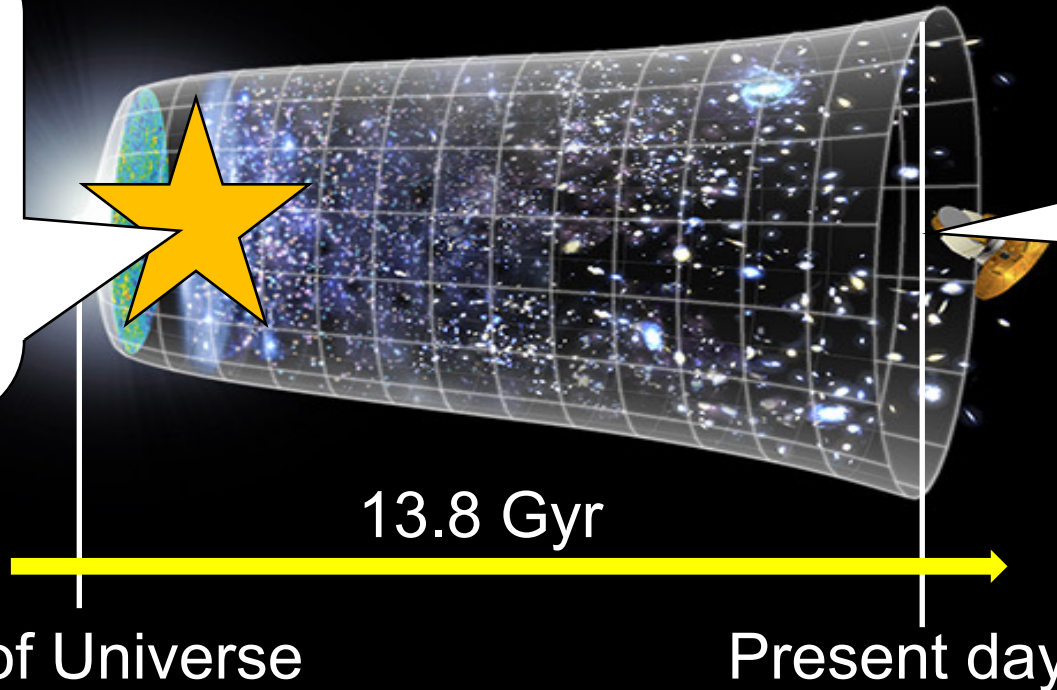


Star Formation in Strong Magnetic Field and Low-Metallicity Environments

Itsuki Murakoso, Masahiro. N. Machida
(Kyushu University)

Image of Universe Evolution

First star (~0.2 Gyr ?)
(metallicity $Z \approx 0$)
Observe :
Challenging
Theoretical : Active



Star in Present day
(metallicity $Z \approx Z_{\odot}$)
Observe : Active
Theoretical : Active

Star : The basic celestial components of the Universe

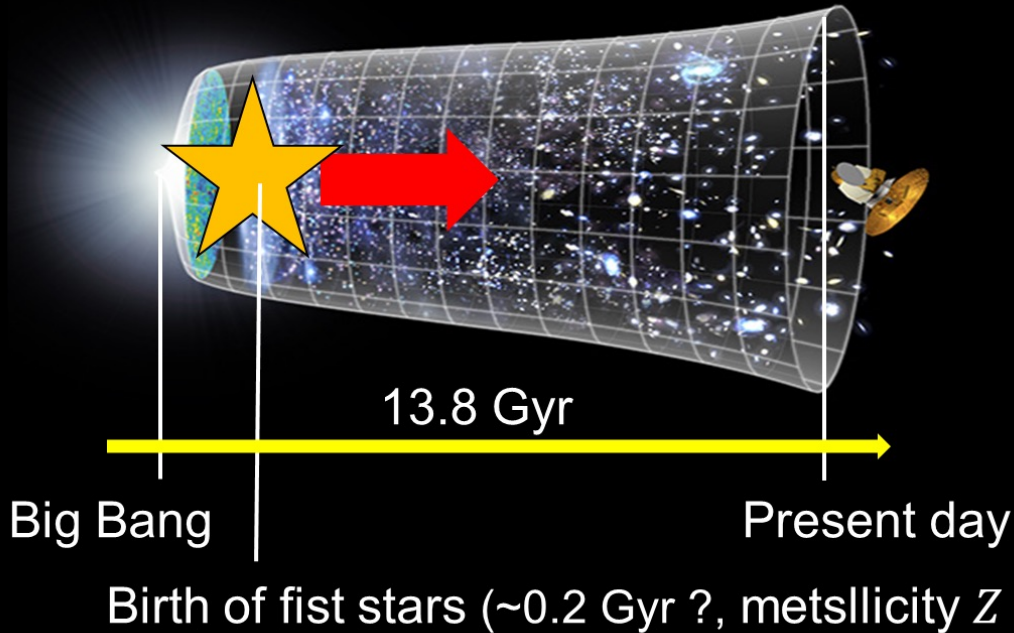
To understand the Evolution of the Universe,

we need to consider of the star formation process.

— How has **the Star-Formation process changed**

from **the First stars** to **those in the present day** ?

Image of the Universe evolution



©NASA/WMAP Science team

Limit of the magnetic strength

in the first star formation area :

$$B_{\max} \sim 1 \mu\text{G}, \quad B_{\min} \sim 10^{-4} - 10^{-2} \text{ pG}$$

(e.g., Ichiki 2006, Neronov & Vovk 2010)

Recent studies have suggested

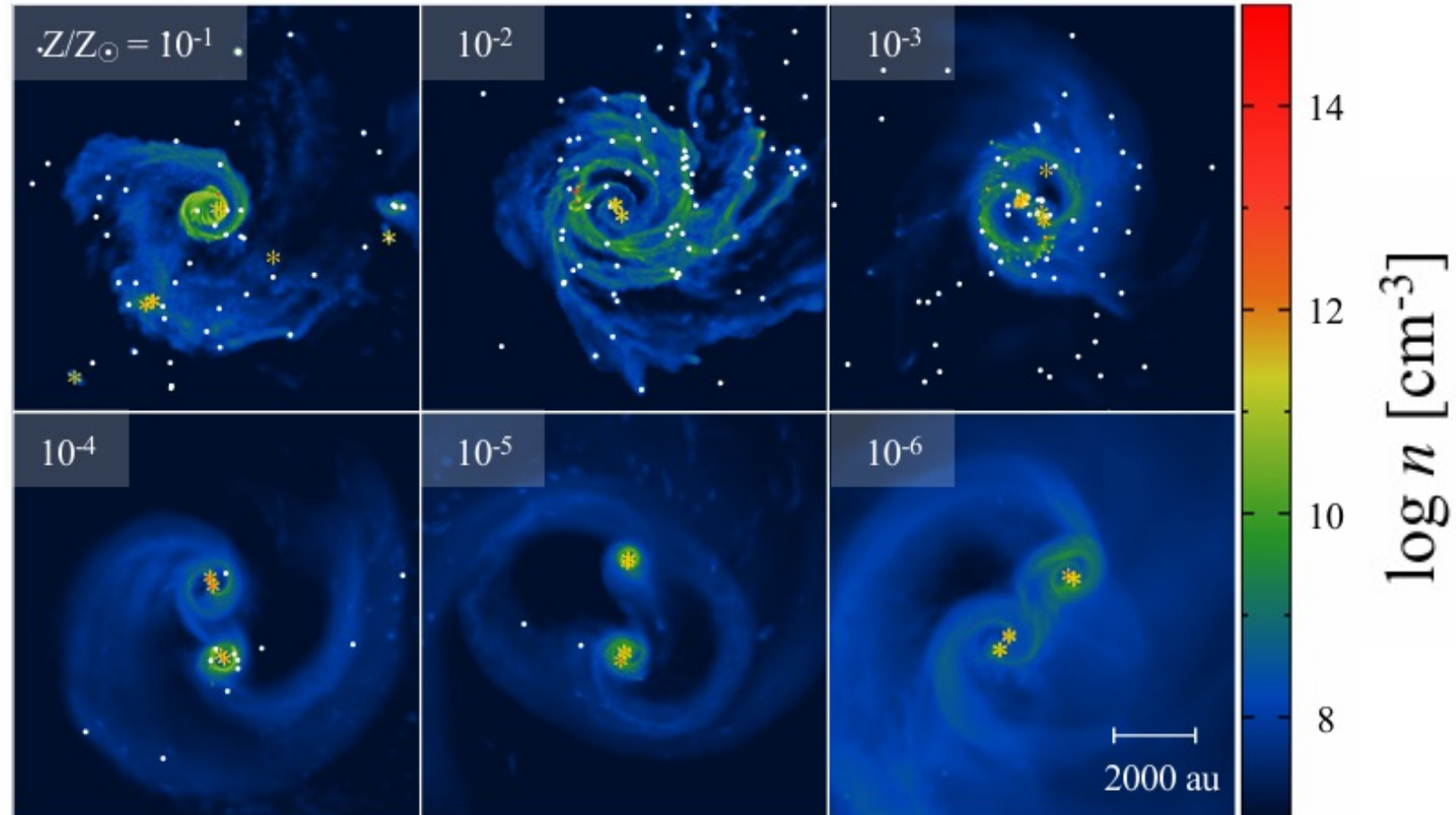
the amplification of magnetic fields.

(e.g., Hirano & Machida 2022)

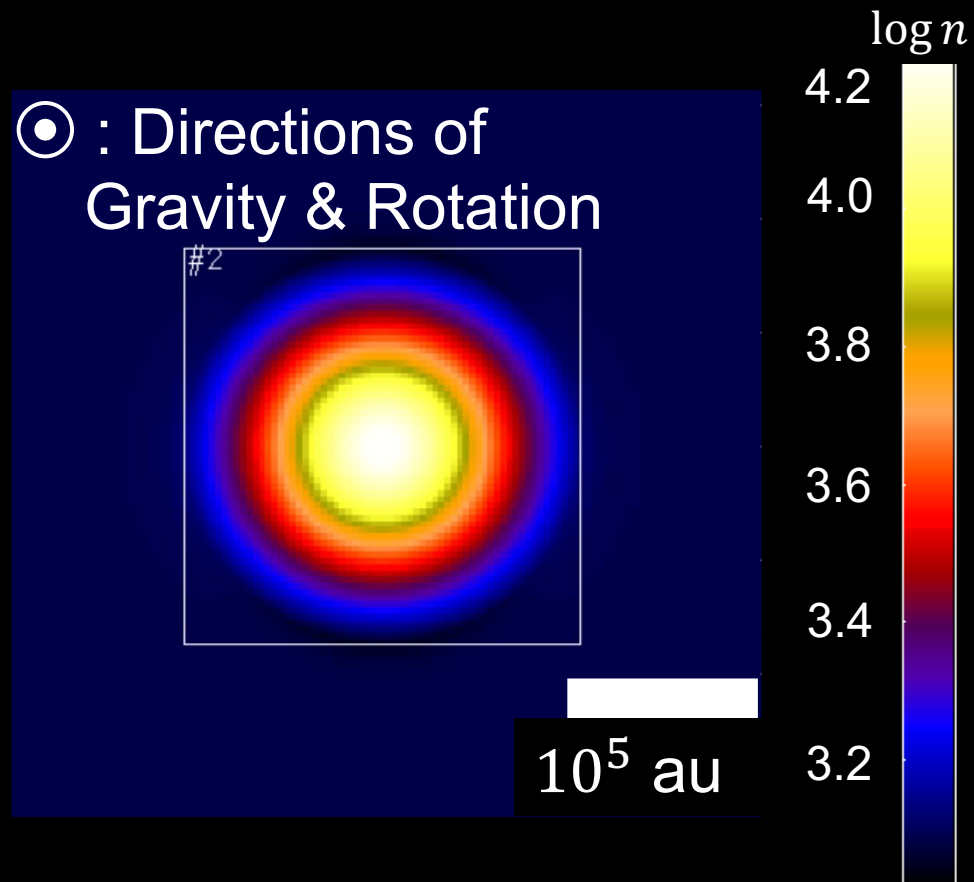
→ Second and later stars could form in strong magnetic fields?

To investigate star formation under strong-field, low-metallicity conditions with 3D non-ideal MHD simulations.

- Chon et al. (2021) :
Using 3D HD simulations
(**no magnetic fields**)
with varying metallicities
- Many low-mass stars
formed by fragmentation
- Observation :
Fewer low-metallicity stars
than suggested
- In the Real,
Fragmentation may be
suppressed
by Magnetic fields



Chon et al. (2021)



Molecular Cloud
(Bonner-Ebert Sphere)

Metallicity : Z/Z_{\odot}	$10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}, 0$
Central Number Density	$n = 10^4 \text{ cm}^{-3}$
Mass-to-flux ratio	$\mu_0 = \frac{M/\Phi}{(M/\Phi)_{\text{cri}}} = 3$
Magnetic field strength	$B \sim 10 \mu\text{G}$
Mass	$M \sim 200 M_{\odot}$

- Start : Molecular Cloud
- End : 100~1000yr after Protostar-Formation
Protostar formation : $n_{\text{max}} \geq 10^{17} \text{ cm}^{-3}$

Basic Equation

- $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0$
- $\rho \frac{\partial v}{\partial t} + \rho (v \cdot \nabla) v = -\nabla P - \frac{1}{4\pi} B \times (\nabla \times B) - \rho \nabla \varphi$
- $\frac{\partial B}{\partial t} = \nabla \times \left[v \times B + \frac{\eta_{AD}}{|B|^2} \{(\nabla \times B) \times B\} \times B - \eta_{OD} (\nabla \times B) \right]$
- $\nabla^2 \varphi = 4\pi G \rho$
- $T = T(\rho)$
- $\eta = \eta(\rho, T)$

Depend on Metallicity

Continuity Equation

Equation of motion

Induction Equation

Poisson Equation

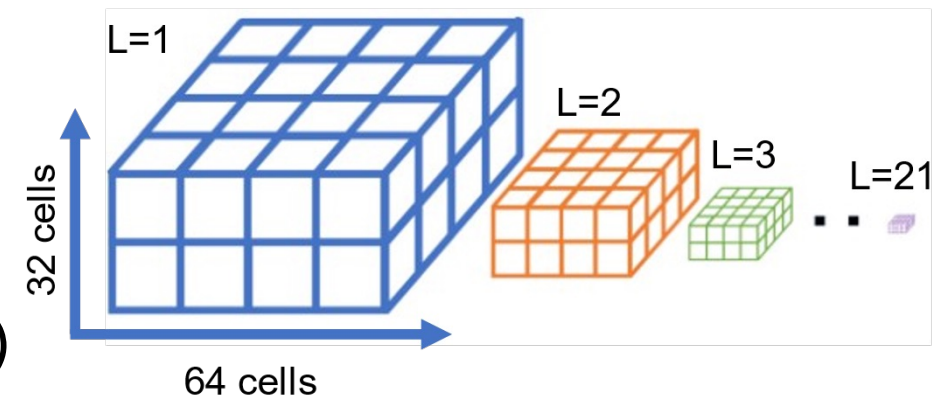
Equation of State

Diffusion Equation

Code : Nested Grid Code (Machida & Basu 2020)

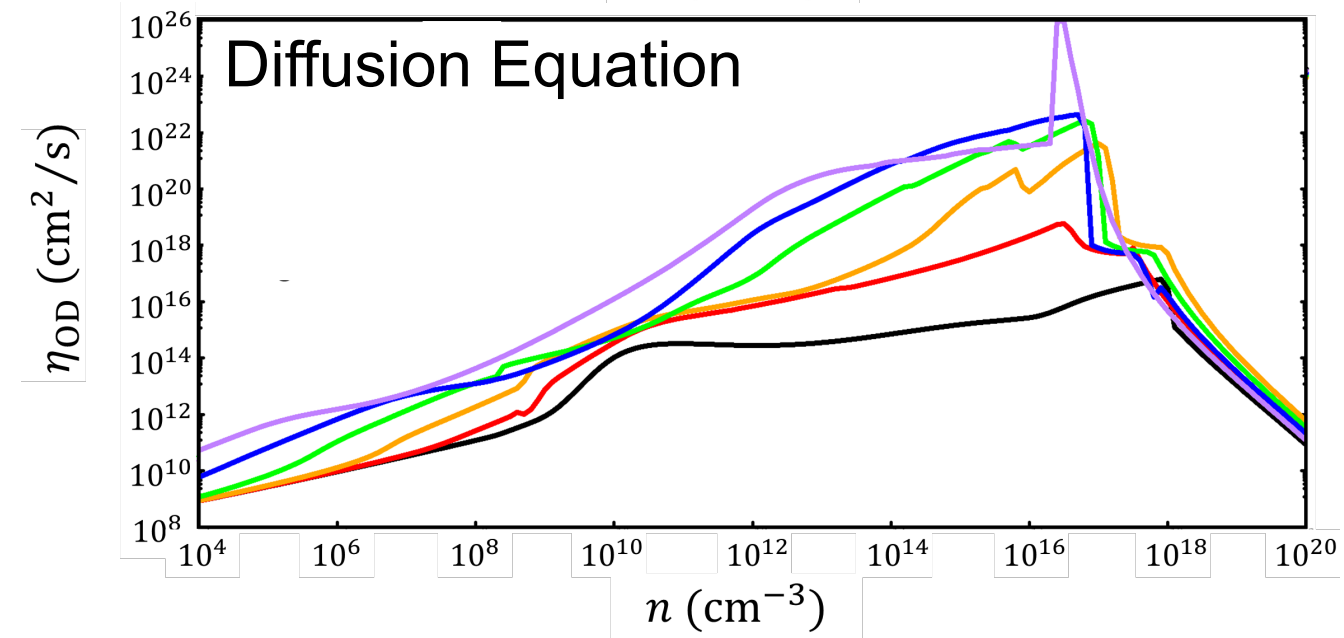
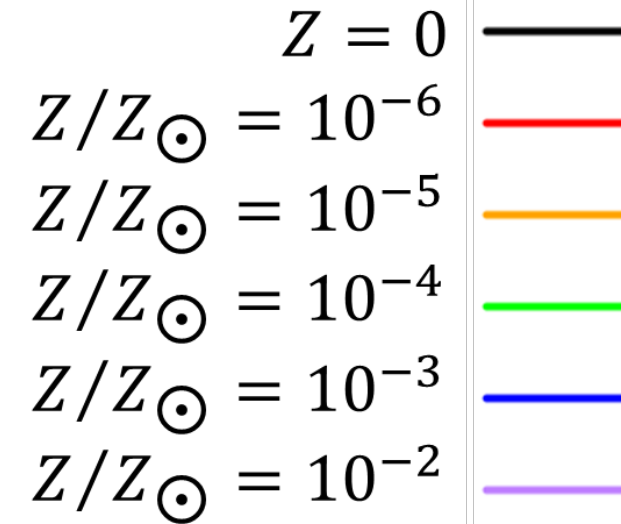
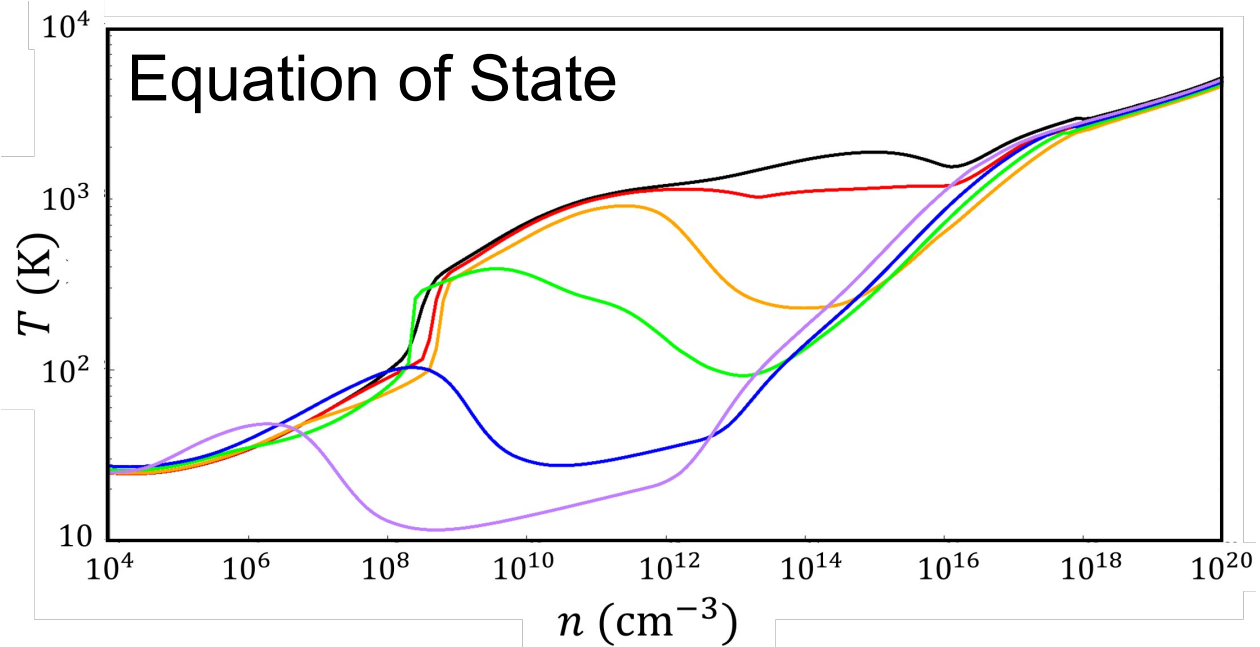
Simulation : Non-ideal MHD

(include Ohm dissipation & Ambipolar diffusion)



Methods : One-zone model

EANAM10



Calculated using
the One-zone approximation
(Omukai et al. 2005, Susa et al. 2015)
→ Reducing computational cost

Result : Evolution of Star

EANAM10

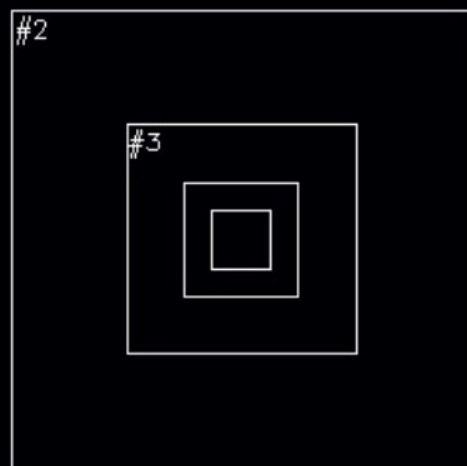
$$Z = 10^{-2} Z_{\odot}$$

$$t_{\text{ps}} = -139 \text{ yr}$$

→ : 20 km/s

z=0-plane

Ring - like structure ?



20 au

log n

16.0

14.0

12.0

x=0-plane

Outflow

20 au

log n

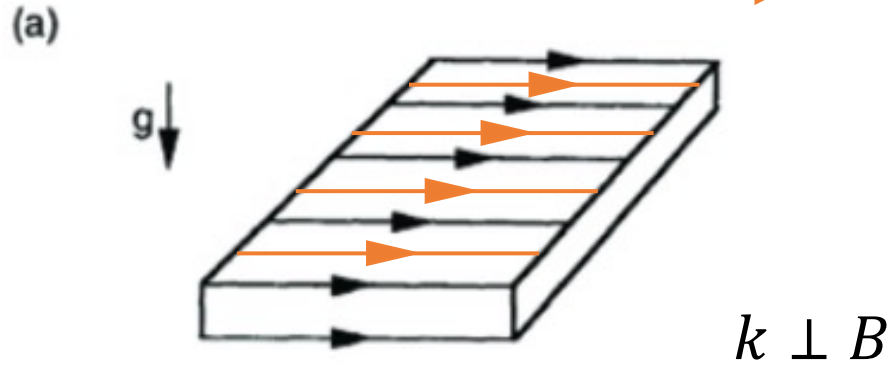
14.0

12.0

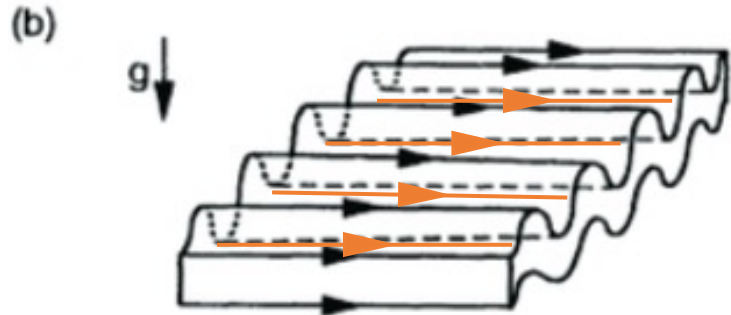
10.0

Interchange-driven structural change

 : Field-line



 Part of the Flux tube rises
Due to Magnetic Buoyancy.

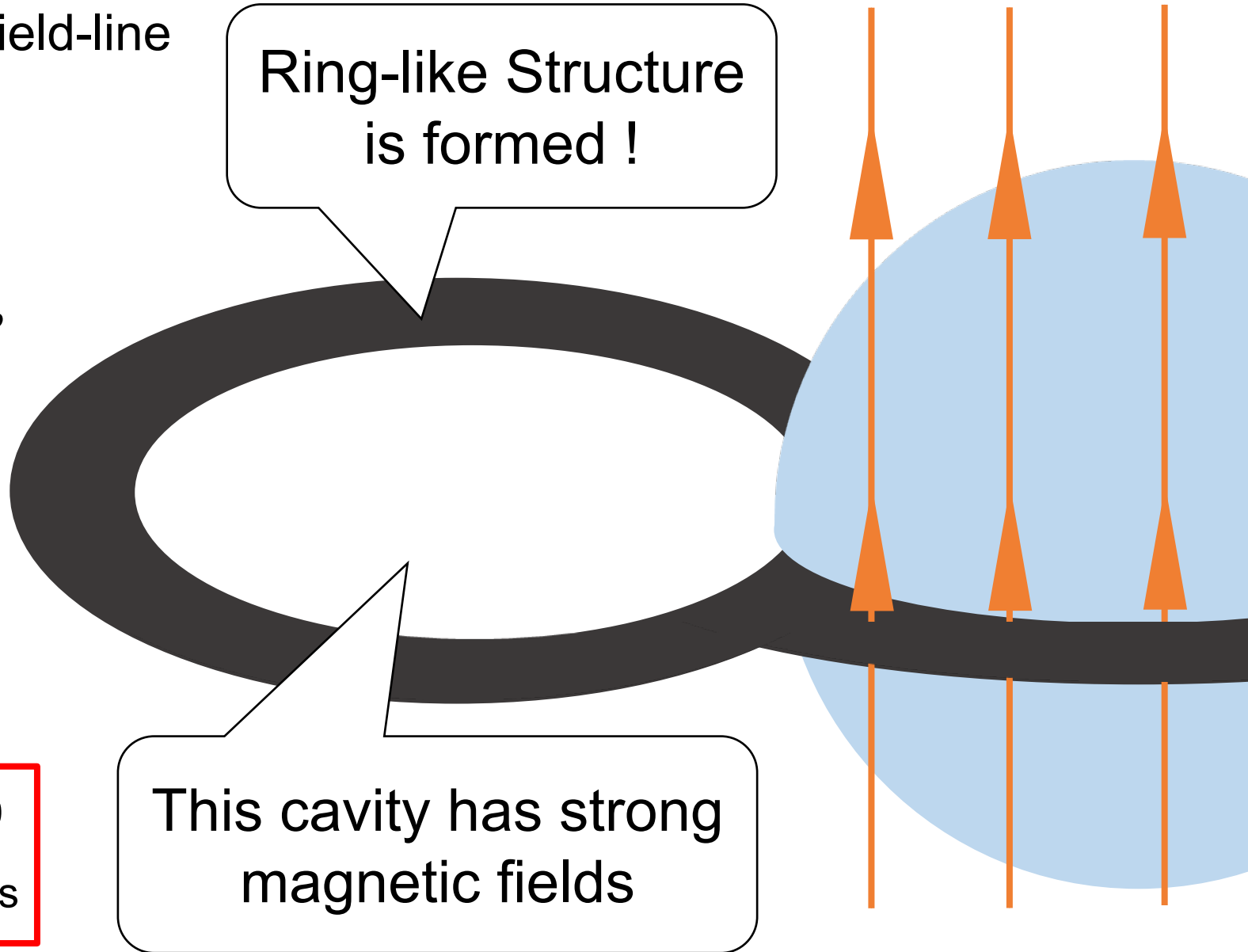


Condition for Interchange : $\nabla \left(\frac{B}{\rho} \right) < 0$
Direction : Gradient of $\frac{B}{\rho}$'s = Gravity's

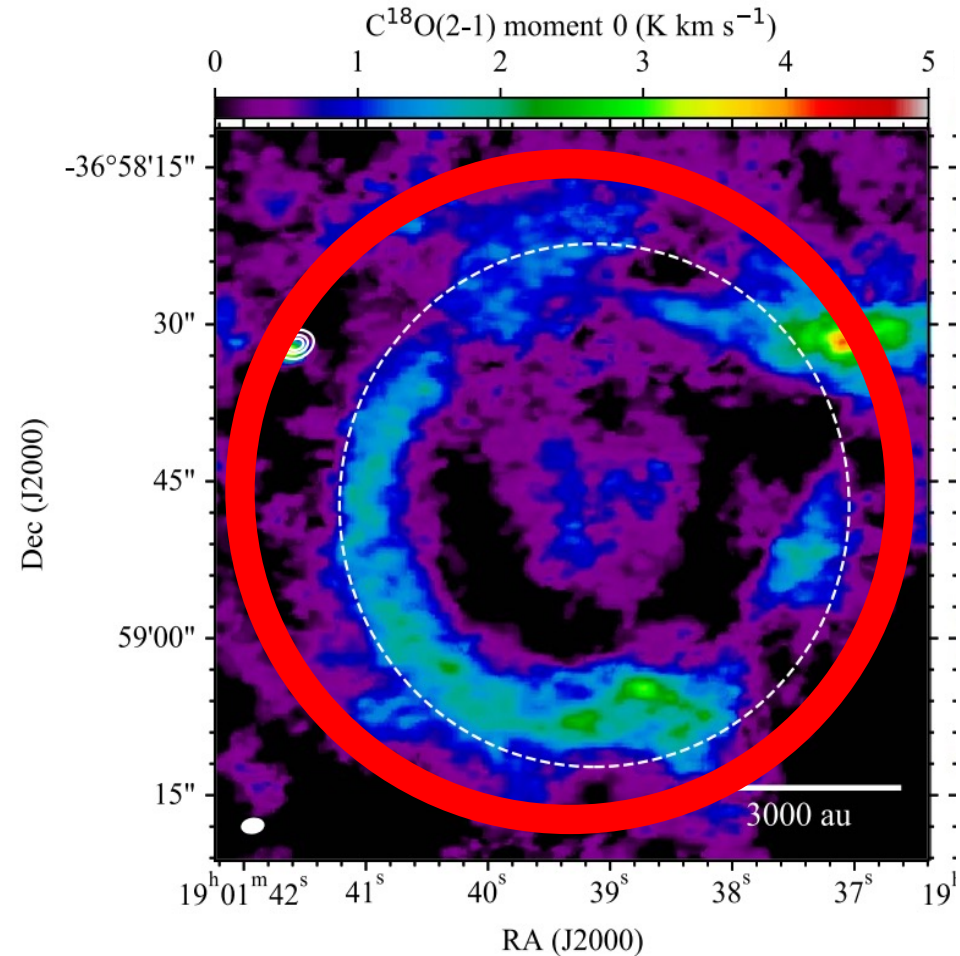
source : Plasma Astrophysics

Ring-like Structure
is formed !

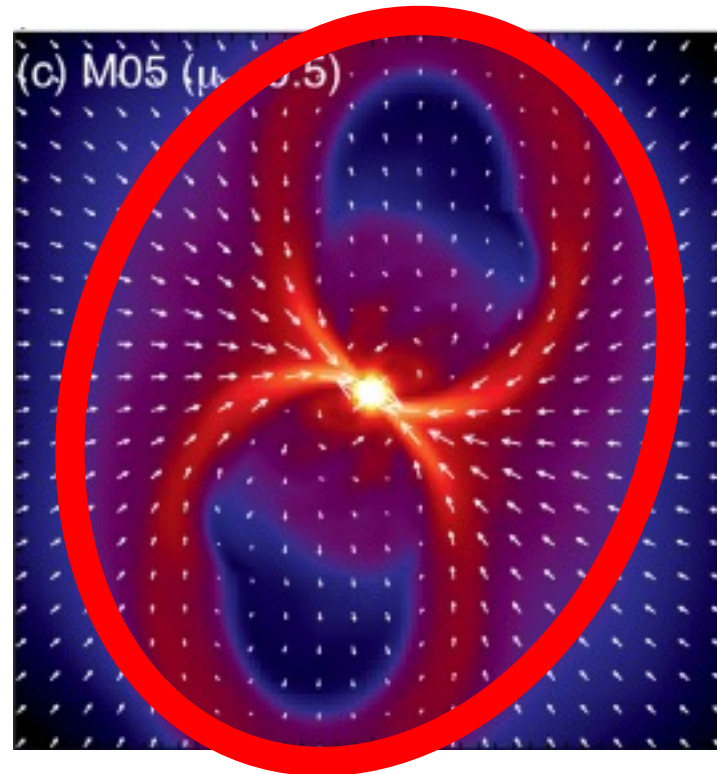
This cavity has strong
magnetic fields



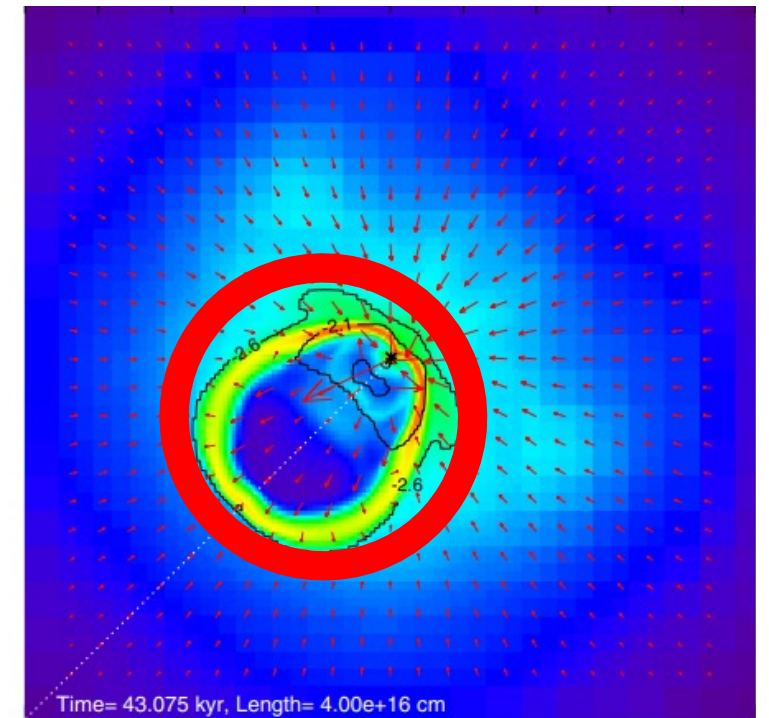
Ring-like structures are observed through both Observations & Simulations in Present day.



Tokuda et al. (2023, 2024)



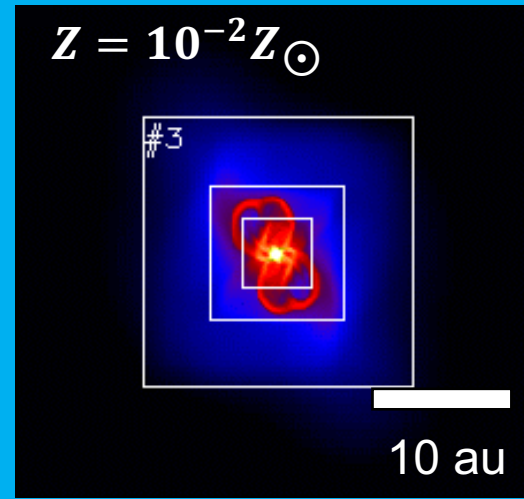
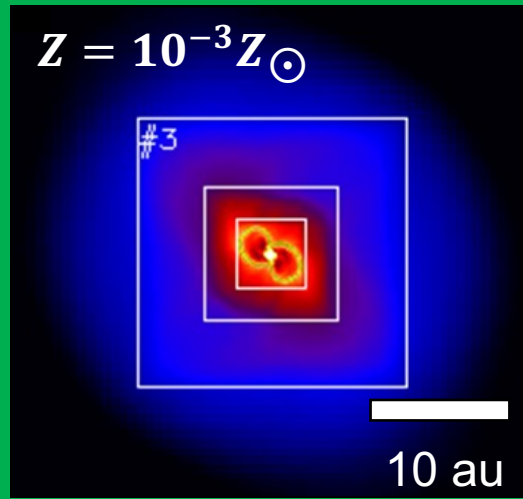
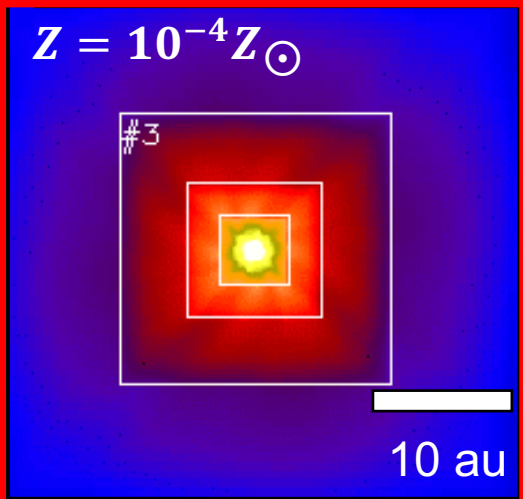
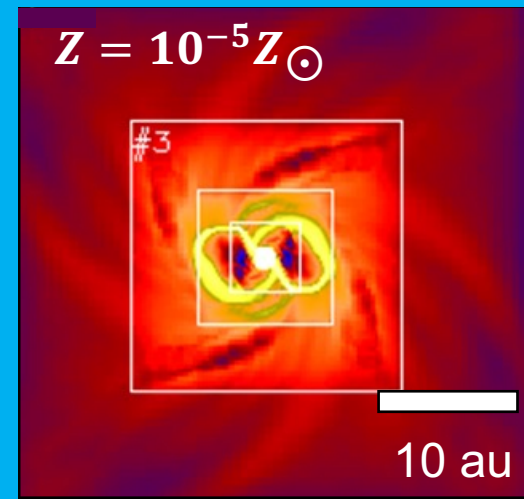
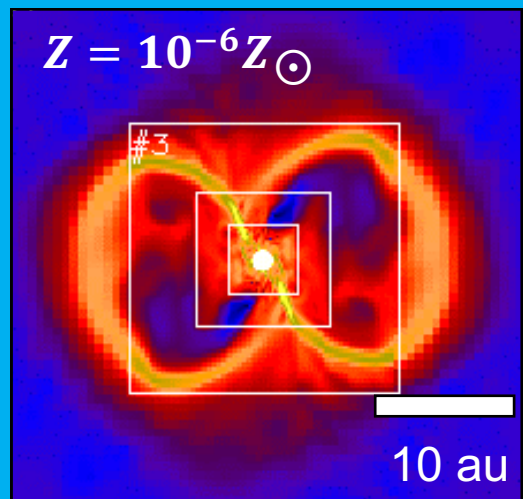
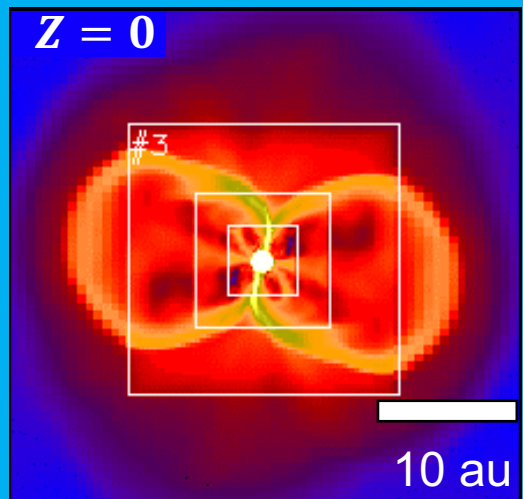
Machida & Basu (2020)



Zhao et al. (2011)

Result : After Star-formation (~ 50 yr)

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- Classified 3 modes by Interchange

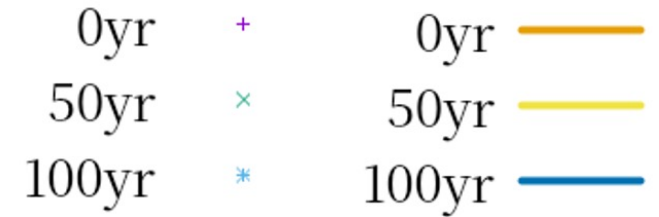
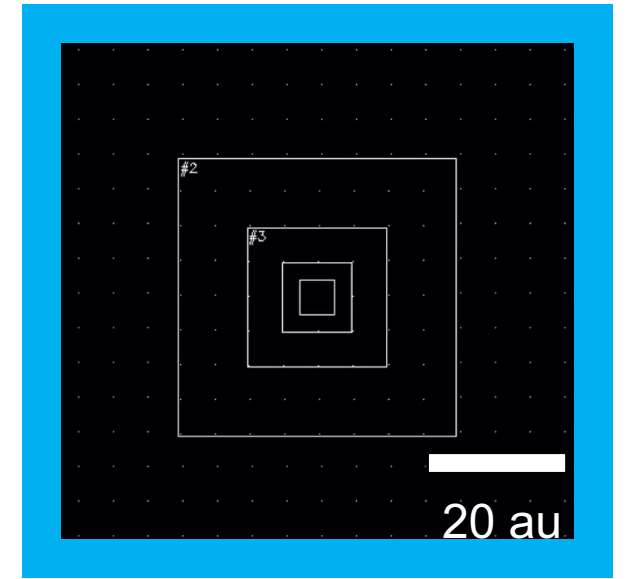
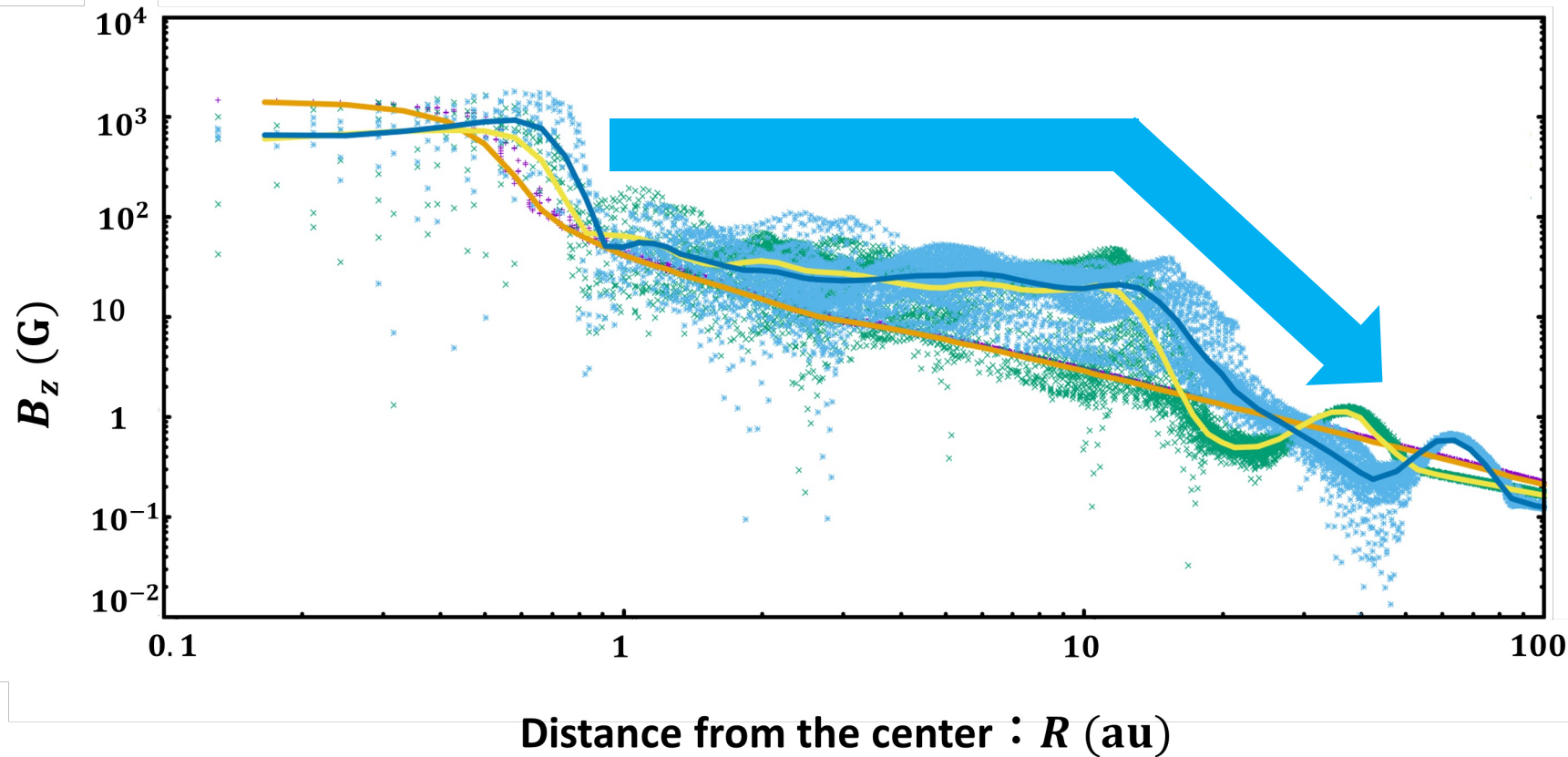
 : Developed

 : Dispersed

 : Undeveloped

Result : Developed ($Z/Z_{\odot} = 10^{-6}$)

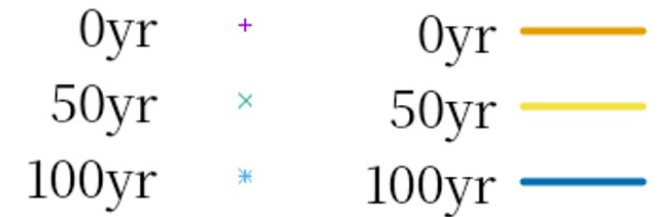
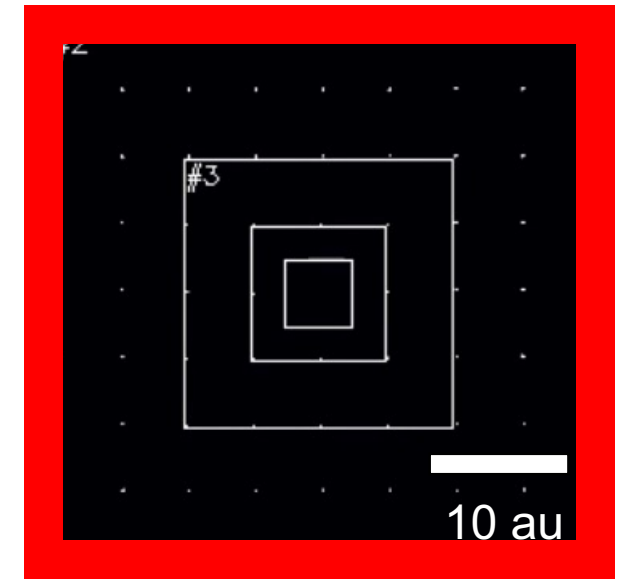
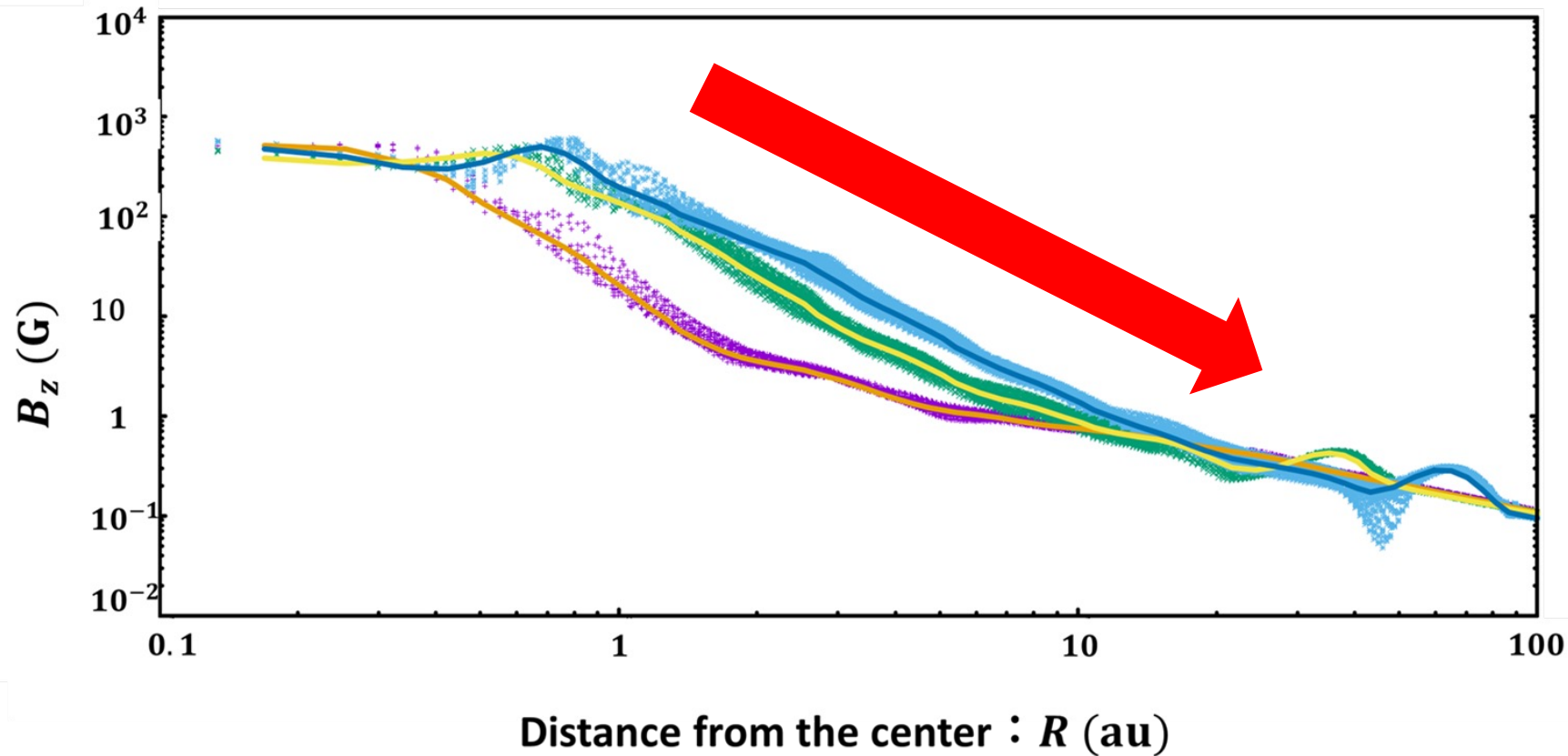
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- B_z in the $z=0$ plane as a function of radial distance R from the center
- In this mode, Interchange guides the outward transport of Magnetic Fields
- Most of model : this mode
→ Interchange-driven magnetic transport dominates in these conditions

Result : Undeveloped ($Z/Z_{\odot} = 10^{-4}$)

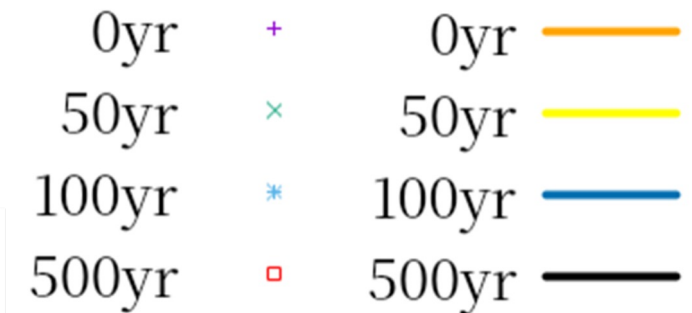
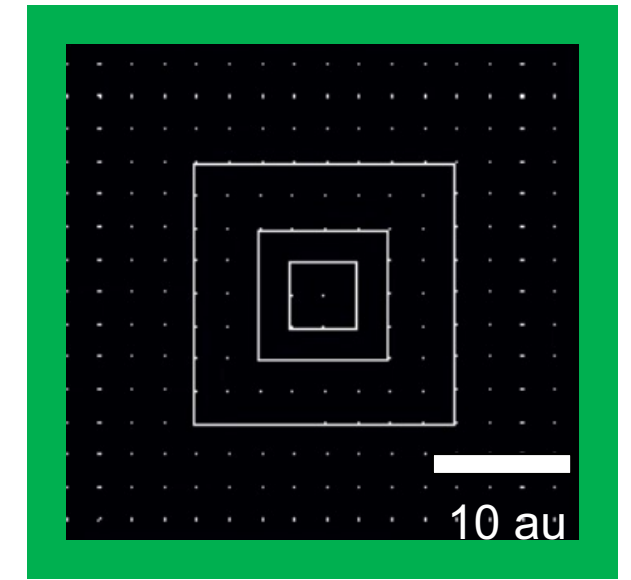
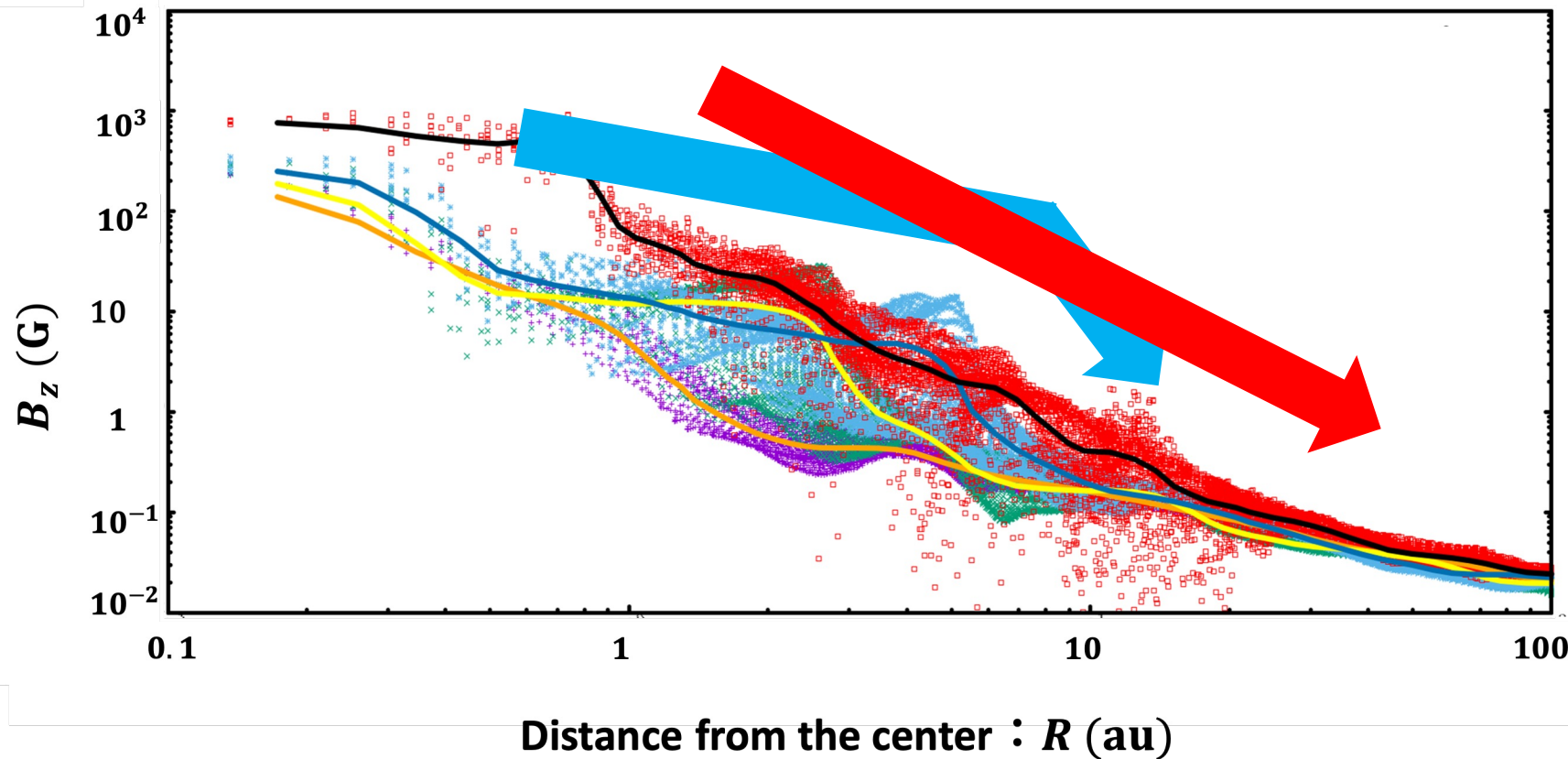
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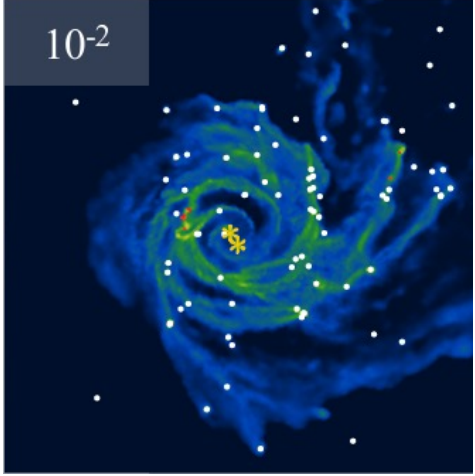
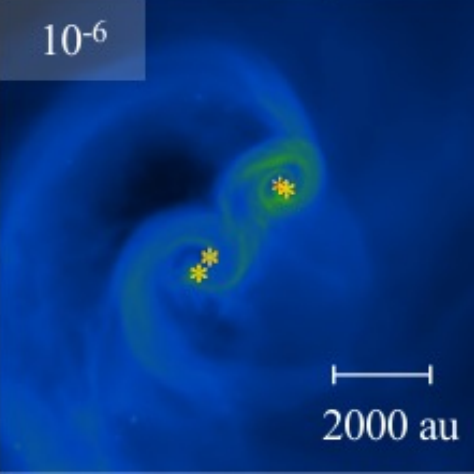
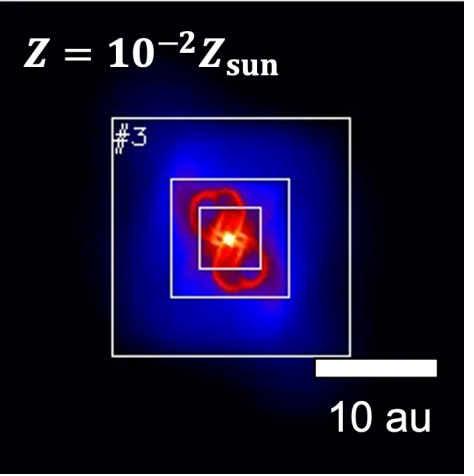
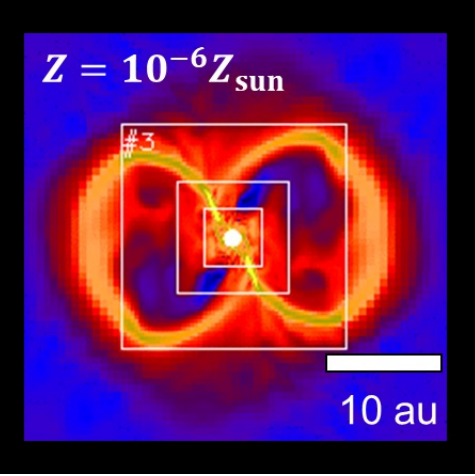
- B_z in the $z=0$ plane as a function of radial distance R from the center
- In this mode, Interchange is undeveloped
→ magnetic field gradient is roughly constant

Result : Dispersed ($Z/Z_{\odot} = 10^{-3}$)

EANAM10



- B_z in the $z=0$ plane as a function of radial distance R from the center
- In this mode, initially behaved like the developed mode, but later changed to resemble the undeveloped mode

	Chon et al. (2021)		Our Research	
Magnetic Fields	No		Include	
Number Density Plot				
Metallicity	$Z/Z_{\odot} = 10^{-2}$	$Z/Z_{\odot} = 10^{-6}$	$Z/Z_{\odot} = 10^{-2}$	$Z/Z_{\odot} = 10^{-6}$

- Strong B-fields suppress fragmentation and disk formation → single star, no or small disk
- Interchange leads to complex structures
- Simulated only up to ~1000 yr → fragmentation still possible
→ Longer-term simulations needed!

Conclusion

- First successful 3D Non-Ideal MHD simulations for late-stage star formation in Strong magnetic field & Low metallicities environments.
- All models become single star with no or, small disk.
- Except for the model of $Z/Z_{\odot} = 10^{-4}$, Interchange confirmed in low-metallicity star formation.
- Interchange plays a key role in outward Magnetic field Transport under our initial conditions.
- Simulated only up to ~ 1000 yr \rightarrow Longer-term simulations needed!

Future Work

- Next, I plan to test weaker Magnetic fields.
- I try to make term of simulation longer.